Recent Results from the IceCube Neutrino Observatory and Potential for the Next Decade of Neutrino Astronomy

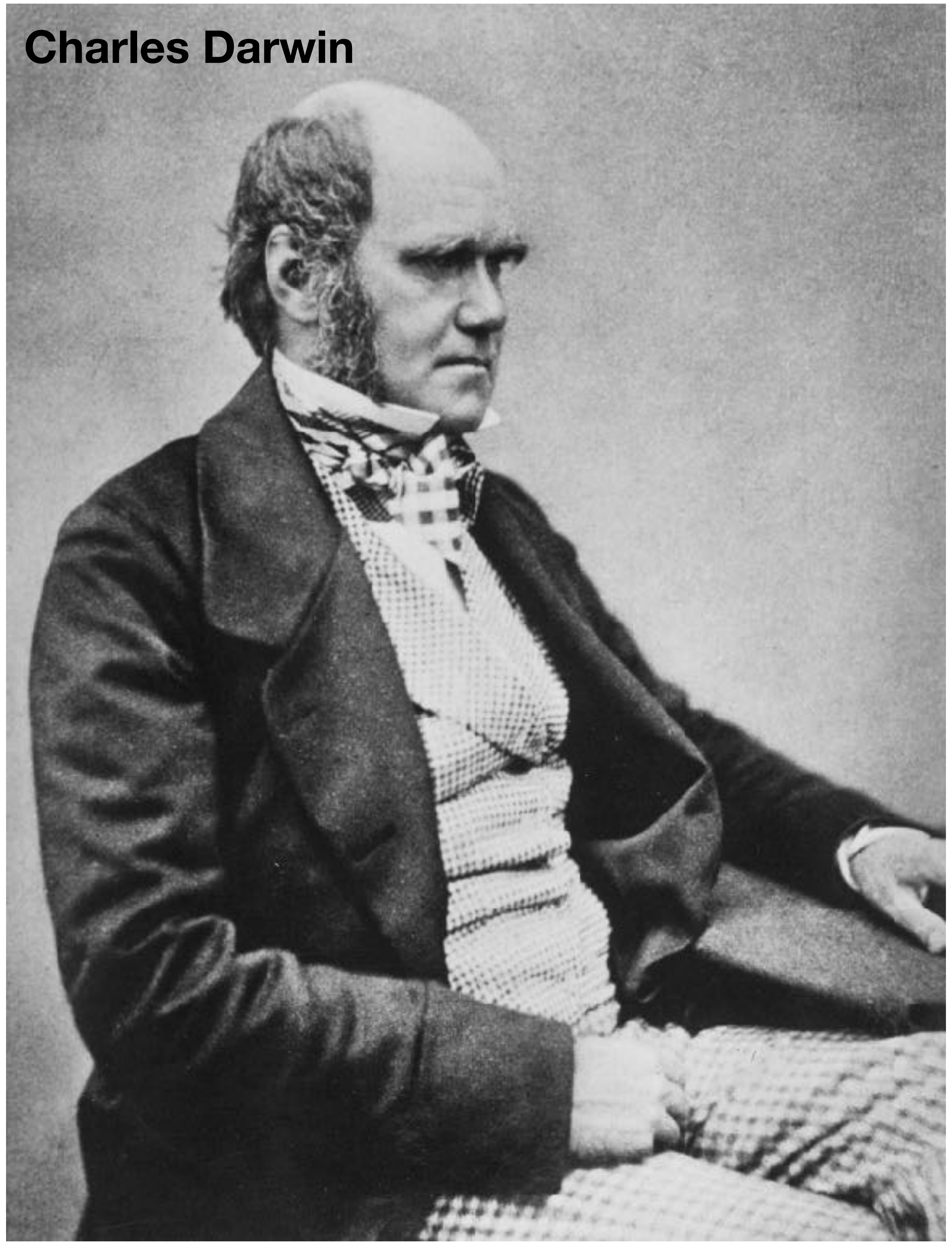
Jeff Lazar

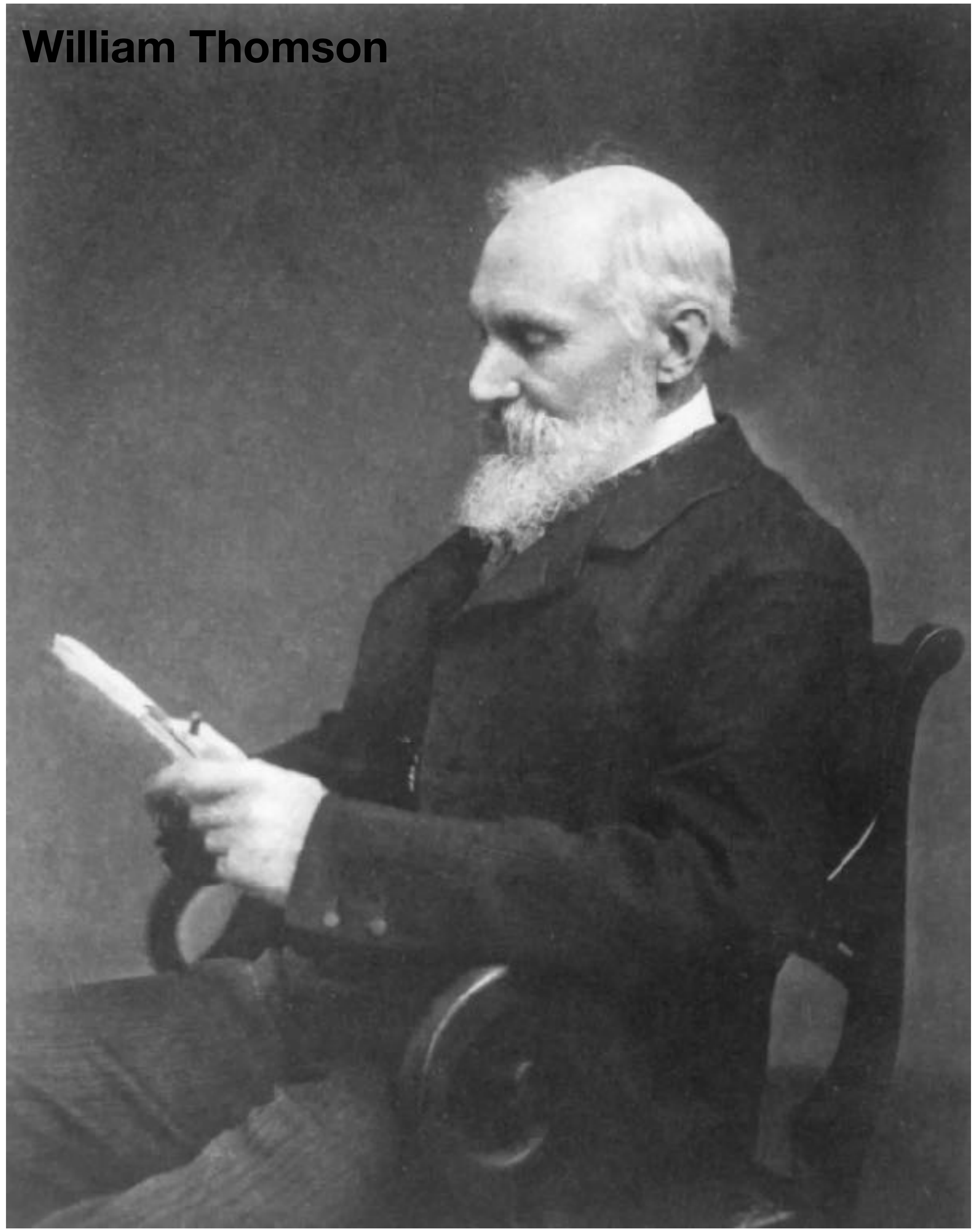
CERN EP Seminar

Geneva, Switzerland

27 Feb., 2024

How Does the Sun Shine ?





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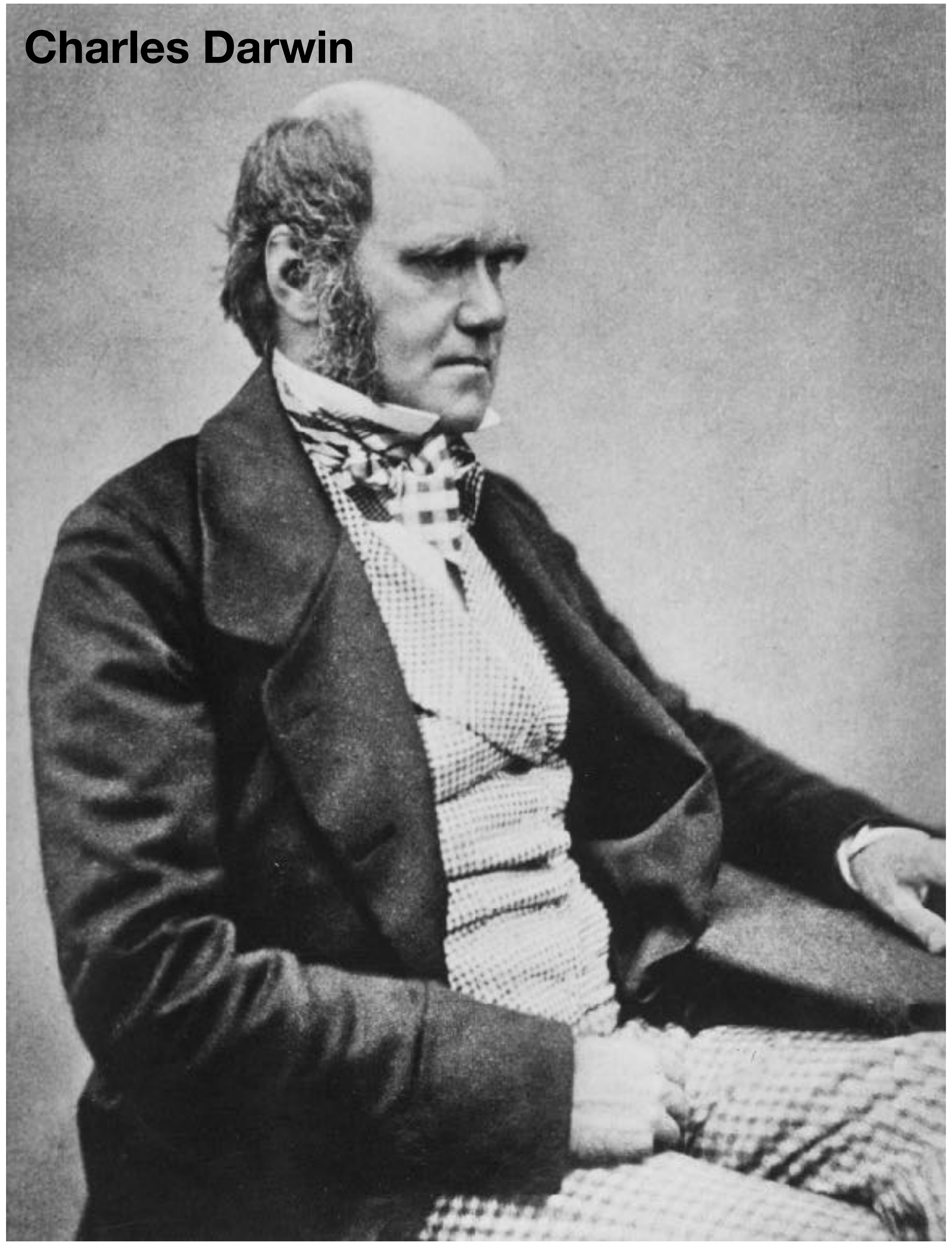
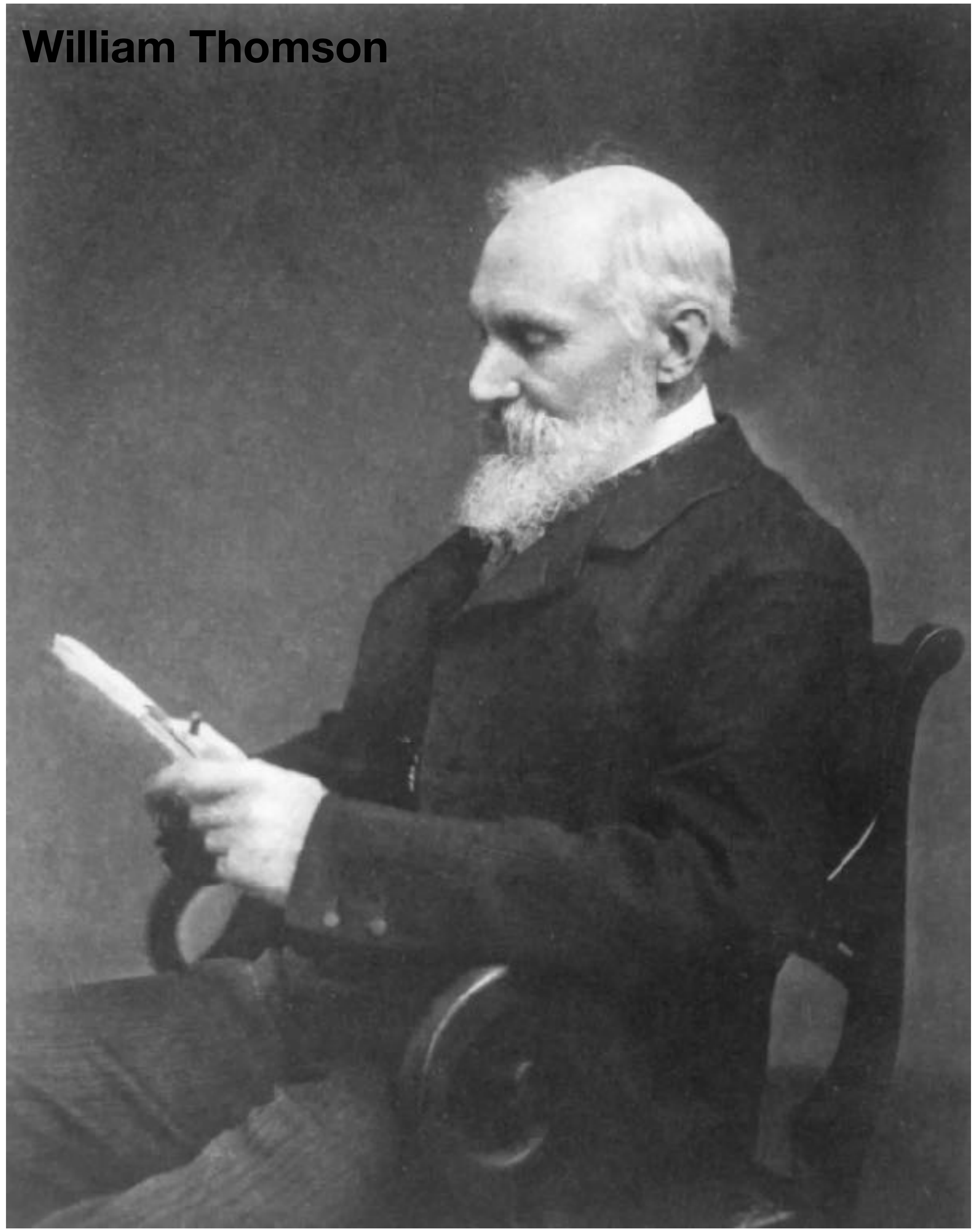


The Earth would need to exist for 300,000,000 years to give rise to the diversity of species I've observe. My observations of erosion in the Weald seem to support such a timeline.



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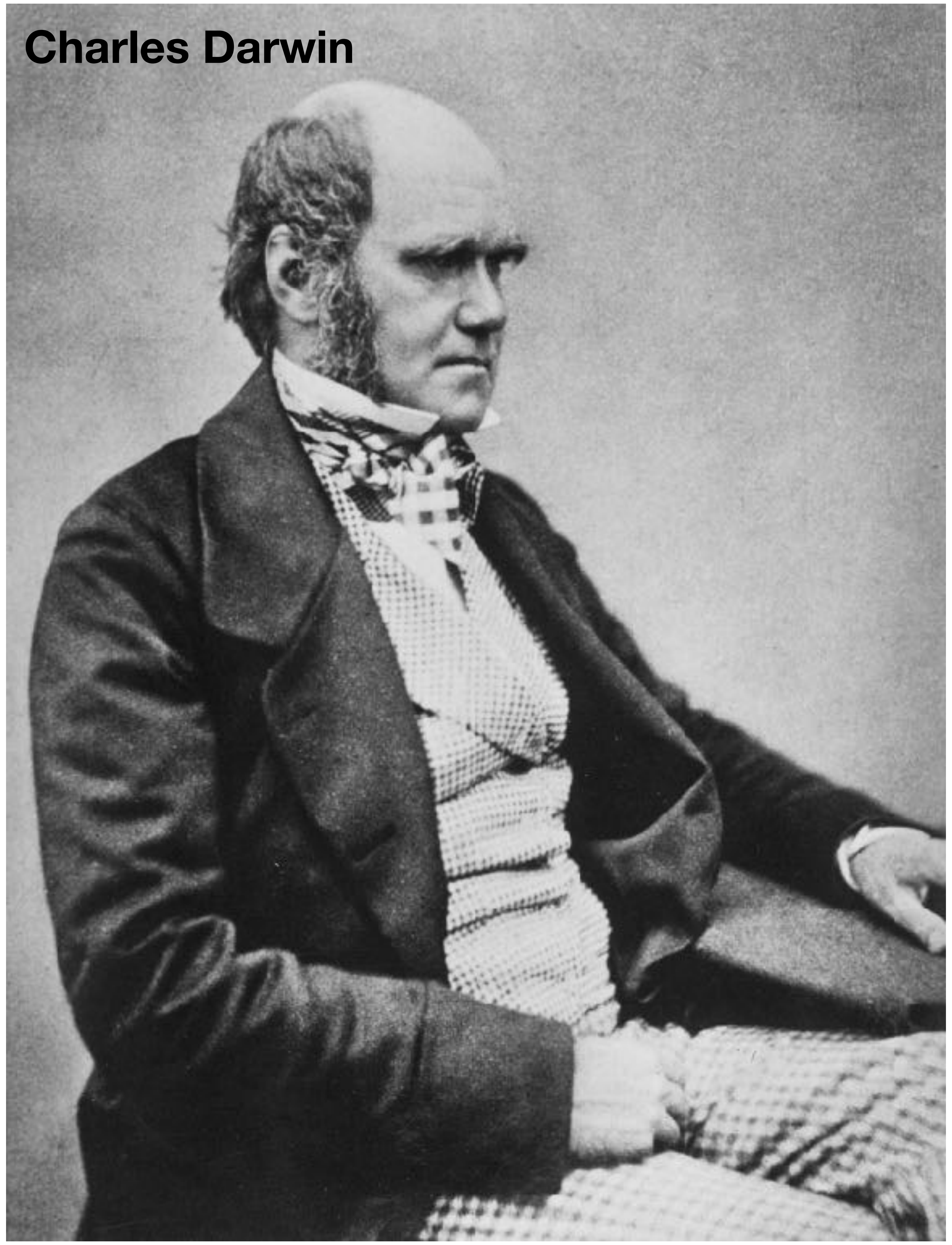

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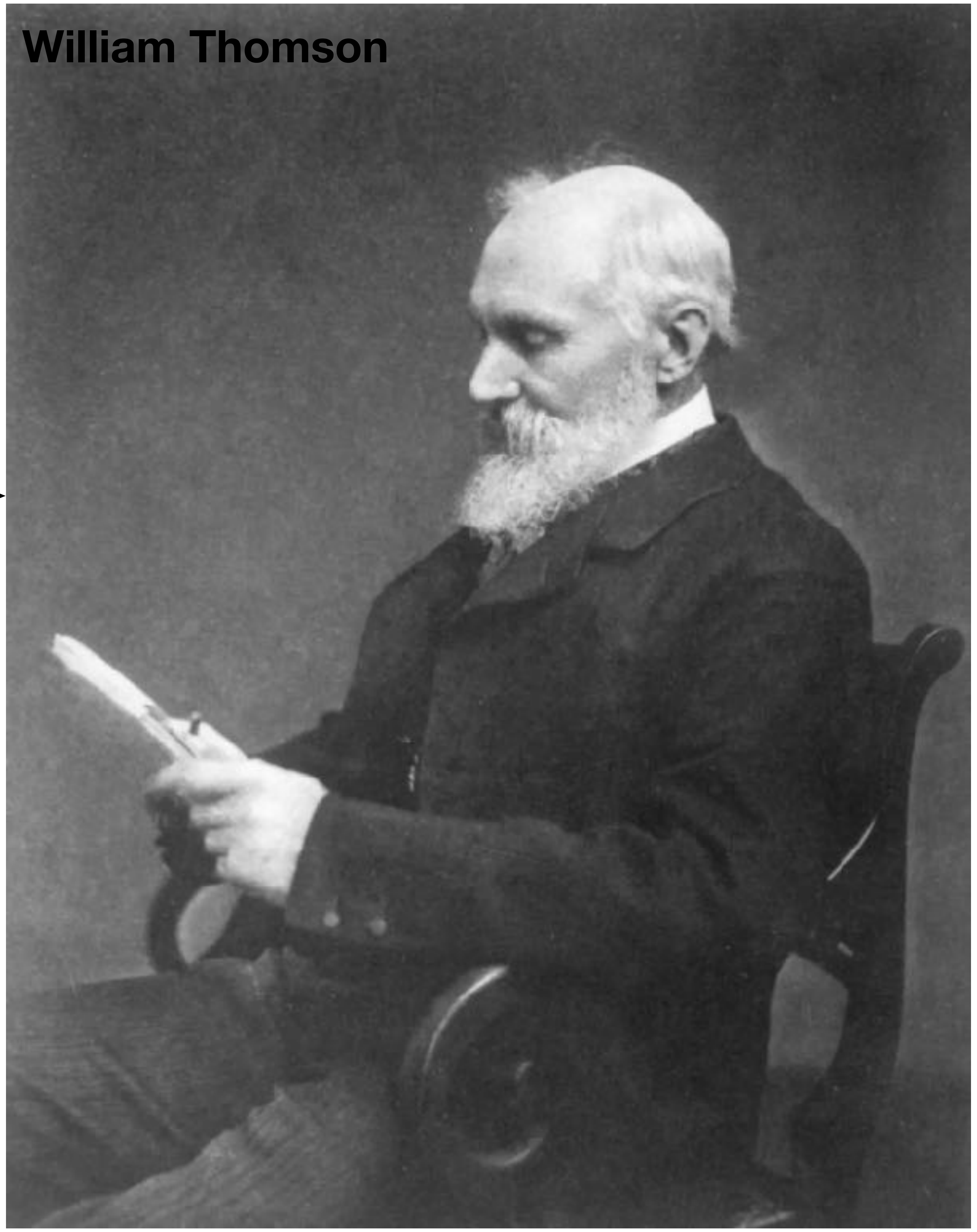
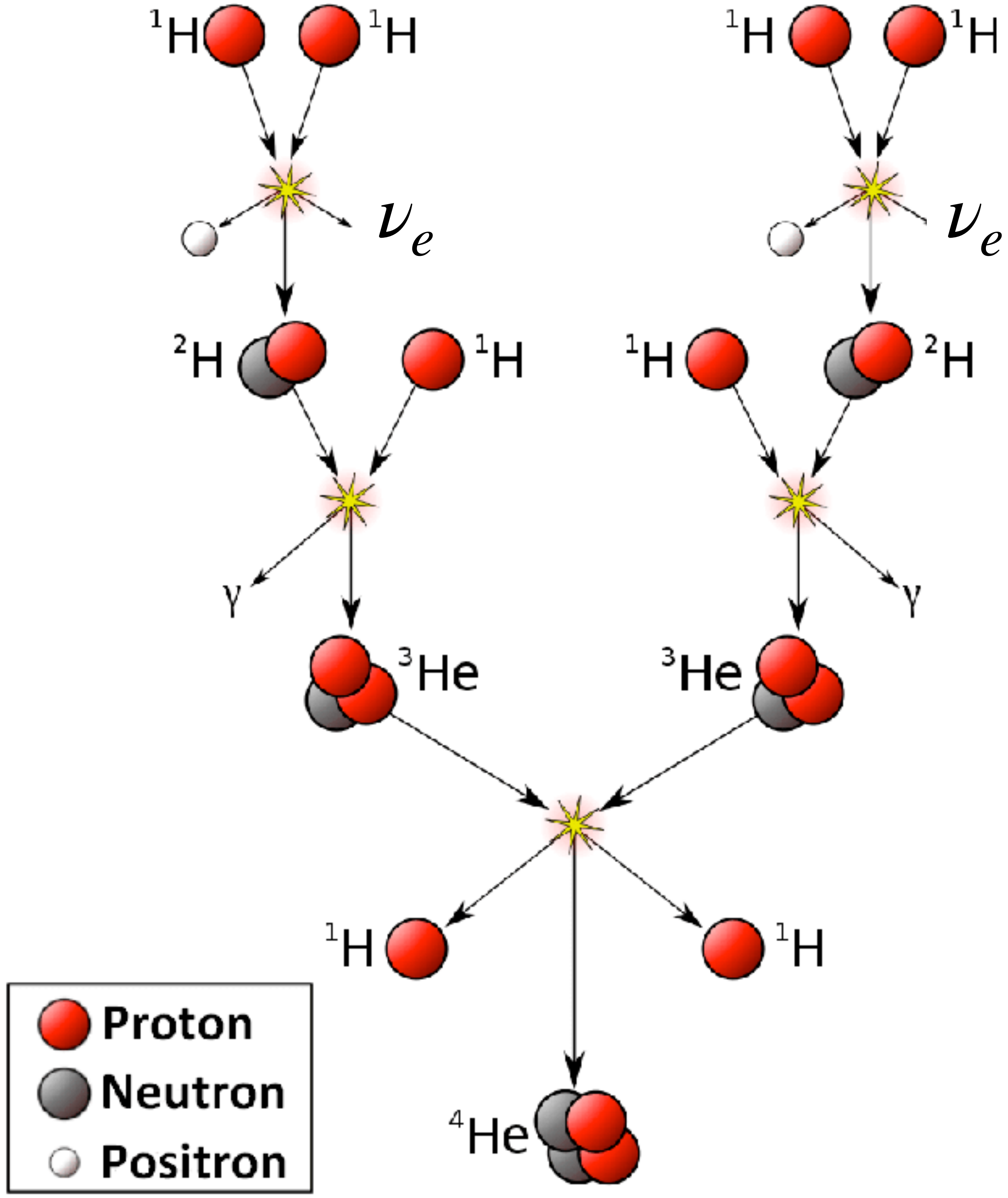
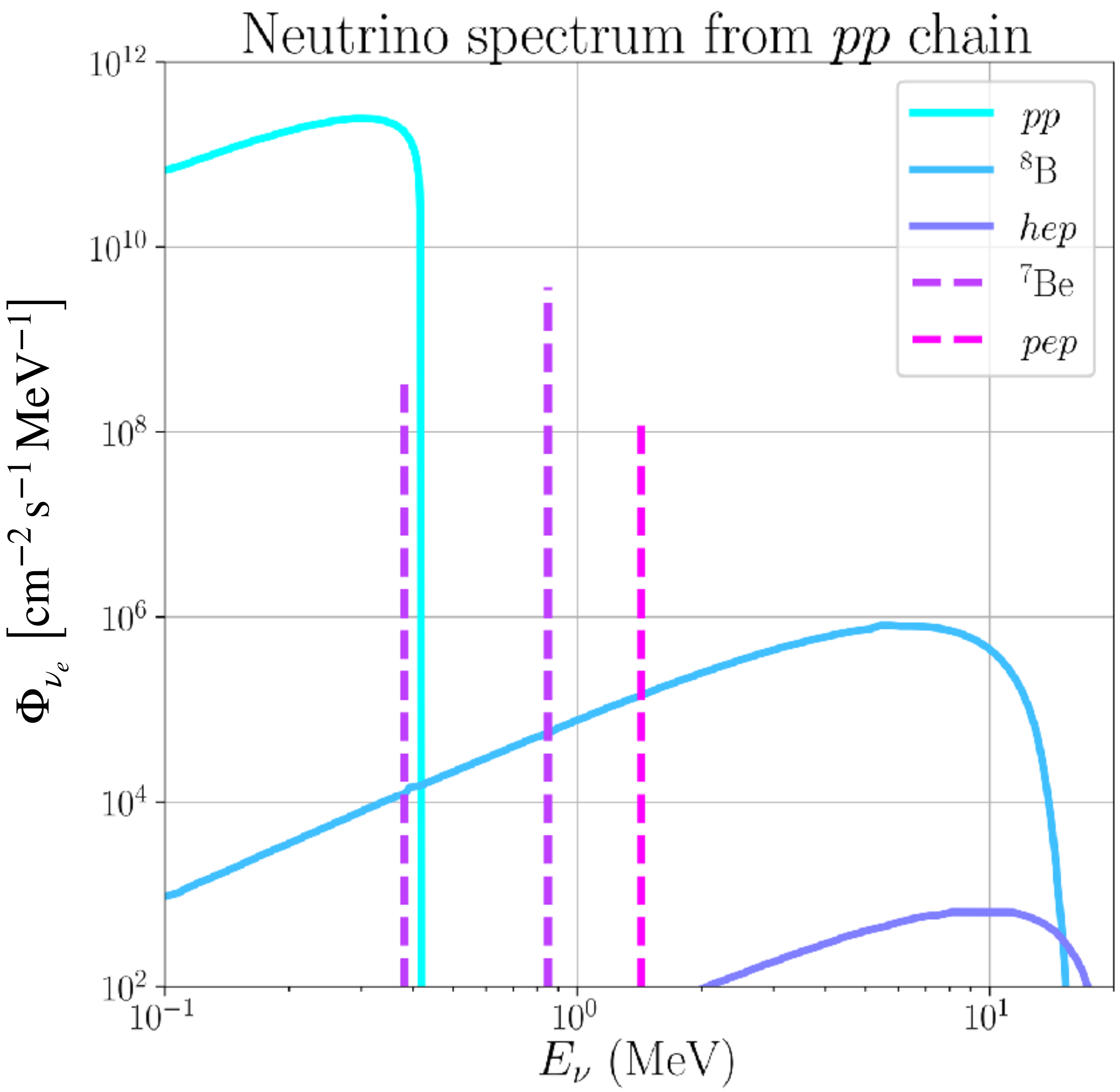
This can't be ! Chemical processes could only power the Sun for 30,000 years and gravitational processes are still well-short.



How Does the Sun Shine ?

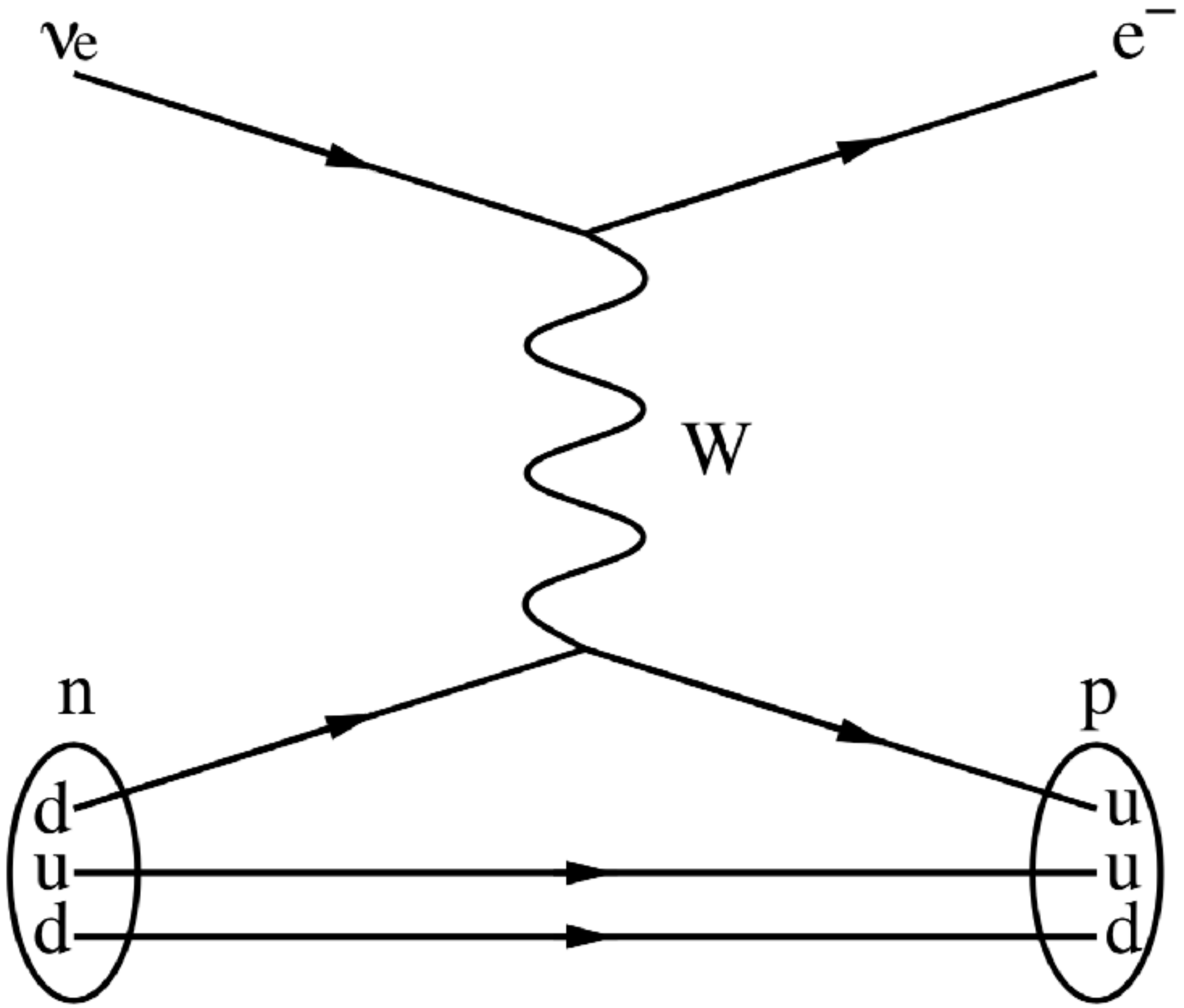
If the Sun generates energy from nuclear fusion, it will emit ***electron*** neutrinos

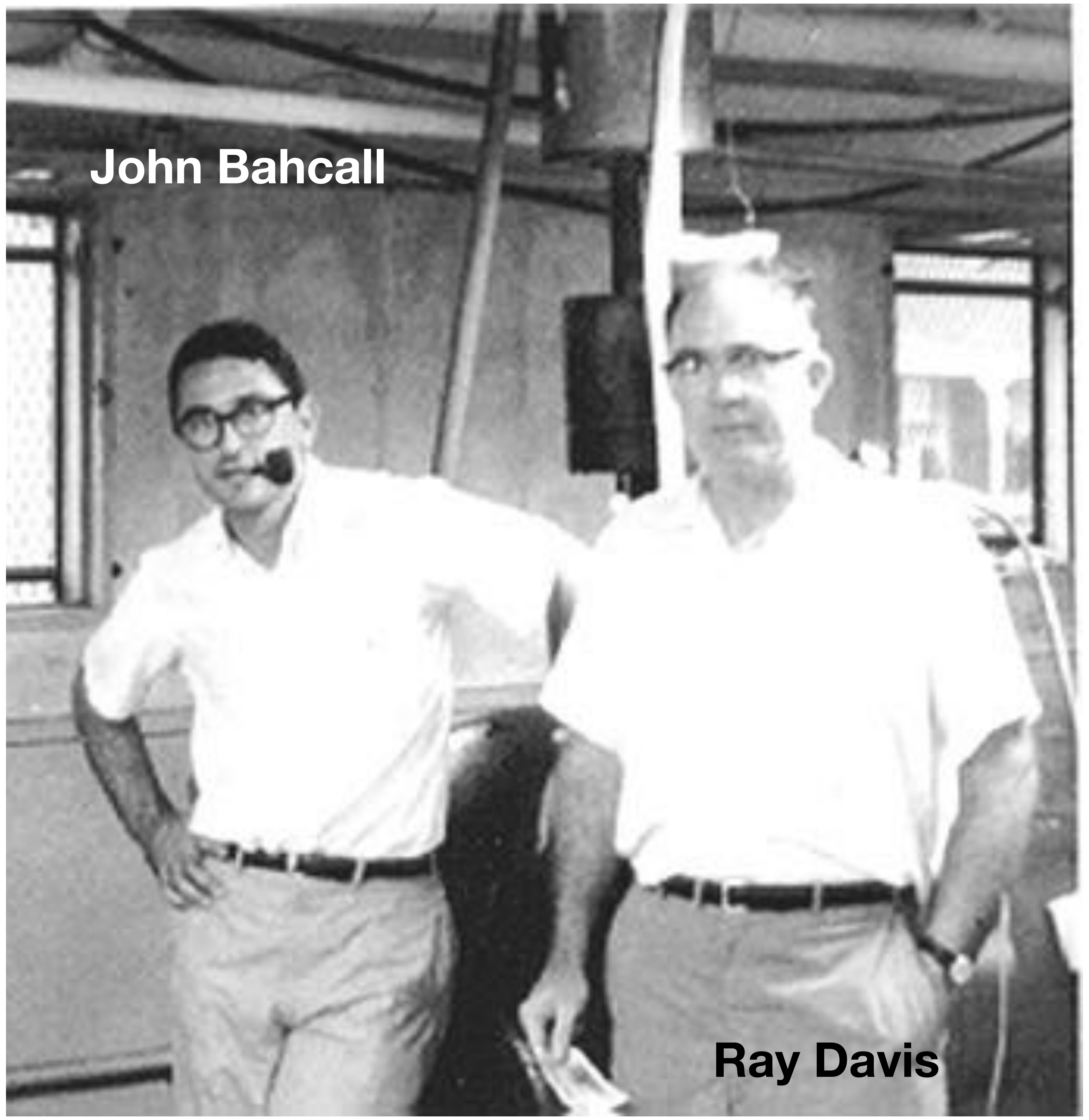




Staring into the Sun

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





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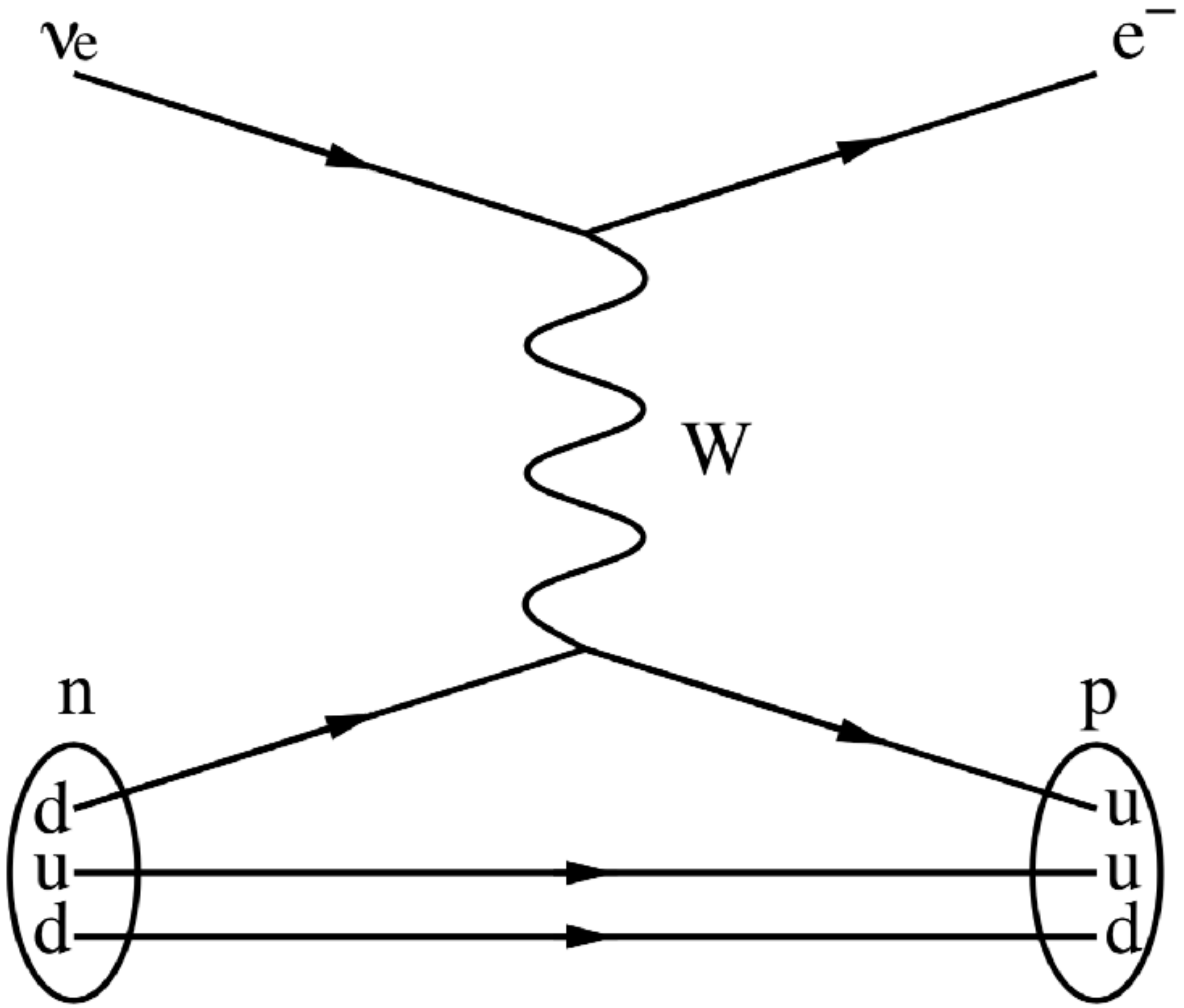
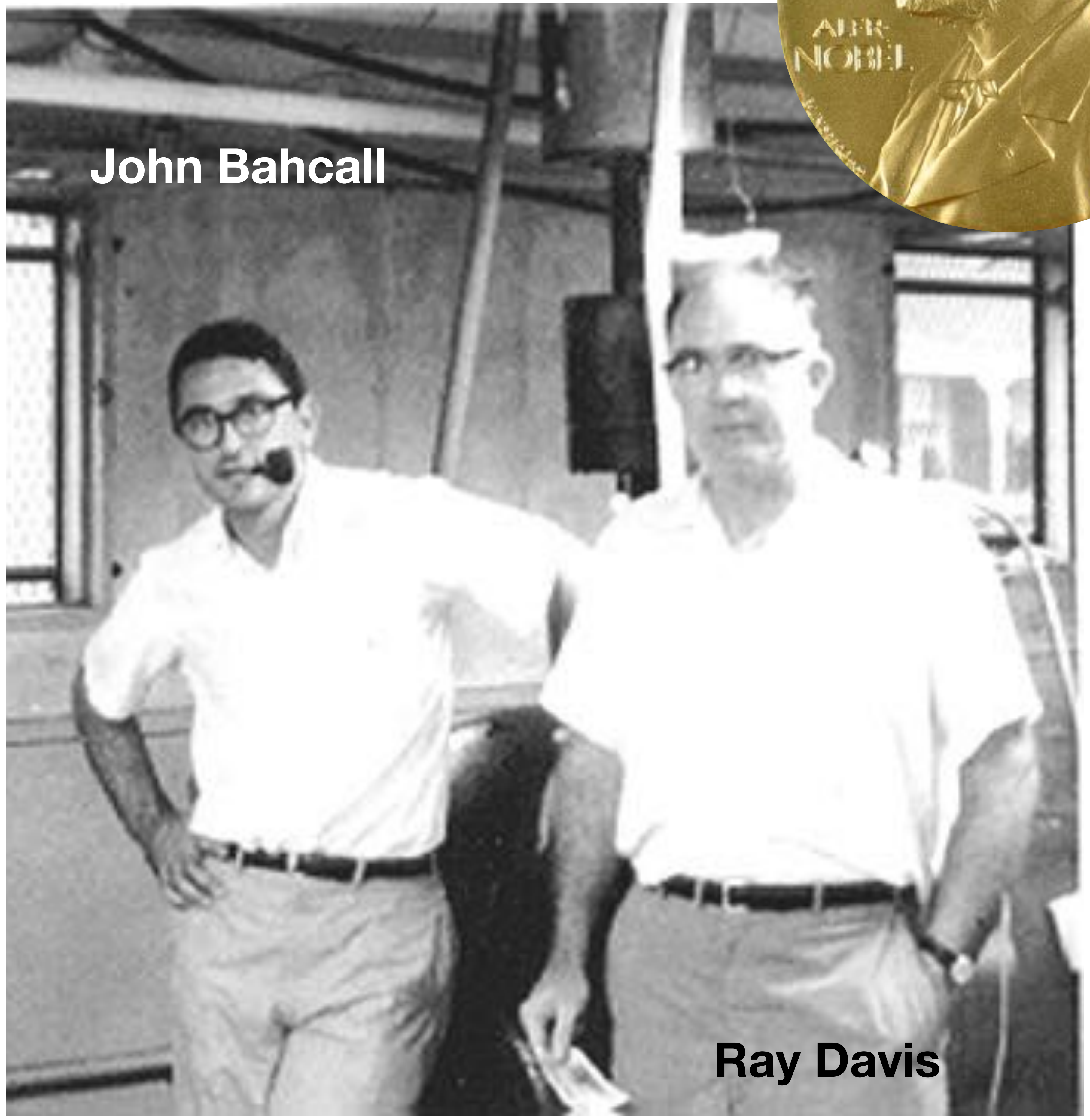
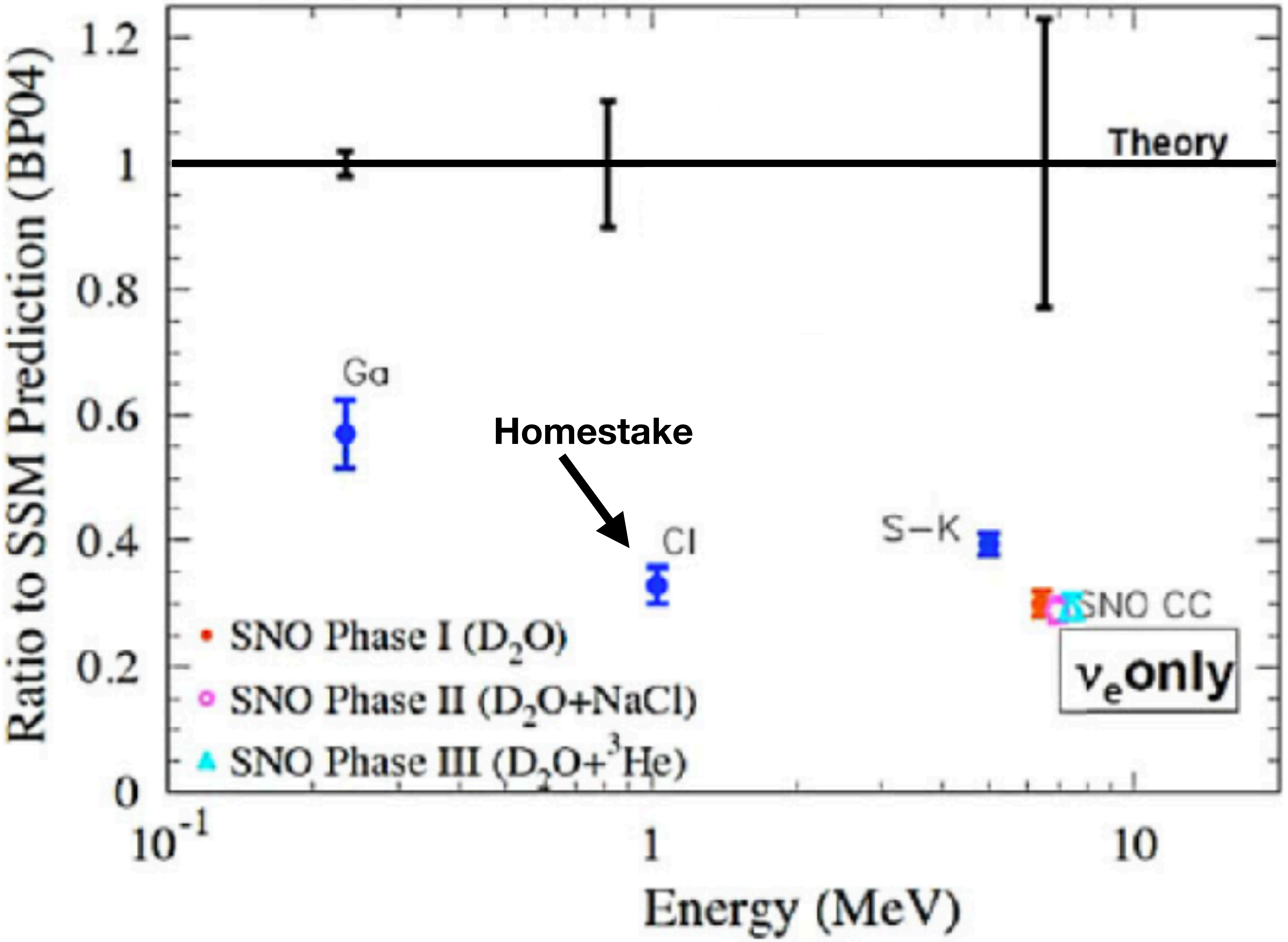




The Solar Neutrino Problem

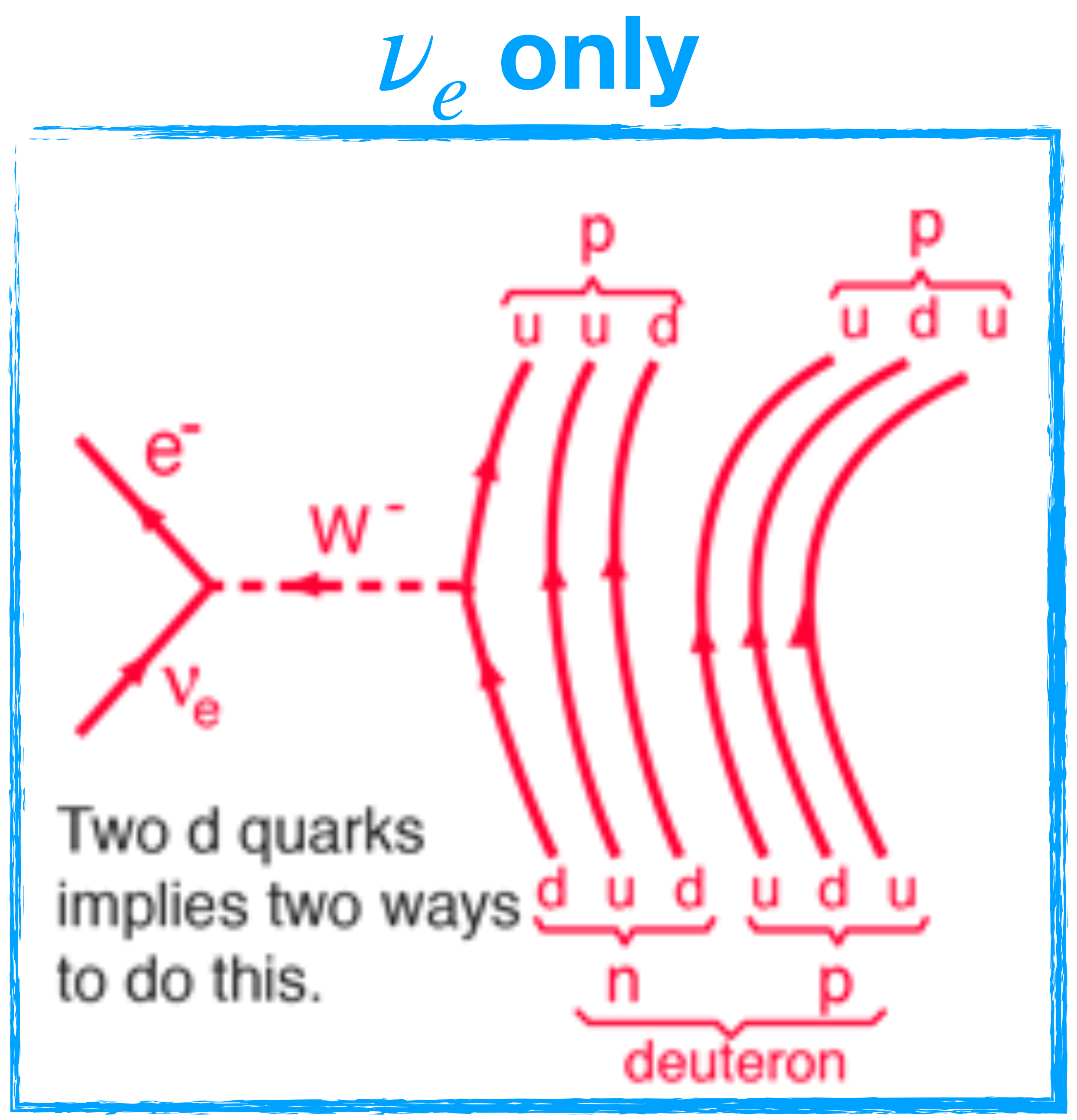
- Flux measured by Homestake was in bad agreement with SSM prediction
- Many experiments continued to prod at this discrepancy, while theory is honed
- Discrepancy persisted

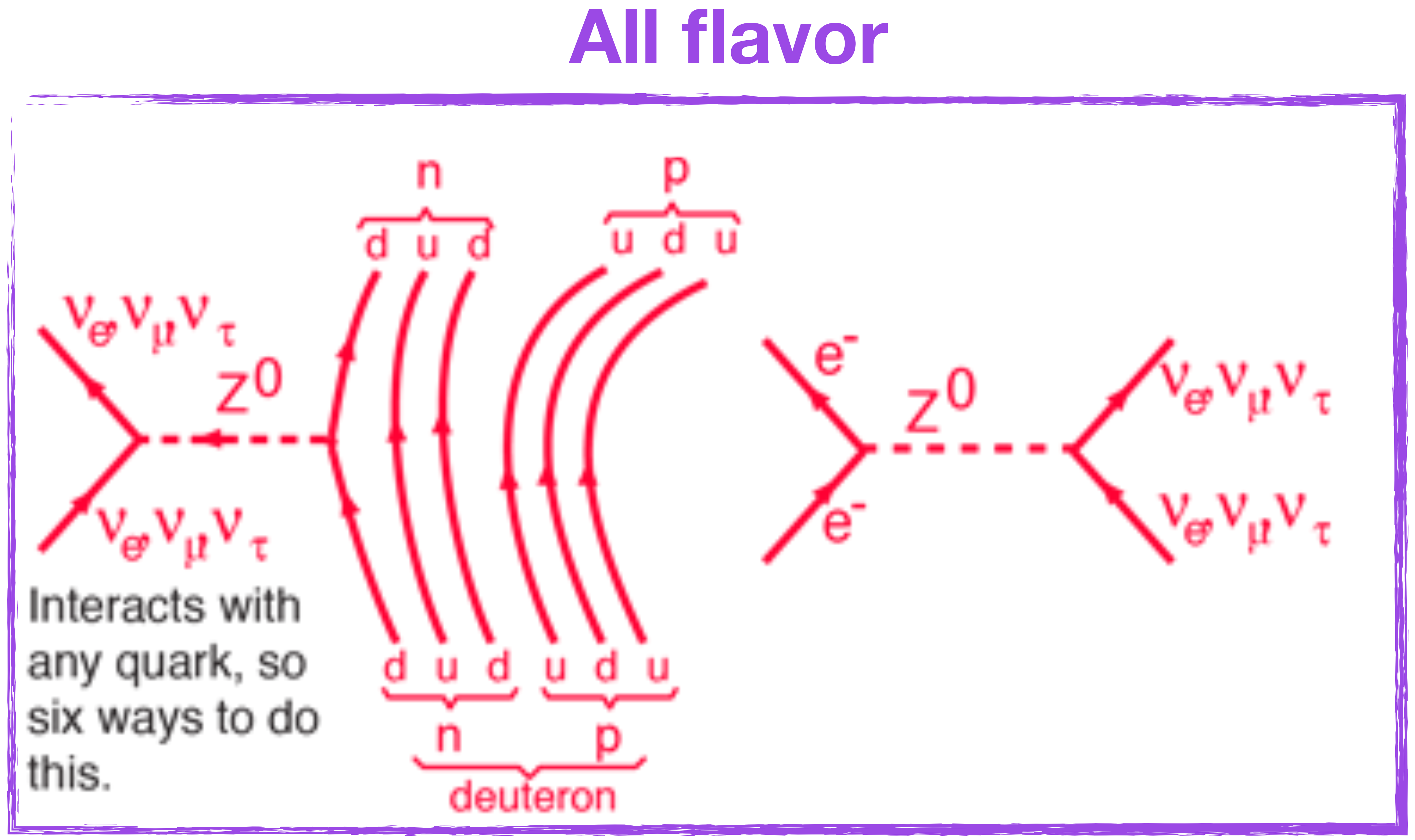


A. McDonald. doi:10.1002/201600031

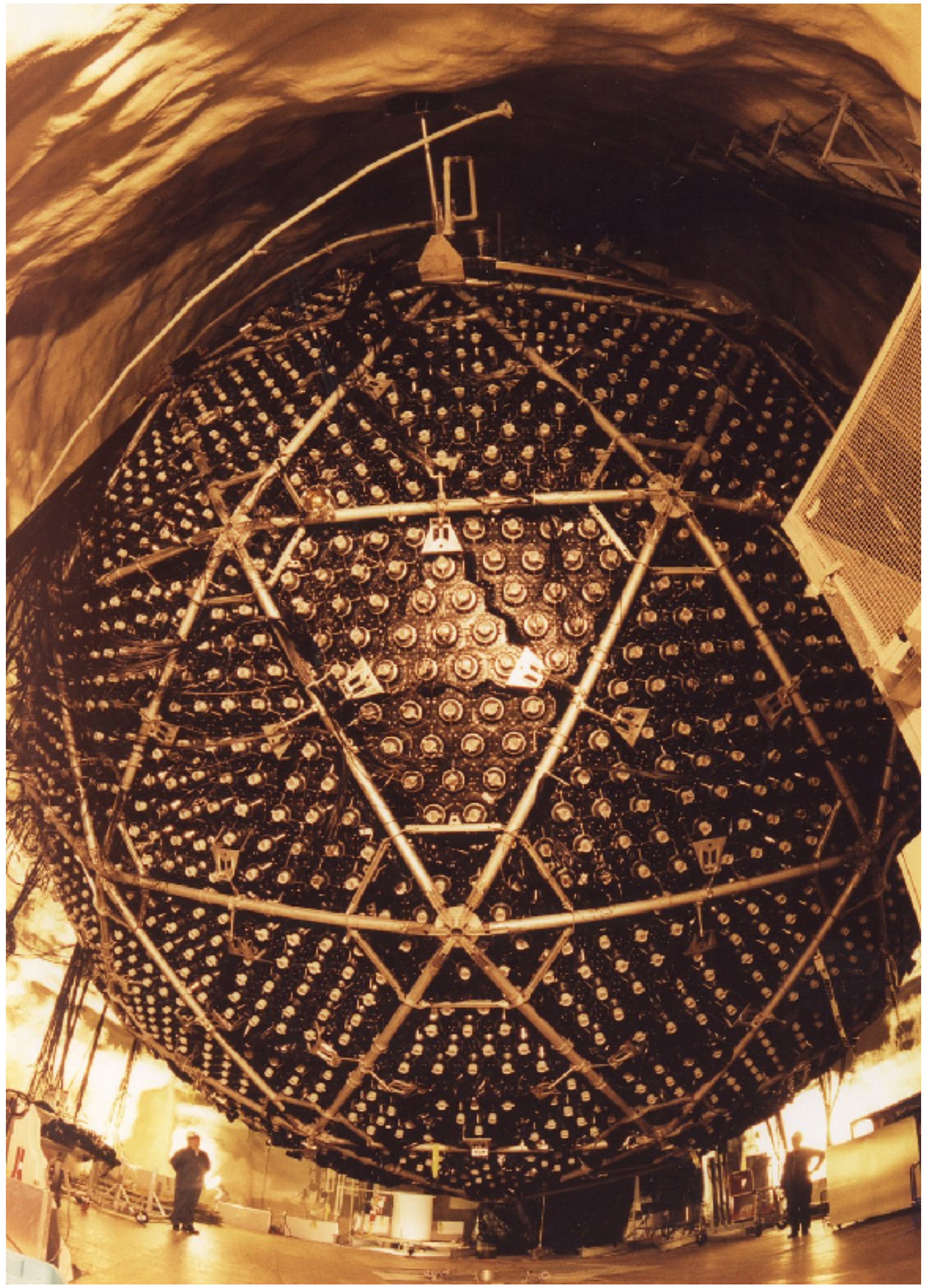
Looking at New Flavors

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





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



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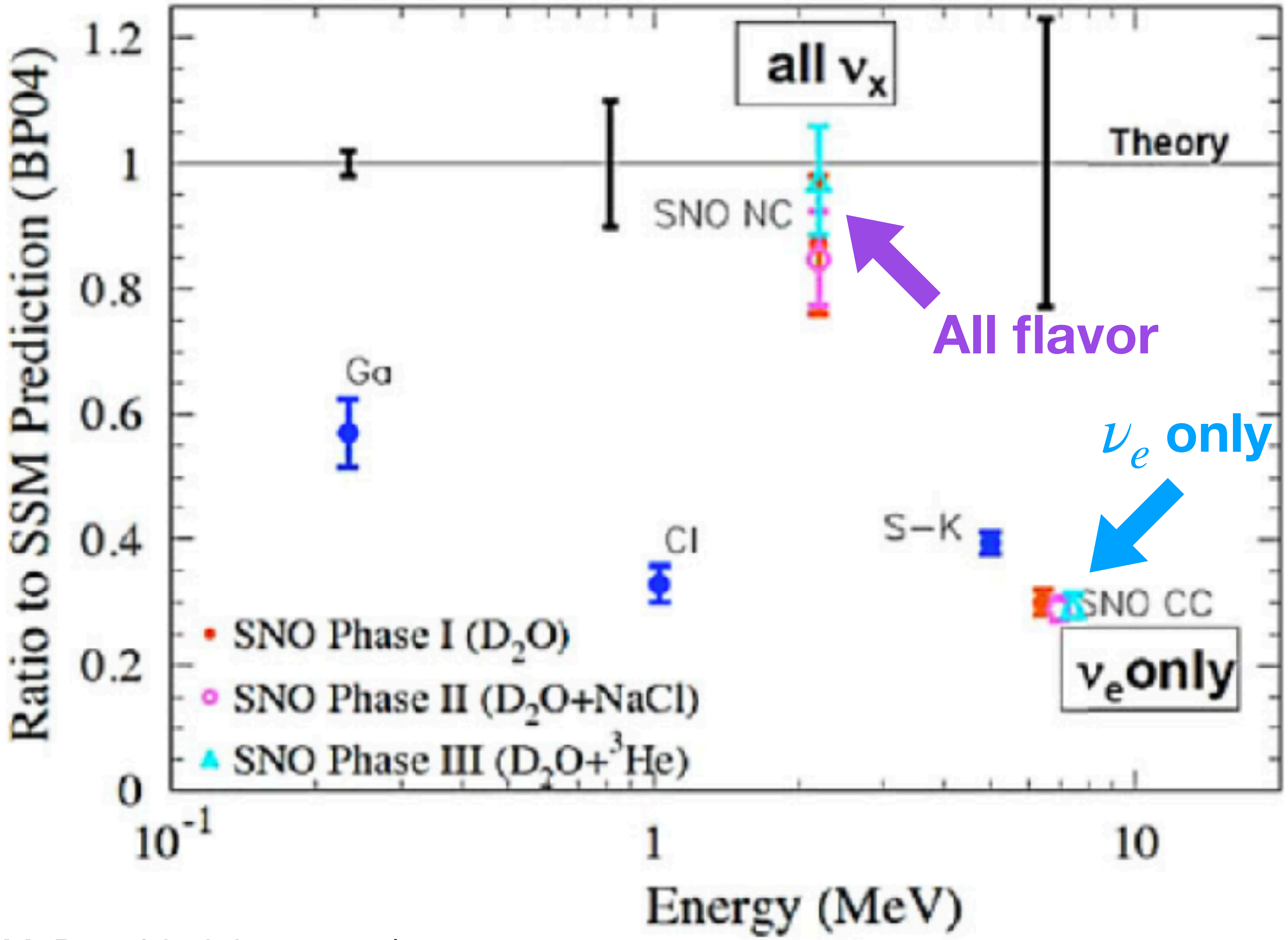

- Discrepancy observed in electron-only measurement
- All flavor measurement in agreement with theoretical predictions

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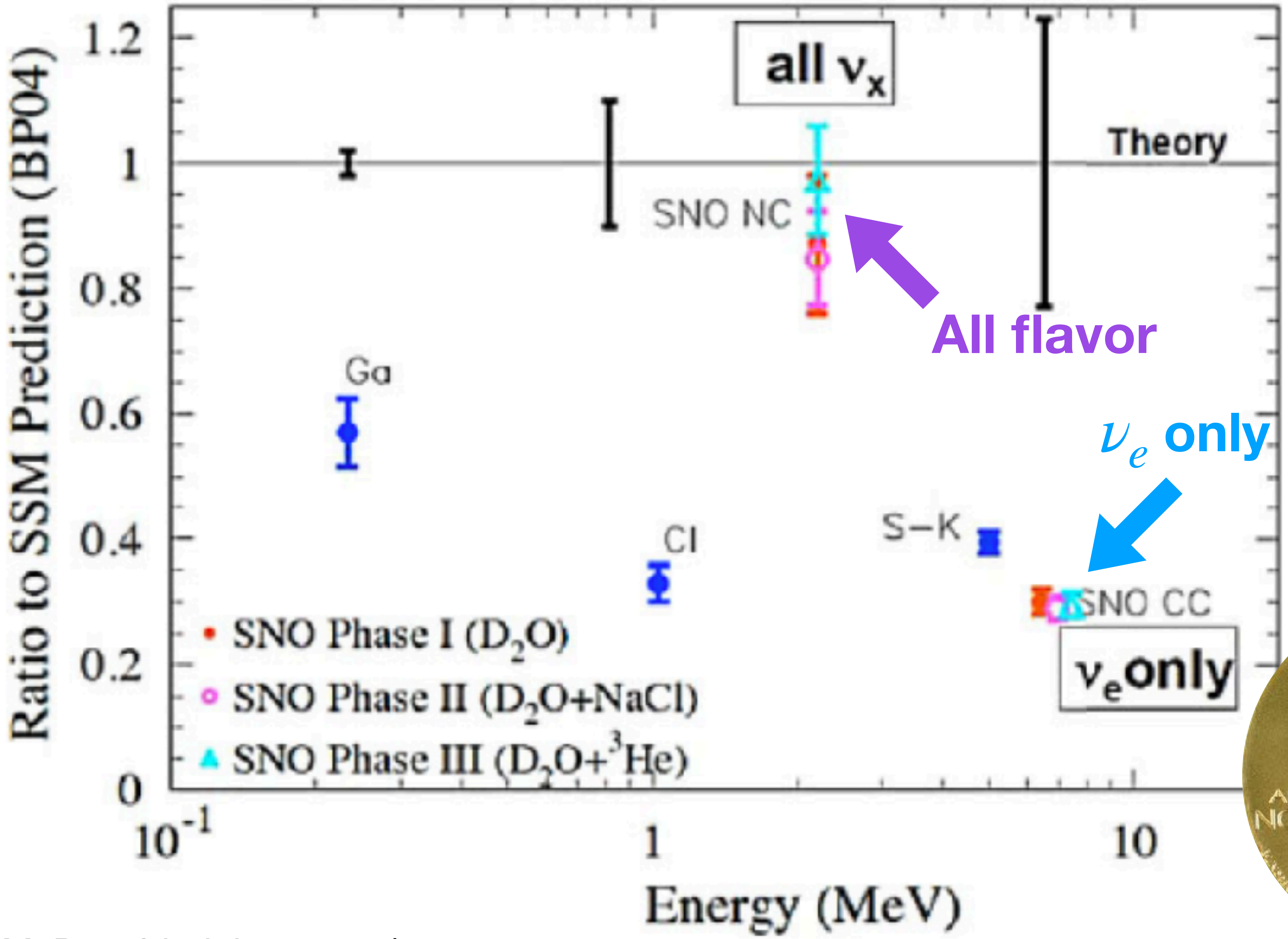

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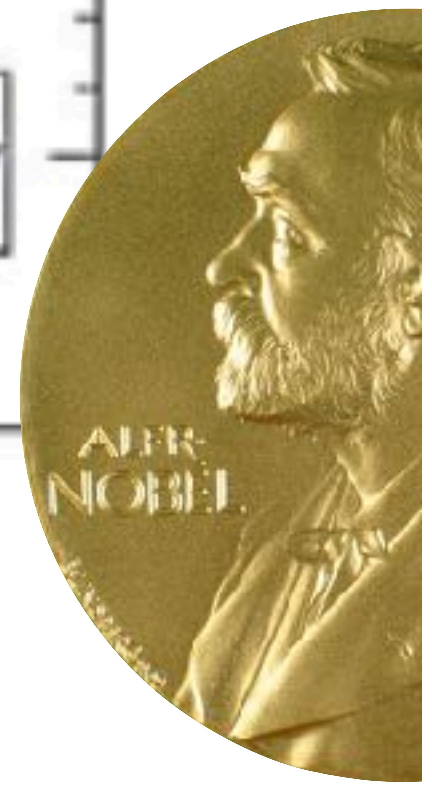

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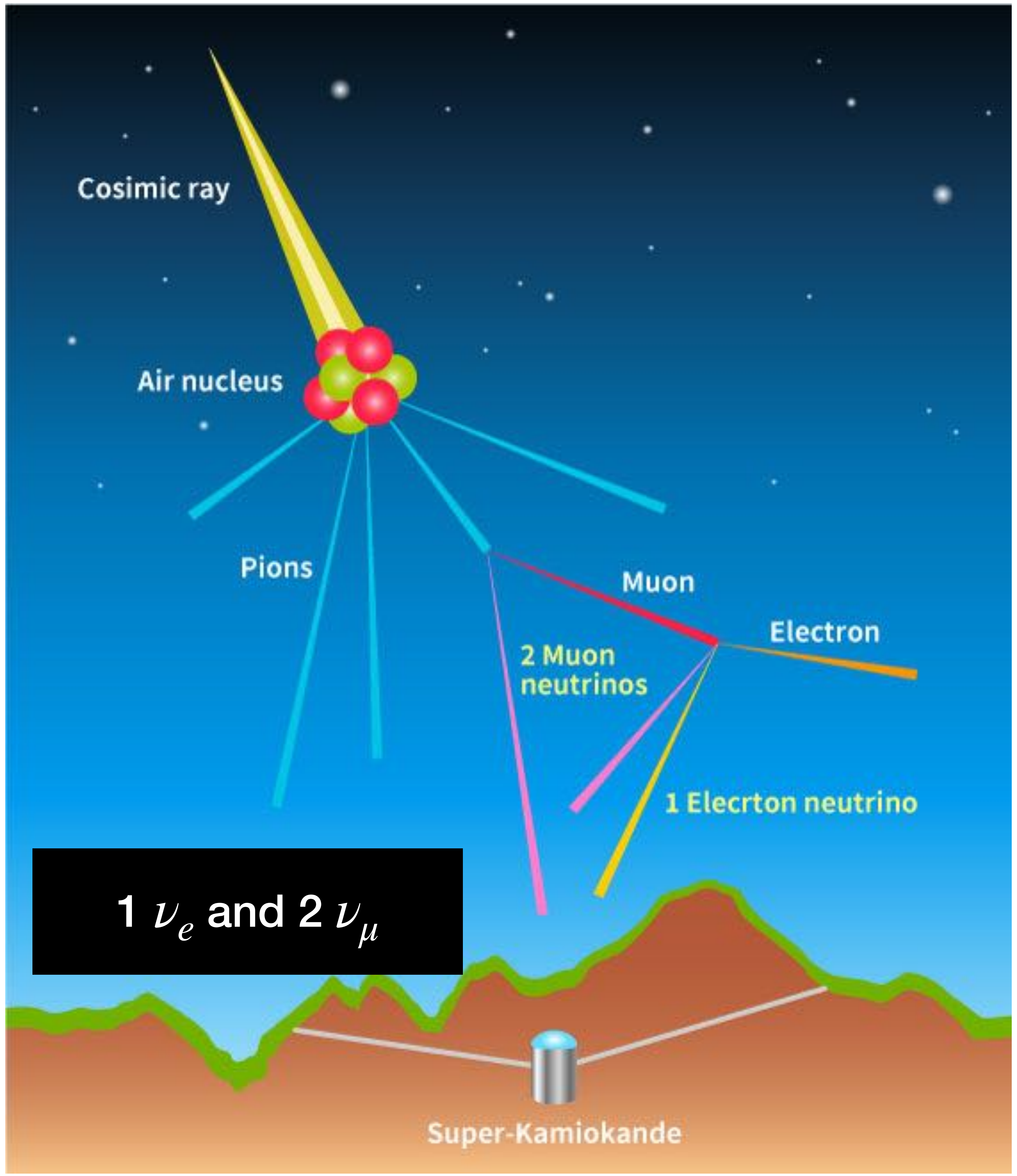
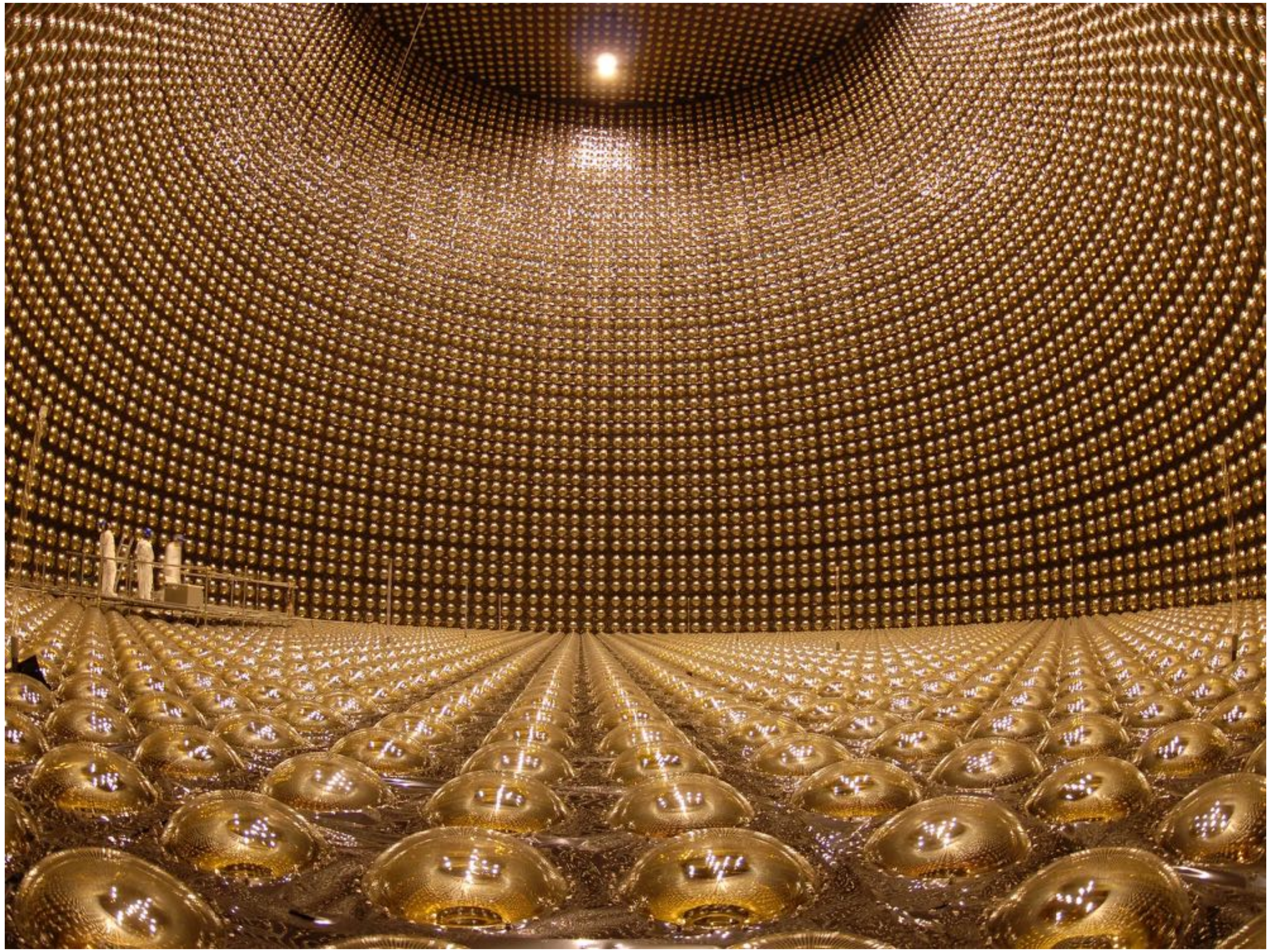
Looking at New Sources





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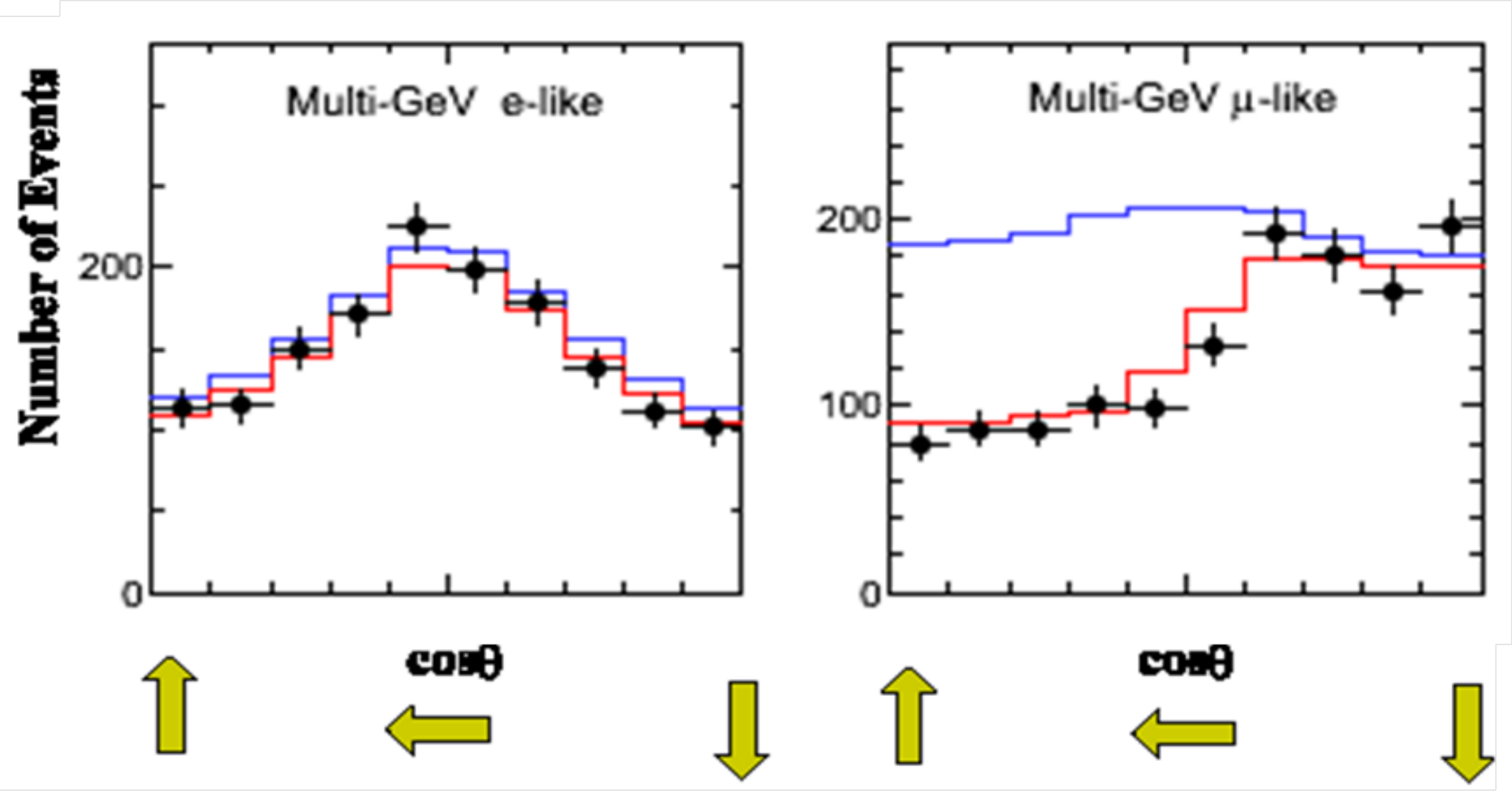
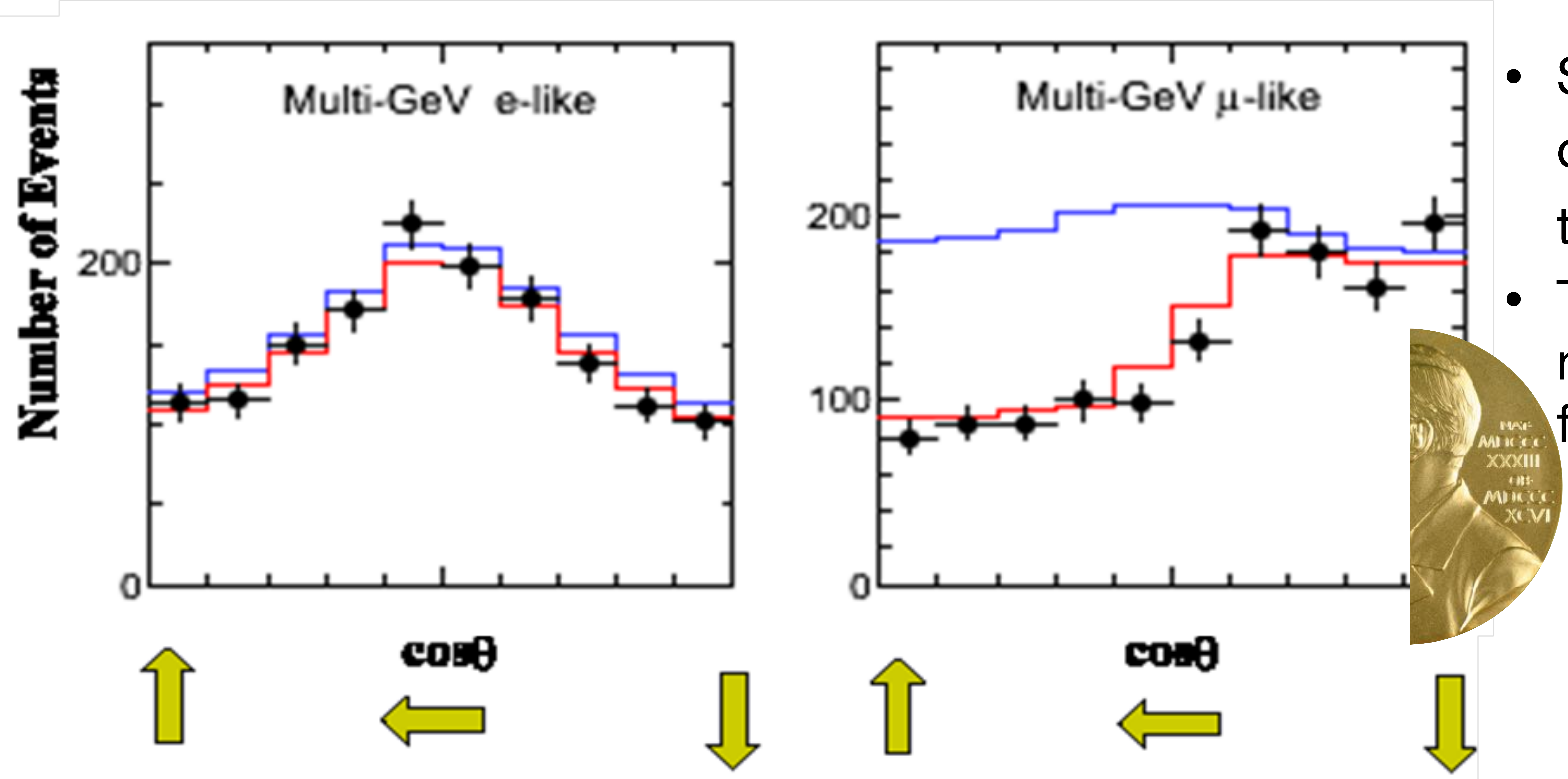


- SuperK saw a deficit of ν_μ coming through the Earth
- This confirmed neutrinos neutrino in-flight flavor change

Looking at New Sources



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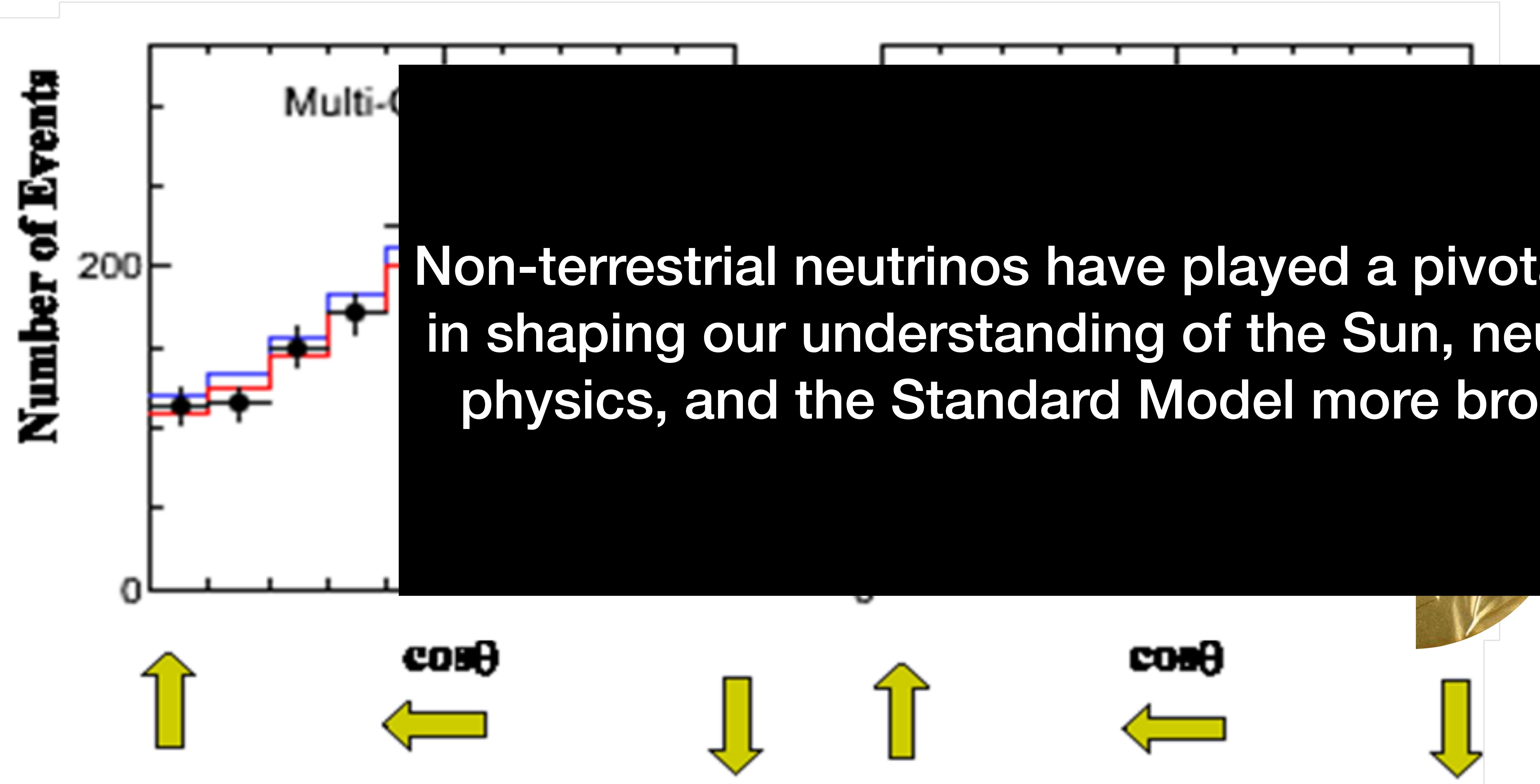

Non-terrestrial neutrinos have played a pivotal role in shaping our understanding of the Sun, neutrino physics, and the Standard Model more broadly

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coming through
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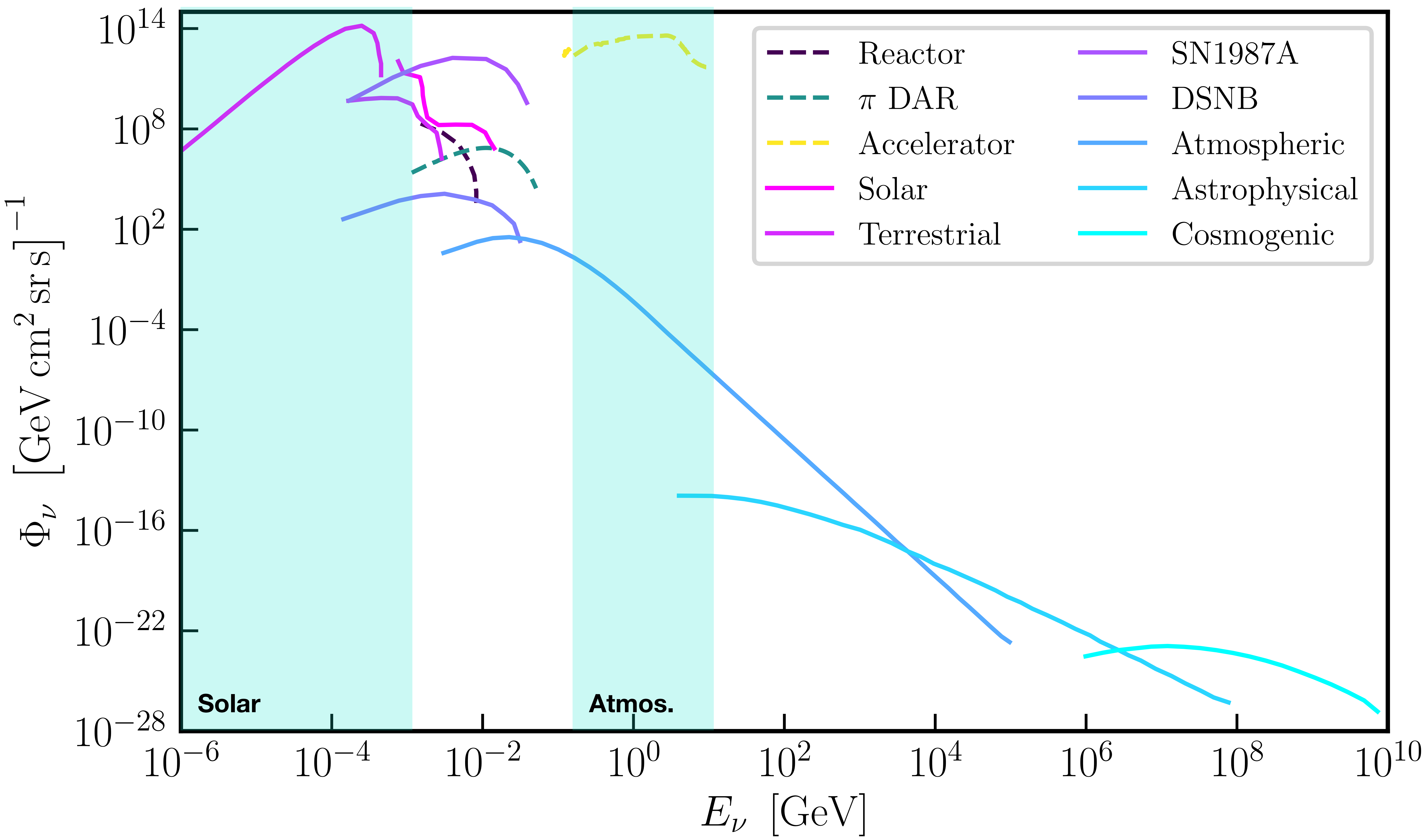
So, where do we go from here ?



Reactor
π DAR
Accelerator
Solar
Terrestrial
SN1987A
DSNB
Atmospheric
Astrophysical
Cosmogenic
Solar
Atmos.
$\Phi_\nu \; [\mathrm{GeV\,cm^2\,sr\,s}]^{-1}$
$E_\nu \; [\mathrm{GeV}]$
10^{14}
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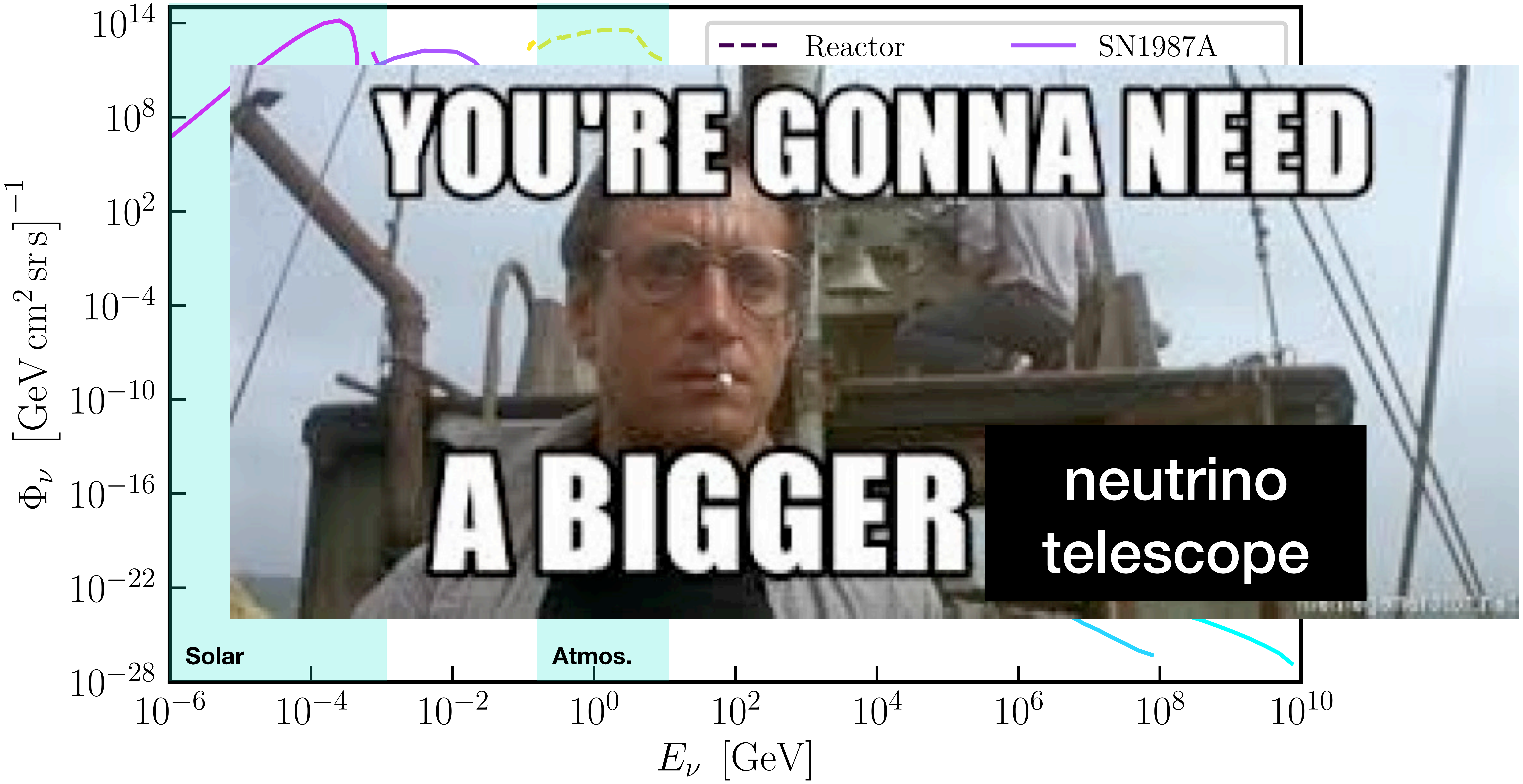
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10^{14}
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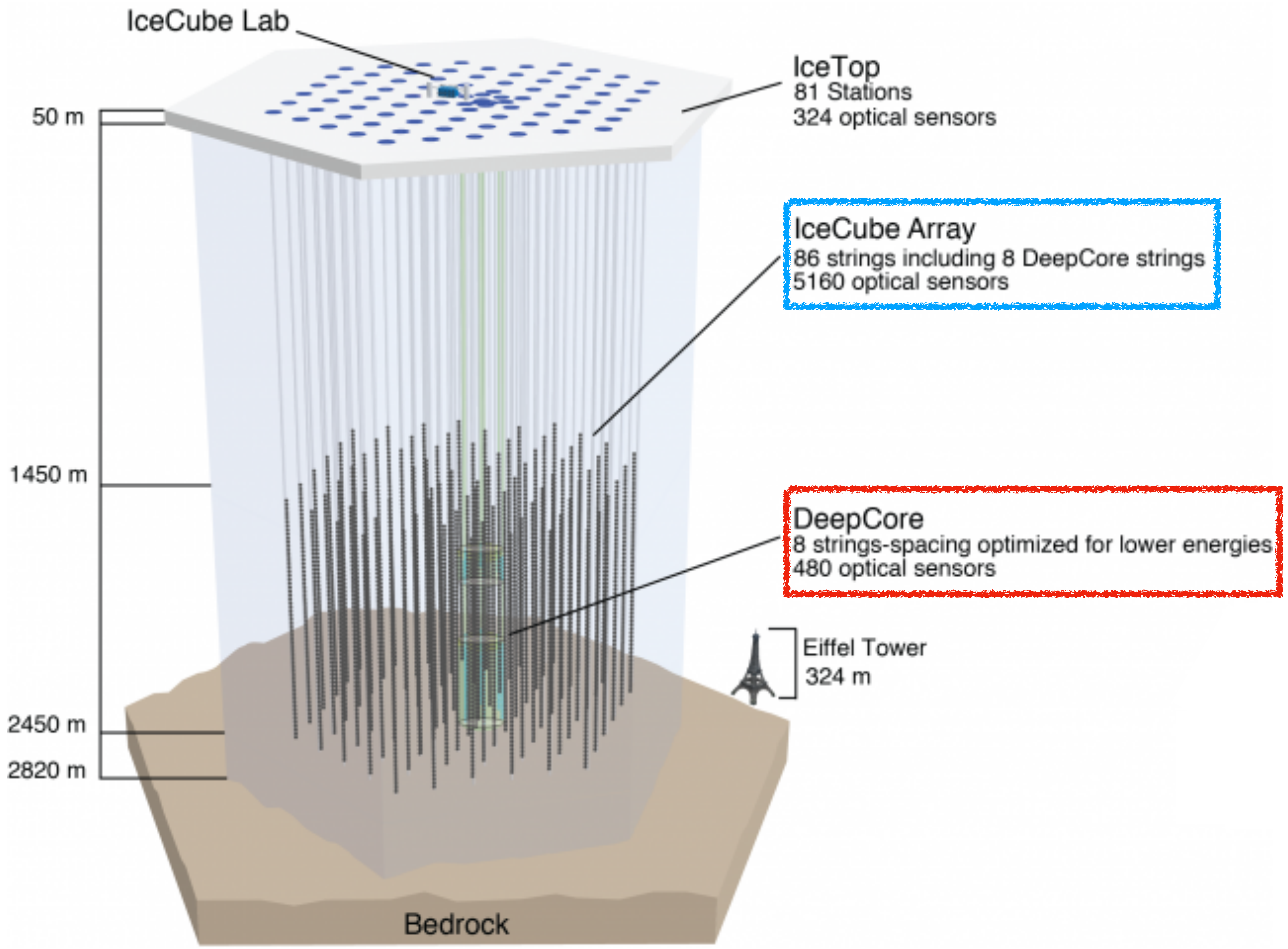
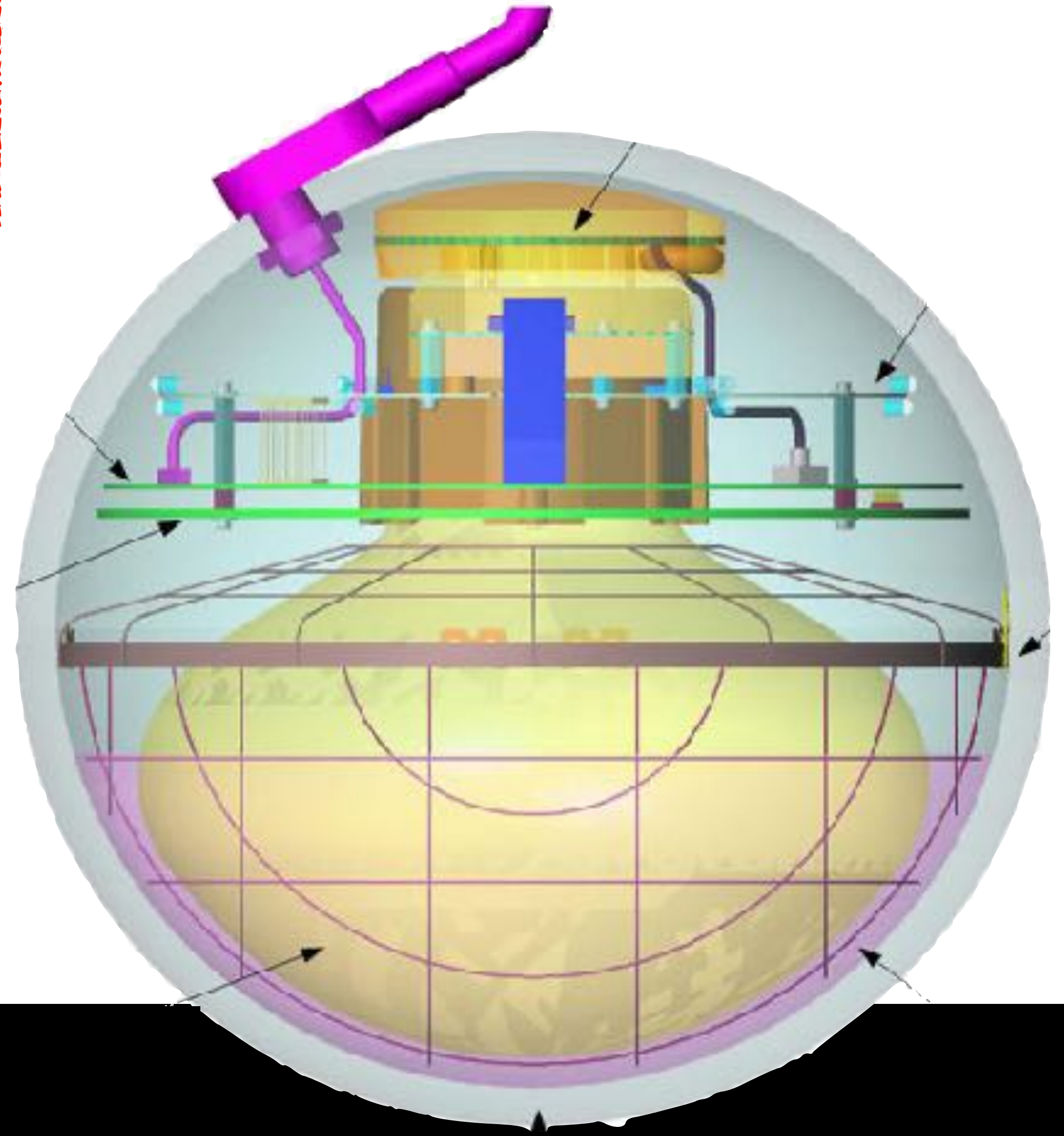
The IceCube Neutrino Observatory



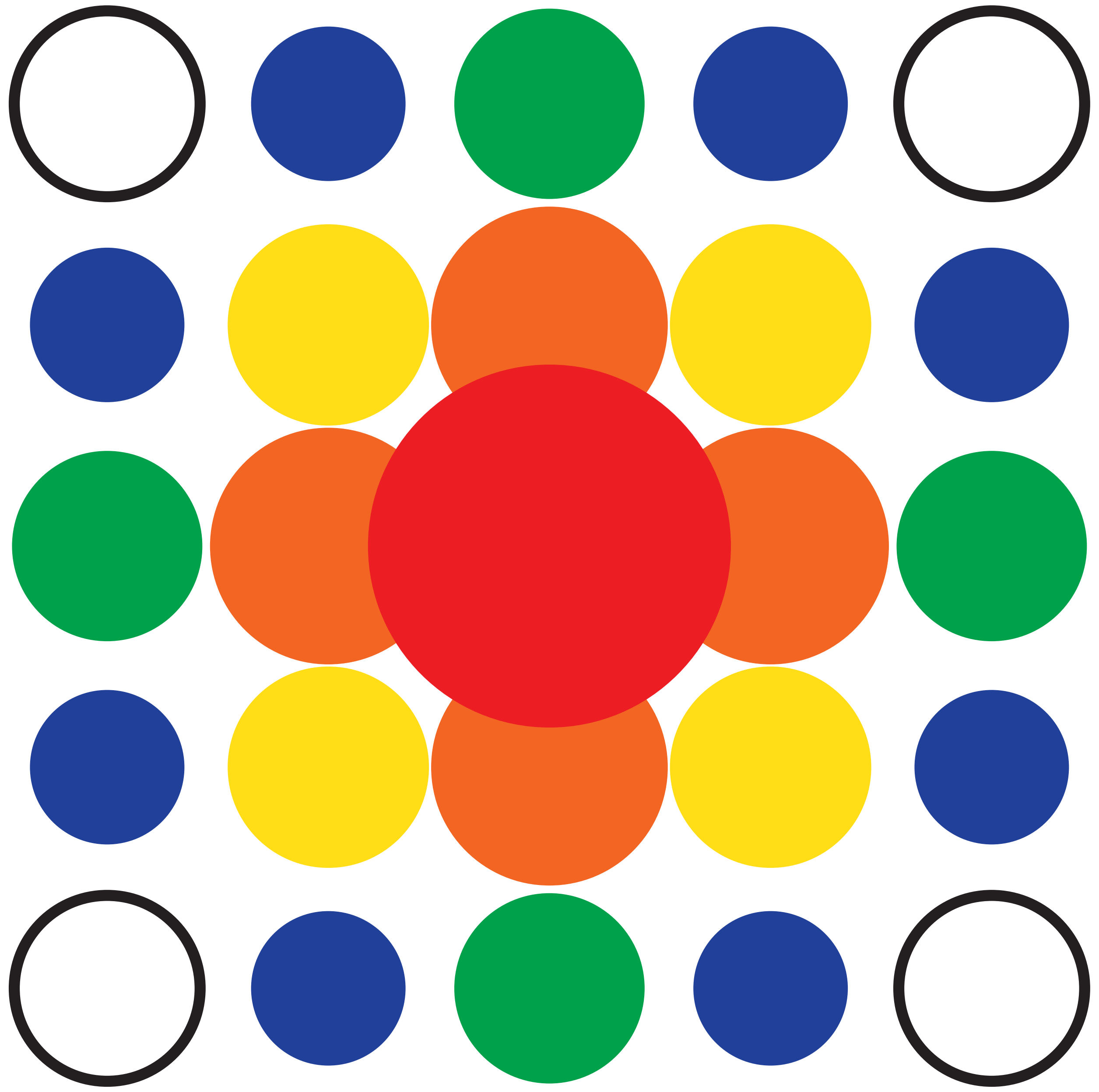
Gigaton scale detector of 5,160 light detecting digital optical modules (DOMs)

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



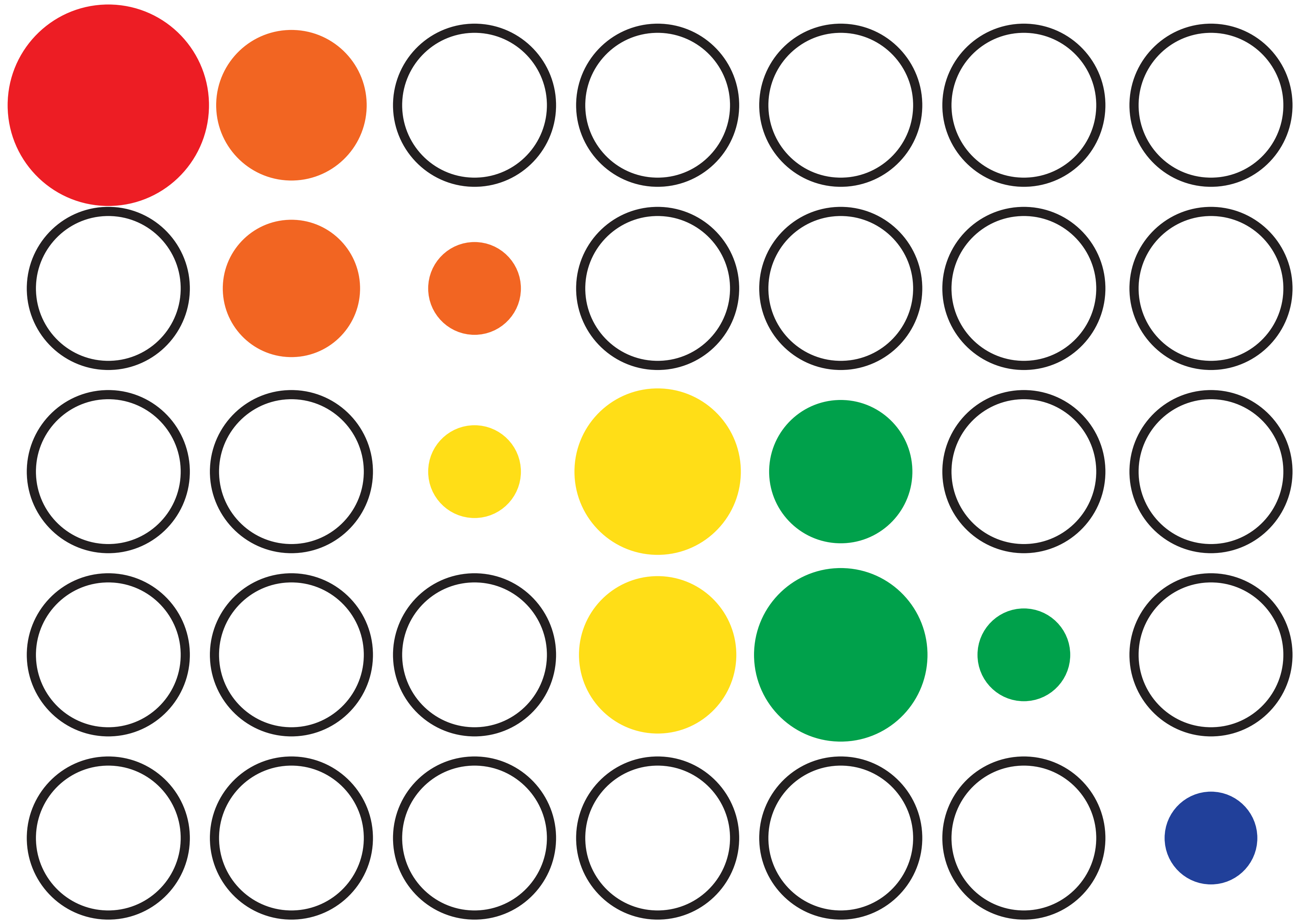
Unfolding Light and Time

Cascades ν_e CC | ν_α NC



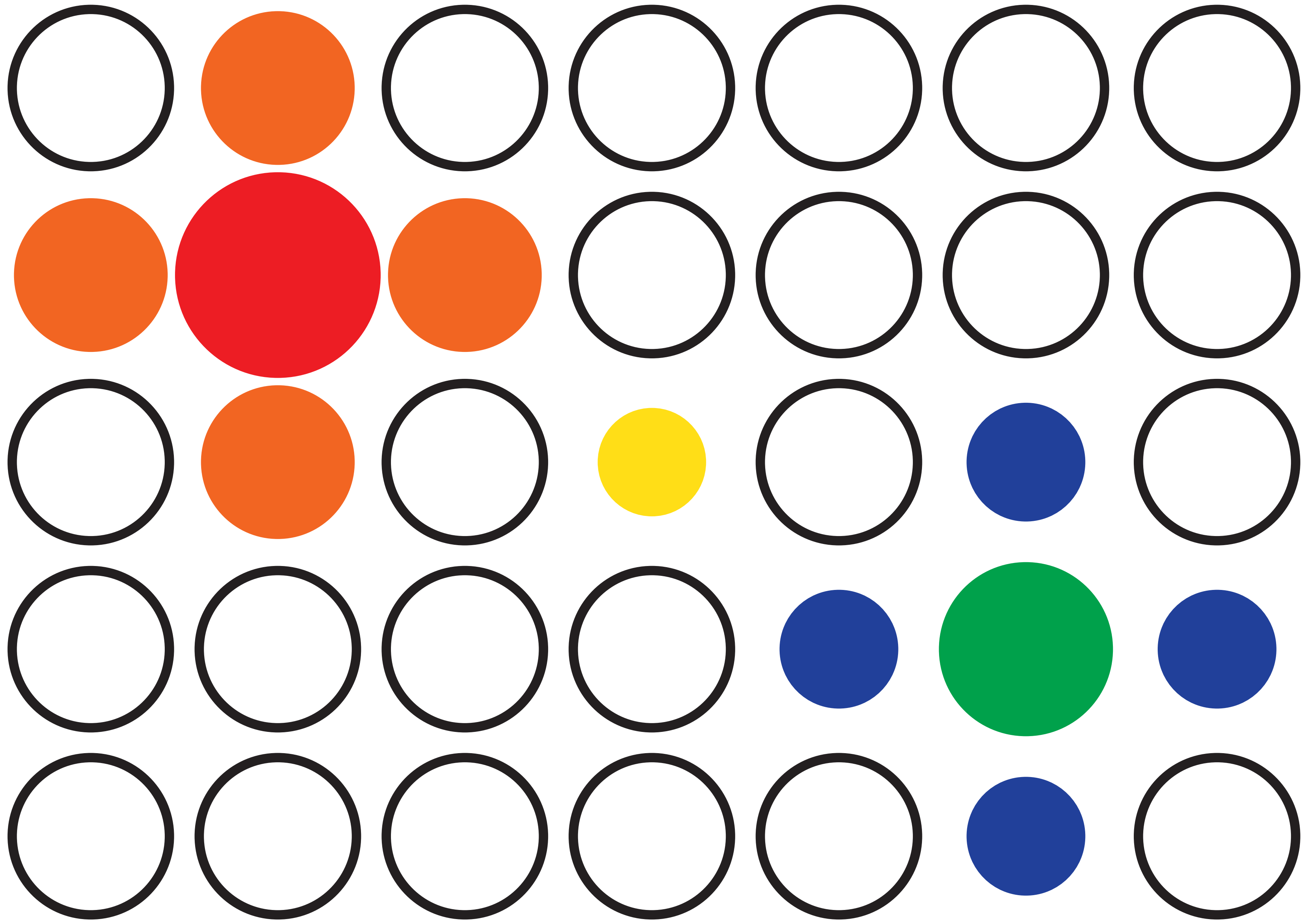
Great energy resolution, but angular reconstruction is challenging

Tracks ν_μ CC



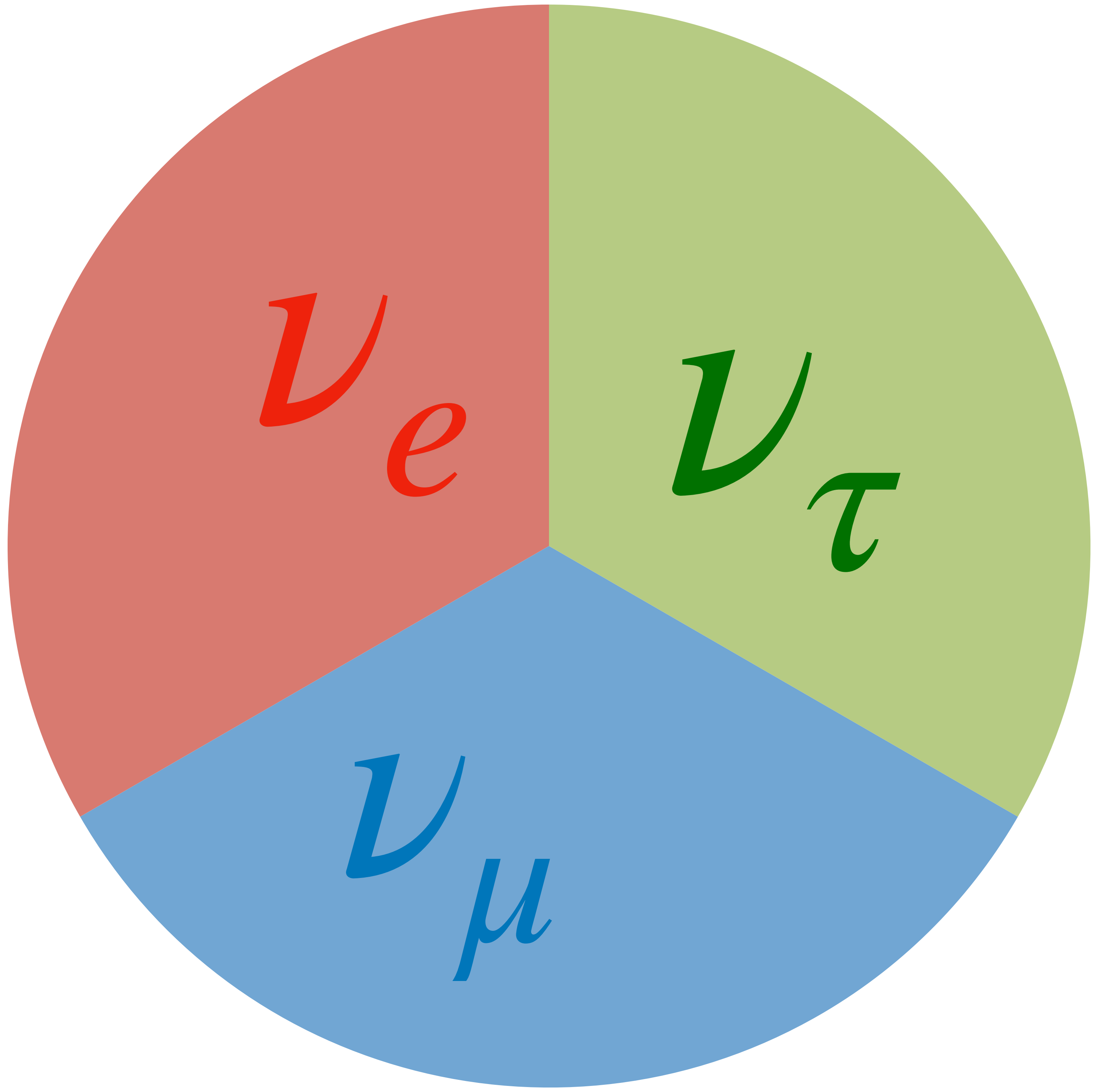
Great directional resolution, but deposited energy not proportional to E_ν

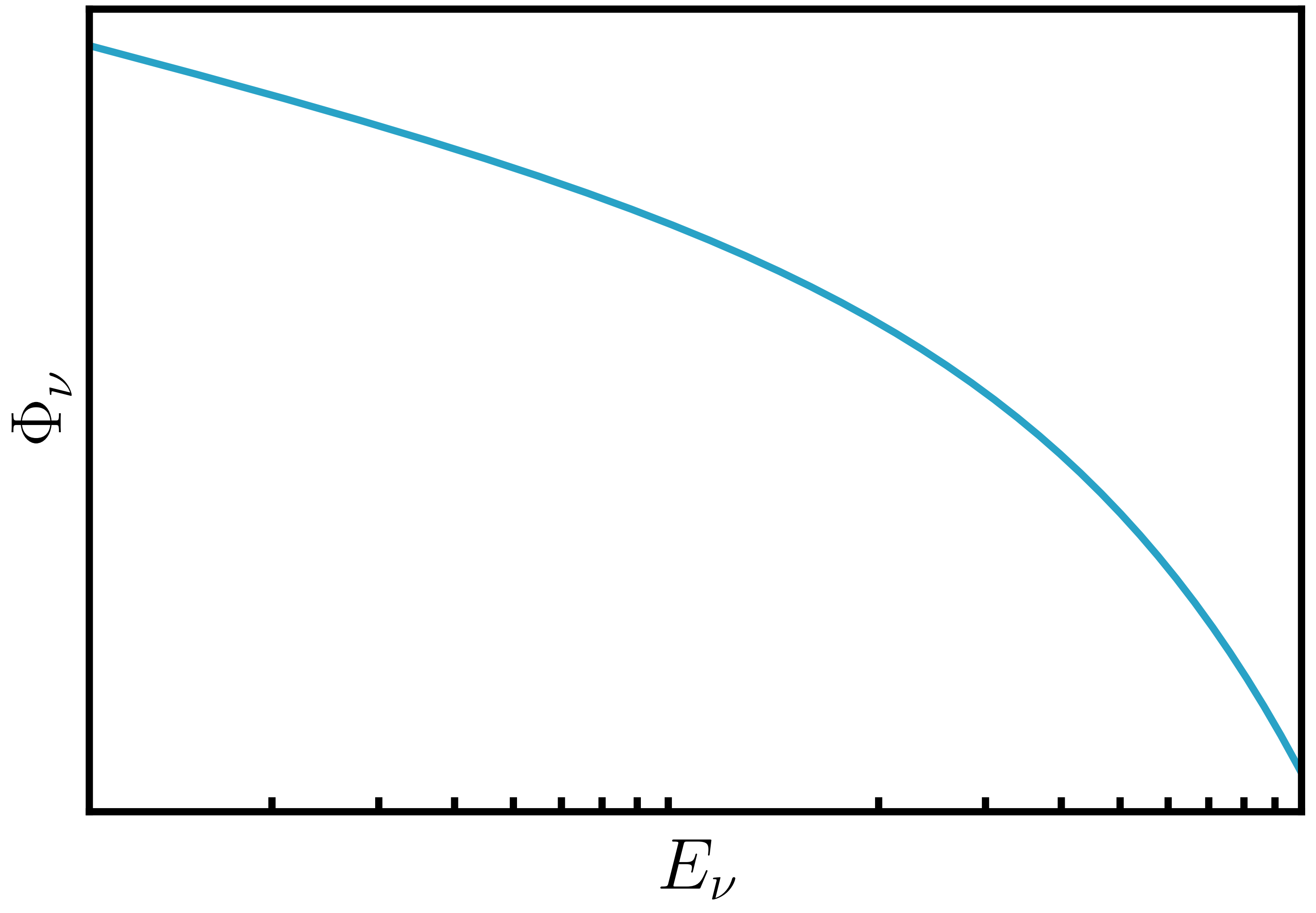
Double bangs ν_τ CC

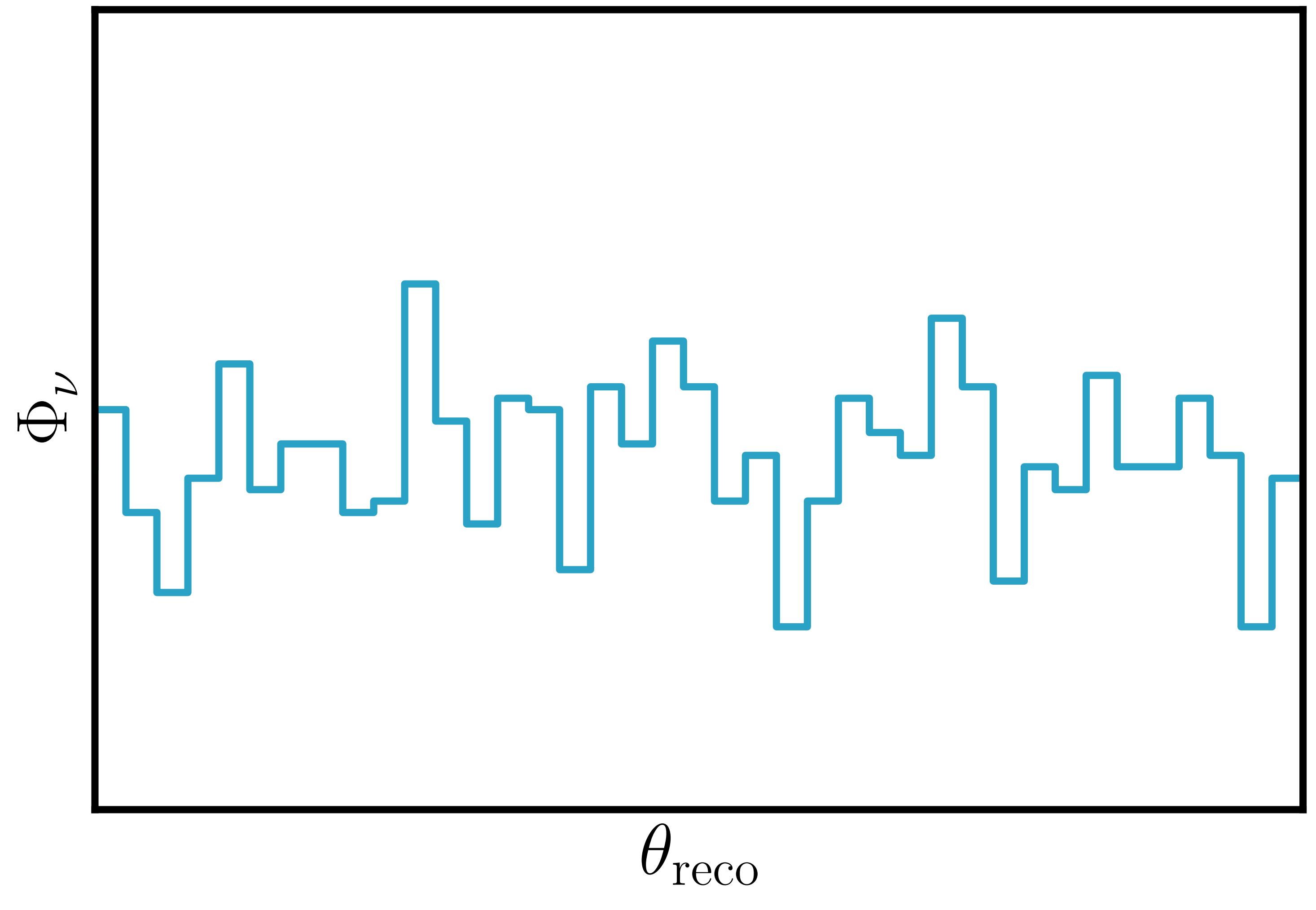


Signature of ν_τ CC events

What Do we look for







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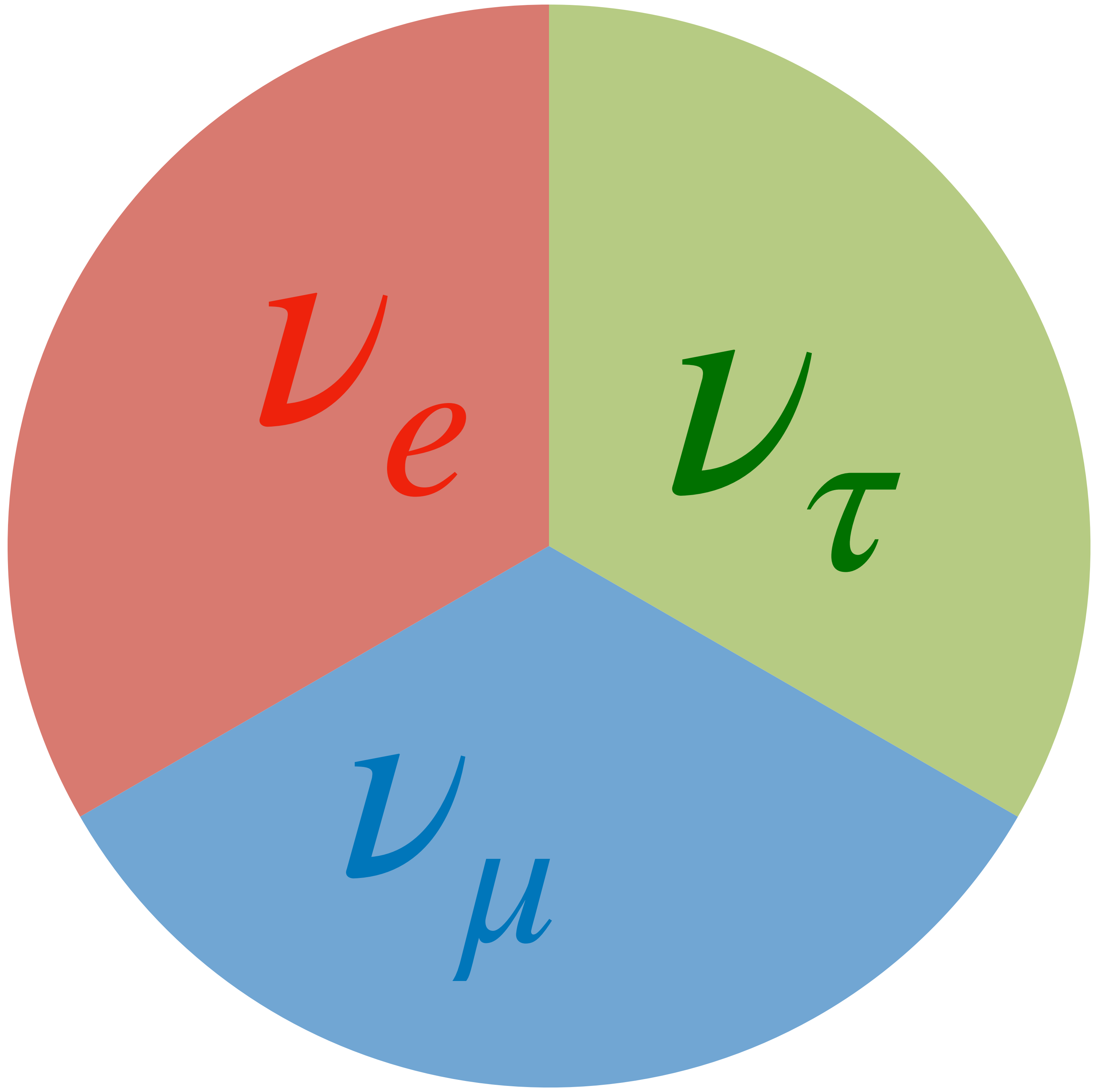

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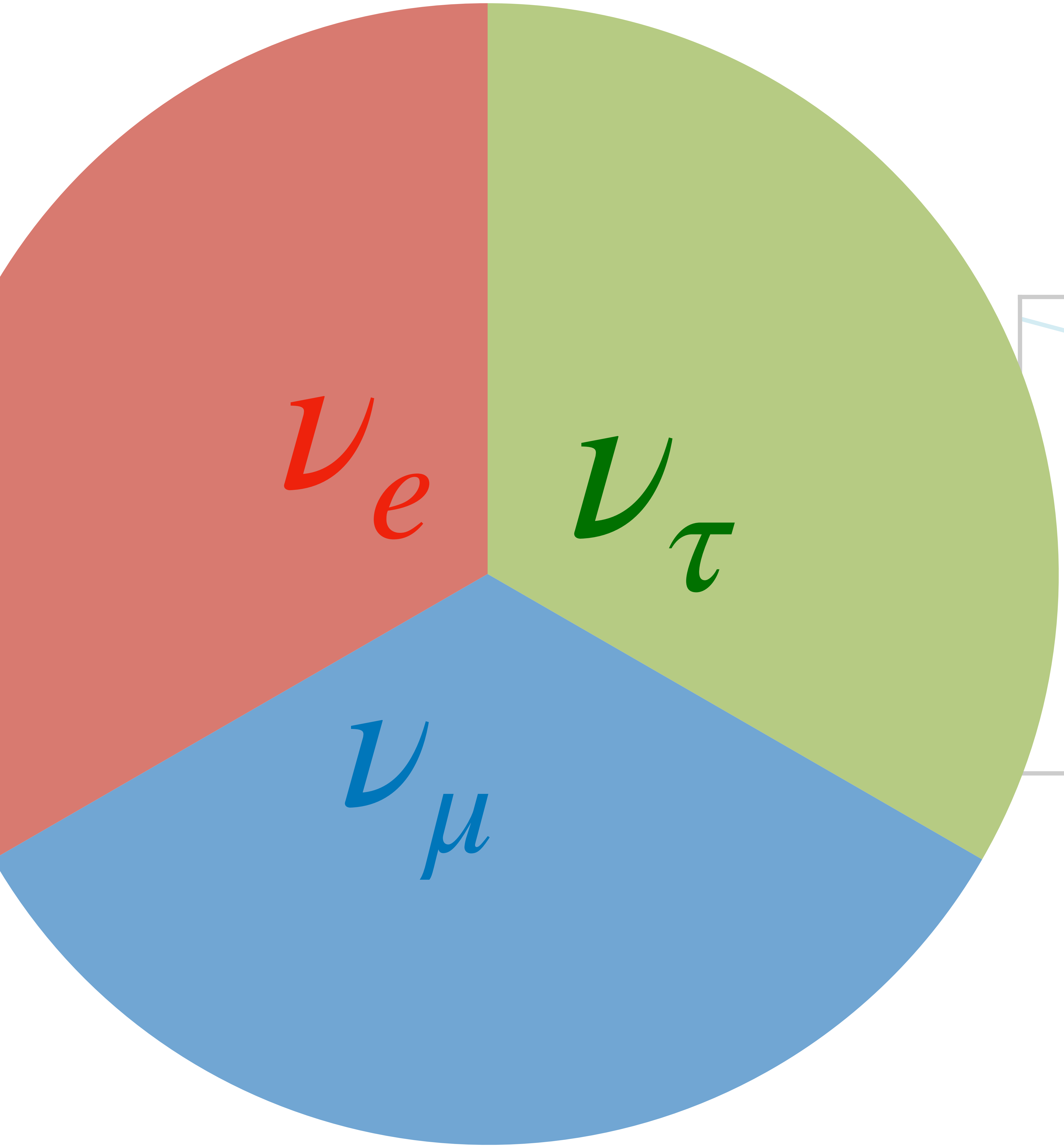

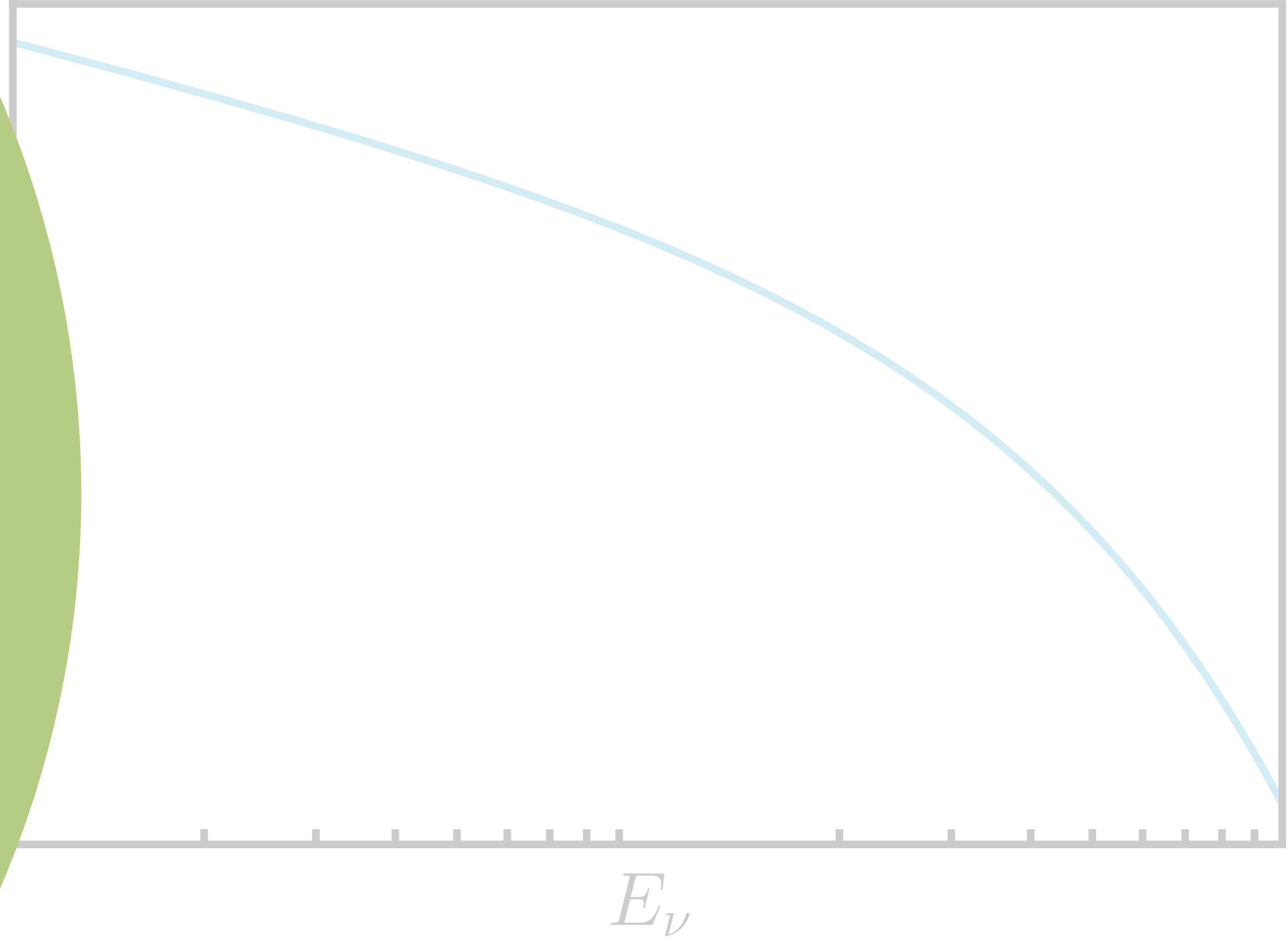

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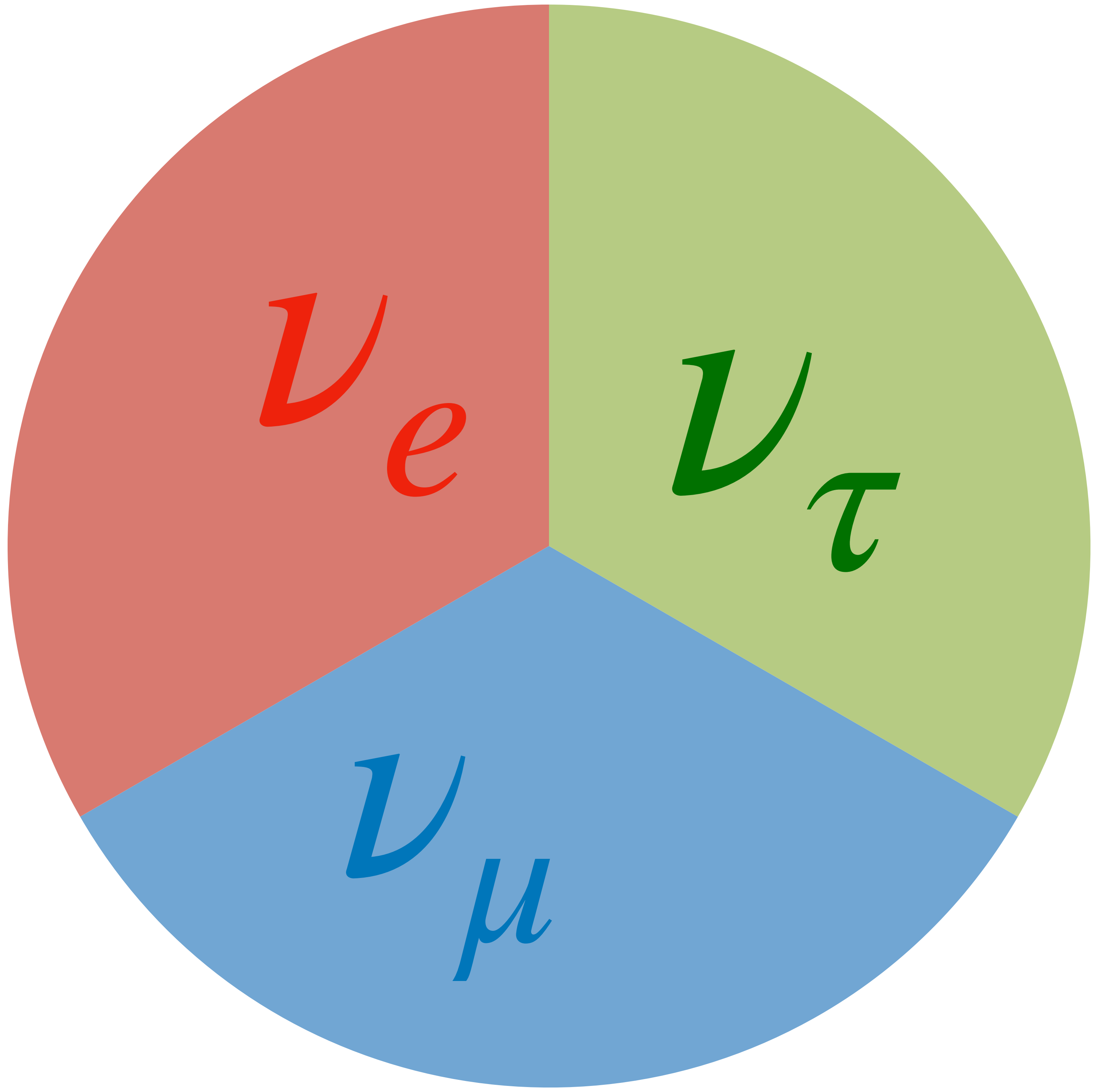

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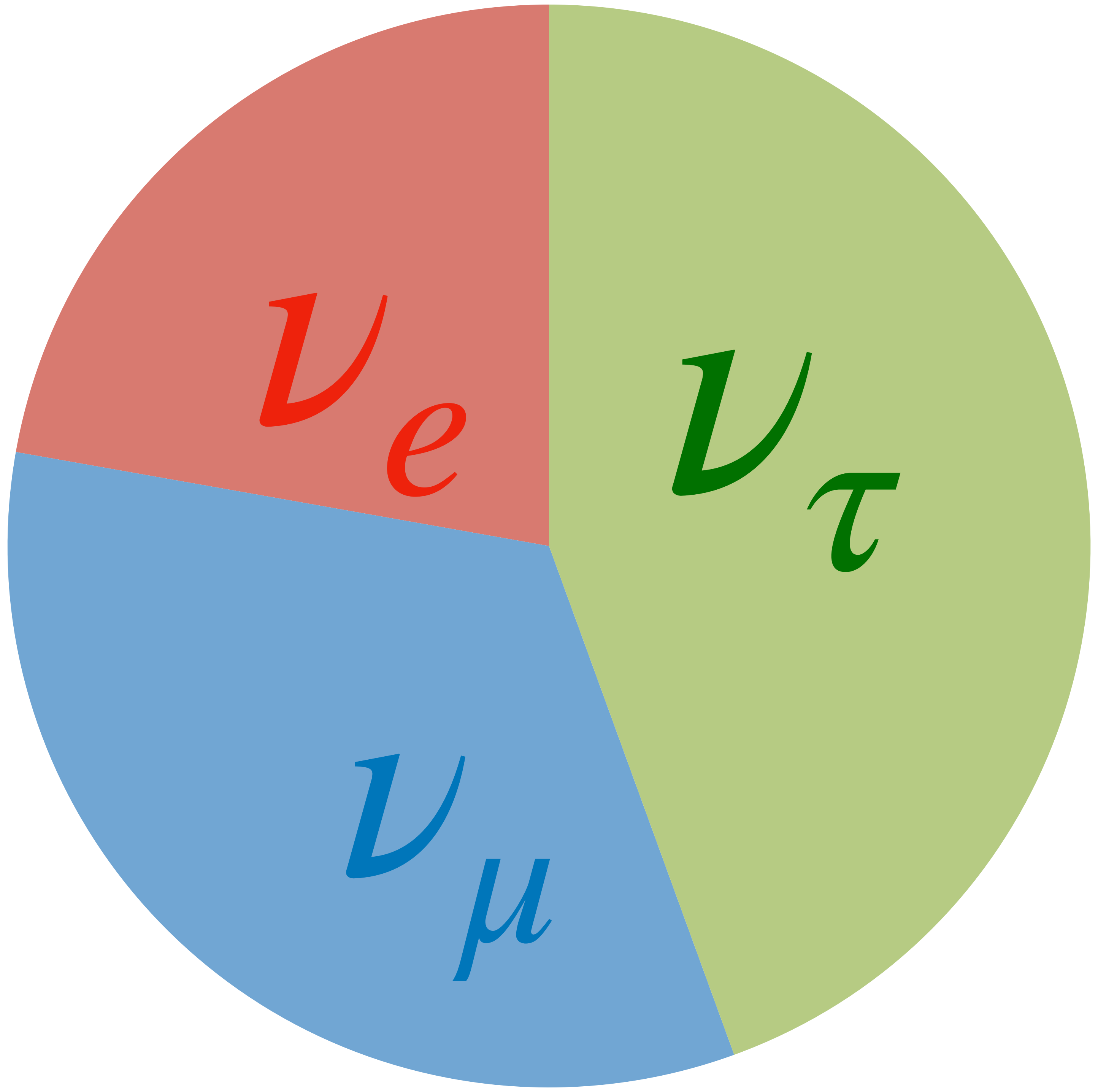

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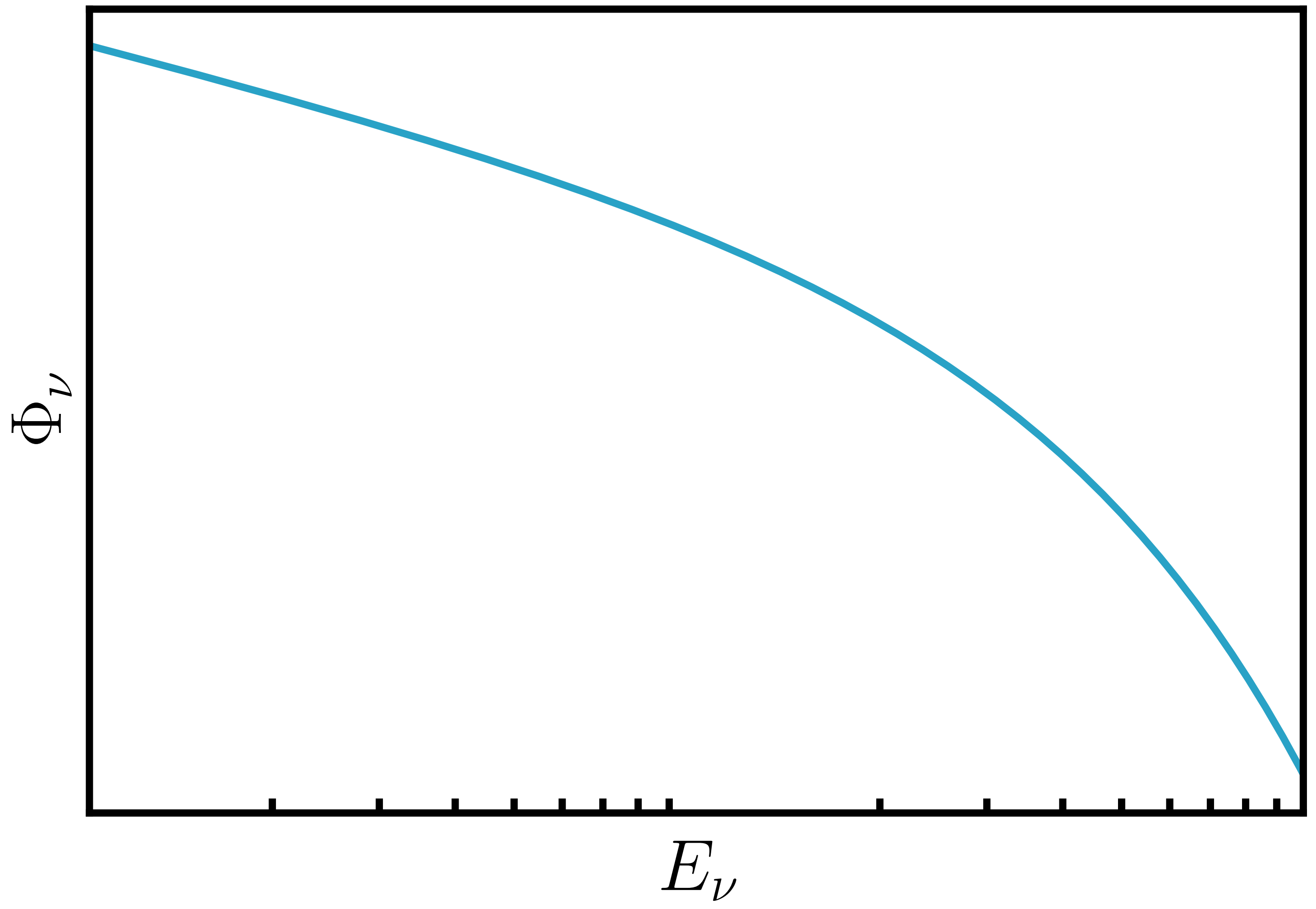

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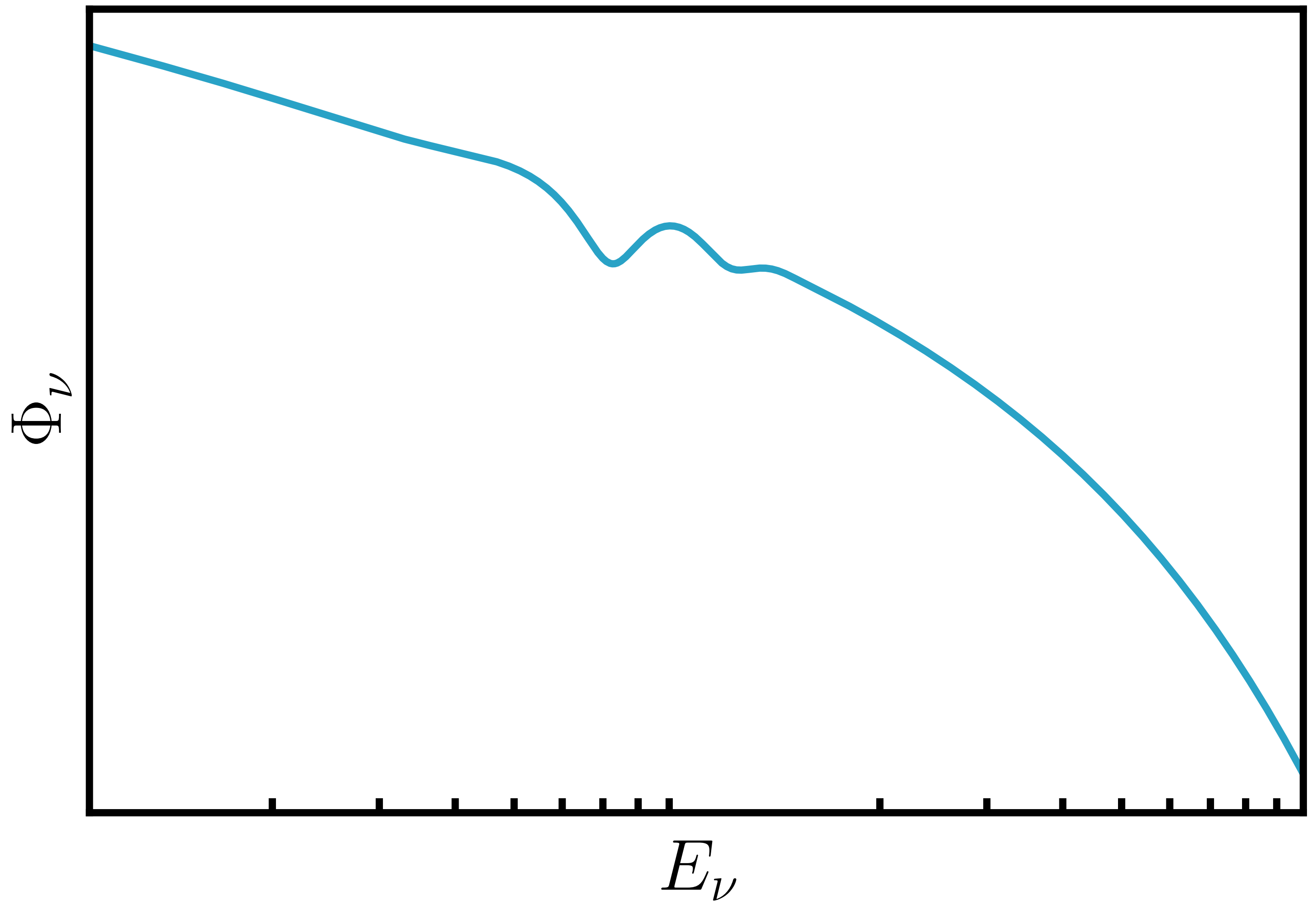

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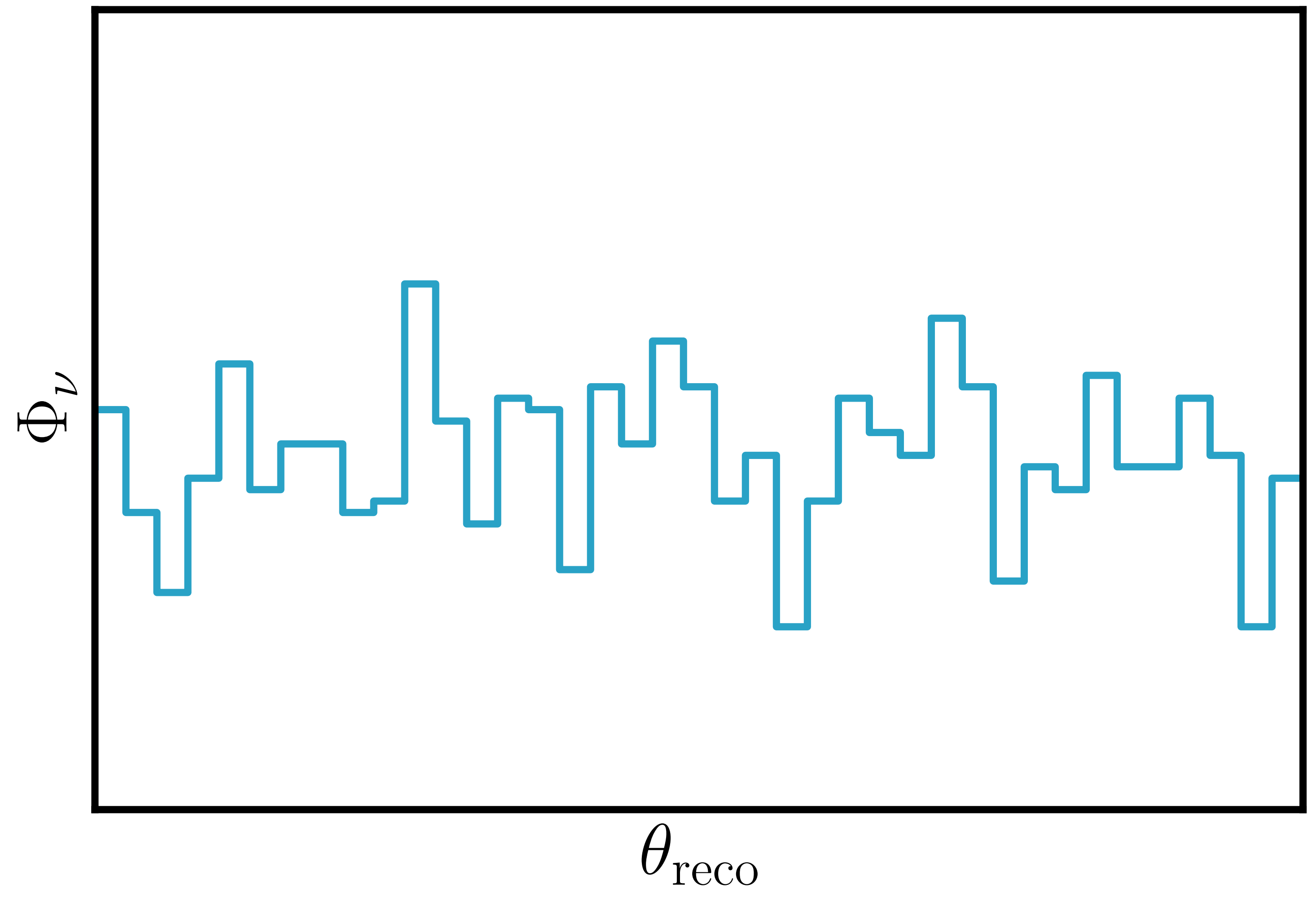

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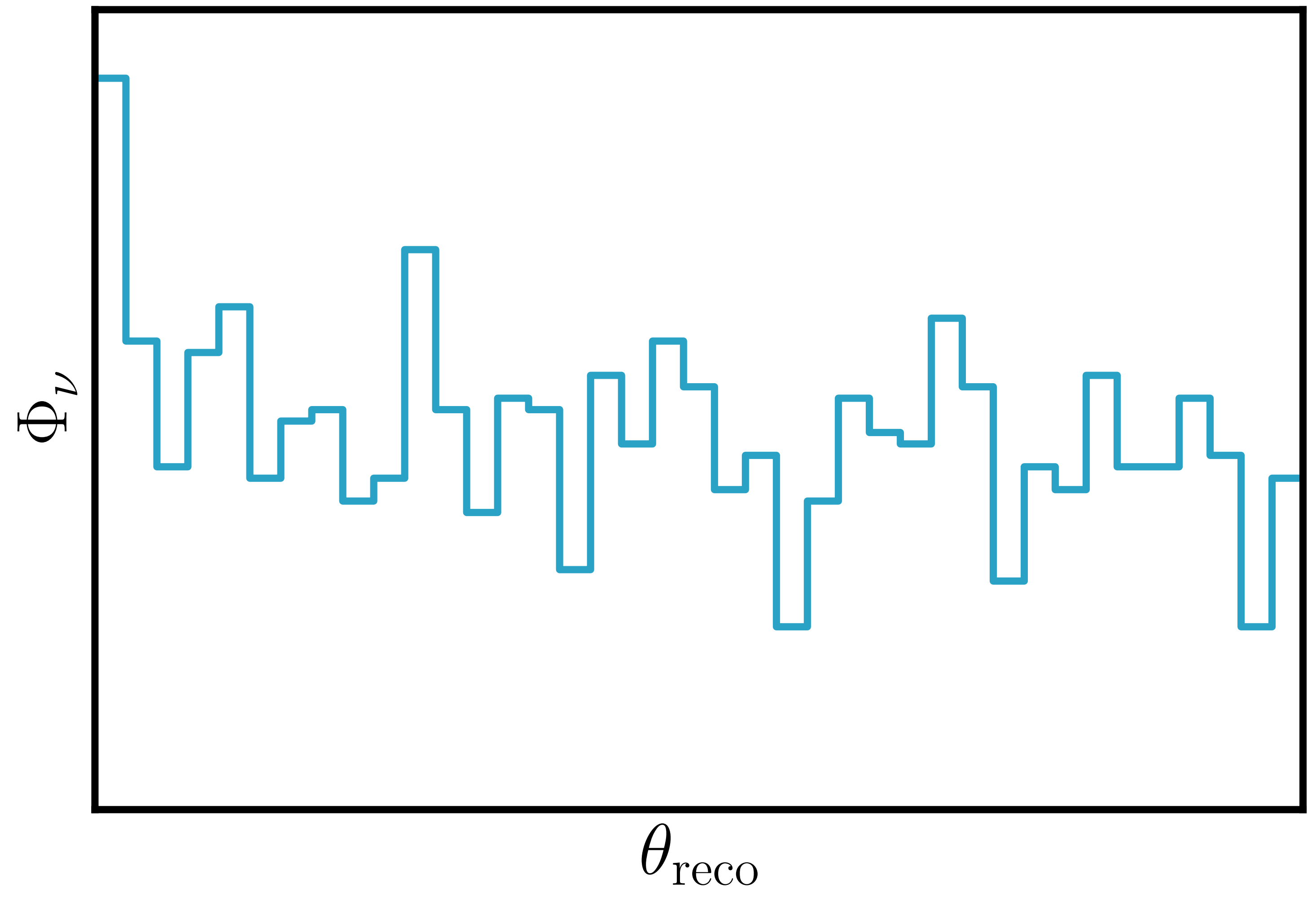
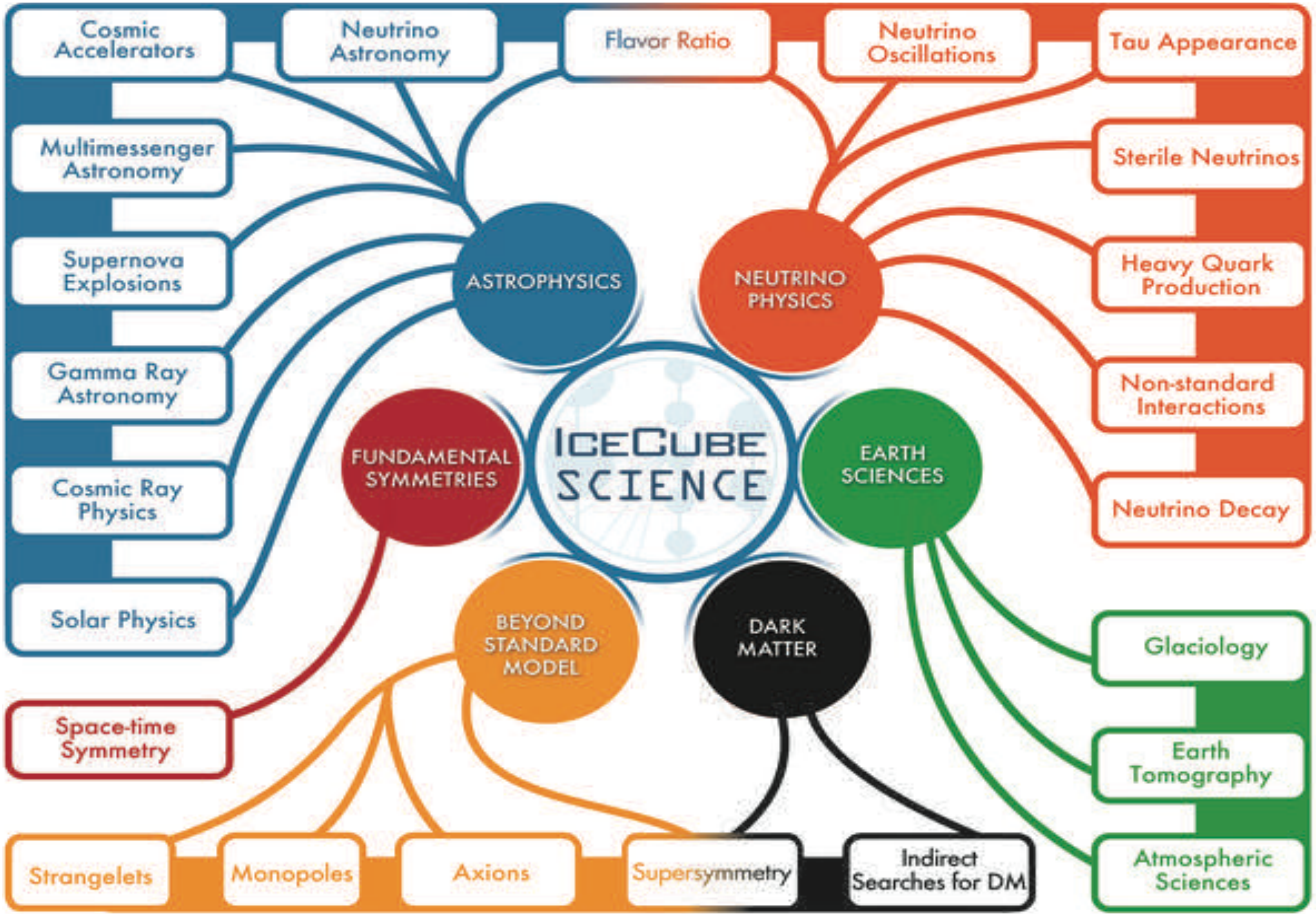


Science Spanning Sectors



IceCube can use the neutrinos it observes to answer questions from the from particle physics up to cosmology !

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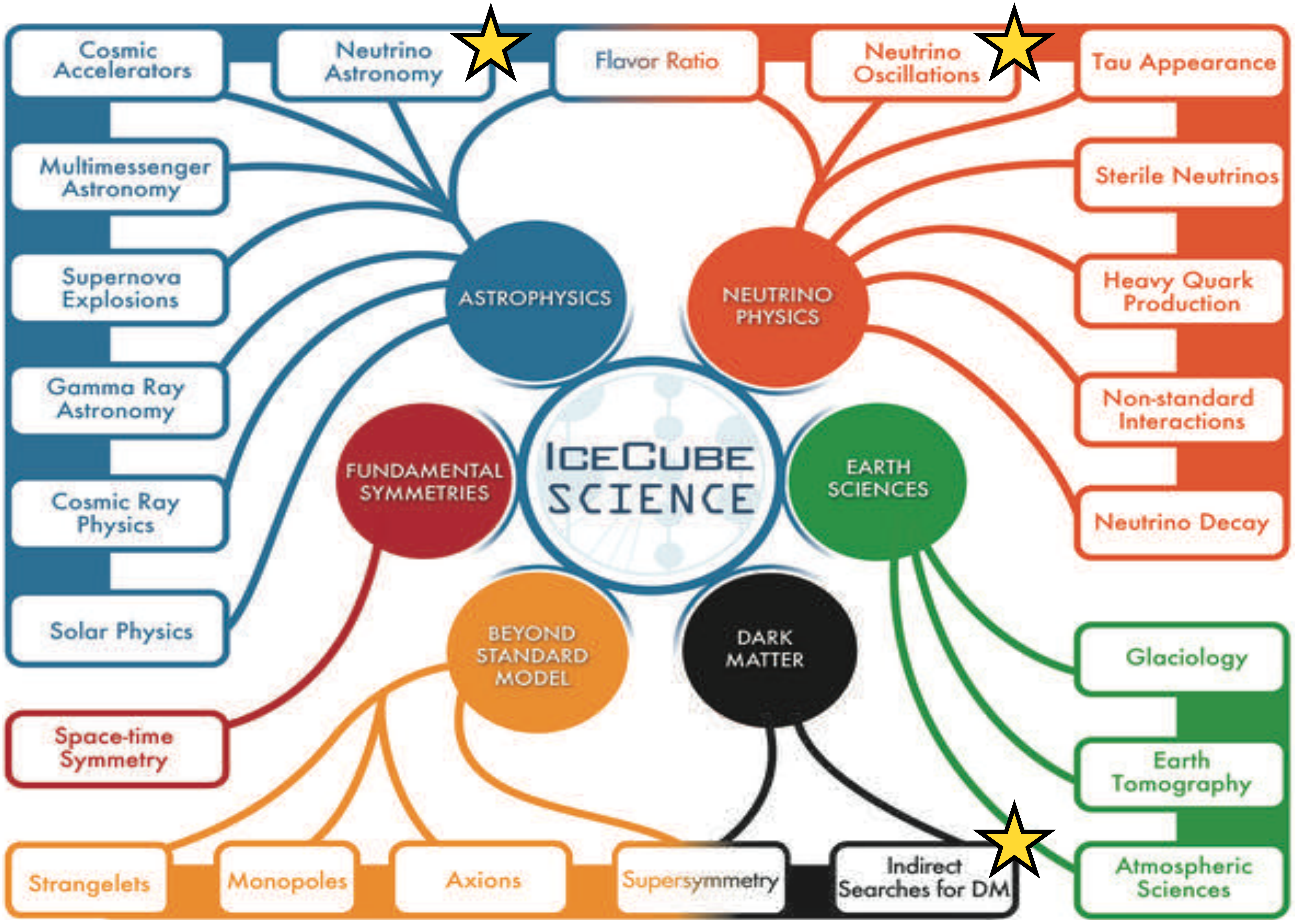

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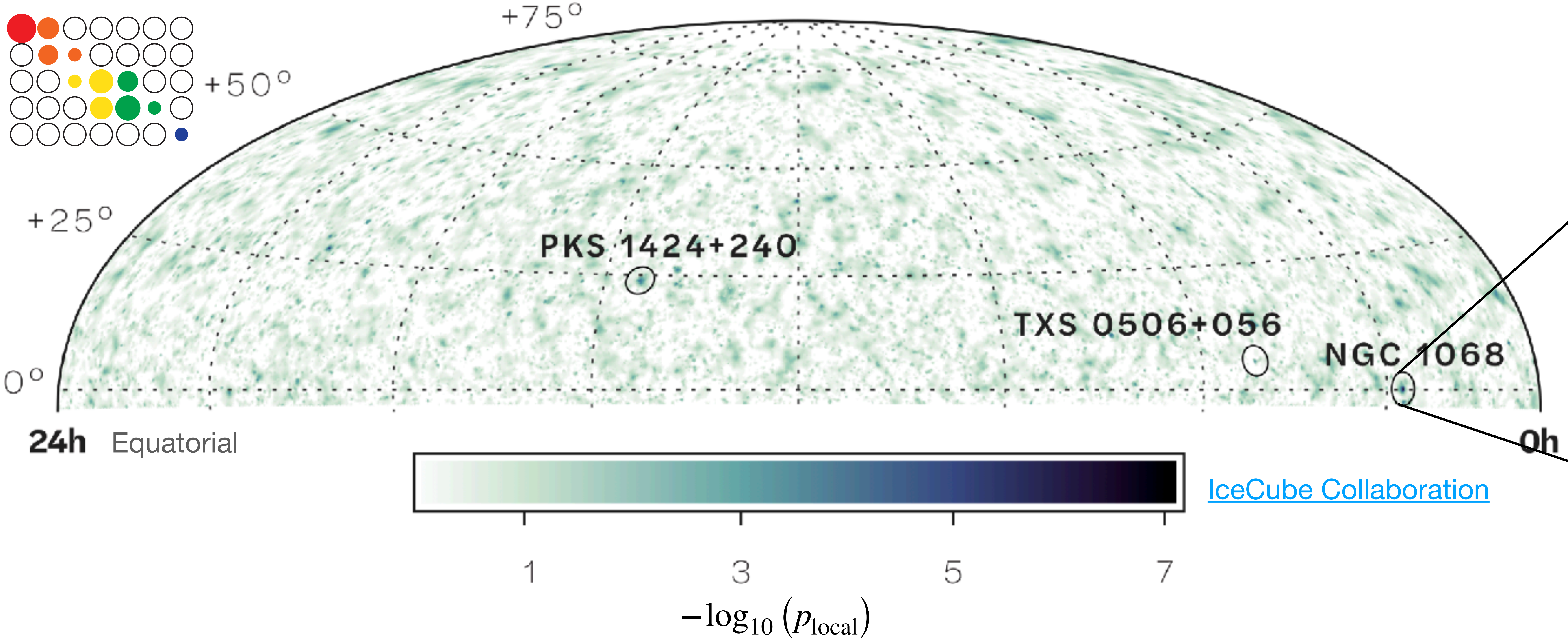
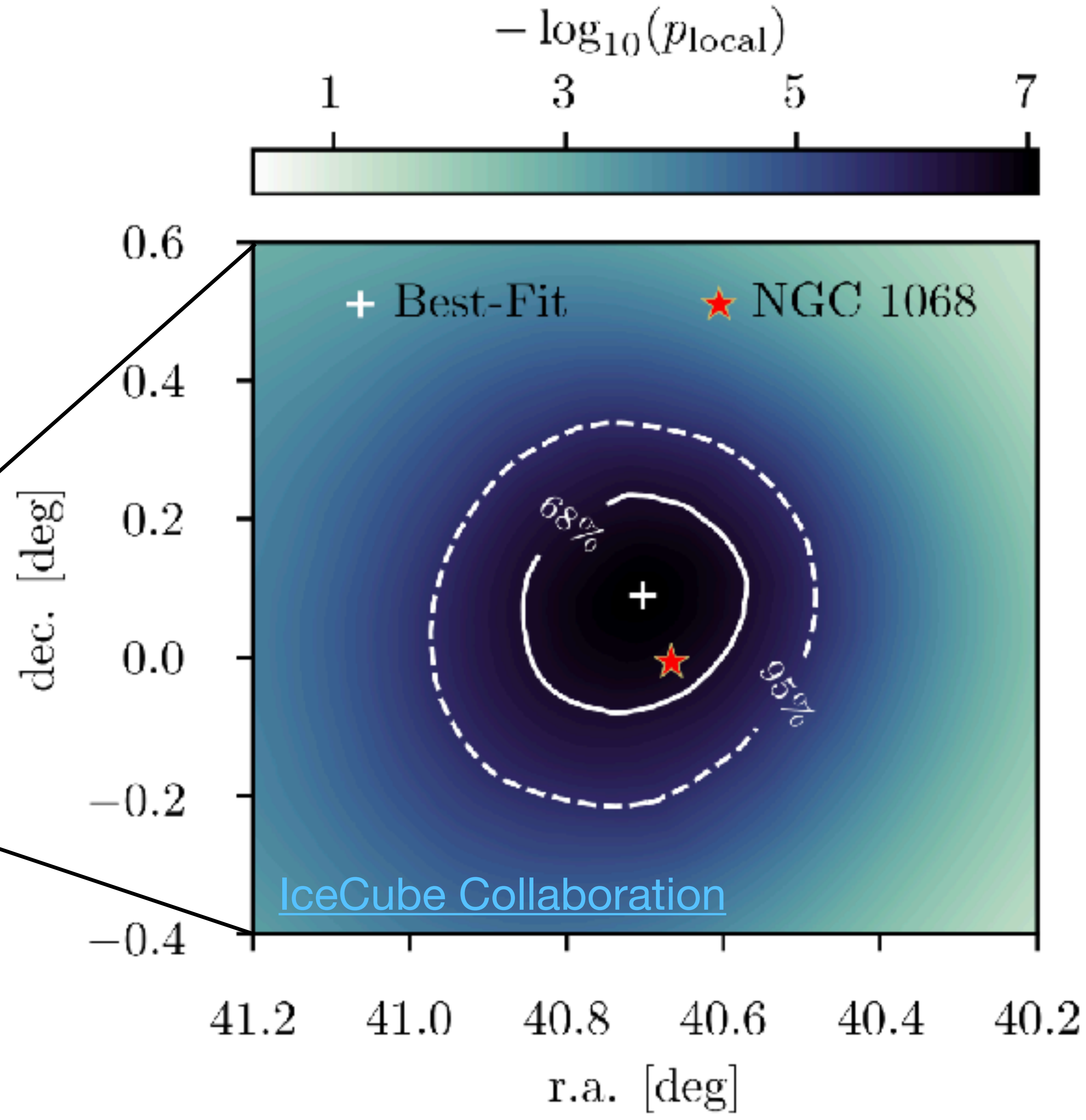
Hunting for Neutrino Sources

Search of northern-sky, track data set with three searches

1. General clustering of neutrinos in the northern sky
2. An excess of events from known γ-ray emitters
3. An excess of events from k known γ-ray emitters



IceCube Collaboration



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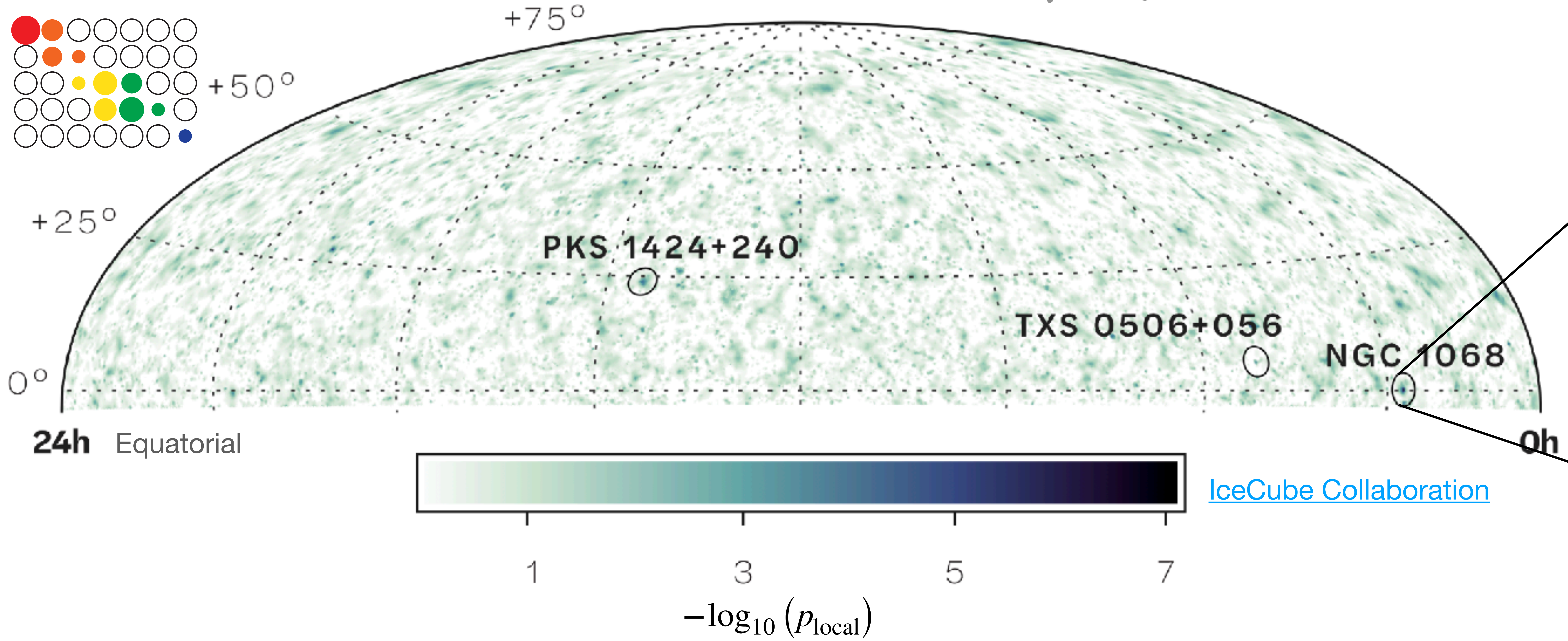
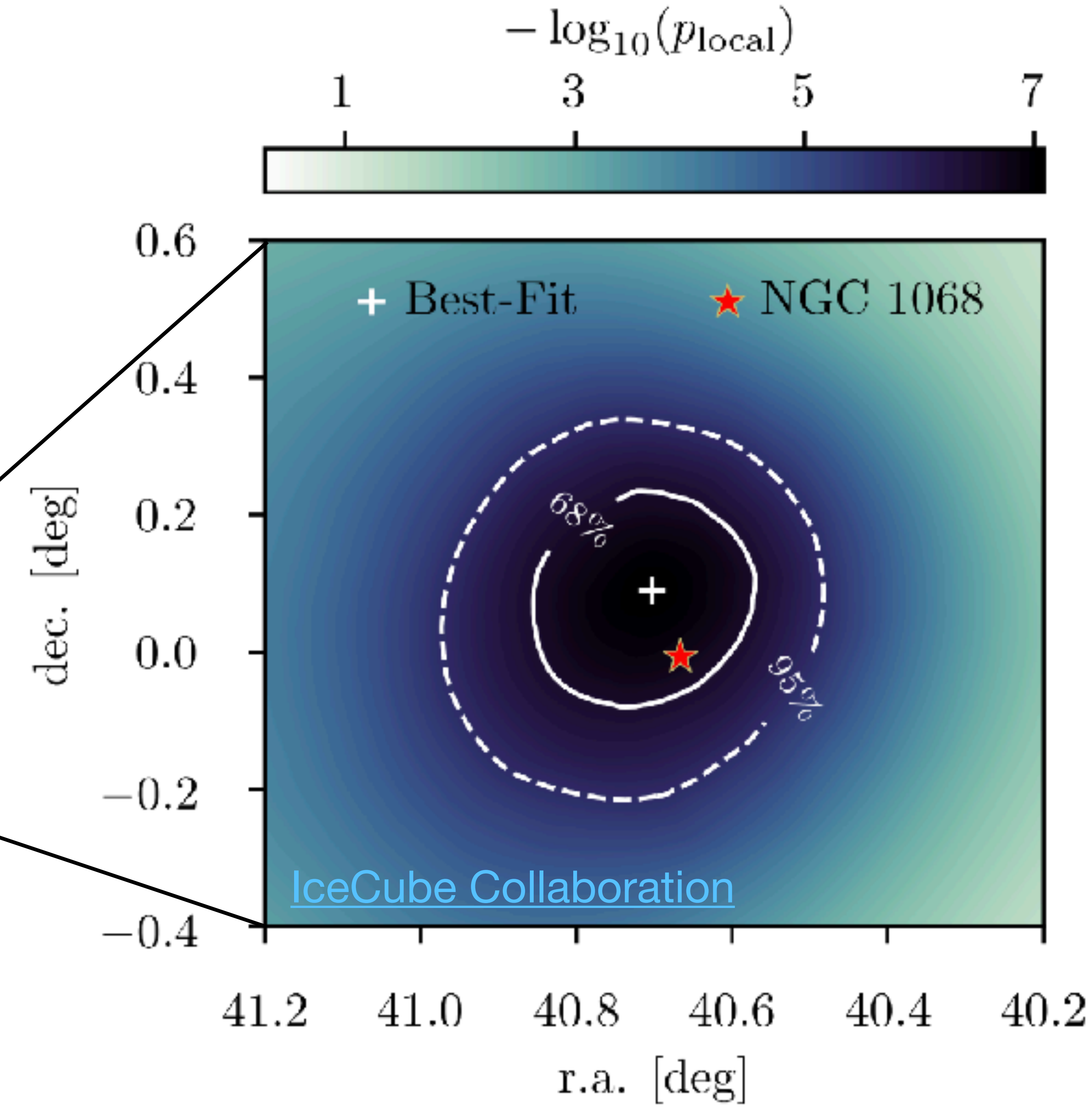
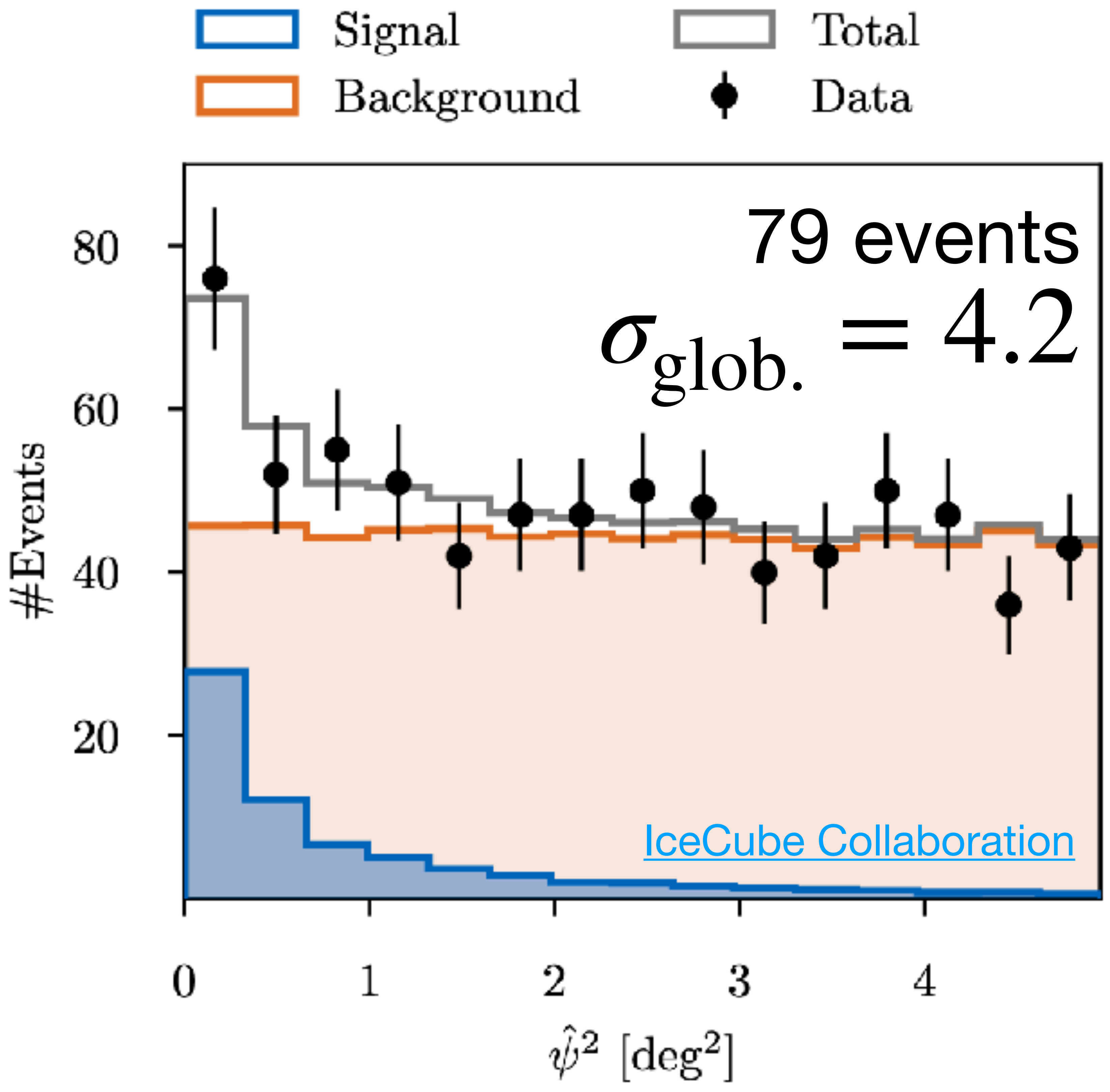
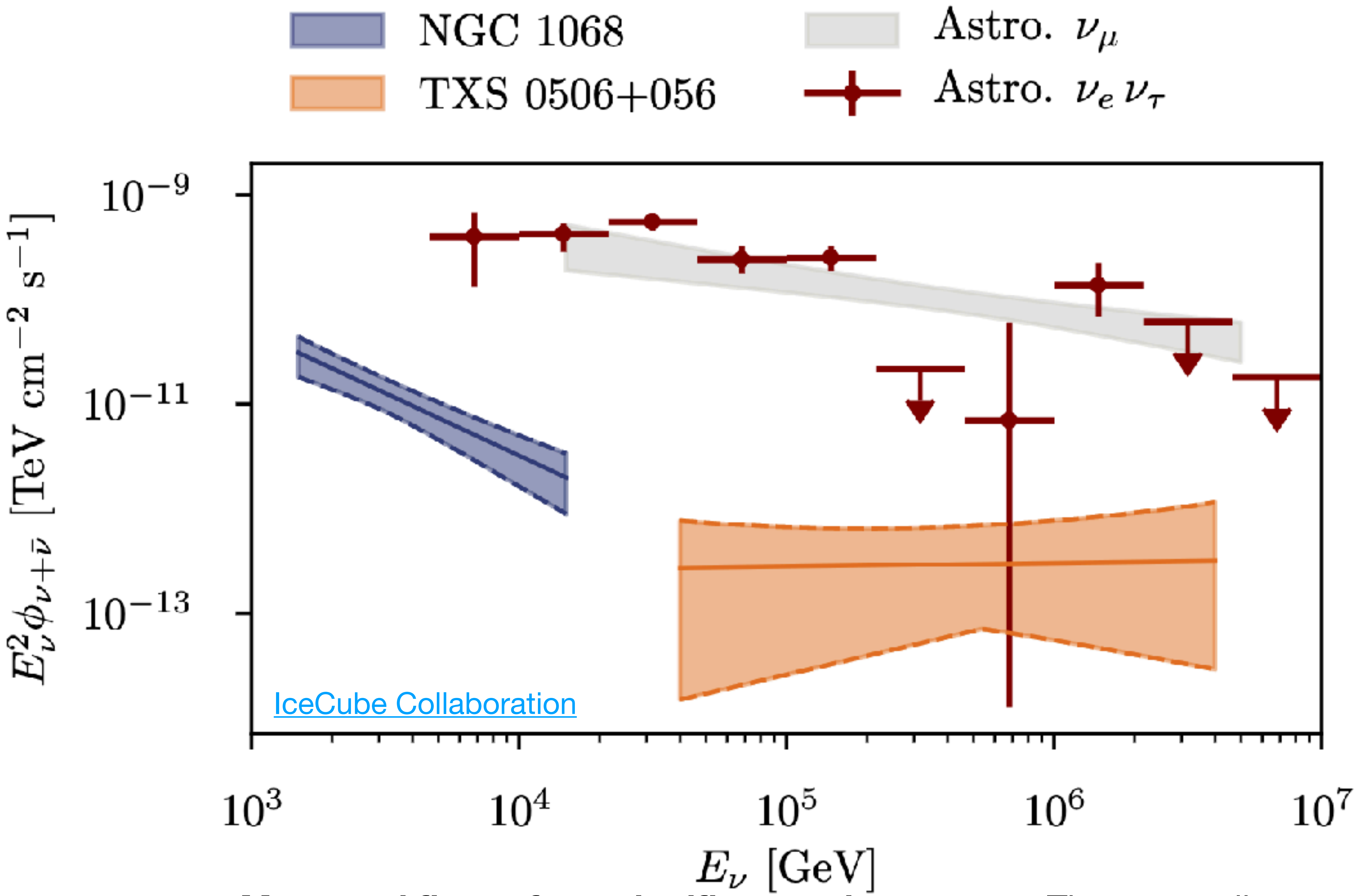




The First Strong Evidence of Neutrino Sources

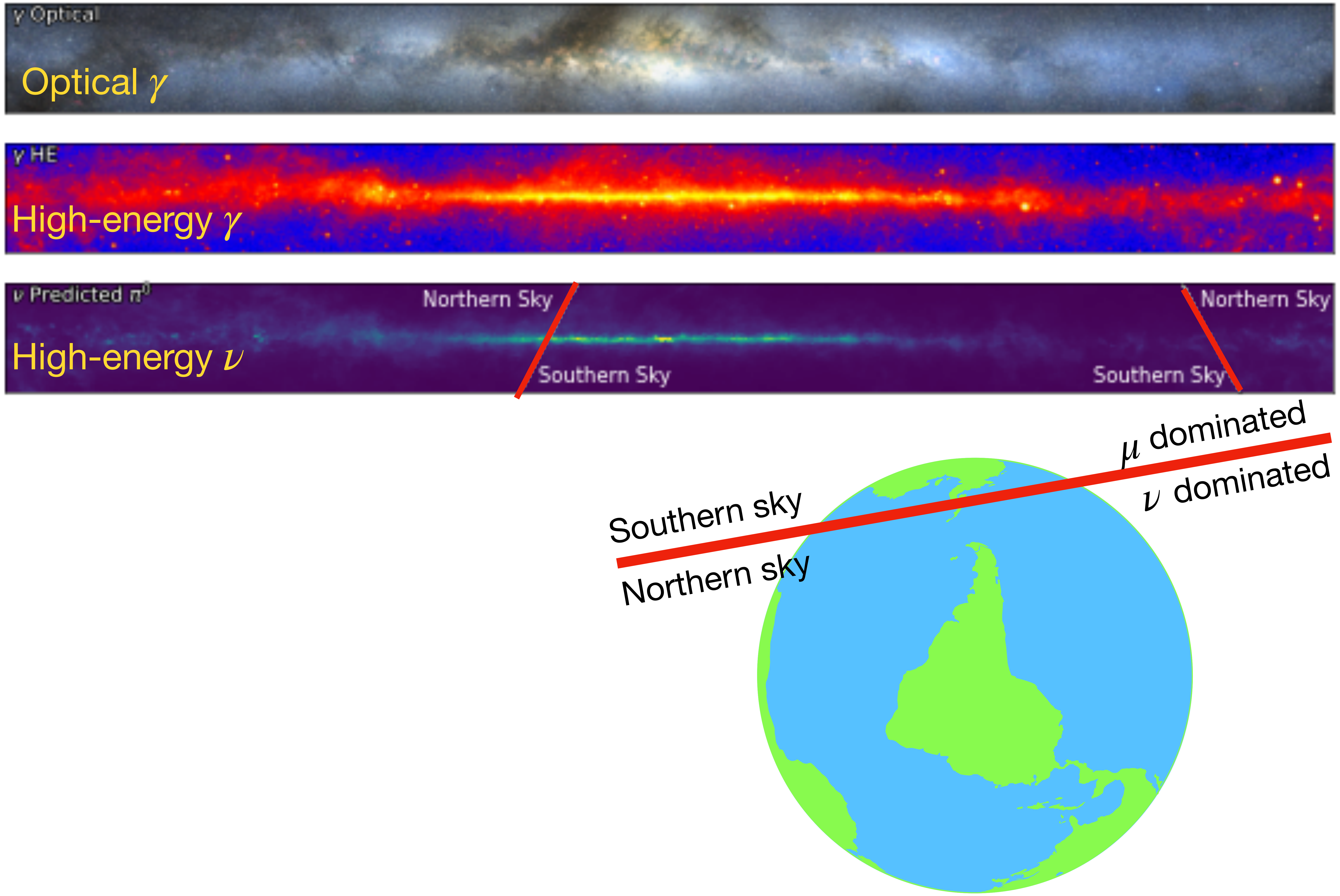


Events as a function of opening angle from NGC-1068. As one can see there is a distinct peak at angles between 0°^{2} and 0.3°^{2}



Measured fluxes from significant point sources. These contribute to the total flux at the percent level

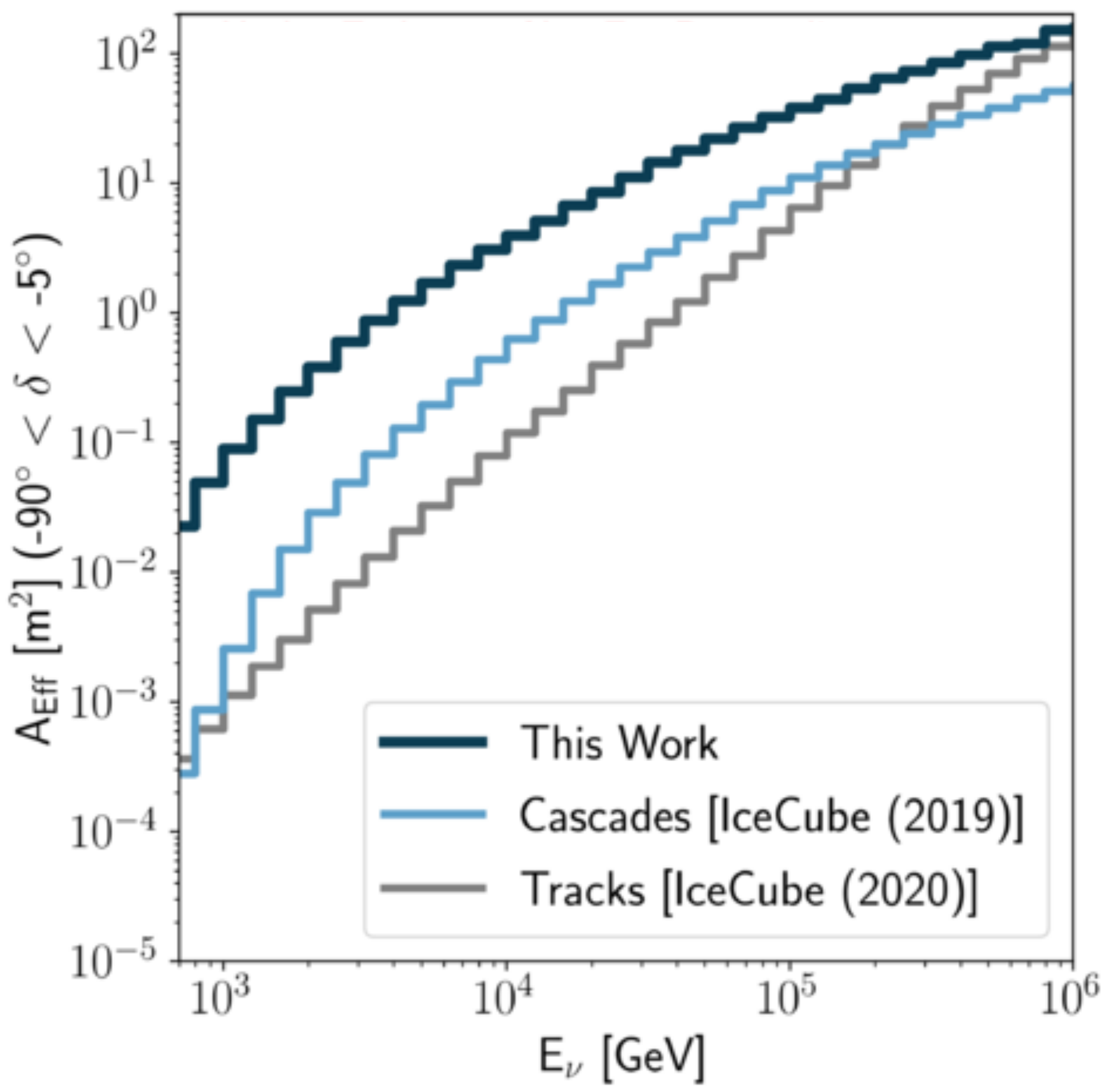
Neutrinos From Our Back Yard

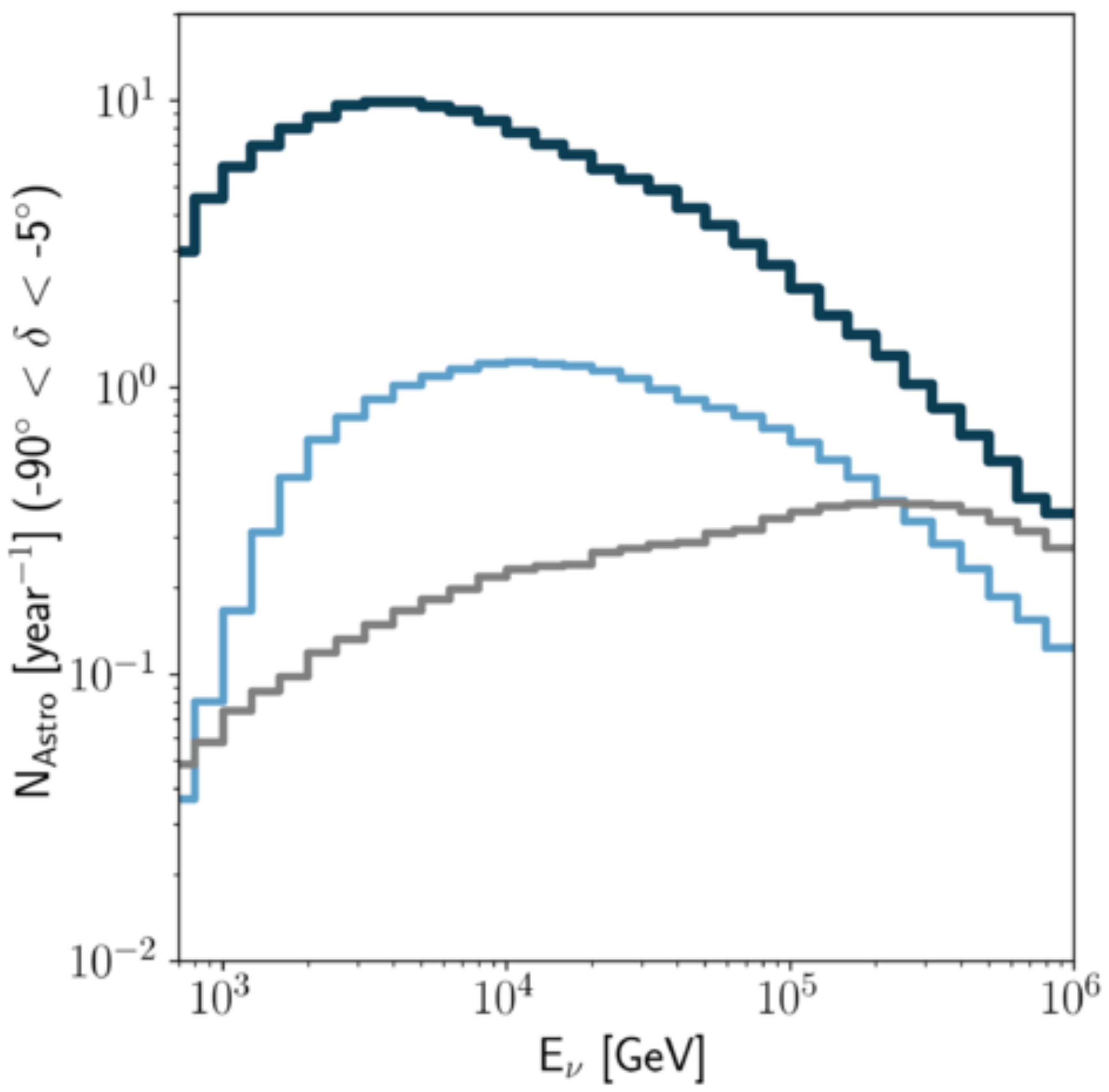


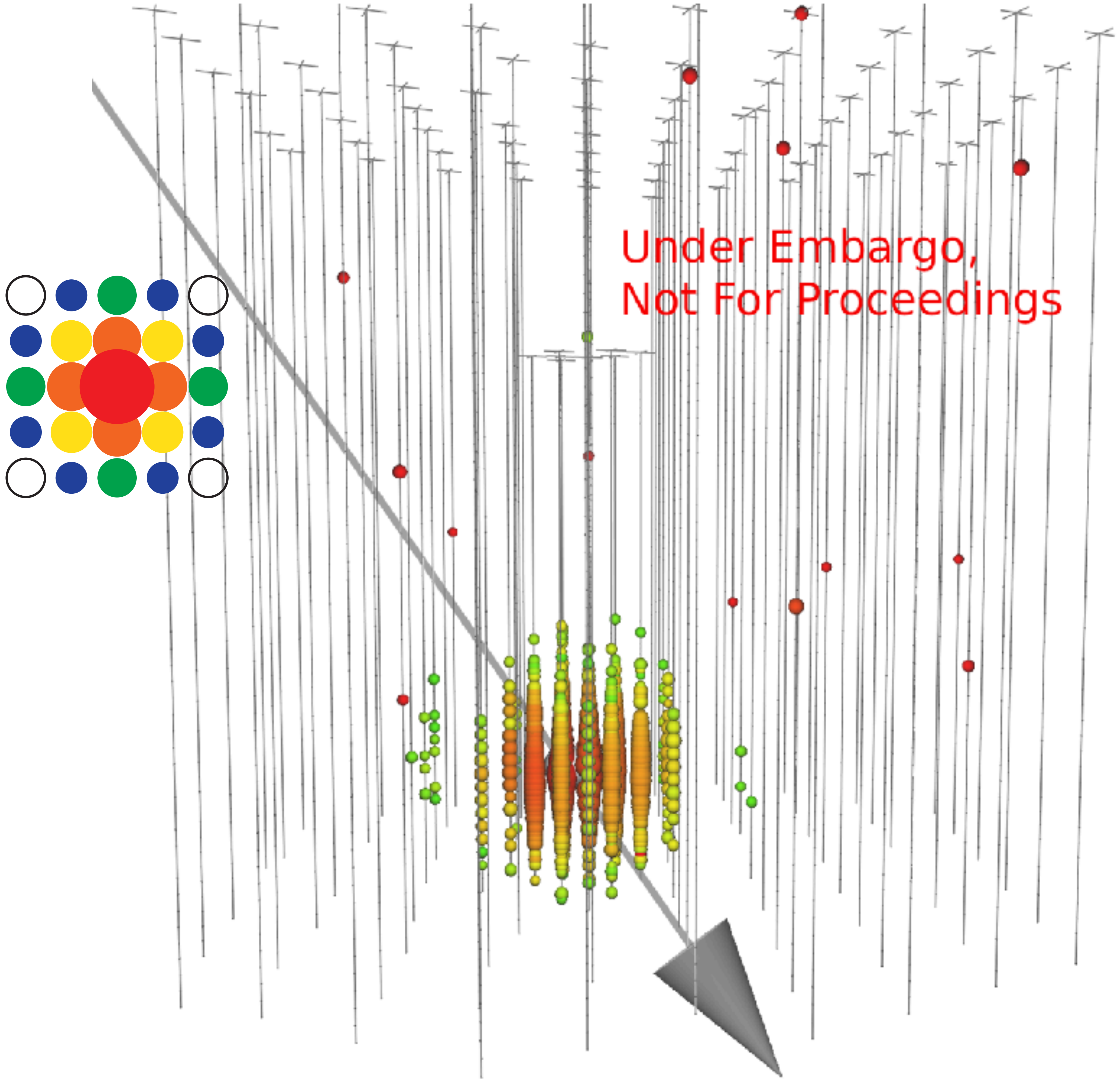
- There should be a neutrino counterpart to galactic γ rays
- Galactic center and much of galactic plane in southern sky $\implies$ tracks will be difficult !

Cascades to the Rescue

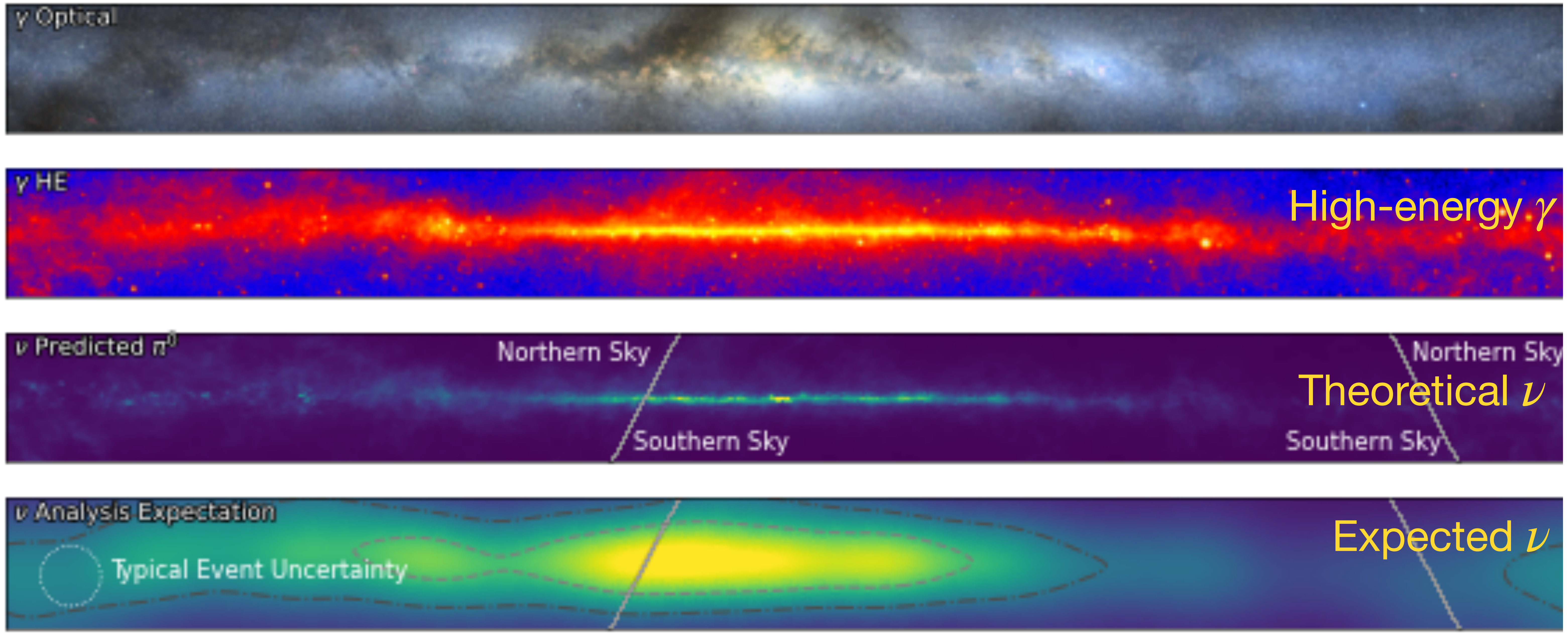
- Containment cuts allow on to veto atmospheric μ
- Order of magnitude increases in acceptance in southern sky

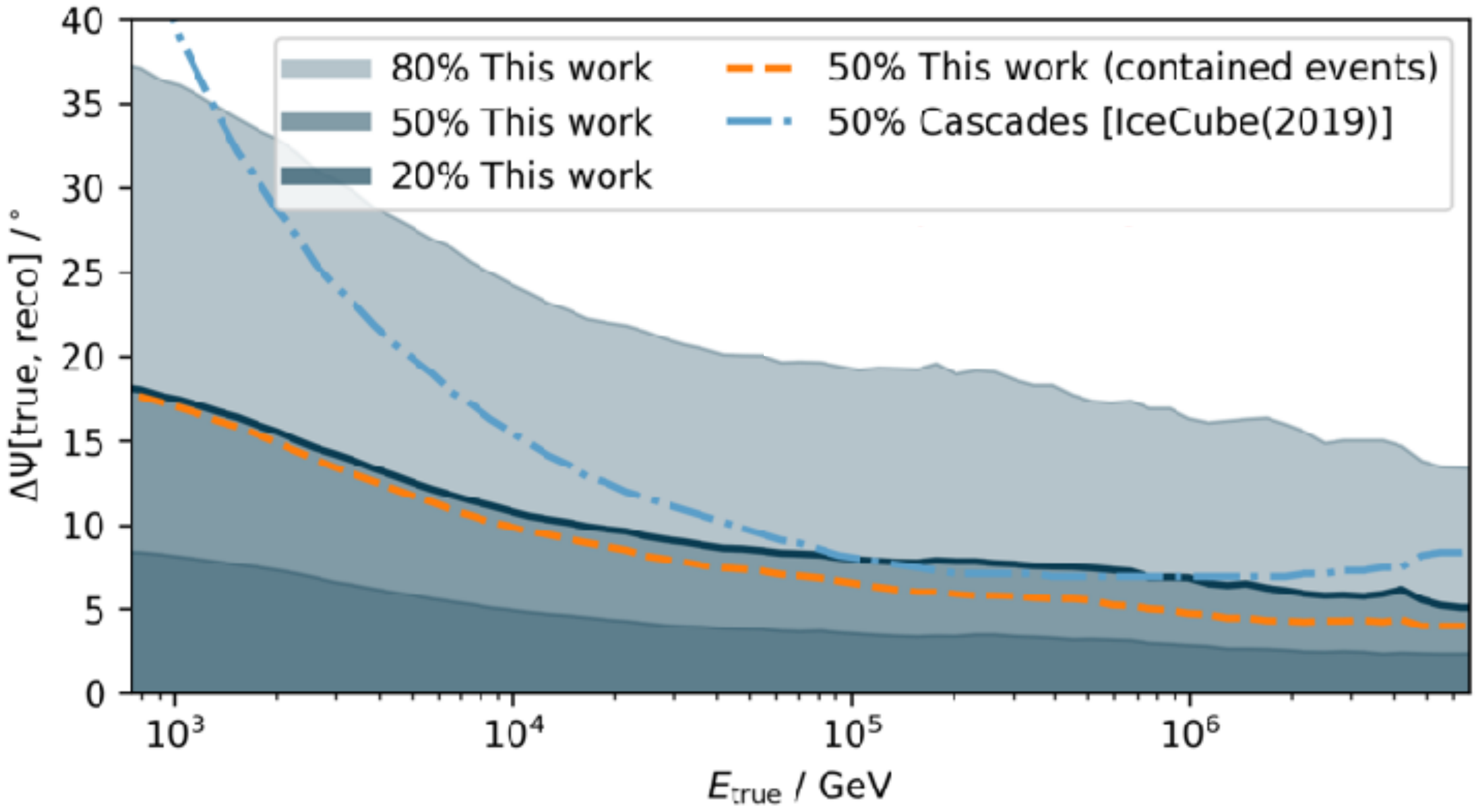






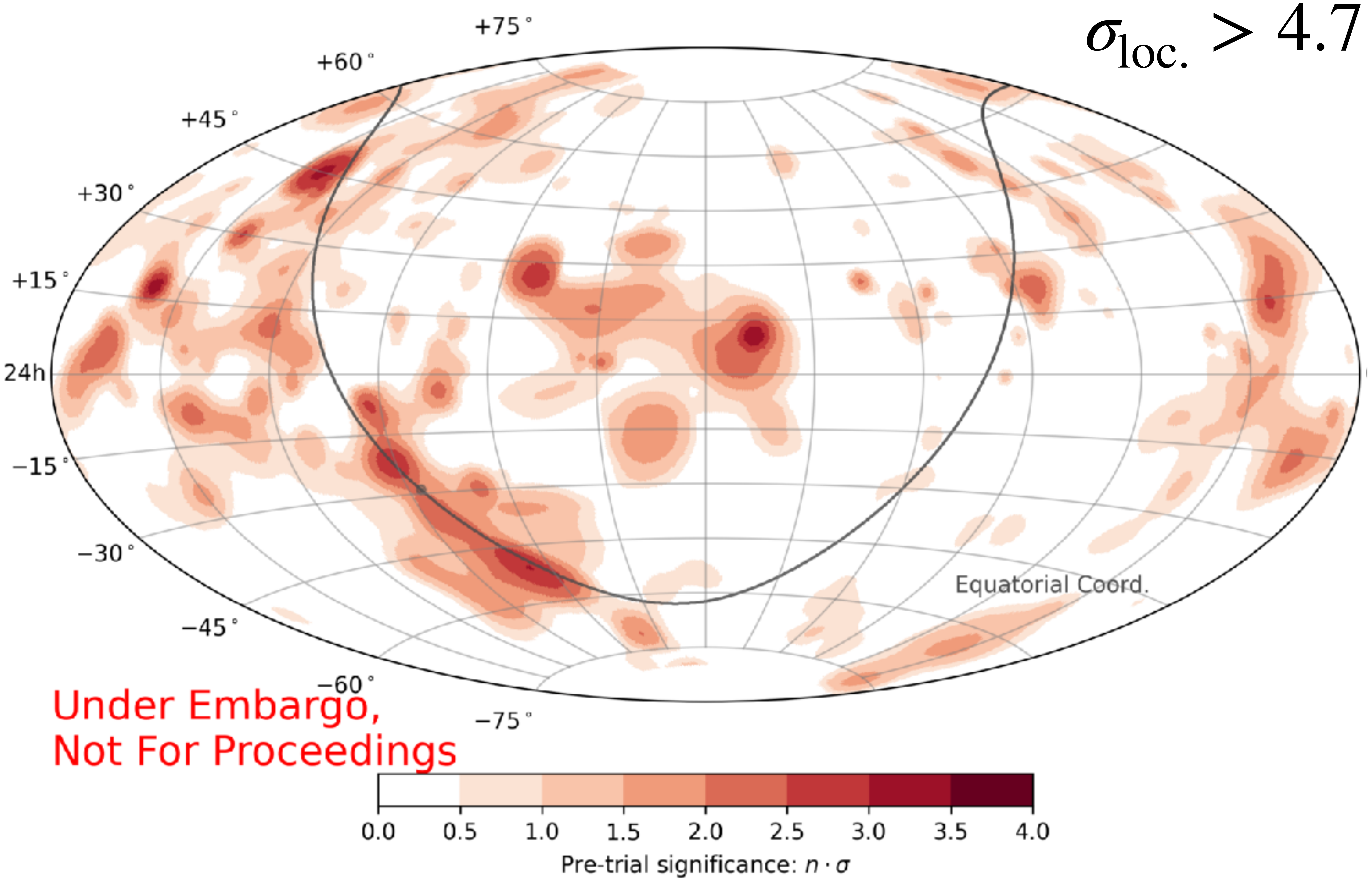
Predicted Distribution

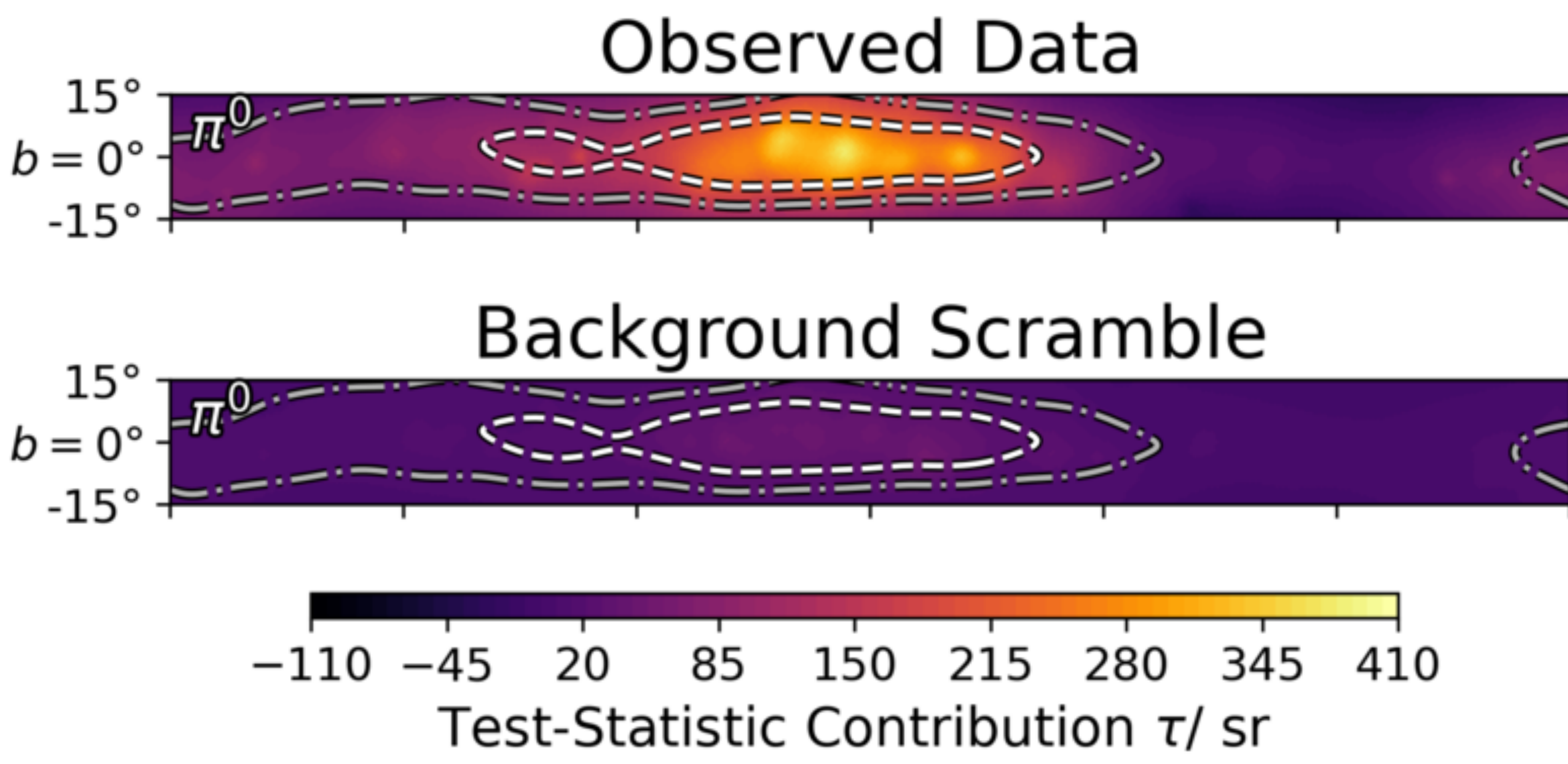




High-Significance Observation of the Galactic Plane

$\sigma_{\text{loc.}} > 4.7$





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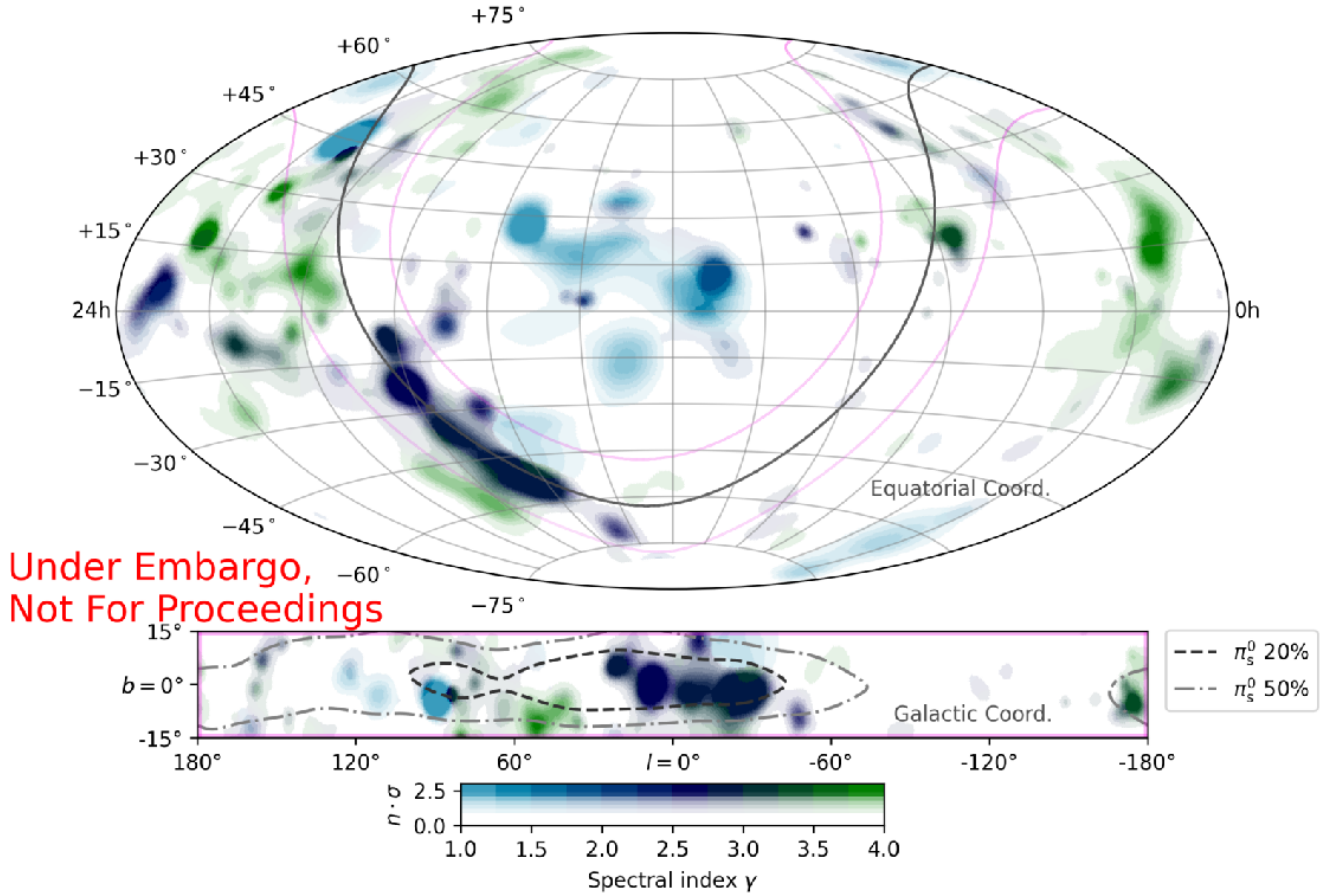

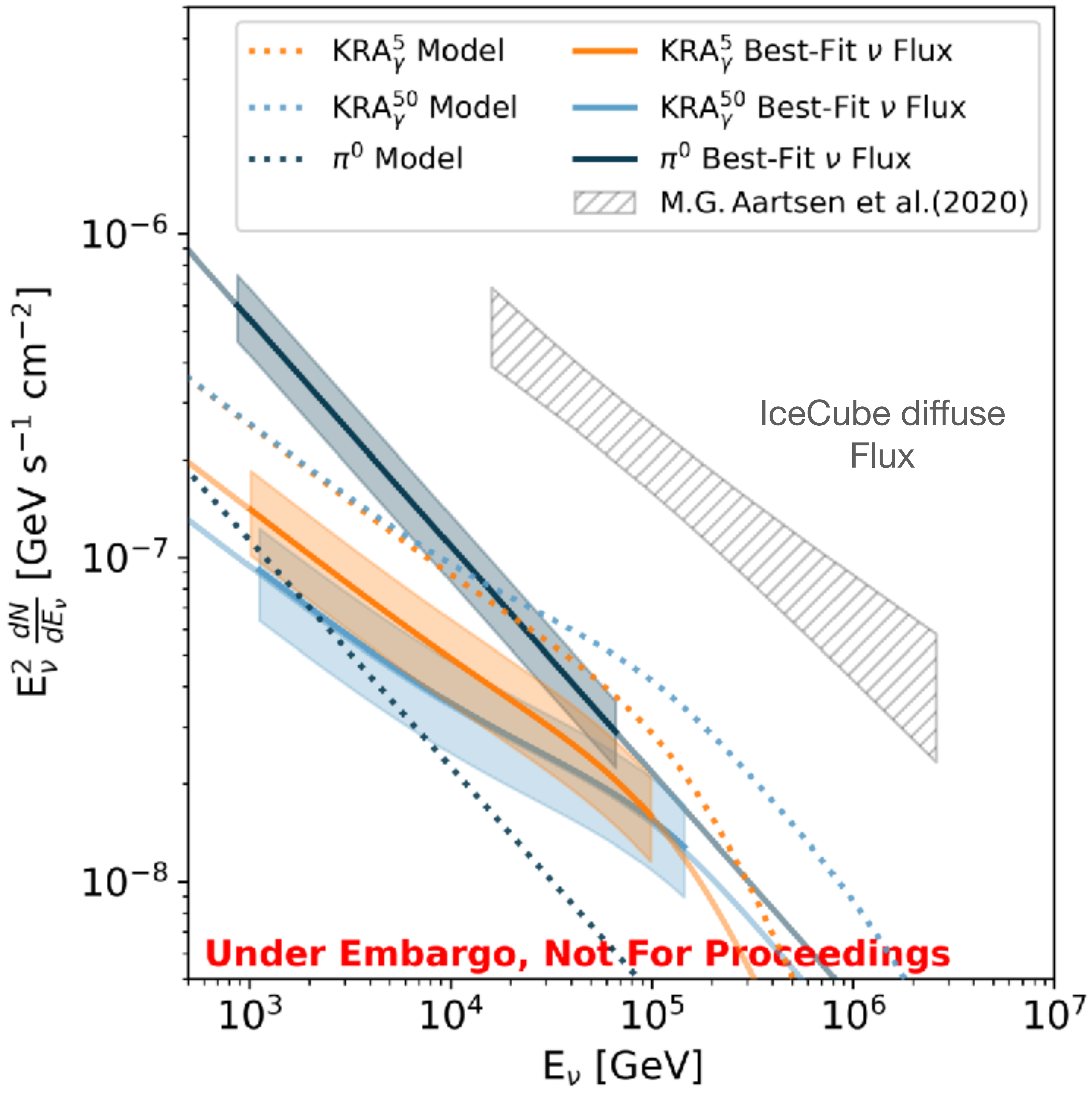


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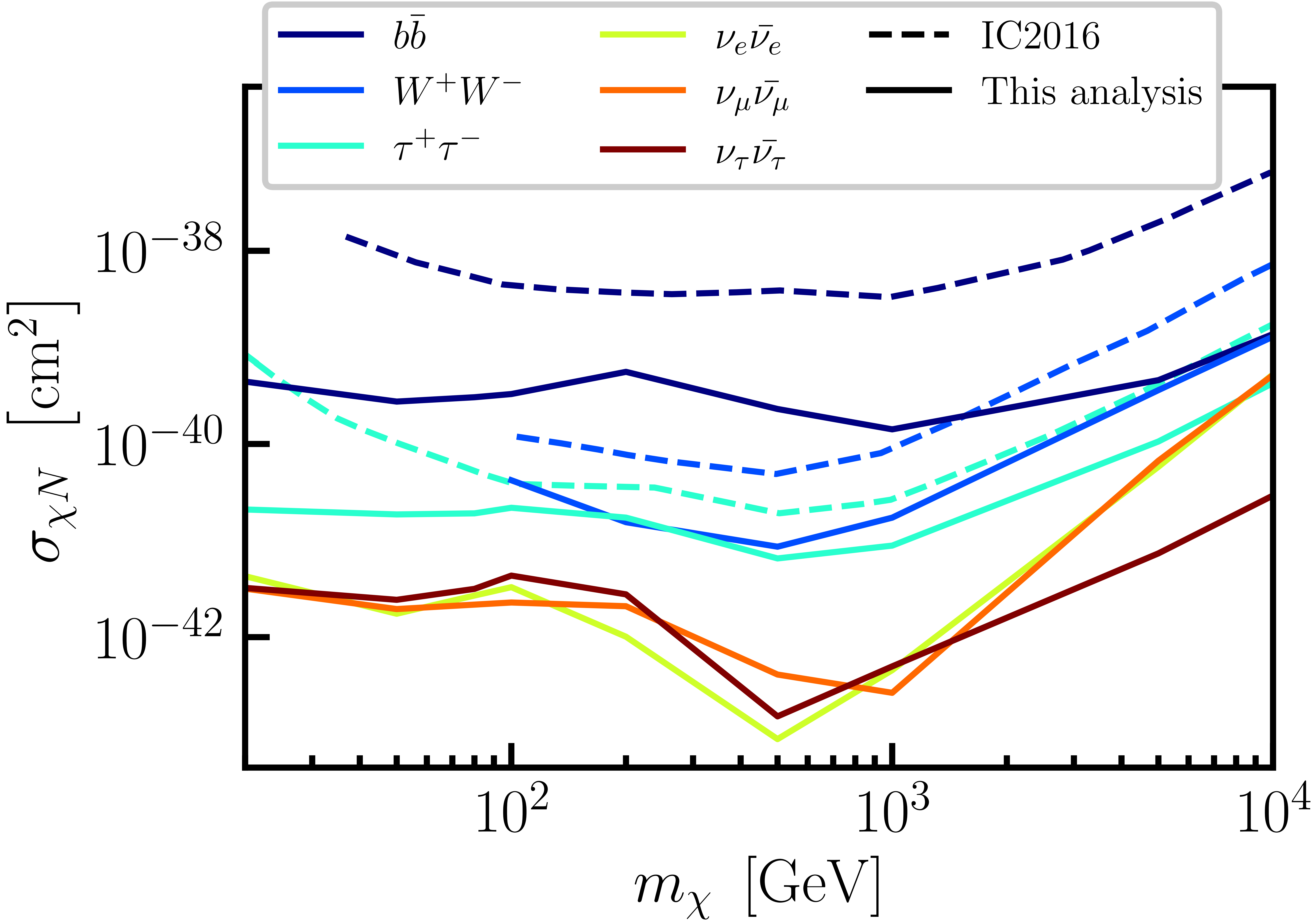
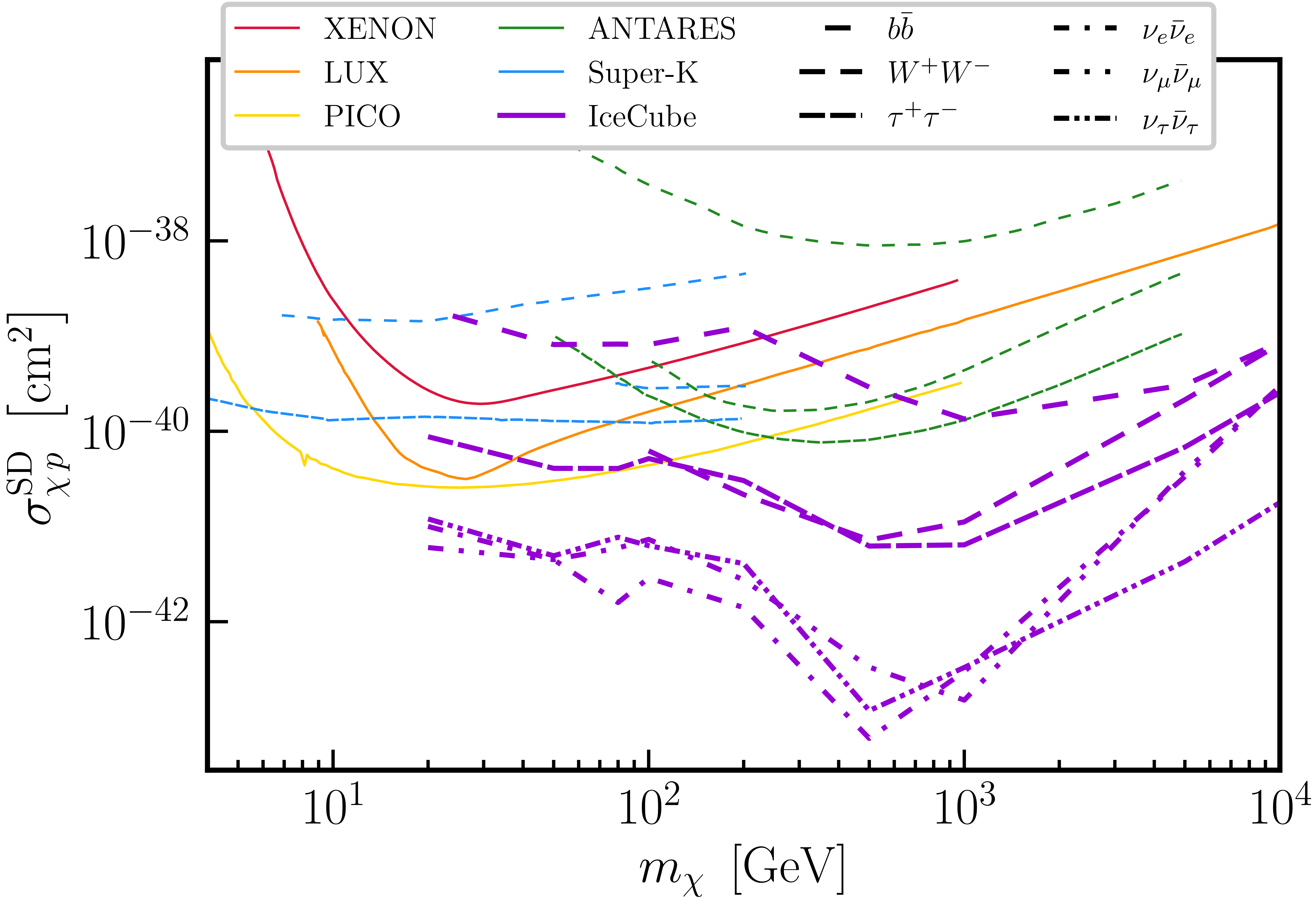
An All-Energy Solar WIMP Search

- Combined data from main array and DeepCore gives sensitivity to three order of magnitude of WIMP masses
- Order-of-magnitude improvements at lowest and highest energies compared to previous analysis

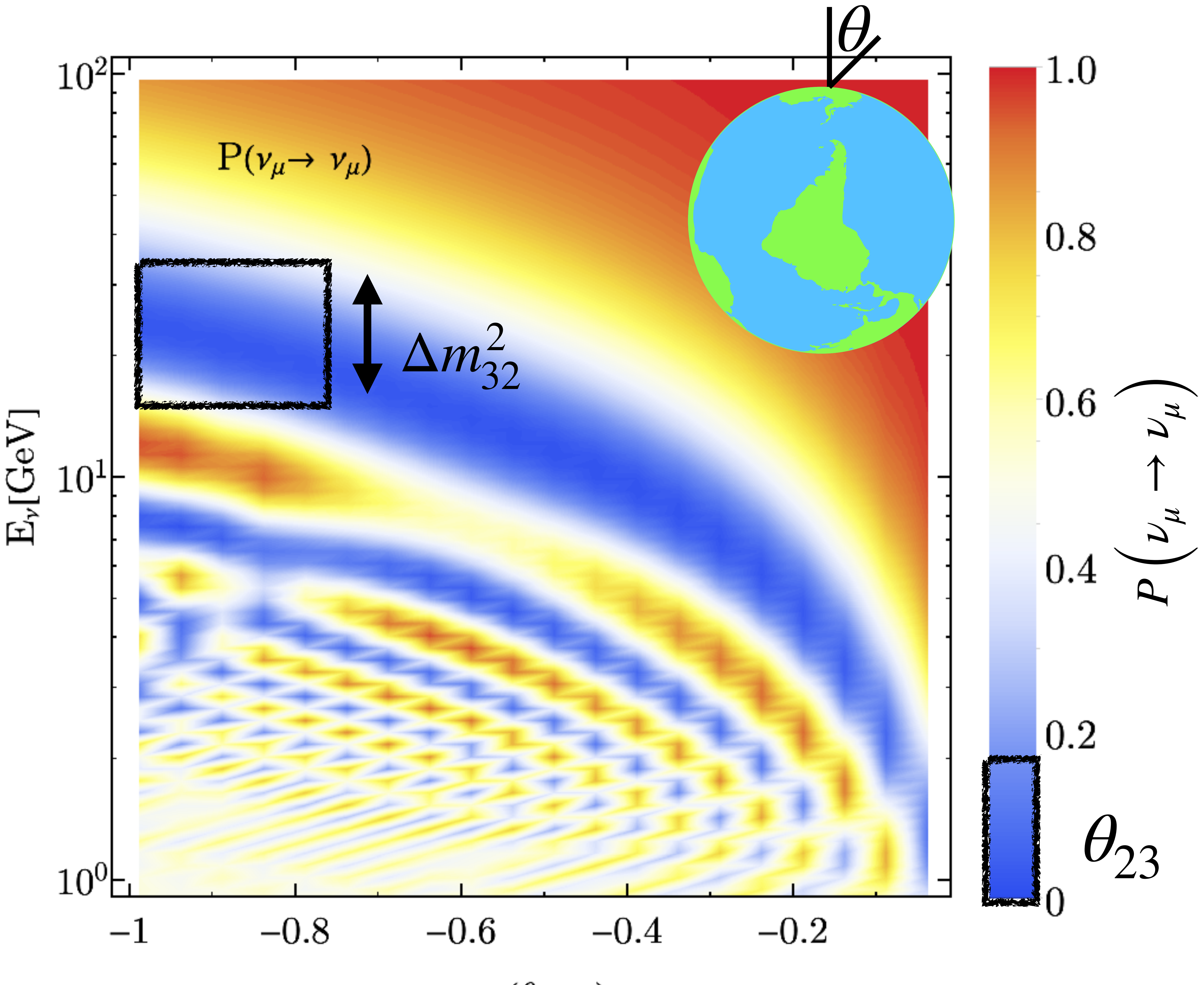


World-Leading Limits

- Unfortunately, we did not find dark matter
- Limits on spin-dependent WIMP-nucleon cross section are world leading above 100 GeV for most annihilation channels



Atmospheric Neutrino Oscillations



C.A. Argüelles, et al.

$$P_{\nu_\mu \to \nu_\mu} \sim 1 - \sin^2(2\theta_{23}) \sin\left(1.27 \Delta m^2_{23} \frac{L}{E}\right)$$

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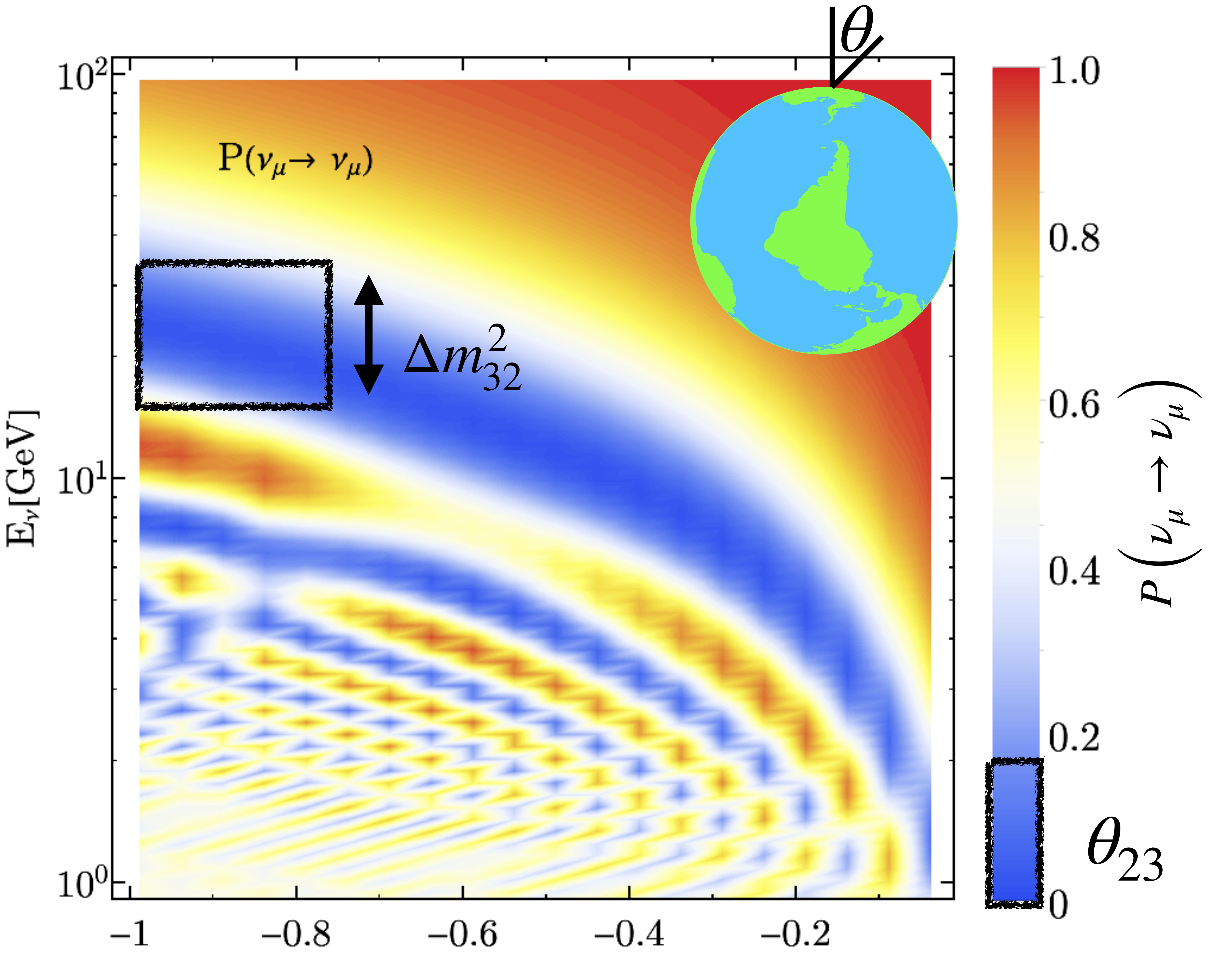

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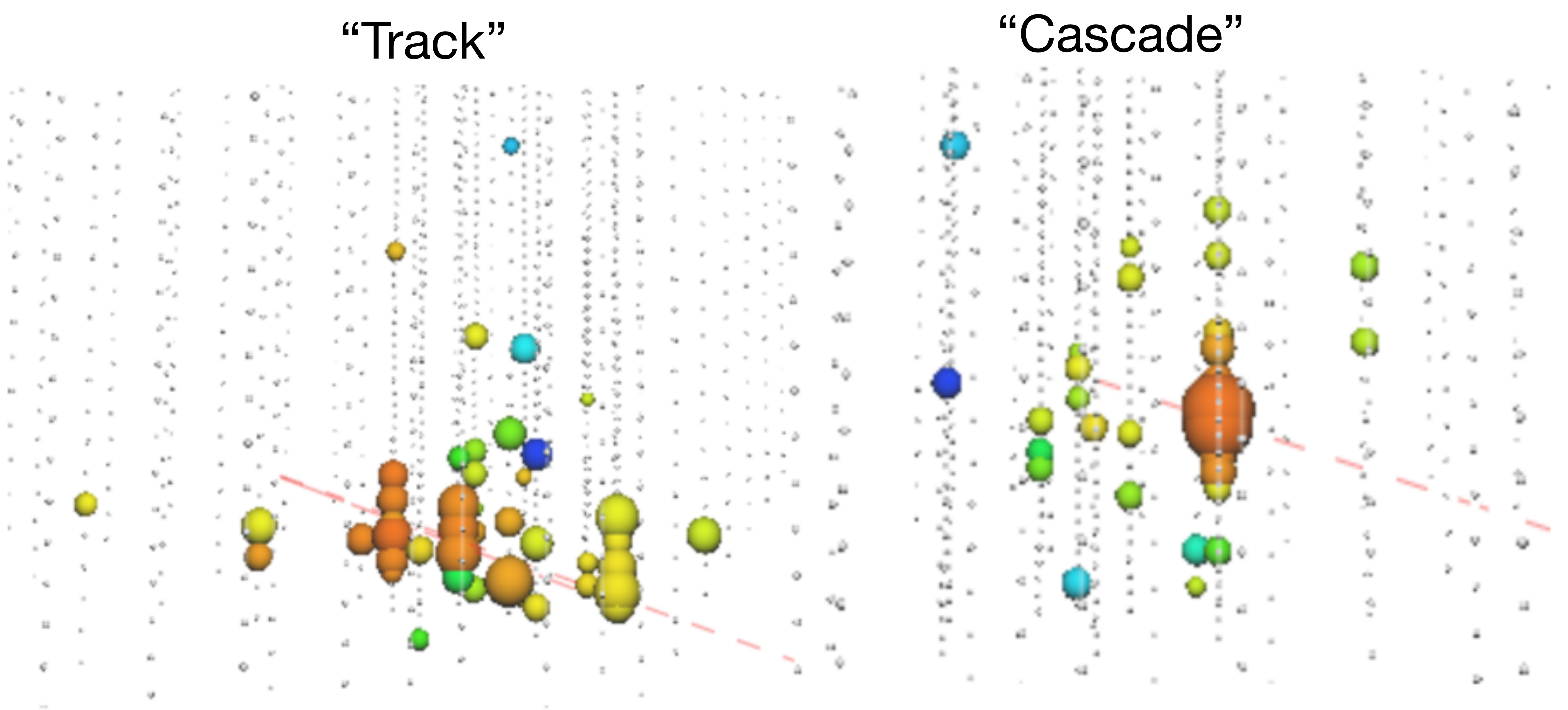
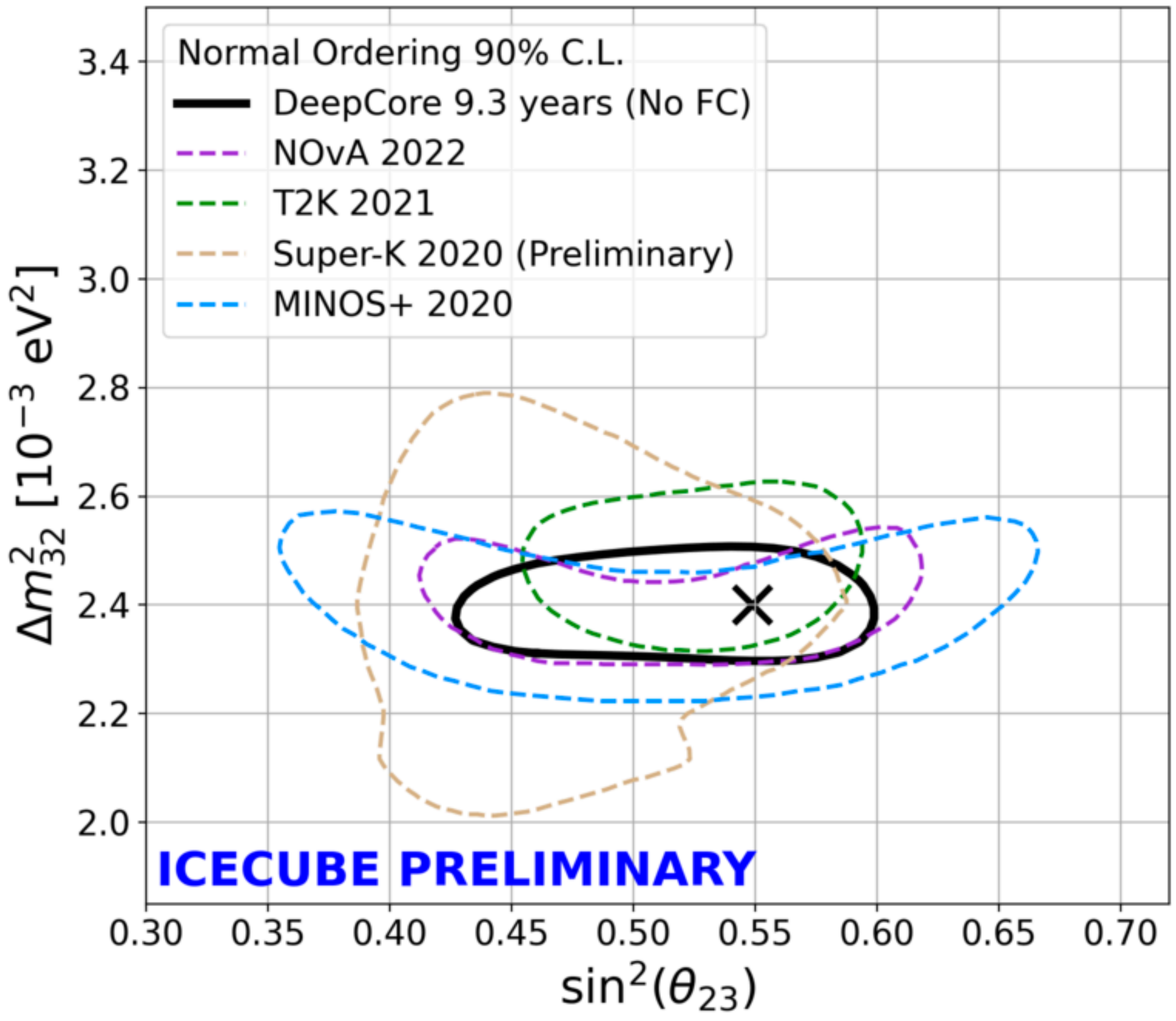


Look Out Accelerators !

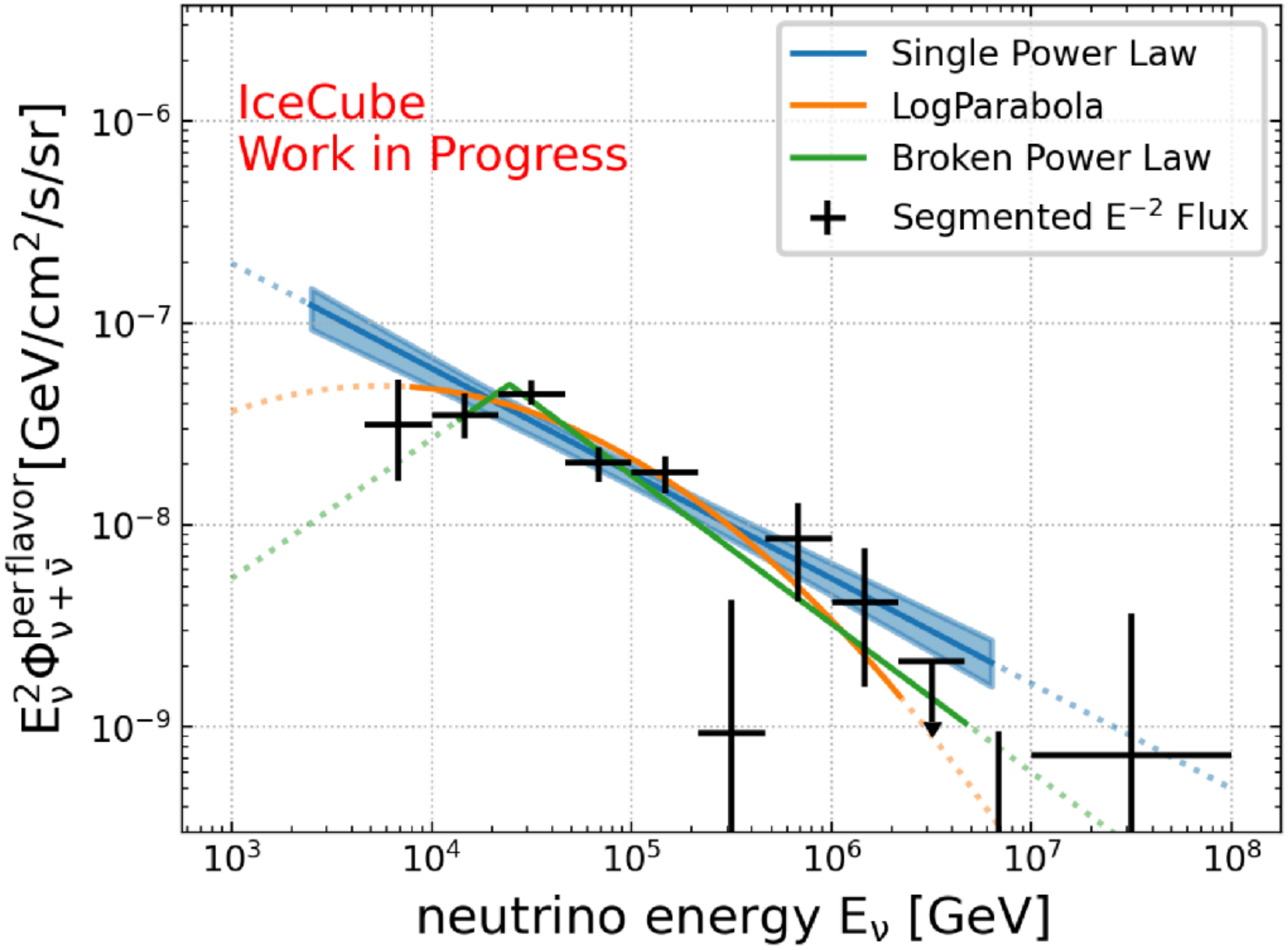


Atmospheric neutrinos have precision comparable to accelerator measurements !

A Decade of Success

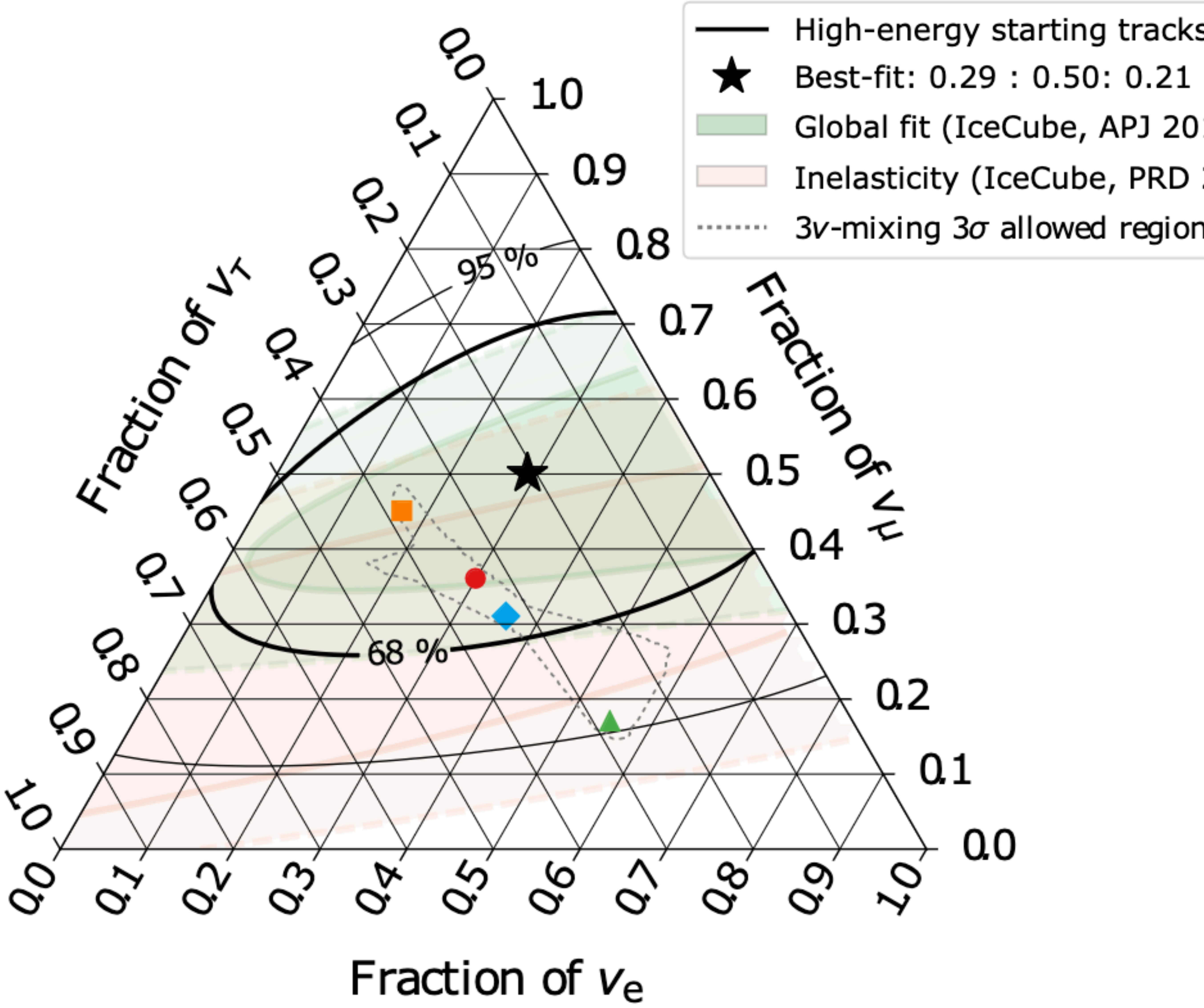
- In it’s first decade of operation, IceCube has opened the window to the neutrino universe
  - We are seeing the first hints of galactic and extragalactic neutrino sources
  - Neutrino parameter measurements from neutrino telescopes is comparable with accelerator measurements and will outstrip these in the next decade
  - A robust BSM program is searching for possible signs of new physics in the weak sector
- However, despite a promising first decade, there are certain challenges that IceCube cannot address alone

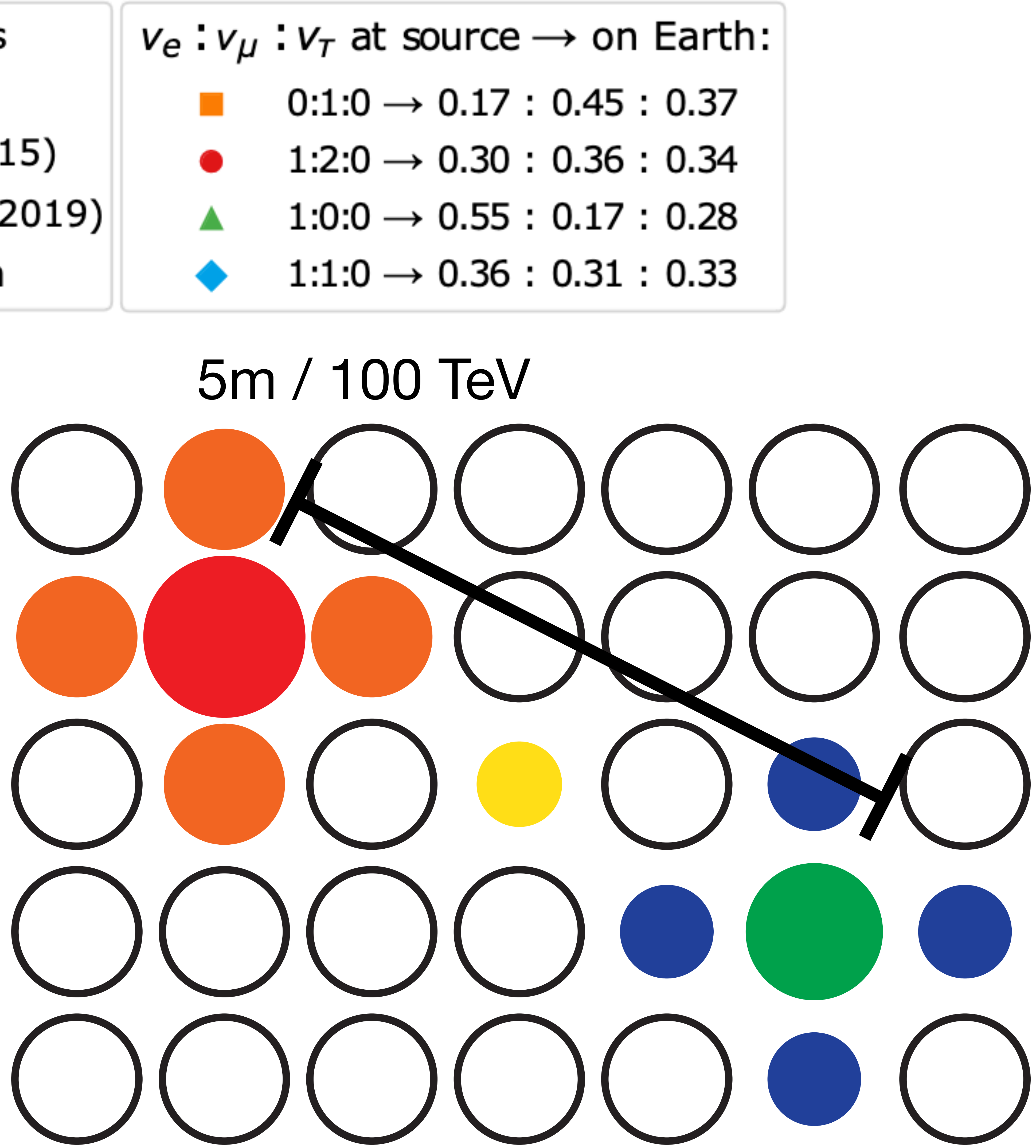
New shapes



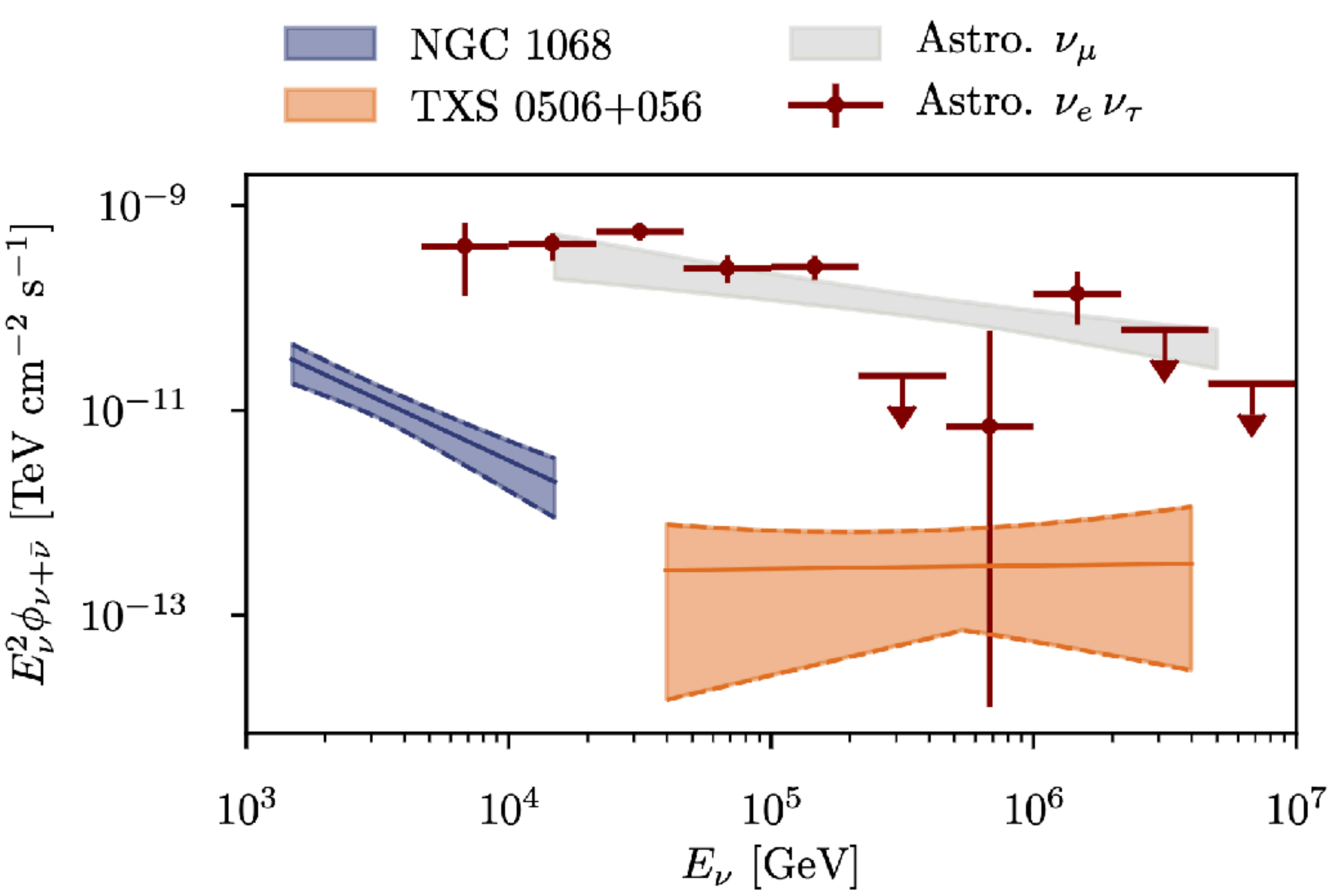
- Most recent global fit of the data shows a moderate preference flux models besides single power law
- Atmospheric neutrinos at low energy and small flux at high energies limit our ability to resolve this
- Both exotic shapes preferred over power law at $\sim 2\sigma$

Flavor Degeneracy





Where Are the Rest of the Sources ?



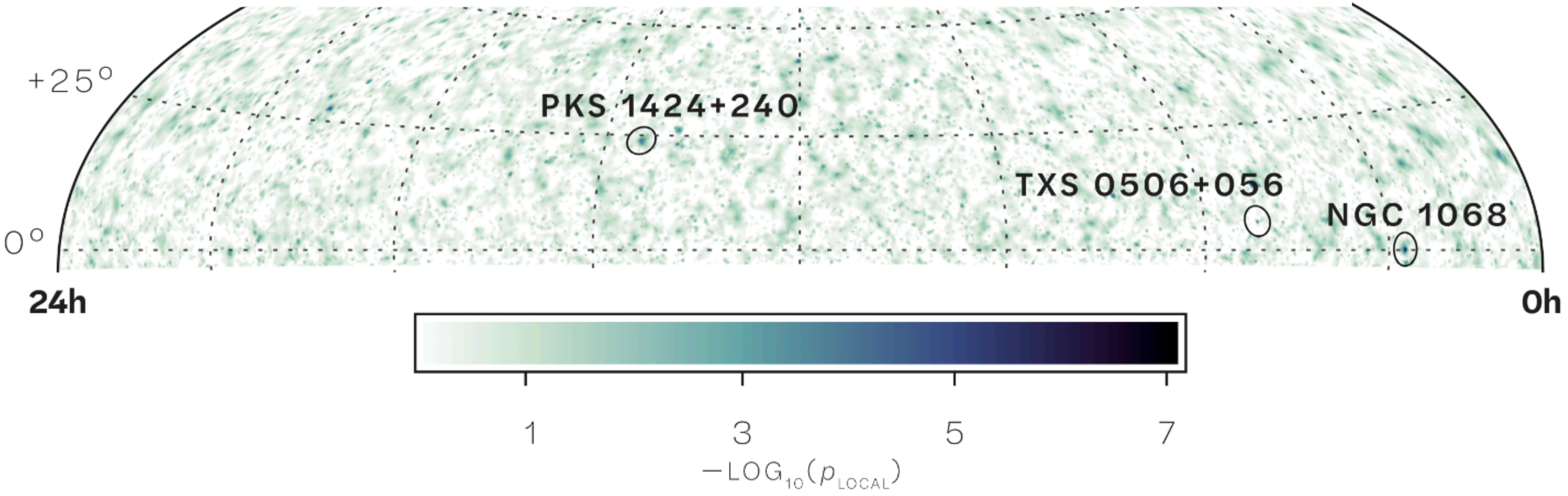
- IceCube has identified three point source candidates, two of which have enough event to fit a spectrum
- They can only make up a tiny fraction of the measured diffuse spectrum

Trials and Tribulations

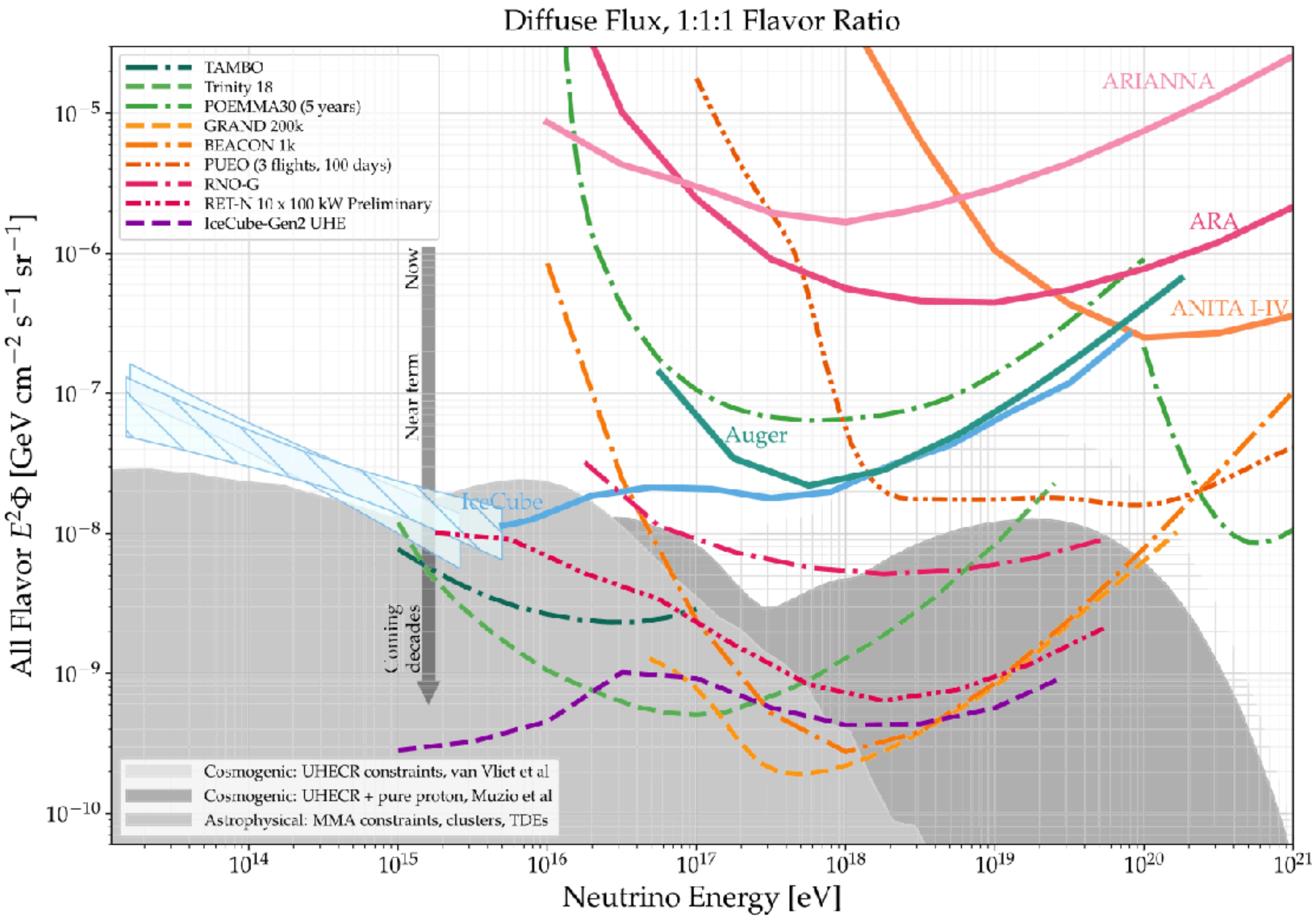
Test type	Pre-trial p-value (p_{local})	Post-trial p-value (p_{global})
Northern Hemisphere scan	5.0×10^{-8} ($5.3\,\sigma$)	2.2×10^{-2} ($2.0\,\sigma$)
List of candidate sources, single test	1.0×10^{-7} ($5.2\,\sigma$)	1.1×10^{-5} ($4.2\,\sigma$)
List of candidate sources, binomial test	4.6×10^{-6}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

$\sim 445{,}000$ trials

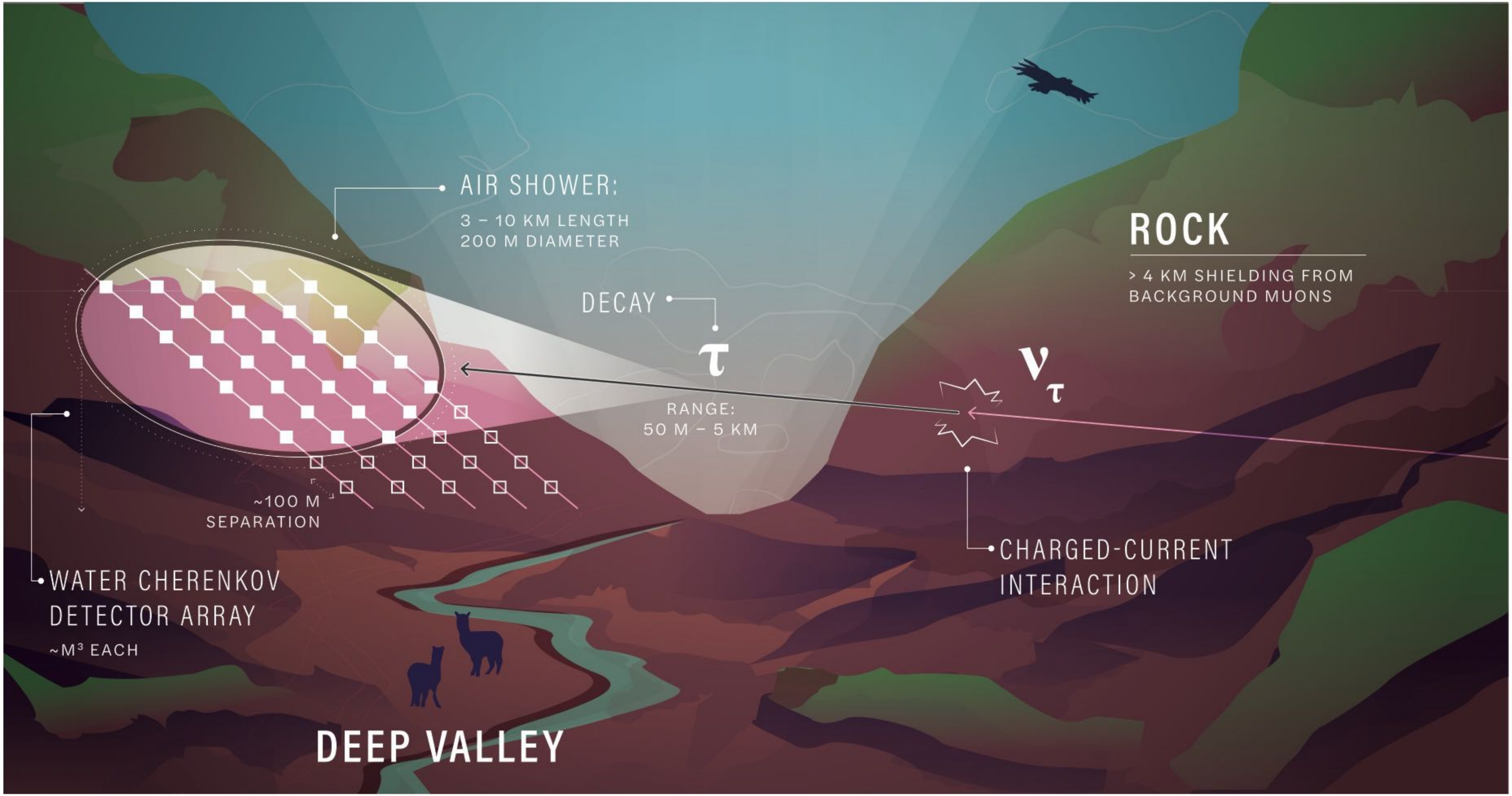
$\implies 19.8 \frac{\text{trials}}{\circ^2}$



We're Not Short on Ideas

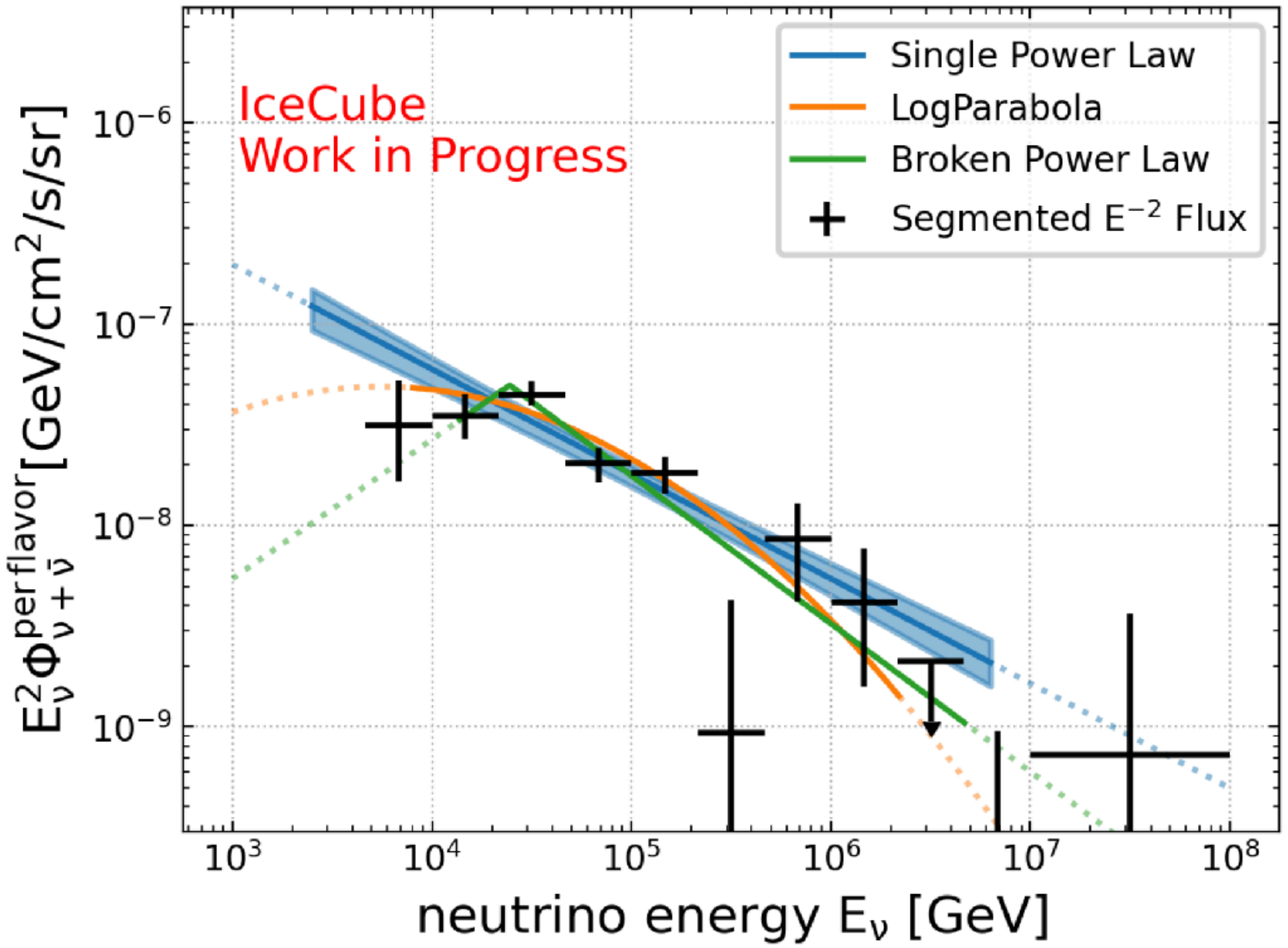


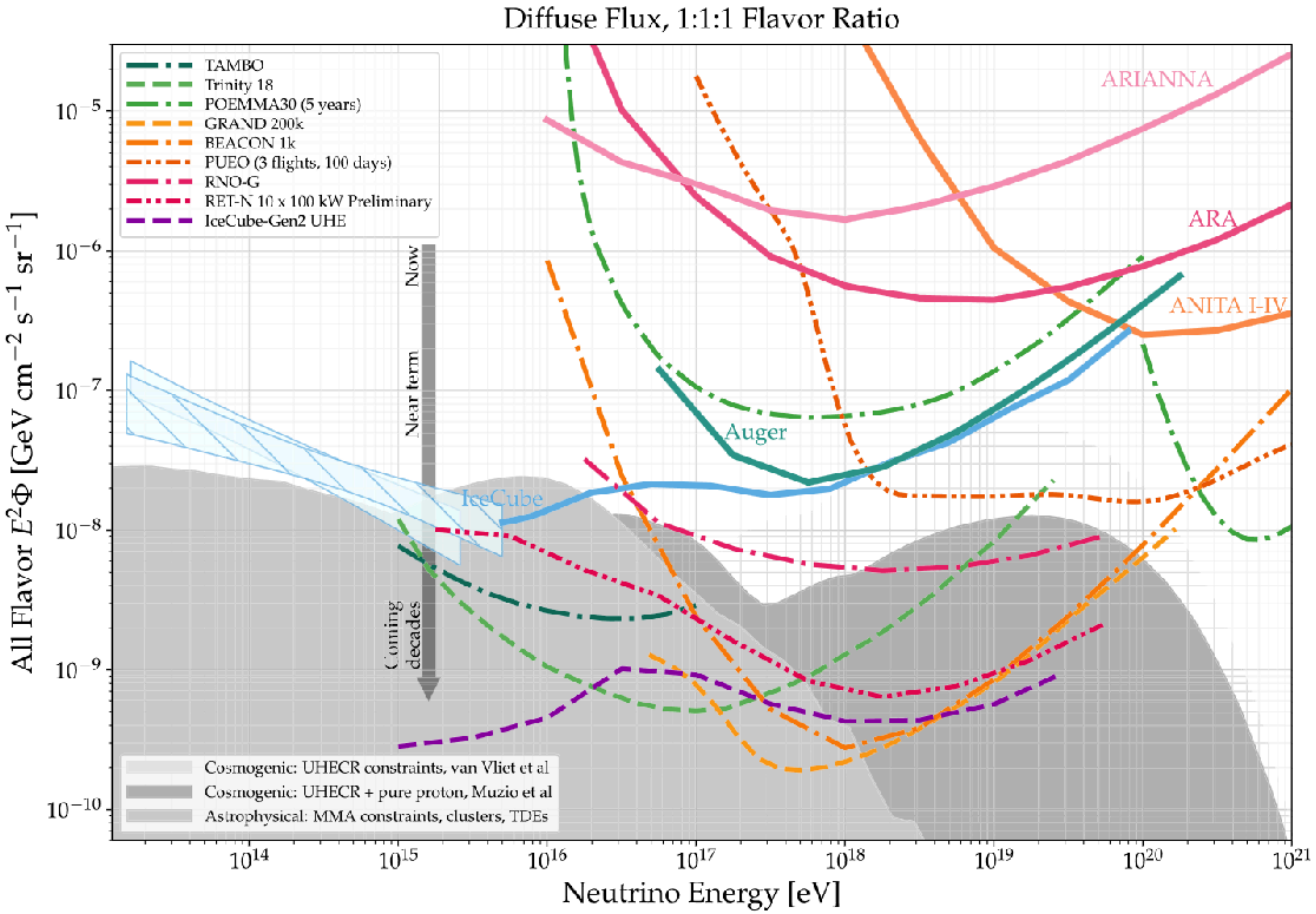
- Many next generation detectors will target 100 TeV to 10 EeV neutrinos
- New technologies and detector principles will enable this push



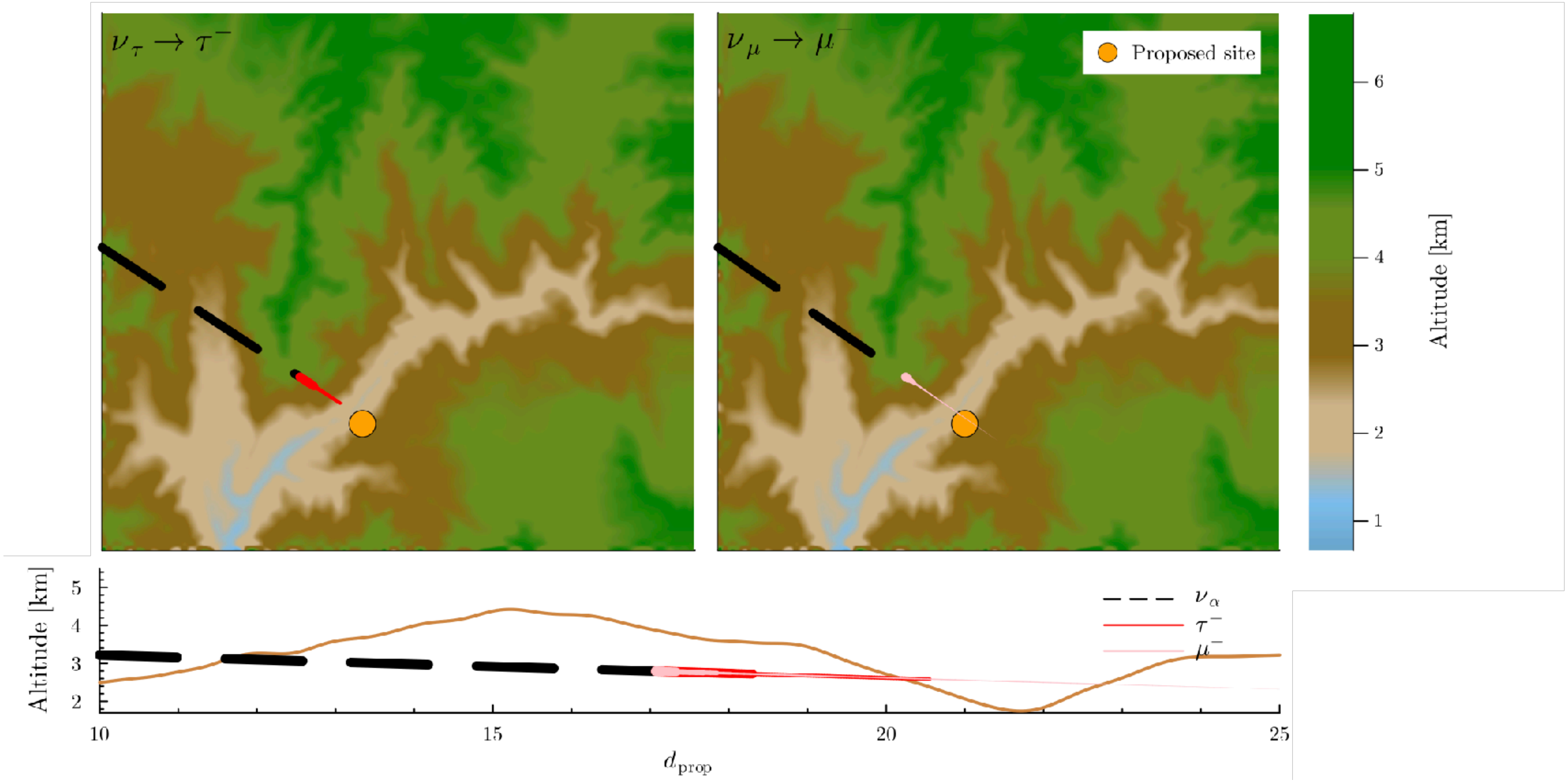
TAU AIR-SHOWER MOUNTAIN-BASED OBSERVATORY (TAMBO) · COLCA VALLEY, PERU

Passing the Energy Baton

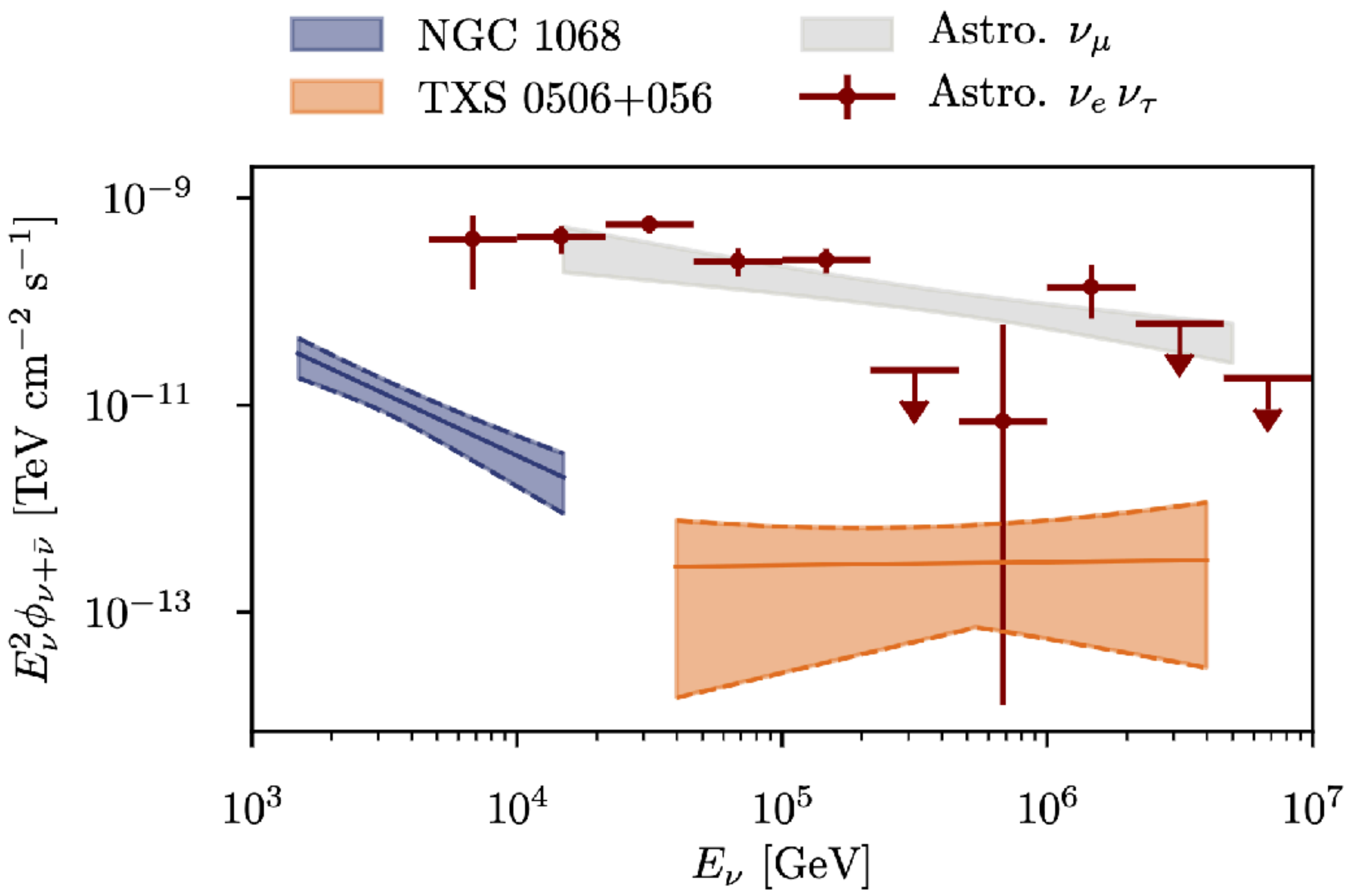


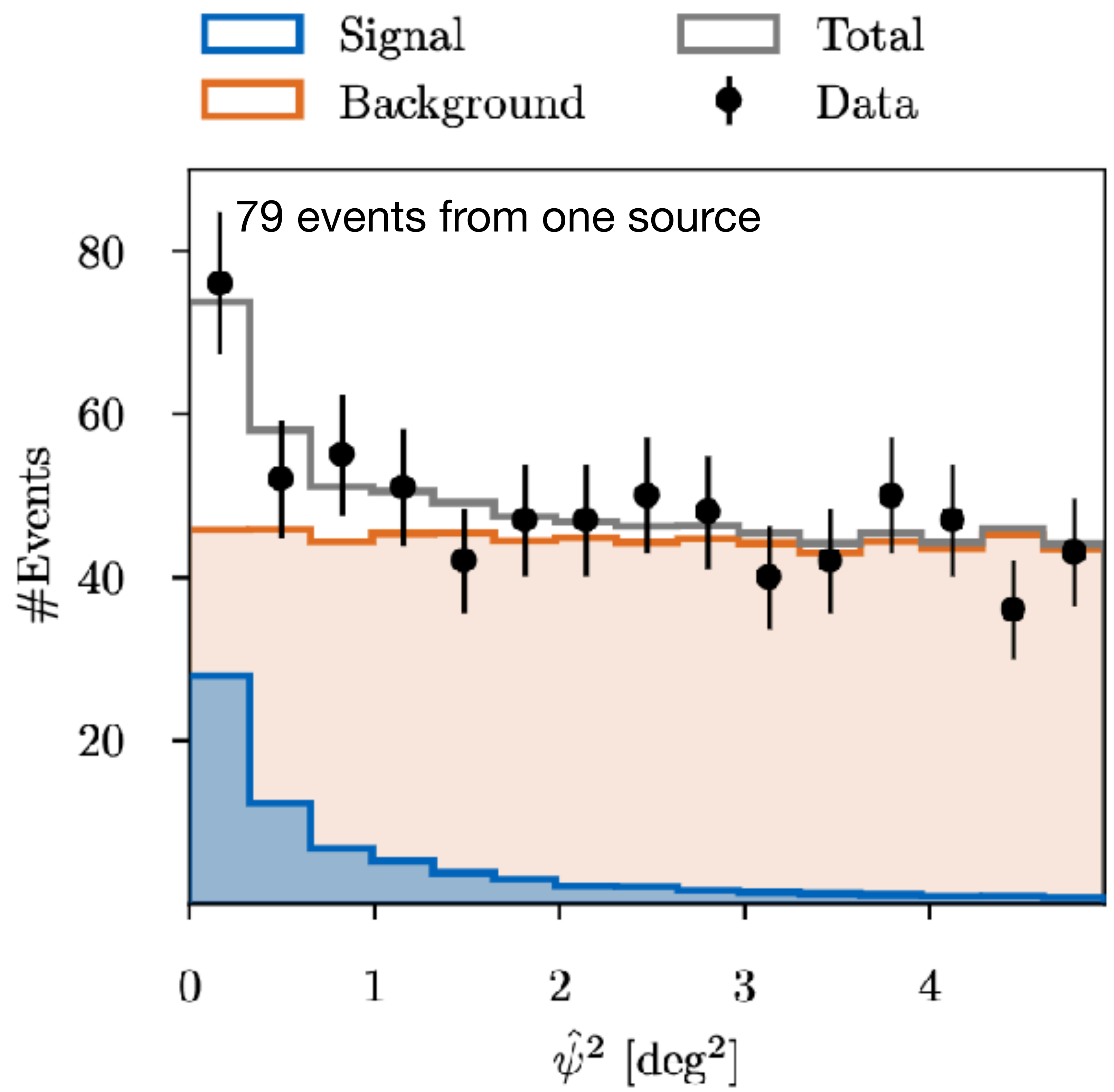


A ν_τ Sieve

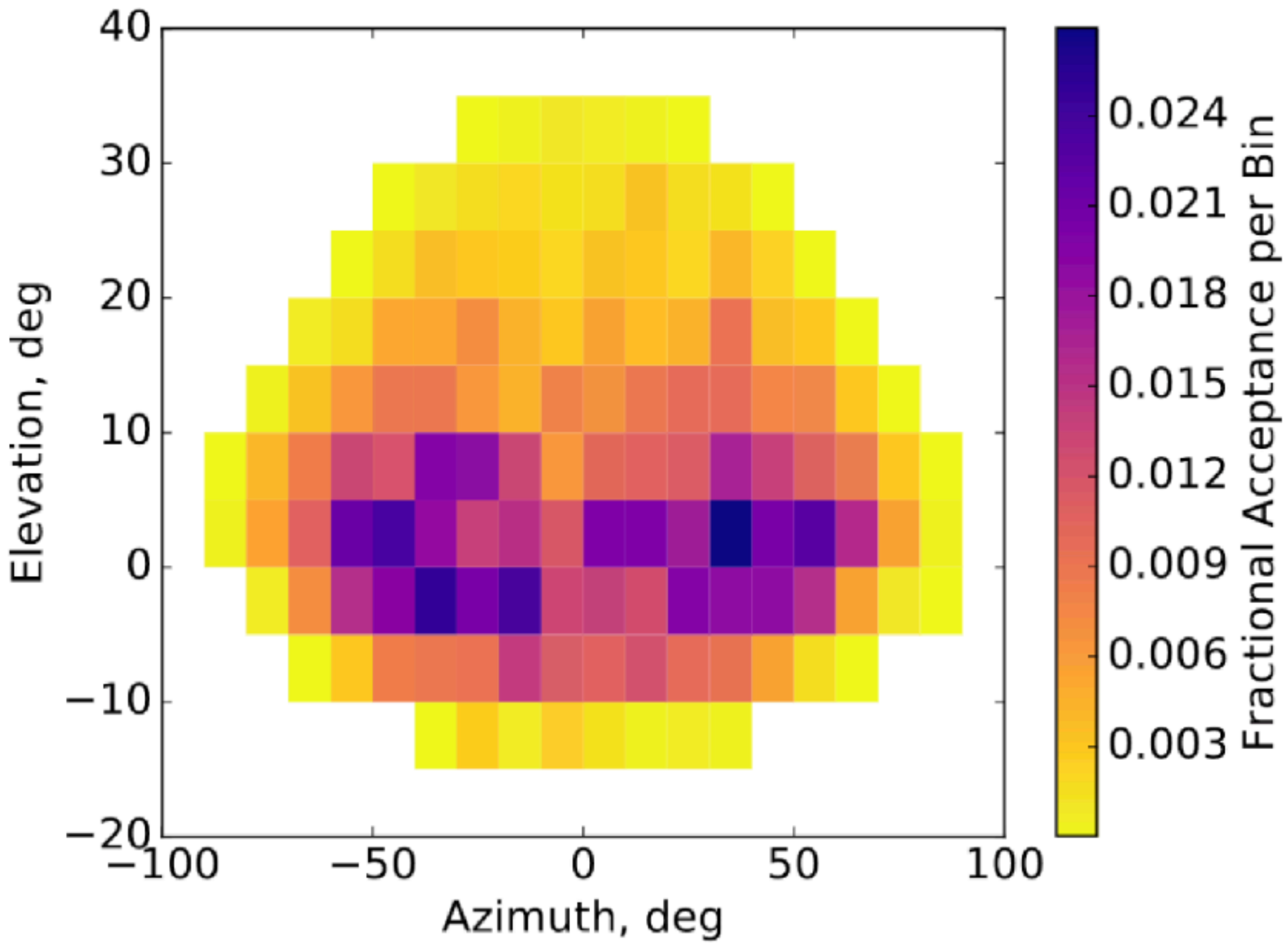


Power-Law Sources

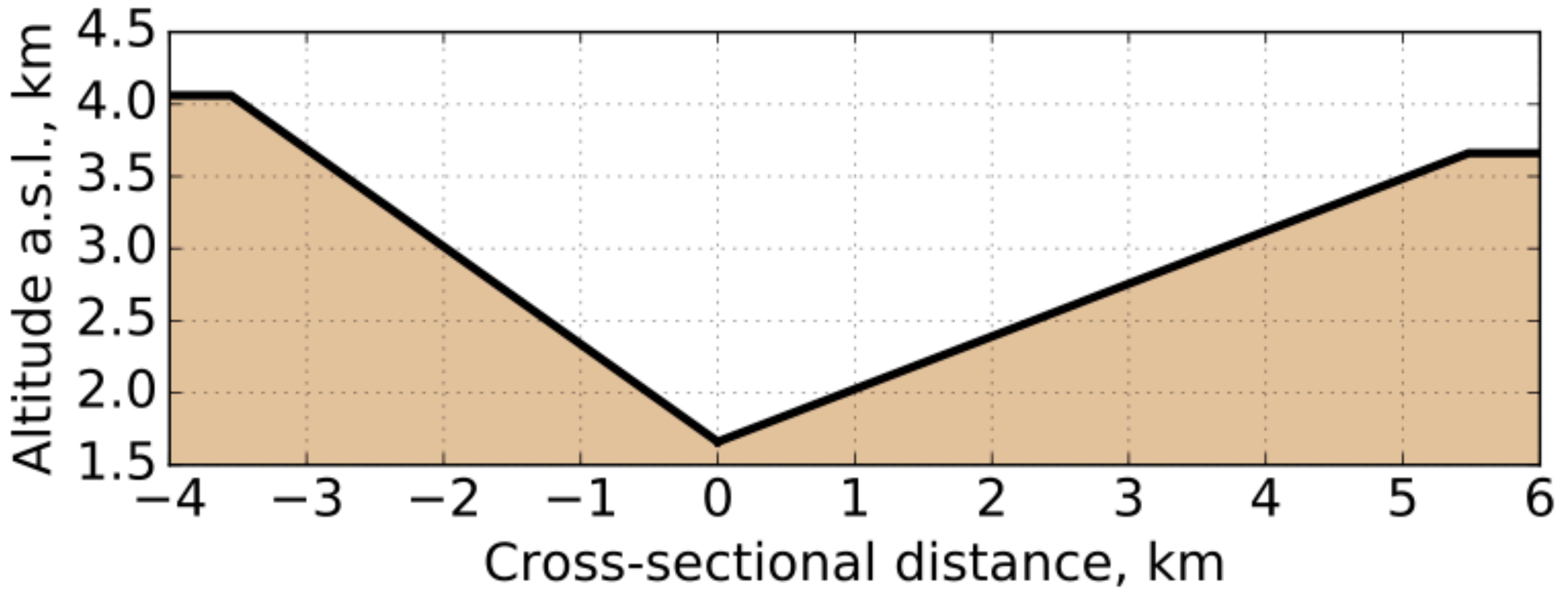




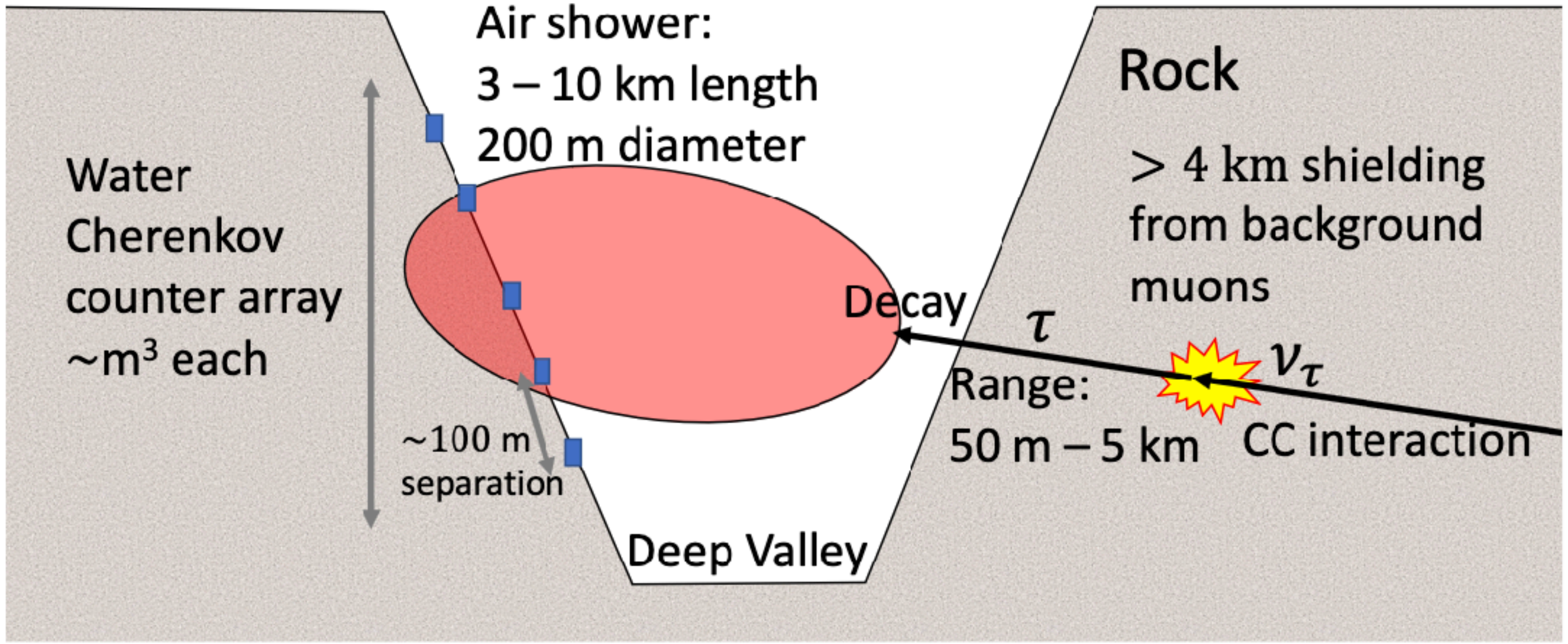
Is this totally crazy ?



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

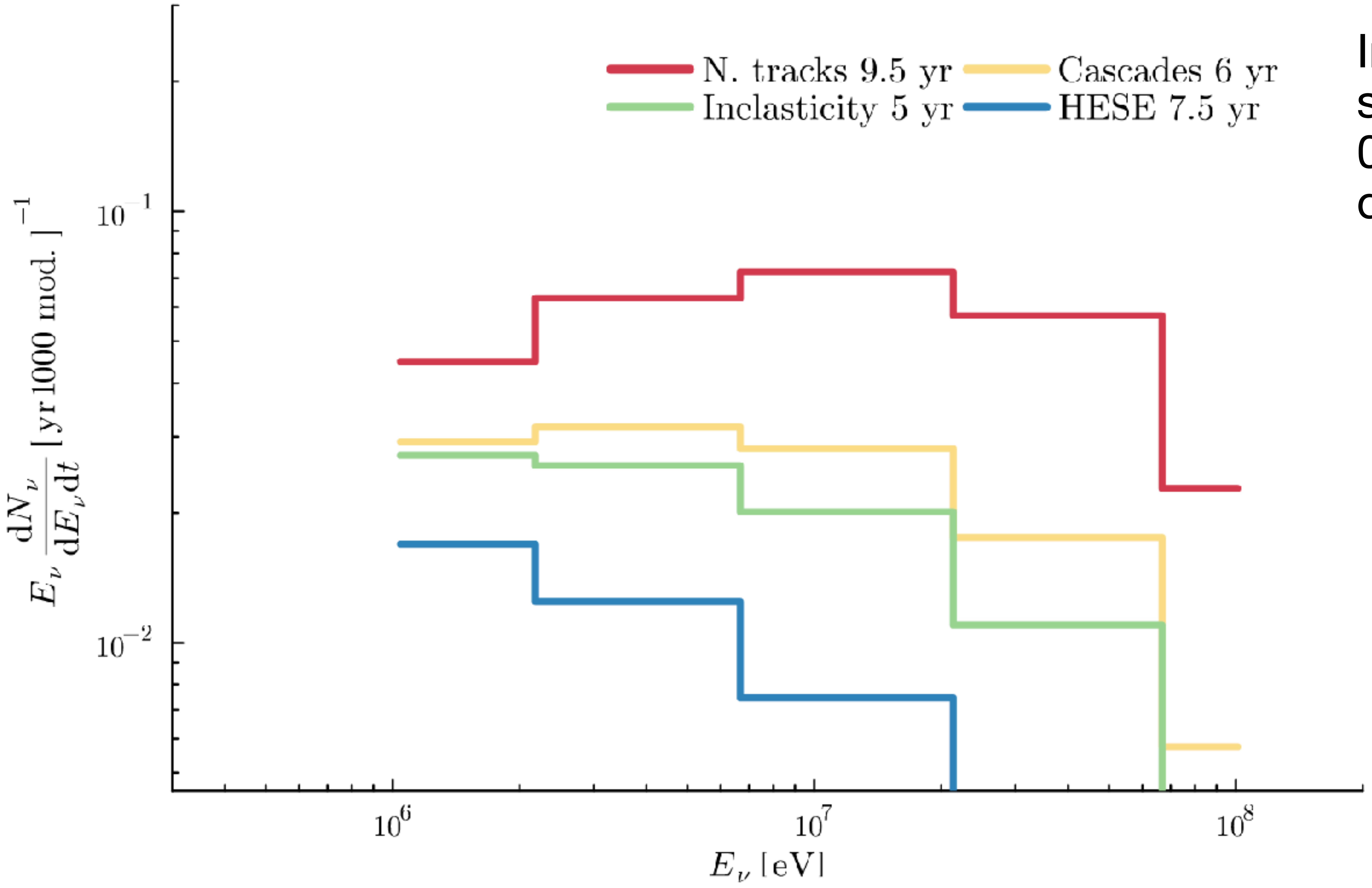


Well, Kind of…



- 22,000 is a lot of tanks, and that is a lot of water to lift
- ~160 kilometers of valley would need to be instrumented…

But Not Entirely



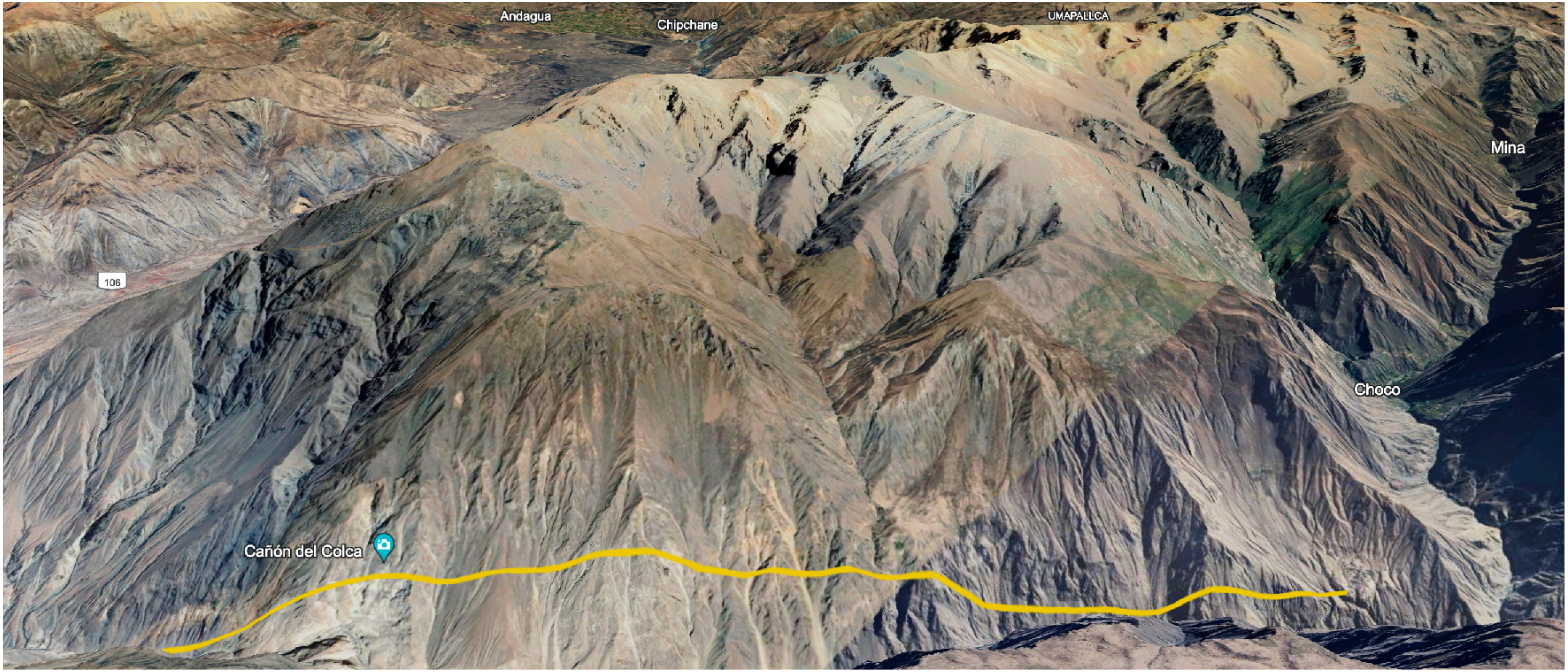
Initial calculation showed that we should expect between 0.27 and 0.04 detections per year per 1,000 detectors

Site Selection Trip

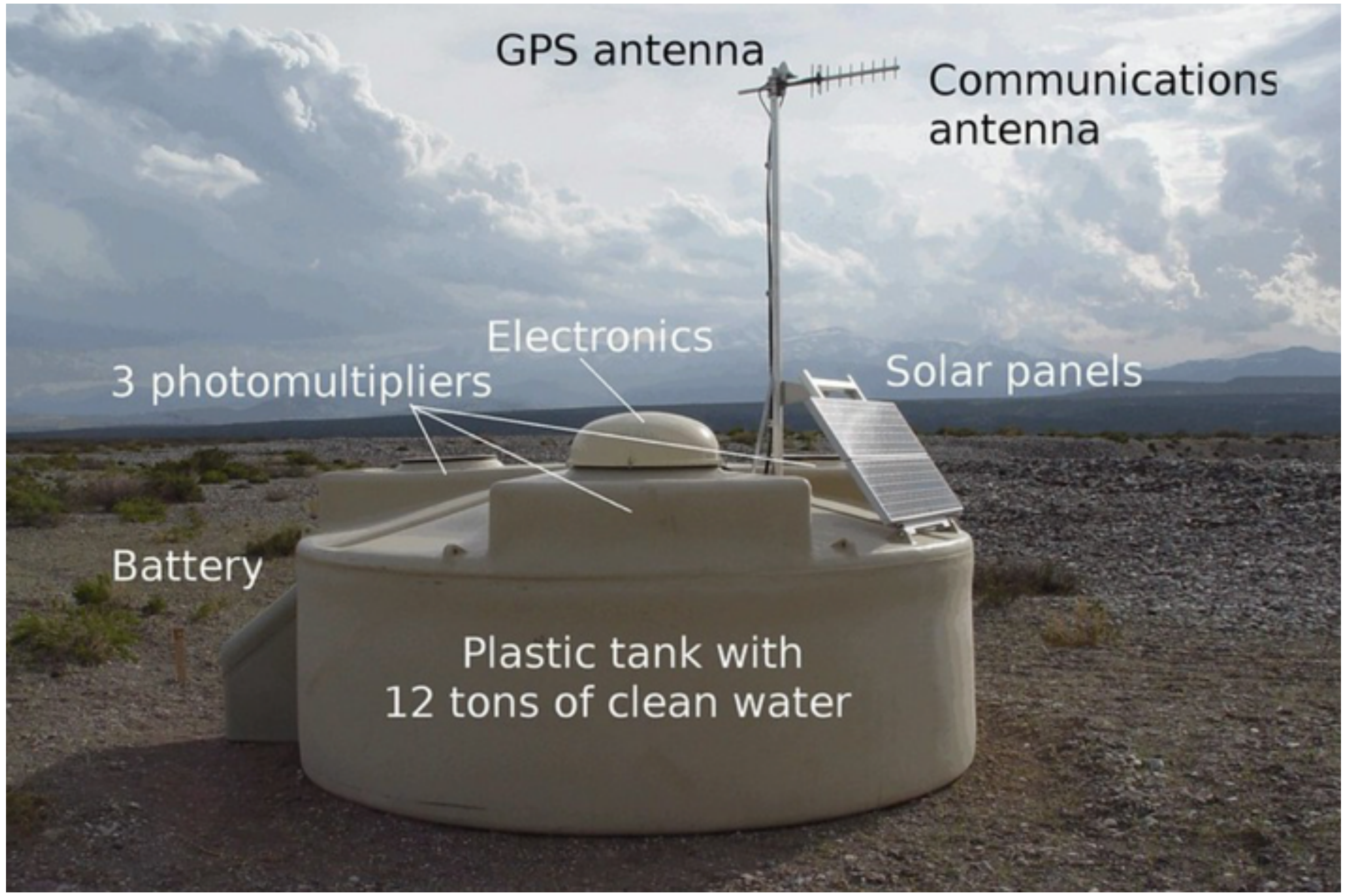
- A few of us from Harvard went to the Colca Valley to look at sites and assess infrastructure
- The planned site is very far out, but there are less remote places that are viable for a test array

Potential Test and Main Array Location

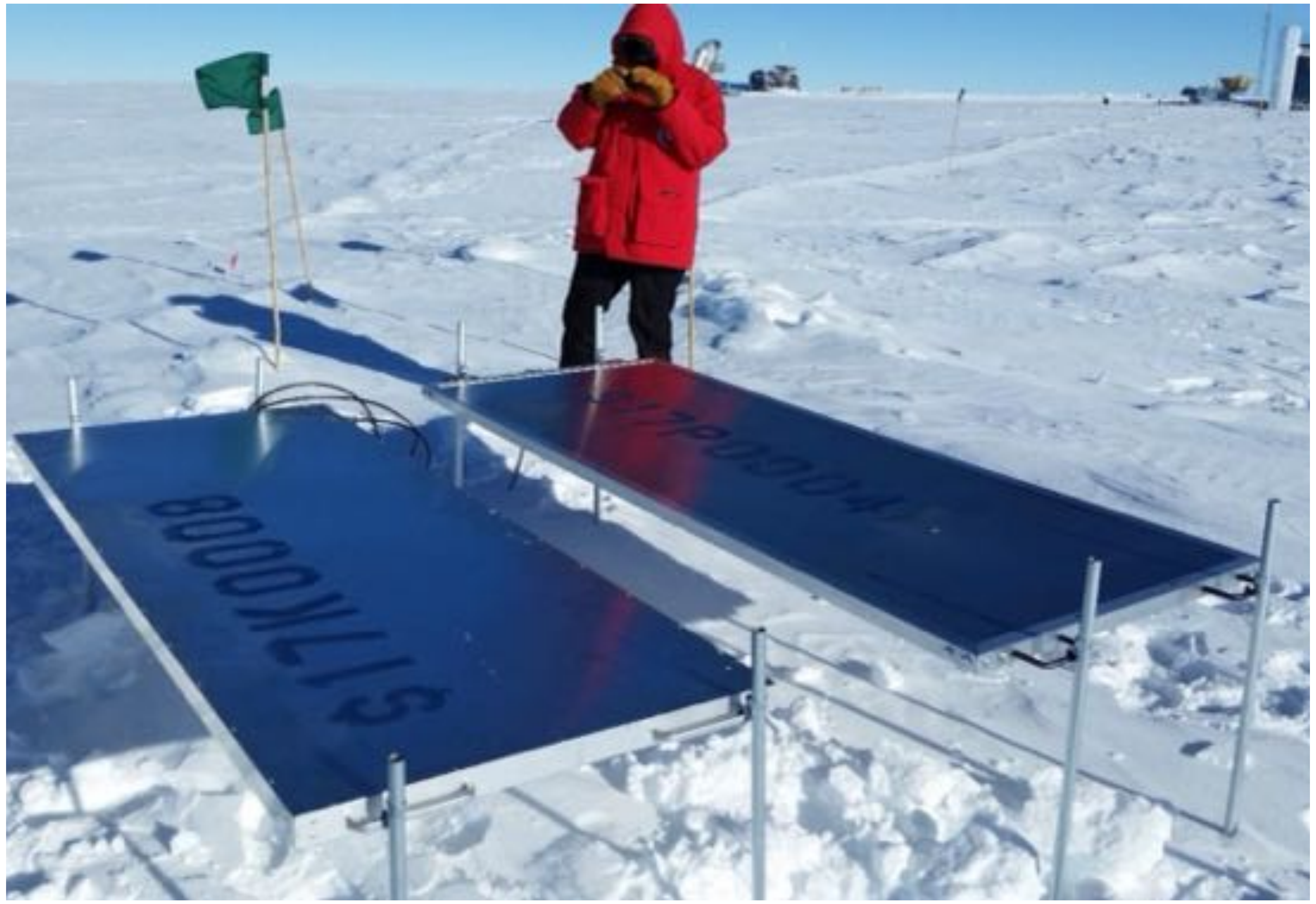
Main Array Candidate Site



Hardware Studies



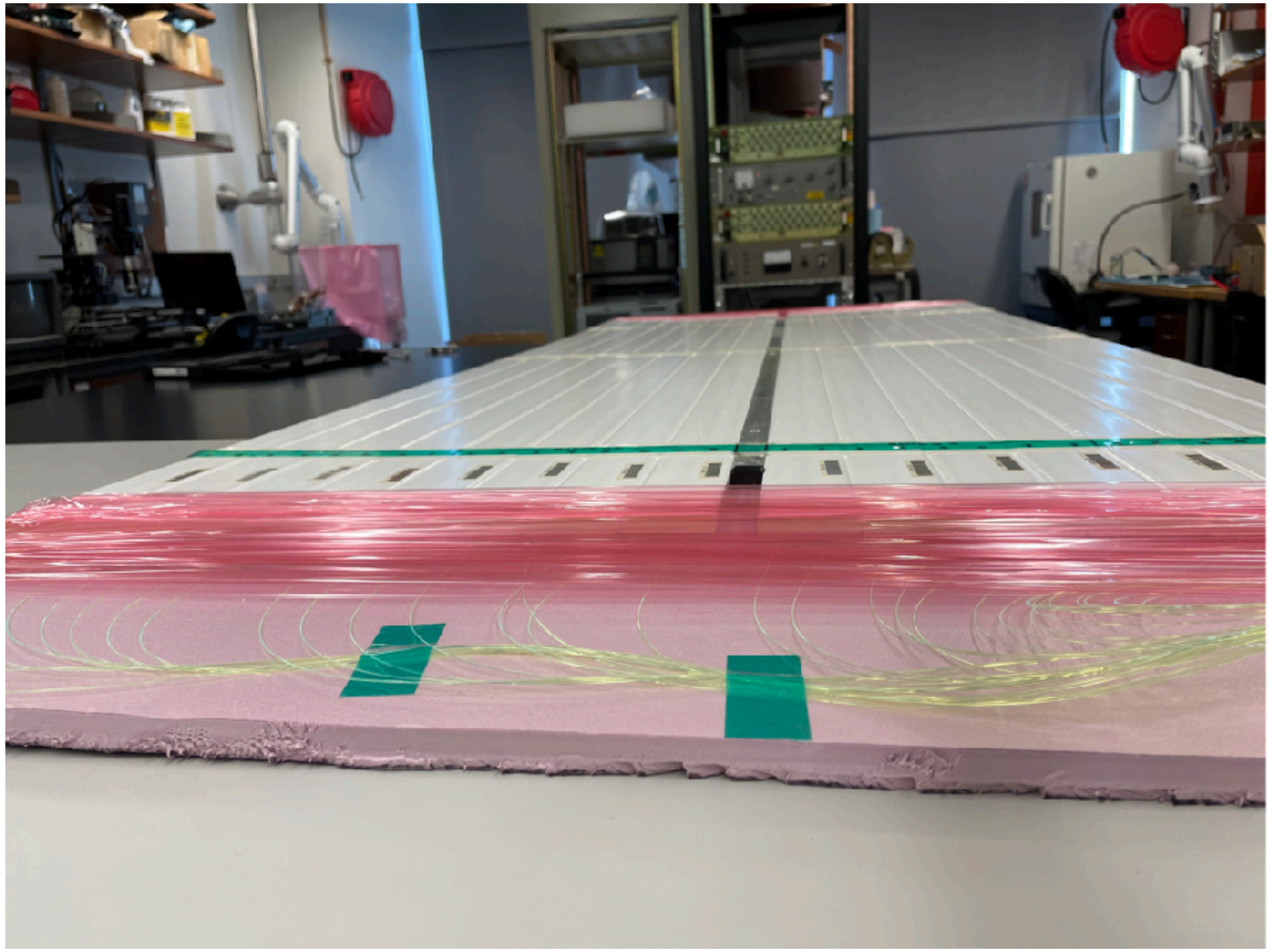
Pierre Auger Collaboration, ICRC(2021)

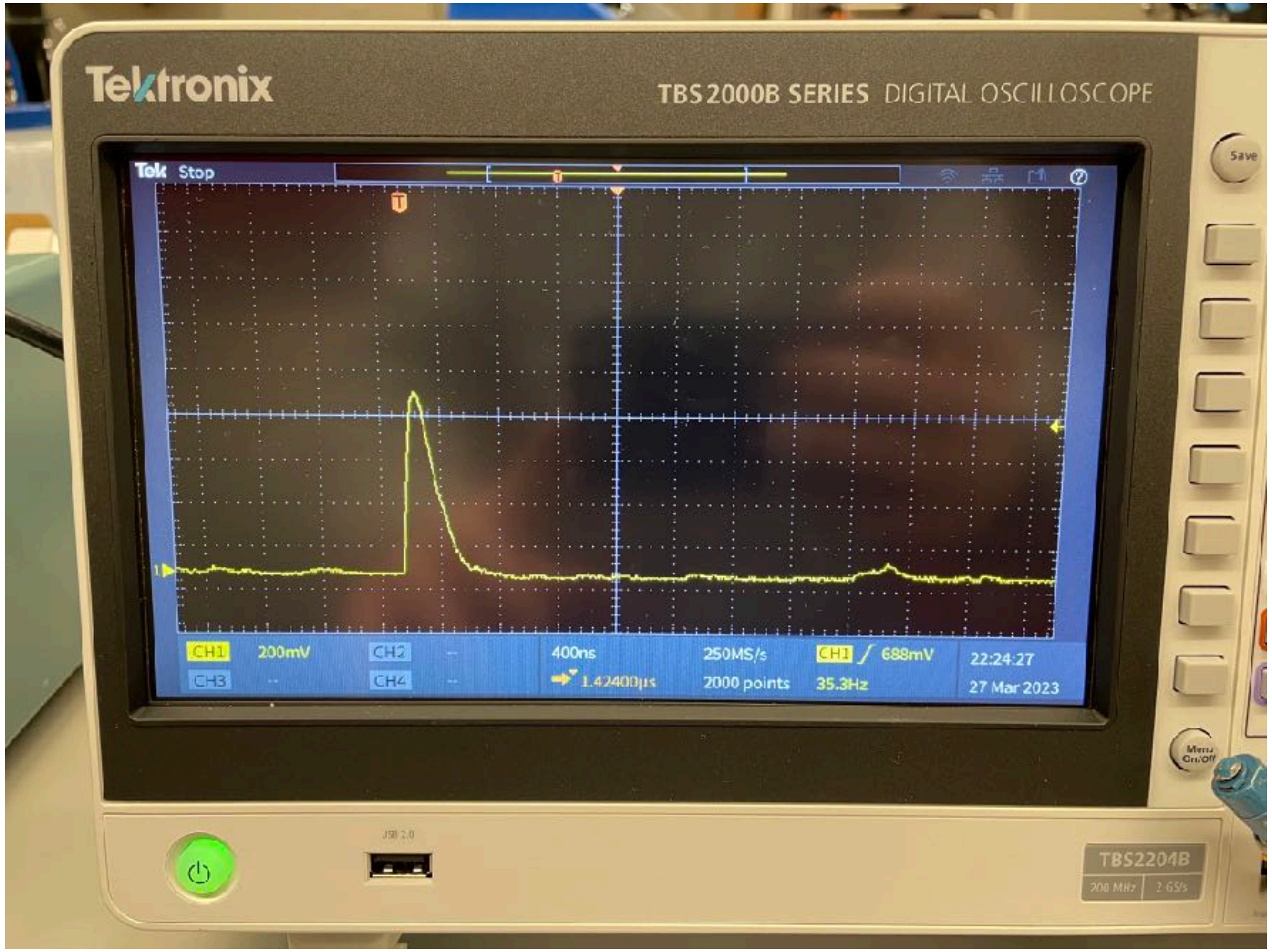


IceCube Collaboration, EPJ Web Conf. **210** (2019)

- 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

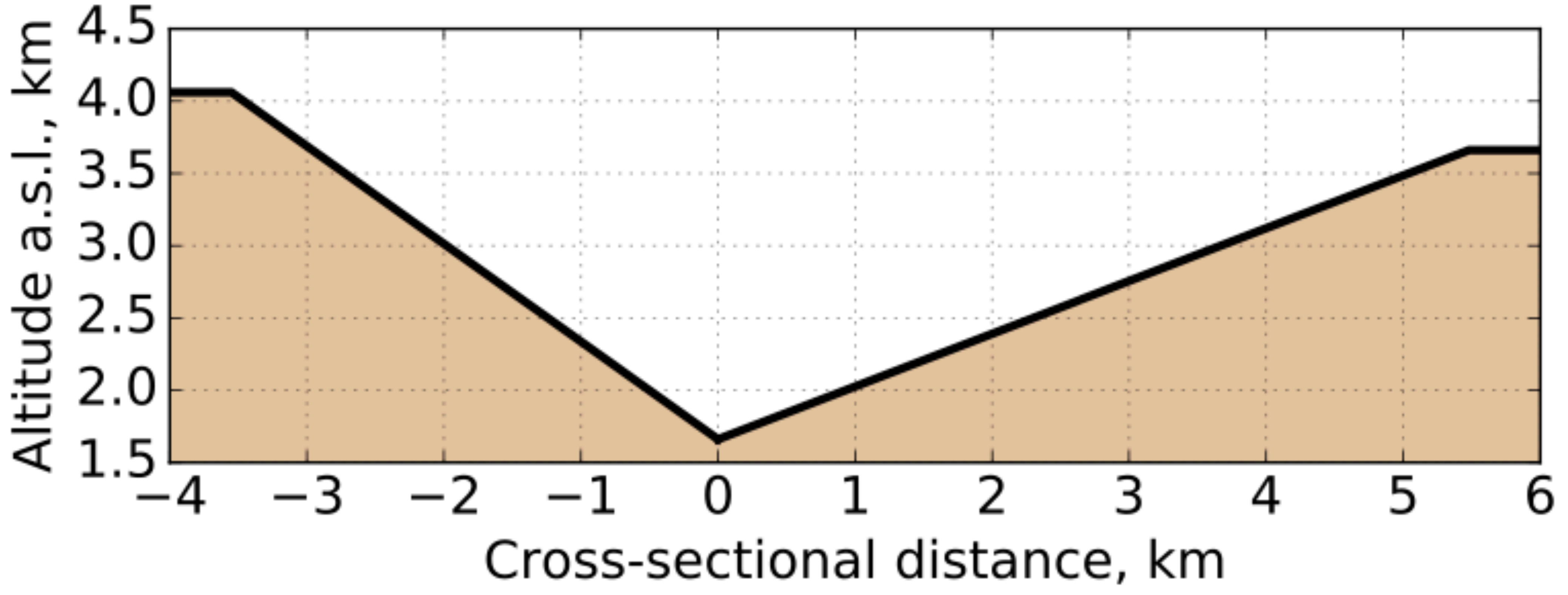
First Light from Cosmic Rays

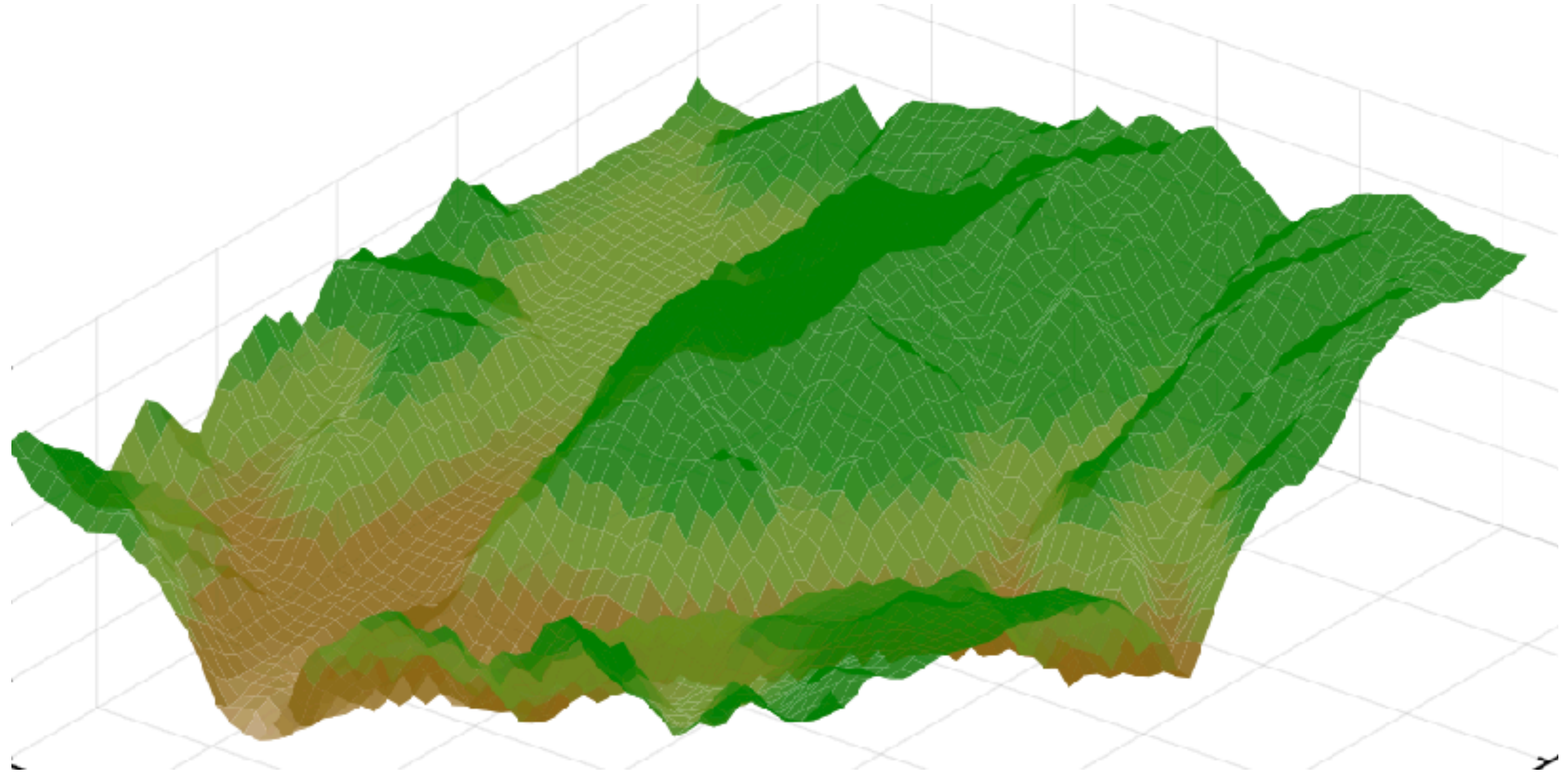




- First light from scintillator panels at Harvard
- Enough material to build 10 panels in total, which we expect to have by the end of the year

Towards a Full Monte Carlo

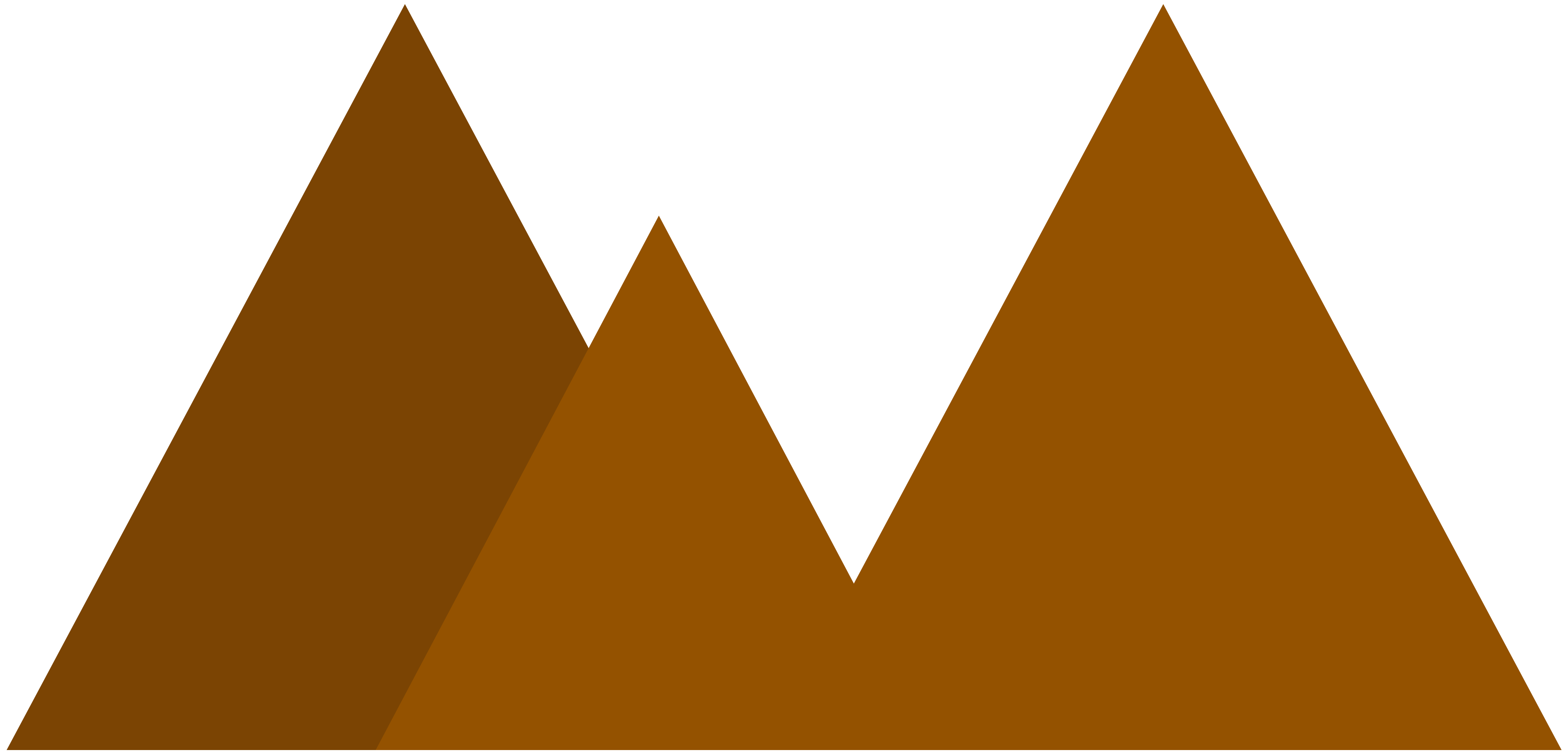




- Simplified geometry
- No treatment of $\tau^{\pm}$ energy losses
- Approximation of air-shower physics

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

Developing a Full Monte Carlo Chain



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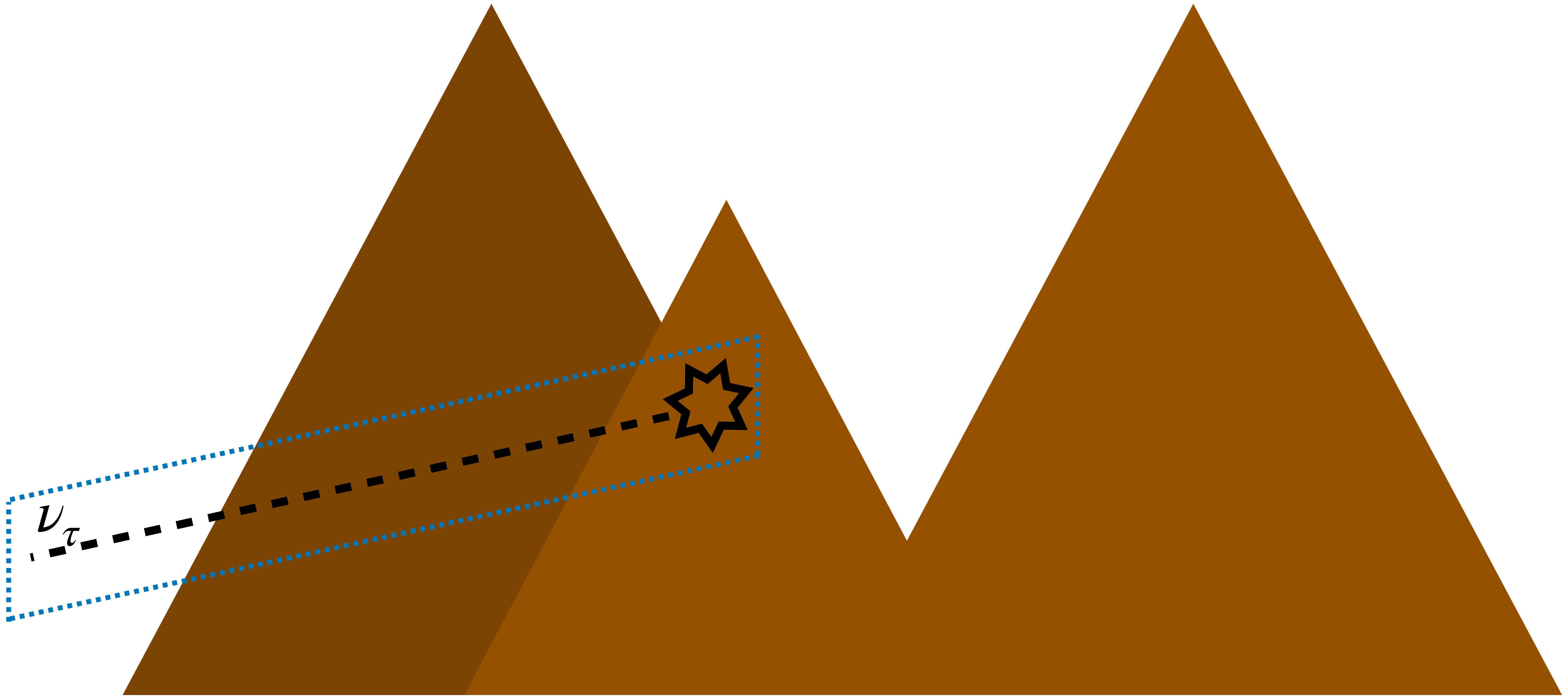
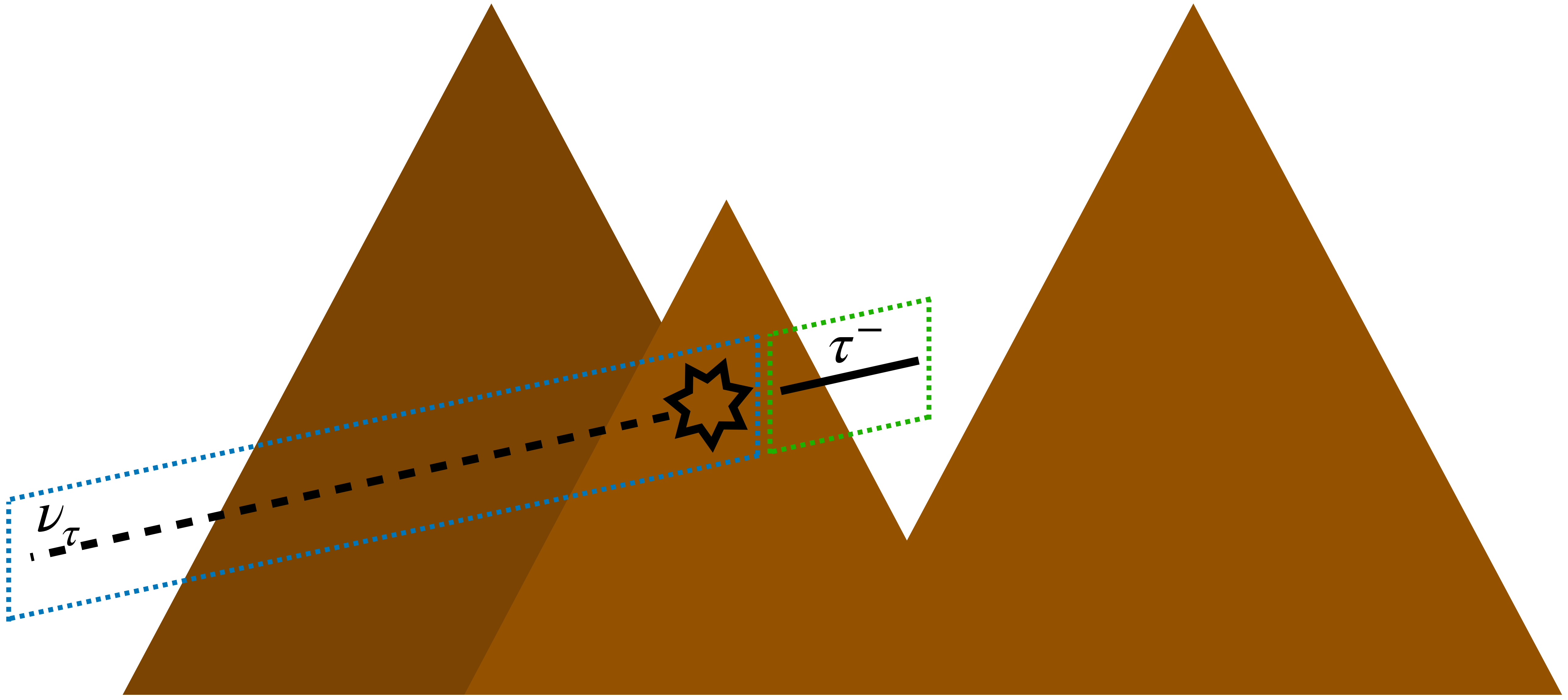


Initial neutrino injection: Select initial neutrino properties, *i.e.* energy, direction, interaction vertex, *etc.*

Developing a Full Monte Carlo Chain



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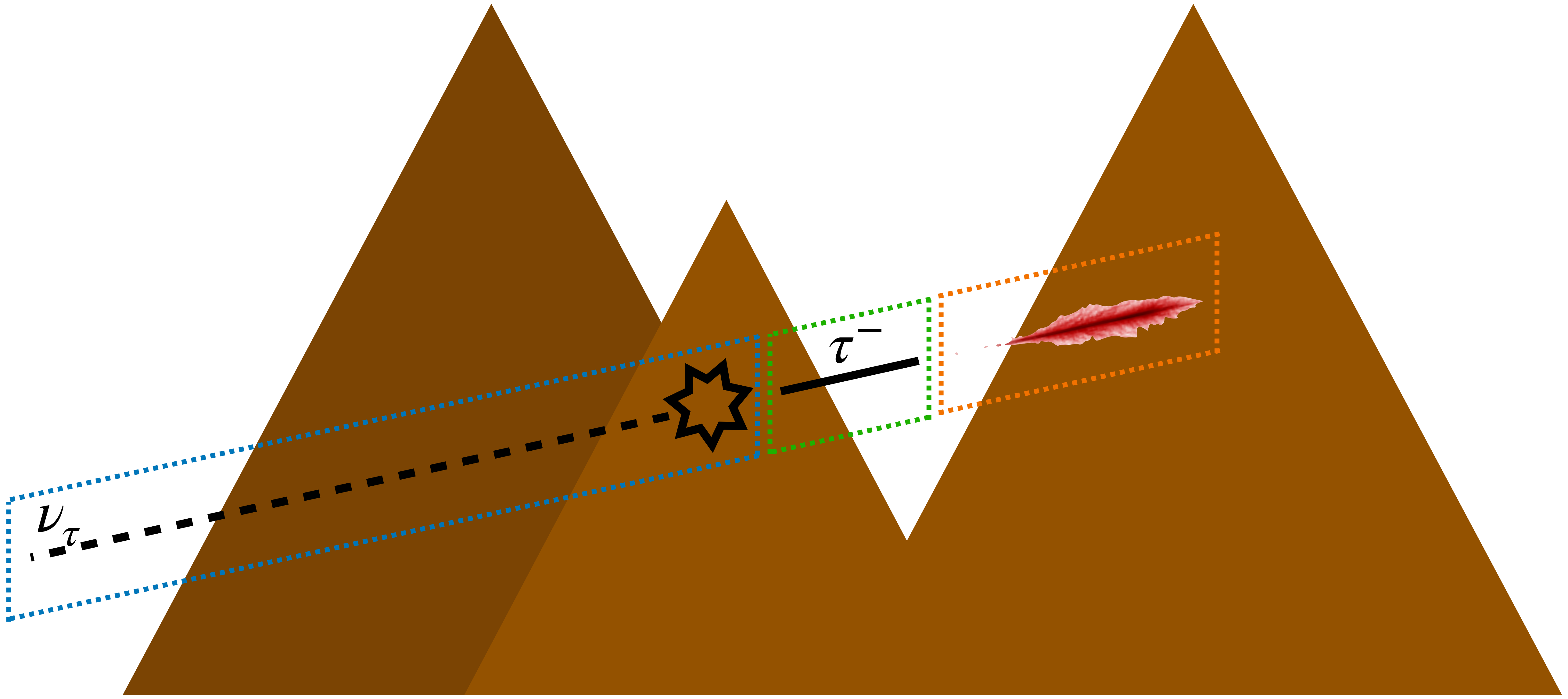
Charged lepton propagation: Propagate outgoing charged lepton, accounting for energy losses and decay, to find decay point

Developing a Full Monte Carlo Chain



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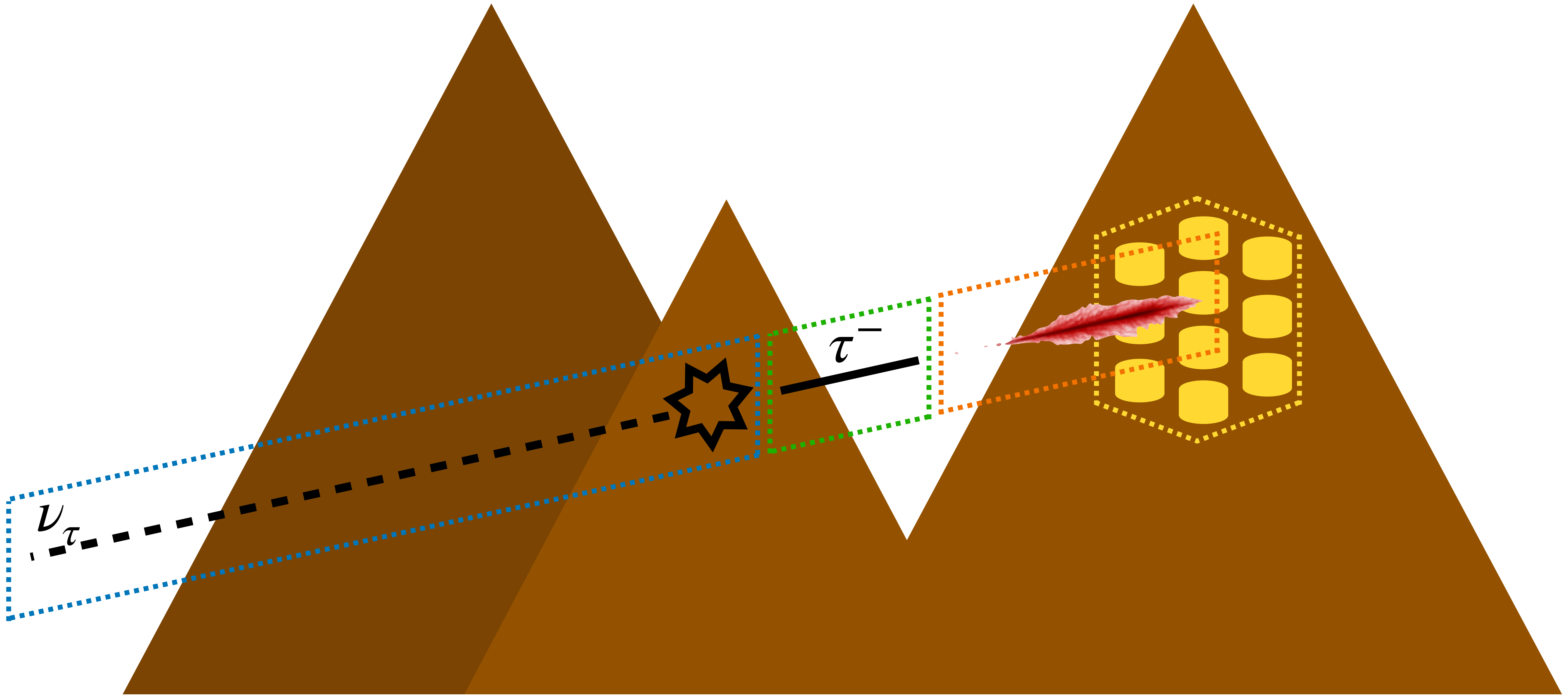

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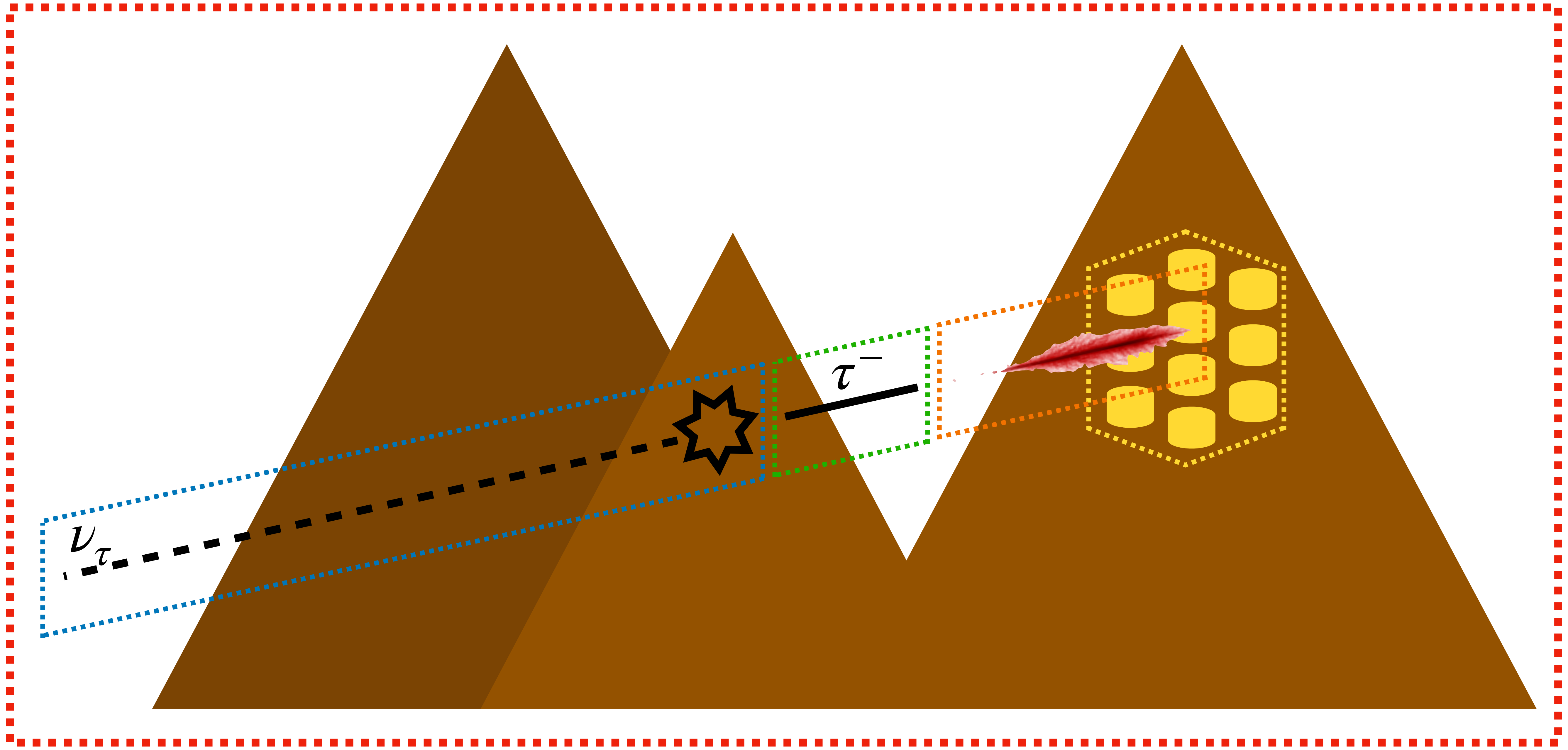

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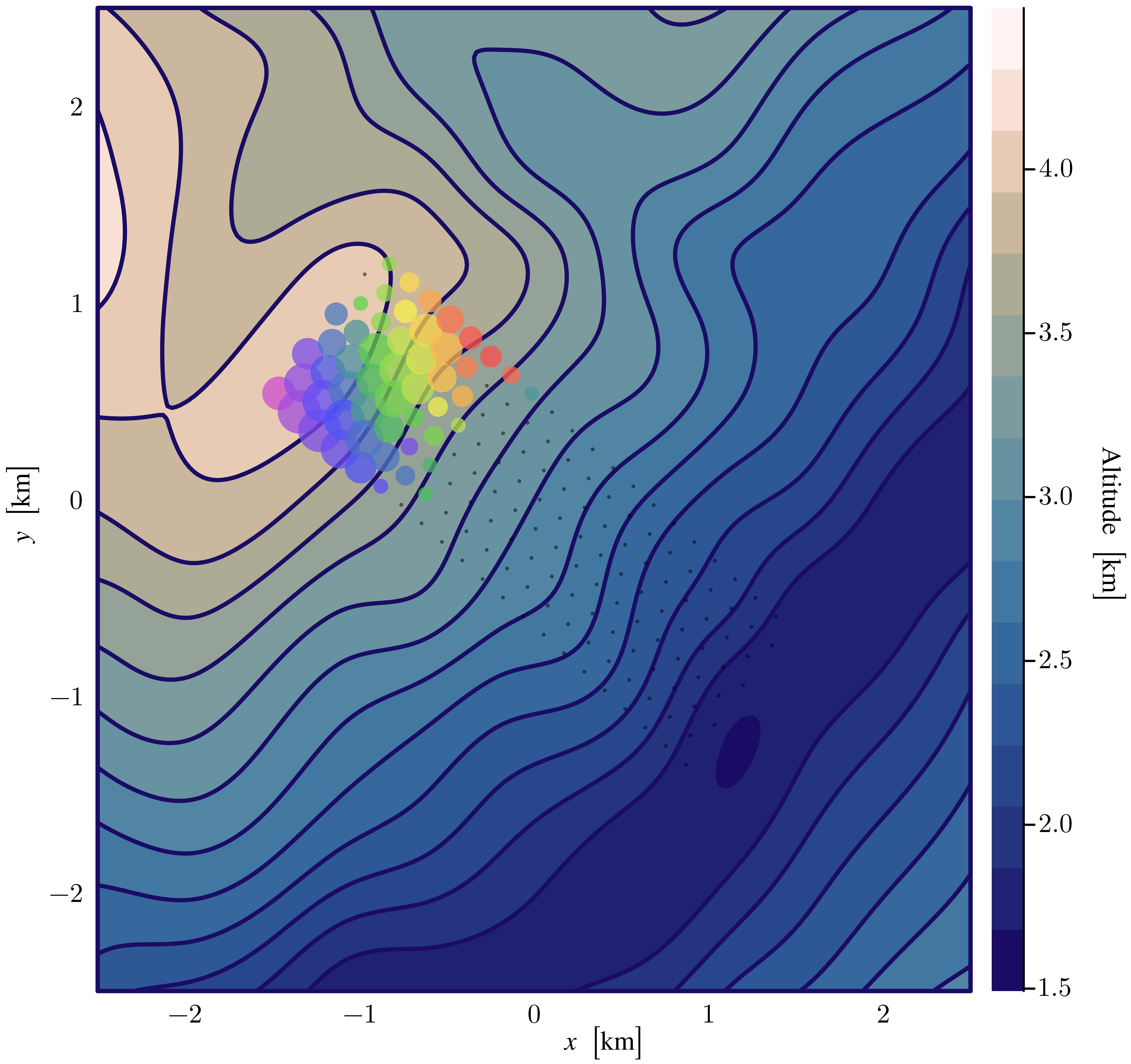
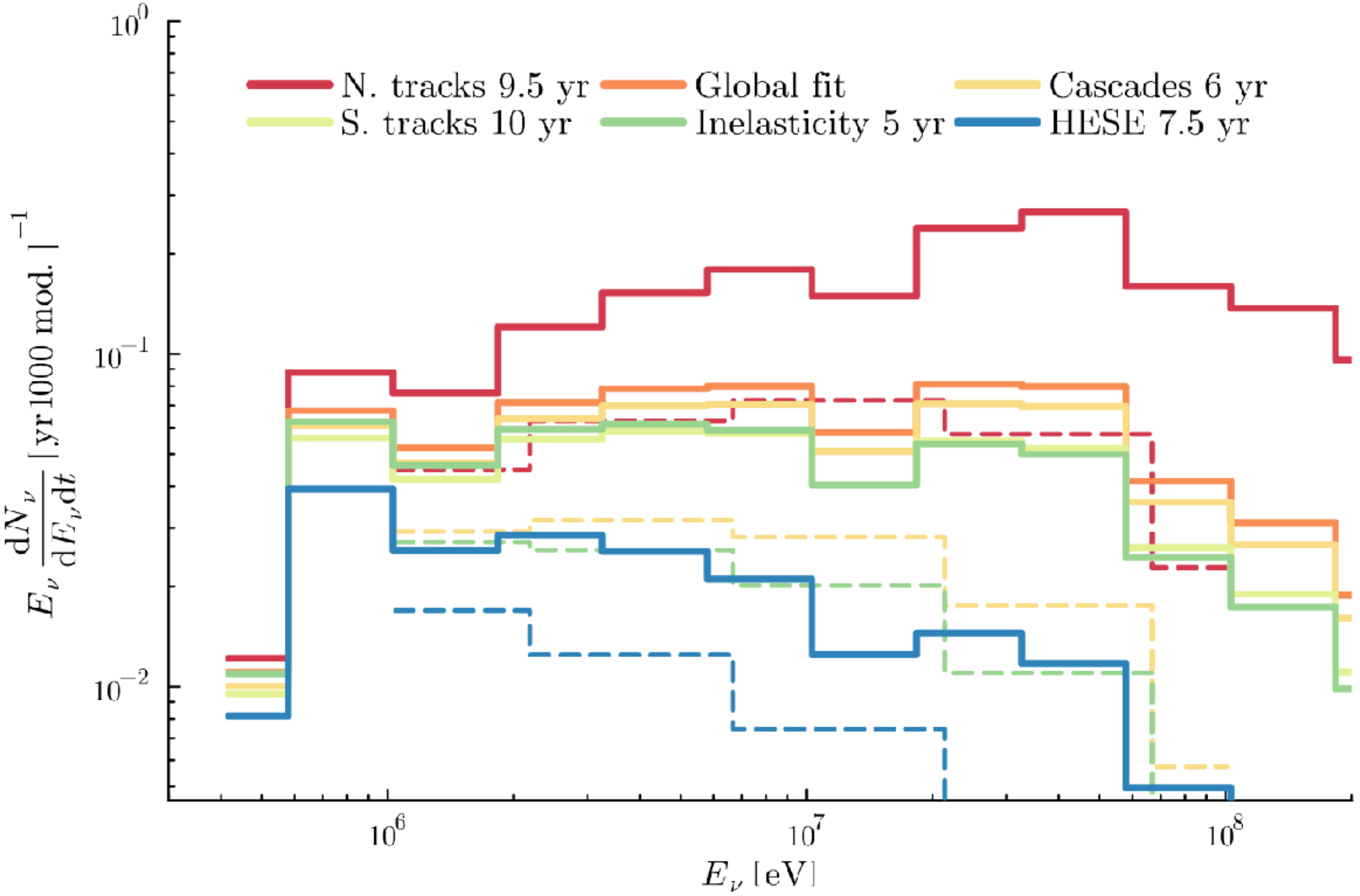
Detector response: Simulate internal hardware to model what we will see

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



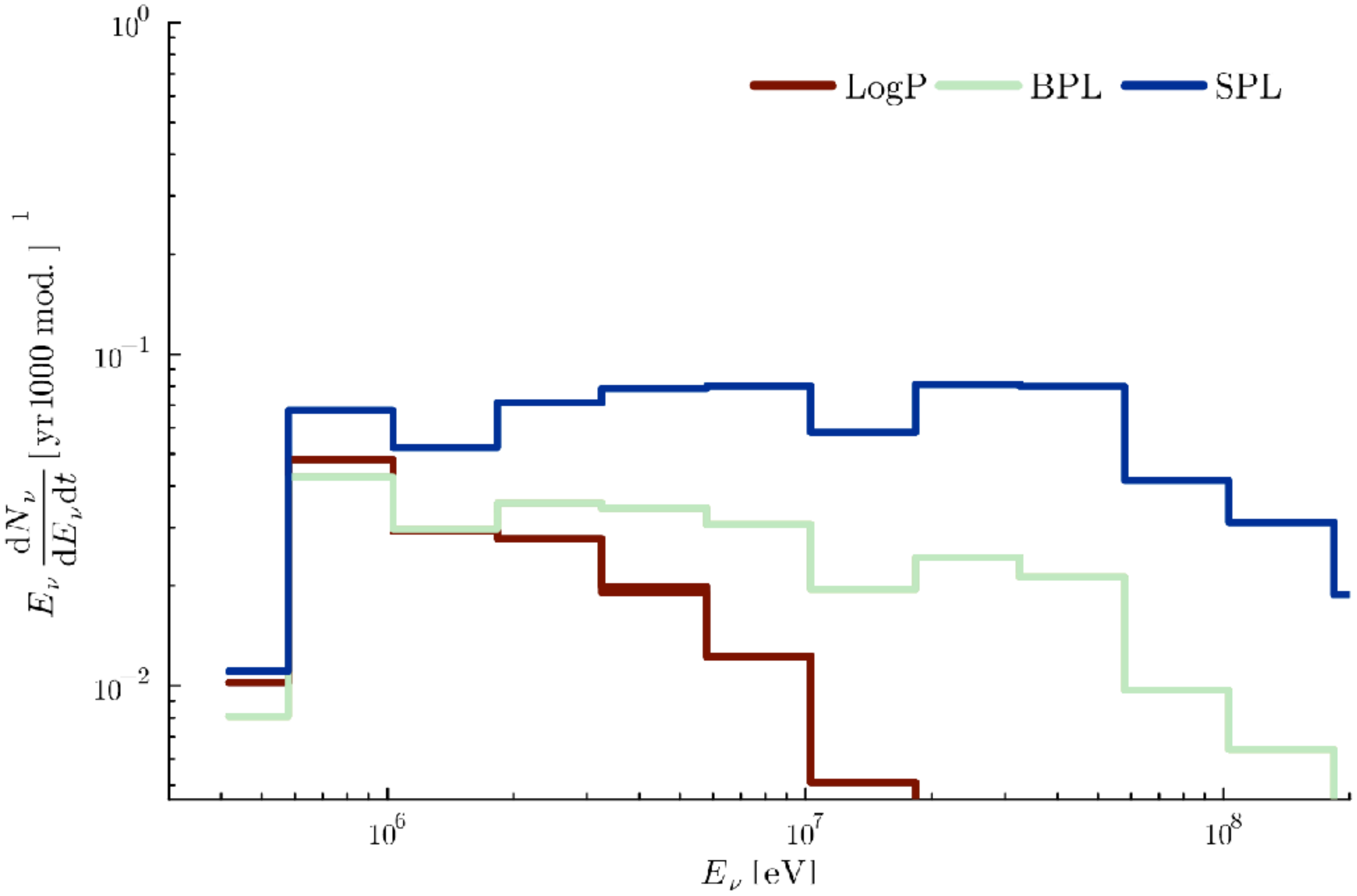
New simulation enables more accurate event rate predictions as well as reconstruction studies

Updated Event Rates



- Rates from the new calculation higher than initial estimation by a factor of ~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

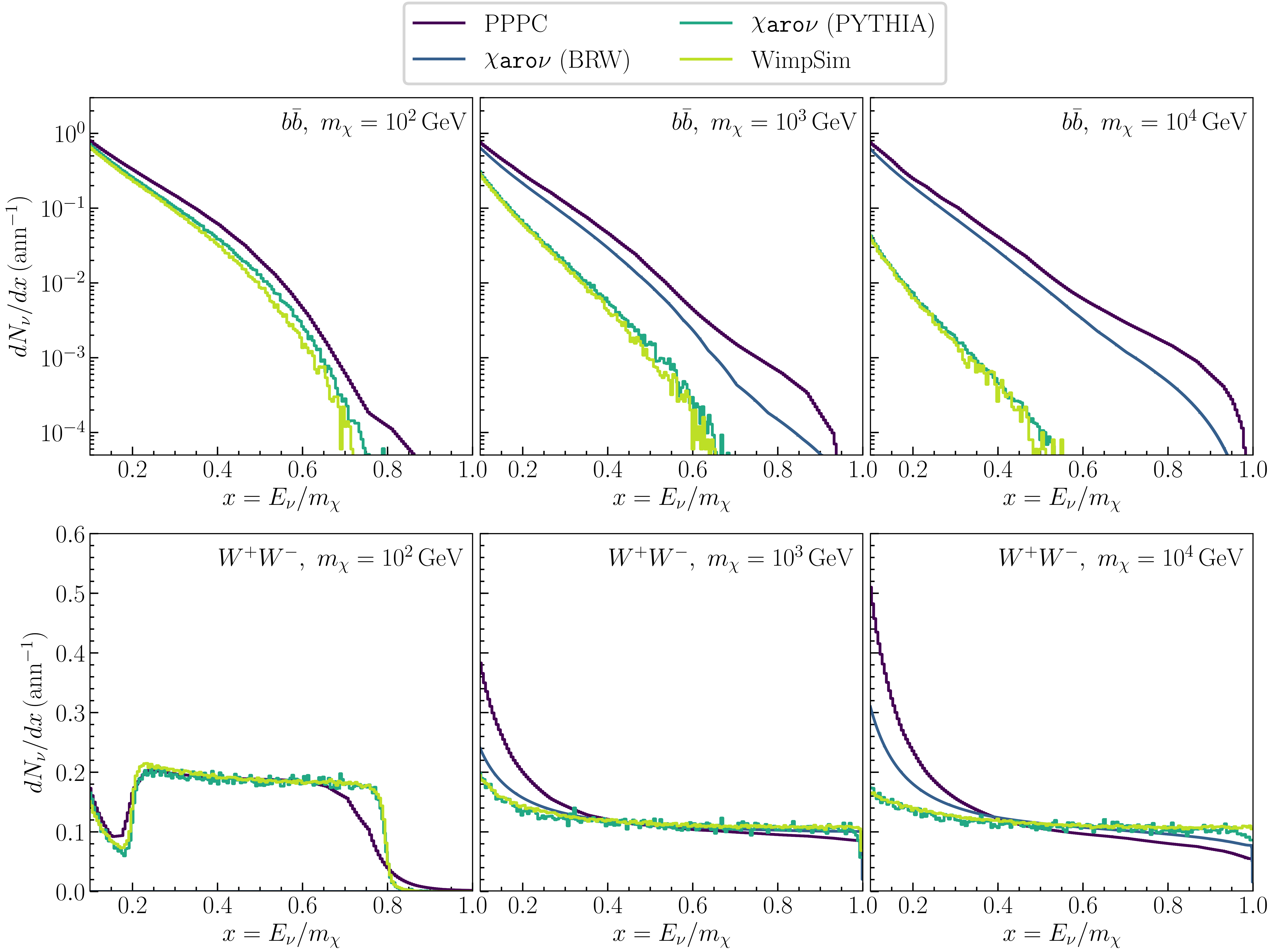
- Met with the mayor of Chivay to discuss potential partnerships between the collaboration and the local community
- Recently held a workshop at the Harvard Radcliffe Institute to explore different sociological aspects of particle physics experiments in different cultural contexts

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



PPPC
χaroν (BRW)
χaroν (PYTHIA)
WimpSim
$b\bar{b},\ m_\chi = 10^2$ GeV
$b\bar{b},\ m_\chi = 10^3$ GeV
$b\bar{b},\ m_\chi = 10^4$ GeV
$W^+W^-,\ m_\chi = 10^2$ GeV
$W^+W^-,\ m_\chi = 10^3$ GeV
$W^+W^-,\ m_\chi = 10^4$ GeV
$dN_\nu/dx\,(\mathrm{ann}^{-1})$
$x = E_\nu/m_\chi$

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

$$P_{\text{osc}} \sim \sin^2\left(\Delta m^2 \frac{L}{4E_\nu}\right)$$