The Tau Air-Shower Mountain-Based Observatory

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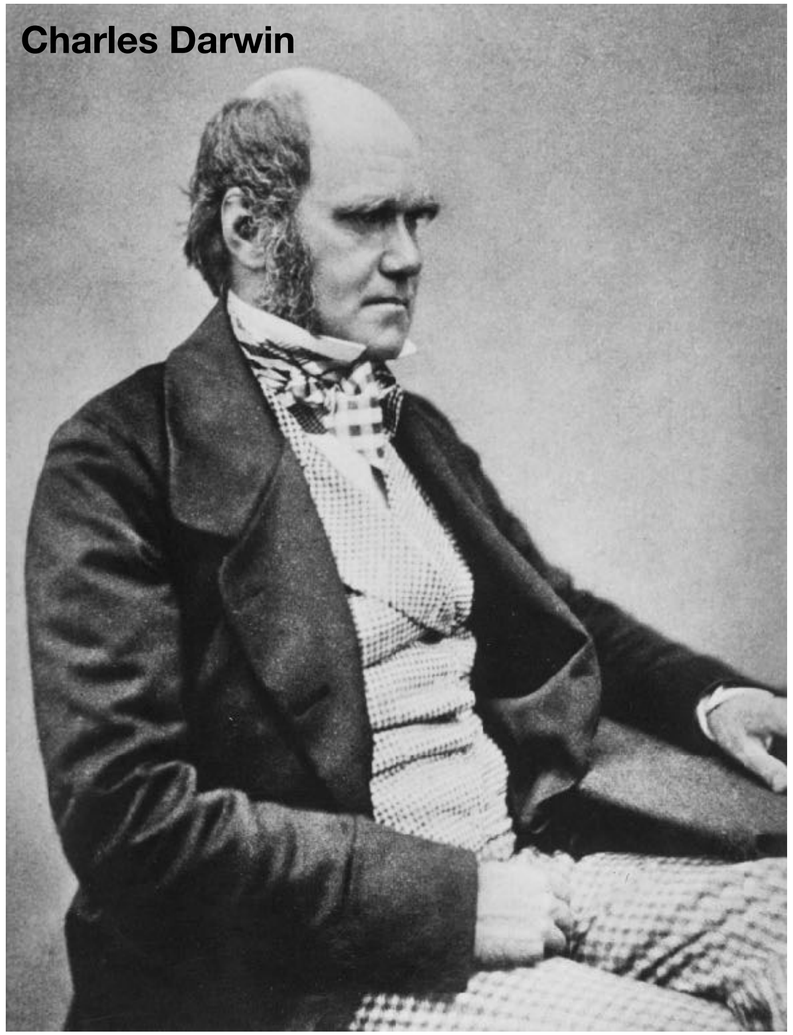
Roadmap

- A very brief history of neutrino astronomy
- Open questions in neutrino astronomy
- TAMBO overview
- Realizing TAMBO

How Does the Sun Shine ?

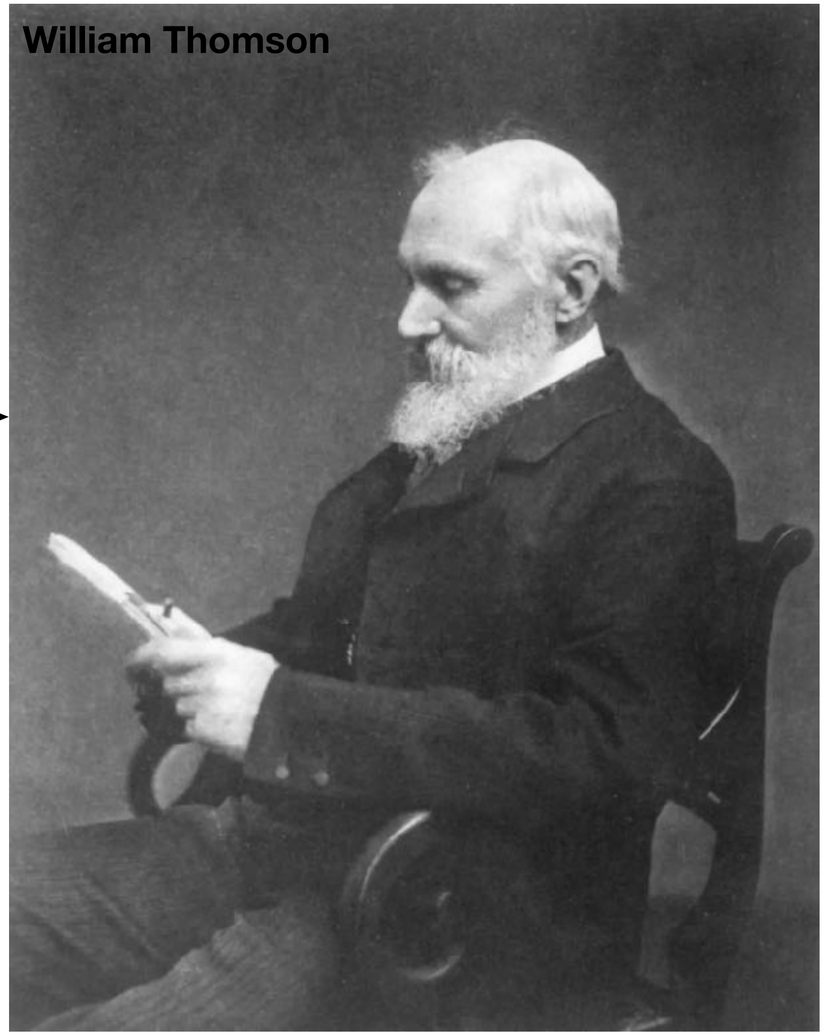
Charles Darwin



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.

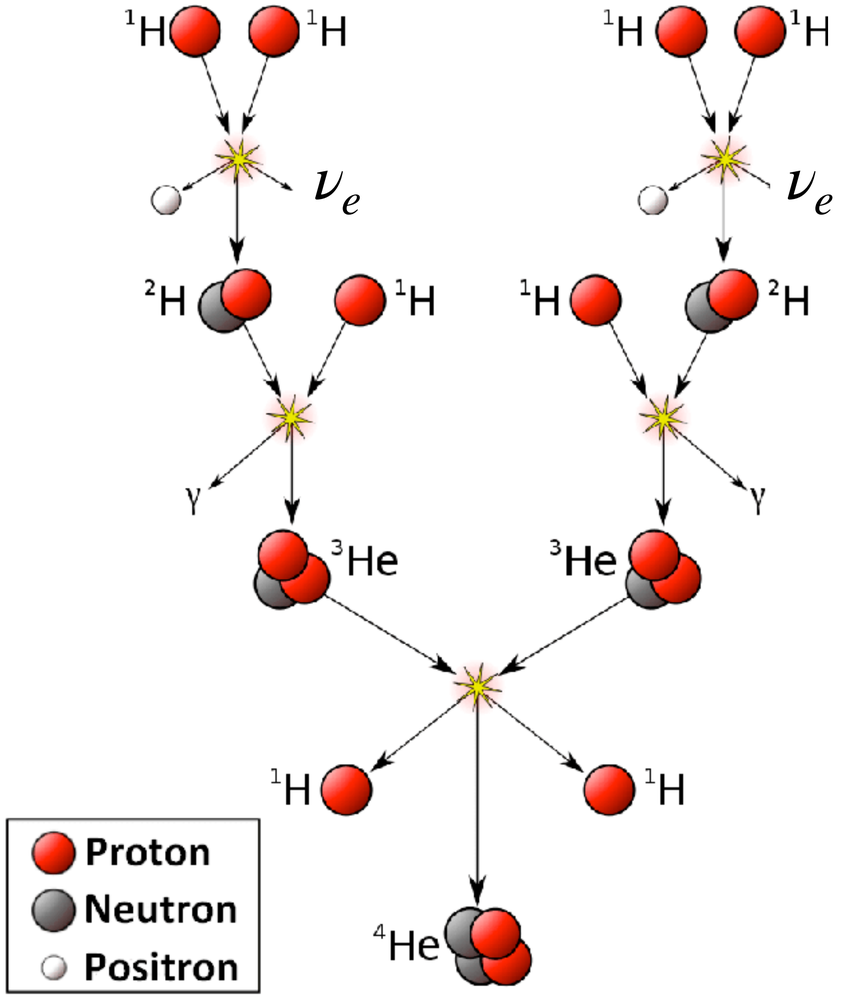
This can't be ! Chemical processes could only power the Sun for 30,000 years and gravitational processes are still well-short.

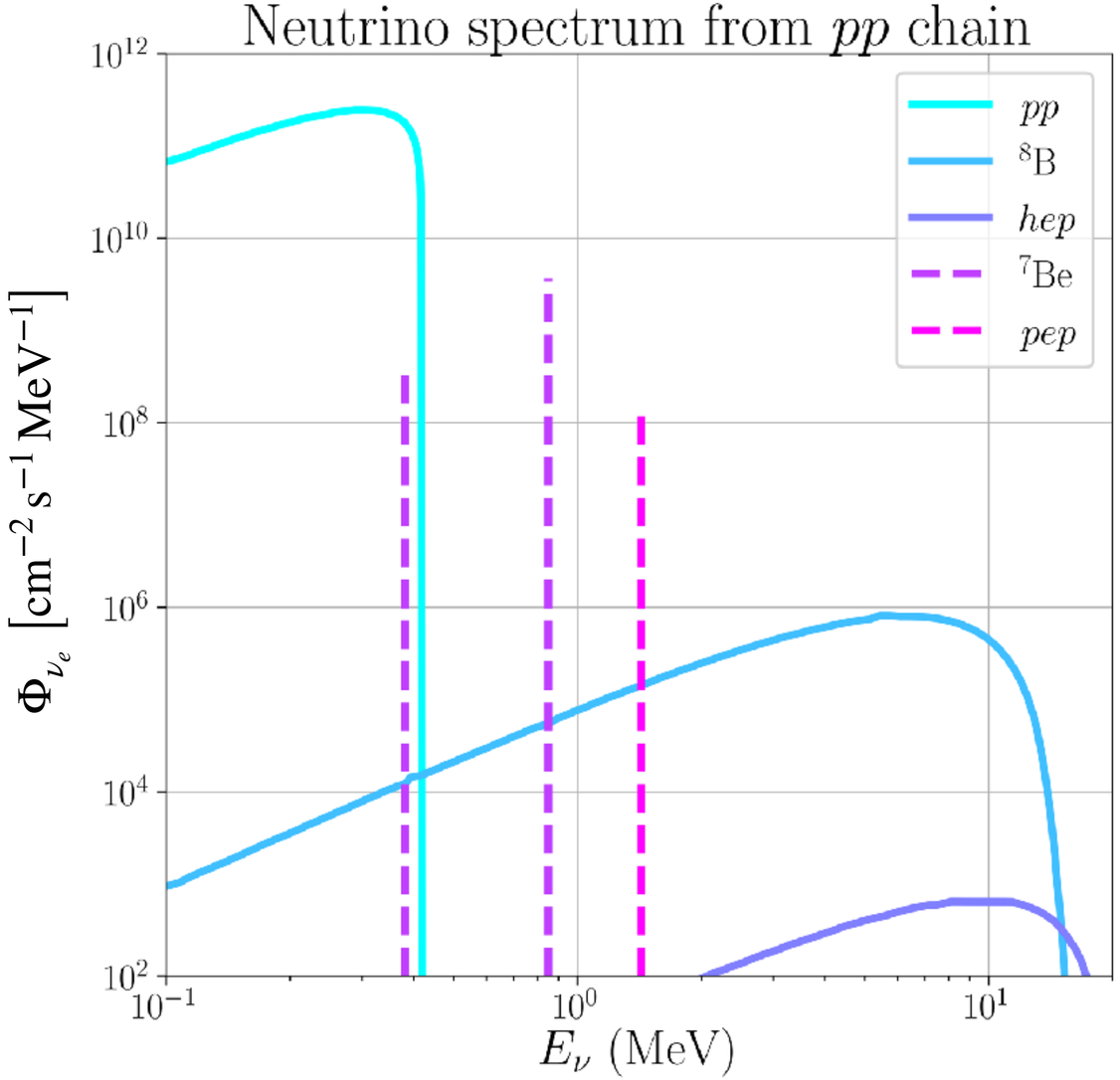
William Thomson



How Does the Sun Shine ?

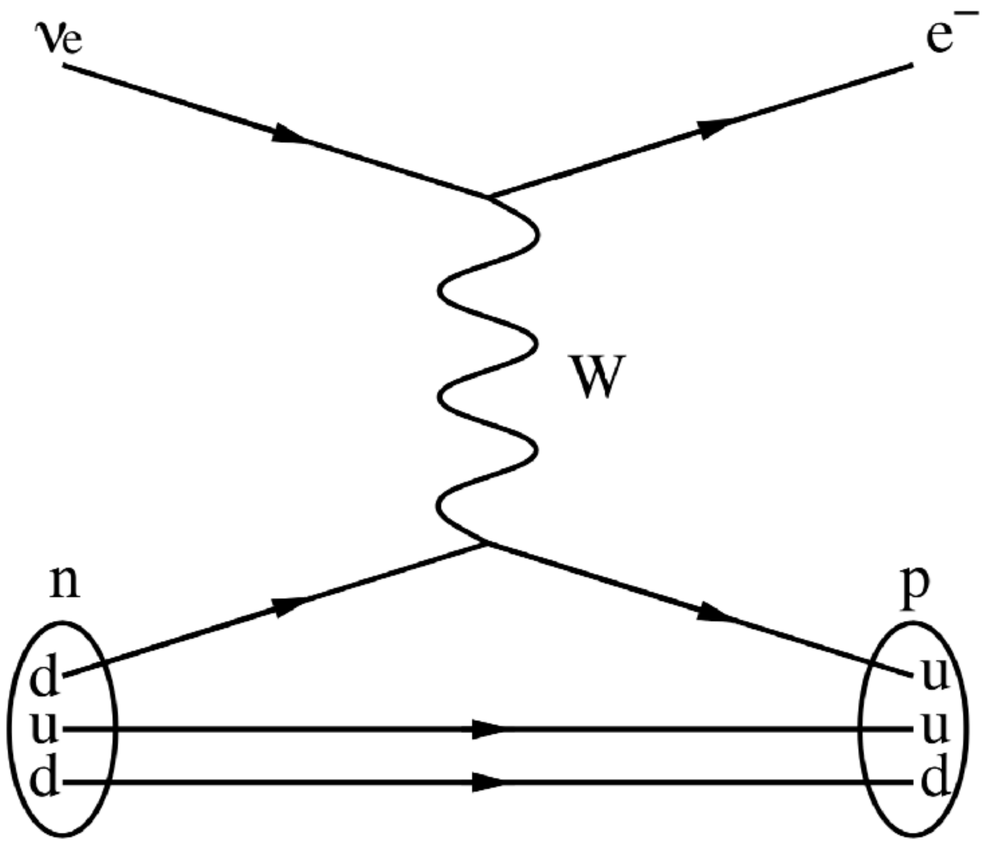
If the Sun generates energy from nuclear fusion, it will emit ***electron*** neutrinos

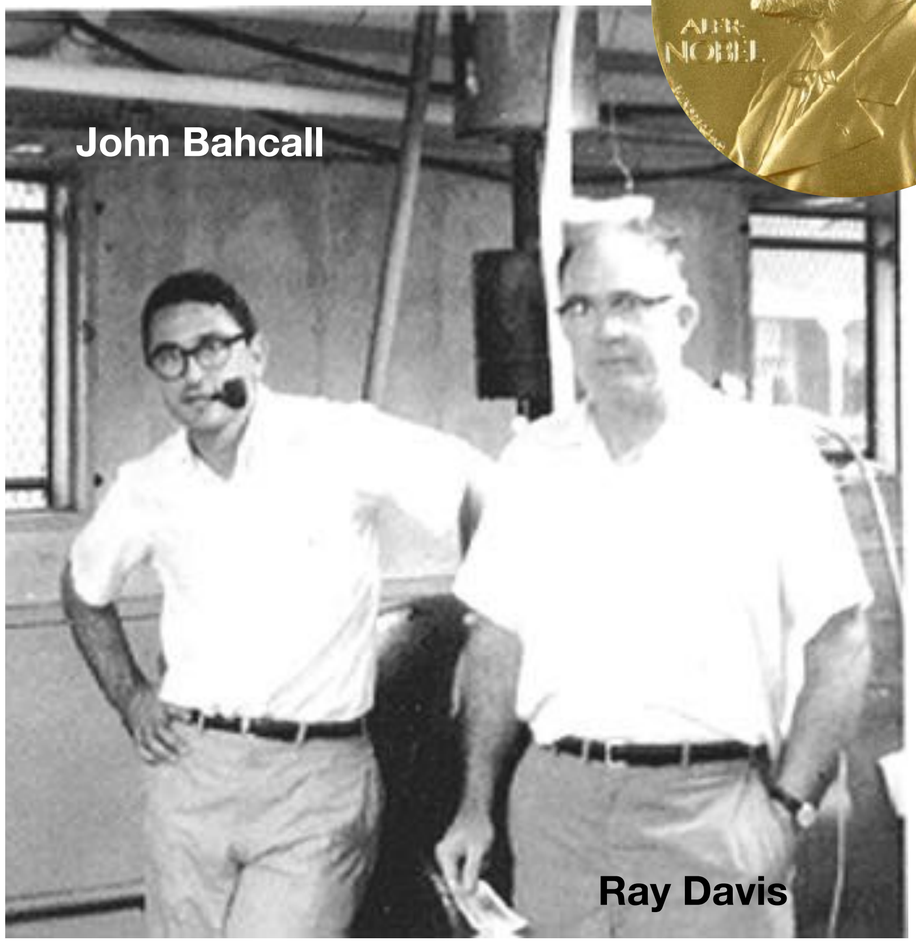




Staring into the Sun

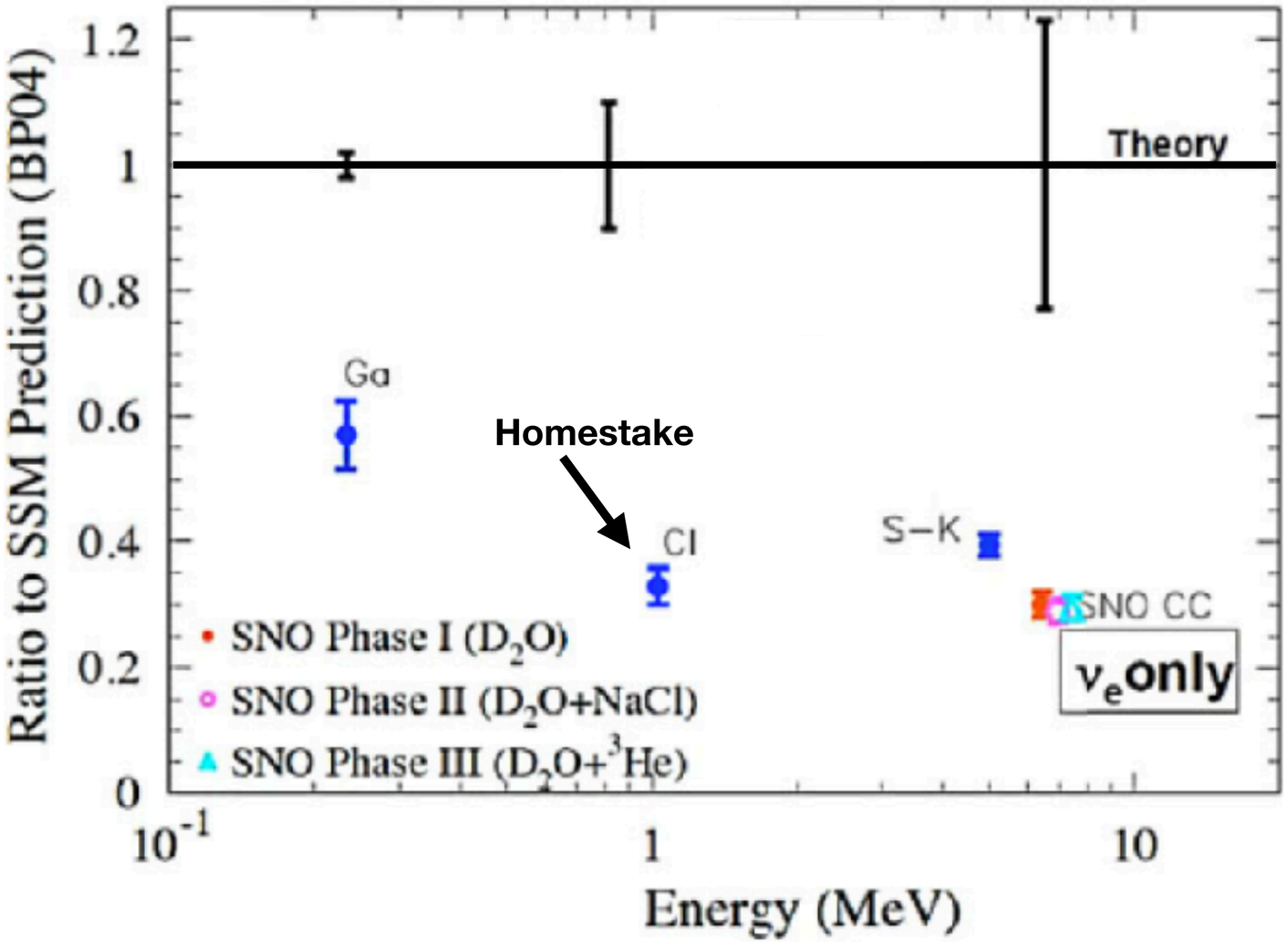
- Homestake experiment looked for solar ν_e via $^{37}\mathrm{Cl} + \nu_e \rightarrow ^{37}\mathrm{Ar} + e^-$
- First observation of solar neutrinos !





The Solar Neutrino Problem

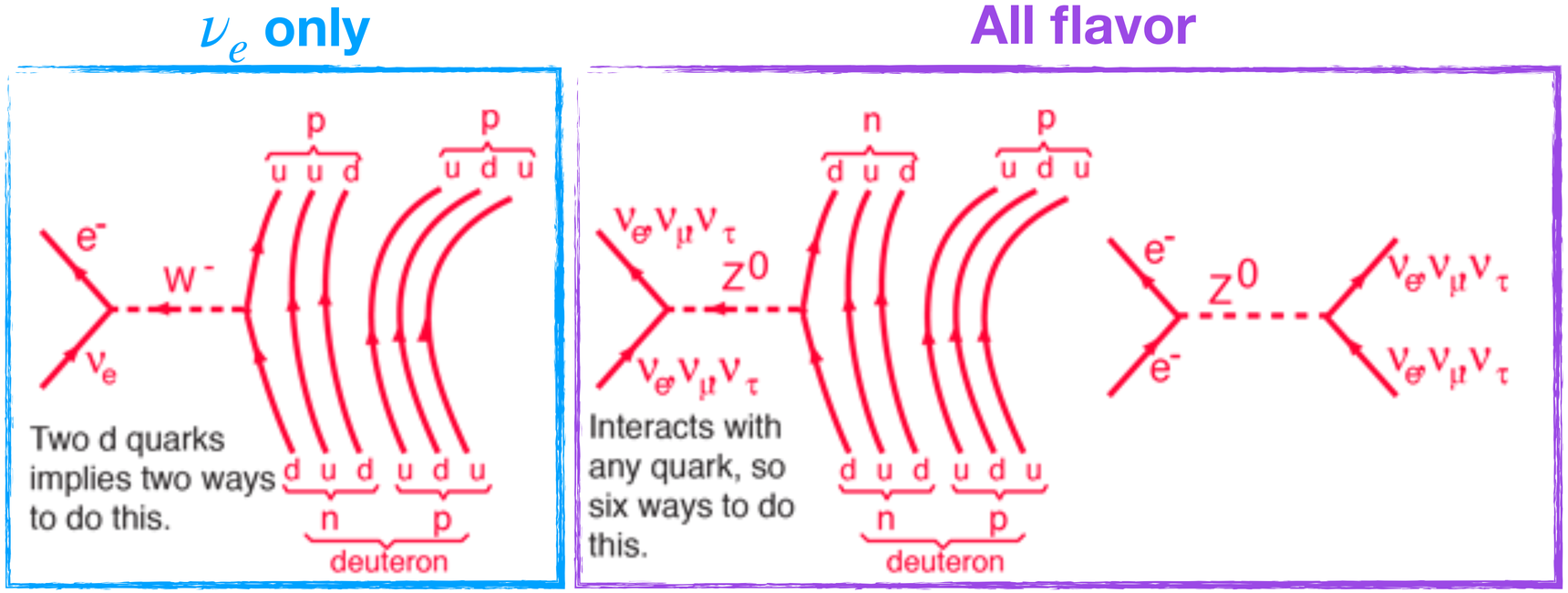
- Flux measured by Homestake was in bad agreement with SSM prediction
- Many experiments continued to prod at this discrepancy, while theory is honed
- Discrepancy persisted

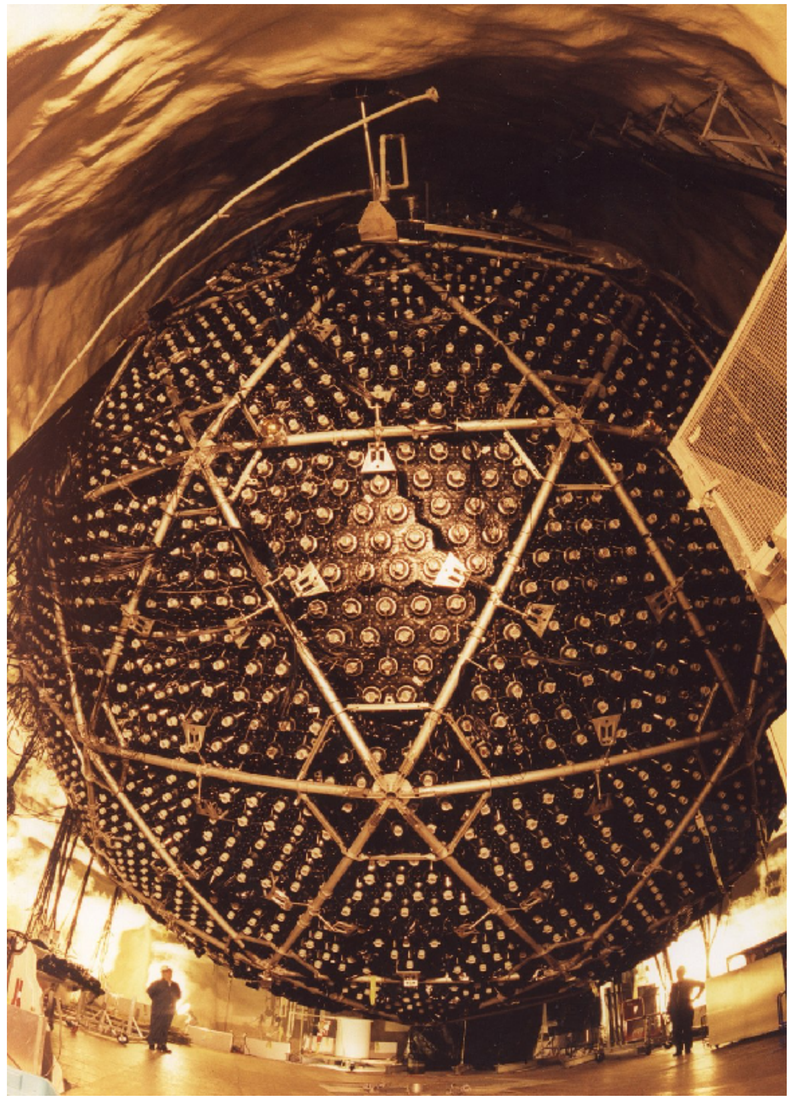


A. McDonald. doi:10.1002/201600031

Looking at New Flavors

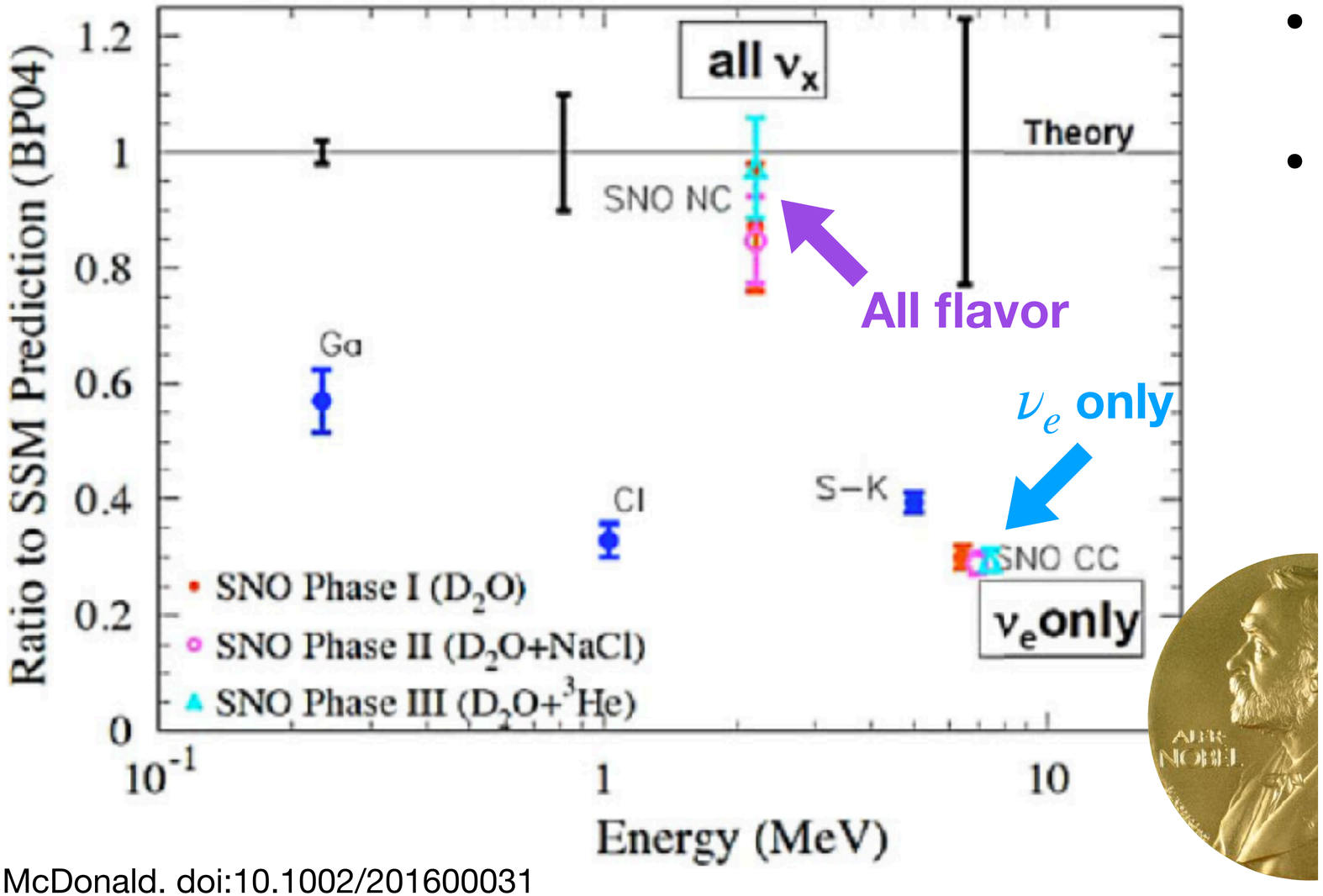
- Sudbury Neutrino Observatory used heavy water water $\left(D_2O\right)$ to measure all-flavor NC processes





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

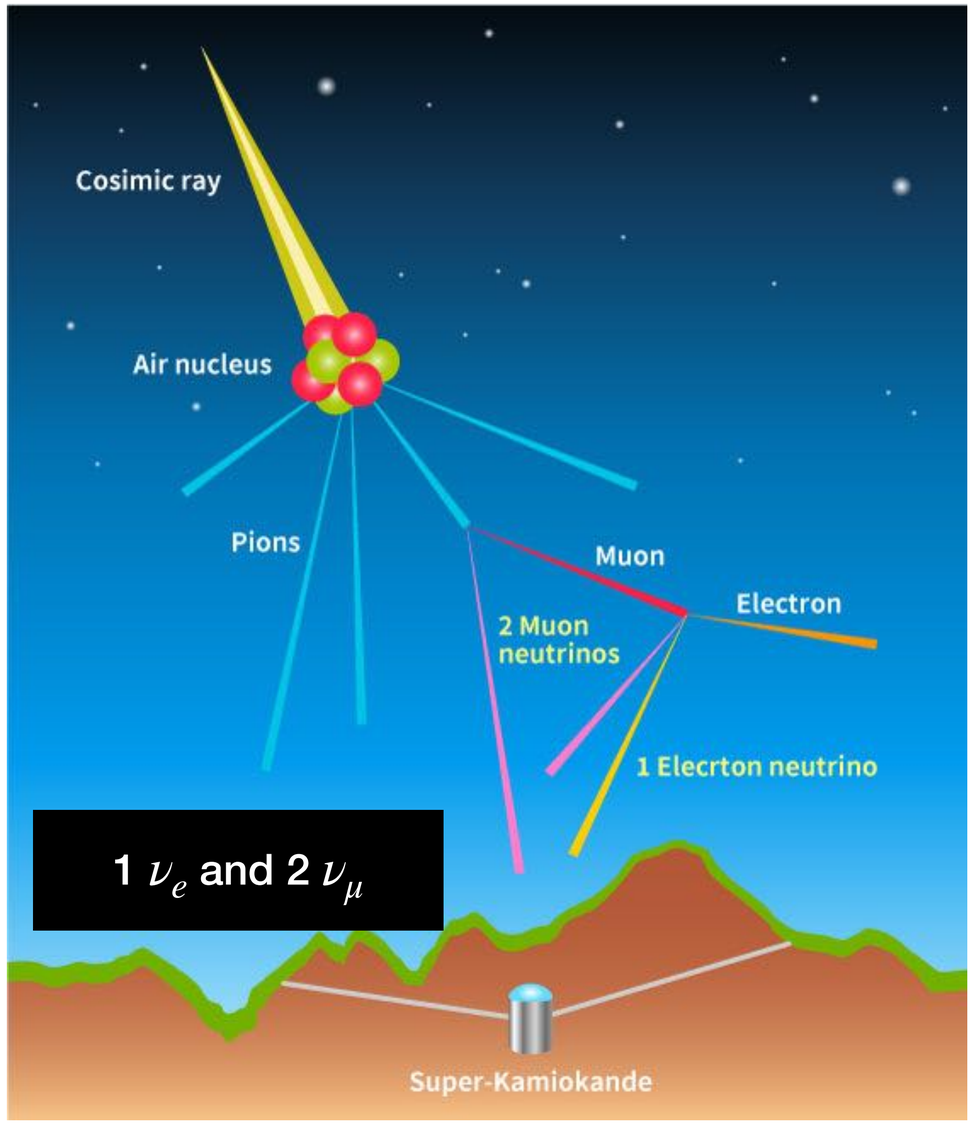
Looking at New Flavors

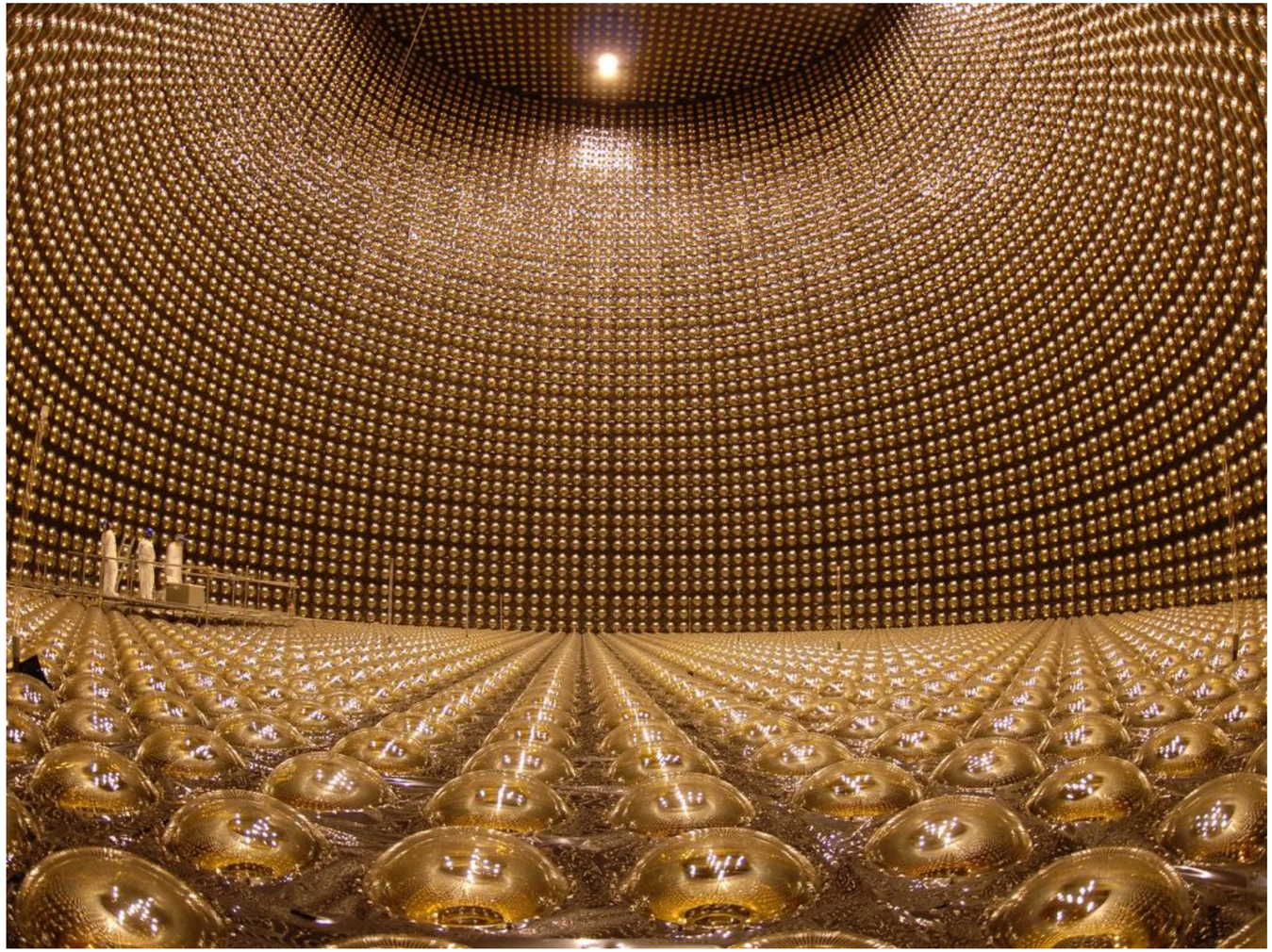


- Discrepancy observed in electron-only measurement
- All flavor measurement in agreement with theoretical predictions

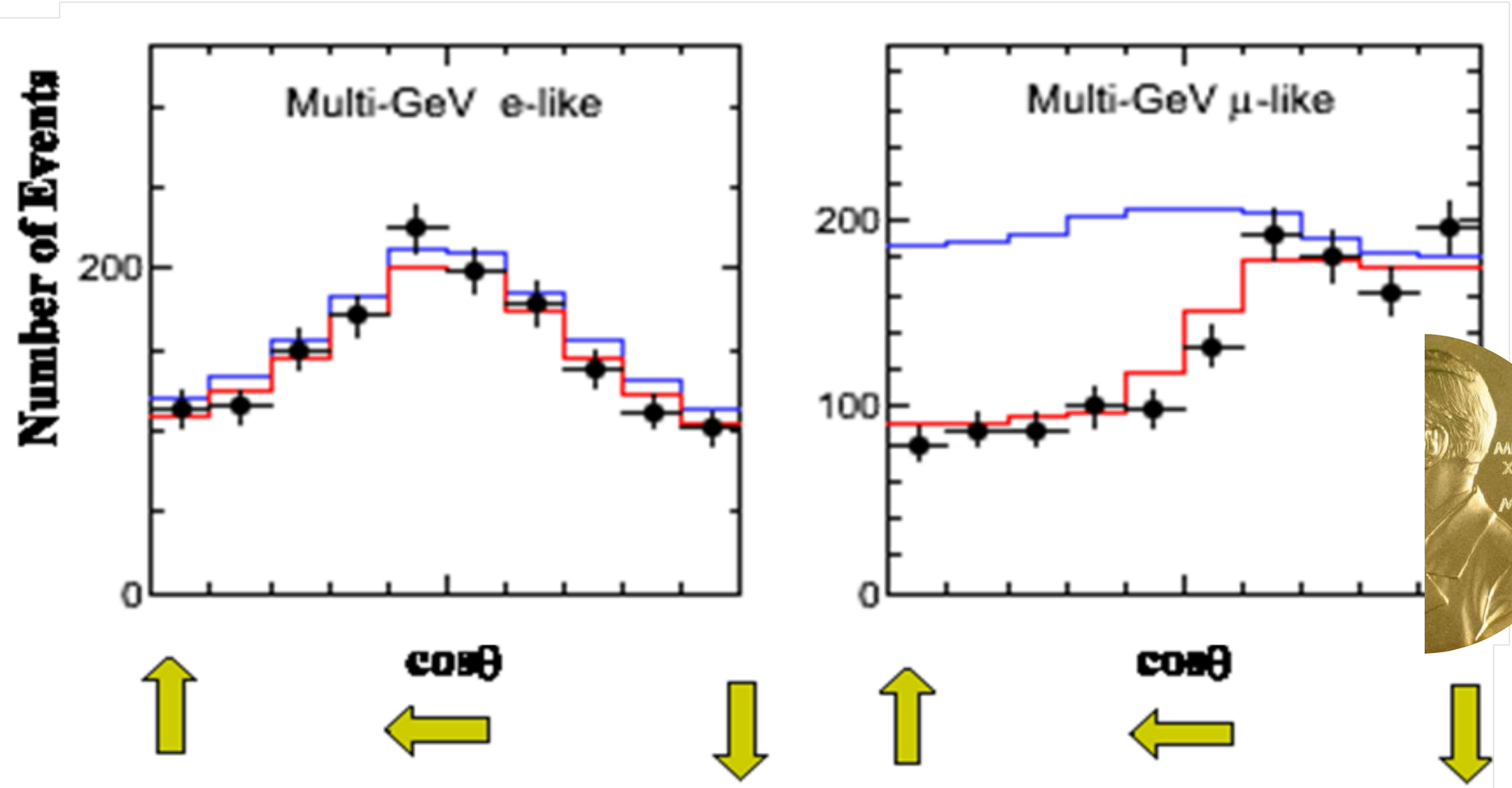
A. McDonald. doi:10.1002/201600031

Looking at New Sources





Looking at New Sources

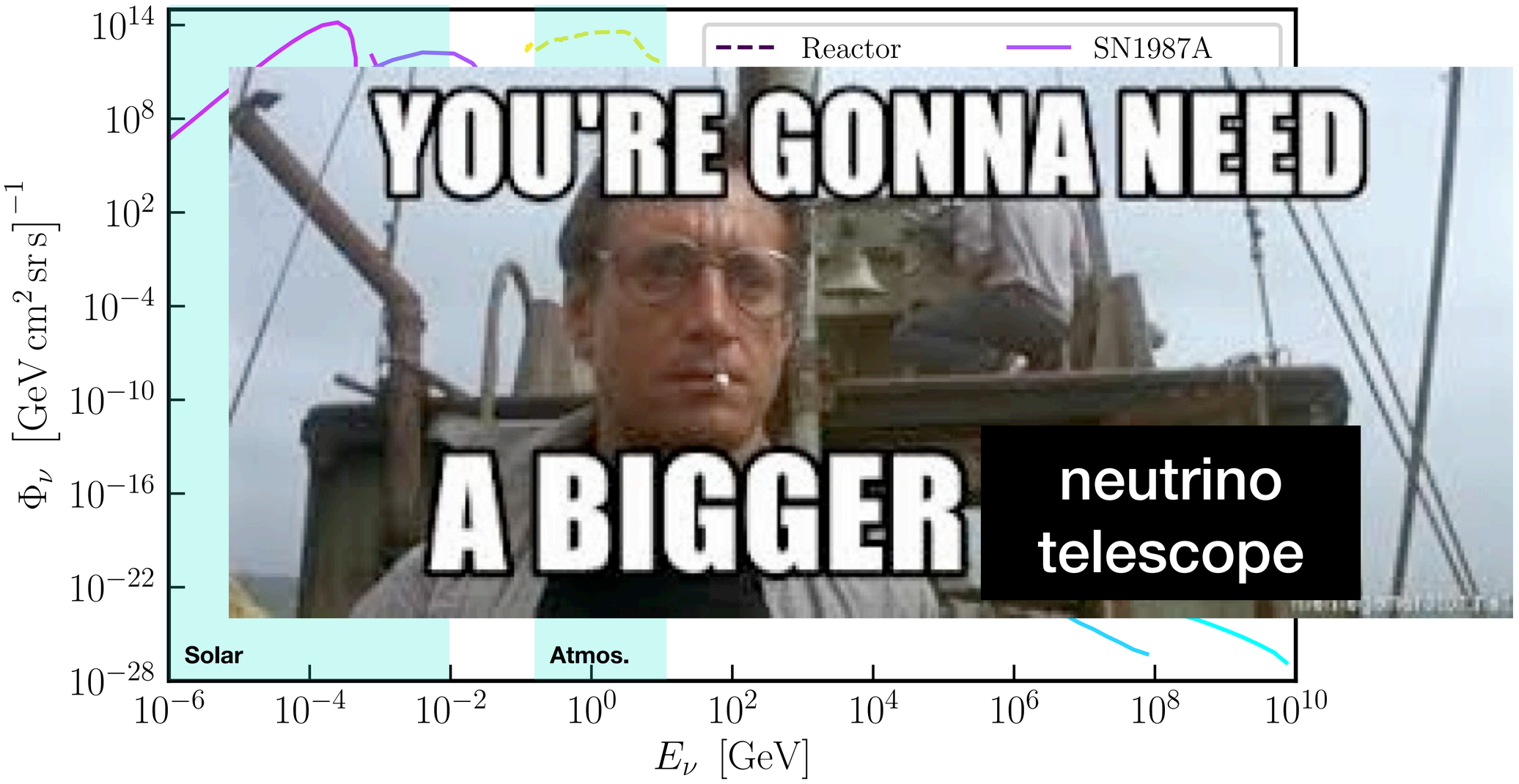


- SuperK saw a deficit of ν_μ coming through the Earth
- This confirmed neutrinos neutrino in-flight flavor change

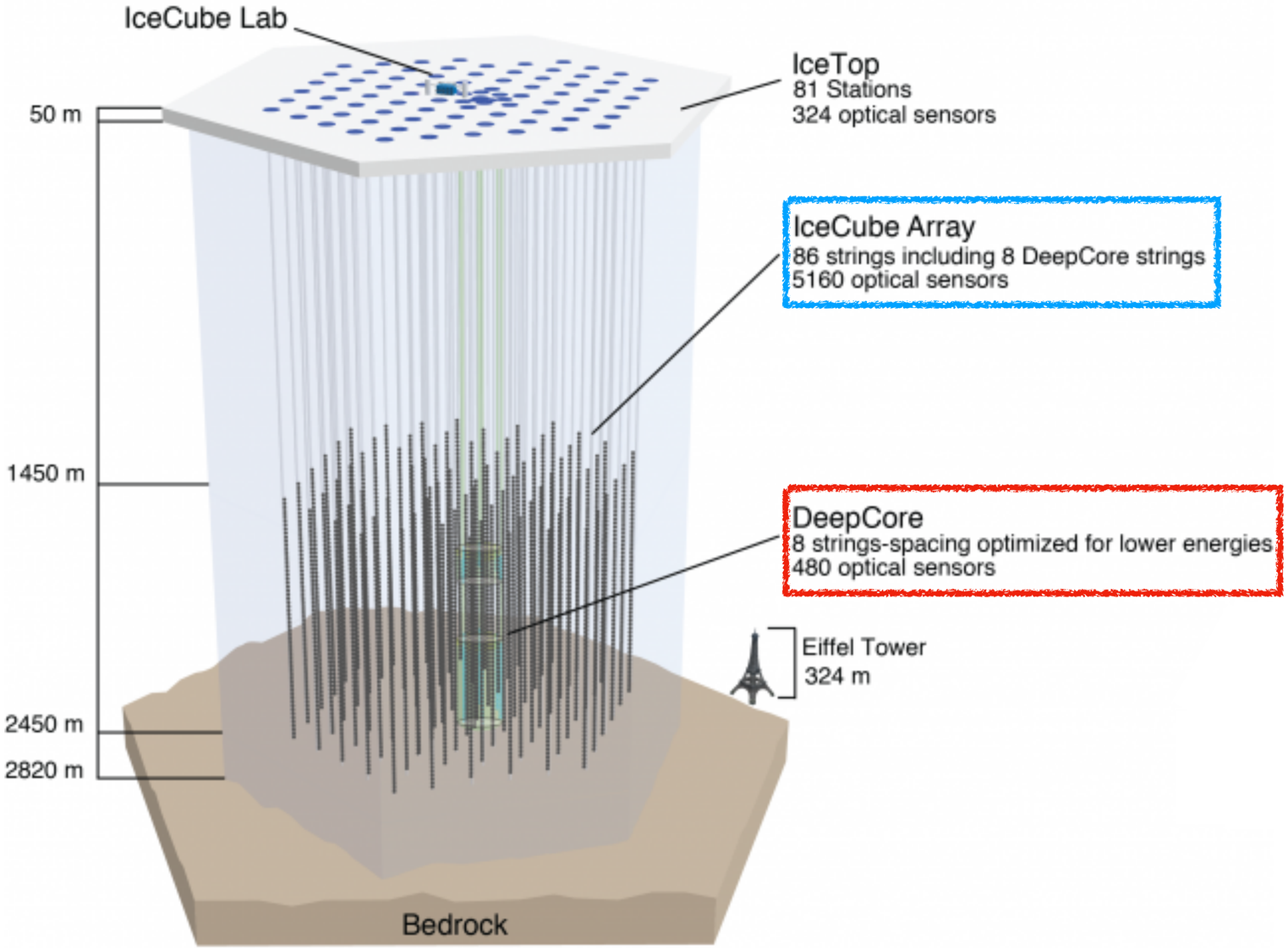
Understanding the ***flavor***, ***energy***, and ***directional*** information of non-terrestrial neutrinos have played a pivotal role in shaping our understanding of the Sun, neutrino physics, and the Standard Model more broadly

So, where do we go from here ?

Well-understood / measured

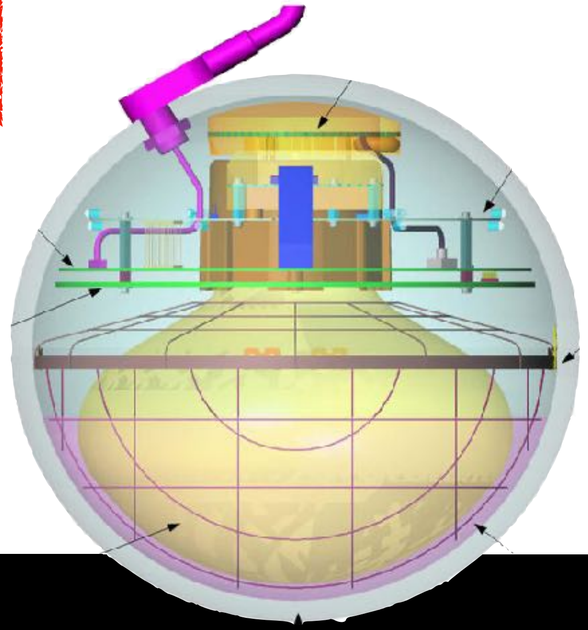


The IceCube Neutrino Observatory



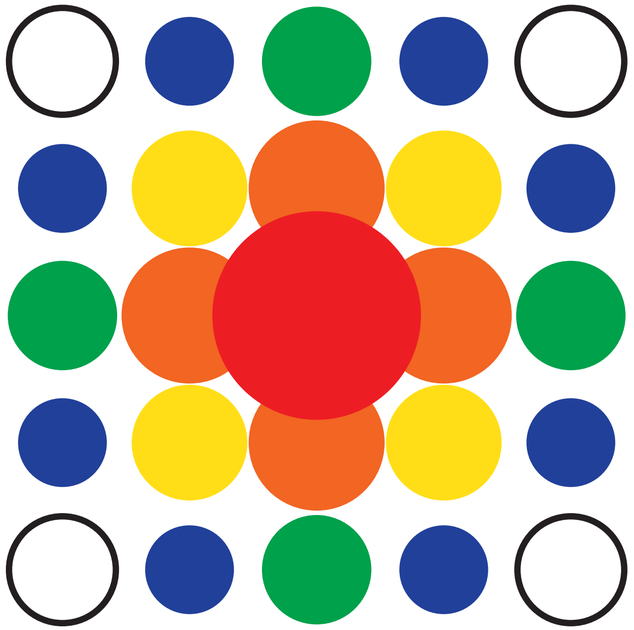
Gigaton scale detector of 5,160 light detecting digital optical modules (DOMs)

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



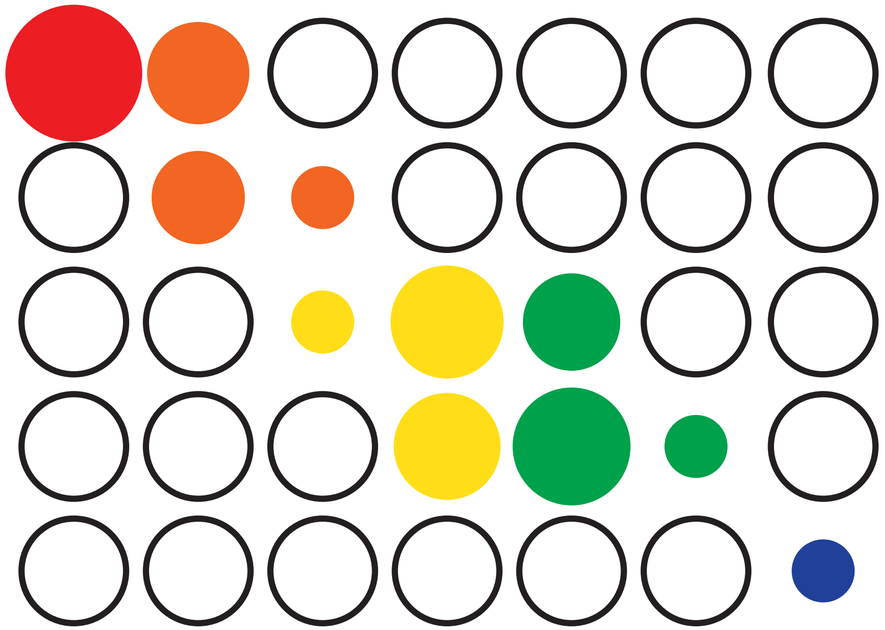
Unfolding Light and Time

Cascades ν_e CC | ν_α NC



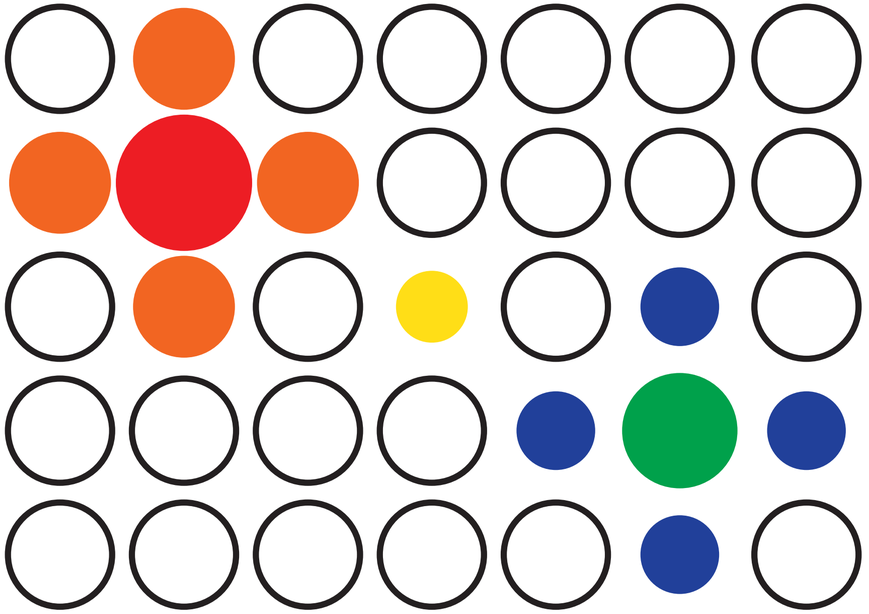
Great energy resolution, but angular reconstruction is challenging

Tracks ν_μ CC



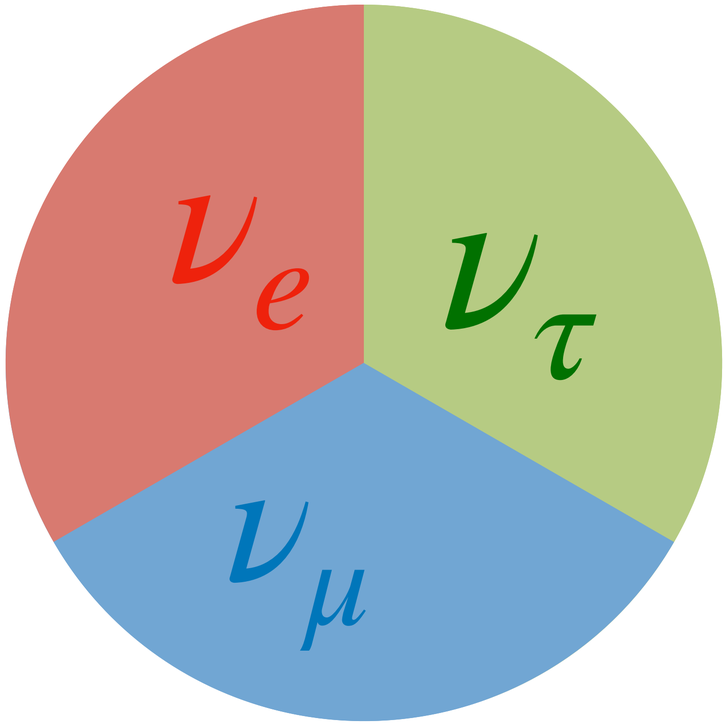
Great directional resolution, but deposited energy not proportional to E_ν

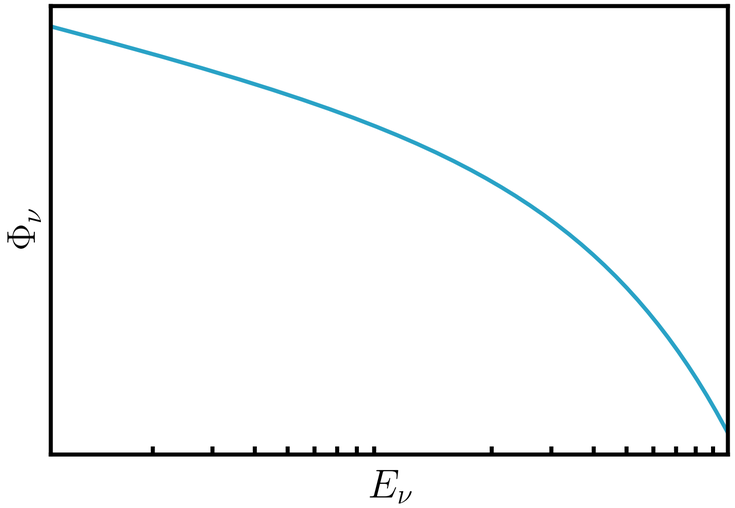
Double bangs ν_τ CC

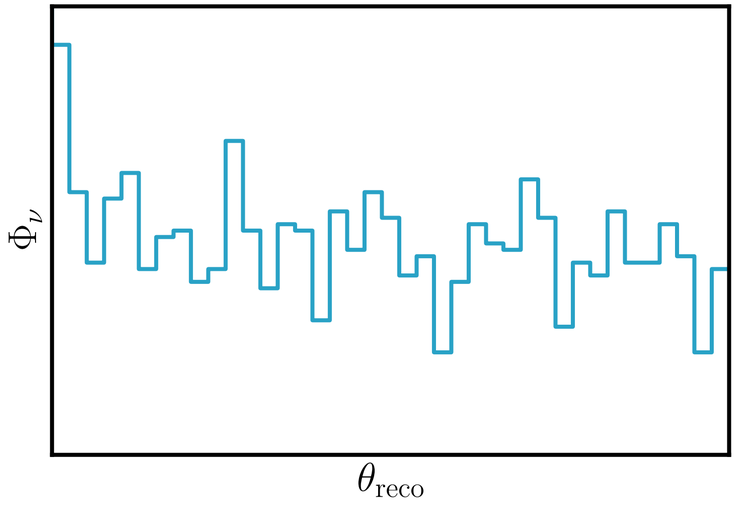


Signature of ν_τ CC events

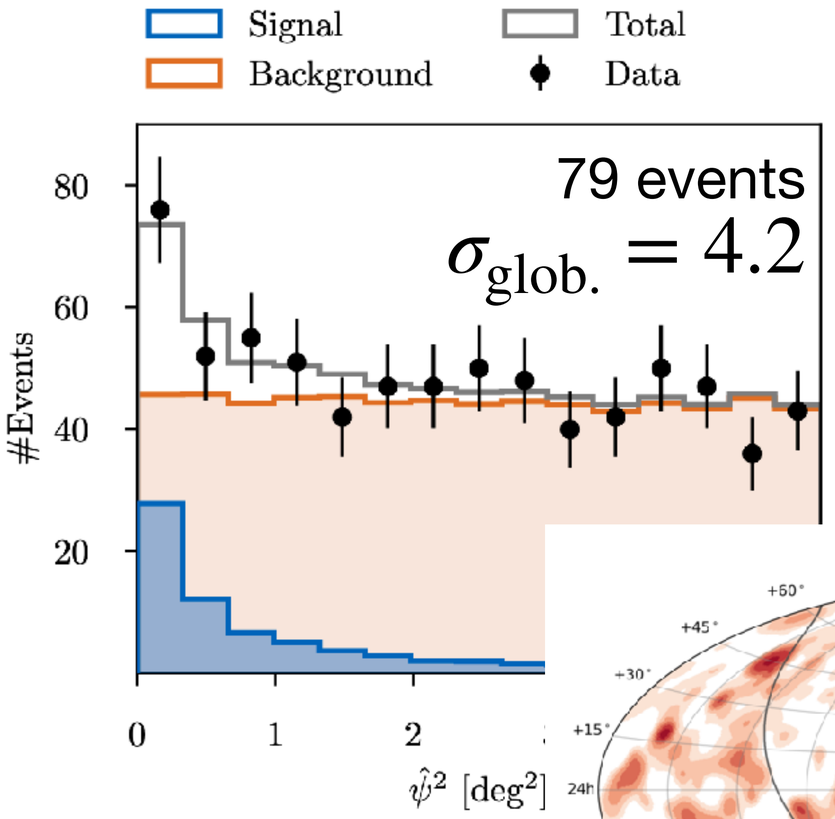
What Do we look for

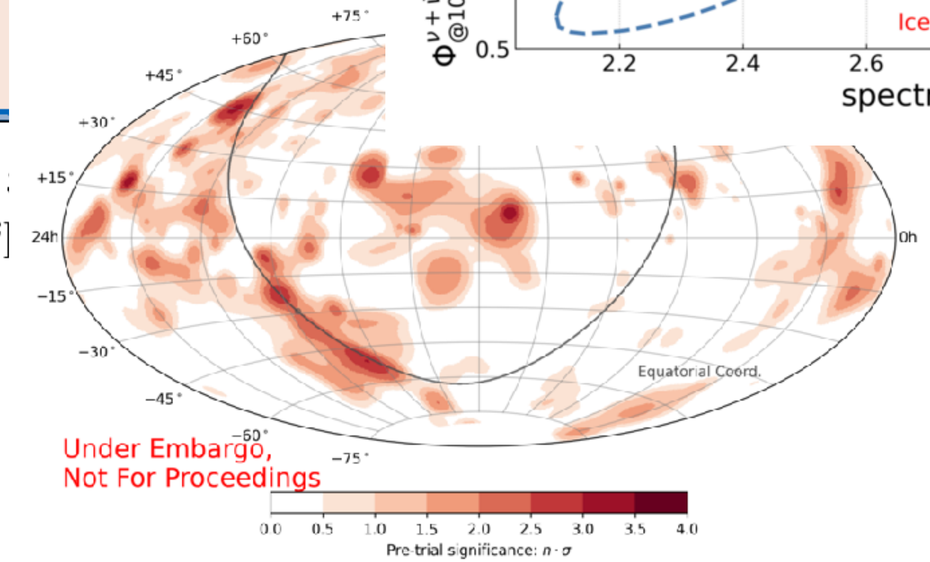


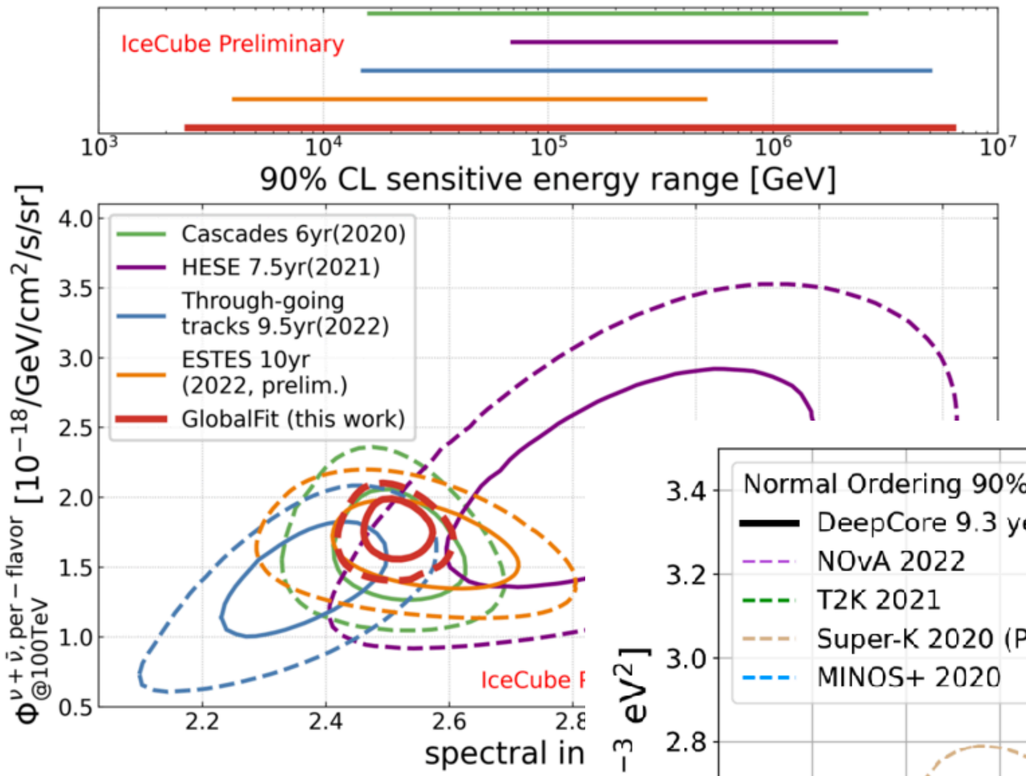


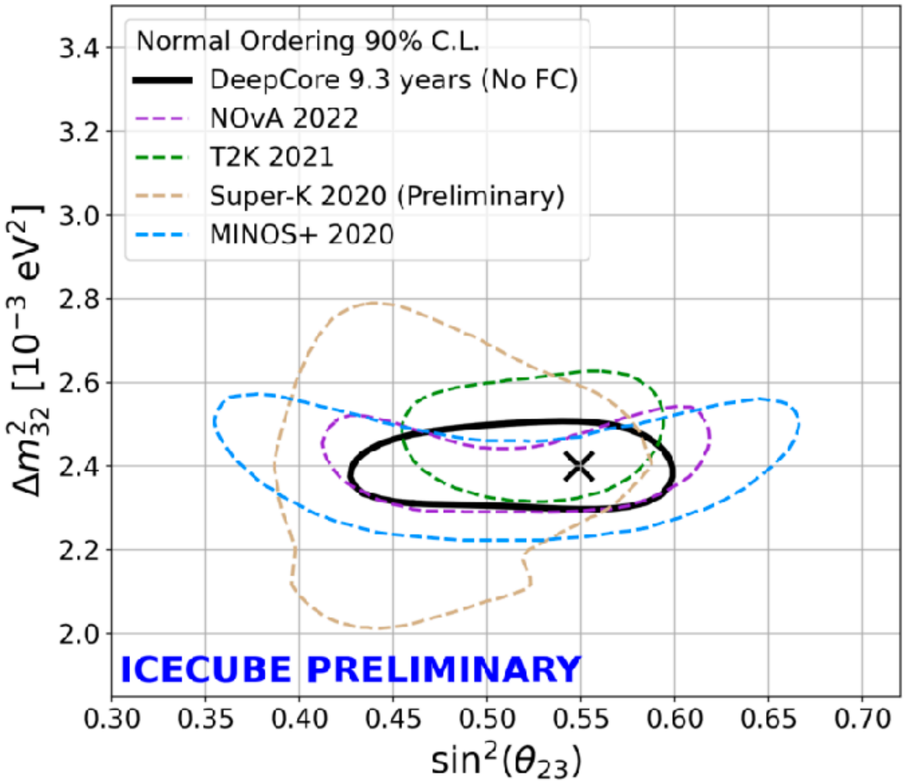


A Decade of Delivering



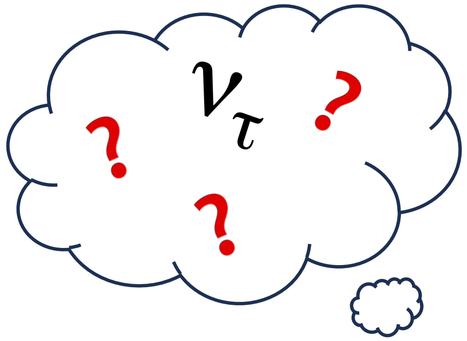


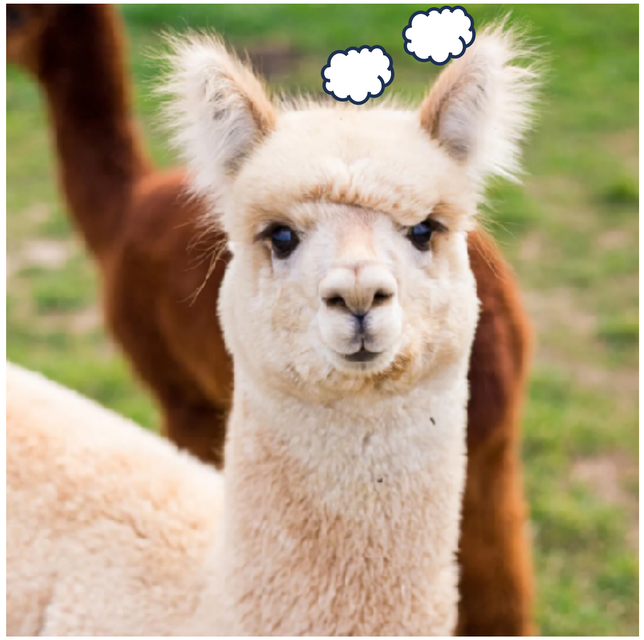




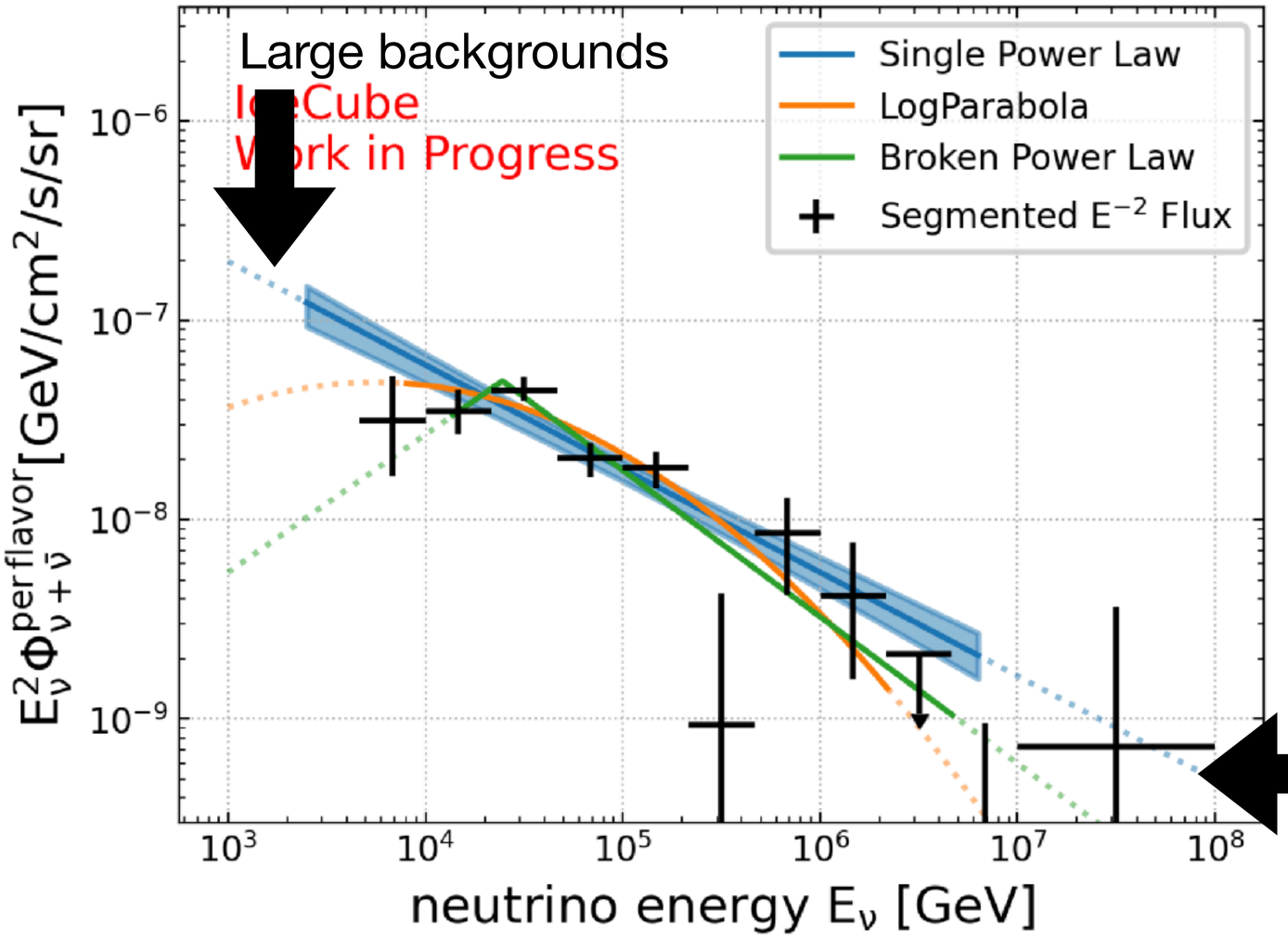
Roadmap

- A very brief history of neutrino astronomy
- Open questions in neutrino astronomy
- TAMBO overview
- Realizing TAMBO





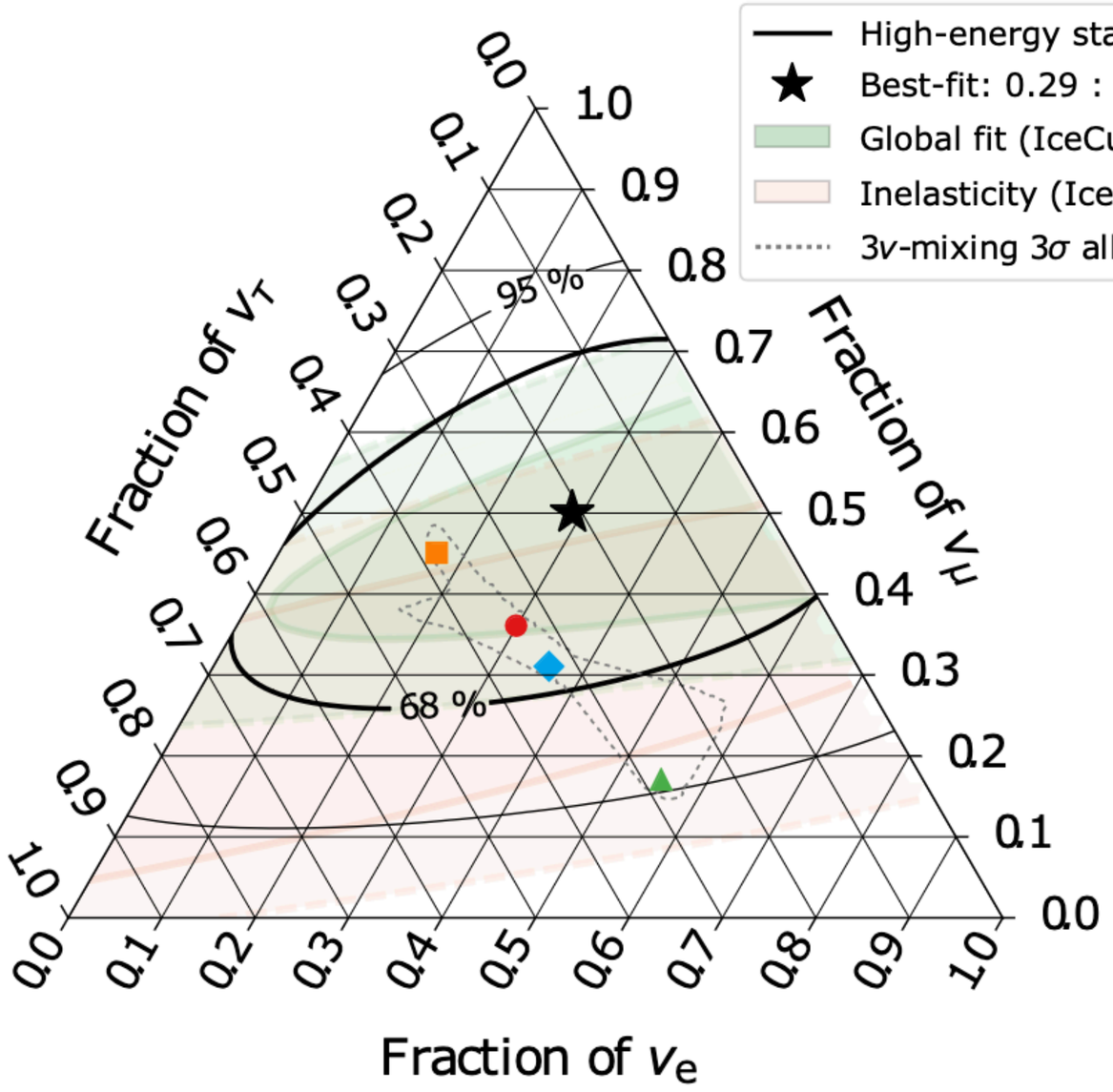
New Shapes



- 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 $\sim 2\sigma$

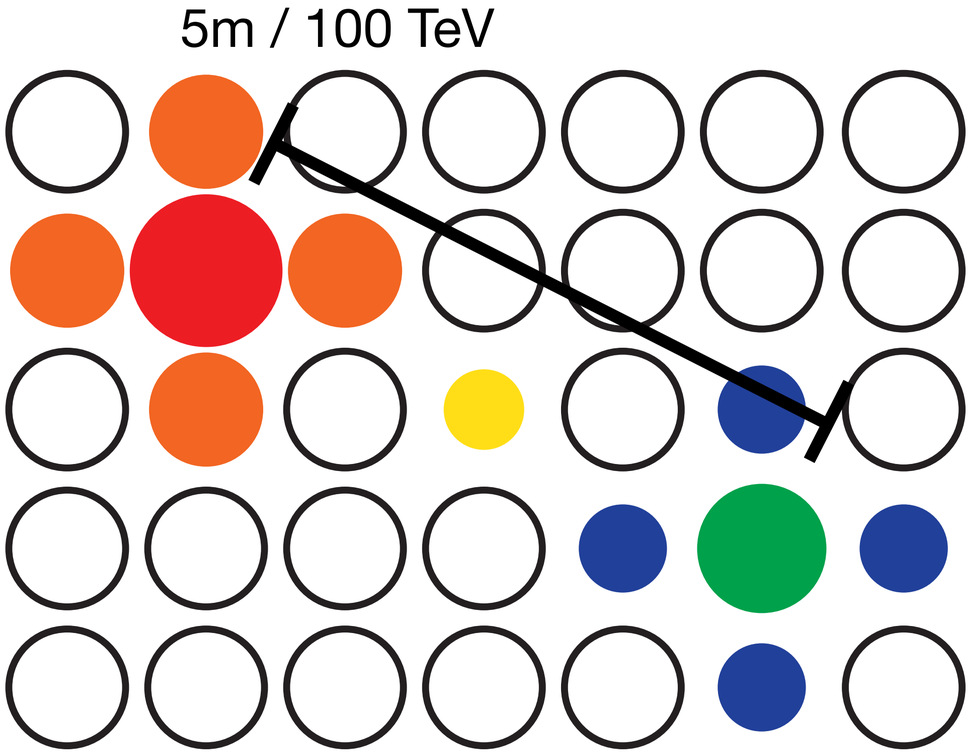
Small stats

Flavor Degeneracy



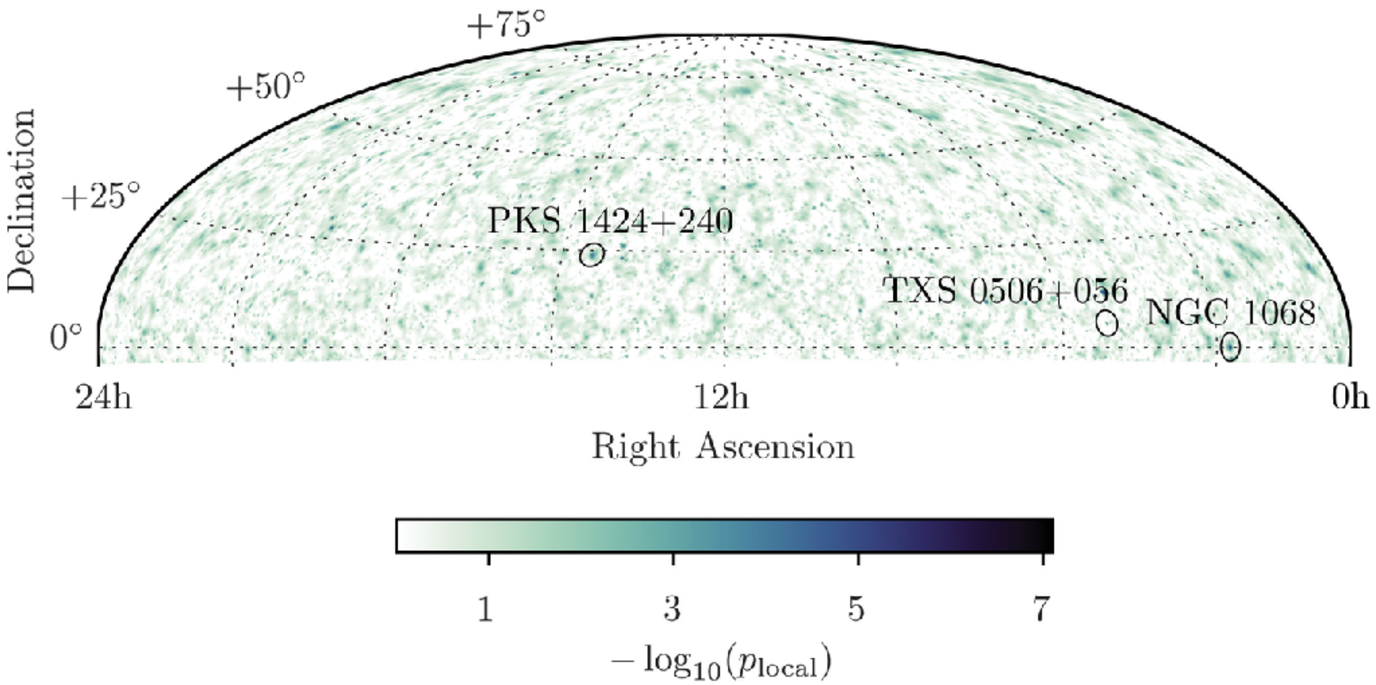
$\nu_e : \nu_\mu : \nu_\tau$ at source → on Earth:

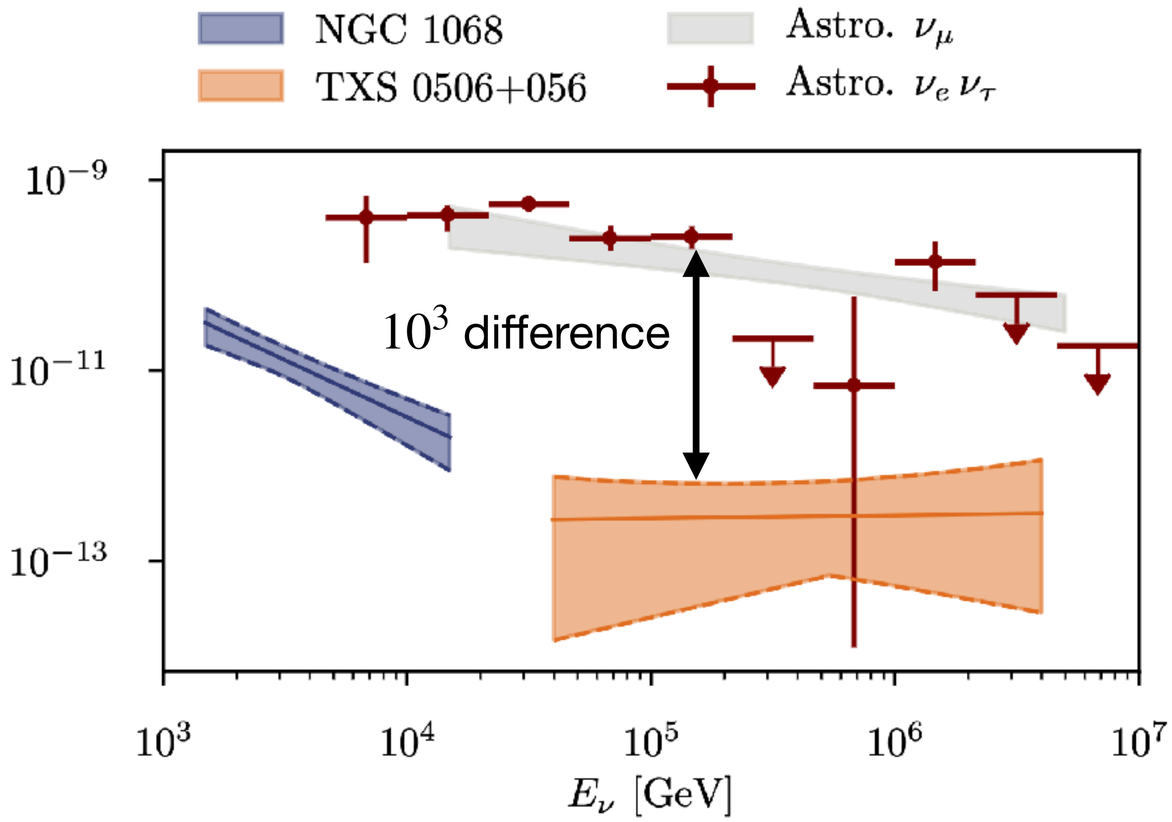
- 0:1:0 → 0.17 : 0.45 : 0.37
- 1:2:0 → 0.30 : 0.36 : 0.34
- 1:0:0 → 0.55 : 0.17 : 0.28
- 1:1:0 → 0.36 : 0.31 : 0.33



Where Are the Rest of the Sources ?

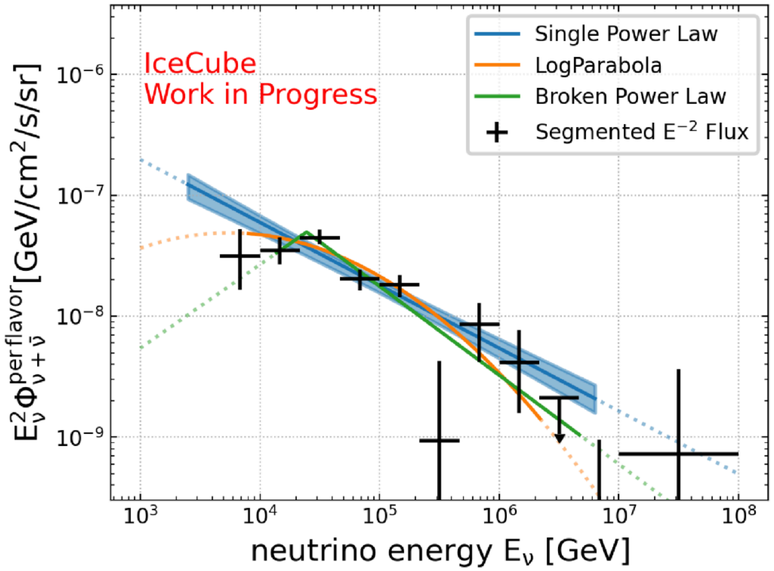
Test type	Pre-trial p-value (p_{local})	Post-trial p-value (p_{global})
Northern Hemisphere scan	5.0×10^{-8} ($5.3\,\sigma$)	2.2×10^{-2} ($2.0\,\sigma$)

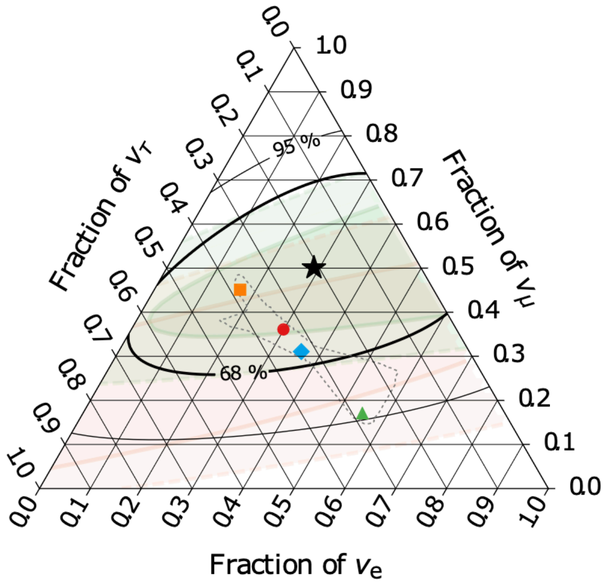


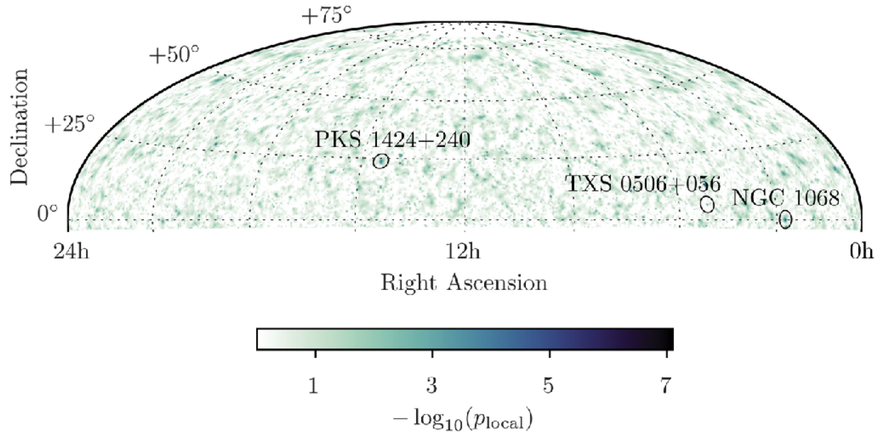


- The number of neutrino sources has increased by ∞% in the last six years
- …But this is only a small fraction of the diffuse flux

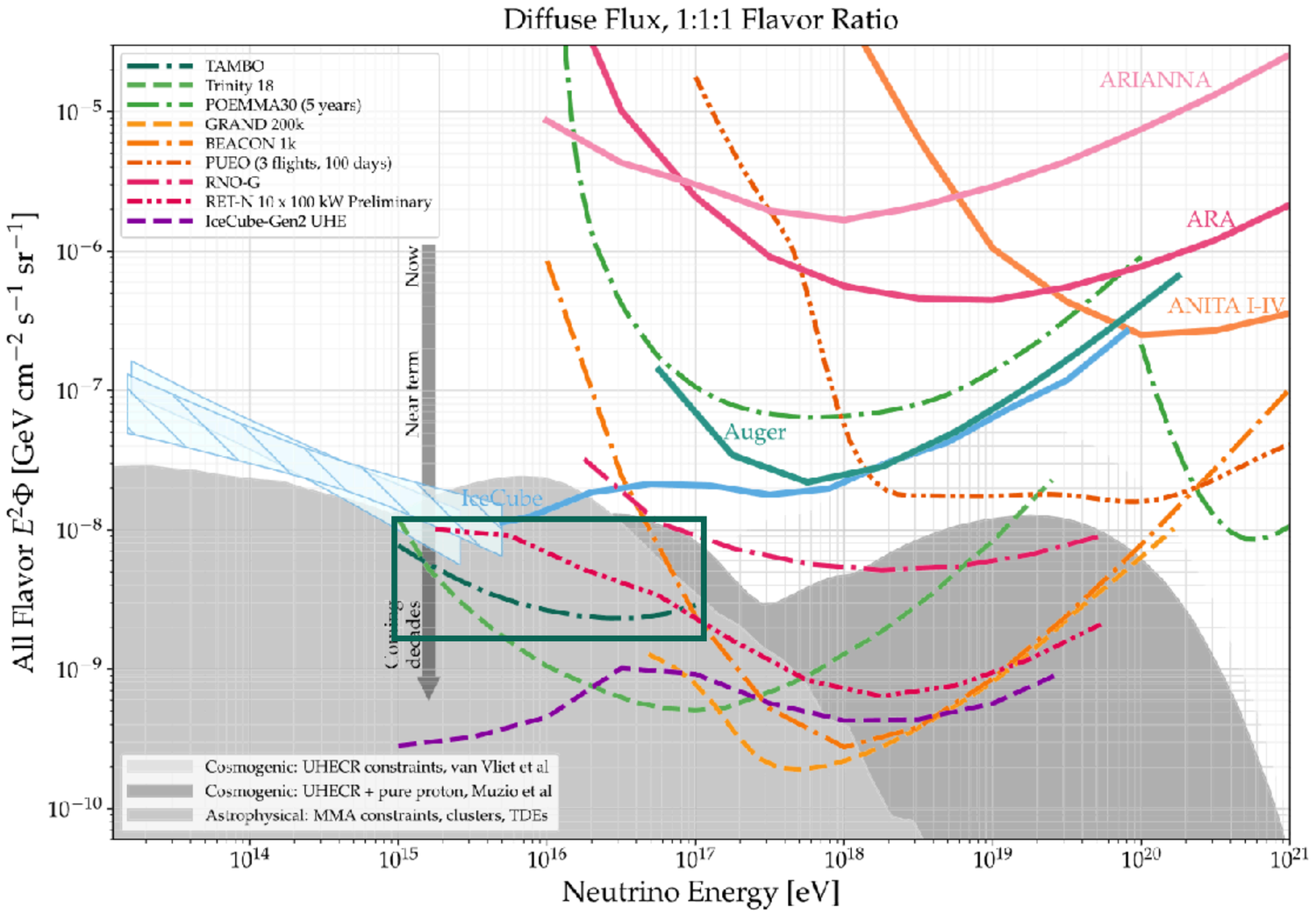
Roadmap towards Future Discoveries







Next-Generation Prospects



- 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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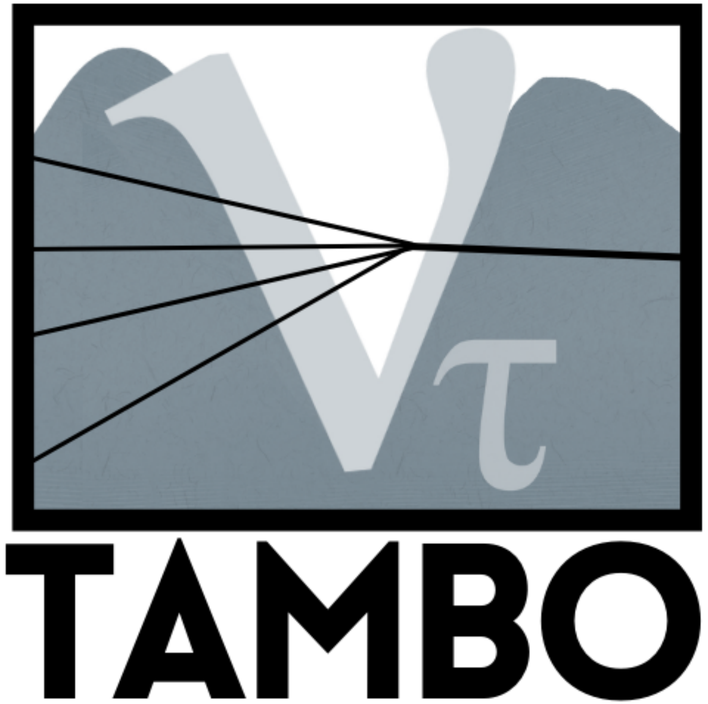
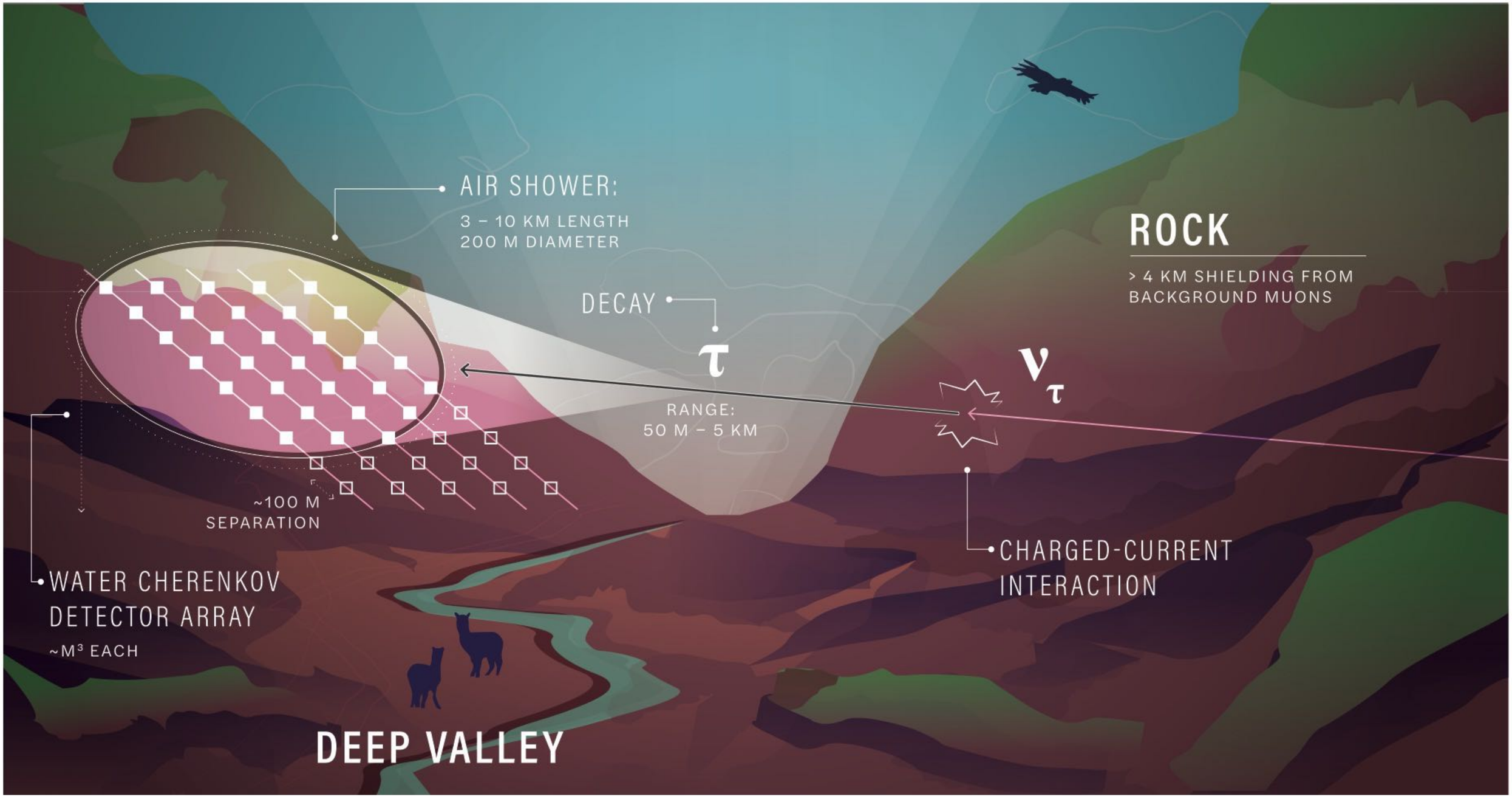
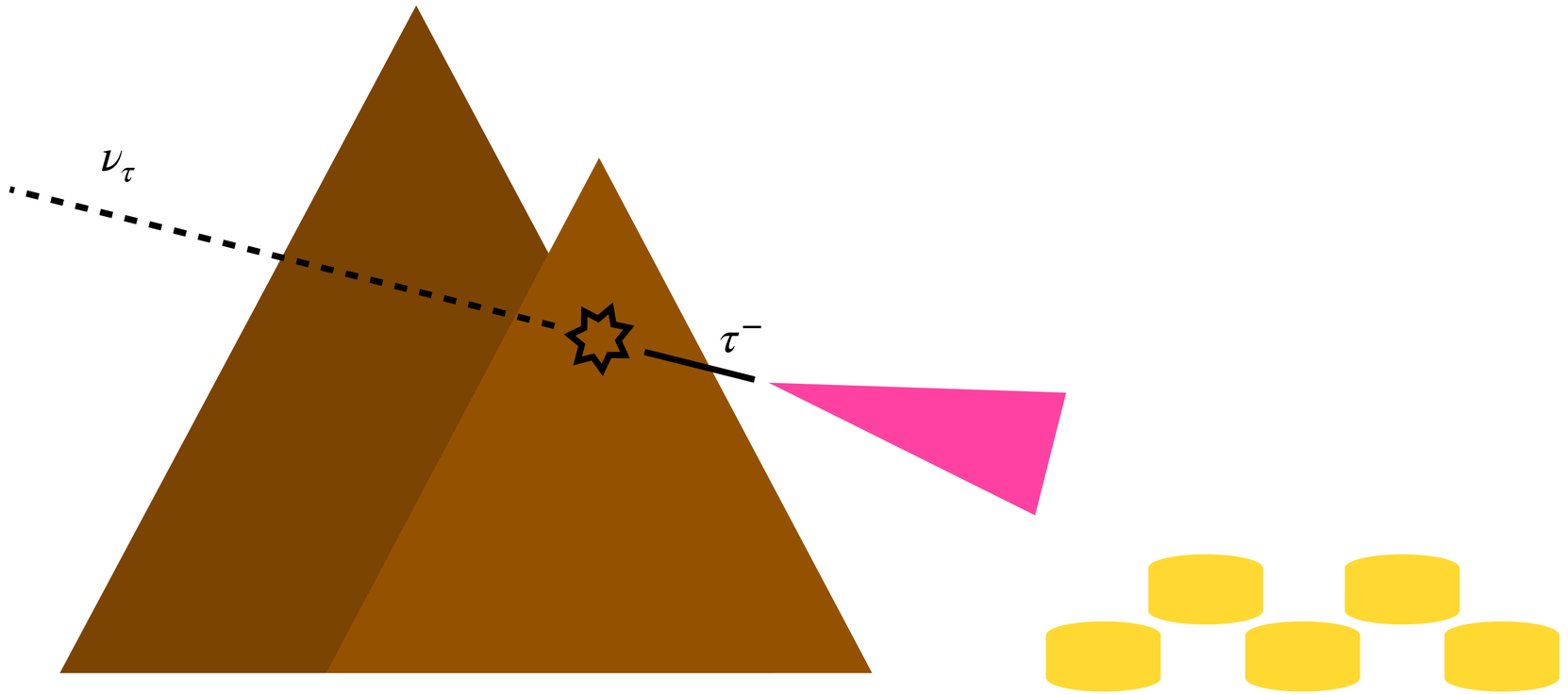




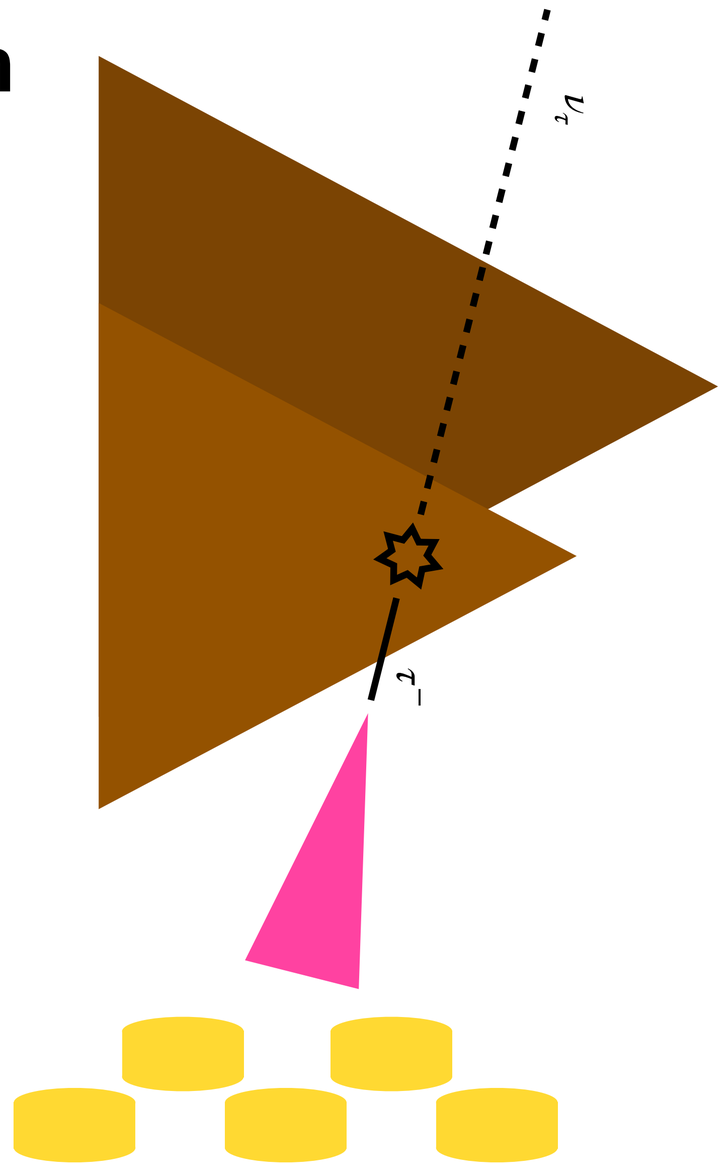
TAU AIR-SHOWER MOUNTAIN-BASED OBSERVATORY (TAMBO) · COLCA VALLEY, PERU

Why Put a Detector in a Canyon



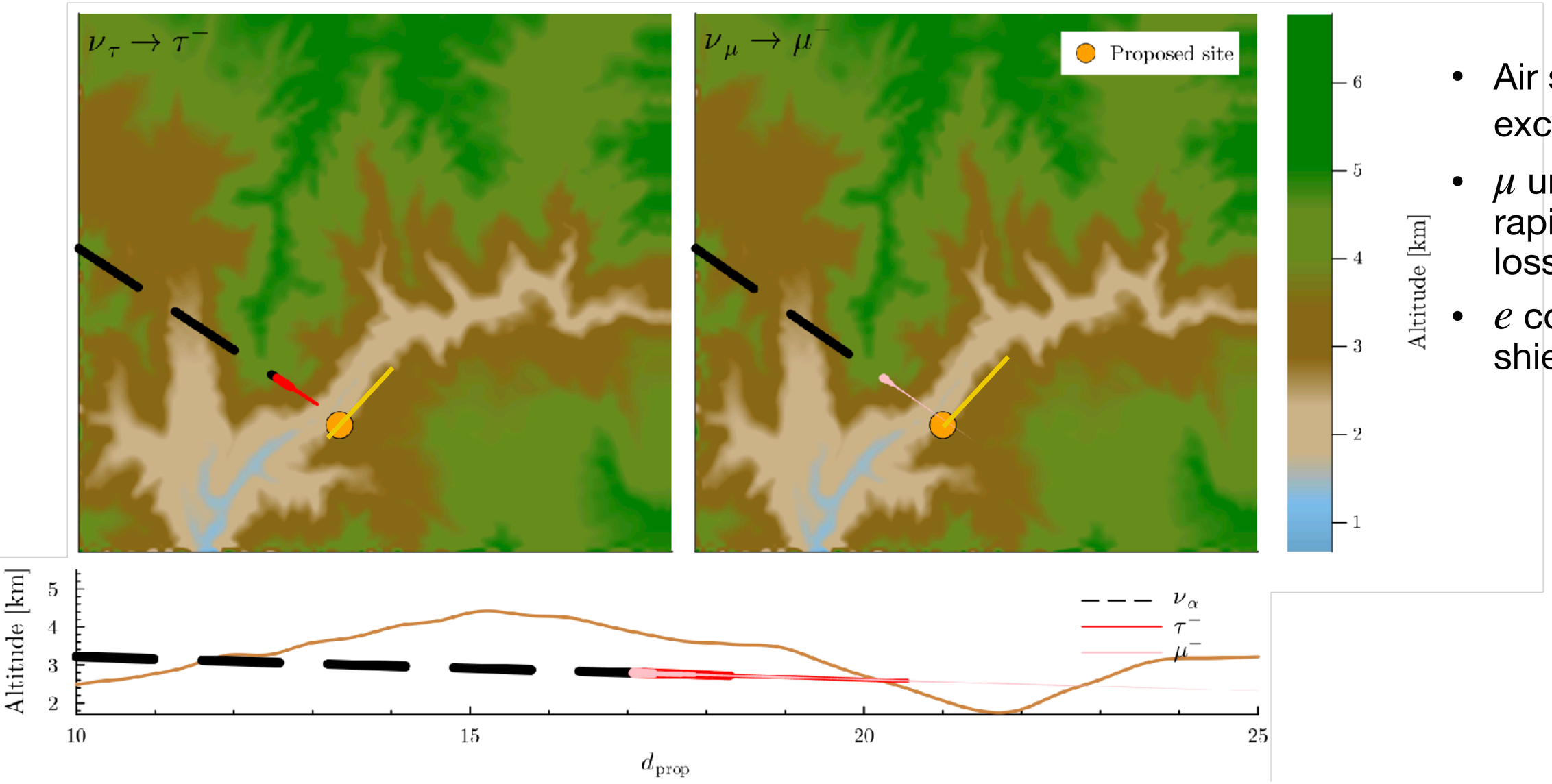
Inherently low geometrical acceptance

Why Put a Detector in a Canyon



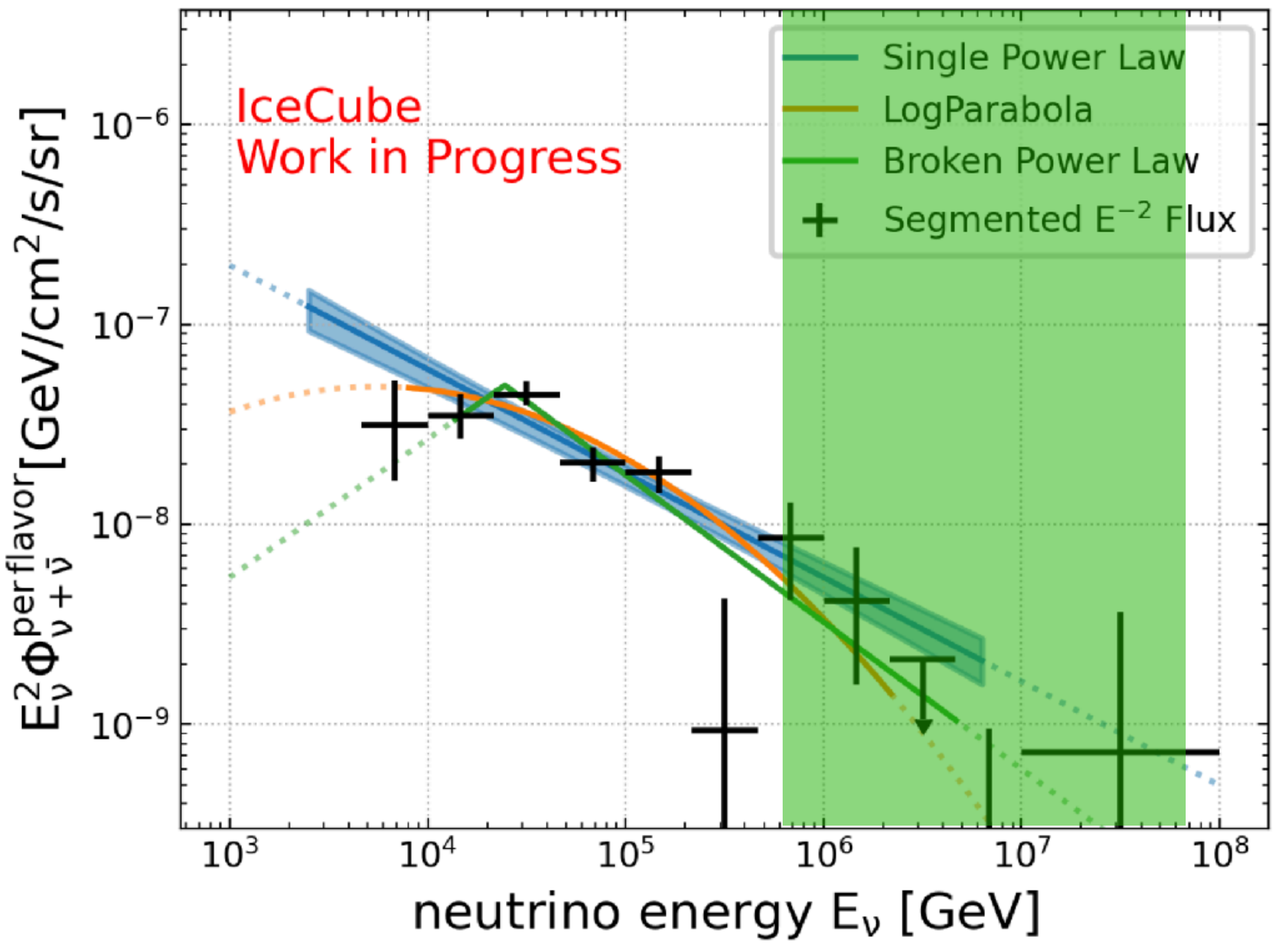
Better for physics, but the engineers are not thrilled

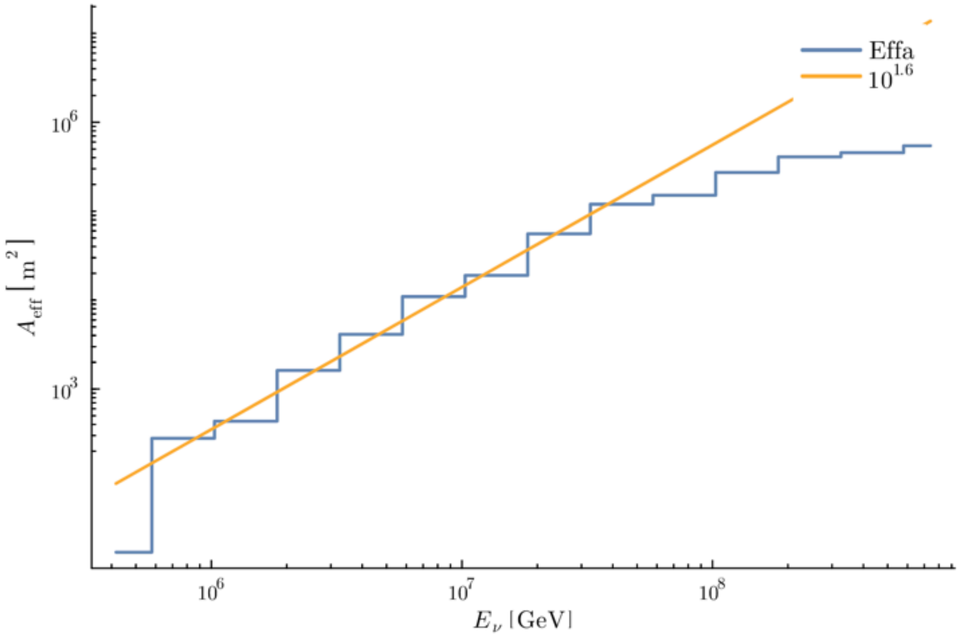
A ν_τ Sieve



- Air shower ie exclusive to ν_τ
- μ undergoes rapid energy loss
- e completely shielded

Passing the Energy Baton



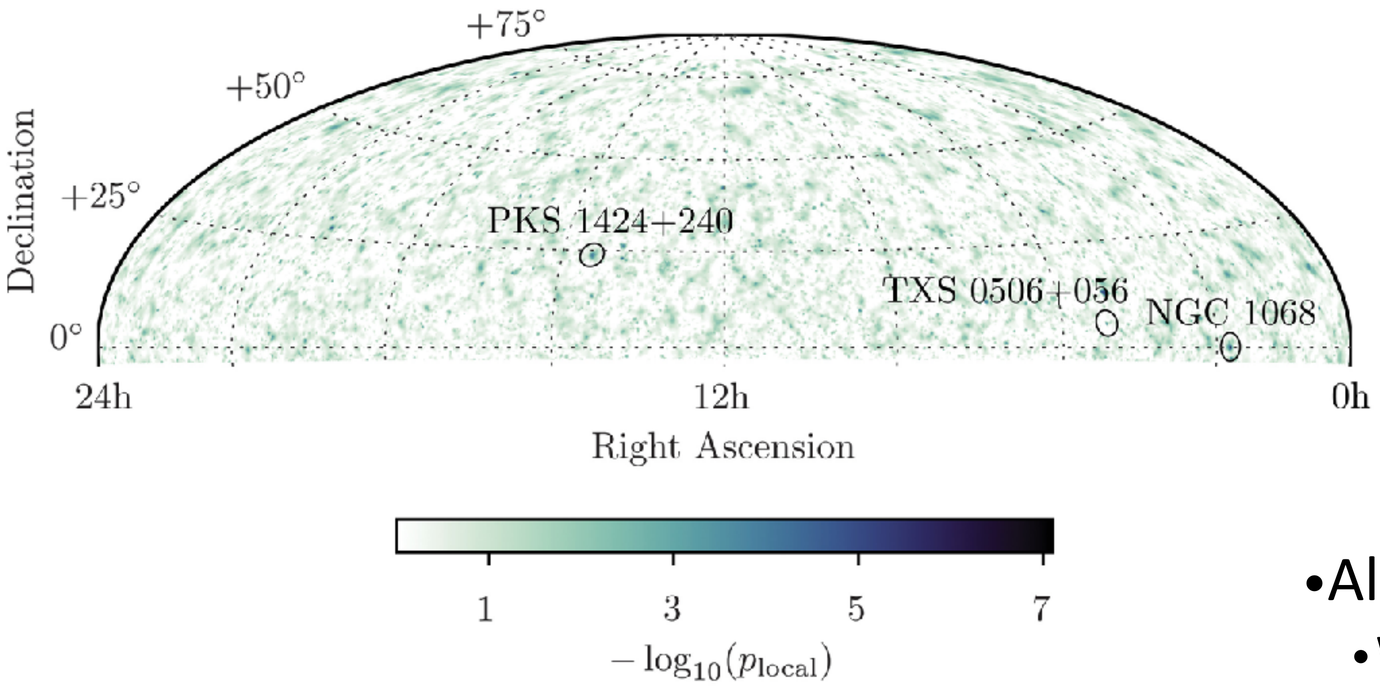


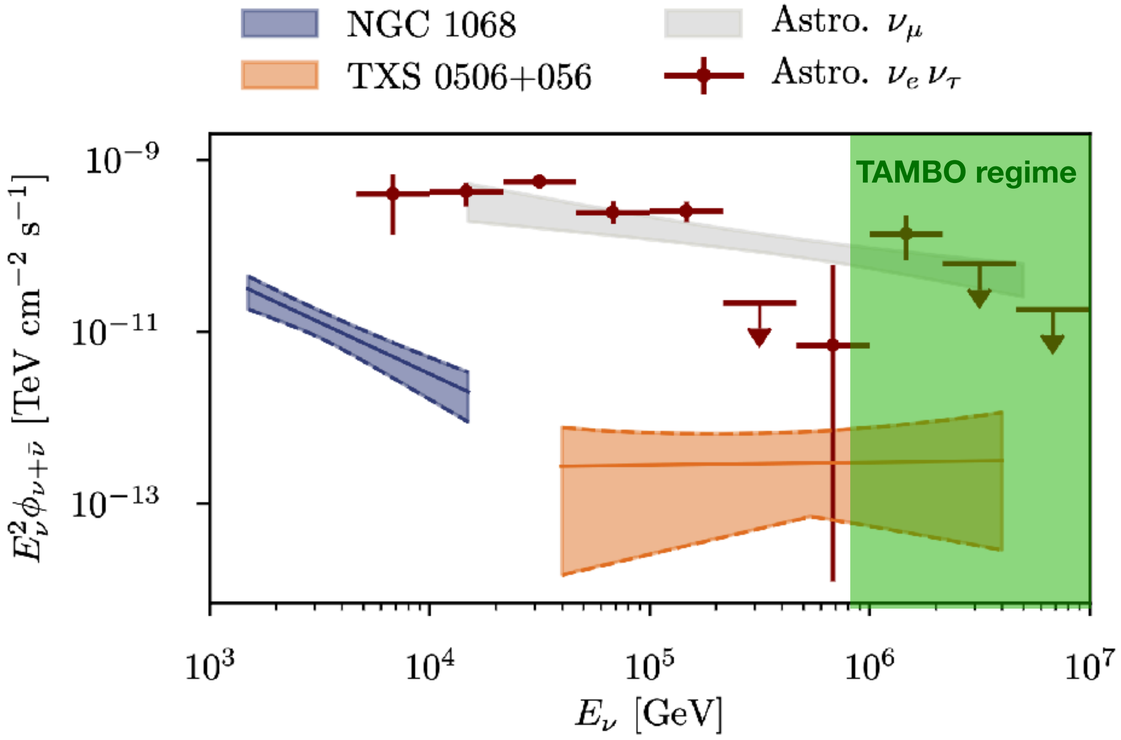
TAMBO becomes sensitive right towards the end of IceCube's sensitivity

TAMBO regime

Removing IceCube's Trials Factor

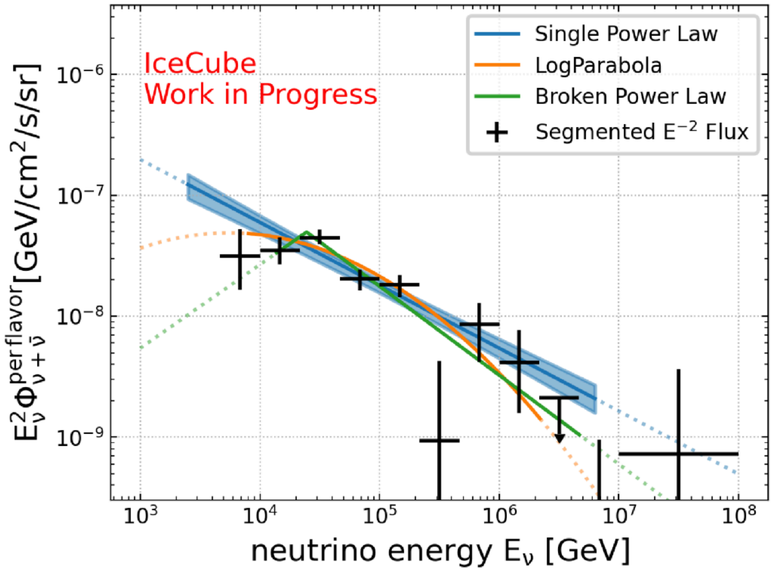
Test type	Pre-trial p-value (p_{local})	Post-trial p-value (p_{global})
Northern Hemisphere scan	5.0×10^{-8} (5.3 σ)	2.2×10^{-2} (2.0 σ)

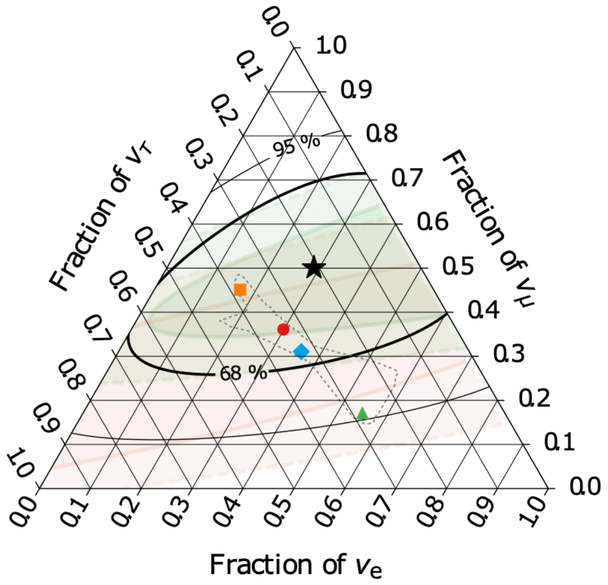


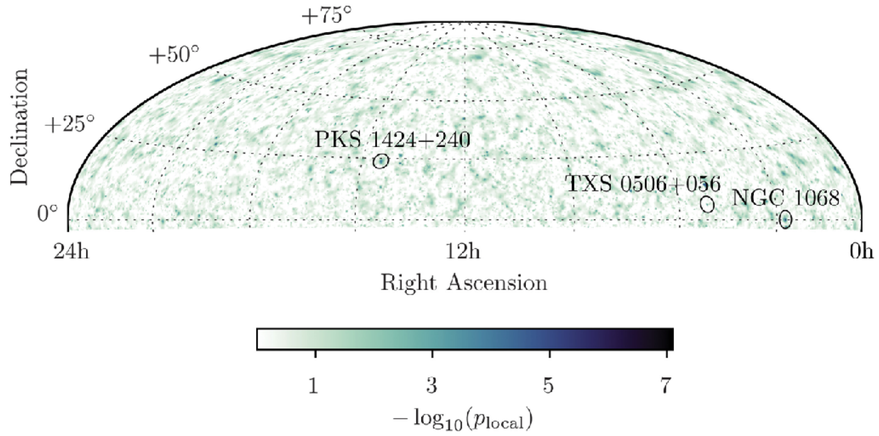


- All-sky search limits IceCube sensitivities
  - What if we knew exactly where to point?
- Low-background ν_τ from TAMBO remove trial factor from IceCube

Goals of TAMBO







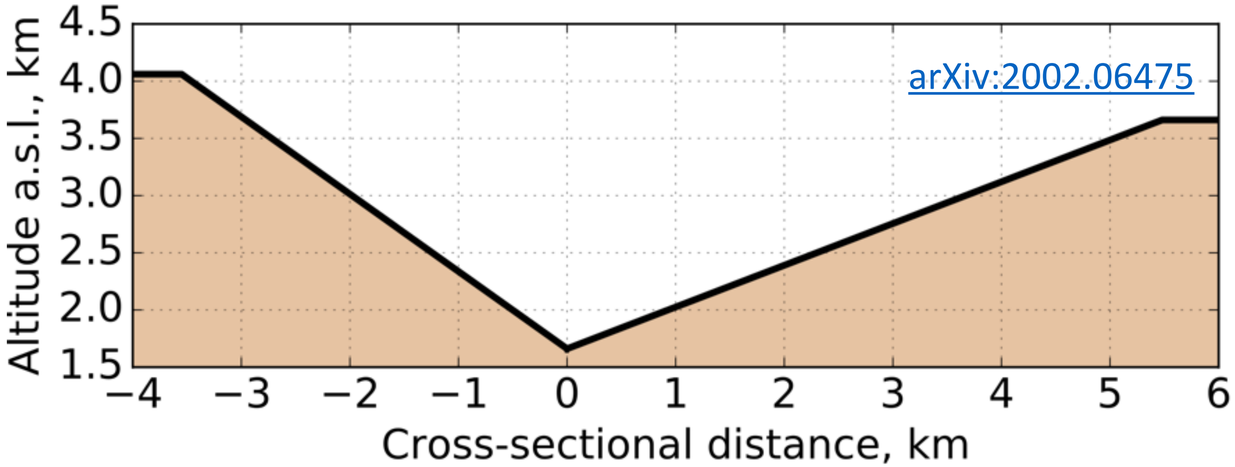
Determine high-energy behavior of diffuse spectrum

Characterize ν_τ component of astrophysical flux

Discover new neutrino point sources

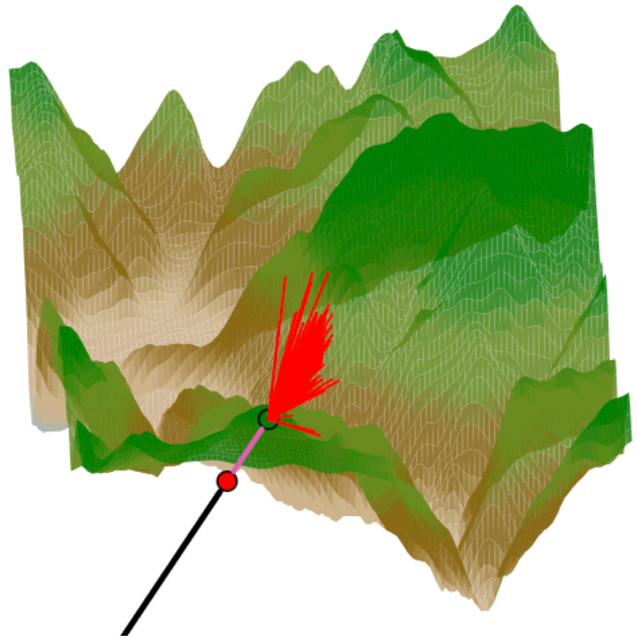
An Initial Estimation

Initial Calculation



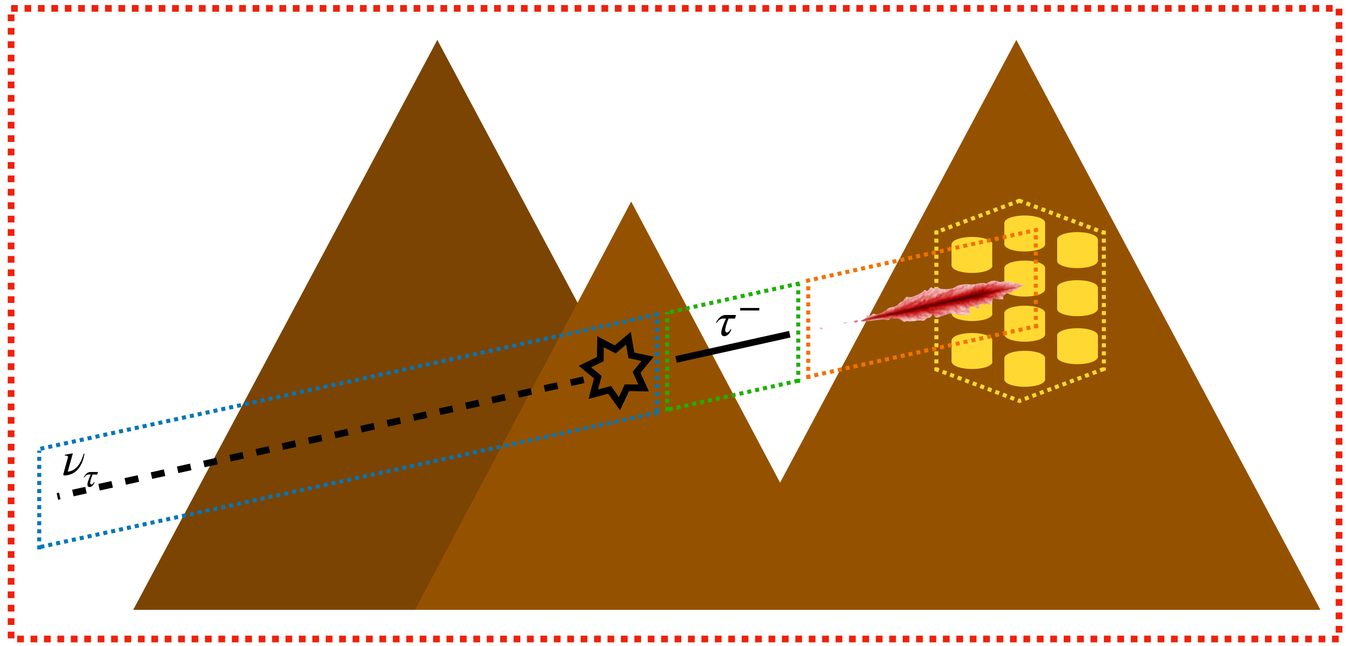
- Simplified geometry
- No treatment of $\tau^{\pm}$ energy losses
- Approximation of air-shower physics

Updated Simulation



- Realistic geometry
- Full treatment of $\tau^{\pm}$ energy losses
- Air-shower simulation with CORSIKA 8

Developing a Full Monte Carlo Chain



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

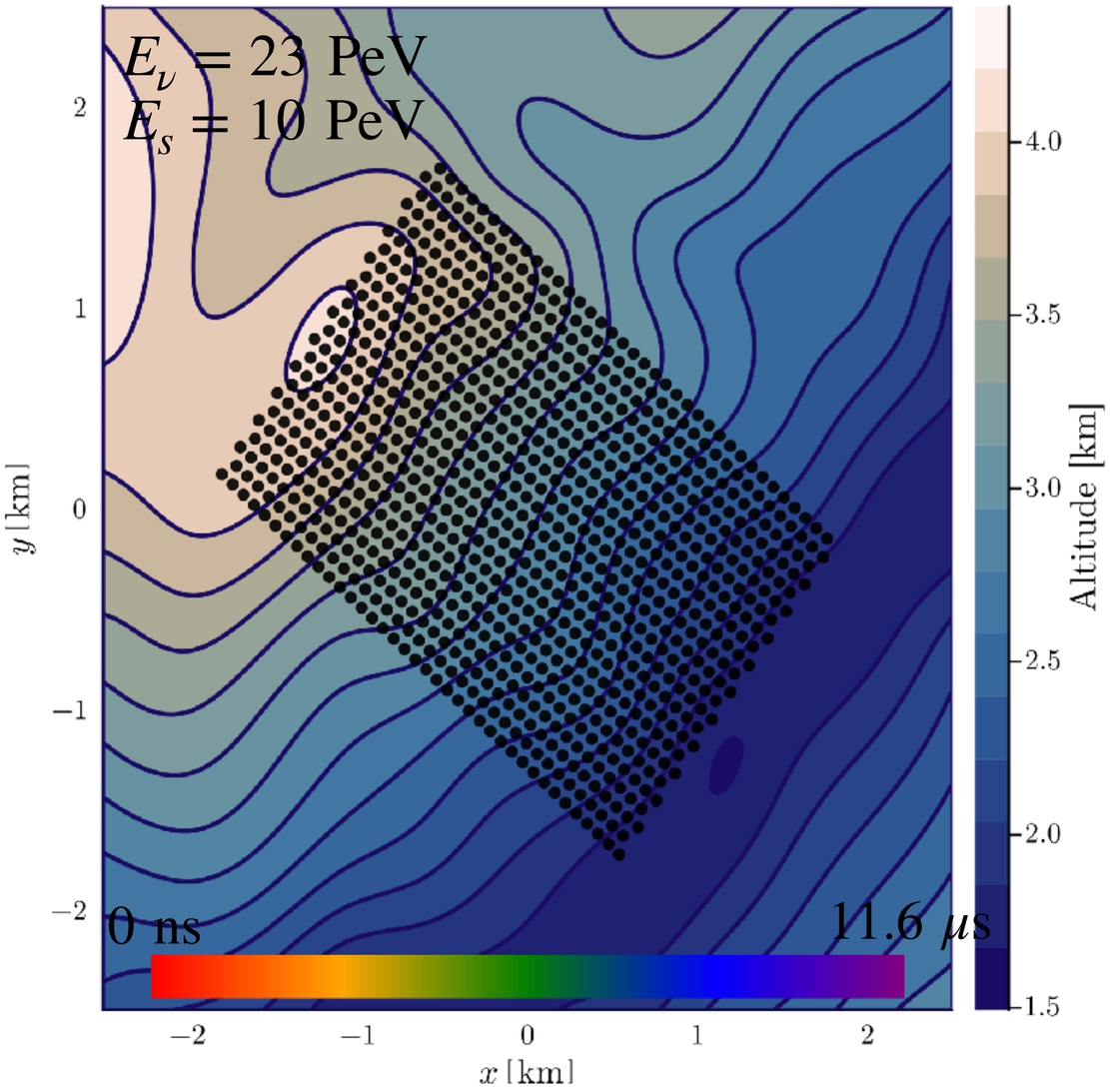
Charged lepton propagation: Propagate outgoing charged lepton, accounting for energy losses and decay, to find decay point

Air-shower simulation: Model shower development from lepton decay

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

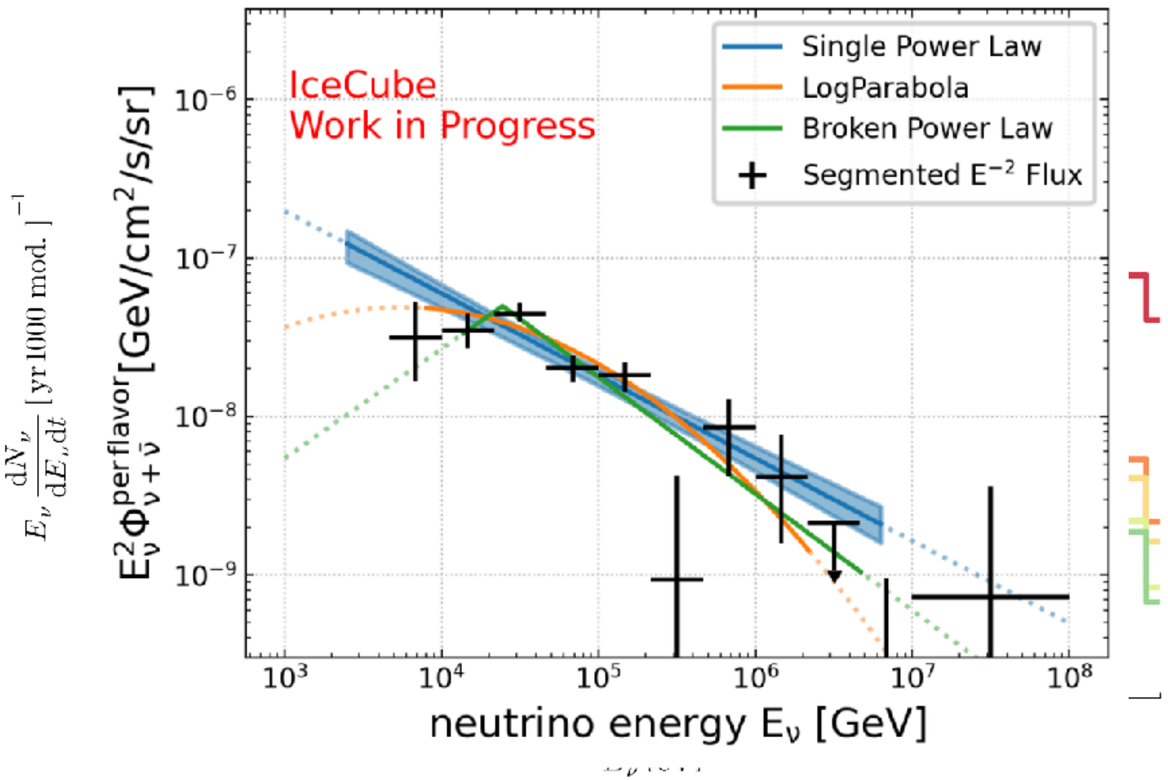
Event weighting: Remove unphysical remnants from selection of initial neutrino properties

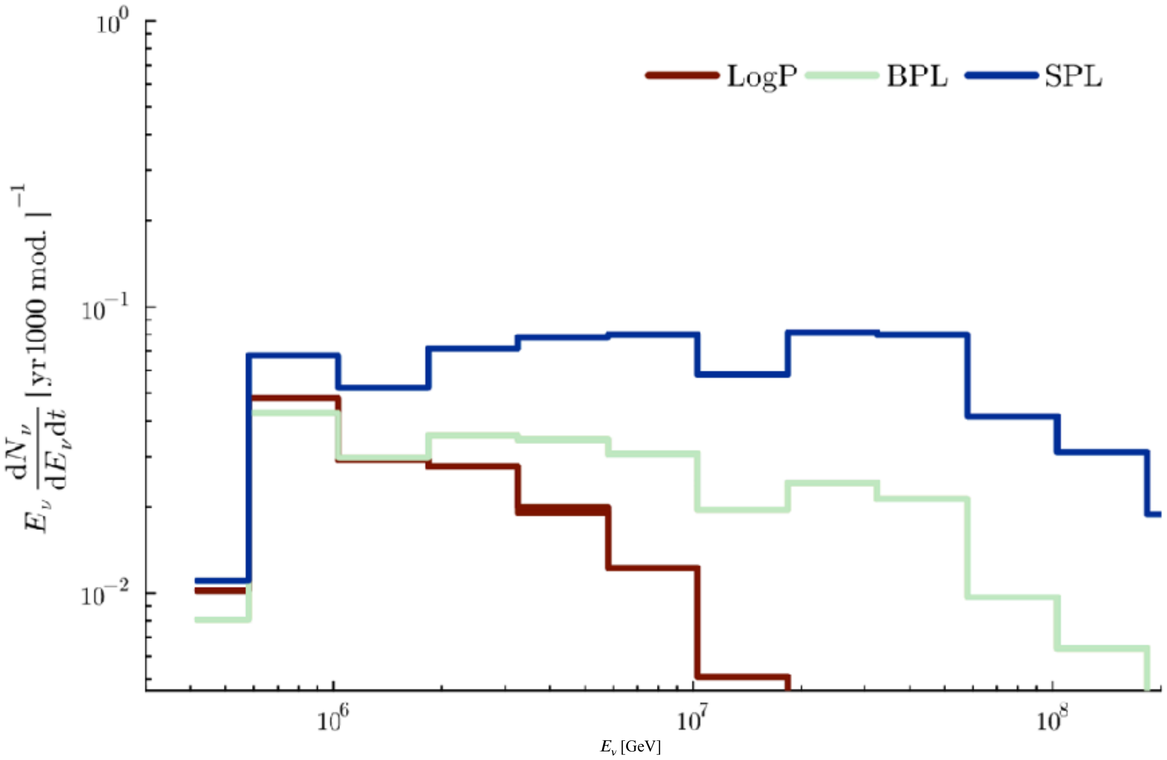
Full Timing Information



- Full MC gives timing information
- We are currently working with GraphNeT team to reconstruct event directions

Expected Event Rates

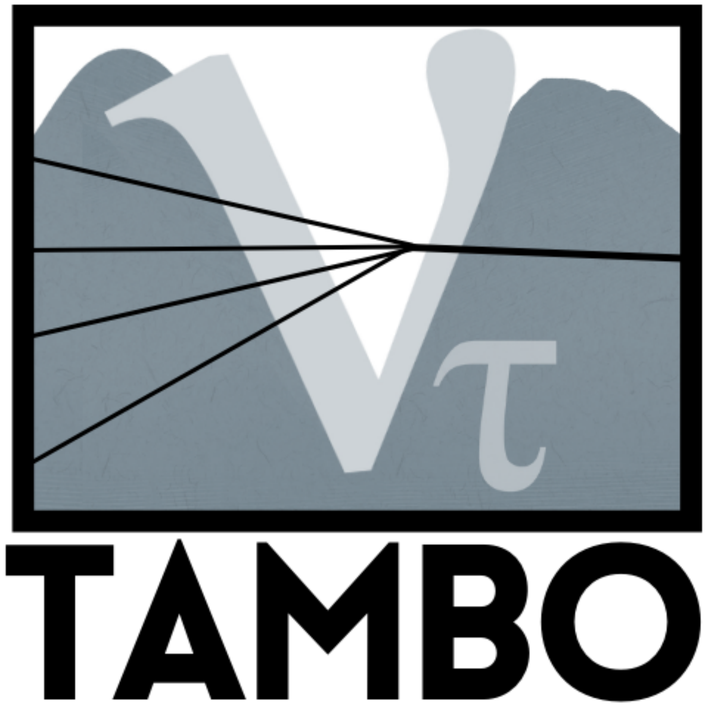




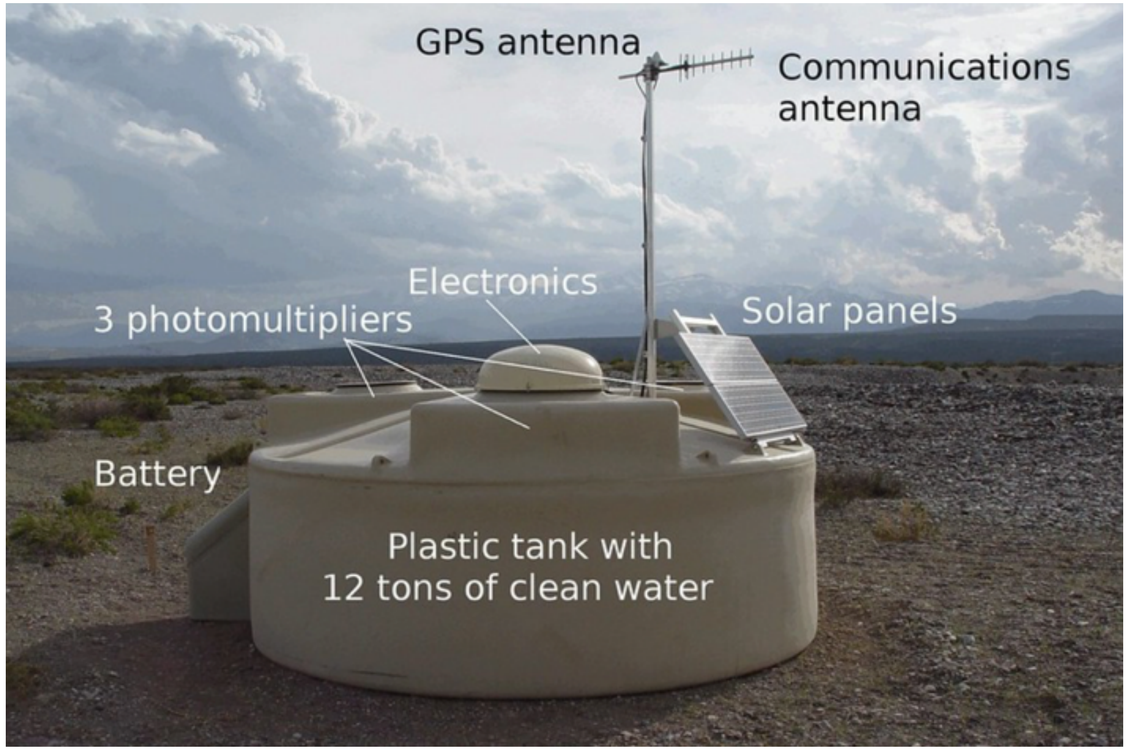
- Updated Simulation shows 2x-3x improvement in rate
- >3σ ability to reject single power law with 5,000 and 3 years of data

Roadmap

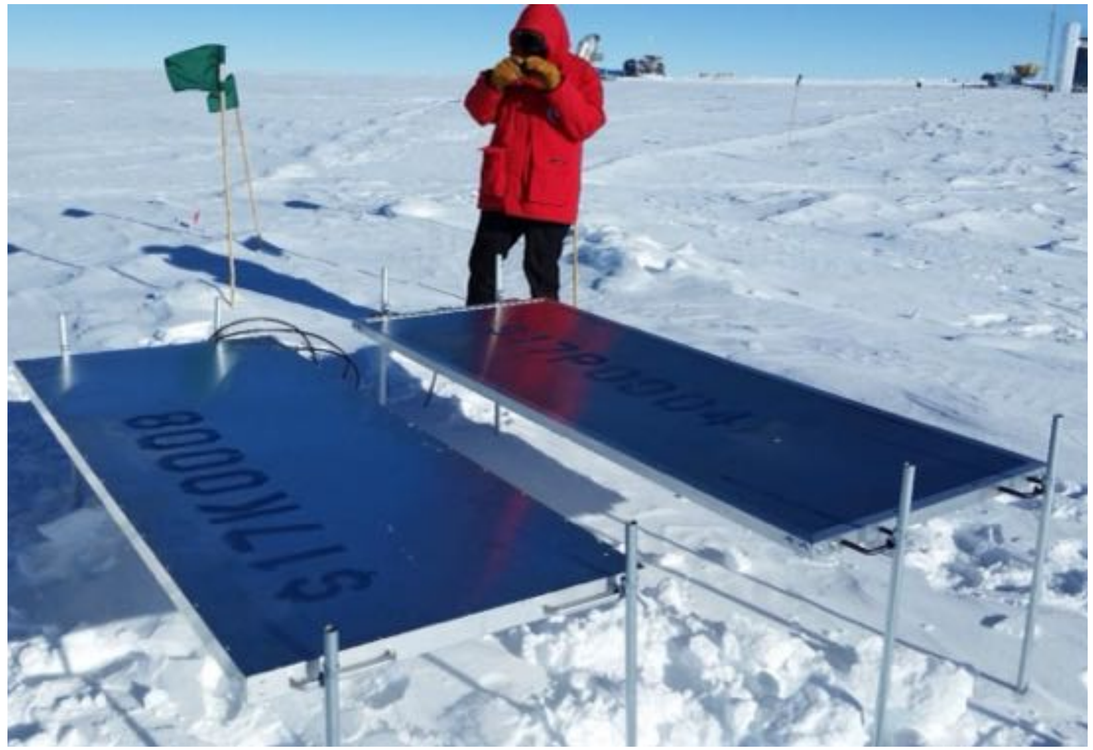
- A very brief history of neutrino astronomy
- Open questions in neutrino astronomy
- TAMBO overview
- Realizing TAMBO



Detector Development



Pierre Auger Collaboration, ICRC(2021)

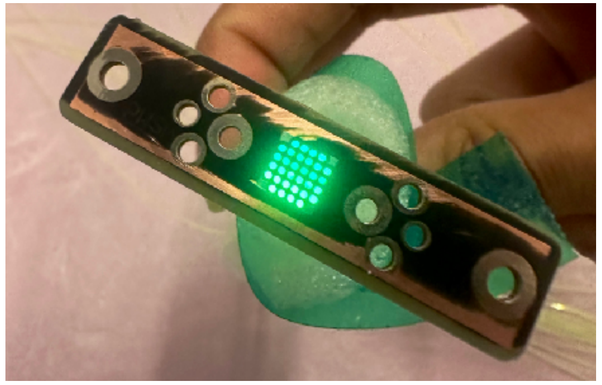


IceCube Collaboration, EPJ Web Conf. **210** (2019)

- 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

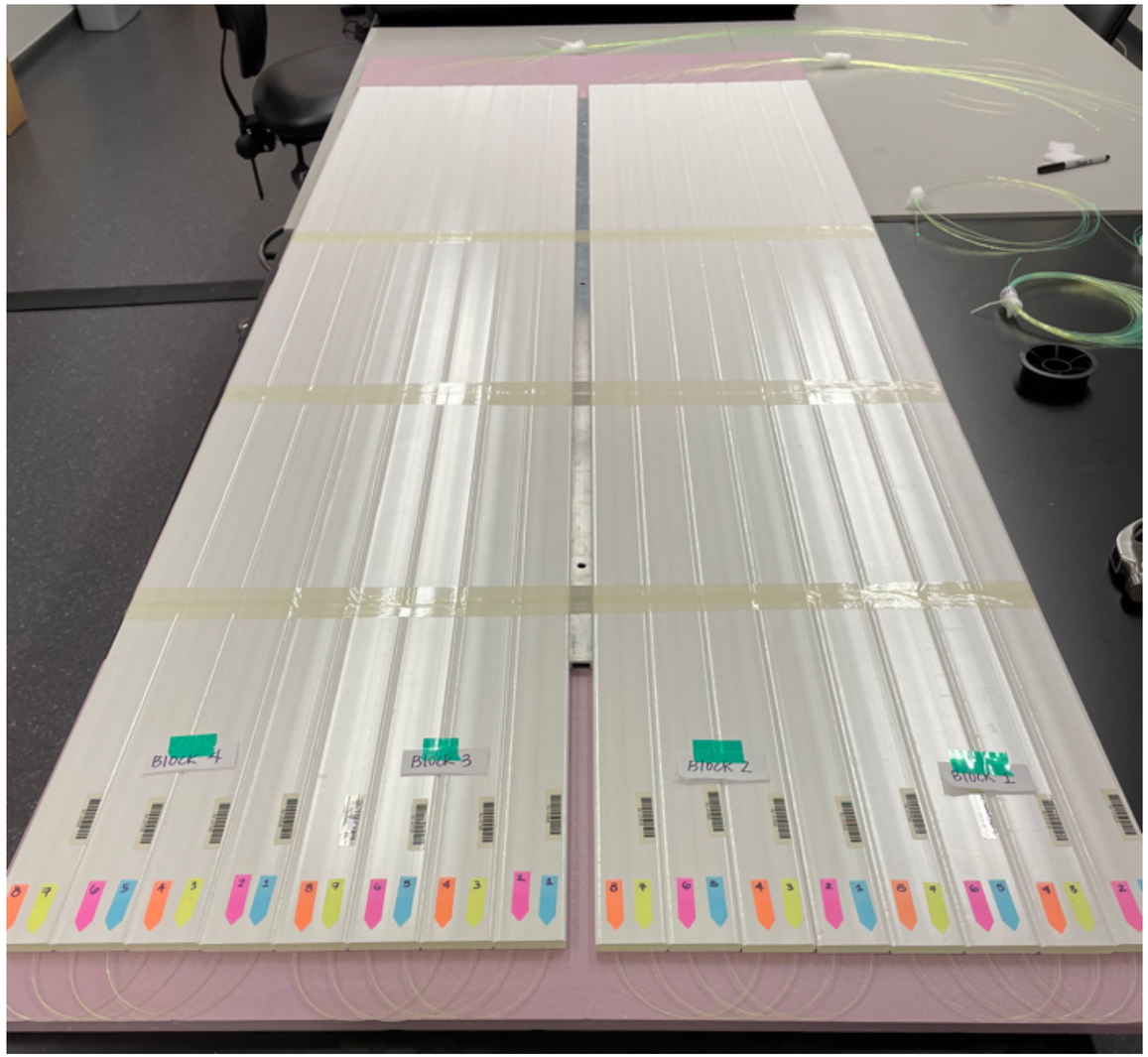
Detector Development

- Harvard group currently constructing test scintillator panels
- Allows to test fabrication speed and DAQ system

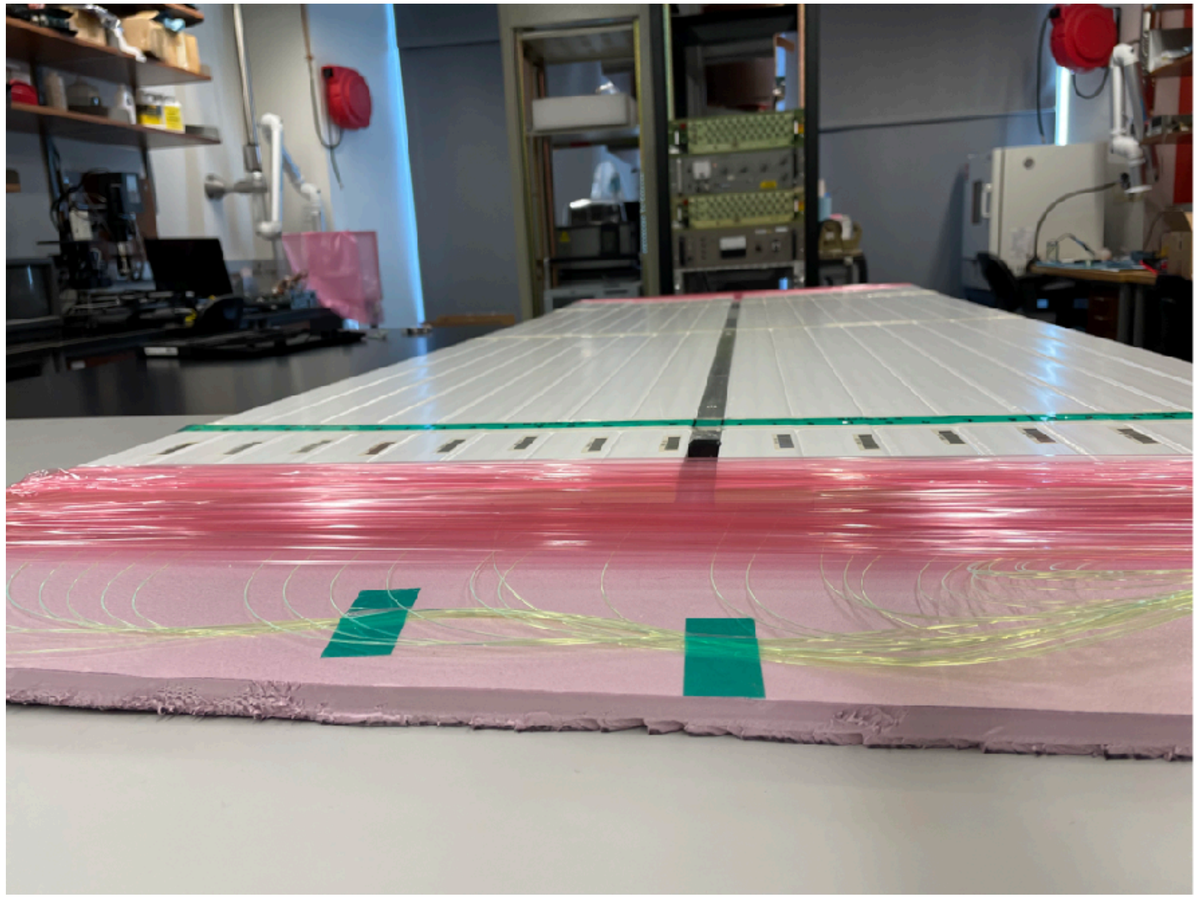


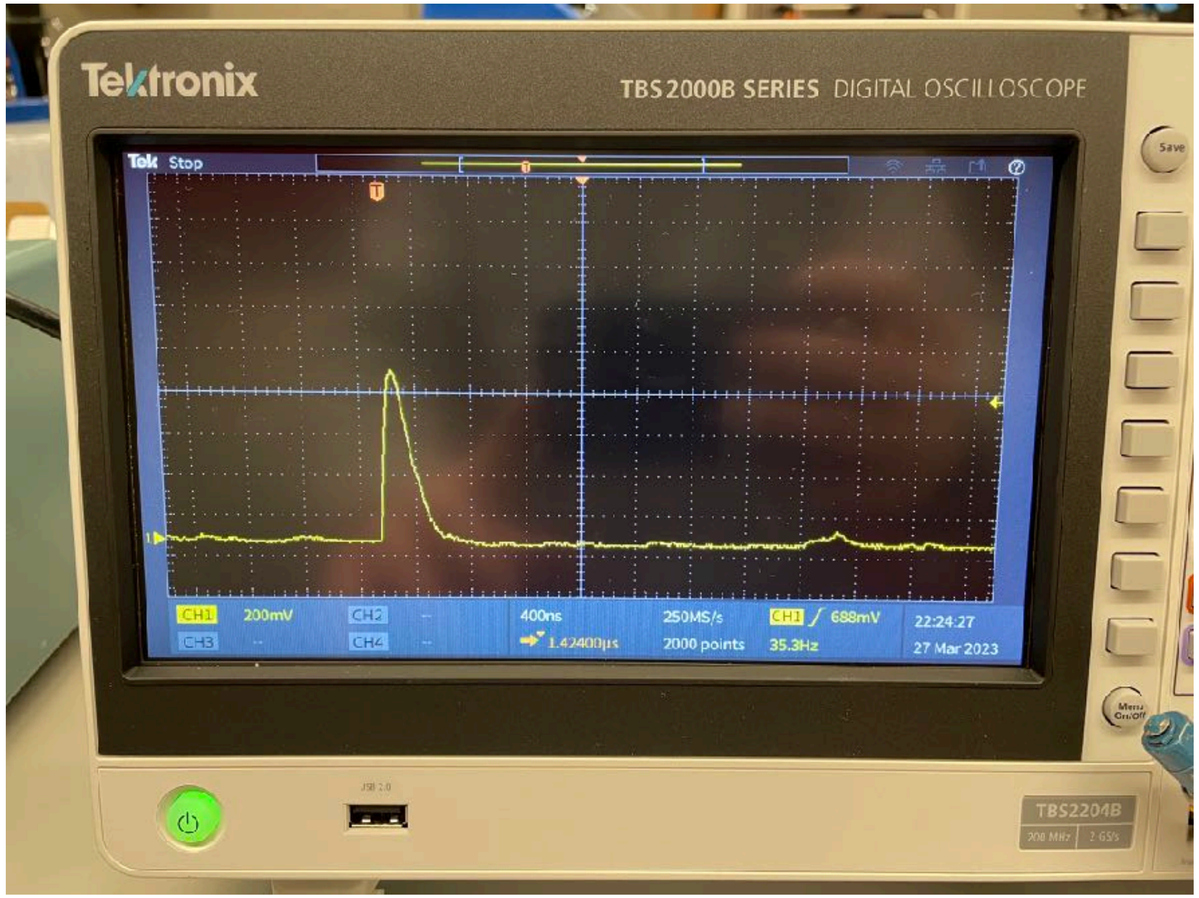
Diyaselis Delgado

William Thompson



First Light from Cosmic Muons

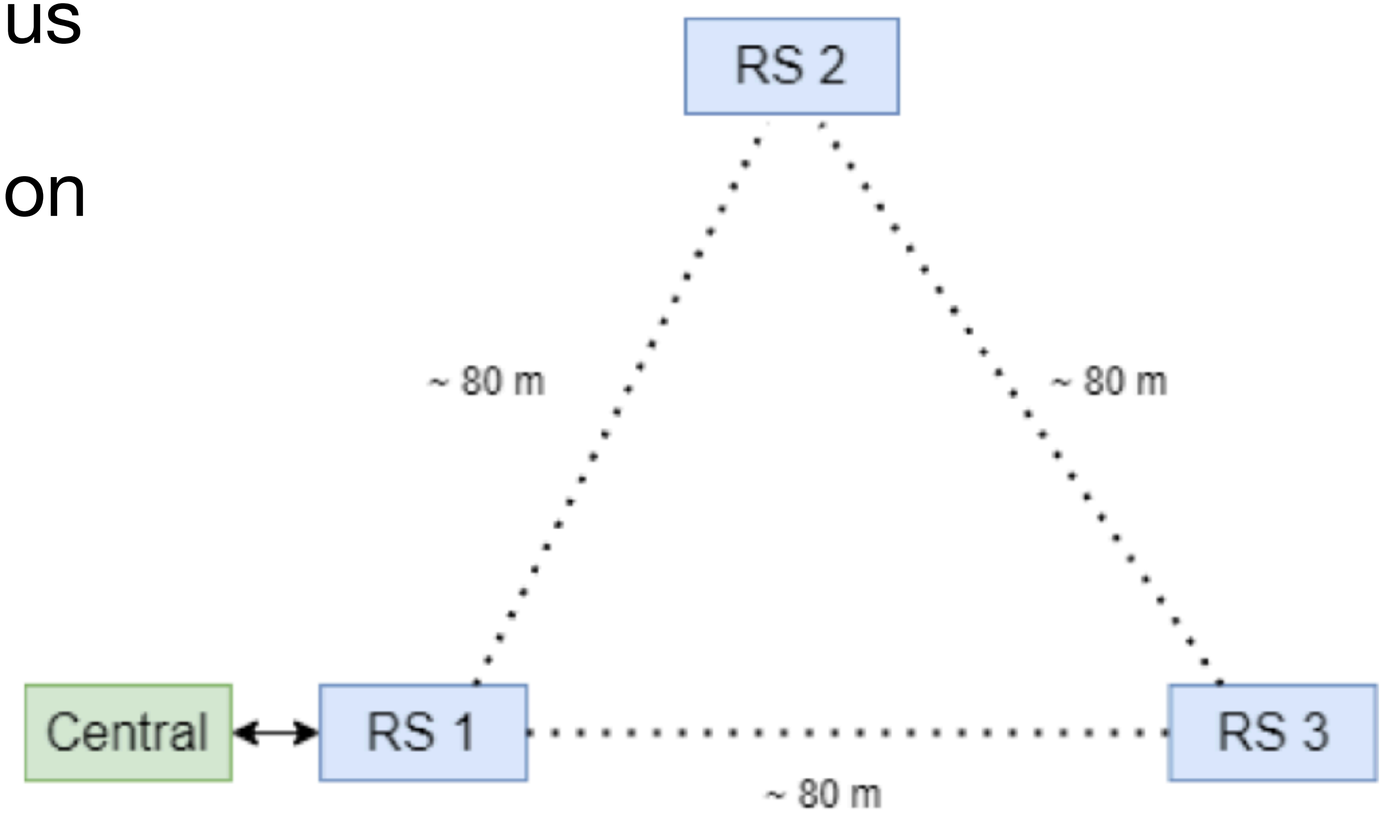




- First light from scintillator panels
- Enough material to build 10 panels in total, which we expect to have by the end of the year

Proof-of-Concept Test Array

- PUCP group developing three station deployment will allow us to test:
  1. Inter-module communication
  2. Synchronisation protocol
  3. Data acquisition and management
- We may identify air showers with this set up



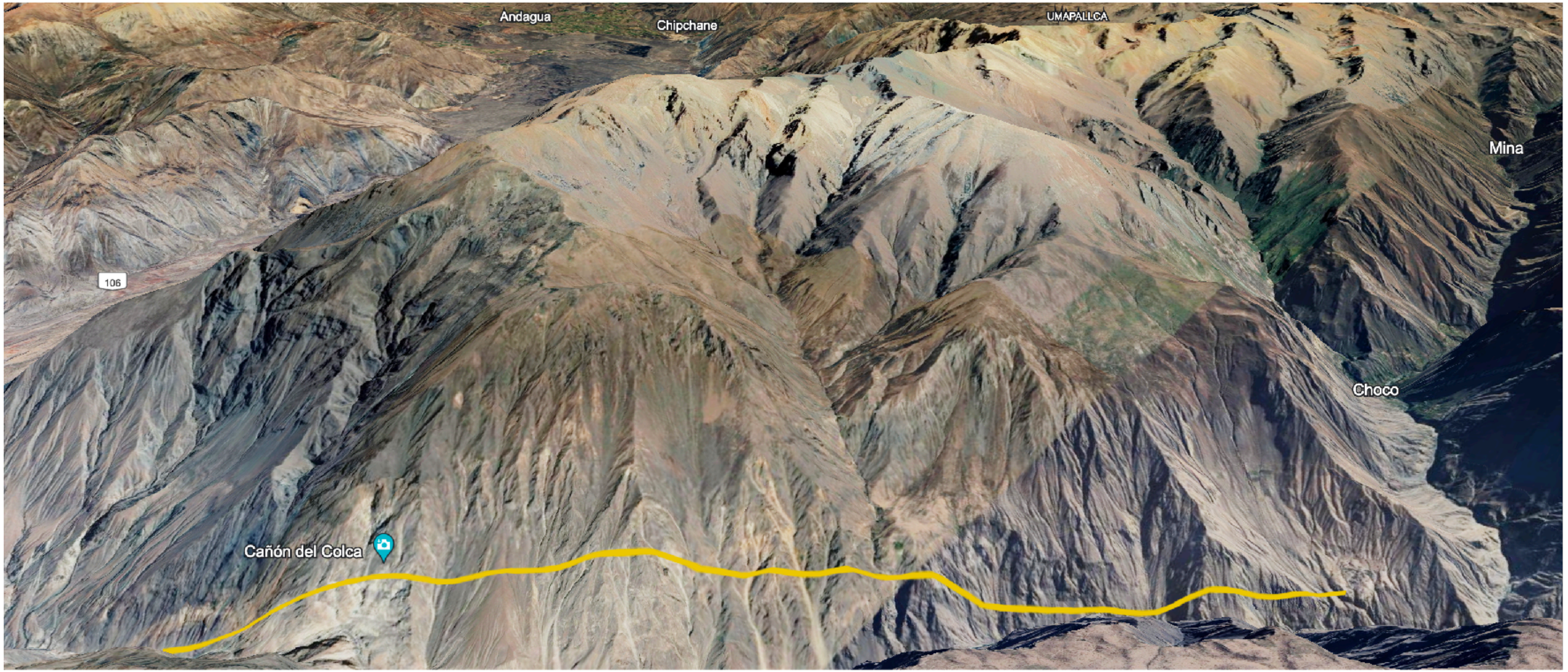
Site Selection Trip

Photo Credit: Universidad Nacional de San Agustin de Arequipa

Travelled to Peru to meet with officials and visit potential sites

Potential Test and Main Array Location

Main Array Candidate Site

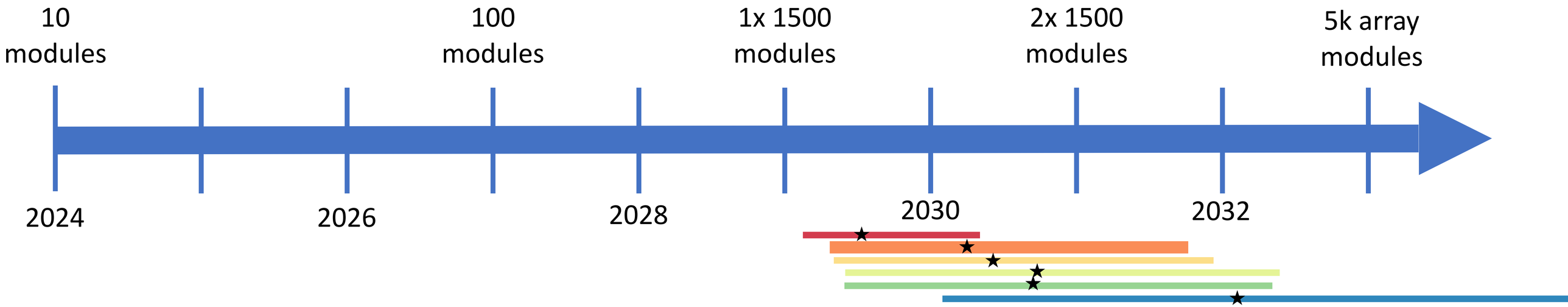


Societal Impact

- We want local community to embrace not just accept
- First steps: met with mayor of Chivay and held a workshop with Peruvian social scientists and officials

Tentative Timeline

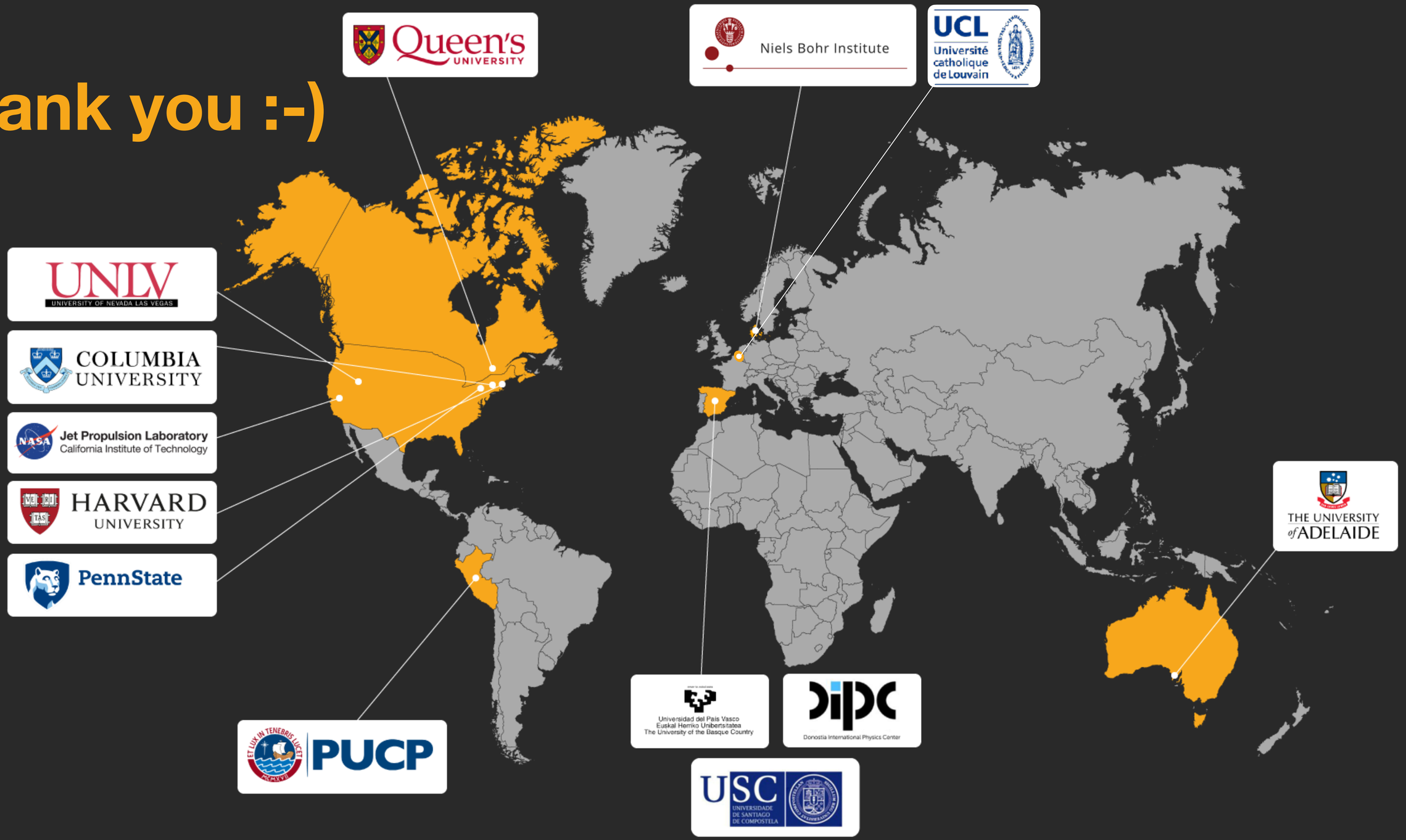
- Initially deploy ~10 modules followed by ~100 modules for R&D
- Full array could be deployed in 1500-module segments
- Expect to see neutrinos in <2 years



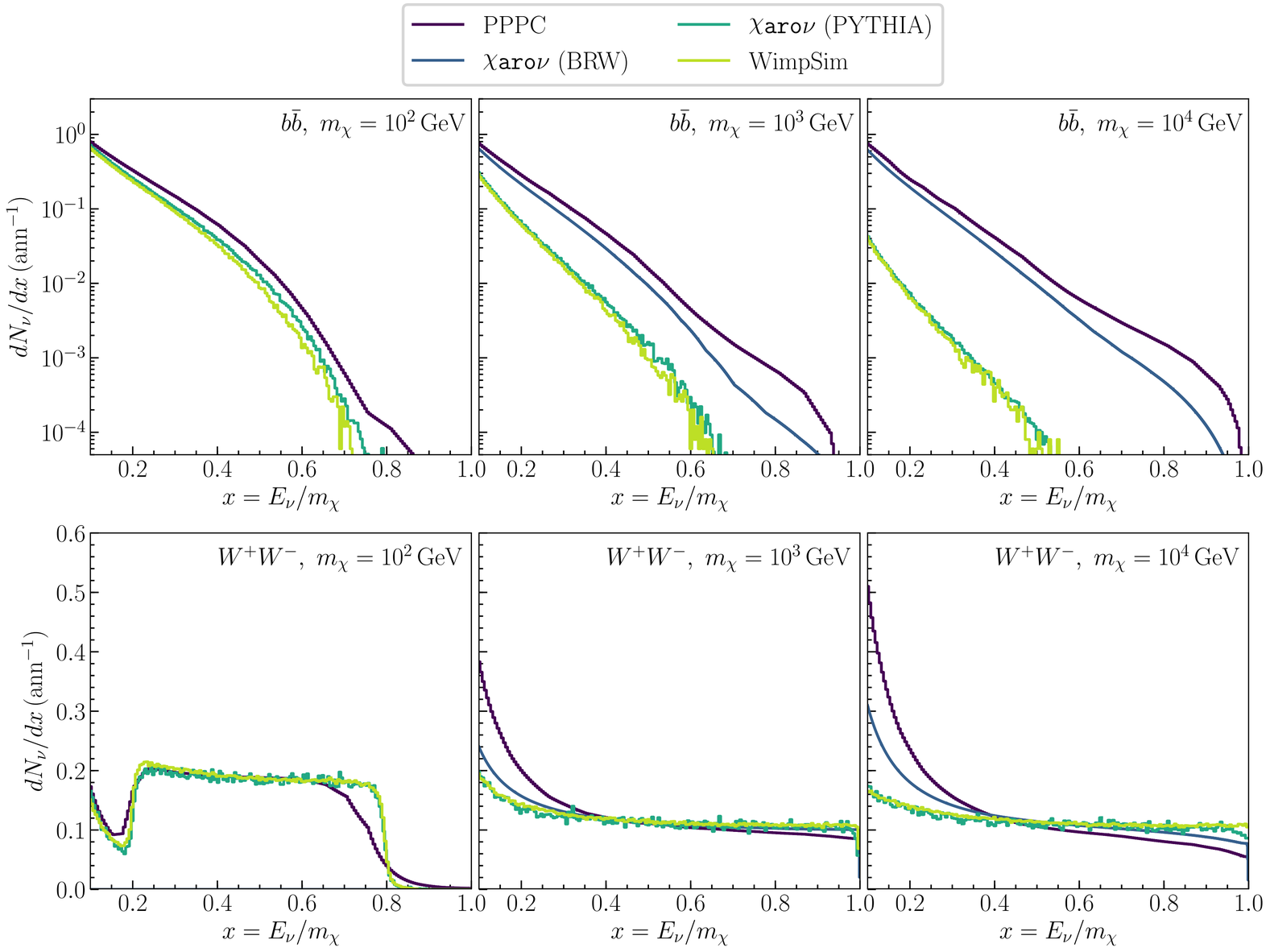
Conclusions

- TAMBO will:
  - Bridge gap between HE and UHE neutrino telescopes
  - Enable the discovery of hidden neutrino sources
- Fully-featured simulation nearing completion
- Development of prototype detectors underway
- Interested in joining? Contact (Will Thompson || Carlos Argüelles || Mauricio) at will_thompson@g.harvard.edu, carguelles@g.harvard.edu

Thank you :-)

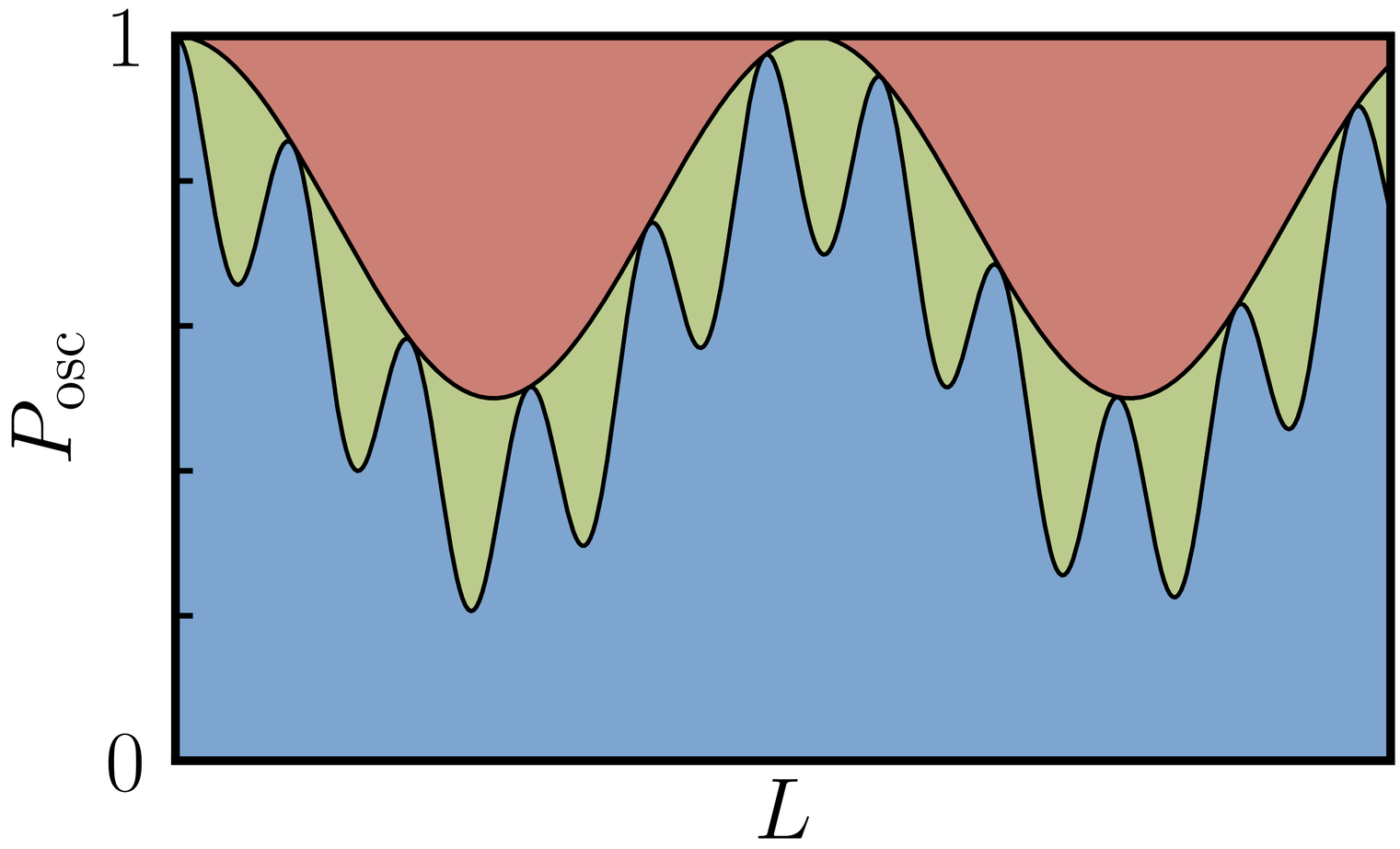

Queen's UNIVERSITY
Niels Bohr Institute
UCL Université catholique de Louvain
UNLV UNIVERSITY OF NEVADA LAS VEGAS
COLUMBIA UNIVERSITY
Jet Propulsion Laboratory California Institute of Technology
HARVARD UNIVERSITY
PennState
THE UNIVERSITY of ADELAIDE
PUCP
Universidad del País Vasco Euskal Herriko Unibertsitatea The University of the Basque Country
DIPC Donostia International Physics Center
USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

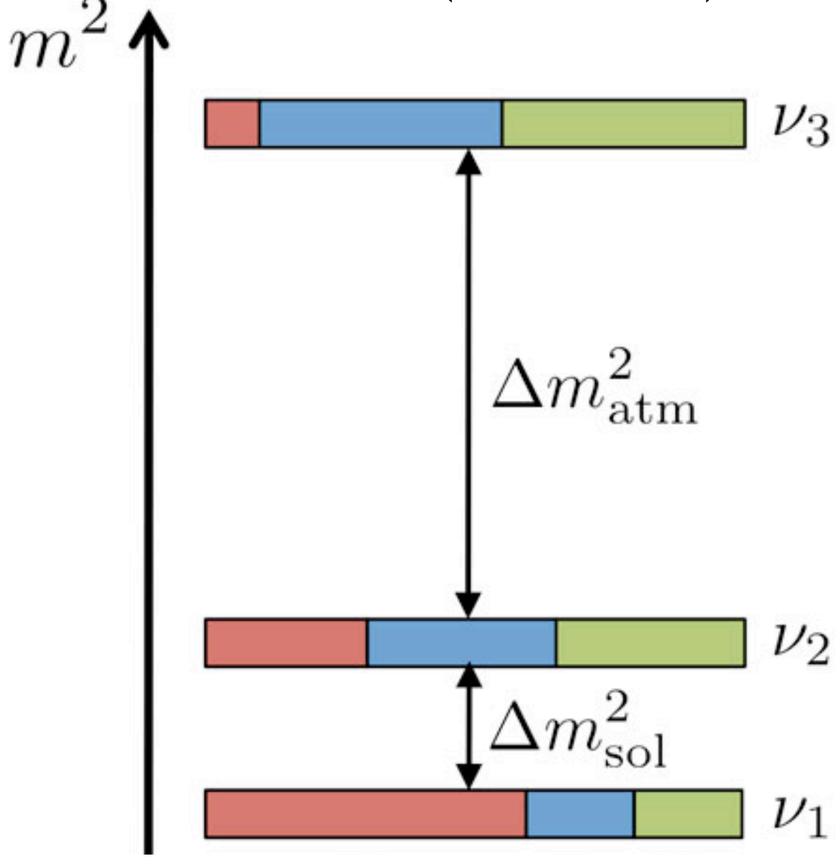
Backups


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

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





Thank you :-)