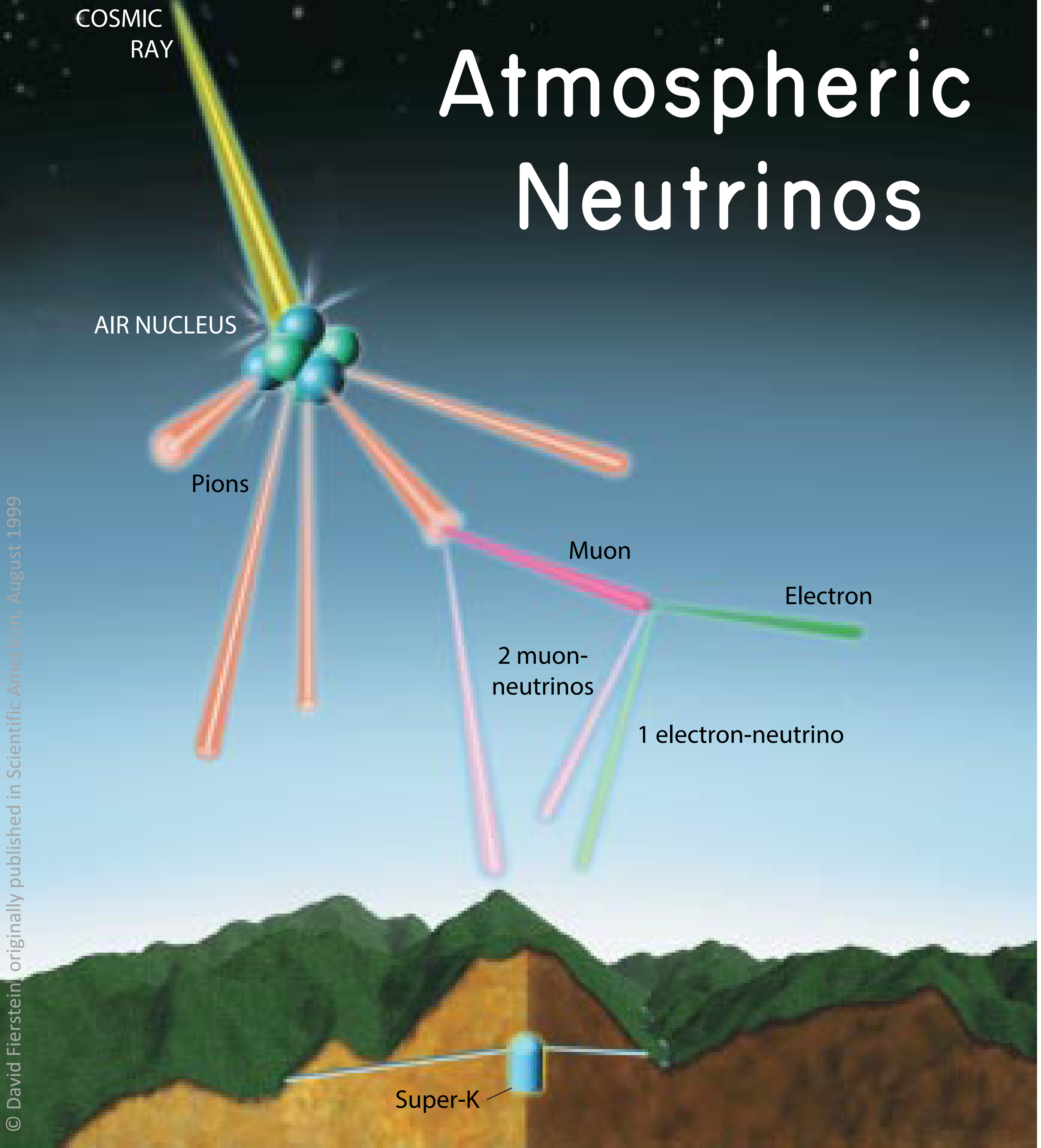
Atmospheric Neutrinos



14th International Neutrino Summer School at the Fermilab NPC

07–19 August 2023

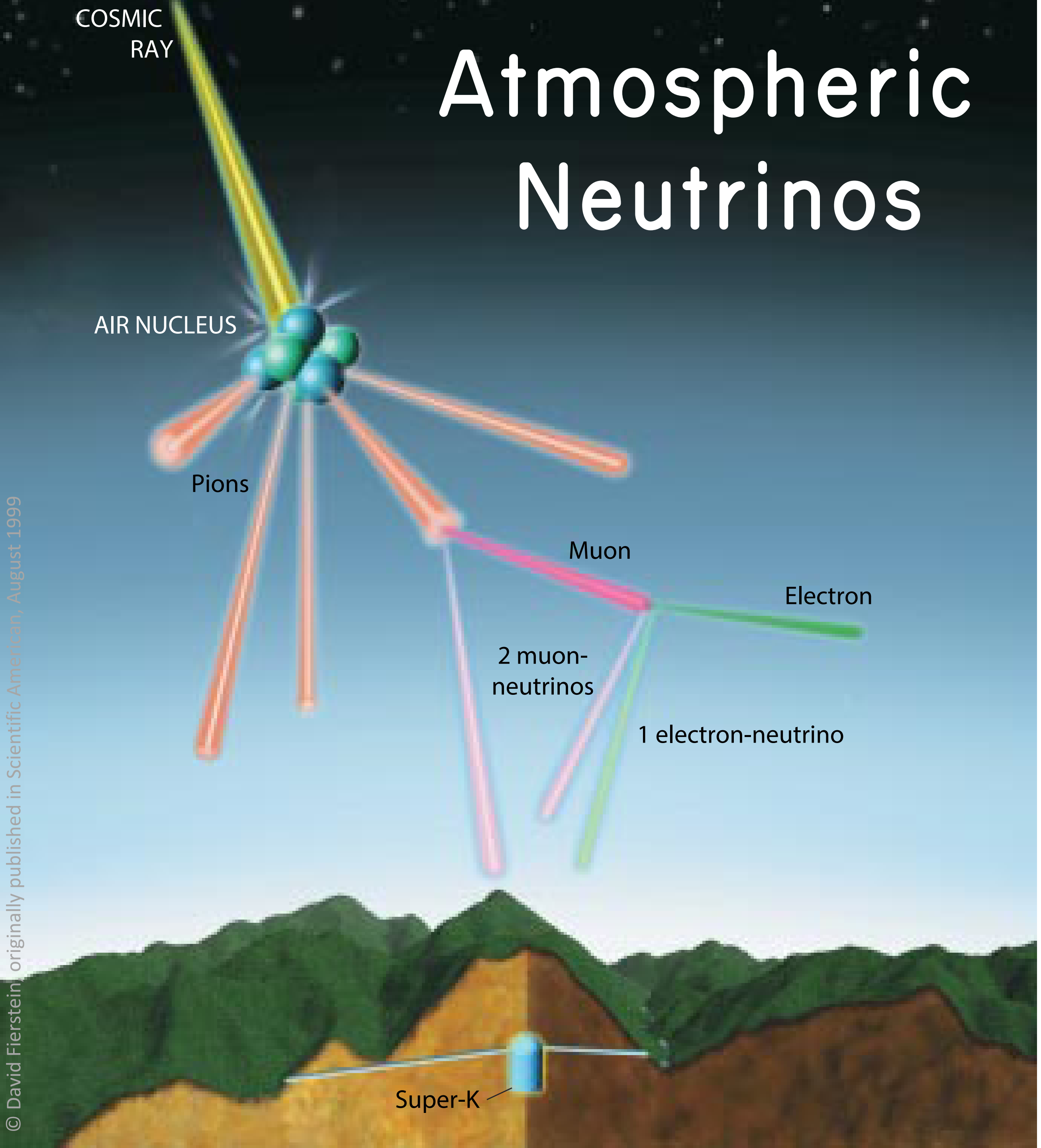
Ed Kearns

Boston University

kearns@bu.edu

CDF, MACRO, Super-K, K2K, T2K, MiniCLEAN, LBNE, LAriAT, Hyper-K, EMPHATIC, DUNE

LECTURE 2



Lecture 1:

Early stuff – history

Atmospheric ν Anomaly

Elements of the Experiment

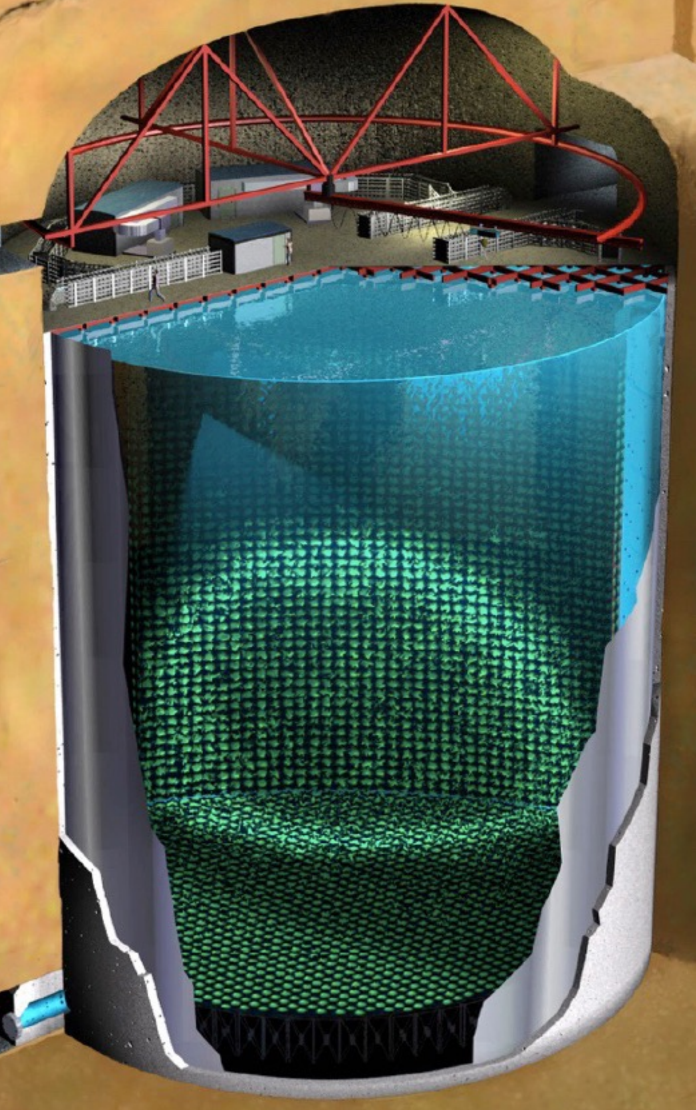
Lecture 2:

Resolution of the Anomaly

Current results

Future experiments

Super-Kamiokande



IMB and Kamiokande collaborations merged (plus, new collaborators added)

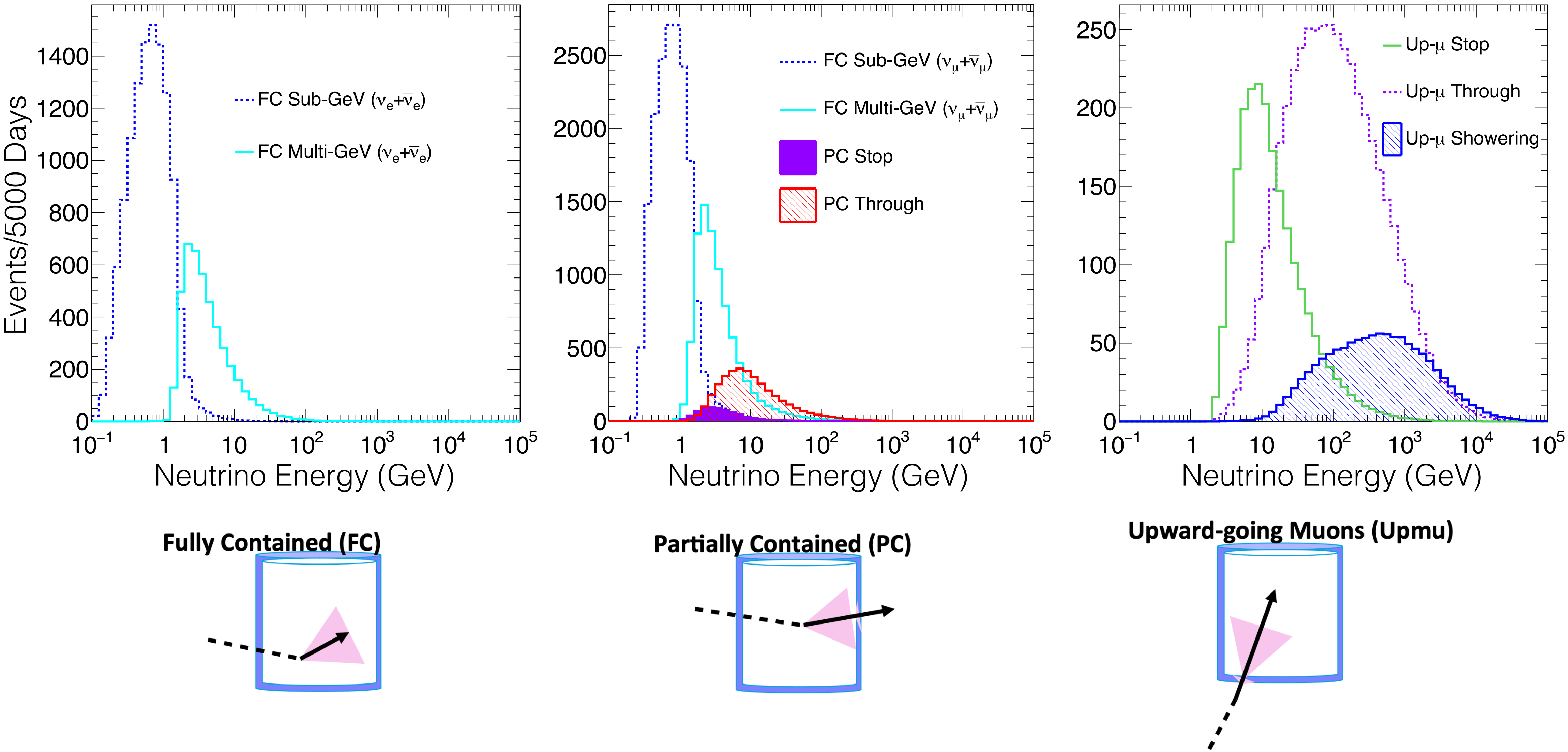
50000 tons of water (22.5 kton fiducial)
11000 50-cm PMTs
Outer detector (1900 smaller PMTs from IMB)

Energy threshold (solar) ~ 5 MeV
10 atmospheric neutrinos per day
7.5x10^{33} protons, 6x10^{33} neutrons

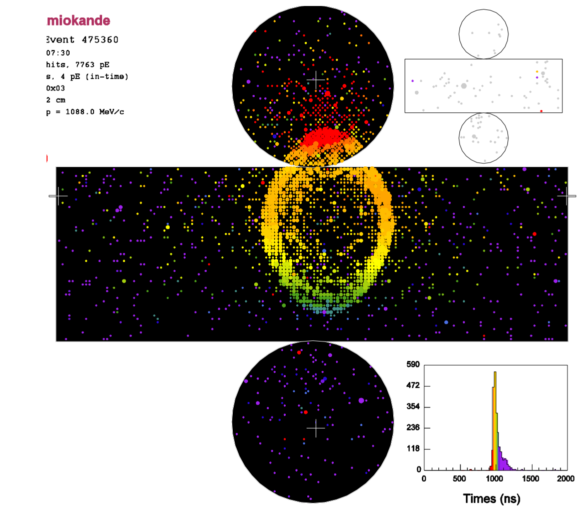
Several upgrades (+ one destructive accident)

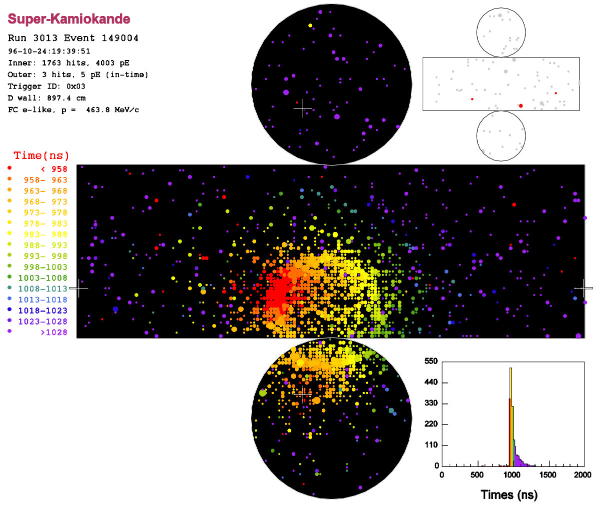
Office of Science
U.S. DEPARTMENT OF ENERGY

Event Categories → Neutrino Energy



1st Super-K paper – March 1998

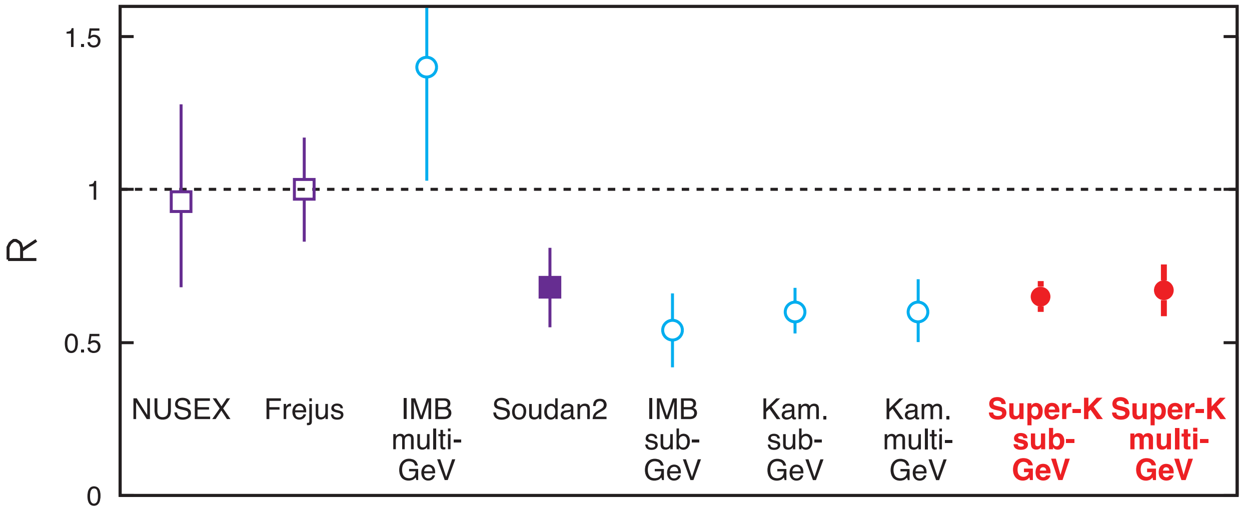




Measurement of a small atmospheric ν_μ/ν_e ratio

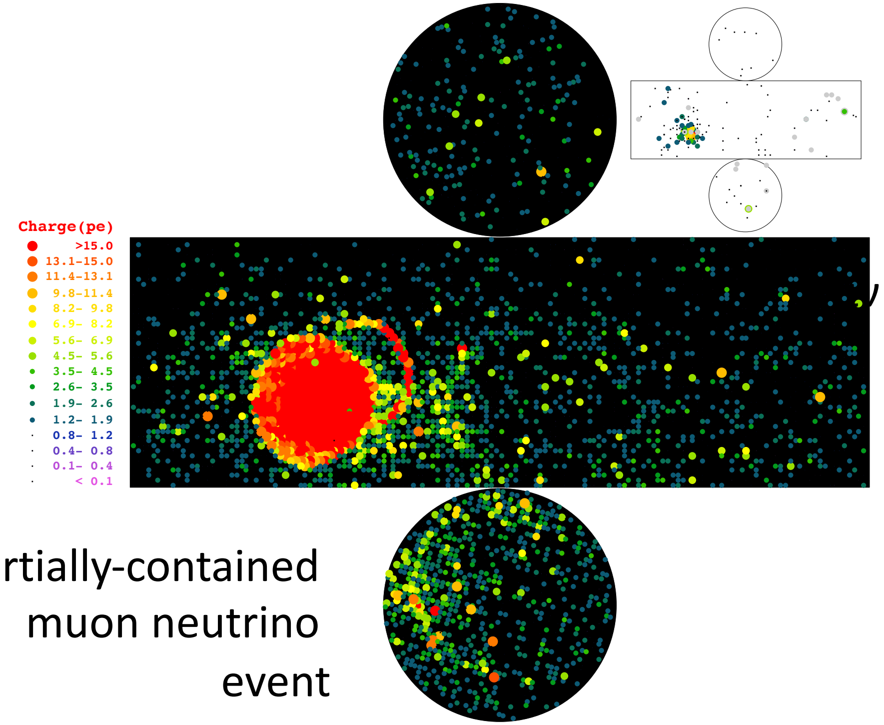
firmed the existence of a smaller atmospheric ν_μ/ν_e ratio than predicted. We obtained $R = 0.61 \pm 0.03(\text{stat.}) \pm 0.05(\text{sys.})$ for events in the sub-GeV range. The Super-Kamiokande detector has much greater fiducial mass and sensitivity than prior experiments. Given the relative certainty in this result, statistical fluctuations can no longer explain the deviation of R from unity.

25.5 kton yr (414 days data)
Sub-GeV only
Two independent analyses

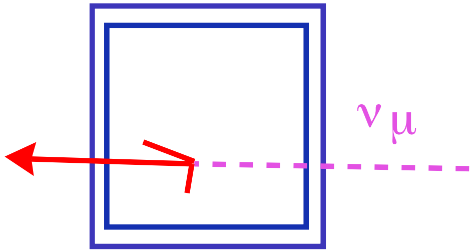


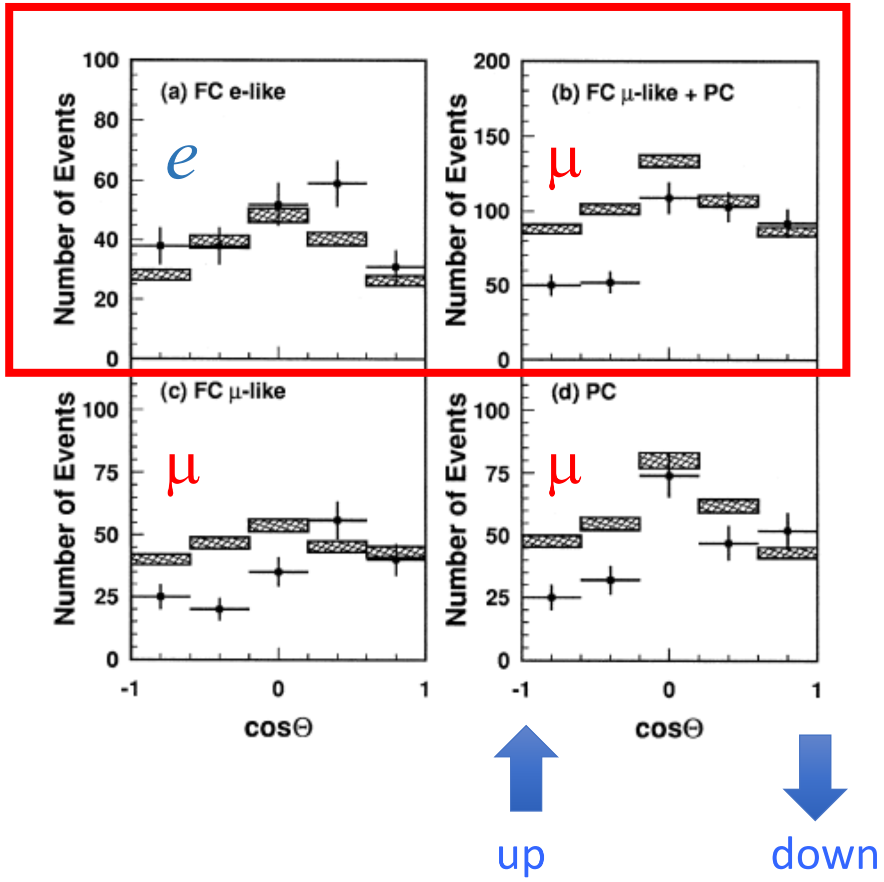
2nd Super-K paper – May 1998

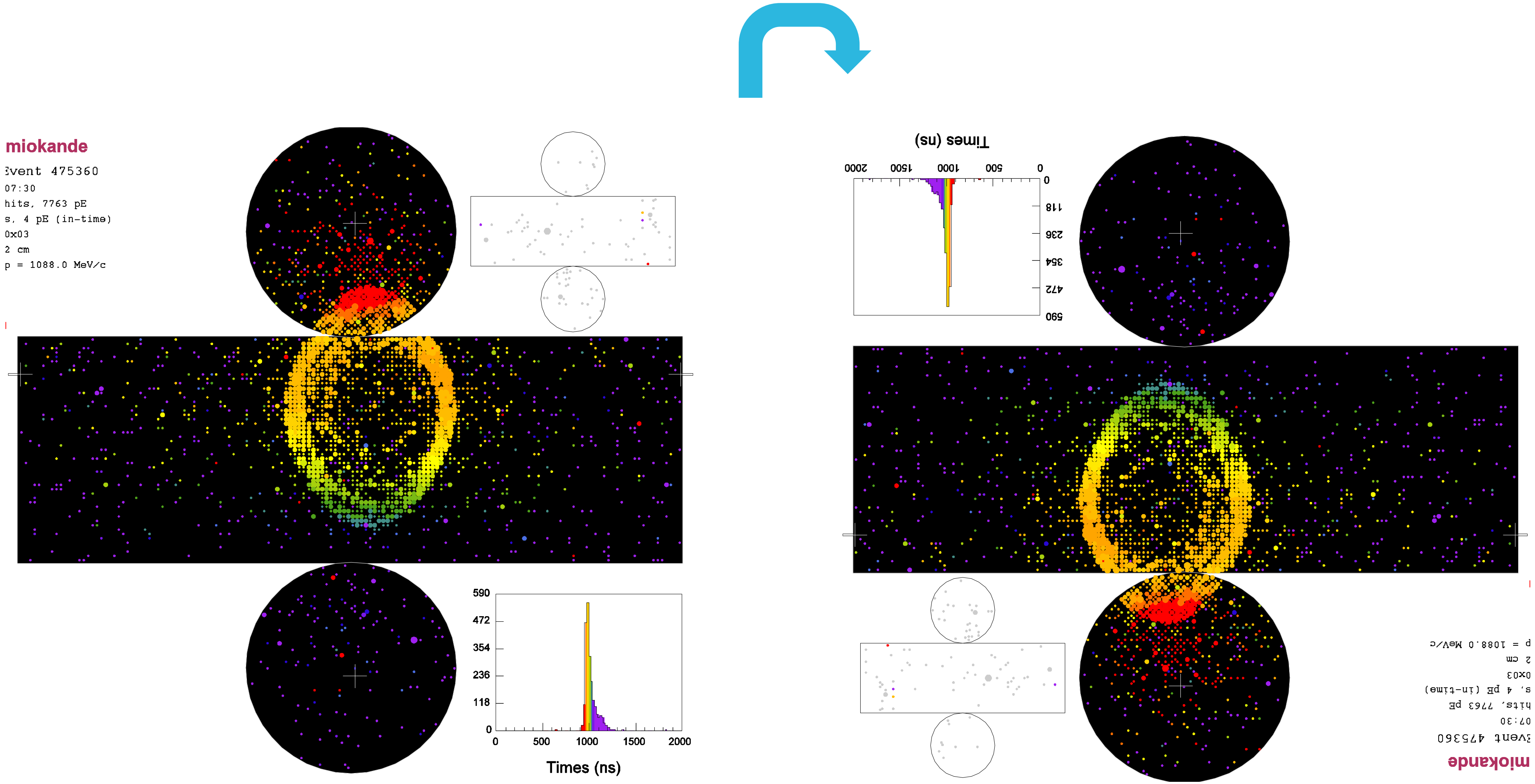
Study of the atmospheric neutrino flux
in the multi-GeV energy range



Partially-contained
muon neutrino
event

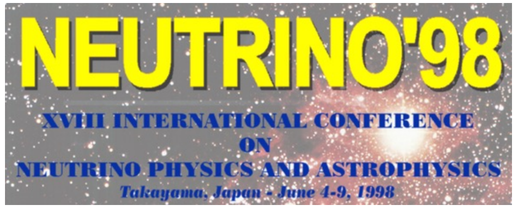


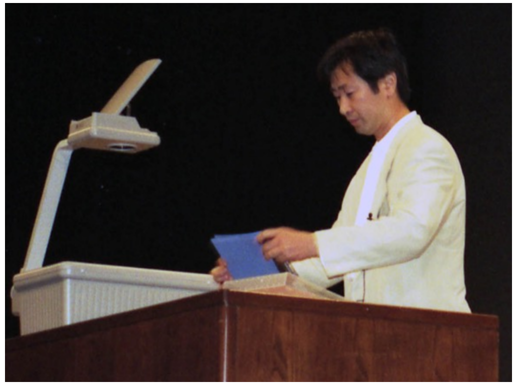




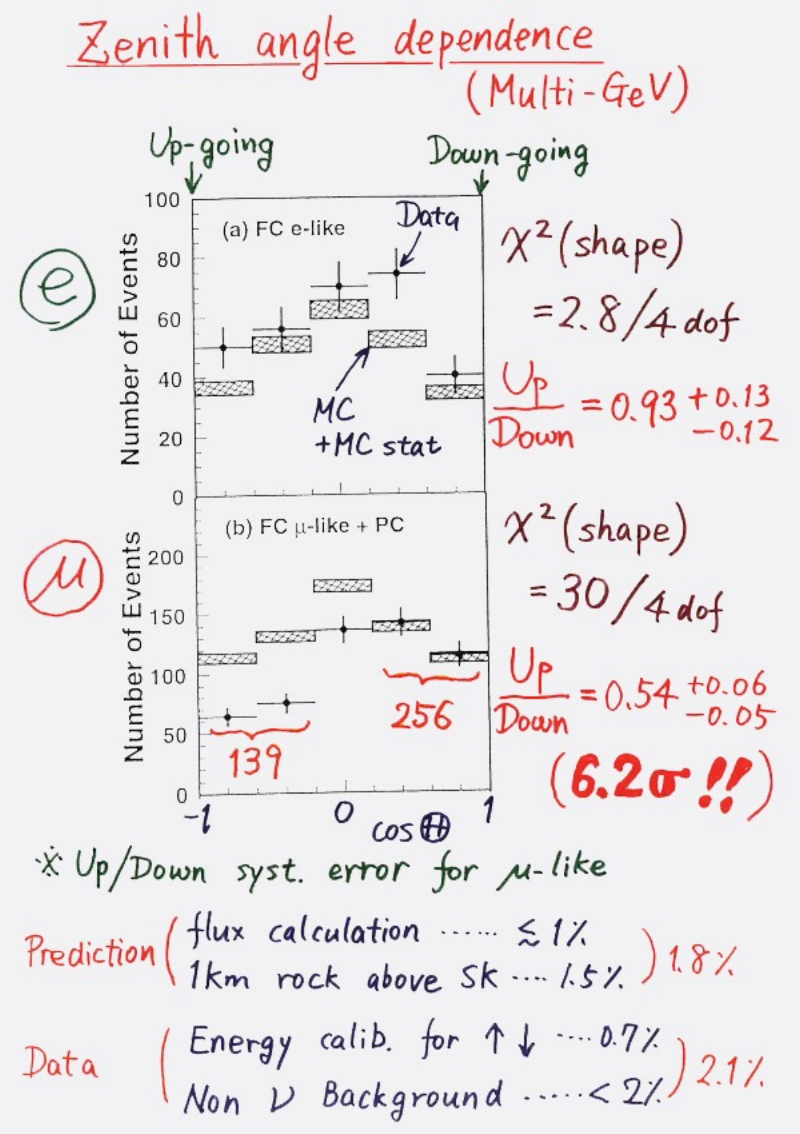
hard to imagine counting half as many of the right compared to the left

Discovery of Neutrino Oscillations





2015 Nobel Prize:
Takaaki Kajita



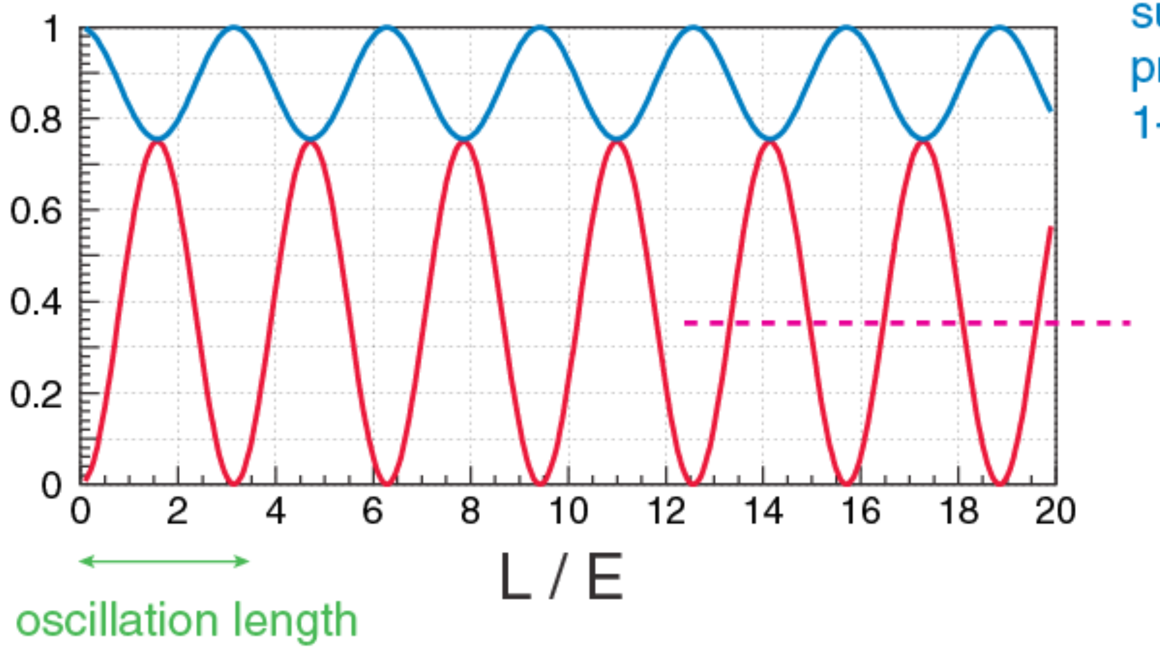
1-Slide Review: Two Flavor Neutrino Oscillations

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2 \frac{1.27 \Delta m^2 L}{E}$$

km and GeV or
m and MeV

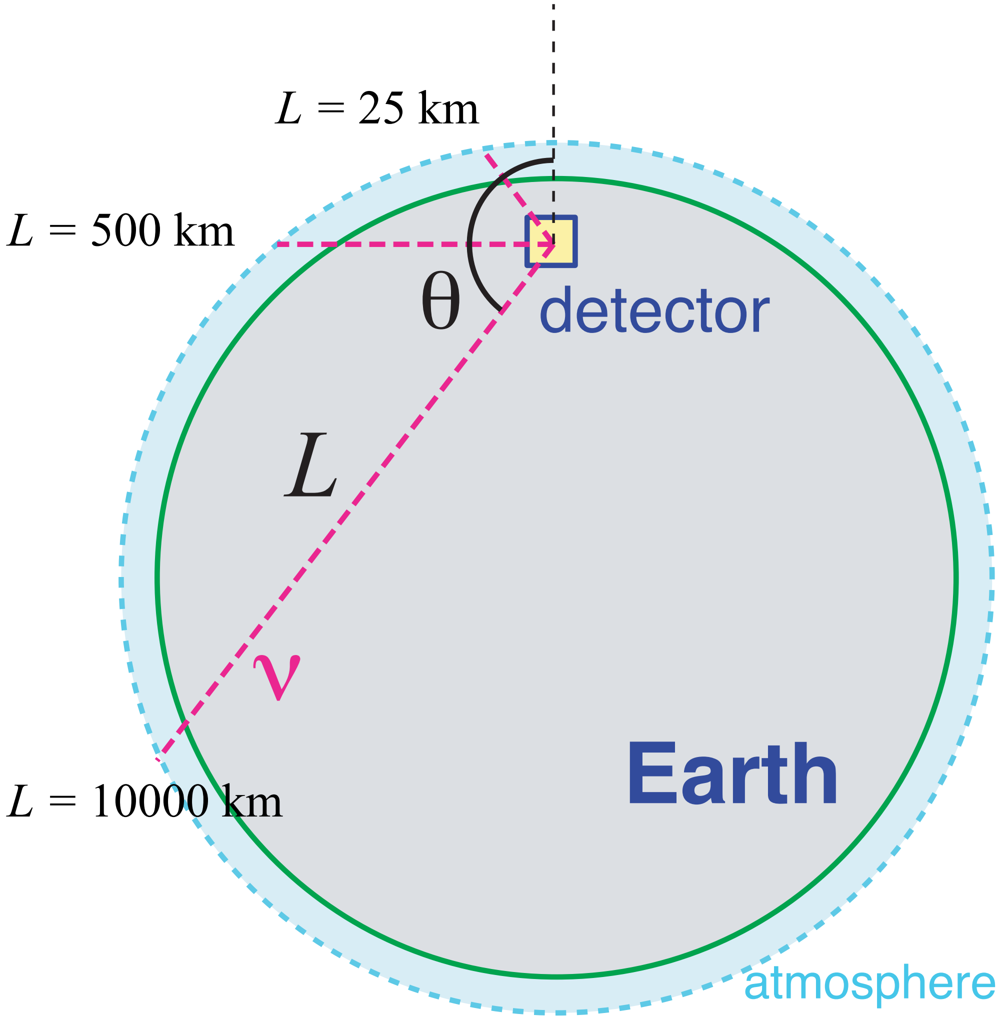
$\sin^2 2\theta$

oscillation probability $P_{\alpha\beta}$

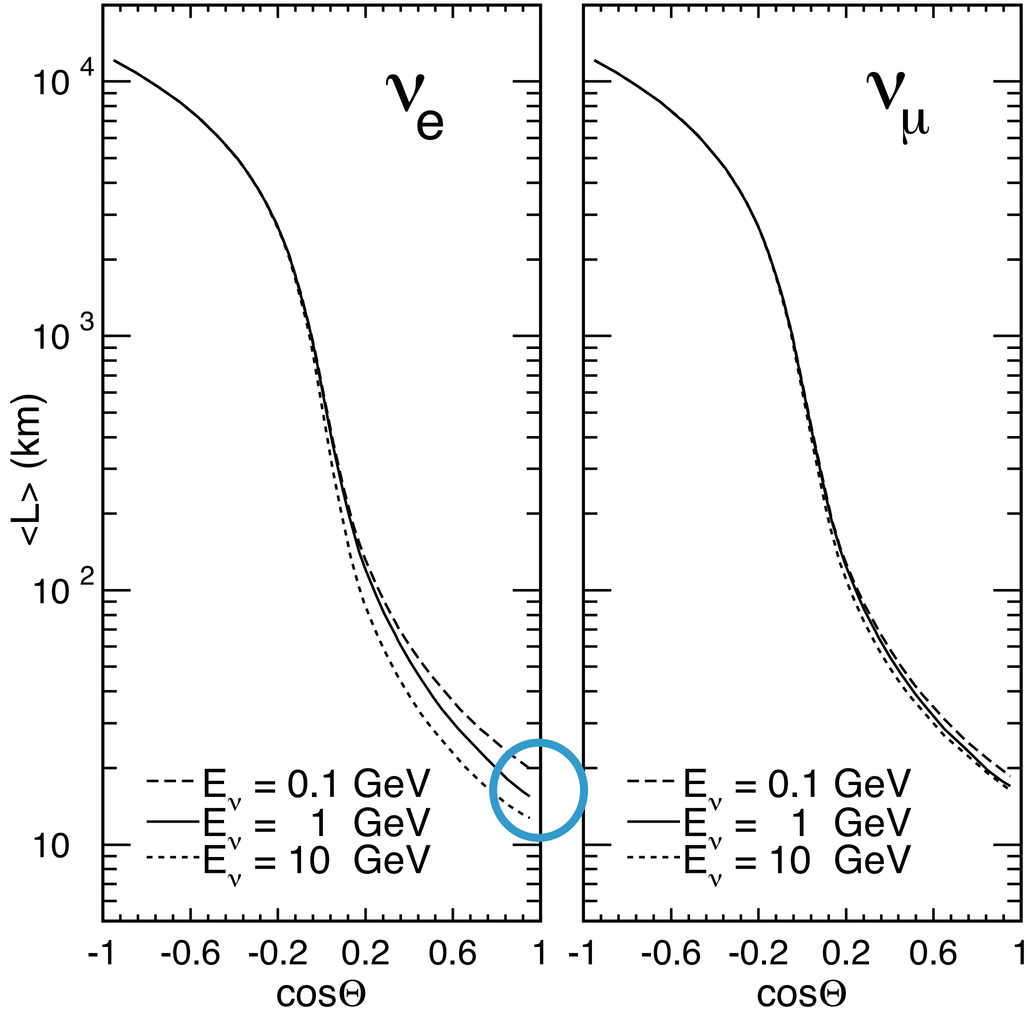


survival probability $1\text{-}P_{\alpha\beta}$

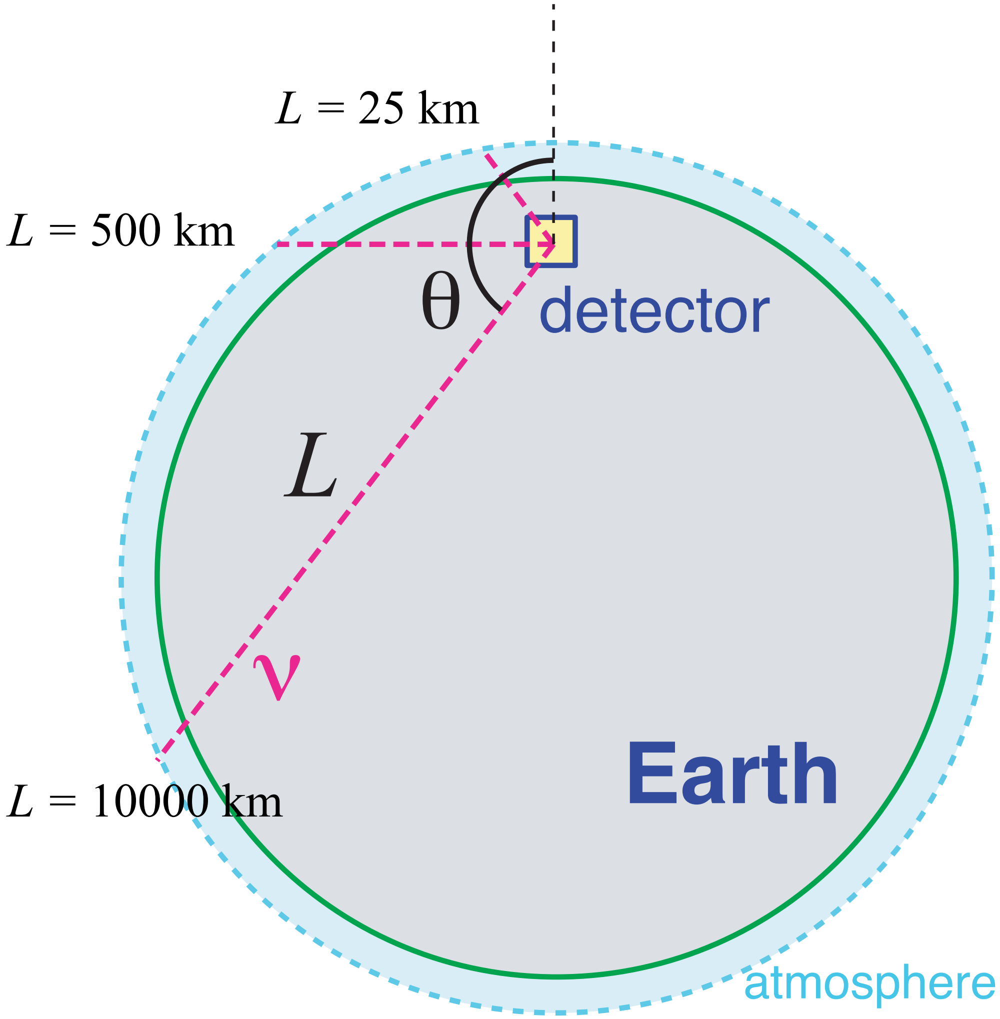
experimental resolution may average out to $\frac{1}{2}\sin^2 2\theta$



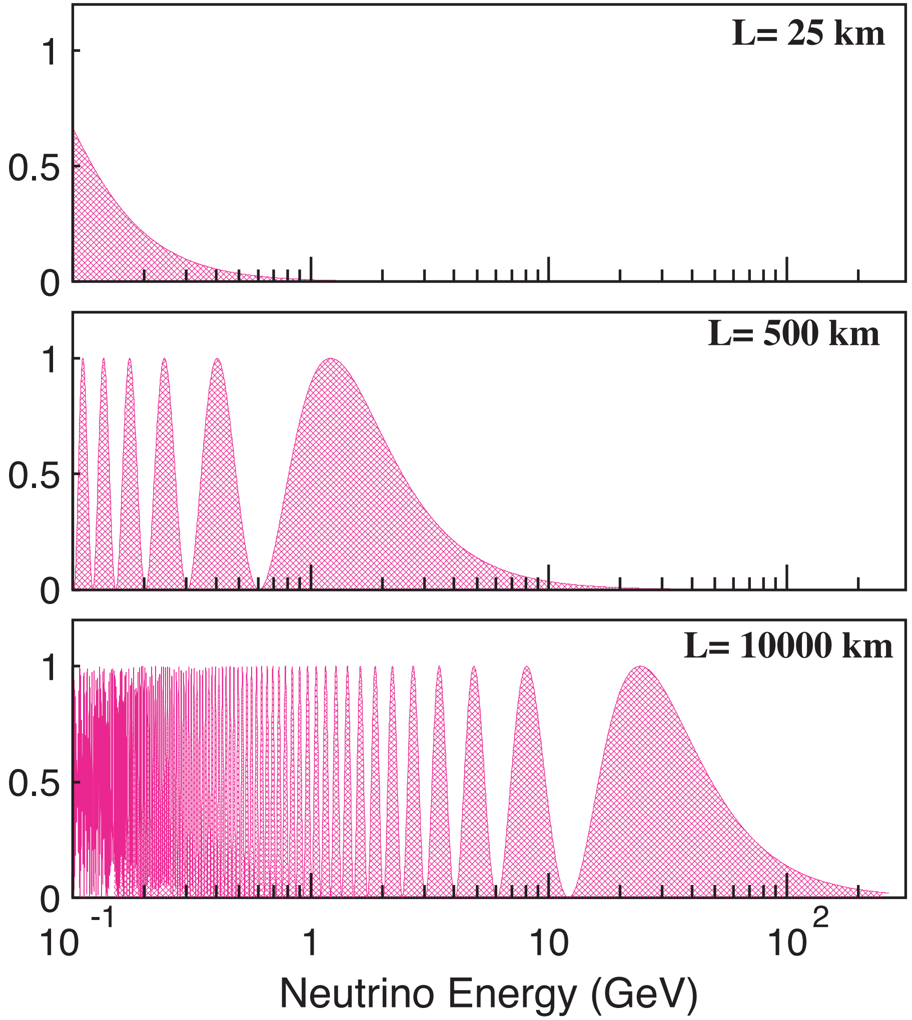
$$L(\theta) = -R\cos\theta + \sqrt{2Rh + h^2 + R^2\cos^2\theta}$$



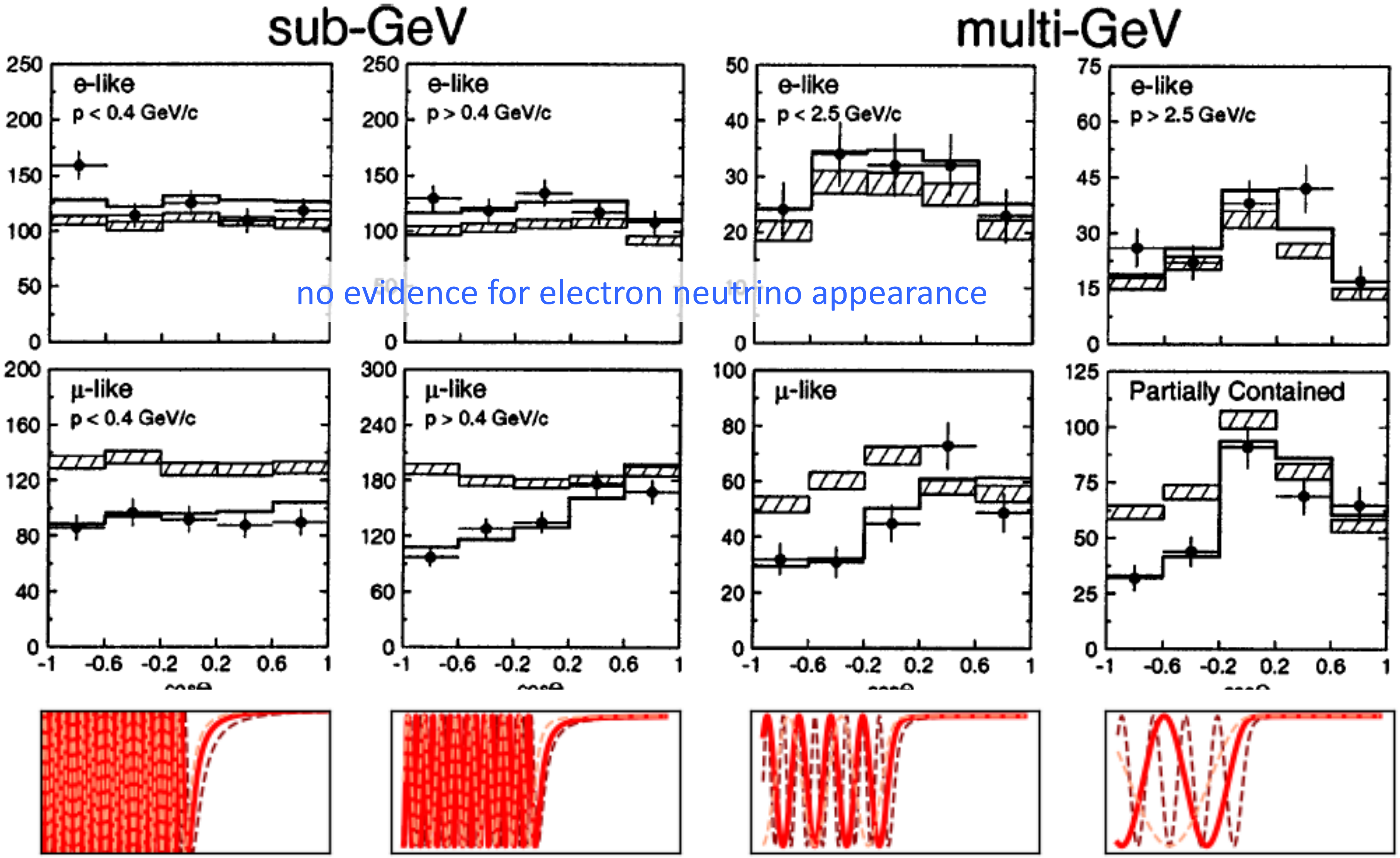
model production height
(depends on energy,
important for down-going ν)



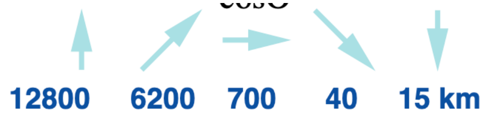
$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2 \frac{1.27\Delta m^2 L}{E}$$



3rd Super-K paper – August 1998



no evidence for electron neutrino appearance



Note: lepton direction is not assumed to be neutrino direction

Monte Carlo is supposed to model the data as perfectly as possible

3rd Super-K paper – August 1998

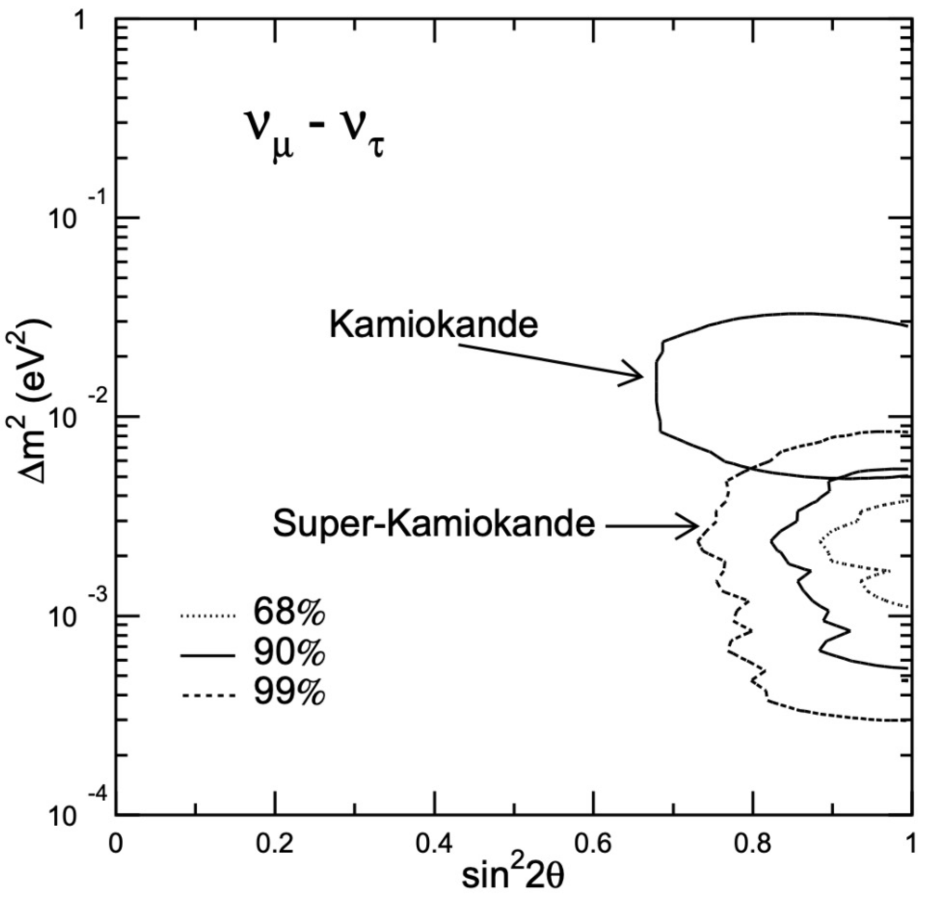
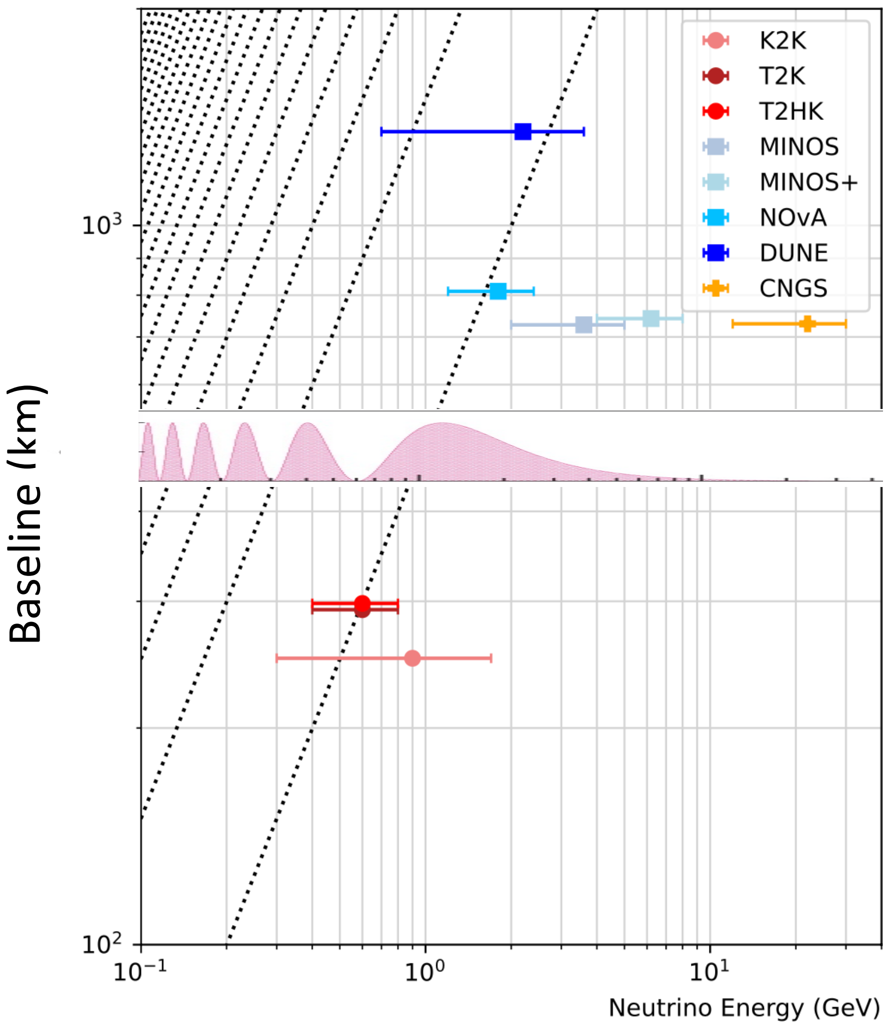


FIG. 2. The 68%, 90% and 99% confidence intervals are shown for $\sin^2 2\theta$ and Δm^2 for $\nu_\mu \leftrightarrow \nu_\tau$ two-neutrino oscillations based on 33.0 kiloton-years of Super–Kamiokande data. The 90% confidence interval obtained by the Kamiokande experiment is also shown.

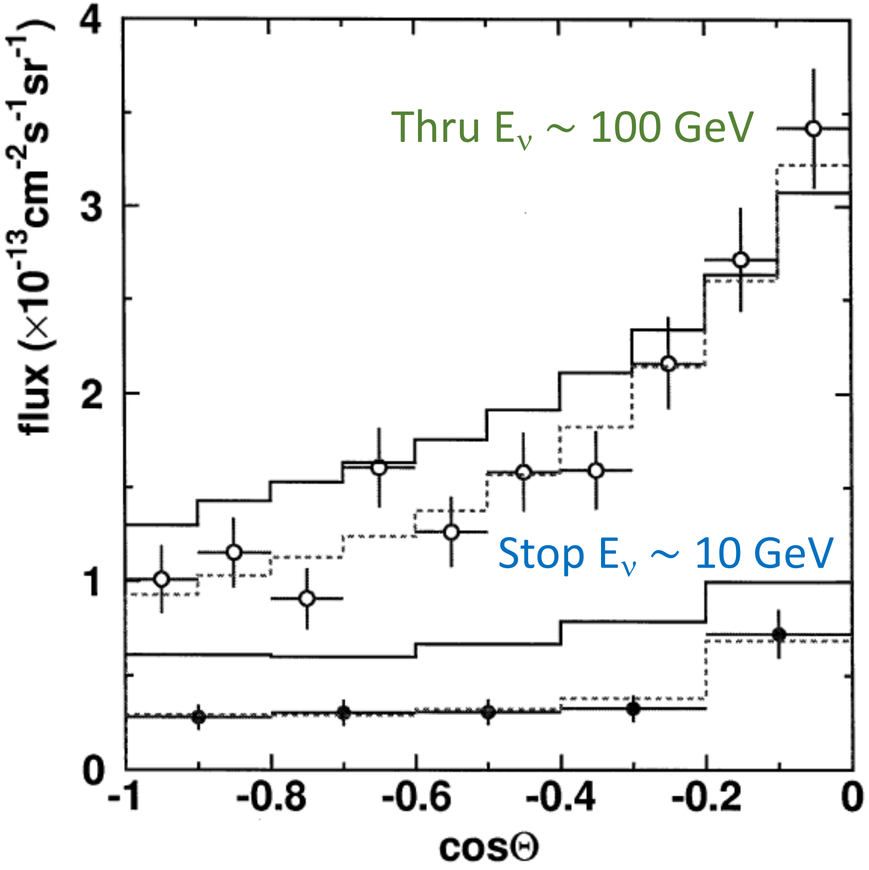
Mark Messier lecture

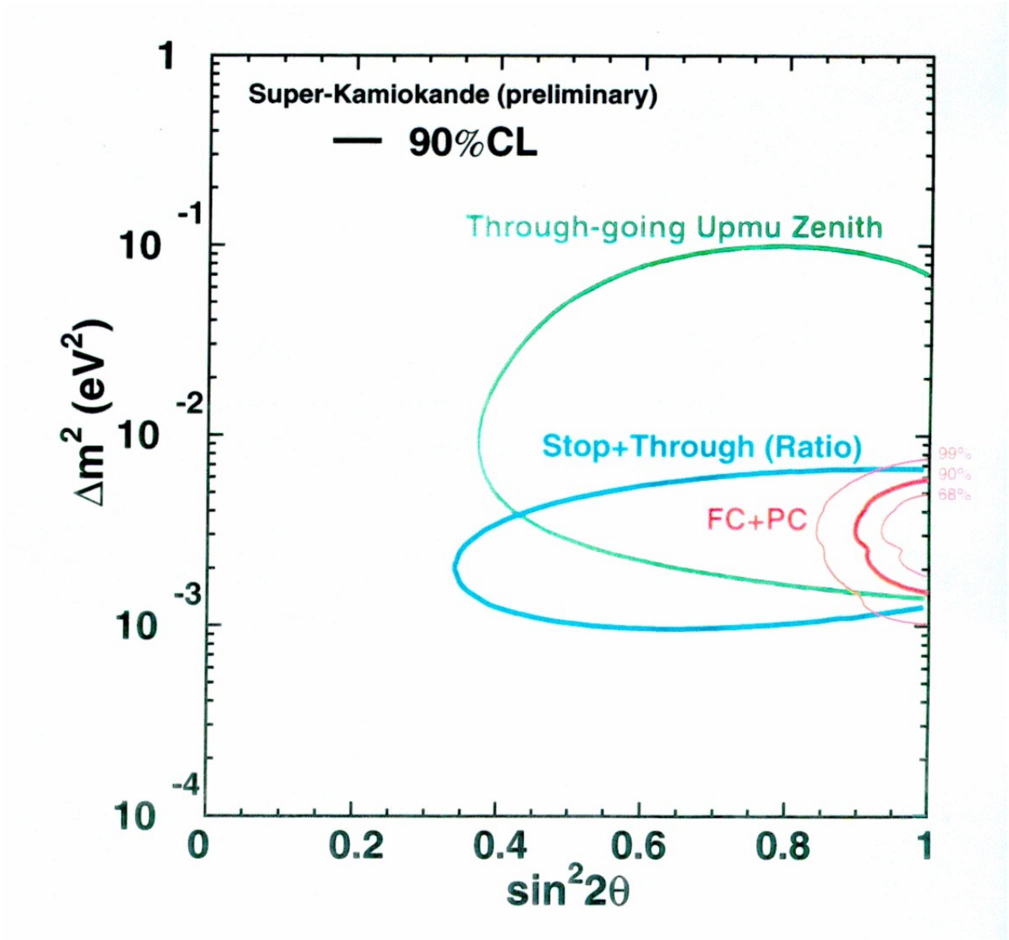


Long-Baseline Experiments must adapt to low Δm^2

4^{th} and 5^{th} papers – Upward Going Muons

December 1998 and August 1999



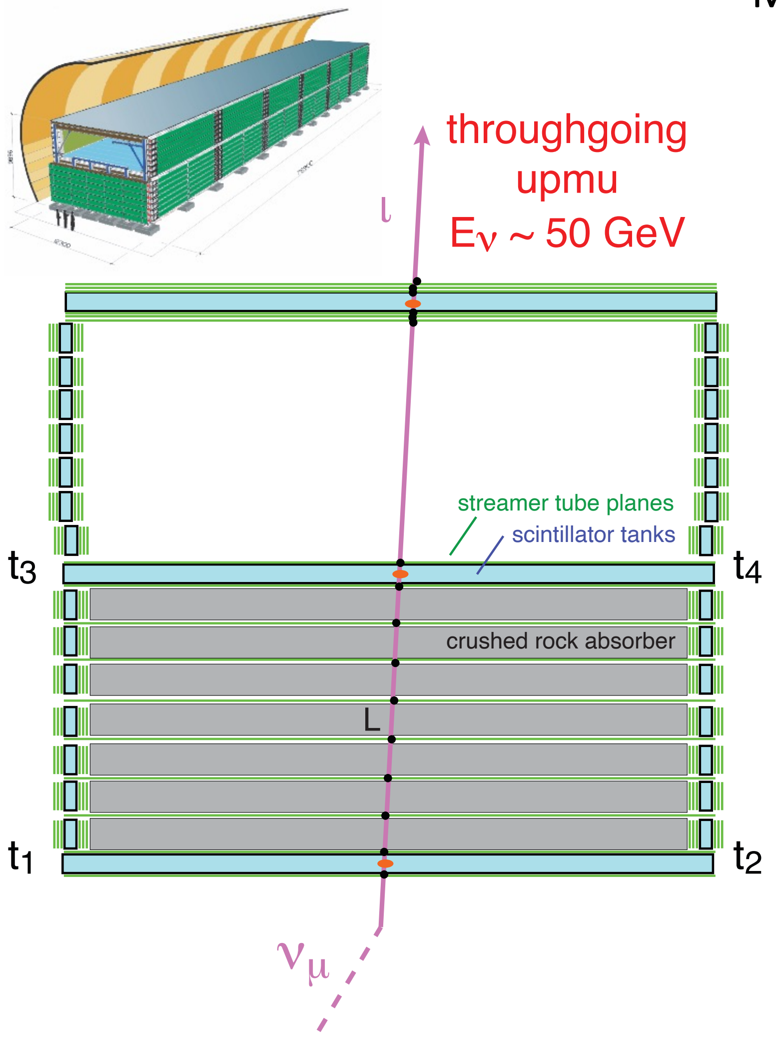


confirmed oscillations parameters with statistically and systematically different data set

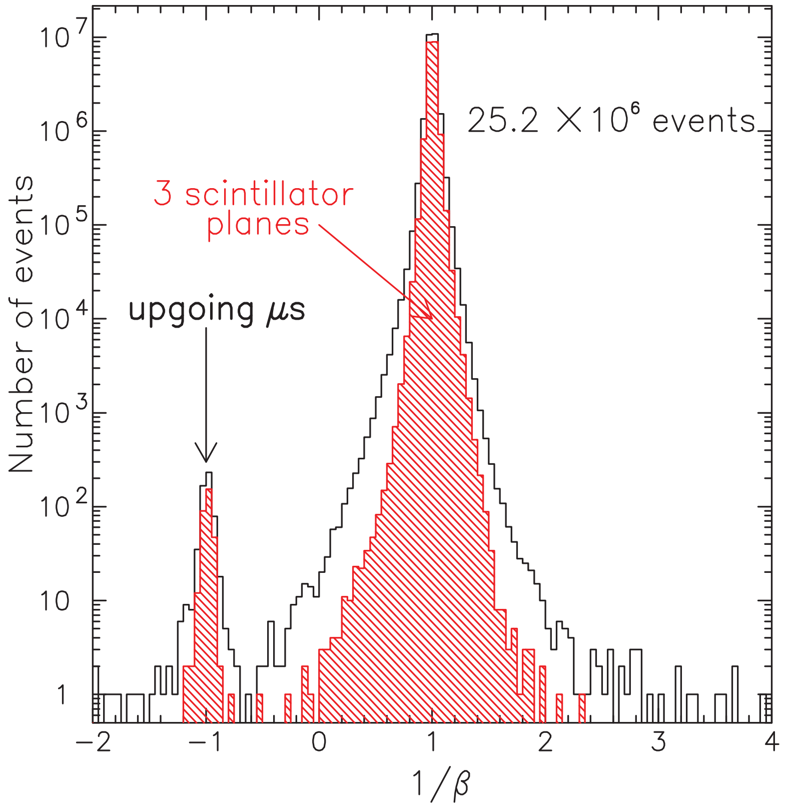
Independent Confirmation – MACRO upward-μ

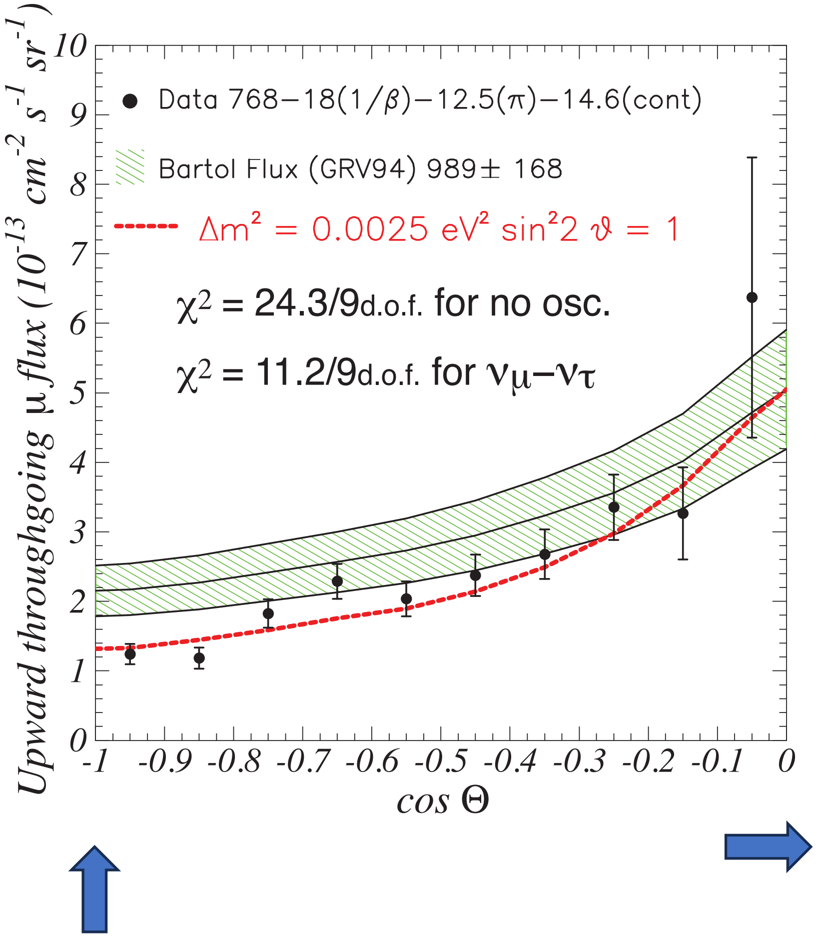
Phys.Lett.B 434 (1998)

Monopole Astrophysics Cosmic Ray Observatory



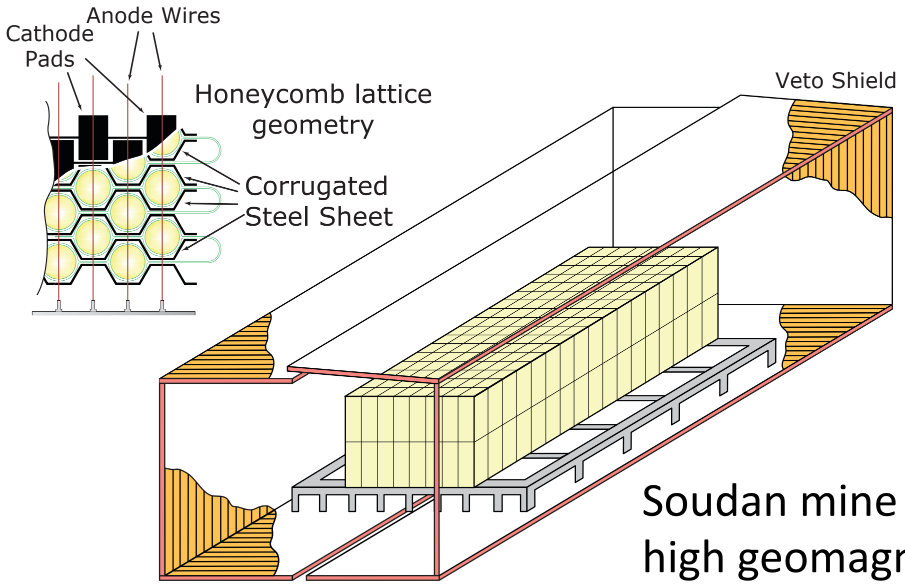
$$\frac{1}{\beta} = \frac{(t_1 + t_2 - t_3 - t_4)}{2L}$$



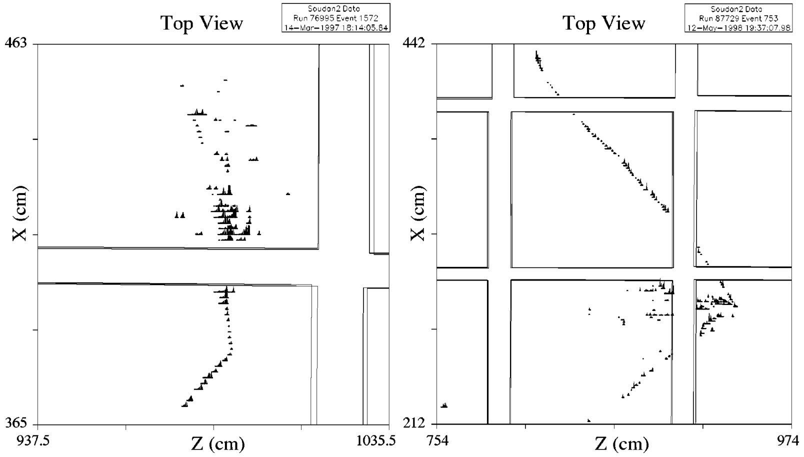


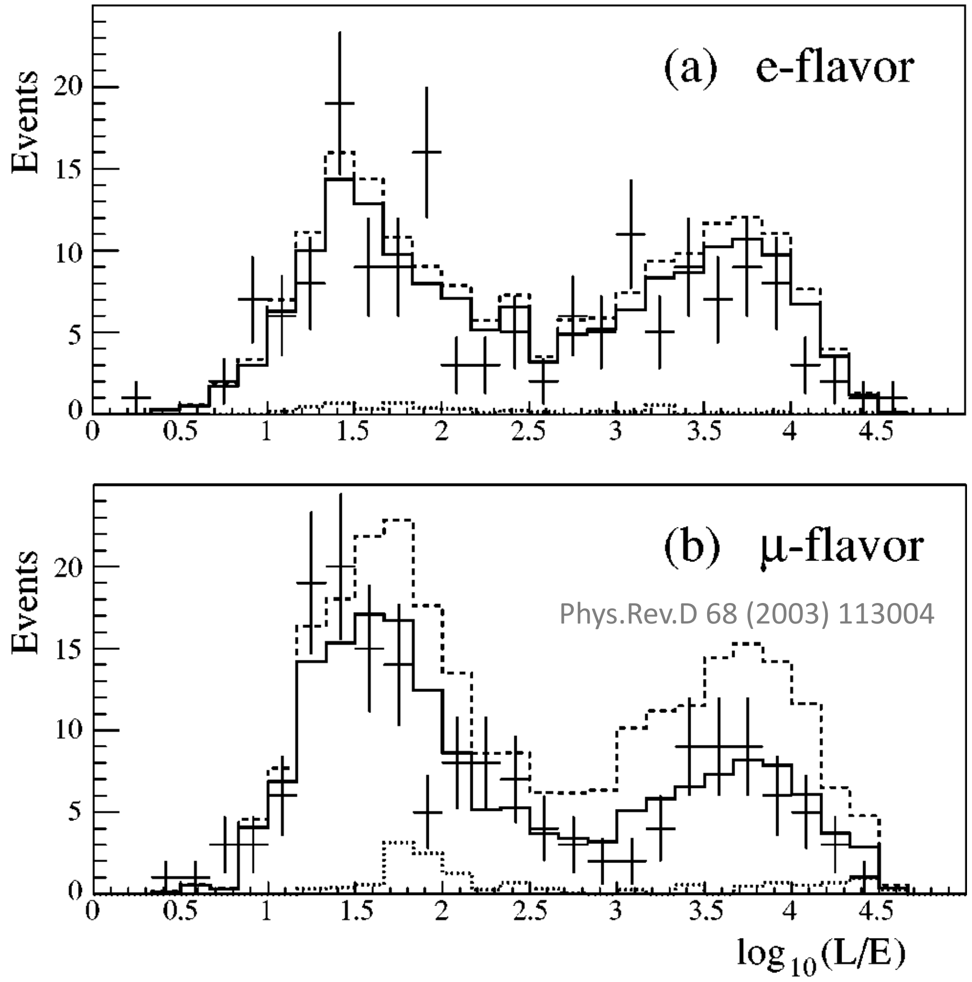
Independent Confirmation – Soudan 2

Phys.Lett.B449:137-144,1999



Soudan mine (Minnesota)
high geomagnetic latitude



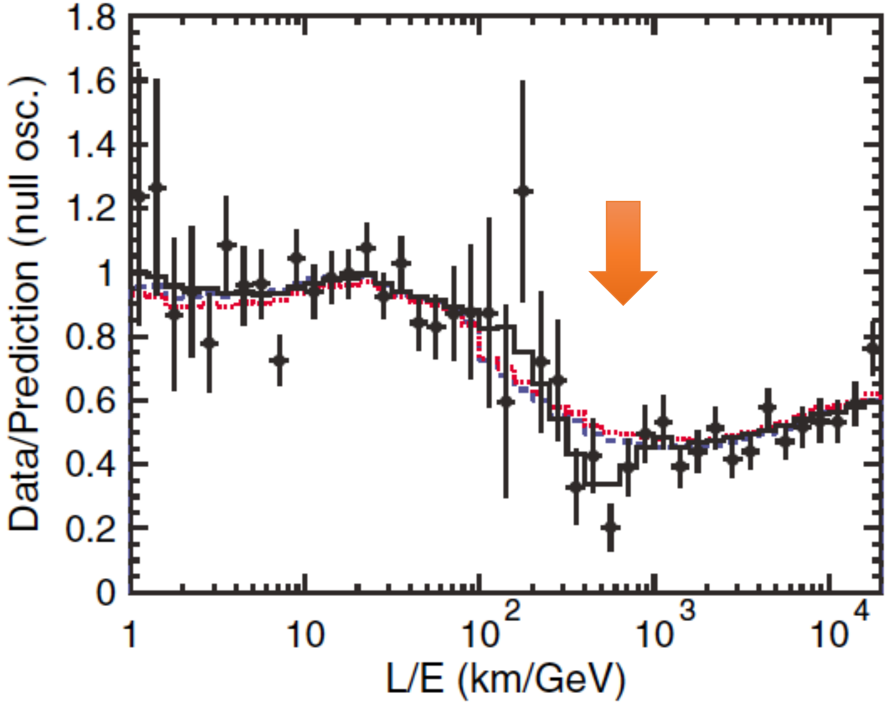


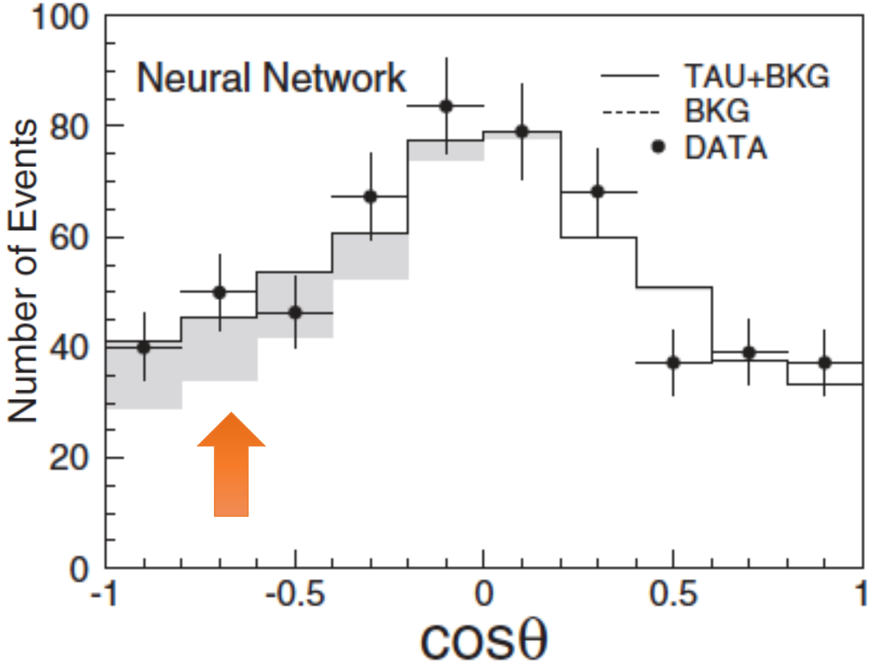
μ/e double ratio resolves iron target issue from 1980's
Later: zenith angle dependence

2000 **Tau Neutrinos Favored over Sterile Neutrinos in Atmospheric Muon Neutrino Oscillations**

no matter effect suppression for E > 15 GeV & no NC disappearance

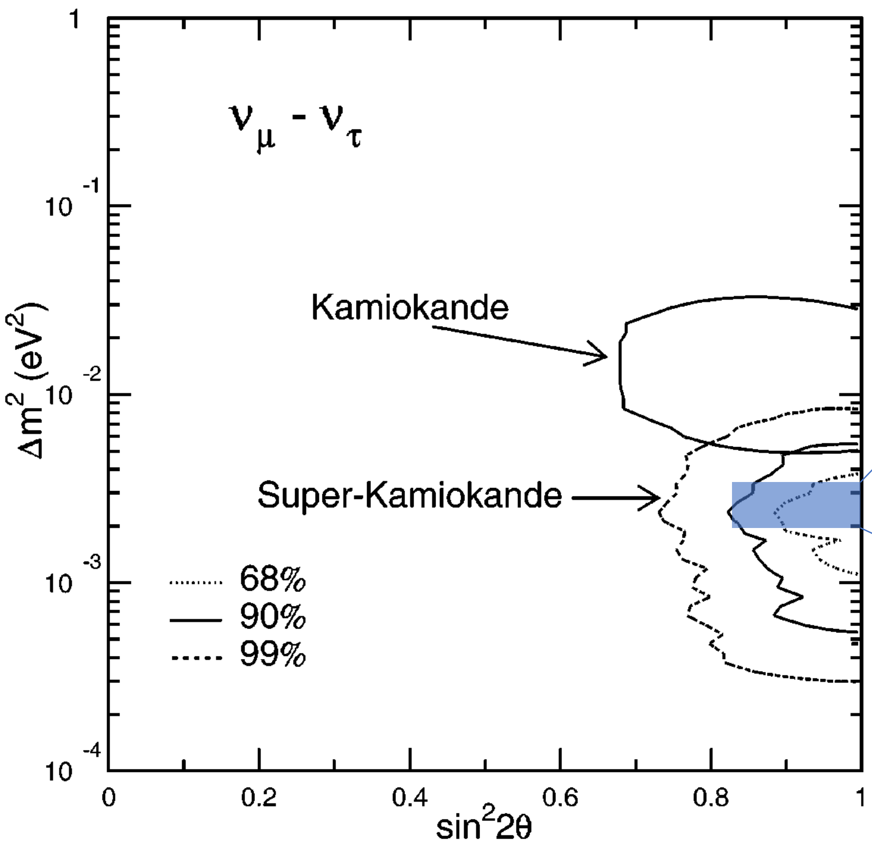
2004 **Evidence for an Oscillatory Signature in Atmospheric Neutrino Oscillations**



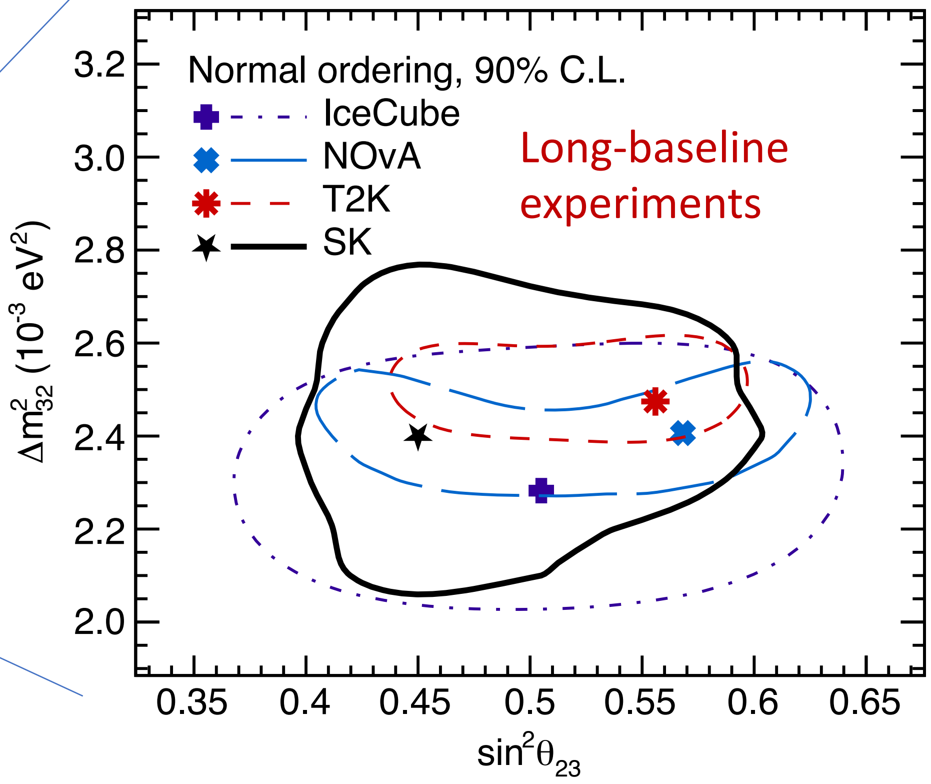


2006 **Measurement of Atmospheric Neutrino Flux Consistent with Tau Neutrino Appearance**

1998



2023



Next: 2023 and beyond

3-flavors, matter effects, mass ordering

The Three Unknowns of 3-flavor ν Oscillation

"Mass Ordering" a.k.a. "Mass Hierarchy" or sign of Δm^2?

"Octant": is θ_{23} different from 45˚?

CP violation?

Parameter	best-fit	rough 1σ uncertainty
Δm^2_{21} [10^{-5} eV ^{2}]	7.37	± 0.17 (2.3%)
$\lvert\Delta m^2\rvert$ [10^{-3} eV ^{2}]	2.50 (2.46)	± 0.06 (2.4%)
$\sin^2\theta_{12}$	0.297	± 0.017 (5.7%)
$\sin^2\theta_{23}$, $\Delta m^2 > 0$	0.437	$^{+8\%}_{-5\%}$
$\sin^2\theta_{23}$, $\Delta m^2 < 0$	0.569	$^{+5\%}_{-9\%}$
$\sin^2\theta_{13}$, $\Delta m^2 > 0$	0.0214	± 0.0012 (5.5%)
$\sin^2\theta_{13}$, $\Delta m^2 < 0$	0.0218	
δ/π	1.35 (1.32)	$0 \leftrightarrow 2\pi$ at 1σ

From 2016 RPP by PDG, based on 1601.07777 (Bari group)

We can investigate all of these with atmospheric neutrinos

Three Flavor Neutrino Oscillation in Matter

Freund, M. PRD 64 (2001) 053003

$$P(\nu_\mu \to \nu_e) \cong T_1 \sin^2 2\theta_{13} - T_2 \alpha \sin 2\theta_{13} + T_3 \alpha \sin 2\theta_{13} + T_4 \alpha^2$$

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

$$T_1 = \sin^2\theta_{23} \frac{\sin^2[(1-x)\Delta)]}{(1-x)^2}$$

CP violating

$$T_2 = \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

CP conserving

$$T_3 = \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

$$T_4 = \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2}$$

for anti-neutrinos
sign of x and
sign of sin δ_{cp}
is changed

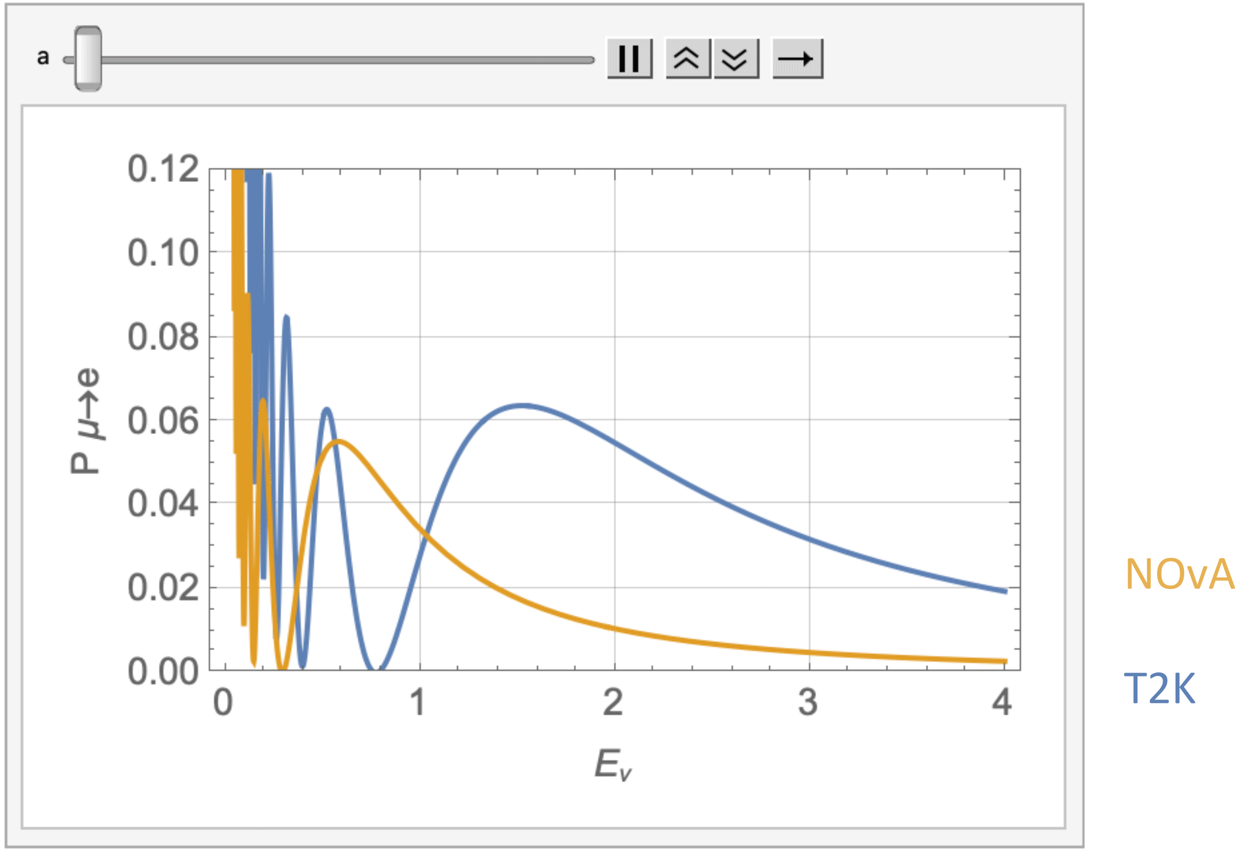
Resonance condition
for ν_e if normal ordering
for $\bar{\nu}_e$ if normal ordering

sign encodes
mass ordering:

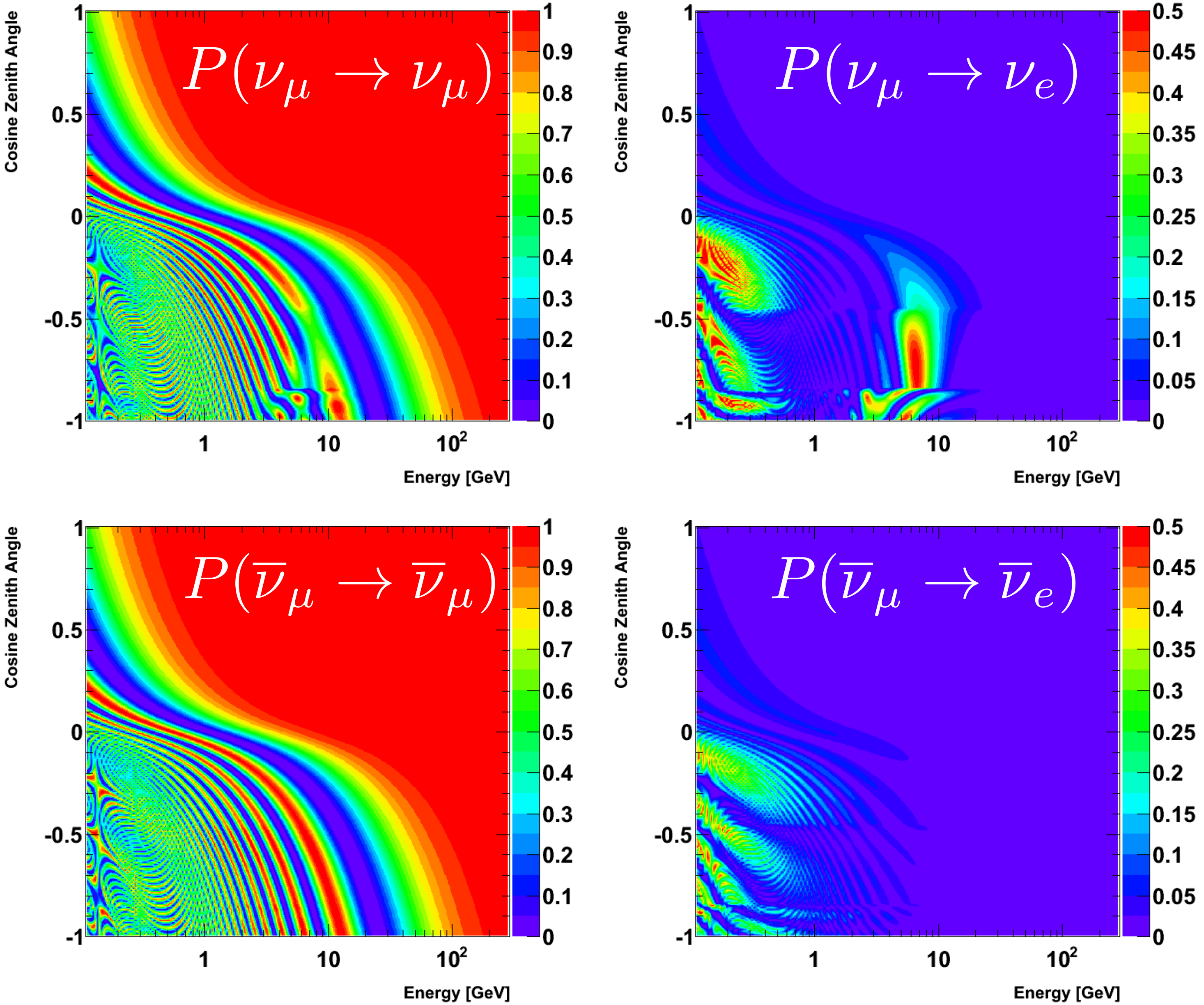
$$\Delta m^2_{31} = m^2_3 - m^2_1$$
> 0 normal
< 0 inverted

$$\Delta = \frac{\Delta m^2_{31} L}{4E} \qquad x = \frac{2\sqrt{2} G_F N_e E}{\Delta m^2_{31}} \sim \frac{E}{12\ \mathrm{GeV}}$$

Try it out!



Oscillograms



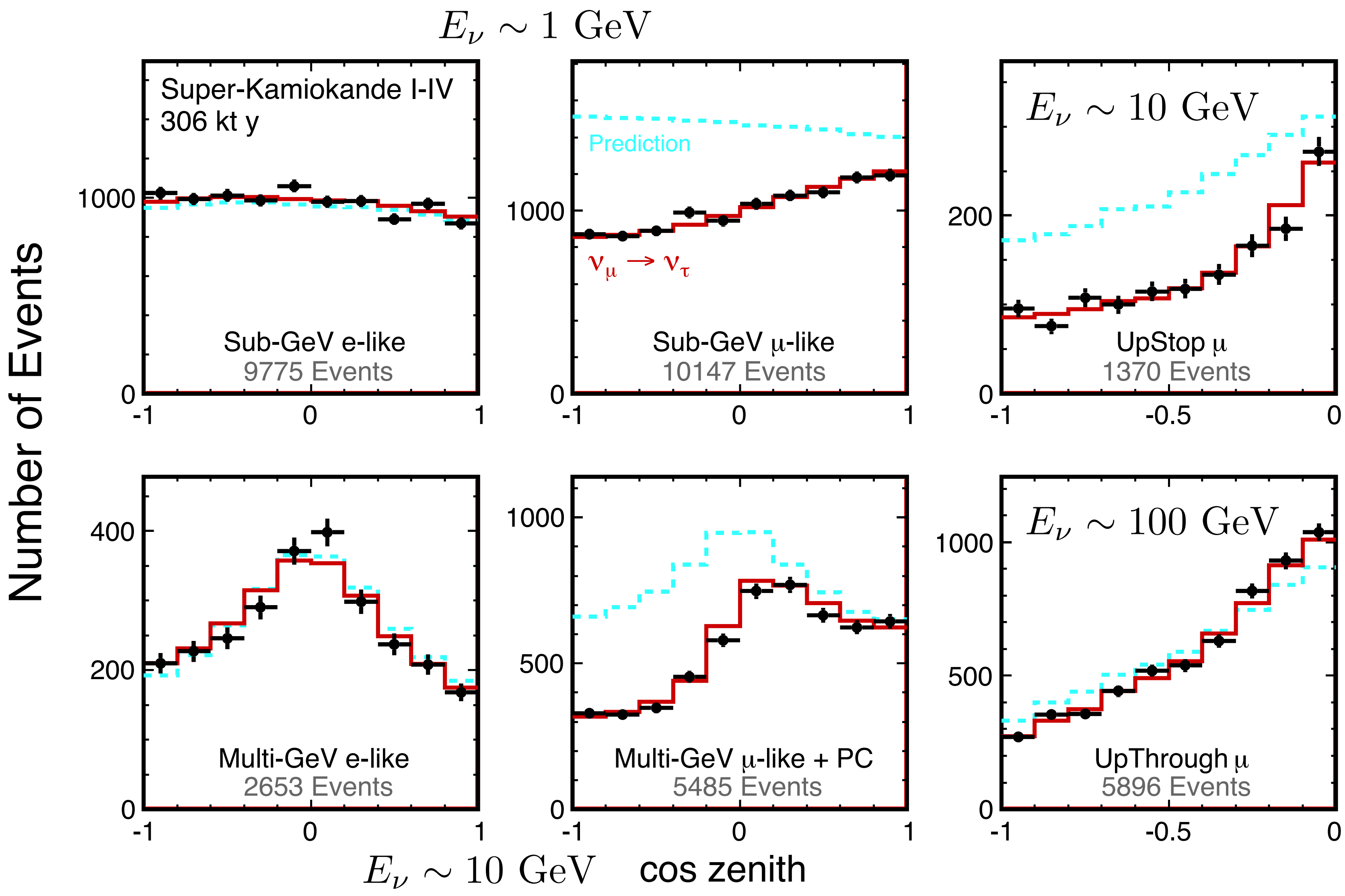
Remember:
Statistics is lower at high energy
Pointing is better at high energy

Matter effect resonance in ν for normal ordering

If inverted ordering, top/bottom plots exchange and the resonance is in anti-ν

Super-K I-II-III-IV (1996-2018) data set

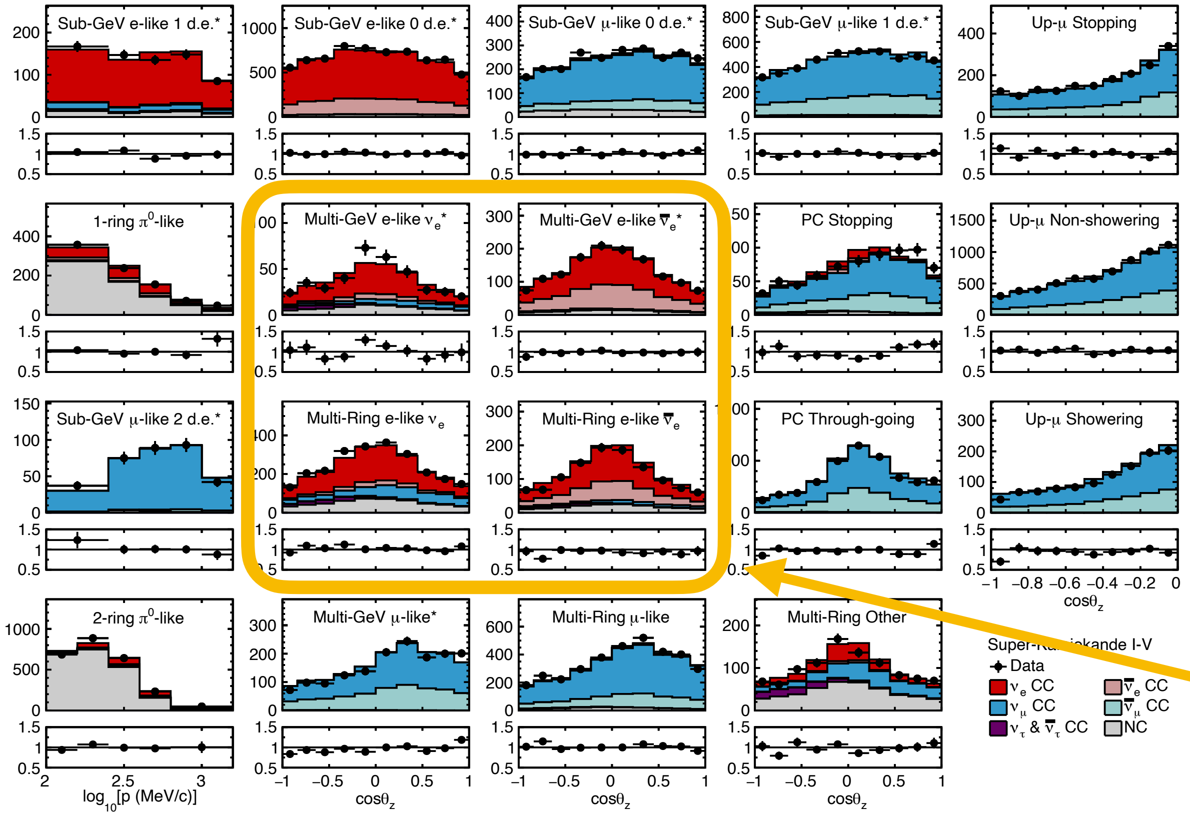
35000 atmospheric neutrinos



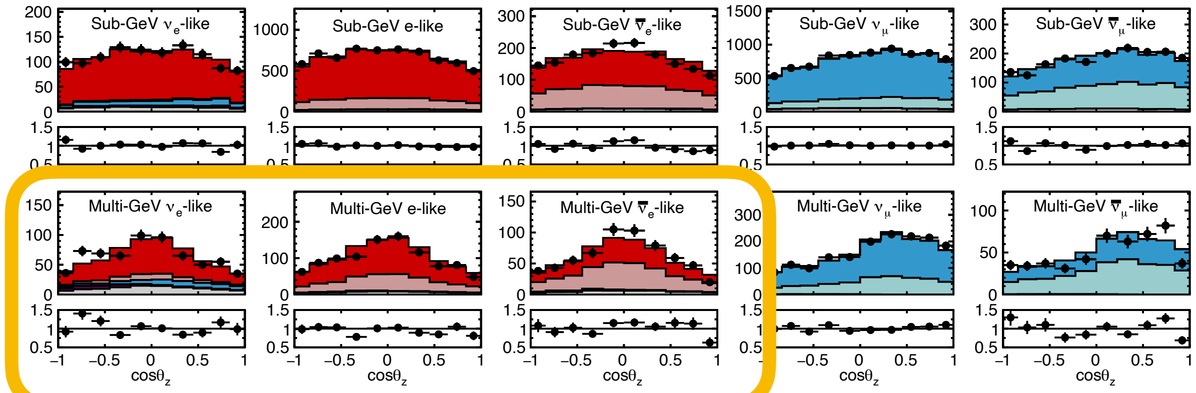
Blue contributions are muon neutrinos
Drives 2-3 parameter determination
Normalizes flux and cross section
Built-in “near detector”)

Super-K I-V data set finely binned

T. Wester



SK IV-V fully contained single ring samples with neutron tagging selection



Red contributions are **electron neutrinos**
Select categories with higher energy and good pointing

Contribution from ν_e **appearance:**
200 events (normal ordering)
50 events (inverted ordering)

Neutrino – Antineutrino in Water Cherenkov

Decay electrons: More from neutrinos than anti-neutrinos

$$\nu_e + p \rightarrow p + e^- + \pi^+ \longrightarrow \pi^+ \rightarrow \mu^+ \rightarrow e^+$$

Decay *e* observed
~ few μs later

$$\bar{\nu}_e + p \rightarrow p + e^+ + \pi^-$$

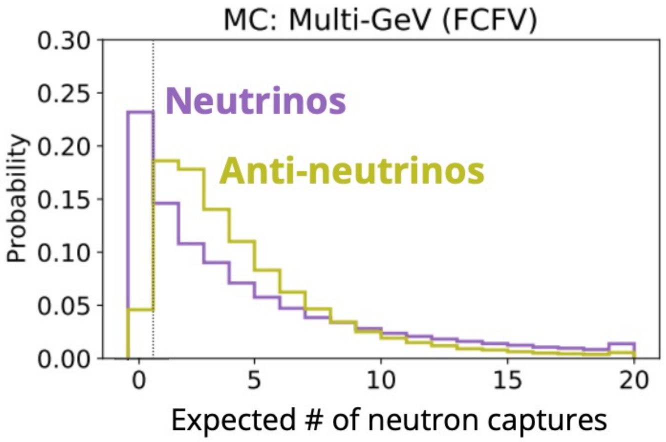
π^- absorbed in H_2O
No decay *e*

T. Wester

Neutron captures: More for anti-neutrinos than neutrinos, observed in SK IV+

$$\nu_e + n \rightarrow e^- + p$$

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

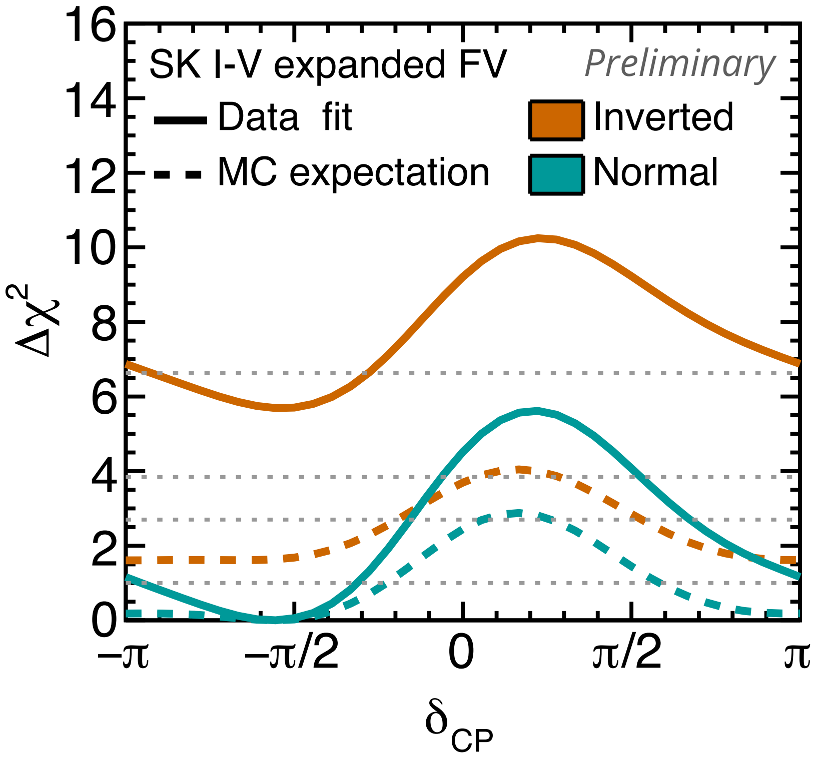


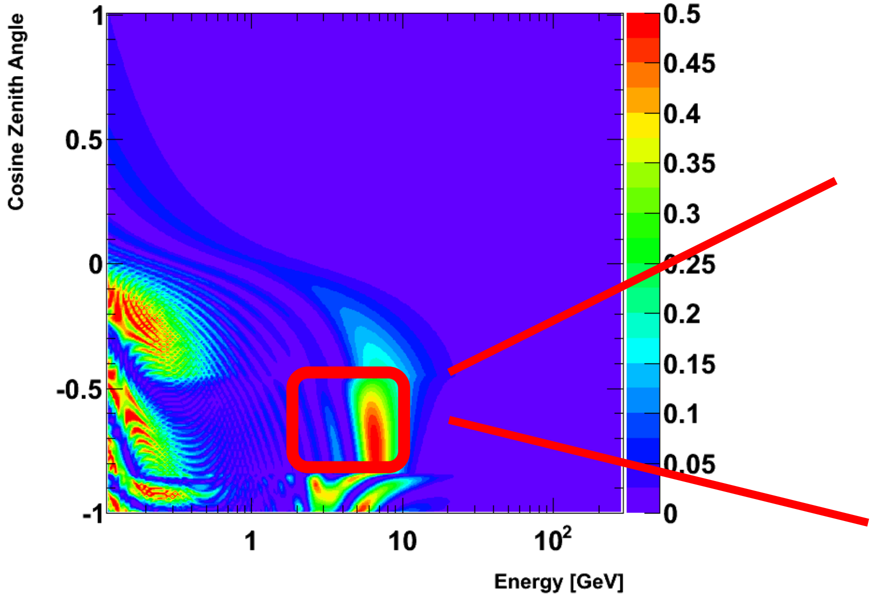
- ~200 μs capture time on hydrogen
- 26% efficiency, neural net selection

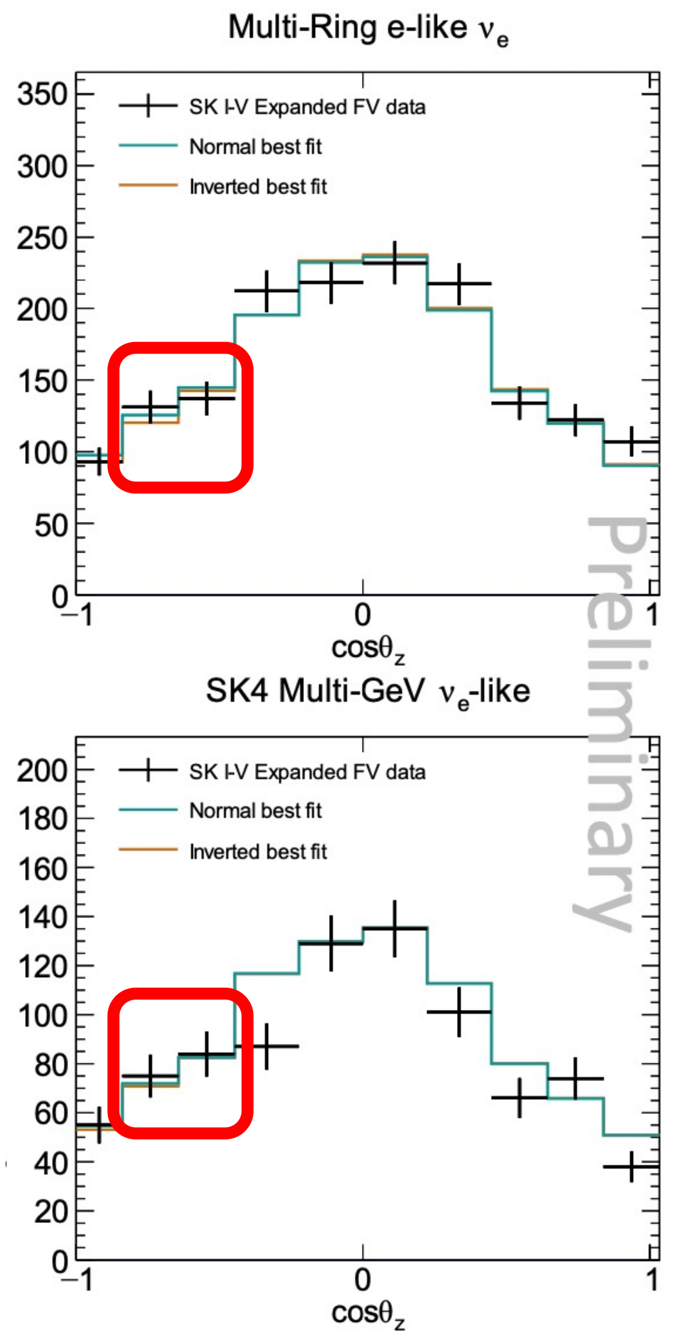
Super-K I-V Results

2-3 Parameters shown earlier this talk

Mass Ordering and δCP:
Prefer Normal ordering ~ 2-sigma level*
Result exceeds sensitivity







* See upcoming paper for precise statement

Super-K I-V Results

2-3 Parameters shown earlier this talk

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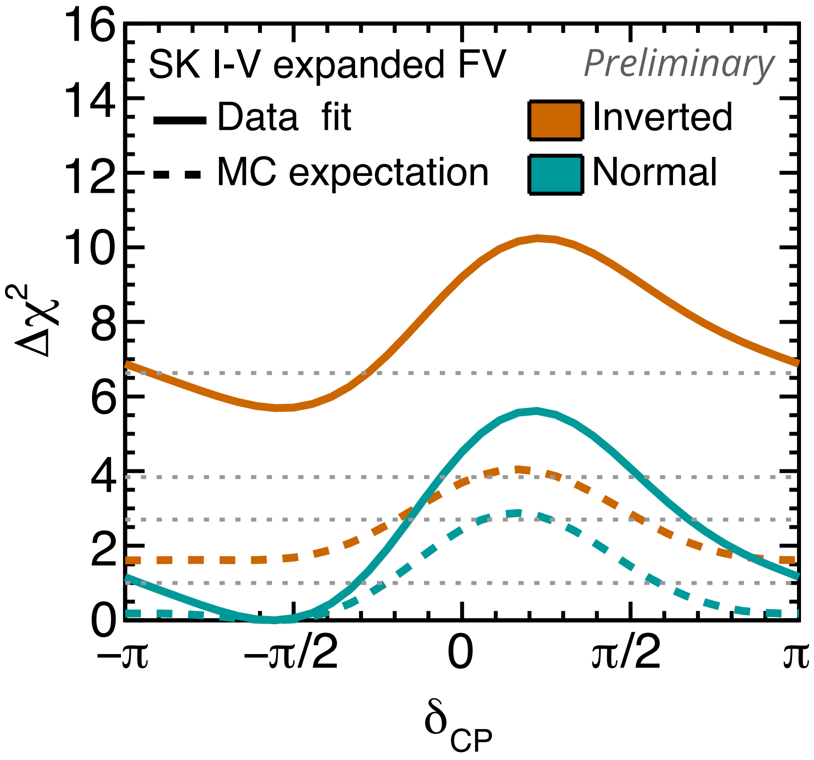

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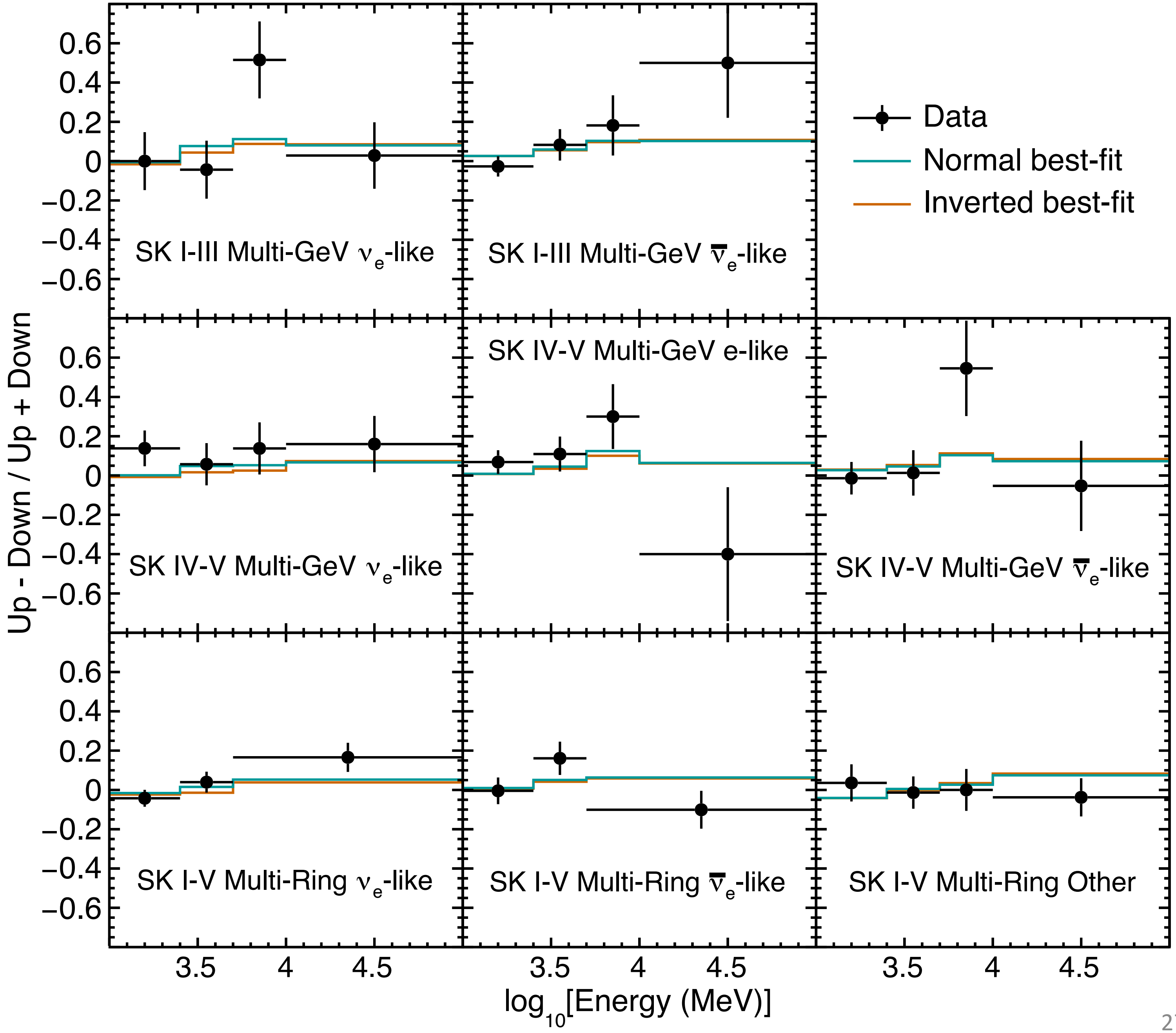
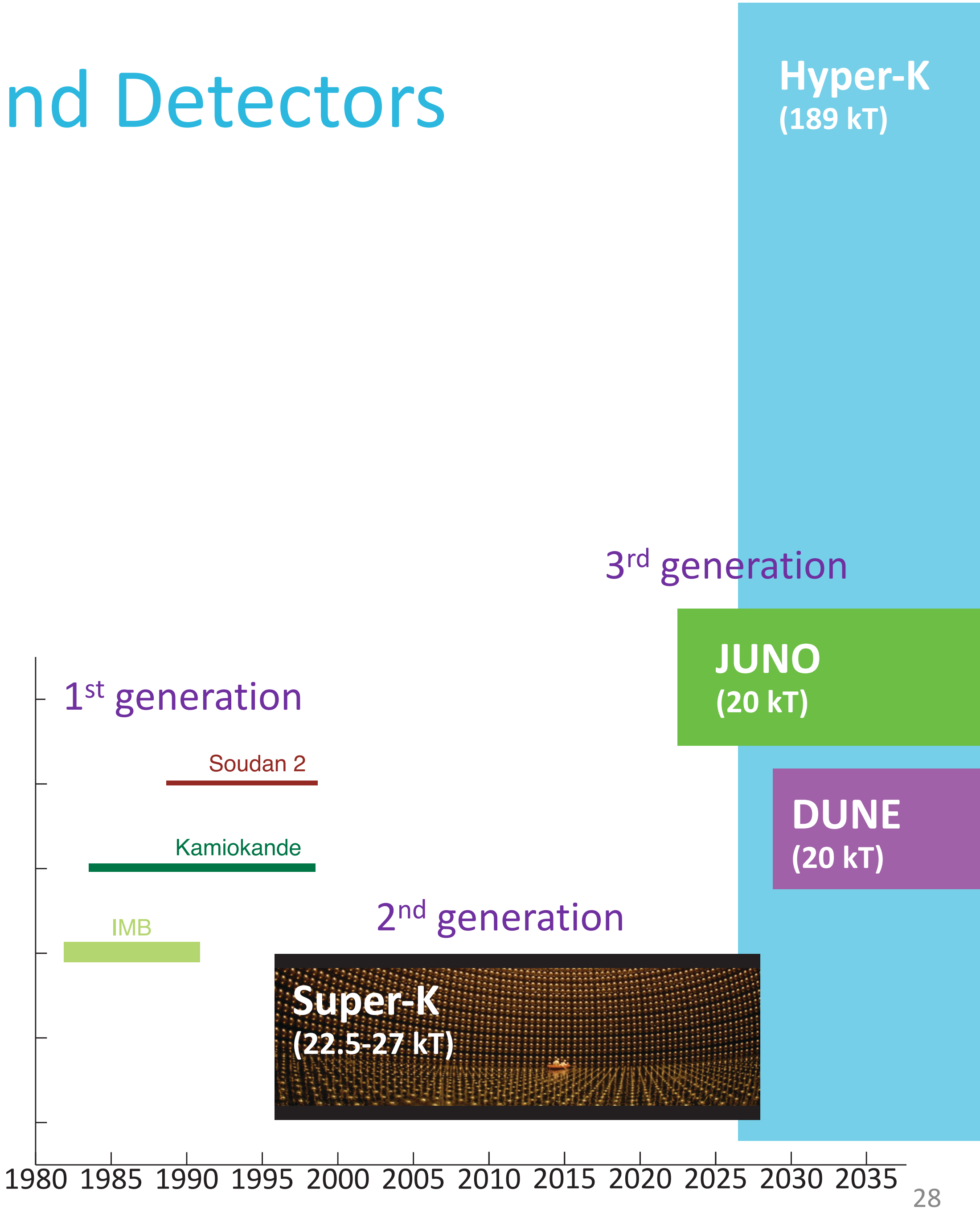


Third Generation Large Underground Detectors

Interest in neutrino oscillation has motivated a
third generation of massive underground detectors.

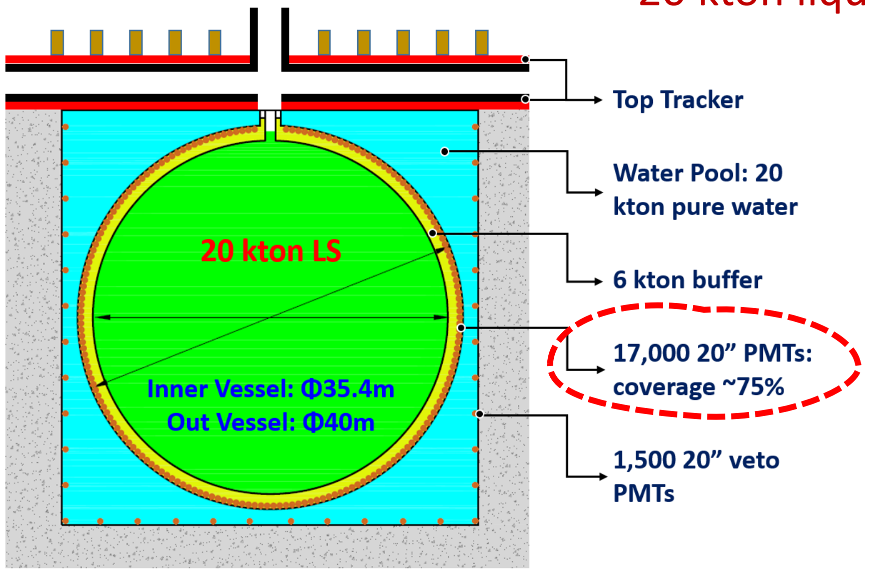


Off scale in mass: **IceCube, KM3Net**
but higher energy threshold (10 GeV-ish)
and limitations in detailed event identification
(i.e. not proton decay capable)

JUNO Jiangmen Underground Neutrino Observatory

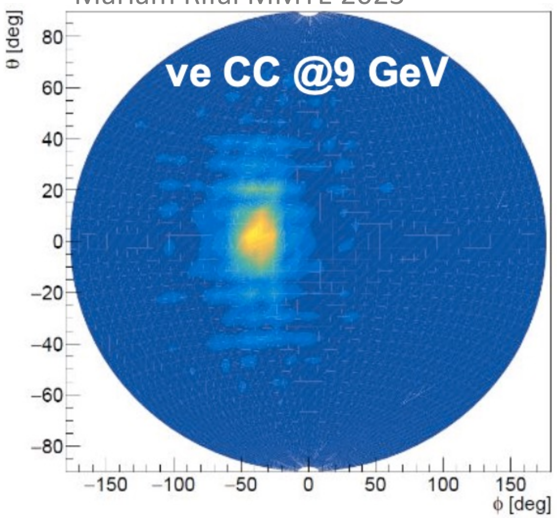
arXiv:1508.07166v2

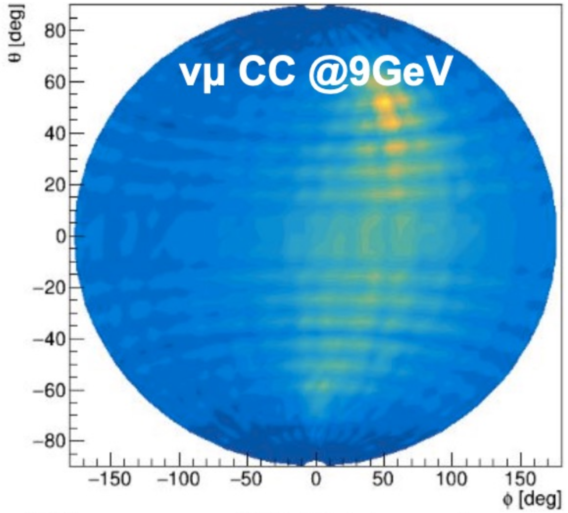
20 kton liquid scintillator detector



3” PMTs and 20” PMTs

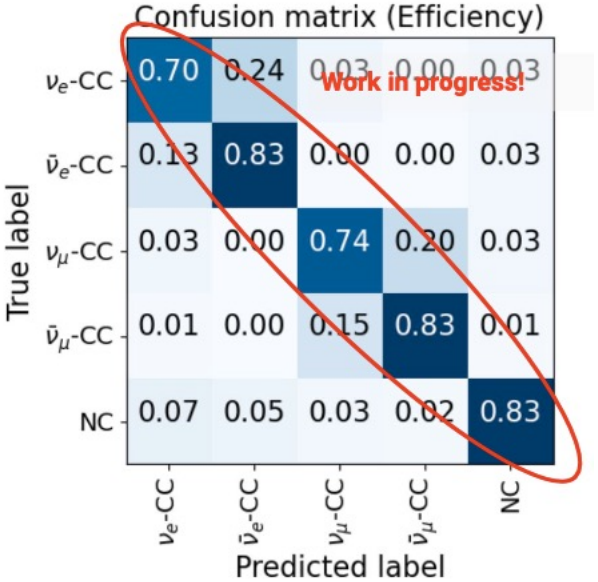
Mariam Rifai MMTE 2023





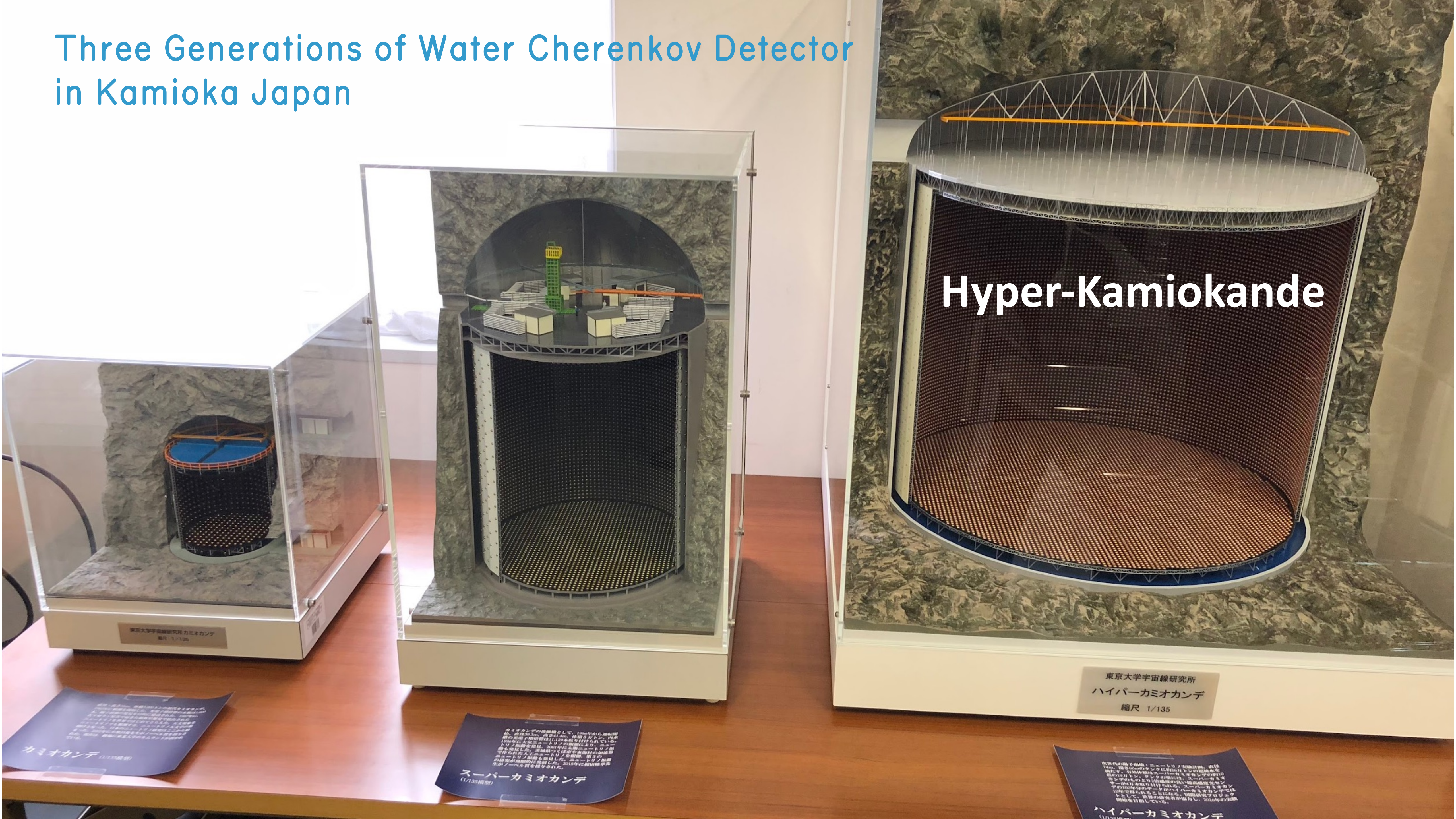
Hitmap on 3” PMT system

machine learning



True label \ Predicted label	ν_e-CC	$\bar{\nu}_e$-CC	ν_μ-CC	$\bar{\nu}_\mu$-CC	NC
ν_e-CC	0.70	0.24	0.03	0.00	0.03
$\bar{\nu}_e$-CC	0.13	0.83	0.00	0.00	0.03
ν_μ-CC	0.03	0.00	0.74	0.20	0.03
$\bar{\nu}_\mu$-CC	0.01	0.00	0.15	0.83	0.01
NC	0.07	0.05	0.03	0.02	0.83

Three Generations of Water Cherenkov Detector in Kamioka Japan



Three Generations of Water Cherenkov Detector in Kamioka Japan

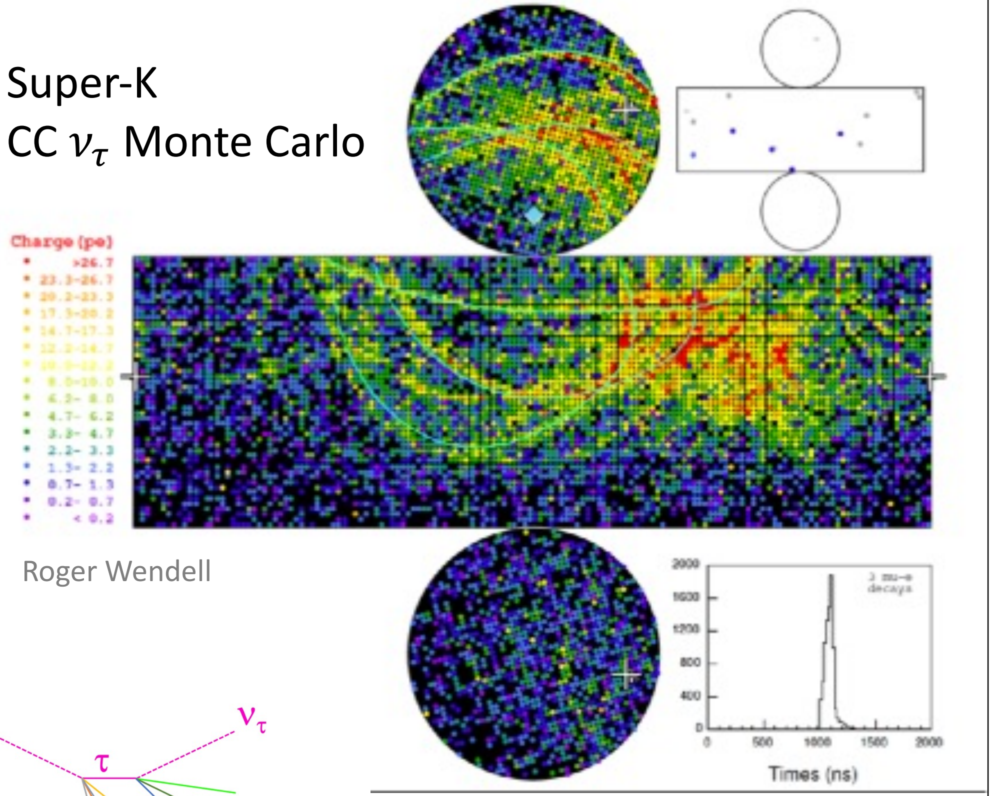
- **186.5** kton fiducial volume (258 kton total)
- Optically separated into
  - Inner Detector
    - **20,000** 50cm High QE B&L PMTs
    - + O(1) k mPMT Modules
  - Outer Detector 1885 8” PMTs
- Pure water neutron tagging > 40%
- Now under construction – Data taking in 2027

50 cm HQE Box&Line PMT

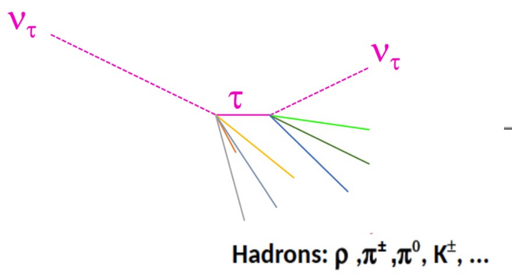
SK QE × 2
SK σ_τ × 2
SK Pres. Tol × 2

Super-K

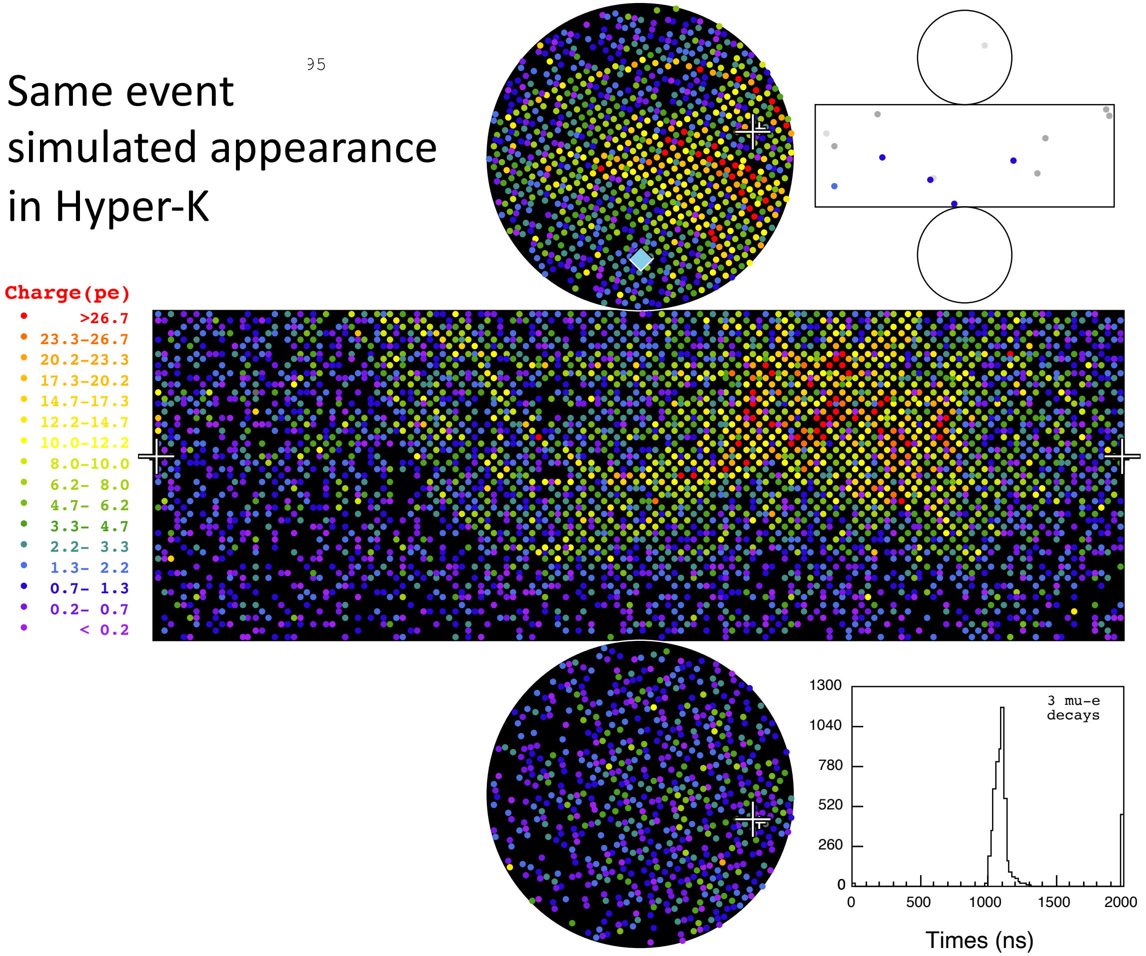
CC ν_τ Monte Carlo



Roger Wendell



Same event simulated appearance in Hyper-K

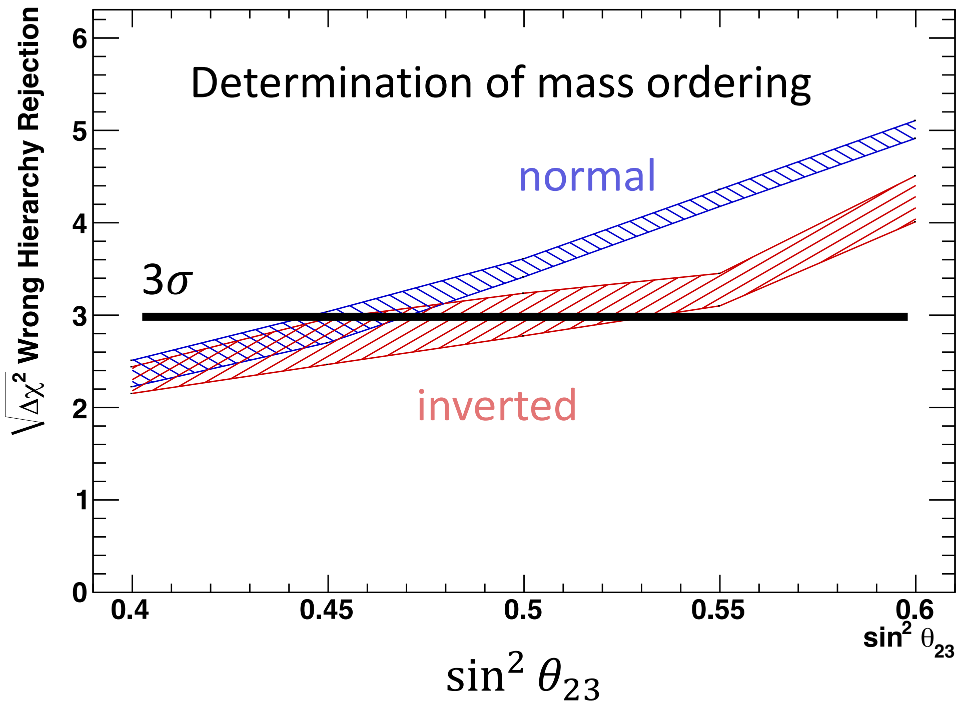


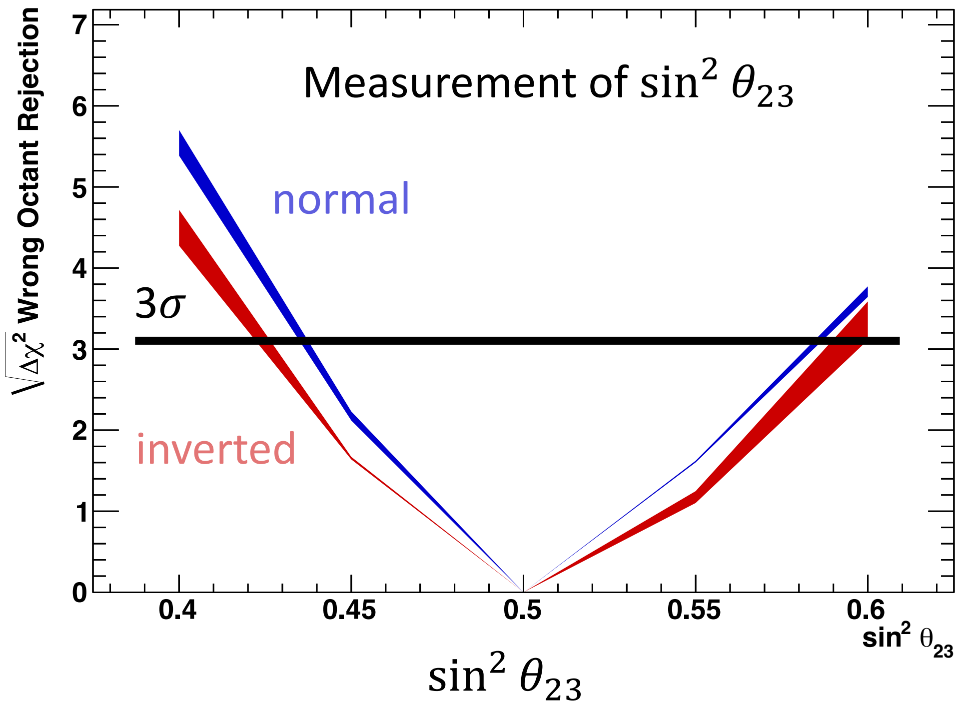
20% B&L PMT coverage

+ equivalent light collection from mPMT

Sensitivity: 10-year Hyper-K atmospheric neutrinos

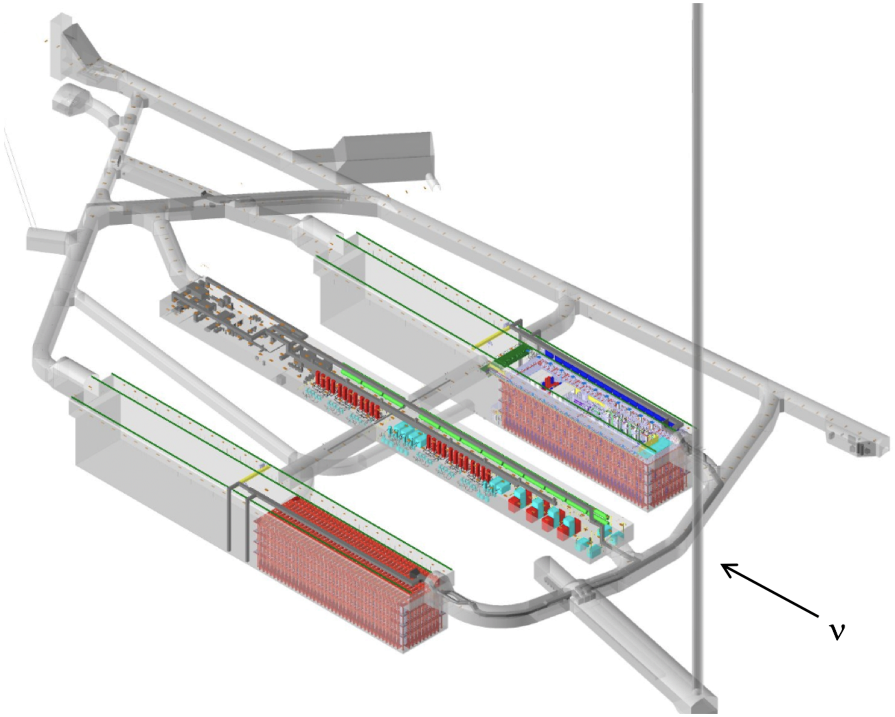
https://arxiv.org/pdf/1805.04163.pdf

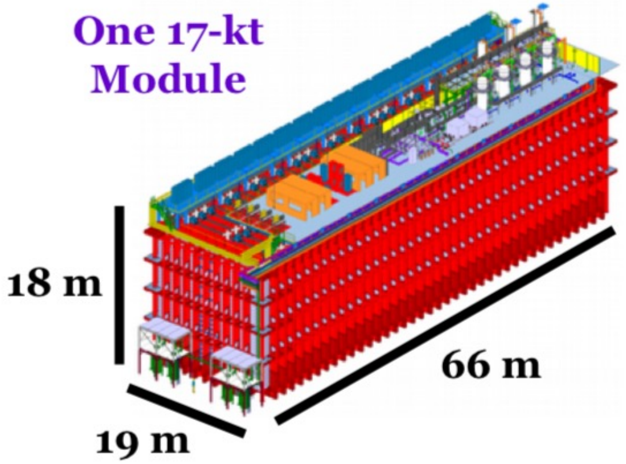




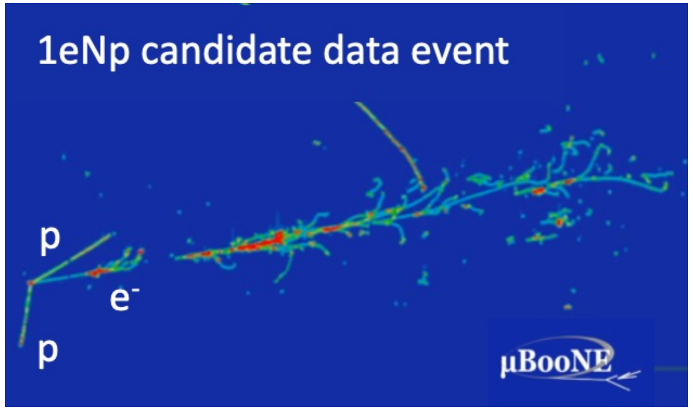
Width of bands reflects unknown δ_{CP}

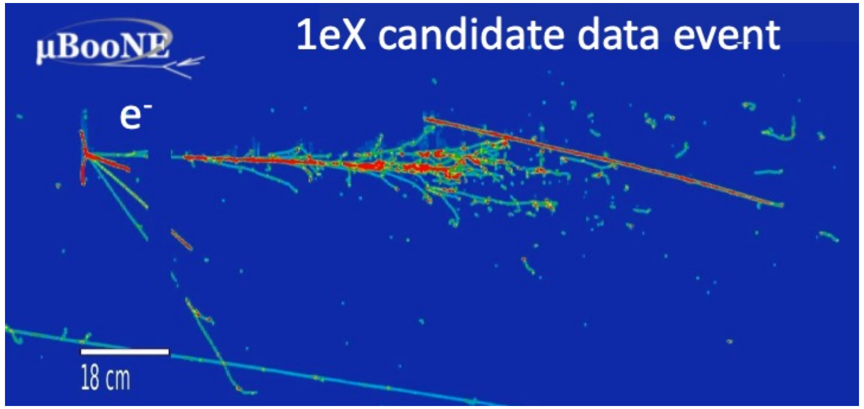
DUNE (Deep Underground Neutrino Experiment)





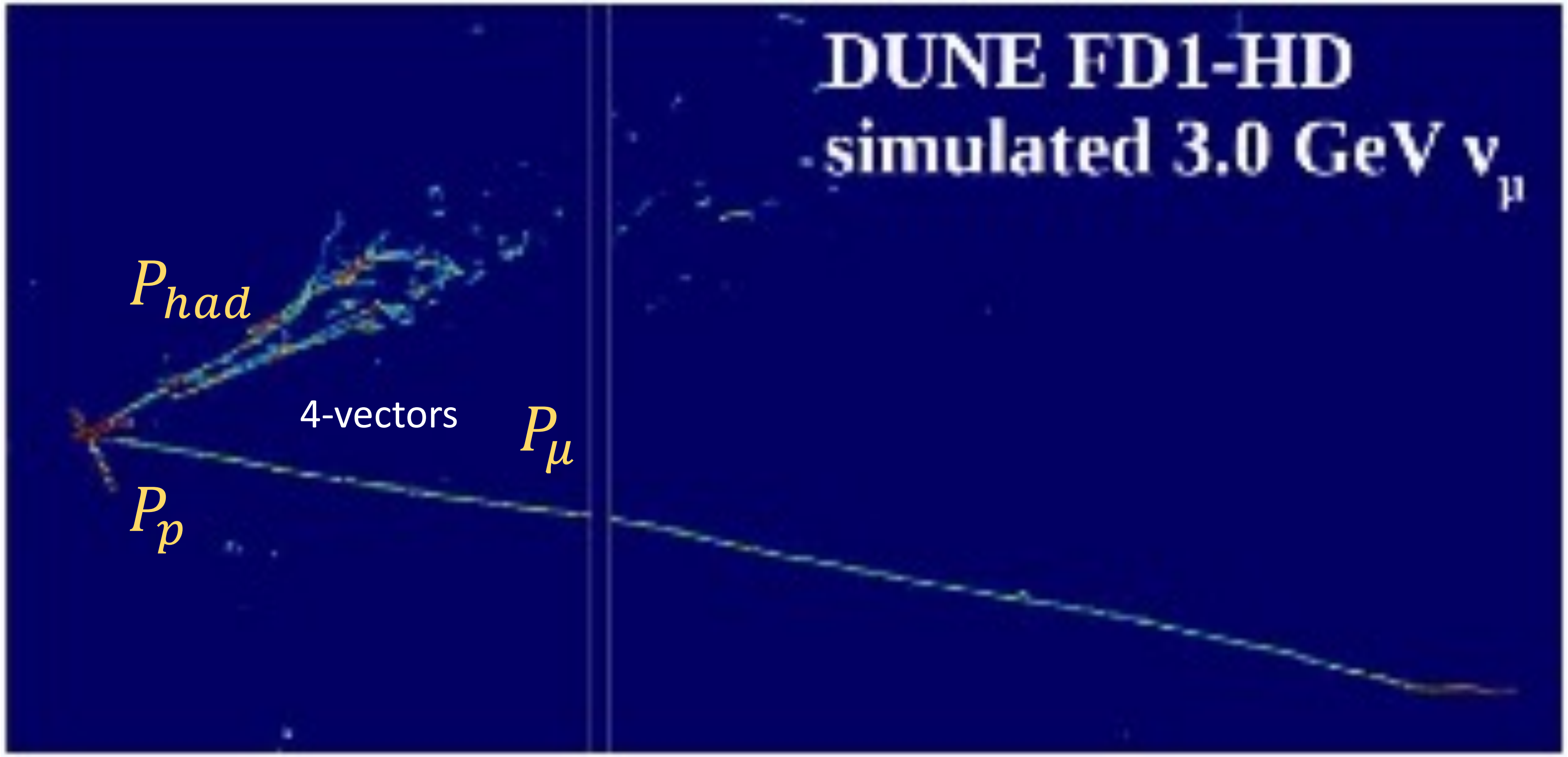
Liquid Argon Time Projection Chamber (LArTPC)





Event displays courtesy S. Zeller

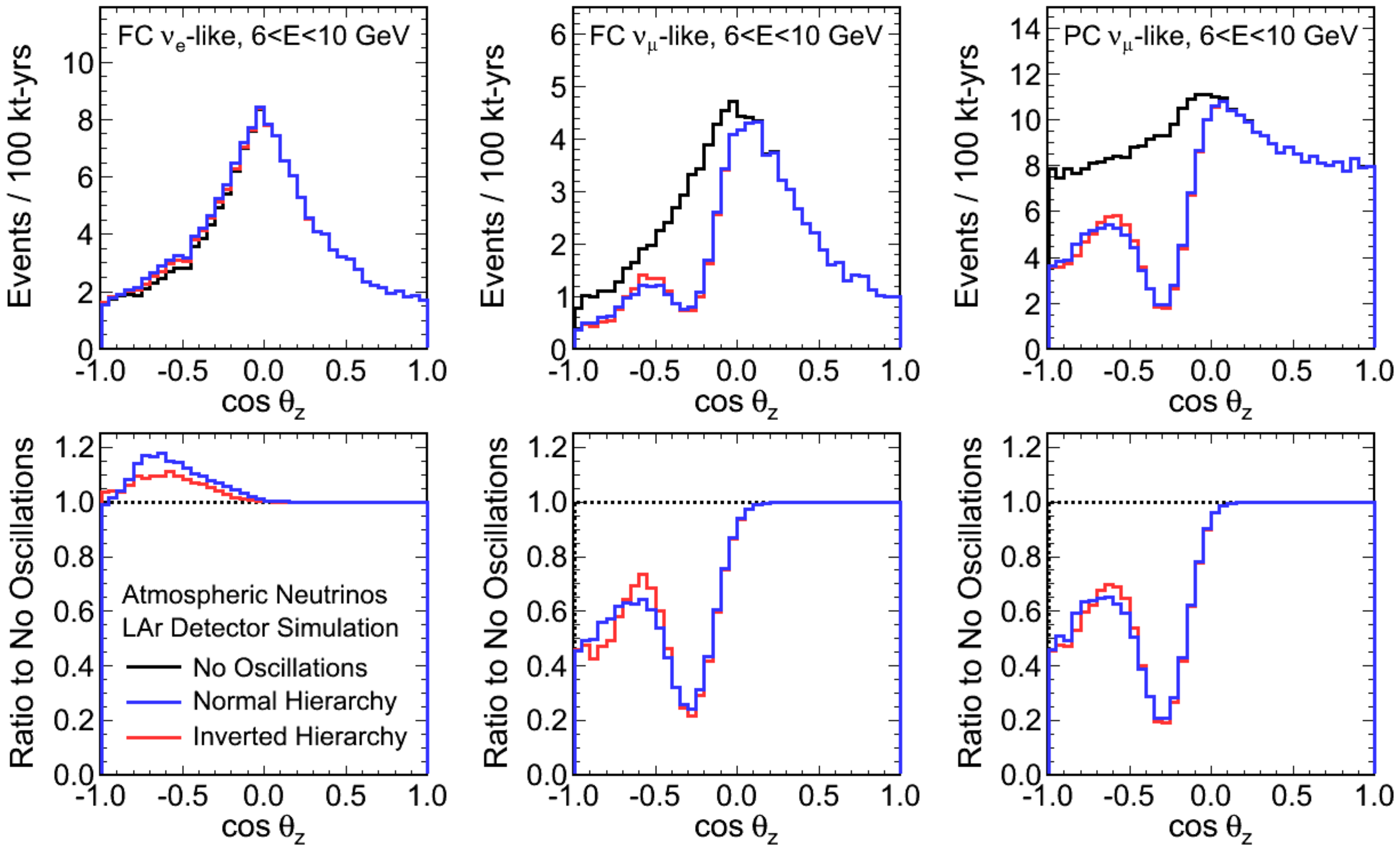
1.5 km deep in SURF (South Dakota)
modular … up to 4 x 10 kt total fiducial mass
Neutrino beam from Fermilab
Sensitive to ν_e from supernova



Tarak Thakore

$$P_\nu = P_p + P_{had} + P_\mu = (E_\nu\,, \vec{p}_\nu)$$

DUNE: Resolution of Oscillation Pattern

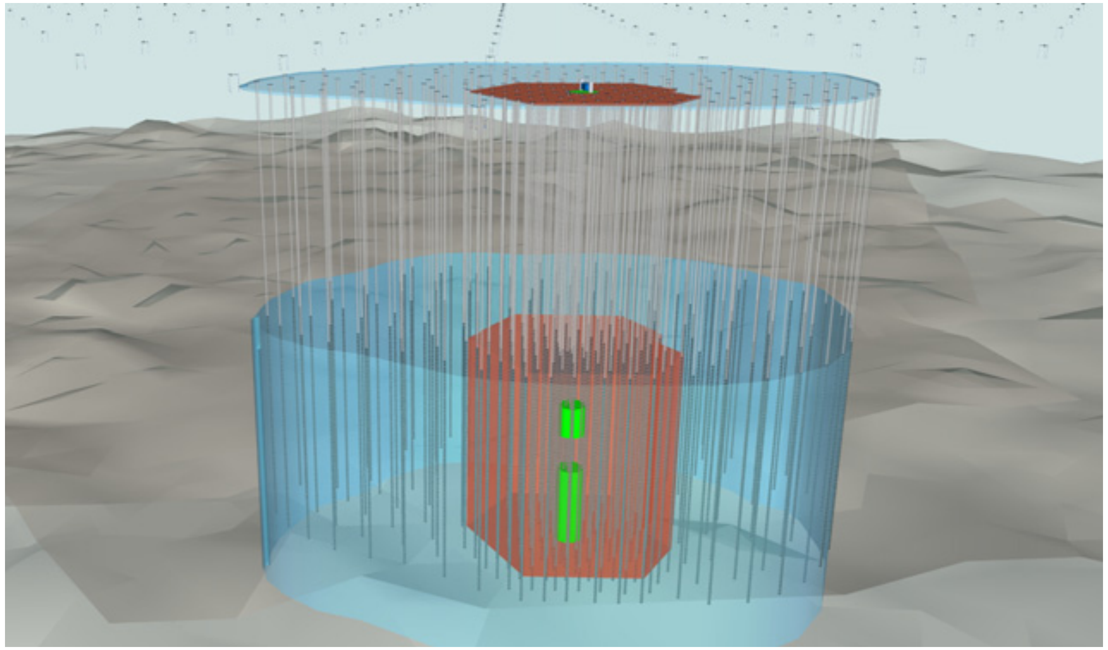


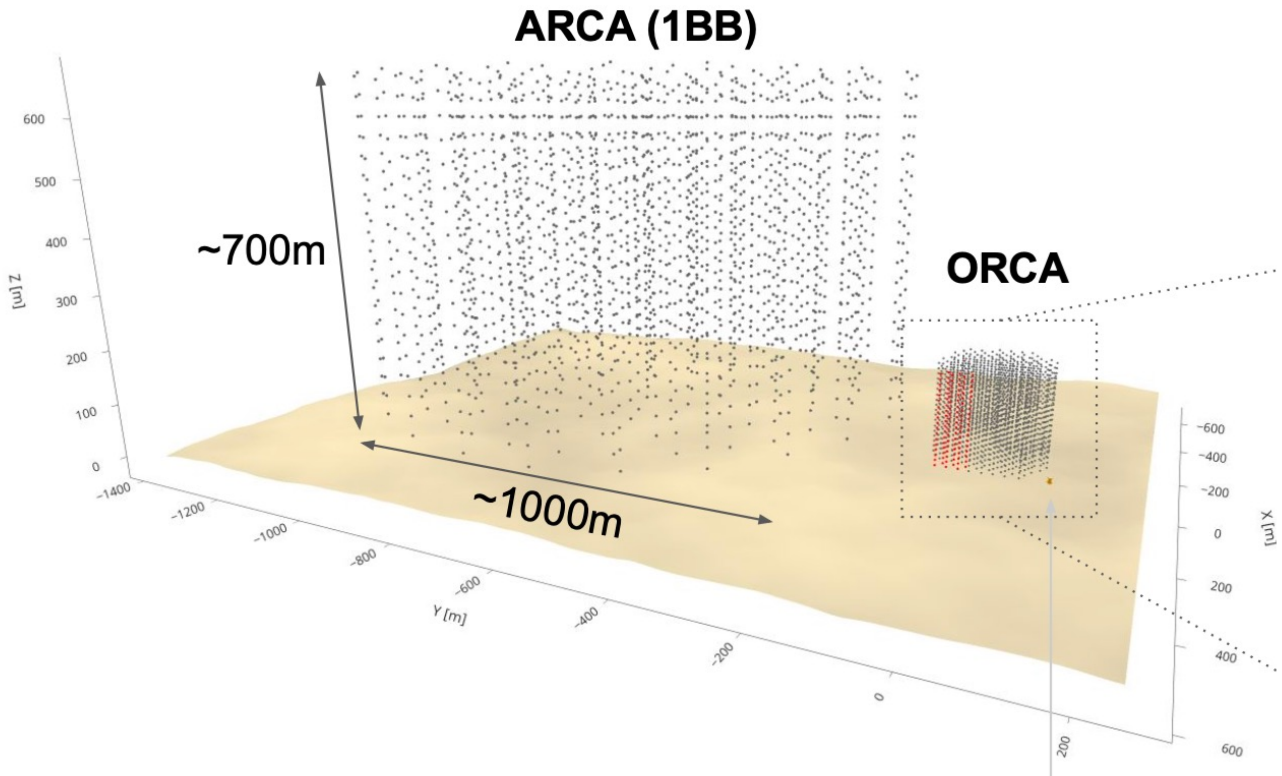
Binned quantity is reconstructed neutrino direction (not lepton direction as in SK/HK)

Kilometer-scale arrays

IceCube & DeepCore & upcoming Gen2

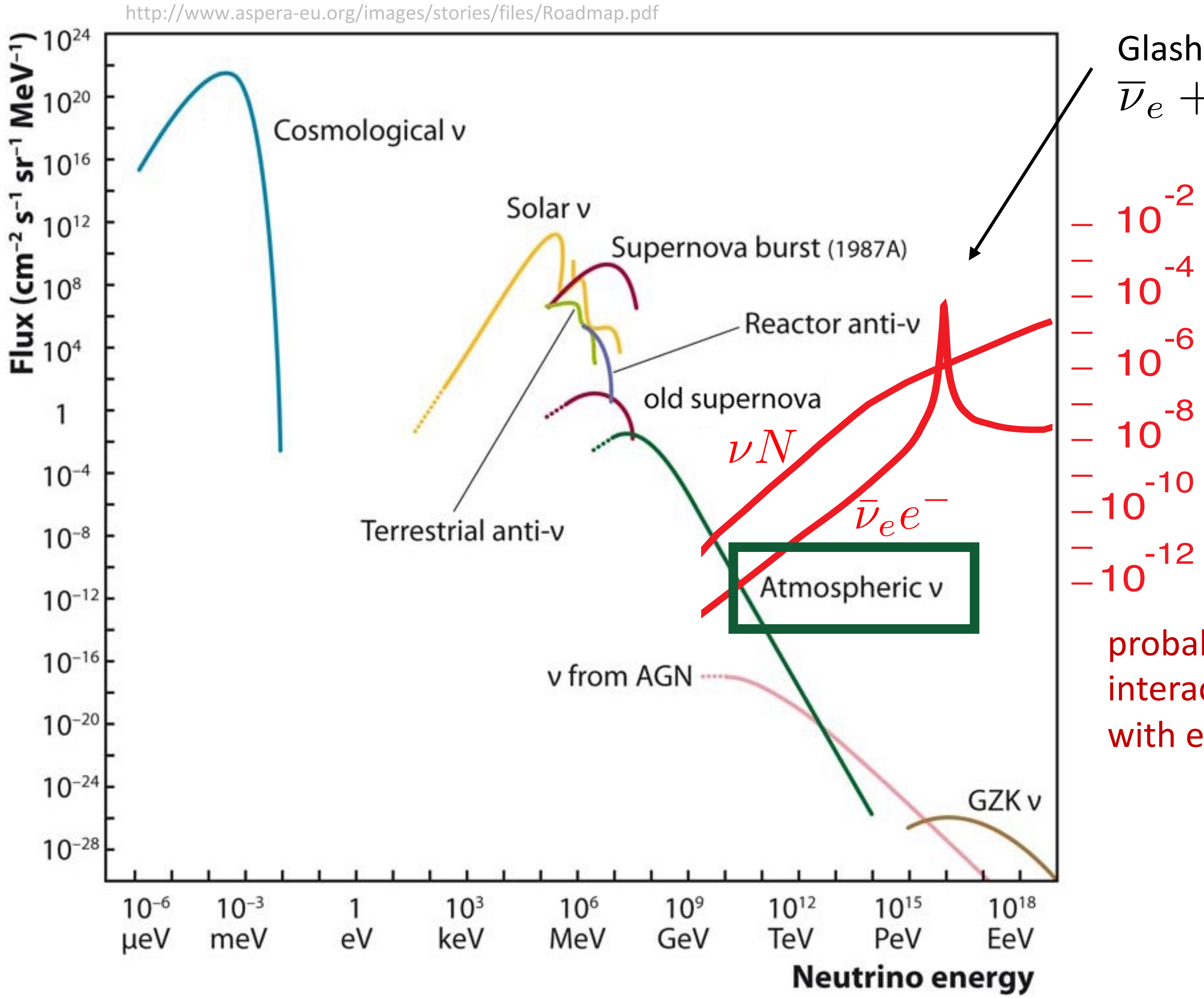
KM3Net: ARCA and ORCA





kilometer-scale ice/water Cherenkov detectors
Huge statistics, specializing in **highest energy neutrinos**
Deep Core (10 Mton): high density infill to achieve 10 GeV threshold
Gen2 Upgrade (2 Mton): seven more strings with new PMT sensors
achieve 1 GeV threshold

Mediterranean Sea
Two locations



Glashow resonance

$$\overline{\nu}_e + e^- \rightarrow W^-$$

One event DETECTED!

https://doi.org/10.1038/s41586-021-03256-1

Cross section

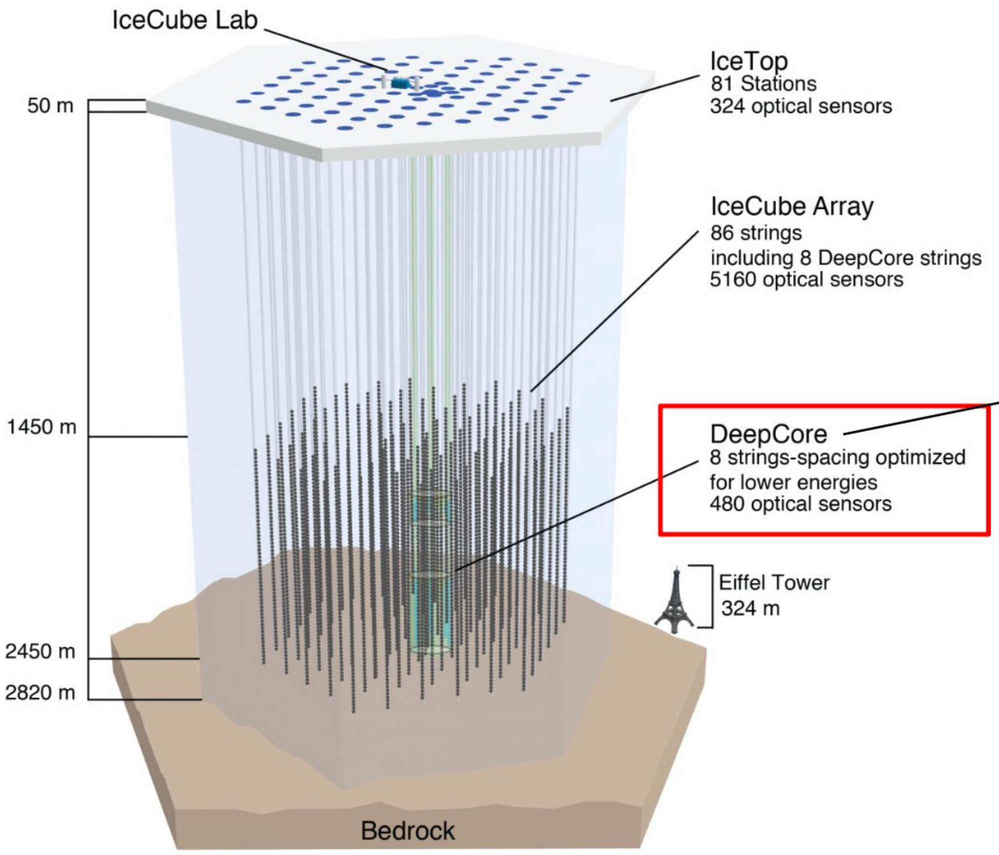
σ

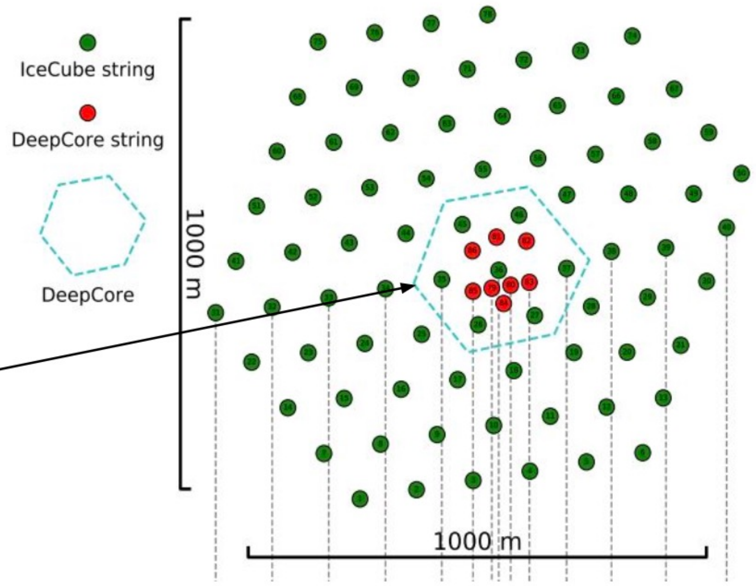
millibarn (mb)

(1 mb = 10^{-27} cm^2)

probability of interaction increases with energy

IceCube-DeepCore Neutrino Telescope





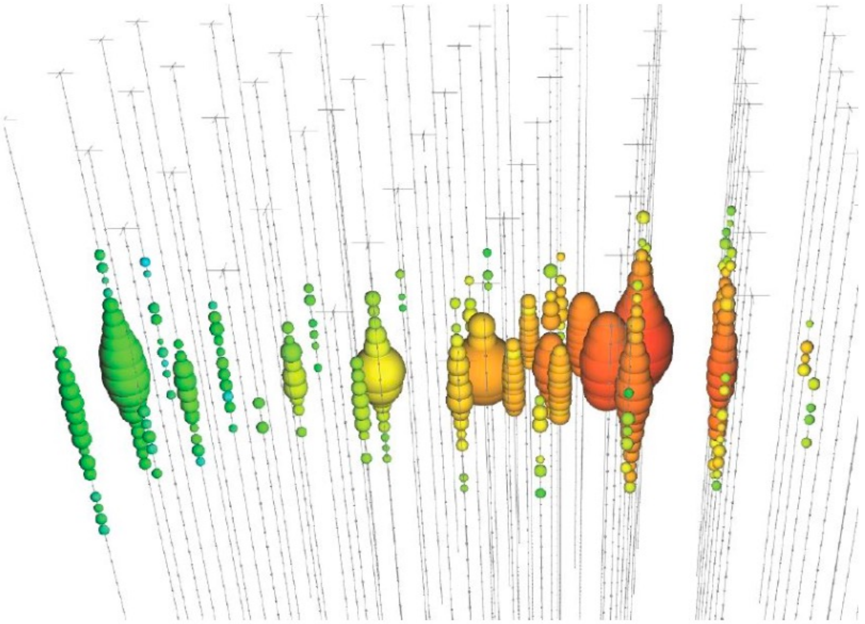
DeepCore

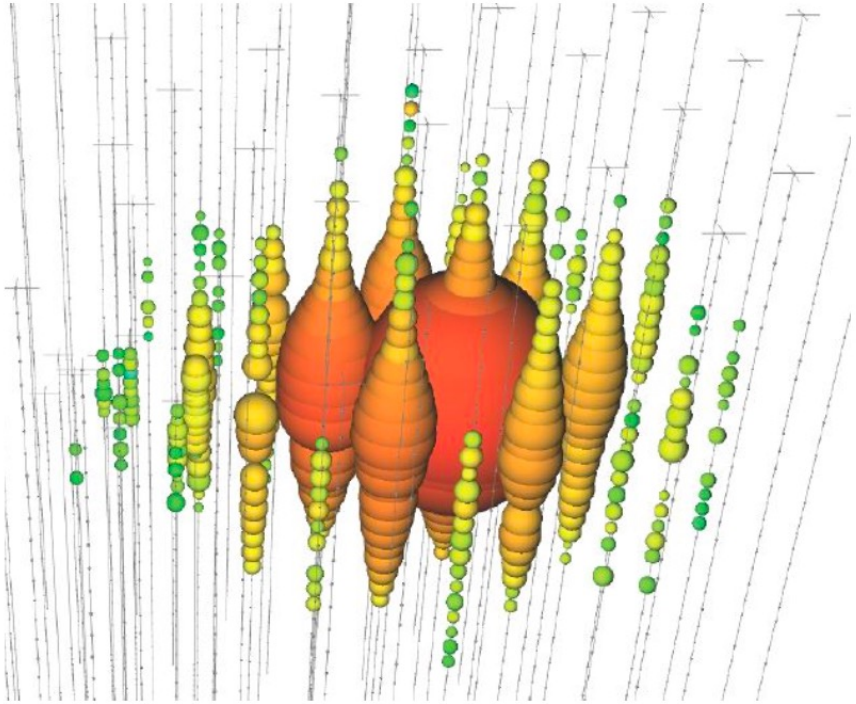
- 8 dedicated strings with denser spacing
- Optimized for GeV scale neutrinos
- Uses IceCube as VETO
- Fiducial volume ~ 10 Mton

Ref. : The design and performance of IceCube DeepCore (2012) **Astroparticle Physics, 35(10), 615-624 (2012)**

Track-like (muon neutrino)

Cascade-like (electron, tau neutrino, NC)



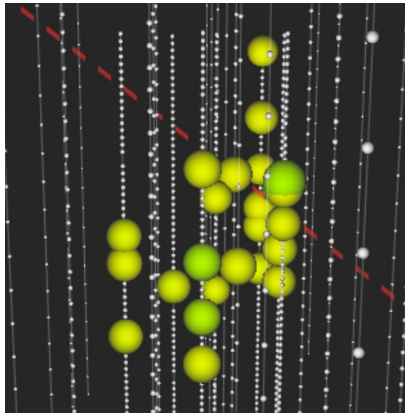


IceCube

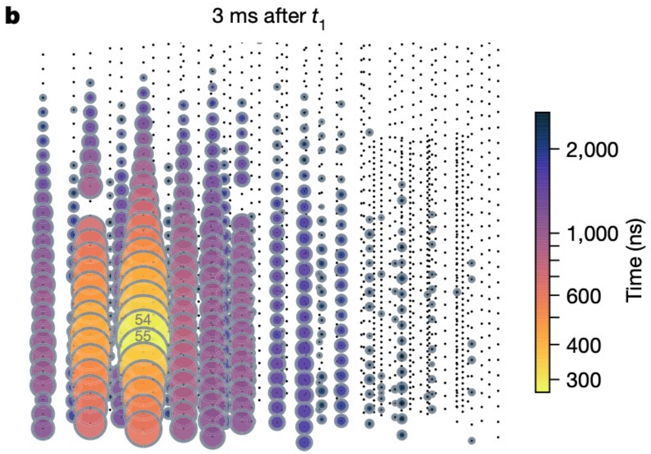
late ← early

Agarwal, Koskinen

4 GeV upgoing ν_μ



Deep Core with Upgrade

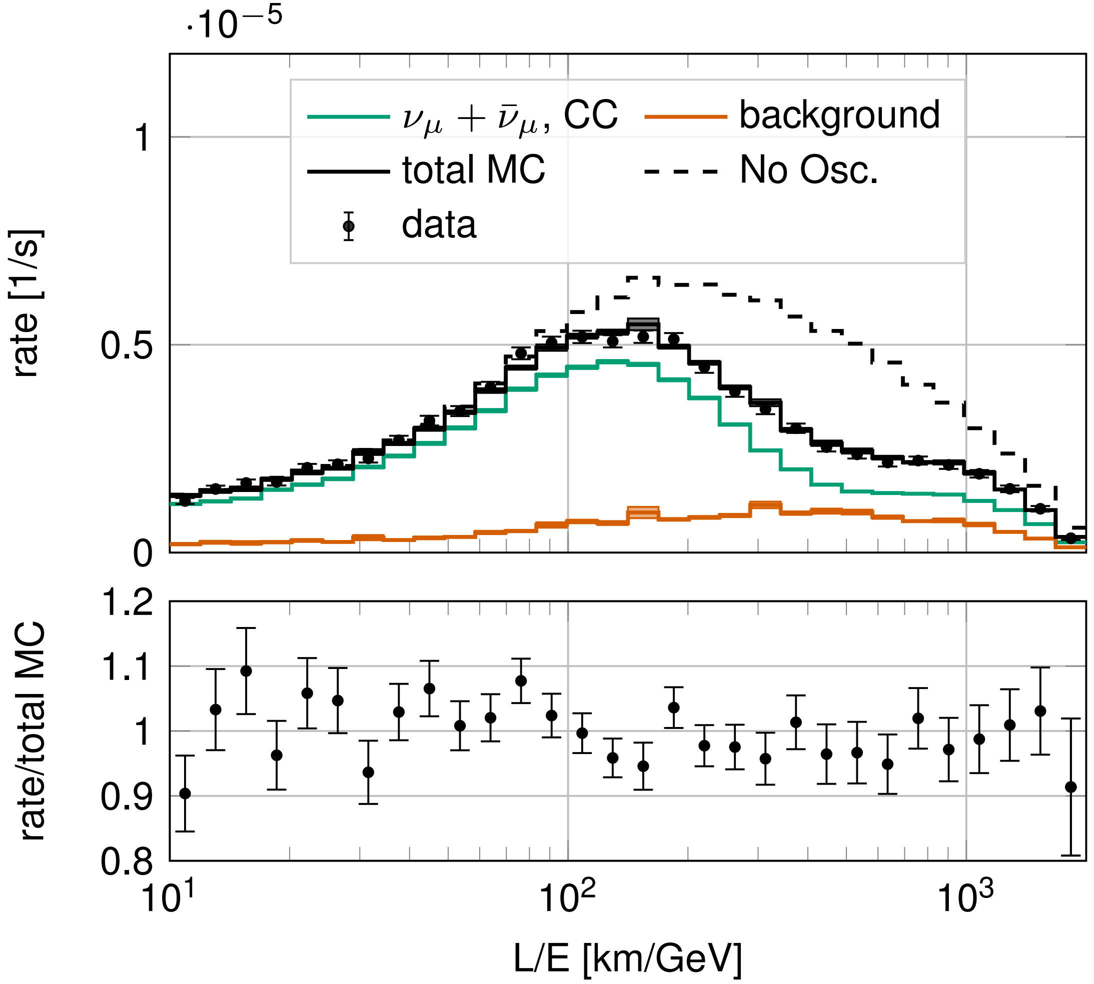


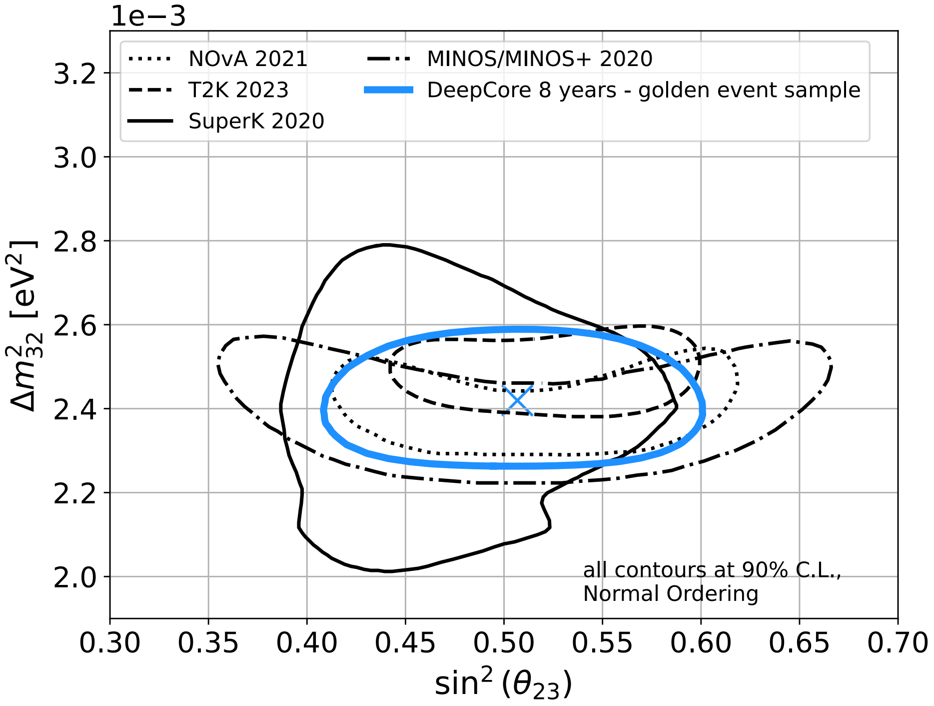
Glashow resonance event

https://arxiv.org/abs/2304.12236

IceCube DeepCore 2023 Golden Sample

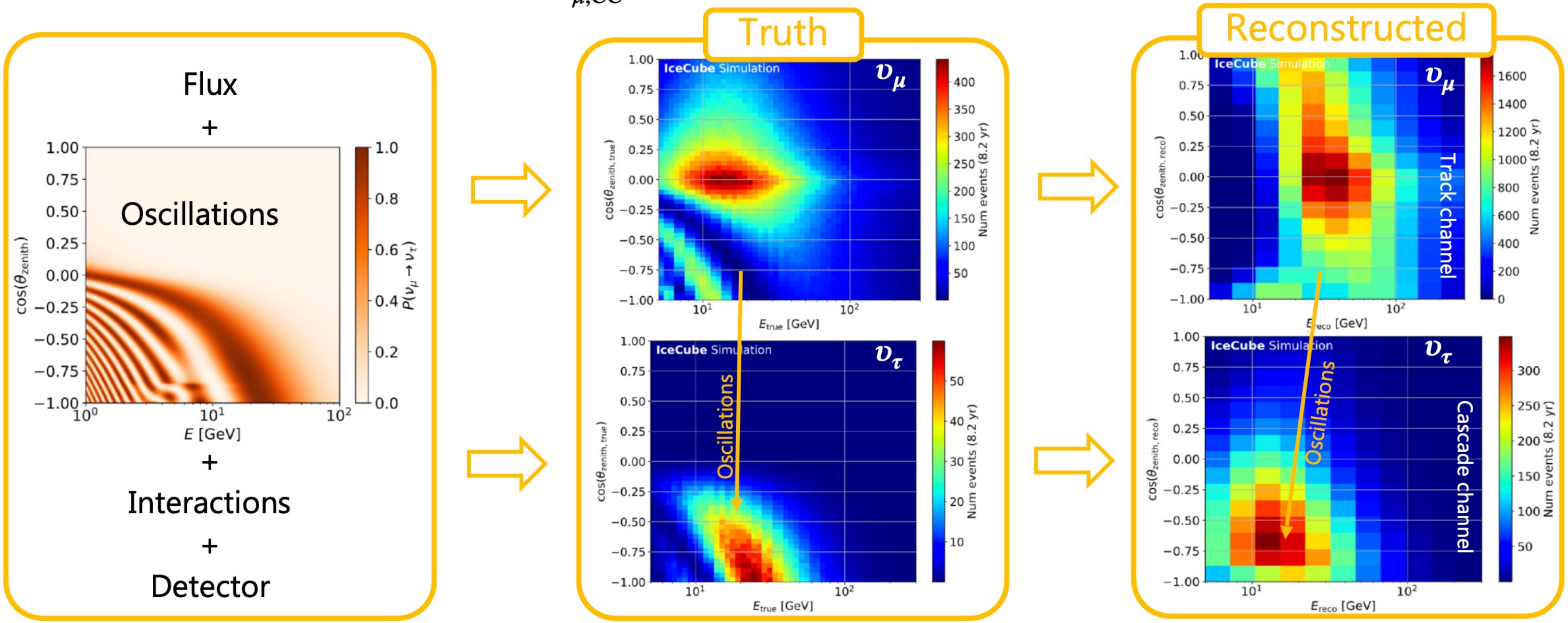
23000 events (10% of full data set)





Enormous statistics: hope to take real oscillogram

- Measure 3D distortions in reconstructed [energy, zenith, particle type]
  - Robust against systematic uncertainties
  - Particle identification discriminates $\nu_{\mu,CC}$ interactions vs all other flavors/channels



Koskinen - TeVPA 2022

Koskinen

Thanks for all your attention and questions!