Physics in Collision 2019

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Atmospheric Neutrino

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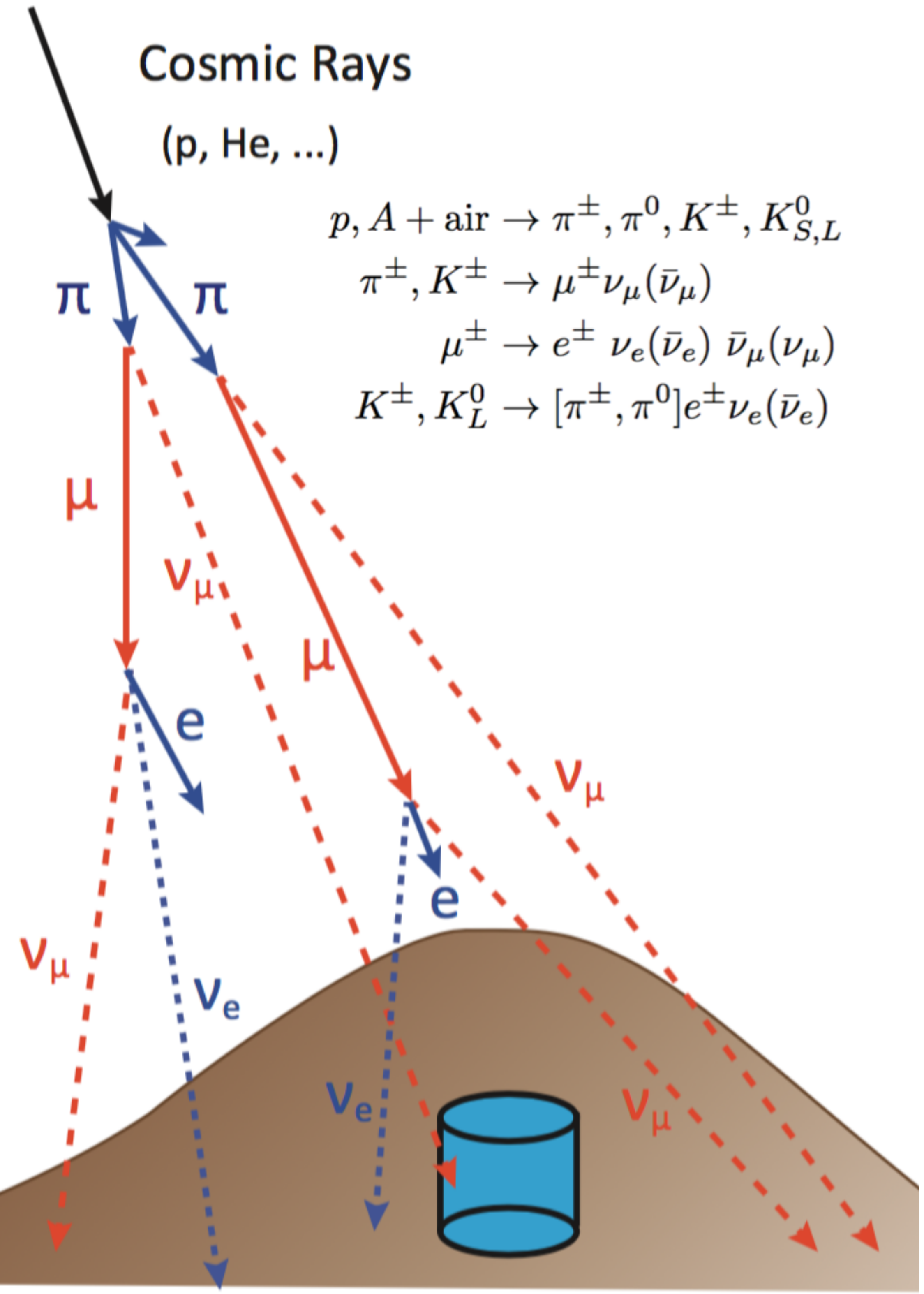
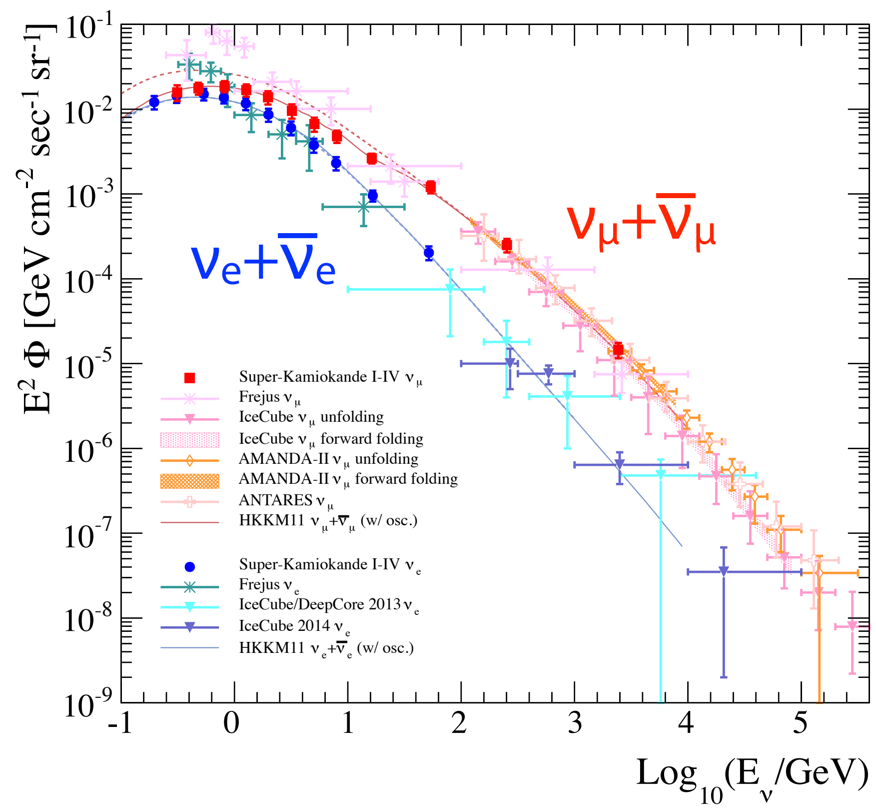
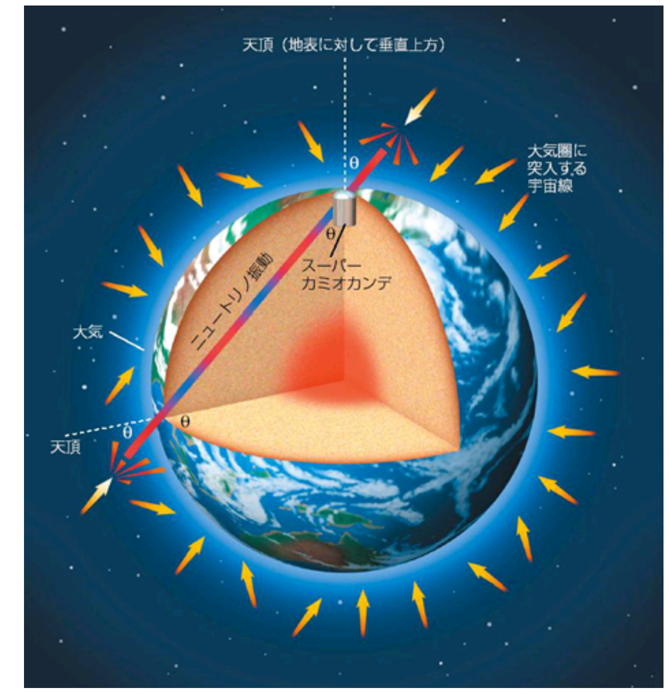
Atmospheric Neutrinos

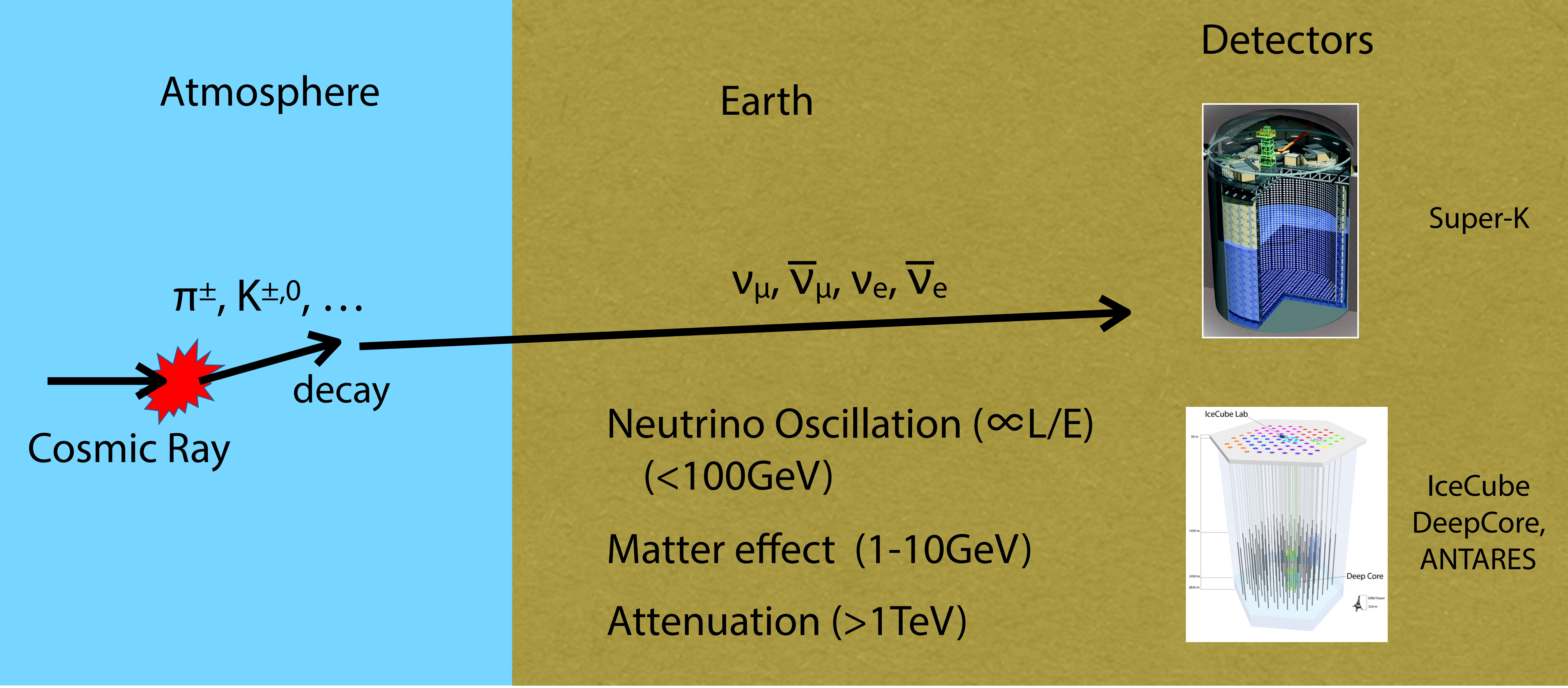


$$p, A + \mathrm{air} \to \pi^{\pm}, \pi^{0}, K^{\pm}, K^{0}_{S,L}$$
$$\pi^{\pm}, K^{\pm} \to \mu^{\pm}\nu_{\mu}(\bar{\nu}_{\mu})$$
$$\mu^{\pm} \to e^{\pm}\ \nu_{e}(\bar{\nu}_{e})\ \bar{\nu}_{\mu}(\nu_{\mu})$$
$$K^{\pm}, K^{0}_{L} \to [\pi^{\pm}, \pi^{0}]e^{\pm}\nu_{e}(\bar{\nu}_{e})$$





- Decay products of secondaries by cosmic ray interactions with atmosphere. ($\nu_\mu : \nu_e \sim 2 : 1$)
- Energy spectrum: power-law like ($\sim E^{-3.7}$), ranges from sub-GeV to ~100 TeV
- Cutoff by geomagnetic field below 1 GeV.
- Path length: distributed in O(10)km ~ 13,000km depending on zenith angle



GeV < E < TeV:

Oscillation physics

- Mass hierarchy
- Tau appearance
- Sterile search

E > TeV:

Test of SM in TeV

- Neutrino cross section
- Inelasticity
- Glashow resonance

Many physics opportunities

Neutrino Oscillation Physics

PMNS matrix:

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 1 & 0 \end{pmatrix}$$

Atmospheric, LBL

$$\Delta m^2_{32} \simeq 2.4 \times 10^{-3} \mathrm{eV}^2$$

$$\sin^2\theta_{23} = 0.4 \sim 0.6$$

Reactor, LBL

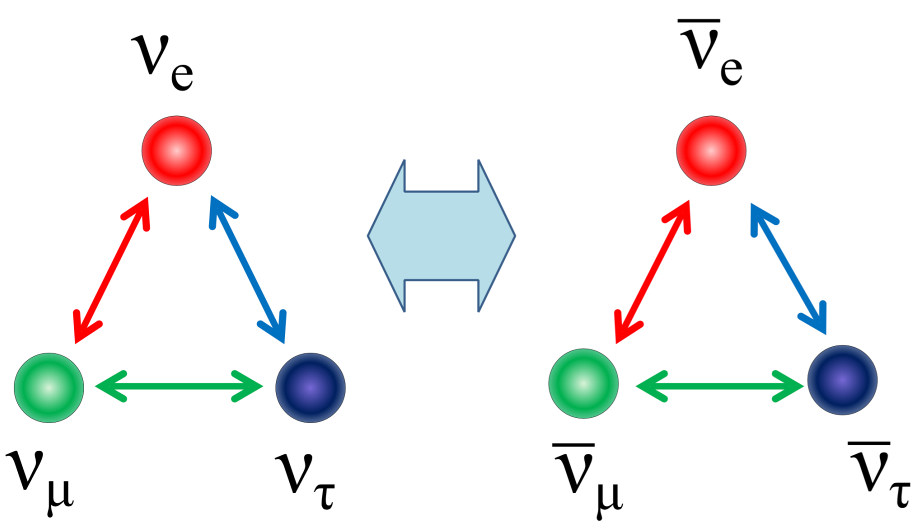
$$\sin^2\theta_{13} \simeq 0.021$$

Solar, KamLAND

$$\Delta m^2_{21} \simeq 7.5 \times 10^{-5} \mathrm{eV}^2$$

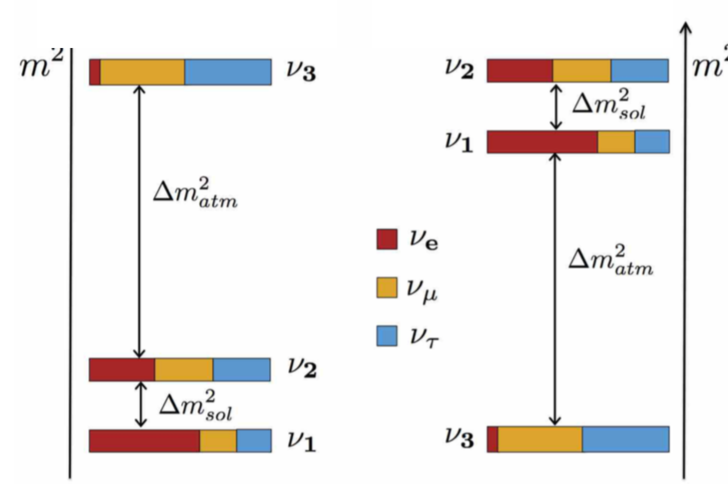
$$\sin^2\theta_{12} \simeq 0.30$$

Open question:

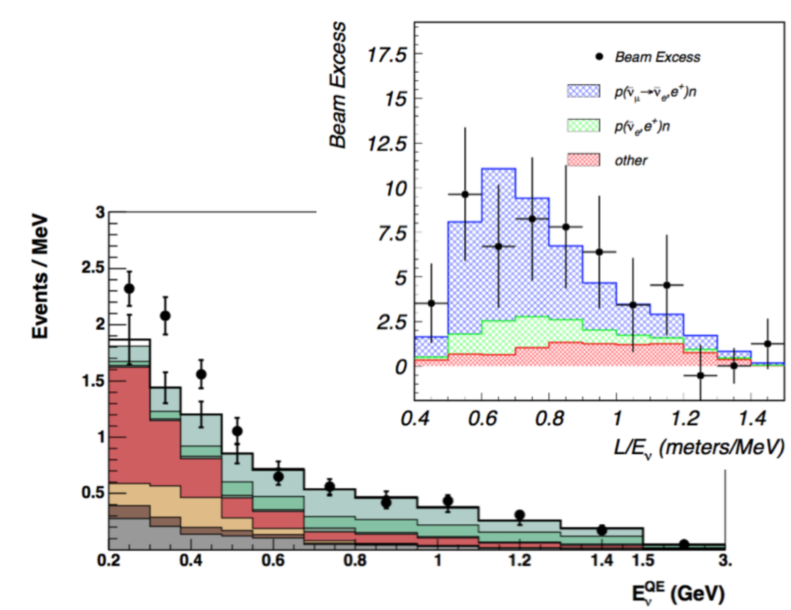


Leptonic CP (δ_{CP})

Normal ($\Delta m^2_{32}>0$)   Inverted ($\Delta m^2_{32}<0$)



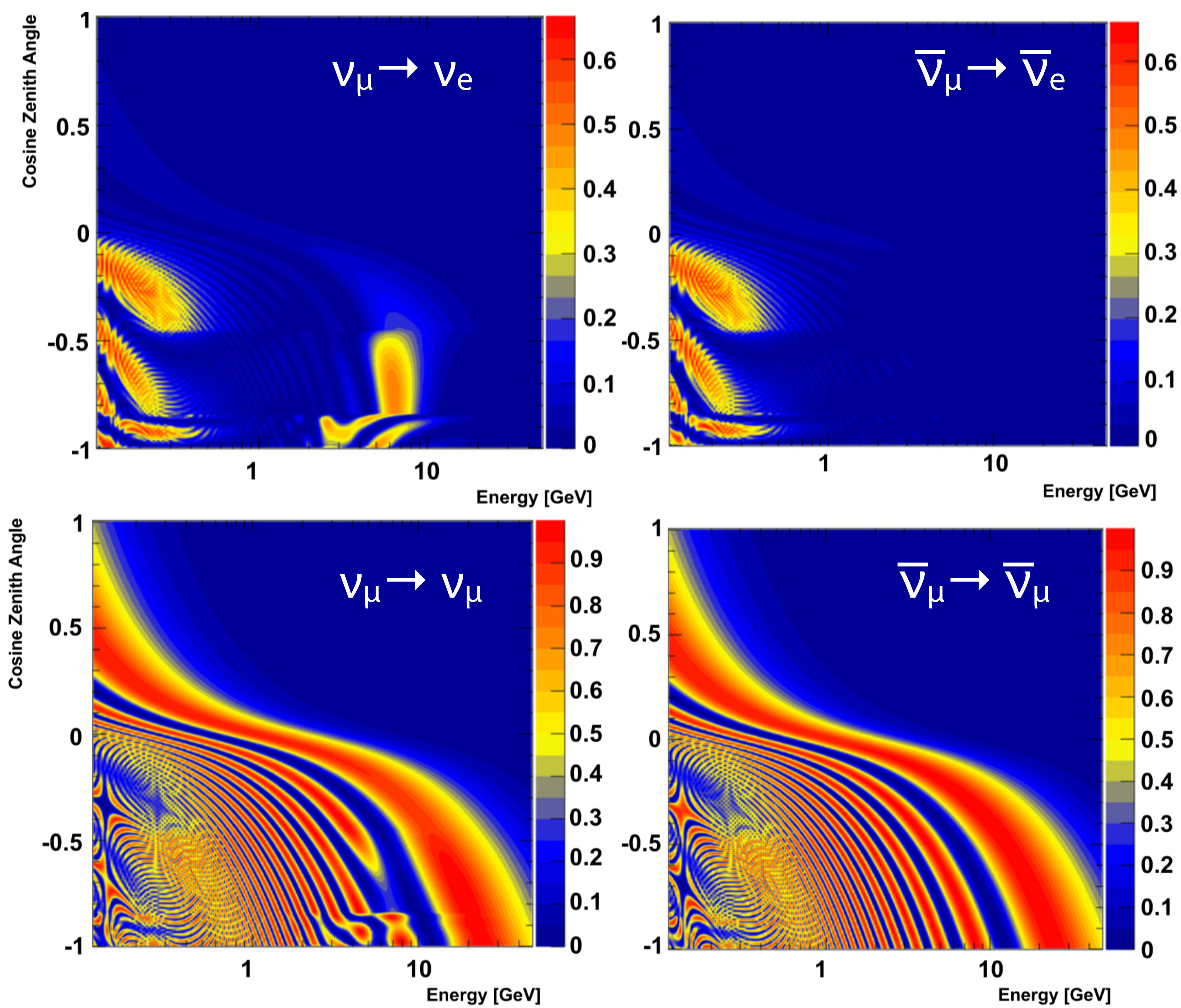
Mass Hierarchy
(Mass Ordering)



Sterile

Matter Effect and Mass Hierarchy

Normal hierarchy ($\Delta m^2_{32}>0$)



- Neutrino propagating in matter affected by additional potential of forward scattering with electron
- Effective mixing angle changes
- Resonance takes place in multi-GeV energy
- Only for neutrino for normal hierarchy

Effective mixing angle in matter:

$$\sin 2\theta_{13}^M = \frac{\sin 2\theta_{13}}{\sqrt{\left(\frac{A}{\Delta m^2_{32}} - \cos 2\theta_{13}\right)^2 + \sin^2 2\theta_{13}}}$$

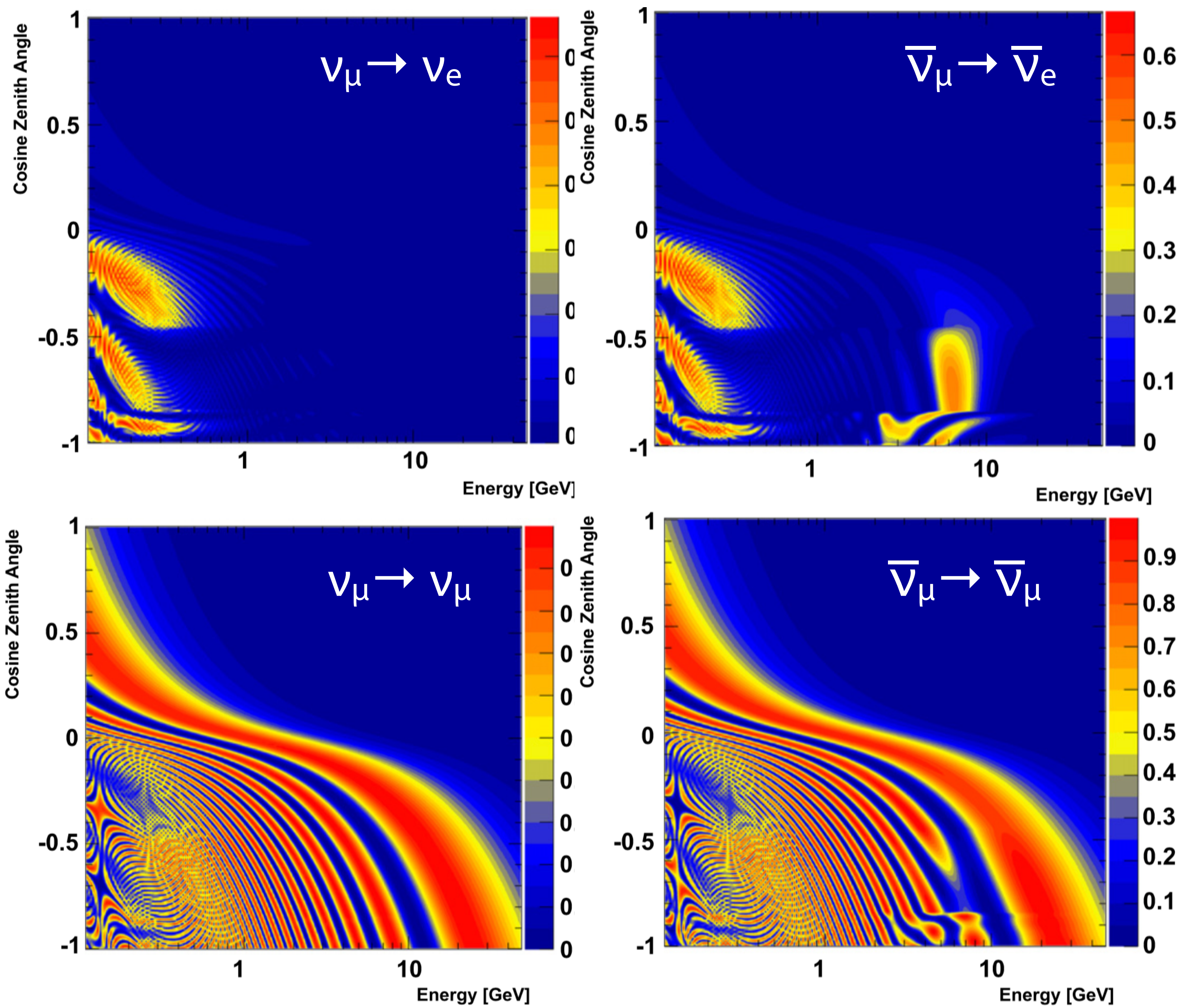
$$A = \pm 2\sqrt{2} G_F E_\nu n_e$$

Resonance condition:

$$A \sim \Delta m^2_{32} \cos 2\theta_{13} \quad \rightarrow \quad \theta_{13}^M \gg \theta_{13}$$

Matter Effect and Mass Hierarchy

Inverted hierarchy ($\Delta m^2_{32}<0$)



- Neutrino propagating in matter affected by additional potential of forward scattering with electron
- Effective mixing angle changes
- Resonance takes place in multi-GeV energy
- Only for anti-neutrino for inverted hierarchy

Effective mixing angle in matter:

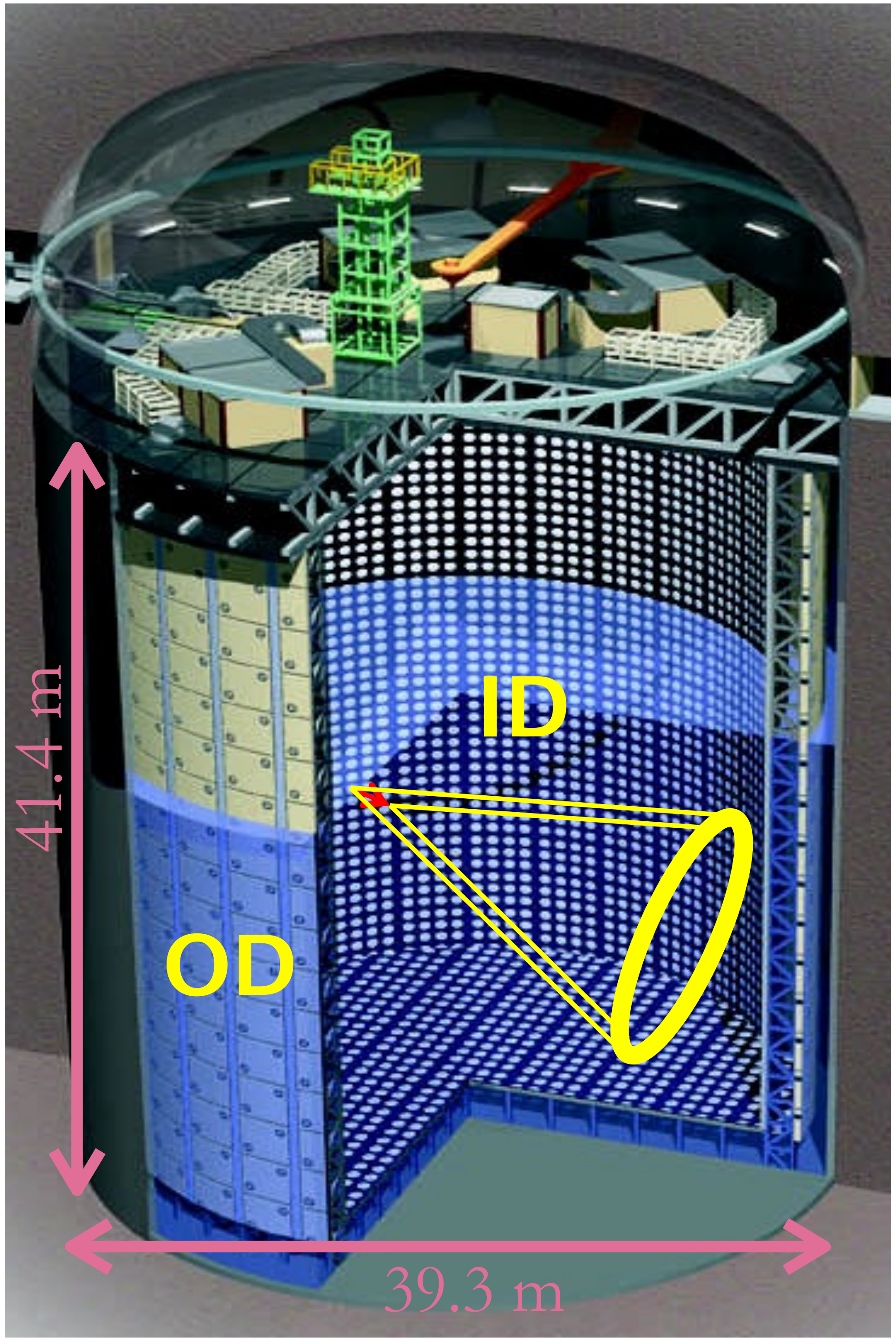
$$\sin 2\theta_{13}^M = \frac{\sin 2\theta_{13}}{\sqrt{\left(\frac{A}{\Delta m^2_{32}} - \cos 2\theta_{13}\right)^2 + \sin^2 2\theta_{13}}}$$

$$A = \pm 2\sqrt{2} G_F E_\nu n_e$$

Resonance condition:

$$A \sim \Delta m^2_{32} \cos 2\theta_{13} \quad \rightarrow \quad \theta_{13}^M \gg \theta_{13}$$

Super-Kamiokande Detector

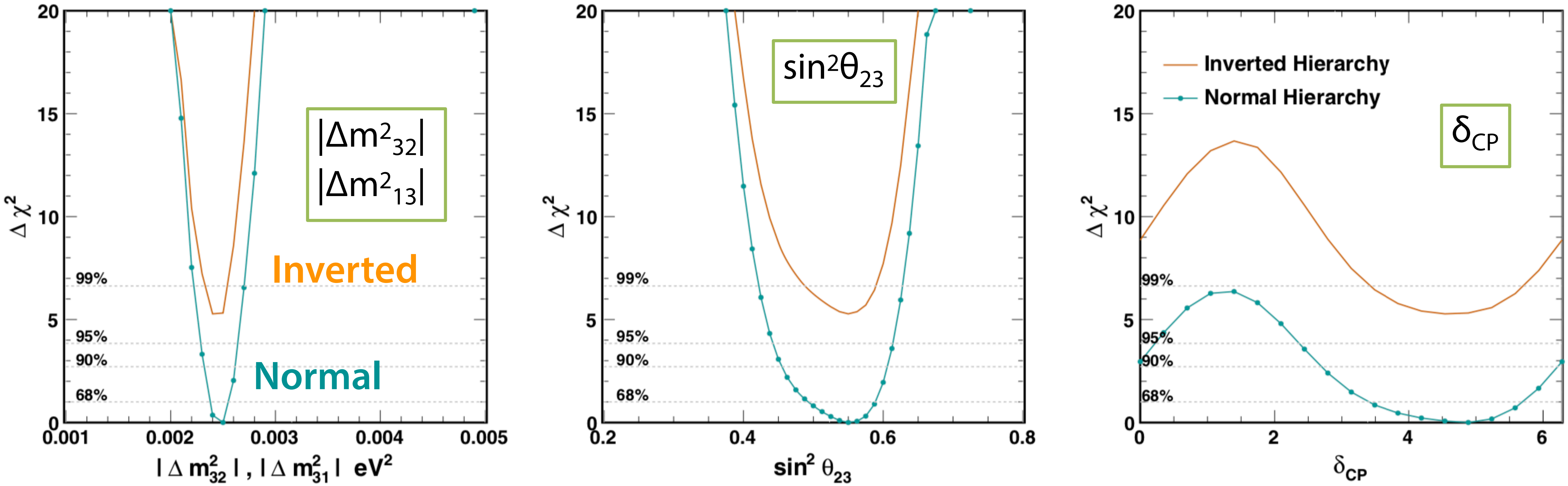


- Water Cherenkov imaging detector
- 1000 m underground in Kamioka mine
- 50 kton volume (fiducial 22.5 kton)
- ~11100 20" PMTs in inner detector (ID) for Cherenkov ring imaging
- ~1800 8" PMTs for outer detector (OD)

Phase	Period	# of PMTs
SK-I	1996.4 ~ 2001.7	11146 (40%)
SK-II	2002.10 ~ 2005.10	5182 (20%)
SK-III	2006.7 ~ 2008.8	11129 (40%)
SK-IV	2008.9 ~ 2018.5	
SK-V	2019.4 ~	

Oscillation fit with reactor and T2K model

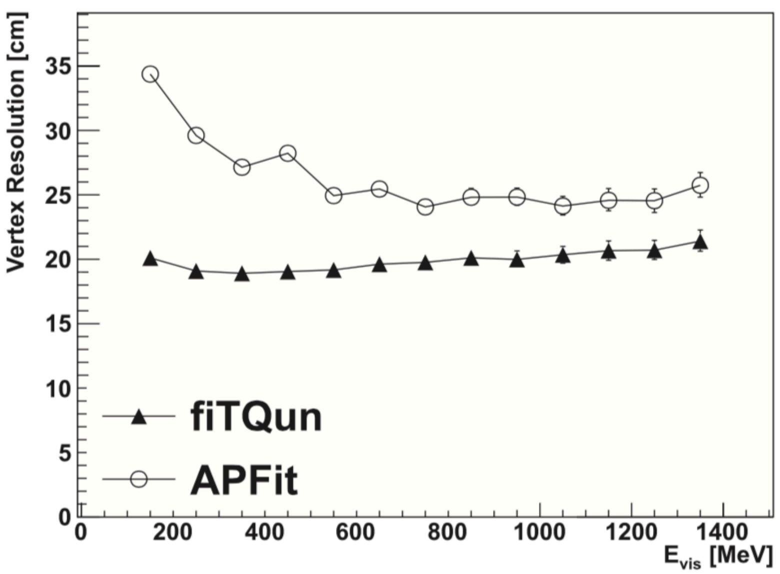
PRD 97, 072001 (2018)



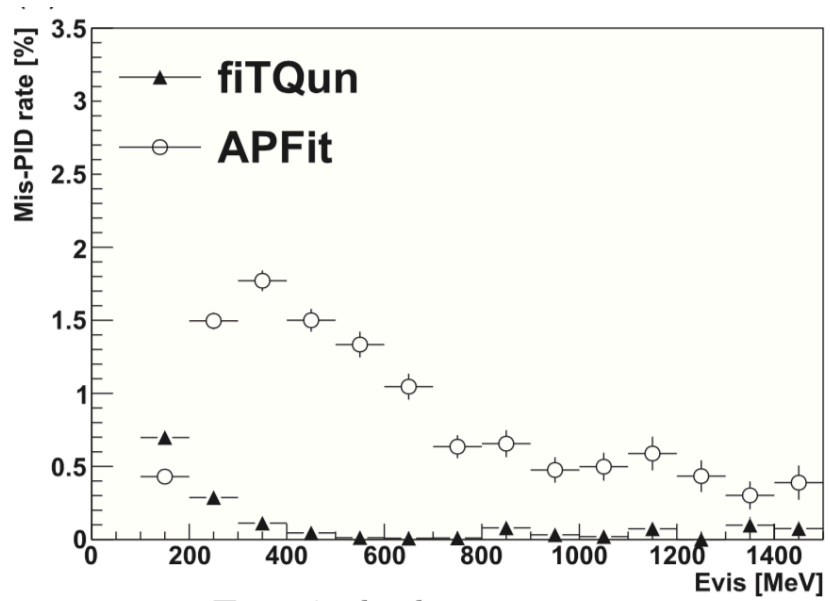
- Full 3-flavor fit performed with reactor θ_{13} and T2K constraints
- T2K data gives stronger constrain on Δm^2 and θ_{23}, improving mass hierarchy sensitivity
- Normal hierarchy is preferred:
  $\Delta\chi^2 = \chi^2_{NH} - \chi^2_{IH} = -5.27$
- p-value of true IH is 0.023

	$\lvert\Delta m^2_{32}\rvert$	$\sin^2(\theta_{23})$	δ_{CP}
NH	2.5×10^{-3}	0.550	4.88
IH	2.4×10^{-3}	0.550	4.54

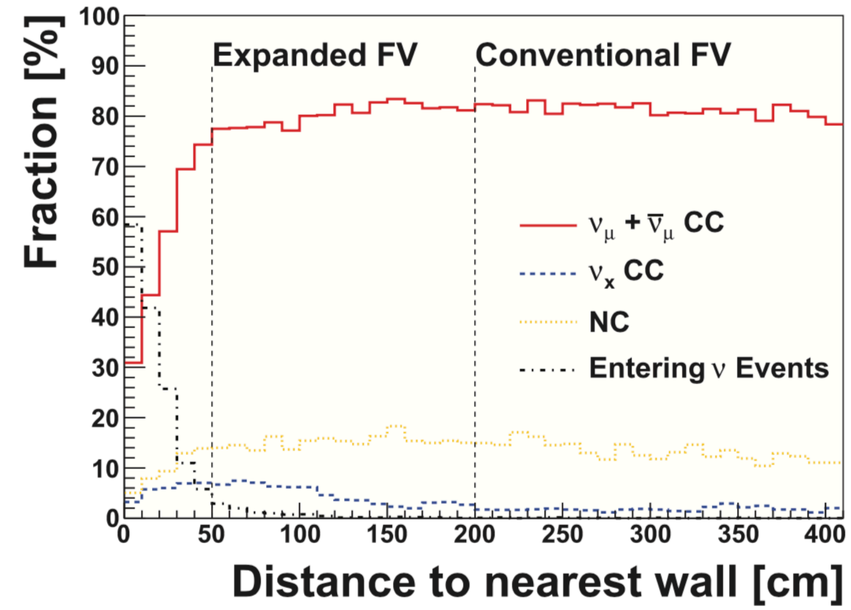
Recent Improvements in SK

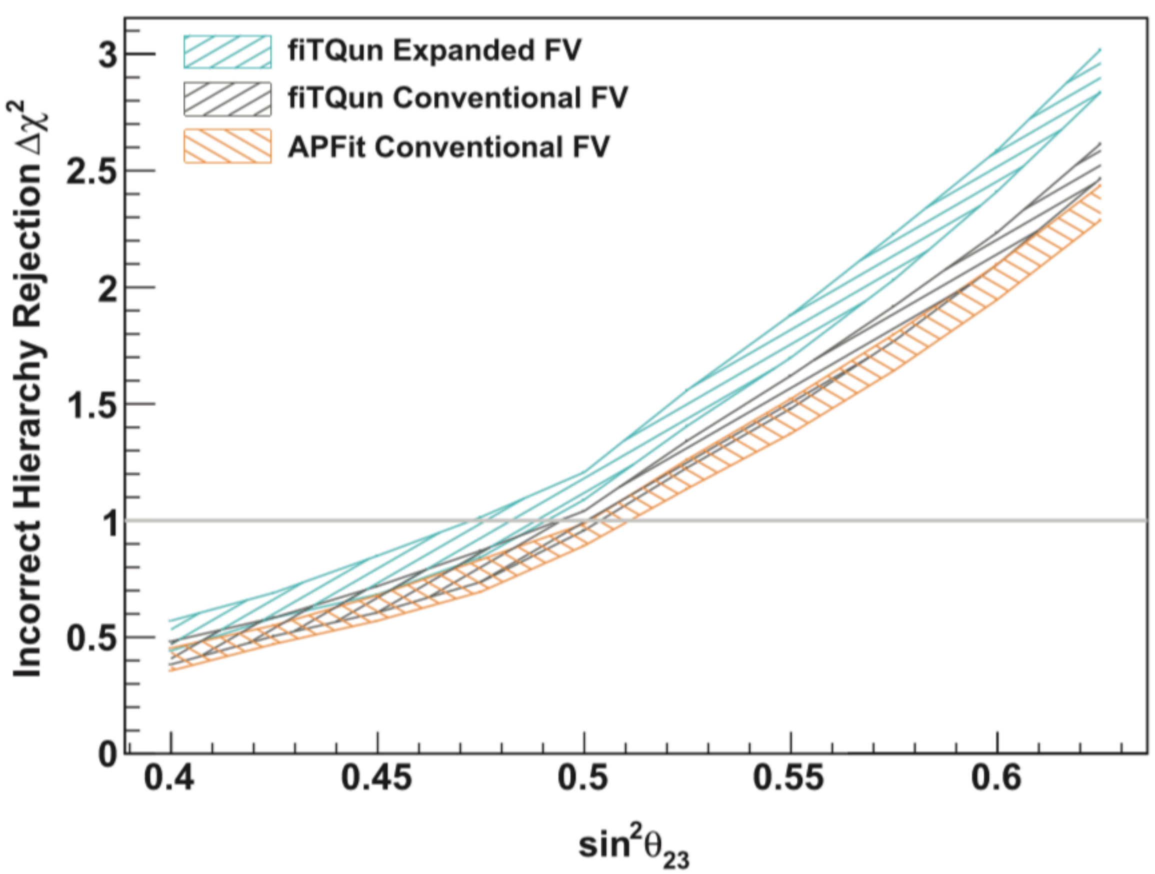


True electron event with single ring



True single-electron events.

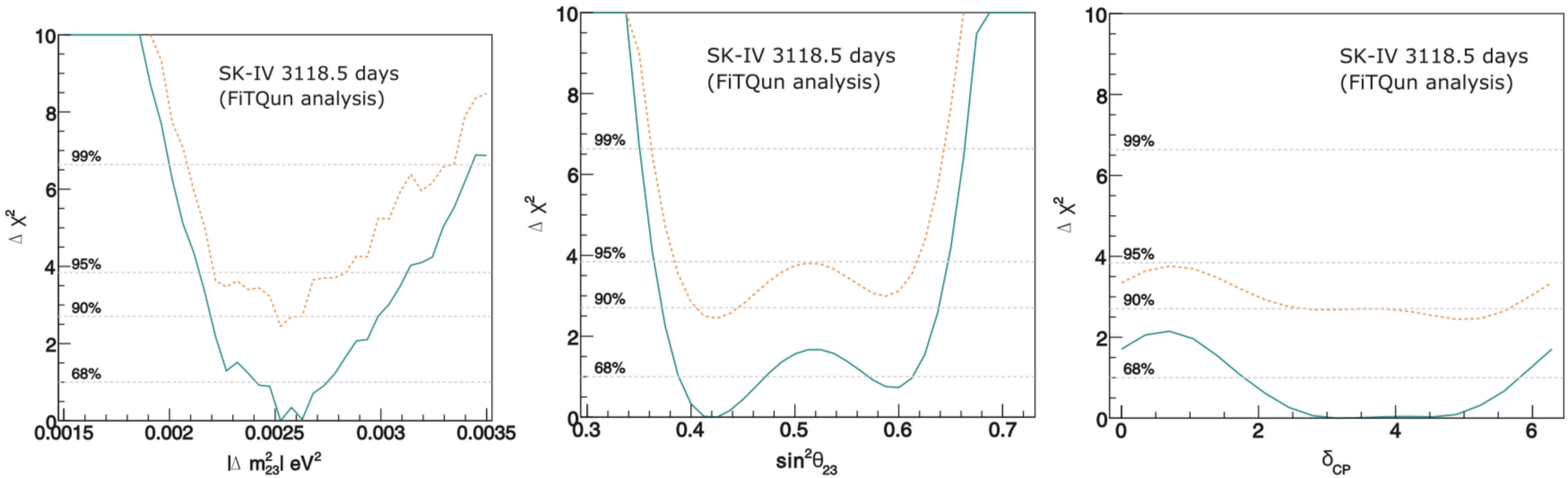




- Improved event reconstruction (vertex, energy, PID, etc) by new algorithm
- Fiducial volume extension (Dwall=2m 0.5m) : +30% increase in event rate
- Resulting better sensitivities in mass hierarchy

Result with New Reconstruction

Prog. Theor. Exp. Phys. 2019, 053F01

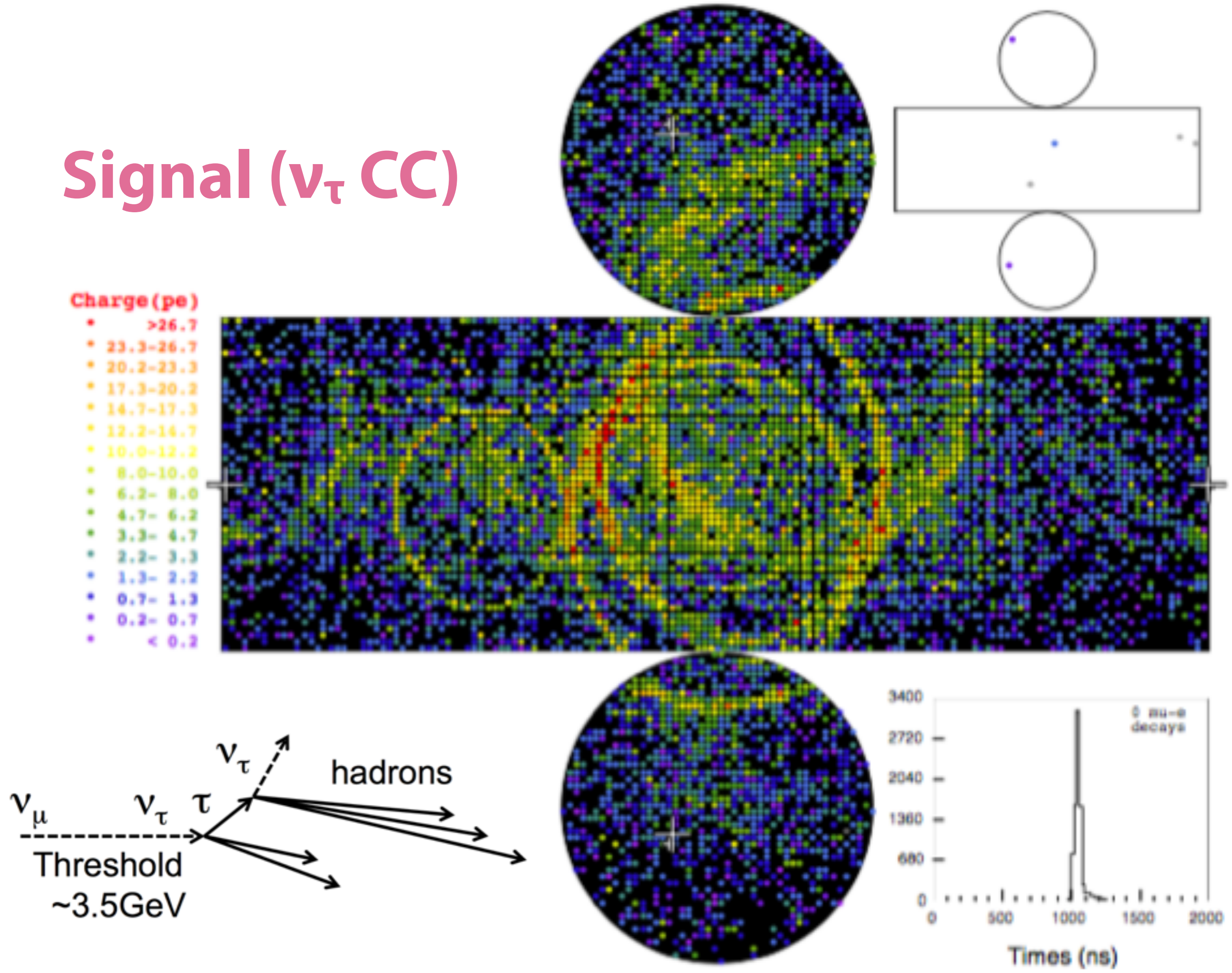


- SK-IV data only (3118.5 days of livetime) with reactor constraint
- Still normal hierarchy is preferred:
  $\Delta\chi^2 = \chi^2_{NH} - \chi^2_{IH} = -2.45$
- p-value for IH is 0.025 - 0.072 depending on true $\sin^2(\theta_{23})$=0.4-0.6

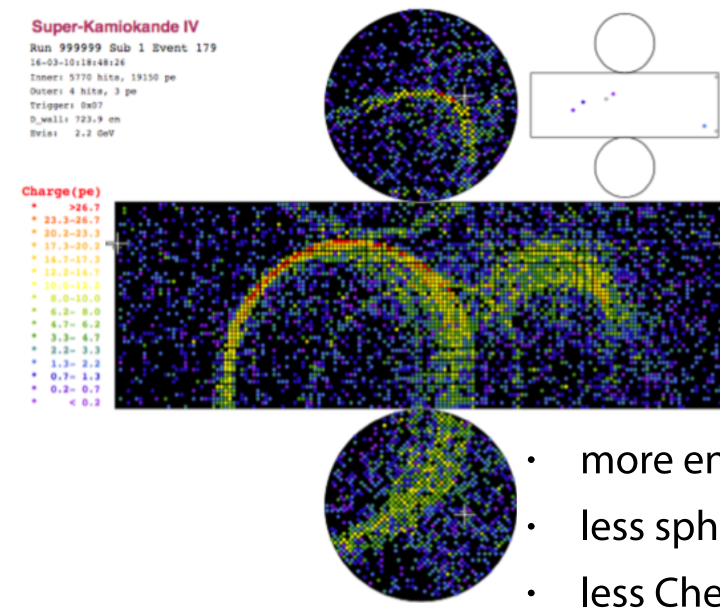
	$\lvert\Delta m^2_{32}\rvert$	$\sin^2(\theta_{23})$	δ_{CP}
NH	2.53×10^{-3}	0.425	3.14
IH	2.53×10^{-3}	0.425	4.89

Tau Appearance in SK

Signal (ν_τ CC)



Background (ν_μ CC)

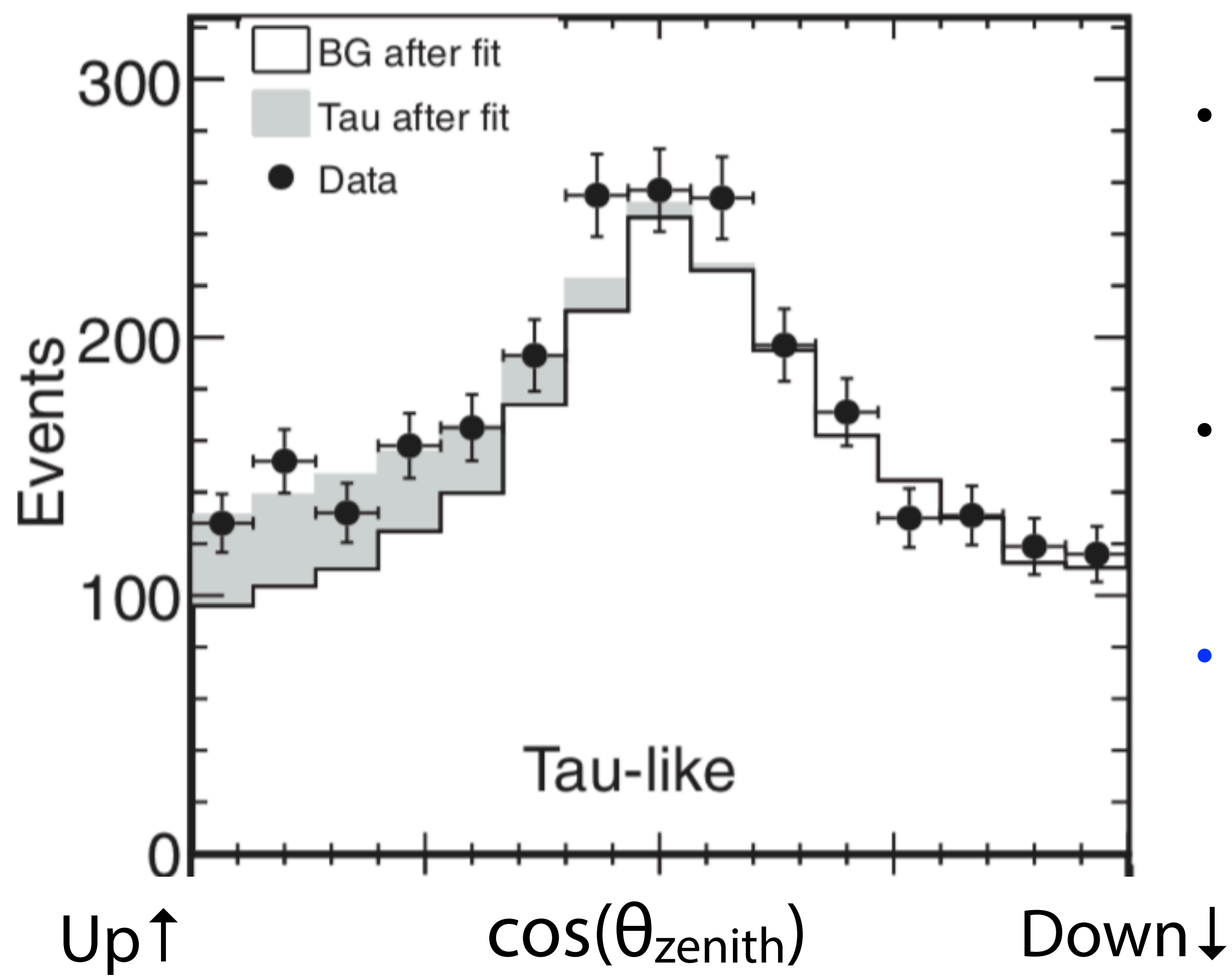


- more energy in 1st ring
- less sphericity
- less Cherenkov rings
- less mu-e decays
- …

- In the standard 3-flavor oscillation, ν_μ disappearance is explained by ν_μ -> ν_τ oscillation
- Direct detection of oscillated ν_τ is critical for verifying neutrino SM
- Aim to detect hadronic decay (branching ratio: 65%)
- Detection in SK is difficult: low signal rate (~1 event / kton year)
- Large backgrounds (ν_eCC, ν_μCC, NC)

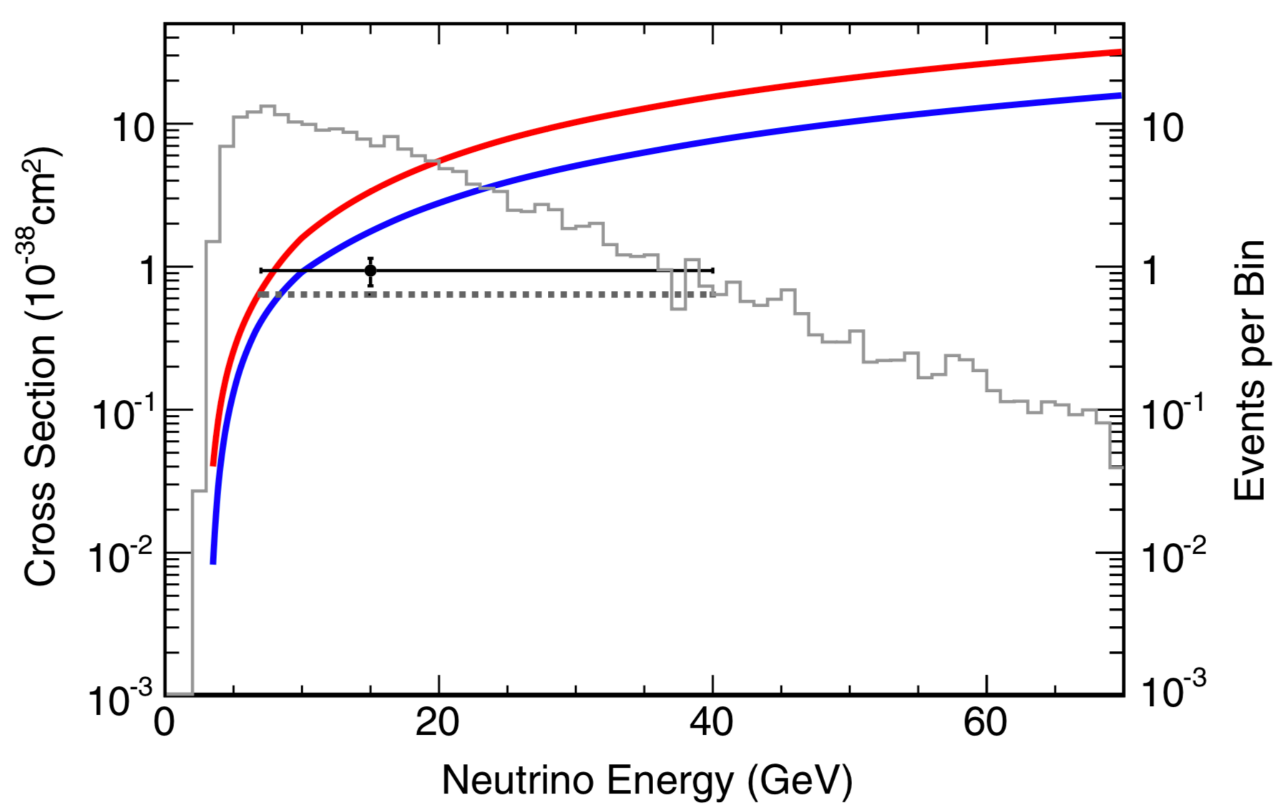
Tau Appearance in SK

PRD 98, 052006 (2018)



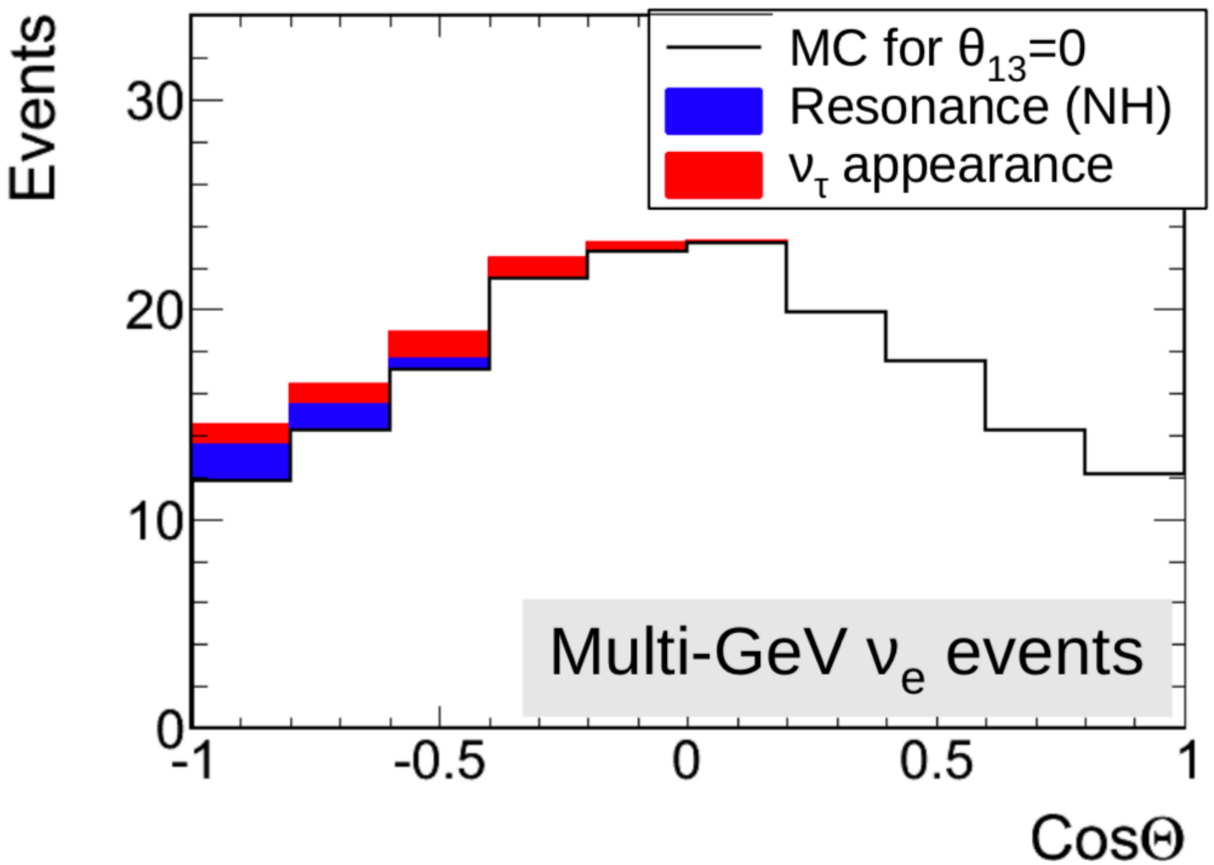
- Utilize neural network (NN) to discriminate tau signal using kinematical variables
- Expected to be appeared in upward direction
- Clear excess seen in final sample (4.6σ)

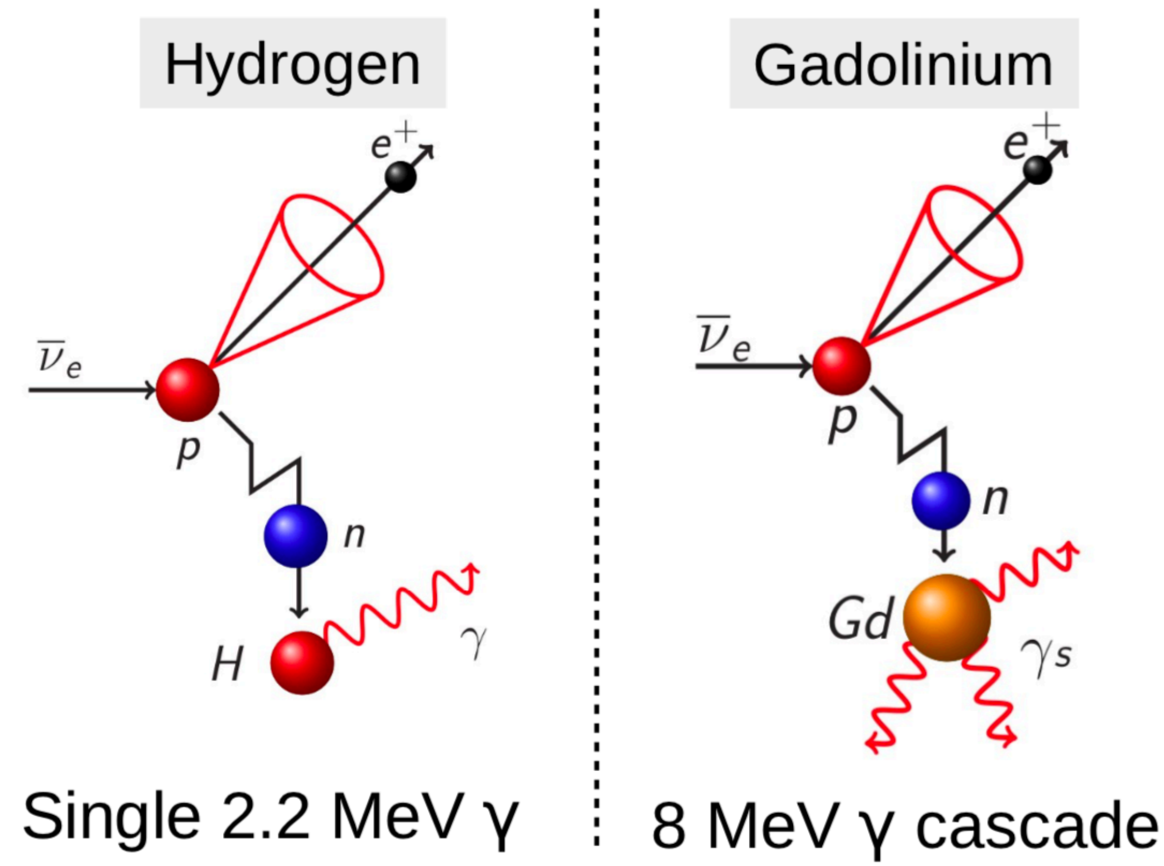
- Estimated cross section is 1.47 times larger compared to prediction
- Still consistent with SM within 1.5σ



Future Plan in SK

C. Bronner, NuFact 2019





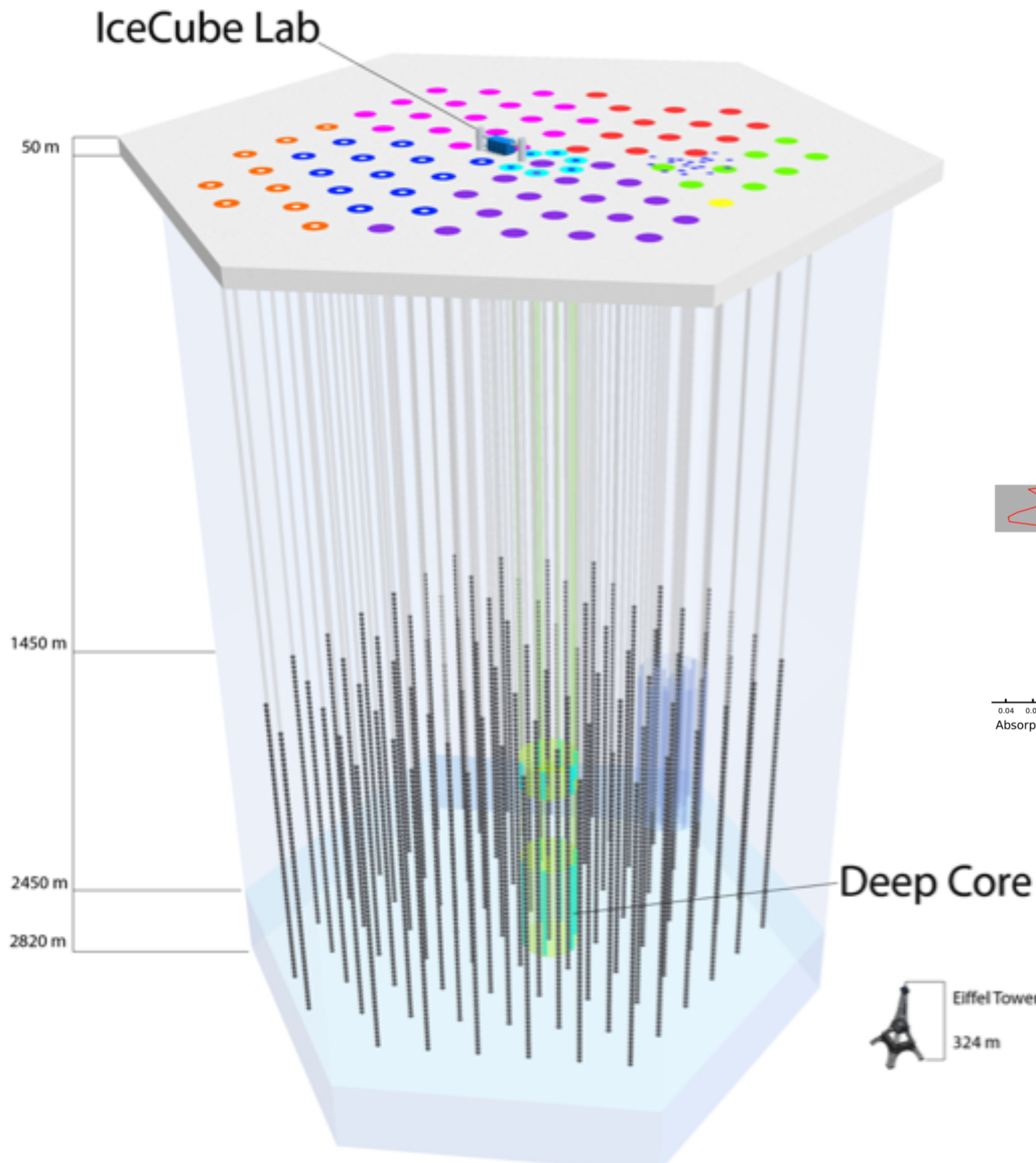
Use tau NN for oscillation analysis

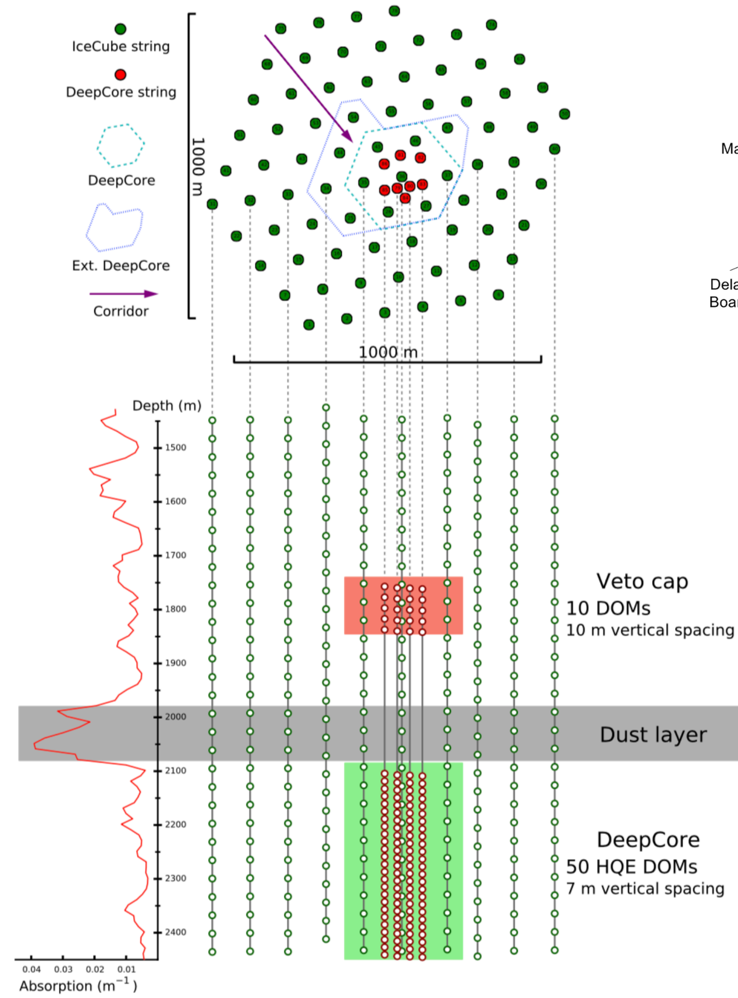
- ν_τ events could be background for mass hierarchy ν_e signal
- ν_τ cross section has 25% uncertainty
- Apply tau NN to mass hierarchy sample to isolate ν_τ background

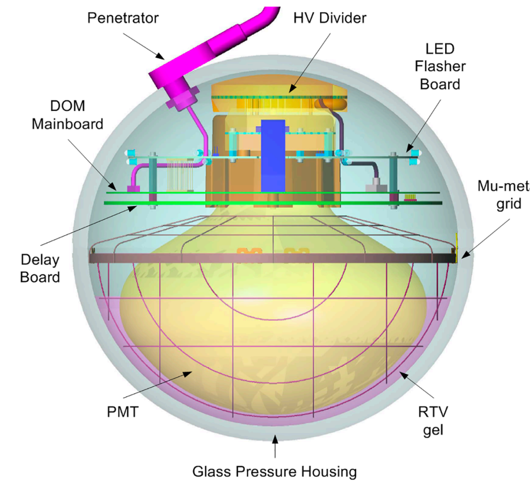
Neutron tagging in SK-Gd

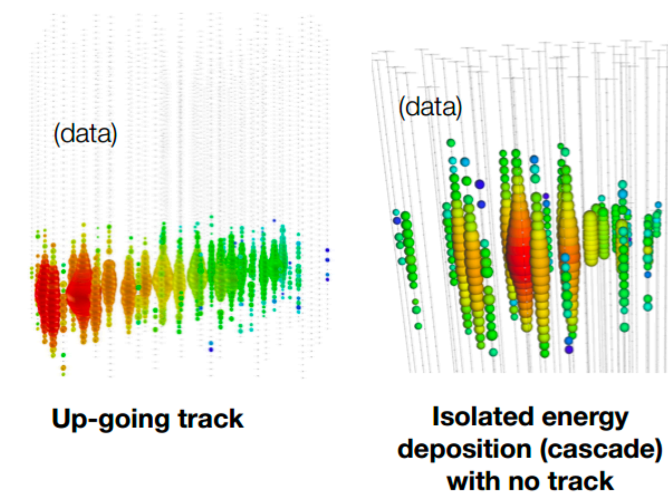
- 0.2% Gd will be dissolved in Super-K to enhance neutron detection (eff. ~ 80%)
- More statistical ν_e / $\overline{\nu}_e$ separation becomes possible, improving MH and δ_{CP} sensitivities

IceCube Experiment





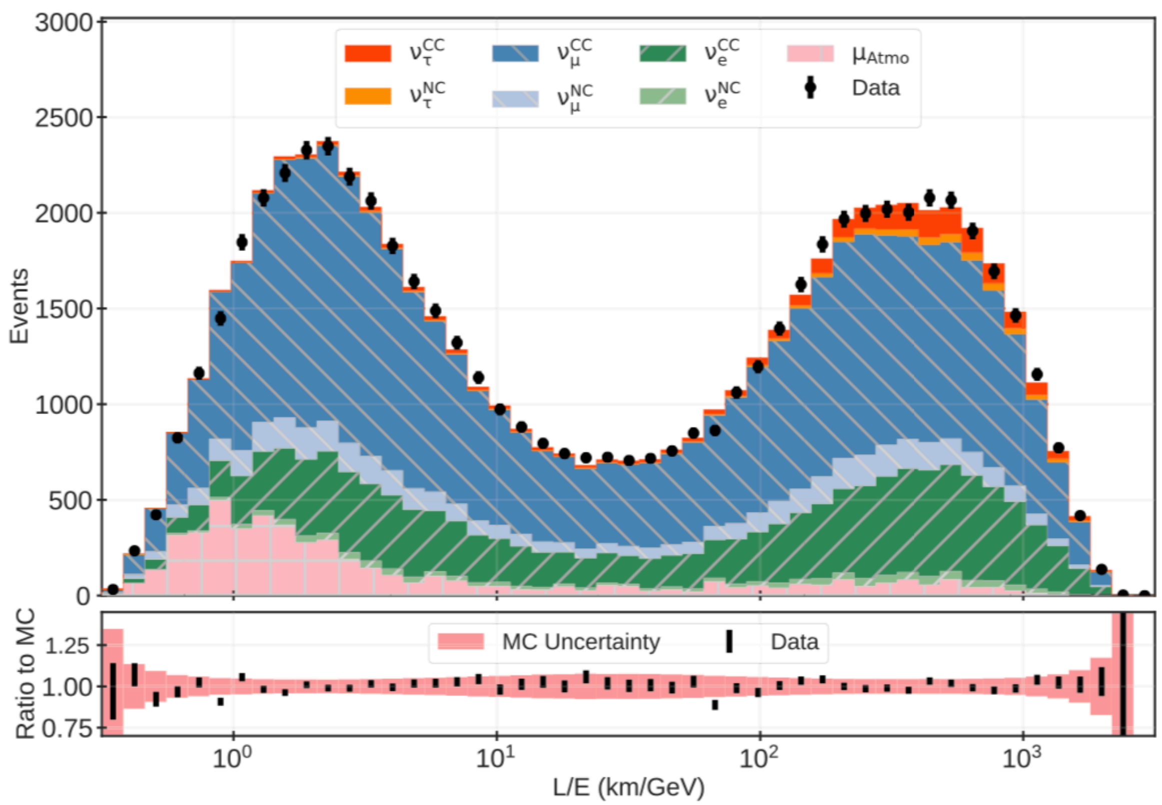


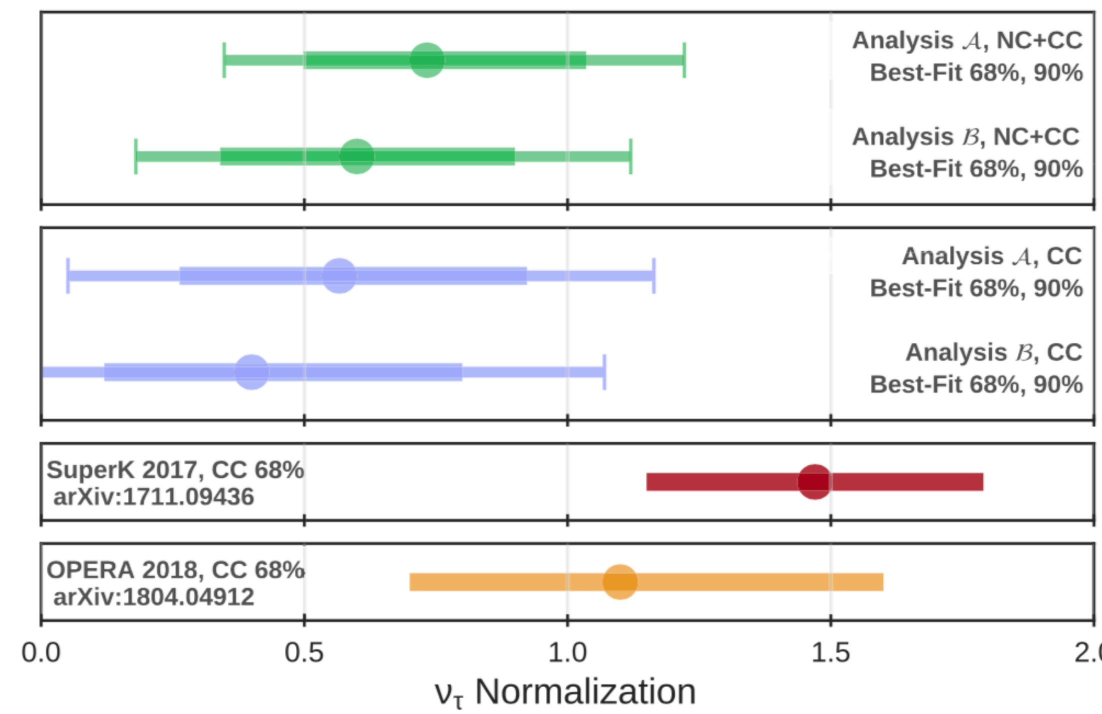


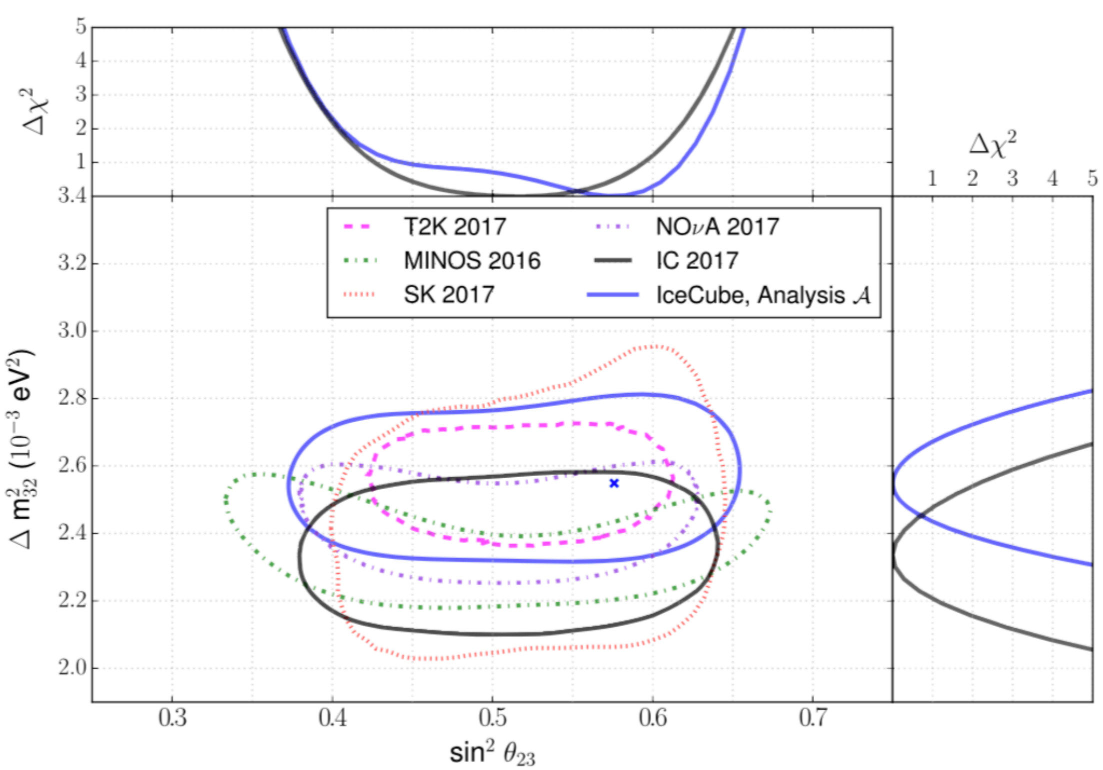
- IceCube: $\sim$1km^3 volume detector using natural ice in Antarctic
- DeepCore: extension for lower energies
- Event sample: track-like (CC ν_μ) and cascade-like (CC ν_e, NC)

IceCube Oscillation Results

PRD 99, 032007 (2019)

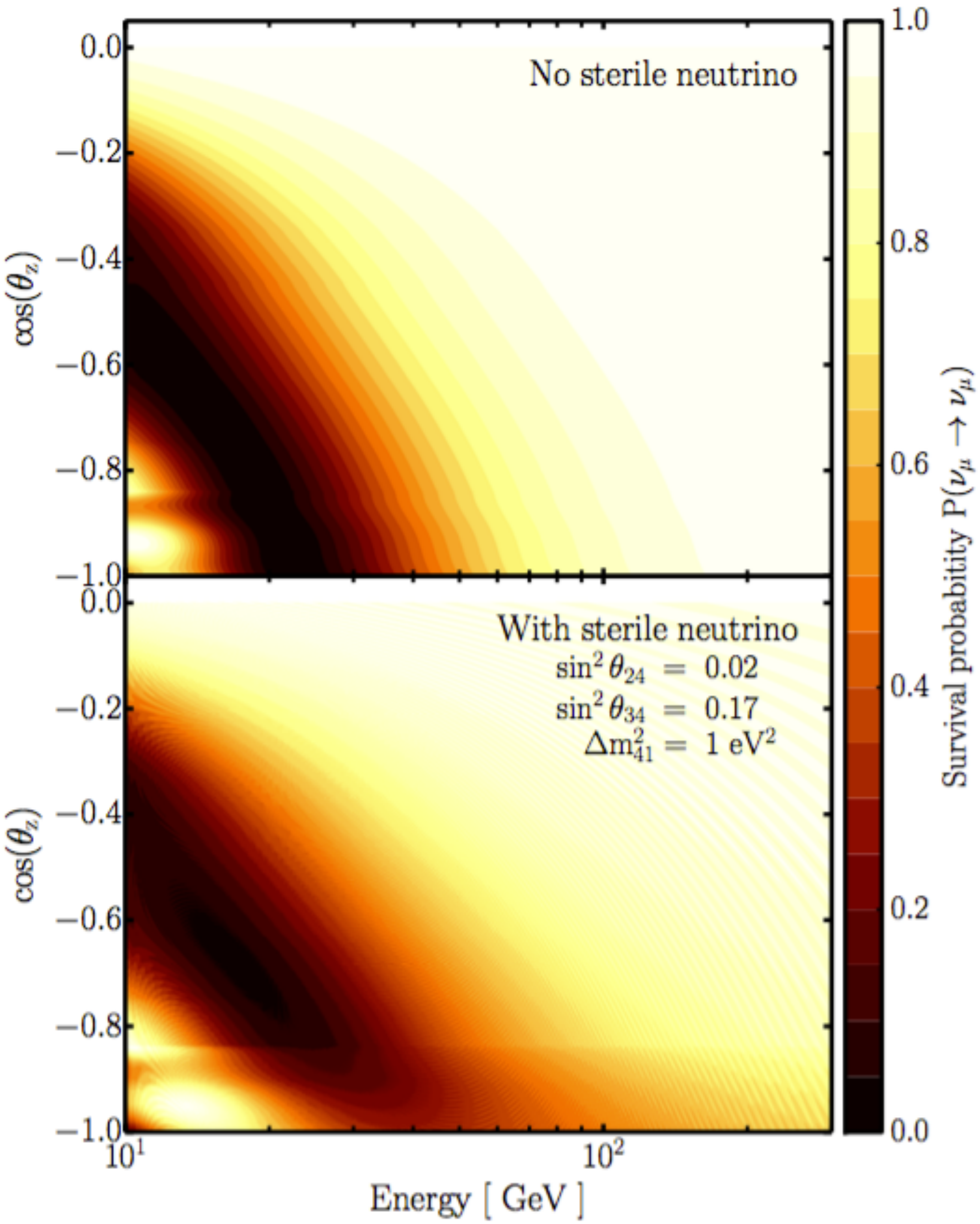


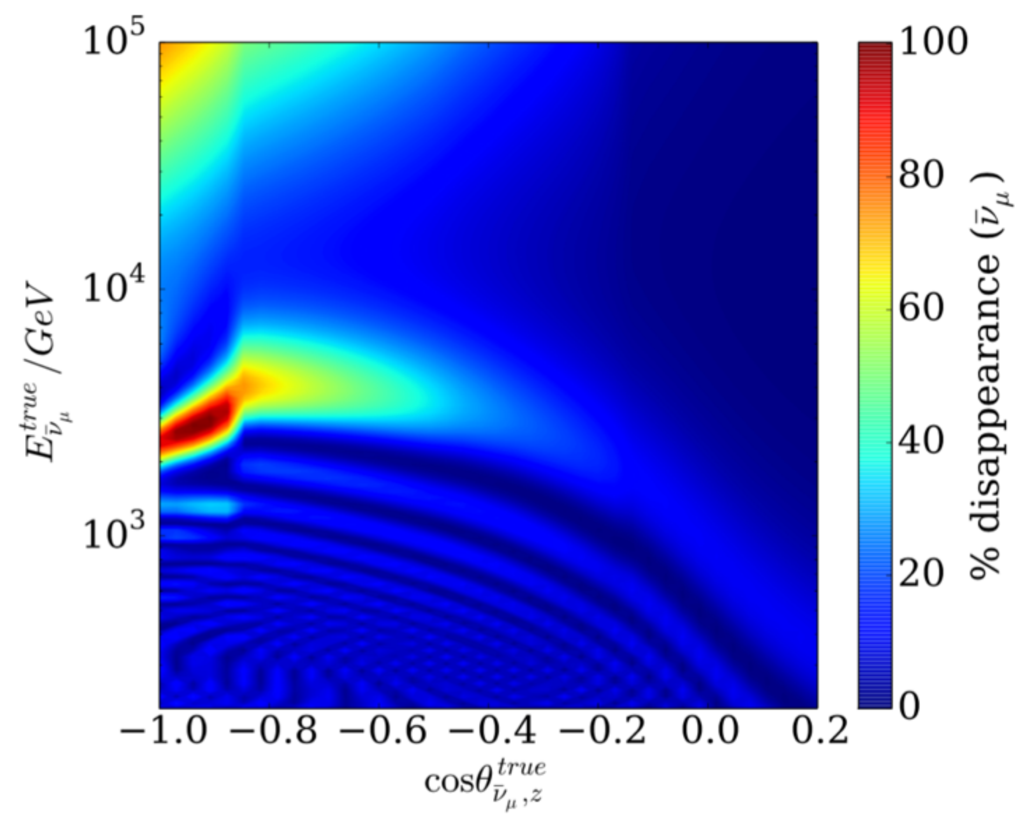




- Three years of DeepCore data in 5.6~56 GeV
- Δm^2 shifted to larger due to energy scale and calibration error
- Tau appearance with 3.2σ significance
- Measure smaller normalization compared to other experiments but still consistent with SM

Sterile Neutrino Search





Sterile neutrino will produces several effects:

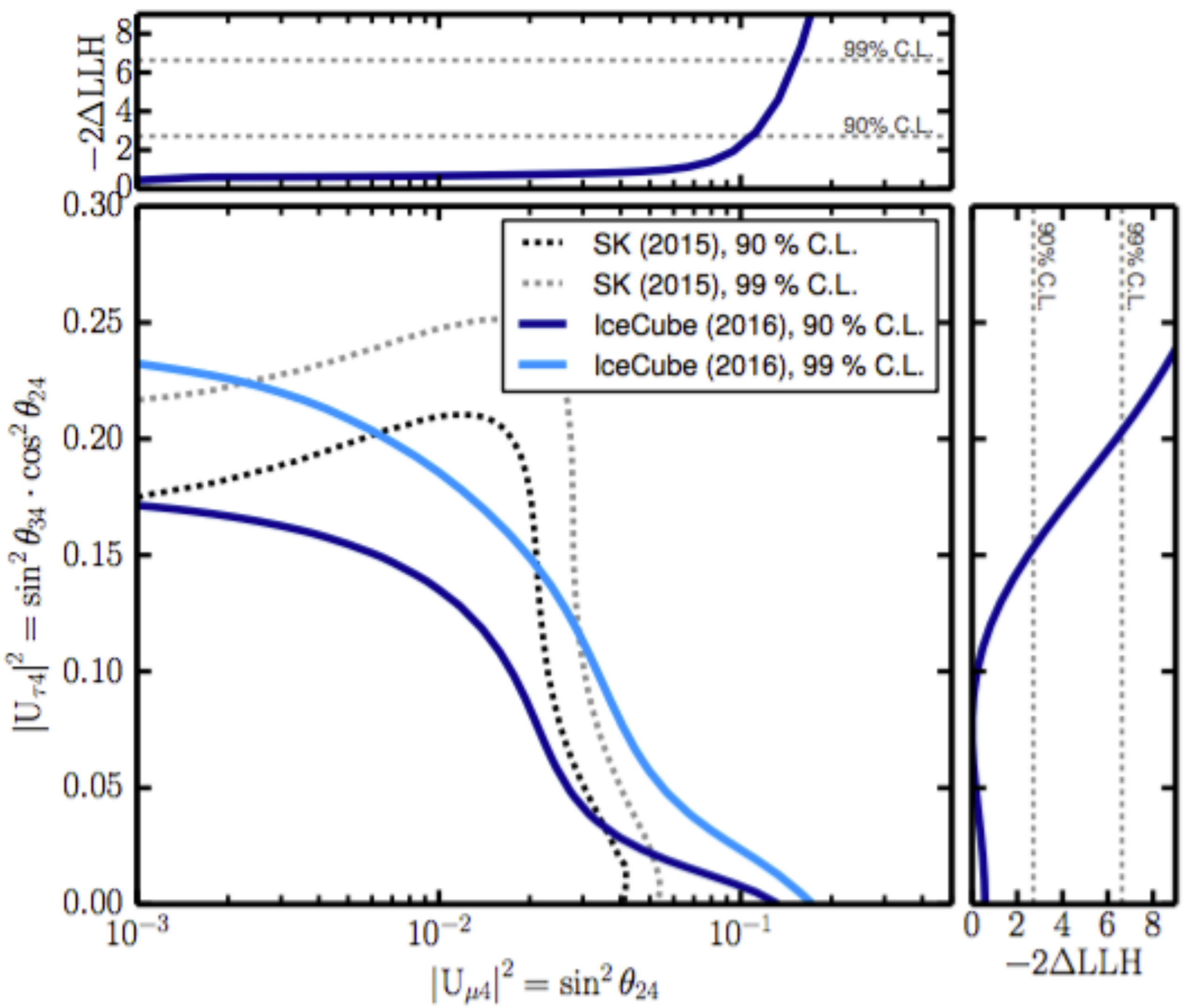
1. Additional energy-independent deficit in νμ disappearance because of rapid sterile oscillation

2. Matter oscillation in 10 GeV is modified due to different matter potential from active neutrino

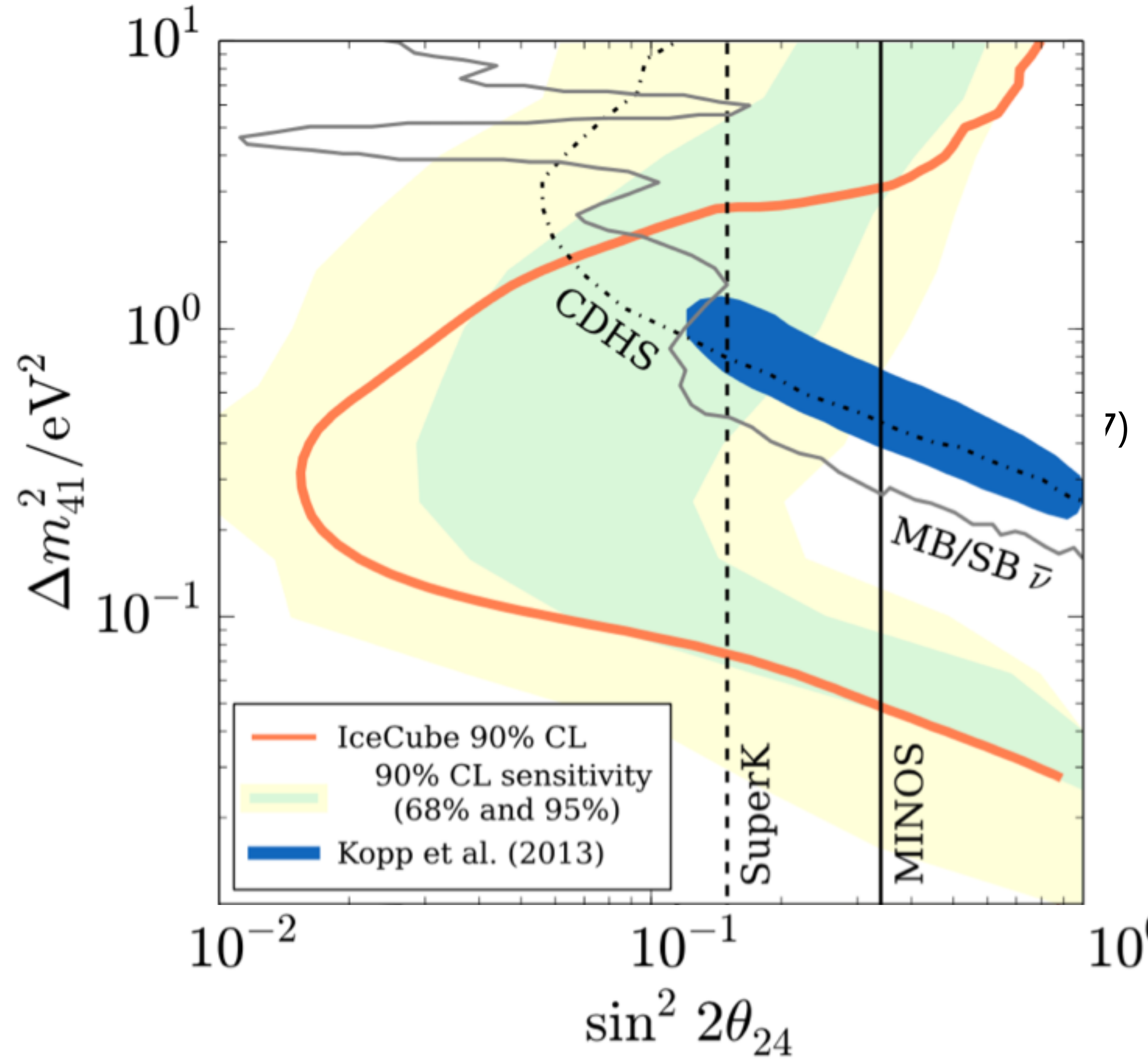
3. Large sterile mass ($\Delta m^2 \sim 1 eV^2$) would produce matter resonance in TeV, resulting distinct signature in energy spectrum

Sterile Neutrino Search

PRD 95, 112002 (2017)



PRL 117 071801 (2016)



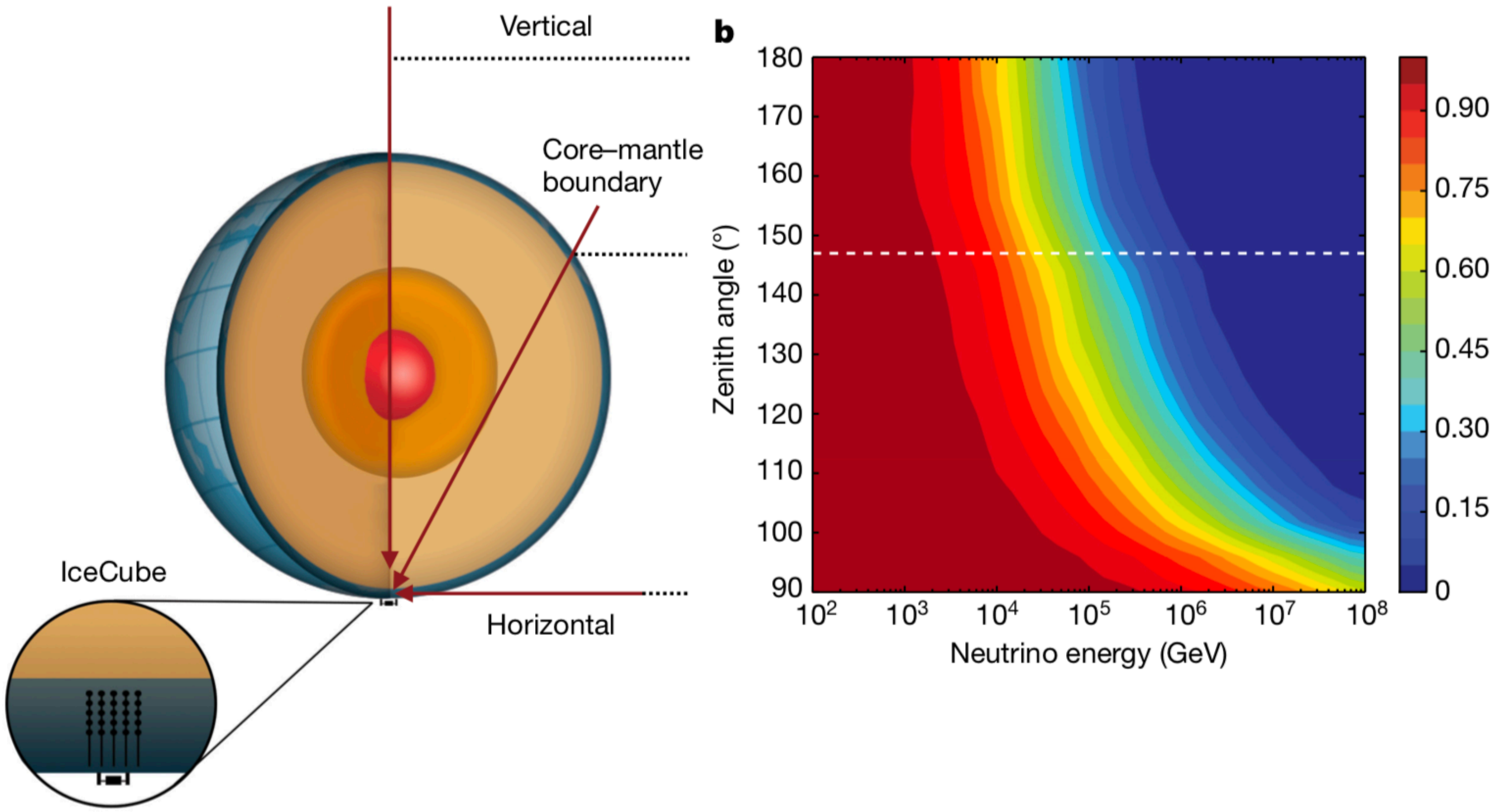
- Limits on elements of mixing matrix:
  $|U_{\mu 4}|^2 < 0.11$, $|U_{\tau 4}|^2 < 0.15$
- Another limit given by sterile mass resonance:
  $\sin^2(2\theta_{24}) < 0.02$ at $\Delta m^2 \sim 0.3\,\text{eV}^2$

$$\mathbf{U} \equiv \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

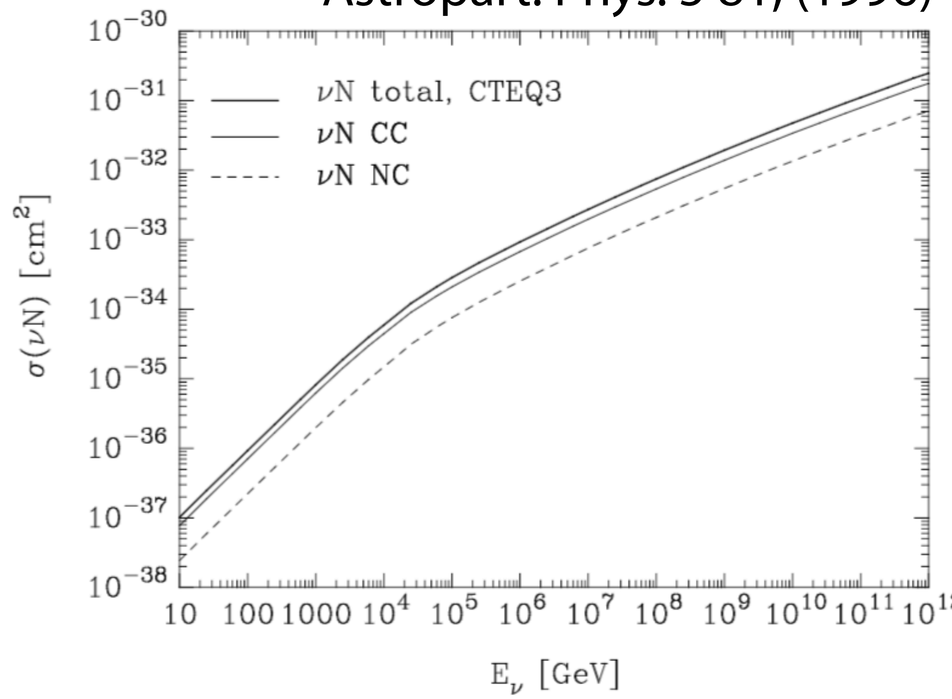
$$|U_{\mu 4}|^2 = \sin^2\theta_{24},$$
$$|U_{\tau 4}|^2 = \cos^2\theta_{24}\cdot\sin^2\theta_{34}$$

Neutrino cross section in TeV

Nature, Vol551 596 (2017)
PRL 122, 041101 (2019)



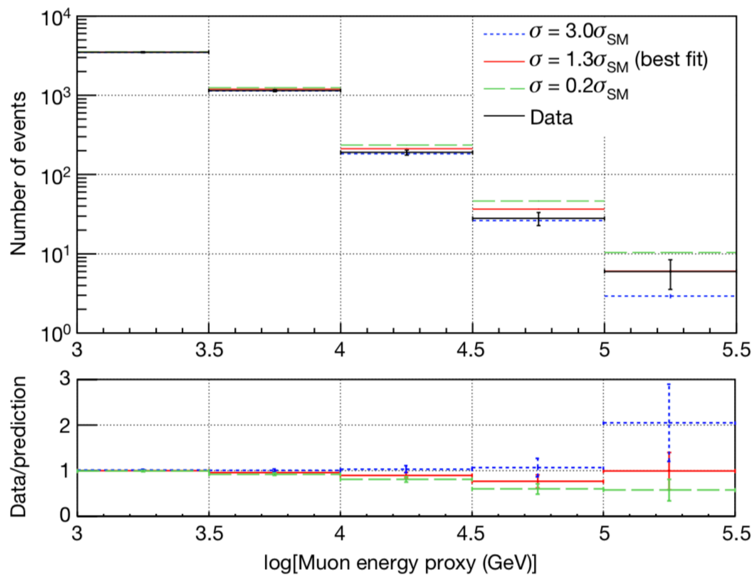
Astropart. Phys. 5 81, (1996)

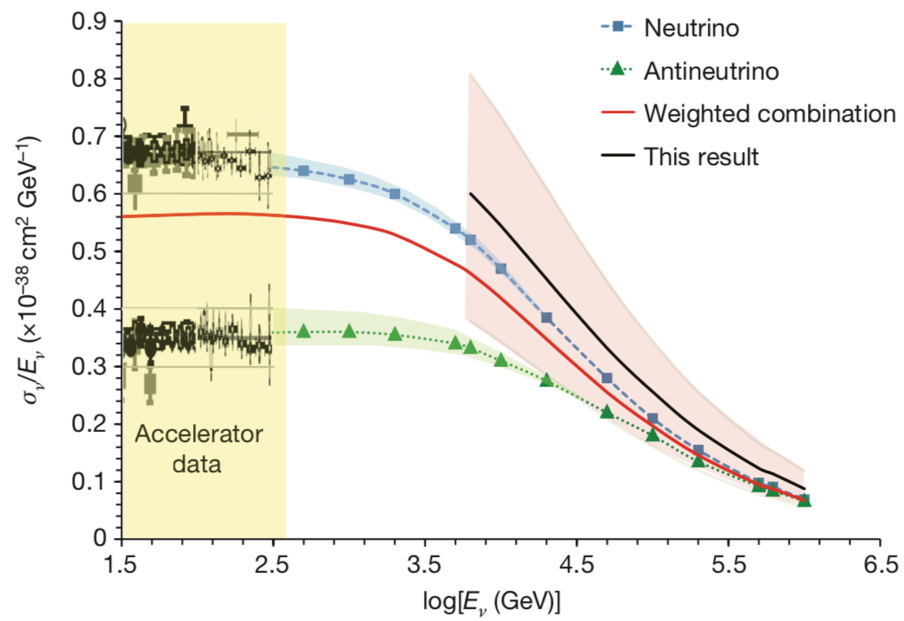


- Neutrinos propagating in the Earth is attenuated above 40 TeV
- Transmission probability depends on energy and zenith angle
- Increase of cross section will moderate above 10 TeV due to finite $W^\pm/Z^0$ mass
- Some BSM models (extra dimension., leptoquark) predict increase of cross section

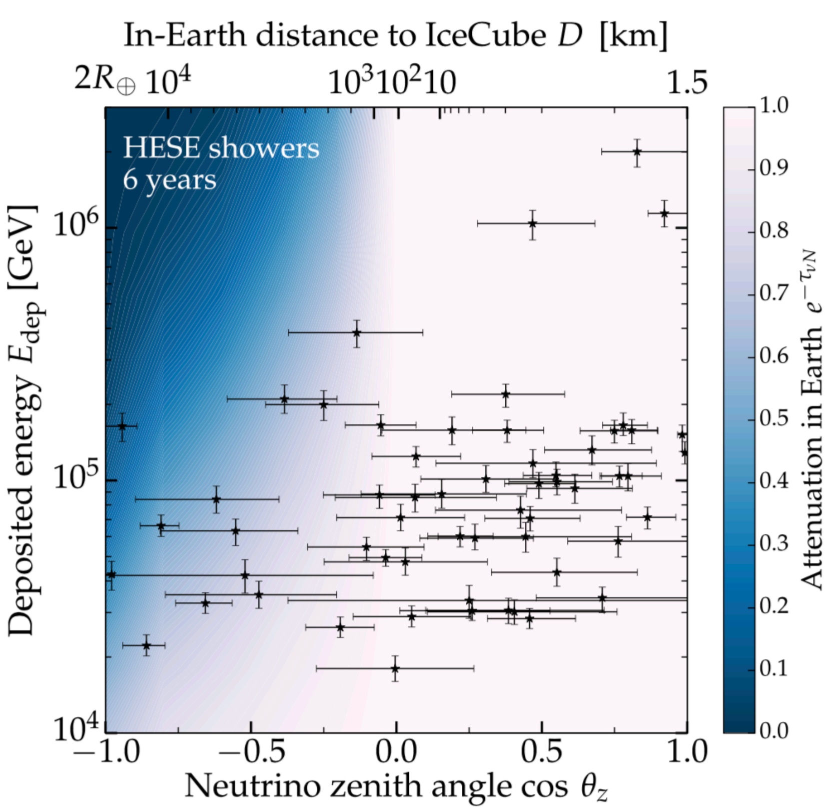
Neutrino cross section in TeV

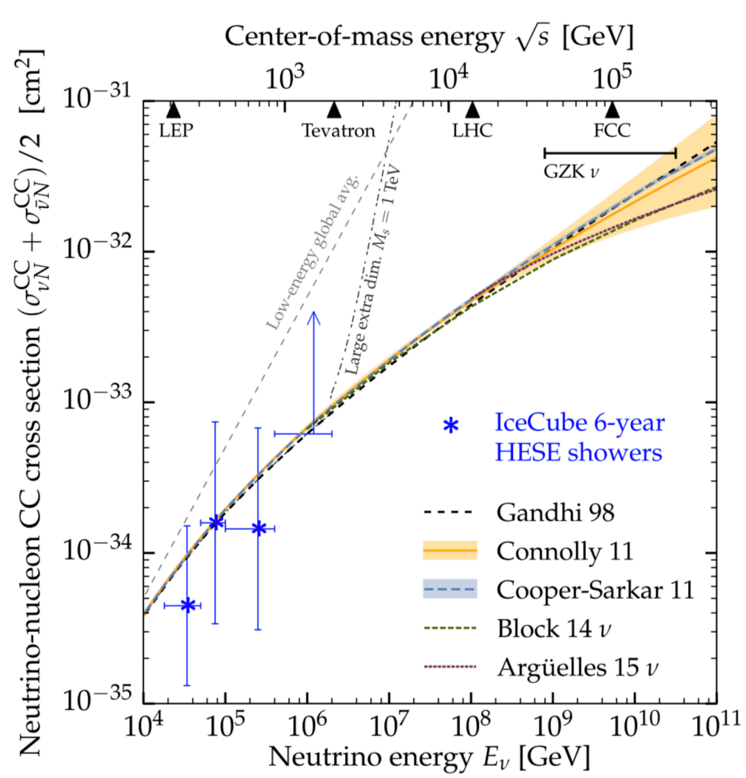
Nature, Vol551 596 (2017)
PRL 122, 041101 (2019)





- IceCube measured cross section in 6.3 - 980 TeV
- Data is compared with averaged $\nu+\bar{\nu}$ prediction with normalization factor
- Measured 1.3 times larger than prediction, but still consistent

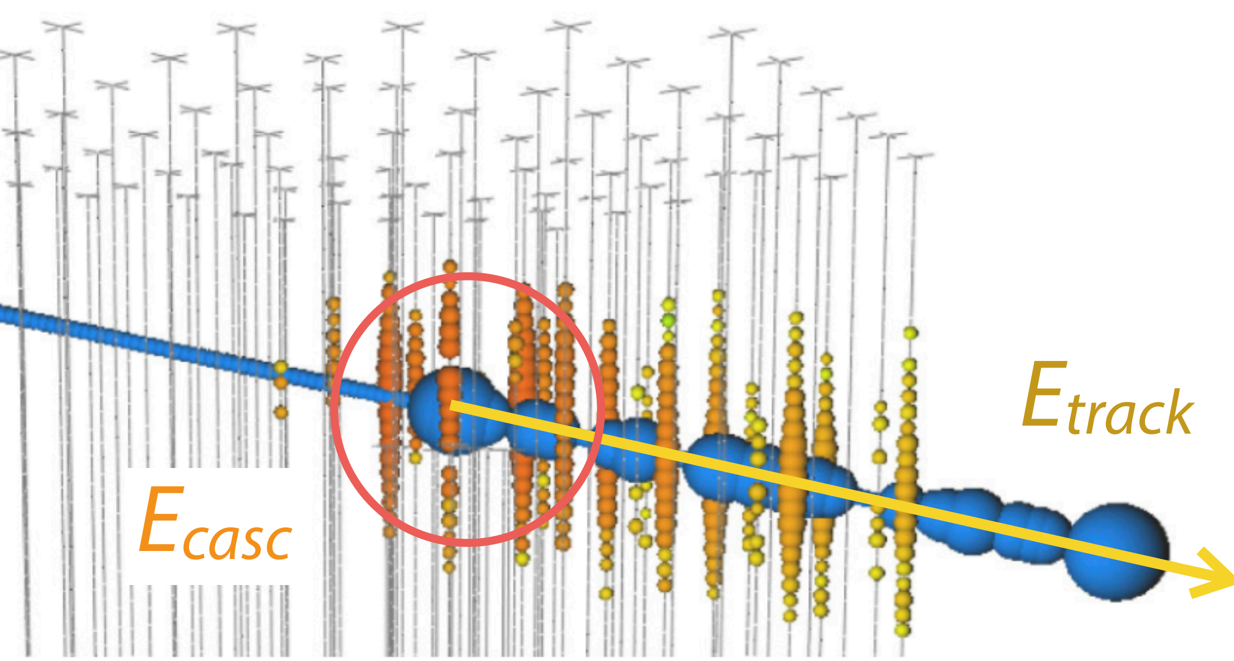


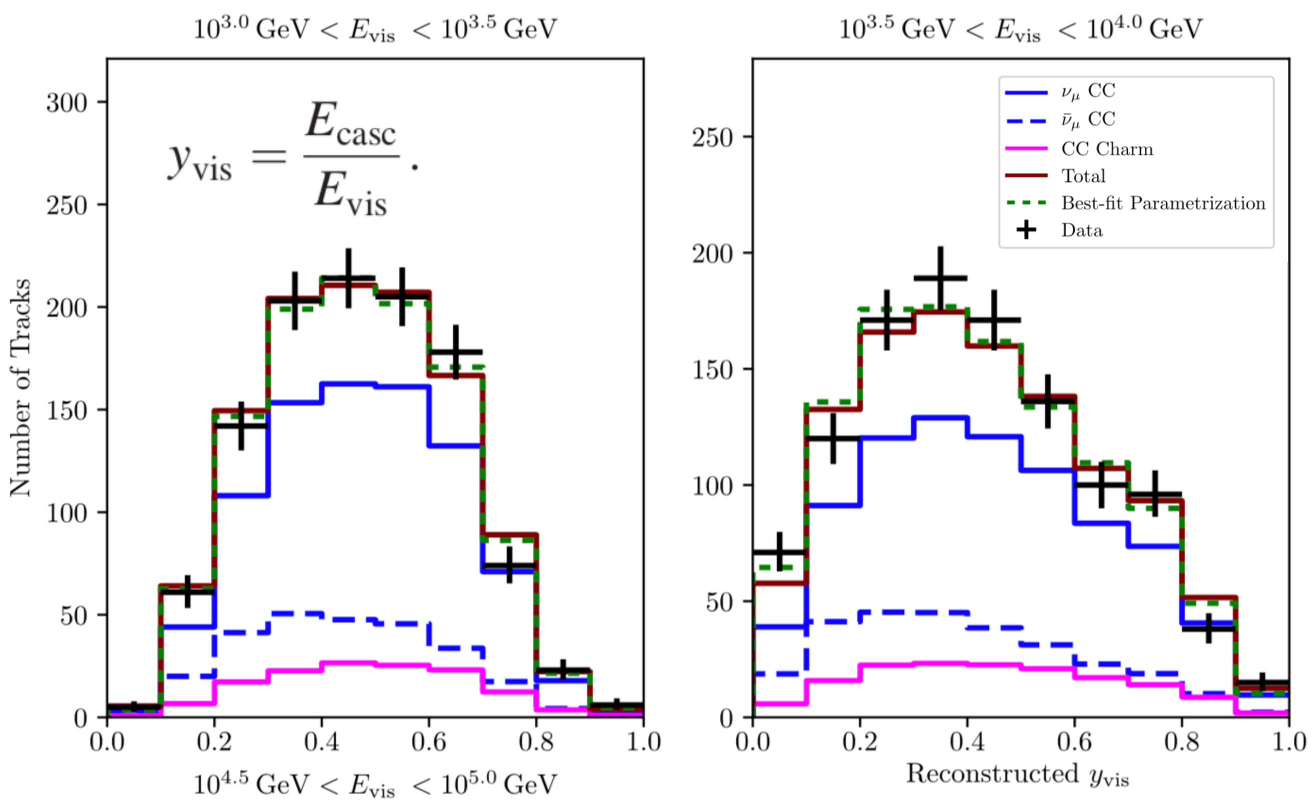


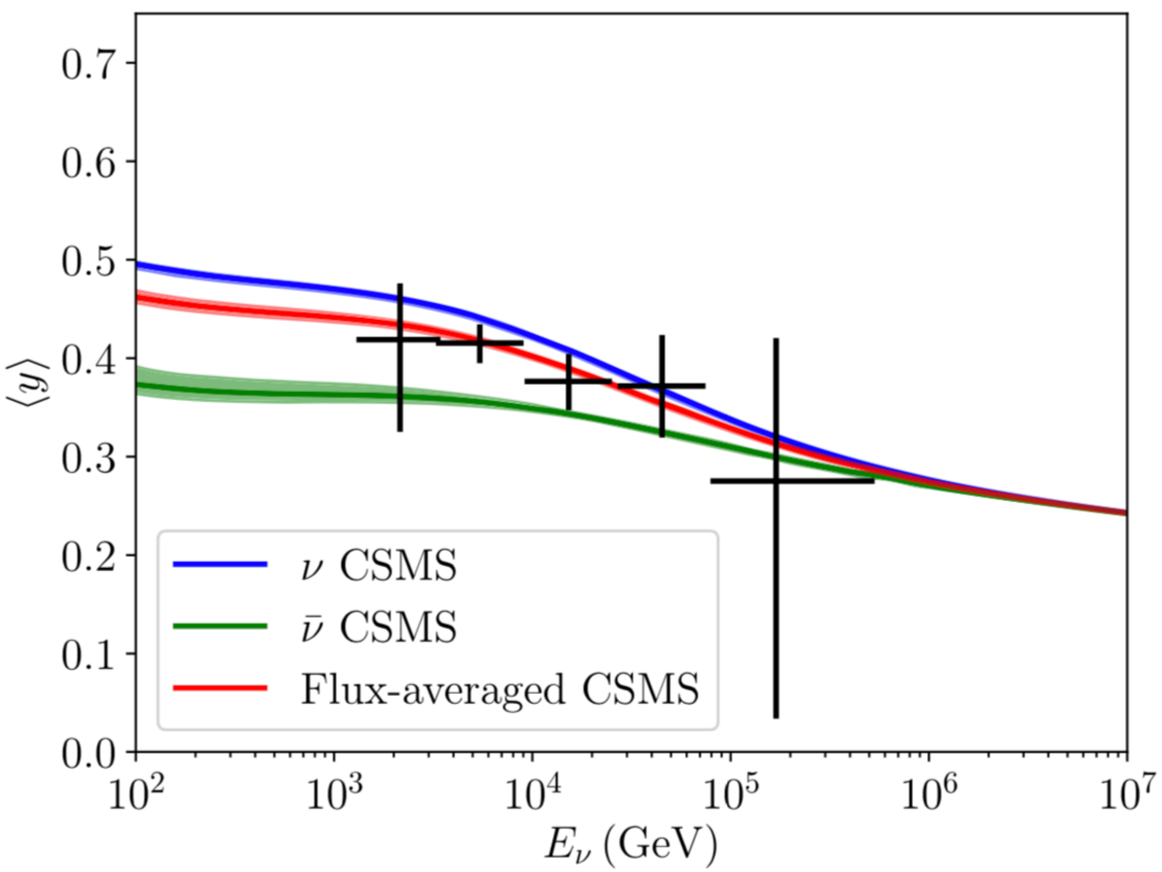
- Analysis extended recently for cascade events up to 2 PeV
- Differential cross section agrees with predicted softer-than-linear dependence

Inelasticity Measurement

PRD 99, 032004 (2019)

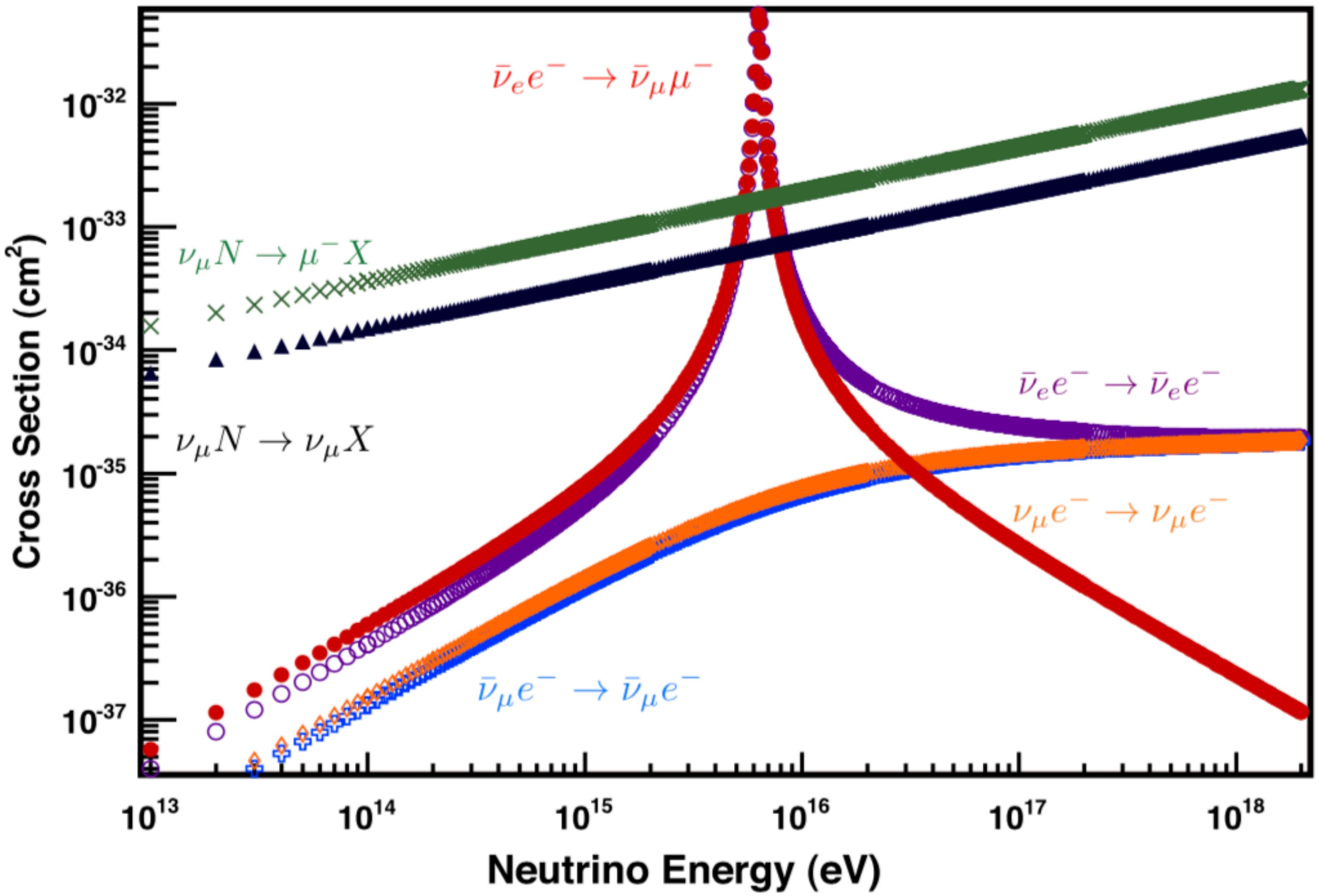


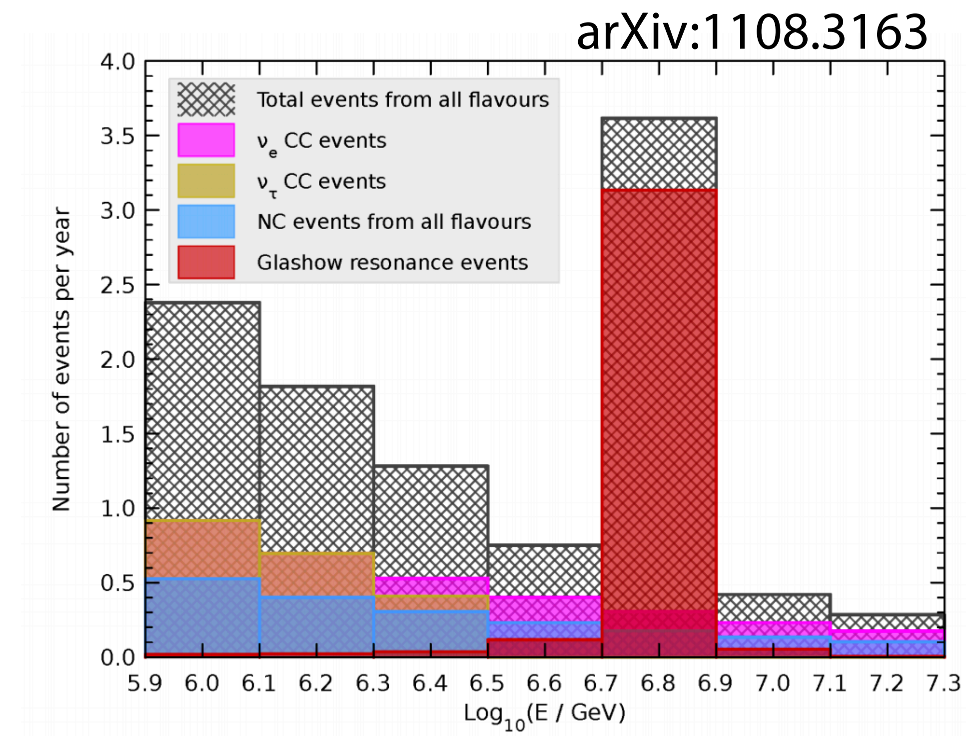




- Inelasticity: energy fraction transferred to hadrons
- So far measured up to 250 GeV by NuTeV
- Estimate with muon track energy and cascade energy around vertex
- Reconstructed visible inelasticity (y_{vis}) compared to expectation with charm contribution
- Measurement agrees with SM in 1~100 TeV

Glashow Resonance





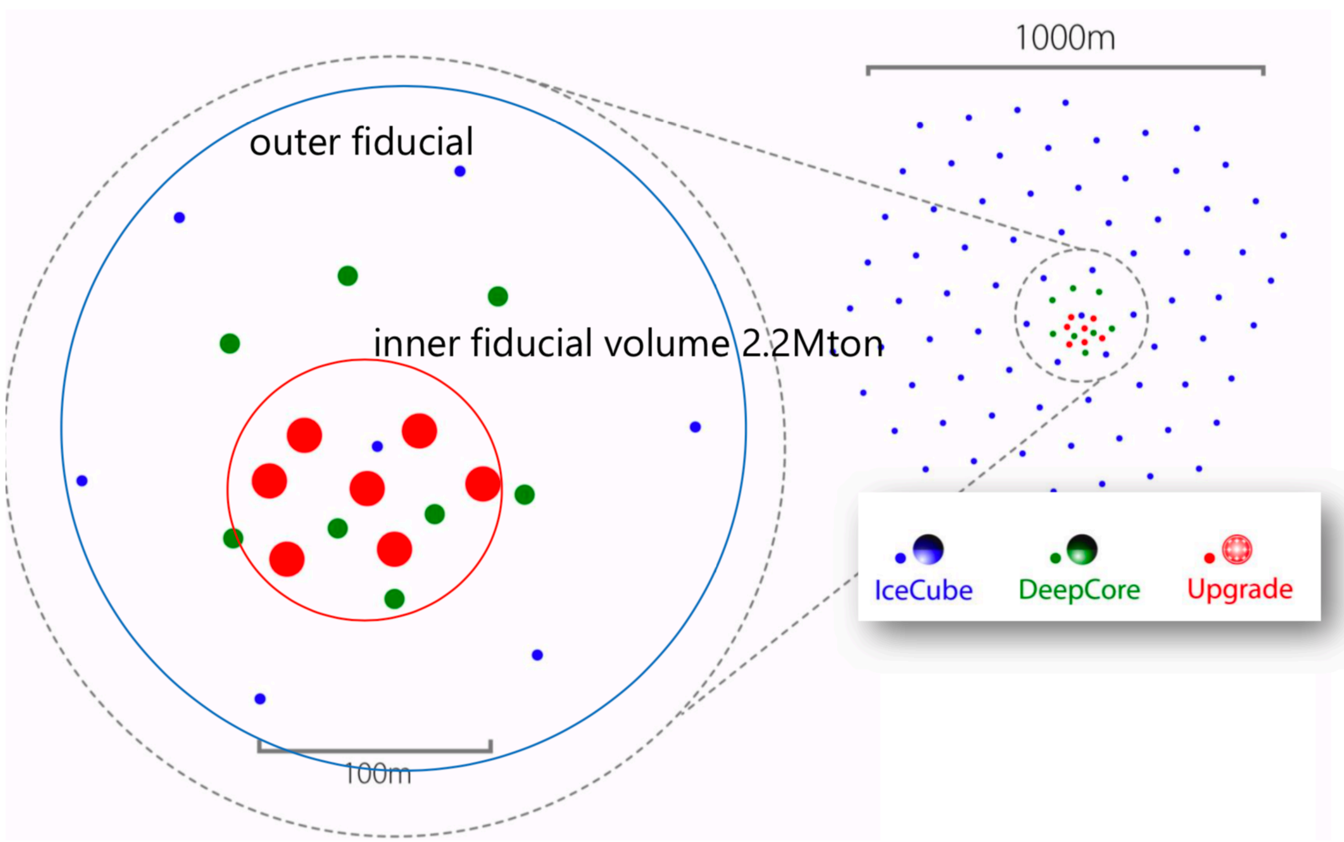
- $\bar{\nu}_e$ cross section with electron in matter increased at W boson mass (~6.3 PeV)
    - channel: $\bar{\nu}_e + e^- \rightarrow W^- \rightarrow \bar{\nu}_X + X^-$
- Resonance rate will exceed at corresponding energy
- So far one candidate observed, but not yet conclusive

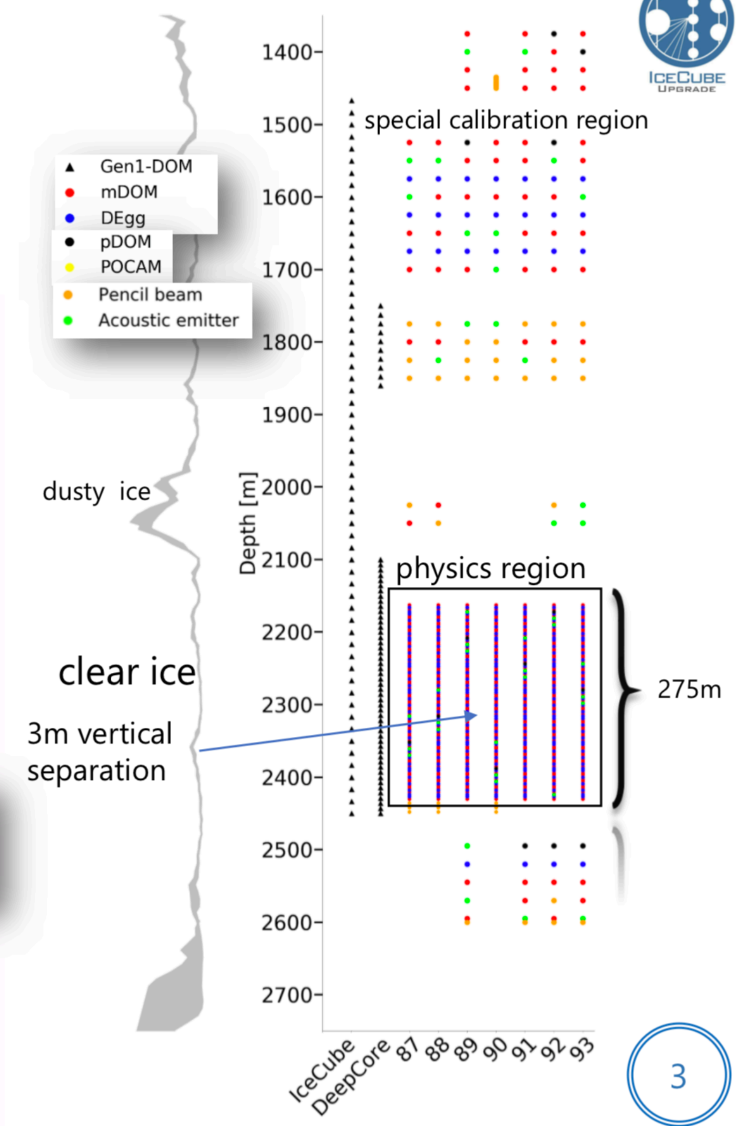
IceCube Upgrade

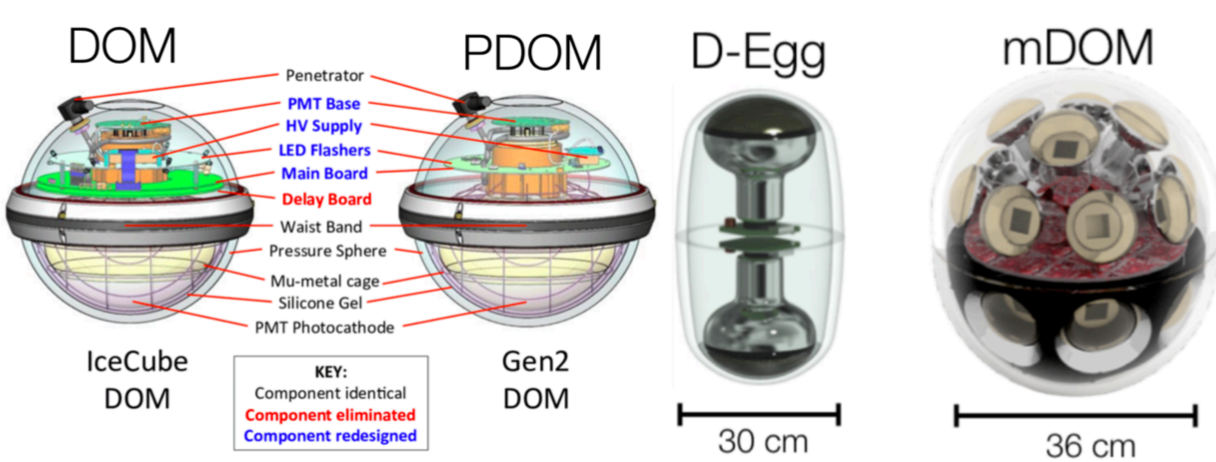
A. Ishihara, ICRC 2019
Win Yan Ma, TAUP 2019

IceCube Upgrade

Geometry optimized for
- GeV neutrinos
- Calibration of the IceCube detector



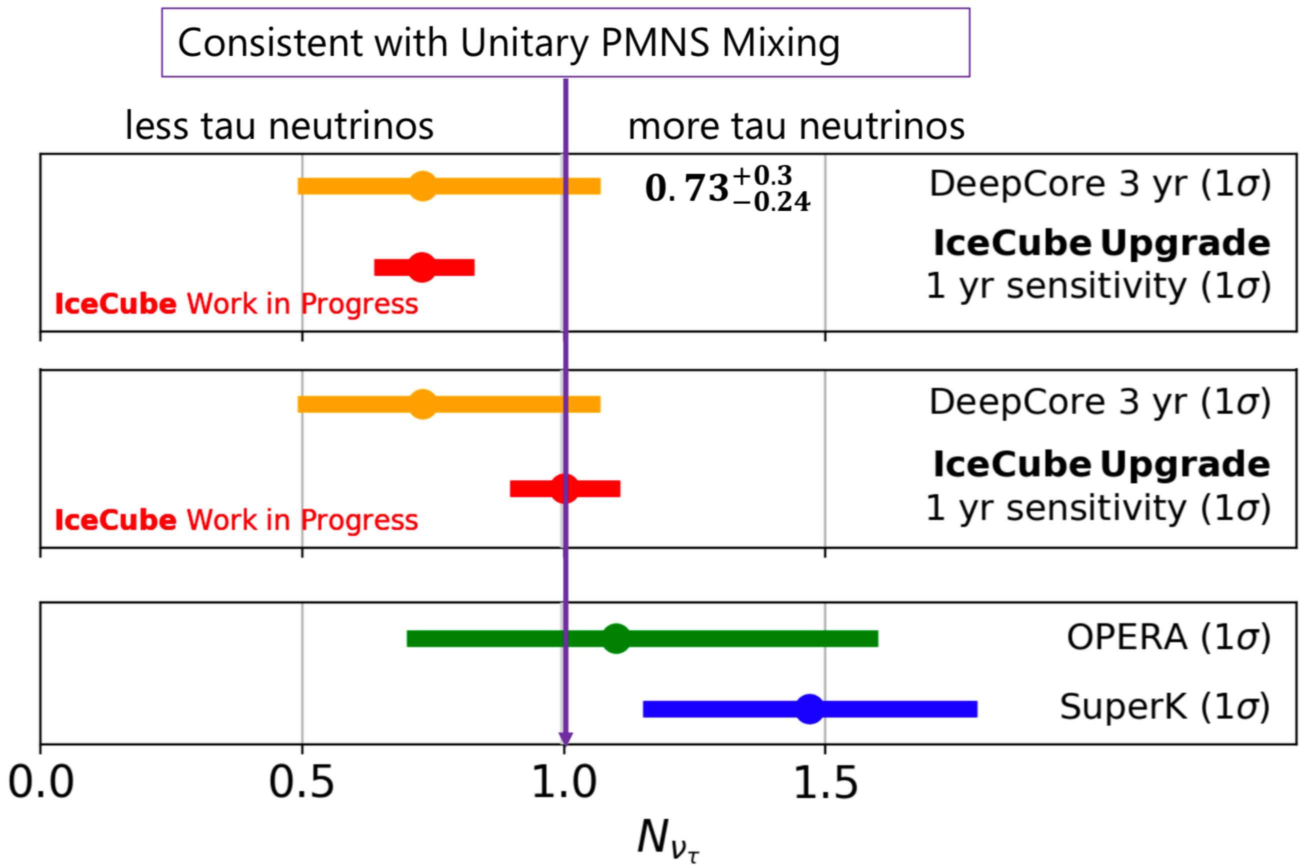


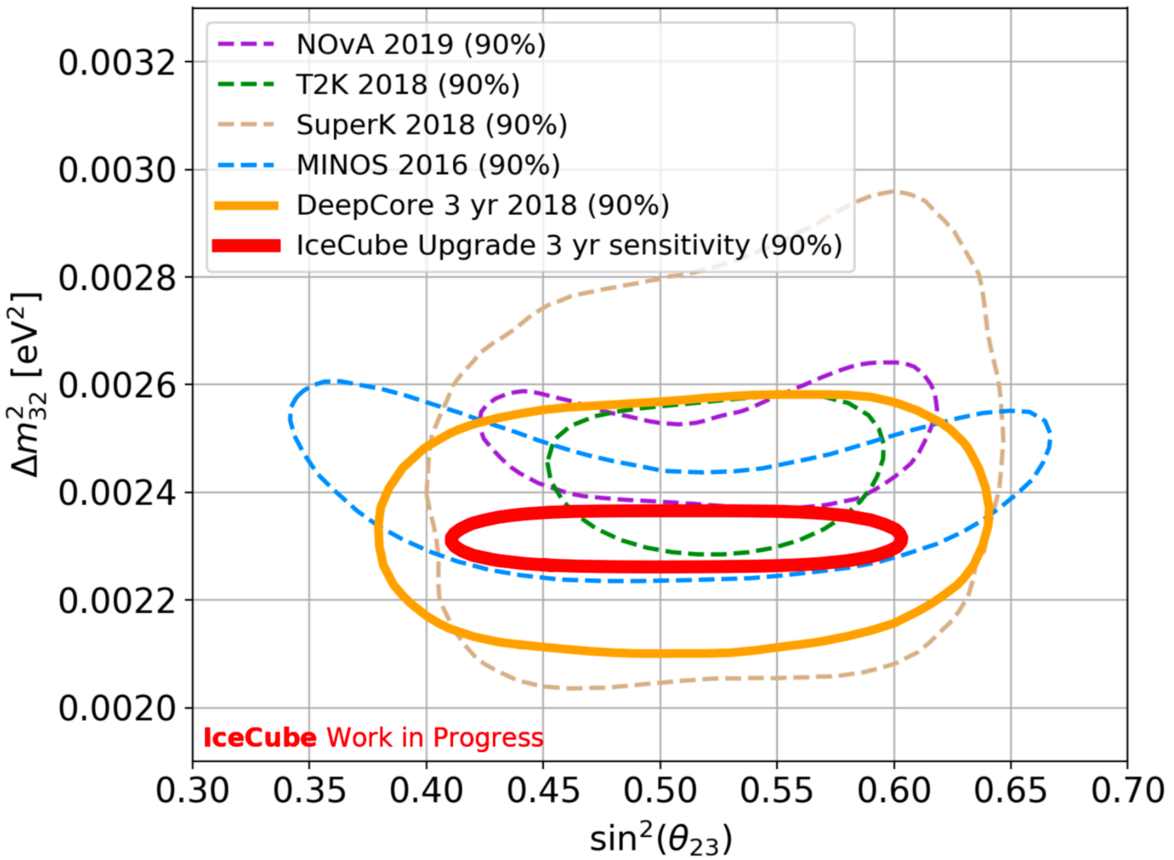


- Install additional 7 strings
- Testing new devices for IceCube-Gen2
- Re-calibration of detector
- Improve oscillation physics at GeV

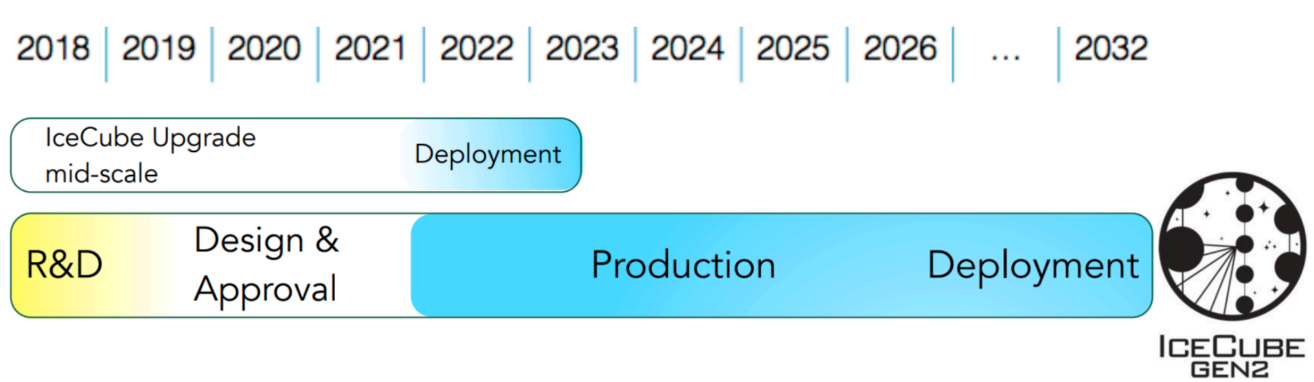
IceCube Upgrade

A. Ishihara, ICRC 2019
Win Yan Ma, TAUP 2019





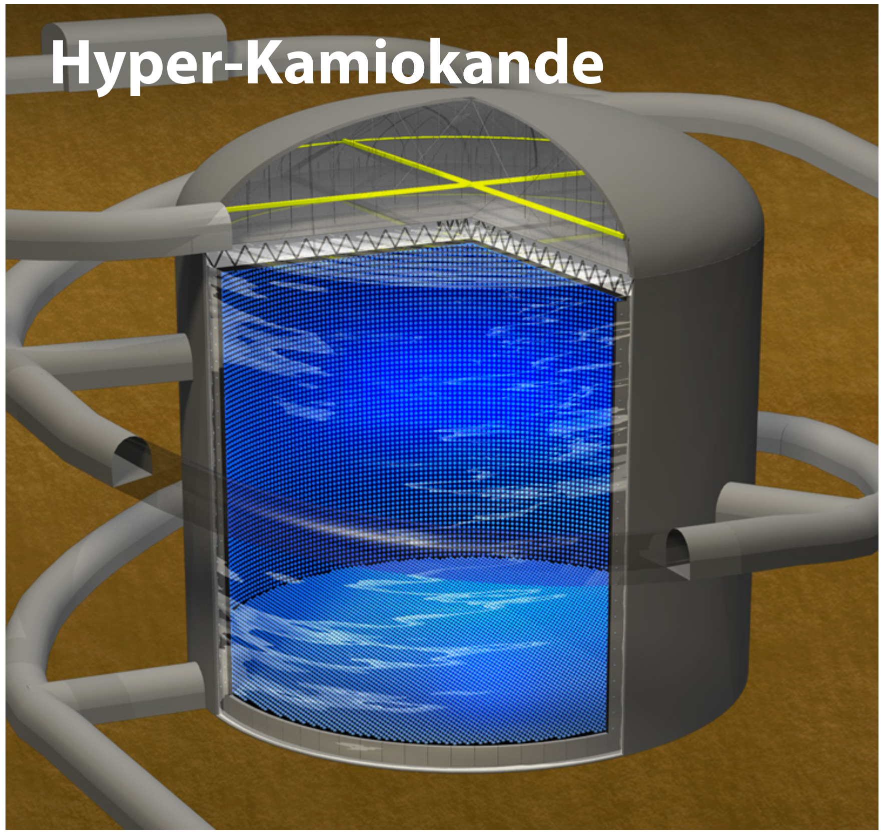
Schedule



- 10% accuracy of tau normalization expected in 1yr observation
- Comparable precision in oscillation parameters with other experiments

Future Projects

Hyper-K & DUNE

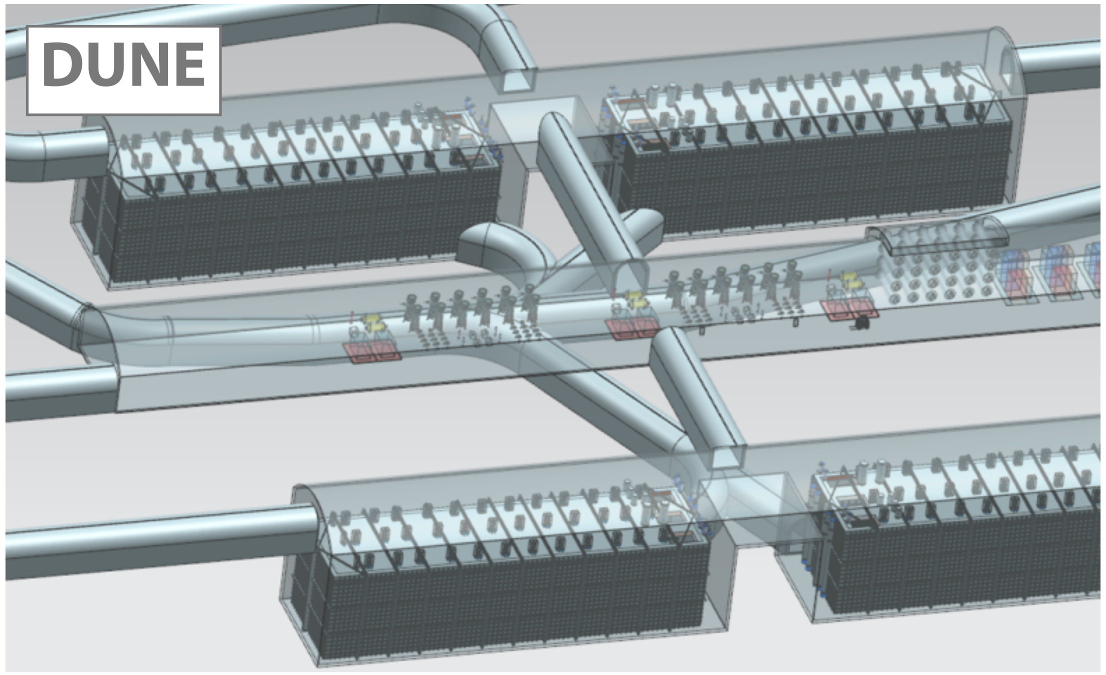


Hyper-Kamiokande

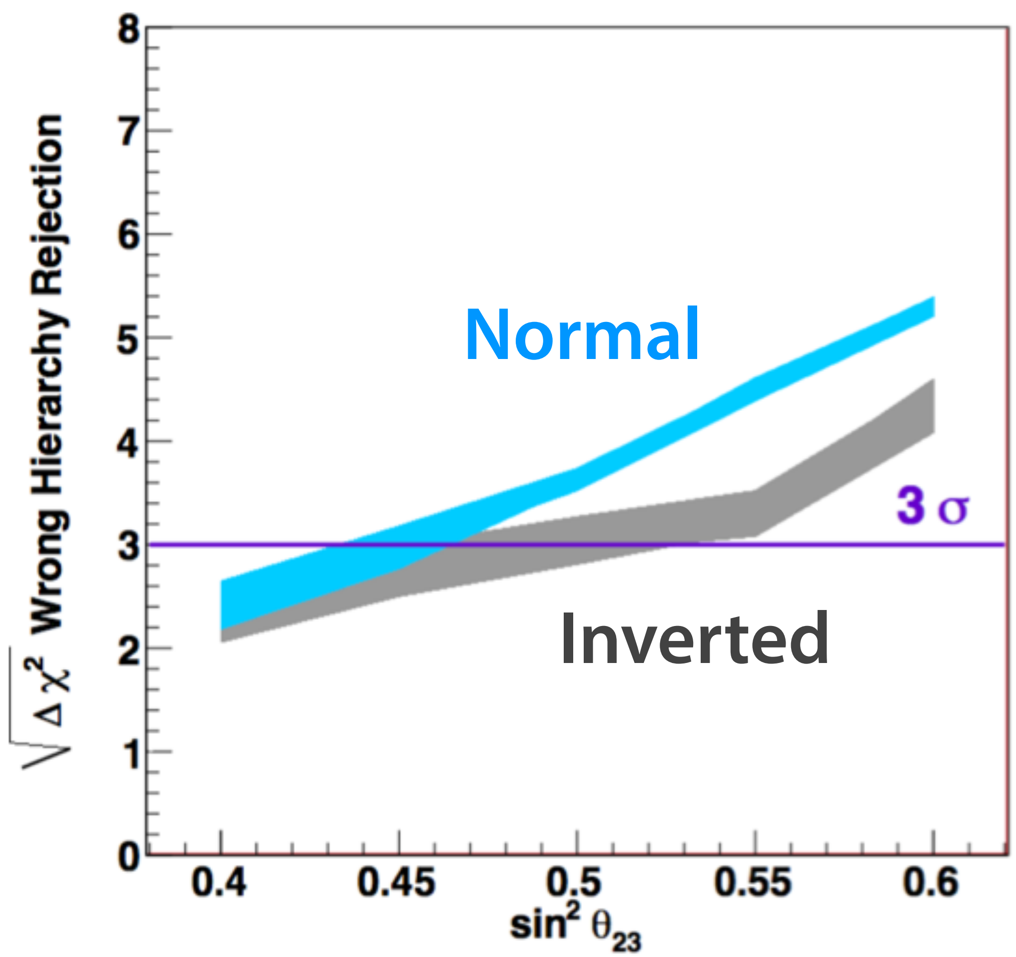
- Water Cherenkov detector
- ~10 times of Super-K in fiducial volume
- 40,000 PMT (~40% coverage) of improved photo-detection efficiency(x2 compared to SK PMT)

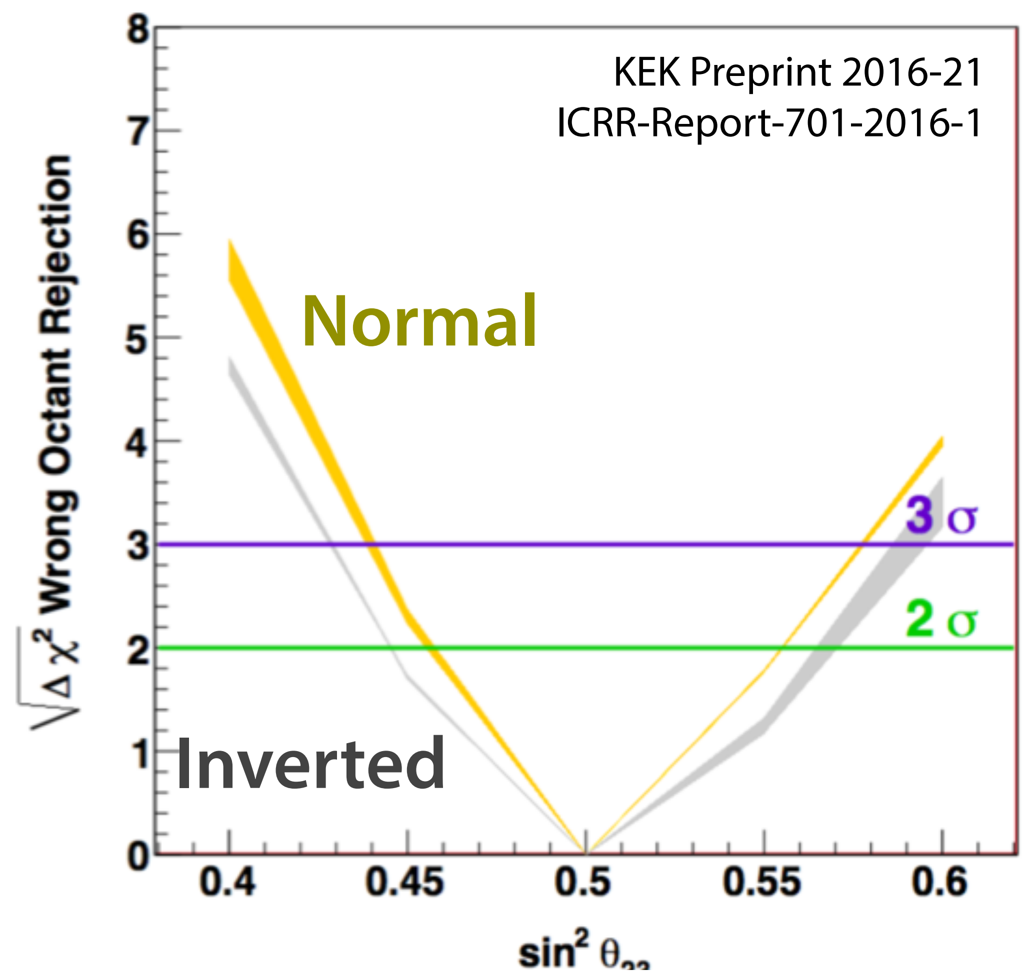
DUNE

- Liquid Argon detector based time projection chamber technique (TPC)
- 4 caverns x 10 kton (40 kton in total)
- high resolution imaging would offer possibilities to discriminate ν and $\overline{\nu}$



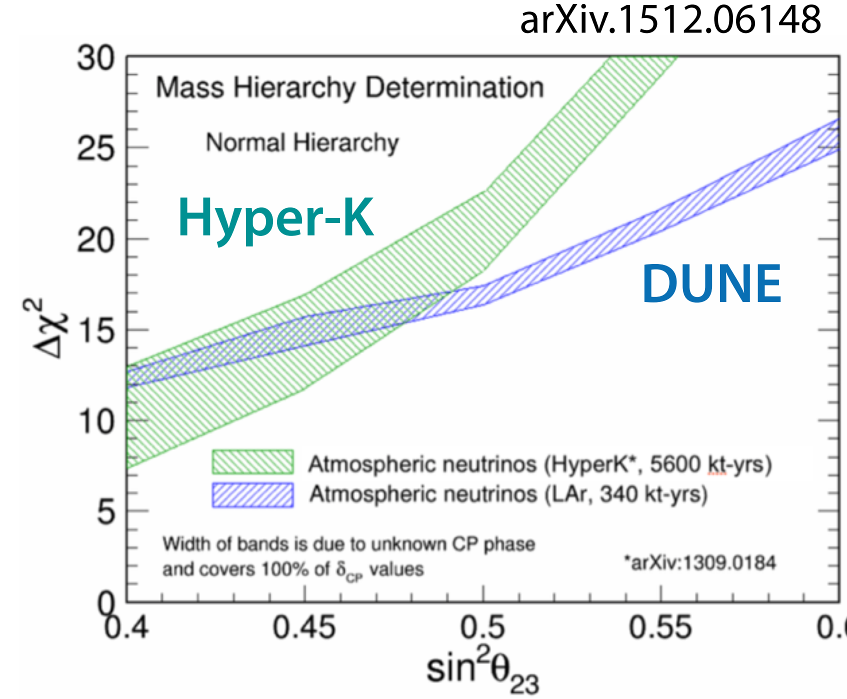
Hyper-K & DUNE sensitivities



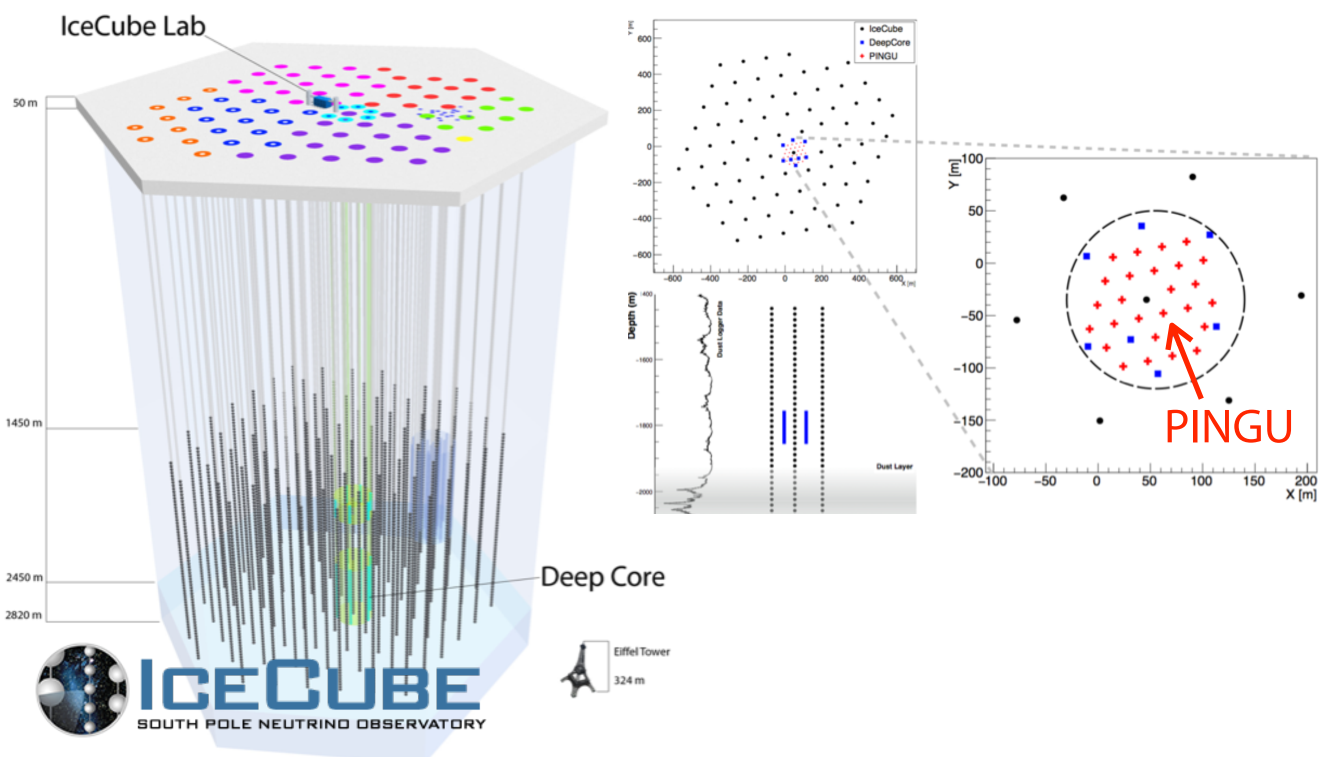


- >3σ sensitivity for both MH cases for $\sin^2\theta_{23}>0.45$ with 10yr data (2.6Mtonyr)
- Possible to discriminate θ_{23} octant at >3σ for $|\theta_{23}-45|>4$deg
- Comparable sensitivity for DUNE

arXiv.1512.06148



PINGU and ORCA

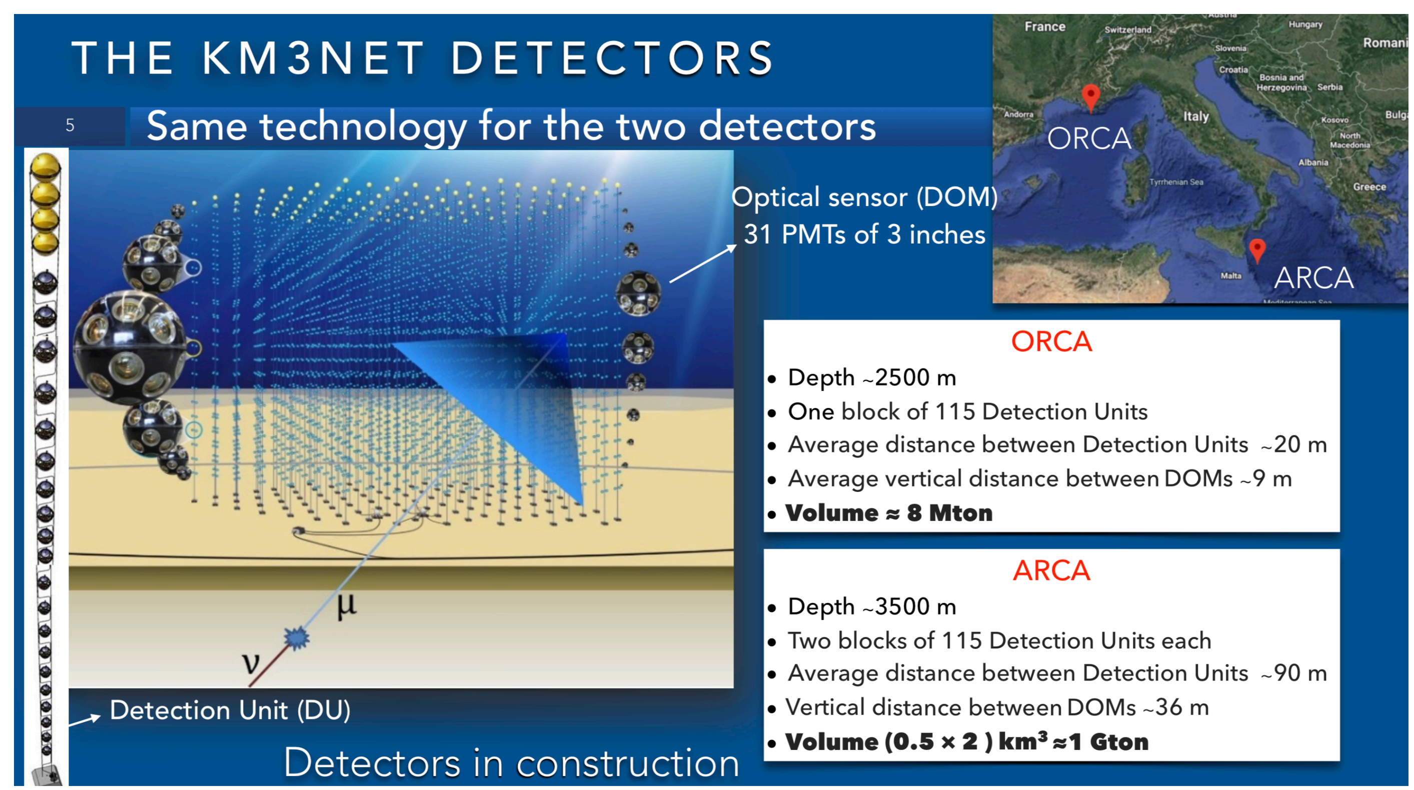


IceCube / PINGU:

- Inner detector configuration of IceCube/DeepCore at South pole
    - 6 Mton effective mass
- Lower threshold (~GeV) with 22 m spacing of string
- ~60,000 atm. ν / year expected

KM3NET / ORCA:

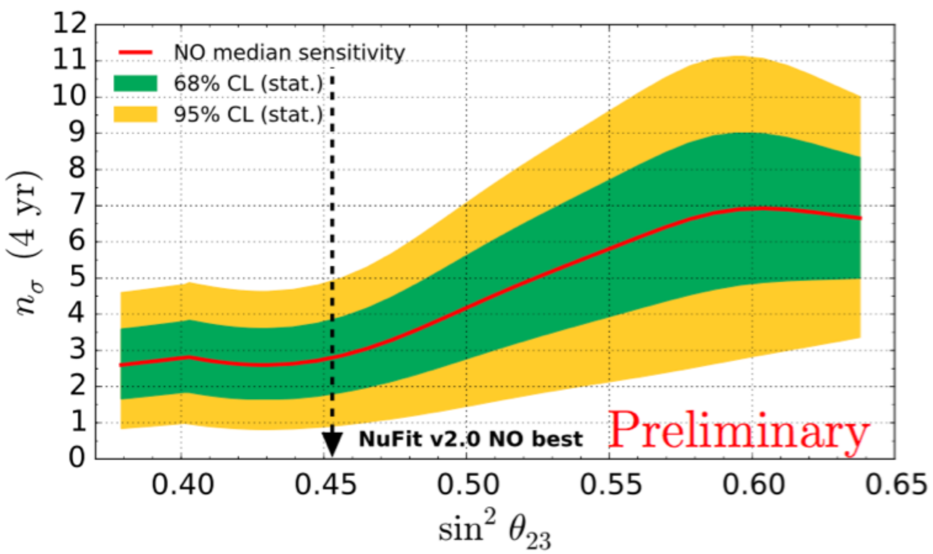
- Low energy branch of KM3NeT in Mediterranean Sea
- Dense array of multi-PMT digital optical modules (DOMs)

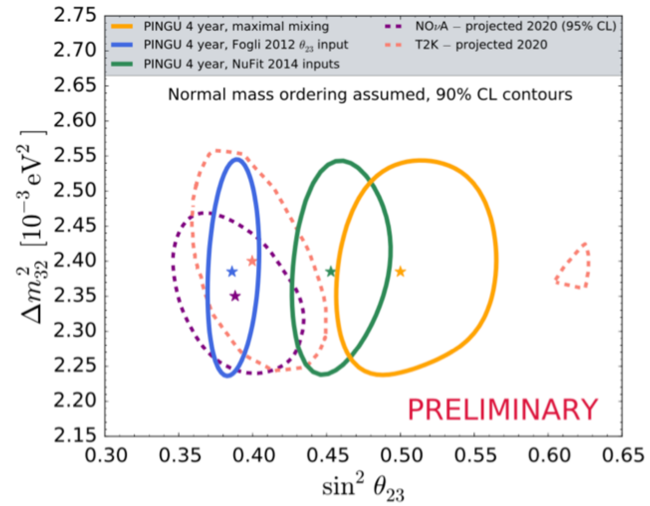


PINGU / ORCA Sensitivities

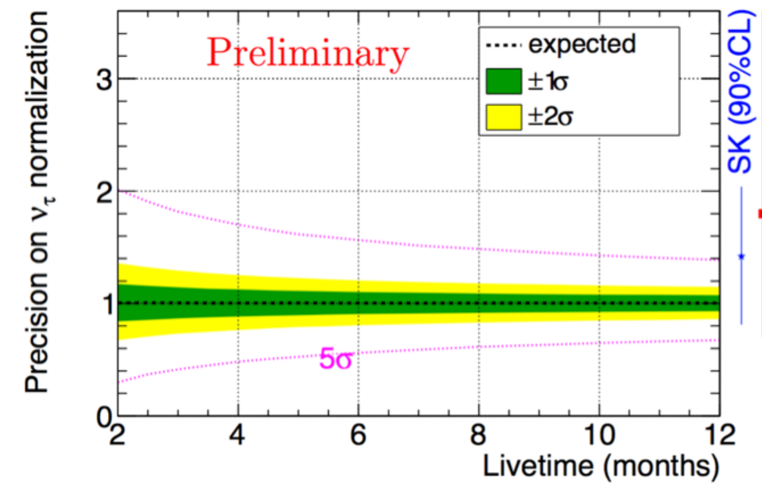
Mass Hierarchy | **θ_{23} Octant** | **ν_τ Appearance**

PINGU

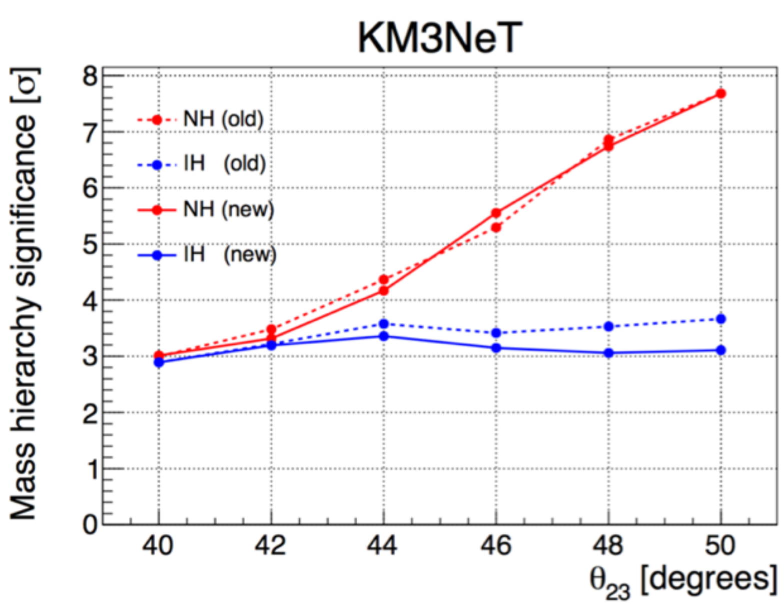


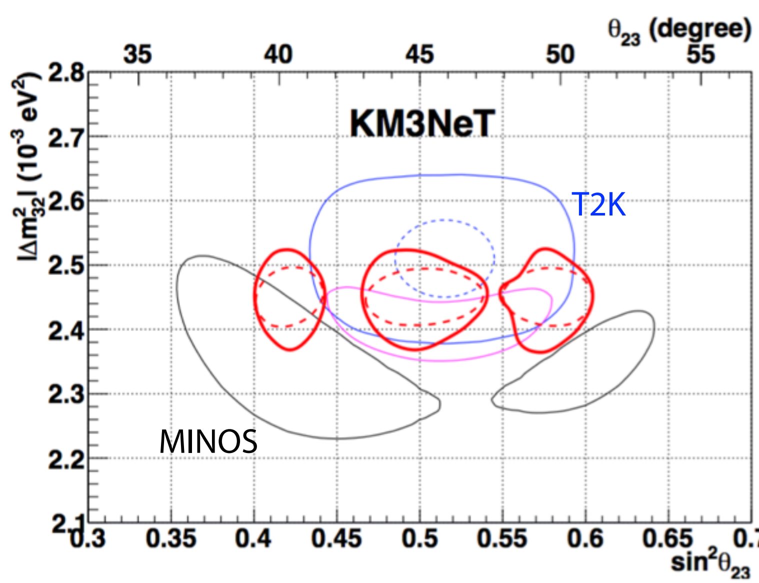


J. Phys. G44, 054006 (2017)

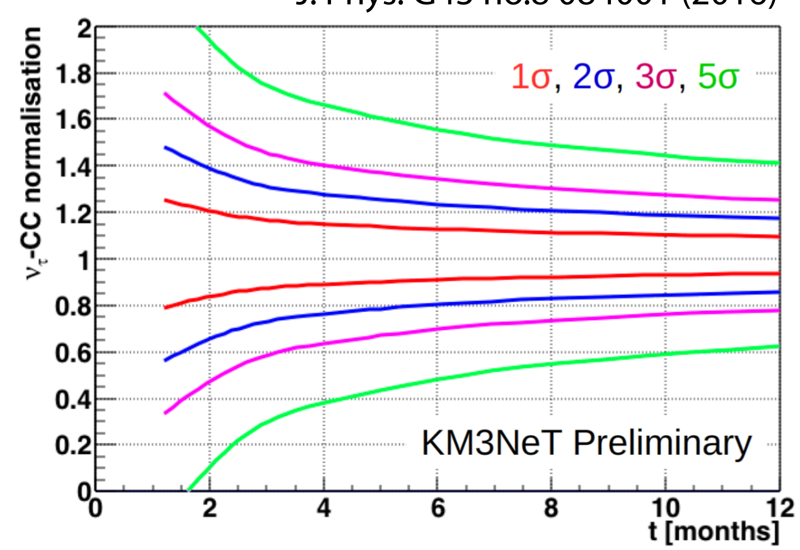


ORCA





J. Phys. G43 no.8 084001 (2016)



Summary

- Atmospheric neutrino measurement is a kind of particle physics utilized by natural beam
- Wide energy range from sub-GeV to ~100 TeV providing many physics opportunities
- Oscillation physics can be performed below 100 GeV
  - Normal hierarchy is preferred
  - tau appearance confirmed by Super-K and IceCube
  - No sterile signal
- IceCube/DeepCore observation provides unprecedented test of SM in TeV energies
- More studies are expected in future projects:
  SK-Gd, IceCube upgrade, Hyper-K, DUNE, PINGU, ORCA, ..

Stay Tuned !

END