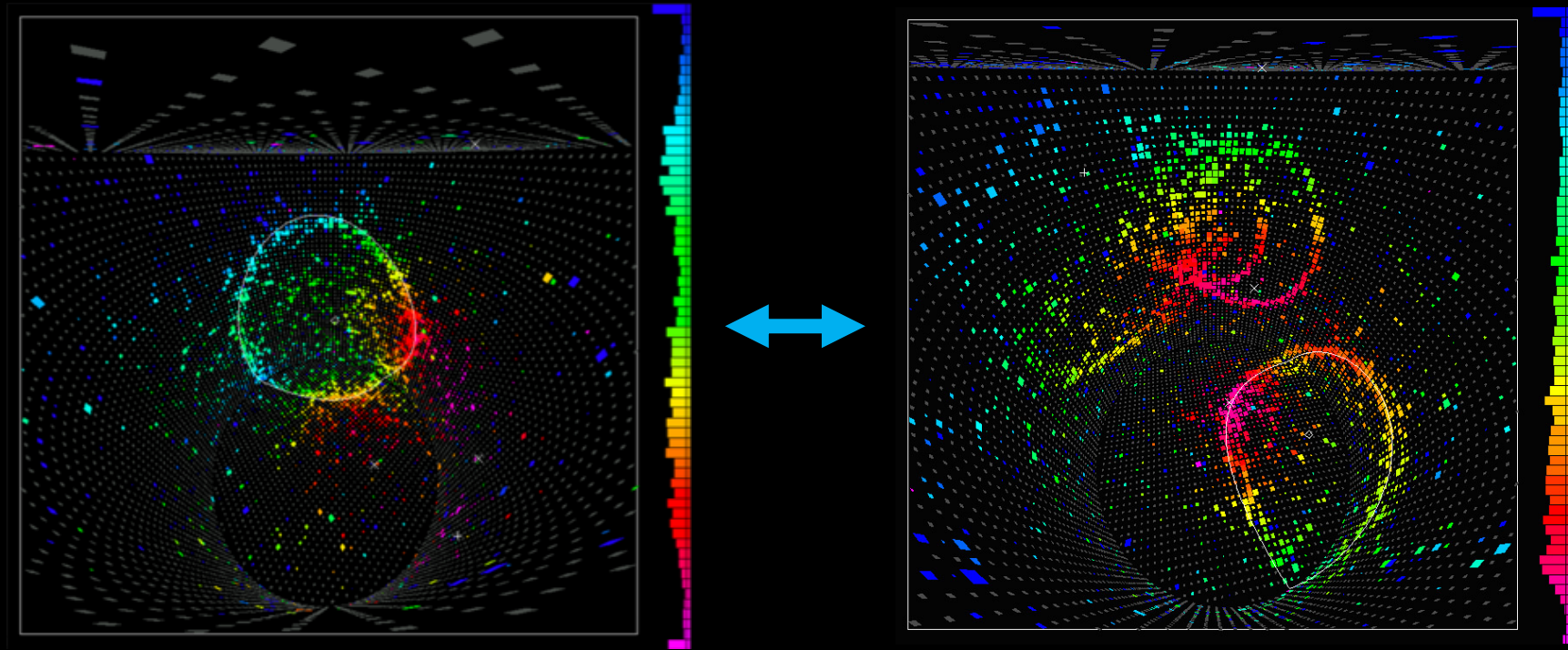
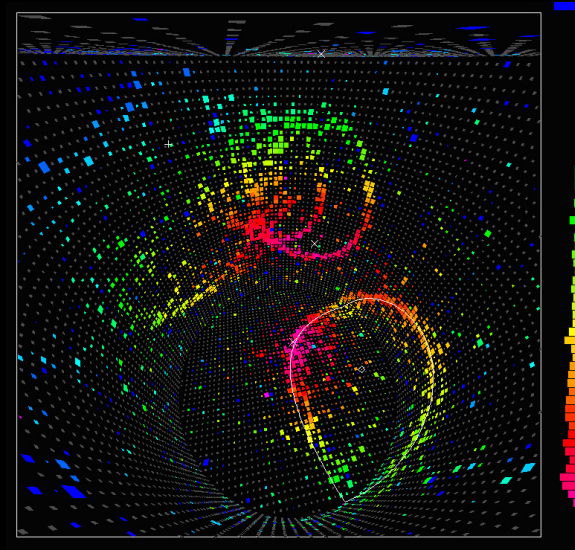
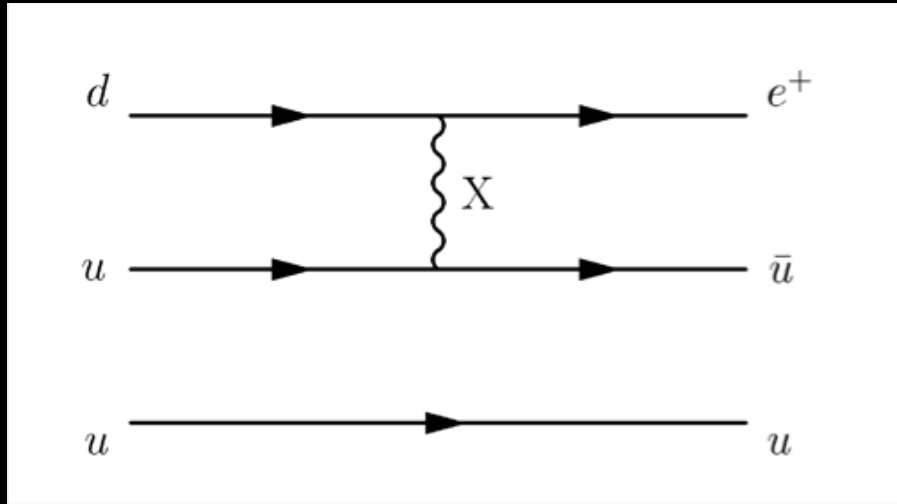


Atmospheric Neutrinos And Proton Decay



Roger Wendell
Kyoto University
2019.08.09
Toronto, Canada

It all begins with the search for proton decay



$\Delta B \neq 0$ needed to explain present day matter-antimatter asymmetry

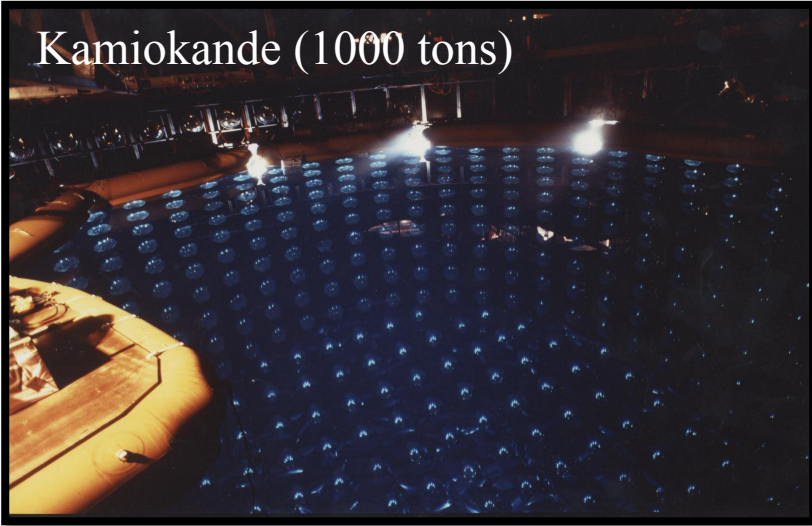
Grand Unified Theories (GUT) first proposed in the late 1970's

- SU(5) predicts proton decay with lifetime $\sim 10^{28} - 10^{32}$ years
 - Corresponds to $O(10) \sim O(100k)$ events /kton/year
- Flagship modes $p \rightarrow e^+ \pi^0$, $p \rightarrow \nu K^+$
- Experiments built to test this prediction in the early 1980's

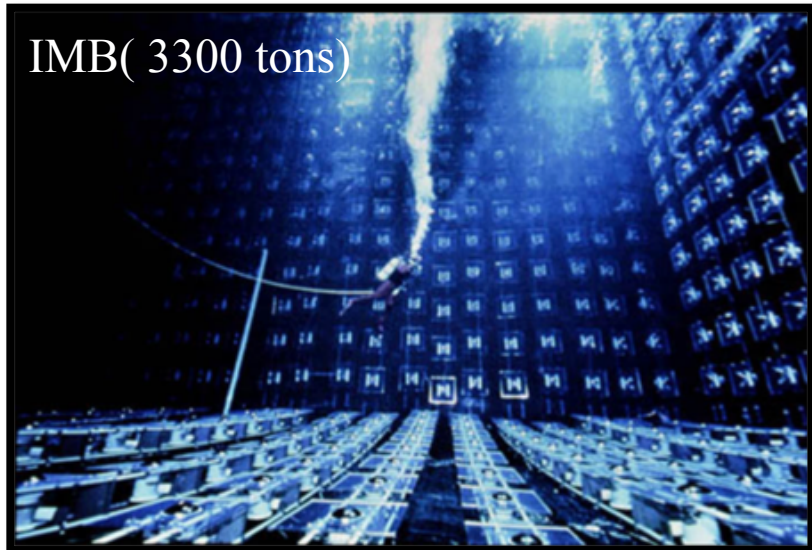
Proton Decay Experiments from the 1980's

Kamiokande Proposal

Kamiokande (1000 tons)



IMB(3300 tons)



研究目的

Research Objective

本研究の目的は、素粒子の大統一理論が预言する核子崩壊現象を直接実験することにより検証すること、その崩壊モードを詳しく調べることを主要課題とし、更に理論的研究と協力しつつ、より究極的統一理論が左右対称か否かを検定するため、ニュートリノ振動現象の有無を実験的に探索すること、また大統一理論が必然的に预言する磁気単極子など質量の大きい粒子を探索することにある。

昭和56年 9 月

September 1981

... to verify grand unification theories by direct direction of their predicted nucleon decay phenomena...

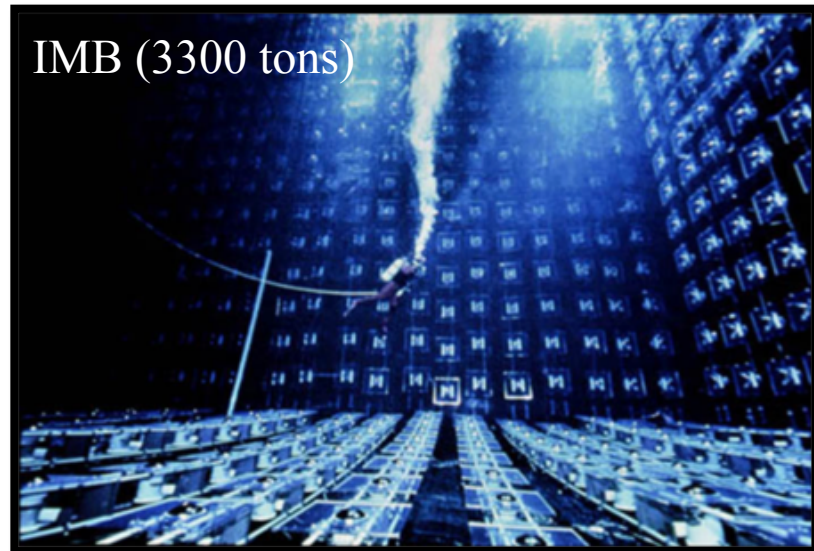
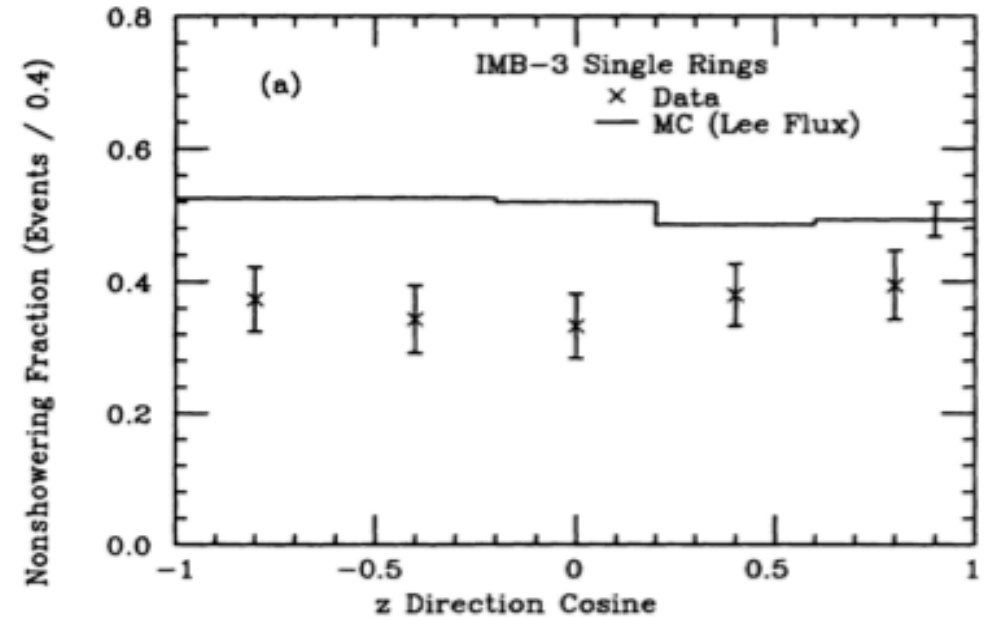
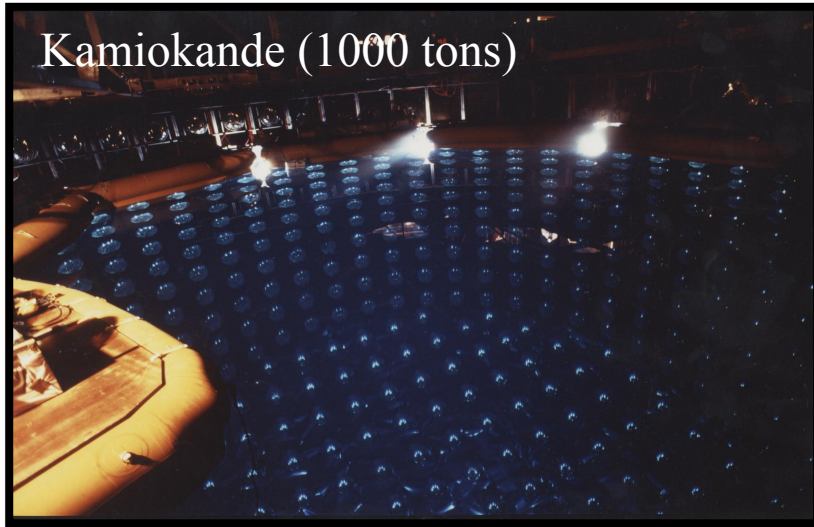
...experimentally search for the existence, or lack thereof, of neutrino oscillation phenomena ...

~ 0.5 events / kton / day

Atmospheric Neutrino Measurements

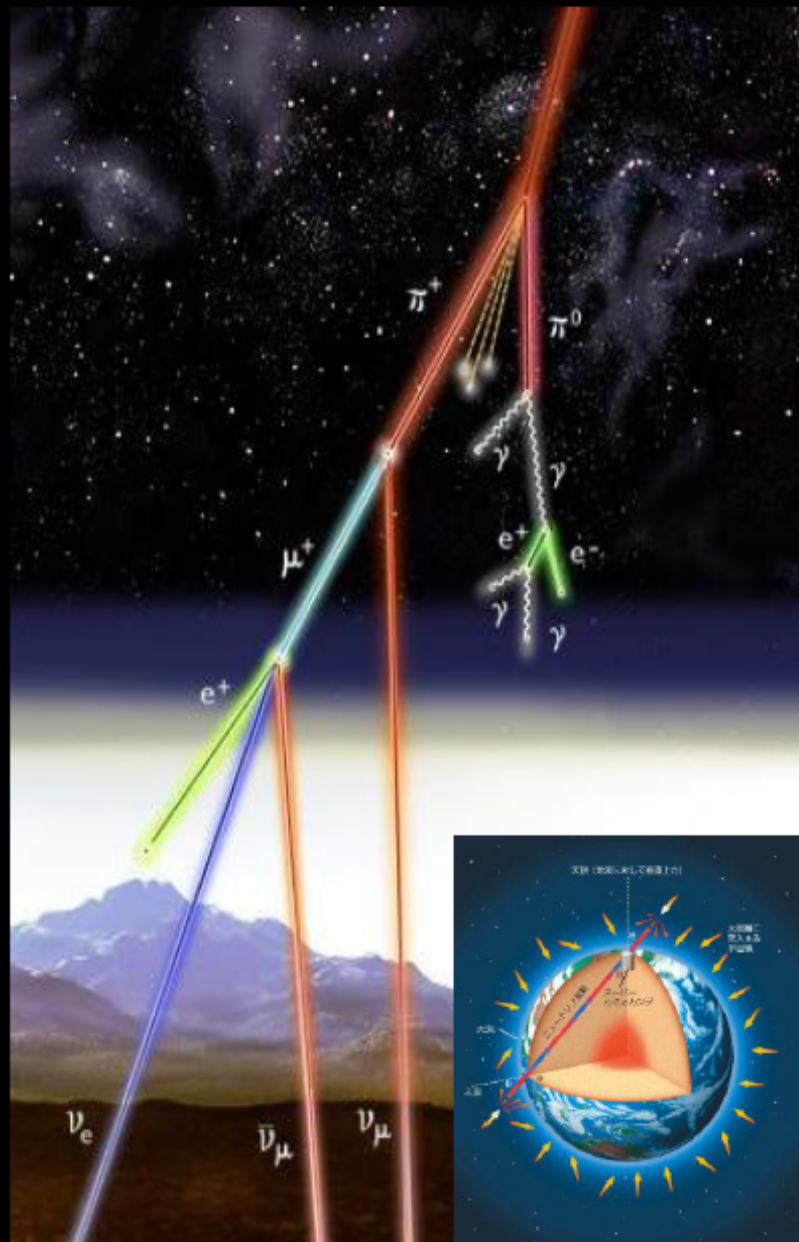
Phys. Rev. Lett. 66, 2561 (1991)

Phys. Rev. D 46, 3720 (1992)



- No observation of proton decay (in any experiments), ruling out SU(5)
 - $\tau_p \rightarrow (e+\pi^0) > 2.6 \times 10^{32}$ years (90% C.L.)
- However, both Kamiokande and IMB observed hint of data/MC discrepancy

Atmospheric Neutrinos



- Neutrinos are produced by the interactions of protons with nuclei in the atmosphere

$$p, A + \text{air} \rightarrow \pi^{\pm}, \pi^0, K^{\pm}, K_{S,L}^0$$

$$\pi^{\pm}, K^{\pm} \rightarrow \mu^{\pm} \nu_{\mu} (\bar{\nu}_{\mu})$$

$$\mu^{\pm} \rightarrow e^{\pm} \nu_e (\bar{\nu}_e) \bar{\nu}_{\mu} (\nu_{\mu})$$

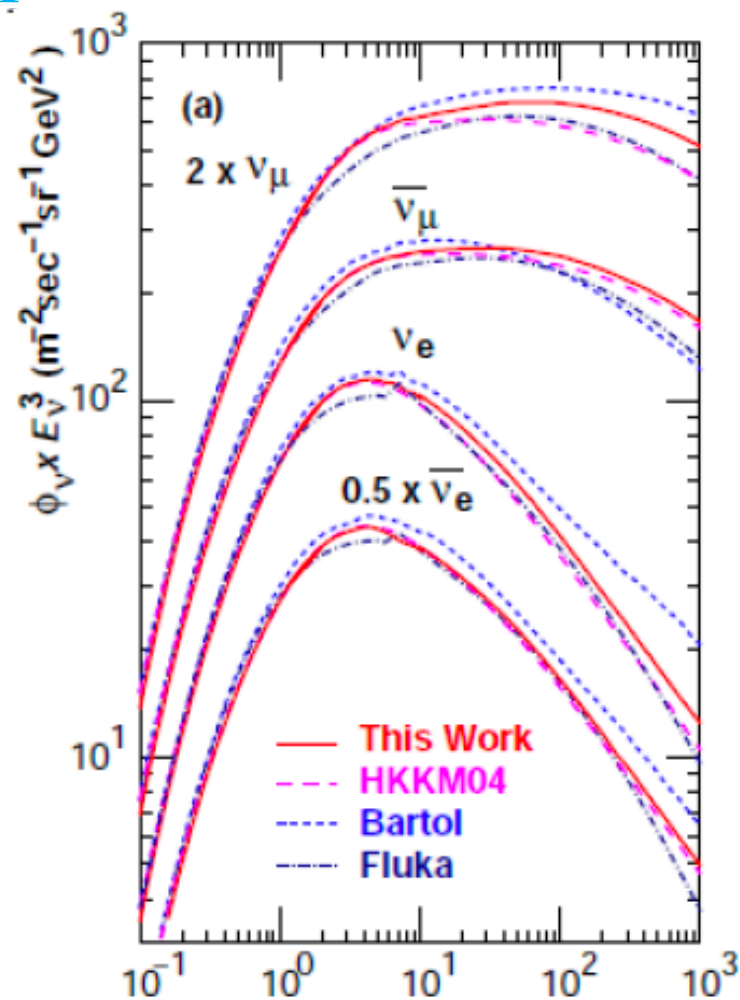
$$K^{\pm}, K_L^0 \rightarrow [\pi^{\pm}, \pi^0] e^{\pm} \nu_e (\bar{\nu}_e)$$

- Isotropic about the earth, producing neutrinos of **MeV~PeV+** energies

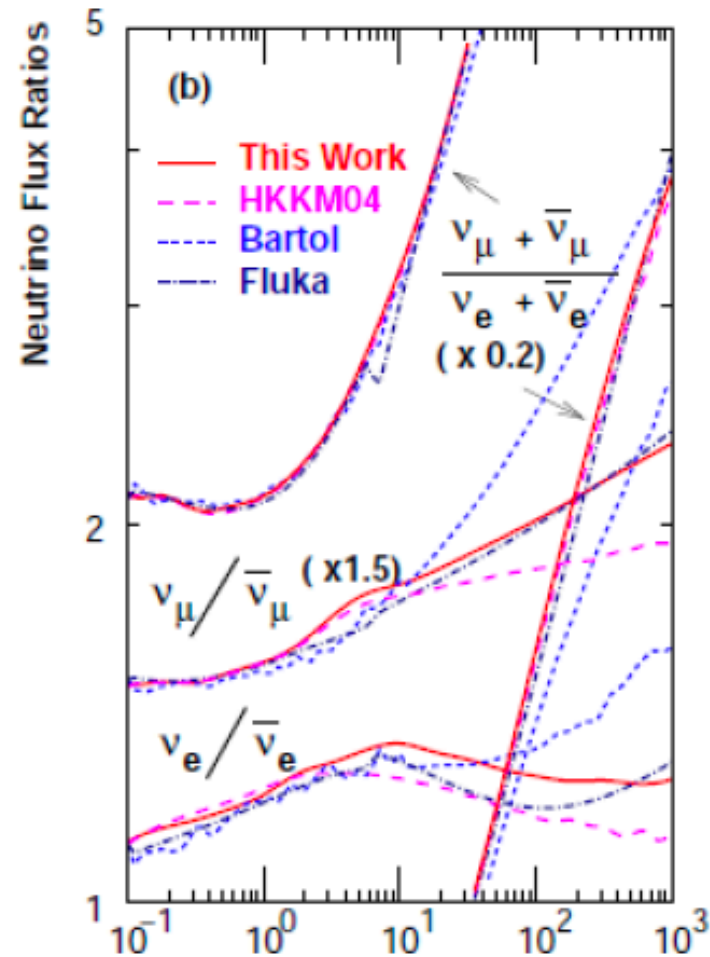
- Path Lengths of **10 ~ 13,000** km

- Neutrino energy, direction, timing, flavor, CP sign are not known a priori, must be determined from interaction products

Atmospheric Neutrino Flux



M. Honda, et. al Phys.Rev.D75:043006,2007

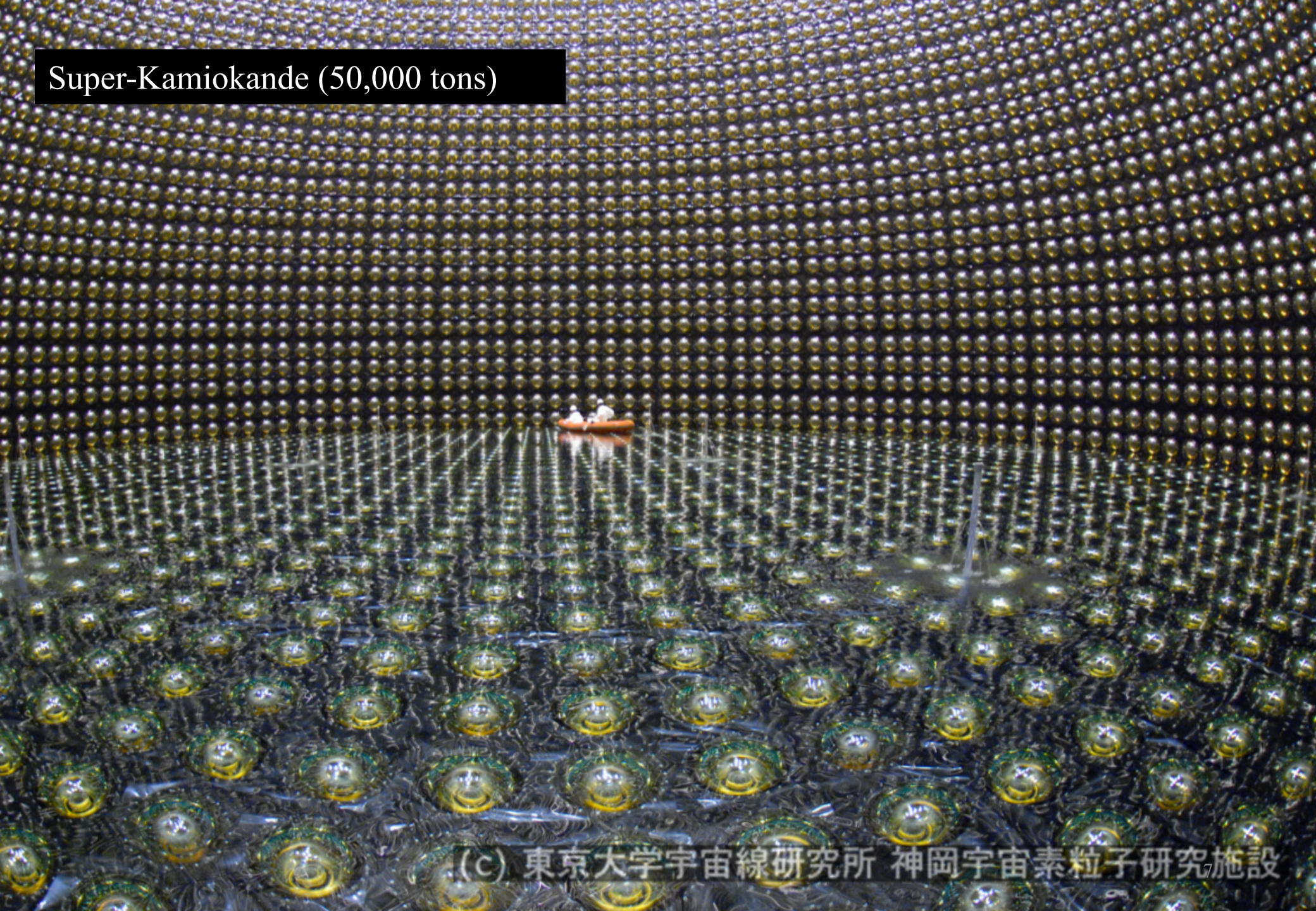


■ At low energies

■ Muon-to-electron neutrino ratio is $\sim 2:1$

■ Neutrino-to-antineutrino ratios are $\sim 1:1$

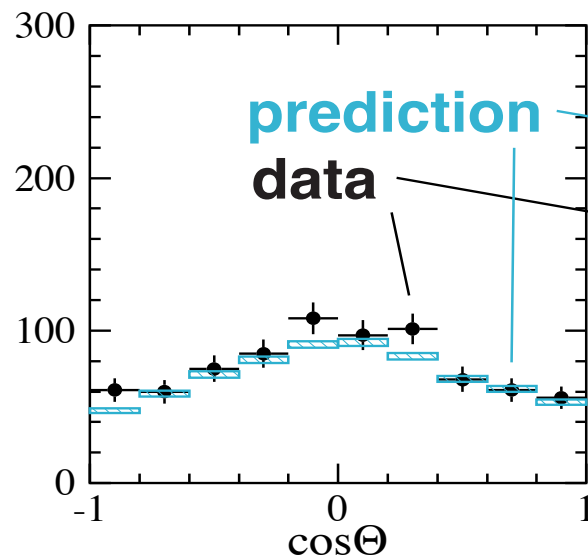
Super-Kamiokande (50,000 tons)



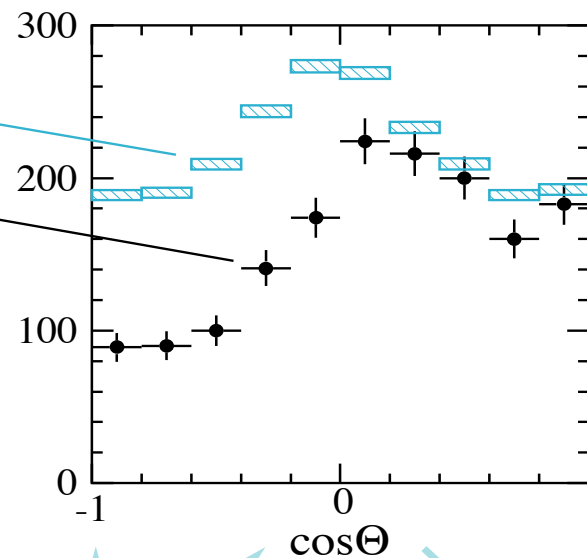
(c) 東京大学宇宙線研究所 神岡宇宙素粒子研究施設

Super-Kamiokande (50,000 tons)

**electron
neutrinos**



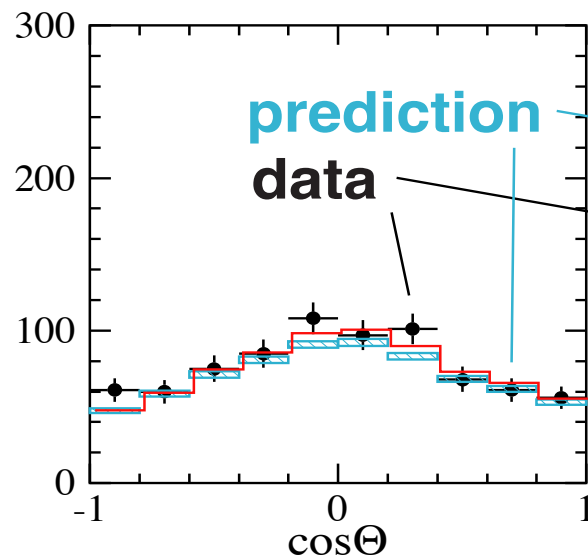
**muon
neutrinos**



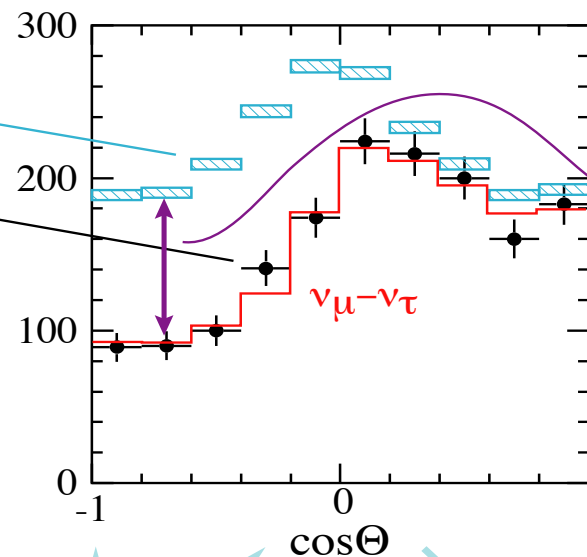
Neutrino travel distance(L): 12800 6200 700 40 15 km

Super-Kamiokande (50,000 tons)

**electron
neutrinos**



**muon
neutrinos**

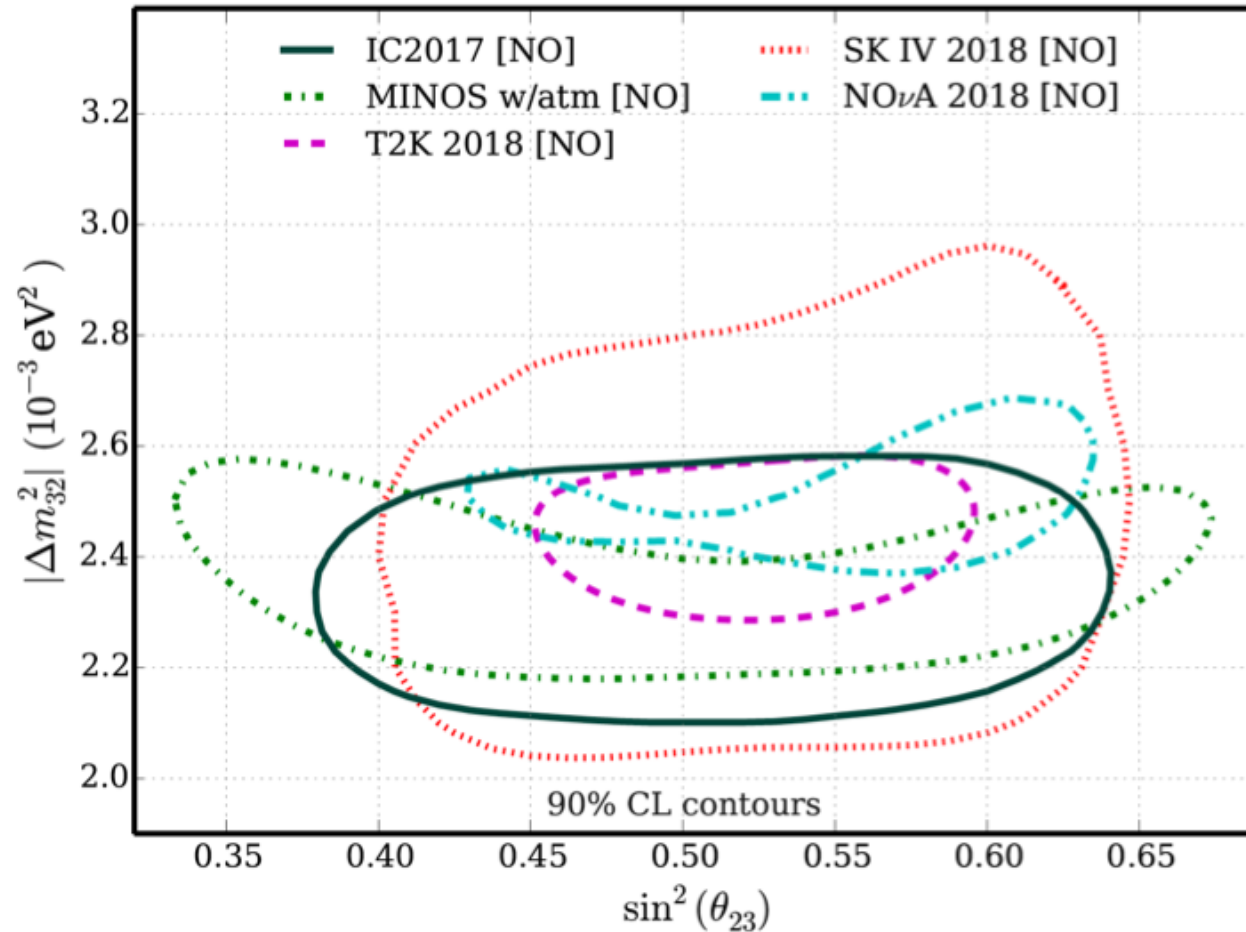


Neutrino travel distance(L): 12800 6200 700 40 15 km

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 (\text{eV}^2) L (\text{km})}{E_\nu (\text{GeV})} \right)$$



Atmospheric Mixing Measurements

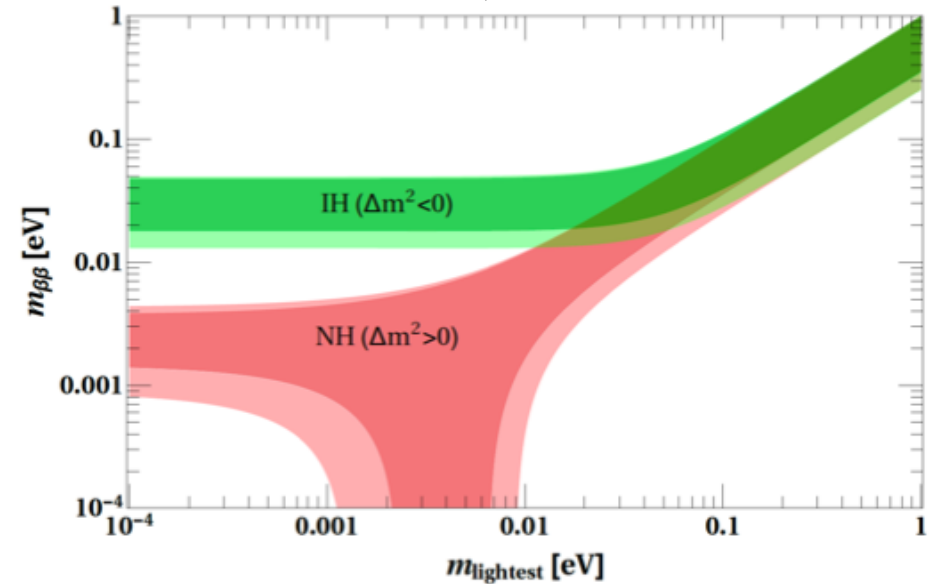


- Atmospheric neutrino oscillation parameter measurements are now dominated by results from accelerator neutrino experiments (c.f. M. Messier 2019.08.09)
- What is left for atmospheric neutrinos ?

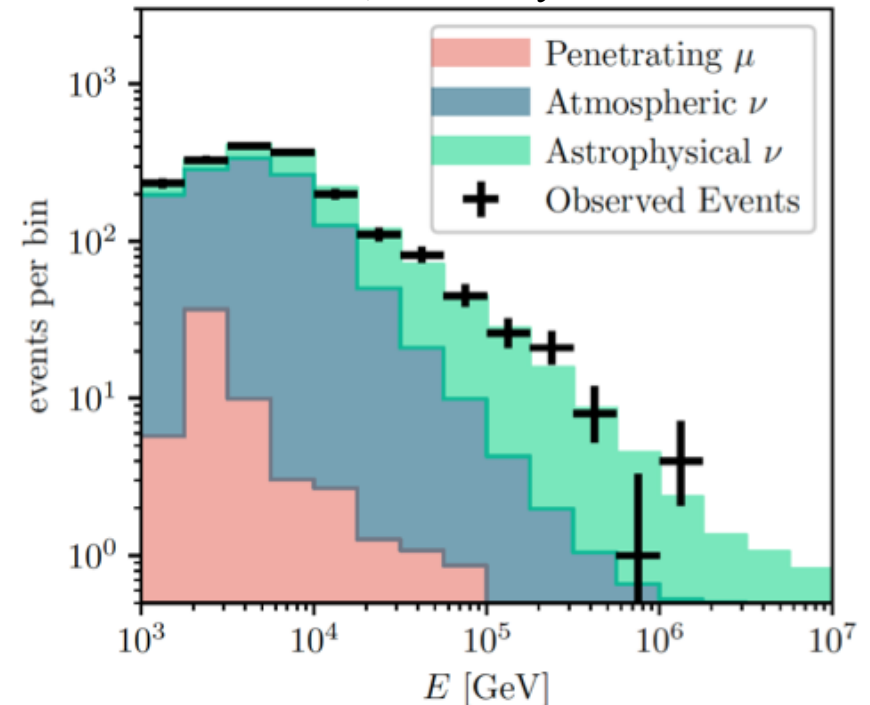
The Program

- There Flavor Oscillations
 - Mass Hierarchy
 - CP Violation
- Cross Section Measurements
 - NC Elastic
 - Tau production
 - Neutrino Absorption in the Earth
 - Inelasticity at high energies
- Exotic Oscillations
 - Sterile Neutrinos
 - Non-standard Interactions
 - Lorentz Violation
- Atmospheric neutrinos are still the dominant background for PDK, SN relic neutrinos, dark matter, astrophysical neutrinos...

AHEP Volume 2016, Article ID 2162659

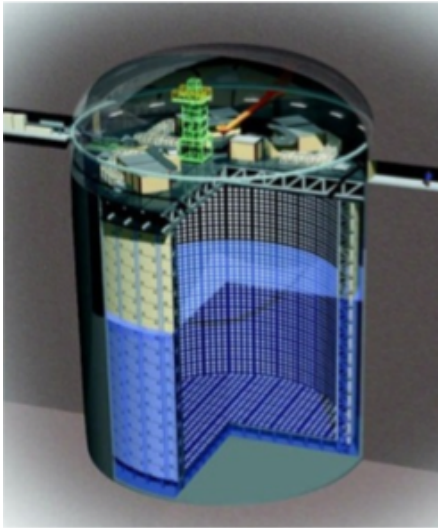


arxiv/1907.06714, c.f. J.Kiryluk 2019.08.09

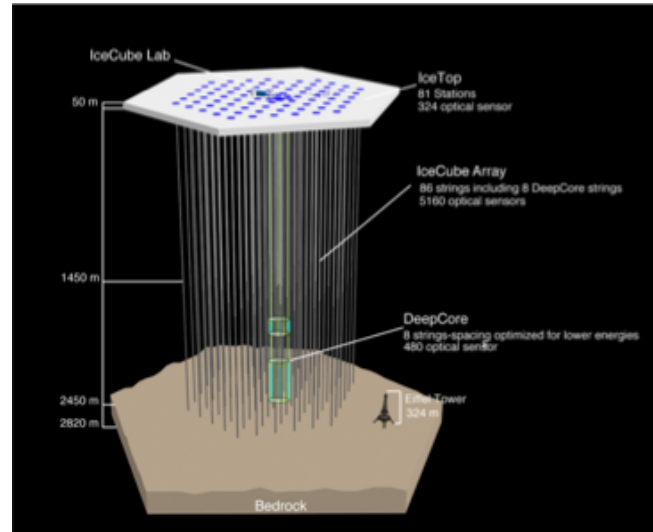


Current Experiments and Recent Results : Atmospheric Neutrinos

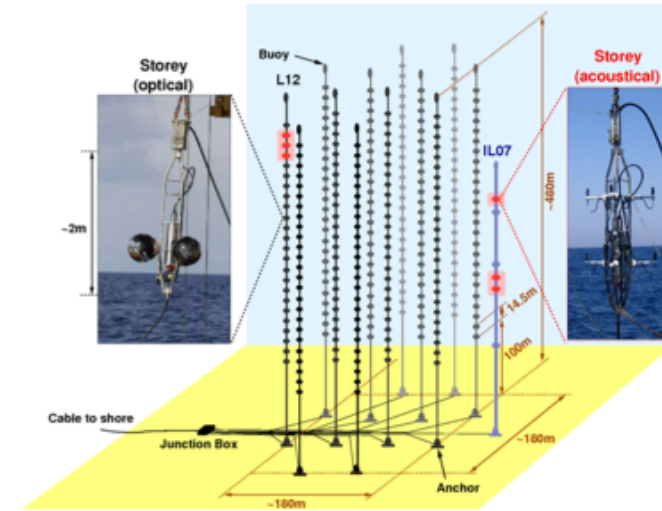
Super-Kamiokande



IceCube DeepCore



Antares



	Super-K	IC / DeepCore	Antares
Threshold	5 MeV	5 GeV	20 GeV
Size	50 kton	1 km ³	0.02 km ³
PID CC ne / nm	e-like / μ -like	Cascade / Track	Shower / Track
Operational	1996 ~	2009 ~	2008 ~

- N.B. All are Cherenkov detectors, none can discriminate neutrinos from antineutrinos on an even-by-event basis

Oscillation Hamiltonians : PMNS

$$H = U M U^\dagger + V_e \quad M = \frac{1}{2E} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} \quad V_e = \pm \sqrt{2} G_F \begin{pmatrix} N_e & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

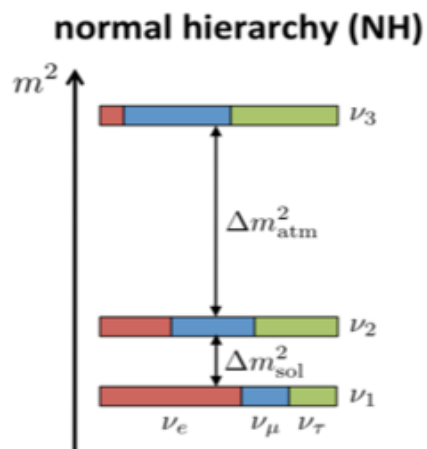
Atmospheric

Reactor, LBL

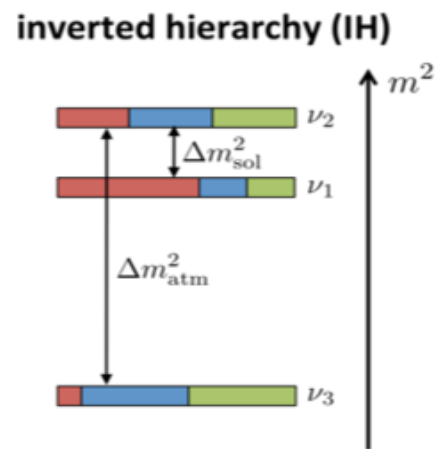
Solar

Local number of electrons

Mass Ordering is Unknown

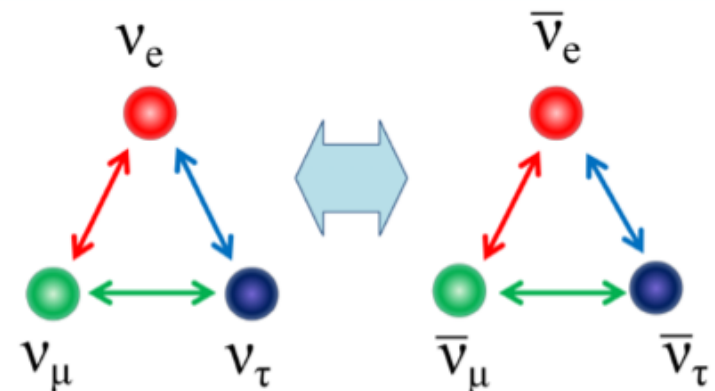


$$\Delta m_{32}^2 > 0$$



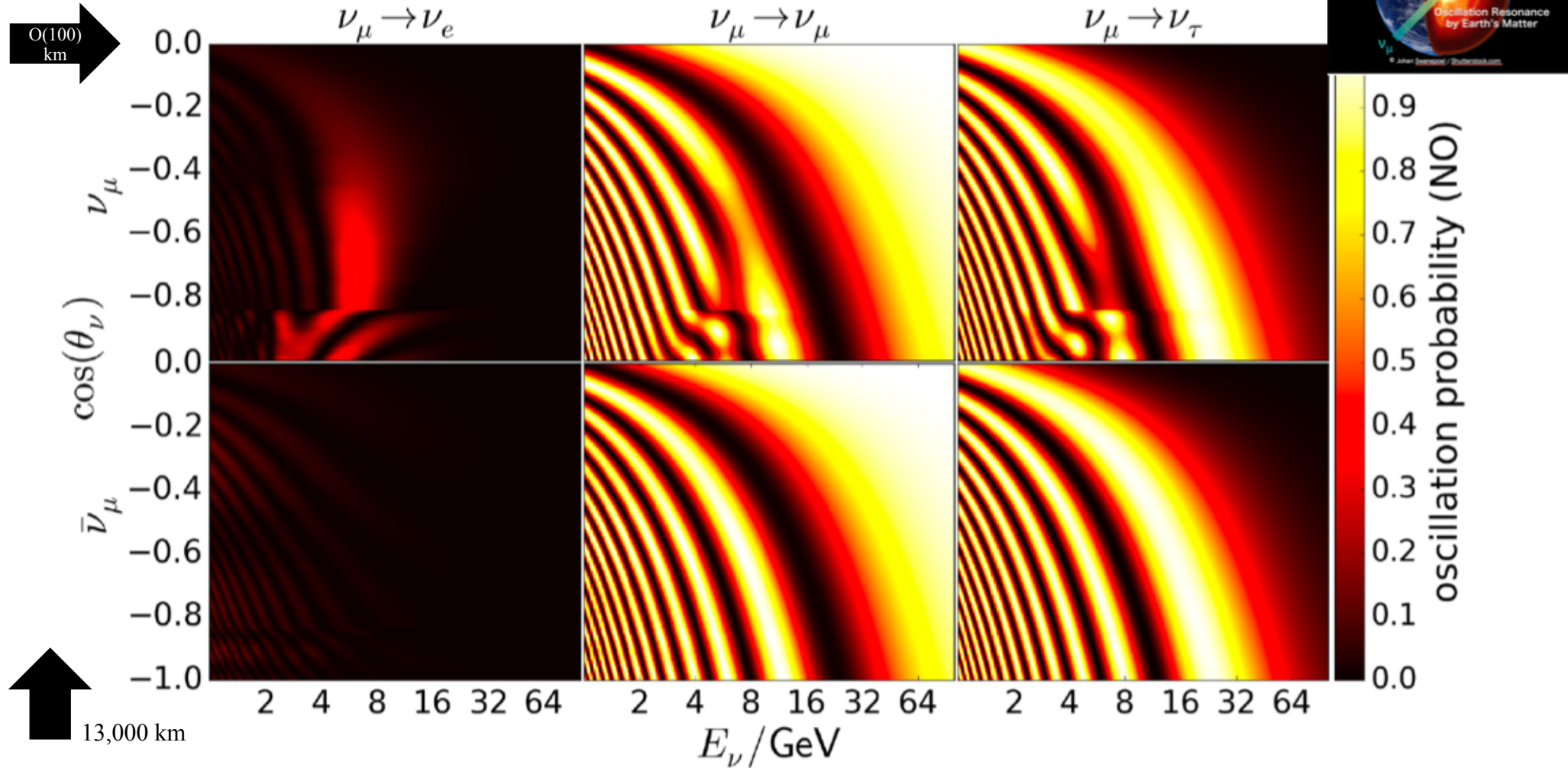
$$\Delta m_{32}^2 < 0$$

CP Violation?



PMNS Oscillations: Normal Ordering

arXiv:1902.07771v1

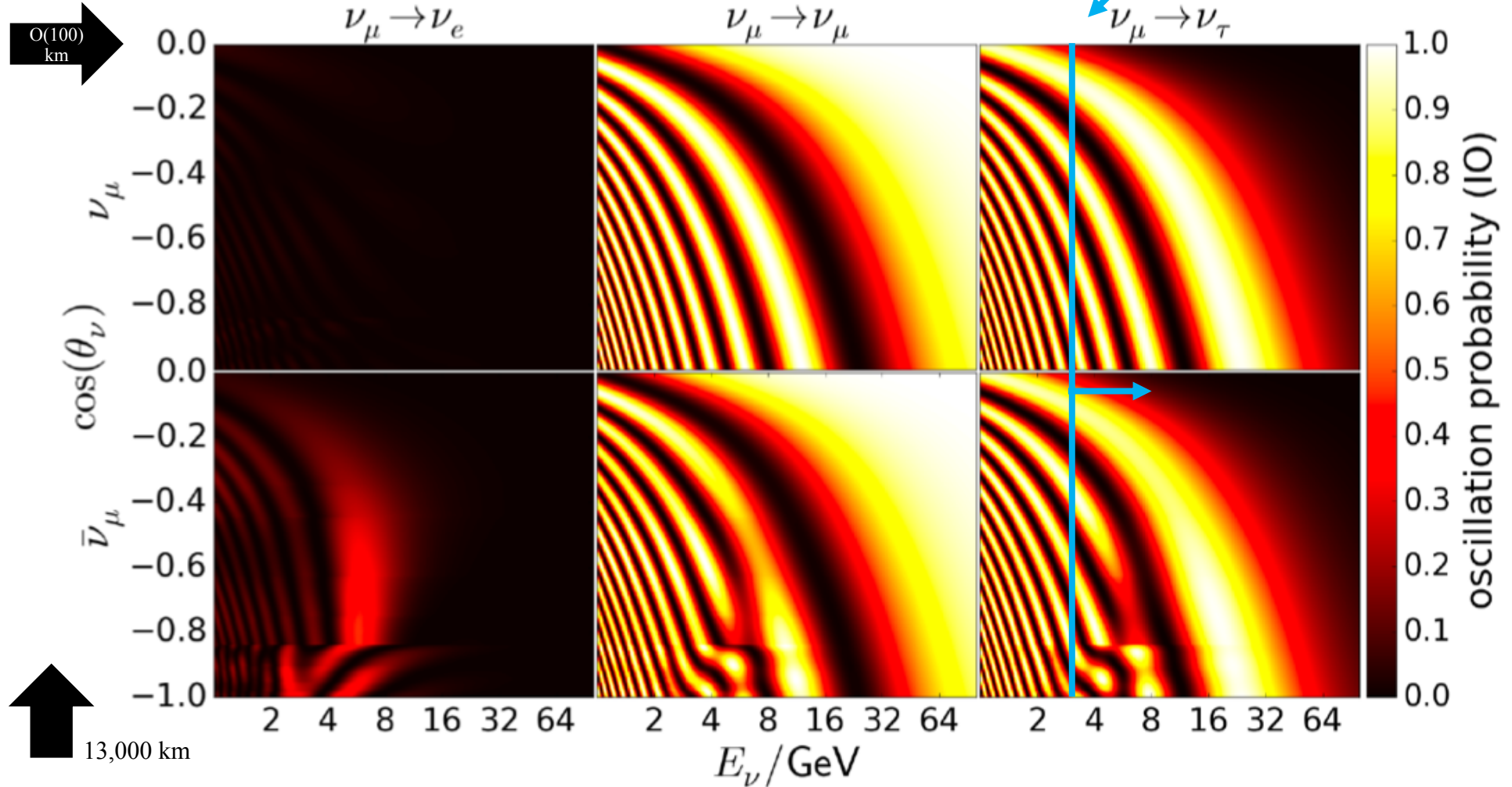


- Size of 2~10 GeV resonance depends on MH , θ_{13} , θ_{23} , and δ_{CP} (in order of strength)
- No PMNS oscillations above ~50 GeV for any neutrino pathlength

PMNS Oscillations: Inverted Ordering

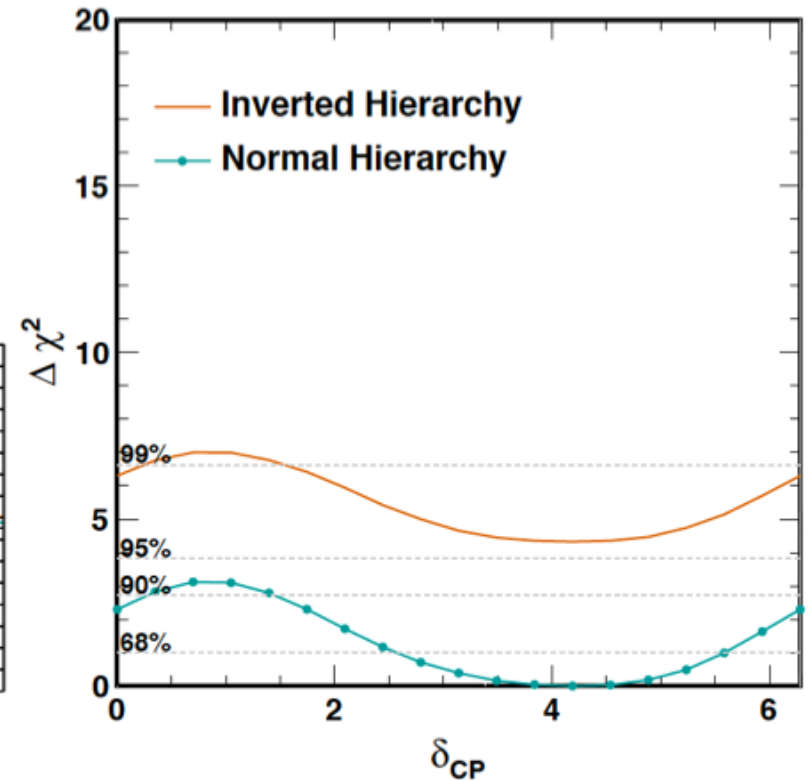
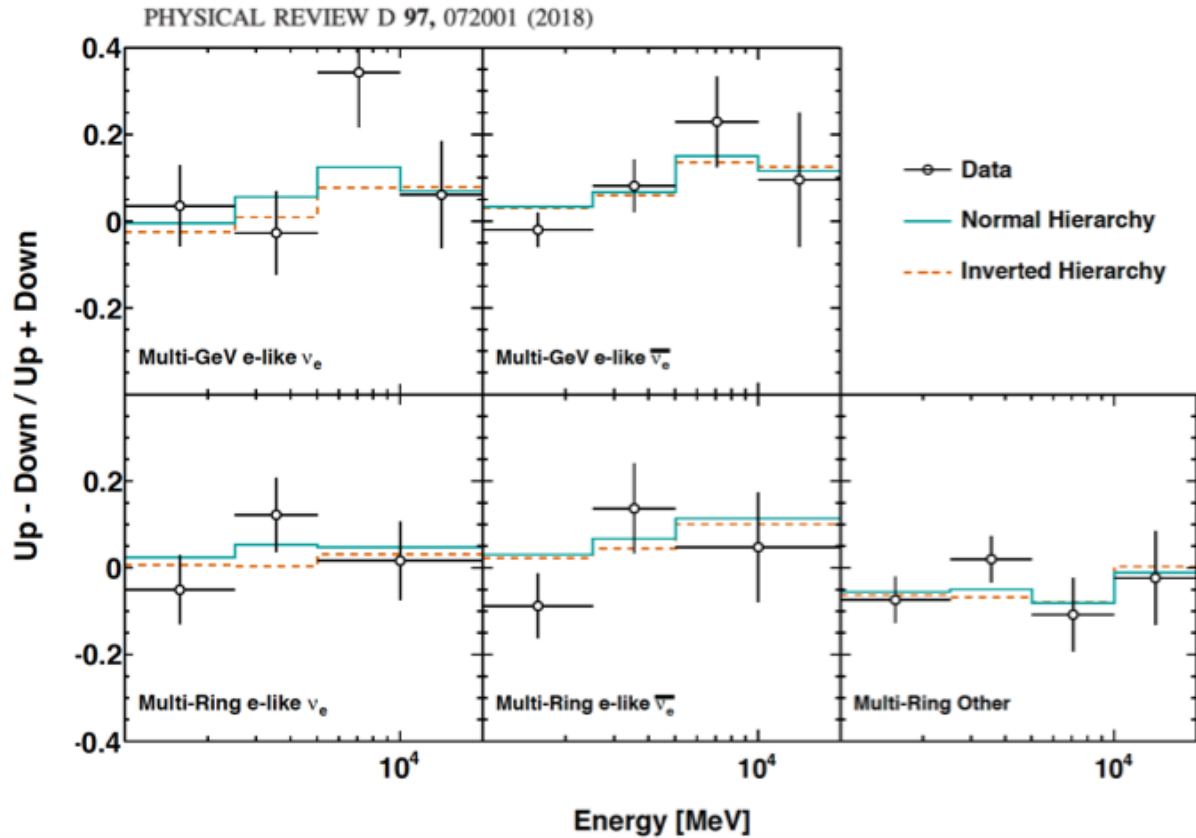
arXiv:1902.07771v1

CC $\nu\tau$ threshold



- Size of 2~10 GeV resonance depends on MH , θ_{13} , θ_{23} , and δ_{CP} (in order of strength)
- No PMNS oscillations above ~ 50 GeV for any neutrino pathlength

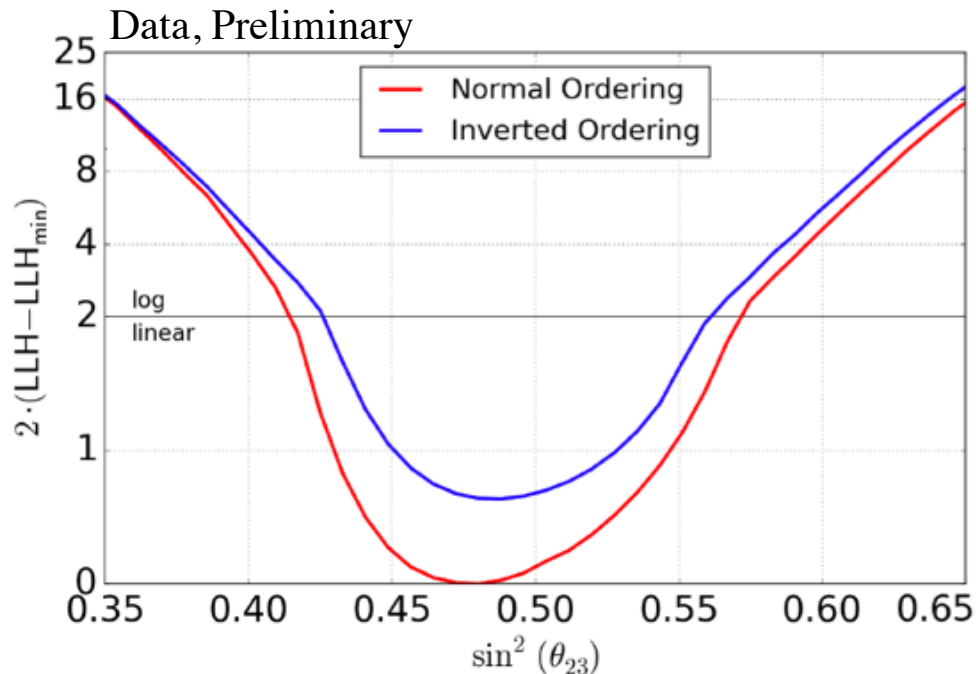
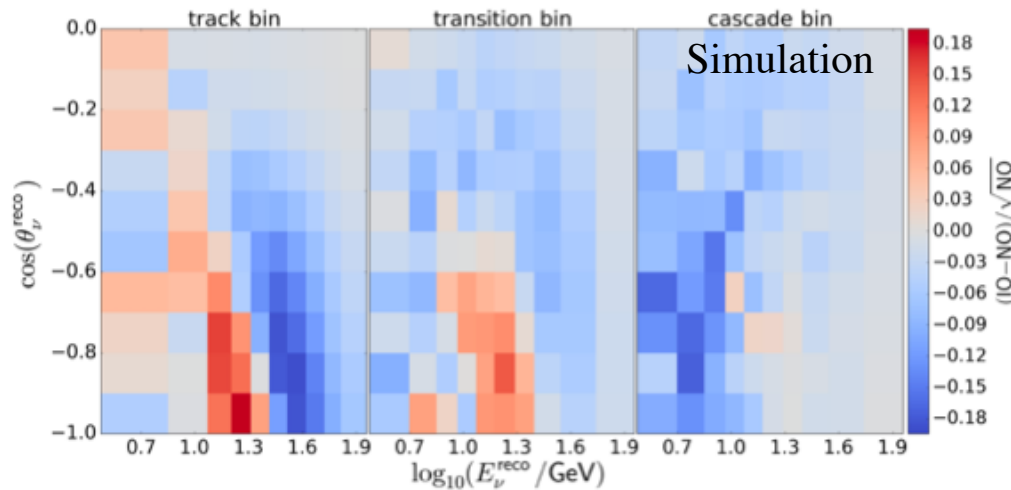
Hierarchy and δ_{cp} : Super-K (only)



- Atmospheric mixing angles consistent with other experiments, weak preference for $\sin^2\theta_{23} > 0.5$ ($< 1\sigma$)
 - $\Delta m_{32}^2 = 2.5^{+0.13}_{-0.20} \times 10^{-3} \text{ eV}^2$
 - $\sin^2\theta_{23} = 0.588^{+0.031}_{-0.064}$
- **Normal hierarchy preference:** CL_s 82.9-96.7% (91.9-94.4% with T2K constraint)
- $\delta_{cp} \sim 1.33\pi$

Hierarchy : IceCube DeepCore

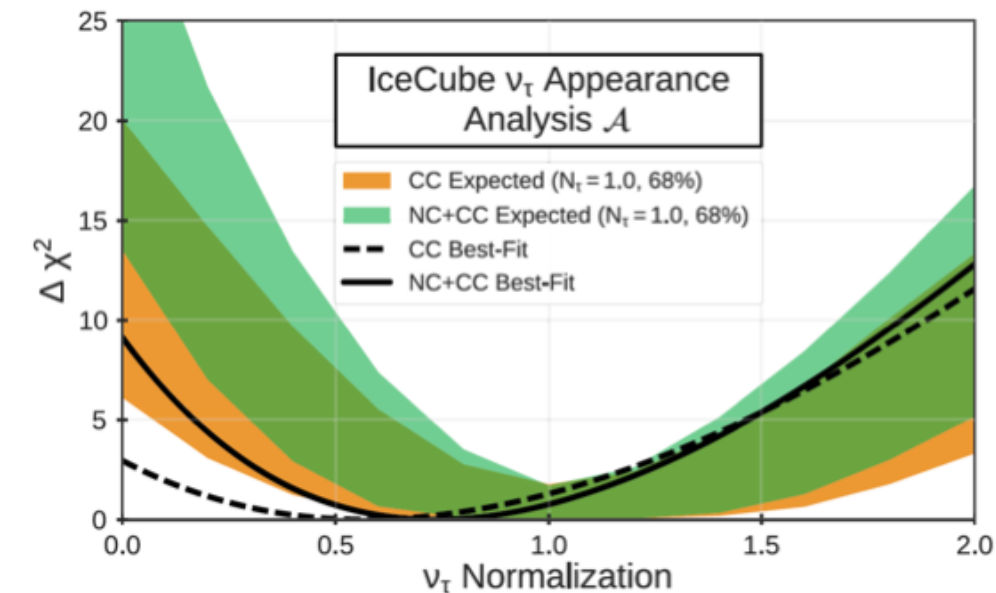
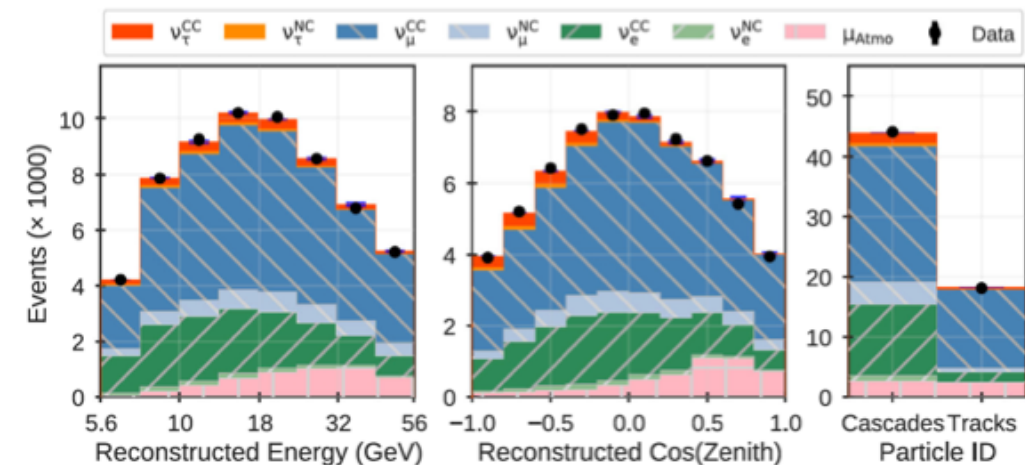
arXiv:1902.07771v1



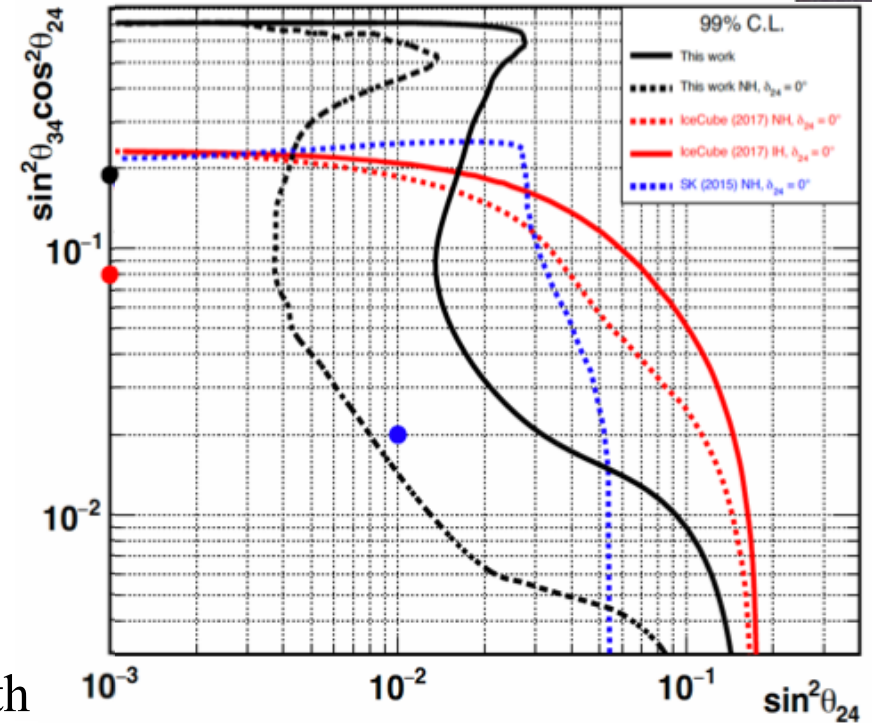
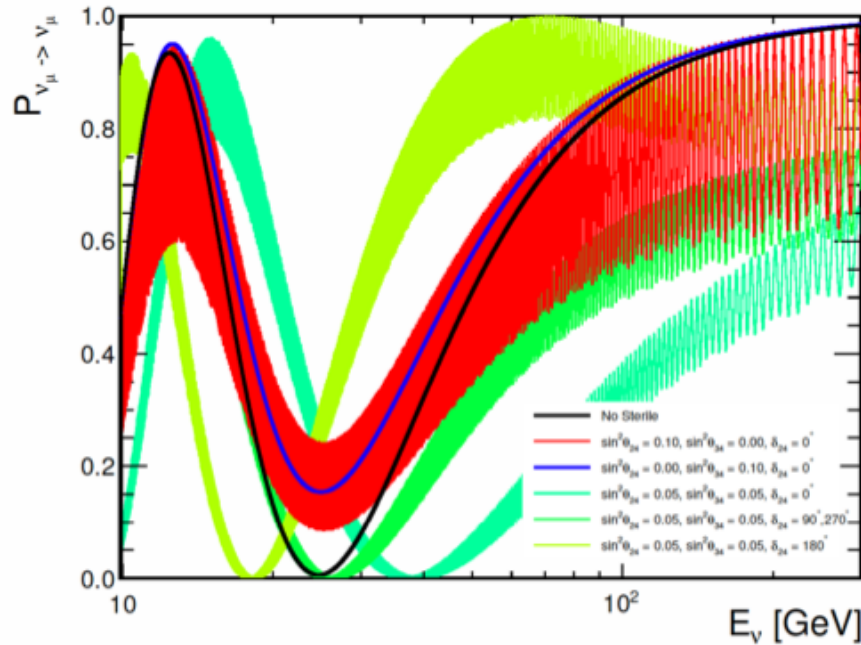
- Complementary search for the MH using both track-like and cascade-like events, higher energy threshold
- 3 years of DeepCore Data, 43,000 Events
- Search for zenith angle- and energy-dependent distortion consistent with MH
- Weak preference for the **normal hierarchy**
 $p_{\mathcal{A}}(\mathcal{H}_{\text{NO}}) = 71.1\%$ ($\text{CL}_s^{\mathcal{A}}(\mathcal{H}_{\text{NO}}) = 83.0\%$),
 $p_{\mathcal{A}}(\mathcal{H}_{\text{IO}}) = 15.7\%$ ($\text{CL}_s^{\mathcal{A}}(\mathcal{H}_{\text{IO}}) = 53.3\%$),
- Expected sensitivity:
 - $0.5 \sim 0.6\sigma$ at $\sin^2\theta_{23} = 0.5$

Search for Tau Neutrinos

PHYS. REV. D 99, 032007 (2019)



- No ν_τ in atmospheric flux below 100 TeV
- Search for evidence of oscillation-induced tau interactions
- Appear as increase in number of cascade-like events (hadronic decay) or track-like (leptonic decay)
- Use BDTs to extract signal, incurs large backgrounds, constrained by zenith and energy distributions
- IceCube finds 3.2σ significance for appearance of tau events (CC+NC)
- Complementary to other recent searches
 - 6.1σ from Opera (acc. 2018)
 - 4.6σ from Super-K (atm. 2018)



- Add an additional mass state for a neutrino with no weak interactions and expand mixing matrix accordingly

- Assume Δm_{32}^2 is dominant

- Track-like events from 20~100 GeV
- Result is compatible with pure PMNS mixing, though best fit weakly favors a sterile component

$$U_{\mu 4} = e^{-i\delta_{24}} \sin \theta_{24}$$

$$U_{\tau 4} = \sin \theta_{34} \cos \theta_{24}$$

$$|U_{\mu 4}|^2 < 0.007 \text{ (0.13) at 90\% (99\%) CL,}$$

$$|U_{\tau 4}|^2 < 0.40 \text{ (0.68) at 90\% (99\%) CL.}$$

Lorentz Violating Oscillations

$$H = U M U^\dagger + V_e + H_{LV}$$

- Include Lorentz-violating terms for isotropic LV field based on effective field theory (Standard Model Extension)

$$H_{LV} = \hat{a}^{(3)} - E \hat{c}^{(4)} + E^2 \hat{a}^{(5)} - E^3 \hat{c}^{(6)} \dots$$

$$\hat{c}^{(6)} = \begin{pmatrix} \hat{c}_{\mu\mu}^{(6)} & \hat{c}_{\mu\tau}^{(6)} \\ \hat{c}_{\mu\tau}^{(6)*} & -\hat{c}_{\mu\mu}^{(6)} \end{pmatrix}$$

- Assume LV terms are small enough to induce limited $\nu_\mu \rightarrow \nu_e$ transitions, then at high energy

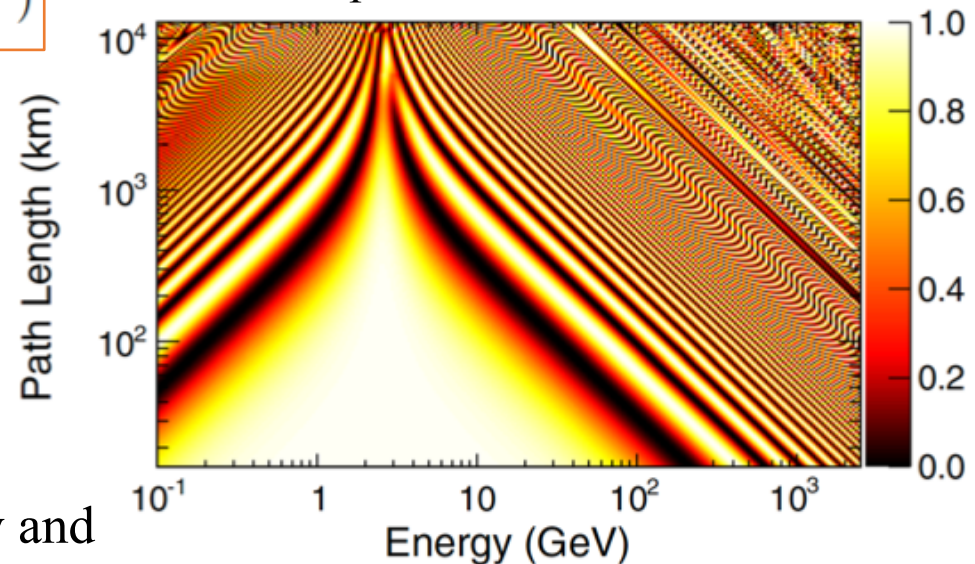
$$P(\nu_\mu \rightarrow \nu_\tau) = \frac{|\hat{a}_{\mu\tau}^{(d)} - \hat{c}_{\mu\tau}^{(d)}|^2}{\rho_d^2} \sin^2(L\rho_d \cdot E^{d-3})$$

Recall , PMNS $\sim L/E$

$$\rho_d \equiv \sqrt{(\hat{a}_{\mu\mu}^{(d)})^2 + \text{Re}(\hat{a}_{\mu\tau}^{(d)})^2 + \text{Im}(\hat{a}_{\mu\tau}^{(d)})^2} \\ \sqrt{(\hat{c}_{\mu\mu}^{(d)})^2 + \text{Re}(\hat{c}_{\mu\tau}^{(d)})^2 + \text{Im}(\hat{c}_{\mu\tau}^{(d)})^2}$$

- Effects are expected to increase with energy and path length

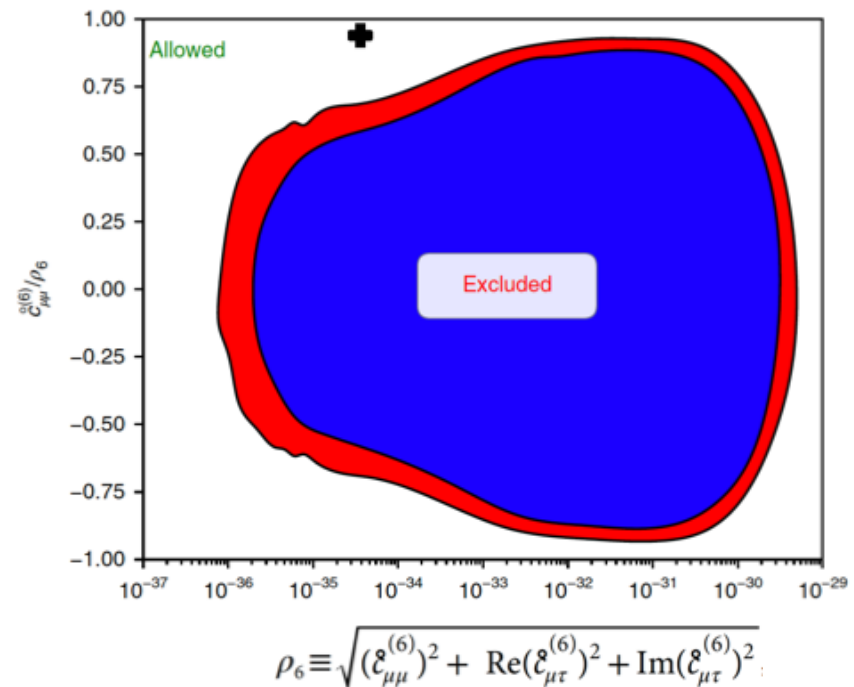
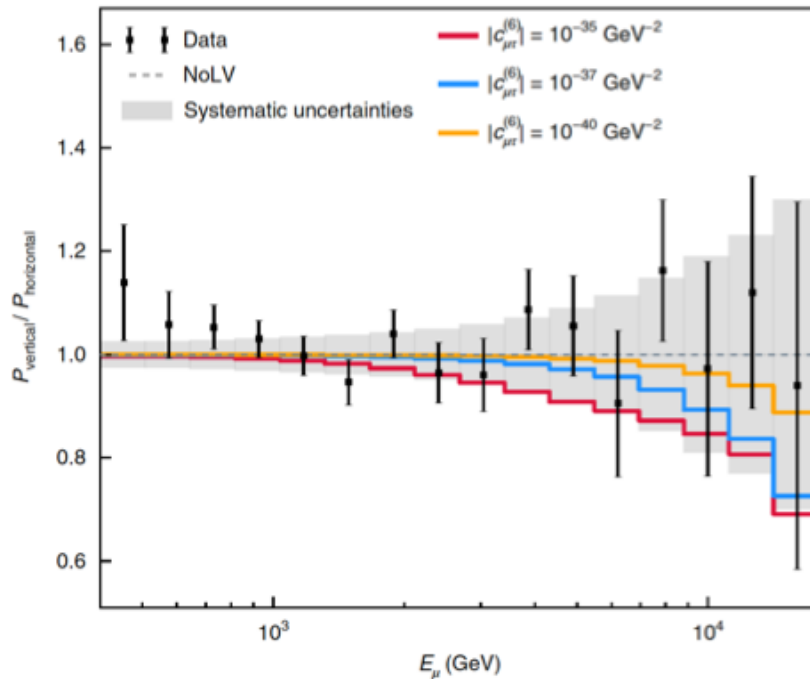
Example for d=4



$$\nu_\mu \rightarrow \nu_\mu, c_{\mu\tau}^{TT} = 7.5 \times 10^{-23}$$

Lorentz Violating Oscillations

Nature Physics VOL 14 (2018) 961



- Effects are expected to increase with energy and path length, ideal for IceCube
- Significantly improve constraints on d=3 through d=8 LV coefficients,
 - For d=3,4 up to order of magnitude more stringent than previous results
 - New oscillation-based limits for higher dimension operators

$$|\text{Re}(\hat{a}_{\mu\tau}^{(3)})|, |\text{Im}(\hat{a}_{\mu\tau}^{(3)})| < 2.9 \times 10^{-24} \text{ GeV}$$

$$< 2.0 \times 10^{-24} \text{ GeV}$$

$$|\text{Re}(\hat{c}_{\mu\tau}^{(4)})|, |\text{Im}(\hat{c}_{\mu\tau}^{(4)})| < 3.9 \times 10^{-28}$$

$$< 2.7 \times 10^{-28}$$

$$|\text{Re}(\hat{a}_{\mu\tau}^{(7)})|, |\text{Im}(\hat{a}_{\mu\tau}^{(7)})| < 8.3 \times 10^{-41} \text{ GeV}^{-3}$$

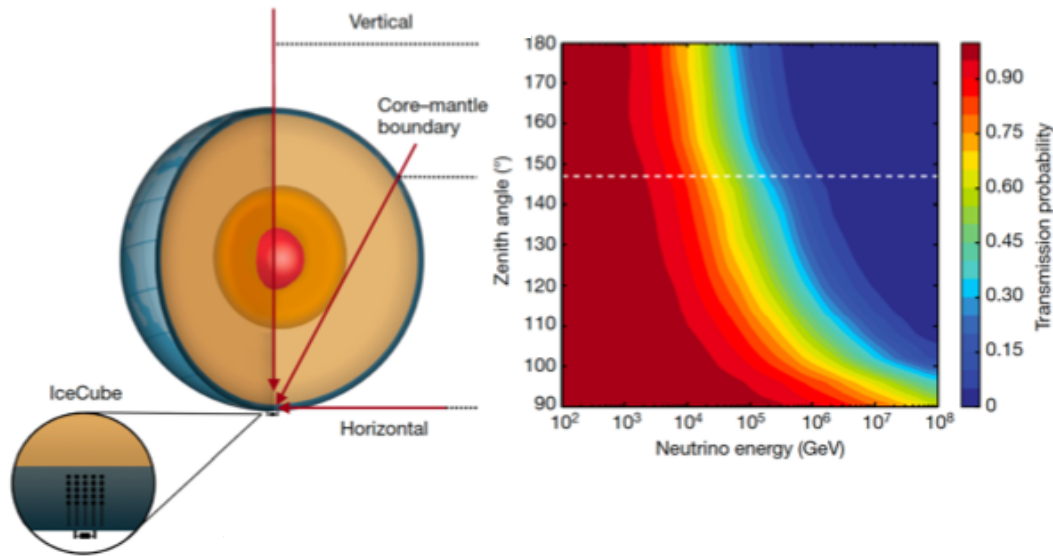
$$< 3.6 \times 10^{-41} \text{ GeV}^{-3}$$

$$|\text{Re}(\hat{c}_{\mu\tau}^{(8)})|, |\text{Im}(\hat{c}_{\mu\tau}^{(8)})| < 5.2 \times 10^{-45} \text{ GeV}^{-4}$$

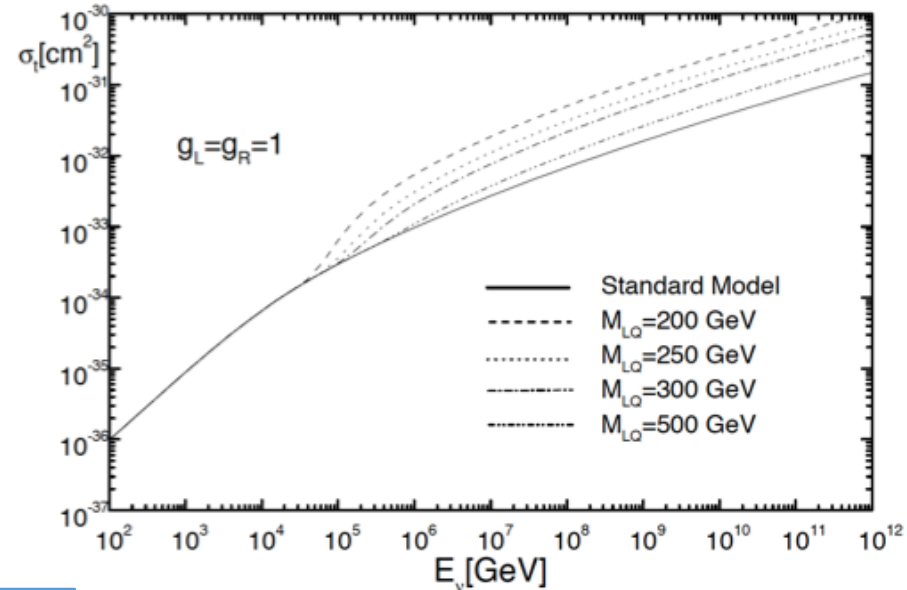
$$< 1.4 \times 10^{-45} \text{ GeV}^{-4}$$

High Energy Neutrino Interaction Cross Section

NATURE 551 (2017)



J. High Energy Phys. 2009, 111 (2009)

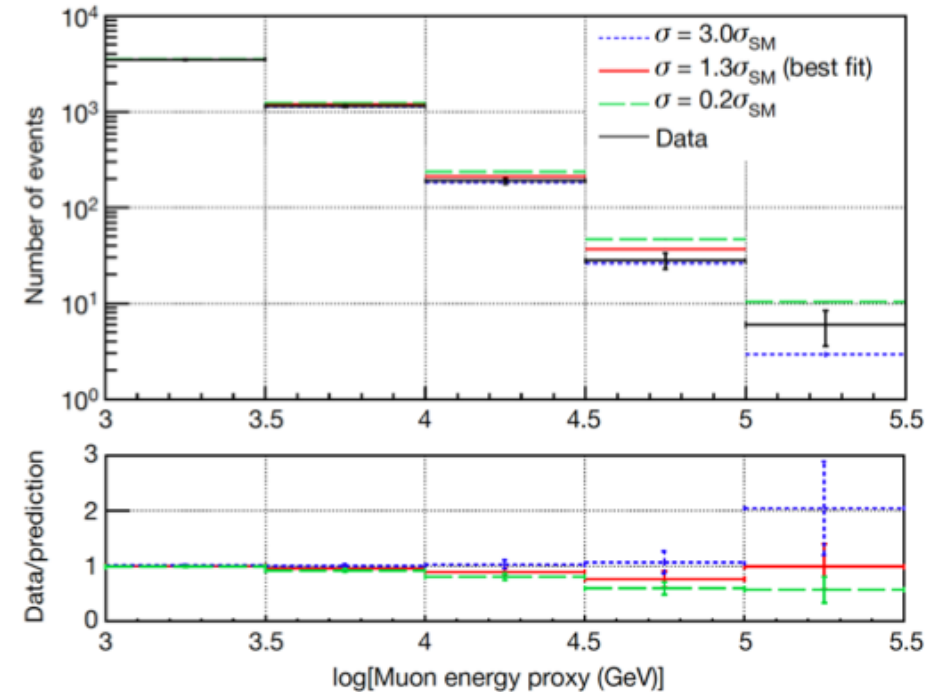
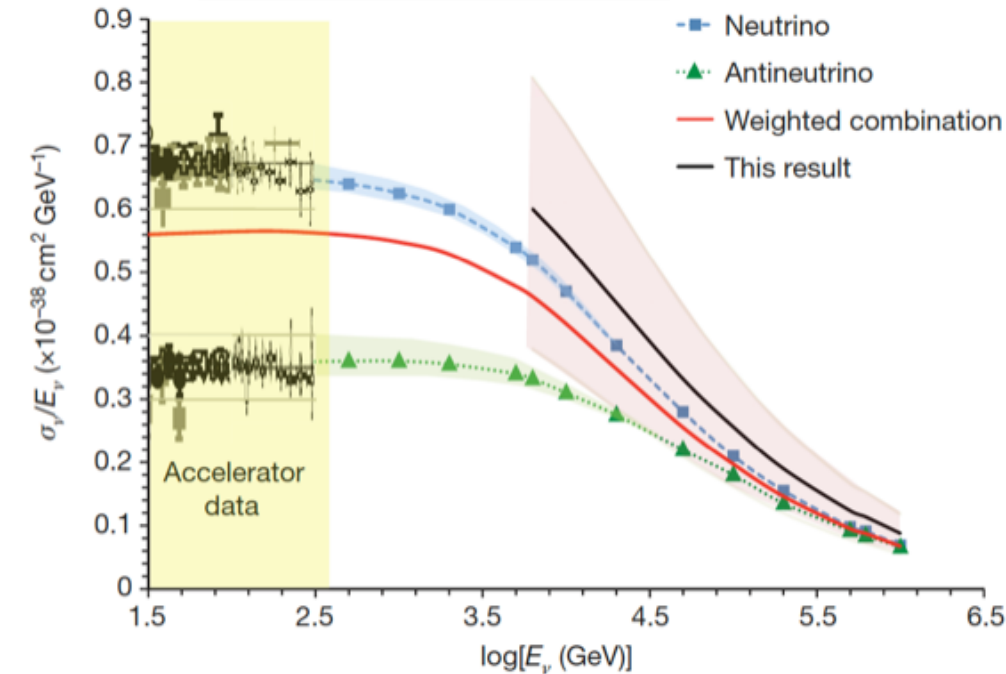


$$\frac{d^2\sigma(\nu_l N \rightarrow l^- X)}{dxdy} = \frac{2G_F^2 ME}{\pi} \left(\frac{M_W^2}{Q^2 + M_W^2} \right)^2 [xq(x, Q^2) + x\bar{q}(x, Q^2)(1-y)^2]$$

- At TeV energies the Earth becomes increasingly opaque to neutrinos
 - Observable as a depletion in the upward-going neutrino rate
- Interaction cross section is proportional to neutrino energy at low energies
 - For momentum transfer comparable to the weak boson mass, increase with energy slows
 - BSM physics can enhance and supplement the cross section

High Energy Neutrino Interaction Cross Section

NATURE 551 (2017)

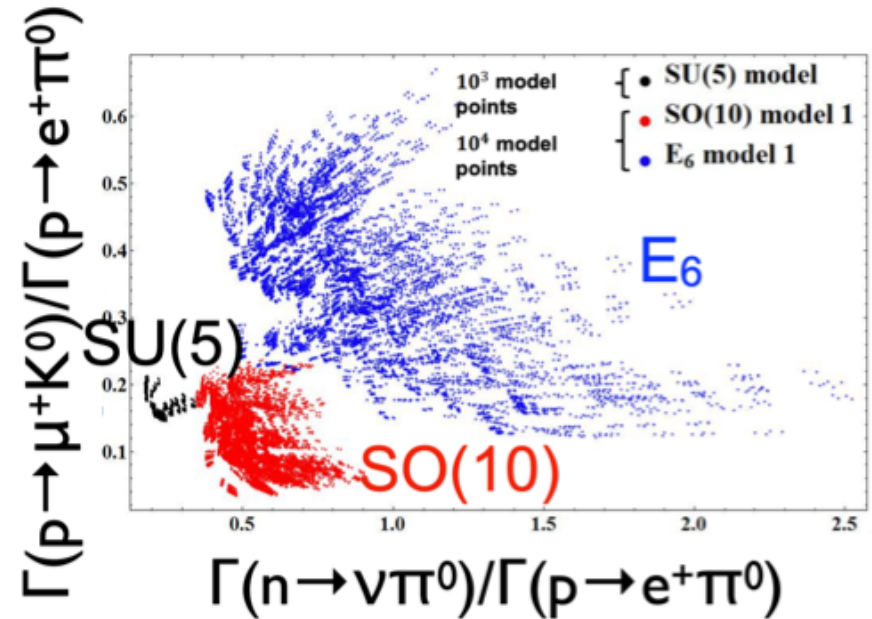
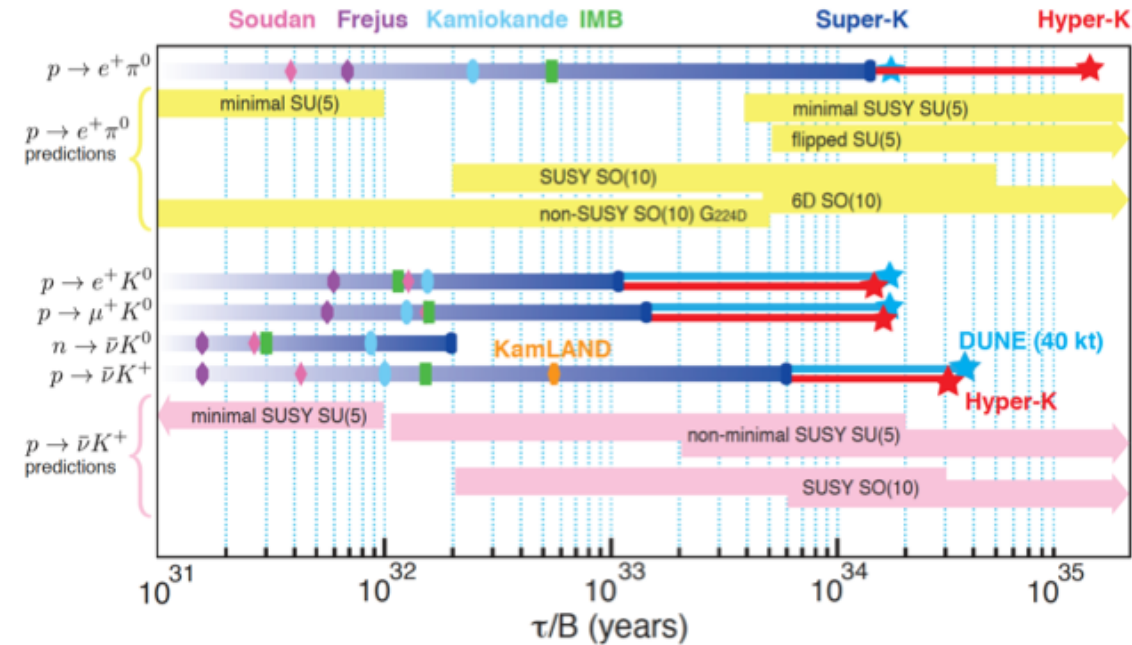


- Analysis uses 10,784 upward-going muons from IceCube-79 data

$$\sigma = 1.30_{-0.19}^{+0.21}(\text{stat})_{-0.43}^{+0.39}(\text{syst.}) \sigma_{\text{SM}}$$

- No indication of deviation from SM
- First measurement about 370 GeV, extensible to higher energies with next-generation detectors

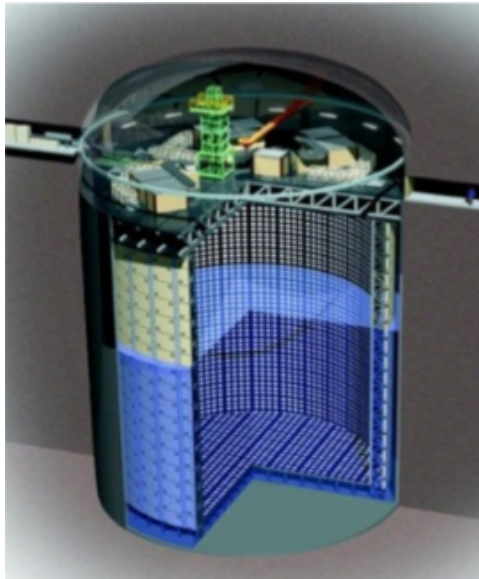
Current Experiments and Recent Results : Proton Decay



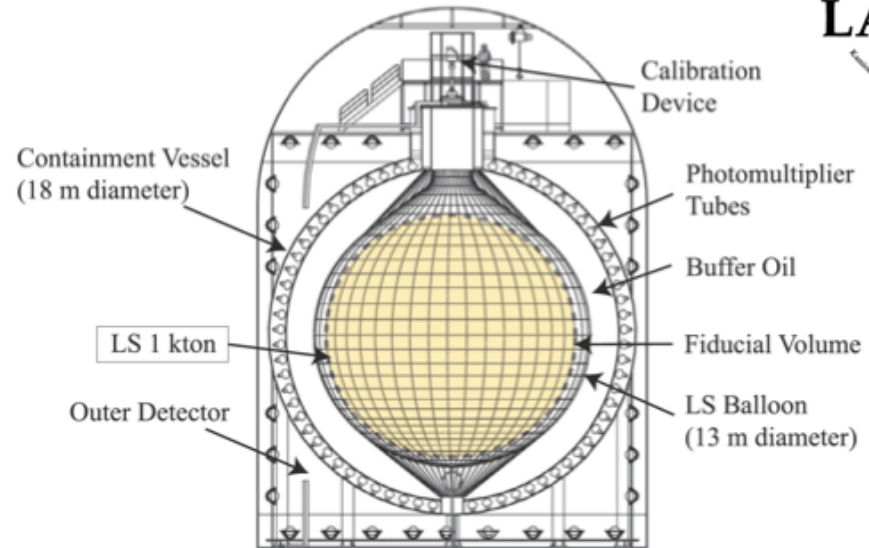
- Observation of proton decay would be a clear indication of GUTs
- Measuring the branching fractions of different decay modes will constrain the particular model

Current Experiments and Recent Results : Proton Decay

Super-Kamiokande



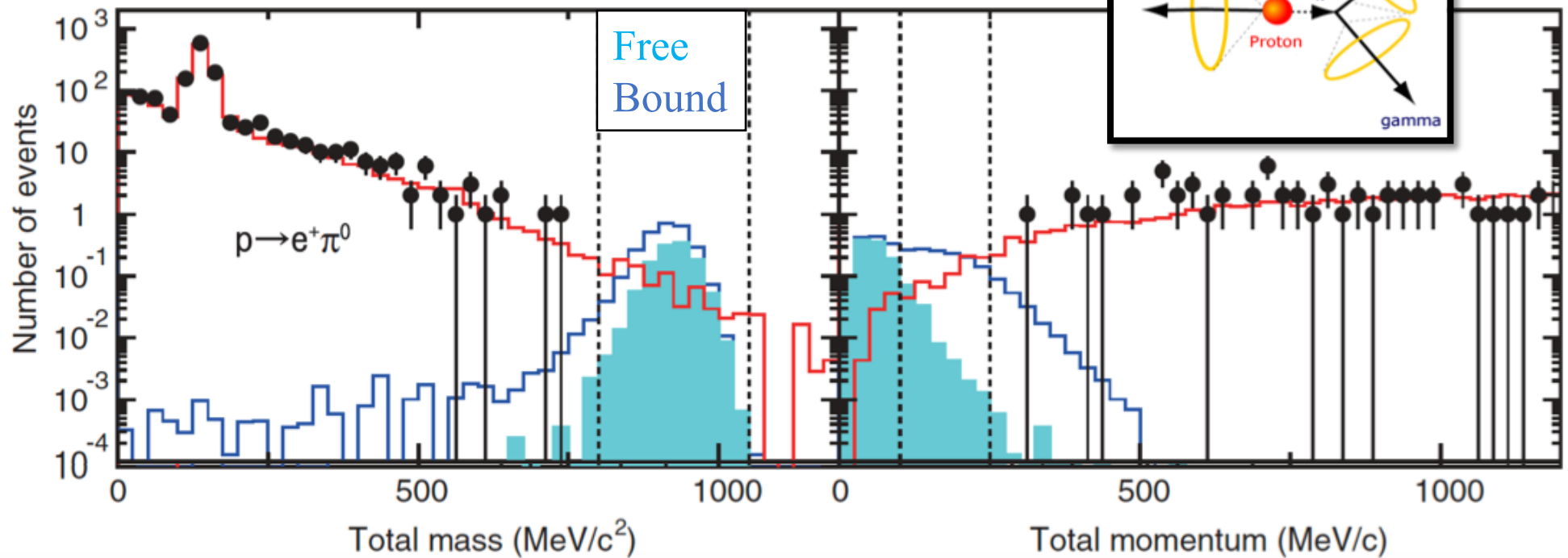
KamLAND



	Super-K	KamLAND
Threshold	5 MeV	1 MeV
Size	50 kton	1 kton
Operational	1996 ~	2001~

■ N.B. Thresholds are too high at neutrino telescopes for proton decay

Proton Decay into $e^+\pi^0$



- Back-to-back signal topology with all final state particles visible
- Fully reconstruct initial proton kinematics \rightarrow powerful background discrimination

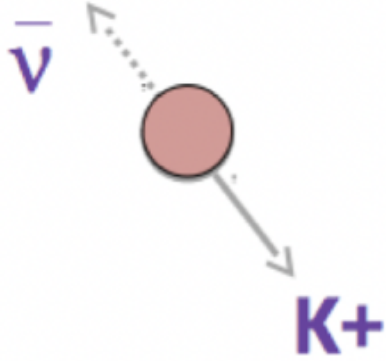
	Low- P_{tot}	High- P_{tot}
ϵ_{all} (%)	19.0 ± 0.3	19.0 ± 0.3
ϵ_{free} (%)	78.4 ± 1.4	7.7 ± 0.4
ϵ_{bound} (%)	4.2 ± 0.2	21.8 ± 0.4
BG (/Mt/yr)	0.030 ± 0.021	1.116 ± 0.132

Preliminary

No Candidates \rightarrow $\tau_p > 1.9 \times 10^{34}$ years

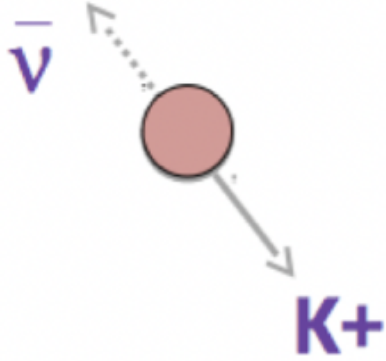
365 kton-yr exposure

Proton Decay into $\bar{\nu}K^+$

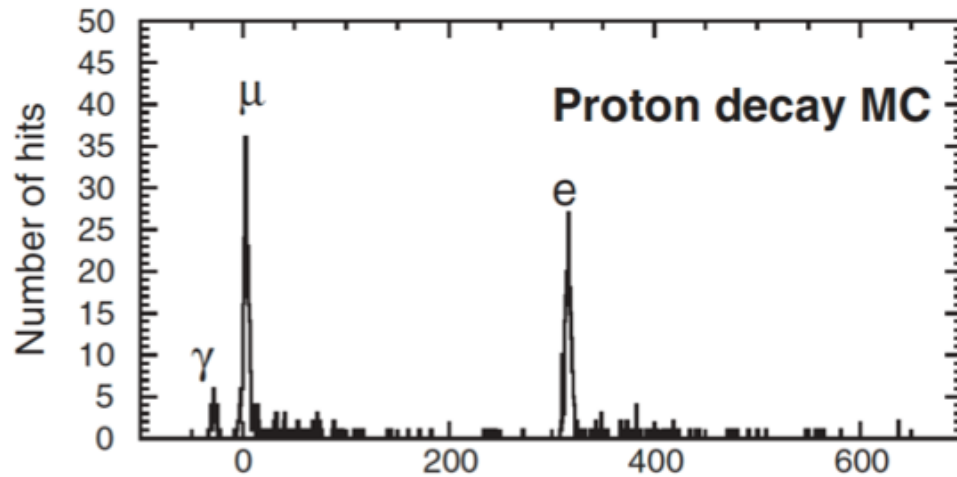


- Two body decay: K^+ momentum is 340 MeV/c
- Cherenkov threshold is 560 MeV/c , impossible to reconstruct initial proton state
- Tag K^+ decay products instead:

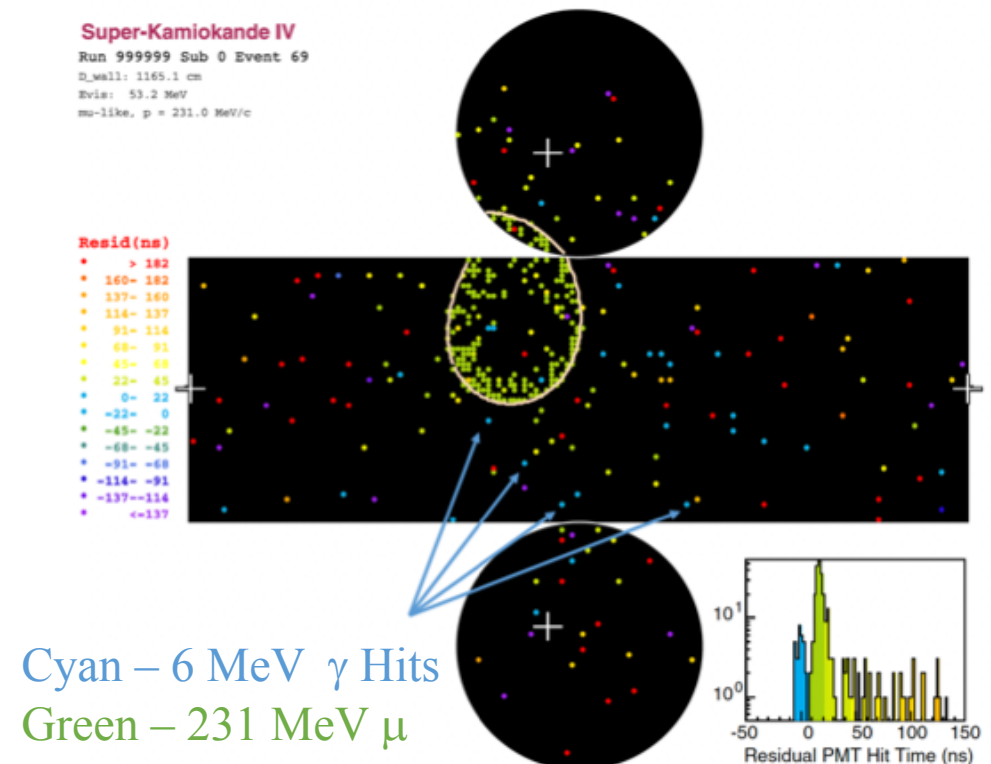
Proton Decay into $\bar{\nu}K^+$



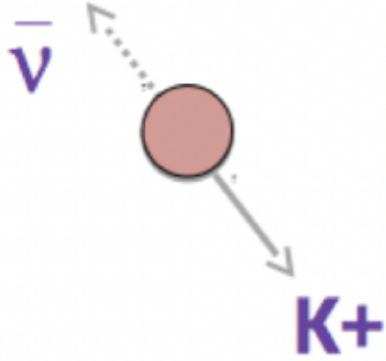
- Two body decay: K^+ momentum is 340 MeV/c
- Cherenkov threshold is 560 MeV/c , impossible to reconstruct initial proton state
- Tag K^+ decay products instead:
- (B.R. 64%) $\rightarrow \nu_\mu \mu^+$ (236 MeV/c) with 6 MeV photon (40%) from nuclear de-excitation



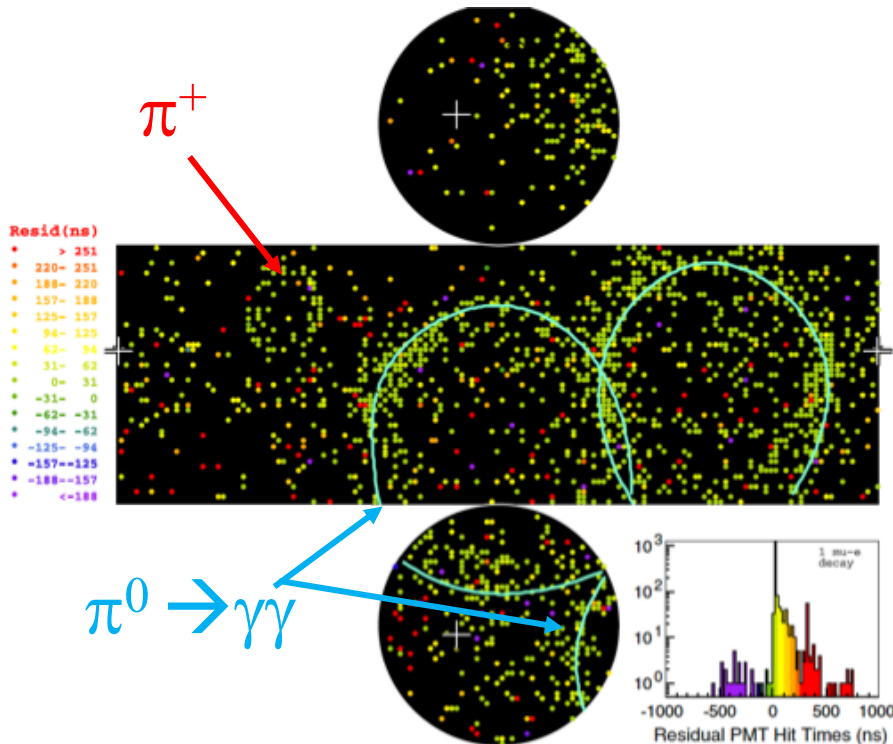
- Signal efficiency: $9.1 \pm 0.1 \%$
- Background: 1.5 ± 0.3 ev/Mton-yr



Proton Decay into $\bar{\nu}K^+$



- Two body decay: K^+ momentum is 340 MeV/c
- Cherenkov threshold is 560 MeV/c , impossible to reconstruct initial proton state
- Tag K^+ decay products instead:
- (B.R. 21%) $\rightarrow \pi^0\pi^+$ (205 MeV/c)



- Charged pion only barely above threshold (147 MeV/c)
- Efficiency: $10.0 \pm 0.1 \%$
- Background: 2.0 ± 0.3 ev/Mton-yr

No Candidates

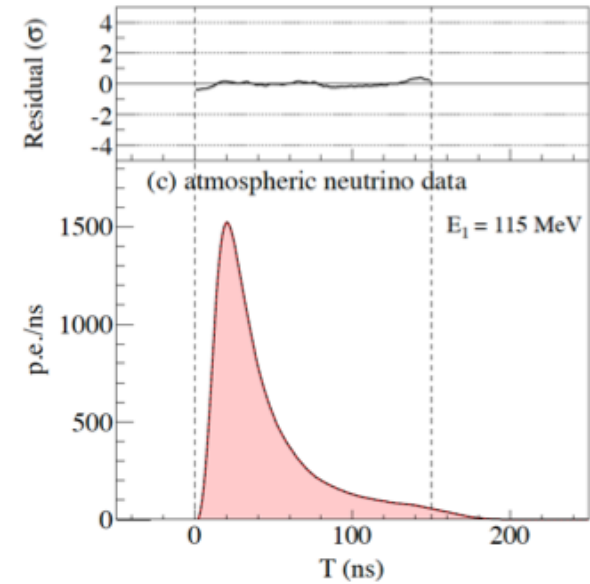
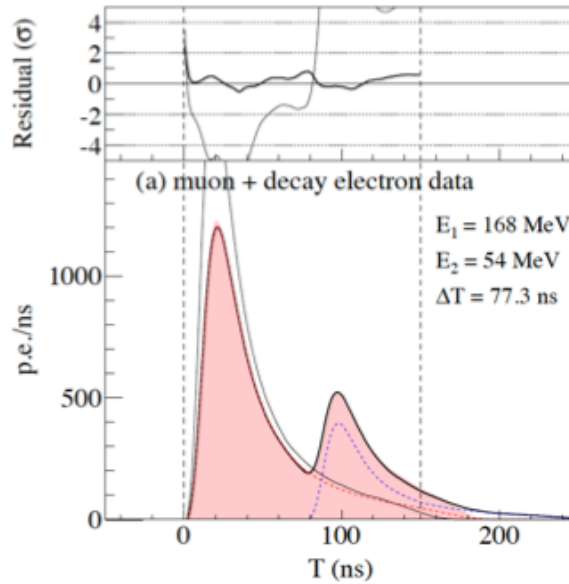
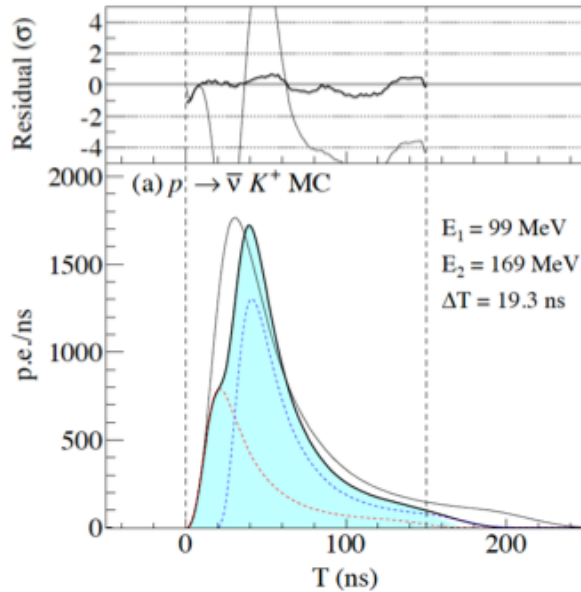
$$\tau_p > 0.8 \times 10^{34} \text{ years}$$

365 kton-yr exposure

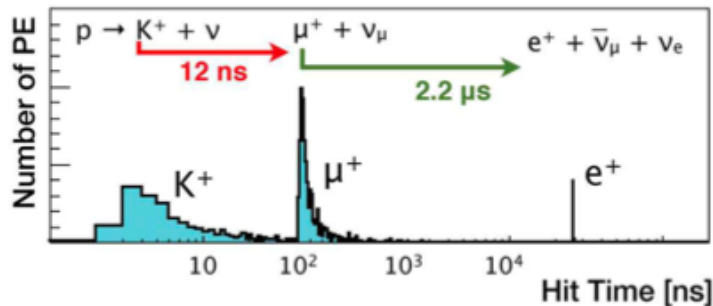
Preliminary

Search for $p \rightarrow \nu K^+$: KamLAND

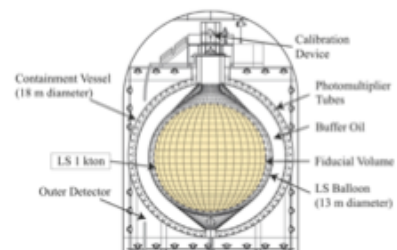
PRD92 (2015) 5, 052006



arXiv:1507.05612

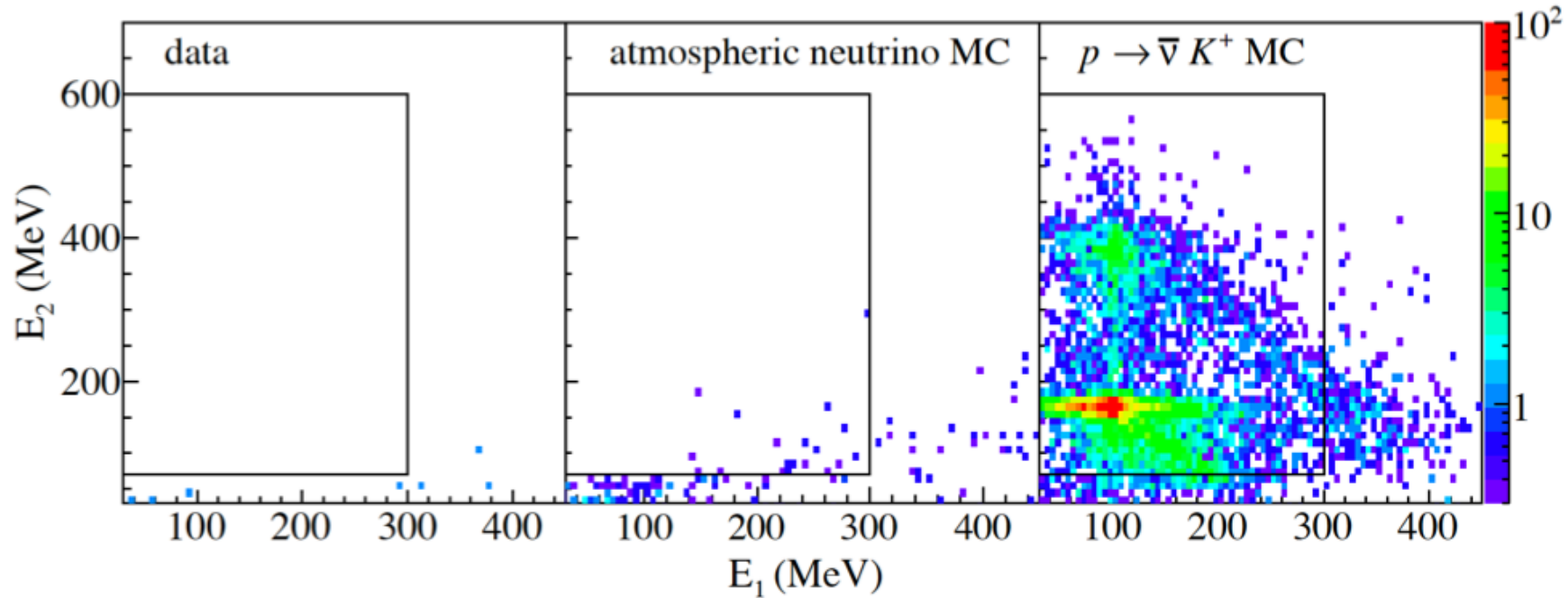


- Scintillation light from K^+ visible (KE 105 MeV), limited uncertainty from modeling of nuclear deexcitation
- Scintillator time constant of the same order as the Kaon lifetimes $O(10)\text{ns}$, discriminating waveforms of primary (K^+) and its daughters (μ^+ , $\pi^+\pi^0$) a challenge



Search for $p \rightarrow \nu K^+$: KamLAND

PRD92 (2015) no.5, 052006



- Signal efficiency of $44.4 \pm 5.3\%$
- Background rate: 101 ± 22 / Mton-yr
- No candidates found in 8.97 kton-yr exposure

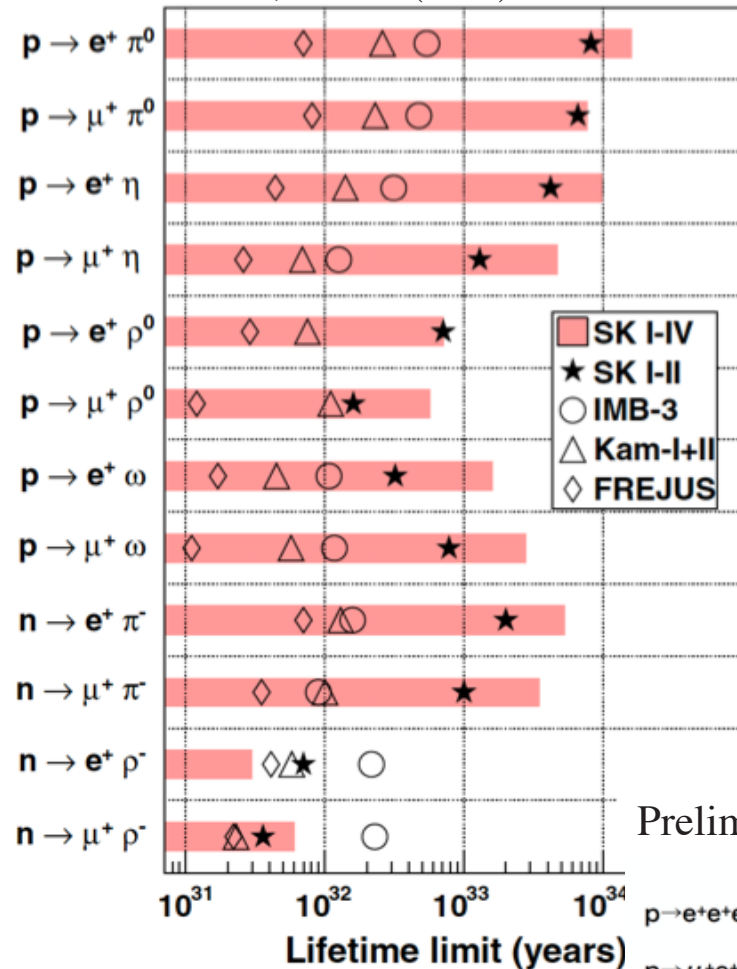
No Candidates

$$\tau_p > 5.4 \times 10^{32} \text{ years}$$

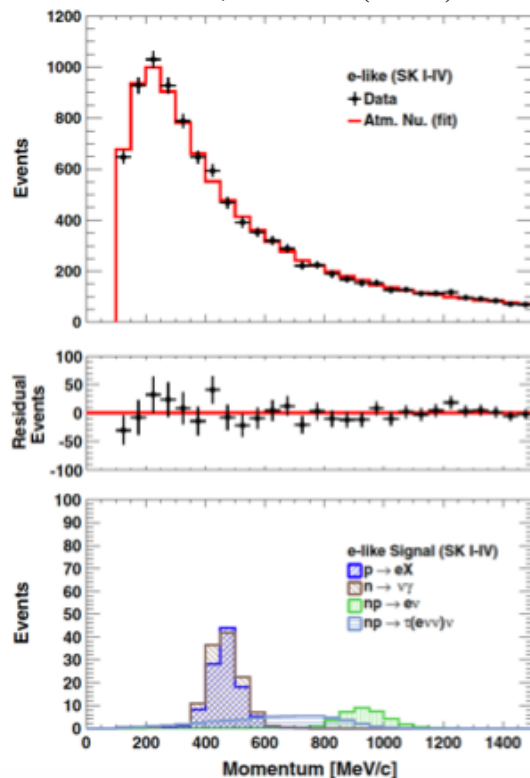
- KamLAND is the first experiment to demonstrate this technique with a large volume liquid scintillator (913 tons)

Many Modes, Searches, and Null Results

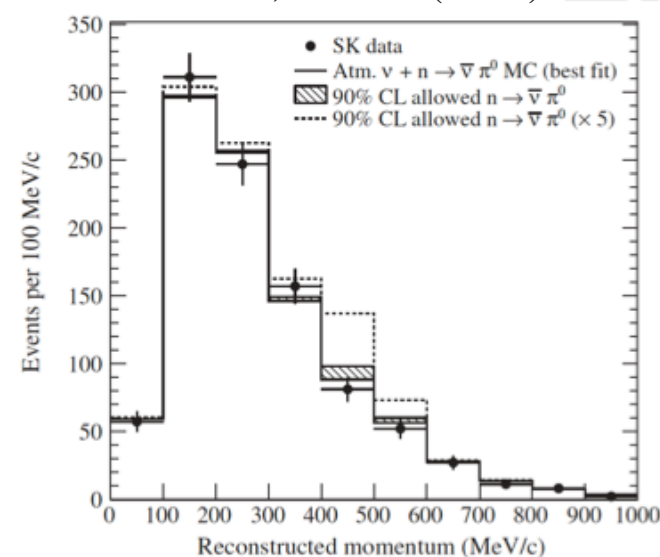
PRD 96, 012003 (2017)



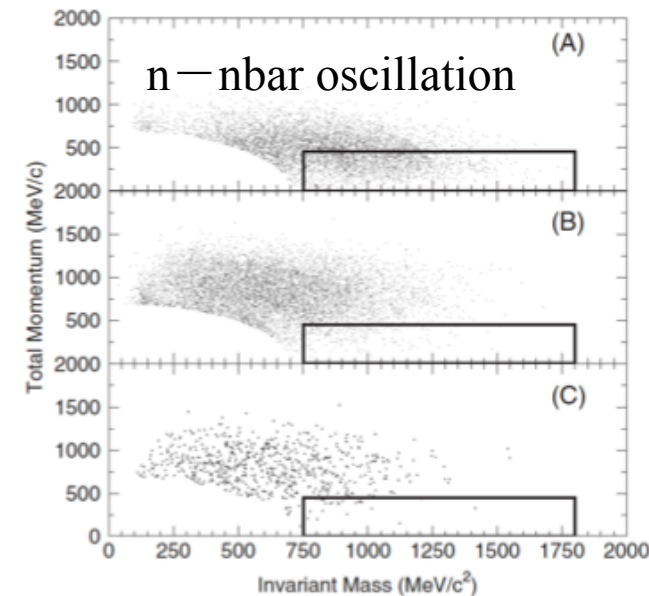
PRL 115, 121803 (2015)



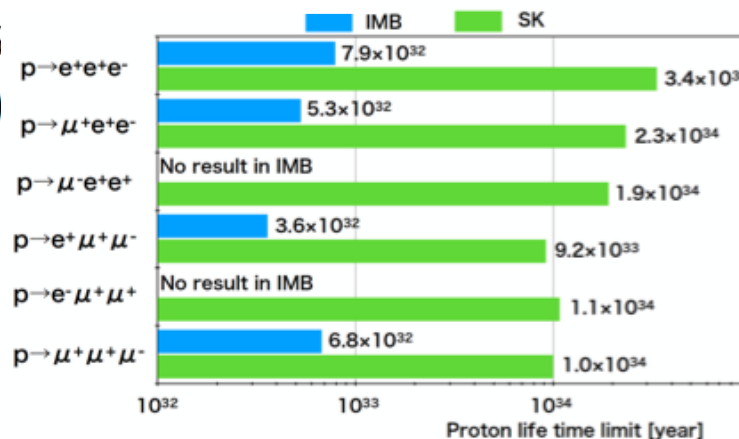
PRL 113, 121802 (2014)



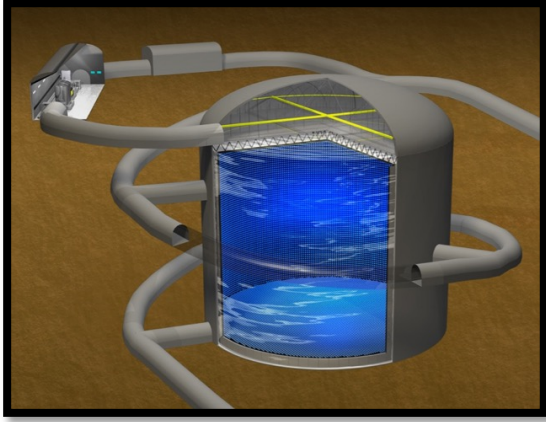
PRD 91, 072006 (2015)



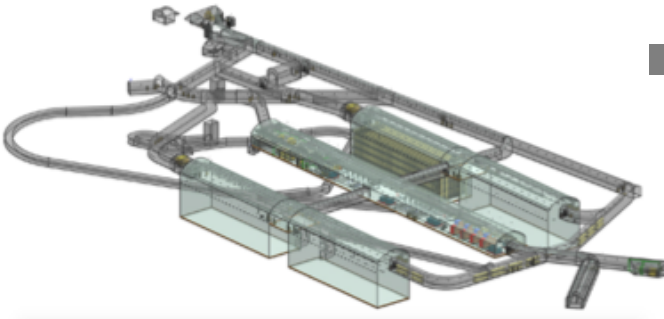
Preliminary (2019)



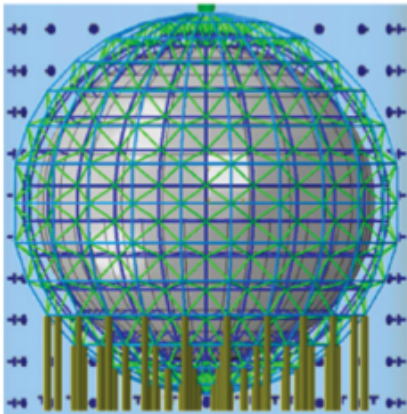
Future : Proton Decay



- Hyper-Kamiokande – Water Cherenkov (2026~)
 - 190 kt Fiducial Volume (8.6 times Super-K)
 - 40% photocathode coverage with 2x photon yield of SK(Related: M. Hartz 2019.08.07)

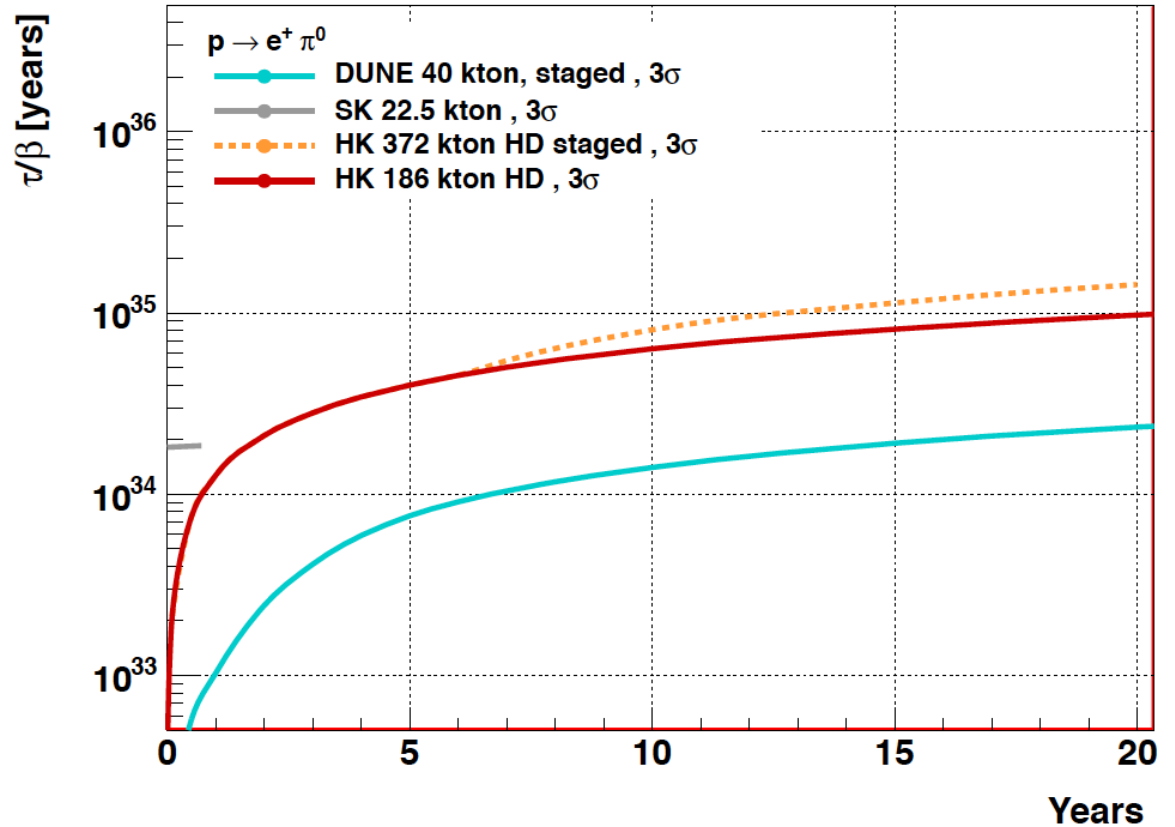
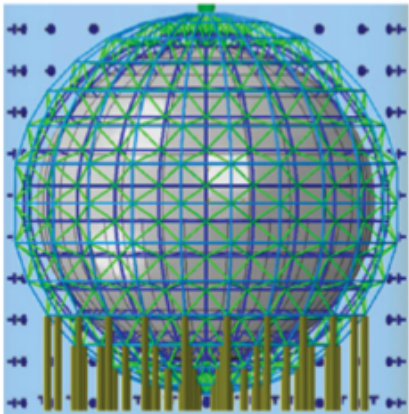
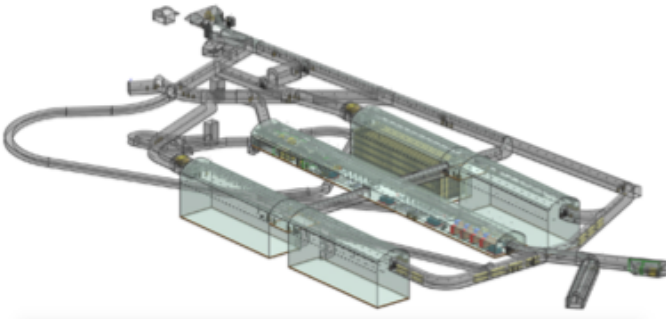
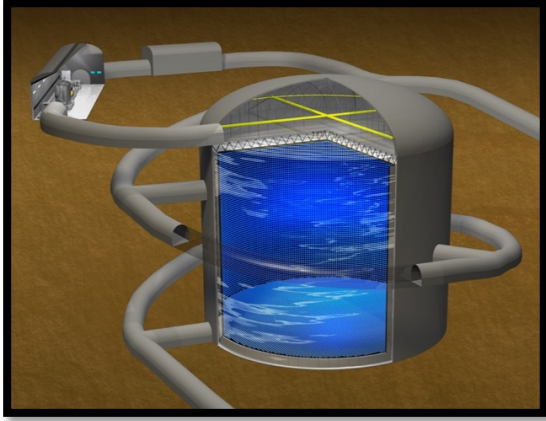


- DUNE – Liquid Argon TPC (2025~)
 - 40 kt Volume
 - Low KE Tracking thresholds
 - Exquisite particle tracking → highly efficient PDK(Related A.Weber 2019.08.07)



- JUNO – Liquid Scintillator (2021~)
 - 20 kt Volume (20 times KamLAND)
 - 0.2 MeV threshold
 - 3% energy resolution(Related S. Chen 2019.08.09)

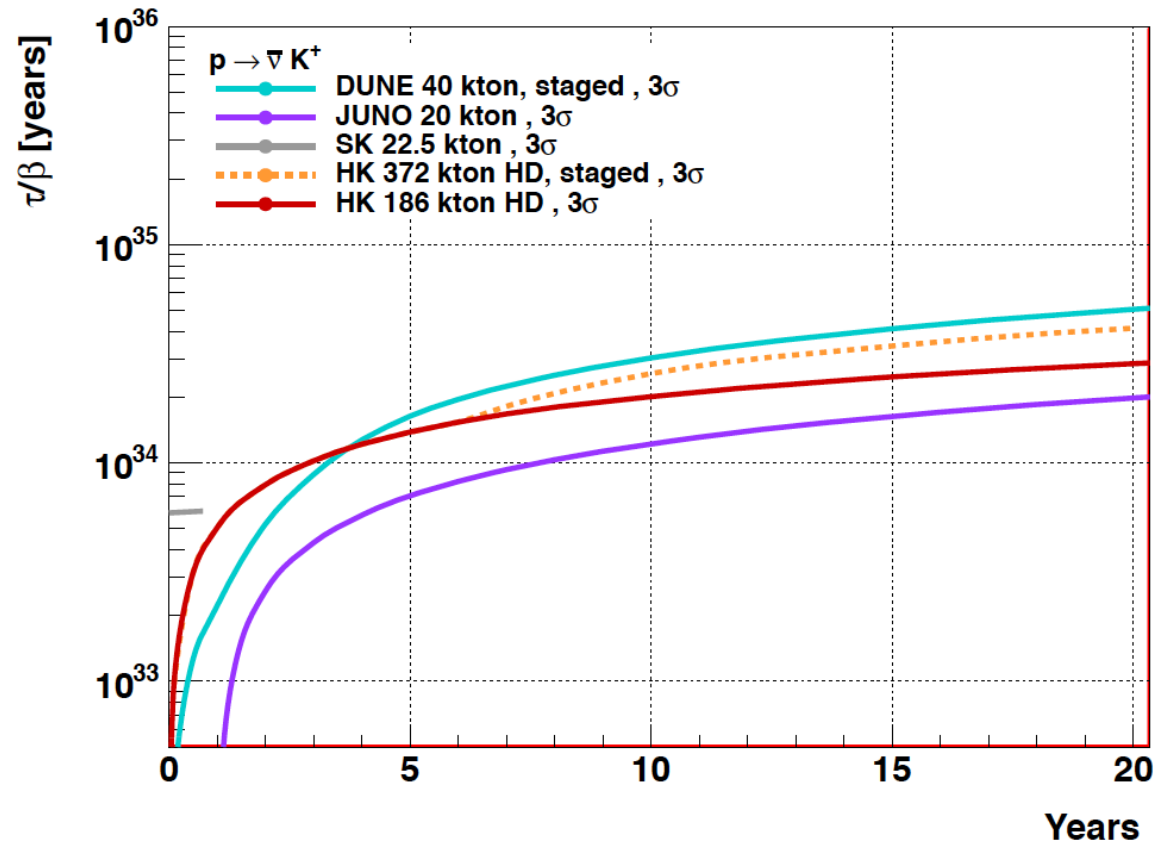
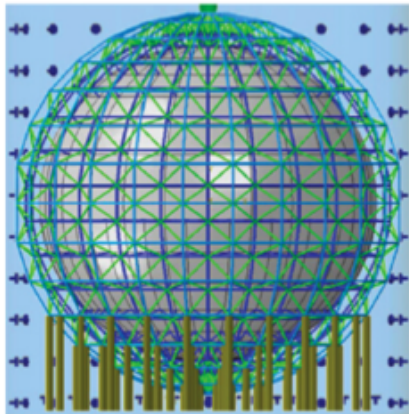
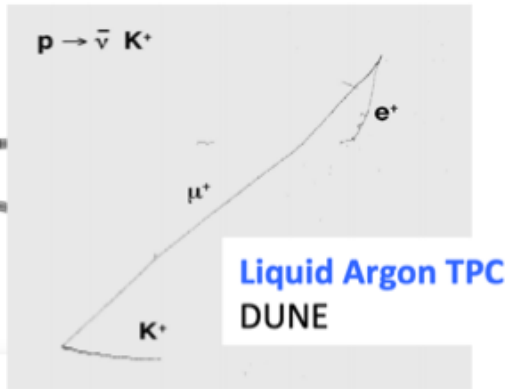
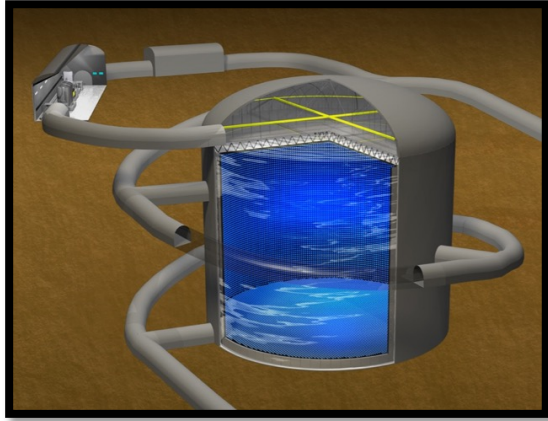
Future : Proton Decay $e^+ \pi^0$



	Hyper-K	DUNE
Efficiency (%)	18.7 / 19.4	45
BKG (Mton-yr) ⁻¹	0.06 / 0.62	1.0

- Expect to reach 10^{35} years with Hyper-K
 - Current limit is 1.9×10^{34} years

Future : Proton Decay νK^+

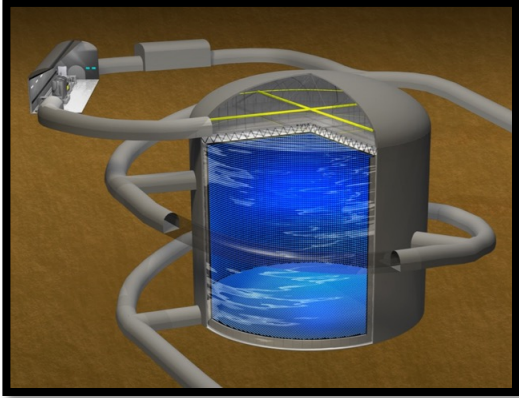


	Hyper-K	DUNE	JUNO
Efficiency (%)	12.2 / 10.8	97	65
BKG (Mton-yr) ⁻¹	0.9 / 0.7	1.0	2.5

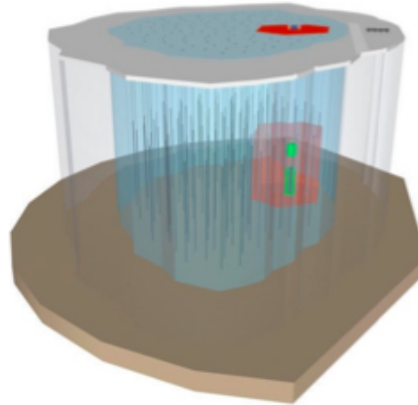
- Discovery reaches into 10^{34} years for all technologies, dominated by DUNE
- DUNE may also improve modes with many pions (eg. $n-\bar{n}$)

Future : Atmospheric Neutrinos

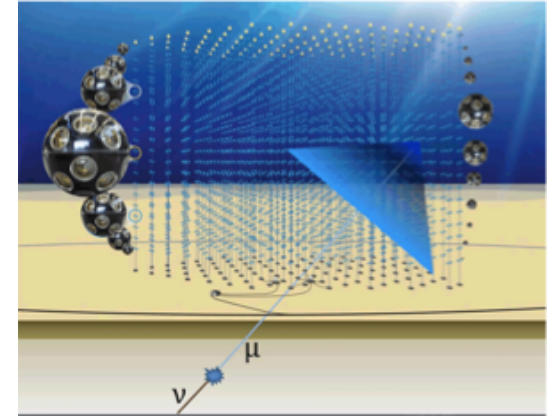
Hyper-Kamiokande



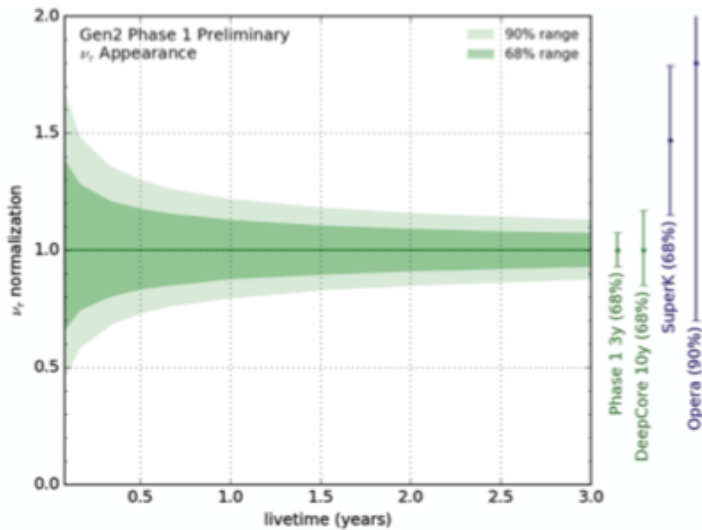
IceCube Gen2 – 10 km³



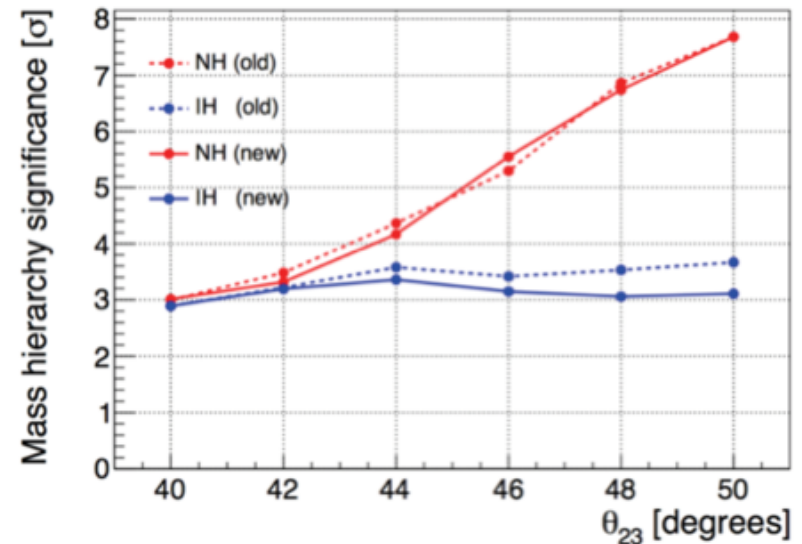
KM3NeT – 1km³



IceCube Gen2 K. Clark TAUP2017



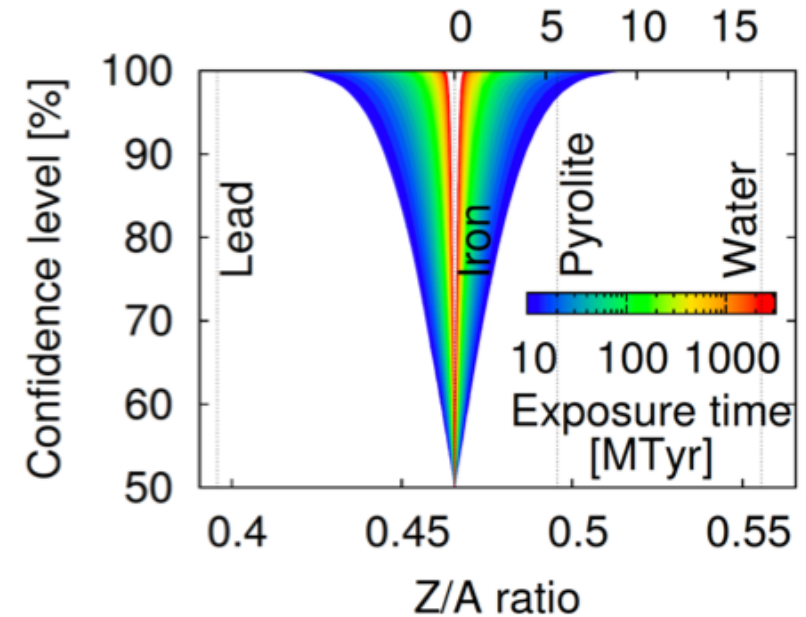
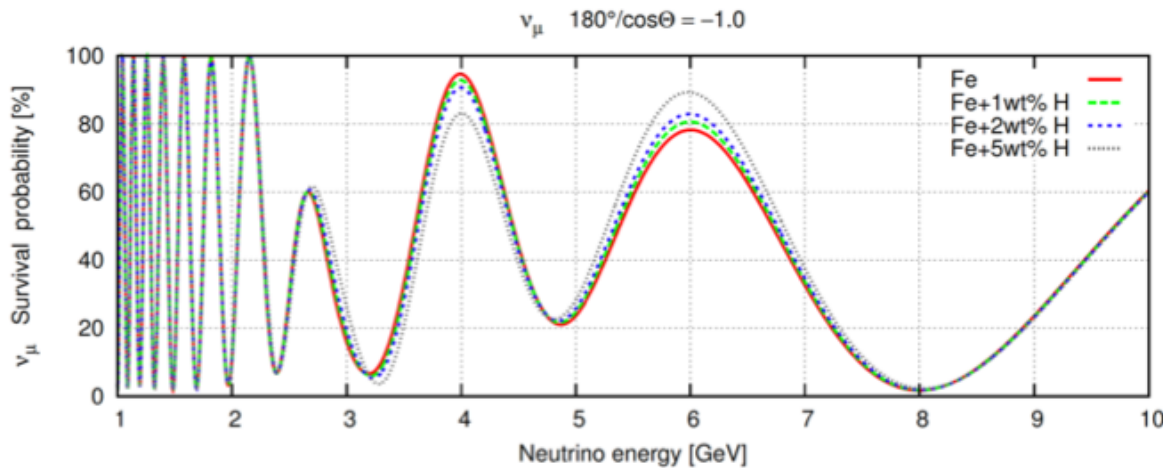
KM3NeT



- Generically expect improved precision on measurements presented above
- Other projects: INO-ICAL, Baikal-GVD, DUNE

Future : Earth Tomography with Atmospheric Neutrinos

Nature Scientific Reports volume 5, 15225 (2015)



- Core-crossing atmospheric neutrinos can probe electron density of the core via its impact on their oscillations
- High-statistics observations can be used to **determine the electron content of the Earth**
- Important in geophysics for understanding the origin of the Earth's magnetic field
 - Cannot be done by other means at present and is **currently completely unmeasured**

Example of tomographical studies with public data here : NATURE PHYSICS 15(2019) 37–40

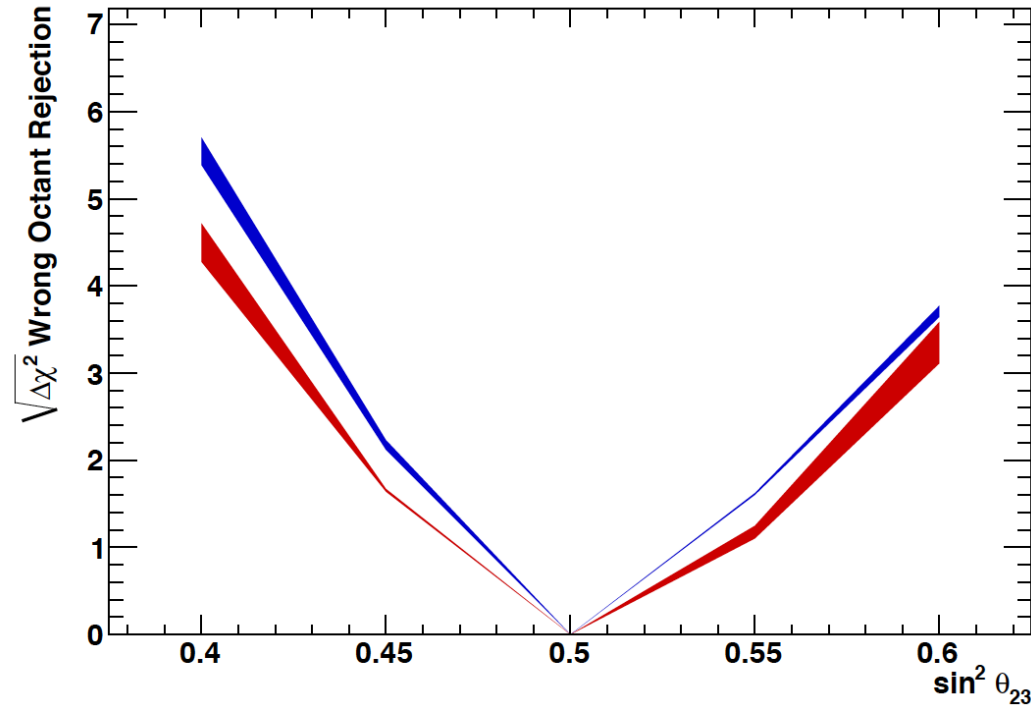
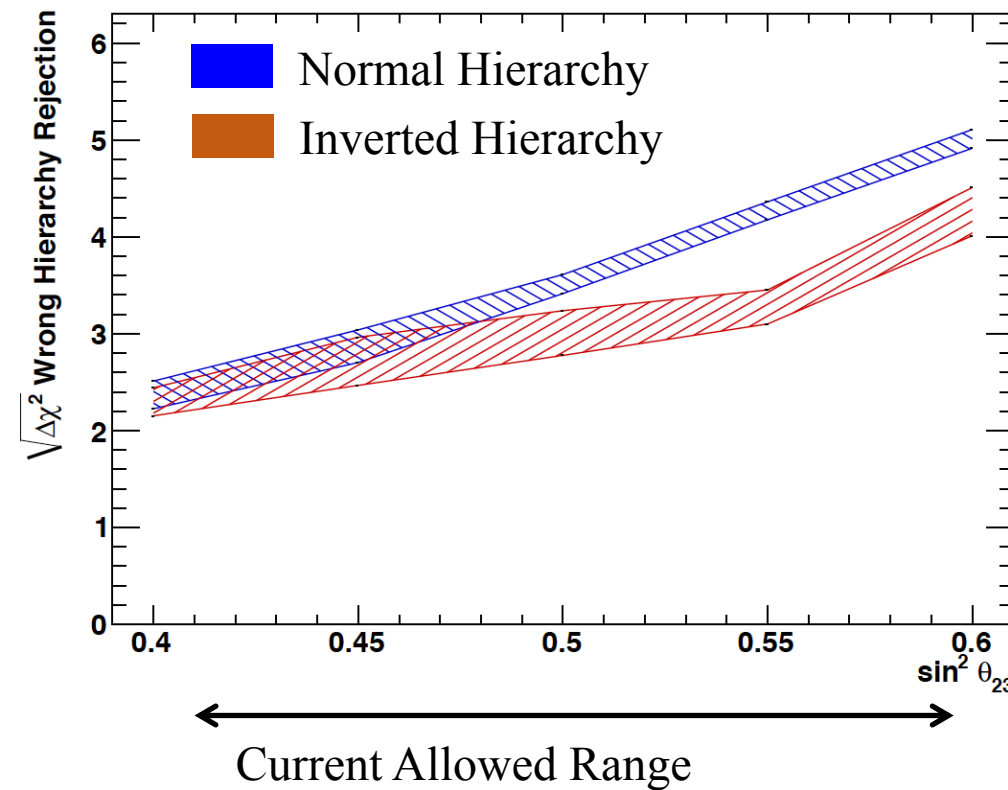
Summary :

- Efforts to understand proton decay background opened the neutrino oscillation frontier
- Now atmospheric neutrinos are being used to probe a variety of effects
 - **Weak preference** for the **normal mass hierarchy** seen in SK and IceCube, as well as $\nu\tau$
 - No evidence of exotic physics (LV, Sterile Neutrinos)
 - Highest energy atmospheric neutrinos have been used study interaction cross section
- Expect further sensitivity improvements at next generation facilities
- Despite a plethora predictions and accompanying searches for proton decay, no evidence so far
- Limits on flagship modes: $p \rightarrow e^+\pi^0 > 1.9 \times 10^{34}$ years and $p \rightarrow \nu K^+ > 0.8 \times 10^{34}$ years
- Discovery prospects at next-generation experiments are good, supported by proof-of-principle measurements at current facilities

Supplements

Mass Hierarchy Sensitivity After 10 Years (186 kton)

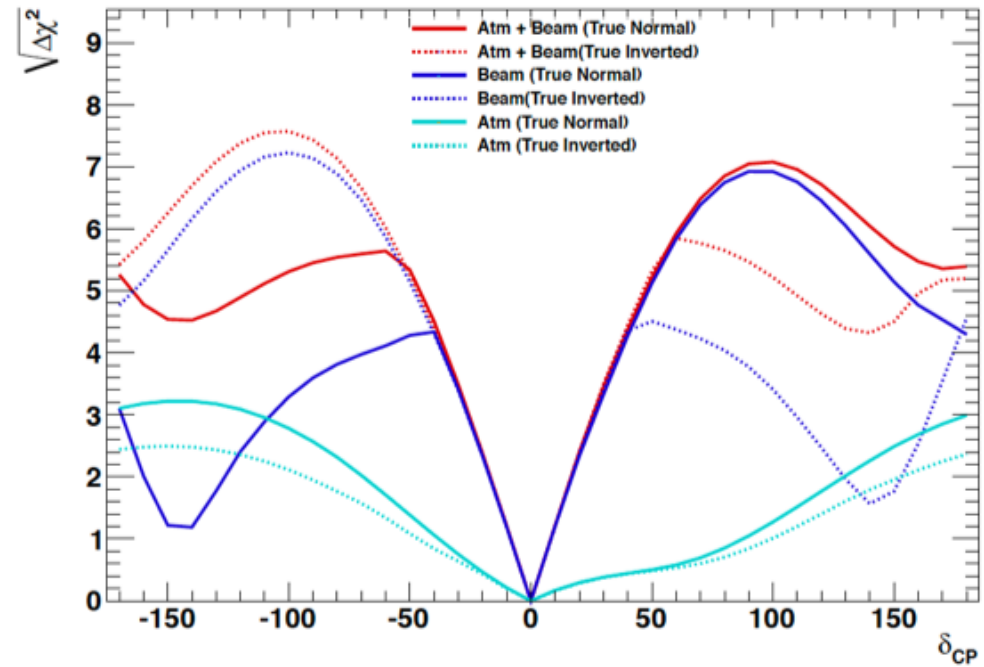
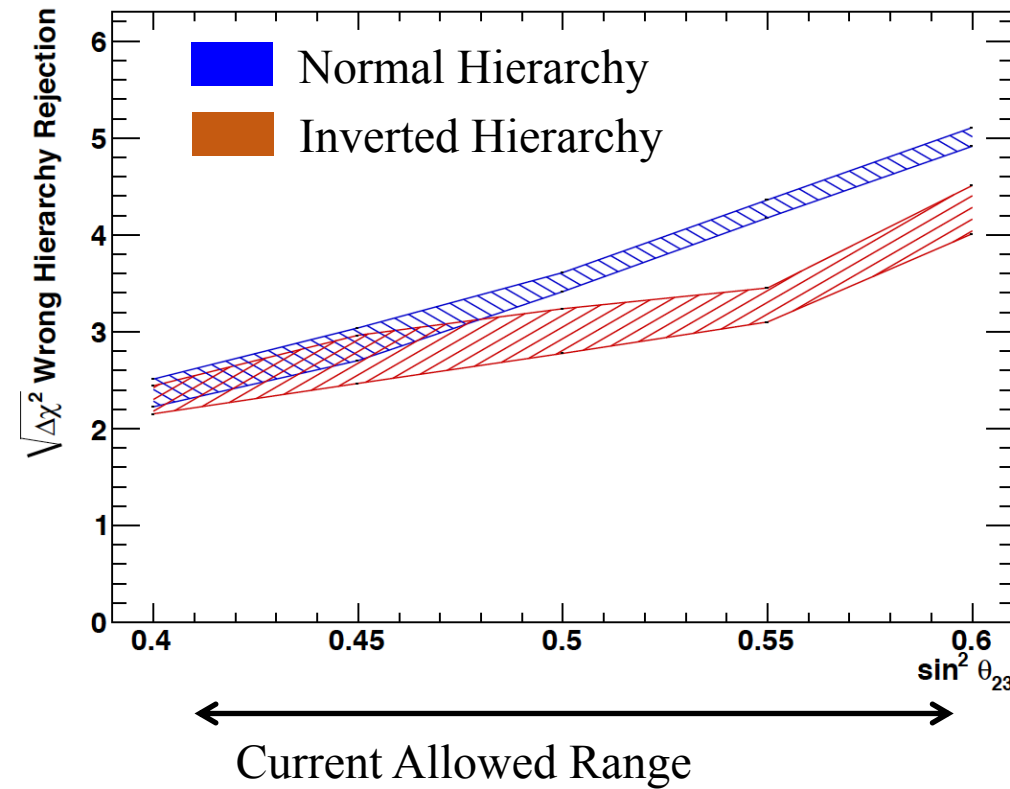
Atmospheric ν Only



- Mass hierarchy sensitivity $>2\sigma$
 - $>3\sigma$ depending upon hierarchy and true value of $\sin^2 \theta_{23}$
- Octant discrimination $>3\sigma$ if $|\theta_{23} - 45| > 4$ degrees
- Error bands denote uncertainty from δ_{CP}
- Precision on δ_{CP} limited by uncertainties

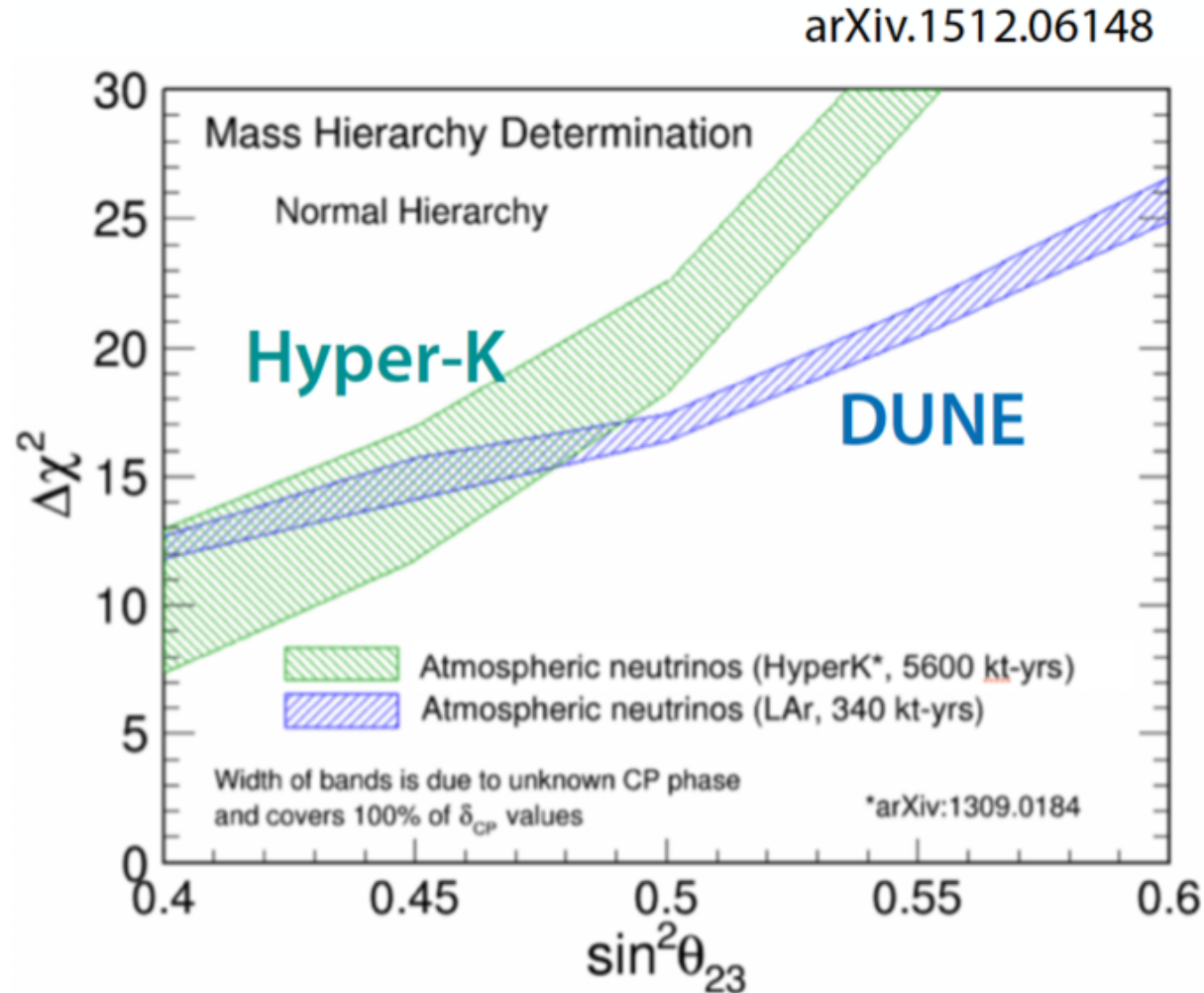
Mass Hierarchy Sensitivity After 10 Years (186 kton)

Atmospheric ν Only



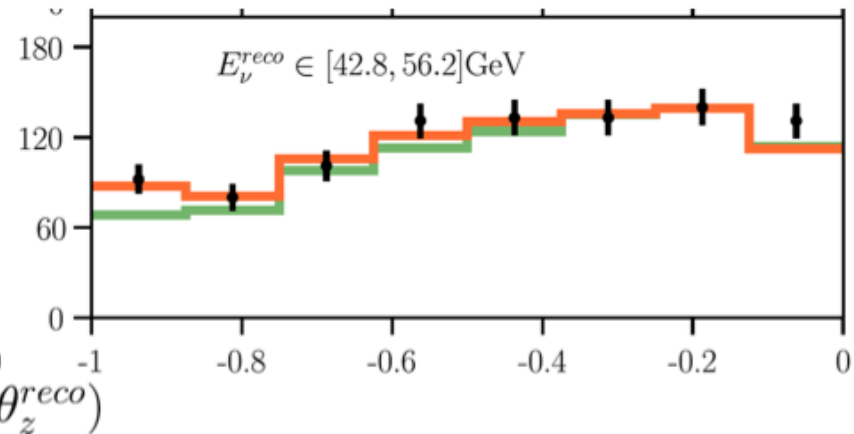
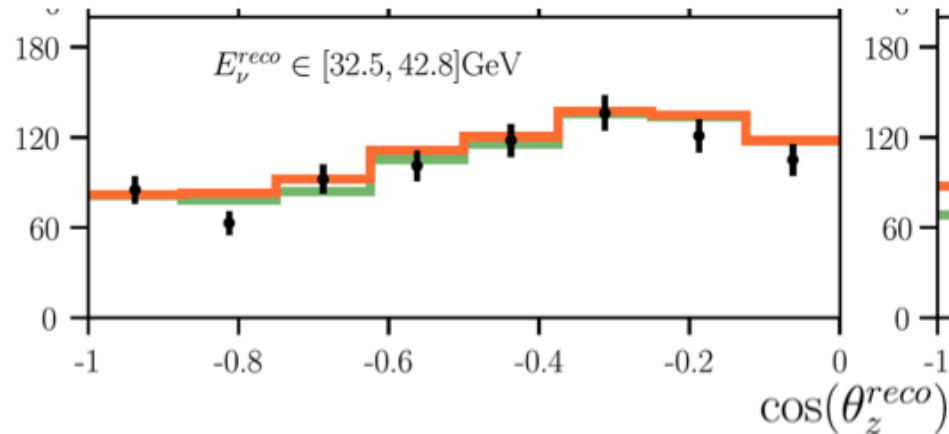
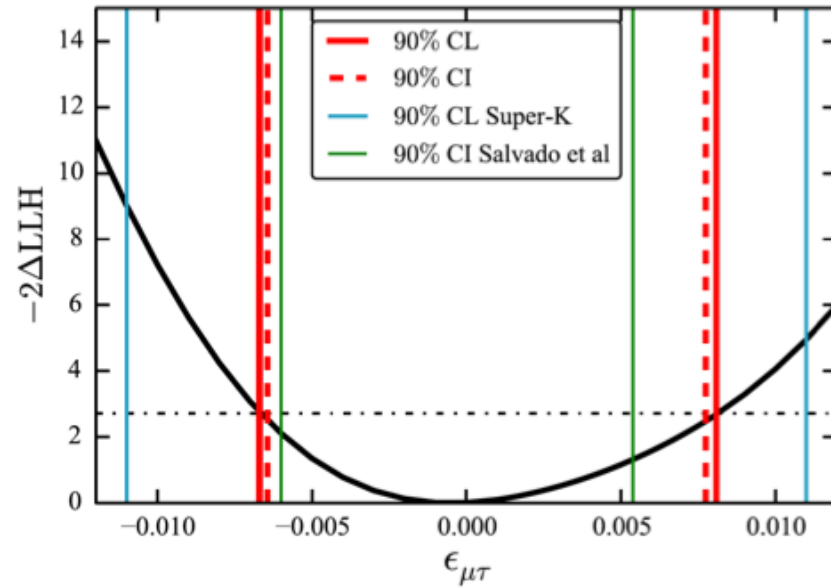
- Mass hierarchy sensitivity $>2\sigma$
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- Error bands denote uncertainty from δ_{CP}
- Precision on δ_{CP} limited by uncertainties

Mass Hierarchy At Future Detectors : Atmospheric ν Only



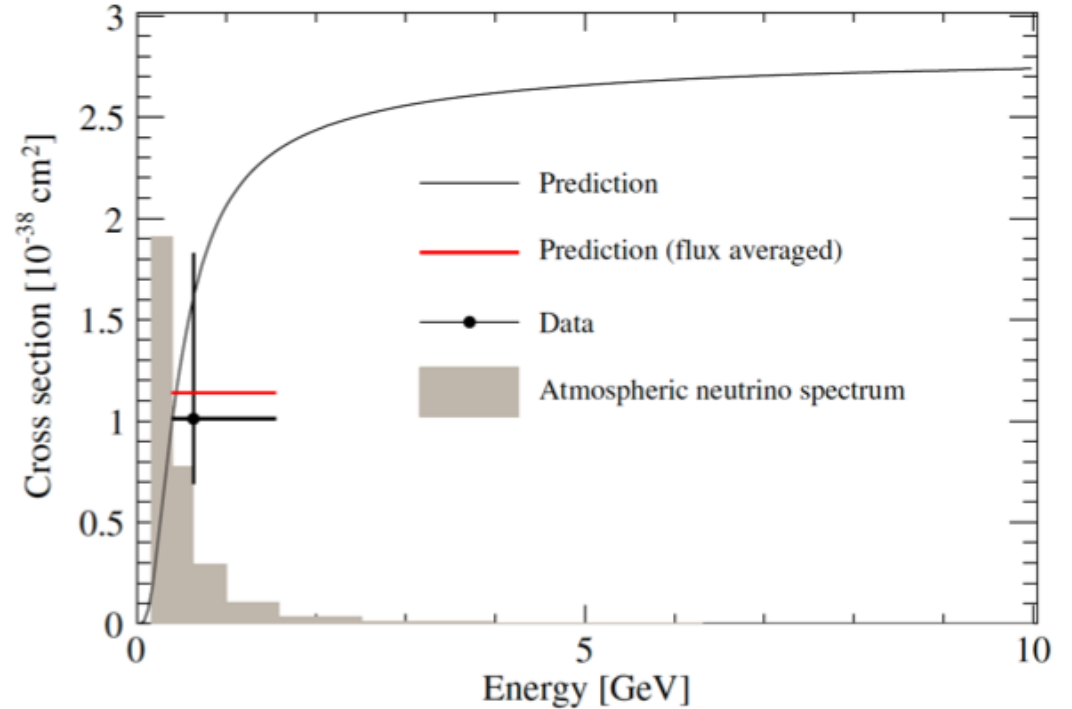
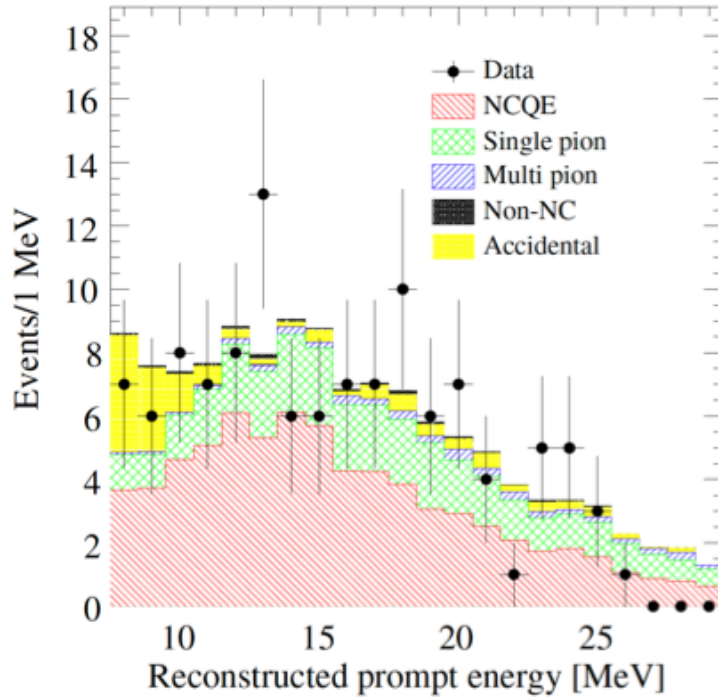
Non-Standard Interactions with Matter

PHYS. REV. D 97, 072009 (2018)



NC Quasi-Elastic Scattering With Atmospheric Neutrinos

PHYS. REV. D 99, 032005 (2019)

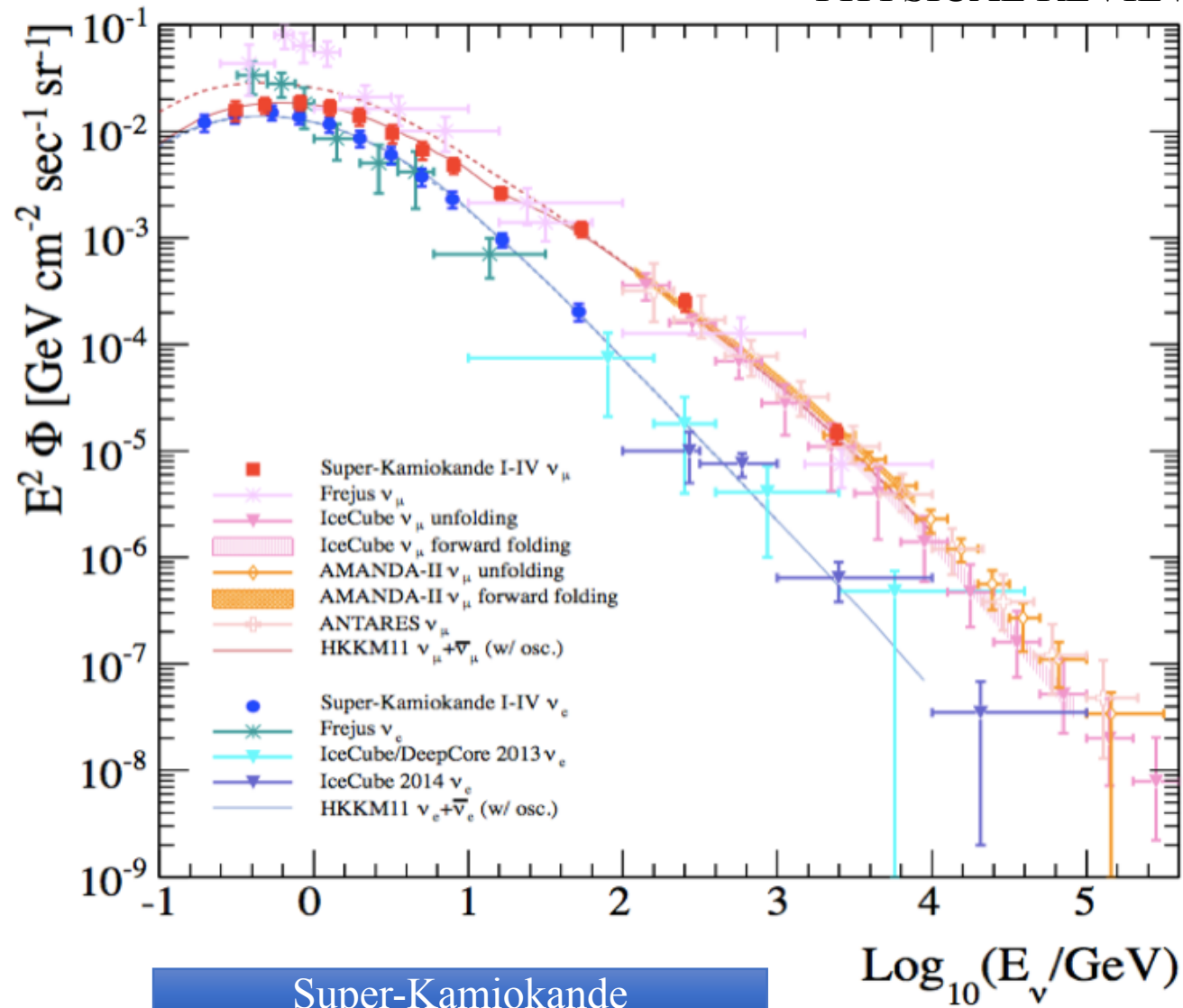


$$\langle \sigma_{\text{NCQE}}^{\text{theory}} \rangle = \frac{\int_{160 \text{ MeV}}^{10 \text{ GeV}} \sum_{i=\nu, \bar{\nu}} \phi_i(E_\nu) \times \sigma_i(E_\nu)^{\text{theory}}_{\text{NCQE}} dE_\nu}{\int_{160 \text{ MeV}}^{10 \text{ GeV}} \sum_{i=\nu, \bar{\nu}} \phi_i(E_\nu) dE_\nu}$$

$$= 1.14 \times 10^{-38} \text{ cm}^2,$$

Atmospheric Neutrino Flux:

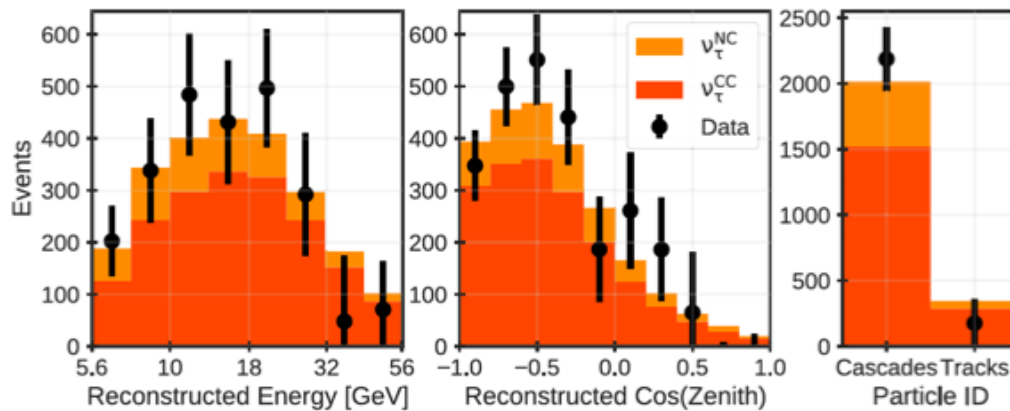
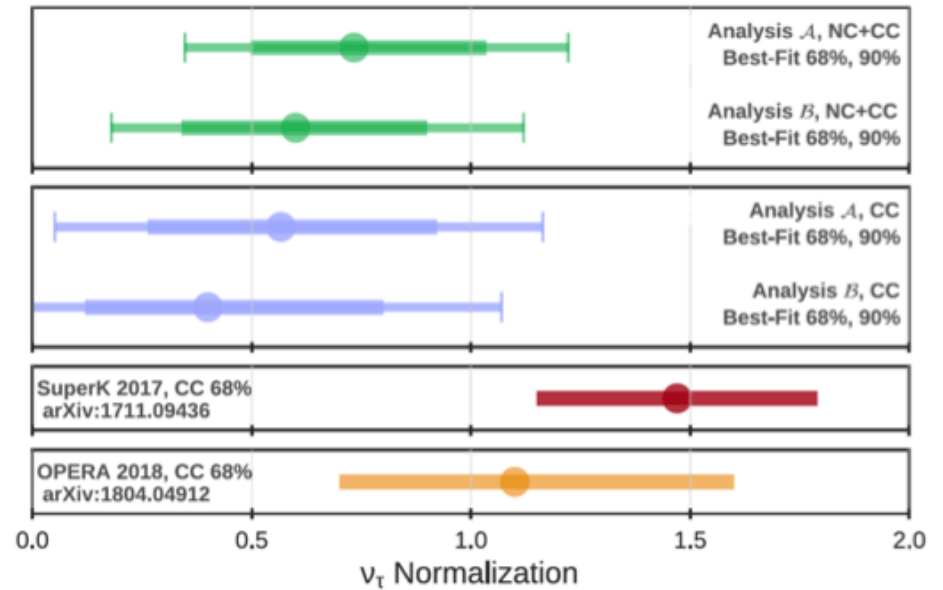
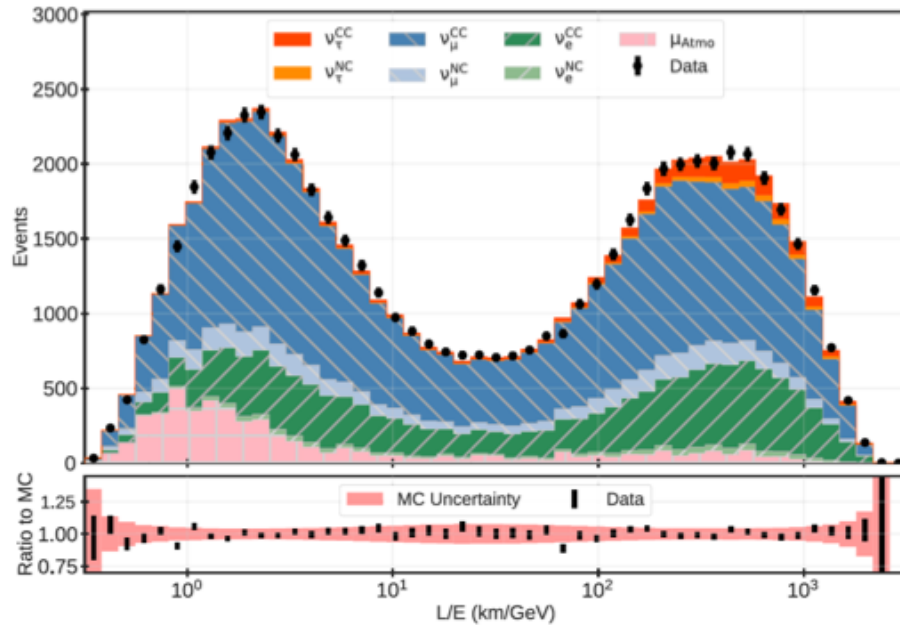
PHYSICAL REVIEW D 94, 052001 (2016)



Tau Neutrino Appearance at IceCube

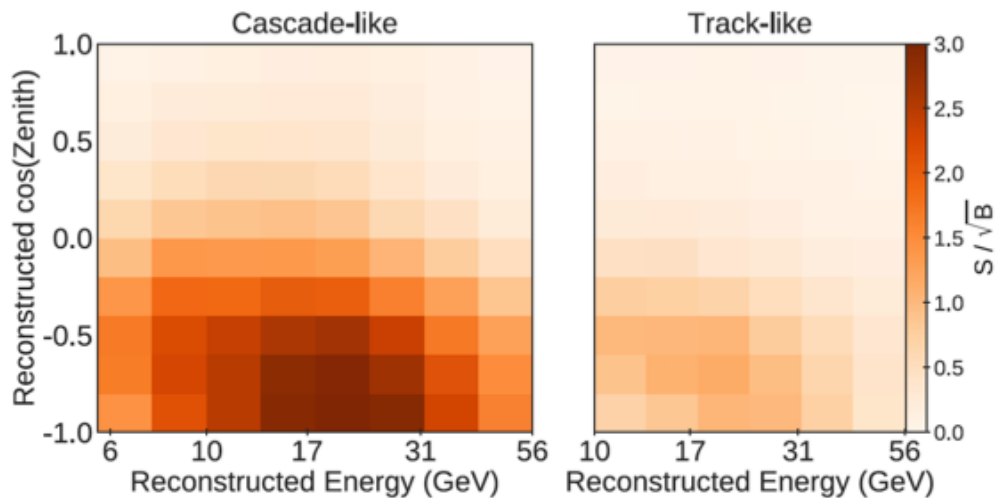
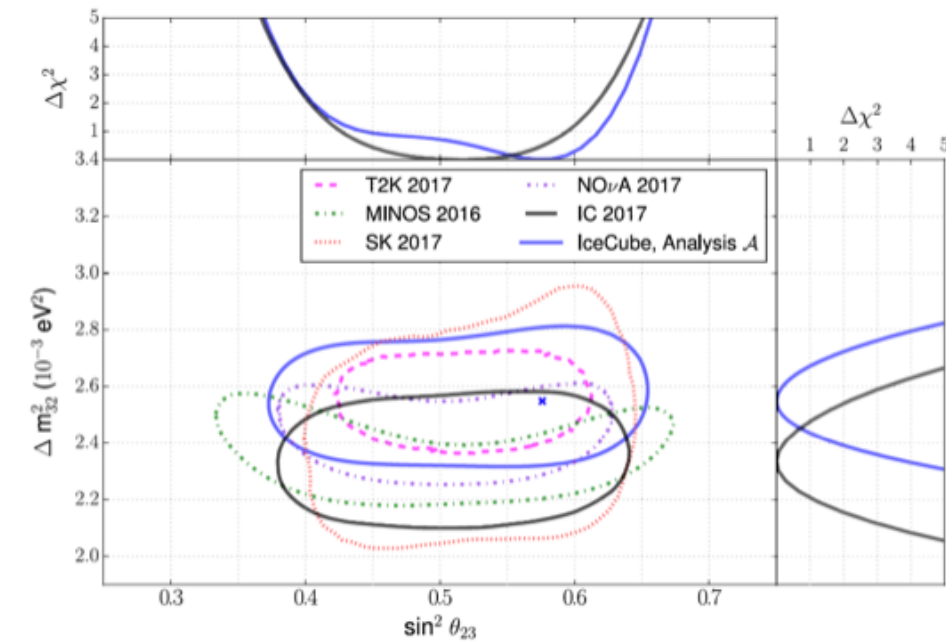


PHYS. REV. D 99, 032007 (2019)



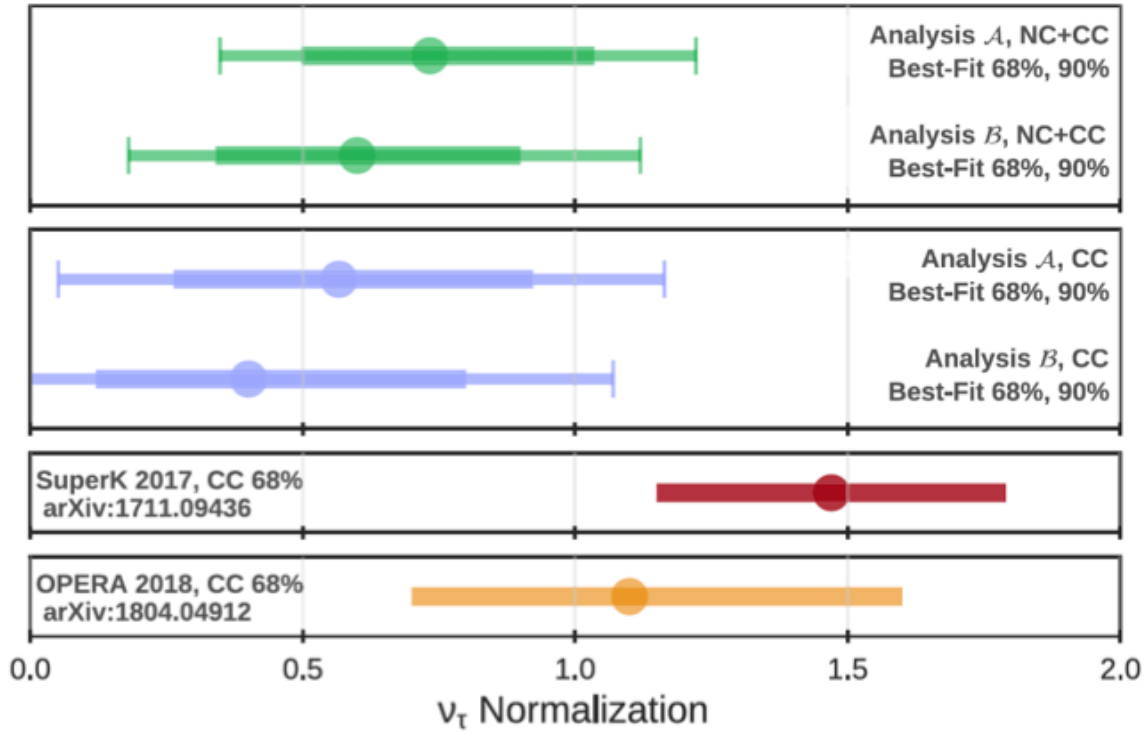
Atmospheric Oscillations at IceCube

PHYS. REV. D 99, 032007 (2019)

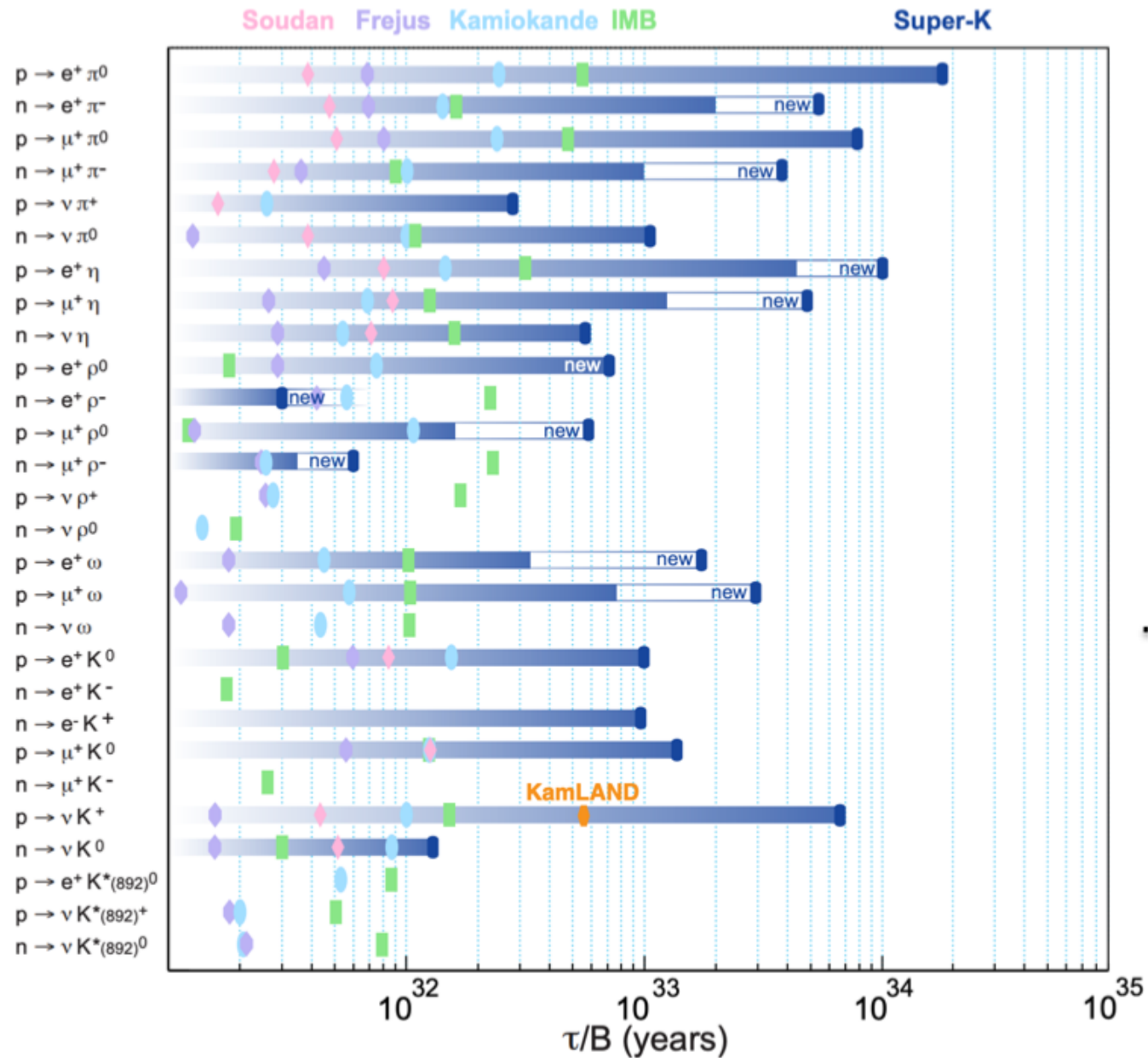


Search for Tau Neutrinos

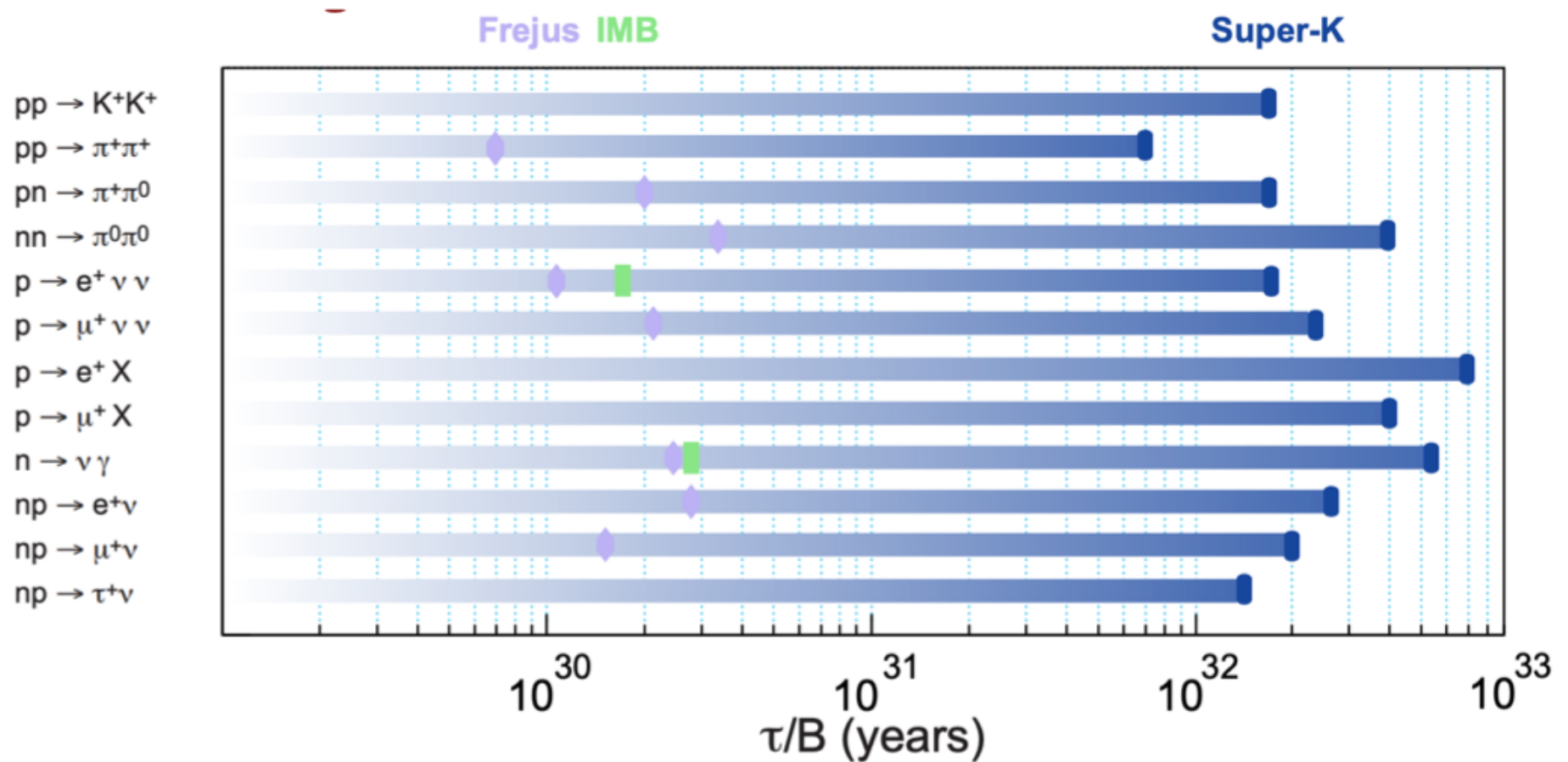
PHYS. REV. D 99, 032007 (2019)



Summary of Nucleon Decay Limits (2017)



Summary of Nucleon Decay Limits (2017)



E. Kearns BLV2017

		Mega Water Ch.		Big LAr (generic, Bueno et al.)	
Mode		Efficiency	BG Rate (/Mt y)	Efficiency	BG Rate (/Mt y)
B-L	$e^+\pi^0$	38%	0.7	45%	1
	νK^+	22.5%	1.6	97%	1
	$\mu^+ K^0$	10%	5-10	47%	<2
B+L	$\mu^- \pi^+ K^+$?	?	97%	1
	$e^- K^+$	10%	3	96%	<2
$\Delta B=2$	$n \bar{n}$	12%	260	?	?

