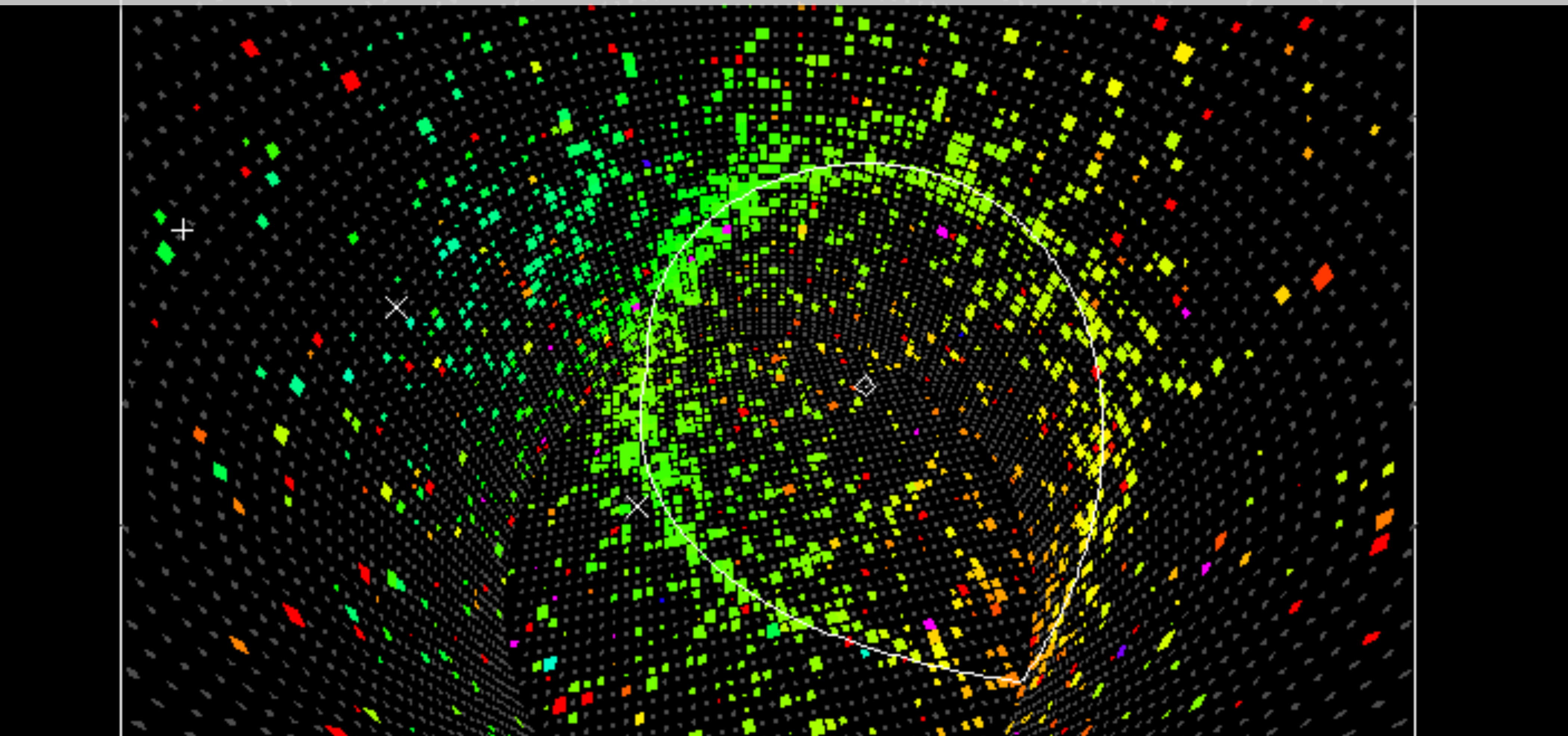
Results and Opportunities in Atmospheric Neutrinos and Searches of Proton Decays



Kimihiro OKUMURA（ICRR, Univ. of Tokyo)

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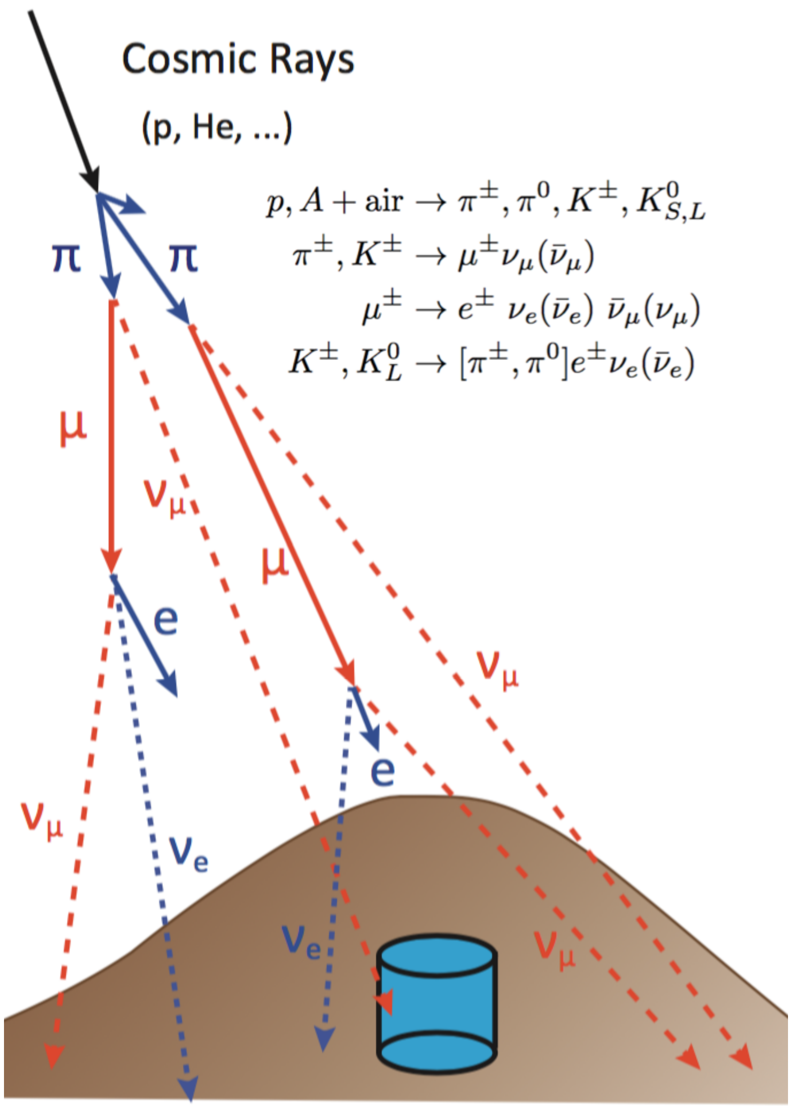
XXVIII International Symposium on Lepton Photon Interactions at High Energies (LP2017)

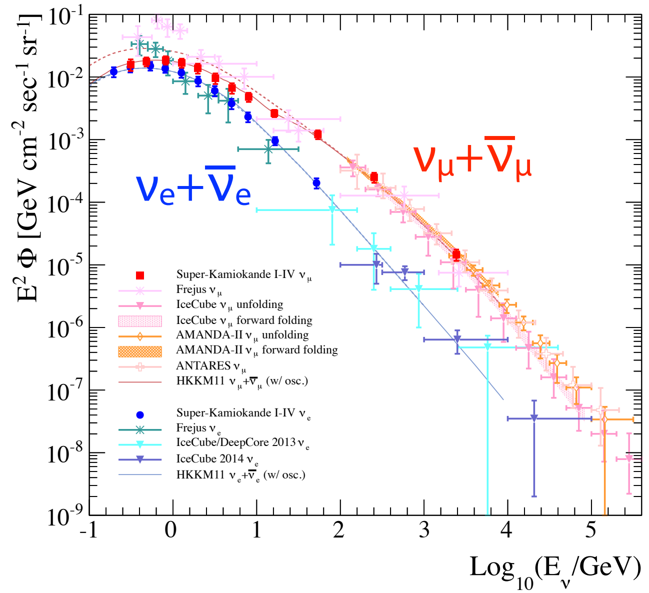
8-12 Aug 2017, SYSU in GuangZhou, CHINA

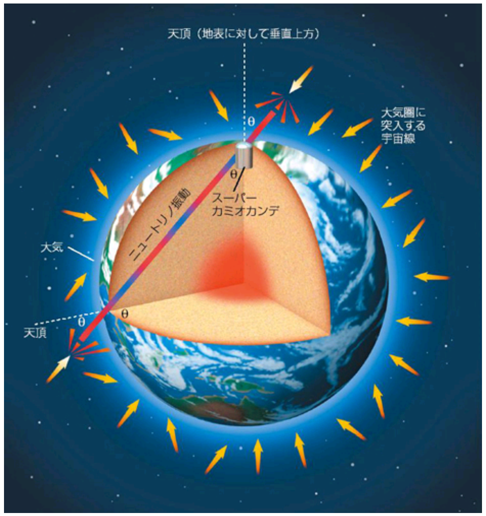
ICRR
Institute for Cosmic Ray Research
University of Tokyo

Atmospheric Neutrinos



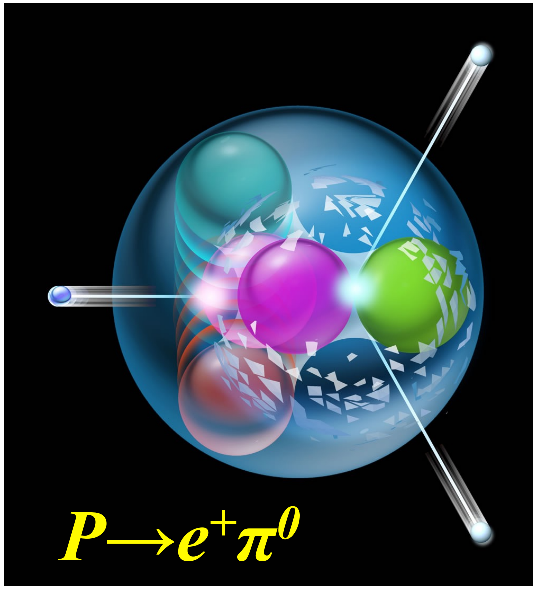
$$p, A + \text{air} \rightarrow \pi^{\pm}, \pi^{0}, K^{\pm}, K^{0}_{S,L}$$
$$\pi^{\pm}, K^{\pm} \rightarrow \mu^{\pm}\nu_{\mu}(\bar{\nu}_{\mu})$$
$$\mu^{\pm} \rightarrow e^{\pm}\ \nu_{e}(\bar{\nu}_{e})\ \bar{\nu}_{\mu}(\nu_{\mu})$$
$$K^{\pm}, K^{0}_{L} \rightarrow [\pi^{\pm}, \pi^{0}]e^{\pm}\nu_{e}(\bar{\nu}_{e})$$

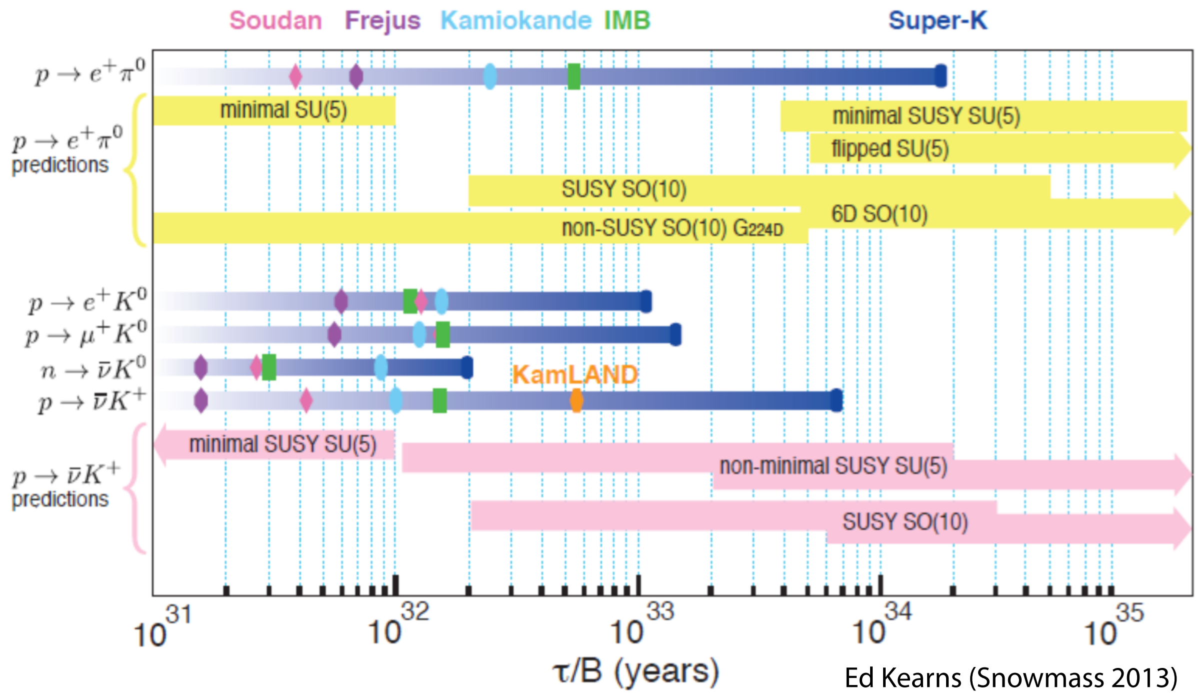




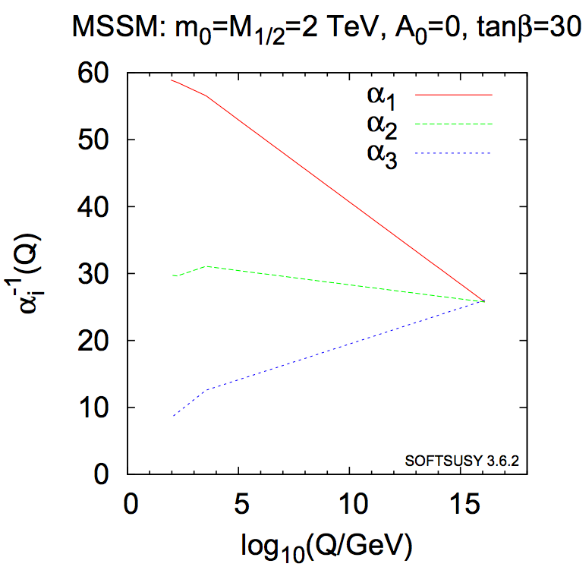
- Decay products of secondaries by cosmic ray interactions with atmosphere. (**$\nu_{\mu} : \nu_{e}$ ~ 2 : 1**)
- Energy spectrum: **cutoff by geomagnetic field** below 1 GeV. Extended to high energies with **power-law**
- Path length: distributed in **O(10)km ~ 13,000km** depending on zenith angle direction
- Neutrino oscillation driven by atmospheric Δm^2_{32} (~2.5 x10^{-3} eV^2) below O(10) GeV

Proton Decay





Ed Kearns (Snowmass 2013)

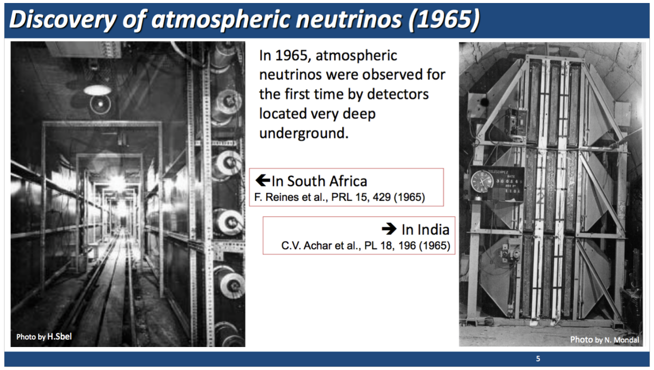


- Proton decay is predicted by **GUTs (Grand Unified Theory)**
  - Provide the method for baryon asymmetry Universe
  - Open direct path to "Beyond SM" if detected
- **Many GUT predictions** — SU(5), SO(10), SUSY GUT
- Benchmark modes: **$P \to e^+\pi^0$, $P \to \bar{\nu} K^+$**
- Background: atmospheric neutrino

Atm. ν and Proton Decay Experiments

Atm. ν and Proton Decay Experiments

T. Kajita (TAUP2017)



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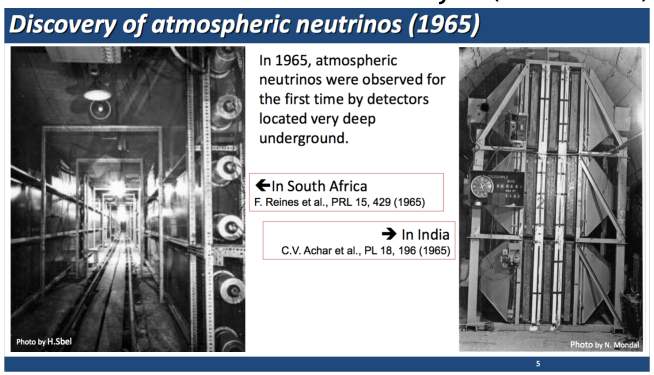

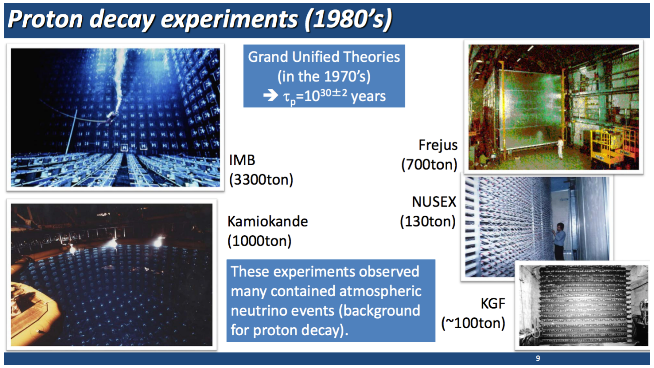

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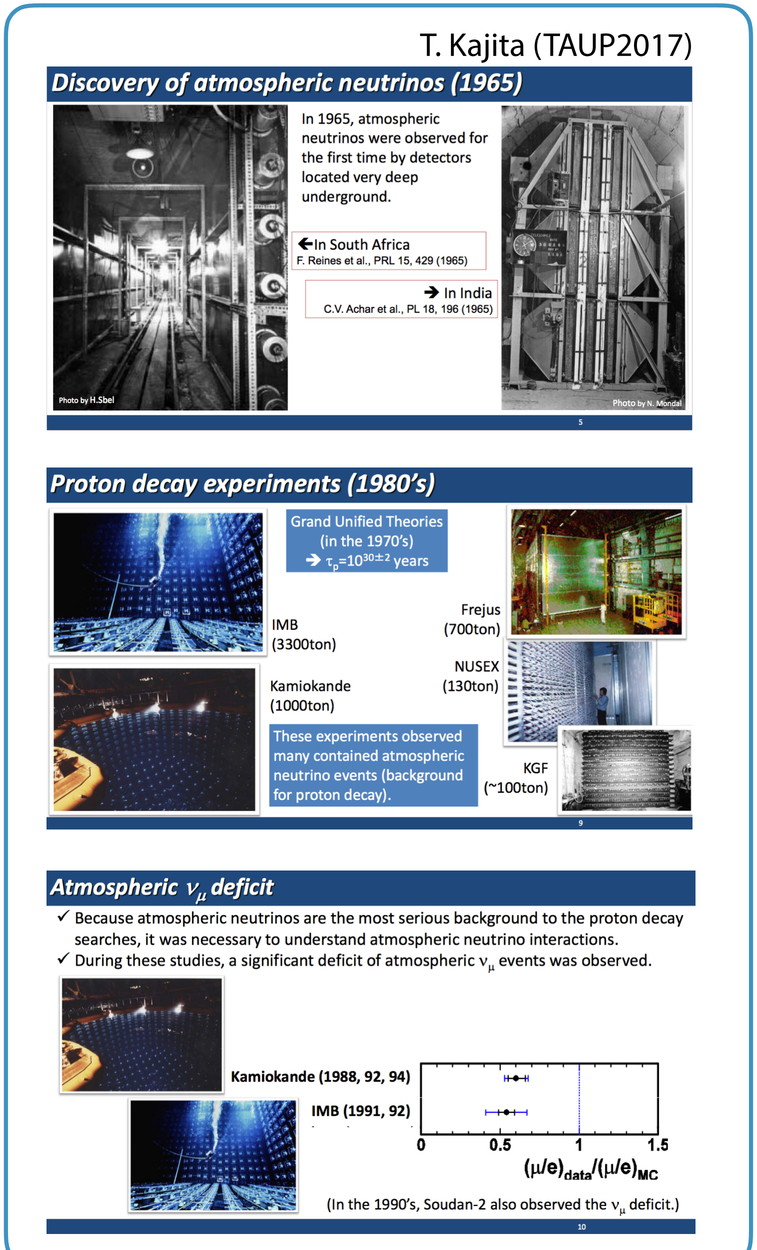

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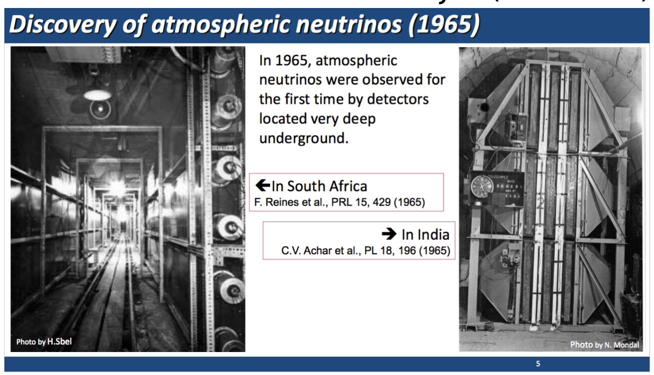

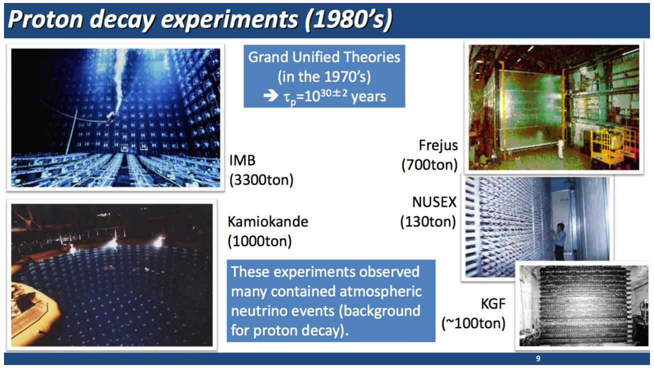

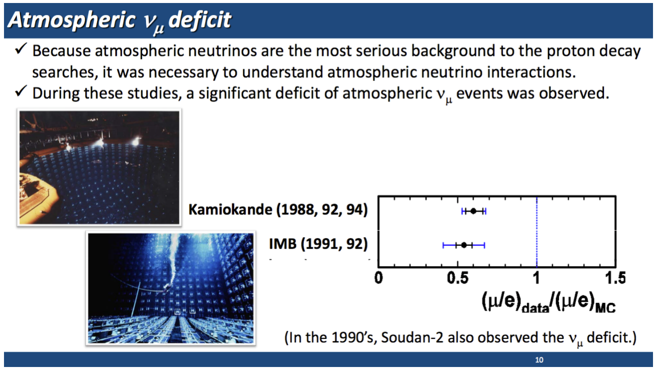

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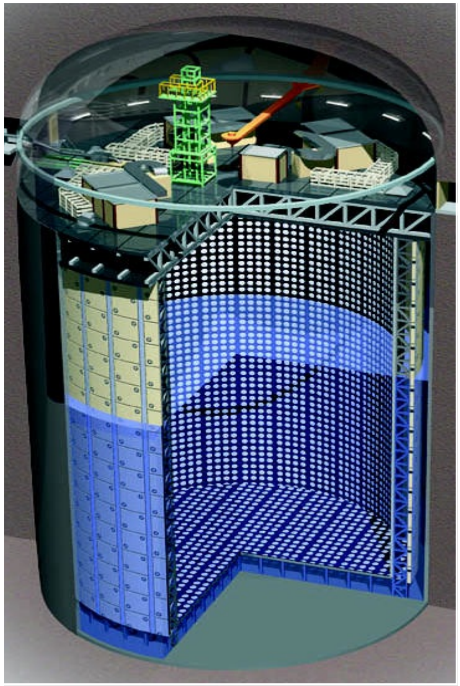

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Discovery of atmospheric neutrinos (1965)

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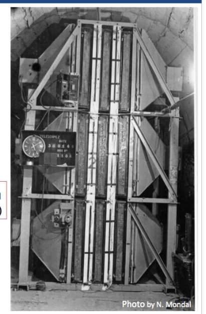
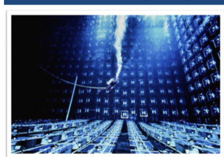


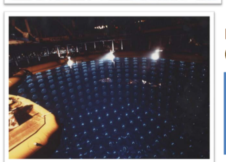
Proton decay experiments (1980's)



IMB (3300ton)

Grand Unified Theories (in the 1970's) → $\tau_p = 10^{30\pm2}$ years

Frejus (700ton)



Kamiokande (1000ton)

NUSEX (130ton)

These experiments observed many contained atmospheric neutrino events (background for proton decay).

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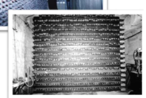

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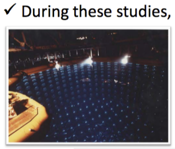

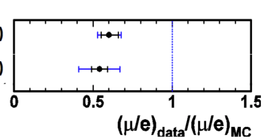

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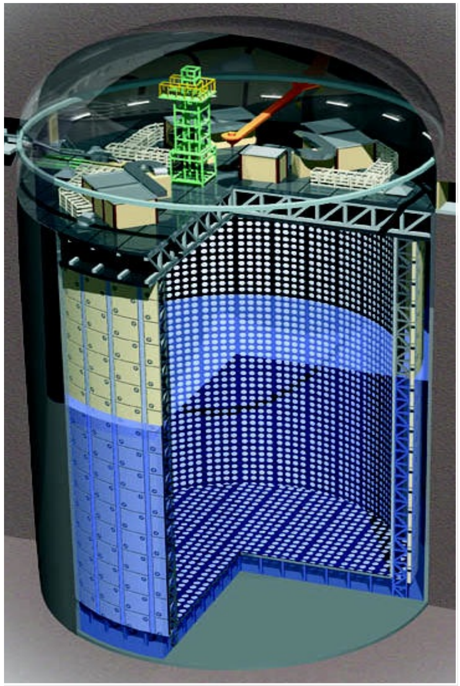

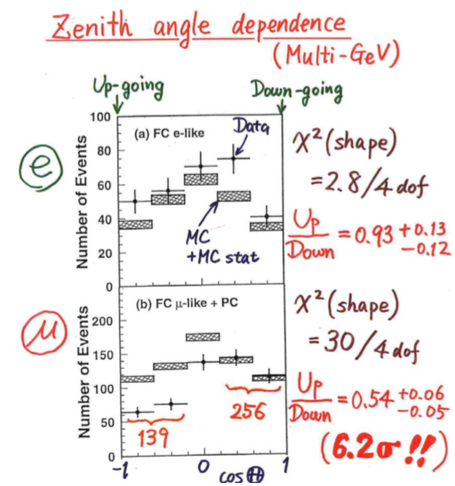

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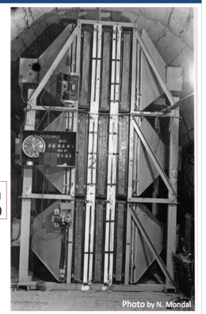

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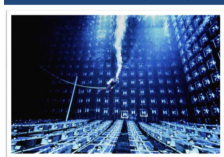

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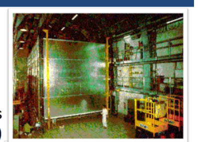

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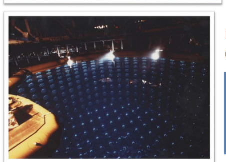

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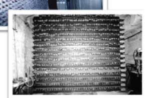

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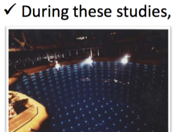

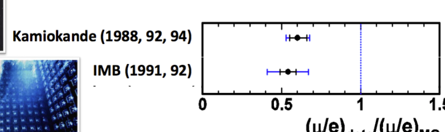

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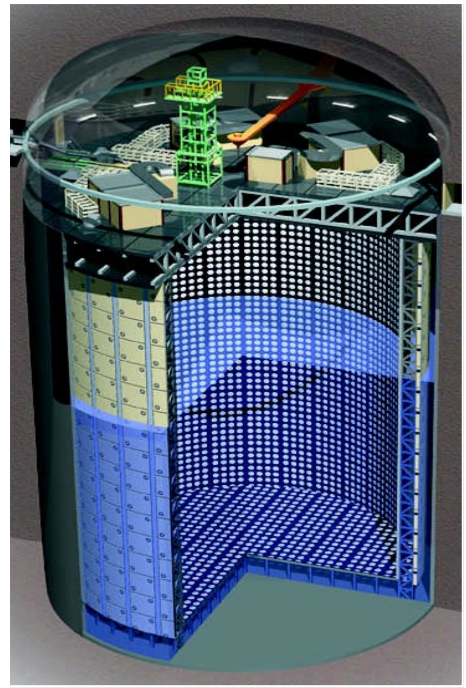

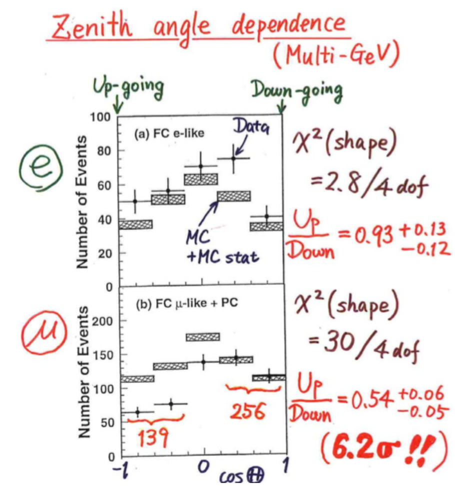

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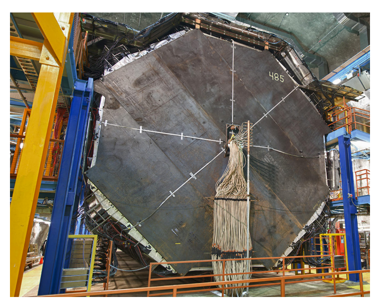

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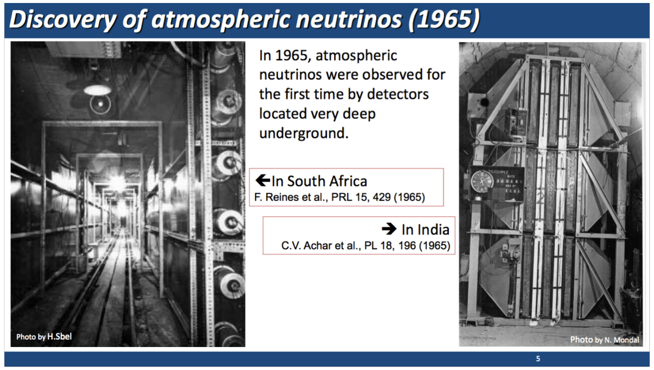

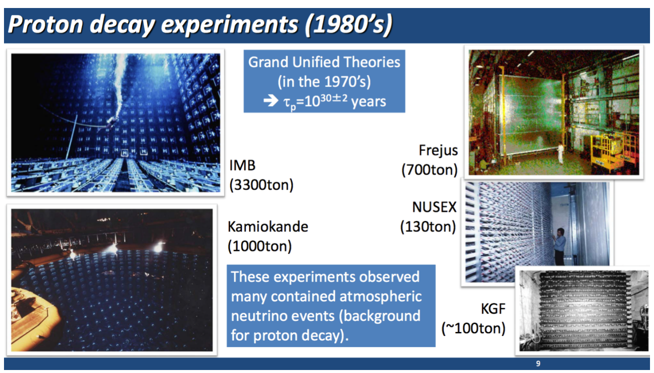

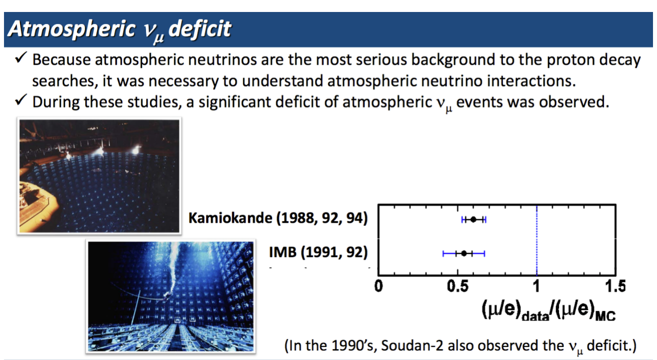

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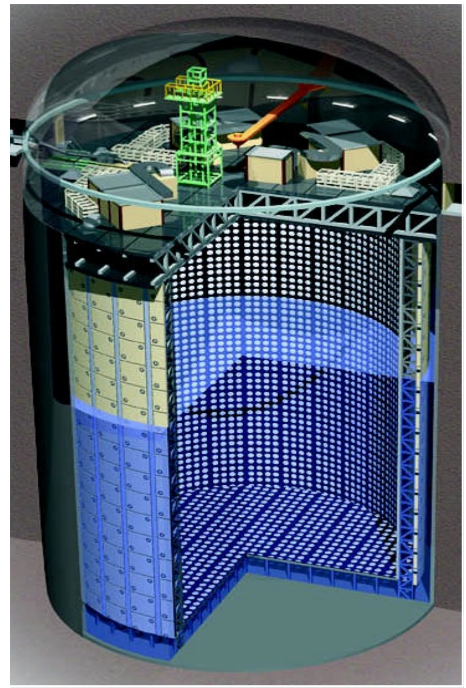

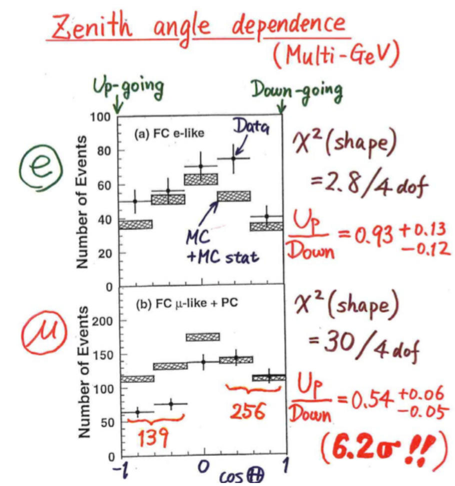

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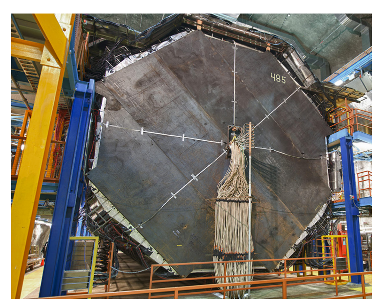
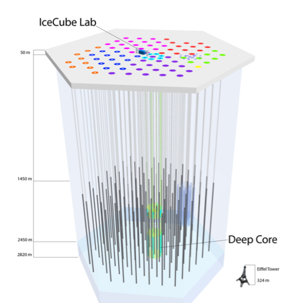
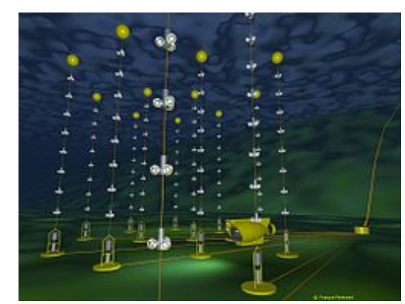


IceCube/DeepCore (2010~)



ANTARES (2008~)



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

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

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

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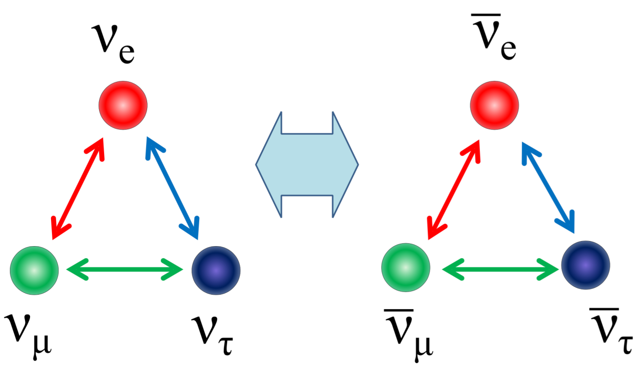

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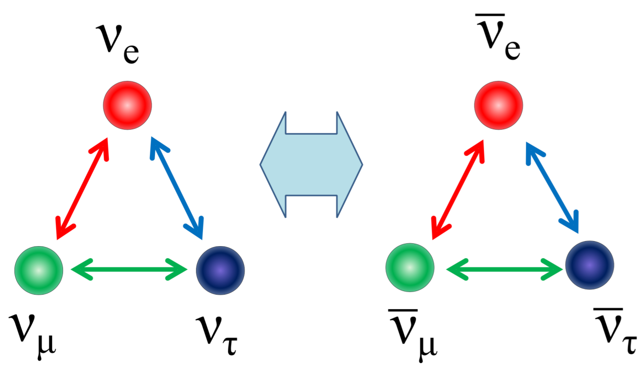

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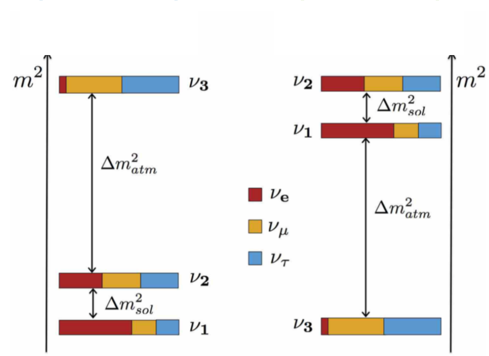

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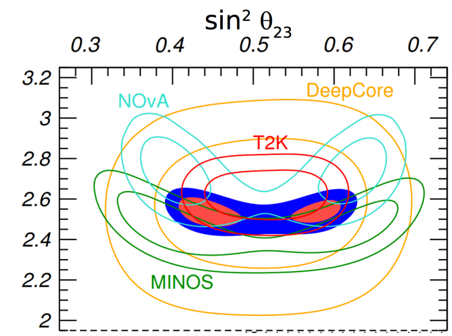

θ_{23} Octant

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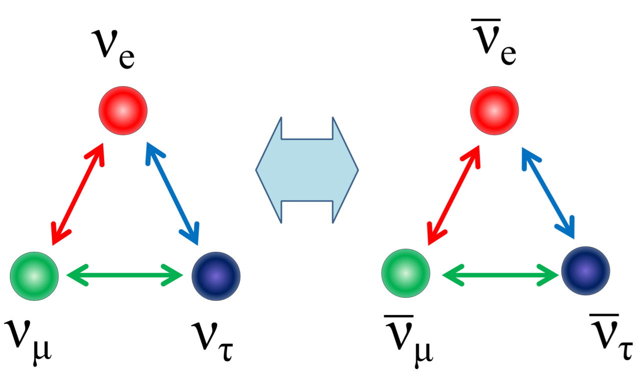

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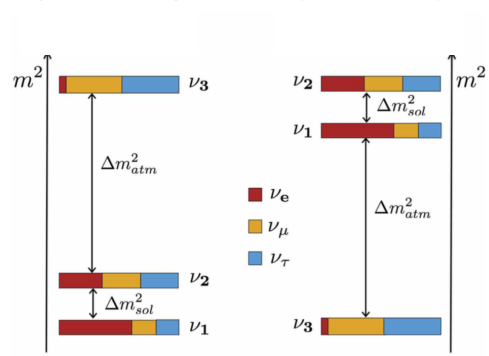

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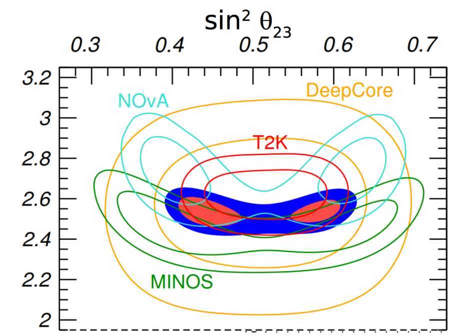

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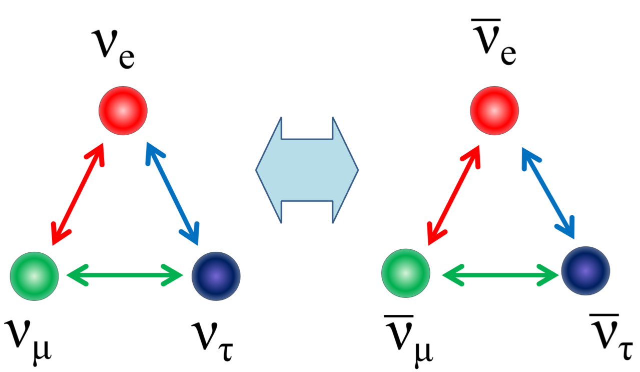

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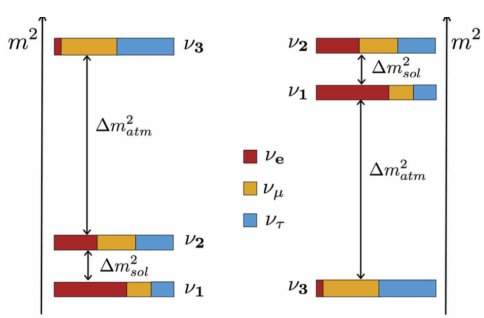
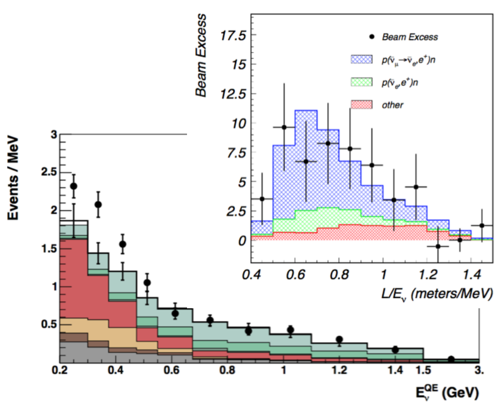
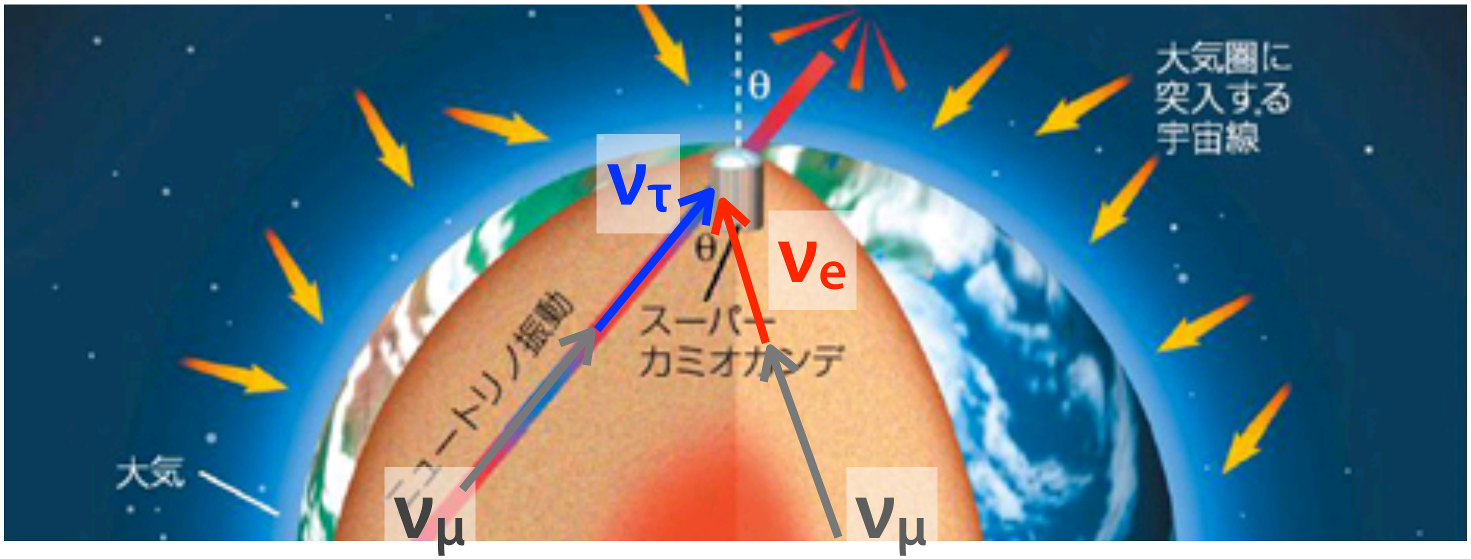


Mass Hierarchy
(Mass Ordering)

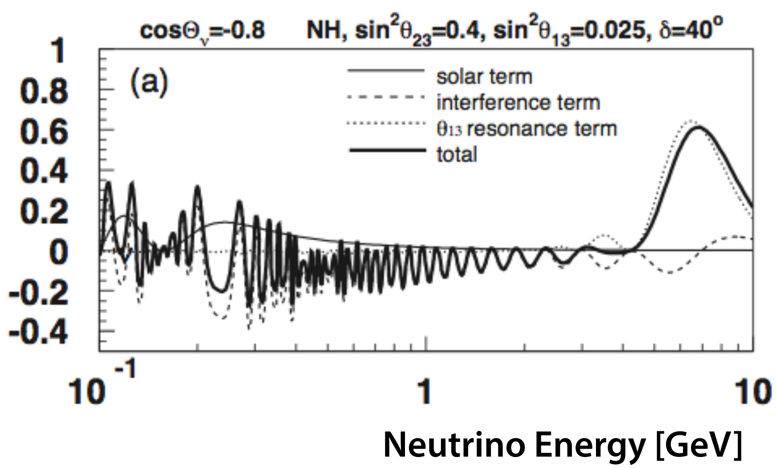


Sterile

Atmospheric Oscillation Physics



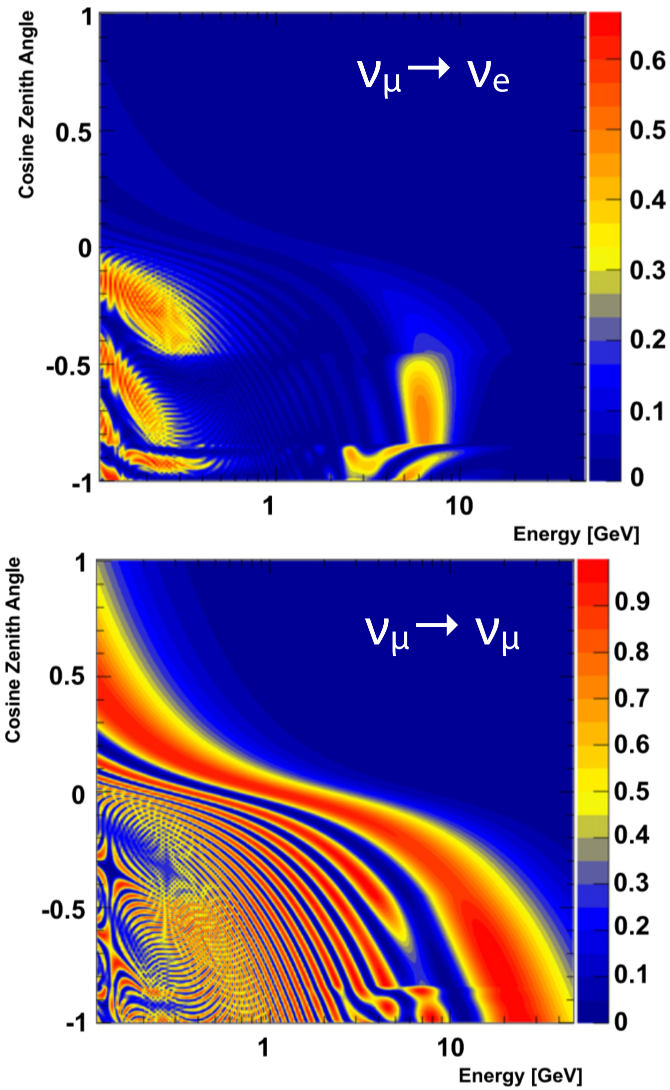
ν_e flux change due to sub-dominant oscillation:



- Many opportunities to test three flavor mixing:
  - ν_μ disappearance by ν_μ-> ν_τ (Δm^2_{32}, θ_{23})
  - **Sub-dominant oscillation in ν_e sample:** mass hierarchy (sign of Δm^2_{32}), δ_{CP}, θ_{23} octant
  - **ν_τ appearance**
- Exotic mode (**sterile**, NSI, ..)

Matter Effect and Mass Hierarchy

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



- Neutrino is affected by additional potential due to forward scattering with electrons (**matter effect**)

$$i\frac{d\nu(t)}{dt} = H_0\nu(t) \qquad H_0 \rightarrow H_0 + \frac{1}{2E}\begin{pmatrix} A & 0 \\ 0 & 0 \end{pmatrix}$$

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

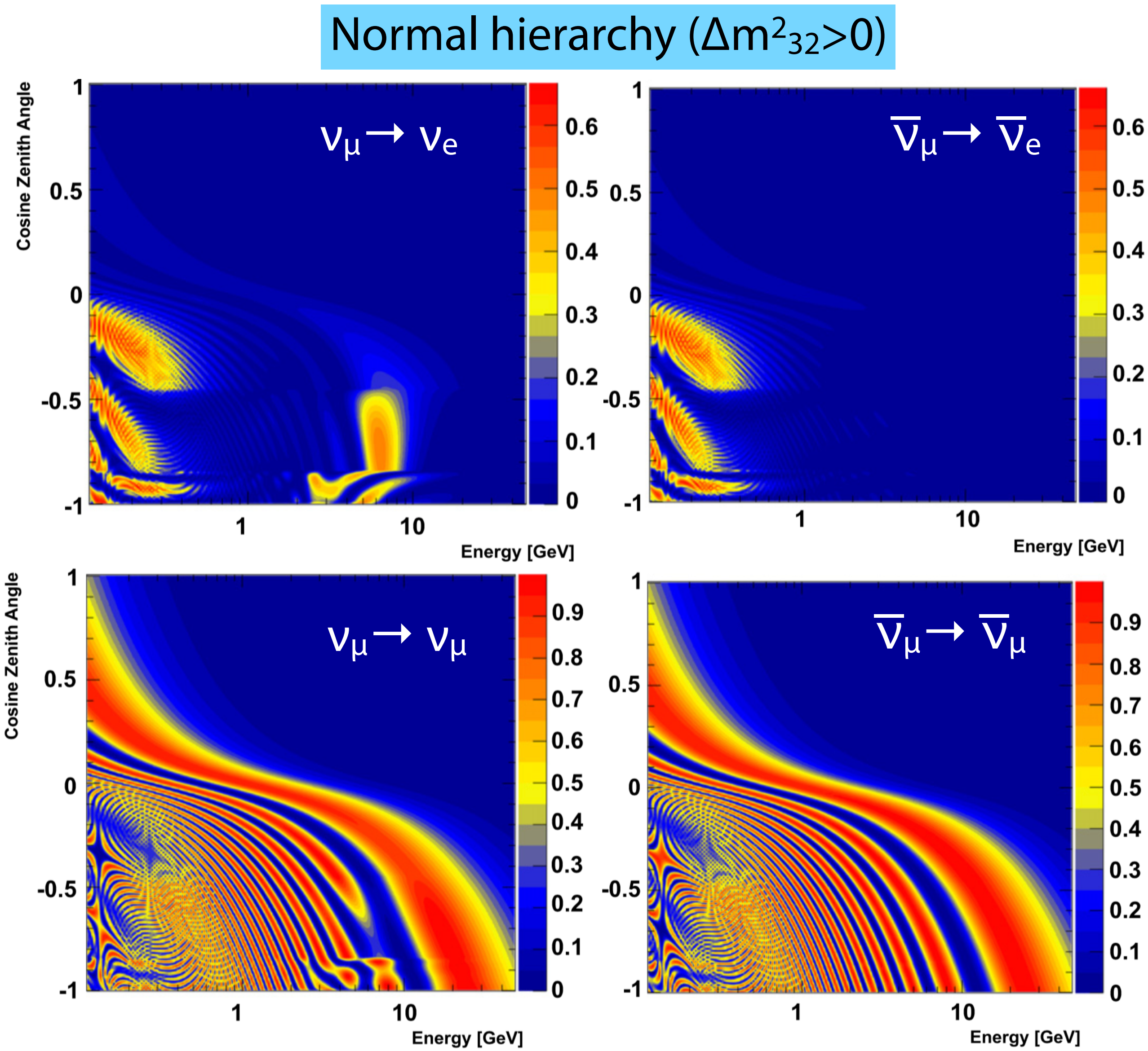
- Effective mixing angle in matter:

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

- At resonance region in multi-GeV:

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

Matter Effect and Mass Hierarchy



- Neutrino is affected by additional potential due to forward scattering with electrons (**matter effect**)

$$i\frac{d\nu(t)}{dt} = H_0\nu(t) \qquad H_0 \to H_0 + \frac{1}{2E}\begin{pmatrix} A & 0 \\ 0 & 0 \end{pmatrix}$$

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

- Effective mixing angle in matter:

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

- At resonance region in multi-GeV:

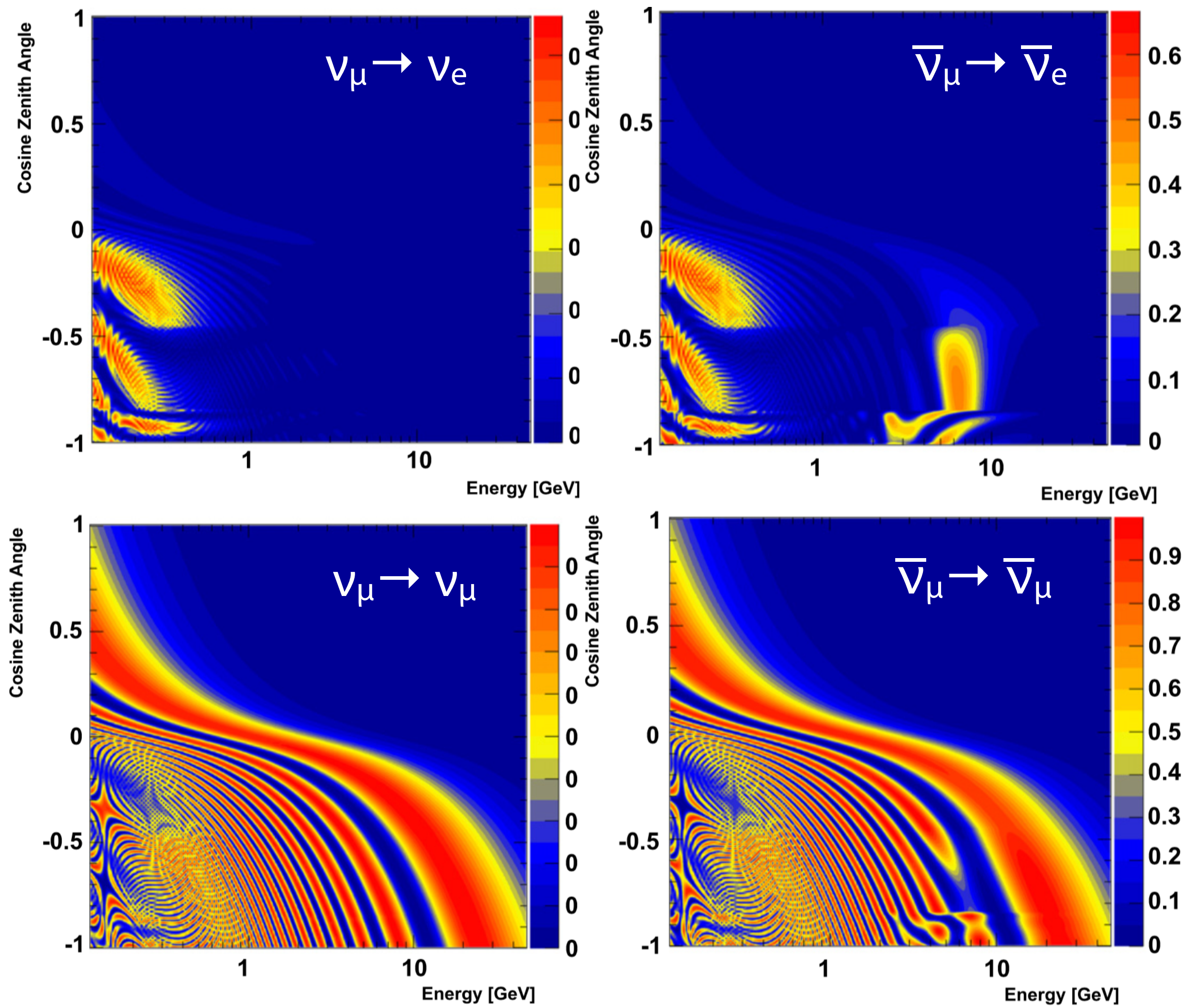
$$A \sim \Delta m^2_{32}\cos 2\theta_{13} \quad \to \quad \theta_{13}^M \gg \theta_{13}$$

- Presence of resonance depends:

  - **ν / $\bar{\nu}$ (A→ -A)**

Matter Effect and Mass Hierarchy

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



- Neutrino is affected by additional potential due to forward scattering with electrons (matter effect)

$$i\frac{d\nu(t)}{dt} = H_0\nu(t) \qquad H_0 \rightarrow H_0 + \frac{1}{2E}\begin{pmatrix} \mathrm{A} & 0 \\ 0 & 0 \end{pmatrix}$$

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

- Effective mixing angle in matter:

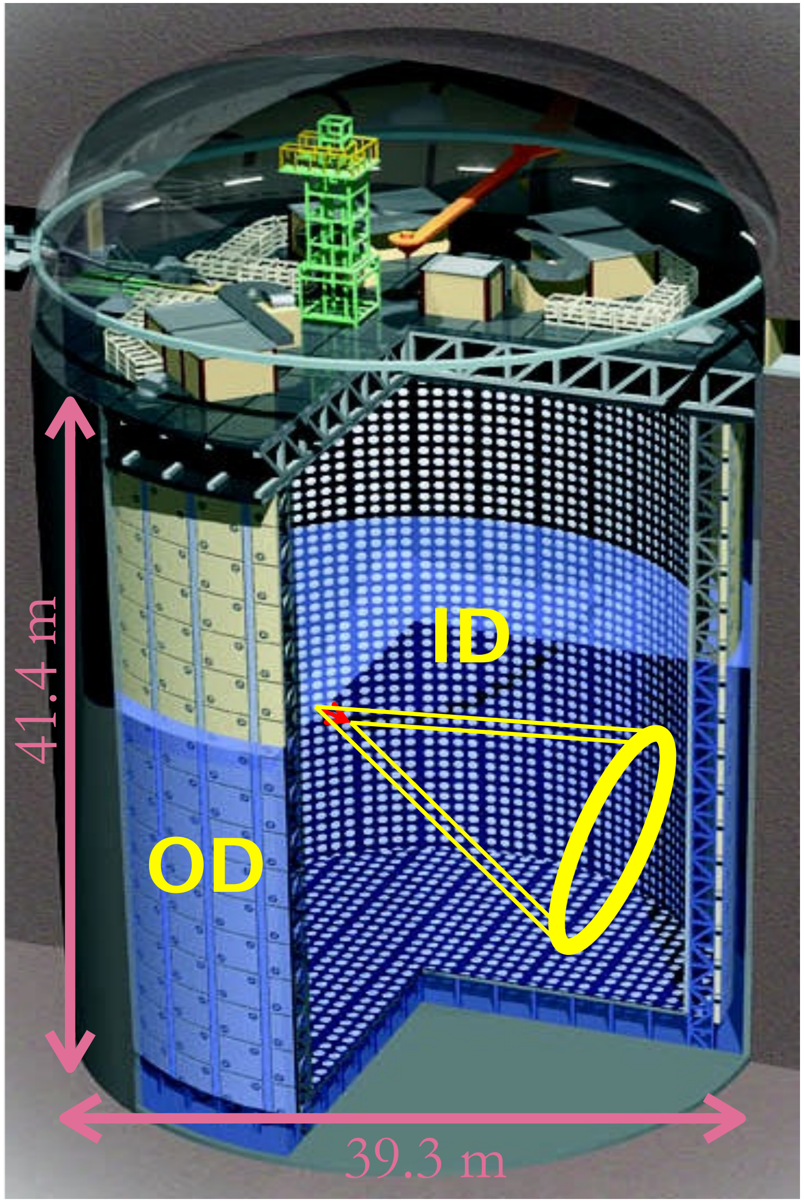
$$\sin 2\theta^M_{13} = \frac{\sin 2\theta_{13}}{\sqrt{\left(\frac{A}{\Delta m^2_{32}} - \cos 2\theta_{13}\right)^2 + \sin^2 2\theta_{13}}}$$

- At resonance region in multi-GeV:

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

- Presence of resonance depends:
  - ν / $\bar{\nu}$ (A→ -A)
  - Mass hierarchy ($\Delta m^2_{32} \rightarrow -\Delta m^2_{32}$)

Super-Kamiokande Detector

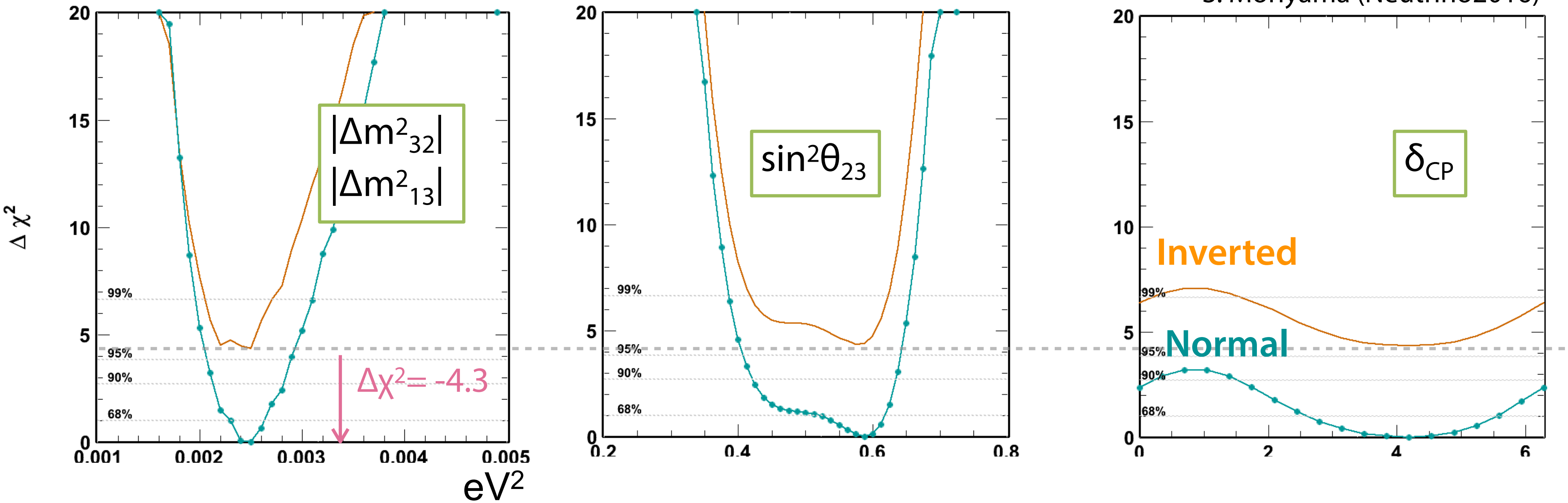


- Water Cherenkov imaging detector
- **1000 m underground** in Kamioka mine
- **50 kton volume** (fiducial 22.5 kton)
- **11129 20″ PMTs** in inner detector (ID) for Cherenkov ring imaging
- 1885 8″ PMTs for outer detector (OD)

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 ~	

Three Flavor Fit (w/ reactor constraint)

S. Moriyama (Neutrino2016)



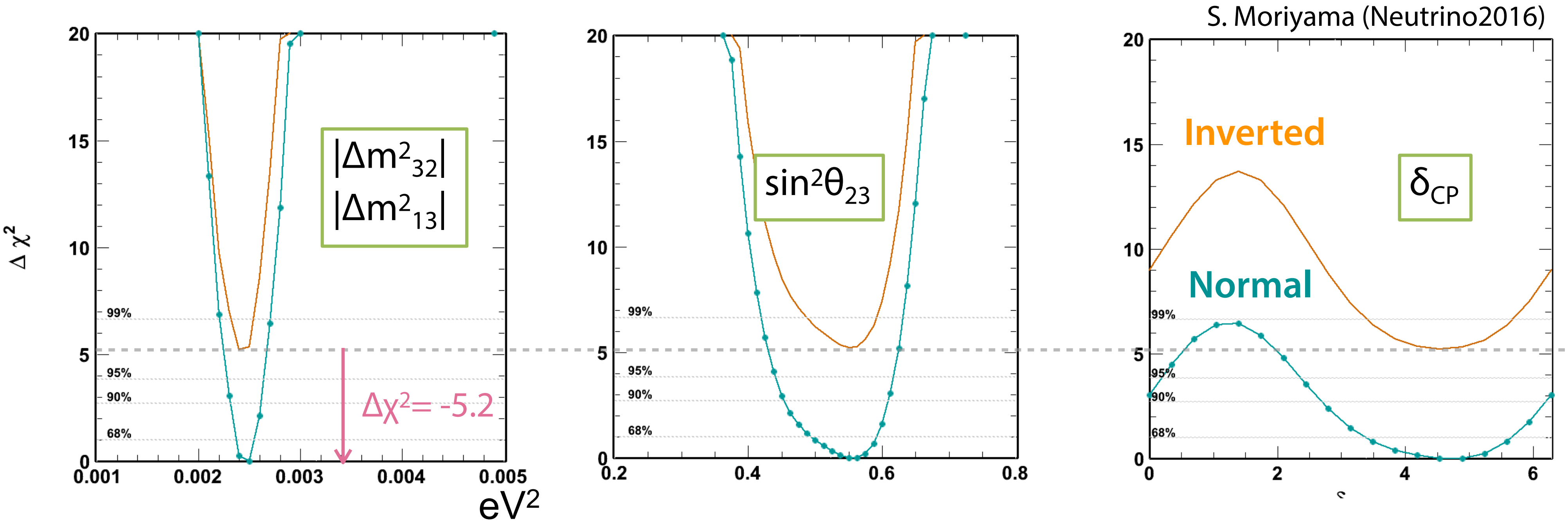
- Perform full parameter fit with additional constraints from reactor ($\sin^2\theta_{13}$=0.0219):
  $\Delta\chi^2 = \chi^2_{NH} - \chi^2_{IH} = -4.3$ (-3.1 expected)

- Under IH hypothesis, the probability to obtain $\Delta\chi^2$ of -4.3 or less is 0.031 ($\sin^2\theta_{23}$=0.6) and 0.007 ($\sin^2\theta_{23}$=0.4). Under NH hypothesis, the probability is 0.45 ($\sin^2\theta_{23}$=0.6).

	δ_{CP}	$\sin^2\theta_{23}$	$\lvert\Delta m^2_{32}\rvert$ (eV²)
Inverted	4.189	0.575	2.5×10^{-3}
Normal	4.189	0.587	2.5×10^{-3}

Three Flavor Fit (w/ reactor and T2K constraints)

S. Moriyama (Neutrino2016)



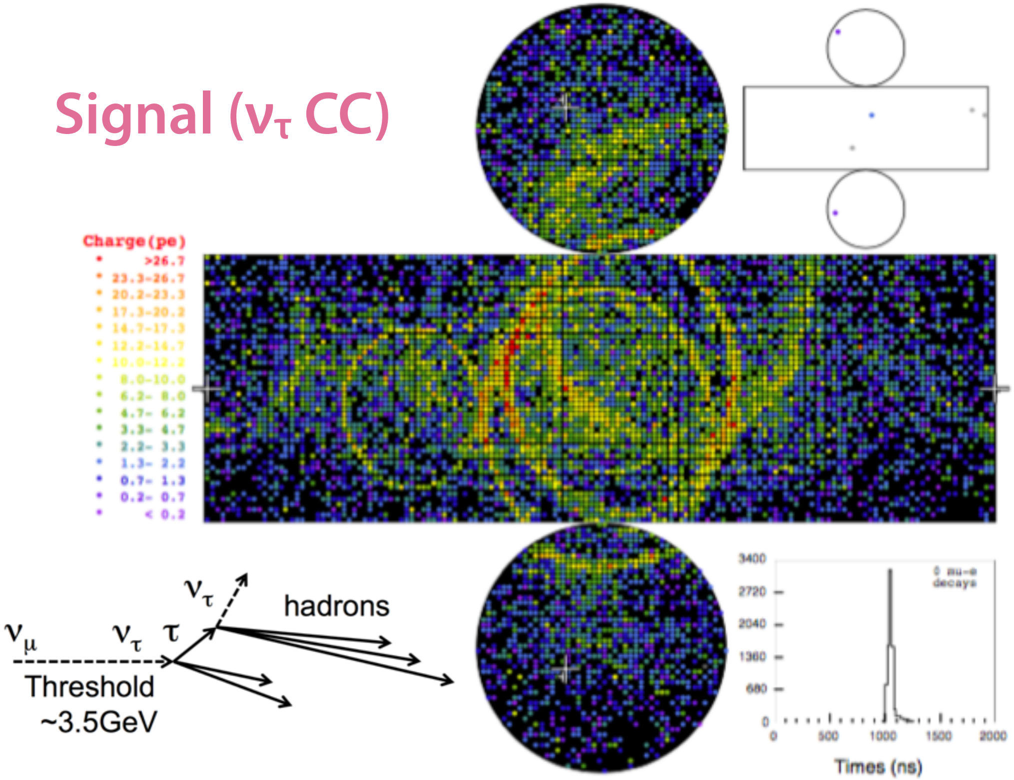
- Include constraint from T2K public data.
- **Normal hierarchy is slightly preferred:** $\Delta\chi^2 = \chi^2_{NH} - \chi^2_{IH} = -5.2$ (-3.8 exp. for SK best, -3.1 for combined best)
- p-value of Inverted hypothesis is 0.024 ($\sin^2\theta_{23}$=0.6) and 0.001 ($\sin^2\theta_{23}$=0.4).

	δ_{CP}	$\sin^2\theta_{23}$	$\|\Delta m^2_{32}\|$ (eV^2)
Inverted	4.189	0.575	2.5×10^{-3}
Normal	4.189	0.587	2.5×10^{-3}
Inverted	4.538	0.55	2.5×10^{-3}
Normal	4.887	0.55	2.4×10^{-3}

w/ T2K constraint

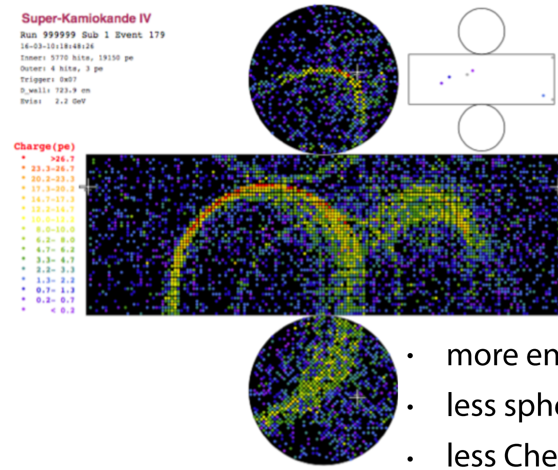
Tau Appearance

Signal (ν_τ CC)



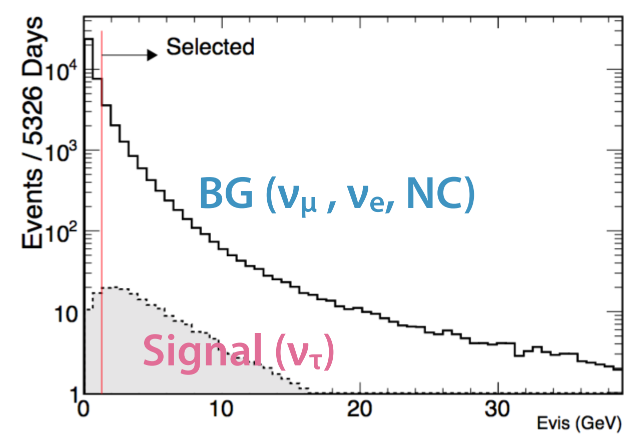
$\leftrightarrow$

Background (ν_μ CC)

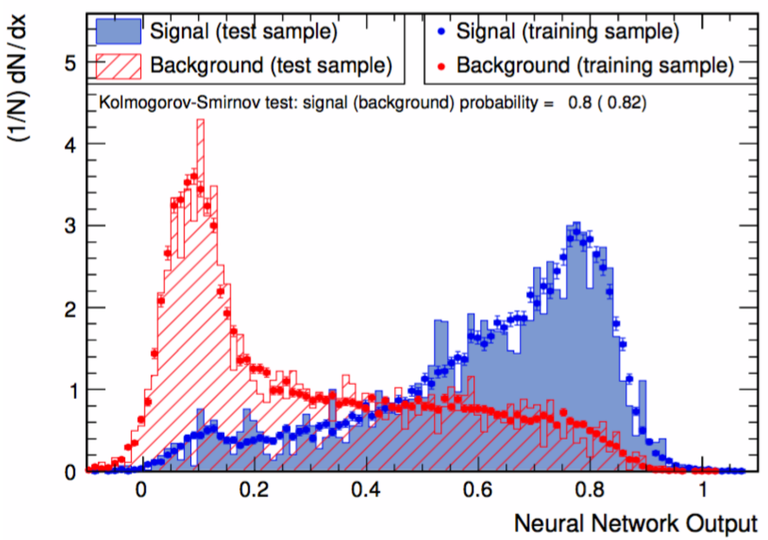


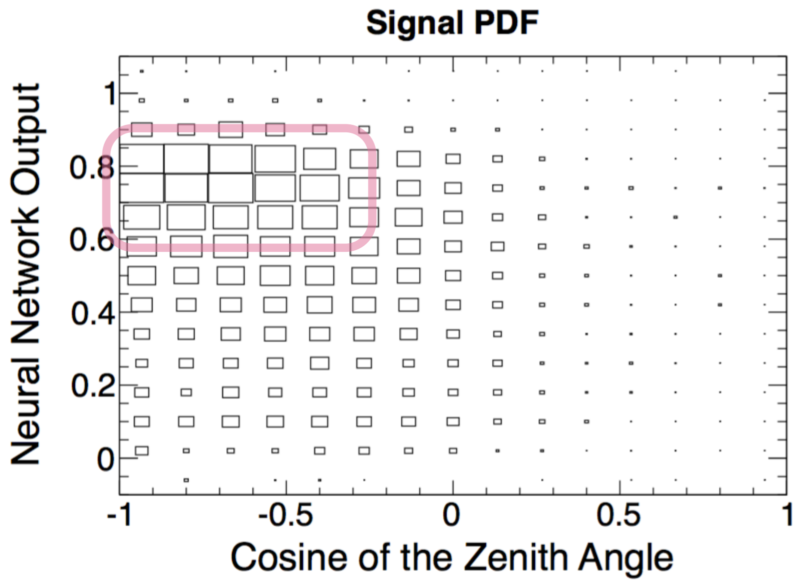
- more energy in 1st ring
- less sphericity
- less Cherenkov rings
- less mu-e decays
- …

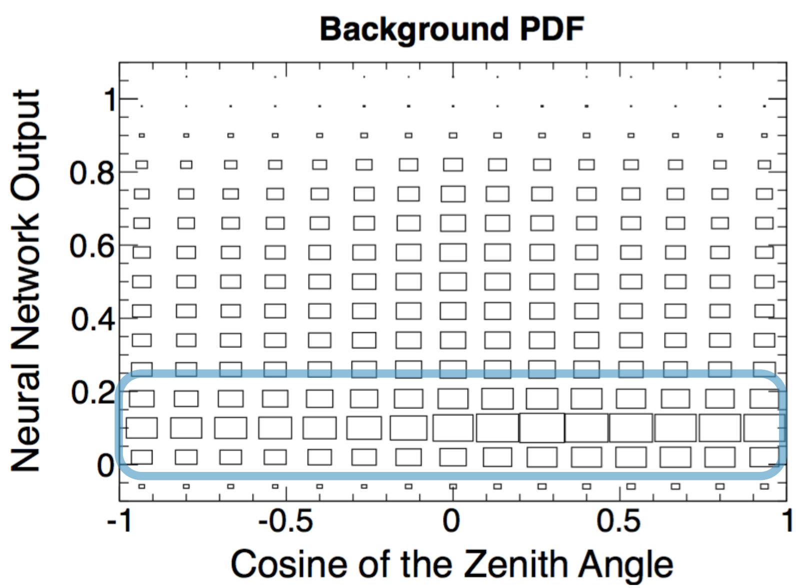
- Direct detection of tau appearance induced by $\nu_\mu \rightarrow \nu_\tau$ is critical for verifying three-flavor mixing scheme
- Detection is challenging: **low signal rate** (~1 event / kton year) with **large backgrounds**
- Search for **hadronic modes of tau decay** (branching ratio: 65%)



Tau Signal Discrimination



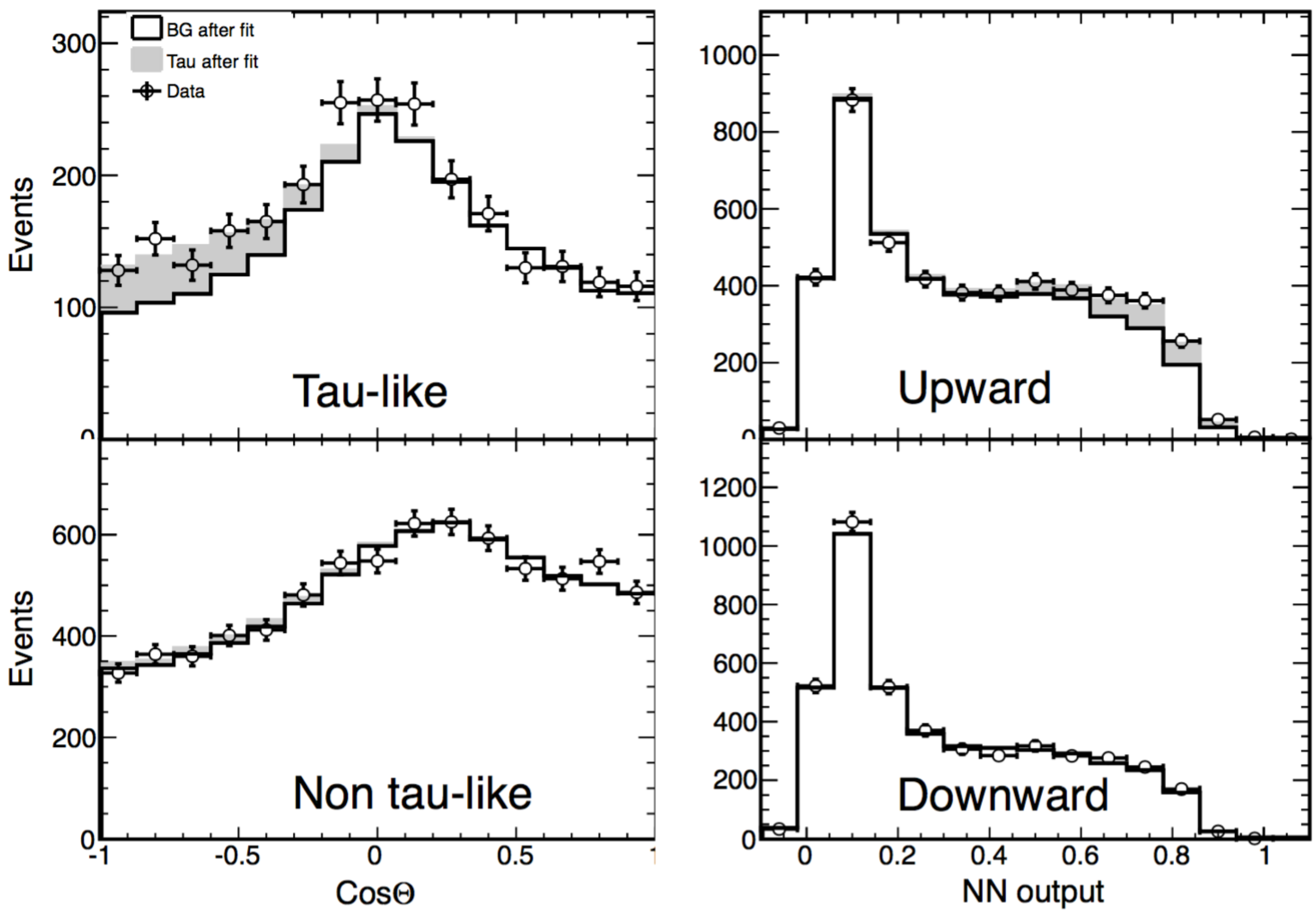




- Employ **neural network (NN)** technique to discriminate tau signal from background
  - Signal eff. 76%, 26% of background remains by NN>0.5 cut
- Tau events have higher NN output and enhanced in **upward direction**
- Perform 2-dim. fit with signal scale parameter:

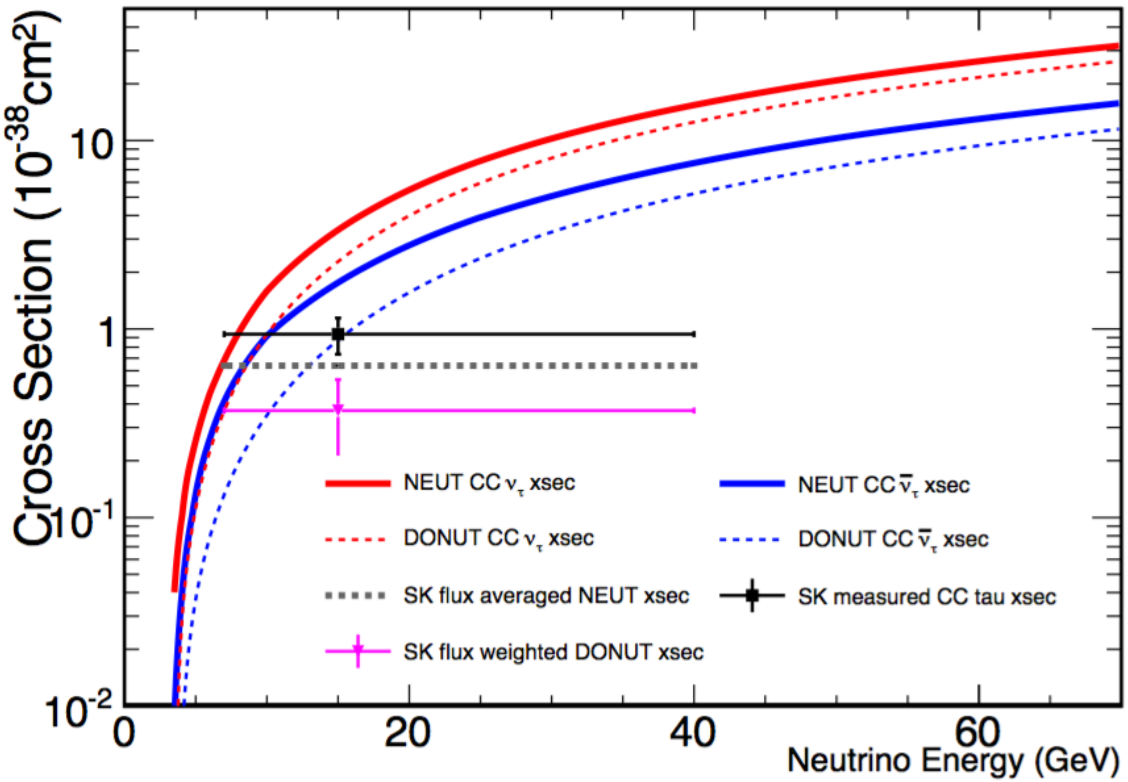
$$Data = PDF_{BG} + \alpha \times PDF_{tau} + \sum \epsilon_i \times PDF_i$$

Tau Appearance Result



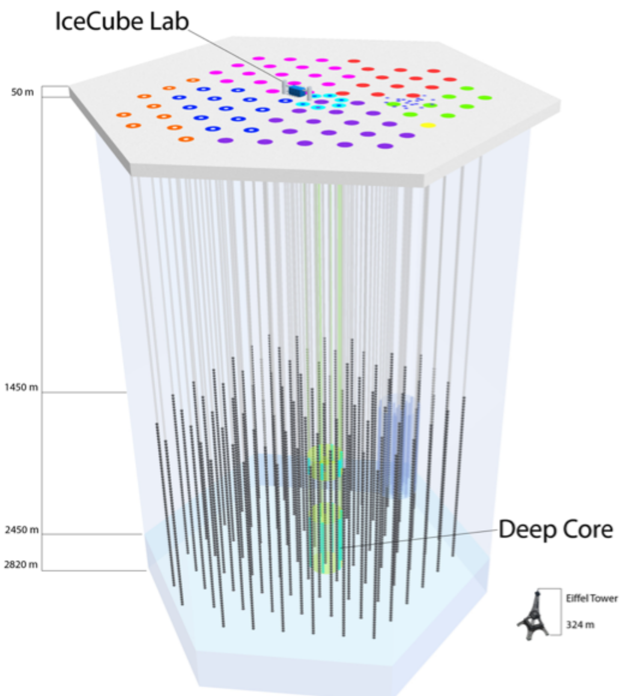
- Data: **SK-I~IV 5,326 days**
- Fitted tau normalization:
  α = **1.47 ± 0.32** (stat+syst)
  - Observed events:
    338.1 ± 72.7 events
    (exp'd: 224.5)
- Excluding no tau appearance hypothesis with **4.6 σ** **(exp'd 3.3σ)**
- Still dominated by statistical uncertainty

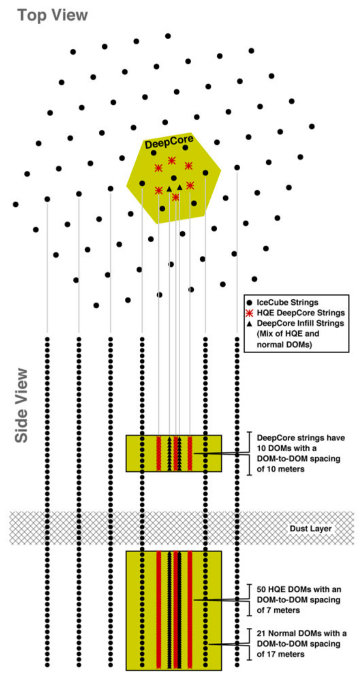
Tau Neutrino Cross Section



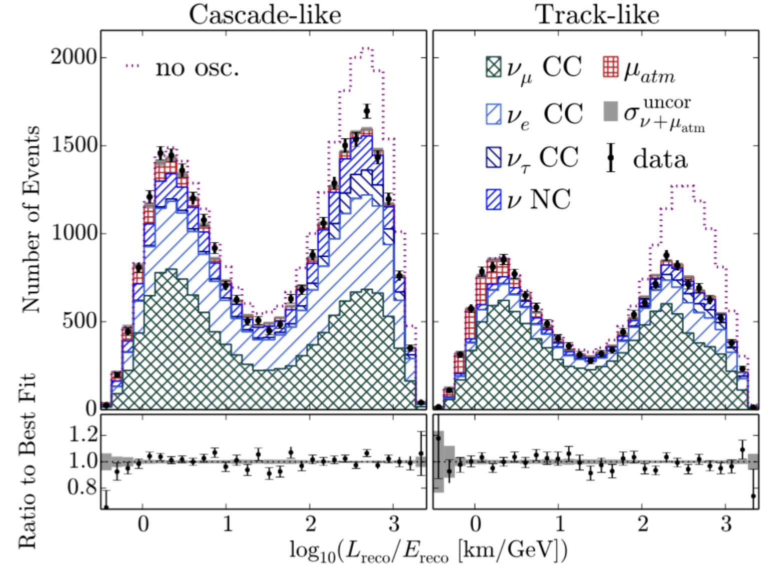
- Large CC ν_τ sample offers the opportunity to **measure CC ν_τ cross section**
- Sensitive energy: 3.5 ~ 70 GeV
- Flux averaged cross section ($\times 10^{-38}$cm^2):
  - **measured: 0.94 ± 0.20**
  - **theory: 0.64**
- **Consistent with SM prediction** within 1.5 sigma
- Larger than scaled σ measured by DONUT at 111 GeV

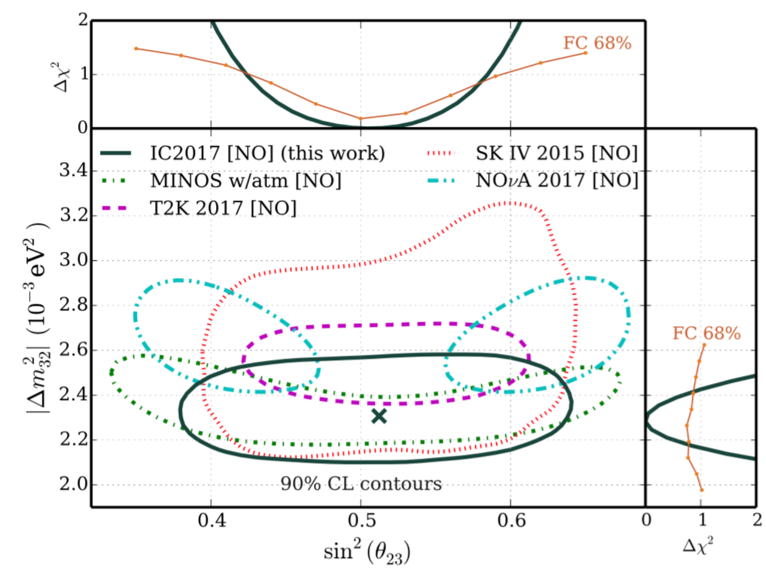
IceCube Oscillation Measurement





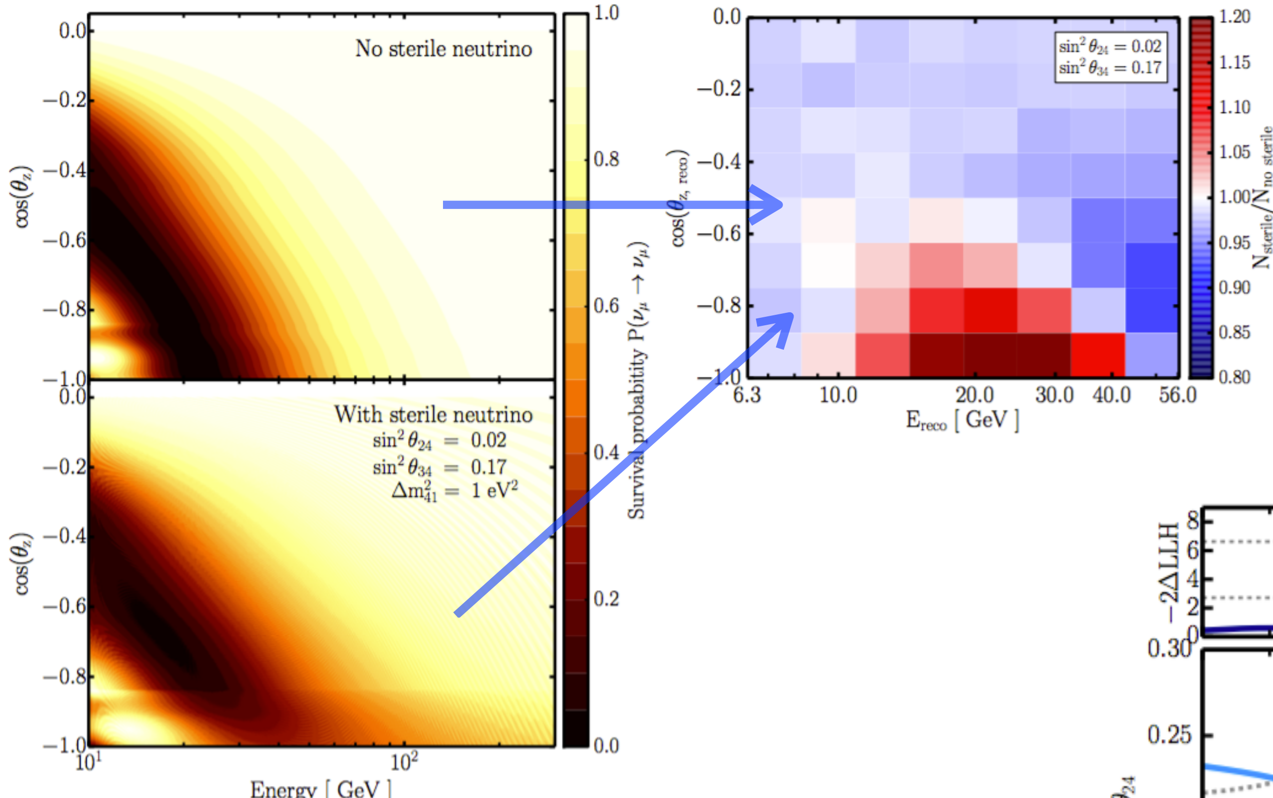
hep-ex arXiv:1707.07081





- DeepCore: 8 vertical strings with 7~17 m spacing.
- Lowering energy threshold (**5.6 ~ 56 GeV**)
- Separate **track-like / cascade-lik**e events by event topology to enhance ν_μ and ν_e interactions
- $\Delta m^2_{32}=2.31^{+0.11}_{-0.13} \times 10^{-3}$ eV^2 , $\sin^2\theta_{23}=0.51^{+0.07}_{-0.09}$

Search for Sterile Oscillation

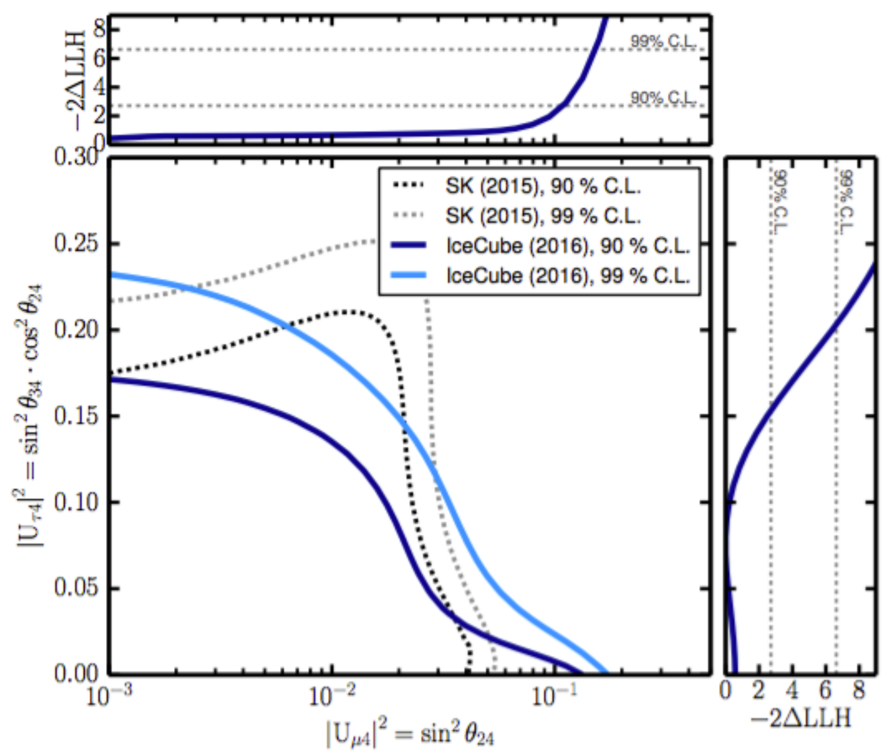


3+1 sterile model:

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

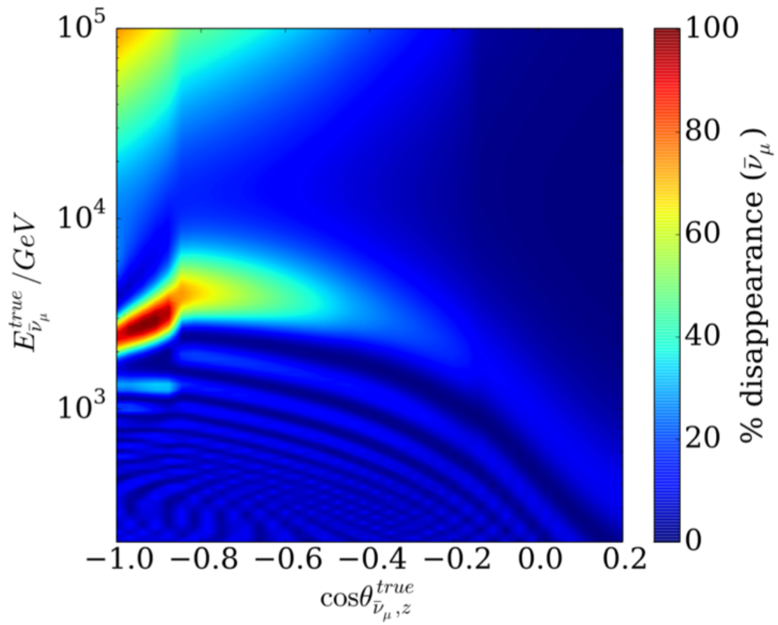
$$|U_{\mu 4}|^2 = \sin^2\theta_{24},$$
$$|U_{\tau 4}|^2 = \cos^2\theta_{24} \cdot \sin^2\theta_{34}$$

PRD 95, 112002 (2017)



- **Different matter potential** between active-sterile vs because sterile does not interact with matter, which imprints on standard three flavor oscillations
- Search for sterile via νμ disappearance in **10 - 60 GeV**
- Limits on matrix elements: $|U_{\mu 4}|^2 < 0.11$ (90% C.L.), $|U_{\tau 4}|^2 < 0.15$ (90% C.L.),

Another Sterile Search via Matter Resonance

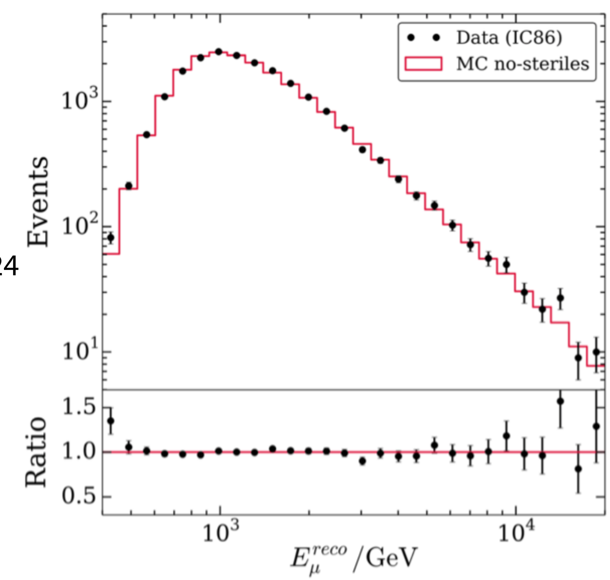


- Existing sterile mass of **0.1 < Δm² < 10 eV²** will enhance sterile oscillation in **320 GeV - 20 TeV** by **matter resonance**

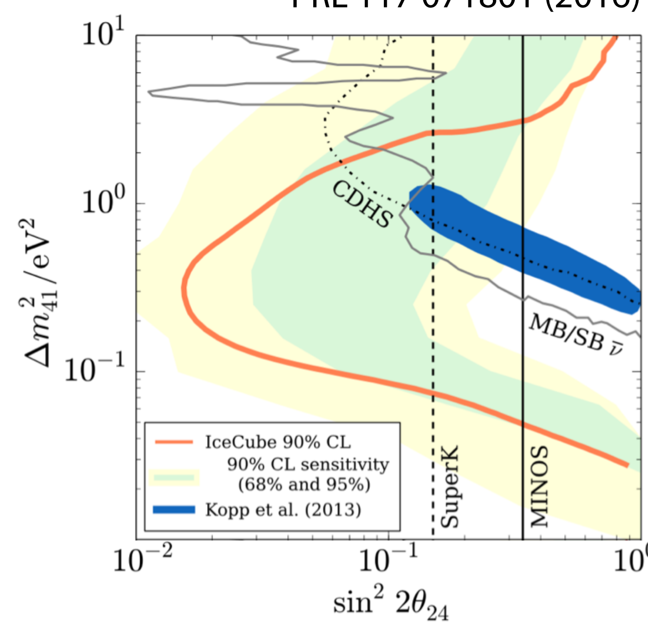
$$A = 2\sqrt{2}G_F E_\nu n_e \sim \Delta m^2_{41}\cos 2\theta_{24} \quad \rightarrow \quad \theta^M_{24} \gg \theta_{24}$$

- Would produce distinctive signature in ν_μ energy spectrum

- **No significant distortions** observed
- Δm^2-dependent constraint on θ_{24}
- **Reject allowed region** indicated by existing experiments and 3+1 sterile model



PRL 117 071801 (2016)



Proton Decay Measurements

(S. Mine, NNN16)

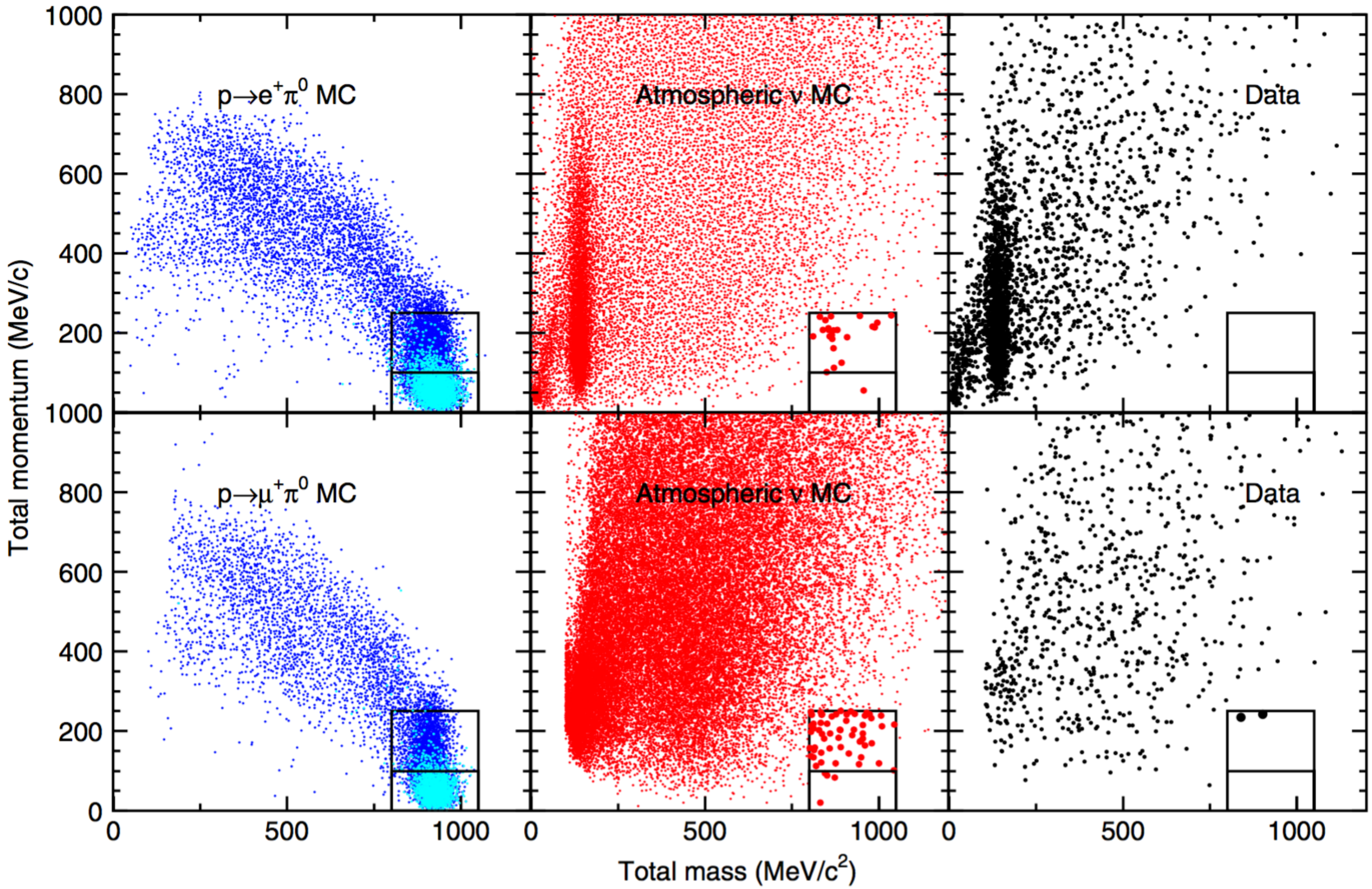
Recent nucleon decay and n-$\bar{n}$ results in SK

Decay mode	$\lvert\Delta(B-L)\rvert$	Lifetime lower limit at 90% CL (years)	Paper	
$p \to e^+\pi^0$	0	1.6×10^{34}	arXiv:1610.03597 (submitted to PRD)	(*)
$p \to \nu K^+$	$0(\bar{\nu})$, $2(\nu)$	6.6×10^{33}	PRD 90, 072005 (2014)	Updated
$p \to \mu^+\pi^0$	0	7.7×10^{33}	arXiv:1610.03597 (submitted to PRD)	(*)
$p \to (e^+,\mu^+)(\eta,\rho,\omega)$, $n \to (e^+,\mu^+)(\pi,\rho)$	0	$(0.03\text{-}10) \times 10^{33}$	will submit to PRD	(**)
$p \to \mu^+K^0$	0	1.6×10^{33}	PRD 86, 012006 (2012)	
$\bar{n} \to \nu\pi^0$, $\bar{p} \to \nu\pi^+$	0	1.1×10^{33}, 3.9×10^{32}	PRL 113, 121802 (2014)	
$p \to (e^+,\mu^+)\nu\nu$	$0(\bar{\nu}\nu)$, $2(\nu\nu,\bar{\nu}\bar{\nu})$	$1.7/2.2 \times 10^{32}$	PRL 113, 101801 (2014)	
$p \to (e^+,\mu^+)X$	?	$7.9/4.1 \times 10^{32}$	PRL 115, 121803 (2015)	
$n \to \nu\gamma$	$0(\bar{\nu})$, $2(\nu)$	5.5×10^{32}	PRL 115, 121803 (2015)	
$pp \to K^+K^+$	2	1.7×10^{32}	PRL 112, 131803 (2014)	
$pp \to \pi^+\pi^+$, $pn \to \pi^+\pi^0$, $nn \to \pi^0\pi^0$	2	7.2×10^{31}, $1,7 \times 10^{32}$, 4.0×10^{32}	PRD 91, 072009 (2015)	
$np \to (e^+,\mu^+,\tau^+)\nu$	$0(\bar{\nu})$, $2(\nu)$	$(0.22\text{-}5.5) \times 10^{32}$	PRL 115, 121803 (2015)	
n-$\bar{n}$ oscillation	2	1.9×10^{32}	PRD 91, 072006 (2015)	

(*) published in PRD 95, 012004 (2017)
(**) published in PRD 96, 012003 (2017)

Searches for $P \rightarrow e^+\pi^0$ and $P \rightarrow \mu^+\pi^0$

PRD 95, 012004 (2017)



$P \rightarrow e^+\pi^0$:

- 0 event
- **>1.6 x 10^{34} yrs** (90%C.L.)

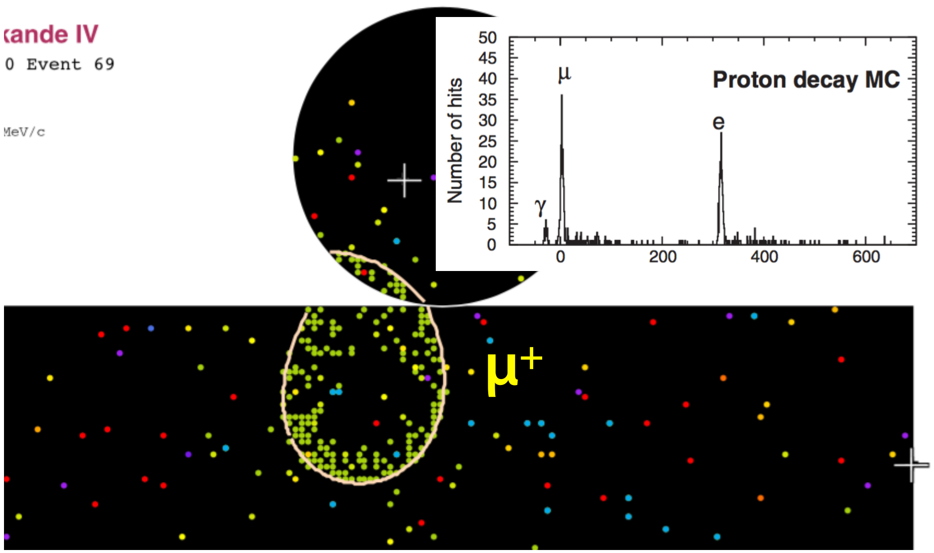
$P \rightarrow \mu^+\pi^0$:

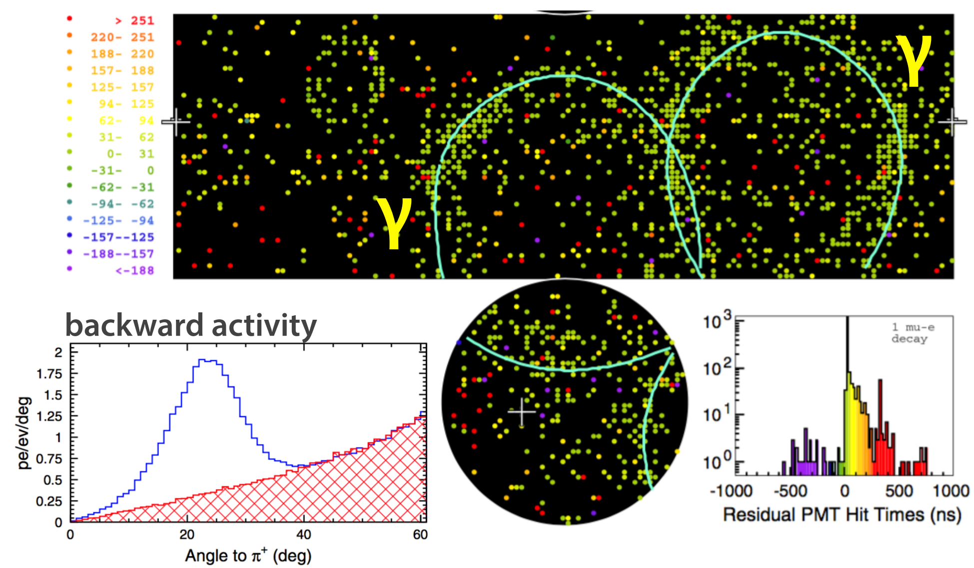
- 2 events (0.87 BG exp'd)
- **>7.7x 10^{33} yrs** (90%C.L.)

Search for $P \rightarrow \overline{\nu}\ K^+$

(A) $K^+ \rightarrow \nu_\mu\ \mu^+$ **(BR: 64%)**

(B) $K^+ \rightarrow \pi^0\ \pi^+$ **(BR: 21%)**



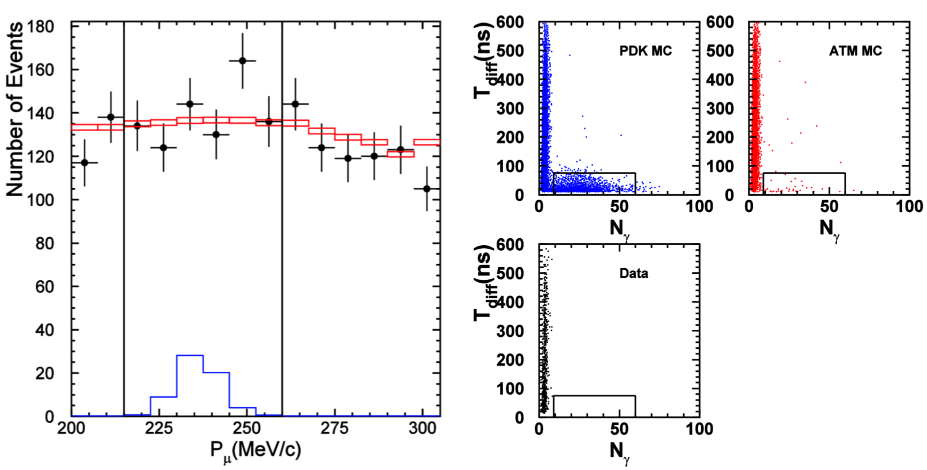


- **Single mono-energetic muon** (Pμ=236MeV/c) from K^+ decay with following μ-e decay
- Require **prompt 6 MeV gamma** from excited oxygen nuclei
- Search for **$\pi^0 \rightarrow 2\gamma$ decay** (P_{π^0}=205MeV/c) event with **faint π^+ activity** in backward direction

Search for $P \rightarrow \overline{\nu} K^+$

(A) $K^+ \rightarrow \nu_\mu \; \mu^+$

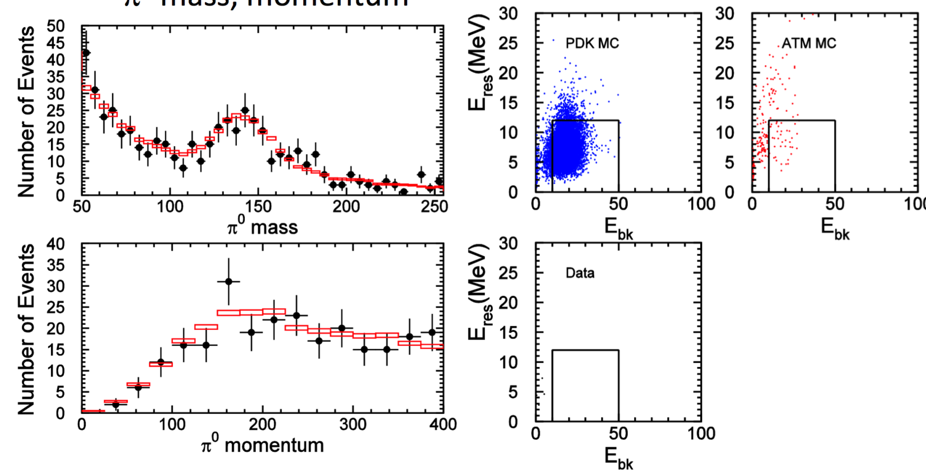
Pμ   Nγ vs Tdiff



(B) $K^+ \rightarrow \pi^0 \; \pi^+$

2-ring

π^0 mass, momentum

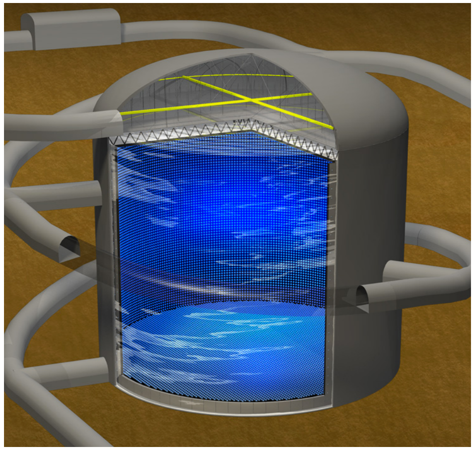


	SK1			SK2			SK3			SK4		
	Eff (%)	BG (ev)	Obs (ev)	Eff (%)	BG (ev)	Obs (ev)	Eff (%)	BG (ev)	Obs (ev)	Eff (%)	BG (ev)	Obs (ev)
Pr.γ	7.9 ±0.1	0.078	0	6.5 ±0.1	0.082	0	7.5 ±0.1	0.018	0	9.4 ±0.1	0.112	0
$\pi^+\pi^0$	7.8 ±0.1	0.21	0	6.5 ±0.1	0.19	0	8.3 ±0.1	0.07	0	9.6 ±0.1	0.13	0

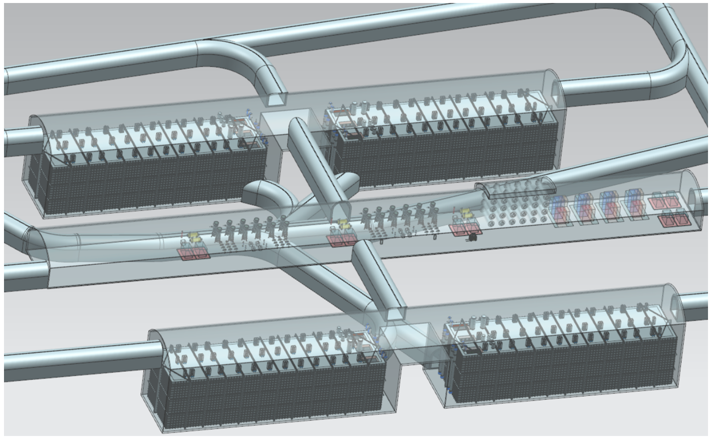
- **No candidate events** are observed for both modes in 349 kton·year exposure
- Lifetime limit: **>8.0 x 10^{33} years** (90% C.L.)

Future Projects: Atmospheric ν

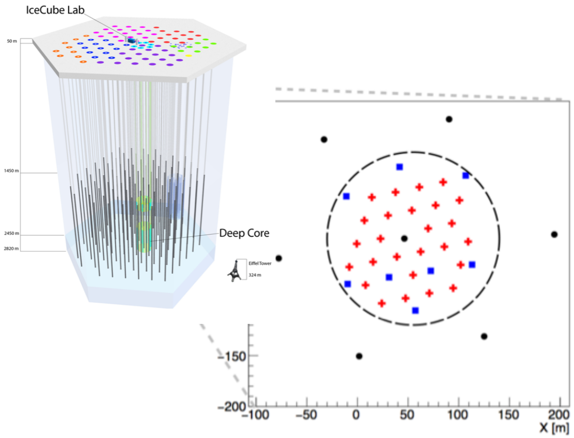
Hyper-Kamiokande



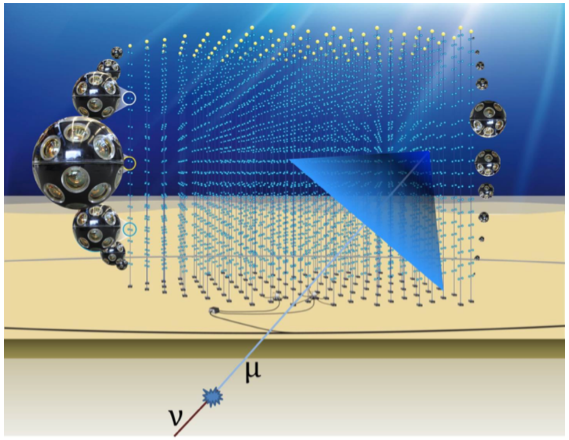
DUNE



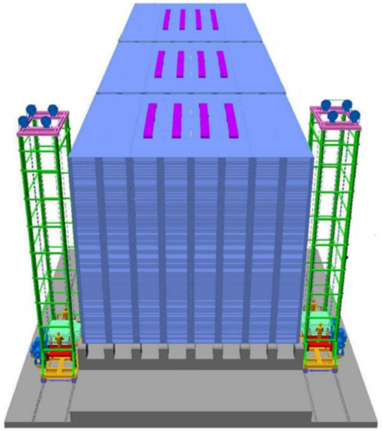
IceCube/PINGU



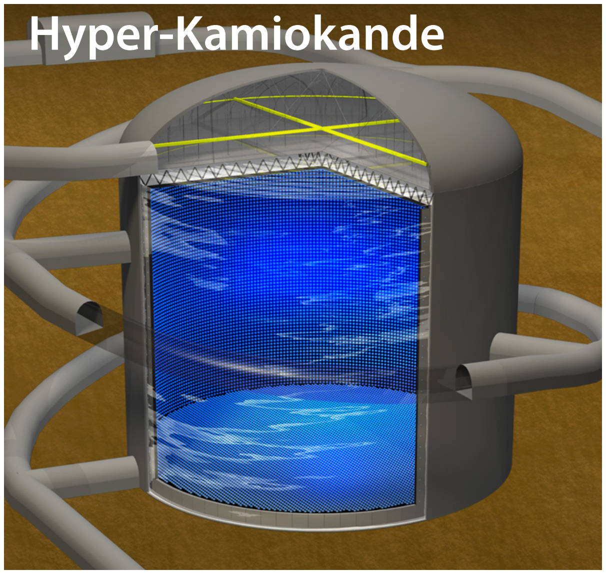
KM3NET/ORCA



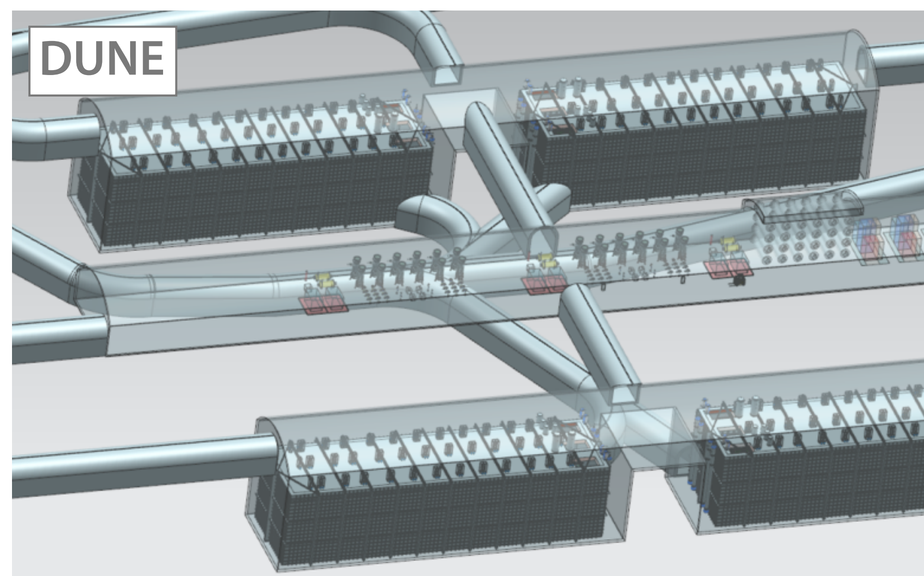
INO/ICAL



Hyper-K & DUNE

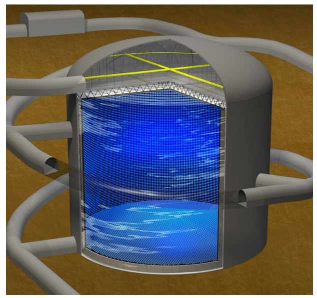


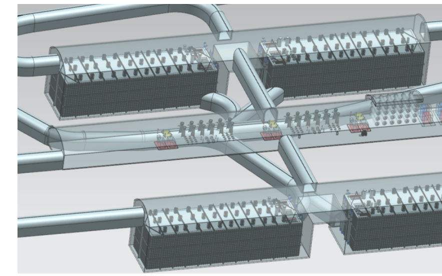
- **Water Cherenkov detector**
- **190 kton fiducial volume** (1tank conf.) corresponding to ~10 times of Super-K
- 40,000 PMT (~40% coverage) of improved photo-detection efficiency(x2 compared to SK PMT)
- Increase 2.2 MeV gamma detection eff. by n-H capture



- **Liquid Argon detector** based time projection chamber technique (TPC)
- Though fiducial mass is relatively small (**40 kton**), high resolution imaging would offer possibilities to discriminate ν and $\overline{\nu}$

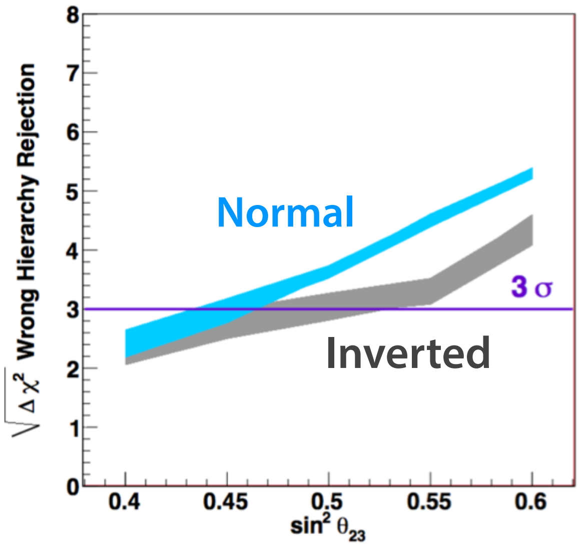
Hyper-K & DUNE Atmospheric Sensitivities

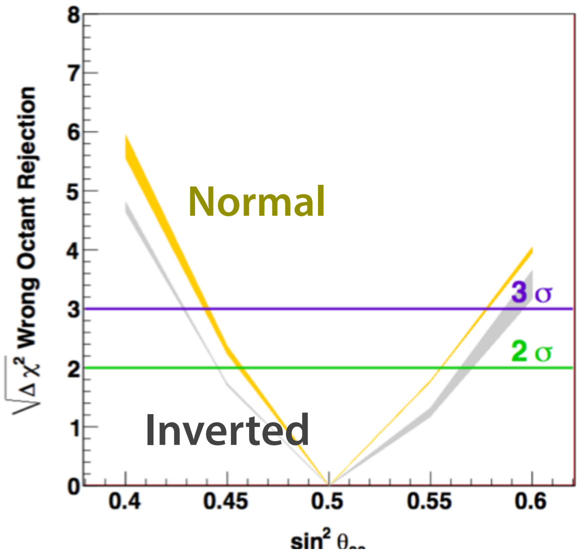


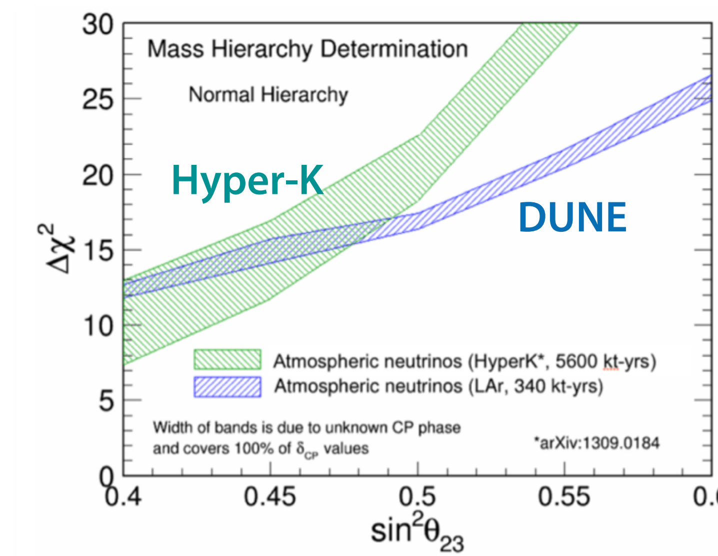


KEK Preprint 2016-21
ICRR-Report-701-2016-1

arXiv.1512.06148



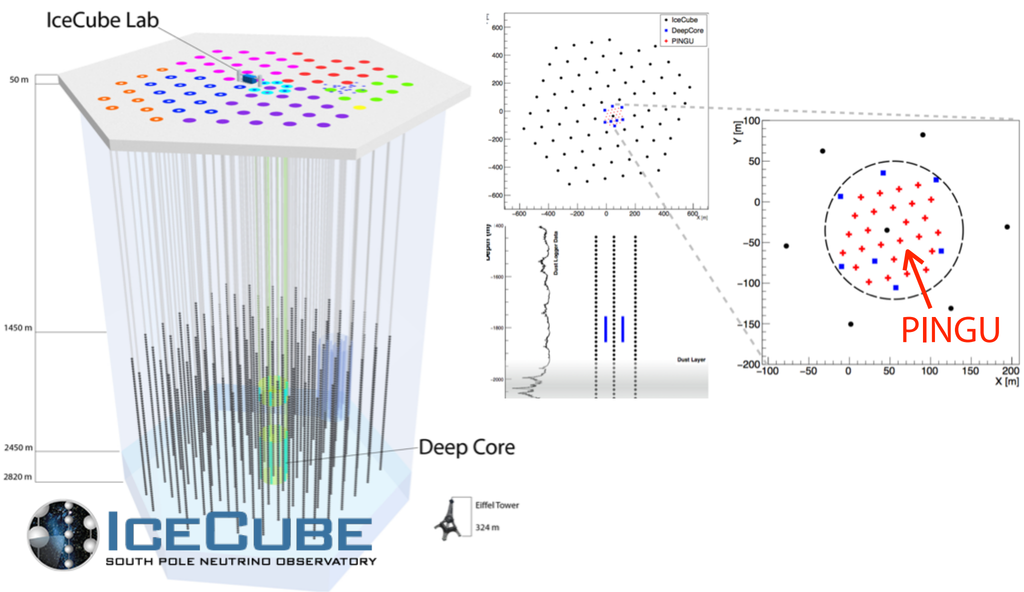




- **>3σ sensitivity for both MH cases** for $\sin^2\theta_{23}>0.45$ with 10yr data (2.6Mtonyr)
- Possible to discriminate θ_{23} octant at **>3σ for $|\theta_{23}-45|>4$deg**

- **Comparable MH sensitivity** to Hyper-K due to high detector resolution

PINGU and ORCA

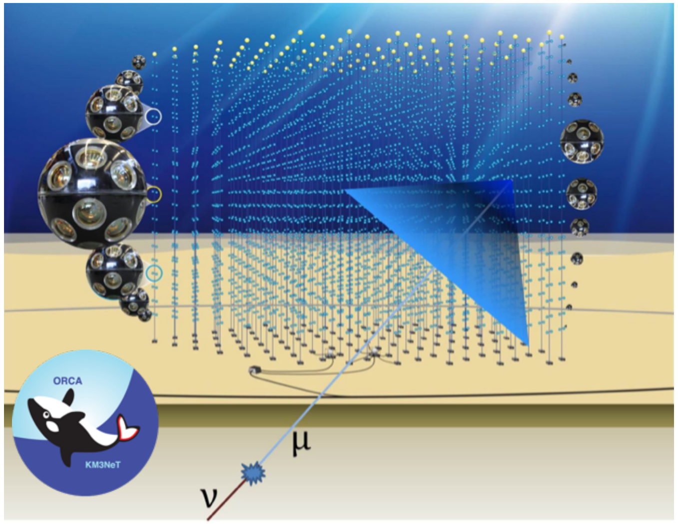


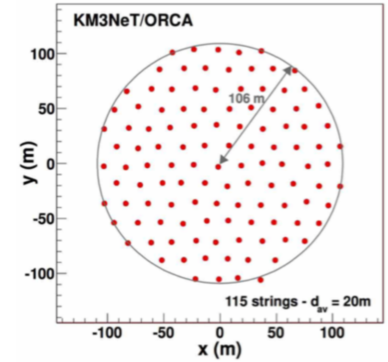
IceCube / PINGU:

- **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)



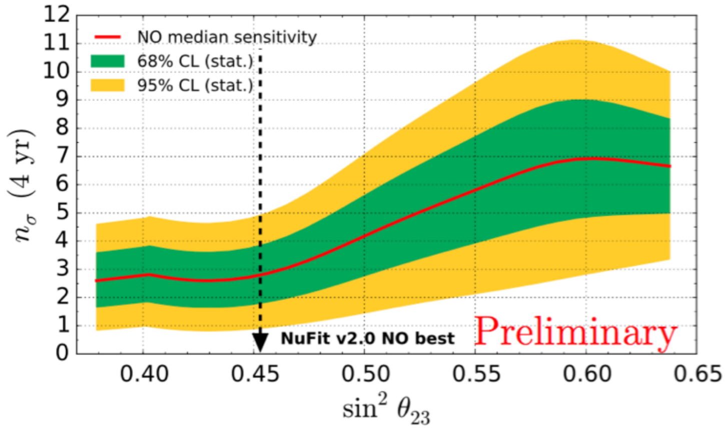


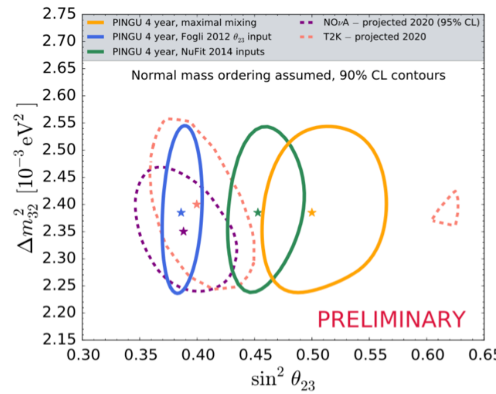
	ARCA	ORCA
Location	Italy	France
String dist. [m]	90	20
DOM spacing [m]	36	6
Volume [10^6 m^3]	~500	~3.8

PINGU / ORCA Sensitivities

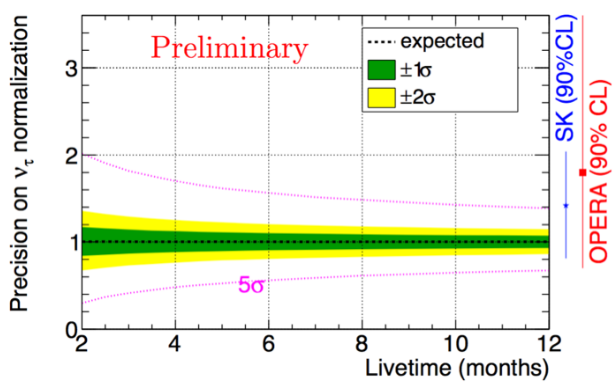
	Mass Hierarchy	θ_{23} Octant	ν_τ Appearance

PINGU

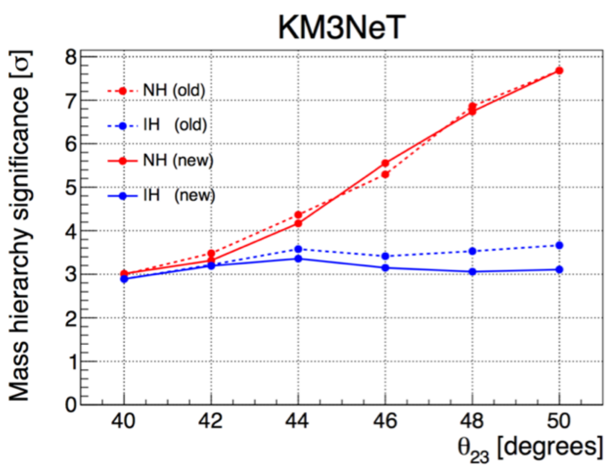


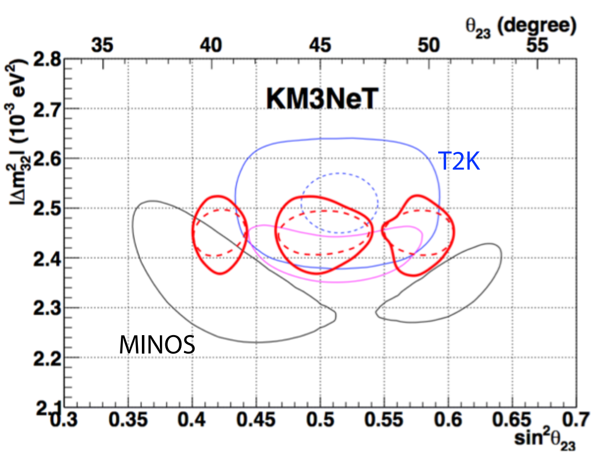


J. Phys. G44, 054006 (2017)

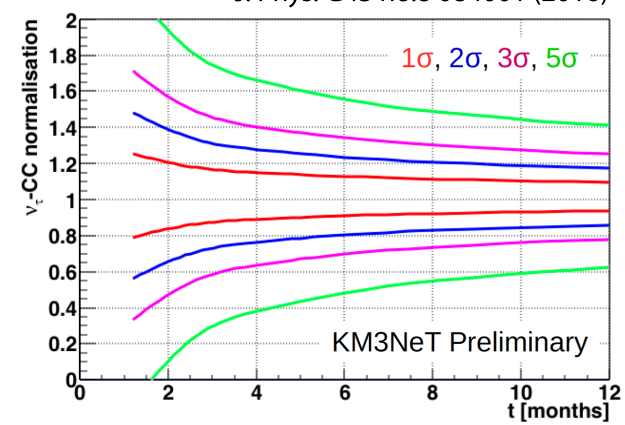


ORCA



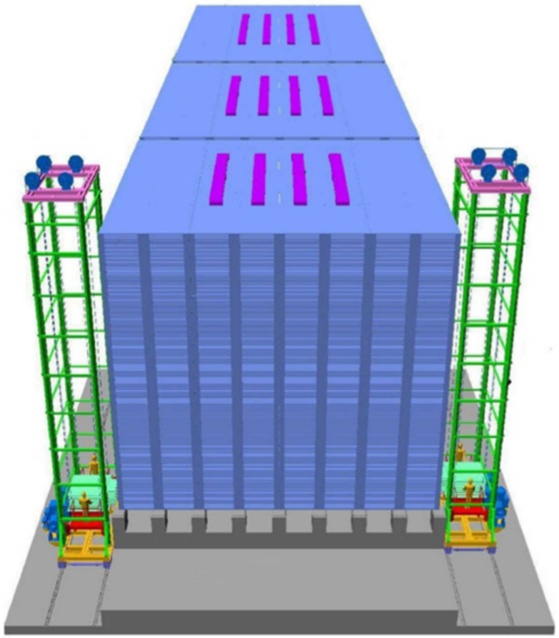


J. Phys. G43 no.8 084001 (2016)

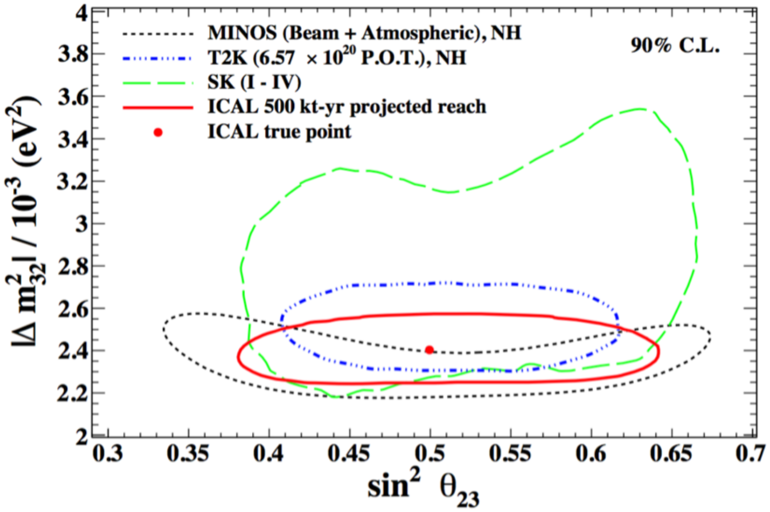


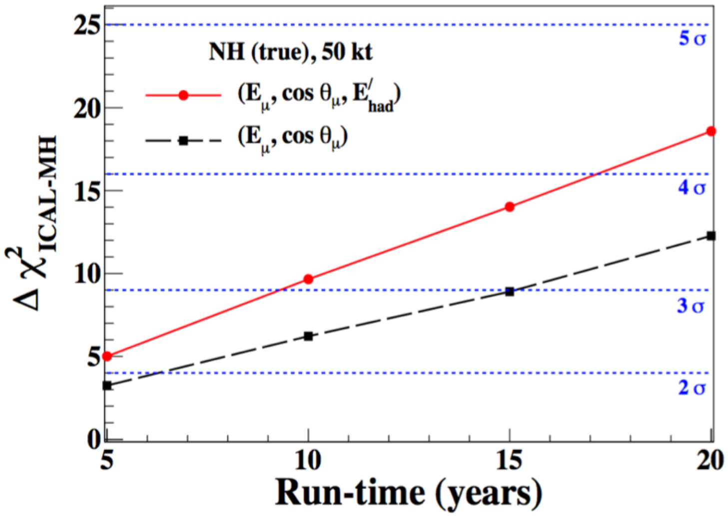
INO / ICAL

Pramana - J. Phys. (2017) 88 : 79



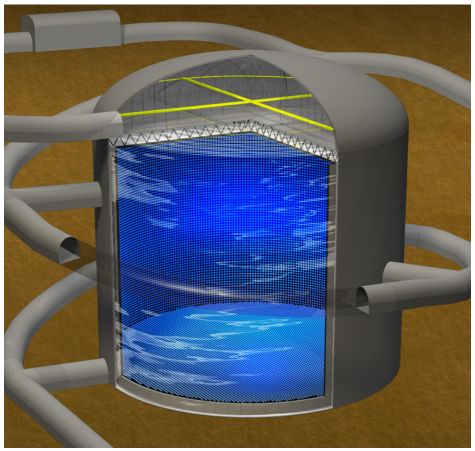
- **Magnetized Iron Calorimeter** (ICAL) composed of resistive plate chamber (RPC) in India
    - 48x16x14.5 m, 50 kton mass
- **ν and $\bar{\nu}$ separation** by muon charge
- Expect MH determination at **2.2σ using 10 yr data** (3σ if hadron information is introduced)



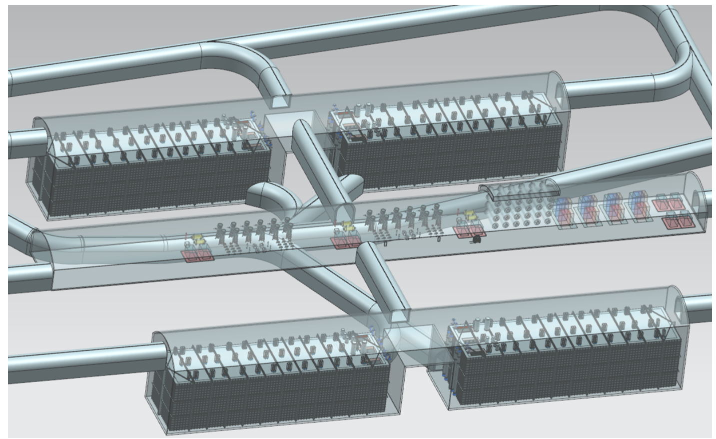


Future Projects: Proton Decay

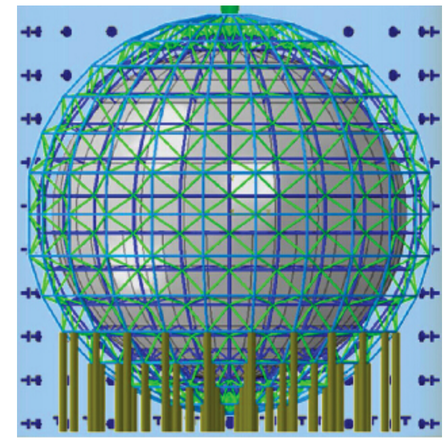
Hyper-Kamiokande



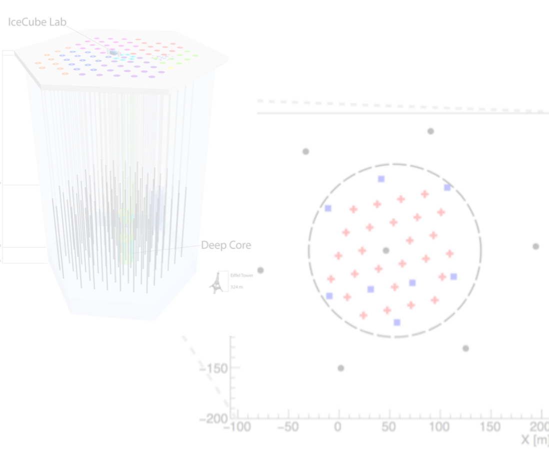
DUNE



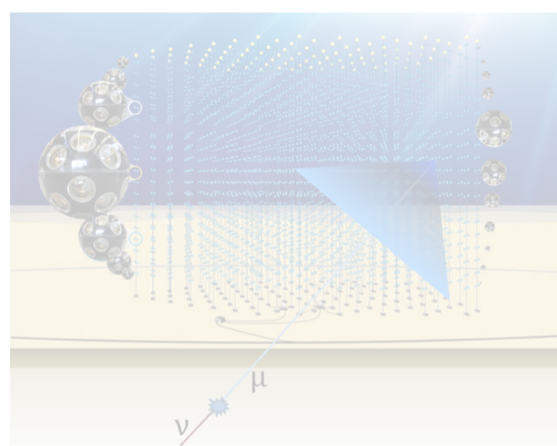
JUNO



IceCube/PINGU



KM3NET/ORCA

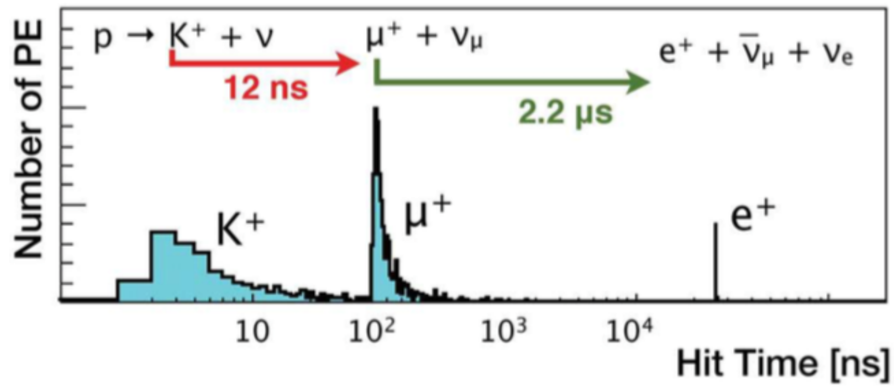


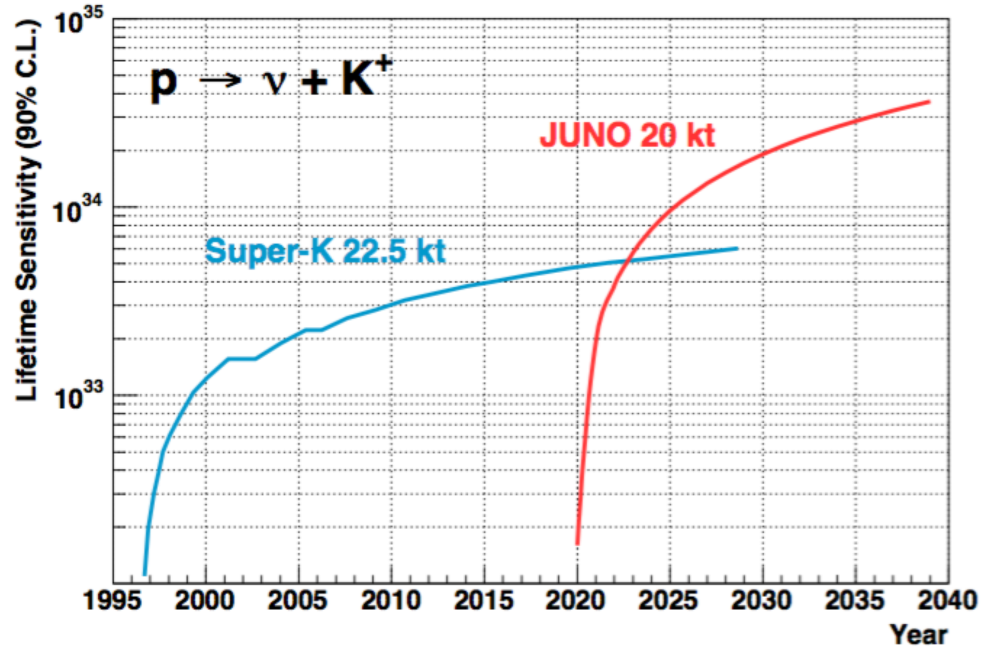
INO/ICAL

JUNO $P \rightarrow \overline{\nu} K^+$ Sensitivity

arXiv:1507.05613

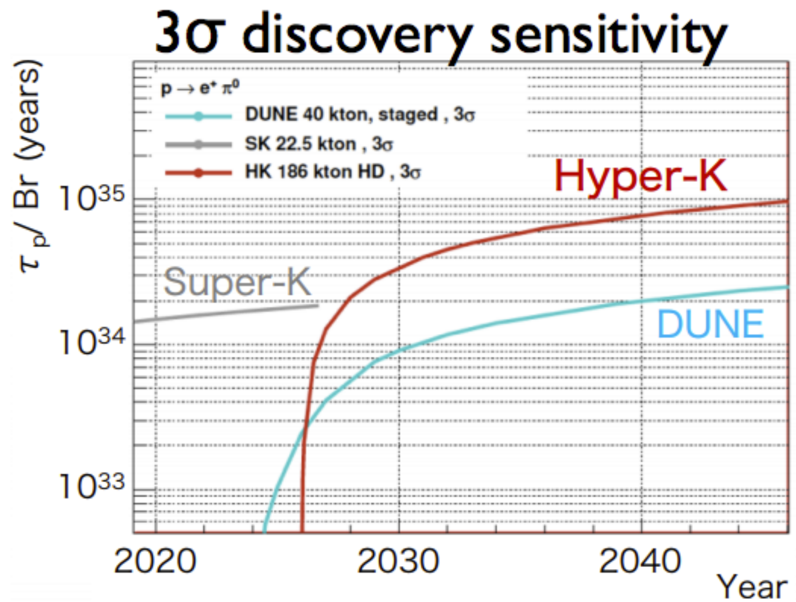
- Main target: $K^+ \longrightarrow \mu^+ \nu_\mu$
- **Three-fold coincidence** of K^+, μ^+, e^+ with well-defined energies (K^+:105 MeV, μ^+: 152 MeV)
- **Signal efficiency: 64%**
- Background: neutrino induced K^+ production total 0.05 ev/yr





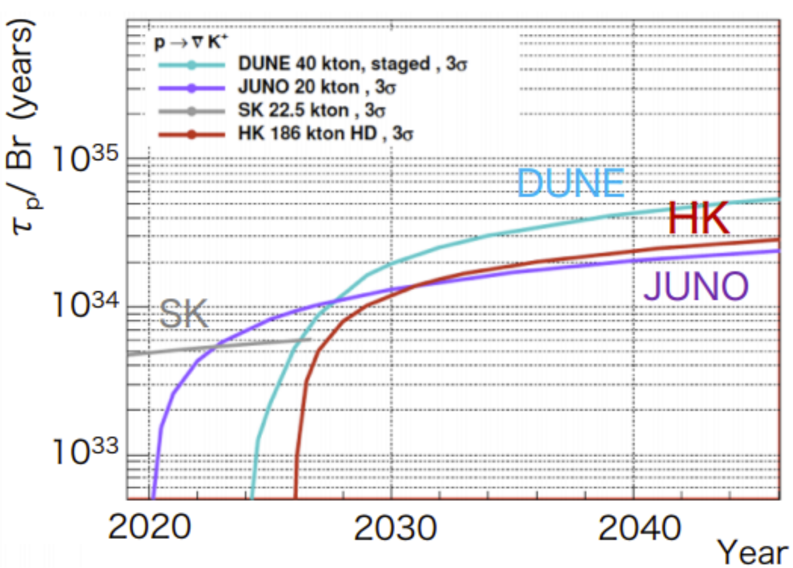
Prospect of Proton Decay Searches

H. Tanaka (TAUP2017)



$P \rightarrow e^{+}\pi^{0}$:

- Hyper-K will reach 10^{35} yrs
- High eff. (~70%) and almost BG free (0.06 ev/Mton·yrs)
- Large BG reduction becomes possible by tagging 2.2 MeV γ from neutron capture



$P \rightarrow \bar{\nu} K^{+}$:

- Better sensitivity for DUNE
- High eff. (97%) with low BG rate (~1 ev/yrs) by high resolution imaging performance

Summary

Atmospheric Neutrino:

- Still interesting for testing standard three flavor mixing scheme.
- **Matter oscillation** produces sensitivity of neutrino **mass hierarchy**. SK data **weakly prefers normal hierarchy** ($\Delta m^2_{32}>0$).
- **ν_τ appearance is established** with ~5 σ. Measured ν_τ cross section consistent with prediction.
- **Strong constraints on sterile neutrino** from atmospheric neutrino observation.

Proton Decay:

- Unique method to probe GUT theory.
- **No evidence for proton decay yet.** Lifetime limit improved: **1.6×10^{34}** and **8.0×10^{33}** years for $P \rightarrow e^+\pi^0$ and $P\rightarrow\overline{\nu}K^+$, respectively.

Future:

- **>3 σ potential** for detecting mass hierarchy (HK, DUNE, PINGU, ORCA, INO).
- **x10 improvement** will be possible for proton decay.

END