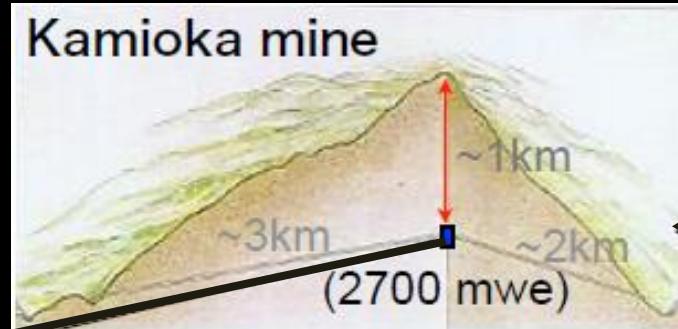
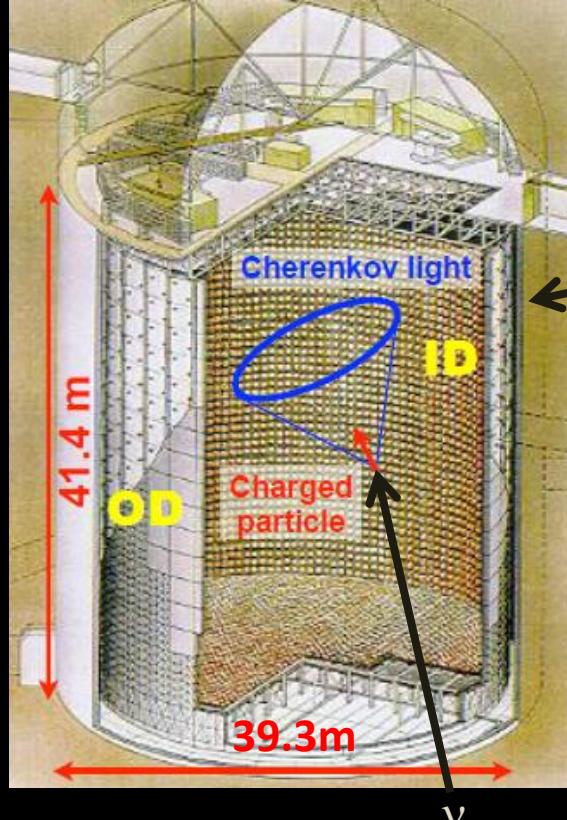


Recent results from Super-K

S.Mine (University of California, Irvine)
for Super-K collaboration

Super-Kamiokande (Super-K, SK)



[[Nucl. Instr. & Meth, A 737C \(2014\)](#)]

Phase		SK-I	SK-II	SK-III	SK-IV
Period	start end	1996 Apr. 2001 Jul.	2002 Oct. 2005 Oct.	2006 Jul. 2008 Sep.	2008 Sep. (running)
Number of PMTs	ID (photo-coverage)	11146 (40%)	5182 (19%)	11129 (40%)	11129 (40%)
	OD	1885			
Anti-implosion container	no	yes	yes	yes	
OD segmentation	no	no	yes	yes	
Front-end electronics	ATM (ID) OD QTC (OD)				QBEE

- SK total \sim 17 years

Super-Kamiokande Collaboration



1 Kamioka Observatory, ICRR, Univ. of Tokyo, Japan
2 RCCN, ICRResearch, Univ. of Tokyo, Japan
3 University Autonoma Madrid, Spain
4 University of British Columbia, Canada
5 Boston University, USA
6 Brookhaven National Laboratory, USA
7 University of California, Irvine, USA
8 California State University, USA
9 Chonnam National University, Korea
10 Duke University, USA
11 Fukuoka Institute of Technology, Japan
12 Gifu University, Japan
13 GIST College, Korea
14 University of Hawaii, USA

15 KEK, Japan
16 Kobe University, Japan
17 Kyoto University, Japan
18 Miyagi University of Education, Japan
19 STE, Nagoya University, Japan
20 SUNY, Stony Brook, USA
21 Okayama University, Japan
22 Osaka University, Japan
23 University of Regina, Canada
24 Seoul National University, Korea
25 Shizuoka University of Welfare, Japan
26 Sungkyunkwan University, Korea
27 Tokai University, Japan
28 University of Tokyo, Japan

29 Kavli IPMU (WPI), University of Tokyo, Japan
30 Dep. of Phys., University of Toronto, Canada
31 TRIUMF, Canada
32 Tsinghua University, China
33 University of Washington, USA
34 National Centre For Nuclear Research, Poland

~120 collaborators
34 institutions
7 countries

Recent published papers by SK

(2014-2015)

Detector Calibration:

- Calibration of SK Detector [NIM, A 737C \(2014\)](#)

this talk

Nucleon Decay Searches:

- Search for proton decay via $p \rightarrow vK^+$ using 260 ktyr data of SK [PRD 90, 072005 \(2014\)](#)
- Search for Nucleon Decay via $n \rightarrow v\pi^0$ and $p \rightarrow v\pi^+$ in SK [PRL 113, 121802 \(2014\)](#)
- Search for Trilepton Nucleon Decay via $p \rightarrow e\nu\nu$ and $p \rightarrow \mu\nu\nu$ in SK [PRL 113, 101801 \(2014\)](#)
- Search for Dinucleon Decay into Kaons in SK [PRL 112, 131803 \(2014\)](#)

Atmospheric Neutrino Oscillation Analyses:

- Limits on Sterile Neutrino Mixing using Atmospheric Neutrinos in SK [arXiv:1410.2008](#) (accepted for publication in PRD)
- Test of Lorentz Invariance with Atmospheric Neutrinos [PRD 91, 052003 \(2015\)](#)

Solar Neutrino Oscillation Analysis:

- First Indication of Terrestrial Matter Effects on Solar Neutrino Oscillation [PRL 112, 091805 \(2014\)](#)

Supernova Relic Neutrino Search:

- Supernova Relic Neutrino Search with Neutron Tagging at SKIV [AP 60 \(2014\) 41](#)

Nucleon Decay Searches

(atmospheric neutrinos as BKG)

Grand Unified Theory (GUT)

- single symmetry group $G \supset SU(3)_{\text{color}} \times SU(2)_L \times U(1)_Y \rightarrow$ single coupling constant, quantization of electric charge, etc.

- popular models:

- SO(10) GUT:

- 15 fermions and $\nu_R (= \nu_L^c)$ in single representation, etc.
 - ν_R as partner in seesaw mechanism $\rightarrow \nu_L$ mass light

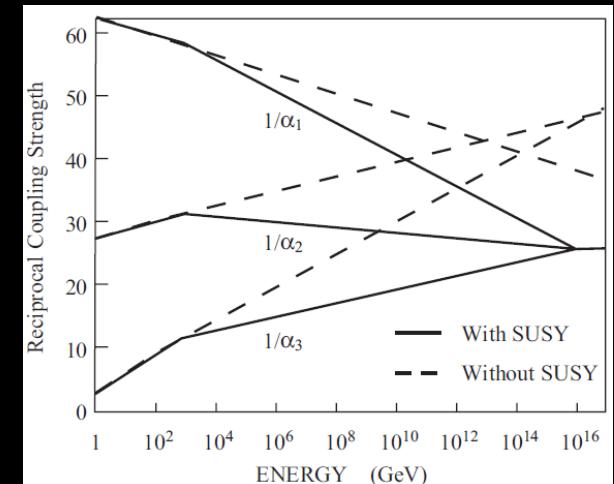
- supersymmetry (SUSY) GUT:

- 3 coupling constants meet at $\sim 10^{16} \text{ GeV}$, gravity, etc.

- GUT predicts instability of nucleon

ν_L	d_R^c	d_G^c	d_B^c	u_R	u_G	u_B	e^+
e^-	u_R^c	u_G^c	u_B^c	d_R	d_G	d_B	ν_L^c
5*				10			1

$SU(2)_L$
 $SU(2)_R$
 $SU(4)_c$



Nucleon decay searches in SK

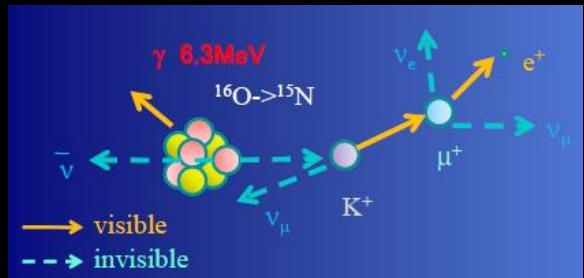
- SK has the world's best sensitivities on nucleon lifetime:
 - large fiducial volume (V)
 - $22.5\text{kt} \rightarrow \sim 7.5 \times 10^{33}$ protons
 - long stable detector operation since 1996 (T)
- lifetime limit $\propto \begin{cases} \varepsilon_{\text{sig}} / 2.3 \cdot VT & \text{(BKG free)} \\ \varepsilon_{\text{sig}} / \sqrt{\#BKG} \cdot \sqrt{VT} & \text{(BKG dominant)} \end{cases}$
 - important to increase signal efficiency and BKG rejection
- several new results published recently
 - many analysis improvements in $p \rightarrow \nu K^+$
 - several new searches for the first time by SK

$p \rightarrow v K^+$ search

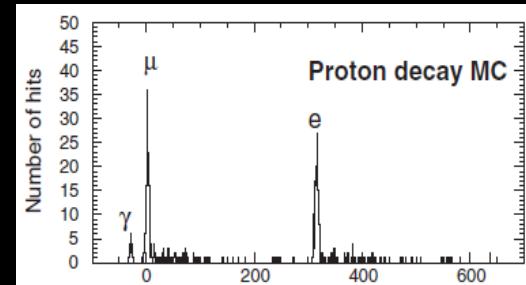
- dominant decay mode in SUSY GUTs
 - some models predict lifetime $< \sim 10^{34}$ years \rightarrow probed by this experimental search
- many improvements in the analysis and published in [Phys. Rev. D.90, 072005 \(2014\)](#)
 - highlighted with Synopsis by APS editor
- major improvements since SK publication in 2005 (SK-I data):
 - new data from SK-II to SK-IV \rightarrow total: 260kt·year
 - event reconstructions and selections
 - new front-end electronics in SK-IV \rightarrow higher Michel-e ε

Prompt γ method:

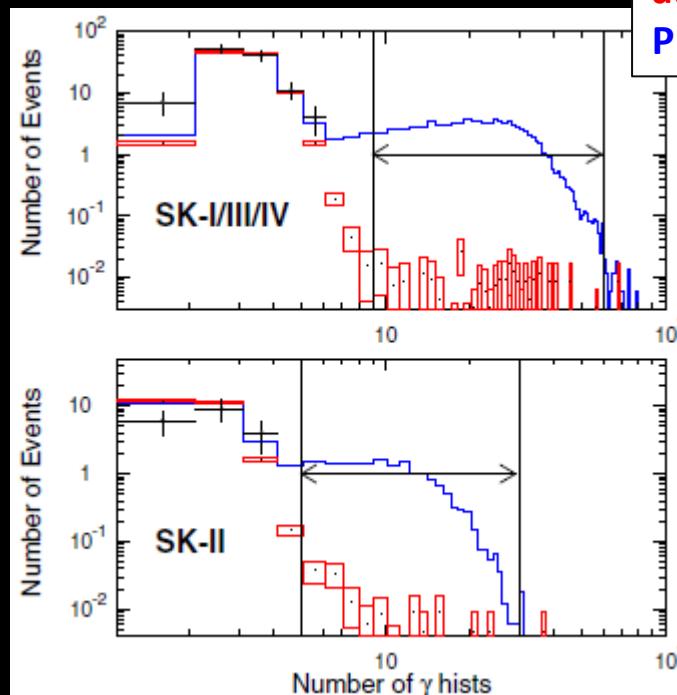
($p \rightarrow \nu K^+$, $K^+ \rightarrow \mu\nu$ with prompt γ)



- event selections:
 - 1 μ -like with Michel-e, $215 < P_\mu < 260 \text{ MeV}/c$
 - proton ring rejection
 - $-8(4) < N_\gamma < 60(30)$ for SK-I, III, IV (SK-II), $T_\mu - T_\gamma < 75 \text{ ns}$
- major improvements in event rec.:
 - Michel-e
 - μ/p separation (new)
- in SK-I:
 - expected #BKG: $0.7 \rightarrow 0.08$
 - signal ϵ : $8.6\% \rightarrow 7.9\%$
- no data candidate

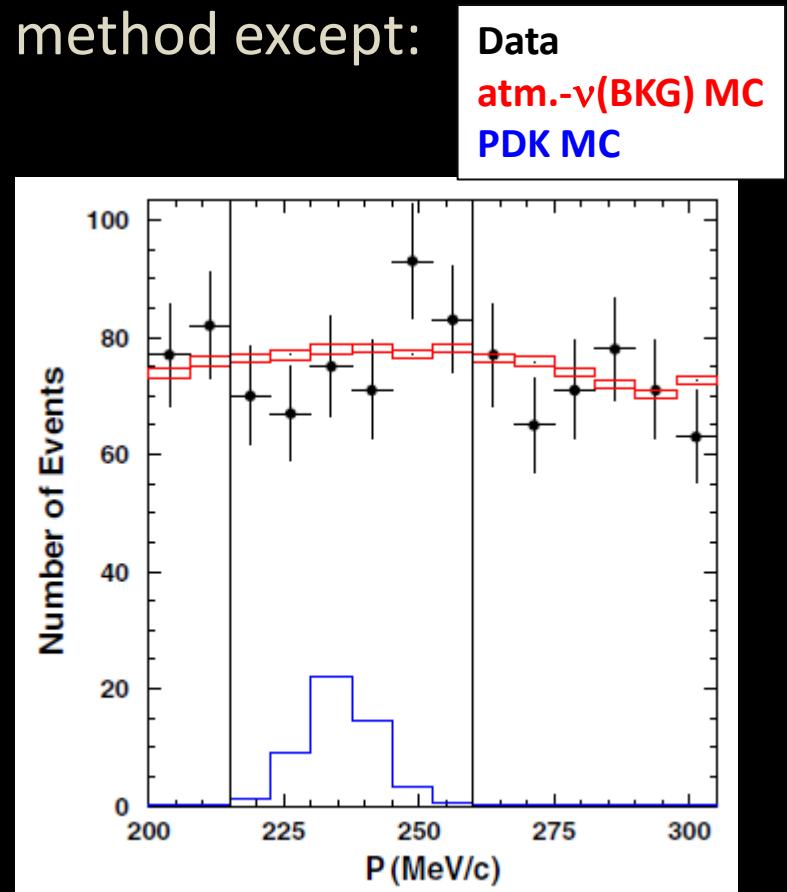


Data
atm.- ν (BKG) MC
PDK MC



P_μ spectrum method: $(p \rightarrow \nu K^+, K^+ \rightarrow \mu \nu)$

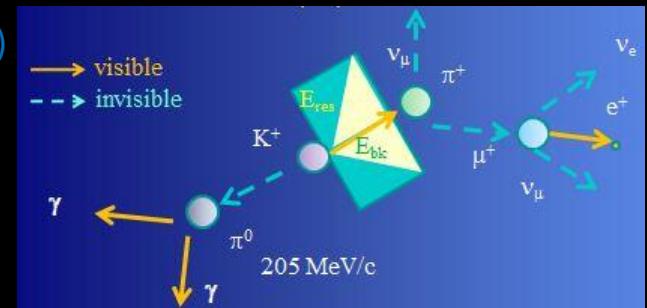
- Event selections same as prompt γ method except:
 - relaxed momentum cut
 - no prompt γ hits
- no data excess in signal region



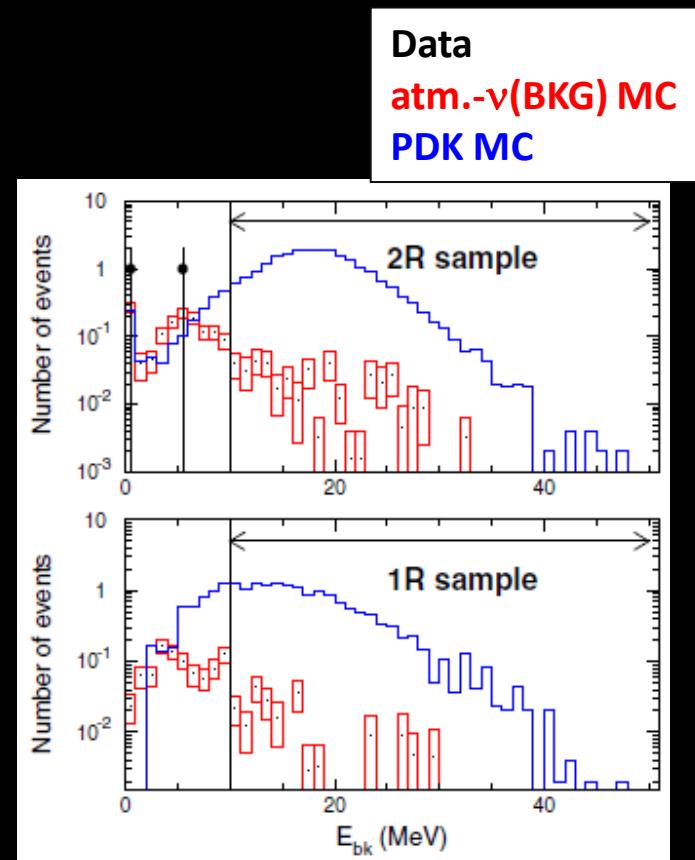
$\pi^+\pi^0$ method:

($p \rightarrow v K^+$, $K^+ \rightarrow \pi^+\pi^0$)

(M.Miura)



- event selections:
 - 1 or 2 e-like rings with Michel-e
 - $85 < M_{\pi^0} < 185 \text{ MeV}/c^2$, $175 < P_{\pi^0} < 250 \text{ MeV}/c$
 - charge profile likelihood for π^+
 - $10 < E_{\text{bk}} < 50 \text{ MeV}$ (E_{bk} : visible energy for π^+)
- major improvements in event rec.:
 - single-ring π^0 fitter (new)
 - π^+ charge profile
- in SK-I:
 - expected #BKG: $0.6 \rightarrow 0.18$
 - signal ϵ : $6.0\% \rightarrow 7.8\%$
- no data candidate



Result on $p \rightarrow v K^+$ search

	SK-I	SK-II	SK-III	SK-IV
Exp.(kton · yrs)	91.7	49.2	31.9	87.3
Prompt γ	Eff. (%) 7.9 ± 0.1 (8.6%) BKG/Mt · yr 0.8 ± 0.2	6.3 \pm 0.1 2.8 \pm 0.5	7.7 \pm 0.1 0.8 \pm 0.3	9.1 \pm 0.1 1.5 \pm 0.3
	BKG OBS	0.08 (0.7) 0	0.14 0	0.03 0
P_μ spec.	Eff. (%) 33.9 ± 0.3 BKG/Mt · yr 2107 ± 39	30.6 \pm 0.3 1916 \pm 35	32.6 \pm 0.3 2163 \pm 40	37.6 \pm 0.3 2556 \pm 47
	BKG OBS	193 177	94.3 78	69.0 85
$\pi^+ \pi^0$	Eff. (%) 7.8 ± 0.1 (6.0%) BKG/Mt · yr 2.0 ± 0.4	6.7 \pm 0.1 3.4 \pm 0.6	7.9 \pm 0.1 2.3 \pm 0.4	10.0 \pm 0.1 2.0 \pm 0.3
	BKG OBS	0.18 (0.6) 0	0.17 0	0.09 0

K. Kobayashi et al., Phys. Rev. D 72, 052007 (2005)

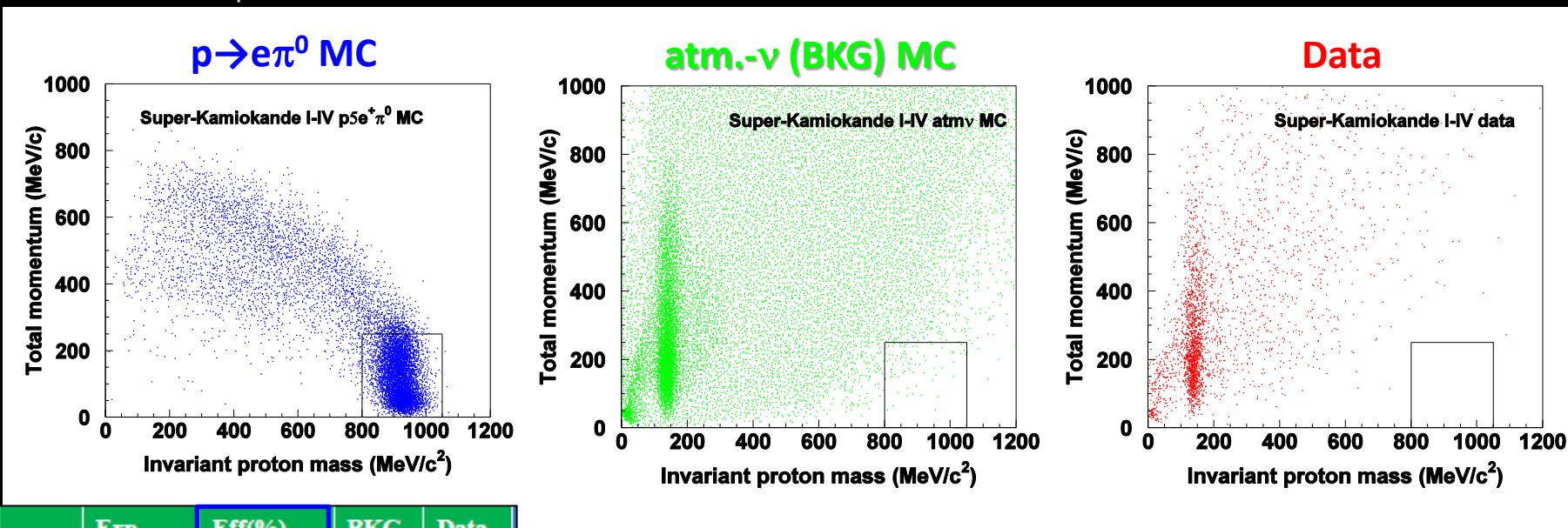
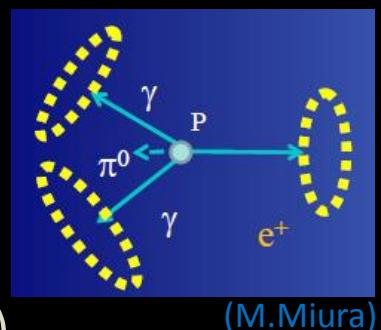
- total expected #BGK < 1 for prompt $\gamma/\pi^+\pi^0$ methods
- no data excess above BGK expectation

$$\tau/B_{p \rightarrow v K^+} > 5.9 \times 10^{33} \text{ years (90% CL)}$$

- world's best limit
- 2.5 times more stringent than previous result (2005)
- constrains recent SUSY GUT models

$p \rightarrow e^+ \pi^0$ search

- dominant decay mode in non-SUSY GUTs
- event selections:
 - 2 or 3 rings, all e-like, no Michel e, $85 < M_{\pi^0} < 185 \text{ MeV}/c^2$ (3-ring)
 - $800 < M_p < 1050 \text{ MeV}/c^2$, $P_{\text{tot}} < 250 \text{ MeV}/c$

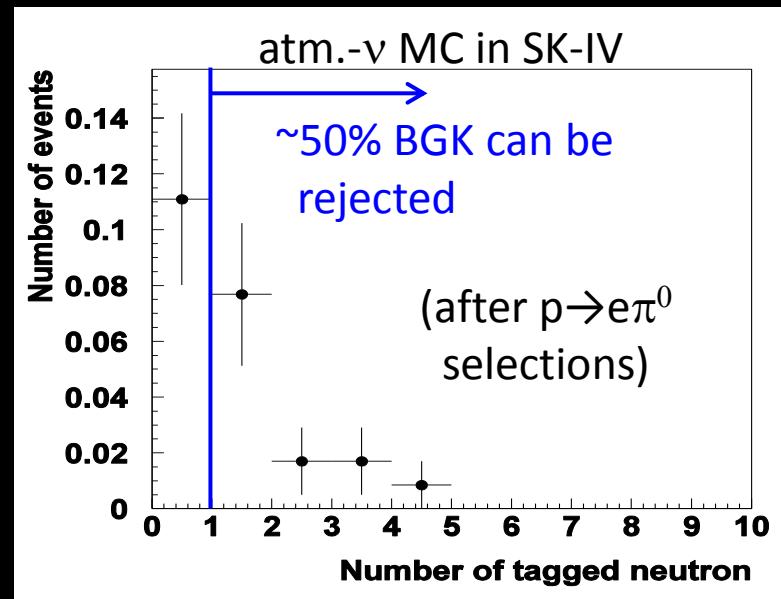
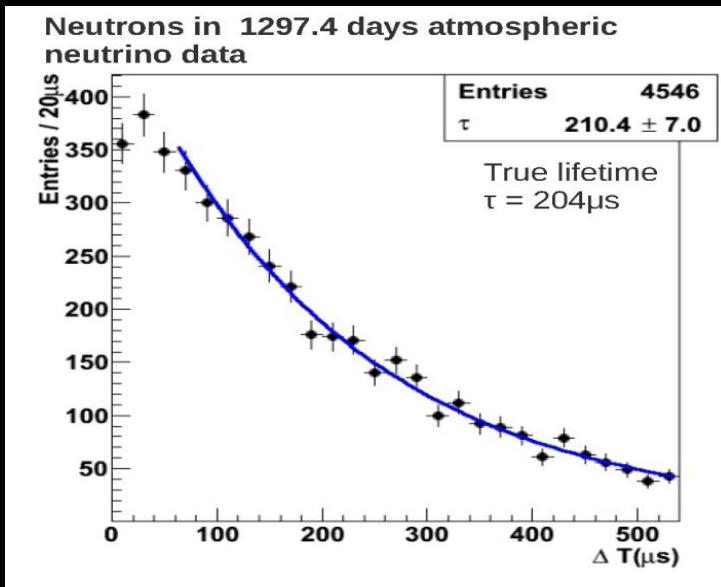


	Exp. ($\text{kt}\cdot\text{yr}$) λ	Eff(%) ϵ	BKG b	Data n
SK1	91.7	39.2 ± 0.7	0.27	0
SK2	49.2	38.5 ± 0.7	0.15	0
SK3	31.9	40.1 ± 0.7	0.07	0
SK4	87.3	39.5 ± 0.7	0.22	0
Total	260.1		0.71	0

- signal $\epsilon \sim 40\%$, total expected #BKG ~ 0.7
#BKG validated with K2K ν beam data [PRD 77,032003(2008)]
 - no data candidate
- $\tau/B_{p \rightarrow e\pi^0} > 1.4 \times 10^{34} \text{ years}$ (90% CL)
(world's best limit)

- major on-going improvements :
 - neutron tag in SK-IV
 - $n + p \rightarrow d + \gamma$ (2.2MeV)
 - sophisticated event reconstruction algorithm
 - reduction of systematic errors, etc.

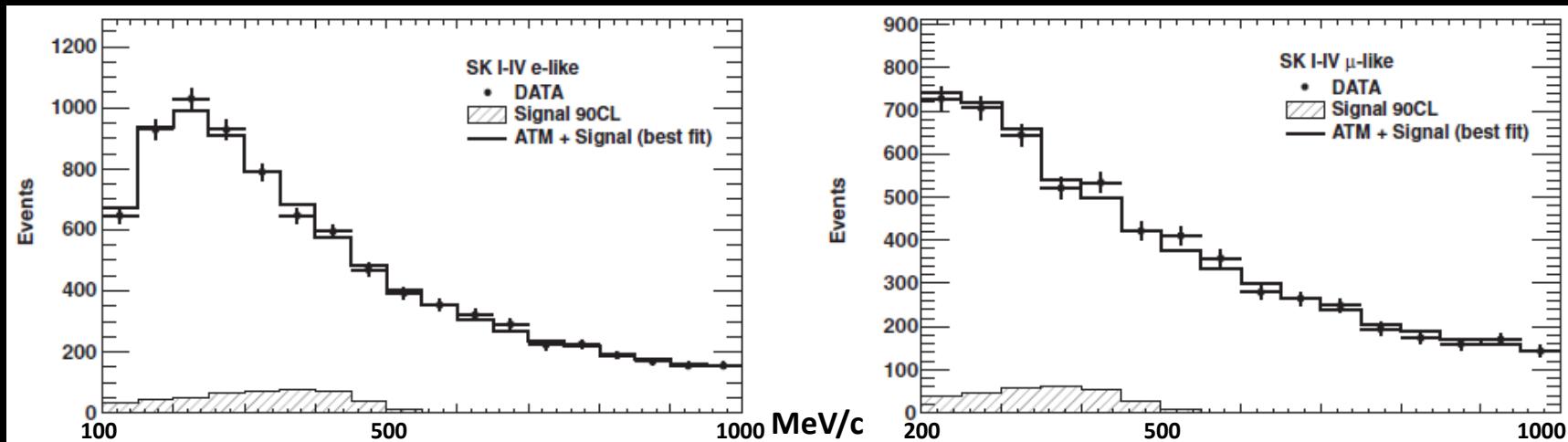
ex.) neutron tag performance



$p \rightarrow e\nu\nu$ and $p \rightarrow \mu\nu\nu$ searches

[Phys. Rev. Lett. 113, 101801 \(2014\)](#)

- some SO(10) models embedded in Pati-Salam's left-right symmetric model predict lifetimes around 10^{30-33} years
- $|\Delta(B-L)| = 2$, unusual for standard nucleon decay channels
- data from SK-I to SK-IV \rightarrow total exposure: $273.4 \text{ kt}\cdot\text{year}$



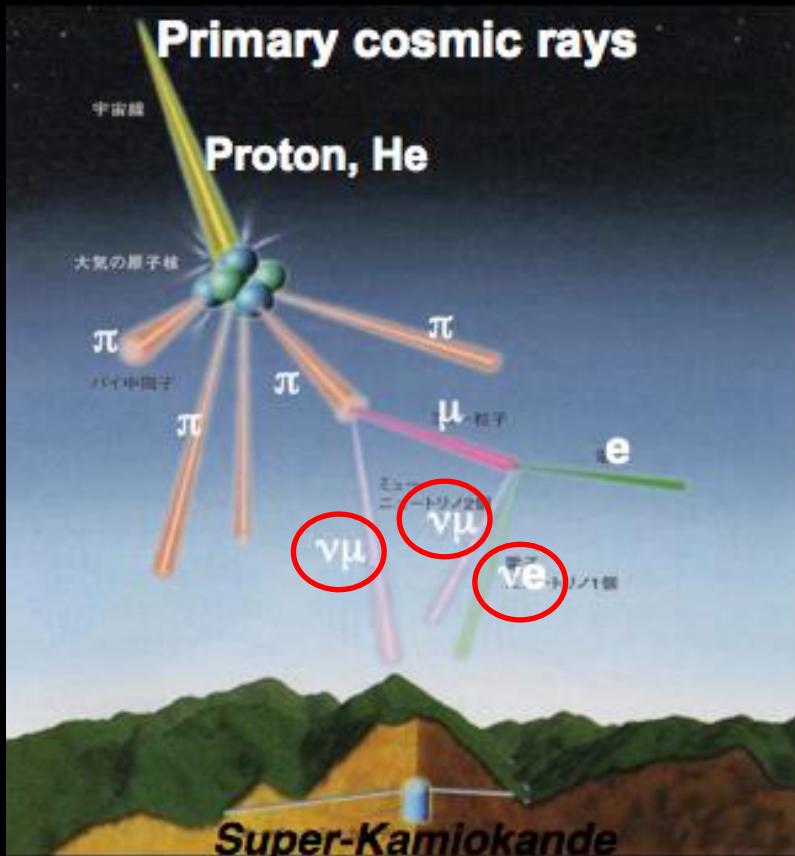
no significant excess in signal region:

$$\tau/B_{p \rightarrow e\nu\nu} > 1.7 \times 10^{32} \text{ and } \tau/B_{p \rightarrow \mu\nu\nu} > 2.2 \times 10^{32} \text{ years (90\% CL)}$$

- world's best limit
- an order of magnitude improvement over previous results
- provide strong constraints to the models

Atmospheric ν Oscillation Analyses

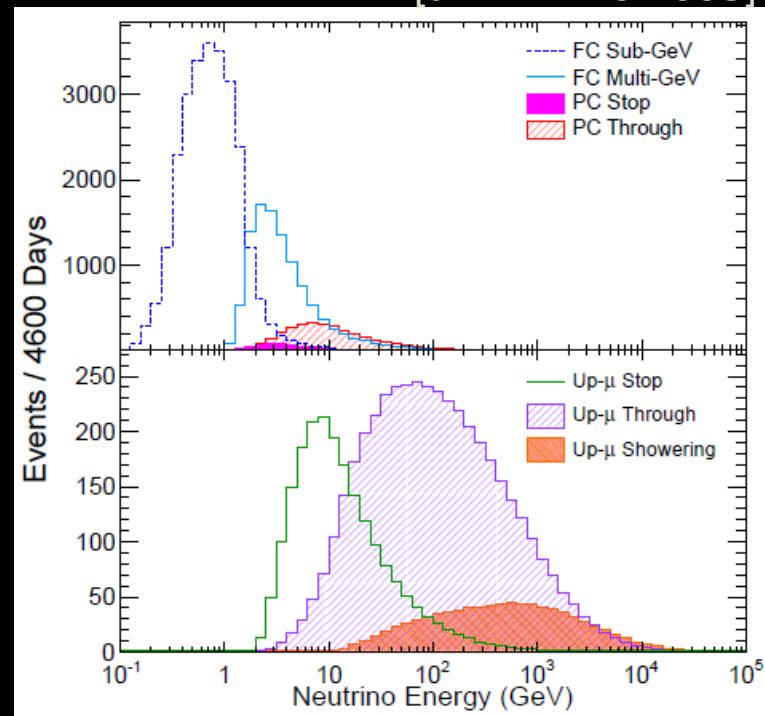
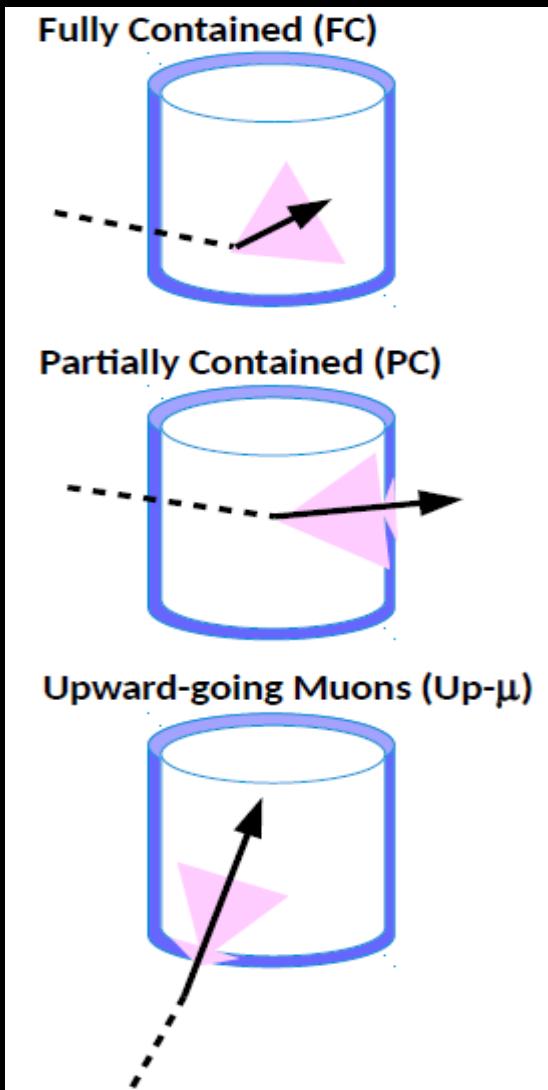
Atmospheric neutrinos



- cosmic rays strike air nuclei and decay of hadrons gives νs
 - # $\nu s > 40,000$ in SK
 - νs travel length: $\sim 10\text{-}10,000\text{ km}$
 - νs energy: $\sim 0.1\text{-}10^4\text{ GeV}$
 - both νs and $\bar{\nu}s$
 - $\sim 30\%$ for $\bar{\nu}s$ in final samples
- excellent tool for broad studies of neutrino oscillations
- background for nucleon decay searches

Atmospheric neutrino event topologies

[arXiv:1410.2008]

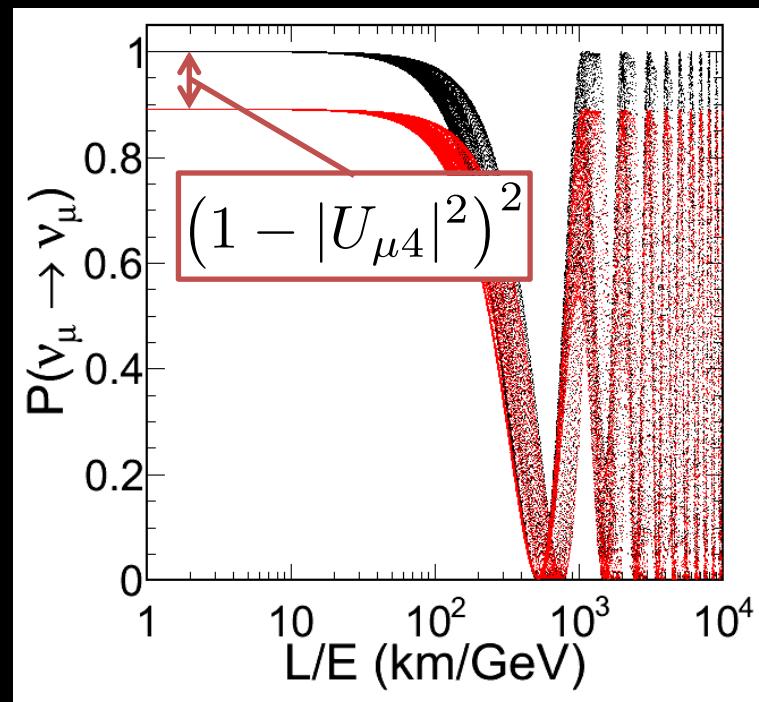


average energies:

- FC: $\sim 1\text{GeV}$
- PC: $\sim 10\text{GeV}$
- Up- μ : $\sim 100\text{GeV}$

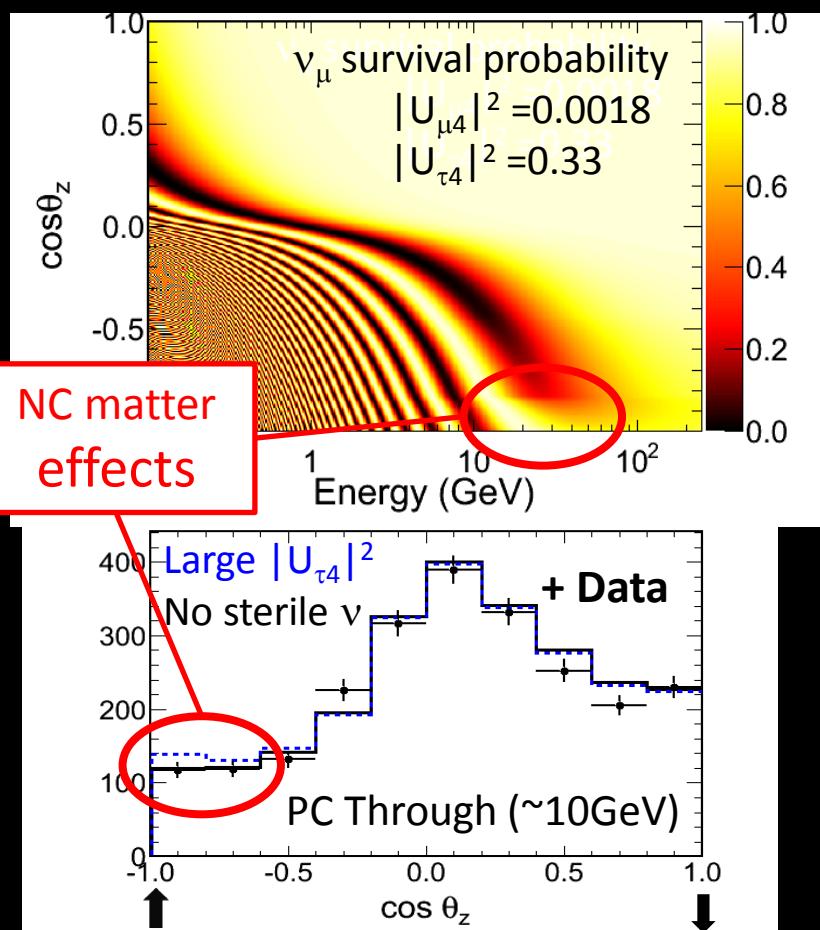
Sterile neutrino oscillations in atmospheric neutrinos

$$U = \begin{pmatrix} \text{PMNS} & & & \text{Sterile} & & \\ U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots & \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \cdots & \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \cdots & \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & \cdots & \\ \vdots & \vdots & \vdots & \vdots & \ddots & \end{pmatrix}$$

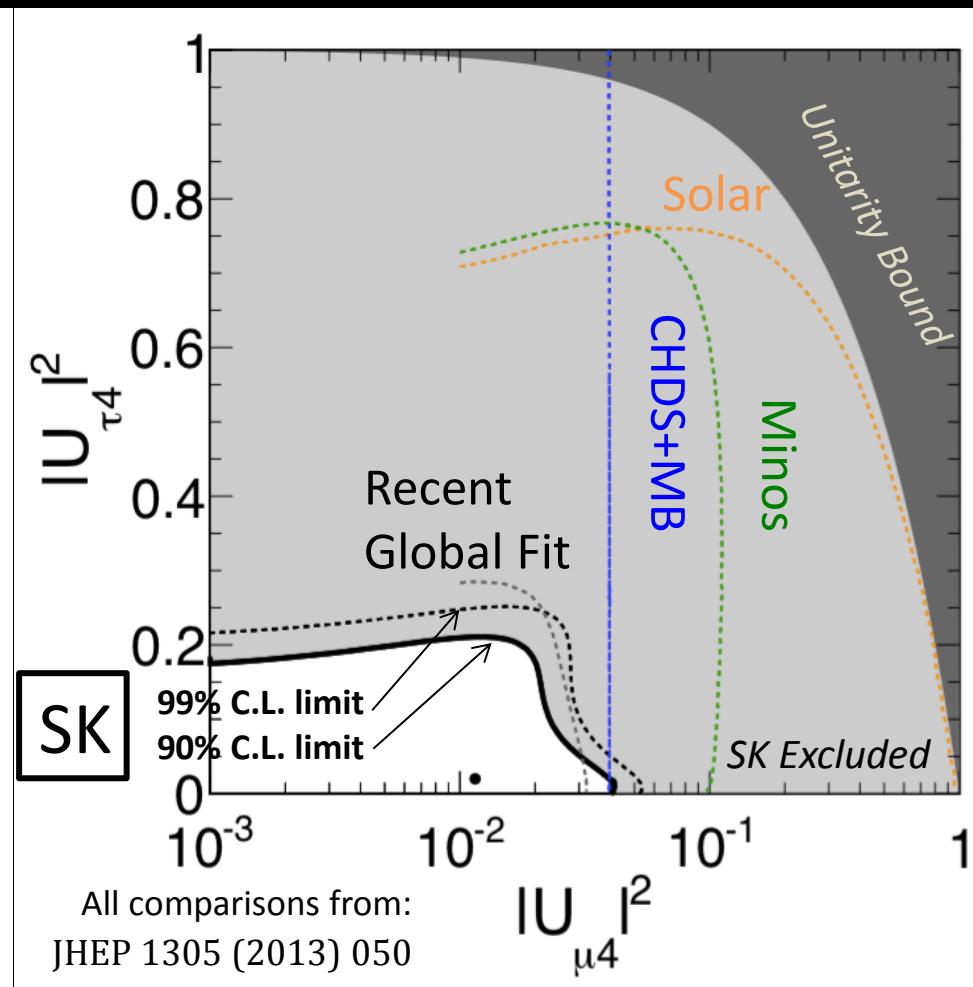
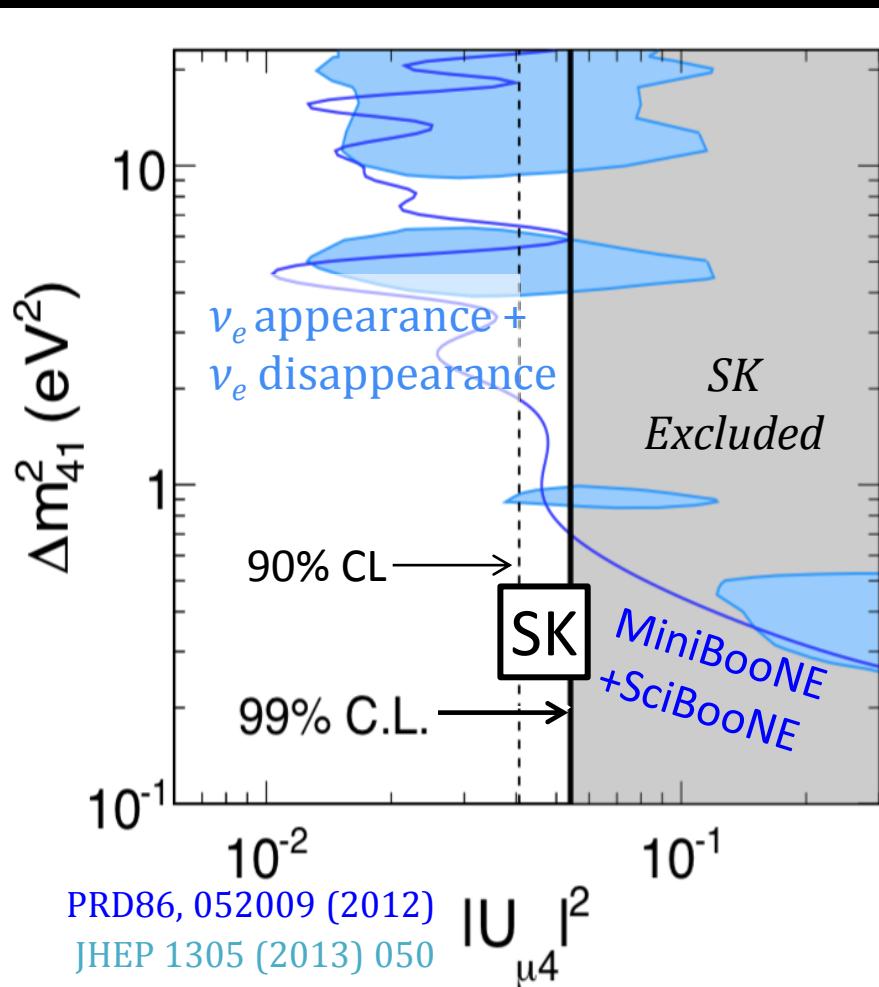


$|U_{\mu 4}|^2$ Induces a decrease in event rate of μ -like data of all energies and zenith angles. Not sensitive on Δm^2 due to fast oscillations

$|U_{\tau 4}|^2$ Shape distortion of angular distribution of higher energy μ -like data



Limits on sterile neutrino oscillations

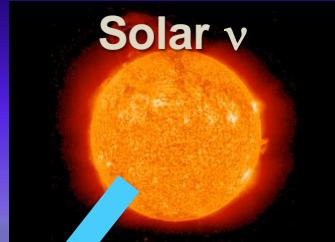
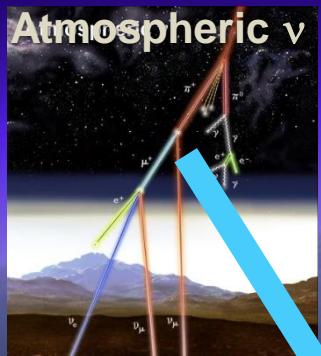


$|U_{\mu 4}|^2 < 0.054$ at 99% CL

$|U_{\tau 4}|^2 < 0.23$ at 99% CL

- no evidence of sterile ν oscillations

Hyper-Kamiokande (Hyper-K)



LOI: arXiv:1109.3262[hep-ex]
LBL study: arXiv:1502.05199

ν ν ν

Super-Kamiokande



ν

J-PARC
High intensity neutrino and anti-neutrino beam

Hyper-Kamiokande

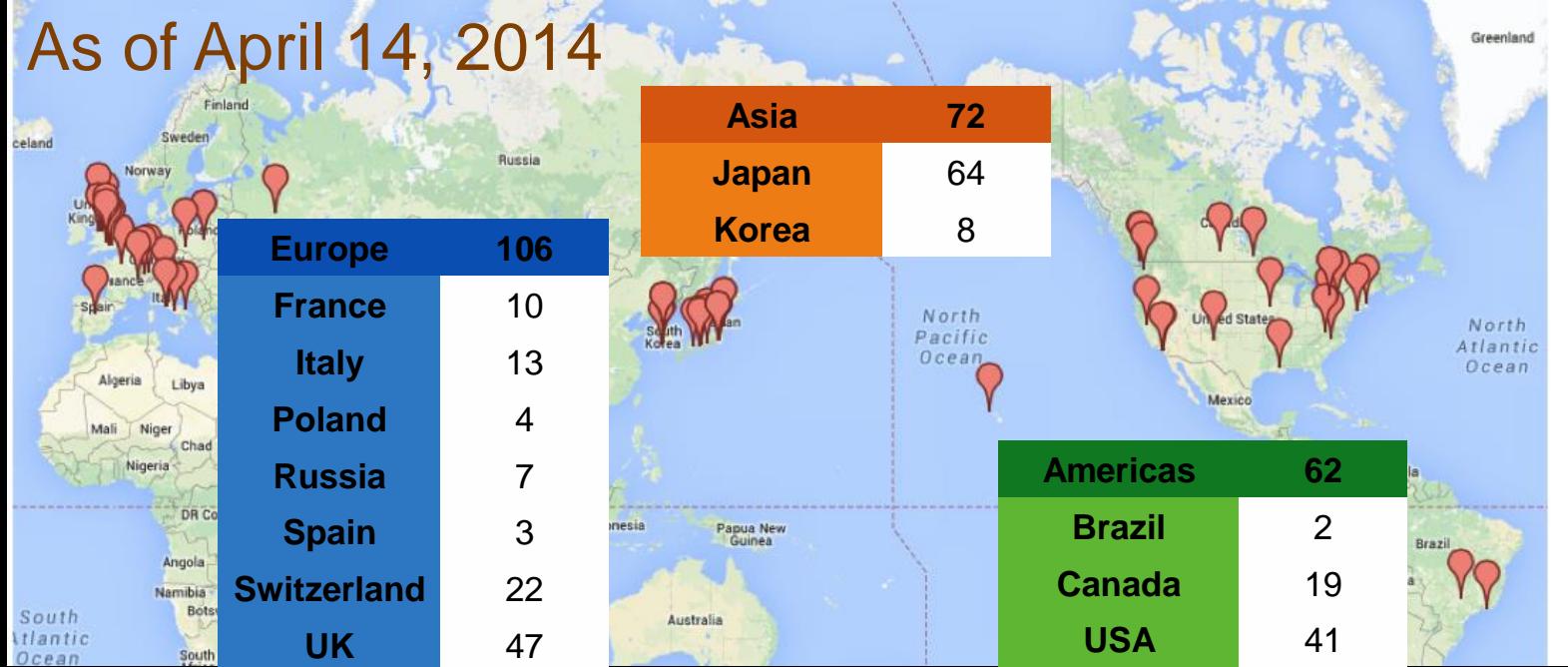
25 x Super-K fiducial mass
as neutrino target and proton decay source



Hyper-Kamiokande International Group

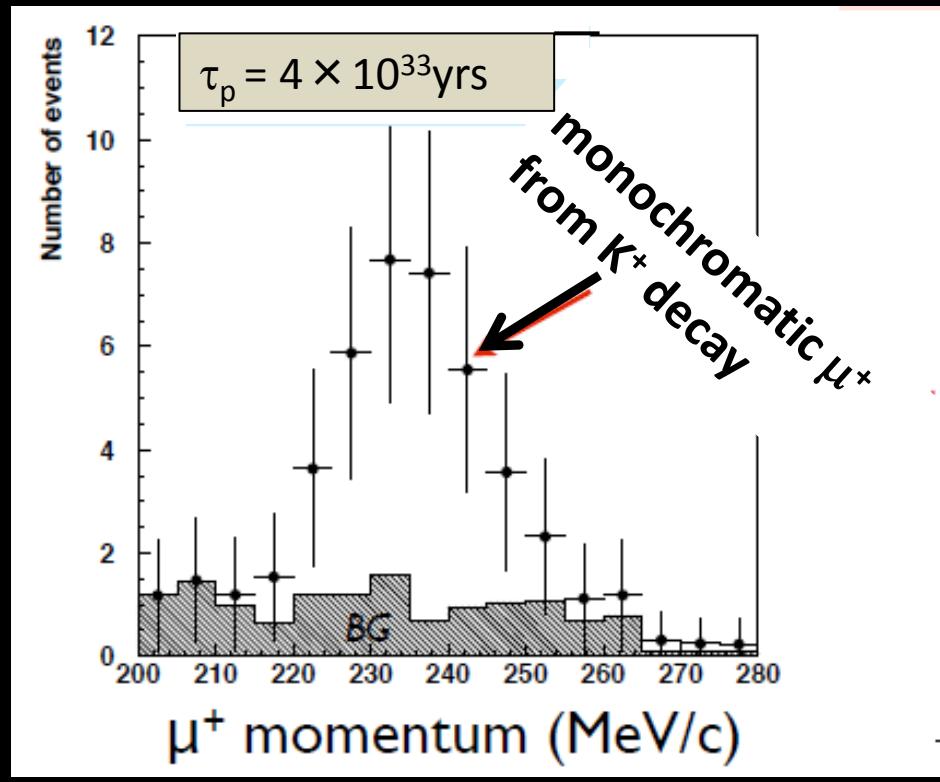
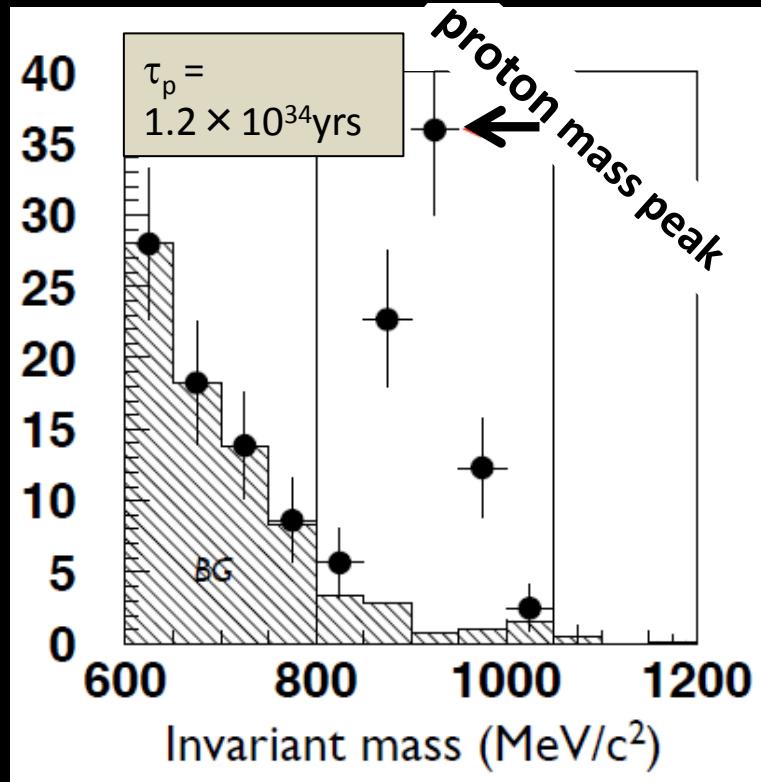


As of April 14, 2014



- 240 people and growing!
- Hyper-K Governance Structure has been defined
 - Steering Committee, International Board Representatives, and Convener Board
- R&D fund and travel budget already secured in some countries, and more in securing processes.

Nucleon decay searches in HK



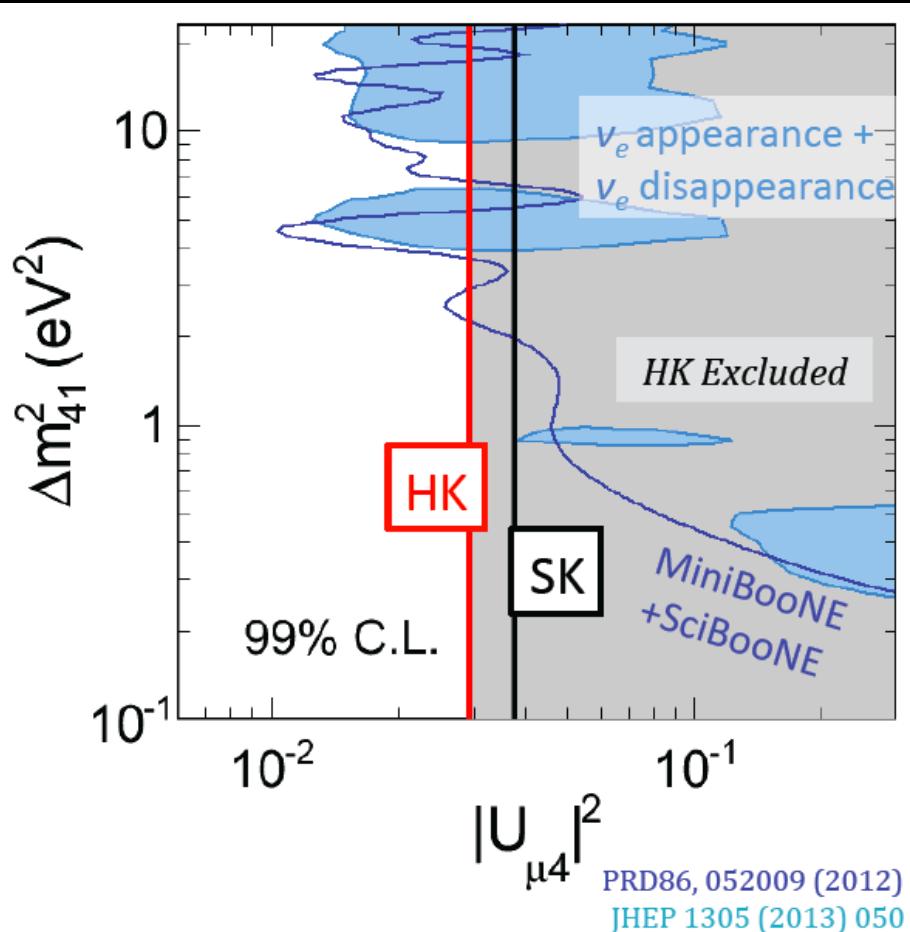
Limit (90% CL)

$$\tau/B_{p \rightarrow e\pi^0} > 1 \times 10^{35} \text{ yrs (HK 10 yrs)}$$

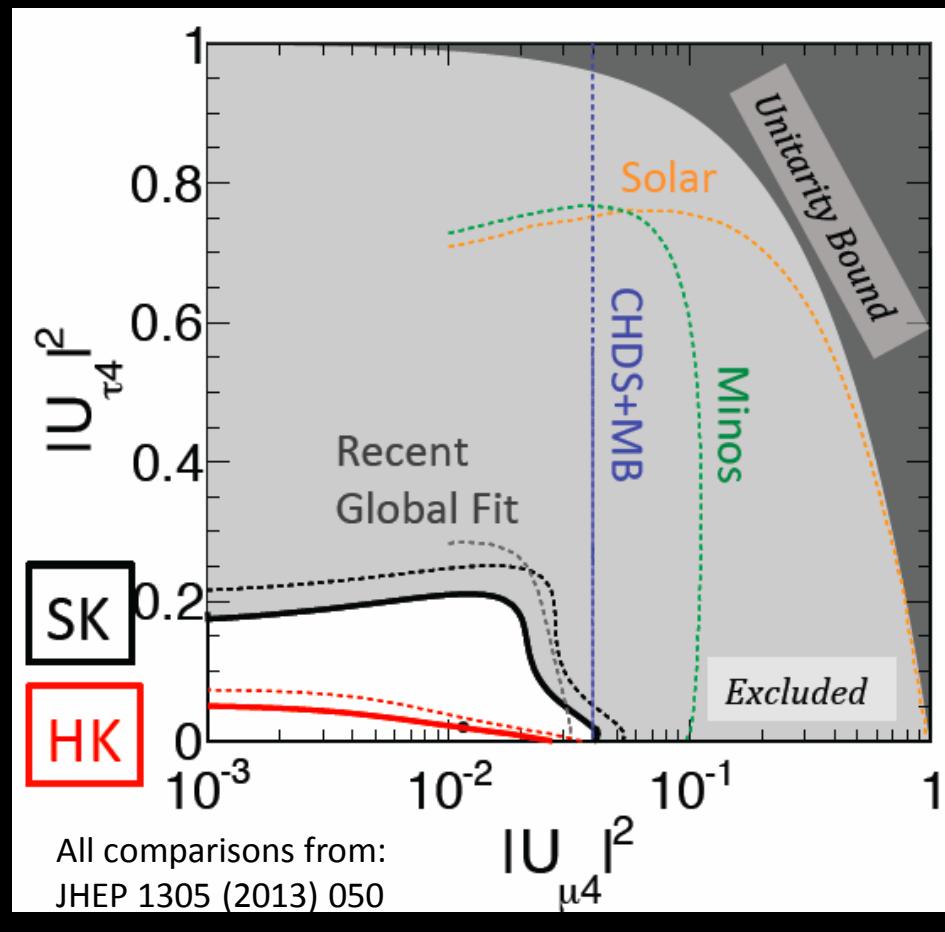
Limit (90% CL)

$$\tau/B_{p \rightarrow \nu K^+} > 3 \times 10^{34} \text{ yrs (HK 10 yrs)}$$

Sterile ν oscillations in atmospheric vs in HK



$|U_{\mu 4}|^2 < 0.029$ @ 99% CL (HK)



$|U_{\tau 4}|^2 < 0.066$ @ 99% CL (HK)

Hyper-Kamiokande EU meeting@CERN

27-28 April 2015

- Meeting to discuss the European effort in Hyper-K
- Open to anyone who has interest in Hyper-K, or is planning to join Hyper-K, or is contributing
- <http://indico.cern.ch/e/ThirdEUHyperK>



Third Hyper-Kamiokande EU meeting

27-28 April 2015
CERN
Europe/Zurich timezone

Search

Overview

Timetable

Registration

Participant List

Accommodation

Past Hyper-Kamiokande EU meetings

- Meeting to discuss the European effort in the Hyper-Kamiokande experiment.
- Open to anyone who has interests in Hyper-K, or is planning to join Hyper-K, or is contributing.
- Detailed information about your Country in Hyper-K can be discussed with your representatives in the Hyper-Kamiokande International Board Representatives, its chair if no representatives are available yet or the international Steering Committee chair.



Starts 27 Apr 2015 11:00
Ends 28 Apr 2015 18:00
Europe/Zurich



CERN
IT Amphitheatre



Registration for this event is now open
Deadline: 26 Apr 2015

Register now ➤

Summary

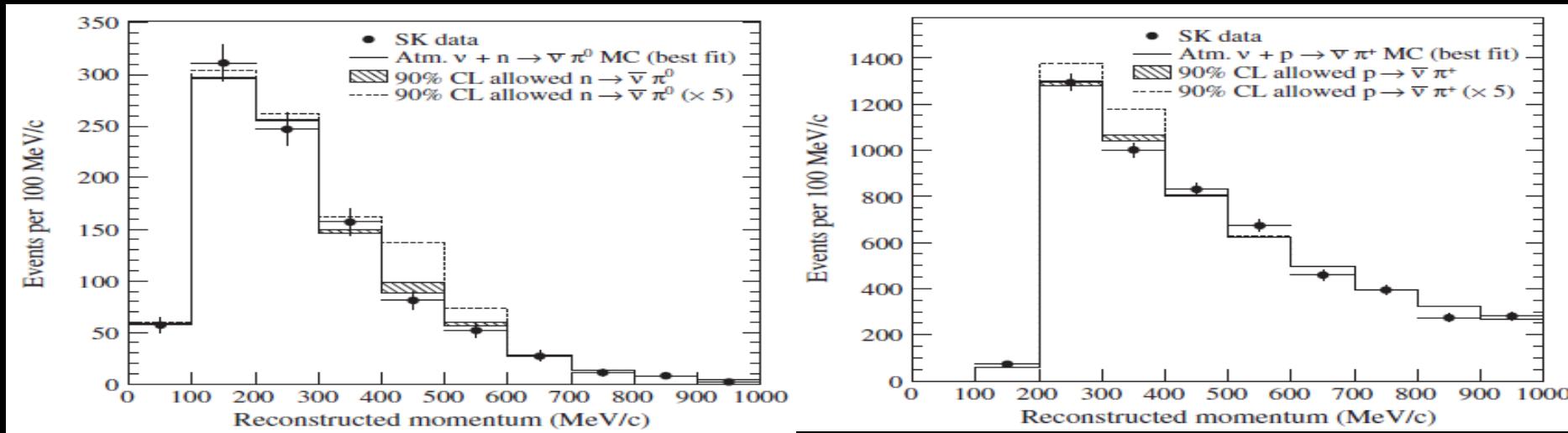
- Nucleon decay searches:
 - no evidence so far → most stringent lifetime limits in the world
 - keep discovery potential and increase statistics
- Atmospheric neutrino oscillation analyses:
 - no indication of non-standard models → stringent limits on relevant parameters
- Prospect of sensitivity improvements by sophisticated reconstruction algorithm, reducing systematic errors, etc.
- Hyper-K EU meeting @ CERN on 27-28 April 2015
 - <http://indico.cern.ch/e/ThirdEUHyperK>

Supplement

$n \rightarrow \bar{\nu} \pi^0$ and $p \rightarrow \bar{\nu} \pi^+$ searches

[Phys. Rev. Lett. 113, 121802 \(2014\)](#)

- minimal SUSY SO(10) model with a **126** Higgs field predicts $\tau(n \rightarrow \bar{\nu} \pi^0) = 2\tau(p \rightarrow \bar{\nu} \pi^+) \leq 5.7-13 \times 10^{32}$ years
- data from SK-I to SK-III \rightarrow total exposure: $172.8 \text{kt}\cdot\text{year}$



no excess in signal region:

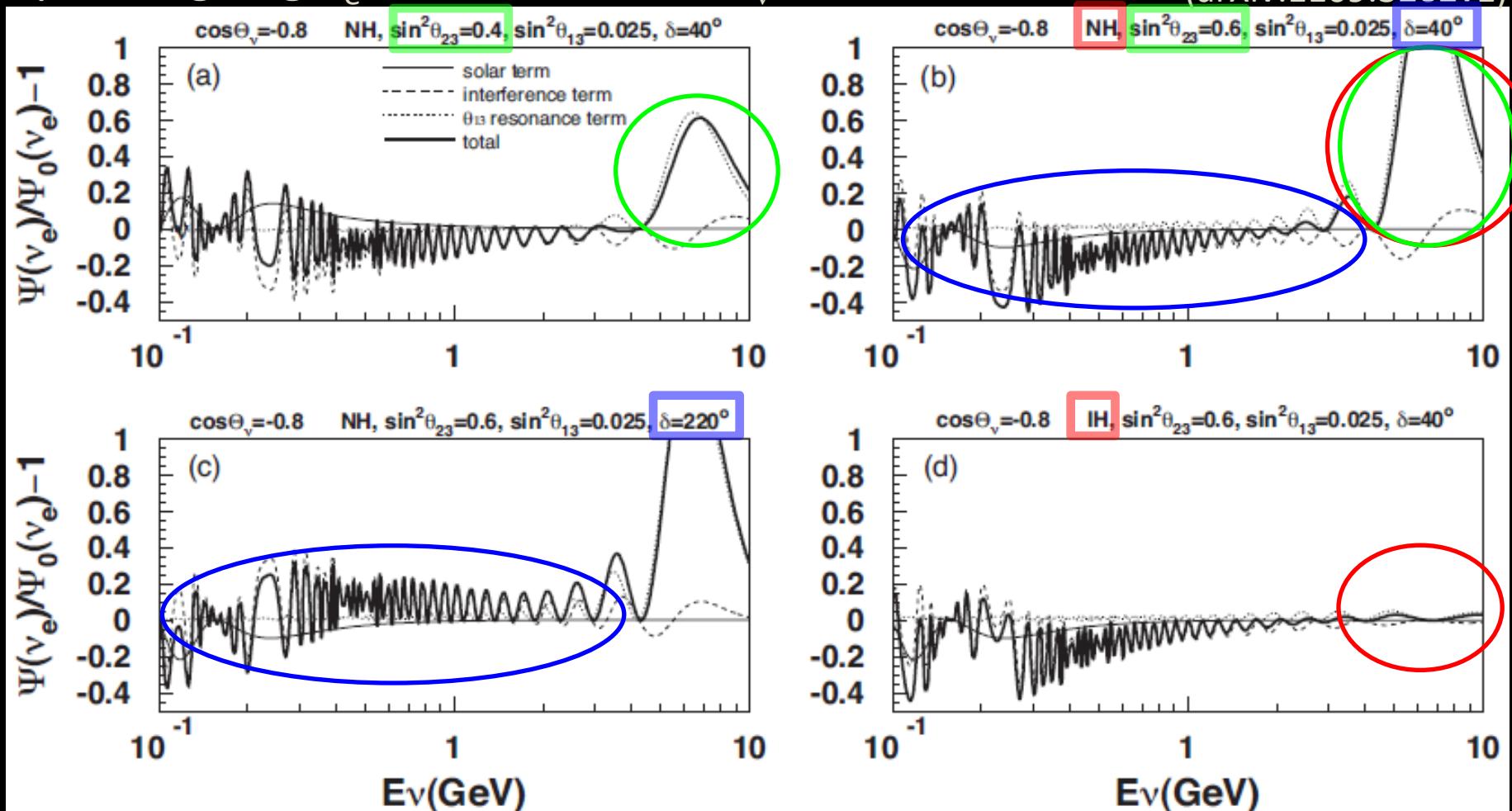
$$\tau/B_{n \rightarrow \bar{\nu} \pi^0} > 1.1 \times 10^{33} \text{ and } \tau/B_{p \rightarrow \bar{\nu} \pi^+} > 3.9 \times 10^{32} \text{ years (90\% CL)}$$

- world's best limit
- model's allowed ranges nearly ruled out
- an order of magnitude improvement over previously published limits

Oscillation probabilities in three flavor mixing scheme

upward-going ν_e s with zenith $\cos\Theta_\nu = -0.8$:

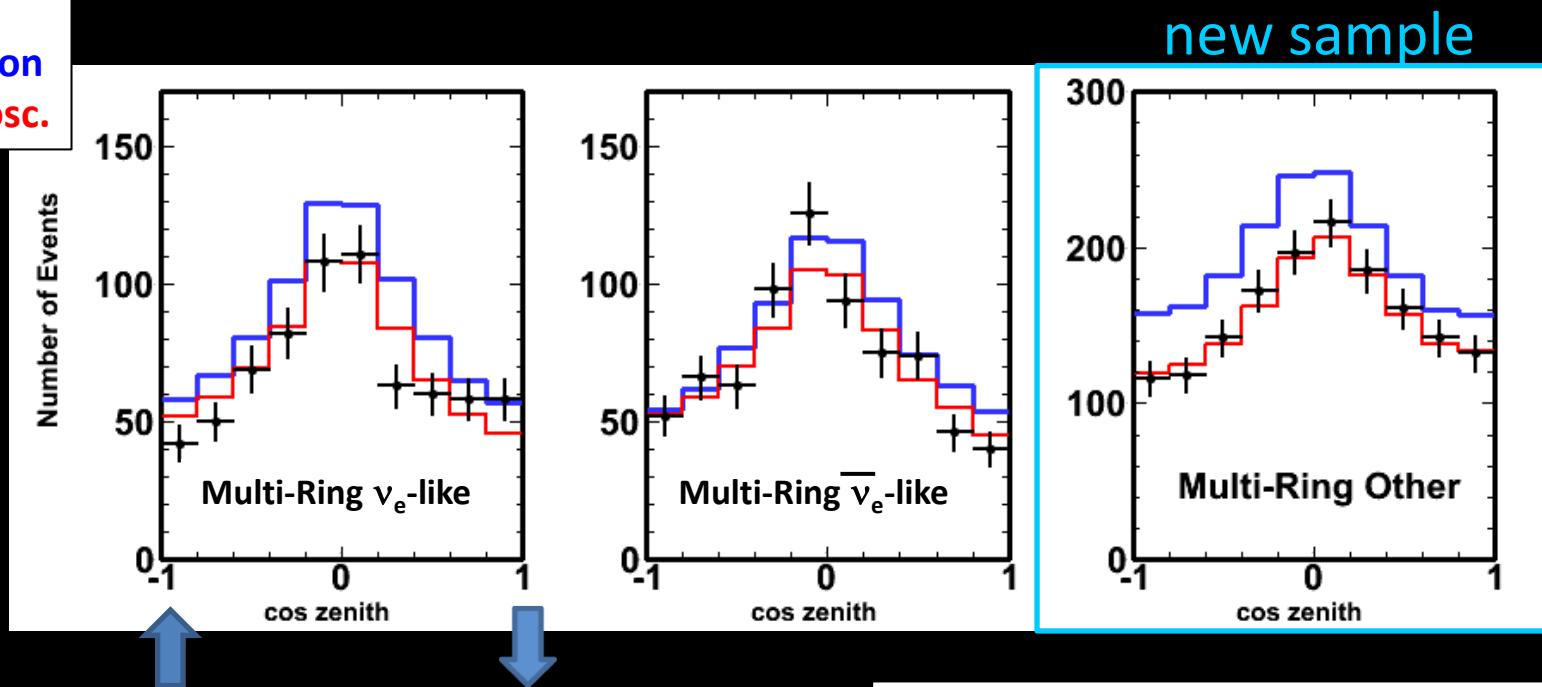
(arXiv:1109.3262v1)



- we have sensitivity to mass hierarchy, θ_{23} octant, and CPV

Updates to three flavor oscillation analyses

Data
prediction
 $\nu_\mu \rightarrow \nu_\tau$ osc.

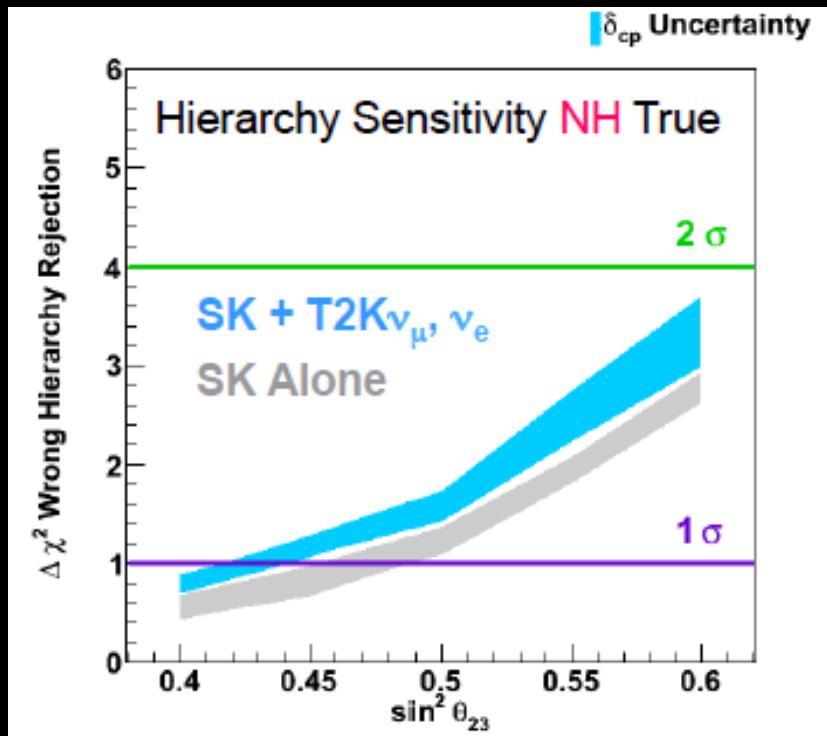


- “**Multi-Ring Other**”: events which fail multi-ring e-like CC purification likelihood
- improved systematic errors
- 282.2kt·year

Multi-Ring e-like Sample Purities

Purity	$cc\nu_e$	$cc\nu_\mu$	$cc\nu_\tau$	NC
ν -like	72.2%	8.3%	3.2%	16.1%
$\bar{\nu}$ -like	75.0%	6.5%	2.8%	15.6%
other	30.9%	33.4%	5.1%	30.5%

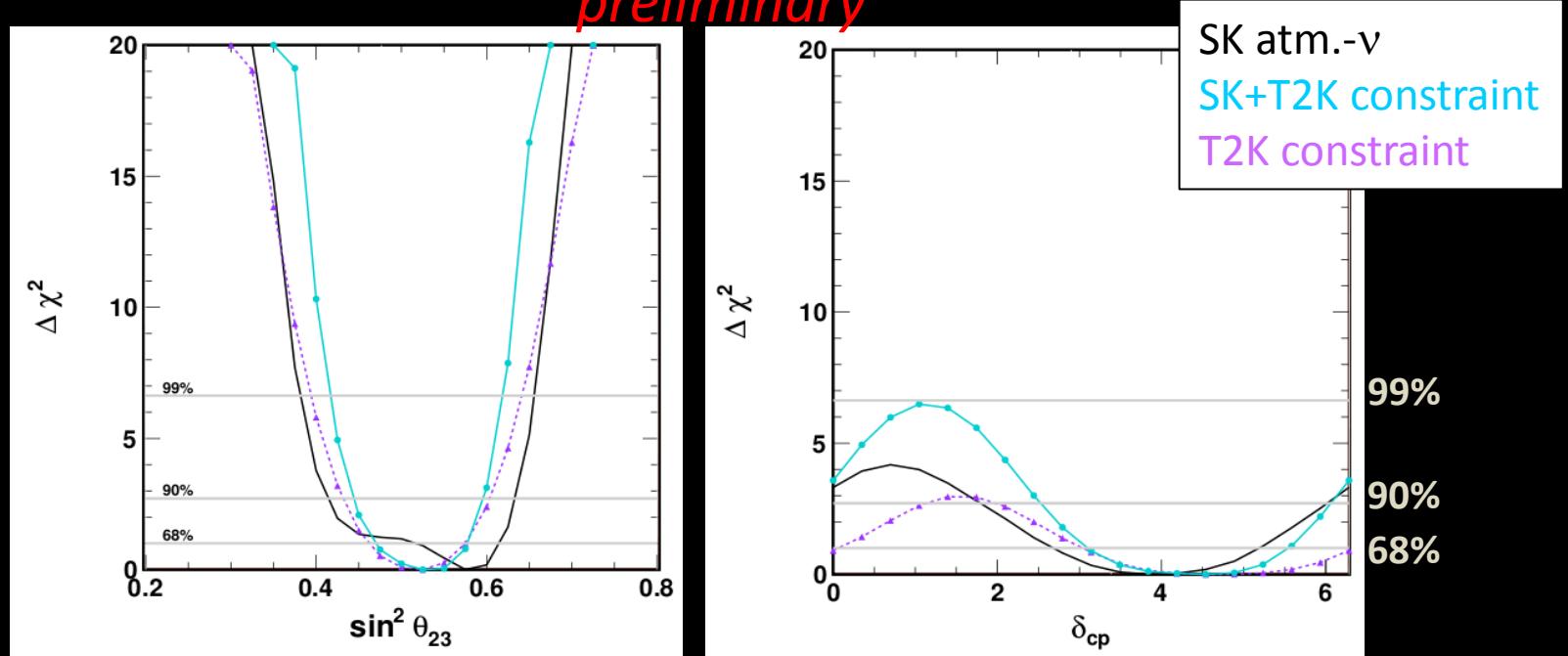
External constraints with T2K



- T2K constraints on θ_{23} and Δm^2_{32} enhance mass hierarchy discrimination
- using a common SK detector, systematic errors handled in consistent way

Results with T2K constraints

preliminary

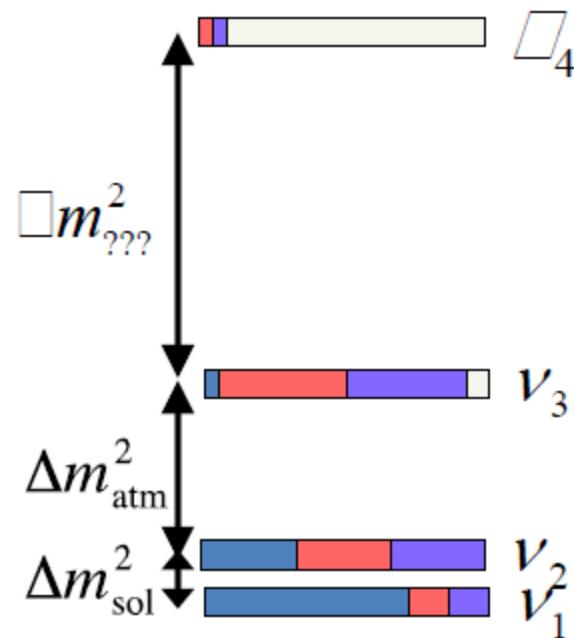
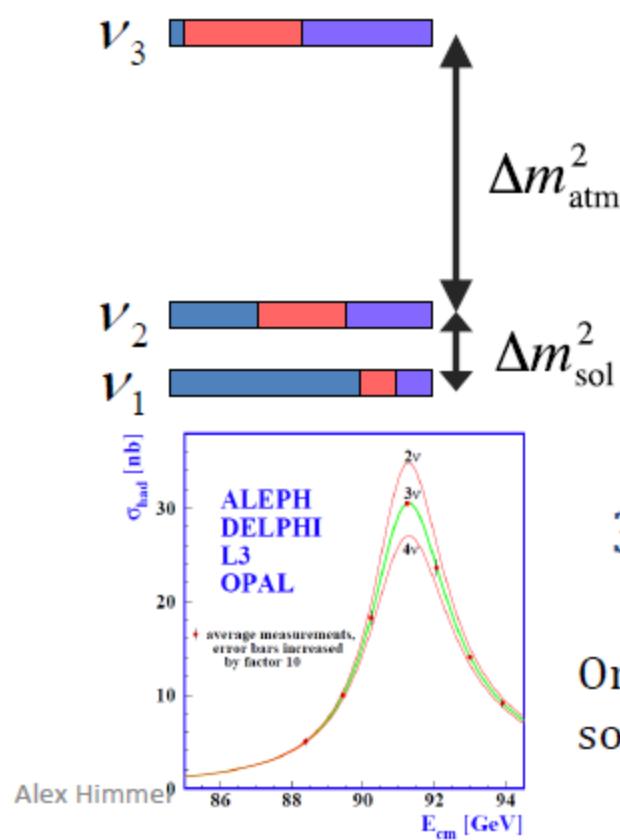


Fit (543 dof)	χ^2	θ_{13} (fixed)	δ_{cp}	θ_{23}	$\Delta m_{23} \times 10^{-3}$
SK + T2K (NH)	578.2	0.025	4.19	0.55	2.5
SK + T2K (IH)	579.4	0.025	4.19	0.55	2.5

- θ_{23} : 2nd octant slightly favored
- δ_{CP} : preference near $3\pi/2$, CP conservation ($\sin\delta_{\text{CP}}=0$) allowed at 90% CL
- $\chi^2_{\text{IH}} - \chi^2_{\text{NH}} = 1.2$ (0.9 SK only), NH slightly favored

What is a Sterile Neutrino?

3 neutrinos \rightarrow 2 mass splittings



3 mass splittings \rightarrow 4 neutrinos

One of which does not couple to the Z and so does not interact weakly, i.e. **sterile**

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What is a Sterile Neutrino?

PMNS

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

- One more neutrino adds 7 complex matrix elements
 - but not all independent.
- 1 Δm^2 , 3 “angles”, 2 phases – varying parameterizations
 - $|U_{e4}|^2, |U_{\mu 4}|^2, |U_{\tau 4}|^2$ or $\theta_{14}, \theta_{24}, \theta_{34}$
- One more neutrino adds 8 more parameters

Alex Himmel

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Test of Lorentz invariance

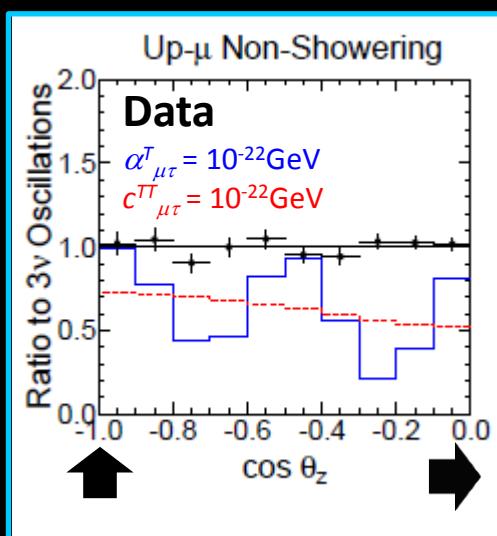
[arXiv:1410.4267](https://arxiv.org/abs/1410.4267)

$$H = UMU^\dagger + V_e + H_{LV},$$

$$H_{LV} = \begin{pmatrix} 0 & a_{e\mu}^T & a_{e\tau}^T \\ (a_{e\mu}^T)^* & 0 & a_{\mu\tau}^T \\ (a_{e\tau}^T)^* & (a_{\mu\tau}^T)^* & 0 \end{pmatrix}$$

$$- E \begin{pmatrix} 0 & c_{e\mu}^{TT} & c_{e\tau}^{TT} \\ (c_{e\mu}^{TT})^* & 0 & c_{\mu\tau}^{TT} \\ (c_{e\tau}^{TT})^* & (c_{\mu\tau}^{TT})^* & 0 \end{pmatrix}$$

Coefficient	Unit	d	CPT	Oscillation Effect
Isotropic				
$a_{\alpha\beta}^T$	GeV	3	odd	$\propto L$
$c_{\alpha\beta}^{TT}$	-	4	even	$\propto LE$



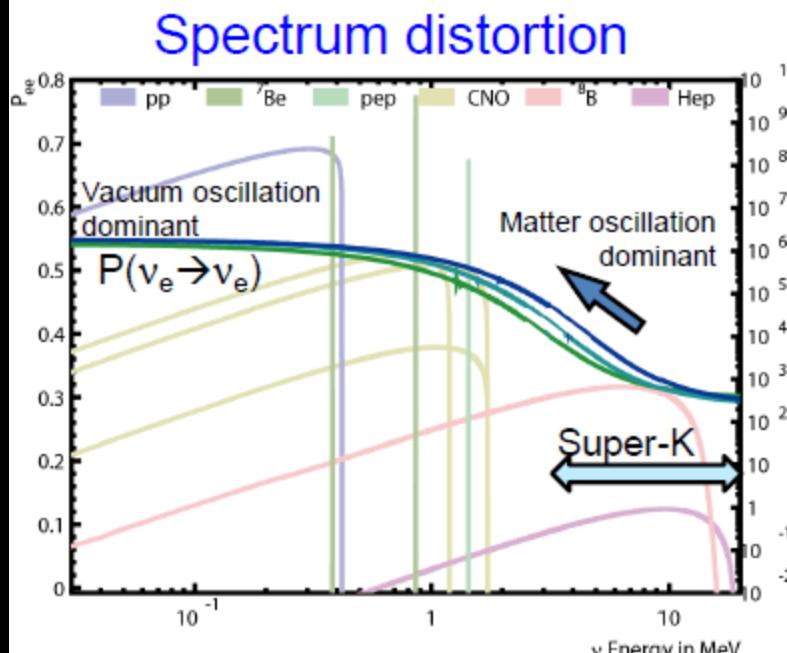
LV Parameter	95% Upper Limit	Best Fit	No LV $\Delta\chi^2$	Previous Limit
$e\mu$	$1.8 \times 10^{-23} \text{ GeV}$	$1.0 \times 10^{-23} \text{ GeV}$	1.4	$4.2 \times 10^{-20} \text{ GeV}$ [51]
	$1.8 \times 10^{-23} \text{ GeV}$	$4.6 \times 10^{-24} \text{ GeV}$		
	1.1×10^{-26}	1.0×10^{-28}		
	1.1×10^{-26}	1.0×10^{-28}	0.0	9.6×10^{-20} [51]
$e\tau$	$4.1 \times 10^{-23} \text{ GeV}$	$2.2 \times 10^{-24} \text{ GeV}$	0.0	$7.8 \times 10^{-20} \text{ GeV}$ [52]
	$2.8 \times 10^{-23} \text{ GeV}$	$1.0 \times 10^{-28} \text{ GeV}$		
	1.2×10^{-24}	1.0×10^{-28}		
	1.4×10^{-24}	4.6×10^{-25}	0.3	1.3×10^{-17} [52]
$\mu\tau$	$6.5 \times 10^{-24} \text{ GeV}$	$3.2 \times 10^{-24} \text{ GeV}$	0.9	—
	$5.1 \times 10^{-24} \text{ GeV}$	$1.0 \times 10^{-28} \text{ GeV}$		
	5.8×10^{-27}	1.0×10^{-28}		
	5.6×10^{-27}	1.0×10^{-27}	0.1	—

- no evidence of Lorentz violation observed (4,438 days $\sim 274 \text{ kt}\cdot\text{year}$)
- set limits for the first time in neutrino $\mu\tau$ sector of SME
- improved existing limits by up to 7 orders of magnitude

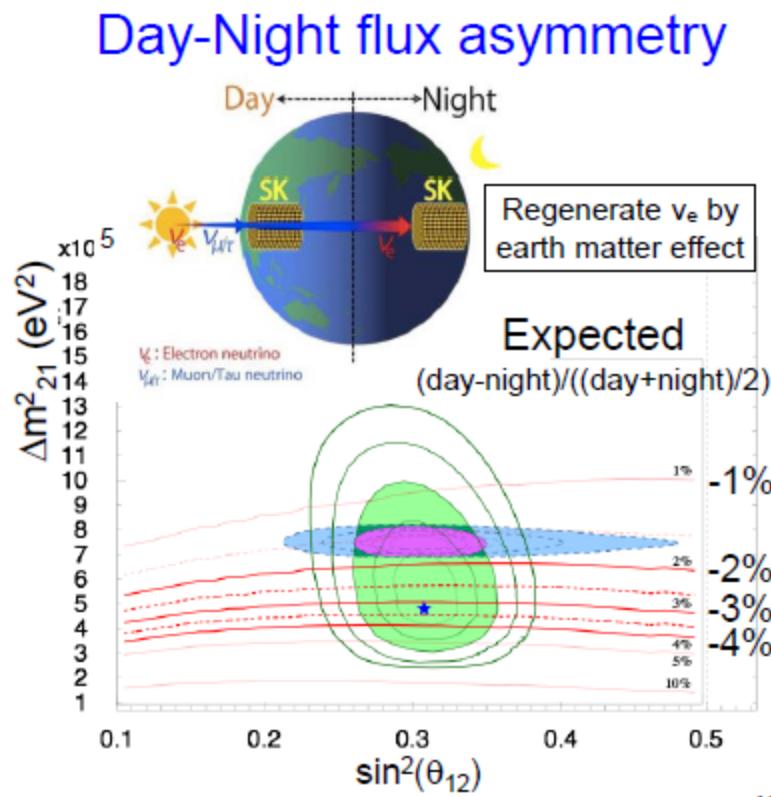


⁸B solar neutrino measurement

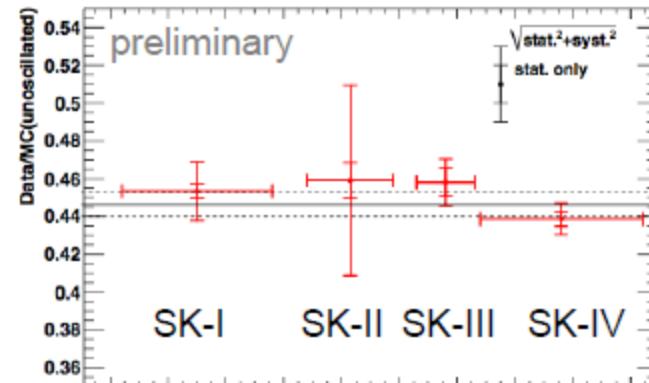
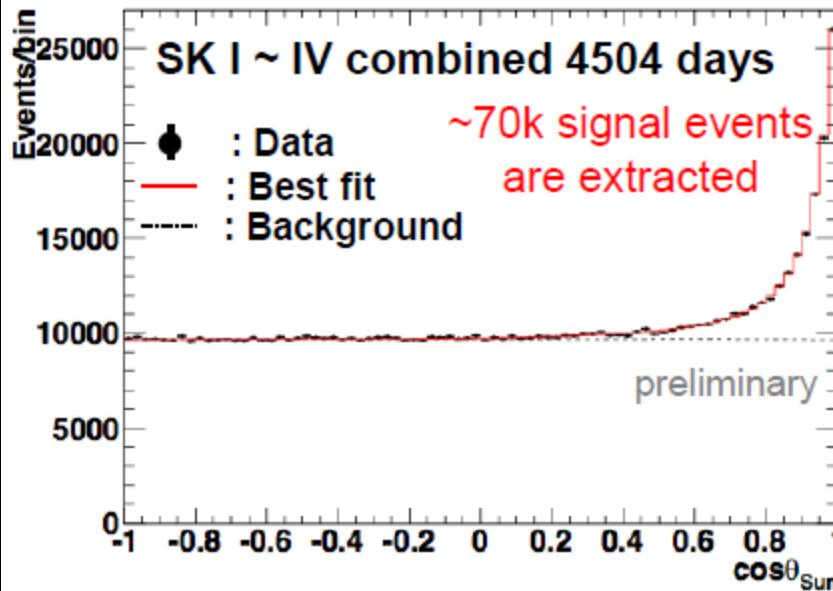
- High statistics (~20events/day) measurement of ⁸B solar neutrinos
 - Possible time variation of the flux
 - Energy spectrum distortion due to solar matter effect
 - Day-night flux asymmetry due to earth matter effect



Super-K can search for the spectrum "upturn" expected by neutrino oscillation MSW effect



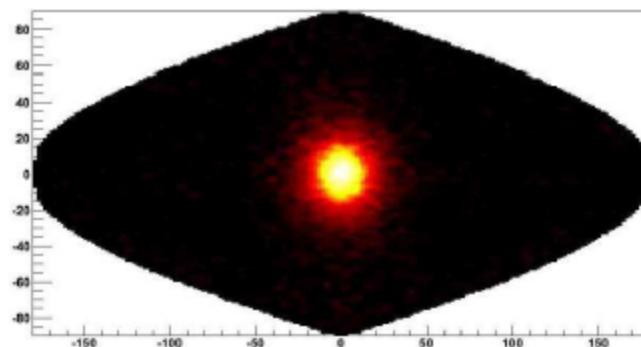
${}^8\text{B}$ solar neutrino flux



Fluxes from all SK phases are consistent to each other within their errors.

SK I-IV combined flux:

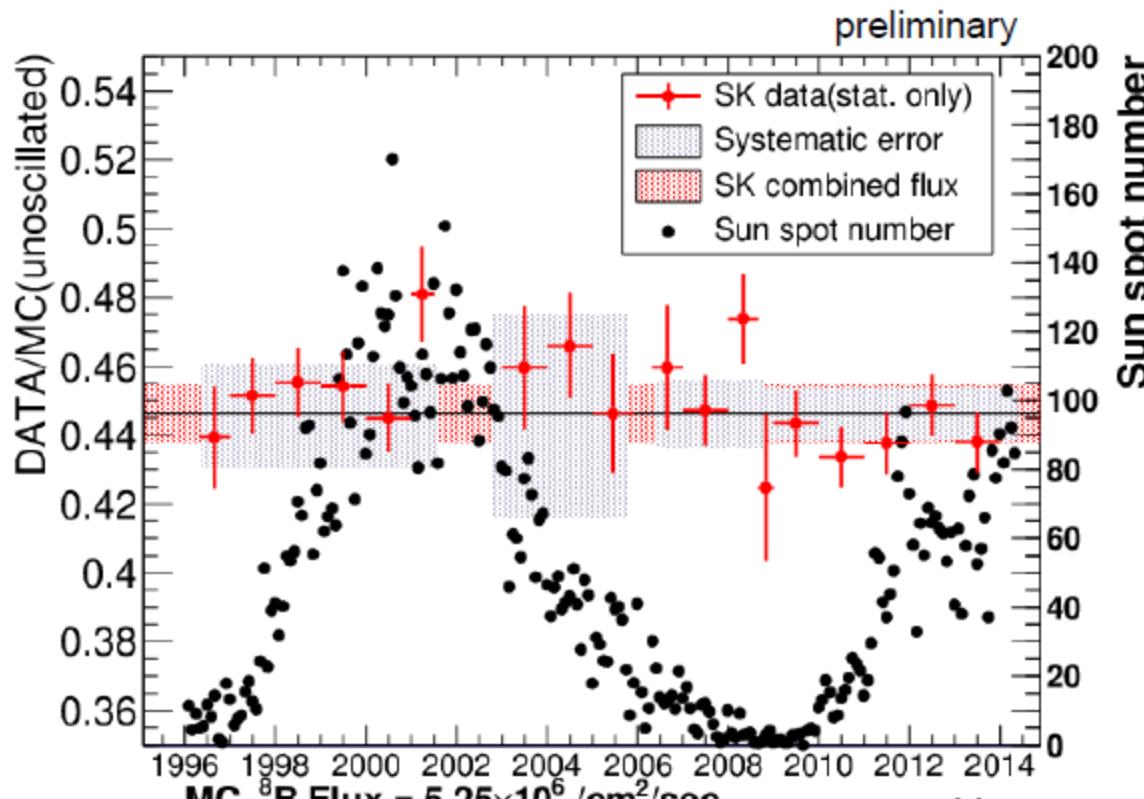
DATA/MC = 0.4463 ± 0.0085 (stat.+sys.)
(MC ${}^8\text{B}$ flux: $5.25 \times 10^6/\text{cm}^2/\text{s}$)



Observed effective ${}^8\text{B}$ flux :

2.343 ± 0.044 (stat.+sys.) $[10^6/\text{cm}^2/\text{s}]$

${}^8\text{B}$ solar neutrino flux yearly plot



Sun spot number from http://solarscience.msfc.nasa.gov/greenwch/spot_num.txt

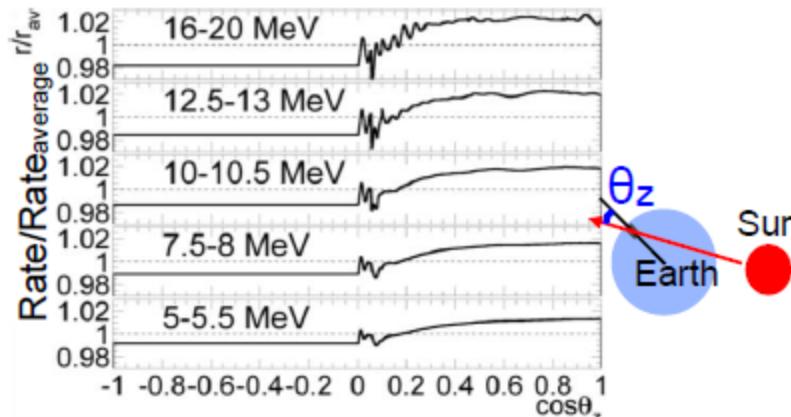
$\chi^2 = 13.53 / 17 \text{ D.O.F.} \rightarrow \text{prob.} = 70\%$

No significant correlation with the solar activity is seen.

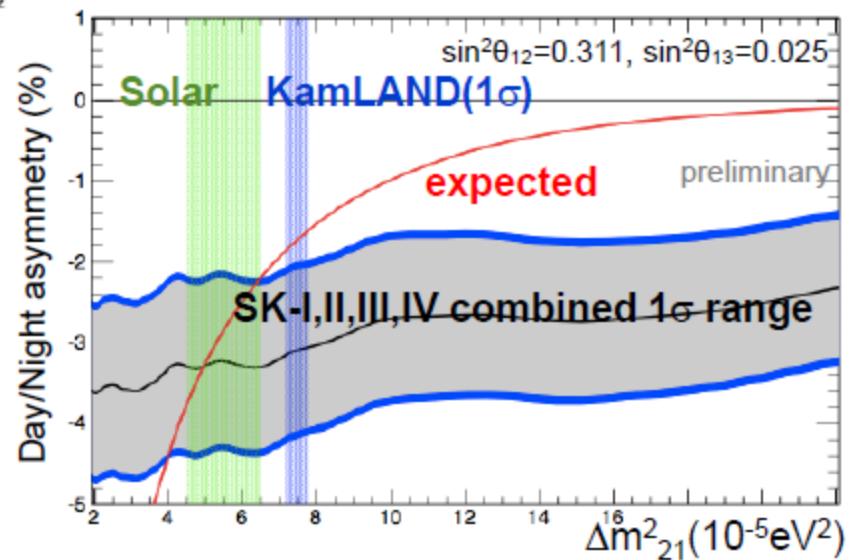
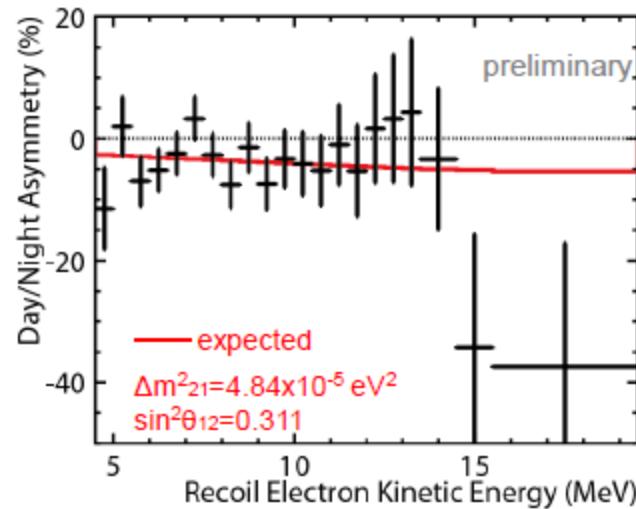
Day/Night asymmetry (A_{DN})



Assuming the expected time variation as a function of $\cos\theta_z$ like below, amplitude of A_{DN} was fitted.

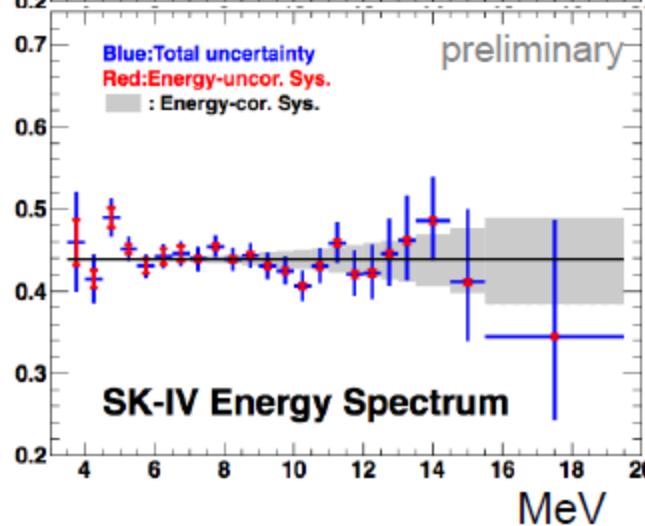
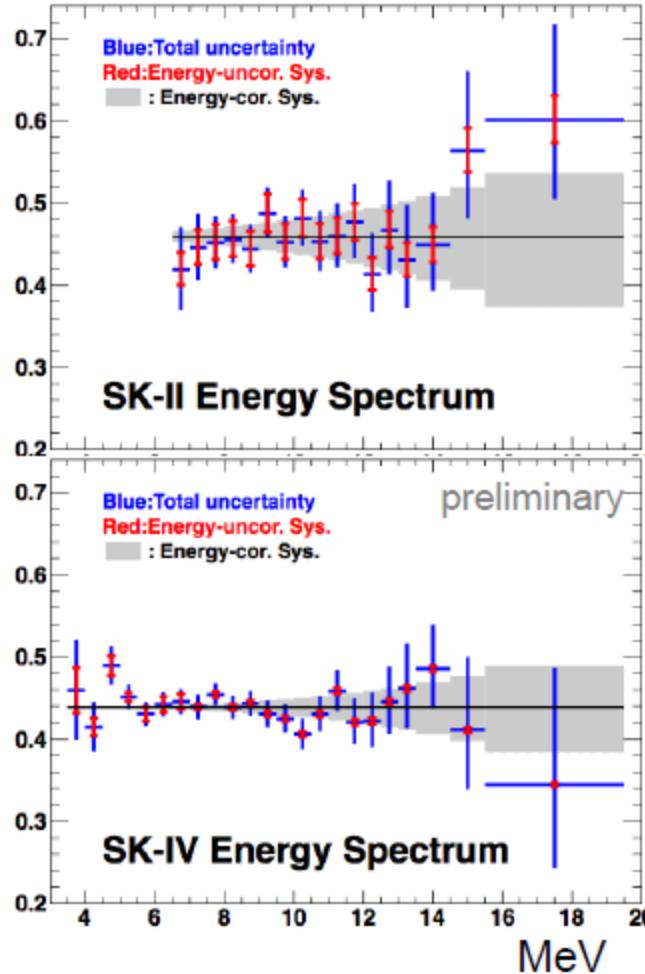
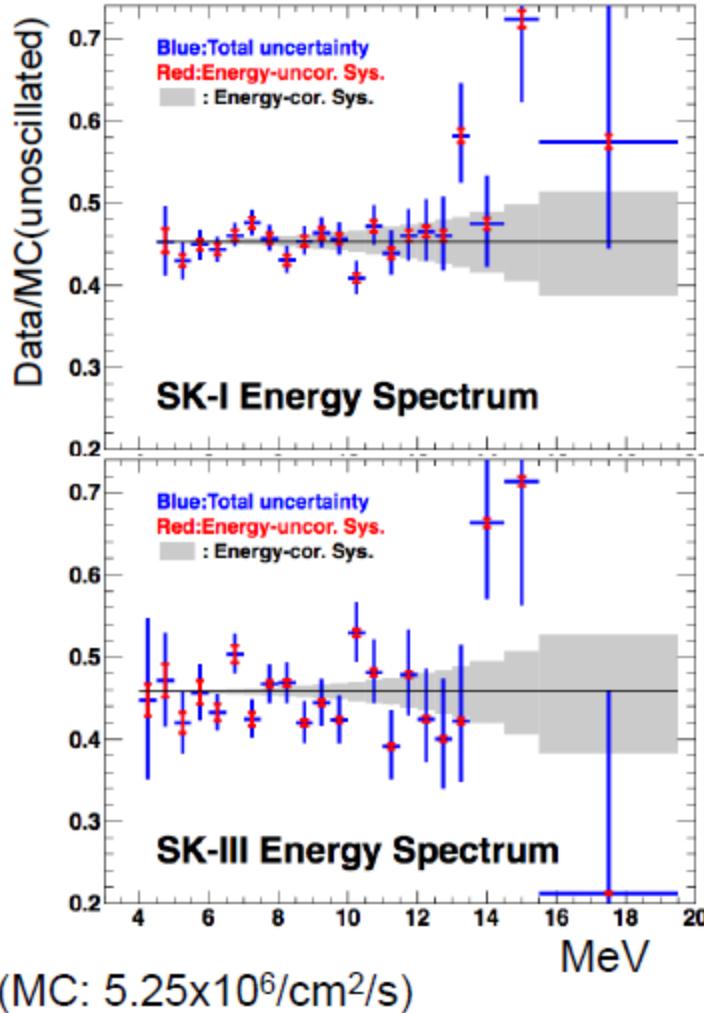


	A_{DN}
SK-I	$-2.0 \pm 1.8 \pm 1.0\%$
SK-II	$-4.4 \pm 3.8 \pm 1.0\%$
SK-III	$-4.2 \pm 2.7 \pm 0.7\%$
SK-IV	$-3.6 \pm 1.6 \pm 0.6\%$
combined	$-3.3 \pm 1.0 \pm 0.5\%$
non-zero significance	3.0σ



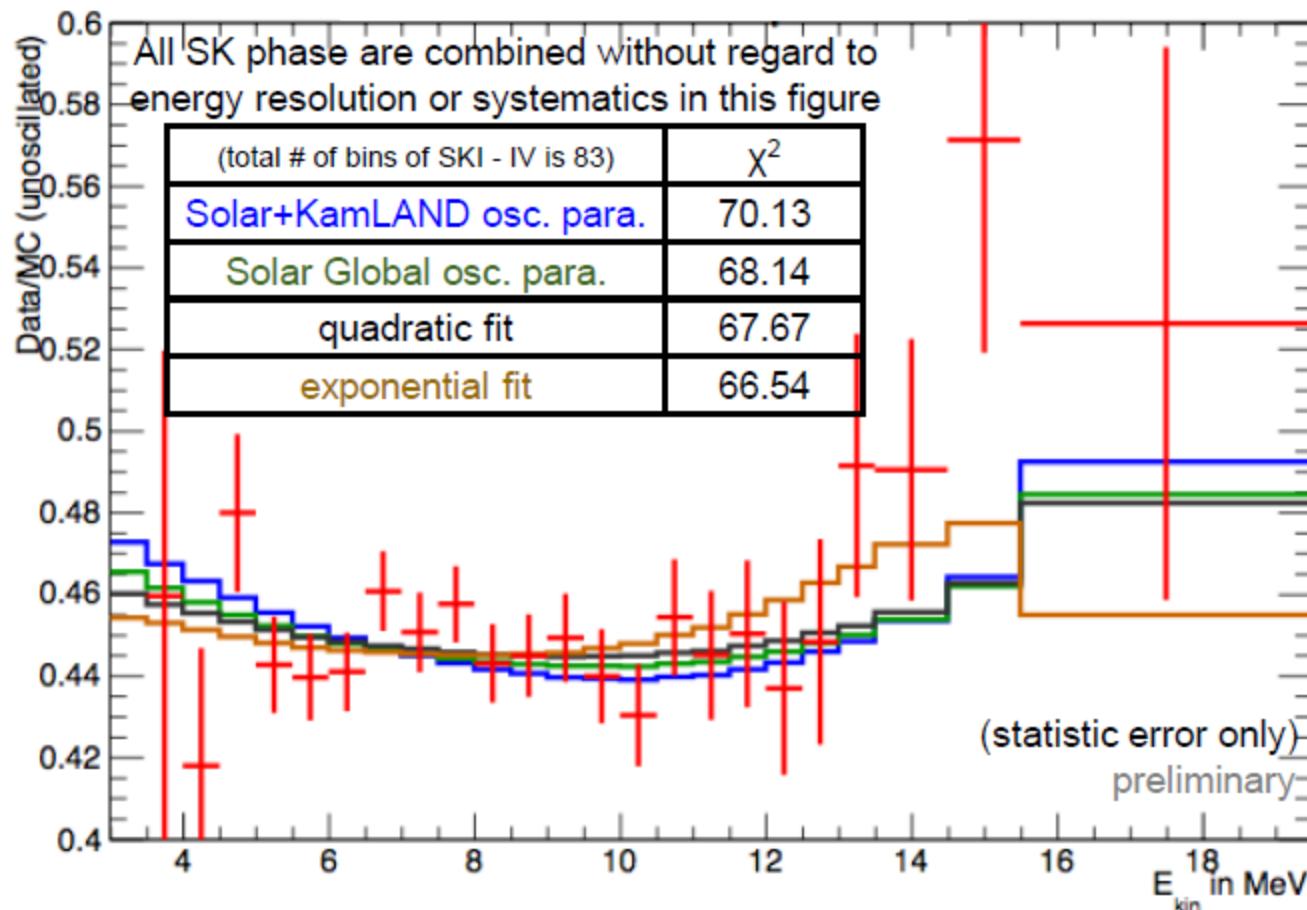
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Recoil electron spectrum of each phase



SK-IV Energy Spectrum

SK I-IV combined Recoil electron spectrum



MSW is slightly disfavored by $\sim 1.7\sigma$ using the Solar+KamLAND best fit parameters, and $\sim 1.0\sigma$ using the Solar Global best fit parameters.

Multi-purpose detector, Hyper-K

Letter of Intent, Hyper-K WG,
arXiv:1109.3262 [hep-ex]

LBL study, Hyper-K WG,
arXiv:1502.05199 and
submitted to PTEP

- Proton decay 3σ discovery potential
 - 5×10^{34} years for $p \rightarrow e^+ \pi^0$
 - 1×10^{34} years for $p \rightarrow \nu K^+$
- Comprehensive study on ν oscillations
 - CPV (76% of δ space at 3σ), $< 20^\circ$ precision
 - MH determination for all δ by J-PARC/Atm ν
 - θ_{23} octant: $\sin^2 \theta_{23} < 0.47$ or $\sin^2 \theta_{23} > 0.53$
 - $< 1\%$ precision of Δm^2_{32}
 - test of exotic scenarios by J-PARC/Atm ν
- Astrophysical neutrino observatory
 - Supernova up to 2Mpc distance, $\sim 1SN / 10$ years
 - Supernova relic ν signal ($\sim 200\nu$ events/10yrs)
 - Dark matter neutrinos from Sun, Galaxy, and Earth
 - Solar neutrino $\sim 200\nu$ events/day

