

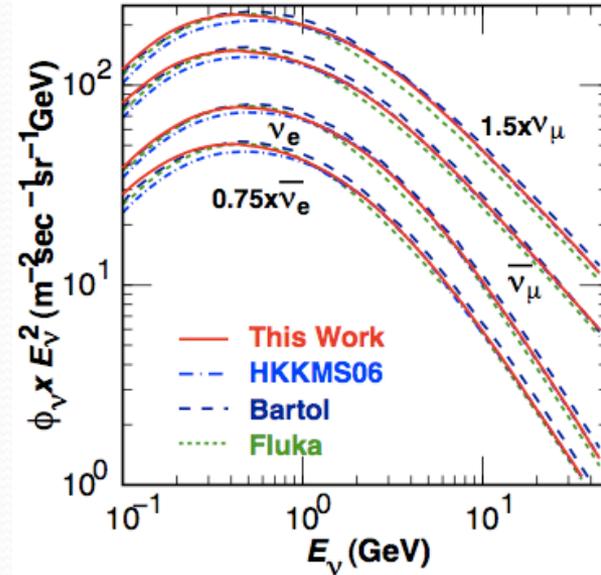
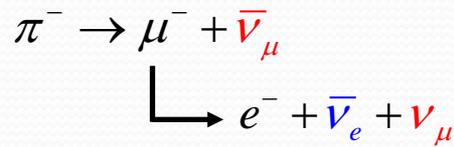
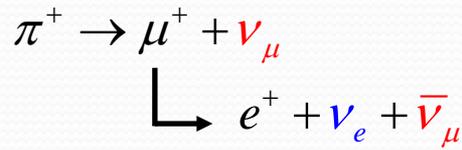
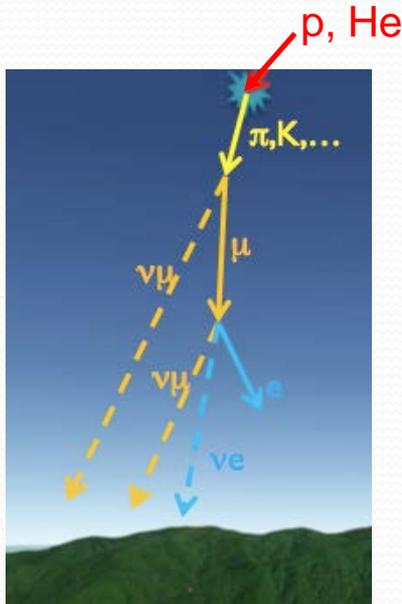
スーパーカミオカンデにおける 大気ニュートリノの研究

奥村公宏 (東大宇宙線研)

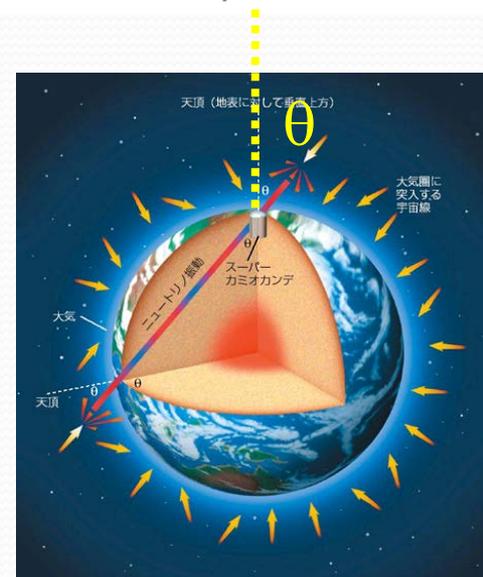
新学術領域研究「ニュートリノフロンティア」研究会

2013年12月7日 @ クロスウェーブ府中

大気ニュートリノ

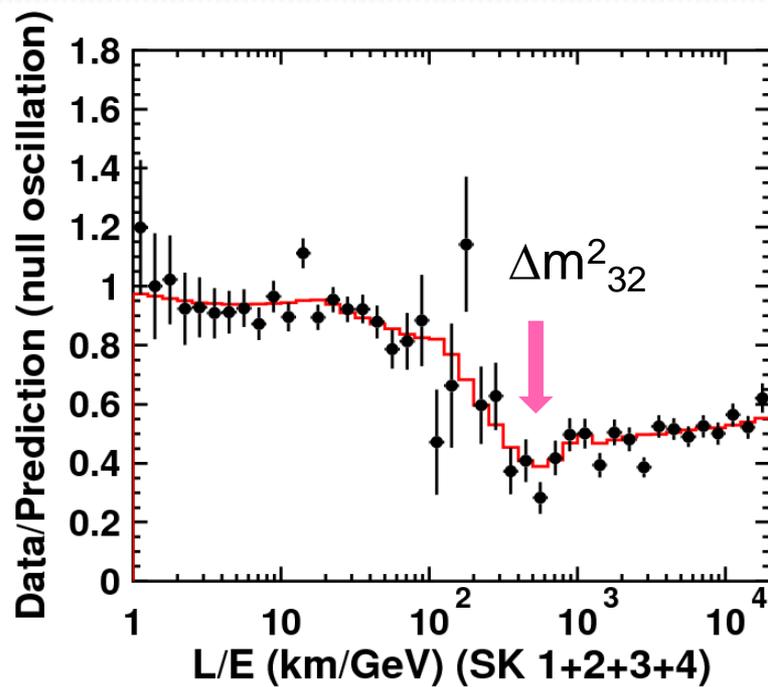
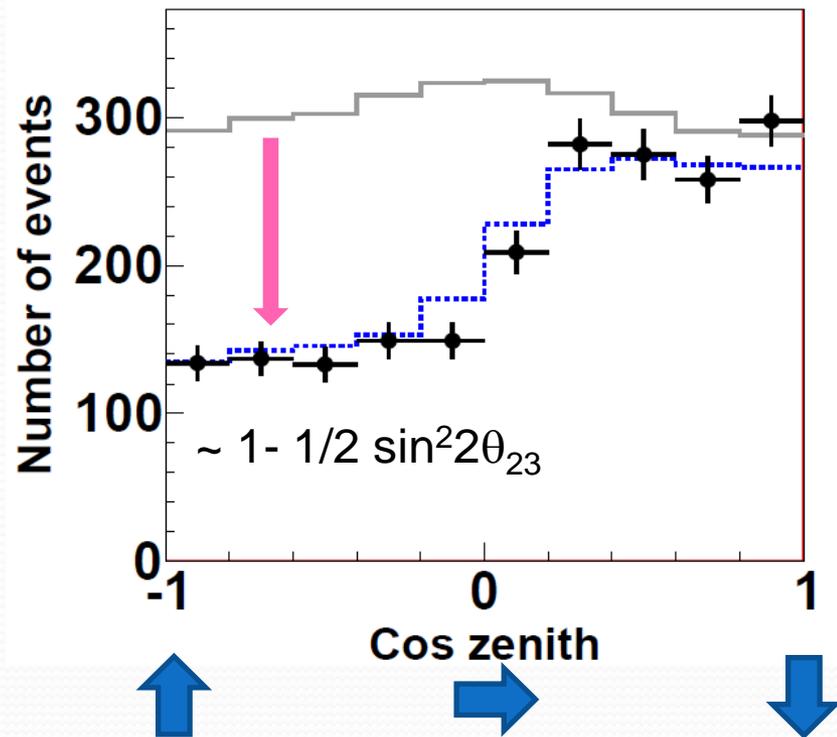


- $\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$
- 広いエネルギースペクトル
sub-GeV \sim TeV, PeV, ...
- 飛行距離の天頂角依存
 $O(10\text{km}) \sim 10^4\text{km}$
- Free !



天頂角分布、L/E

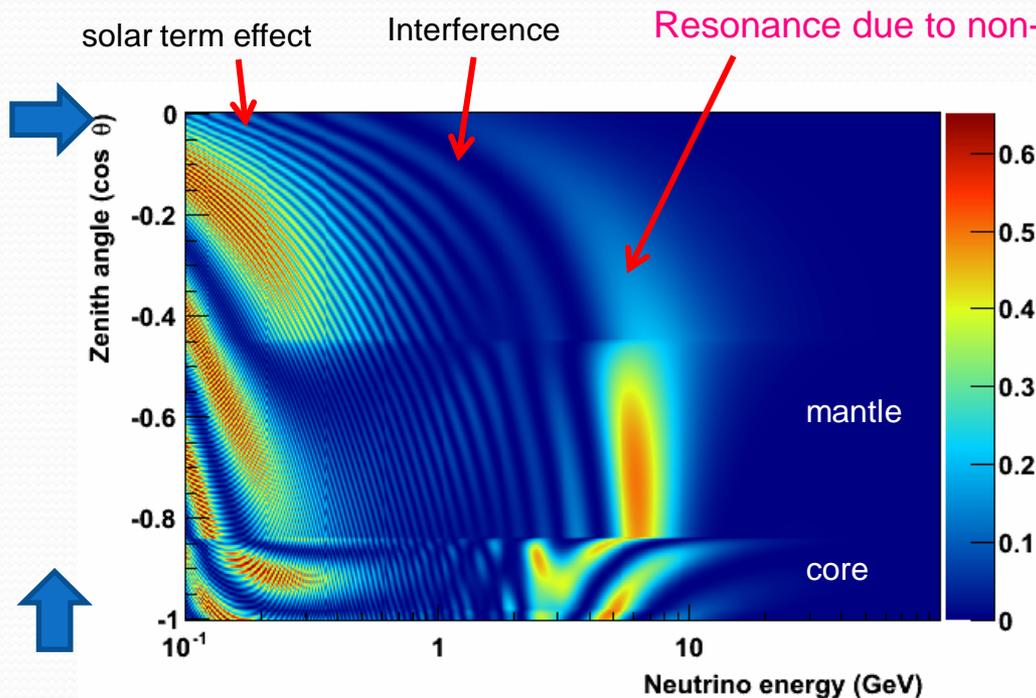
Two-flavor oscillation:
$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2 \left(\frac{1.27 \Delta m_{32}^2 L}{E} \right)$$



Sub-dominant 振動モード

原子炉・加速器ニュートリノ測定による θ_{13} の発見:

- 大気ニュートリノで θ_{13} による $\nu_{\mu} \rightarrow \nu_e$ 振動
- 物質効果による質量階層性の識別が可能
- δ_{CP} 、 θ_{23} octant にも感度あり



$\nu_{\mu} \rightarrow \nu_e$ 振動確率

(1) solar term Δm_{21}^2 による振動
sensitive to θ_{23} octant

(2) Interference
sensitive to δ_{CP}

(3) θ_{13} による resonance
sensitive to θ_{23} , θ_{13} , MH
(2~10GeV領域)

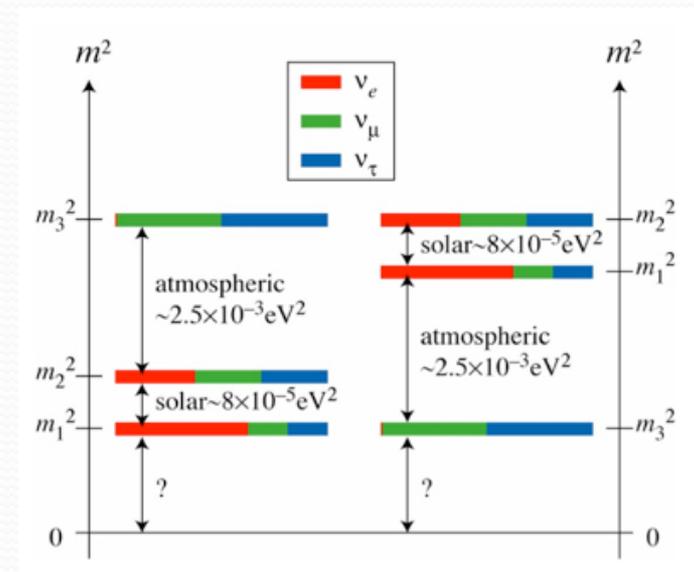
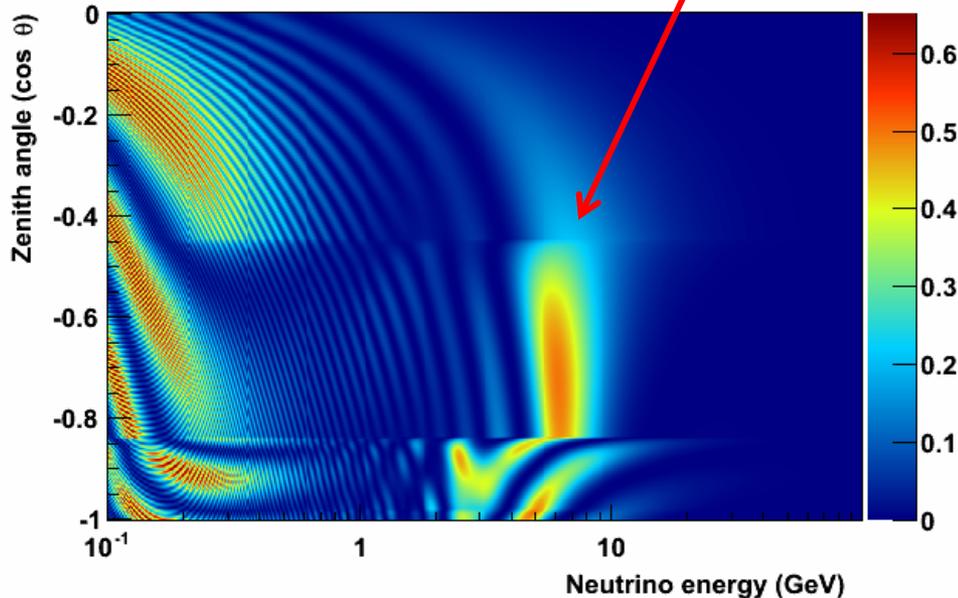
物質効果と質量階層性 (MH)

物質中での $\nu_\mu \rightarrow \nu_e$ 振動確率 (solar term Δm_{21}^2 を無視)

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 \theta_{23} \sin^2 2\theta_{13}^M \sin^2 \left(\frac{1.27 \Delta m_{32,M}^2 L}{E} \right)$$

$$\sin^2 2\theta_{13}^M = \frac{\sin^2 2\theta_{13}}{\left(\cos 2\theta_{13} - \frac{A_{CC}}{\Delta m_{32}^2} \right)^2 + \sin^2 2\theta_{13}} \quad (A_{CC} = 2\sqrt{2}G_F N_e E)$$

Resonance: $A_{CC} \sim \Delta m_{32}^2 \cos 2\theta_{13}$



Normal Hierarchy
($\Delta m_{32}^2 > 0$)

Inverted Hierarchy
($\Delta m_{32}^2 < 0$)

$\bar{\nu}$ の場合 $A_{CC} \rightarrow -A_{CC}$

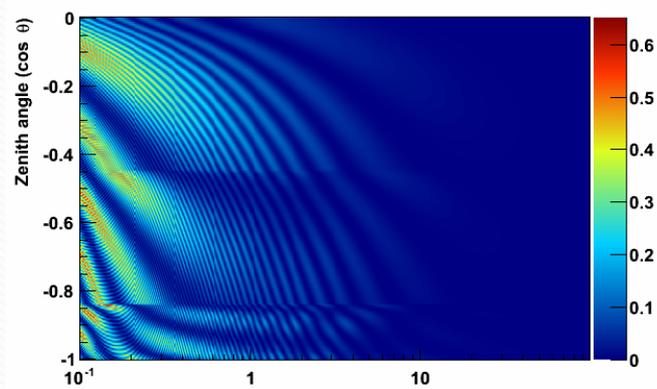
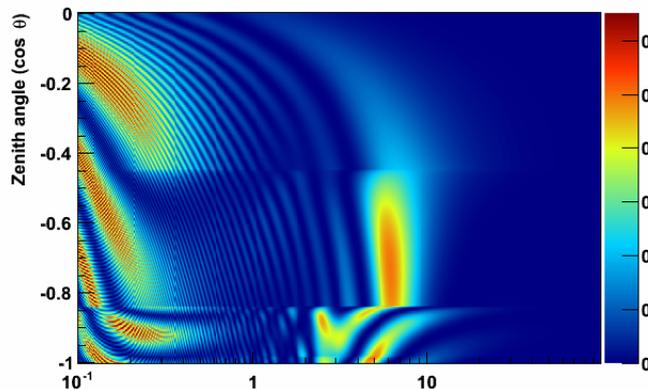
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物質効果と質量階層性 (MH)

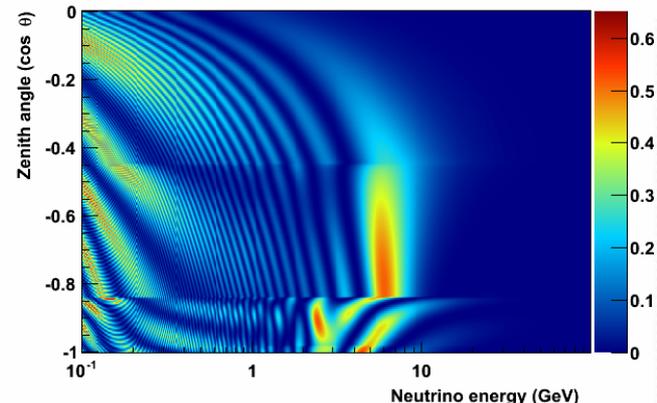
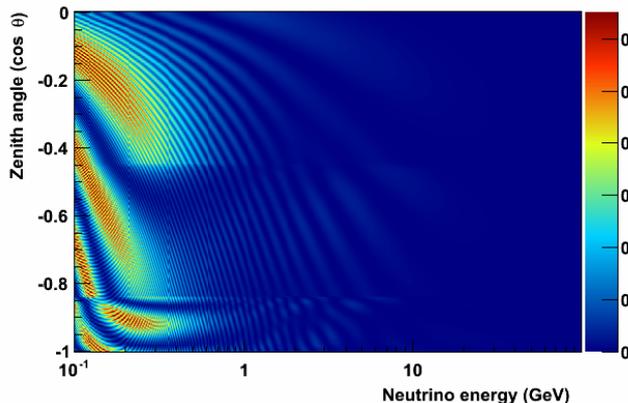
$$\nu_\mu \rightarrow \nu_e$$

$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

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

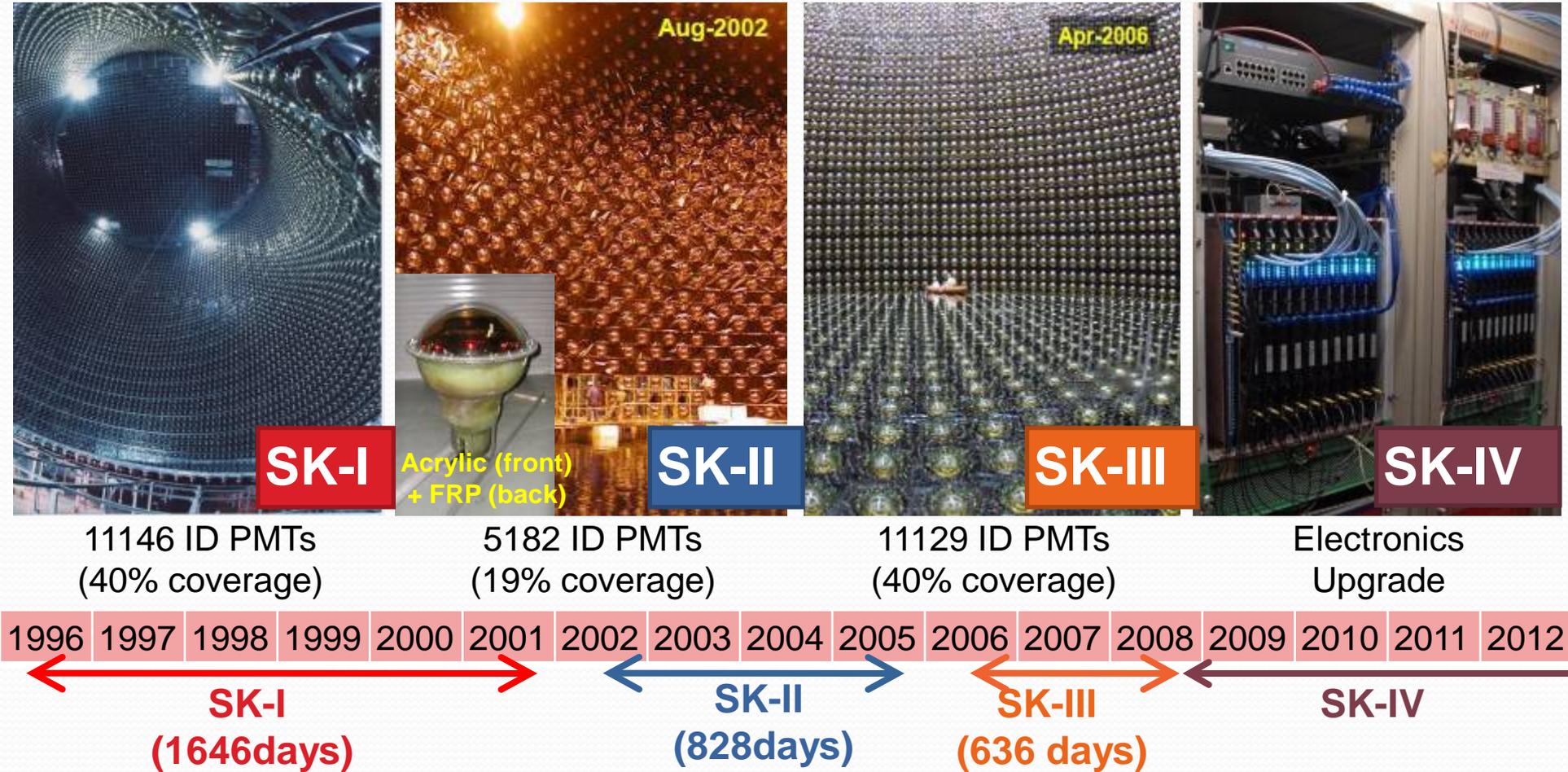


Inverted hierarchy
($\Delta m_{32}^2 < 0$)



ニュートリノ事象と反ニュートリノ事象を区別できれば、MH識別の可能性あり

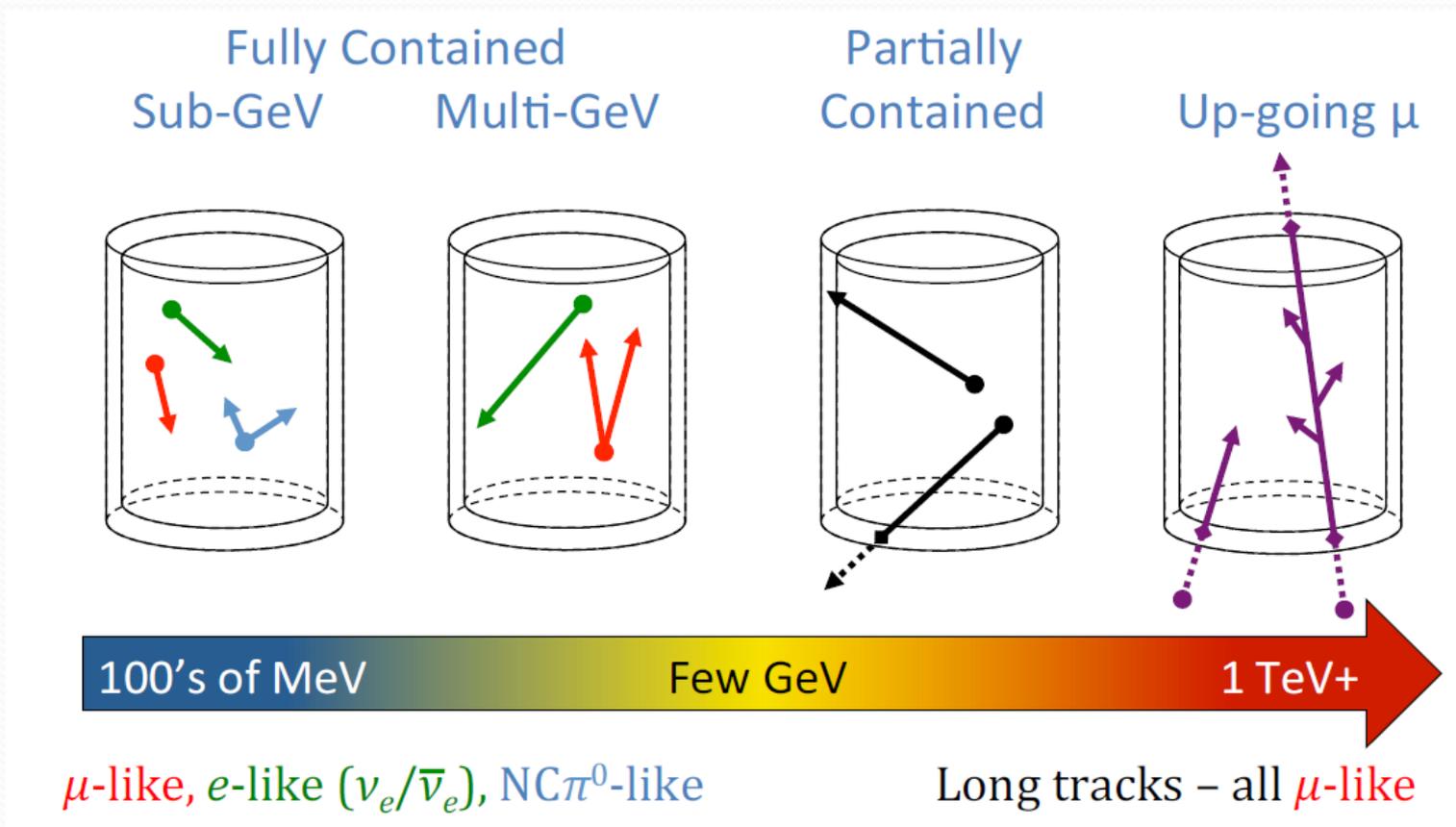
Super-Kamiokande



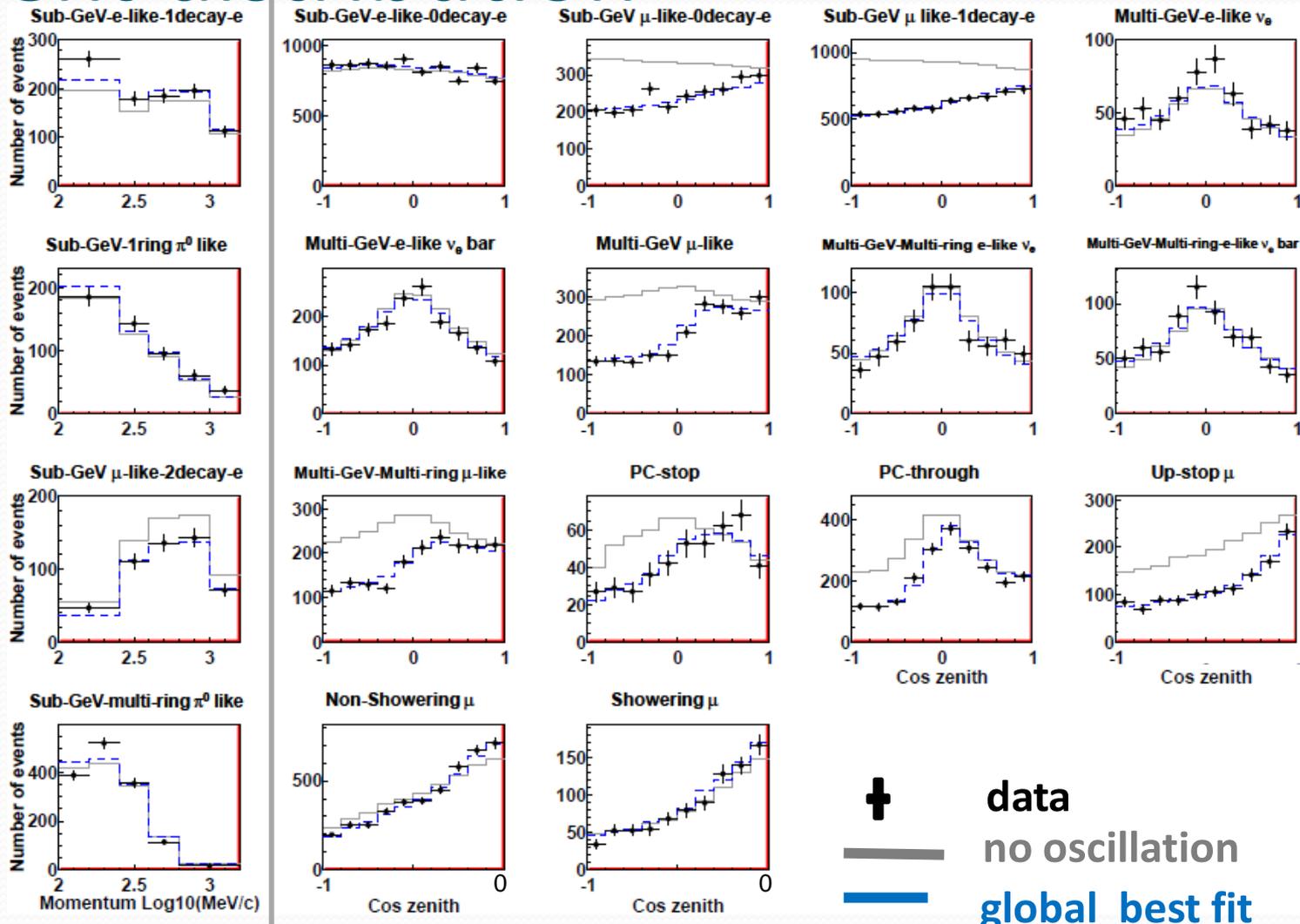
50kt水チェレンコフ検出器 (FV22.5kt)

SK-IV 2008年10月より

大気ニュートリノの事象タイプ



Event distribution



運動量分布
[log10(MeV)]

天頂角分布
[cos θ_{zen}]

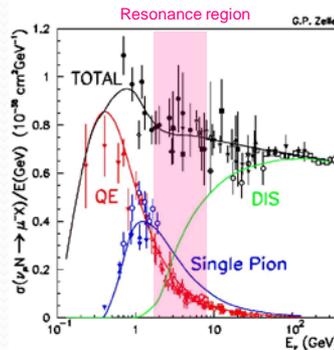
(-1:up 1:down)

$\nu_e / \bar{\nu}_e$ 識別

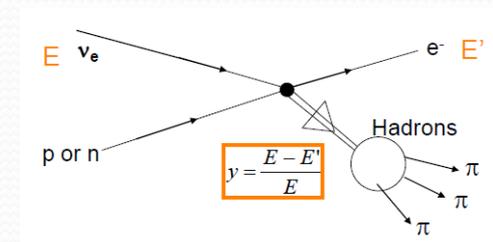
- 水チェレンコフでレプトン電荷による $\nu / \bar{\nu}$ 識別はほぼ不可能
- Kinematics の違いや π 粒子の終状態による統計的な分別を行う

π 粒子の終状態:

- π^+ → 散乱、崩壊電子
- π^- → 水中で absorption



Kinematics による違い:



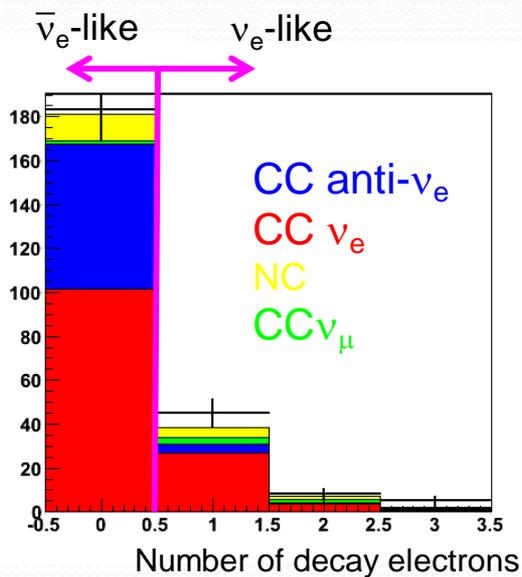
	ニュートリノ	反ニュートリノ
QE	$\nu + n \rightarrow l^- + p$	$\bar{\nu} + p \rightarrow l^+ + n$
	$\nu + p \rightarrow l^- + p + \pi^+$	$\bar{\nu} + n \rightarrow l^+ + n + \pi^-$
S-Pi	$\nu + n \rightarrow l^- + p + \pi^0$	$\bar{\nu} + p \rightarrow l^+ + n + \pi^0$
	$\nu + n \rightarrow l^- + n + \pi^+$	$\bar{\nu} + p \rightarrow l^+ + p + \pi^-$
DIS	$\nu + n \rightarrow l^- + N' + m \pi$	$\bar{\nu} + p \rightarrow l^+ + N' + m \pi$
	$\nu + p \rightarrow l^- + N' + m \pi$	$\bar{\nu} + n \rightarrow l^+ + N' + m \pi$
	+1 or +2	0 or -1

	CC ν_e	CC anti- ν_e
レプトンエネルギー比率	Smaller	Larger
Transverse momentum (P_T)	Larger	Smaller
チェレンコフリング数	More	Less

ν_e / 反 ν_e 識別

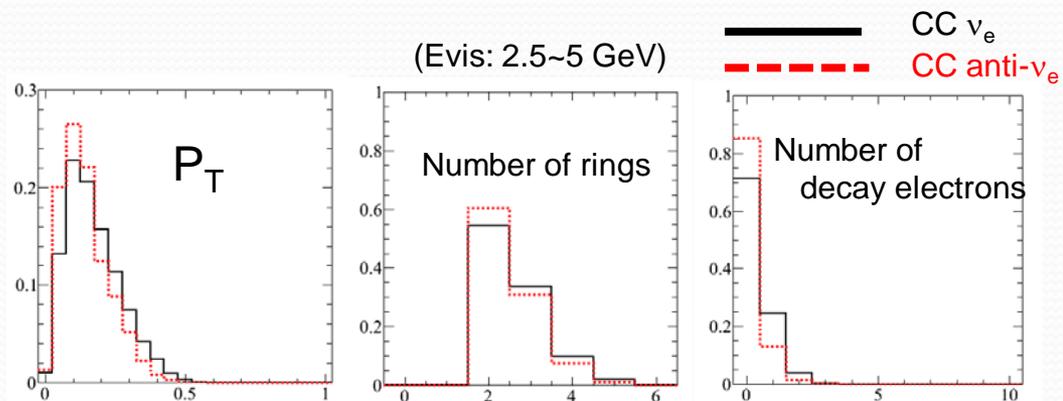
Single-Ring 事象 :

崩壊電子の有無で分別



Multi-Ring 事象:

反応 kinematics、崩壊電子数を用いた Likelihood 法による分別:

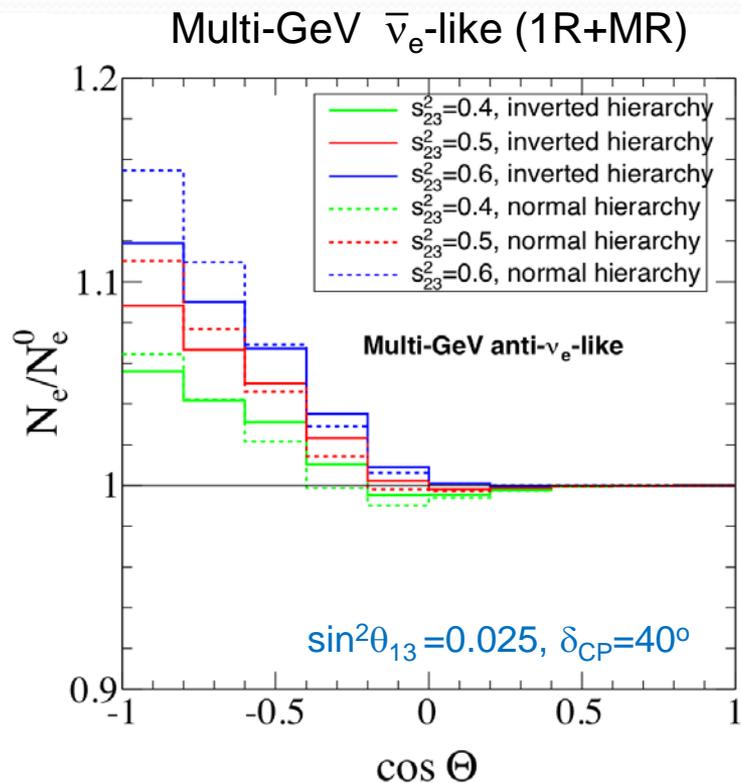
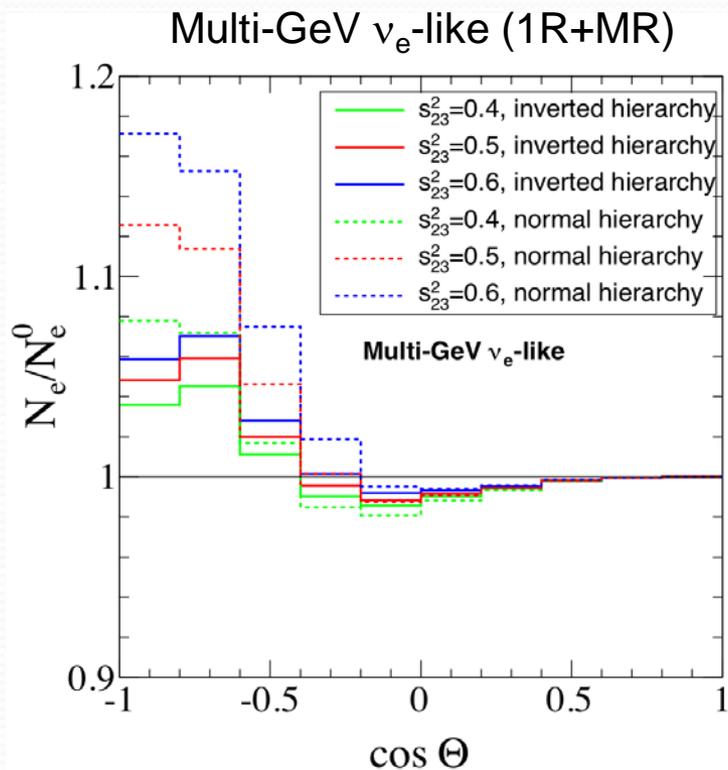


Separation後:

Composition (%)		CC ν_e	CC anti- ν_e	CC ν_μ + anti- ν_μ	NC
ν_e like	1R	60.2	10.6	13.5	14.8
	MR	57.5	17.4	10.7	13.7
Anti- ν_e like	1R	55.7	36.6	1.1	6.4
	MR	51.9	20.7	8.2	19.7

MH、 $\sin^2\theta_{23}$ effect

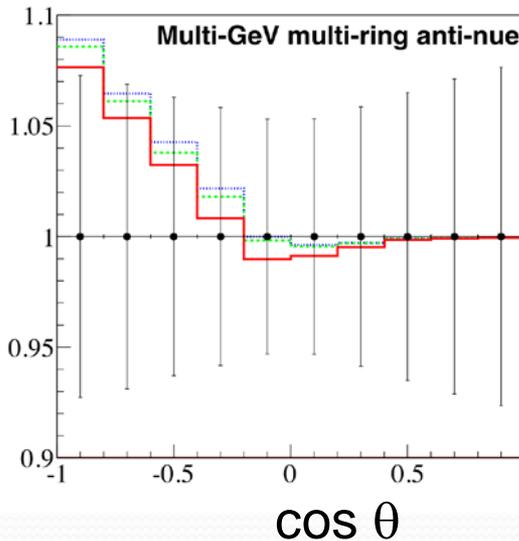
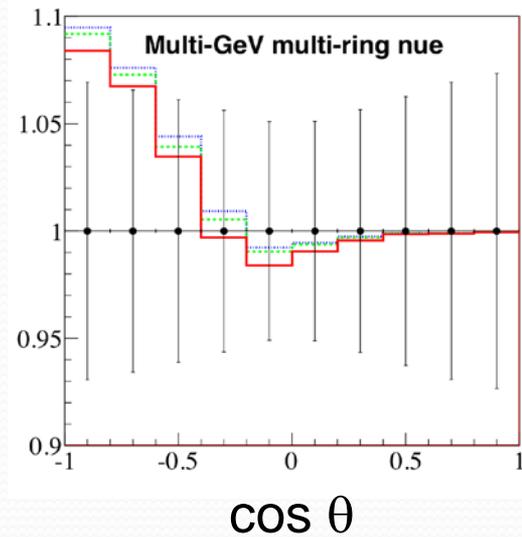
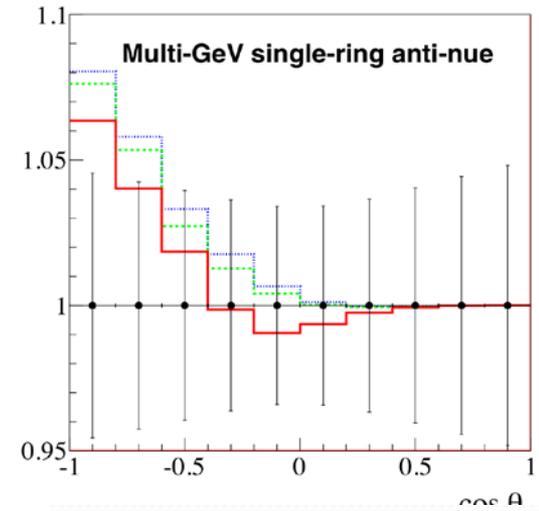
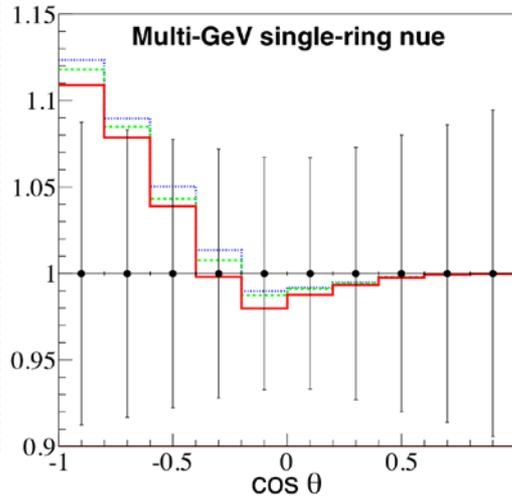
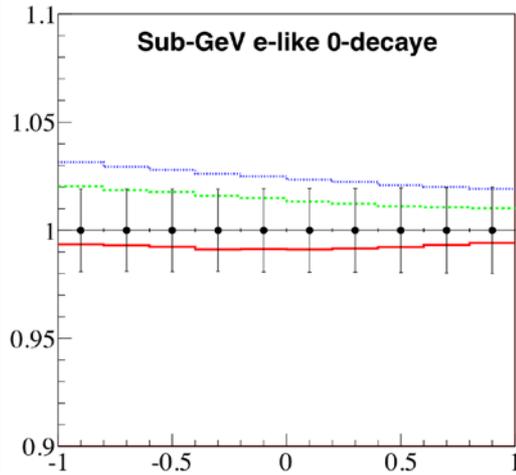
$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 \theta_{23} \sin^2 2\theta_{13}^M \sin^2 \left(\frac{1.27 \Delta m_{31,M}^2 L}{E} \right)$$



Normal / Inverted で ν_e -like と anti- ν_e -like での増加量に違い
 $\sin^2\theta_{23}$ にも依存

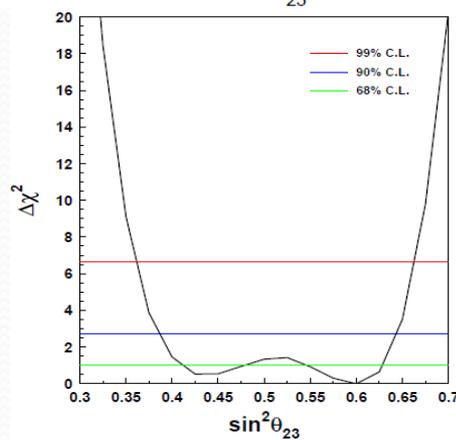
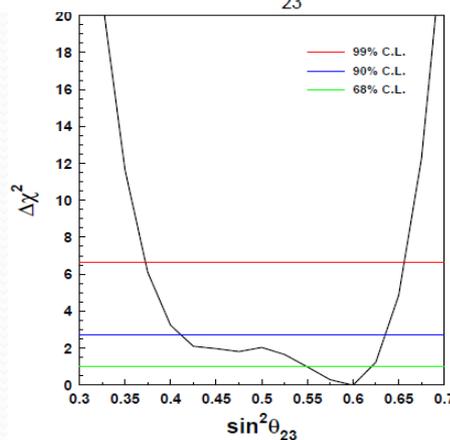
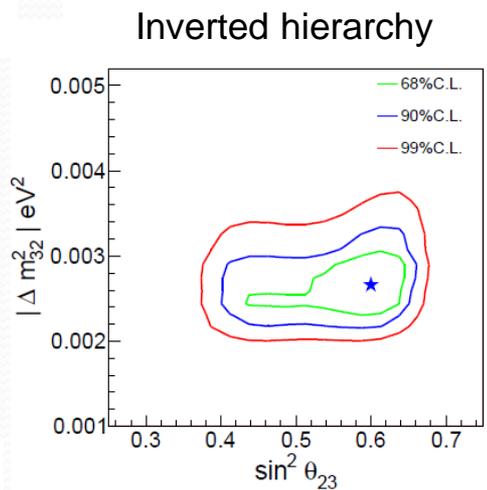
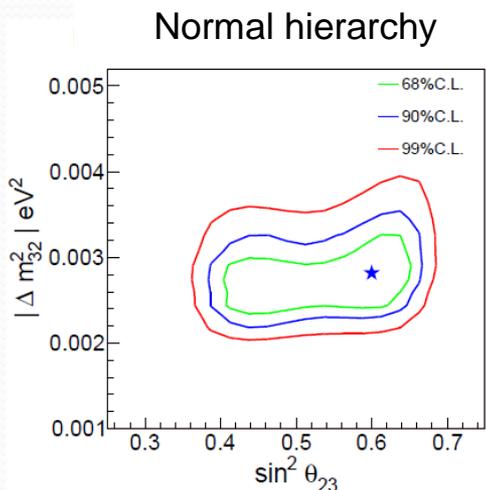
CP phase effect

error bar: Super-K 10 yrs

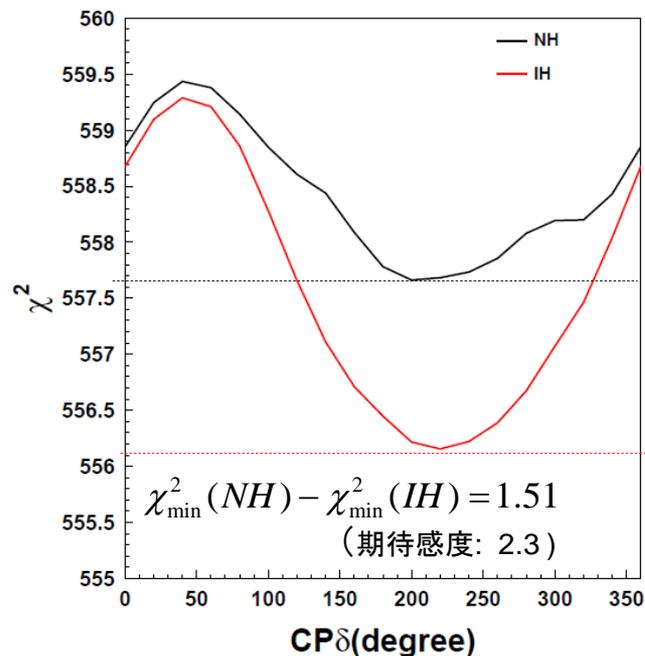


解析結果

P-cos θ 分布を NH/IH, Δm^2_{32} , θ_{23} , δ_{CP} で χ^2 フィット
 $\sin^2\theta_{13}$ は 0.025 に fixed



Normal vs Inverted

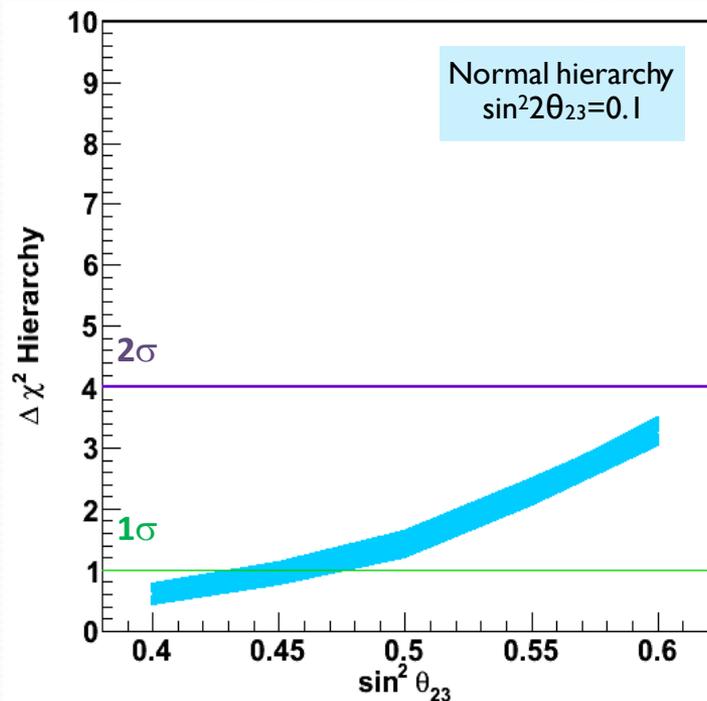


SK data slightly preferred:

- Inverted hierarchy
- $\delta_{CP} \sim 220$ deg
- 2nd octant

今後の期待感度 (Current SK + 5yrs)

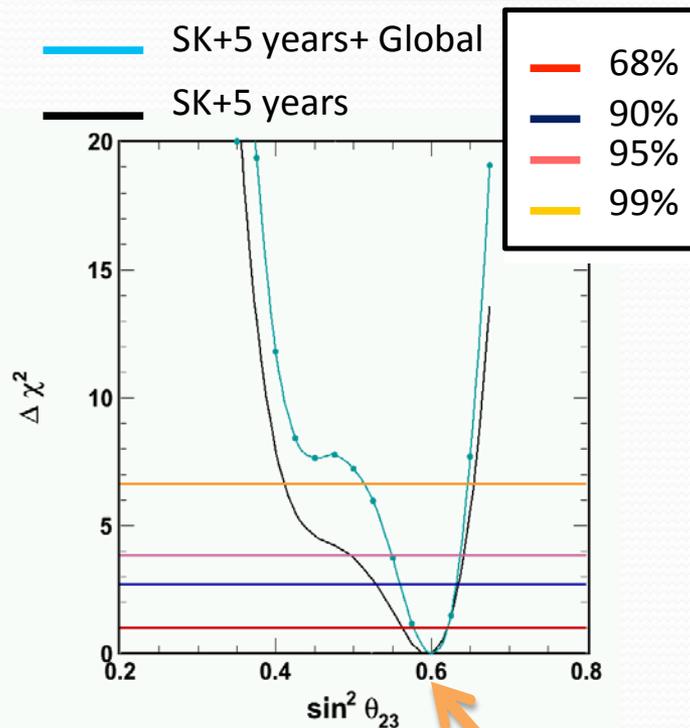
質量階層性の決定感度



- バンド幅はCPδ依存性
- 階層性決定確度~2σ @ $\sin^2\theta_{23}=0.6$

θ_{23} octant決定感度

Normal hierarchy
 $\sin^2 2\theta_{23}=0.1$



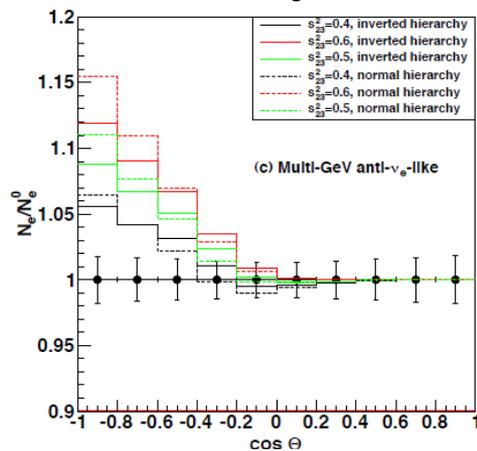
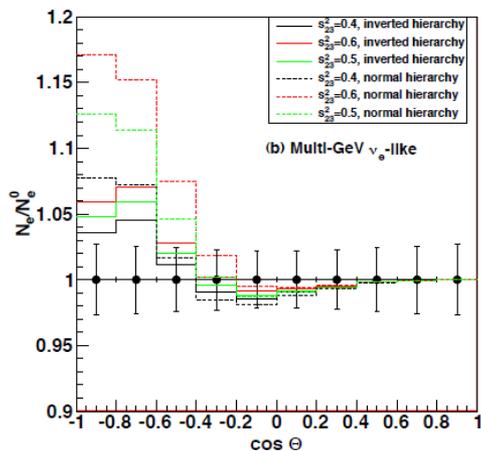
仮定パラメター

- octant決定確度~2σ @ $\sin^2\theta_{23}=0.6$ (SK only)

Hyper-K MH sensitivity

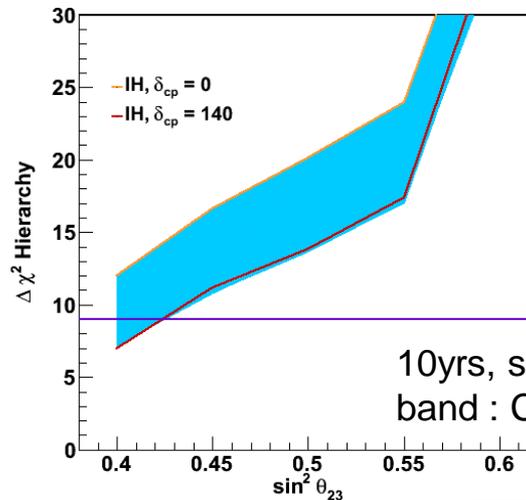
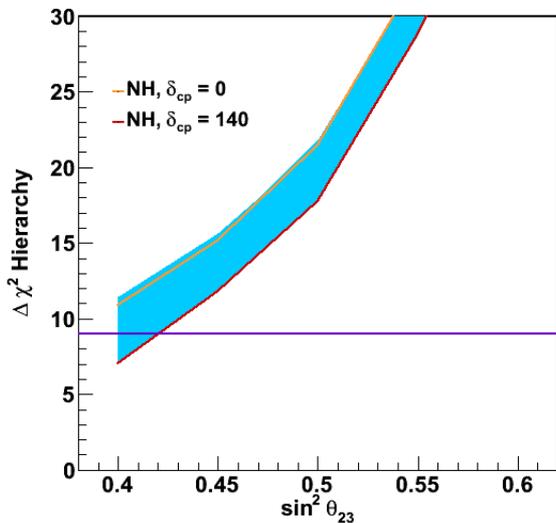
Multi-GeV ν_e -like (1R+MR)

Multi-GeV $\bar{\nu}_e$ -like (1R+MR)



- 10年で3σ以上で決定可能
- 2nd octantでsignificanceが大

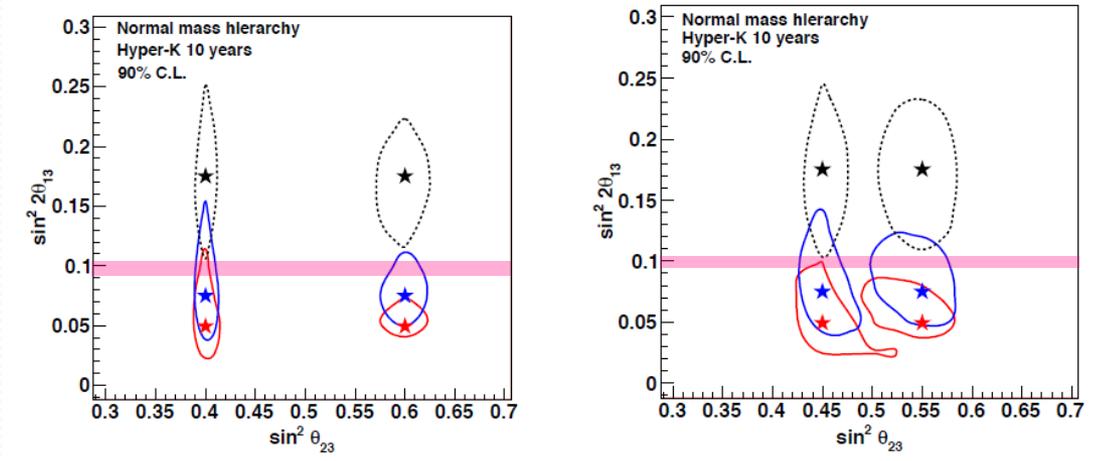
Promising !



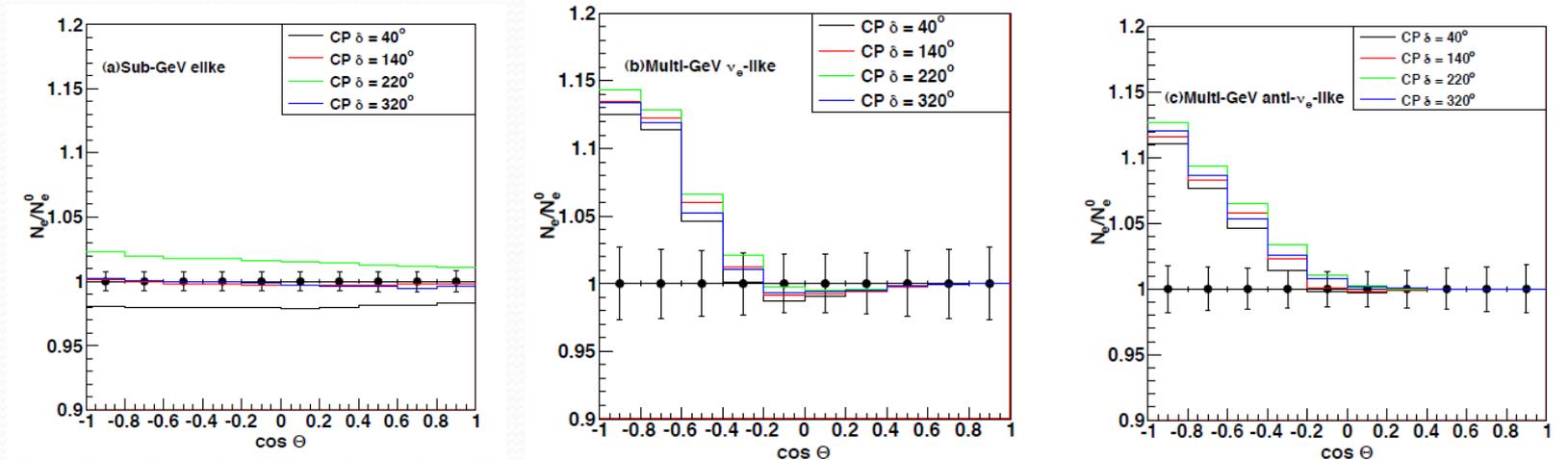
10yrs, $\sin 2(\theta_{13})=0.098$ fixed
band : CP uncertainties

Hyper-K θ_{23} octant, CP sensitivity

θ_{23} Octant



CP



その他のTopics

- Sterile neutrino
- 大気ニュートリノフラックス測定

Sterile Neutrinos

- Searches using SK atmospheric data are independent of sterile Δm^2 and number of sterile neutrinos
 - 3+1 models and 3+N models have same signature in Super-K

PMNS

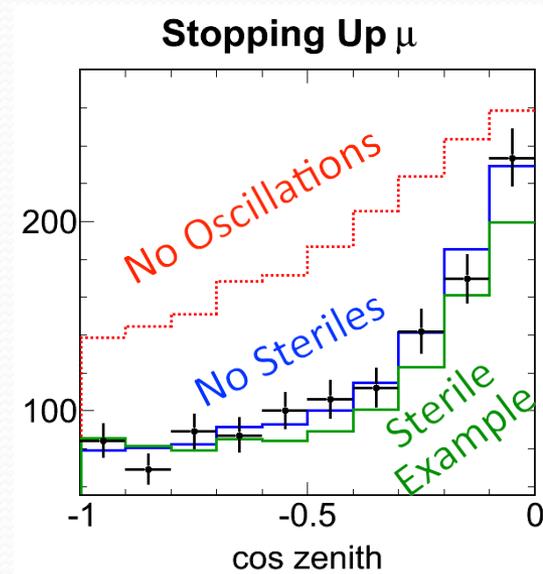
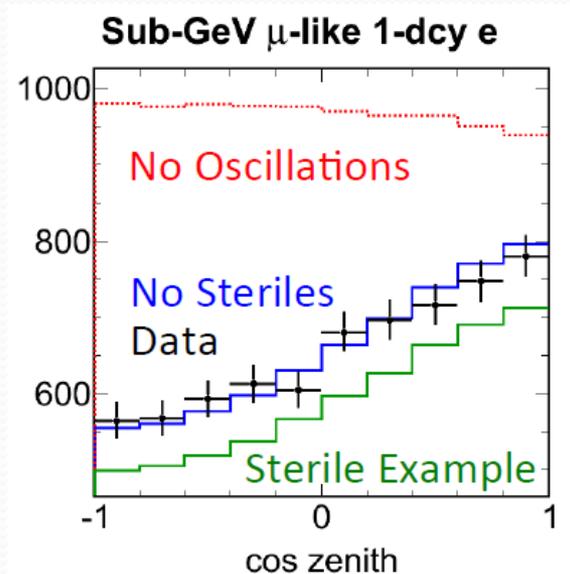
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

(Note: The $U_{\mu4}$ element in the matrix is circled in red in the original image.)

- Atmospheric neutrinos can say something about:

$|U_{\mu4}|^2$: Signature is extra ν_μ disappearance in all μ -like data samples, at all energies and angles

$|U_{\tau4}|^2$: Signature is shape distortion in angular distribution of higher energy subsamples



Sterile Neutrinos

Reactors/Ga $\sim |U_{e4}|^2$

SBL $\nu_{\mu} \rightarrow \nu_e \sim |U_{e4}|^2 |U_{\mu 4}|^2$

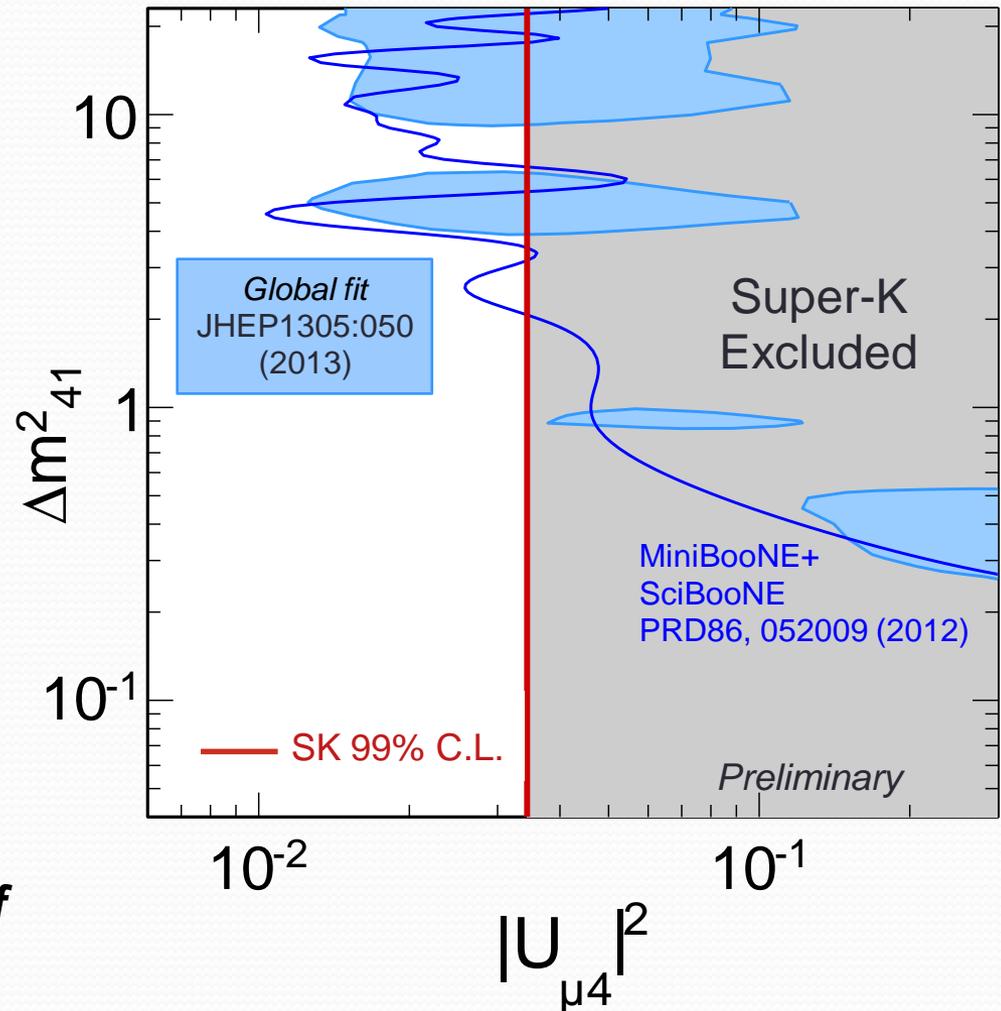
Global fit to both, assuming 3+1,
gives allowed regions in $|U_{\mu 4}|^2$

Fit for $|U_{\mu 4}|^2$ in SK-I+II+III+IV
data (1631 days):

$|U_{\mu 4}|^2 < 0.021$ at 90% C.L.

$|U_{\mu 4}|^2 < 0.031$ at 99% C.L.

***SK excludes a large portion of
the global allowed regions.***



Sterile Neutrinos

Fit for $|U_{\tau 4}|^2$ in SK-I+II+III+IV data (1631 days):

$$|U_{\tau 4}|^2 < 0.22 \text{ at 90\% C.L.}$$

$$|U_{\tau 4}|^2 < 0.27 \text{ at 99\% C.L.}$$

$$|U_{\tau 4}|^2 \approx \frac{P(\mu \rightarrow s)}{P(\mu \rightarrow *)}$$

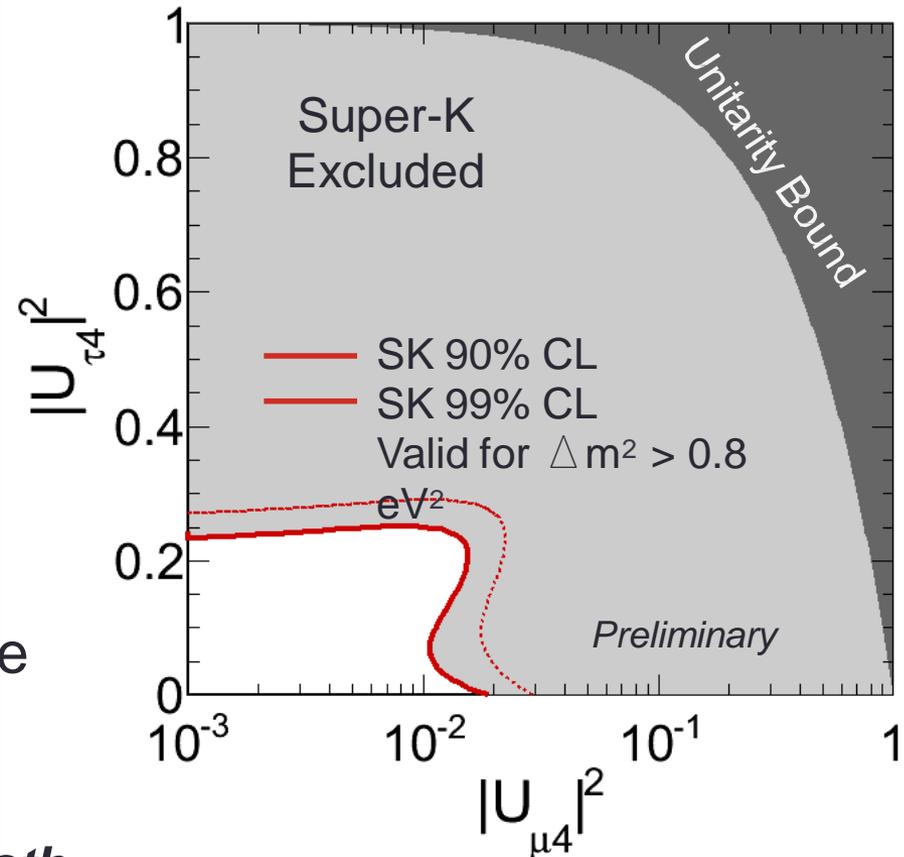
$$\text{as } |U_{\mu 4}|^2 \rightarrow 0$$

Constraint from *not* seeing sterile matter effect

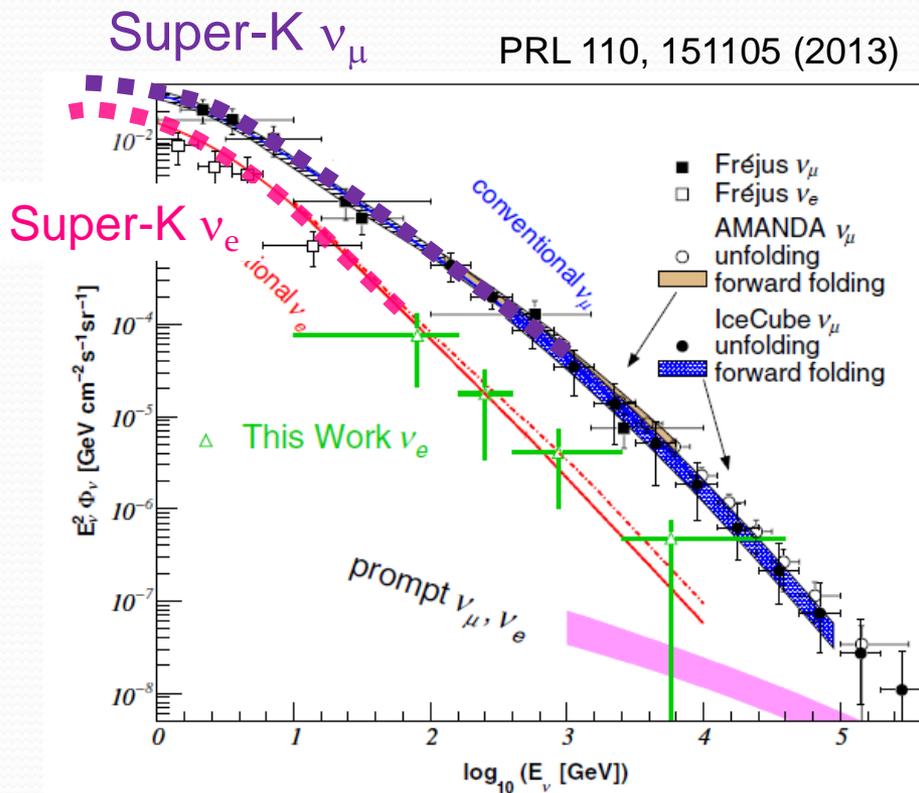
Conclusion from both fits:

Limits from SK are applicable to both 3+1 and 3+N models.

SK sees no evidence of oscillations with sterile neutrinos.



大気ニュートリノフラックス測定



- 本新学術研究による共同研究
A03(大気ニュートリノ)
A04(宇宙ニュートリノ)
- Super-KとIceCubeによる広いエネルギー領域(sub-GeV $\sim 10^{14}$ eV)の測定データ
- Super-K: フラックス計算でのハドロン生成による不定性に制限
- IceCube: PeV領域の宇宙ニュートリノ測定のバックグラウンド系統誤差の縮小
- 共同研究によりさらなる研究課題発掘を期待

Summary

- 有限の θ_{13} による $\nu_{\mu} \rightarrow \nu_e$ 振動、物質効果により、大気ニュートリノで Mass hierarchy 決定の可能性
- 統計的 ν / 反 ν 識別を行い、MH感度を向上させた
- 今後、解析手法の改良によりさらなる感度向上を目指すと共に、Hyper-K計画を進める
- Sterile: SKで兆候なし。 $|U_{\mu 4}|^2$, $|U_{\tau 4}|^2$ について制限
- 大気ニュートリノフラックス測定において、新学術グループ内の共同研究を進めている