Super-Kamiokande

Kamioka Observatory, Institute for Cosmic Ray Research, U of Tokyo, and
Kamioka Satellite, Institute for the Mathematics and Physics of the Universe, U of Tokyo

Masato Shiozawa

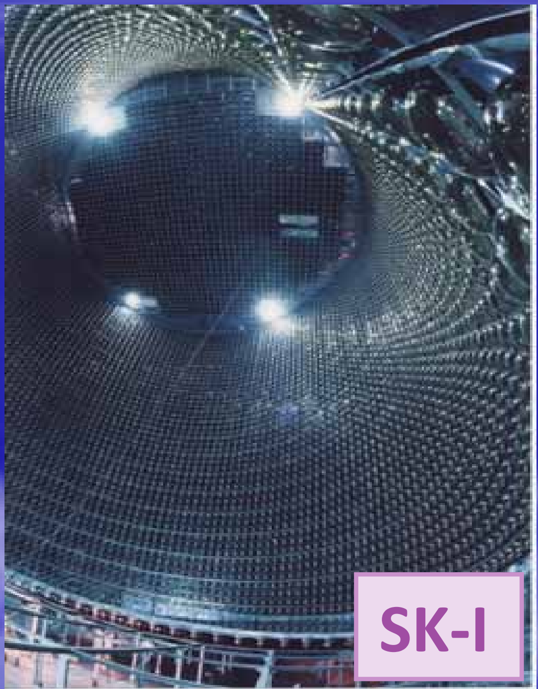
for the Super-Kamiokande collaboration

Super-Kamiokande History

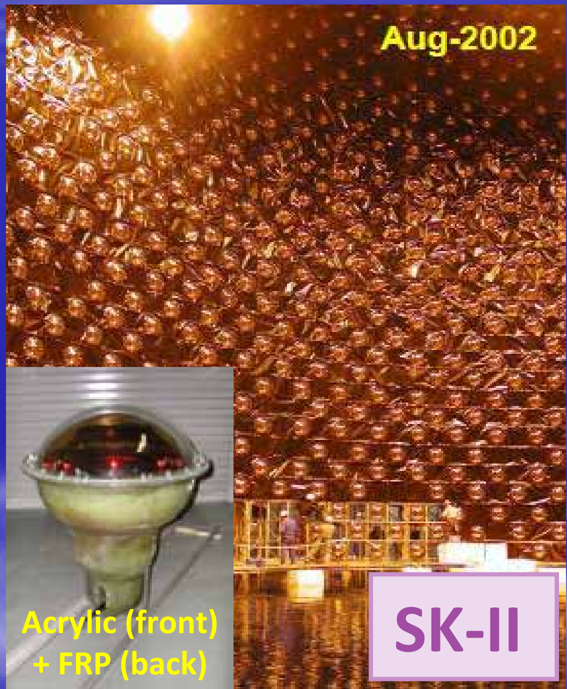
inner detector mass: 32kton   fiducial mass: 22.5kton

1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009

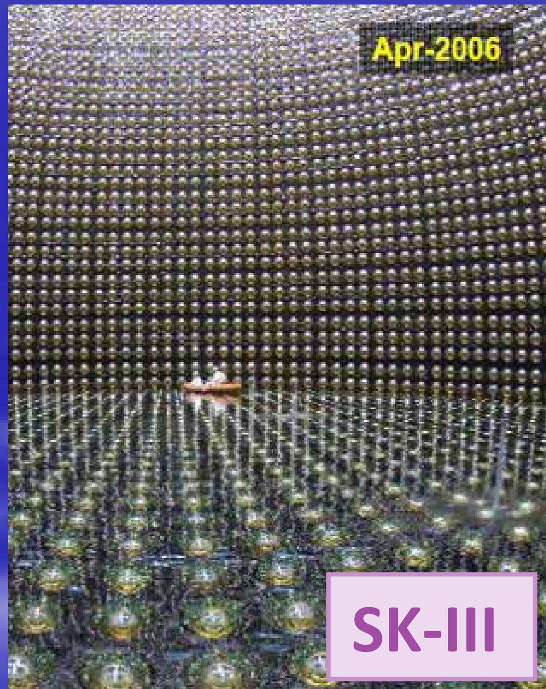
SK-I   SK-II   SK-III   SK-IV



11146 ID PMTs
(40% coverage)



5182 ID PMTs
(19% coverage)



11129 ID PMTs
(40% coverage)

Electronics
Upgrade

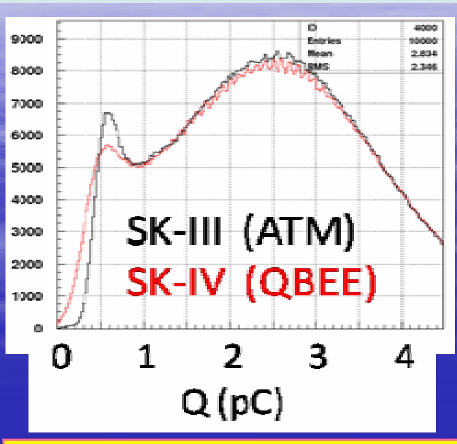
Energy Threshold (total electron energy)

SK-I	SK-II	SK-III	SK-IV
5.0 MeV	**7.0 MeV**	**4.5 MeV** work in progress	**< 4.0 MeV** target

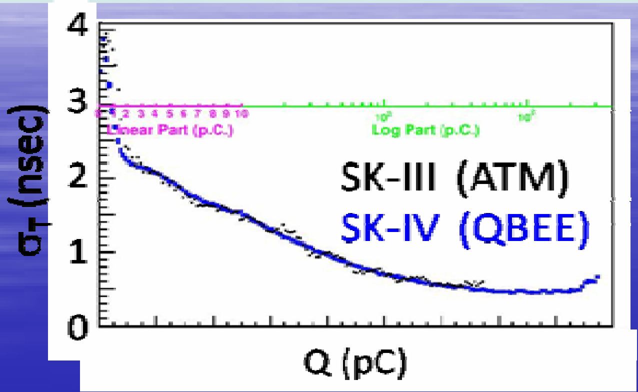
SK-IV commissioning since Sep.-2008

detector calibrations and detector simulation tuning

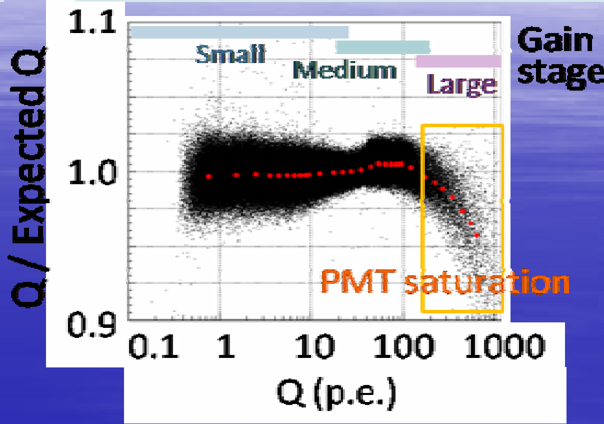
Single p.e. distribution (by Ni)



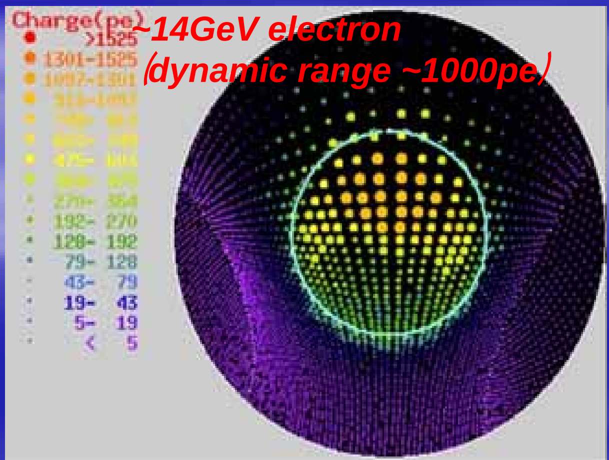
Timing resolution (by Laser)



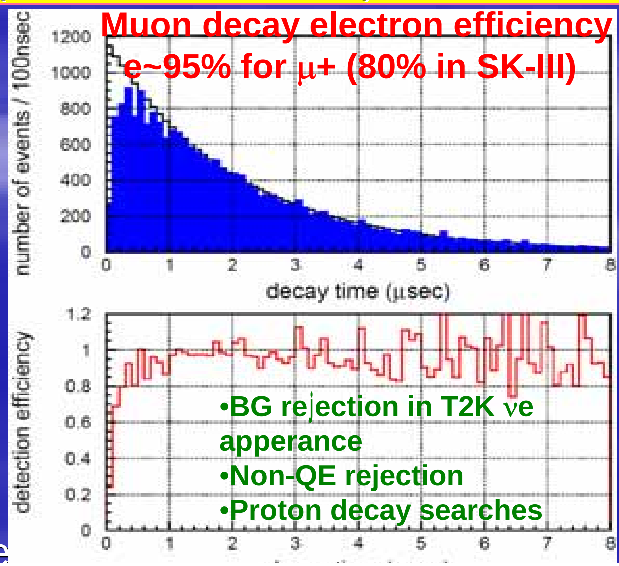
Charge linearity (by Laser)

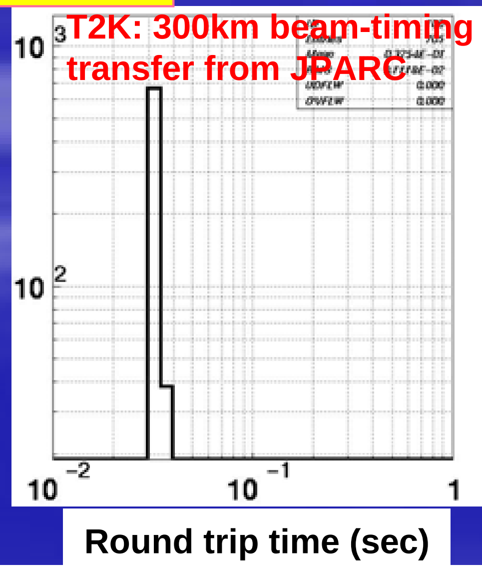


- Aiming to expand observation windows
  - Lower energy (<5MeV) solar ν and high energy (>10GeV) atmospheric ν
  - Better efficiency of muon decay electrons
  - Nearby supernova (~0.4kpc, 10,000,000events)
  - Neutron tagging from anti electron neutrino interactions
  - Observe accelerator ν (T2K from this winter)

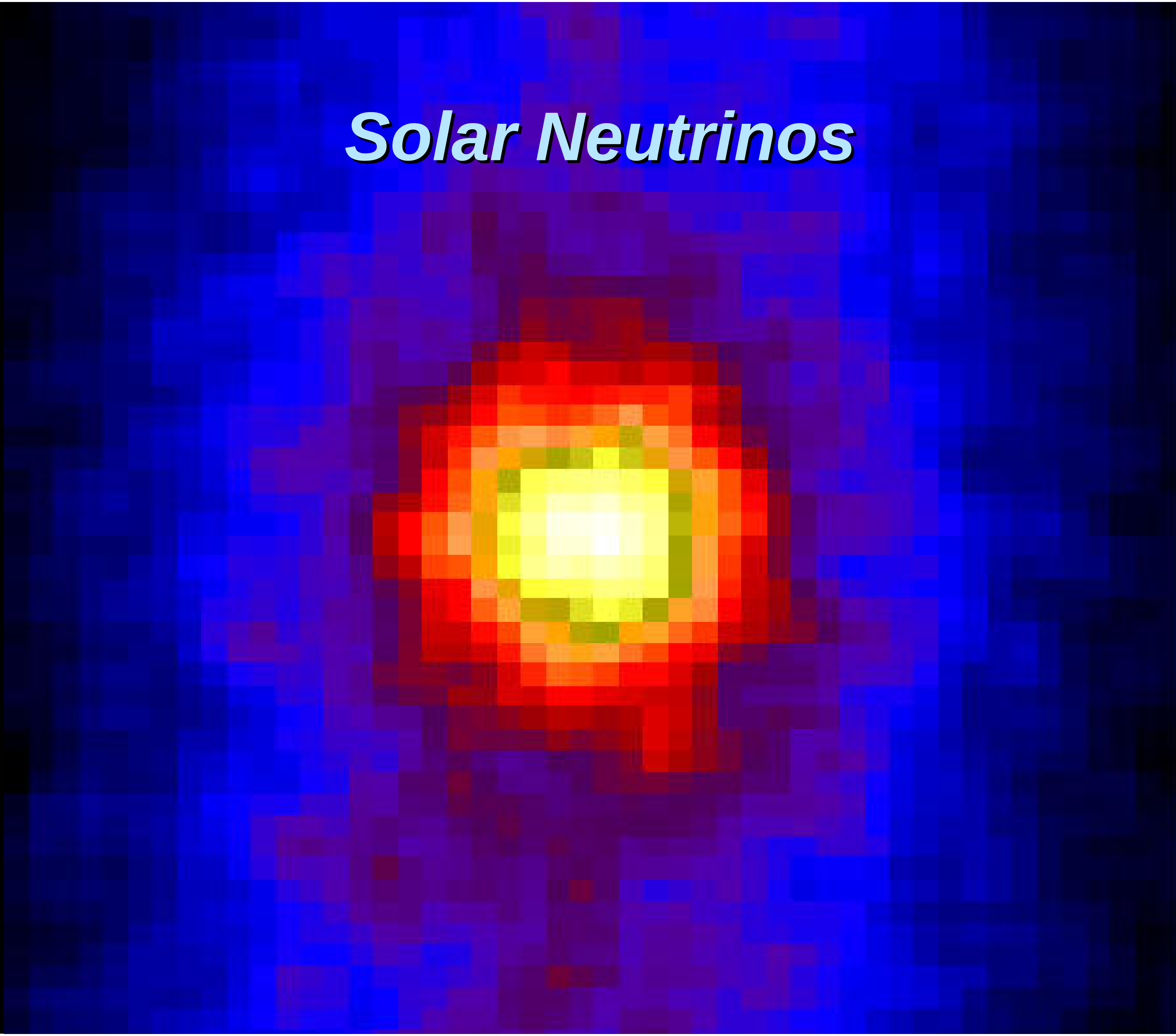


νe apperance (θ13) in atm ν



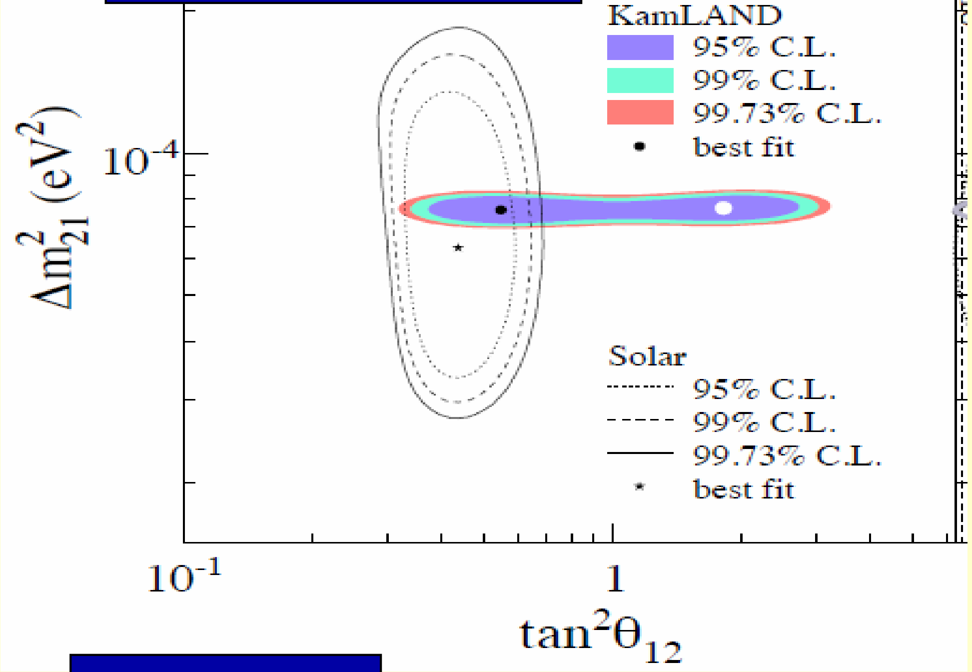


Solar Neutrinos

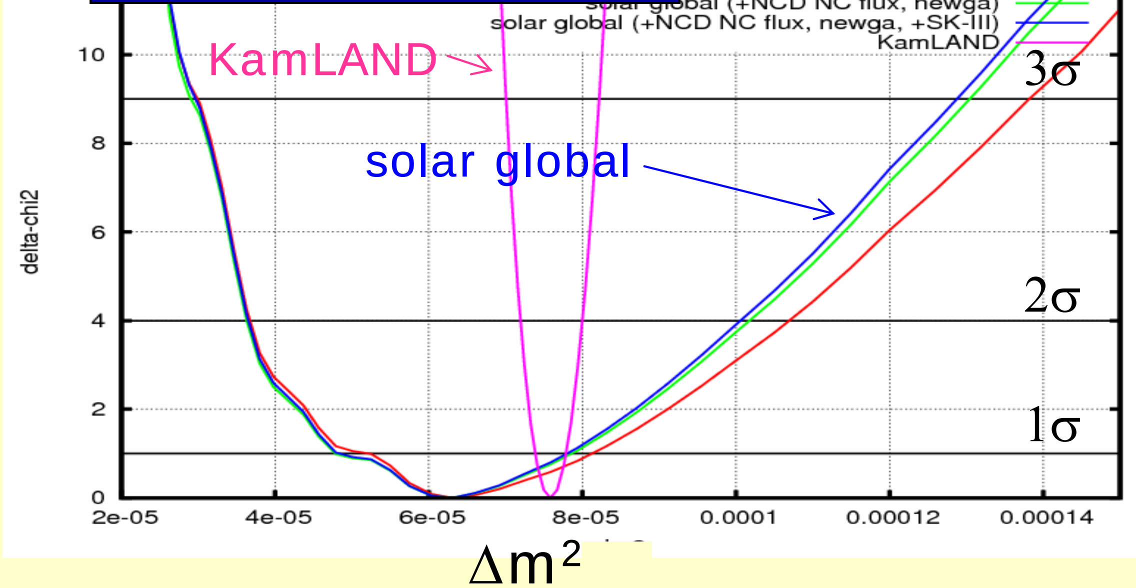


Solar global and KamLAND

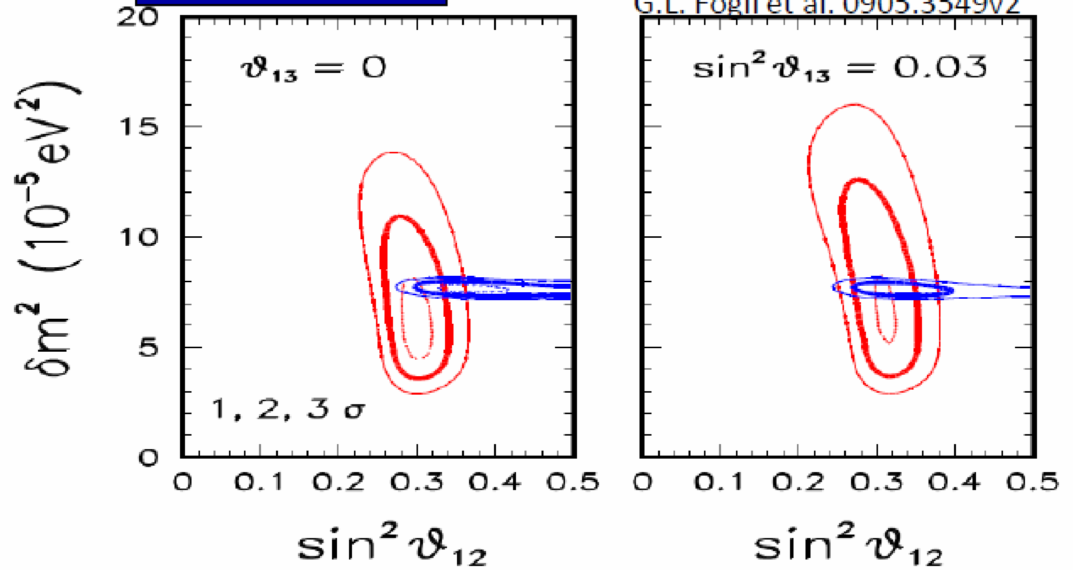
KamLAND paper

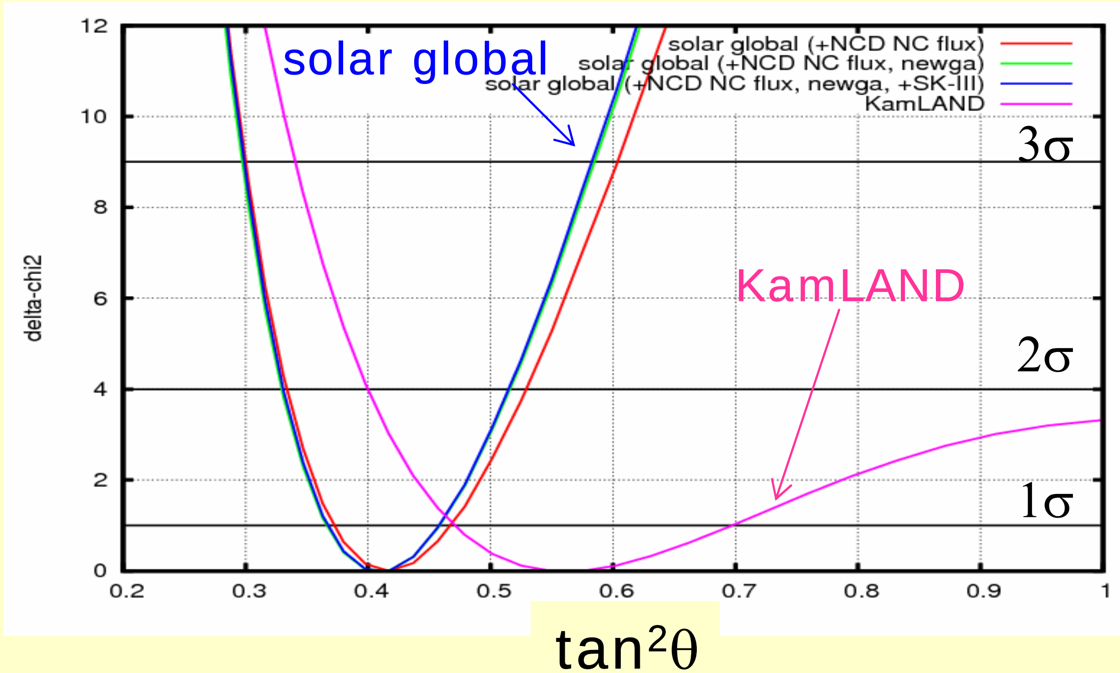


Latest global analysis

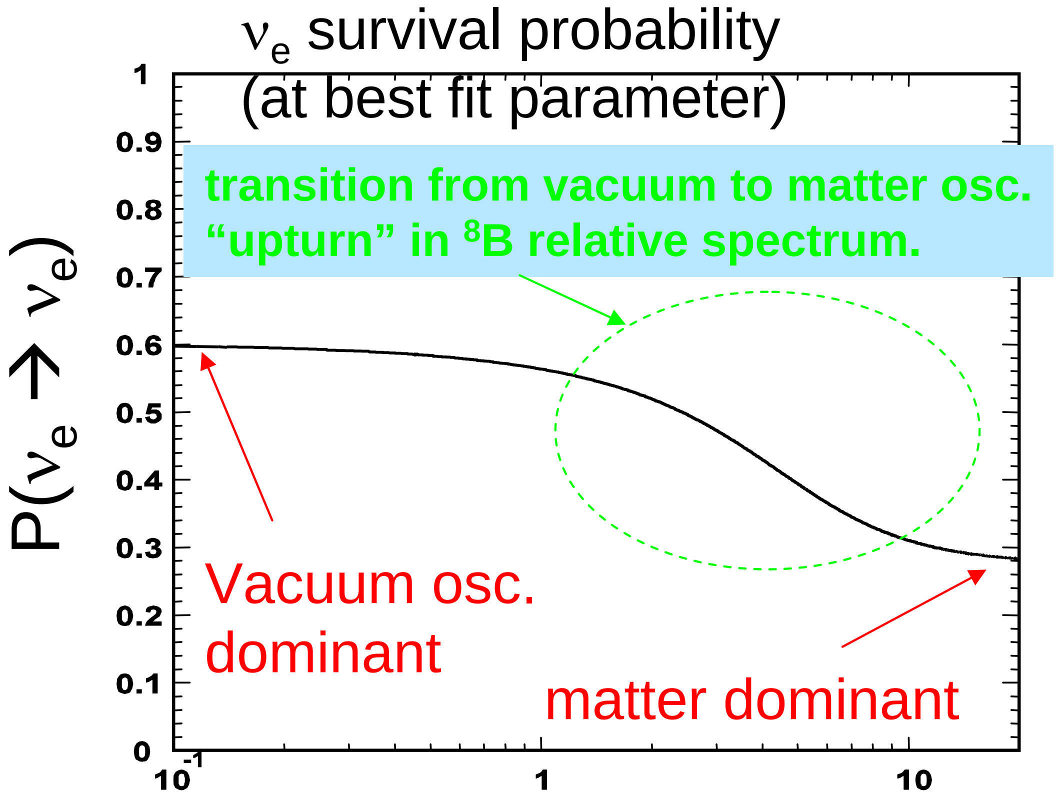


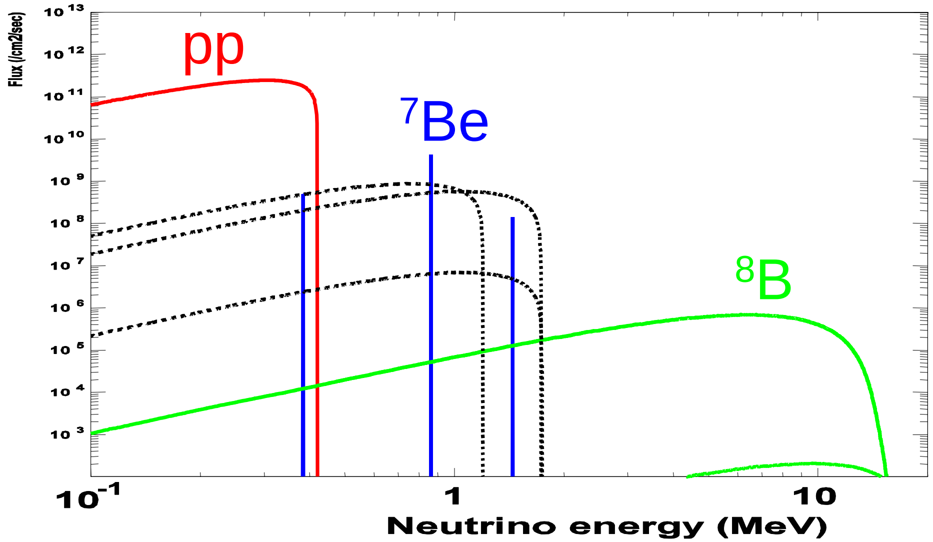
Fogli et al.

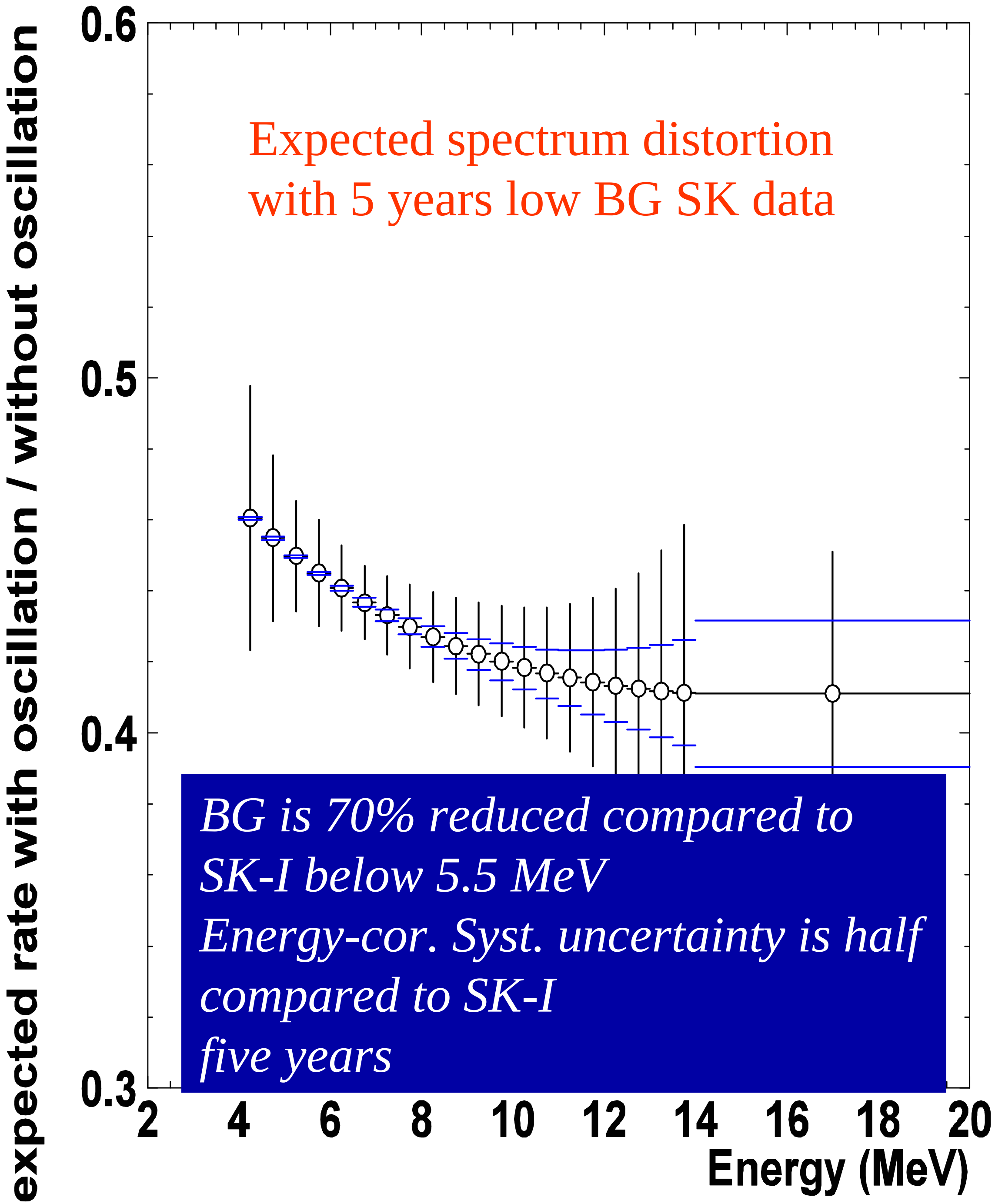




Solar Neutrino Future Prospects in SK

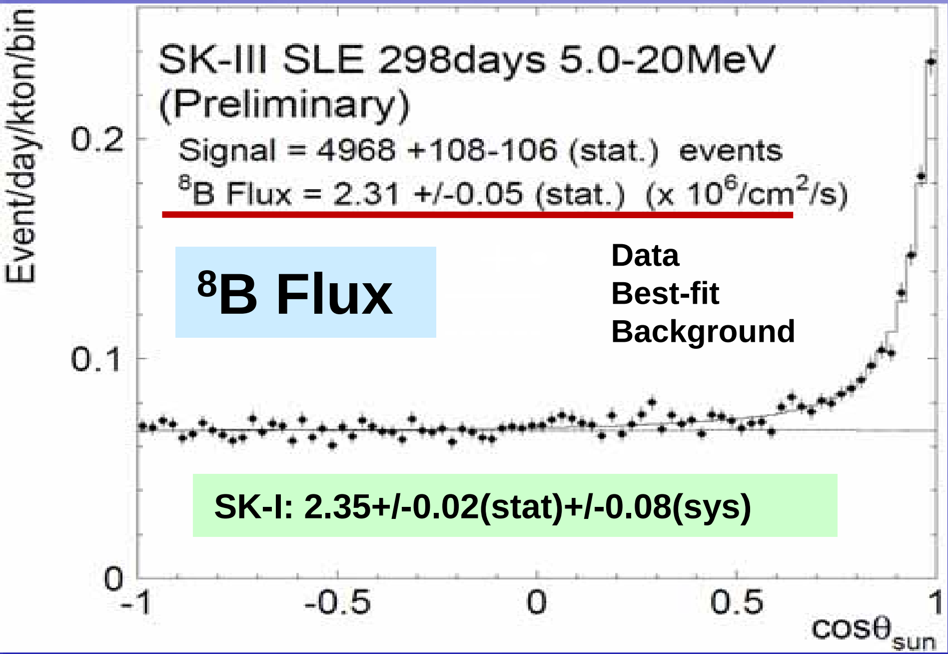


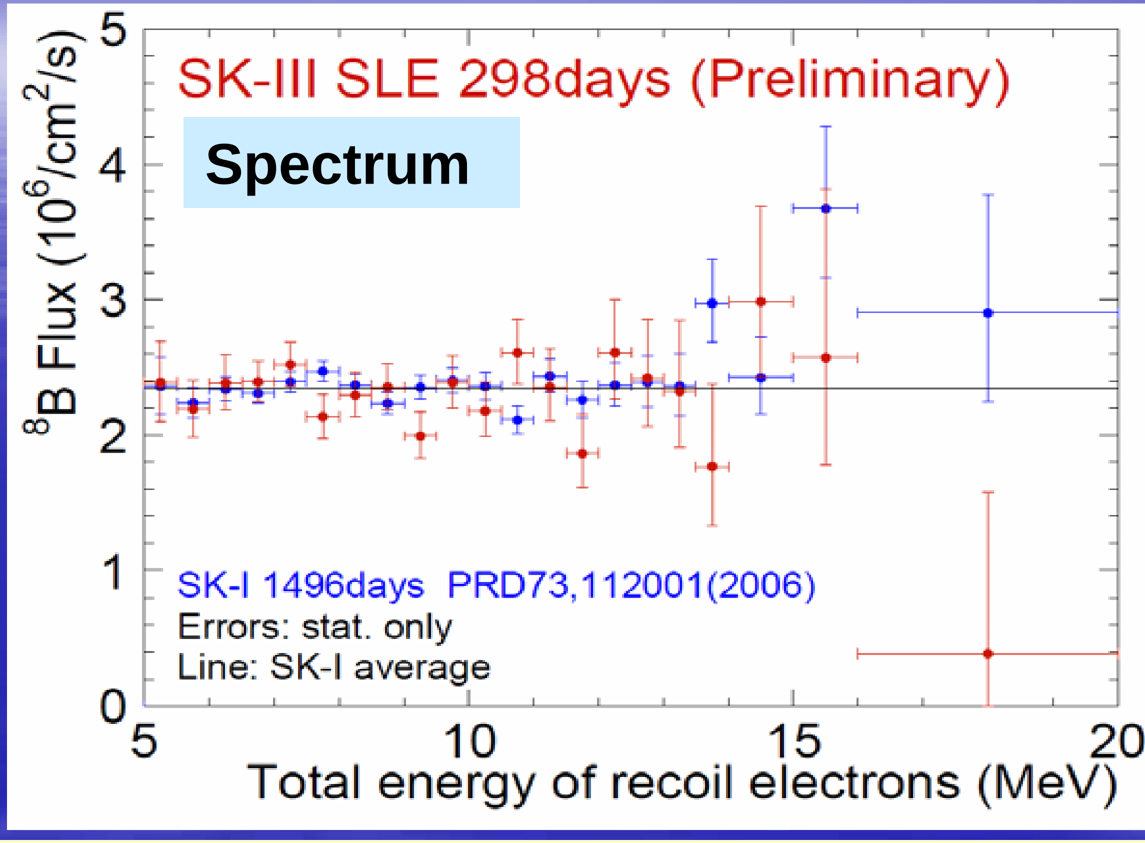


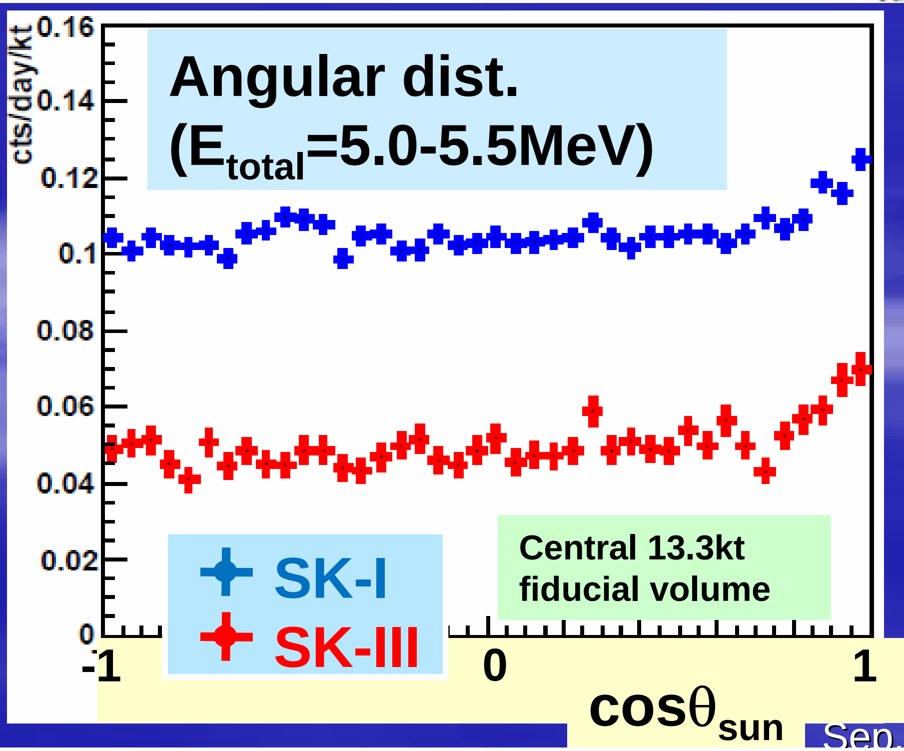


BG is 70% reduced compared to SK-I below 5.5 MeV
Energy-cor. Syst. uncertainty is half compared to SK-I
five years

recovered original threshold (SK-III)

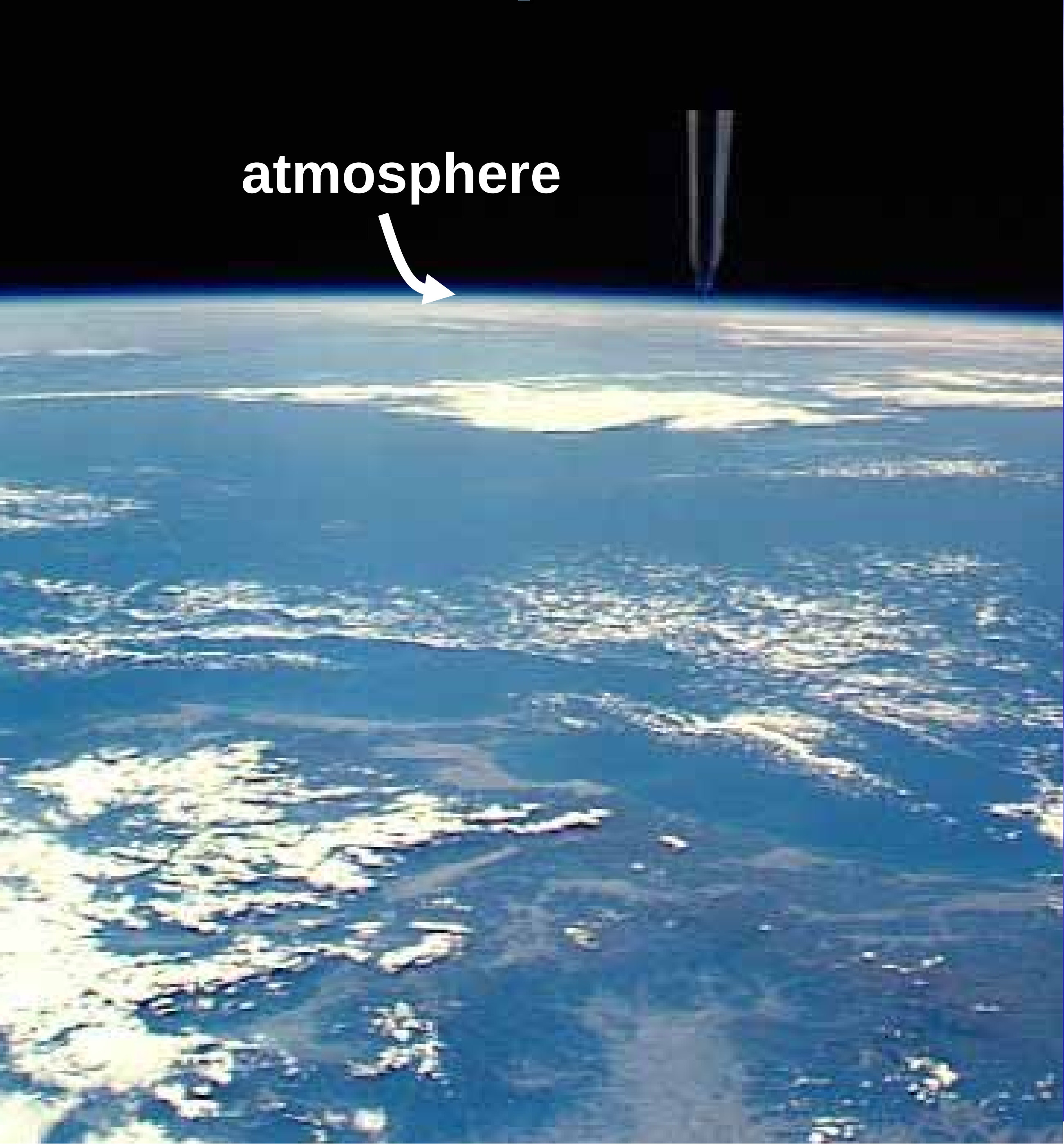


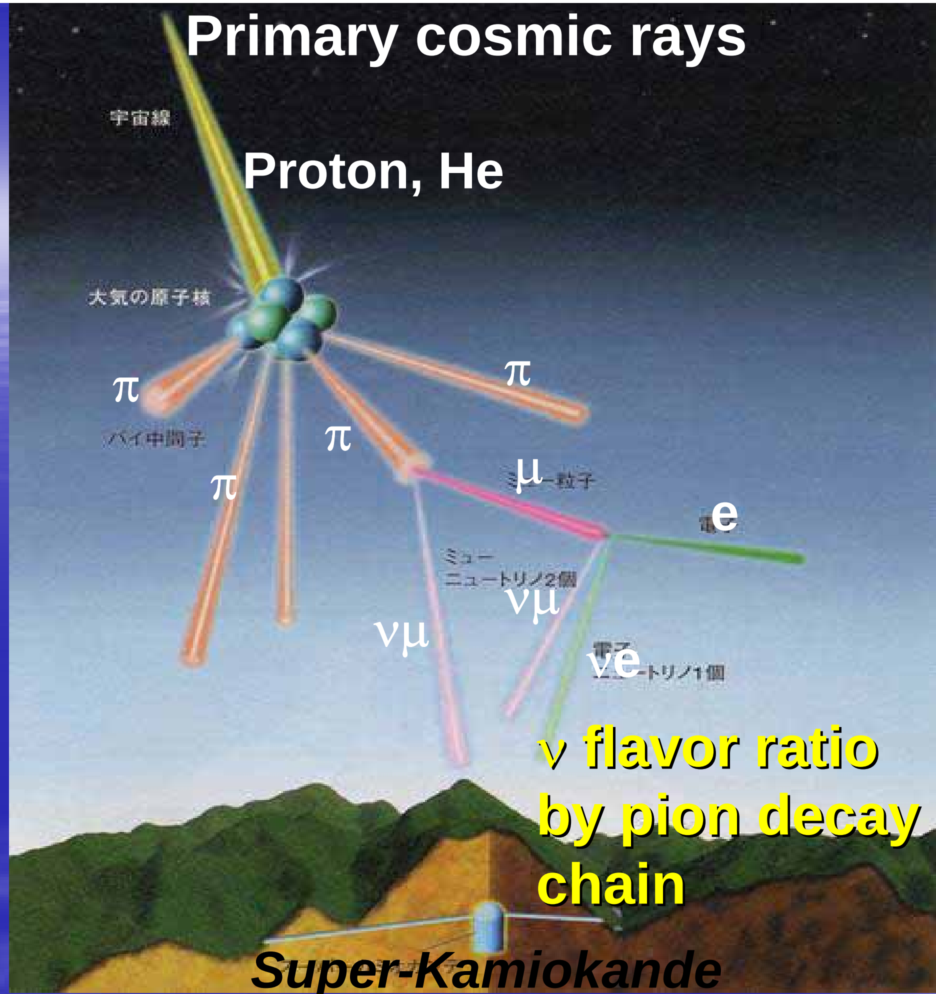


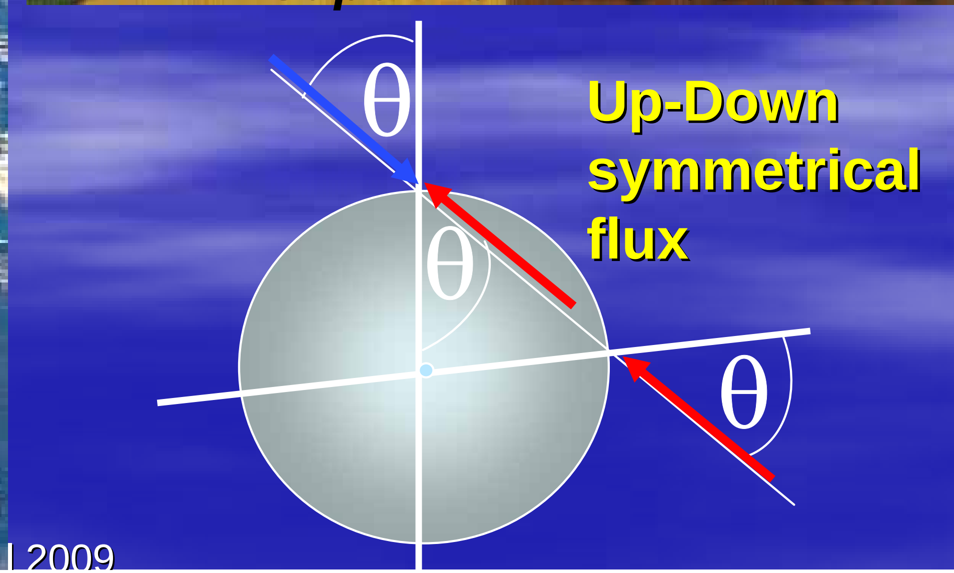


- We tuned reconstruction program and analysis programs. (almost done)
- Better angular resolution: 10% better than SK-I
- Lower BG rate than before is obtained in SK-III low energy regions

Atmospheric ν's

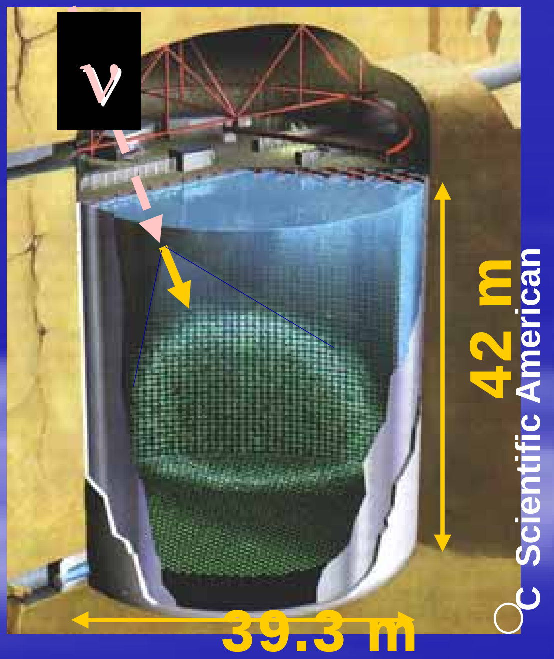


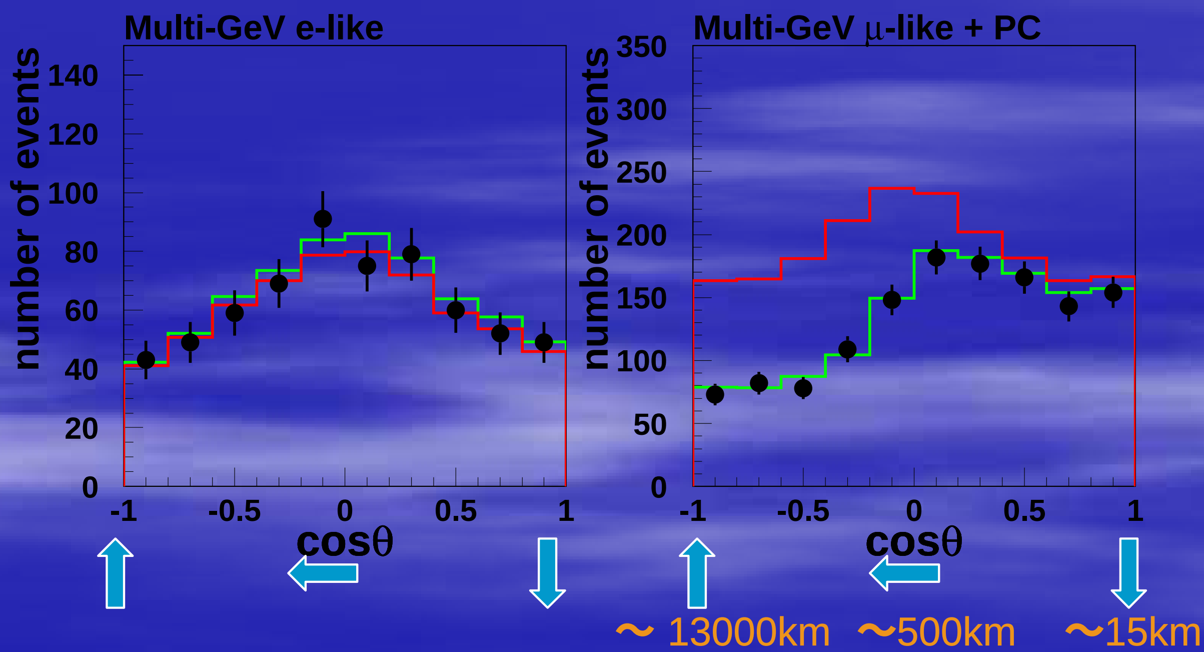




discovery of neutrino oscillation

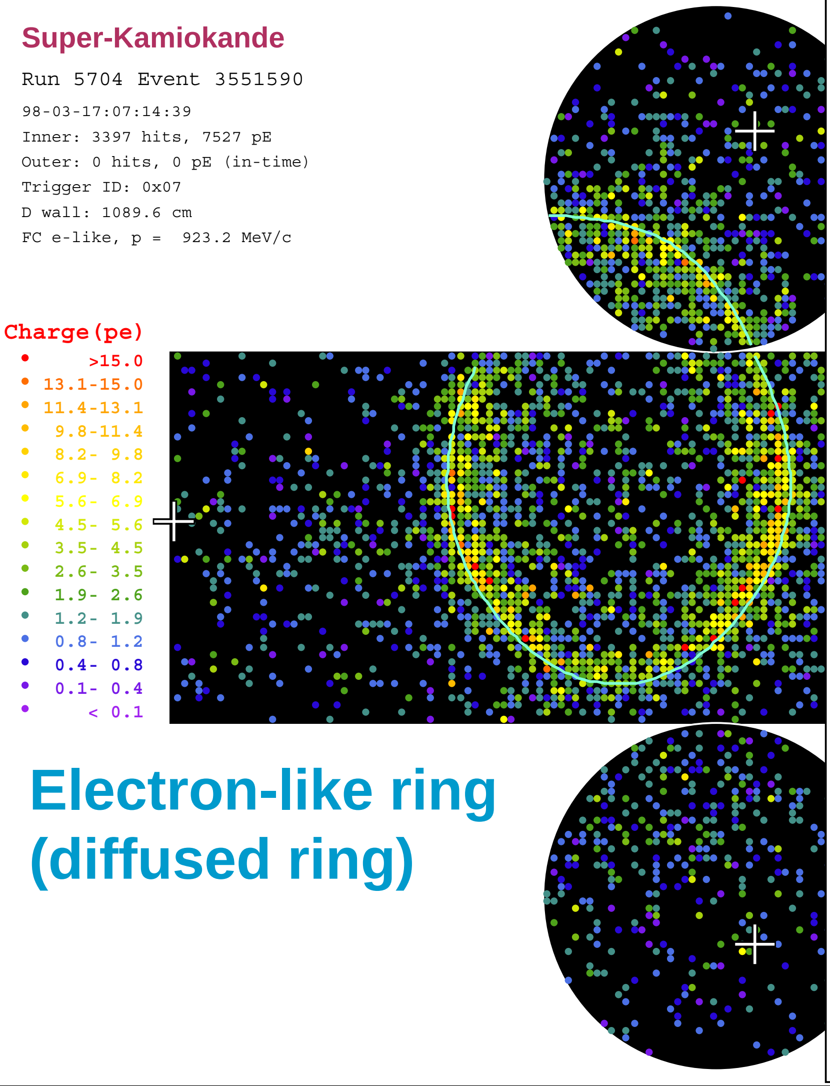
- 1998, Atmospheric neutrino observation at Super-Kamiokande
  - deficit of upward going muon (neutrinos)
  - electron (neutrino) as is expected
  - consistent with pure $\nu\mu \rightarrow \nu\tau$
    - $\sin^2\theta_{23} > 0.82$, $5\times10^{-4} < \Delta m^2_{23} < 6\times10^{-3}$ eV^2



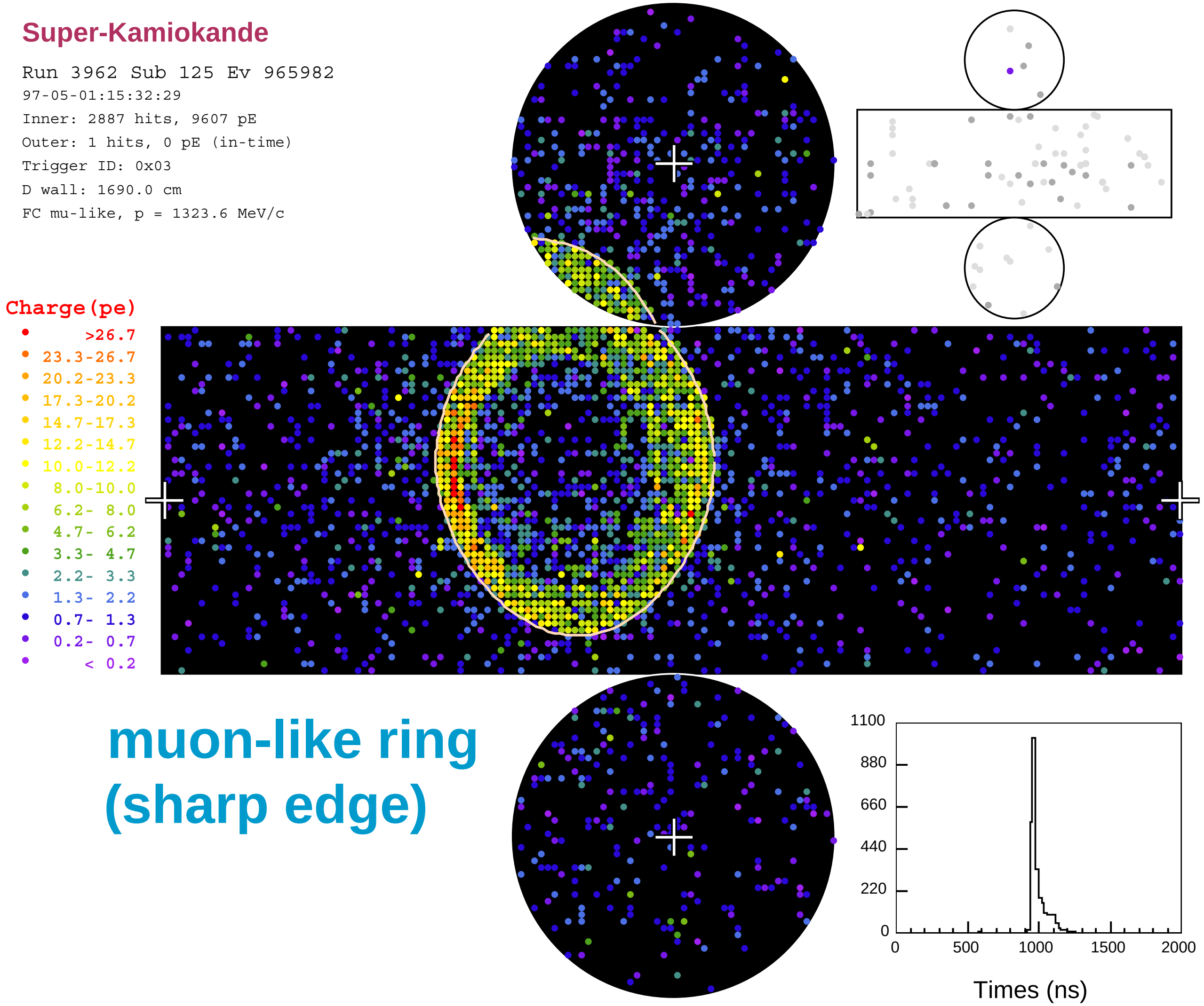


NOW: More than 28,000 events have been recorded.
Provide evidence and still provide largest statistics

Particle ID and the number of Cherenkov rings



Electron-like ring (diffused ring)

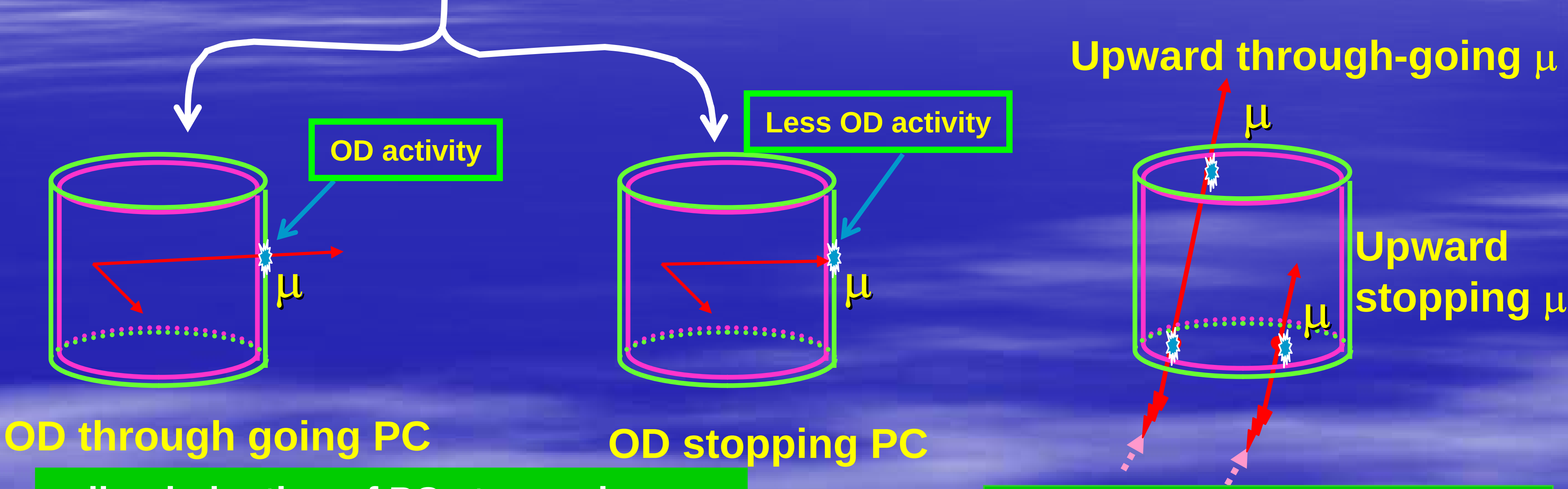


muon-like ring (sharp edge)

Event category 2 (PC and upμ)

Particle ID and # of Cherenkov rings are not used.

Partially Contained (PC) | Upward μ

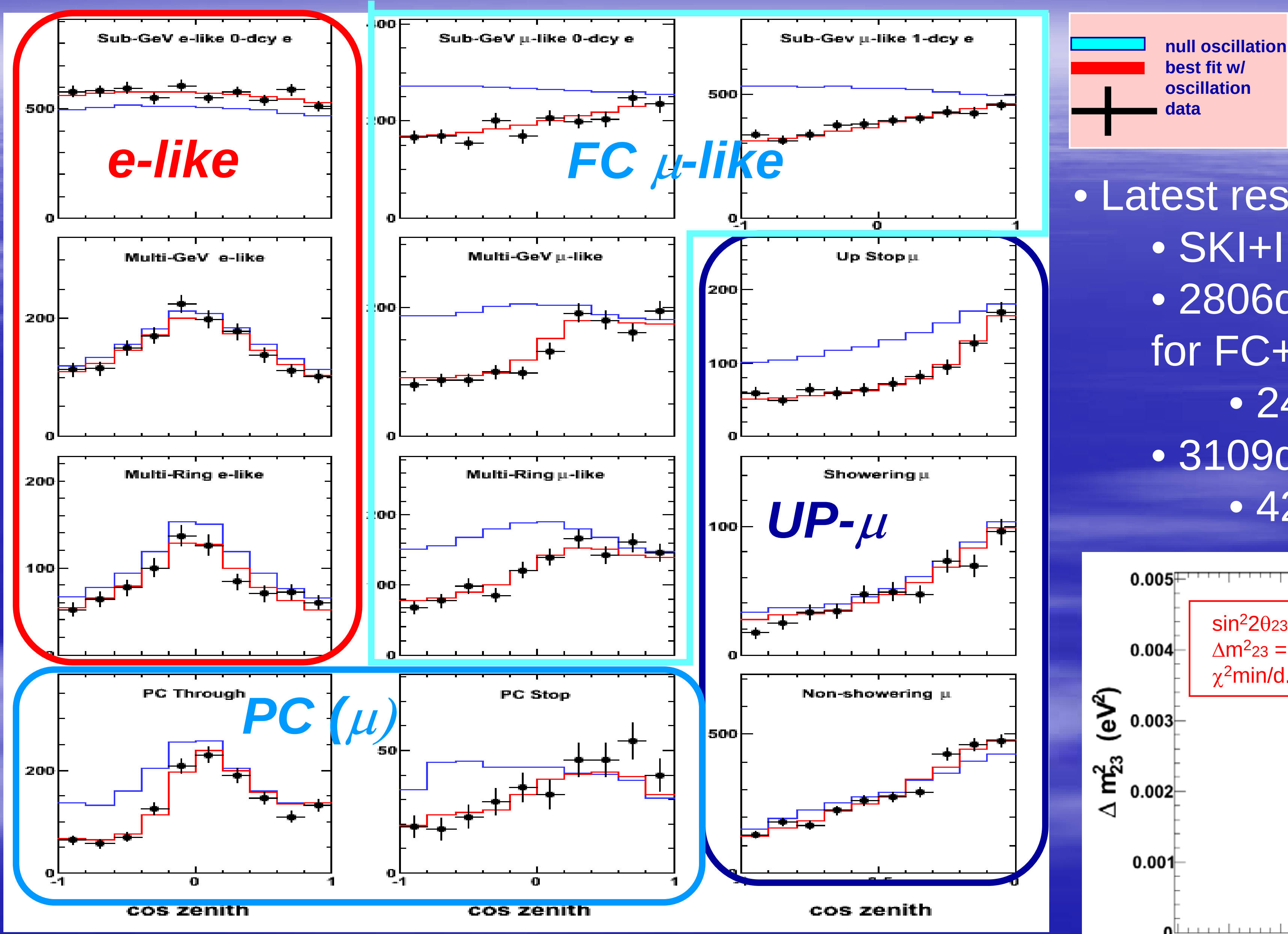


- discrimination of PC stop and through by deposited energy in the outer detector
- PC stop is a kind of FC events and energy can be reconstructed.

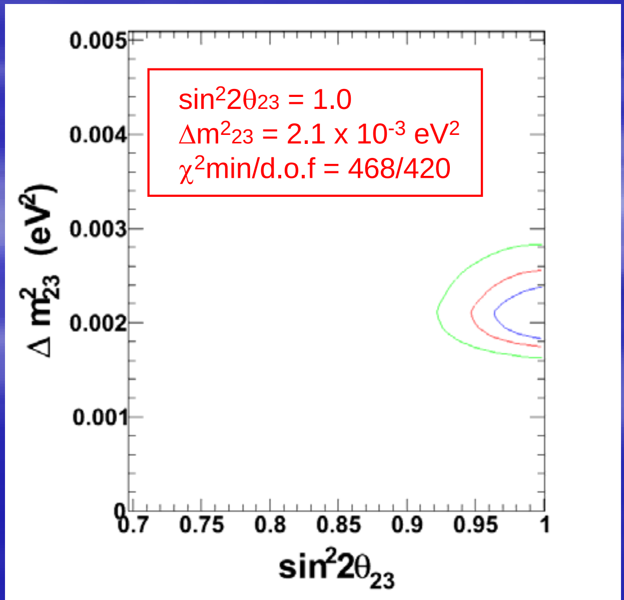
- target is rock (water for FC and PC)
- different energy scale and detection technique

2 flavor oscillation analysis

zenith angle (SK-I +II+III combined)

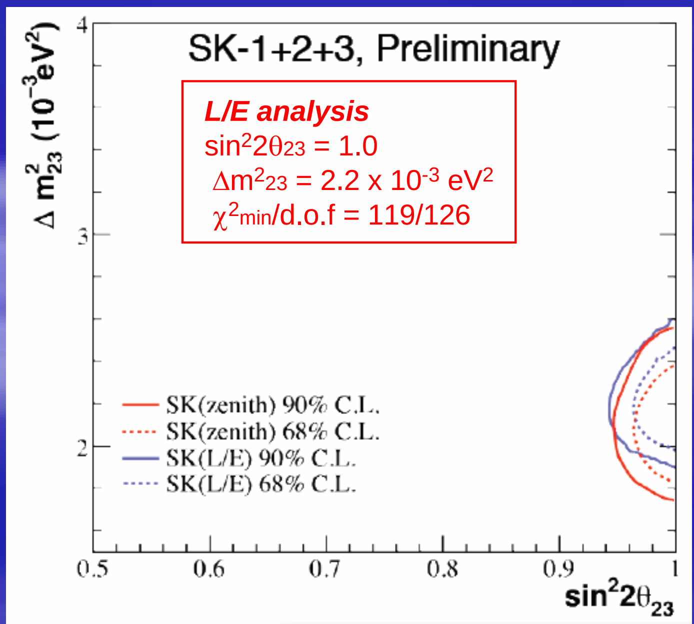


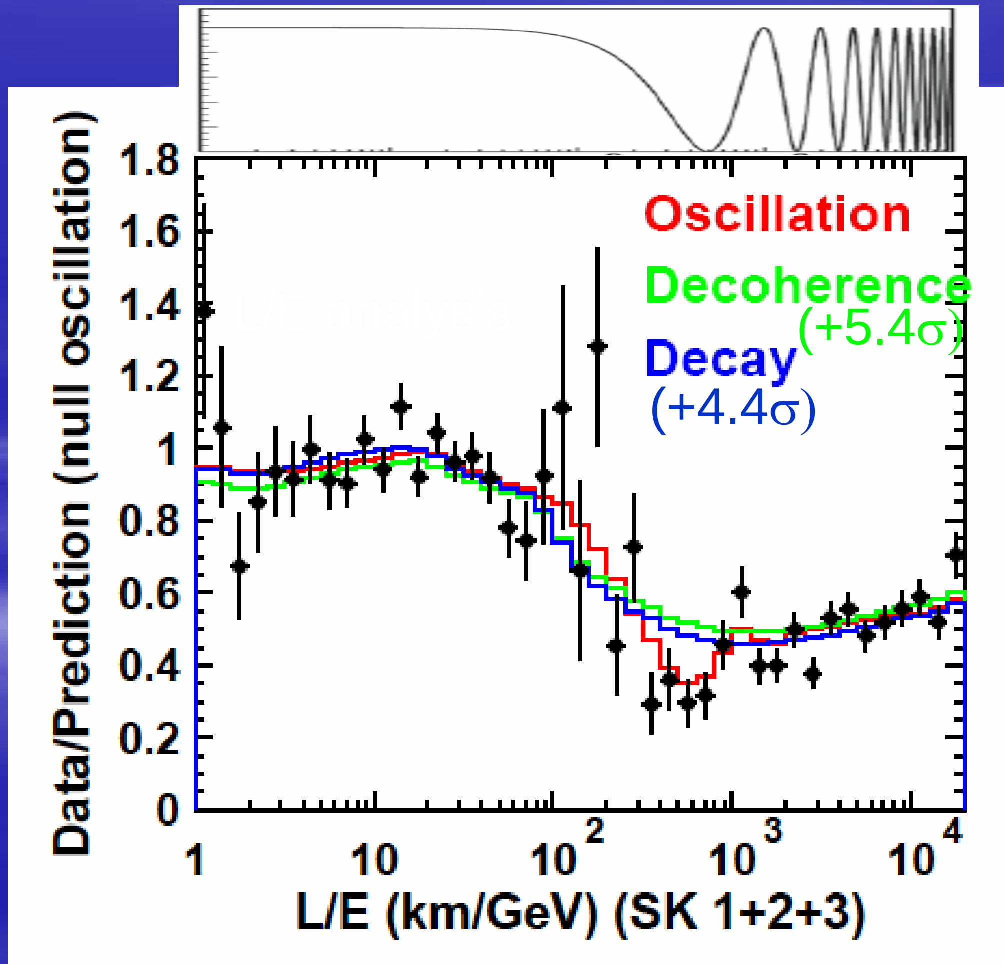
- Latest results
  - SKI+II+III combined
  - 2806days (173ktyr) for FC+PC
    - 24841 events
  - 3109days for UP-μ
    - 4238 events



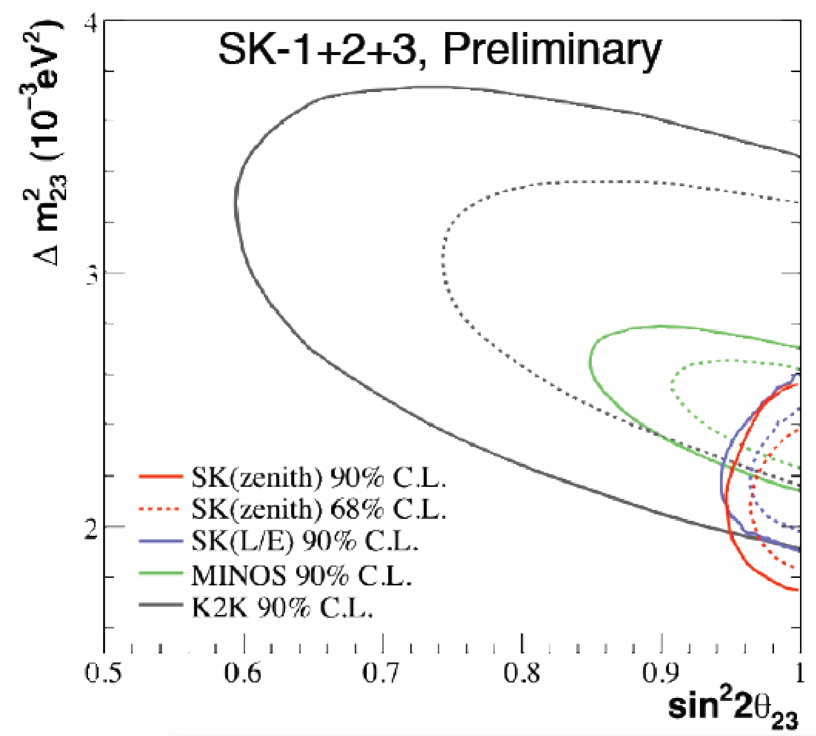
L/E analysis (SK-I +II+III)

- Zenith analysis
  - Use almost all sub-samples, binned by zenith angle
- L/E analysis
  - Select events with good L/E (Δ(L/E)<70%)
  - Binned by L/E
    - Position of the dip $(L/E)^{-1} \sim \Delta m^2$
    - Aim to directly determine Δm^2
    - *Do see the dip at L/E~500*





Compilation of measurements



- $\Delta m^2_{23} = 2.11^{+0.11}_{-0.19} \times 10^{-3}$ eV^2 (68%($\Delta\chi^2$=1)) (atm ν: zenith)
- $\Delta m^2_{23} = 2.19^{+0.14}_{-0.13} \times 10^{-3}$ eV^2 (68%) (atm ν: L/E)
- $\Delta m^2_{23} = 2.43^{+0.13}_{-0.13} \times 10^{-3}$ eV^2 (68%) (MINOS, PRL101(08))

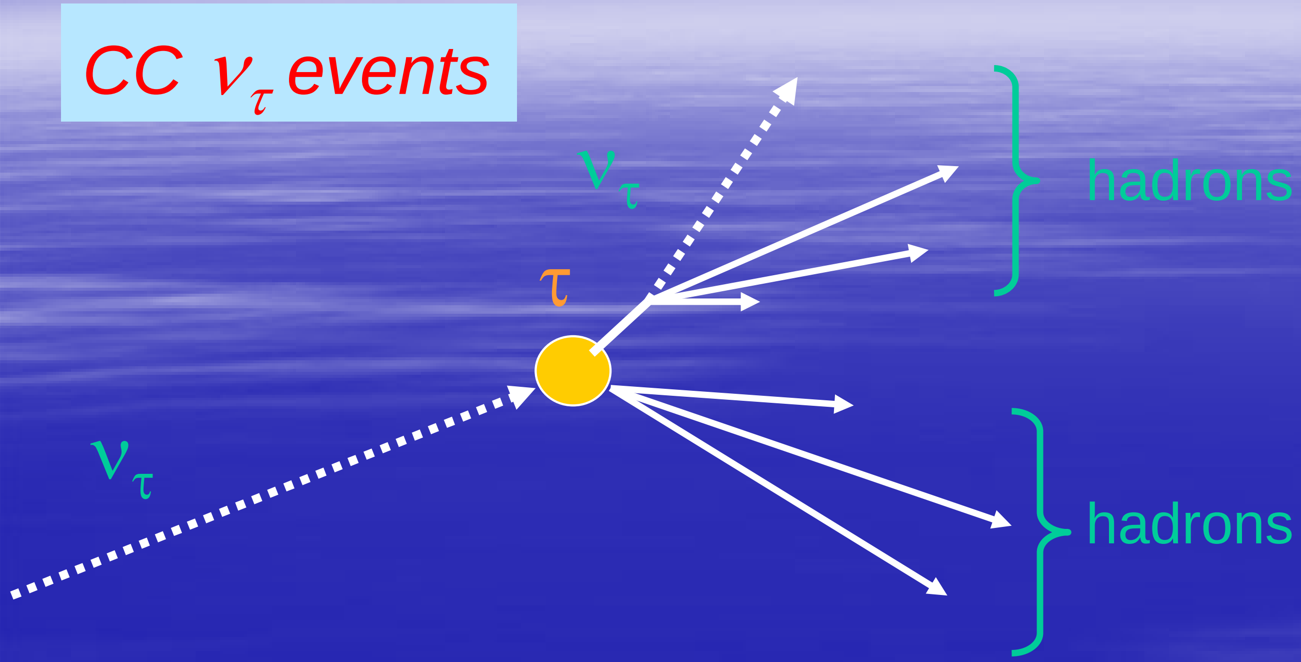
→ Δm^2: comparable accuracies

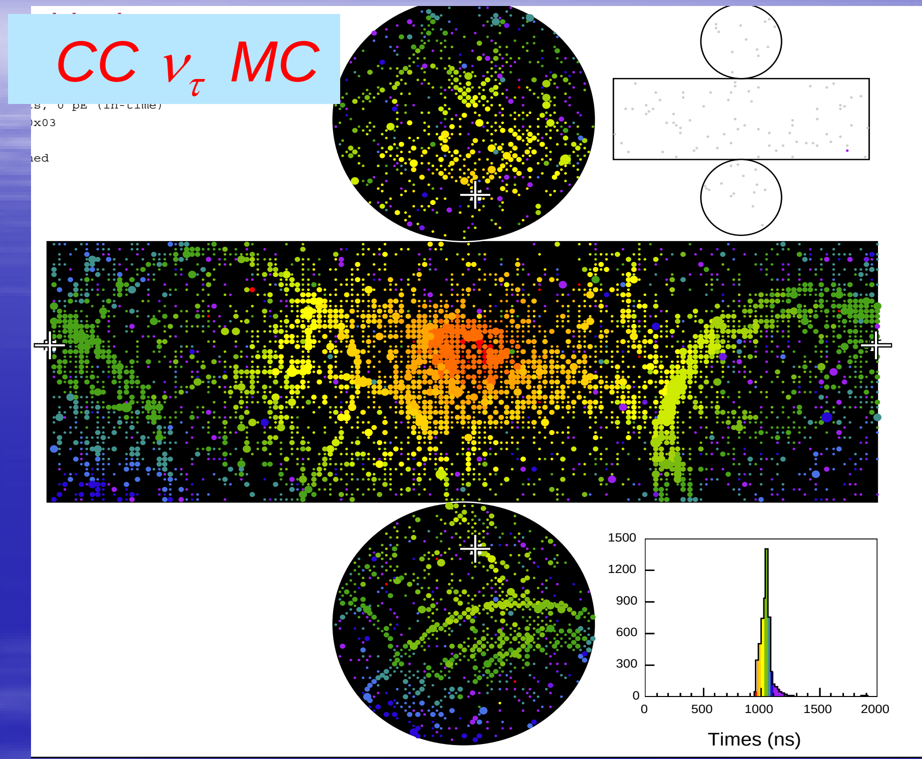
- $\sin^2 2\theta > 0.96$ (90%($\Delta\chi^2$=2.7)) (atm ν)
- $\sin^2 2\theta > 0.90$ (90%) (MINOS)

→ $\sin^2 2\theta$: better by atm ν

- future: - atm $\nu \propto$ 1/sqrt(statistics)
  - LBLE will be probably better

Search for CC ν_τ events





<u>Signature of CC ν_τ events</u>

- Higher multiplicity of Cherenkov rings
- More $\mu \rightarrow e$ decay signals
- Spherical event pattern

Likelihood and neural network analysis

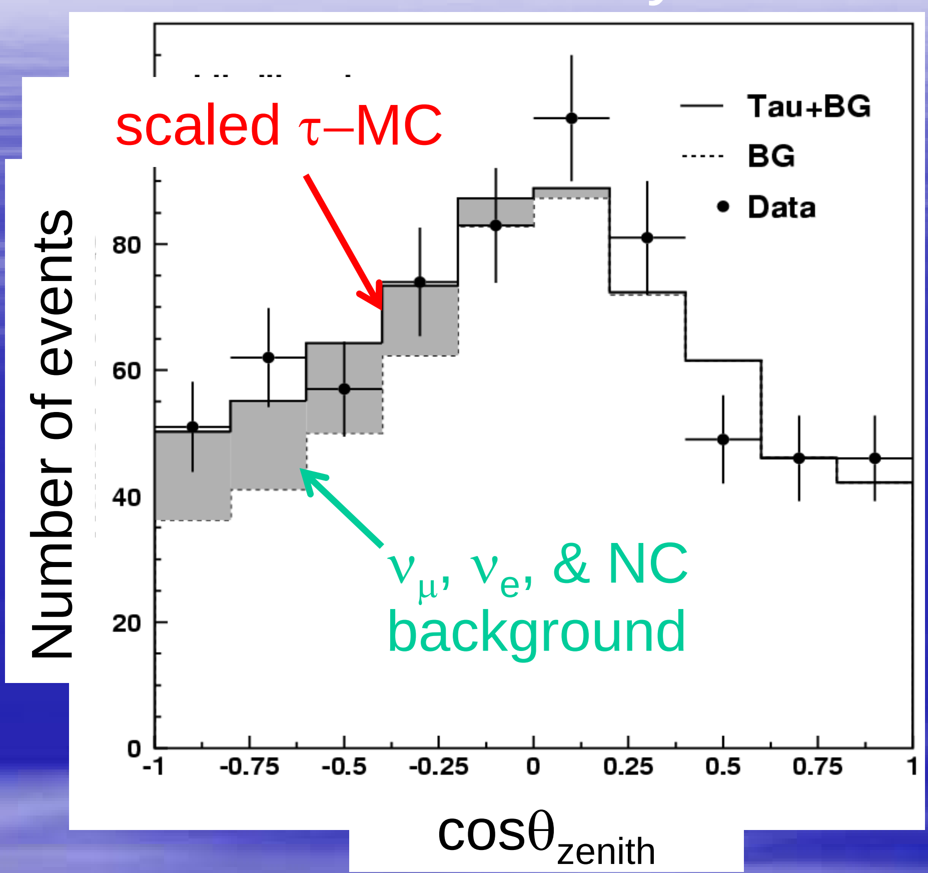
Only ～ 1.0 CC ν_τ FC events/kton・yr

(BG (other ν events) ～ 130 ev./kton・yr)

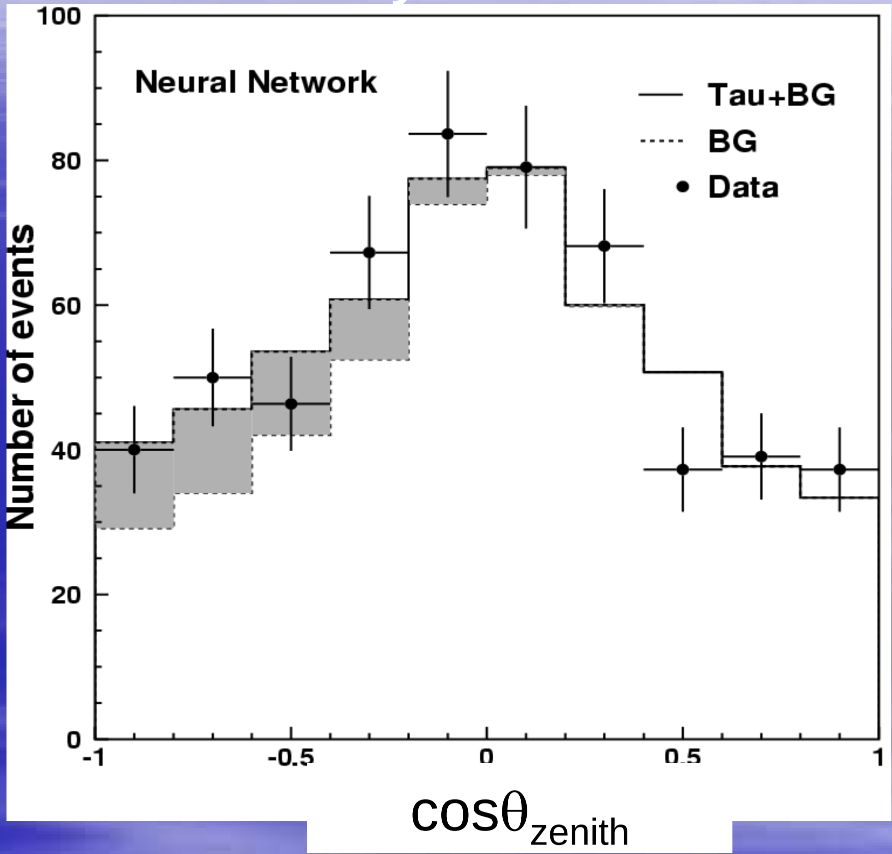
OLD
(to be updated)

Zenith angle dist. and fit results

Likelihood analysis



NN analysis



2.4σ significance

	Likelihood analysis	NN analysis
Fitted # of τ events	138±48(stat) +15 / -32(syst)	134±48(stat) +16 / -27(syst)
Expected # of τ events	78±26(syst)	78±27 (syst)

Soon; 1, combine both analyses to improve signal/BG
2, add SK-II + III (double statistics)

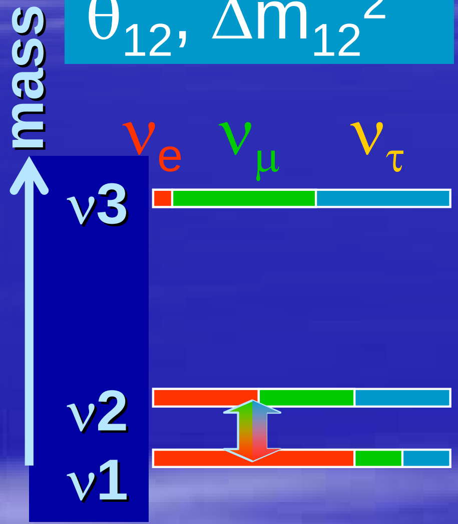
Remaining problems for atm-ν

ν mass and mixing parameters:

$\theta_{12}, \theta_{23}, \theta_{13}, \delta, \Delta m_{12}^2, \Delta m_{13}^2(=\Delta m_{23}^2)$

Known:

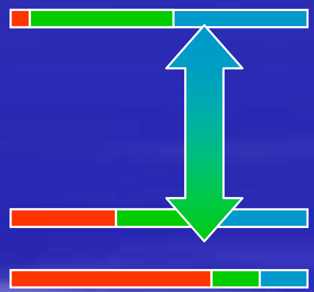
$\theta_{12}, \Delta m_{12}^2$



Solar,

KamLAND

θ_{23}, $|\Delta m_{23}^2|$

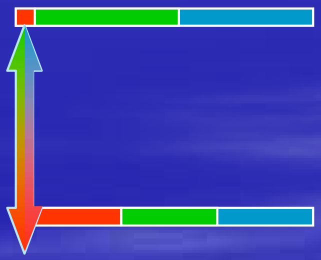


Atmospheric

Long baseline

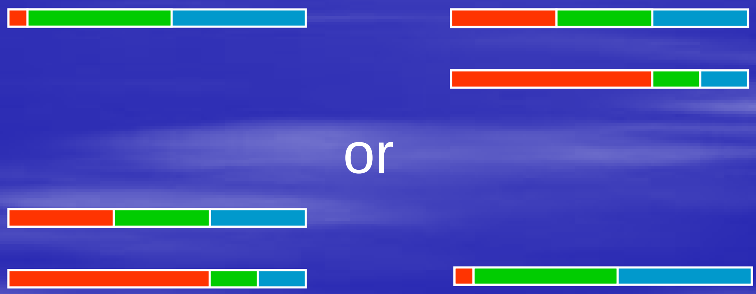
Unknown:

θ_{13}



If $\theta_{23} \neq \pi/4$,
is it $>\pi/4$ or $<\pi/4$?

Sign of Δm_{23}^2
(mass hierarchy)

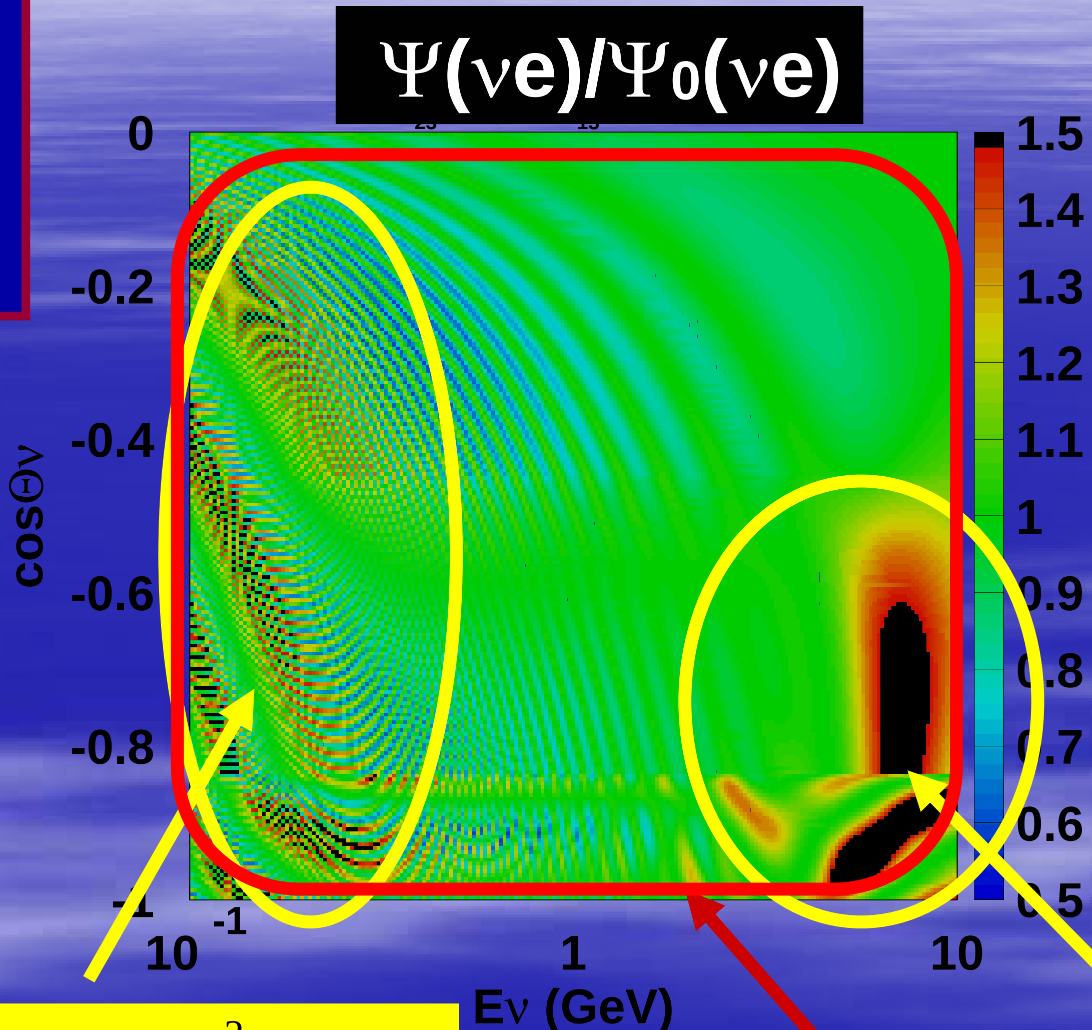


CPV ?

Look for sub-dominant oscill. effect in νe
+ smaller effect in $\nu\mu$ sample

Global picture of oscillation effects

$s^2 2\theta_{12}=0.825$
$s^2\theta_{23}=0.4$
$s^2\theta_{13}=0.04$
$\delta cp=45^o$
$\Delta m^2_{12}=8.3e\text{-}5$
$\Delta m^2_{23}=2.5e\text{-}3$



Pares and Smirnov hep - ph/0309312 (at Sub - GeV range)

$$\frac{\Psi(\nu e)}{\Psi_0(\nu e)} - 1 \cong P_2(r\cdot c_{23}^2 - 1) \quad \text{LMA}$$

$$- r\cdot \tilde{s}_{13}\cdot \tilde{c}_{13}^2 \cdot \sin 2\vartheta_{23}(\cos\delta_{CP}\cdot R_2 - \sin\delta_{CP}\cdot I_2) \quad \text{interference}$$

$$+ 2\tilde{s}_{13}^2(r\cdot s_{23}^2 - 1) \quad \vartheta_{13}\ \text{resonance}$$

r : μ/e flux ratio (~2 at low energy)

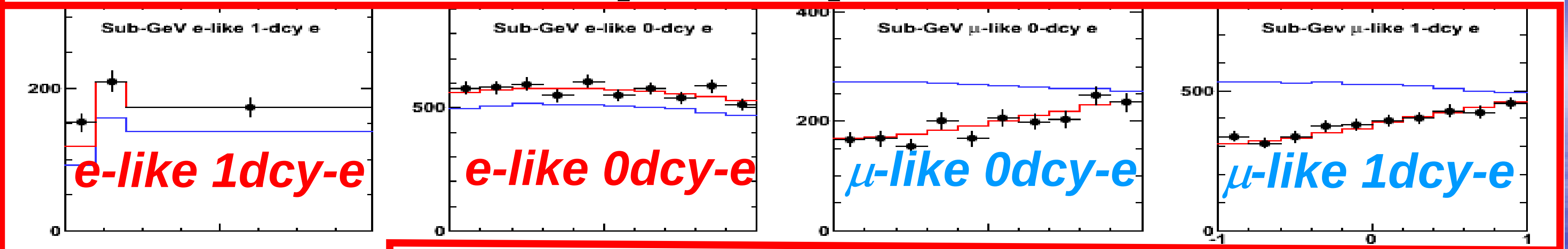
$P_2 = |A_{e\mu}|^2$: 2ν transition probability $\nu_e \rightarrow \nu_{\mu\tau}$ in matter
$R_2 = \mathrm{Re}(A^*_{ee}A_{e\mu})$
$I_2 = \mathrm{Im}(A^*_{ee}A_{e\mu})$
A_{ee} : survival amplitude of the 2ν system
$A_{e\mu}$: transition amplitude of the 2ν system

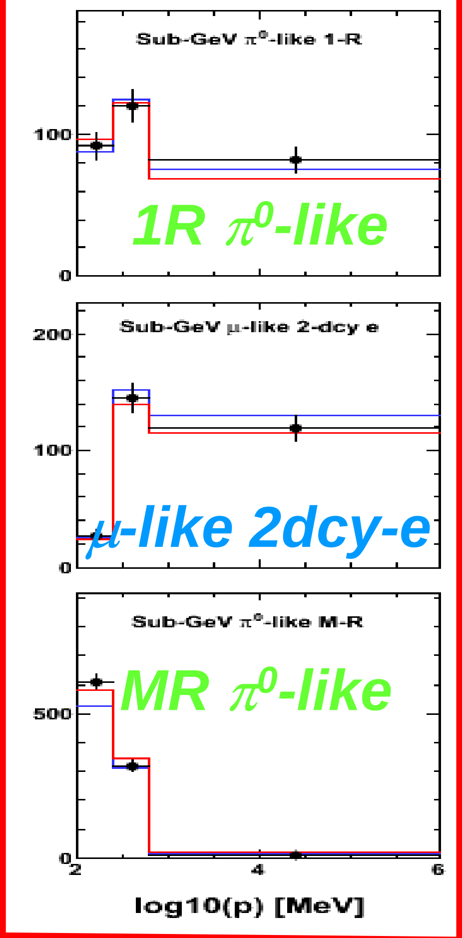
$\text{LMA} \propto (r\cdot\cos^2\vartheta_{23} - 1)$

$\text{interference (CPV)}$

ϑ_{13} resonance
$\propto \sin^2\vartheta^m_{13}(r\cdot\sin^2\vartheta_{23} - 1)$

new sub-samples (SK-I +II+III combined)





- Sub-GeV samples are further sub-divided
  - by decay-e and π0-likelihood
  - improve sensitivity to oscillation effect in low energy

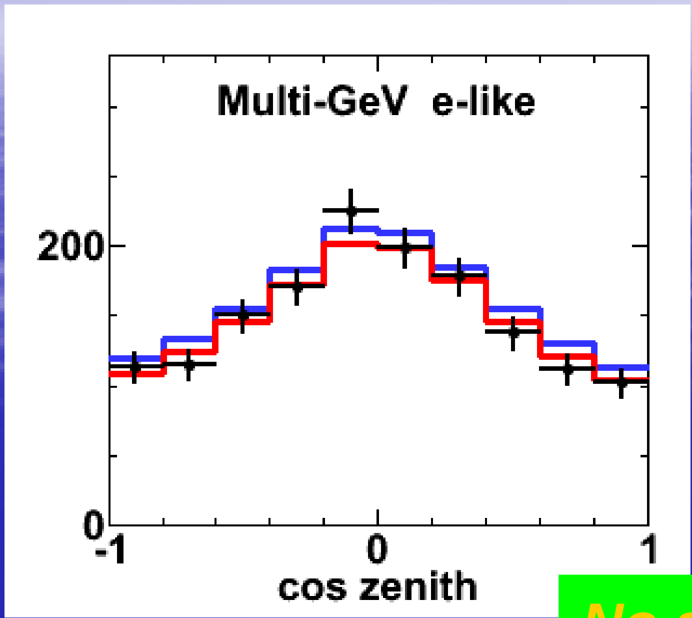
e-like

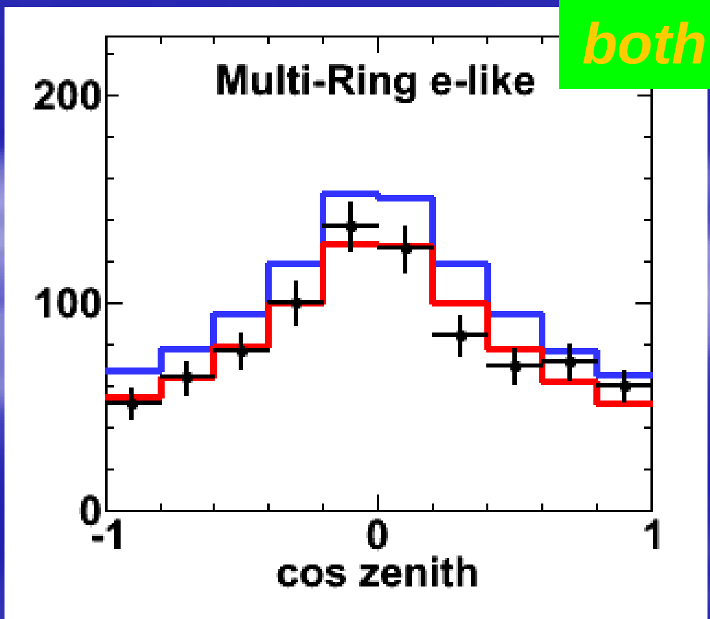
		FC sub-GeV single-ring e-like			FC sub-GeV single-ring e-like
		0-DKe	1-DKe	π^0-like	
number of MC events		2663.2	210.9	191.8	2996.4
CC $\nu_e + \bar{\nu}_e$	Q.E.	77.7 %	3.8 %	10.6 %	70.6 %
	single meson	12.4 %	50.3 %	7.0 %	15.2 %
	multi π	1.0 %	9.7 %	1.8 %	1.7 %
	coherent π	1.3 %	8.5 %	0.5 %	1.7 %
CC $\nu_\mu + \bar{\nu}_\mu$		0.6 %	15.2 %	7.0 %	2.0 %
NC		6.8 %	11.2 %	72.0 %	8.7 %

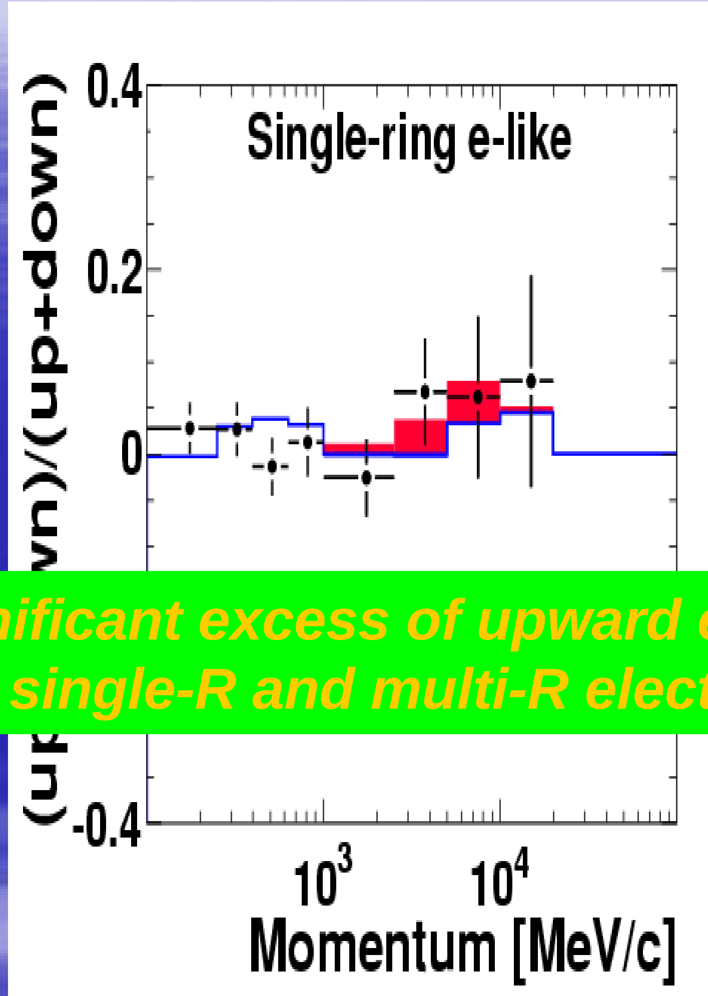
μ-like

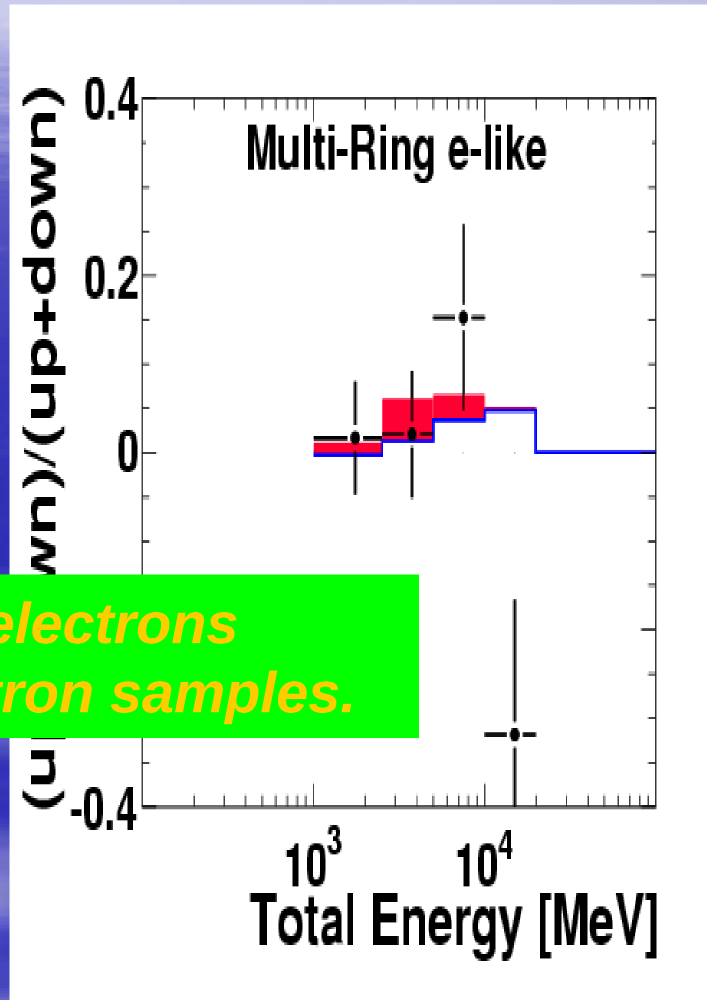
		FC sub-GeV single-ring μ-like			FC sub-GeV single-ring μ-like
		0-DKμ	1-DKμ	2-DKμ	
number of MC events		1412.4	2745.4	164.3	4297.8
CC $\nu_\mu + \bar{\nu}_\mu$	Q.E.	71.3 %	78.5 %	5.8 %	74.7 %
	single meson	12.9 %	15.5 %	65.7 %	16.7 %
	multi π	1.1 %	1.5 %	14.9 %	1.9 %
	coherent π	0.8 %	1.5 %	8.6 %	1.6 %
CC $\nu_e + \bar{\nu}_e$		1.8 %	<0.1 %	<0.1 %	0.7 %
NC		11.8 %	2.6 %	3.3 %	4.3 %

θ_{13} search (SK-I +II+III)





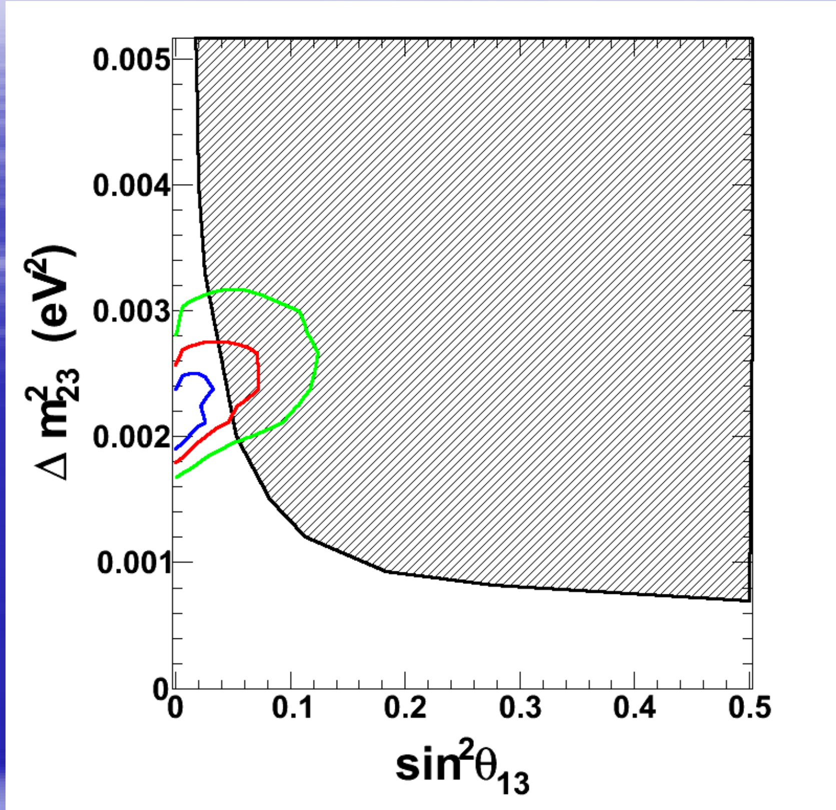




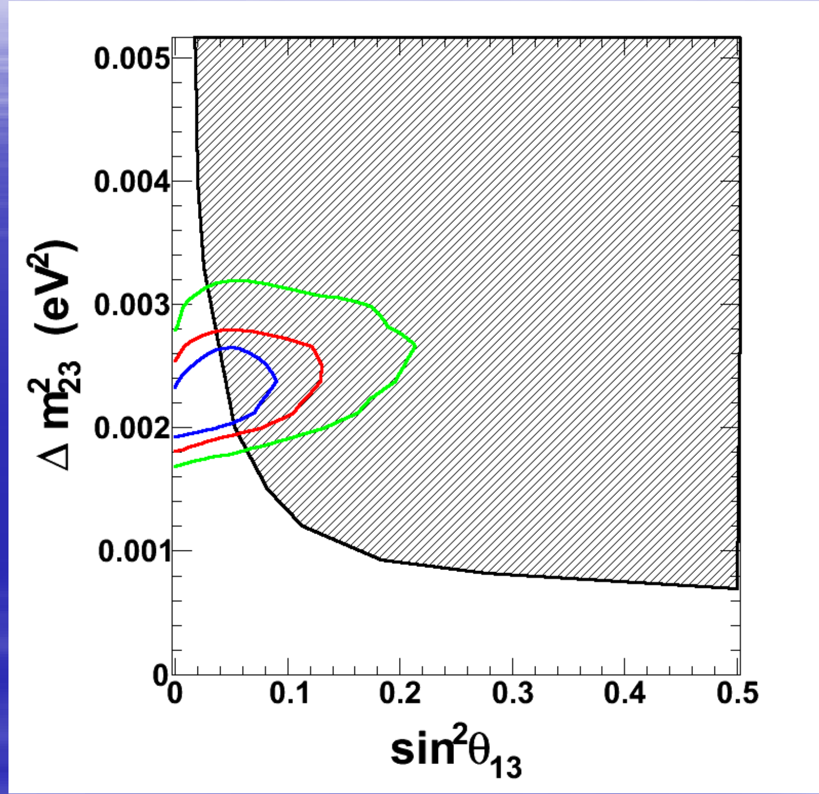
No significant excess of upward electrons both in single-R and multi-R electron samples.

Current constraint on θ_{13} (SK-I +II+III)

$\Delta m^2>0$



$\Delta m^2<0$



No evidence for nonzero θ_{13} so far

CHOOZ reactor: $\sin^2\theta_{13} < 0.04$ @ 90%CL

SK atm-ν: $\sin^2\theta_{13} < 0.066$ (normal hierarchy)

< 0.131 (inverted hierarchy)

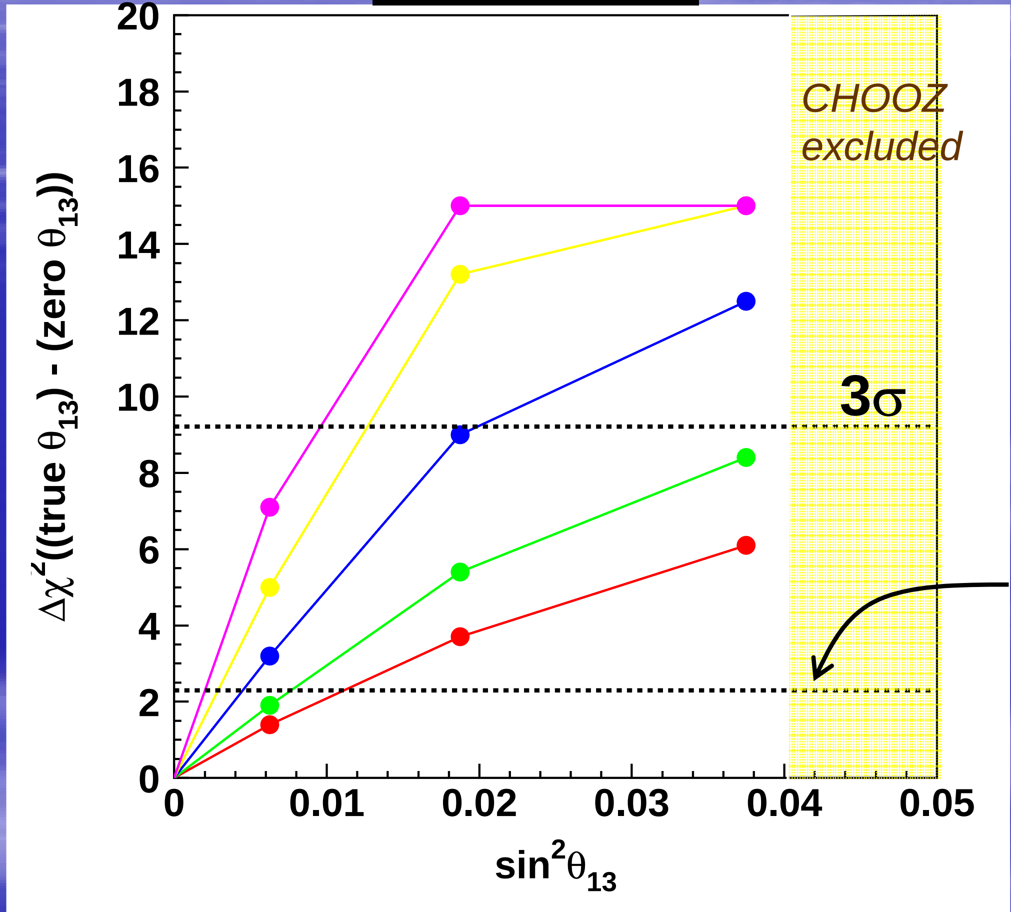
LBLE K2K: $\sin^2\theta_{13} < 0.075$ PRL93(04)

MINOS: $\sin^2\theta_{13} < 0.073$ PRL101(08)

Significance for nonzero θ_{13}

$s^2 2\theta_{12}=0.825$
$s^2\theta_{23}=0.40 \sim 0.60$
$s^2\theta_{13}=0.00\sim0.04$
$\delta cp=45^{\circ}$
$\Delta m^2_{12}=8.3e\text{-}5$
$\Delta m^2_{23}=2.5e\text{-}3$

20yrs SK



$s^2_{23}=0.40$
0.45
0.50
0.55
0.60

ϑ_{13} resonance
$\propto \sin^2\vartheta^m_{13}(r\cdot\sin^2\vartheta_{23}-1)$

3σ for 80yrs SK
~4yrs HK

Positive signal for nonzero θ_{13} can be seen if θ_{13} is near the CHOOZ limit and $s^2\theta_{23} > 0.5$

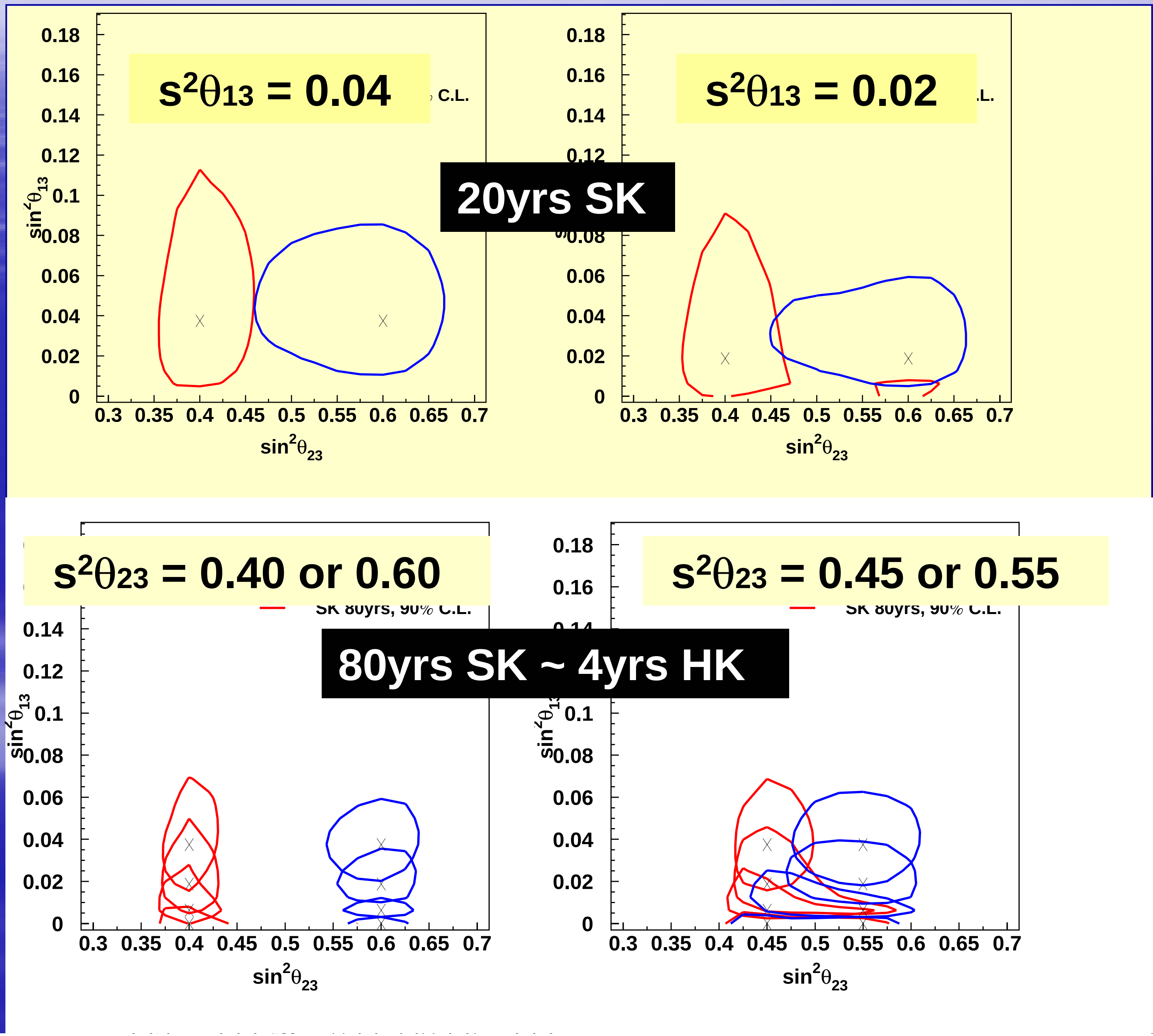
Discrimination of θ_{23} octant

SK-I+II+II
$0.441 < \sin^2\theta_{23} < 0.561$ (68%)

$s^2 2\theta_{12} = 0.825$
$s^2\theta_{23} = 0.4$ or 0.6
$s^2\theta_{13} = 0.00 \sim 0.04$
$\delta cp = 45^o$
$\Delta m^2_{12} = 8.3\text{e-}5$
$\Delta m^2_{23} = 2.5\text{e-}3$

With 20yrs SK, discrimination may possible for $\sin^2\theta_{13} > 0.02$

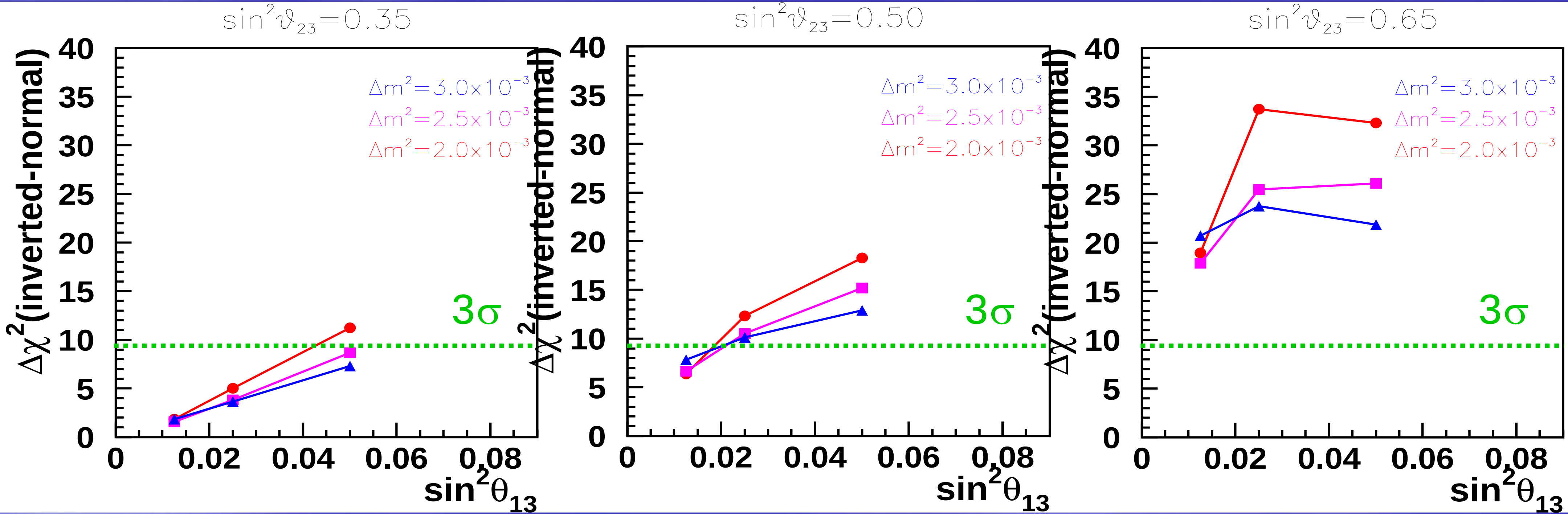
More statistics will increase power.



Discrimination of mass hierarchy (1)

1.8 Mton•yr = 3.3yr HK

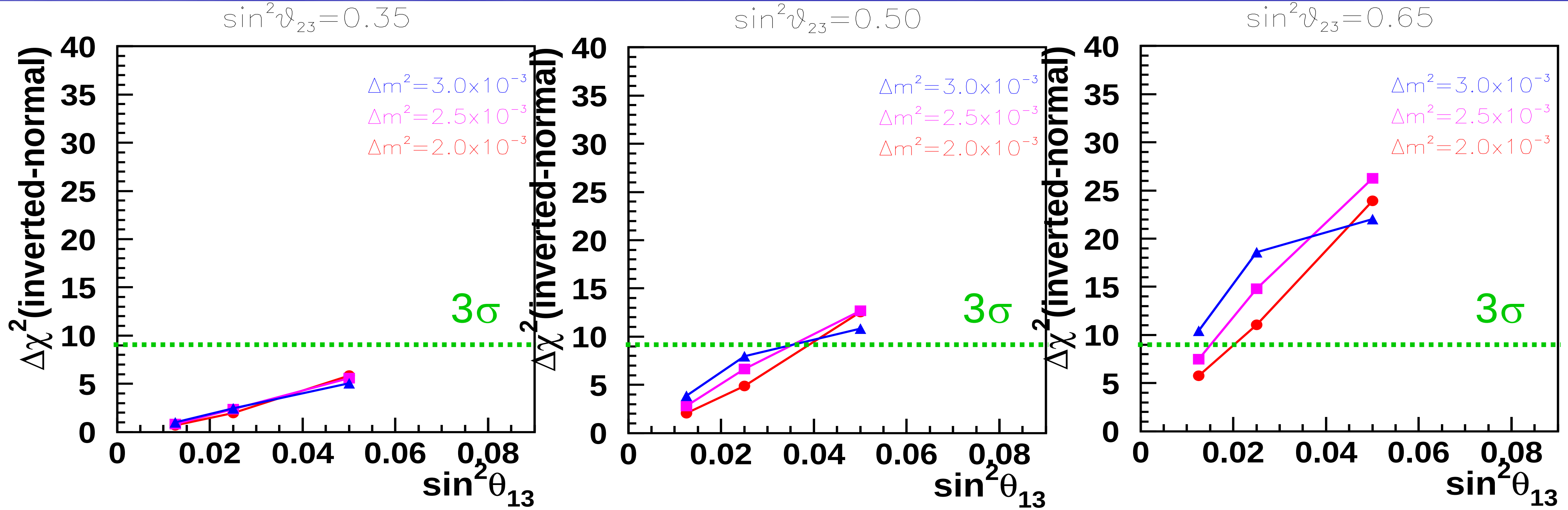
True : normal mass hierarchy



Discrimination of mass hierarchy (2)

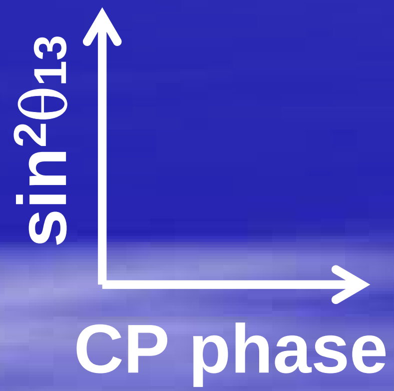
1.8 Mton・yr = 3.3yr HK

True : inverted mass hierarchy

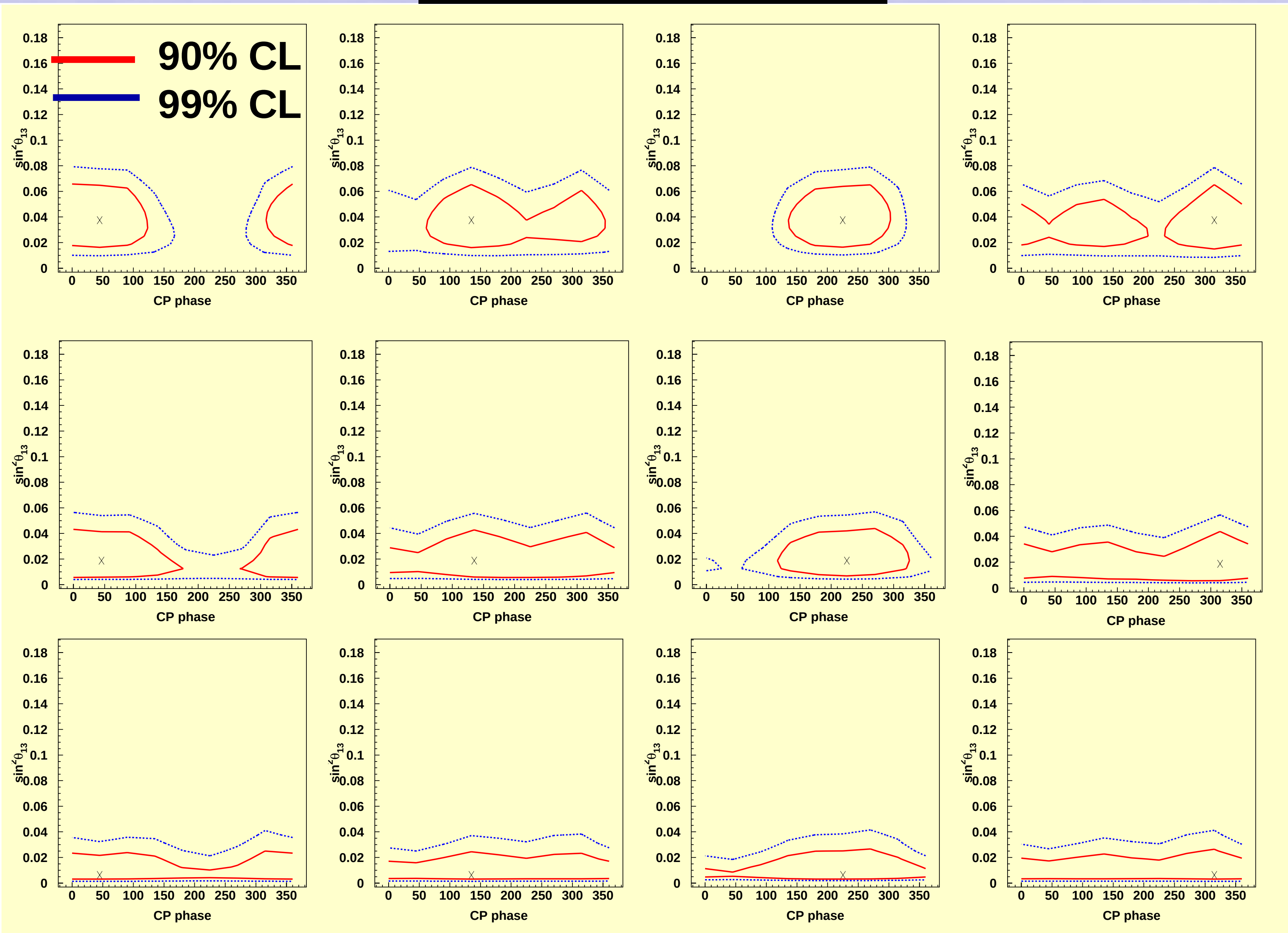


δ_{CP} sensitivity

$s^2 2\theta_{12}=0.825$
$s^2\theta_{23}=0.5$
$s^2\theta_{13}=0.00\sim0.04$
$\delta cp=0^\circ\sim360^\circ$
$\Delta m^2_{12}=8.3e\text{-}5$
$\Delta m^2_{23}=2.5e\text{-}3$

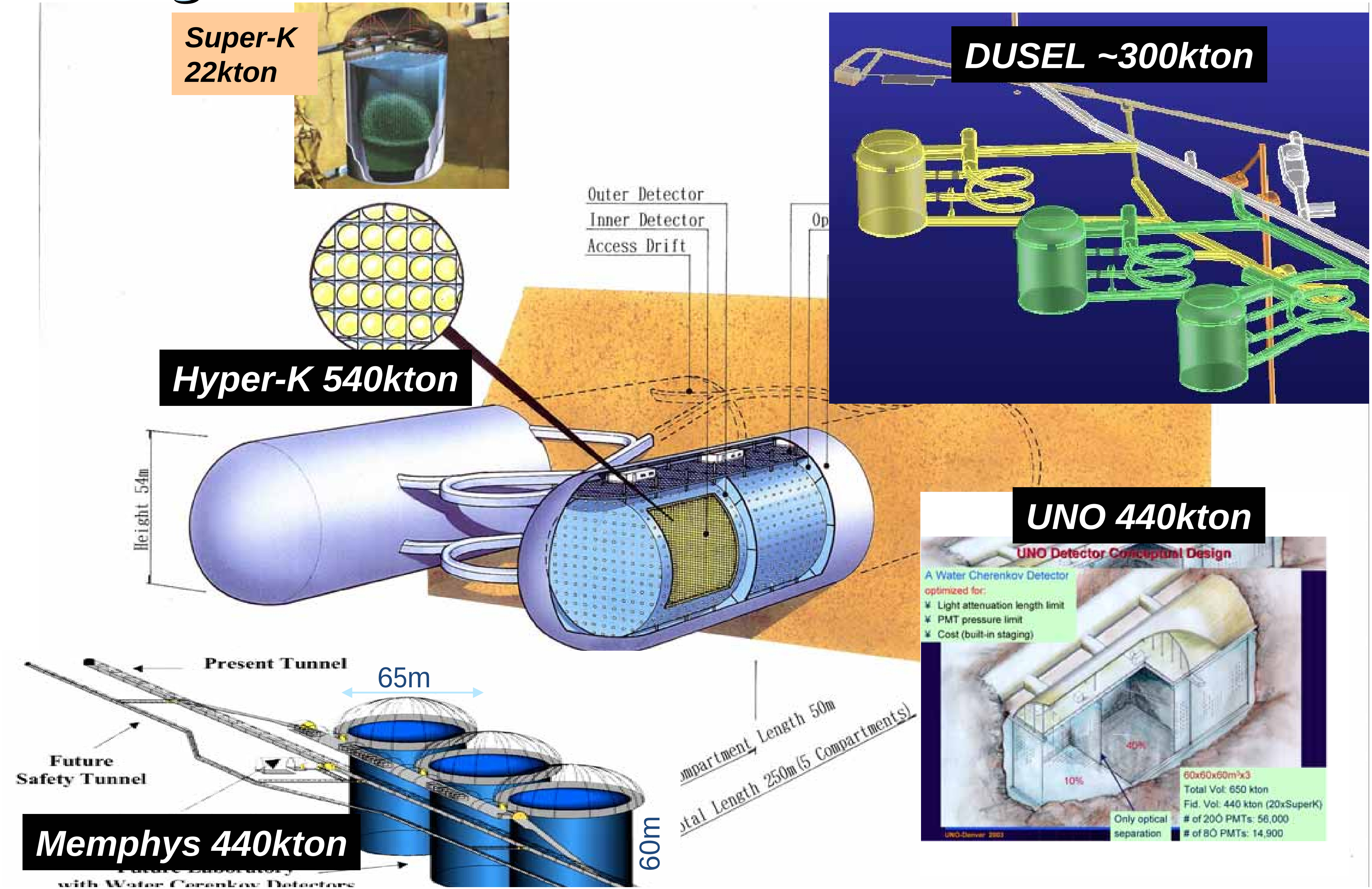


80yrs SK ~ 4yrs HK

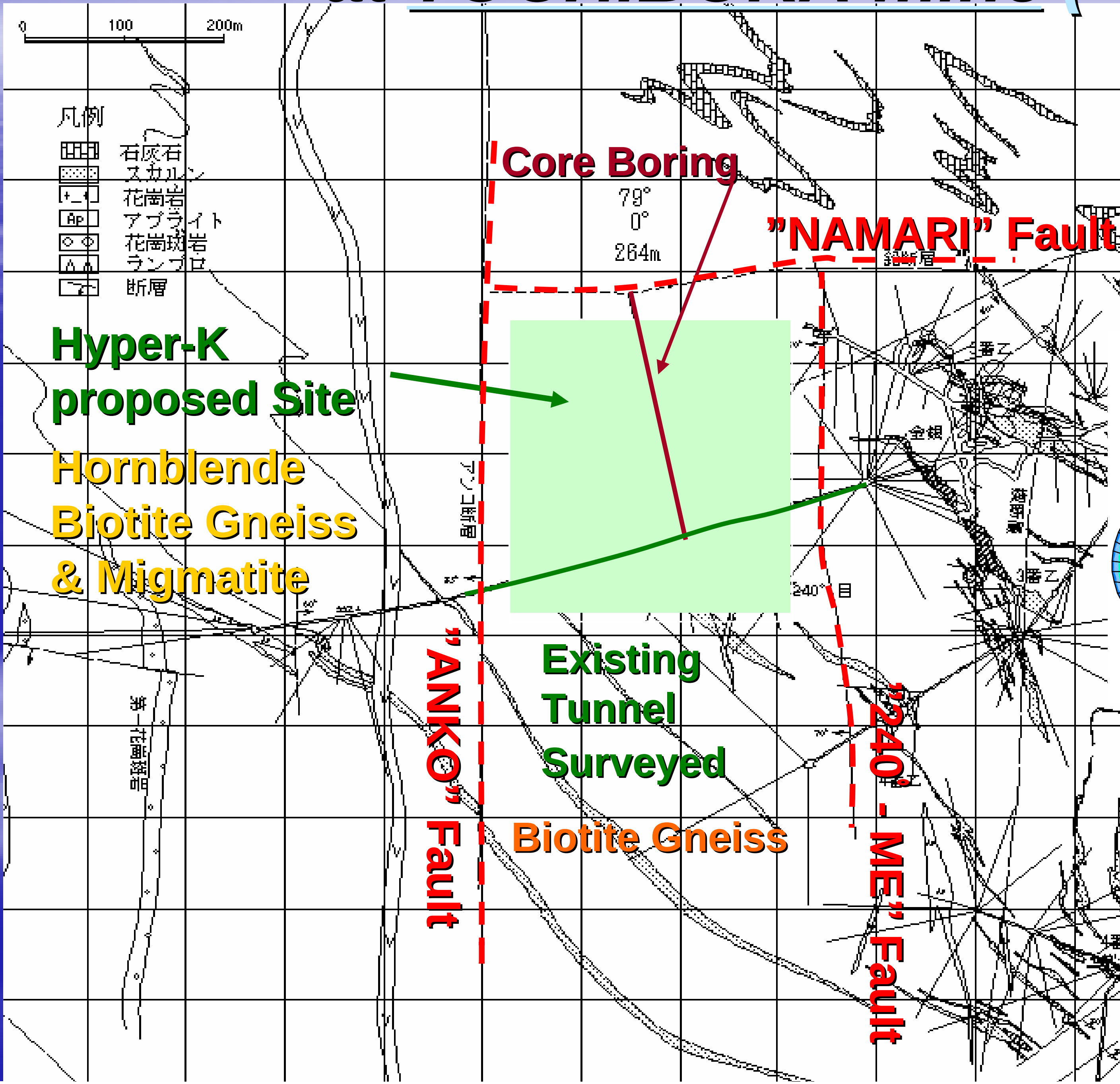


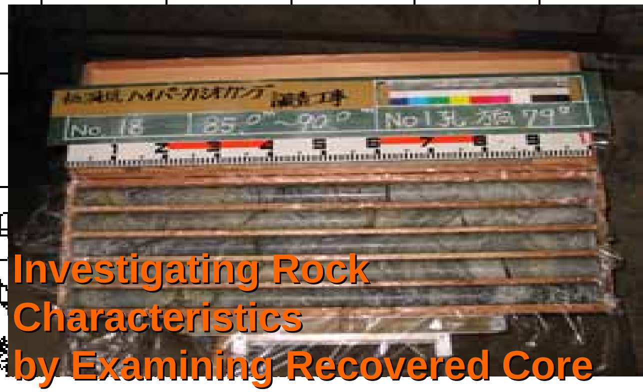
CP phase could be seen if θ13 is close to the CHOOZ limit.

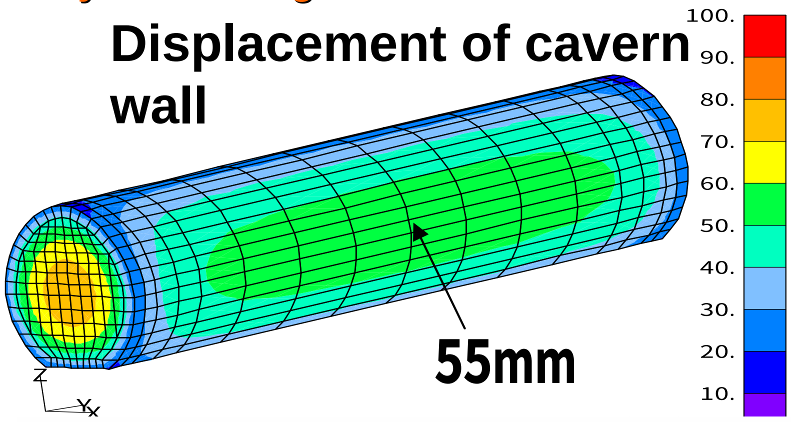
Megaton scale water Cherenkov detectors

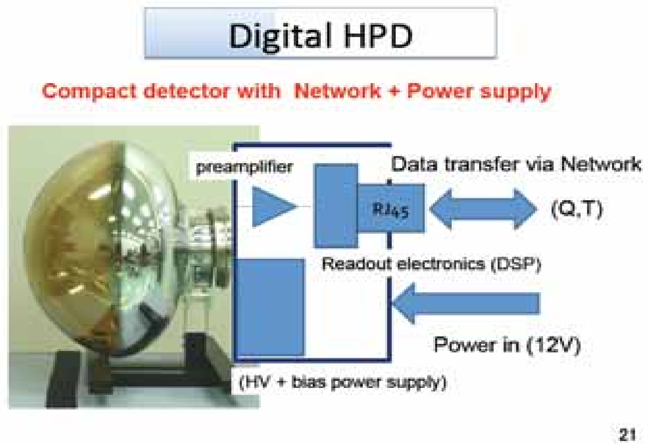


Geological Map of Proposed Site at TOCHIBORA mine (+ 550mEL)









Physics goals

- *CPV with accelerator ν (LBLE)*

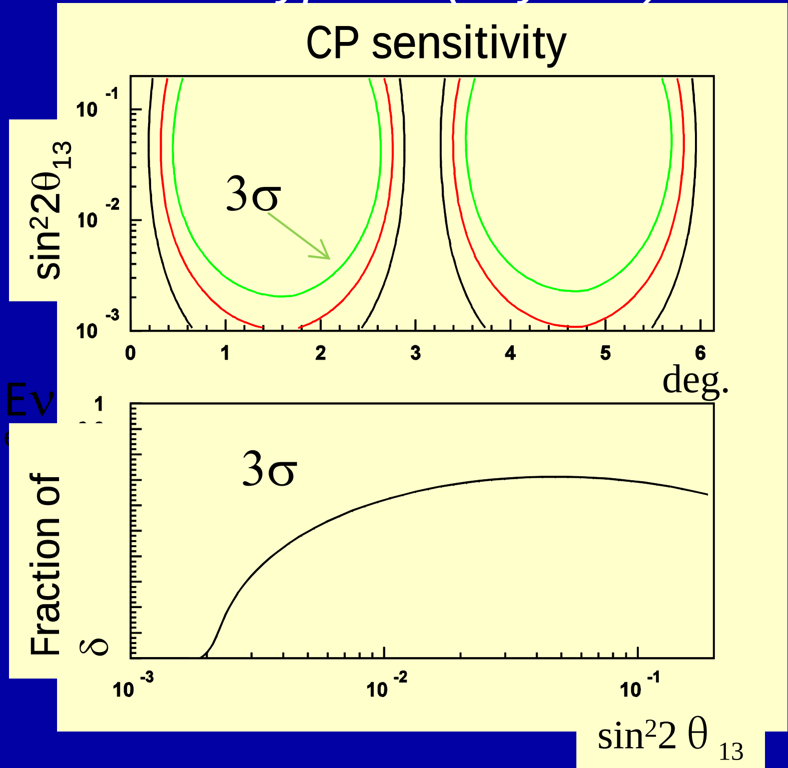
- proton decay searches
  - ~10^{35} years for $p \rightarrow e^+\pi^0$

- *precise meas. of atmospheric ν*
  - δ, θ_{13}, mass hierarcy ($\sin^2\theta_{13}$ >~0.01)
  - θ_{23} octant

- *supernova ν*
  - mechanism of stellar collapse
  - mass hierarchy?

- *solar ν*
  - day-night flux (matter effect)
  - Hep ν

JPARC upgraded 1.66MW beam + 540kton Hyper-K (10years)



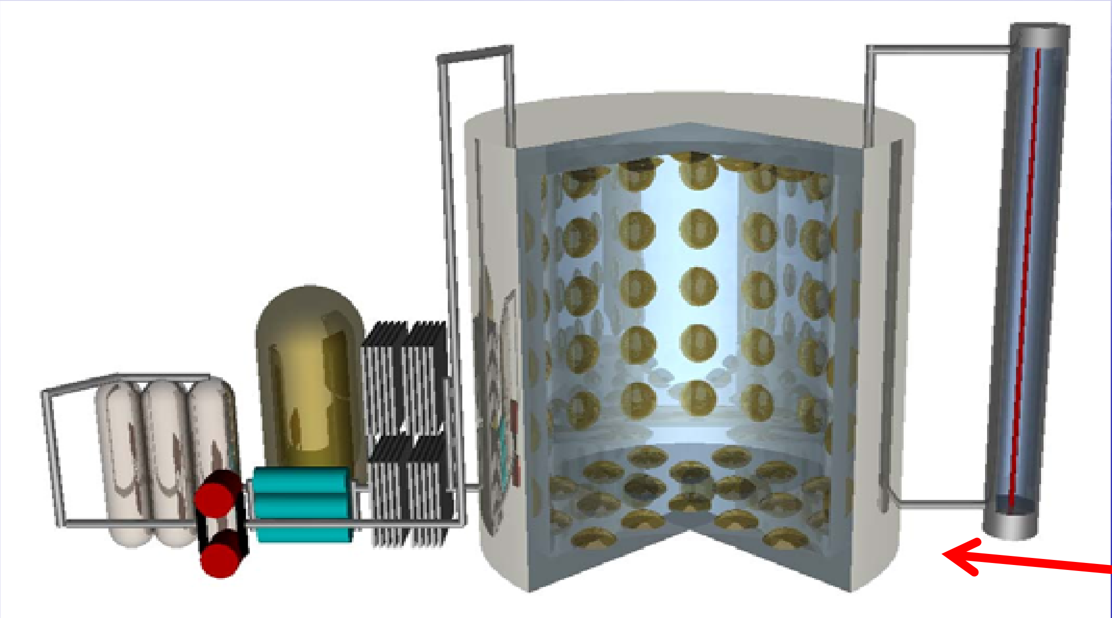
Summary

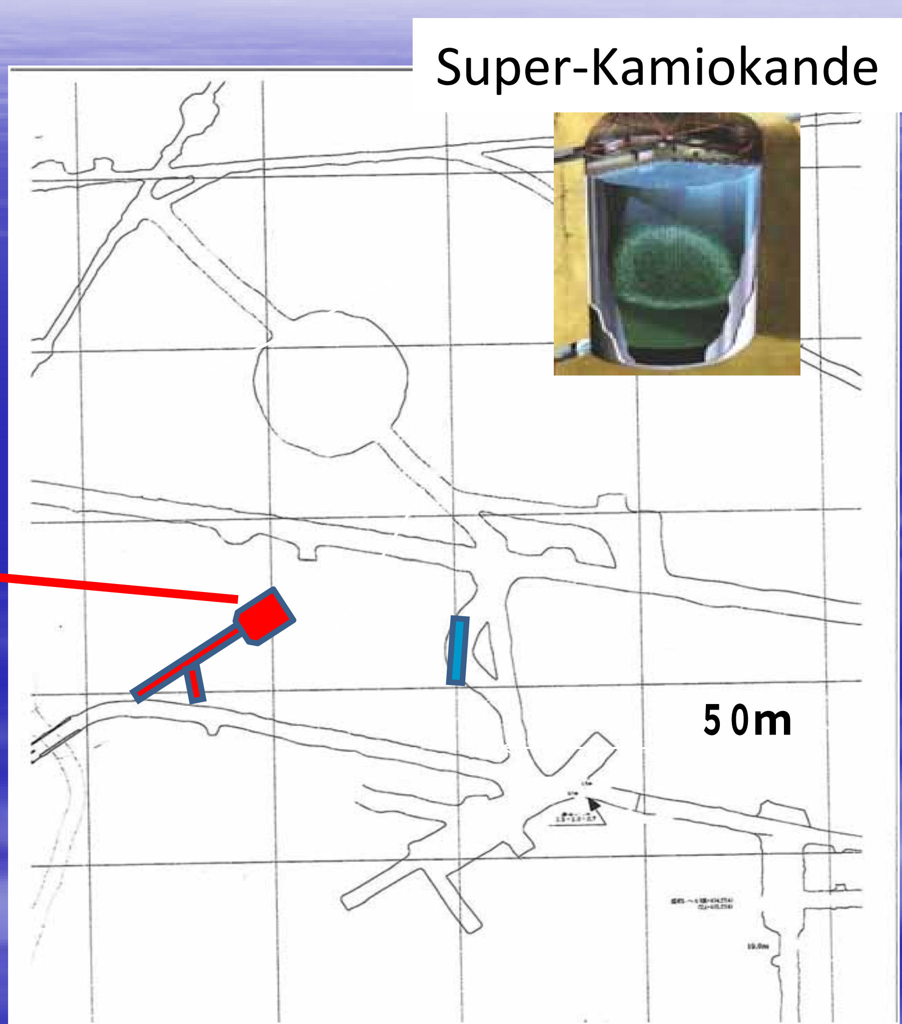
- Super-K is now back on solar ν business
  - Aiming to reach 4 MeV (new electronics, lower BG, better reconstruction, smaller systematics)

- Atm-ν is providing information on $\nu\mu \rightarrow \nu\tau$
  - Δm^2_{23}= $2.19^{+0.14}_{-0.13}$x10^{-3} eV^2 (68% by L/E study)
  - $\sin^2 2\theta_{23}$>0.96 @ 90% CL
  - 2.4 σ level $\nu\tau$ significance

- LBLE era
  - MINOS, T2K, Noνa, LBLE with Mton-size…
  - Atm-ν could also give us information on θ_{13}, octant of θ_{23}, mass hierarchy, and CP phase in future (especially in the case of $\sin^2\theta_{13}$ >~0.01)

Gadolinium test tank (under construction)





- Hall excavation (Sep.-2009 to Dec.)
- 200ton tank with PMTs
- Test the effect of Gd on light attenuation length, purification method, corrosion of detector materials…