25 minutes

Past, Present and Future of Neutrino Oscillation Experiments @Alexei Smirnov Fest

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and

Kavli IPMU, University of Tokyo

60 years old birthday is very special

- Two ways to count years (old days in Japan)
  - 12 years cycle: the twelve animal signs of the zodiacs
  - 10 years cycle: five elements & two sides (dark side and light side)

五行 (5 elements)	陰陽(light/dark)	十干	
木 (wood)	陽 (light side)	甲	1
	陰 (dark side)	乙	2
火 (fire)	陽 (light side)	丙	3
	陰 (dark side)	丁	4
土 (soil)	陽 (light side)	戊	5
	陰 (dark side)	己	6
金 (metal)	陽 (light side)	庚	7
	陰 (dark side)	辛	8
水 (water)	陽 (light side)	壬	9
	陰 (dark side)	癸	10

- Least Common Multiple of 12 and 10 → 60

→1 life cycle of calendar

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2012
Dragon
Water
light

- Least Common Multiple of 12 and 10 ➔ 60

➔1 life cycle of calendar

60 → Back to the baby

- Wear red (means baby in Japanese) vest at the 60 years old birthday

Brief history of Neutrino Oscillation

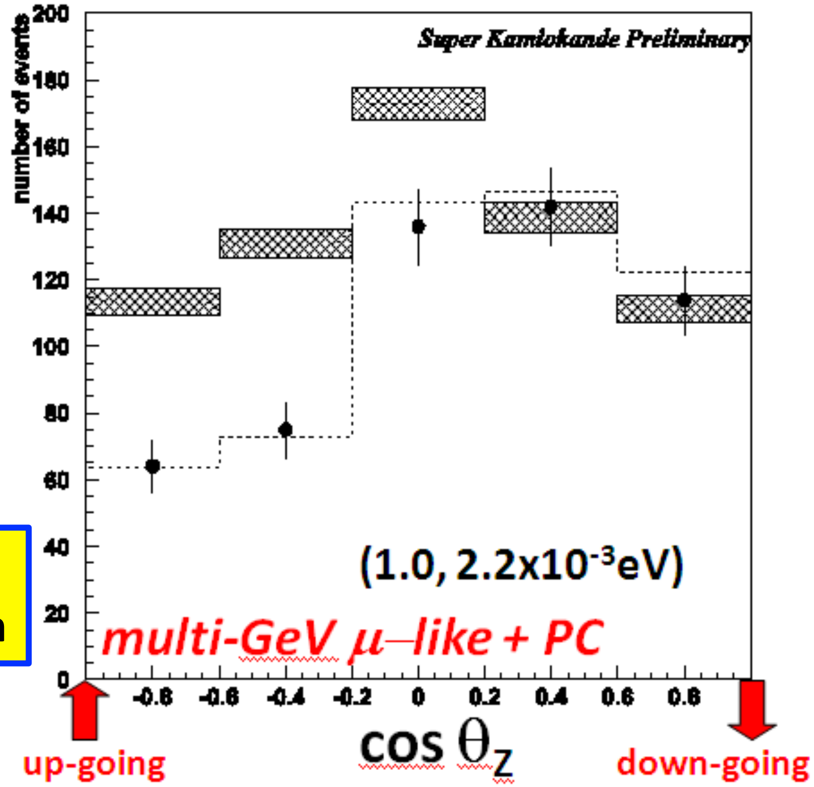
- 1952 (00)
- 1957 (05): Pontecorvo $(\nu \leftrightarrow \bar{\nu})$
- 1962 (10): Maki-Nakagawa-Sakata (flavor)
- <1970 (18): Solar neutrino problem
- 1978 (26): Wolfenstein
- 1986 (34): MSW (MS) effect
- 1988 (36): Atmospheric neutrino anomaly
- 1998 (46): Discovery of atmospheric neutrino oscillation (θ_{23})
- 2001 (49): Solar neutrino oscillation (θ_{12})
- 2011 (59): Non-zero θ_{13}
- 2012 (60): Large θ_{13}

θ_{23}

past

- Atmospheric neutrino anomaly comes later than solar neutrino problem but resolved earlier
- **June 1998: Atmospheric Neutrino Oscillation (*Super-Kamiokande*)**
  - Asymmetry in zenith angle distribution
  - ν_μ deficits (up-going)
- **K2K and MINOS** confirmed the oscillation by accelerator neutrinos

$\Delta\chi^2$ = 69.8 for no oscillation



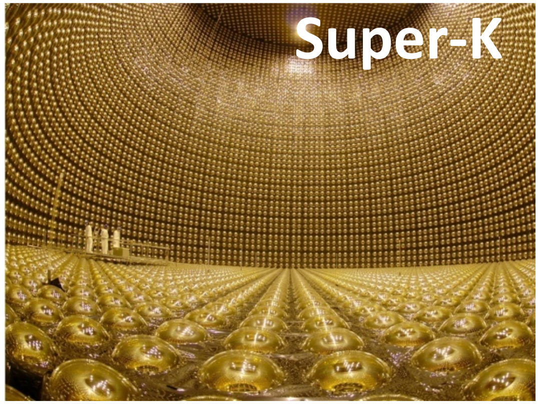
θ_{12}

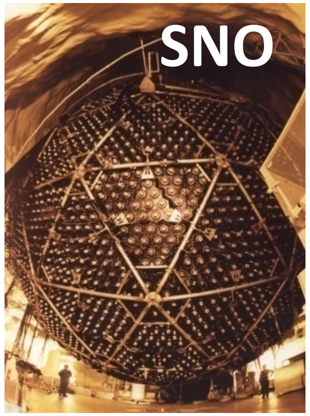
past

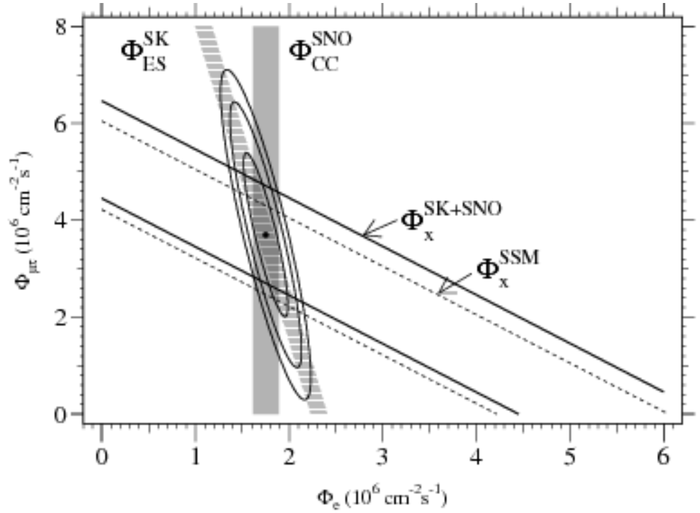
- June-2001: **Solar Neutrino Oscillation (*SNO+Super-Kamiokande*)**
  - SNO: charged current → ν_e
  - SK: Electron Scattering → $\nu_e + 0.15(\nu_\mu + \nu_\tau)$

3.3 σ

In 2002, SNO NC + CC 5.3 σ



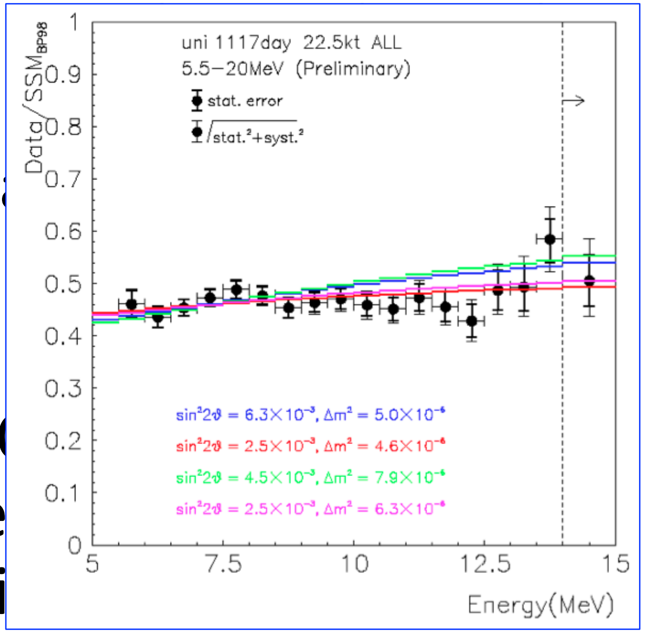


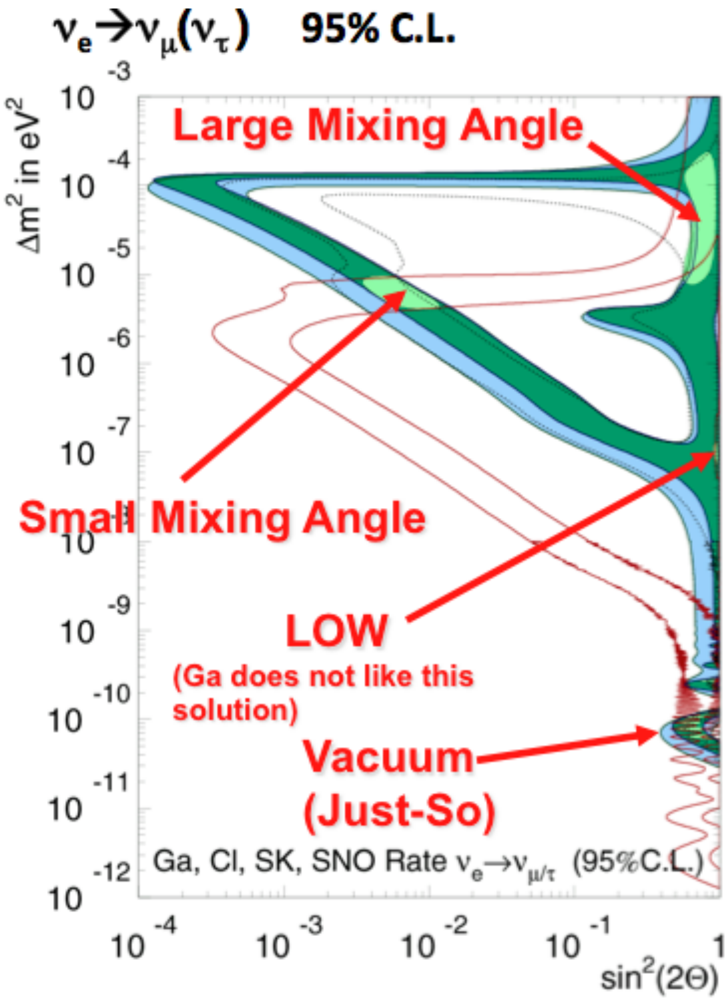


- **KamLAND** confirmed the oscillation and resolve the ambiguity of the parameter space.

MSW effect in solar neutrinos

- MSW was very attractive and beautiful to explain the large osillation effect from the small mixing angle solution.
- But we neutrin mixing
- MSW d energy and SN discove oscillati





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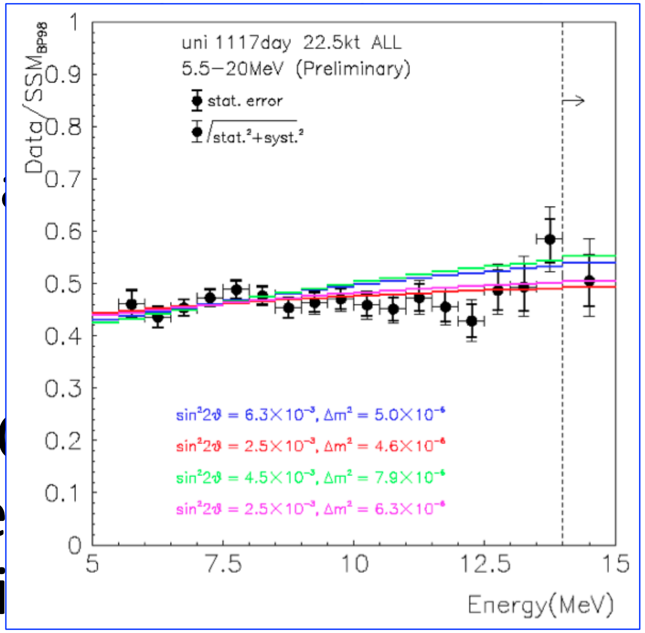
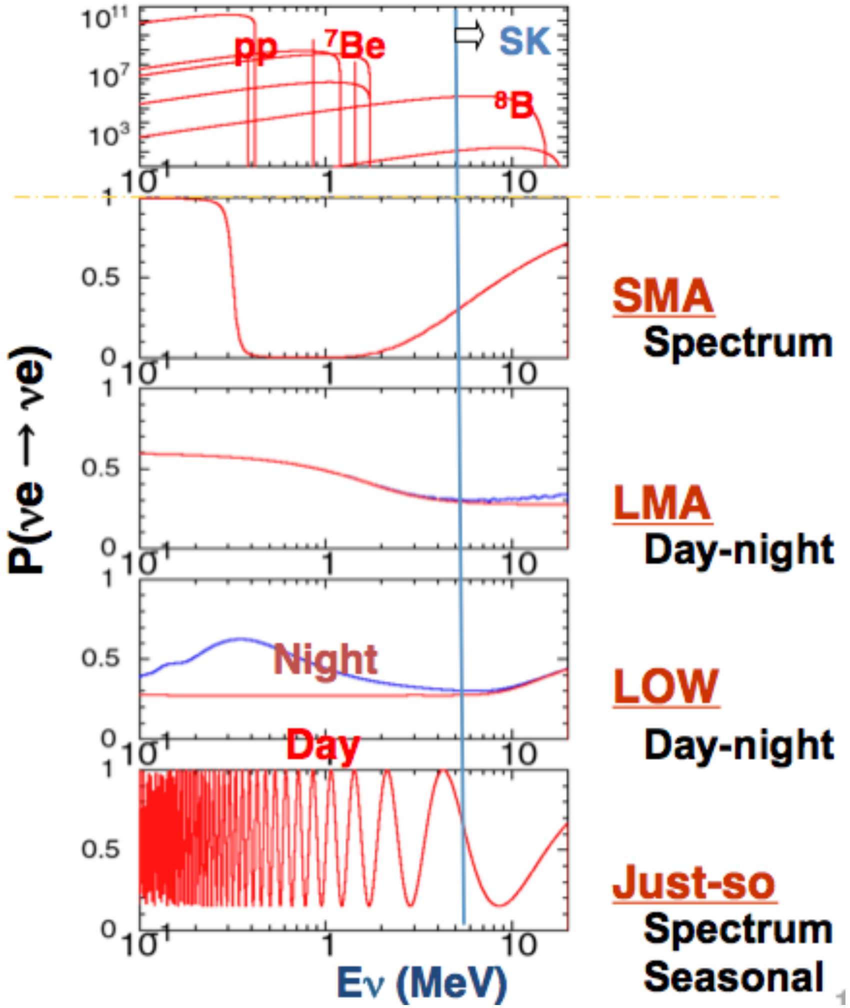
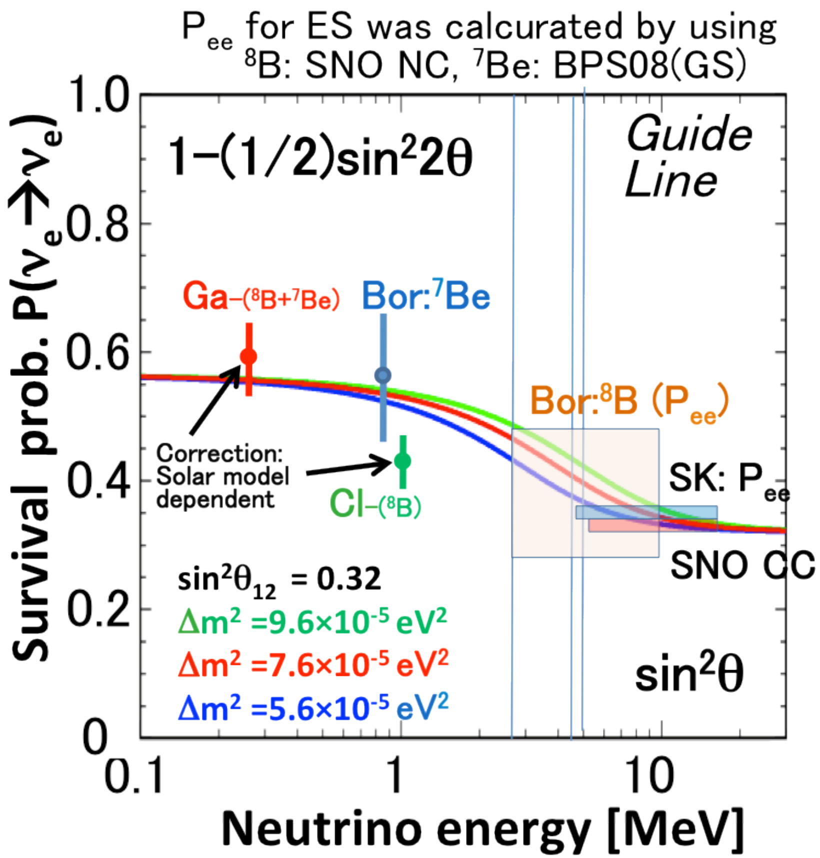




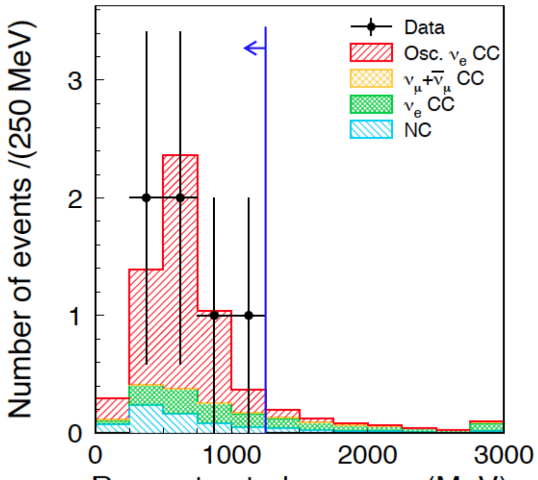
MSW effect in solar neutrinos

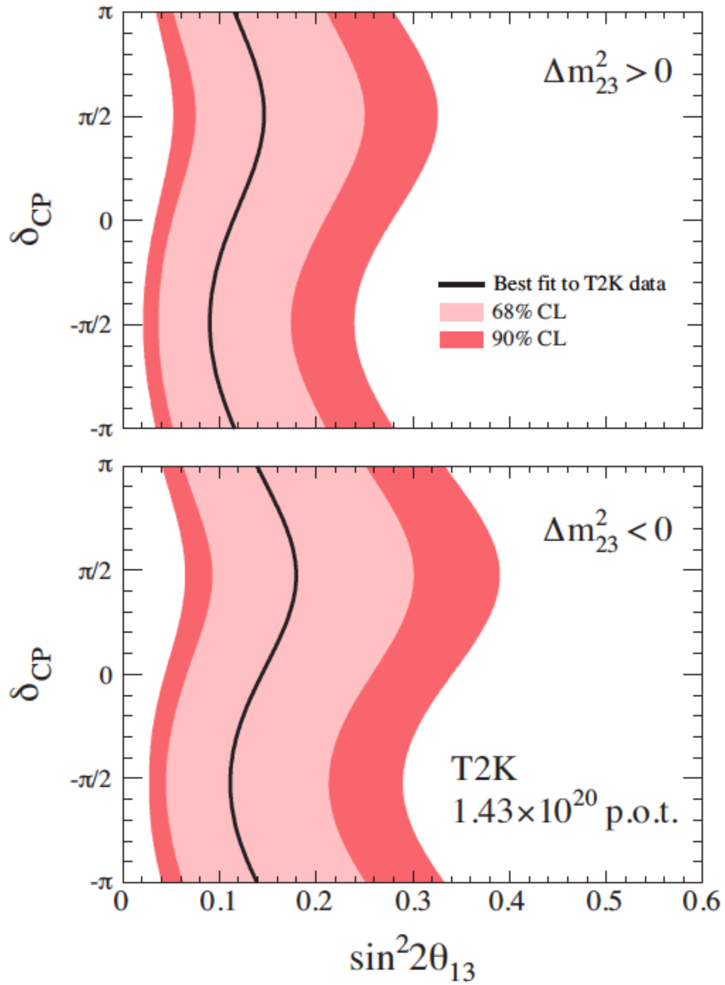
- MSW was very attractive and beautiful to explain the large osillation effect from the small mixing angle solution.
- But we now know that solar neutrino oscillation is large mixing angle solution.
- MSW did work in higher energy region where Super-K and SNO observed and discovered solar neutrino oscillations



θ_{13} *past*

- June, 2011: T2K observed 6 e-like events with 1.5 ± 0.3 (syst.) backgrounds → ***2.5 σ***
  - 0.03(0.04)< $\sin 2\theta_{13}$ < 0.28(0.34) @90% for normal (inverted) hierarchy.
- **MINOS and Double CHOOZ followed**



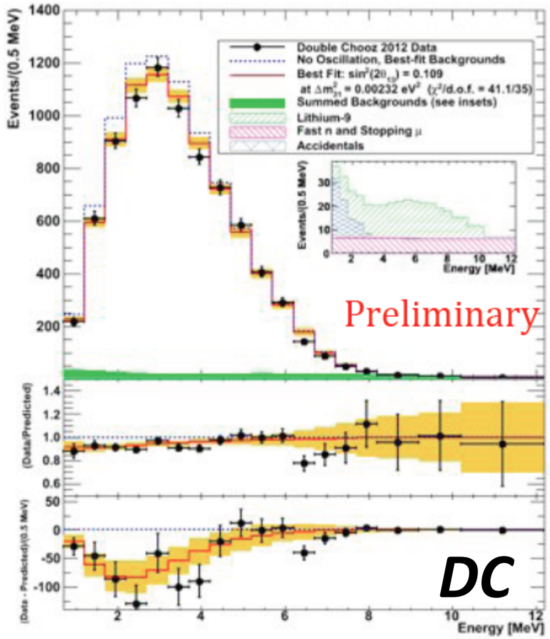


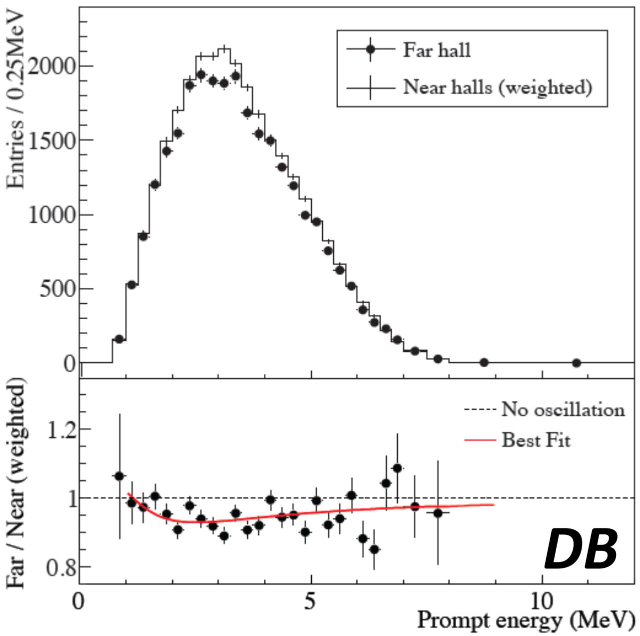
Present Situation

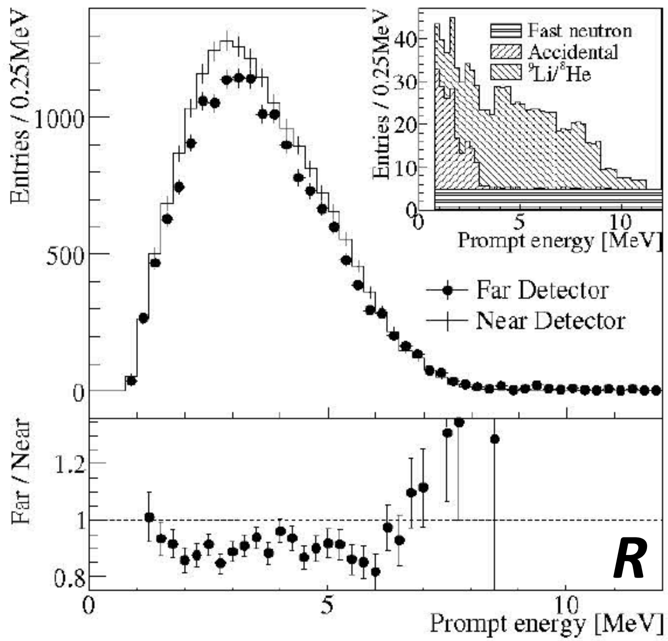
θ_{13}

present

- $\sin^2 2\theta_{13}$ = 0.109±0.030(stat)±0.025(syst) Double CHOOZ
- $\sin^2 2\theta_{13}$ = 0.089±0.010(stat)±0.005(syst) Daya Bay **7.7σ effect**
- $\sin^2 2\theta_{13}$ = 0.113±0.013(stat)±0.019(syst) RENO







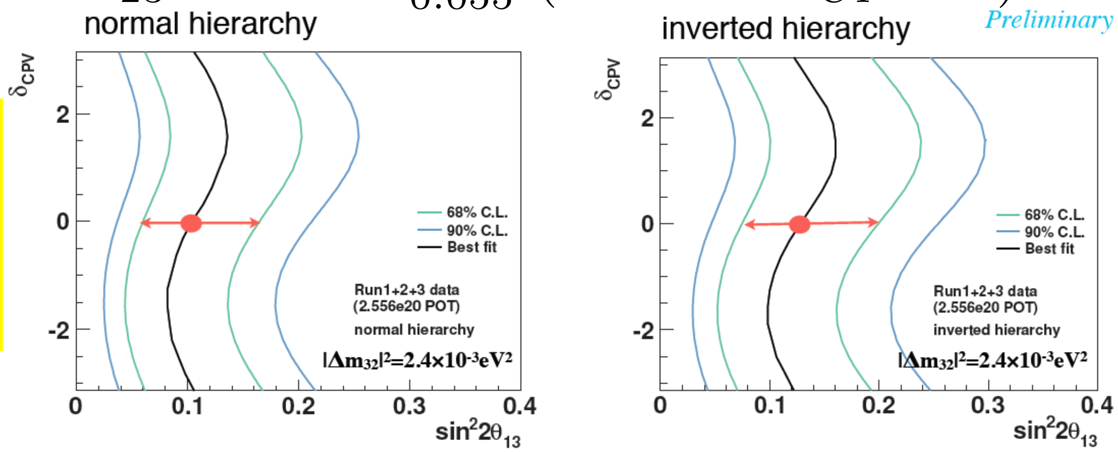
10% level measurements ➔ 5% in future

θ_{13} *present*

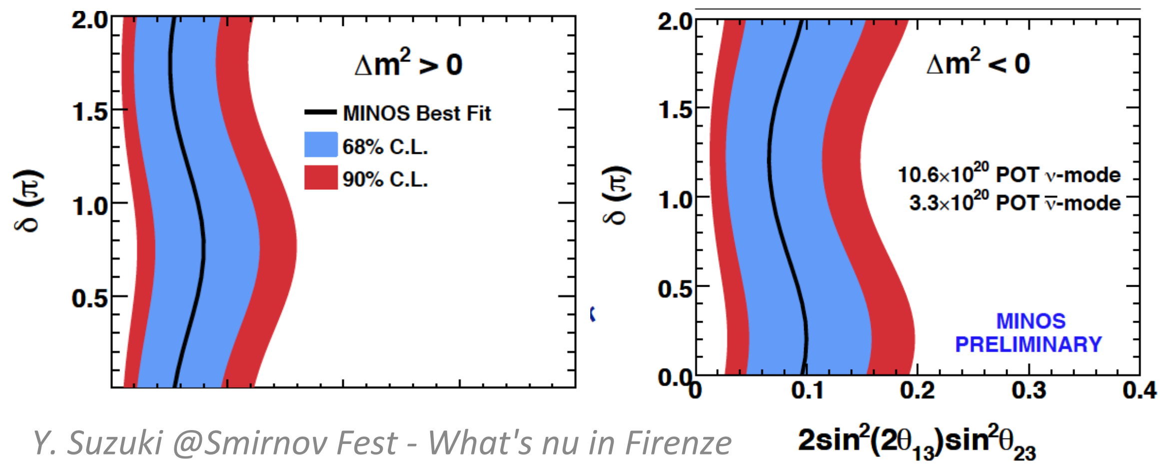
- T2K

$$2\sin^2 2\theta_{13}\cdot\sin^2\theta_{23} = 0.104^{+0.060}_{-0.045}\ (\text{normal: } \delta_{CP}=0)$$
$$2\sin^2 2\theta_{13}\cdot\sin^2\theta_{23} = 0.128^{+0.070}_{-0.055}\ (\text{inverted: } \delta_{CP}=0)$$

In future, octant of θ_{23} may be explored by comparing acc. ($\theta_{13}+\theta_{23}$) and reactor (θ_{13}) results



- MINOS



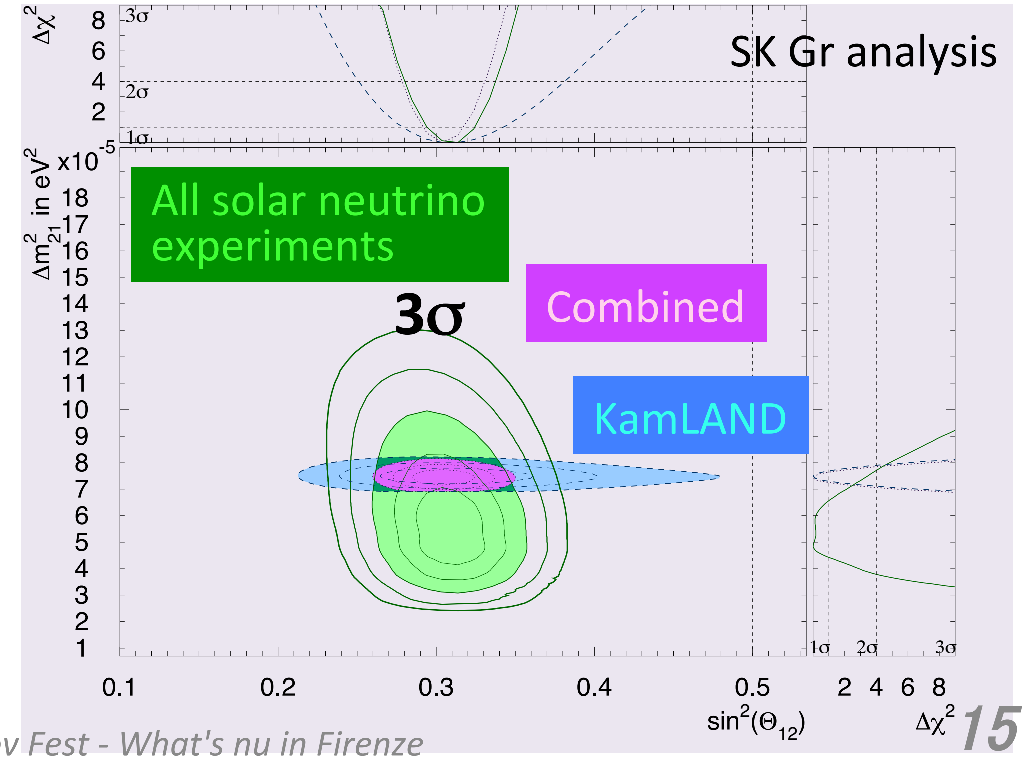
θ_{12}

present

- Using θ_{13} as an input: $\sin^2\theta_{13} = 0.025$
- All combined

$$\sin^2\theta_{12} = 0.310 \pm 0.013$$
$$\Delta m_{12}{}^2 = 7.44^{+0.20}_{-0.19} \times 10^{-5} eV^2$$

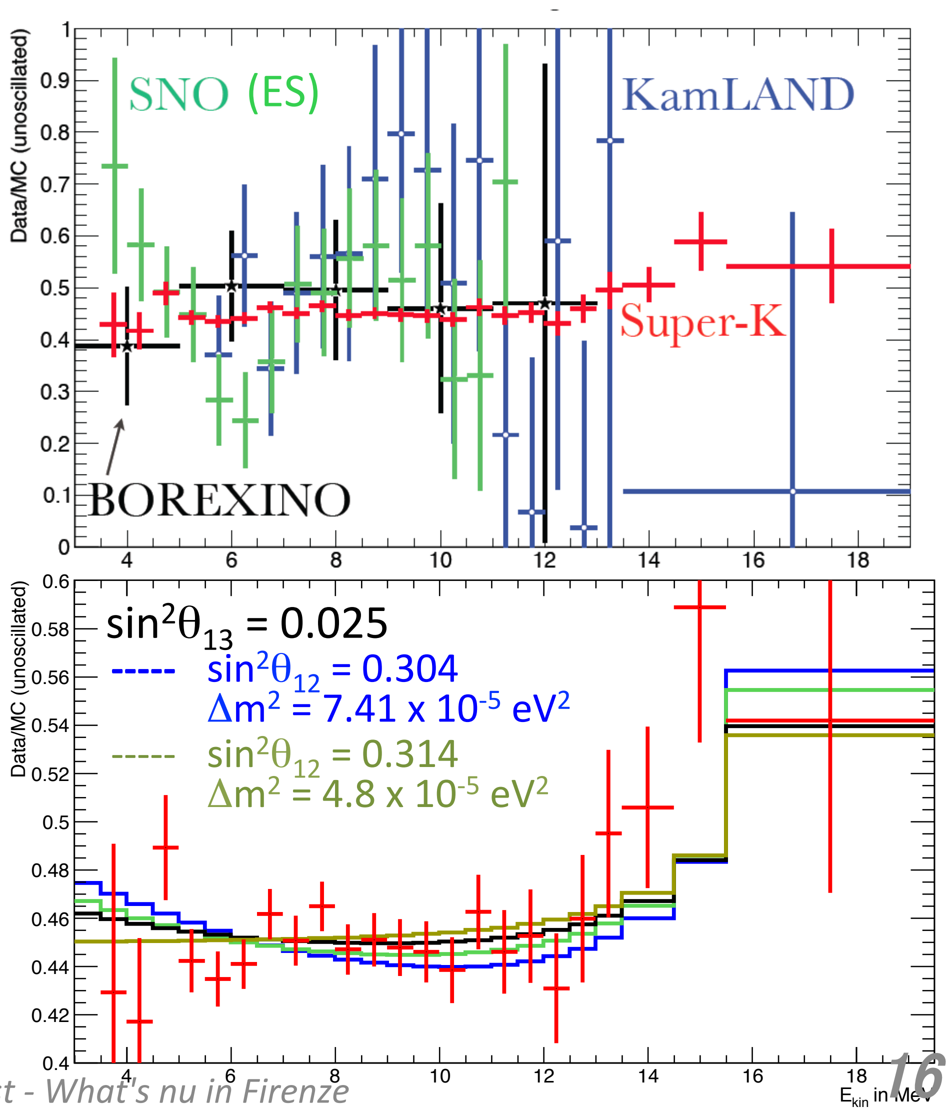
- 1.5 σ difference between KamLAND and solar neutrino experiments in $\Delta m_{12}{}^2$



Upturn ($E_{sol\nu}$)

present

- No observation of upturn yet
- Simple statistical fluctuation ?
  - or may be a trouble
  - or something interesting there
- SK threshold: 3.5 keV
  - aim to 3.0 MeV soon.

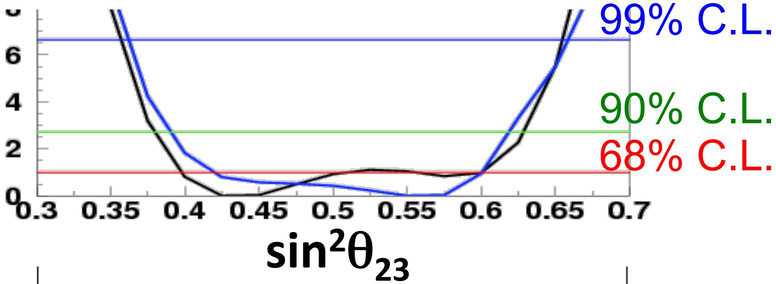


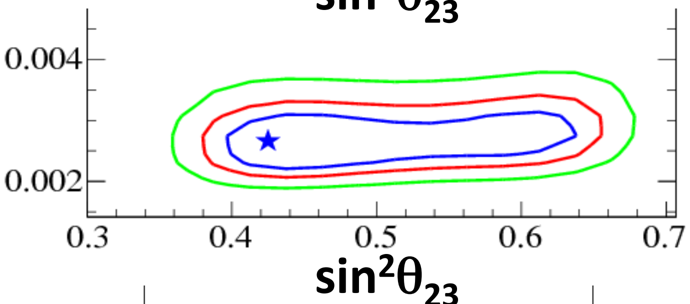
θ_{23} Octant (atmospheric ν) *present*

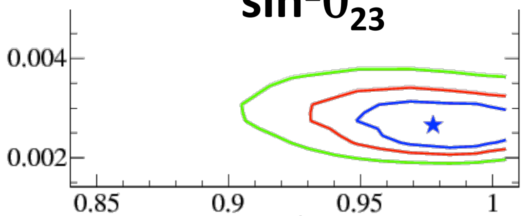
Super-Kamiokande atmospheric neutrino 3 flavor analysis
--- θ_{13} free in the fitting
--- θ_{13} fixed at the best value

We may start to see 1 σ level effect ??

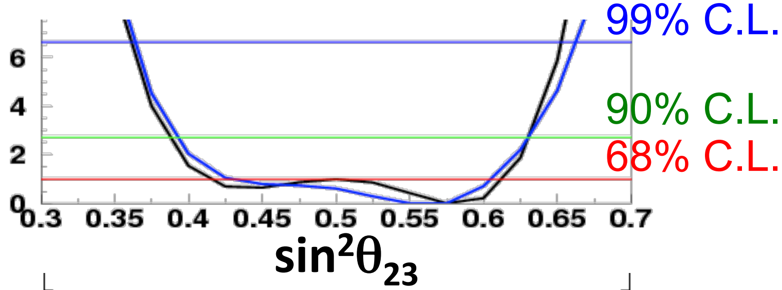
- Normal Mass Hierarchy
- Best fit value: 0.425

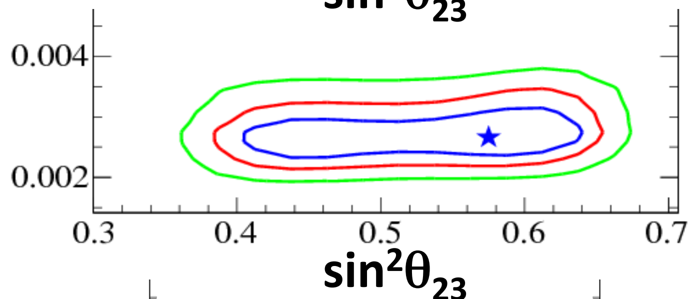


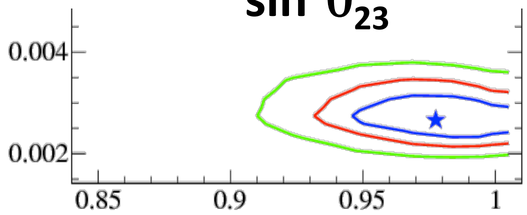




- Inverted Mass Hierarchy
- Best fit value: 0.575

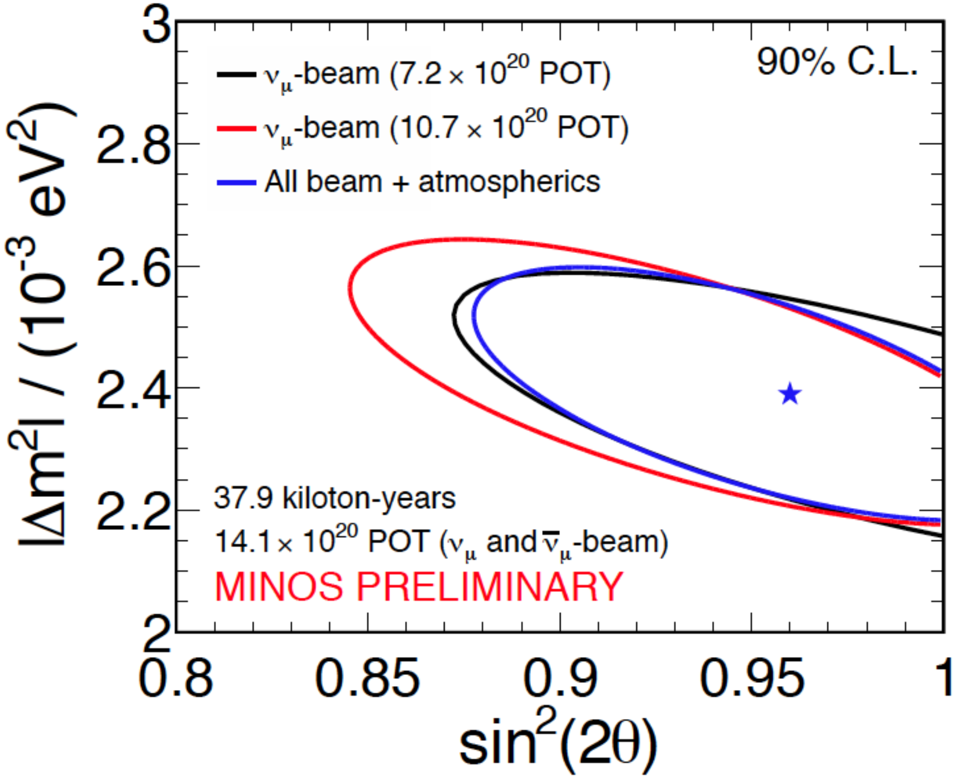


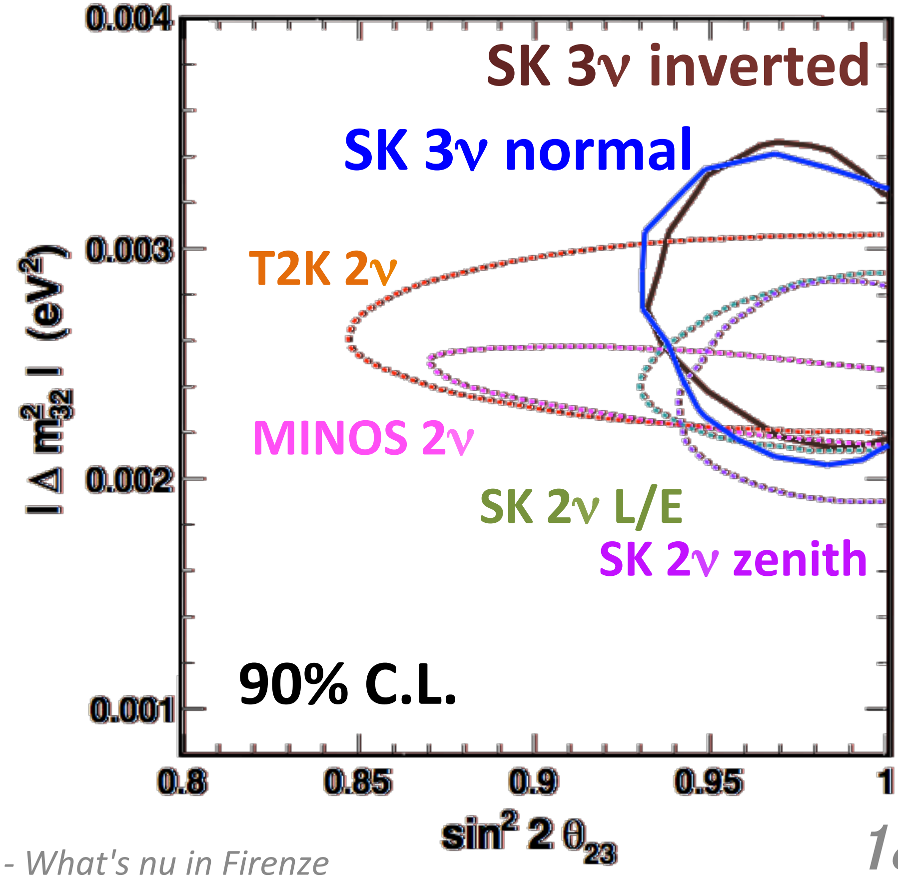




θ_{23} *present*

- Best: $\sin^2 2\theta_{23}$=1.00 > 0.96 (1 par. 90%) [SKI+II+II+IV Atm ν, zenith]
- Best: $\Delta m^2 = 2.39^{+0.09}_{-0.10} \times 10^{-3} eV^2$ [MINOS beam + atmospheric]

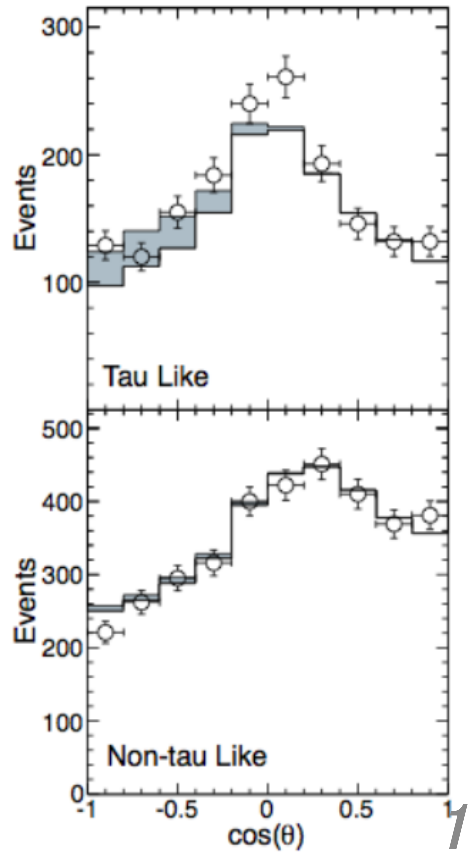




Tau Appearance

present

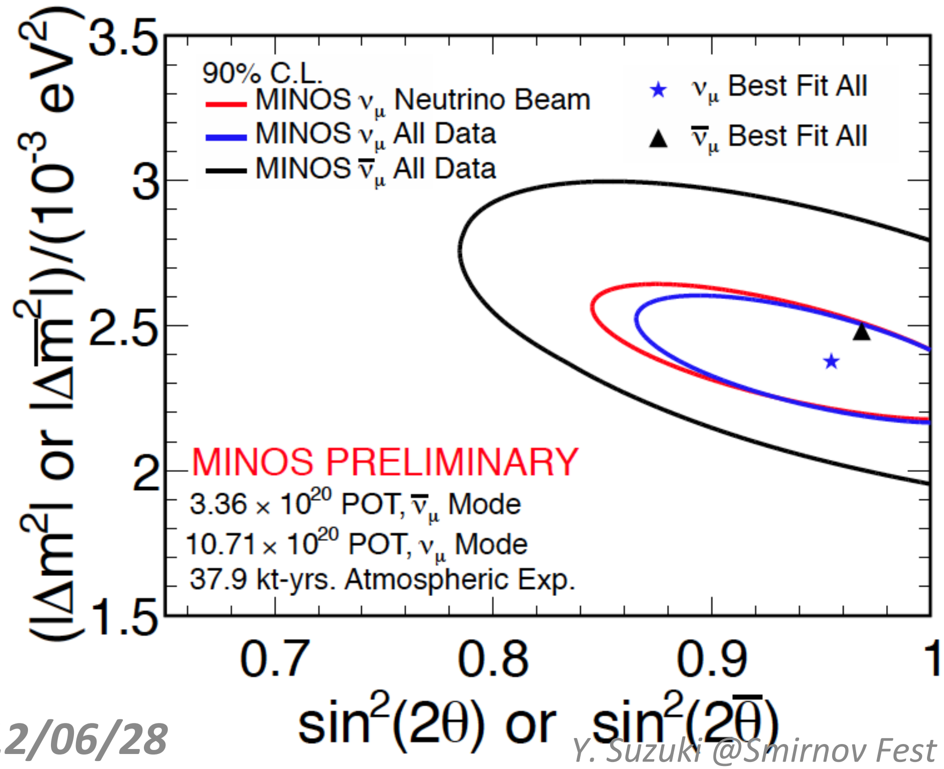
- OPERA results:
  - Found 1 more candidate of ν_τ (total 2 ν_τ events)
    - expected events 2.1
    - with 0.2 backgrounds
- SK results:
  - 2806 days of data
  - Found $180.1 \pm 44.3(stat)^{+17.8}_{-15.2}(syst)$
  - Expected $120.2^{+34.2}_{-34.8}(syst)$
  - Excluded no tau production at **3.8σ**



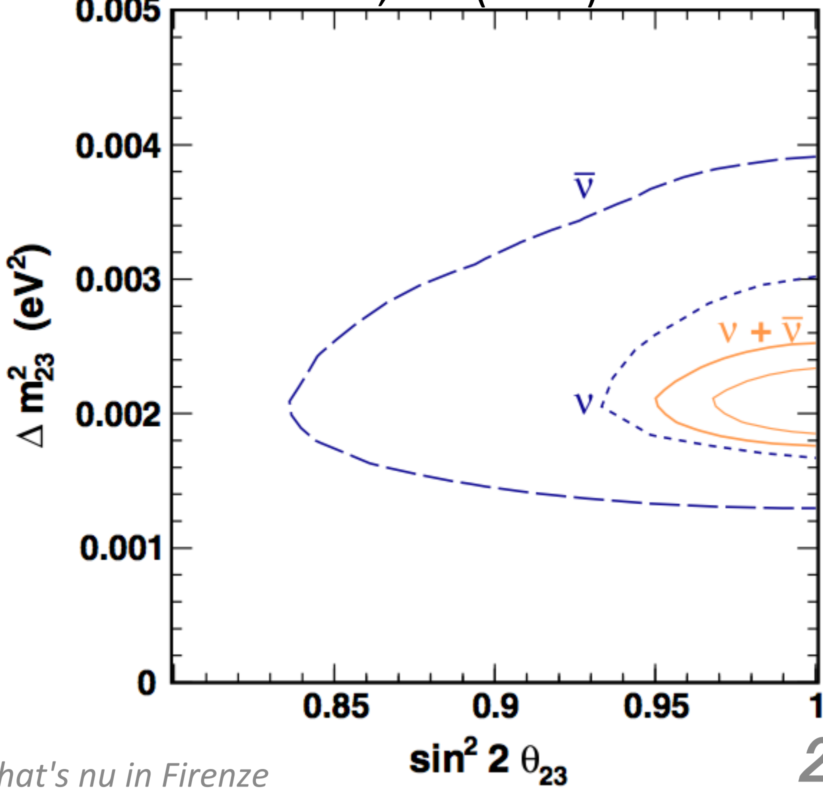
CPT

present

- SK
- MINOS: more data → no difference



SK: PRL, 107(2011)241801

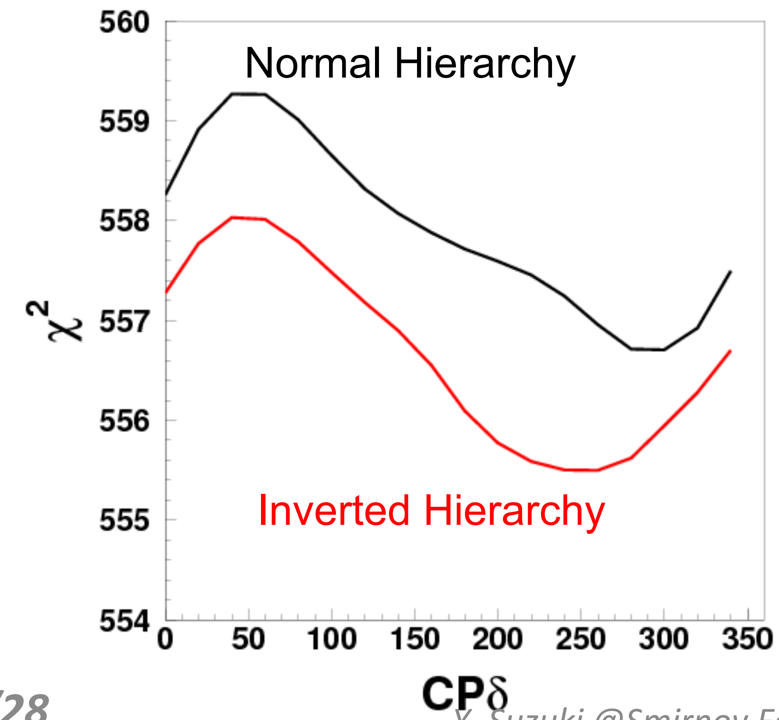


Mass Hierarchy and CP phase (SK Atm ν)

present

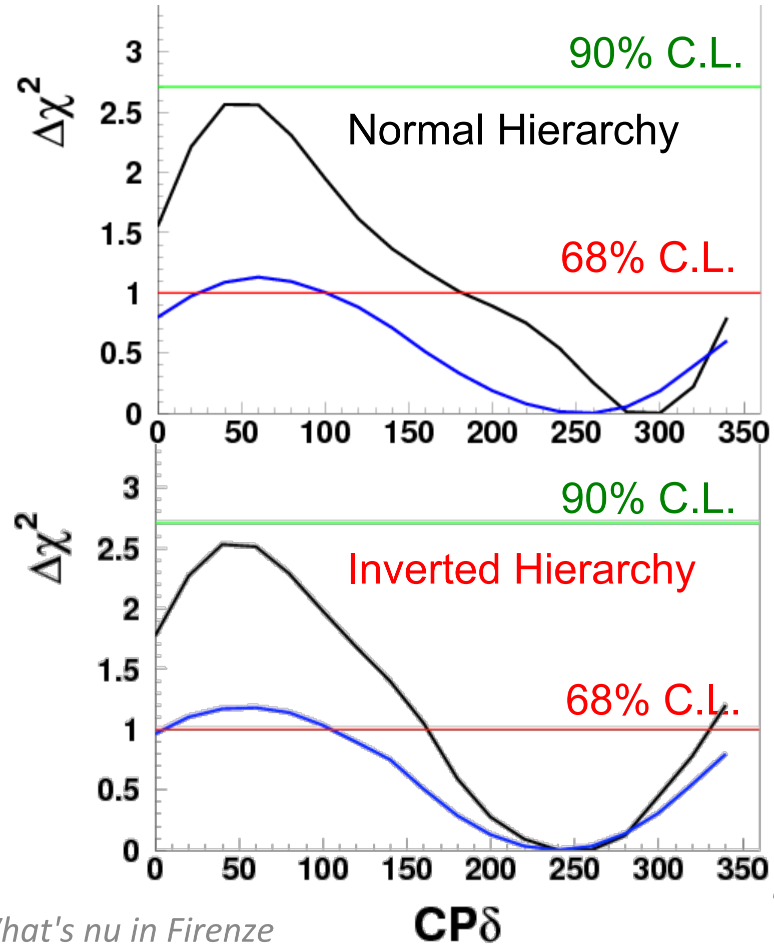
- There may be a hit in Atm ν (SK)
  - NH: χ^2_{min} = 556.7 / 477 dof
  - IH : χ^2_{min} = 555.5 / 477 dof

χ^2_{min} (NH) – χ^2_{min} (IH)= 1.2



--- θ_{13} free in the fitting

--- θ_{13} fixed at the best value



Oscillation Parameters

~14 years after the discovery

present

$$U_{\alpha i} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric ν Acc. LBL	Reactor, Acc. LBL	Solar ν Reactor LBL

Best parameter value from a single experiment (except solar ν)

$\Delta m_{12}{}^2$	$= 7.58^{+0.21}_{-0.20} \times 10^{-5} eV^2$	$(\sim 2.8\%\ @\Delta\chi^2 = 1)$	$[KamLAND]$
$\sin^2\theta_{12}$	$= 0.310^{+0.014}_{-0.014}$	$(\sim 4.5\%\ @\Delta\chi^2 = 1)$	[all solar experiments]
$\Delta m_{23}{}^2$	$= 2.39^{+0.09}_{-0.10} \times 10^{-3} eV^2$	$(\sim 4.2\%\ @\Delta\chi^2 = 1)$	$[MINOS]$
$\sin^2\theta_{23}$	$= 0.575^{+0.038}_{-0.075}$	$(\sim 13\%\ @\Delta\chi^2 = 1)$	[Super-Kamiokande 3ν Inv.MH, read from fig.]
$\sin^2\theta_{13}$	$= 0.0223 \pm 0.0028$	$(\sim 13\%\ @\Delta\chi^2 = 1)$	[Daya Bay]

Missing:

Mass hierarchy, CP phase, Majorana phase,.

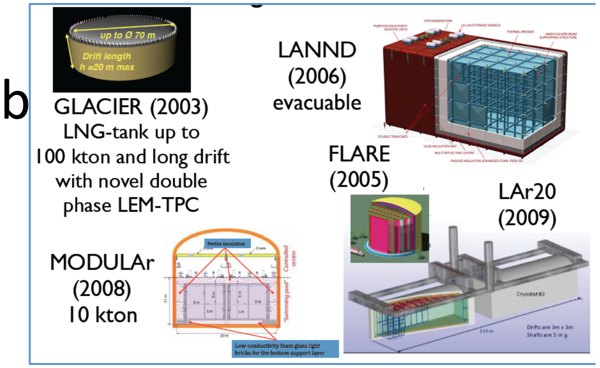
Future

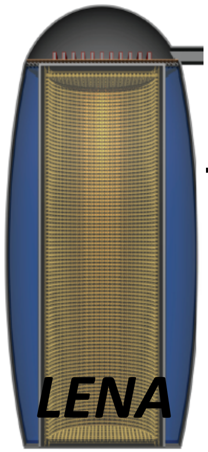
Very personal opinion as usual.

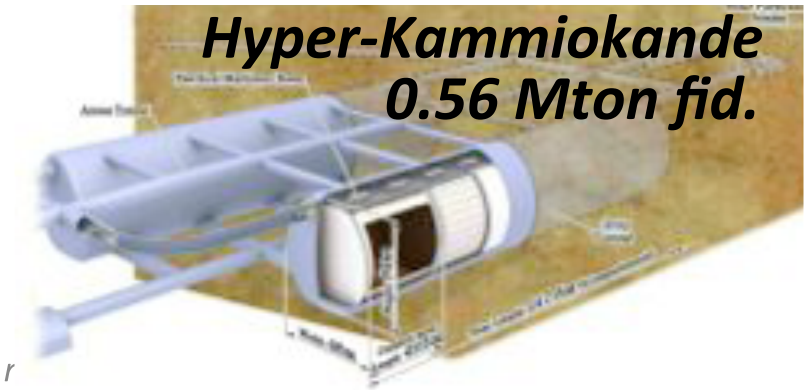
Mainstream

- Mass hierarchy, Octant, CPV and unexpected
- Larger or sophisticated detectors & Intense neutrino beams (many talks….)
  - liq. Ar.
    - US. Homestake w/ ν−beam from Fermilab
    - Europe: example, Pyhäsalmi <- CERN
    - Japan: Okinoshima <- JPARC
  - Water
    - Japan: 0.5 Mton water Cherenkov w/ν−beam from JPARC
  - Liq. Scint.
    - Europe: many options

Several Concepts, A. Rubia @NEUTRINO2012



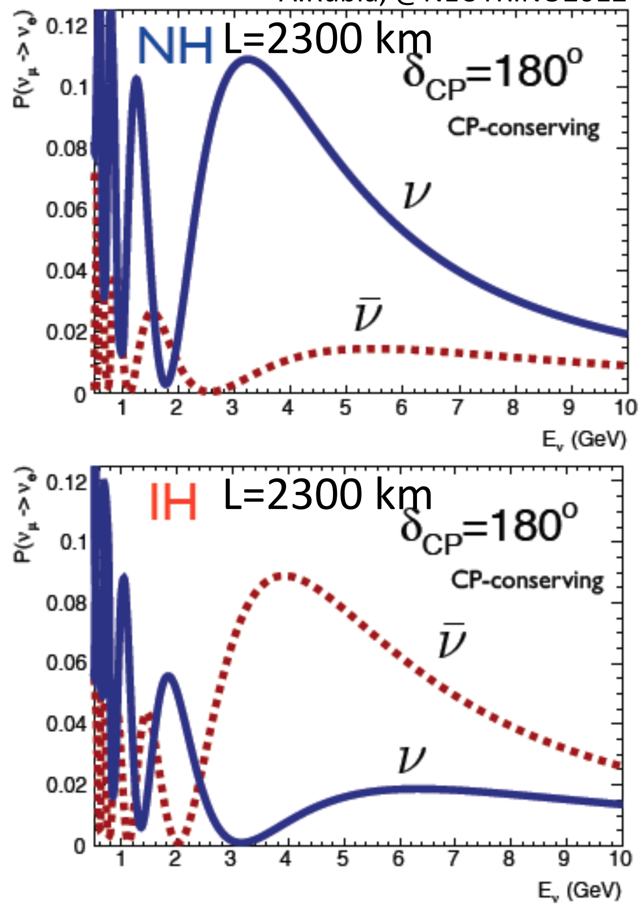




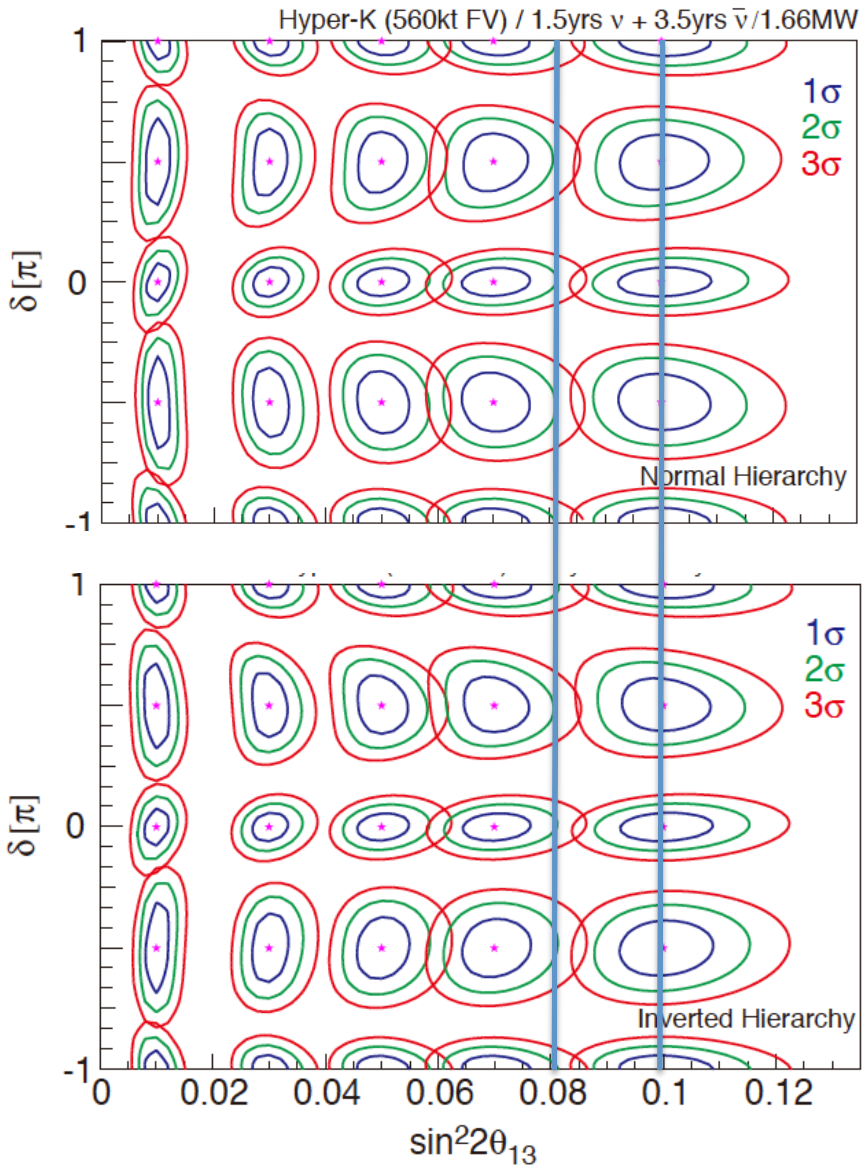
Sensitivity

- Mass hierarchy (MH)
  - ➔ MH is an exclusive OR (On/Off) problem
  - ➔ 2~3σ effect is enough to judge.
  - – Find a place no obstacles from other parameters
  - – Very long baseline (ex): Clear difference Normal MH ⇔ Inverted MH
  - – But there may be a dark horse !
- CP phase
  - – We hope that MH will be resolved before the CPV experiments.
  - – If not,
    - then you can obtain results for two cases (NMH & IMH), do not need to mix up MH and CPV.
  - – Shorter distance may be justified for a good CPV experiment

A.Rubia, @NEUTRINO2012



CP phase



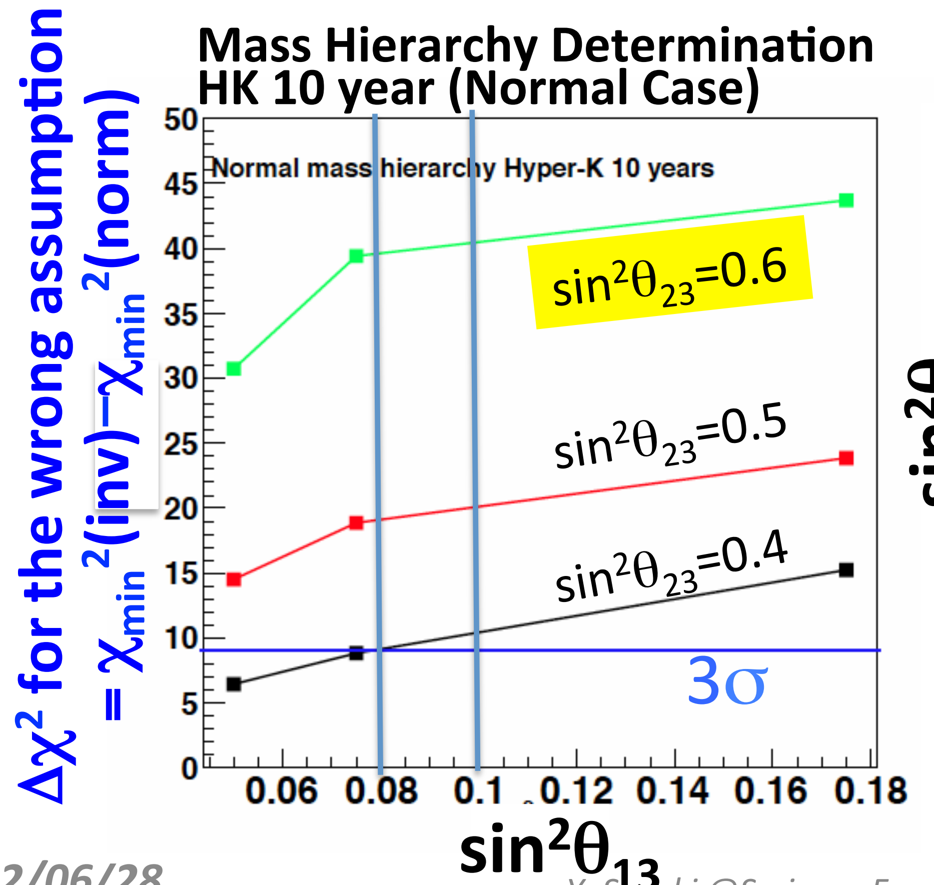
- HK (0.56 Mt)+JPARC
  - 295 km baseline
  - 0.75 MW x10 (3+7) yrs
  - 5% systematics

➔ 74% of δ can be covered and determined with 3σ effect (for known MH)

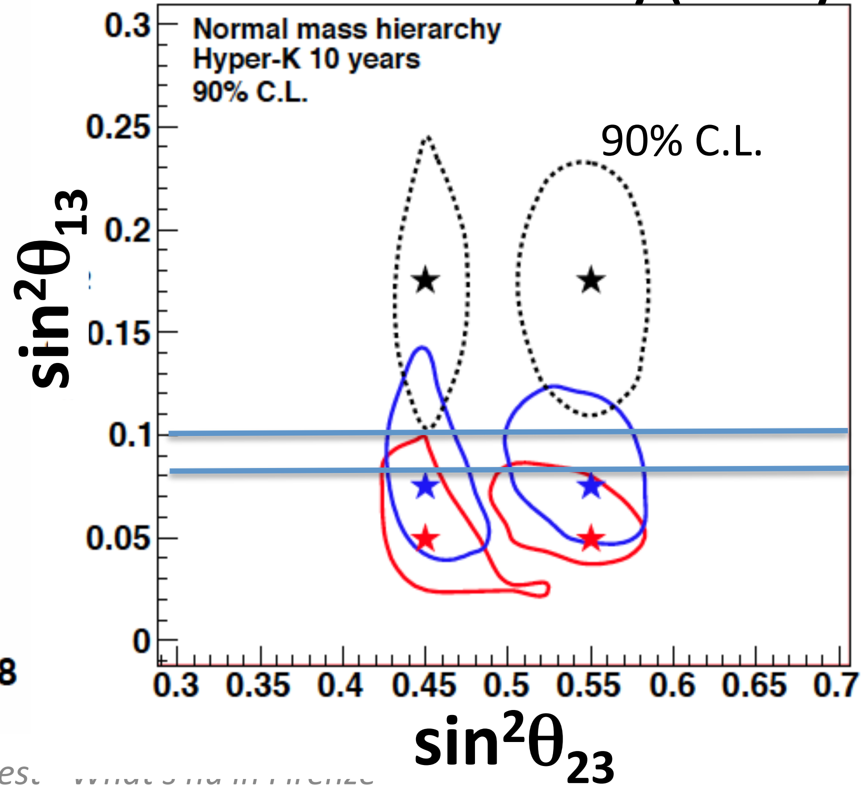
Atmospheric neutrinos
(Complementary or Short Cut for MH & Octant)

- Atmospheric ν: larger θ_{13} is a good news for atmospheric neutrinos

Mass Hierarchy Determination
HK 10 year (Normal Case)



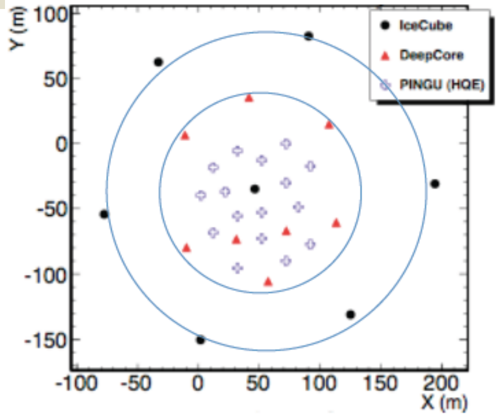
Octant Determination
Normal mass hierarchy (HK10 yrs)



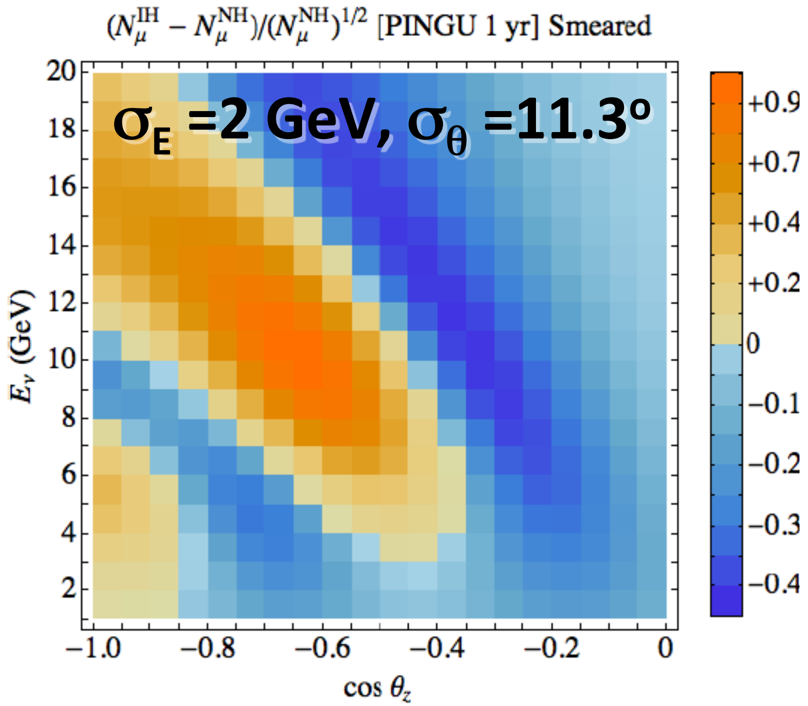
Quick MH ?

- PINGU ?
  - Add 20 strings with ~1000 optical modules inside the IceCUBE Deep Core region
  - Expected energy threshold of 1 GeV
  - Multi-Megaton effective mass
  - Shorter path to the MH
    - E. Akhmedov, S. Razzaque, A. Smirnov: arXiv: 1205.7071v2

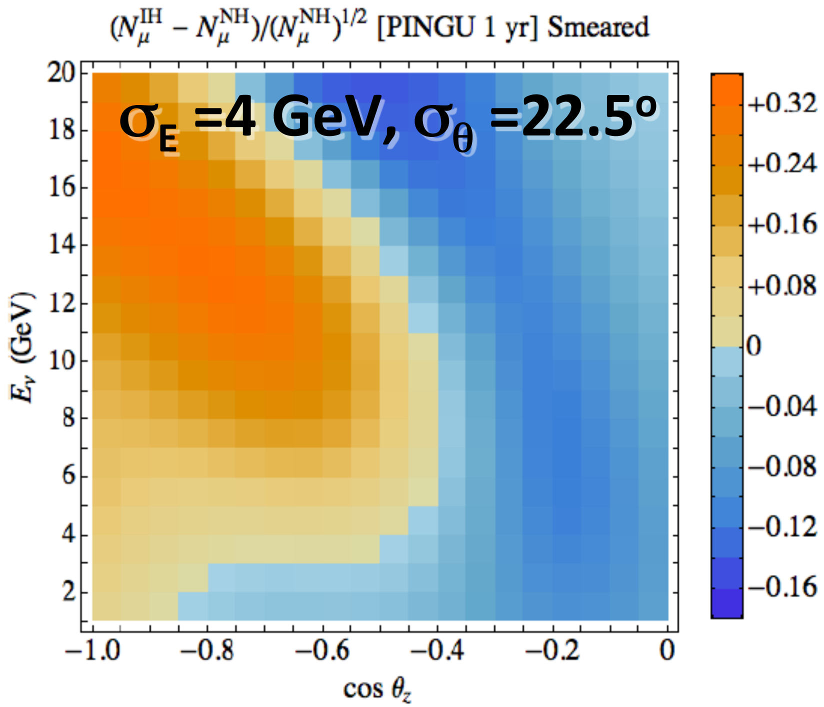
PINGU geometry
(more compact version also studied)



S^{tot} = 7.2σ for 10% systematics



S^{tot} = 3.0σ for 10% systematics



Is future bright?

- Yes ….Mass Hierarchy, CPV → Origin of Matter..
- but may be difficult…..(by other reason than science)

Is future bright?

- Yes ….Mass Hierarchy, CPV ➔ Origin of Matter..
- but may be difficult…..(by other reason than science)

Debt and politics in America and Europe

Turning Japanese

The absence of leadership in the West is frightening—and also rather familiar

Jul 30th 2011 | from the print edition

The Economist

http://www.economist.com/node/21524874

How we justify FUTURE under such serious environments

- For our funding agencies and general public
  - One number δ_{cp} may not justify spending a few hundred million Euros/dollars and a few 10s billion yen for the large detectors
- Need Neutrino Oscillation + alpha……
  - Multi-purpose is really important and essential
    - Discovery potential + Measurement

➔ Proton decay and Astrophysics….

More ingredients

- Proton decay and astrophysics can even justify even larger detectors.
- Multi-Megaton
  - PINGU (but need much lower threshols and much higher resolution)
  - TITAND (multi-Megaton a la SK/HK)

➔ Proton Decay: 10^{36} years

➔ Supernova Neutrinos: Burst detection every year (5 events for 5 Mton @5Mpc (1SN/yr))

➔ More money to the detector !

Summary

- We have measured all the mixing angles.
- Need to determine/measure Mass Hierarchy, θ_{23} Octant, CP-phase.
- Determination of MH and CP-phase measurement can be done separately.
- Large Neutrino detector may need to be justified for the large amount of money
- Important to include other physics, like proton decay, supernova burst detection and so on.

Epilog

- Congratulation again the 60 years birthday.
- We, experimentalists, thank Alexei Smirnov for his bright ideas and many suggestions for us to study Neutrino Oscillations.
- I, personally, have spent very nice time and really enjoyed the SAGA towards the discovery of neutrino oscillations with many distinguished theorists like Alexei for more than 20 years.

Story Continues