Invisibles 16 workshop
Padova, Sep. 12, 2016

Status and prospect of neutrino oscillation experiments

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Outline

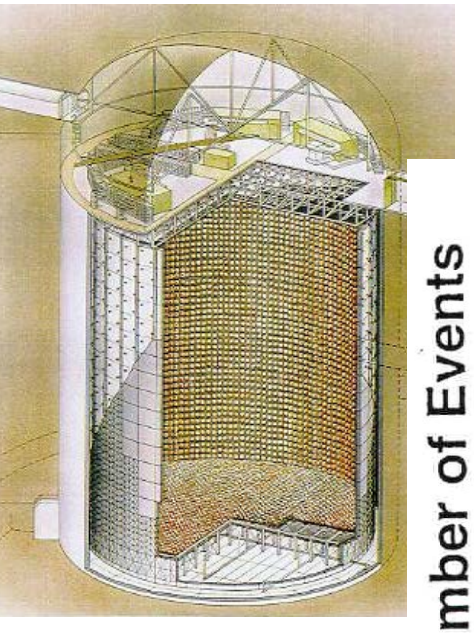
- *Introduction and present status of neutrino oscillations*
- *Future oscillation studies*
- *Other physics with future experiments*
- *Summary*

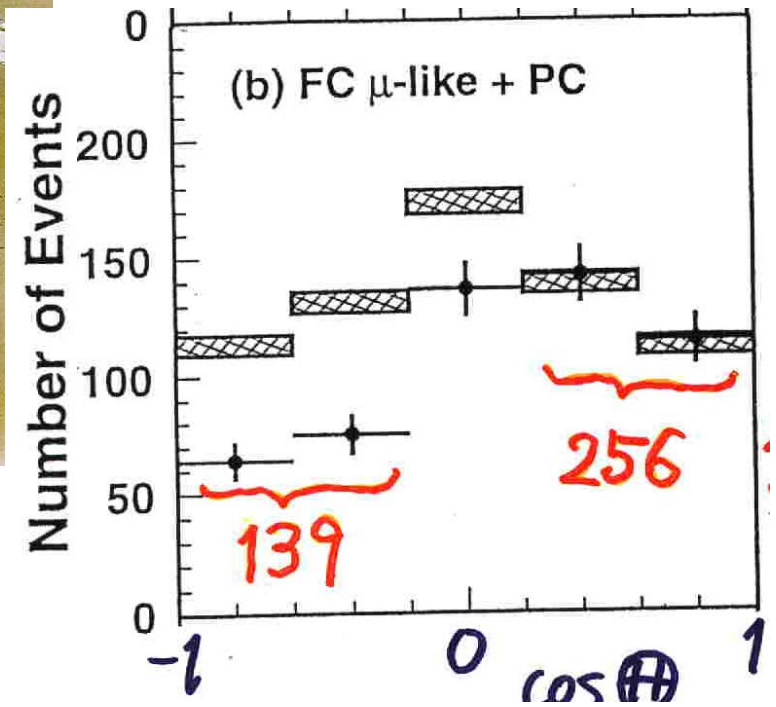
Introduction and present status of neutrino oscillations

Introduction: Discovery of neutrino oscillations

Super-K, PRL 81 (1998) 1562

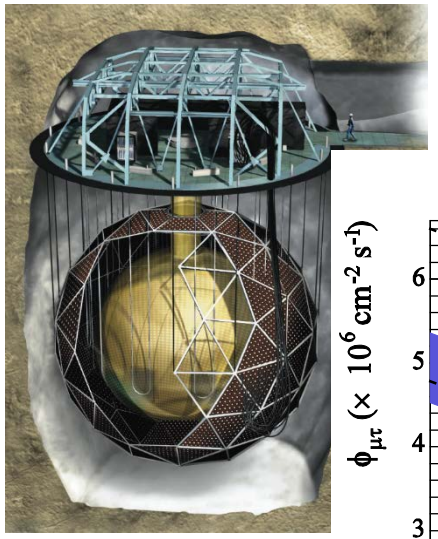
Atmospheric neutrino oscillations

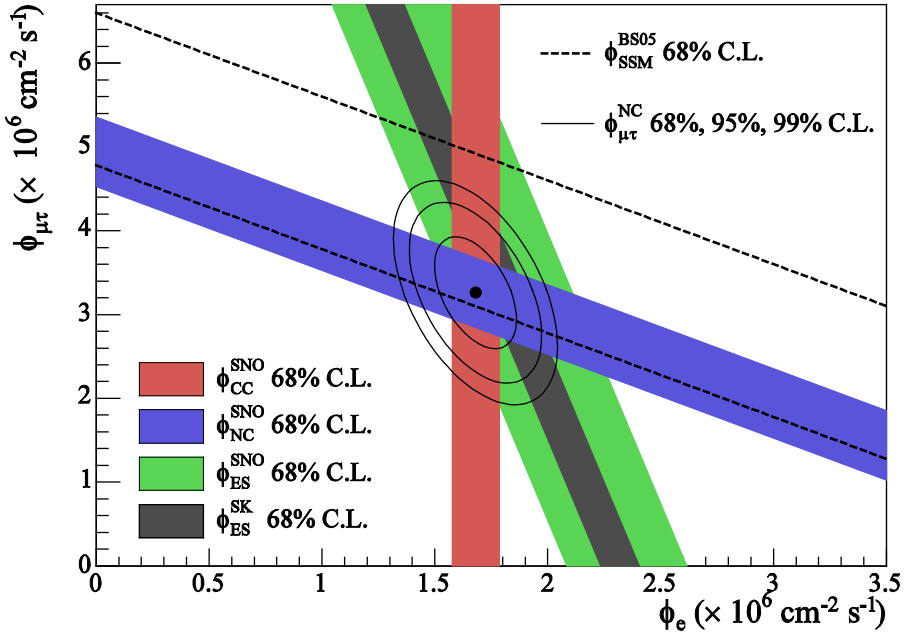




SNO PRL 89 (2002) 011301
SNO PRC 72, 055502 (2005)

Solar neutrino oscillations





The very small neutrino masses opened a window to study the physics beyond the Standard Model of particle physics!

Status of neutrino oscillation studies

$\nu_\mu \rightarrow \nu_\tau$ oscillations (Δm_{23}, θ_{23})

Atmospheric: Super-K, Soudan-2, MACRO IceCube/Deepcore, …

LBL: K2K, MINOS, OPERA, T2K, NOvA, …

$\nu_e \rightarrow (\nu_\mu + \nu_\tau)$ oscillations (Δm_{12}, θ_{12})

Solar: SNO, Super-K, Borexino, …

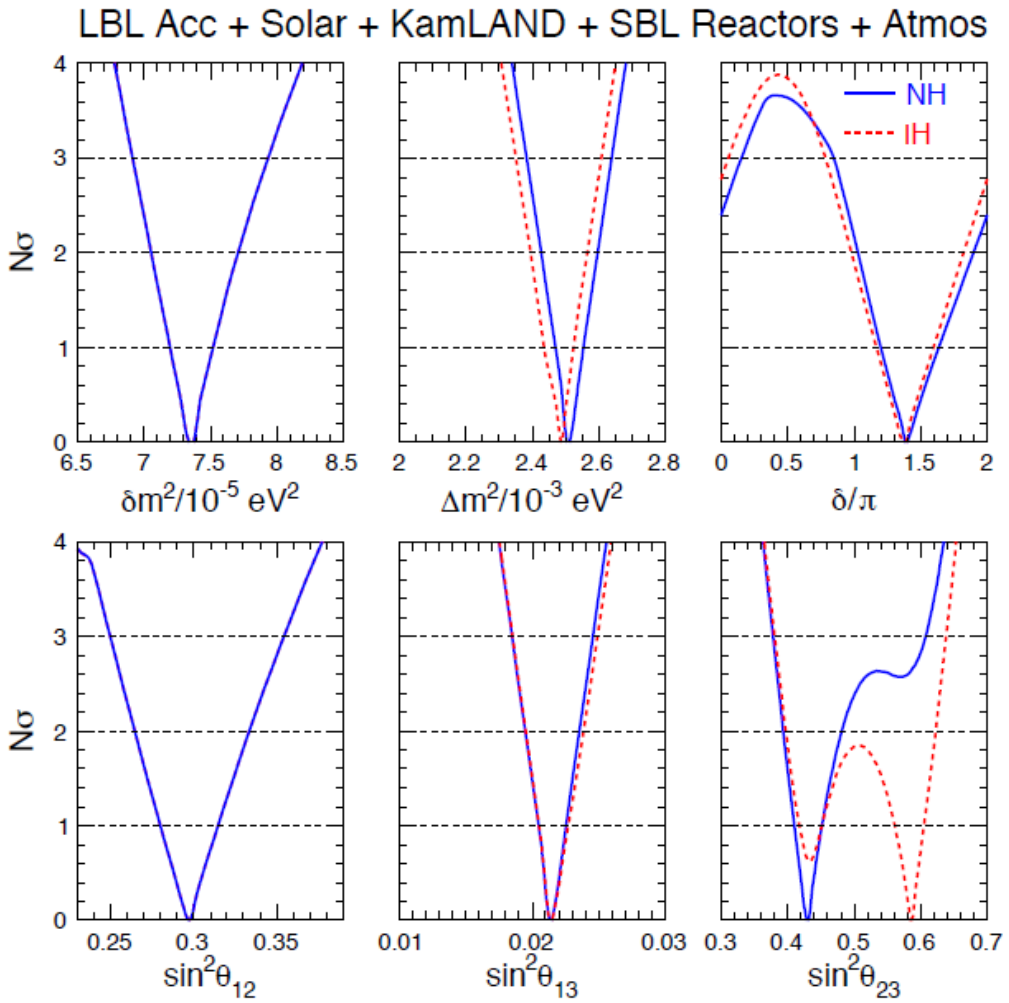
Reactor: KamLAND

θ_{13} experiments

LBL: MINOS, T2K, NOvA, …

Reactor: Daya Bay, Reno, Double Chooz

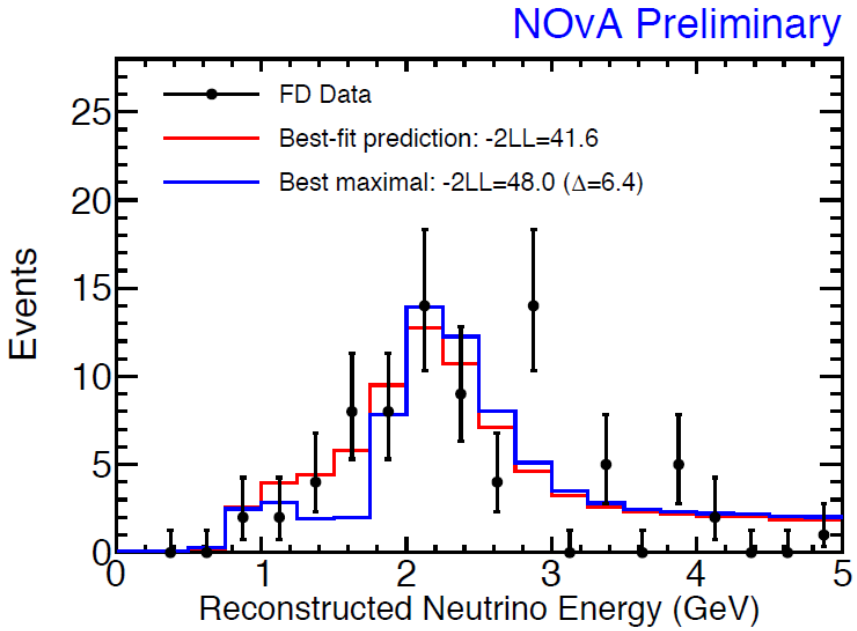
Status *(A. Marrone, @Neutrino 2016)*



Basic structure for 3 flavor oscillations has been understood!

Some tensions (ν_μ disappearance)

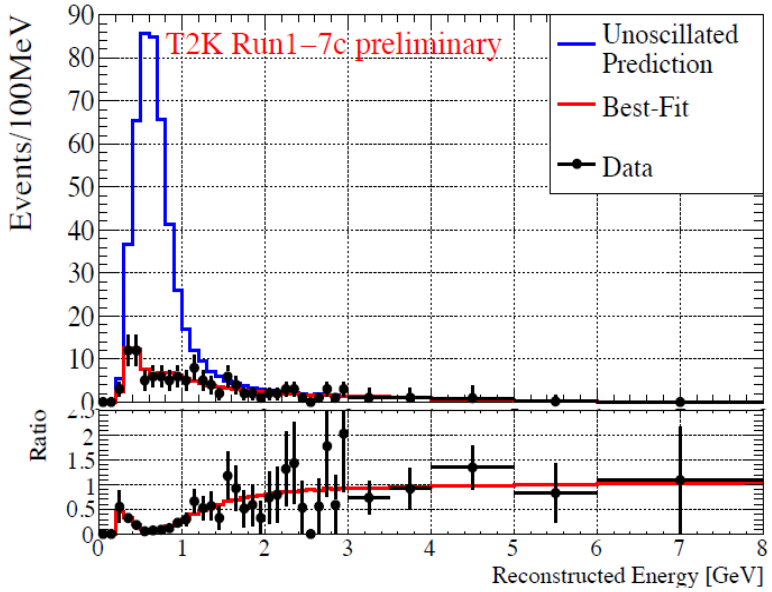
NOvA @Neutrno2016

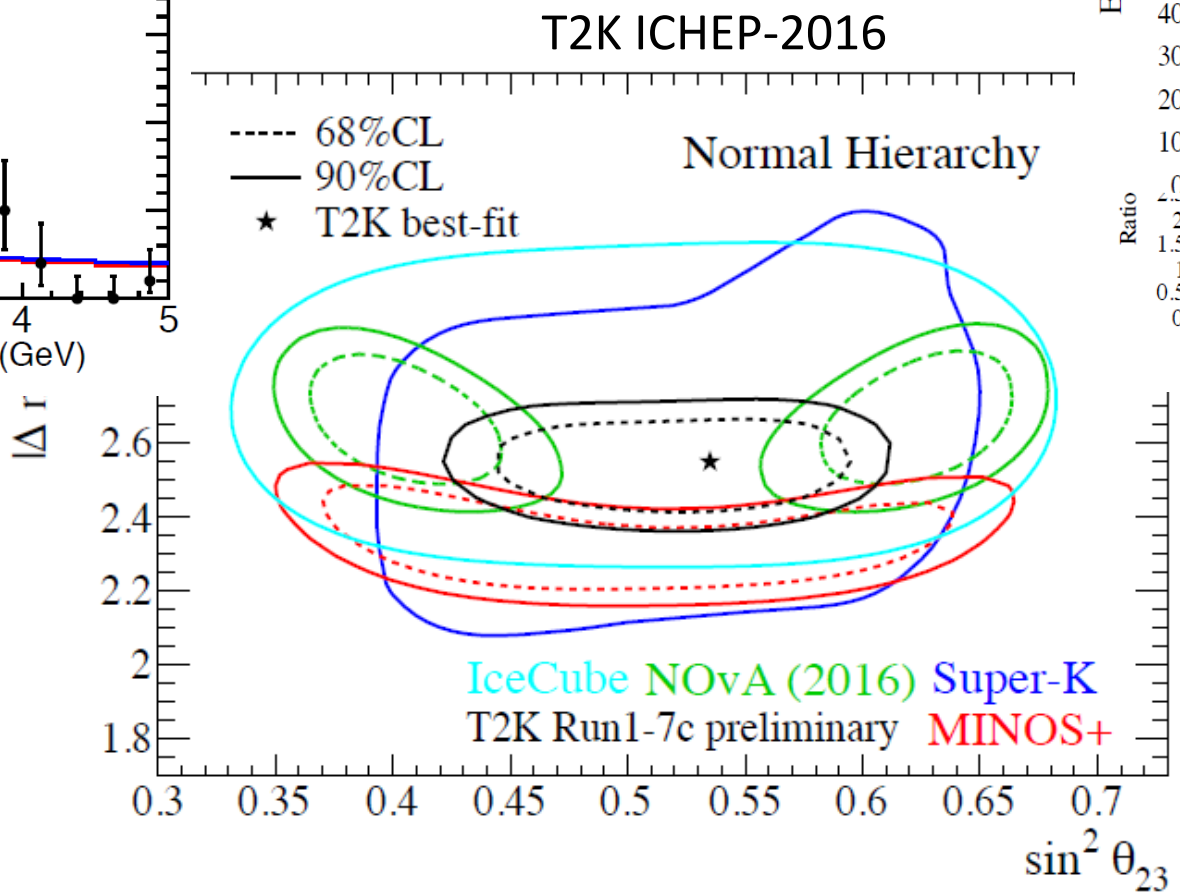


Maximal mixing excluded at 2.5σ.

T2K

T2K, PRL 112 (2014) 181801
T2K@ICHEP 2016



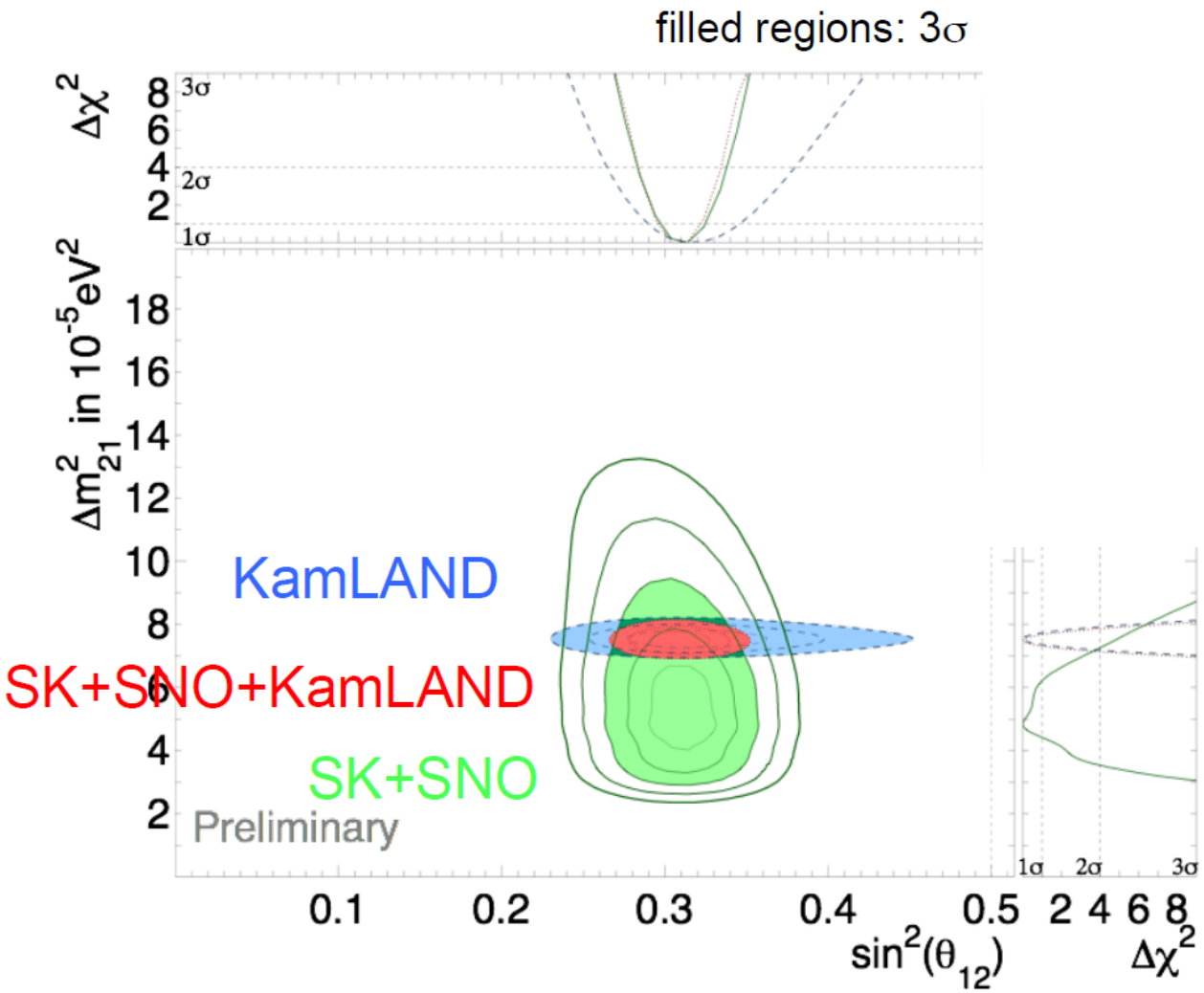


Consistent with maximal mixing…

Some tensions (solar neutrino oscillations and day/night effect)

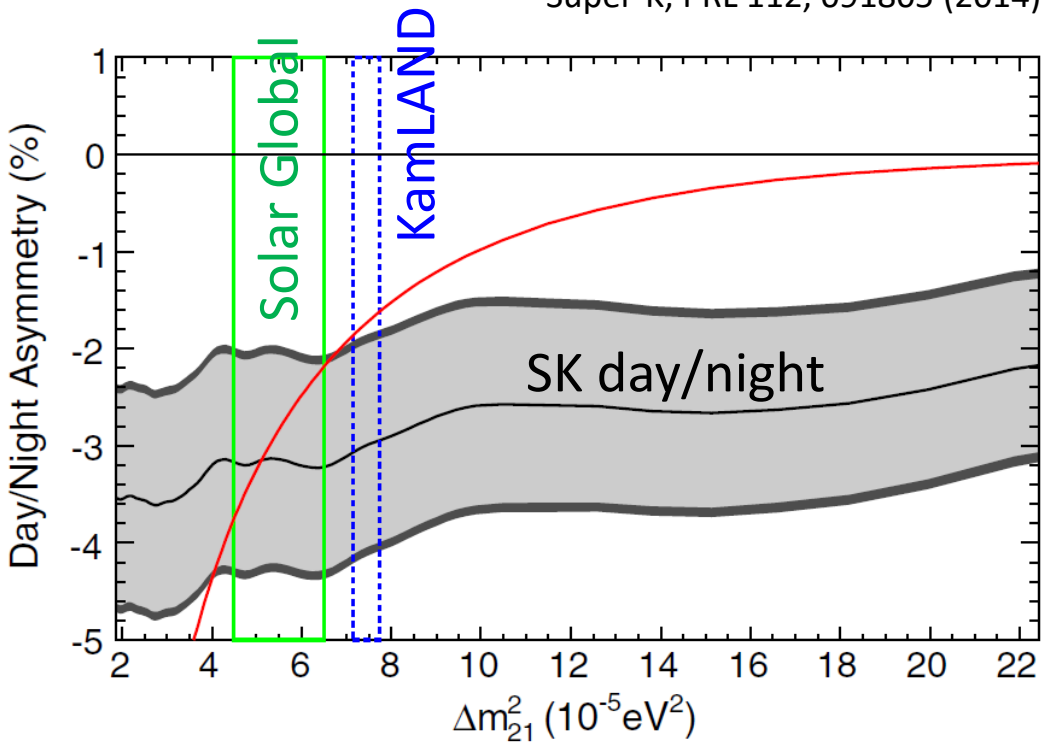
Status of the 12-parameter measurements

S. Moriyama (Super-K), Neutrino 2016



SK day/night and Δm_{12}^2

Super-K, PRL 112, 091805 (2014)

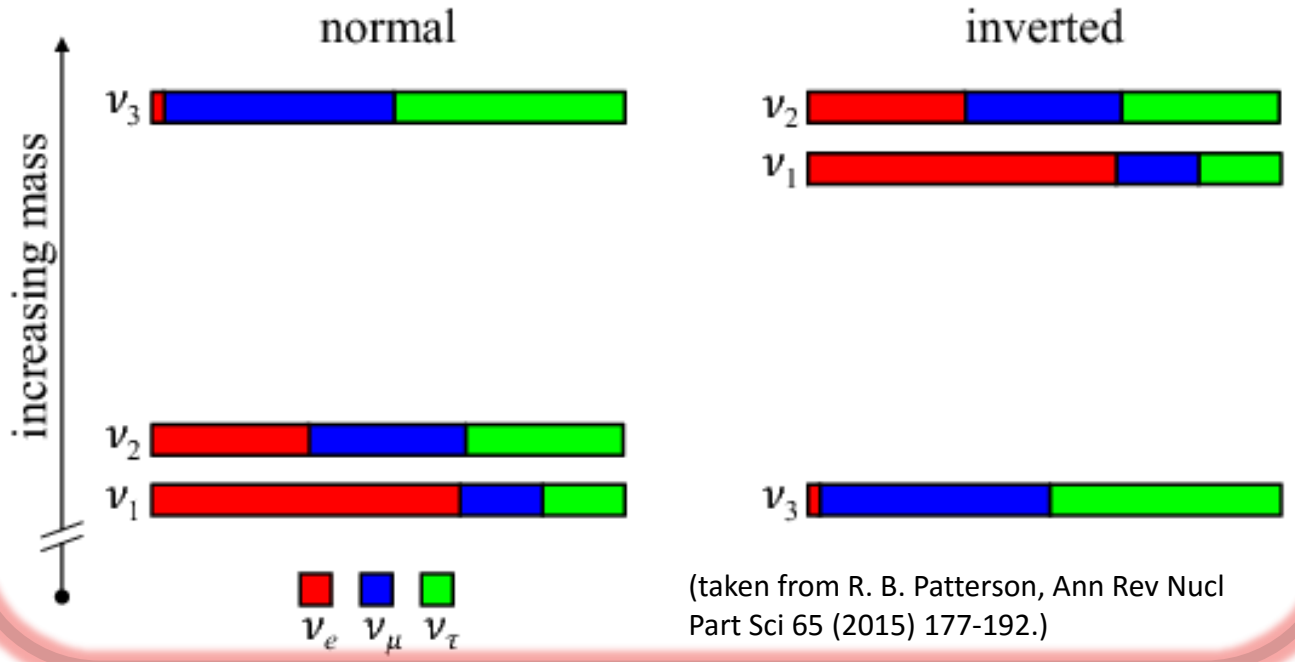


✓ The data might indicate that there is something interesting going on in solar neutrinos…. (will came back later.)

Future oscillation studies

Agenda for the future neutrino measurements

Neutrino mass hierarchy?



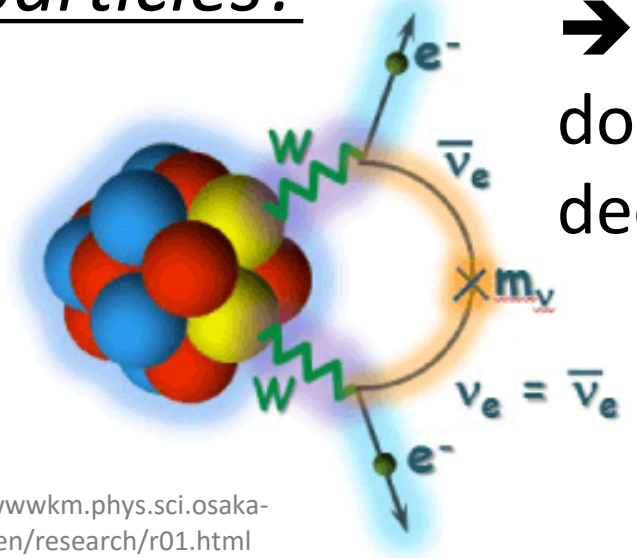
(taken from R. B. Patterson, Ann Rev Nucl Part Sci 65 (2015) 177-192.)

CP violation?

$$P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \ ?$$

Baryon asymmetry of the Universe?

Are neutrinos Majorana particles?



http://wwwkm.phys.sci.osaka-u.ac.jp/en/research/r01.html

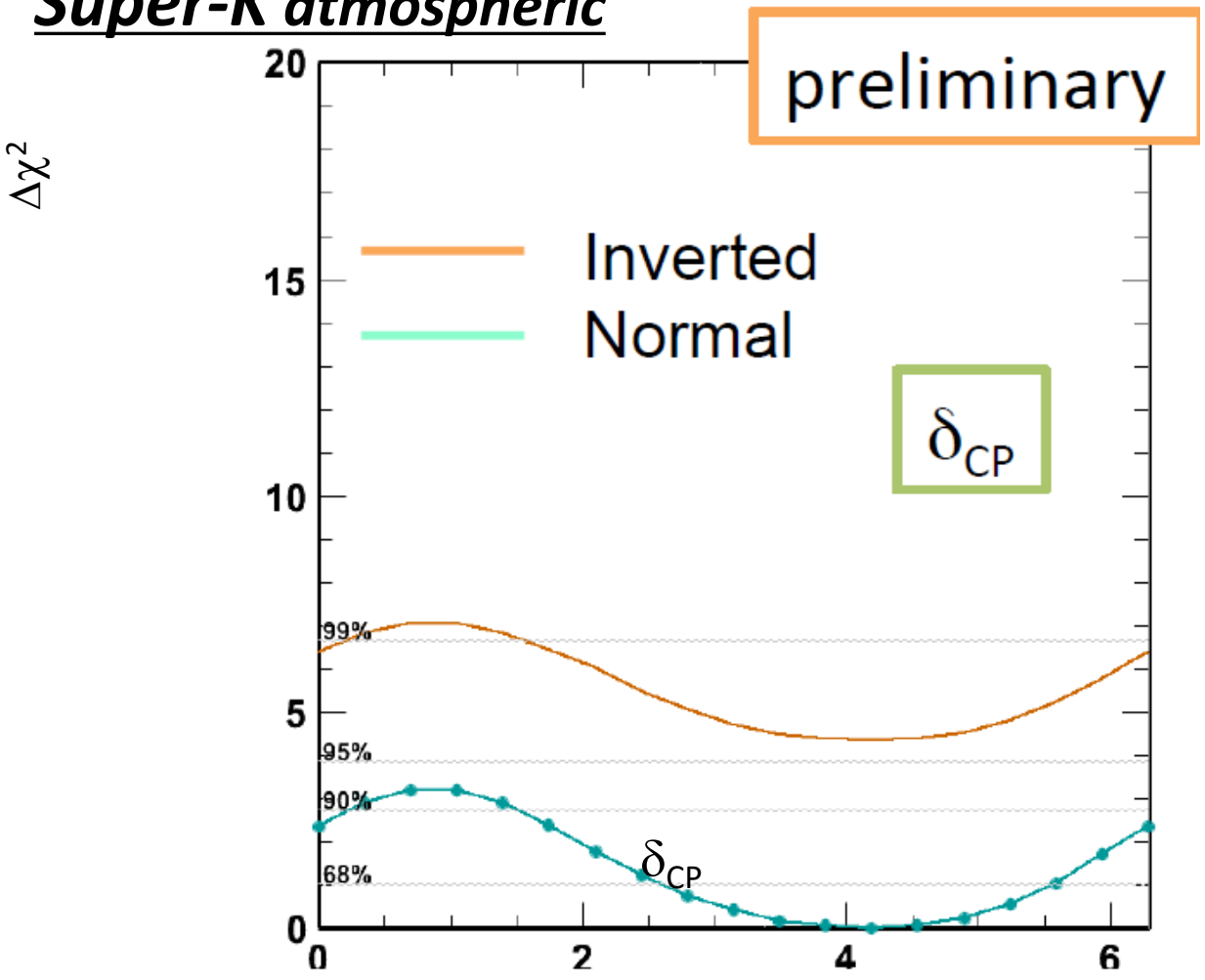
➔ Neutrinoless double beta decay

Absolute neutrino mass?

Beyond the 3 flavor framework? (Sterile neutrinos?)

Mass hierarchy and CP violation measurements @Neutrino 2016

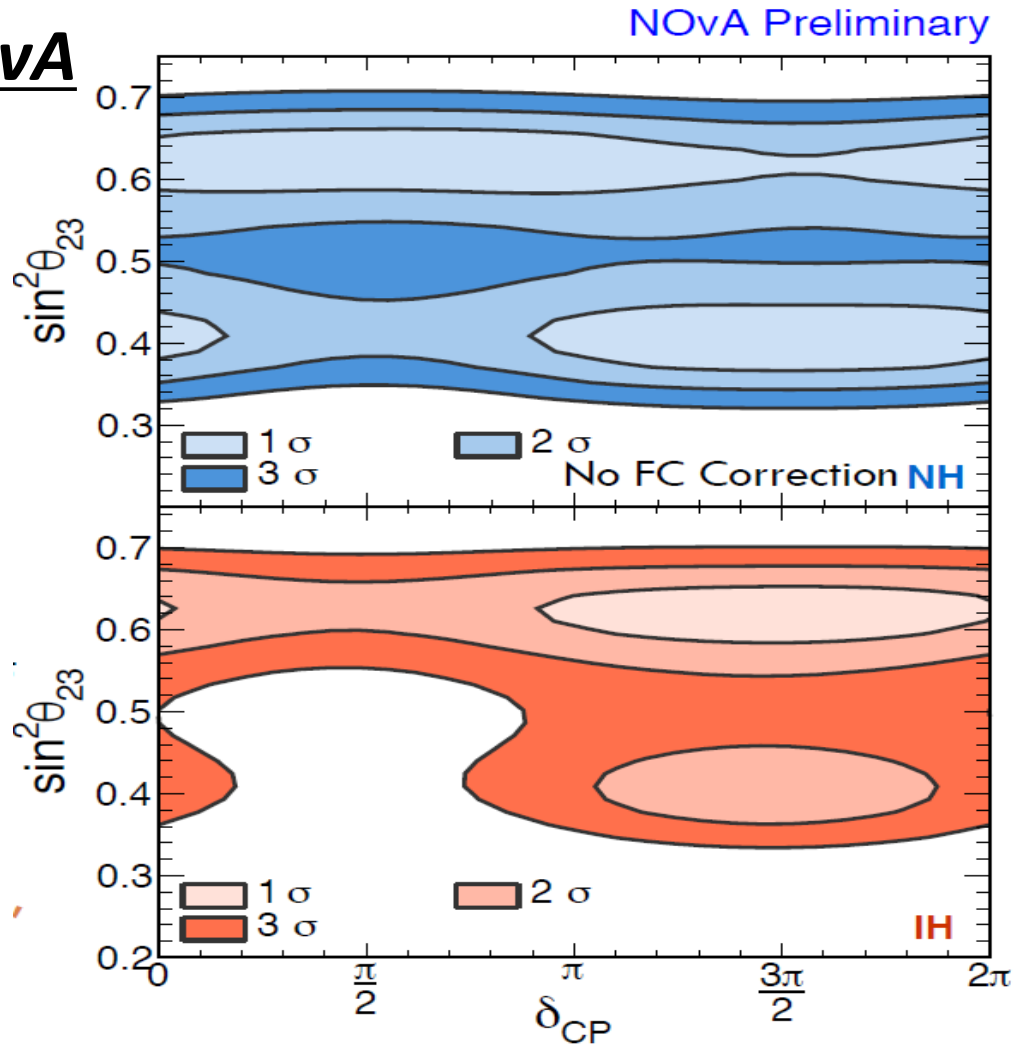
Super-K atmospheric



Best fit at δ_{CP} = ~1.33π (NH)

$\Delta\chi^2$ (IH-NH) = 4.3 (expt'd = 3.1)

NOvA



Best fit at δ_{CP} = 1.49π (NH)

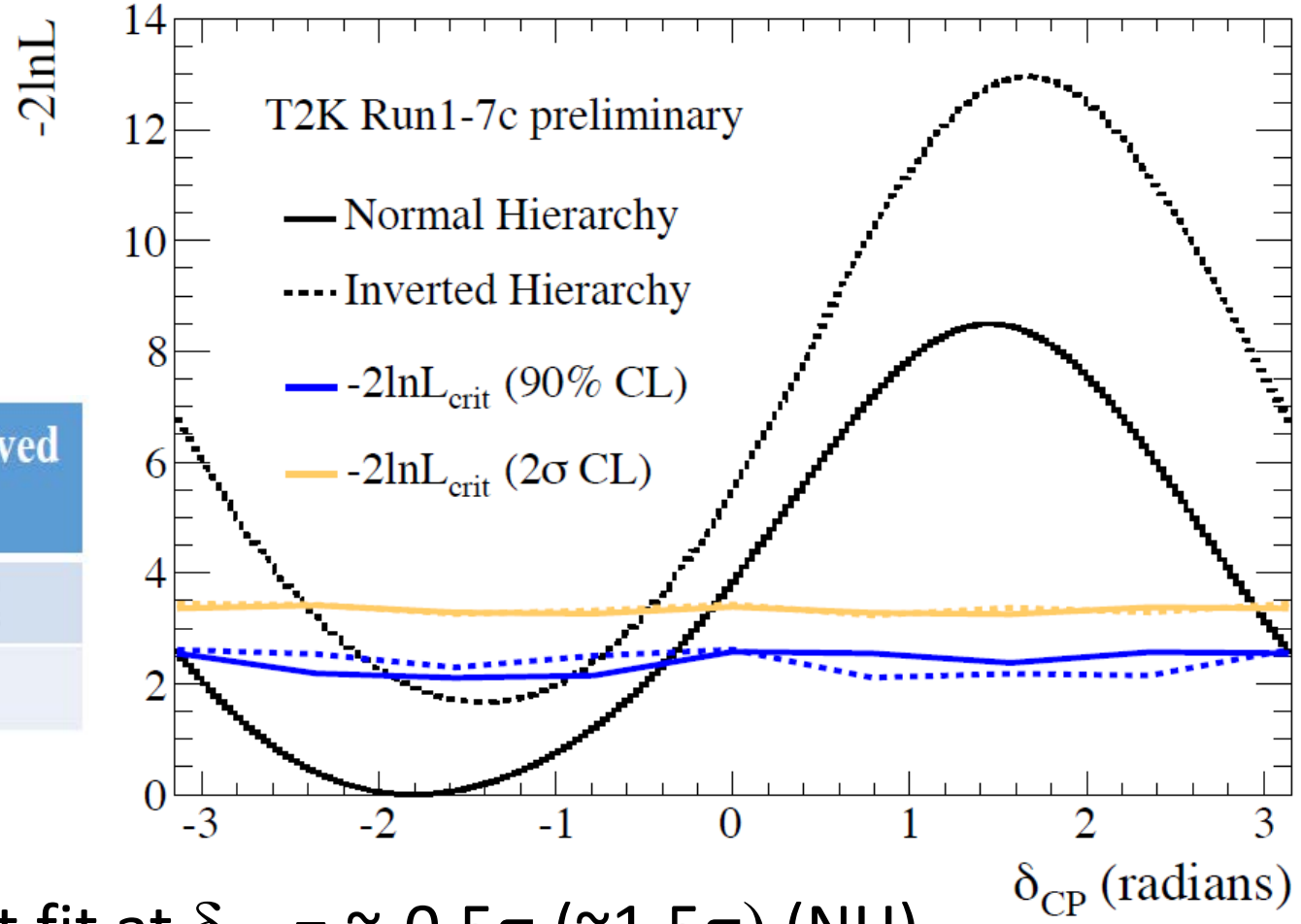
$\Delta\chi^2$ (IH-NH) = 0.47

Mass hierarchy and CP violation measurements @ICHEP-2016

T2K

32 ν_e events observed
4 anti-ν_e events observed

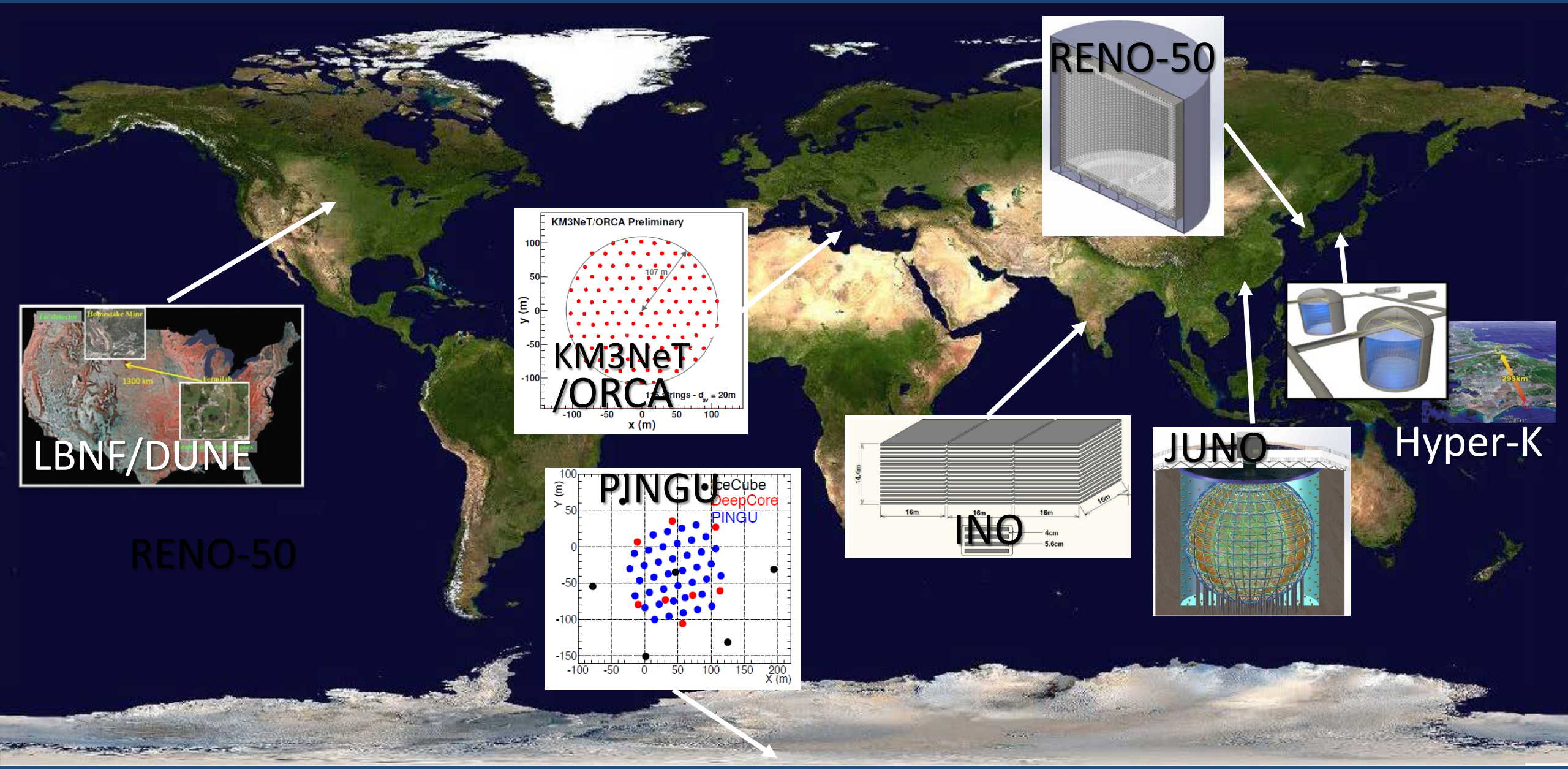
	$\delta_{cp} = -\pi/2$ (NH)	$\delta_{cp} = 0$ (NH)	$\delta_{cp} = +\pi/2$ (NH)	$\delta_{cp} = \pi$ (NH)	Observed
ν_e	28.7	24.2	19.6	24.1	32
$\bar{\nu}_e$	6.0	6.9	7.7	6.8	4



δ_{CP} =0 and π disfavored at 90%CL. Best fit at δ_{CP} = ~-0.5π (~1.5π) (NH)
$\Delta\chi^2$ (IH-NH) = ~1.5

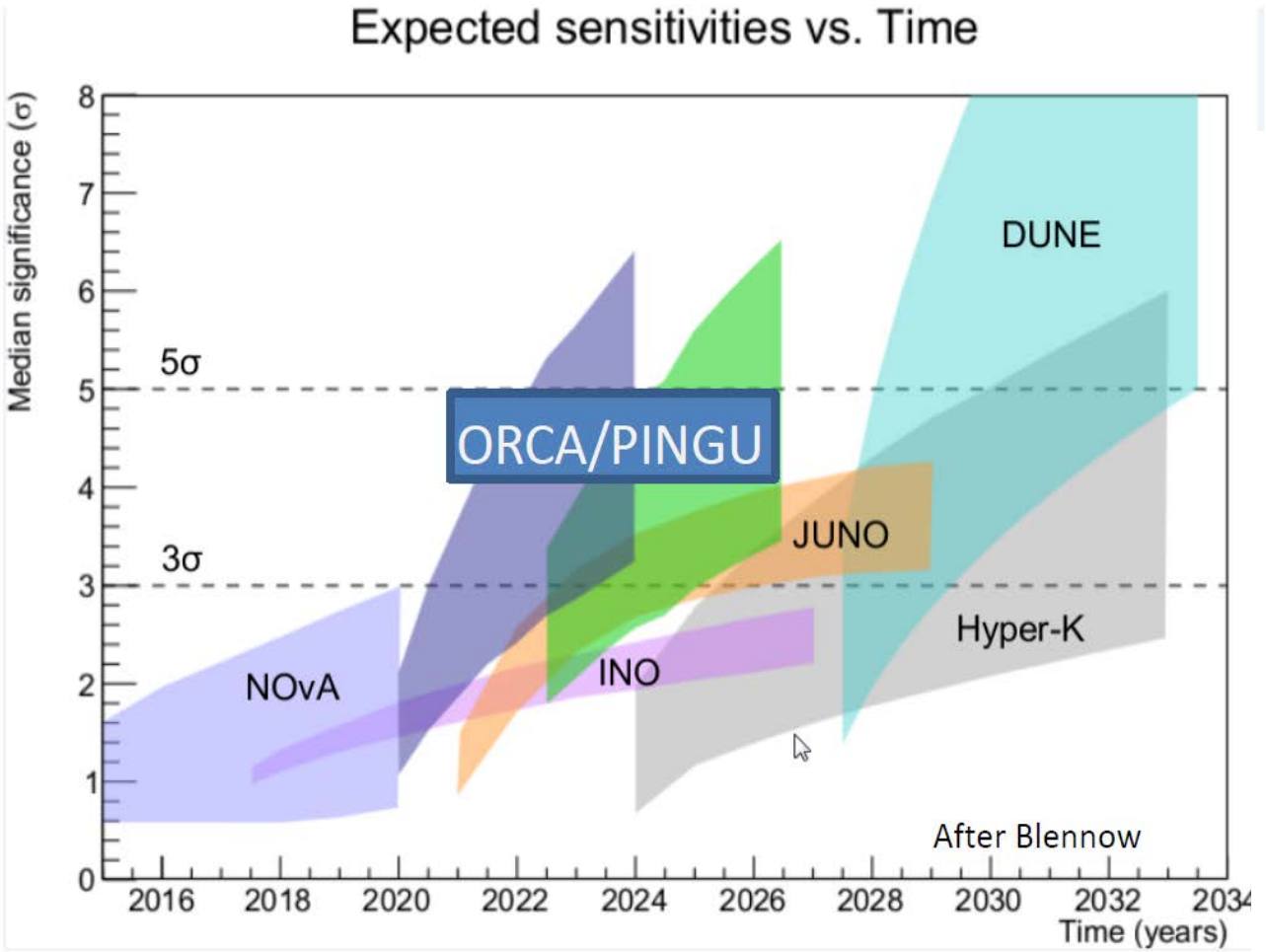
Already some interesting hints from 3 experiments!

Neutrino mass hierarchy measurements

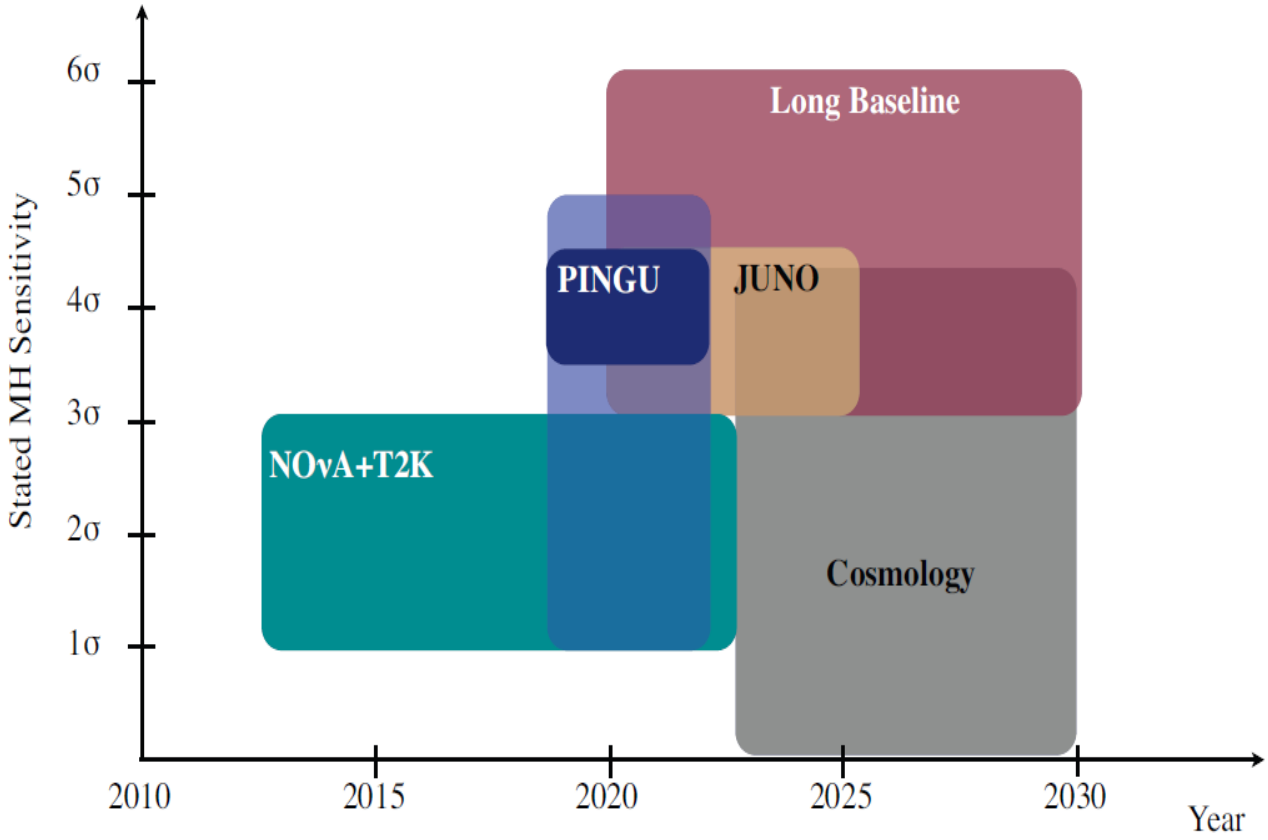


Timeline: neutrino mass hierarchy

A. Heijboer, NOW2016
M. Blennow et al, JHEP 1403 (2014) 028



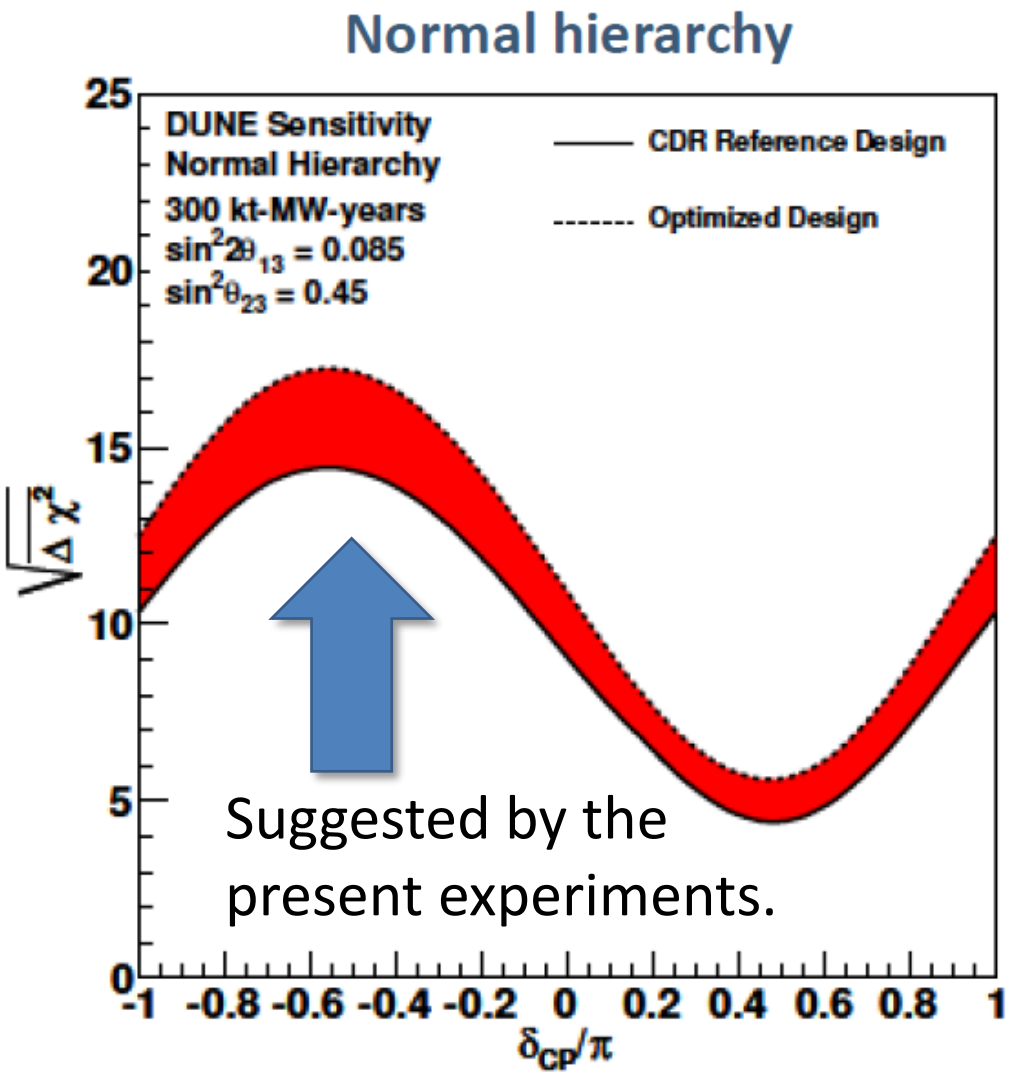
P. Huber, NOW2016

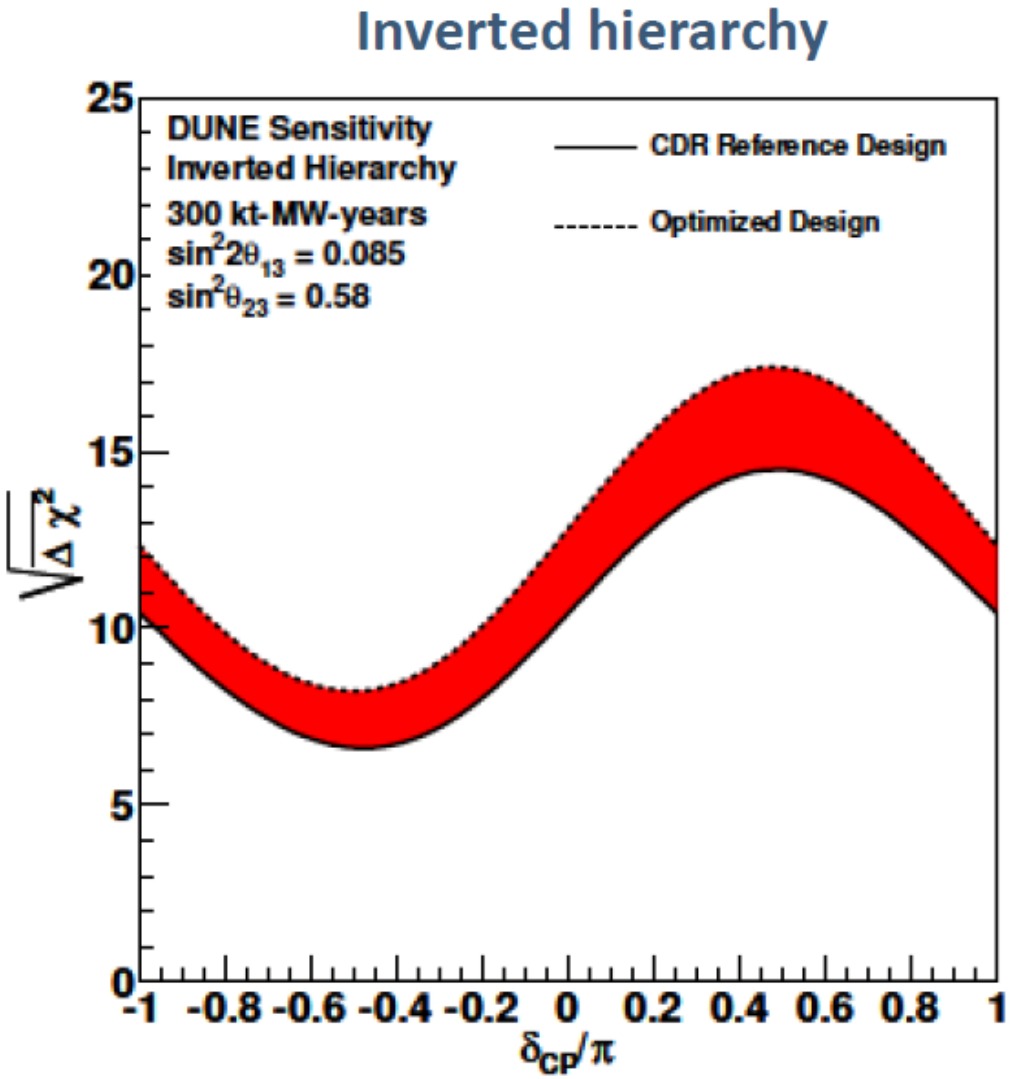


Sensitivity to mass hierarchy in DUNE

DUNE 300 kt-MW-years (~ 7 years, 40kton, 1.07MW)

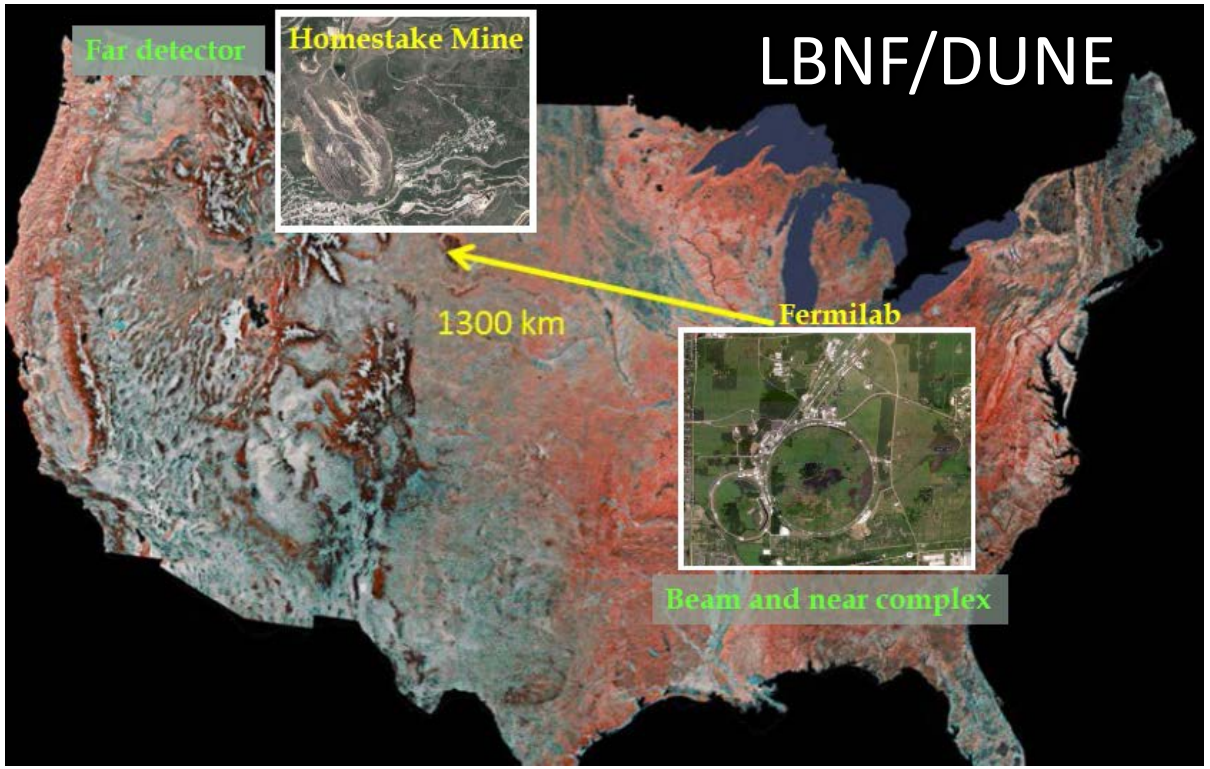
D. Stefan, NOW2016

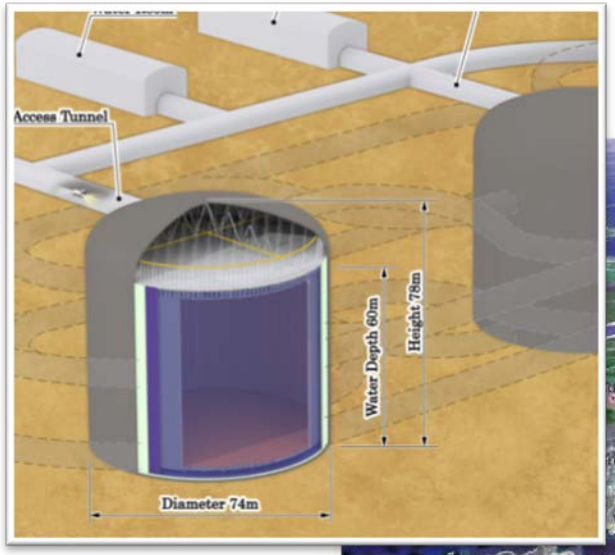




CP violation measurements

- ✓ We want to observe if $\nu_\mu \rightarrow \nu_e$ oscillation of neutrinos and those of anti-neutrinos are different.
- ✓ This is a difficult experiment. We need the next generation long base line experiments with much higher performance neutrino detectors.





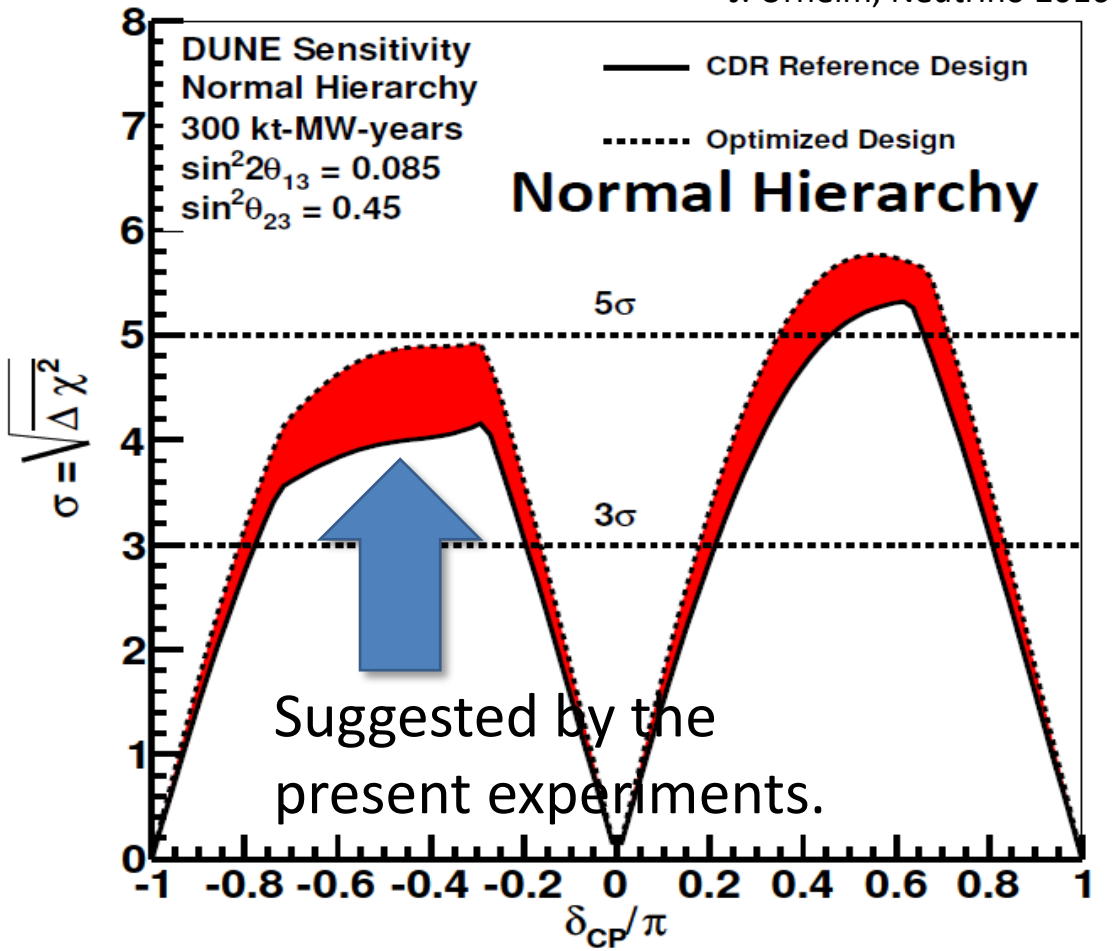
Hyper-Kamiokande

J-PARC

CP violation sensitivities

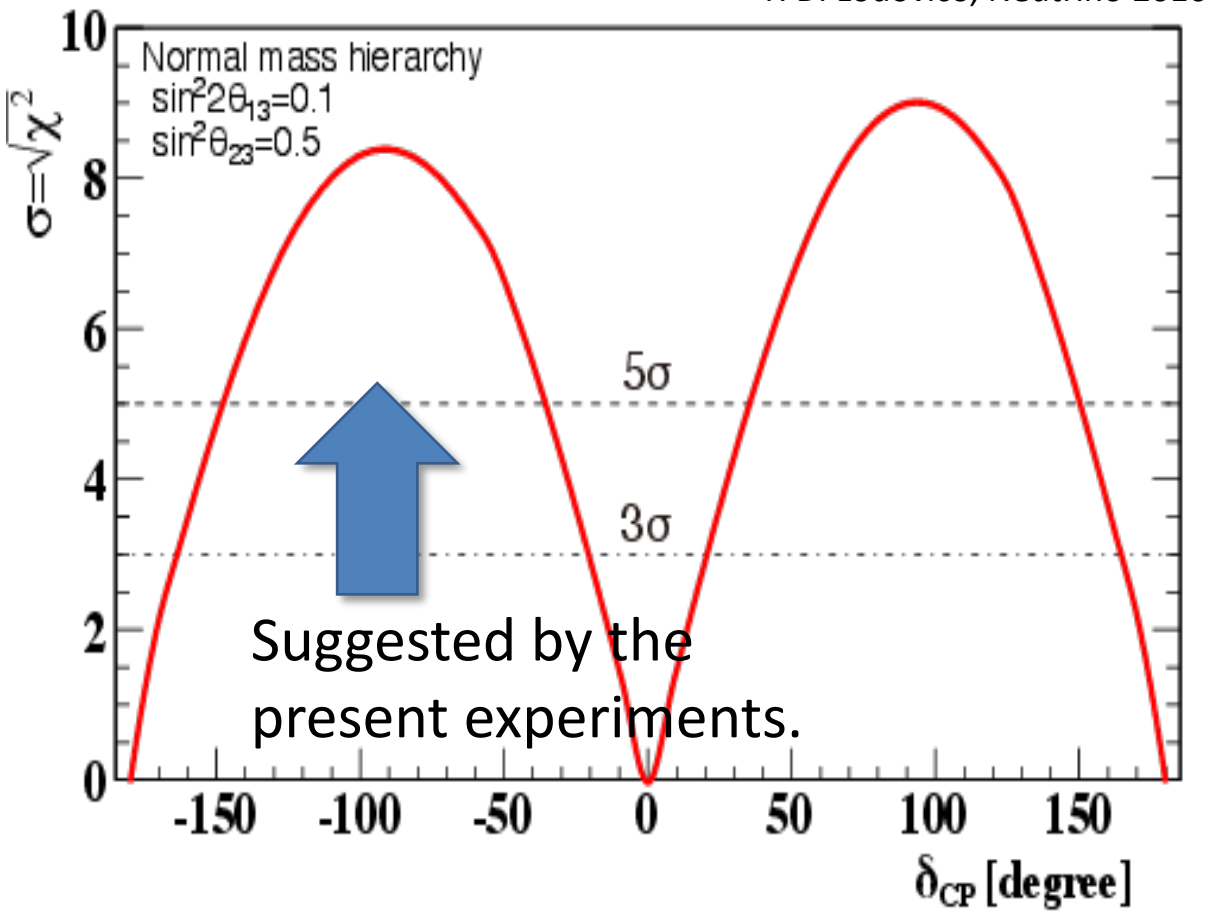
DUNE (7 years, 1.07MW)

J. Urheim, Neutrino 2016



Hyper-K (10 years, 1.3MW)

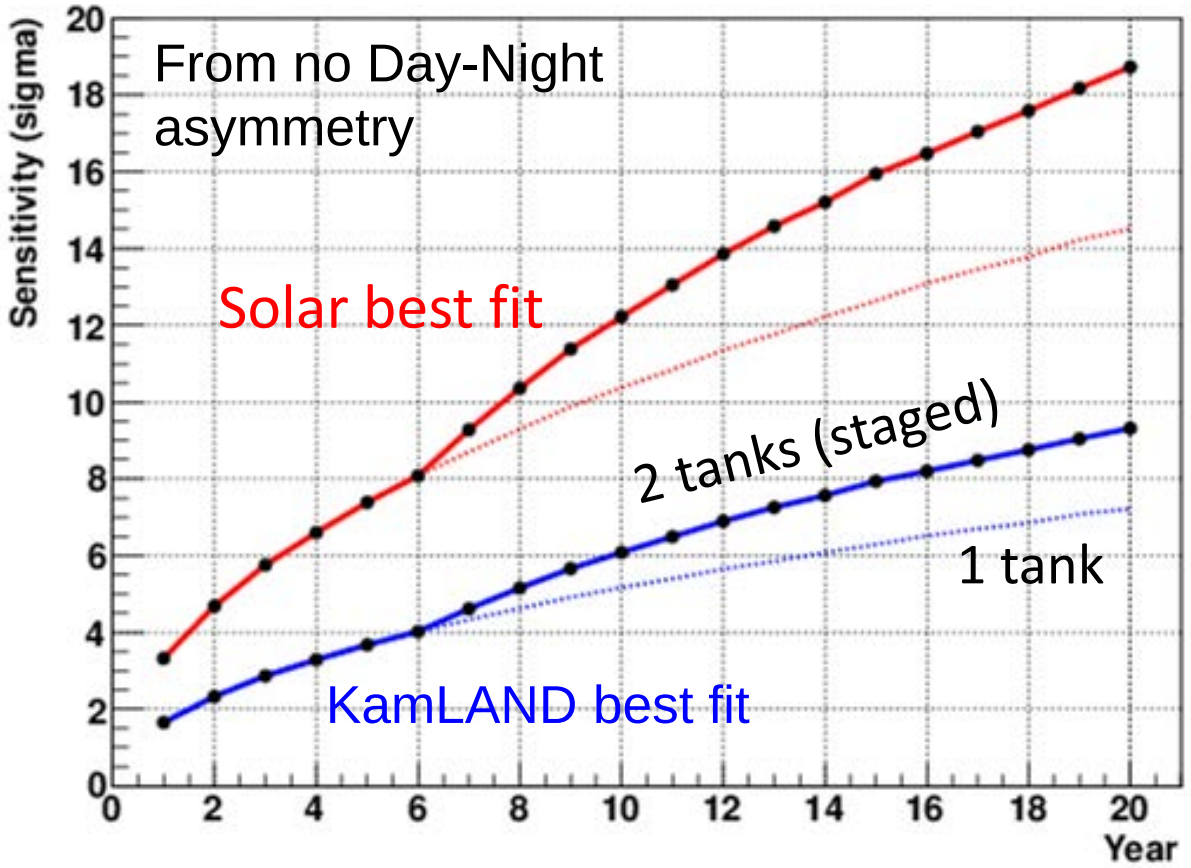
F. Di Lodovico, Neutrino 2016



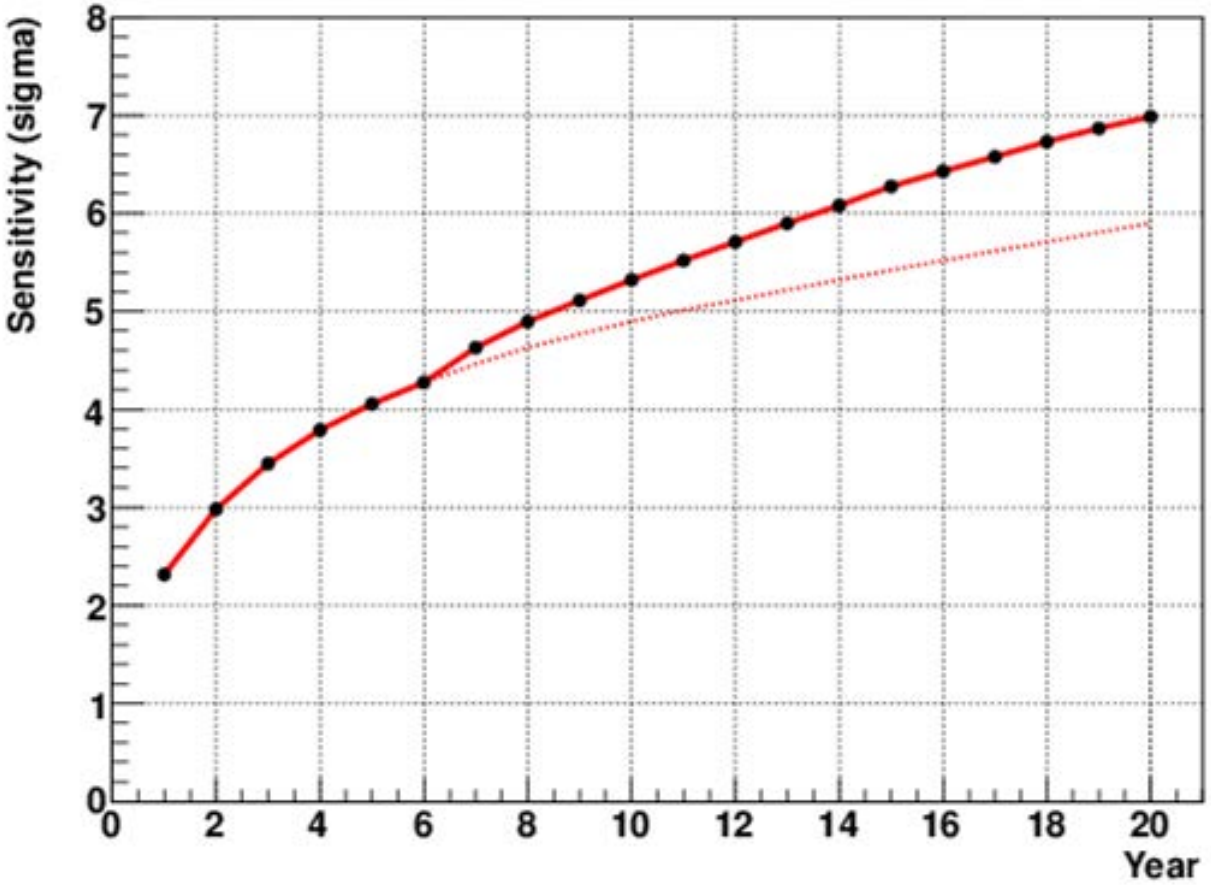
Both projects have high sensitivities to CP violation. (These 2 plots cannot be compared the sensitivities with these figures due to different assumptions)

Appendix: Solar neutrino measurements (Hyper-K)

Day-night asymmetry sensitivity



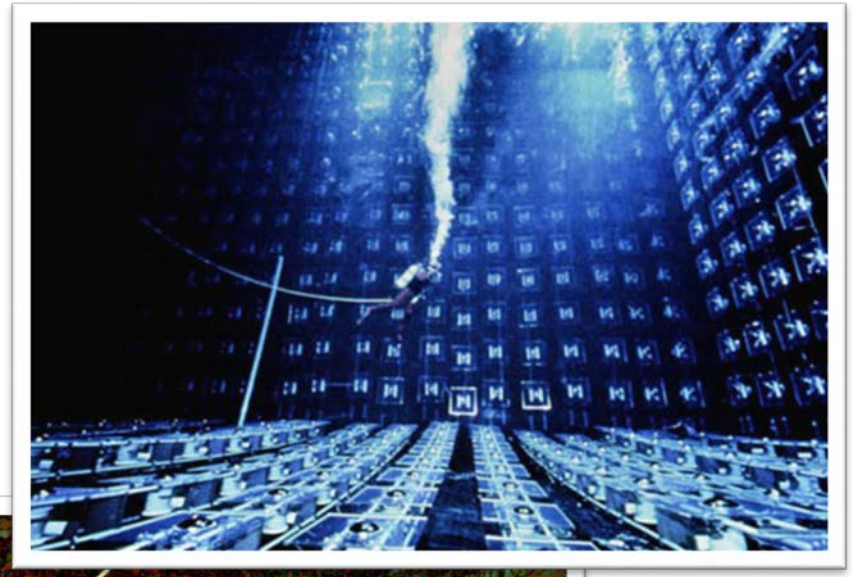
Spectrum upturn sensitivity



Other physics with future experiments

Proton decay experiments (1980's)

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

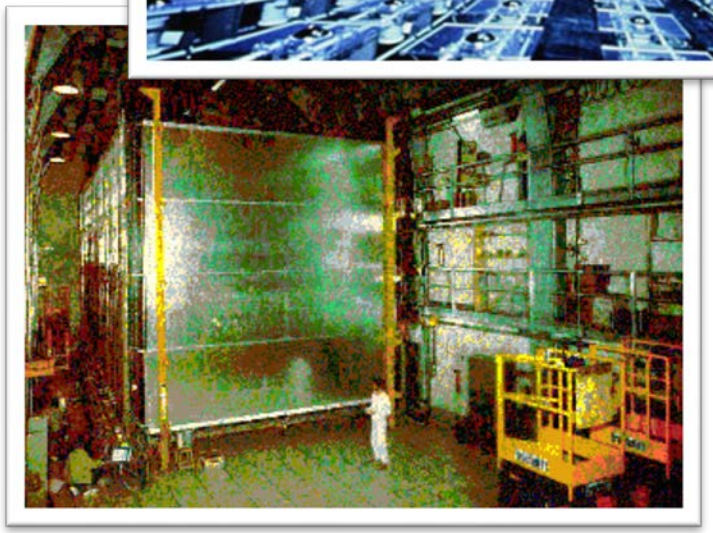


Kamiokande
(1000ton)

IMB
(3300ton)

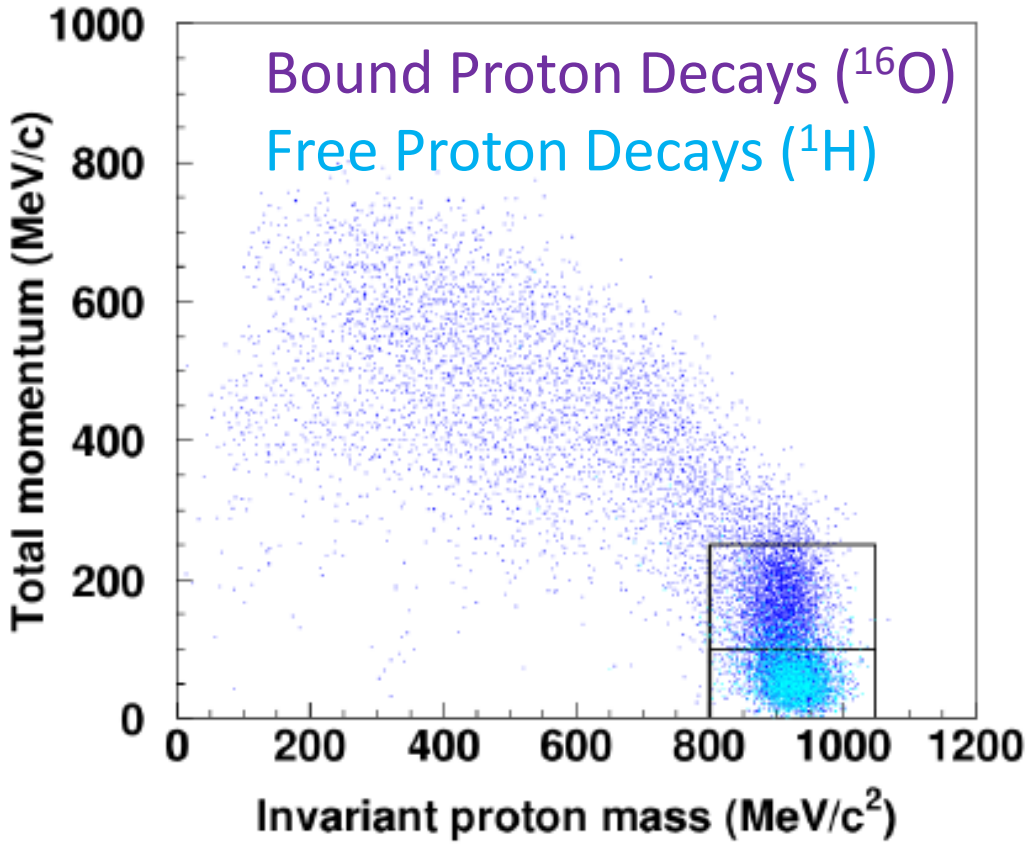
NUSEX
(130ton)

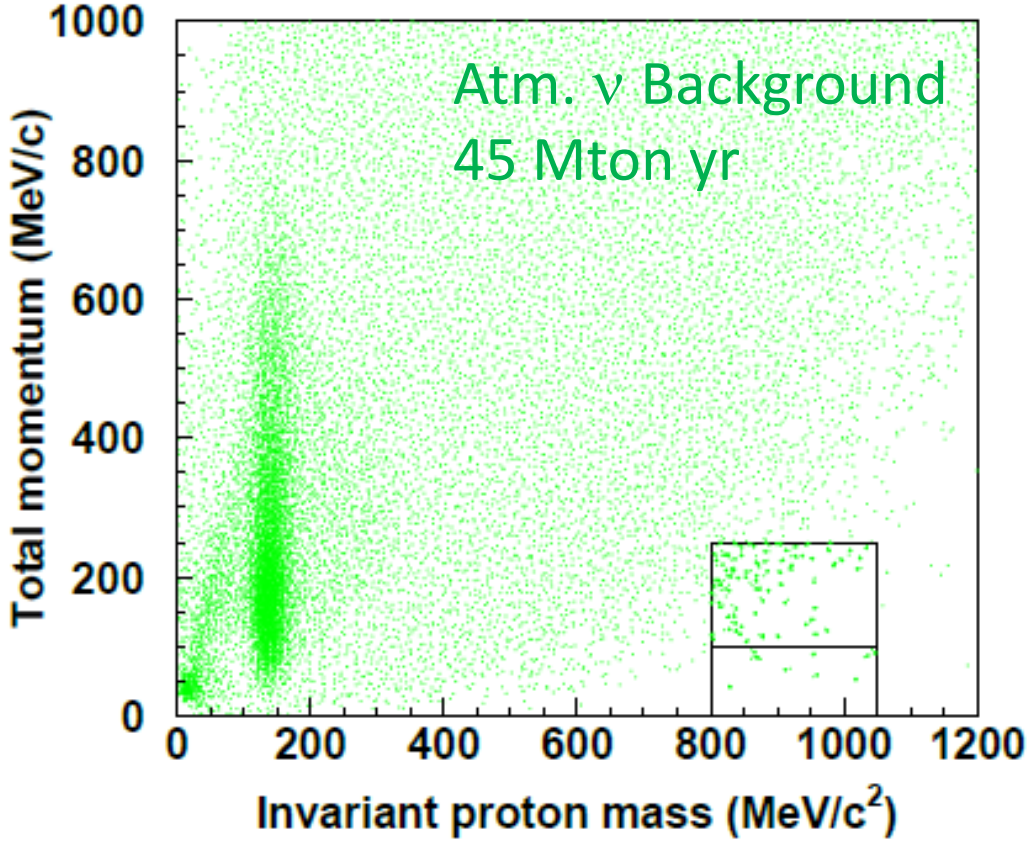
Frejus
(700ton)



These experiments did not observe proton decays and excluded the original GUTs.
However, we should not forget about the importance of proton decays!

Proton decay ($p \rightarrow e^+ \pi^0$)

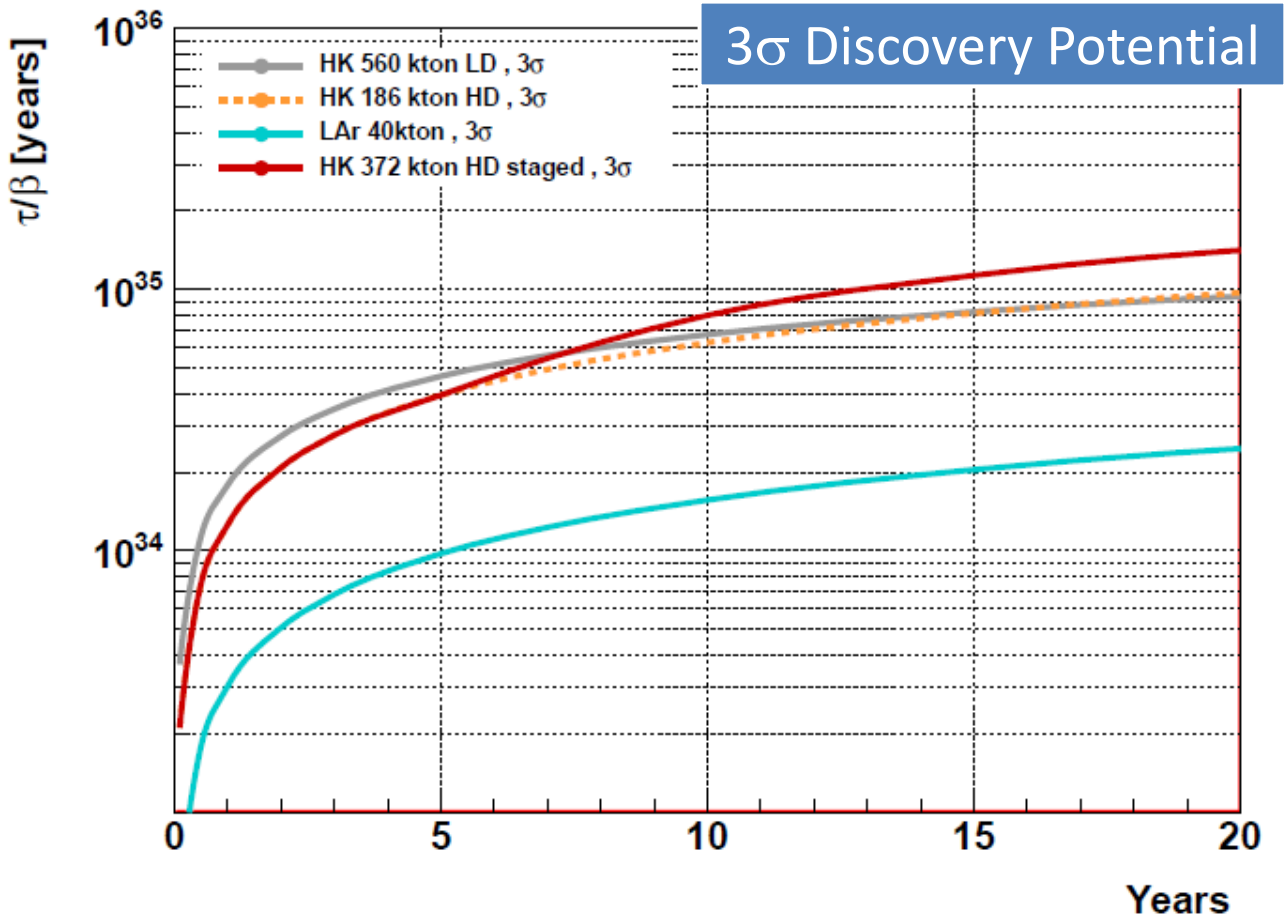


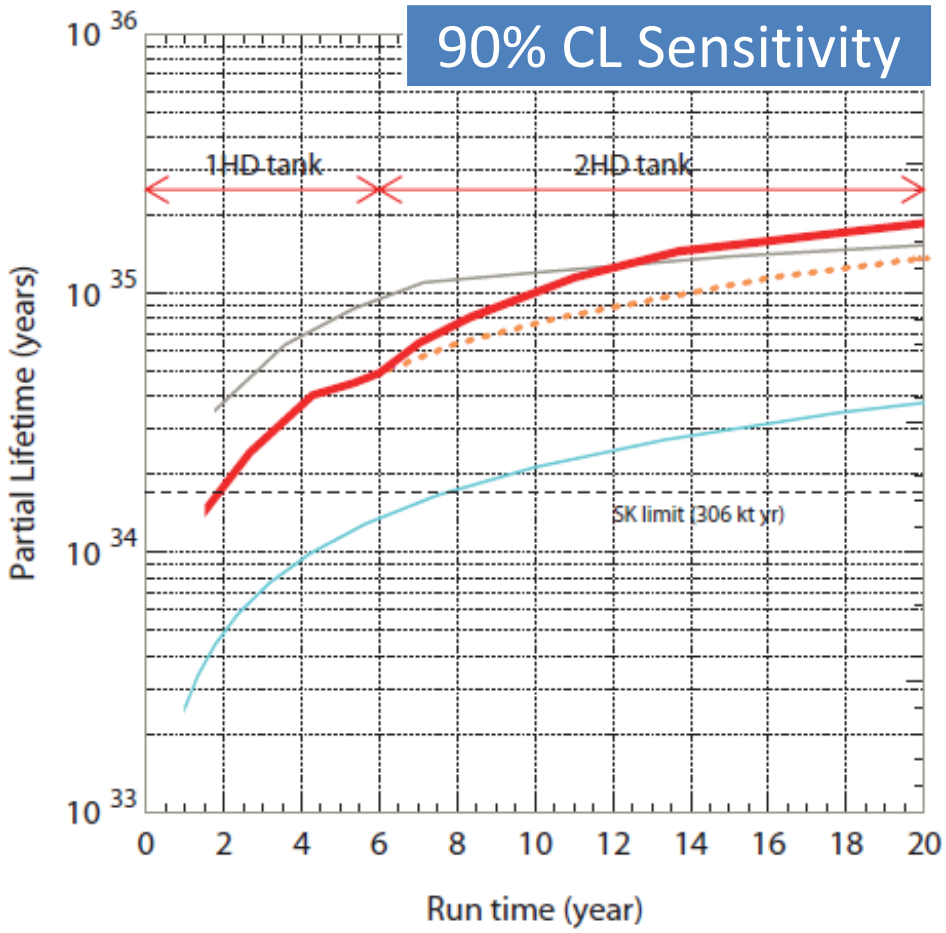


	$P_{total} < 100$ MeV/c		$P_{total} < 250$ MeV/c	
	efficiency	Background (/Mtonyr)(*)	Efficiency	Background (/Mtonyr)(*)
Hyper-K	18.7%	0.06	38.1%	0.68

(*) Neutron tagging included to reduce the background

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

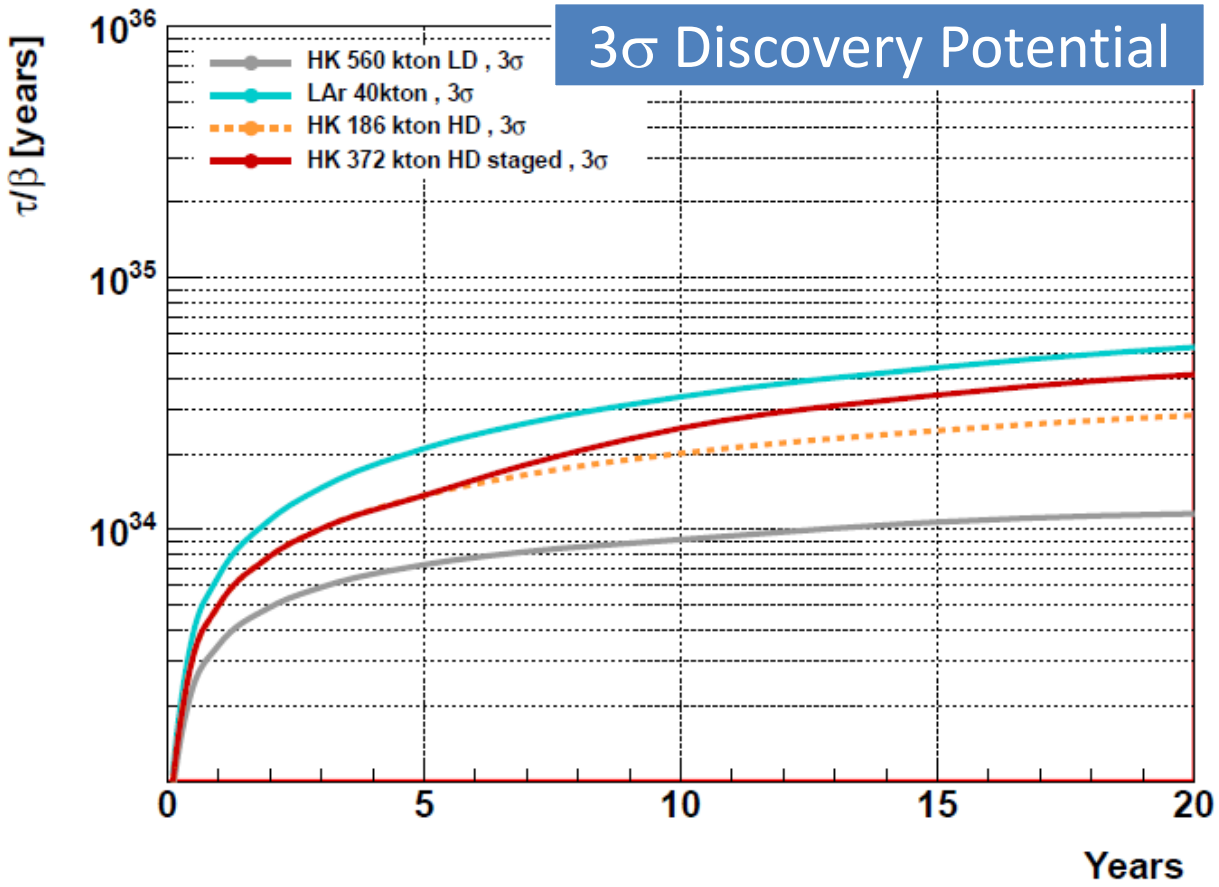


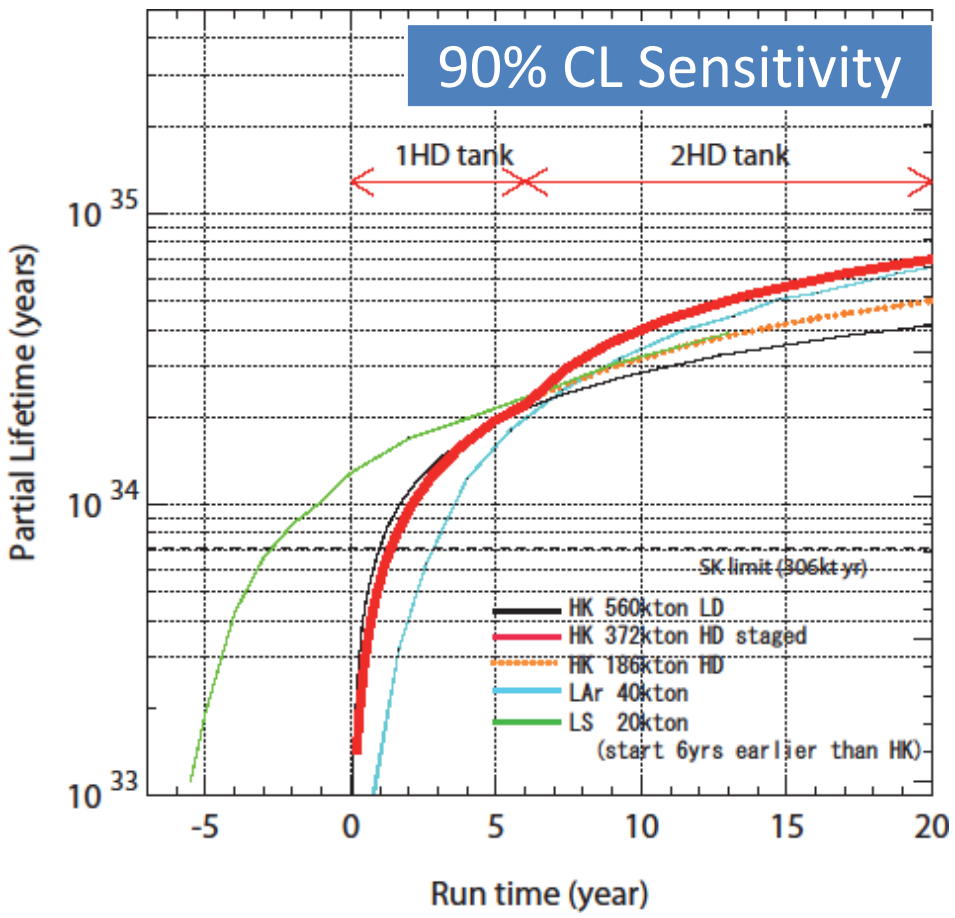


✓ > 1×10^{35} years after 2.7 Mton yr (90%CL) or 3σ discovery with 4.0 Mtonyr.

(Lines for the liquid argon experiment have been generated based on numbers in the literature (efficiency: 45% bkg: 1 event/Mtonyr).)

$P \rightarrow \nu K^+$: sensitivity





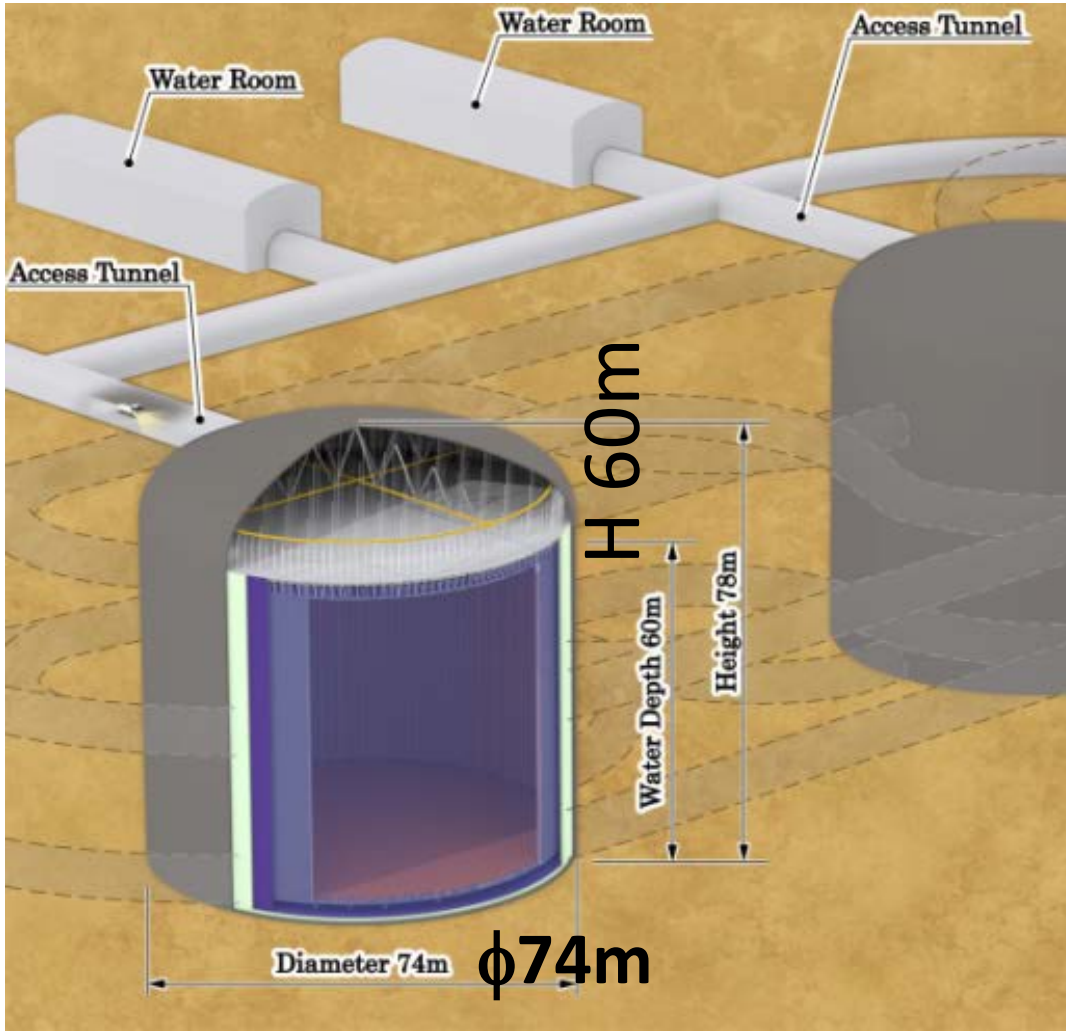
✓ Discovery potential higher in Liq. Ar. (Hyper-K slightly better for 90%CL limit.)

(Discovery potential for the Lar experiment has been generated based on numbers in the literature (efficiency: 97%, bkg: <1 event/Mton year).

Appendix: Status of Hyper-K

- ✓ The baseline design was changed to "0.26Mton X 2 tanks (0.38Mton fid. mass) with staging construction" due to the cost issue.
- ✓ However, due to the successful R&D on the PMT improvements, the expected overall performance is not changed substantially.
- ✓ The plan of Hyper-K was submitted to the Japanese Council of Japan. If things goes well, Hyper-K will be listed as one of the "Master Plan Projects".
- ✓ Hyper-K will be reviewed by the Ministry of the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) in 2017. If it is evaluated highly, it will be listed in the MEXT "Roadmap".
- ✓ Then, …

(There is a new possibility to construct the 2nd detector in Korea.)



Summary

- *Since the discovery of neutrino oscillations, various experiments have studied neutrino oscillations. We have almost understood the basic structure of neutrino oscillations.*
- *However, we still do not know some key features of neutrino properties. Neutrinos are one of the keys to understand the physics beyond the Standard Model of particle physics.*
- *It is very good that there are many planned/on-going future neutrino oscillation experiments.*
- *It is also good that these future experiments are sensitive to other important physics, such as proton decay.*
- *We will learn much more on neutrinos in the coming years!*