"Prospects of Neutrino Physics"
Kavli IPMU, Kashiwa, Japan
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Prospects in Neutrino Experiments

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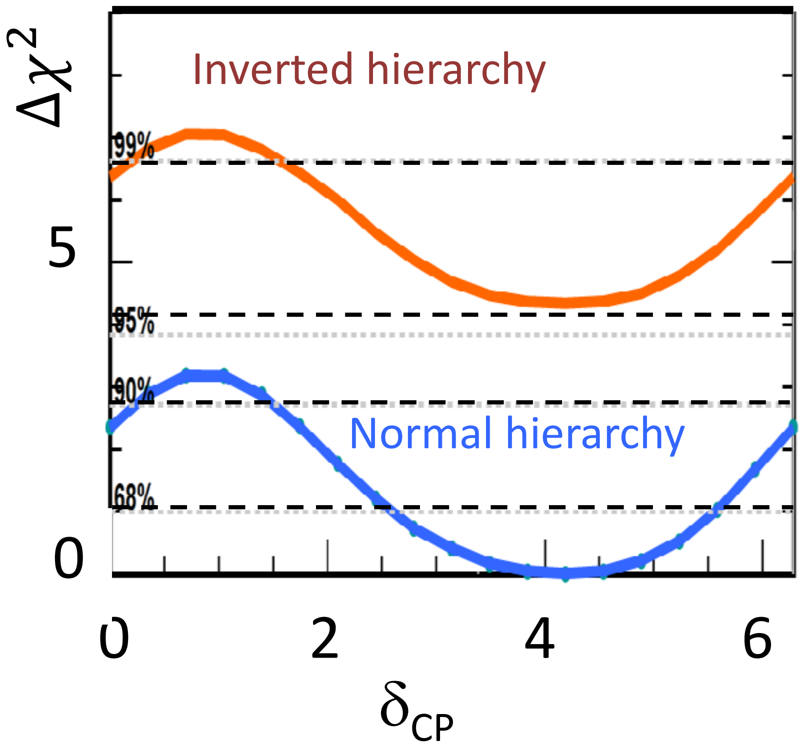
Outline

- *Introduction: Present Status*
- *Neutrino Mass Ordering (short)*
- *CP violation*
- *Double beta decay*
- *Appendix 1: Proton decay*
- *Appendix 2: IUPAP Neutrino Panel*
- *Summary*

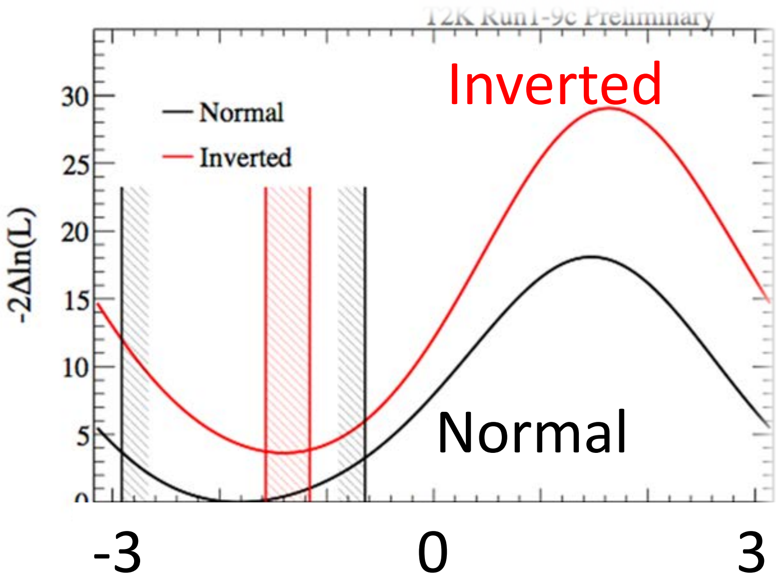
Introduction: Present status

Some of the new results at Neutrino 2018

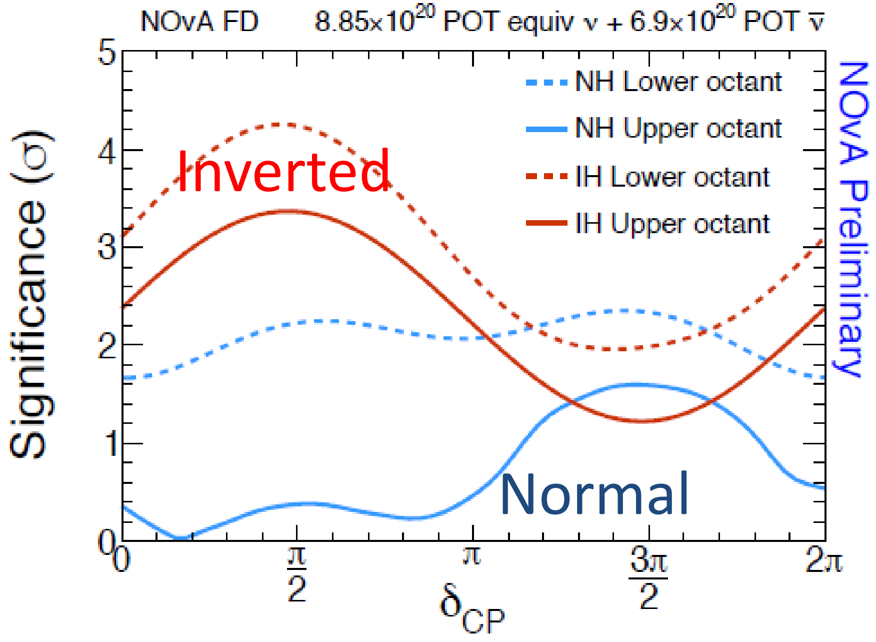
Super-K atmospheric (Y. Hayato)



T2K (M. Wascko)



NOvA (M. Sanchez)



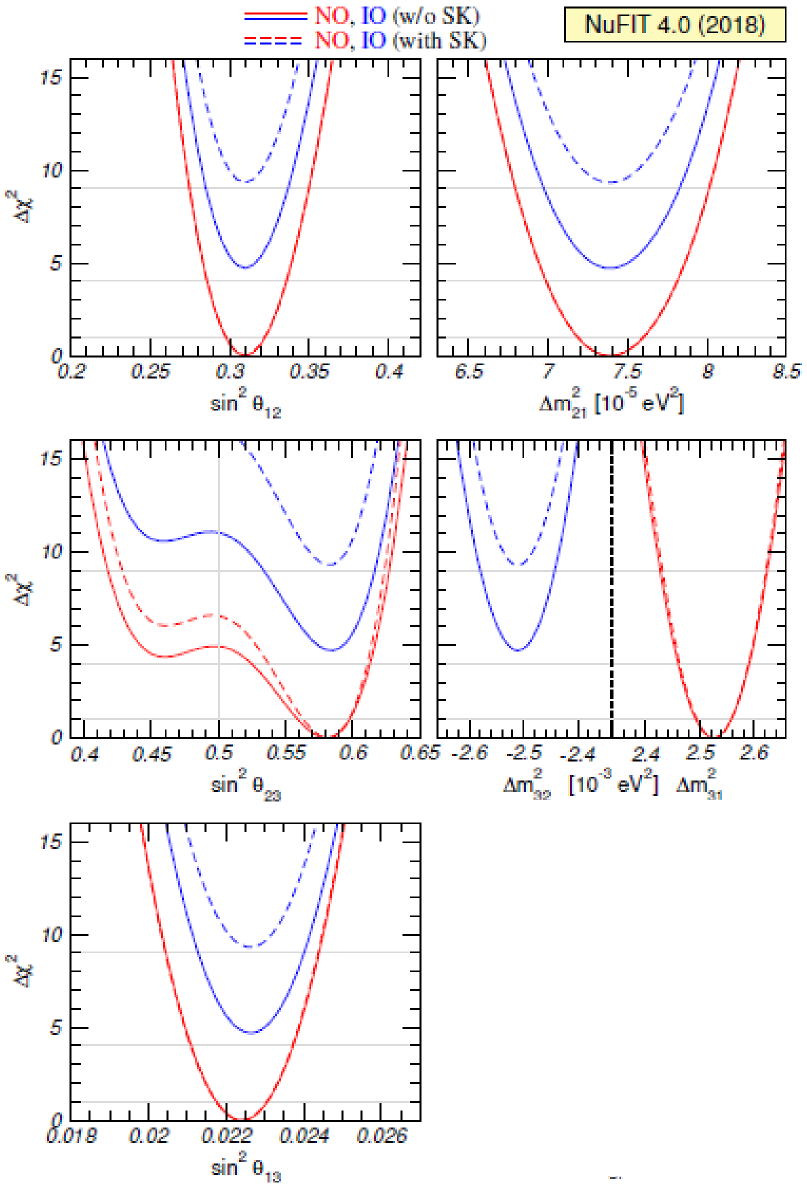
Already some interesting indications:

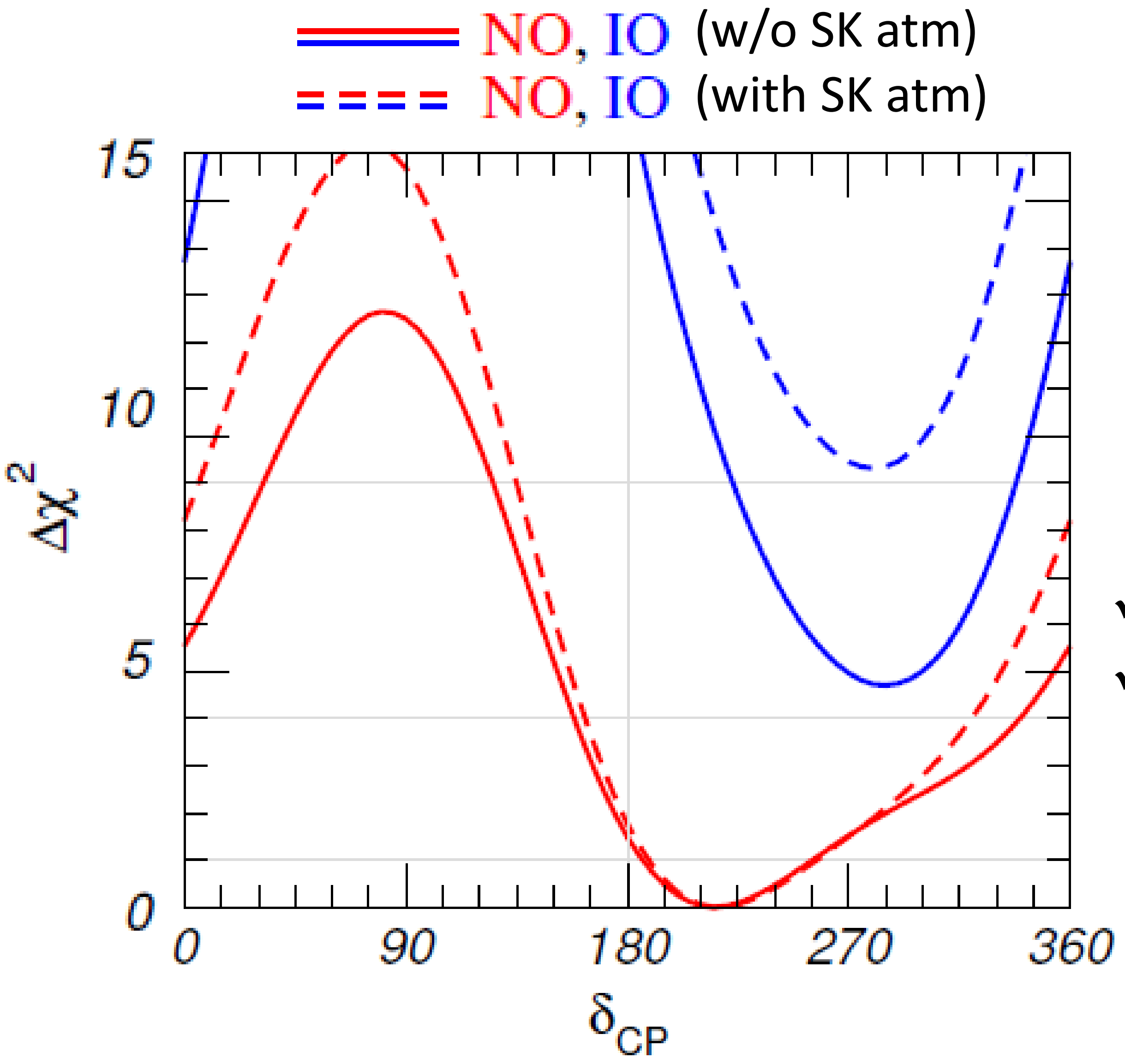
➔ NO favored by these 3 experiments at ~(1 ~ 2) sigma level each.

➔ These experiments give some favored δ_{CP} region(s).

Global fit (example)

I. Esteban et al., JHEP 1901 (2019) 106

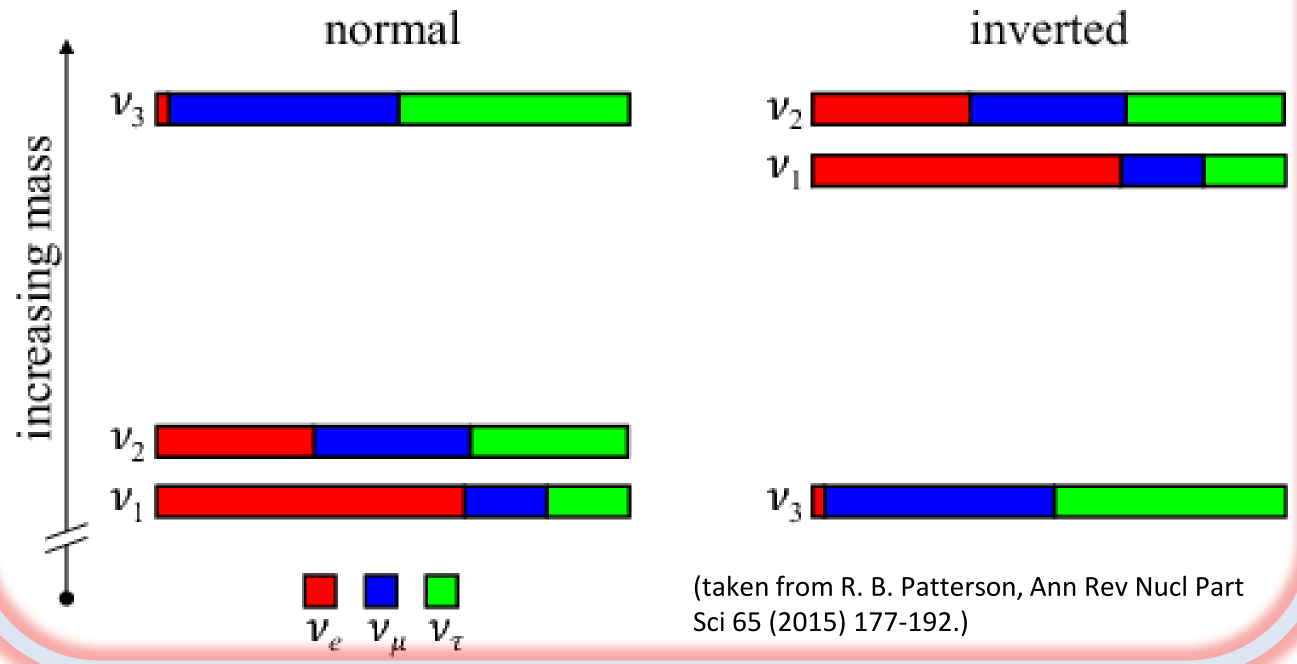




- ✓ NO favored.
- ✓ Suggested δ_{CP} range(s)

Agenda for the future neutrino measurements

Neutrino mass ordering?



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

Absolute neutrino mass?

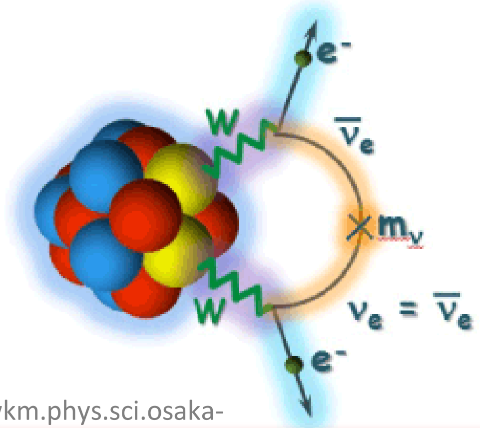
Beyond the 3 flavor framework? (Sterile neutrinos?)

CP violation?

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

Baryon asymmetry of the Universe?

Are neutrinos Majorana particles?



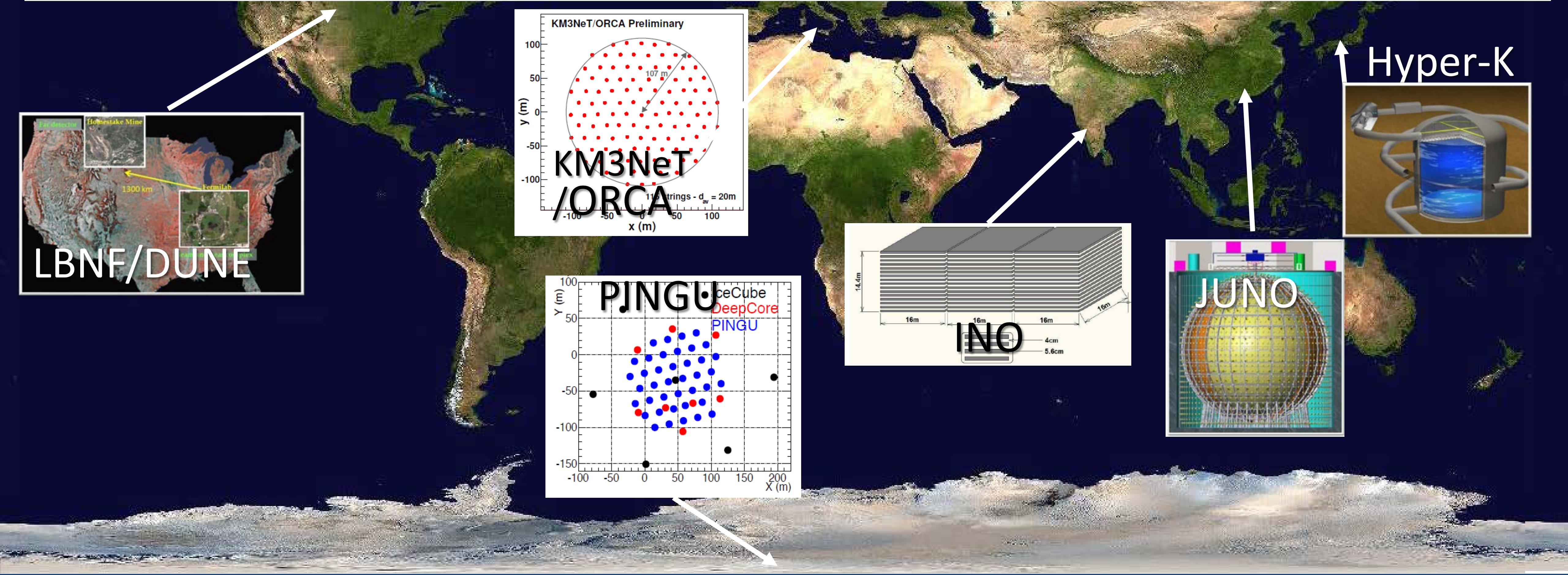
http //wwwkm.phys.sci.osaka-u.ac.jp/ /research/r01.html

➔ Neutrinoless double beta decay

Neutrino Mass Ordering

Future experiments that will tell us the neutrino masses ordering

Very good to have many projects for the MO measurements.
We would like to be convinced the neutrino mass ordering by consistent results from several different technologies/methods with > 3 σ CL from each exp.



CP Violation

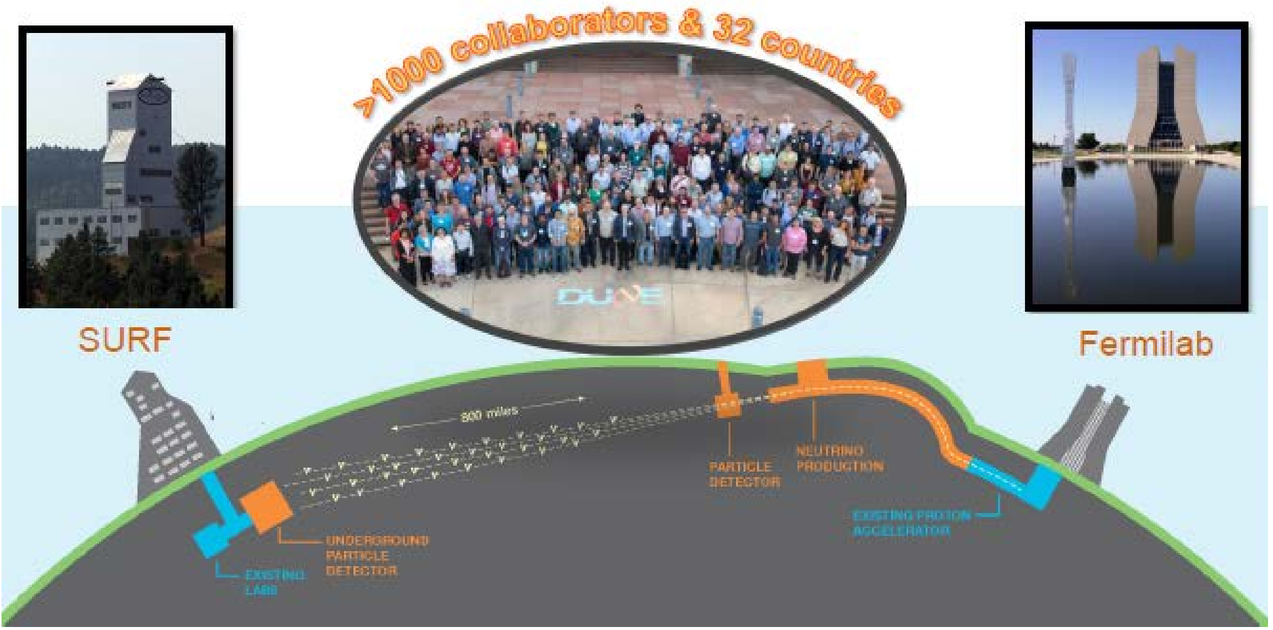
Motivation

- ✓We would like to confirm that CP is violated in the neutrino sector.
- ✓CP violation in the neutrino sector might be the key to understand the baryon asymmetry of the Universe (Leptogenesis).
- ✓…

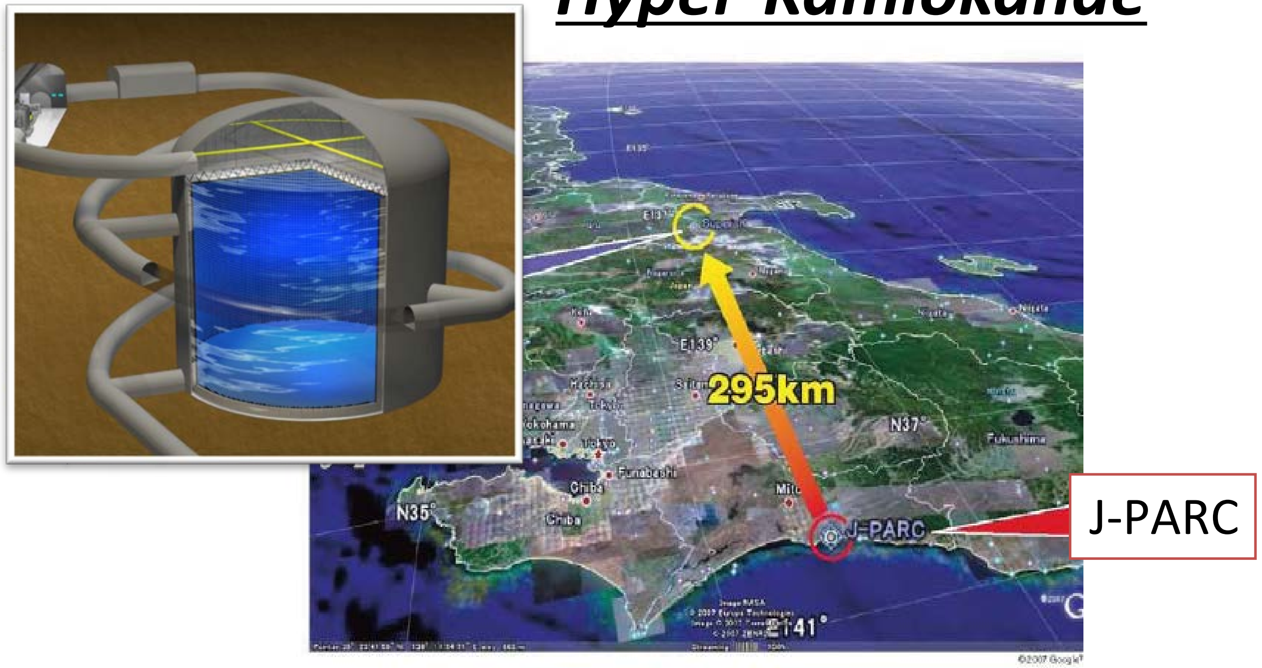
Next generation neutrino CPV experiments

✓We would like to observe if oscillation of neutrinos and those of anti-neutrinos are different.

DUNE



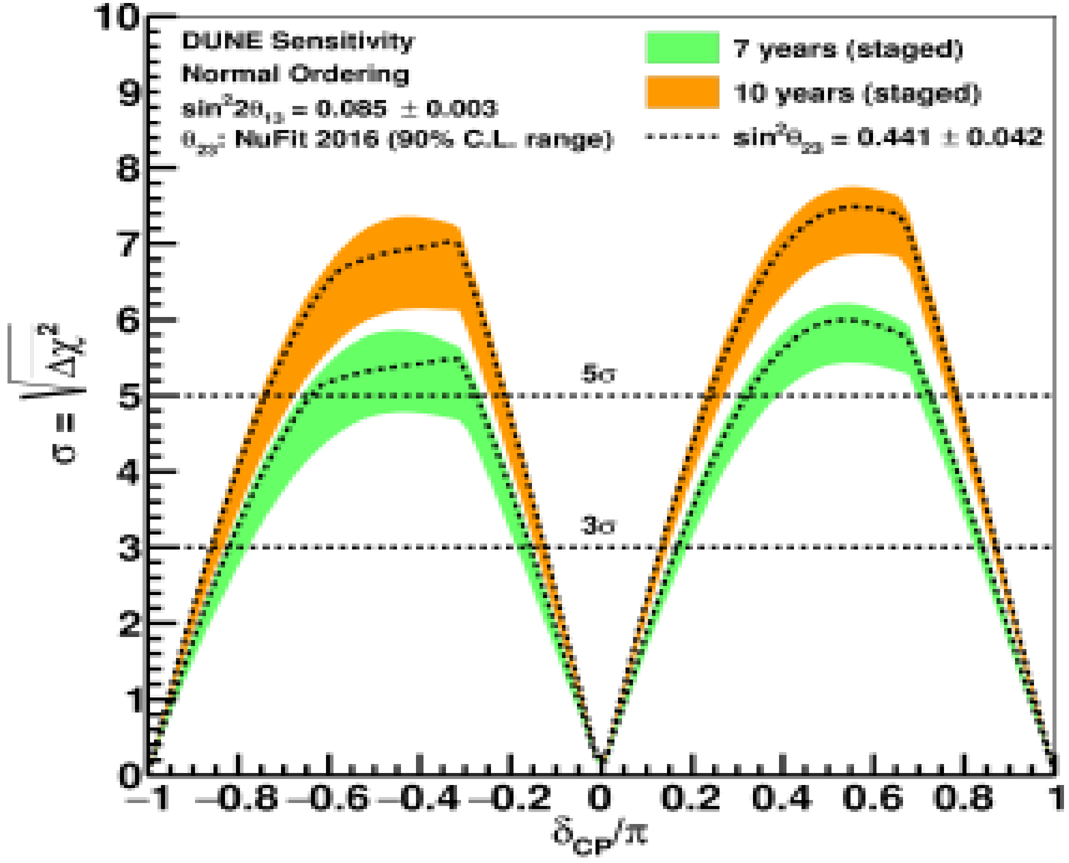
Hyper-Kamiokande



Sensitivities

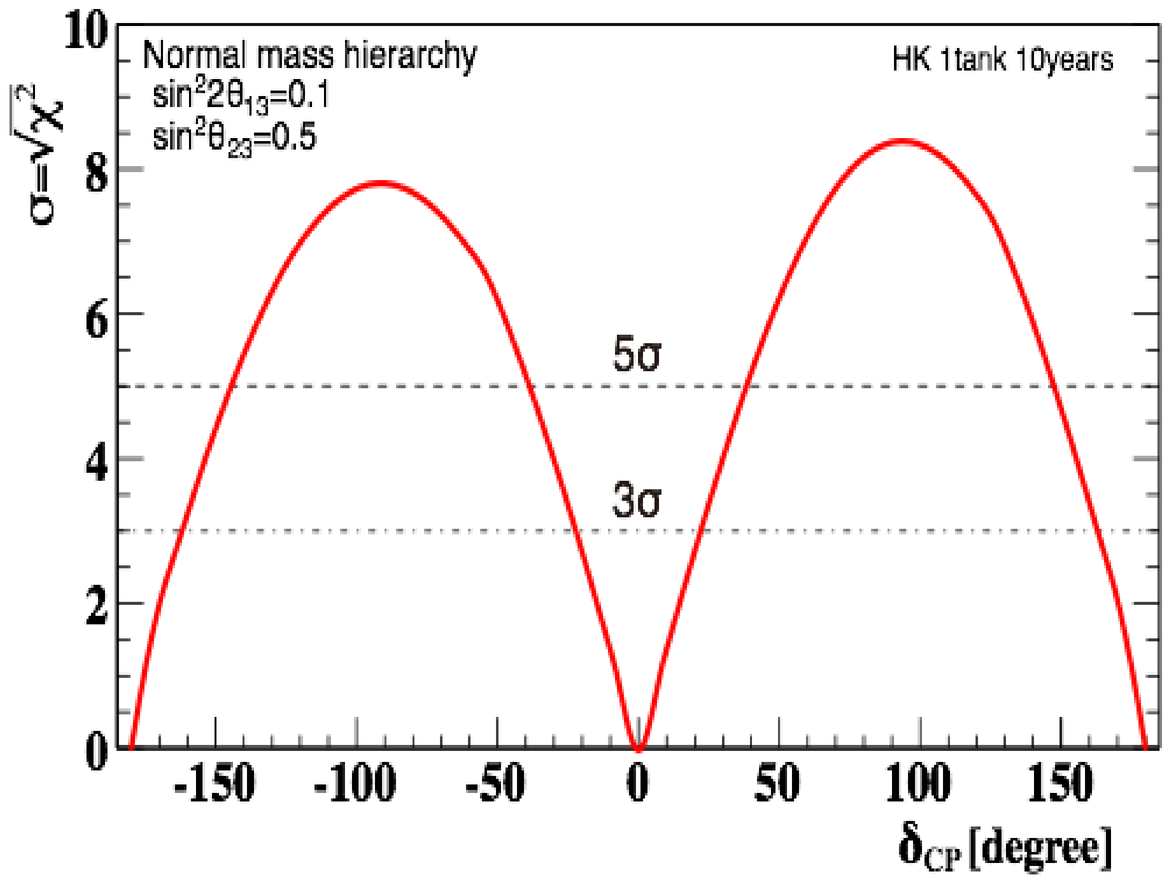
DUNE

(E. Worcester, nu2018)



Hyper-K

(M. Shiozawa, nu2018)



Complementarity

	DUNE	Hyper-K
Baseline	1300km ➔ Large matter effect (Good for Mass Ordering determination)	295km ➔ Small matter effect (Smaller effect of matter density uncertainty in δ_{CP})
Beam energy	~ Multi-GeV	~ Sub-GeV
Detector technology	Liq. Ar TPC	Water Cherenkov

- ✓ ***We would like to be convinced the CP violation by the consistent results from these 2 experiments with very different systematics.***
- ✓ ***We hope that these 2 experiments will carry out the experiments in a similar timeline.***

Status of Hyper-K

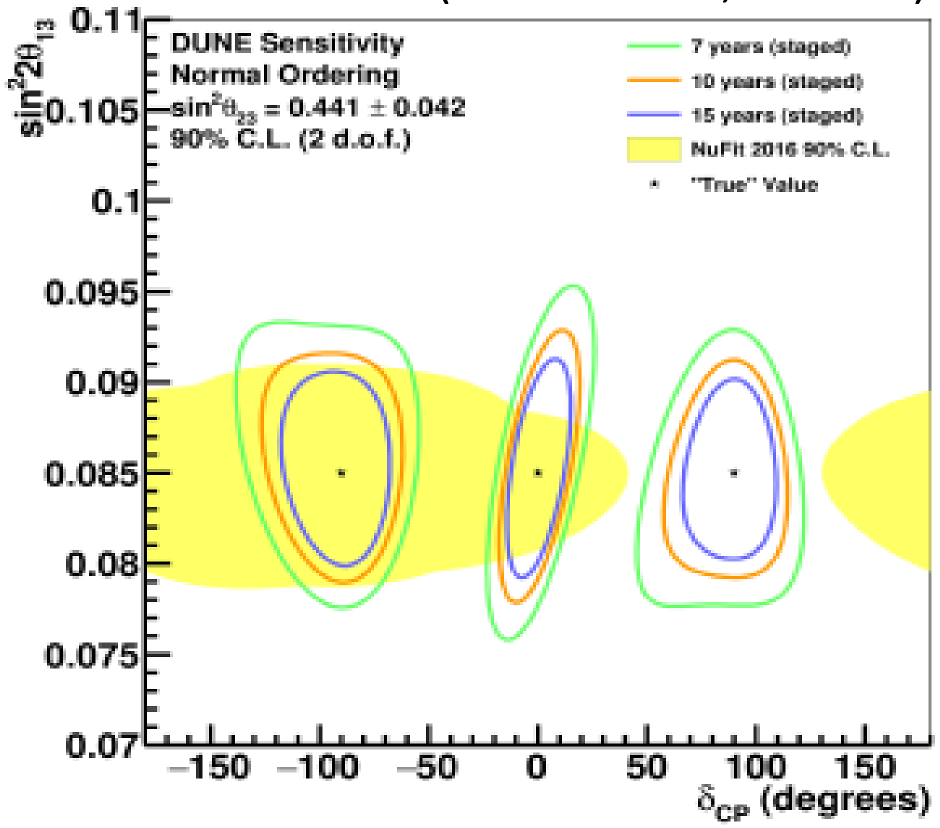
- ✓ Hyper-K has been selected as one of the 7 large scientific projects in the Roadmap of the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) in 2017.
- ✓ Since then, we have been discussing intensively with MEXT.
- ✓ In the FY2019 Japanese budget (April 2019 - March 2020), "funding for feasibility study" for Hyper-K is included. This budget is equivalent to "seed funding" in some other countries. This funding is usually for 1 year (or 2 years).
- ✓ The President of the Univ. of Tokyo, in recognition of both the project's importance and value both nationally and internationally, pledged to ensure construction of the Hyper-Kamiokande detector commences in April 2020.

Hyper-K construction will begin in April 2020!
(The construction will take 7-8 years!)
You are most welcome to join Hyper-K!

After the initial CP results...

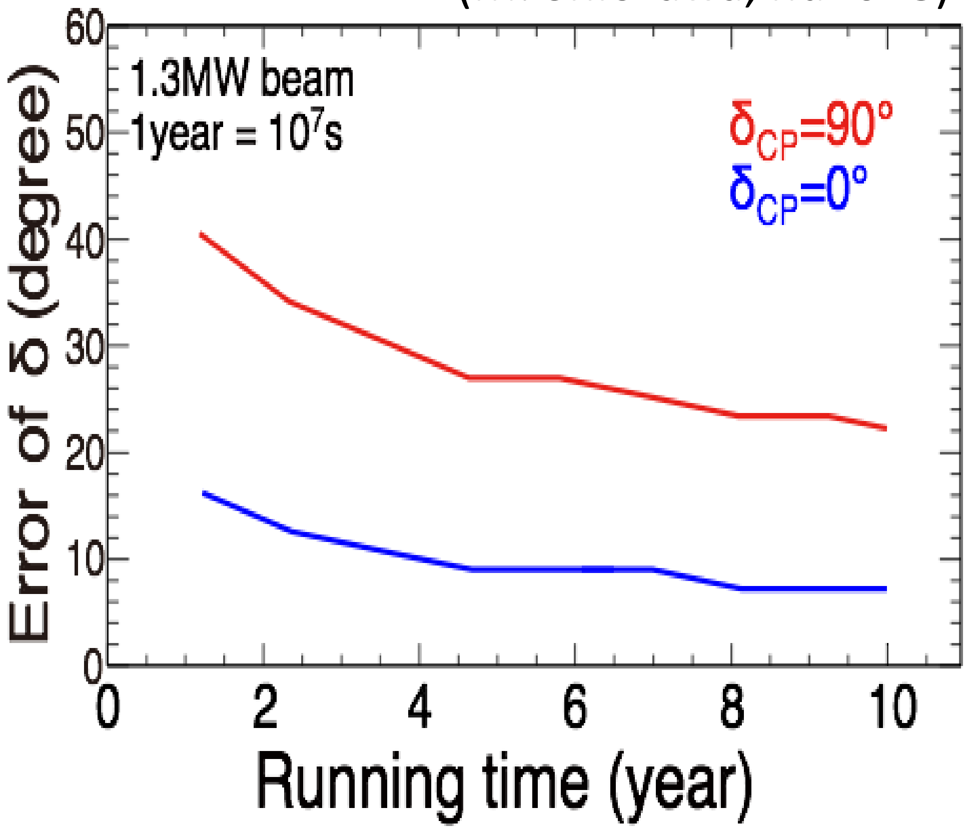
DUNE

(E. Worcester, nu2018)



Hyper-K

(M. Shiozawa, nu2018)



If the suggested CP phase by T2K, Super-K, and NOvA (IO) (around $3/2\pi$ or $-\pi/2$) is close to the real value, the determination of the CP phase angle will be rather poor.

➔ Should we better measure the phase angle? We would like to get inputs from theorists.

Double beta decay

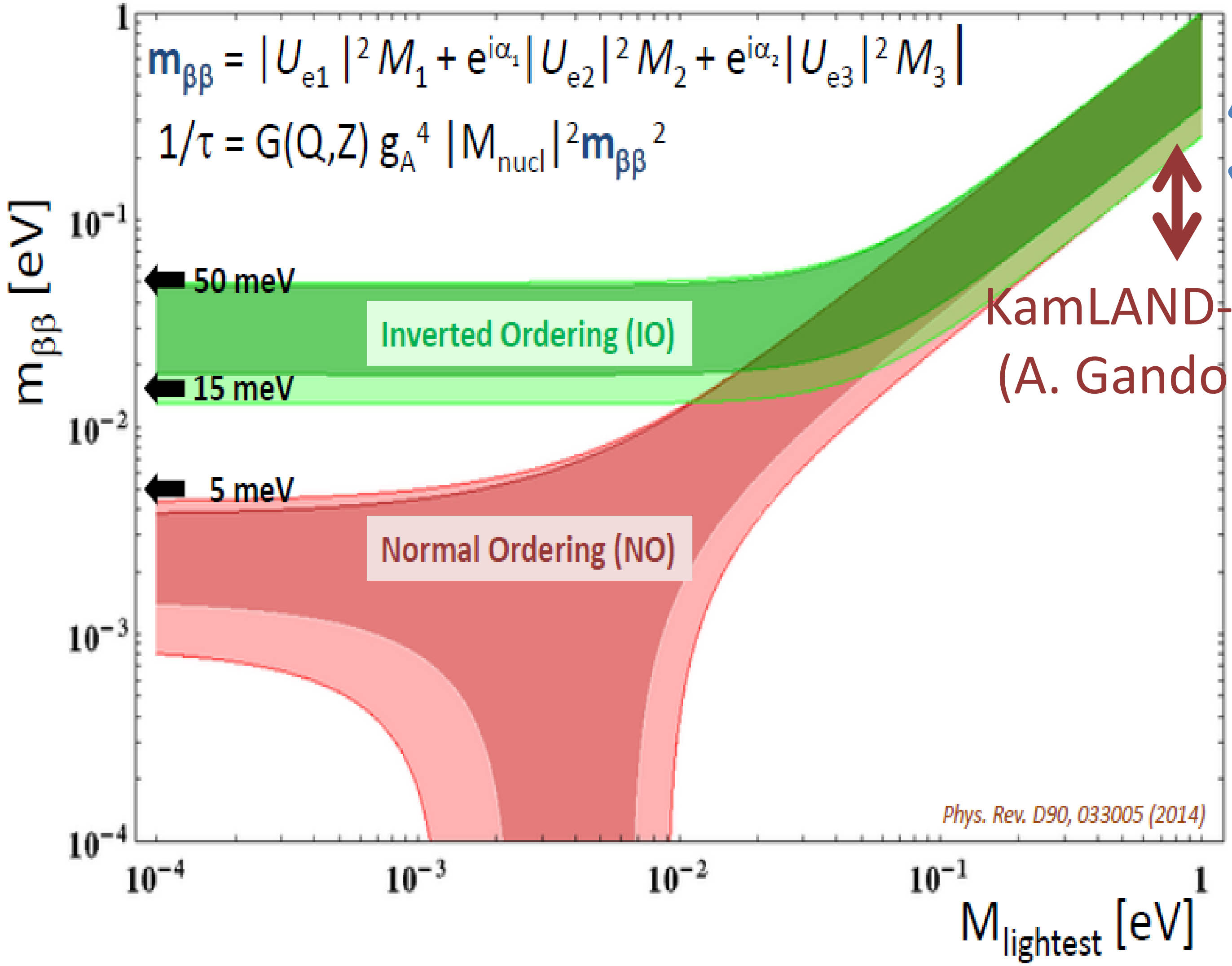
Motivation

✓We would like to know if neutrinos are Majorana particles.

- Key to understand the neutrino mass mechanism.
- Maybe very important step toward the understanding of the baryon asymmetry of the Universe (Leptogenesis).
- ….

Results presented at Neutrino 2018

(A. Giuliani)



CUORE (J. Ouellet)

EXO-200 (G. Gratta)

MAJORANA DEMONSTRATOR (V. Guiseppe)

GERDA (A. Zsigmond, estimated from $\tau_{1/2}$)

KamLAND-Zen (A. Gando)

The constraints are approaching (or reaching) 100 meV!

These experiments have been doing fantastic jobs: Low back ground, good understanding of background and systematics, …

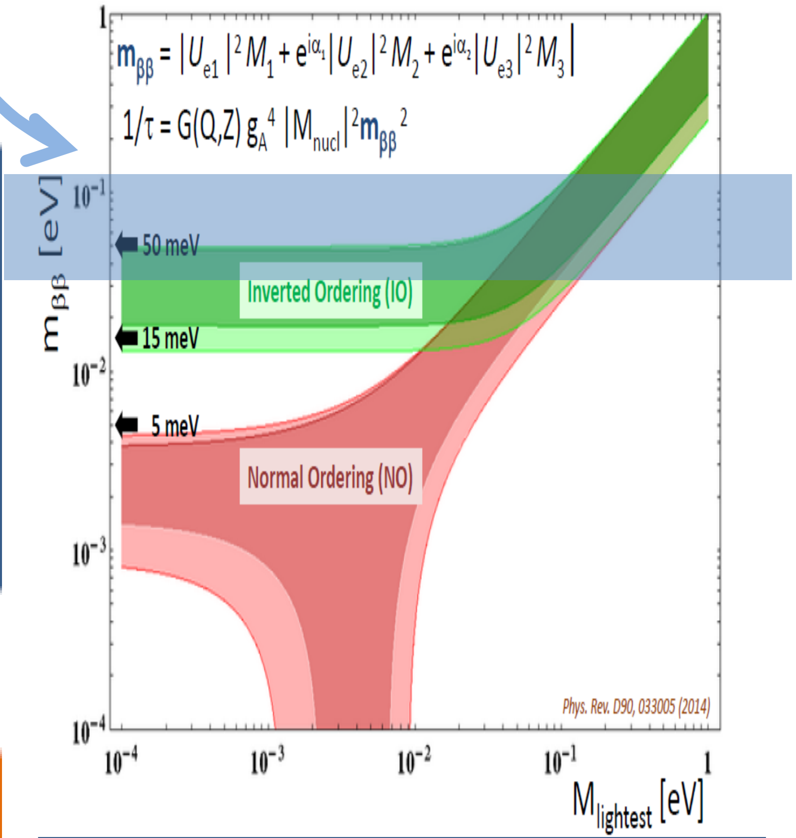
What next ?

(A. Giuliani, nu2018)

source = detector

		NOW	MID-TERM	LONG-TERM
Scalability — **Fluid embedded source**	Xe-based TPC	EXO-200		nEXO
		NEXT-10	NEXT-100 PandaX-III	NEXT-2.0 PandaX-III 1t
	Liquid scintillator as a matrix	KamLAND-Zen 800		KamLAND2-Zen
		SNO+ phase I		SNO+ phase II
High ΔE and ε — **Crystal embedded source**	Germanium diodes	GERDA-II MJD	LEGEND 200	LEGEND 1000
	Bolometers	AMoRE pilot, I	AMoRE II	
		CUORE CUPID-0, CUPID-Mo		CUPID

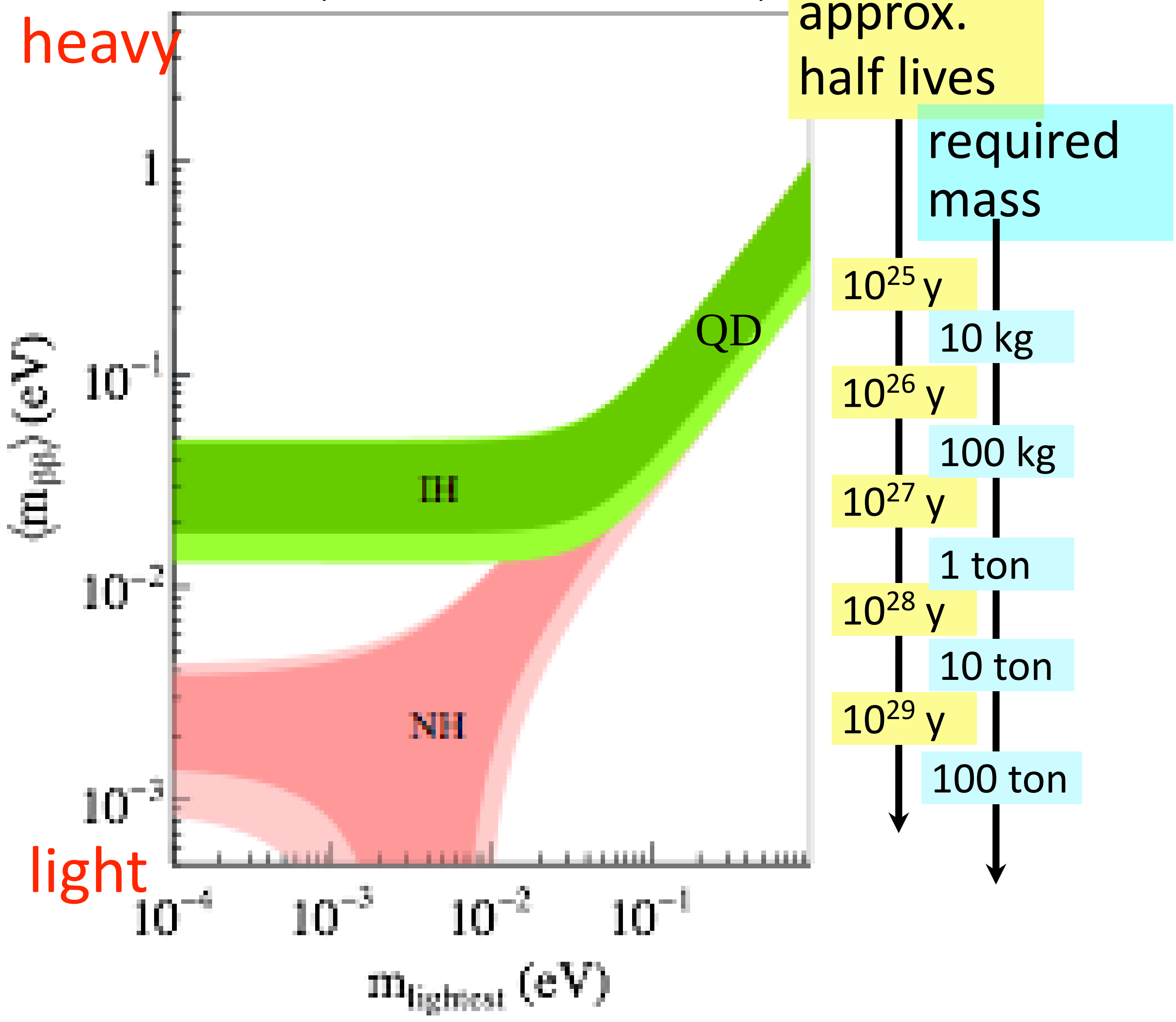
(A. Giuliani)



Very exciting that the near future experiments begin to explore the IO region!

Toward NO

(K. Inoue, ICFA Seminar, 2017)



If we want to cover most of NO, we need;

- ✓ ~100 ton class detector,
- ✓ with reduced background (BG rate must be reduced by 1/mass･time or better),
- ✓ ….

Because of the importance of 0νββ, I really hope that the global neutrino community work together, and find the best way to observe them.

Appendix 1: Proton decay

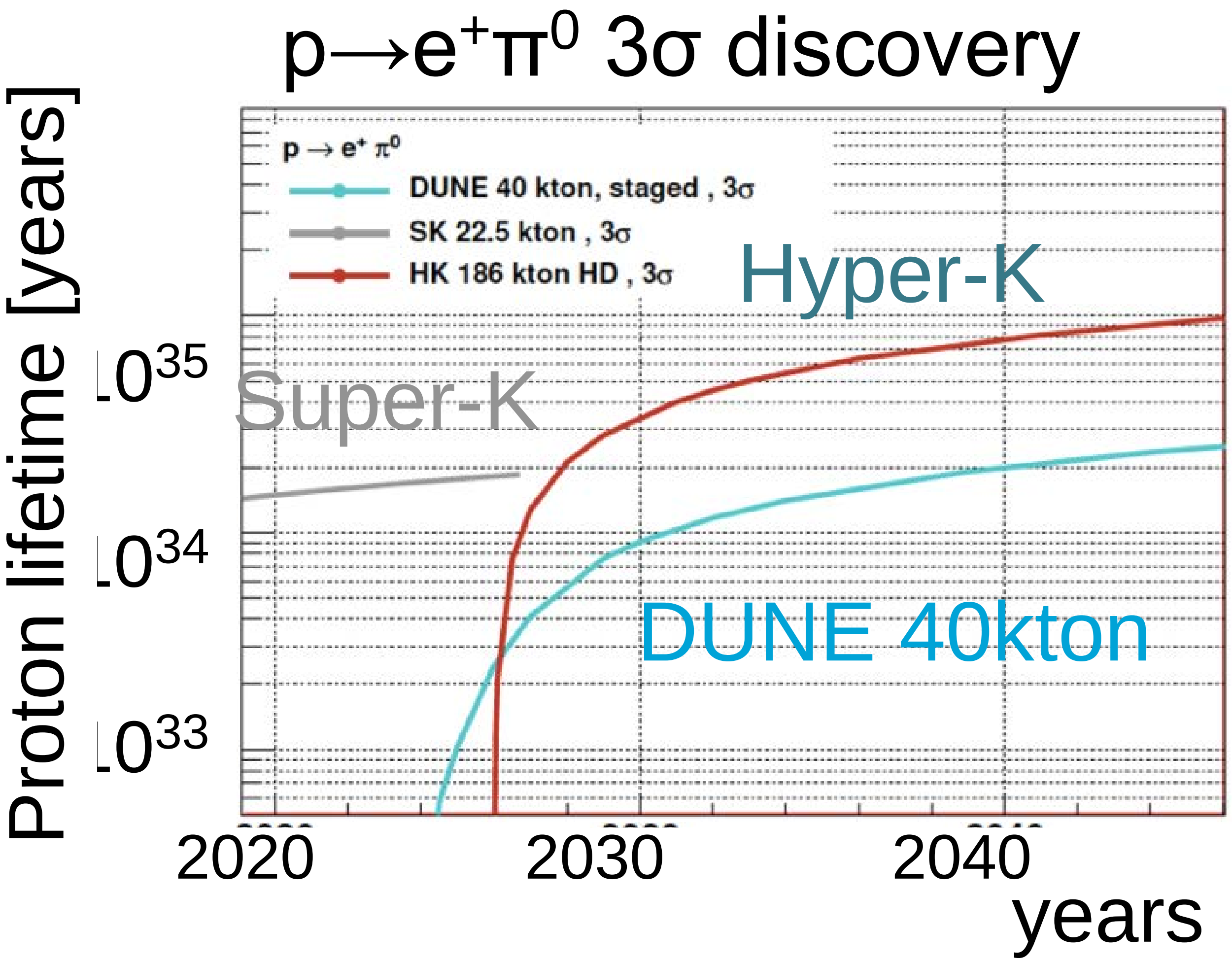
Motivation

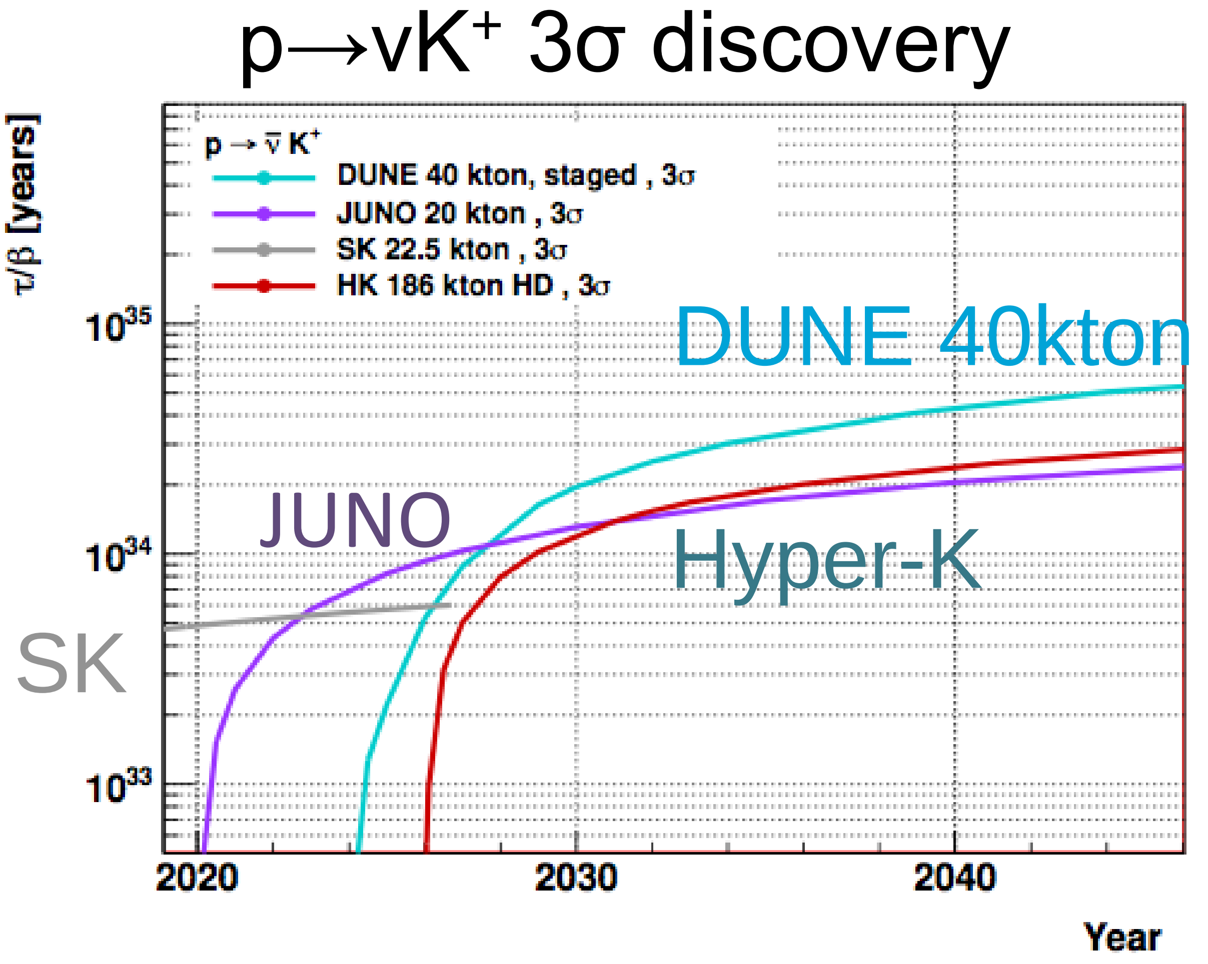
- ✓It is clear that proton decay is very important for understanding of physics at the very high energy scale (GUTs).
- ✓Neutrino masses/mixings and proton decays might be related to the physics at very high energy scale.

- ✓We are in an extremely interesting era. New large neutrino detectors (JUNO, DUNE and Hyper-K) will (or are planed to) begin the operation in the near future. These detectors are also very good proton decay detectors.
- ✓Therefore, we should not forget the proton decay searches in the next generation "neutrino experiments".

Sensitivities

DUNE arXiv:1601.05471
HK arXiv:1805.04163v1
JUNO arXiv:1507.05613



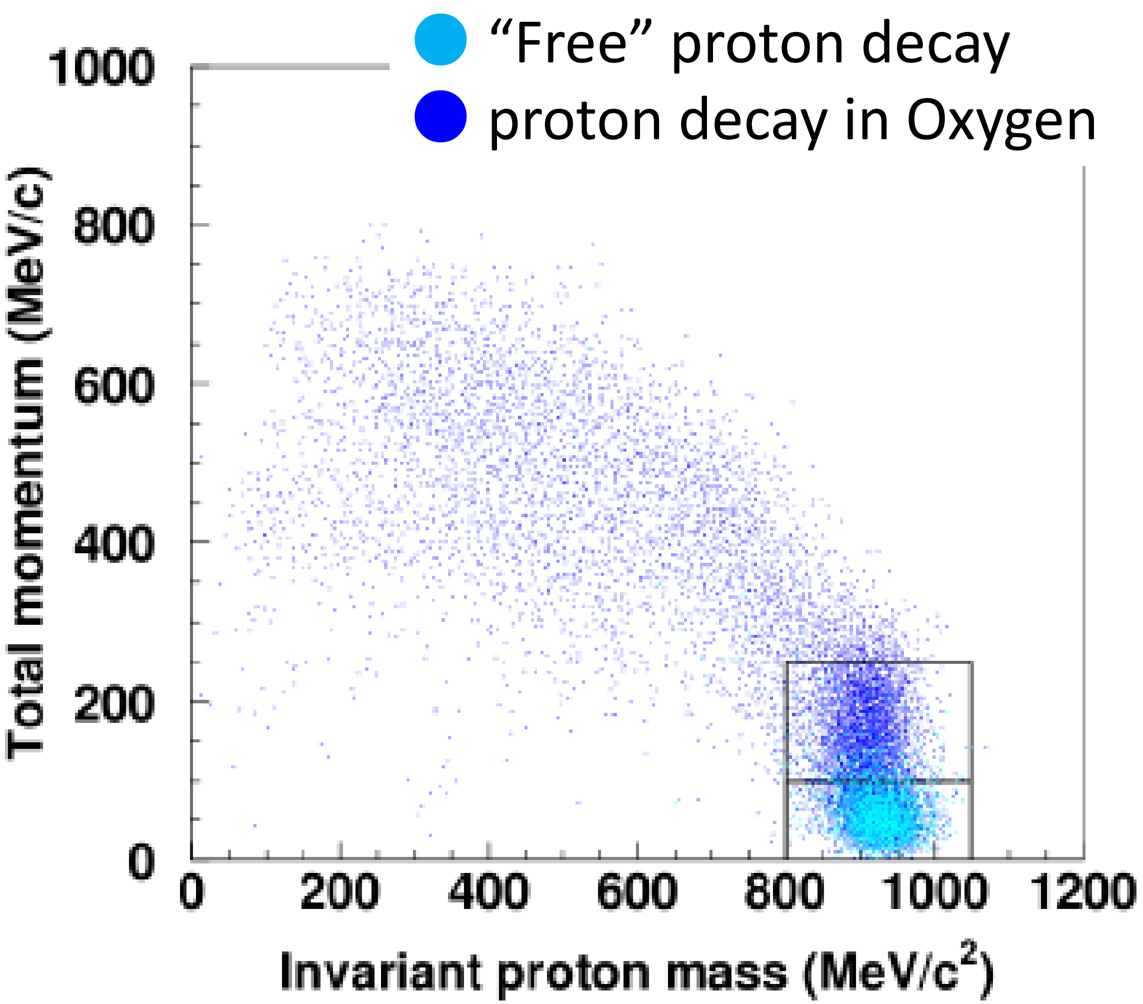


3σ discovery potential, if $\tau_p < 10^{35}$ years ($e\pi^0$) or $< 5*10^{34}$ years (νk^+)

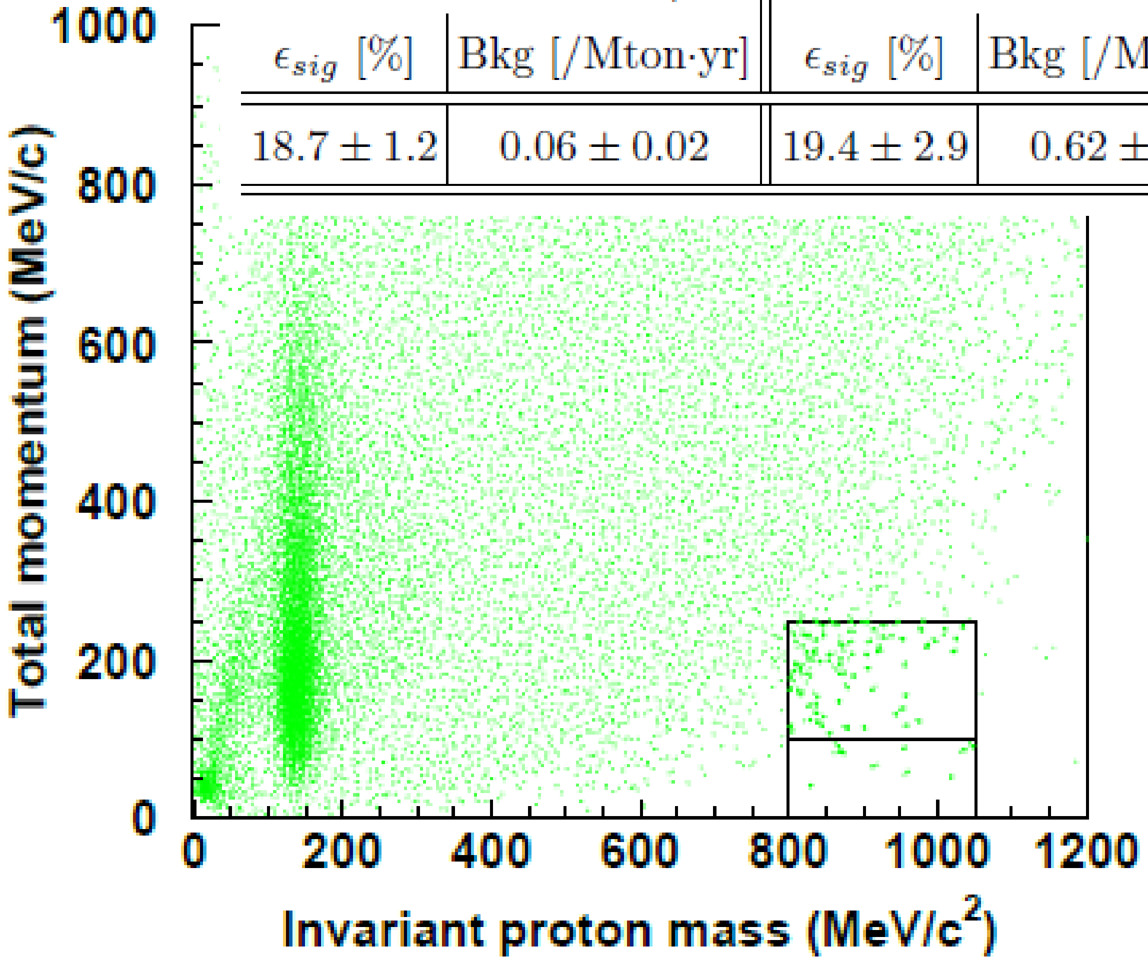
(Lines for DUNE and JUNO experiment have been generated based on numbers in the literature.)

Key plots for confirming p → e π^0

(Hyper-K, arXiv:1805.04163v1)



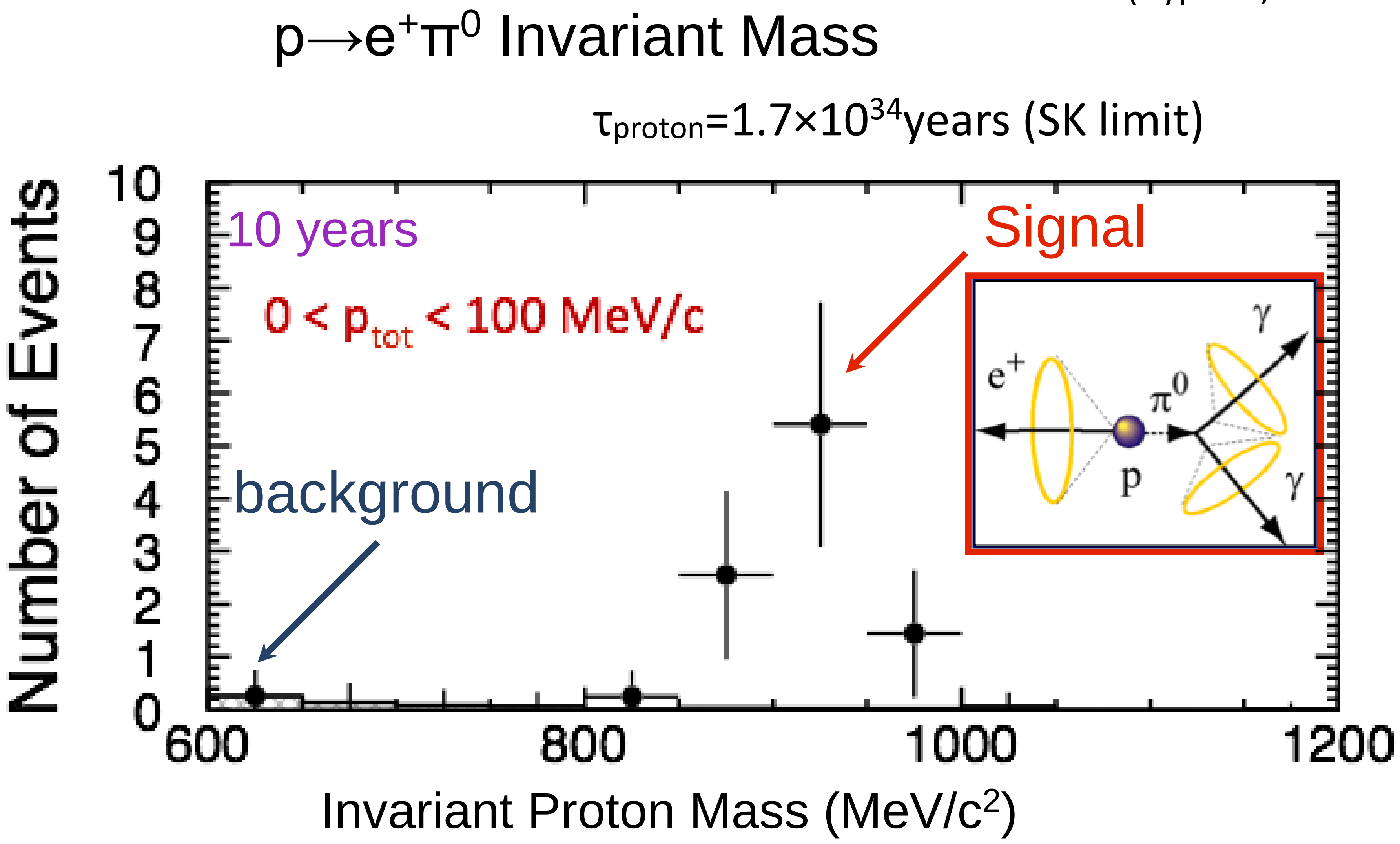
$0 < p_{tot} < 100$ MeV/c		$100 < p_{tot} < 250$ MeV/c	
ϵ_{sig} [%]	Bkg [/Mton·yr]	ϵ_{sig} [%]	Bkg [/Mton·yr]
18.7 ± 1.2	0.06 ± 0.02	19.4 ± 2.9	0.62 ± 0.20



In order to reach 10^{35} years, "free" proton decay (from Hydrogen) is very important!

Key plots for confirming p → e π^0

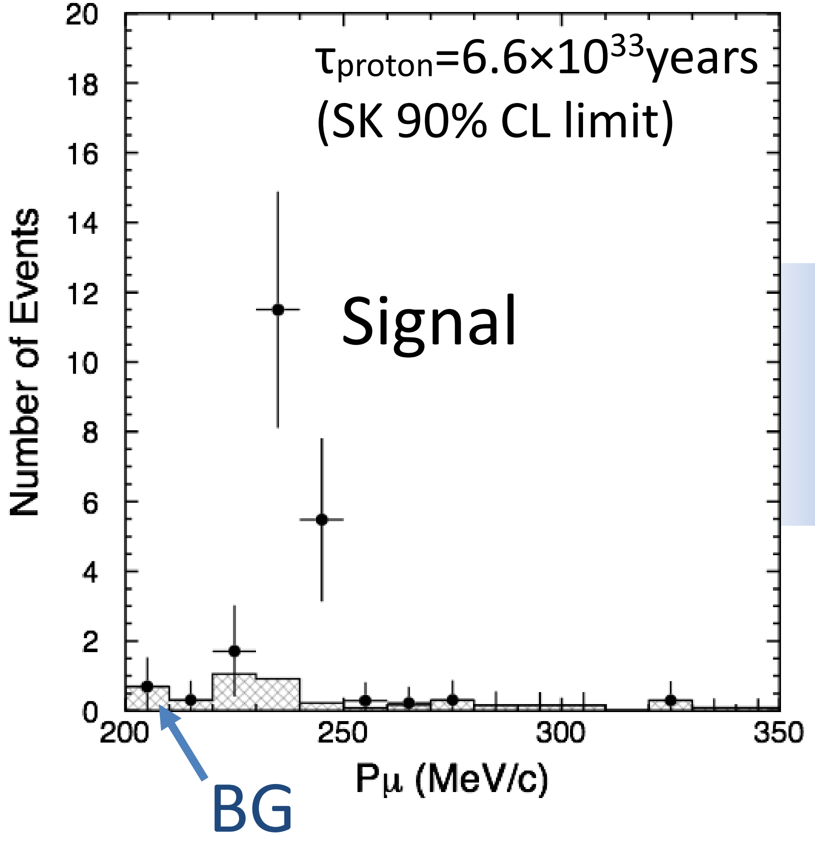
(Hyper-K, arXiv:1805.04163v1)



Key plots for confirming p → ν K⁺

Hyper-K

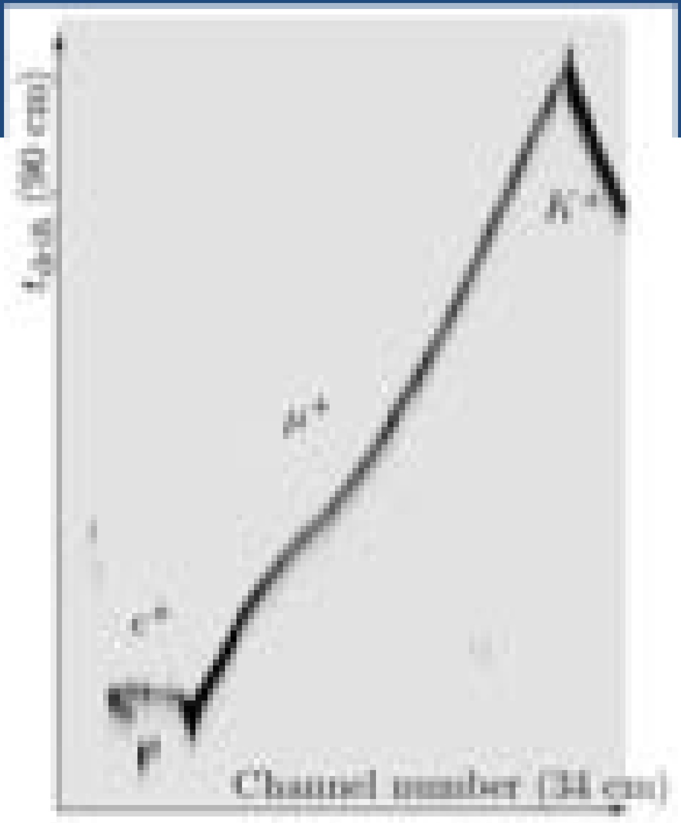
(arXiv:1805.04163v1)



Evidence for the stopped K⁺ decay…

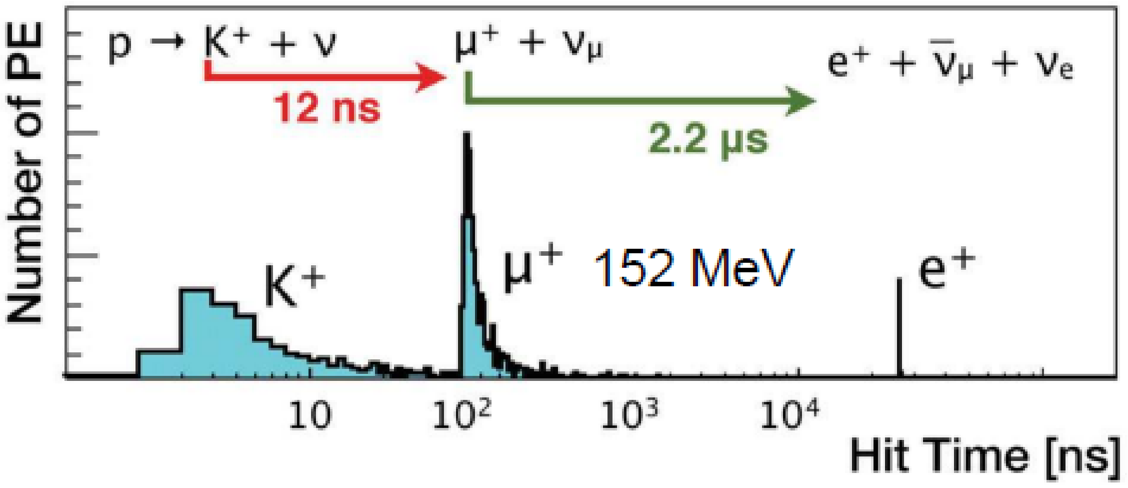
DUNE

JHEP04(2007)041



We want to confirm that the Kaon momentum is consistent with proton decay.

JUNO



Appendix 2: IUPAP Neutrino Panel

An announcement: IUPAP neutrino panel

IUPAP has established the Neutrino Panel with the mandate: “to promote international cooperation in the development of an experimental program to study the properties of neutrinos and to promote international collaboration in the development of future neutrino experiments to establish the properties of neutrinos.”

M. Sajjad Athar	AMU, Aligarh, India
Steve Barwick	UCI Physics and Astronomy
Thomas Brunner	McGill University
Jun Cao	IHEP, Beijing
Mikhail Danilov	Lebedev Physical Inst., Russian Acad. of Sci.
Renata Zukanovich Funchal	University of São Paulo
Kunio Inoue	Tohoku University
Takaaki Kajita **(+)**	University of Tokyo
Marek Kowalski	DESY
Manfred Lindner **(+)**	Max Planck Institute for Nuclear Phys.
Ken Long	Imperial College, London
Nathalie Palanque-Delabrouille	CEA
Heidi Schellman	Oregon State University
Kate Scholberg	Duke University
Seon-Hee Seo	IBS, Center for Underground Physics
Nigel Smith **(+)**	SNOLAB
Walter Winter	DESY-Zeuthen
Sam Zeller	Fermilab

(+) Co-chairs

Objectives (draft): IUPAP neutrino panel

- Through consultation with the broad neutrino-physics community, funding agency and laboratory management and other stakeholders, the Panel will carry out a review of:
  (a) The present status of the global neutrino physics programme and the development that can be expected on a 5 to 10-year timescale through a science driven white paper;
  (b) The measurements and R&D (including software development) that are required for the near-term (<10-year) and medium- to long-term (10 – 25-year) programme to fulfil their potential.
- The Panel will identify opportunities within neutrino physics, mutual benefits of global connections within neutrino physics and other fields, as well as the synergies of an international programme.
- The Panel will provide written updates to the C11 Commission at key milestones in its programme and a final report to the IUPAP General Council by October 2020.

Summary

- In the last 2 decades, neutrino physics had a great progress.
- However, many important questions are still unanswered.
- We have to continue work hard.