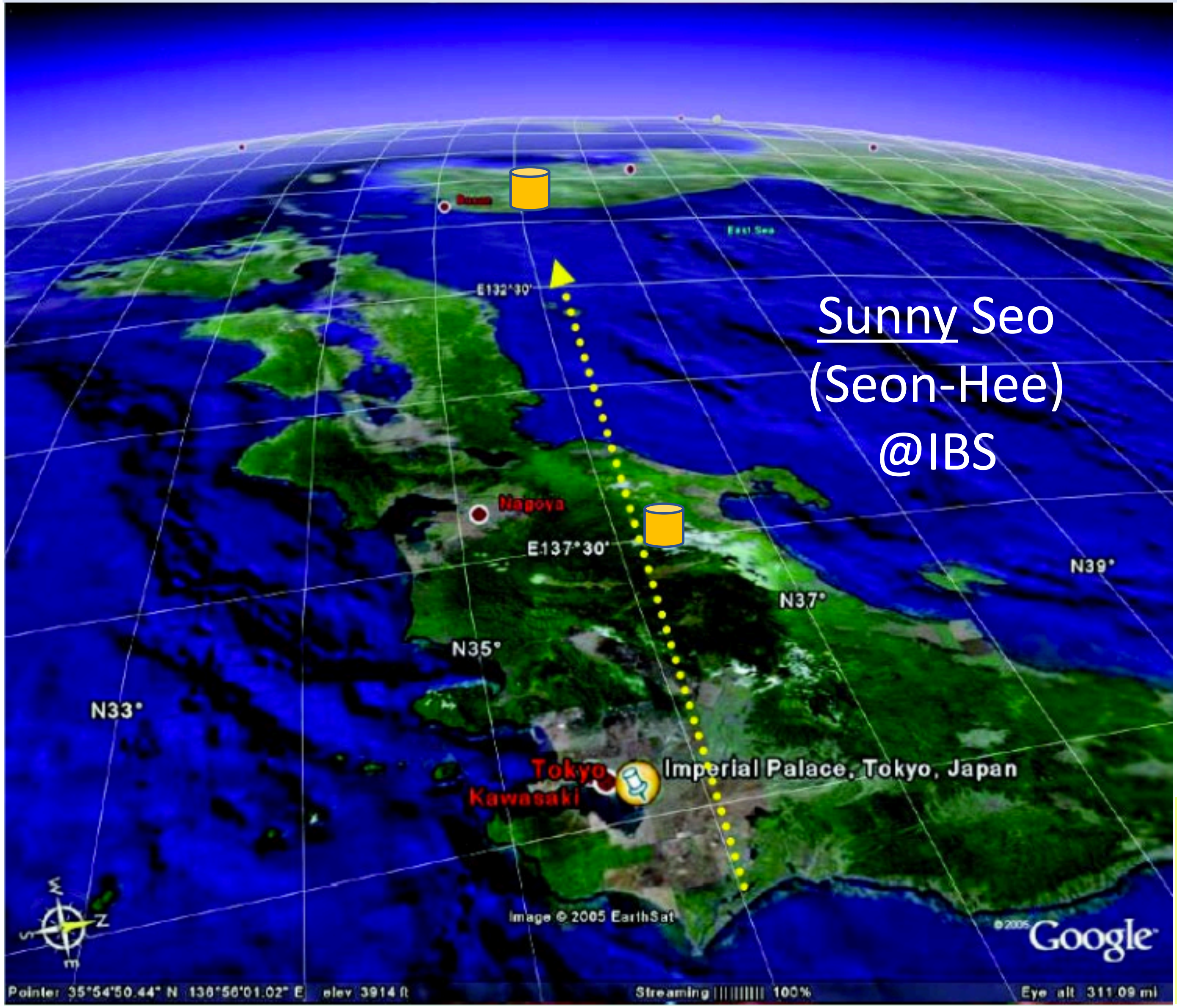
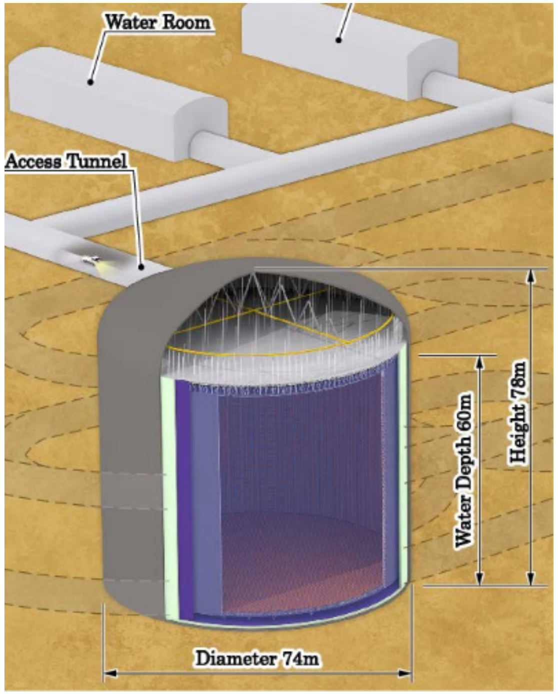
# Physics with T2HKK



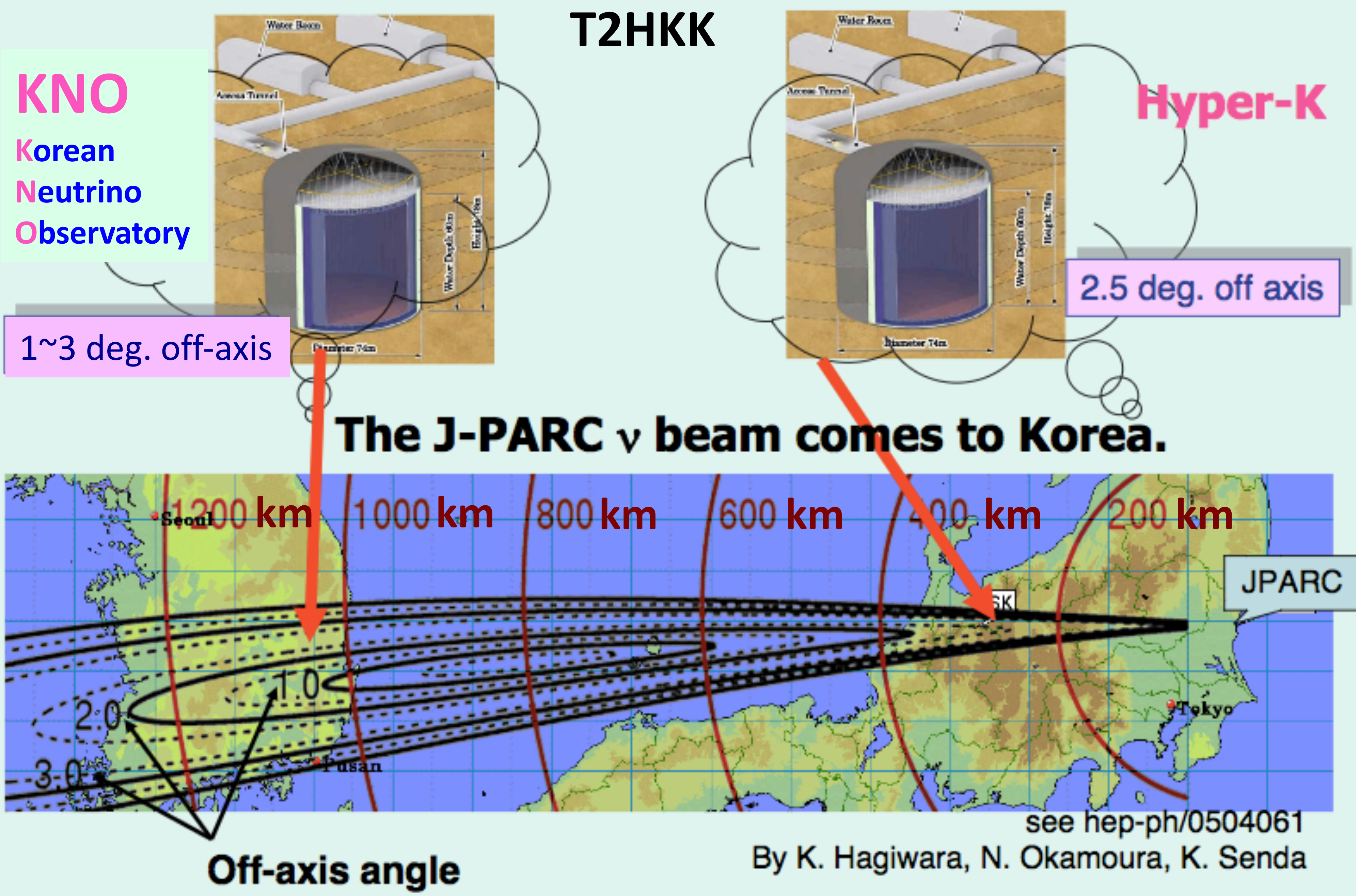

Sunny Seo
(Seon-Hee)
@IBS

Hyper-Kamiokande




Prospects of ν Phys.
IPMU
2019.04.09

# Hyper-K Two Detectors

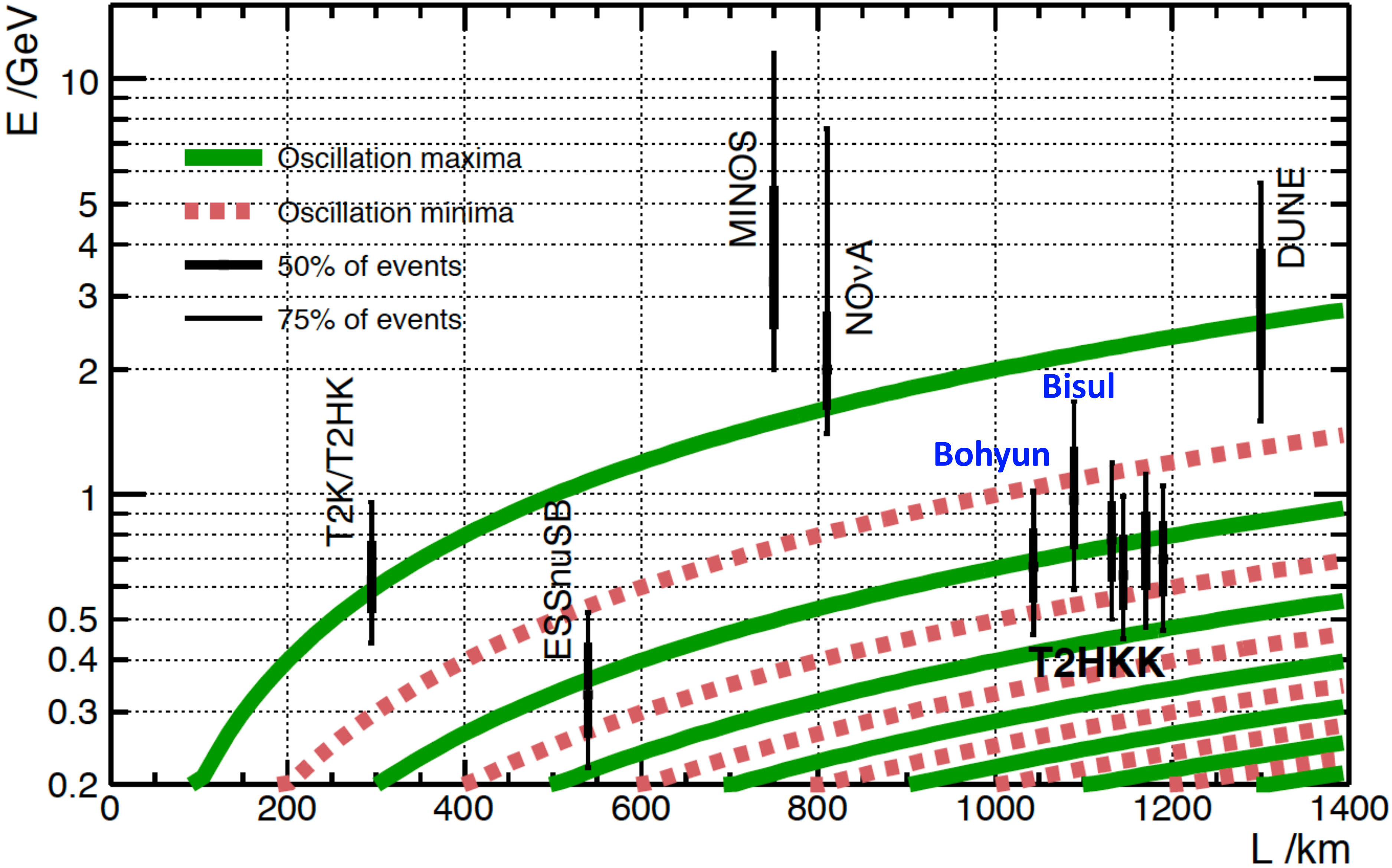


E. Witten

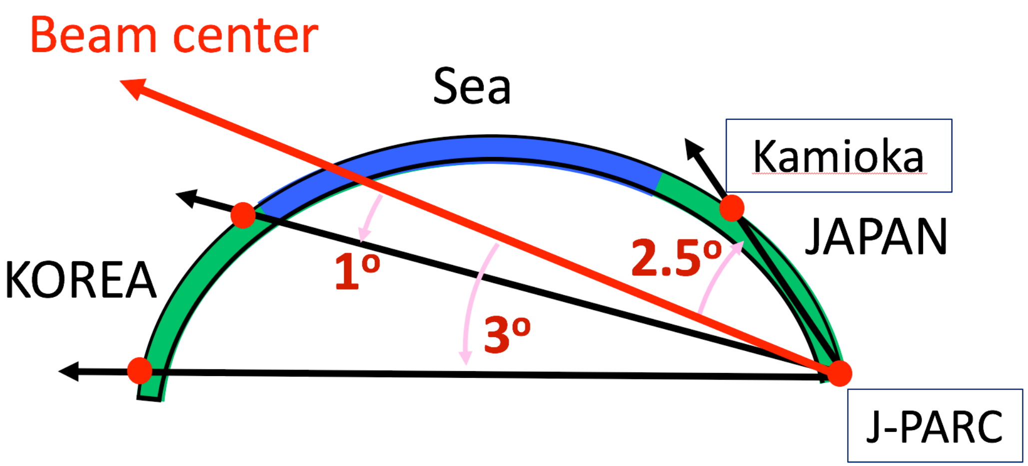
"Why don't you bring one of the 2 tanks to Korea ?"
@EPP2010

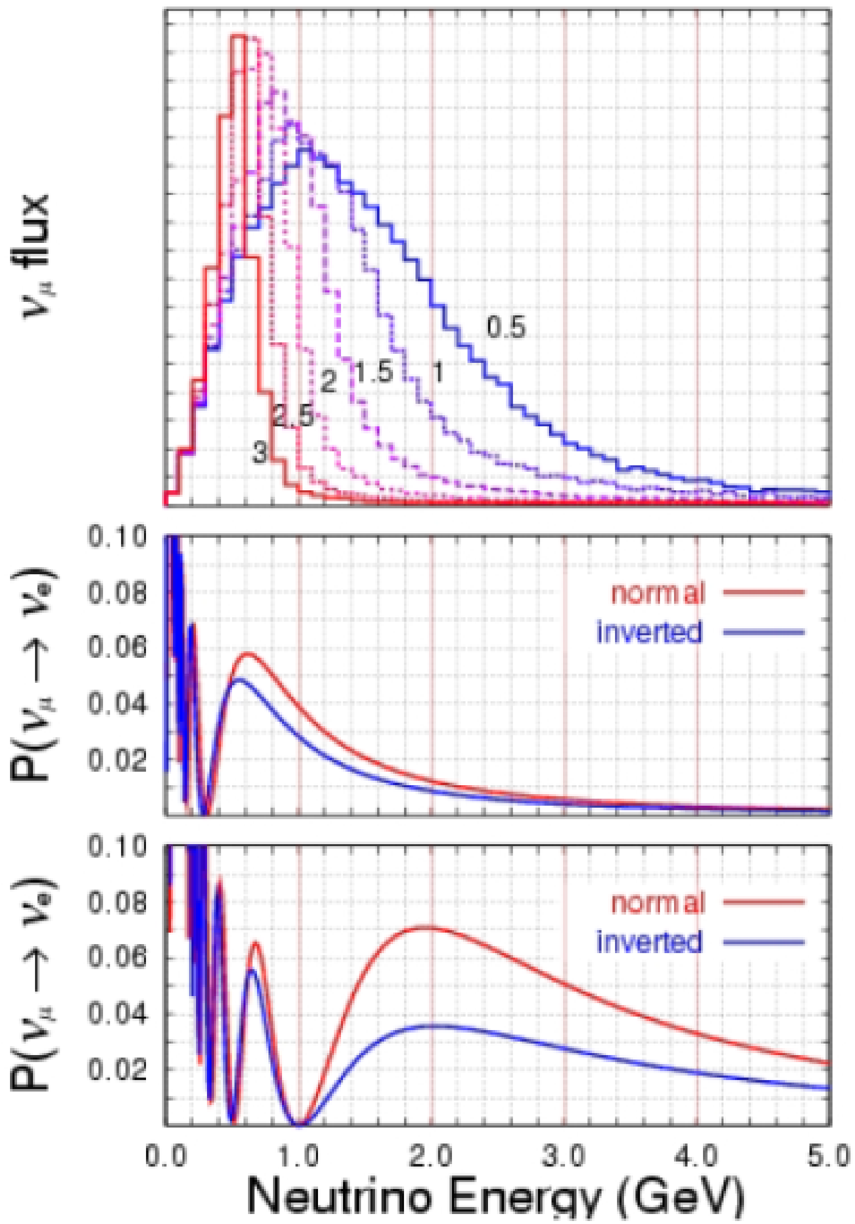
# T2HKK Inauguration
## July 10th 2016, London

# Energy vs. Baseline



# Neutrino Oscillations in Kamioka & Korea




← Profile of off-axis beams

← $P(\nu_\mu \to \nu_e)$ at SK/HK (Japan)
($L$ = 295 km)

← $P(\nu_\mu \to \nu_e)$ at Korea
($L$=1000km)

# Unique benefits of a Korean Detector

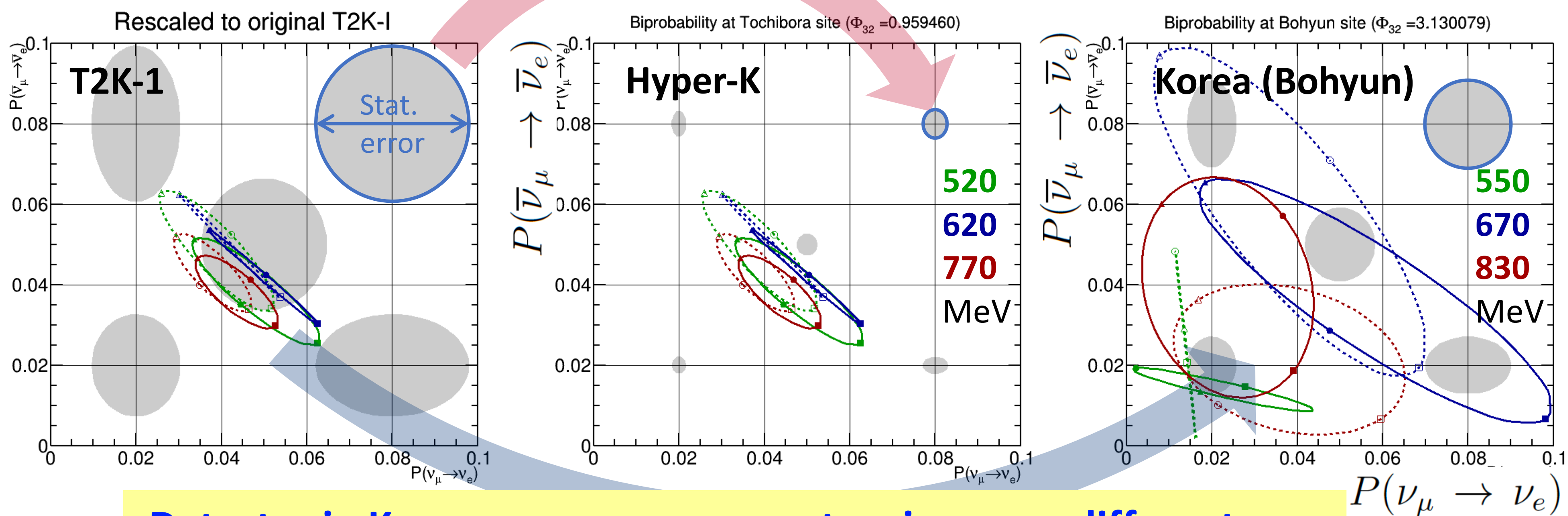
Biprobablitiy plots often used to compare experiments. (e.g. T2K vs NO$\nu$A). Extend these to multiple energies, to gain understanding of 2nd maxima measurement.

Larger ellipses mean less sensitivity to systematic errors.
Shape differences unpick degeneracies with other parameters. (e.g. $\theta_{23}$)

Solid lines: Normal Hierarchy
Dotted lines: Inverted Hierarchy

**New detector at Kamioka improves statistics**

Blue: Energy of peak QE rate
Red: median of high-energy tail
Green: " " low-energy "




**Detector in Korea measures parameters in a very different way**

# Benefits of the 2nd Detector in Korea

T2HKK = Tokai to(2) HK to Korea

The following physics sensitivities are improved by locating the 2nd detector to Korea

- Neutrino mass ordering determination
- Leptonic CP violation measurement

← **1st&2nd oscillation maxima**

- Non-standard neutrino interaction

← **Higher ν energy Longer baseline Higher matter density**

- Solar/SRN/ν geo physics sensitivities

← **Deeper site: 650 vs. 1000 m**

See a talk given by S.K. Agarwalla on this Friday.

# Important Questions

expected to be answered by Hyper-K/T2HKK.

- Leptonic CPV ?
- $\nu$ mass ordering determination ?
- NSI ?
- Supernova relic neutrinos ?
- Proton decay ?
- Dark matter ?
- etc.

In this talk

# Why Leptonic CPV ?

1. Which flavor symmetry model ?

Understanding pattern of ν mixing

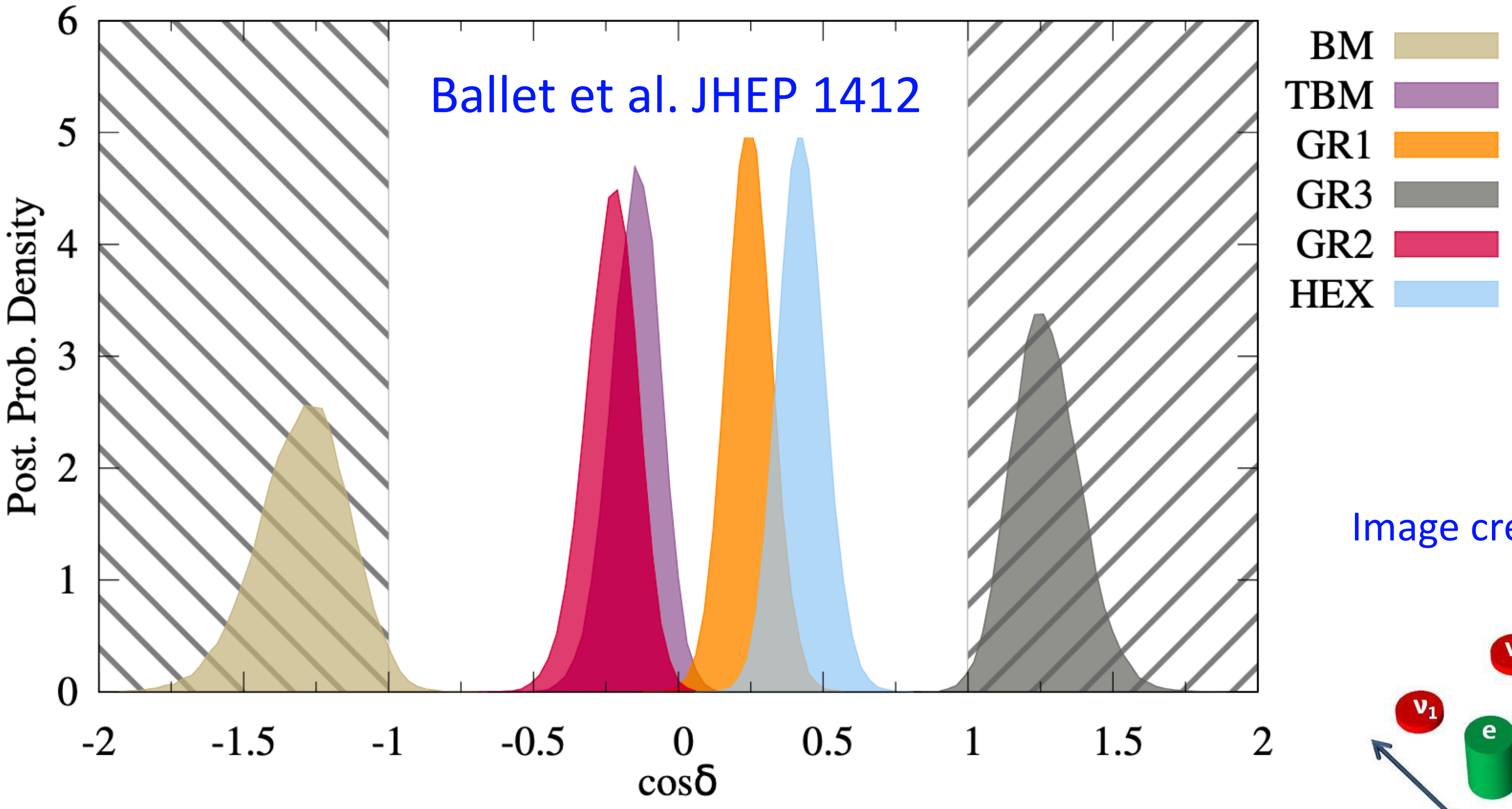
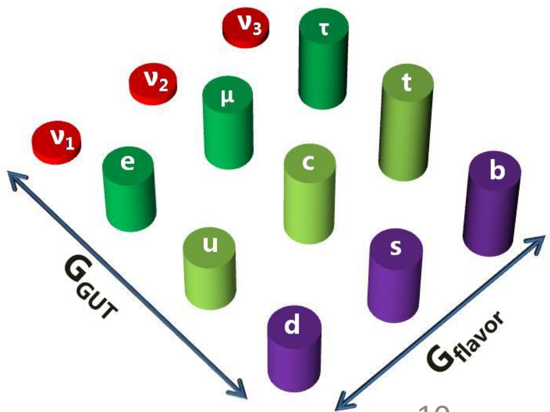



Image credit: T. Ohlsson @KTH



# Why CPV in Lepton Sector?

- CP structure in quark sector is well known.
  → Small CPV in quark sector ( < $10^{-7}$ %)
  can not explain baryon asymmetry of the universe.

- However, **leptogenesis** may explain baryon asymmetry, provided with large CPV in lepton sector.

- There is **hint** of maximal CPV in lepton sector.
  (~ 2sigma @T2K, NOvA)

CP

$$\nu_\mu \to \nu_e \quad \Longleftrightarrow \quad \bar{\nu}_\mu \to \bar{\nu}_e$$

T $\Updownarrow$ $\Updownarrow$ T

$$\nu_e \to \nu_\mu \quad \Longleftrightarrow \quad \bar{\nu}_e \to \bar{\nu}_\mu$$

CP

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23}$$
$$\sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$$

# $\delta_{CP}$ & MO Sensitivity Studies

**** Simulation parameters ****

- $2.7\times10^{22}$ POT with $\nu : \bar{\nu} = 1 : 3$ operation ratio

  → 10 years of operation with 1.3 MW beam

- 187 kton fiducial volume (compared to 22.5 kton for SK)
- Baseline to Korea is 1100 km
- Off-axis beam: 1.5°, 2.0°, 2.5°
- Oscillation parameters: →

$$|\Delta m_{32}^2| = 2.5\times10^{-3}\ \mathrm{eV}$$
$$\sin^2\theta_{23} = 0.5$$
$$\sin^2 2\theta_{13} = 0.085$$
$$\Delta m_{21}^2 = 7.53\times10^{-5}\ \mathrm{eV}$$
$$\sin^2\theta_{12} = 0.304$$
$$\delta_{cp} = 0, \pi/2, \pi, 3\pi/2$$

◆ Note: Relatively simple systematic uncertainty model is used. More realistic systematic uncertainty implementation is needed.

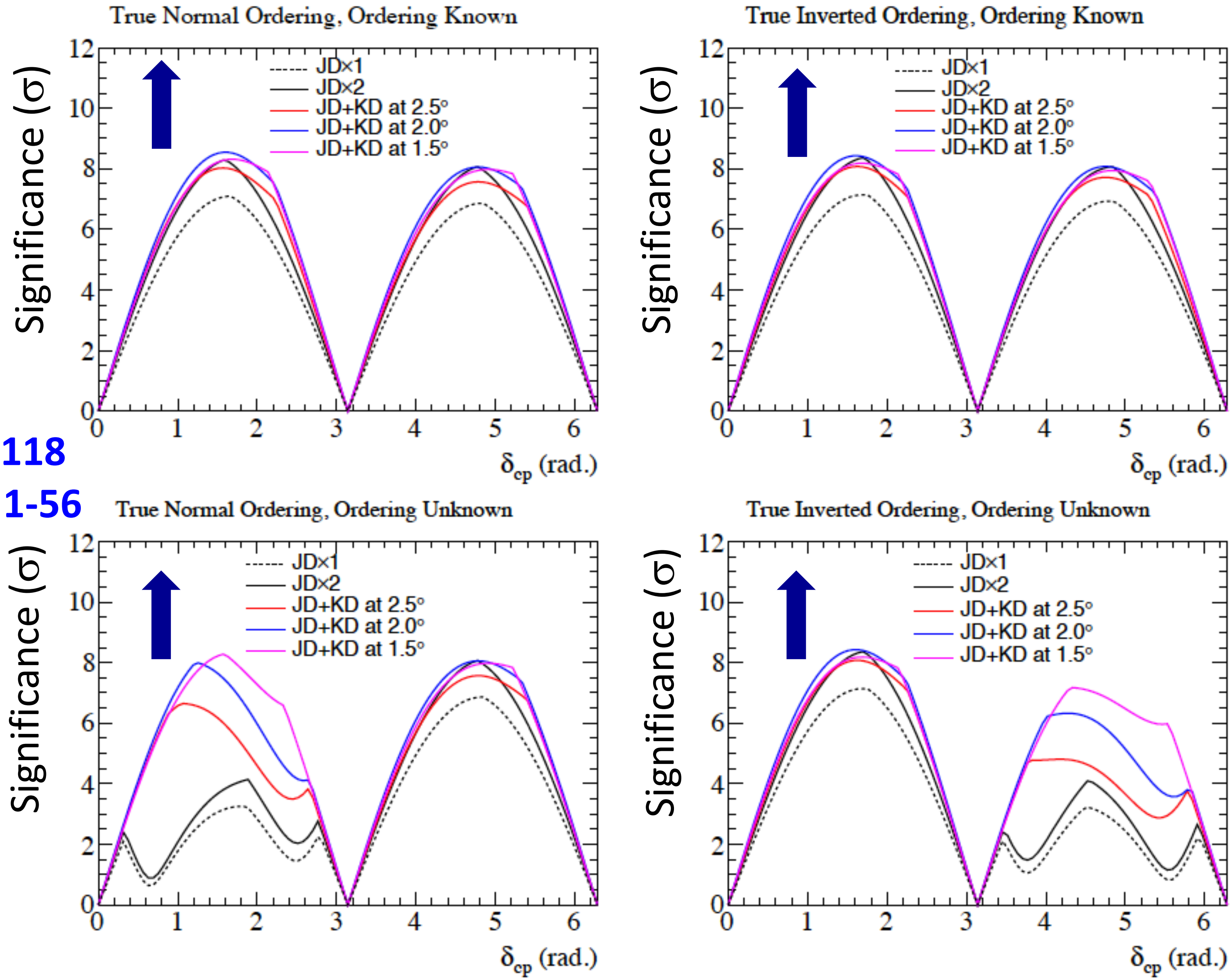
# $\delta_{CP}$ Sensitivities

Known MO

**arXiv:1611.06118**

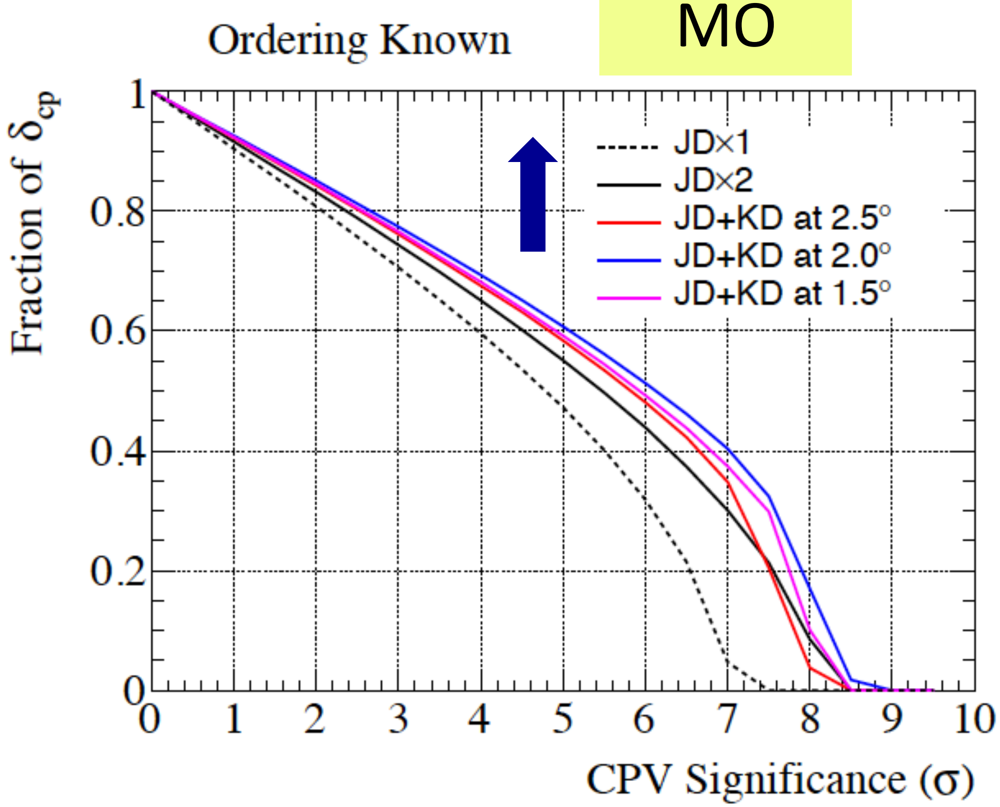
**PTEP 2018, 6, 1-56**

Unknown MO

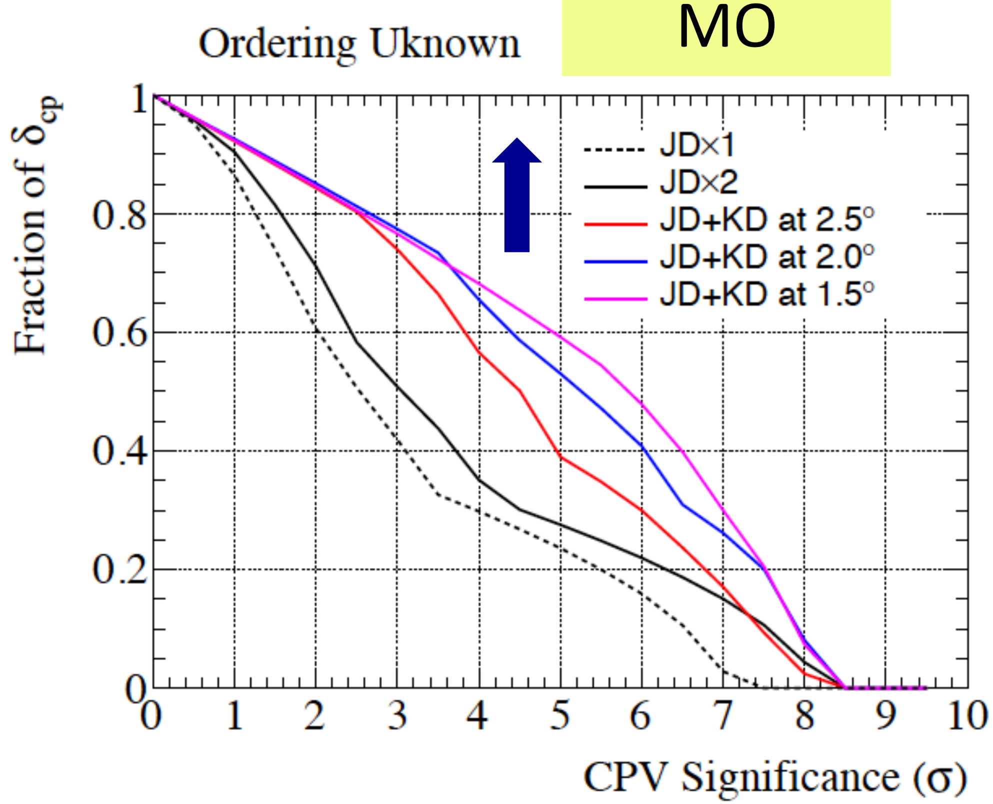


# Fraction of $\delta_{CP}$

**Known**
MO




**Unknown**
MO

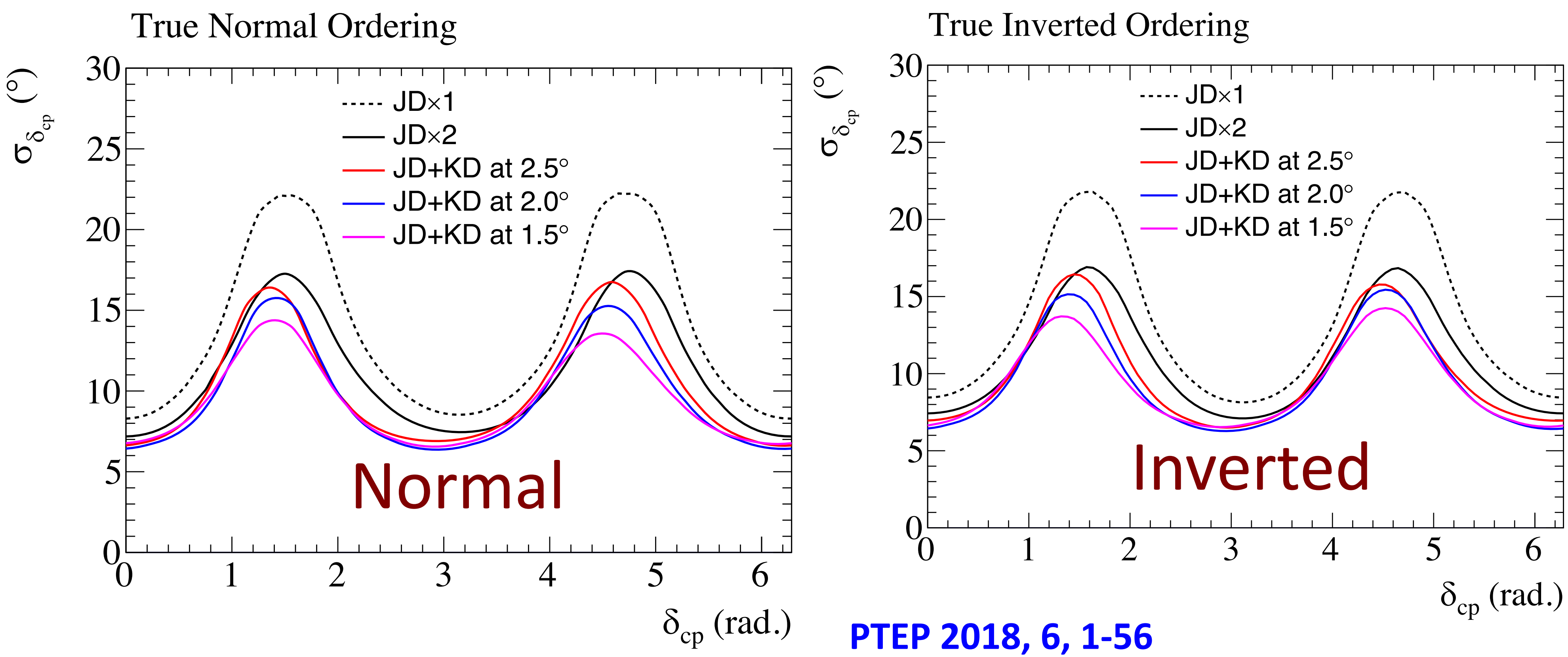



**arXiv:1611.06118**
**PTEP 2018, 6, 1-56**

Note: LBL sensitivity study was also independently done using GLoBES in PRD 96,033003 (2017).

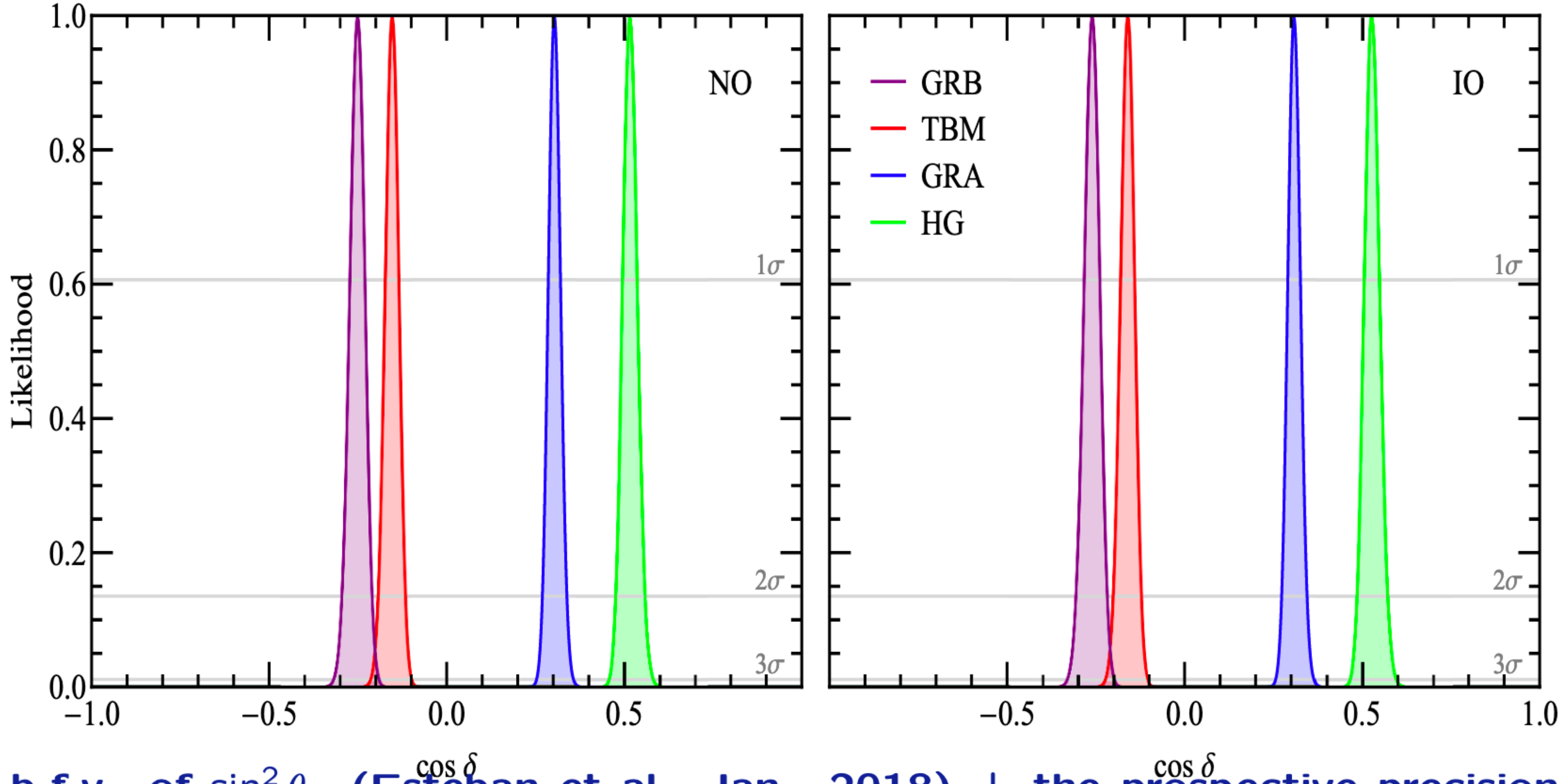
# $\delta_{CP}$ Precision Sensitivities

→ Very important for flavor symmetry model of neutrino mixing
S. Petcov in ICHEP 2018




**PTEP 2018, 6, 1-56**

At maximum CP violation: JD+KD 1.5°: $\sigma(\delta_{CP})$ = 13~14 degree
JD x 2 : $\sigma(\delta_{CP})$ ~ 17 degree
JD x 1 : $\sigma(\delta_{CP})$ ~ 22 degree




**b.f.v. of $\sin^2\theta_{ij}$ (Esteban et al., Jan., 2018) + the prospective precision used.**

F. Capozzi et al. 2018
(arXiv:1804.09678)

4.4% → $\delta(\sin^2\theta_{12}) = 0.7\%$ **(JUNO),**

3.7(IO)-3.8(NO)% → $\delta(\sin^2\theta_{13}) = 3\%$ **(Daya Bay),**

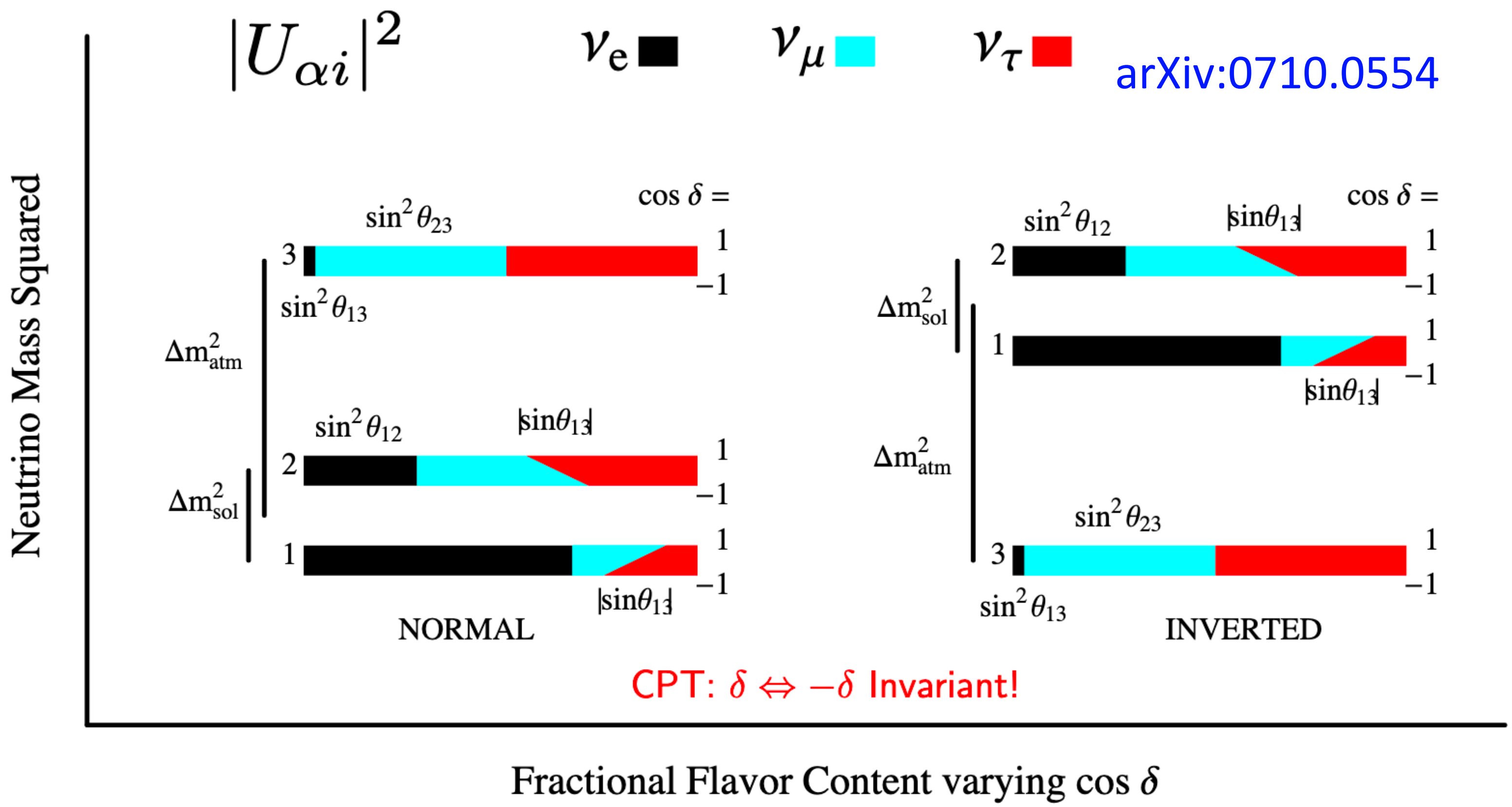
4.8(IO)-5.2(NO)% → $\delta(\sin^2\theta_{23}) = 3\%$ **(T2HK, DUNE; T2K+NO$\nu$A(?)).**

$25^{O}$(IO)-$37^{O}$(NO) → $\boxed{\delta(\delta) = 10^\circ \text{ (THKK?)}}$

**Prospective (useful/requested) precision:**

S. Petcov talk @ICHEP2018

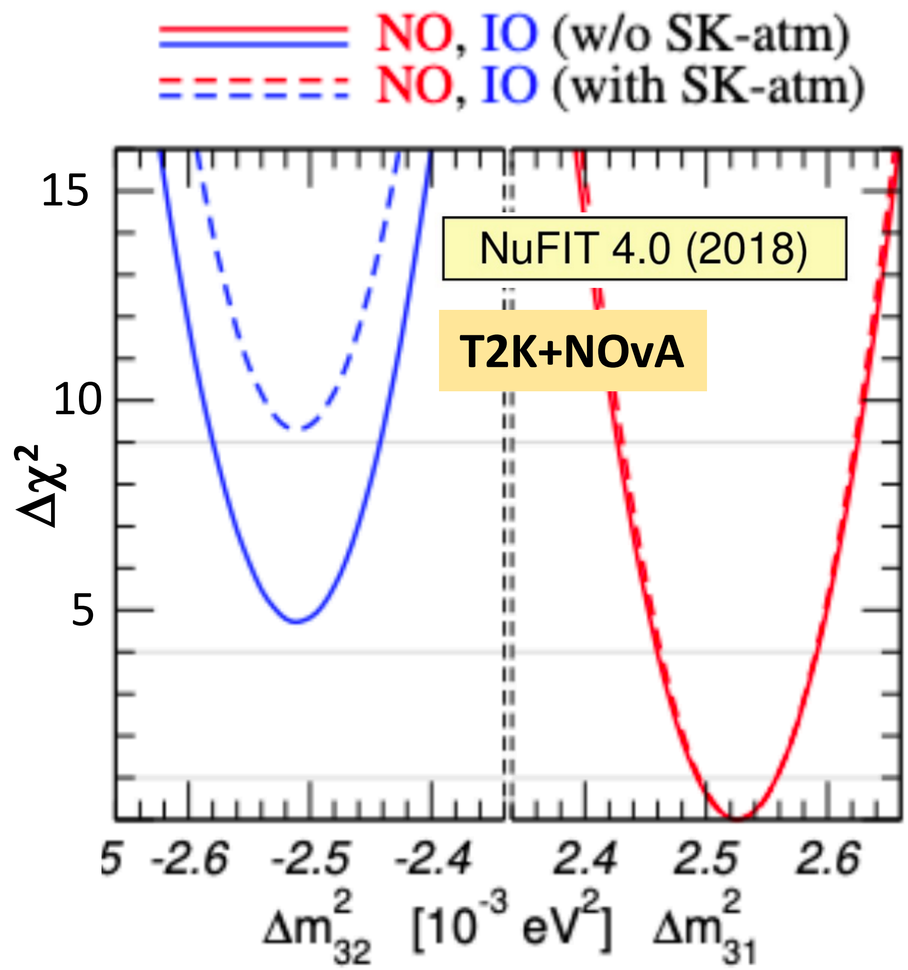
# Why ν Mass Ordering (MO) ?

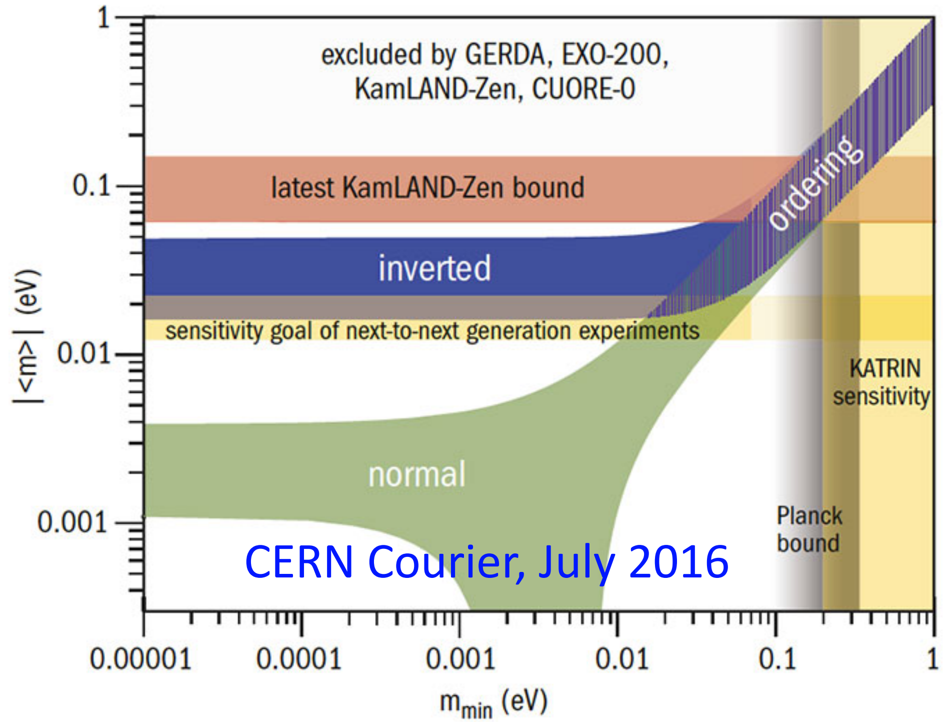



1. Important input to CPV measurement

2. Important input to flavor models

# Current Status of ν MO




** Cosmological measurement
(indirect / independent)
favors normal ordering 3 times
more from sum of ν mass

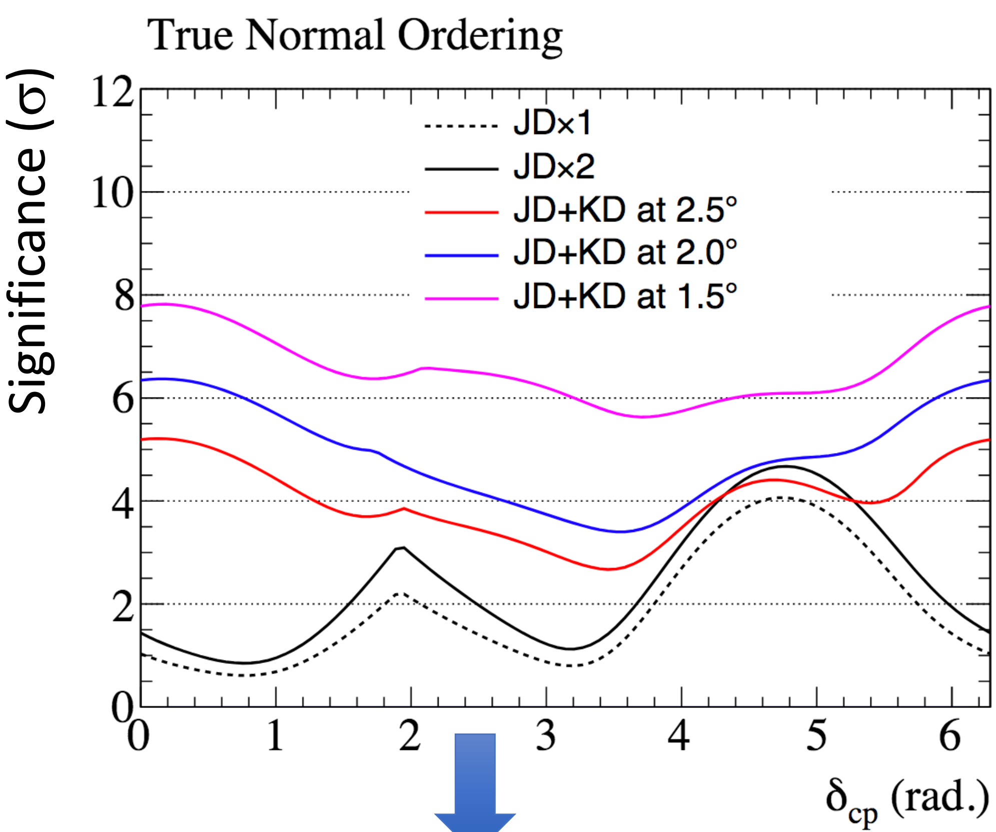
- Current best fit: normal ordering at **3.4 σ** from global fit

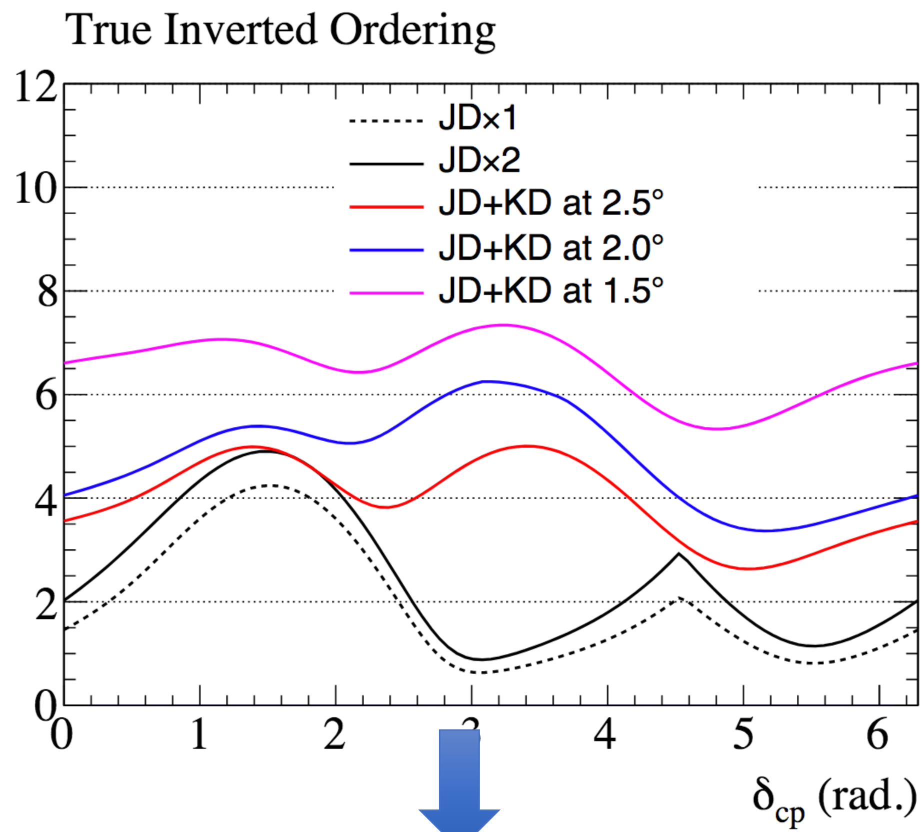
Front. Astron. Space Sci., 09 October 2018

(T2K, NOvA) + (SK) + (DB, RENO, DC)

# Mass Ordering Sensitivities (Beam ν)

**Normal** PTEP 2018,6, 1-56 **Inverted**

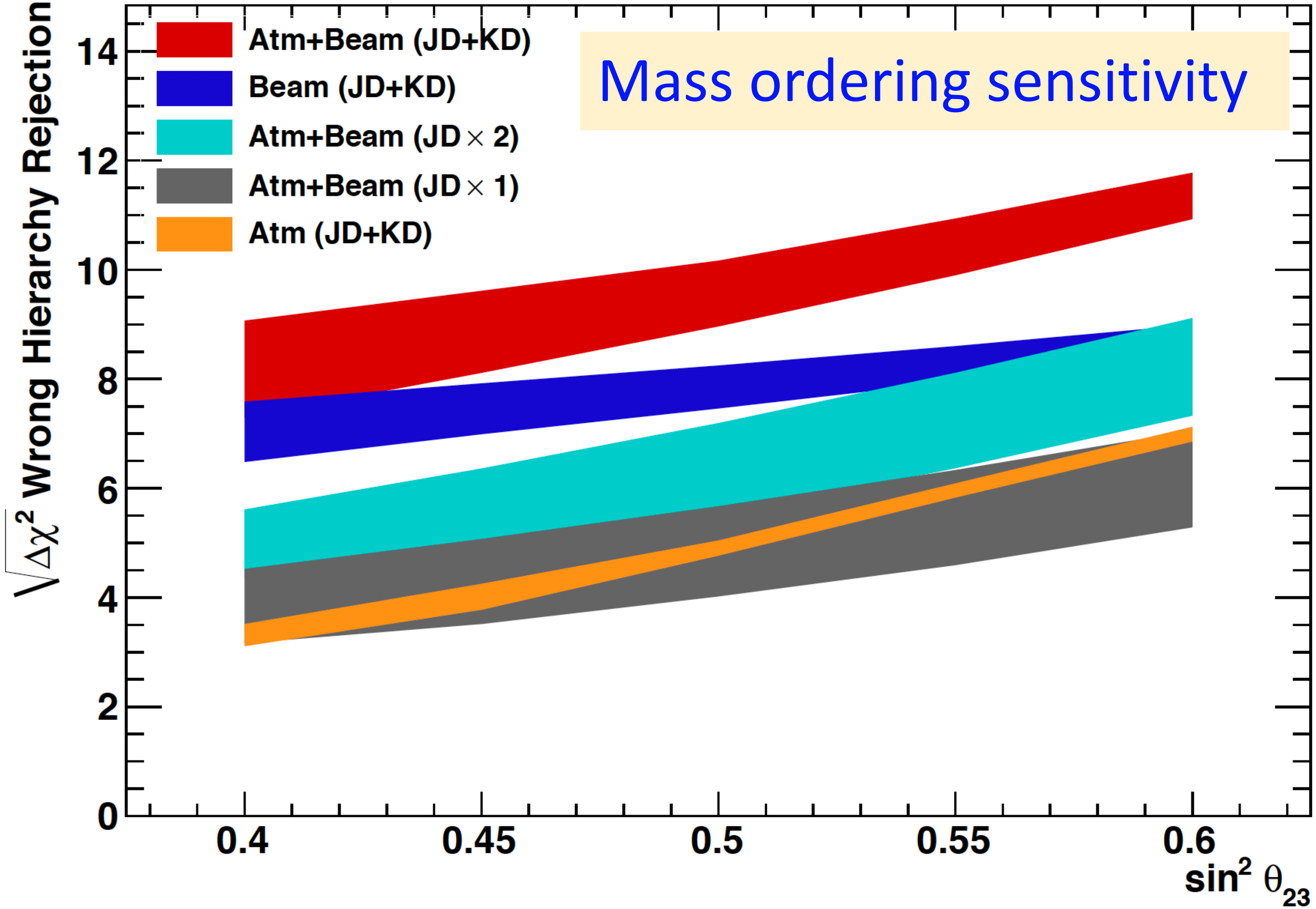



JD+KD 1.5°: 6 ~ 8 σ for all $\delta_{CP}$
JD x2 : 1 ~ 4.5 σ for all $\delta_{CP}$
(< 3 σ for most cases)

JD+KD 1.5°: 5.5 ~ 7 σ for all $\delta_{CP}$
JD x2 : 1 ~ 5 σ for all $\delta_{CP}$
(< 3 σ for most cases)

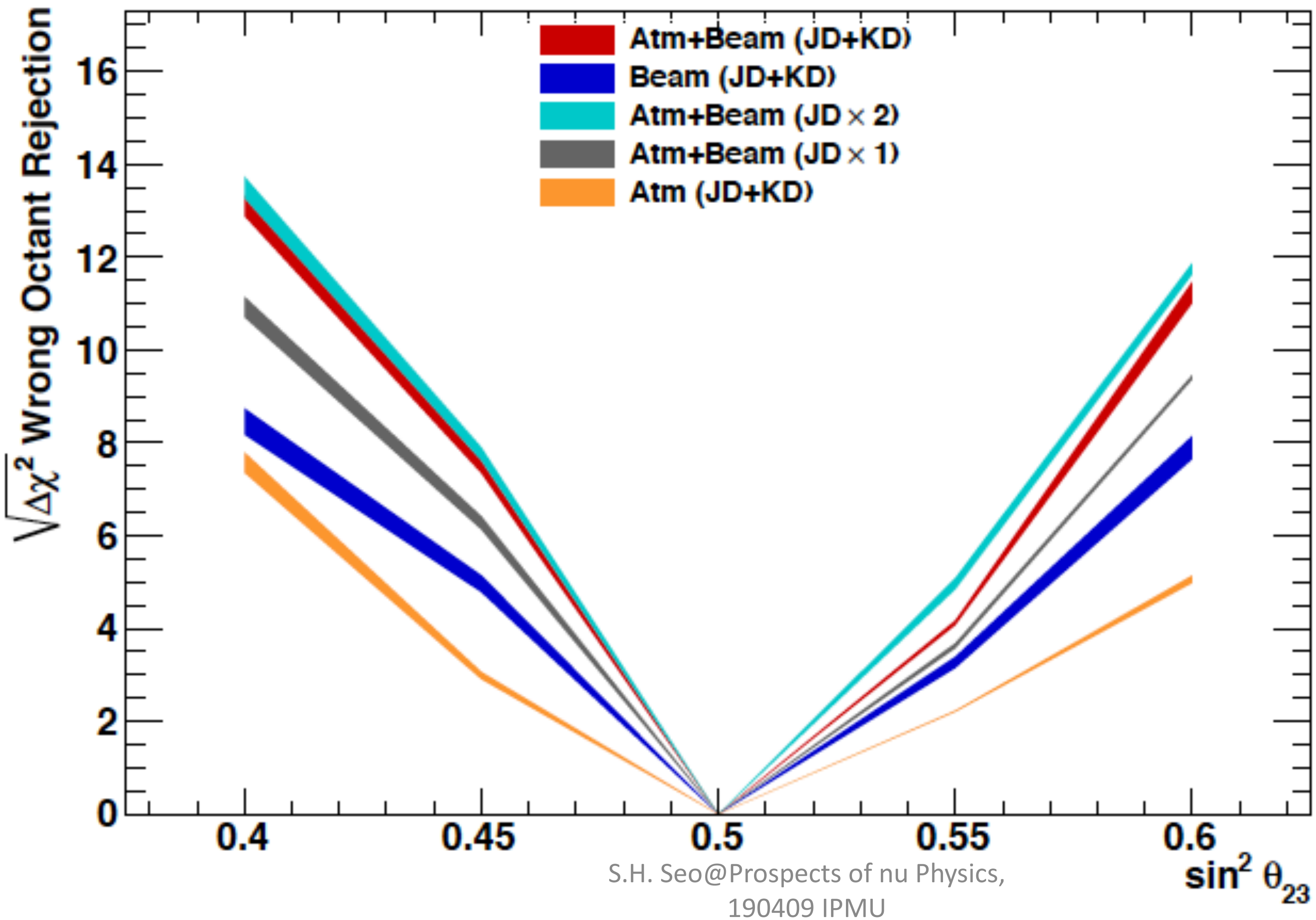
# Beam + Atm. ν Data




→ Best way to determine ν mass ordering among [[ ν oscillation, 0νββ, cosmology ]]

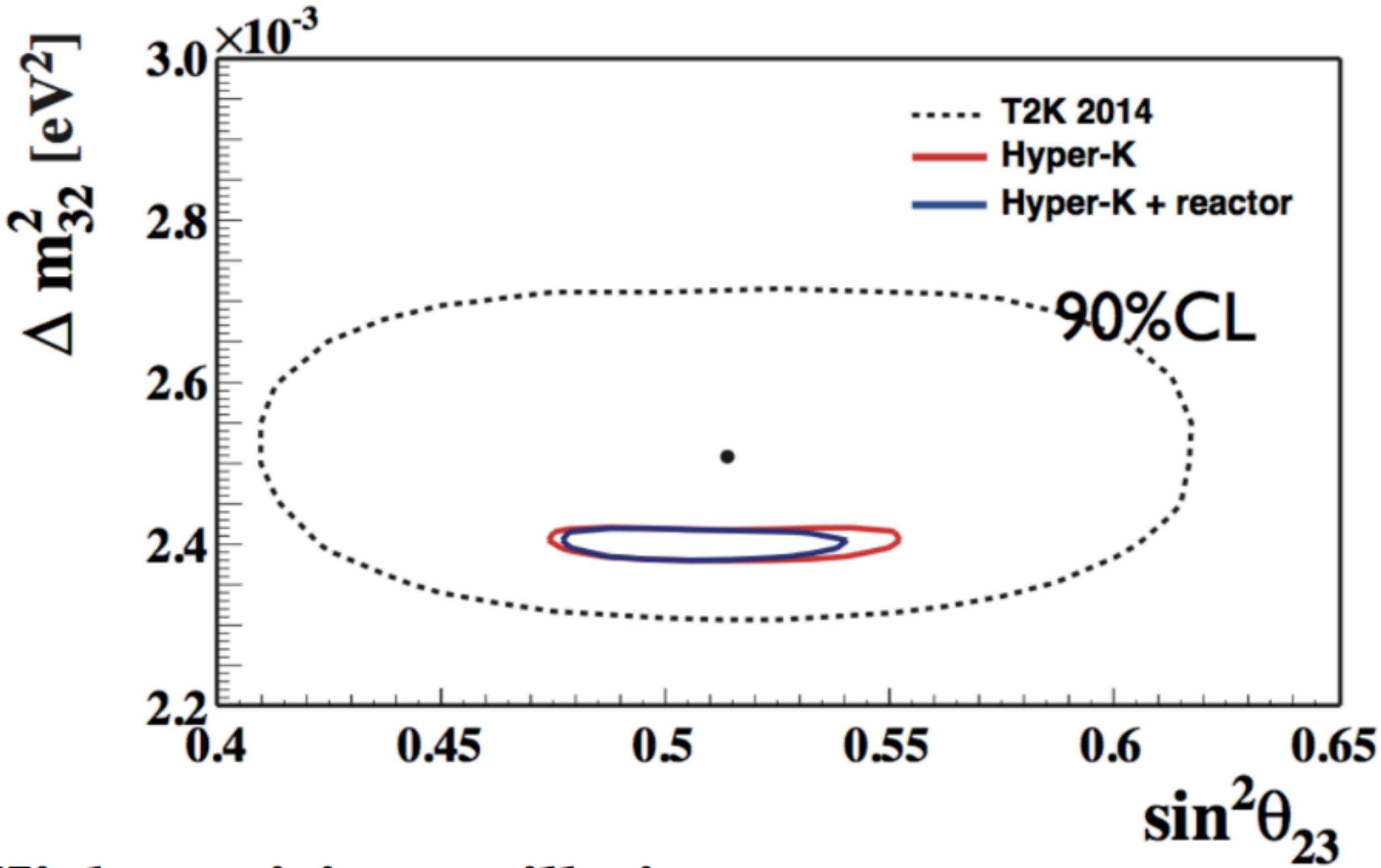
# Octant Sensitivity: Beam + Atm.

$\theta_{23}$ octant sensitivity → Important for MO & CPV measurements



# Atmospheric Parameter Sensitivity

## Neutrino oscillation parameters




**High precision oscillation parameter measurement:**

1.3% $\delta(\sin^2\theta_{23}) \sim 0.006$ (for $\sin^2\theta_{23}$=0.45)

3% $\delta(\sin^2\theta_{23}) \sim 0.015$ (for $\sin^2\theta_{23}$=0.50)

$\delta(\Delta m^2_{32}) \sim 1.4\times10^{-5}\mathrm{eV}^2$ ~0.6%

15

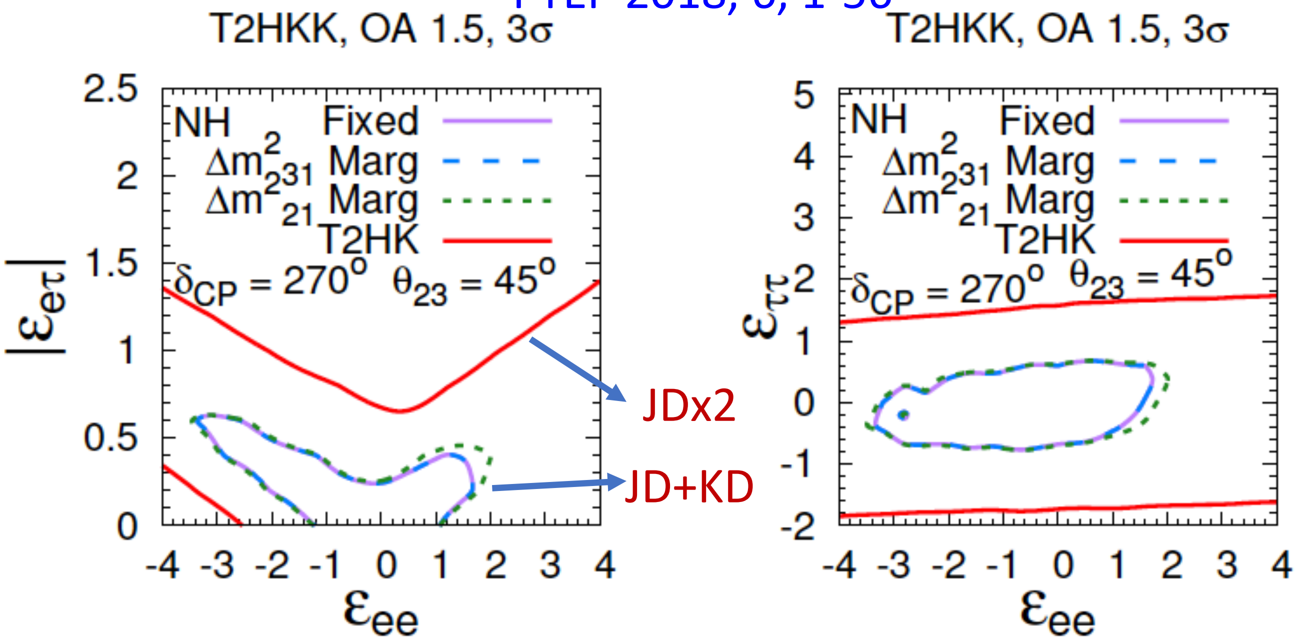
# Non-standard ν Interaction Sensitivity

$$H = \frac{1}{2E}\left[U\begin{pmatrix} 0 & 0 & 0 \\ 0 & \delta m^2_{21} & 0 \\ 0 & 0 & \delta m^2_{31}\end{pmatrix}U^\dagger + V\right]$$

$$V = A\begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu}e^{i\phi_{e\mu}} & \epsilon_{e\tau}e^{i\phi_{e\tau}} \\ \epsilon_{e\mu}e^{-i\phi_{e\mu}} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}e^{i\phi_{\mu\tau}} \\ \epsilon_{e\tau}e^{-i\phi_{e\tau}} & \epsilon_{\mu\tau}e^{-i\phi_{\mu\tau}} & \epsilon_{\tau\tau}\end{pmatrix}$$

$$A \equiv 2\sqrt{2}G_F N_e E,$$

arXiv:1611.06118
PTEP 2018, 6, 1-56



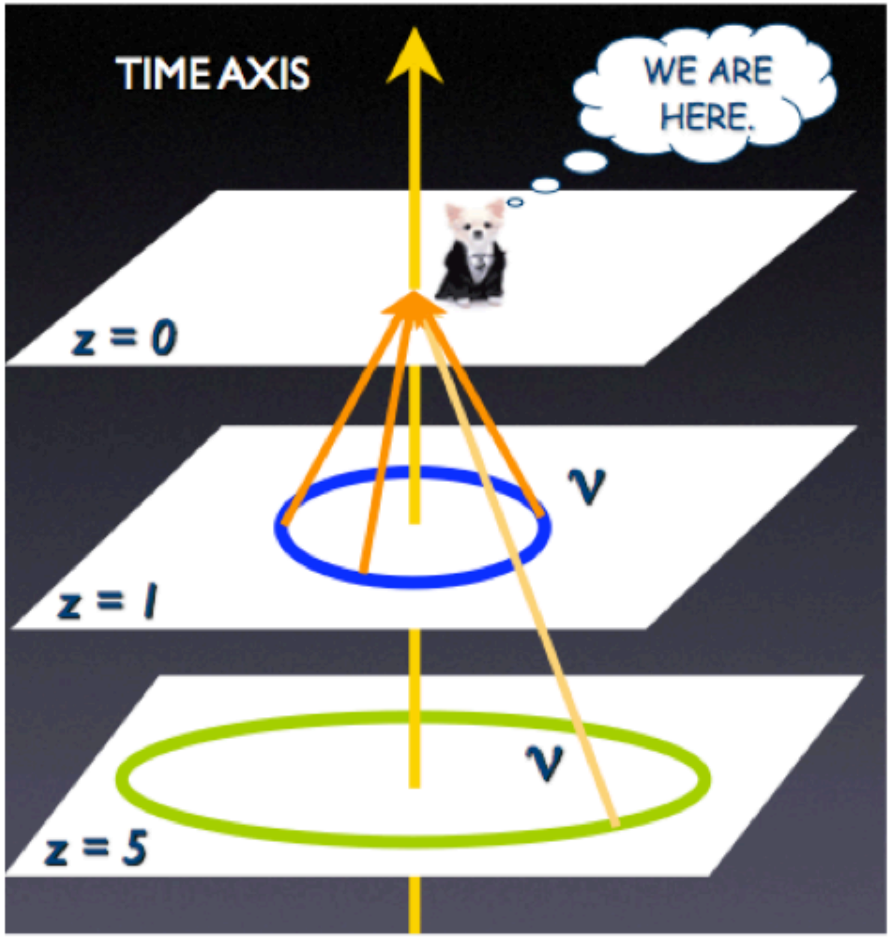

D. Marfatia@ICHEP2018: arXiv:1612.01443 See D. Marfatia's talk this Friday !

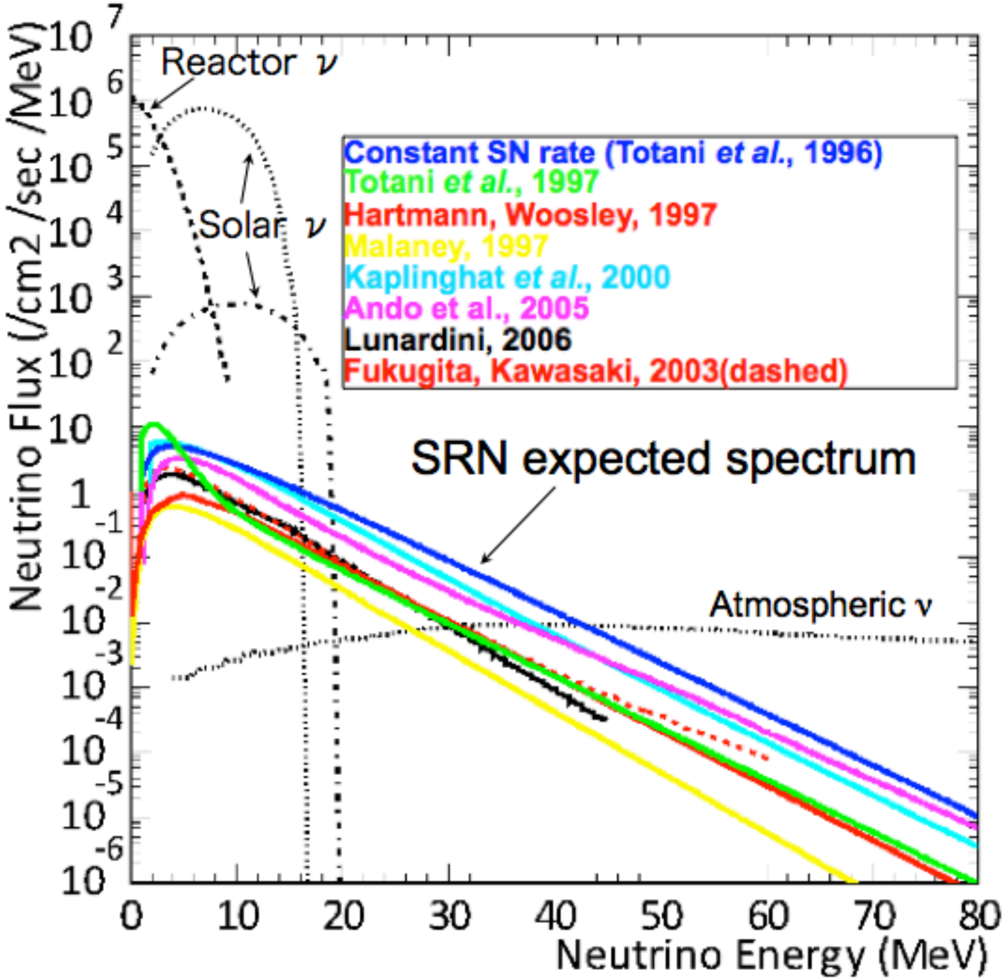
**"T2HKK has the best sensitivity to CP phase (even) in the presence of NSI."**

# Supernova Relic Neutrinos (SRN)

## Neutrinos emitted from past supernovae

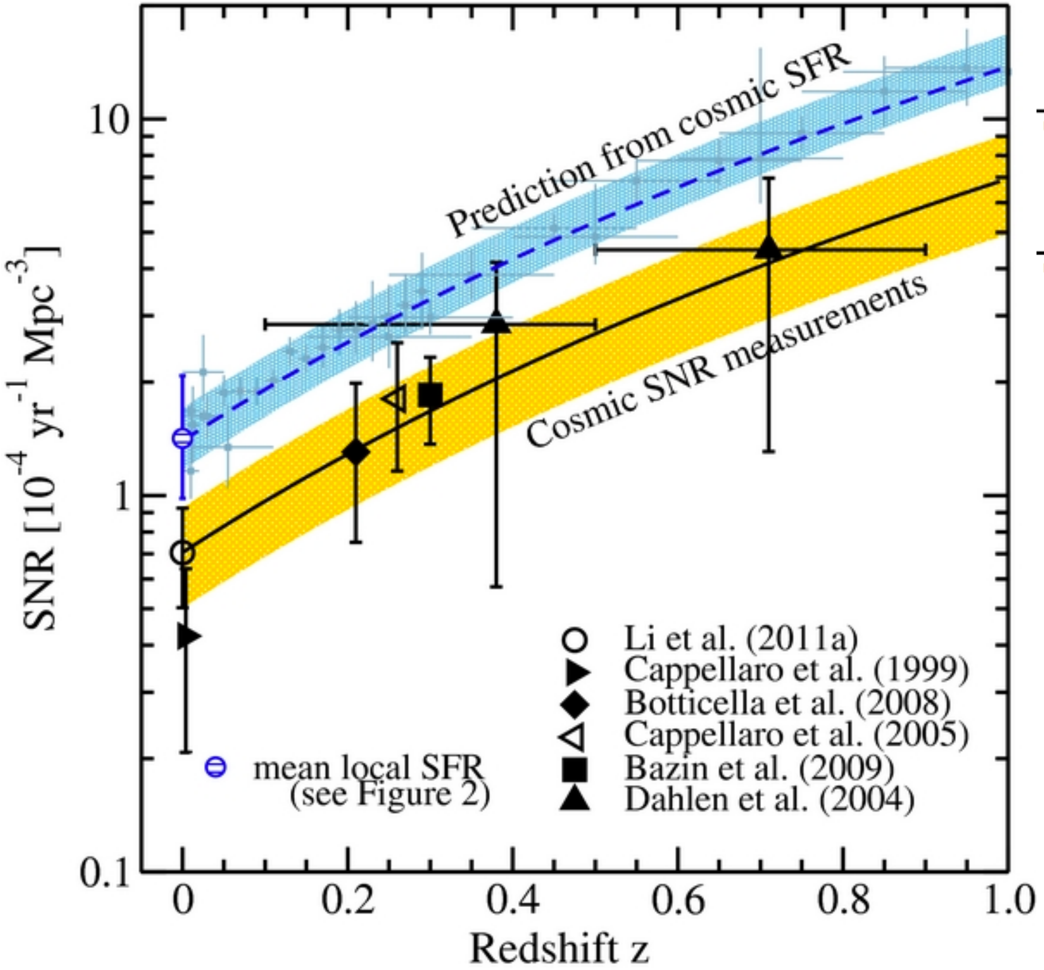
S.Ando



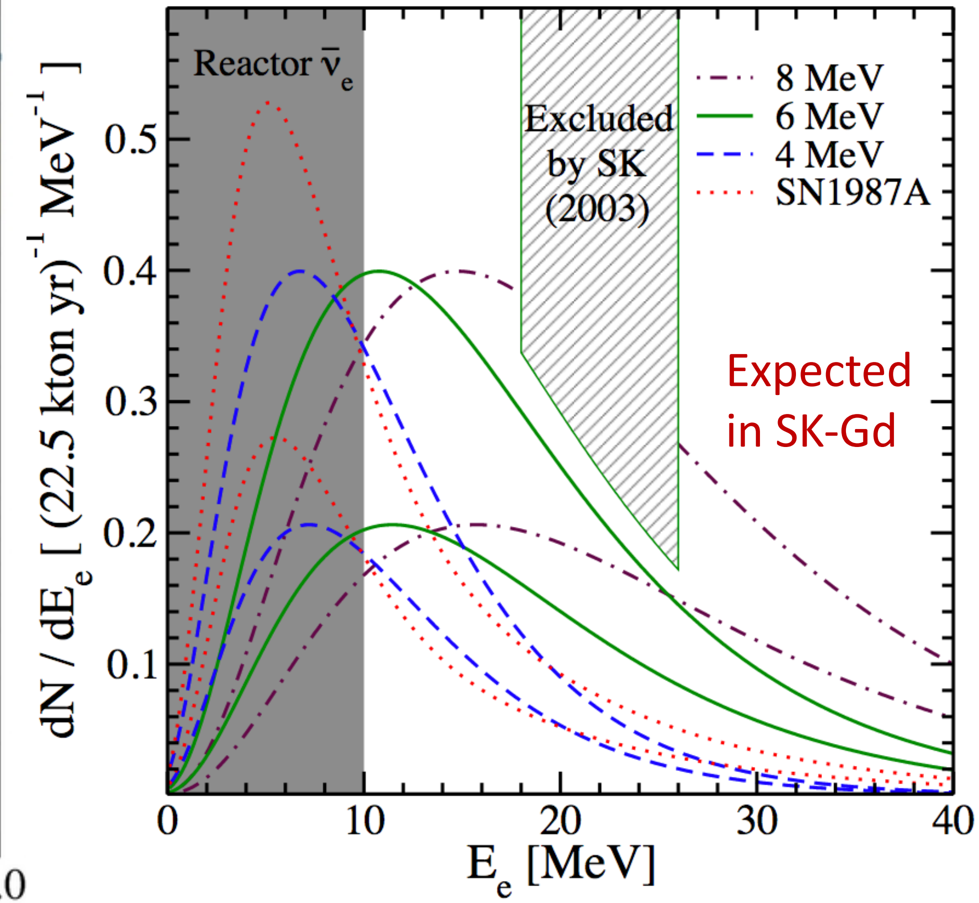



# SRN: Physics Motivation

**S.Horiuchi et. al (2011)**




**S.Horiuchi et. al (2009)**

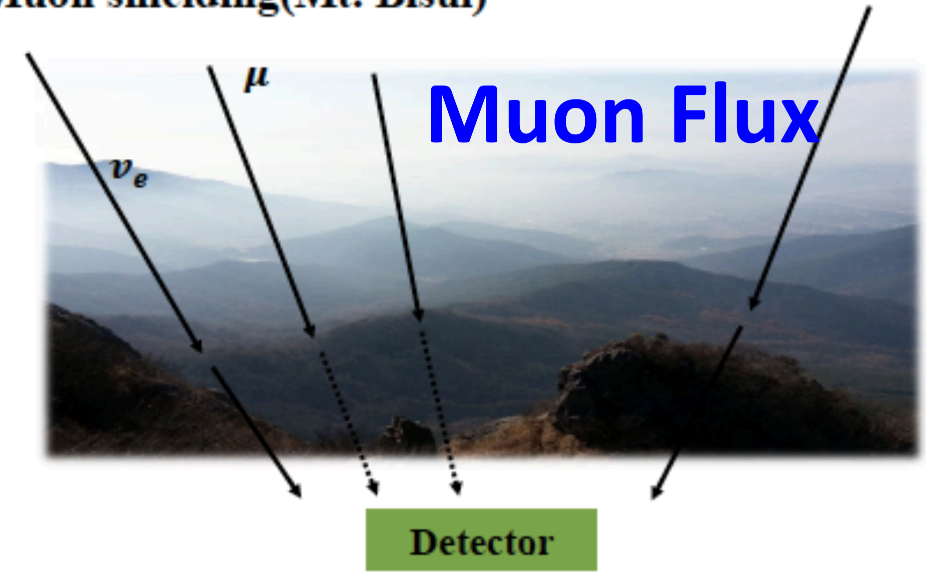



SuperNova Rate problem: ~1.8 ($^{+1.6}_{-0.6}$)

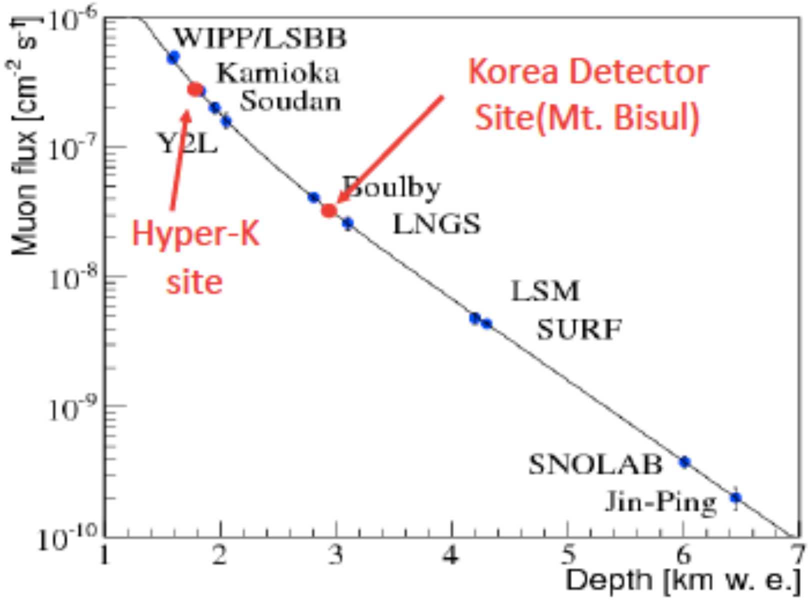
SRN spectrum may solve the supernova rate problem.

# Muon Flux

**Muon shielding(Mt. Bisul)**

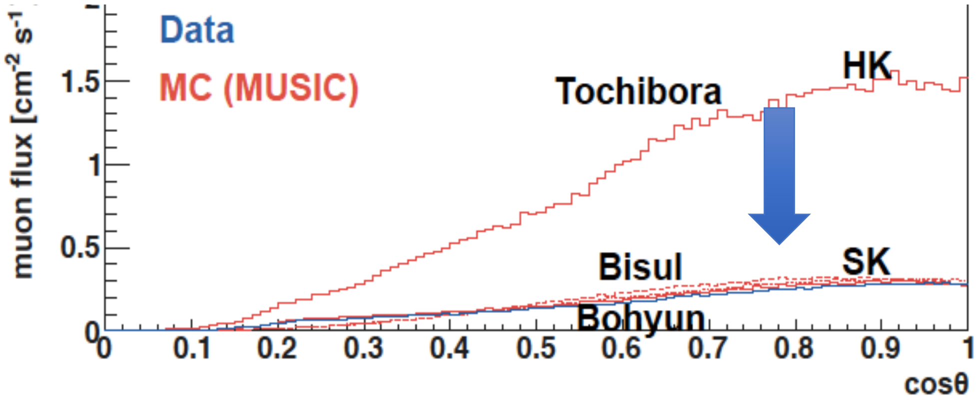


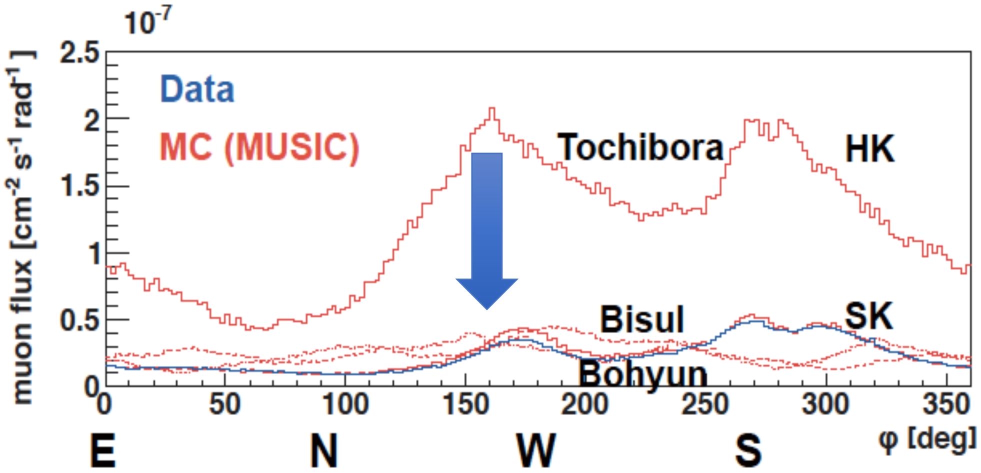

Due to the detector being located deep underground,
The background level is decreased




Muon flux to each laboratory

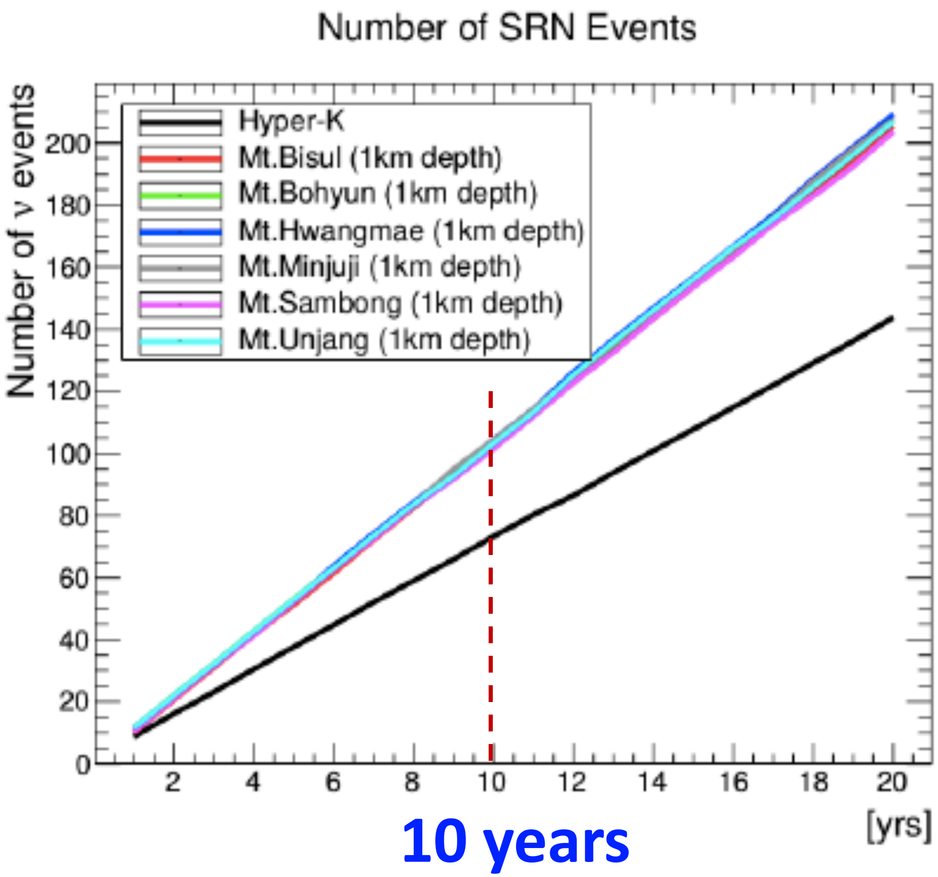
| Detector site (overburden) | $\Phi$ ($10^{-7}$ cm$^{-2}$s$^{-1}$) | $\overline{E}_\mu$ (GeV) |
|---|---|---|
| Mt. Bisul (820 m) | 3.81 | 233 |
| Mt. Bohyun (820 m) | 3.57 | 234 |
| Mt. Bisul (1,000 m) | 1.59 | 256 |
| Mt. Bohyun (1,000 m) | 1.50 | 257 |
| Hyper-K (Tochibora, 650 m) | 7.55 | 203 |
| Super-K | 1.54 | 258 |

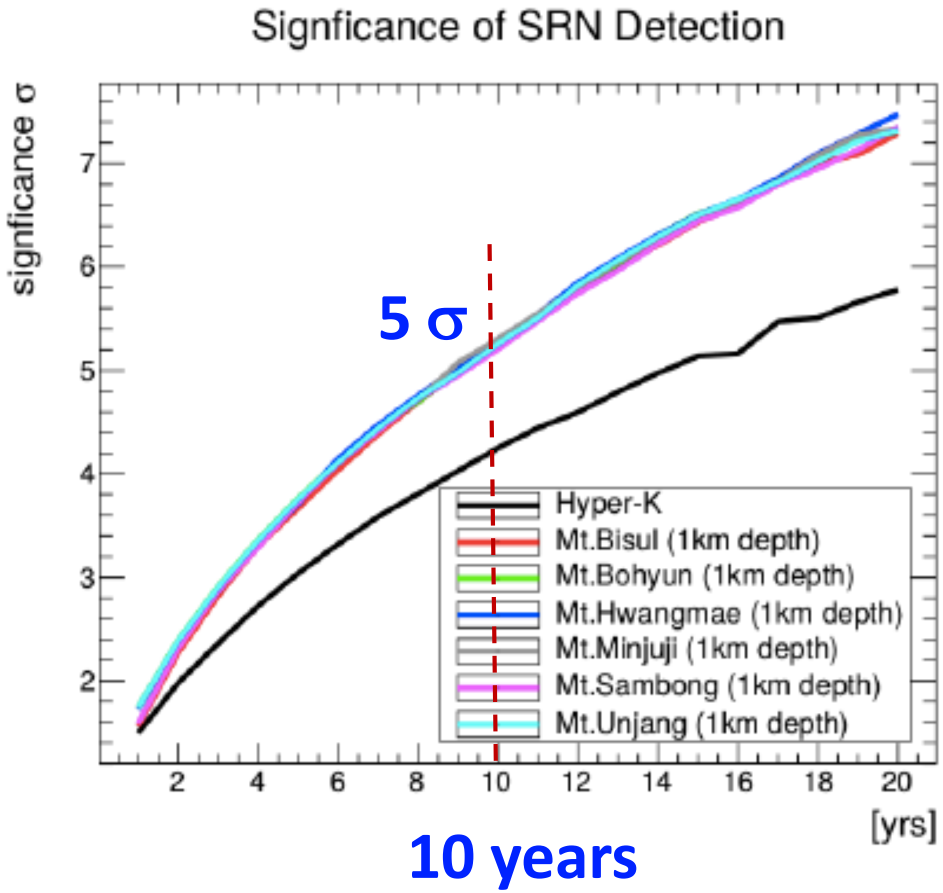


# SRN Sensitivity 1000 m overburden

- Expected SRN events & significance plot



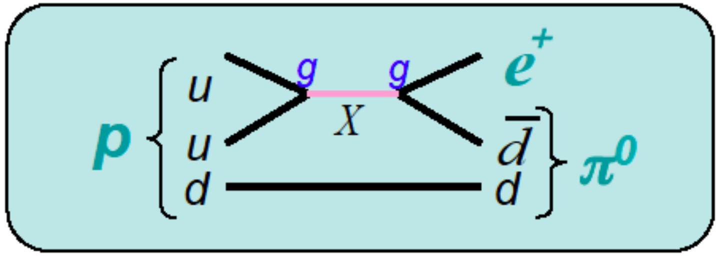




> 6 σ discovery with JD+KD using 10 years data

# Why Proton Decay Search ?

- Only way to directly probe Grand Unified Theory
- Two major modes predicted by many models

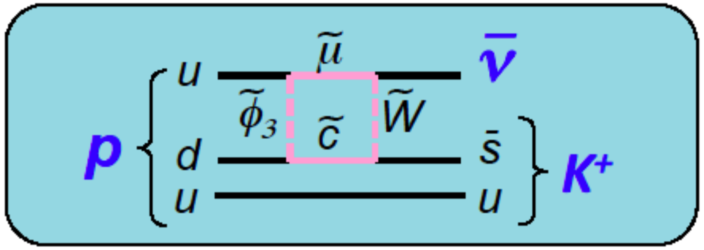
Mediated by gauge bosons




$p \to e^+\pi^0$

$$\Gamma(p \to e^+\pi^0) \sim \frac{g^4 m_p^5}{M_X^4}$$

SUSY mediated



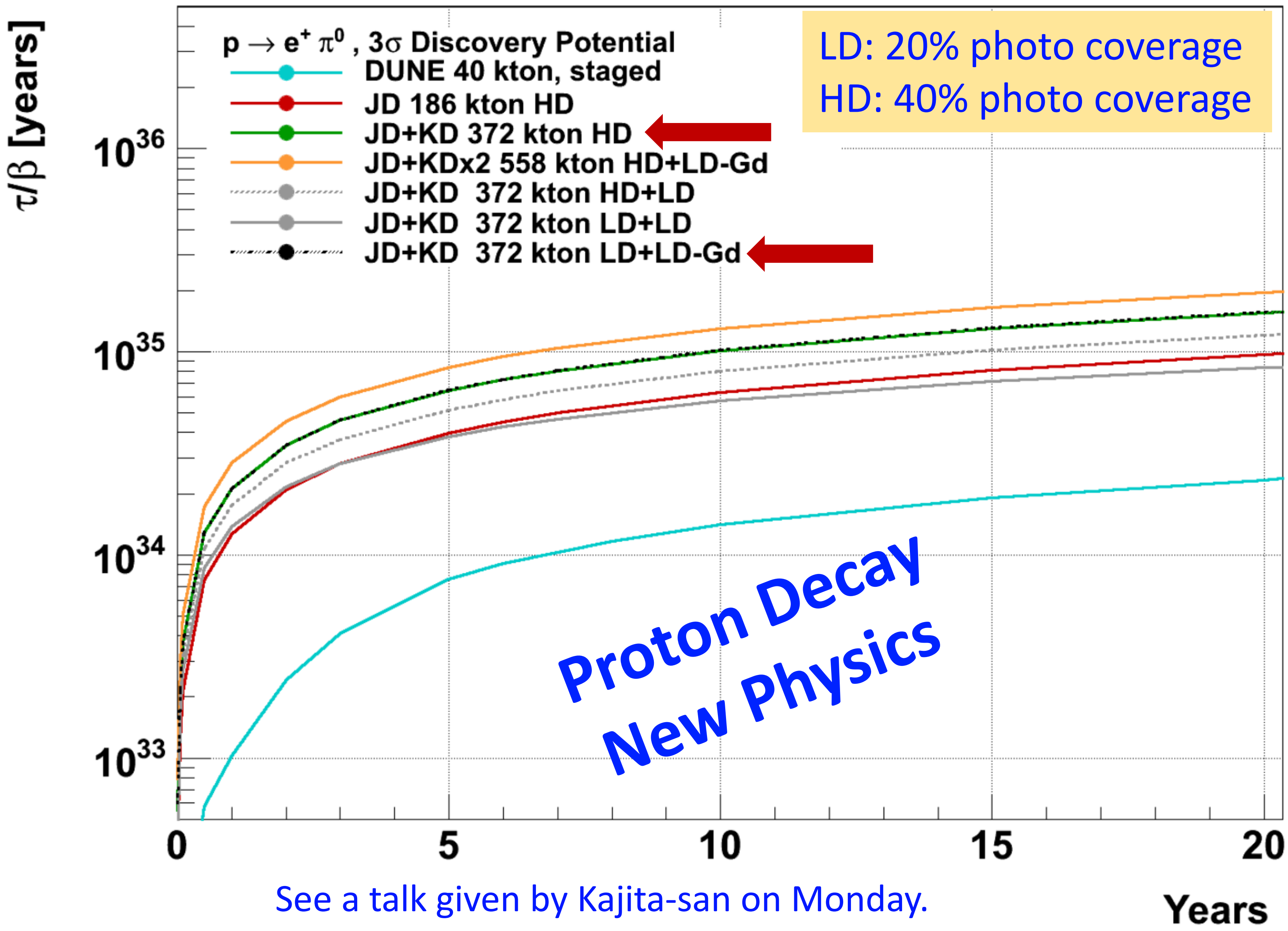

$p \to \nu K^+$

$$\Gamma(p \to \bar{\nu}K^+) \sim \frac{\tan^2\beta \times m_p^5}{M_{\tilde{q}}^2 \times M_3^2}$$

- Need broad searches including other possible modes

See a theory talk by Natsumi Nagata on this Friday.

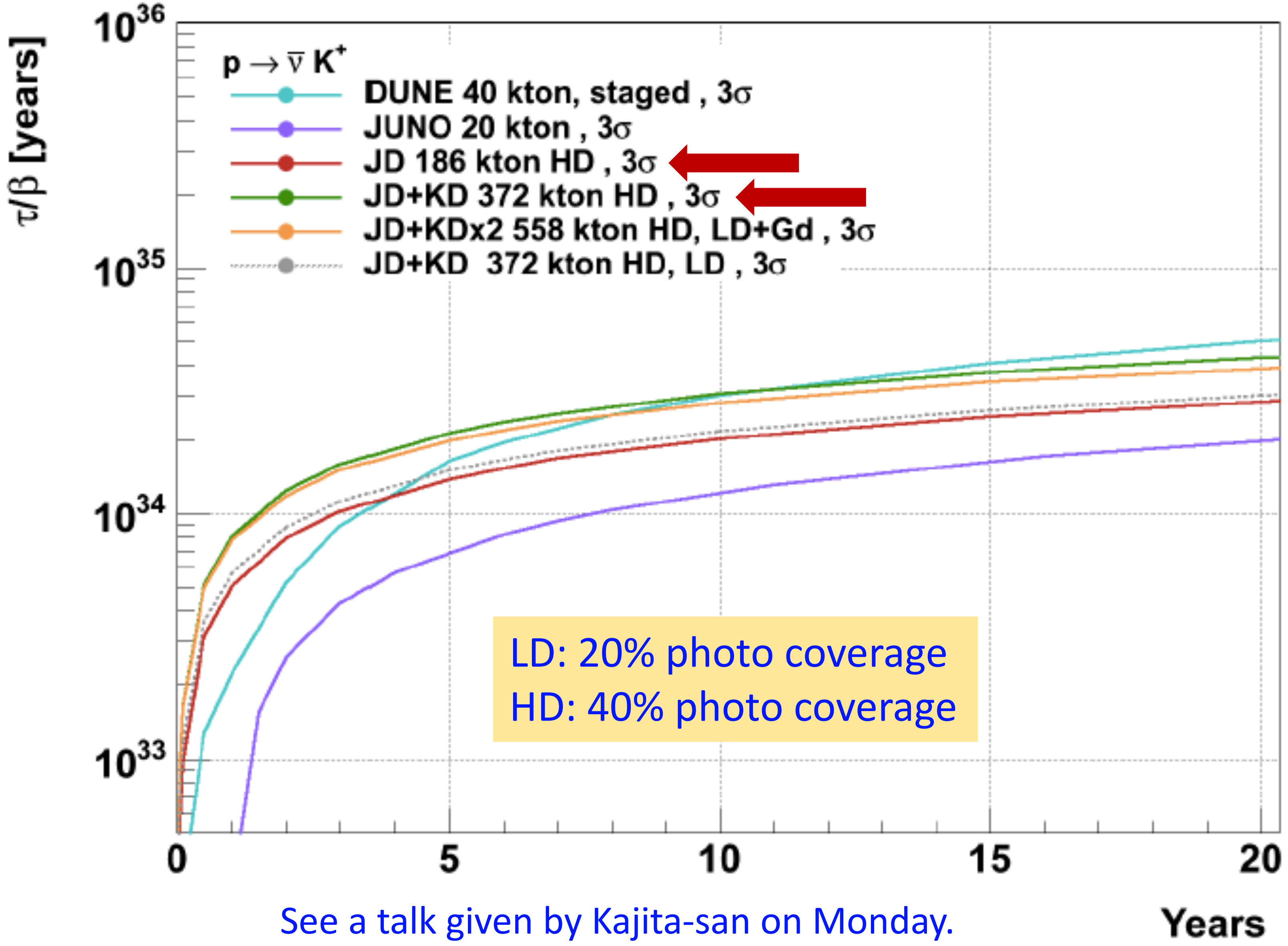
# Discovery Potential for $p \to e^+\pi^0$




See a talk given by Kajita-san on Monday.

- This mode's efficiency does not depend much on cathode coverage above 20%
- Background reduction though is improved by Gd loading

# Discovery Potential for p -> νK$^+$

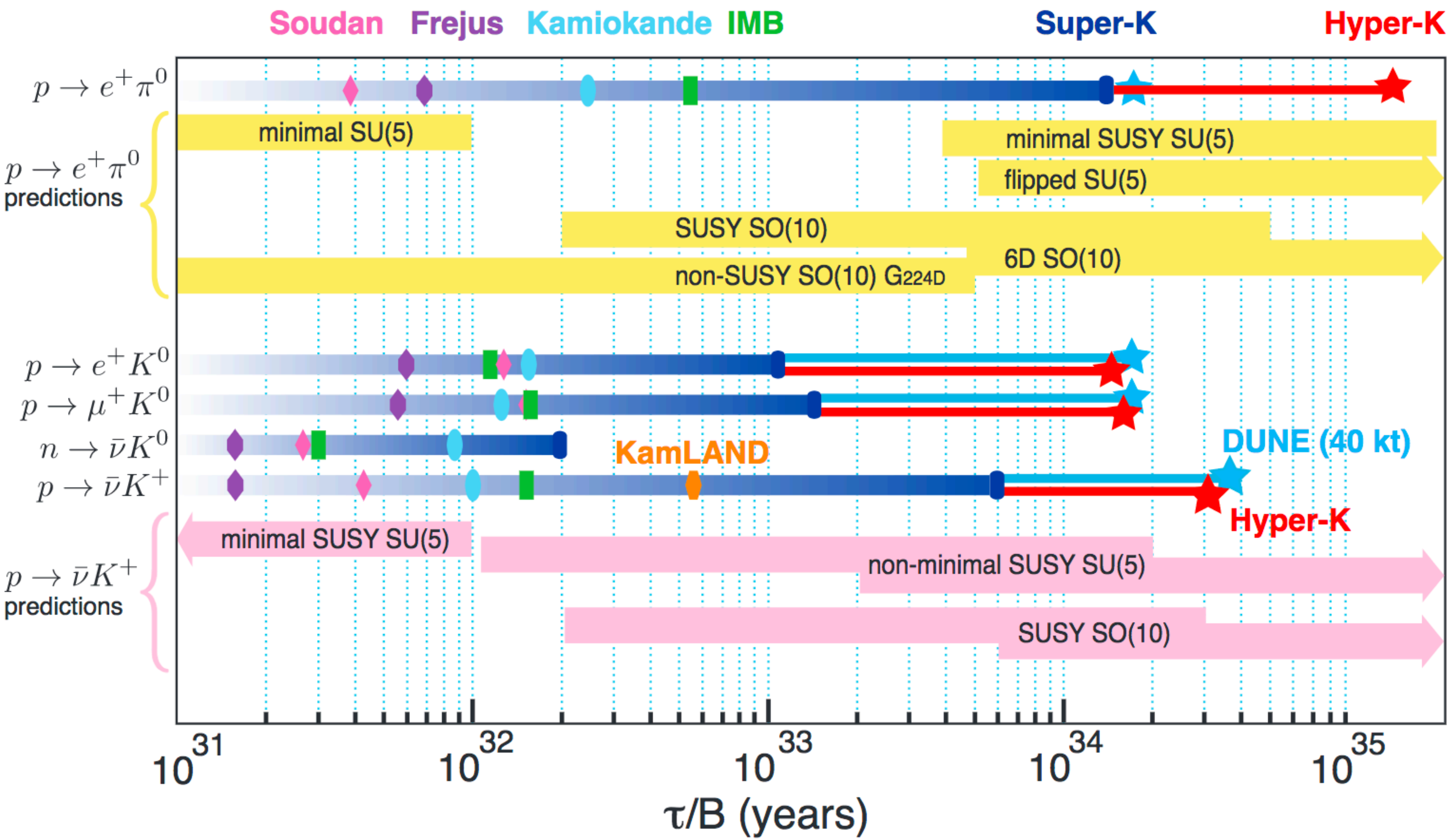



See a talk given by Kajita-san on Monday.

- Efficiency depends considerably on coverage
- Background reduction is improved by Gd loading

# Proton Decay Limits & Sensitivities

Only way to directly probe GUT



# T2HKK White Paper
## November 21st 2016

~ 4 months later
from the inauguration

arXiv:1611.06118 → Updated version is published. PTEP 2018,6, 1-56

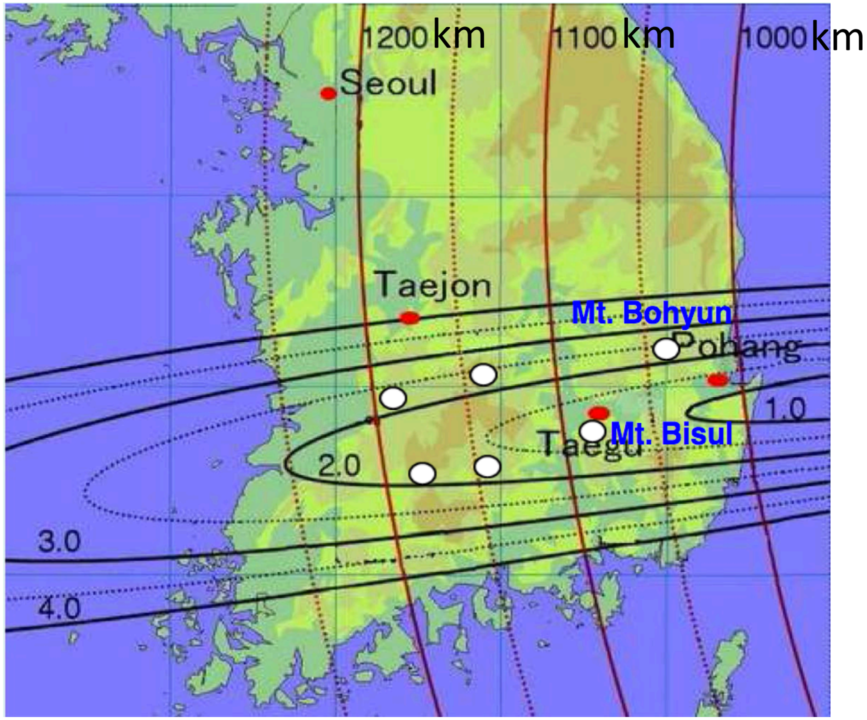
(60 pages)

**Physics Potentials with the Second Hyper-Kamiokande Detector in Korea**

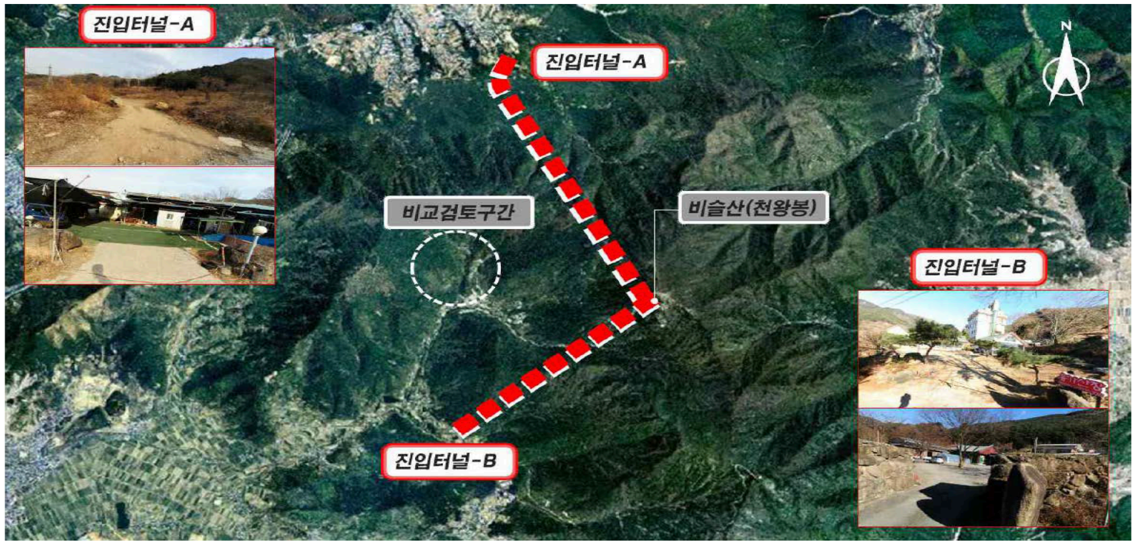
**(Hyper-Kamiokande Proto-Collaboration)**

K. Abe,[57,59] Ke. Abe,[24] H. Aihara,[59,60] A. Aimi,[18] R. Akutsu,[58] C. Andreopoulos,[28,43] I. Anghel,[21] L.H.V. Anthony,[28] M. Antonova,[20] Y. Ashida,[25] M. Barbi,[44] G.J. Barker,[66] G. Barr,[40] P. Beltrame,[11] V. Berardi,[16] M. Bergevin,[3] S. Berkman,[2] T. Berry,[45] S. Bhadra,[73] F.d.M. Blaszczyk,[1] A. Blondel,[12] S. Bolognesi,[6] S.B. Boyd,[66] A. Bravar,[12]

# Mt. Bisul Site

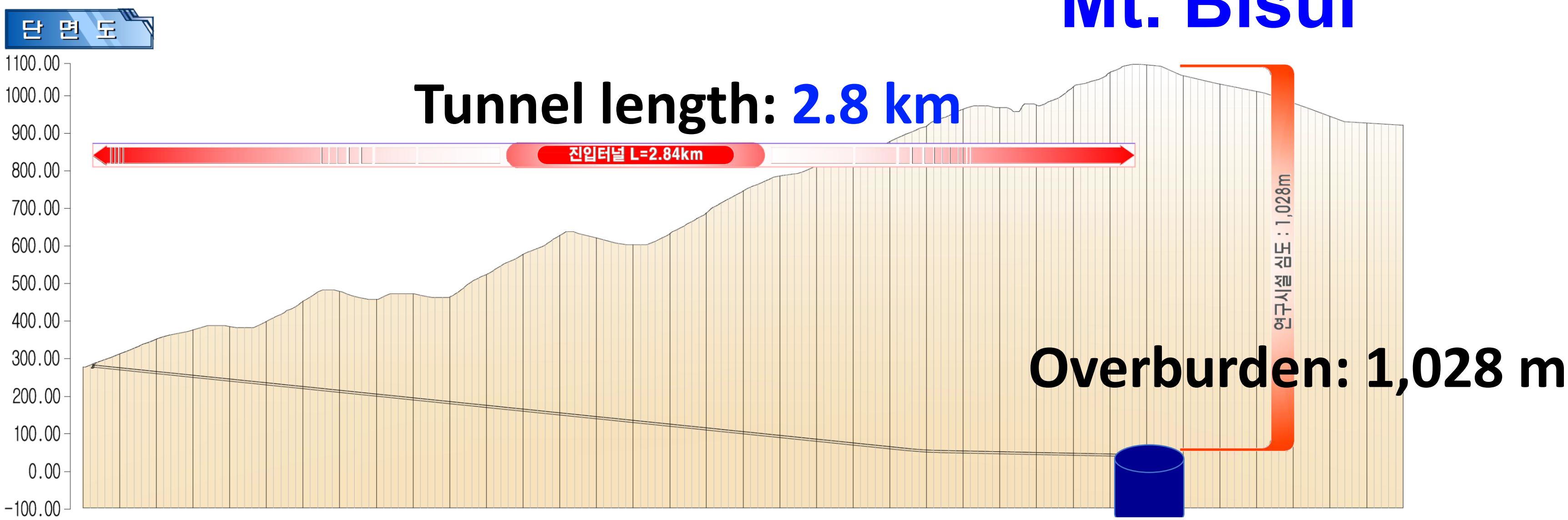


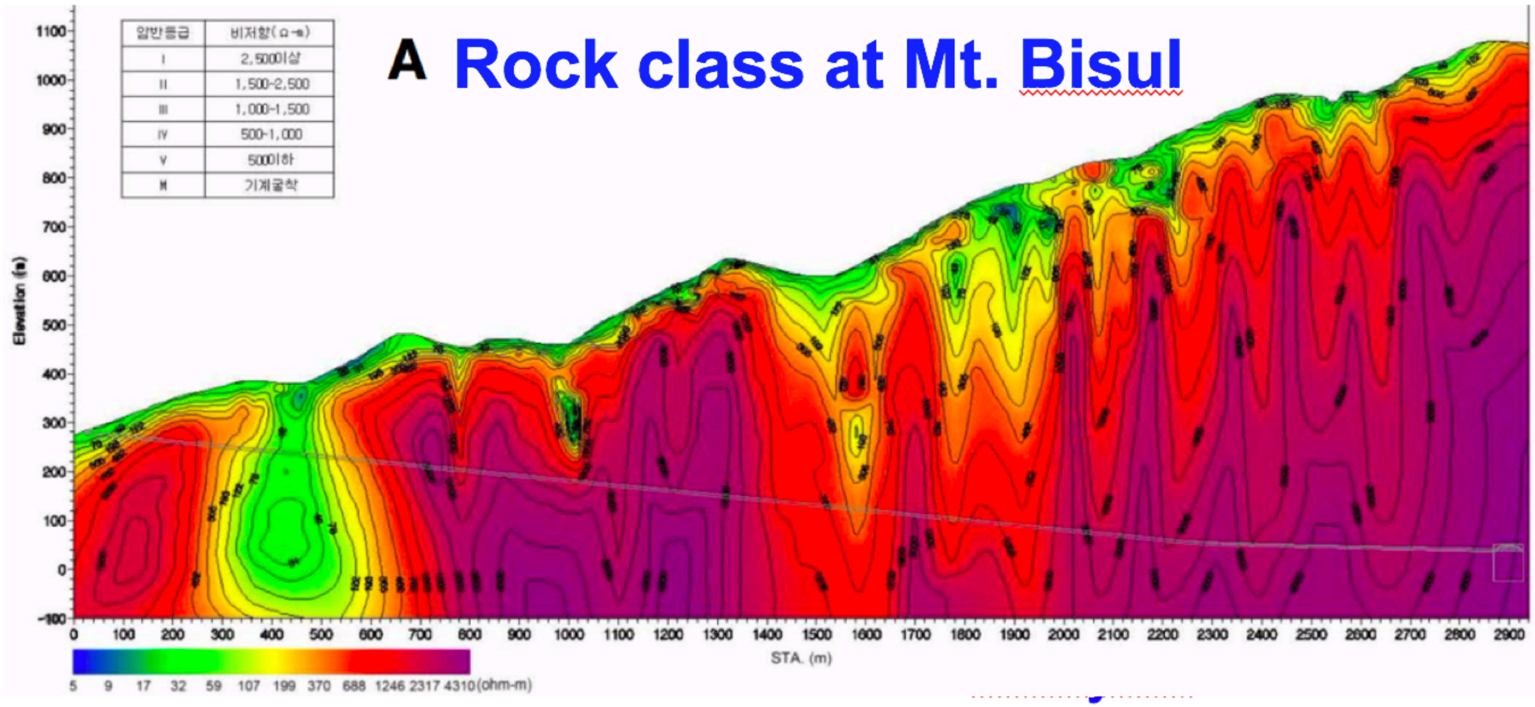




# Mt. Bisul Site

A구간 진입시 종단면도

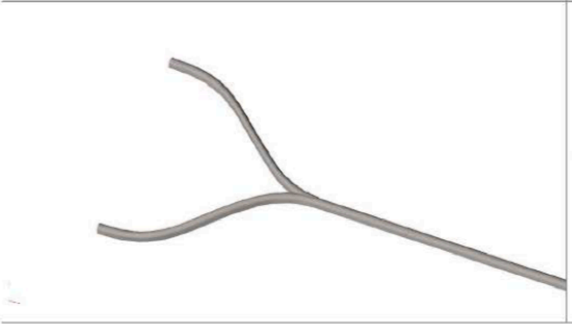
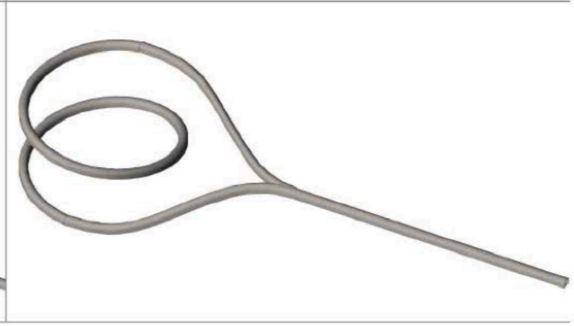



| 암반등급 | 비저항(Ω-m) |
|---|---|
| I | 2,500이상 |
| II | 1,500-2,500 |
| III | 1,000-1,500 |
| IV | 500-1,000 |
| V | 500이하 |
| M | 기계굴착 |

# Experimental Hall (Cavern) Construction

10.3.3 지하실험실구간 시공순서

| 진입터널 굴착 | 주회터널 굴착 |
|---|---|
|  |  |
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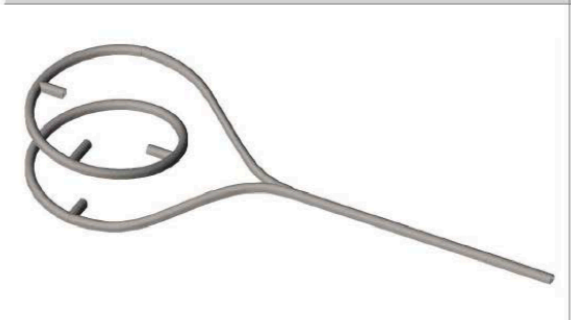
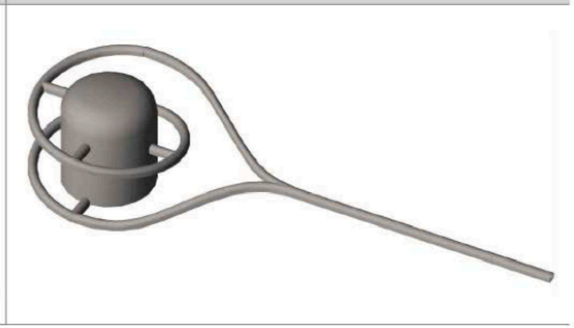
|  |  |
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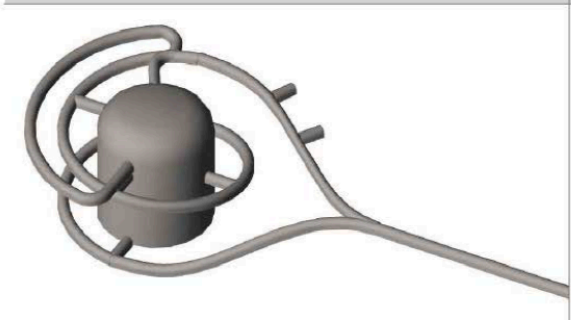
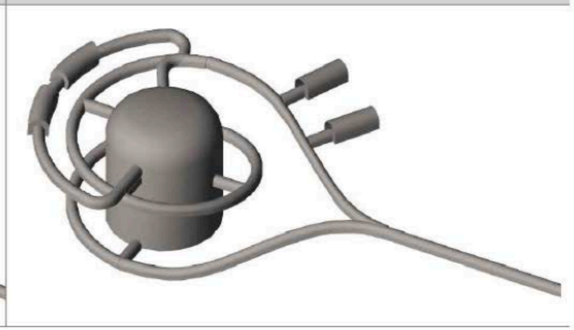
|  |  |

# T2HKK Detector Options

- ❑ Twice bigger detector w/ less photo coverage?
- ❑ Gd loading ? (proton decay, SRN)
- ❑ Water-based Liquid Scintillator?
- ❑ PMT options:
  - 20 inch PMT
  - mPMT
  - SiPM etc..

→ We need sensitivity studies/R&D/detector design.

→ You have lots of opportunities in T2HKK/KNO !

**Huge opportunities for new international collaborators !**

Join us !

# WbLS Detector at Yemilab

Good demonstrator for T2HKK

arXiv:1903.05368

**Neutrino Telescope at Yemilab, Korea**

Seon-Hee Seo*

*Center for Underground Physics,*

*Institute for Basic Science,*

*55 Expo-ro Yuseong-gu, Daejeon 34126, Korea*

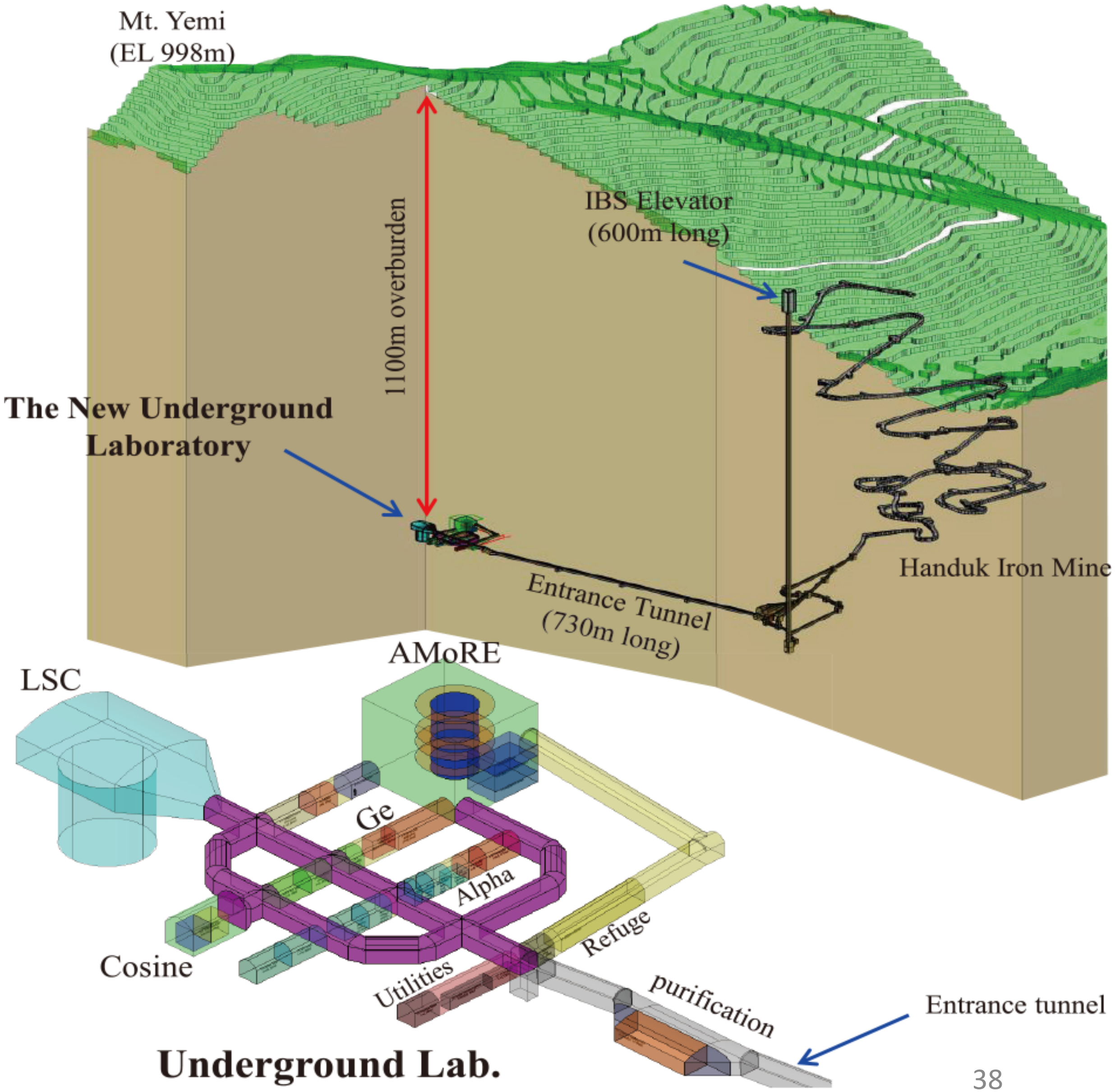
(Dated: March 13, 2019)

A new underground lab, Yemilab, is being constructed in Handuk iron mine, Korea. The default design of Yemilab includes a space for a future neutrino experiment. We propose to build a water-based liquid scintillator (WbLS) detector of 4∼5 kiloton size at the Yemilab. The WbLS technology combines the benefits from both water and liquid scintillator (LS) in a single detector so that low energy physics and rare event searches can have higher sensitivities due to the larger size detector with increased light yield. No experiment has ever used a WbLS technology since it still needs some R&D studies, as currently being performed by THEIA group. If this technology works successfully with kiloton scale detector at Yemilab then it can be applied to future T2HKK (Hyper-K $2^{nd}$ detector in Korea) to improve its physics potentials especially in the low energy region.

# Yemilab @Handuk iron mine


~1 km depth

To be completed
at the end of 2020



# Summary

- ❑ Hyper-K: next generation multi-purpose ν experiment.

2 x 260 kton water detectors MeV – TeV

- ❑ Physics sensitivities are improved w/ the 2nd detector in Korea.

  - Neutrino mass ordering determination
  - CPV, CP precision, CP coverage
  - Non-standard ν interaction
  - Solar/SN/SRN etc…

- ❑ World class discoveries are expected to be made in Hyper-K.

CPV, SRN, proton decay etc…

- ❑ Thanks to the construction of the 1st detector in Japan starts in April 2020, Korean community starts to prepare our proposal to Korean government. → Big opportunities for potential international collaborators.