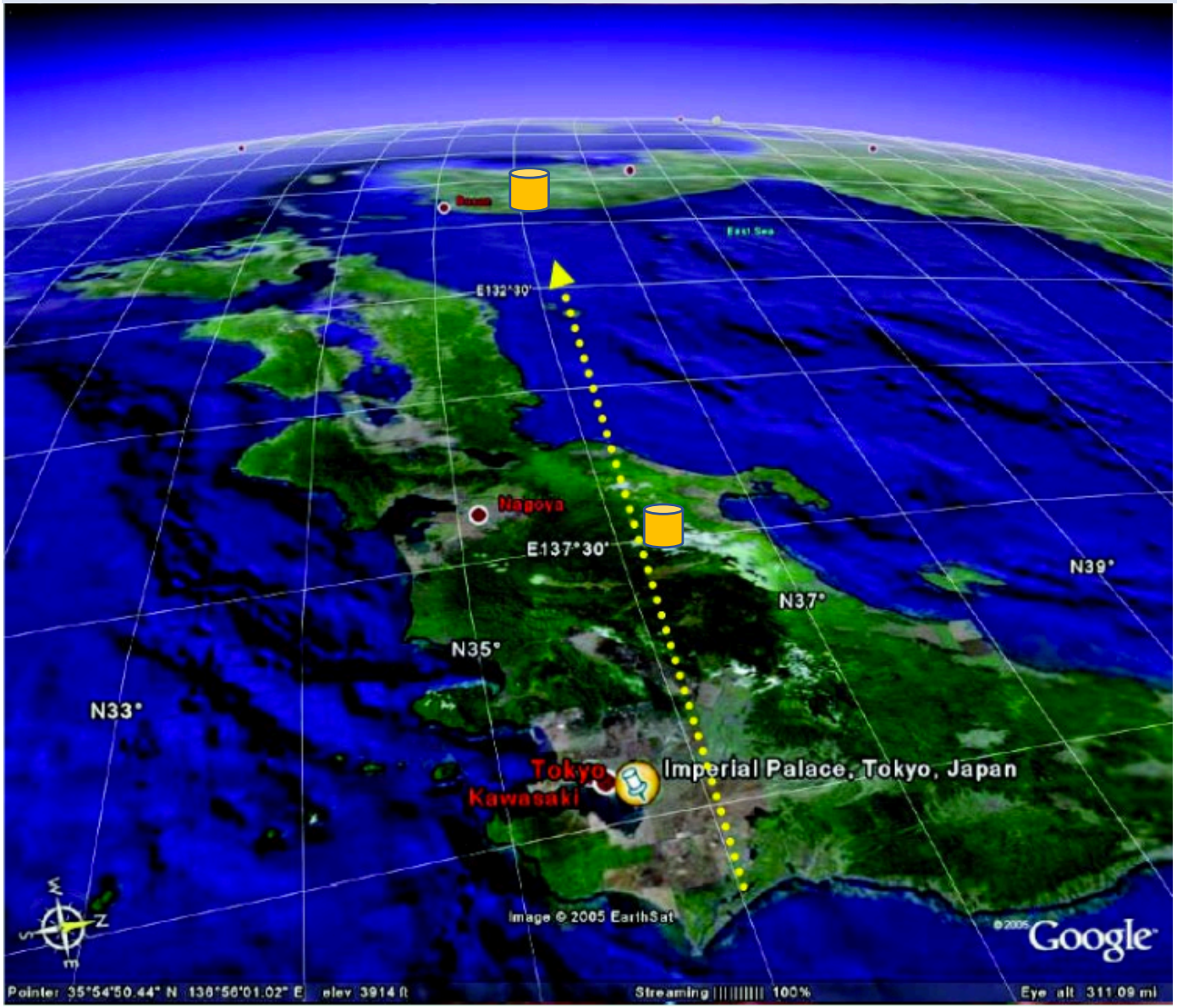
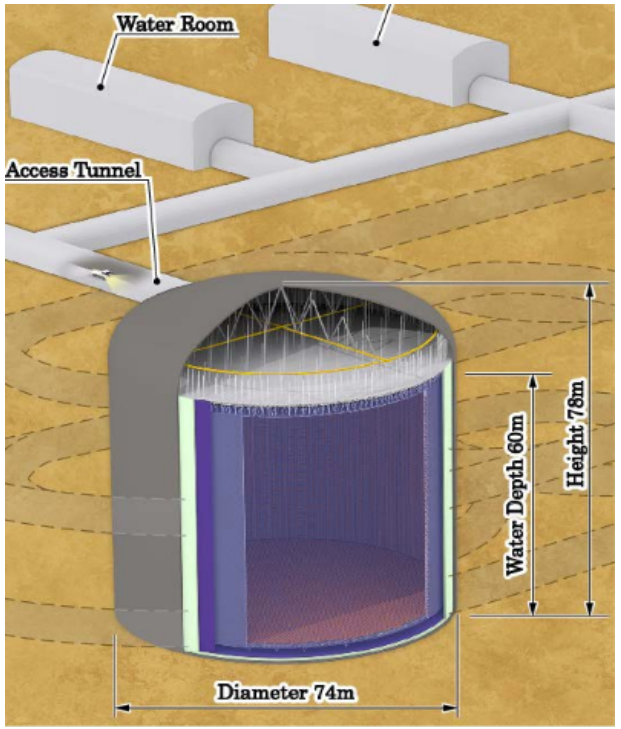
KNO / T2HKK





Sunny Seo
IBS

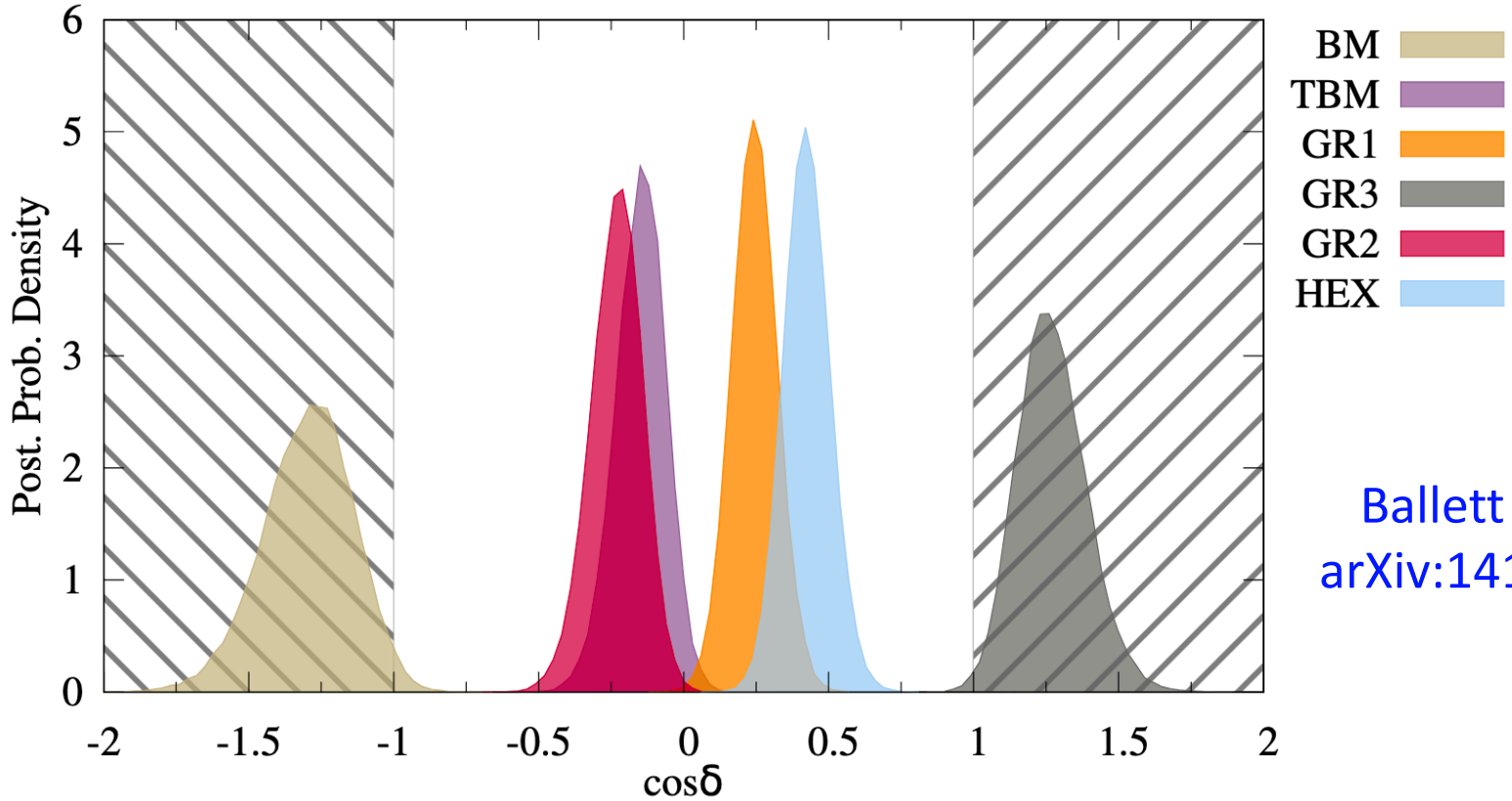
Snowmass 2021
NF01 Workshop
2020.10.23

Why Leptonic CPV ?

1. If there is a large CPV in a lepton sector, leptogenesis may explain baryon asymmetry.

2. Understanding pattern of ν mixing

Which flavor symmetry model ?



Ballett et al.
arXiv:1410.7573

@ Neutrino 2020

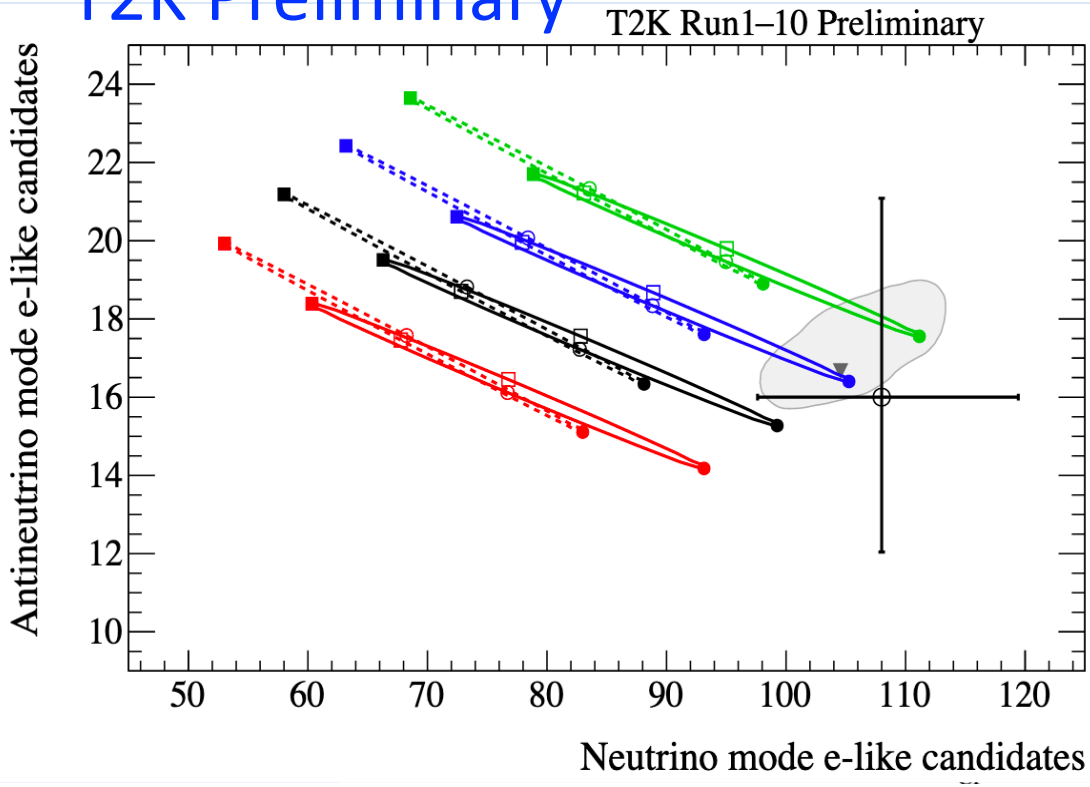
Neutrinos: 19.7 x 10^{20} POT

Anti-nu : 16.3 x 10^{20} POT

Neutrinos: 13.6 x 10^{20} POT

Anti-nu : 12.5 x 10^{20} POT

T2K Preliminary



$\sin^2\theta_{23} = 0.45, 0.50, 0.55, 0.60$

$\Delta m^2_{32} = 2.49\times10^{-3}\ eV^2$

$\Delta m^2_{31} = -2.46\times10^{-3}\ eV^2$

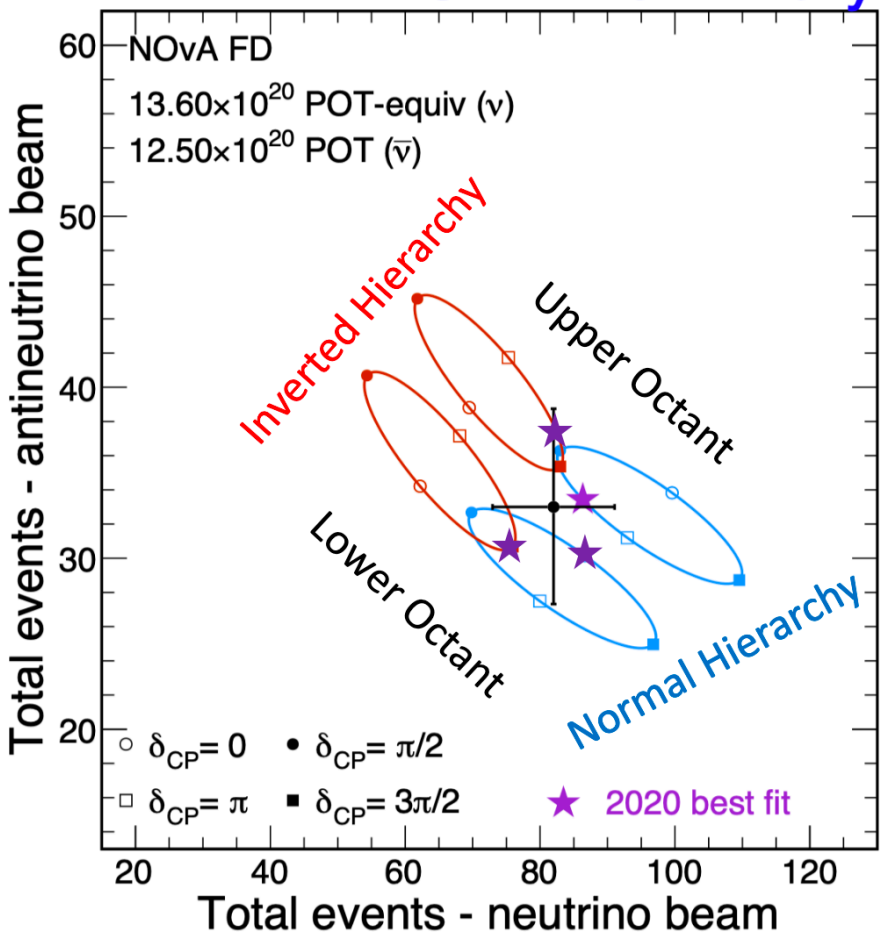
○ $\delta_{CP} = \pi$

■ $\delta_{CP} = +\pi/2$

□ $\delta_{CP} = 0$

● $\delta_{CP} = -\pi/2$

NOvA Preliminary

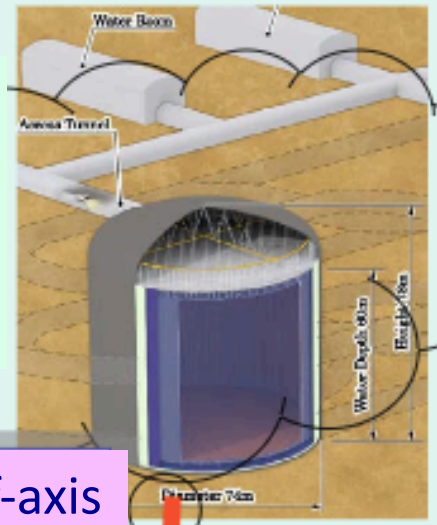


T2HKK / KNO

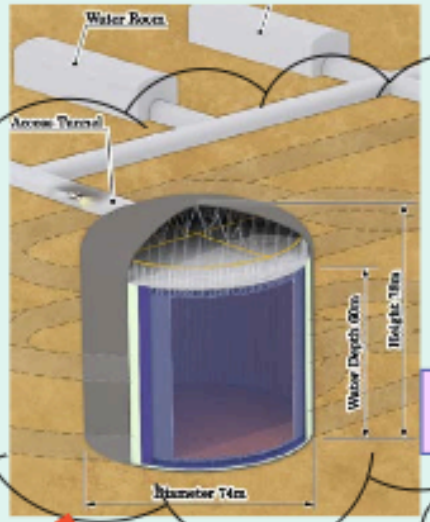
T2HKK

KNO

Korean
Neutrino
Observatory



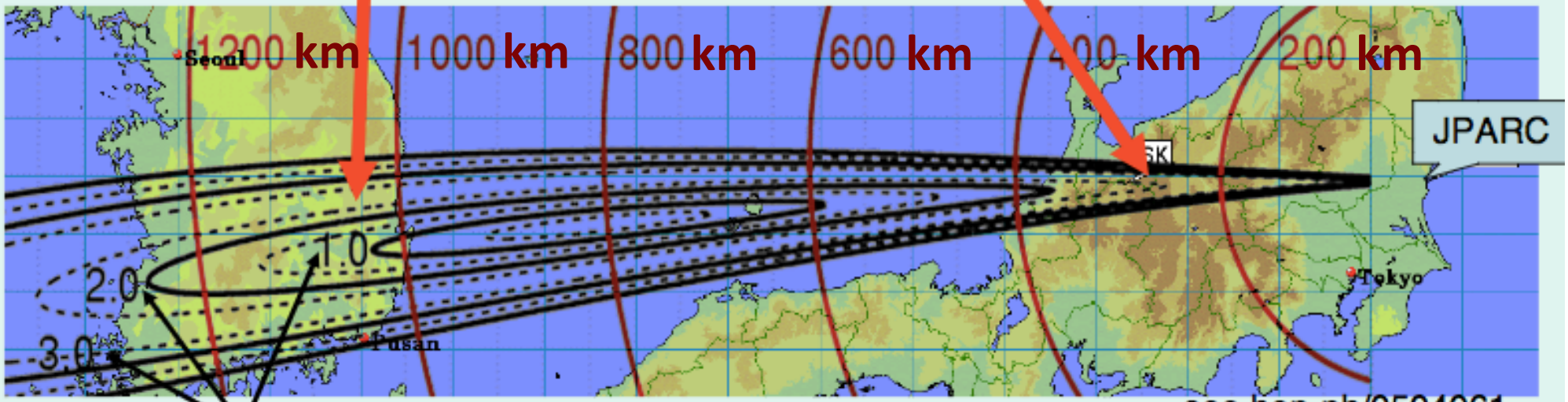
1~3 deg. off-axis



Hyper-K

2.5 deg. off axis

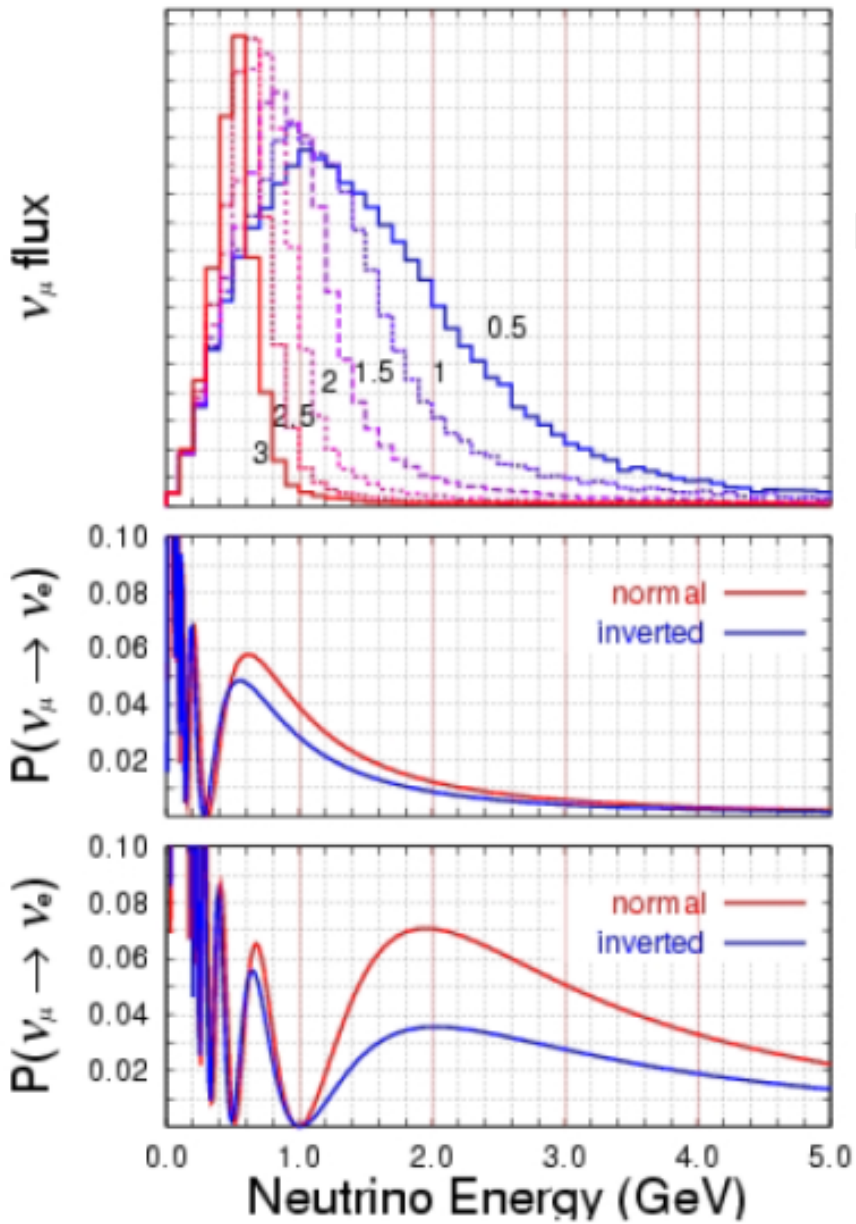
The J-PARC ν beam comes to Korea.

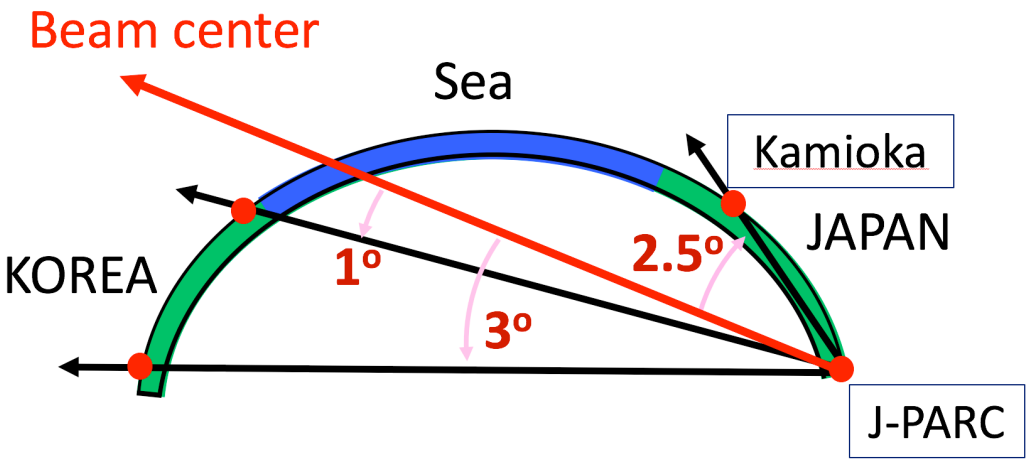


Off-axis angle

see hep-ph/0504061
By K. Hagiwara, N. Okamoura, K. Senda

Neutrino Oscillations in Kamioka & Korea



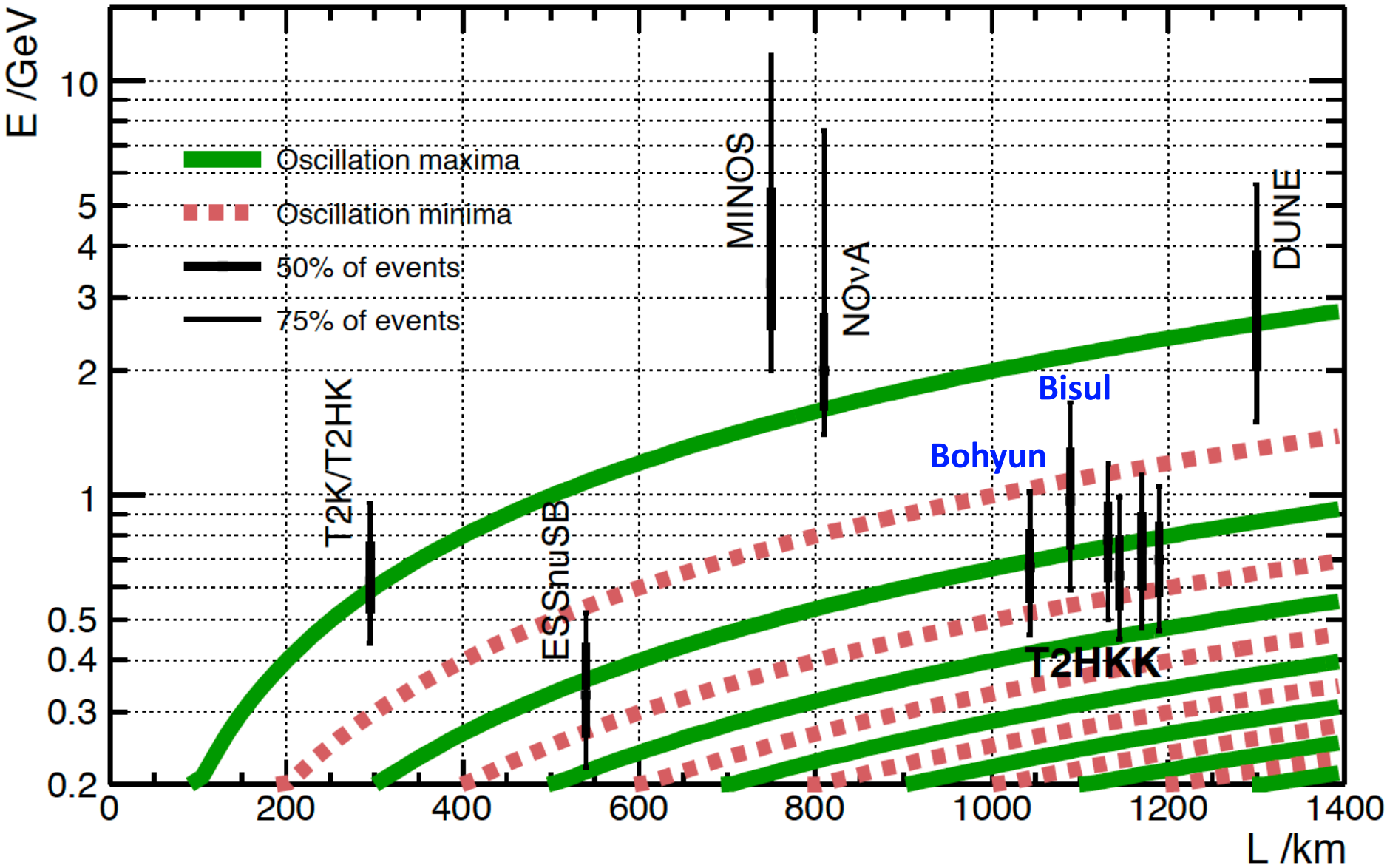


← Profile of off-axis beams

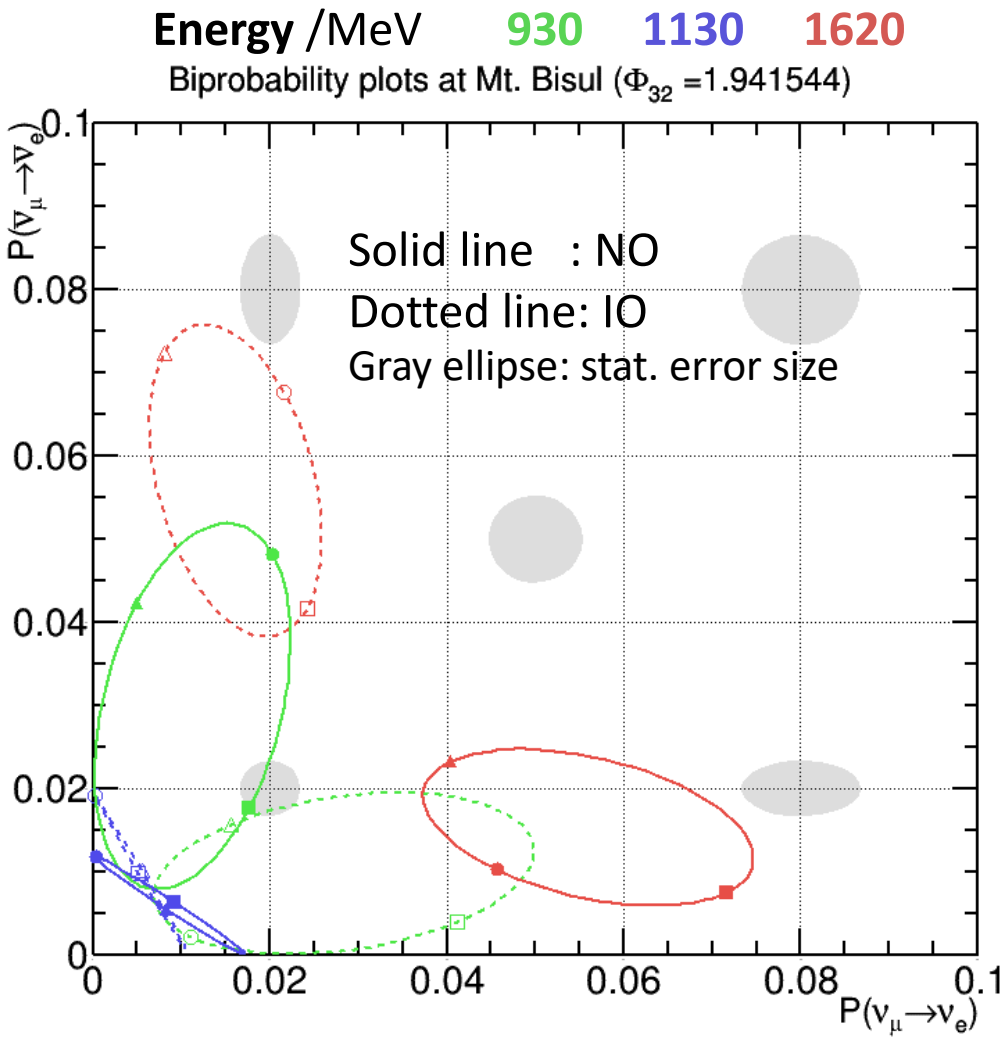
← $P(\nu_\mu \to \nu_e)$ at SK/HK (Japan)
(L = 295 km)

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

Energy vs. Baseline



Mt. Bisul Site



This is the high energy option.

- Good separation between MO especially at **high-energy**
- means very little appearance at **flux peak**. Instead most effect is in "tail" regions.
- **Stats** are quite good because of small OA angle.
- Inversion of MO enhancement for **low-energy** events

Degeneracies break up !

Benefits of the 2nd Detector in Korea

T2HKK = **T**okai to(**2**) **HK** to **K**orea

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

T2HKK Inauguration
July 10th 2016, London

δ_{CP} & MO Sensitivity Studies

**** Simulation parameters ****

- 2.7×10^{22} POT with $\nu : \bar{\nu} = 1 : 3$ operation ratio

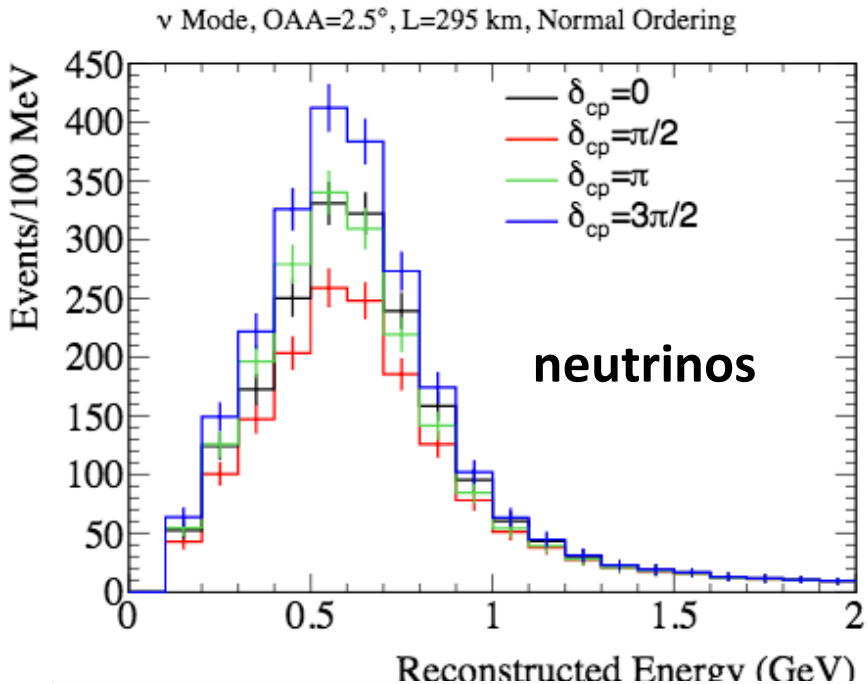
  → 10 years of operation with 1.3 MW beam

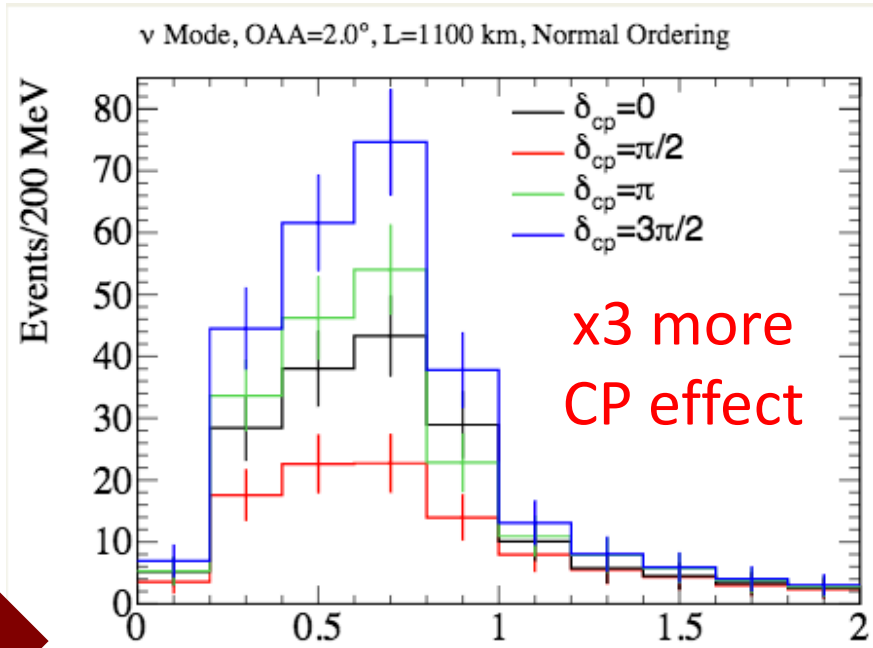
- 187 kton fiducial volume (compared to 22.5 kton for SK)
- Baseline to Korea is 1100 km
- Off-axis beam: 1.5°, 2.0°, 2.5°
- Oscillation parameters: →

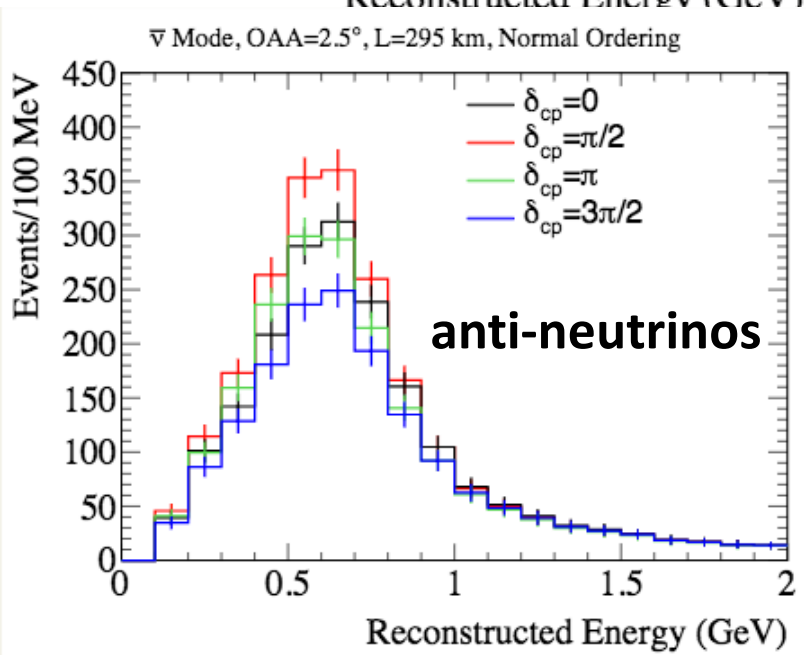
$$|\Delta m^2_{32}| = 2.5 \times 10^{-3}\ \text{eV}$$
$$\sin^2\theta_{23} = 0.5$$
$$\sin^2 2\theta_{13} = 0.085$$
$$\Delta m^2_{21} = 7.53 \times 10^{-5}\ \text{eV}$$
$$\sin^2\theta_{12} = 0.304$$
$$\delta_{cp} = 0, \pi/2, \pi, 3\pi/2$$

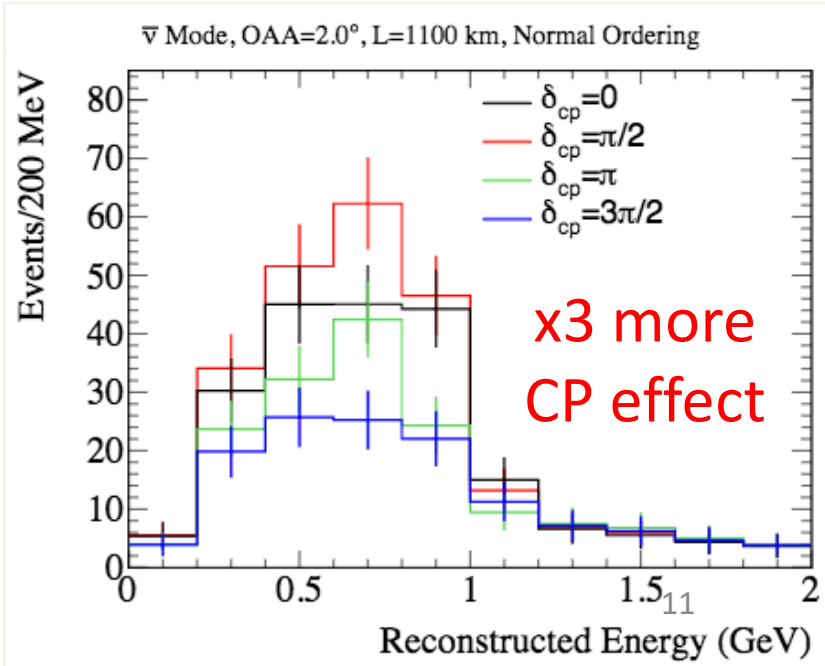
◆Note: Relatively simple systematic uncertainty model is used. More realistic systematic uncertainty implementation is needed.

HK x 1 (295 km) ν_e candidates T2HKK (1100 km)





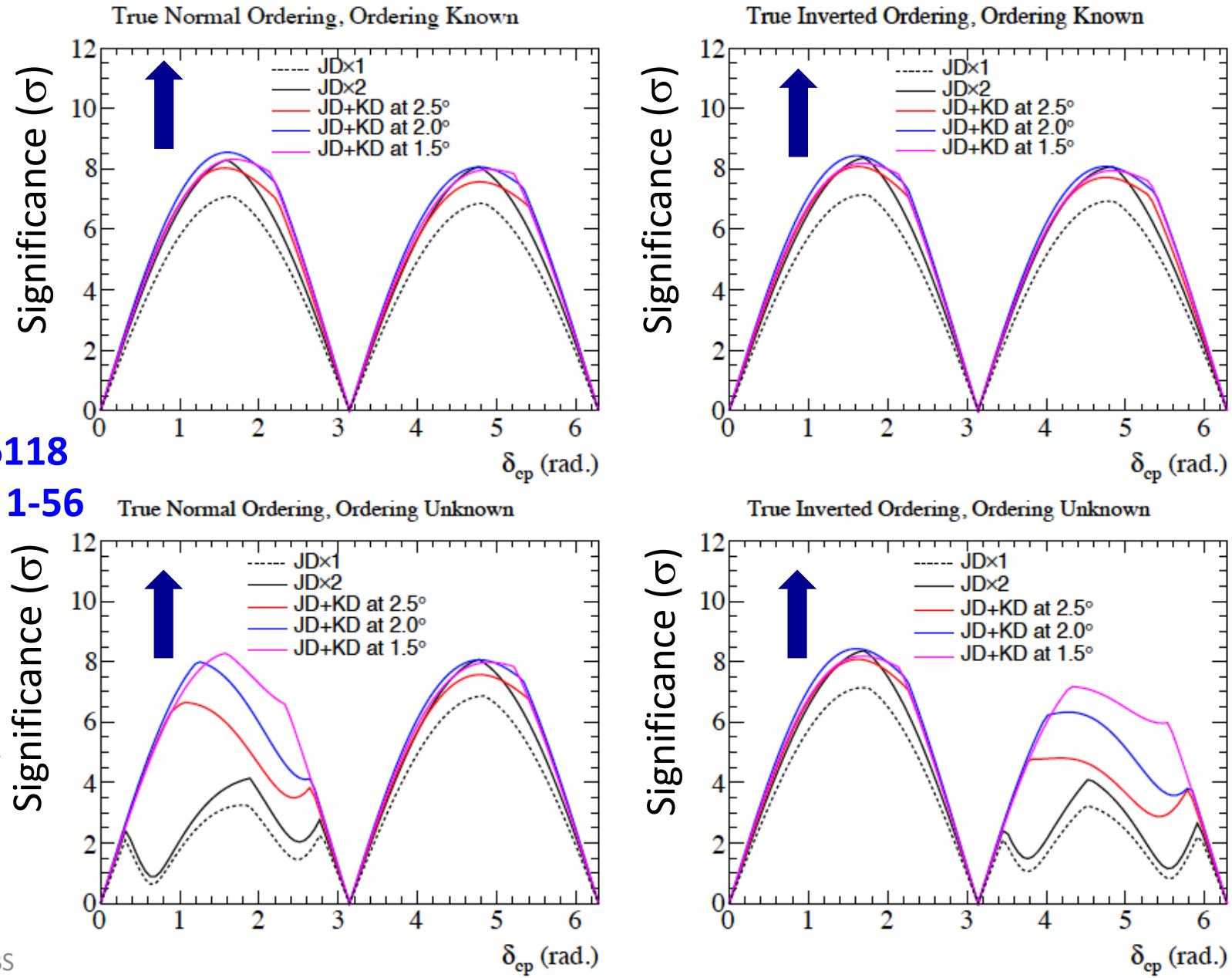




δ_{CP} Sensitivities

Known MO

Unknown MO

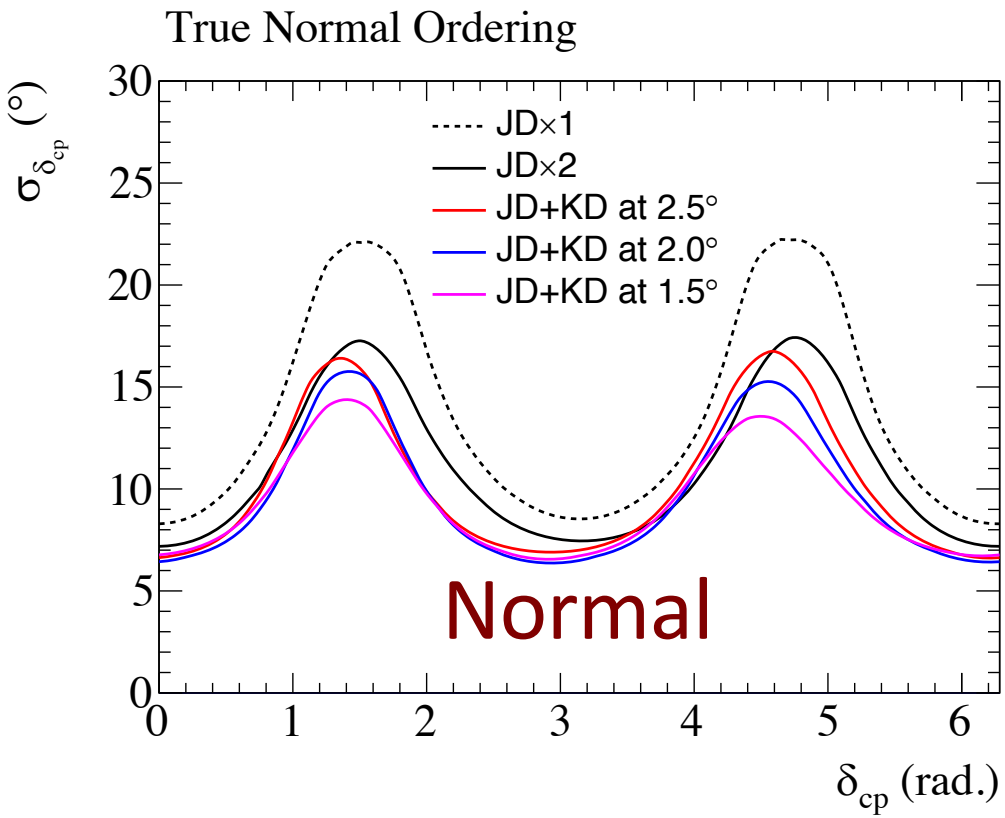


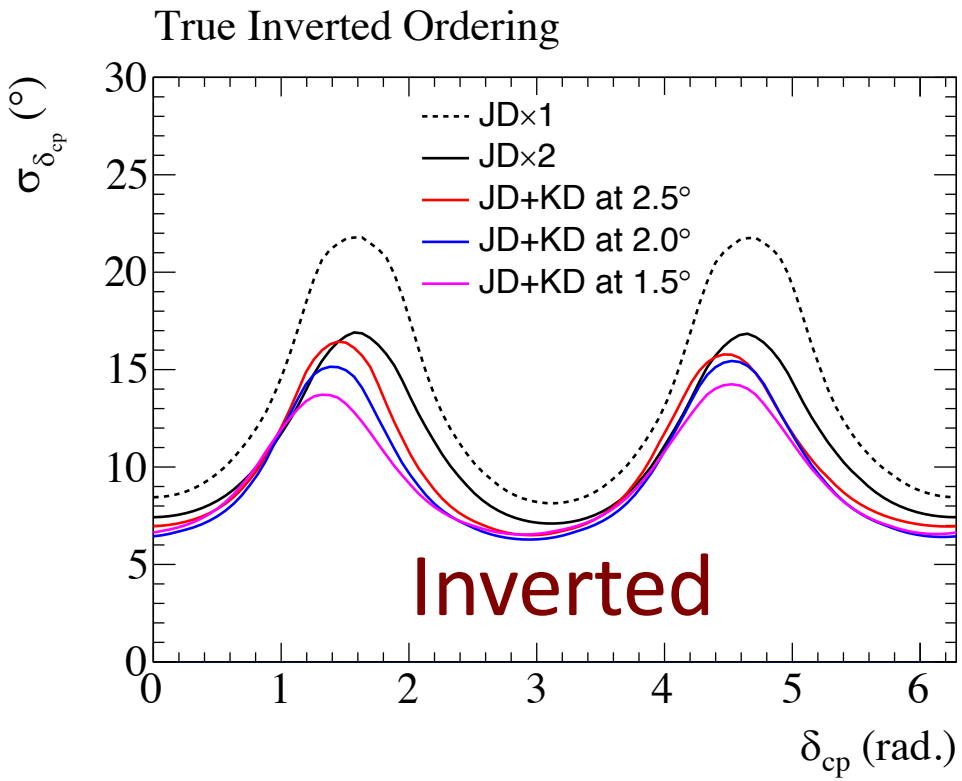
arXiv:1611.06118

PTEP 2018, 6, 1-56

δ_{CP} Precision Sensitivities

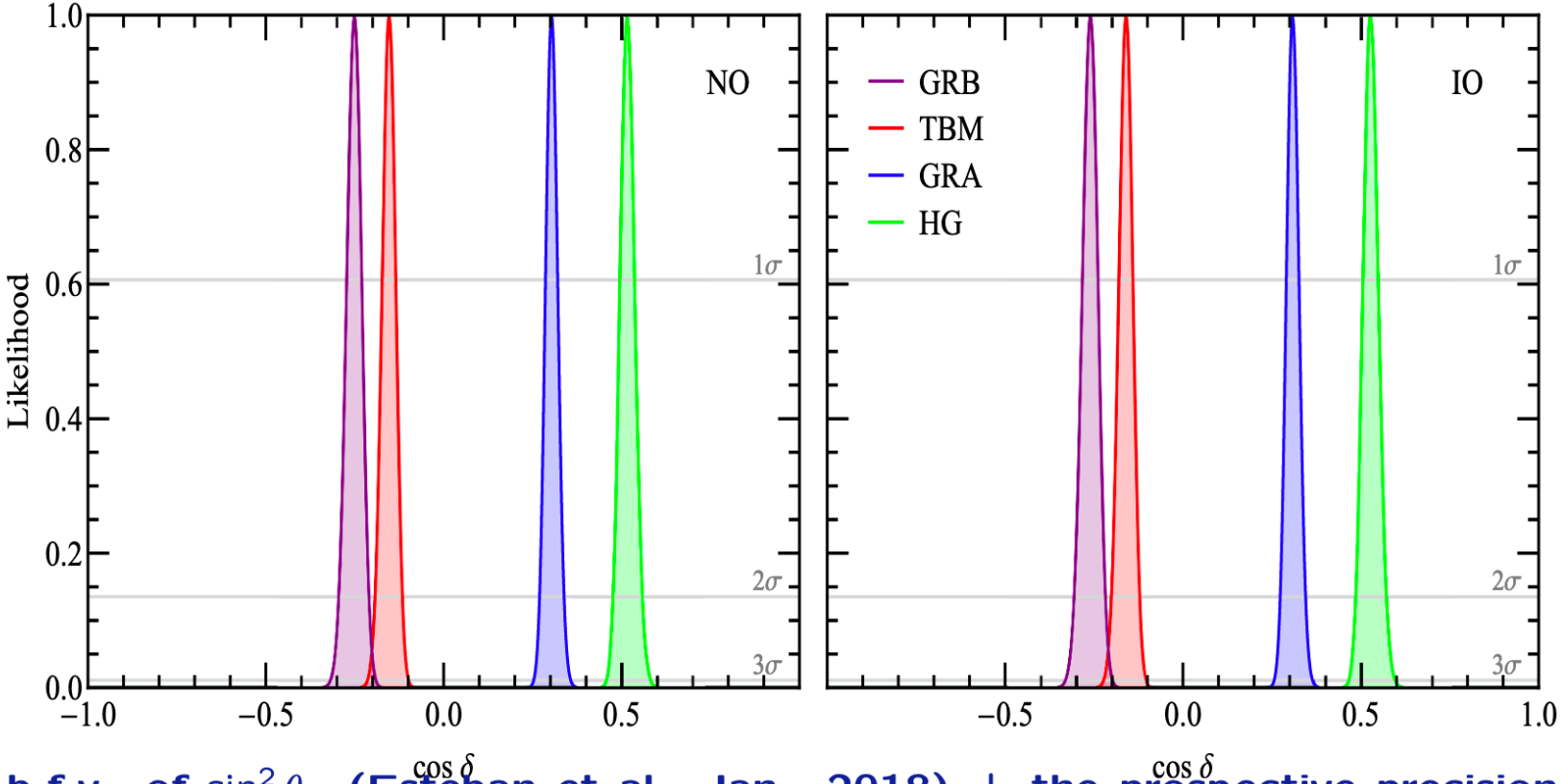
→ Very important for flavor symmetry model of neutrino mixing
S. Petcov in ICHEP 2018





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+NOνA(?)).**

25°(IO)-37°(NO) → $\delta(\delta) = 10^{\circ}$ **(THKK?)**

Prospective (useful/requested) precision:

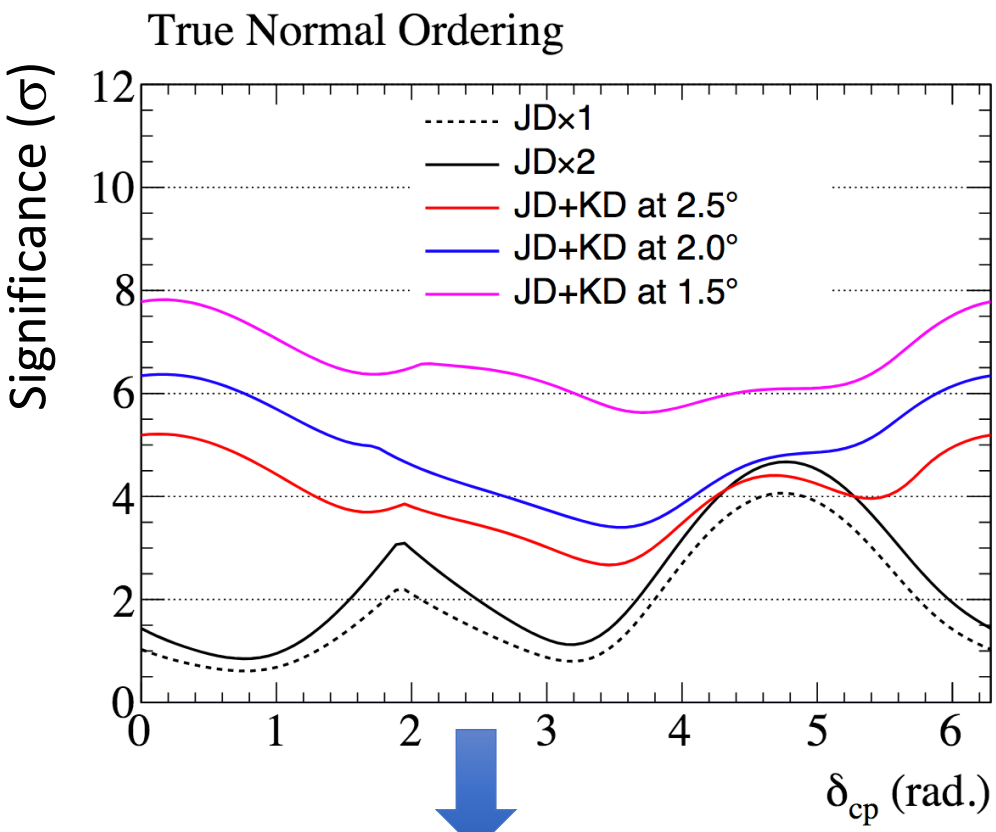
S. Petcov talk @ICHEP2018

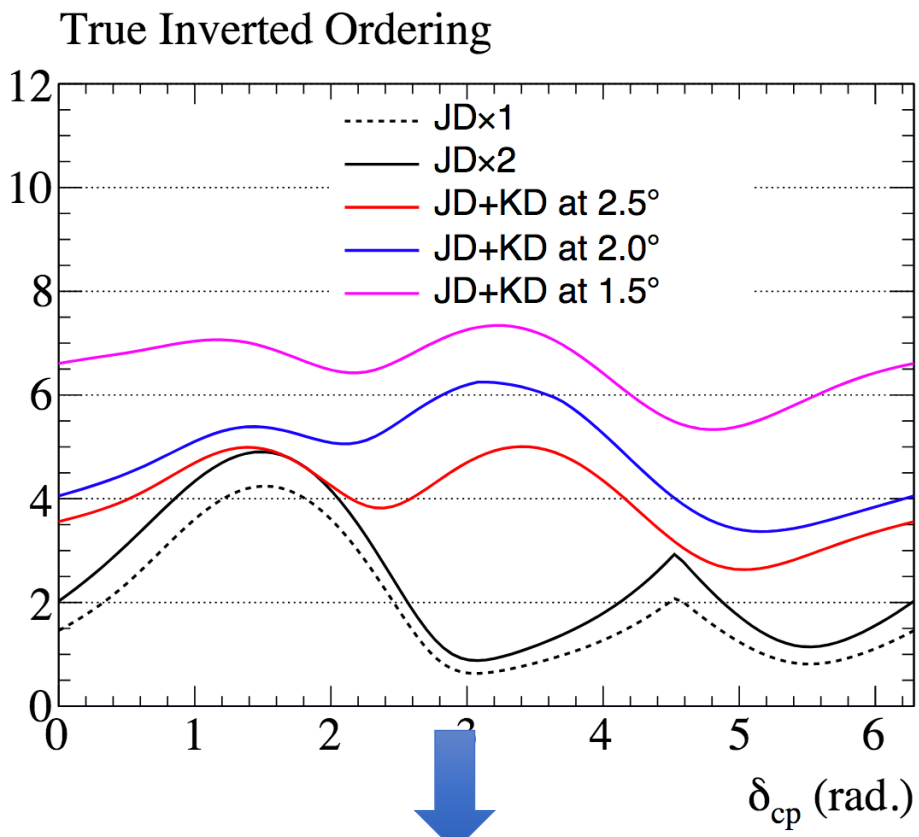
Mass Ordering Sensitivities (Beam ν)

Normal

PTEP 2018,6, 1-56

Inverted

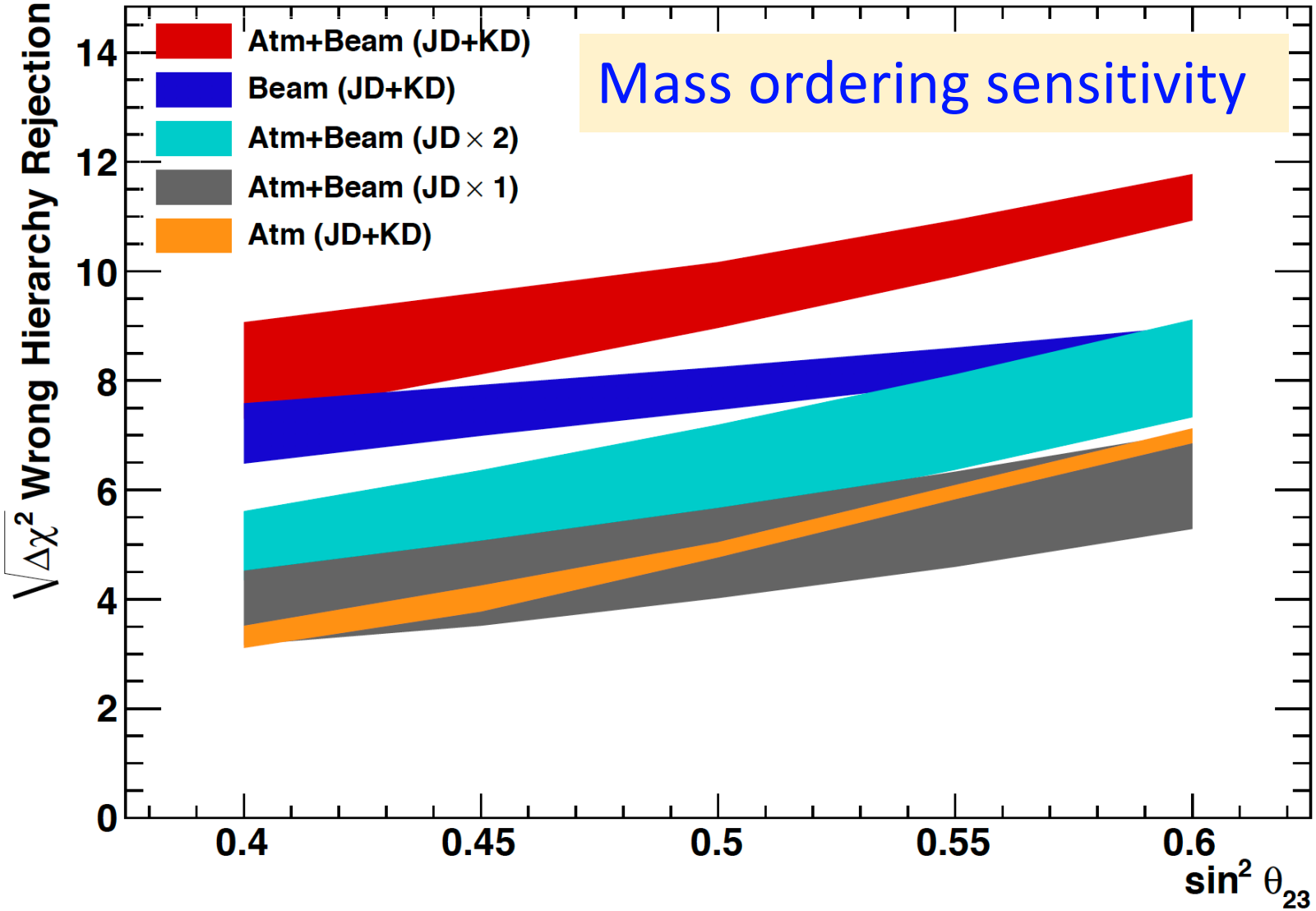




JD+KD 1.5°: 6 ~ 8 σ for all δ_{CP}
JD x2 : 1 ~ 4.5 σ for all δ_{CP}
(< 3 σ for most cases)

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

Beam + Atm. ν Data



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

Non-standard ν Interaction Sensitivity

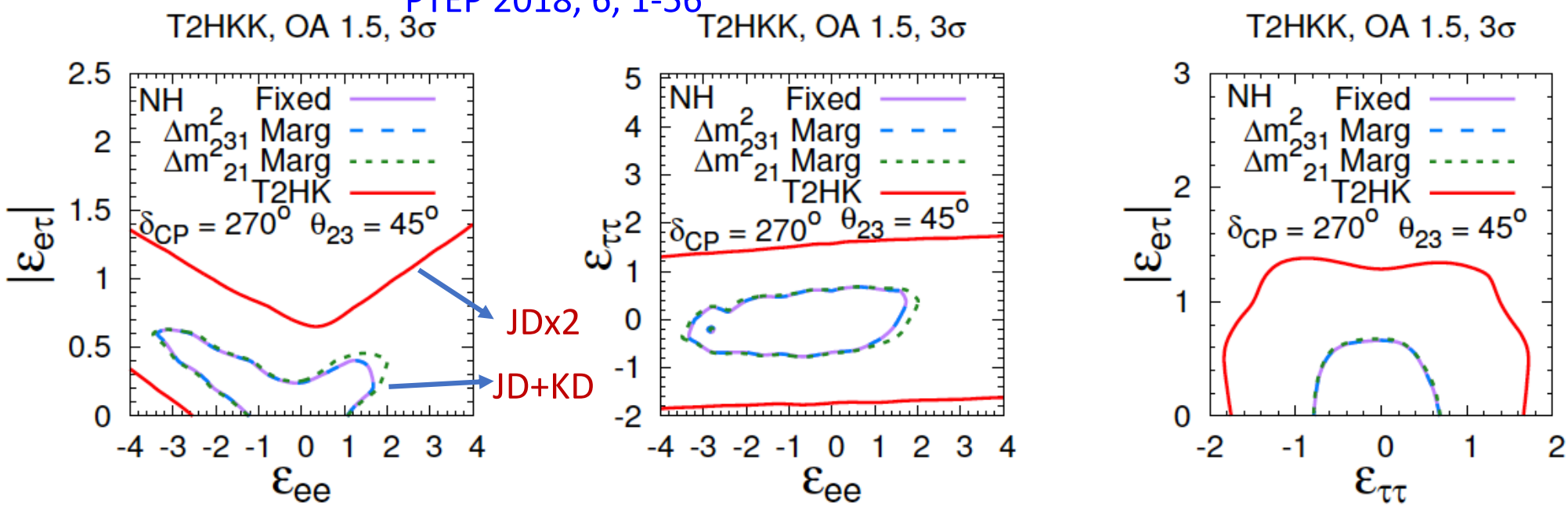
$$H = \frac{1}{2E}\left[U\begin{pmatrix} 0 & 0 & 0 \\ 0 & \delta m^2_{21} & 0 \\ 0 & 0 & \delta m^2_{31}\end{pmatrix}U^\dagger + V\right]$$

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

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

arXiv:1611.06118

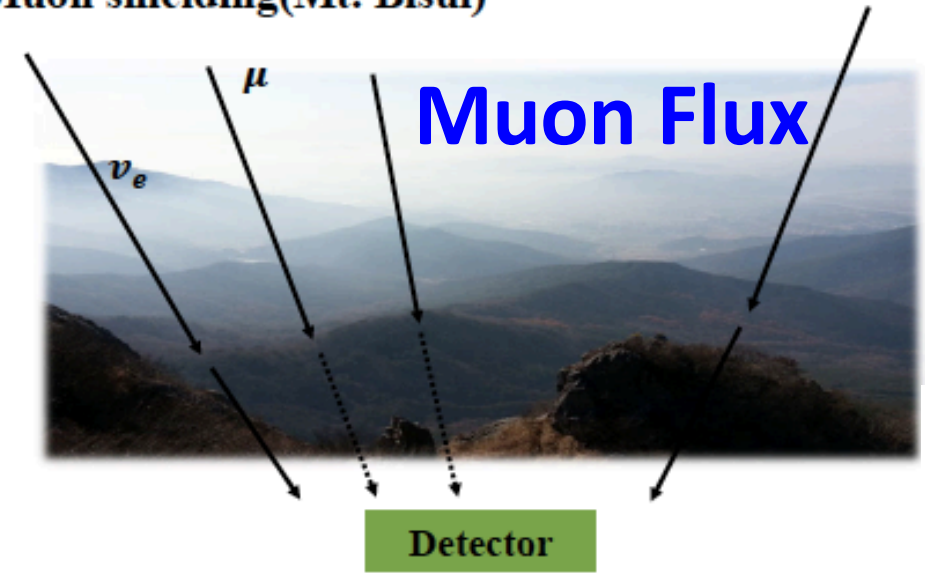
PTEP 2018, 6, 1-56



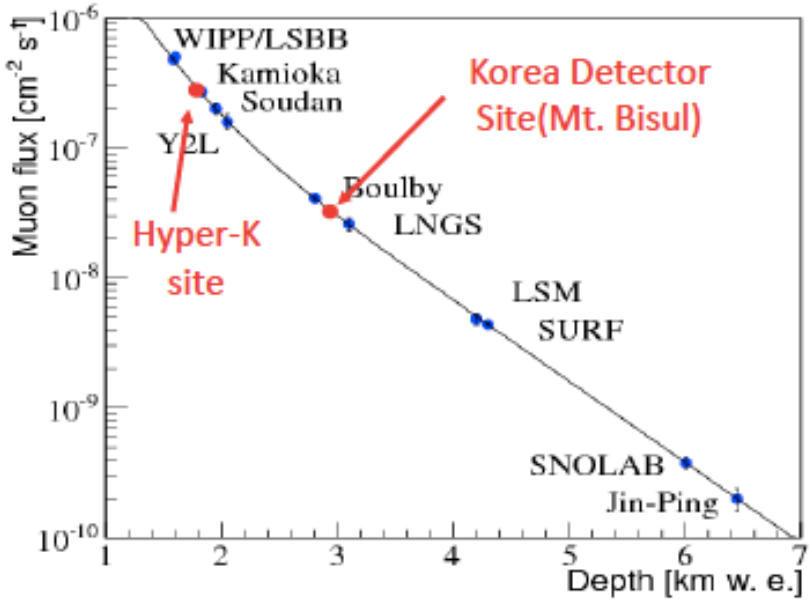
D. Marfatia@ICHEP2018: arXiv:1612.01443

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

Muon shielding(Mt. Bisul)

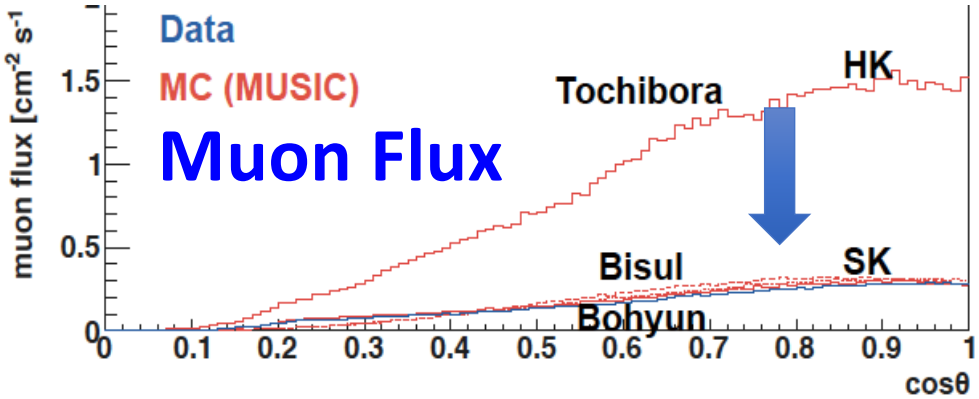


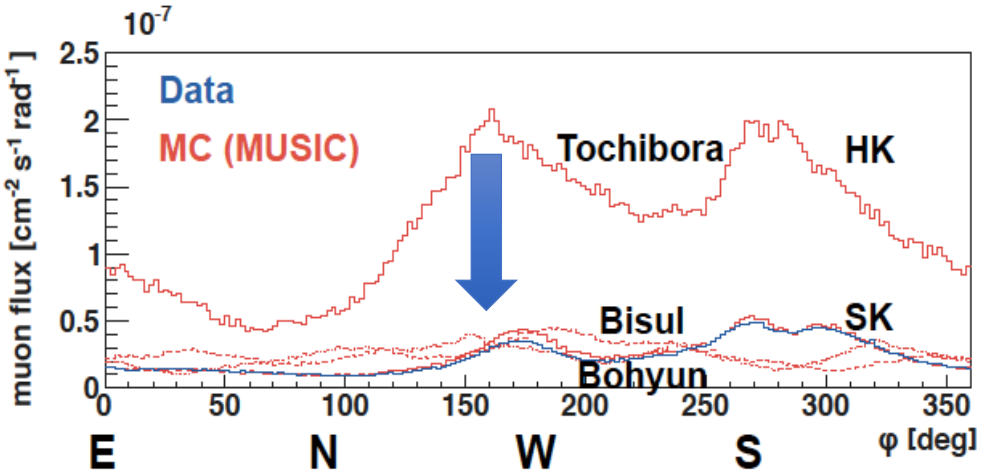
Due to the detector being located deep underground,
The background level is decreased



Muon flux to each laboratory

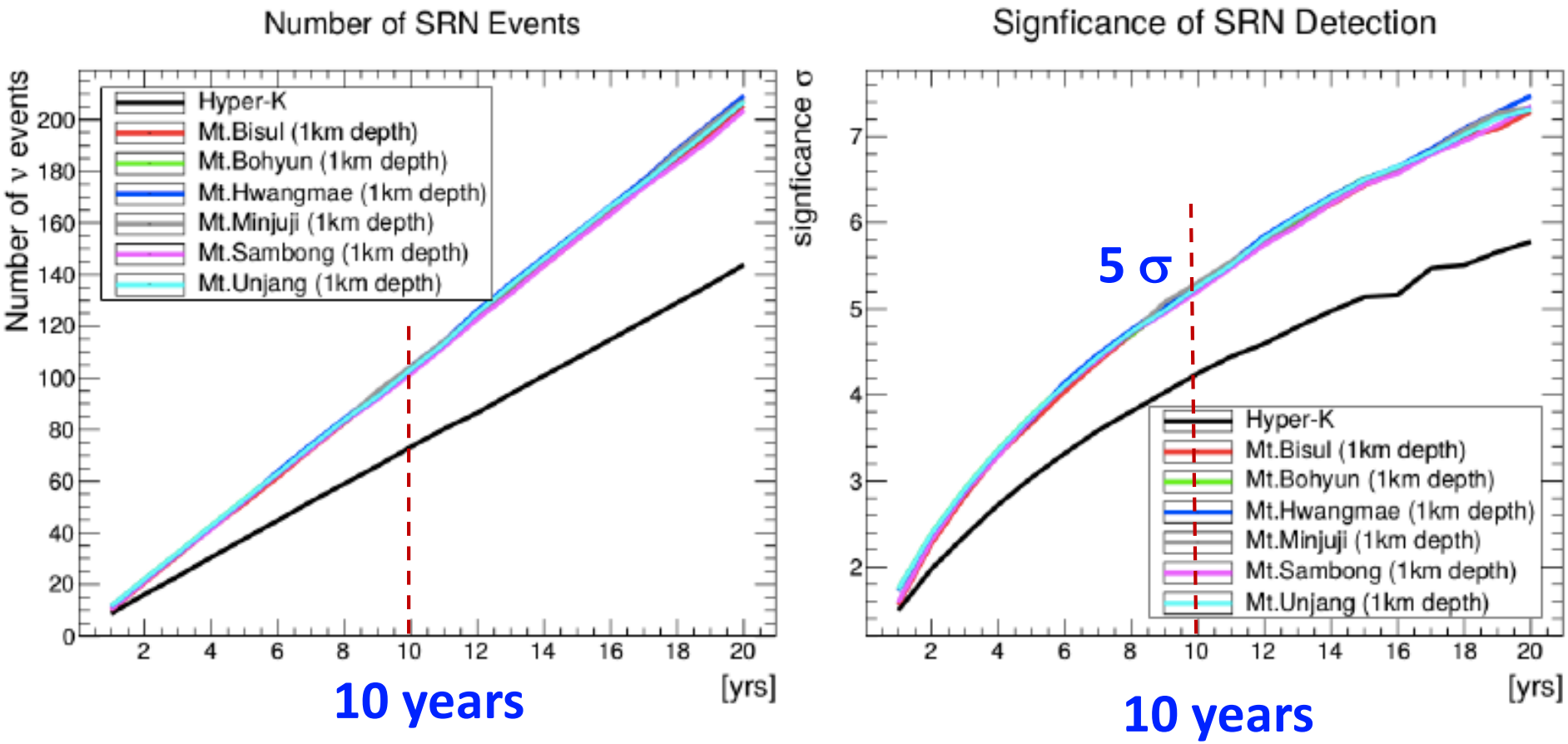
Detector site (overburden)	Φ (10^{-7} cm^{-2}s^{-1})	$\overline{E}_\mu$ (GeV)
Mt. Bisul (820 m)	3.81	233
Mt. Bohyun (820 m)	3.57	234
Mt. Bisul (1,000 m)	1.59	256
Mt. Bohyun (1,000 m)	1.50	257
Hyper-K (Tochibora, 650 m)	7.55	203
Super-K	1.54	258





Supernova Relic ν (SRN) Sensitivity

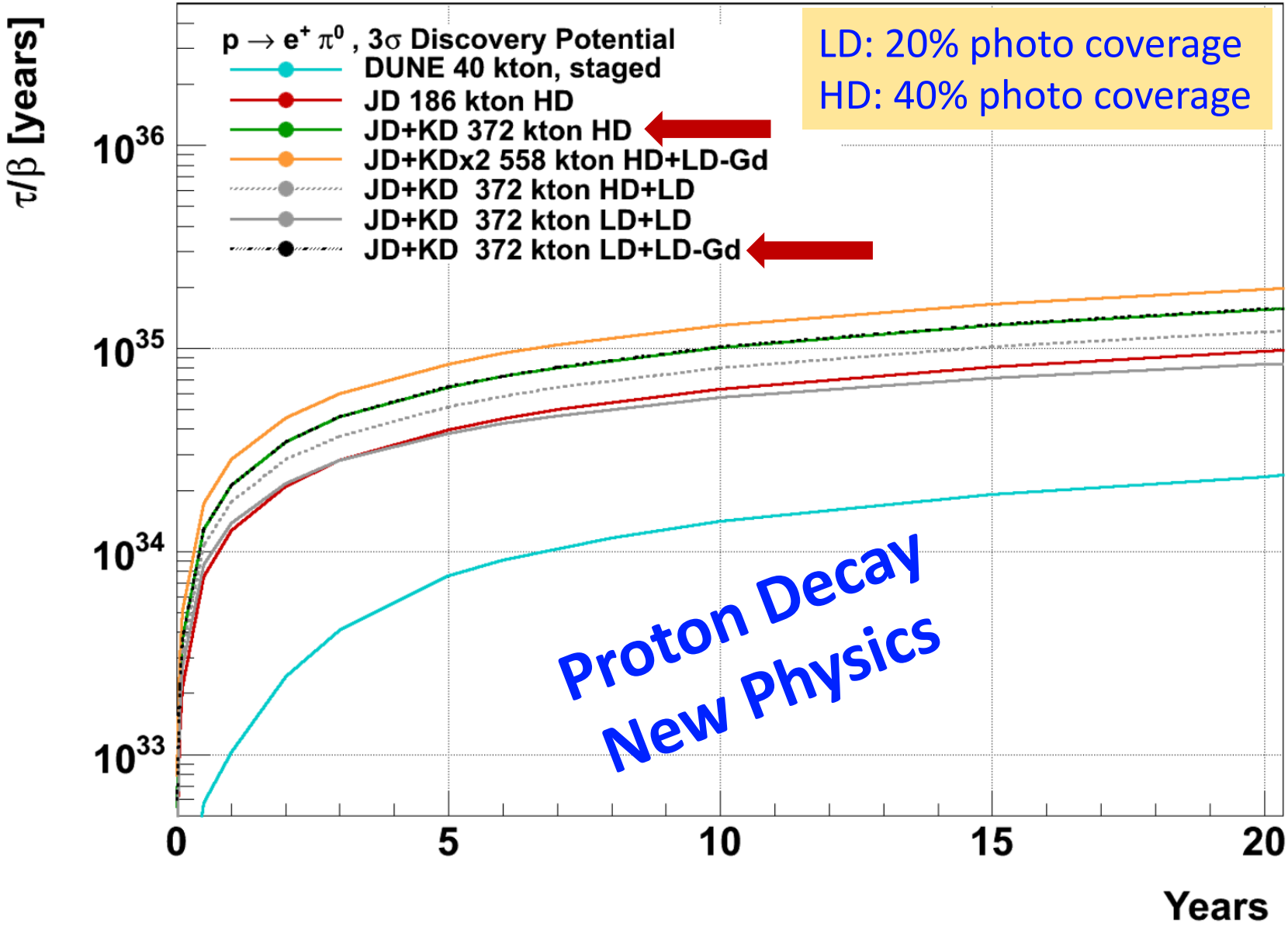
- Expected SRN events & significance plot



Difference due to 650 m (Japan) vs 1000 m (Korea) overburden

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

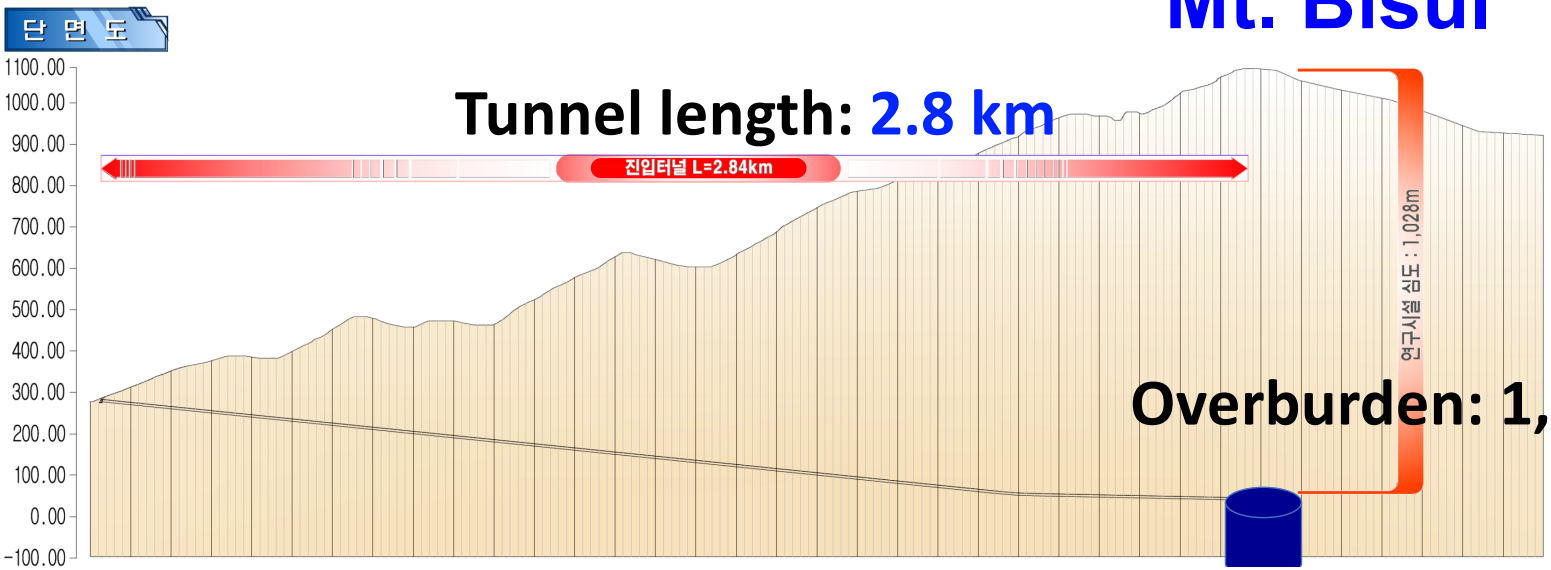
Discovery Potential for p -> $e^+\pi^0$

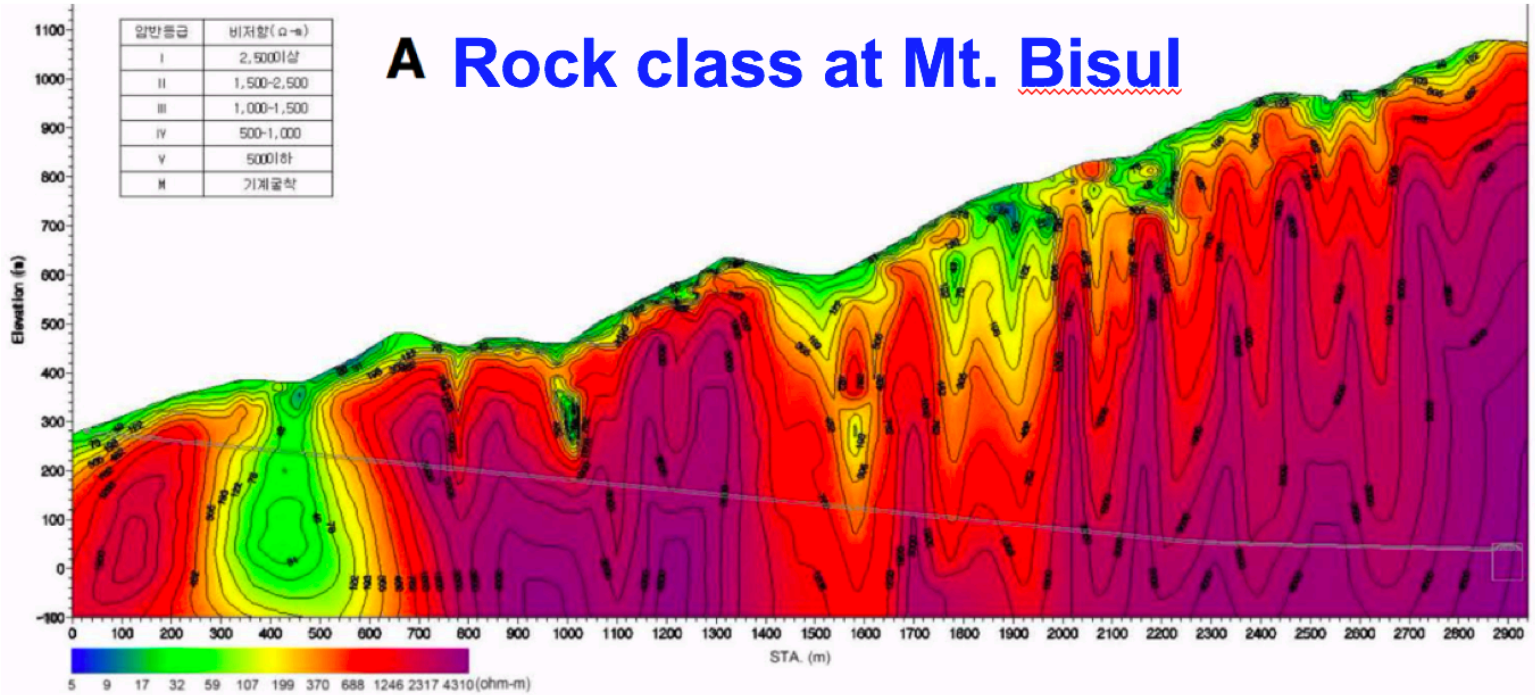


- This mode's efficiency does not depend much on cathode coverage above 20%
- Background reduction though is improved by Gd loading

Mt. Bisul Site

A구간 진입시 종단면도





Recent Activities in KNO

- ❑ Internal meetings to discuss progresses in KNO.
- ❑ Activities for KNO Detector R&D are on-going.
- ❑ Several detector-configurations are considered.
- ❑ Multi-messenger meeting activities w/ Astronomy
- ❑ Activities to get funding are also on-going.

Summary

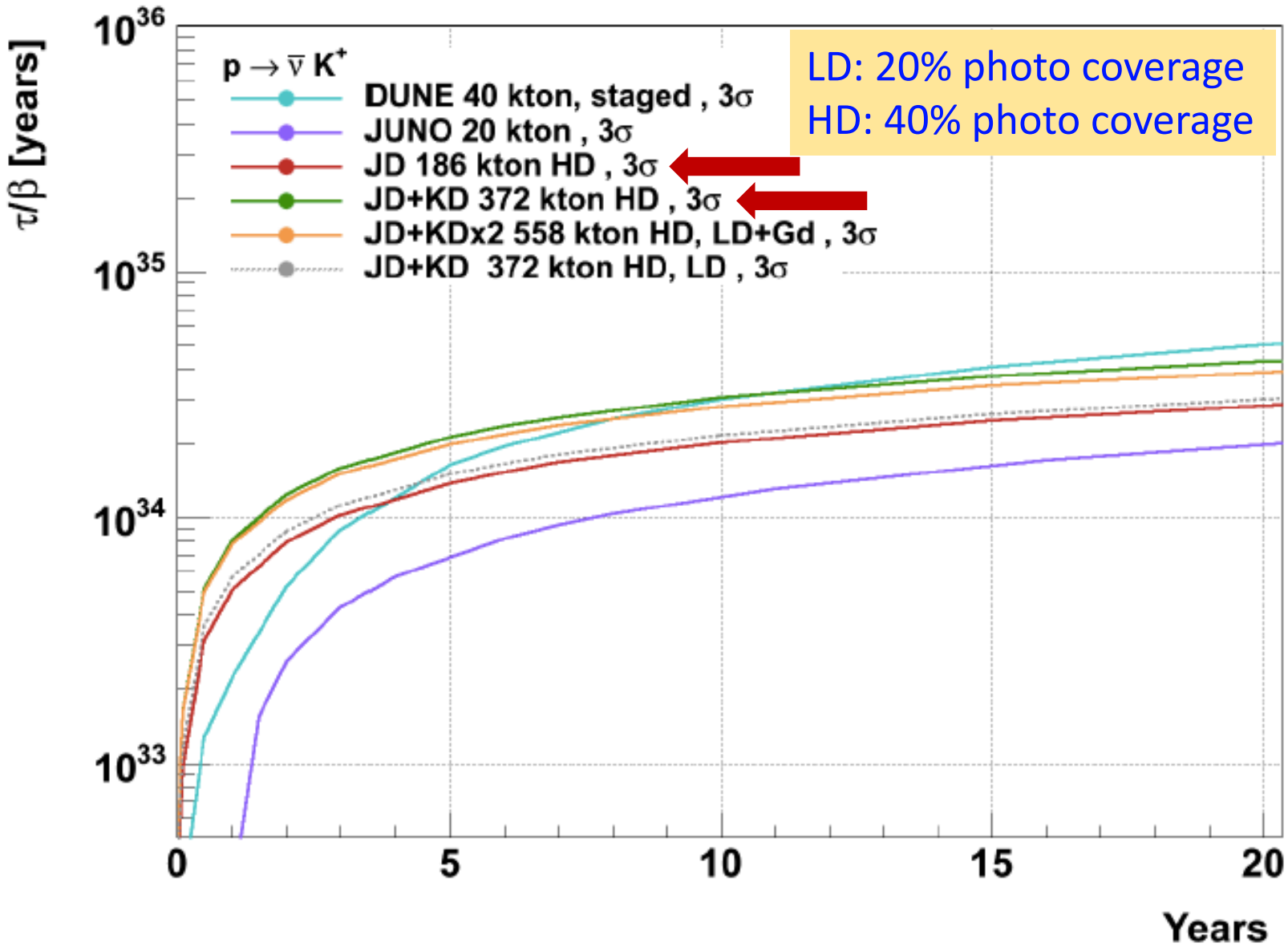
- We need T2HKK to get excellent physics results.
  - Neutrino mass ordering determination
  - CPV, CP precision, CP coverage
  - Non-standard ν interaction
  - Solar/SN/SRN etc…

- KNO Detector R&D is going well.
  - Various PMT options are considered
  - water purification system
  - Radon detector etc.

- Aim to get funding ASAP.

International collaboration is absolutely needed !

Discovery Potential for p -> νK^+



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

Systematic Uncertainties

- **Total systematic errors:**
- JD: 4~5 %
- KD: ~4% at 1.5^{O} OAA

- **Dominant systematic errors** in KD:
- Extrapolation : 2.5~3 %
- Far detector model: 2~2.7%

→ **Need to focusing on reducing these errors!**

In the future study, we expect cancelation of systematic uncertainty by JD + KD ?

	Percent Error (%)				
Error Source	ν 1Rμ	$\bar{\nu}$ 1Rμ	ν 1Re	$\bar{\nu}$ 1Re	(ν 1Re)/($\bar{\nu}$ 1Re)
OAA=2.5°, L = 1100 km					
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$, $\sigma_{\bar{\nu}_e}/\sigma_{\bar{\nu}_\mu}$	0.00	0.00	2.10	1.68	3.12
Energy Scale	0.02	0.02	0.01	0.01	0.01
Matter Density	0.04	0.08	0.43	0.09	0.53
NCπ^+ Bgnd.	1.28	1.25	0.00	0.00	0.00
ν_e & NCπ^0 Bgnd.	0.00	0.00	1.32	1.41	1.88
CC non-QE Fraction	2.76	1.88	1.98	1.29	2.35
Extrapolation	2.70	2.60	2.44	3.06	1.95
Far Detector Model	2.64	2.64	2.08	2.08	0.00
Total	4.69	4.16	4.54	4.47	4.86
OAA=2.0°, L = 1100 km					
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$, $\sigma_{\bar{\nu}_e}/\sigma_{\bar{\nu}_\mu}$	0.00	0.00	2.01	1.67	3.07
Energy Scale	0.02	0.01	0.01	0.01	0.01
Matter Density	0.02	0.06	0.55	0.12	0.67
NCπ^+ Bgnd.	1.47	1.29	0.00	0.00	0.00
ν_e & NCπ^0 Bgnd.	0.00	0.00	1.26	1.29	1.76
CC non-QE Fraction	0.87	0.82	1.24	0.76	1.51
Extrapolation	2.68	2.68	2.38	3.00	1.92
Far Detector Model	2.64	2.64	2.08	2.08	0.00
Total	3.89	3.83	4.18	4.27	4.39
OAA=1.5°, L = 1100 km					
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$, $\sigma_{\bar{\nu}_e}/\sigma_{\bar{\nu}_\mu}$	0.00	0.00	1.72	1.41	2.67
Energy Scale	0.01	0.01	0.01	0.01	0.01
Matter Density	0.01	0.06	0.24	0.28	0.53
NCπ^+ Bgnd.	1.61	1.30	0.00	0.00	0.00
ν_e & NCπ^0 Bgnd.	0.00	0.00	1.42	1.37	1.93
CC non-QE Fraction	0.44	0.30	0.52	0.37	0.75
Extrapolation	2.67	2.60	2.23	2.88	1.84
Far Detector Model	2.64	2.64	2.08	2.08	0.00
Total	3.83	3.81	3.84	4.11	3.91
OAA=2.5°, L = 295 km					
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$, $\sigma_{\bar{\nu}_e}/\sigma_{\bar{\nu}_\mu}$	0.01	0.00	2.44	1.82	3.53
Energy Scale	0.04	0.03	0.42	0.63	0.21
Matter Density	–	–	–	–	–
NCπ^+ Bgnd.	2.33	1.79	0.00	0.00	0.00
ν_e & NCπ^0 Bgnd.	0.00	0.00	0.94	1.22	1.51
CC non-QE Fraction	1.68	1.72	2.07	1.00	2.25
Extrapolation	2.60	2.56	2.51	3.05	1.96
Far Detector Model	2.64	2.64	2.08	2.08	0.00
Total	4.13	4.15	4.71	4.47	4.90
OAA=2.5°, L = 295 km (Hyper-K Design Report)					
Total	3.6	3.6	3.2	3.9	–

arXiv:1611.06118
PTEP 2018, 6, 1-56