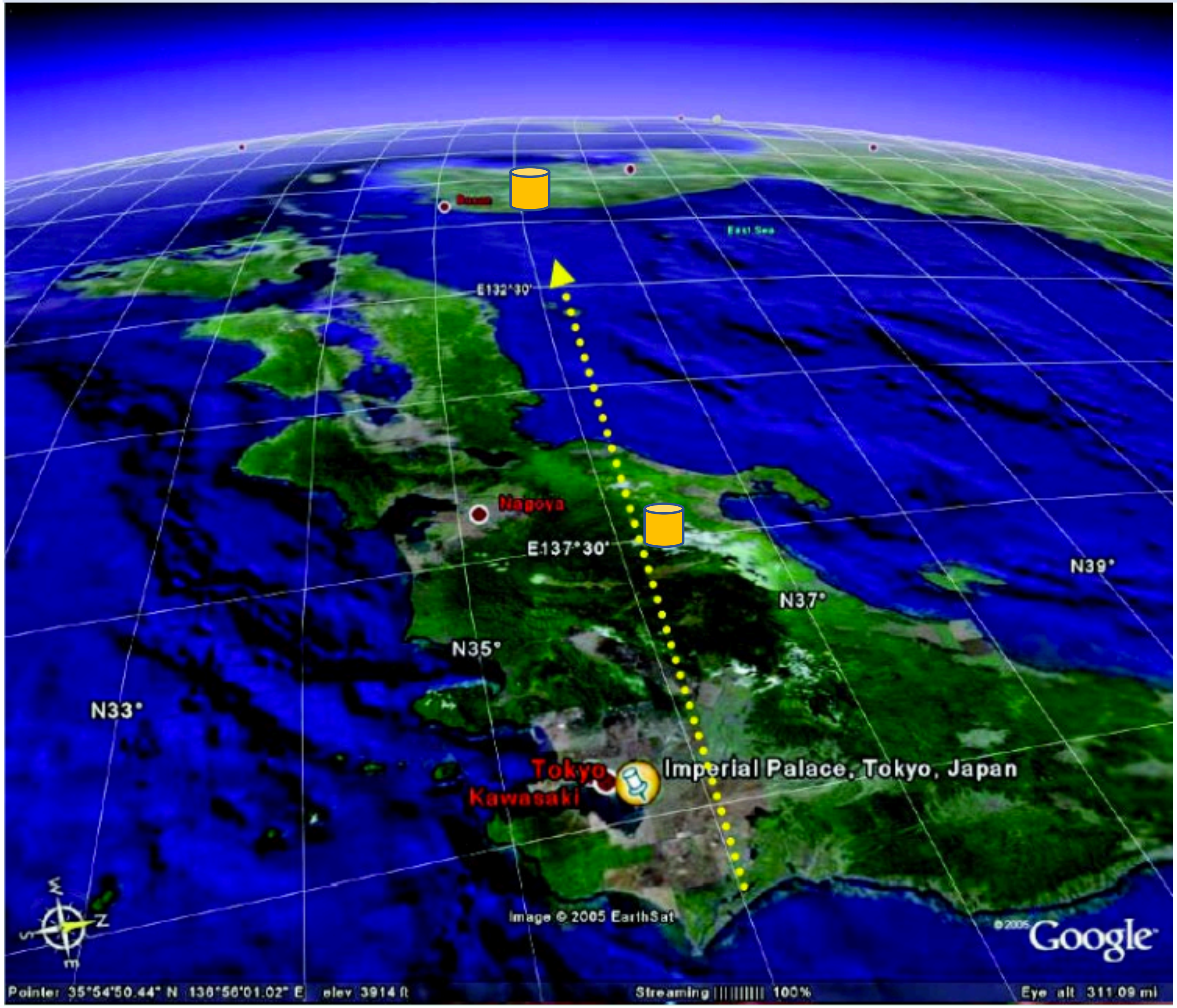
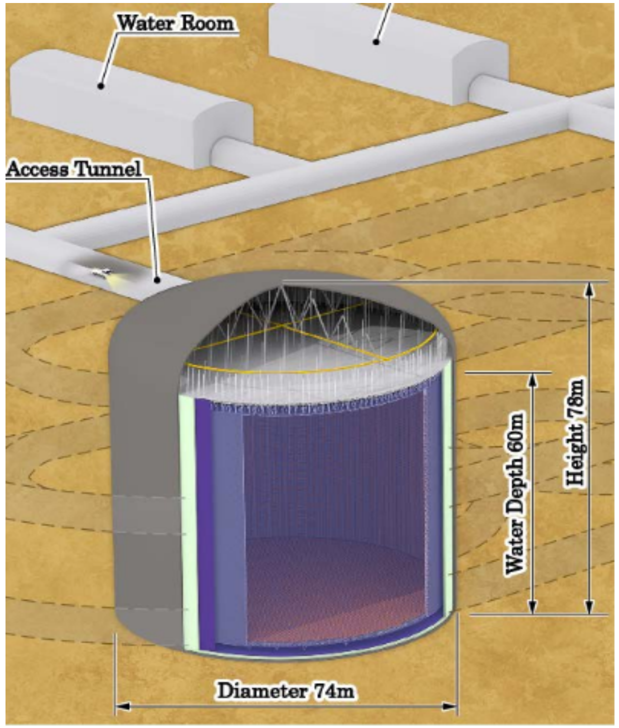
Particle Physics in Korean Neutrino Observatory





Sunny Seo
IBS

KNO Satellite Meeting
NuFACT 2019
2019.08.25

Why Korean Neutrino Observatory?

✓ Excellent physics cases (CPV, MO, proton decay,..) using long baseline neutrino beam.

Different systematics from Hyper-K & DUNE

✓ J-PARC neutrino beam passes through Korea.

We need to build only a detector.

✓ Excellent astronomy/astrophysics cases:
Supernova burst/relic ν, solar ν, multi-messenger…

ν_e appearance probability: address 3 key parameters

If Normal/Inverted Ordering,
(-/+) sign is for ν
(+/-) sign is for $\bar{\nu}$

Mass ordering

θ_{23} and octant

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \approx 4s_{23}^2 s_{13}^2 \frac{1}{(1\mp r_A)^2} \sin^2\frac{(1\mp r_A)\Delta_{31}L}{4E}$$
$$+ \sin 2\theta_{12} \sin 2\theta_{23} s_{13} \left(\frac{\Delta_{21}L}{2E}\right) \sin\frac{(1\mp r_A)\Delta_{31}L}{4E} \cos\left(\pm\delta - \frac{\Delta_{31}L}{4E}\right)$$
$$+ c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{21}L}{4E}\right)^2 - 4s_{23}^2 s_{13}^4 \frac{1}{(1\mp r_A)^2} \sin^2\frac{(1\mp r_A)\Delta_{31}L}{4E}$$

CP

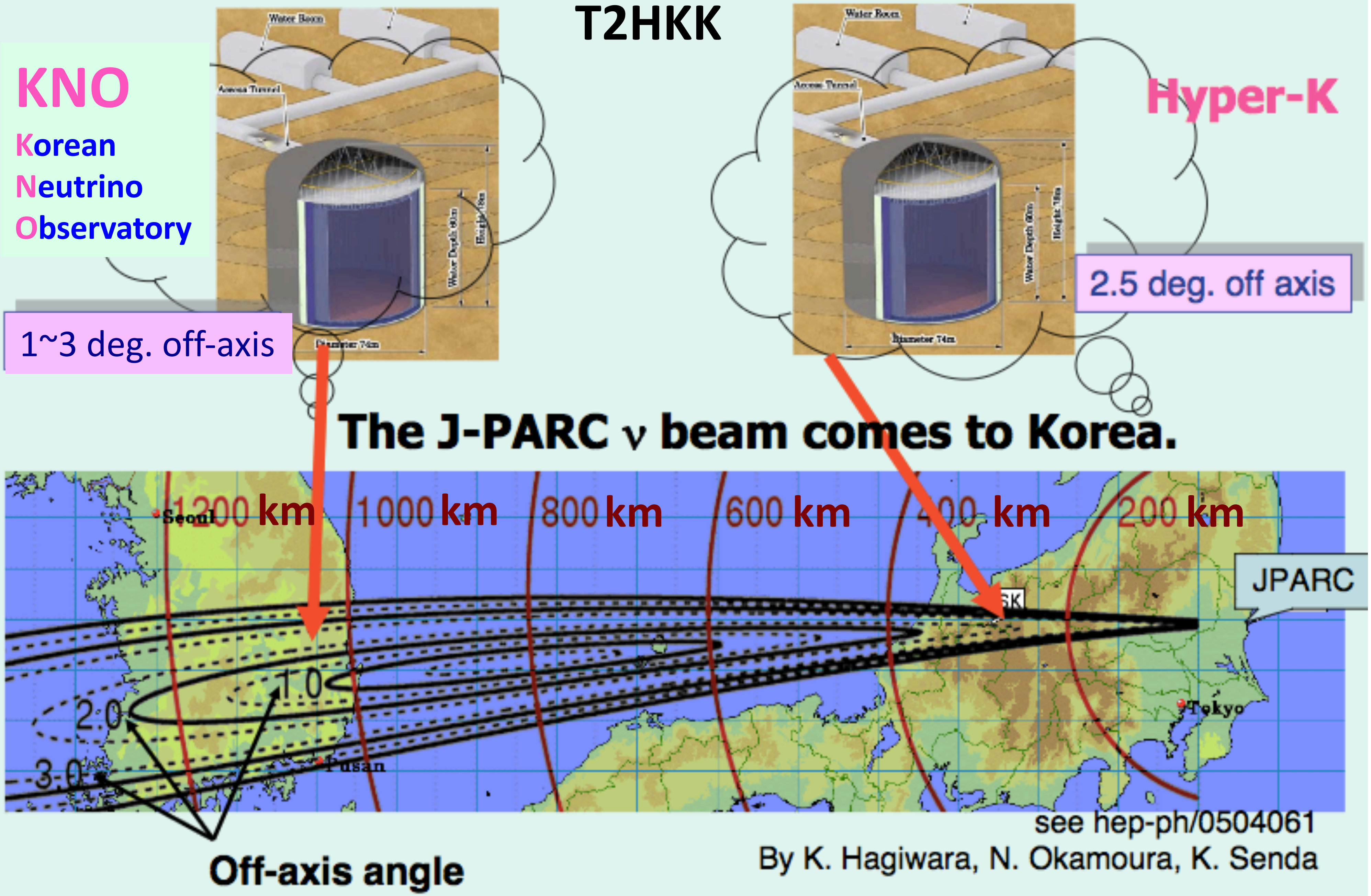
solar term: suppressed by Δ^2_{21}

O(10^{-3}) @ 1st osc. Max
O(10^{-2}) @ 2nd osc. Max

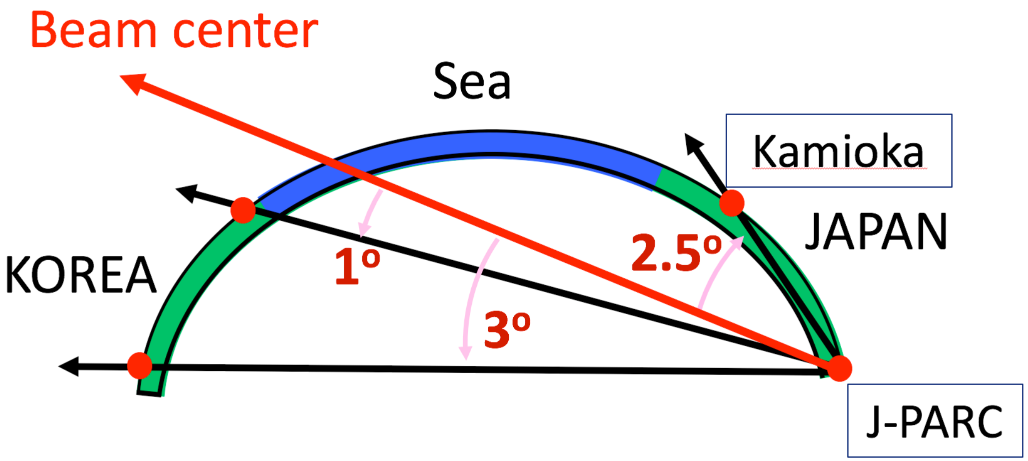
suppressed by $\sin^4\theta_{13}$

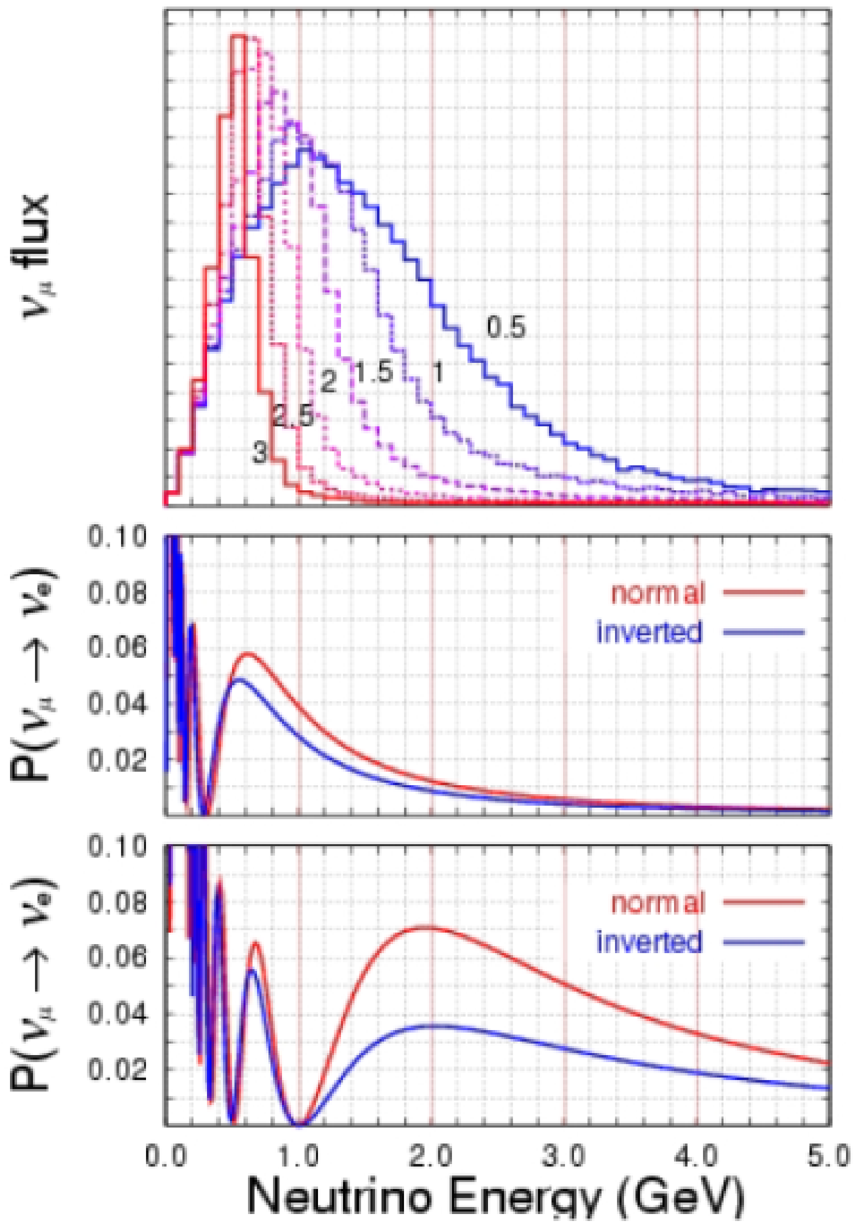
2% correction to the 1st term

Korean Neutrino Observatory



Neutrino Oscillations in Kamioka & Korea



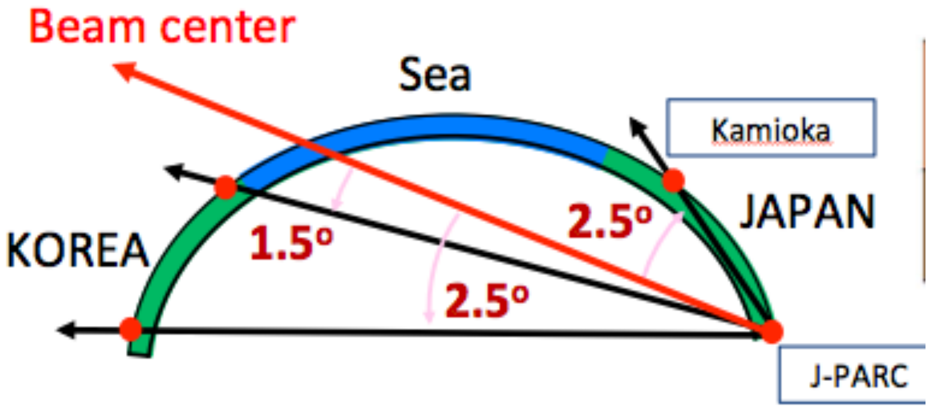


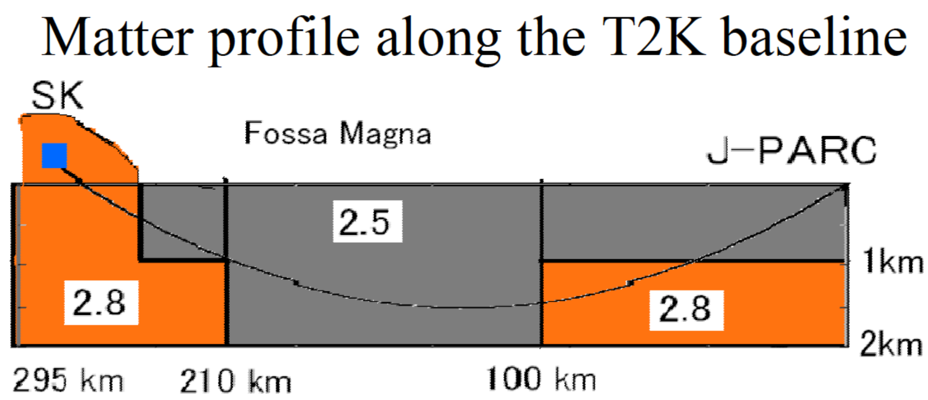
← Profile of off-axis beams

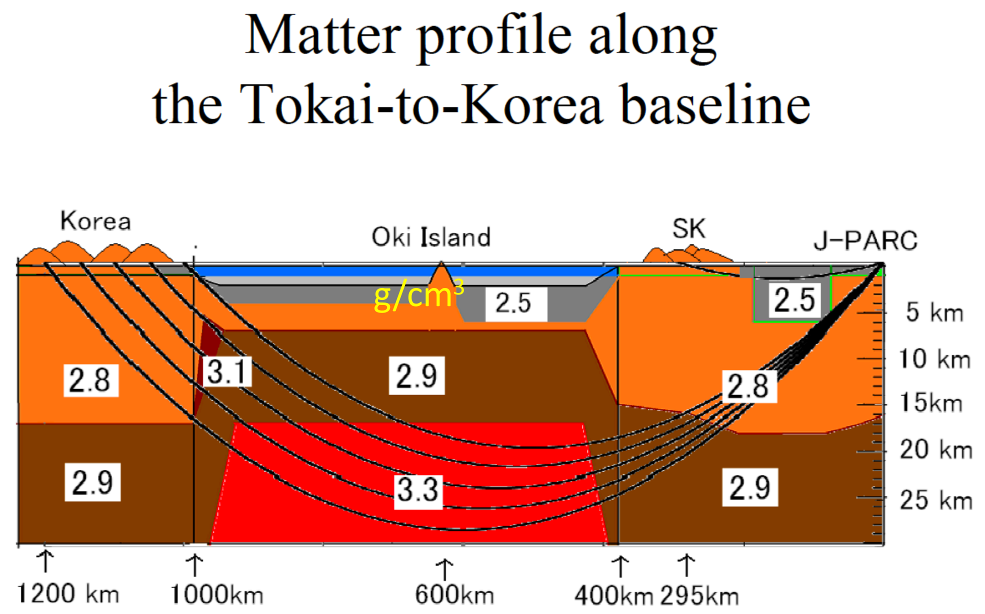
← $P(\nu_\mu \to \nu_e)$ at SK/HK (Japan)
(L = 295 km)

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

Off-axis Beam and Matter Density







Matter term:

$$r_A = 2\sqrt{2} G_F N_e E_\nu / \Delta m^2_{31}$$

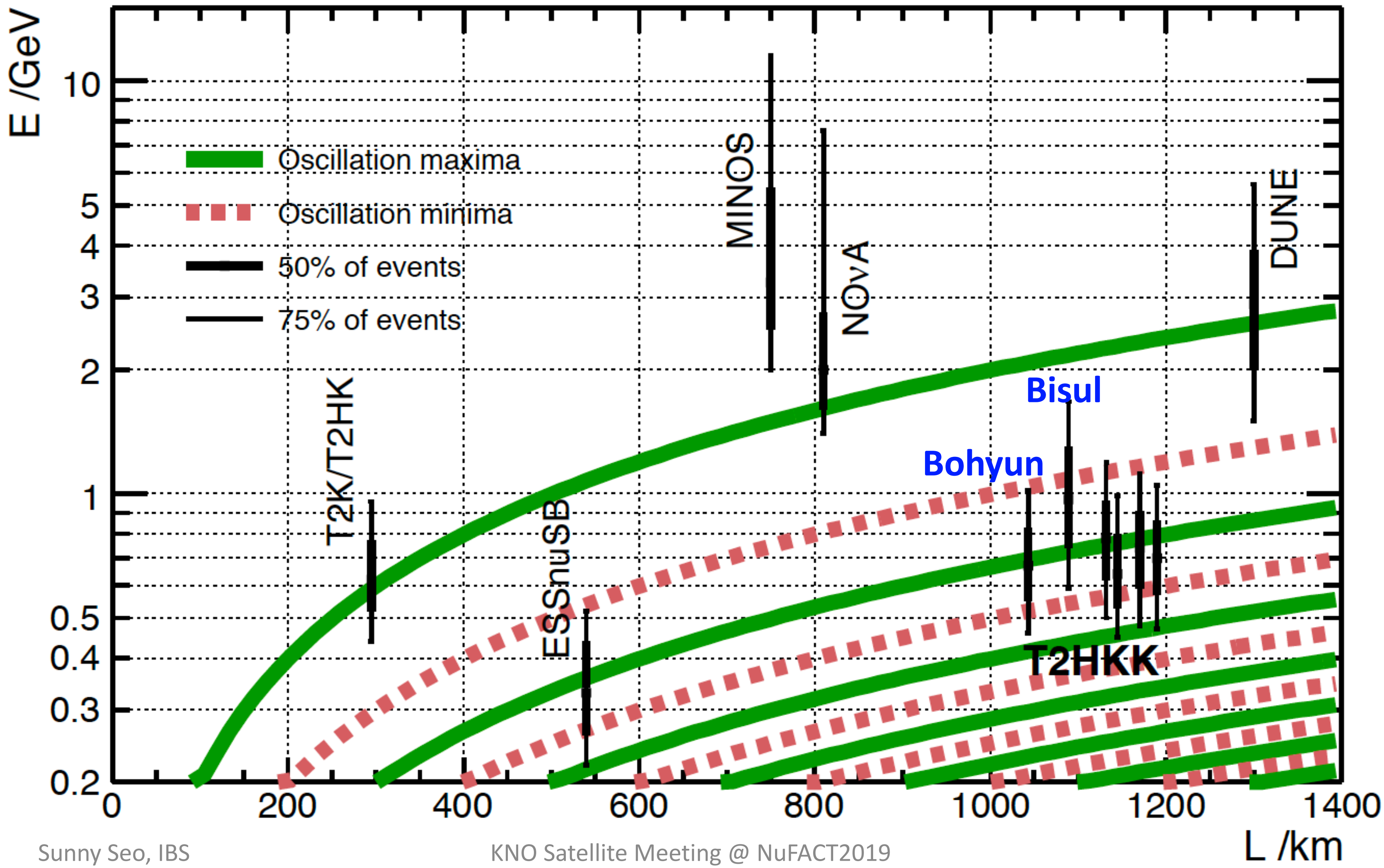
More matter effects

→ better MO determination

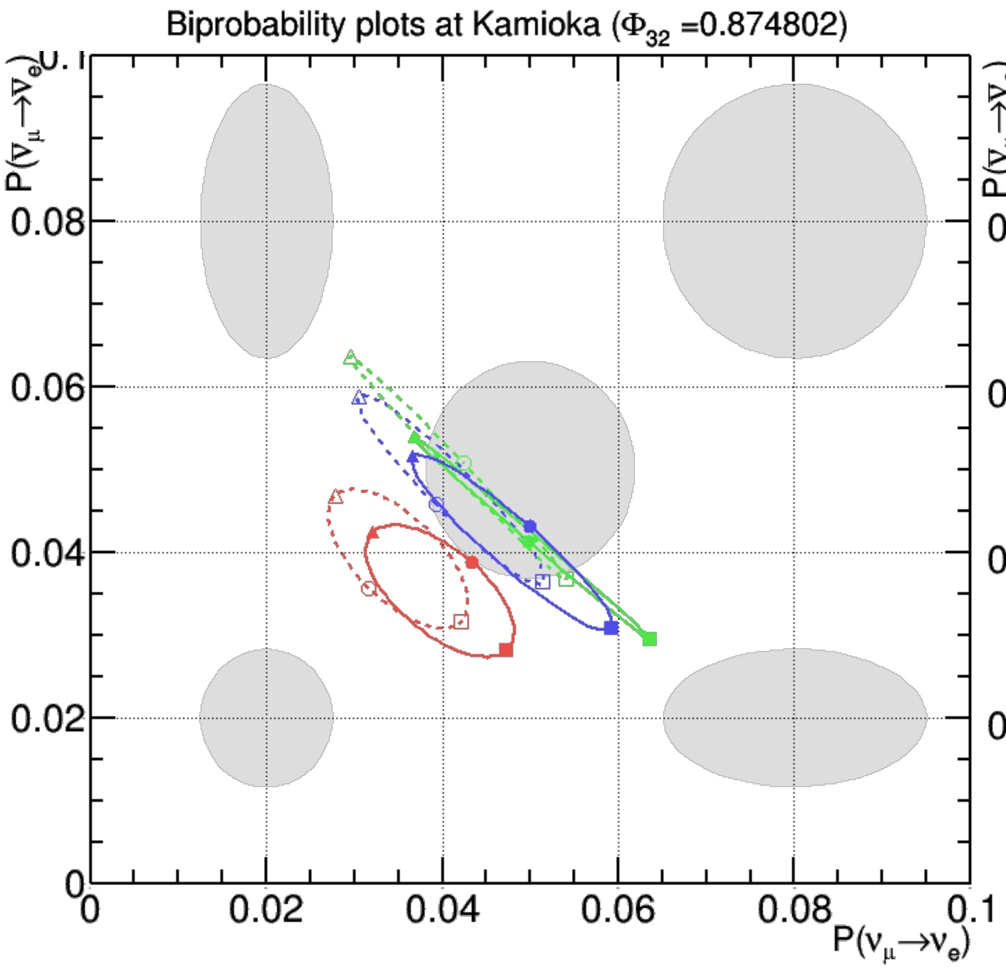
- Longer baseline
- Higher neutrino energy
- Higher matter density

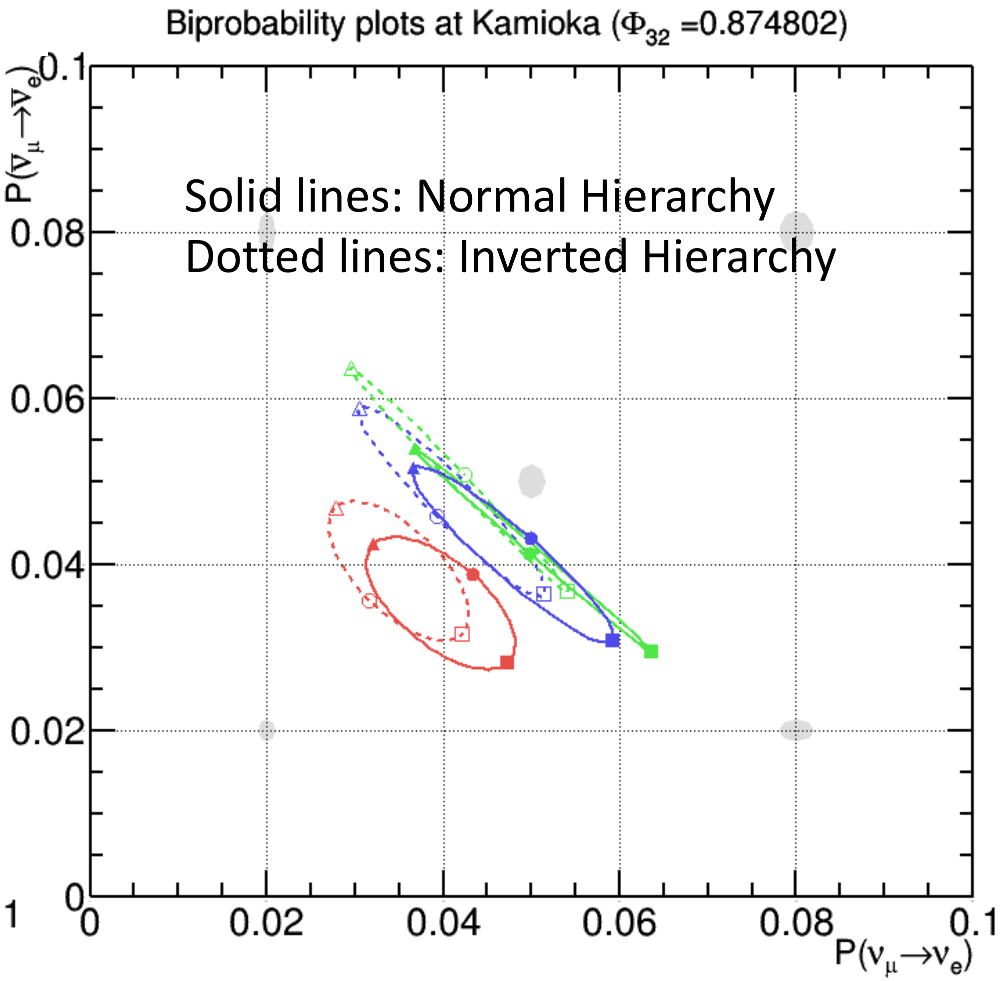
Energy vs. Baseline

2nd Oscillation maxima in Korean sites



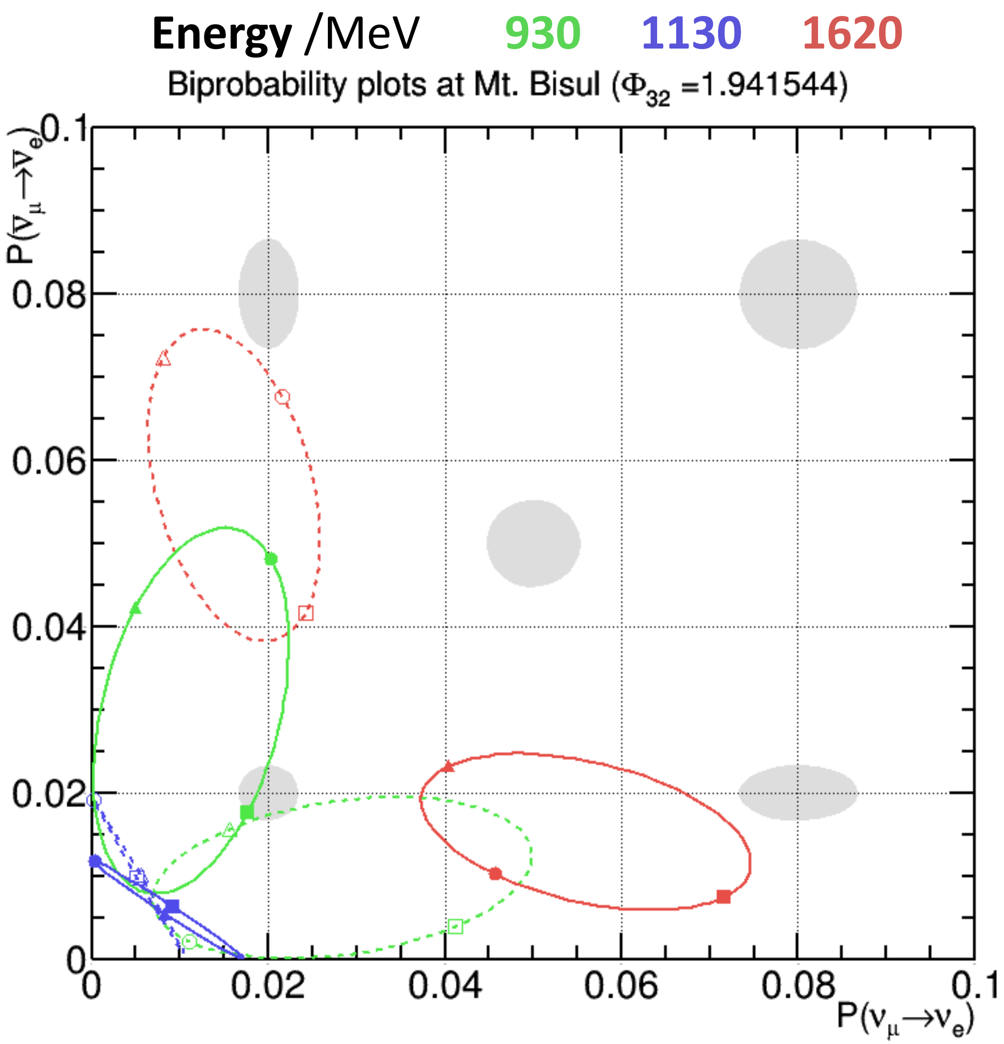
Super-K (2027) → Hyper-K (2037)





Statistical errors are reduced very much at HK but no improvement in degeneracies.

Mt. Bisul Site

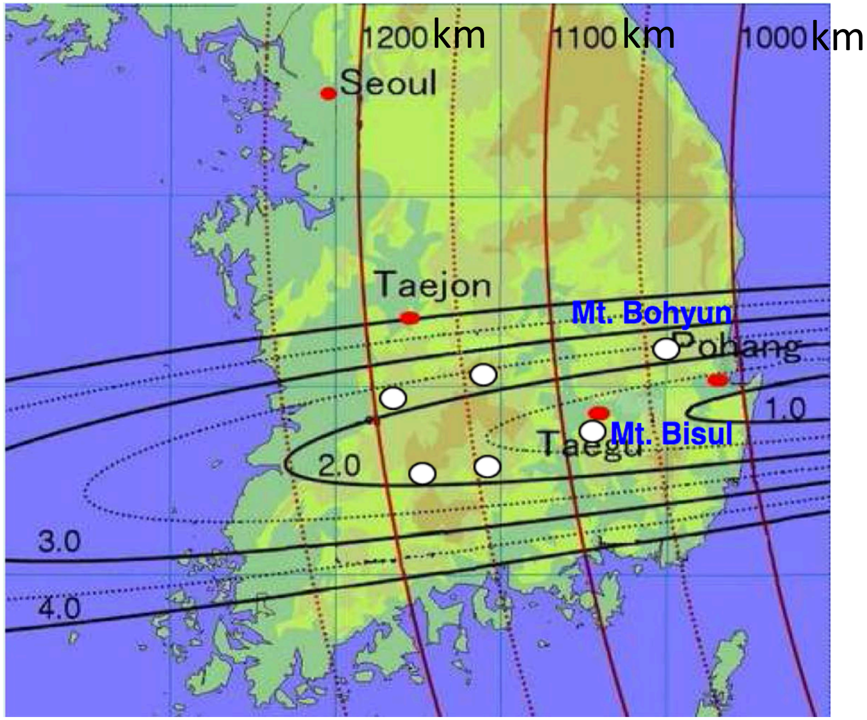


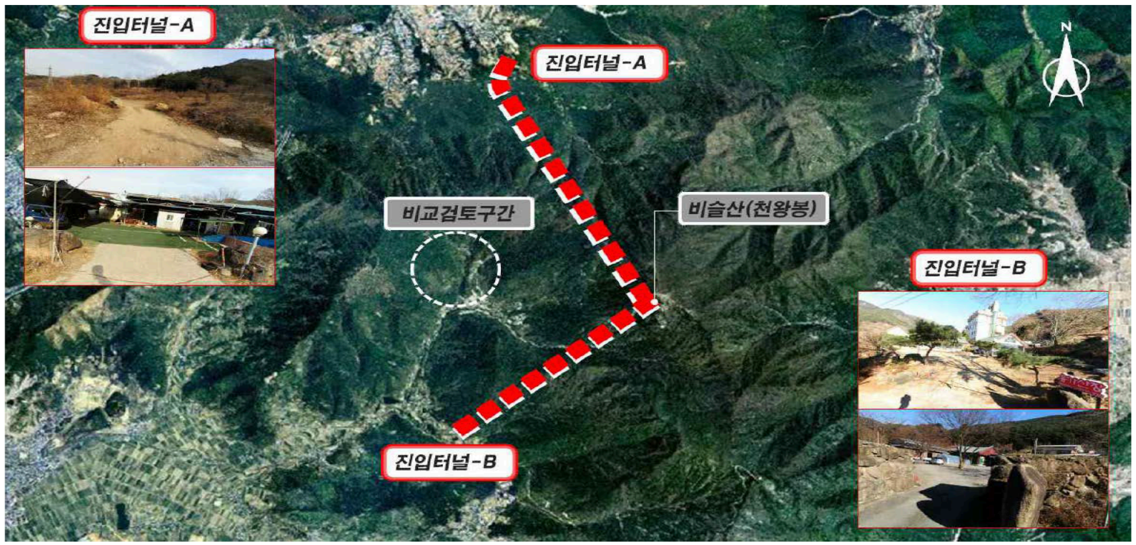
This is the high energy option.

- Good separation between hierarchies 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 Hierachy enhancement for **low-energy** events

Degeneracies break up !

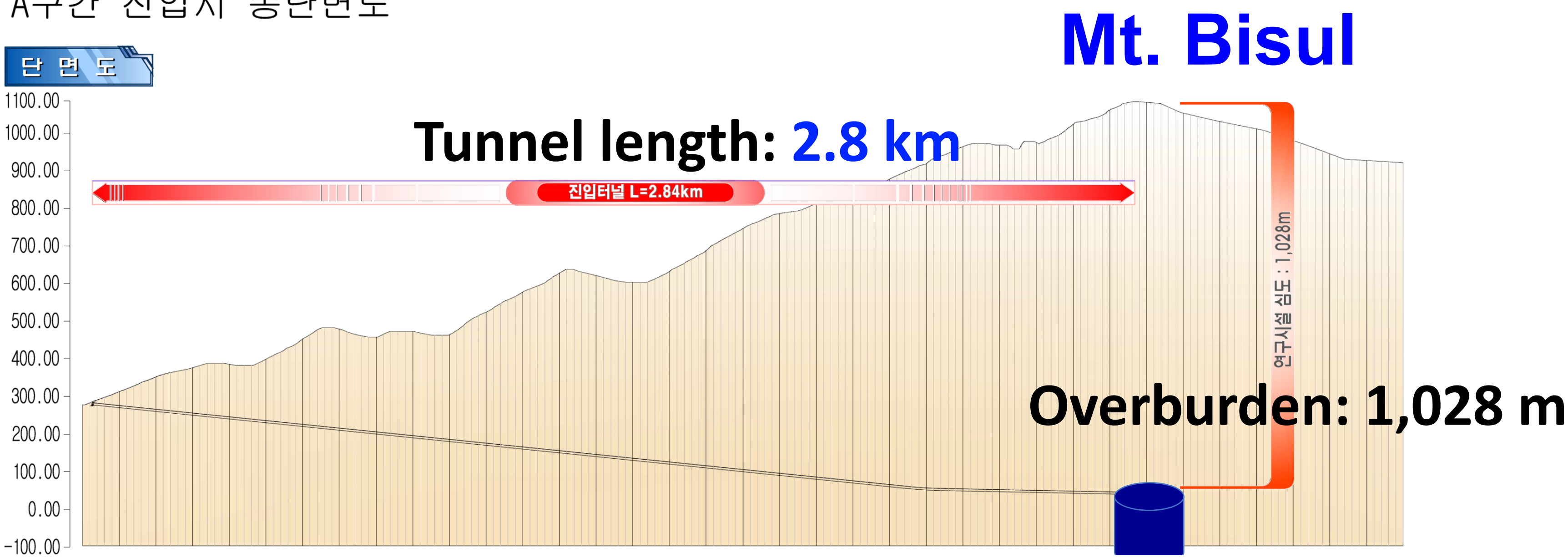
Mt. Bisul Site

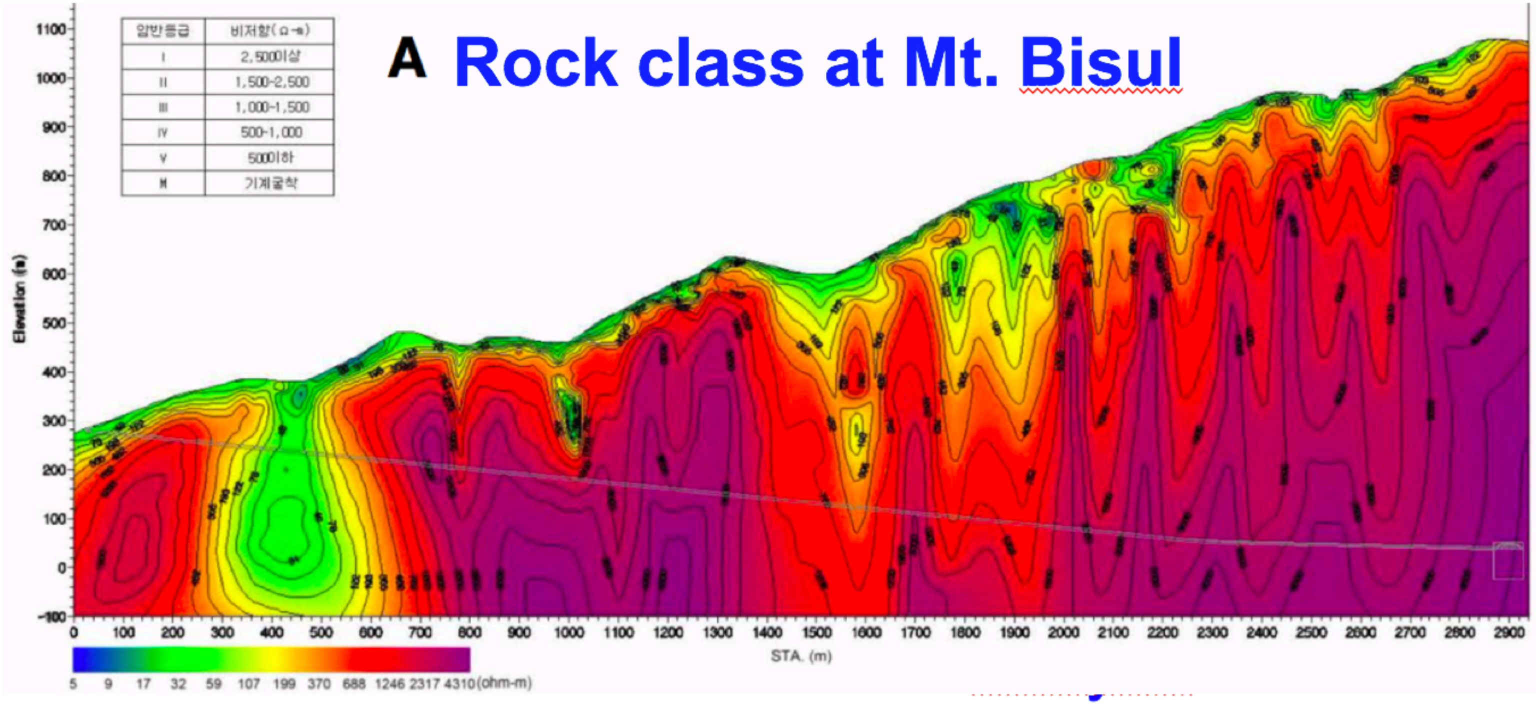




Mt. Bisul Site

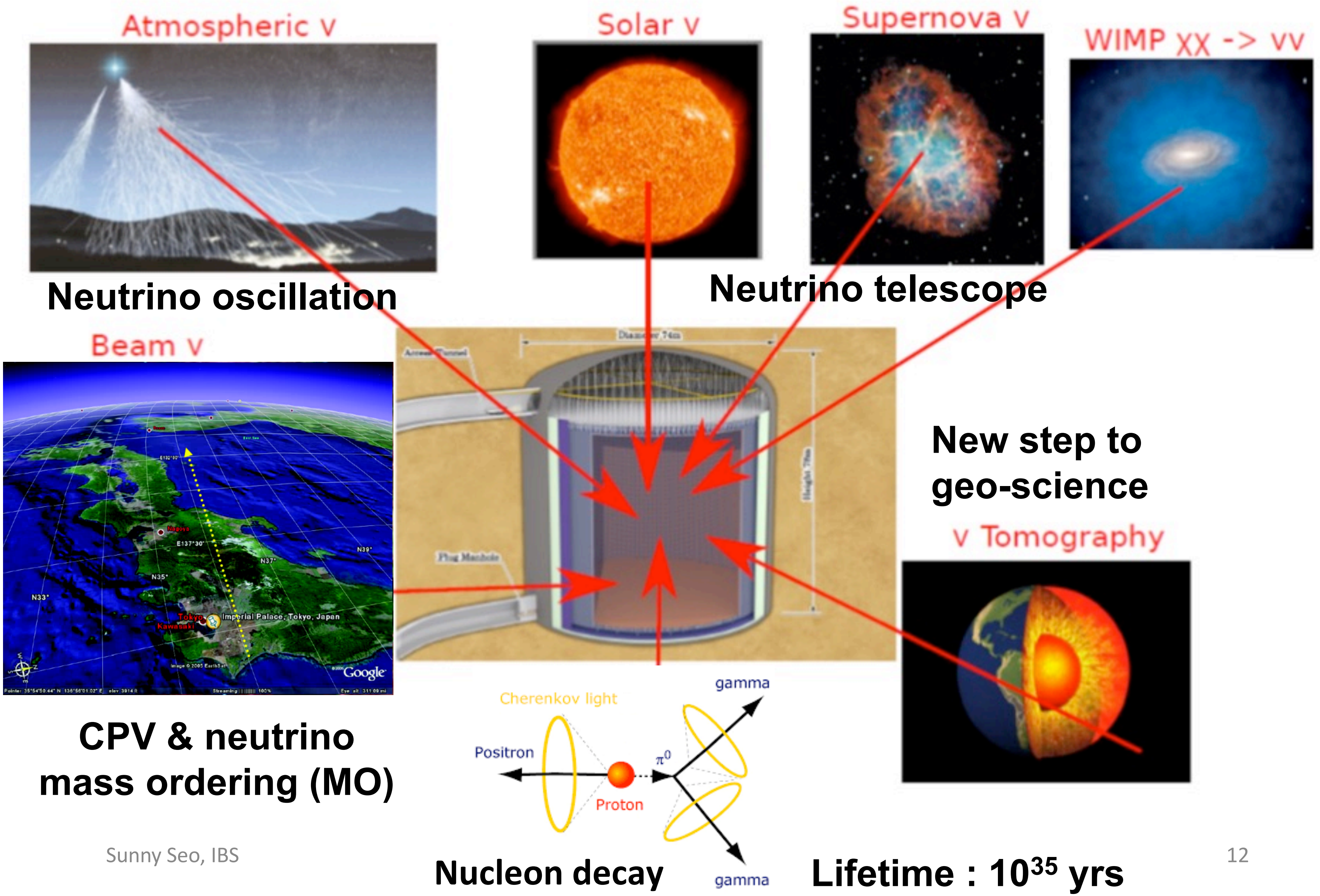
A구간 진입시 종단면도



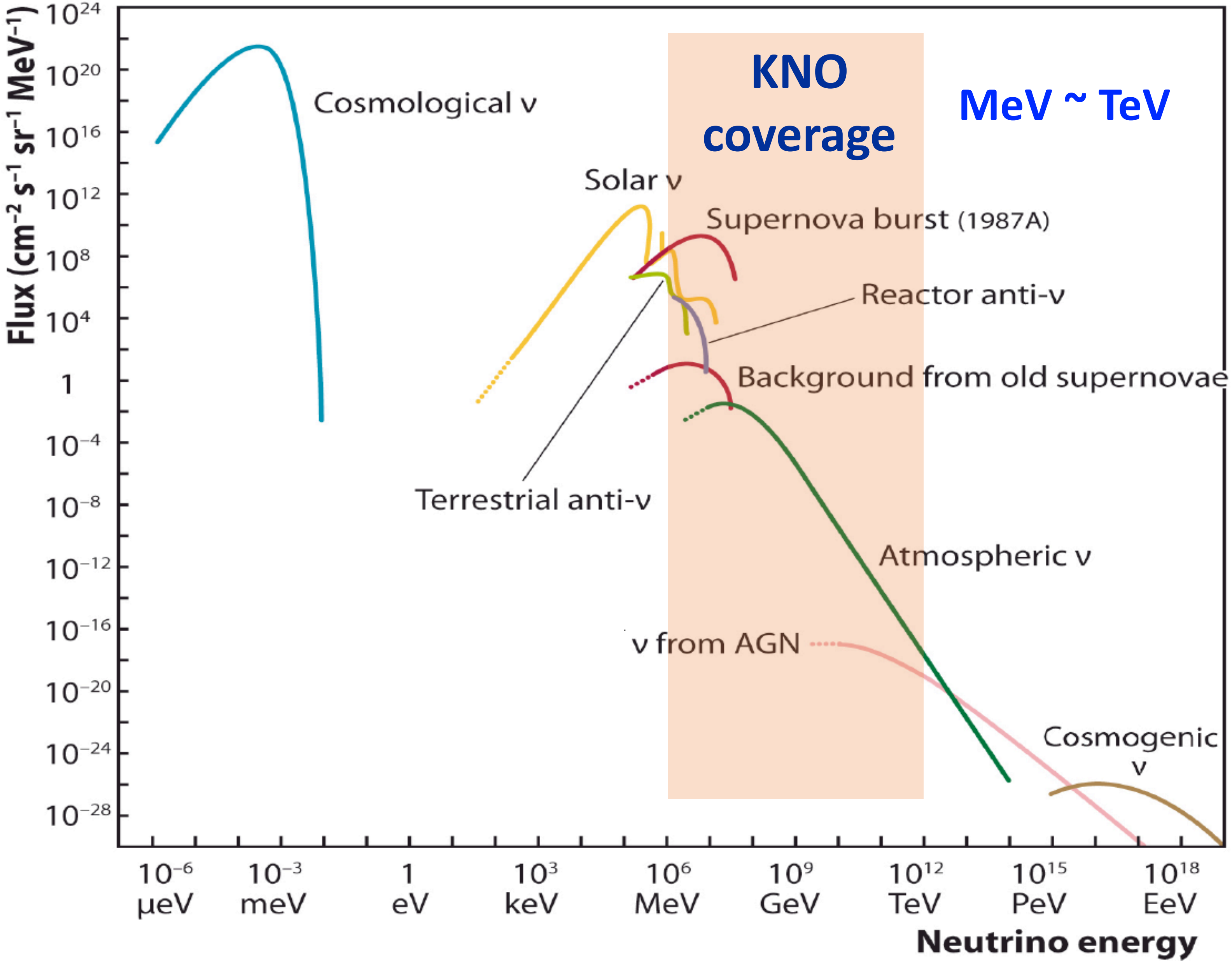


암반등급	비저항(Ω-m)
I	2,500이상
II	1,500-2,500
III	1,000-1,500
IV	500-1,000
V	500이하
M	기계굴착

Broad Physics Program

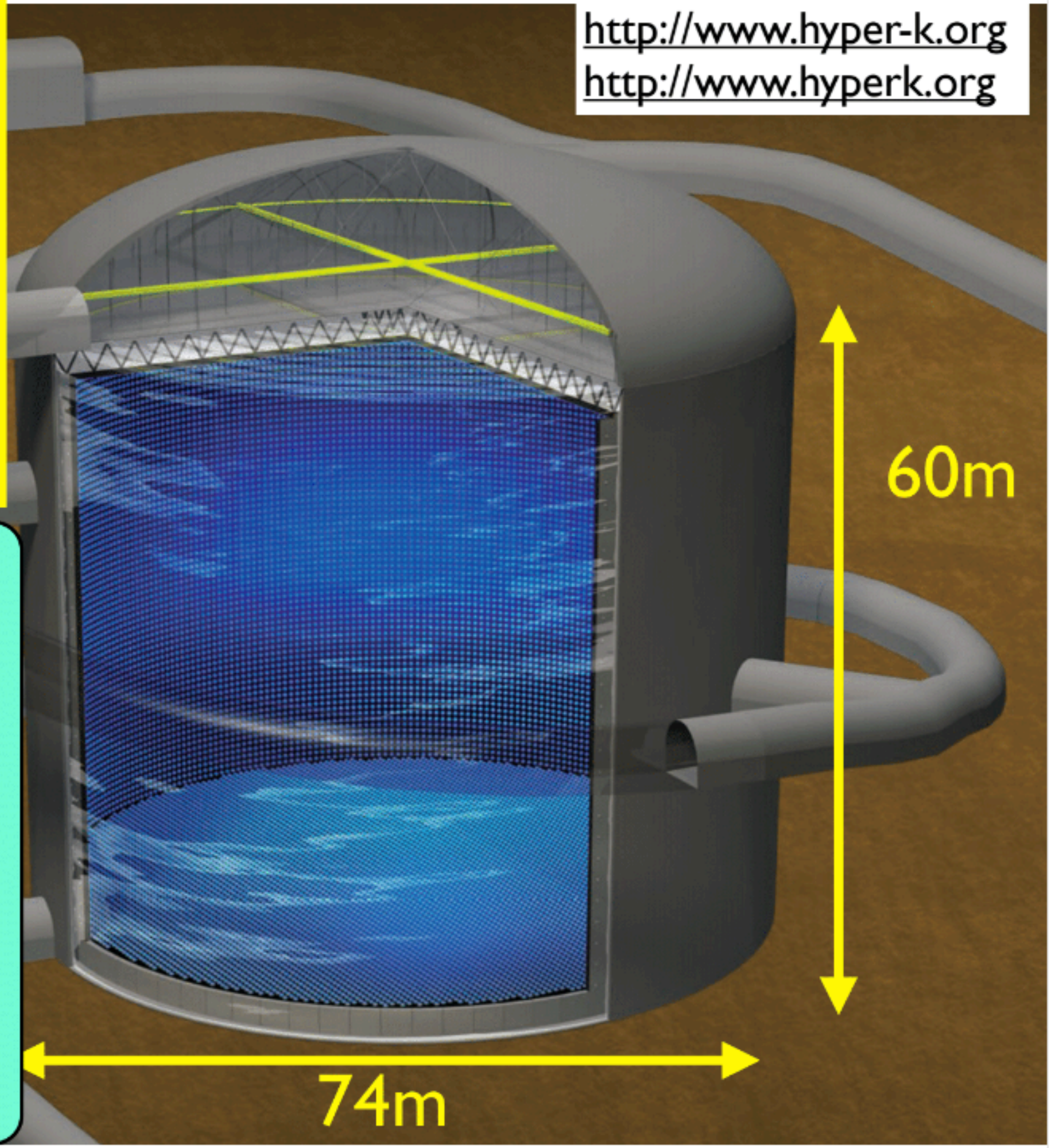


Neutrino Sources & Fluxes



The Hyper-Kamiokande detector

superb capabilities for a broad area of science, proven feasibility



Optimized for cost and quick start

Total volume: 260kton per tank

Fiducial volume: 190kton per tank

(~×10 of Super-K per tank)

Start with one tank (funding request)

40% coverage with new sensor

×2 photon sensitivity

~40,000 50cm PMTs for inner det.

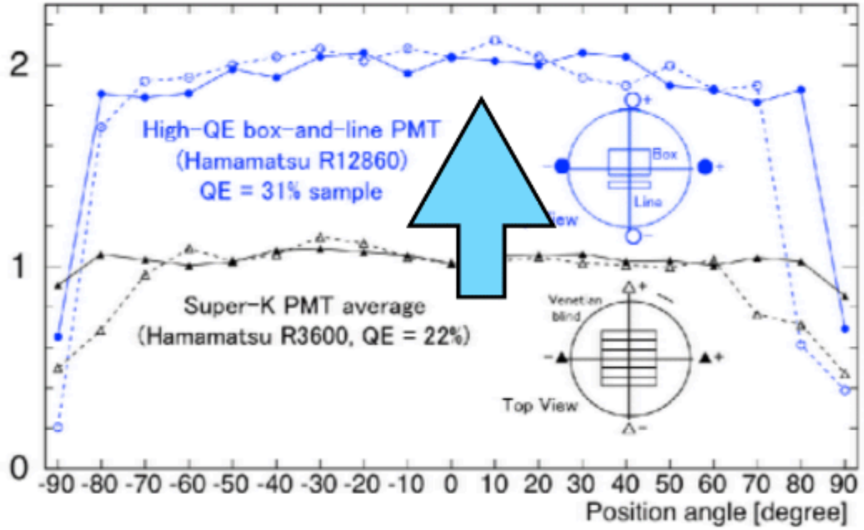
~~~6,700 20cm~~ PMTs for outer det.

~15k 3 inch PMTs for OD (cheaper, less dark rate)
~~~

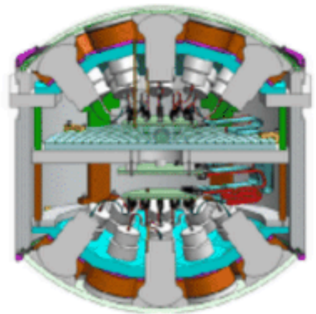
Enabling technology: new photosensors

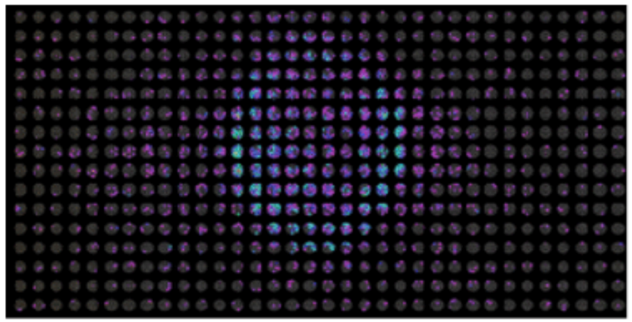
HPK R12860

50cm



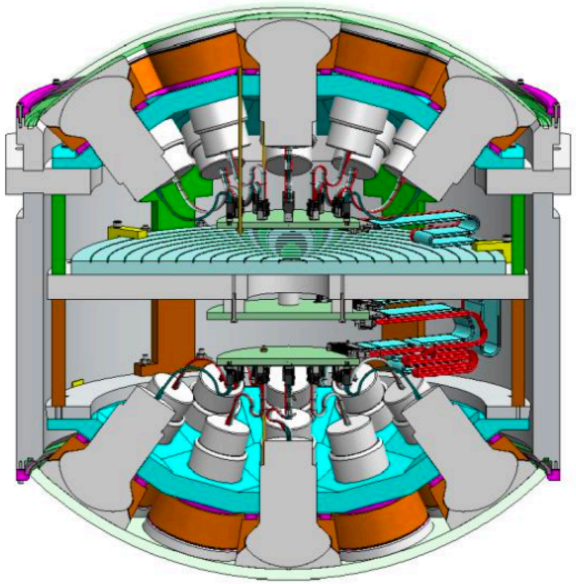
- Better performance than SK-PMT (R3600)
  - Photon detection efficiency ×2
  - Timing resolution ×2
  - Better pressure tolerance
- Intensive R&D for "multi-PMT" option by an international collaboration
  - Module of small PMTs in an enclosure





Multi-PMT

International Effort in Hyper-K



- Collection of small size (3 inch) PMTs in a single enclosure
- Adapted from KM3NET's original mPMT
- **Pro:**
  --better timing properties
  --better directionality
  --better pressure tolerance
  --better vertex reconstruction near wall
  → fiducial volume increase
- **Con:**
  larger number of channels
  → more expensive and power consumption

KNO Detector Options

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

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

→ You have lots of opportunities in T2HKK/KNO !

Some R&D activities are on-going.

Why Leptonic CPV ?

1. Which flavor symmetry model ?

Understanding pattern of ν mixing

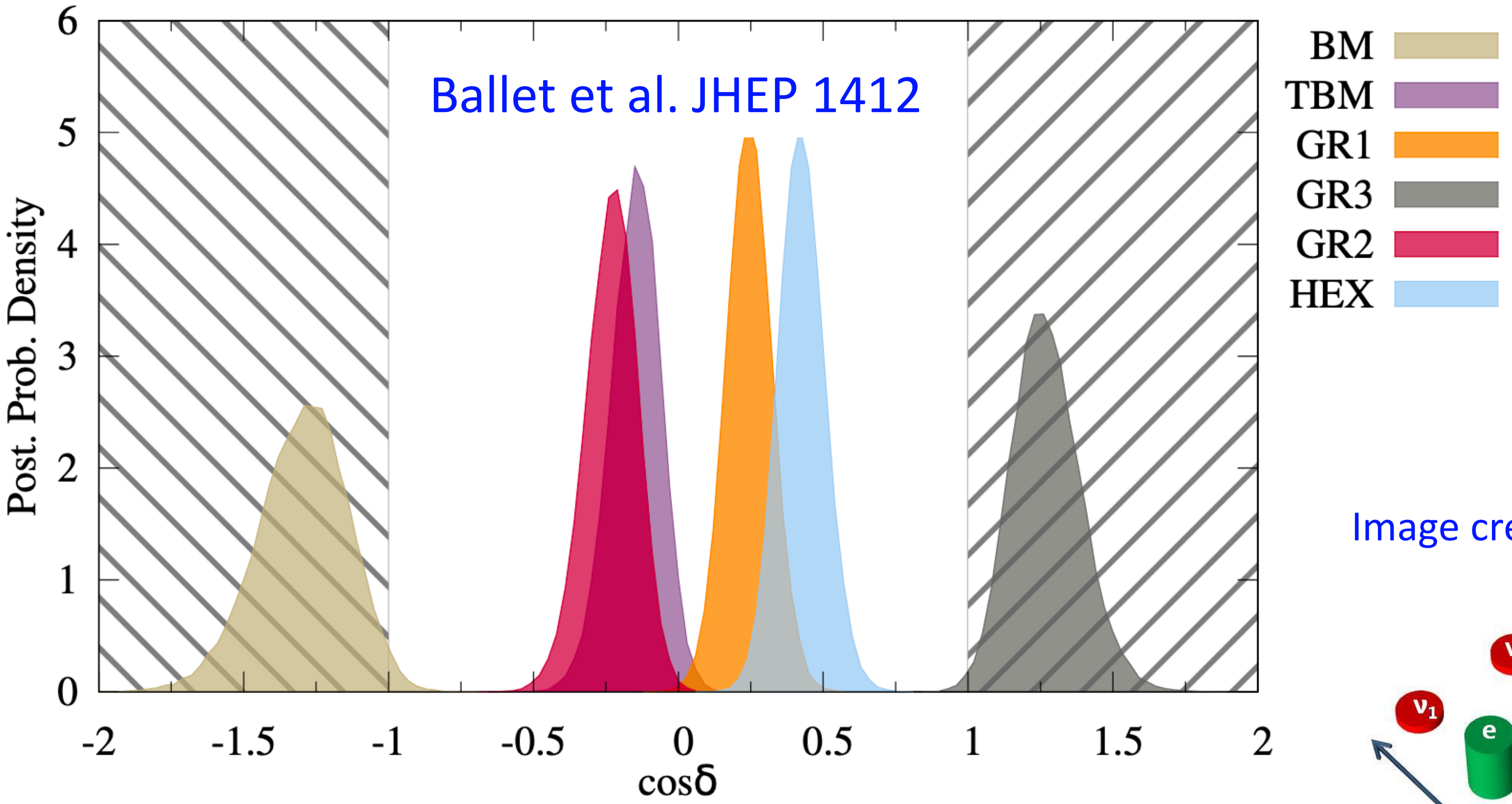
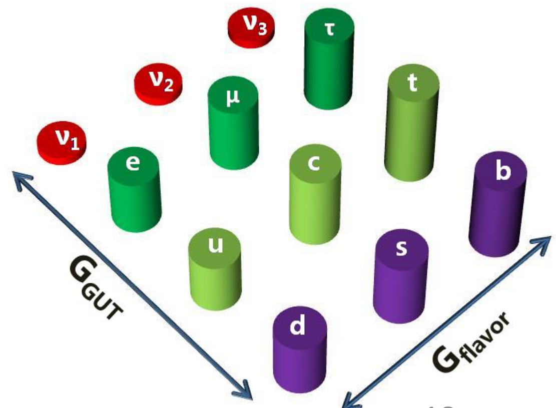


Image credit: T. Ohlsson @KTH

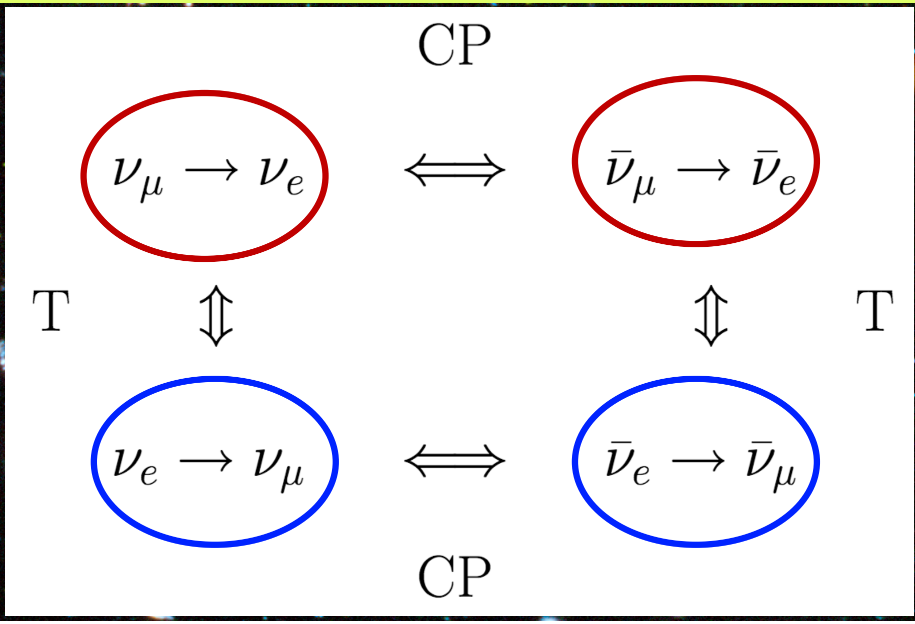


Why CPV in Lepton Sector?

- 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 <u>**hint**</u> of maximal CPV in lepton sector.
  (~ 2sigma @T2K, NOvA)



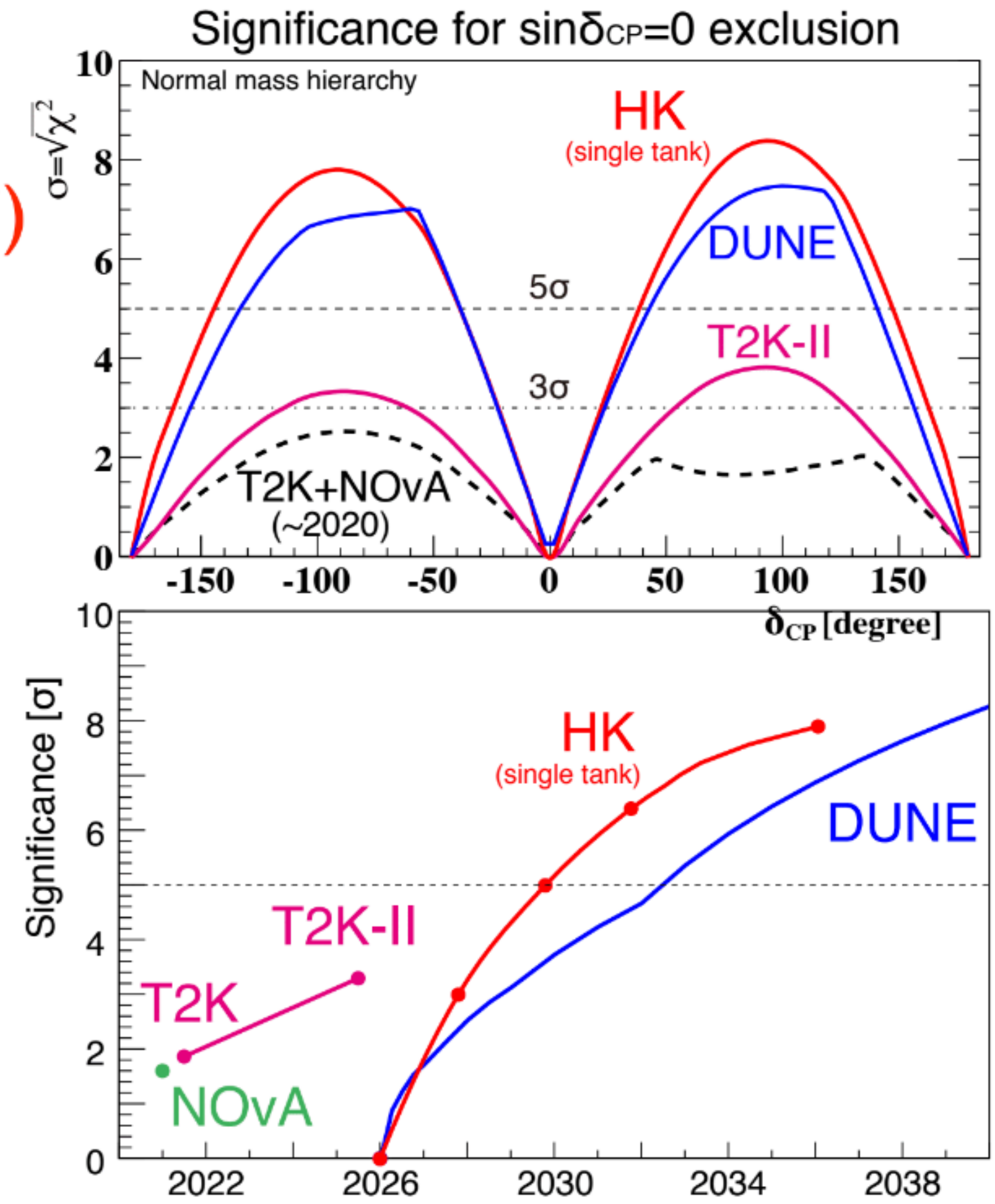
$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$$

Expected sensitivity: CP violation

- Exclusion of $\sin\delta_{CP}$=0
  - ~8σ(6σ) for δ=±90°(±45°)
  - >3σ(>5σ) significance for ~76%(58%) of δ_{CP} space
- δ_{CP} resolution:
  - 22° for δ_{CP}=±90°
  - 7° for δ_{CP}=0°or 180°

Seamless program of Japan-based experiments for study of CP-violation

T2K→T2K-II→HK



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]

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: →

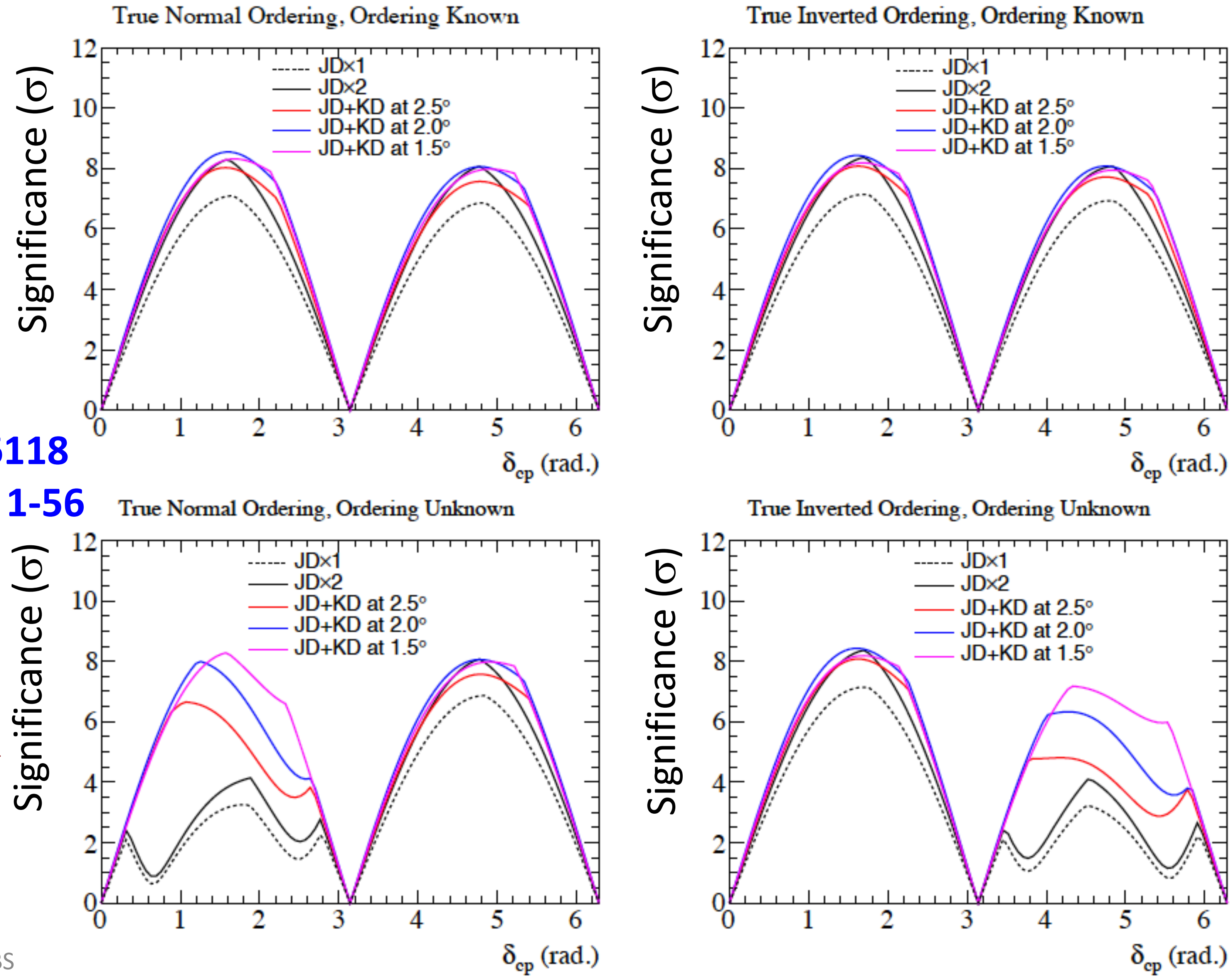
$$|\Delta m^2_{32}| = 2.5\times10^{-3}\ \mathrm{eV}$$
$$\sin^2\theta_{23} = 0.5$$
$$\sin^2 2\theta_{13} = 0.085$$
$$\Delta m^2_{21} = 7.53\times10^{-5}\ \mathrm{eV}$$
$$\sin^2\theta_{12} = 0.304$$
$$\delta_{cp} = 0, \pi/2, \pi, 3\pi/2$$

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

δ_{CP} Sensitivities

Known MO

Unknown MO

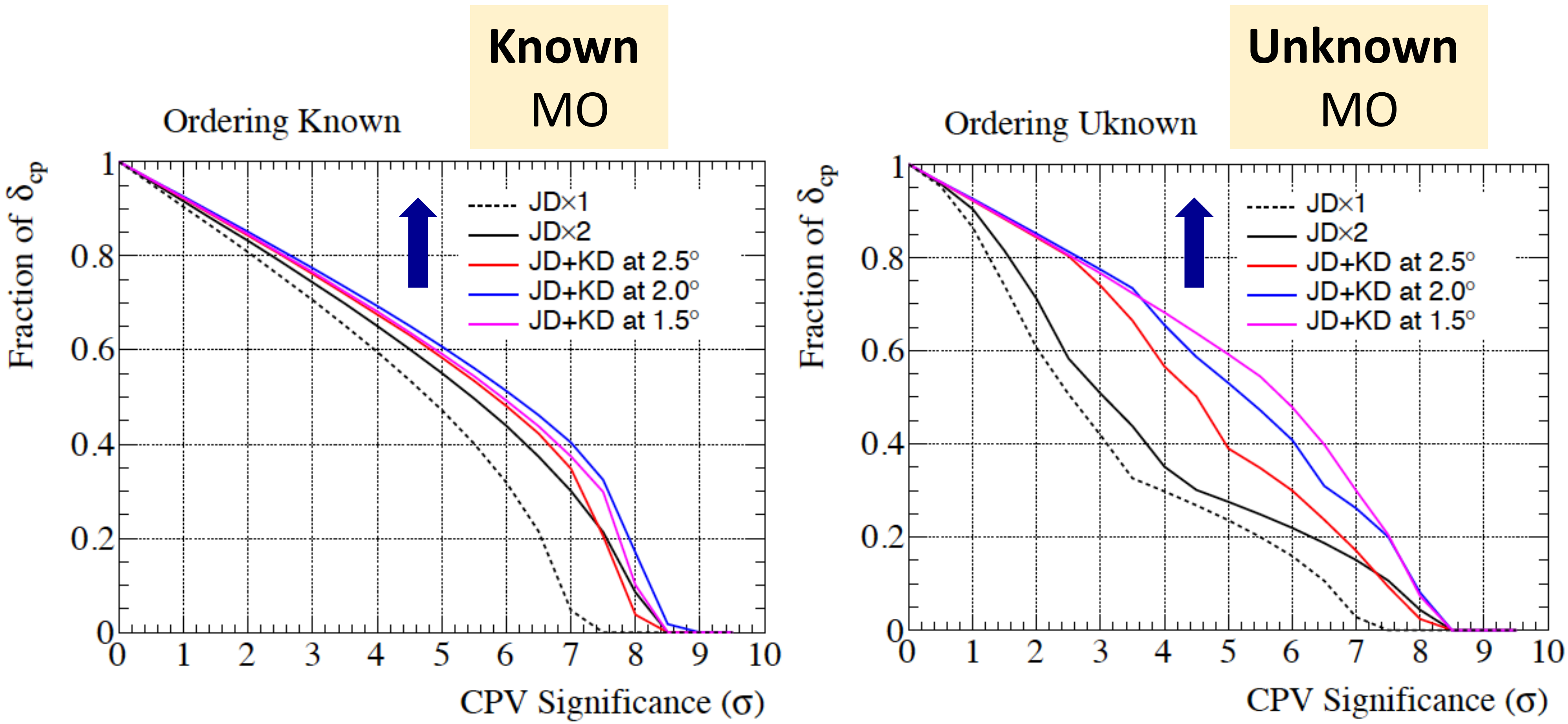


arXiv:1611.06118

PTEP 2018, 6, 1-56

Sunny Seo, IBS

Fraction of δ_{CP}

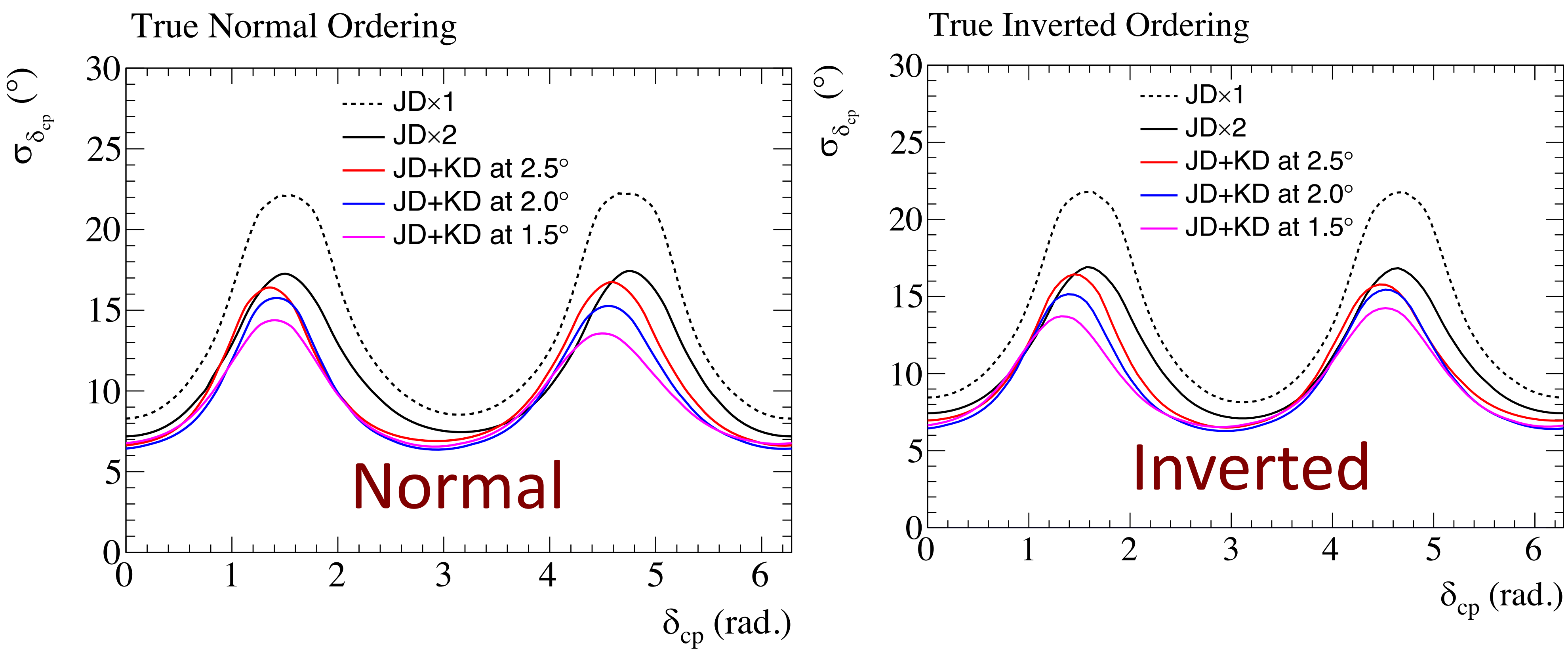


arXiv:1611.06118
PTEP 2018, 6, 1-56

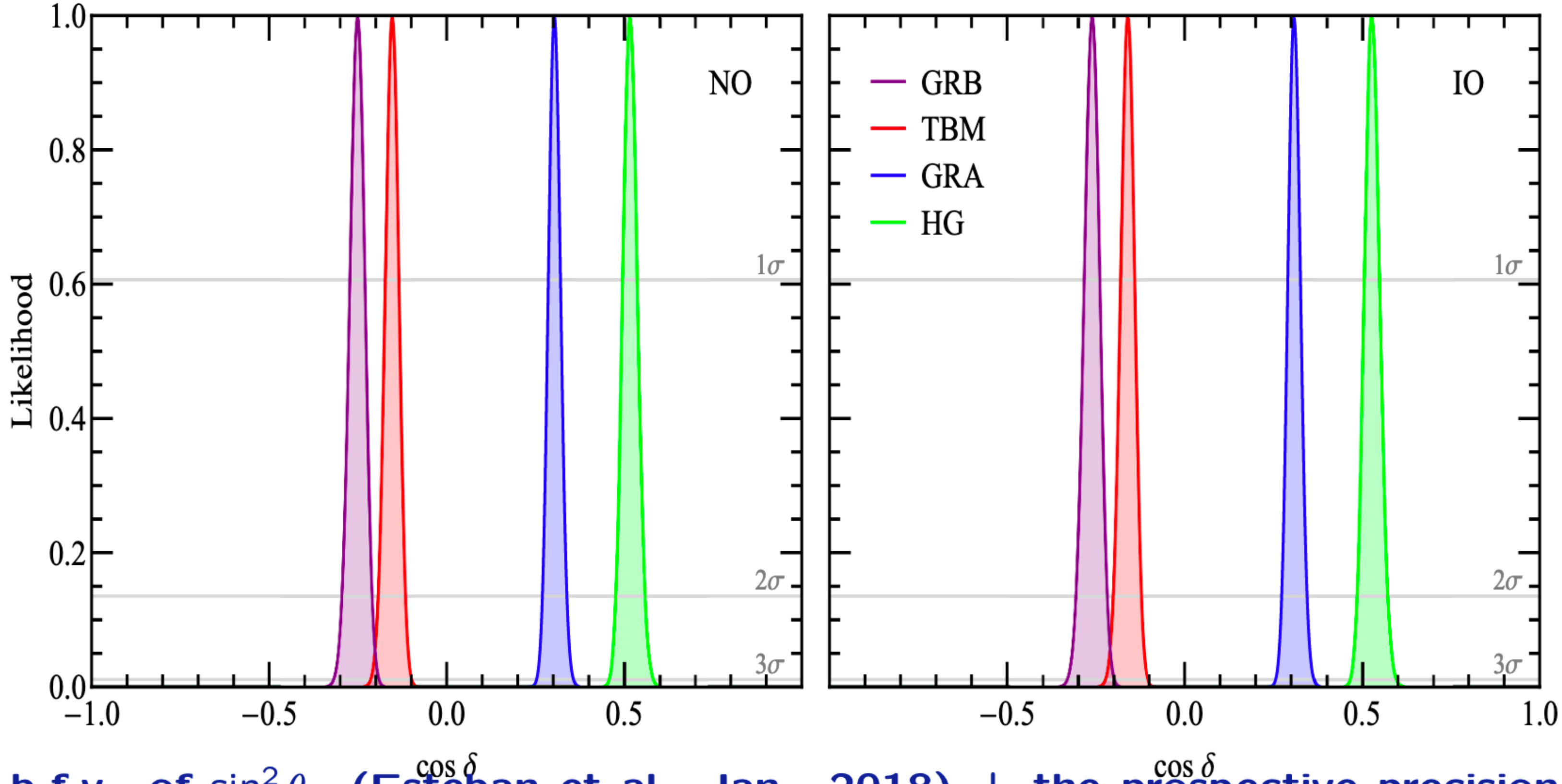
Note: LBL sensitivity study was also independently done using GLoBES in PRD 96,033003 (2017).

δ_{CP} Precision Sensitivities

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



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),**

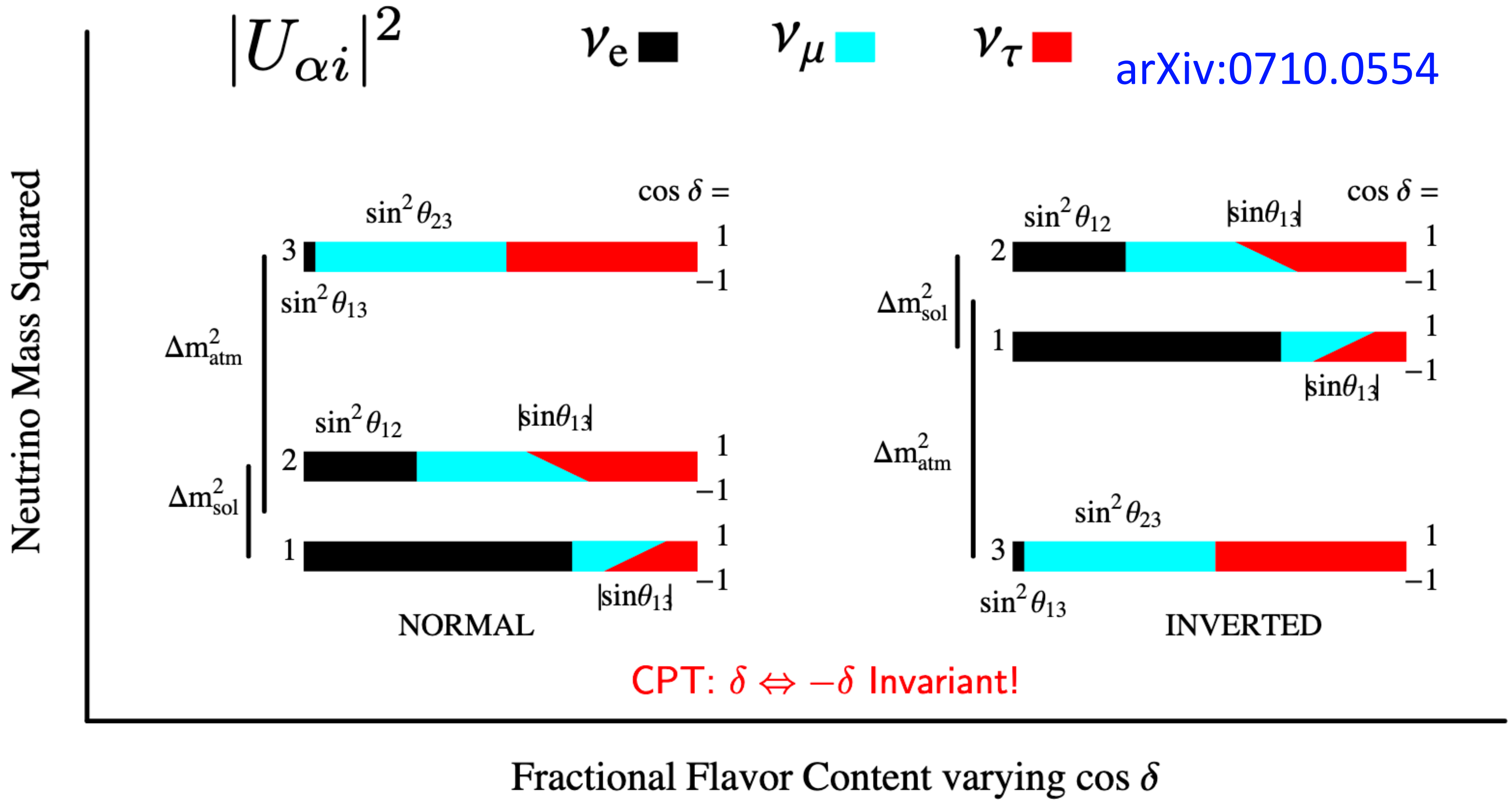
4.8(IO)-5.2(NO)% → $\delta(\sin^2\theta_{23}) = 3\%$ **(T2HK, DUNE; T2K+NOνA(?)).**

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

Prospective (useful/requested) precision:

S. Petcov talk @ICHEP2018

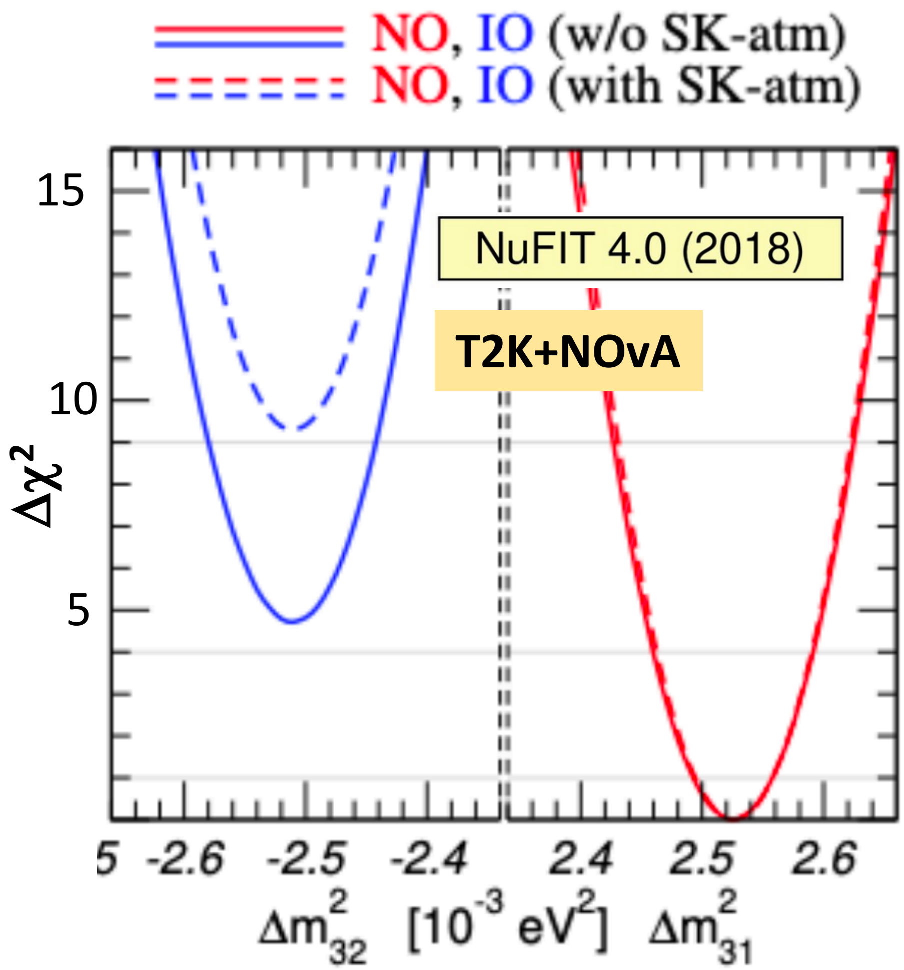
Why ν Mass Ordering (MO) ?

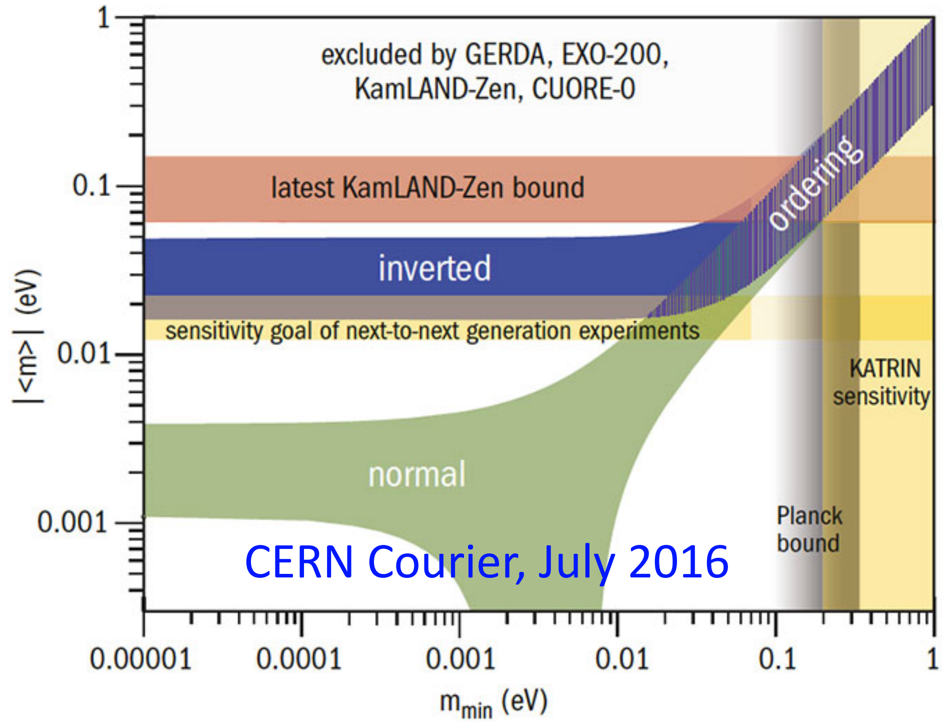


1. Important input to CPV measurement

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

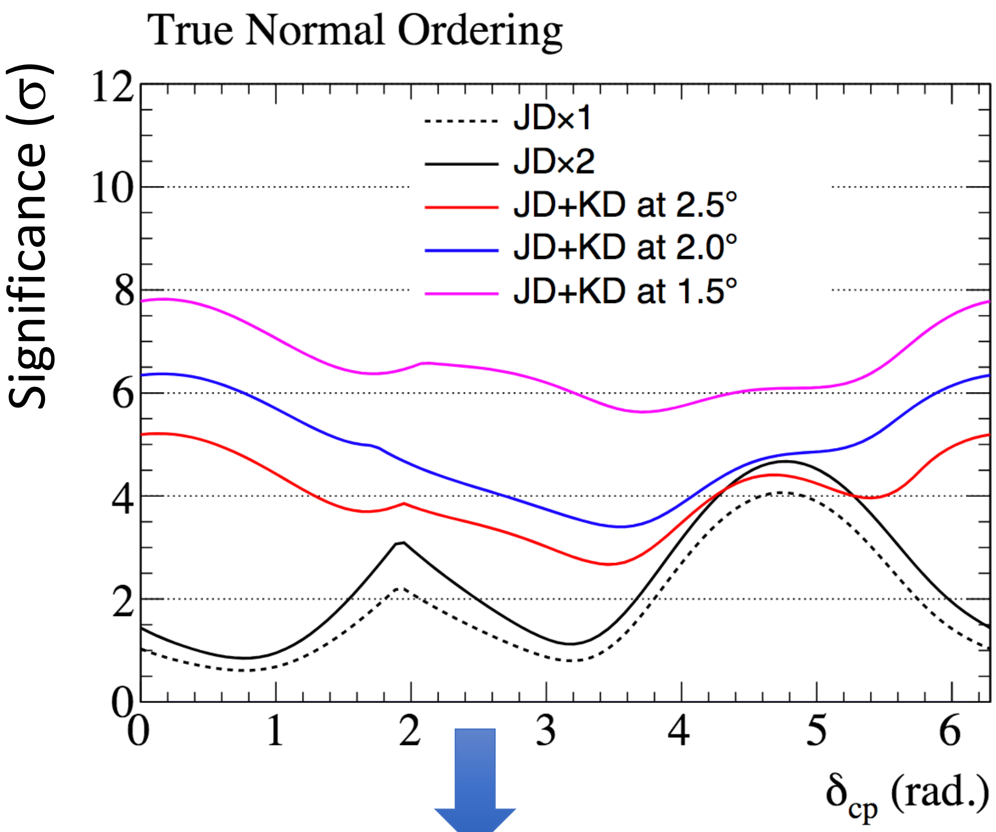
Front. Astron. Space Sci., 09 October 2018

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

Mass Ordering Sensitivities

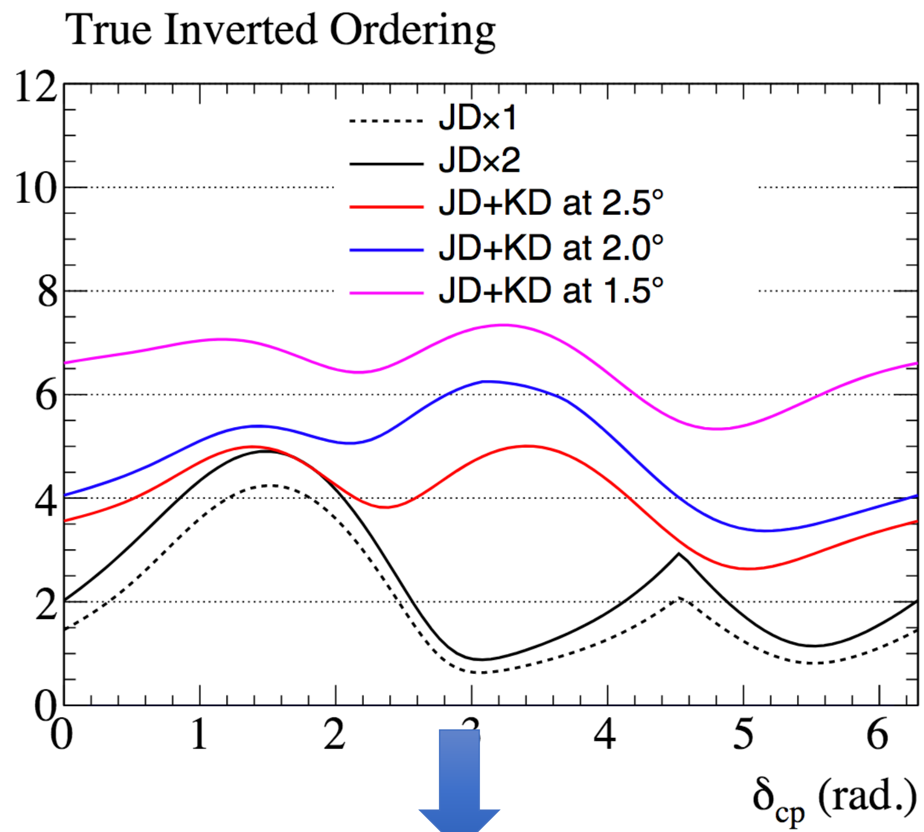
arXiv:1611.06118
PTEP 2018, 6, 1-56

Normal



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)

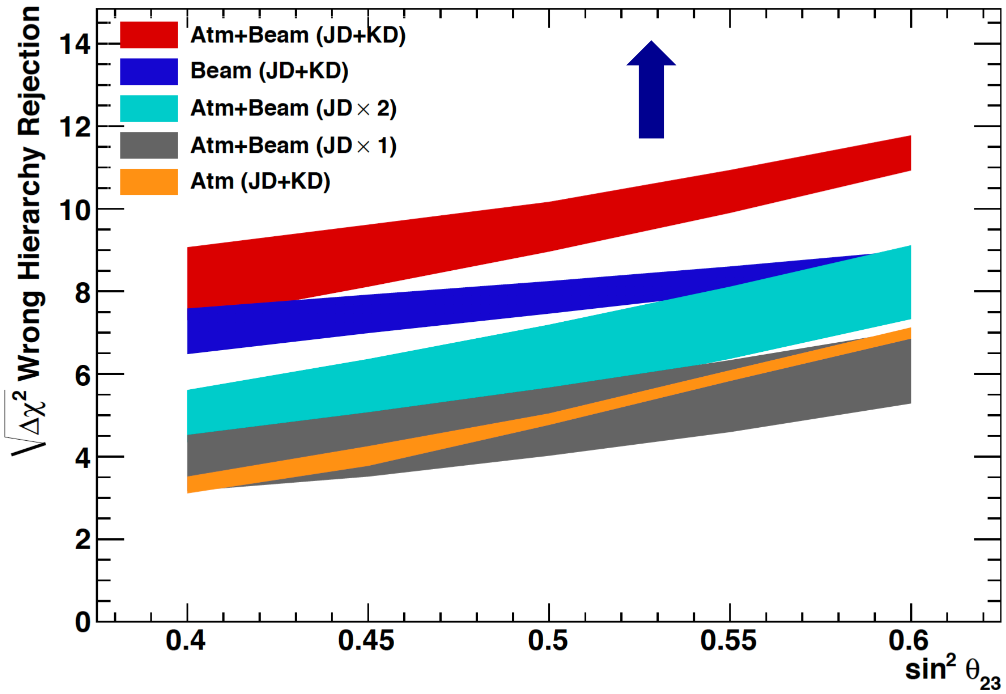
Inverted

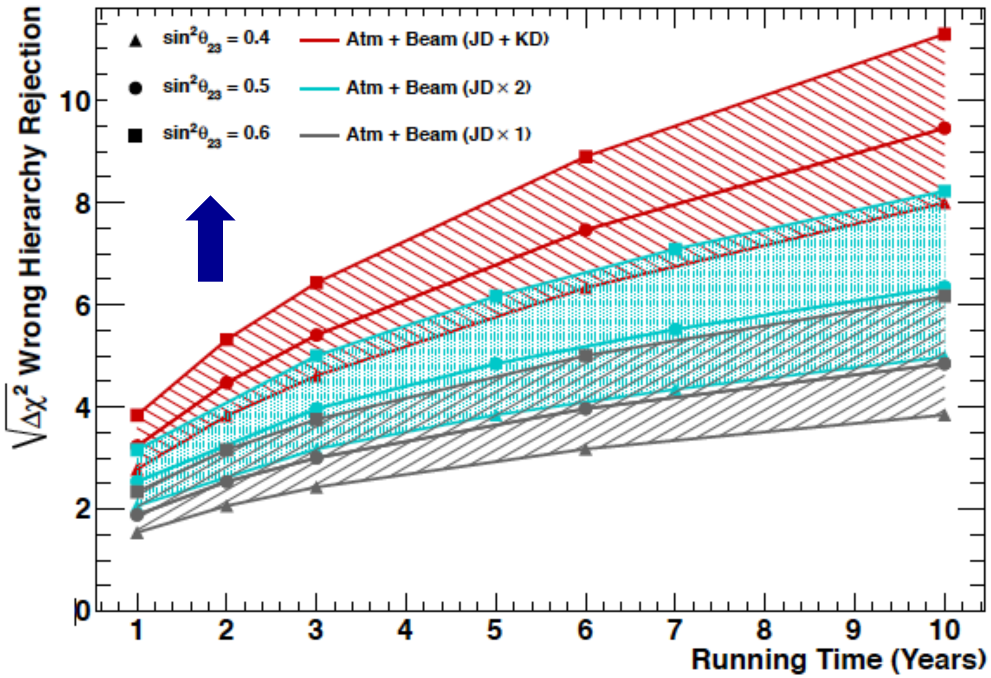


JD+KD 1.5°: 5.5 ~ 7 σ for all δ_{CP}
JD x2 : 1 ~ 5 σ for all δ_{CP}
(< 3 σ for most cases)

Beam + Atm. Data

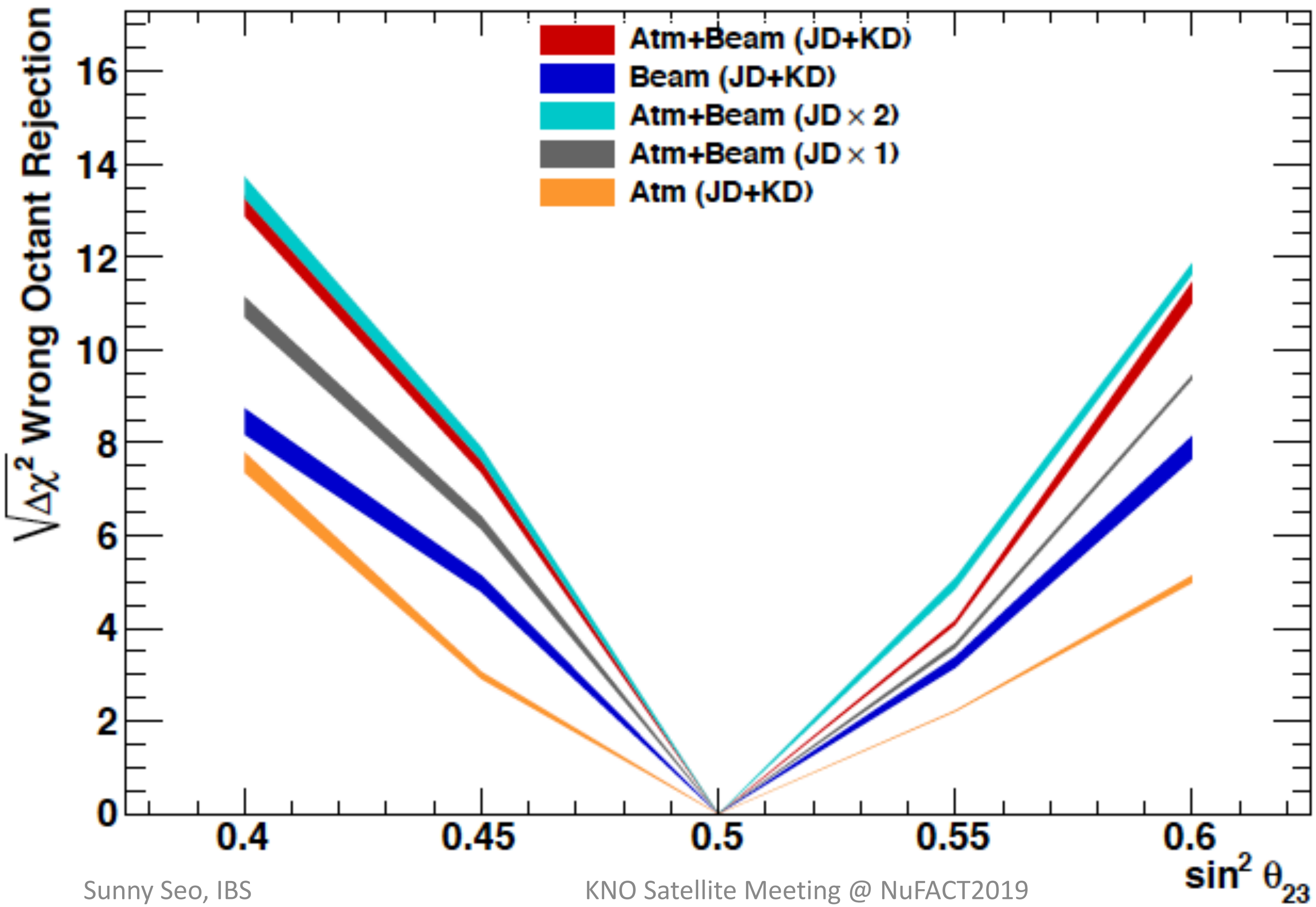
Mass ordering sensitivity





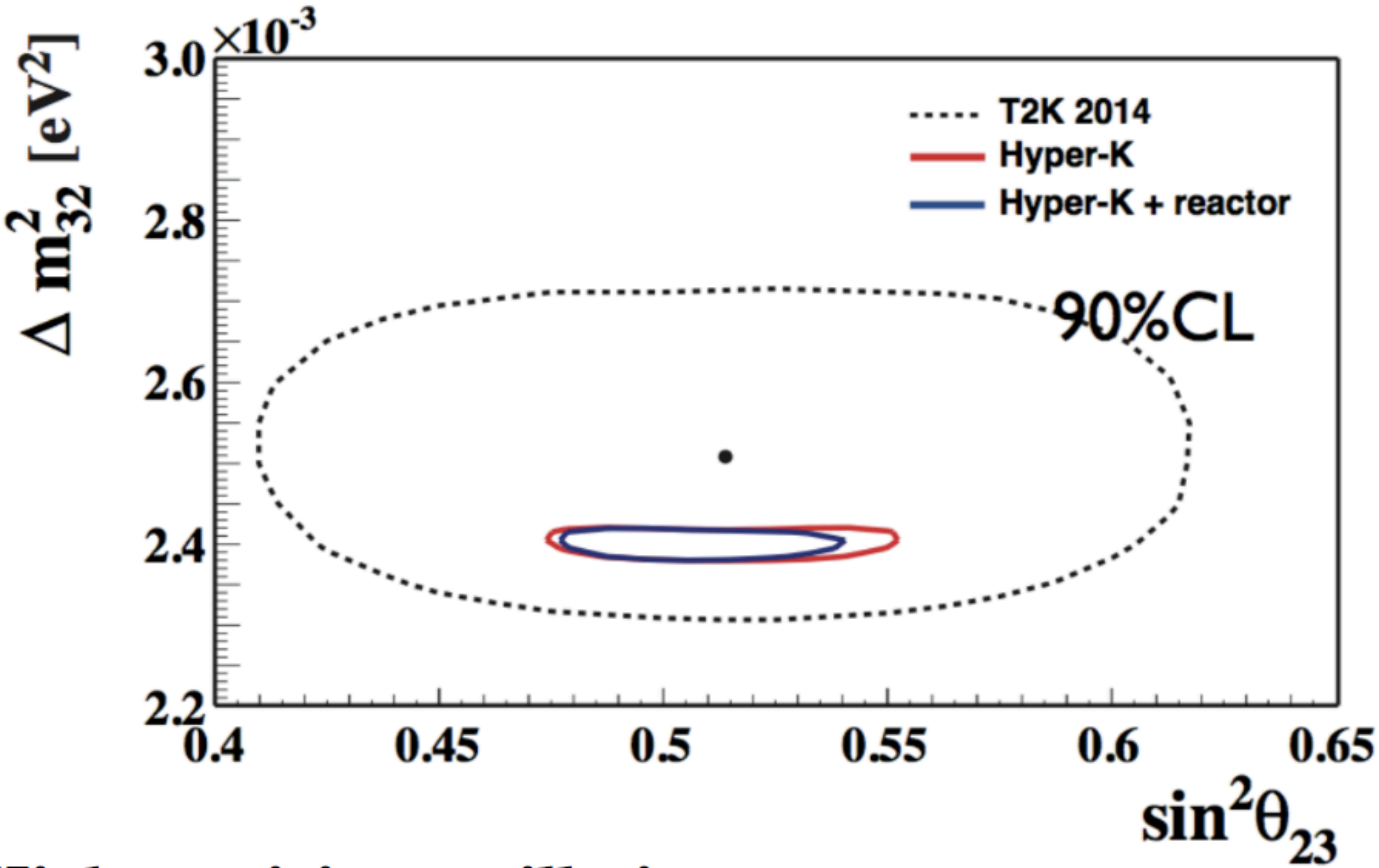
Octant Sensitivity: Beam + Atm.

θ_{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 $\sin^2\theta_{23}=0.50$)

$\delta(\Delta m^2_{32}) \sim 1.4\times10^{-5}\text{eV}^2$

~0.6%

15

Non-standard ν Interaction Sensitivity

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

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

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

arXiv:1611.06118

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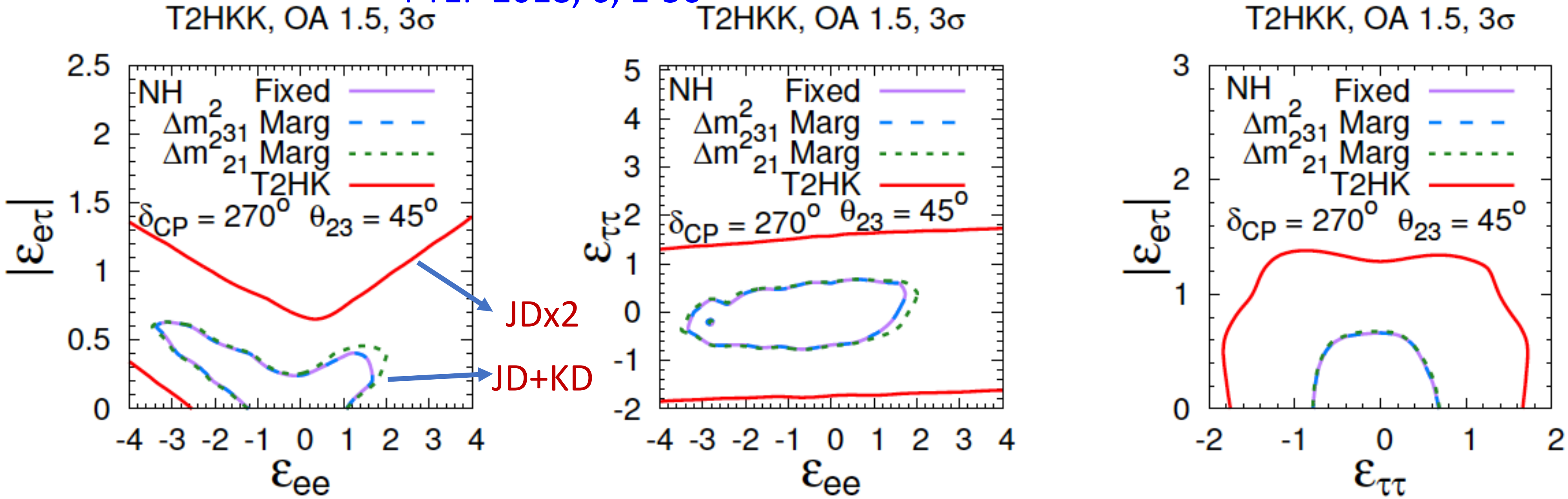


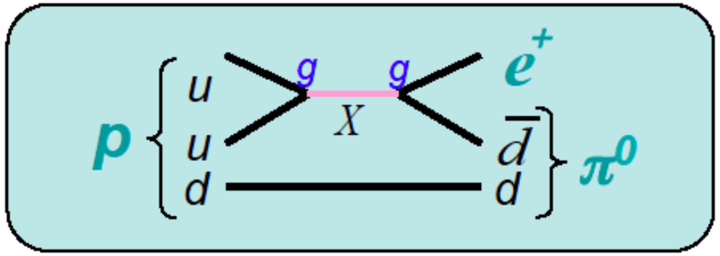
D. Marfatia@ICHEP2018: arXiv:1612.01443

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

Proton Decay Search

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

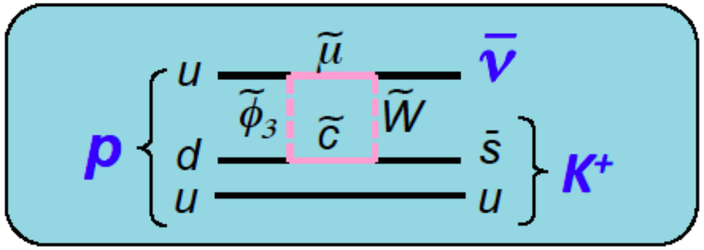
Mediated by gauge bosons



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

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

SUSY mediated

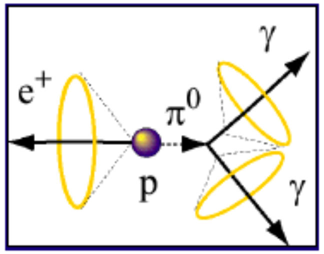


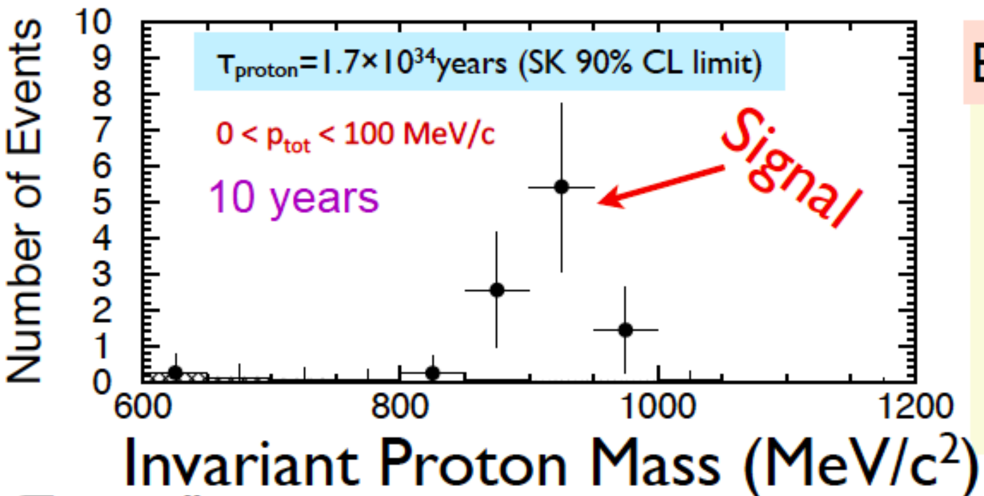
$p \to \nu K^+$

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

- Need broad searches including other possible modes

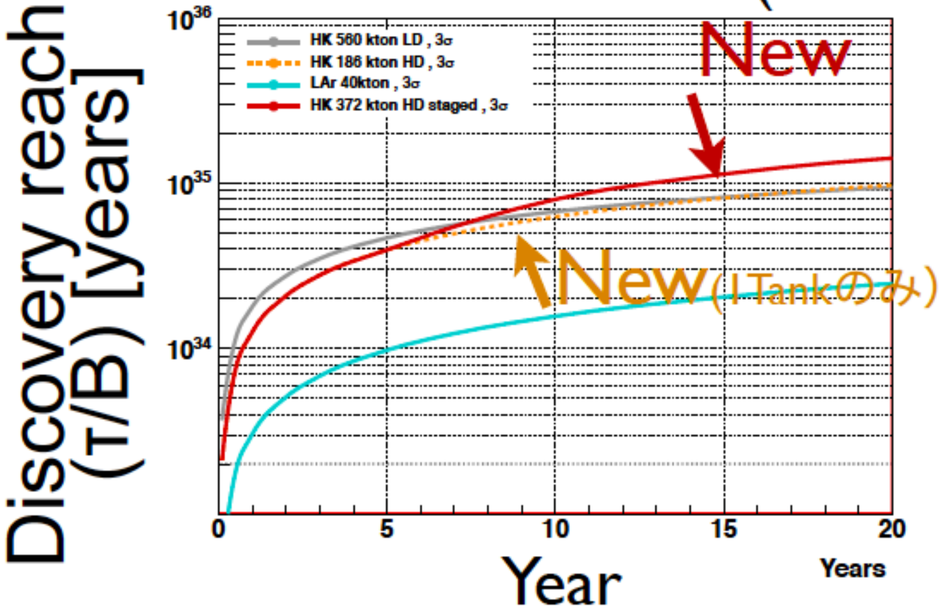
$p \rightarrow e^+\pi^0$ search in Hyper-K





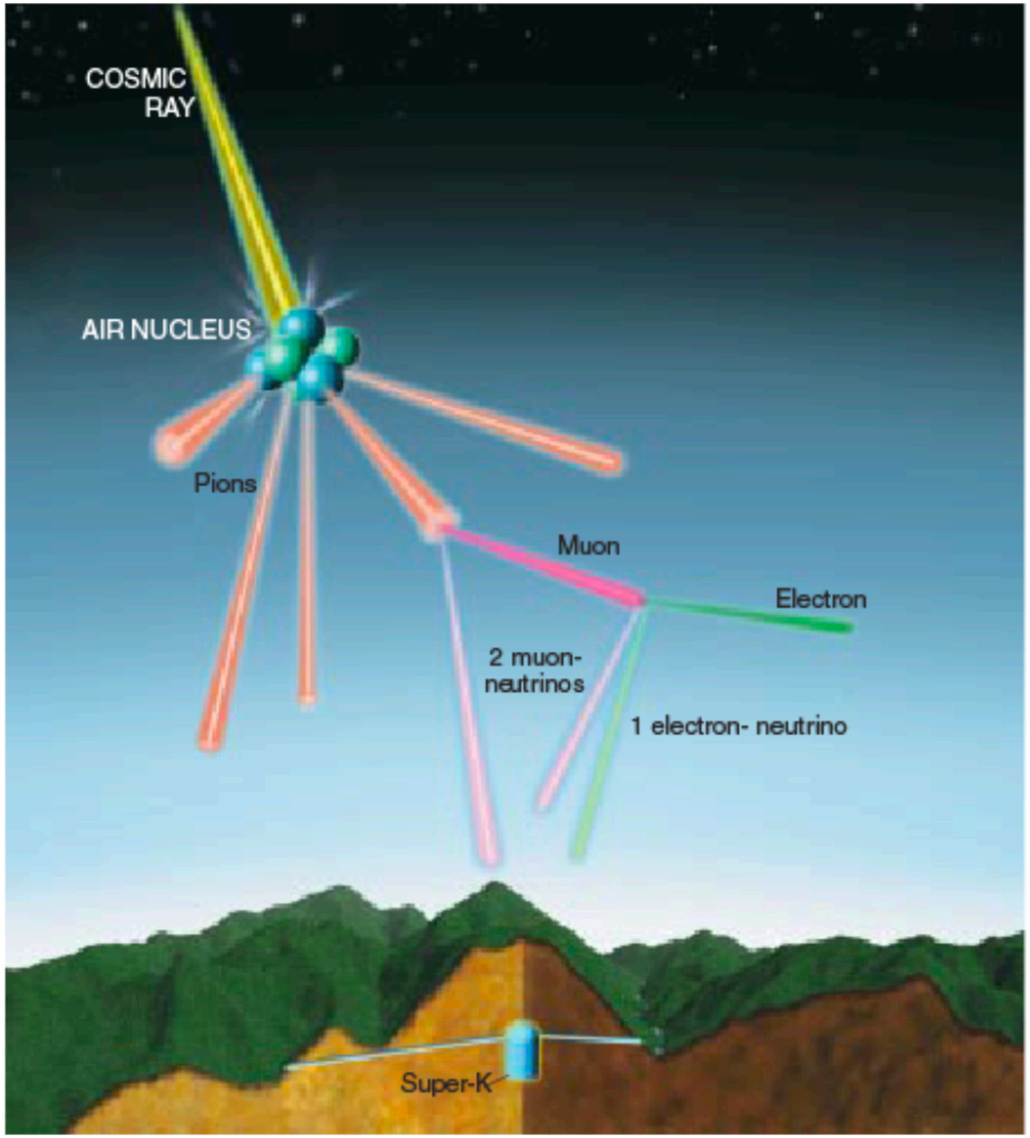
BG free by high-sensitive PMTs

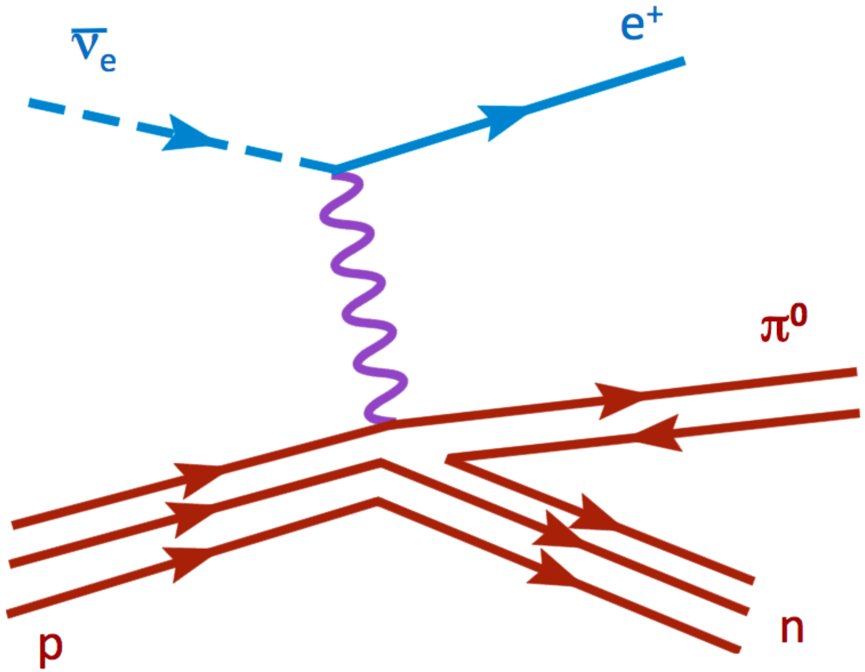
For the case of
τ_{proton}= 1.4×10^{34}years
(Super-K limit)
~9σ discovery@HK



- Only realistic proposal to reach to 10^{35} years@3σ

Background: Atmospheric Neutrinos

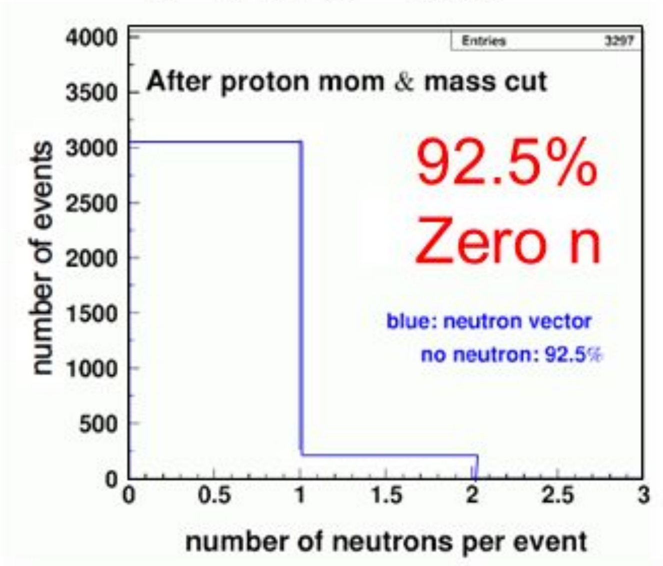




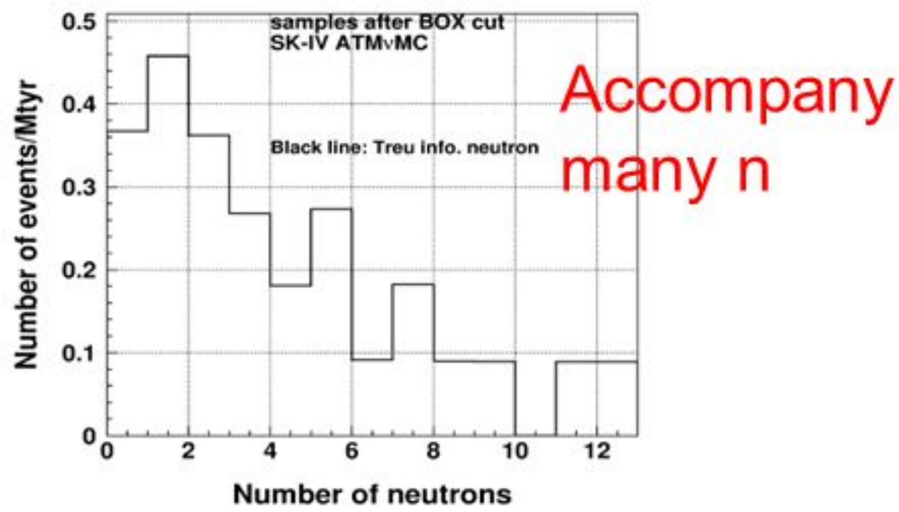
Improvement for Proton decay **w/ Gd**

Neutron multiplicity for

$P \rightarrow e^+\pi^0$ MC



Atmospheric ν BG



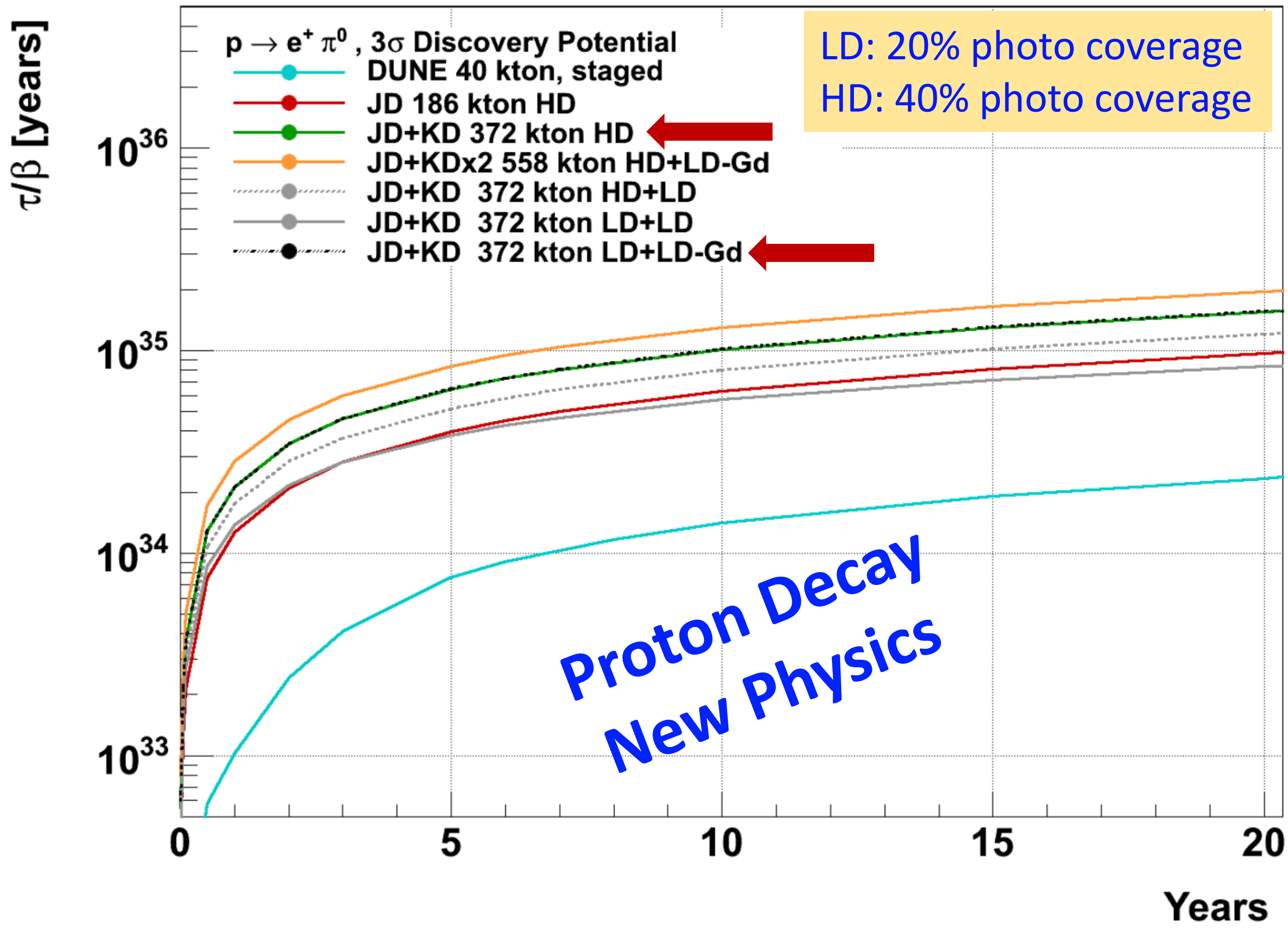
<u>If one proton decay event is observed at Super-K after 10 years</u>

Current background level: 0.58 events/10 years

Background with neutron anti-tag: 0.098 events/10 years

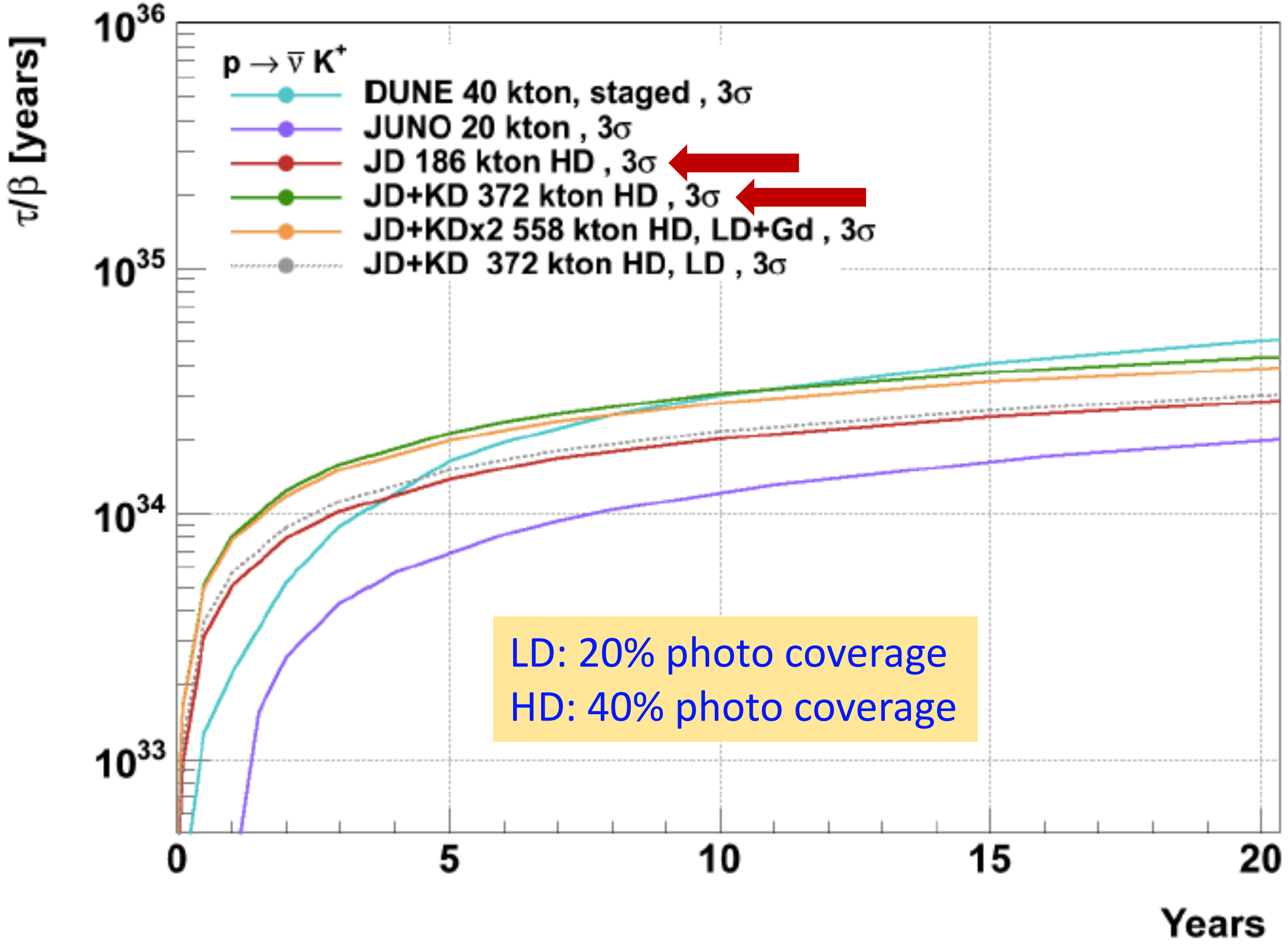
Background probability will be decreased from 44% to 9%.

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



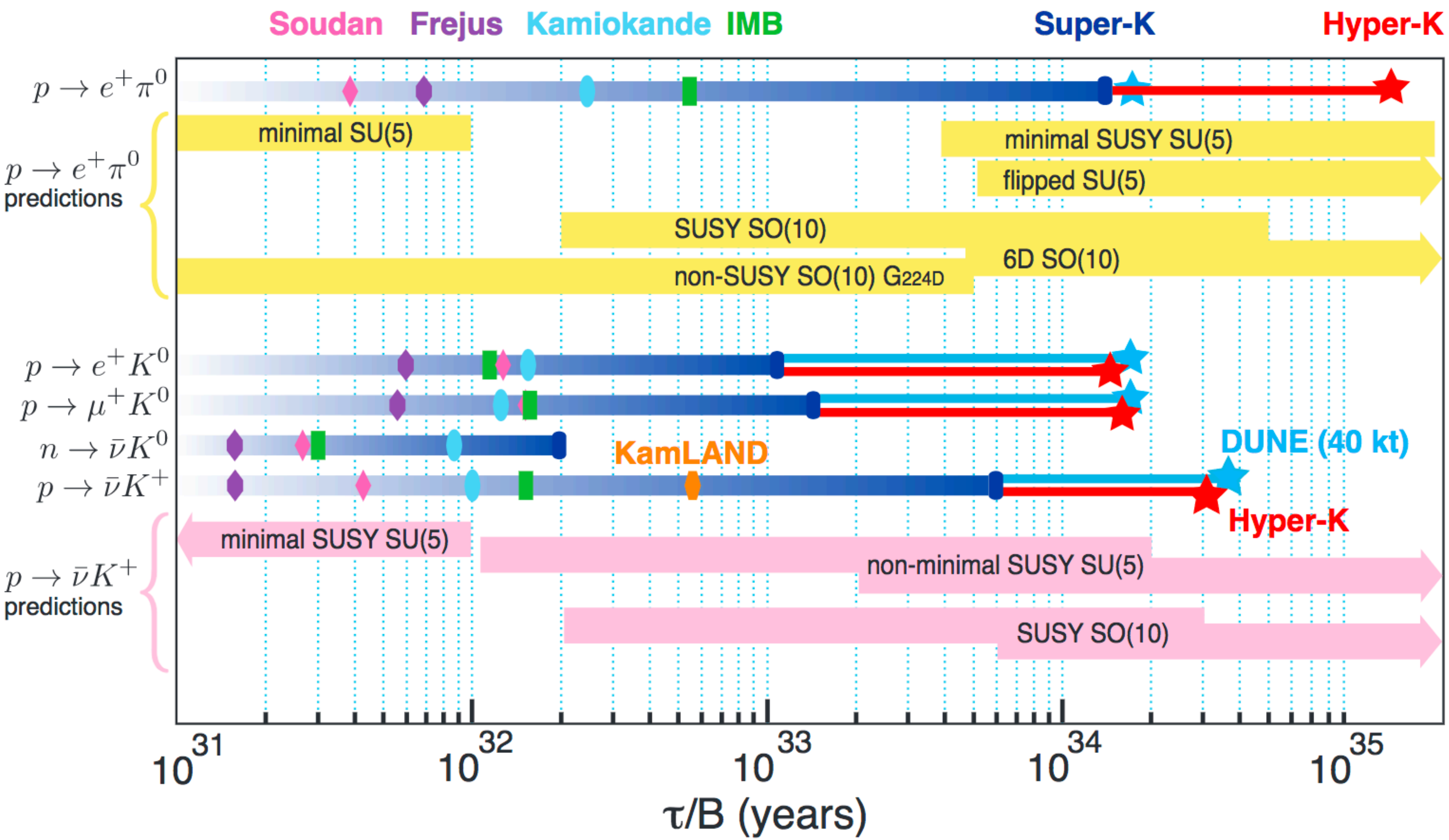
- This mode's efficiency does not depend much on cathode coverage above 20%
- Background reduction though is improved by Gd loading

Discovery Potential for p -> νK⁺



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

Proton Decay Limits & Sensitivities



Conclusion

- ❑ Excellent physics cases w/ different systematics.
  - Neutrino mass ordering determination
  - CPV, CP precision, CP coverage
  - Non-standard ν interaction
  - Solar/SN/SRN etc…

- ❑ Physics sensitivities are better w/ the KNO detector.

- ❑ World class discoveries are expected to be made.

CPV, MO, SN/SRN, proton decay (?) etc…

- ❑ Huge opportunities for you in KNO !