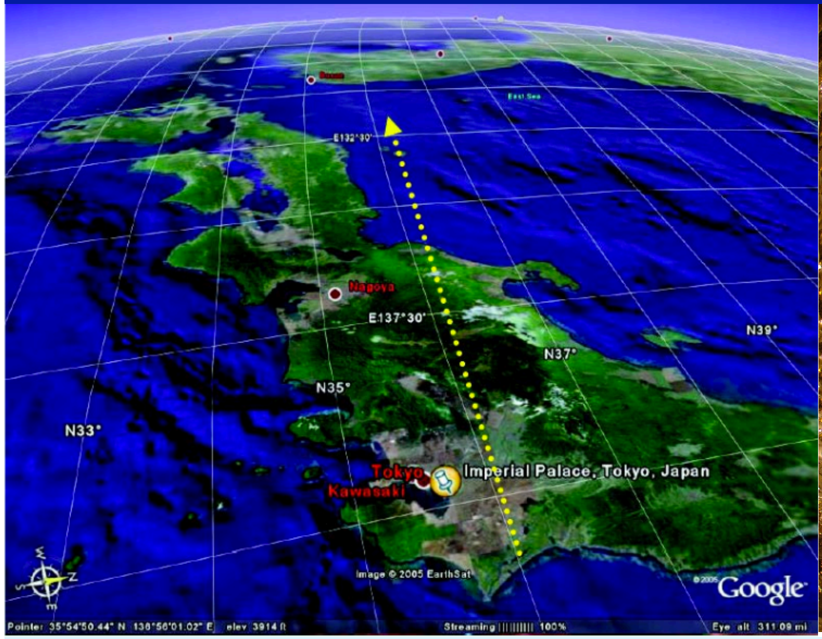
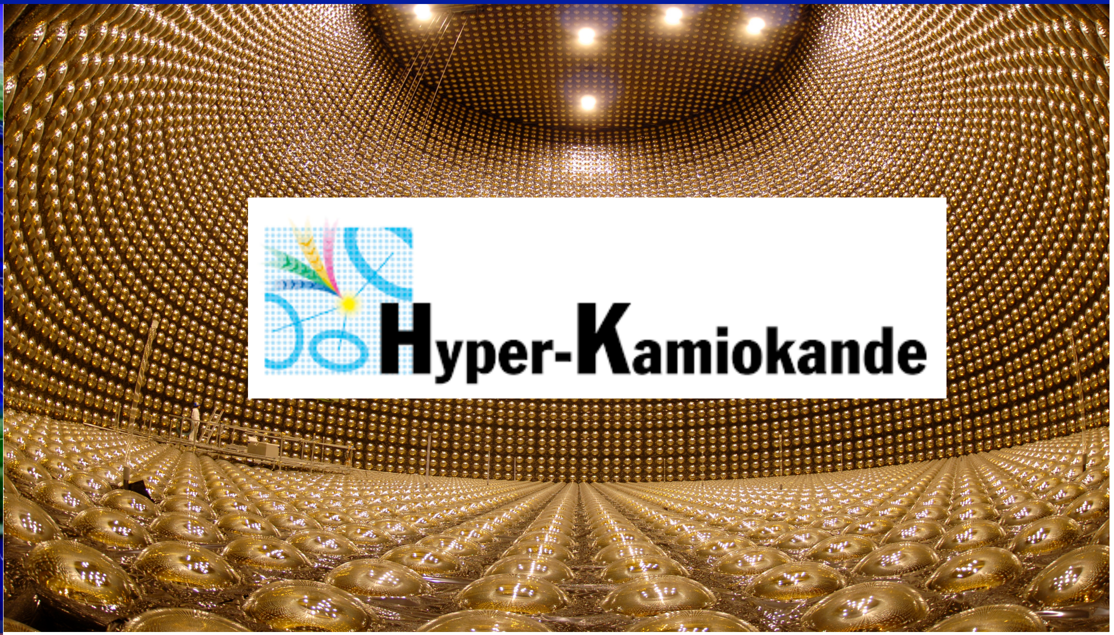
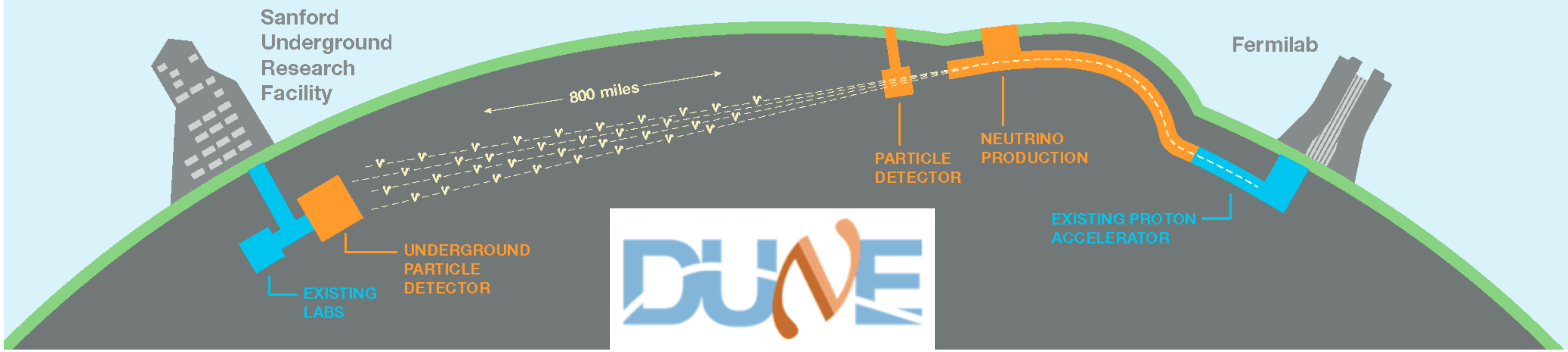
Future Long Baseline ν Experiments





Sunny (Seon-Hee) Seo
Seoul National Univ.



Neutrino Oscillation & PMNS Matrix

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \boxed{\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

- **P**ontecorvo
- **M**aki
- **N**akagawa
- **S**akaga

1962

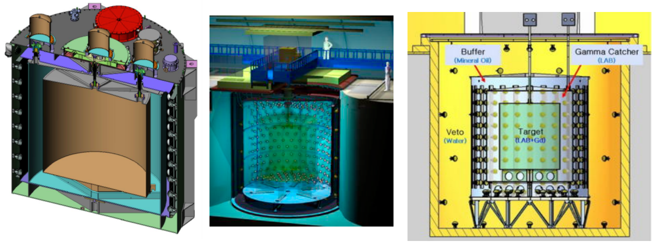
$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

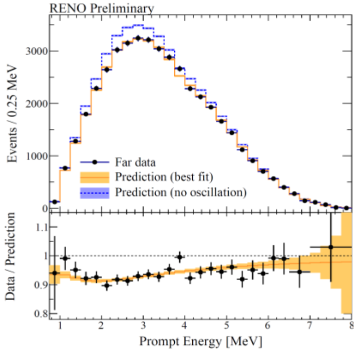
1998: θ_{23} = ~45°
Super-K, K2K

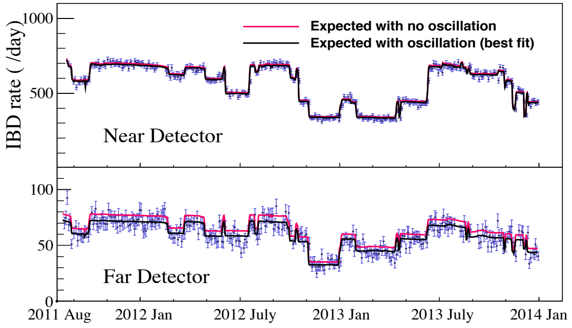
2012: $\theta_{13} \approx 9°$
Daya Bay, RENO

2001: $\theta_{12} \approx 34°$
SNO, Super-K

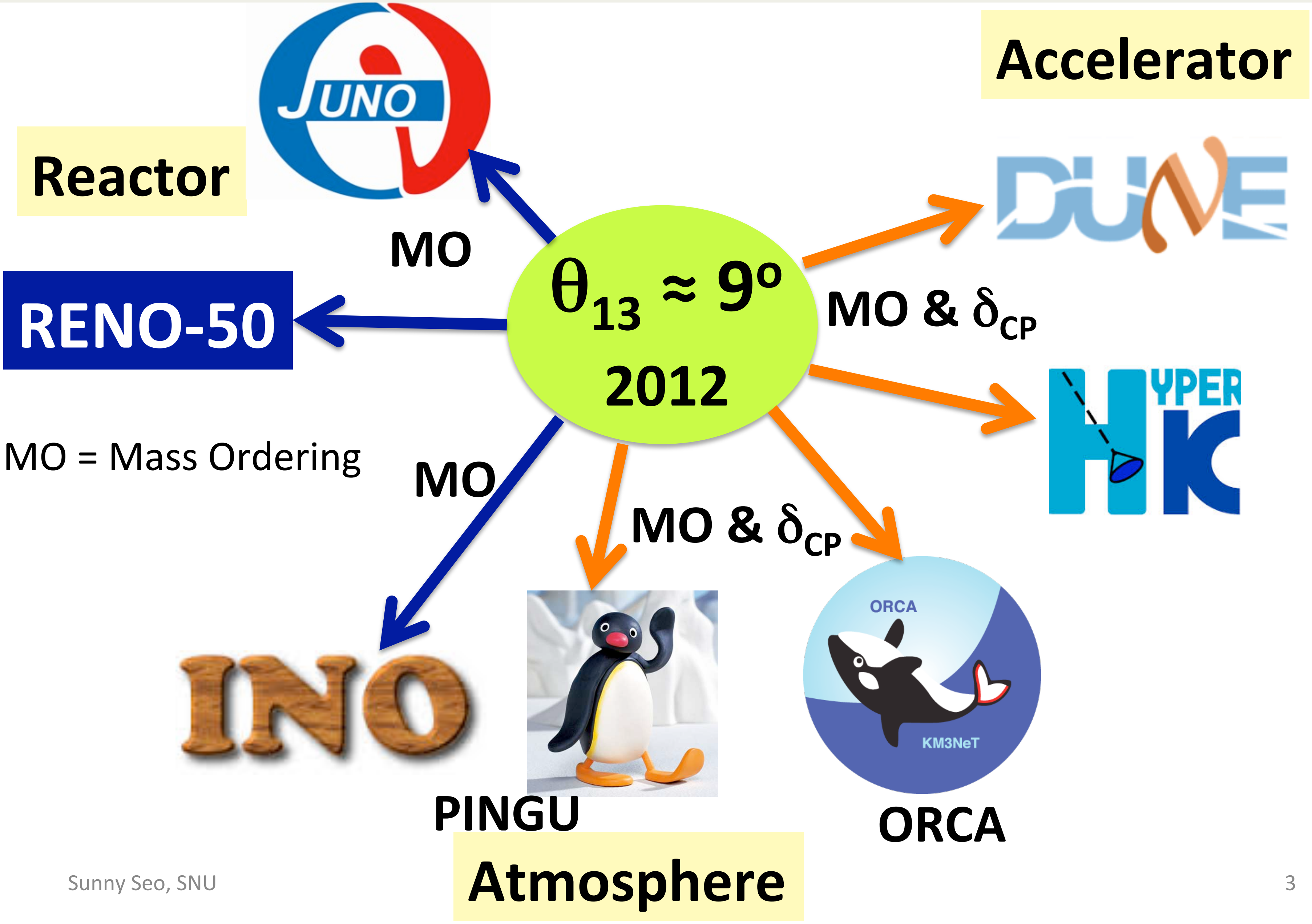
2012 Measurement of the smallest mixing angle θ_{13}







θ_{13} and Future ν Experiments



$\theta_{13} \approx 9^o$

2012

Reactor

MO

RENO-50

MO = Mass Ordering

MO

Accelerator

MO & δ_{CP}

MO & δ_{CP}

PINGU

ORCA

Atmosphere

3 Generations of Kamiokande

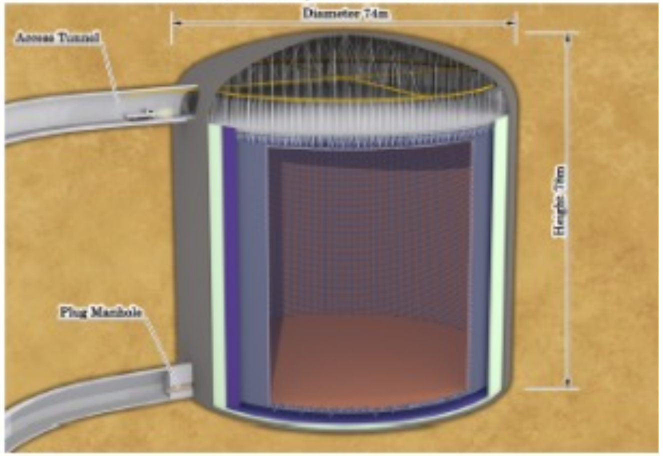
Kamiokande (1983-1996)
3000 ton

- Neutrinos from SN1987a.
- Atmospheric neutrino deficit.
- Solar neutrinos.

Super-Kamiokande (1996-)
50,000 ton

- Atmospheric neutrino oscillation.
- Solar neutrino oscillation with SNO.
- Far detector for KEK-PS (K2K) and J-PARC beam (T2K): electron neutrino appearance.
- World leading limit on proton lifetime $> 10^{34}$ years.

Hyper-Kamiokande ($\sim$2026-)
$2\times$260,000 ton

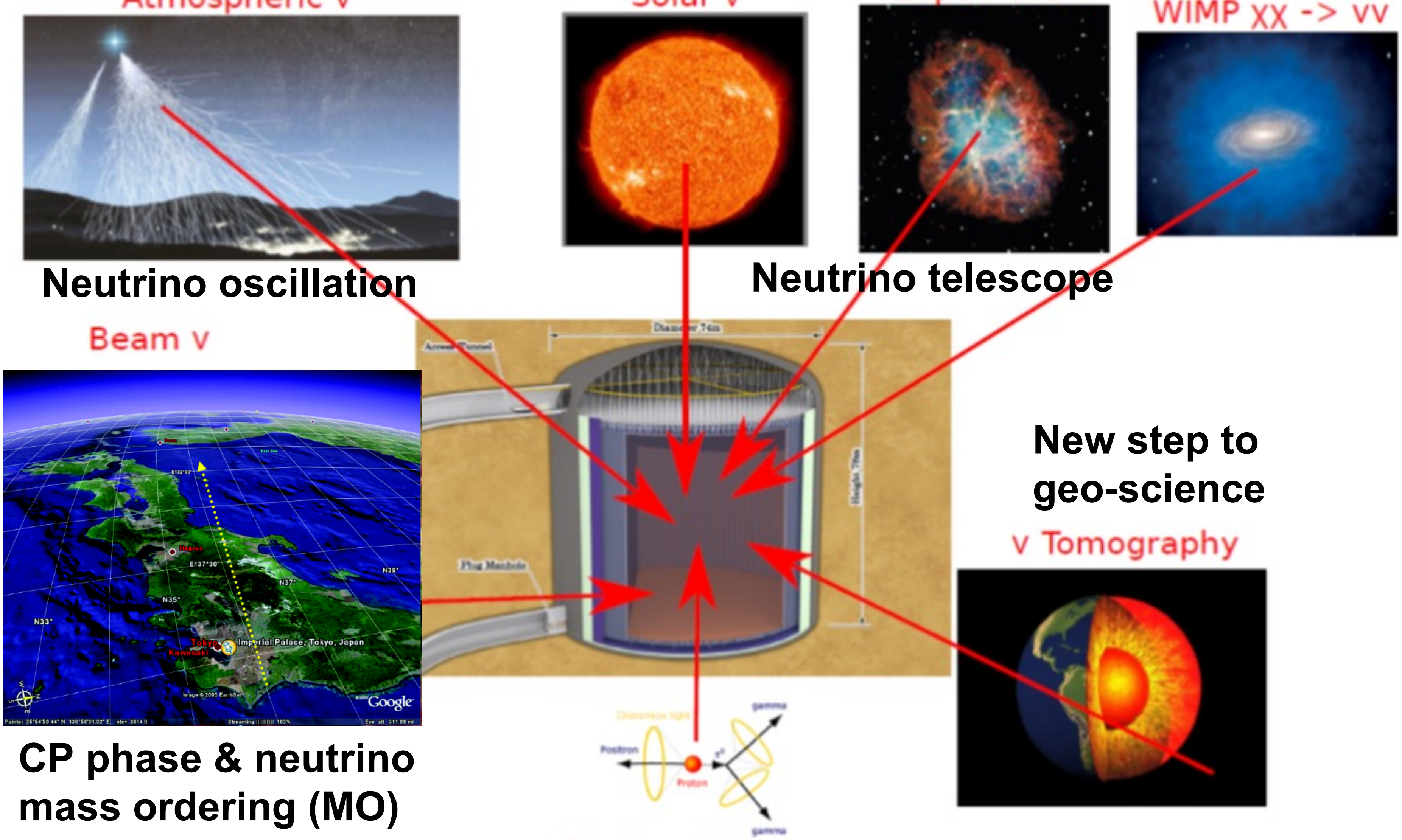


Physics programme:

- Neutrino oscillations: Mass Hierarchy, Leptonic CP violation, θ_{23} Octant,...
- Nucleon decay: $p\to e^+\pi^0$, $p\to K^+\bar{\nu}$,...
- Neutrino astrophysics: Solar neutrinos, Supernova neutrinos, WIMP searches

(?)

Hyper-K Physics Program



Atmospheric ν

Solar ν

Supernova ν

WIMP χχ -> νν

Neutrino oscillation

Neutrino telescope

Beam ν

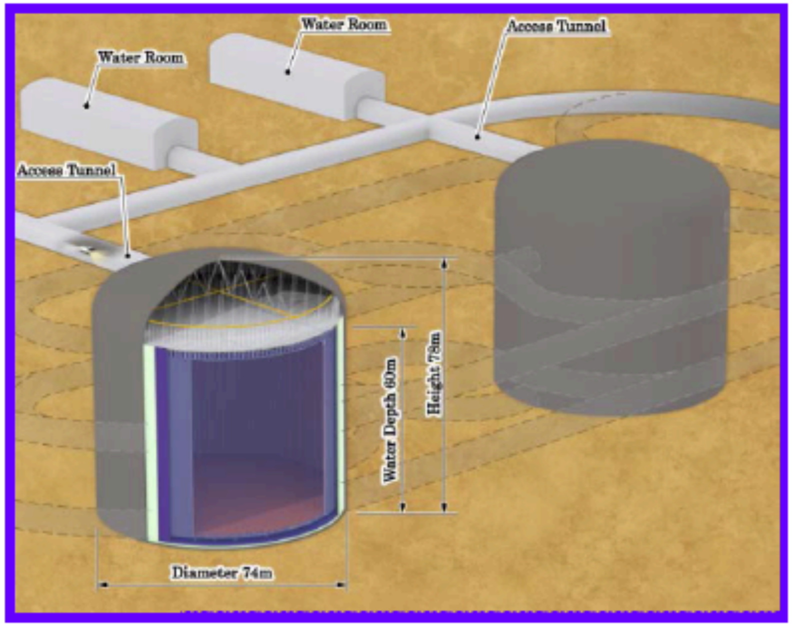
New step to geo-science

ν Tomography

CP phase & neutrino mass ordering (MO)

Nucleon Decay **Lifetime : 10^{35} yr**

Hyper-Kamiokande (Hyper-K)

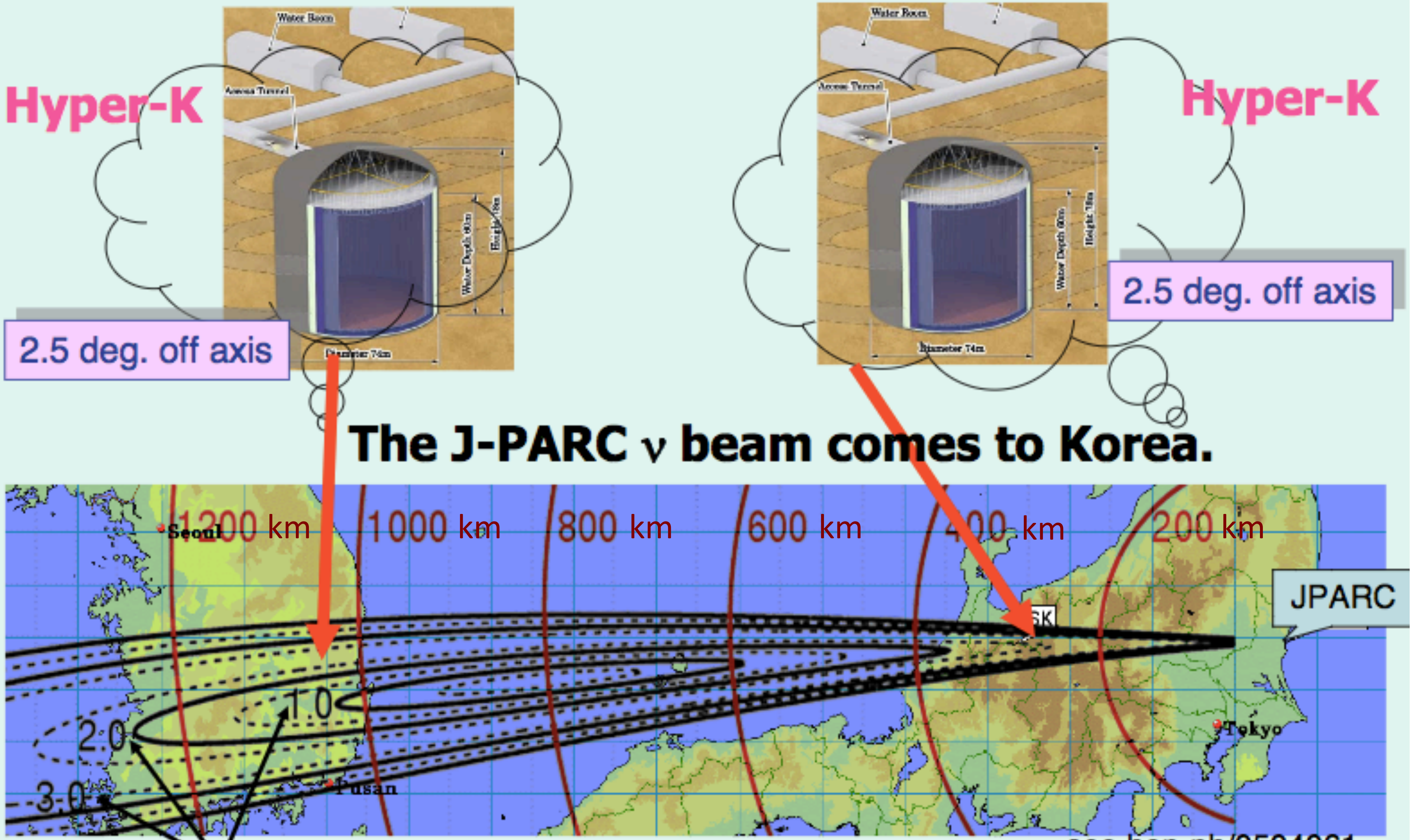


Hyper-K

Inauguration: Jan. 2015

Hyper-K proto-collaboration: 14 countries, ~300 members and growing

2nd Hyper-K Detector in Korea

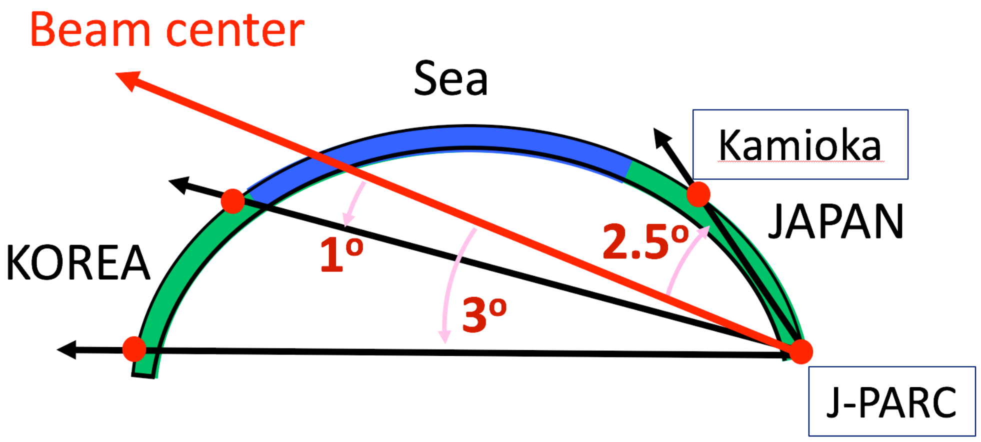


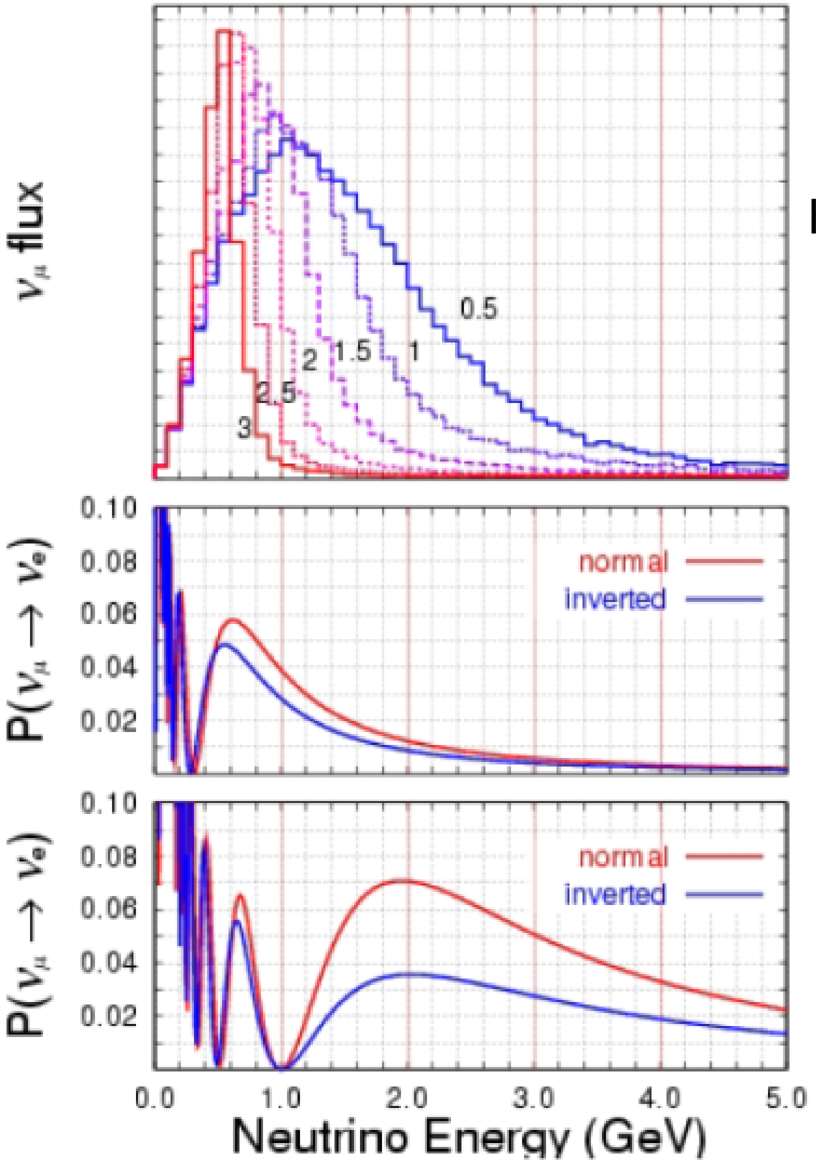
The J-PARC ν beam comes to Korea.

Off-axis angle

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

Neutrino Oscillations in Kamioka & Korea

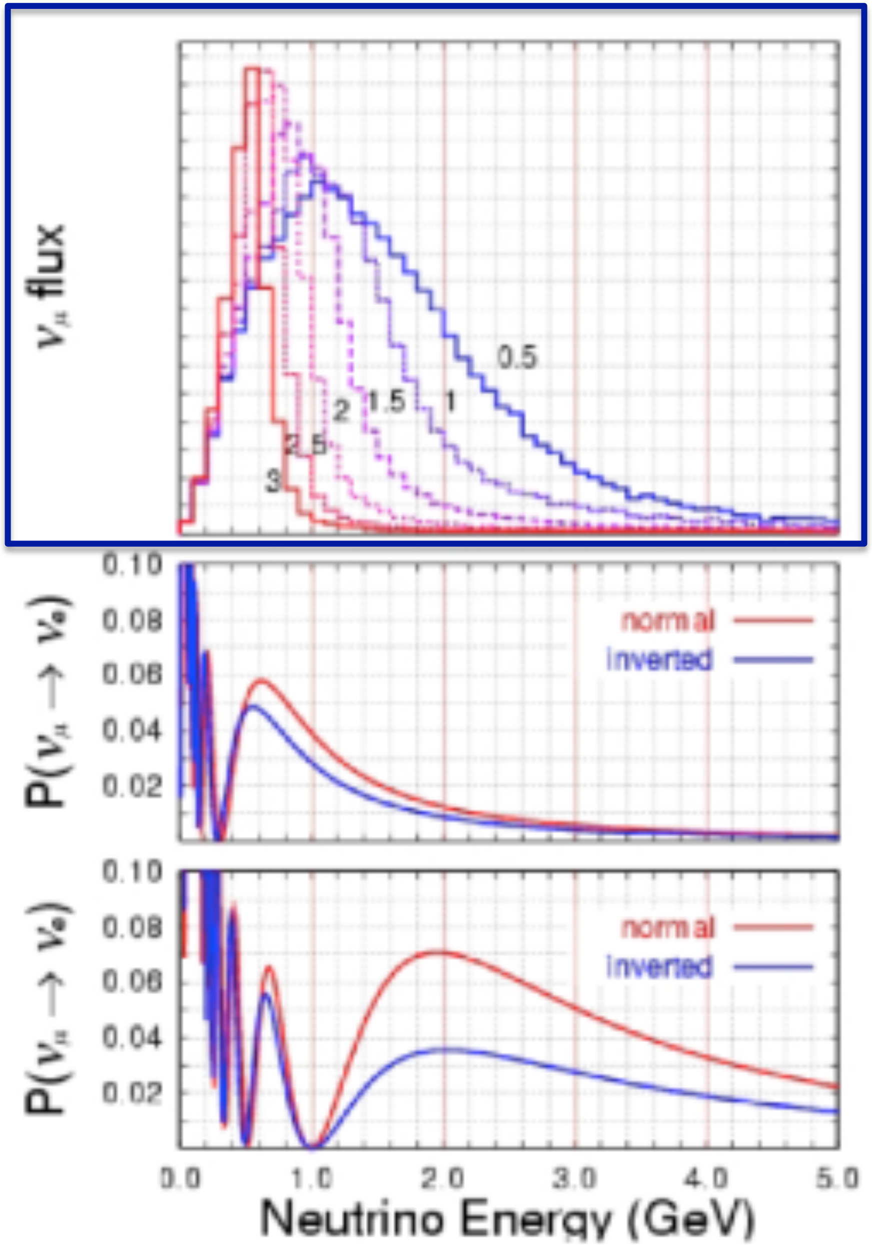




← Profile of off-axis beams

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

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

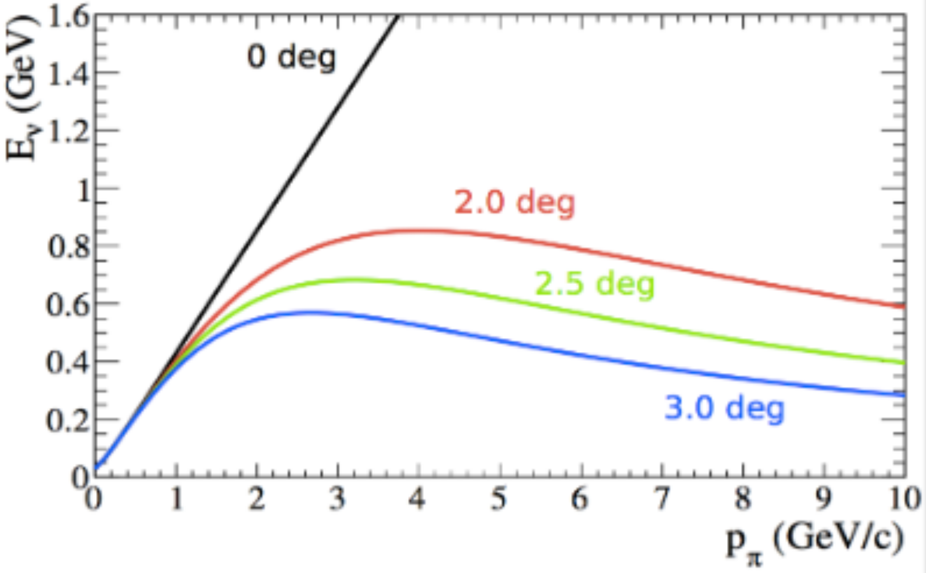


Pion mass

$$E_\nu = \frac{M^2 - m_\mu^2}{2(E - p\cos\theta)}$$

Pion energy

Pion momentum



ν_e appearance probability: address 3 key parameters

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

θ_{23} octant

ν mass ordering

CP

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

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

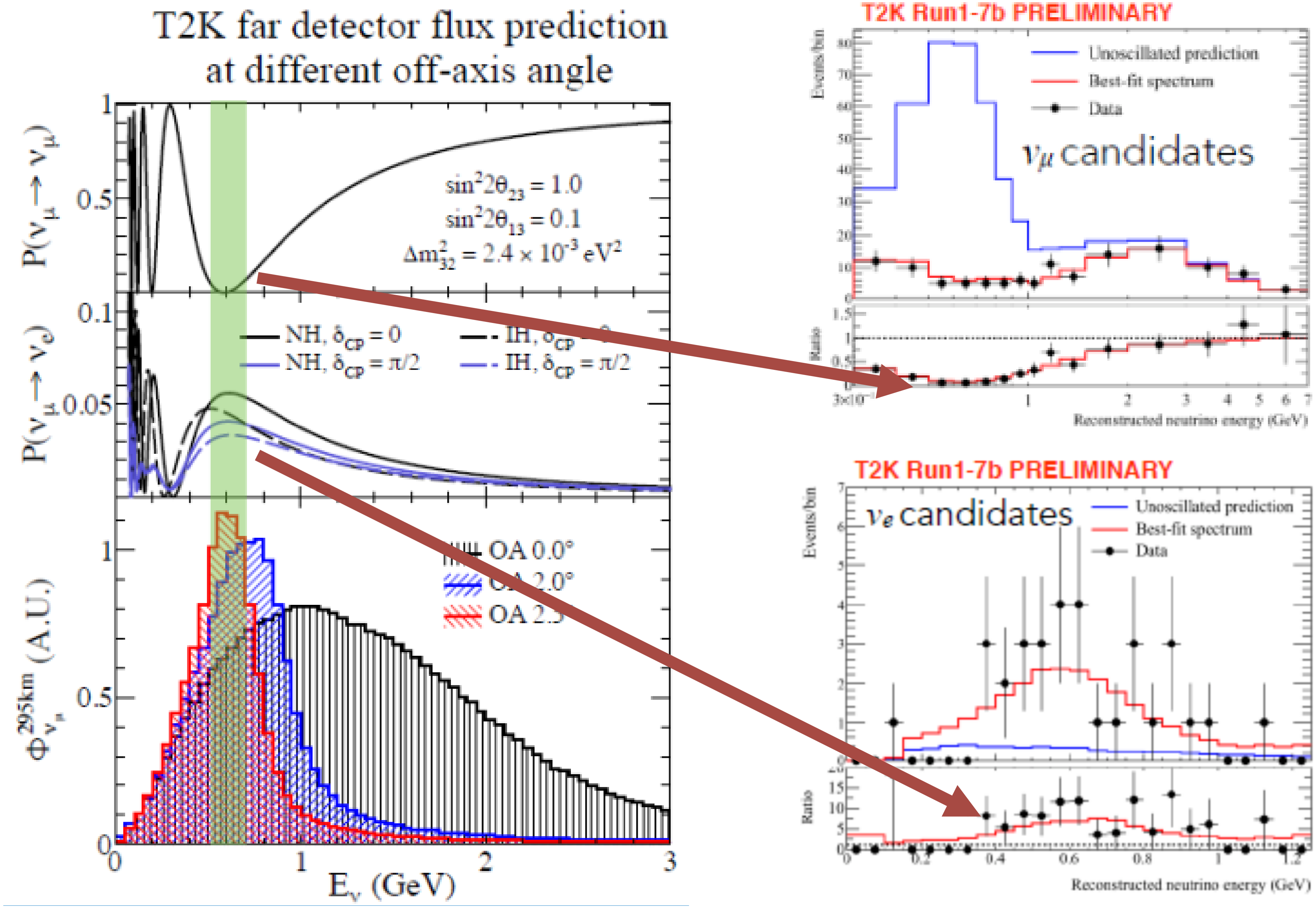
solar term: suppressed by Δ^2_{21}

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

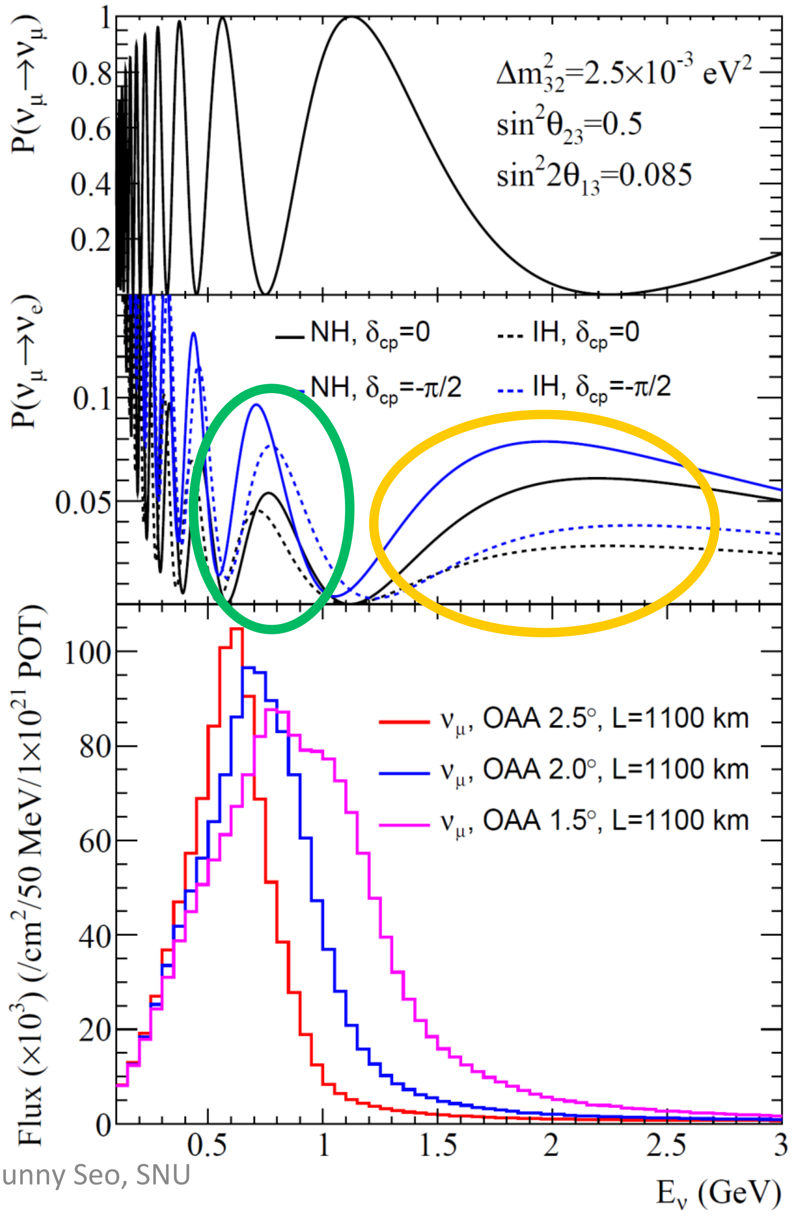
suppressed by $\sin^4\theta_{13}$

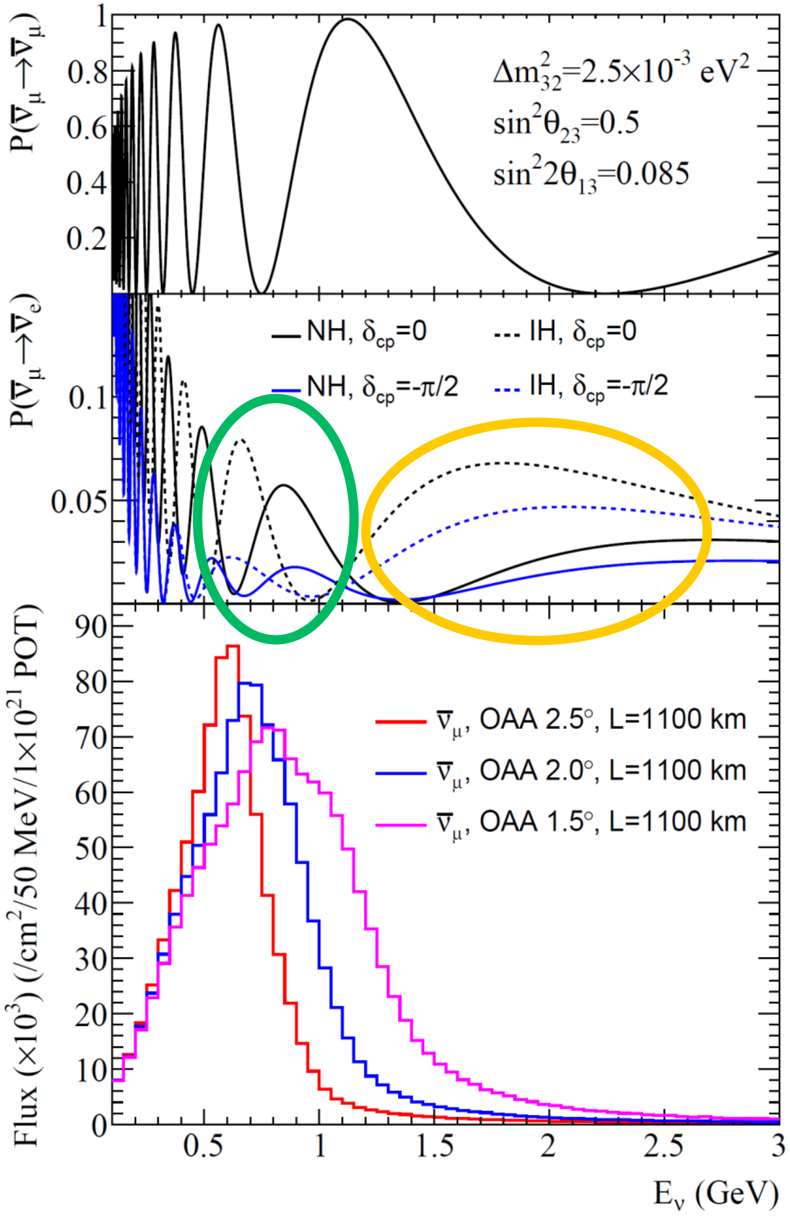
2% correction to the 1st term

1st Oscillation Maximum in Kamioka



1st and 2nd Oscillation Maxima in Korea





Sunny Seo, SNU

Benefits of T2HKK

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

- Neutrino mass ordering determination
- Leptonic CP violation phase measurement

1st&2nd oscillation maxima

- Non-standard neutrino interaction

Longer baseline
Higher ν energy
Higher matter density

- Solar/SN/SRN/ν geo physics sensitivities

Deeper site:
650 vs. 1000 m

Unique benefits of a Korean Detector

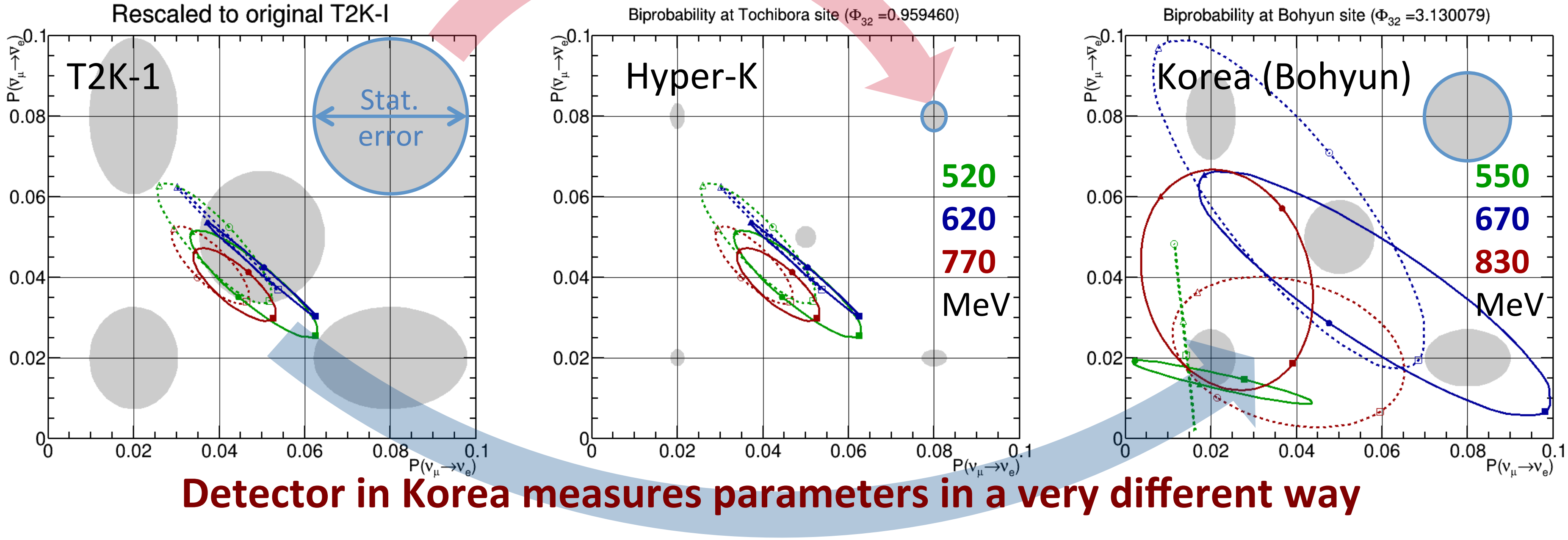
Biprobablitiy plots often used to compare experiments. (e.g. T2K vs NOνA). Extend these to multiple energies, to gain understanding of 2nd maxima measurement.

Larger ellipses mean less sensitivity to systematic errors.
Shape differences unpick degeneracies with other parameters. (e.g. $\theta\downarrow23$)

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

T2HKK Inauguration
July 10th 2016, London

Meeting after the first T2HKK proposal talk in London

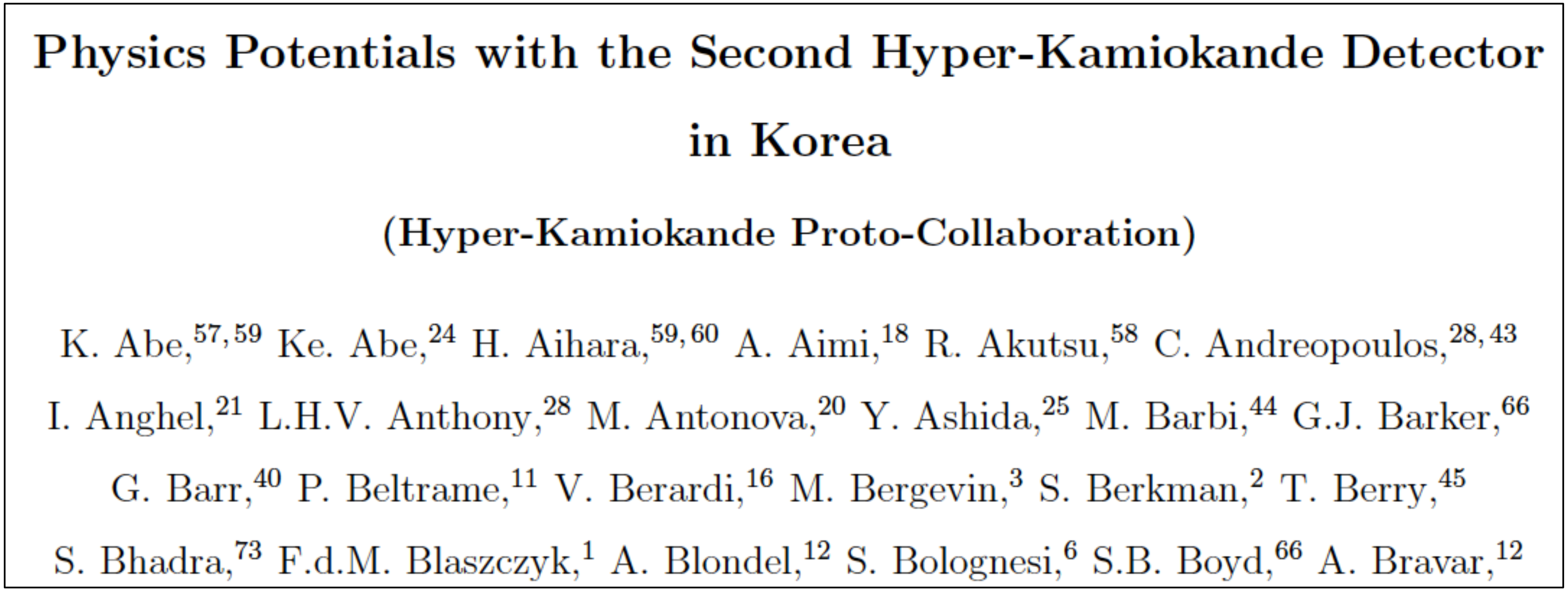
T2HKK White Paper

November 21st 2016

~ 4 months later
from the inauguration

arXiv:1611.06118

(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]

1st T2HKK Workshop @SNU

☐ 1st T2HKK workshop (Nov. 21-22) at SNU was successfully finished.

1st T2HKK Workshop @SNU

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: →

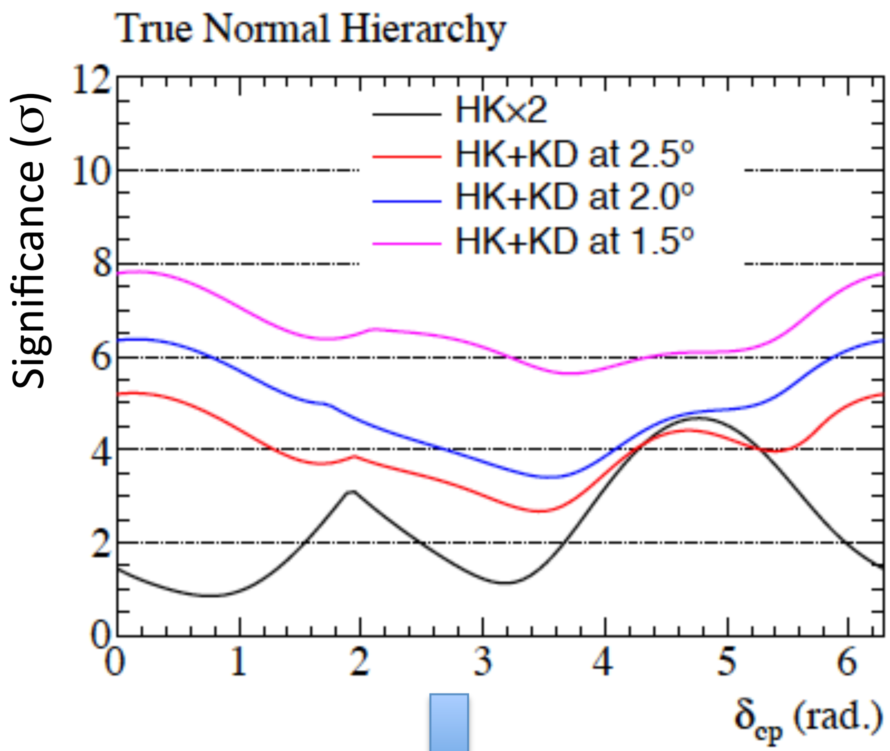
$$|\Delta m^2_{32}| = 2.5 \times 10^{-3}\ \text{eV}$$
$$\sin^2\theta_{23} = 0.5$$
$$\sin^2 2\theta_{13} = 0.085$$
$$\Delta m^2_{21} = 7.53 \times 10^{-5}\ \text{eV}$$
$$\sin^2\theta_{12} = 0.304$$
$$\delta_{cp} = 0, \pi/2, \pi, 3\pi/2$$

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

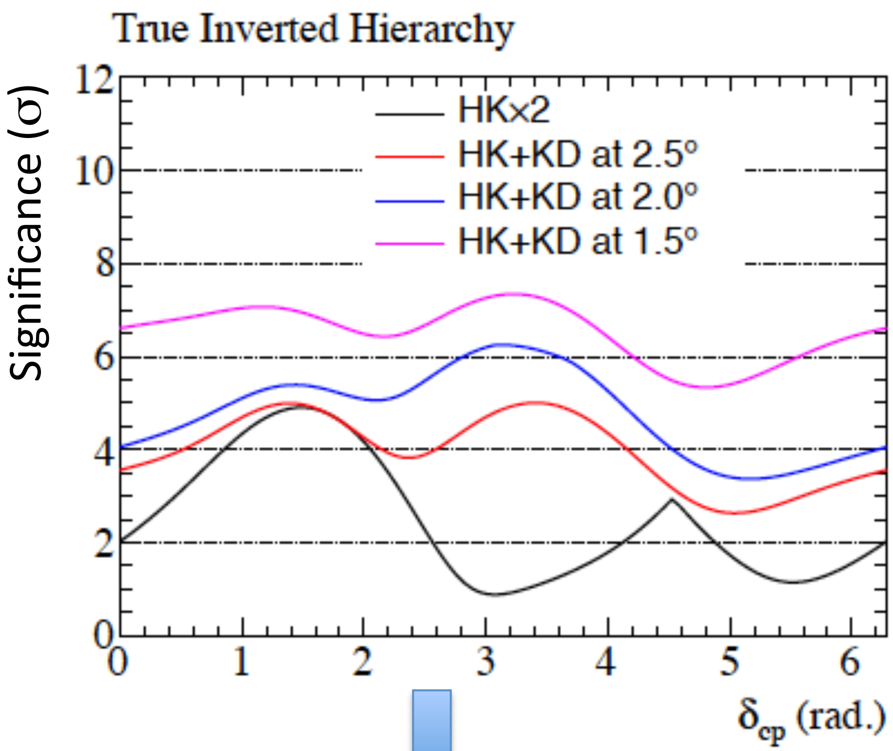
Mass Ordering Sensitivities

arXiv:1611.06118

Normal



Inverted



HK+KD 1.5^o: $6 \sim 8\ \sigma$ for all δ_{CP}

HK x2 : $1 \sim 4.5\ \sigma$ for all δ_{CP}

($< 3\ \sigma$ for most cases)

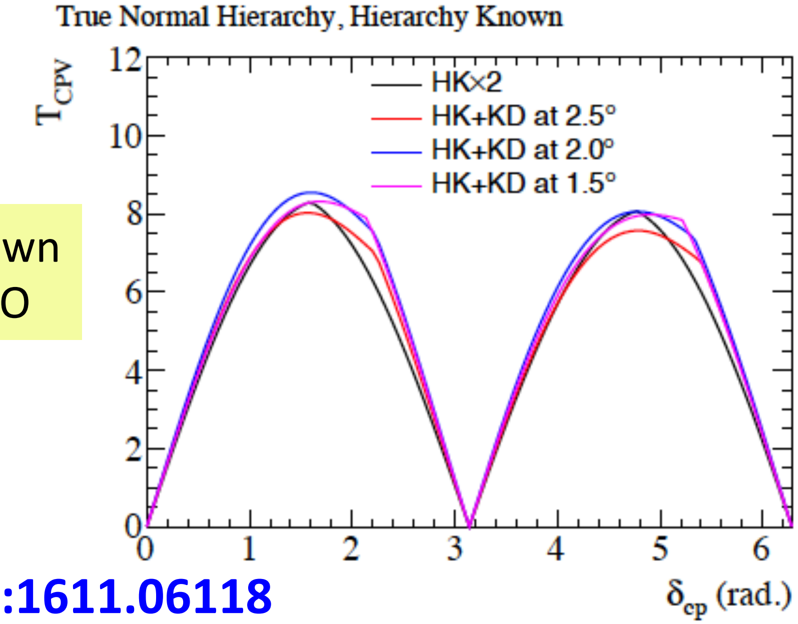
HK+KD 1.5^o: $5.5 \sim 7\ \sigma$ for all δ_{CP}

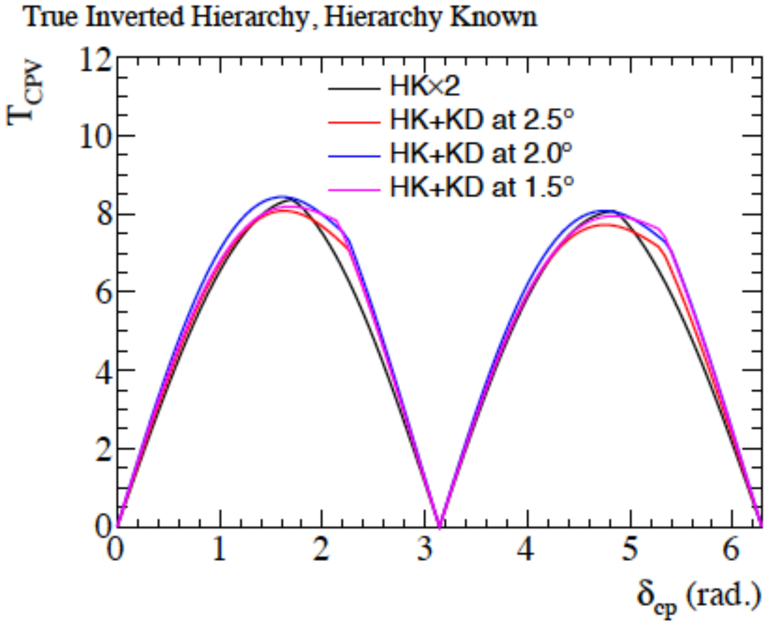
HK x2 : $1 \sim 5\ \sigma$ for all δ_{CP}

($< 3\ \sigma$ for most cases)

CP Sensitivities

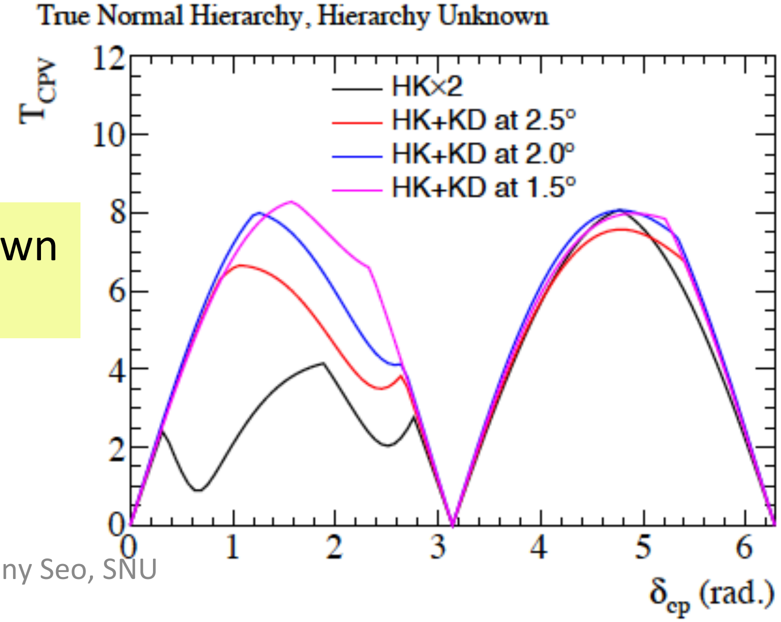
Known MO

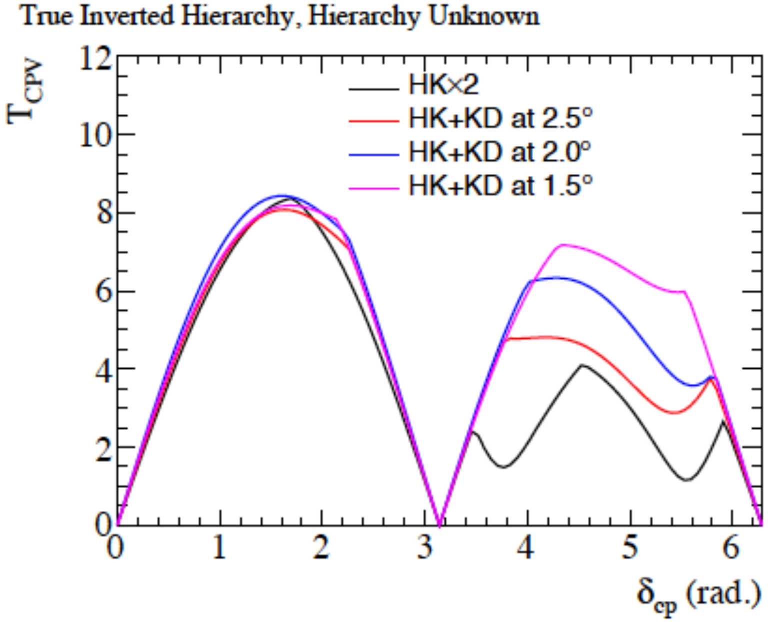




arXiv:1611.06118

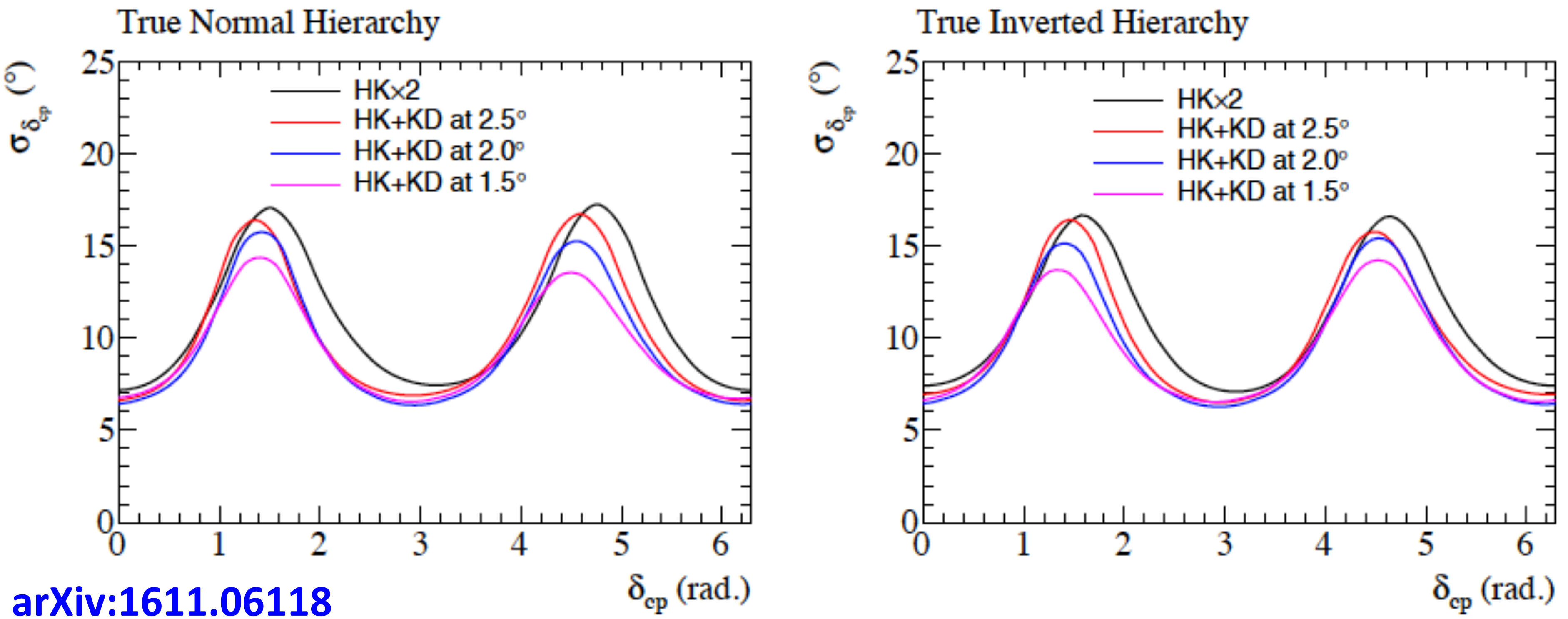
Unknown MO





δ_{CP} Precision Sensitivities

→ Important for flavor symmetry model of neutrino mixing

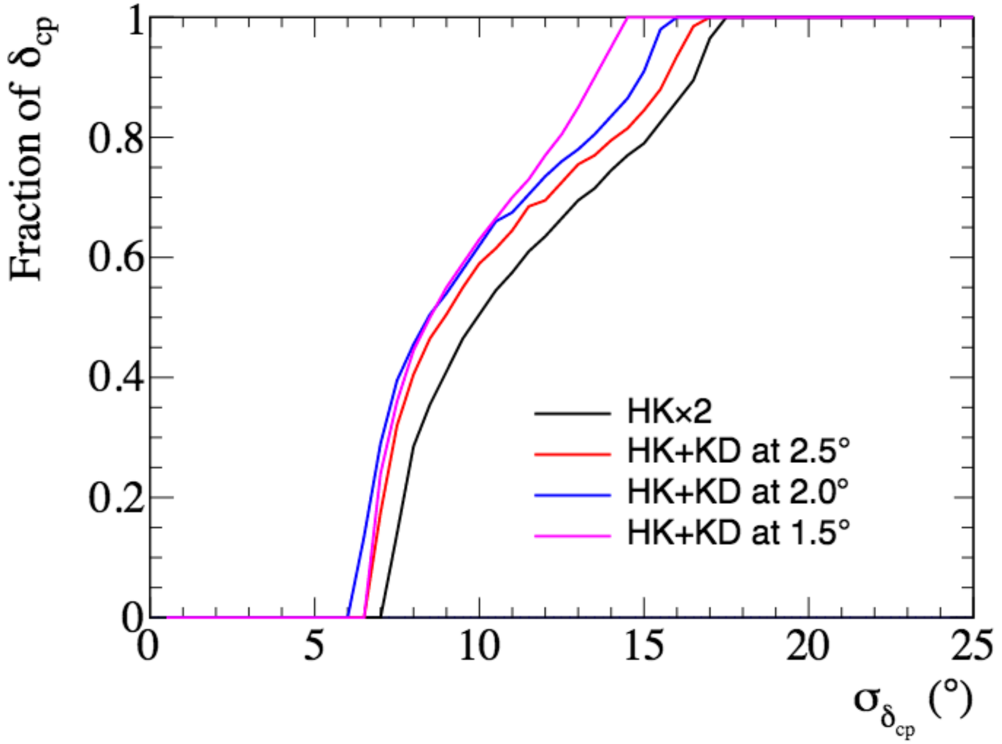


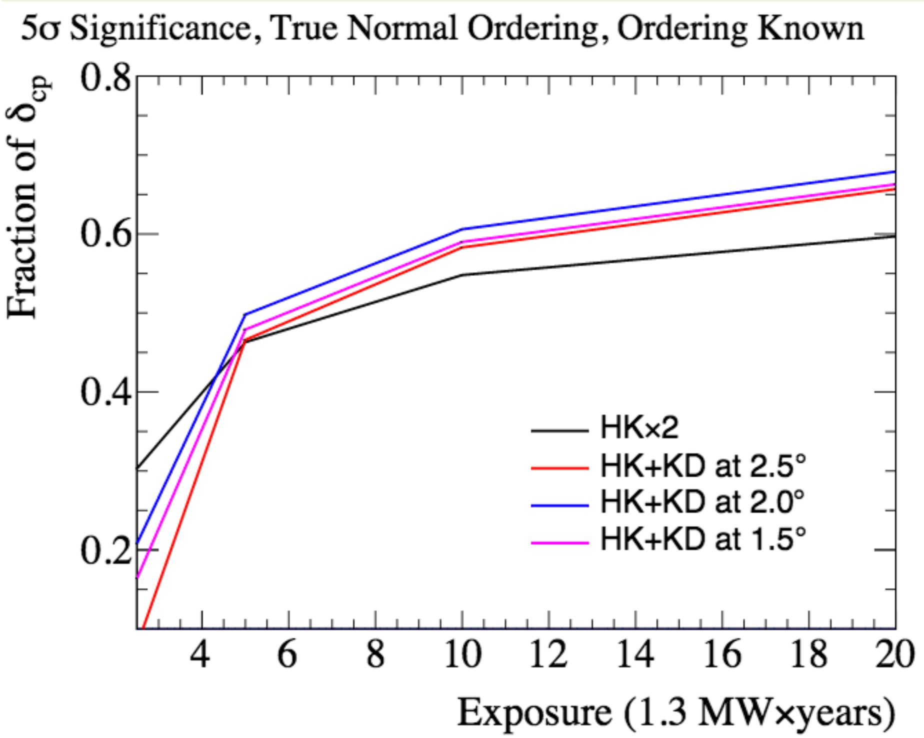
arXiv:1611.06118

At maximum CP violation: HK+KD 1.5°: $\sigma(\delta_{CP})$ = 13~14 degree
HK x2 : $\sigma(\delta_{CP})$ ~ 17 degree

Fraction of δ_{CP}

How much fraction of δ_{CP} can we cover ?

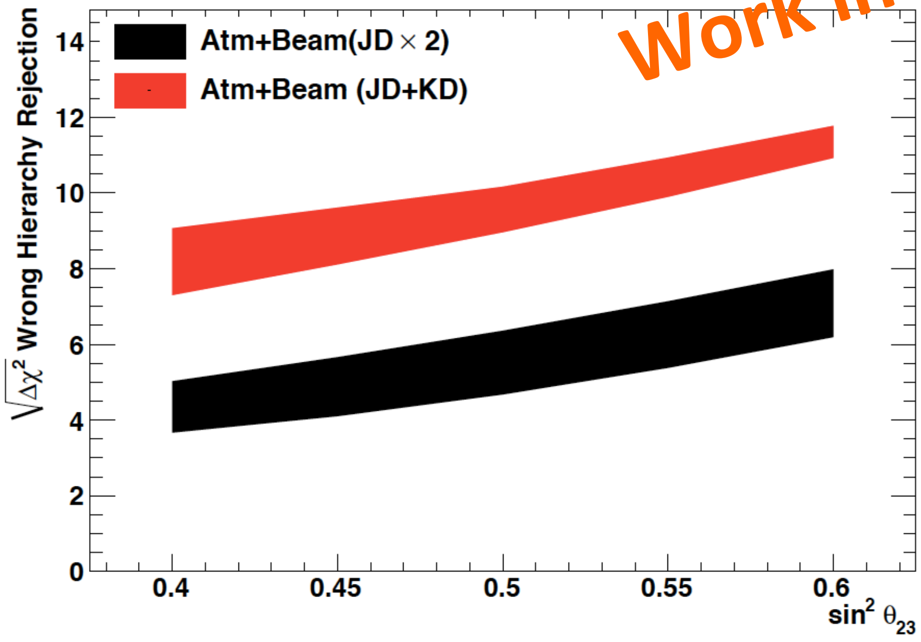


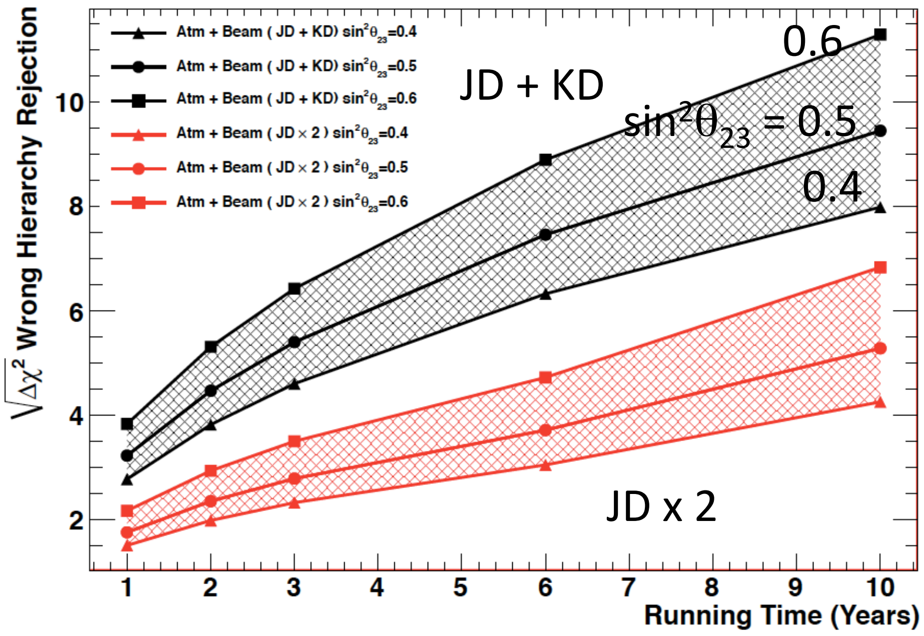


Beam + Atm. Data

Mass ordering sensitivity

Work in progress

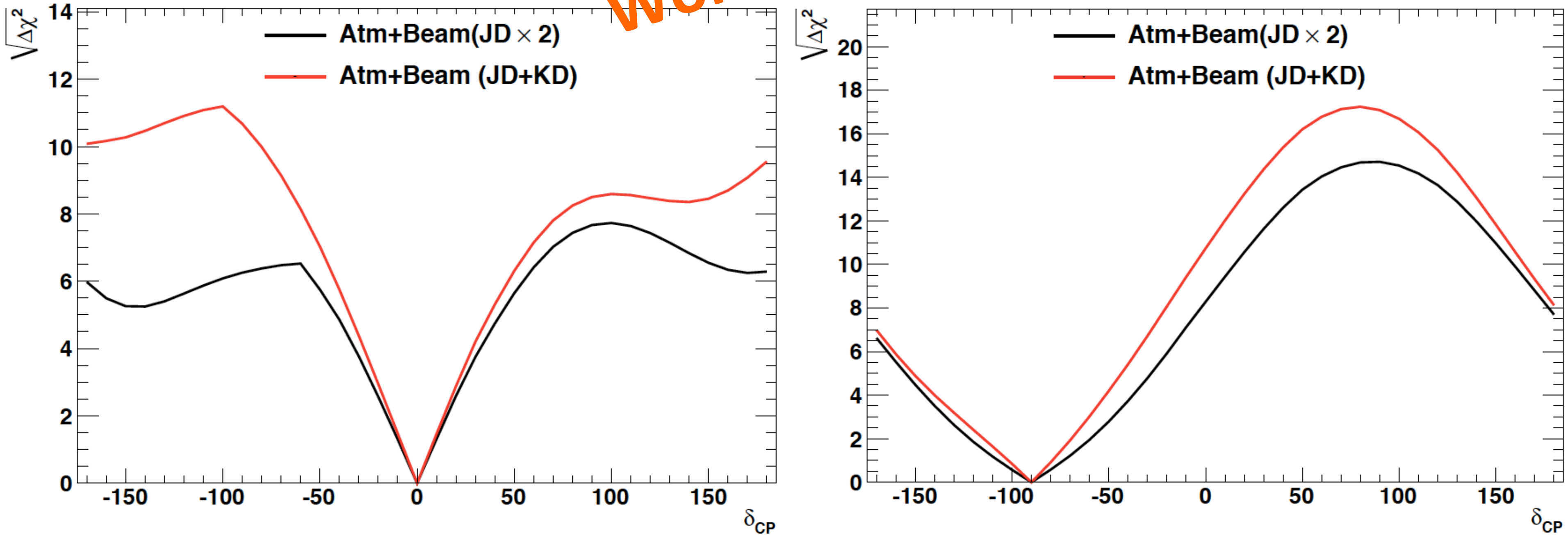




Beam + Atm. Data

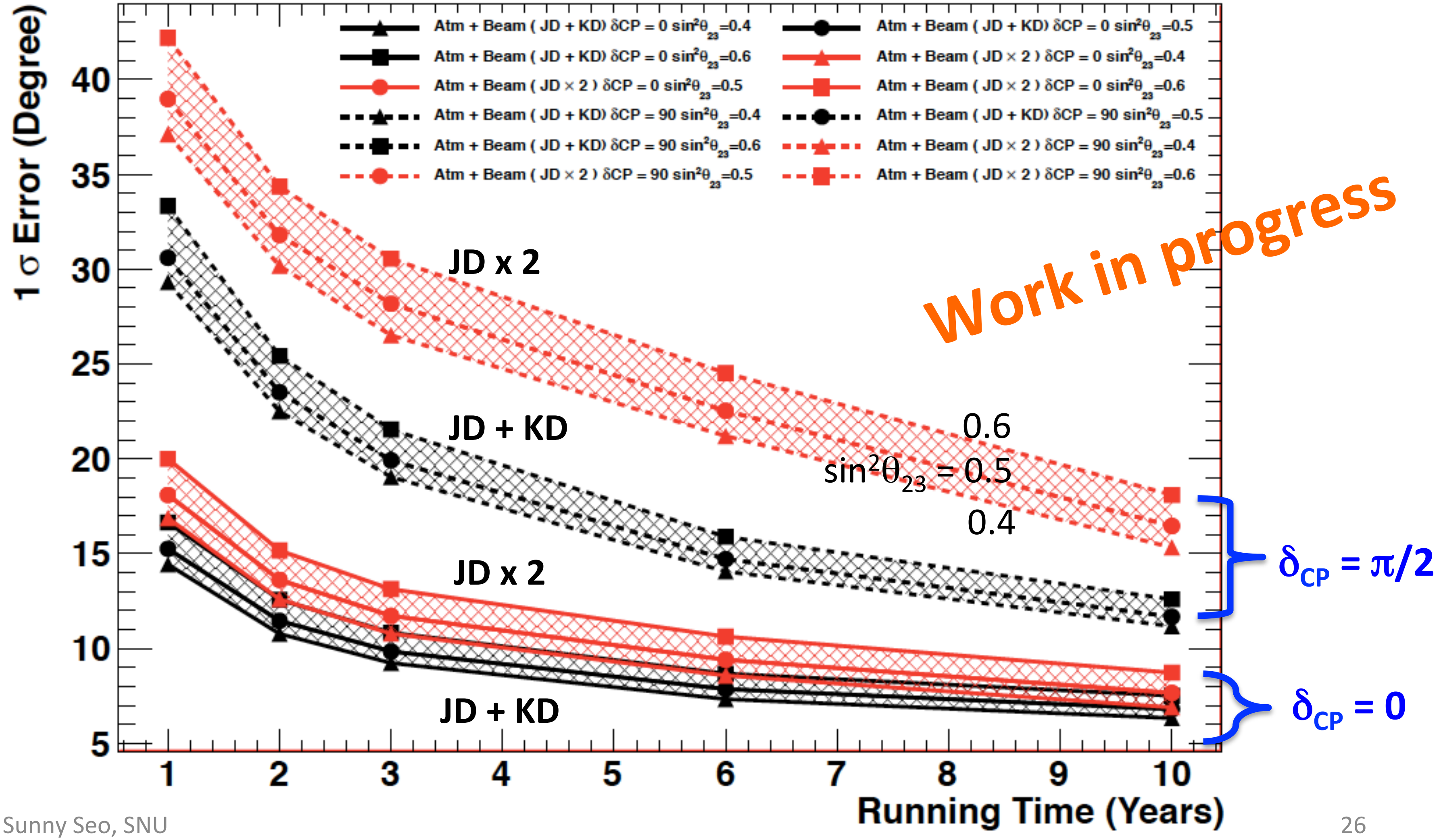
CP sensitivity

Work in progress



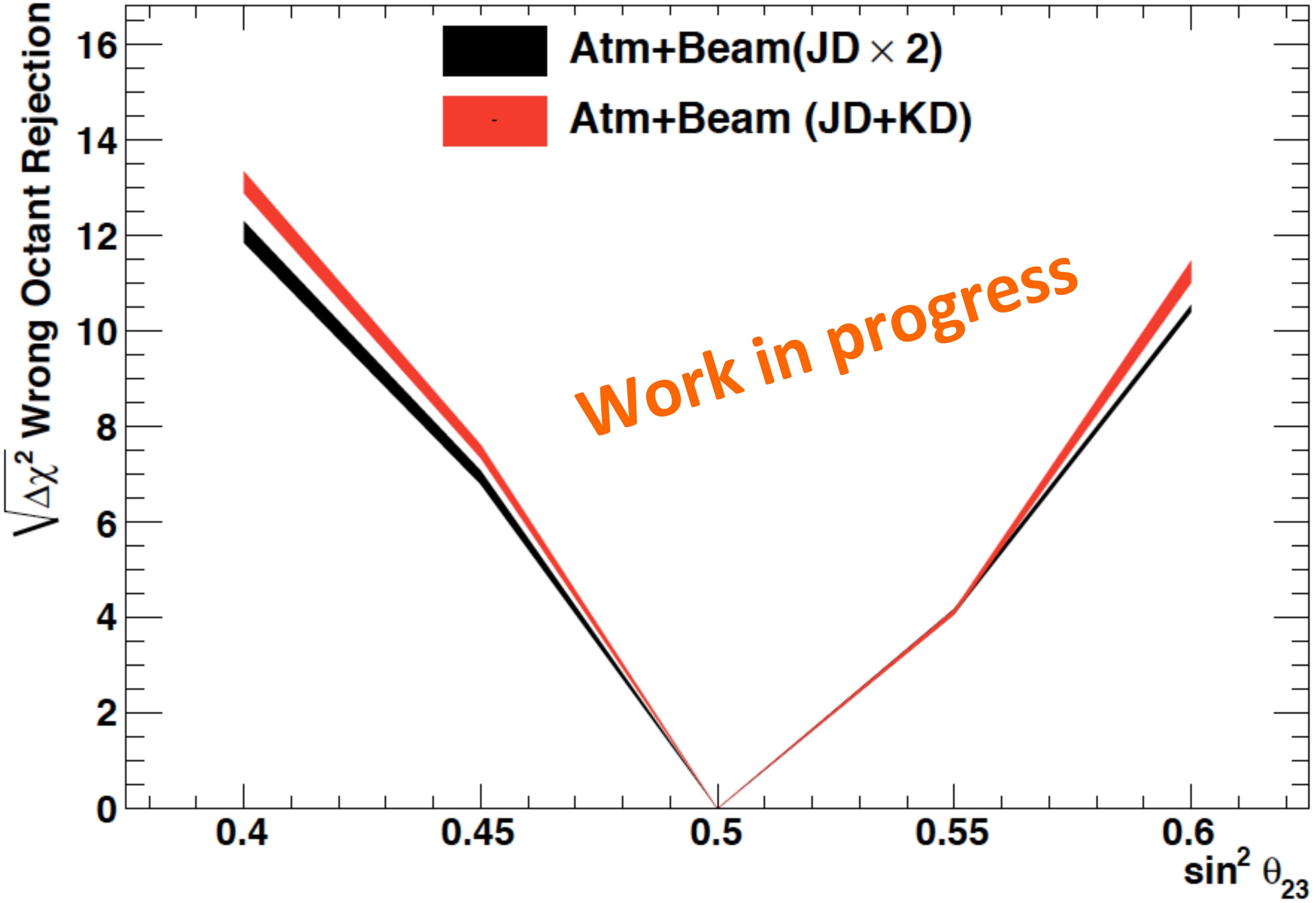
Beam + Atm. Data

δ_{CP} precision sensitivity



Beam + Atm. Data

Octant sensitivity



Low E benefits

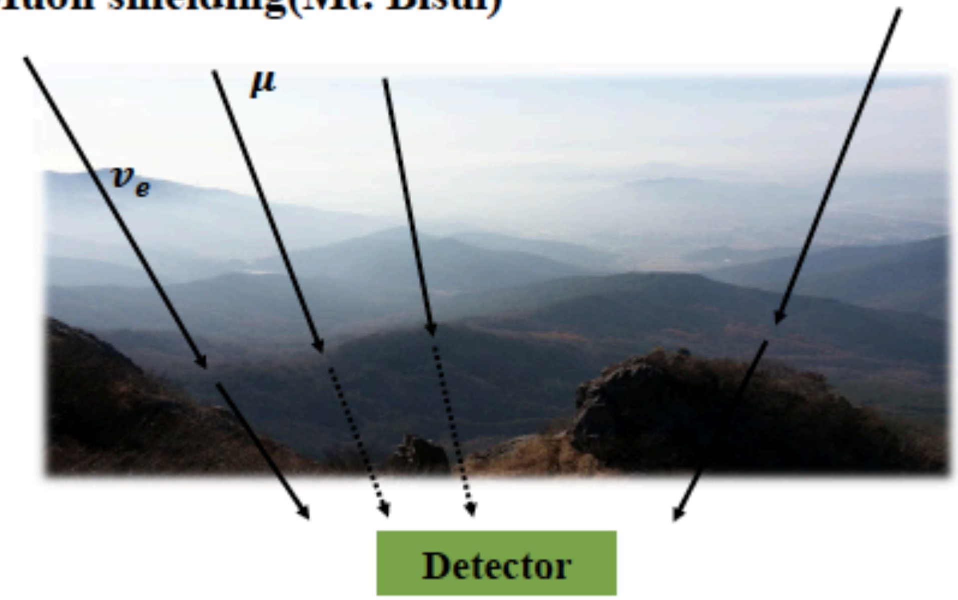
1. Deeper site:

lower muon flux,
lower spallation BKG

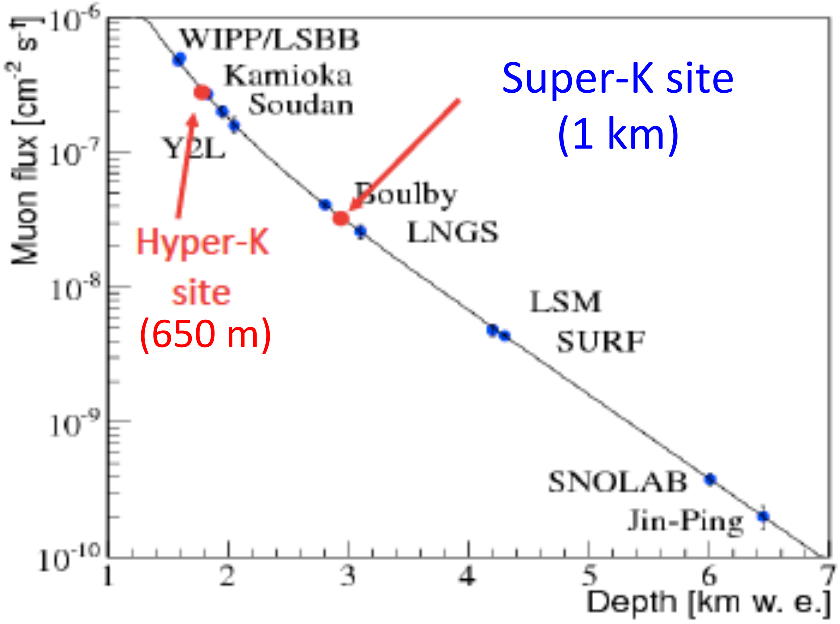
2. Geographical separation:

signal coincidence,
degeneracy break-up

Muon shielding(Mt. Bisul)



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



Muon flux to each laboratory

Low Energy Physics Benefits

☐ Solar neutrino physics

(1) Day/night asymmetry due to MSW matter effect in Earth
(2) HEP solar neutrinos
(3) energy spectrum upturn

Sensitivity improves

☐ Super-Nova Relic neutrino detection

(1) SRN detection capability below 20 MeV improves
(2) Detection efficiency is more than twice in [16, 18] MeV than HK site.

☐ Neutrino geophysics

☐ Non-standard new physics

(1) Quantum decoherence,
(2) tiny violation of Lorentz symmetry without/with CPT invariance,
(3) nonstandard neutrino interactions with matter

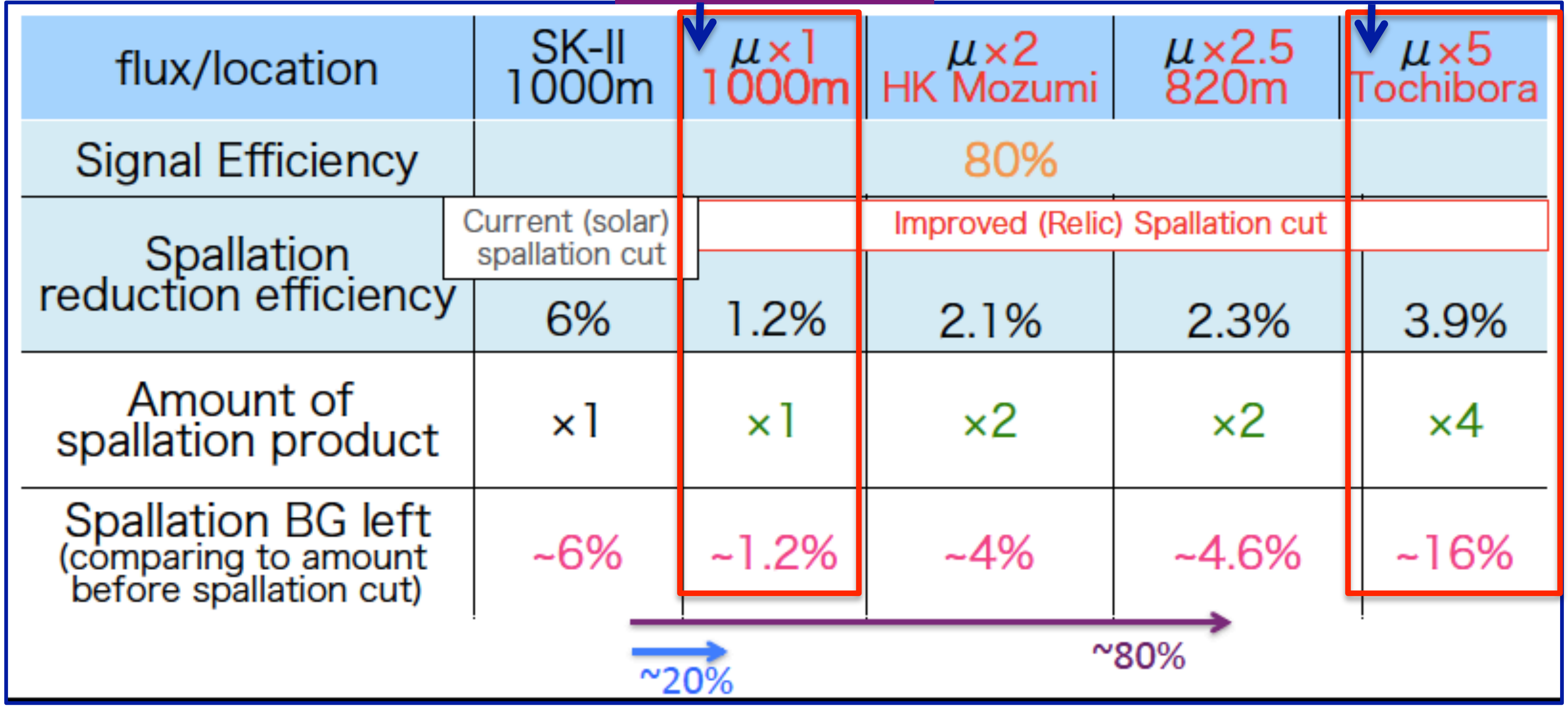
Phys. Rev. D 77, 073007 (2008)

→ In most cases, these are improved with T2HKK configuration

Solar ν

Korean site

Japan site



flux/location	SK-II 1000m	μ×1 1000m	μ×2 HK Mozumi	μ×2.5 820m	μ×5 Tochibora
Signal Efficiency	80%				
Spallation reduction efficiency	Current (solar) spallation cut 6%	Improved (Relic) Spallation cut 1.2%	2.1%	2.3%	3.9%
Amount of spallation product	×1	×1	×2	×2	×4
Spallation BG left (comparing to amount before spallation cut)	~6%	~1.2%	~4%	~4.6%	~16%

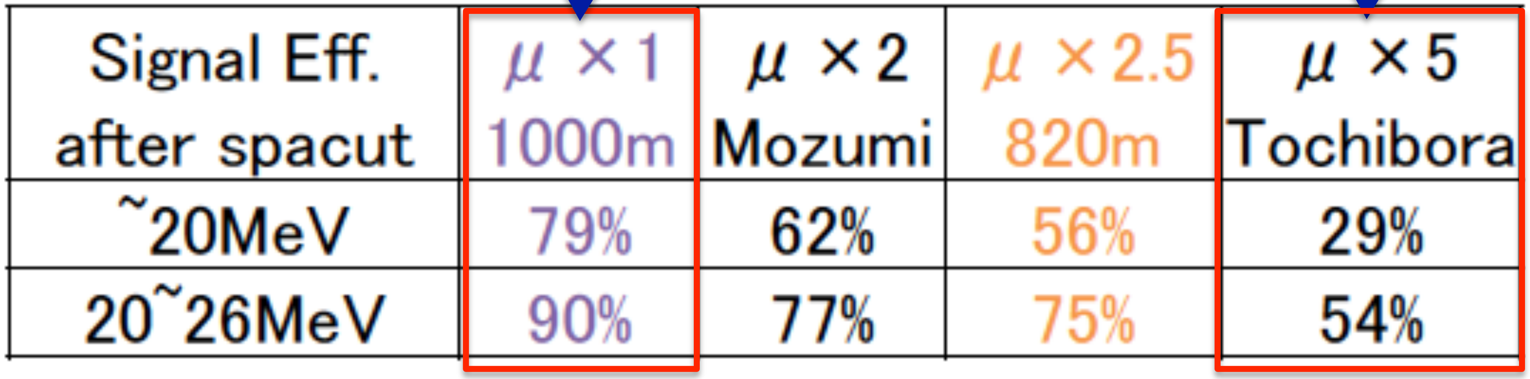
~20%

~80%

SRN

Korean site

Japan site



Signal Eff. after spacut	μ ×1 1000m	μ ×2 Mozumi	μ ×2.5 820m	μ ×5 Tochibora
˜20MeV	79%	62%	56%	29%
20˜26MeV	90%	77%	75%	54%

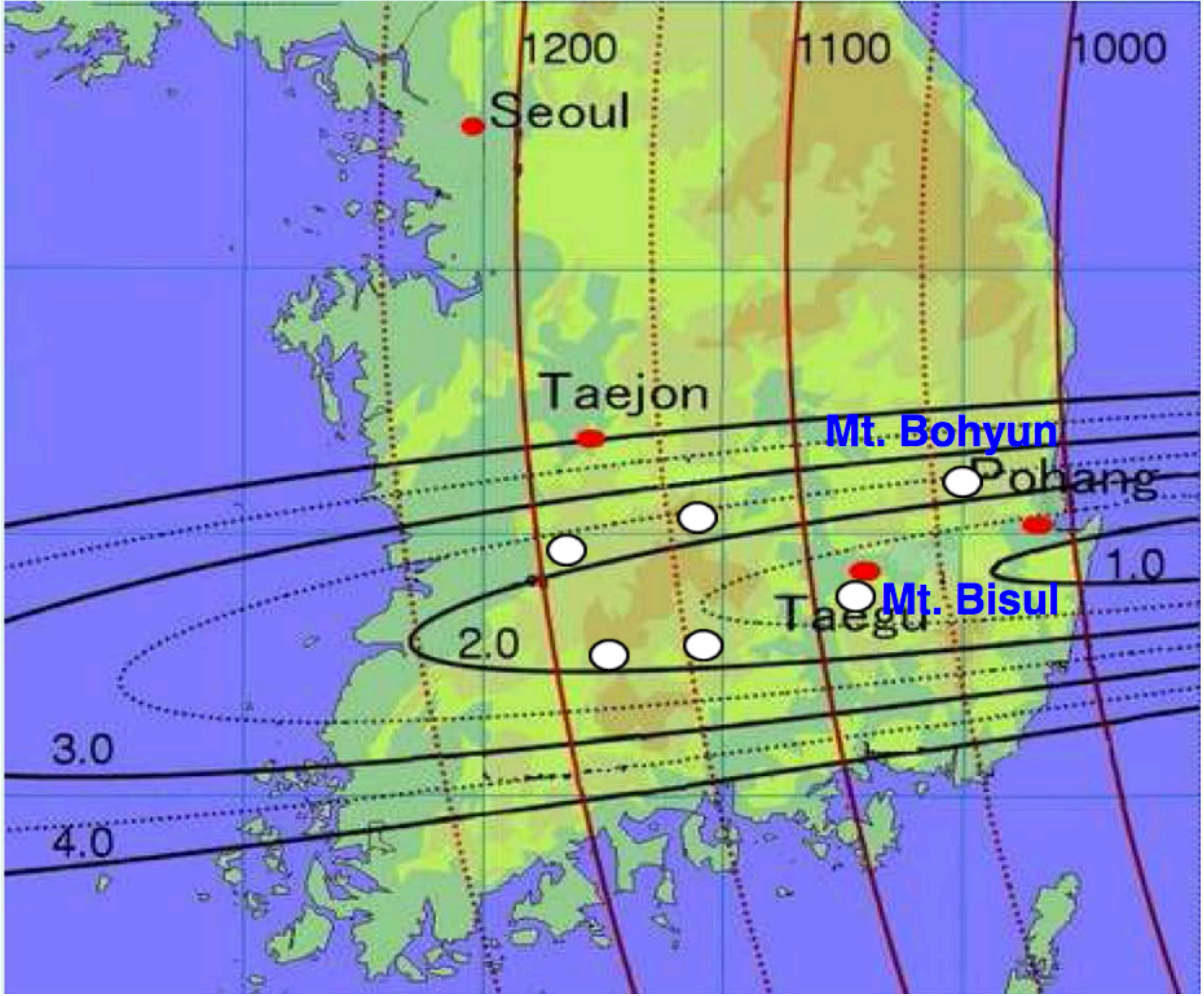
Some candidate sites in Korea

Site candidates for a 2nd osc. maximum detector in Korea

- -- Baselines with 1,000~1,200 km
- -- 2.0~2.5° or 1.5~2.0° off axis beam directions
- -- >1,000 m high mountains with hard granite rocks

Site	OAB	Baseline [km]	Height [m]
Mt. Bisul	**~1.3°**	**1088 km**	**1084 m**
Mt. Hwangmae	~1.8°	1140 km	1113 m
Mt. Sambong	~1.9°	1180 km	1186 m
Mt. Bohyun	**~2.2°**	**1040 km**	**1126 m**
Mt. Minjuii	~2.2°	1140 km	1242 m
Mt. Unjang	~2.2°	1190 km	1125 m

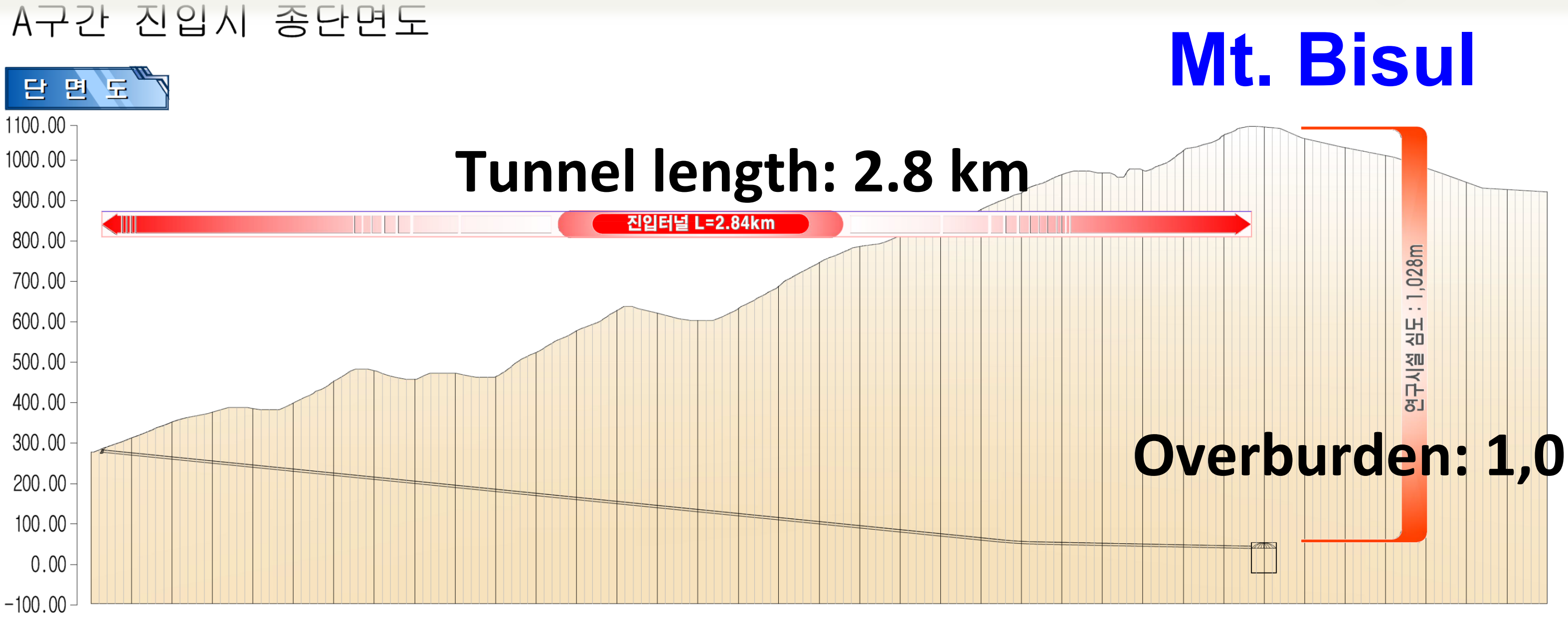
Some Candidate Sites



Mt. Bisul at Dalsung (1,084m high)

- Excellent accessibility: Dalsung district in the city of Daegu ← near Technopolis area, KTX from Seoul, access road, electricity, water

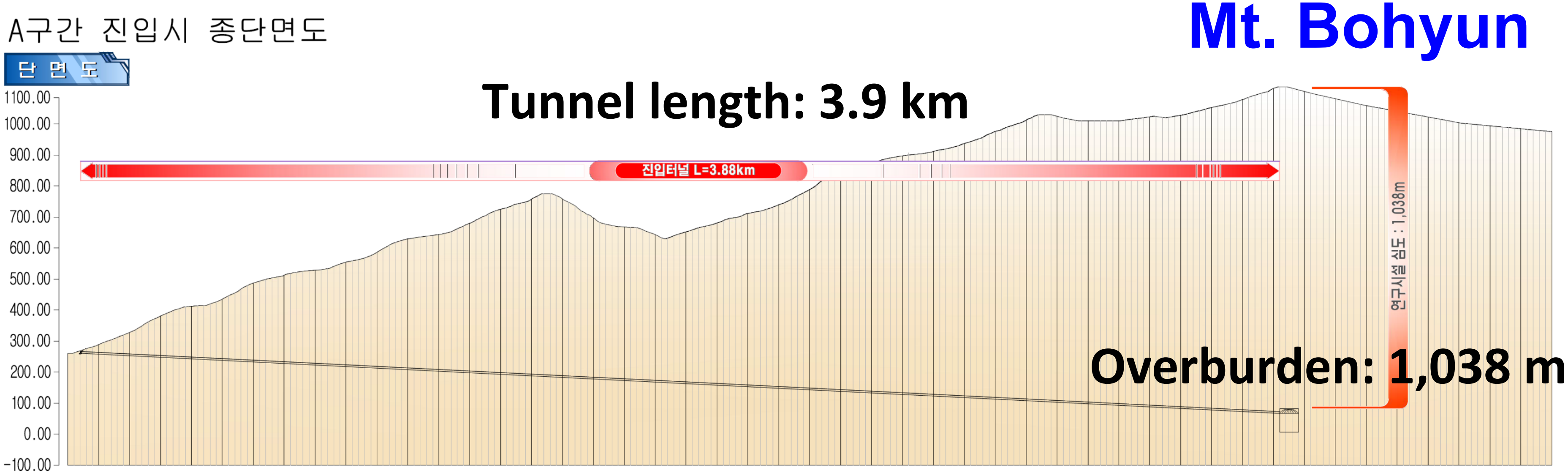
Tunnels at Mt. Bisul & Bohyun



Mt. Bisul

Tunnel length: 2.8 km

Overburden: 1,028 m

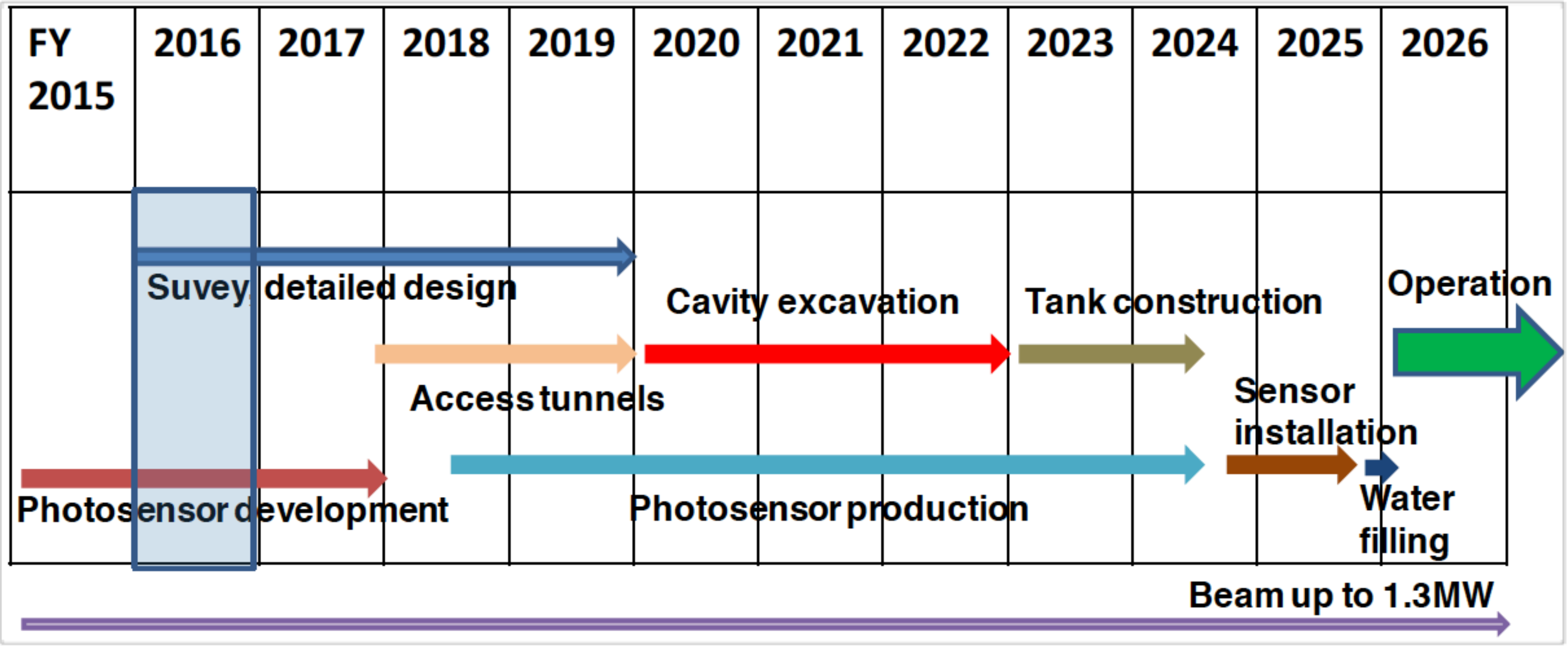


Mt. Bohyun

Tunnel length: 3.9 km

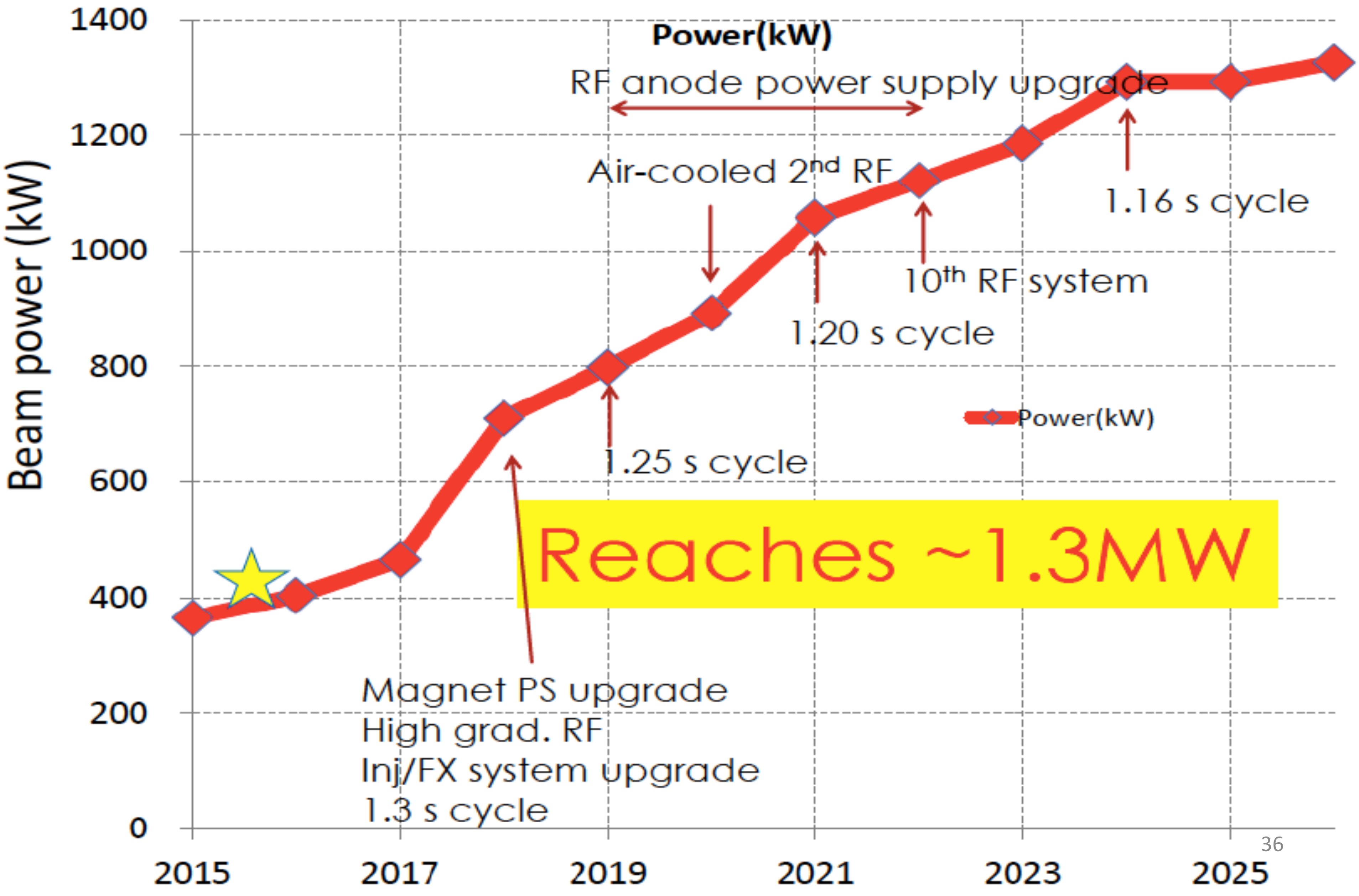
Overburden: 1,038 m

Hyper-K Schedule



- Assuming funding from 2018
- The 1st detector construction in 2018~2025
  - Cavern excavation: ~5 years
  - Tank (liner, photosensors) construction: ~3 years
  - Water filling: 0.5 years

J-PARC Beam Power Plan



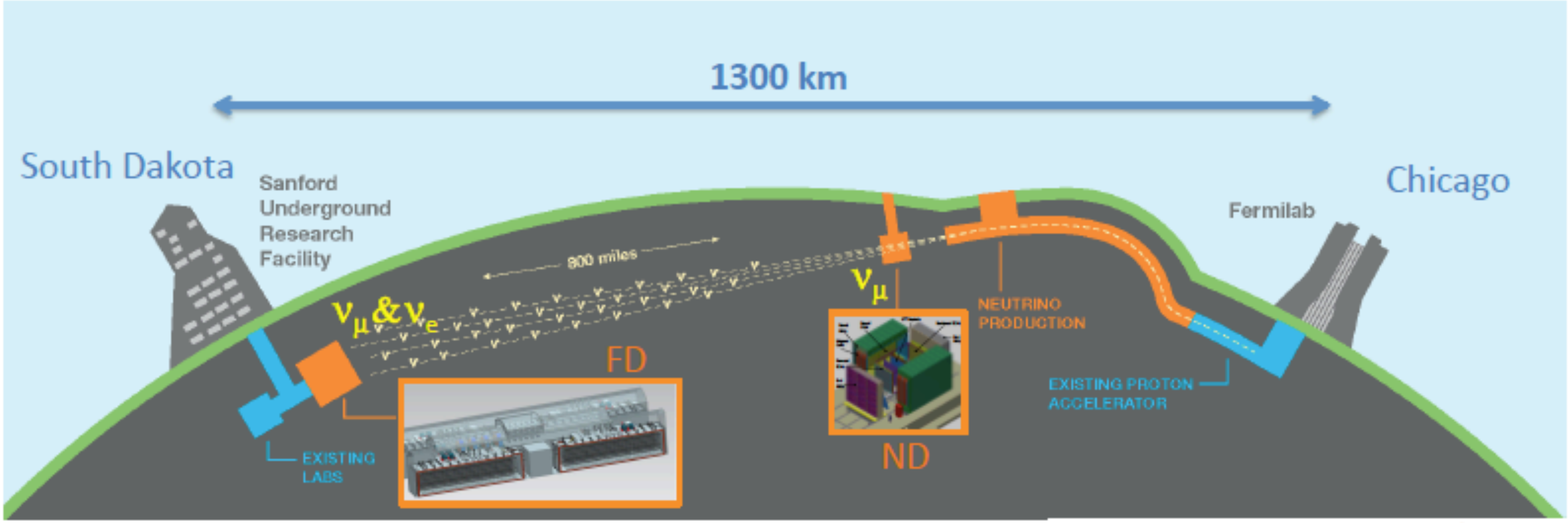
Reaches ~1.3MW

LBNF/DUNE

I took slides from Ed Blucher's talk
at Fermilab user's meeting on June 8th, 2017

LBNF/DUNE Overview

- Muon neutrinos/antineutrinos from high-power proton beam
  - **1.2 MW** from day one; upgradeable to 2.4 MW In 2032
- Massive underground Liquid Argon Time Projection Chambers
  - **4 x 17 kton** fiducial mass of > 40 kton
- Near detector to characterize the beam (100s of millions of neutrino interactions)



3 8 June 2017 Ed Blucher I Fermilab Users Meeting

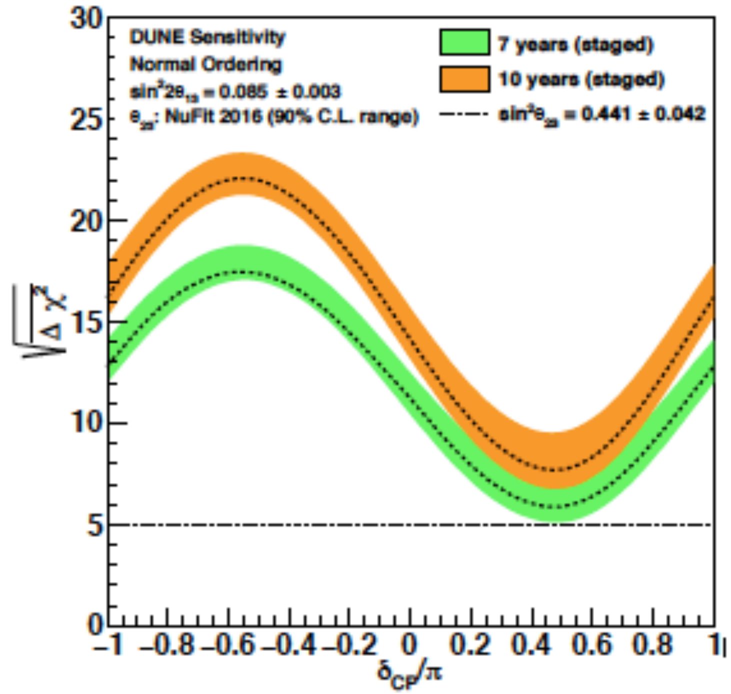
DUNE Science Program

- Neutrino Oscillation Physics
  - **Search for leptonic (neutrino) CP Violation**
  - Resolve the mass hierarchy ($m_3 > m_{1,2}$ or $m_{1,2} > m_3$)
  - Precision oscillation physics
    - Parameter measurements, θ_{23} octant
    - **Testing the current 3-neutrino model, non-standard interactions,** …
- Nucleon Decay
  - Particularly sensitive to $p \rightarrow K^+ \overline{\nu}$
- Supernova burst physics and astrophysics
  - 3000 ν_e events in 10 sec from SN at 10 kpc

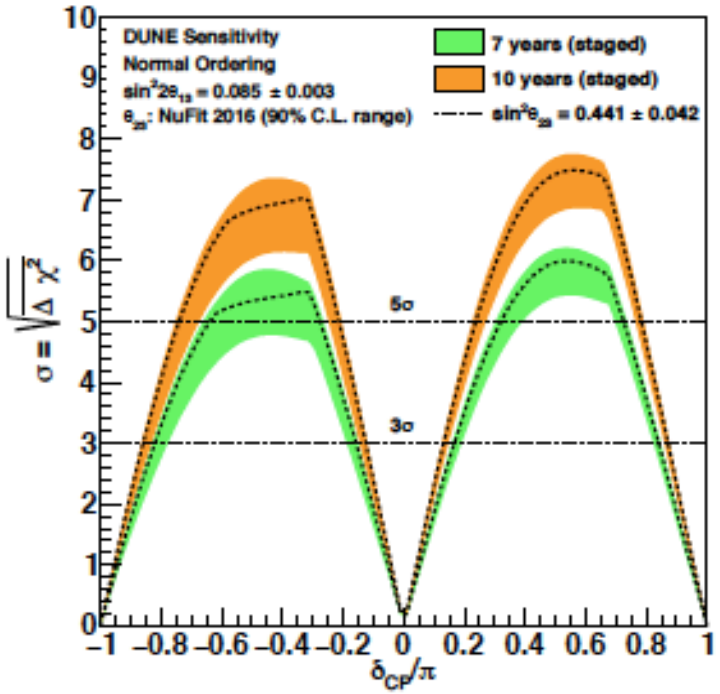
+ many other topics (ν interaction physics with near detector, atmospheric neutrinos, sterile neutrinos, WIMP searches, Lorentz invariance tests, etc.)

Mass Hierarchy and CP Violation

Mass Hierarchy Sensitivity



CP Violation Sensitivity

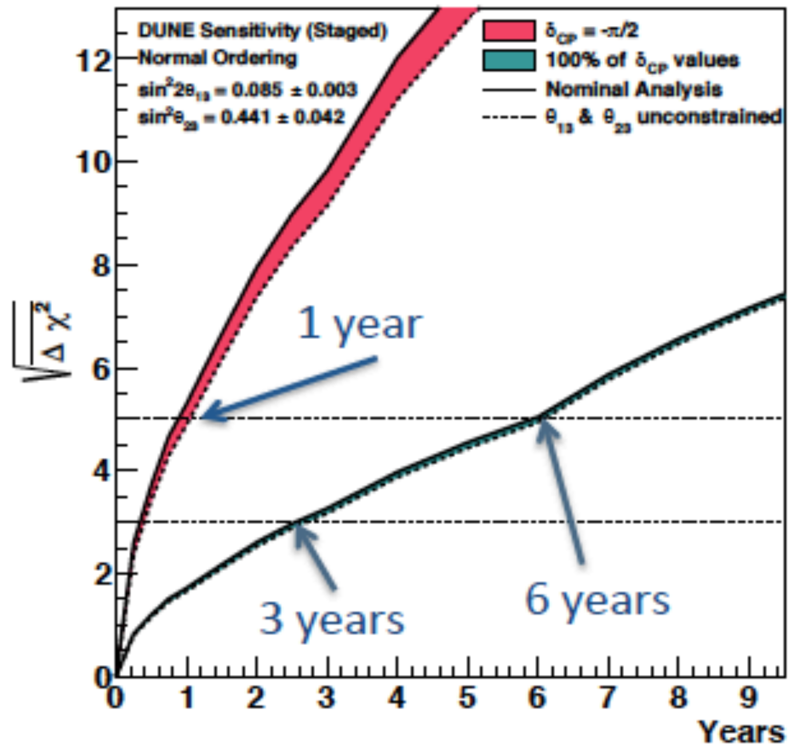


After 7 years (staged):

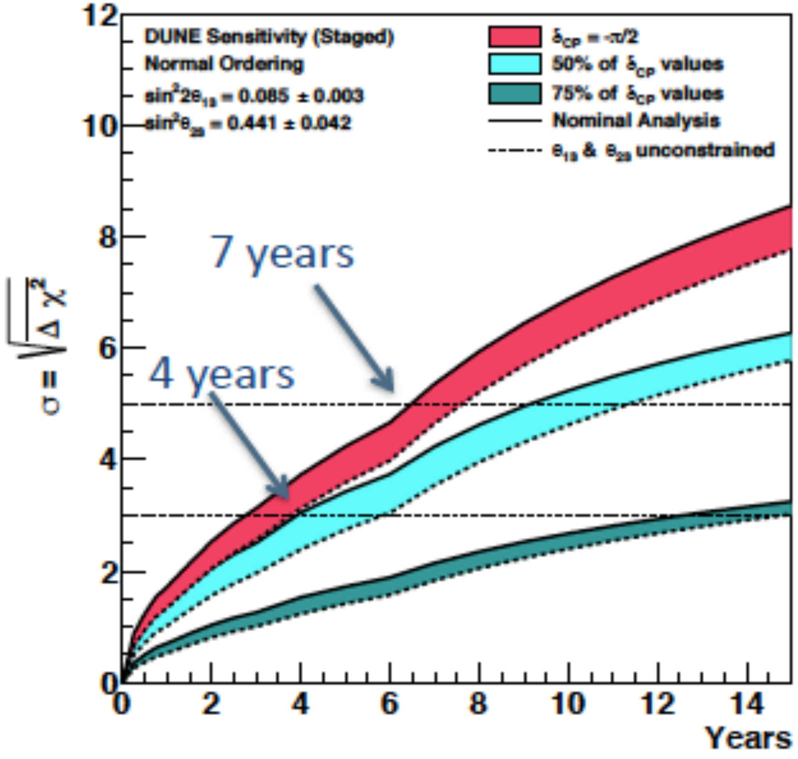
- CP Violation: 5σ if δ_{CP} near $-\pi/2$; 3σ over 65% of δ_{CP} range
- Mass hierarchy determination: > 5σ for all parameter values

Sensitivity vs. time

Mass Hierarchy Sensitivity



CP Violation Sensitivity



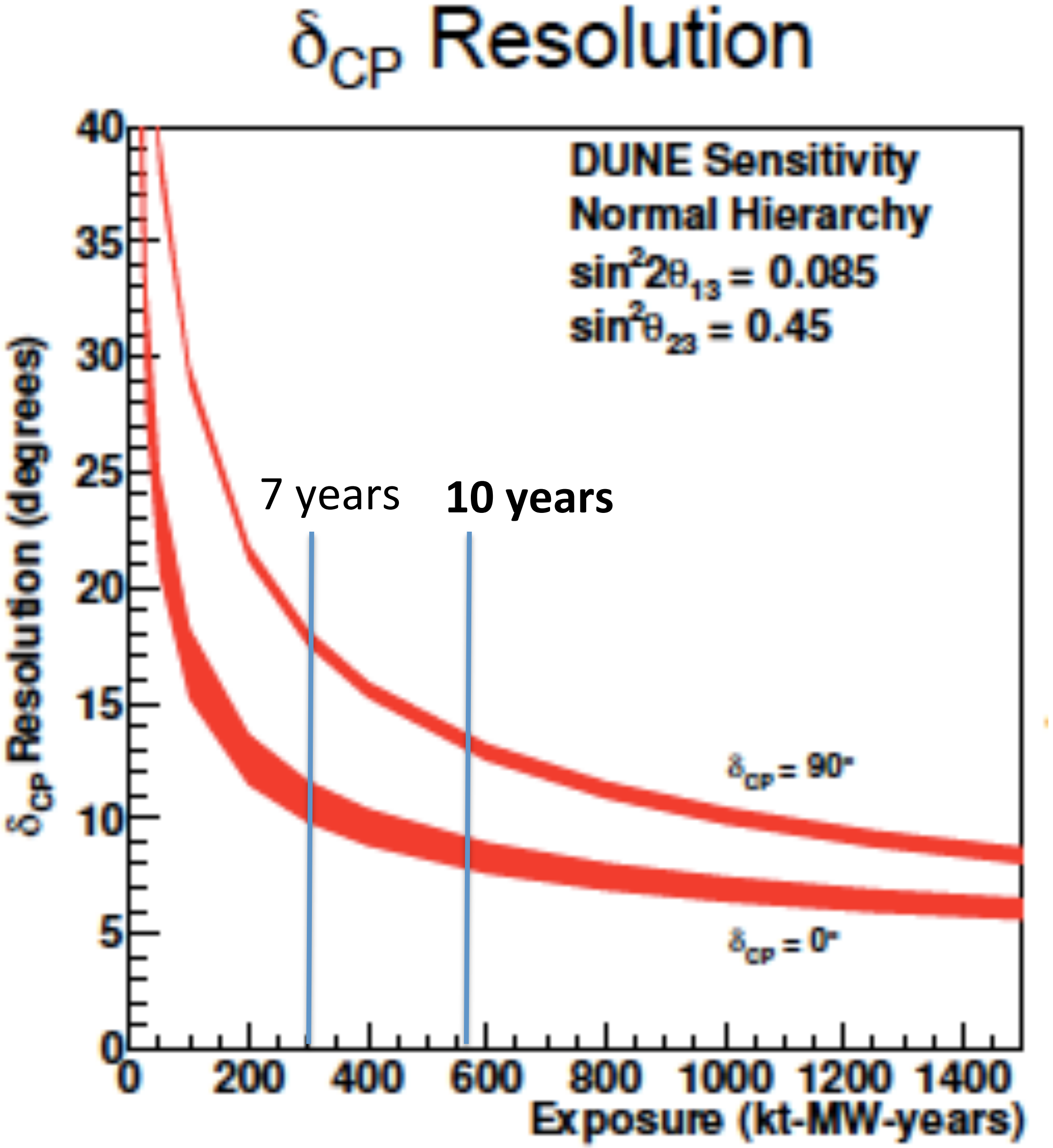
Important sensitivity milestones throughout beam physics program

Staging assumptions

- Year 1 (2026): 20-kt FD with 1.07 MW (80-GeV) beam and initial ND constraints
- Year 2 (2027): 30-kt FD
- Year 4 (2029): 40-kt FD and improved ND constraints
- Year 7 (2032): upgrade to 2.14 MW (80-GeV) beam (technically limited schedule)

Exposure (kt-MW-years)	Exposure (Years)
171	5
300	7
556	10
984	15

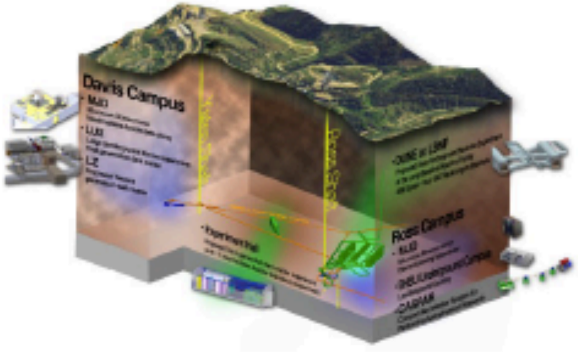
DUNE CDR:

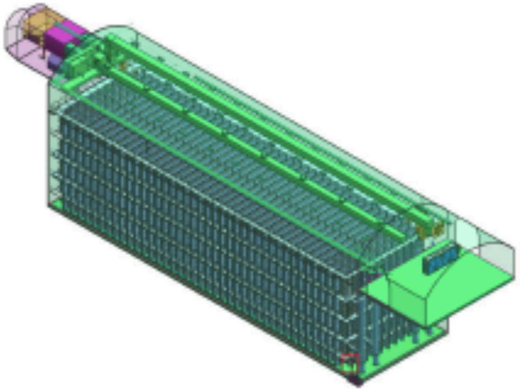


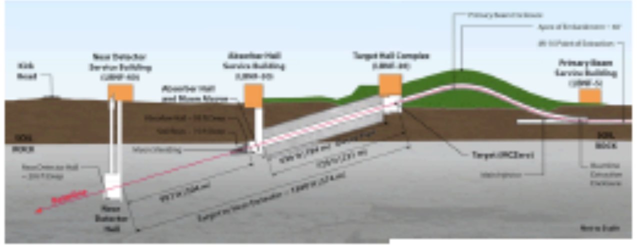
7 years

10 years

DUNE Timeline







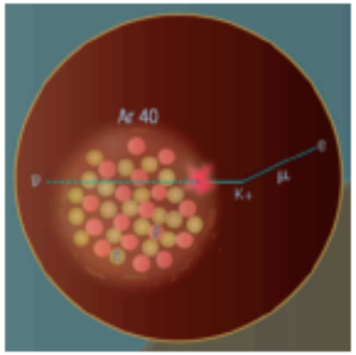
2017: Far Site Construction Begins

2018: protoDUNEs at CERN

2021: Far Detector Installation Begins

2024: Physics Data Begins

2026: Neutrino Beam Available



40 kton + 2 MW beam to follow in subsequent years

Neutrino Physics in 2035

	HK: x2 JD Beam ν	**HK: JD + KD Beam ν**	**HK: JD + KD Beam+ atm. ν**	**DUNE Beam ν**
Baseline	295 km + 295 km	295 km + ~ 1100 km	295 km + ~ 1100 km	1300 km
Detector Fiducial Vol.	2 x 190 kton water	2 x 190 kton water	2 x 190 kton water	40 kton LAr
POT (run time, $\nu:\bar{\nu}$)	2.7 x 10^{22} (10 yrs, 1:3)	2.7 x 10^{22} (10 yrs, 1:3)	2.7 x 10^{22} (10 yrs, 1:3)	556/ kt.MW.yr (10 yrs, 1:1)
$\delta_{CP} = \pi/2, 3\pi/2$ (known N.O.)	~ 8 σ	> 8 σ	> 8 σ	< 8 σ & > 7 σ
δ_{CP} precision @ $\delta_{CP} = 0, \pi$	17^{o}	$13 \sim 14^{o}$	$\sim 11^{o}$	$\sim 9^{o}$
δ_{CP} coverage (known N.O.)	~53 % at 5 σ	~58 % at 5 σ	75 % at 3 σ	65 % at 3 σ
M.O. (true: N.O.)	> 1 σ for all δ_{CP}	> 6 σ for all δ_{CP}	> 7.5 σ for all δ_{CP}	> 8 σ for all δ_{CP}

Summary

☐ Hyper-K and DUNE use different technology to study very challenging but fundamental ν physics . → both are needed.

☐ **T2HKK: 2nd Hyper-K detector in Korea (1st and 2nd osc. Max.)**

will improve MO & CP sensitivities in Hyper-K.
δ_{CP} precision and non-standard ν interaction are also improved.
Solar/SN burst & relic ν sensitivities will be improved as well.

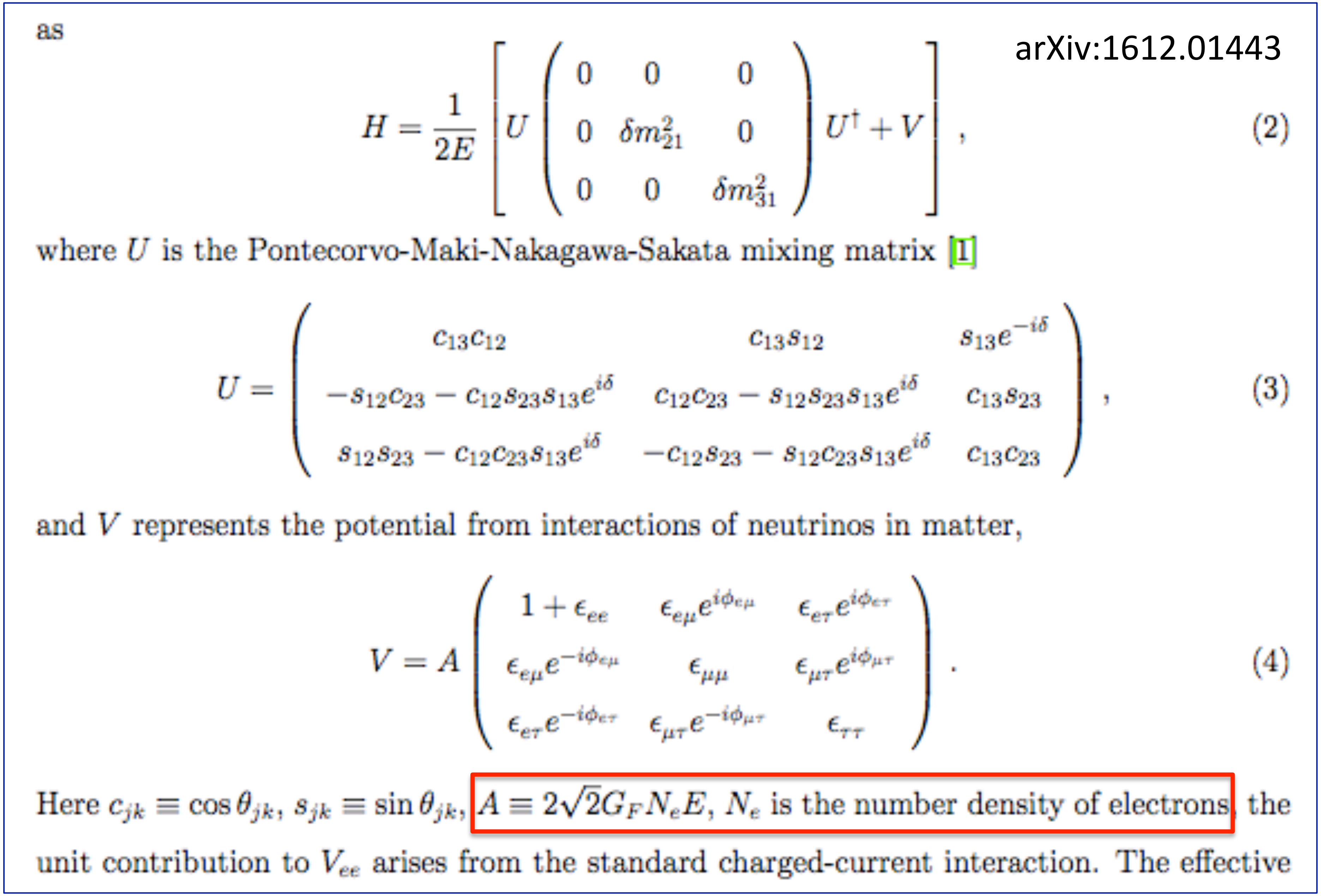
☐ Adding atm. data will improve sensitivities a little more in HK.

☐ Both Hyper-K and DUNE will start taking data in 2026.

☐ By 2035 Hyper-K and DUNE will determine ν MO at high CL & give precision measurements of δ_{CP} (discover ν CPV ?).

Backup slides

Non-standard ν Interaction



arXiv:1612.01443

as

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

where U is the Pontecorvo-Maki-Nakagawa-Sakata mixing matrix [1]

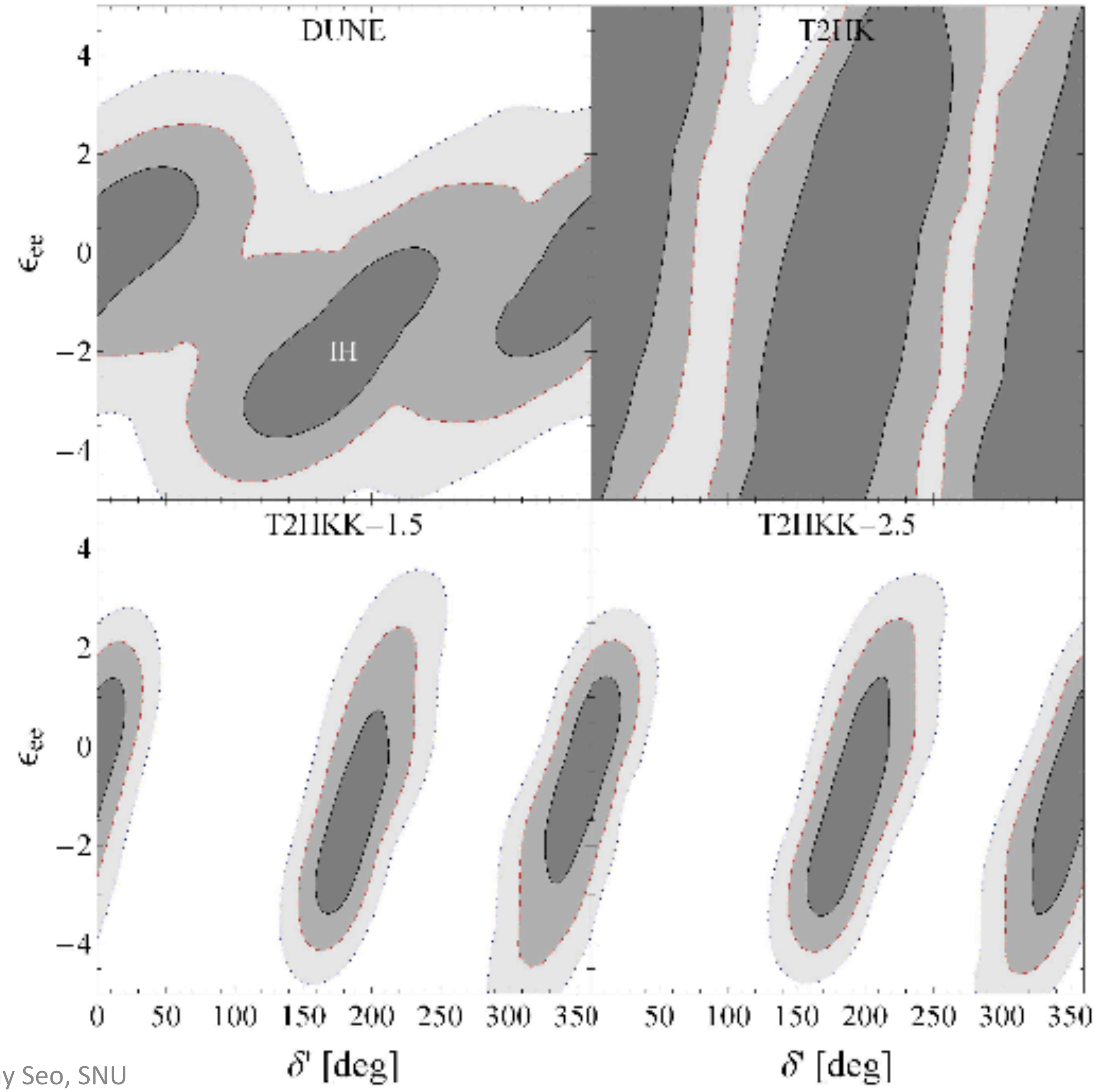
$$U = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{13}c_{23} \end{pmatrix}, \tag{3}$$

and V represents the potential from interactions of neutrinos in matter,

$$V = A\begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu}e^{i\phi_{e\mu}} & \epsilon_{e\tau}e^{i\phi_{e\tau}} \\ \epsilon_{e\mu}e^{-i\phi_{e\mu}} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}e^{i\phi_{\mu\tau}} \\ \epsilon_{e\tau}e^{-i\phi_{e\tau}} & \epsilon_{\mu\tau}e^{-i\phi_{\mu\tau}} & \epsilon_{\tau\tau} \end{pmatrix}. \tag{4}$$

Here $c_{jk} \equiv \cos\theta_{jk}$, $s_{jk} \equiv \sin\theta_{jk}$, $A \equiv 2\sqrt{2}G_F N_e E$, N_e is the number density of electrons, the unit contribution to V_{ee} arises from the standard charged-current interaction. The effective

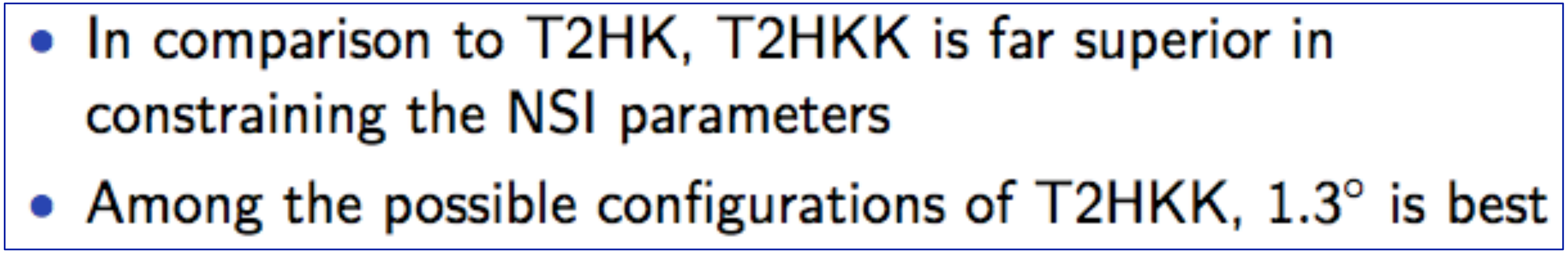
Non-standard ν Interaction



arXiv:1612.01443

Non-standard ν Interaction

Conclusion:



- In comparison to T2HK, T2HKK is far superior in constraining the NSI parameters
- Among the possible configurations of T2HKK, 1.3° is best

arXiv:1611.06141 arXiv:1612.01443

→ There is an update on this study
from Yasuda-san's group (M. Ghosh) tomorrow.

Estimated Muon Fluxes

820 m overburden

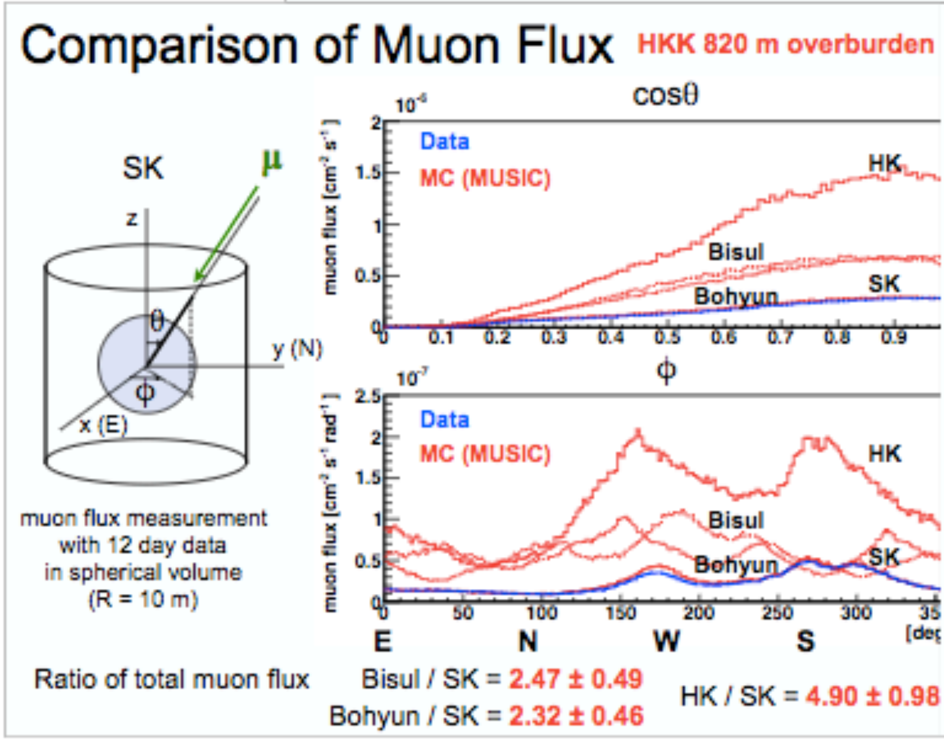
Ratio of total muon flux $(\mathrm{HKK}_{\mathrm{Bisul}}$ / SK) = **2.47 ± 0.49**

Ratio of rate $(^{16}\mathrm{N})$ $(\mathrm{HKK}_{\mathrm{Bisul}}$ / SK) = **1.99 ± 0.44**

1,000 m overburden

Ratio of total muon flux $(\mathrm{HKK}_{\mathrm{Bisul}}$ / SK) = **1.03 ± 0.21**

Ratio of rate $(^{16}\mathrm{N})$ $(\mathrm{HKK}_{\mathrm{Bisul}}$ / SK) = **1.03 ± 0.21**



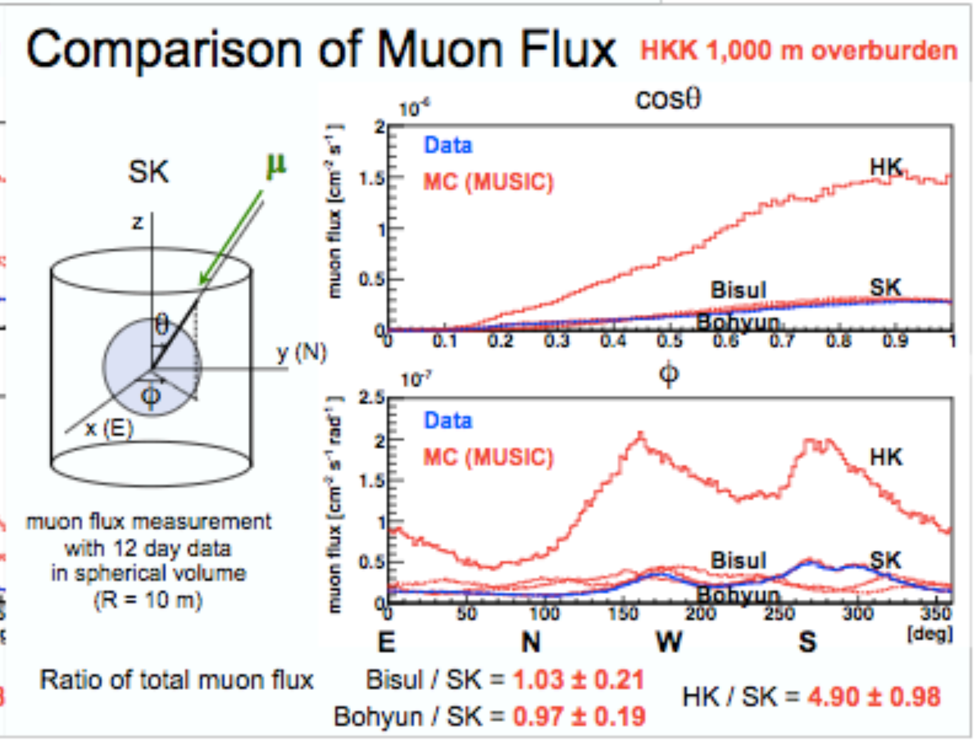
Comparison of Muon Flux **HKK 820 m overburden**

muon flux measurement
with 12 day data
in spherical volume
(R = 10 m)

Ratio of total muon flux

Bisul / SK = **2.47 ± 0.49**
Bohyun / SK = **2.32 ± 0.46**

HK / SK = **4.90 ± 0.98**



Comparison of Muon Flux **HKK 1,000 m overburden**

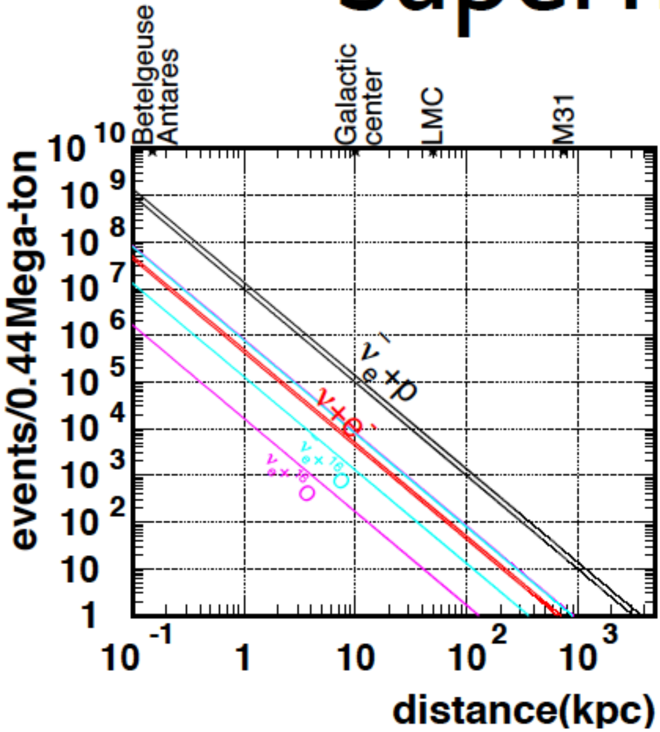
muon flux measurement
with 12 day data
in spherical volume
(R = 10 m)

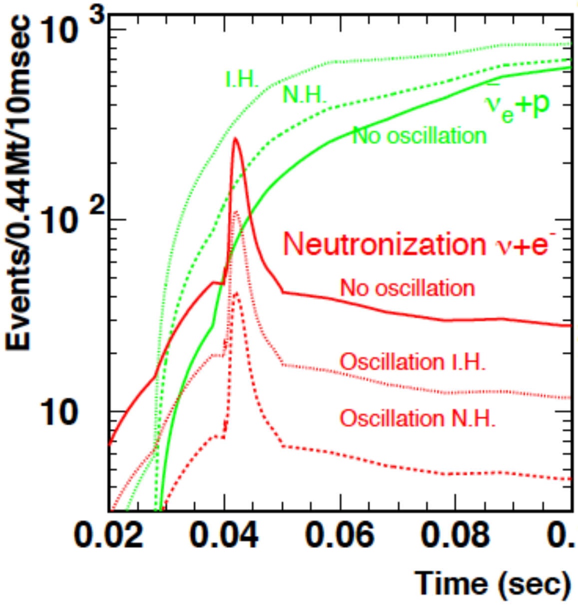
Ratio of total muon flux

Bisul / SK = **1.03 ± 0.21**
Bohyun / SK = **0.97 ± 0.19**

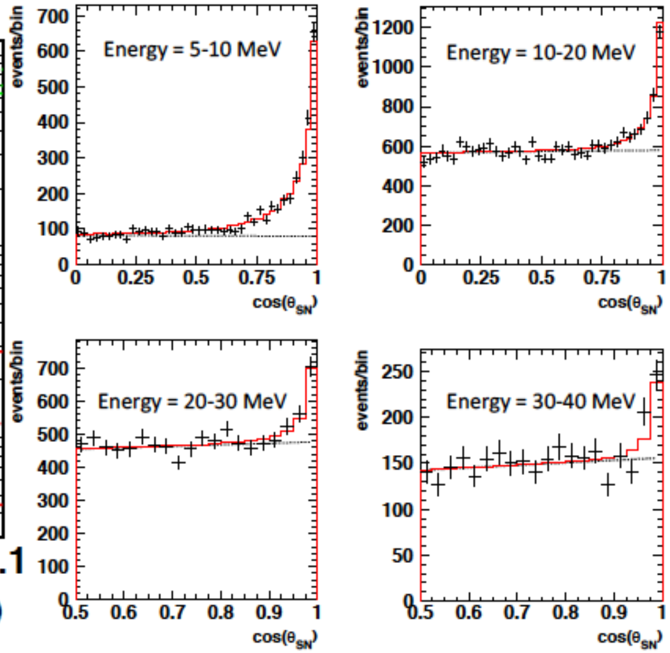
HK / SK = **4.90 ± 0.98**

Supernova burst neutrino





SN explosion mechanism

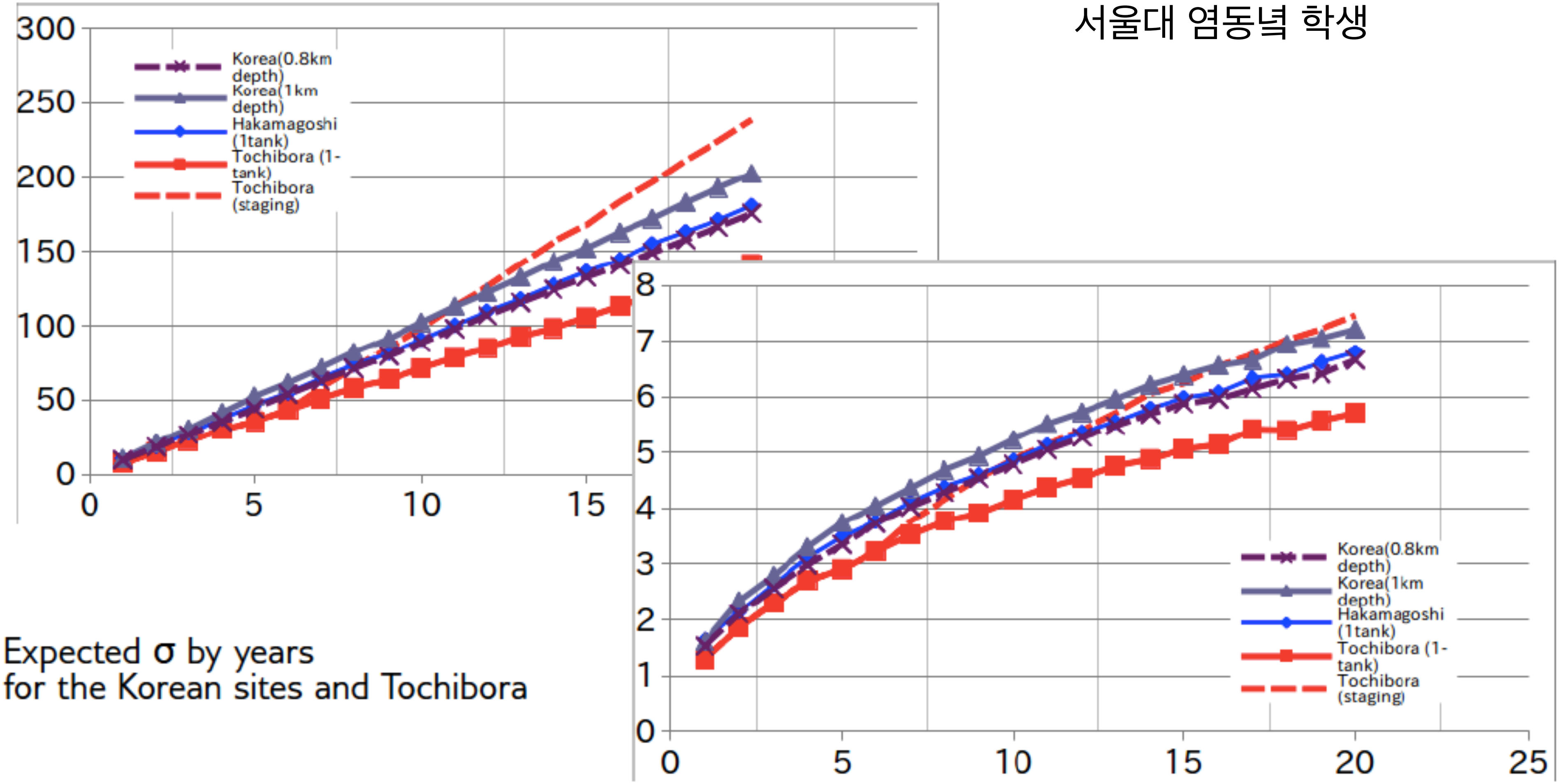


SN directional info.
by ν+e scattering

- Large statistics for galactic SN
  - Precise timing and energy information to probe SN mechanism
  - Pointing (2deg@10kpc) and timing for multi-messenger astronomy
- Nearby (>1Mpc) SN
  - Check of dim SN, coincidence with GW telescope, …

SRN Sensitivity

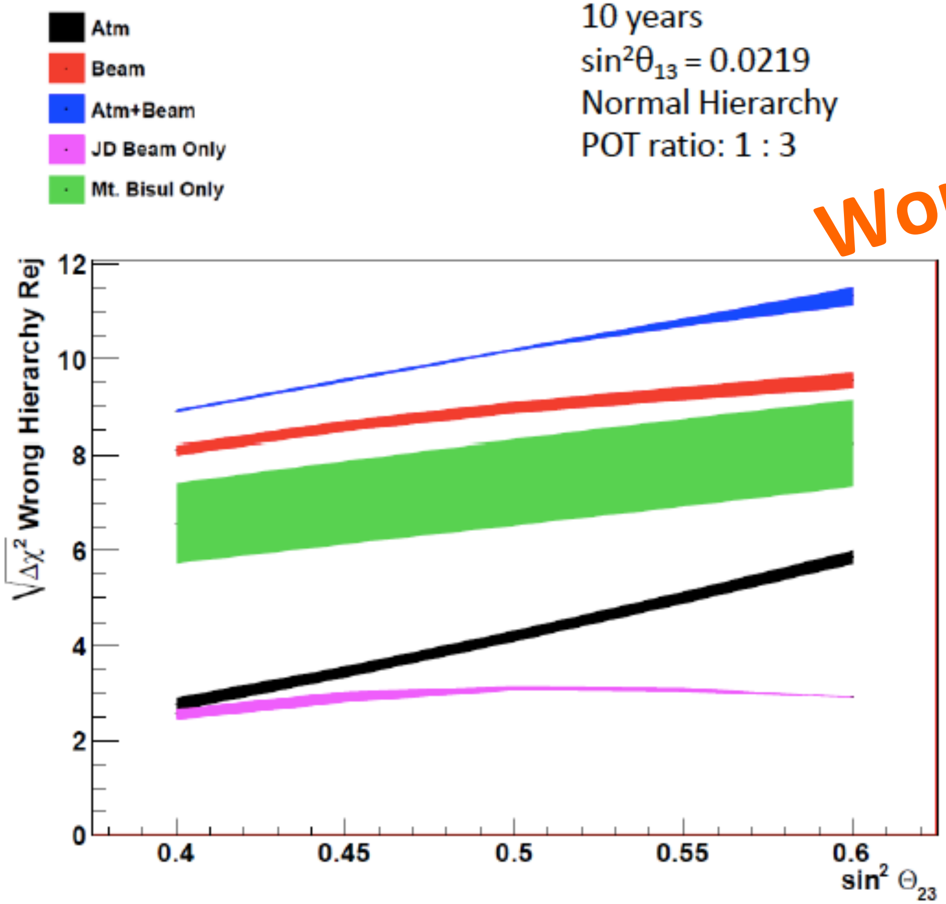
서울대 염동녘 학생



Expected σ by years
for the Korean sites and Tochibora

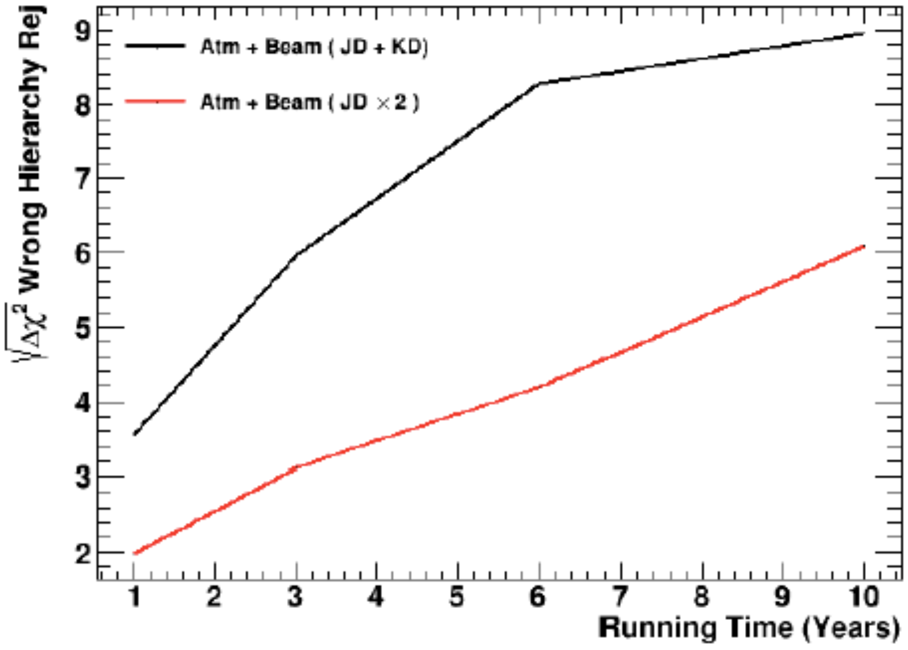
Beam + Atm. Data

Mass ordering sensitivity



10 years
$\sin^2\theta_{13} = 0.0219$
Normal Hierarchy
POT ratio: 1 : 3

Work in progress



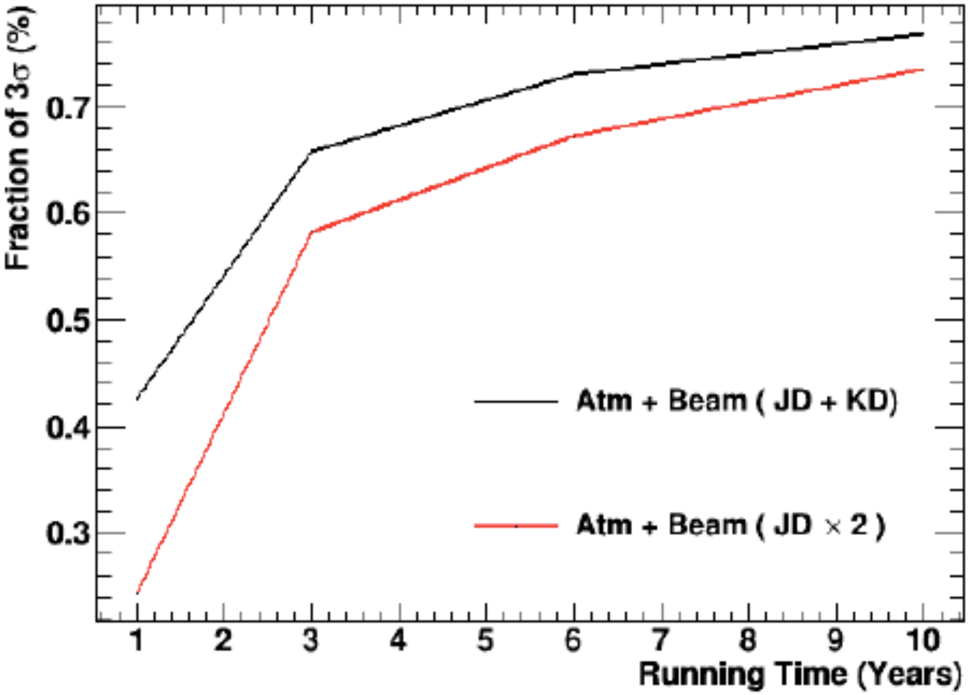
Error bar represents the effect from the uncertainty of δCP.
(Only $\delta_{CP} = 0$ and π are tested.)

Beam + Atm. Data

CP sensitivity

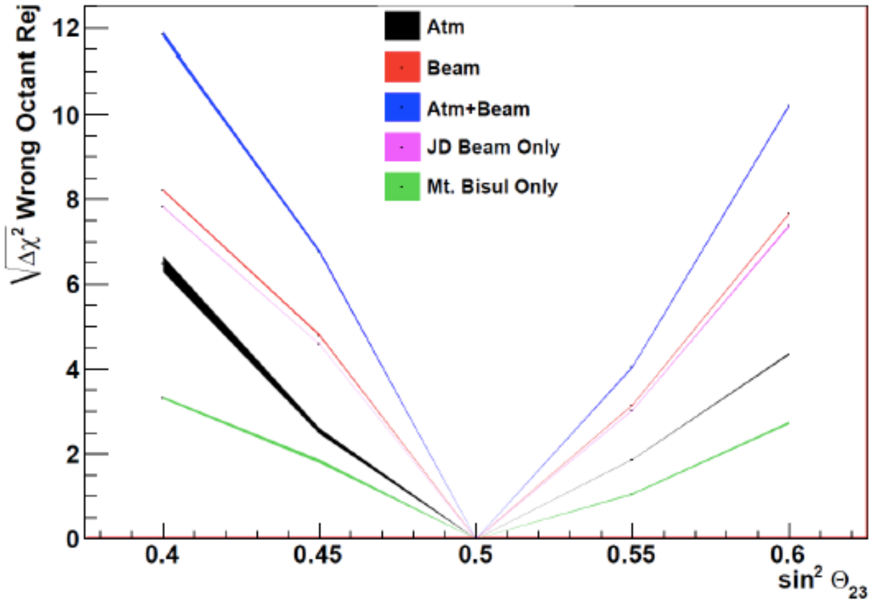
10 years
$\sin^2\theta_{13} = 0.0219$
$\sin^2\theta_{23} = 0.5$
Known Normal Hierarchy
POT ratio: 1 : 3
(Staging only for JD × 2)

Work in progress



Octant sensitivity

10 years
$\sin^2\theta_{13} = 0.0219$
Known Normal Hierarchy
POT ratio: 1 : 3



Beam + Atm. Data

Uncertainty of δ_{CP} vs running time

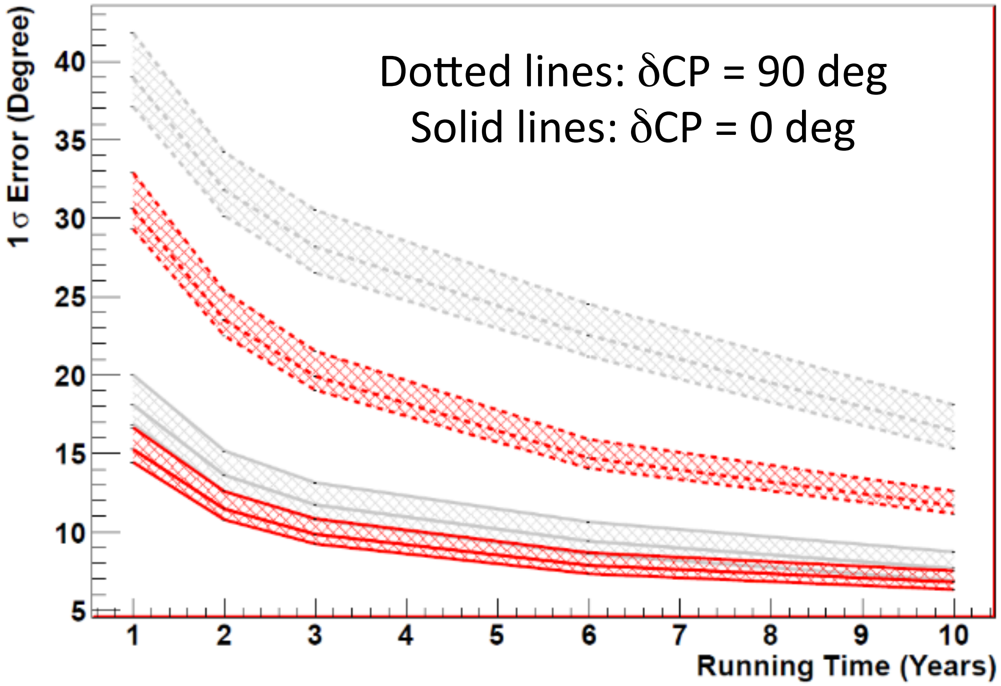
Work in progress

— JD × 2
— JD + KD

$\sin^2\theta_{13} = 0.0219$
$\sin^2\theta_{23} = 0.5$
Known Normal Hierarchy
POT ratio: 1 : 3
(Staging only for JD × 2)

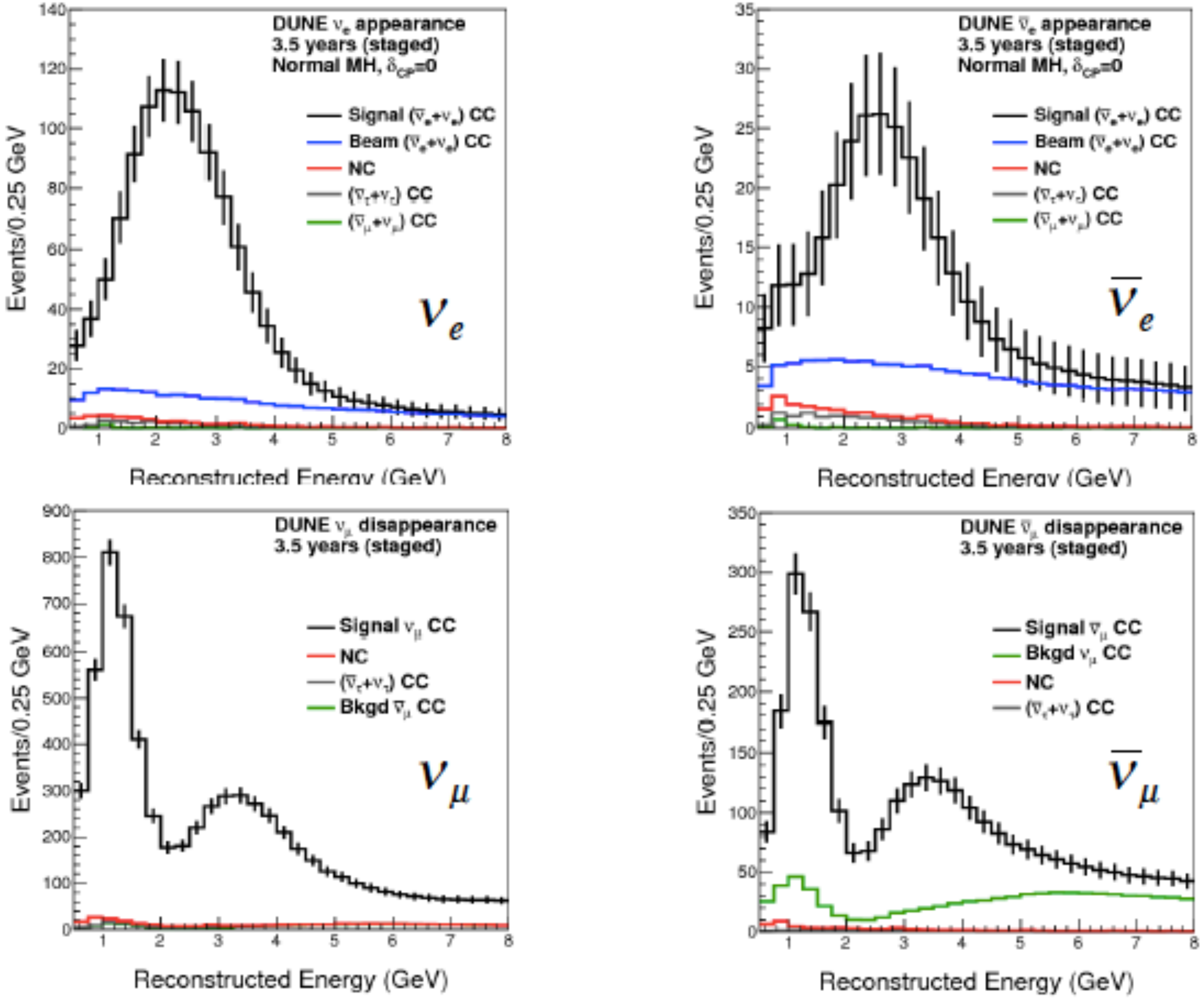
JD + KD has better precision than that of JD × 2, always.

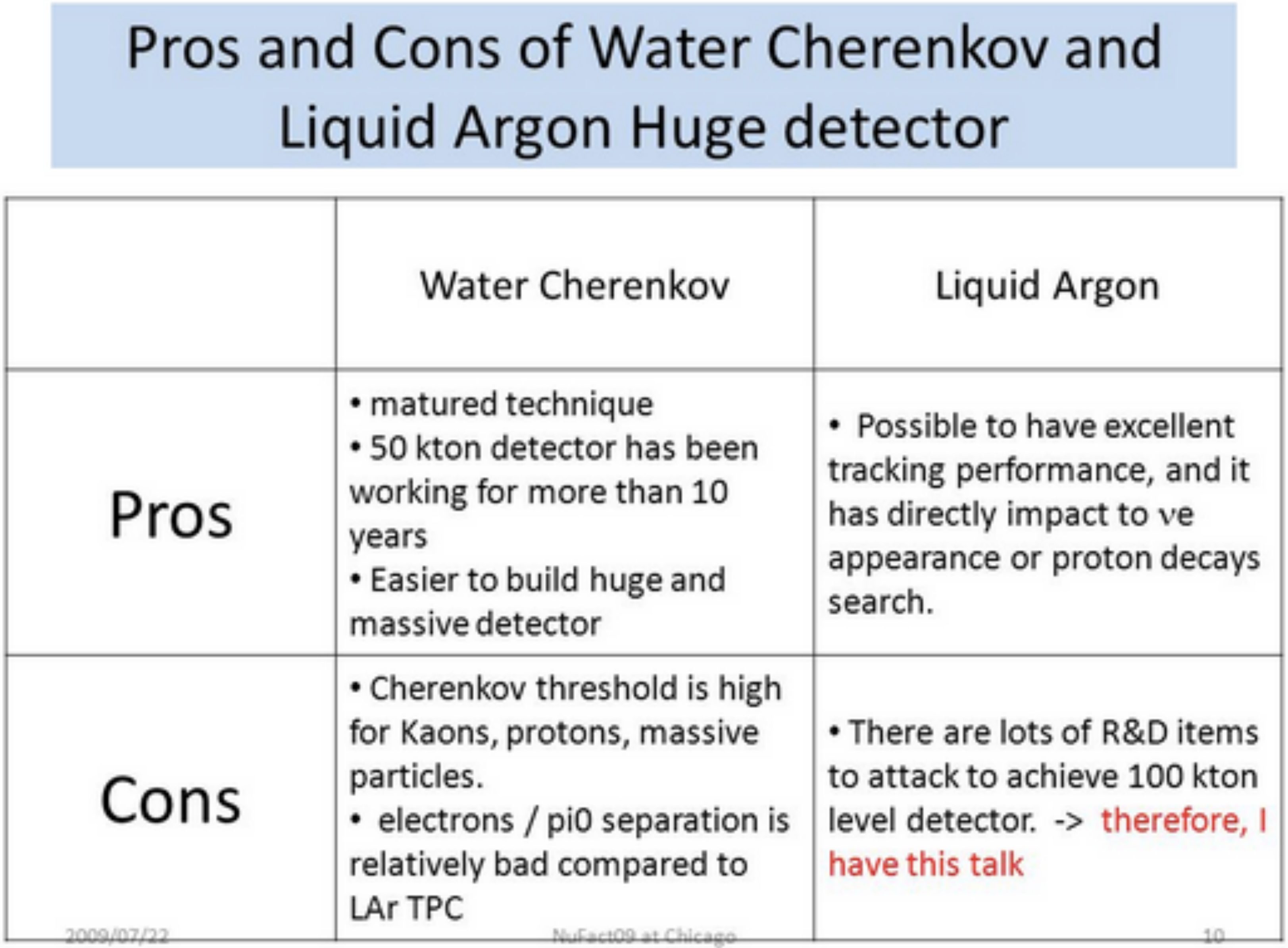
Error bar shows the effect due to the sinθ23.
Three points (0.4, 0.5, 0.6) are tested.



Dotted lines: δCP = 90 deg
Solid lines: δCP = 0 deg

Appearance and disappearance spectra





Pros and Cons of Water Cherenkov and Liquid Argon Huge detector

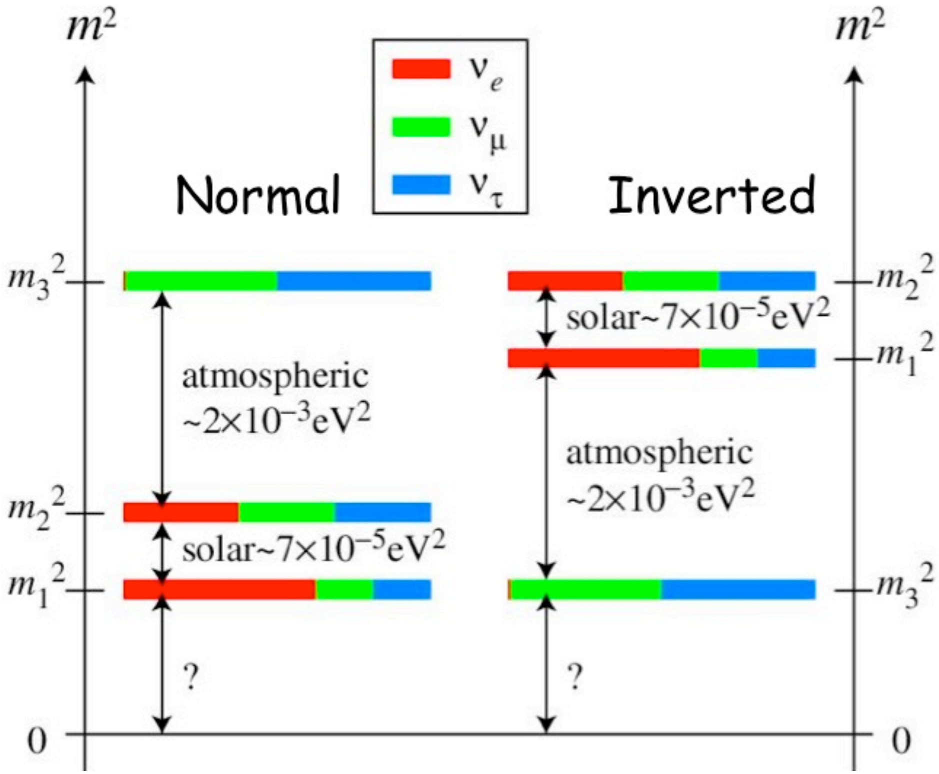
	Water Cherenkov	Liquid Argon
Pros	• matured technique • 50 kton detector has been working for more than 10 years • Easier to build huge and massive detector	• Possible to have excellent tracking performance, and it has directly impact to νe appearance or proton decays search.
Cons	• Cherenkov threshold is high for Kaons, protons, massive particles. • electrons / pi0 separation is relatively bad compared to LAr TPC	• There are lots of R&D items to attack to achieve 100 kton level detector. -> therefore, I have this talk

2009/07/22 NuFact09 at Chicago 10

Neutrino mass ordering

NO: Normal Ordering

IO: Inverted Ordering



- GUT → Normal ordering
- Origin of the universe
  → Inverted ordering
- Connection to Dirac or Majorana nature of ν

Leptonic CP Violation Phase

$$P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)?$$

- Matter anti-matter asymmetry

- flavor symmetry models of neutrino mixing