Neutrinos, present and future

Jan Kisiel
Institute of Physics, University of Silesia
Katowice, Poland
(on behalf of the T2K Collaboration)

8th International Conference on New Frontiers in Physics (ICNFP 2019)

Outline * **

- Neutrinos - present: status of neutrino oscillations
- T2K, NOvA: the running long baseline experiments – some selected results
- Hyper-K and DUNE - future long baseline experiments:

  - CP violation, proton decay.
- JUNO: next generation liquid scintillator neutrino detector
- Program for the future/present neutrino experiments
- Summary

** Based on my personal biases and work for the T2K exp. I have chosen only few topics. Sorry for not covering others.*

*** I will focus on future experiments.*

Neutrino oscillation: 2 flavor mixing (1)

Mass and flavor states are not identical – there is a mixing:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Time evolution of the flavor states in quantum mechanics:

$$|\nu_e\rangle = cos\theta e^{-iE_1 t}|\nu_1\rangle + sin\theta e^{-iE_2 t}|\nu_2\rangle$$

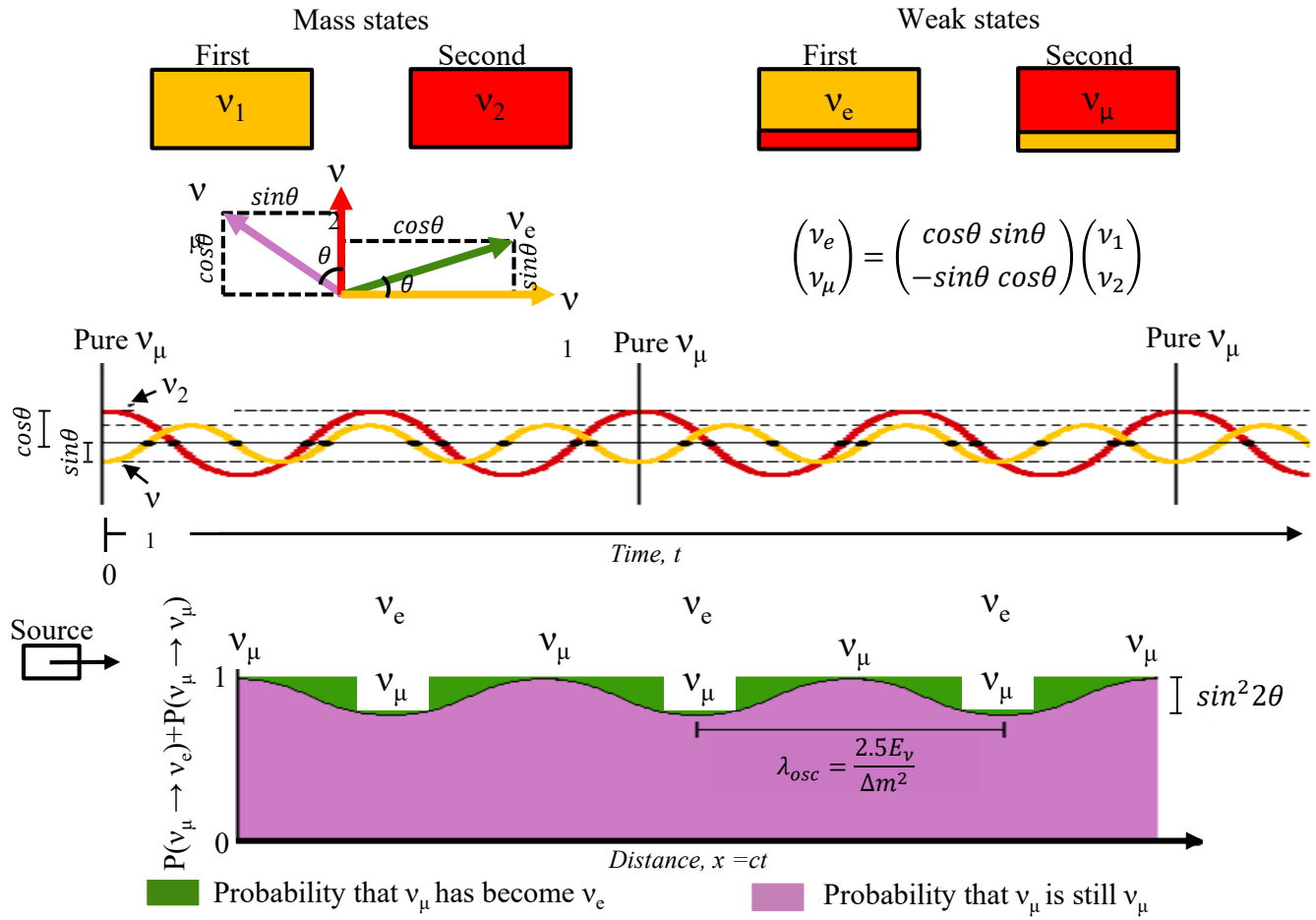
$$|\nu_\mu\rangle = -sin\theta e^{-iE_1 t}|\nu_1\rangle + cos\theta e^{-iE_2 t}|\nu_2\rangle$$

If at t=0 we produce pure muon (flavor α) neutrino beam the probability of observing electron (flavor β) neutrino in a detector placed at distance L:

$$P(\nu_\alpha \rightarrow \nu_\beta) = sin^2 2\theta \cdot sin^2\left(\frac{1.27\ \Delta m^2[eV^2]\ L[km]}{E_\nu[GeV]}\right)$$

Depends on *L/Ev*
***L*: baseline, distance source-detector**
***Ev*: energy of neutrino beam**
(can be chosen for an experiment!)

Neutrino oscillations: 2 flavor mixing (2)



For θ = π/4 and L = L_{osc}/2 there is maximal mixing, i.e. all initial flavor ν_μ becomes ν_e.

From D.Kiełczewska Lectures

Oscillation of 3 neutrino flavors: current picture and questions

Unitary, Pontecorvo-Maki-Nakagawa_Sakata (PMNS) matrix describes the mixing between neutrino flavor and mass eigenstates:

atmospheric/accelerator — accelerator/reactor — solar/reactor

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1 & 0 & 0\\ 0 & C_{23} & S_{23}\\ 0 & -S_{23} & C_{23}\end{pmatrix}\begin{pmatrix}C_{13} & 0 & S_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -S_{13}e^{-i\delta} & 0 & C_{13}\end{pmatrix}\begin{pmatrix}C_{12} & S_{12} & 0\\ -S_{12} & C_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

flavor — mass

$$S_{ij}=\sin(\theta_{ij})$$
$$C_{ij}=\cos(\theta_{ij})$$

In the three flavor model there are 6 parameters to be measured:

2 differences of mass in quadrature, 3 mixing angles and 1 CP phase (for Dirac neutrinos)

Current values, PDG2018, K.Iwamoto, PINS 2019

$\sin^2\theta_{12} = 0.307^{+0.013}_{-0.012}$

$\Delta m^2_{21} = 7.53 \pm 0.18 \times 10^{-5}\ eV^2$

Normal Ordering

$\sin^2\theta_{23} = 0.417^{+0.025}_{-0.028}$ (LO) / $0.597^{+0.024}_{-0.030}$(HO)

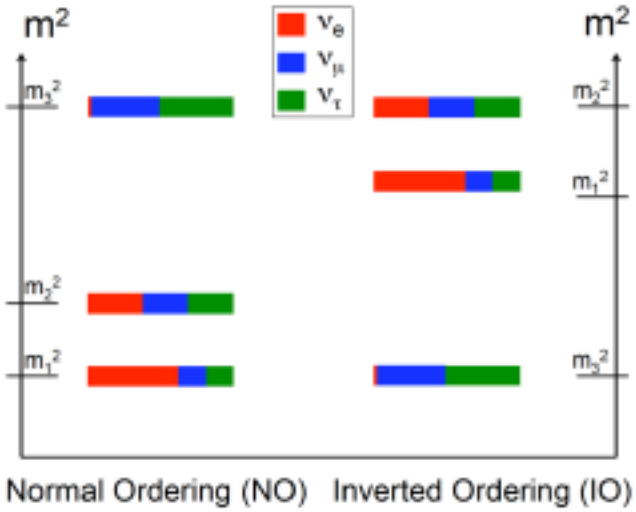
$\Delta m^2_{32} = 2.51 \pm 0.04 \times 10^{-3}\ eV^2$

Inverted Ordering

$\sin^2\theta_{23} = 0.421^{+0.033}_{-0.025}$ (LO) / $0.592^{+0.023}_{-0.030}$(HO)

$\Delta m^2_{31} = -2.56 \pm 0.05 \times 10^{-3}\ eV^2$

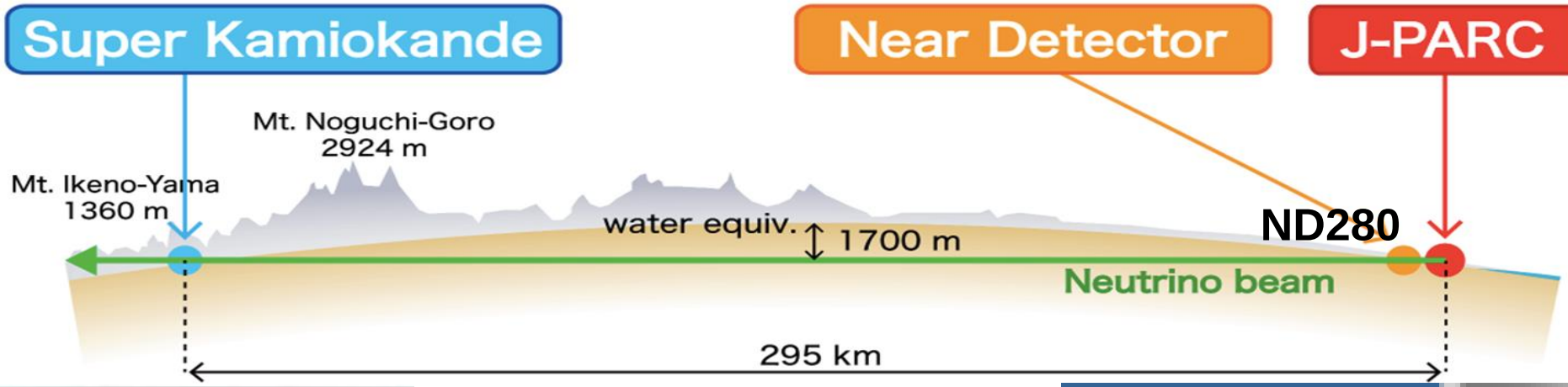
$\sin^2\theta_{13} = 0.0212 \pm 0.0008$

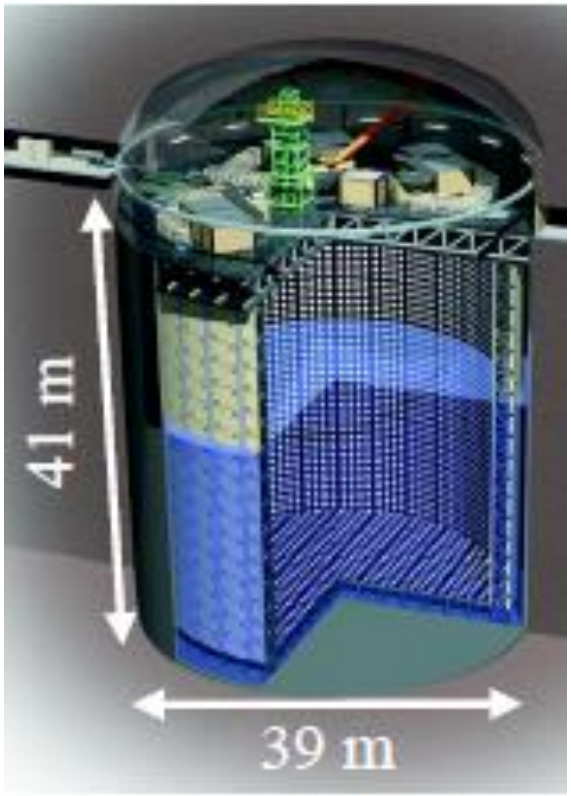


Open questions:

- CPV (δ_{CP} phase)
- mass hierarchy
- $\Theta_{23} > 45^o$ or $\Theta_{23} < 45^o$ or $\Theta_{23} = 45^o$

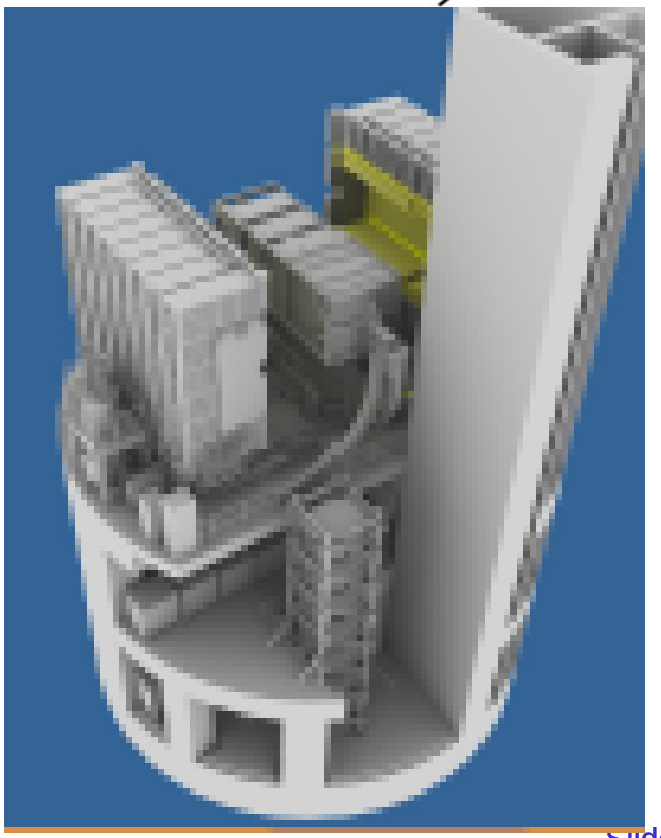
T2K experiment





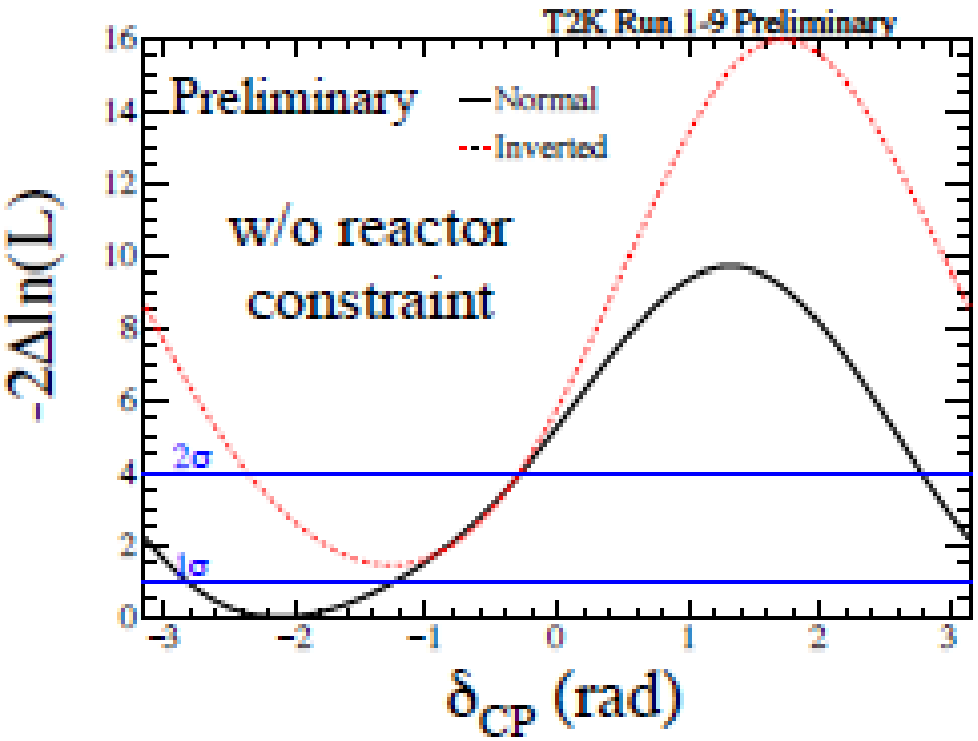
T2K: measurement of J-PARC beam ν and anti-ν interactions in near (ND280) and far (Super-K) detectors.

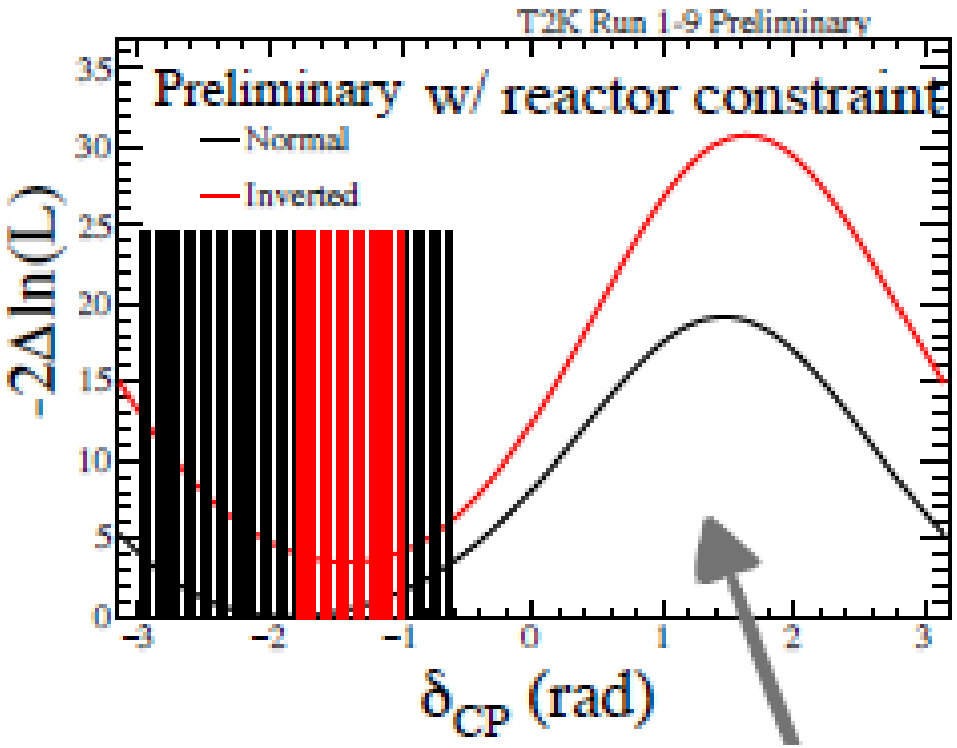
2.5° off-axis neutrino beam peaked at ~ 0.6 GeV; near detector: 280 m baseline; far detector: 295 km baseline, 50 kton water Cherenkov.



T2K: δ_{CP} measurement

T2K data prefer δCP = -π/2: maximize νe appearance and minimize anti-νe appearance





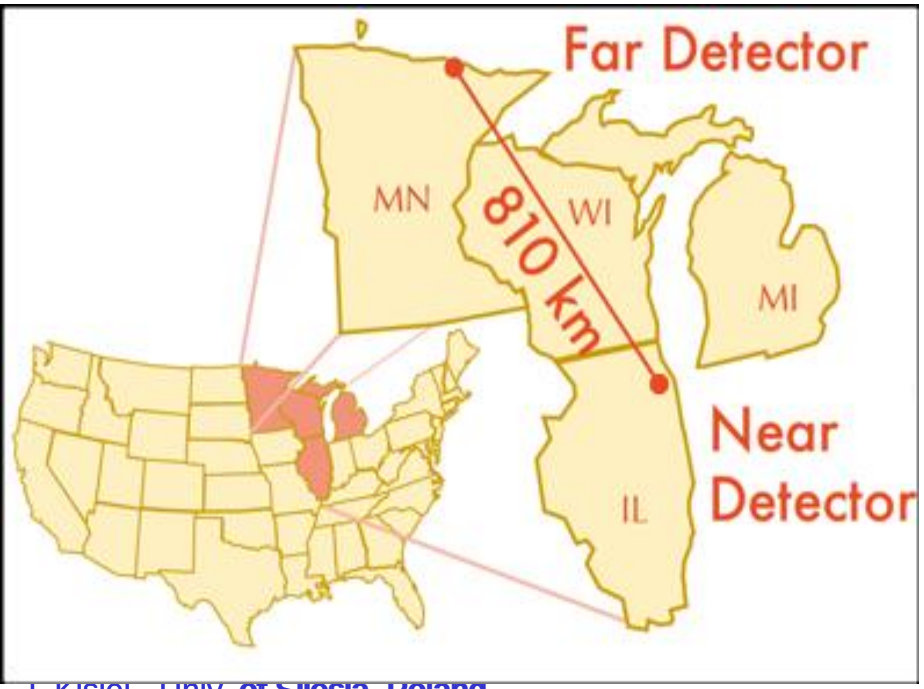
C.L.	Normal hierarchy	Inverted hierarchy
68%	[-2.51, -1.26]	-
90%	[-2.80, -0.84]	-
2σ	[-2.97, -0.63]	[-1.78, -0.98]

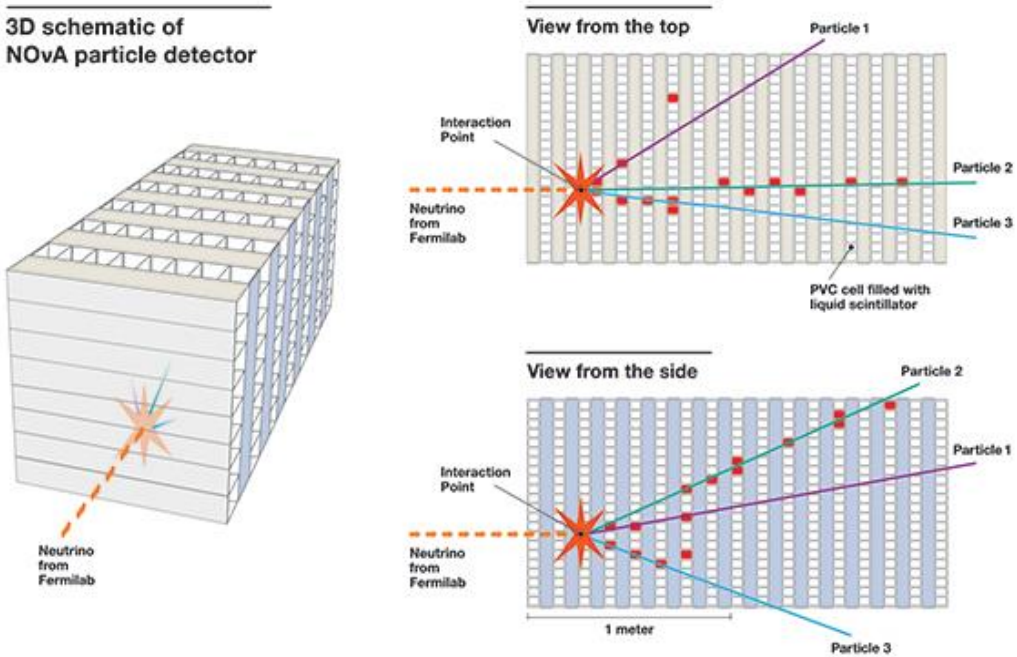
δ_{CP} = 0, π fall outside 2σ interval, i.e. exclusion at 2σ the CP conserving values δ_{CP} = 0 and π

NOvA experiment

NOvA: measurement of Fermilab NuMI beam ν and anti-ν interactions in near and far detectors:

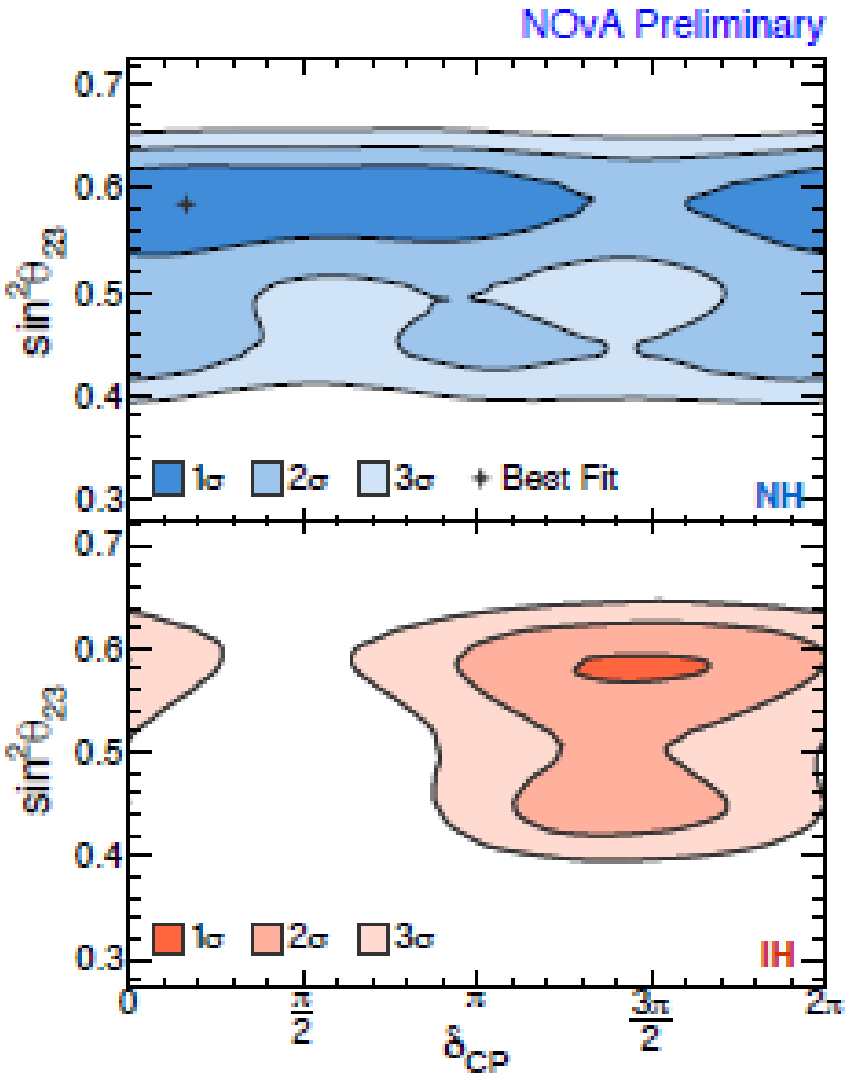
- Functionally identical near and far detectors: plastic and liquid scintillator sampling tracking calorimeters, 14 mrad off-axis.
- Near detector: Fermilab, 300 tons, 1 km baseline.
- Far detector: Ash River, 14 ktons, 810 km baseline.

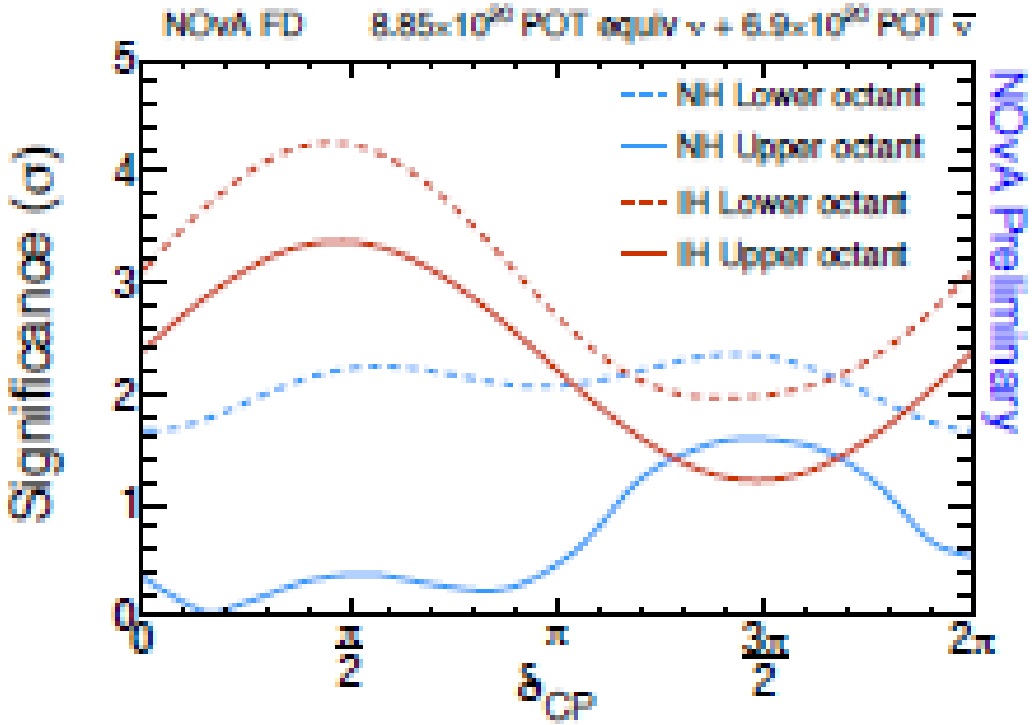




NOvA: oscillation results

NOvA data prefer Normal Hierarchy by 1.8σ. For Inverted Hierarchy δCP = π/2 is excluded at >3σ.





Best fit values:
Normal Hierarchy, $\delta_{CP} = 0.17\pi$,
$\sin^2\theta_{23} = 0.58 \pm 0.03$ (UO),
$\Delta m_2^{23} = (2.51^{+0.12}_{-0.08})\times10^{-3}eV^2$

T2K and NOvA: some (intermediate) conclusions

- Both T2K and NOvA are currently running long baseline neutrino experiments with complementarities: beam energy, baseline, detection technique, …
- Both T2K and NOvA starting to be sensitive to the CP violation in the leptonic sector: an indication of new source of the CP violation.
- Both T2K and NOvA will certainly deliver new results (upgraded beams and detectors) in the next years.
- Also the combination of T2K and NOvA results should bring interesting results.
- However there is a need of the new generation (Hyper-K, DUNE) of long baseline neutrino experiments which could make a great CP violation discovery.

The Sakharov conditions for baryogenesis: imbalance of matter (baryons) and antimatter (antibaryons) in Universe

1) **Baryon number is not conserved (must exist an interaction that violates B-number): can be probed by searches for proton decay.**

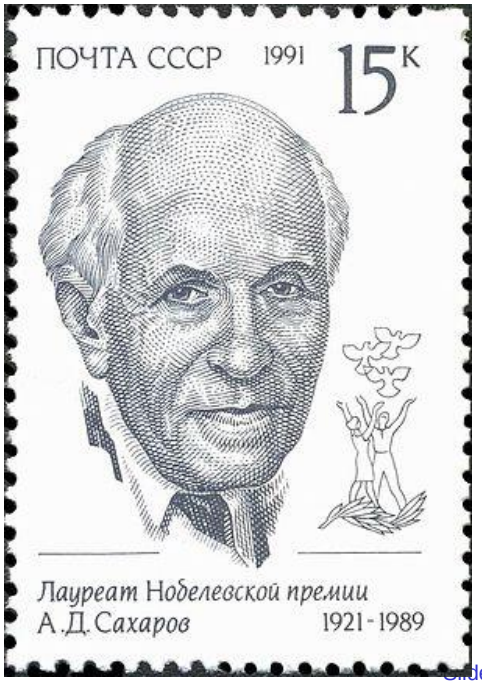
2) **There must be an interaction that violates C and CP symmetries: in the leptonic sector CP can be probed by searches for differences in neutrino/antineutrino oscillations.**

3) **Departure from thermal equilibrium: the B-violating interaction must go out of thermal equilibrium.**

VIOLATION OF CP INVARIANCE, C ASYMMETRY, AND BARYON ASYMMETRY OF THE UNIVERSE

A. D. Sakharov
Submitted 23 September 1966
ZhETF Pis'ma 5, No. 1, 32-35, 1 January 1967

The theory of the expanding Universe, which presupposes a superdense initial state of matter, apparently excludes the possibility of macroscopic separation of matter from antimatter; it must therefore be assumed that there are no antimatter bodies in nature, i.e., the Universe is asymmetrical with respect to the number of particles and antiparticles (C asymmetry). In particular, the absence of antibaryons and the proposed absence of baryonic neutrinos implies a non-zero baryon charge (baryonic asymmetry). We wish to point out a possible explanation of C asymmetry in the hot model of the expanding Universe (see [1]) by making use of effects of CP invariance violation (see [2]). To explain baryon asymmetry, we propose in addition an approximate character for the baryon conservation law.



1) and 2) will be addressed in future neutrino experiments: Hyper-K and DUNE

Hyper-K and DUNE: next generation ν CPV exps.

- Both will measure if oscillation of neutrinos and oscillation of antineutrinos are different.

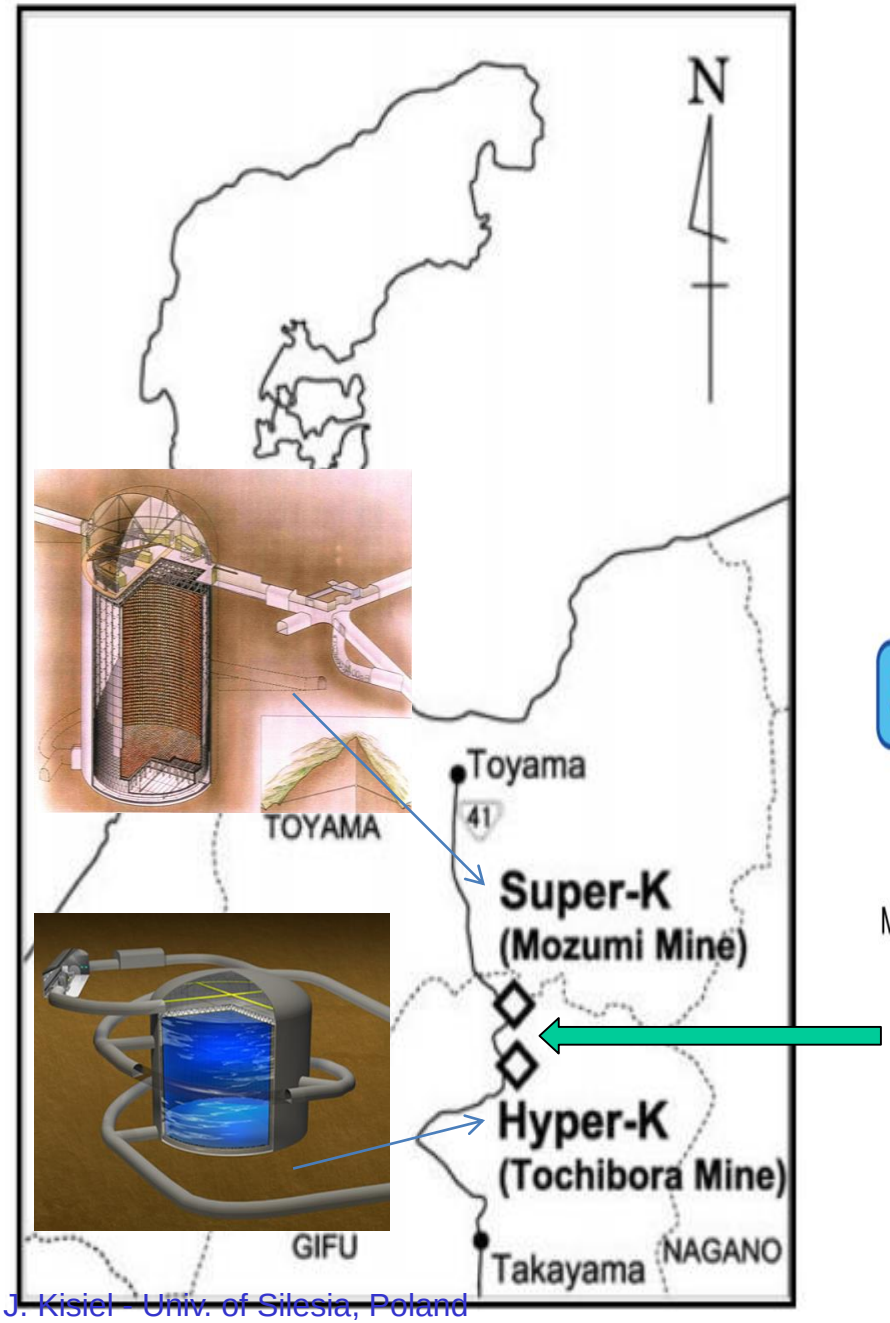
- Both are LBNE (Long Baseline Neutrino Exp.) with different (1) baselines: 295km at Hyper-K (practically no matter effect); 1300km at DUNE (matter effect, good for neutrino mass ordering), and (2) ν beam energy: narrow, ~ 600MeV off axis 1.3MW for Hyper-K; wide ~ 4GeV, initially 1.2MW (upgradeable to 2.4MV) for DUNE.

- Different detector technologies (water Cherenkov vs LAr TPC), both technologies are mature, developed for many years.

- Both are huge, still growing, international collaborations.

- CP violation in neutrino sector will be established by independent, and hopefully convinced and consistent results from these two exps.

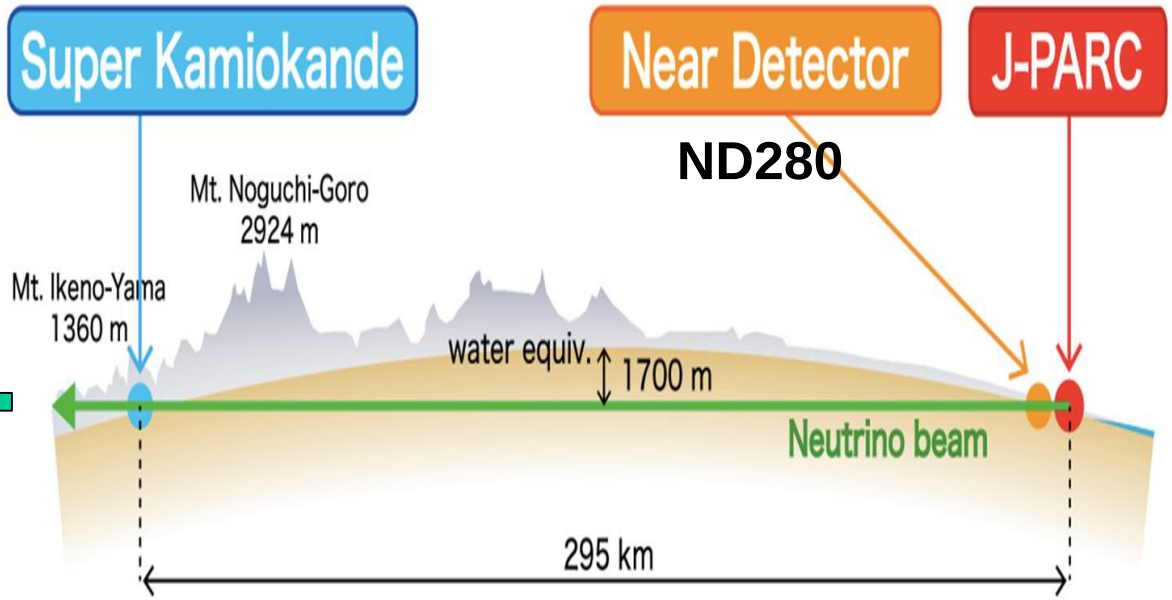
Hyper-K and T2K experiments



Hyper-K experiment (2027 - ...)

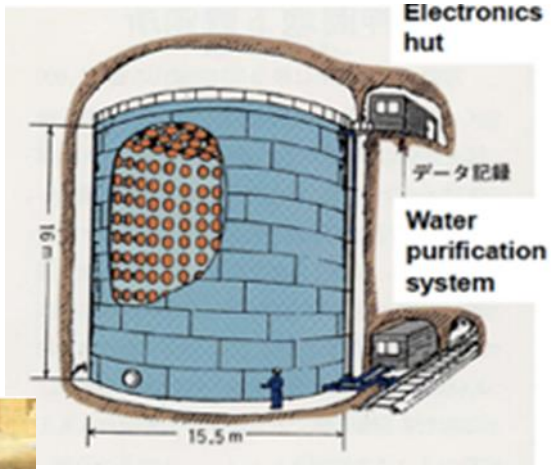
- New: far detector and water intermediate detector
- Upgraded: neutrino beam and ND280

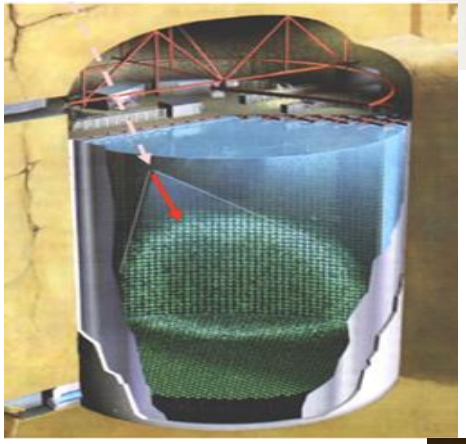
T2K experiment (currently running)

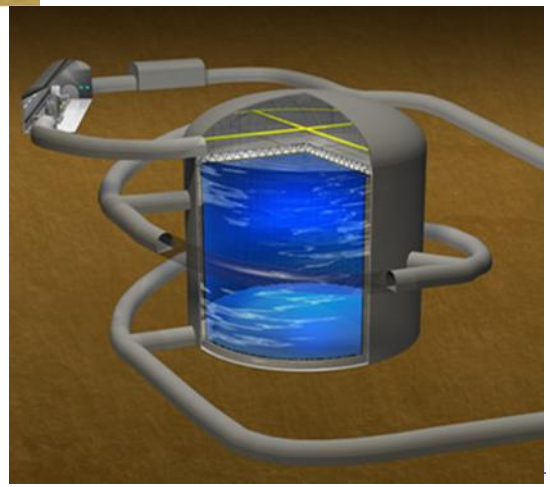


Development of water Cherenkov detectors (in Japan)

- Kamiokande (1983-1996), 4.5 (0.7) kton, 20% PMT coverage: SN1987a neutrinos, ν_{atm} deficit.
- Super-Kamiokande (1996-…), 50 (22.5) kton, 40% PMT coverage: ν_{solar} and ν_{atm} oscillations, proton decay, ν_{atm} appearance, far detector for the T2K exp.
- Hyper-Kamiokande (~2027-…), 258 (187) kton, 40% PMT coverage: CP violation, proton decay, neutrino mass hierarchy,….

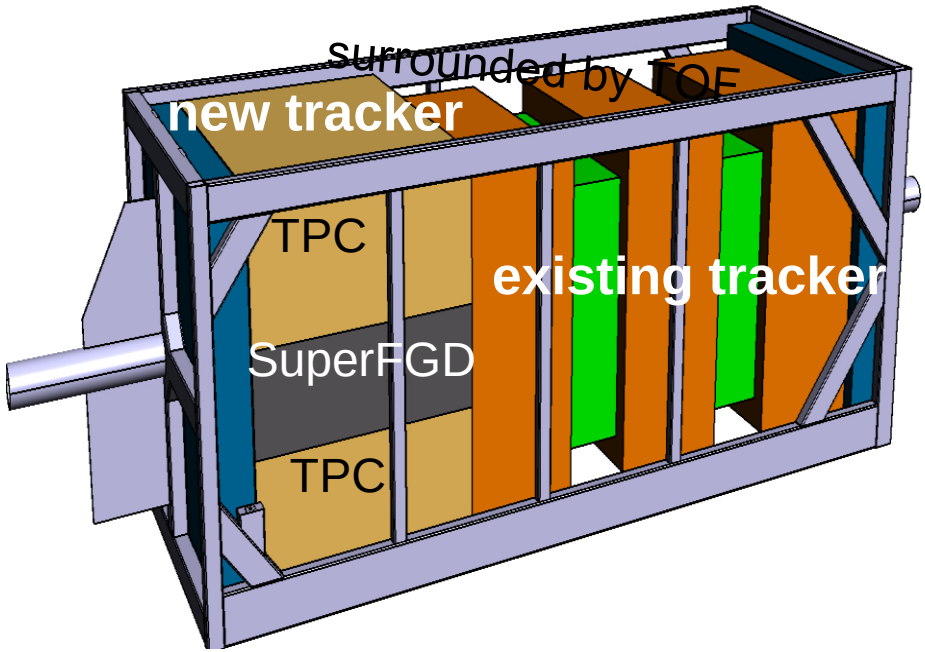






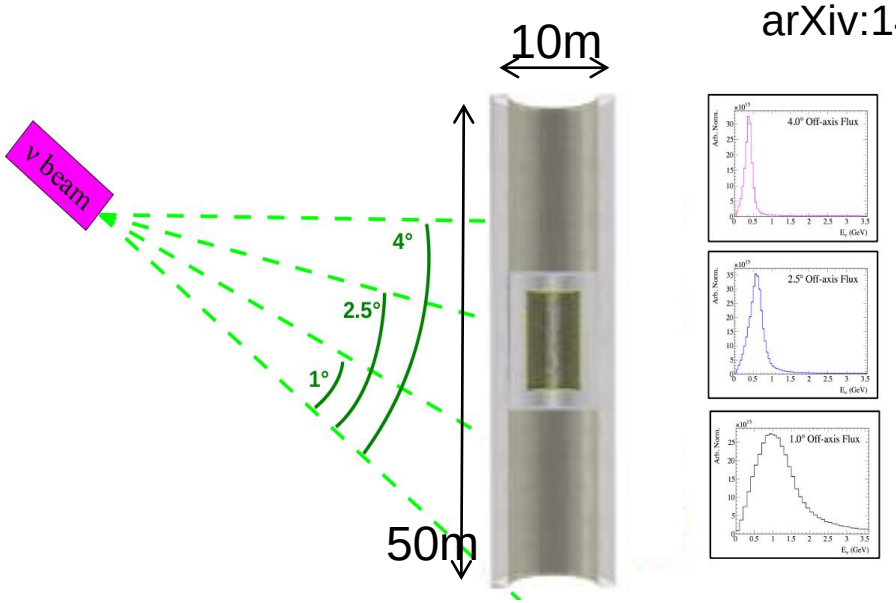
Hyper-K: near and intermediate detectors

- Upgrade of existing ND280 to reduce systematic uncertainties from ~ 18% in 2011 down to ~ 4% in 2020; expanded angular acceptance and lower energy threshold.



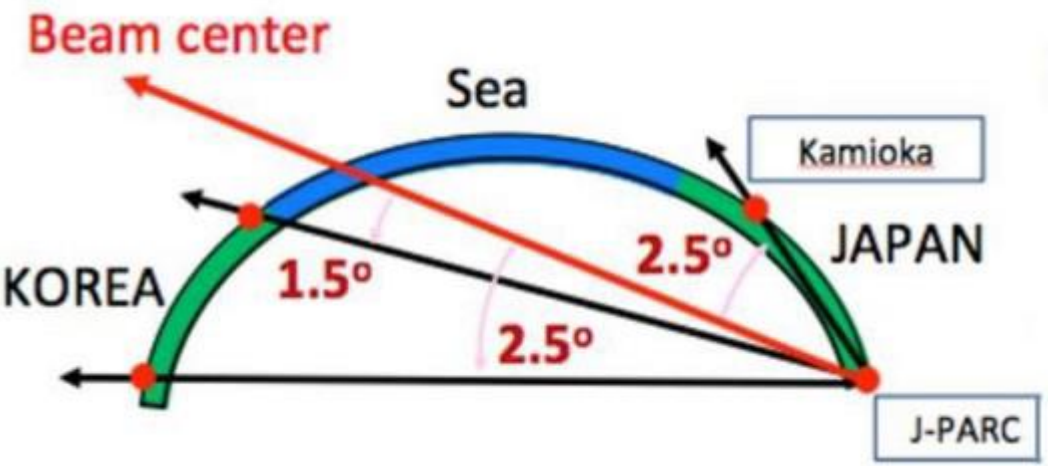
- N61 intermediate water Cherenkov detector at 1-2km:
  - off-axis angle coverage 1-4°,
  - energy dependence of neutrino interactions,
  - Gd loading,
  - further reduction of systematic uncertainties.

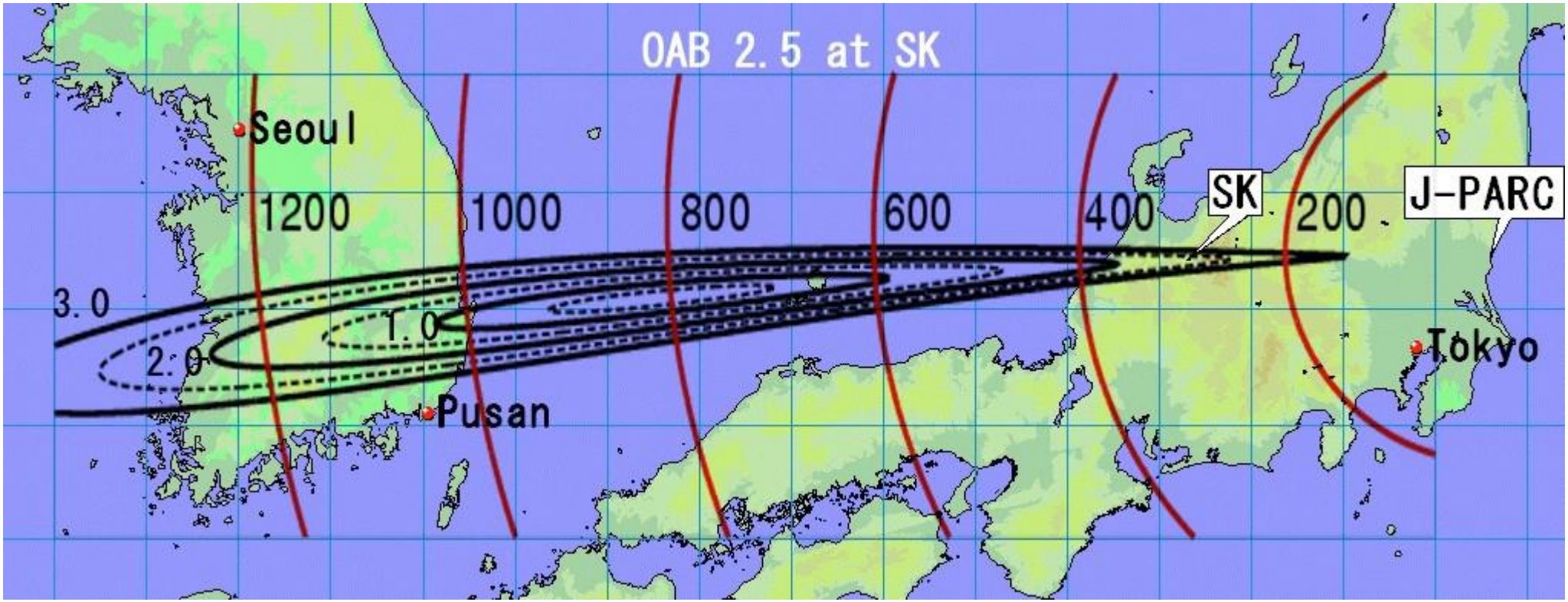
arXiv:1412.3086



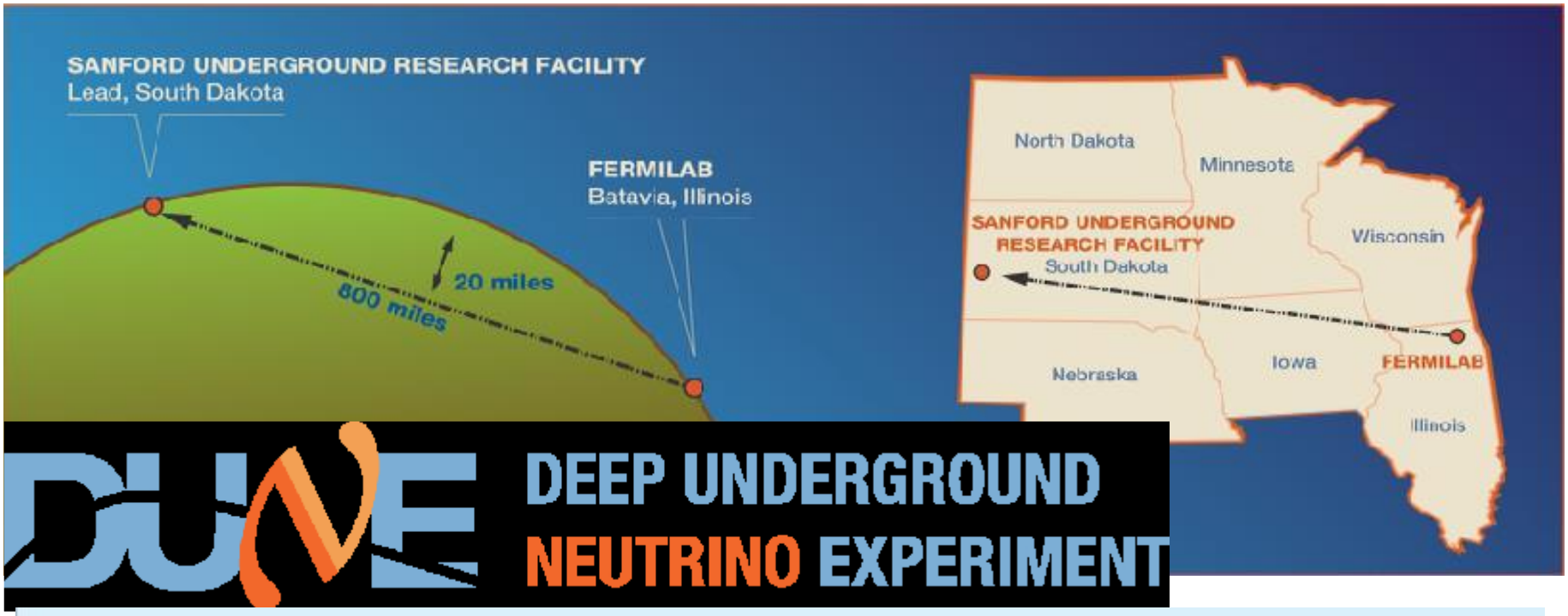
T2HKK: 2nd tank in Korea

- Enhanced sensitivity to CP violation and mass hierarchy.
- Off-axis beam 1.3-3.0°.
- Under consideration.

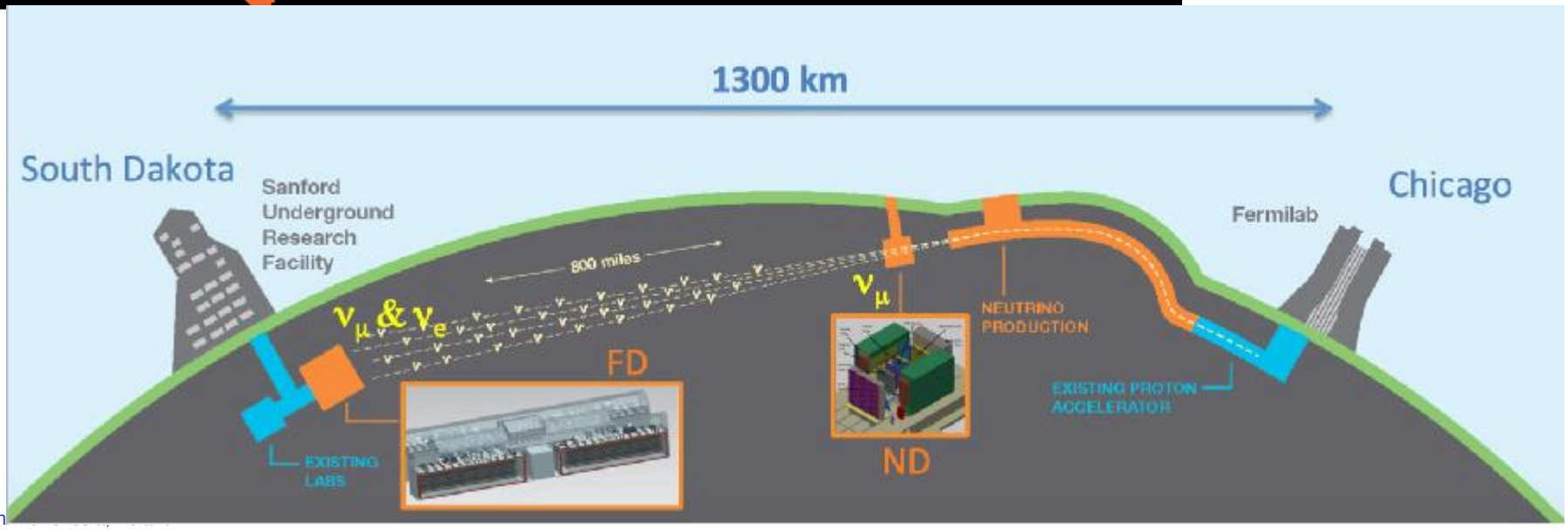




DUNE

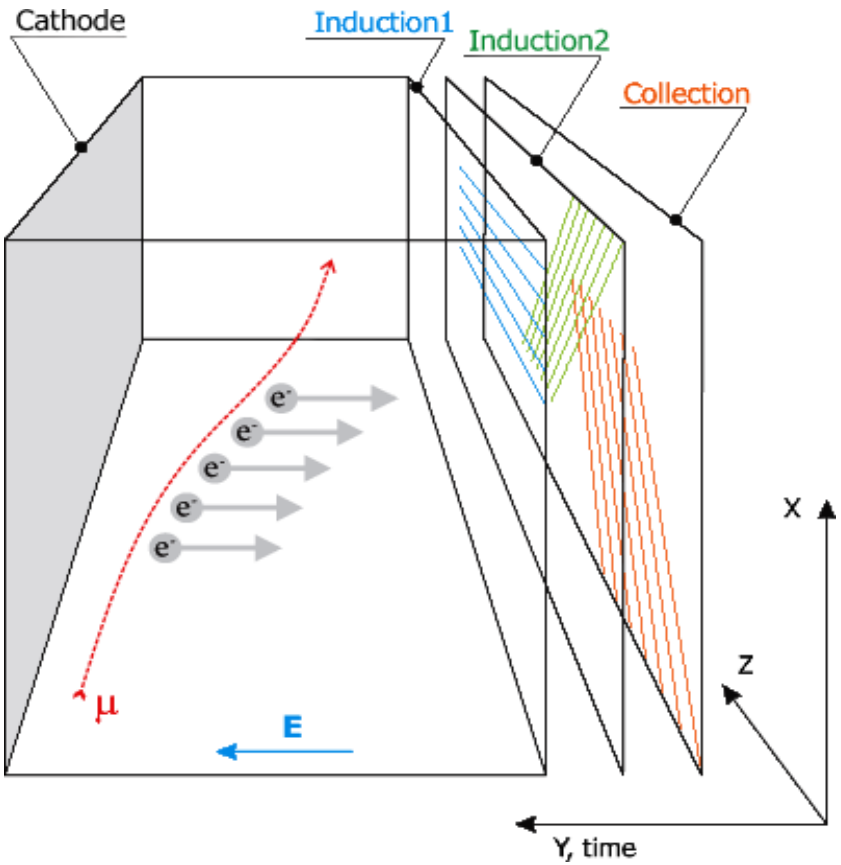


DEEP UNDERGROUND NEUTRINO EXPERIMENT

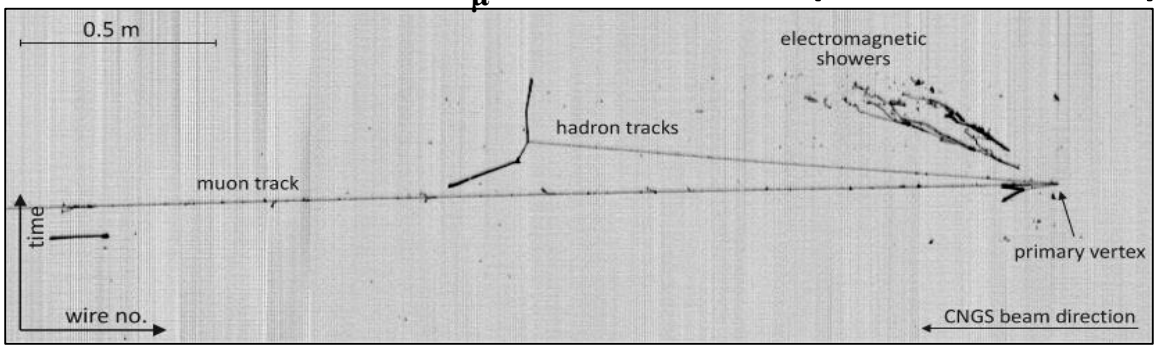


LAr-TPC detection technique

- 2D projection for each of 3 wire planes per TPC
- 3D spatial reconstruction from stereoscopic 2D projections
- charge measurement from Collection plane signals
- Absolute drift time from scintillation light collection



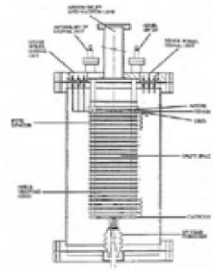
ICARUS T600, CNGS ν_μ CC interaction (Collection view)



Why LAr TPC? A modern bubble chamber.

- Both target and detector with high density,
- Non-destructive readout,
- Continuously sensitive,
- Self-triggering,
- Long electron lifetime,
- Low cost, scalable,
- High spatial granularity.

Development of LAr TPC



CERN

24 cm drift wires chamber

1

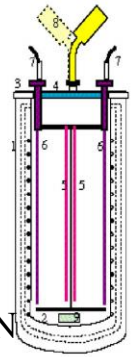
1987: First LAr TPC. Proof of principle. Measurements of TPC performances.

Towards ICARUS T600

2

3 ton prototype

1991-1995: First demonstration of the LAr TPC on large masses. Measurement of the TPC performances. TMG doping.



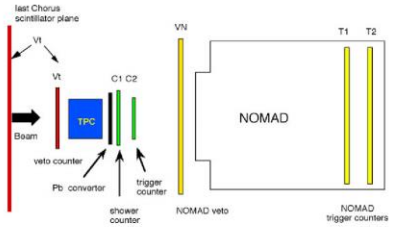
CERN

Laboratory work

3

CERN

50 litres prototype
1.4 m drift chamber



1997-1999: Neutrino beam events measurements. Readout electronics optimization. MLPB development and study. 1.4 m drift test.

Icarus T600 experiment, LNGS, Italy, 2010-2013
CNGS beam data taking

Pavia/Italy

4

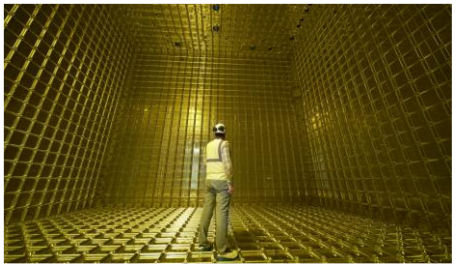
Cooperation with industry

10 m^3 industrial prototype

5

1999-2000: Test of final industrial solutions for the wire chamber mechanics and readout electronics.

… and other examples



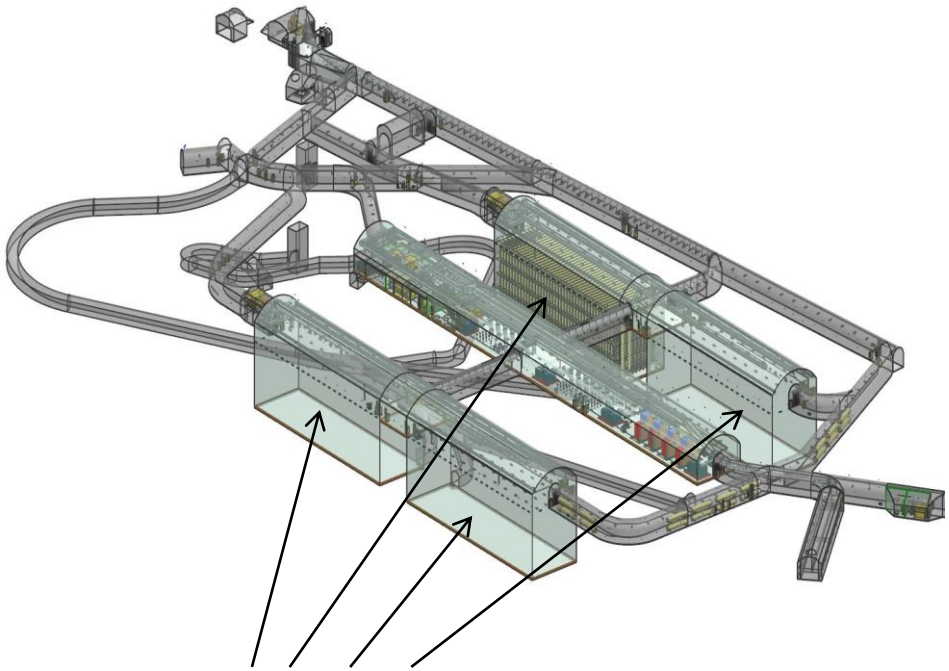
protoDUNE, 2018-…, 800 tons

MicroBooNE, 2015-…, 90 tons

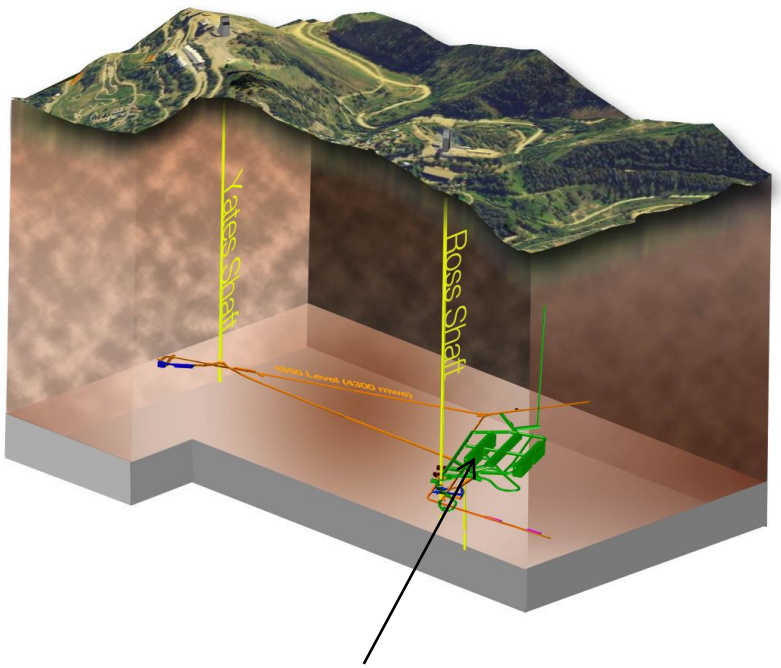
ArgouNeut, 2008-2010, 0.76 tons

DUNE: far detector(s)

- 4 chambers: 62(L)×15(W)×14(H) m^3 interior volume of each cryostat and 10 kton fiducial mass; 70 kton of LAr in total.
- Excavation of 875 ktons of rock in Ross Campus at 4850 ft level of Sanford Underground Research Facility.



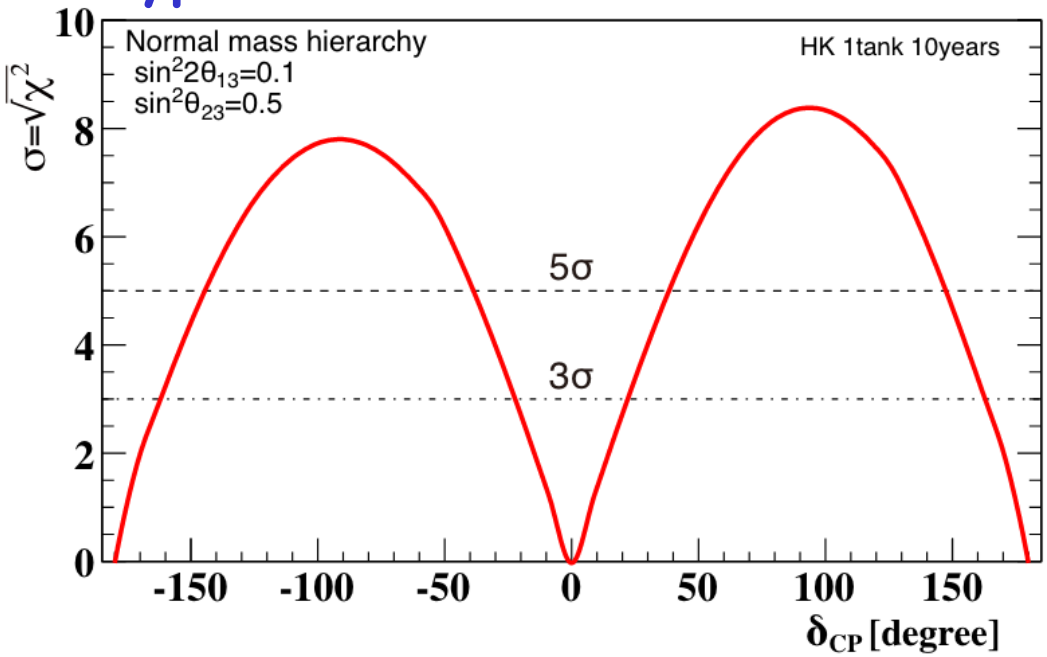
4 LAr TPCs



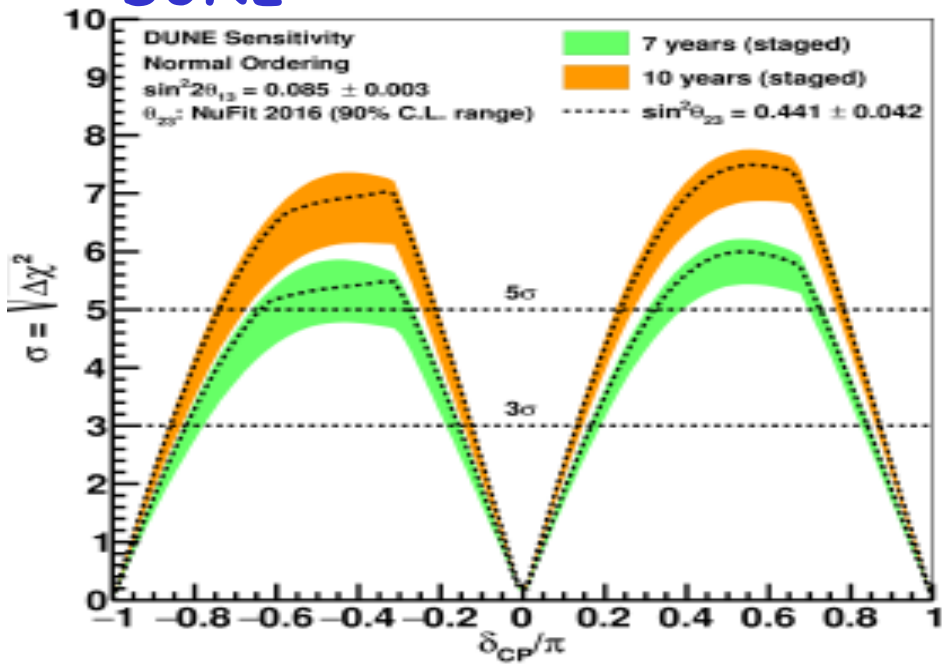
New construction

Hyper-K and DUNE: CPV sensitivity

Hyper-K *M. Shiozawa, Neutrino 2018*



DUNE *E. Worcester, Neutrino 2018*

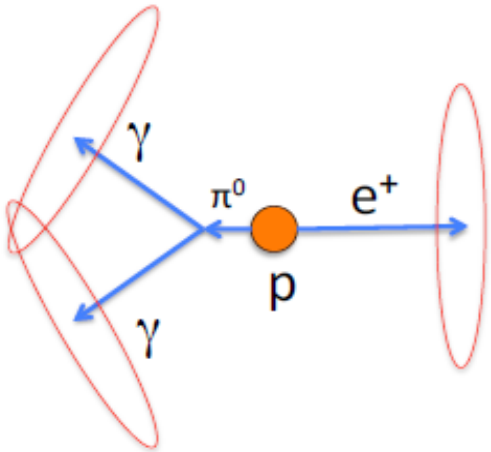


- **Exclusion of $\sin\delta_{CP}$ = 0 with:**
  ~ 8σ if true δ_{CP} = ±90°
  > 5σ for ~ 57% of δ_{CP} values,
  > 3σ for ~ 76% of δ_{CP} values.
- **Error of δ_{CP} (δ_{CP} resolution):**
  ~ 23° precision at δ_{CP} = ±90°
  ~ 7° precision at δ_{CP} = 0 or 180°

- **After 7 years (stages):**
  ~ 5σ if true δ_{CP} near ±90°
  > 5σ for ~ 41% of δ_{CP} range,
  > 3σ for~ 65% of δ_{CP} range.

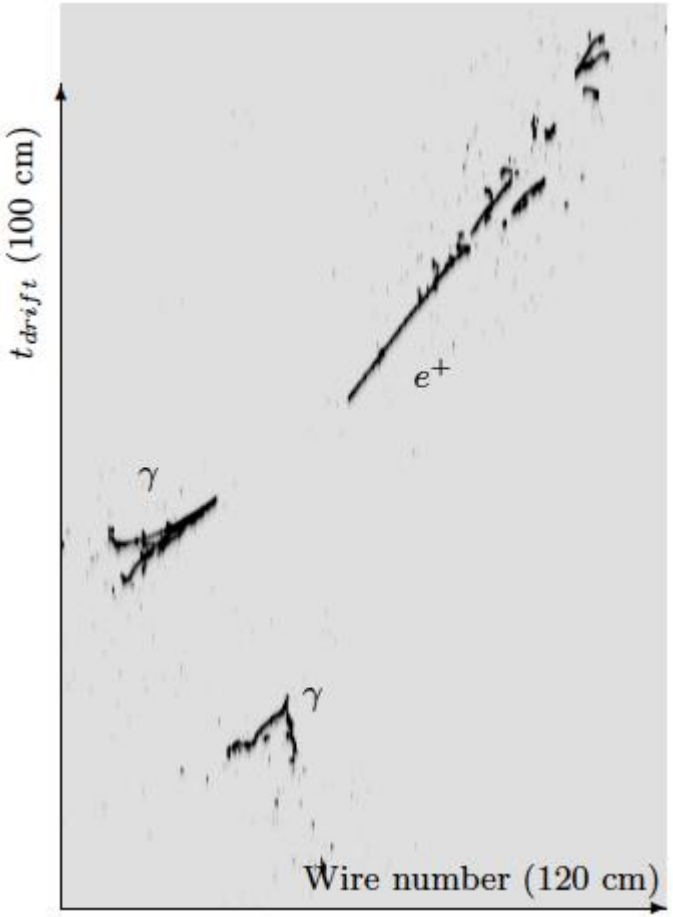
Search for the $p \rightarrow e^+\pi^0$ decay

Hyper-K



- Signature: back-to-back electromagnetic showers, final state fully reconstructed.
- Compelling evidence: invariant proton mass.
- Efficiency of ~45%, dominated by nuclear absorption of π^0.
- Practically background free (0.06 ± 0.02 events/Mton/year).

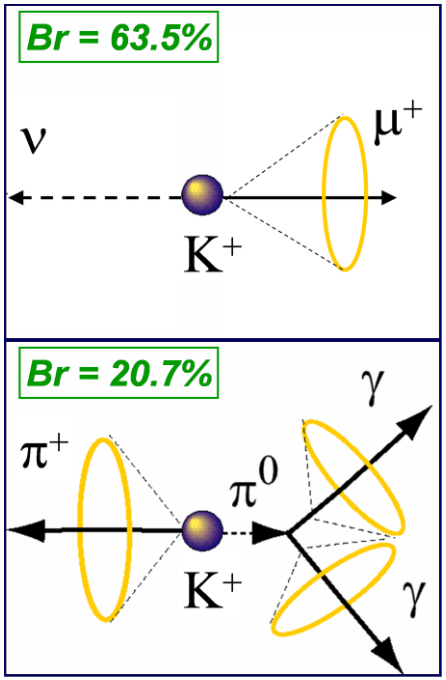
DUNE



simulation, A. Bueono et al.
arXiv: hep-ph/0701101

Search for the $p \rightarrow \nu K^+$ decay

Hyper-K



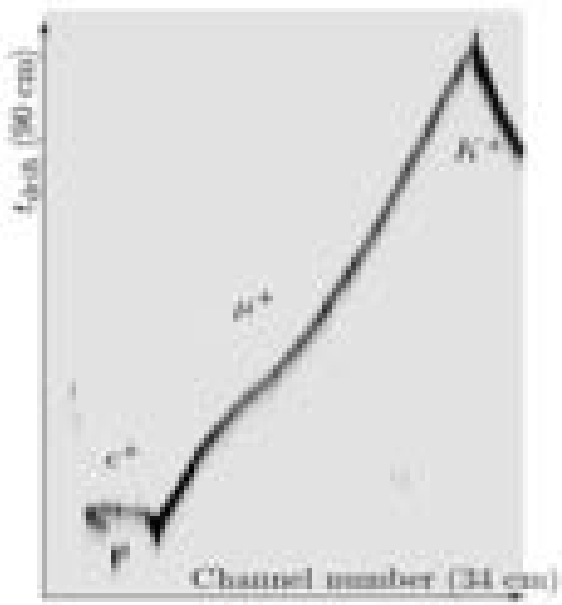
K is below Cherenkov threshold (not visible)

K identified/reconstructed via its decays:

- $K^+ \rightarrow \mu^+ \nu$ (BR=64%): monochromatic (236 MeV) muon.

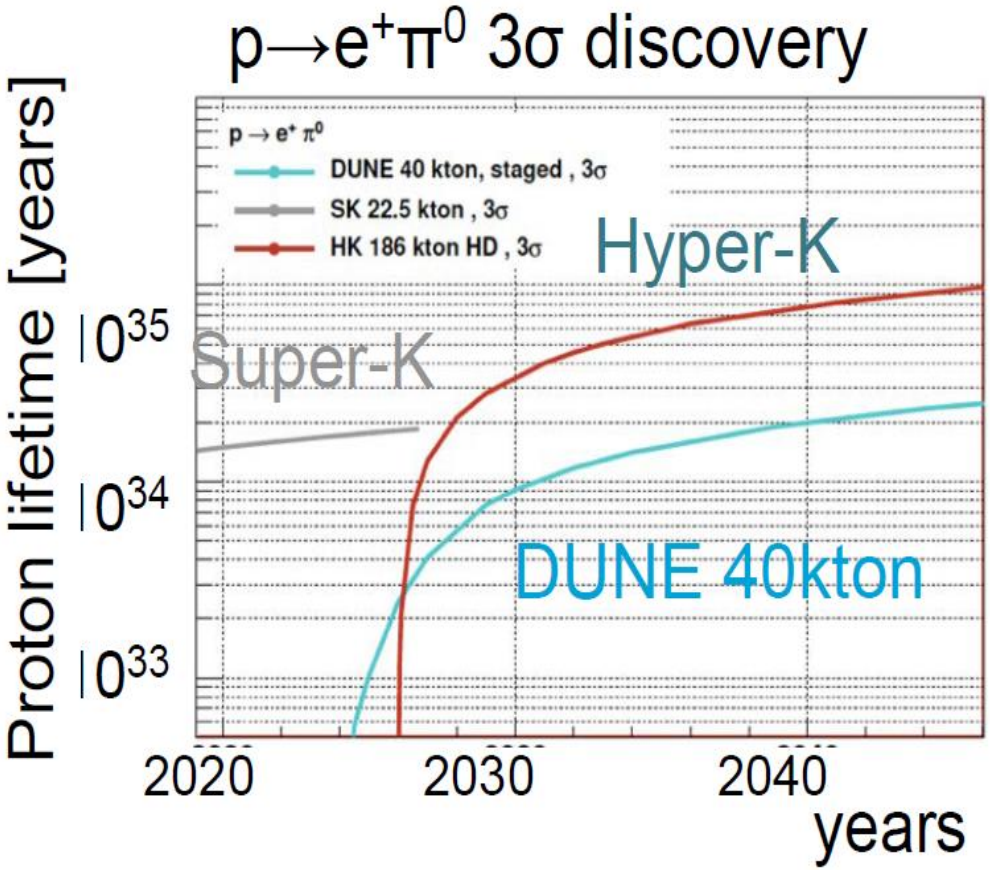
- or search for $K^+ \rightarrow \pi^0 \pi^+$ decay (BR=21%): π^0 momentum ~ 205 MeV/c and opposite π^+.

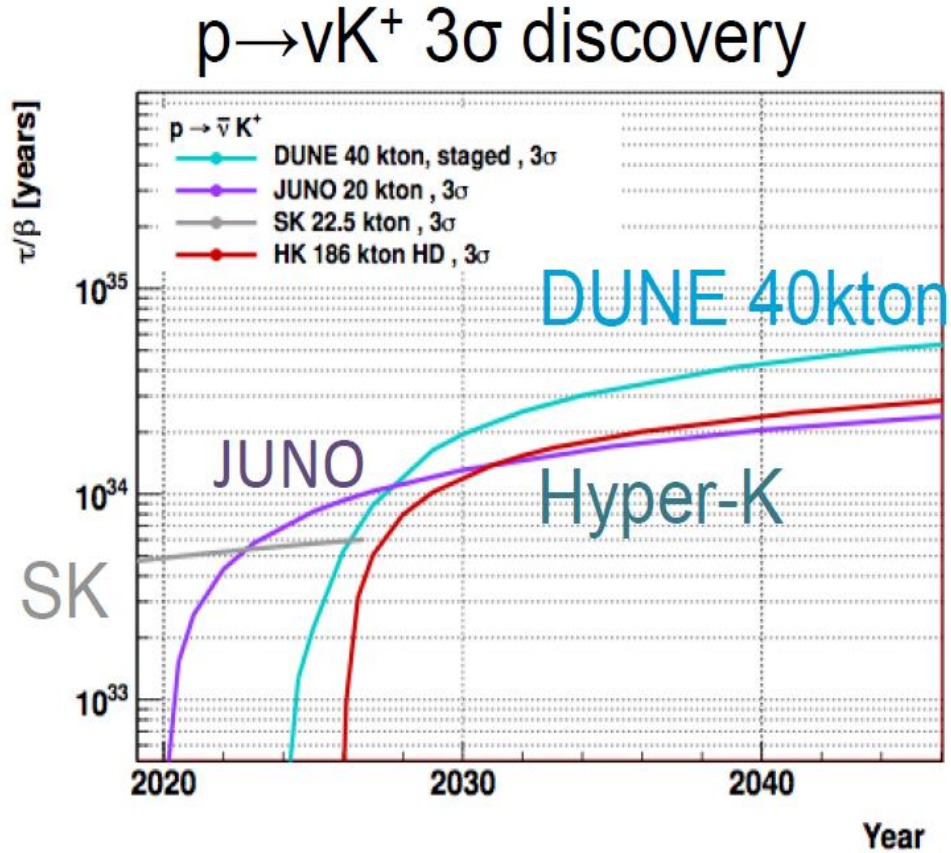
DUNE



- High kaon detection efficiency (>97%): stopping kaons have higher ionization density than pions/muons with the same momentum.
- Signature: isolated charged kaon (for free proton monochromatic with p ≈ 340 MeV/c) + clean reconstruction of its decay modes.
- Overwhelming evidence of p decay for a single event with an isolated K+ of right momentum.

Proton decay: 3σ discovery for 2 selected channels

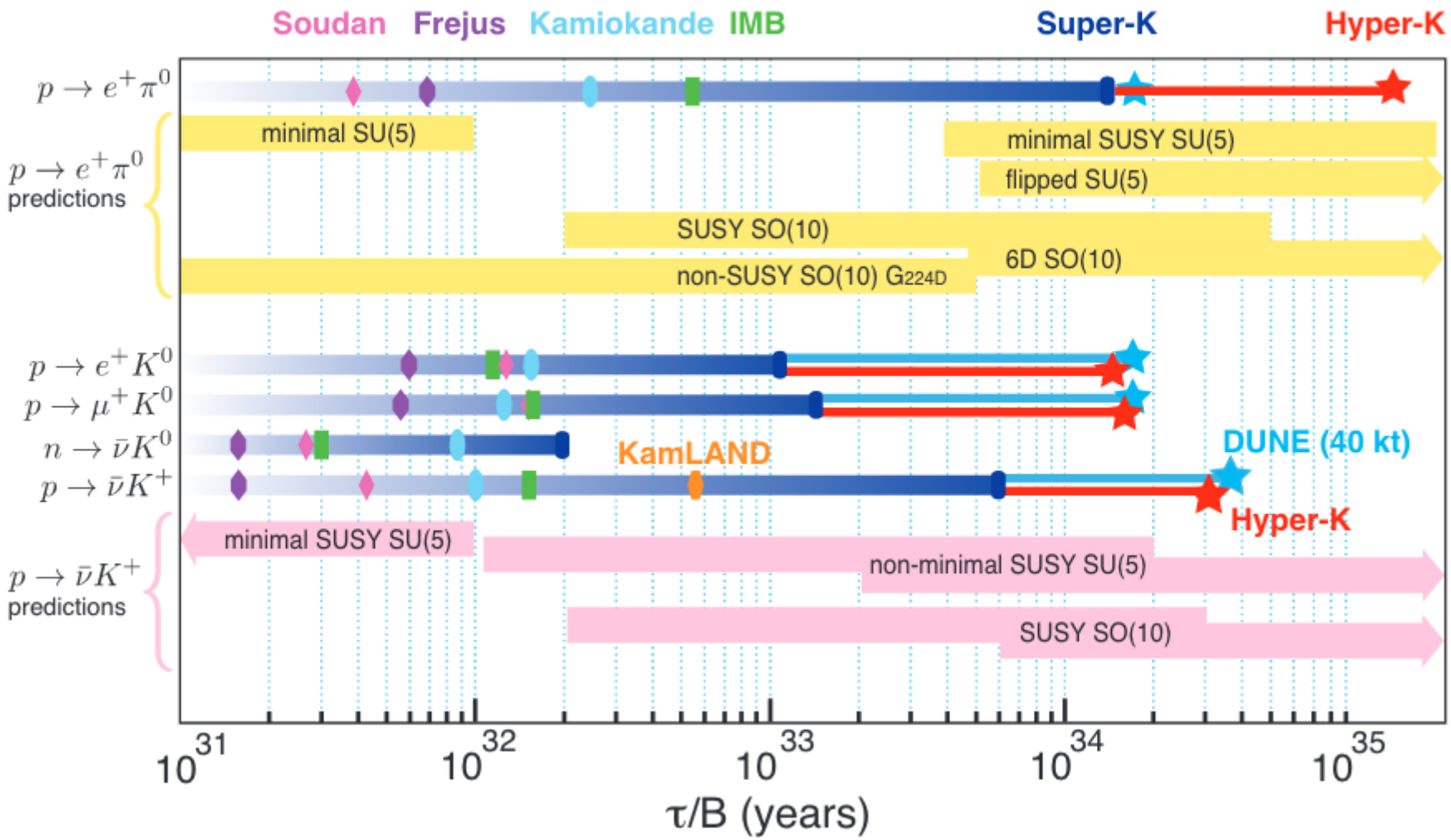




T.Kajita, Neutrino2018, exp. summary

If τ_p ($p \rightarrow e^+\pi^0$) < 10^{35} years or τ_p ($p \rightarrow K^+\nu$) < 5×10^{34} years we may expect 3σ discovery.

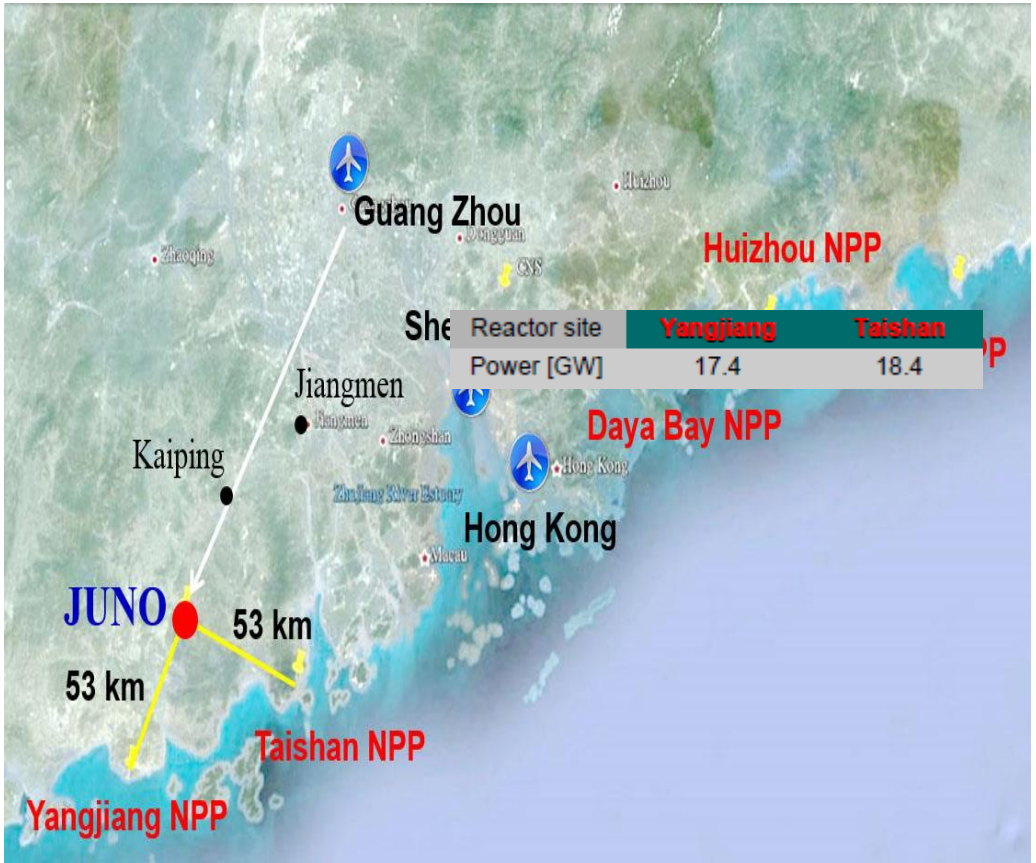
Proton decay: summary



- Hyper-K will extend (3σ @ 20 years) proton lifetime to 10^{35} years, covering much more model predictions than present exps.

JUNO: location and physics program

	KamLAND	Borexino	Daya Bay	JUNO
Mass [t]	~1000	~300	~170	20000
Light yield [p.e./MeV]	250	500	200	1200
Energy resolution	6%/√E	5%/√E	7.5%/√E	3%/√E
Energy calibration	1.4%	1%	1%	< 1%



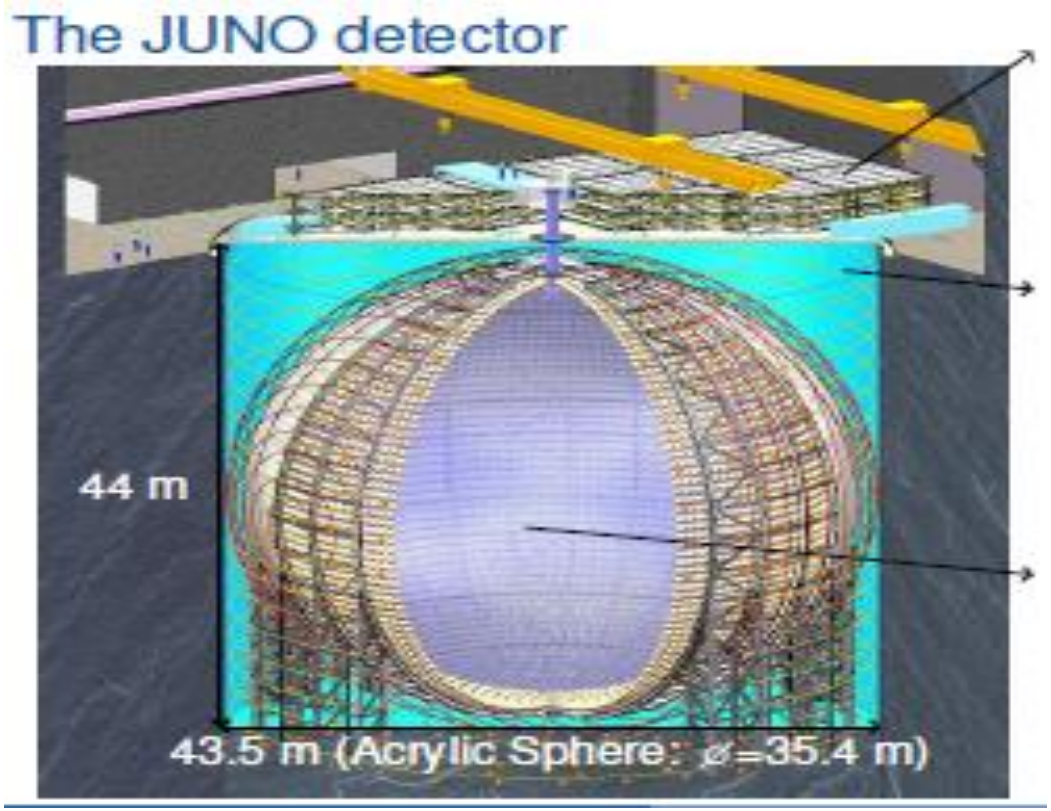
Reactor site	Yangjiang	Taishan
Power [GW]	17.4	18.4

Detection of reactor anti-ve via inverse beta decay with energy threshold =1.8MeV in near and far detectors. Signal signature: prompt photons from e^+ ionization followed by delayed photons from neutron capture on H.

Physics program:

- Mass hierarchy determination: crucial factor for ββ0ν and δCP exps.
- Precision measurement of oscillation parameters.
- Detection of neutrinos from other sources: solar, geoneutrinos, …

JUNO: the next generation liquid scintillator detector



Top Tracker: 3 layers of plastic scintillator for muon detection.

Water Cherenkov: 25 ktons; high muon detection efficiency; protects Central Detector from external radioactivity.

Central Detector: acrylic sphere with 20 ktons of liquid scintillator; anti-ve target; 3% energy resolution @ 1 MeV.

	KamLAND	Borexino	Daya Bay	JUNO
Mass [t]	~1000	~300	~170	20000
Light yield [p.e./MeV]	250	500	200	1200
Energy resolution	6%/√E	5%/√E	7.5%/√E	3%/√E
Energy calibration	1.4%	1%	1%	< 1%

Construction of JUNO is in progress: start of data taking in 2021.

Neutrinos: future

- Program for the future/present neutrino experiments:

- CP violation (baryon asymmetry in the Universe): Hyper-K and DUNE exps.,

- Are neutrinos Majorana particles? ($\beta\beta0\nu$ decay exps.),

- More than three neutrino flavors (sterile ν searches),

- absolute scale of neutrino masses: KATRIN exp., astrophysical and cosmological data,

- neutrino mass ordering (normal or inverted): many exps. including JUNO, also Hyper-K and DUNE.

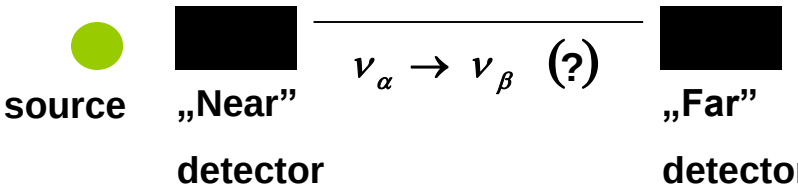
Summary

- Neutrinos: almost 90 years of discoveries since Pauli's postulate (1930) awarded by several Nobel prizes.
- Today we know that neutrinos are not only „missing energy".
- Three flavors neutrino mixing is well established.
- New results will come from present and new detectors measuring neutrinos from diverse sources.
- „It is clear that neutrino physics and astrophysics will play fundamental roles to our better understanding of particles and the Universe." *(T.Kajita, Neutrino 2018, Experimental outlook)*

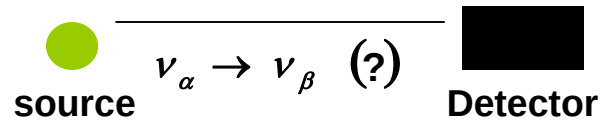
Backup slides

Two kinds of neutrino oscillation experiments with neutrino beam from an accelerator

disappearance



appearance



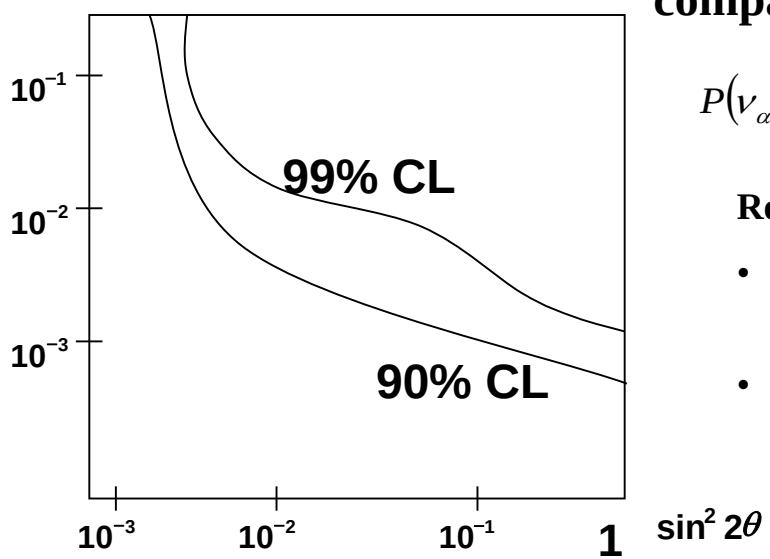
Measurement of change of ν_α flux at distance L and comparison with

$$P(\nu_\alpha \rightarrow \nu_\beta) = 1 - \sin^2 2\theta \cdot \sin^2\left(1.27 \frac{\Delta m^2 \cdot L}{E}\right)$$

Requirements:

- **precise measurement of neutrino flux**
- **two neutrino detectors**

RESULT



Measurement of rare ν_β evets and comparison with

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \cdot \sin^2\left(1.27 \frac{\Delta m^2 \cdot L}{E}\right)$$

Requirements:

- **knowledge of ν_β contamination in ν_α beam**
- **precise background control**