110625
将来計画小委員会
タウンミーティング
＠東大小柴ホール

Future neutrino program in Japan

Takashi Kobayashi
KEK

提言

「ニュートリノ物理」

　θ_{13}が発見された場合、ニュートリノにおける3世代間の混合が確立し、ニュートリノ振動を通したCP対称性の研究と質量階層性の決定が重要なテーマとなる。発見初期は、T2K実験とDouble Choozなどの原子炉実験によりθ_{13}を含むニュートリノ振動パラメータの測定精度を向上させ、CPの破れのヒントを掴むことを目指す。このために、J-PARC加速器の増強、反ニュートリノビームによる振動の測定、原子炉実験における系統誤差の更なる改善、等を行う。

　更に、次世代ニュートリノ研究の中核となる大型ニュートリノ測定器（Hyper-Kamiokande、大型液体アルゴンTPCなど）実現のため、基幹技術の確立と全体設計を国際協力で推進し、測定器の建設開始を目指す。これらの計画は日米欧で競合、協力して進められると考えられるが、日本が主導することが期待される。

　大型ニュートリノ測定器は、大統一理論の直接の証拠となる陽子崩壊探索に対し十分な探索感度を持つようにすべきである。陽子崩壊の探索は、LHC等での発見によっては大統一の機構解明のため、より緊要な課題となる可能性がある。

2009年9月5日　第三回委員会

- 「ニュートリノ」について報告発表と議論
  - ニュートリノに関する理論紹介（村山委員）
  - T2Kの現状と将来のJ-PARCニュートリノビームアップグレード（小林委員）
  - J-PARCニュートリノ将来計画（CPの物理と陽子崩壊）
    - 大型水チェレンコフ測定器（塩澤、東大ICRR）
    - 大型液体アルゴンTPC（丸山、KEK）
  - 海外の情勢（加速器ニュートリノと大型測定器）（中家委員）
  - SK将来：太陽ニュートリノ、大気ニュートリノ、Gd（中畑、東大ICRR）
  - 原子炉ニュートリノ（末包、東北大）
  - KamLANDの現状と将来（井上委員）
  - CANDLESと世界のダブルベータの状況（小川、大阪大）
  - XMASSと世界のダークマター探索の状況（森山、東大IC[illegible]

井上さん

- 高エネルギー宇宙ニュートリノ（吉田、千葉大）
- ニュートリノ精密質量分光実験（笹尾、岡山大）

Contents

- Neutrino physics in Particle Physics
- Where we stand w/ new T2K results
- Neutrino program
  - Near future
  - Future

Neutrino physics in Particle Physics

- Goals of particle physics
  - Understand ultimate matter (& interactions)
  - Understand origin of matter
- What we have
  - Standard model (SM)
- Neutrino: still full of mysteries (~ 40yrs ago of quarks)
  - Exhibit first violation of standard “SM”: Non-zero mass
  - Extremely small mass with unknown reason
    - Indication of new physics at very high energy?
  - Large mixing (contrary to quarks)
    - Some hint to connect quarks and leptons?
  - Possible explanation of matter dominated universe
- Unraveling full nature of neutrino could provide breakthrough to approach our goals of particle physics

3 flavor mixing of neutrinos

Flavor eigenstates — Mass eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

m_1, m_2, m_3

Pontecorvo-Maki-Nakagawa-Sakata Matrix (CKM matrix in lepton sector)

$$U_{MNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} & +s_{12} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

大気、加速器　　(大気)、加速器　　太陽、原子炉

6 independent parameters govern oscillation

θ_{12},　θ_{23},　θ_{13},　δ

Δm_{12}^2, Δm_{23}^2, Δm_{13}^2

$\Delta m_{ij} = m_i^2 - m_j^2$

$c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$

What we have learned

- ν_μ **disappearance established:** θ_{23}, Δm_{23}
  - Indication:Kamiokande, Evidence SK(1998), K2K confirmed➔ ν has non-zero mass!
  - Predominantly to ντ
- ν_e **disappearance established:** θ_{12}, Δm_{12}
  - Homestake/Kamokande/SK/SNO(Solar) + KamLAND (Reactor)
  - Transition to ν_μ(or ν_τ) INDIRECTLY confirmed (NC)
- **θ_{13}, Δm_{13}(~Δm_{23}) are unknown**
  - Only upper limit for θ_{13}
- **CP violating phase δ unknown**
- **Mass hierarchy unknown**
- No established evidence of direct detection of appeared ν type after transition
  - OPERA detected 1evt. 98%CL

$$\Delta m^2_{21} \quad (7.65^{+0.23}_{-0.20})\,10^{-5}\,\mathrm{eV}^2$$

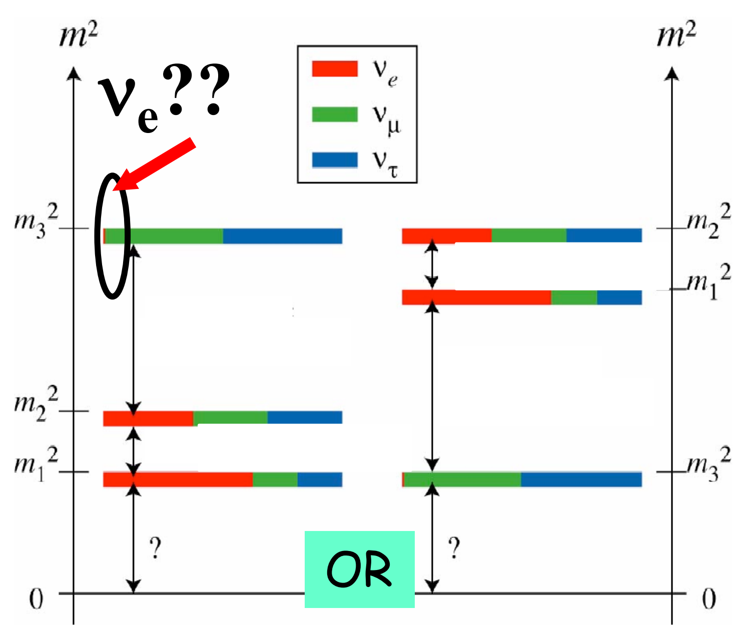
$$\sin^2\theta_{12} \quad 0.304^{+0.022}_{-0.016}$$

$$|\Delta m^2_{31}| \quad (2.40^{+0.12}_{-0.11})\,10^{-3}\,\mathrm{eV}^2$$

$$\sin^2\theta_{23} \quad 0.50^{+0.07}_{-0.06}$$

$$\sin^2\theta_{13} < 0.056 \ @\ 3\sigma$$

Schwetz, Tortola, Valle, New J.Phys.10:113011,2008



Today's Questions in neutrino physics

- Last unknown mixing θ_{13}. 3flavor mixing picture valid?
  - ➔**Long baseline Accelerator neutrino experiments**
  - ➔Reactor neutrino experiments
- CP symmetry violated?
  - Could be a hint to solve origin of matter in universe
  - ➔ **Long baseline Accelerator neutrino experiments**
- Mass hierarchy
  - ➔ **Long baseline Accelerator neutrino experiments**
- Absolute mass?
  - ➔Tritium beta decay spectrum
  - ➔neutrino-less double beta decay
- Neutrino is Dirac? Or Majorana?
  - ➔ neutrino-less double beta decay

Toward one of big goals of particle physics: Origin of Matter-dominated Unvierse

Sakhalov's 3 conditions

- Baryon number violation
  - Proton decay
- CP violation
  - Quark CPV seems not sufficient
  - Lepton CPV may contribute
- Non-equilibulium

$\nu_\mu \rightarrow \nu_e$ appearance and CPV

- **ν_e appearance is golden mode for CPV IF ν_e appearance exist**
  - No CPV effect in disappearance
  - Only νμ beam is presently technically available
  - Small leading CPC term ➔ Large CPV effect (⇔ντ app.)

$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2}\ (1 - 2S_{13}^2)\right)$$

$$+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E}$$

$$-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E}$$ CPV

$$+4S_{12}^2 C_{13}^2 \{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\} \sin^2 \frac{\Delta m_{21}^2 L}{4E}$$ Sol term

CPV effect $\propto \sin\delta \cdot s_{12} \cdot s_{23} \cdot s_{13}$ **Unknown!**

($\sin\theta_{12}$~0.5, $\sin\theta_{23}$~0.7, $\sin\theta_{13}<0.2$)

The size of θ_{13}

Decide future dir.!

1999日本(戸塚＋西川)が
世界で初めて着目→T2K提案

Toward discovery of non-zero θ_{13}

加速器ニュートリノによるθ_{13}

- **ミューニュートリノ**: <E_ν> ~ O(GeV) ➔ νe出現実験
- $P(\nu_\mu \rightarrow \nu_e) = \mathbf{sin^2\theta_{23}} \cdot \mathbf{sin^2 2\theta_{13}} \cdot \sin^2(1.27\Delta m^2_{31} L/E)$ + many terms (incl. δ)

  ➔ Appearance measurement

  ➔ **統計(=ビームパワーx検出器サイズ)勝負**

原子炉ニュートリノによるθ_{13}

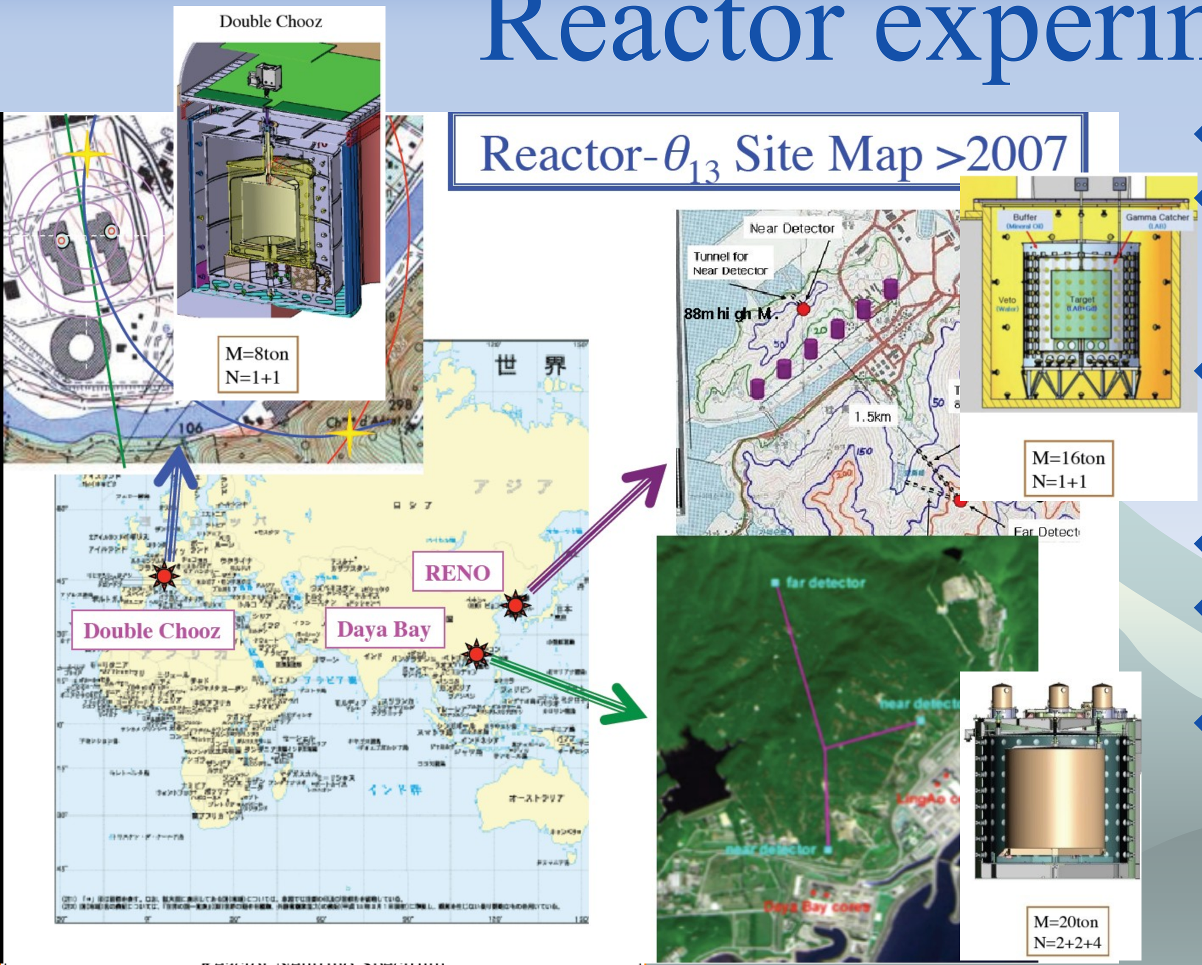
- **反電子ニュートリノ**: <E_ν> ~ a few MeV ➔ $\bar{\nu}_e$消失実験
- $P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \mathbf{sin^2 2\theta_{13}} \cdot \sin^2(1.27\Delta m^2_{31} L/E) + O(\Delta m^2_{21}/\Delta m^2_{31})$

  ➔ Almost **pure** measurement of θ_{13}.

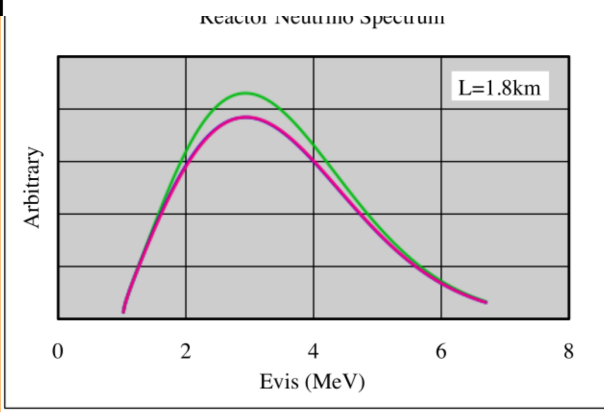
  消失信号が小さい➔ 系統誤差勝負

Severe world competition

Reactor experiments



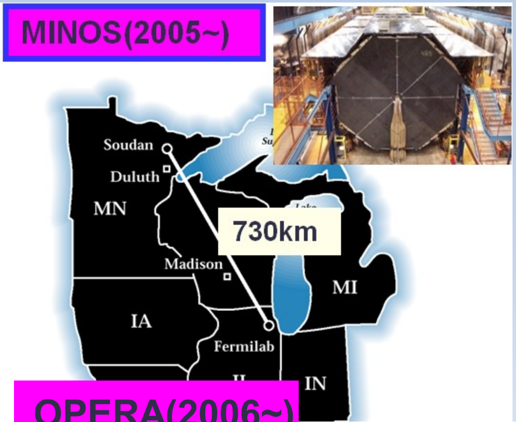
- Disappearance measurement
- Identical detectors at near&far site
  - Reduce syst err
- 90%CL sensitivity ranges 0.01~0.03
  - systematic limited
- Double Chooz started 2011~
- Dayabay, RENO start 2011~(?)
- Competition & complementary w/ acc expt's



	Double Chooz	Dayabay	RENO
Power(GWth)	8.2GW	11.6GWth (17.4GW>2012)	16.1GW
Detector(ton)	8	80	16
Baseline(km)	1.05	1.8	1.4
$\sin^2 2\theta_{13}$ Sensitivity	~0.03	~0.01	~0.02

Accelerator experiments

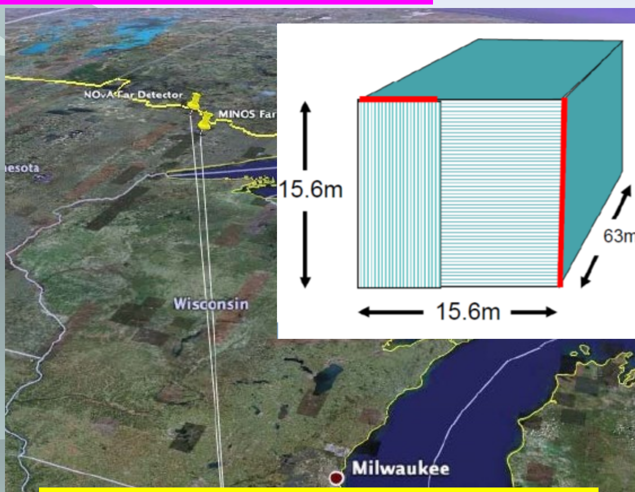
MINOS(2005~)



T2K(2009~)

OPERA(2006~)

NOVA(2014完成予定)



Upgraded MI (700kW)
New ~14kt det @ 810km
Similar sensitivity as T2K
Mass hierarchy

- MINOS/OPERA optimized for Atm ν confirmation ➔ Trying to find nue, w/ limited sensitivity
- T2K & NOvA optimized for nue app discovery

Tokai-to-Kamioka (T2K) experiment

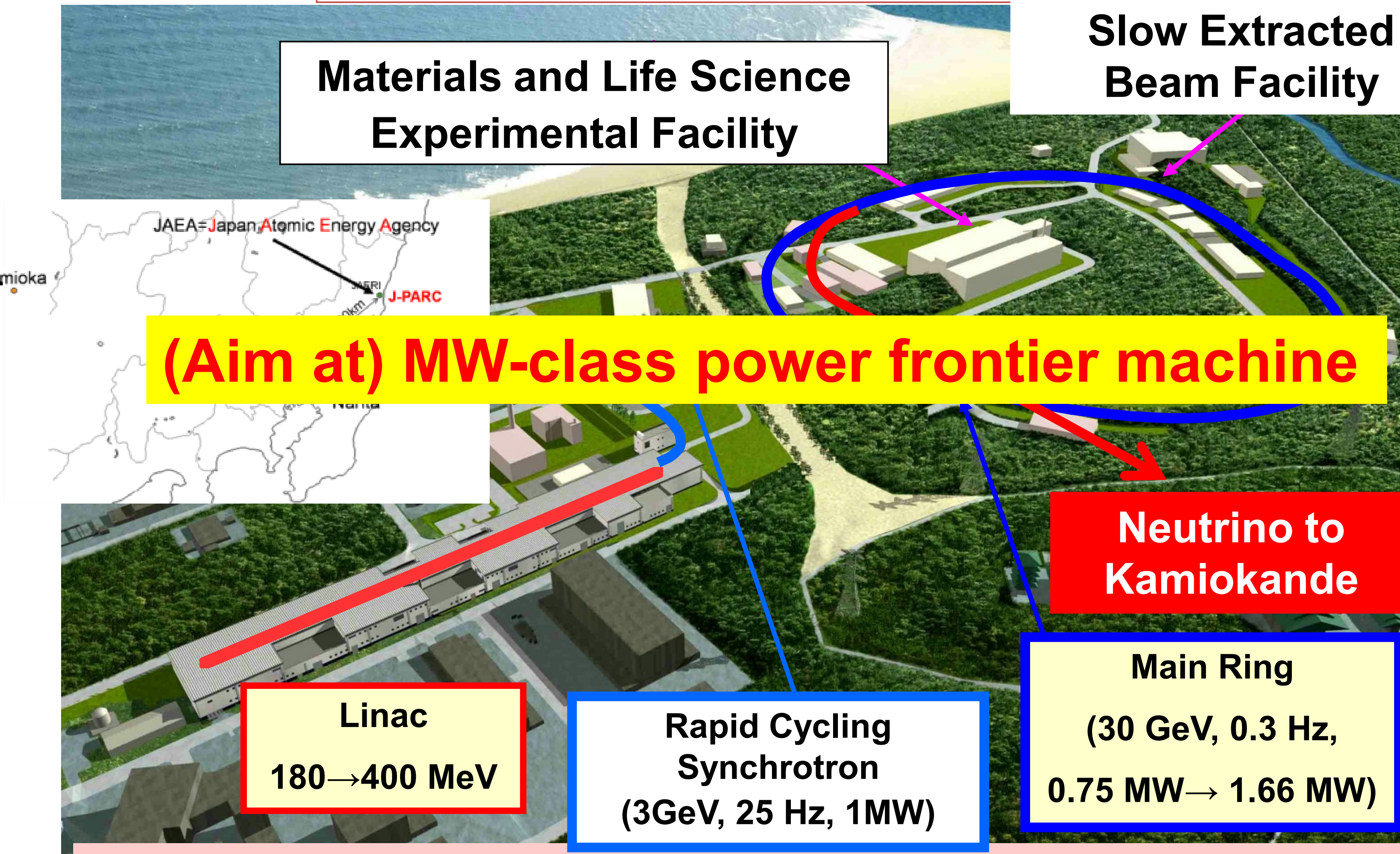
The 1st experiment w/ J-PARC ν facility

- High intensity ν_μ beam from J-PARC MR to Super-Kamiokande @ 295km
- **Discovery of νe appearance → Determine θ_{13}**
  - Last unknown mixing angle
  - **Open possibility to explore CPV in lepton sector**
- Precise meas. of ν_μ disappearance → θ_{23}, Δm_{23}^2
  - Really maximum mixing? Any symmetry? Anything unexpected?

J-PARC

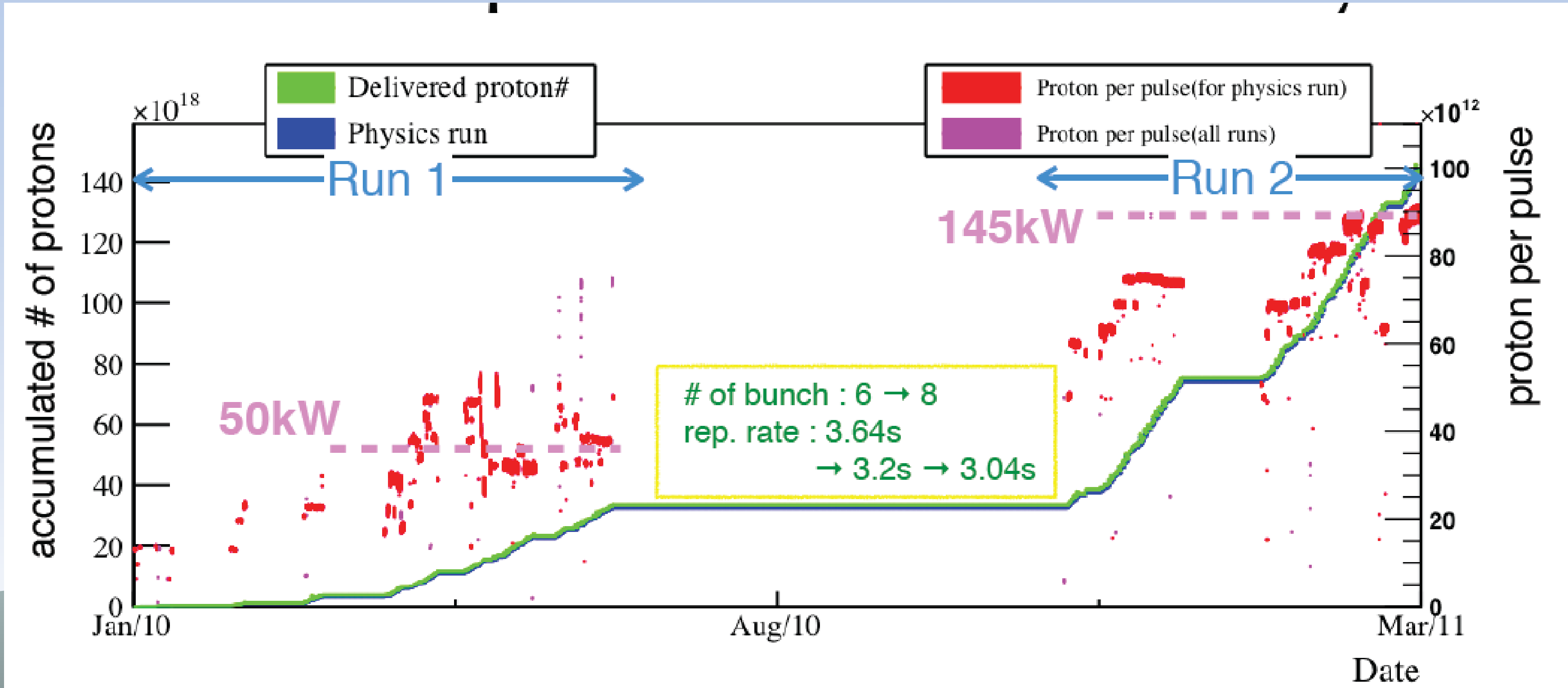
Japan Proton Accelerator Research Complex

Joint Project between KEK and JAEA



Construction: JFY01~08 (Neutrino: JFY04~08)

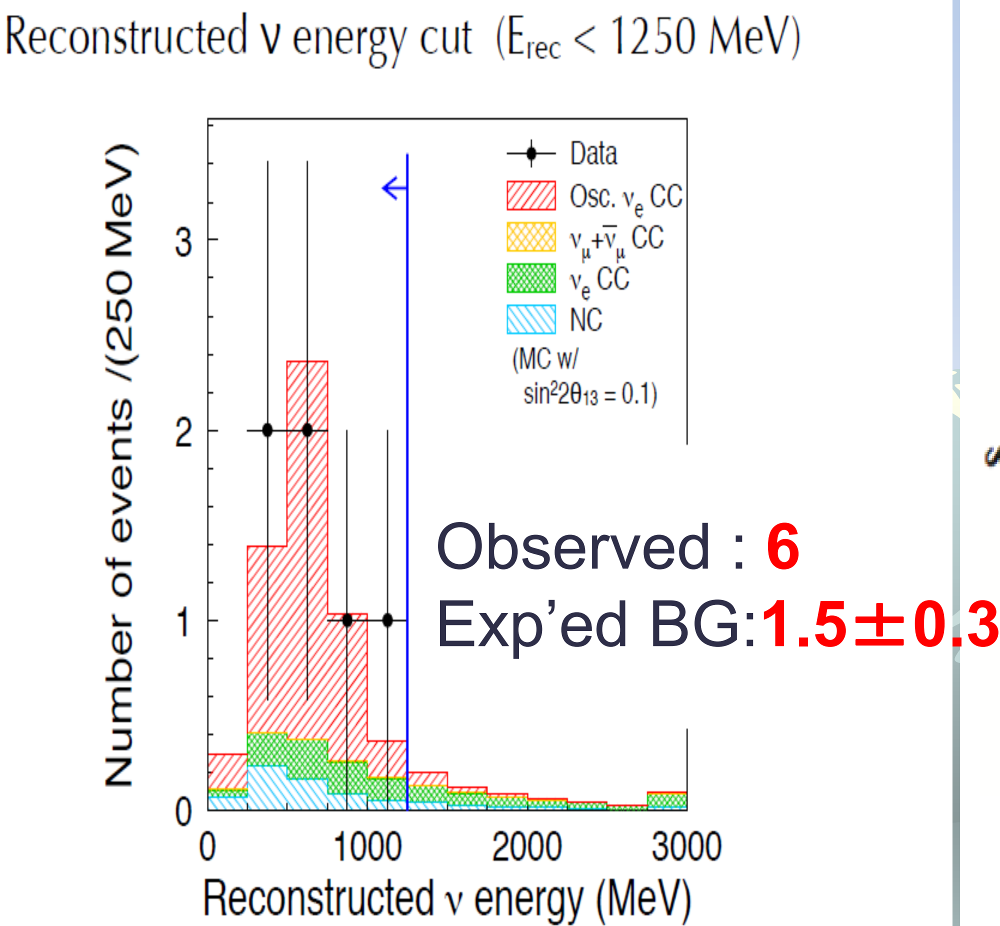
T2Kデータ収集の経過

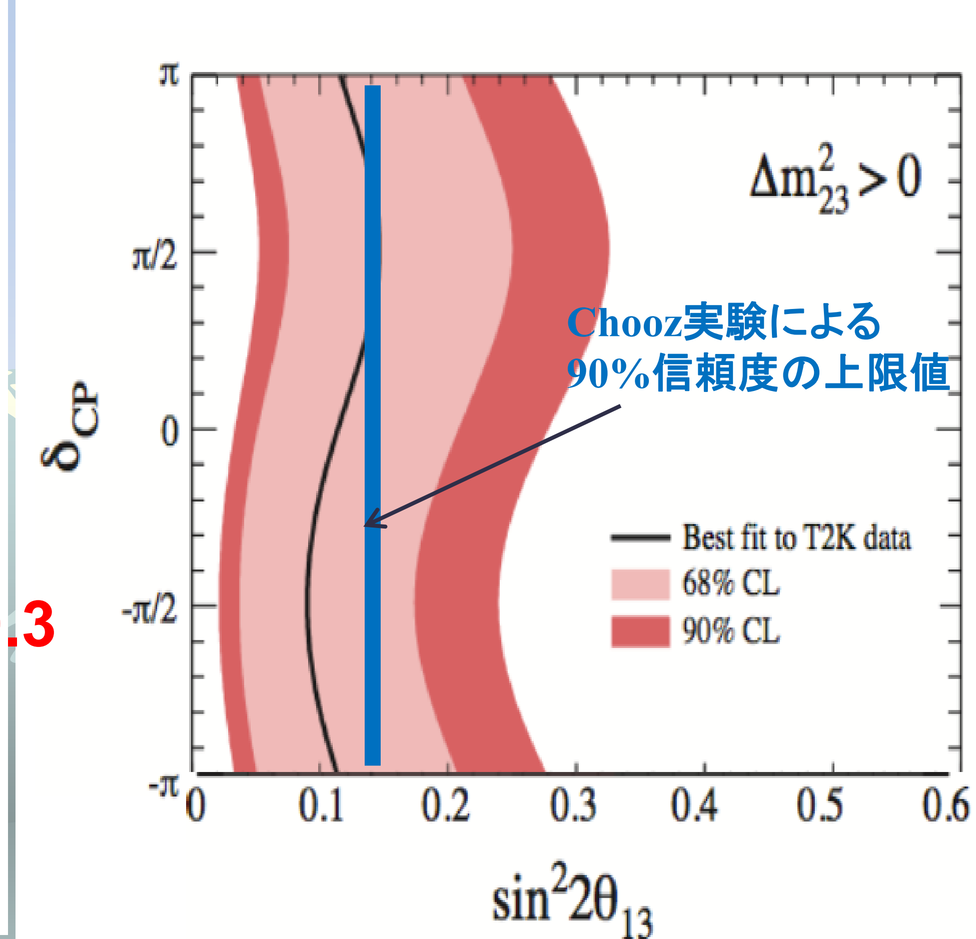


- 2010年1月ニュートリノ振動測定開始
- ビームパワー145kW到達 (設計750kW)
- 2011年3月11日までに$1.43\mathrm{x}10^{20}$個の陽子を標的に照射 (~70 [kW・SNyear])

1SNyear≡10^7s=2800h=116day

Indication of non-zero θ_{13}





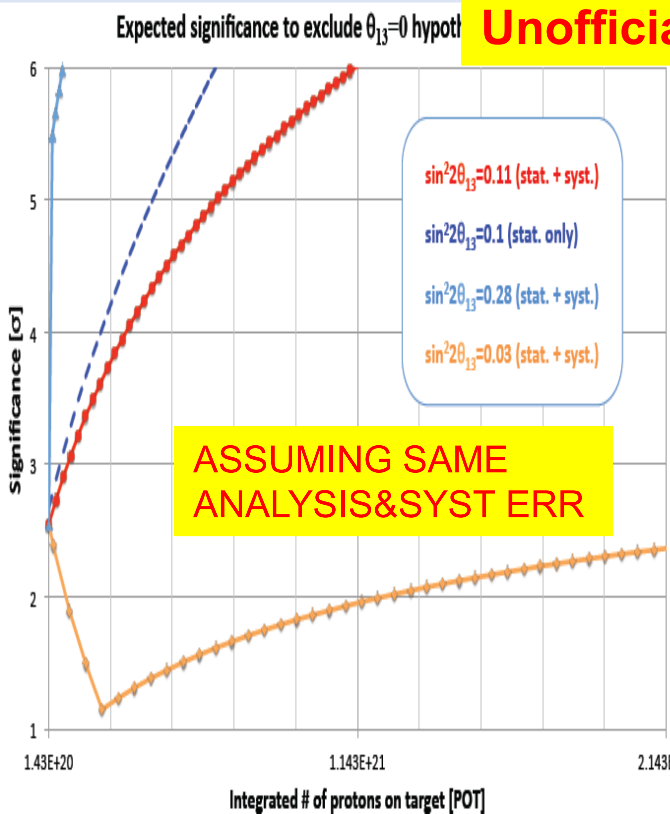
- **Probability to observe >=6 is 0.7%**

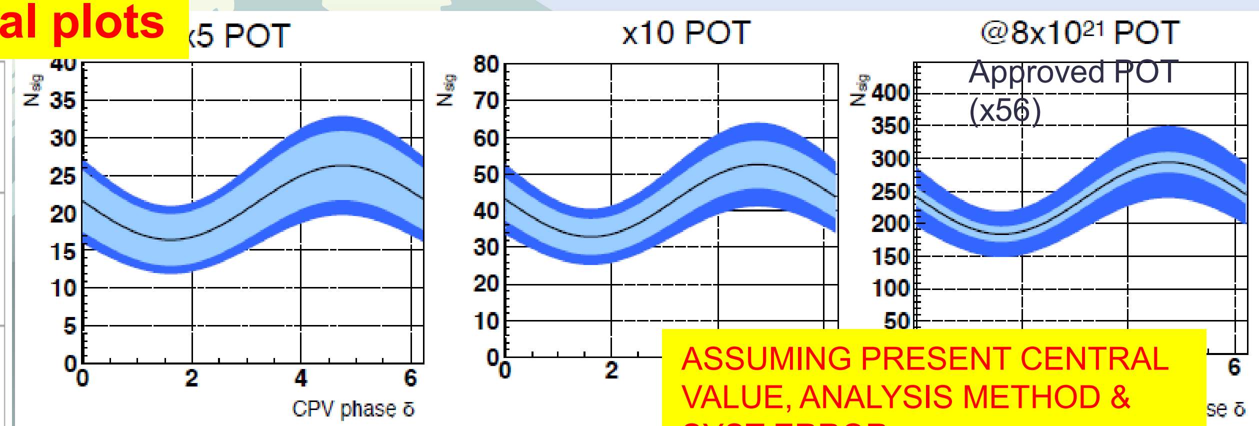
($\Delta m_{23}^2>0$のとき)		($\Delta m_{23}^2<0$のとき)
$0.03 < \sin^2 2\theta_{13} < 0.28$		$0.04 < \sin^2 2\theta_{13} < 0.34$
$\sin^2 2\theta_{13} = 0.11$	中心値	$\sin^2 2\theta_{13} = 0.14$

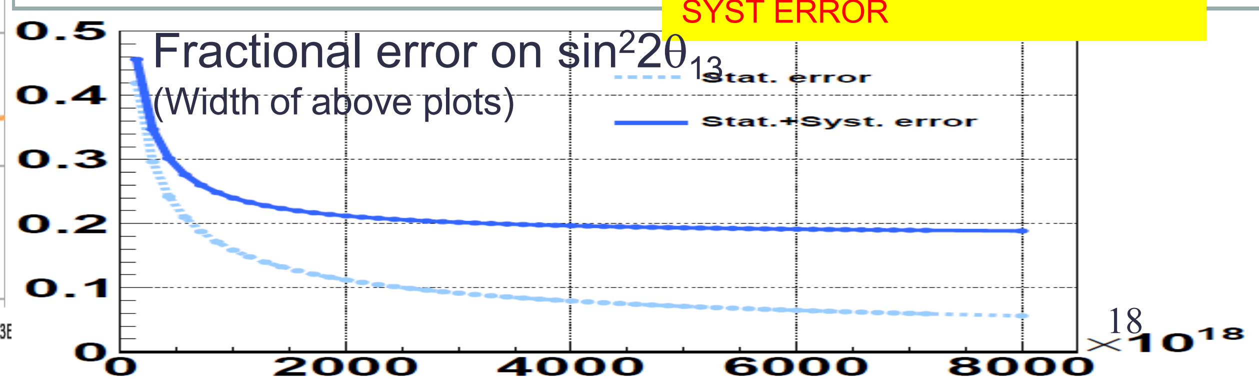
Short term prospect of J-PARC & T2K

- J-PARC will resume operation in 2011 and provide > 2 “cycle” in JFY2011
- LINAC upgrade to 400MeV delayed 2012 ➔ 2013 (JFY2012: Full 9 month operation)
- 5 times more data necessary to establish finite θ_{13} for present central value
- Precision of θ_{13} gradually approach 10%~20% (w/ and w/o present syst)
- Have to/Will improve analysis method (eg Eν info) and syst. Error

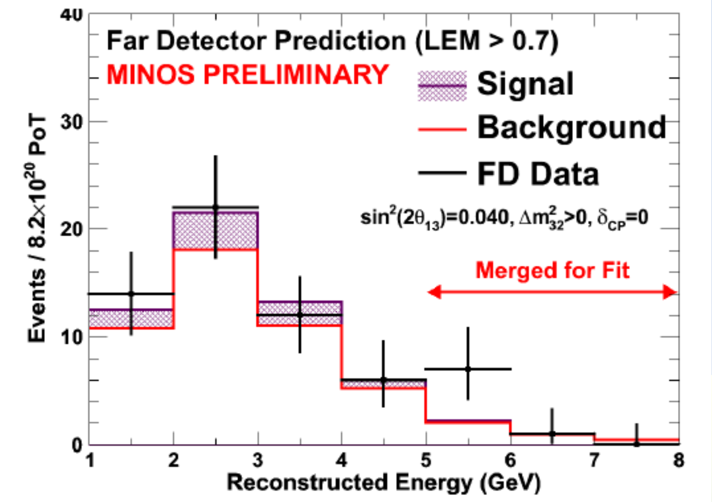
Unofficial plots







MINIS latest results (June 24, 2011)



For LEM>0.7

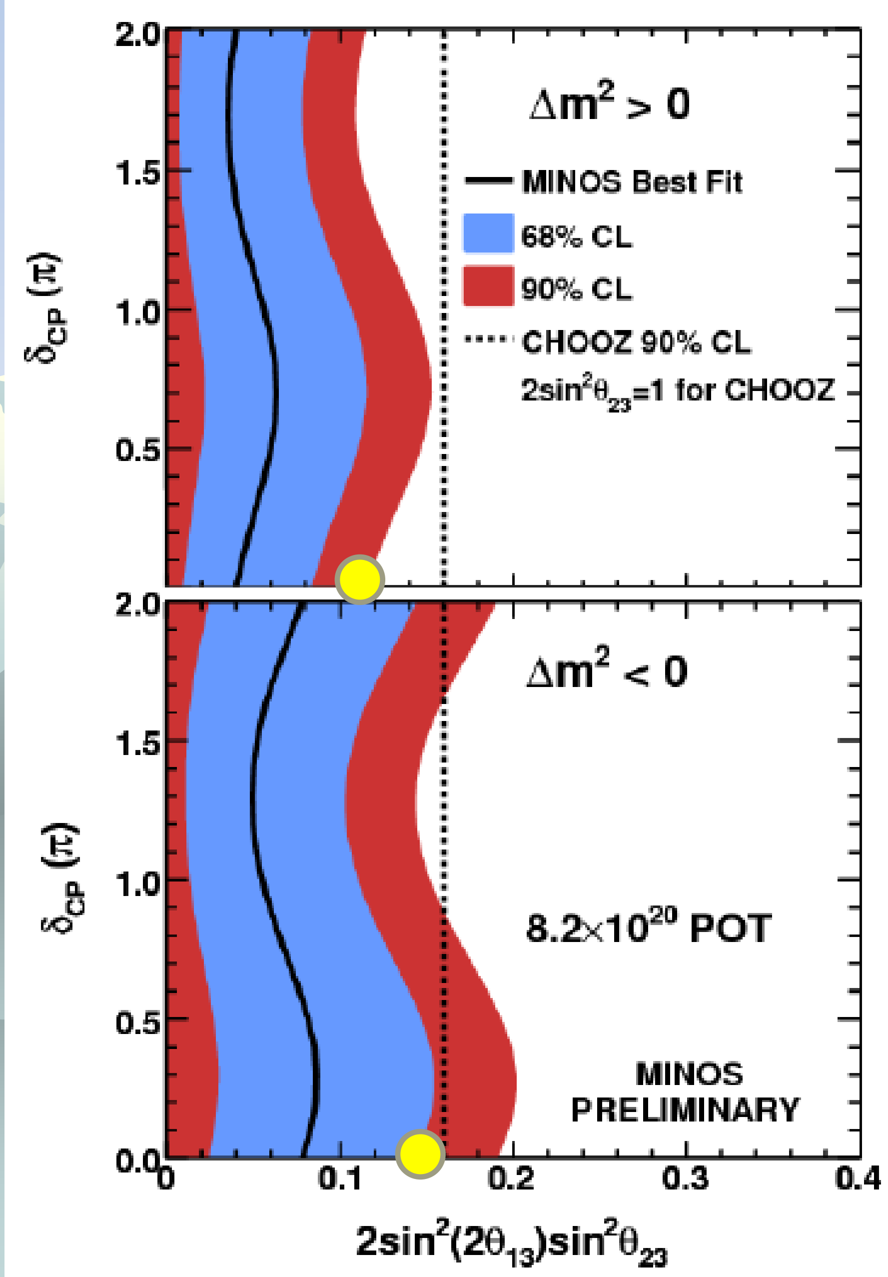
Expected background events:
49.5 ± 2.8 (syst) ± 7.0 (stat)

Observed events in FD data:
62

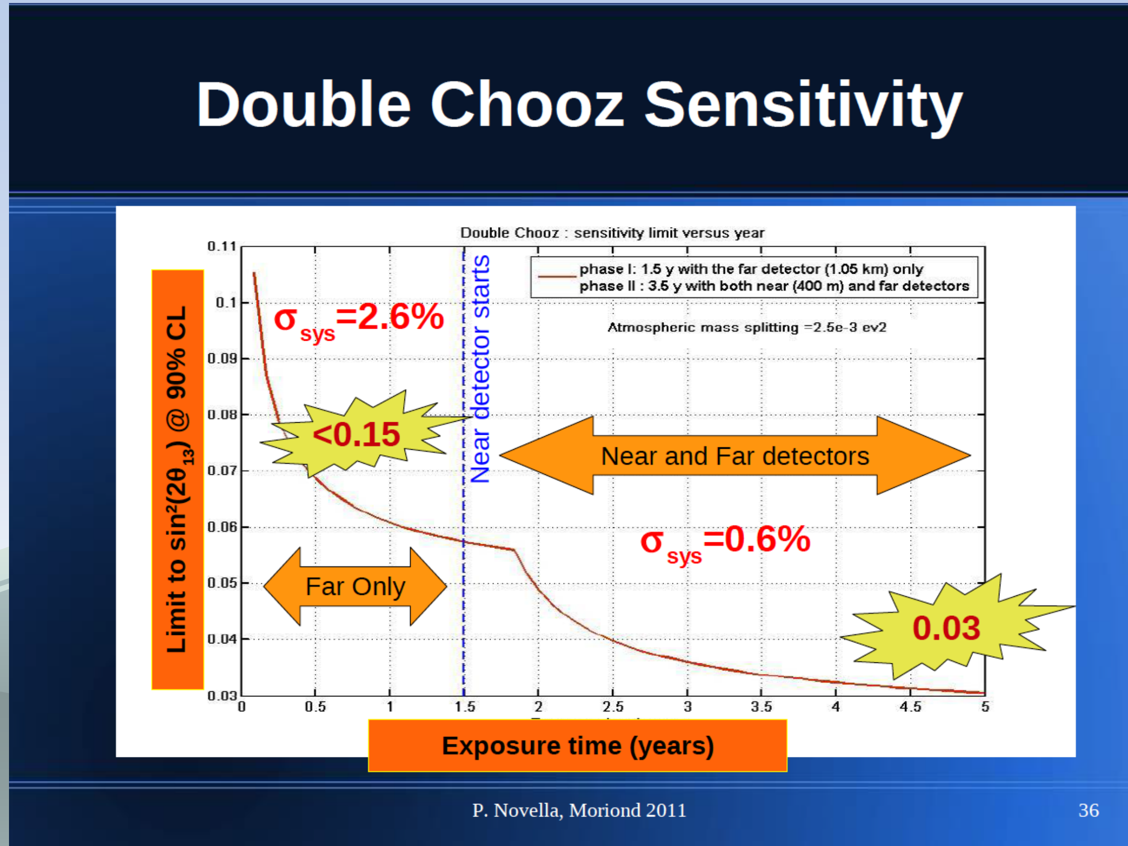
1.7σ excess above background

For $\delta_{CP} = 0$ the allowed values of $2\sin^2(2\theta_{13})\sin^2(\theta_{23})$ at 90% CL are:

0 to 0.12 (normal) central value: 0.04
0 to 0.19 (inverted) central value: 0.08



Prospect of DoubleChooz



- **IF $\sin^2 2\theta_{13}$~0.1**, Dchooz can measure 20~30%
- Near detector will be ready around end of 2012

Quest for the Origin of Matter Dominated Universe

One of the Main Subject of the KEK Roadmap

T2K (2009~)

Discovery of the ν_e Appearance

Neutrino Intensity Improvement

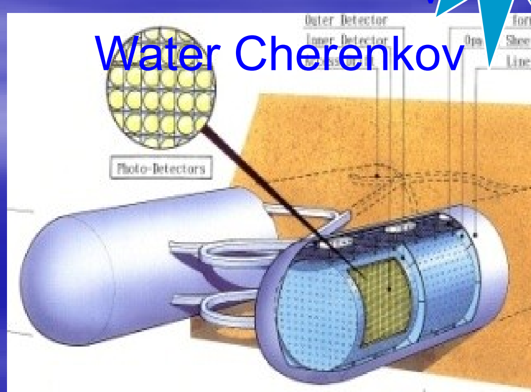
Huge Detector R&D

Establish Huge Detector Technology

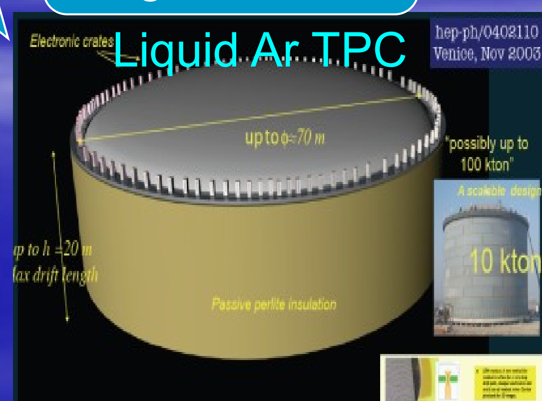
Construction of Huge Detector

Discovery of Lepton CP Violation Proton Decay

Water Cherenkov

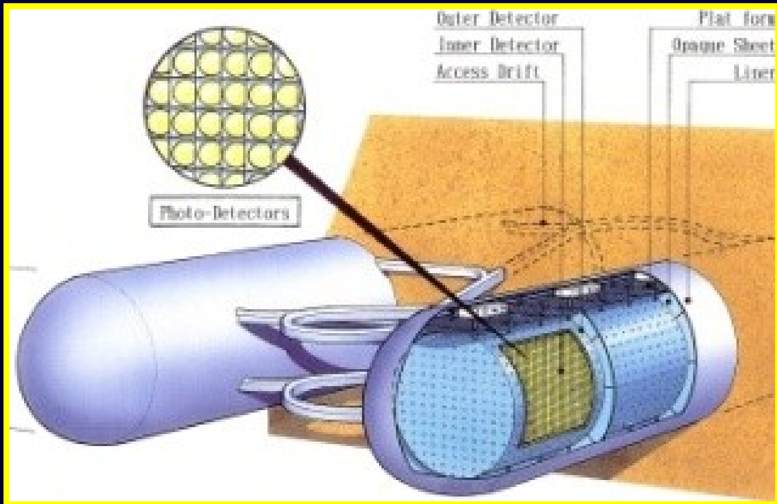


Liquid Ar TPC

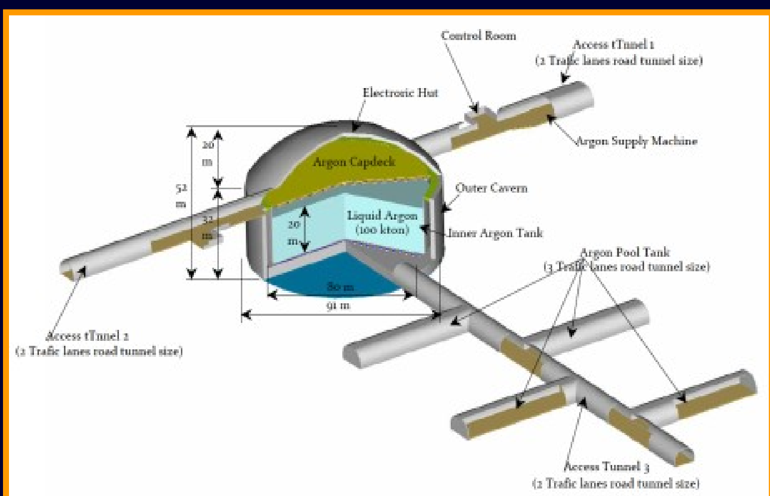


Scenarios from J-PARC

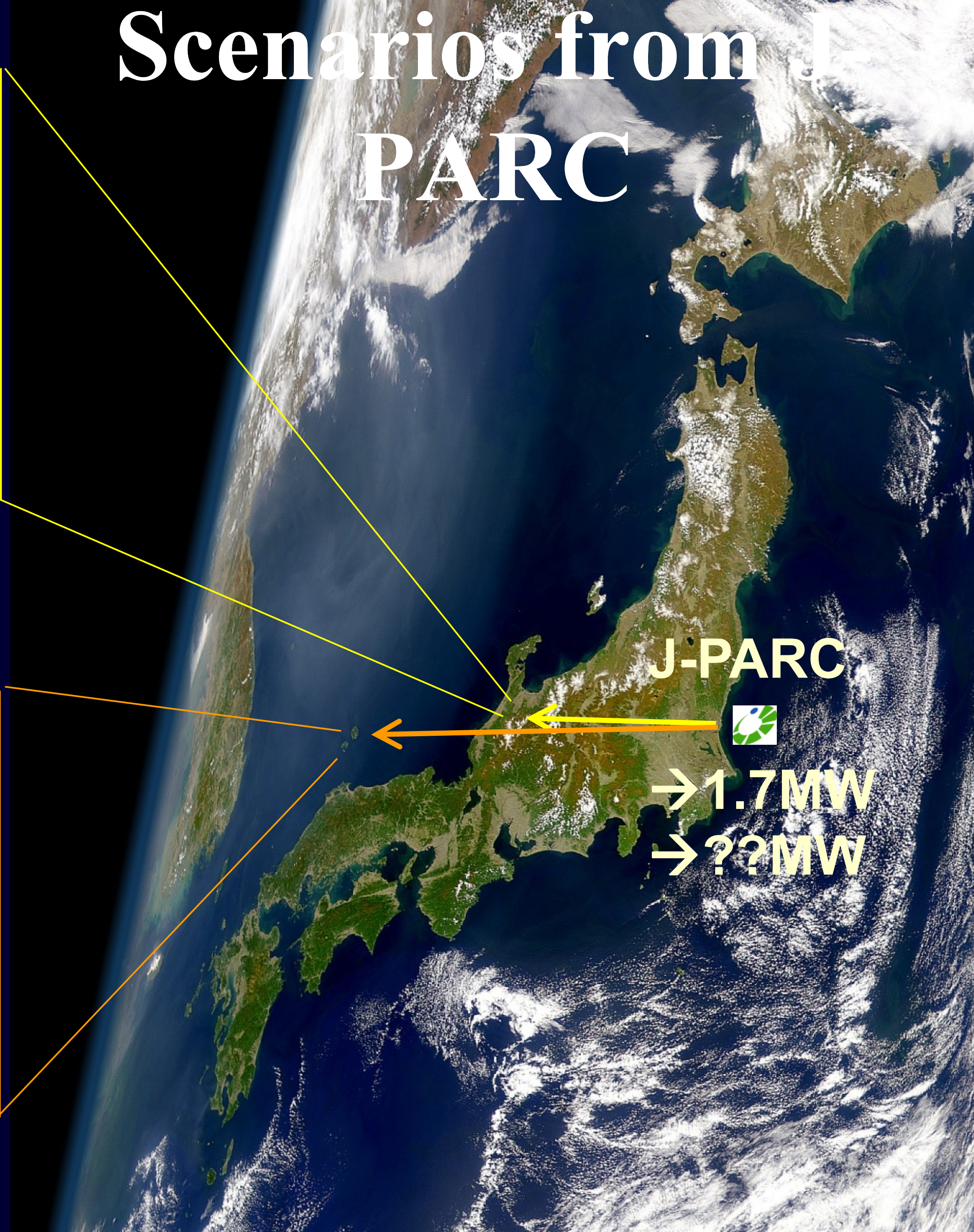
Kamioka L=295km OA=2.5deg



Okinoshima L=658km OA=0.78deg
Almost On-Axis



P32 proposal (Lar TPC R&D)
Recommended by J-PARC PAC
(Jan 2010), arXiv:0804.2111



Essential requirements for CPV discovery

- **High intensity beam (Multi-MW)**
  - Increase statistics
- **High sensitivity huge detector**
  - Increase statistics
  - Increase signal efficiency
  - Reduce background
  - Reduce systematic errors
  - Should also capable for proton decay detection

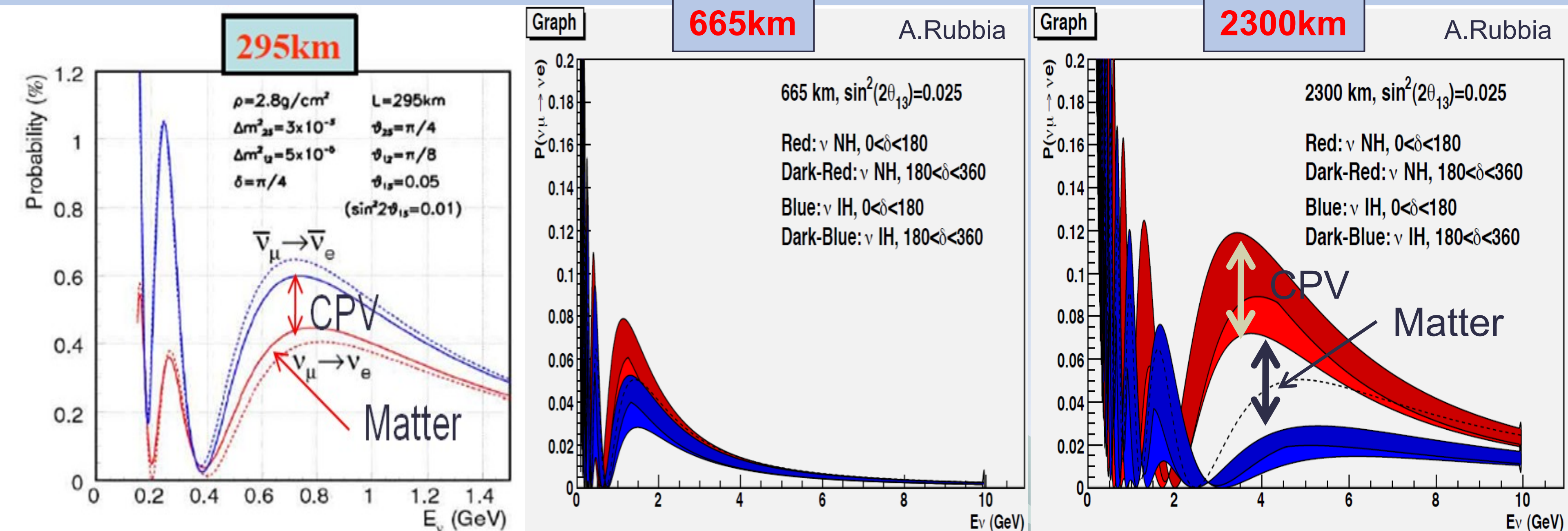
MR Power Improvement Scenario toward MW-class power frontier machine
— KEK Roadmap —

	Day1 Achieved ! (up to Mar.2011)	Next Step	KEK Roadmap
Power(MW)	0.145	0.45	>1.66
Energy(GeV)	30	30	30
Rep Cycle(sec)	3.04	2.2	1.92～0.5
No. of Bunch	8	8	8
Particle/Bunch	1.2×10^{13}	2.5×10^{13}	$4.1\sim8.3\times10^{13}$
Particle/Ring	9.2×10^{13}	2.0×10^{14}	$3.3\sim6.7\times10^{14}$
LINAC(MeV)	181	181	400
RCS	h=2	h=2	h=2 or 1

Combination of **High rep. cycle** and **High beam density**

R&D for Power Supply, RF, and funding are necessary

How to measure CPV & sign(Δm_{23})



- **νe appearance energy spectrum shape**
  - Peak position and height for 1st, 2nd maximum and minimum
  - Measure both sinδ & cosδ terms ➔ can descriminate 0deg vs 180geg
- **Difference between νe and $\overline{\nu e}$ behavior**
  - Sensitive to any mechanism to make asymmetry (No assumption)
  - Basically measure sinδ term
- **Distance:**
  - Larger L (L/E=const➔ higher E) : Matter effect large ➔ Sensitive to sign(Δm_{23}) too
  - Smaller L (lower E): Puerer CPV measurement
    - Note: For large $\sin^2 2\theta_{13}$>~0.1, Matter effect >~ CPV asymmetry, cannot neglect

Scenario 1

J-PARC to Okinoshima

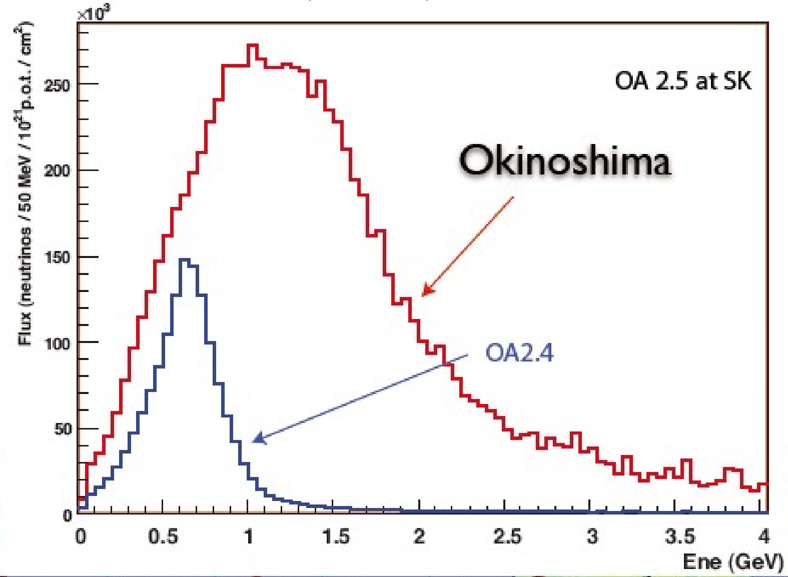
P32 proposal (Lar TPC R&D)
Recommended by J-PARC PAC
(Jan 2010), arXiv:0804.2111

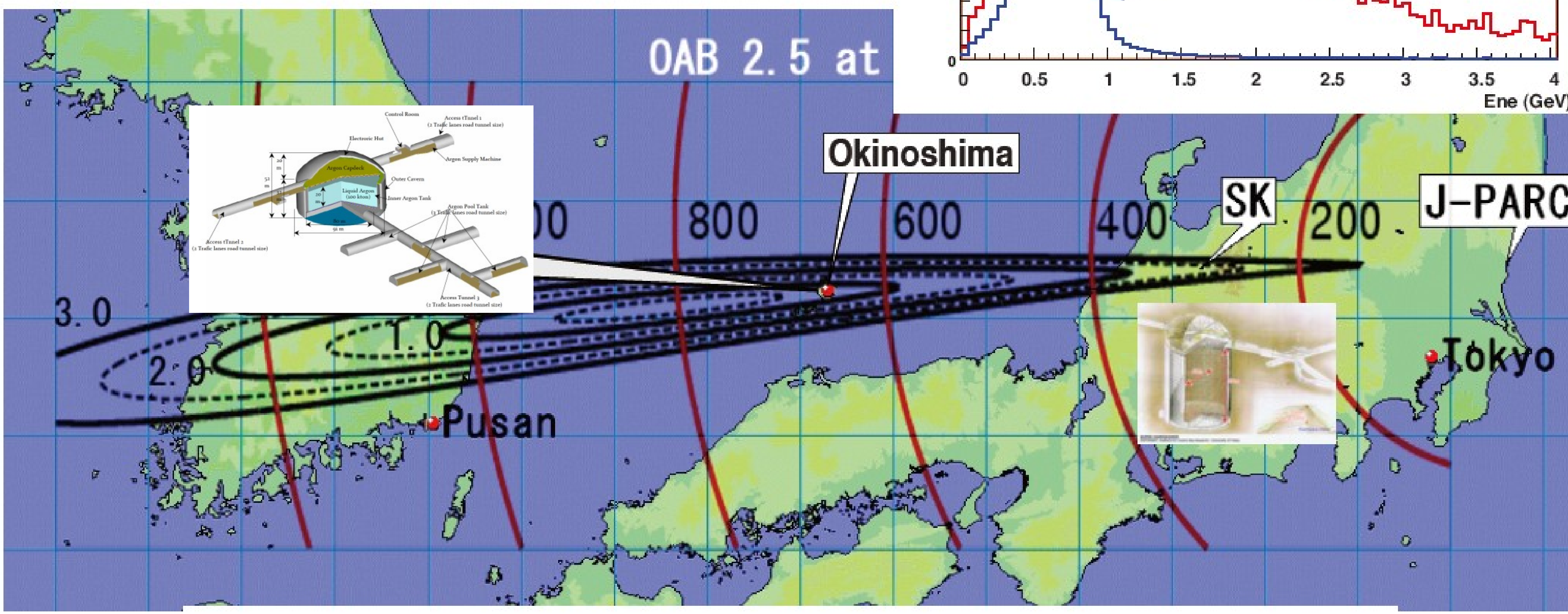
Distance = 658 km

Off-axis angle = 0.76°

(2.5° @ SK)

100 kton liquid Argon





→ Extract δ_{CP} from fit of 1st & 2nd maximum

Scenario 1

J-PARC to Okinoshima

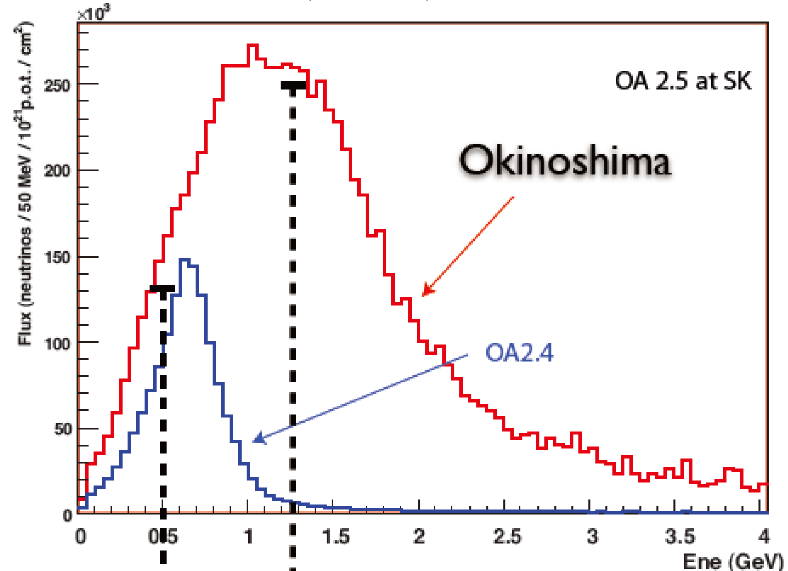
P32 proposal (Lar TPC R&D)
Recommended by J-PARC PAC
(Jan 2010), arXiv:0804.2111

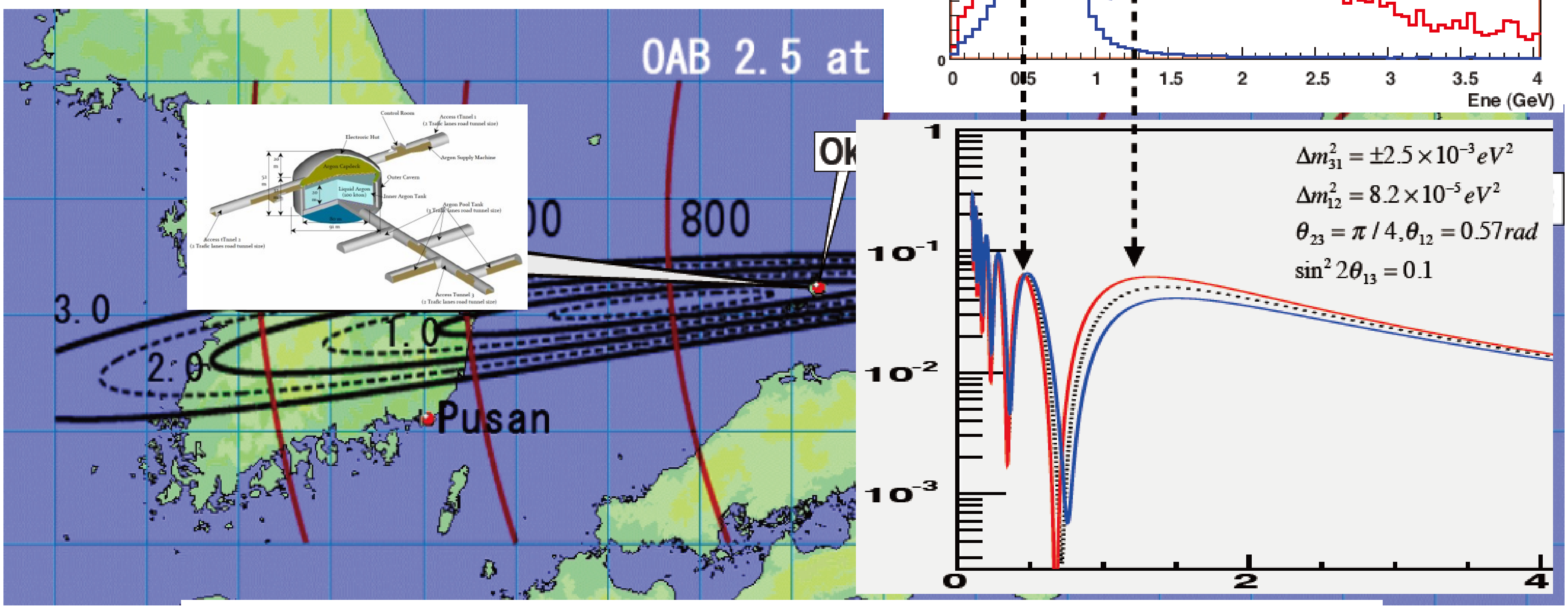
Distance = 658 km

Off-axis angle = 0.76°

(2.5° @ SK)

100 kton liquid Argon





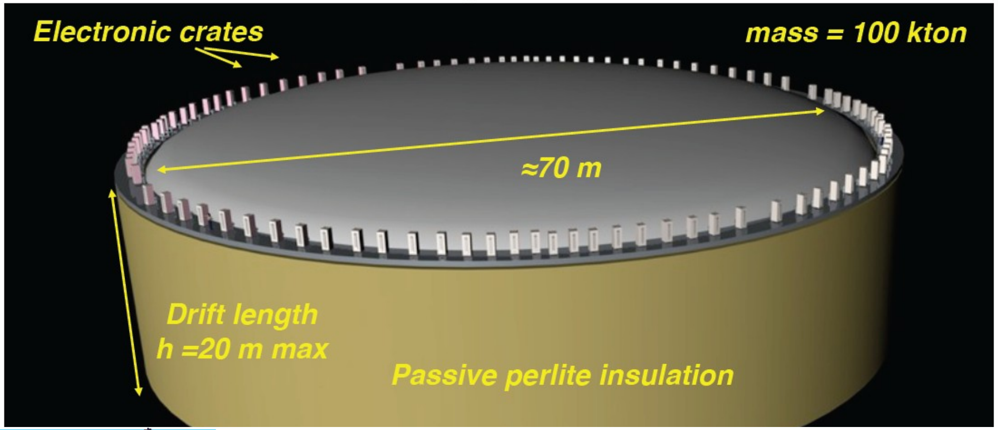
→ Extract δ_{CP} from fit of 1st & 2nd maximum

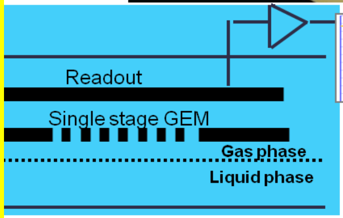
100kt Liq Argon TPC "GLACIER"

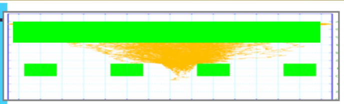
- Extremely high performance
  - "Electronic Bubble Chamber"
  - 3D tracking of all charged particle from very low energy threshold
    - Precise resolution of ~mm
  - Fully active homogeneous 4π detecotor (as WC)
  - Good PID w/ dE/dx, π^0 rejection
- Double phase w/ Gas amplification
- <10ppt purity needed
- LEM readout (~10^6ch)
- 600ton detector realized and working

ant Liquid Argon Charge Imaging ExpeRiment

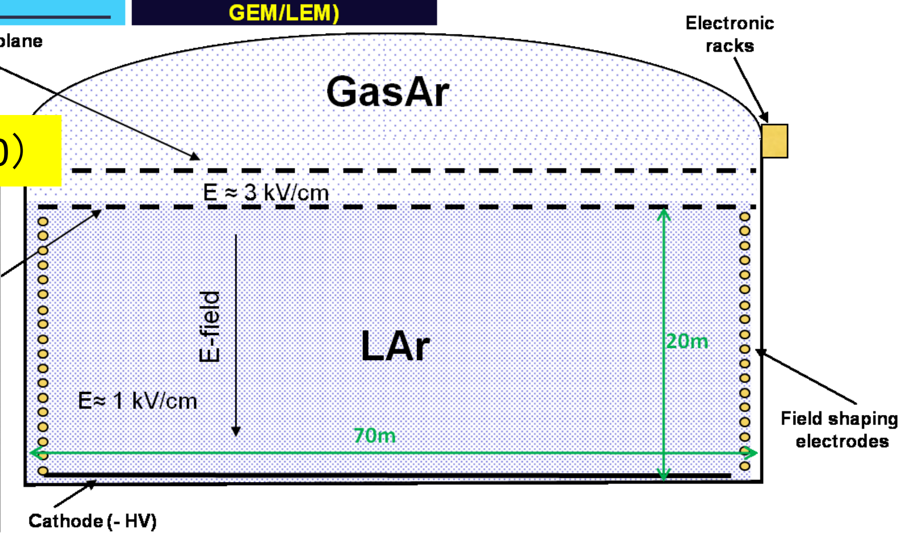
calable detector with a non-evacuable dewar and ionization charge detection with amplification



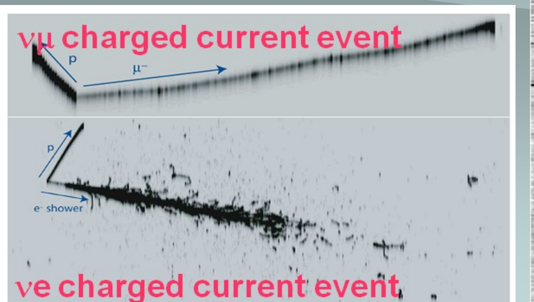




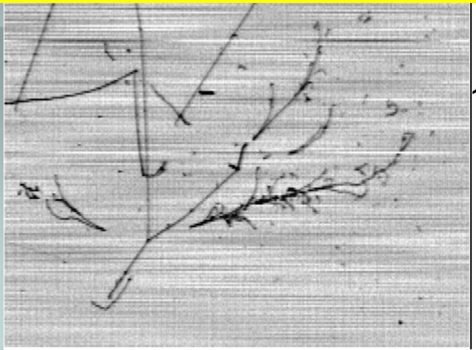
Double phase detector readout using both liquid and gas Argon phases (with GEM/LEM)



Liquid Argon TPC（ICARUS T300）



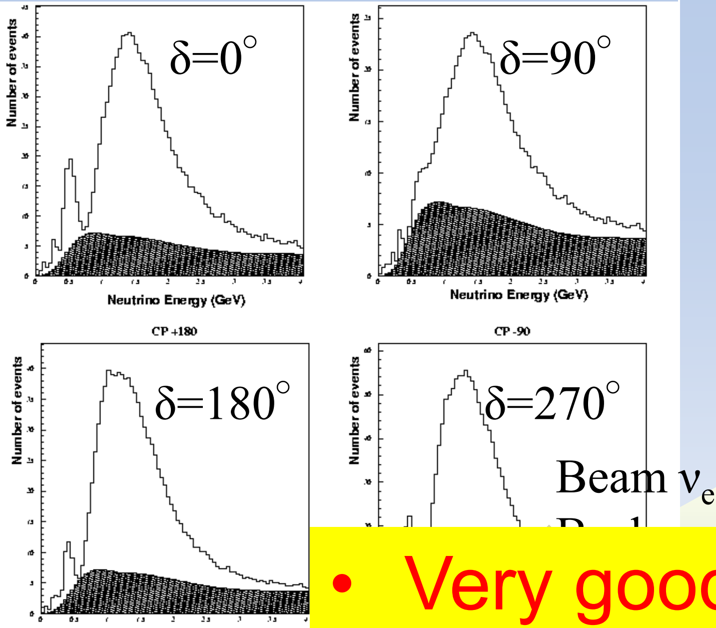
A. Bueno, et.al.,, hep-ph/0701101



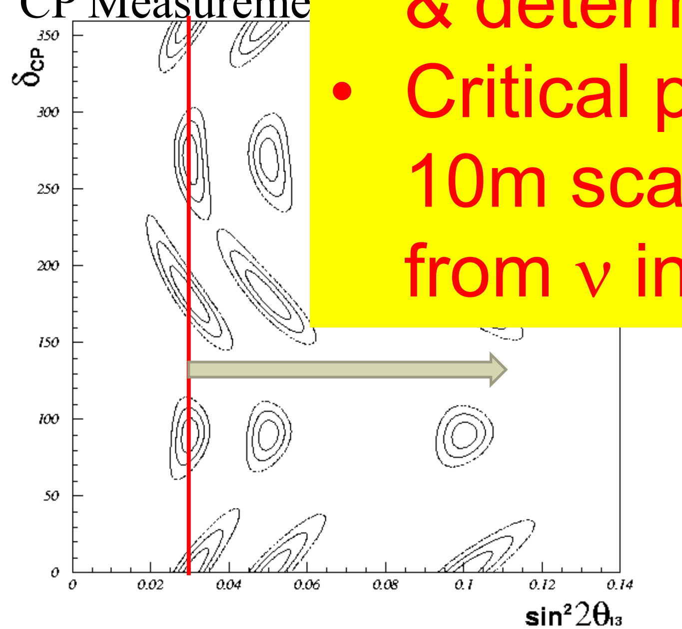
Physics potential

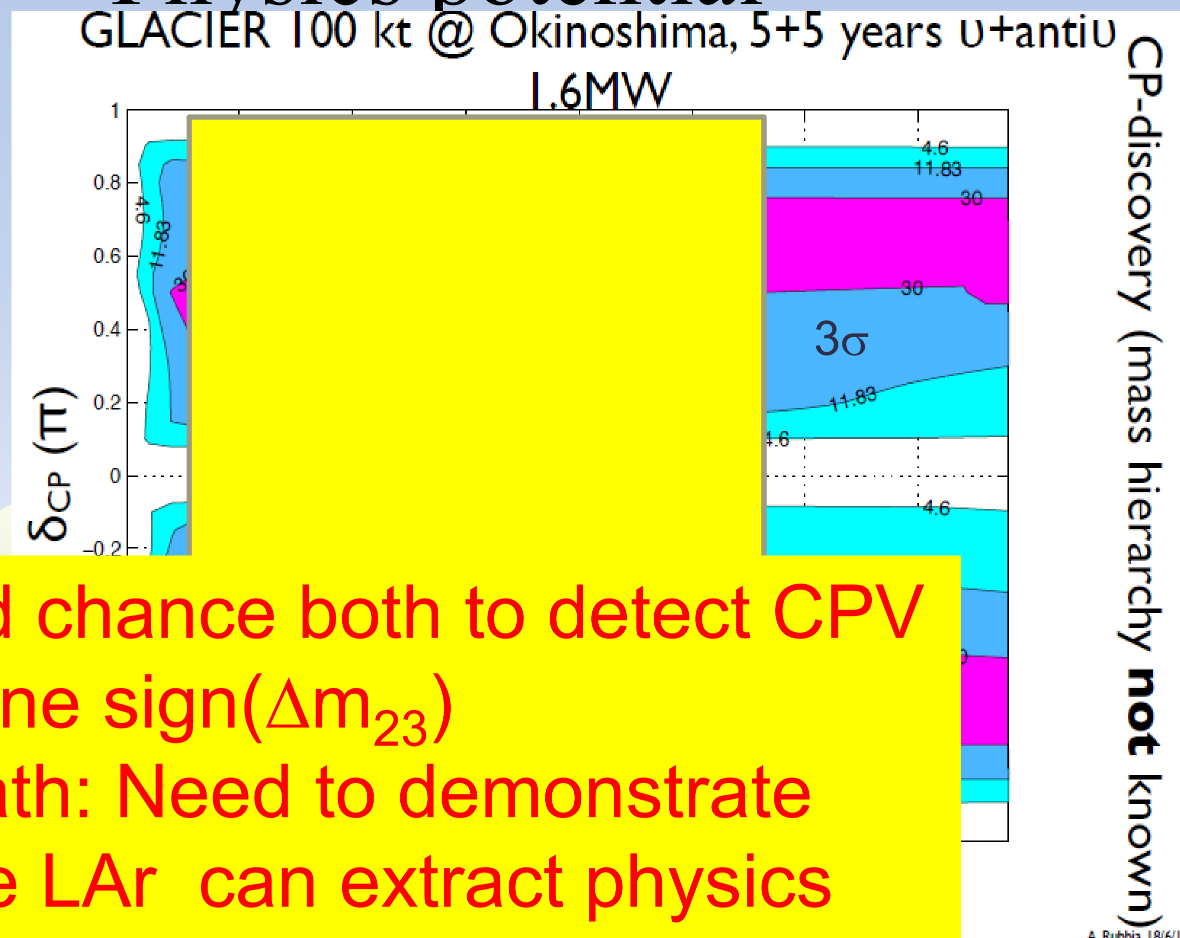
ν_e Spectrum

Nu only, 1.66MWx5yr, $\sin^2 2\theta_{13}=0.03$, NH



CP Measureme





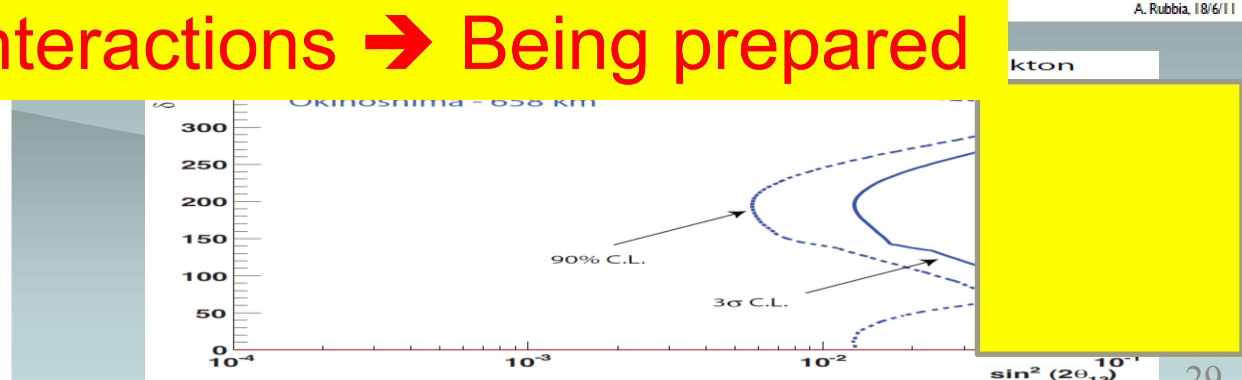
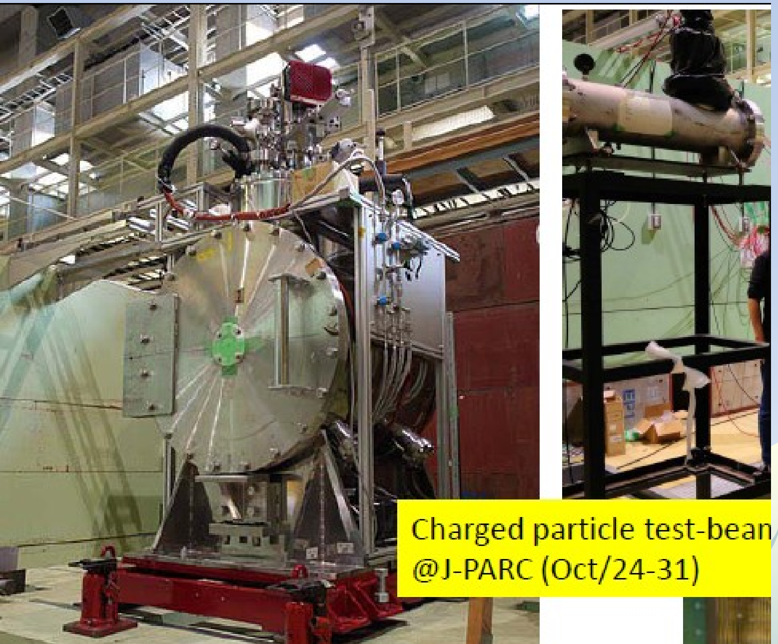


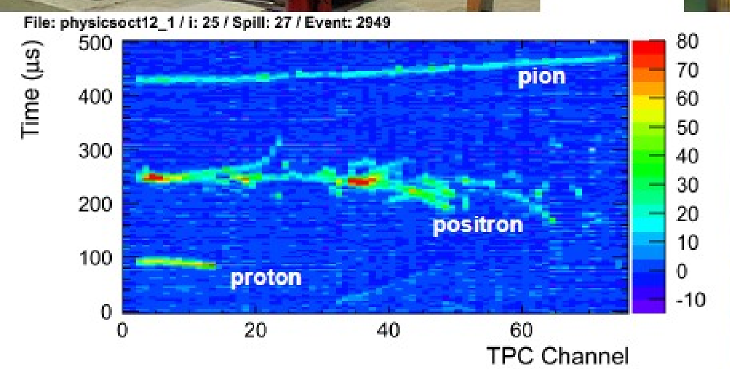
Fig. 10: Mass hierarchy discrimination at 90%C.L. and 3σ for 5+5 years neutrino-antineutrino runs.

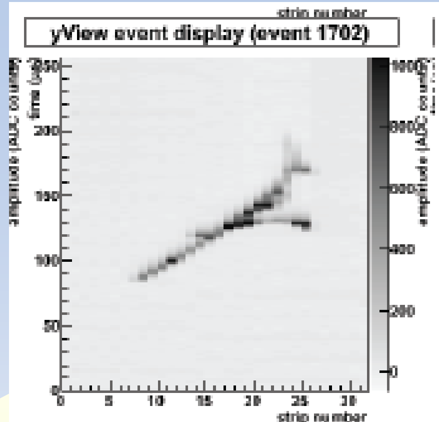
- Very good chance both to detect CPV & determine sign(Δm_{23})
- Critical path: Need to demonstrate 10m scale LAr can extract physics from ν interactions ➔ Being prepared

R&D toward realizing 100kt LArTPC

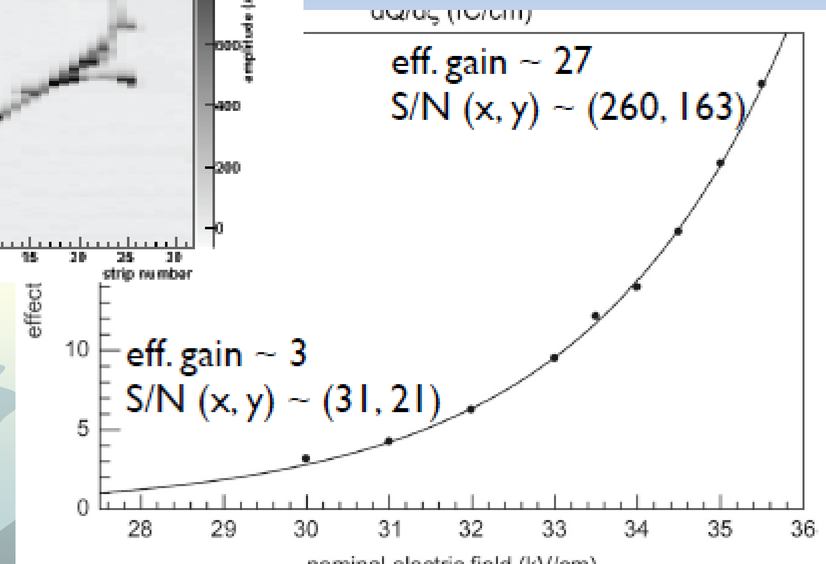


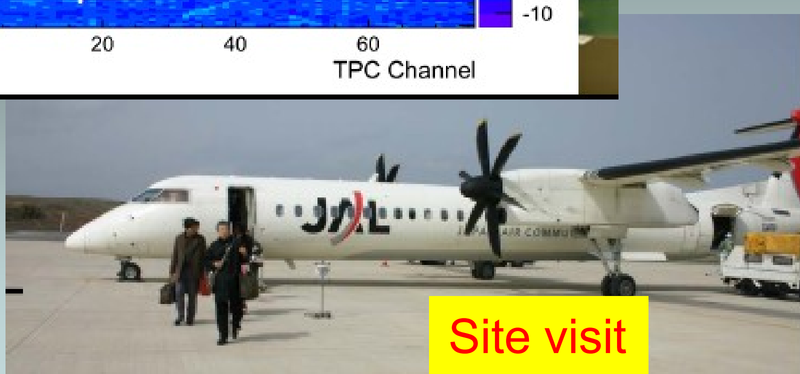
Charged particle test-beam @J-PARC (Oct/24-31)



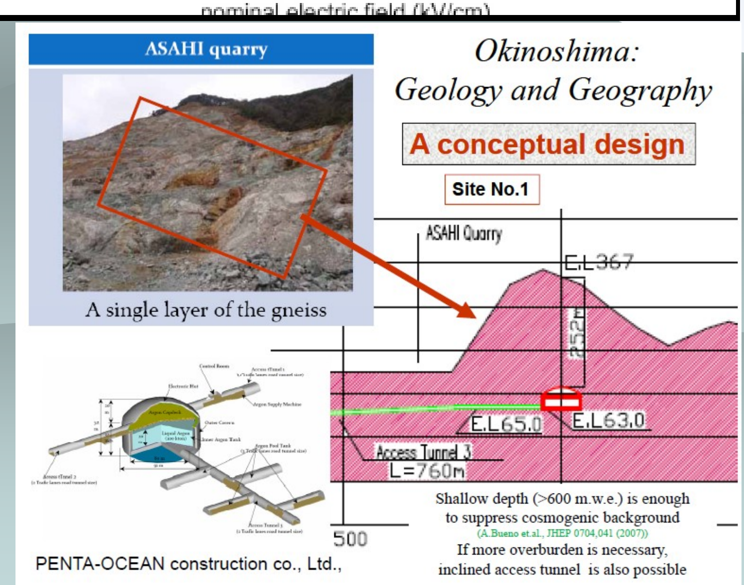


Double phase readout test @ ETHZ

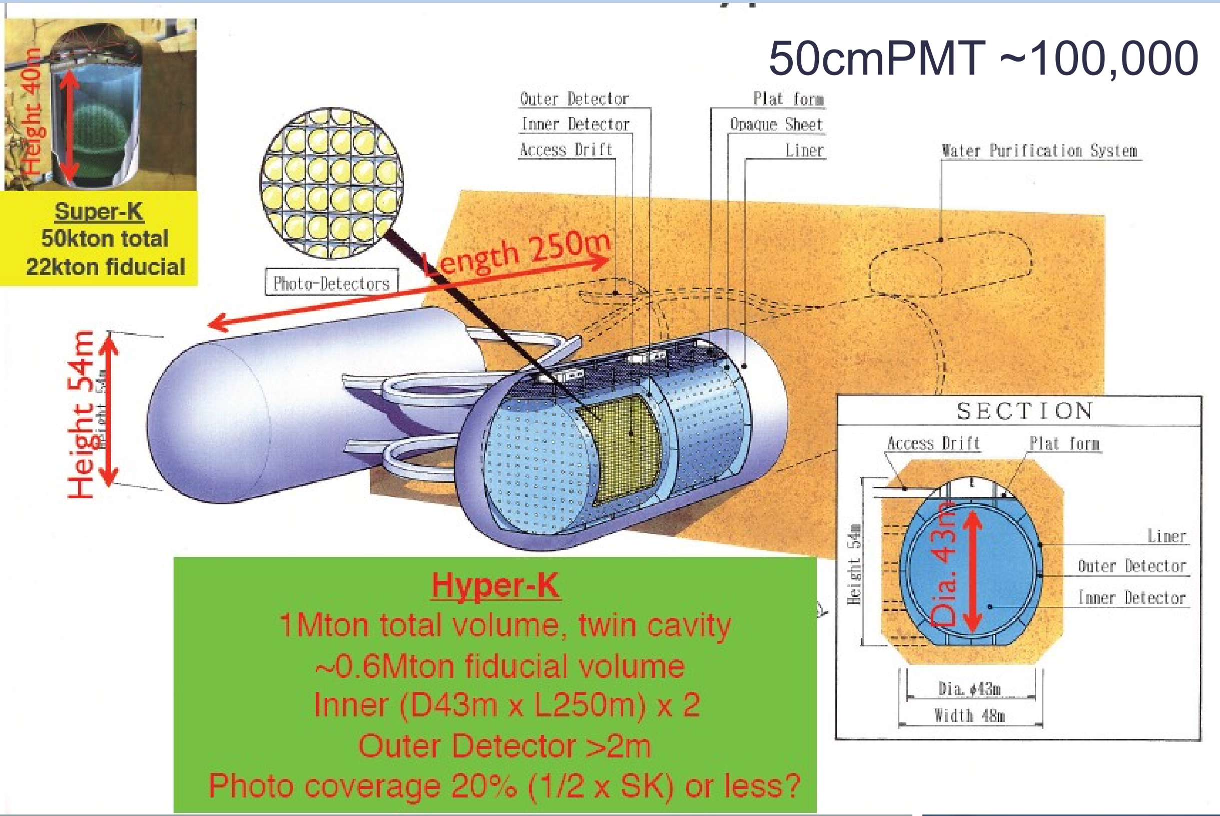




Site visit

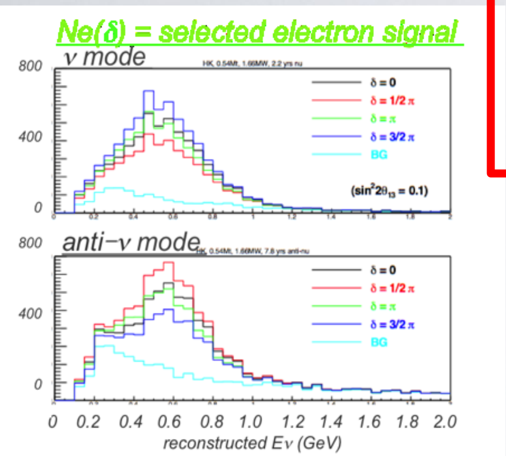


J-PARC to Hyper-Kamiokande

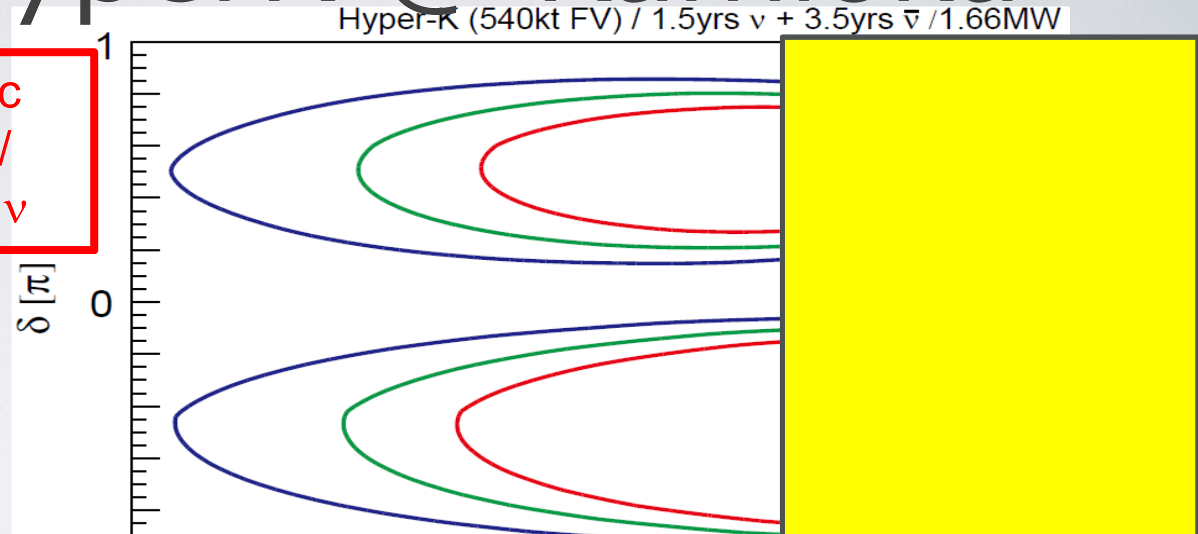


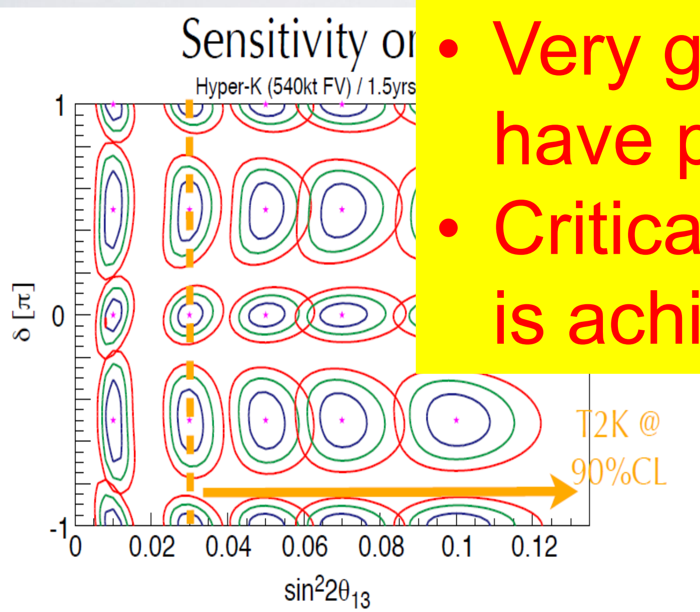
- Excellent performance especially for low energy w/ low multiplicity
- Cherenkov threshold
- Energy reconstruction assuming Ccqe ➔ Efficient for low energy
- Good PID (μ/e)
- Established analysis
- **Good at low E (<1GeV) narrow band beam**
  - Match with low energy off-axis beam

J-PARC-HyperK @ Kamioka



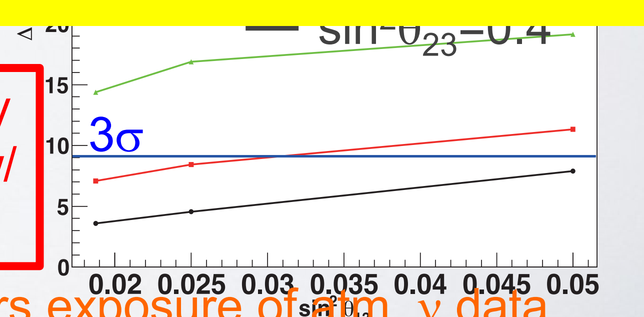
leptonic CPV w/ JPARC ν





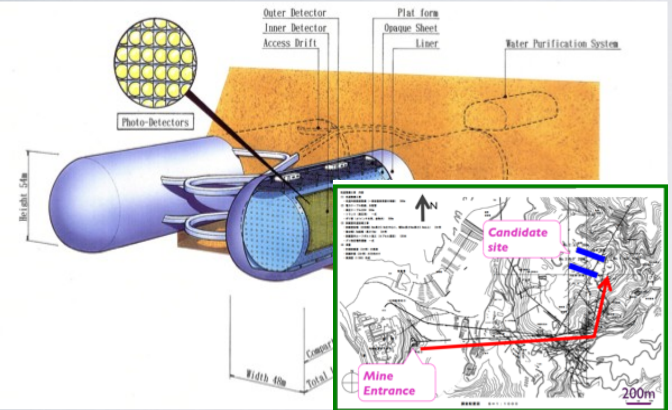
- Very good chance to detect CPV & have potential on sign(Δm_{23}) with atm ν
- Critical path: Need to demonstrate 5% is achievable

mass hierarchy determination w/ atmospheric ν



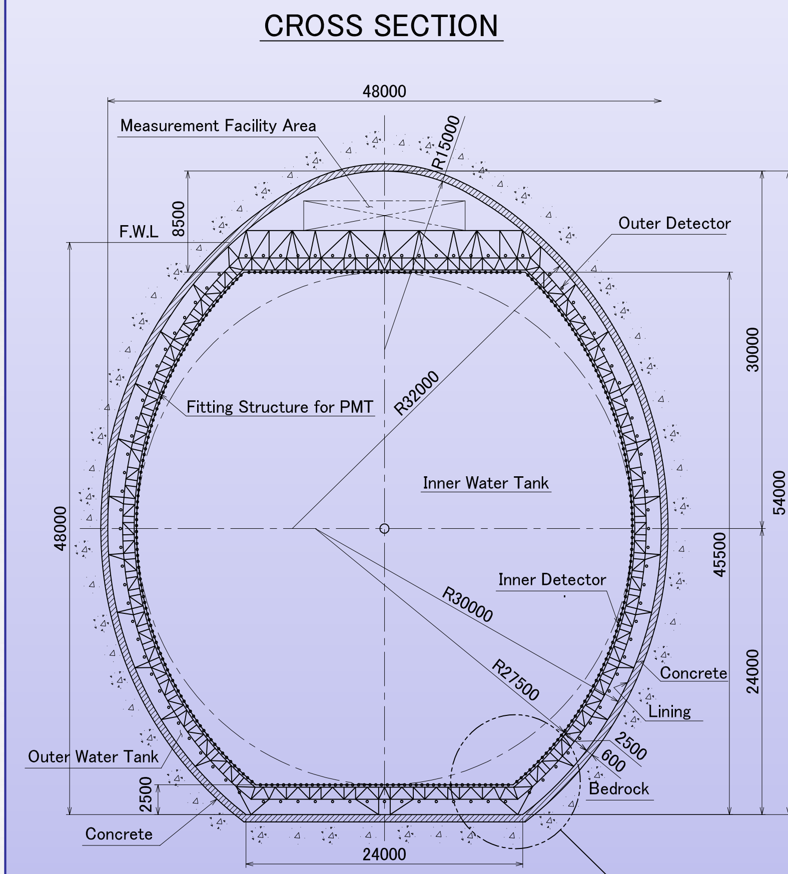
5 yrs of 1.66 MW JPARC ν data.
5% syst. errors are assumed.

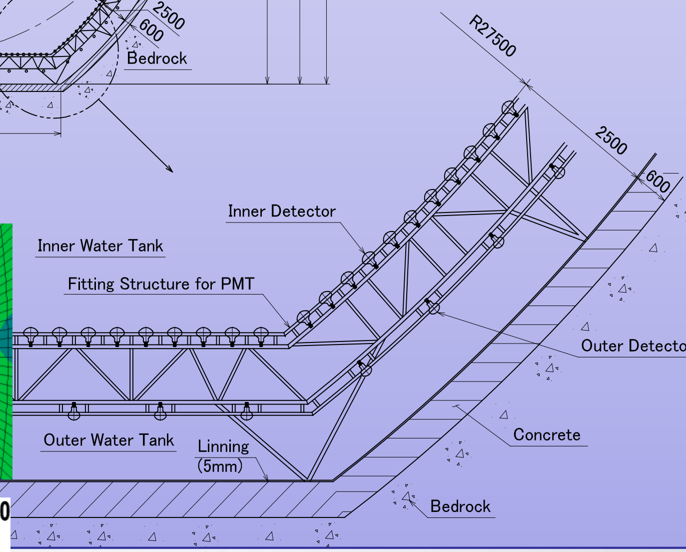
4 yrs exposure of atm. ν data.
Super-K syst. errors are assumed.



Hyper-K Base-Design

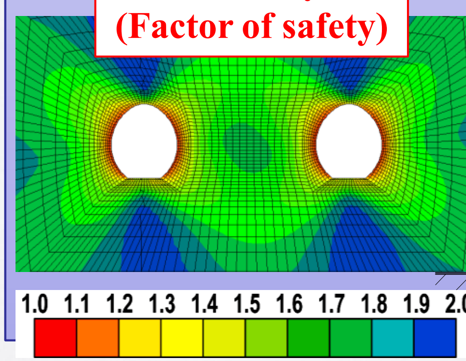
- 1Mton total volume, twin cavity
- 0.54Mton fiducial volume
- Inner (D43m x L250m) x 2
- Outer Detector >2m
- Photo coverage 20% (1/2 x SK)





20" PMT w/ cover

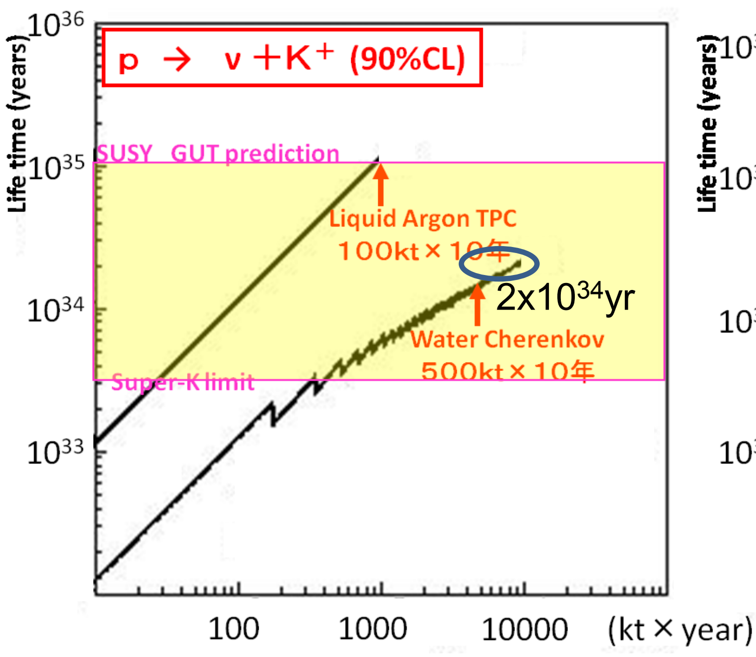
FEM analysis (Factor of safety)

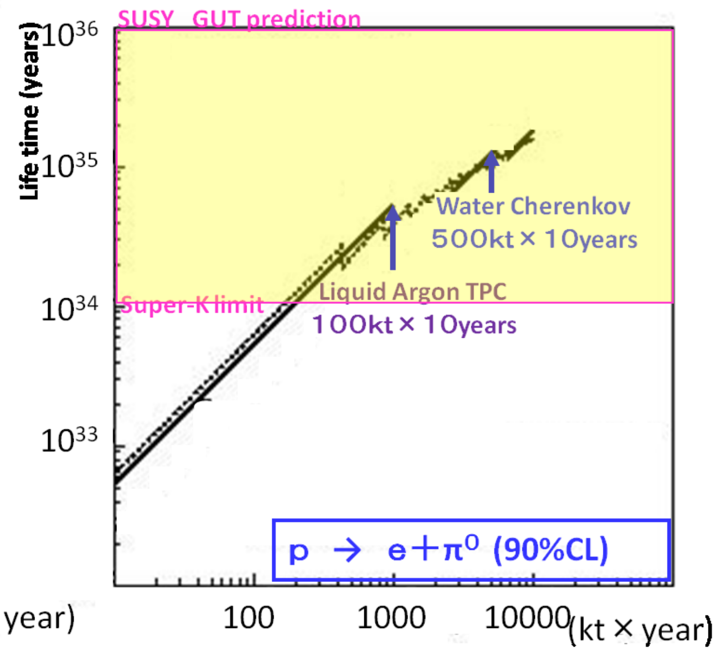


- Base-design to be optimized
- Geological survey of the site is going on
- Qualitative studies on physics potential

Proton decay search

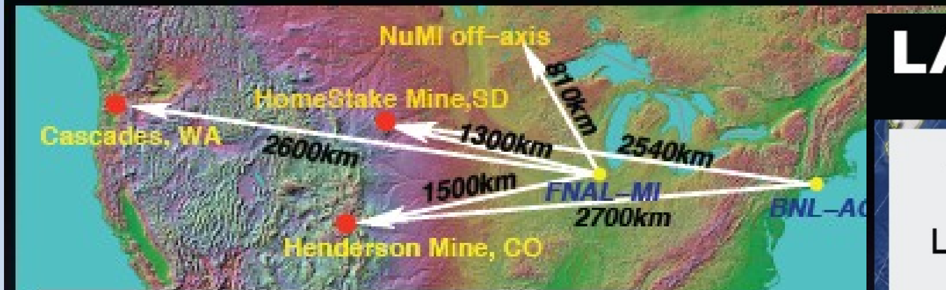
- One of the conditions needed to explain Matter-Anti-Matter Asymmetry
- High sensitivity huge detector for future ν physics should also have high sensitivity to detect proton decay
  - LiqAr' superior efficiency for low energy particle enable drastic improvement on sensitivity on modes such as νK
  - Water Charenkov is very good at "total absorption" modes with relatively high energy (low mass) particles, such as eπ0





- **ν ＋ K^+ mode:** **LAr（100kt×10years）＝～5×WC（500kt×10yeas）**
- **e ＋ π^0 mode: LAr（100kt×10years）＝～1/2×WC（500kt×10years）**

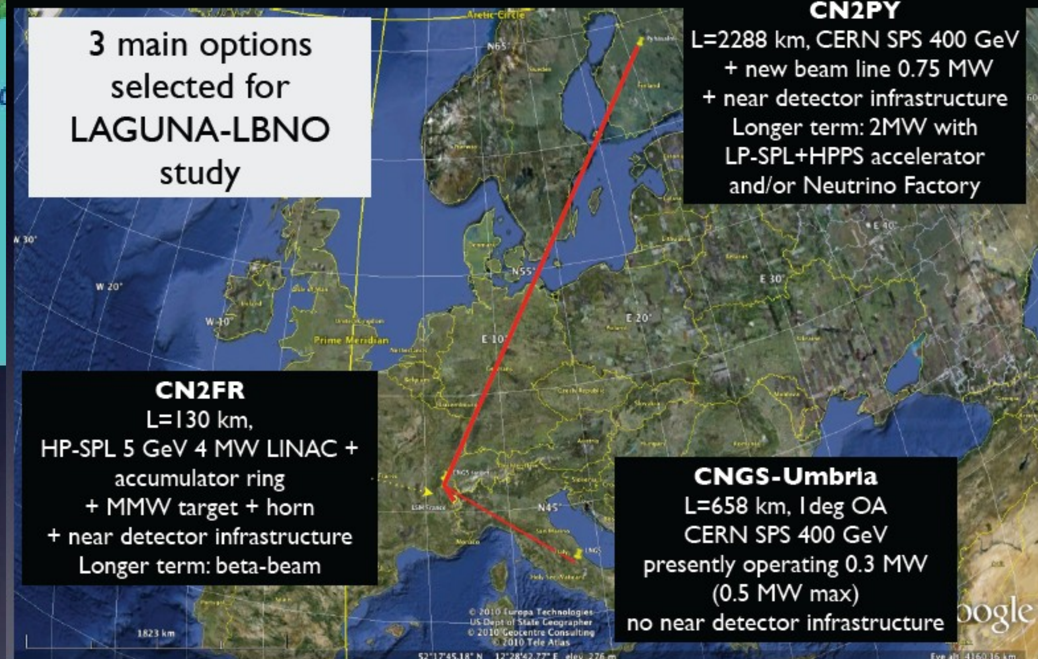
Next generation LBL facilities



Requires new beam (LBNE)
Requires new far site detector (LBNE/DUSEL ?)

In USA

LAGUNA-LBNO study cases



3 main options selected for LAGUNA-LBNO study

CN2PY
L=2288 km, CERN SPS 400 GeV
+ new beam line 0.75 MW
+ near detector infrastructure
Longer term: 2MW with LP-SPL+HPPS accelerator and/or Neutrino Factory

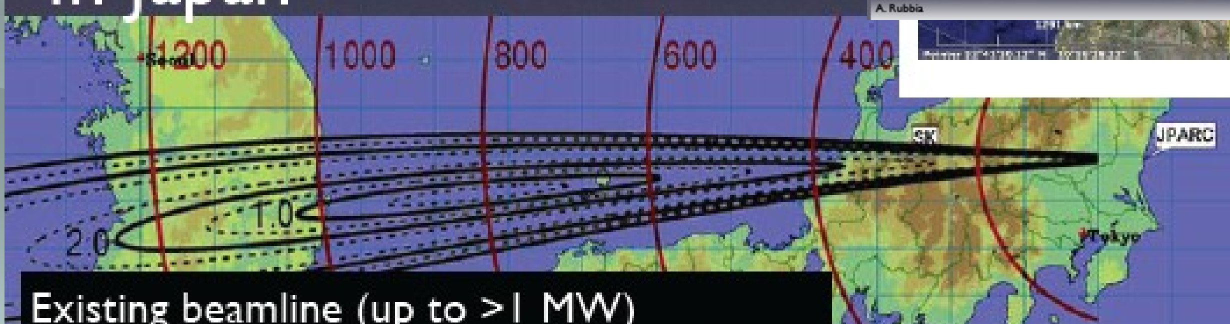
CN2FR
L=130 km,
HP-SPL 5 GeV 4 MW LINAC + accumulator ring
+ MMW target + horn
+ near detector infrastructure
Longer term: beta-beam

CNGS-Umbria
L=658 km, 1deg OA
CERN SPS 400 GeV
presently operating 0.3 MW
(0.5 MW max)
no near detector infrastructure

A. Rubbia XIV International Workshop on Neutrino Telescopes (2011) 33

Requires new far site detector (LAGUNA + LAGUNA-LBNO)
Requires new beam (LAGUNA-LBNO)

In Japan



Existing beamline (up to >1 MW)
Requires upgraded MR proton accelerator

Summary

- Highest priority for now is to establish non-zero θ_{13} and determine it
- Indication of large θ_{13} makes conventional beam long baseline experiment be promising to probe CPV and sign(Δm_{23}^2)
- To realize the next generation experiment,
  - Multi-MW beam power
  - High sensitivity huge detector

  MUST BE REALIZED
- Japan HAS operating, capable of ~MW proton machine ➔ Want/could be earliest to realize the next generation experiment
- Though, significant improvements have to be made on accelerator to achieve Multi-MW
- Two detector options are under consideration:
  - HK & 100kton LiqAr TPC
  - Optimization of physics capabilities are being done
  - R&D of detectors and sites are being made intensively
- Need decision on
  - Experiment configuration (Distance, Energy spectrum, Measurement method)
  - Detector technology

  As soon as possible (~few years)