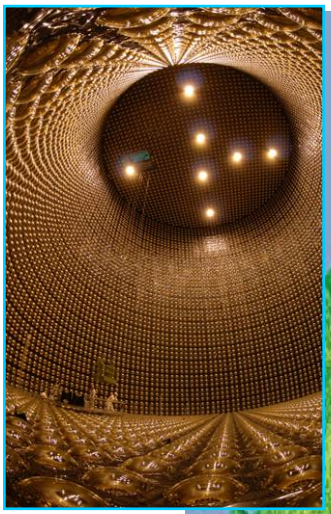
T2K and beyond

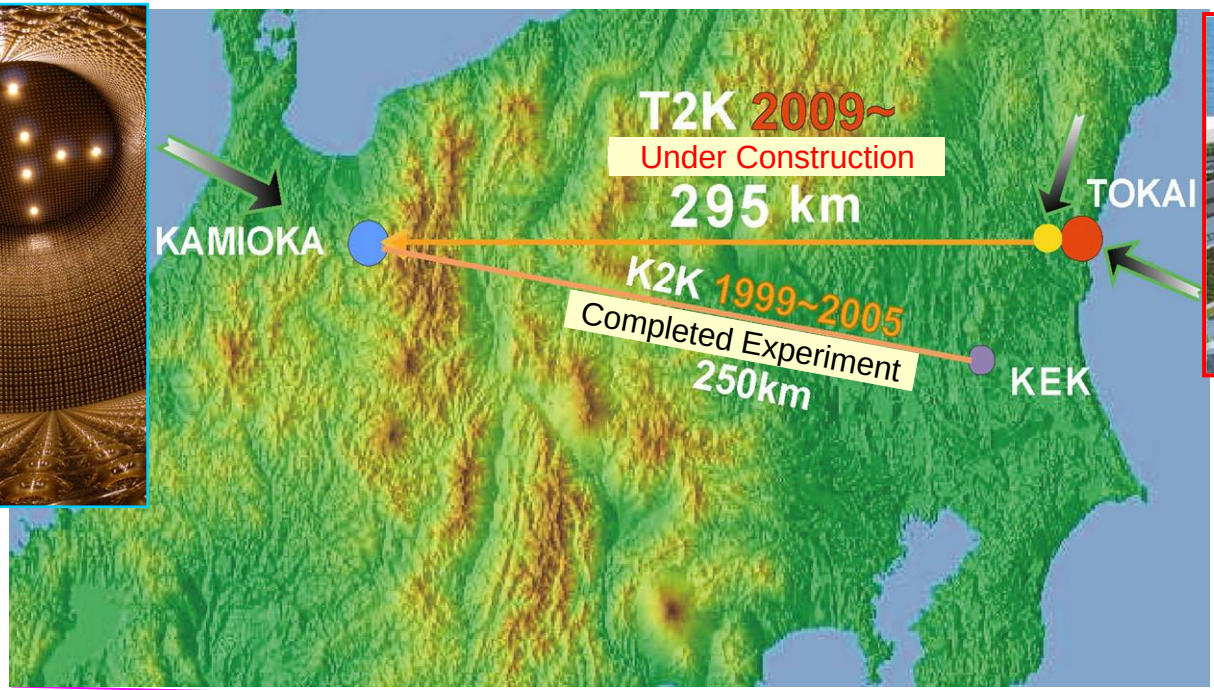
T. Nakadaira

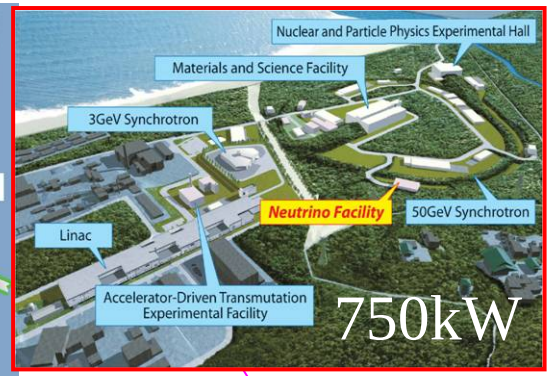
(KEK)

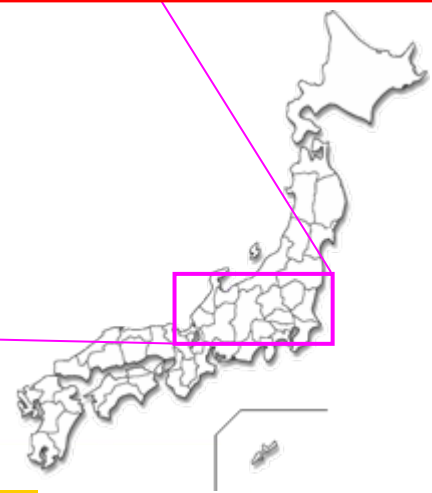
For T2K collaboration

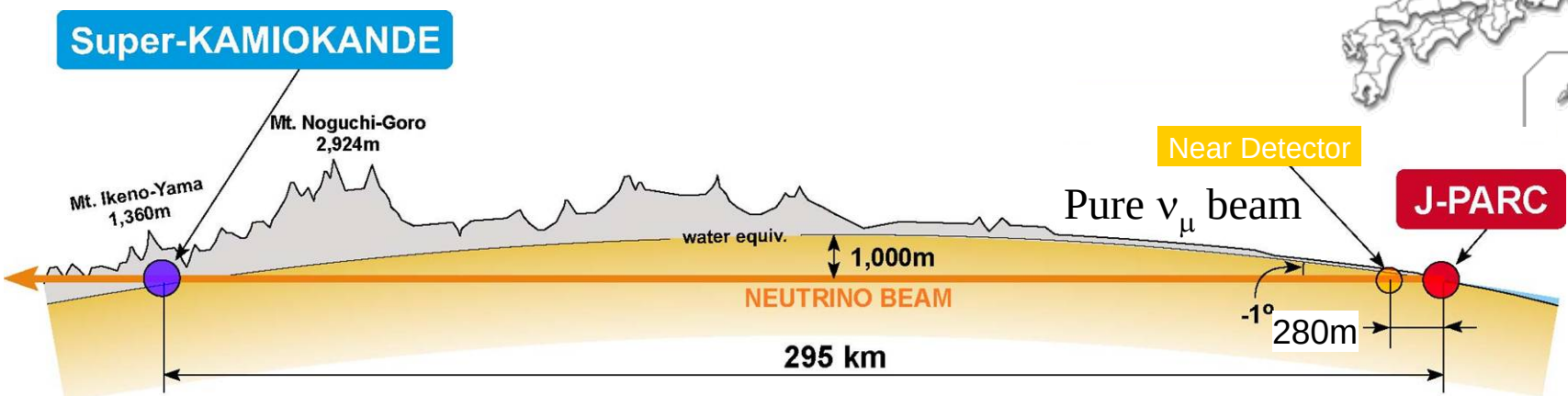
T2K (Tokai to Kamioka) LBL ν experiment











T2K Collaboration

- 11 Countries (number of members)
  - Canada(24), France(8), Italy(11), Japan(46), Korea(9), Poland(1), Russia(8), Spain(12), Switzerland(3), UK(25), USA(42)
  - 58 Institutes, 189 members.

Physics @ T2K PHASE-I

- ν mixing matrix: $\theta_{13} << \theta_{12}, \theta_{23}$

Flavor eigenstate

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

Mass eigenstate

SK Atm., K2K, MINOS
$\theta_{23} \sim 45°$
$\Delta m^2_{23} \sim 2.5 \times 10^{-3}$ [eV^2]

θ_{13},δ are still unknown.

Solar, KamLAND
$\theta_{12} \sim 34°$
$\Delta m^2_{12} \sim 8\times10^{-5}$ [eV^2]

- T2K-I searches for $\nu_\mu \rightarrow \nu_e$.

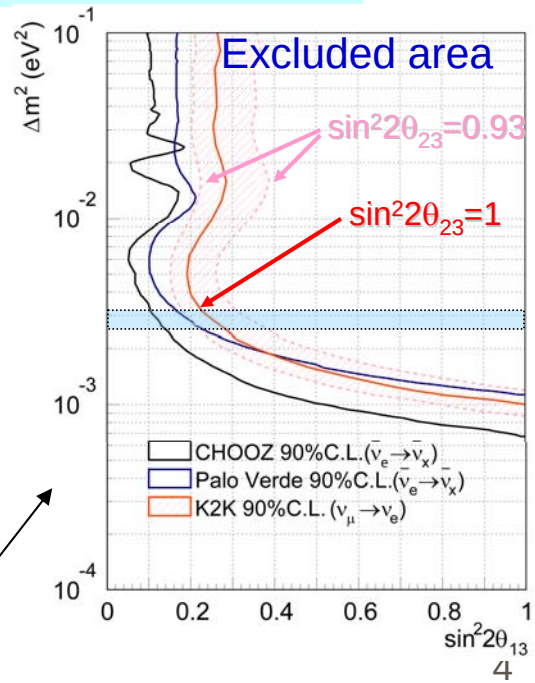
$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\left(\Delta m^2_{31} L/4E\right)$$
$$\mp 4 J_r \sin\delta \left(\Delta m^2_{21} L/2E\right) \sin^2\left(\Delta m^2_{31} L/4E\right) + \ldots$$

– for ν
+ for $\bar{\nu}$

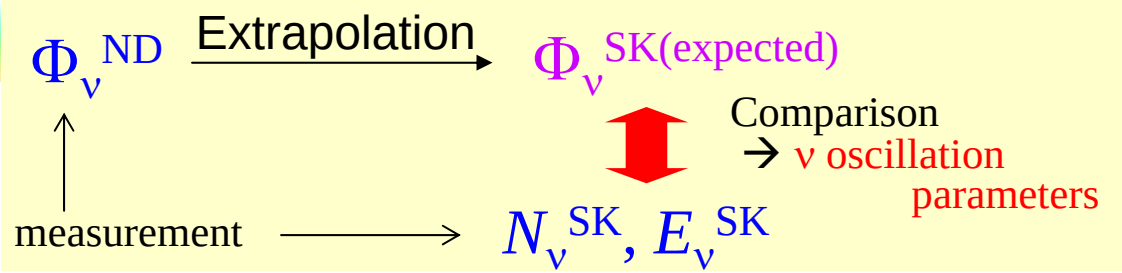
(Approximation @ $\Delta m^2_{31} L/4E \sim \pi/2$, $\Delta m^2_{32} \sim \Delta m^2_{31}$)

$$J_r \equiv \cos\theta_{12} \sin\theta_{12} \cos\theta_{23} \sin\theta_{23} \cos^2\theta_{13} \sin\theta_{13}$$

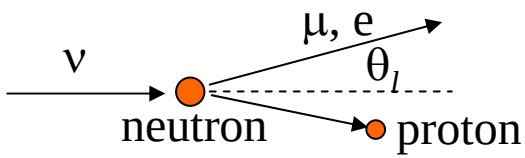
- Size of *CP* asymmetry depends on θ_{13}!!
  - *Matter effect is small in (E_ν, L) in T2K.*
  - $\Delta m^2_{13} = \Delta m^2_{23} - \Delta m^2_{12} \sim 2.5\times10^{-3}$ [eV^2] → $\sin^2 2\theta_{13} < 0.15$



Principle of T2K … Quite similar to K2K

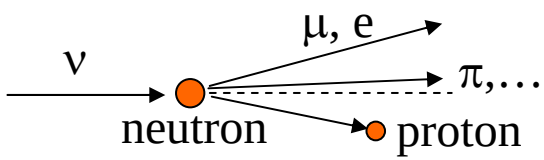


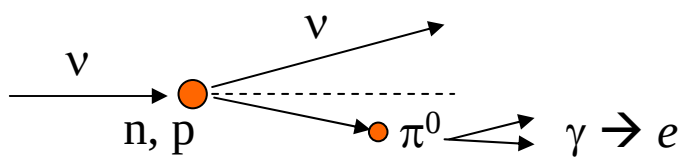
- Δm^2 = ~2.5x10^{-3}[eV^2], L=295km
  →1st Oscillation max. @ E_ν ~ 0.6 GeV
- Use Sub-GeV ν_μ beam
  - CC-QE is dominant process in ν-N interactions.
  - Neutrino Energy reconstruction by CC-QE kinematics … δE/E ~ 10%



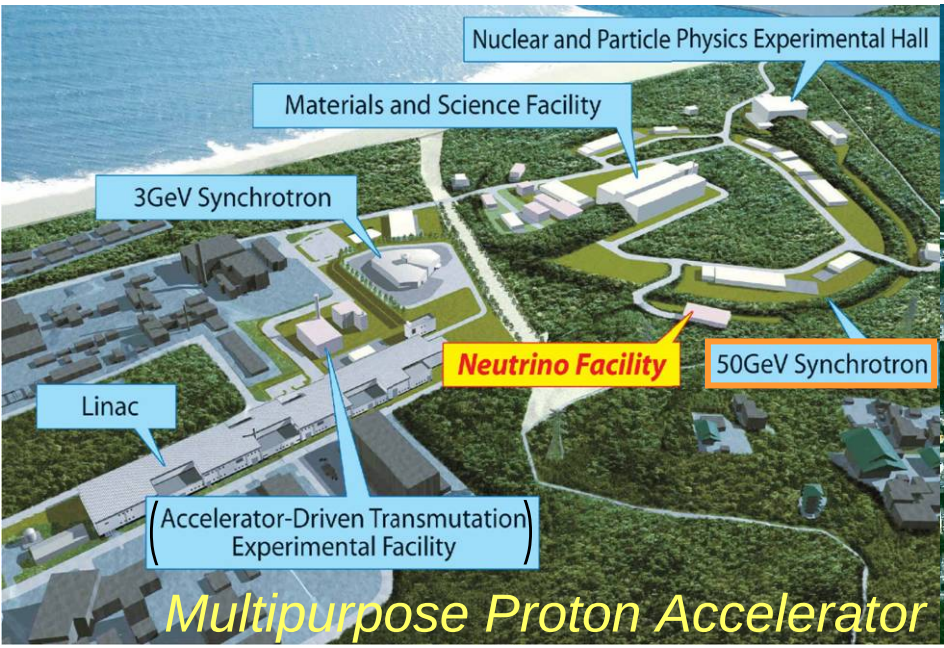
$$E_\nu = \frac{m_N E_l - m_l^2/2}{m_N - E_l + p_l \cos\theta_l}$$

  - Fraction of high energy ν (Eν ~ a few GeV) is required to be small.
    - CC-non QE events are background for Eν reconstruction.
    - π^0 from NC events are dominant background for ν_e signal.





Japan Proton Accelerator Research Complex

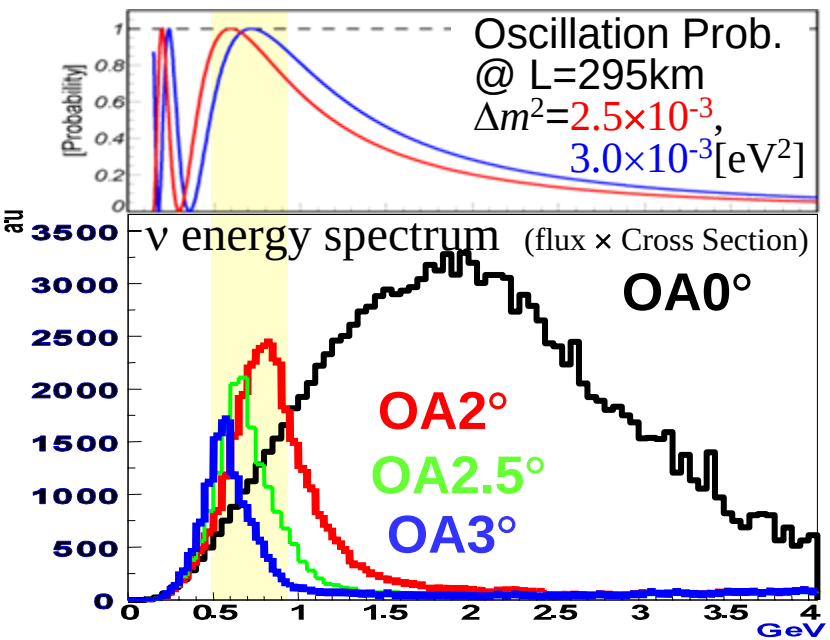


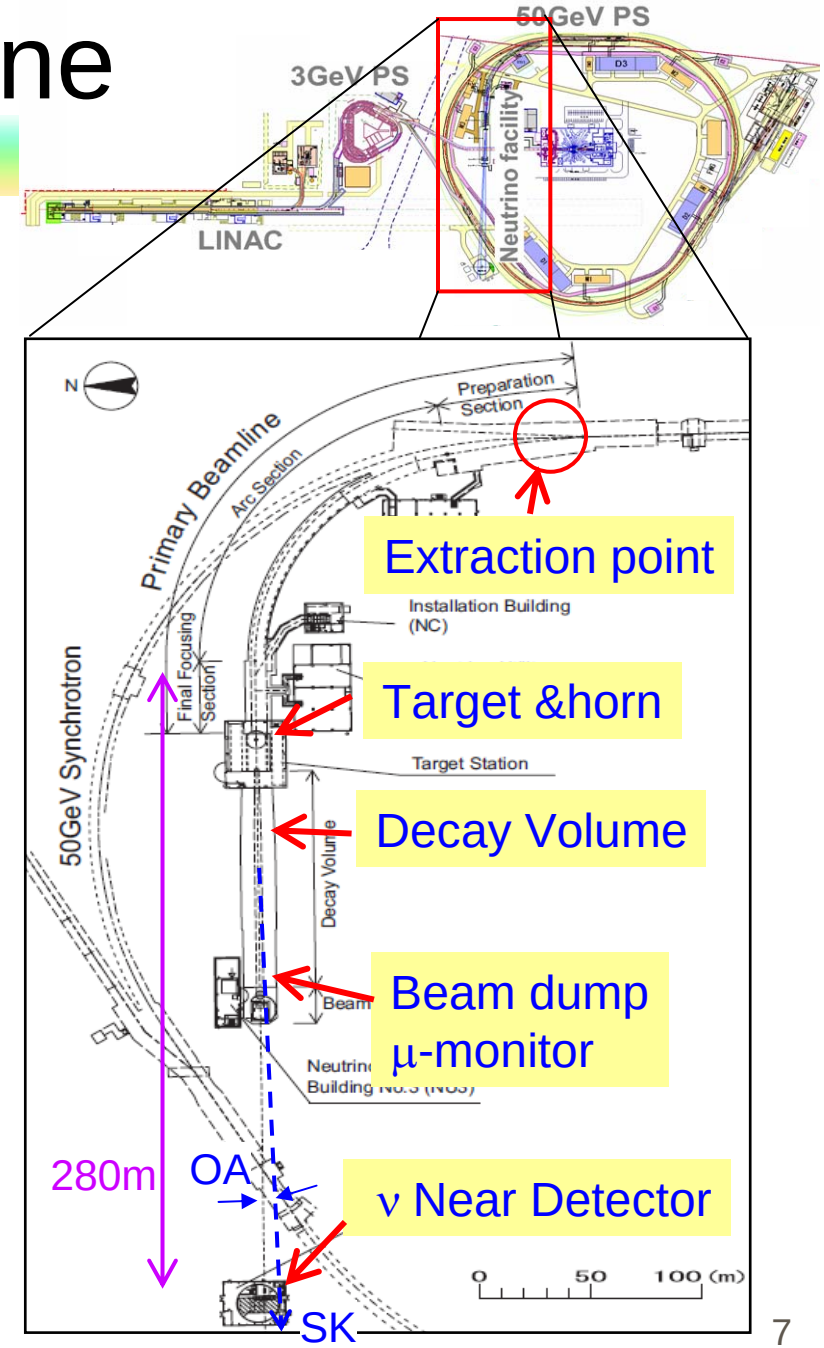
- 400MeV LINAC (200MeV@T=0)
  - → 1MW 3GeV RCS
  - → 0.75MW 50GeV MR (30GeV @ T=0)
    - 1×10^{21} protons/year (130days) [in 50GeV operation.]
      - c.f. K2K: ~1×10^{20} POT(6years)

Joint project by JAEA (former JAERI) and KEK

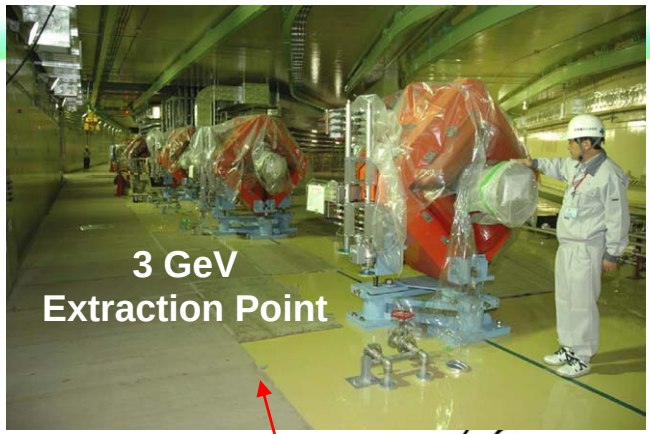
J-PARC ν-beam line

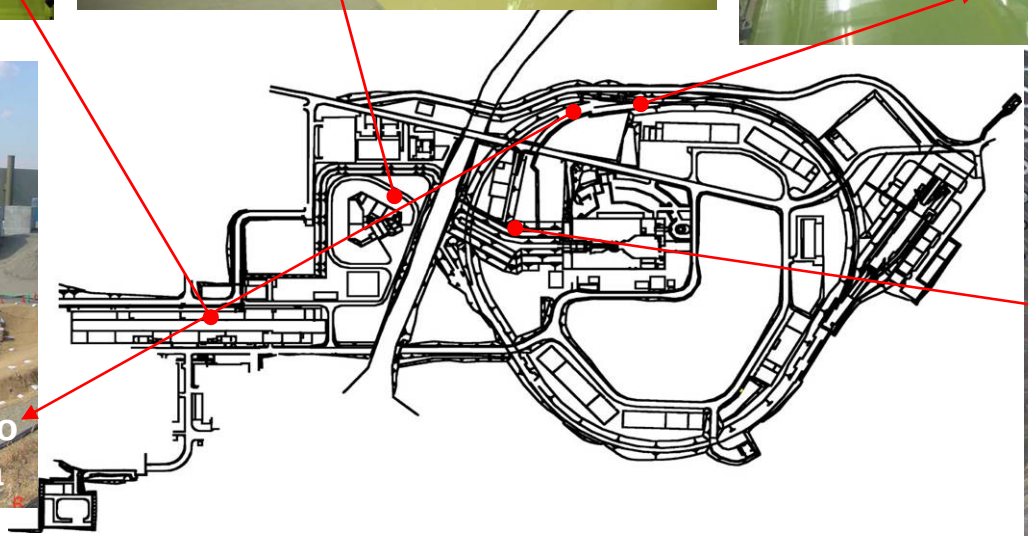
- Conventional ν_μ beam:
  - protons + Graphite target $\rightarrow$ pions
  - π^+ or π^- is focused selectively by 3 electromagnetic horns.
    $\pi^+ \rightarrow \mu^+ + \nu_\mu$ or $\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$
- Pseudo-Monochromatic beam by Off-Axis method: (OA = 2° ~ 2.5°)
  - Set peak of (flux × σ_{CC}) @ oscillation max.
  - Fraction of high energy neutrino is small.

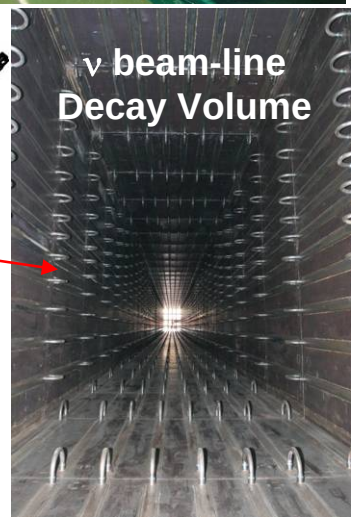




Accelerator construction status







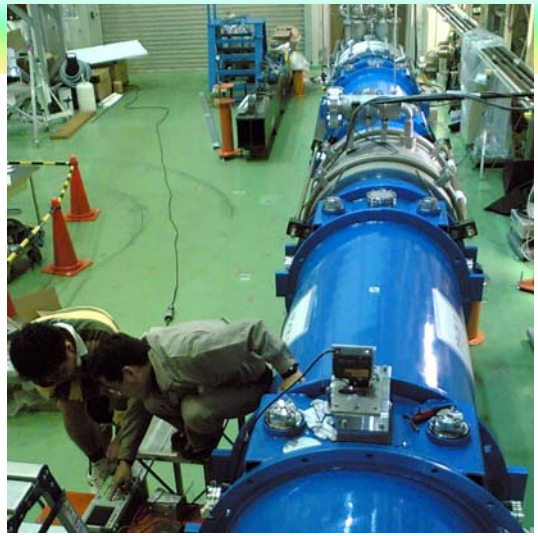
Problem in RF system for MR:

Some of the RF cores discharges with 15kV/gap in long term tests.

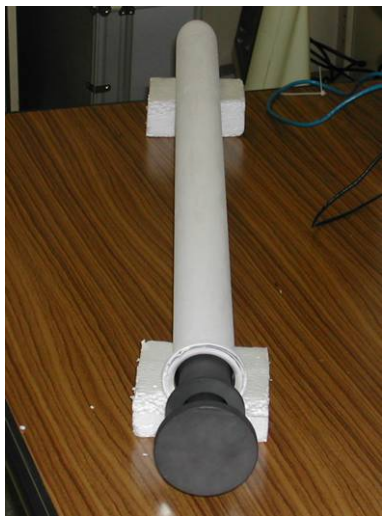
← The failure components have already been identified.

* The MR commissioning will start with current RF system on schedule in low power.
* The parallel R&D work is in progress aiming to replacing RF system around 2010.

ν beam-line Construction is going well !



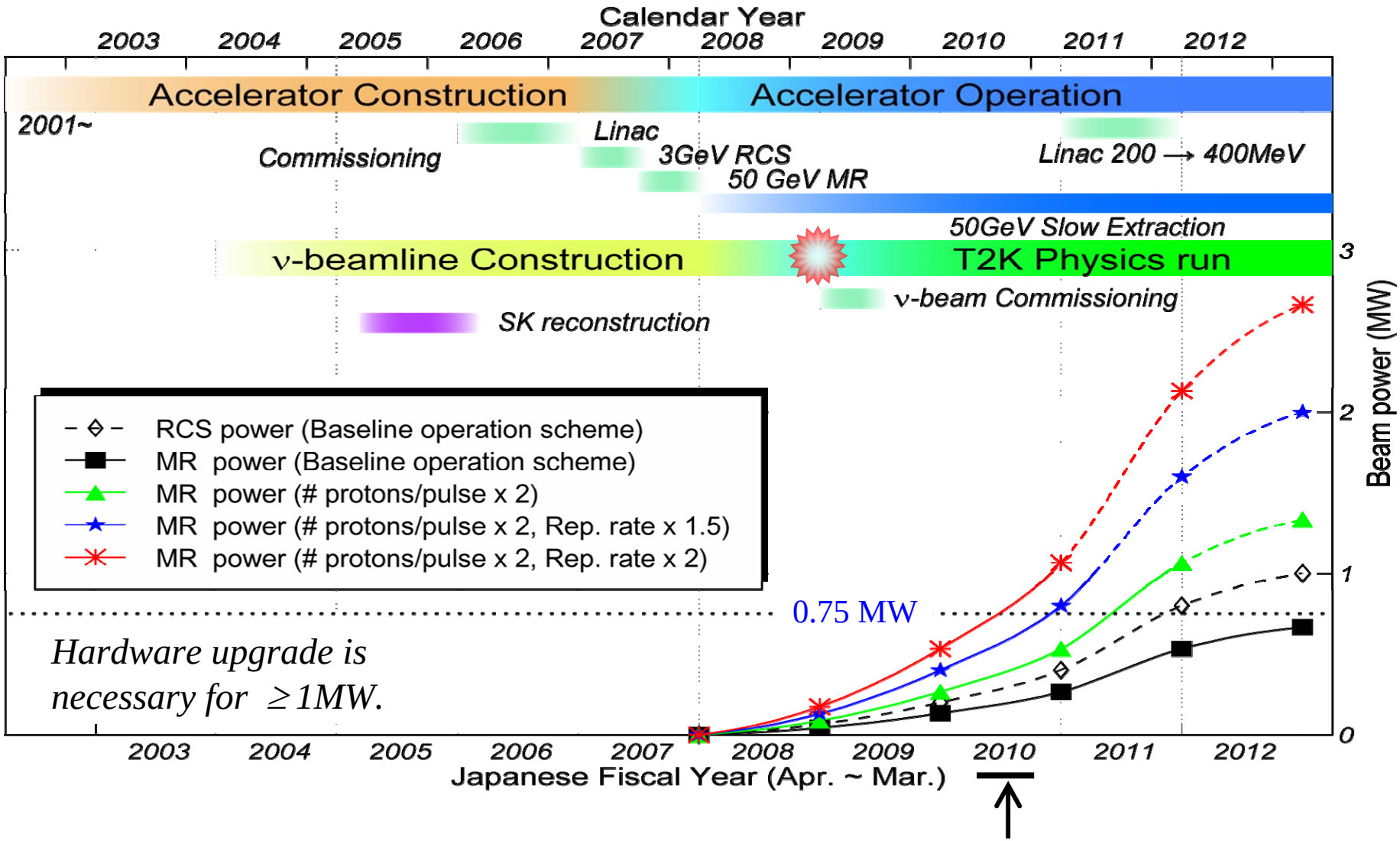
- Superconducting combined function magnet for Proton beam line.
  - First module of production version
  - Cool down test (4.6 K)
  - Excited to 7728A (50GeV operation+5% margin.) w/o quench.



- Mechanical Prototype of Graphite Target
  - Enough thermal shock resistance against 0.75MW beam.
  - He-gas cooling system is constructed.

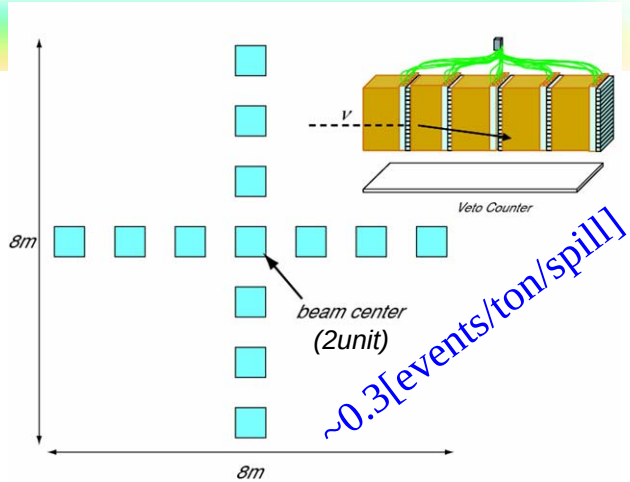
- Prototype of 1st Horn
  - Test operation with 250kA current
  - So far, There is no problem up with this test.

J-PARC schedule & Beam Power estimation

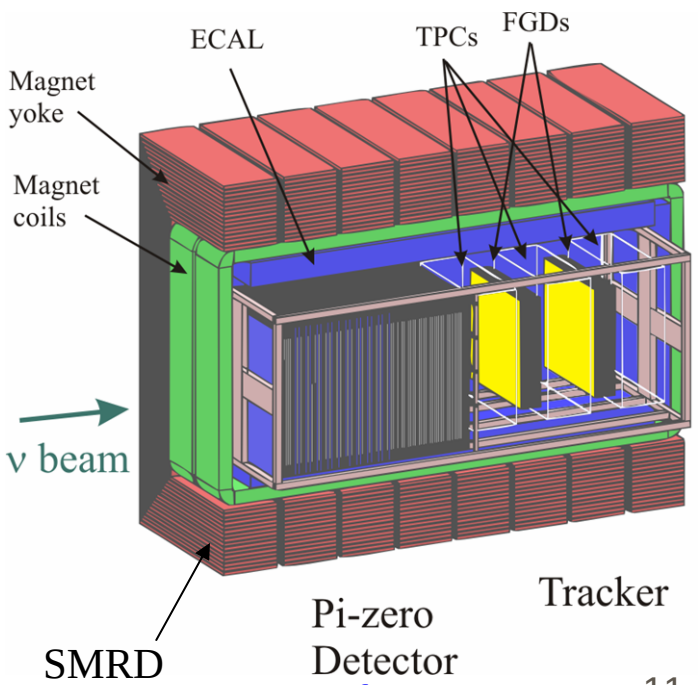


ν Near Detector @ 280m

- On-axis detector
  - Measure ν-beam profile
    → ν-beam direction at 1mrad precision.
  - iron - scintillator stacks × 14 units



- Off-axis detector: In Magnet (*B=0.2T*)
  - Measure ν-flux in SK direction : $\Phi_\nu^{ND}(E_\nu)$.
    - Measure ν_μ, $\overline{\nu}_\mu$ and ν_e+$\overline{\nu}_e$ fluxes separately.
    - Neutrino Energy ← CC-QE kinematics.
  - Cross sections of ν interactions
    - CC-1π/CC-QE … BG for E_ν reconstruction
    - NC-π^0 production … BG for ν_e detection

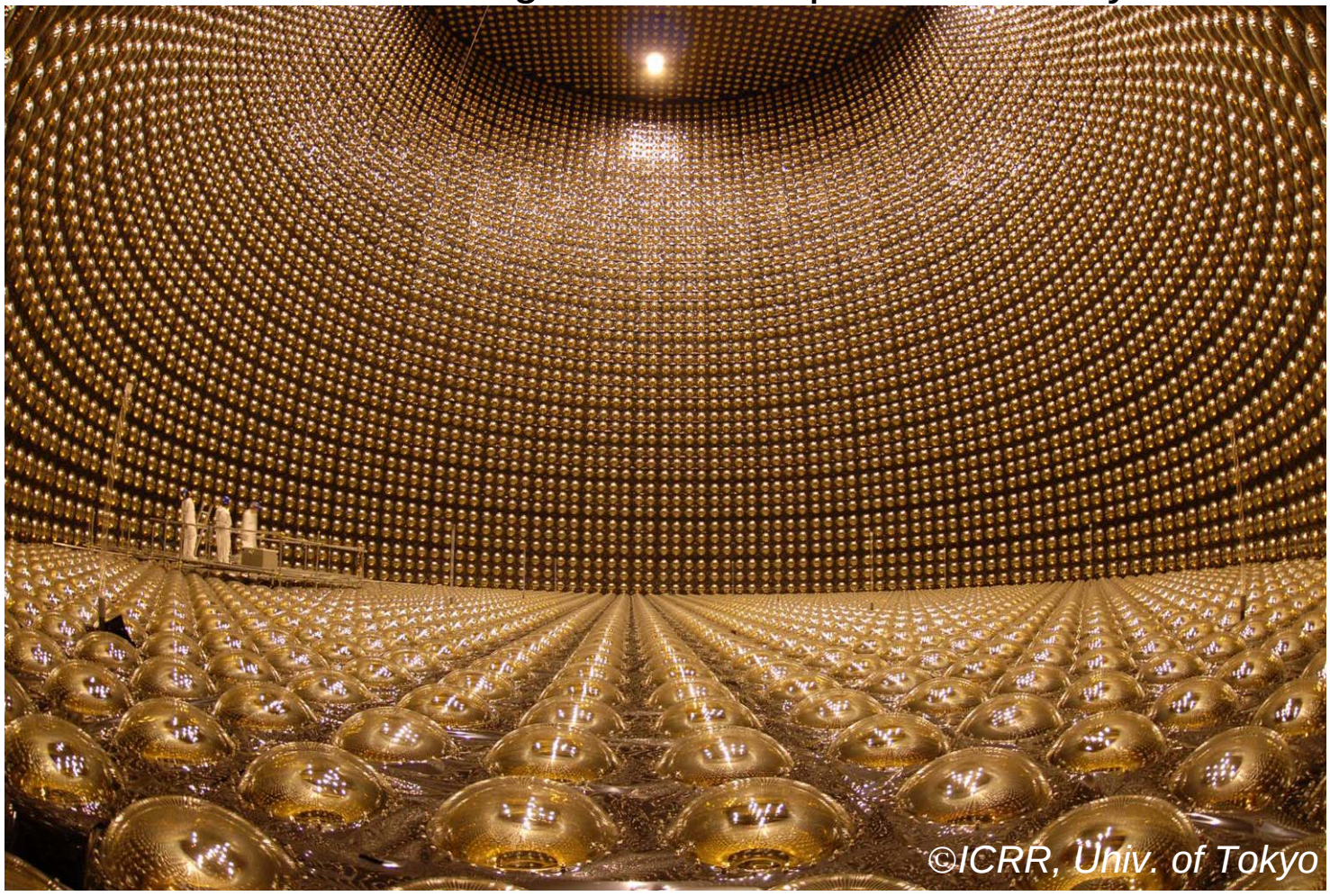


Reuse of UA1 magnet

Far Detector: SK-III

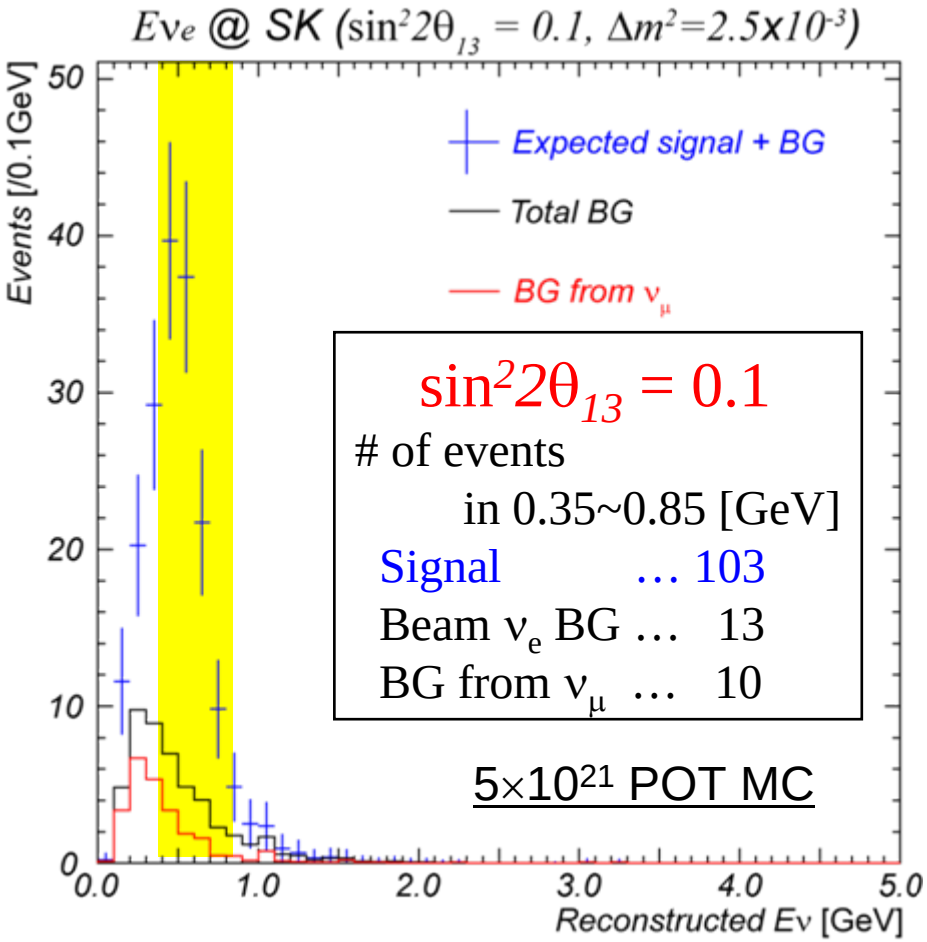
- 50kt Water Cherenkov detector
- SK reconstruction is completed in Apr. 2006.
  → Back to 40% Photo coverage. Start full operation in July, 2006

Ready for T2K !!!



Prospects in T2K Phase-I

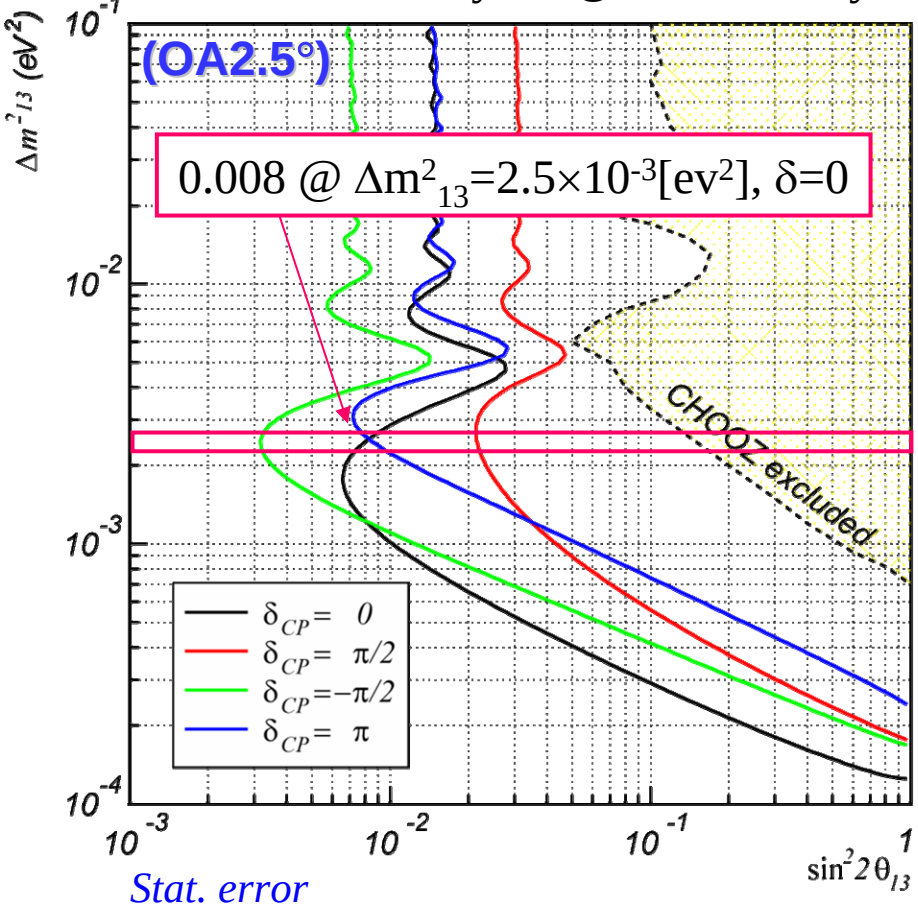
- ν_e appearance



T2K 90%CL sensitivity

$\sin^2 2\theta_{23}$ = 1.0 is assumed.

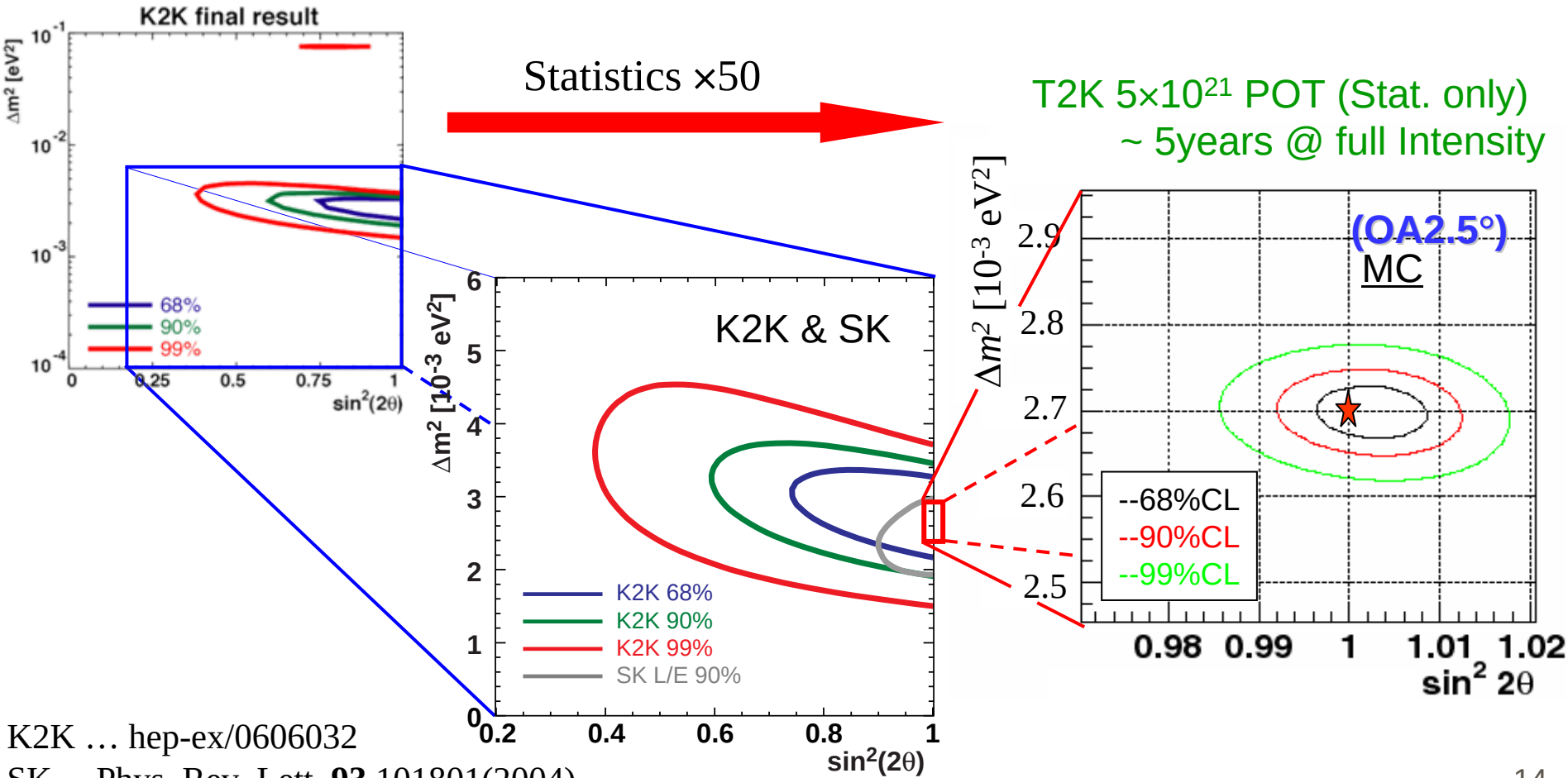
5×10^{21} POT ~ 5 years@ full intensity



Stat. error
+ Syst. error for BG subtraction (10%)

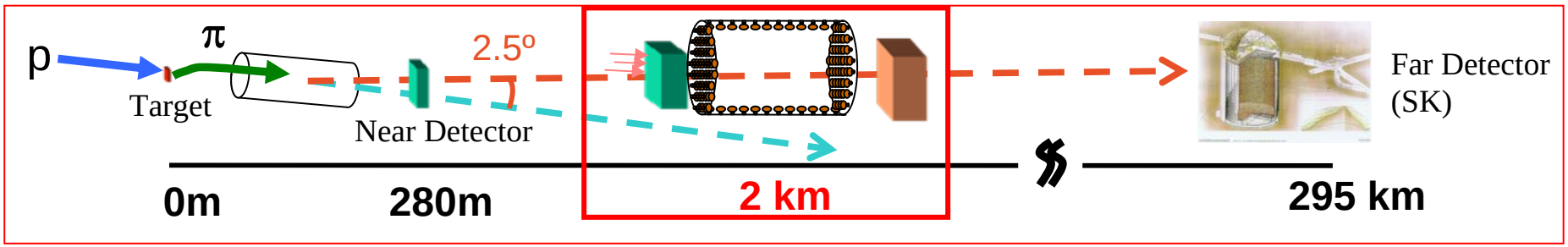
Prospects for T2K Phase-I (Cont'd)

- ν_μ disappearance : $P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2\theta_{23}\sin^2(1.27\,\Delta m^2_{23} L/E)$
  - Goal : $\delta(\sin^2 2\theta_{23}) \sim 0.01$, $\delta(\Delta m^2_{23}) < 1 \times 10^{-4}$ [eV^2]

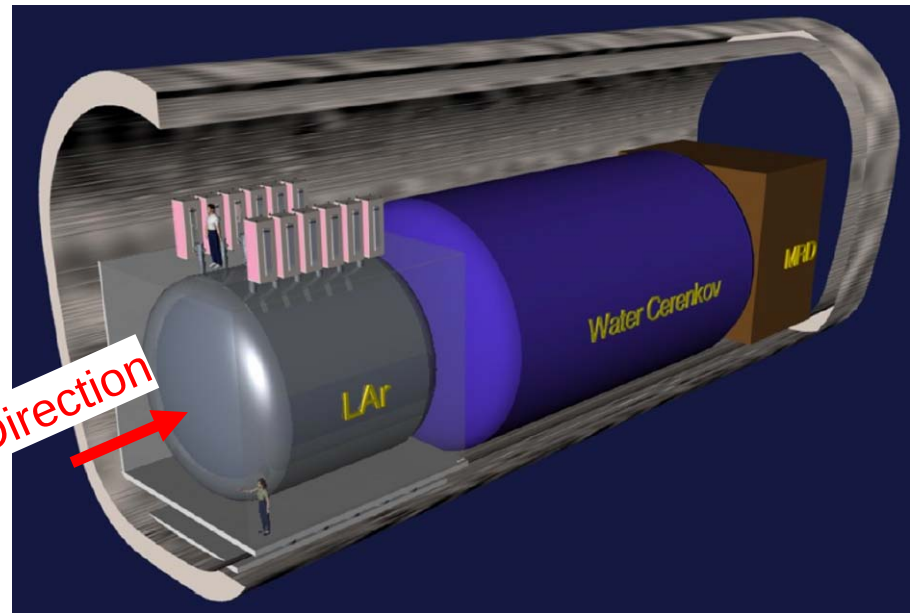


K2K … hep-ex/0606032
SK… Phys. Rev. Lett. **93**,101801(2004)

Intermediate detector @ 2km



- E_ν spectrum @ 2km
  ~ E_ν spectrum @ SK w/o oscillation
  → Uncertainties from Far/Near ratio is smaller than ND@280m.
- Possible Detector configuration
  - Liquid Ar TPC
  - Water Cherenkov
    - Same target & ν reconstruction algorithm as SK
  - Muon Range Detector



Facilities for 2km is to be requested in Japan after the commissioning of J-PARC facilities.

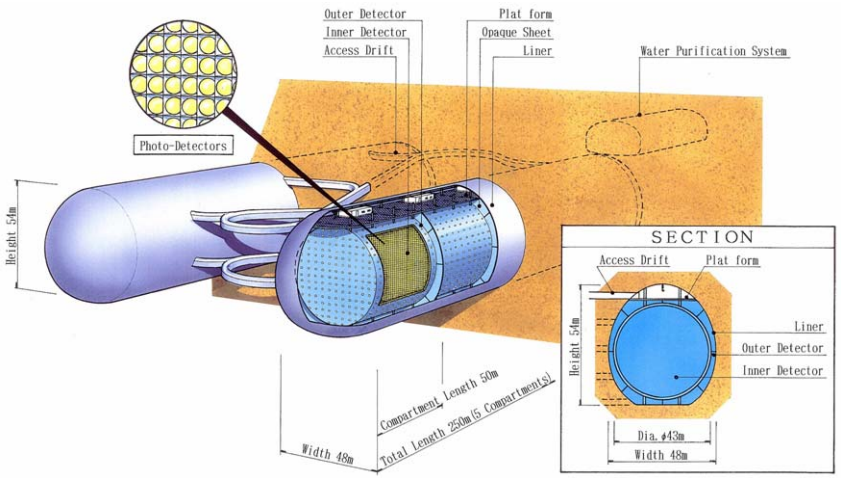
Beyond T2K-I

Possible upgrade: T2K Phase-II

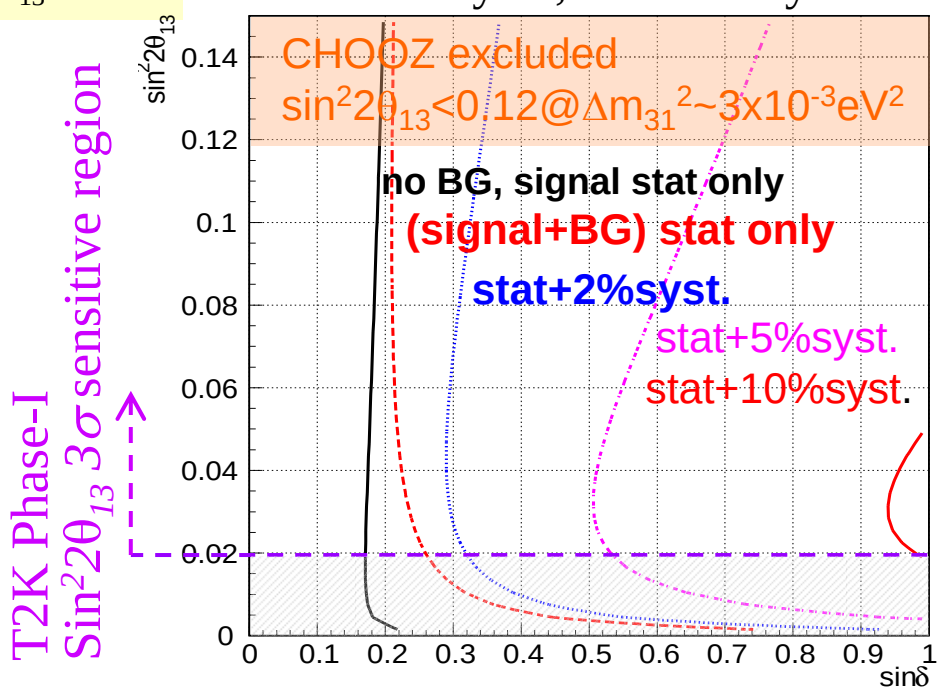
- If $\sin^2 2\theta_{13}$ measured @ T2K-I ≥ 0.01, it paves the way for ν *CP*-violation search.
  - J-PARC upgrade: *0.75MW* → ***4MW***
  - SK (*50kt*) → Hyper Kamiokande (HK): ***~1Mt***
    - Proton decay search: test of GUT.
- Comparison between ν_μ and Anti-ν_μ beam.

Assumptions:
$\Delta m_{21}^2 = 6.9\times10^{-5}\text{eV}^2$
$\Delta m_{32}^2 = 2.8\times10^{-3}\text{eV}^2$
$\theta_{12}=0.594, \theta_{23}=\pi/4$

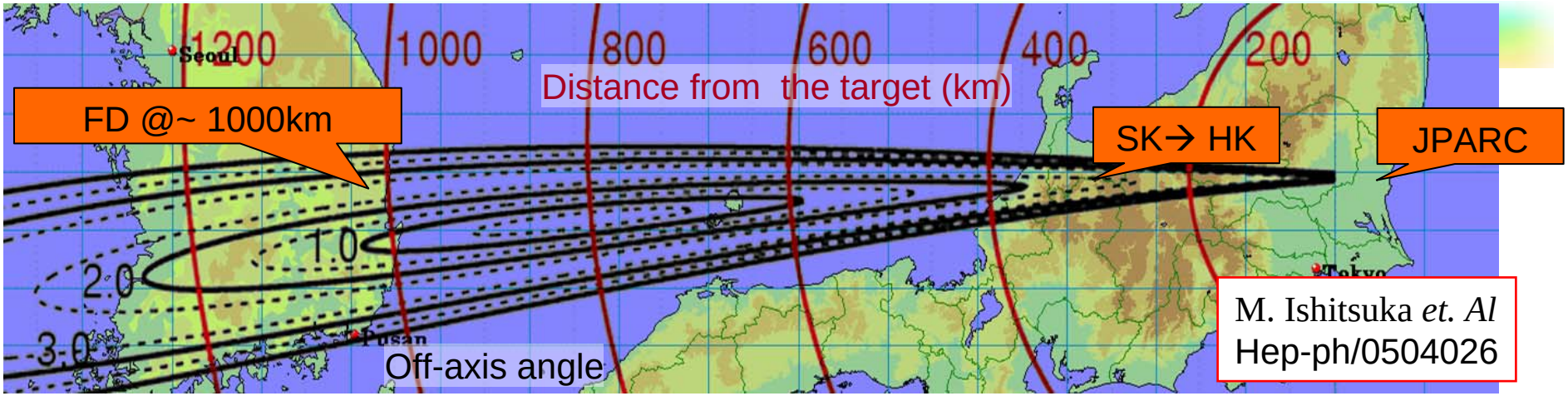
$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \approx \frac{\Delta m_{12}^{\ 2} L}{E} \cdot \frac{\sin 2\theta_{12}}{\sin\theta_{13}} \cdot \sin\delta$$



3σ sensitivity (4MW,540kt)
ν-run=2 year, ν̄-run=6~7year

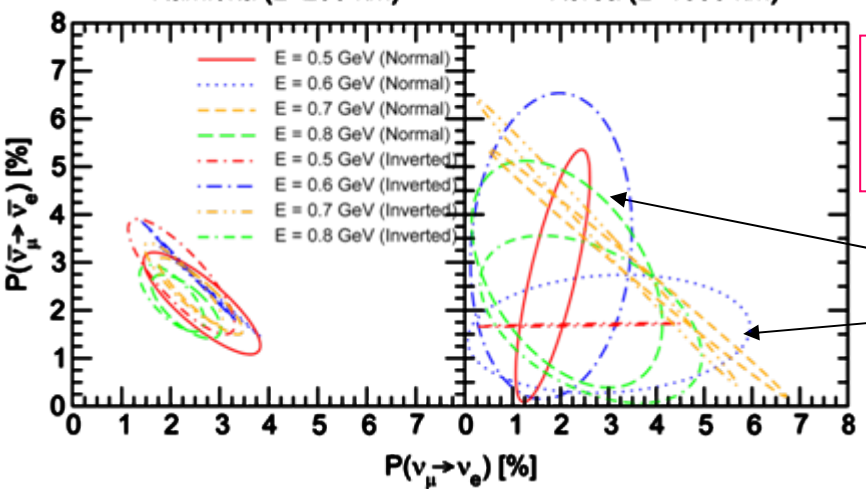


T2KK … Another far detector @ Korea



- Far detector identical with (SK)/HK @ 2nd Oscillation Maximum point.
  - Contribution of CP asymmetric term: ×3 compared to SK position.
  - Matter effect become significant. → Possibility to resolve mass hierarchy

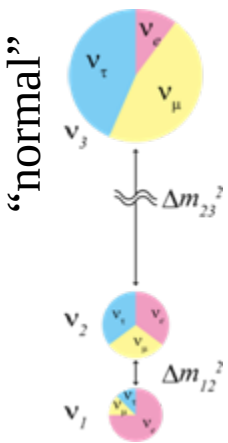
$$CPV \text{ term} \approx \mp 4 J_r \sin\delta\left(\Delta m^2{}_{21} L/2E\right)\sin^2\left(\Delta m^2{}_{31} L/4E\right)$$

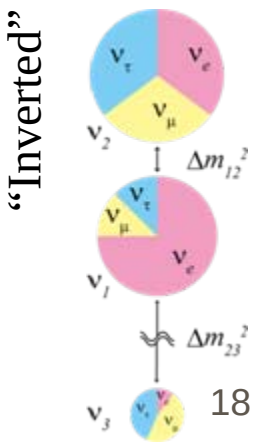


$\sin^2 2\theta_{13}=0.05$

δ … $0\sim 2\pi$

If δ is suitable, it may possible to distinguish.





Summary

- T2K is LBL ν experiment to search $\nu_\mu \rightarrow \nu_e$ using the high intensity ν_μ beam by J-PARC.
  - J-PARC accelerator operation will start in 2008, while parallel R&D is going on to realize the design intensity.
  - ν beam-line will be completed in 2009.
    … The construction proceeds on schedule.
  - T2K Phase-I (2009~)
    - Search for $\nu_\mu \rightarrow \nu_e$ & θ_{13} measurement.
    - Precise measurement of θ_{23} & Δm^2_{23} via ν_μ disappearance.
  - Intermediate detector @ 2km is planed to reduce the systematic uncertainties due to F/N extrapolation.
  - If $\sin^2 2\theta_{13}$ is not too small, T2K Phase-II (201x?) will study *CP* asymmetry and possibly mass hierarchy based on the comparison between $\nu_\mu \rightarrow \nu_e$ & $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$.