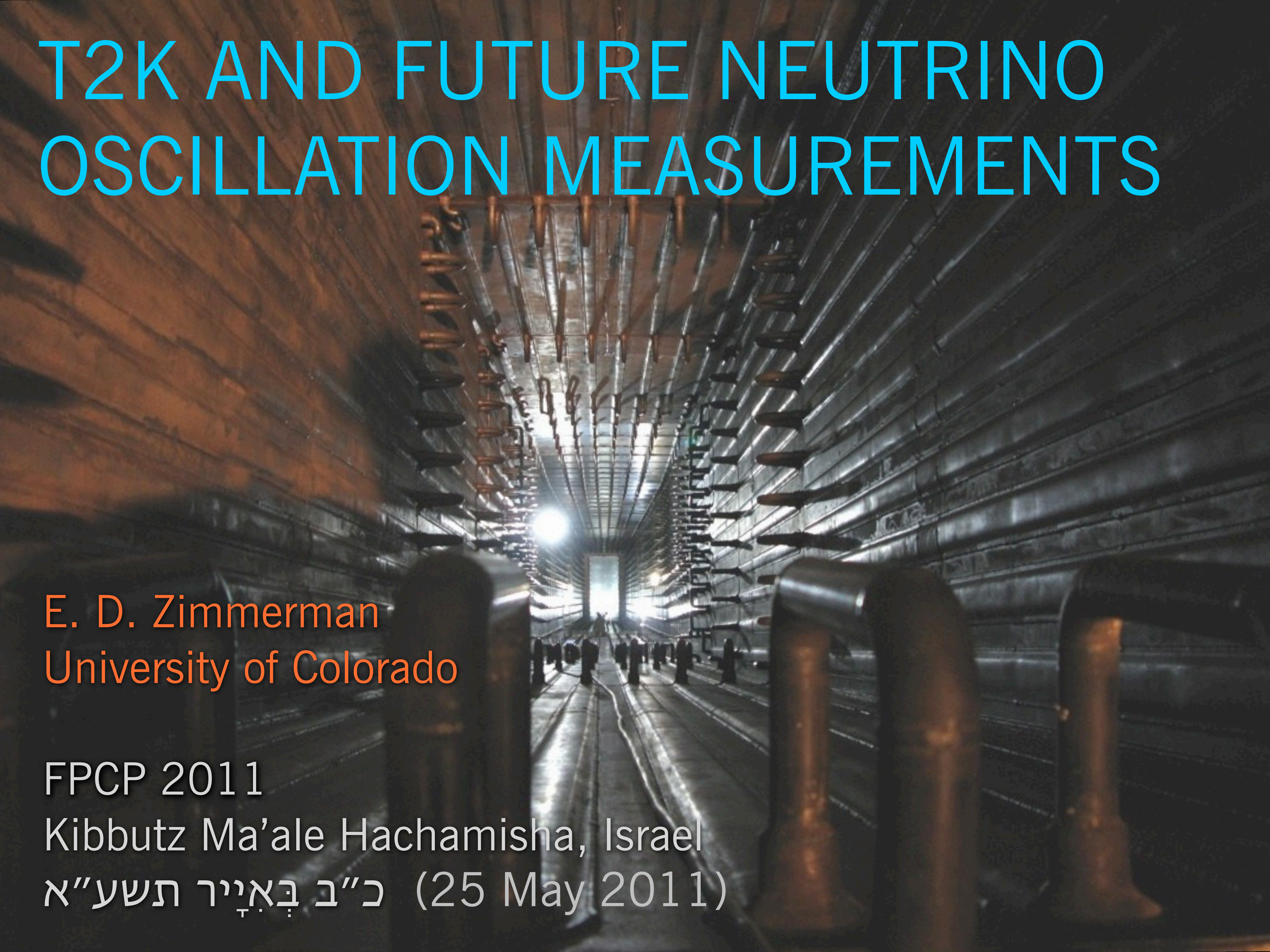
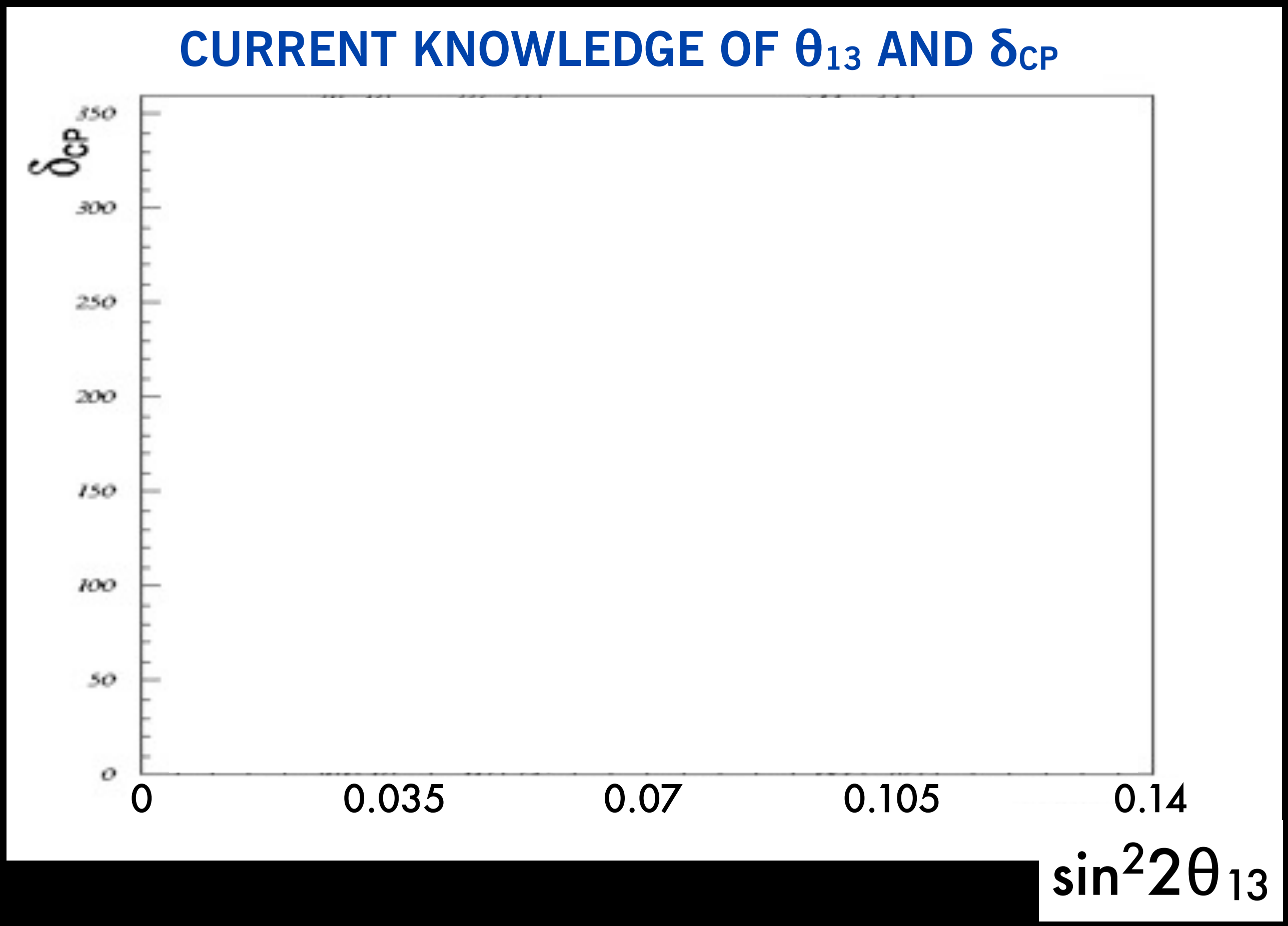


T2K AND FUTURE NEUTRINO OSCILLATION MEASUREMENTS

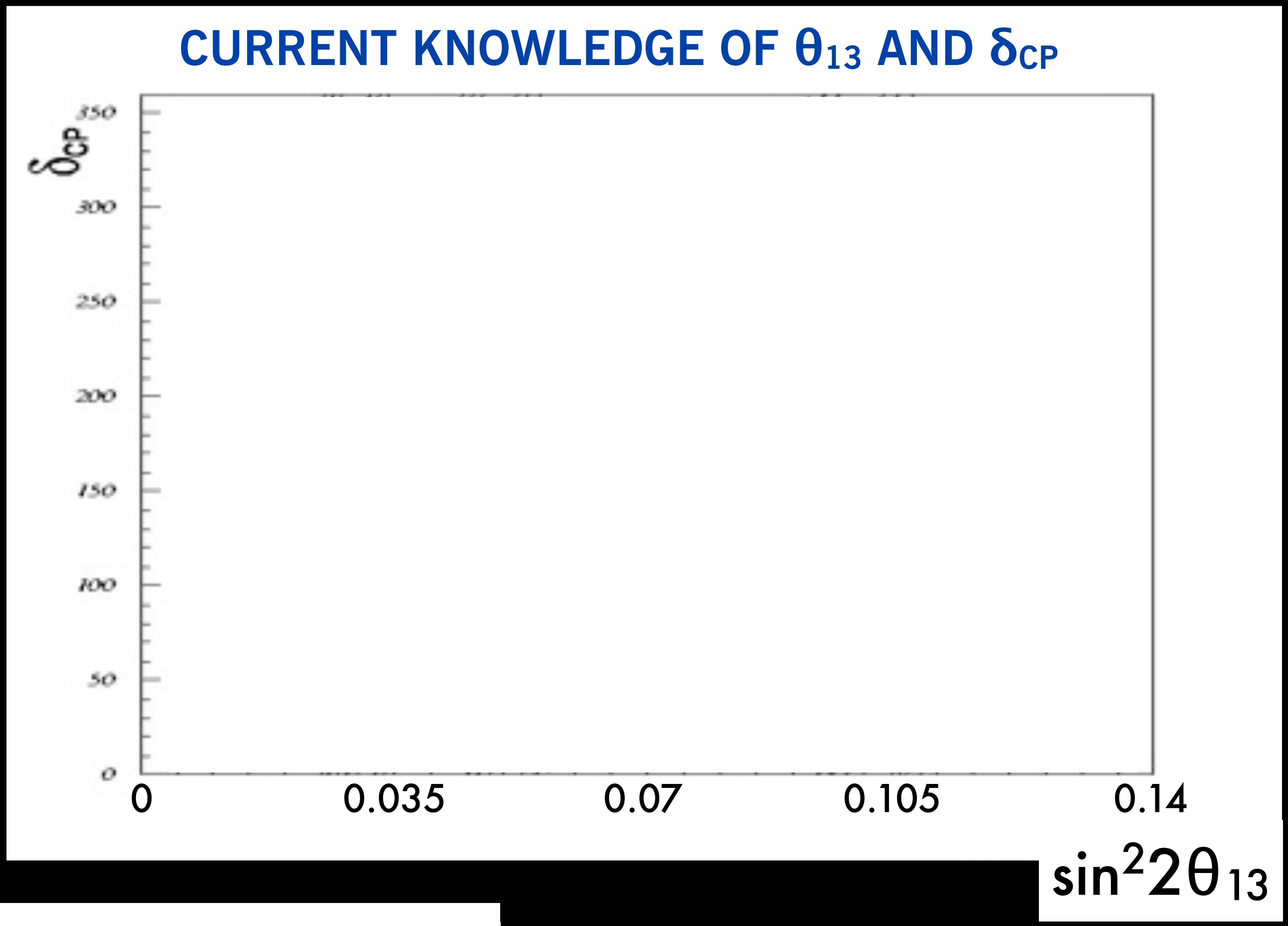
E. D. Zimmerman
University of Colorado

FPCP 2011
Kibbutz Ma’ale Hachamisha, Israel
כ״ב בְּאִיָּר תשע״א (25 May 2011)

How do we get from:



How do we get from:



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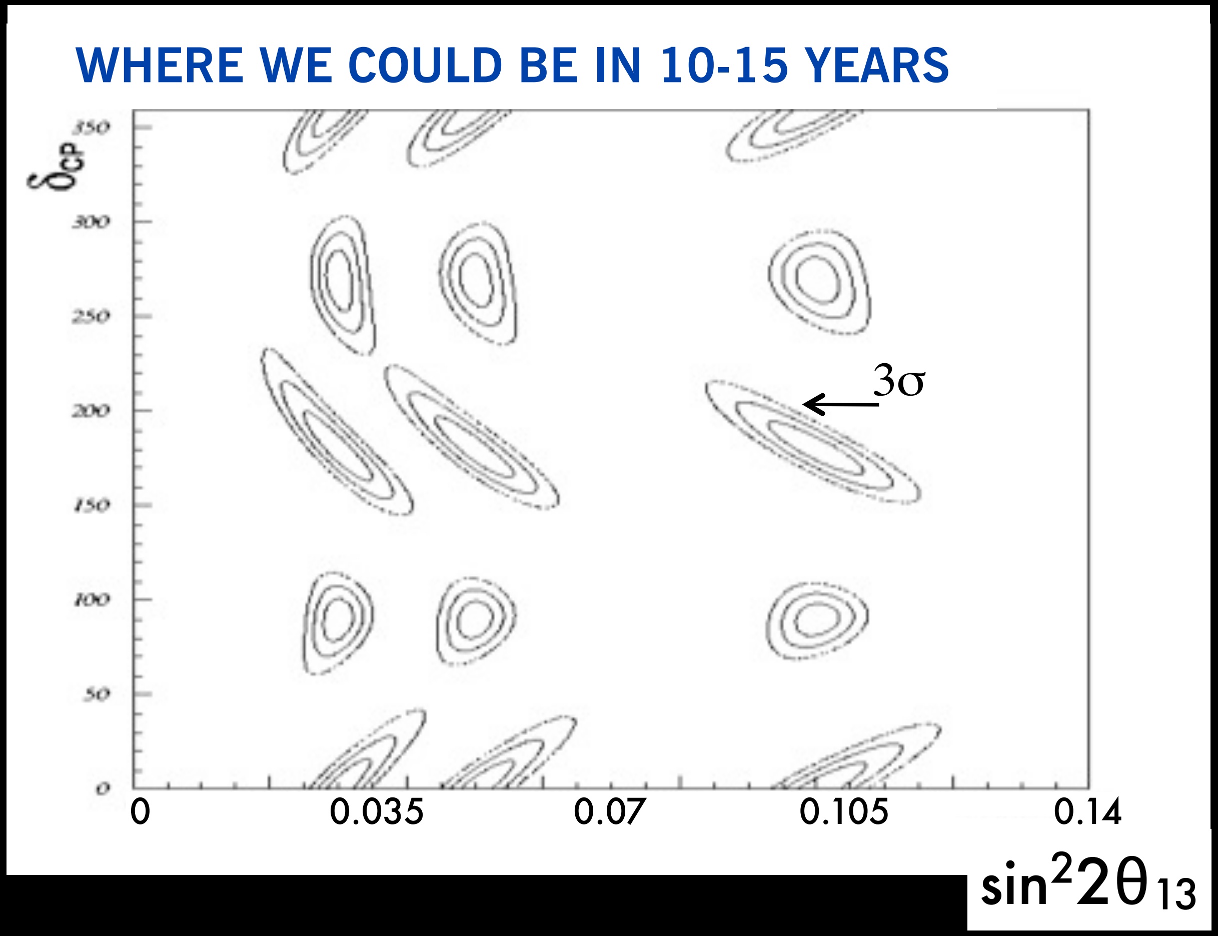


?

T2K and future neutrino oscillation experiments

- Present and near future: T2K
- Near future: reactor-based θ_{13} searches, NOvA
- Far future: LBNE, J-PARC ultimate experiments?

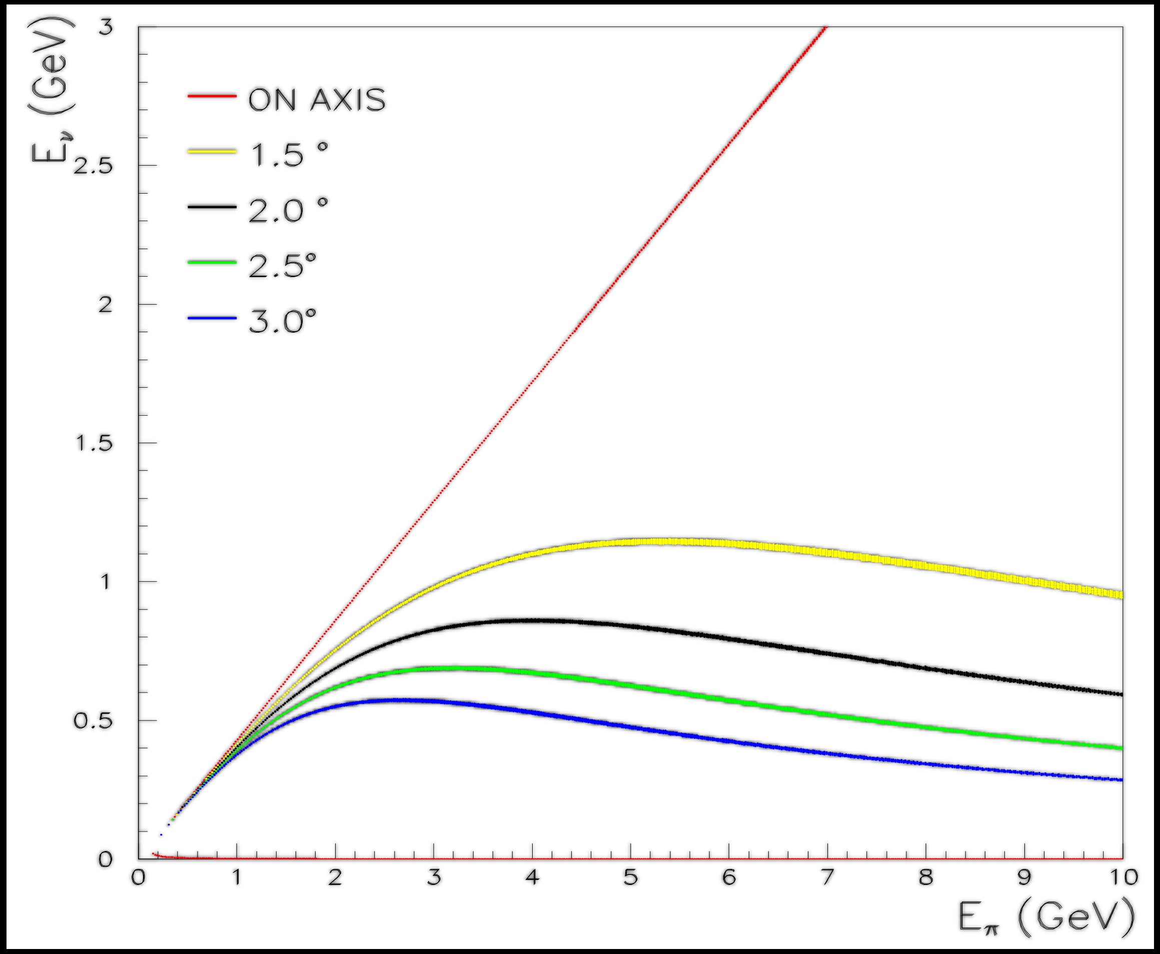
Results from the first T2K physics run

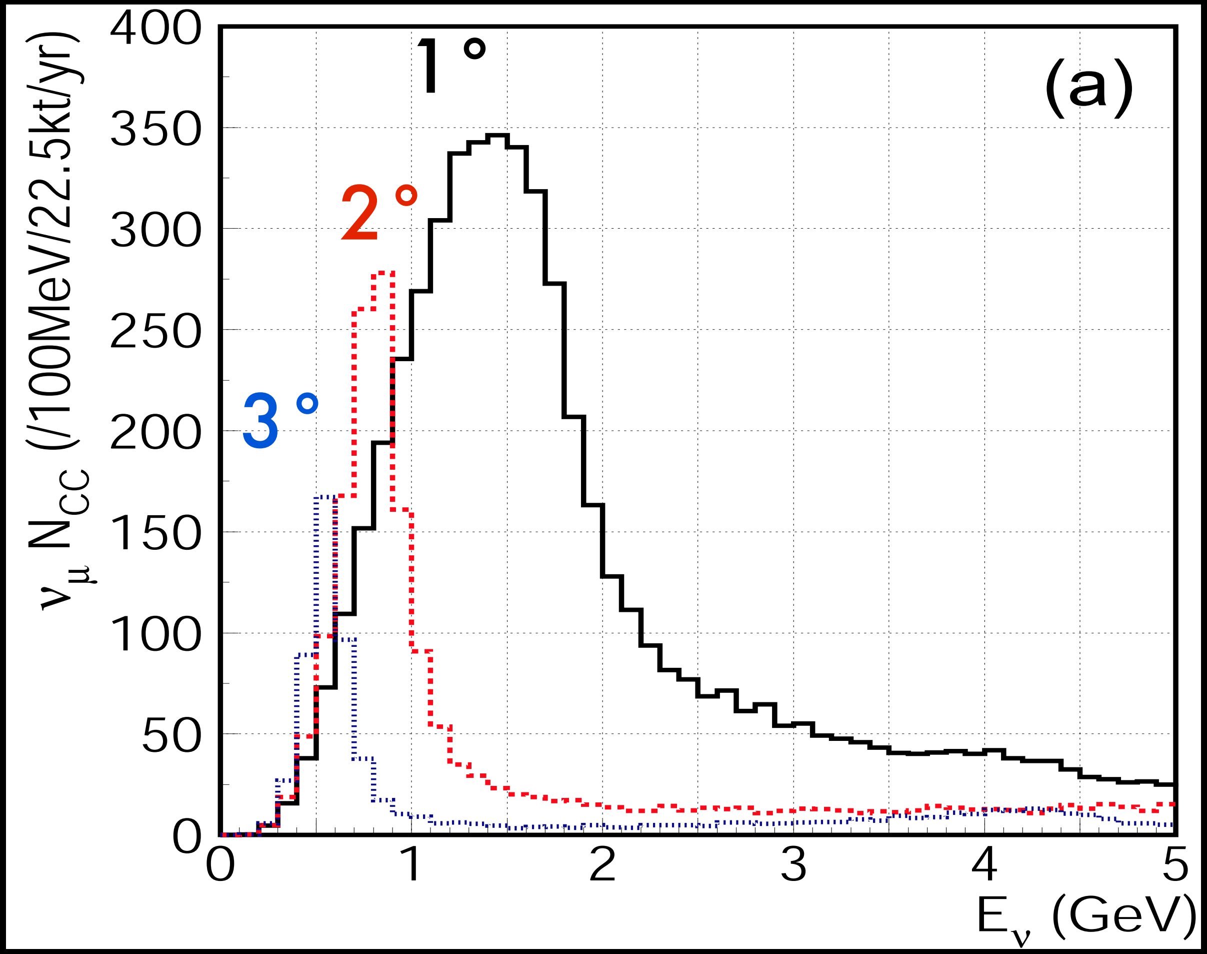
- T2K: experiment and physics goals
- The first oscillation result
- Post-earthquake update

T2K design and physics goals

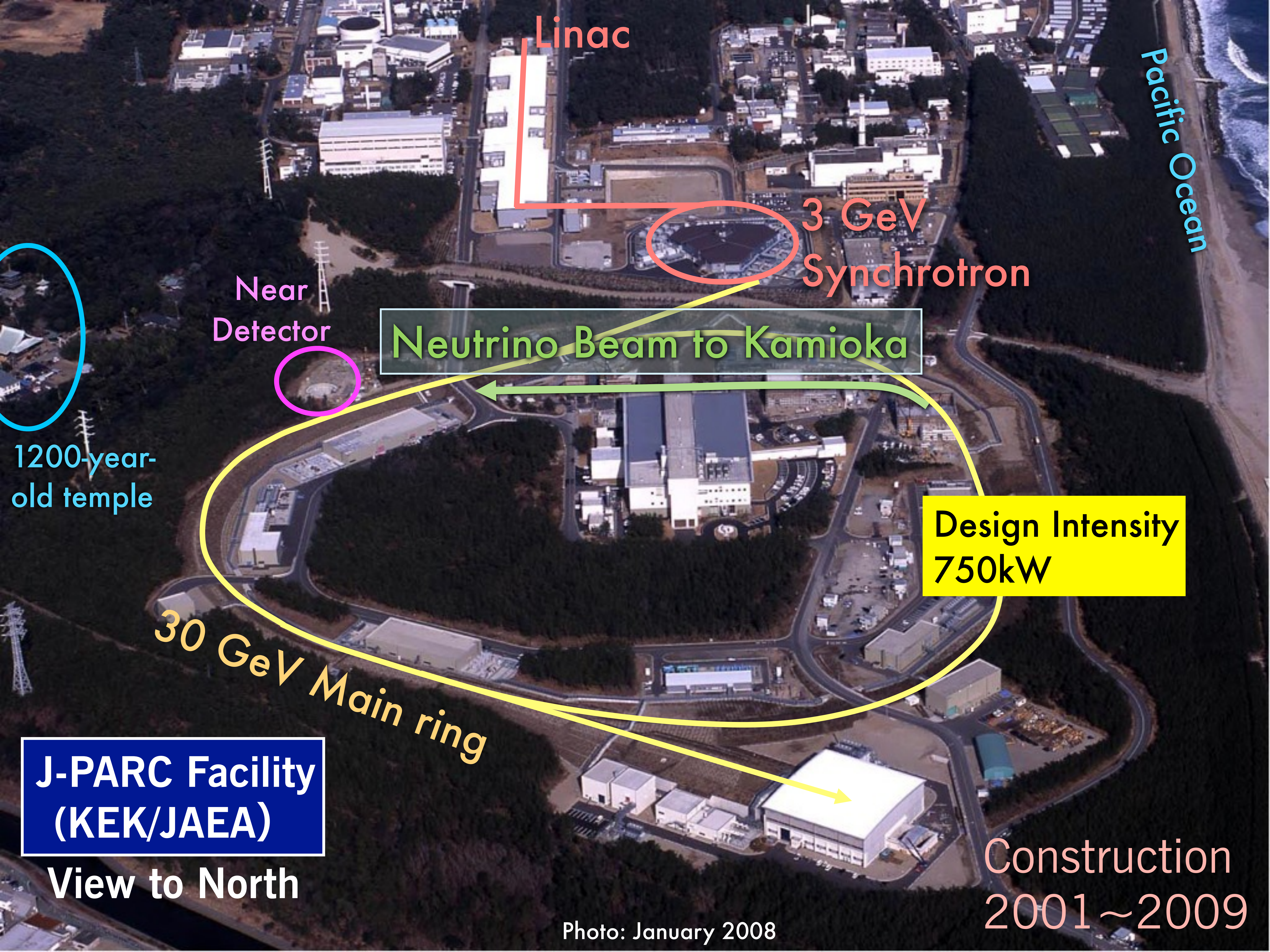
- Design:
    - First experiment to use off-axis technique to produce a narrow-band ν_μ beam
    - High-intensity 30 GeV proton beam from J-PARC sychrotron
    - Beam monitors to measure primary and secondary beam each pulse
    - On- and off-axis near neutrino detectors to characterize beam
    - Far detector Super-Kamiokande, 295 km baseline
- Initial physics goals:
    - Discover ν_e appearance and determine θ_{13}
    - Precise measurement of ν_μ disappearance θ_{23}, Δm^2_{23}
- Future:
    - Possible search for CP violation in lepton sector

Off-axis beam technique

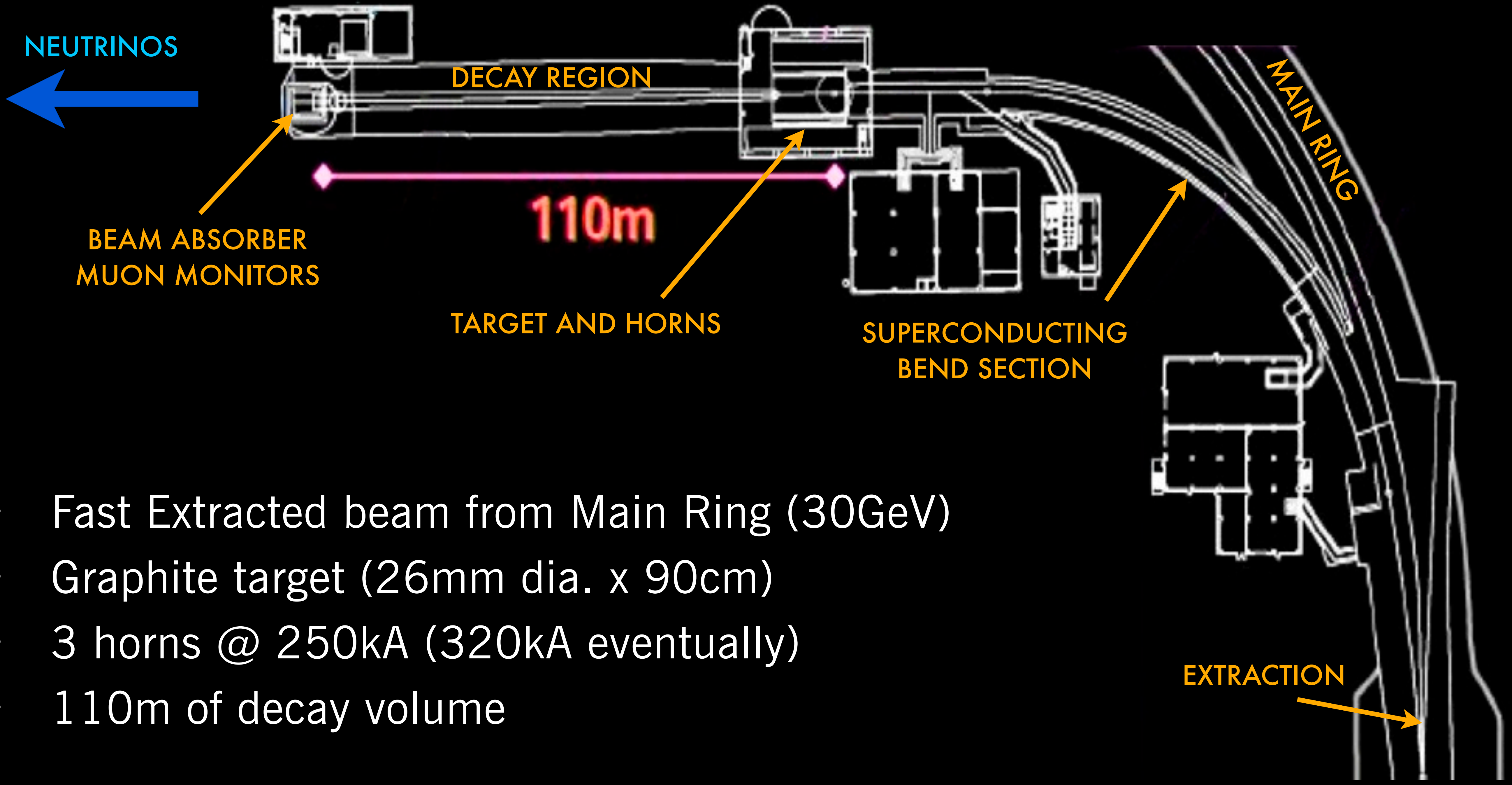




- For wide range of pion momenta, E_ν depends more on decay angle than E_π
- Exploit to make narrow-band ν_μ beams by going off-axis
- At 295 km baseline, first oscillation maximum is at 570 MeV for $\Delta m^2 = 2.4 \cdot 10^{-3}$ eV^2 $\Rightarrow$ T2K wants 2.5° off-axis angle


Linac
Pacific Ocean
3 GeV Synchrotron
Near Detector
Neutrino Beam to Kamioka
1200-year-old temple
Design Intensity 750kW
30 GeV Main ring
J-PARC Facility (KEK/JAEA)
View to North
Construction 2001～2009
Photo: January 2008

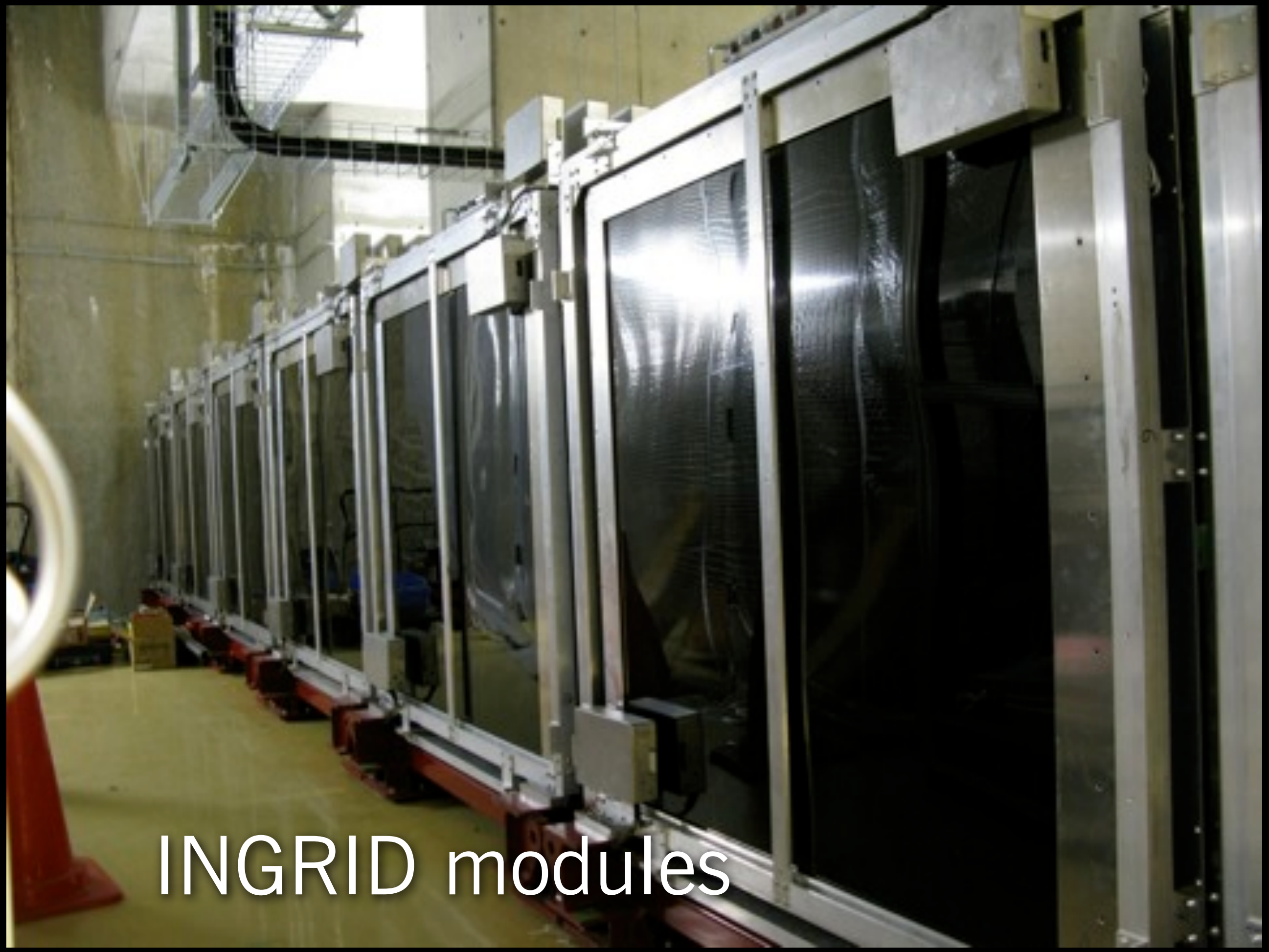
Neutrino Beam



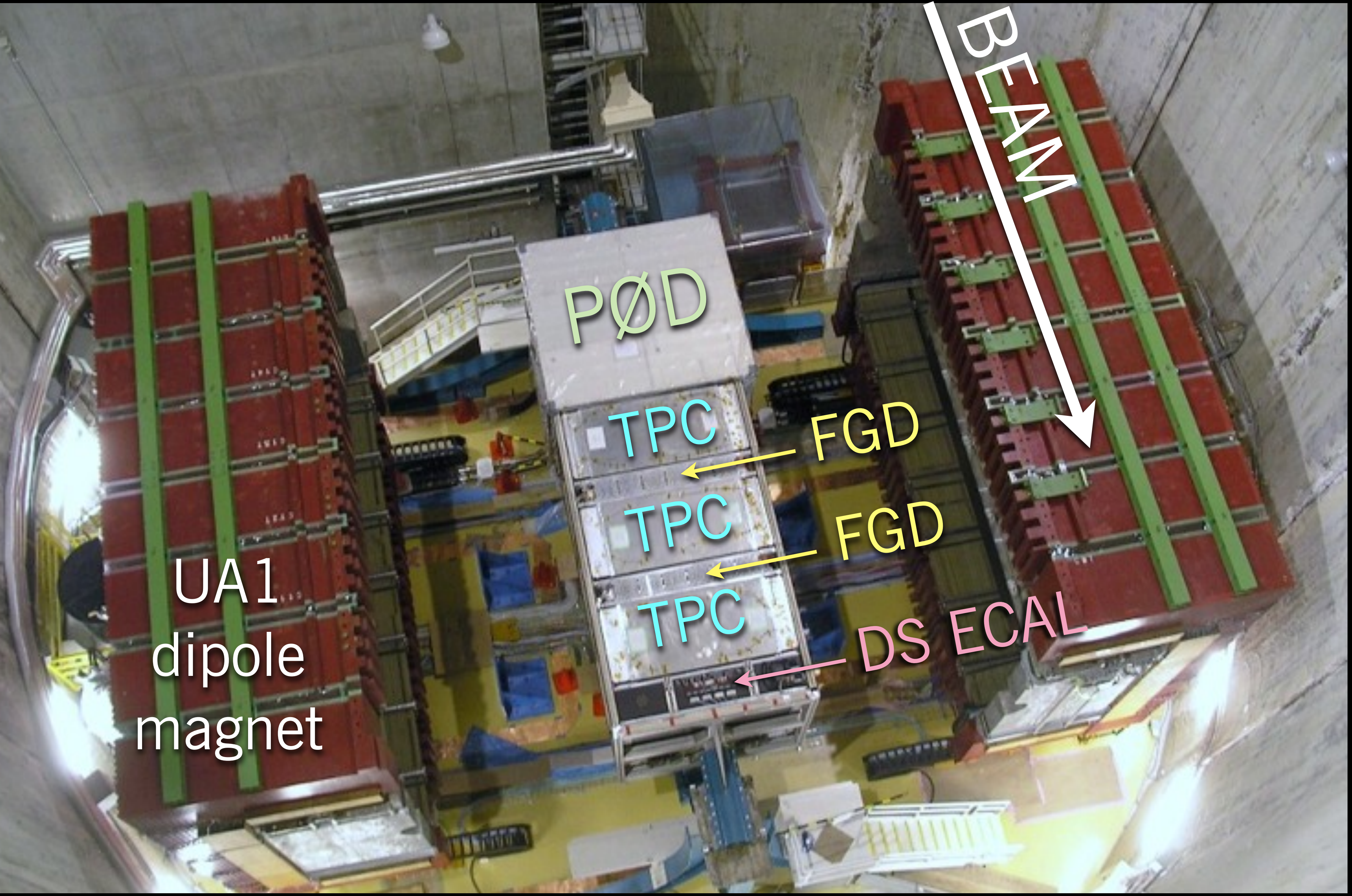
- Fast Extracted beam from Main Ring (30GeV)
- Graphite target (26mm dia. x 90cm)
- 3 horns @ 250kA (320kA eventually)
- 110m of decay volume

280m on-axis near detector: INGRID

- Array of 9-ton iron-scintillator neutrino detectors in cross shape centered on beam axis
- Designed to show neutrino beam profile, event rate, and precise measure of beam center/off-axis angle



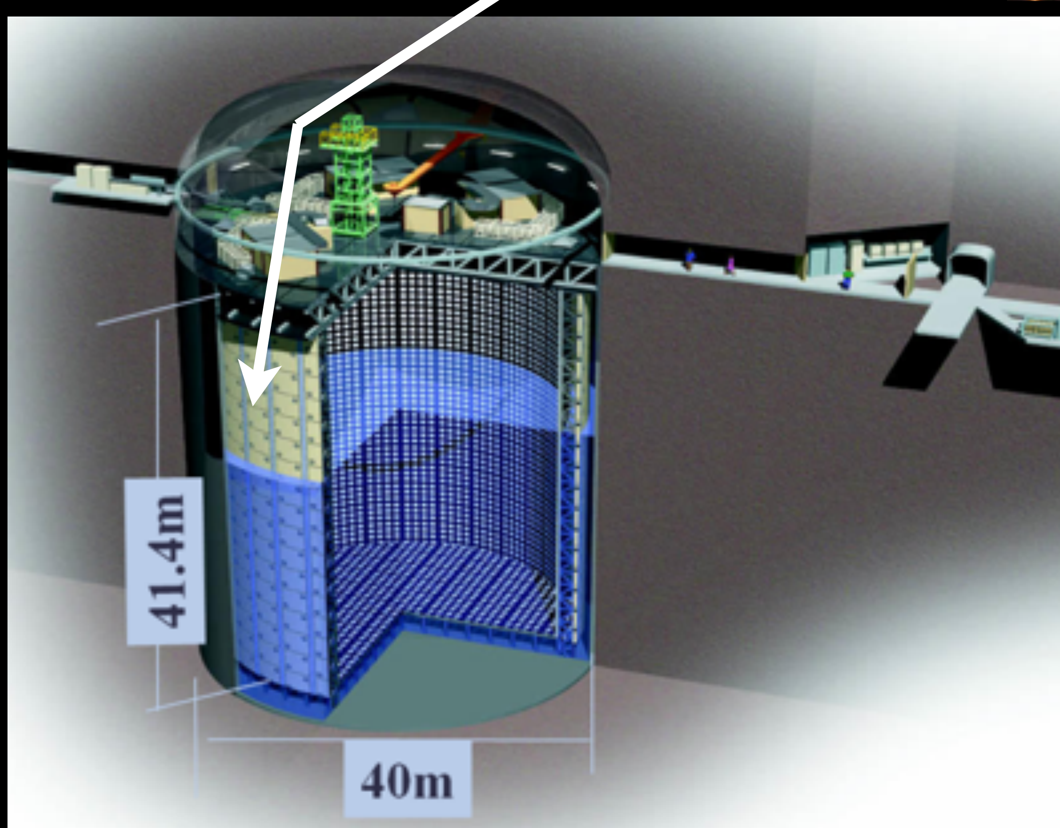
Off-axis Near Detector



- Pi Ø Detector (PØD): optimized for π^0 detection, includes H_2O target
- Tracker: 2 Fine-Grained Detectors (FGD), 3 TPCs: measure fluxes before oscillation
- ECAL: surrounding POD and Tracker, measure EM activity
- Side Muon Range Detector: in the magnet yokes, identify muons

Far detector: Super Kamiokande IV

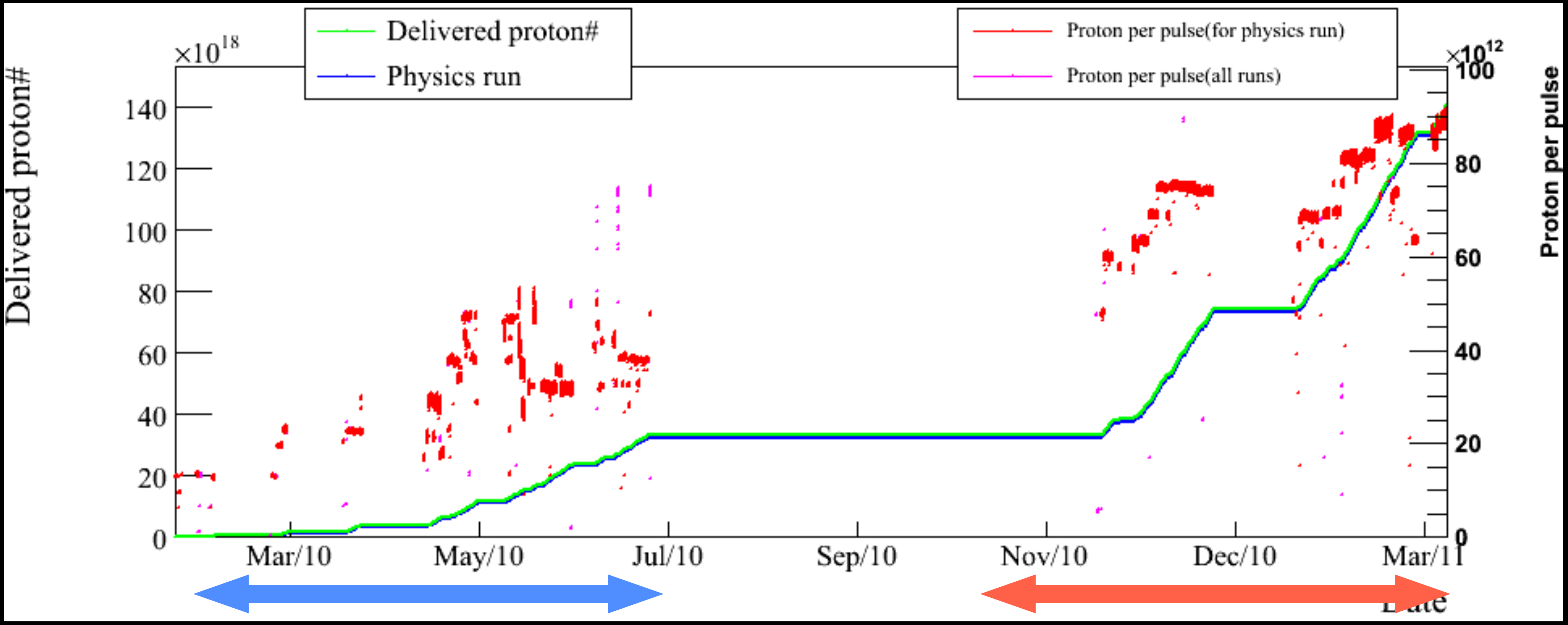
- 50 kt water Cherenkov (22.5 kt fiducial)
- 11129 20-inch PMTs in inner detector; 1885 8-inch PMTs in outer veto detector



- New readout electronics commissioned in 2009: new system has no dead time
- GPS-based time stamp on beam is transmitted to SK, which records all activity within 500 μs of pulse

First neutrino physics runs

- Run 1 January-June 2010;   Run 2 November 2010-March 2011
- Beam power up to 145 kW (most running around 50-100 kW)
- Before March earthquake, accumulated $1.45 \cdot 10^{20}$ protons ($70\ kW \cdot 10^7\ s$) on target, Run 1 result shown here is on $0.32 \cdot 10^{20}$ protons ($16\ kW \cdot 10^7\ s$).

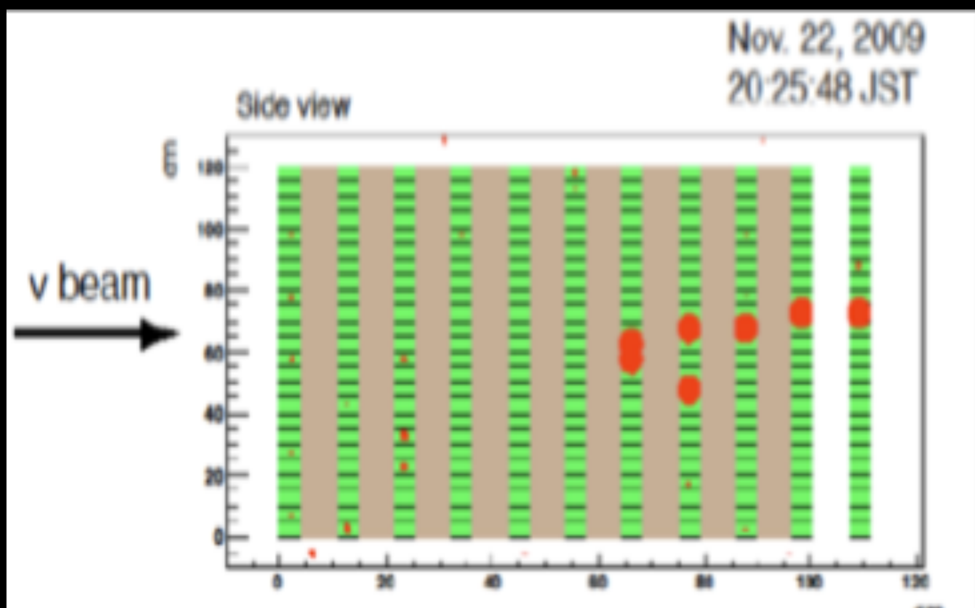


RUN 1: results now

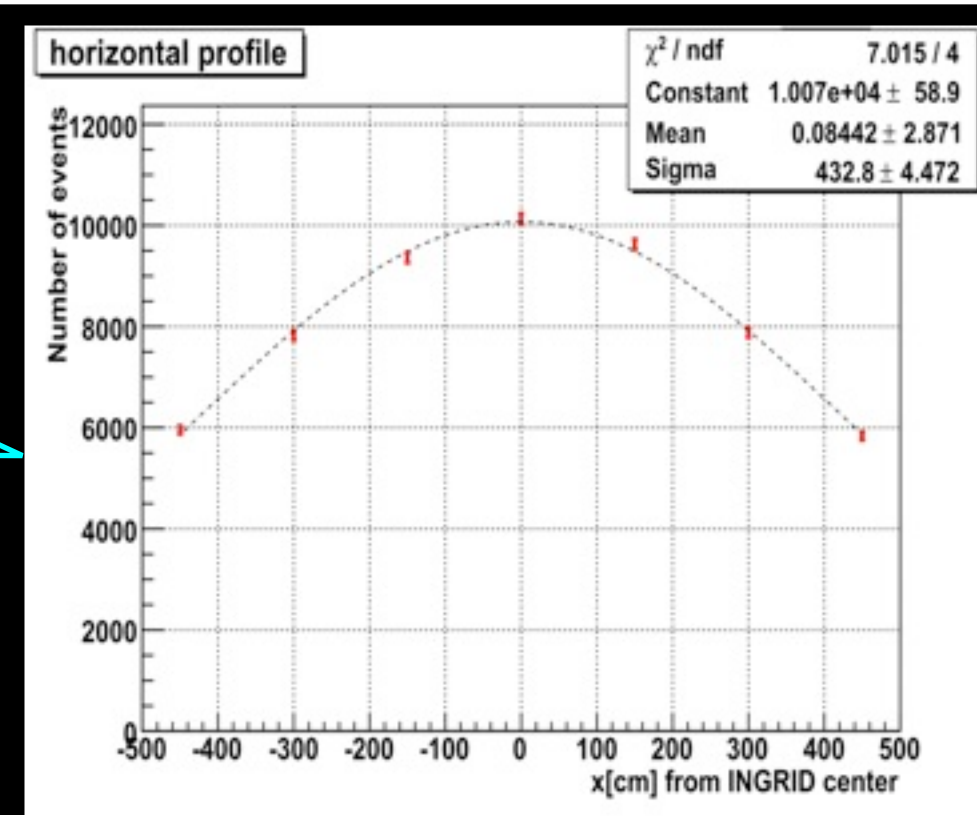
RUN 2: results soon

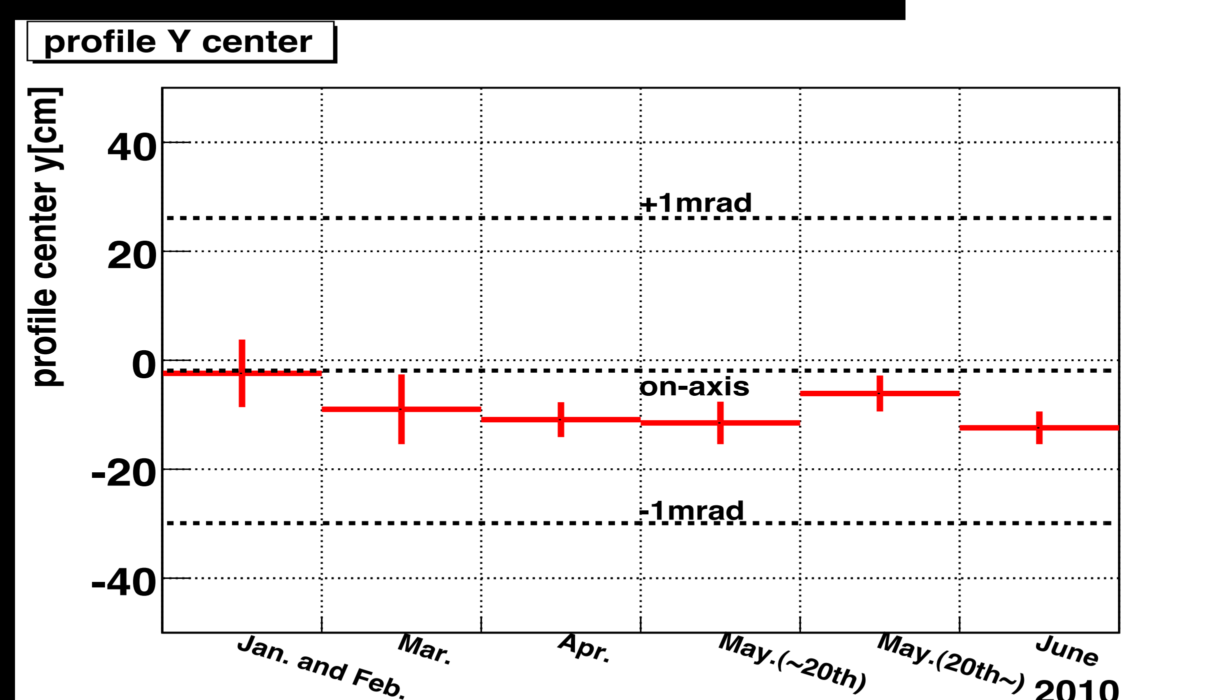
First neutrino physics run: On-axis neutrino monitor (INGRID)

The first INGRID neutrino candidate



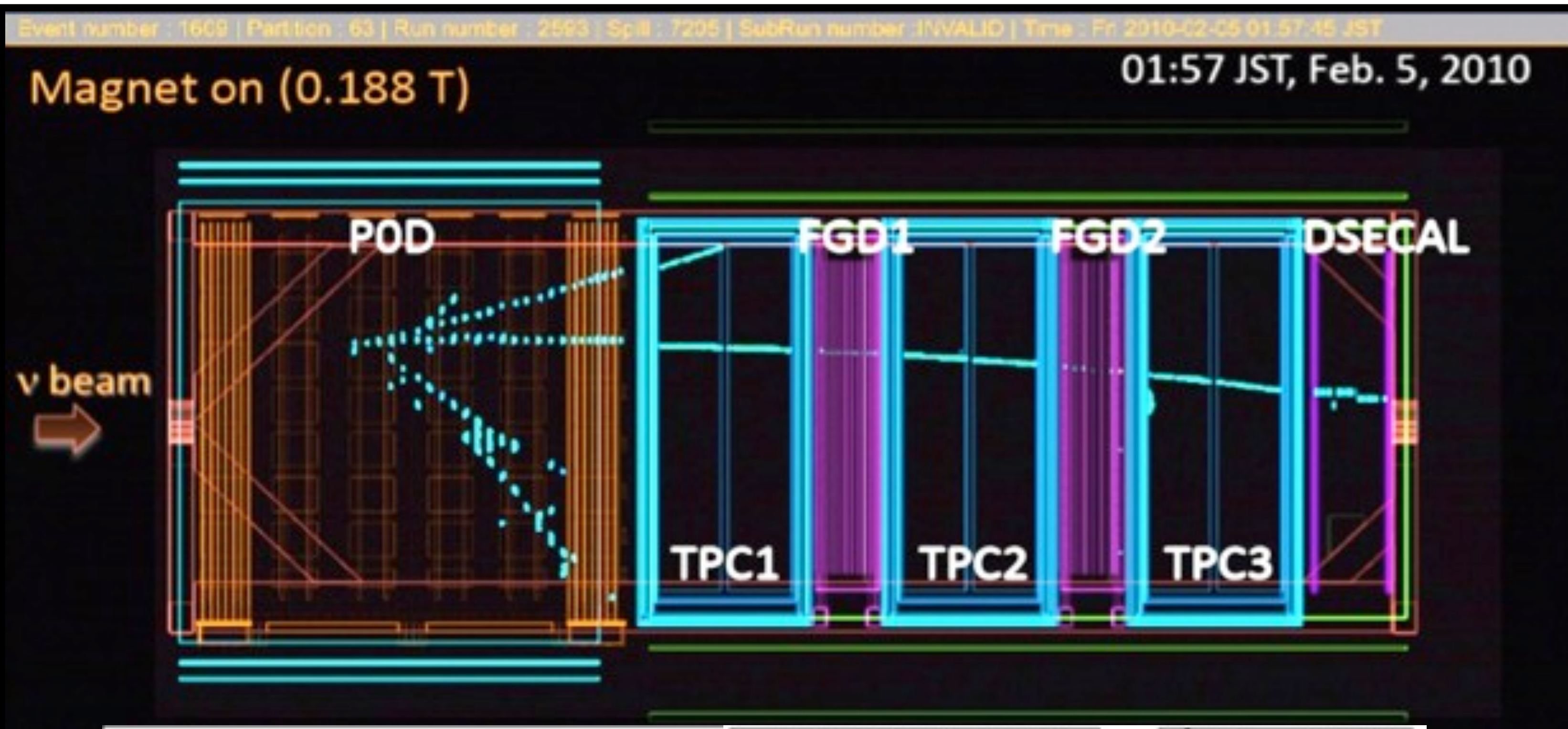
Neutrino event rate shows good symmetry: detectors and beam working well

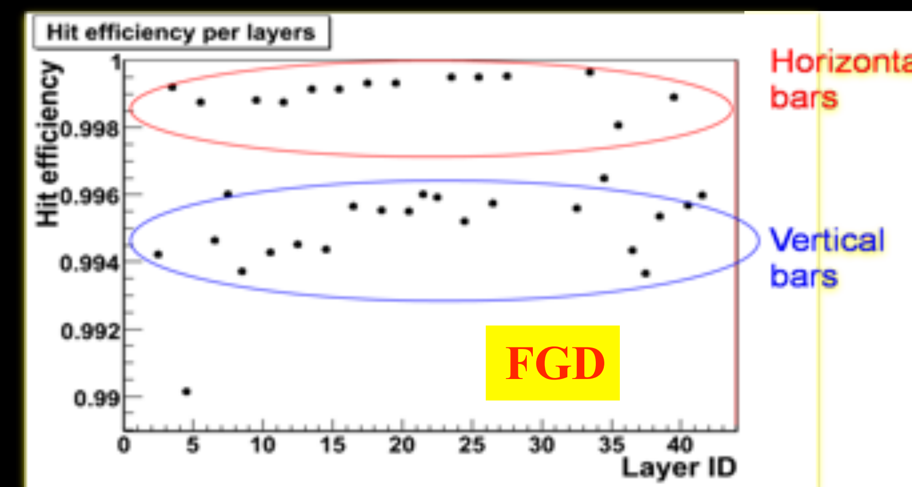


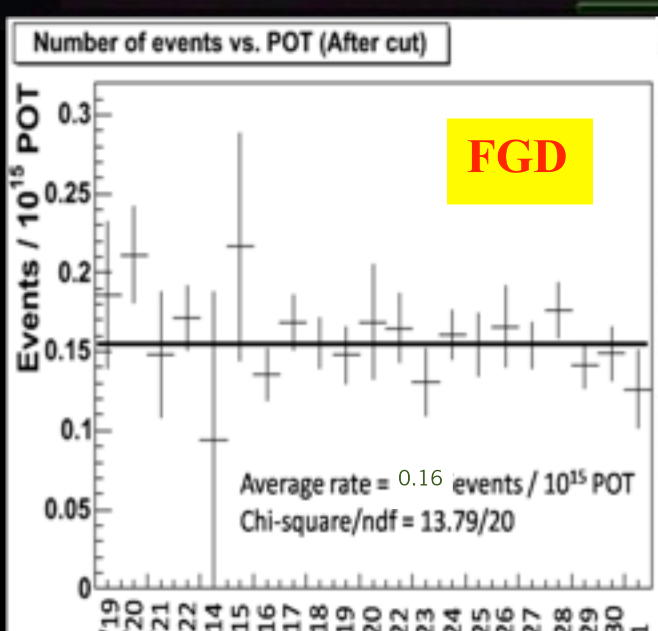


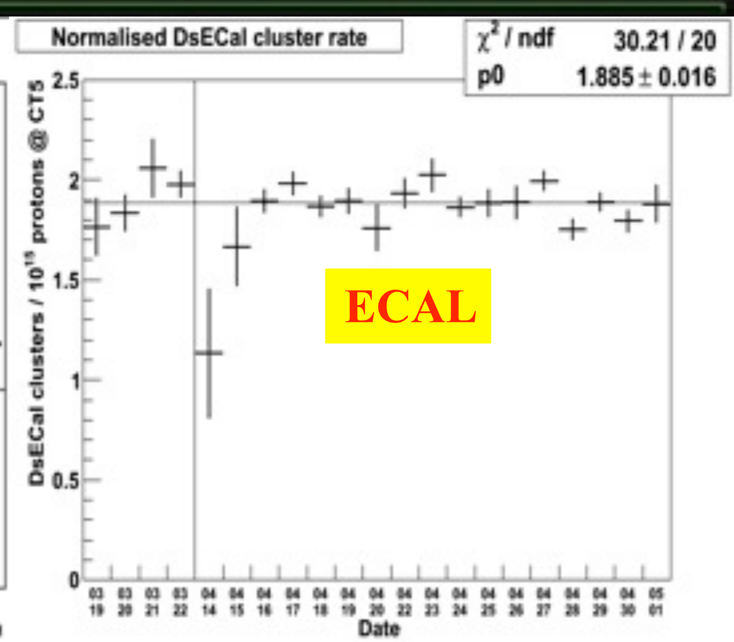
Beam profile center is within 1 mrad requirement

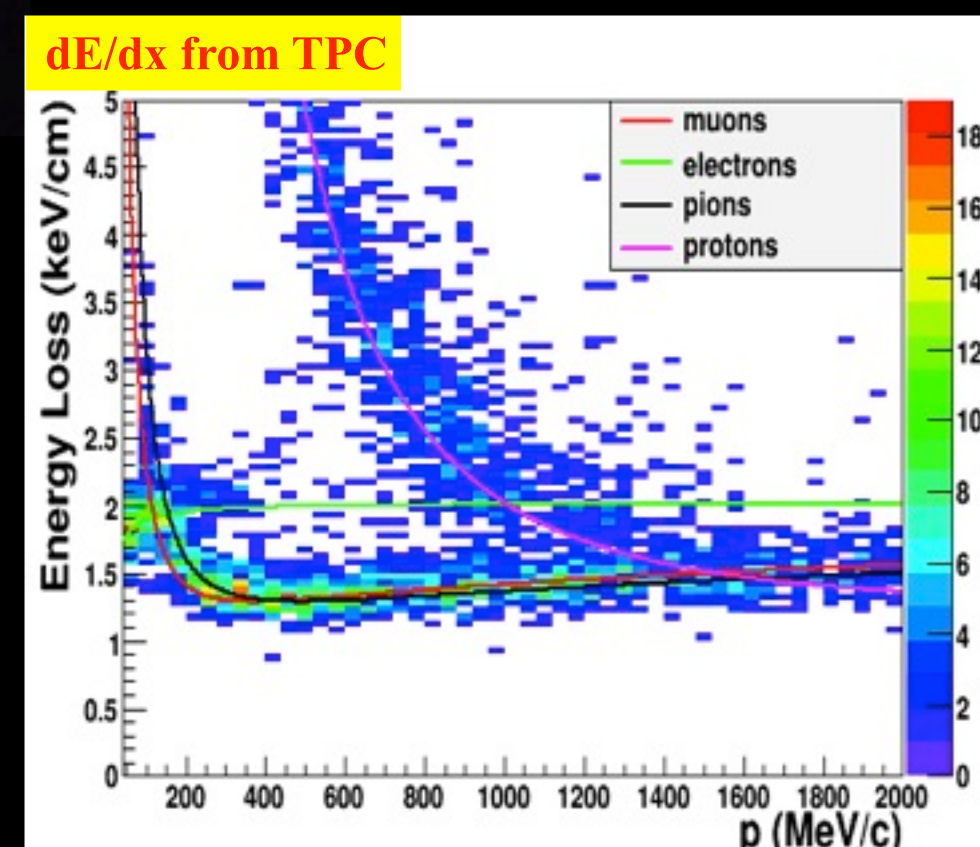
First neutrino physics run: Off-axis neutrino detector











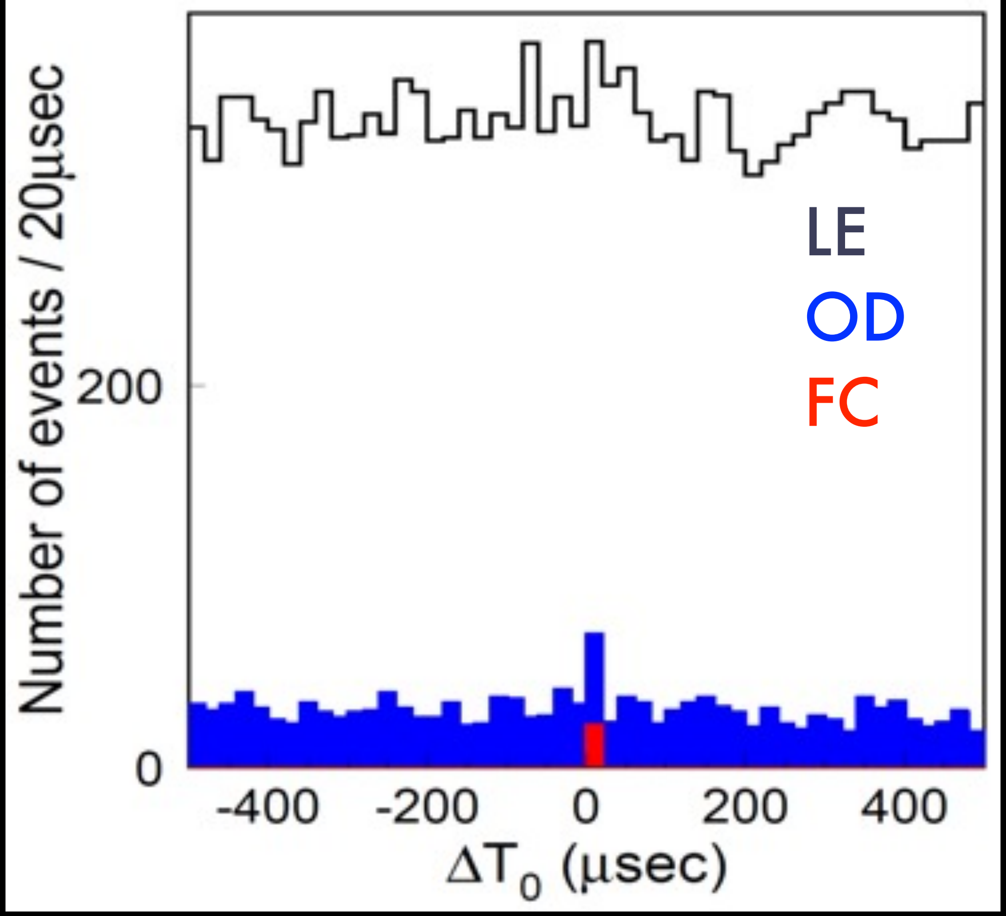
- Detectors are performing well

First neutrino physics run: Super-Kamiokande

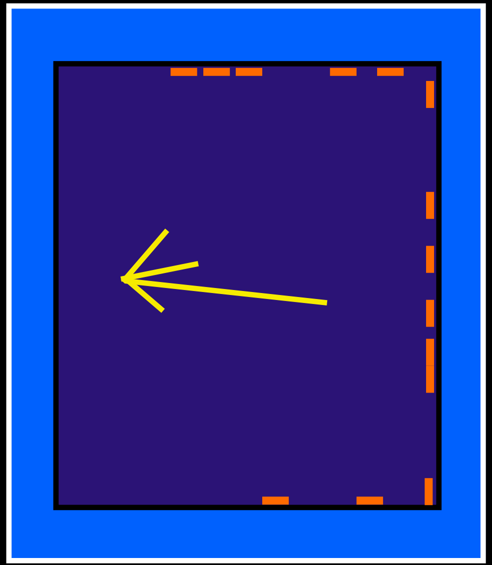
- J-PARC neutrino events selected by event timing using GPS
- SK analysis is very well established
- Event selection & cut values fixed before data collection for this run

For ν_μ disappearance analysis	For ν_e appearance search
Timing coincidence w/ beam timing (+TOF)	
Fully contained (No OD activity)	
Vertex in fiducial volume (>2m from wall)	
Evis > 30MeV	Evis > 100MeV
Number of rings =1	
μ-like ring	e-like ring
	No decay electron
	Forced 2nd ring: $m_{\gamma\gamma} < 105$ MeV
	$E_\nu^{rec} < 1250$MeV

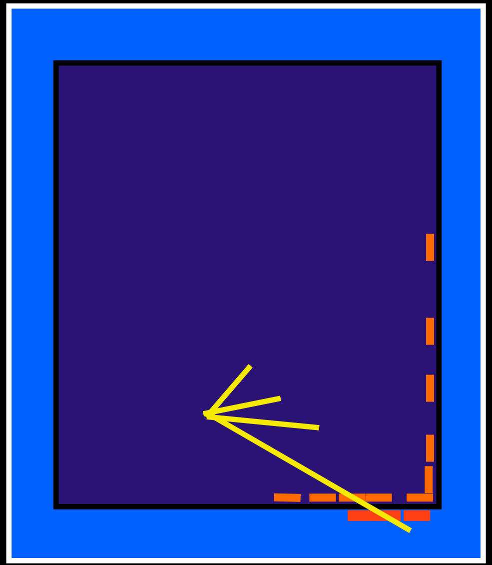
First neutrino physics run: Super-Kamiokande



LE: Low energy triggered events
OD: Outer detector events
FC: Fully contained events



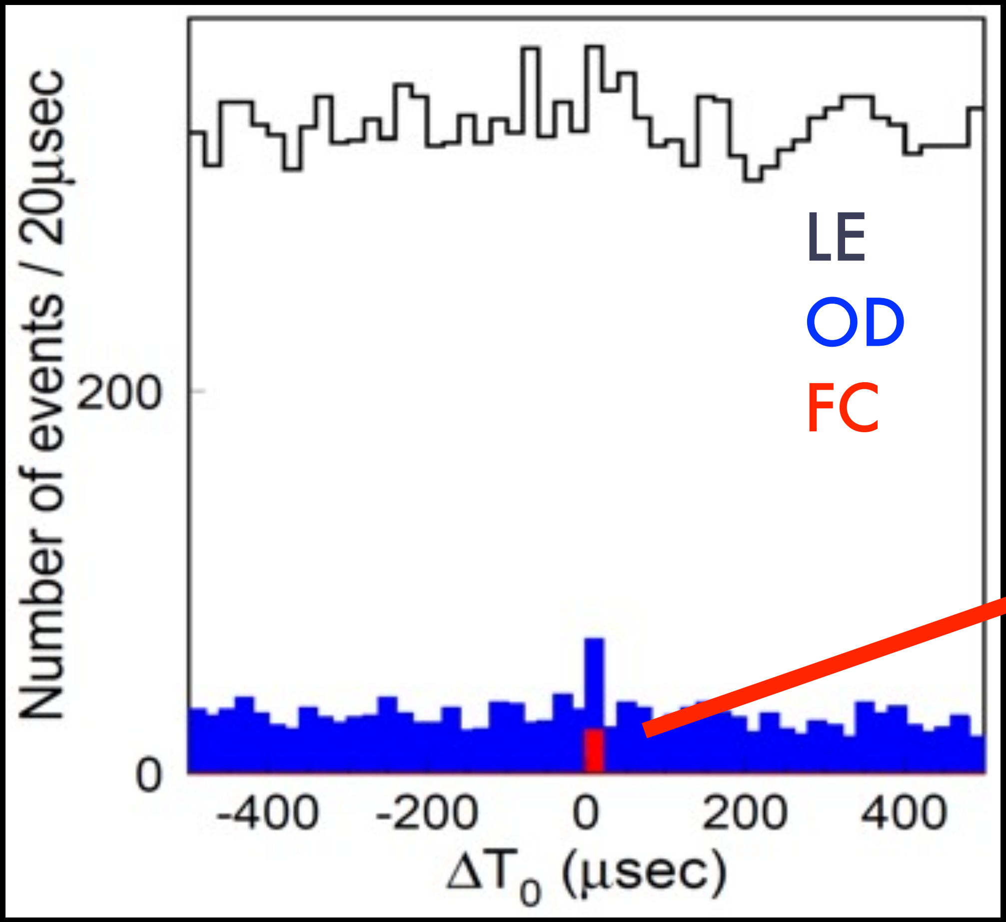
FC: Fully contained event

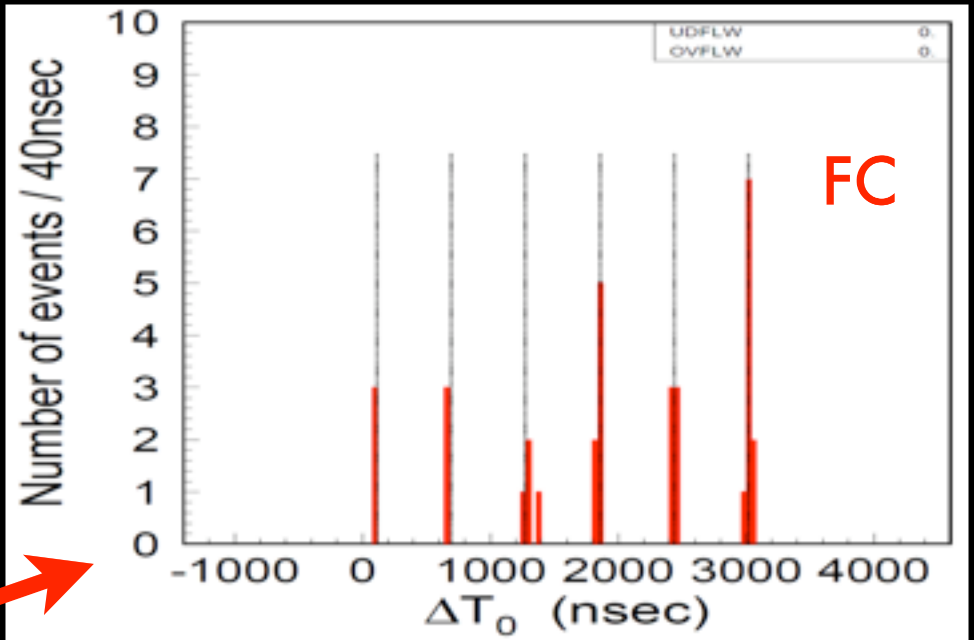


OD: Outer detector event

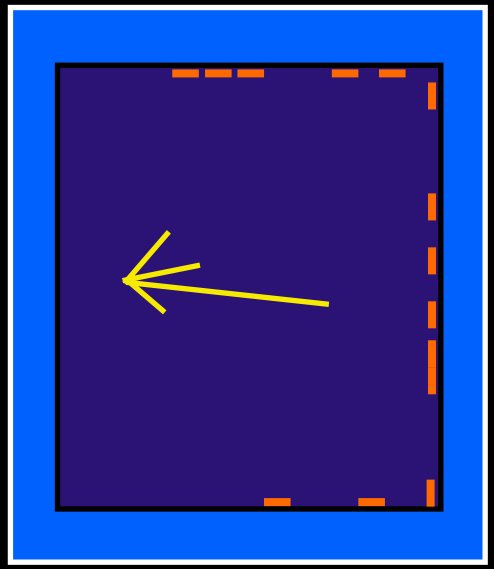
- Event time distribution clearly shows six-bunch beam structure
- Observed # of fully contained events: 33
- Expected non-beam background: $<10^{-3}$ events

First neutrino physics run: Super-Kamiokande

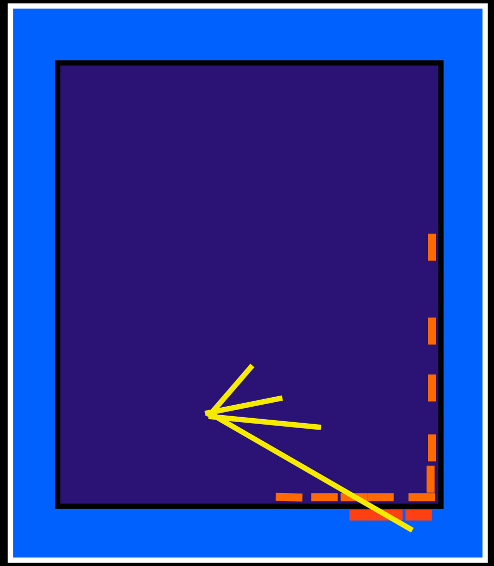




LE: Low energy triggered events
OD: Outer detector events
FC: Fully contained events



FC: Fully contained event



OD: Outer detector event

- Event time distribution clearly shows six-bunch beam structure
- Observed # of fully contained events: 33
- Expected non-beam background: $<10^{-3}$ events

Eventual analysis strategy

- Predict neutrino fluxes using:
  - GEANT3-based beam MC
  - Hadron production measurements from CERN NA61

- Near detector analysis:
  - GEANT4-based detector MC
  - Measure beam flux × cross section at near detector for both ν_μ and ν_e
  - Compare to prediction

- Propagate near detector constraint to far detector using data/MC ratio and near→far flux transfer function developed from beam MC:
  - Predict event rates and spectra at Super-Kamiokande

- Far detector analysis:
  - GEANT3-based Super-K detector MC
  - Measure event rates, spectra
  - Compare to unoscillated prediction→fit results to oscillation hypotheses

Run 1 ν_e appearance analysis strategy

- Predict neutrino fluxes using:
  - GEANT3-based beam MC
  - Hadron production measurements from CERN NA61

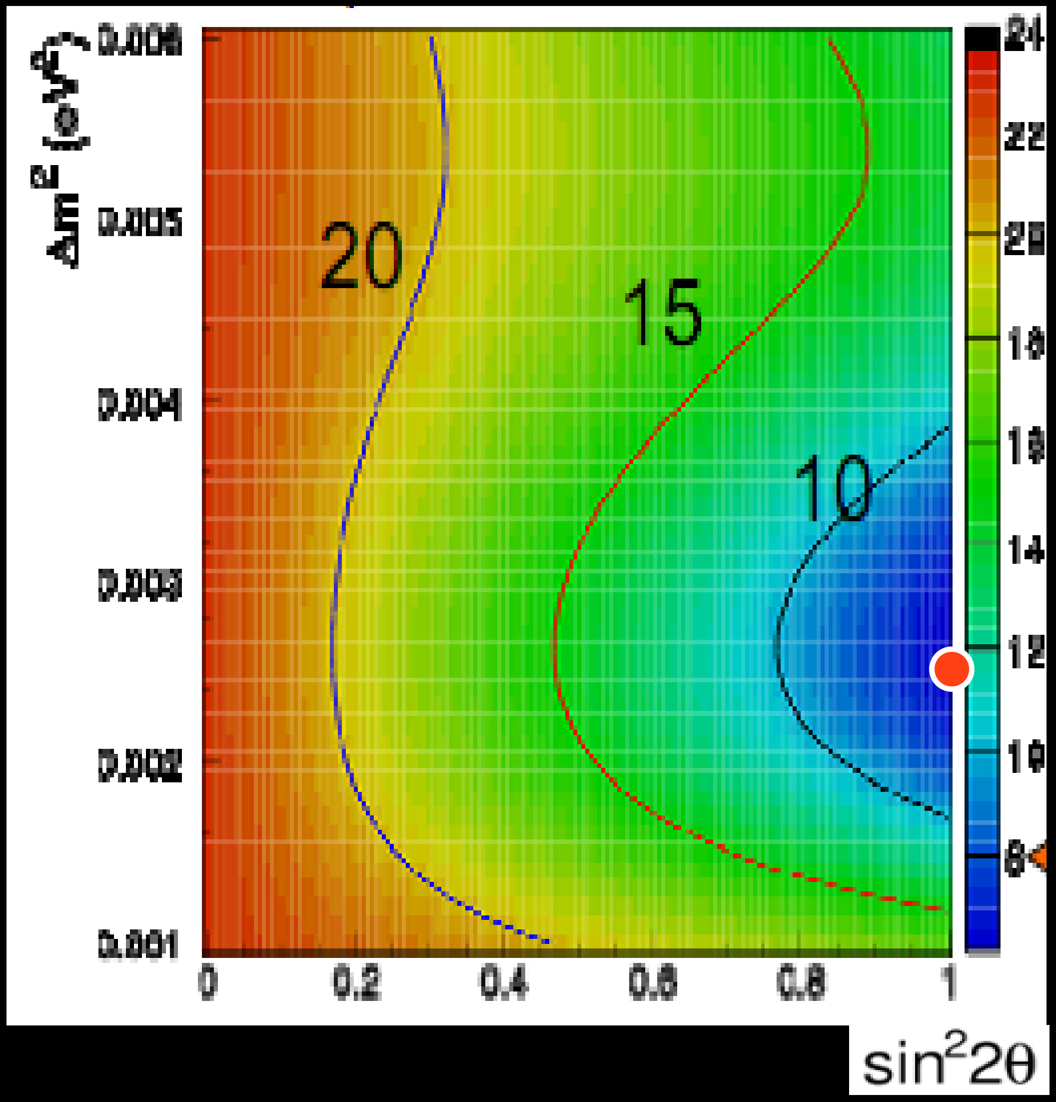
- Near detector analysis:
  - GEANT4-based detector MC
  - Inclusive charged-current event selection; no energy cut

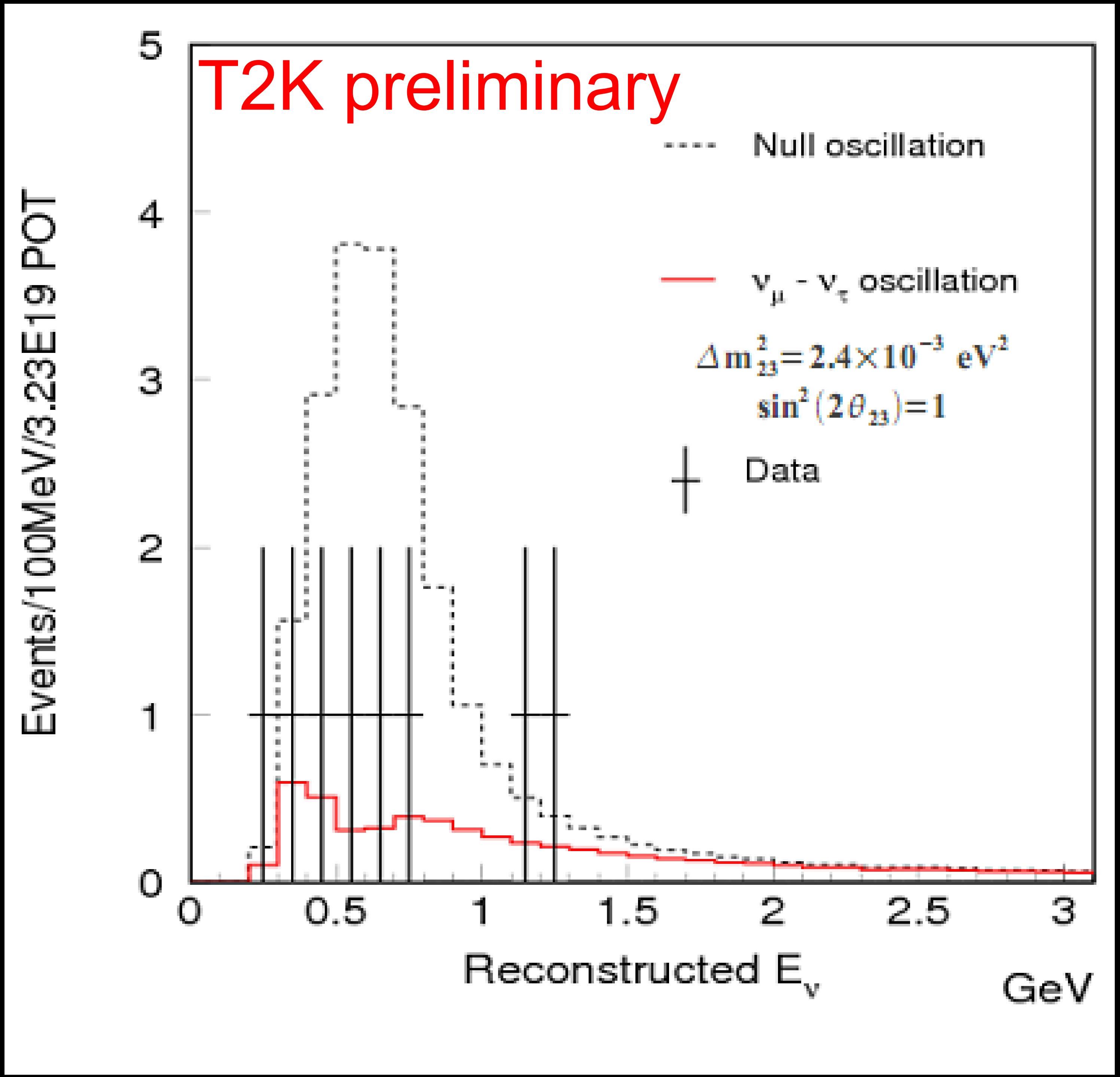
- Predict flux at Super-K using beam MC
- Reweight by near detector Data/MC ratio for inclusive sample (no energy dependence)

- Far detector analysis:
  - GEANT3-based Super-K detector MC
  - Count events that pass appearance cuts
  - Compare this number to oscillated prediction, form confidence regions in oscillation parameter space

ν_μ disappearance analysis

Expected # of events vs oscillation parameters





● Oscillation parameters most favored by MINOS

ν_e appearance analysis

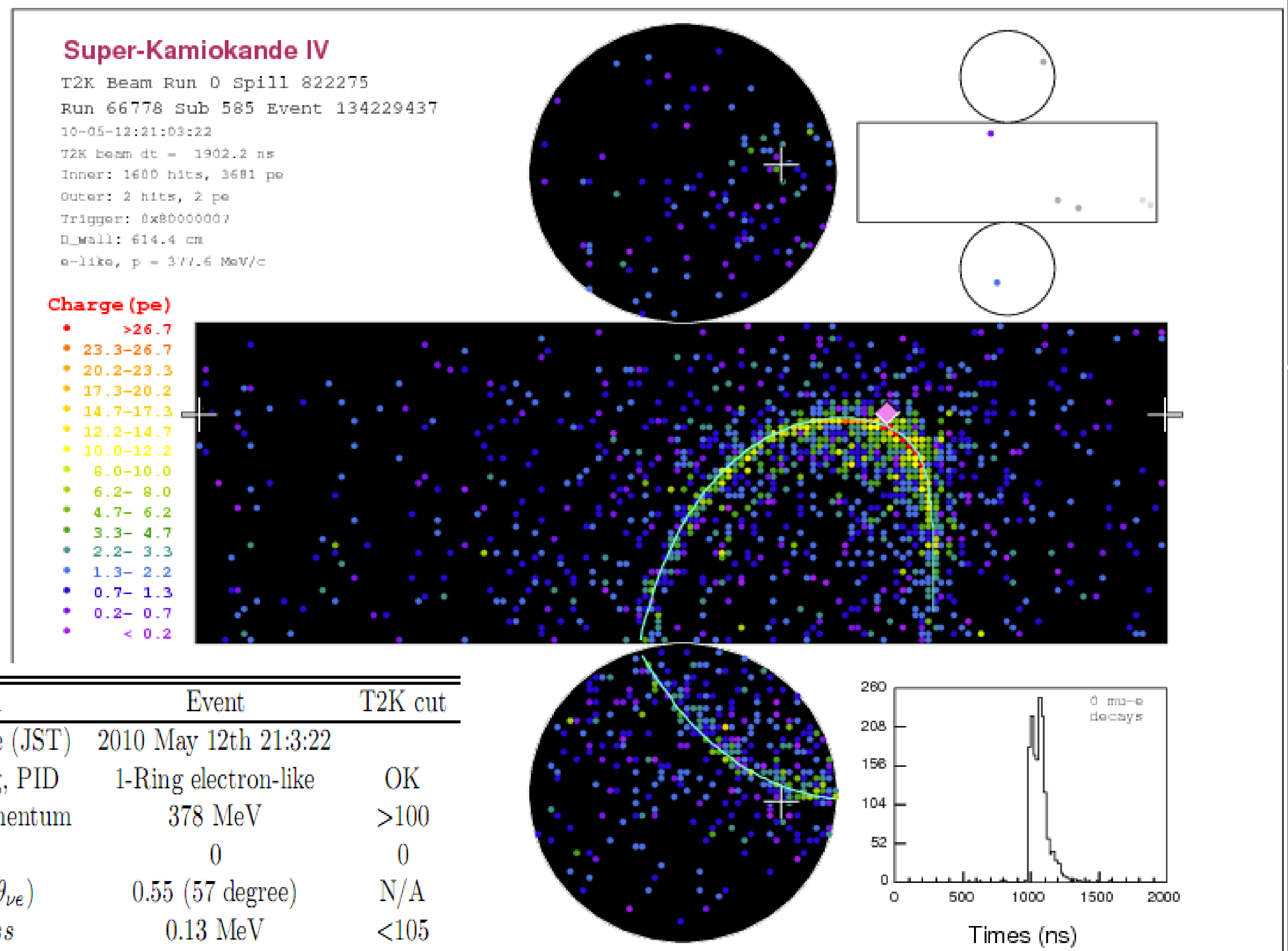
T2K-SK events	Data	MC	
		No oscillation	Oscillation $\Delta m^2 = 2.4 \times 10^{-3}$ (eV^2) $\sin^2 2\theta_{23} = 1.0$ $\theta_{13}=0$
Fully-Contained	33	54.5	24.6
Fiducial Volume, $E_{vis} > 30$MeV	23	36.8	16.7
Single-ring e-like (P_e>100MeV/c)	2	1.5 ±0.7	1.3 ±0.6

- Additional background rejection:
  - no decay electron (cuts one of the two events)
  - $m_{\gamma\gamma} < 105$ MeV/c^2 assuming second ring exists
  - reconstructed $E_\nu < 1250$ MeV
  - These cuts have 66% efficiency for signal

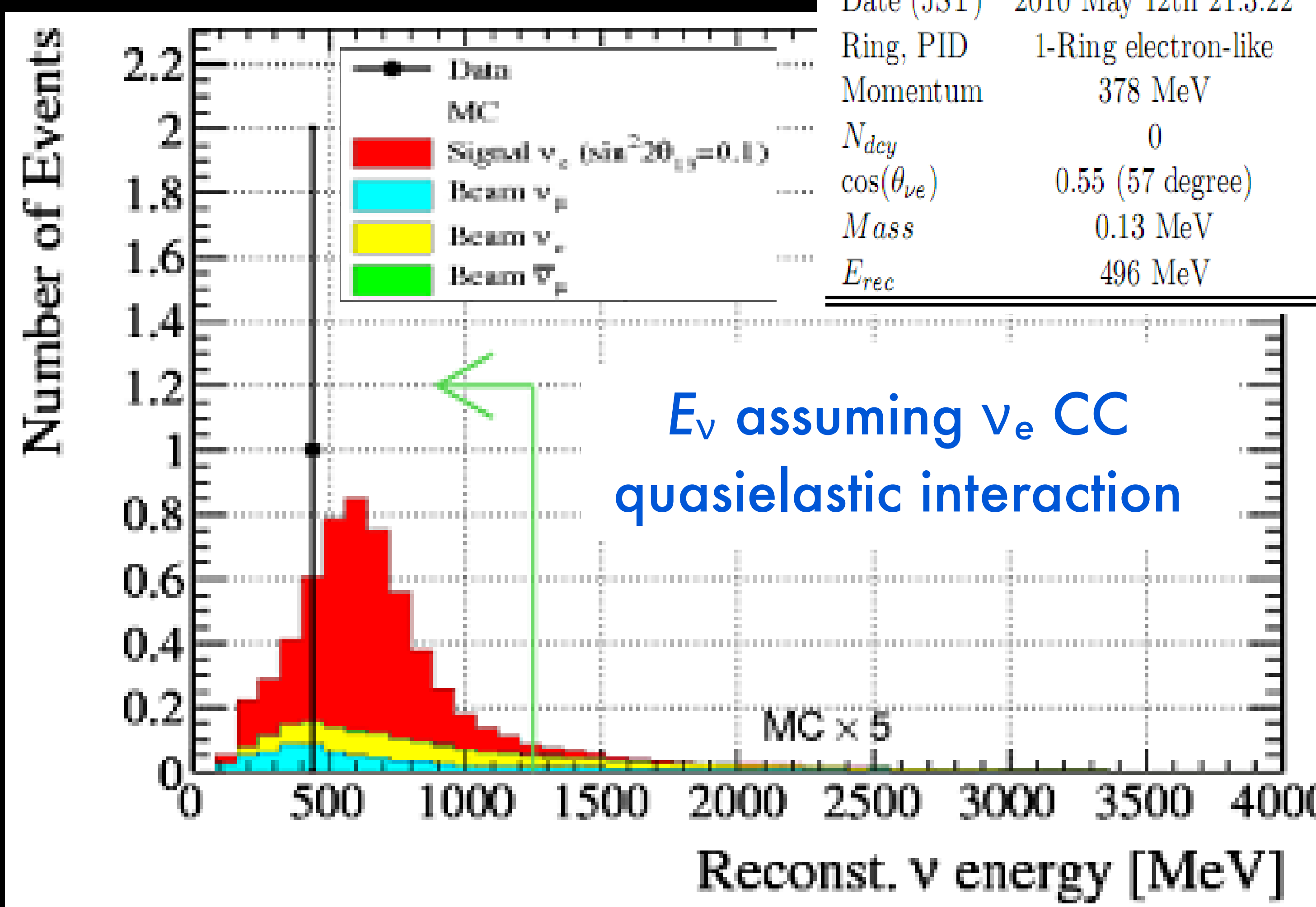
One event remains after all cuts.

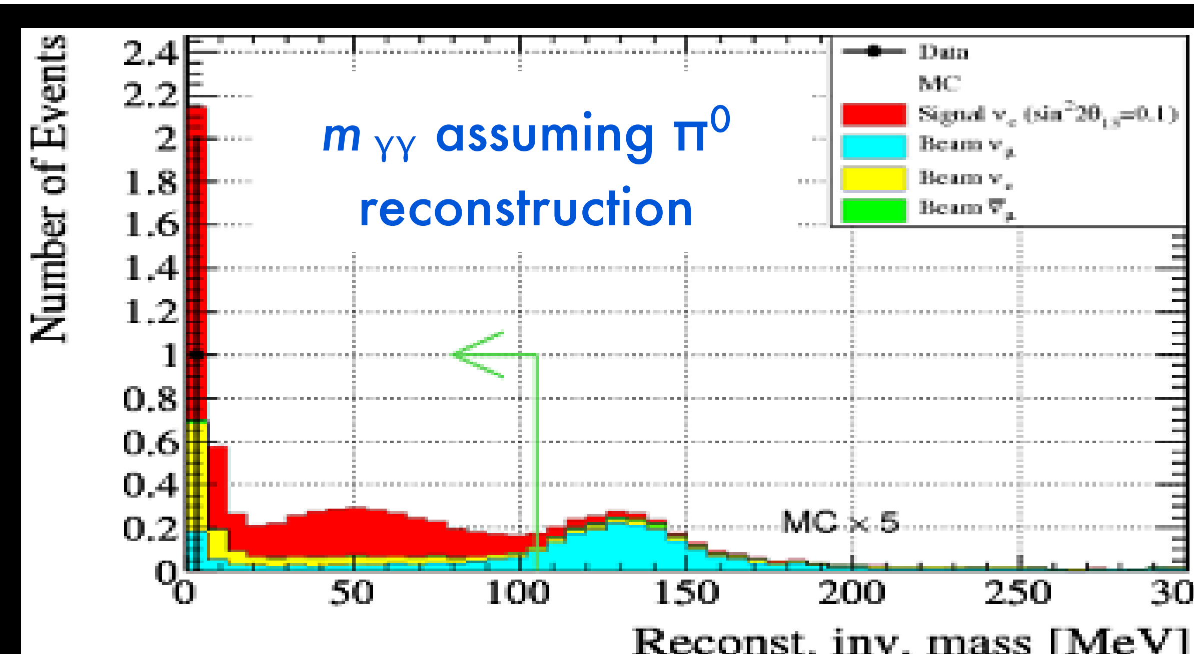
ν_e appearance analysis

- Our event is a good ν_e candidate in all variables



Item	Event	T2K cut
Date (JST)	2010 May 12th 21:3:22	
Ring, PID	1-Ring electron-like	OK
Momentum	378 MeV	>100
N_{dcy}	0	0
$\cos(\theta_{\nu e})$	0.55 (57 degree)	N/A
Mass	0.13 MeV	<105
E_{rec}	496 MeV	<1250

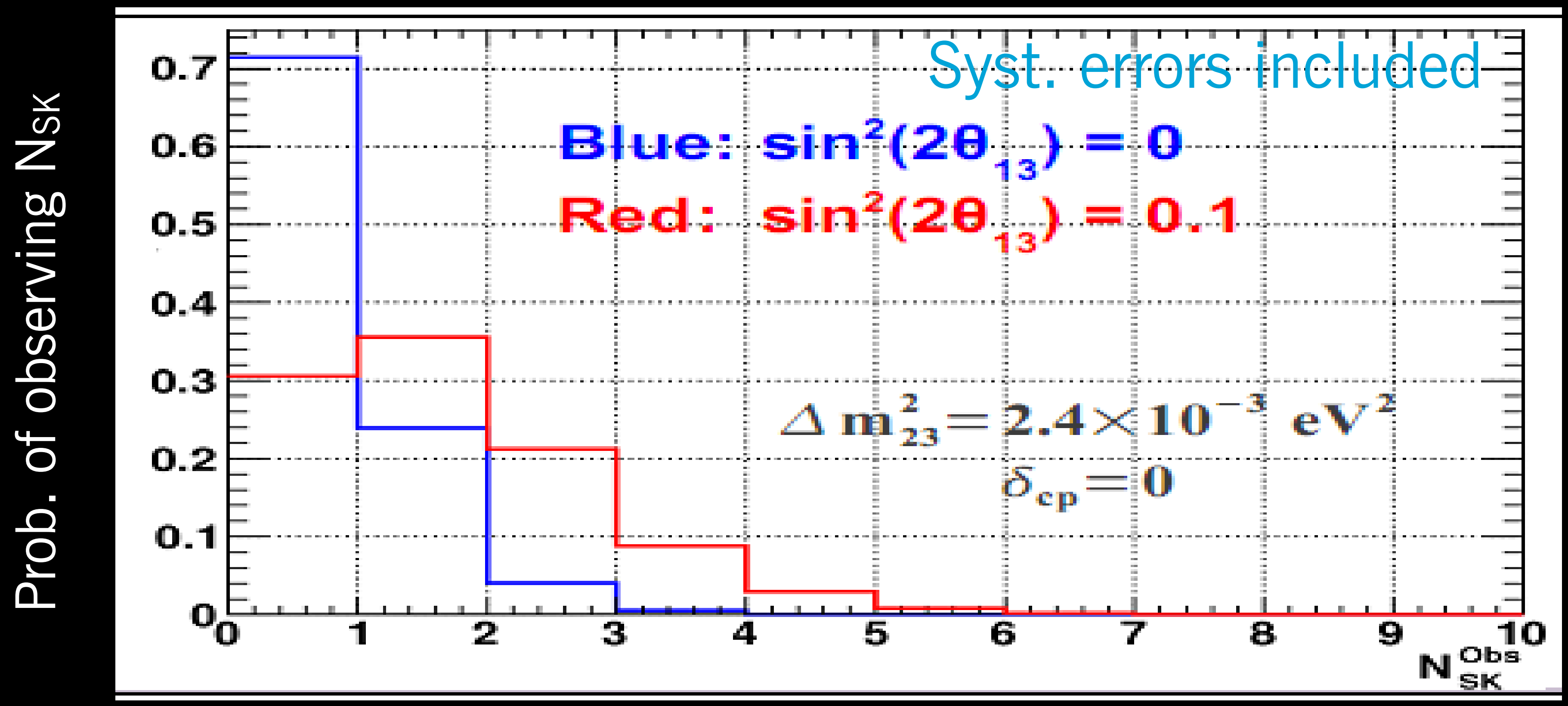




ν_e appearance analysis: expected events

Source	Estimated number
Beam ν_μ (CC+NC)	0.13
Beam $\overline{\nu_\mu}$ (CC+NC)	0.01
Beam ν_e (CC)	0.16
Total background	**0.30 ± 0.07 (syst.)**

Expected background + signal if $\sin^2 2\theta_{13}=0.1$:
1.20 ± 0.23 (syst.)



$\nu_\mu \rightarrow \nu_e$ oscillation limits

- Calculated using both Feldman-Cousins (A) and classical one-sided frequentist limit (B)

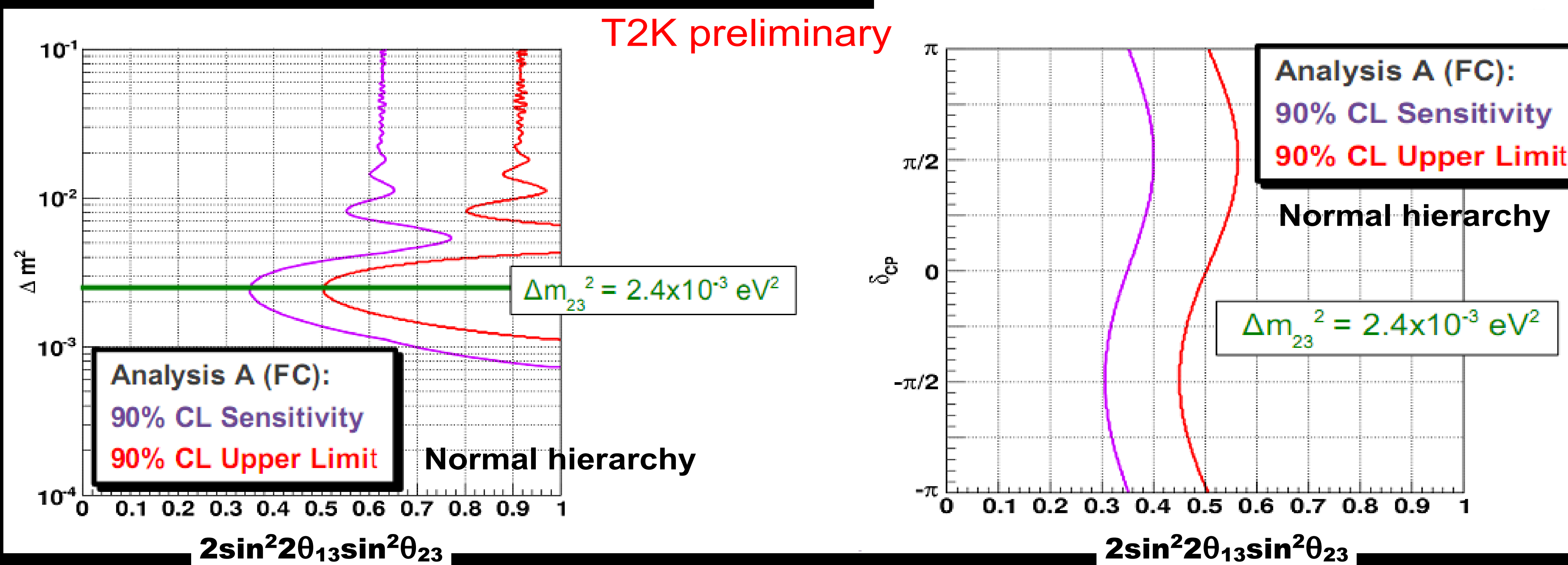
90% limits/sensitivity (Δm^2_{23}=2.4x10^{-3} eV^2, δ=0

A

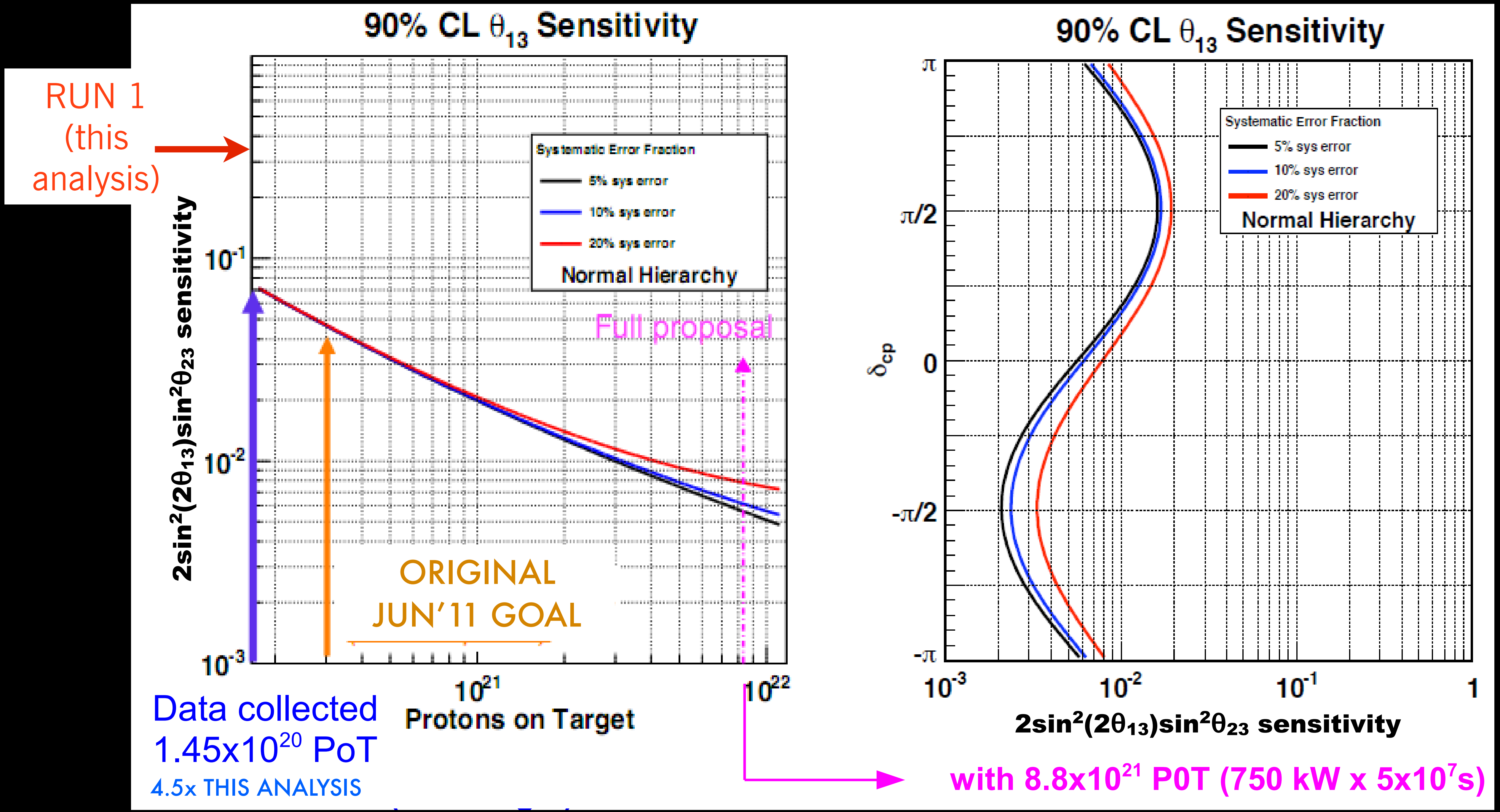
Hierarchy	Upper Limit	Sensitivity
Normal ($\Delta m^2_{23} > 0$)	0.50	0.35
Inverted ($\Delta m^2_{23} < 0$)	0.59	0.42

B

Hierarchy	Upper Limit	Sensitivity
Normal ($\Delta m^2_{23} > 0$)	0.44	0.32
Inverted ($\Delta m^2_{23} < 0$)	0.53	0.39



Future appearance sensitivity

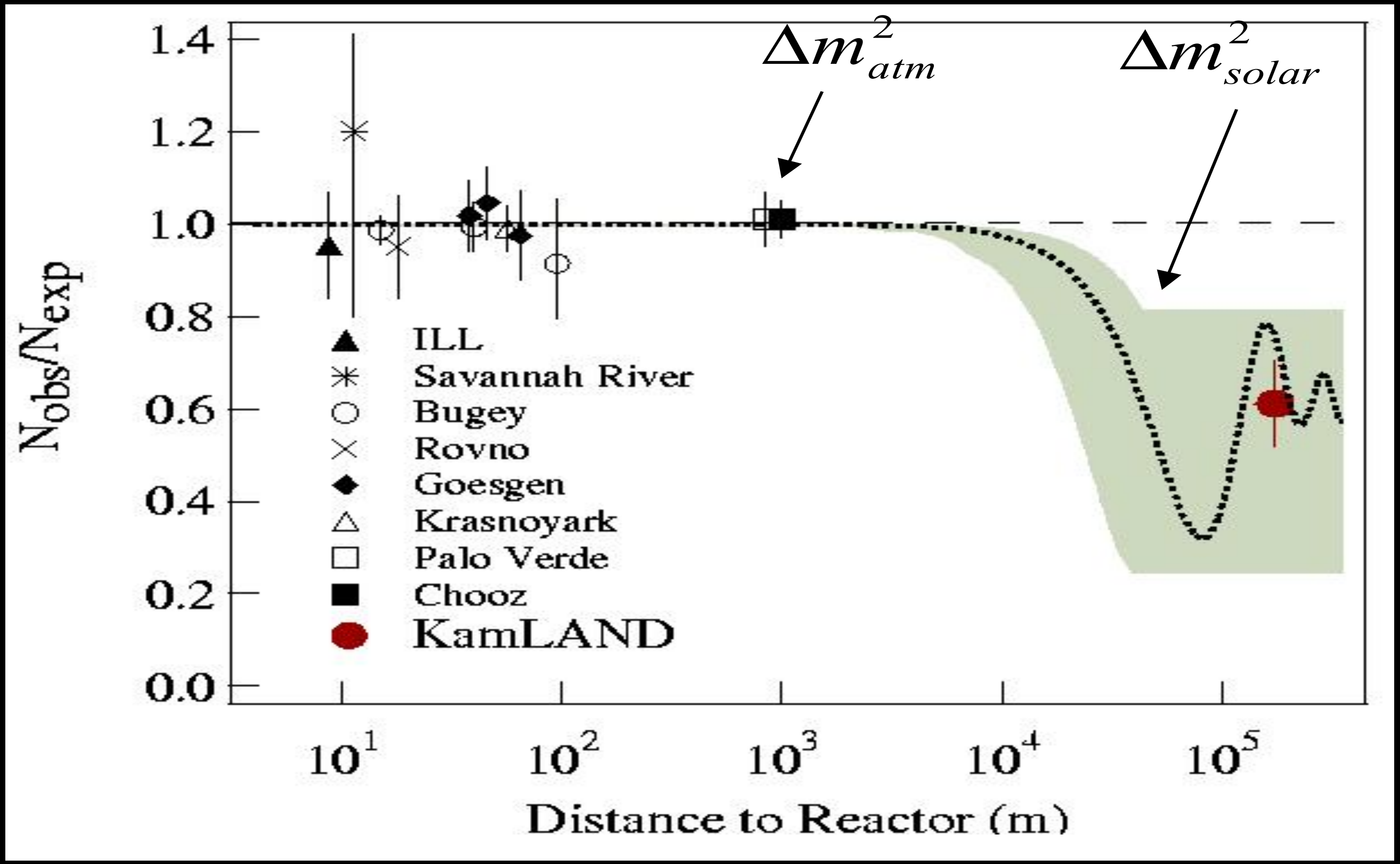


東日本大震災
Damage and recovery plans

- Experiment was operating when the Great East Japan Earthquake Disaster struck on 11 March (accelerator was in maintenance).
- J-PARC site is between Tokyo and the epicenter; near southern end of the most heavily-damaged region. Fortunately, **no major injuries at lab.**
- Tsunami was ~4m high at site, but most laboratory buildings are >10m above sea level. **No tsunami damage to lab.**
- Soil liquefaction on site was widespread; roads and surface buildings damaged. Underground facilities appear to suffer less, and **it appears no major components were destroyed**.
- Detailed inspections are underway, and reconstruction of damaged areas will begin very soon.
- Laboratory plans **restoration of beam to experiments around end of 2011**.

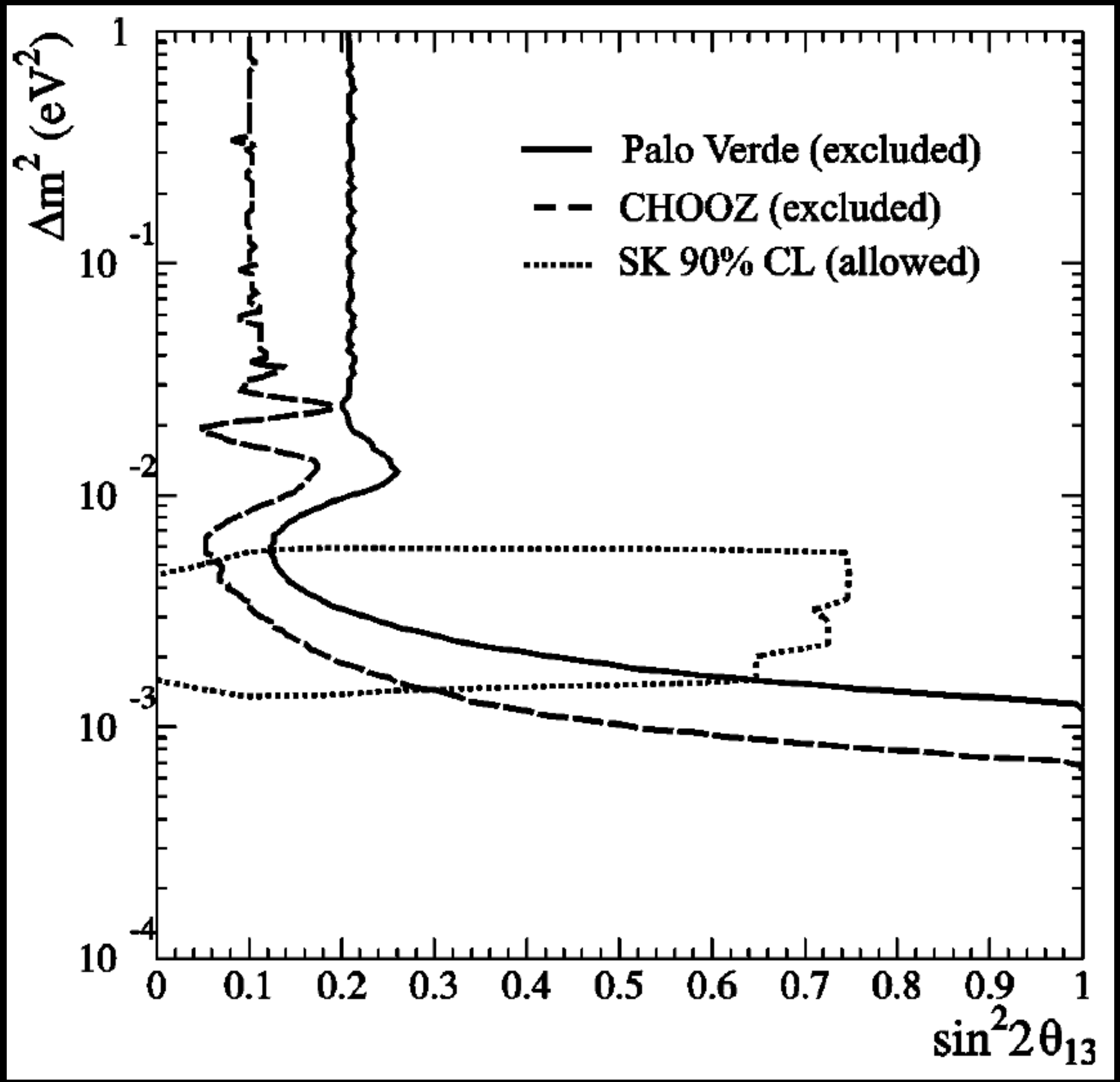
Near future: reactor-based measurements

- Actually, revival of a very old technique (the first to detect neutrinos).
- Principle: fission products are too neutron-rich for stability, so β-decays result: copious $\bar{\nu}_e$ produced in few-MeV range
- Appropriate *L* for atmospheric mass scale is ~1 km
- Detection is via inverse beta decay: $\bar{\nu}_e + p \rightarrow e^+ + n$
- Detect positron, delayed *n* capture
- Only $\bar{\nu}_e$ interact



Best existing reactor limits

- Reactor-based θ_{13} searches are the best current limits
- Chooz reactor in France dominates the results: data collected 1997; result 1999.
- $\sin^2 2\theta_{13} < 0.15$ at $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2
- Dominant systematic errors on disappearance fraction:
  - Reactor neutrino flux: 2%
  - Detector acceptance: 1.5%



Physics goals of coming reactor experiments

- Determine θ_{13} via $\bar{\nu}_e$ disappearance at the atmospheric Δm^2 scale, pushing current limits by order of magnitude.

- In principle, result slightly cleaner than for $\nu_\mu \rightarrow \nu_e$ appearance:

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta_{13}) \sin^2\theta_{23} \sin^2\left(\Delta m^2_{13} \frac{L}{4E}\right) + f(\delta) + f(\text{matter})$$

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2(2\theta_{13}) \sin^2\left(\Delta m^2_{13} \frac{L}{4E}\right) + \text{small terms}$$

- However, need high statistics to establish disappearance effects, and need excellent understanding of cross-section (yes) and flux (maybe).

Upcoming reactor-based neutrino experiments

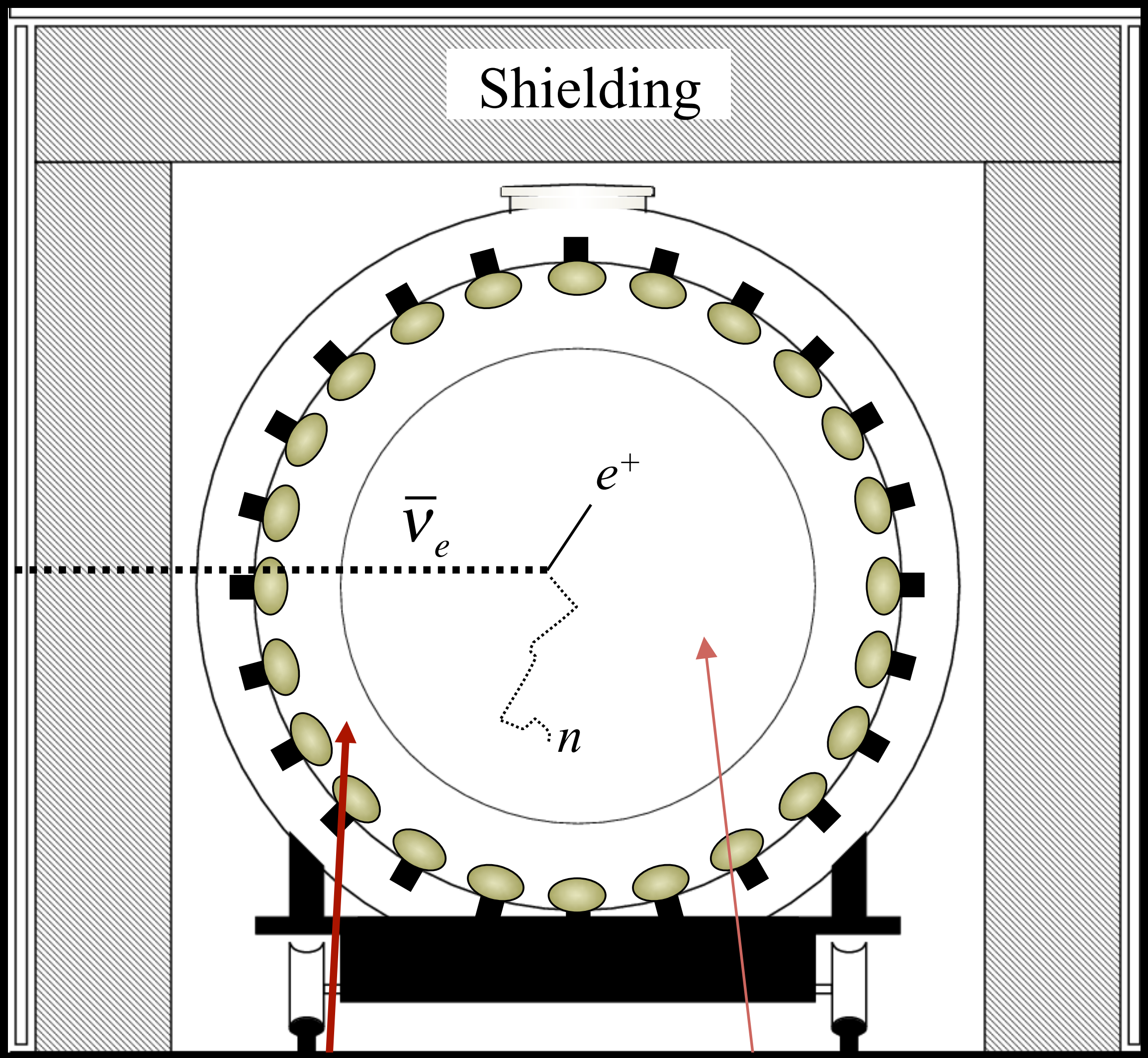
- Three sites have experiments in rapid development:
  - Double Chooz (France)
  - Daya Bay (China)
  - RENO (South Korea)
- Major improvements over previous experiments:
  - ***Near detectors to cancel flux uncertainties!***
  - Baseline selected specifically for (now known) Δm^2
  - Larger detectors, more powerful reactors

Double Chooz

- Same reactor site as Chooz experiment that forms best current θ_{13} limit

Double Chooz

- Central zone with Gd-loaded scintillator surrounded by buffer regions
- Neutrino detection by $\bar{\nu}_e + p \rightarrow e^+ + n$ followed by neutron capture:
- $n + {}^{m}\mathrm{Gd} \rightarrow {}^{m+1}\mathrm{Gd} + \gamma$ (8 MeV); $\tau = 30\mu s$
- Events selected based on coincidence of e^+ signal ($E_{vis}>0.5$ MeV) and γ released from n+Gd capture ($E_{vis}>6$ MeV).
- Near and far detectors each 8 tons



Data collection with far detector only began April 2011. Near detector completion expected next year.

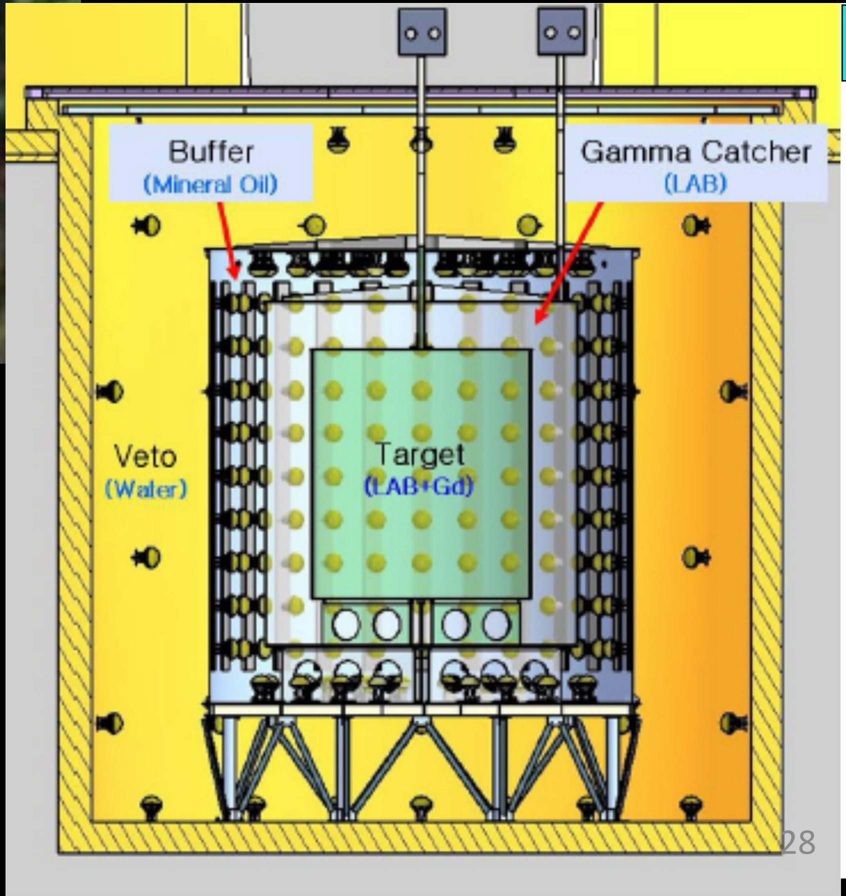
RENO

- Detector in South Korea at Yonggwang power station
- 6 reactors; 16.4 GW total thermal power

RENO geometry

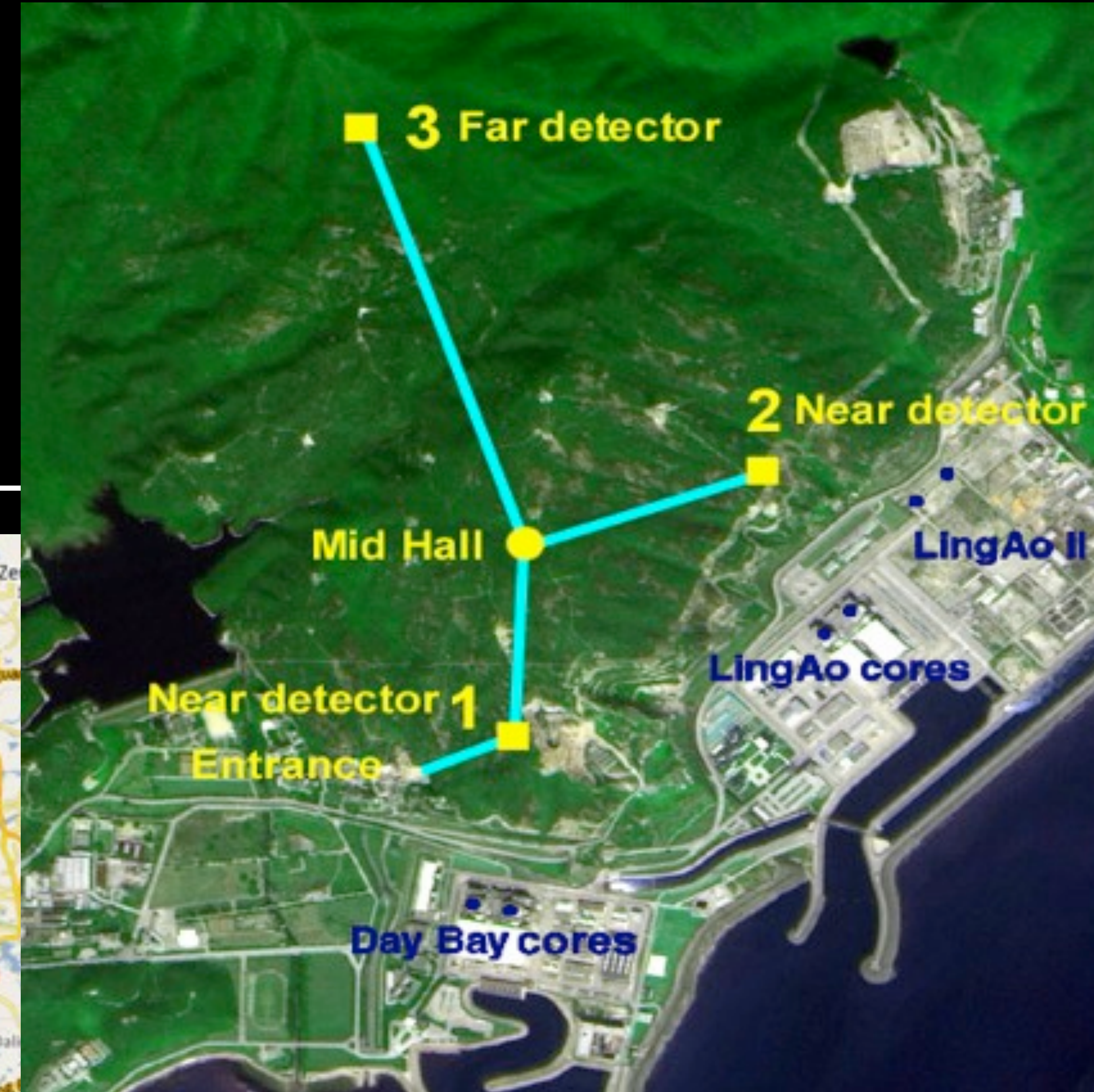
- 6 reactors in a 1.3-km line: near/far geometry is challenging
- Two detectors with flux-averaged baselines ~400 and ~1400 meters
- Data taking starts late spring 2011

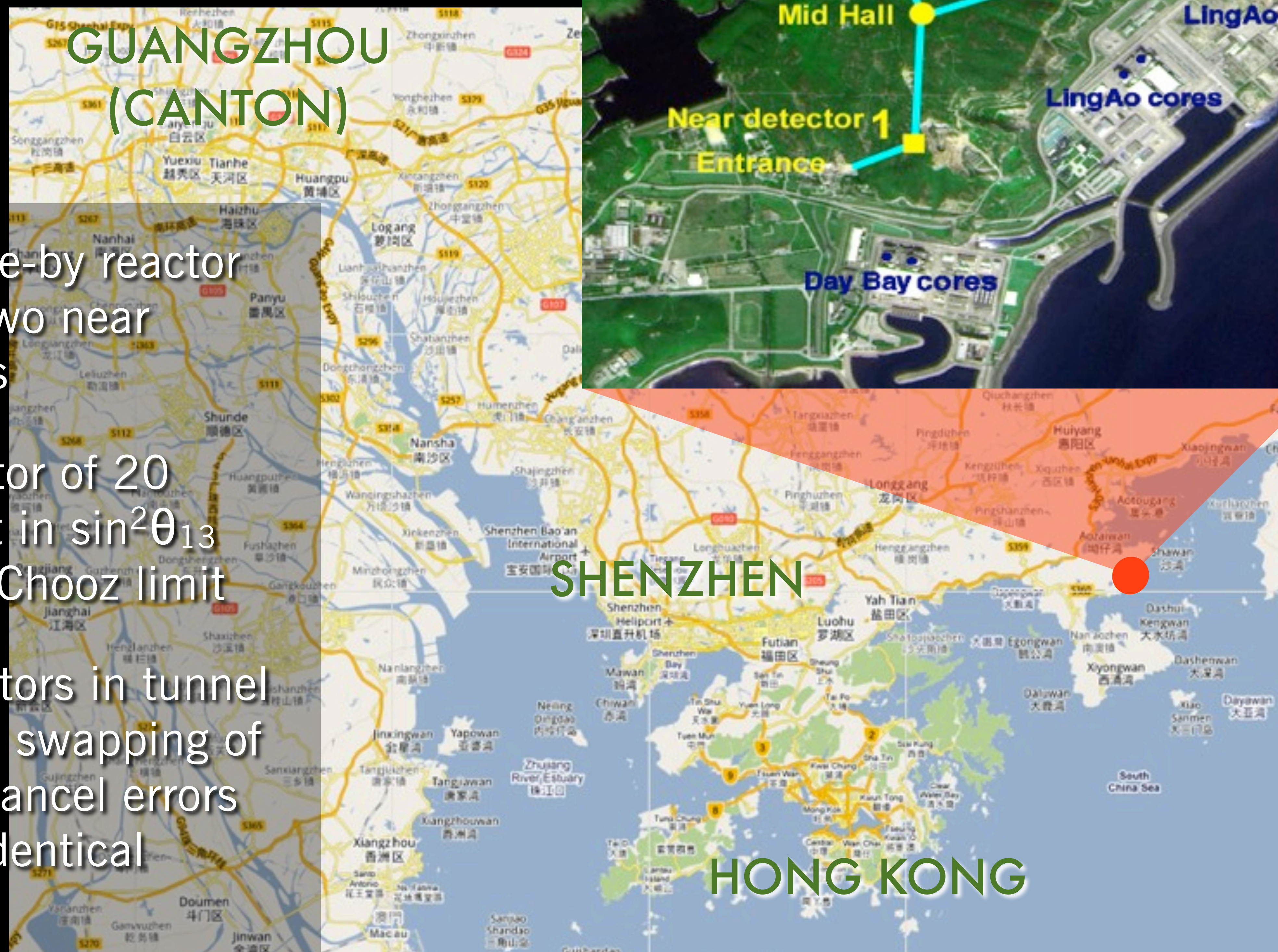
Gd-doped scintillation detection similar to Double Chooz



Finishing PMT installation (2011. 1)

Daya Bay



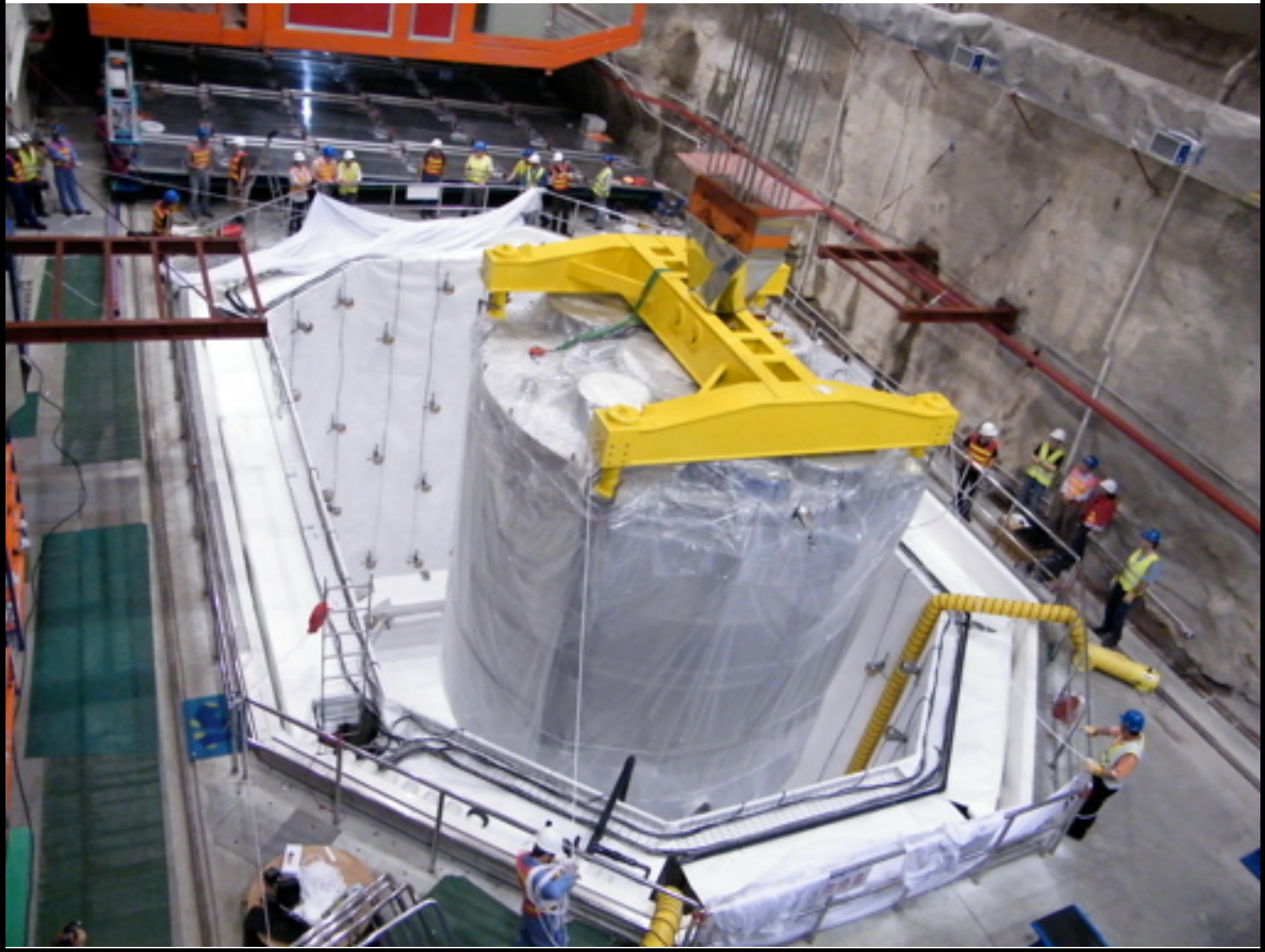


- Multiple close-by reactor sites; need two near detector sites
- Planning factor of 20 improvement in $\sin^2\theta_{13}$ over current Chooz limit
- Mobile detectors in tunnel system allow swapping of modules to cancel errors due to non-identical detectors

Daya Bay

- 2x20 tons at each near site
- 4x20 tons at far site
- First detectors will begin operating summer 2011
- Full suite of detectors by summer 2012

Installation of first AD at Daya Bay Site



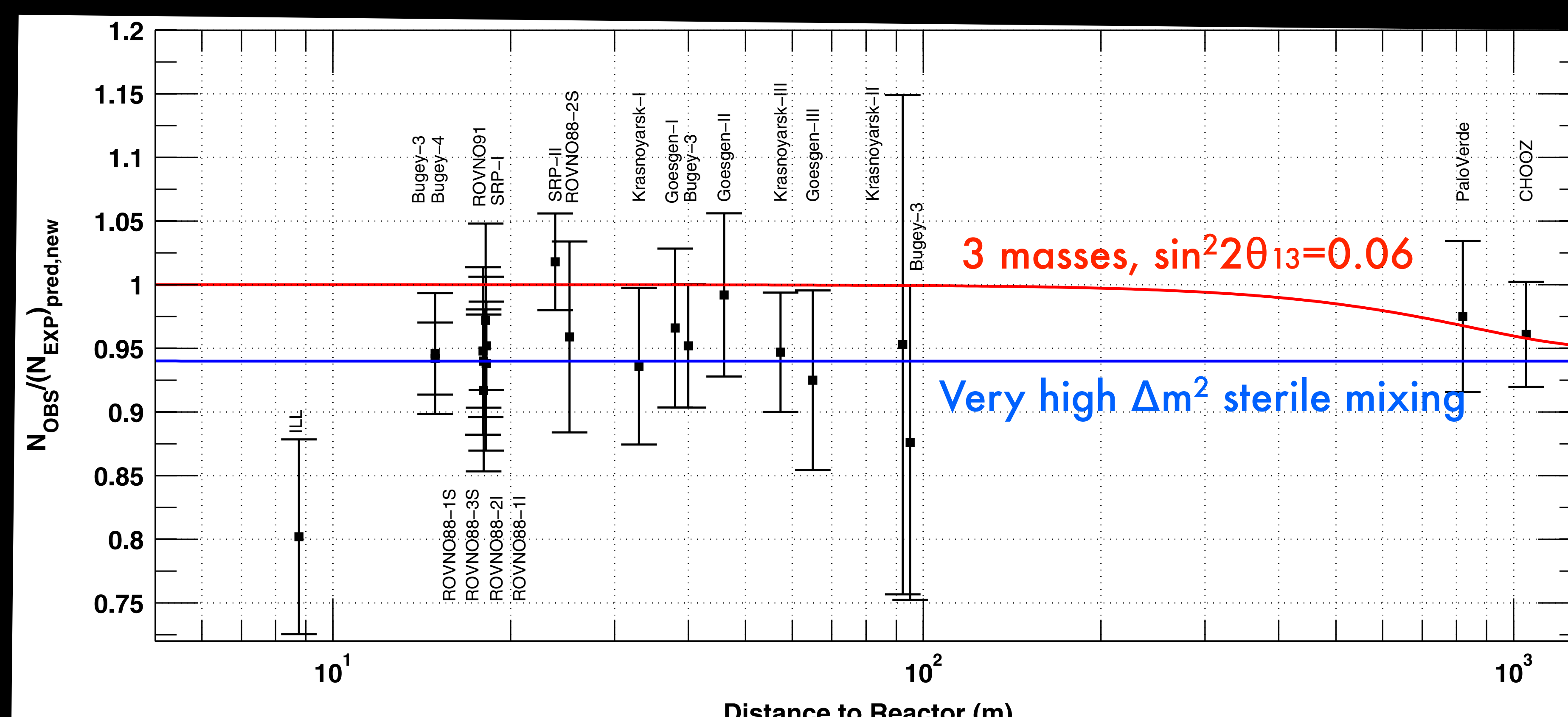
Modern reactor experiments: vital statistics

Experiment	Reactor thermal power (GW)	Detector distance from core (m)		Target mass (tons)		Reported $\sin^2 2\theta_{13}$ sensitivity (90% C.L.)	Commissioning/data schedule
		Near	Far	Near	Far		
Double Chooz	**8.4**	**390**	**1050**	**8**	**8**	**0.03**	Far detector operational April 2011; near detector start 2012
RENO	**17.3**	**290**	**1380**	**16**	**16**	**0.02**	Commissioning; 2011 start
Daya Bay	**17.4**	**360/ 500**	**1985/ 1615**	**80**	**80**	**0.01**	Under construction; 2012 start

Reactor neutrino anomaly?

- New evaluation of reactor antineutrino flux per unit thermal power: G. Mention *et al.*, *Phys. Rev.* **D83** 073006 (2011)
- Predicted flux increases by 3%; average of experimental results now 0.943 ± 0.023 of prediction.

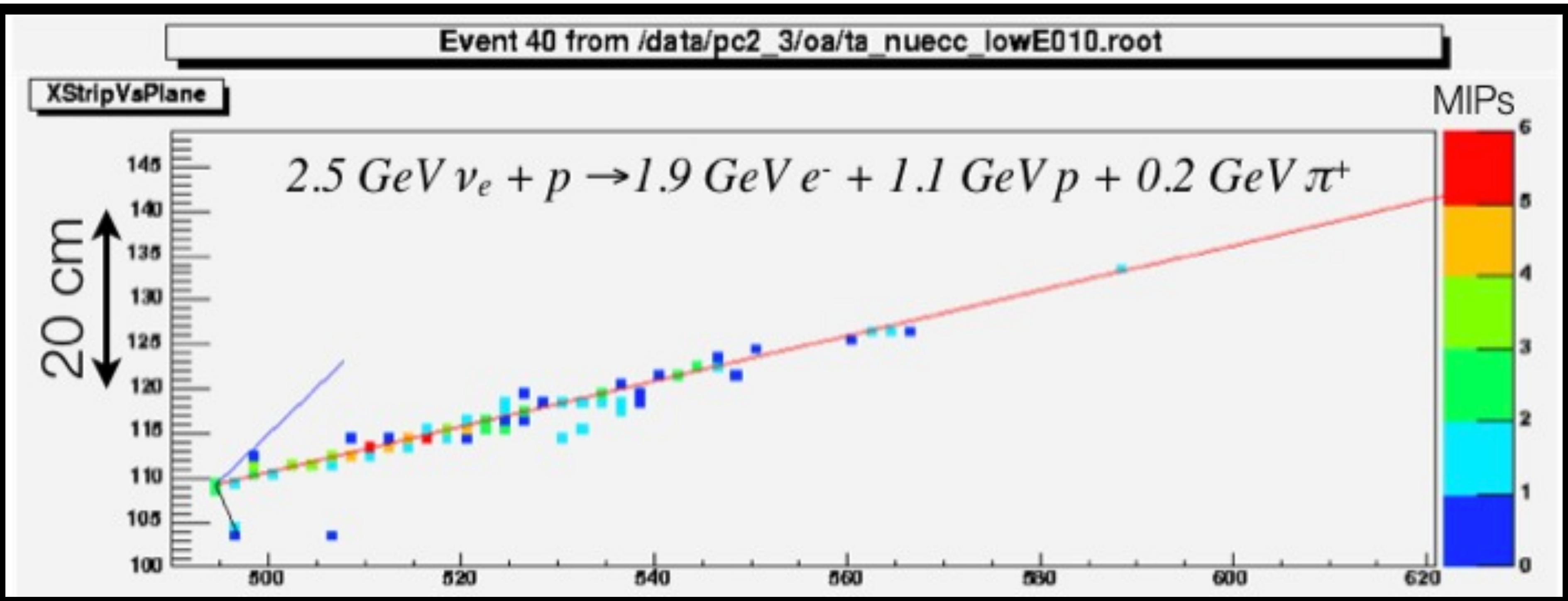
- Could indicate common systematic effect, or error in beta spectrum data
- Also consistent with sterile neutrino mixing at very high Δm^2



Next step with accelerators: NOνA

- Will use the Fermilab NuMI neutrino beam to search for $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations
- Off-axis narrow-band beam
- Antineutrinos *and* longer baseline: sensitive to neutrino mass hierarchy, δ_{CP}, and possible differences in neutrino and antineutrino disappearance rates.

NOνA DETECTOR

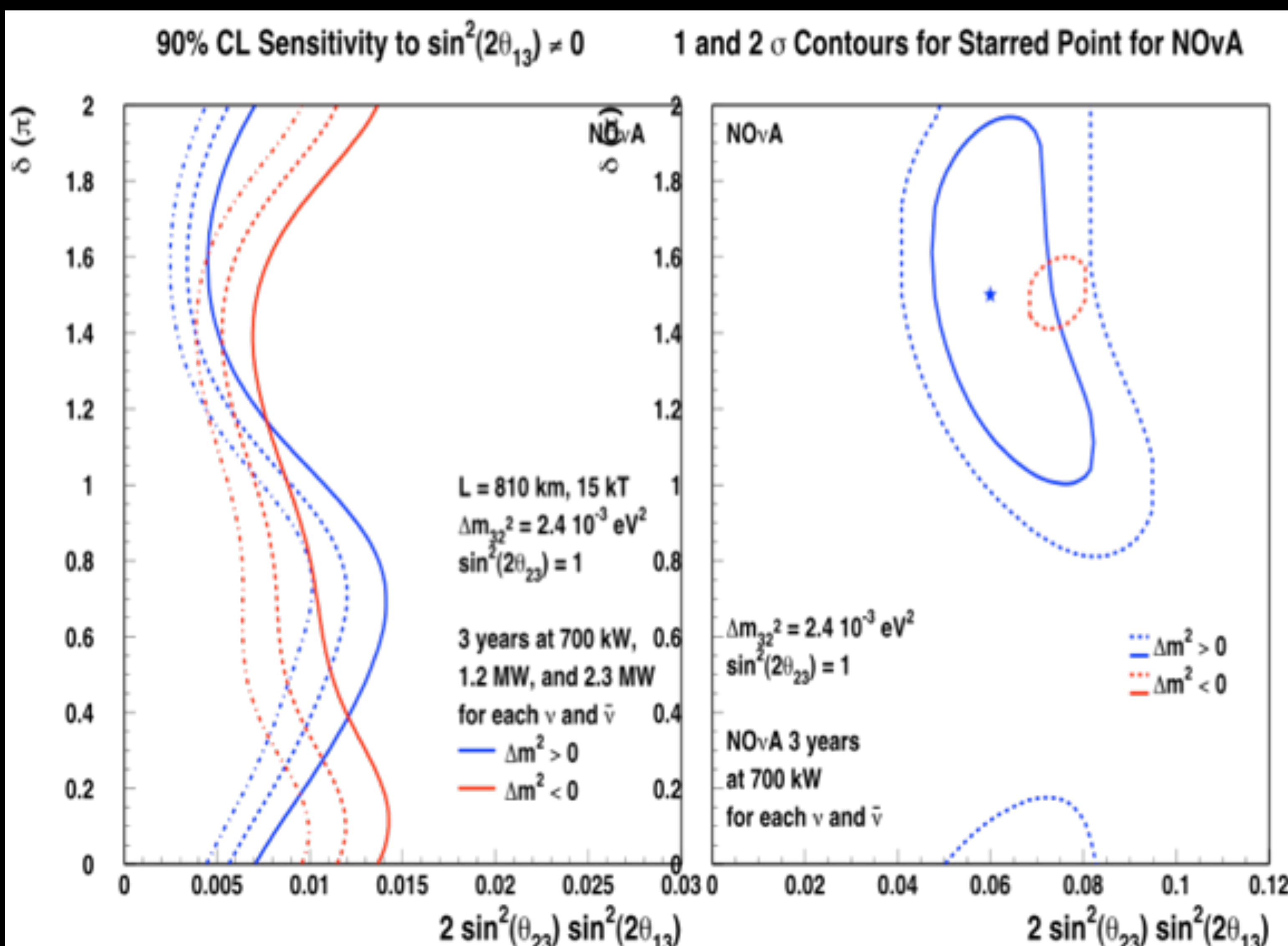


Segmented liquid scintillator detector designed to have large mass, low *Z*, and fine segmentation to separate ν_e CC events from NC events

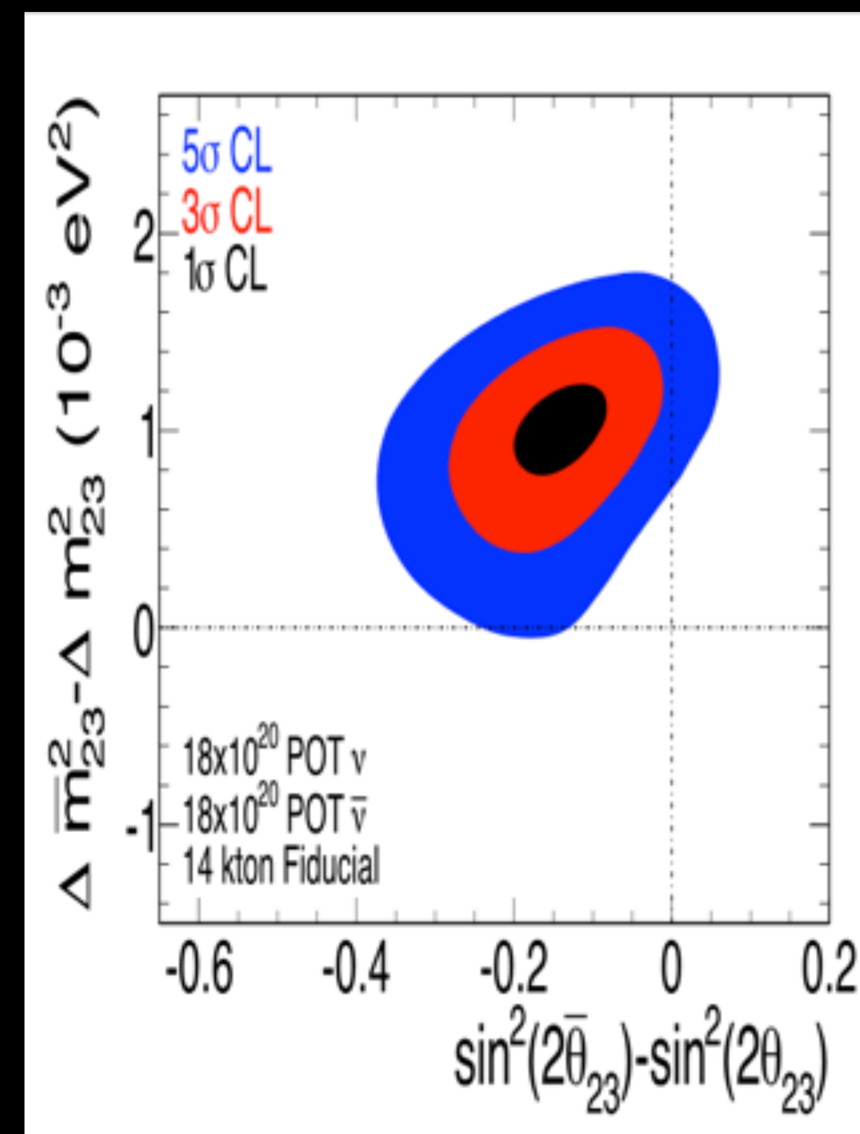
- Far detector laboratory near completion at Ash River MN 810 km from FNAL.
- First detector planes to be installed at end of this year.
- Operating a prototype on surface at FNAL in NuMI and Booster neutrino beams
- Upgrades to NuMI beam intensity during shutdown in 2012.
- First data starting in early 2013
- Far detector completed by end of 2013.

NOvA 3-year physics sensitivity

- ν_e appearance



- ν_μ vs. $\bar{\nu}_\mu$ disappearance

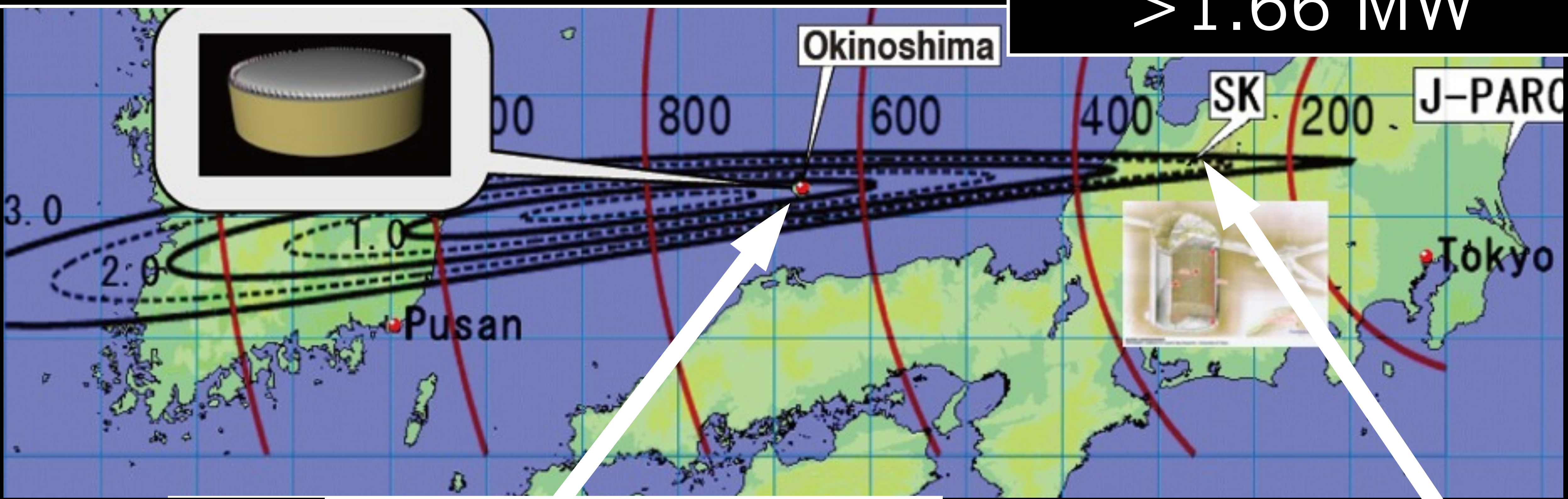


Ultimate(?) long-baseline experiments

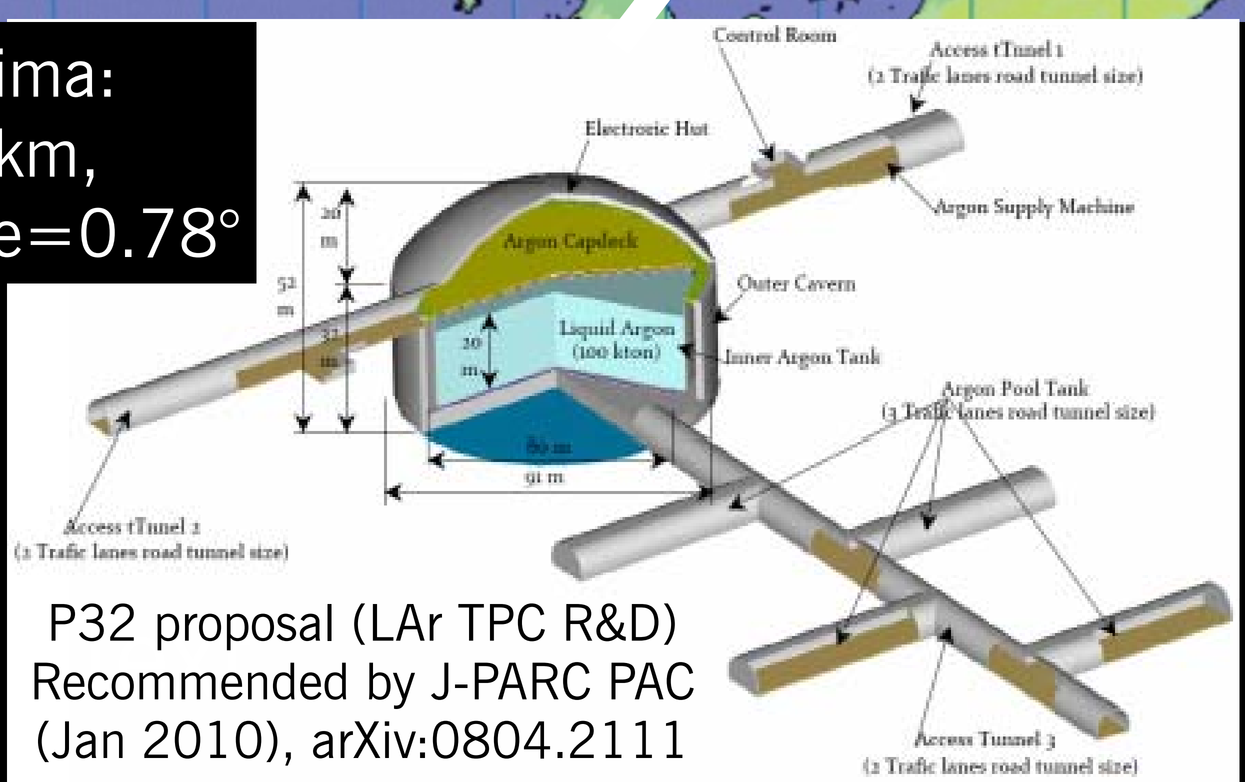
- Definitive resolution of mass hierarchy, CP violation over most of possible parameter space
- Multi-hundred kton scale detectors, megawatt-scale beams:
  - J-PARC to more distant sites in same beam
  - Fermilab LBNE (Homestake)
  - LAGUNA: European proposal

J-PARC upgrades and future detectors

Beam upgrade to >1.66 MW

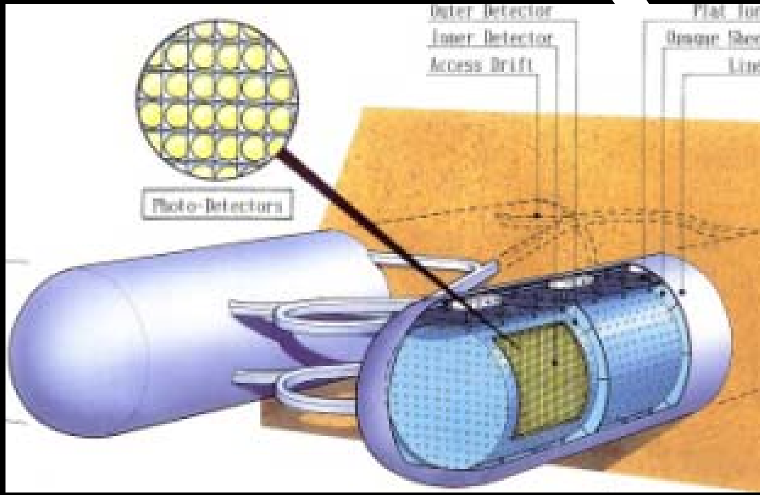


Okinoshima:
L=658km,
Off-axis angle=0.78°

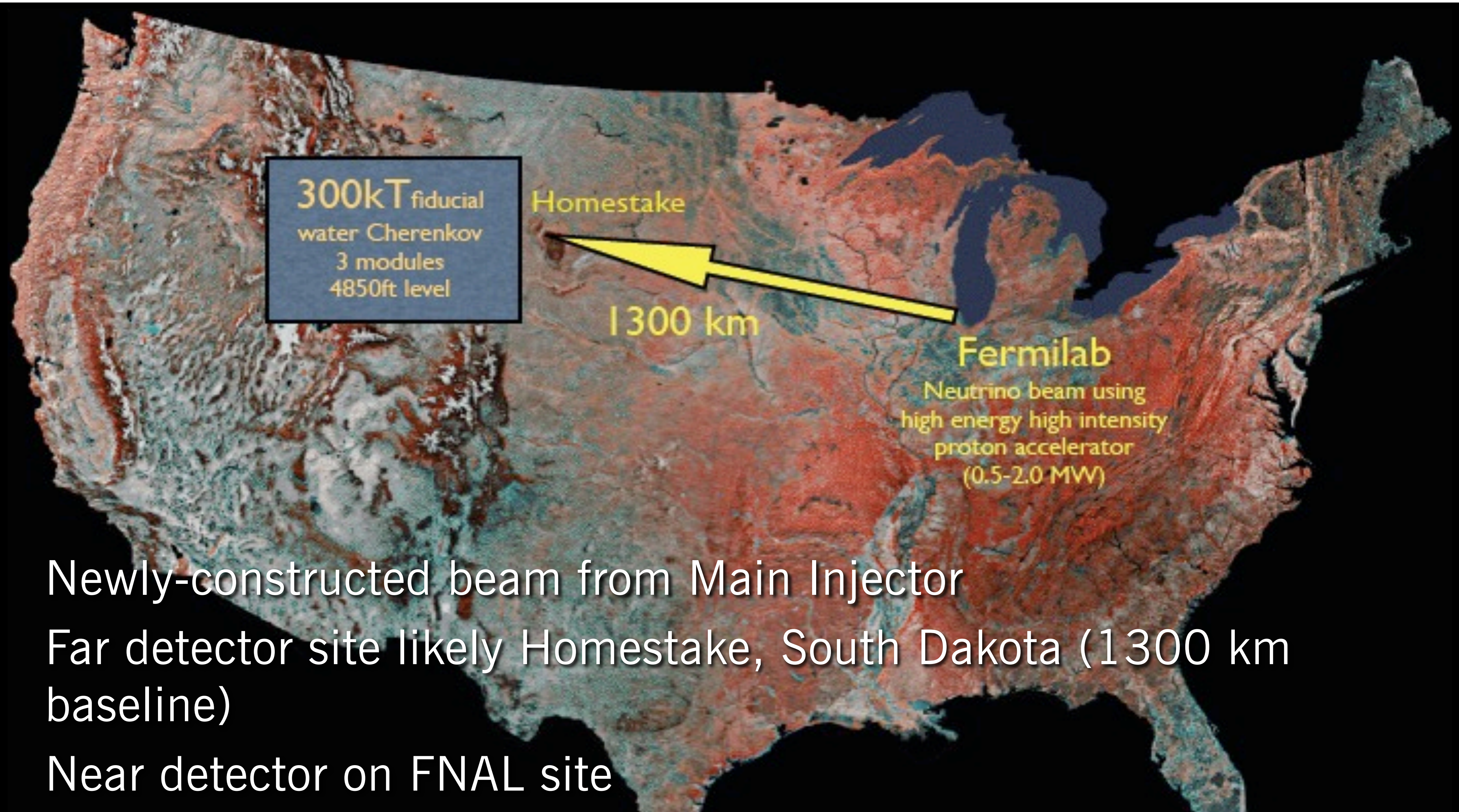


P32 proposal (LAr TPC R&D)
Recommended by J-PARC PAC
(Jan 2010), arXiv:0804.2111

Kamioka:
L=295km,
Off-axis angle=2.50°

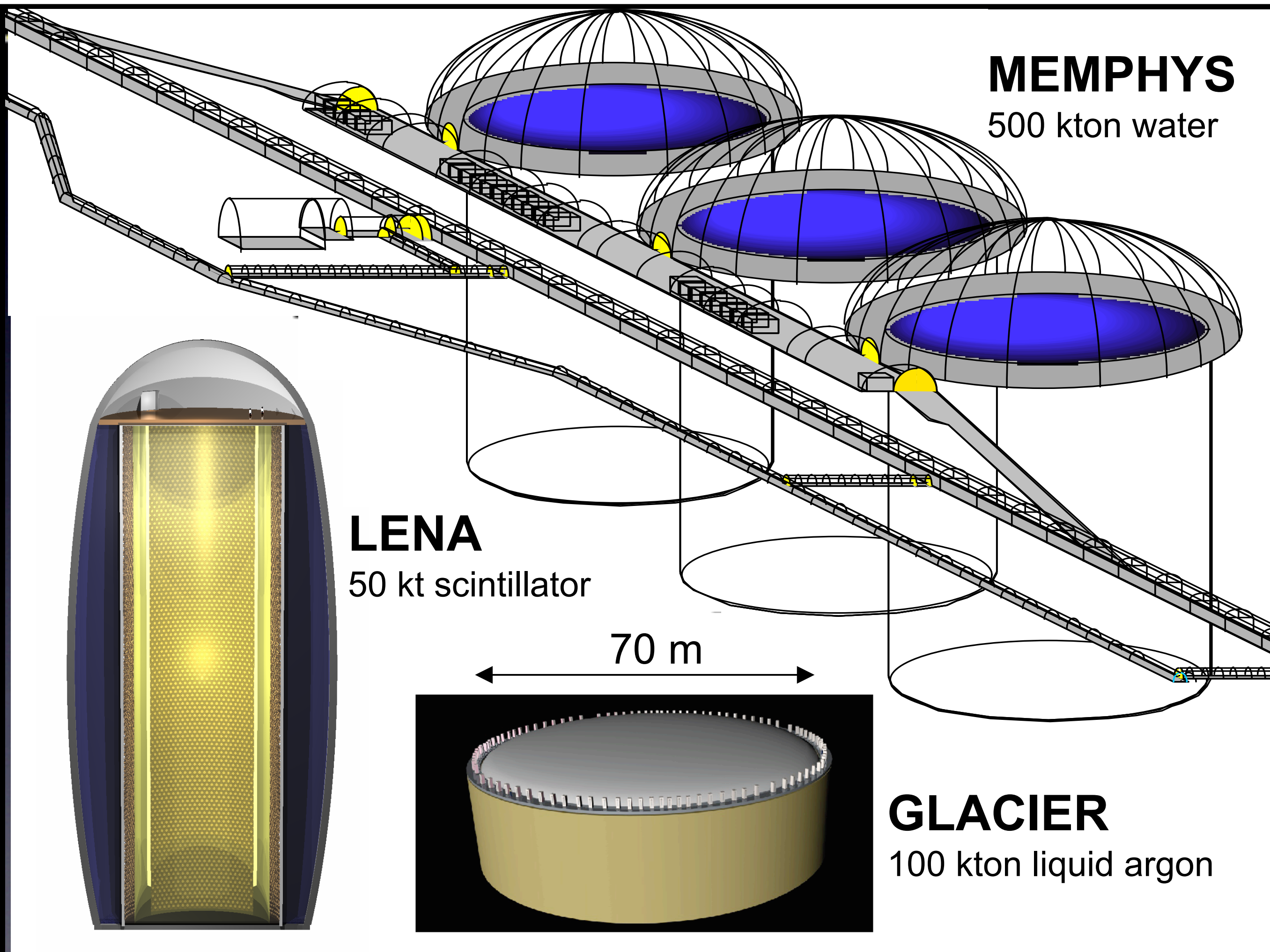


Long Baseline Neutrino Experiment (LBNE) at Fermilab

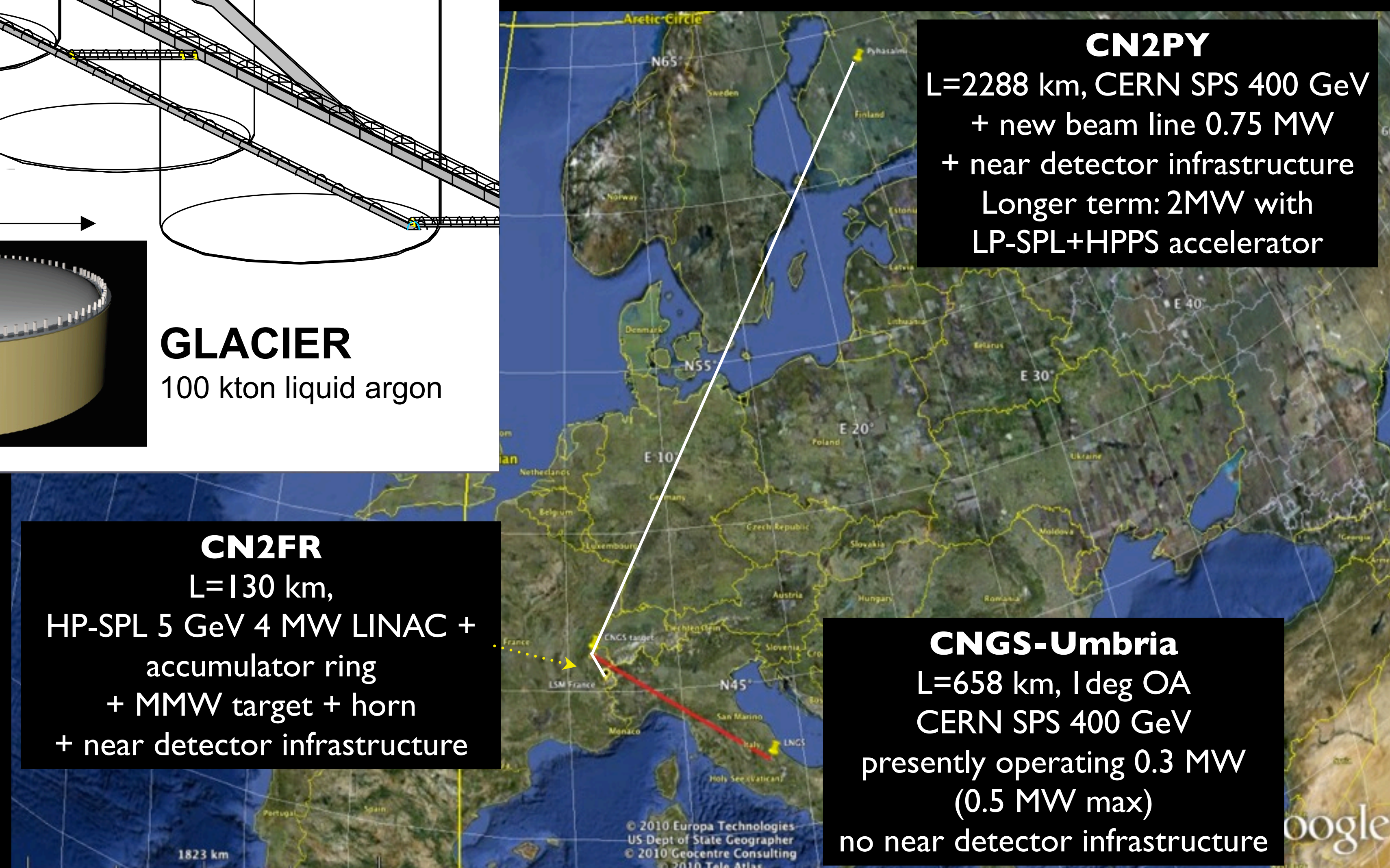


- Newly-constructed beam from Main Injector
- Far detector site likely Homestake, South Dakota (1300 km baseline)
- Near detector on FNAL site
- Detector technology: water Cherenkov and/or liquid argon TPC

LAGUNA: Long baselines in Europe



- Site selection narrowing process complete



- Early proposal stage for large detectors and beam from CERN

No time to discuss

- Proposed short-baseline experiments at FNAL, CERN to study parameter space regions associated with short-baseline anomalies: very exotic physics if *any* of these hold up to more precise studies
- Detector technology developments: liquid argon TPC experiments in particular are very active, hoping to scale up to multi-kiloton range
- Neutrino interaction cross-section measurements: essential for understanding oscillations
- Current and proposed large detectors are also proton decay detectors: positive results here could eclipse neutrino oscillations!

Summary

- T2K is leading the way to the next generation of high-precision oscillation experiments designed to look at rare phenomena beyond ν_μ disappearance
- Very rich program of experiments in the coming years will explore the θ_{13} and δ_{CP} space. The mass hierarchy and leptonic *CP* violation may be in reach!