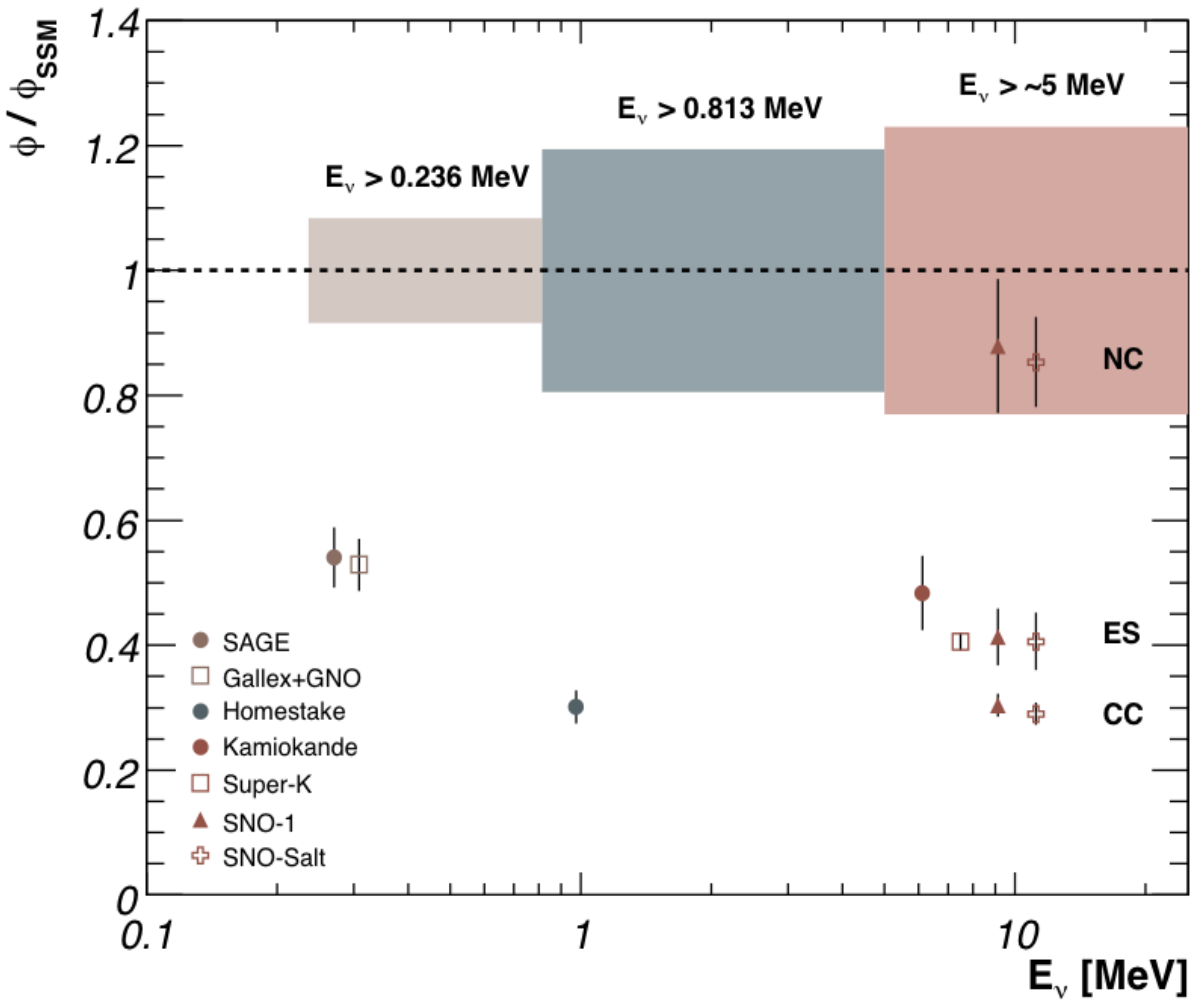
Neutrino Mixing Angle θ_{13}

Dan Dwyer (LBNL)
on behalf of the Daya Bay Collaboration

SLAC Summer Institute
July 23, 2012

Solar Neutrino Deficit

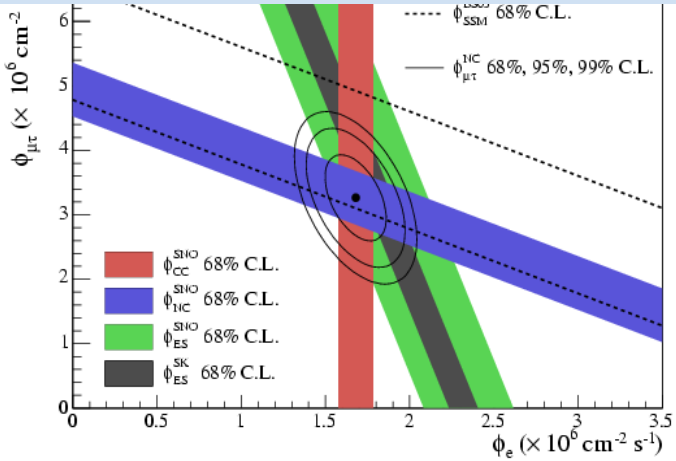


1968: Davis detects 1/3 expected solar neutrinos

2002: SNO shows evidence for flavor-change!

Phys. Rev. Lett. 89, 011301 (2002)

Phys. Rev. Lett. 92, 181301 (2004)



Neutrino Oscillation

Neutrinos change flavor (e,μ,τ) with time

Principle:

Mass eigenstates ≠ Interaction (flavor) eigenstates

$$|\nu_e\rangle = \sum_{m_i} U^*_{ei}{}' |\nu_i\rangle$$

Physical Parameters:

θ:

3 angles between mass/flavor eigenstates set **oscillation amplitude**

We want to know θ and Δm²

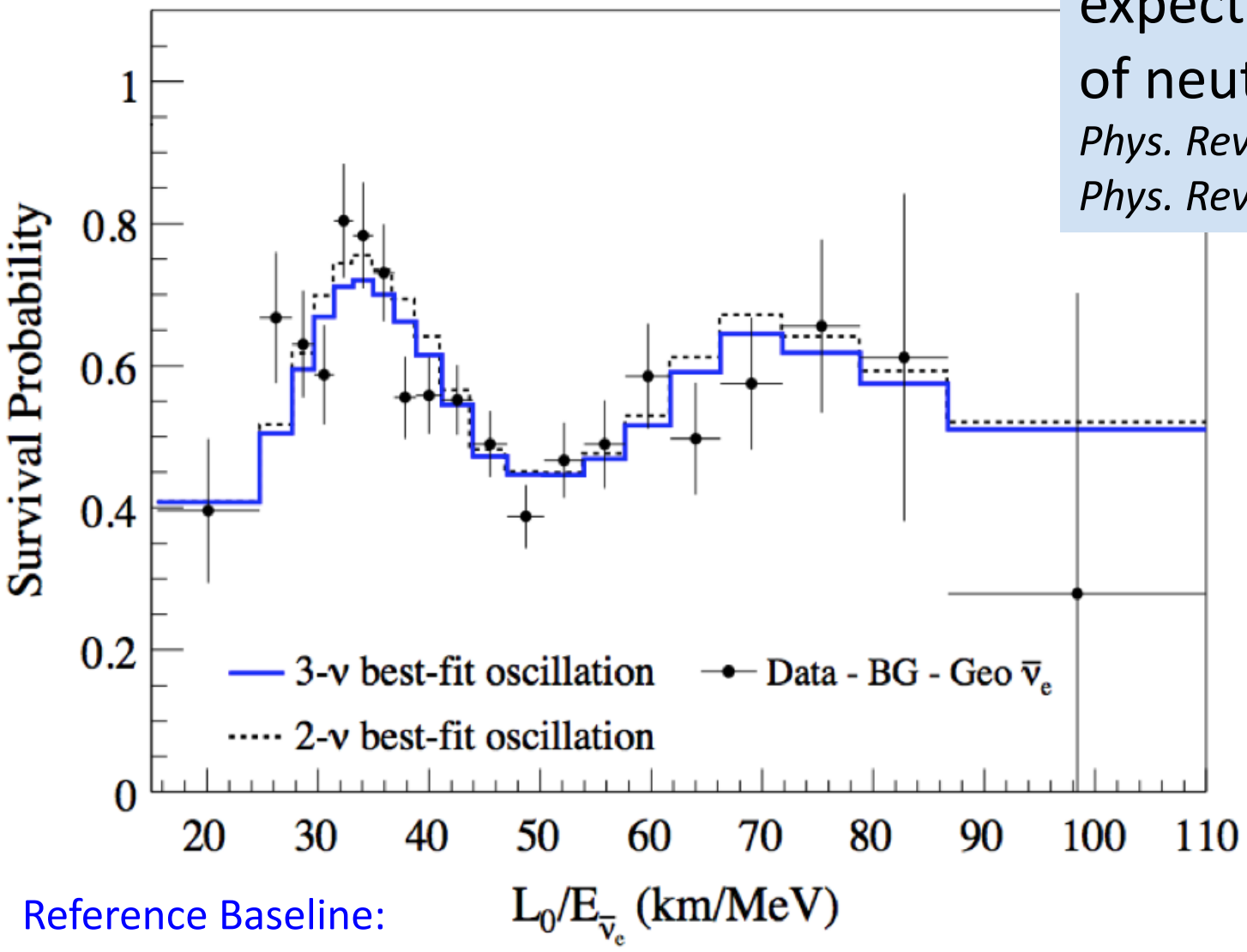
Δm²:

Differences in 3 neutrino masses determine **oscillation frequency** (distance)

Survival Probability: $P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2(2\theta_{12}) \sin^2 \frac{\Delta m^2_{12} L}{4E}$

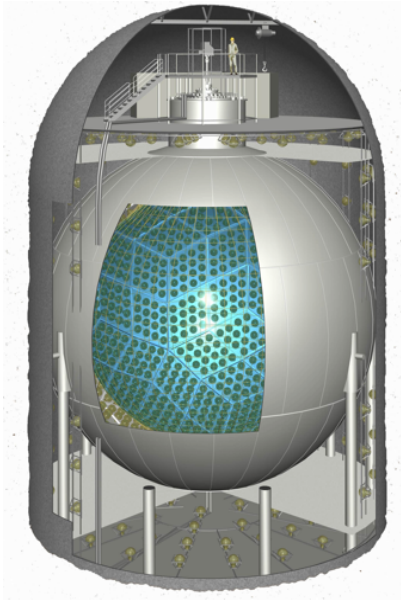
Neutrino Oscillation

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2(2\theta_{12}) \sin^2 \frac{\Delta m^2_{12} L}{4E}$$



2002: KamLAND shows expected signature of neutrino oscillation.

Phys. Rev. Lett. 89, 011301 (2002)
Phys. Rev. Lett. 92, 181301 (2004)



Reference Baseline:
L_0 = 180 km

A Decade of Progress

Clear experimental evidence of neutrino oscillation in recent years

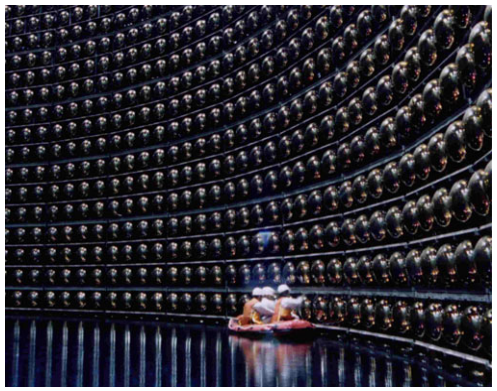
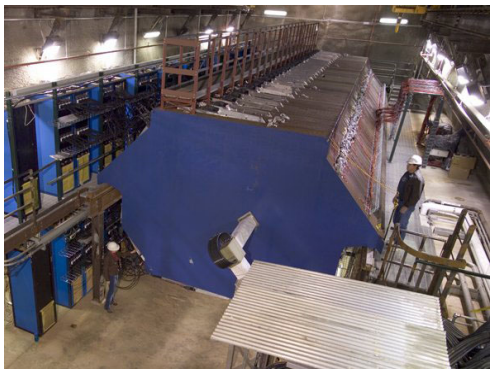
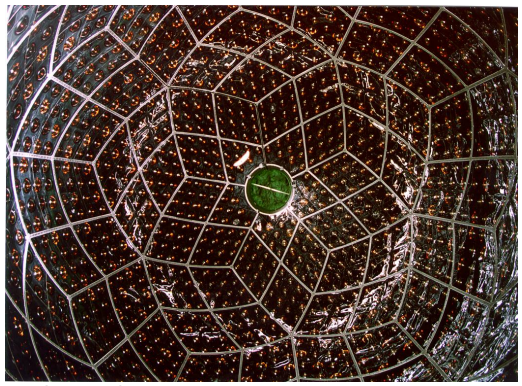
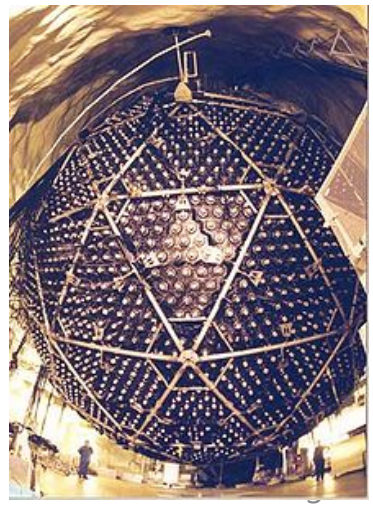
$$c_{ij} \equiv \cos\theta_{ij} \text{ and } s_{ij} \equiv \sin\theta_{ij}$$

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

$\theta_{23} \approx 45^o$
Atmospheric ν
Accelerator ν

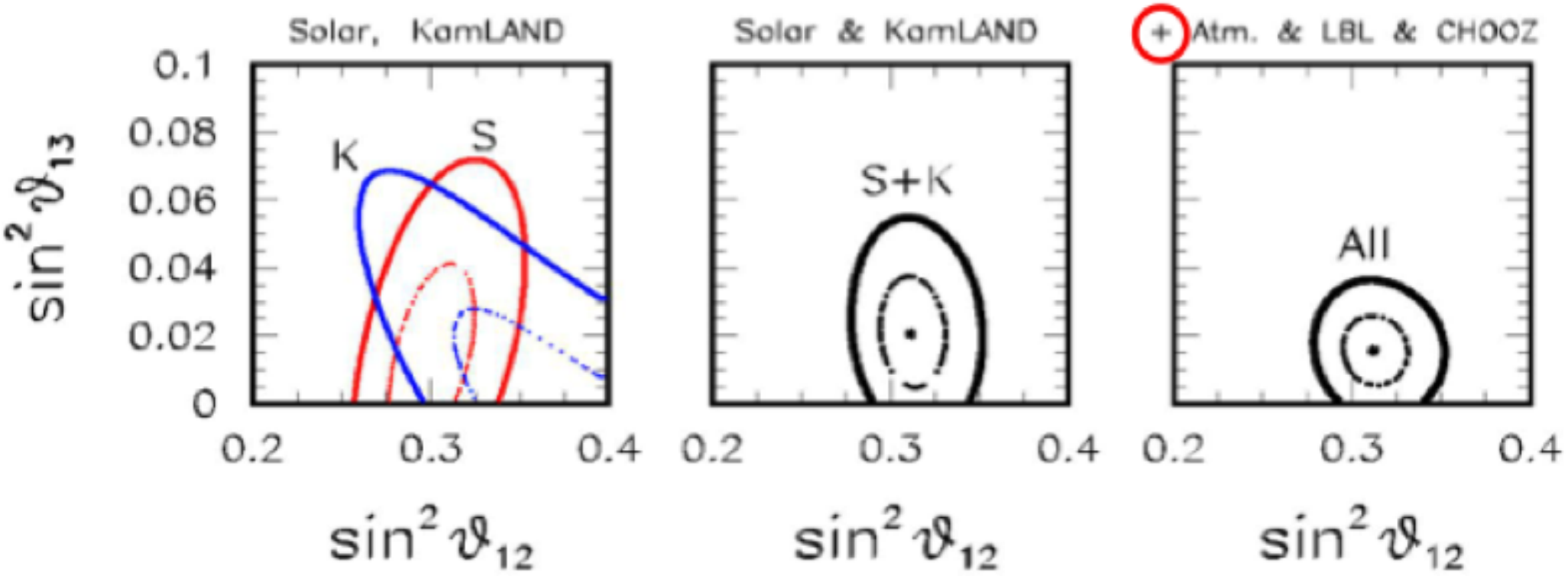
$\theta_{13} < 11^o$
Short-Baseline Reactor ν
Accelerator ν

$\theta_{12} \approx 35^o$
Solar ν
Long-Baseline Reactor ν

Hint of θ_{13}

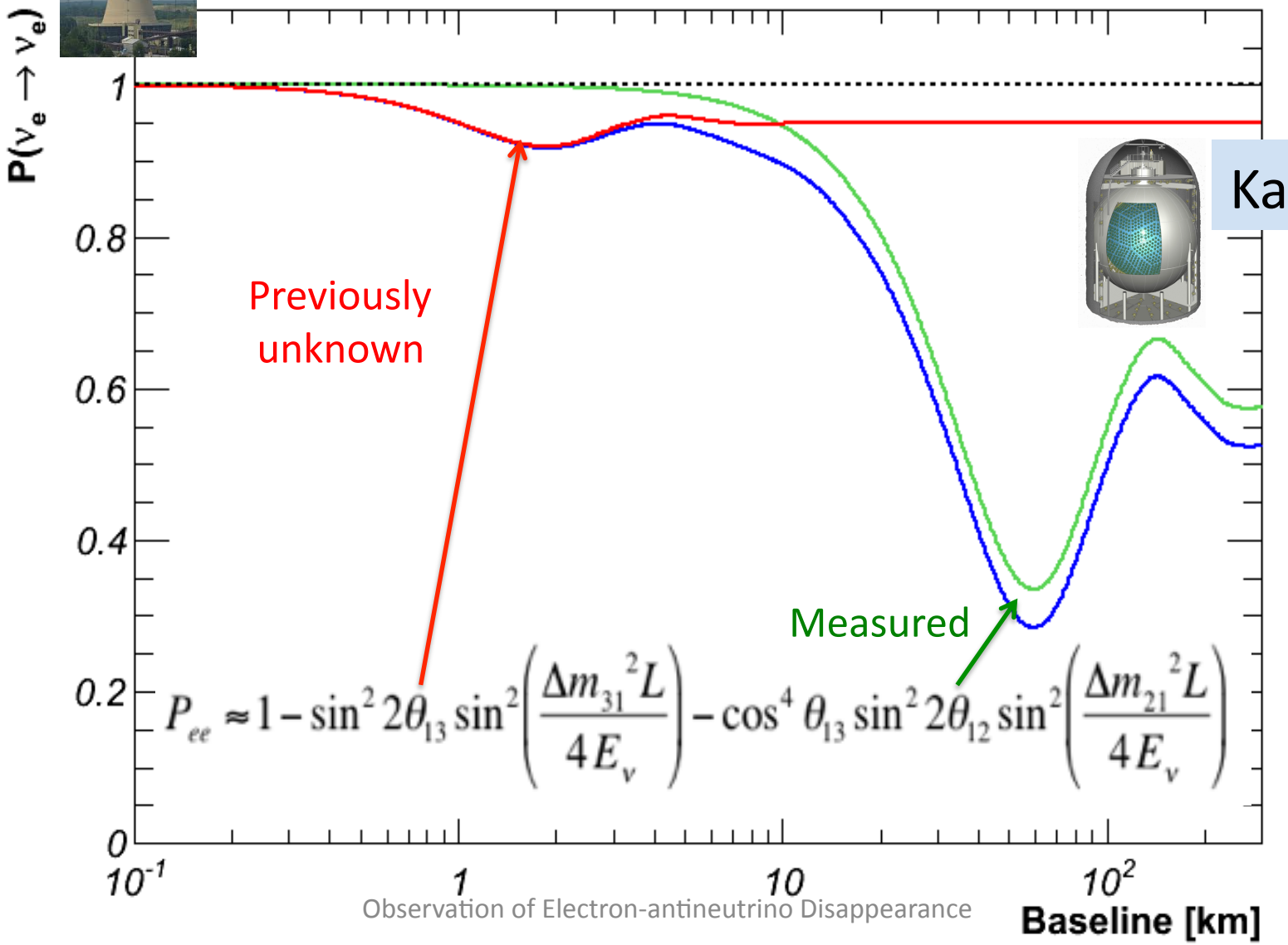
Slight tension between oscillation experiments hint at non-zero θ_{13}



From G. Fogli

Reactor Neutrino Oscillation

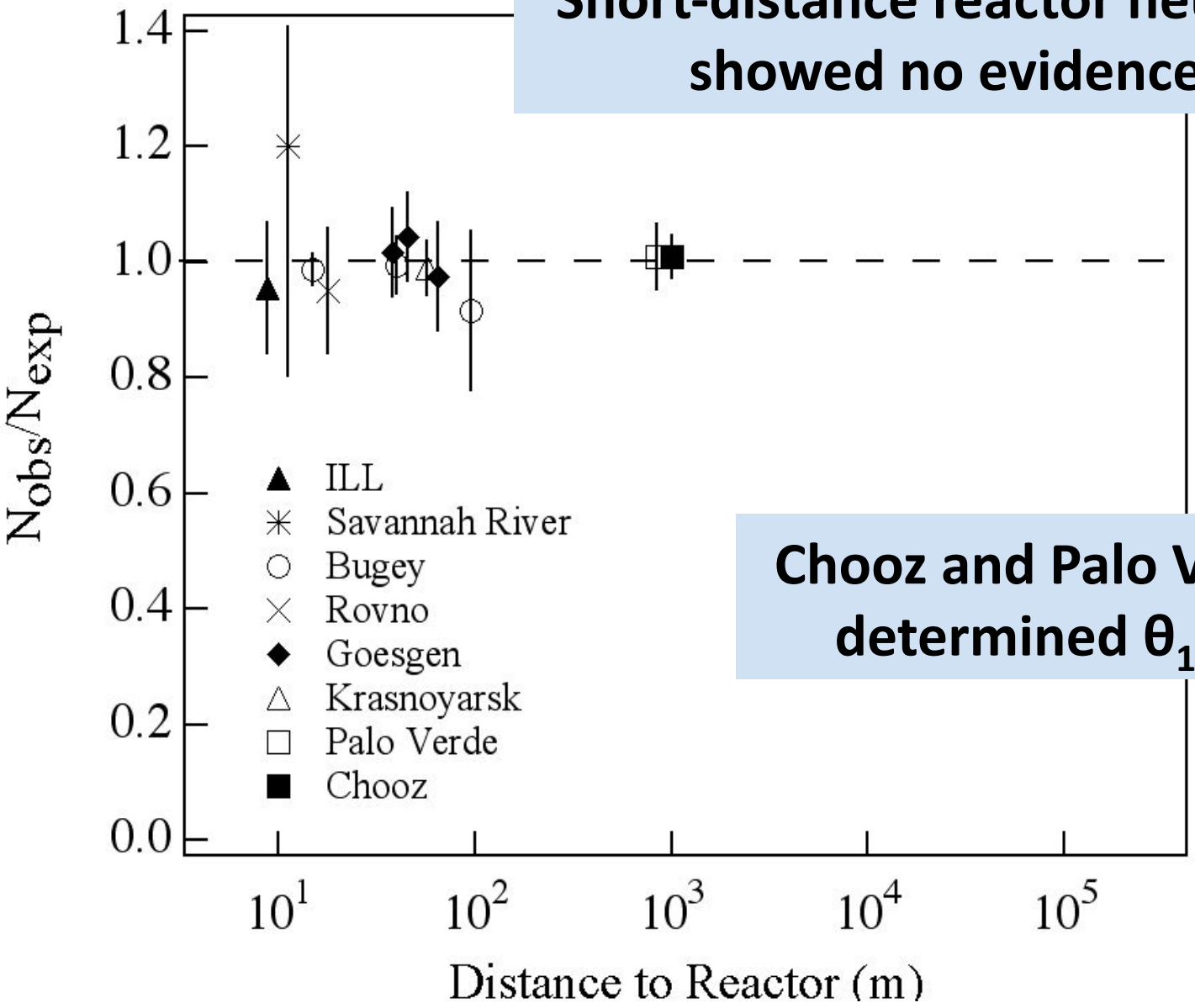
θ_{13} revealed by a deficit of reactor antineutrinos at ~2 km.



KamLAND

Short-Distance Reactor ν

Short-distance reactor neutrino experiments showed no evidence of oscillation



Chooz and Palo Verde experiments determined $\theta_{13} < 11^o$ (90% CL)

Relative Measurement

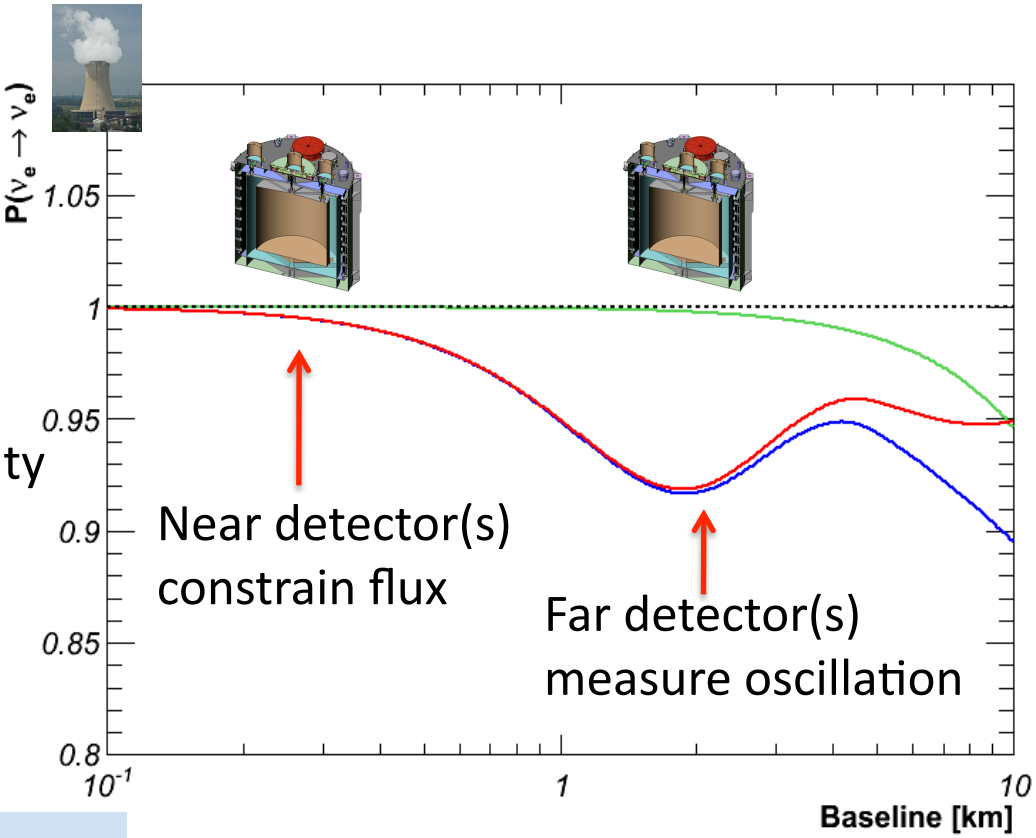
Absolute Reactor Flux:

Largest uncertainty in previous measurements

Relative Measurement:

Multiple detectors removes absolute uncertainty

First proposed by L. A. Mikaelyan and V.V. Sinev, Phys. Atomic Nucl. 63 1002 (2000)



Far/Near ν_e Ratio

Distances from reactor

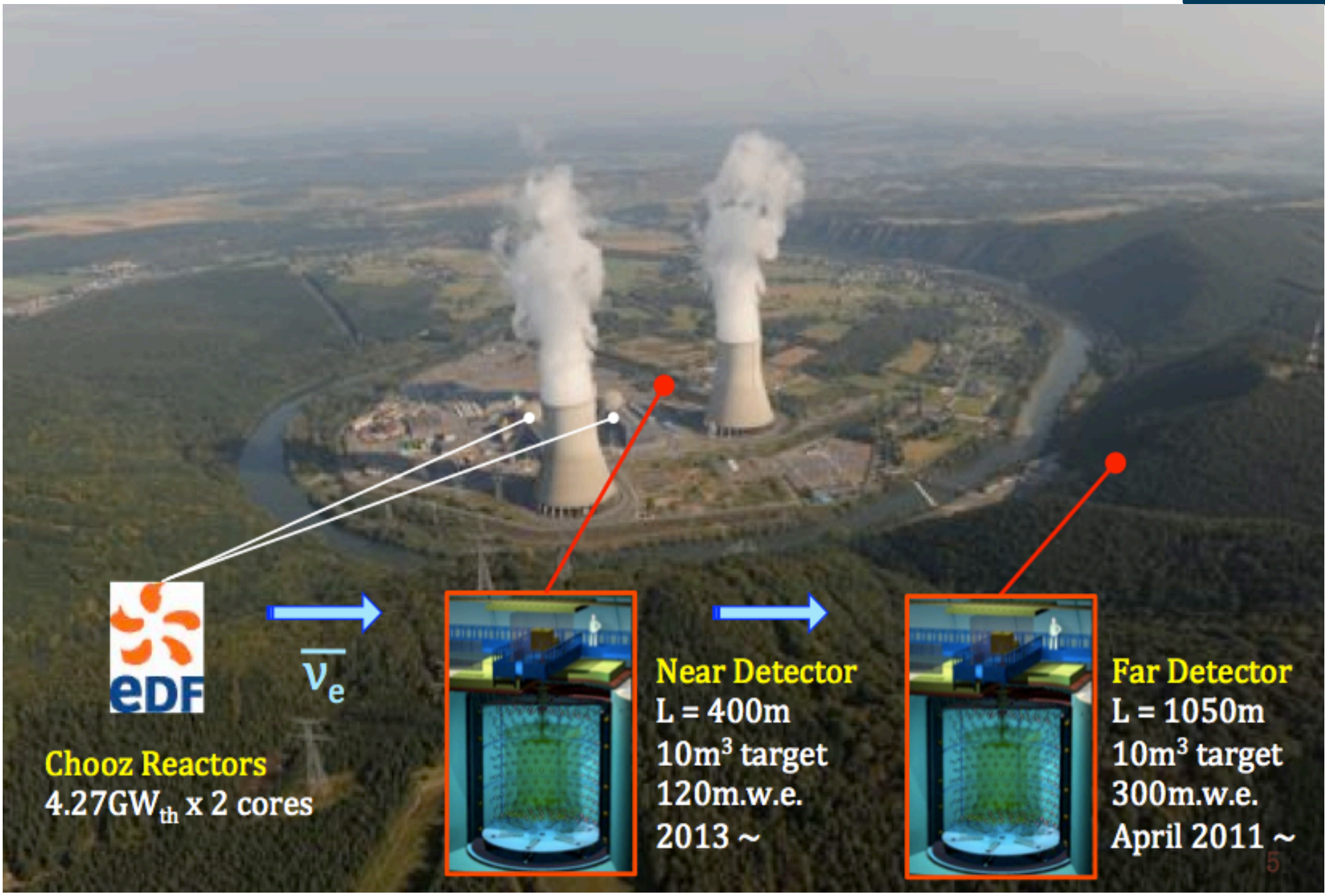
Oscillation deficit

$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left[\frac{P_{sur}(E, L_f)}{P_{sur}(E, L_n)}\right]$$

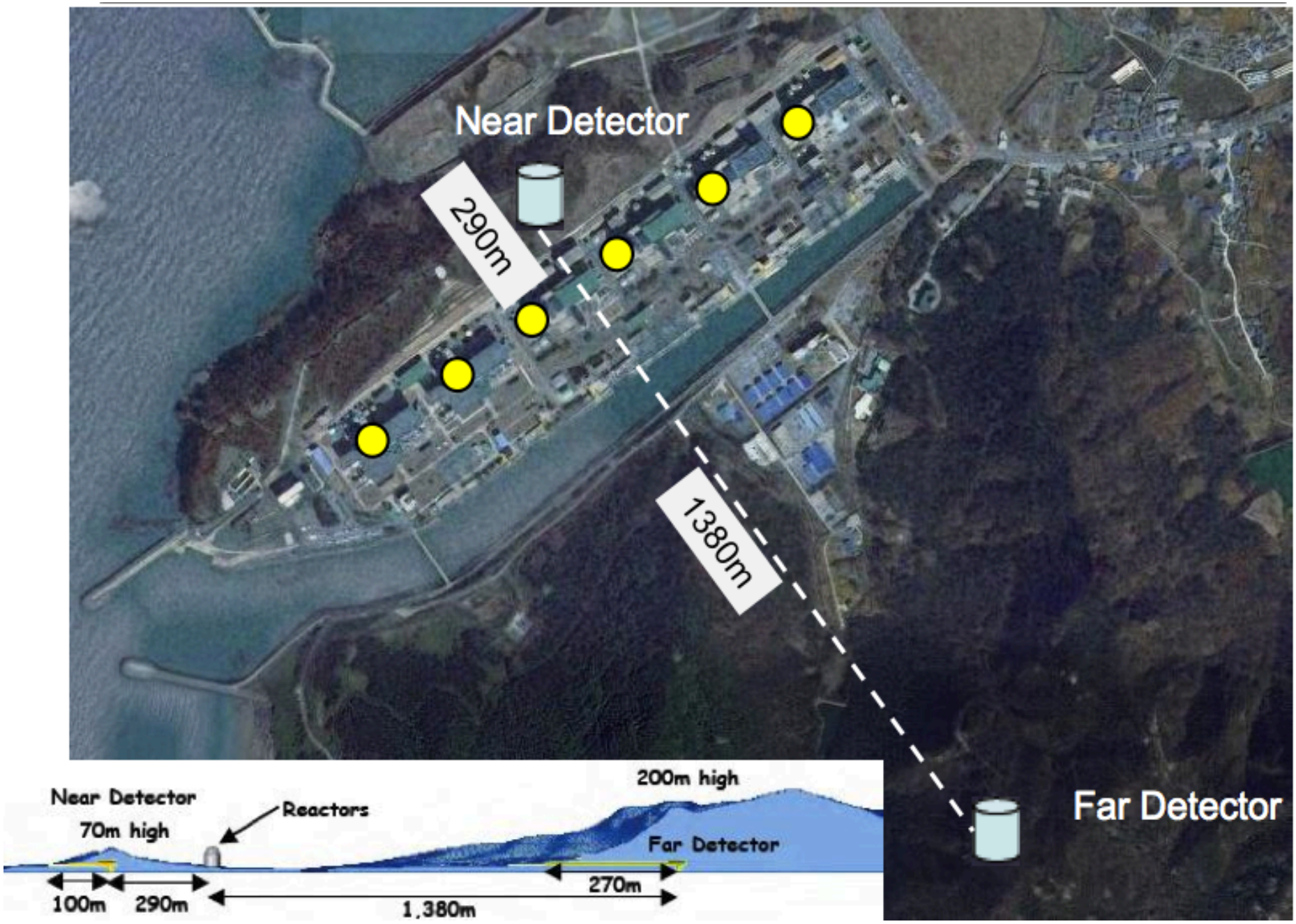
Detector Target Mass

Detector efficiency

Double Chooz



RENO


Near Detector
290m
1380m
Far Detector
Near Detector
70m high
Reactors
200m high
Far Detector
100m
290m
1,380m
270m

The Daya Bay Experiment

Adjacent mountains with horizontal access provide 860 (250) m.w.e cosmic shielding.

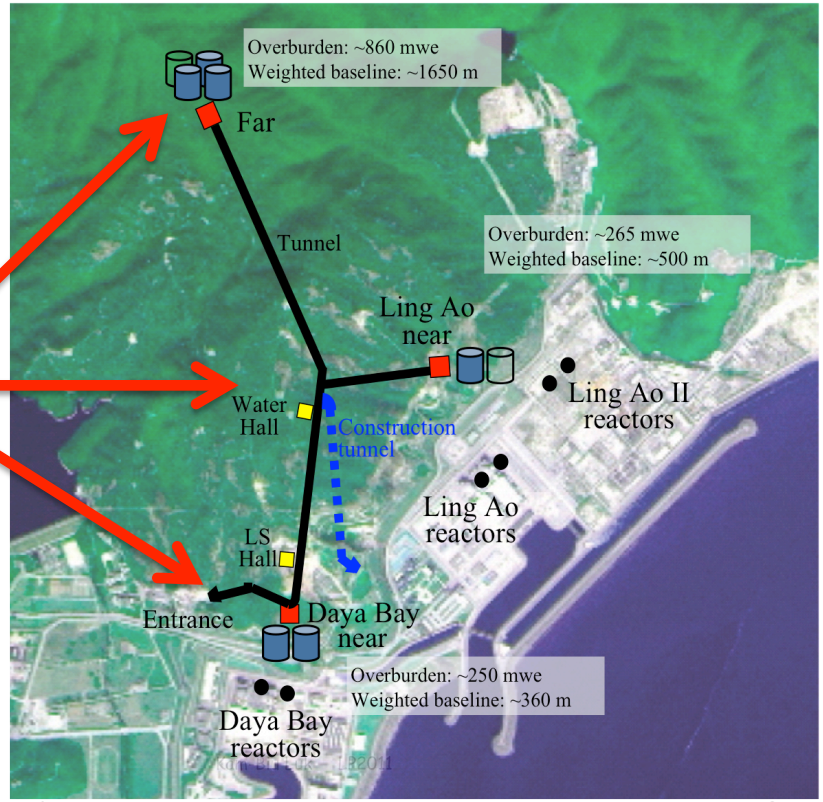
Daya Bay

Ling Ao I + II

6 commercial reactor cores with 17.4 GW_{th} total power.

6 Antineutrino Detectors (ADs) give 120 tons total target mass.

Via GPS and modern theodolites, relative detector-core positions known to 3 cm.



Experiment Comparison

Key factors which determine signal and background rates

	Reactor (GW_{th})	Target (tons)	Depth (m.w.e)
Double Chooz	8.6	16 (2×8)	300, 120 (far, near)
RENO	16.5	32 (2×16)	450, 120
Daya Bay	17.4	120 (6×20)	860, 250

Signal Rate
increases with power and target mass

Background Rate
decreases with depth

Detection Method

Inverse β-decay (IBD):

$$\bar{\nu}_e + p \rightarrow e^+ + n$$
$$\downarrow$$
$$n + {}^{x}Gd \rightarrow {}^{x+1}Gd + \gamma$$

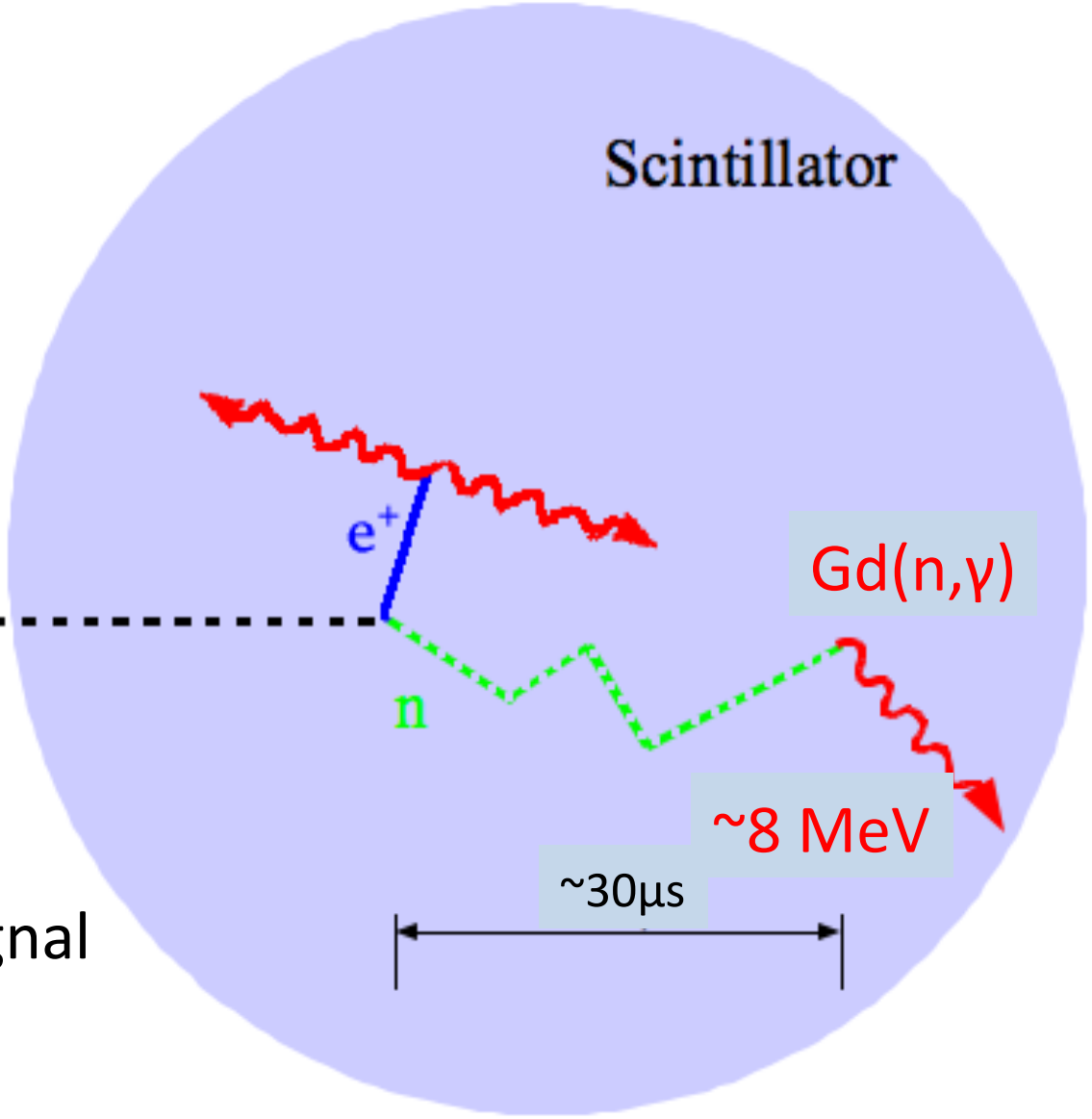
Prompt positron:

Carries antineutrino energy

$E_{e+} \approx E_\nu - 0.8$ MeV

Delayed neutron capture:

Efficiently tags antineutrino signal



Prompt + Delayed coincidence provides distinctive signature

Antineutrino Detectors

6 'functionally identical' detectors:
Reduce systematic uncertainties

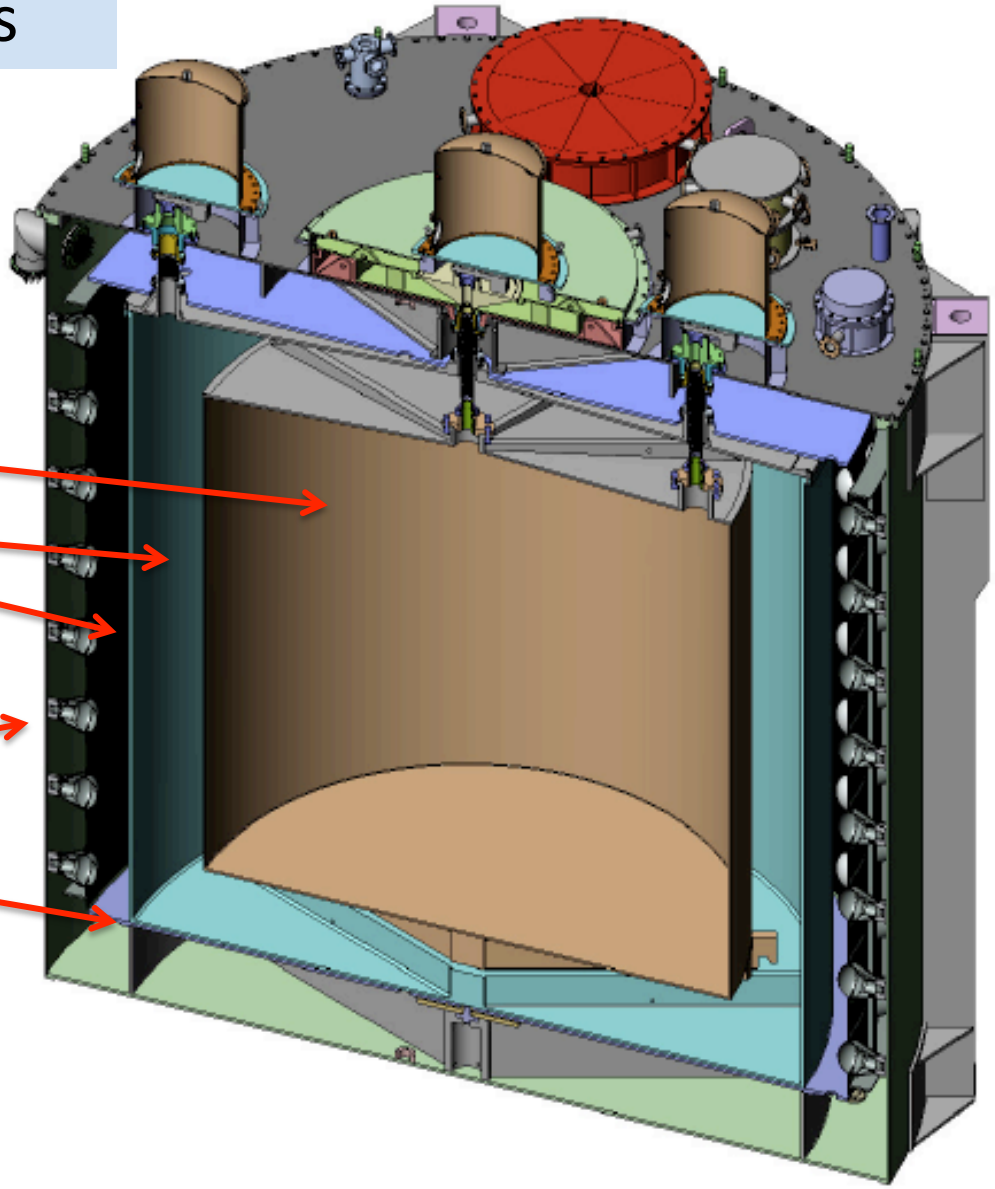
$$\frac{N_{\mathrm{f}}}{N_{\mathrm{n}}} = \left(\frac{N_{\mathrm{p,f}}}{N_{\mathrm{p,n}}}\right)\left(\frac{L_{\mathrm{n}}}{L_{\mathrm{f}}}\right)^2\left(\frac{\epsilon_{\mathrm{f}}}{\epsilon_{\mathrm{n}}}\right)\left[\frac{P_{\mathrm{sur}}(E, L_{\mathrm{f}})}{P_{\mathrm{sur}}(E, L_{\mathrm{n}})}\right]$$

3 nested cylinders:

Inner: 20 tons Gd-doped LS (d=3.1m)
Mid: 20 tons LS (d=4m)
Outer: 40 tons mineral oil buffer (d=5m)

Each detector:

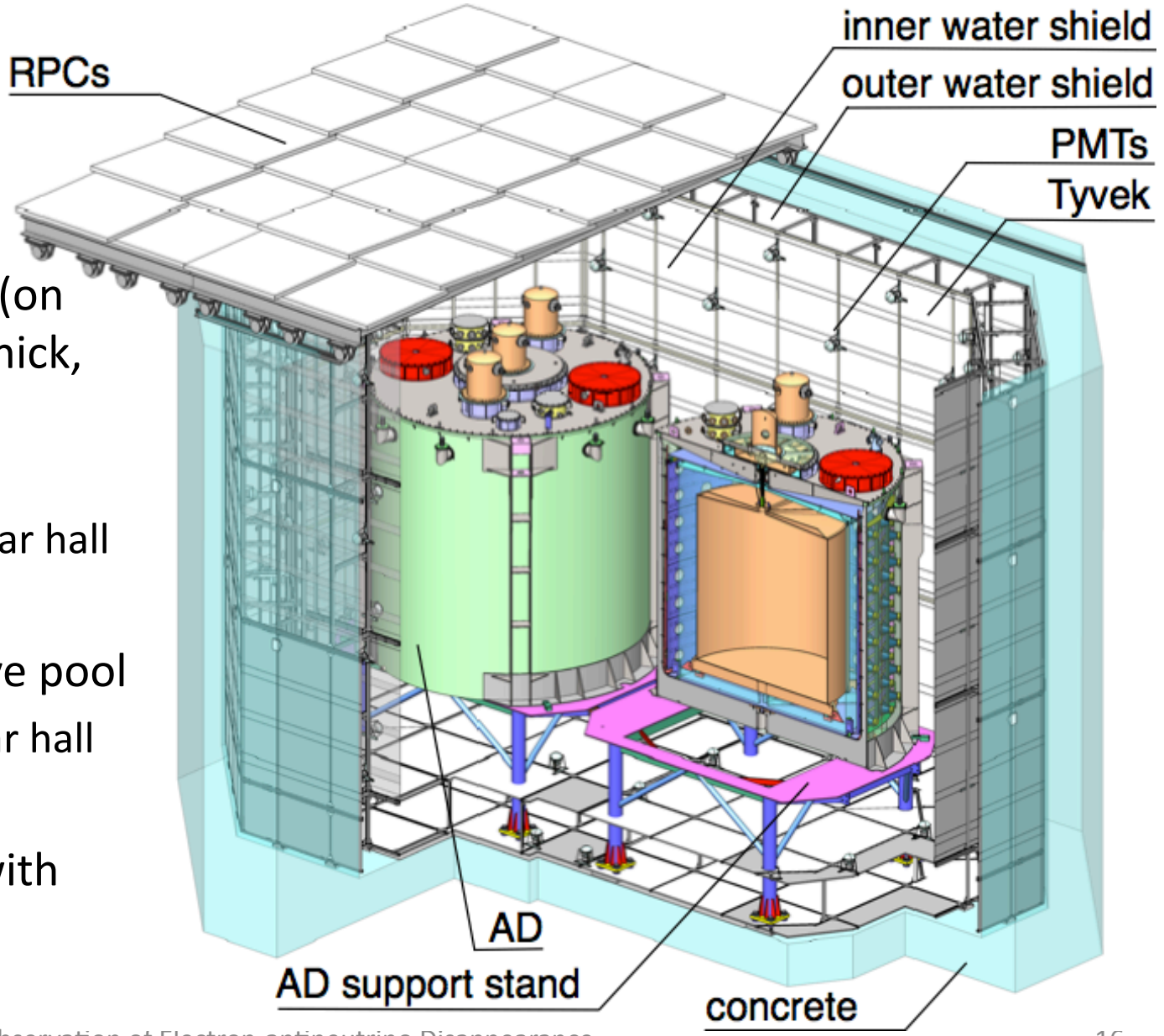
192 8-inch Photomultipliers
Reflectors at top/bottom of cylinder
Provides (7.5 / √E + 0.9)% energy resolution



Muon Tagging System

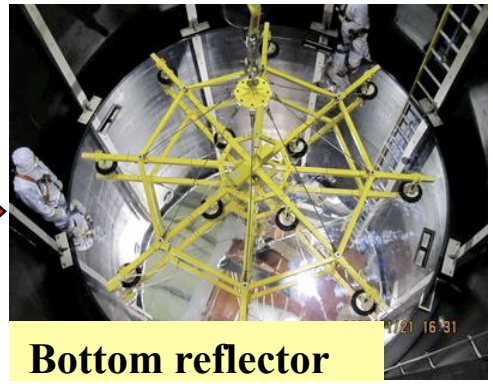
Dual tagging systems: 2.5 meter thick two-section water shield and RPCs

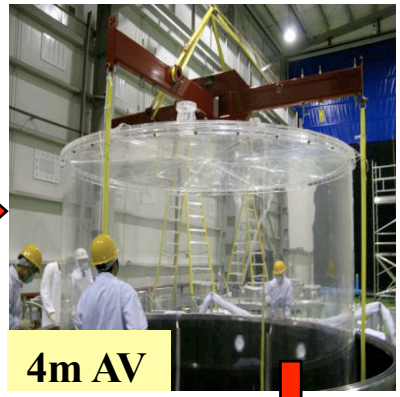
- Outer layer of water veto (on sides and bottom) is 1m thick, inner layer >1.5m. Water extends 2.5m above ADs
  - 288 8” PMTs in each near hall
  - 384 8” PMTs in Far Hall
- 4-layer RPC modules above pool
  - 54 modules in each near hall
  - 81 modules in Far Hall
- Goal efficiency: > 99.5% with uncertainty <0.25%

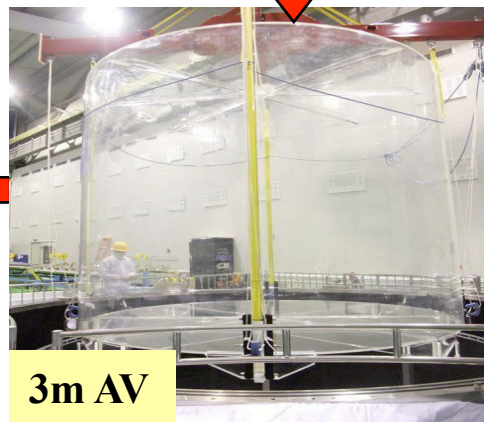


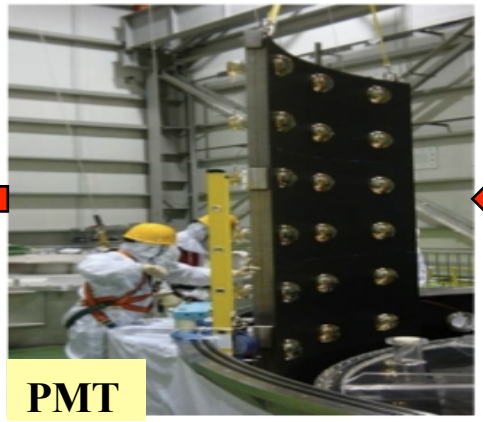
Detector Assembly

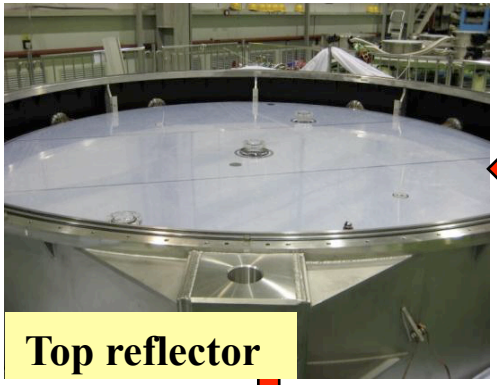
SSV

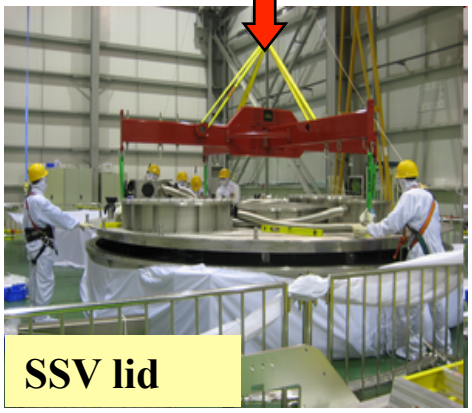

Bottom reflector


4m AV


3m AV


PMT

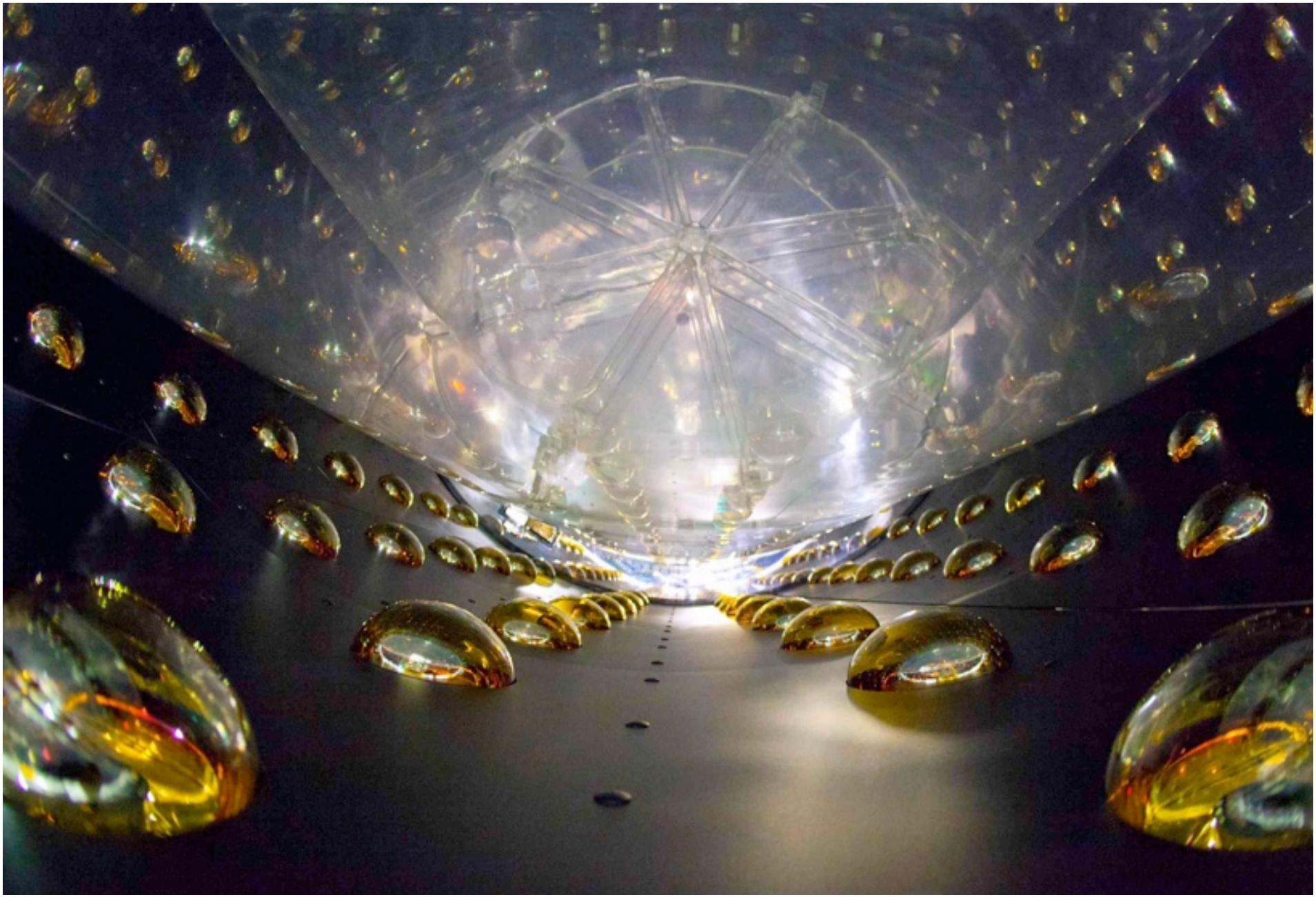

Top reflector


SSV lid

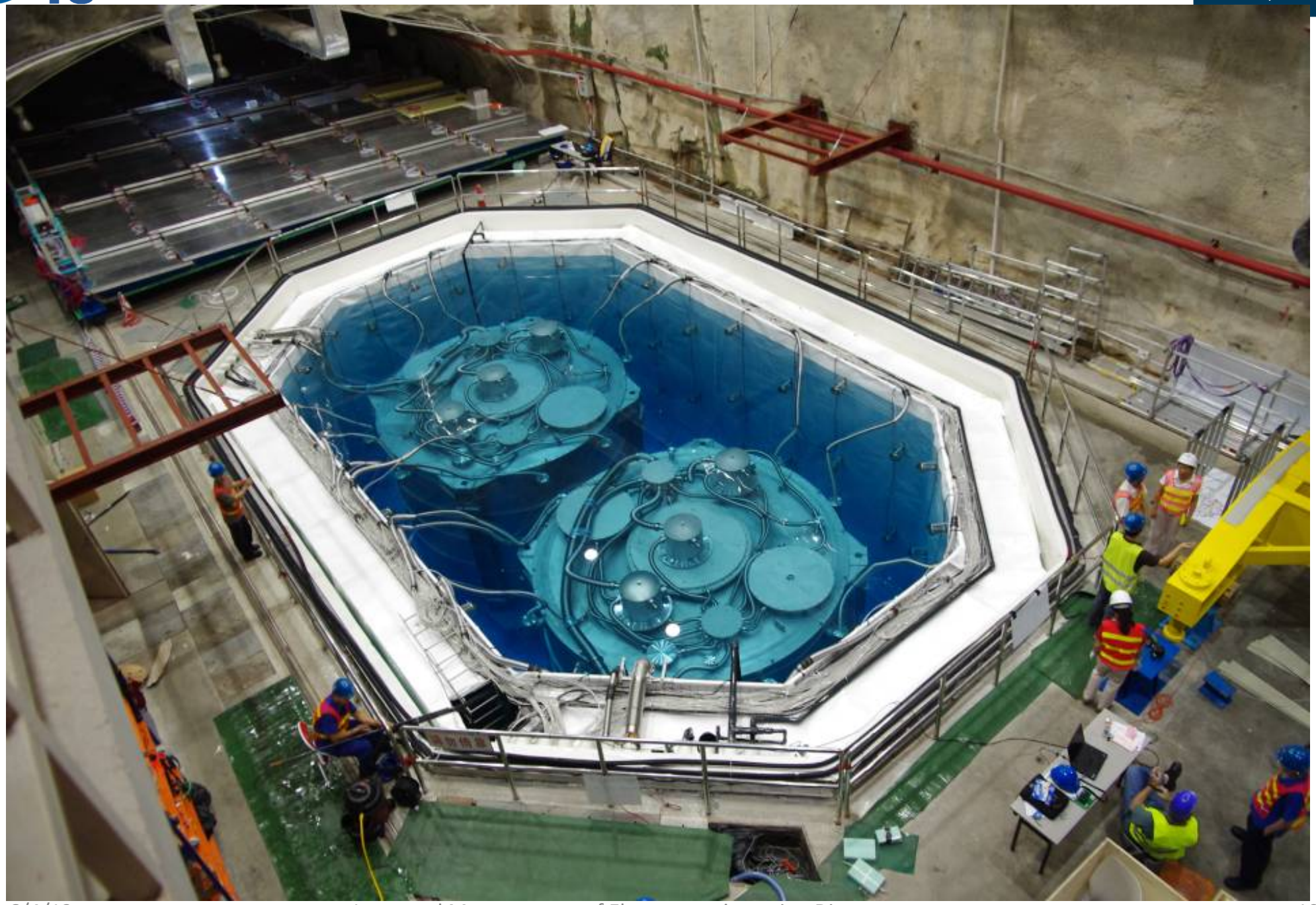
Leak check

ACU

Interior of Antineutrino Detector

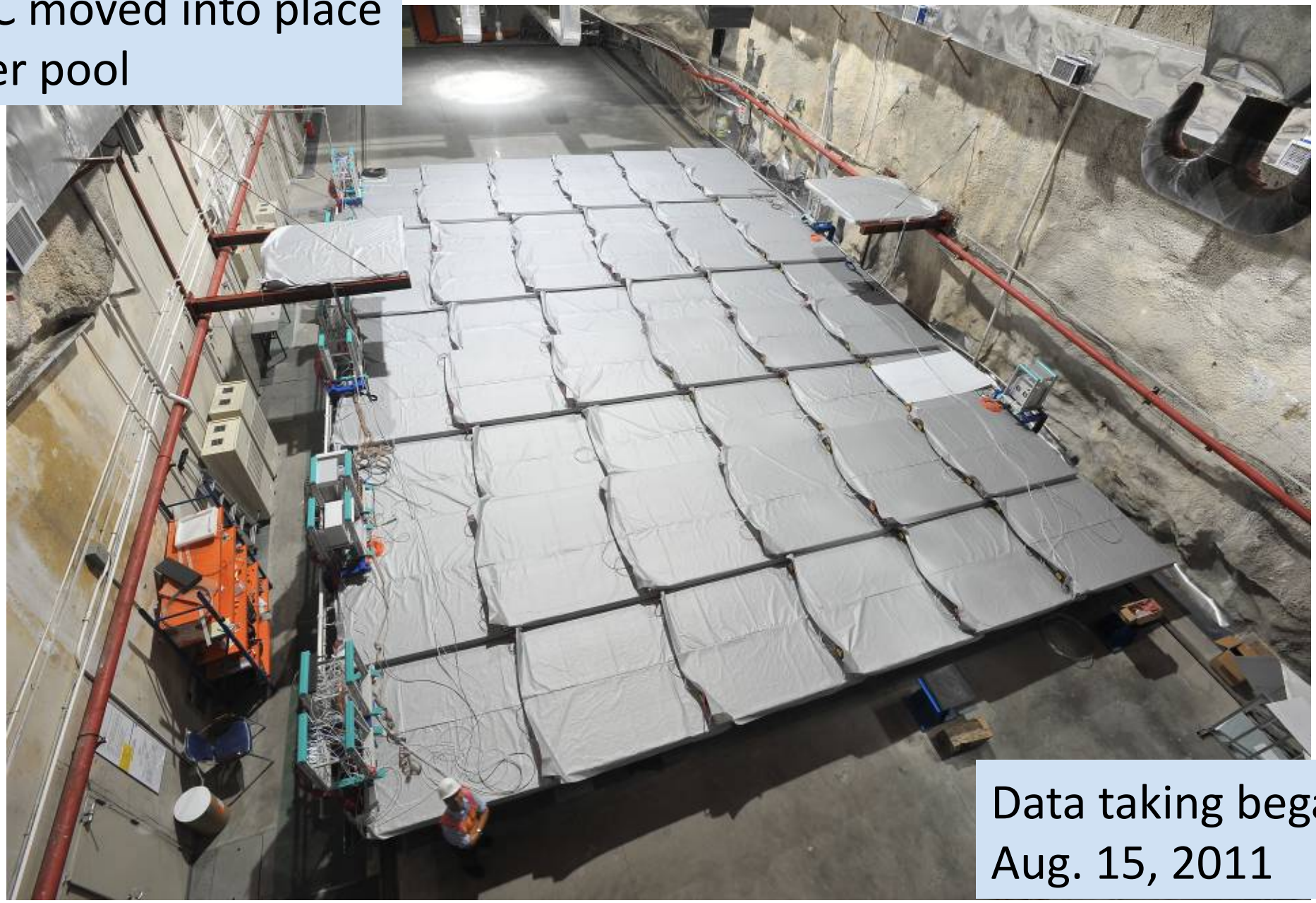


Hall 1: Pool Filled



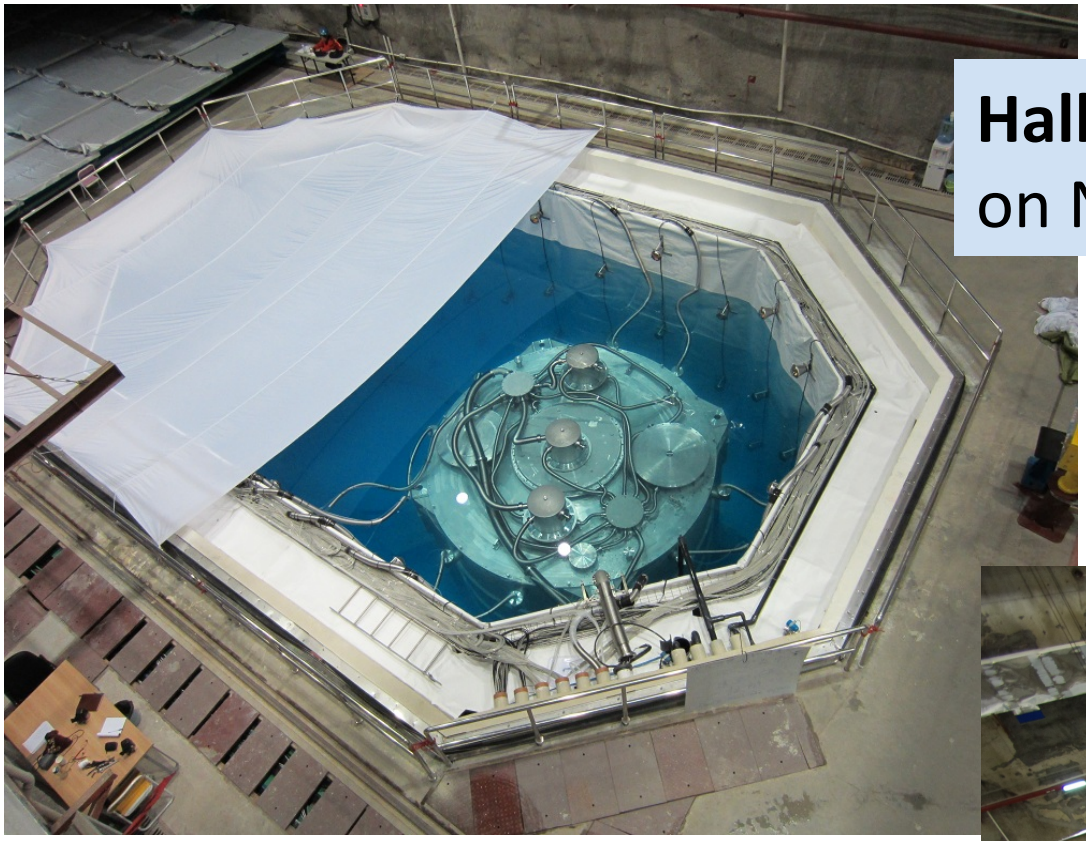
Hall 1: Completed

RPC moved into place over pool



Data taking began Aug. 15, 2011

Hall 2 and Hall 3

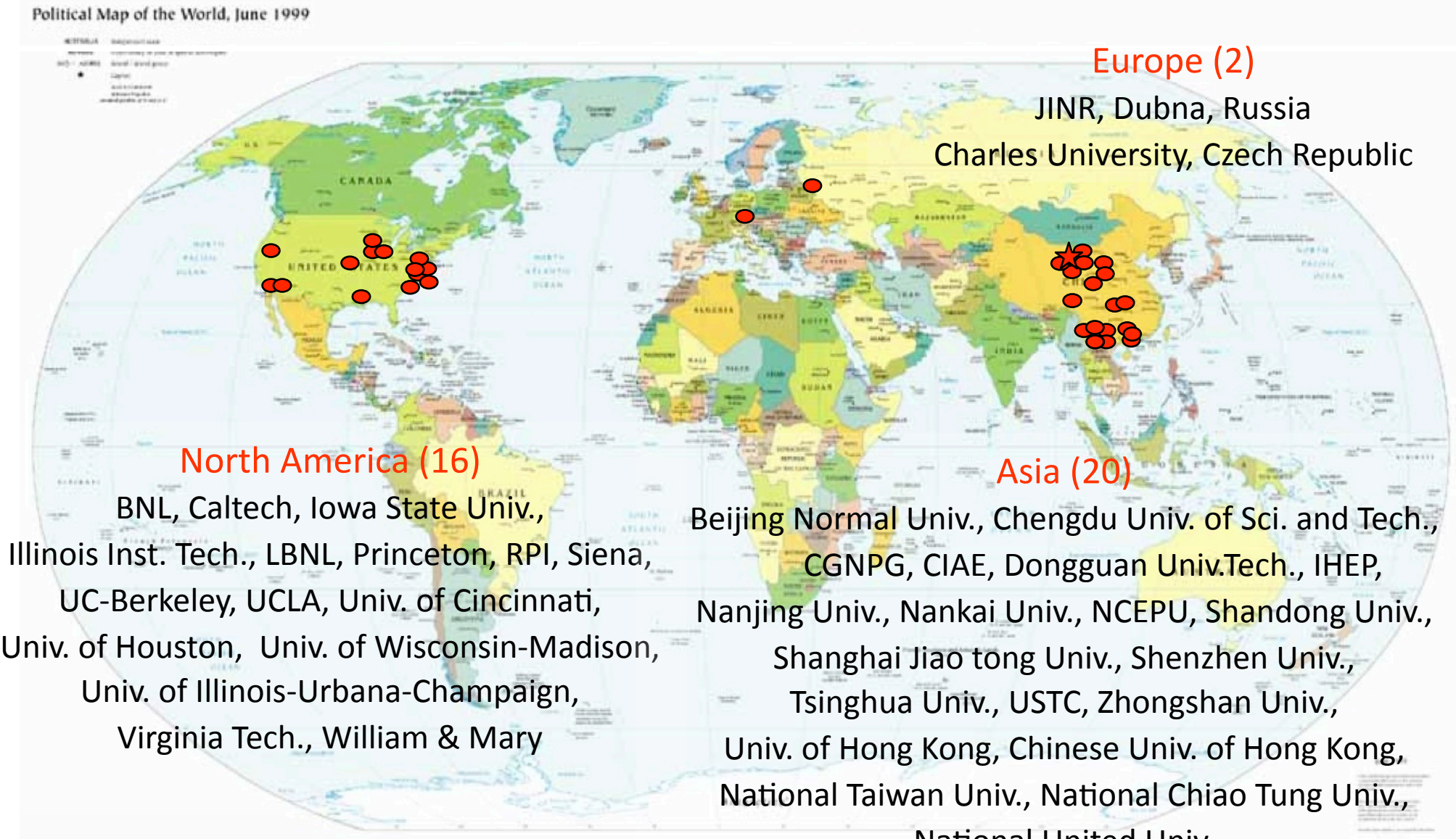


Hall 2: Began 1 AD operation on Nov. 5, 2011

Hall 3: Began 3 AD operation on Dec. 24, 2011

2 more ADs still in assembly; installation planned for late 2012

The Daya Bay Collaboration



Europe (2)

JINR, Dubna, Russia

Charles University, Czech Republic

North America (16)

BNL, Caltech, Iowa State Univ., Illinois Inst. Tech., LBNL, Princeton, RPI, Siena, UC-Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, Univ. of Wisconsin-Madison, Univ. of Illinois-Urbana-Champaign, Virginia Tech., William & Mary

Asia (20)

Beijing Normal Univ., Chengdu Univ. of Sci. and Tech., CGNPG, CIAE, Dongguan Univ.Tech., IHEP, Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiao tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Zhongshan Univ., Univ. of Hong Kong, Chinese Univ. of Hong Kong, National Taiwan Univ., National Chiao Tung Univ., National United Univ.

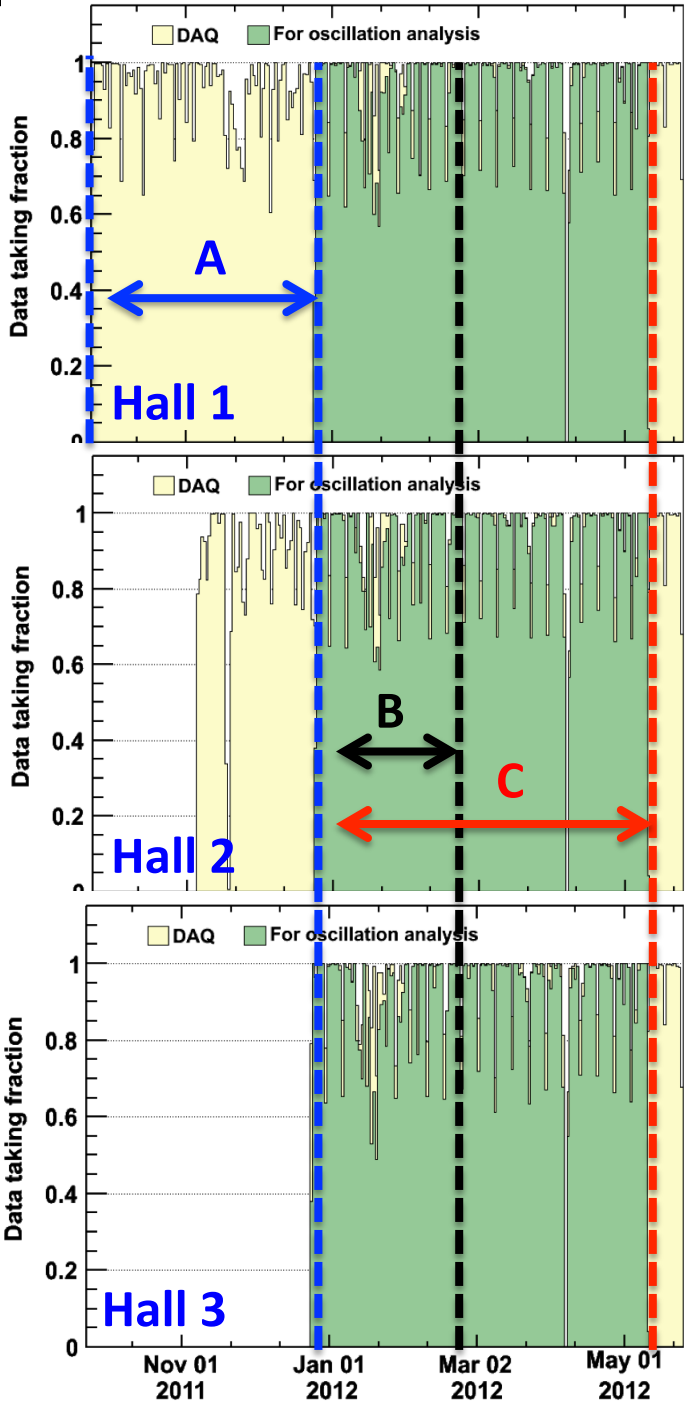
~230 Collaborators

Data Period

A. Two Detector Comparison: arXiv:1202:6181
- Sep. 23, 2011 – Dec. 23, 2011
- Side-by-side comparison of 2 detectors in Hall 1
- Demonstrated detector systematics better than requirements.
- Nucl. Inst. and Meth. **A685**, 78 (2012)

B. First Oscillation Result: arXiv:1203:1669
- Dec. 24, 2011 – Feb. 17, 2012
- All 3 halls (6 ADs) operating
- First observation of $\bar{\nu}_e$ disappearance
- Phys. Rev. Lett. **108**, 171803 (2012)

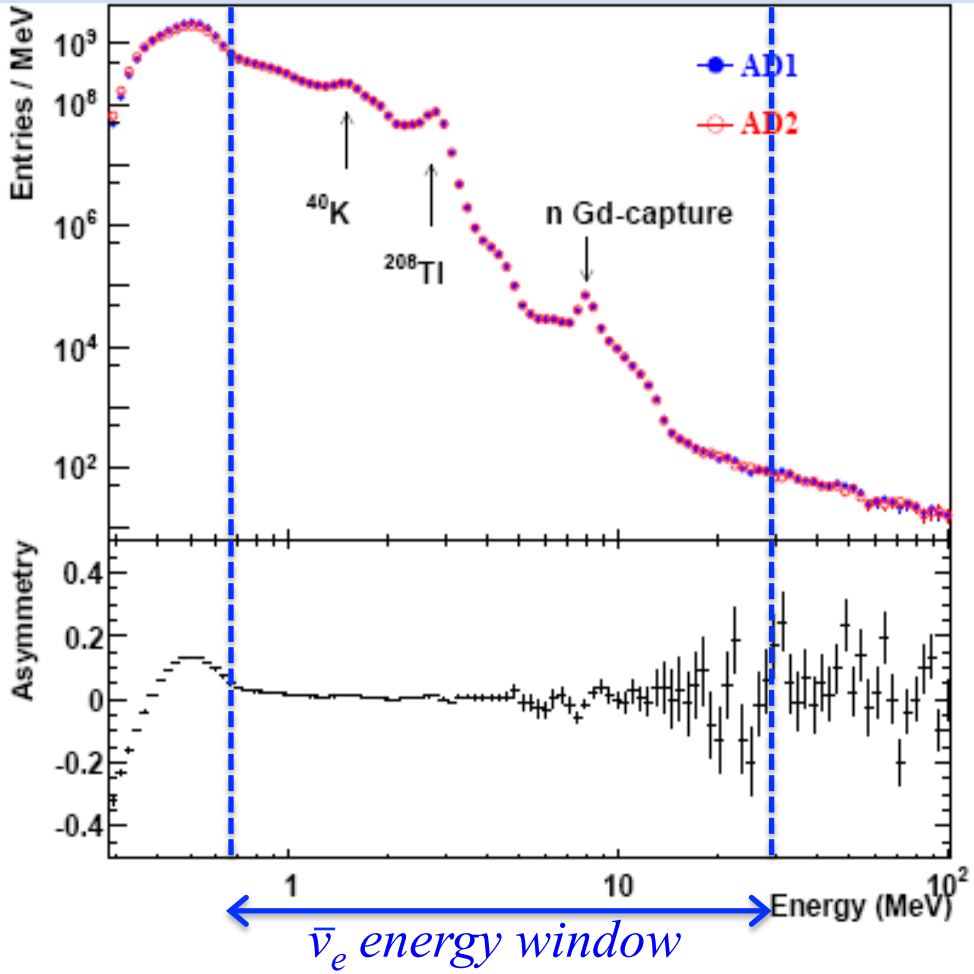
C. Current Result:
- Dec. 24, 2011 – May 11, 2012
- More than 2.5x the previous data set

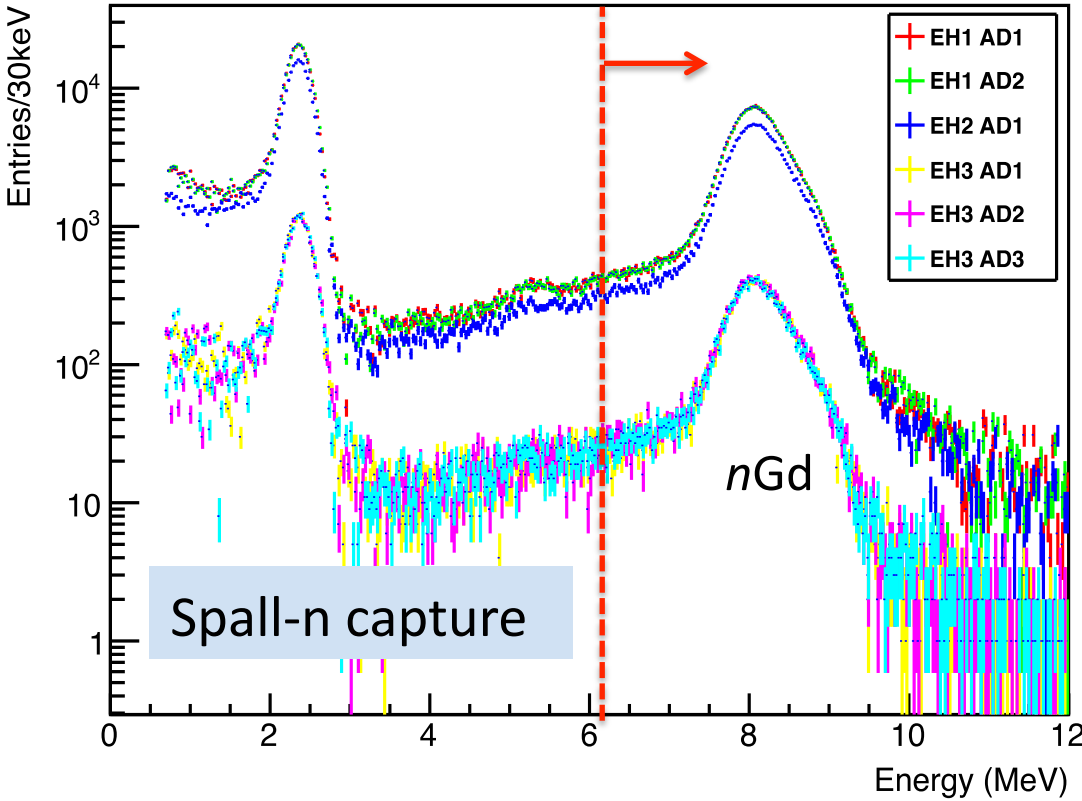


Side-by-Side Comparison

Multiple detectors allows detailed comparison and cross-checks.

Side-by-side detectors have identical spectra and response.





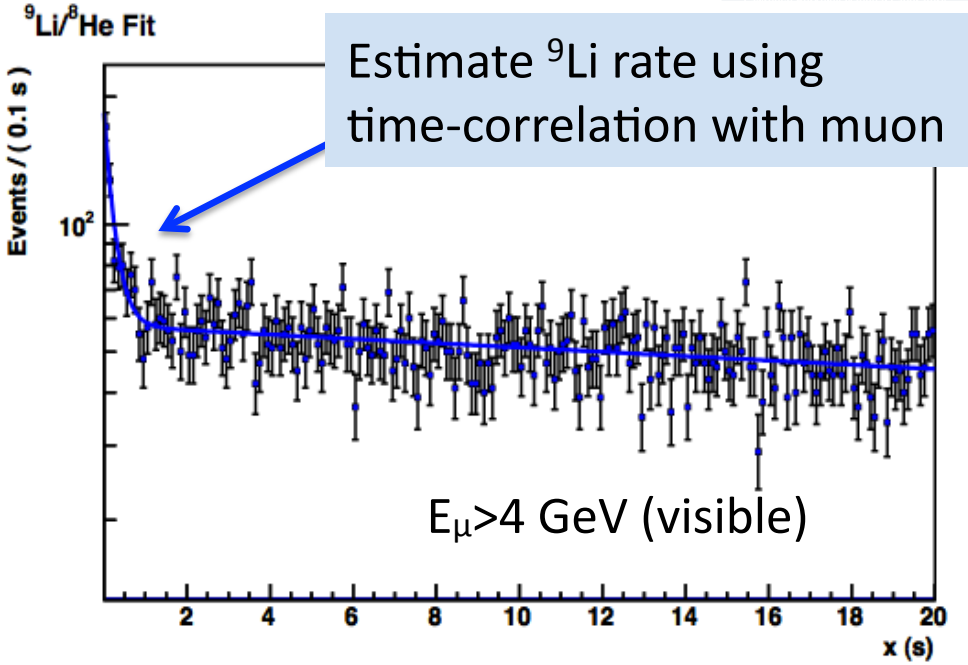
Relative response to neutrons constrains largest systematic.

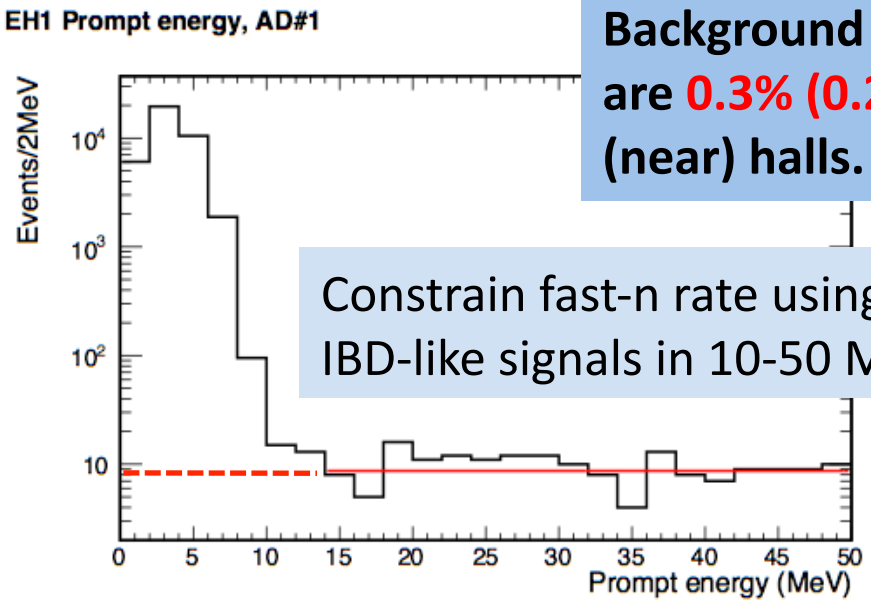
Backgrounds

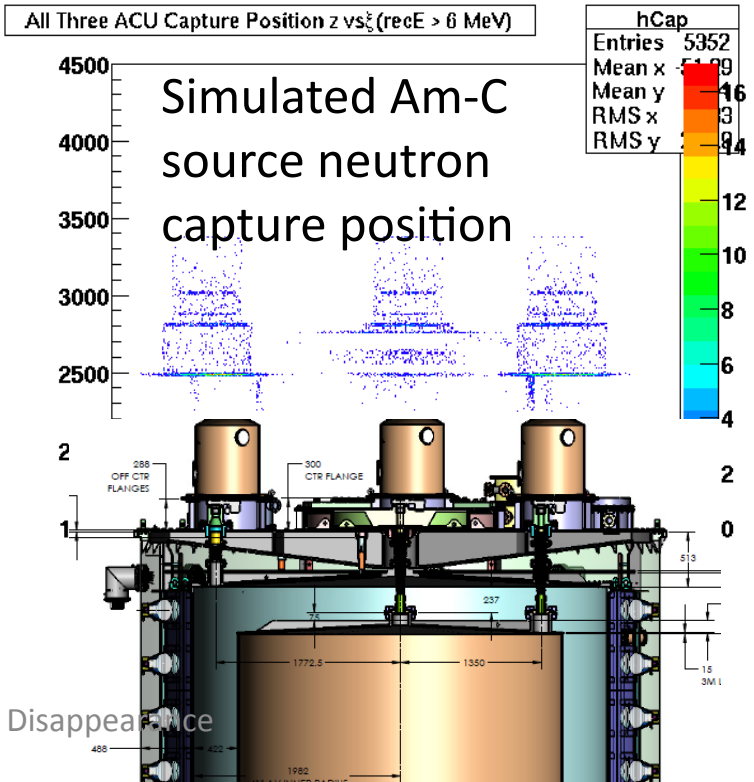
Total backgrounds are 5% (2%) in far (near) halls.

	Near Halls		Far Hall	
	B/S %	$\sigma_{B/S}$ %	B/S %	$\sigma_{B/S}$ %
Accidentals	1.5	0.02	4.0	0.05
Fast neutrons	0.12	0.05	0.07	0.03
^{9}Li/^{8}He	0.4	0.2	0.3	0.2
^{241}Am-^{13}C	0.03	0.03	0.3	0.3
^{13}C(α, n)^{16}O	0.01	0.006	0.05	0.03

Background uncertainties are 0.3% (0.2%) in far (near) halls.







Uncertainty Summary

Detector			
	Efficiency	Correlated	Uncorrelated
Target Protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	90.9%	0.6%	0.12%
Prompt energy cut	99.88%	0.10%	0.01%
Multiplicity cut		0.02%	<0.01%
Capture time cut	98.6%	0.12%	0.01%
Gd capture ratio	83.8%	0.8%	<0.1%
Spill-in	105.0%	1.5%	0.02%
Livetime	100.0%	0.002%	<0.01%
Combined	78.8%	1.9%	0.2%

For near/far oscillation, only uncorrelated uncertainties are used.

Largest systematics are smaller than far site statistics (~1%)

Reactor			
Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
$\overline{\nu}_e$/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%

Influence of uncorrelated reactor systematics reduced by far vs. near measurement.

Data Set Summary

> 200k antineutrino interactions!

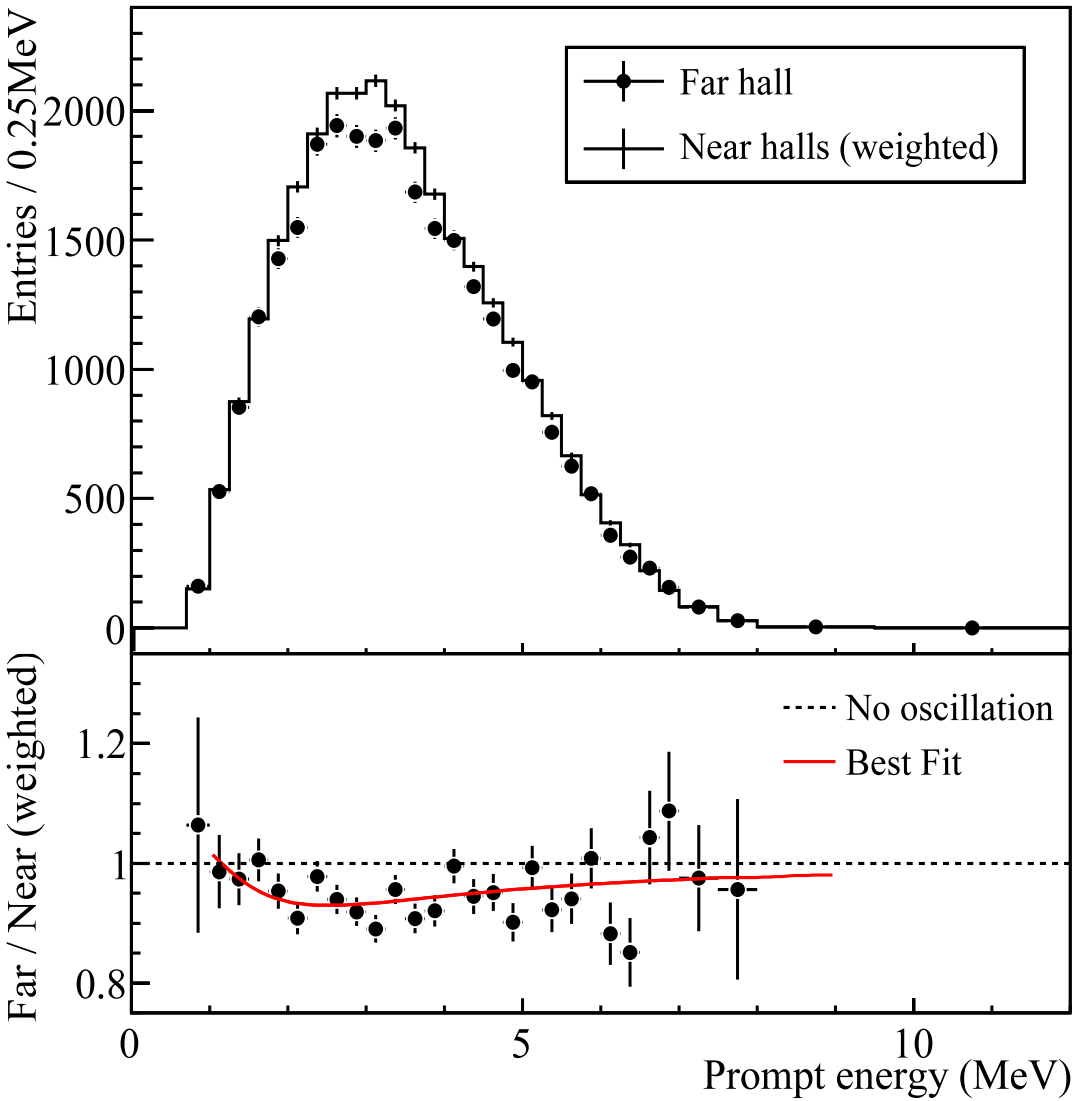
	AD1	AD2	AD3	AD4	AD5	AD6
Antineutrino candidates	69121	69714	66473	9788	9669	9452
DAQ live time (day)	127.5470		127.3763		126.2646	
Efficiency	0.8015	0.7986	0.8364	0.9555	0.9552	0.9547
Accidentals (/day)	9.73±0.10	9.61±0.10	7.55±0.08	3.05±0.04	3.04±0.04	2.93±0.03
Fast neutron (/day)	0.77±0.24	0.77±0.24	0.58±0.33	0.05±0.02	0.05±0.02	0.05±0.02
$^{8}He/^{9}Li$ (/day)	2.9±1.5		2.0±1.1		0.22±0.12	
Am-C corr. (/day)	0.2±0.2					
$^{13}C(\alpha, n)^{16}O$ (/day)	0.08±0.04	0.07±0.04	0.05±0.03	0.04±0.02	0.04±0.02	0.04±0.02
Antineutrino rate (/day)	**662.47 ±3.00**	**670.87 ±3.01**	**613.53 ±2.69**	**77.57 ±0.85**	**76.62 ±0.85**	**74.97 ±0.84**

Consistent rates for side-by-side detectors

Uncertainty currently dominated by statistics

Far vs. Near Comparison

Compare the far/near measured rates and spectra



$$R = \frac{Far_{measured}}{Far_{expected}} = \frac{M_4 + M_5 + M_6}{\sum_{i=4}^{6}(\alpha_i(M_1 + M_2) + \beta_i M_3)}$$

M_n are the measured rates in each detector. Weights α_i, β_i are determined from baselines and reactor fluxes.

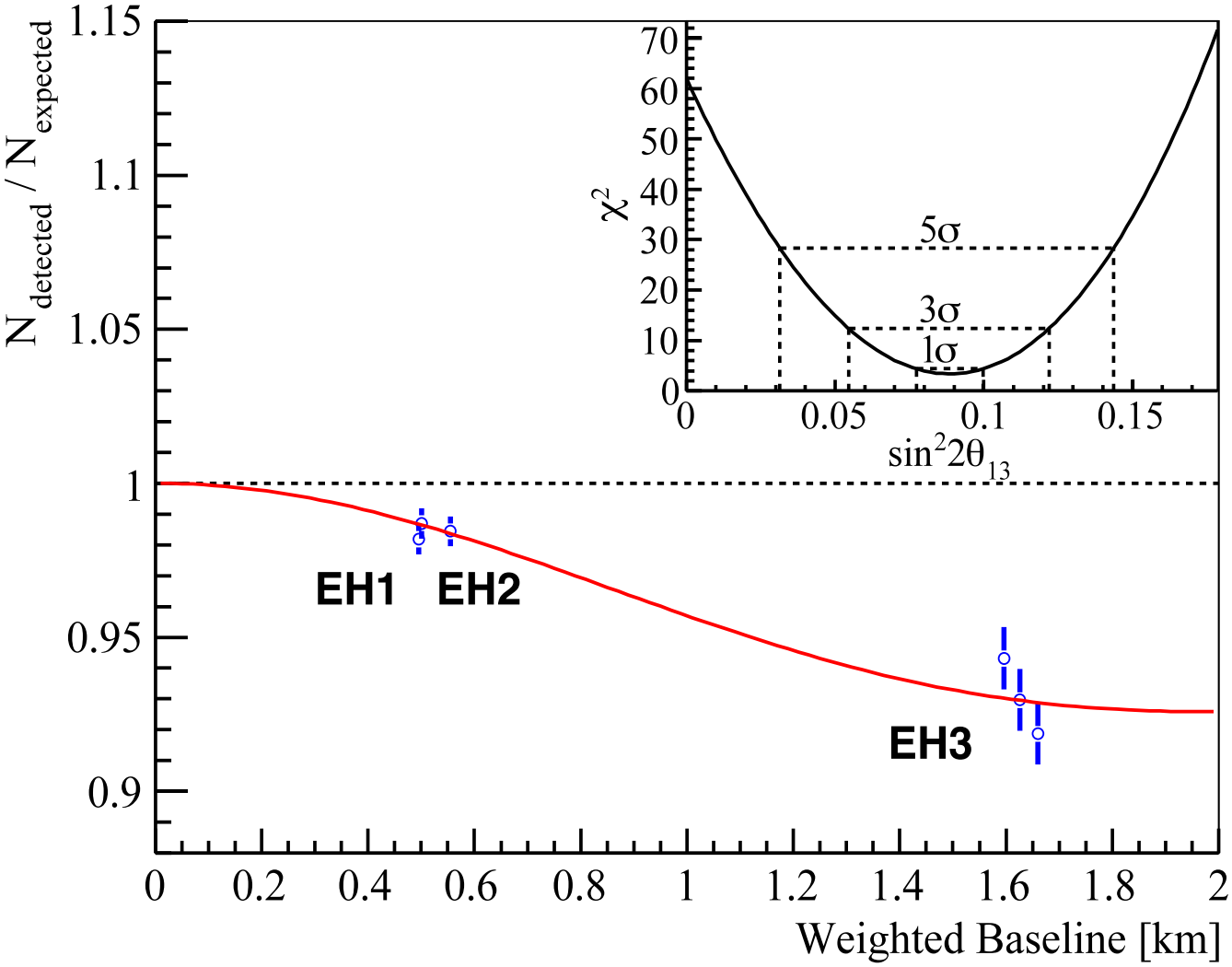
R = 0.944 ± 0.007 (stat) ± 0.003 (syst)

Clear observation of far site deficit.

Spectral distortion consistent with oscillation.

Rate Analysis

Estimate θ_{13} using measured rates in each detector.



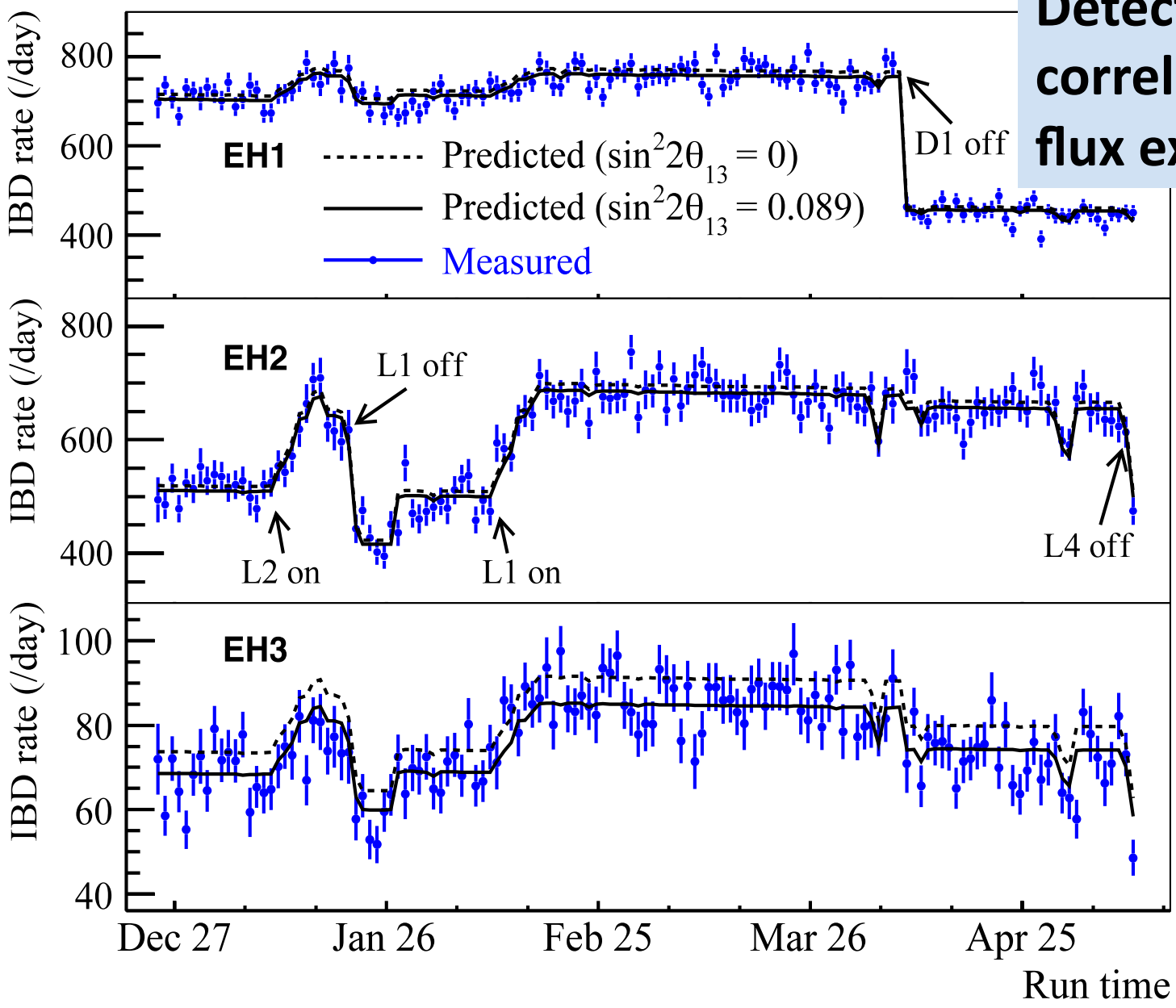
Uses standard χ^2 approach.

Far vs. near relative measurement.
[Absolute rate is not constrained.]

Consistent results obtained by independent analyses, different reactor flux models.

$\sin^2 2\theta_{13} = 0.089 \pm 0.010\ (stat) \pm 0.005\ (syst)$

Antineutrino Rate vs. Time

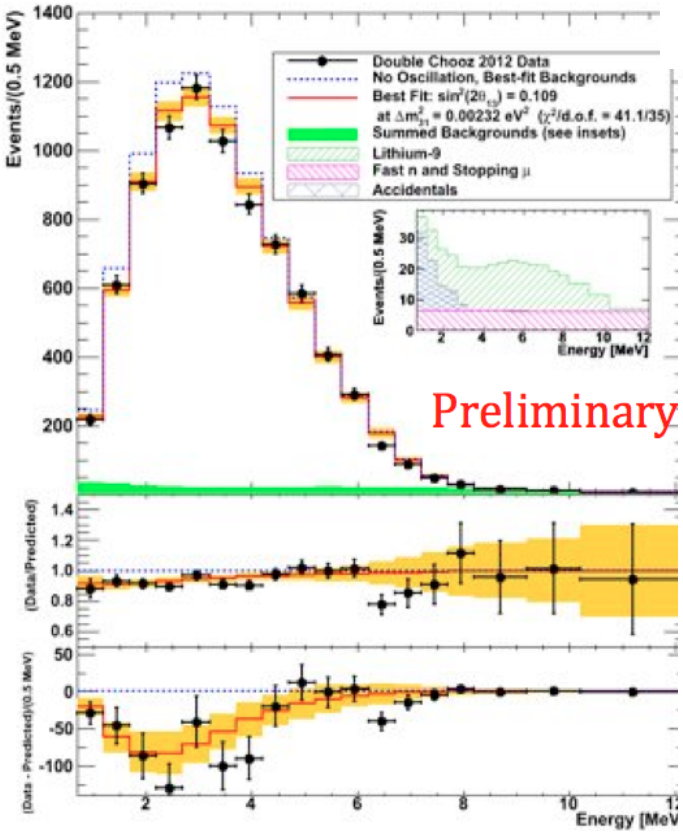


Detected rate strongly correlated with reactor flux expectations.

Summary: Reactor Results

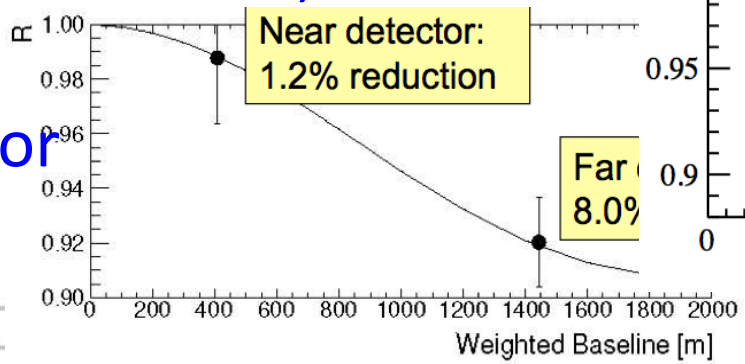
Double Chooz

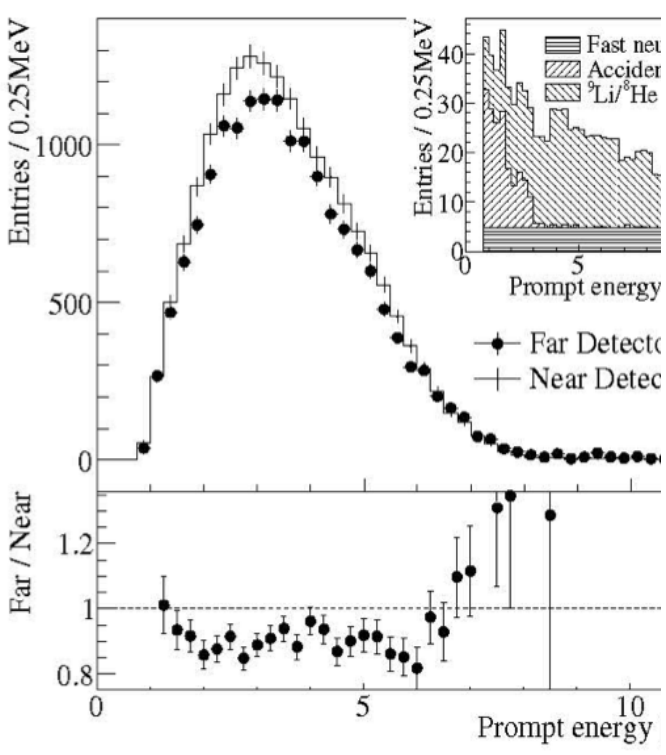
1 far detector only, compared with reactor model.



RENO

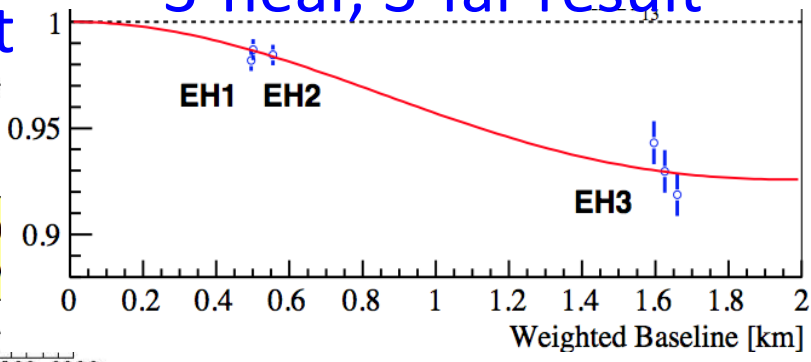
1-near, 1-far result

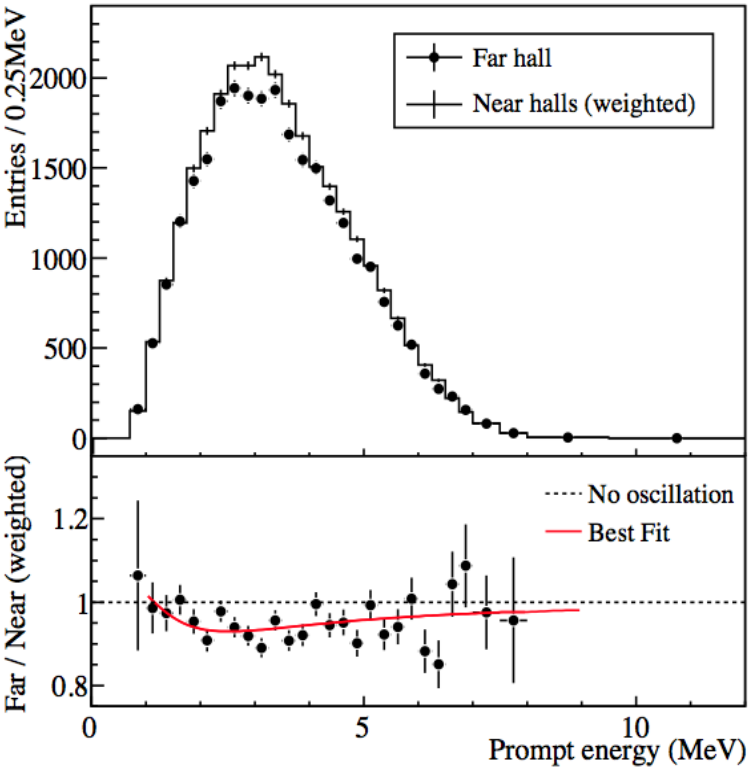




Daya Bay

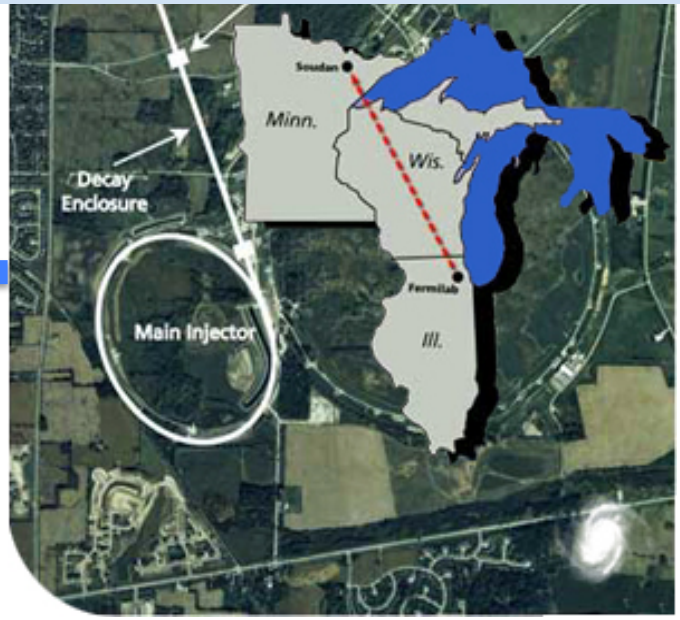
3-near, 3-far result

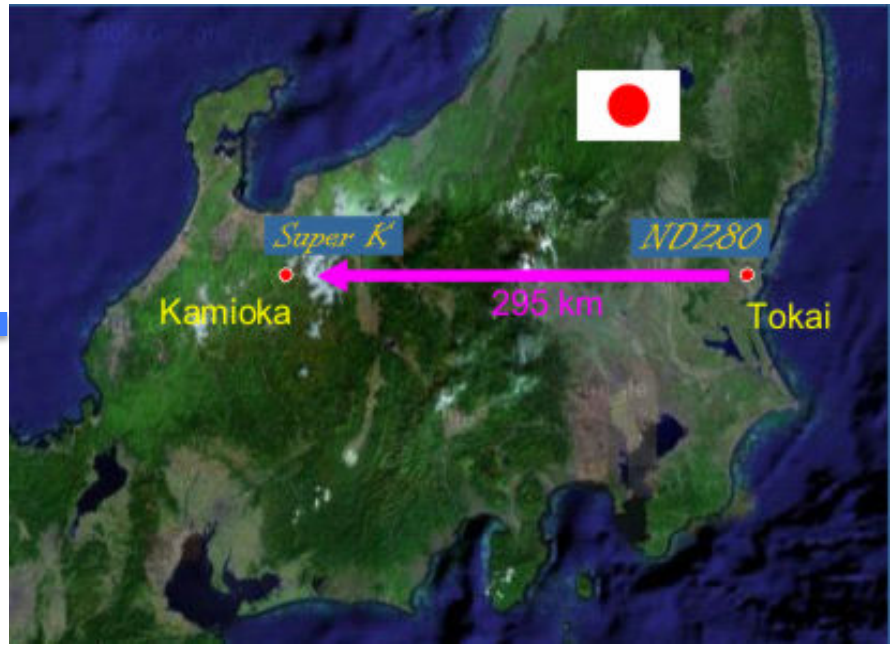




Accelerator Neutrinos

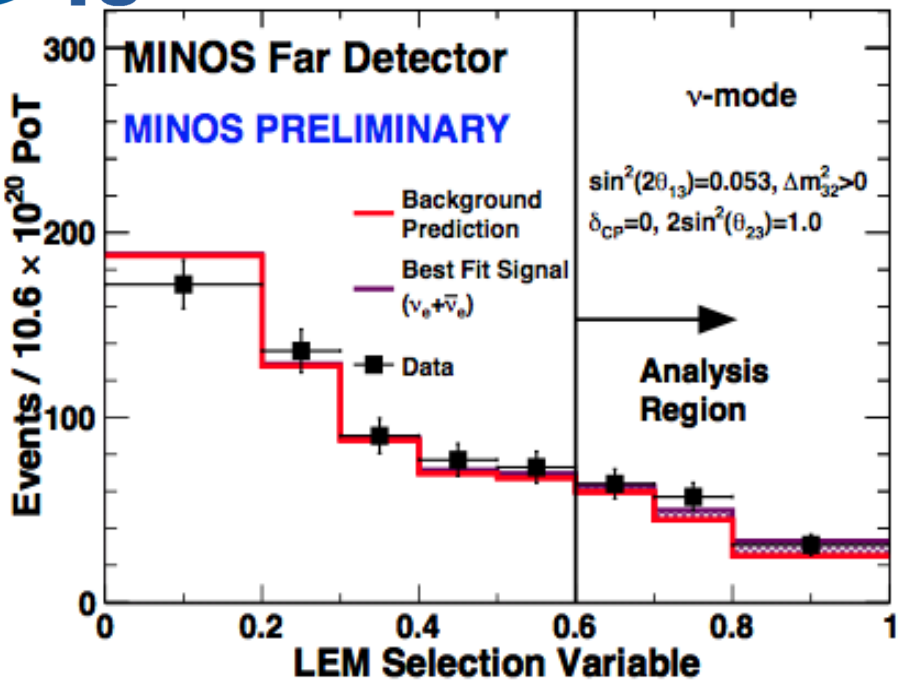
Look for appearance of ν_e in ν_μ beam.

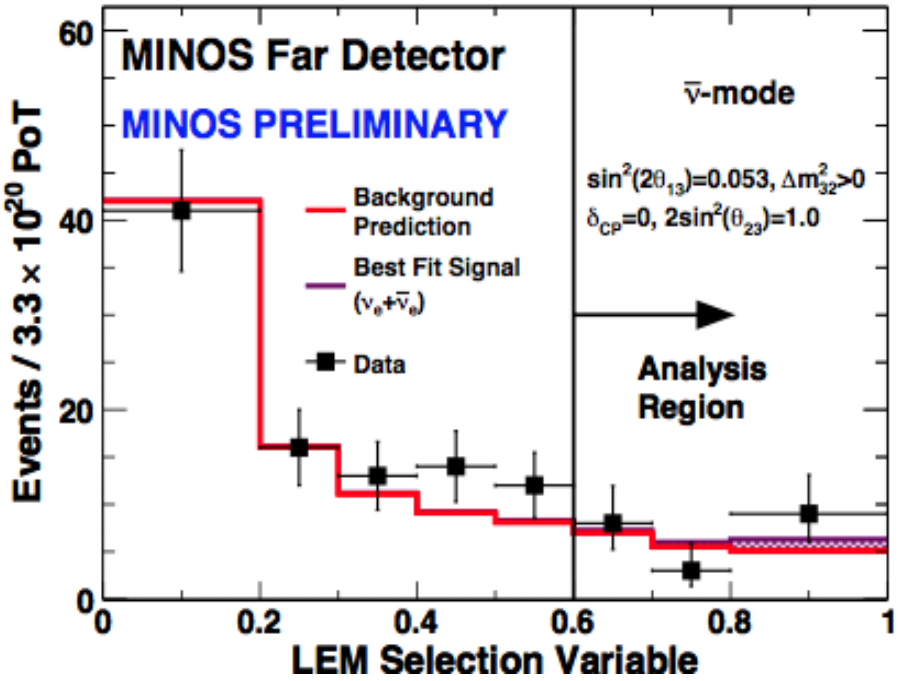


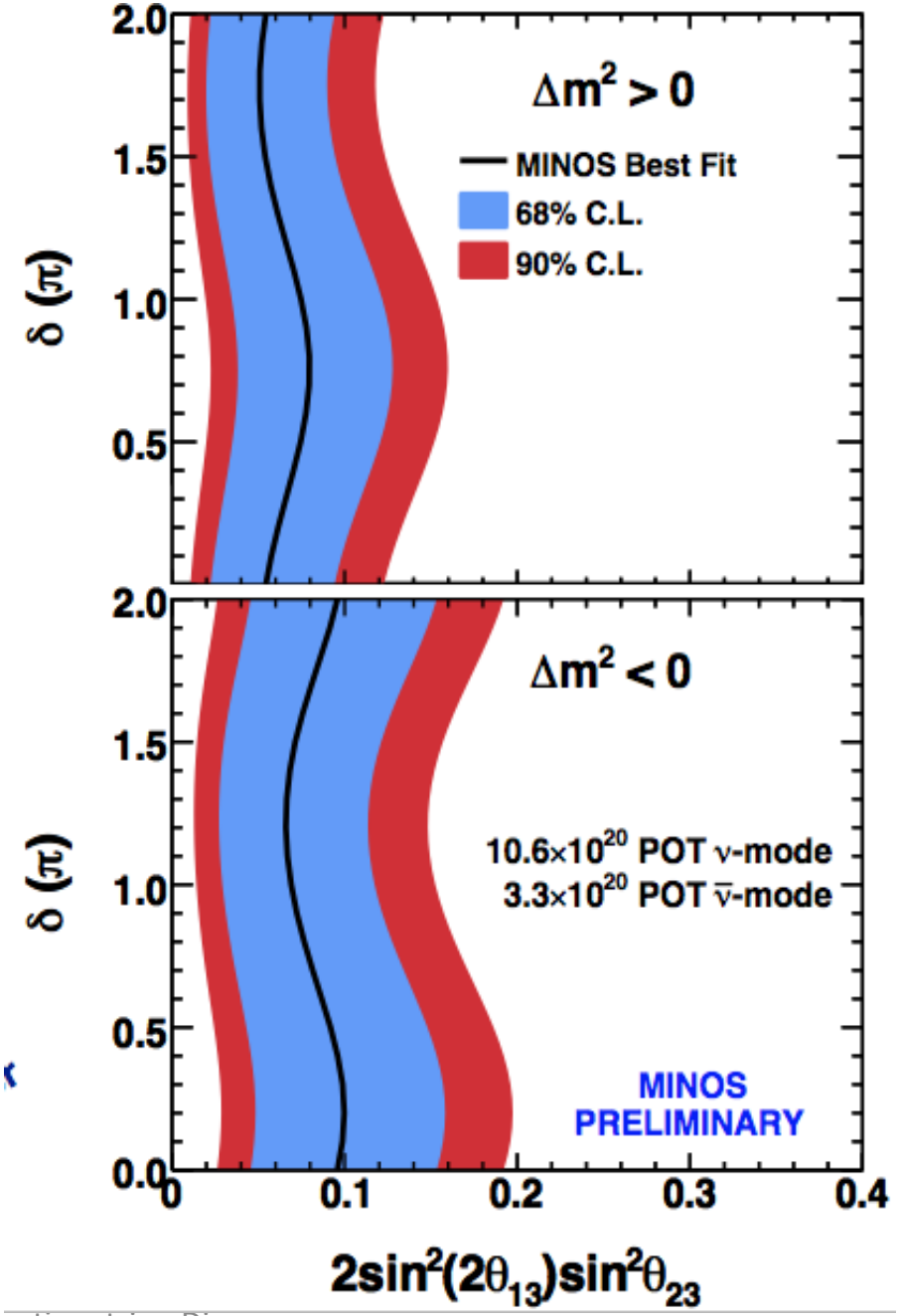


MINOS

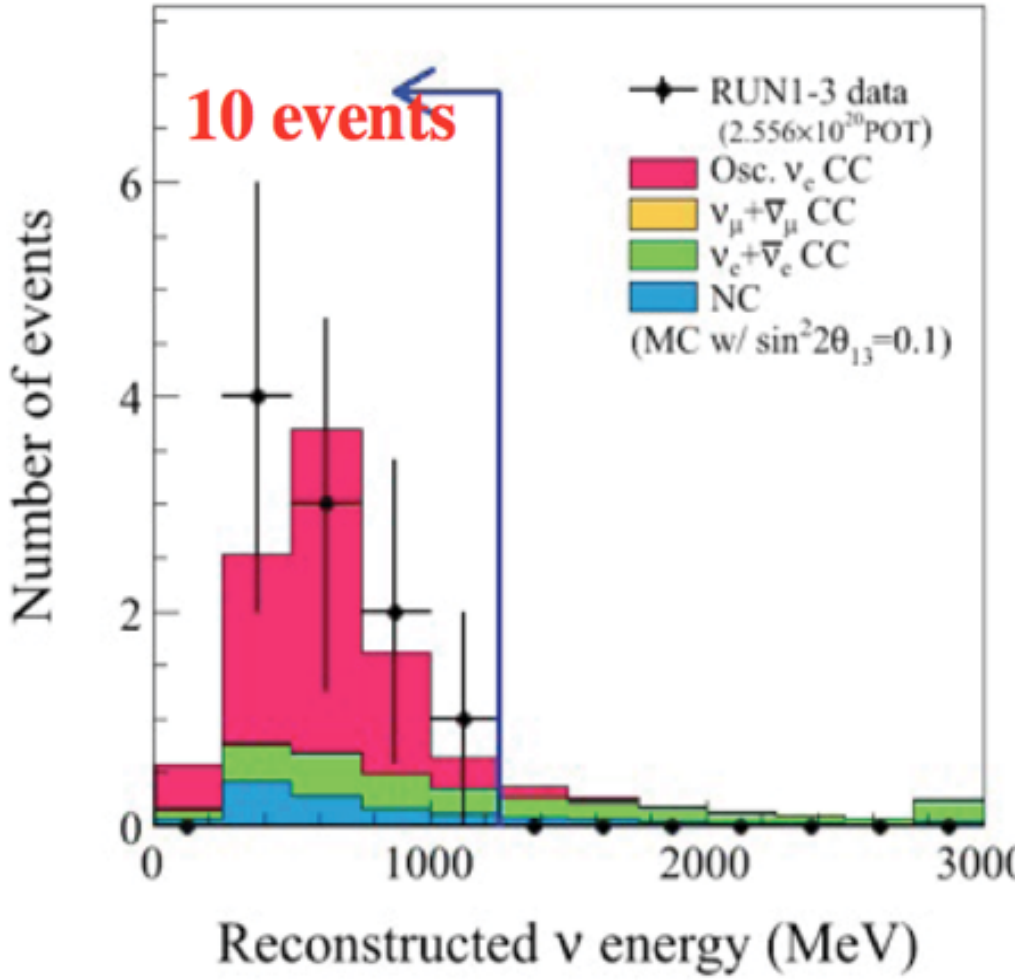
R. Nichol, Neutrino2012

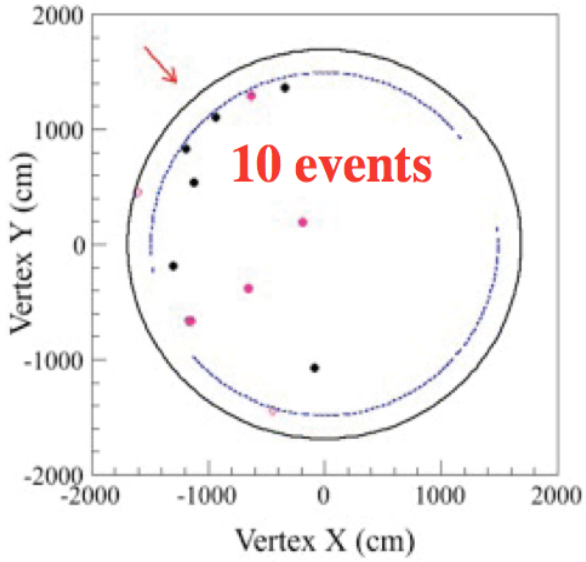


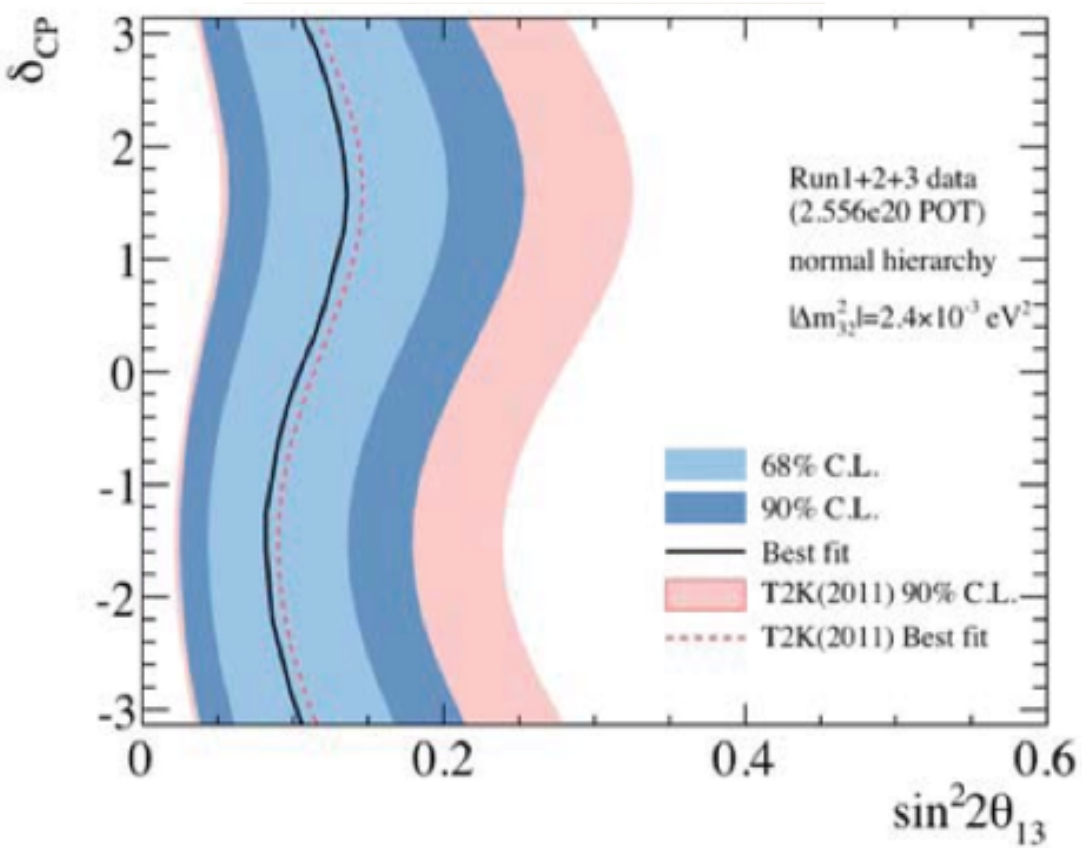




T2K

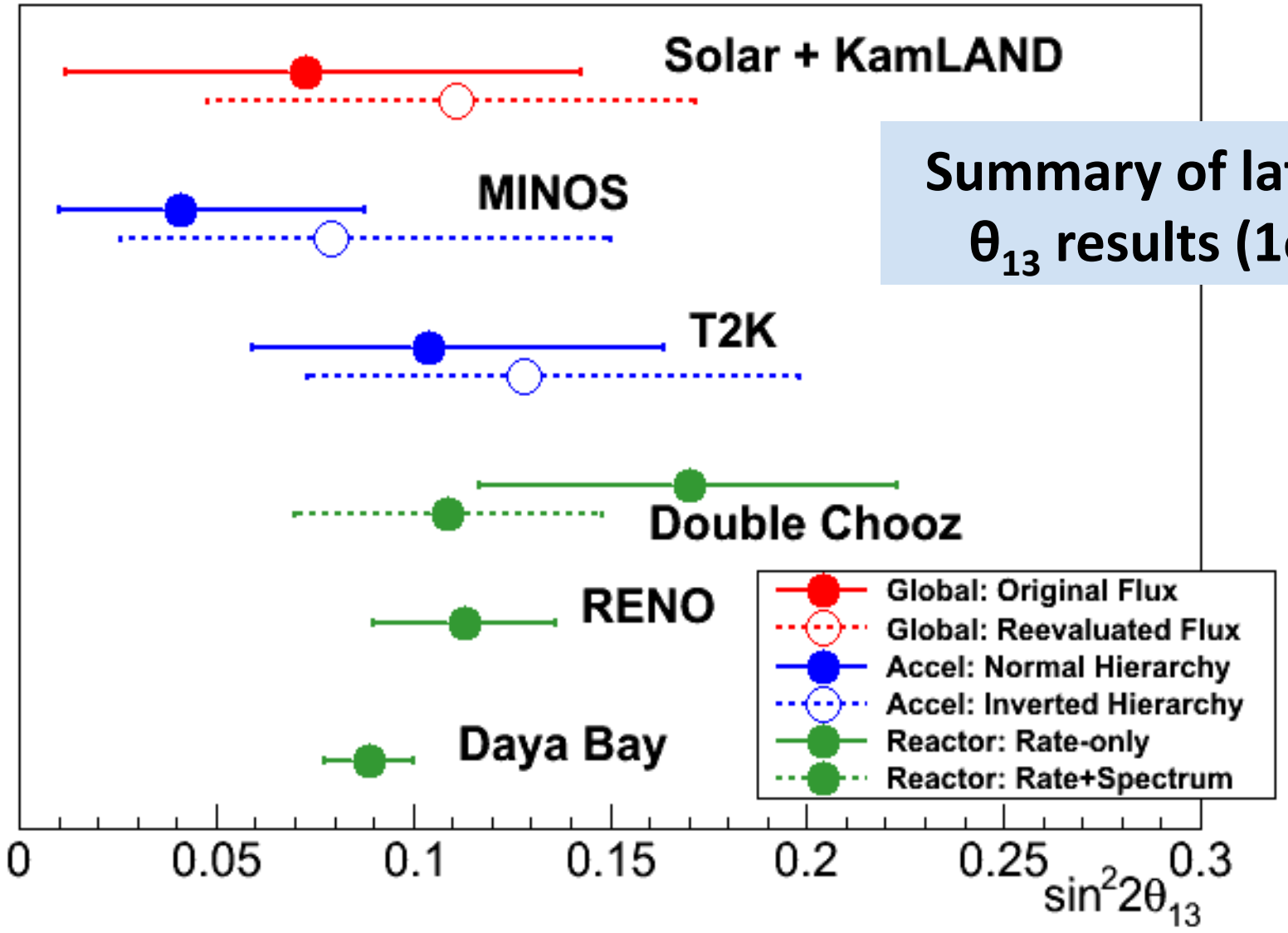






T. Nakaya, Neutrino2012

θ_{13}



Summary of latest θ_{13} results (1σ)

Expect more statistics and further improvements from running experiments.

Neutrino Mixing Matrix

All mixing angles now measured.

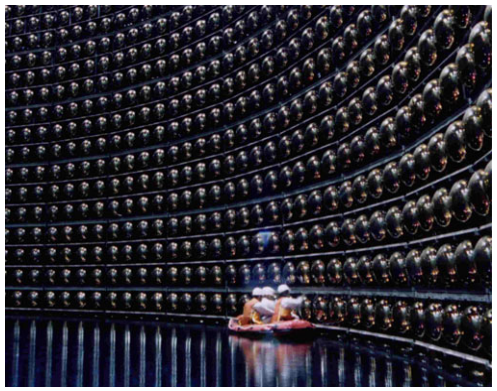
$$c_{ij} \equiv \cos\theta_{ij} \text{ and } s_{ij} \equiv \sin\theta_{ij}$$

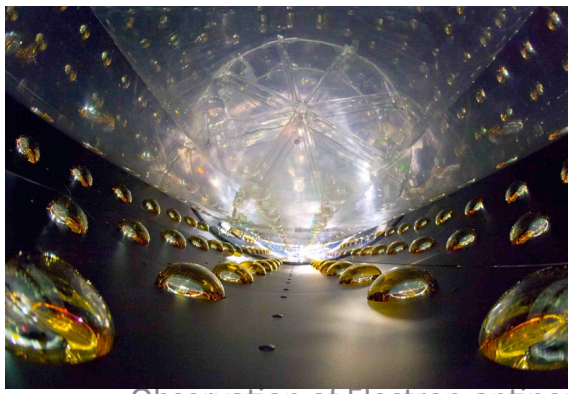
$$U_{if} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

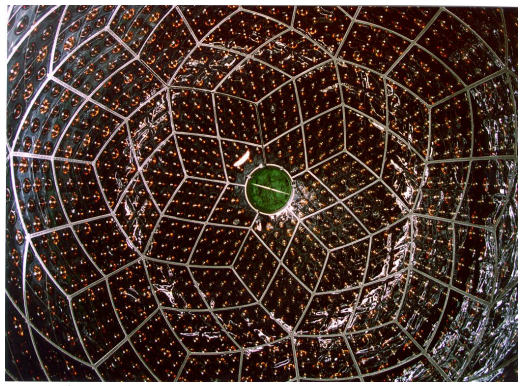
$\theta_{23} \approx 45^o$
Atmospheric ν
Accelerator ν

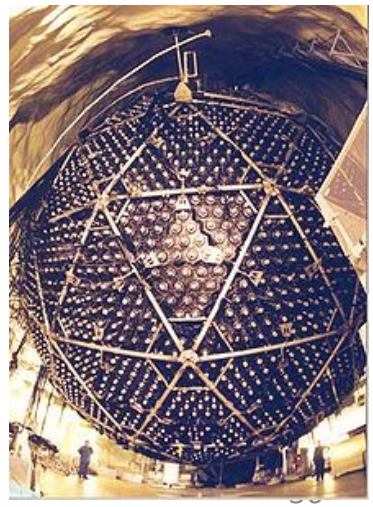
$\theta_{13} \approx 9^o$
Short-Baseline Reactor ν
Accelerator ν

$\theta_{12} \approx 35^o$
Solar ν
Long-Baseline Reactor ν



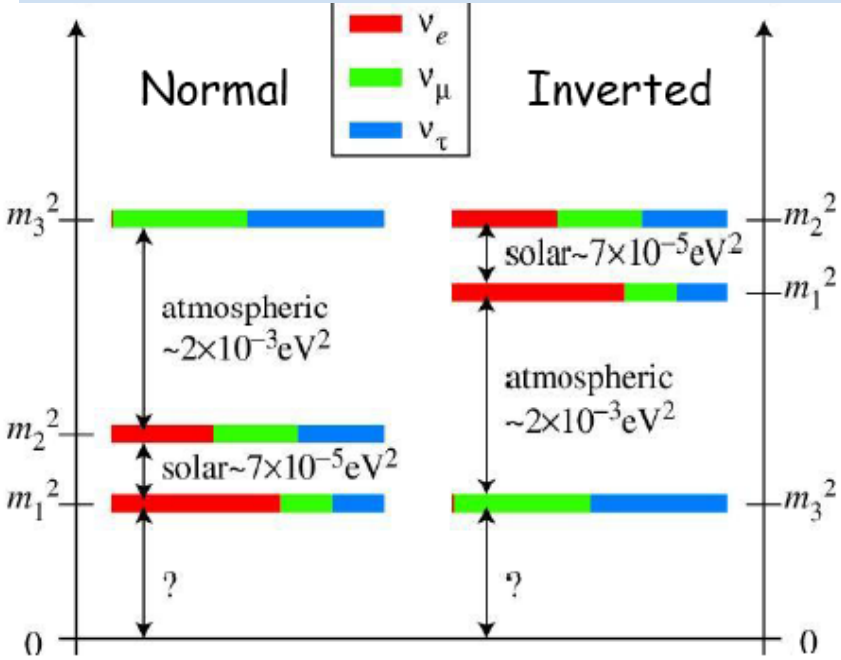




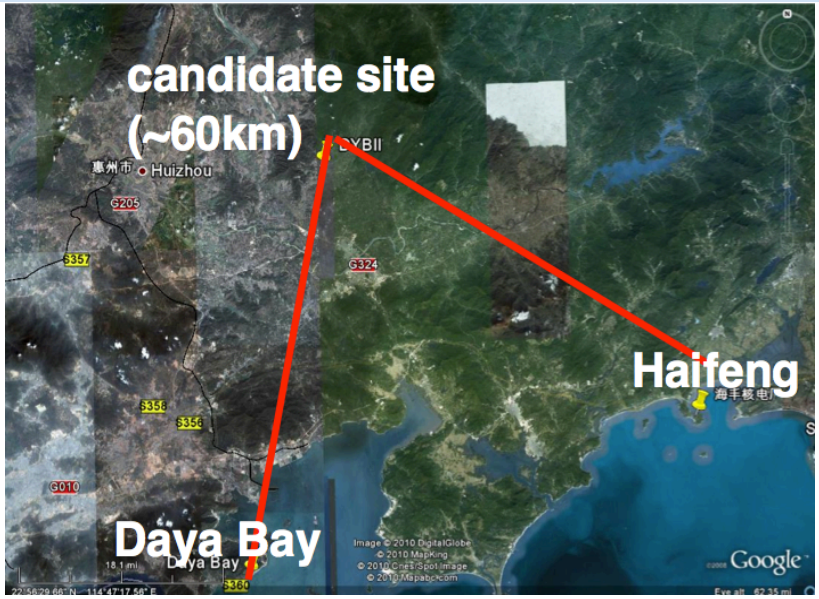


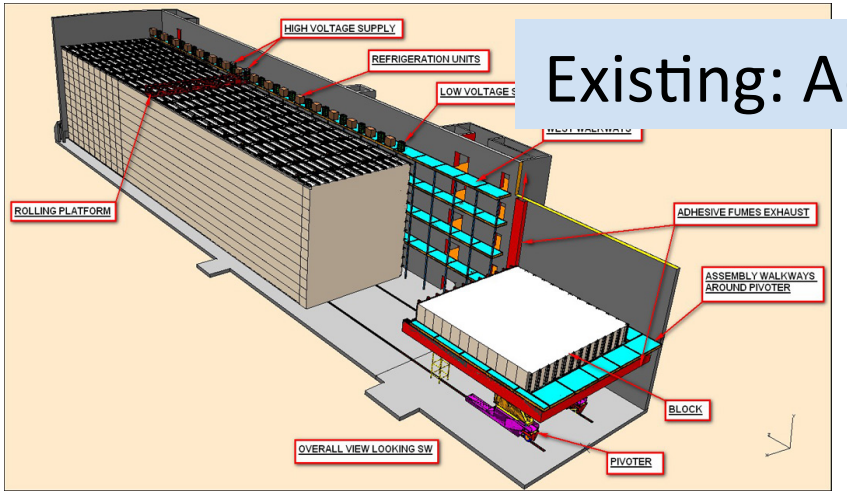
θ_{13} Consequences

Next generation experiments to measure the mass hierarchy

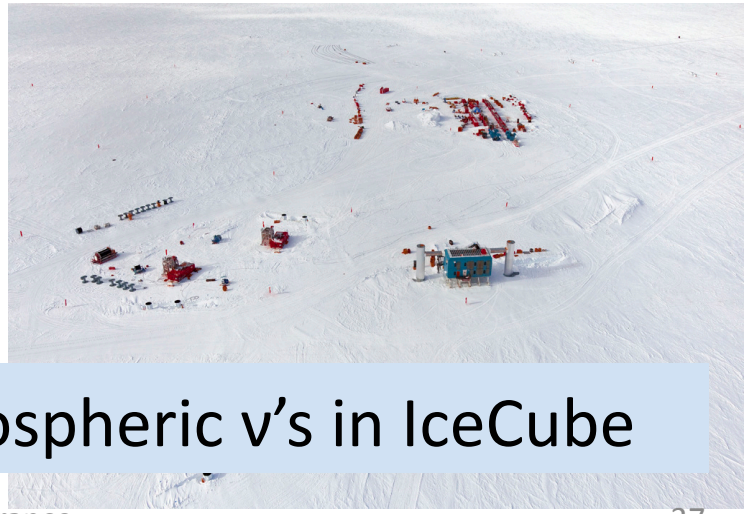


Idea: Reactor neutrinos at 60km





Existing: Accellerator ν's

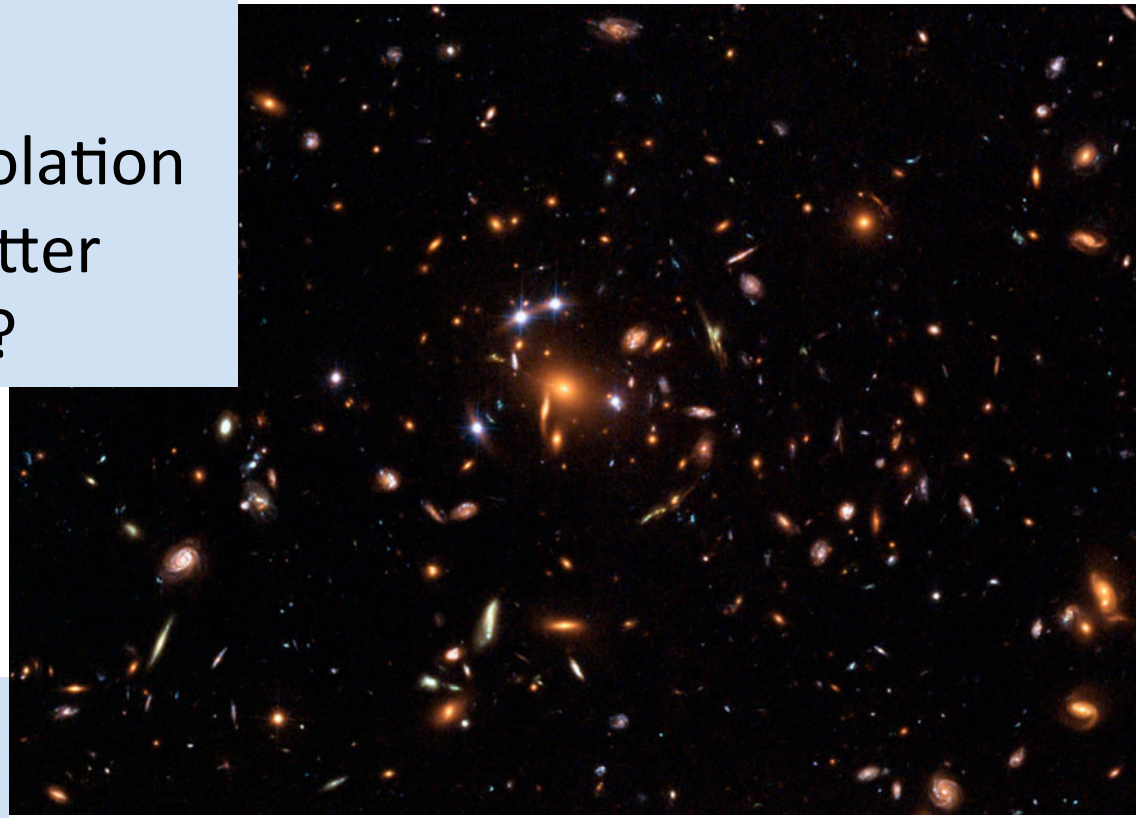


Idea: Atmospheric ν's in IceCube

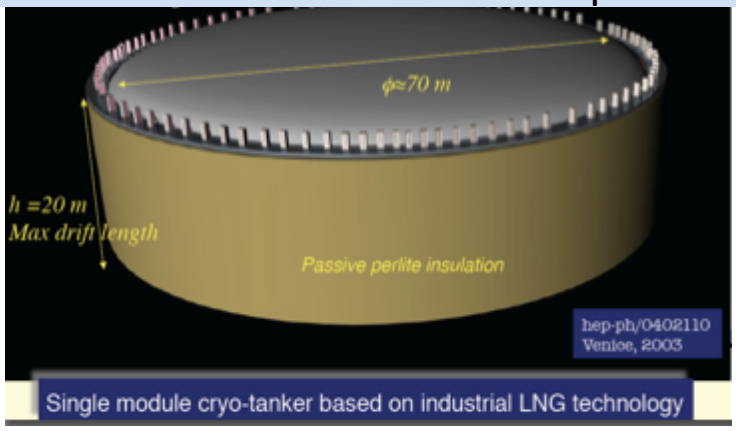
θ_{13} Consequences

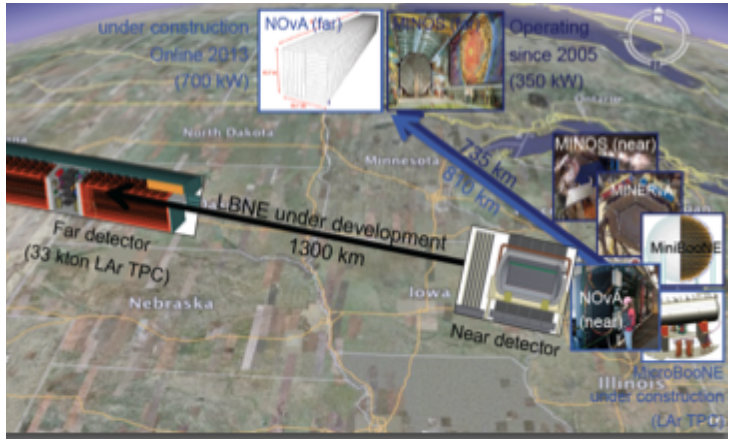
Leptogenesis

Question: Can lepton CP-violation explain the matter/anti-matter asymmetry of the universe?



Next generation experiments aim to measure δ_{cp}

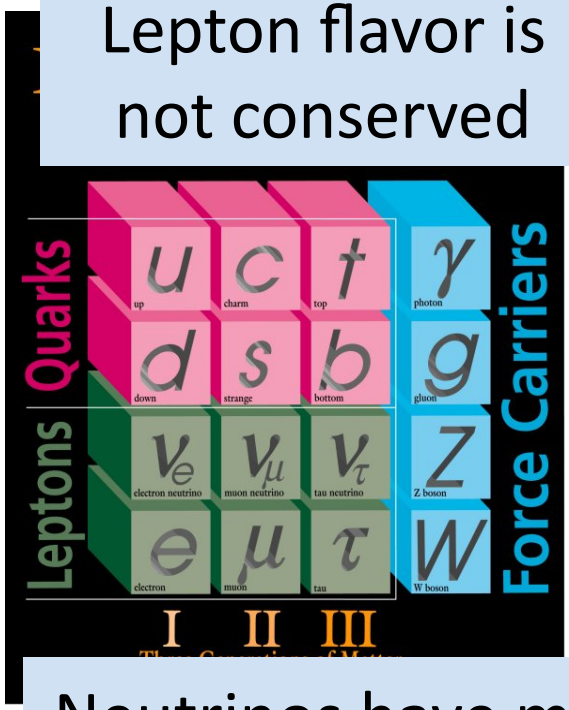




Consequences

Neutrino Oscillation implies…

Lepton flavor is not conserved



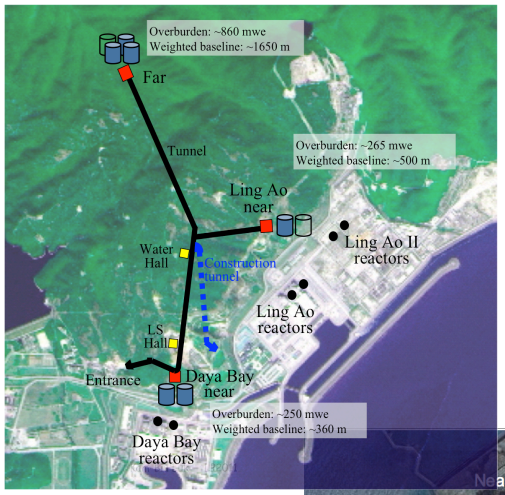
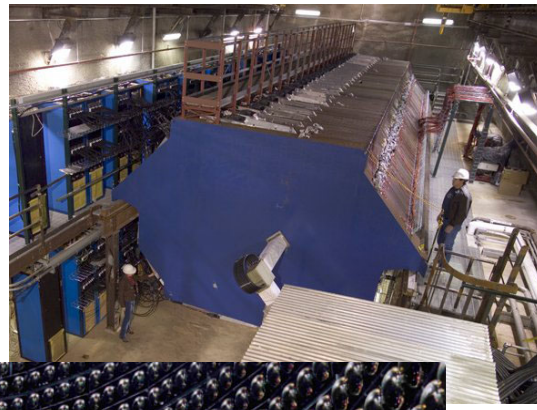
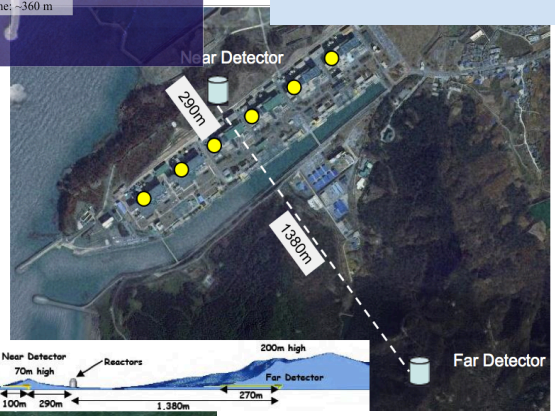
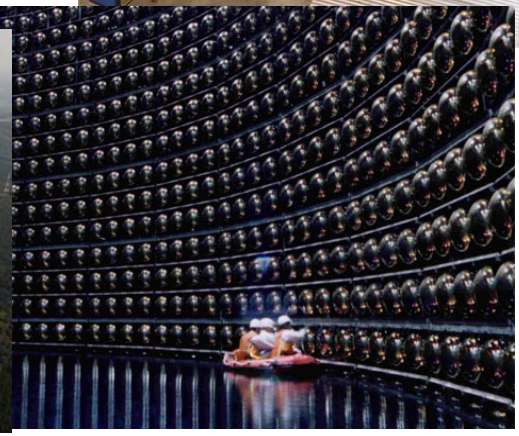
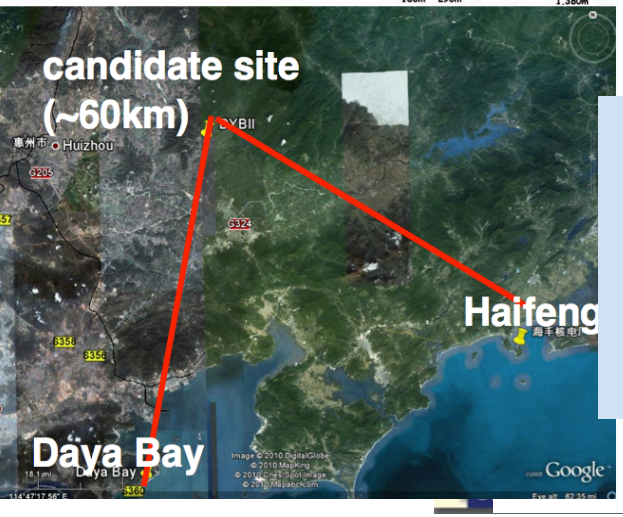
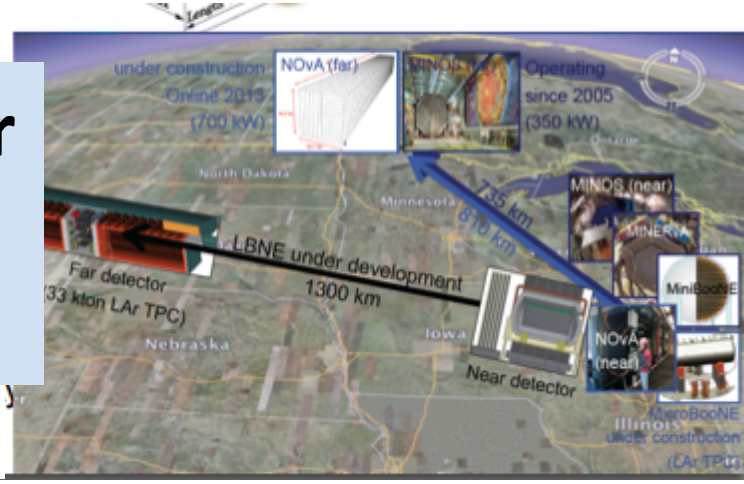
Neutrinos have mass

More mass in neutrinos than all visible stars and galaxies?

Right-handed neutrinos exist

Summary

Past year of results has given us θ_{13}

Running experiments will increase precision

Value of θ_{13} allows for mass hierarchy and δ_{cp} measurements