Recent results and prospects from neutrino oscillation experiments

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10/23/2008
Division of Nuclear Physics (Oakland, Oct. 2008)

Thanks to speakers at
NNN08(Paris, Sep08) and UDiG(BNL, Oct08)

Brief review of oscillations

Assume a 2×2 neutrino mixing matrix.

$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\begin{aligned} \nu_a(t) &= \cos(\theta)\nu_1(t) + \sin(\theta)\nu_2(t) \\ P(\nu_a \to \nu_b) &= |<\nu_b|\nu_a(t)>|^2 \\ &= \sin^2(\theta)\cos^2(\theta)|e^{-iE_2t} - e^{-iE_1t}|^2 \end{aligned}$$

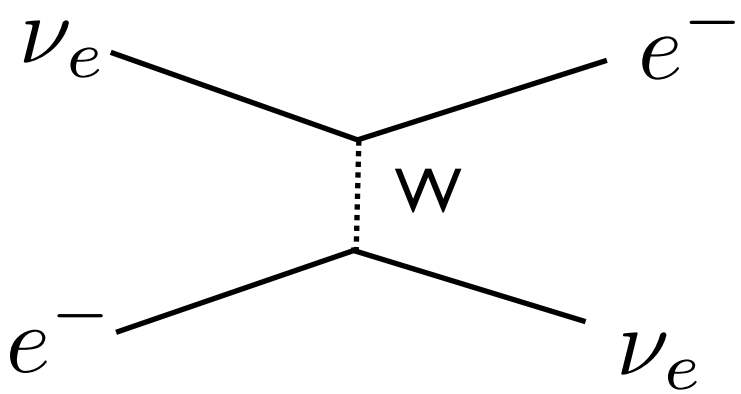
Sufficient to understand most of the physics:

$$P(\nu_a \to \nu_b) = \sin^2 2\theta \sin^2 \frac{1.27((m_2^2 - m_1^2)/eV^2)(L/km)}{(E/GeV)}$$

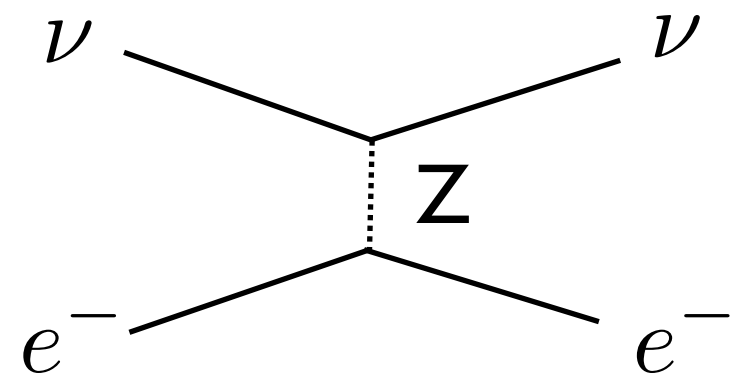
$$P(\nu_a \to \nu_a) = 1 - \sin^2 2\theta \sin^2 \frac{1.27(\Delta m^2/eV^2)(L/km)}{(E/GeV)}$$

Oscillation nodes at $\pi/2, 3\pi/2, 5\pi/2, \ldots$ $(\pi/2)$: $\Delta m^2 = 0.0025 eV^2$, $E = 1GeV$, $L = 494km$.

Matter effect arises from a difference in interaction amplitudes between different species of neutrinos.



Charged Current
for electron type only



Neutral Current
for all neutrino types

Additional potential for ν_e ($\bar{\nu}_e$): $\pm\sqrt{2}G_F N_e$

N_e is electron number density.

Oscillations in presence of matter

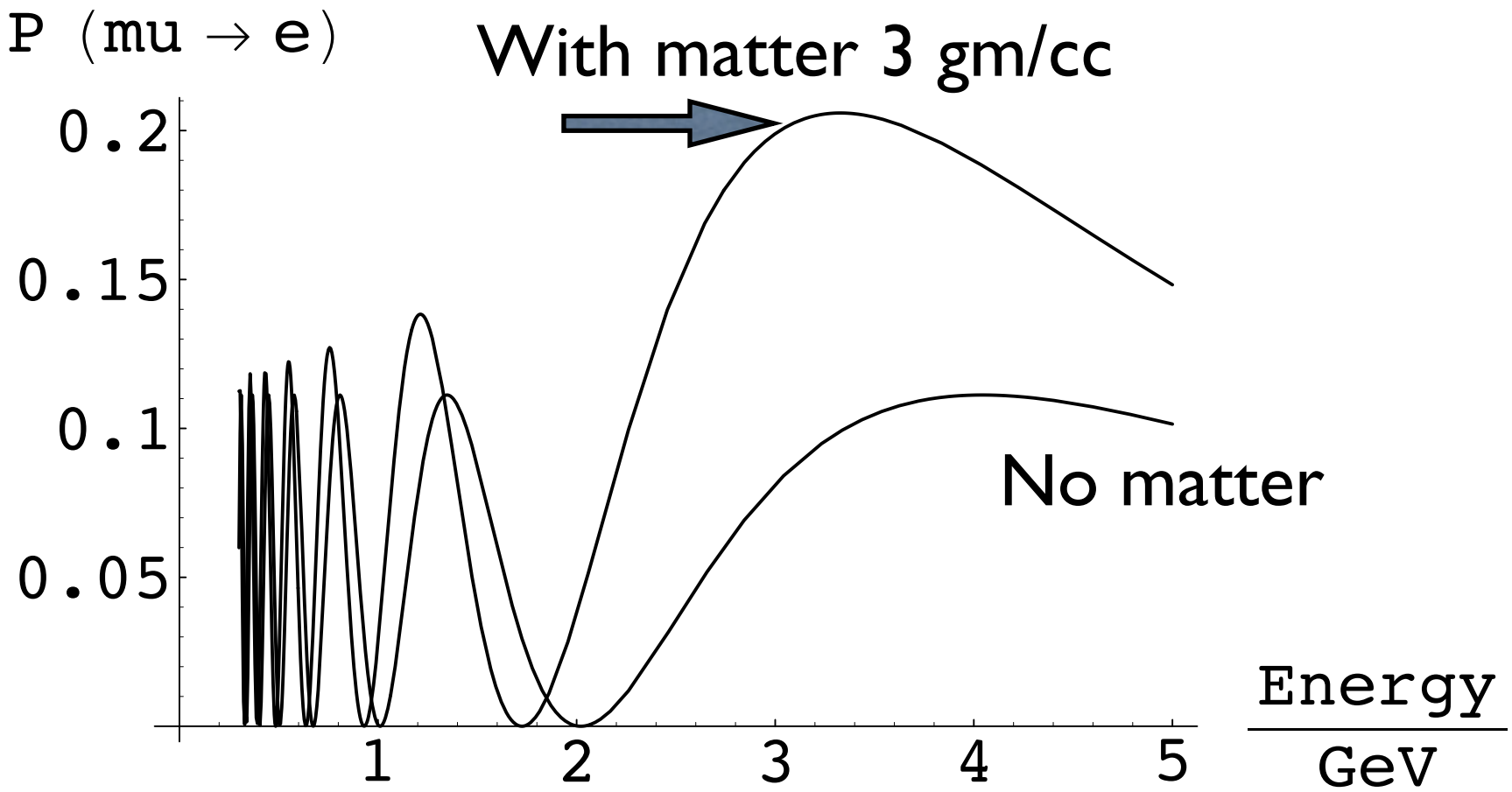
$$i\frac{d}{dx}\nu_f = R_\theta H(\nu_m) + H_{mat}(\nu_f)$$

$$i\frac{d}{dx}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \frac{1}{4E}\left(R_\theta\begin{pmatrix}m_1^2 & 0\\ 0 & m_2^2\end{pmatrix}R_\theta^T + 2E\begin{pmatrix}\sqrt{2}G_F N_e & 0\\ 0 & -\sqrt{2}G_F N_e\end{pmatrix}\right)\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} \quad (3)$$

$$P_{\mu\to e} = \frac{\sin^2 2\theta}{(\cos 2\theta - a)^2 + \sin^2 2\theta}\times\sin^2\frac{L\Delta m^2}{4E}\sqrt{(a-\cos 2\theta)^2 + \sin^2 2\theta}$$

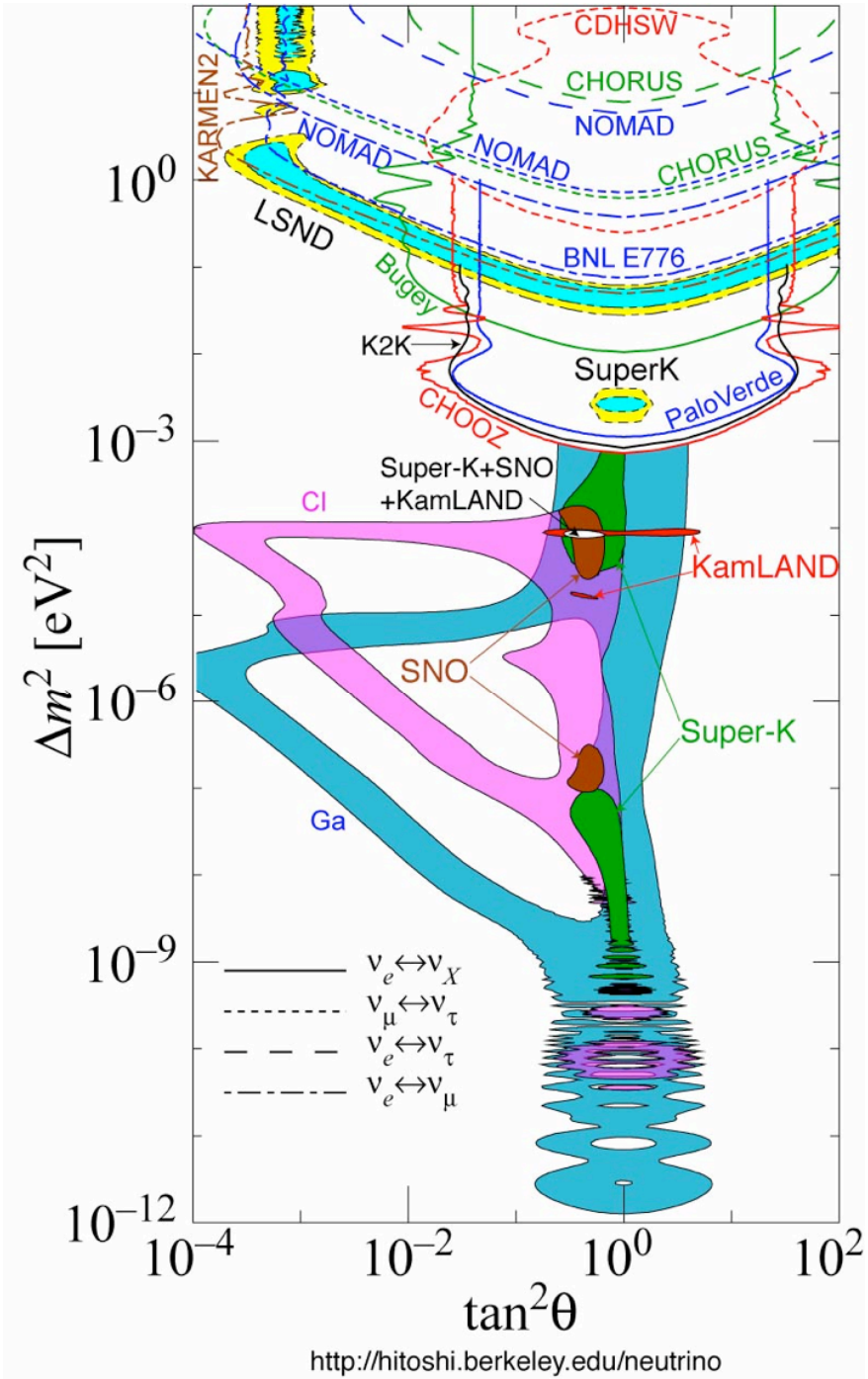
$$\begin{aligned} a &= 2\sqrt{2}EG_F N_e/\Delta m^2 \\ &\approx 7.6\times 10^{-5}\times D/(gm/cc)\times E_\nu/GeV/(\Delta m^2/eV^2) \end{aligned} \quad (4)$$

Matter effect with 2-neutrinos



Osc. probability: 0.0025 eV^2, L= 2000 km, Theta=10deg

Summary of experiments



$\theta_{atmospheric}$ (primarily θ_{23})

θ_{solar} (primarily θ_{12})

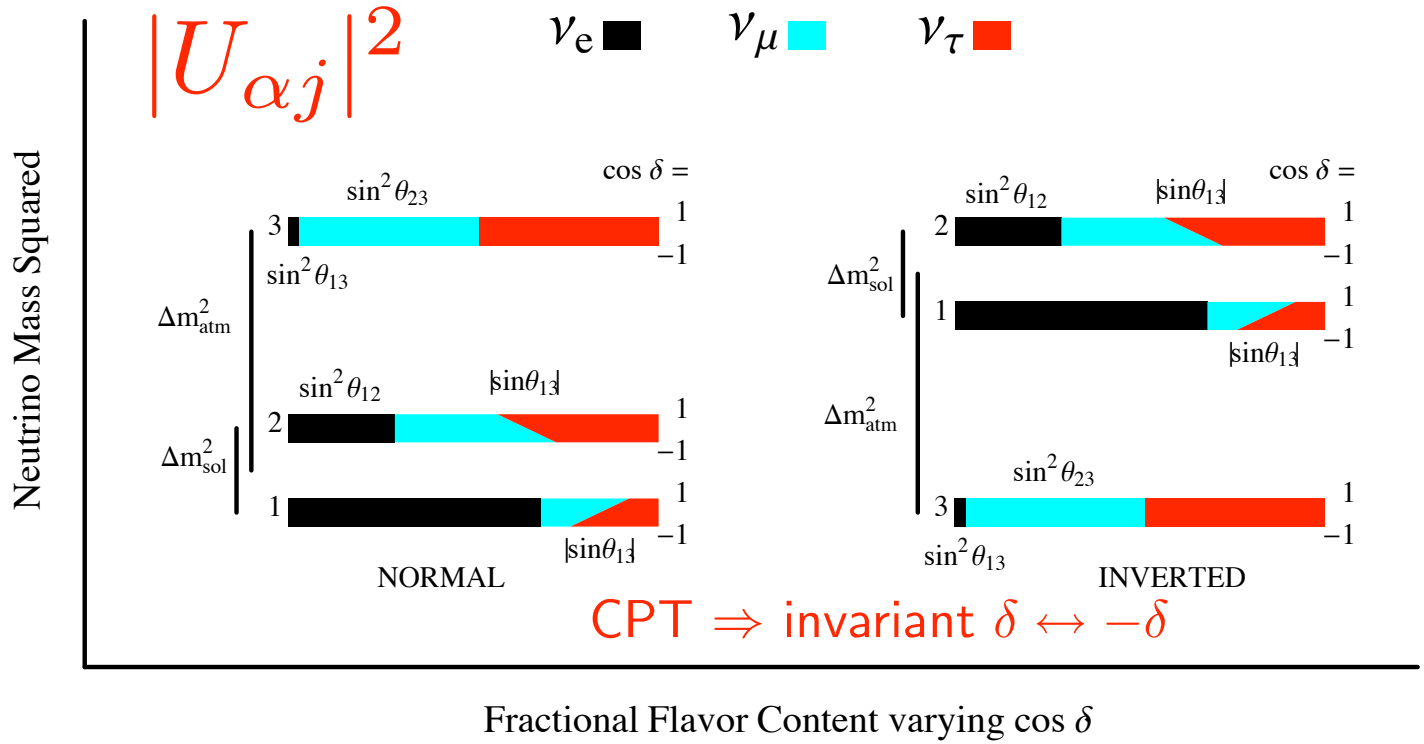
Mixing Matrix:

$$|\nu_e,\ \nu_\mu,\ \nu_\tau\rangle^T_{flavor} = U_{\alpha i}\ |\nu_1,\ \nu_2,\ \nu_3\rangle^T_{mass}$$

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

Atmos. L/E $\mu \to \tau$ Atmos. L/E $\mu \leftrightarrow e$ Solar L/E $e \to \mu, \tau$ $0\nu\beta\beta$ decay

500km/GeV 15km/MeV



$$\delta m^2_{sol} = +7.6 \times 10^{-5}\ eV^2$$

$$|\delta m^2_{atm}| = 2.4 \times 10^{-3}\ eV^2$$

$$|\delta m^2_{sol}|/|\delta m^2_{atm}| \approx 0.03$$

$$\sqrt{\delta m^2_{atm}} = 0.05\ eV < \sum m_{\nu_i} < 0.5\ eV = 10^{-6} * m_e$$

$$\sin^2\theta_{12} \sim 1/3$$

$$\sin^2\theta_{23} \sim 1/2$$

$$\sin^2\theta_{13} < 3\%$$

$$0 \leq \delta < 2\pi$$

One Global Fit:

Dominated by

parameter	best fit	2σ	3σ
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.65^{+0.23}_{-0.20}$	7.25–8.11	7.05–8.34
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$	$2.40^{+0.12}_{-0.11}$	2.18–2.64	2.07–2.75
$\sin^2\theta_{12}$	$0.304^{+0.022}_{-0.016}$	0.27–0.35	0.25–0.37
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	0.39–0.63	0.36–0.67
$\sin^2\theta_{13}$	$0.01^{+0.016}_{-0.011}$	≤ 0.040	≤ 0.056

KamLAND
MINOS
SNO
SuperK
Chooz

arXiv:0808.2016
Schwetz, Tortola, Valle

$\nu_\mu \to \nu_e$ with matter effect

Approximate formula (M. Freund)

matter effect ~E

~7500 km
no CPV.
magic bln

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(\hat{A}-1)^2}\sin^2((\hat{A}-1)\Delta)$$

$$+\alpha\frac{8J_{CP}}{\hat{A}(1-\hat{A})}\sin(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)$$

$$+\alpha\frac{8I_{CP}}{\hat{A}(1-\hat{A})}\cos(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)$$

$$+\alpha^2\frac{\cos^2\theta_{23}\sin^2 2\theta_{12}}{\hat{A}^2}\sin^2(\hat{A}\Delta)$$

CPV term
approximate
dependence
~L/E

solar term

linear dep.

$$J_{CP} = 1/8\sin\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$

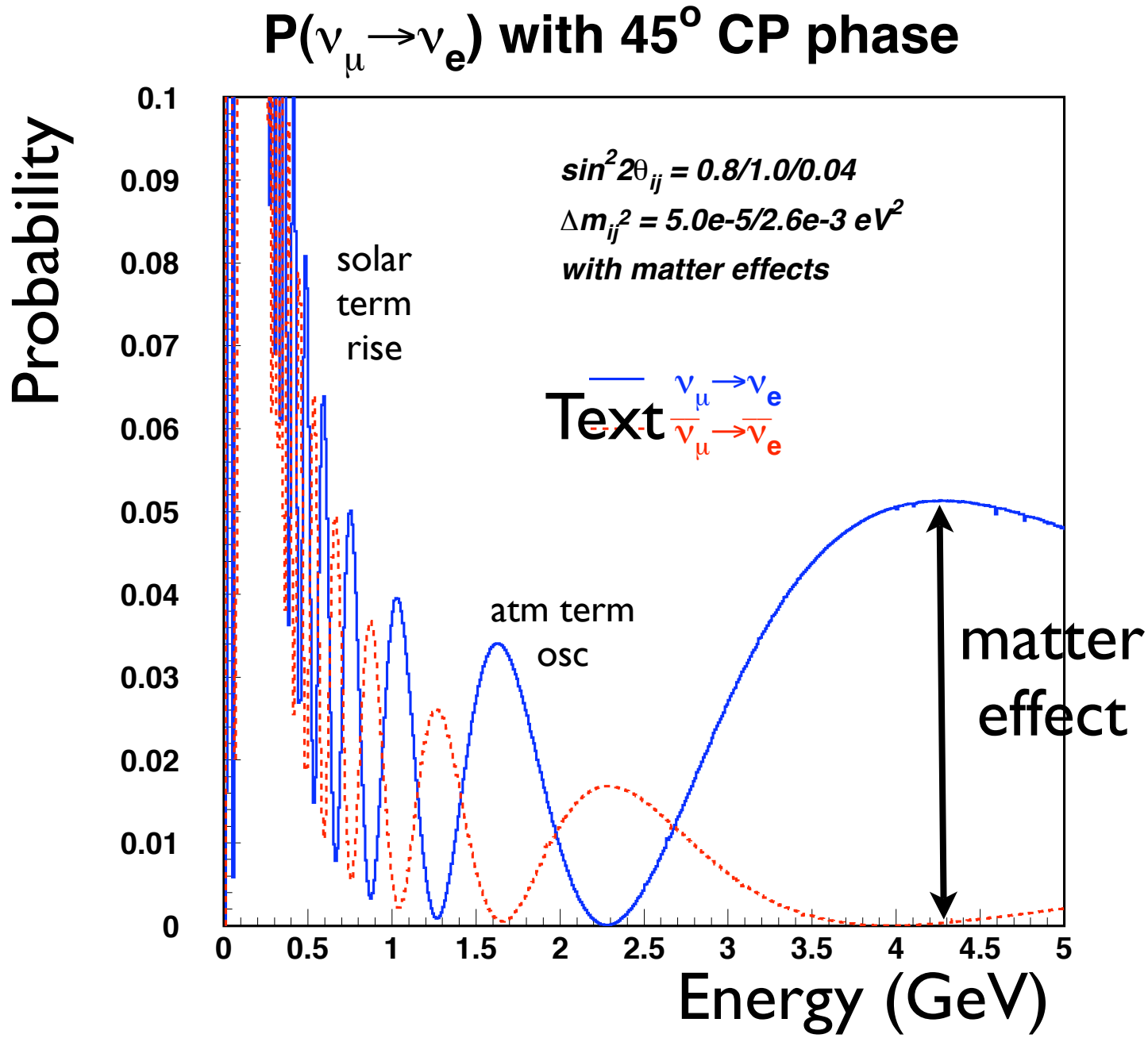
$$I_{CP} = 1/8\cos\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$

$$\alpha = \Delta m^2_{21}/\Delta m^2_{31},\ \Delta = \Delta m^2_{31}L/4E$$

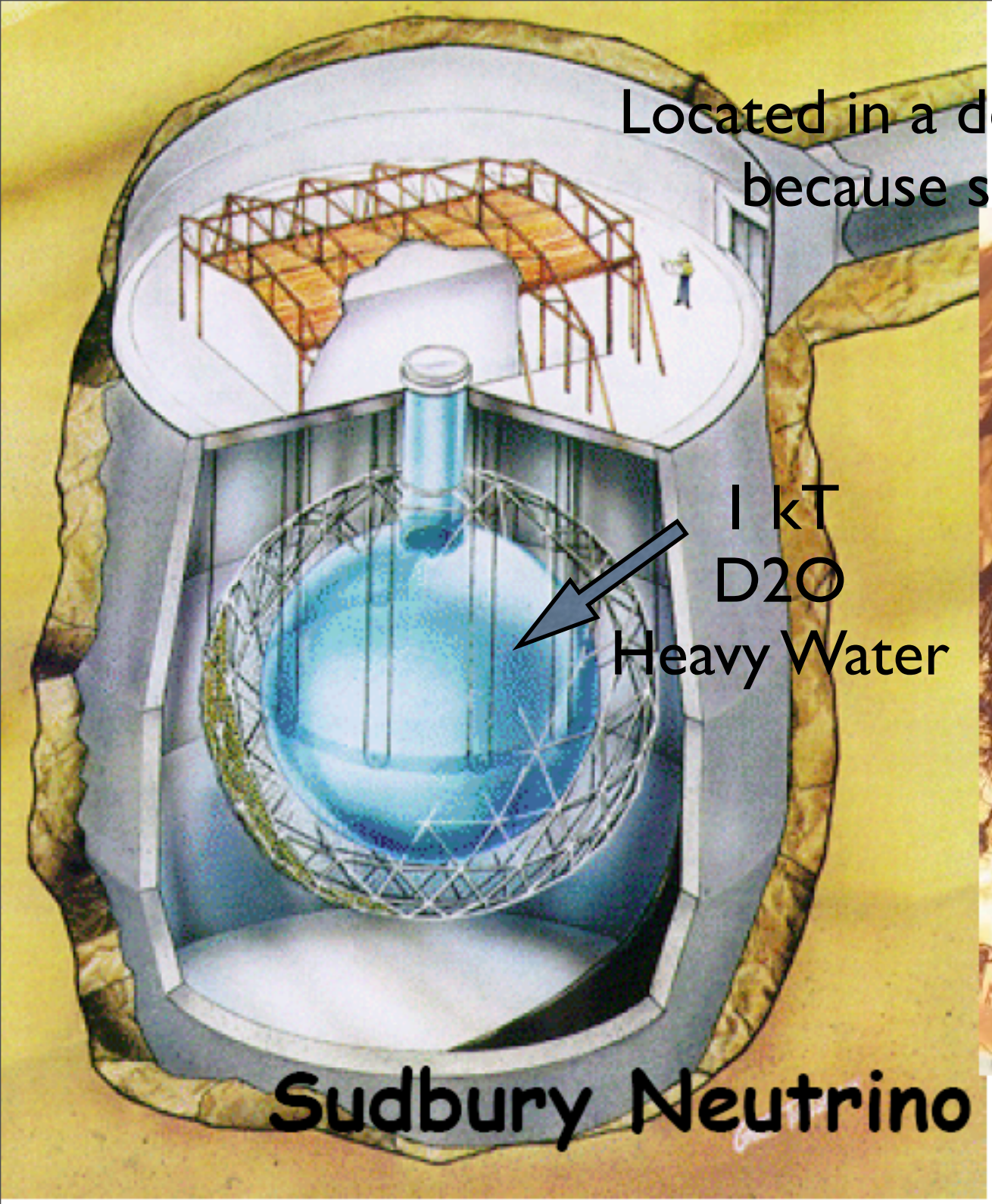
$$\hat{A} = 2VE/\Delta m^2_{31} \approx (E_\nu/GeV)/11 \text{ For Earth's crust.}$$

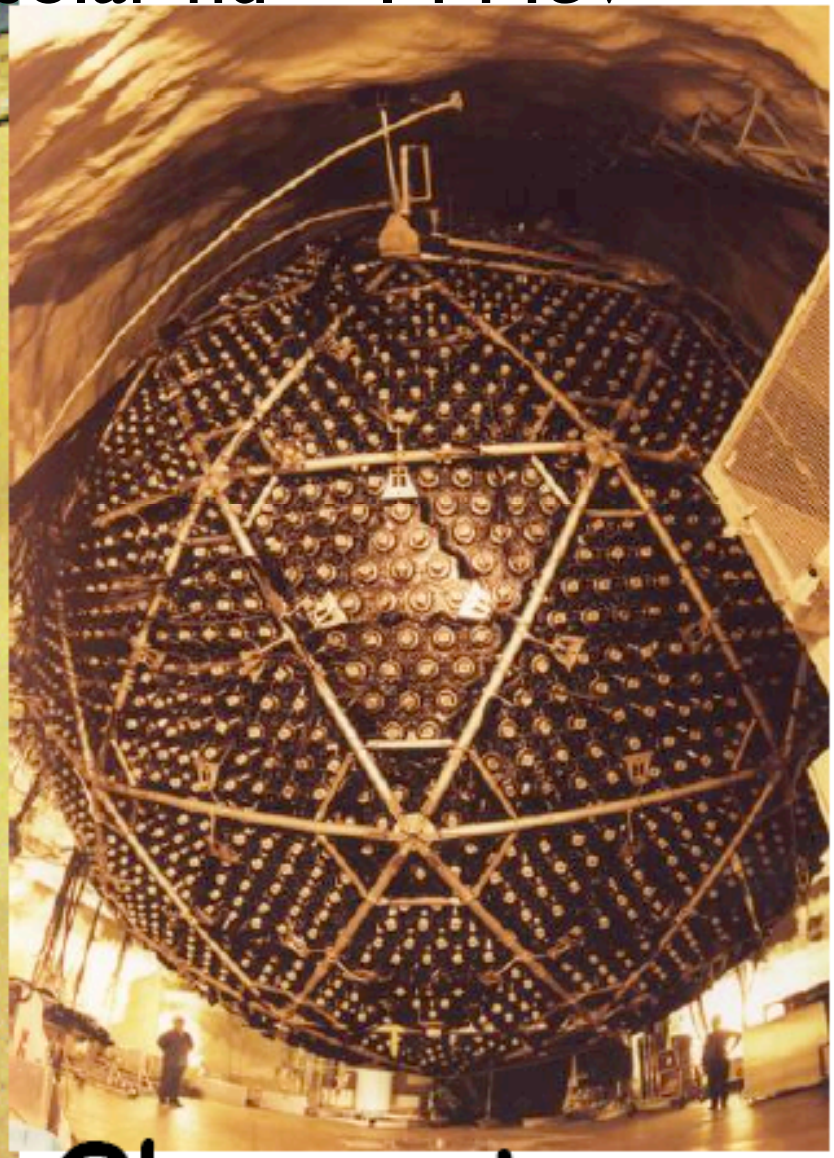
CP asymmetry
grows as θ13
becomes smaller

Example of oscillation probability with matter effects L=2540 km



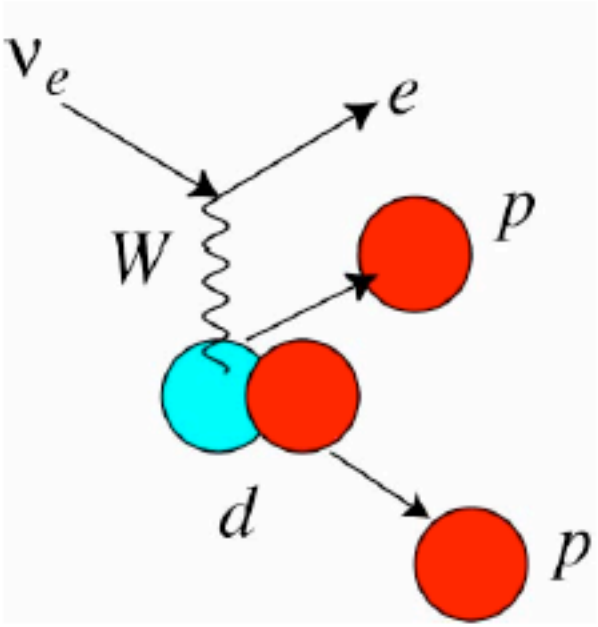
Located in a deep mine ~ 6000 mwe
because solar nu < 14 MeV



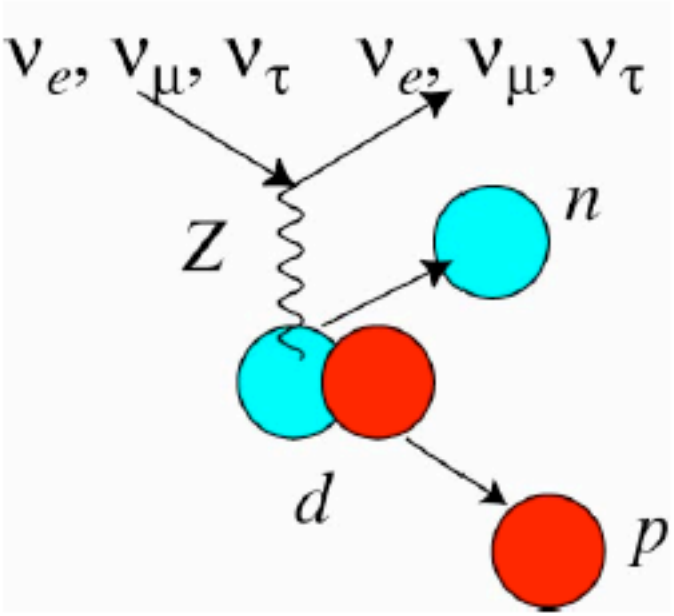


Sudbury Neutrino Observatory

Why does SNO use $300M worth of heavy water?



Charged Current

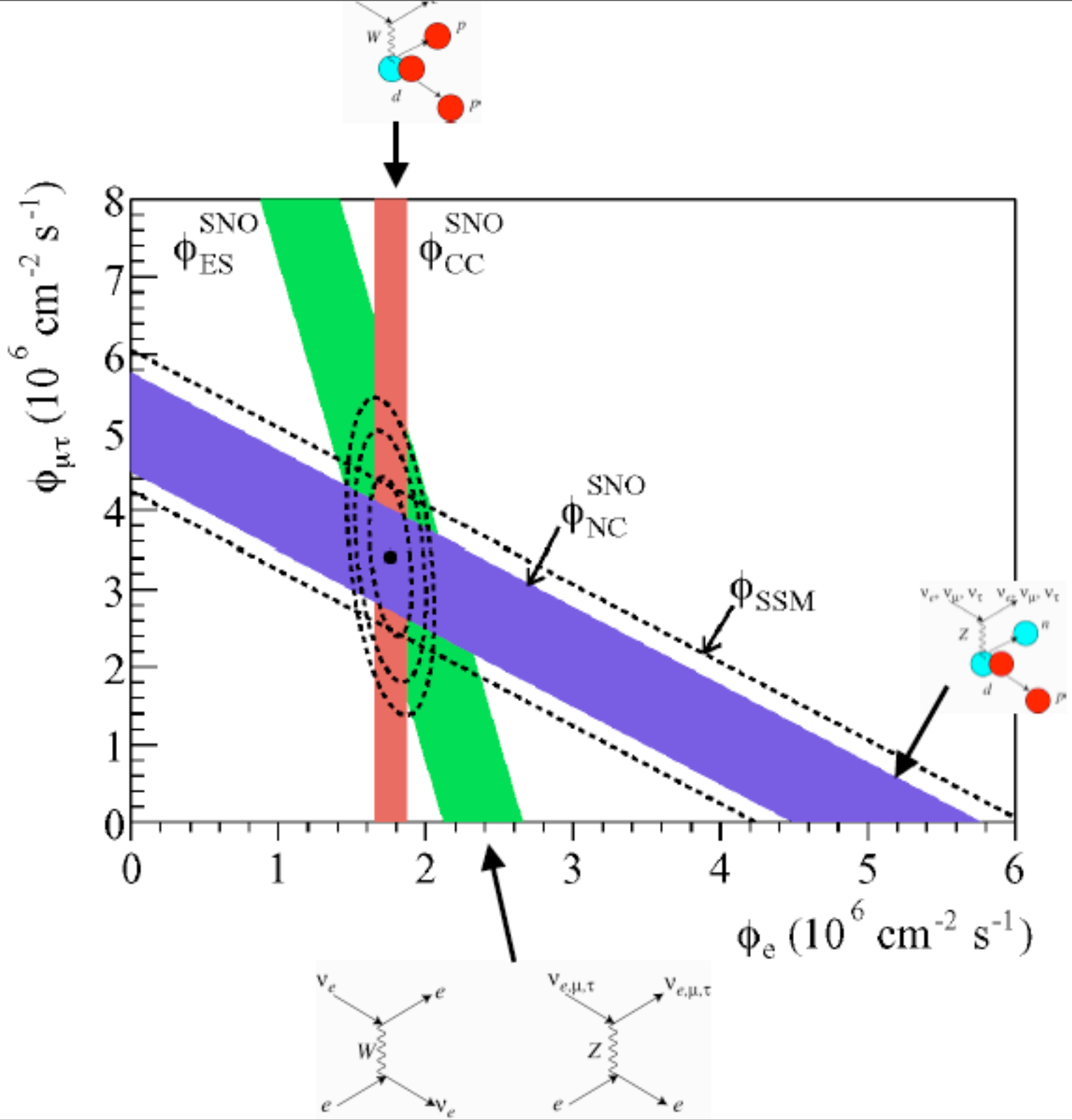


Neutral Current

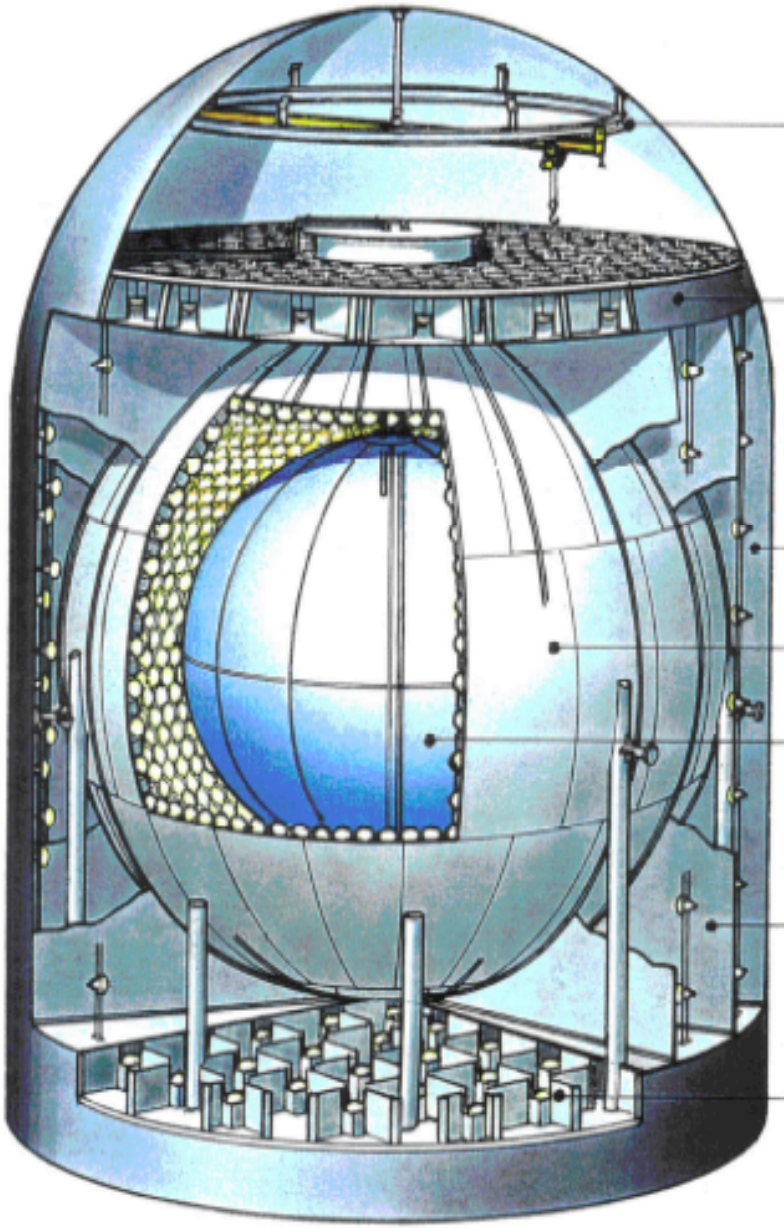
Fluxes

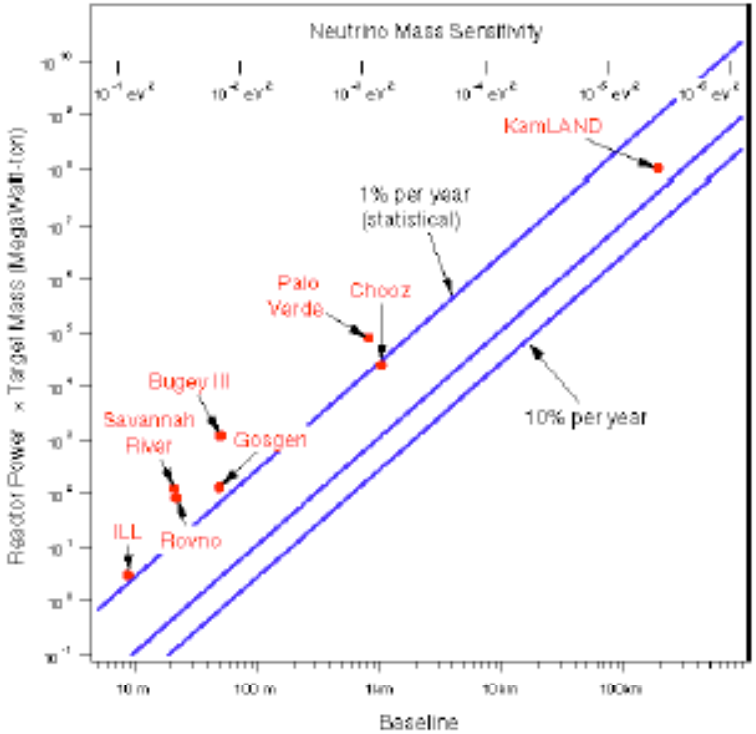
(10^6 cm^{-2} s^{-1})

ν_e:	1.76(11)
$\nu_{\mu\tau}$:	3.41(66)
ν_{total}:	5.09(64)
ν_{SSM}:	5.05



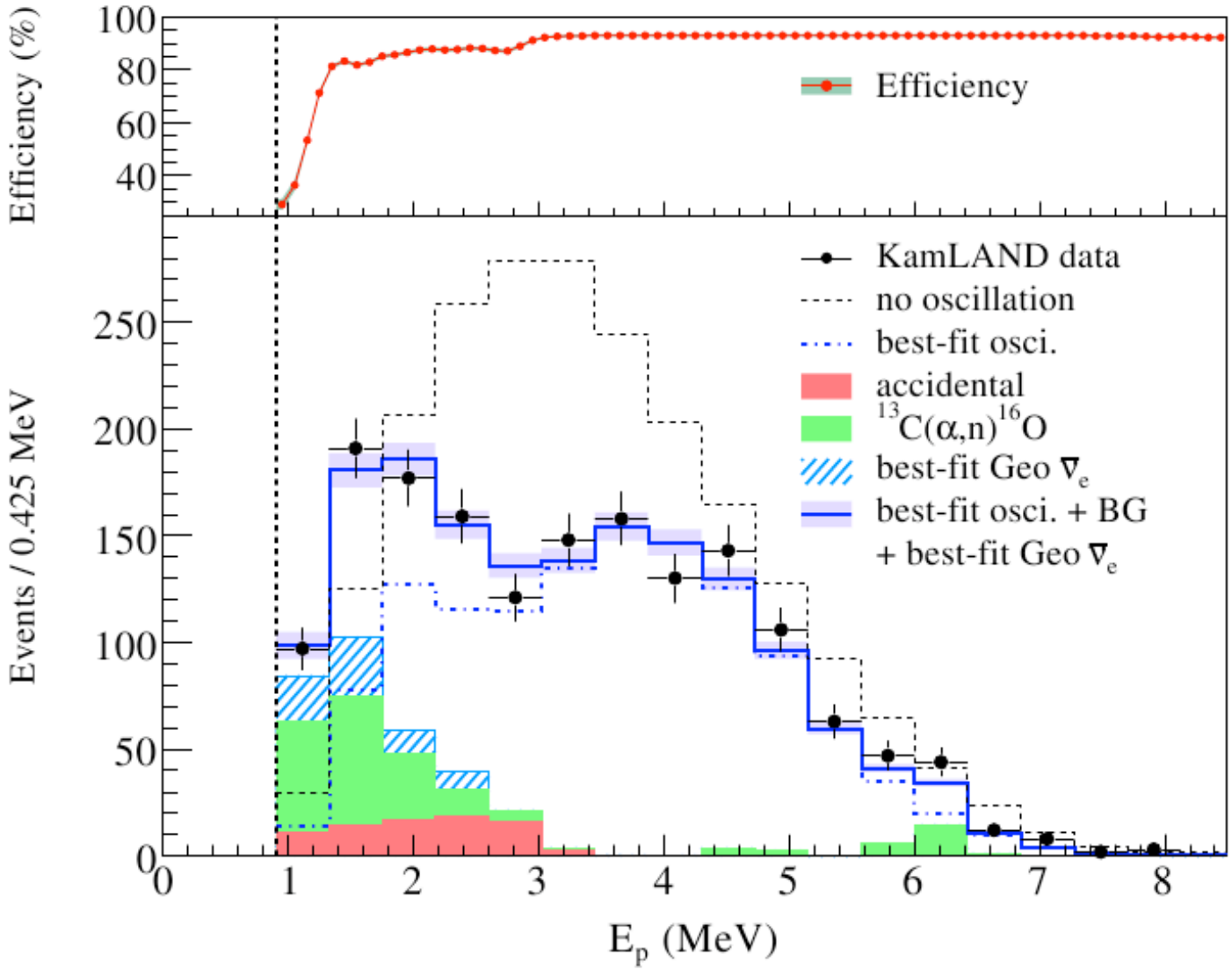
KamLAND


"Dome" Area
Steel Deck
Outer Detector
Water Cherenkov
Steel Sphere
Nylon/EVoH Balloon
Tyvek light baffles
OD PMT's


Neutrino Mass Sensitivity
KamLAND
1% per year
(statistical)
Palo
Verde
Chooz
Bugey III
Savannah
River
Gosgen
ILL
Rovno
10% per year
Reactor Power × Target Mass (MegaWatt-ton)
Baseline
10 m
100 m
1km
10km
100km

China
West Asia
South Korea
KamLAND

The full anti-neutrino energy spectrum



Plot shows the Prompt event energy (e^+ kinetic energy + $2m_e$) which can be converted to

$E_\nu \approx E_{prompt} + 0.8MeV$

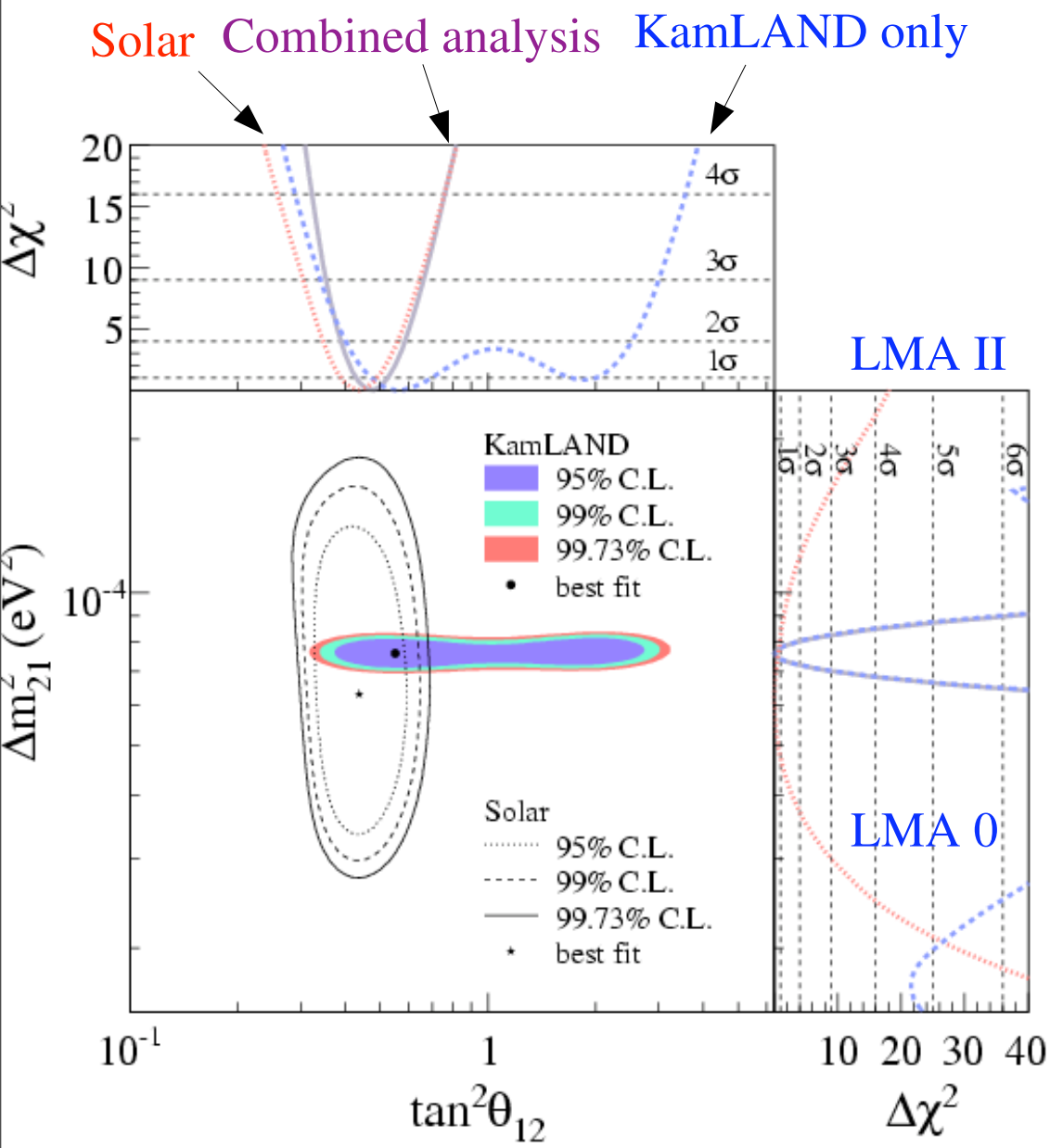
The best fit values:

$\Delta m_{21}^2 = 7.58 \times 10^{-5} (eV^2)$

$\tan^2\theta_{12} = 0.56$

Data taken between March 9, 2002 and May12, 2007, the 2.44×10^{32} proton-year exposure was used. This is the KamLAND only result (using $\theta_{13} = 0$ and taking into account reactor flux time variation). Scaled reactor spectrum (no oscillations included) was excluded at the 5.1σ level.

KamLAND + Solar oscillation analysis



KamLAND only:

$\Delta m^2 = 7.58^{+0.14}_{-0.13}(st) \pm 0.15(syst) \times 10^{-5}\ (eV^2)$

$\tan^2\theta = 0.56^{+0.10}_{-0.07}(st)^{+0.1}_{-0.06}(syst)$

KamLAND+solar:

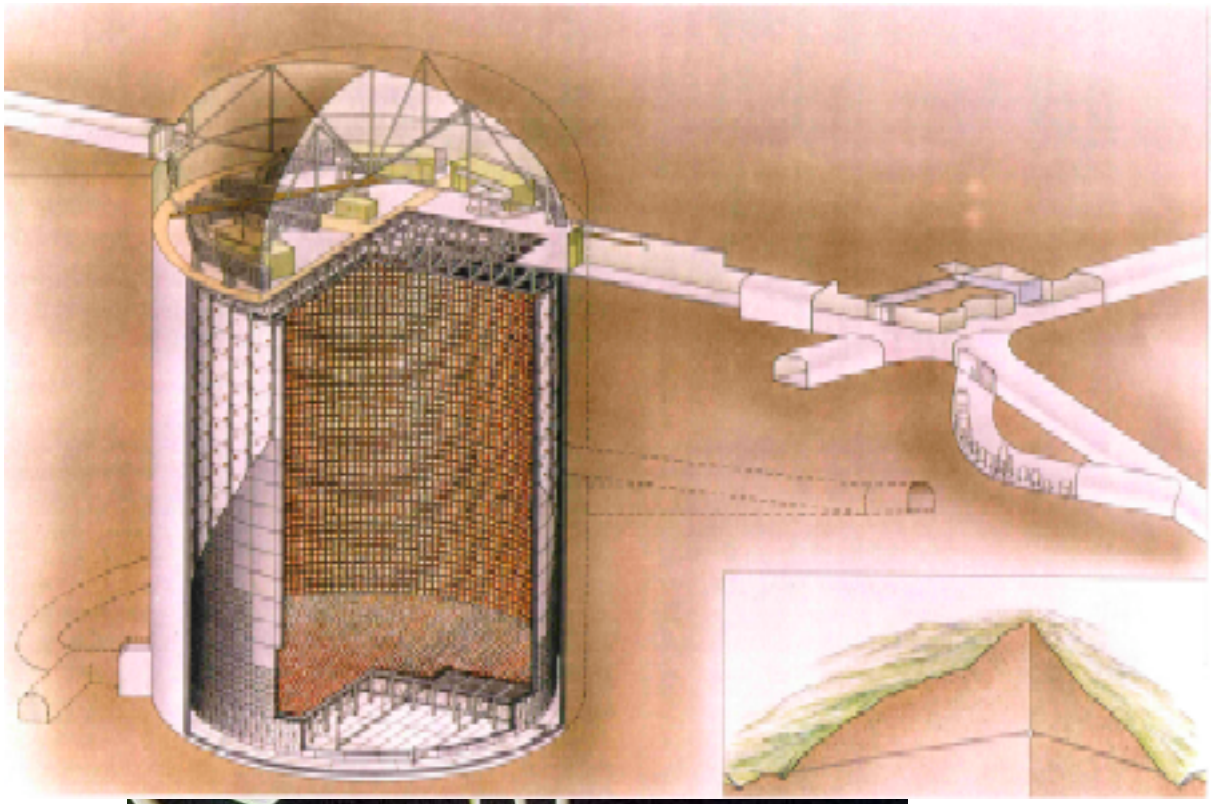
$\Delta m^2 = 7.59 \pm 0.21 \times 10^{-5} (eV^2)$

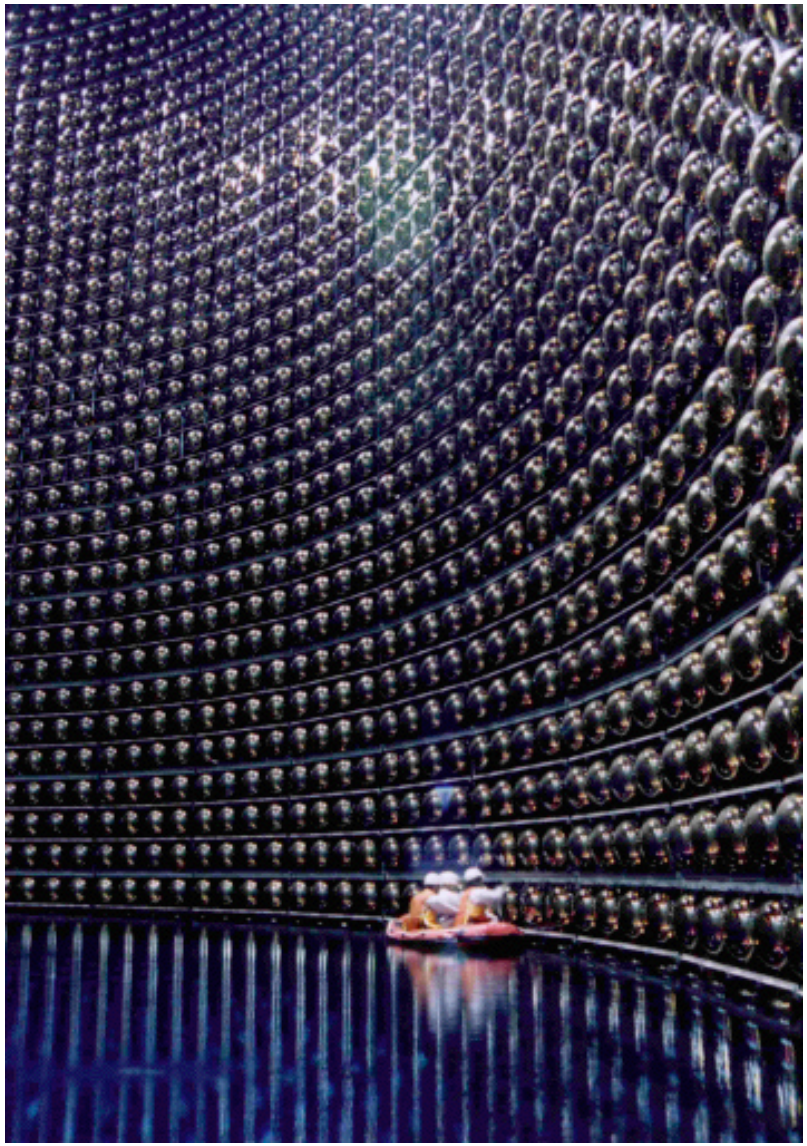
$\tan^2\theta = 0.47^{+0.06}_{-0.05}$

Only the LMA I solution remains

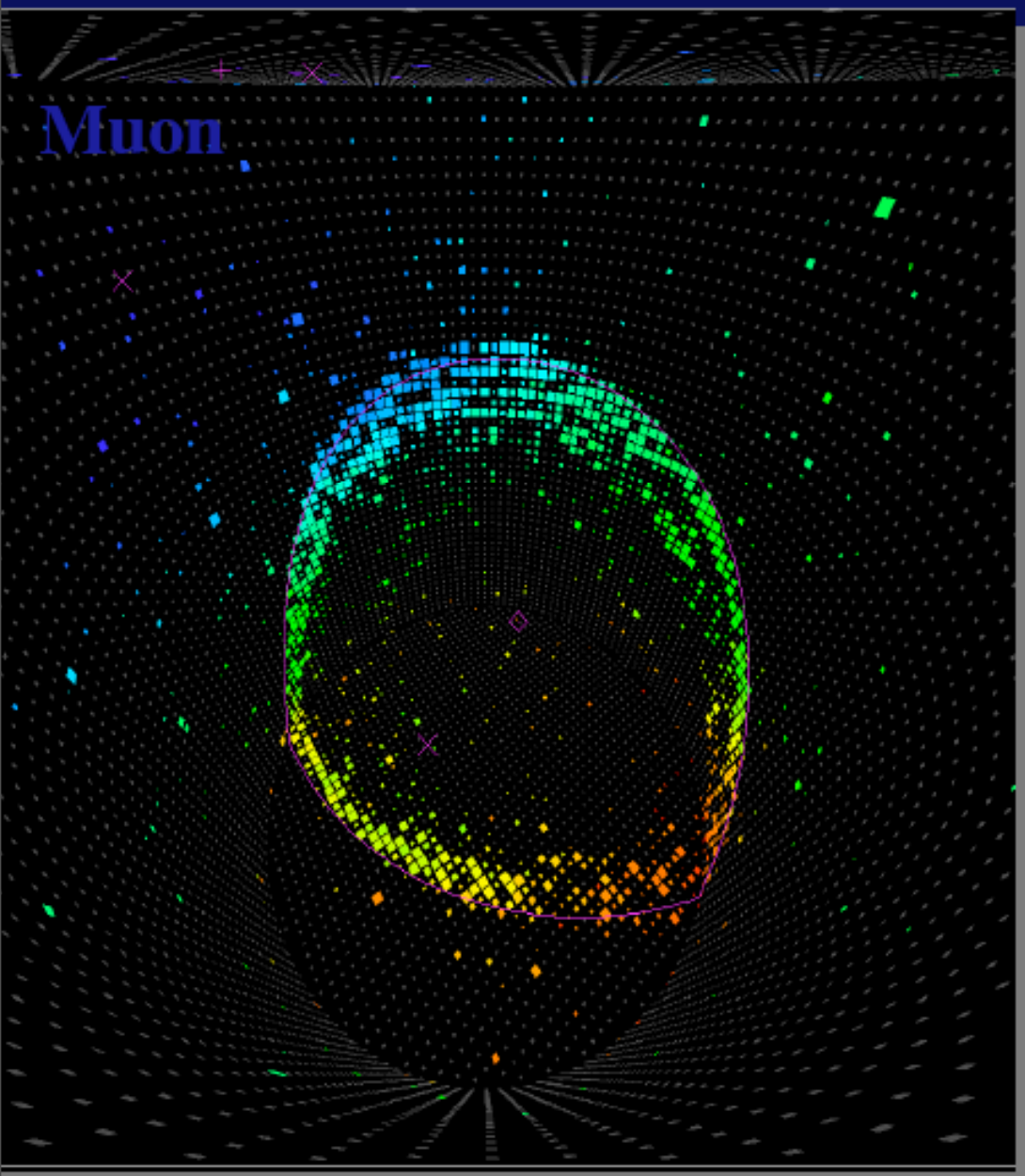
KamLAND improved result for mixing angle and Δm^2. Solar data have no effect on the Δm^2 measurement.

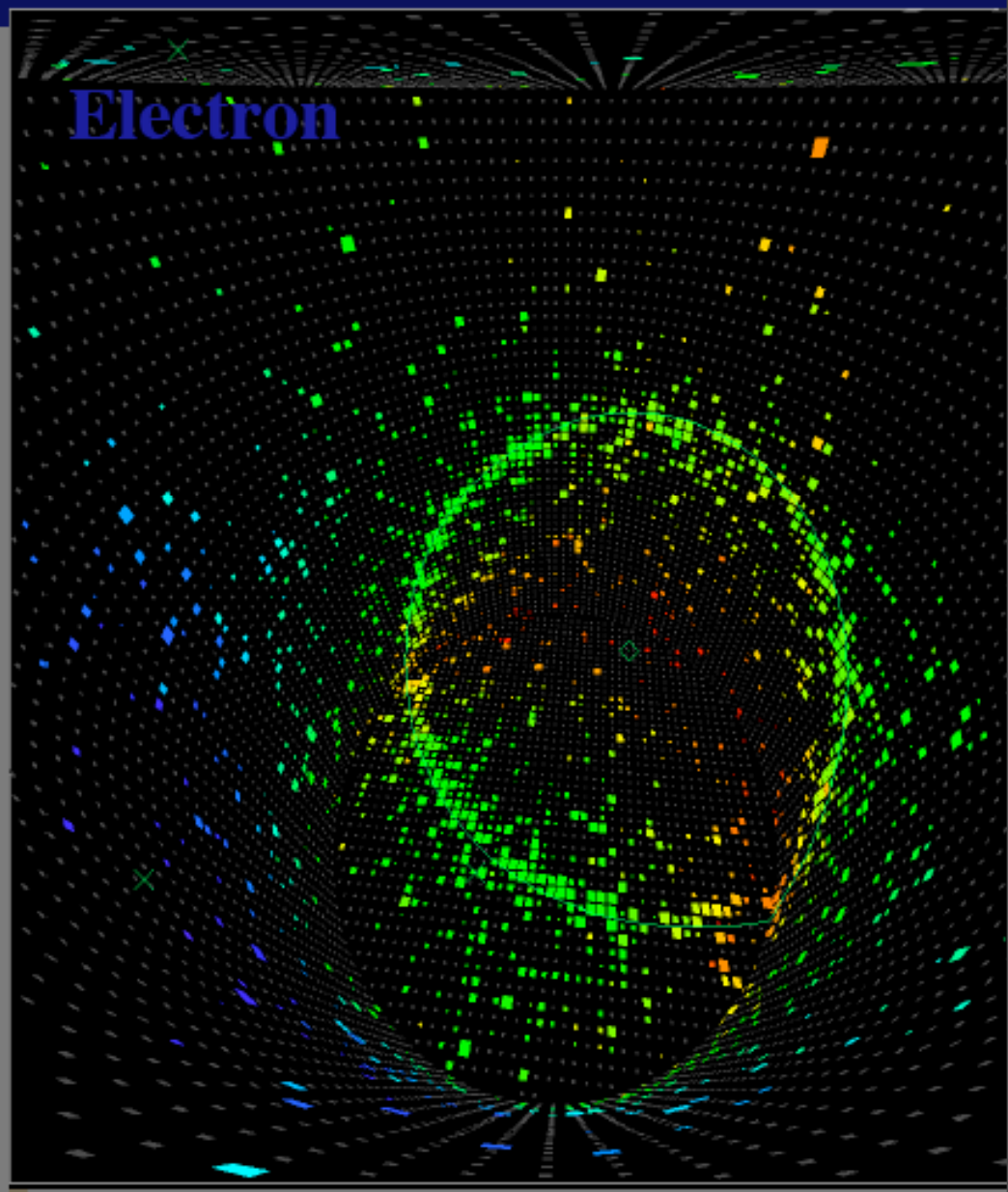
SuperKamiokaNDE





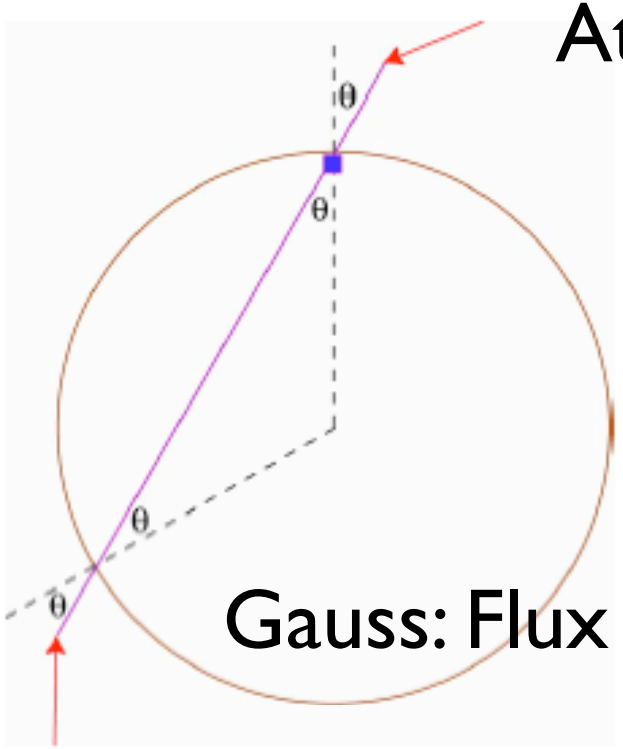
Particle Identification

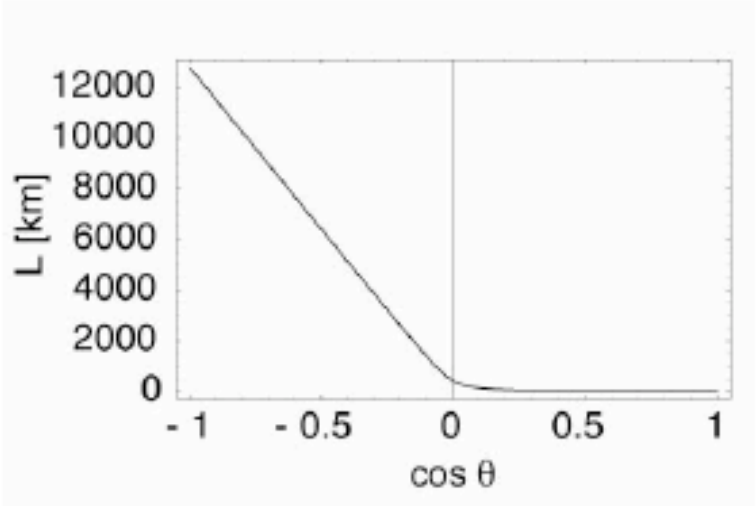


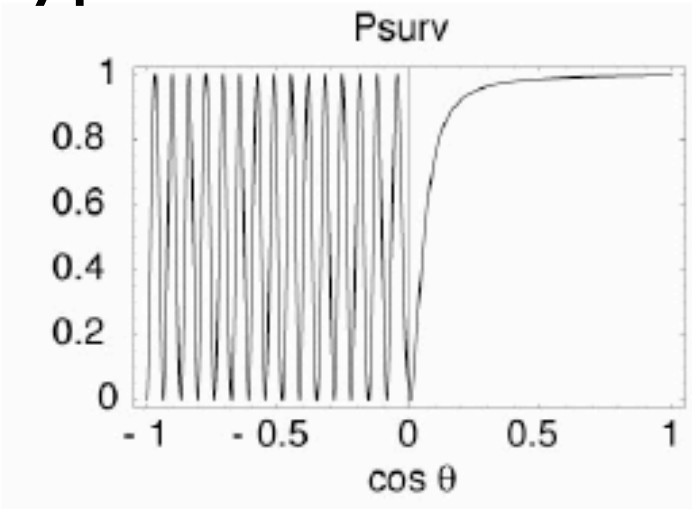


Atmospheric neutrinos as a source for oscillation experiments

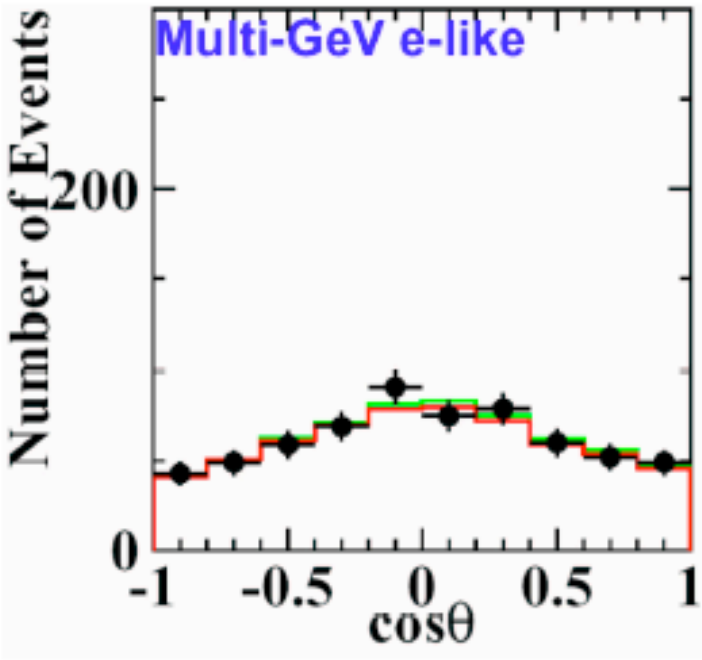
Atm. neutrinos 2:1 mu:e type

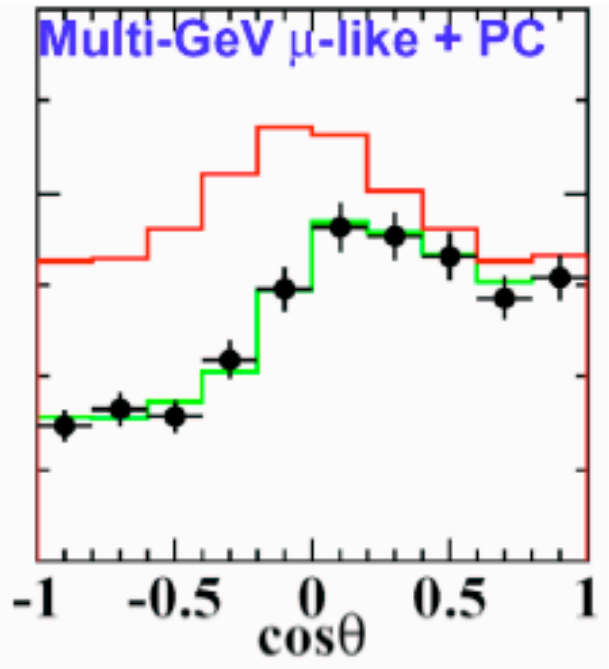






Gauss: Flux inside spherical shell isotropic

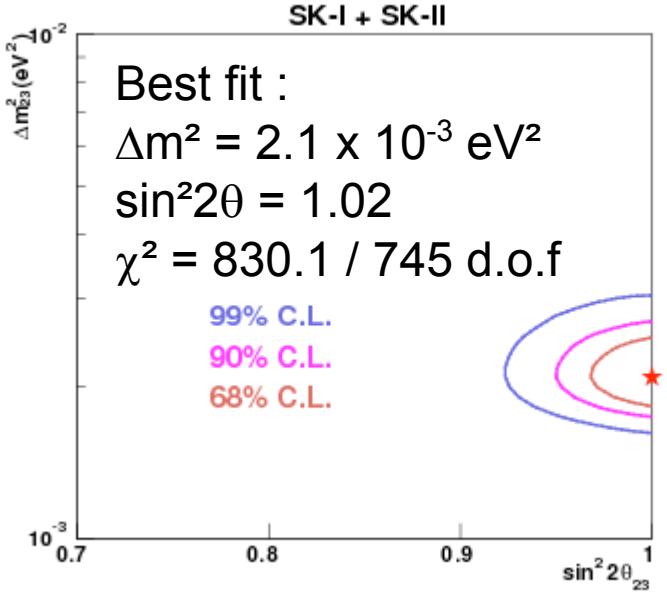




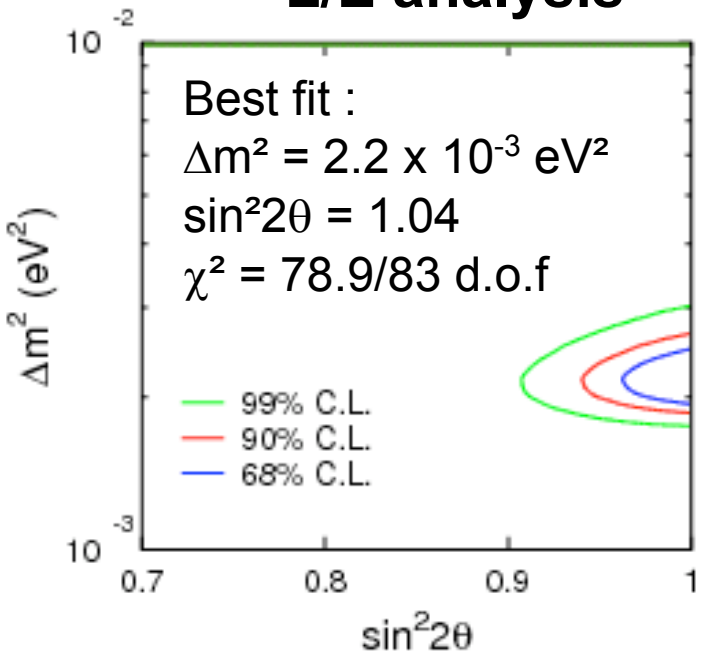
Evidence for neutrino oscillations from SuperK

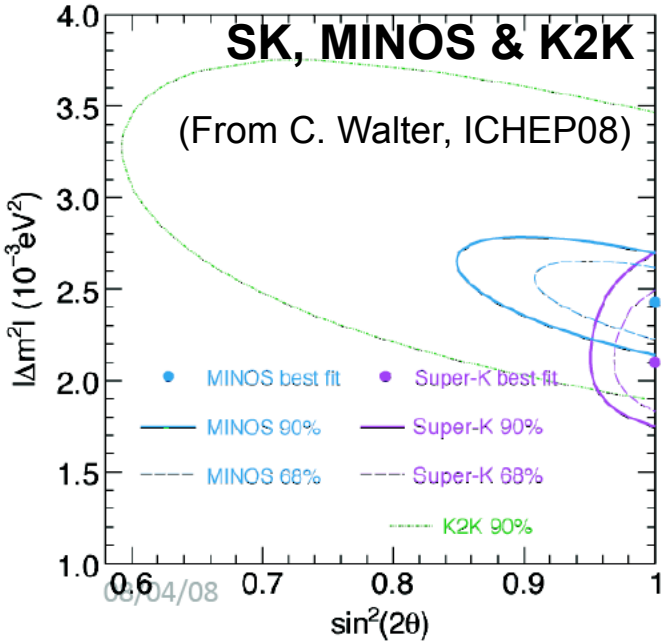
Allowed regions

Zenith angle analysis



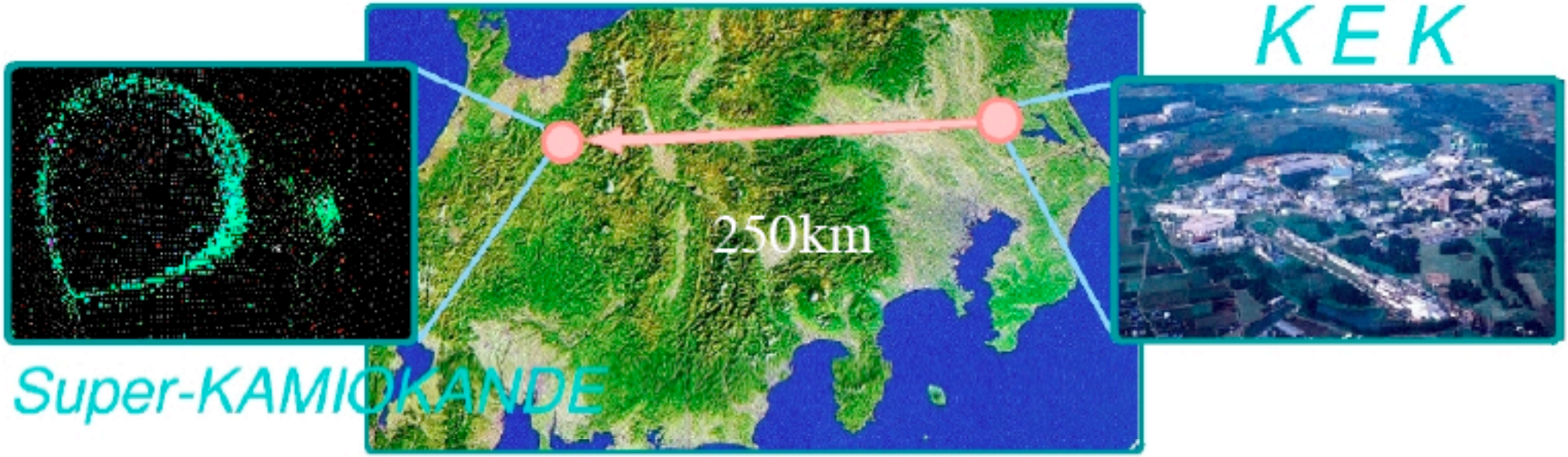
L/E analysis



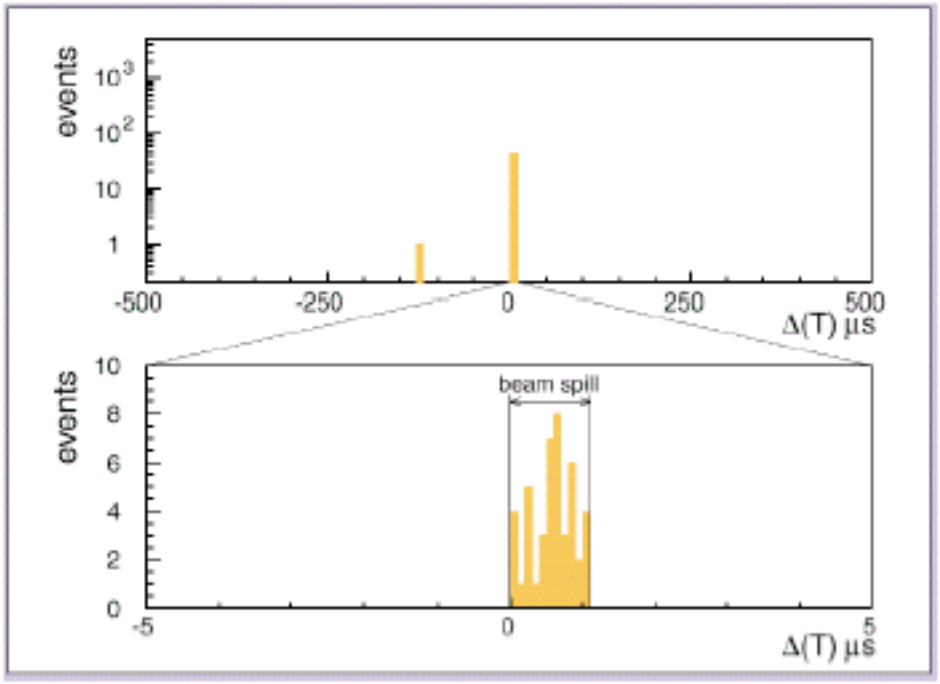


Current best measurement of θ_{23} :
~ 45±4° (10% accuracy)

Long Baseline Experiments



First LBL exp. with positive result

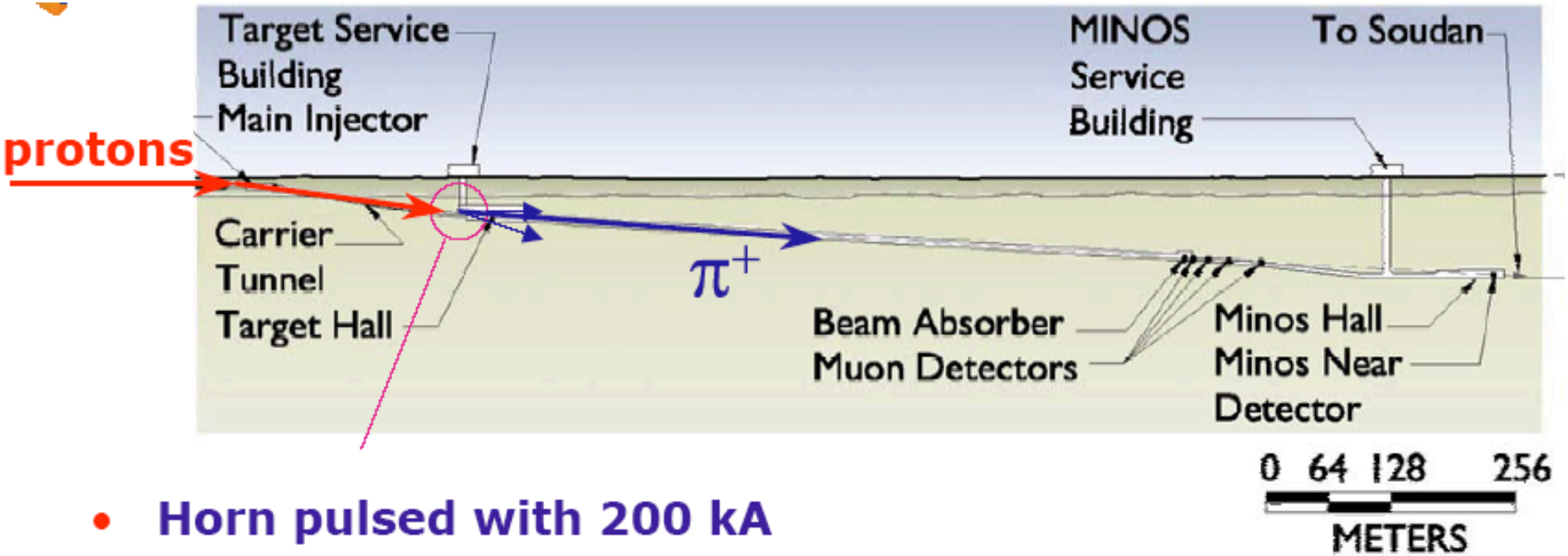


81±8 events no oscillation
56 events observed

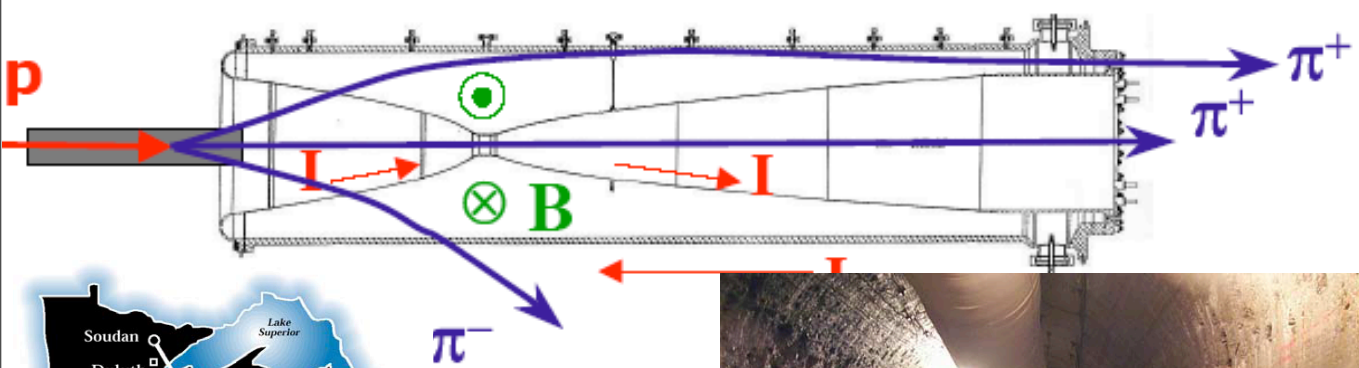
(Fermilab) Main Injector Neutrino Oscillation (MINOS) about to start running.

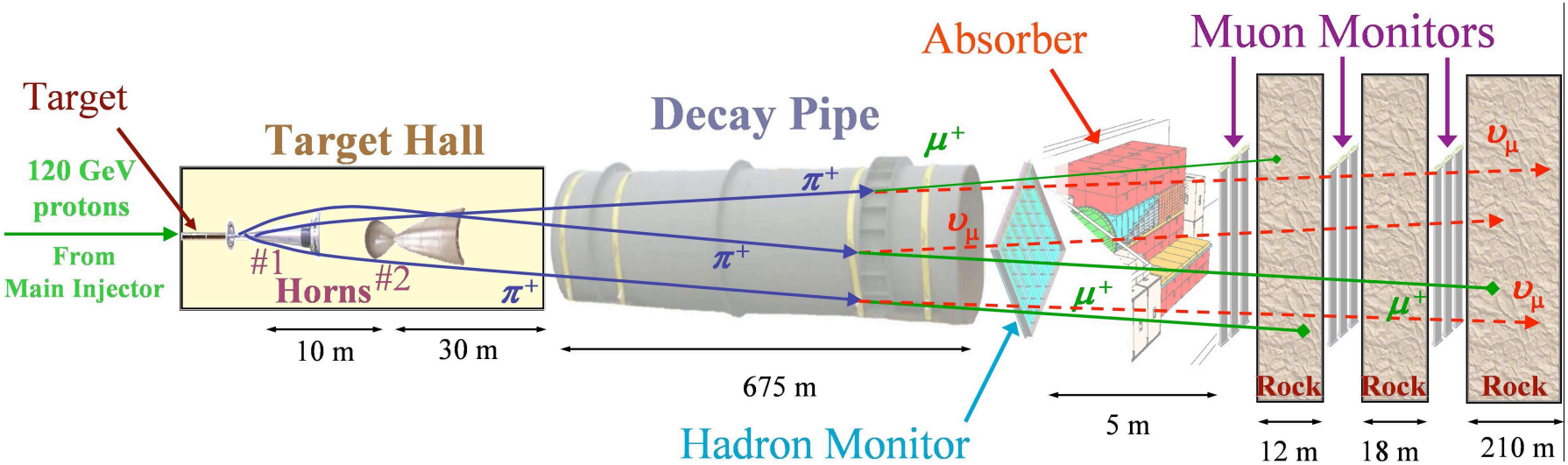
- ★ **120 GeV protons extracted from the MAIN INJECTOR in a single turn (8.7μs)**
- ★ **1.9 s cycle time**
- ★ ***i.e.* ν beam `on' for 8.7μs every 1.9 s**
- ★ **2.5×10^{13} protons/pulse**
- ★ **0.3 MW on target !**
- ★ **Initial intensity**

  2.5×10^{20} protons/year

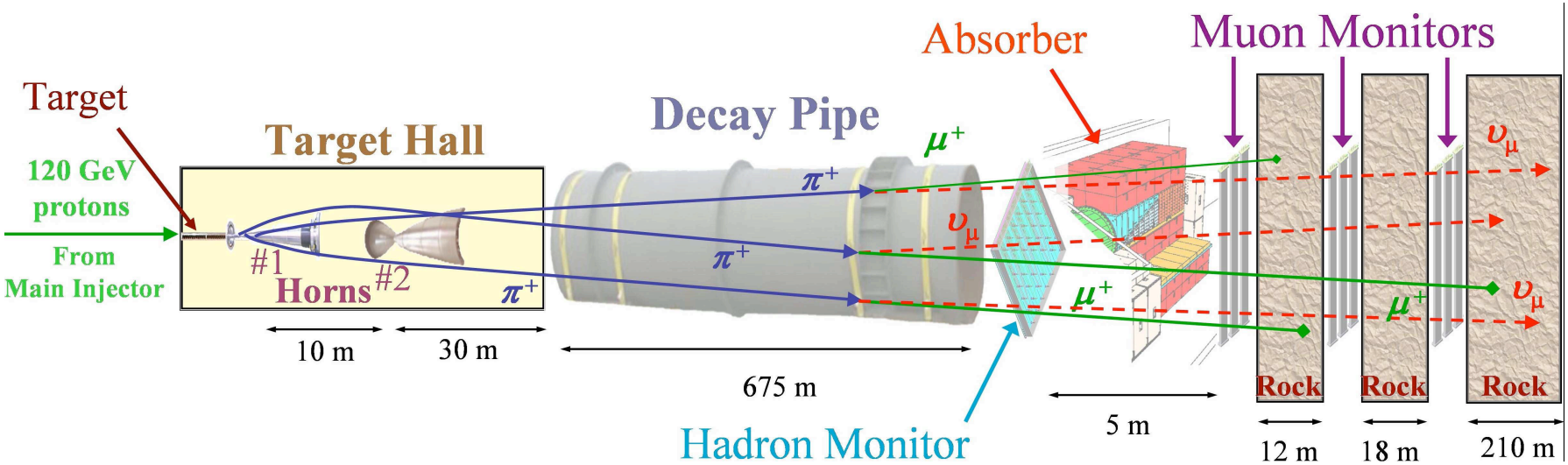


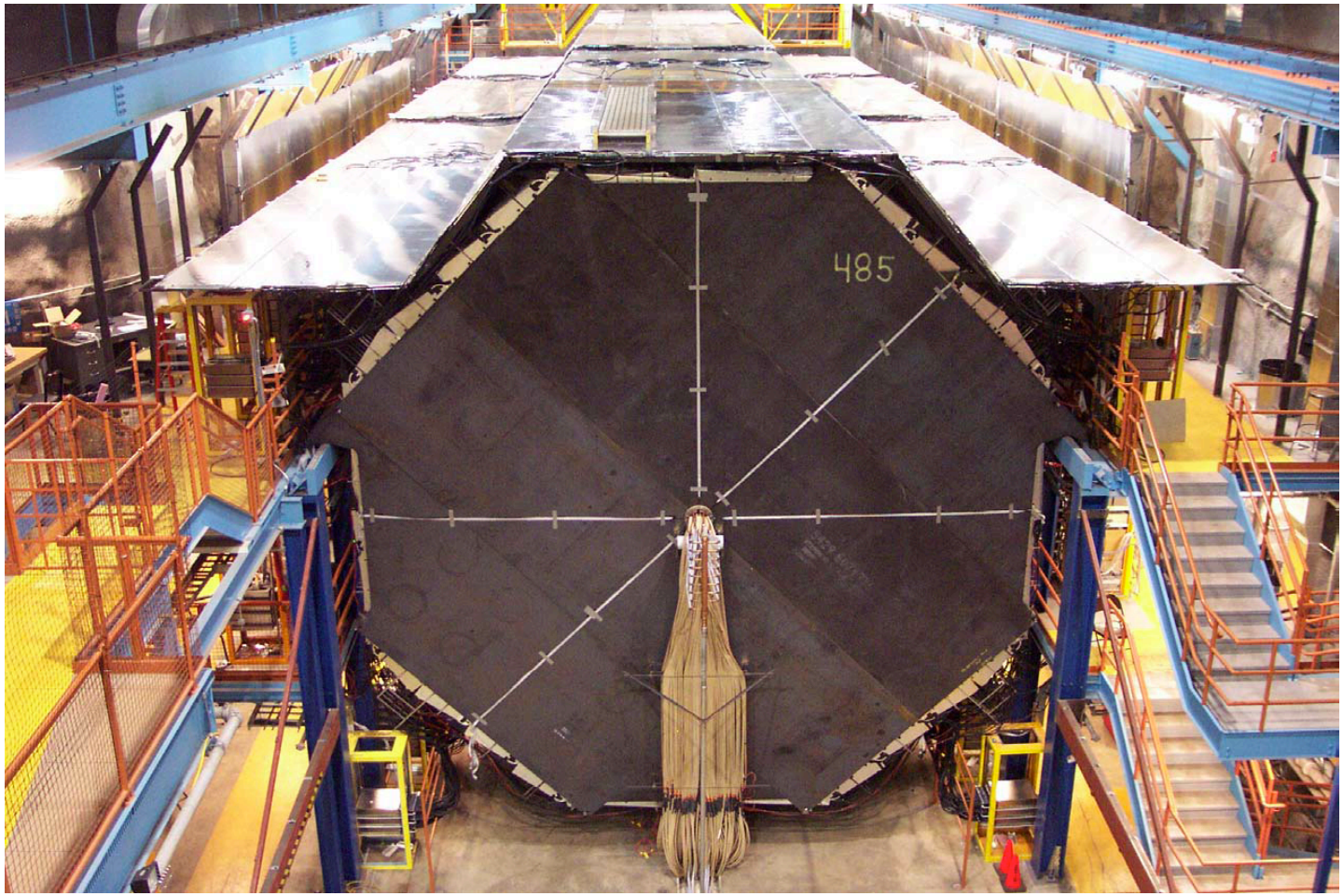
- Horn pulsed with 200 kA
- Toroidal Magnetic field $B \sim I/r$ between inner and outer conducters





Minos detector: Iron/ scintillator 5kT



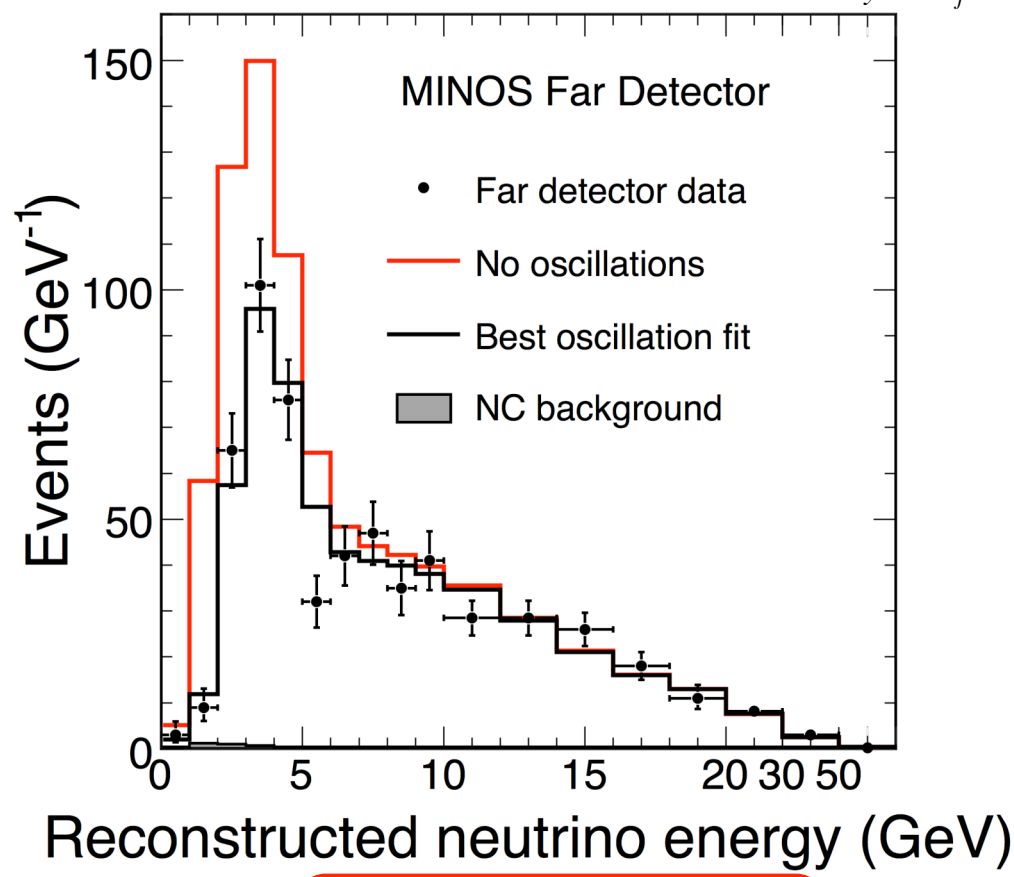


Minos detector: Iron/ scintillator 5kT

CC Energy Spectrum Fit

$$\chi^2 = \sum_{nbins} (2(e_i - o_i) + 2\, o_i \ln(o_i / e_i)) + \sum_{nsys} \frac{\Delta s_j^2}{\sigma_{s_j}^2}$$

- Fit the energy distribution to the oscillation hypothesis:
- Including the three largest sources of systematic uncertainty as nuisance parameters
  - Absolute hadronic energy scale: 10.3%
  - Normalization: 4%
  - NC contamination: 50%



Best Fit:
$|\Delta m^2| = 2.43 \times 10^{-3}$ eV^2
$\sin^2(2\theta) = 1.00$

3.6 10^{20} Protons on target

Allowed Regions

$|\Delta m^2| = (2.43 \pm 0.13) \times 10^{-3}\ eV^2$ (68% C.L.)

$\sin^2(2\theta) > 0.90$ (90% C.L.)

$\chi^2/ndof = 90/97$

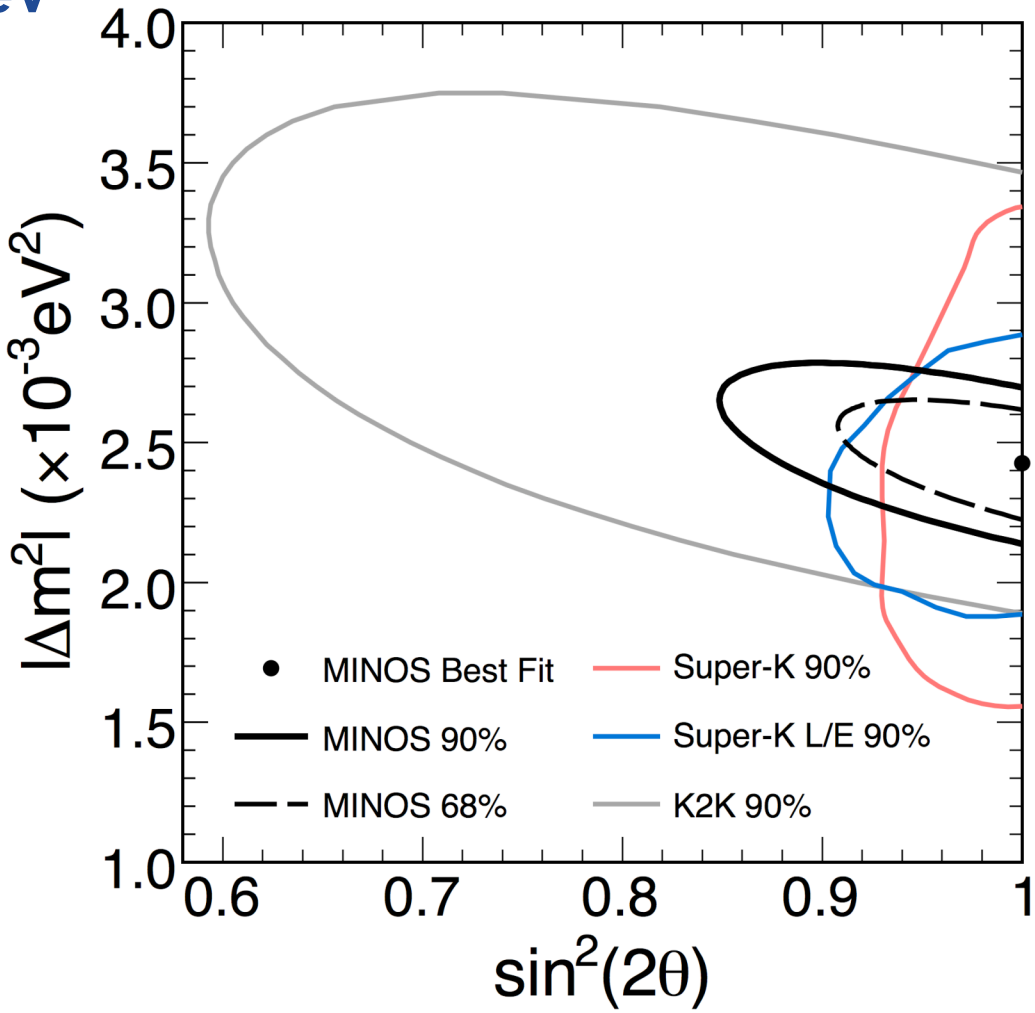
Fit is constrained to the physical region.

Unconstrained:

$|\Delta m|^2 = 2.33 \times 10^{-3}\ eV^2$

$\sin^2(2\theta)=1.07$

$\Delta\chi^2=-0.6$



Accepted by PRL:
arXiv:hep-ex/0806.2237

Most precise measurement of $|\Delta m|^2$ performed to date!

Mixing Matrix:

$$|\nu_e,\ \nu_\mu,\ \nu_\tau\rangle^T_{flavor} = U_{\alpha i}\ |\nu_1,\ \nu_2,\ \nu_3\rangle^T_{mass}$$

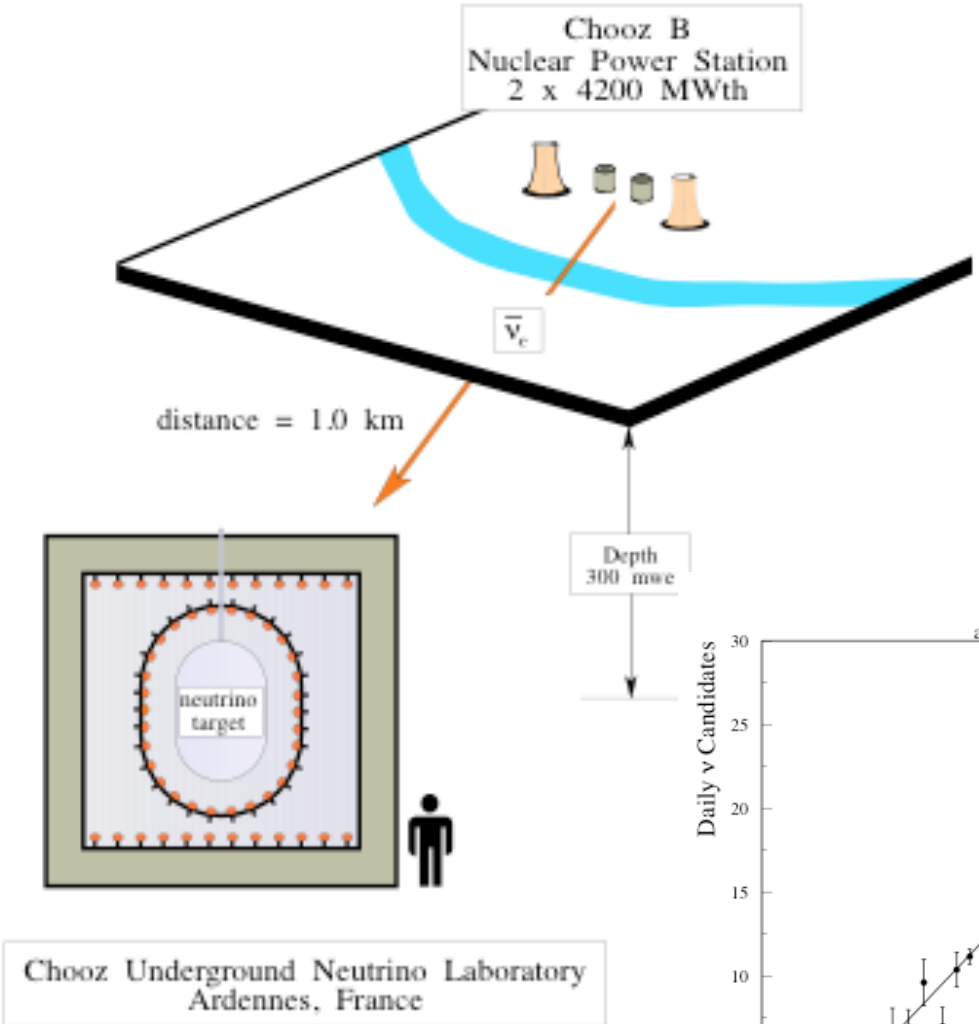
$$U_{\alpha i} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} 1 & & \\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

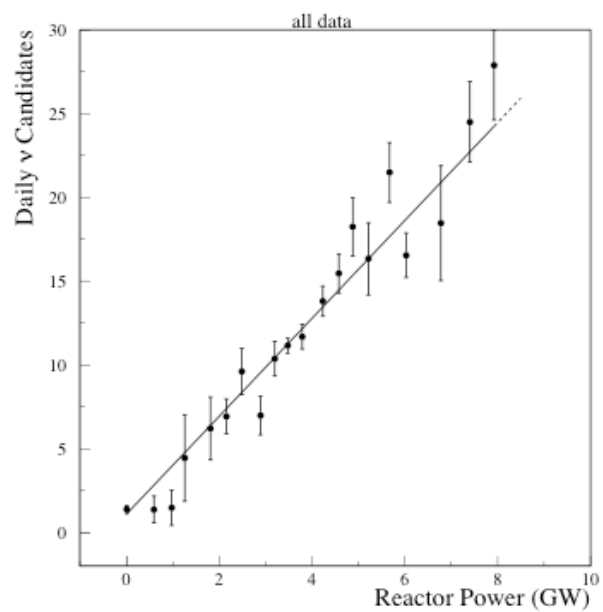
Atmos. L/E $\mu \to \tau$ Atmos. L/E $\mu \leftrightarrow e$ Solar L/E $e \to \mu, \tau$ $0\nu\beta\beta$ decay

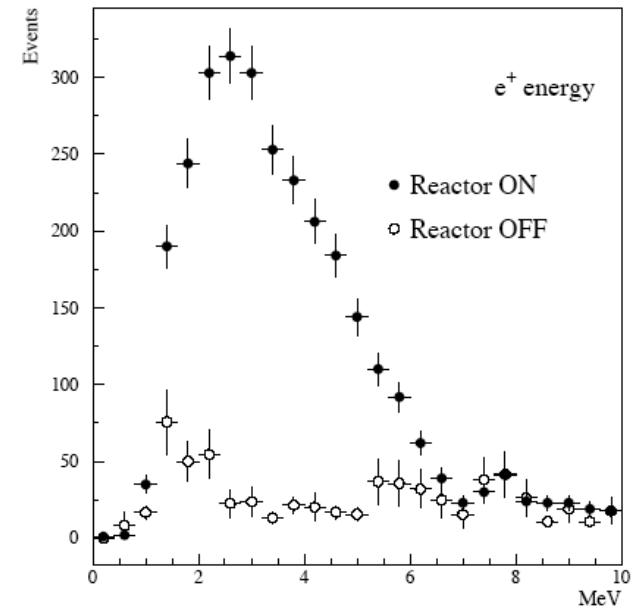
500km/GeV 15km/MeV

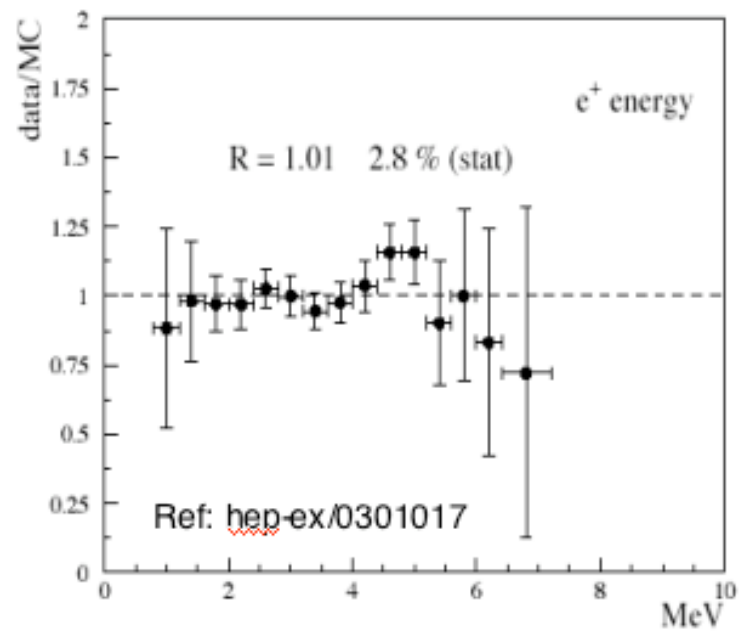
What about θ_{13} and δ ?

CHOOZ


Chooz B
Nuclear Power Station
2 x 4200 MWth
$\bar{\nu}_e$
distance = 1.0 km
Depth
300 mwe
neutrino
target
Chooz Underground Neutrino Laboratory
Ardennes, France

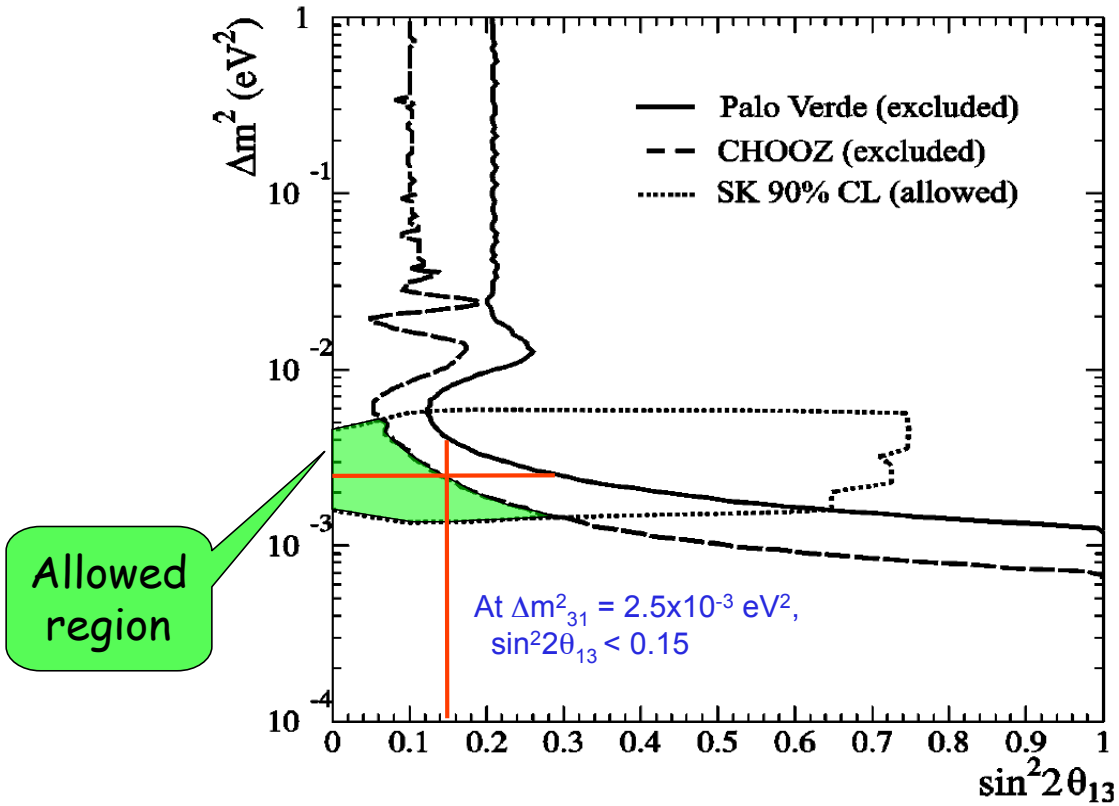

all data
Daily ν Candidates
Reactor Power (GW)

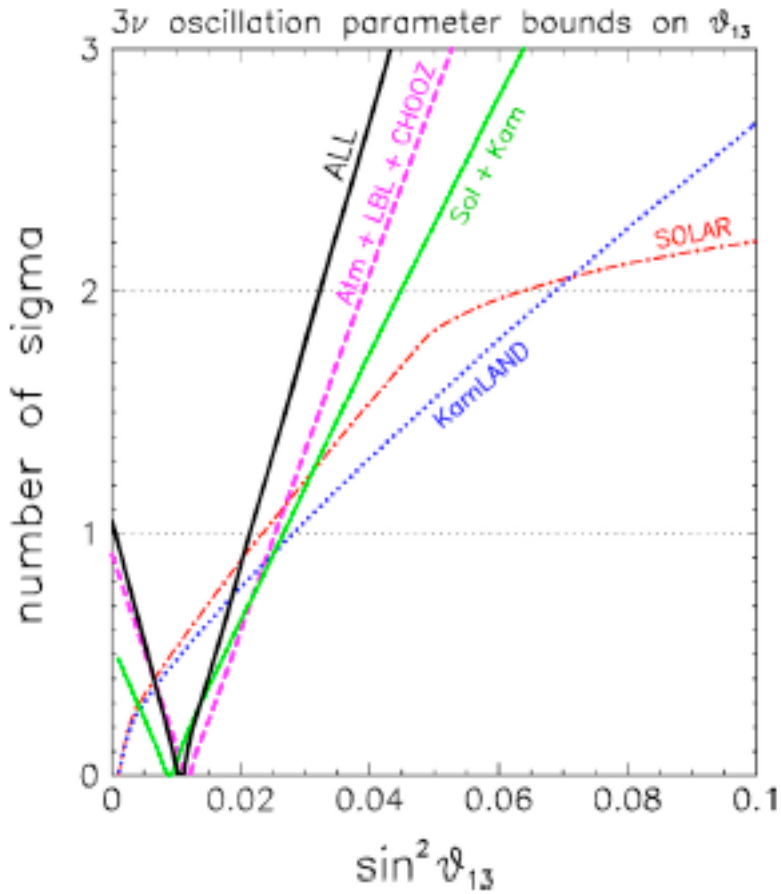

Events
e^+ energy
Reactor ON
Reactor OFF
MeV


data/MC
e^+ energy
R = 1.01 2.8 % (stat)
Ref: hep-ex/0301017
MeV

Global fit

Current direct search limits



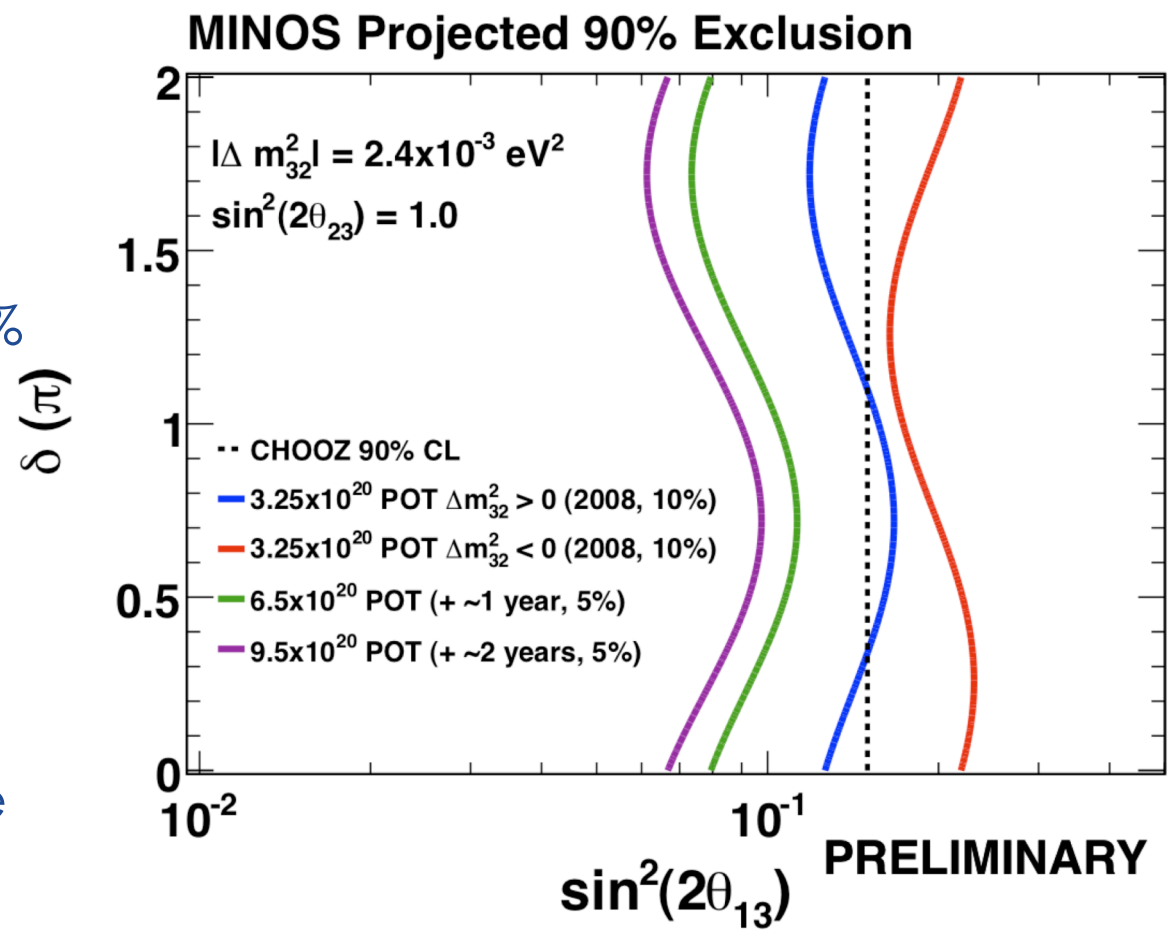


Fogli *et al.*, Venice ν-oscillation workshop(2008) and arXiv:0806.2649 [hep-ph]

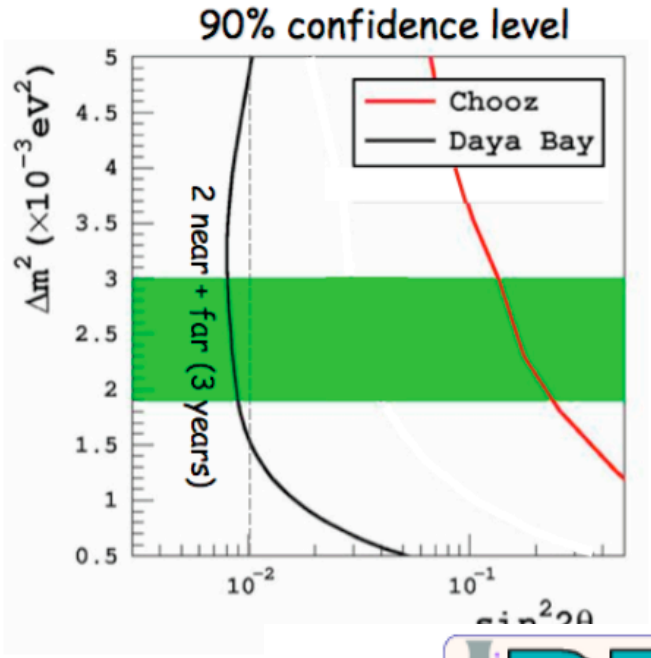
also Balantekin & Yilmaz, J. Phys. G **35**, 075007 (2008) (arXiv:0804.3345 [hep-ph]).

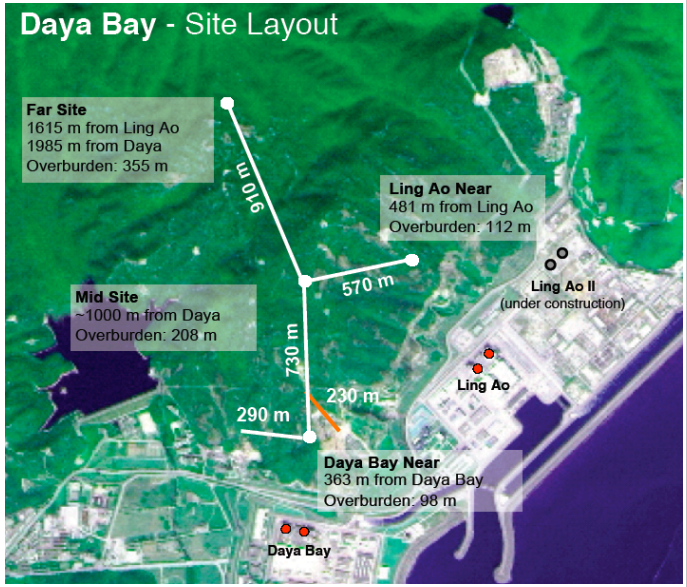
Future θ_{13} Limits

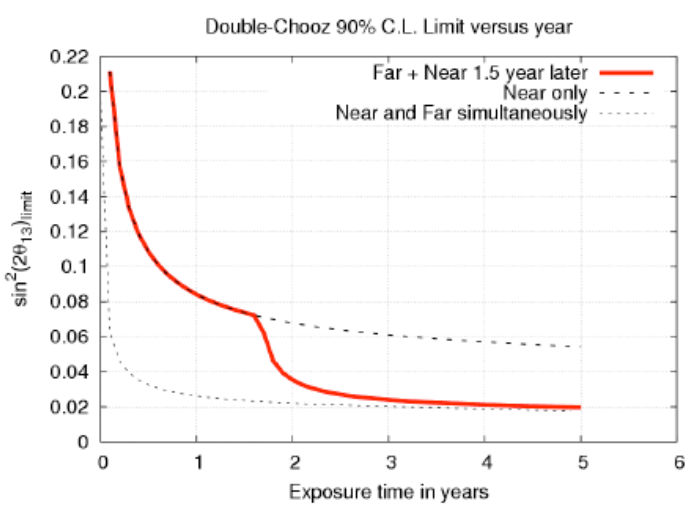
- Expect 12 signal and 42 bg events at the CHOOZ limit for the current exposure
- Data-driven systematics are hoped to drop to 5% in future years
- Inverted hierarchy shown only for lowest exposure for simplicity
- MINOS can improve the CHOOZ limit on θ_{13} by a factor of 2!



Next generation reactor
Double Chooz, Daya Bay
RENO

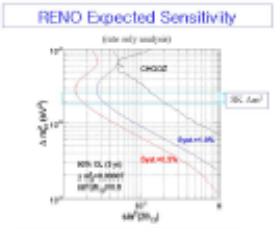


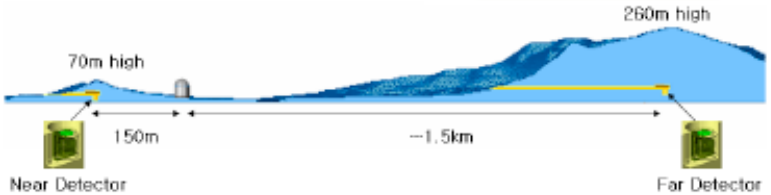




RENO

(Reactor Experiment for Neutrino Oscillation)





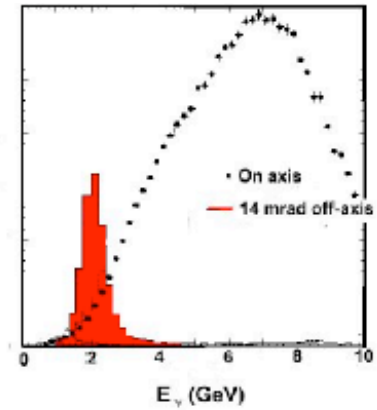
Long Baseline Physics

$$
\begin{array}{ccccc}
 & & \text{CP} & & \\
 & \nu_\mu \to \nu_e & \Longleftrightarrow & \bar{\nu}_\mu \to \bar{\nu}_e & \\
\text{T} & \Updownarrow & \text{CPT across diagonals} & \Updownarrow & \text{T} \\
 & \nu_e \to \nu_\mu & \Longleftrightarrow & \bar{\nu}_e \to \bar{\nu}_\mu & \\
 & & \text{CP} & &
\end{array}
$$

- First Row: Superbeams where ν_e contamination $\sim$1 %
- Second Row: ν-Factory or β-Beams, no beam contamination

Off-Axis Beams

BNL 1994



π^0 suppression

T2K

JHF → Super-Kamiokande

- 295 km baseline
- Super-Kamiokande:
  - 22.5 kton fiducial
  - Excellent e/μ ID
  - Additional π^0/e ID
- Hyper-Kamiokande
  - 20× fiducial mass of SuperK
- Matter effects small
- Study using fully simulated and reconstructed data

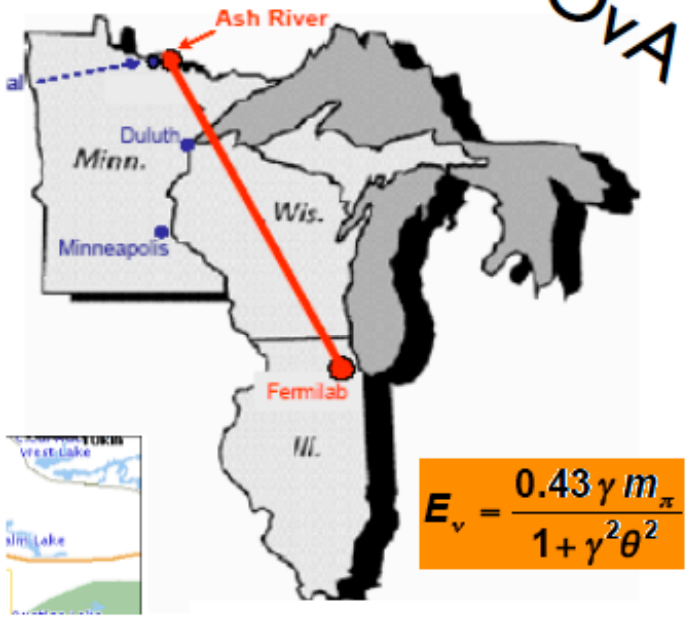
L=295 km and

Energy at Vac. Osc. Max. (vom)

$$E_{vom} = 0.6\ GeV \left\{ \frac{\delta m^2_{32}}{2.5\times10^{-3}\ eV^2} \right\}$$

0.75 upgrade to 4 MW

NOvA



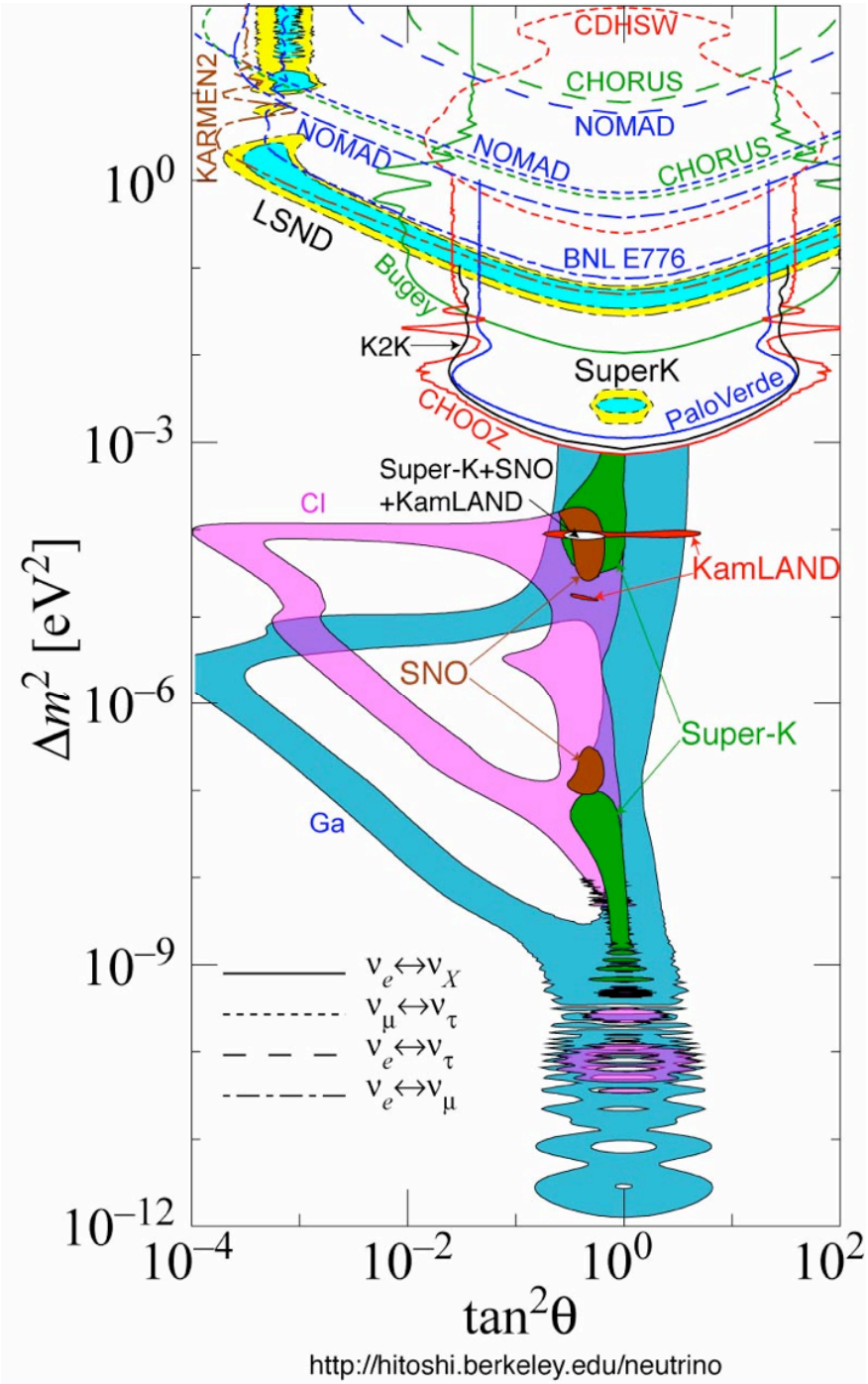
$$E_\nu = \frac{0.43\,\gamma\, m_\pi}{1+\gamma^2\theta^2}$$

L=700 - 1000 km and

Energy near 2 GeV

$$E_{vom} = 1.8\ GeV \left\{ \frac{\delta m^2_{32}}{2.5\times10^{-3}\ eV^2} \right\} \times \left\{ \frac{L}{820\ km} \right\}$$

0.4 upgrade to 2 MW

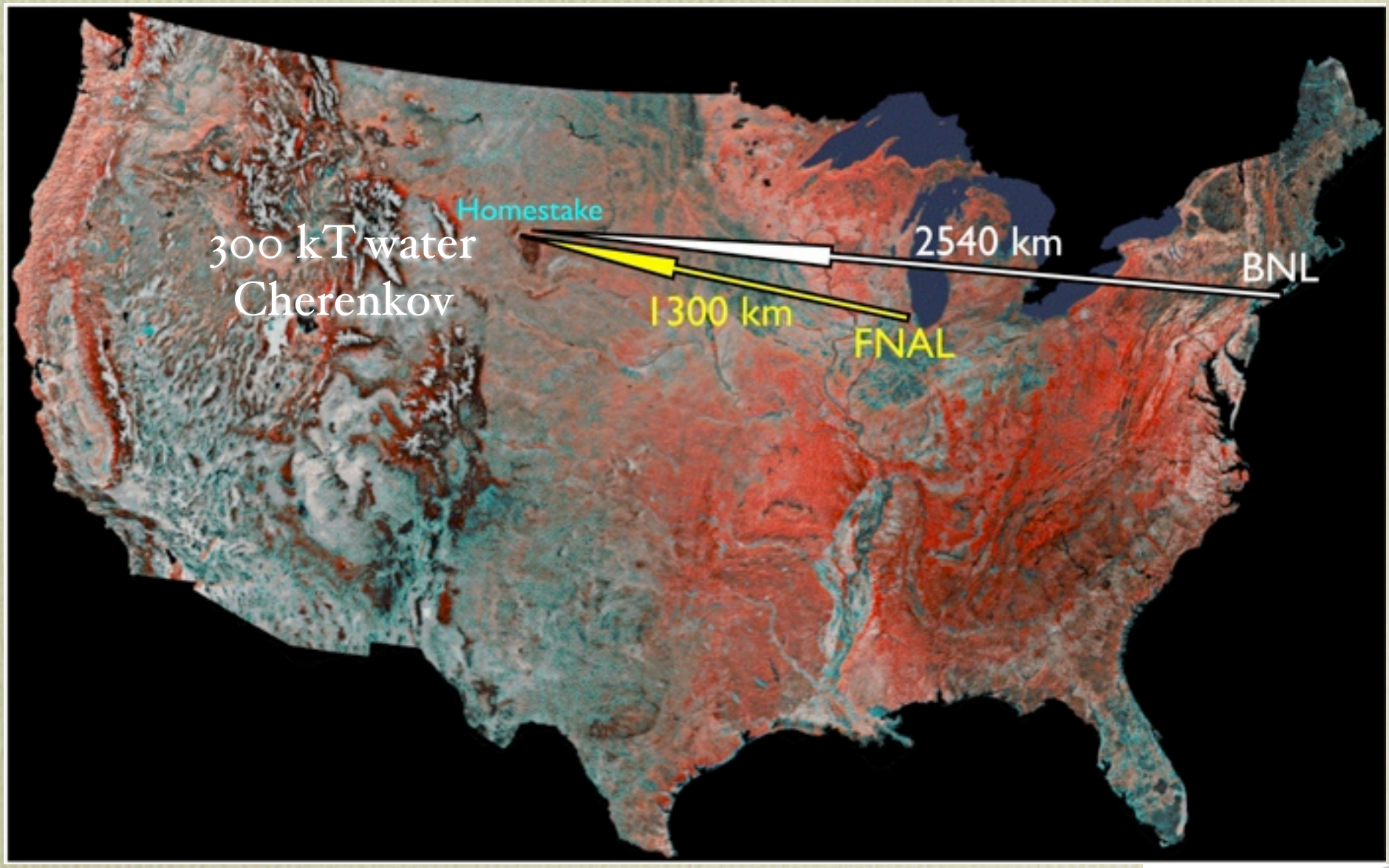


Why did it take this long ?

- Initial hints in Cl experiments set the scale, but knowledge of the source was suspect.
- Intolerance of large mixing !
- Hints from early atmospheric oscillations were considered artifacts because the effect was too large.
- Cosmological arguments for larger masses.
- Failure to grasp the scale of the detector needed for the job.

FNAL to DUSEL long baseline experiment

Beam requirement: >1 MW, 1000 to 2000 km



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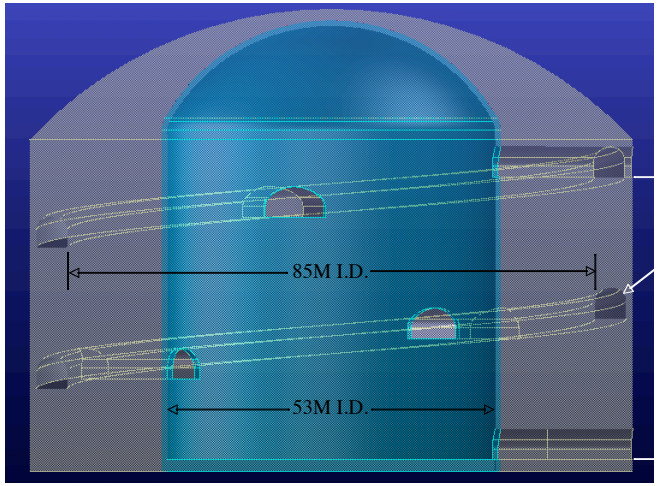
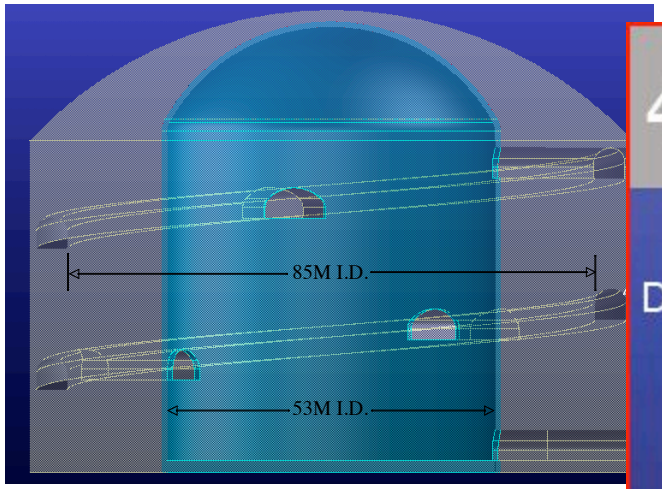
Water Cherenkov Detector at Homestake



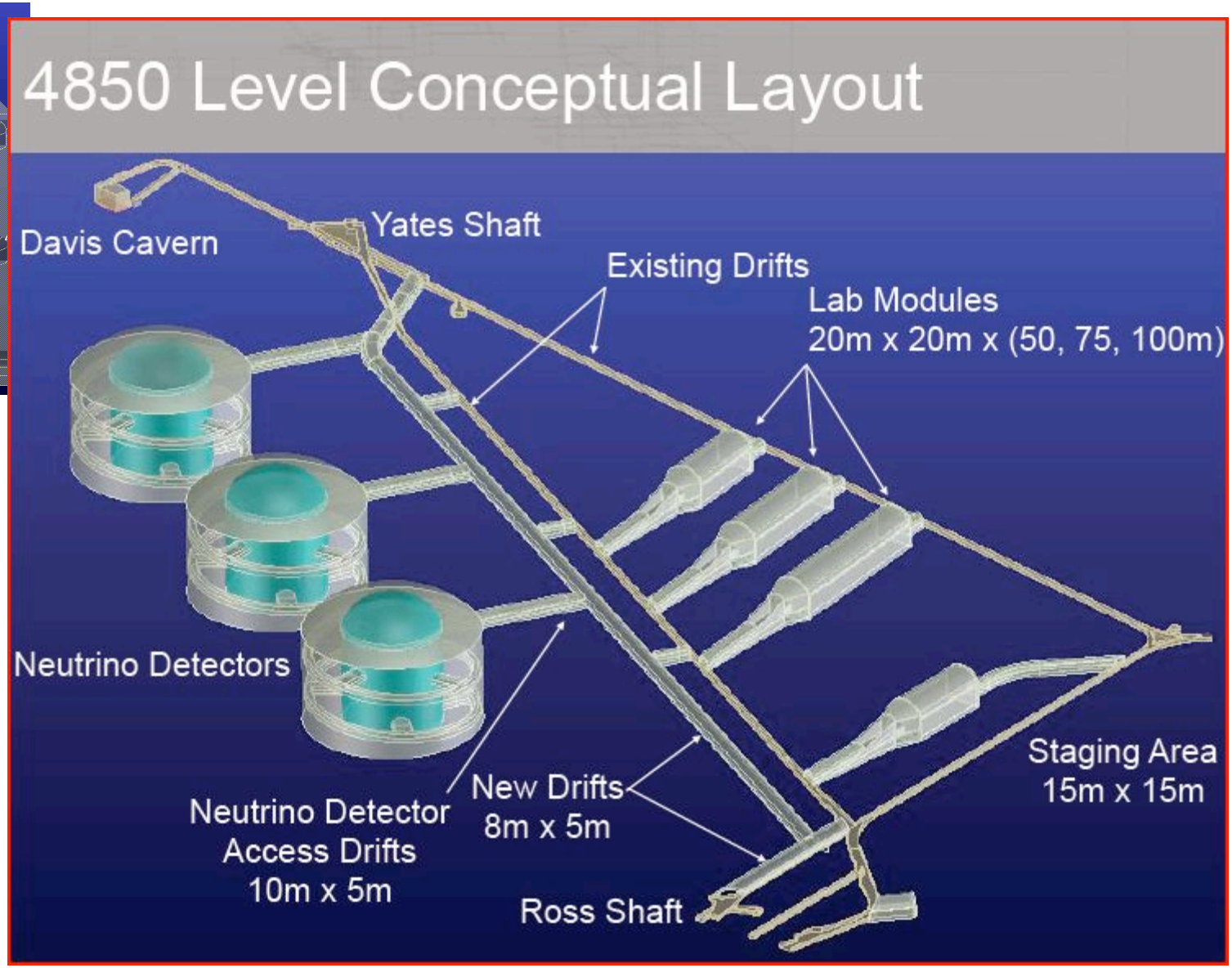
1 module fid:
100 kT

300 kT

Water Cherenkov Detector at Homestake



1 module fid:
100 kT



300 kT

Science to be addressed with next detectors and the beam

- Neutrino Oscillations.

★ What is the size of last mixing angle, θ_{13} ?

★What is the ordering of Neutrino masses?

★Do Neutrinos violate the CP symmetry?

★What is the relationship of leptons and quarks ?

Detector needs to be similar size for both this physics and physics of nucleon decay. Can we do this important physics also ?

Conclusions

- Neutrino oscillation story is an extraordinary journey over 4 decades.
- Culminating in precise measurements of fundamental parameters and new puzzles with profound implications.
- The next steps have clear goals and the scale of the effort needed (well controlled systematics, large event rates, low backgrounds) is well understood.
- All good things take time.

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