Neutrino Mixing: Status and Short Term Prospects

Stanley Wojcicki

22nd Rencontre de Blois
July 19, 2010

Outline

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- Parameters of the PMNS Matrix
  - Solar Sector L/E~15000km/GeV, θ_{12}, Δm_{21}^2
  - Atmospheric Sector L/E~500km/GeV, θ_{23}, Δm_{31}^2
  - Mixed Sector L/E~500km/GeV, θ_{13}, Δm_{31}^2

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SNO Experiment

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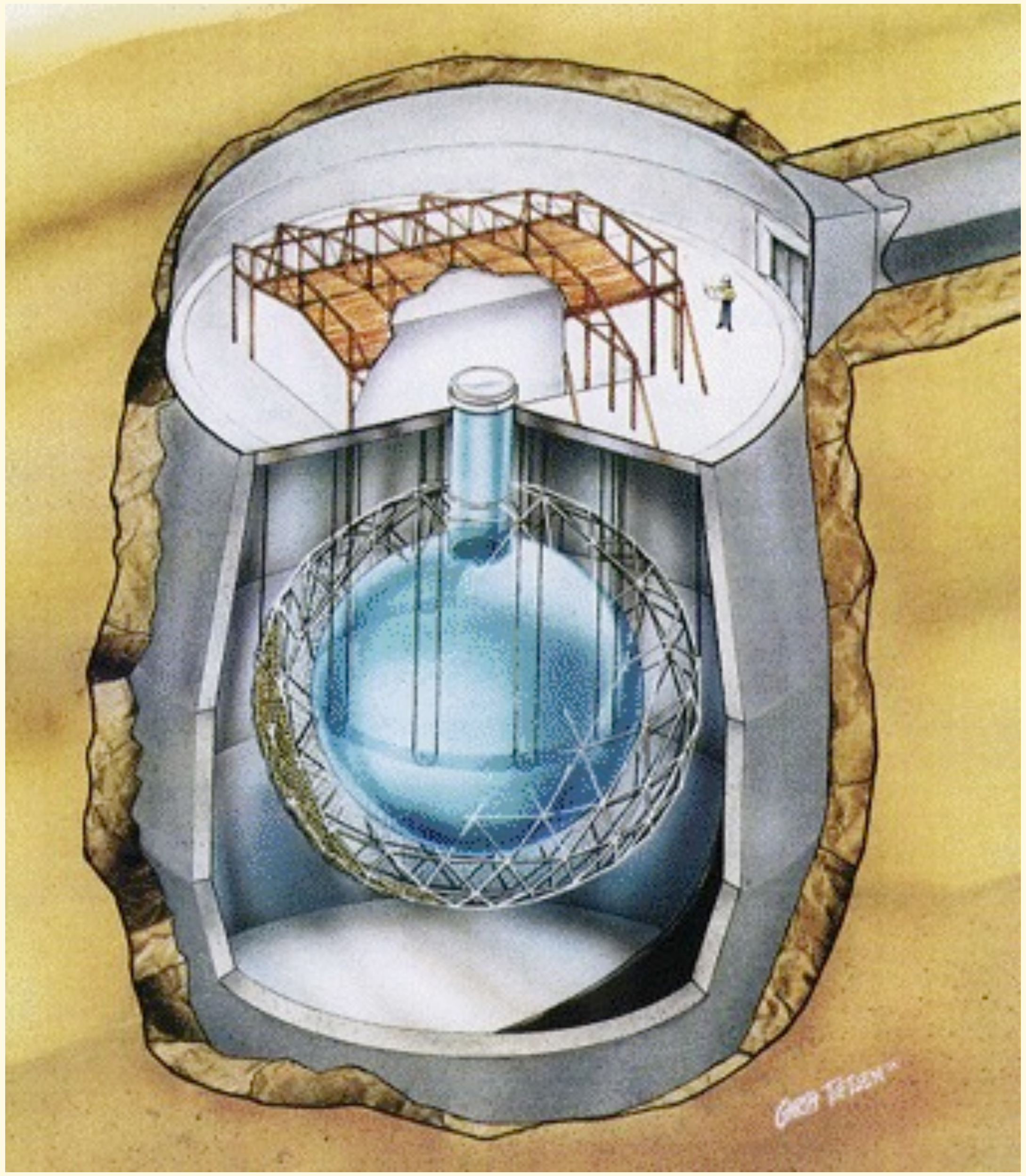

1000 tons of D_2O in a nickel mine
2092 m underground

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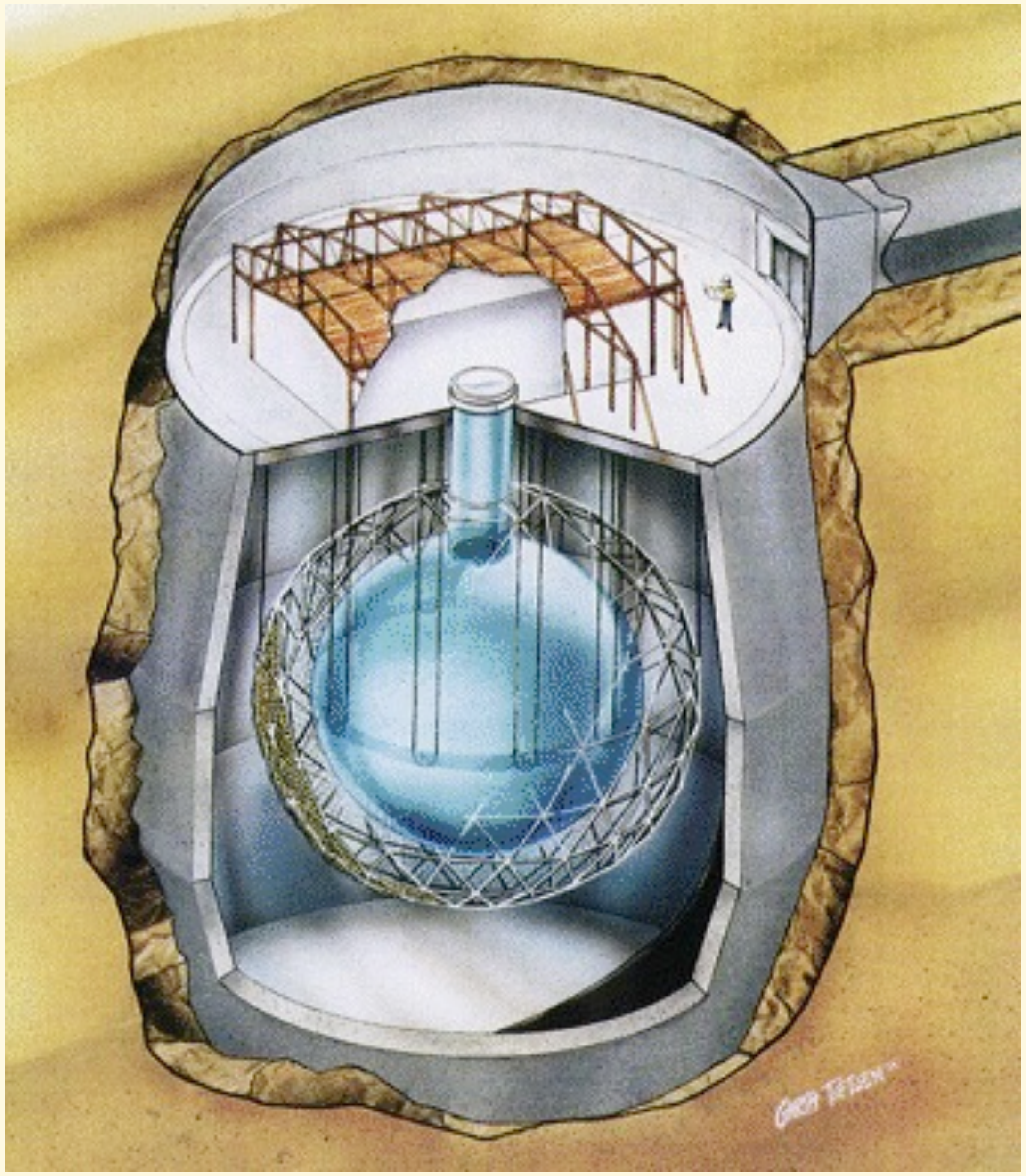

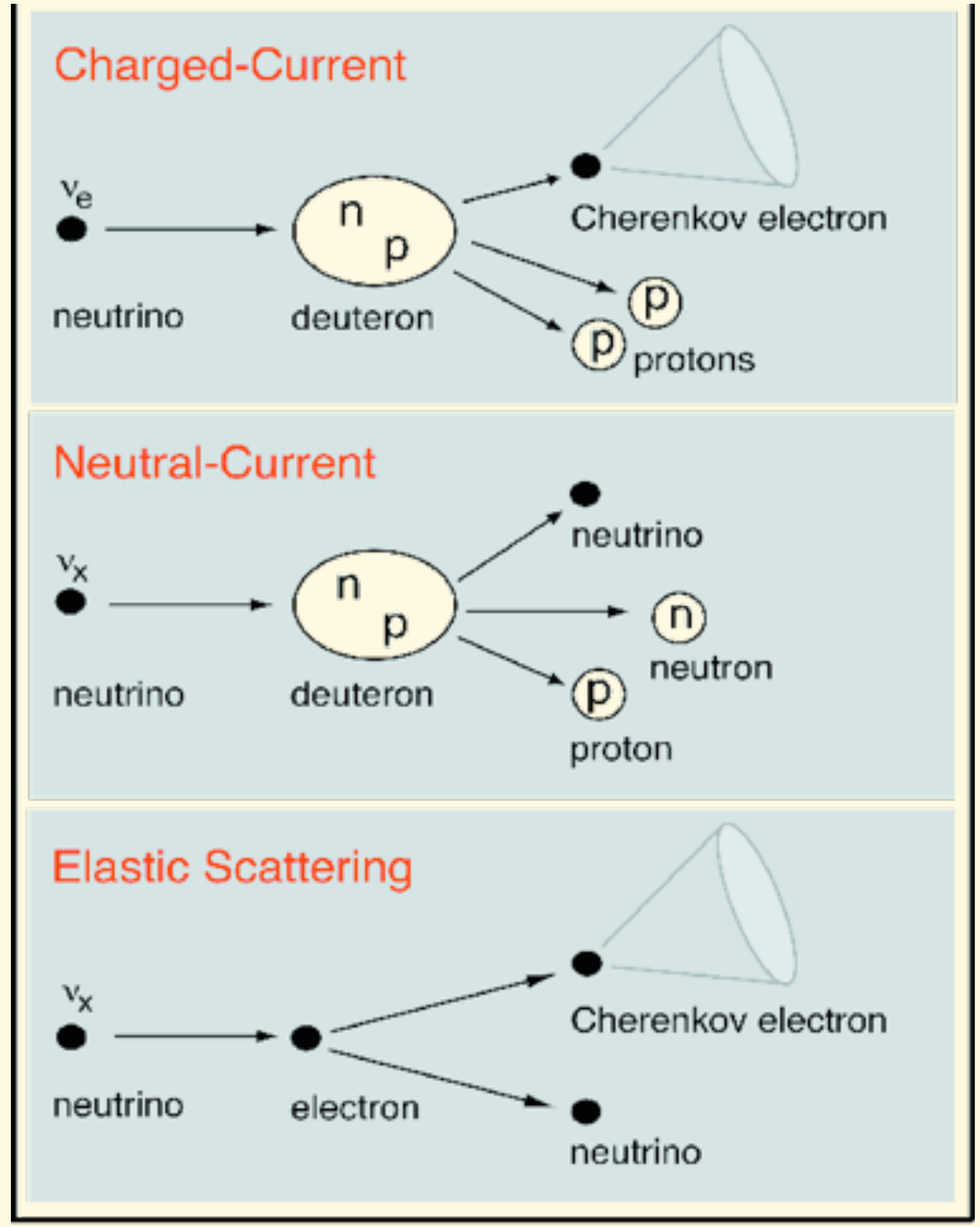

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Separation is done on a statistical basis

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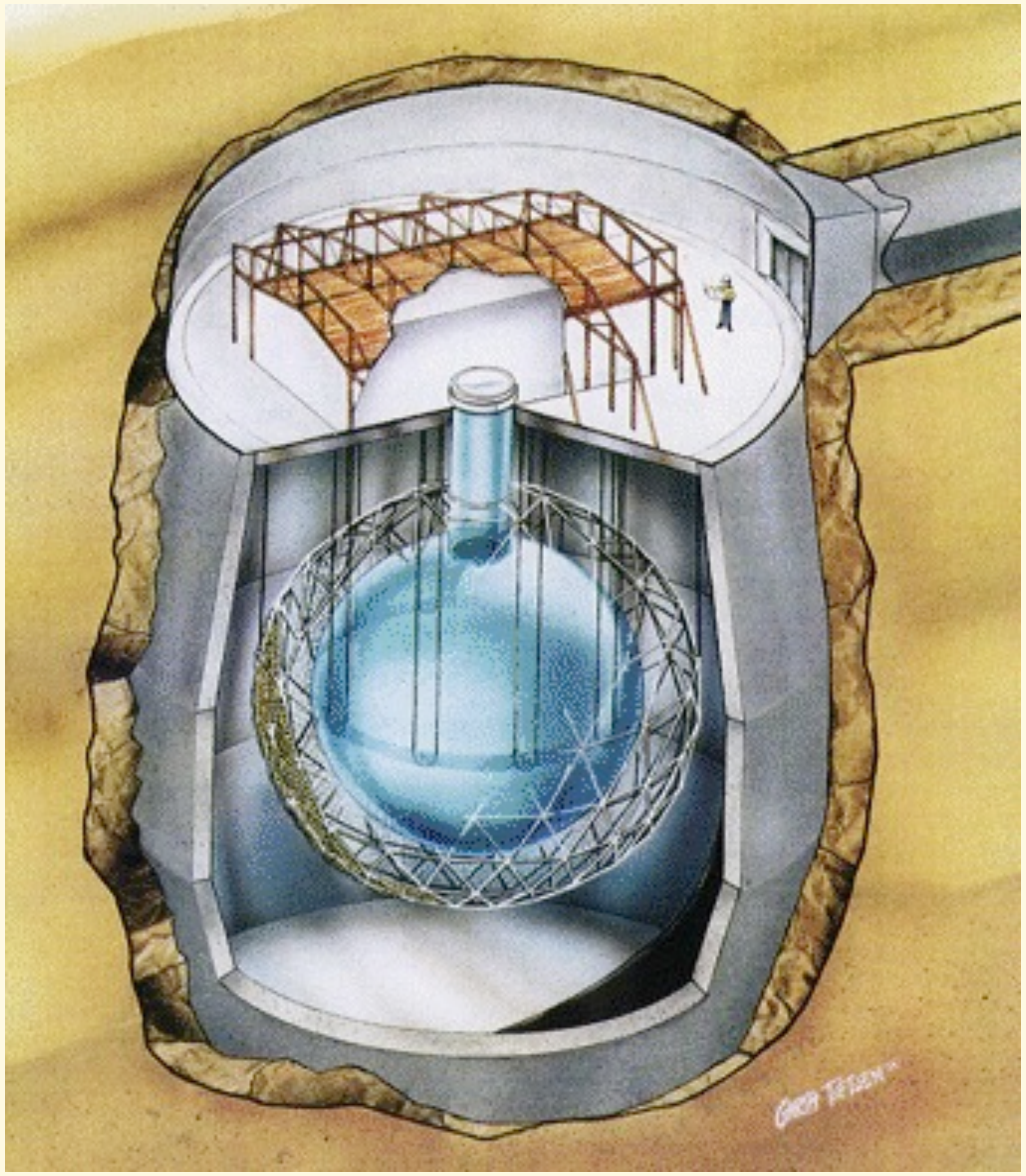

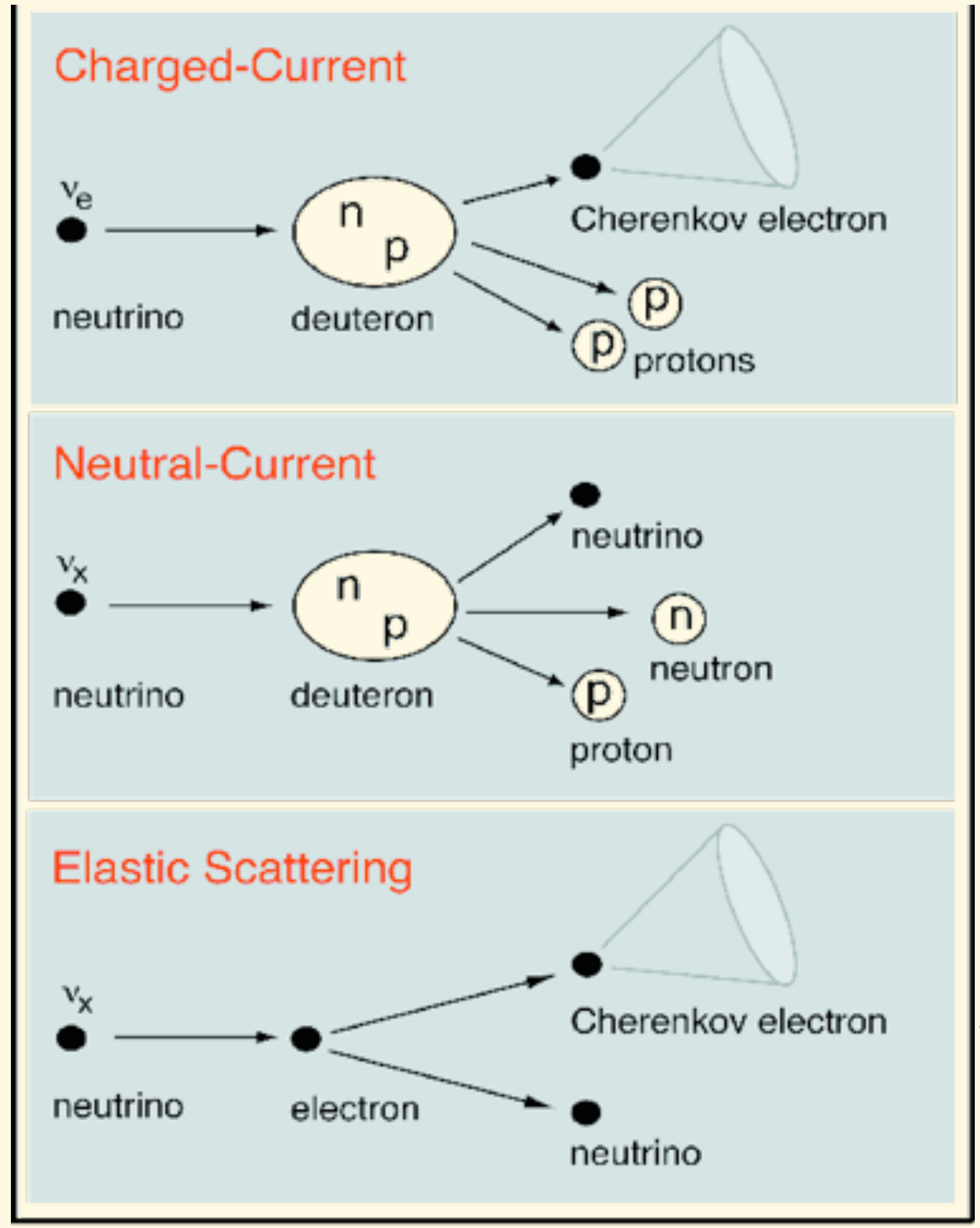

Φ_e

$\Phi_{\mu\tau} + \Phi_e$

$.154\Phi_{\mu\tau}+\Phi_e$

1000 tons of D_2O in a nickel mine
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Separation is done on a statistical basis

Three measurements (CC, NC, ES)
of two quantities (Φ_e,$\Phi_{\mu\tau}$)

KamLAND

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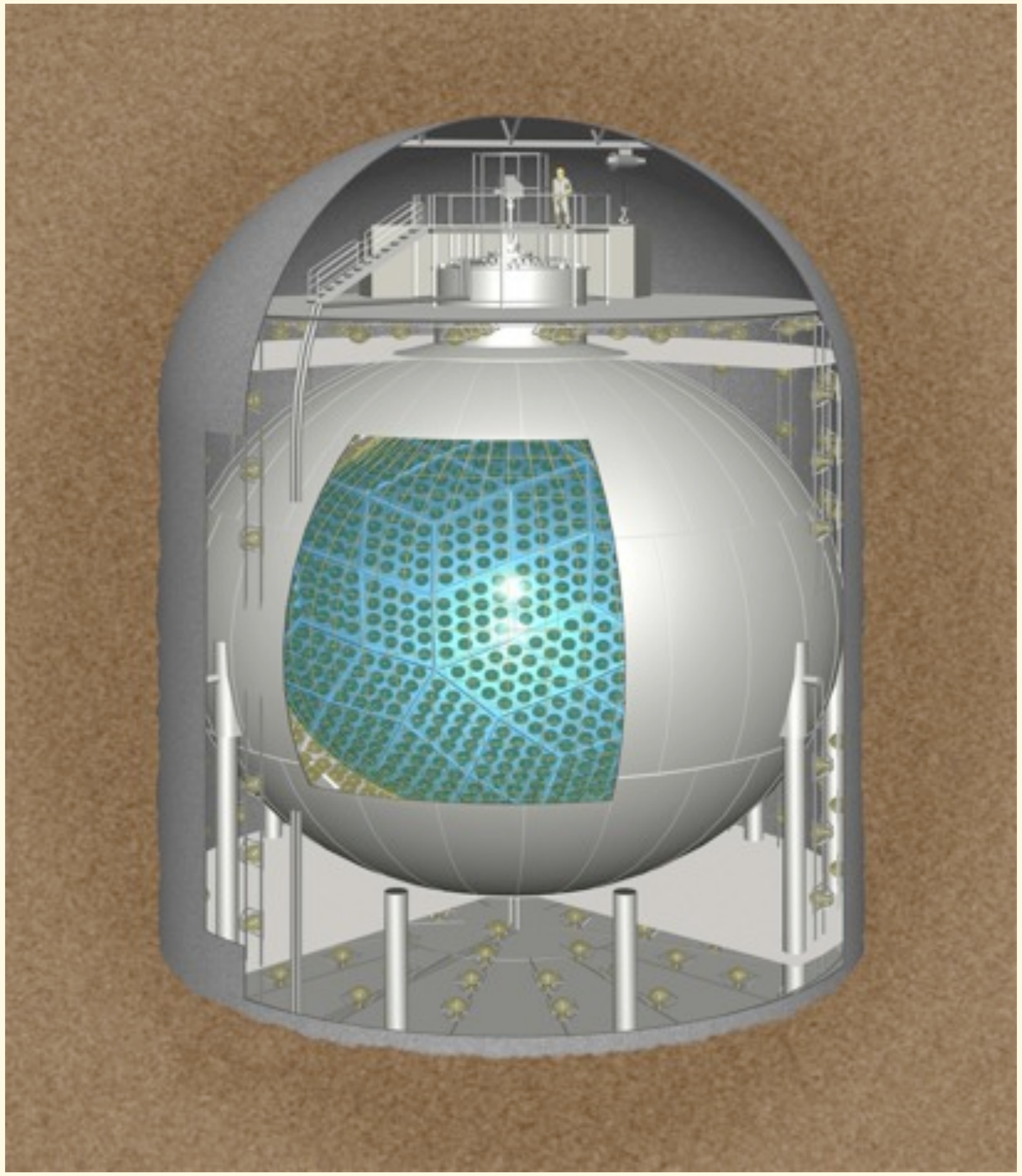

1 kton liquid scintillator
30% photocathode coverage
at 2700 m.w.e. depth

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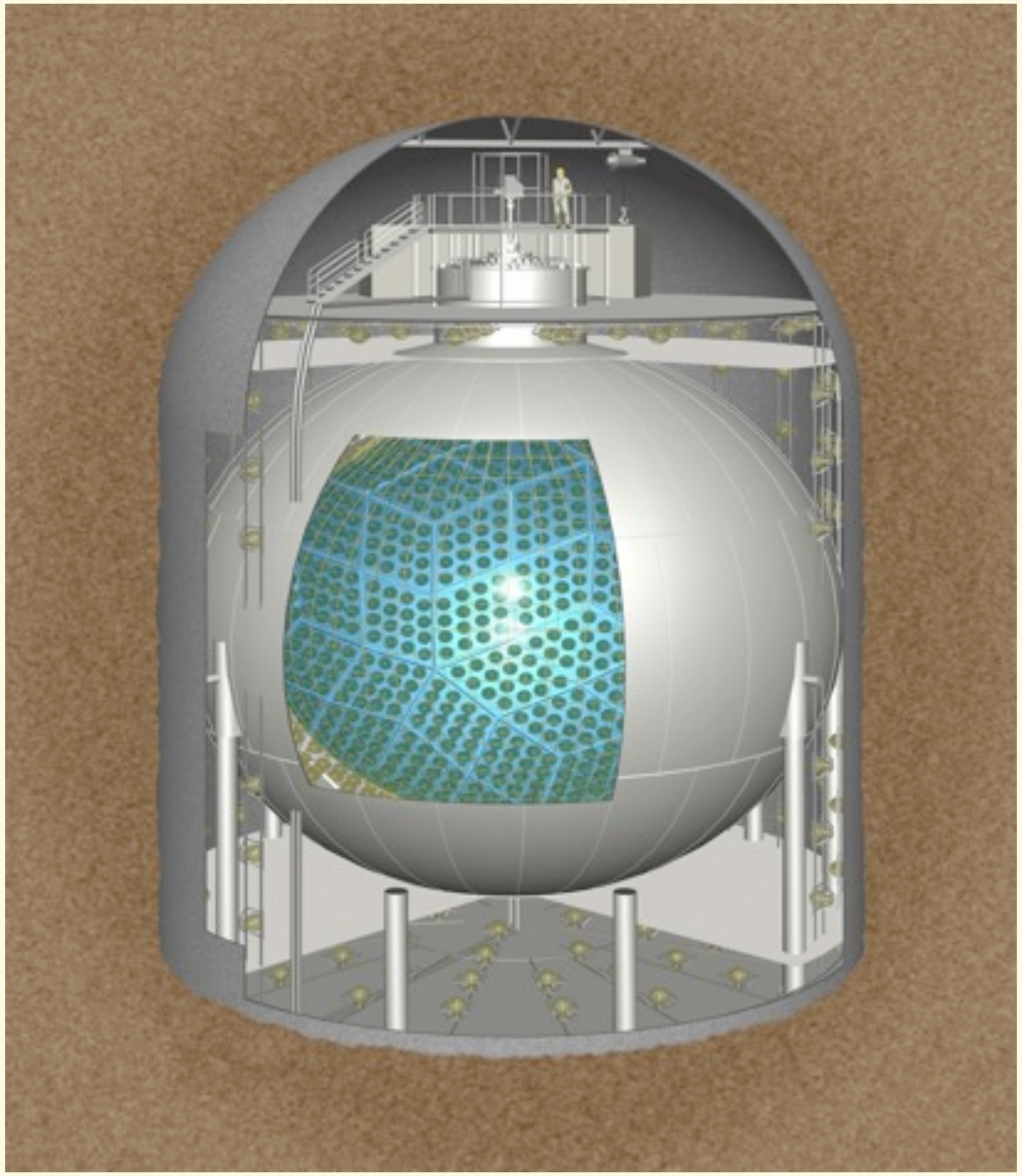
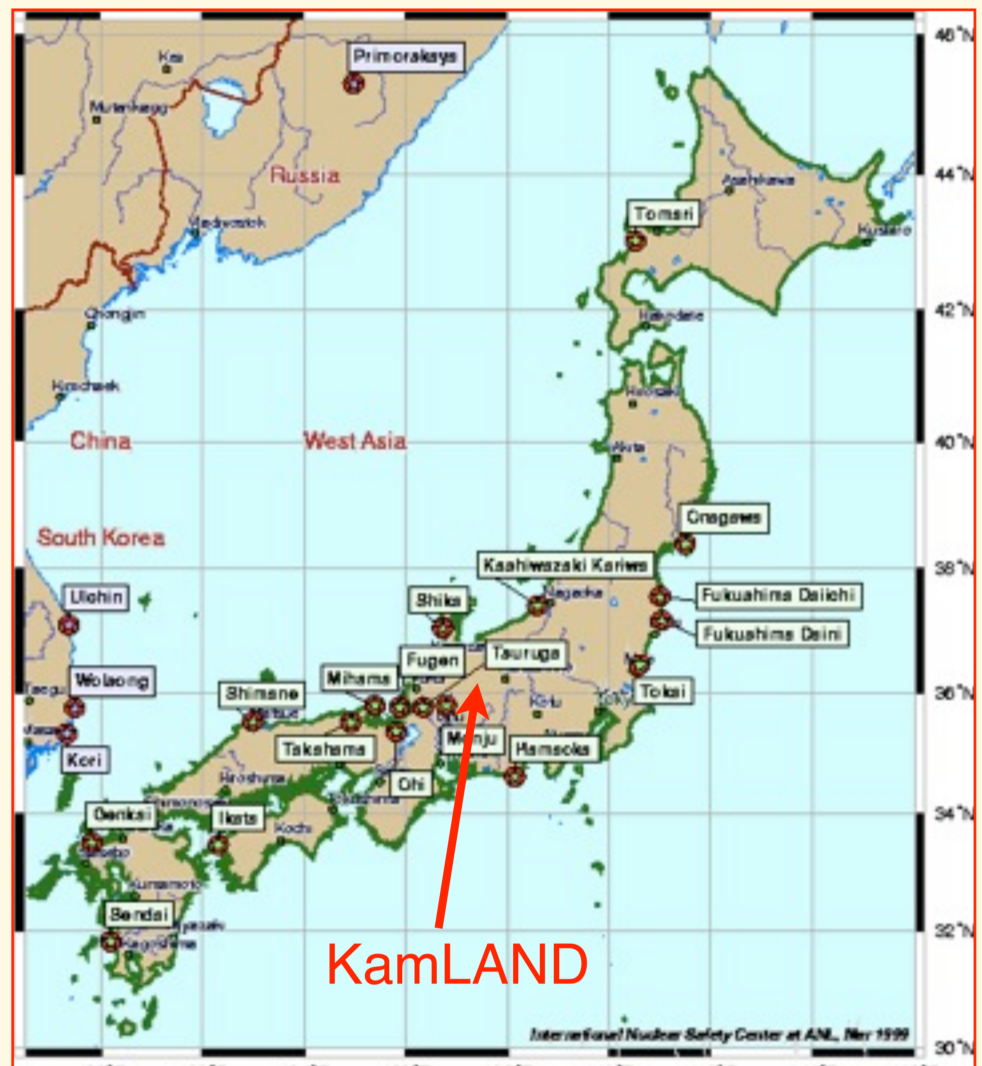


It takes advantage of the former Kamioka cavern that is surrounded by reactors, typically ~180 km away



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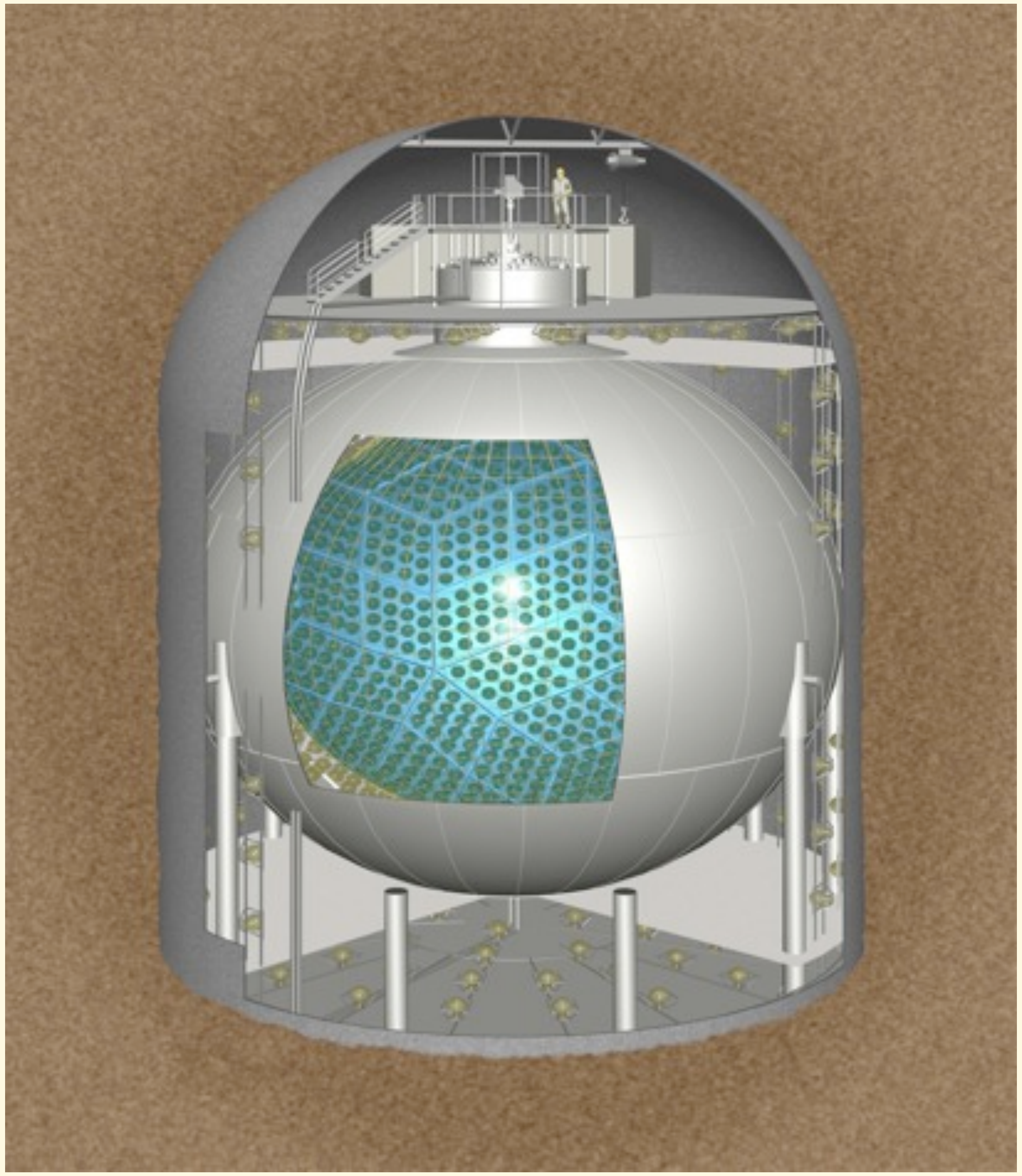

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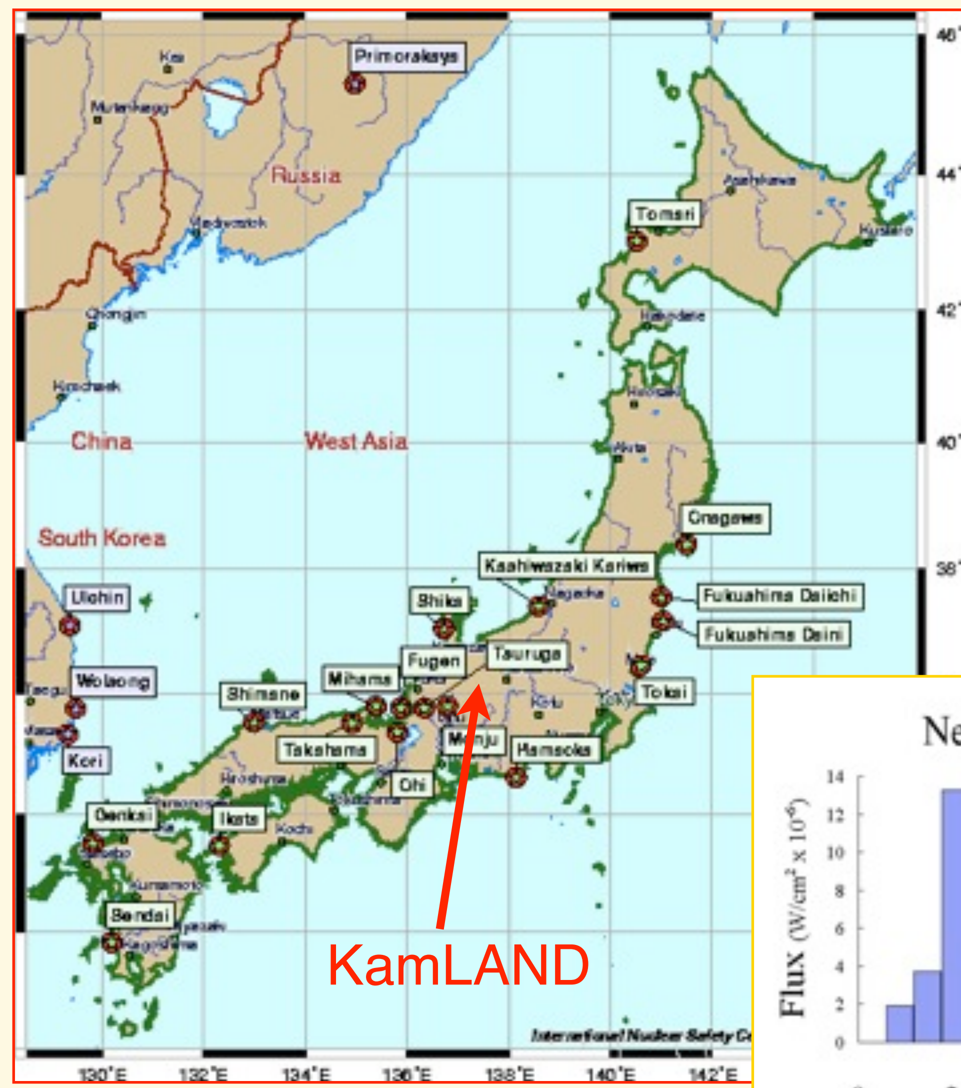

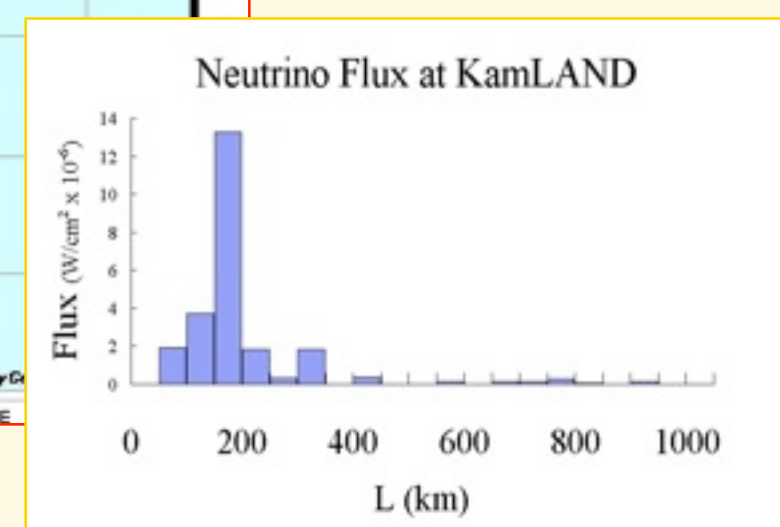

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KamLAND Results

Phys.Rev.Lett.100:221803,2008

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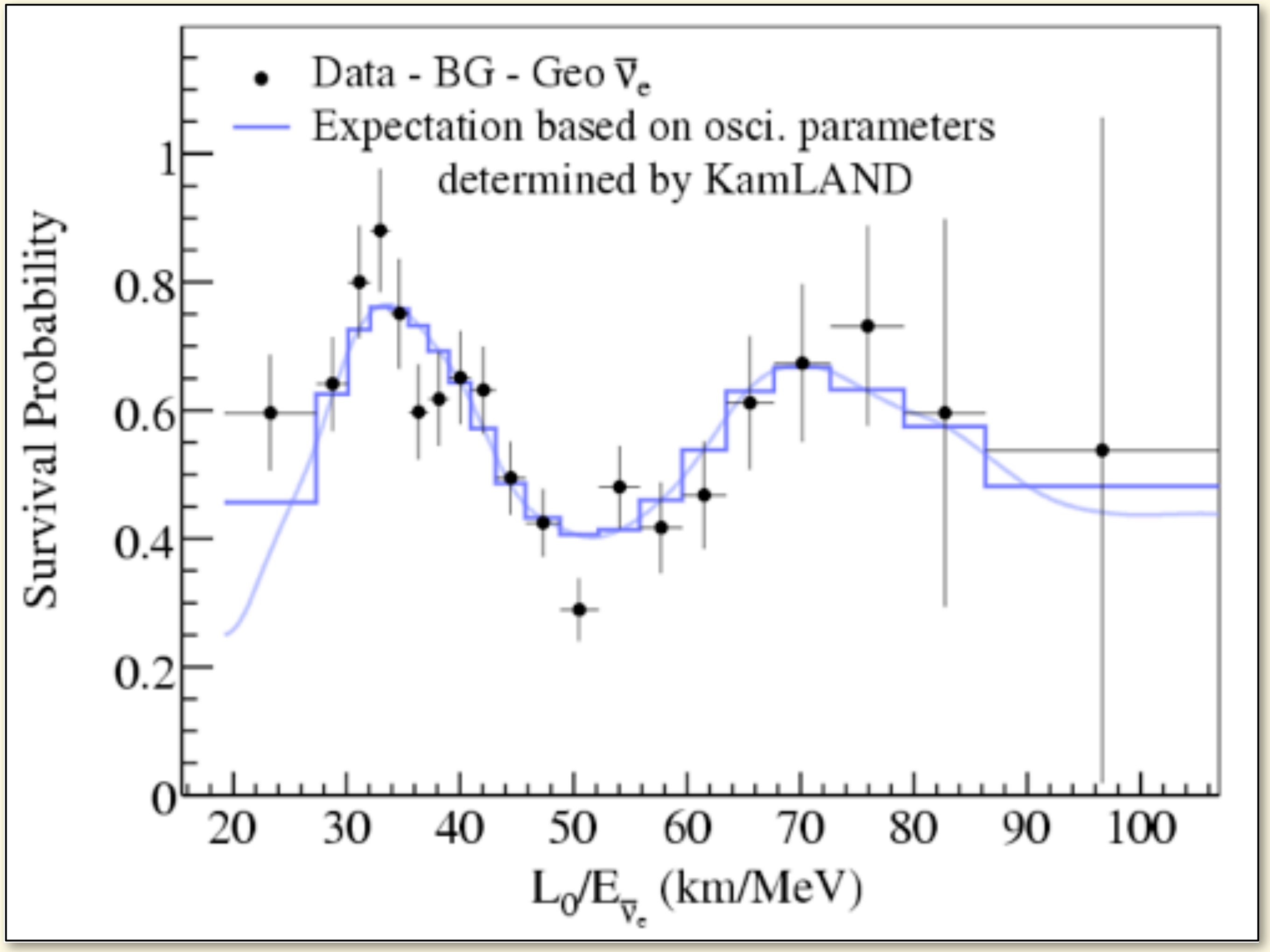

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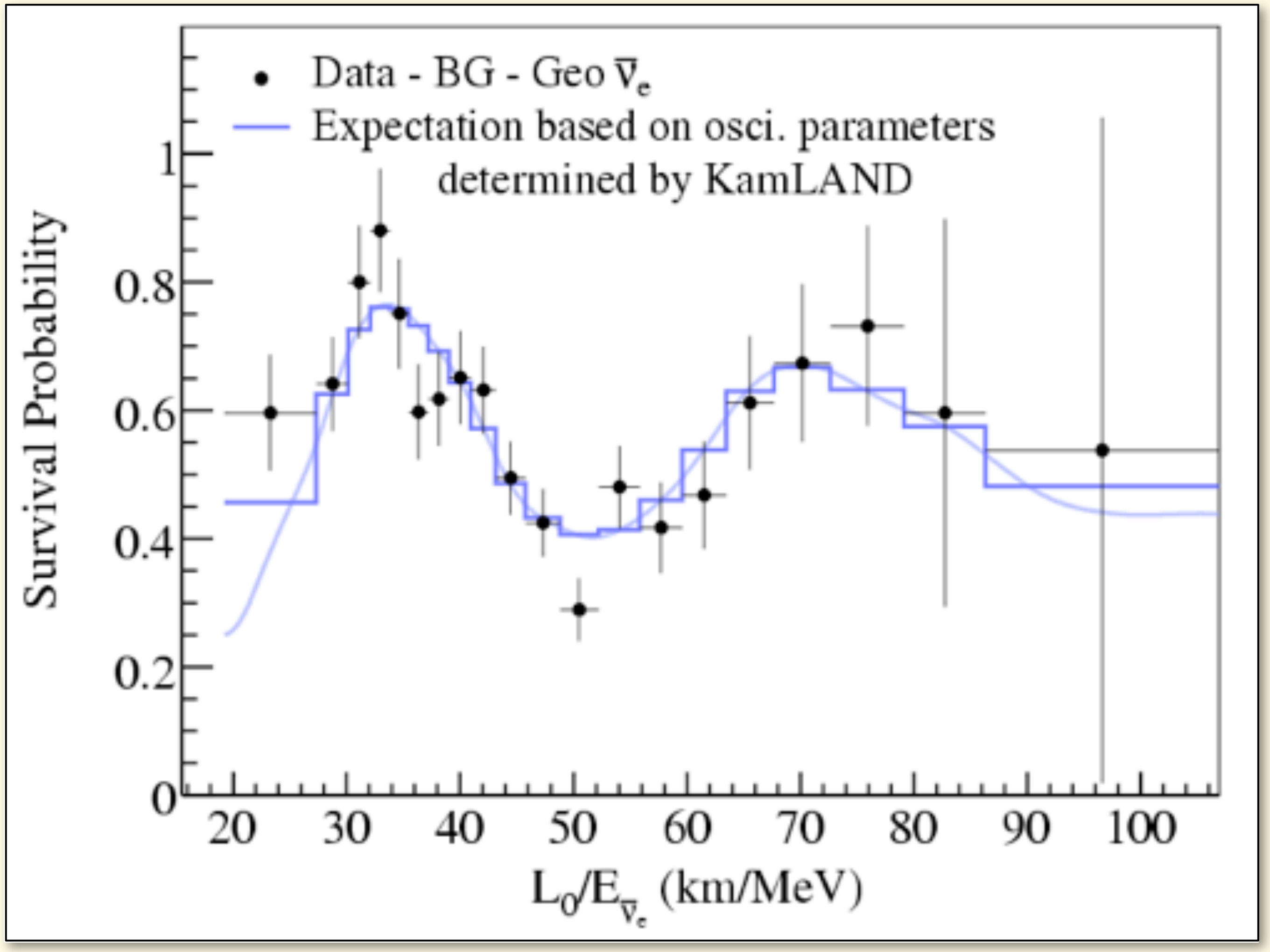

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Good frequency measurement
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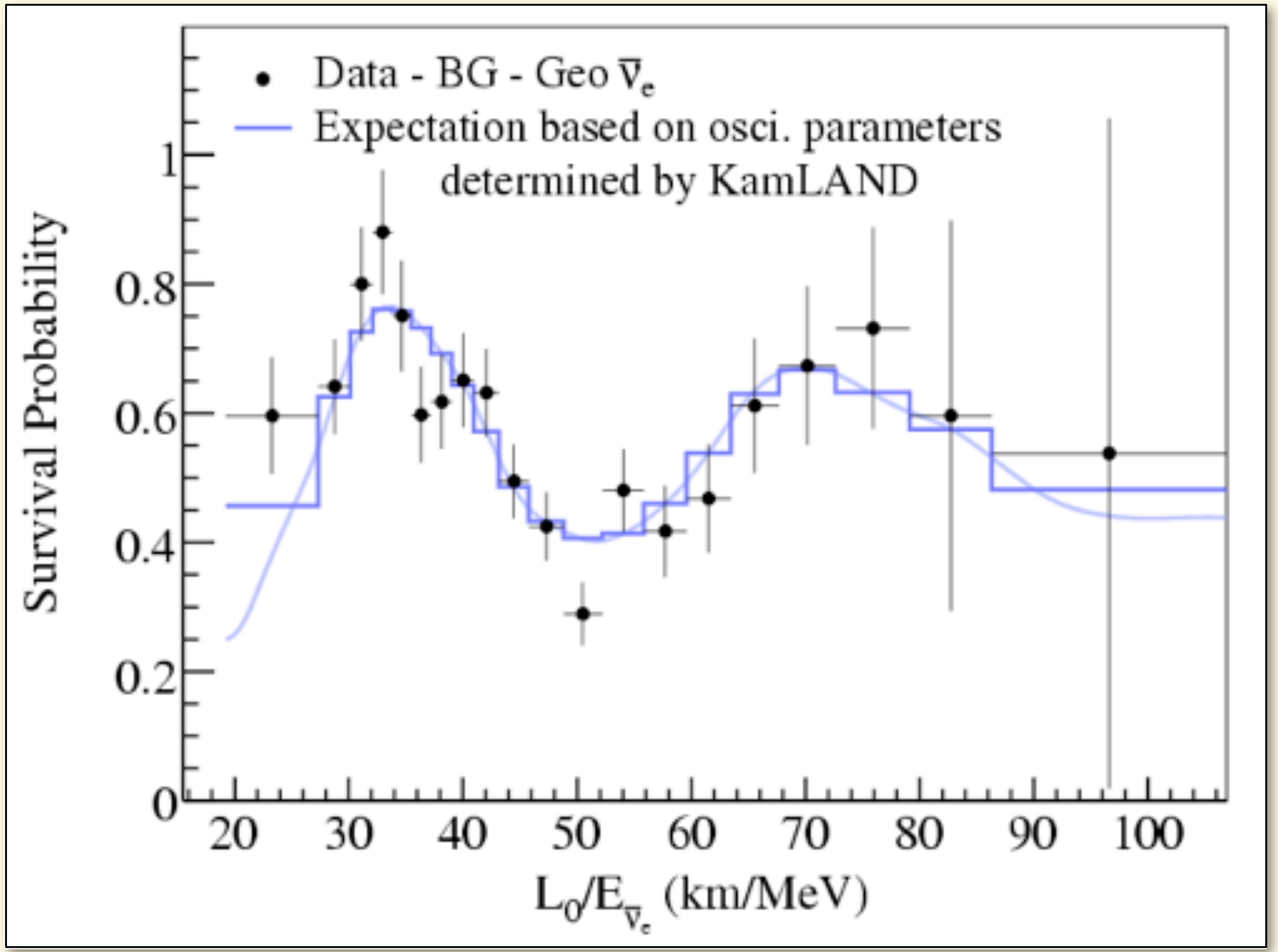

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Solar neutrino experiments - <u>neutrinos</u>
KamLAND - disappearance of <u>antineutrinos</u>

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Solar includes all solar experiments (3 phases of SNO, SuperKamiokande, Chlorine, Gallium and Borexino)

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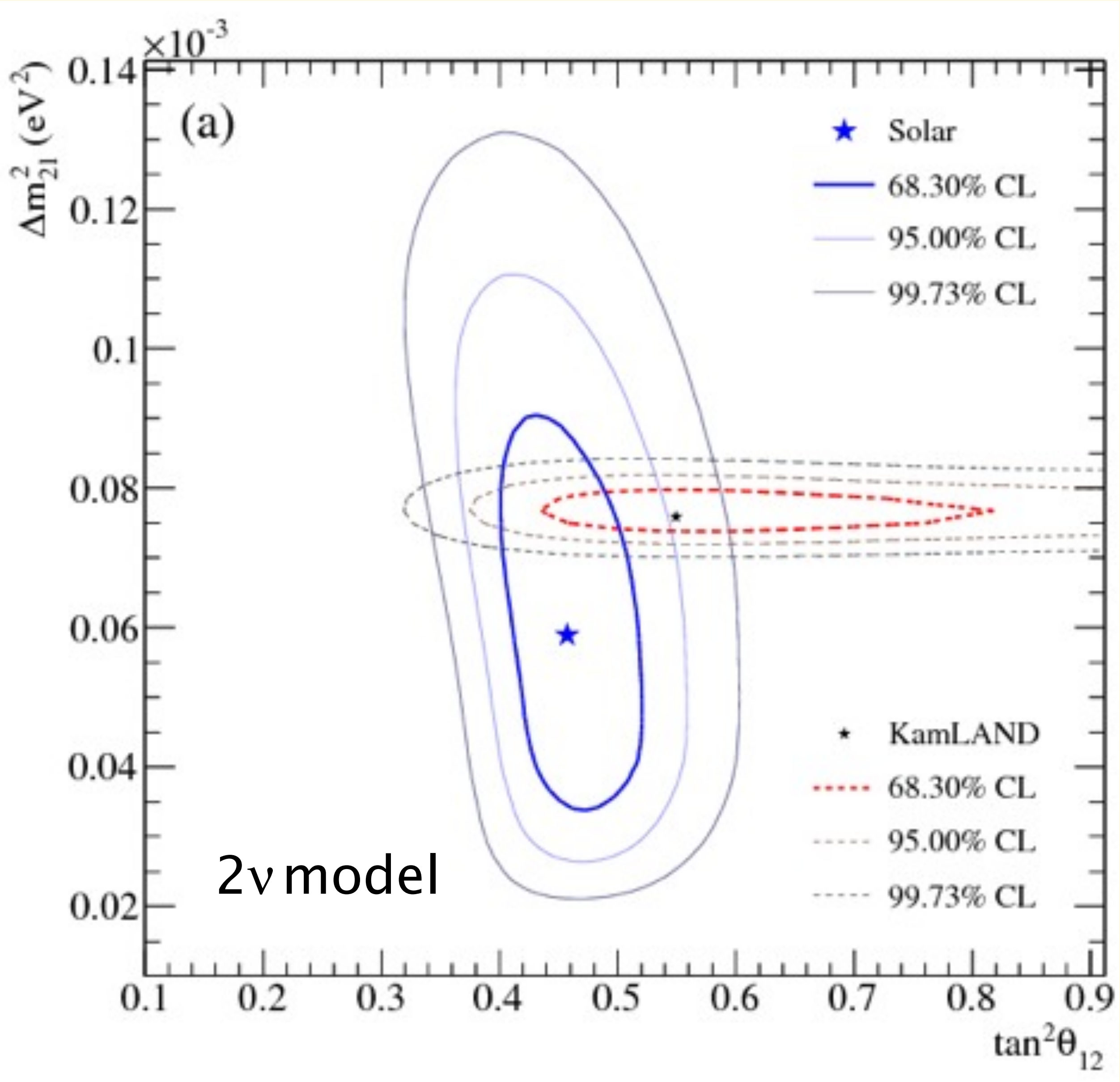

Some tension between 2 results in 2-flavor approximation

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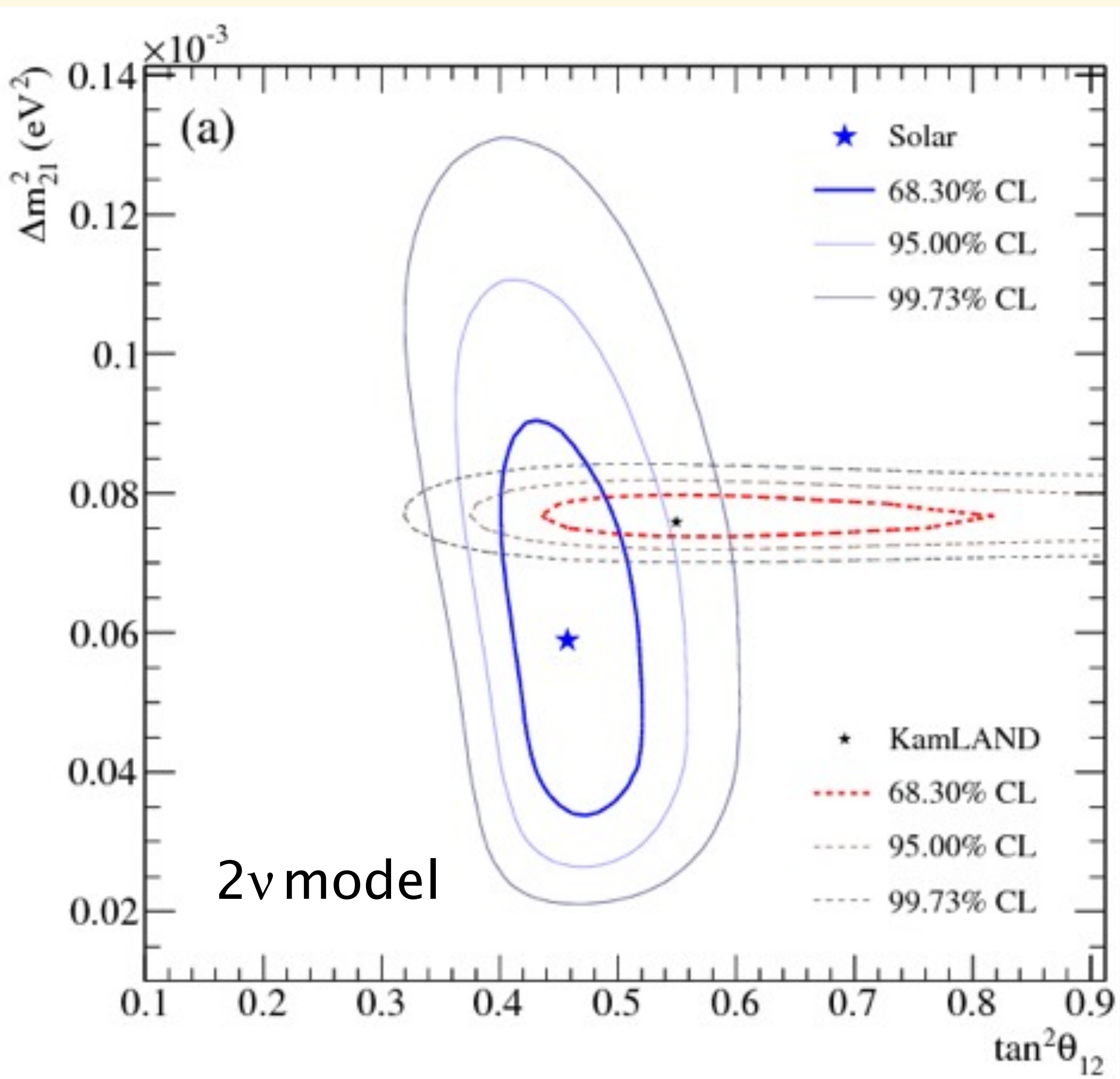

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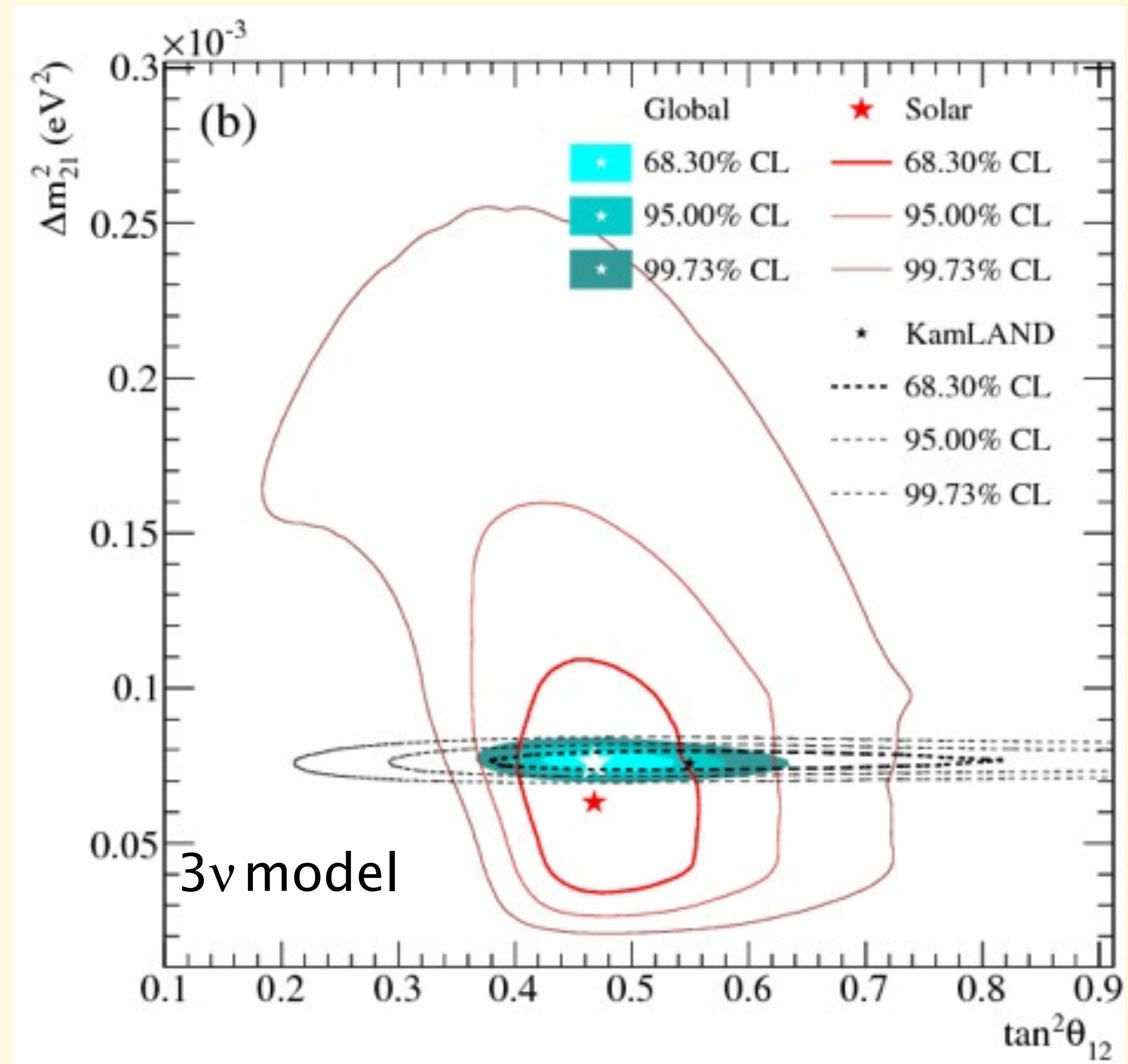

Inclusion of θ_{13} increases contours, gives small non-zero value of θ_{13}

Summary (solar sector)

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Oscillation analysis	$\tan^2\theta_{12}$	Δm^2_{21} (eV^2)
Solar (2ν)	$0.457^{+0.038}_{-0.042}$	$5.89^{+2.13}_{-2.16} \times 10^{-5}$
Solar + KamLAND (2ν)	$0.457^{+0.040}_{-0.029}$	$7.59^{+0.20}_{-0.21} \times 10^{-5}$
Solar + KamLAND (3ν)	$0.468^{+0.042}_{-0.033}$	$7.59^{+0.21}_{-0.21} \times 10^{-5}$

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Going to 3 flavor analysis does not change solar parameters significantly

Solar expts determine $\tan^2\theta_{12}$, KamLAND Δm^2_{21}

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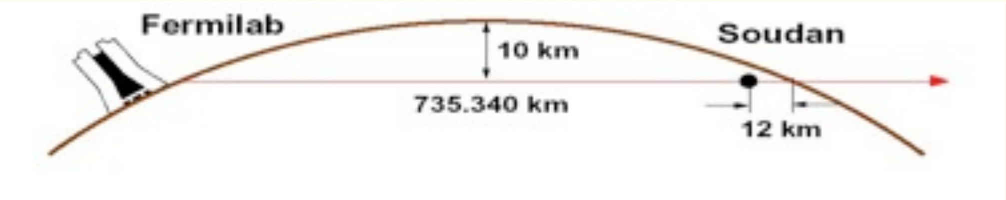

Neutrino beam produced at Fermilab
Near Detector - 1 km from the target
Far Detector - 735 km away and
710 m underground

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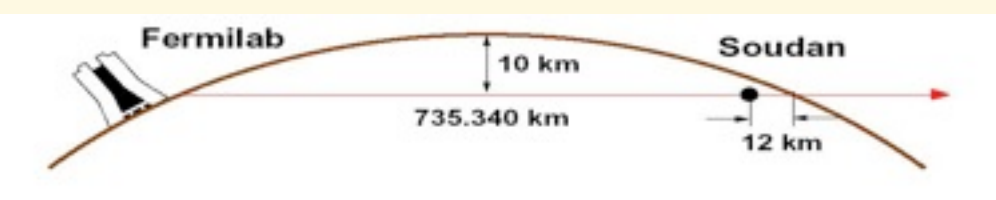

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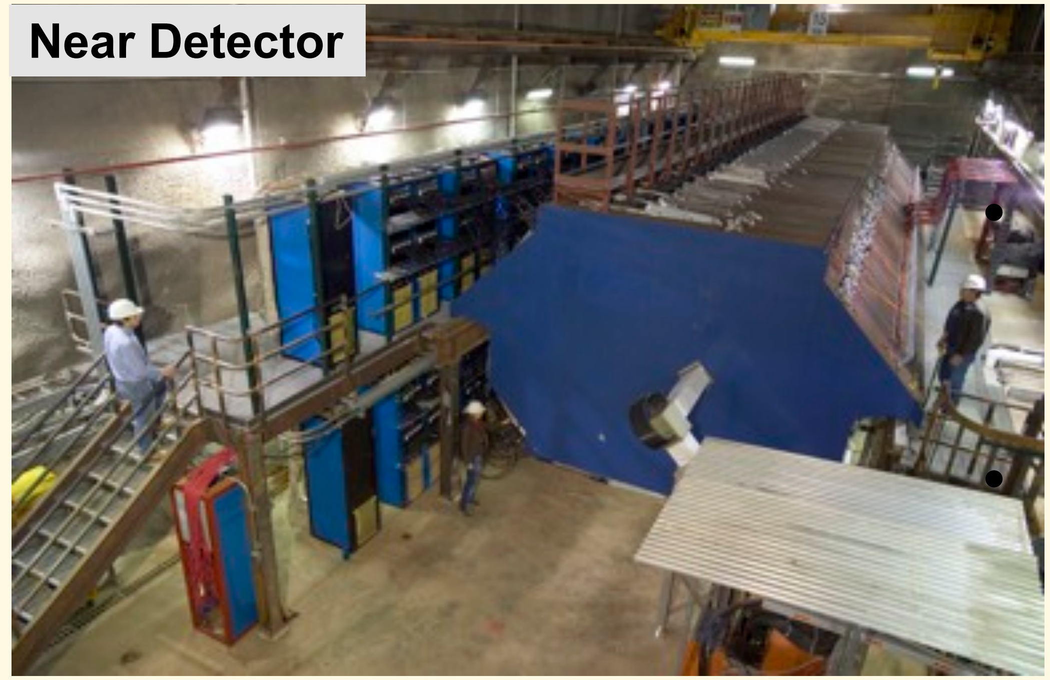

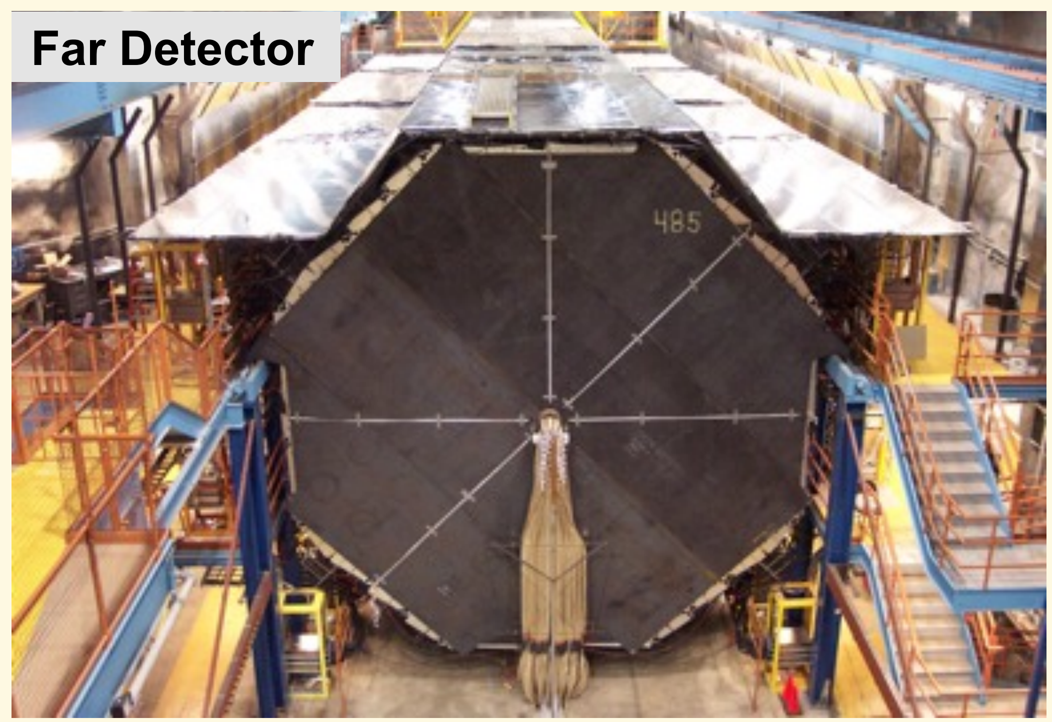

MINOS Detectors

- Large Mass
  - Near: 0.98 kt
  - Far: 5.4 kt
- As similar as possible
  - steel planes
    - 2.5 cm thick
  - scintillator strips
    - 1 cm thick
    - 4.1 cm wide
  - Wavelength shifting fibre optic readout
  - Multi-anode PMTs
  - Magnetised (~1.3 T)

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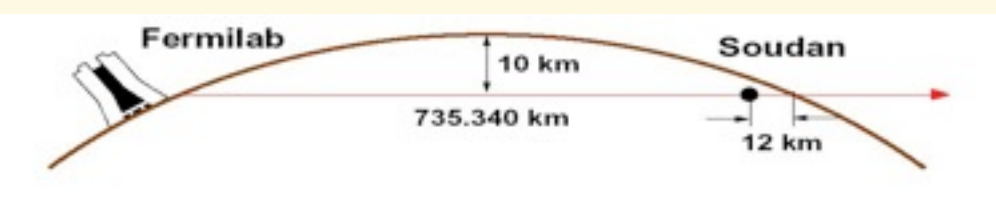

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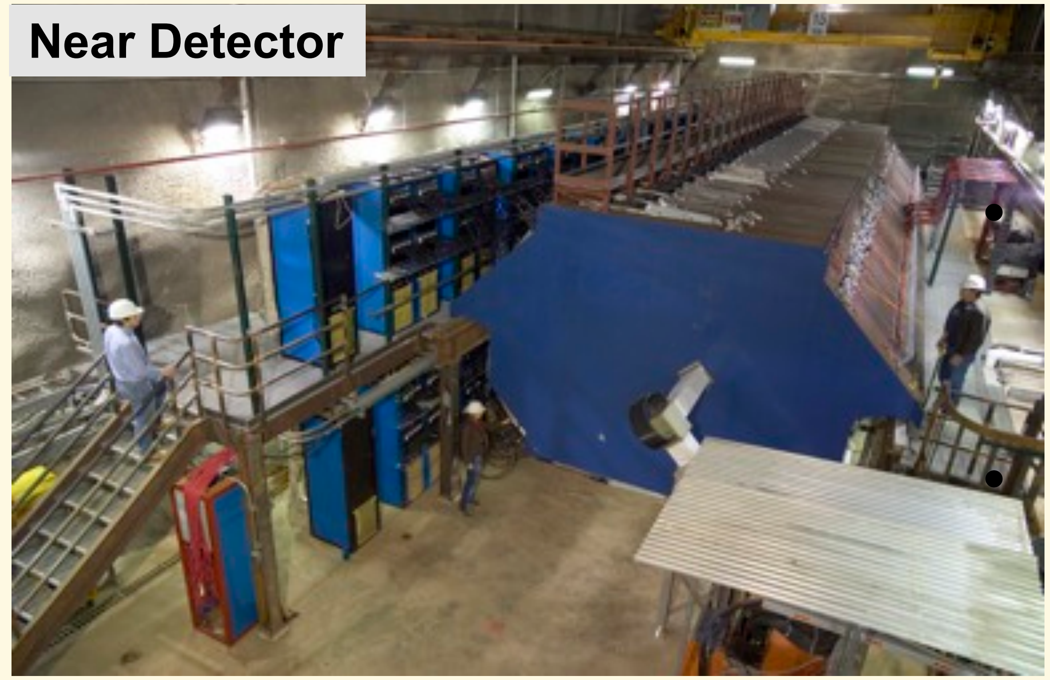

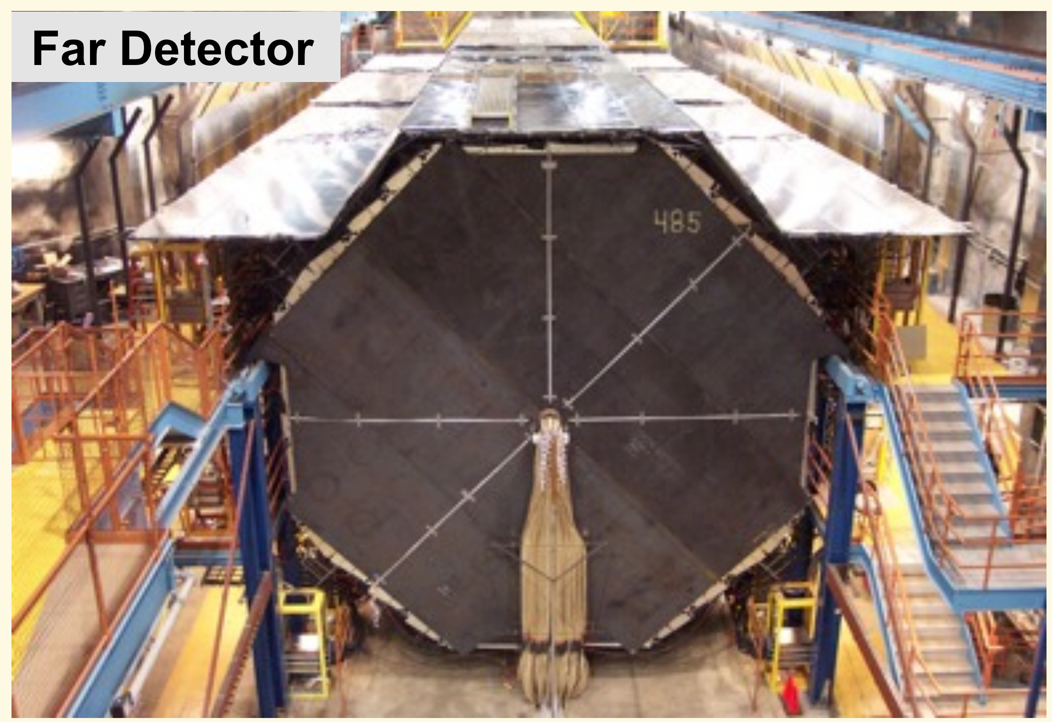

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The flux is measured in the Near Detector and then extrapolated to obtain prediction in the Far Detector

MINOS E_ν Spectrum

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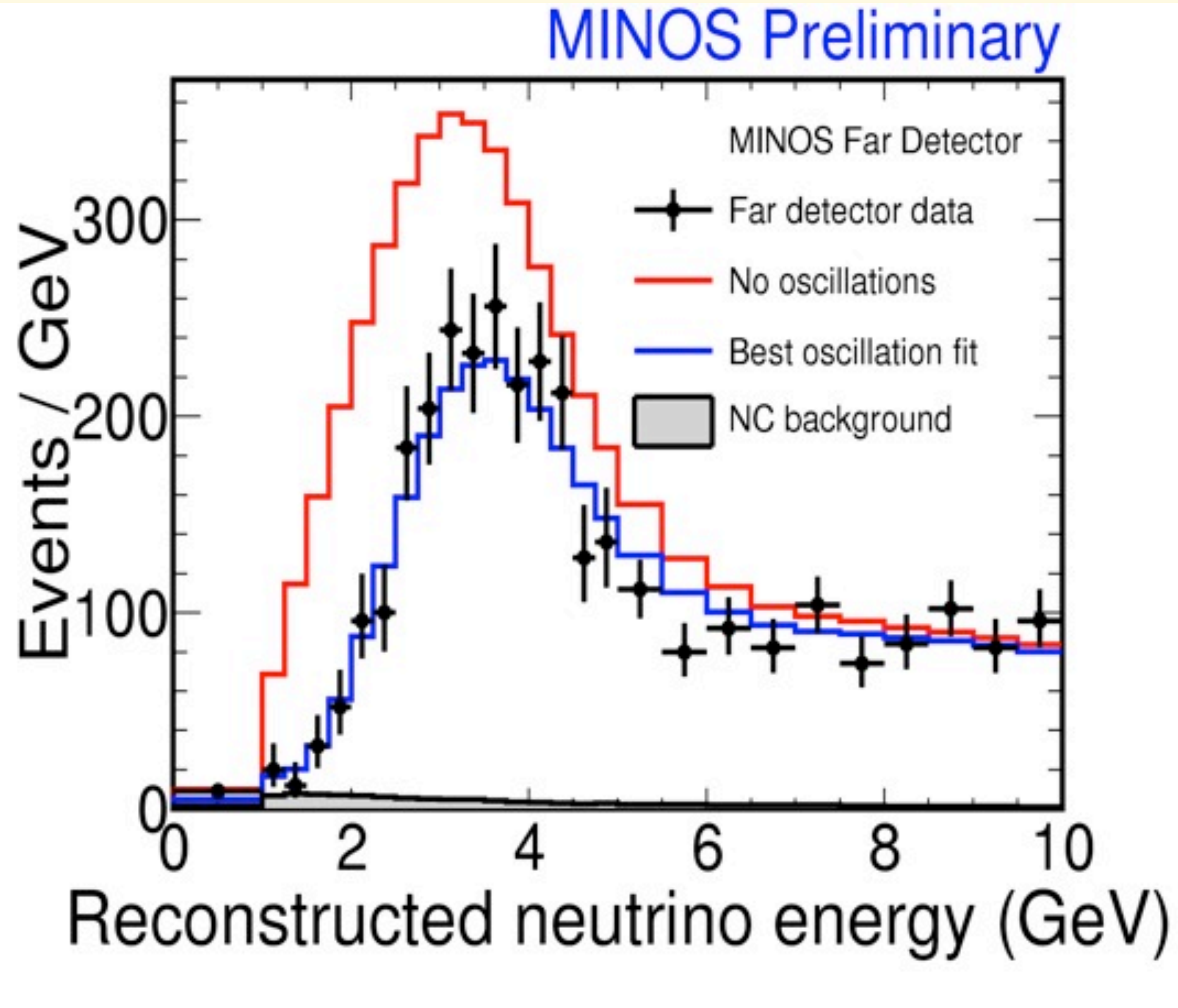

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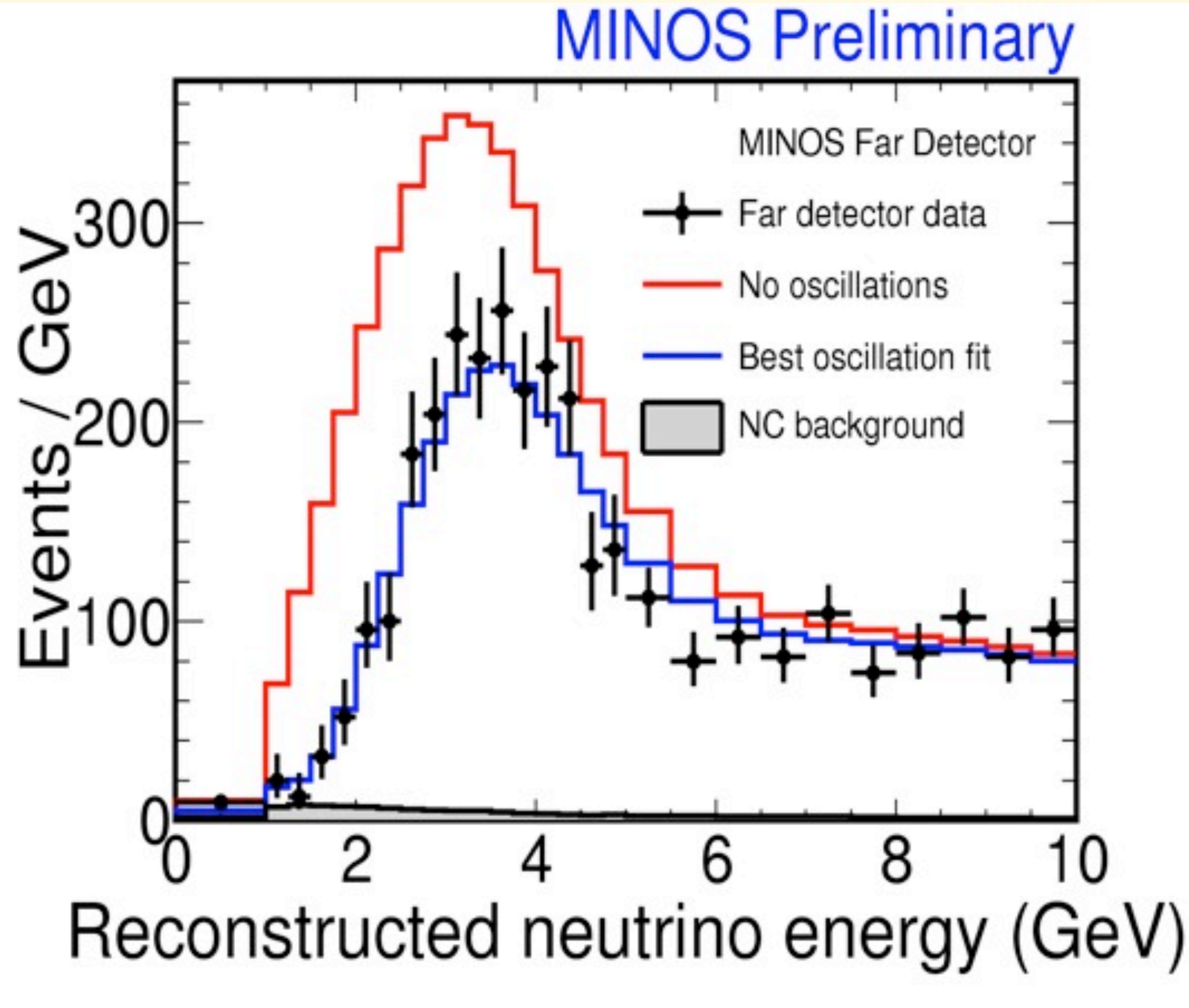

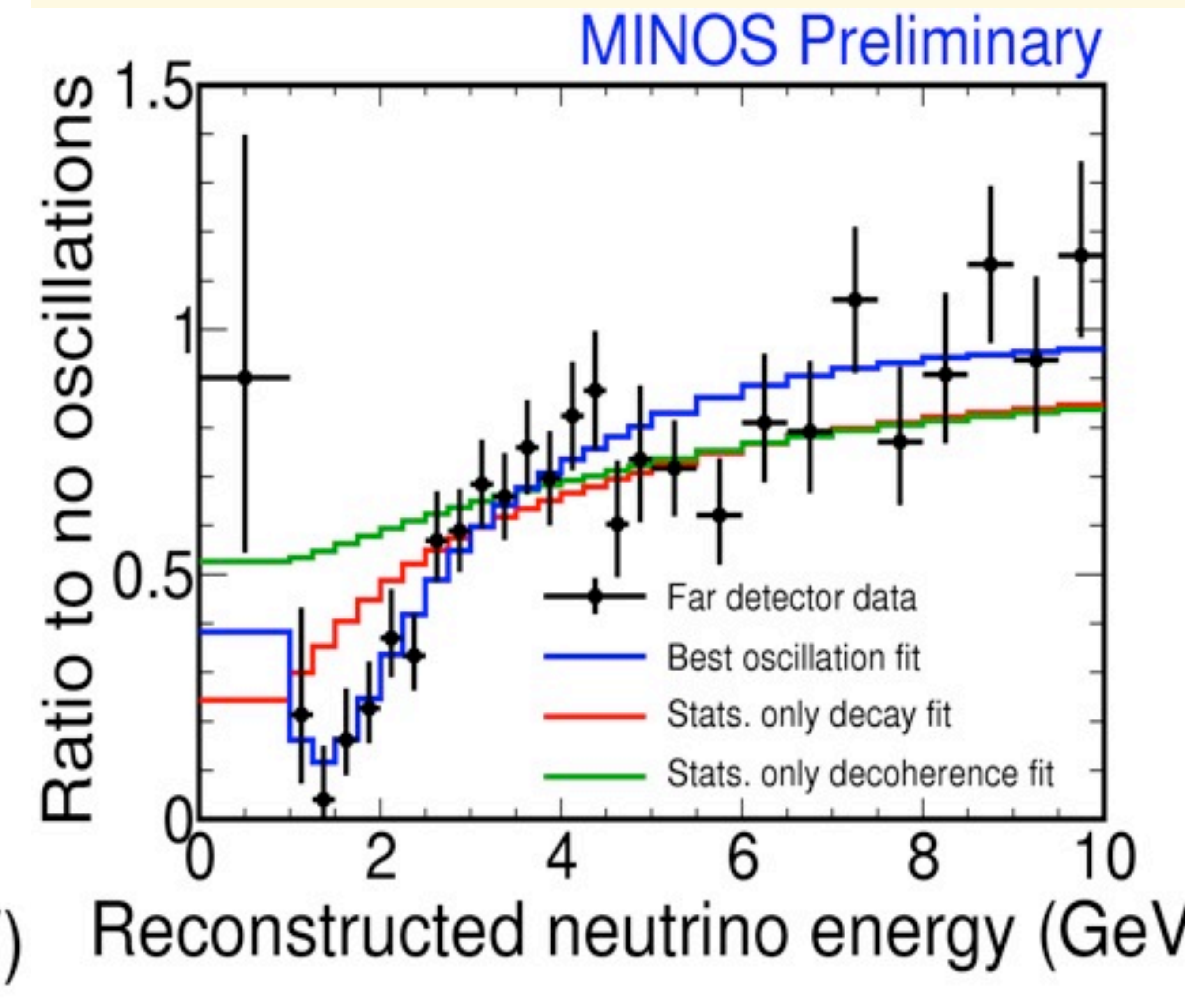

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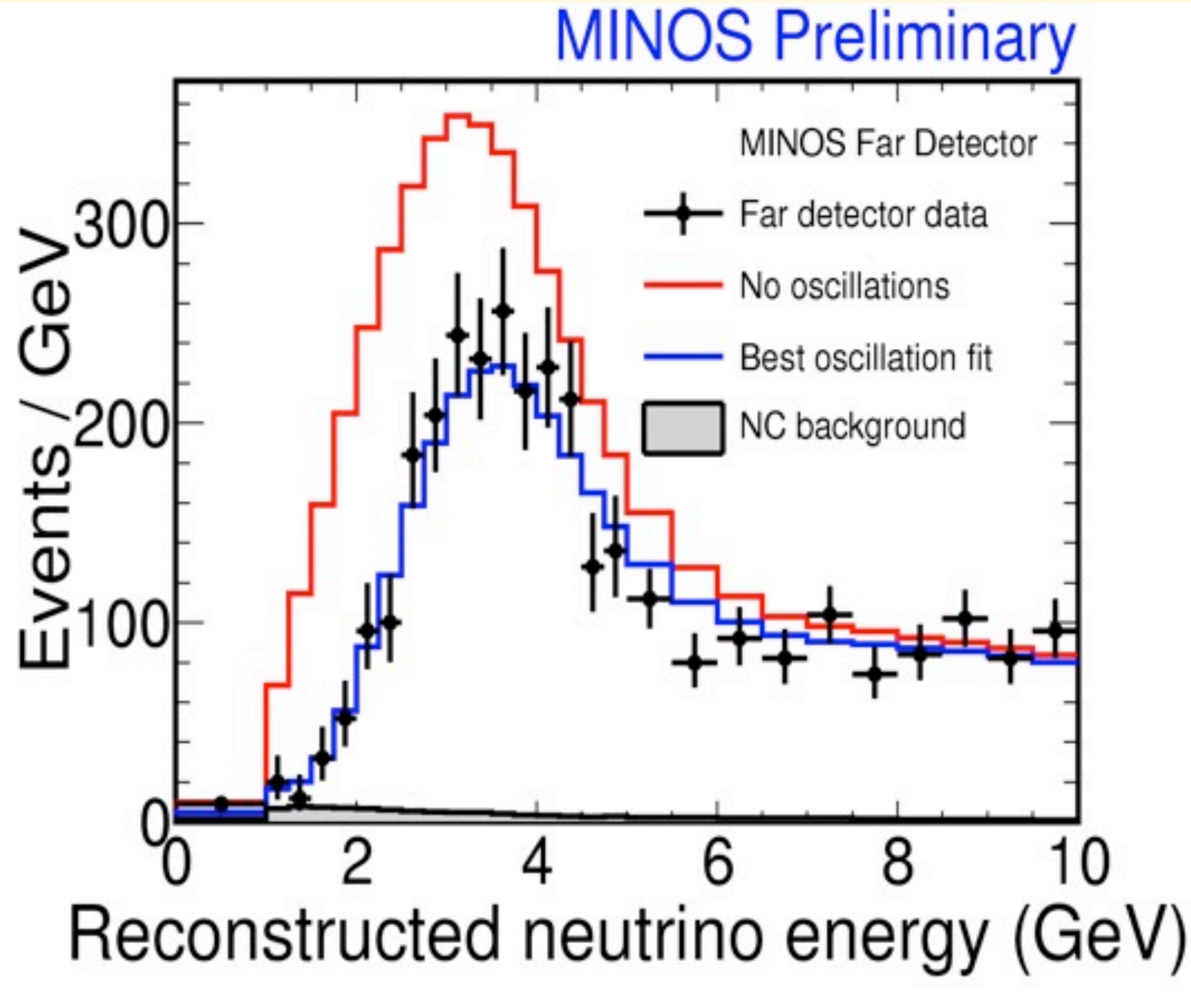

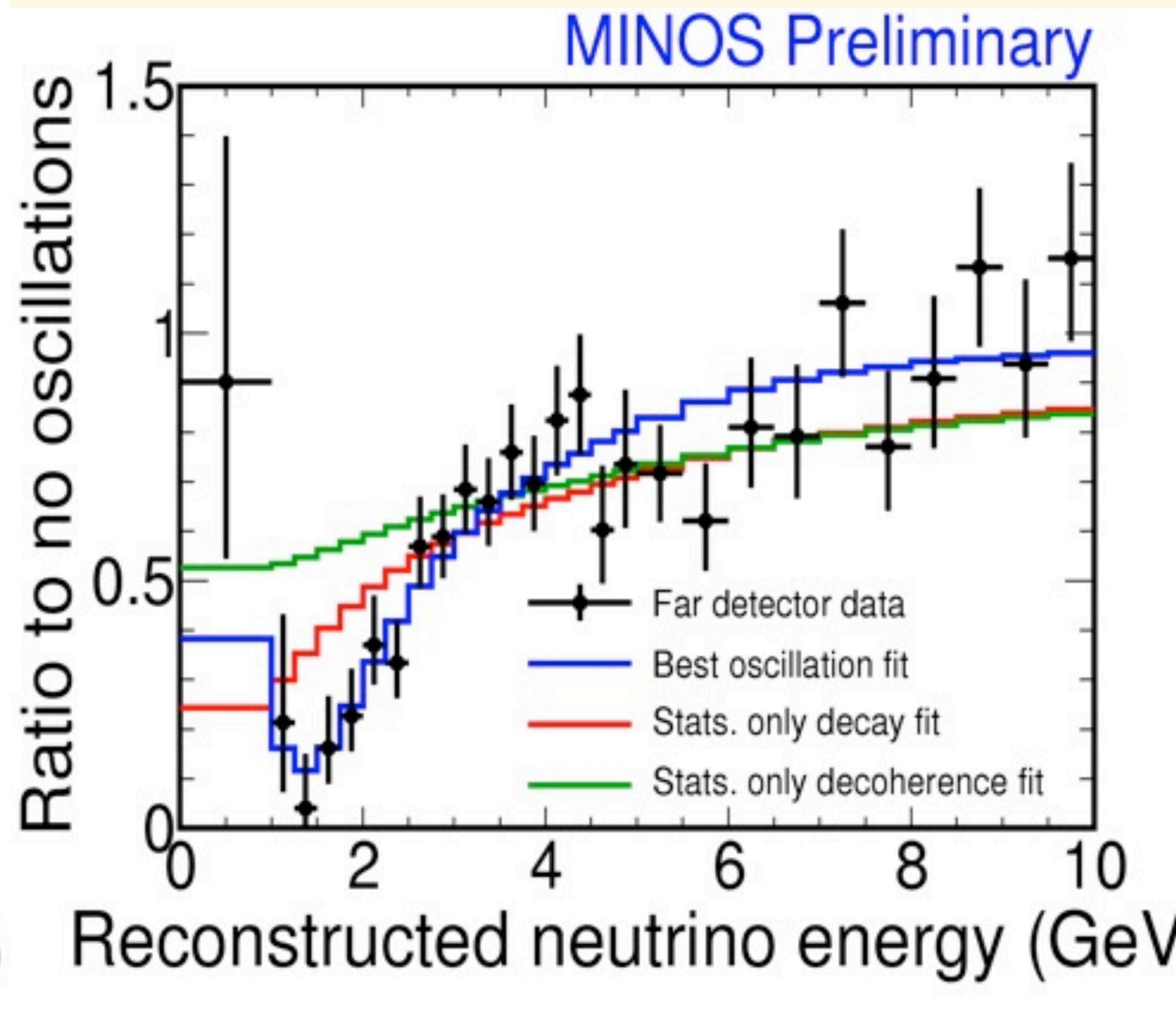

Good agreement with oscillation hypothesis

Alternative hypotheses (decay, decoherence) excluded at a significant level >6σ

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MINOS Contour

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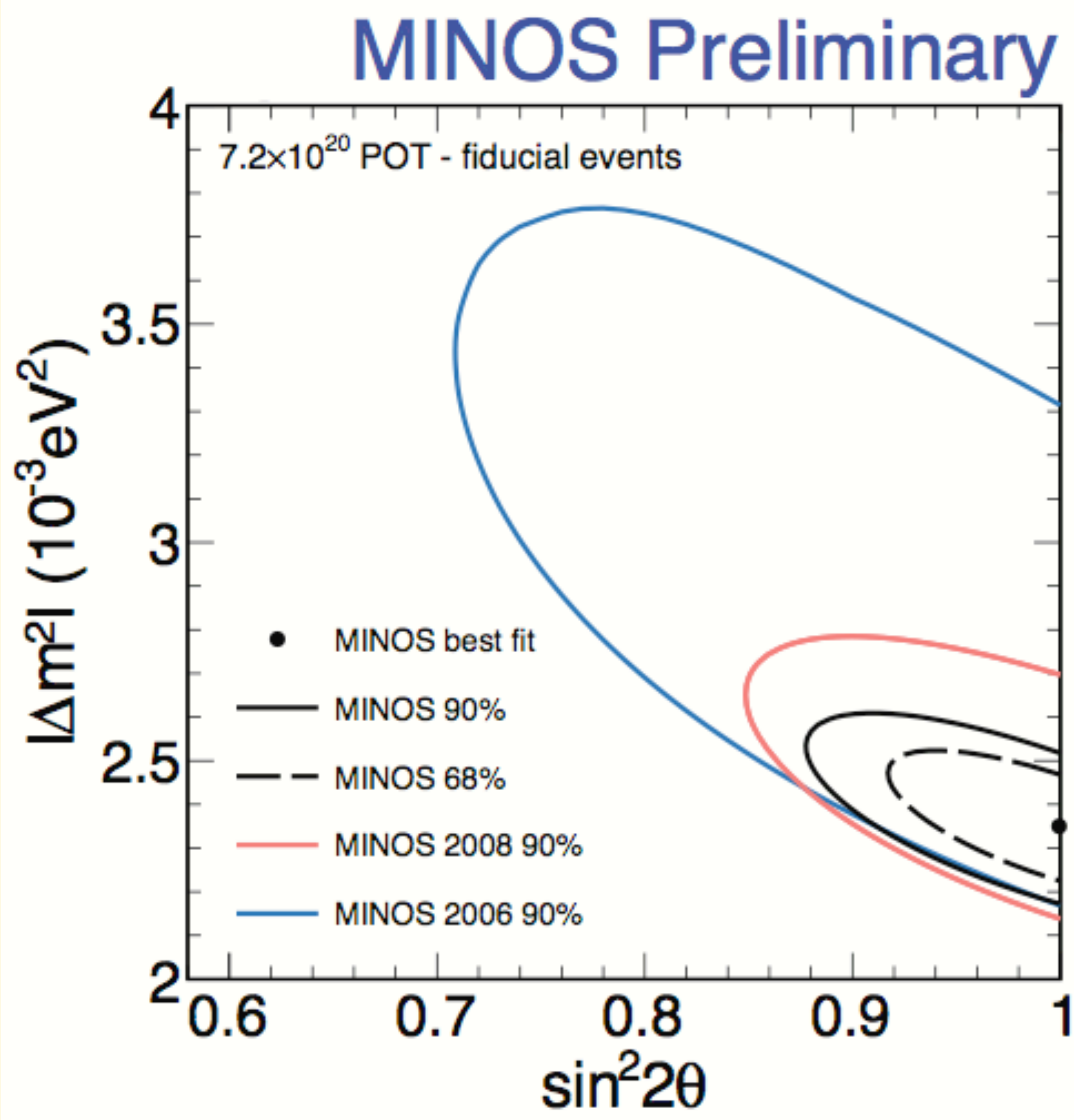

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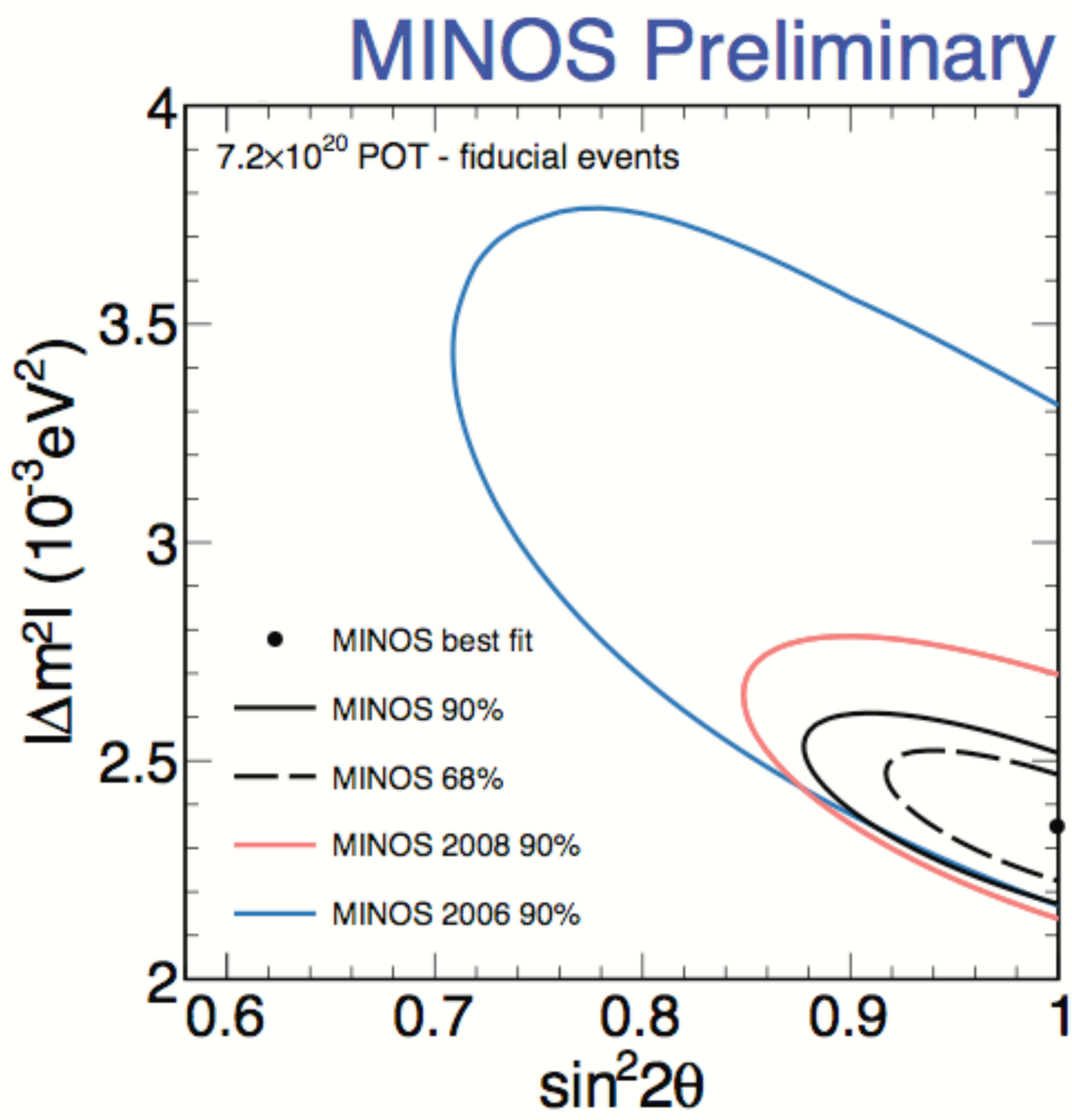

Fit results

$$\left|\Delta m^2\right| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2(2\theta) > 0.91\ (90\%\ \mathrm{C.L.})$$

The fit accounts for the principal systematic effects

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SuperKamiokande

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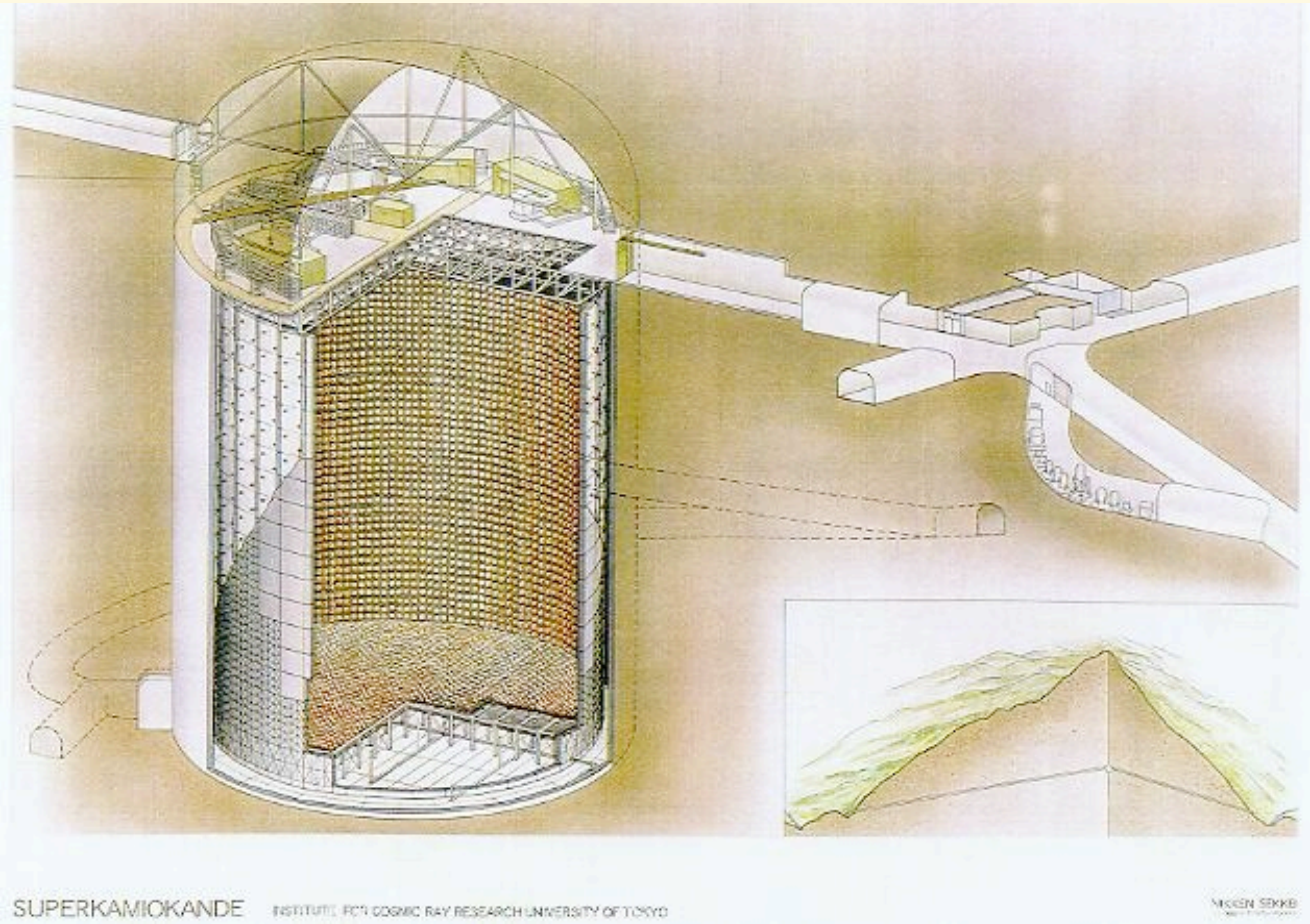
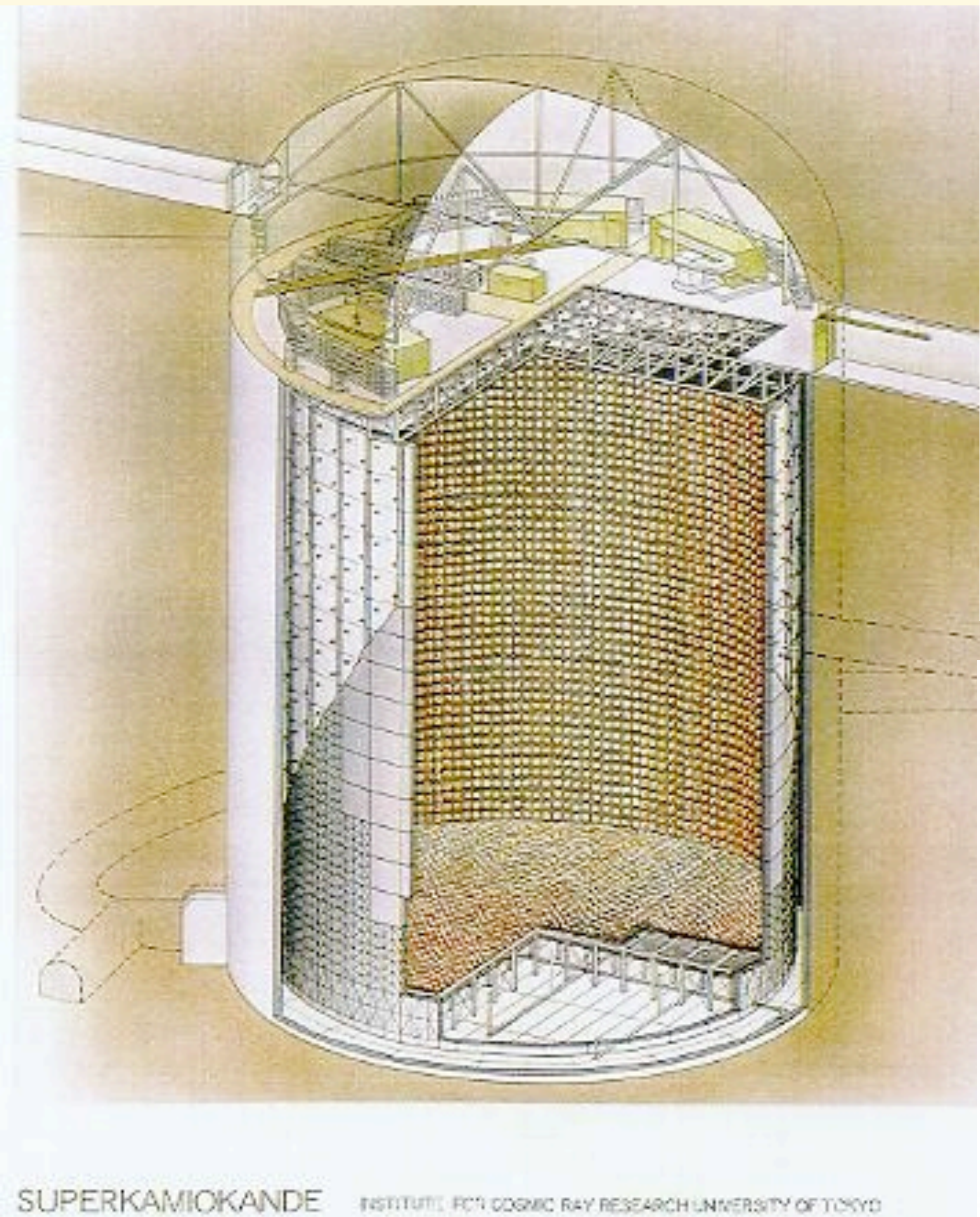
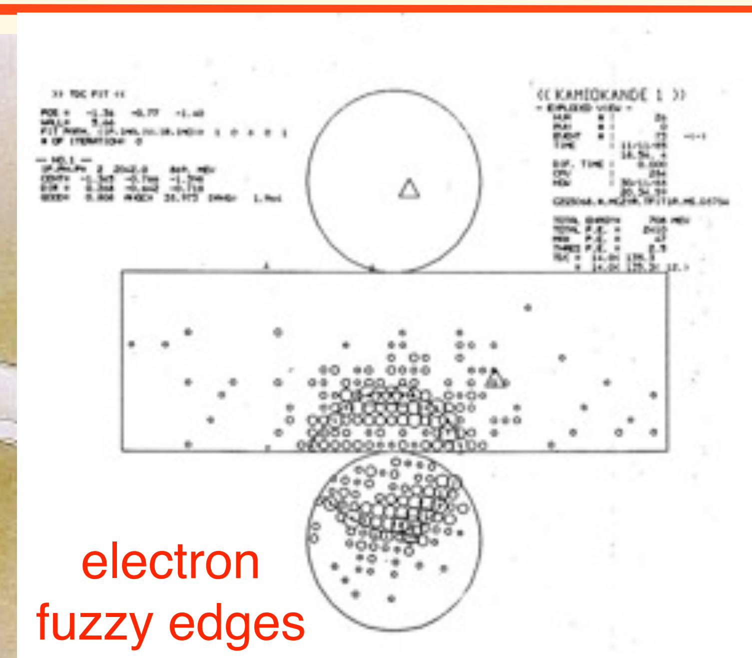
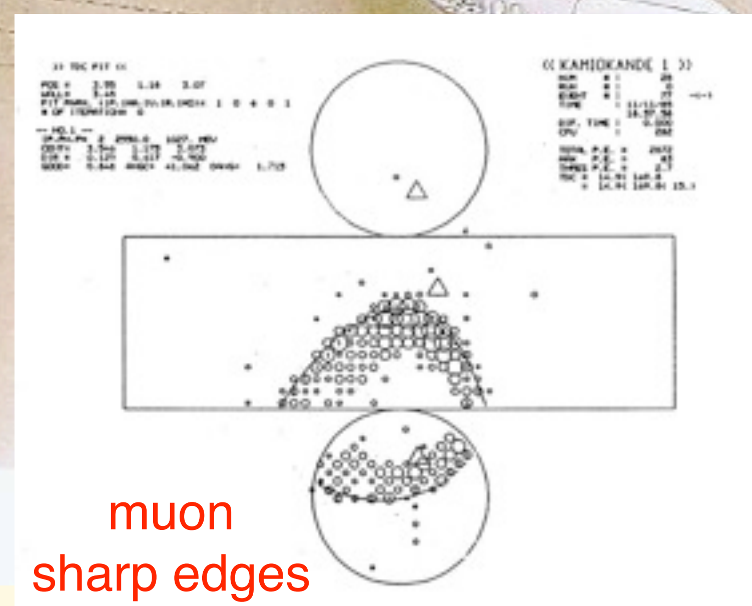


50 kt of water
42m high, 40 m diam
40% PMT coverage
1000m underground

SuperKamiokande







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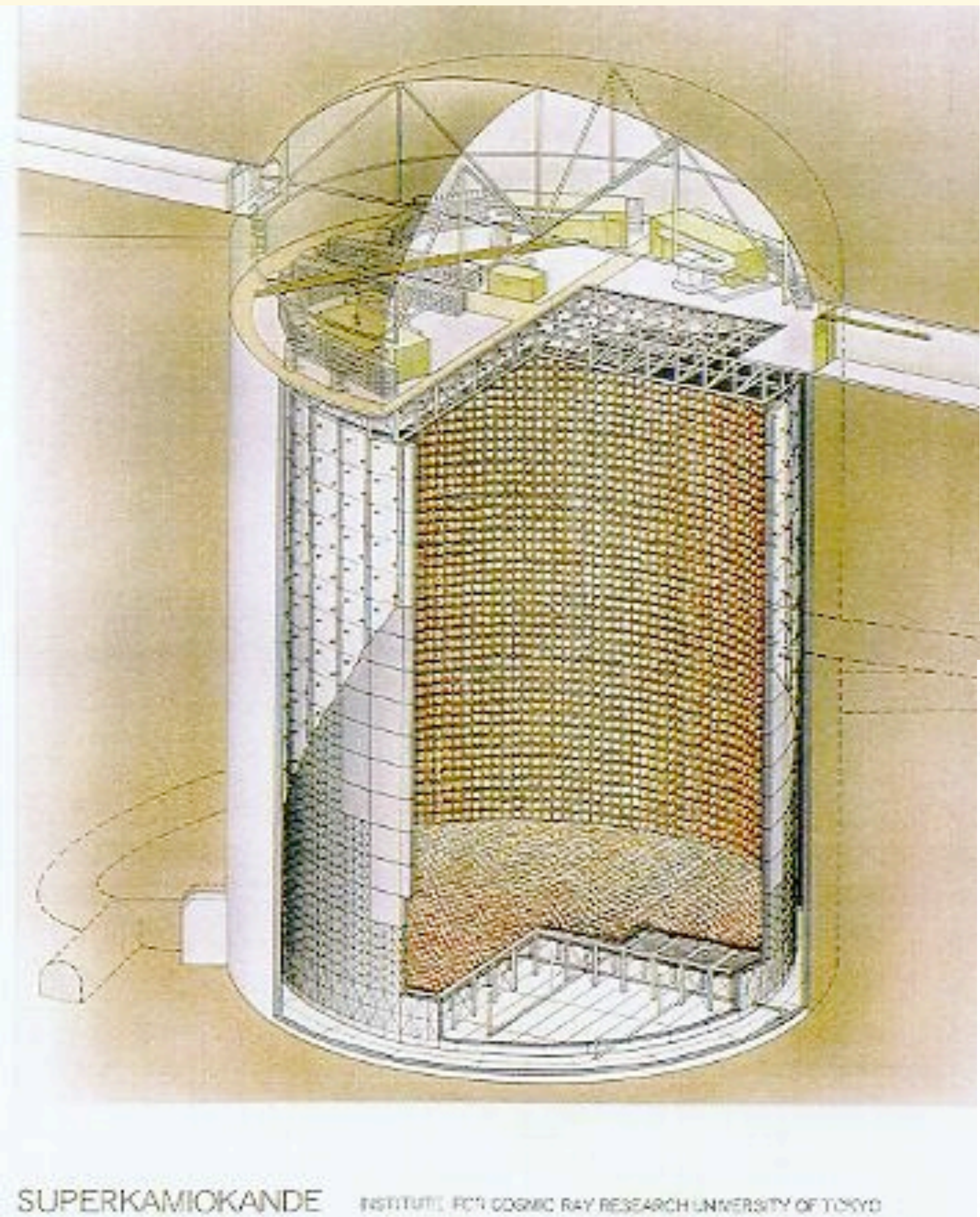

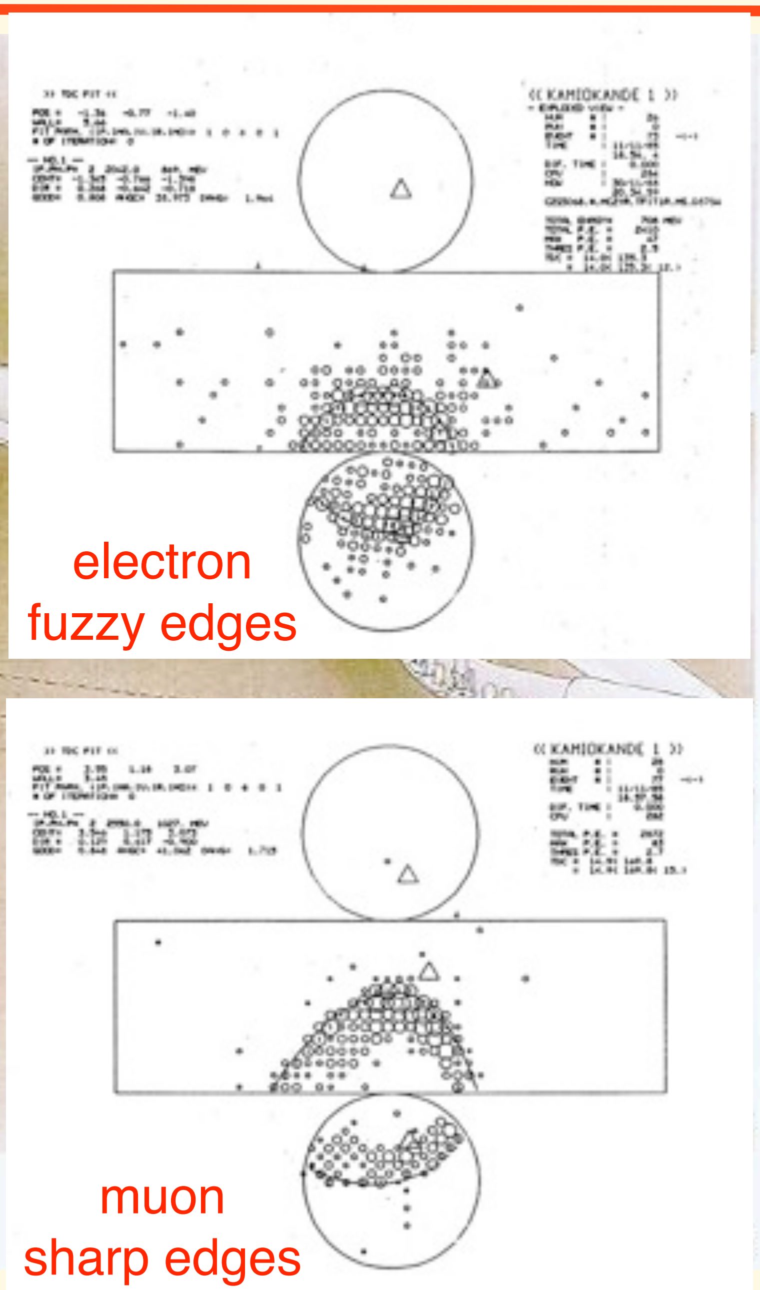

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Zenith angle and L/E distributions are used to extract oscillation parameters

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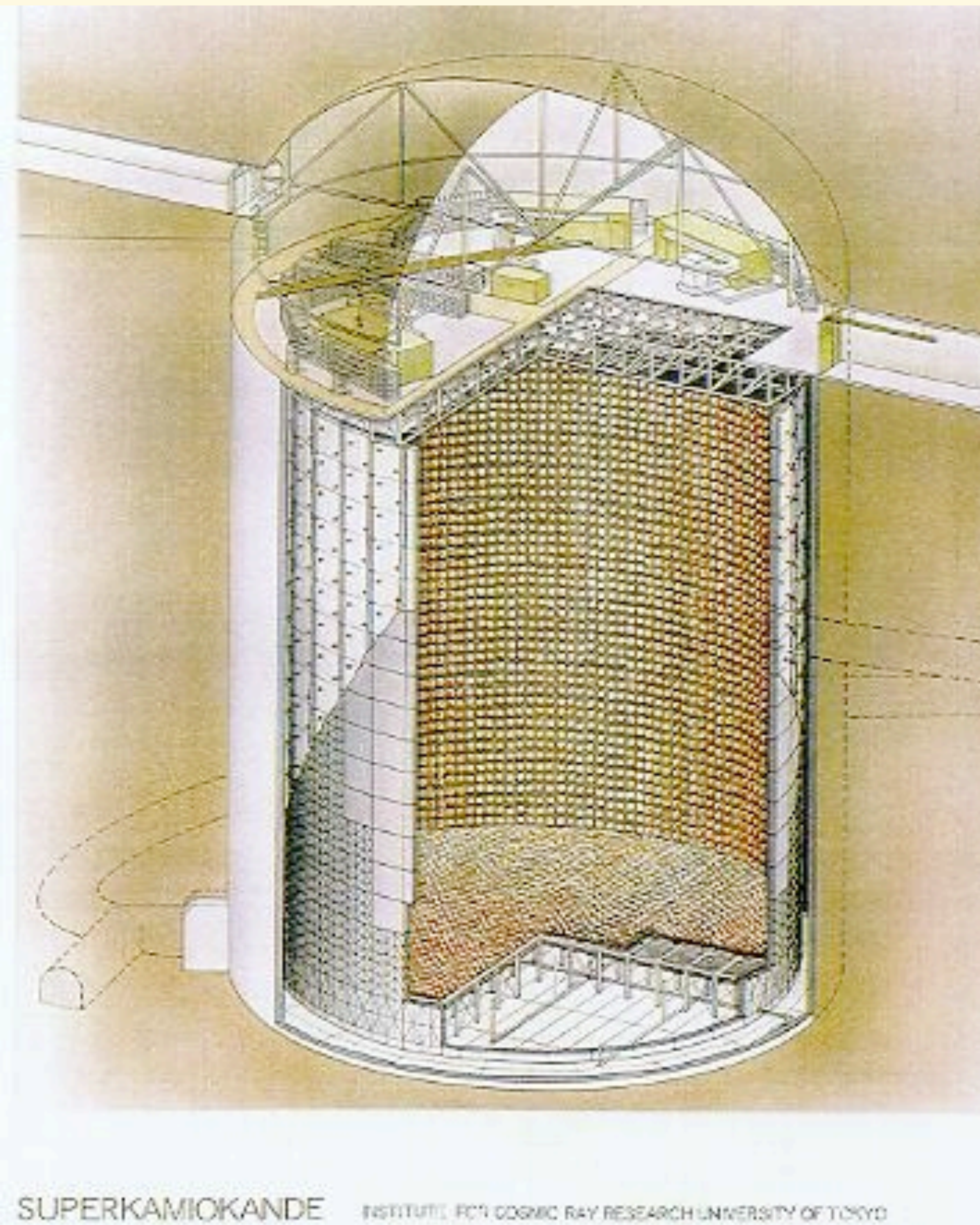

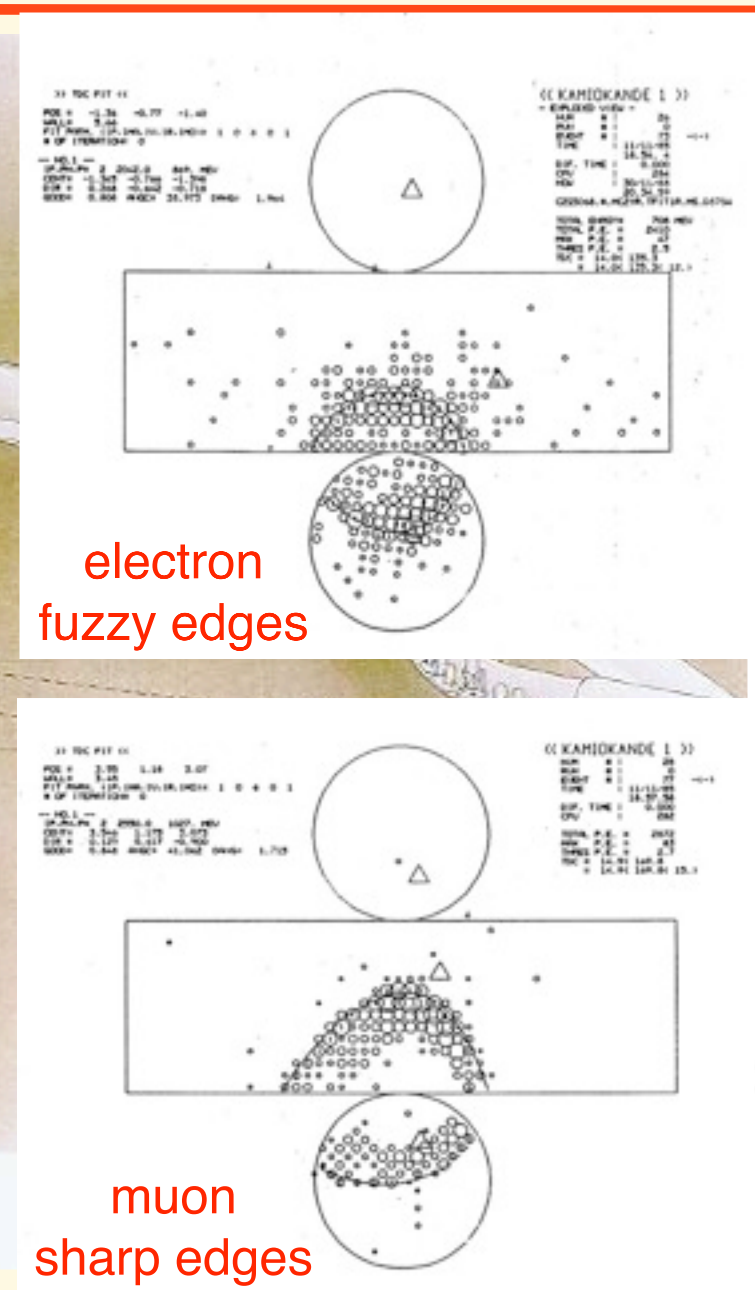

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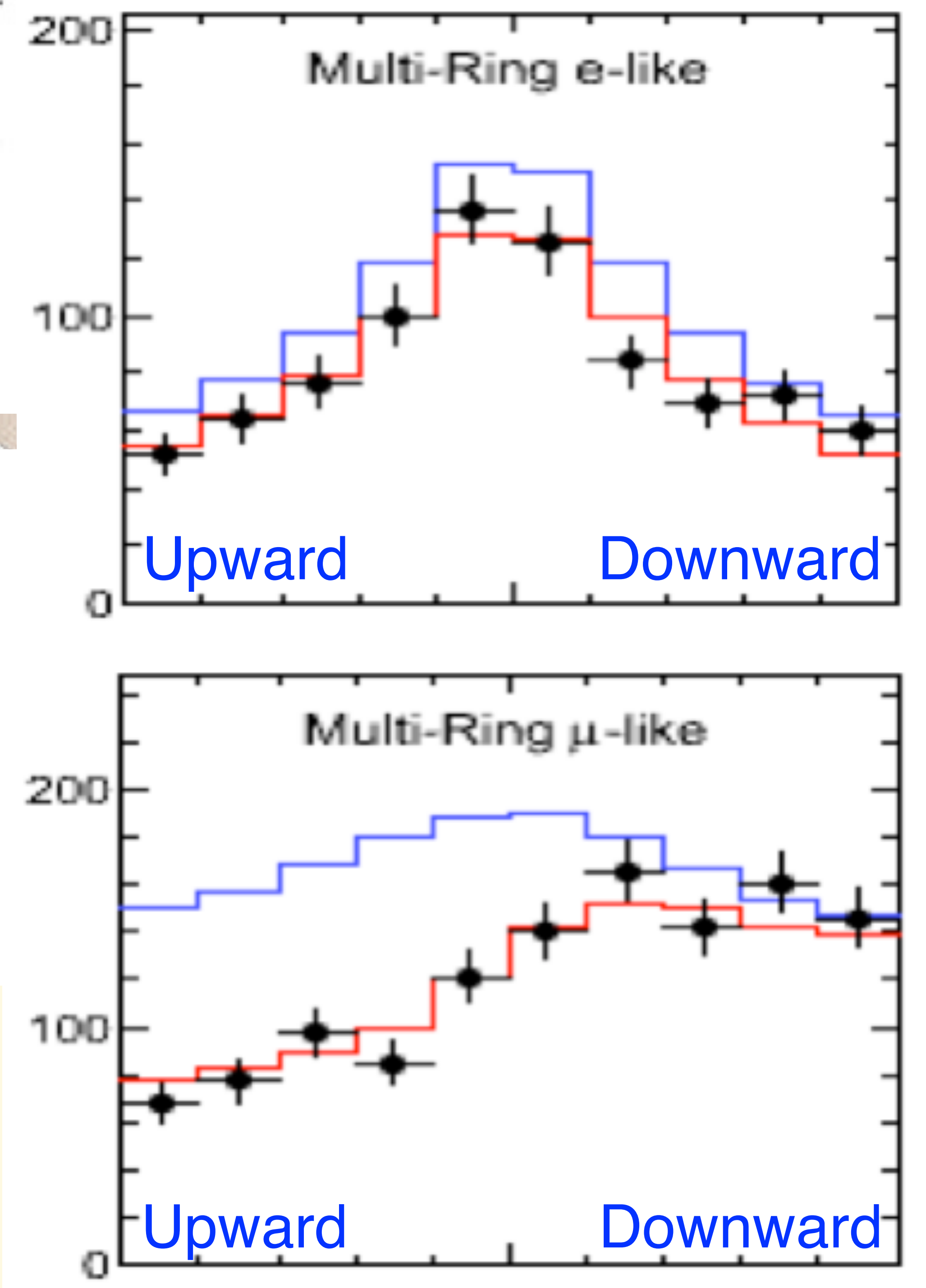
Example distributions



SuperK/MINOS

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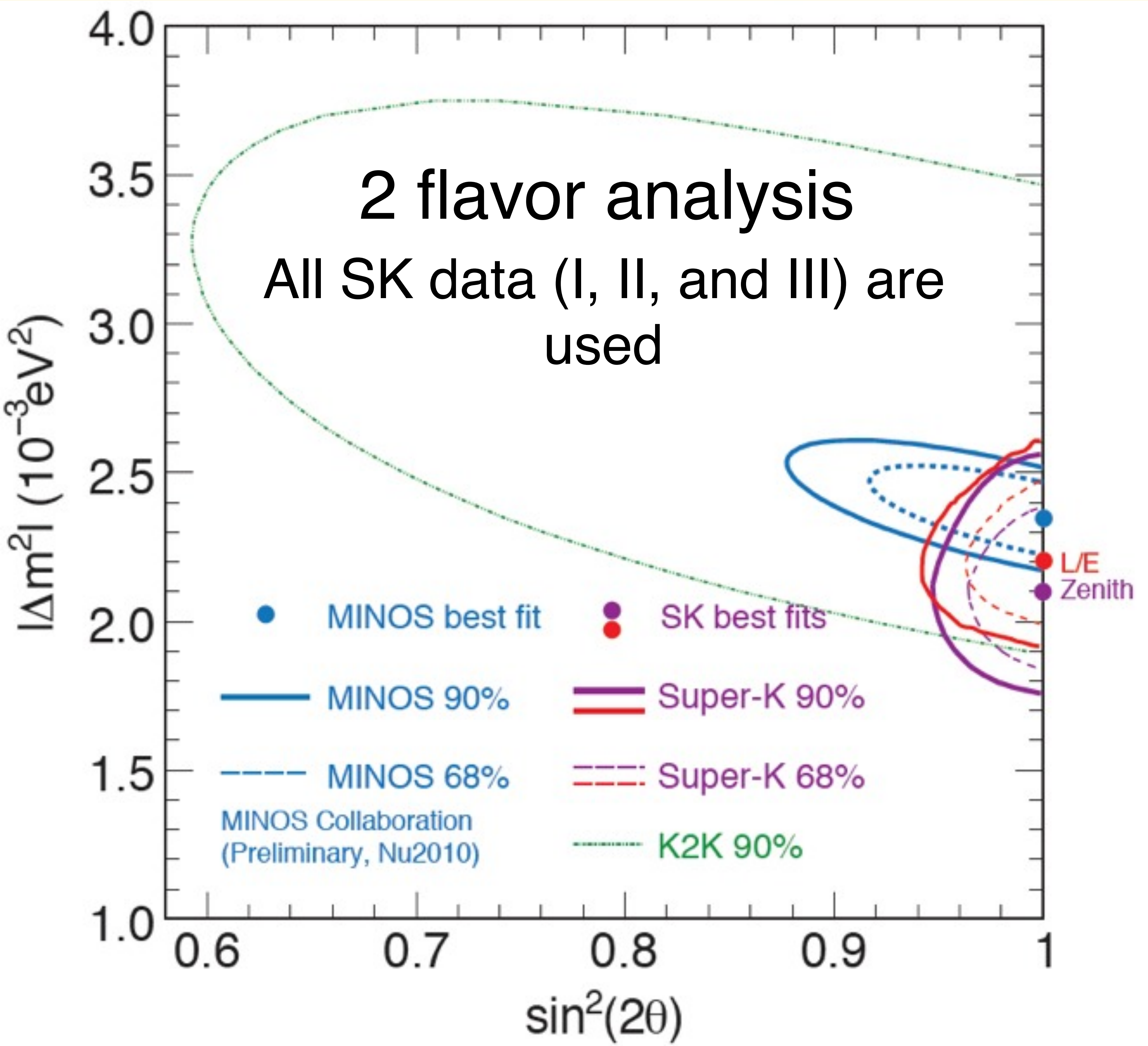

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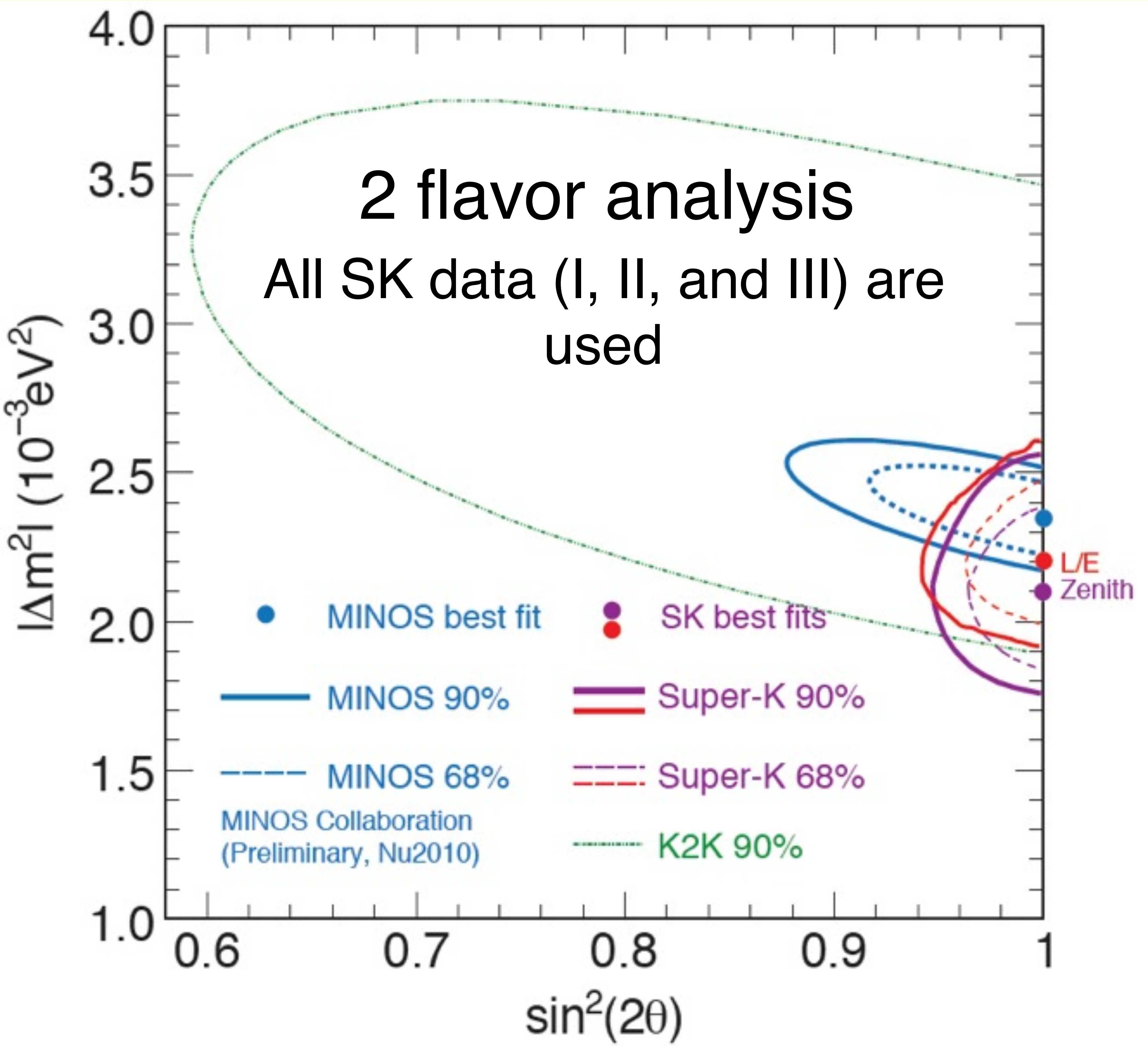

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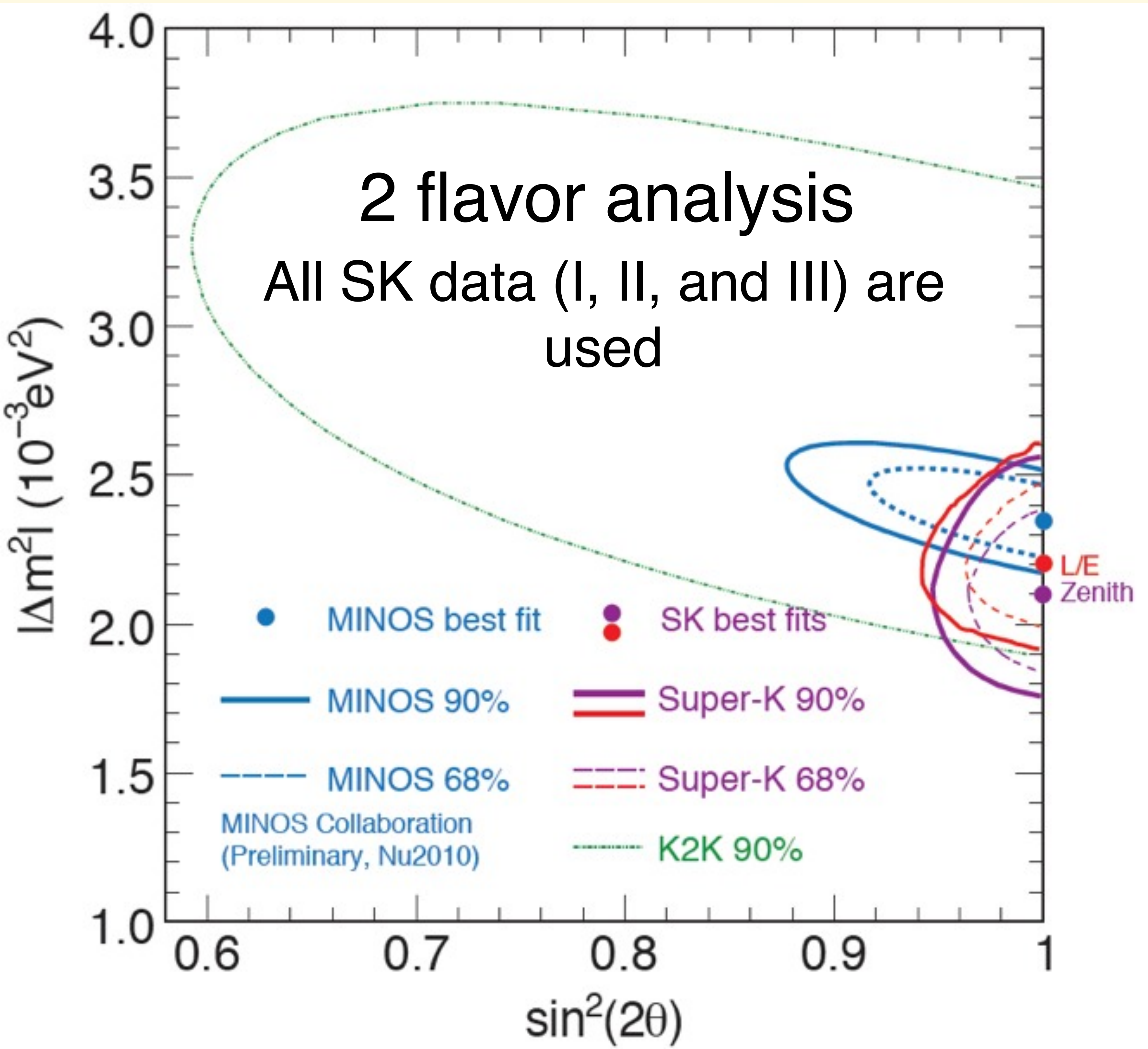

MINOS does better on Δm^2 determination

SuperK does better on the mixing angle

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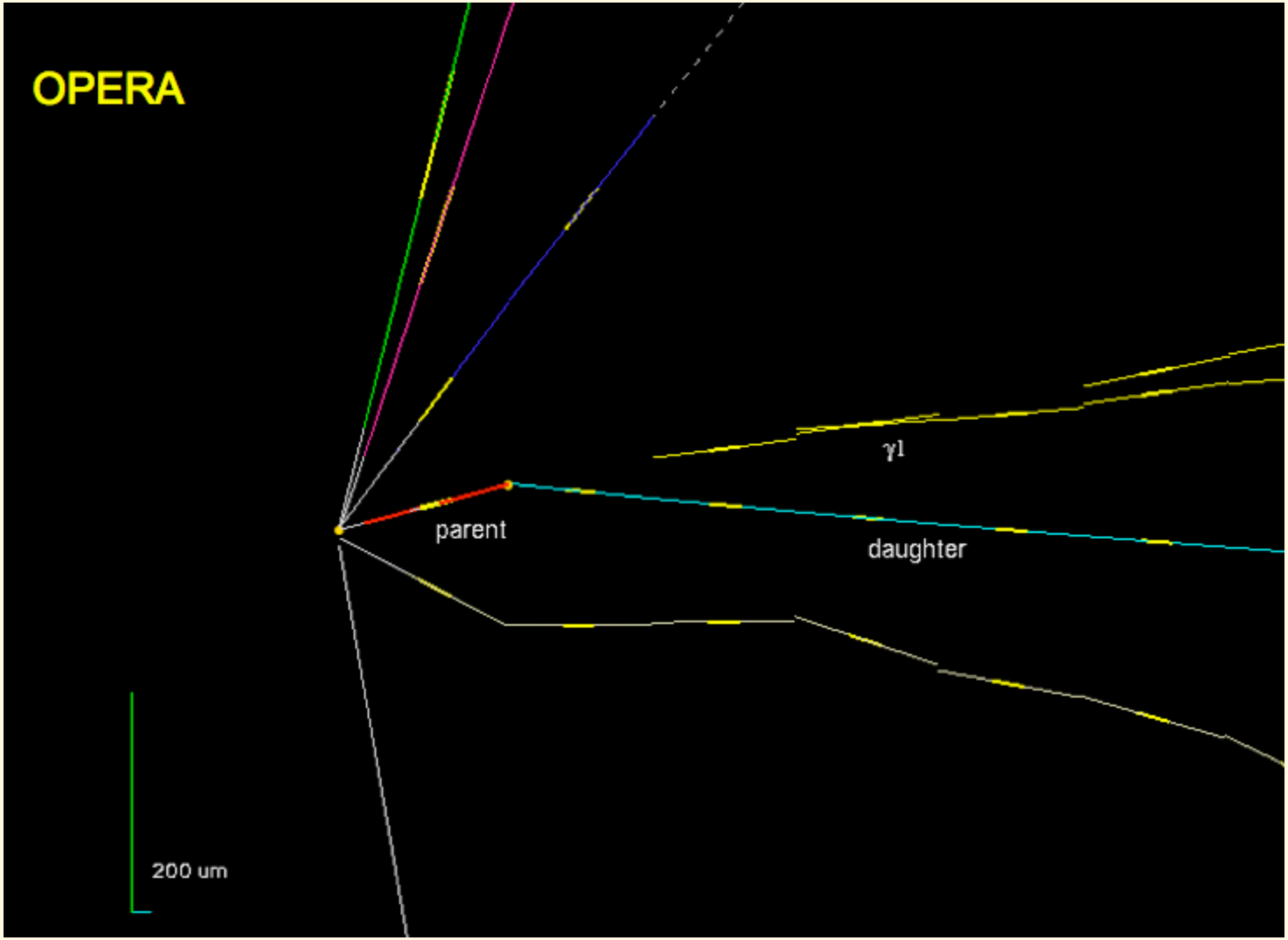
OPERA

→

OPERA



First candidate $\nu_\mu \to \nu_\tau$ $\tau^- \to \pi^- + \pi^0$

Summary - Atmospheric sector

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Oscillation analysis	$\sin^2 2\theta_{23}$ (90% C.L.)	Δm^2_{31} (eV^2)
SuperK (2ν, zenith angle)	>0.96	$2.11^{+0.11}_{-0.19} \times 10^{-3}$
SuperK (2ν, L/E)	>0.96	$2.19^{+0.14}_{-0.13} \times 10^{-3}$
SuperK (3ν, normal mass hierarchy)	>0.93	$2.11^{+0.43}_{-0.12} \times 10^{-3}$
SuperK (3ν, inverted mass hierarchy)		$2.51^{+0.13}_{-0.42} \times 10^{-3}$
MINOS	>0.91	$2.31^{+0.11}_{-0.08} \times 10^{-3}$

Neutrino2010

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No significant preference on mass hierarchy or CP phase seen in SuperK 3 flavor fit

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- Accelerator experiments (appearance):
  - Dependance also on θ_{23}, mass hierarchy, δ_{CP}
- Atmospheric and solar experiments:
  - Look for small effects in 3-flavor analyses

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  - But subtract two large numbers; systematics
- Accelerator experiments (appearance):
  - Dependance also on θ_{23}, mass hierarchy, δ_{CP}
- Atmospheric and solar experiments:
  - Look for small effects in 3-flavor analyses

Caution: Values (limits) are quoted both for $\sin^2(2\theta_{13})$ -accelerators and reactors, and $\sin^2(\theta_{13})$ - 3 flavor

Reactors - CHOOZ limit

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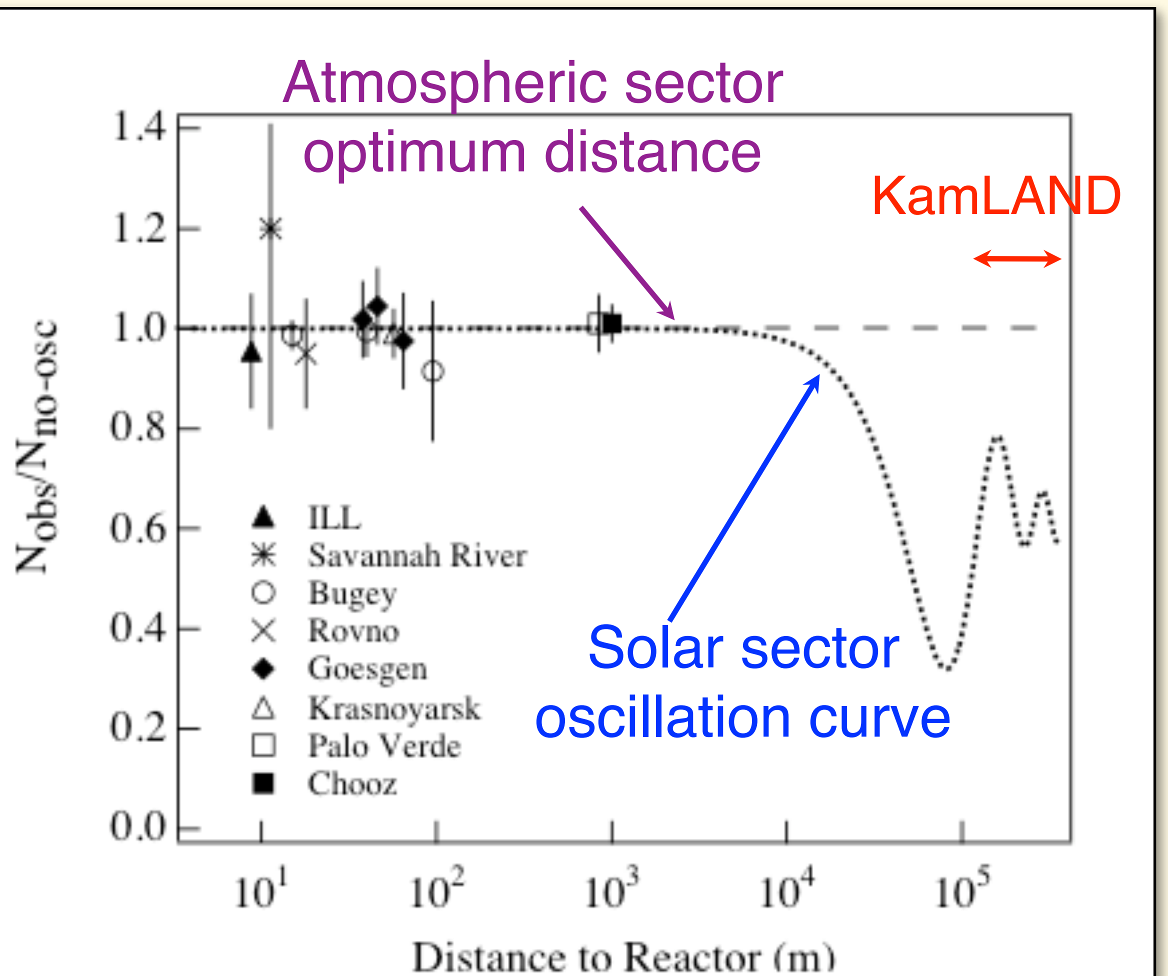

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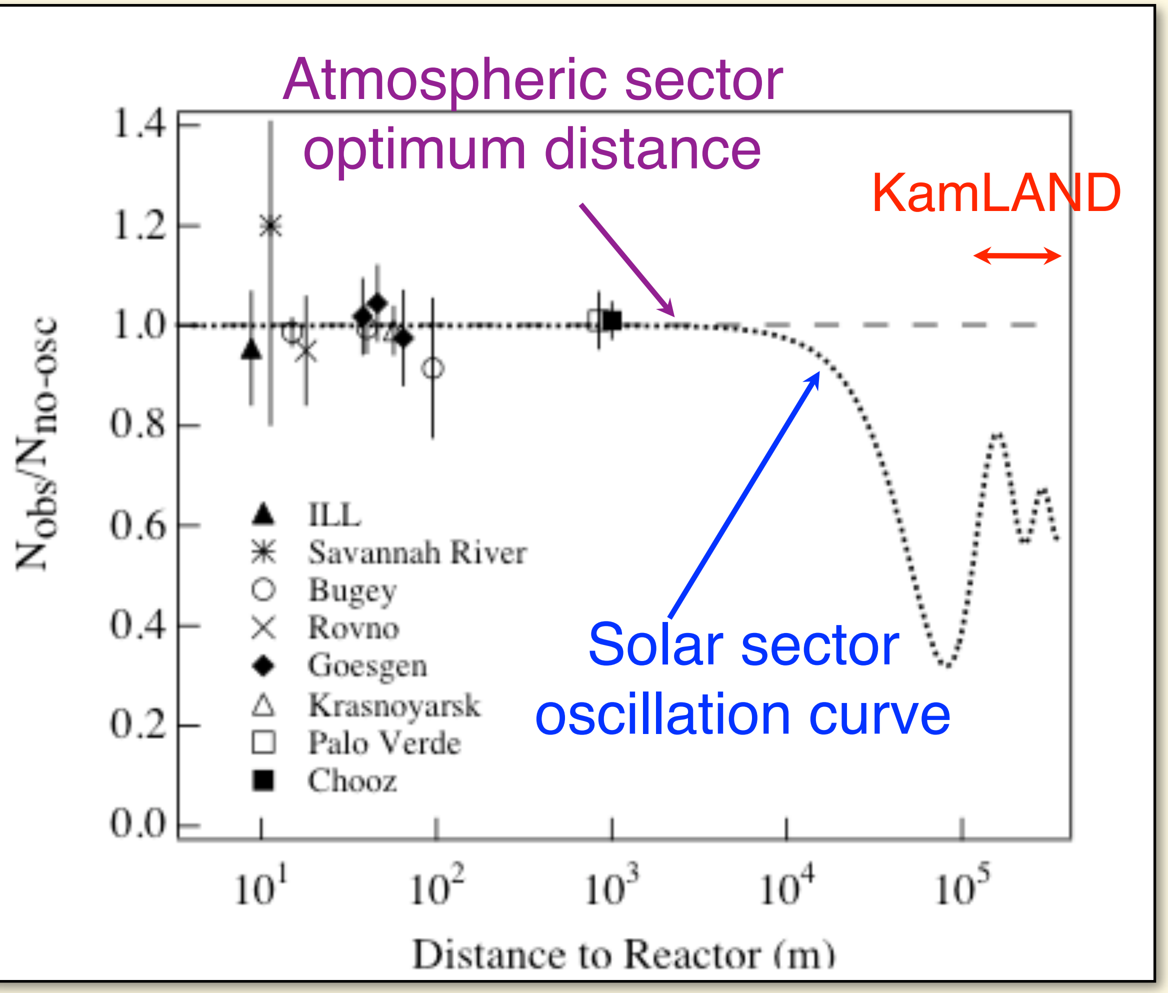
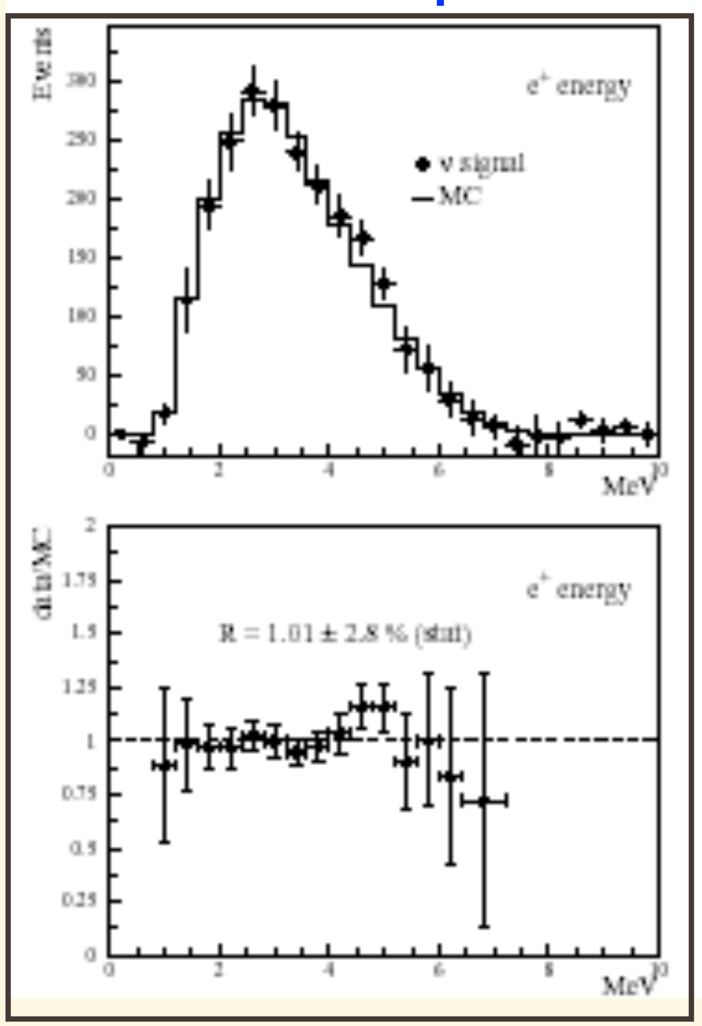


CHOOZ Spectra



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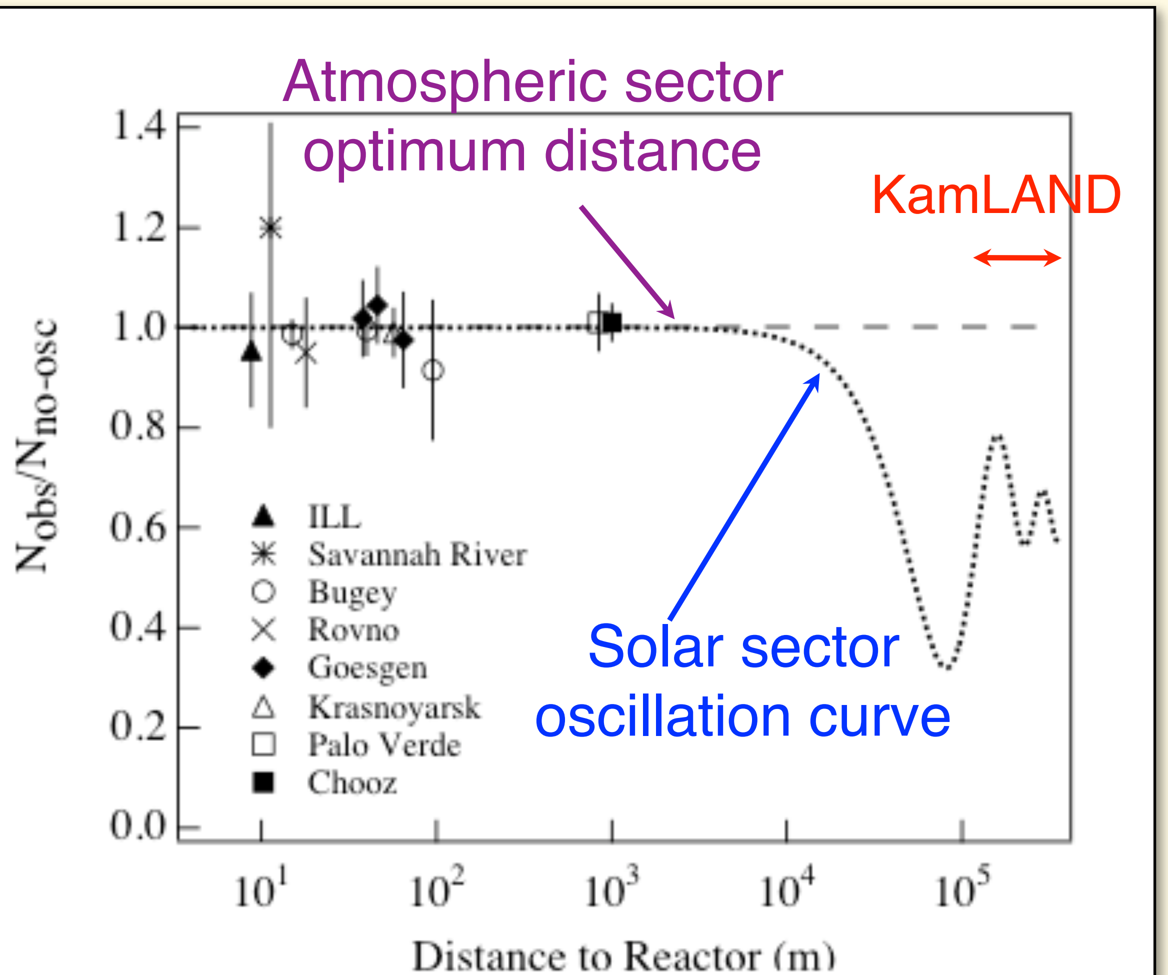

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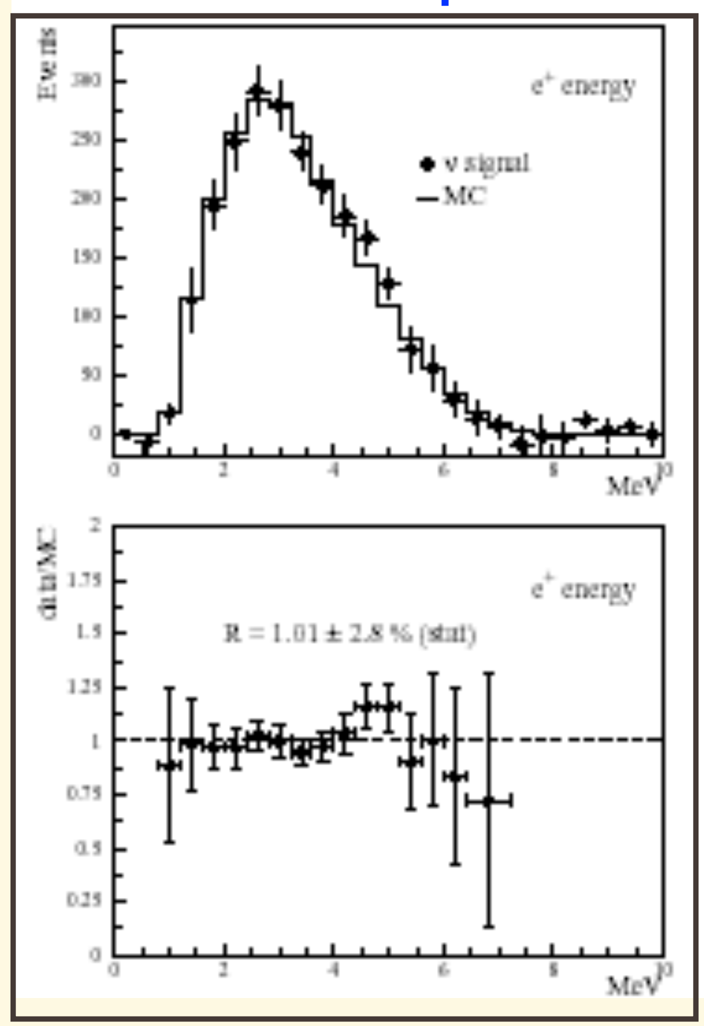

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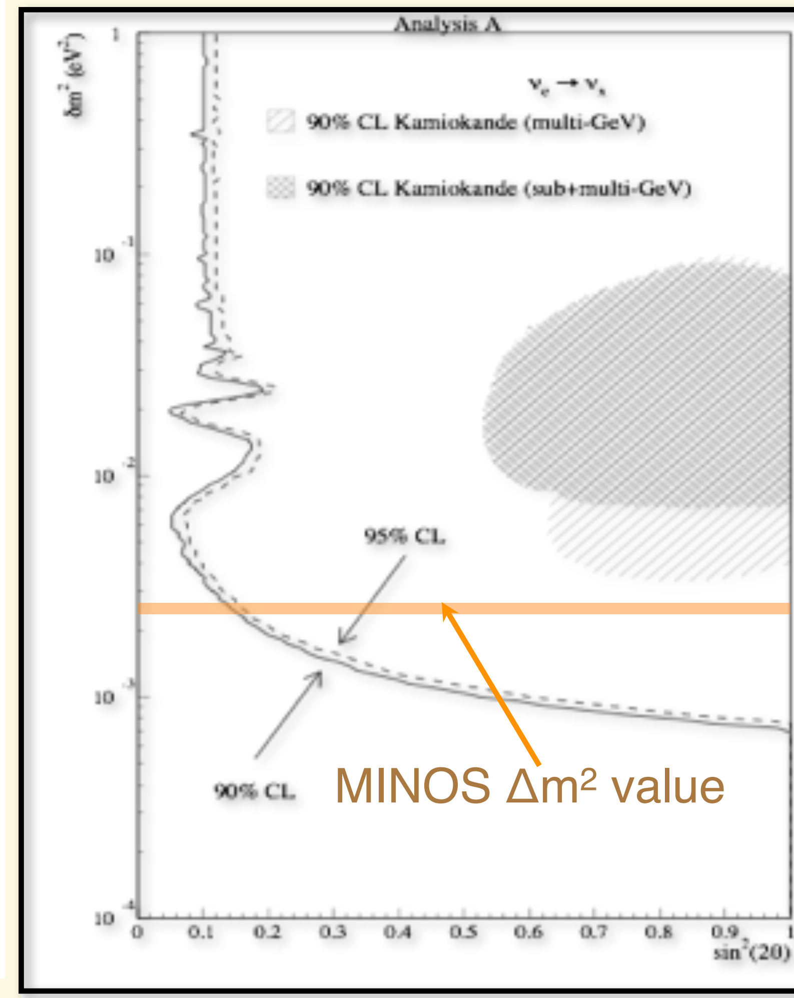

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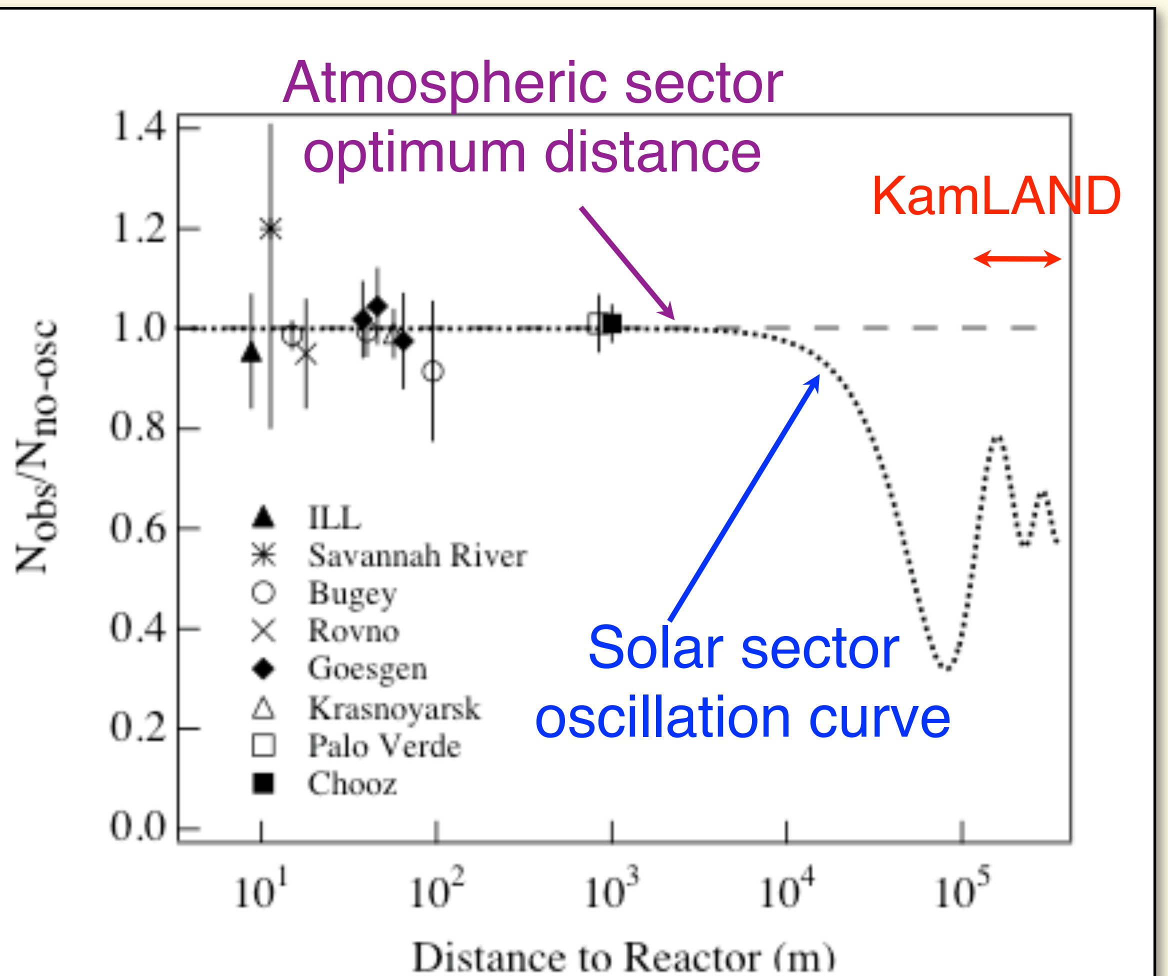

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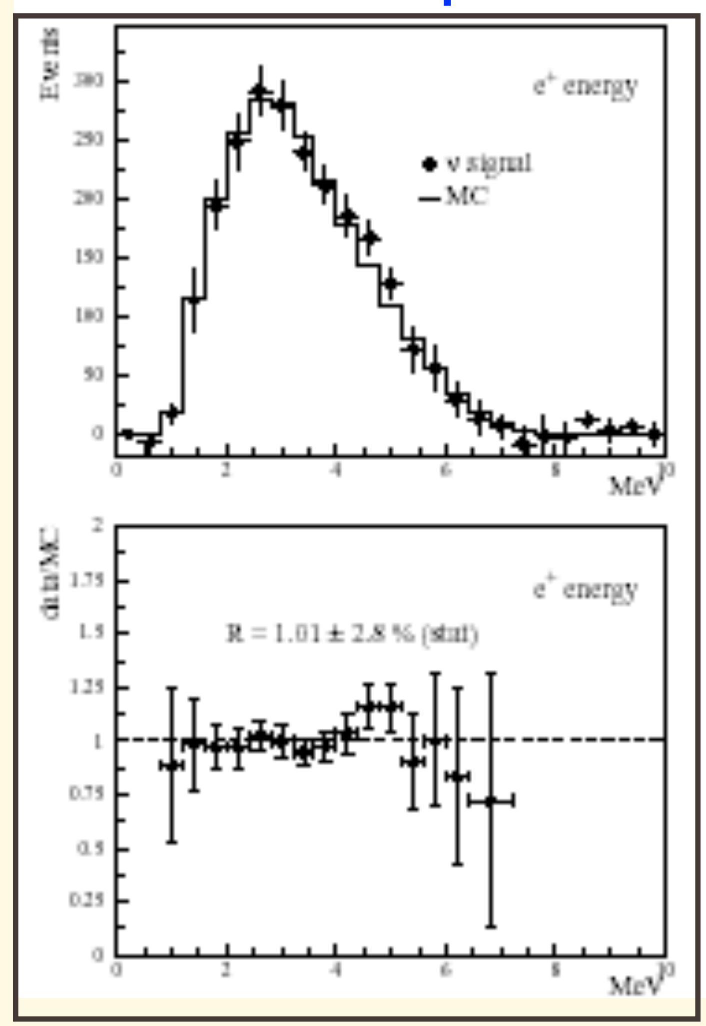

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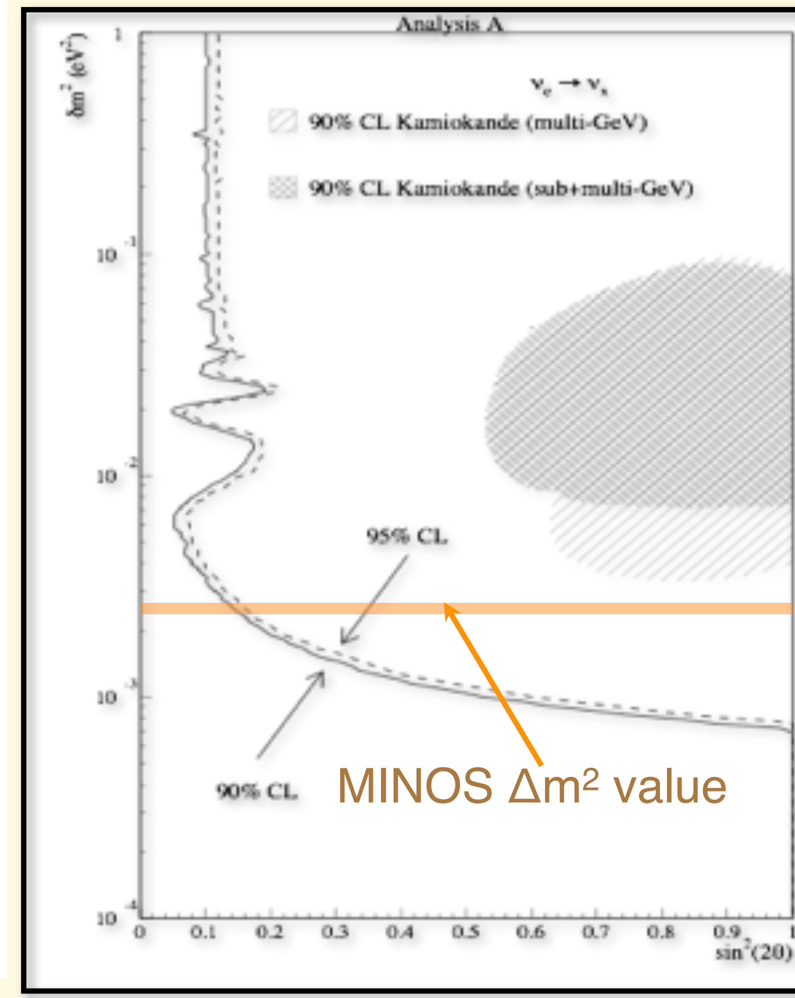

CHOOZ limit: $\sin^2(2\theta_{13})<0.15$ (90% C.L.)

(at $\Delta m^2_{31} = 2.3 \times 10^{-3}\ eV^2$)

ν_e appearance - MINOS

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- A neural network (ANN) using topological variables is used to distinguish NC and CC backgrounds from ν_e signal
- The ANN distribution in the Near Detector is then used to optimize the cuts and predict the background in the Far Detector

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49.1±7.0(stat.)±2.7(syst.)

events in the Far Detector

54 observed, **0.7σ** excess

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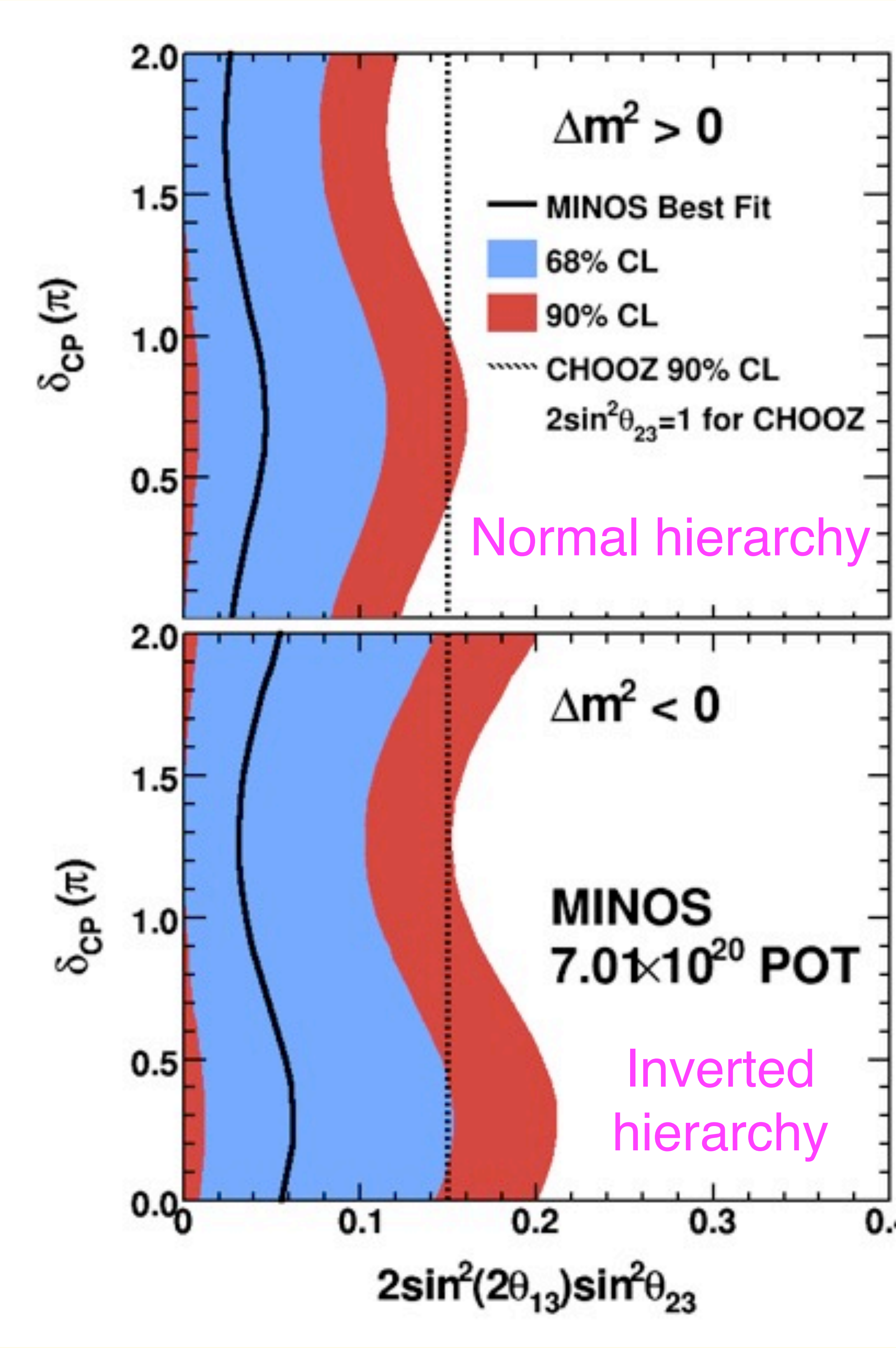

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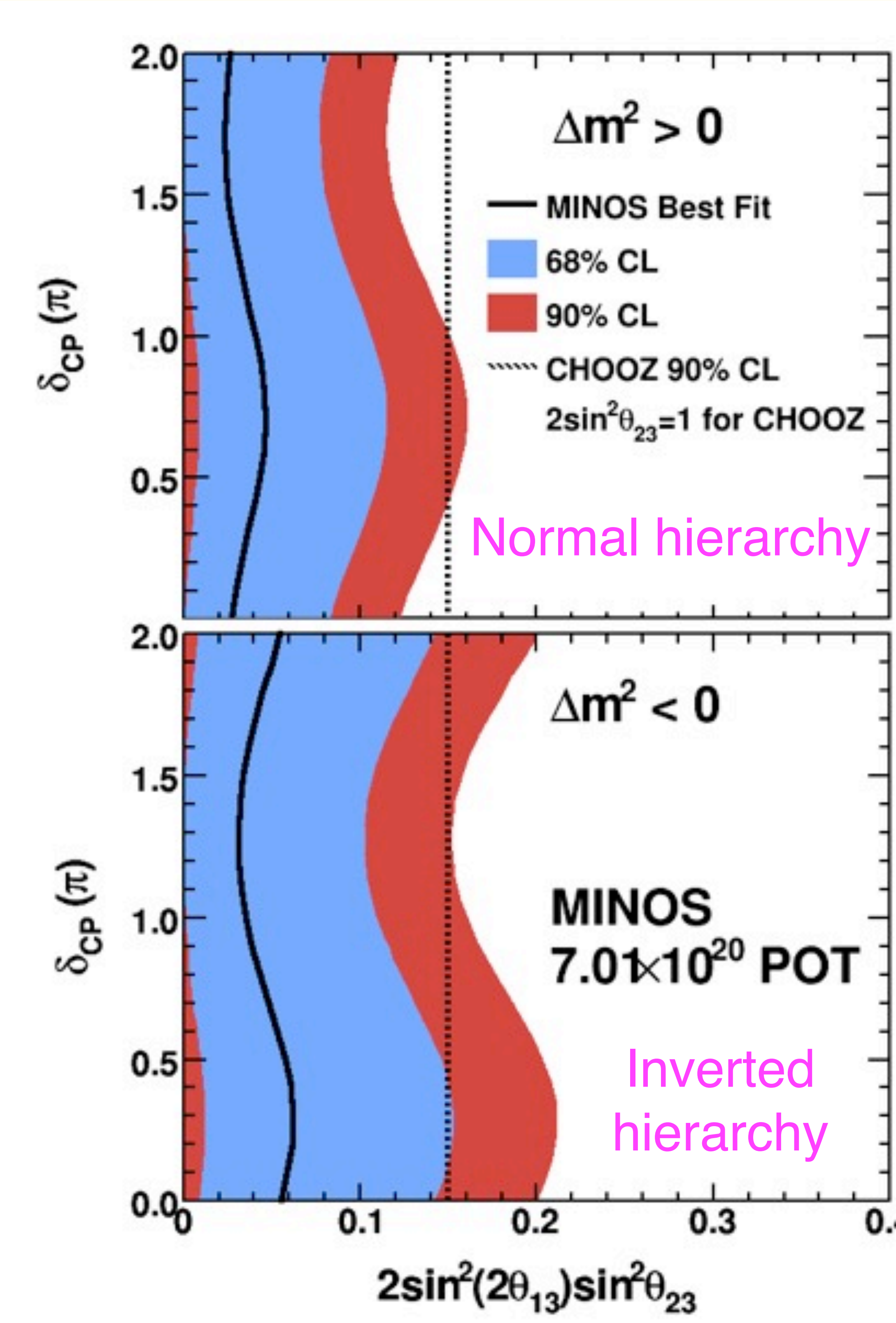
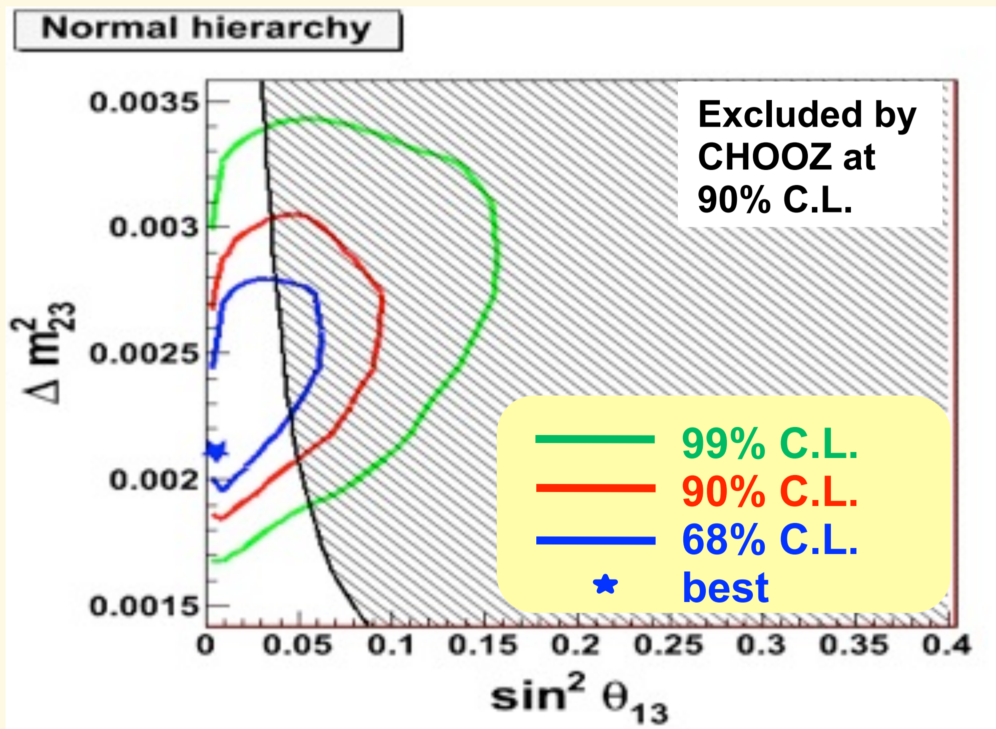


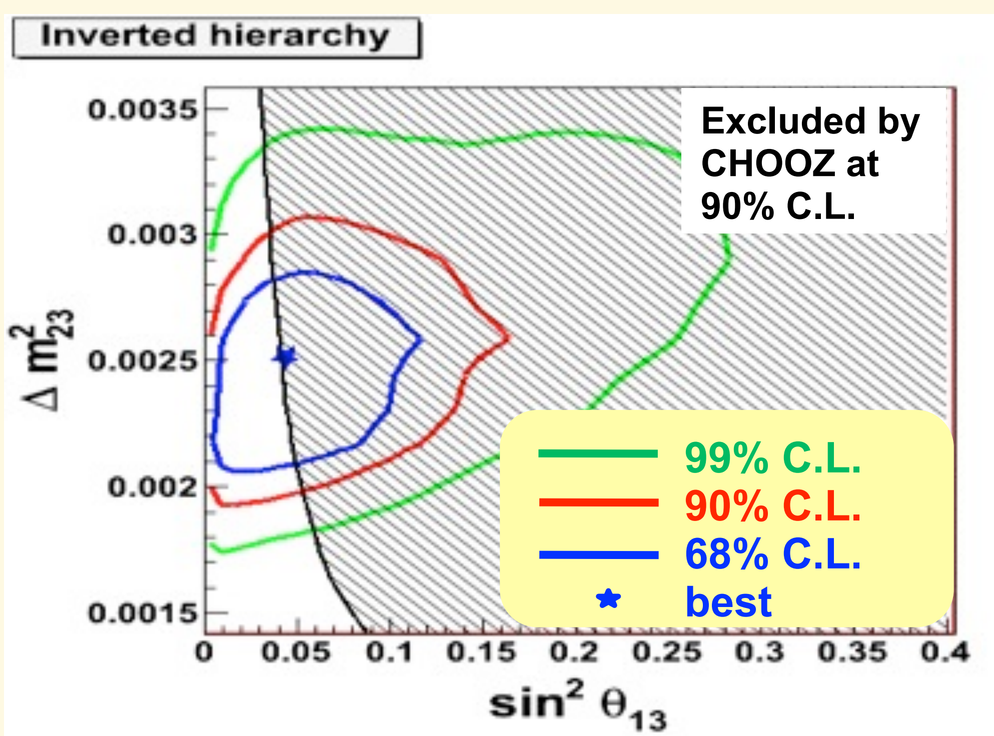
The 90% C.L. limits are:
$\sin^2(2\theta_{13}) < 0.12$ (normal)
$\sin^2(2\theta_{13}) < 0.20$ (inverse)
for
$\sin^2(2\theta_{23}) = 1$, $\delta_{CP} = 0$,
$|\Delta m^2_{31}| = 2.43 \times 10^{-3}$ eV^2

3-flavor Analyses

3-flavor Analyses

SuperK - atmospheric





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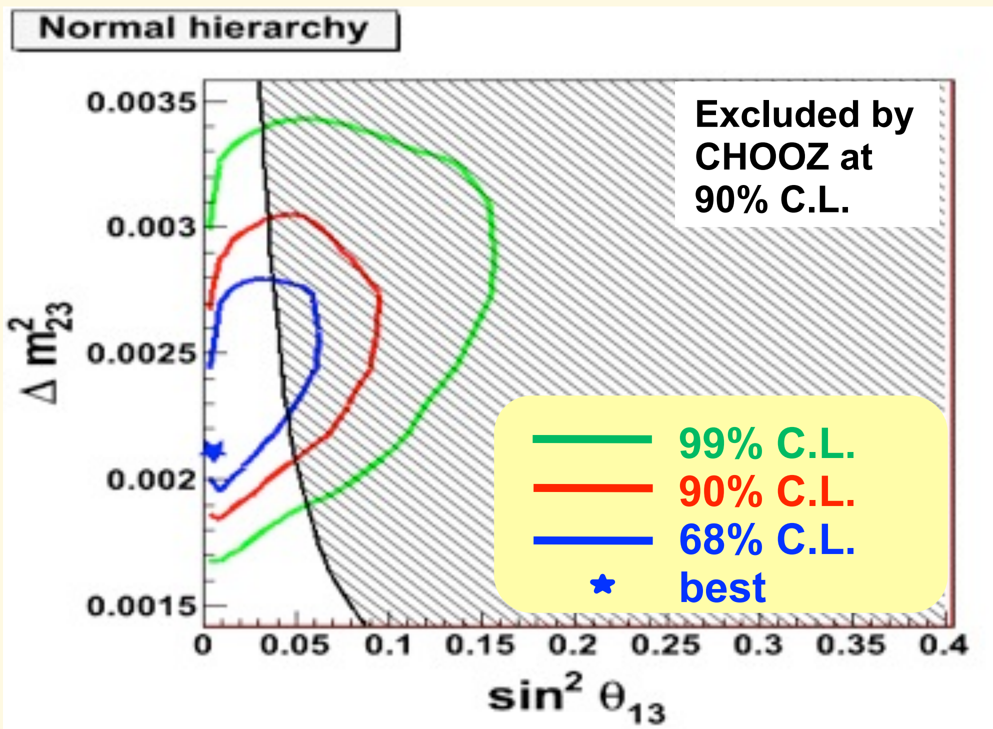
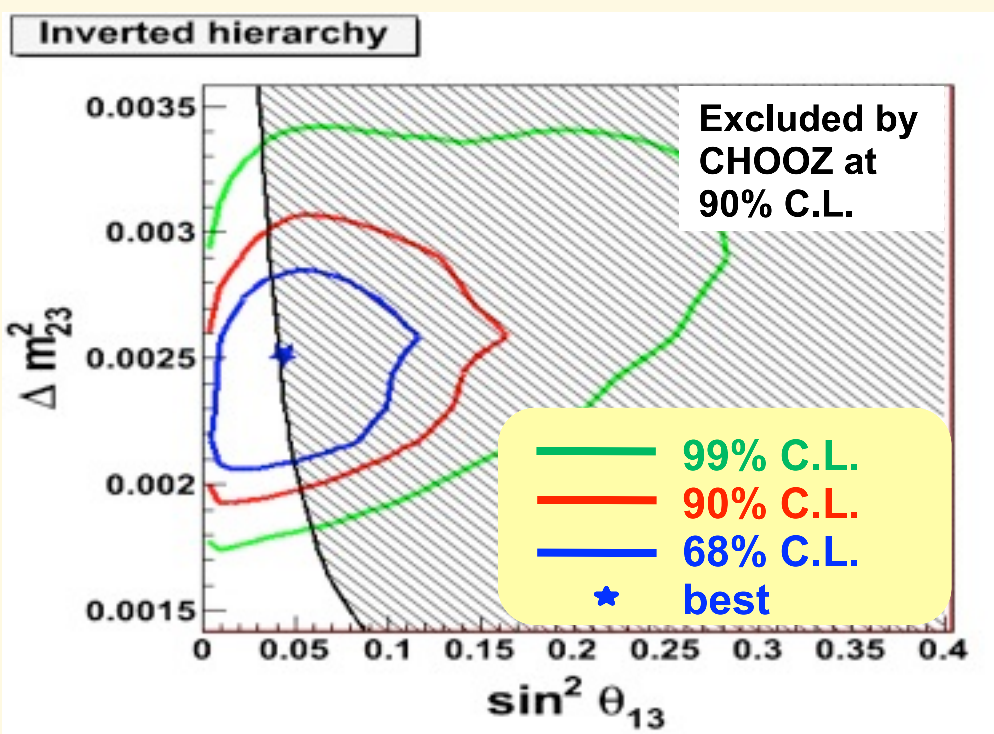
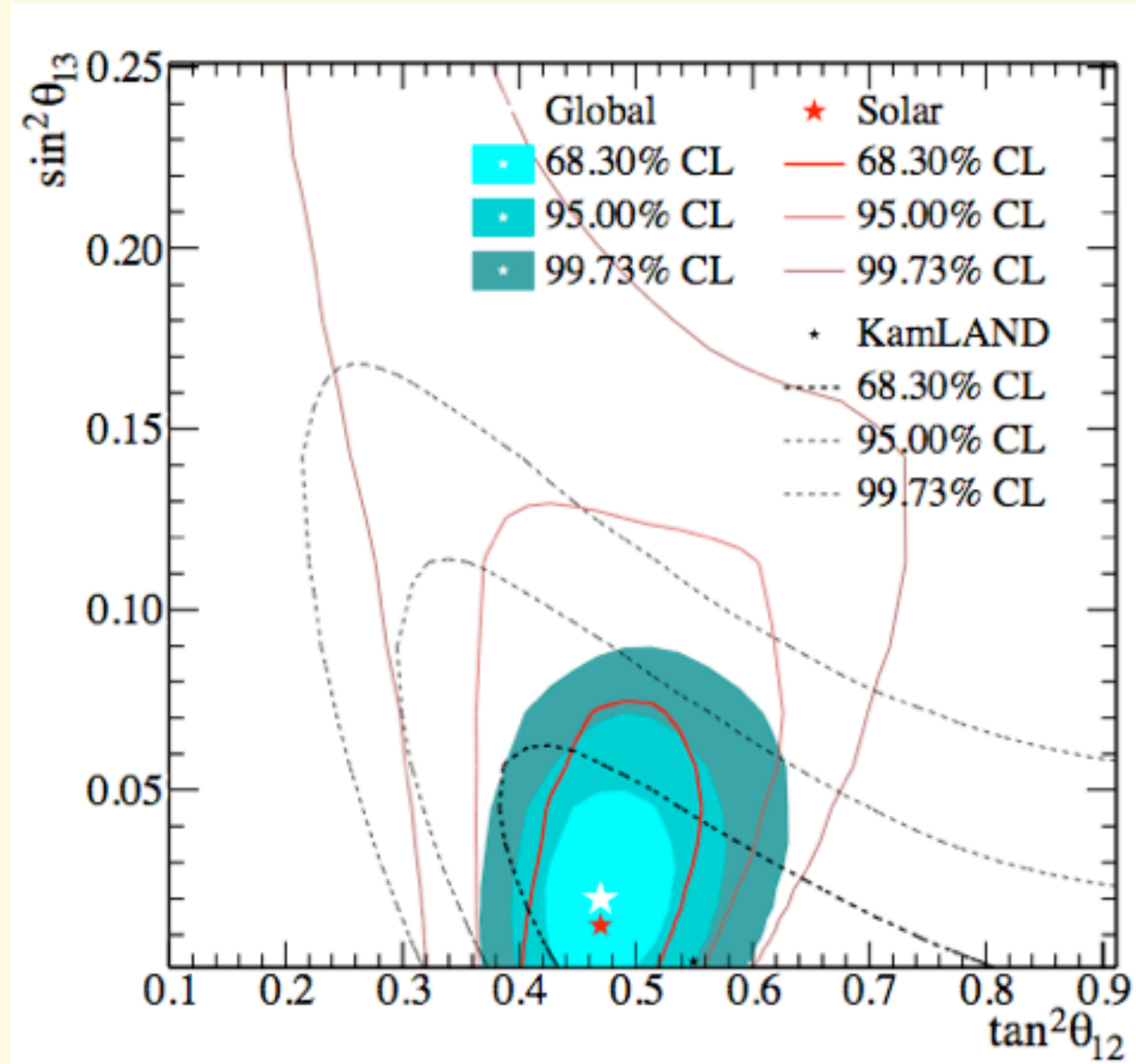




Global solar - SNO analysis



Similar results obtained by SuperK Collaboration

Summary (Mixed)

Oscillation analysis	$\sin^2\theta_{13}$ (value)	$\sin^2\theta_{13}$ (90% C.L.)	$\sin^2\theta_{13}$ (95% C.L.)
SuperK (atmospheric,normal)	$0.006^{+.030}_{-.006}$	<0.066	
SuperK (atmospheric,inverted)	$0.044^{+.041}_{-.032}$	<0.122	
SuperK (solar,global)	$0.025^{+.018}_{-.016}$		<0.059
SNO (solar,global)	$0.020^{+.021}_{-.016}$		<0.057
MINOS (normal) at $\delta_{CP}=0$	$0.007^{+.014}_{-.007}$	<0.03	
MINOS (inverted) at $\delta_{CP}=0$	$0.015^{+.021}_{-.013}$	<0.05	
CHOOZ		<0.037	

Global 3-flavor fit

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Parameter	best fit	2σ	3σ
Δm^2_{21} [10^{-5}eV^2]	$7.59^{+0.23}_{-0.18}$	7.22 - 8.03	7.03 - 8.27
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2]	$2.40^{+0.12}_{-0.11}$	2.18 - 2.64	2.07 - 2.75
$\sin^2\theta_{12}$	$0.318^{+0.019}_{-0.016}$	0.29 - 0.36	0.27 - 0.38
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	0.39 - 0.63	0.36 - 0.67
$\sin^2\theta_{13}$	$0.013^{+0.013}_{-0.009}$	<0.039	<0.053

- Parameters of the PMNS Matrix
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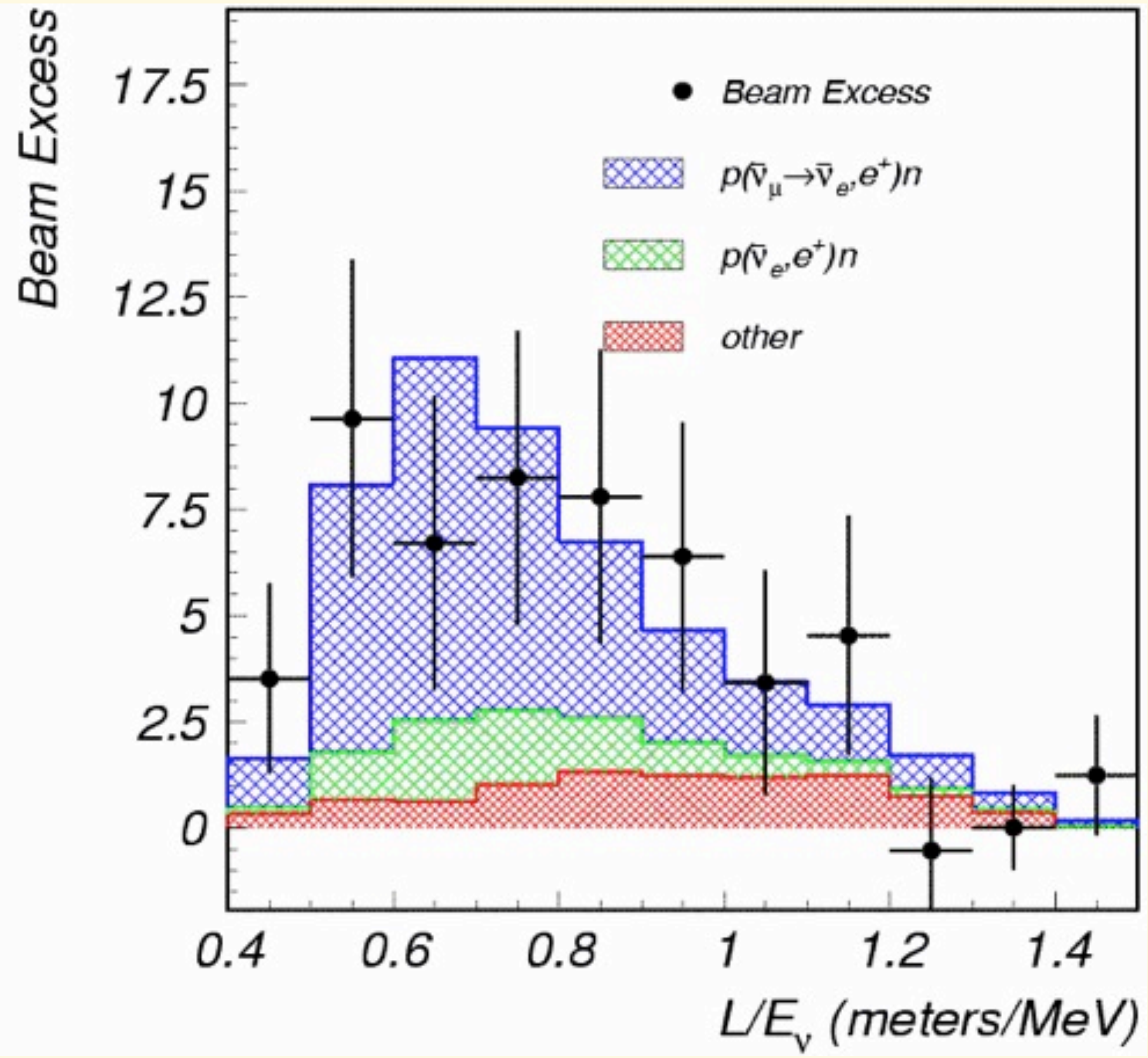
LSND Effect

LSND Effect

Apparent $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ transition



R. Van de Water Nu2010

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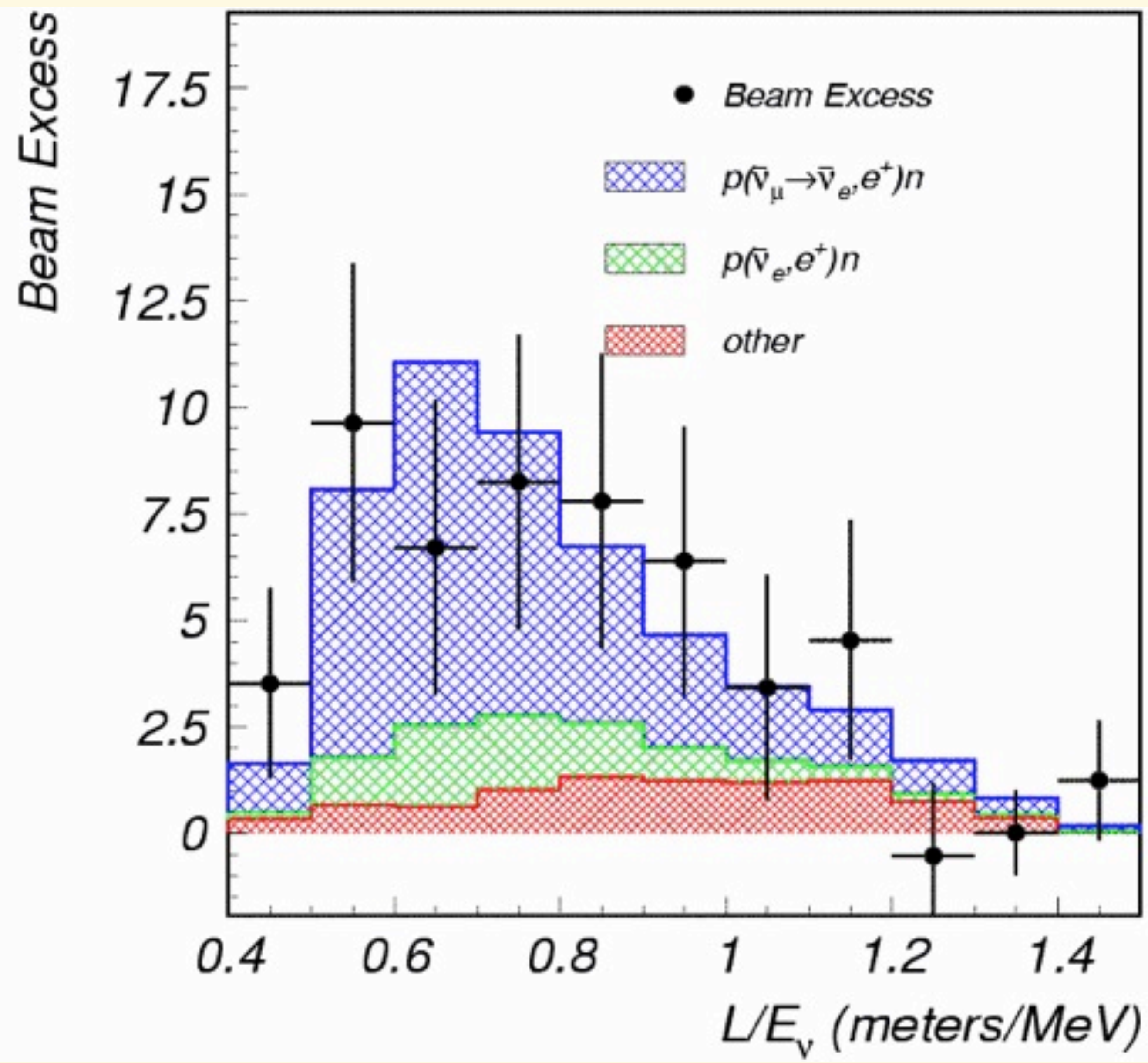
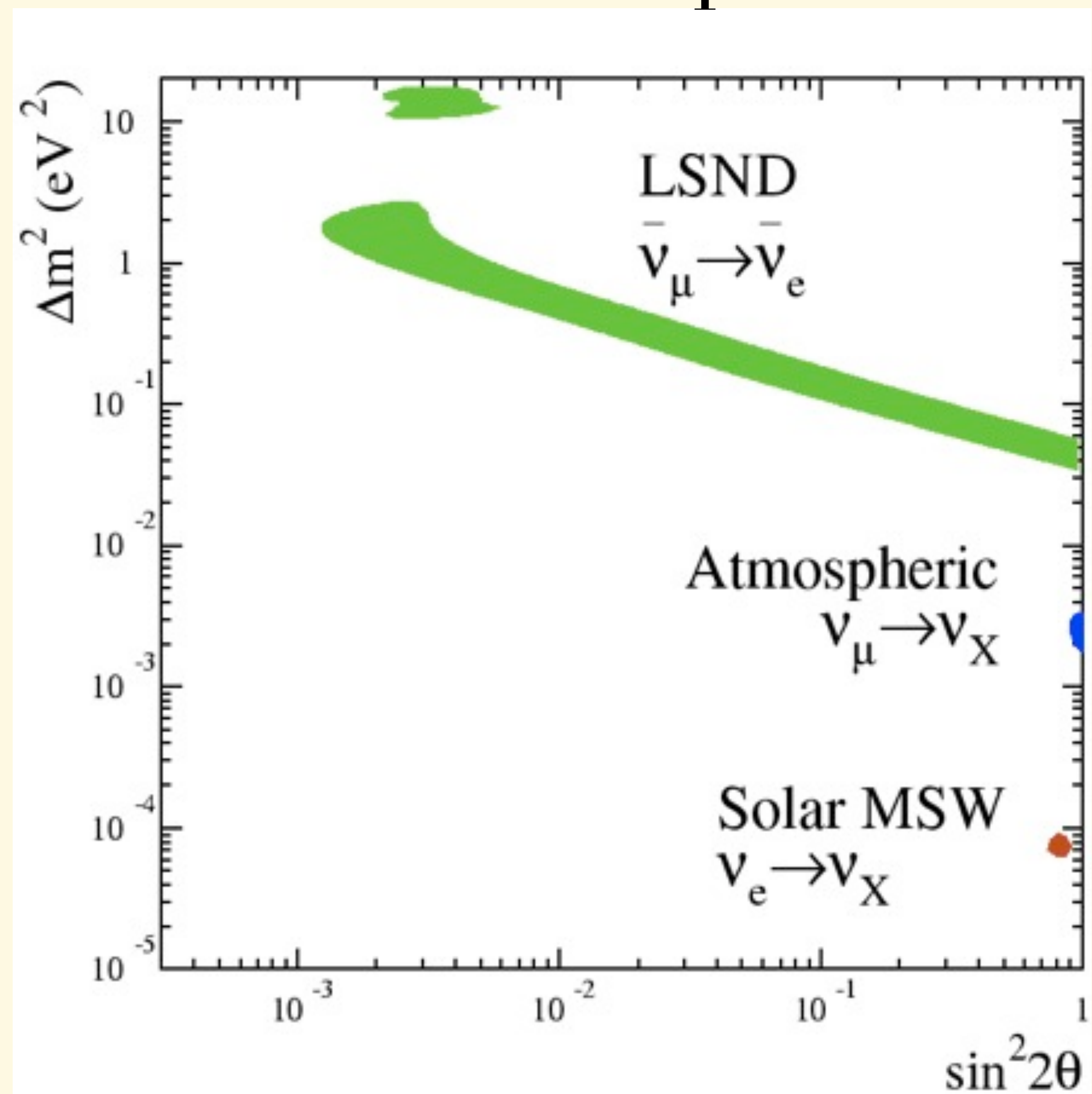


Oscillation interpretation



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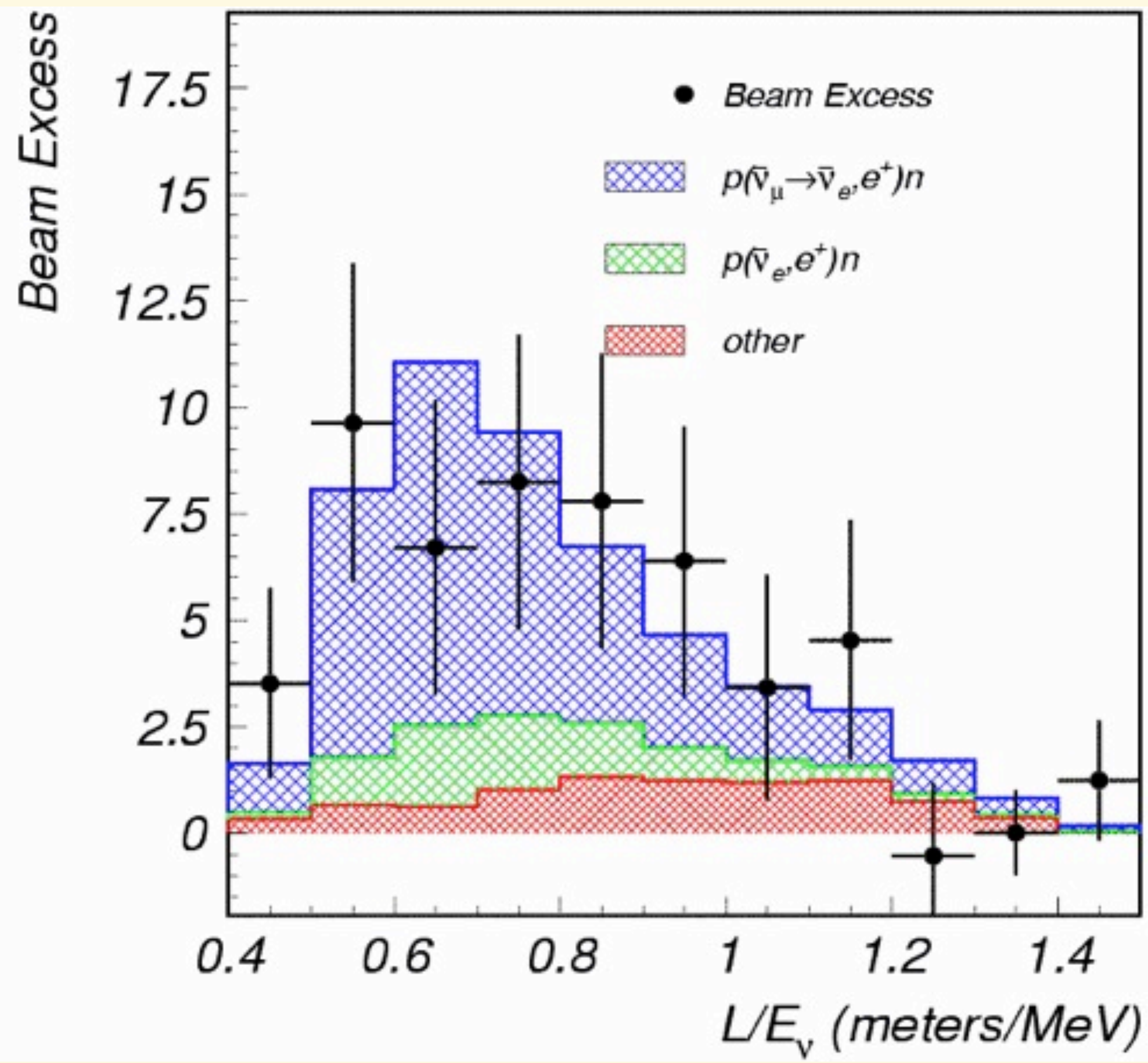

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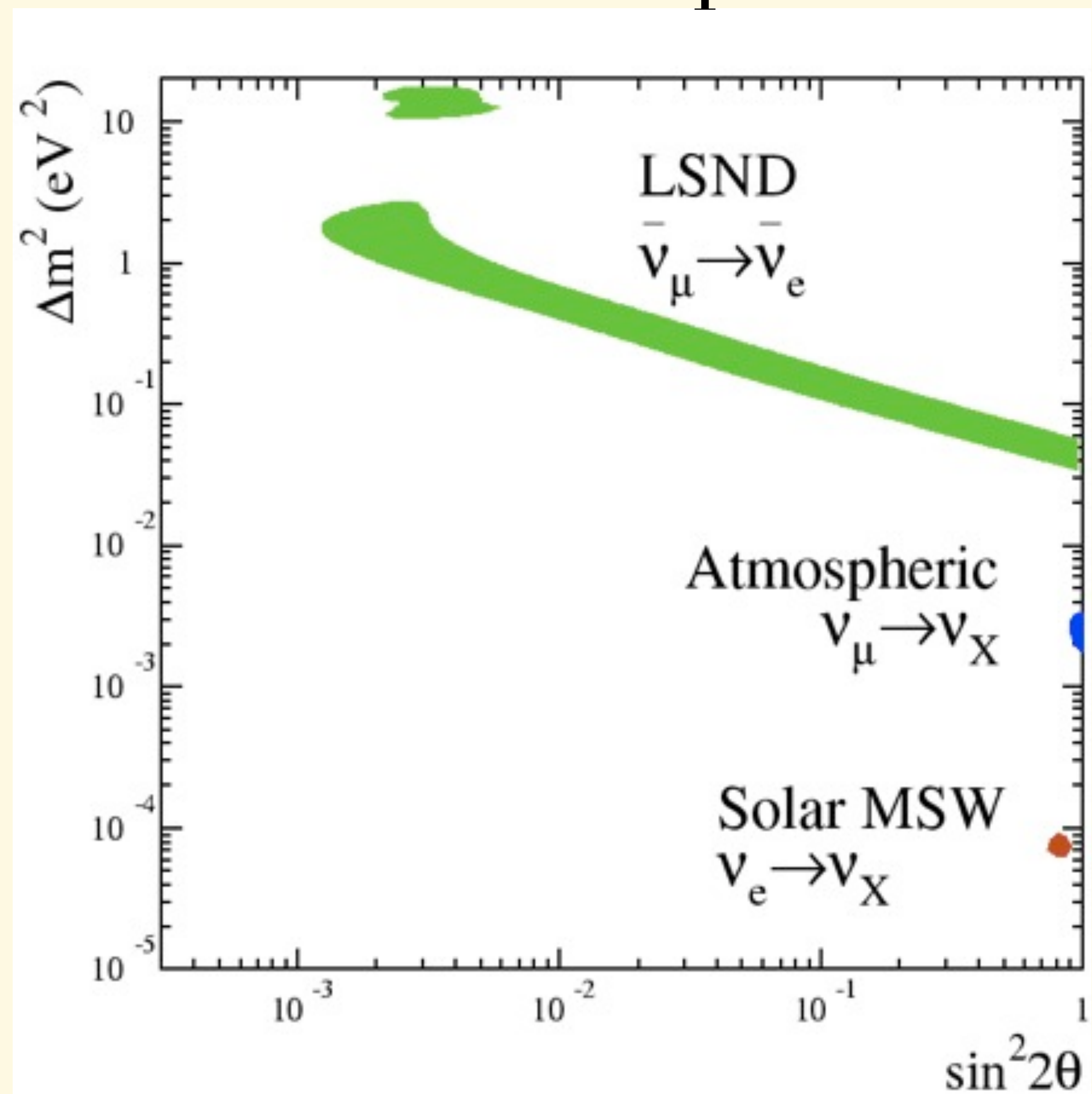

If effect is due to oscillations, there must be a 4th, sterile, neutrino

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MiniBooNE

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MiniBooNE was designed to test the LSND result

L/E is similar to that in LSND but L and E are roughly an order of magnitude larger; different systematics

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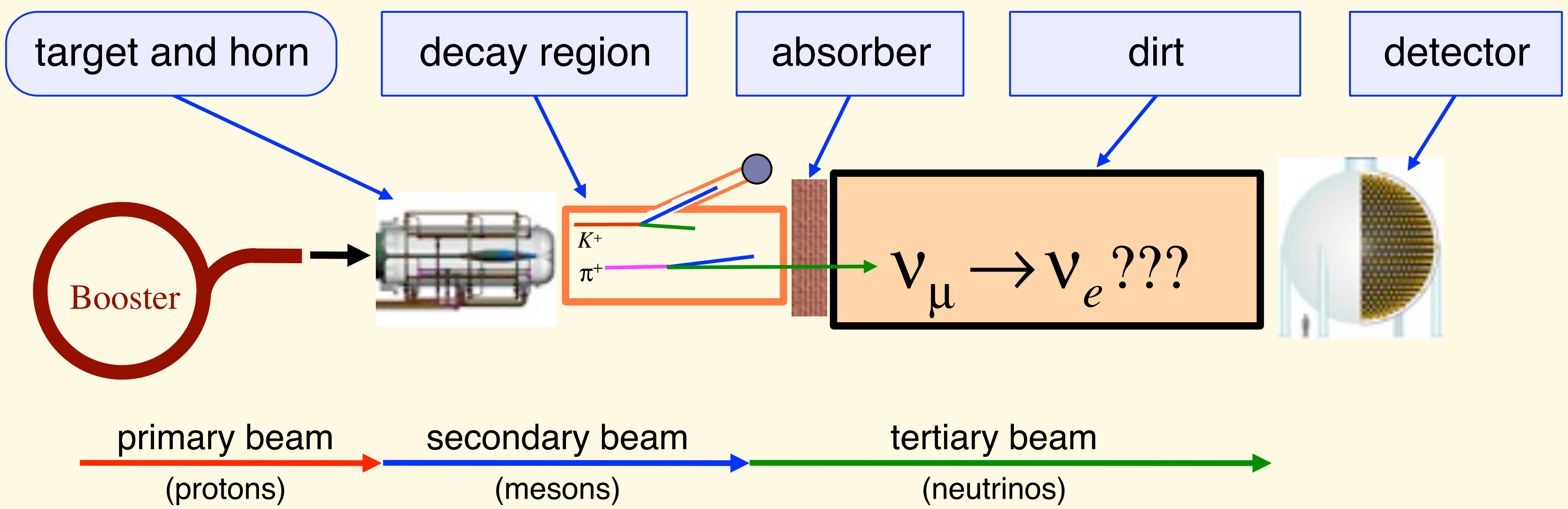

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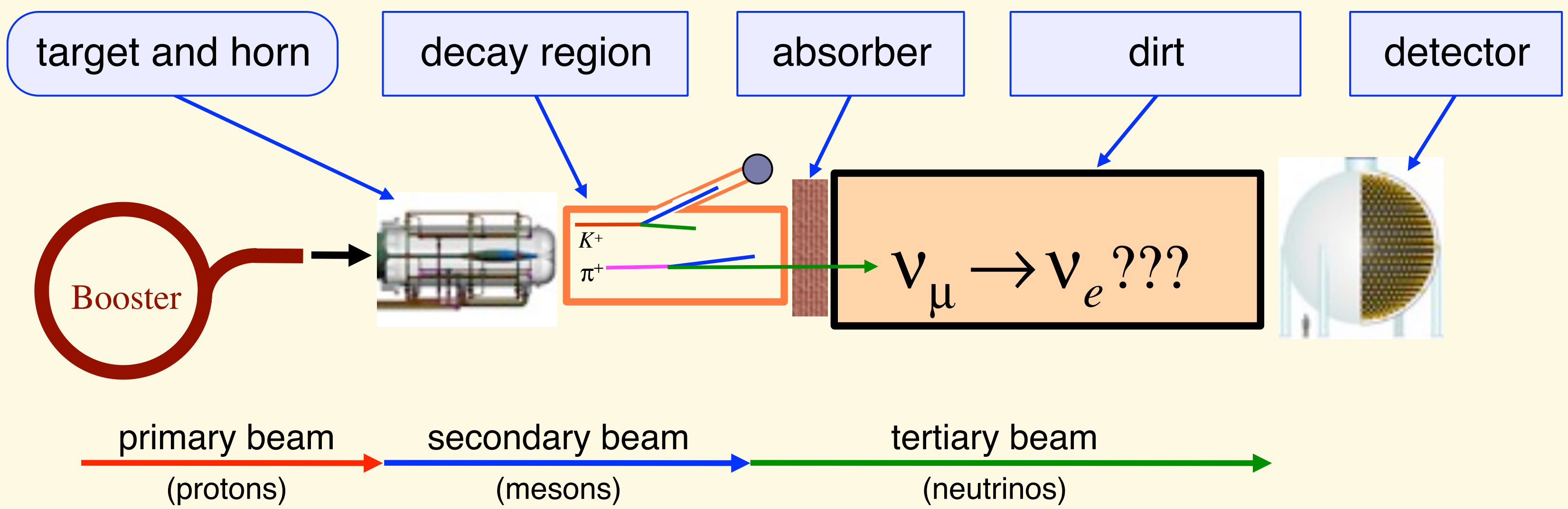


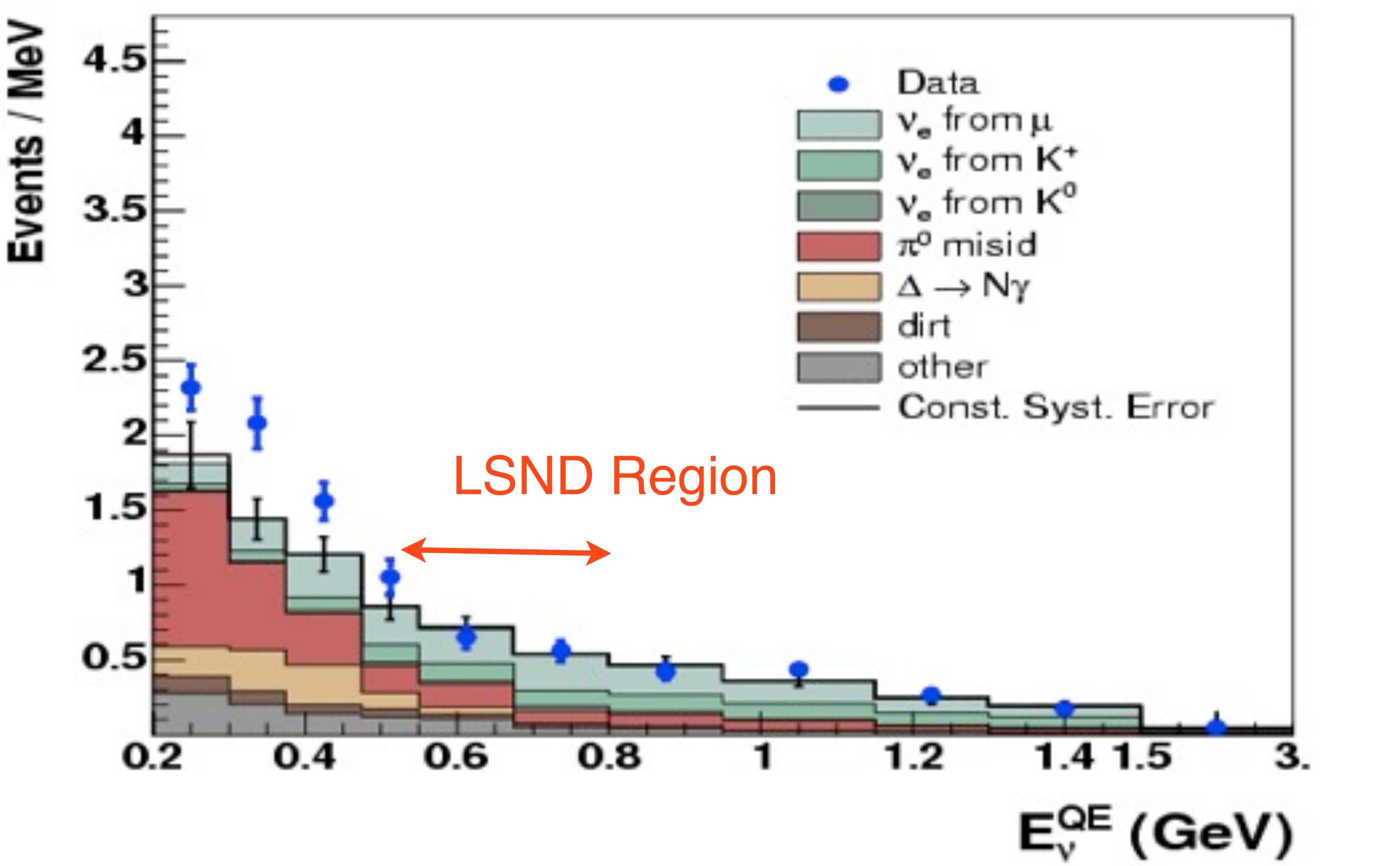
Both neutrino and antineutrino exposures were obtained

Antineutrino run tests the LSND directly

MiniBooNE Results

MiniBooNE Results

Neutrinos - 6.5E20 POT



Neutrinos: Excess of electrons (γ's?) below 475 MeV

No excess in the LSND region

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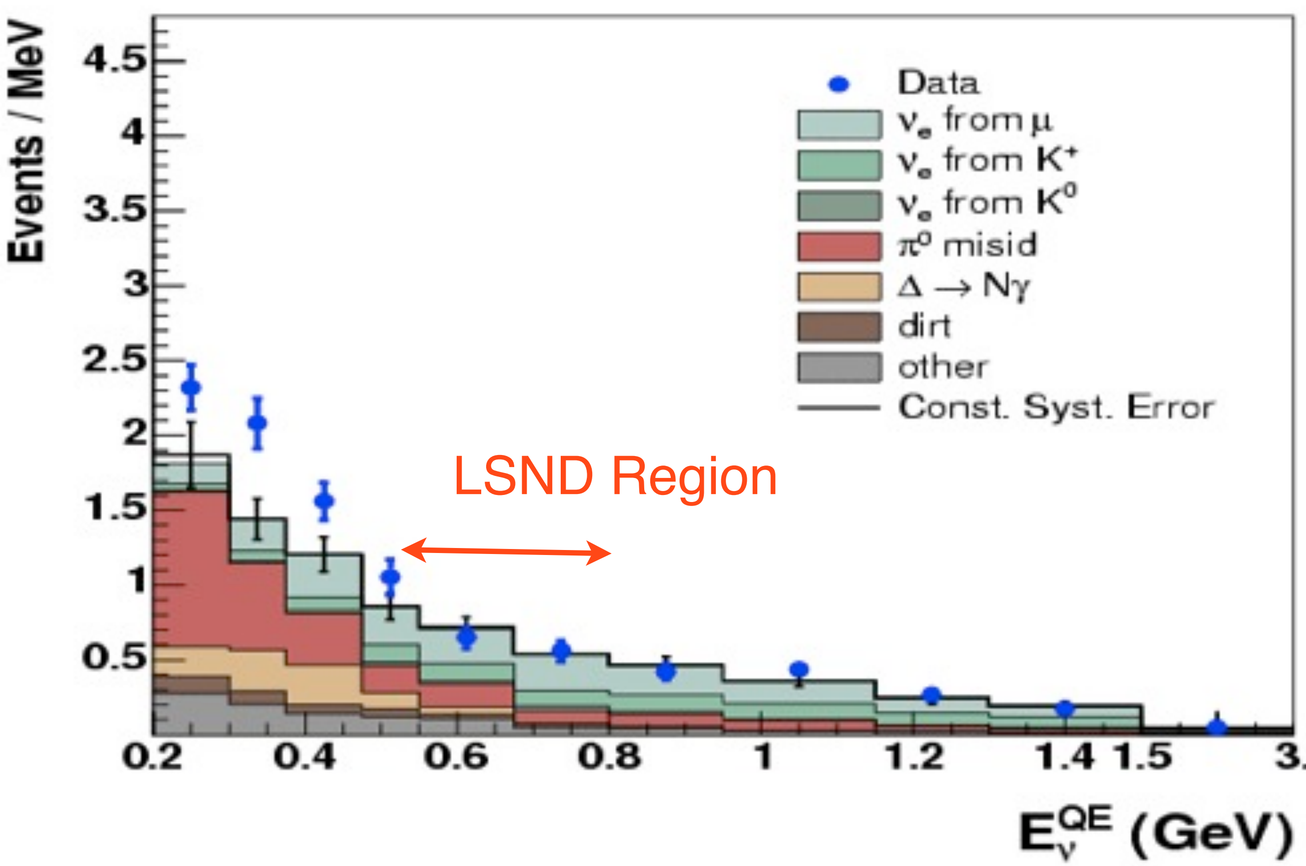

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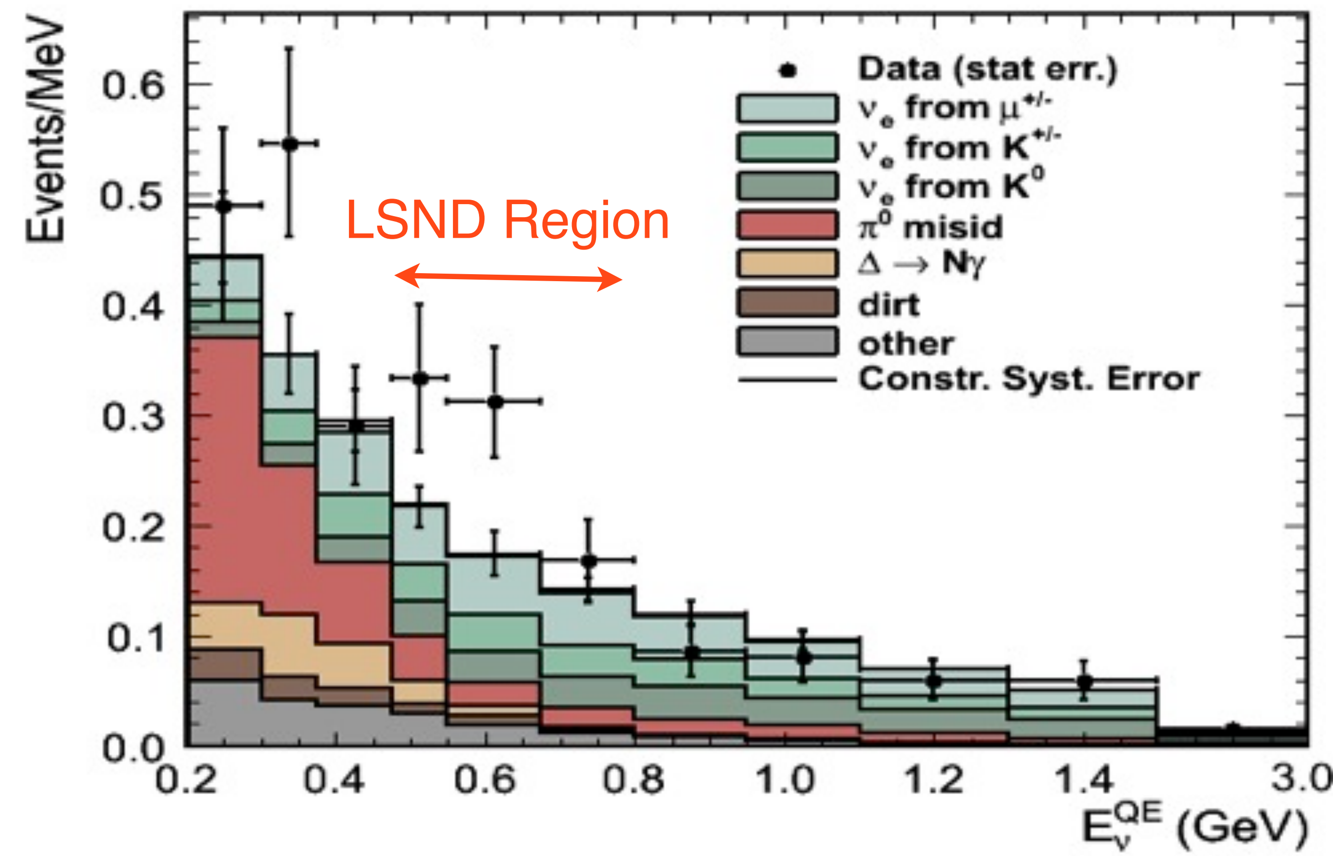

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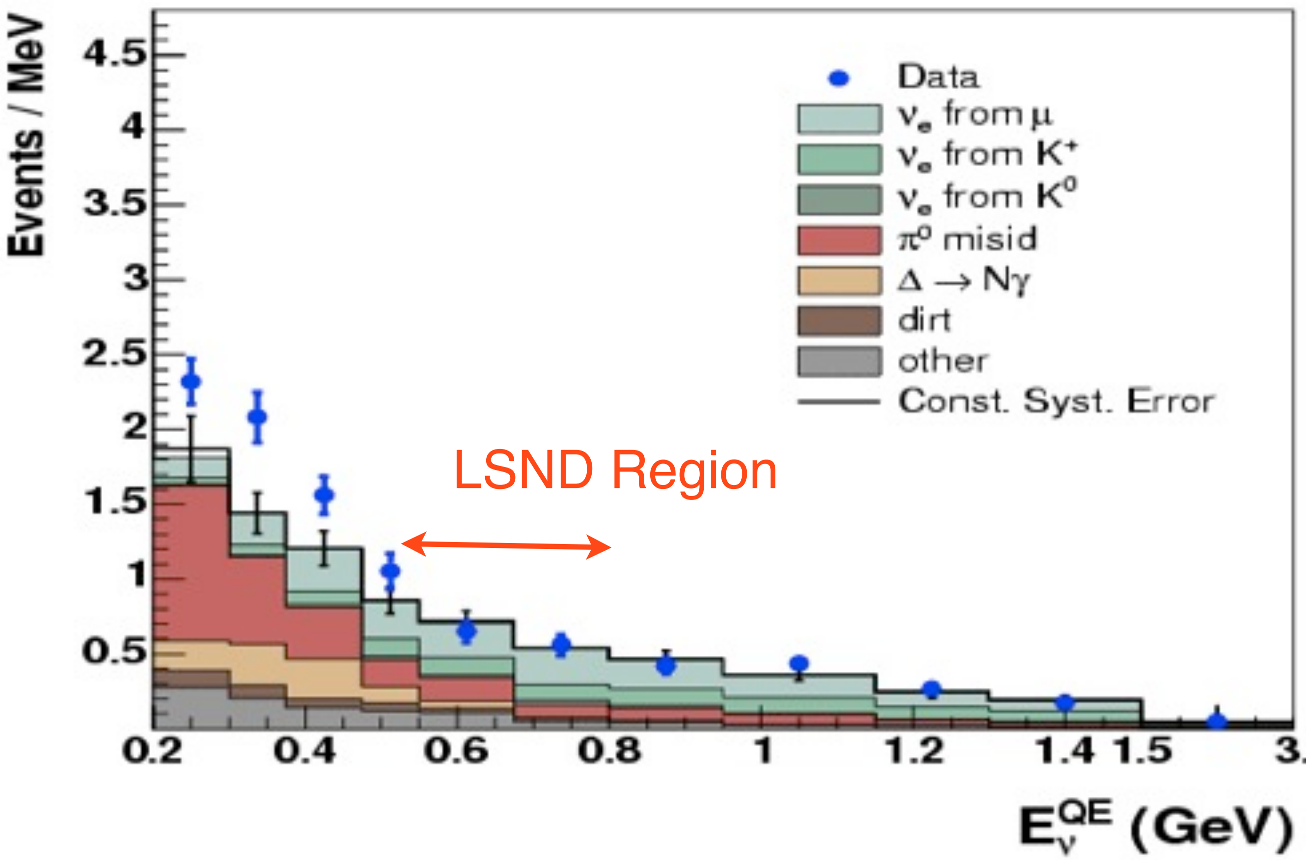

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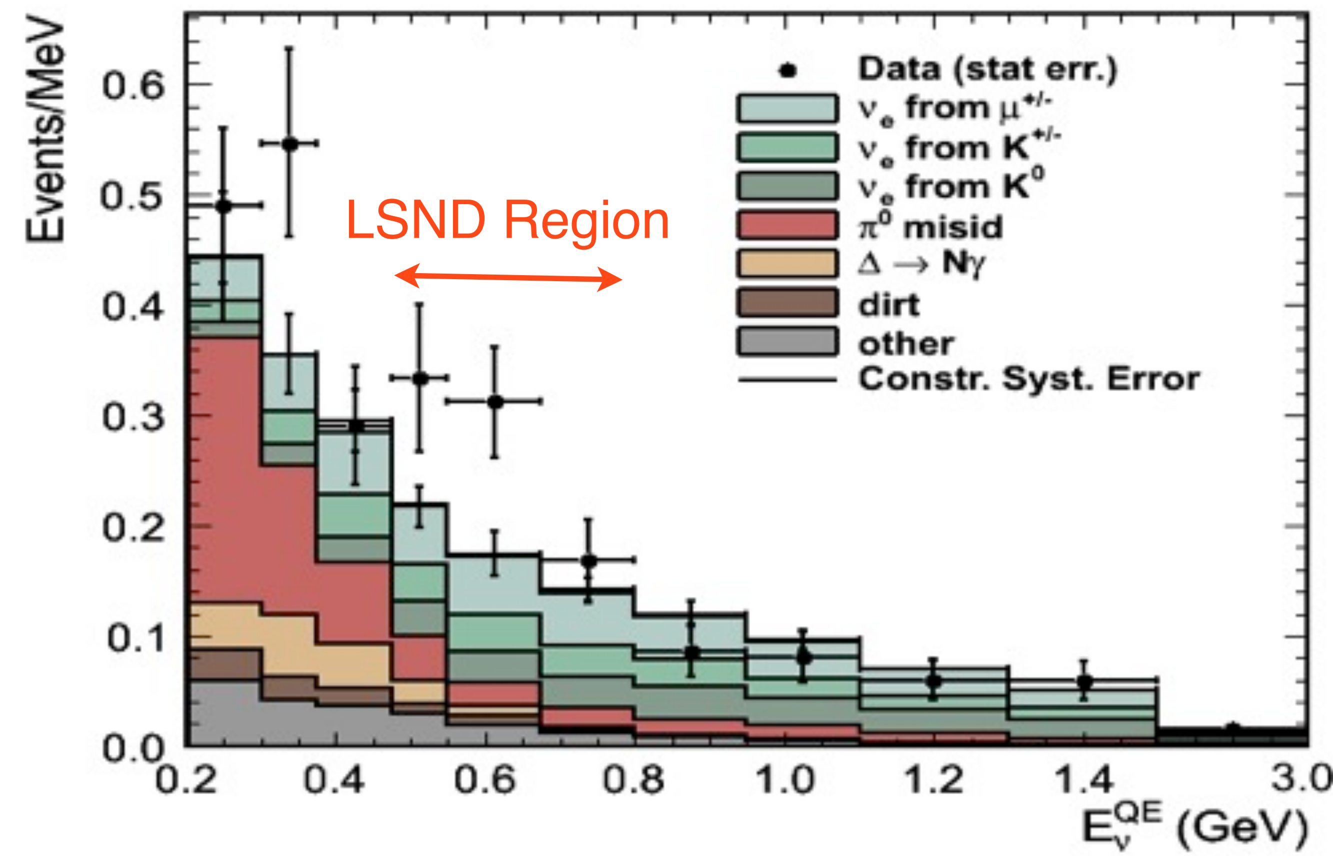

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10E20 POT in $\overline{\nu}$ mode requested to resolve the issue

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Mild dependence on the assumption regarding θ_{13} since ν_e events would be classified as NC

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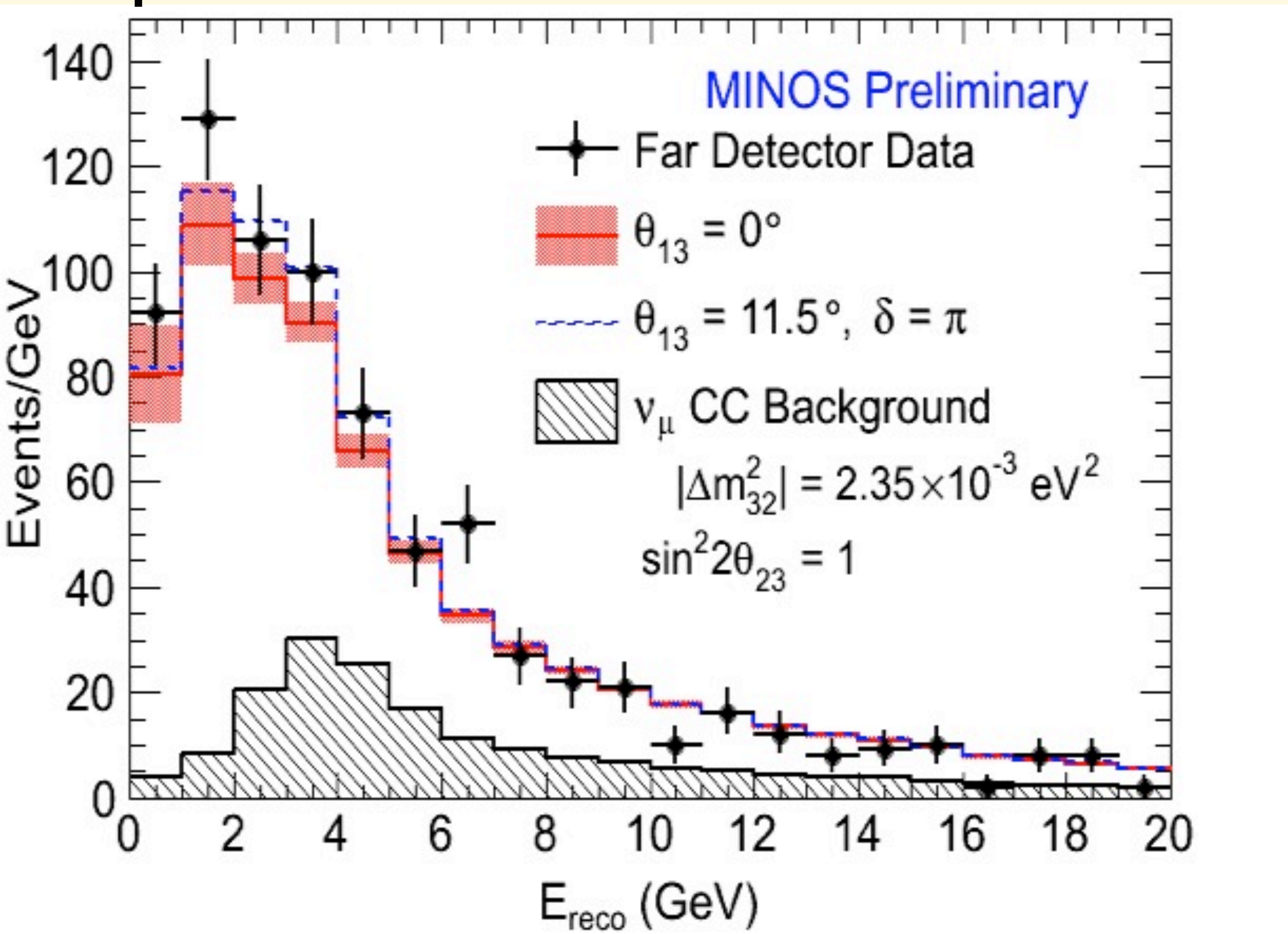
Spectrum of NC events in FD



P.Vahle Neutrino2010

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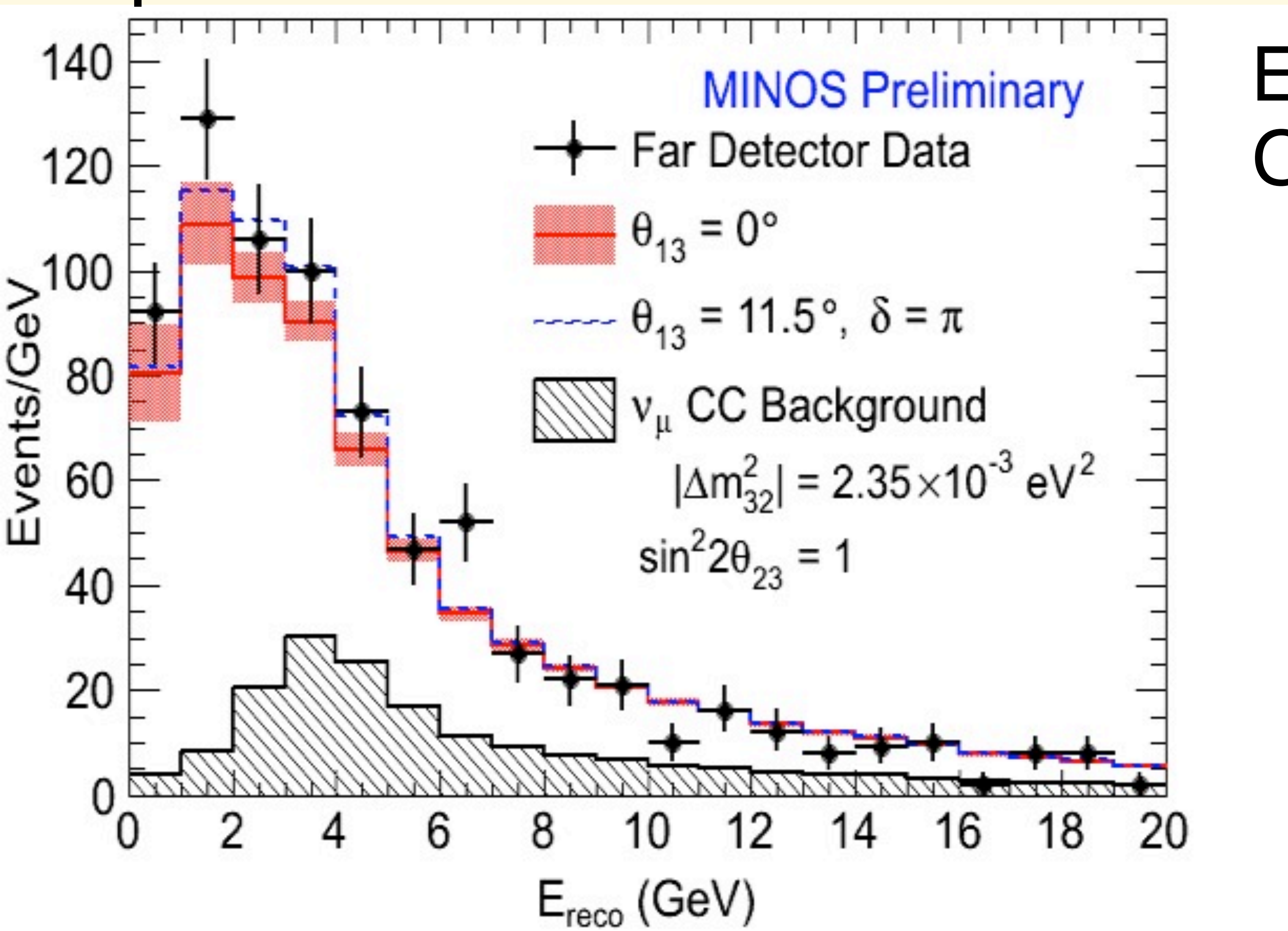

Expect (no ν_e): 757 events
Observe: 802 events

No depletion seen

P.Vahle Neutrino2010

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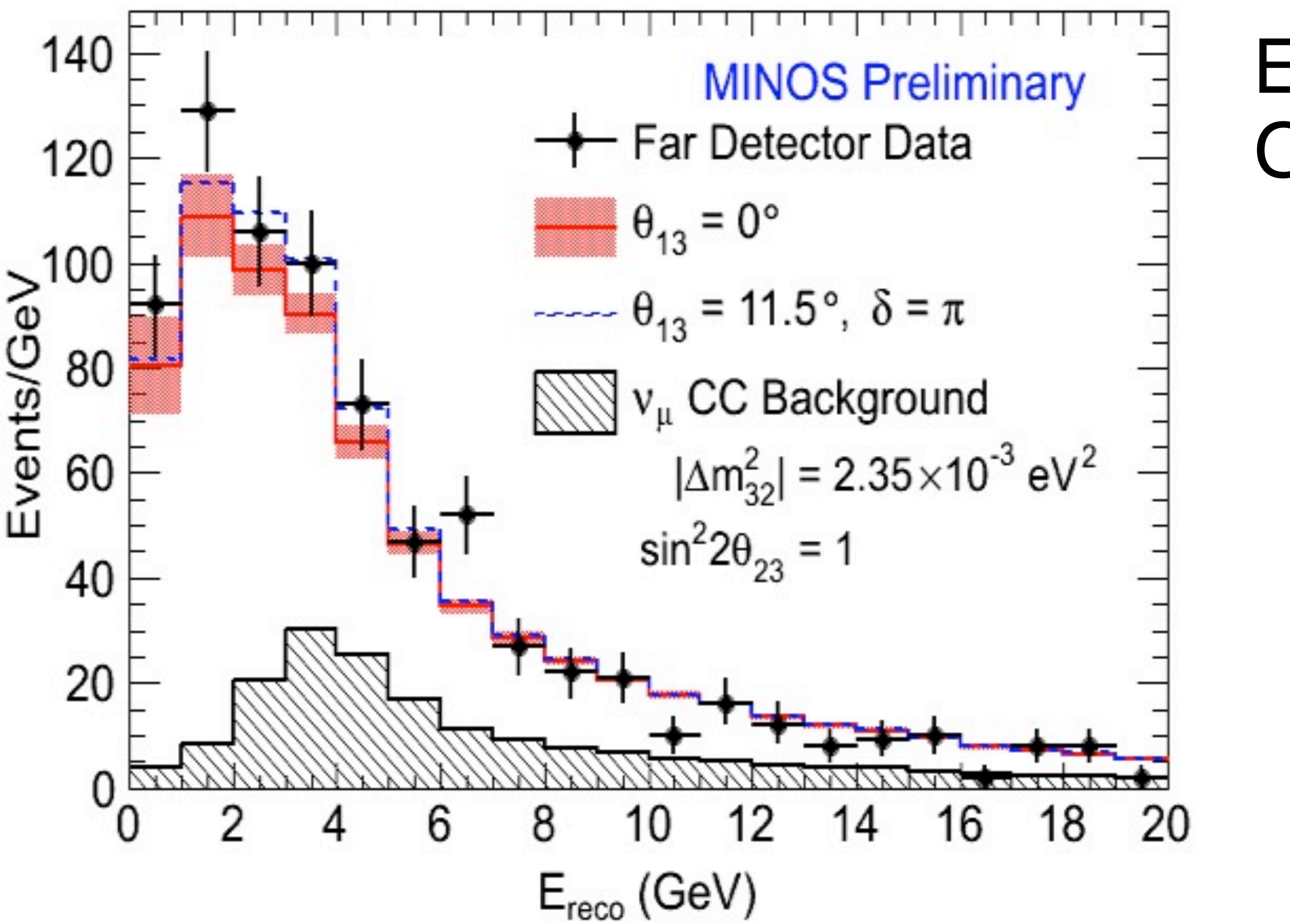

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Define: $R = \frac{N_{data} - BG}{S_{NC}}$

1.09 ± 0.06 (stat.) ± 0.05 (syst.)
(no ν_e appearance)

1.01 ± 0.06 (stat.) ± 0.05 (syst.)
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P.Vahle Neutrino2010

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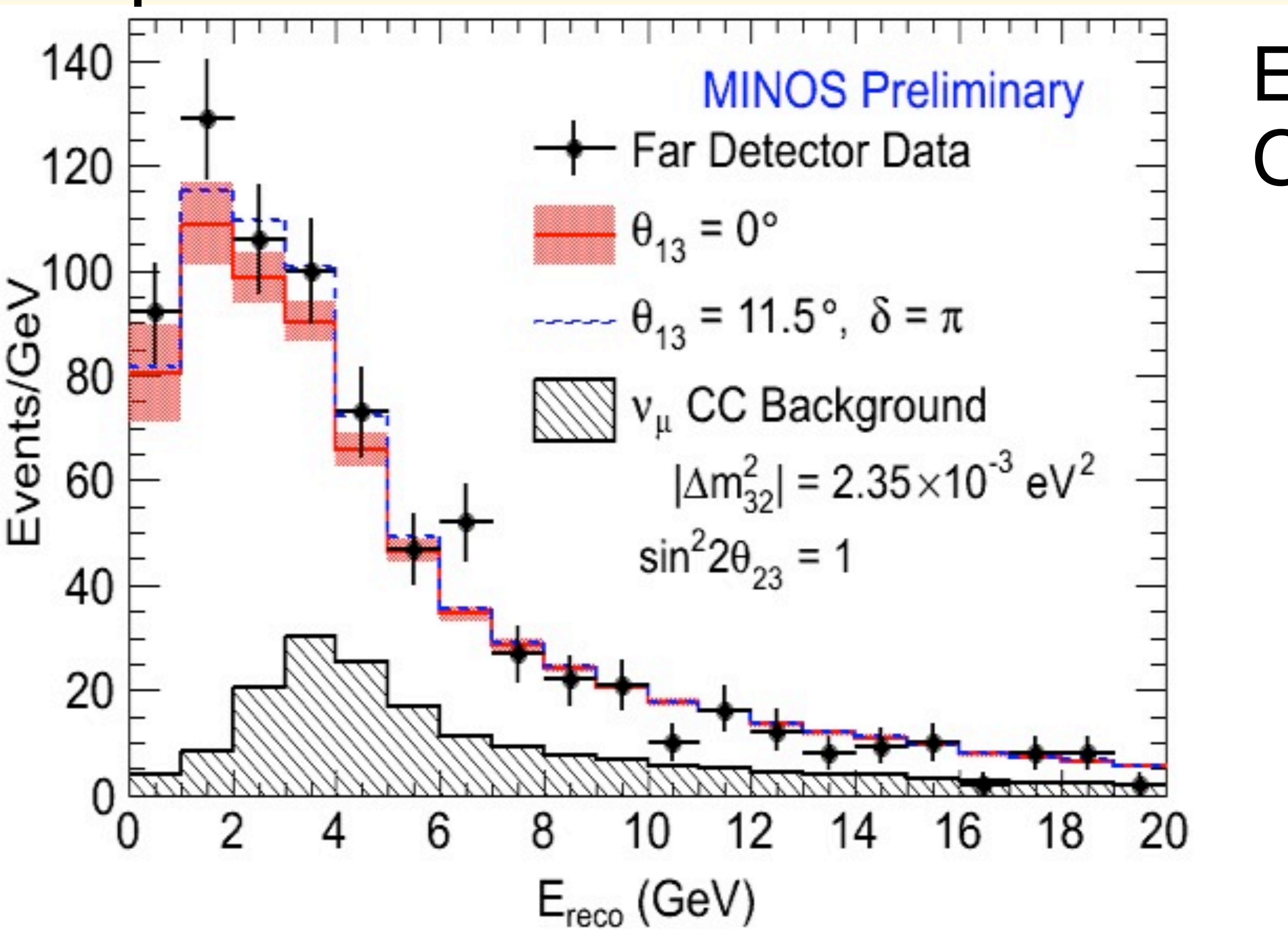

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Limit on fraction, f_s, of oscillated ν_μ converting to ν_s:

$$f_s \equiv \frac{P_{\nu_\mu \to \nu_s}}{1 - P_{\nu_\mu \to \nu_\mu}} < 0.22\ \ (0.40)\ \text{at } 90\%\ \text{C.L.}$$

P.Vahle Neutrino2010

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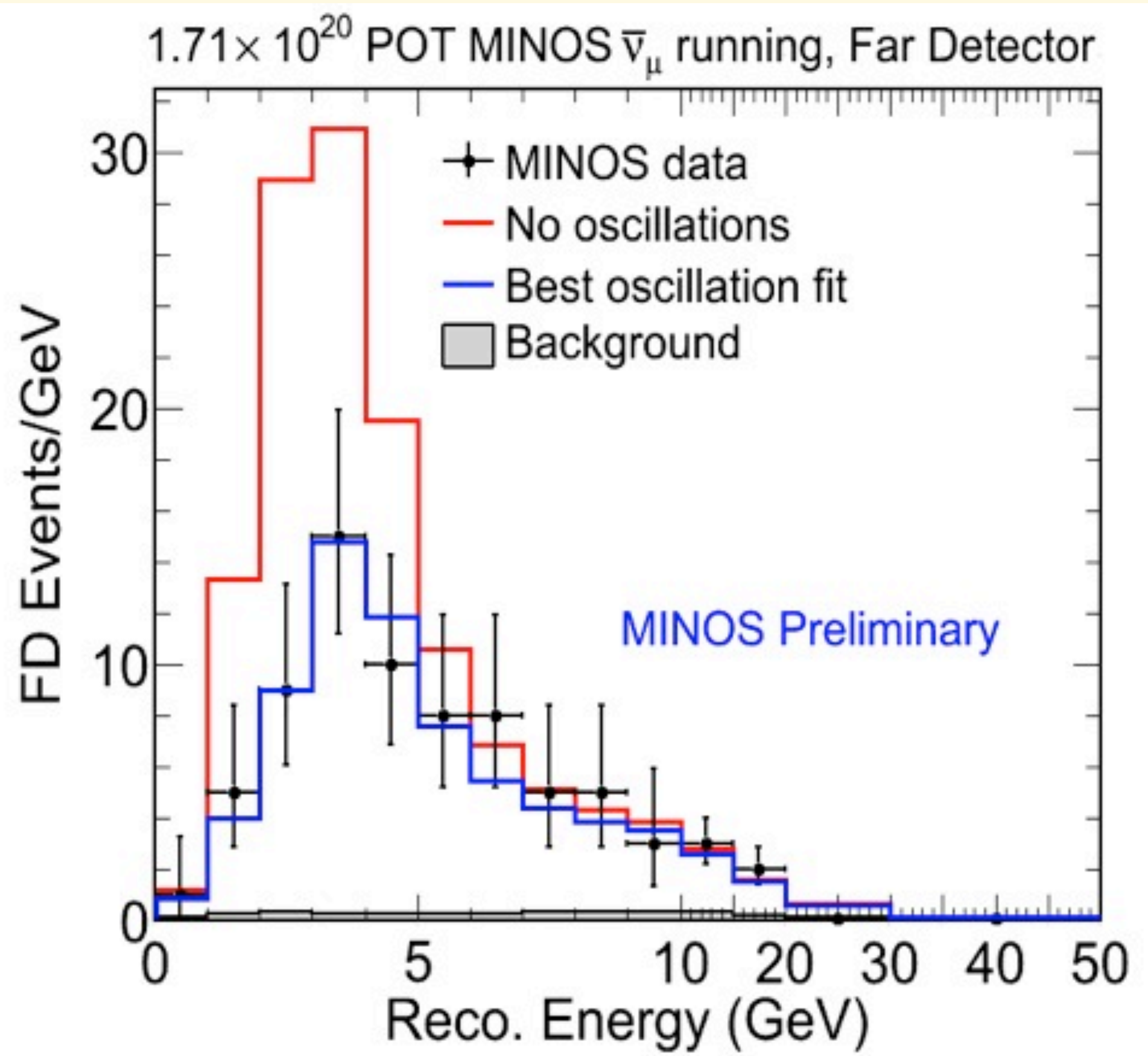

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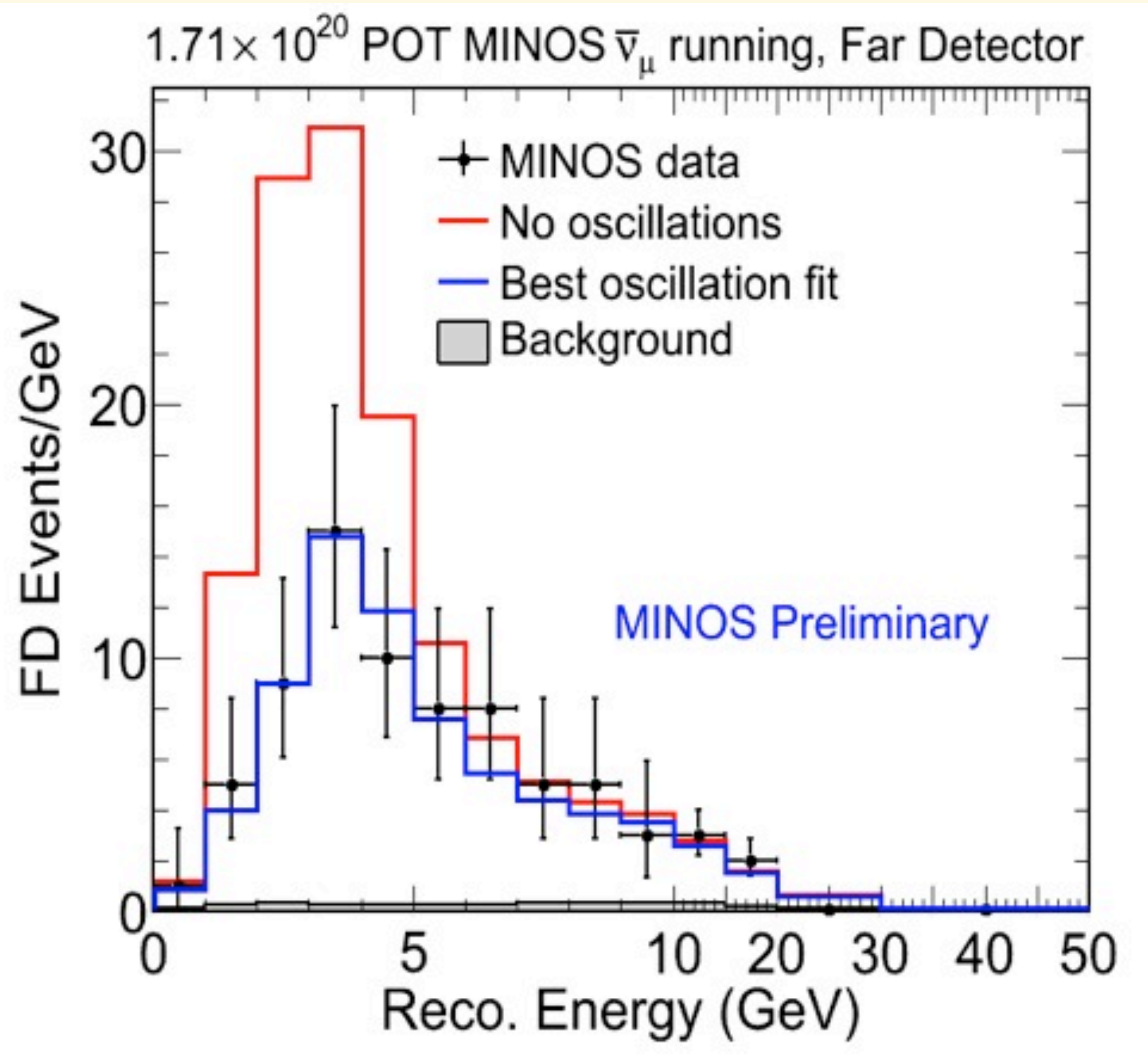

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$$\sin^2(2\overline{\theta}) = 0.86 \pm 0.11$$

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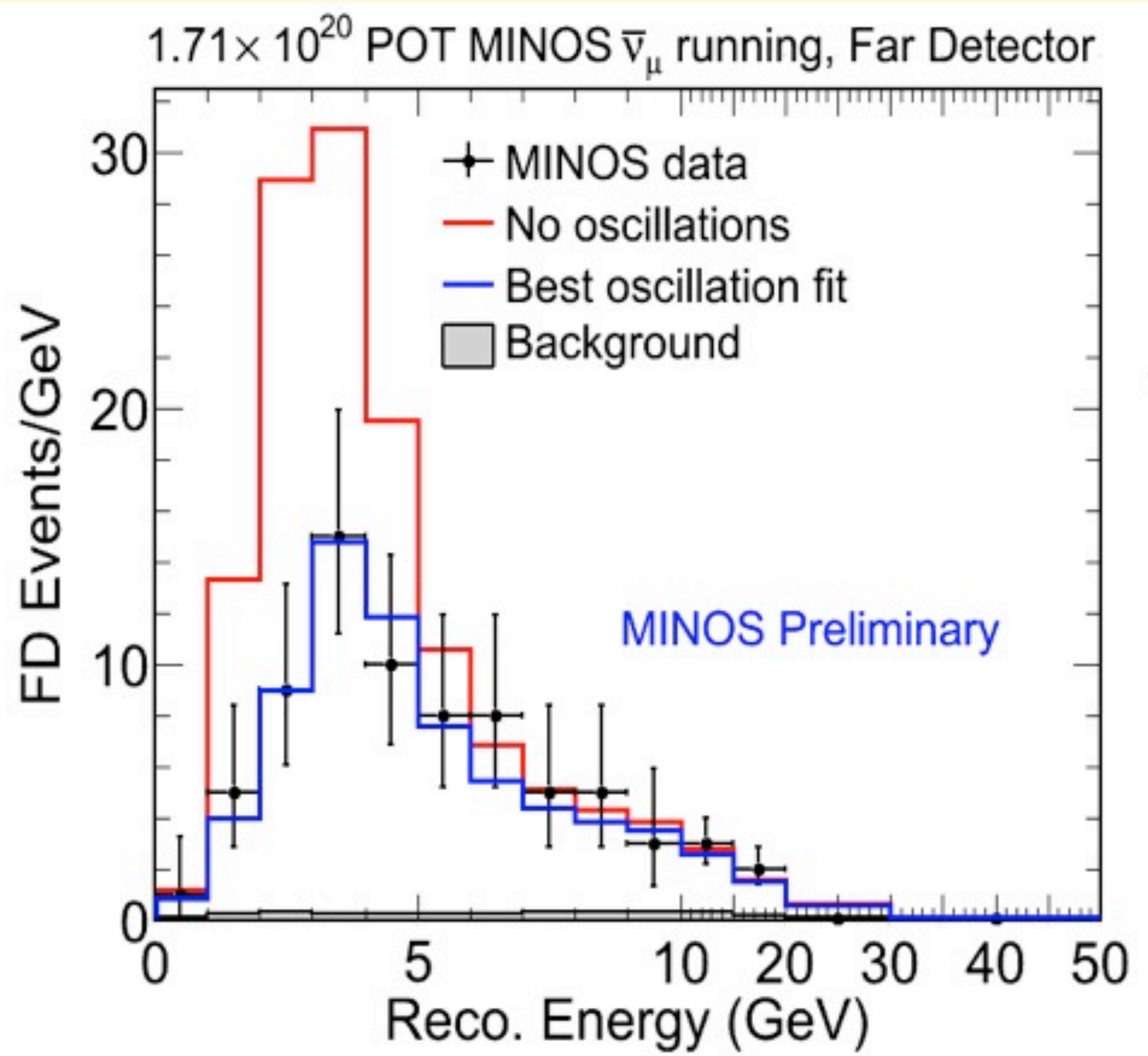

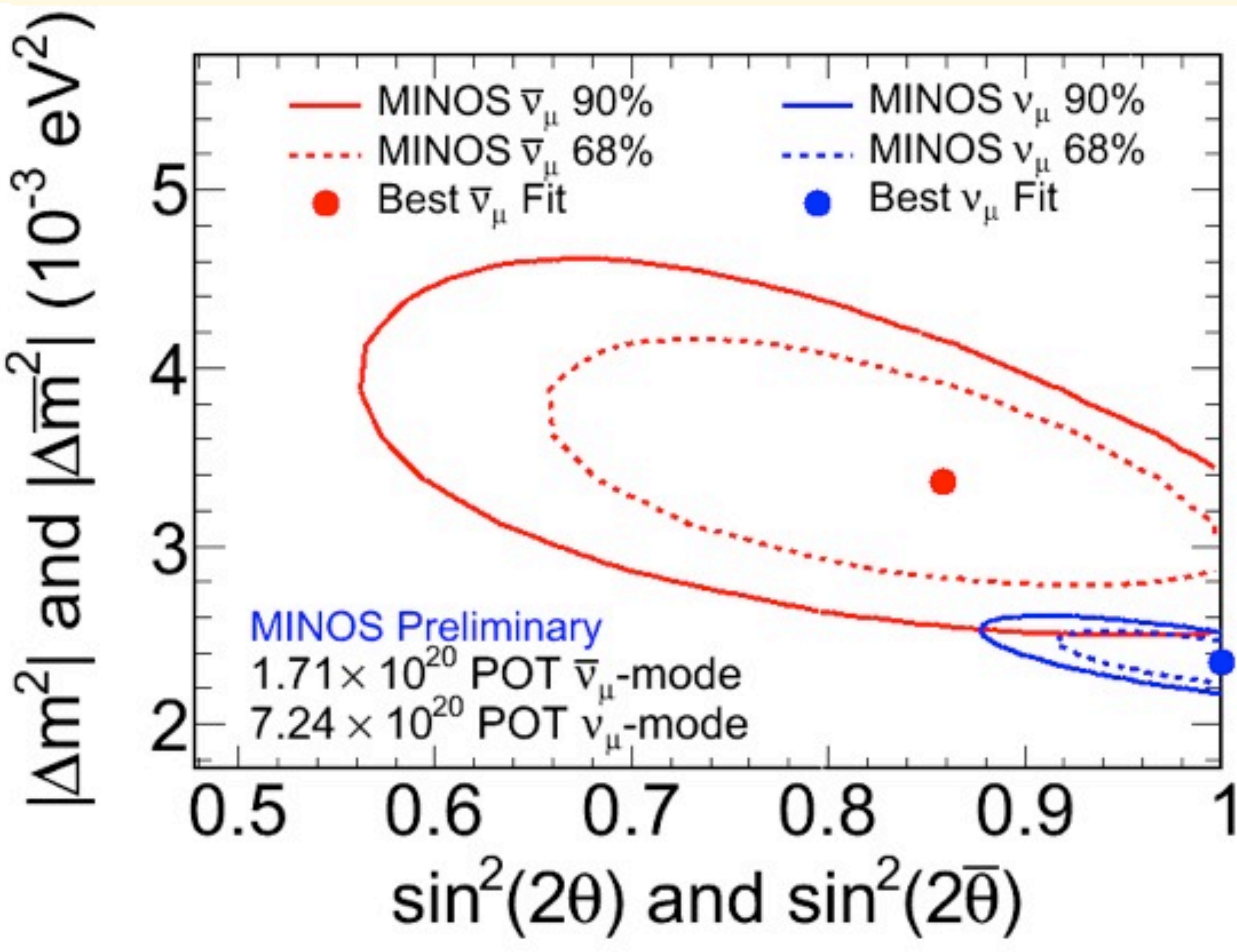

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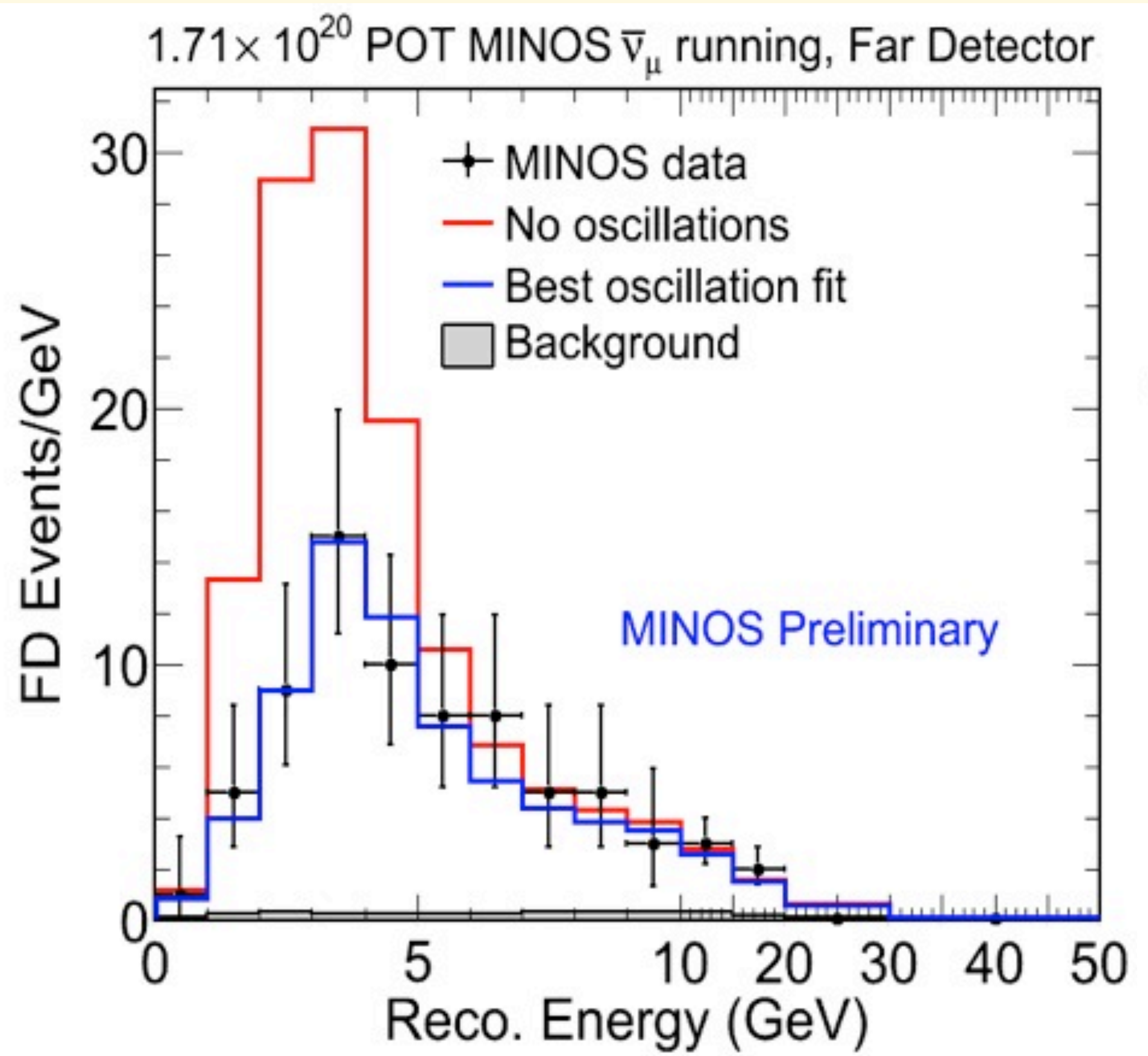

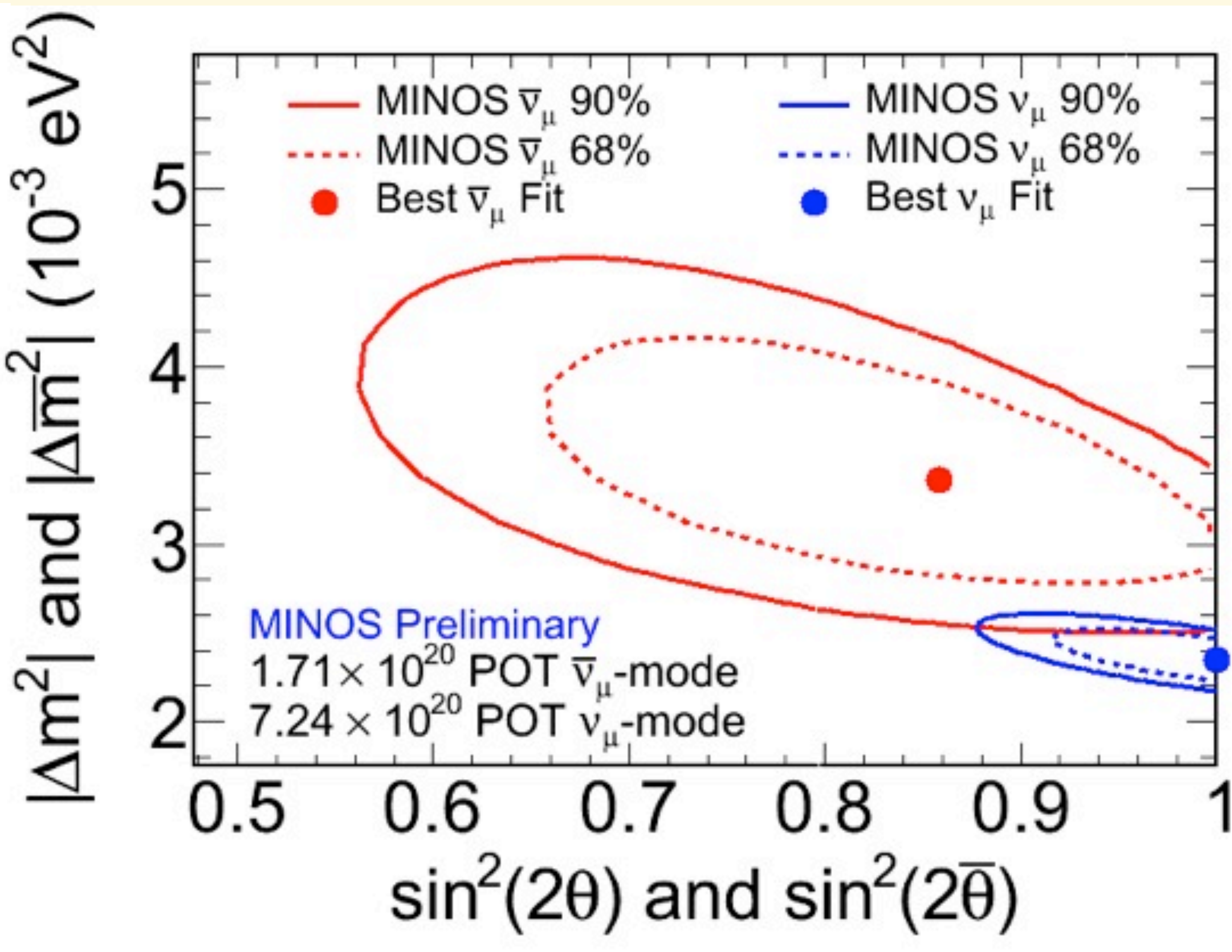

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There is a request to increase the data set to 4E20 POT

P.Vahle Neutrino2010

Atmospheric ν's

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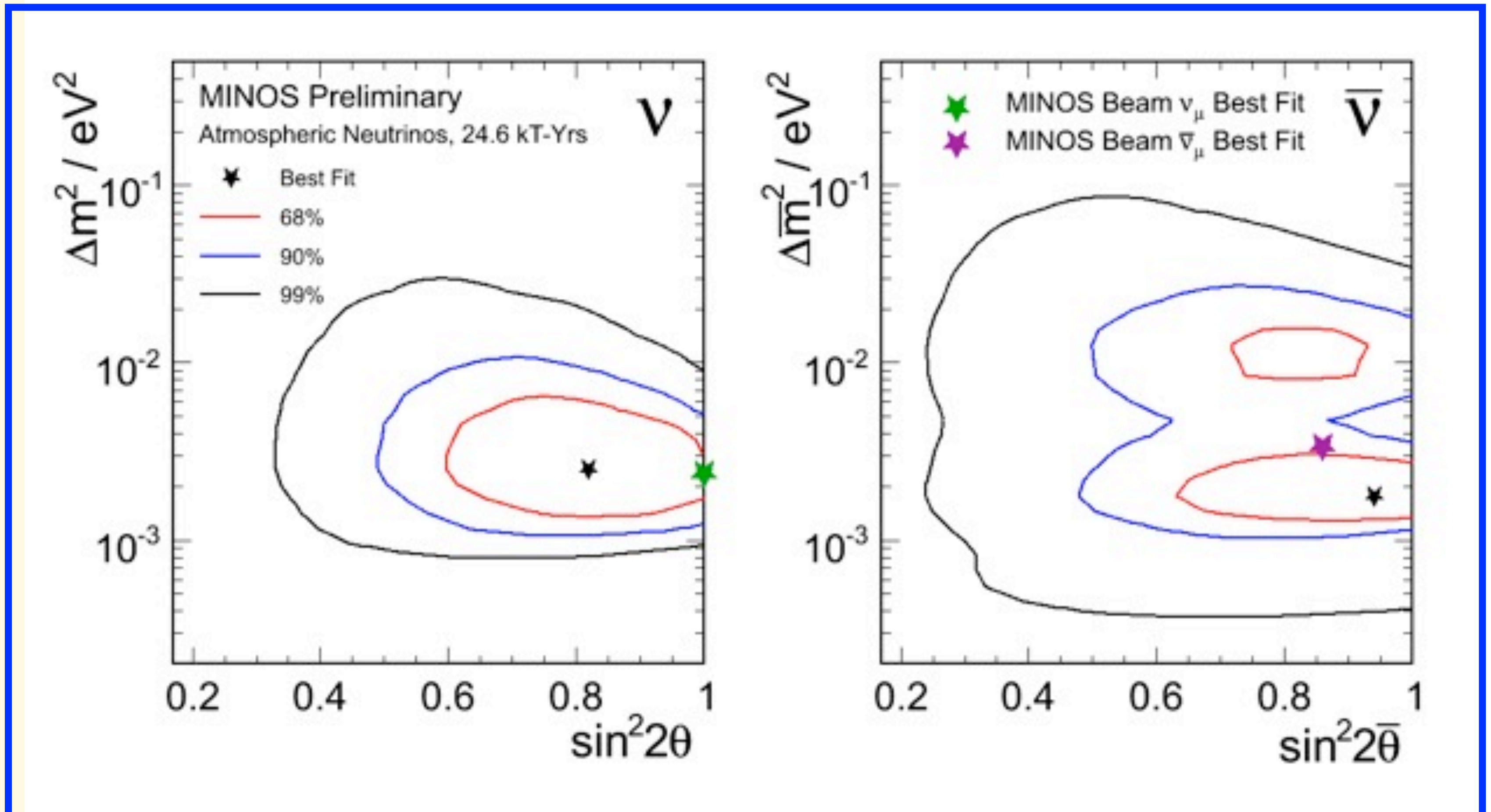

$$R^{data}_{\overline{\nu}/\nu} / R^{MC}_{\overline{\nu}/\nu} = 1.04^{+0.11}_{-0.10} \pm 0.10$$

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A.Blake, Poster Nu2010

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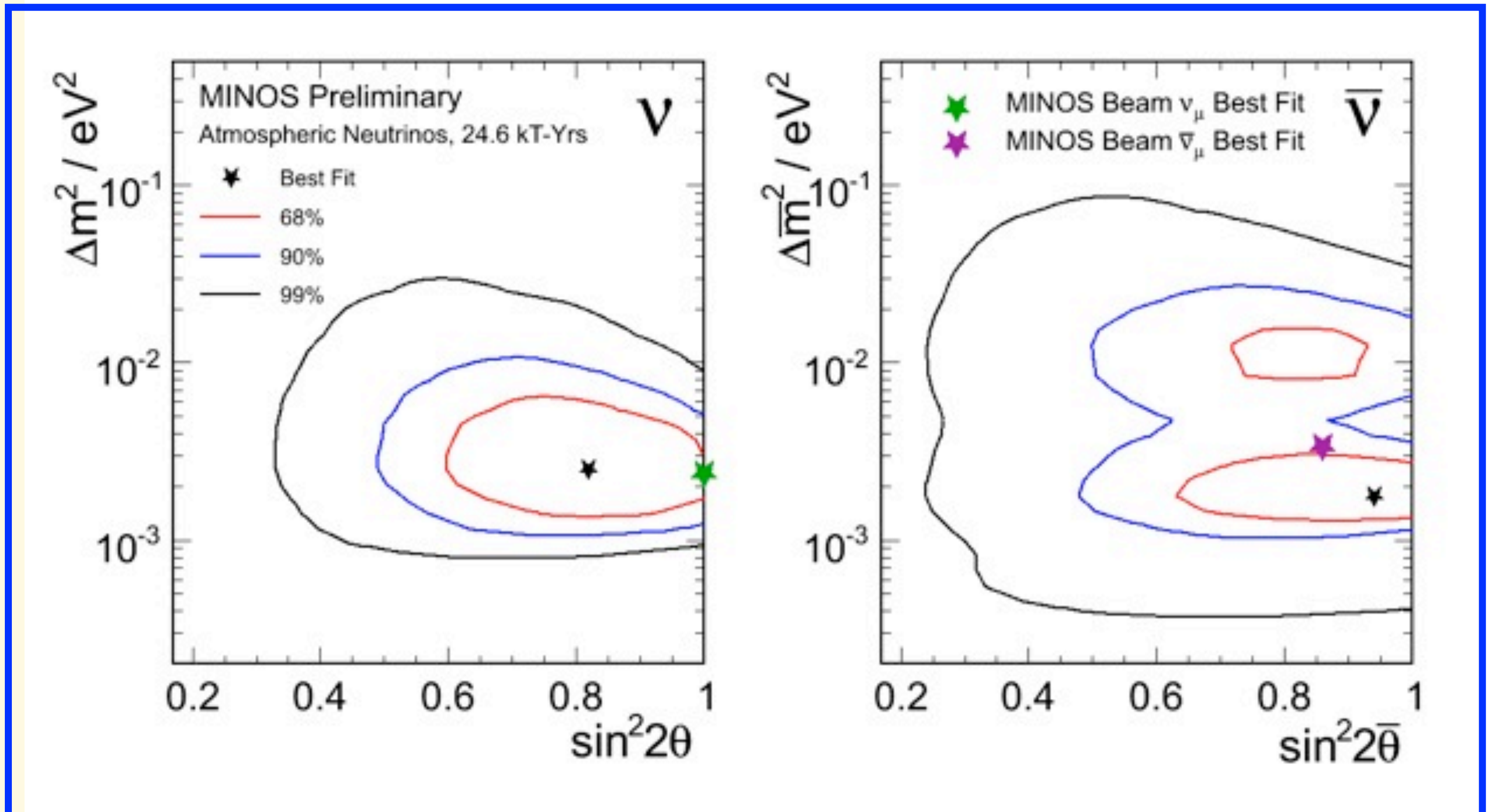

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A.Blake, Poster Nu2010

SuperK analysis

Y.Takeuchi Neutrino2010

Neutrino:

$\Delta m_{32}^2 = 2.2 \times 10^{-3} \mathrm{eV}^2$

$\sin^2 2\theta_{23} = 1.0$

Anti-neutrino:

$\Delta m_{32}^2 = 2.0 \times 10^{-3} \mathrm{eV}^2$

$\sin^2 2\theta_{23} = 1.0$

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Reactor Experiments

- Next generation experiments aim at measurement of θ_{13} using $\overline{\nu}_e$ disappearance
- The new feature is the use of one or more additional detectors to reduce the systematics
- 3 different efforts, aiming for $\sin^2(2\theta_{13})$ sensitivity in the 0.01-0.03 range
  - DoubleChooz - France
  - RENO - South Korea
  - Daya Bay - China
- Initial results in 2011/2012 time frame

More on Reactors

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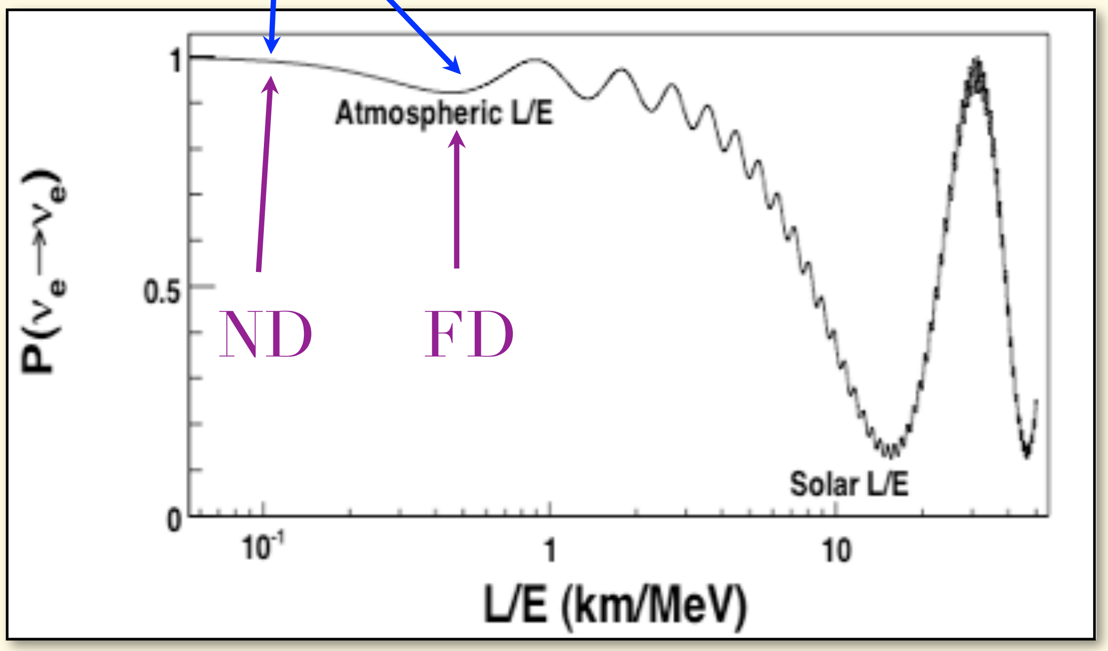
The Challenge



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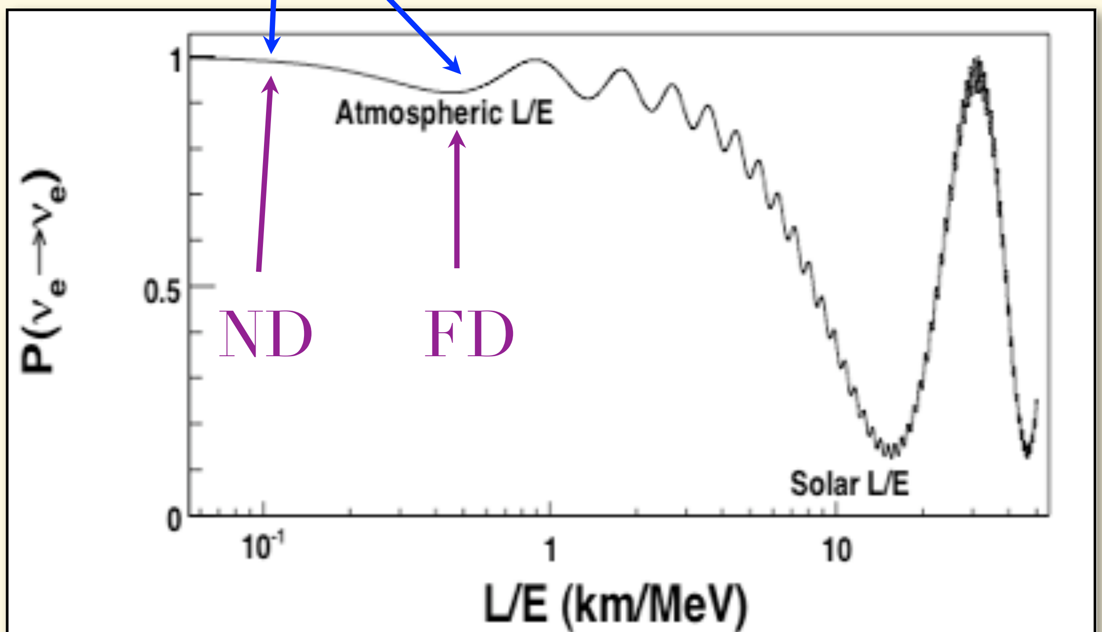

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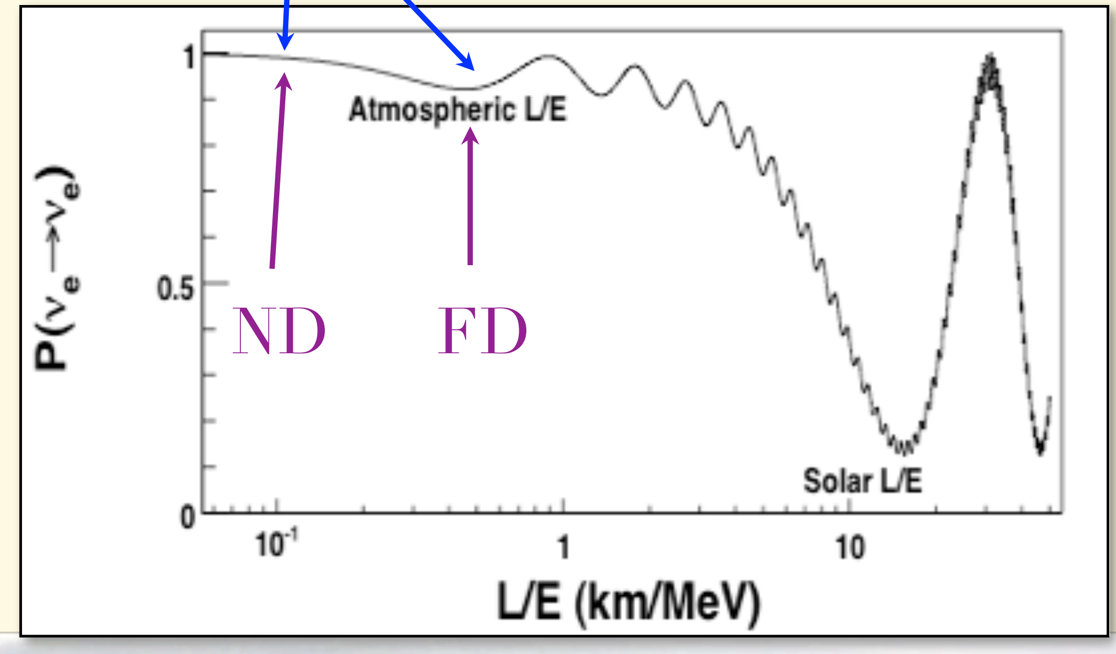

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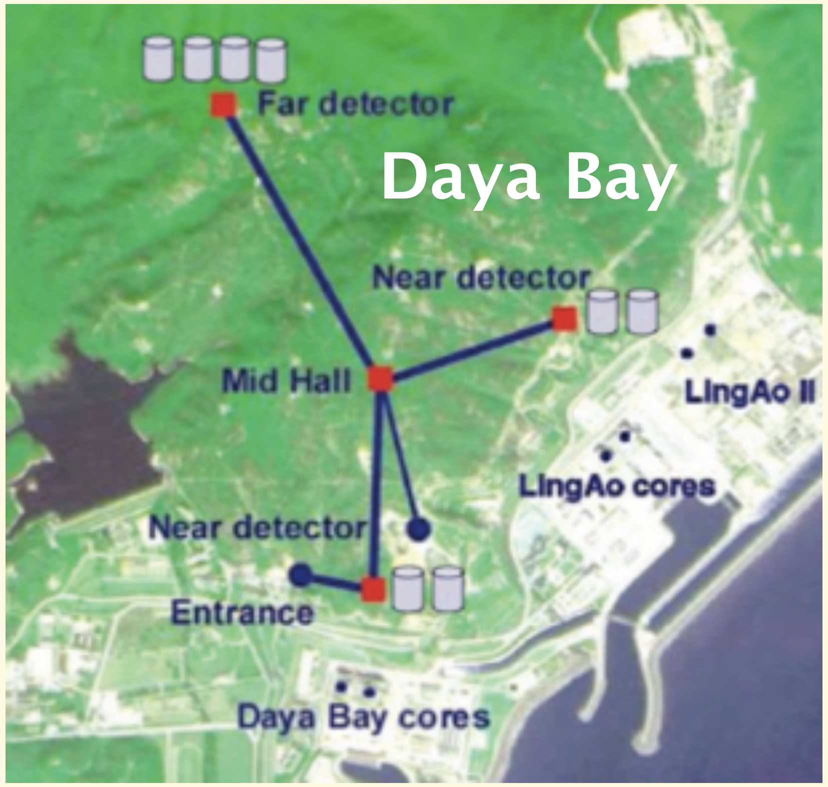

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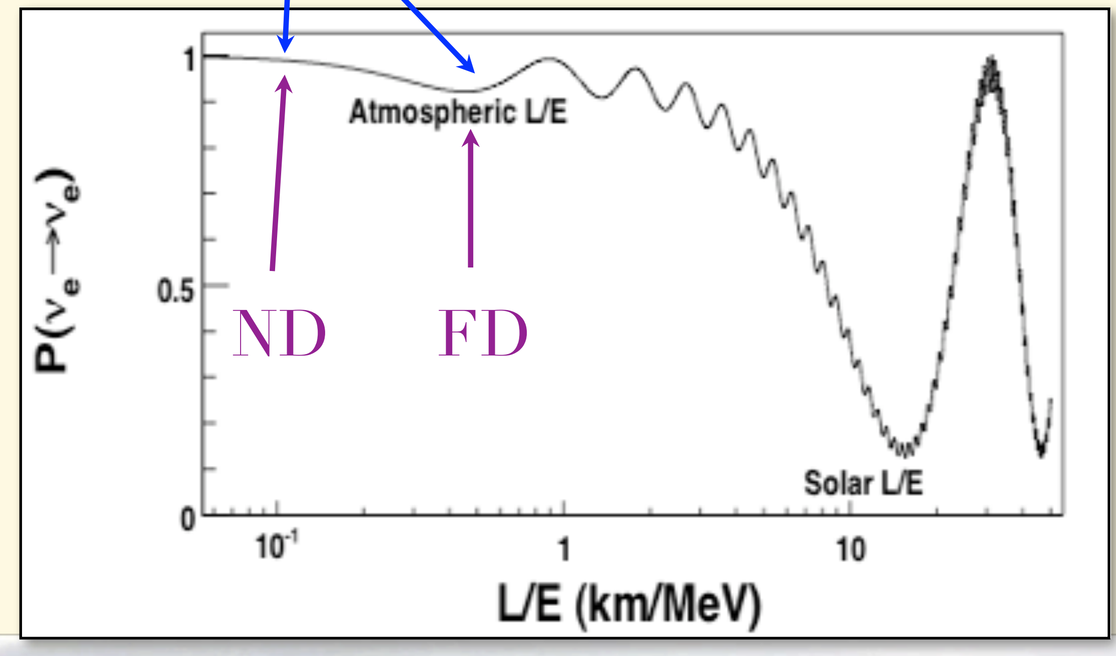

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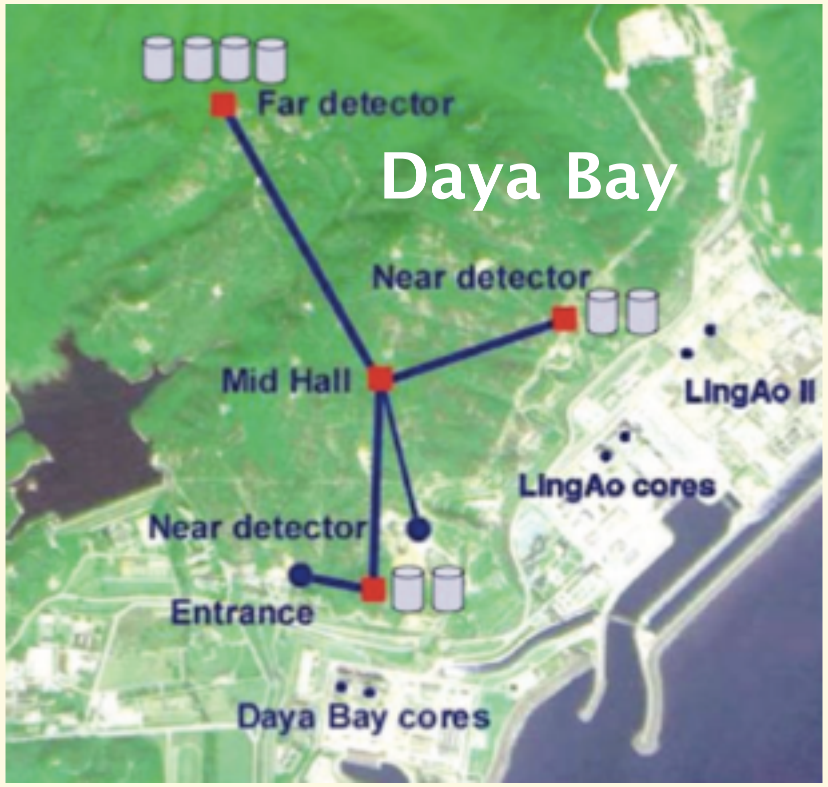

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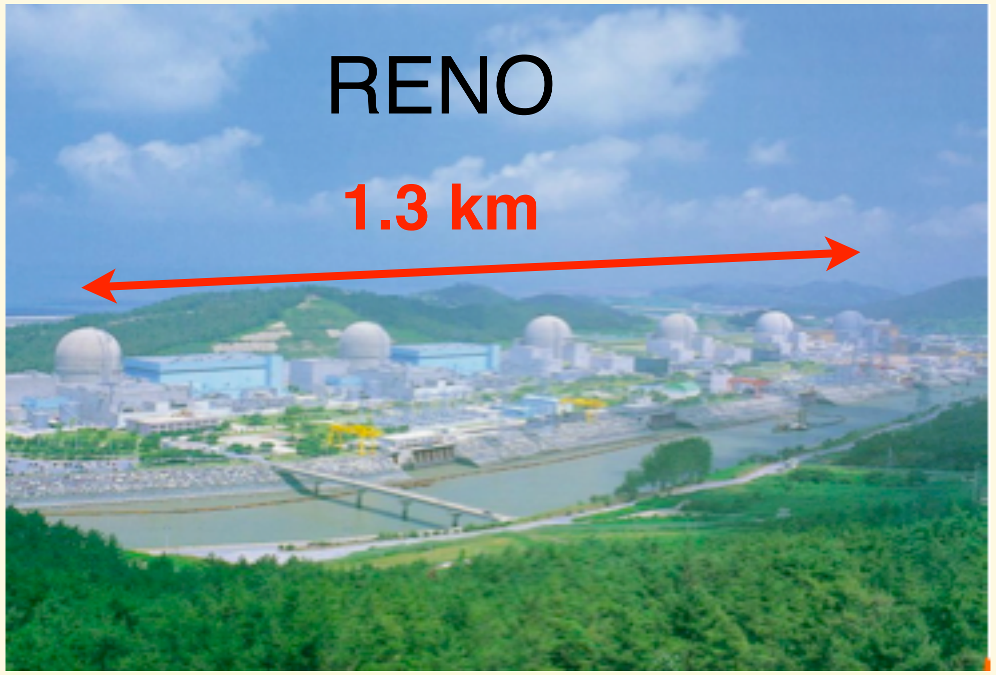

In South Korea

More on Reactors

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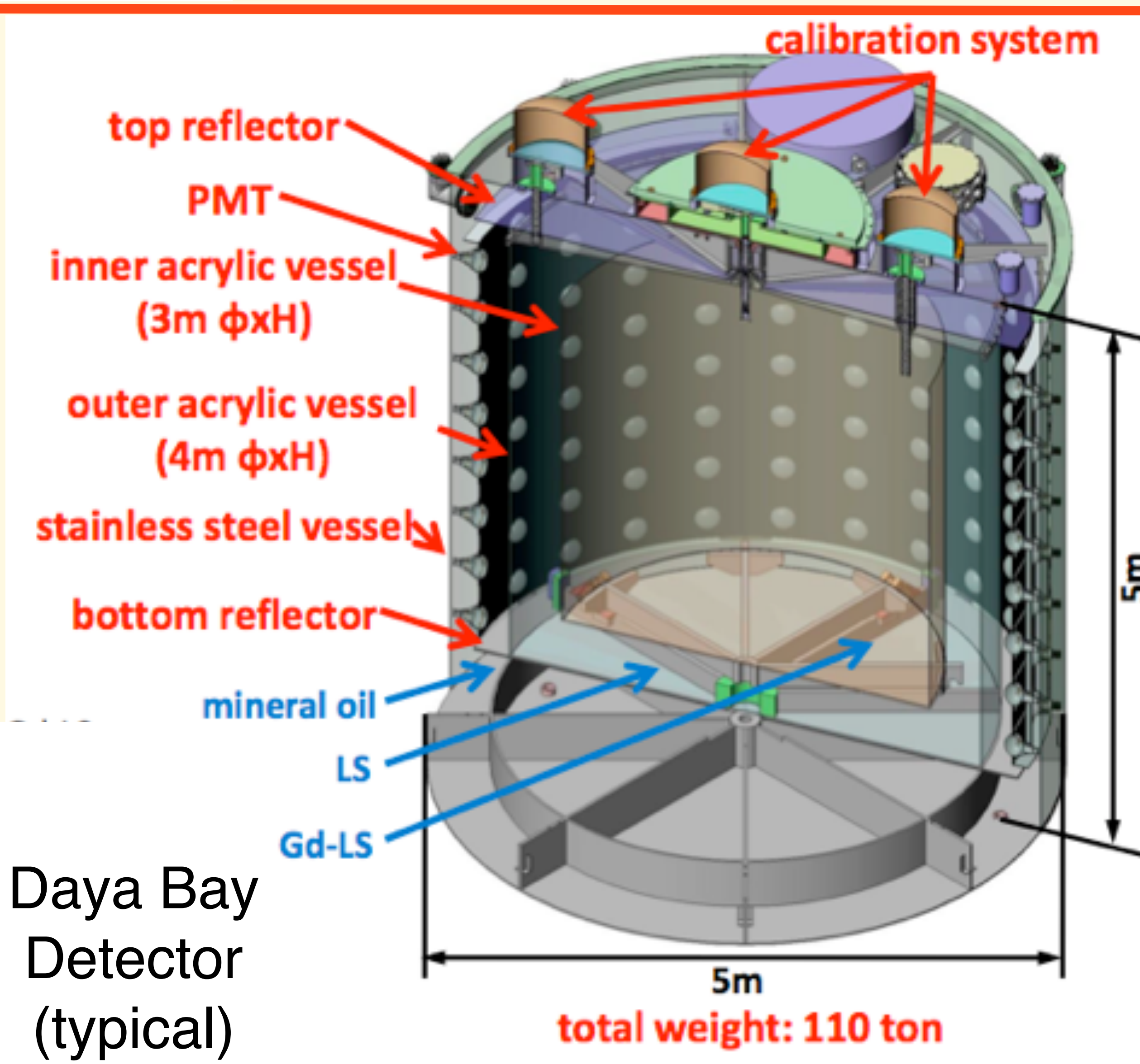

Daya Bay Detector (typical)

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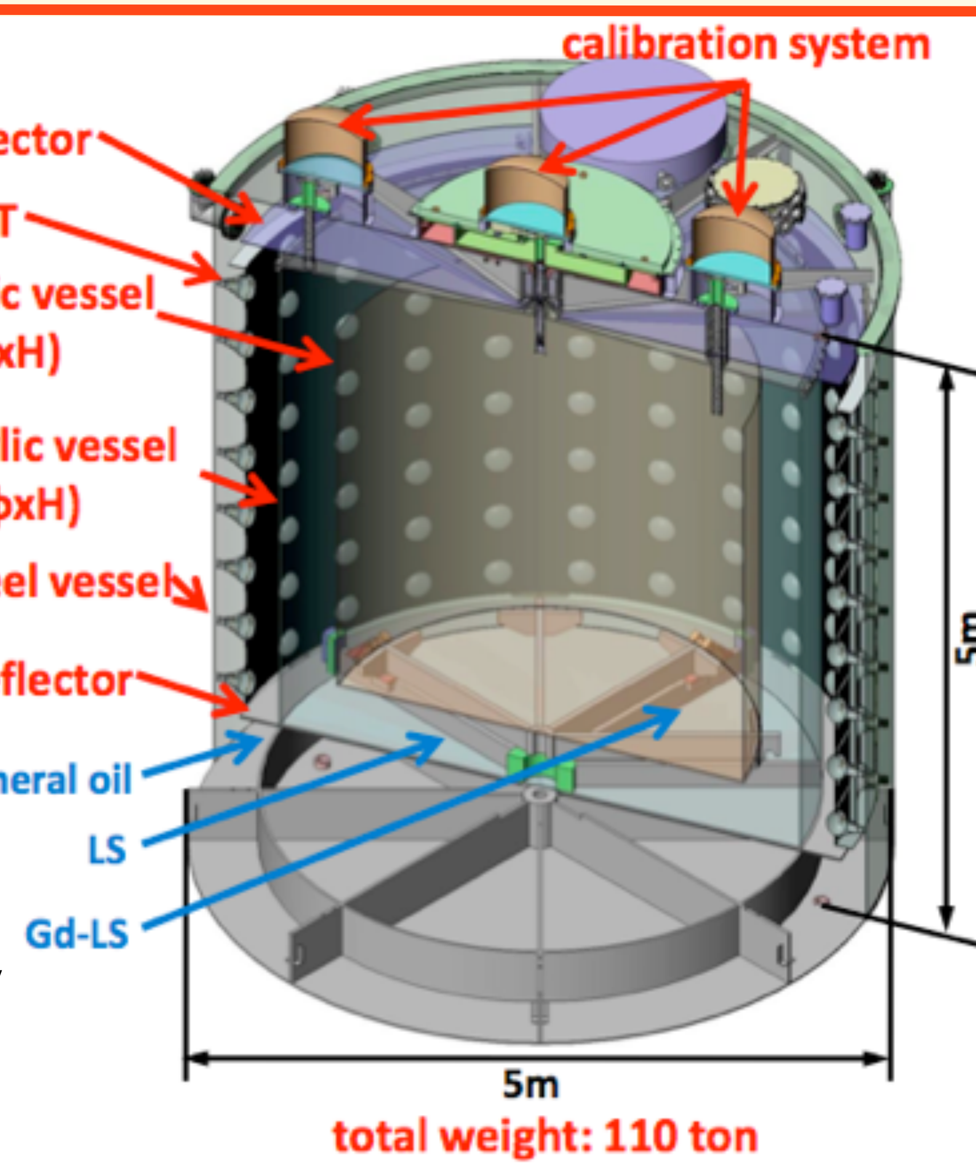

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DoubleChooz: Far Hall - Sept/10
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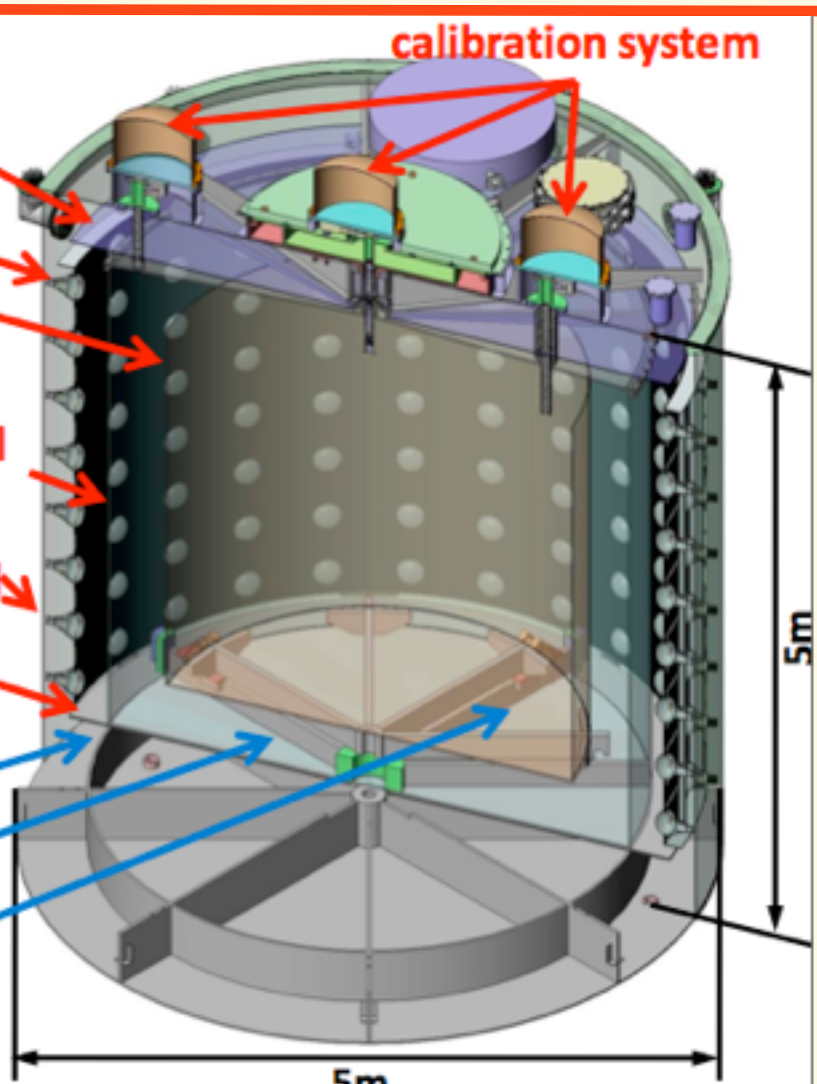

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DoubleChooz	France	8.7	410/1050	115/300	10/10
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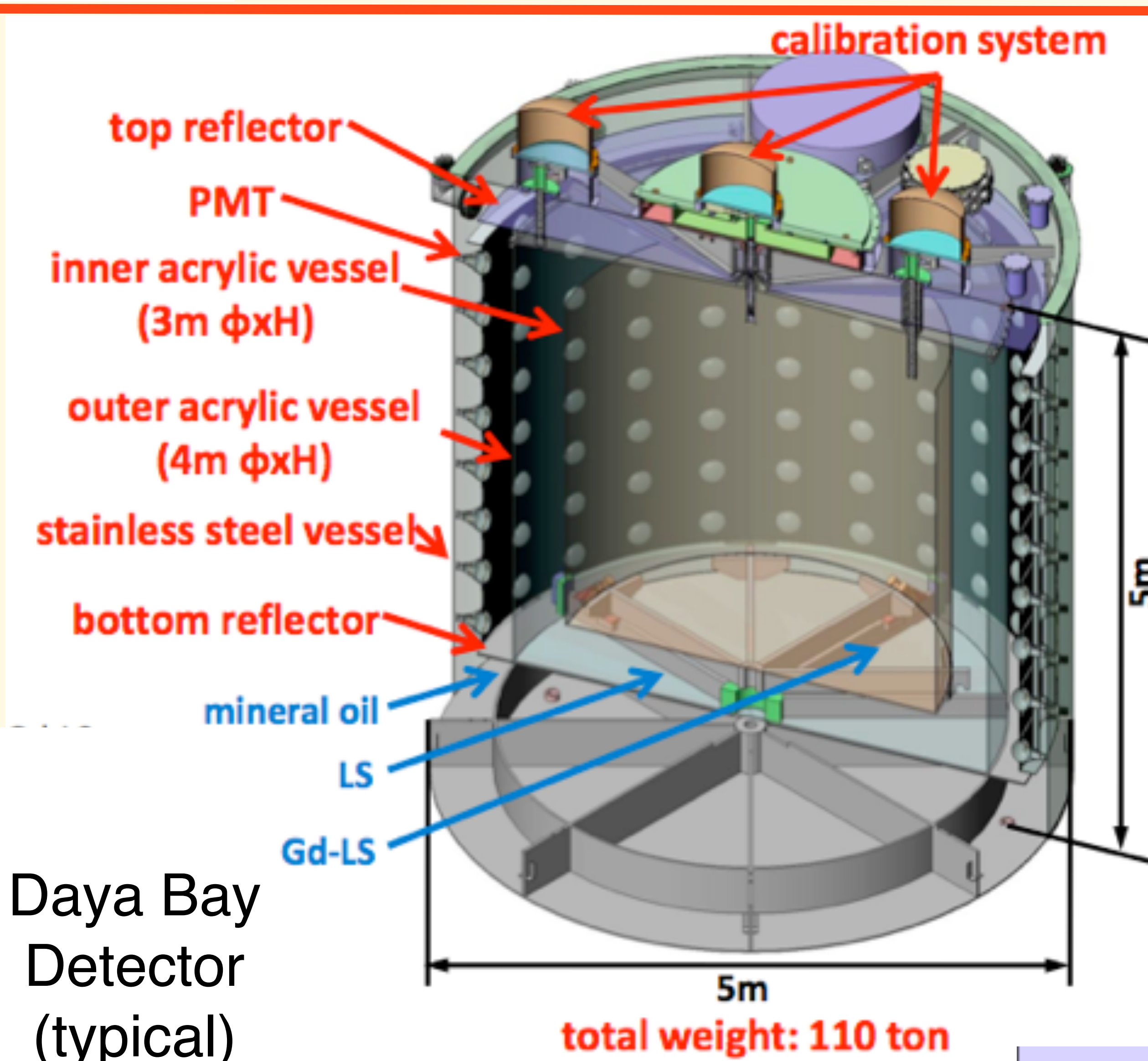

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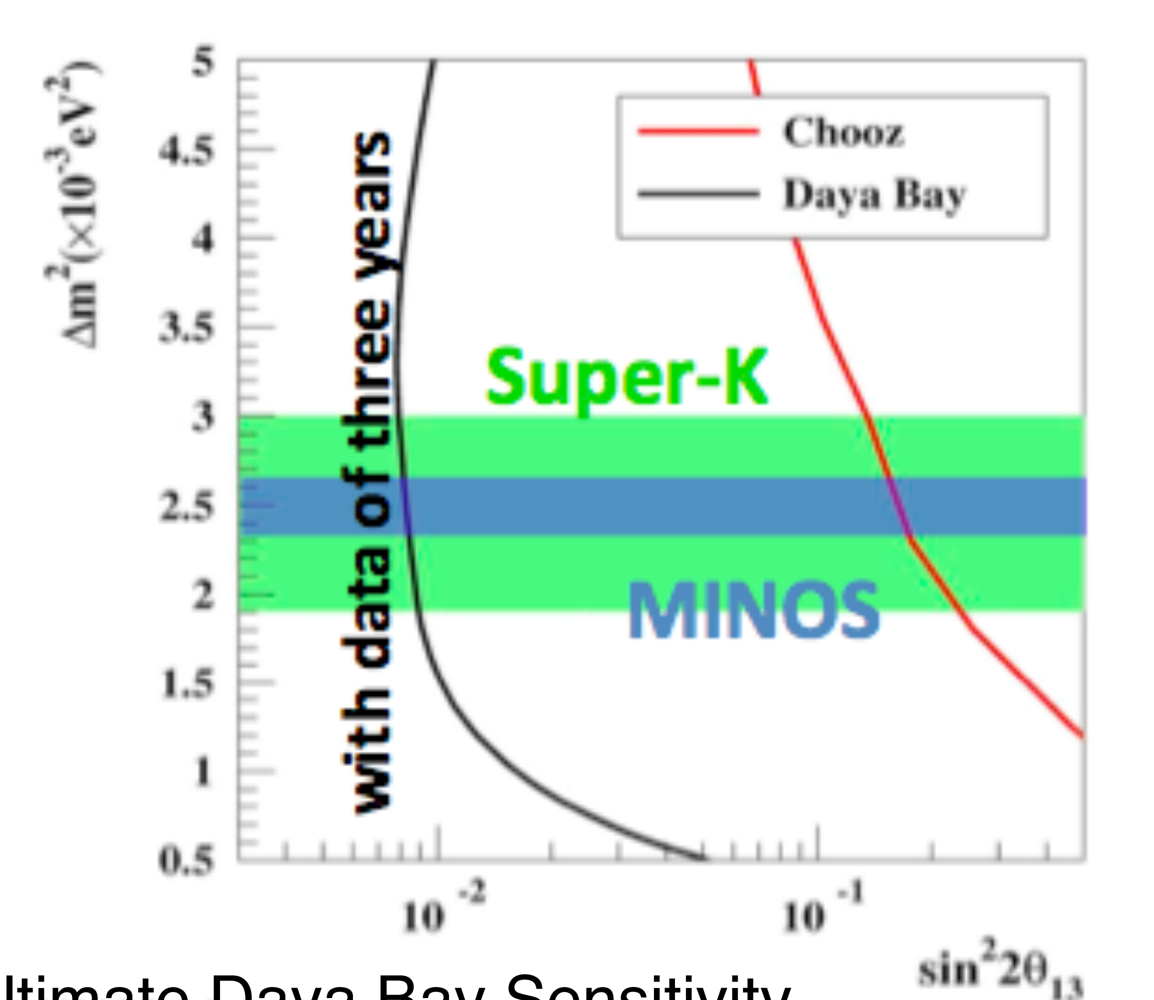

Ultimate Daya Bay Sensitivity
Other 2 experiments 2-3 worse

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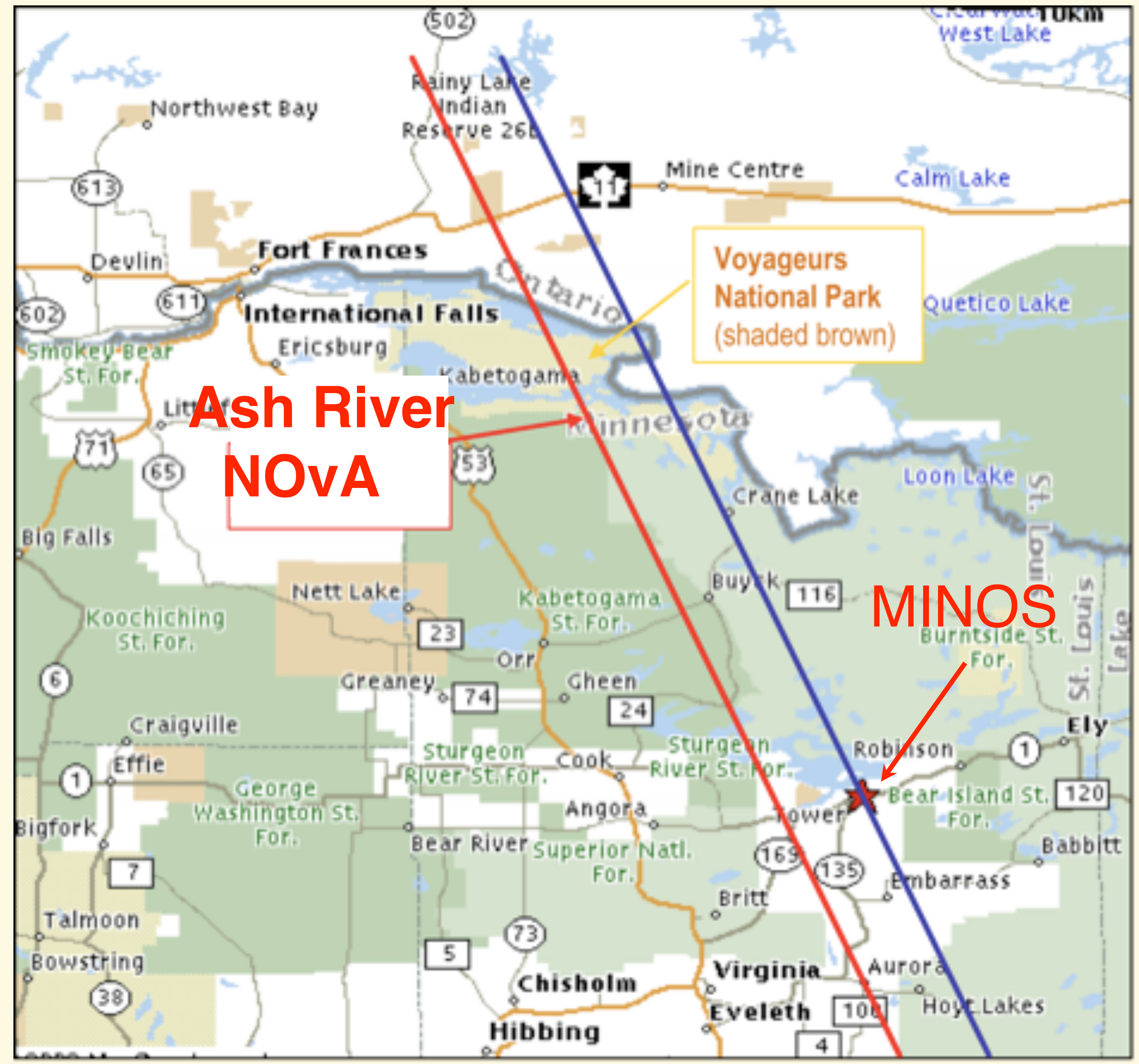
NOvA Beamline and Location



Existing beamline (NuMI) at Fermilab
New Detector on a new site (810 km away)

Data taking might start in late 2011 with partial detector

T2K and NOvA

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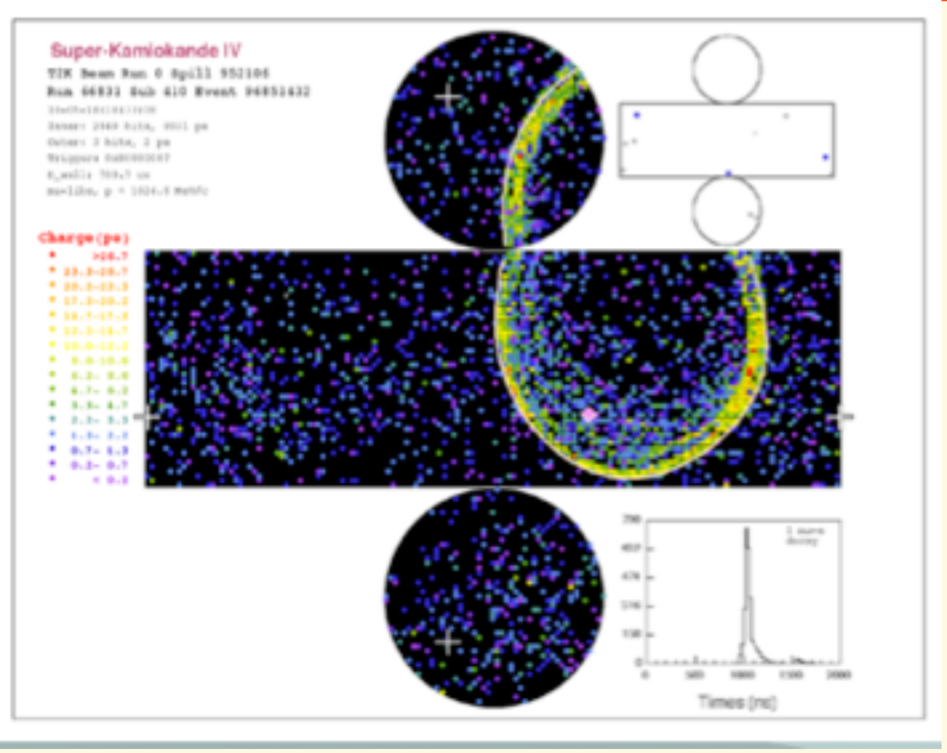

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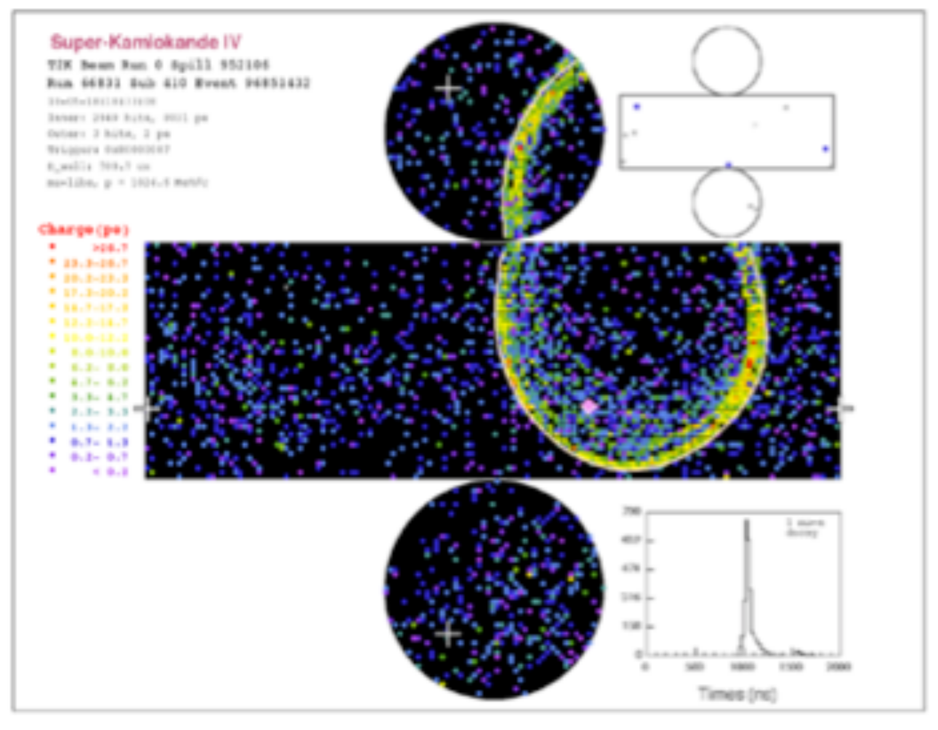

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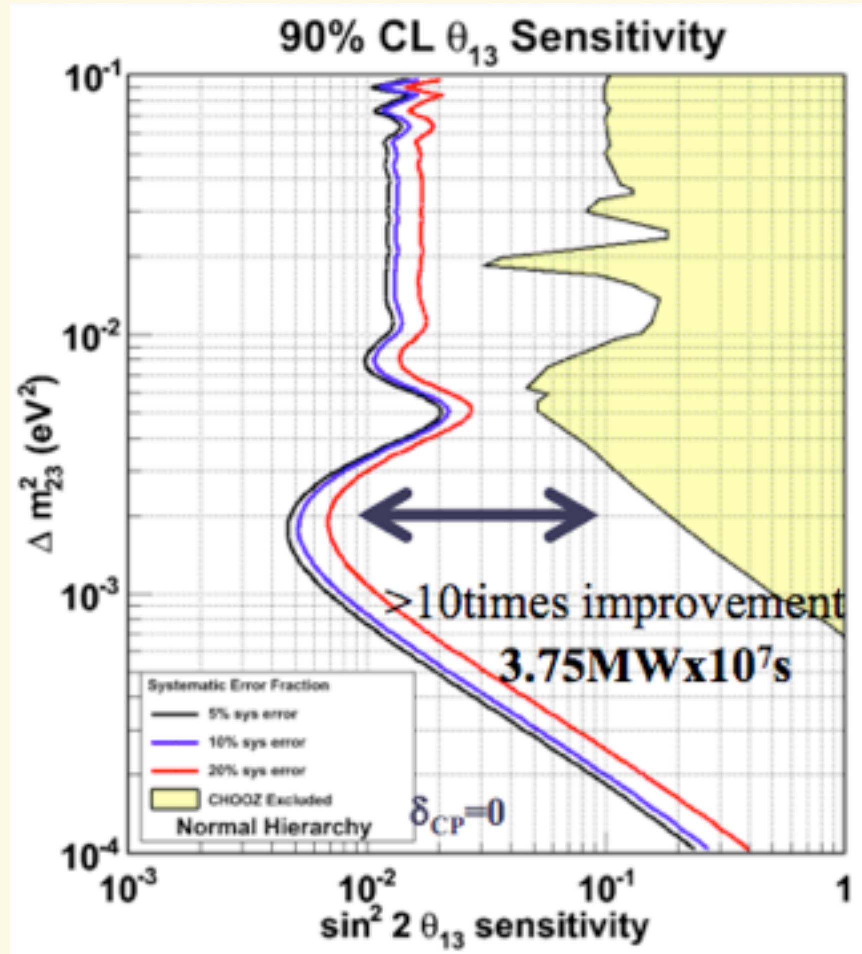

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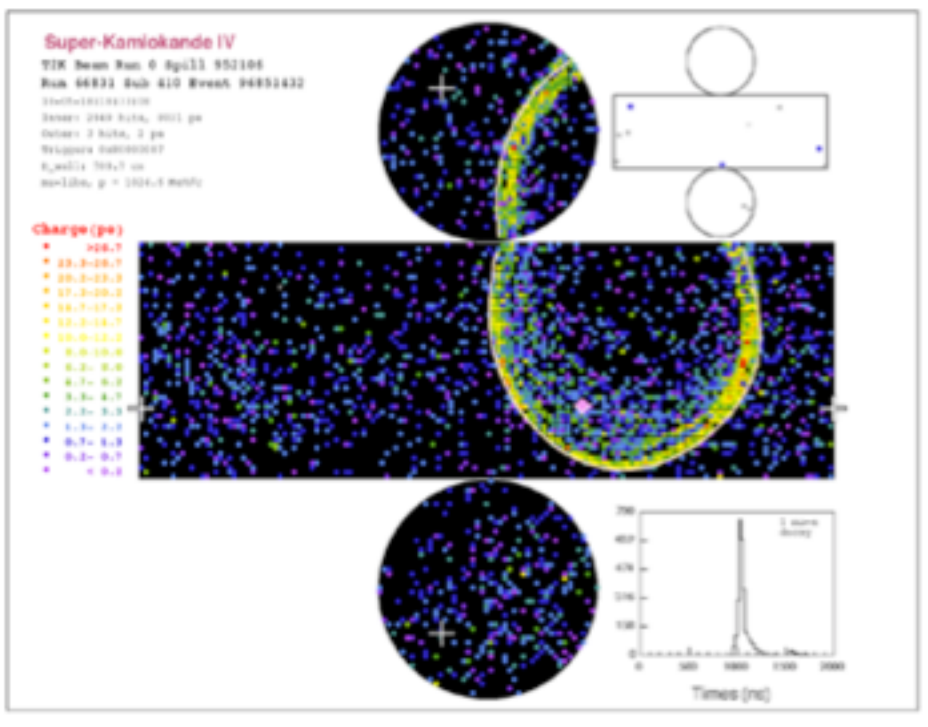

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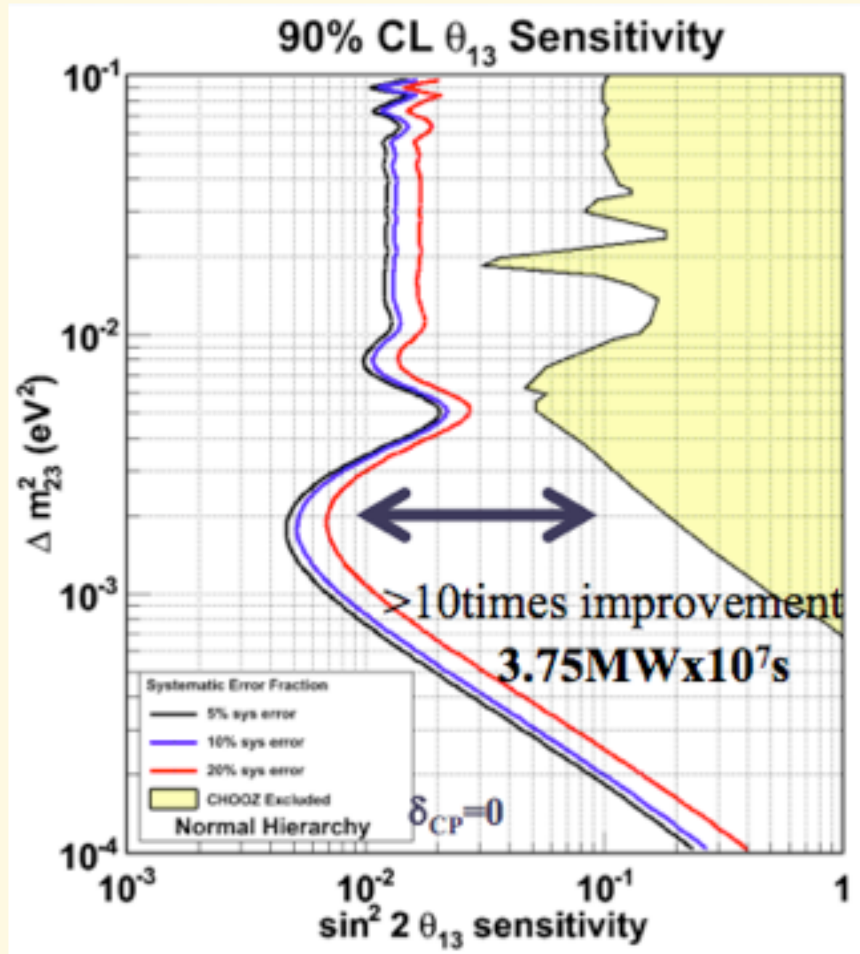

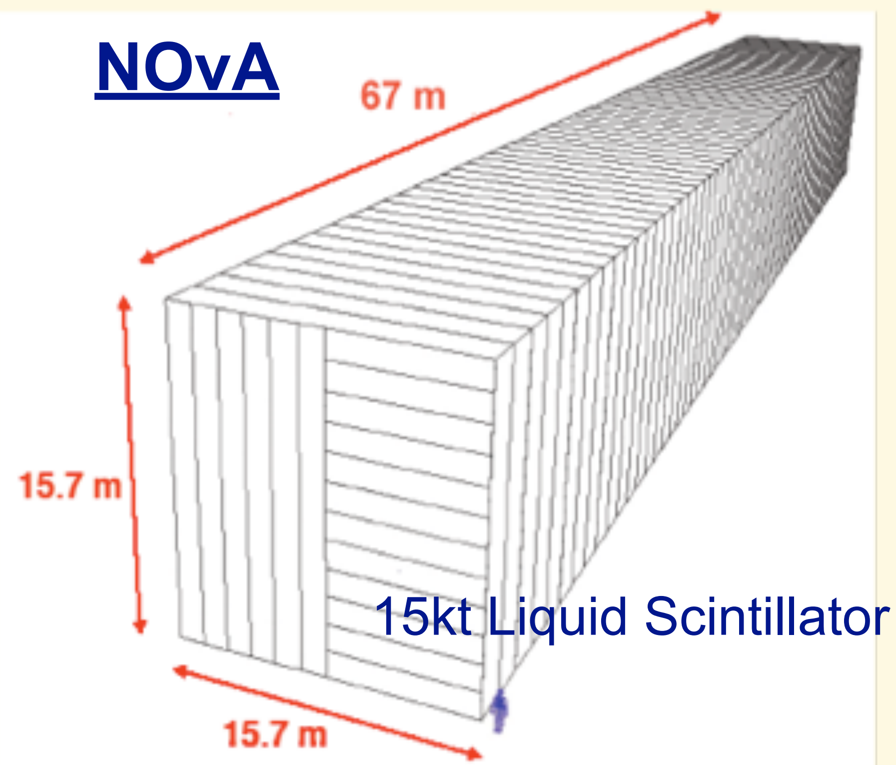

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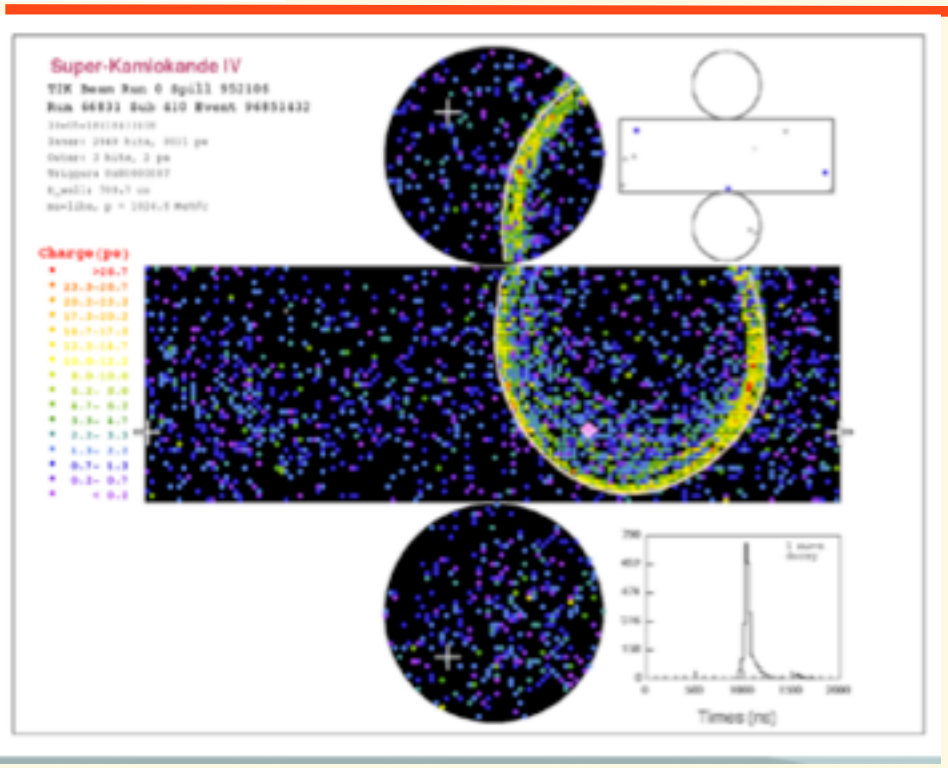

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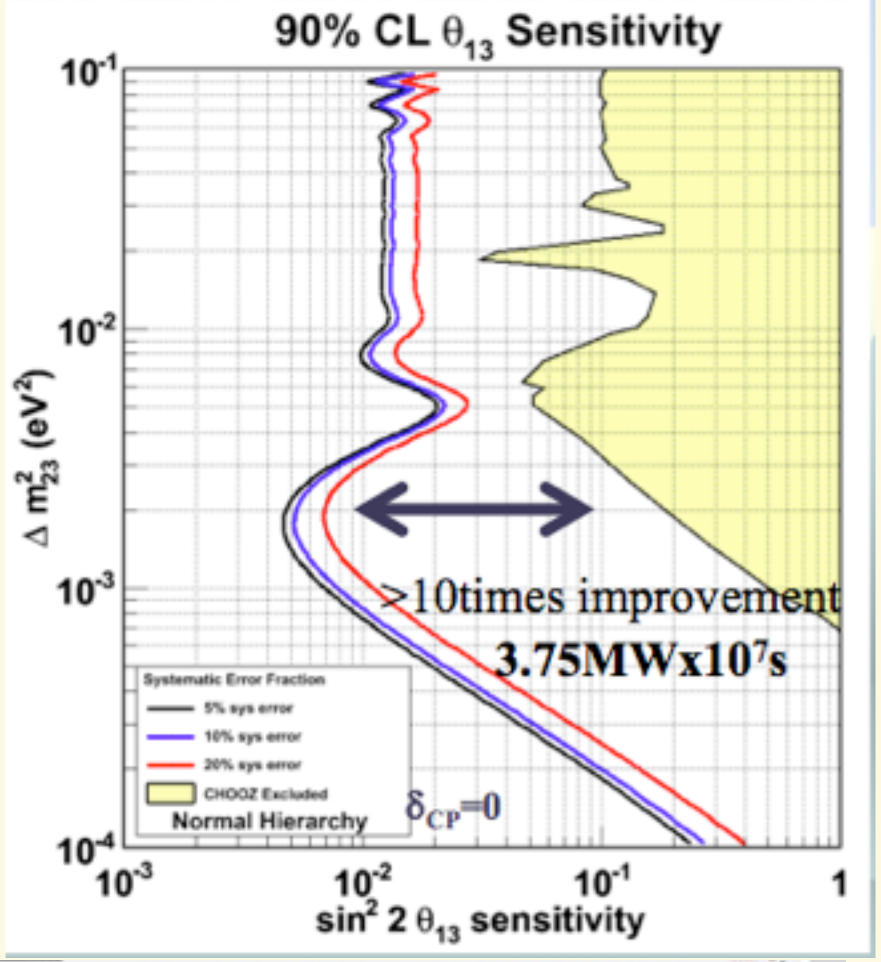

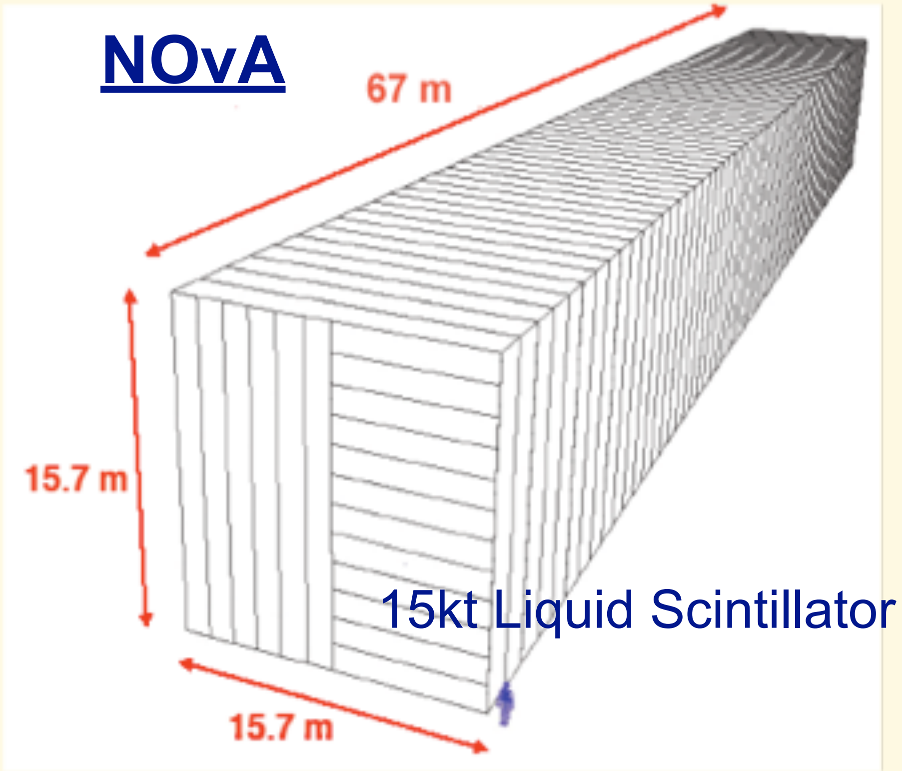

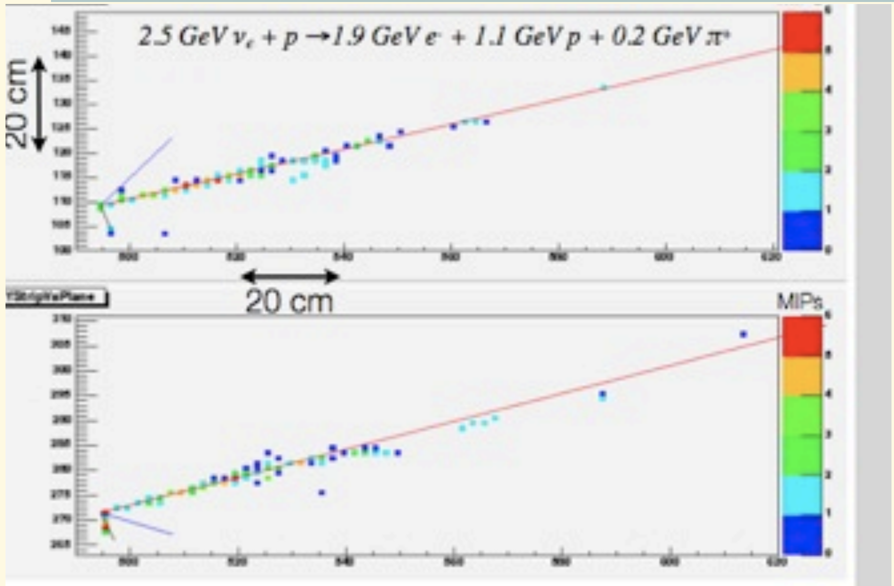

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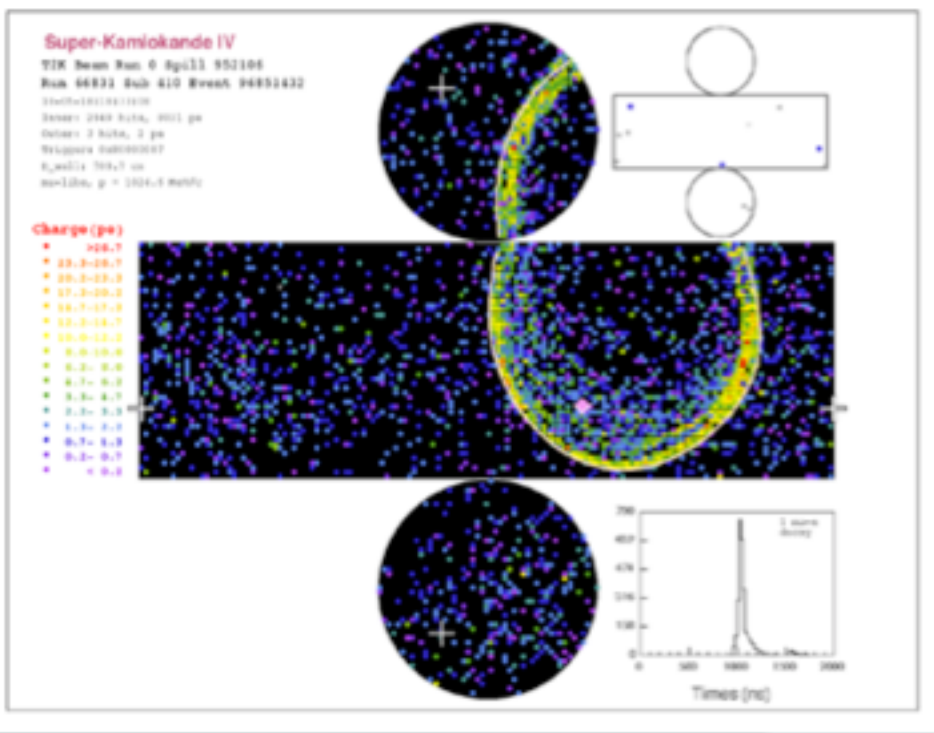

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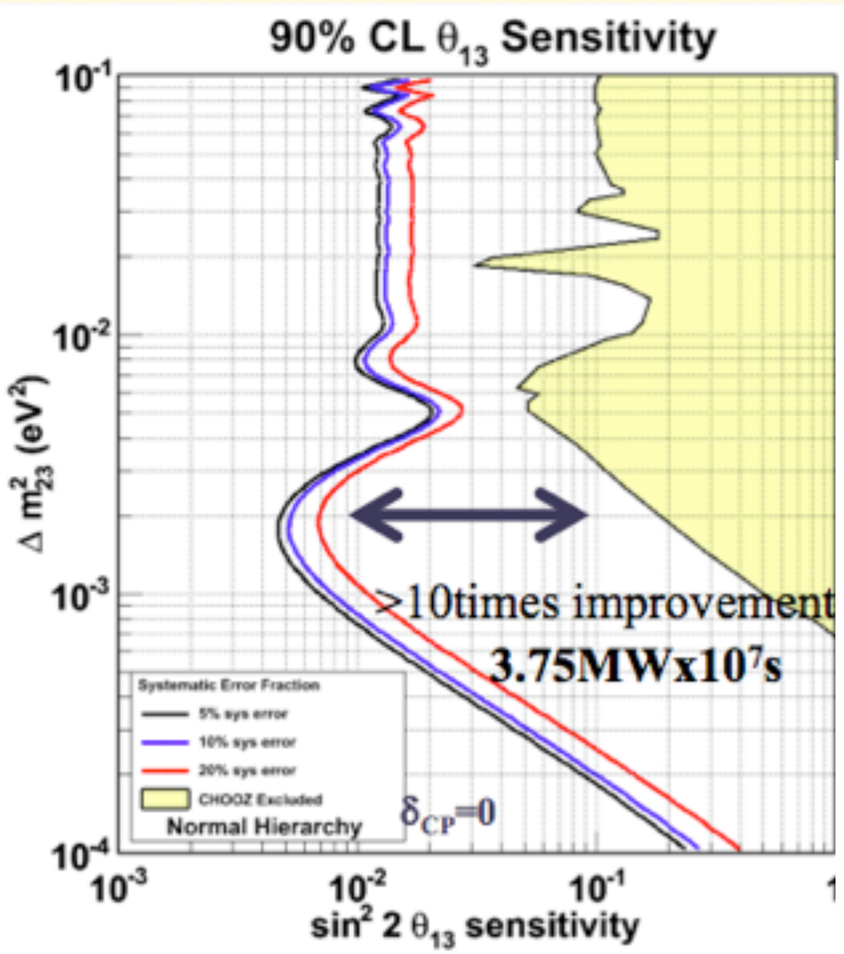
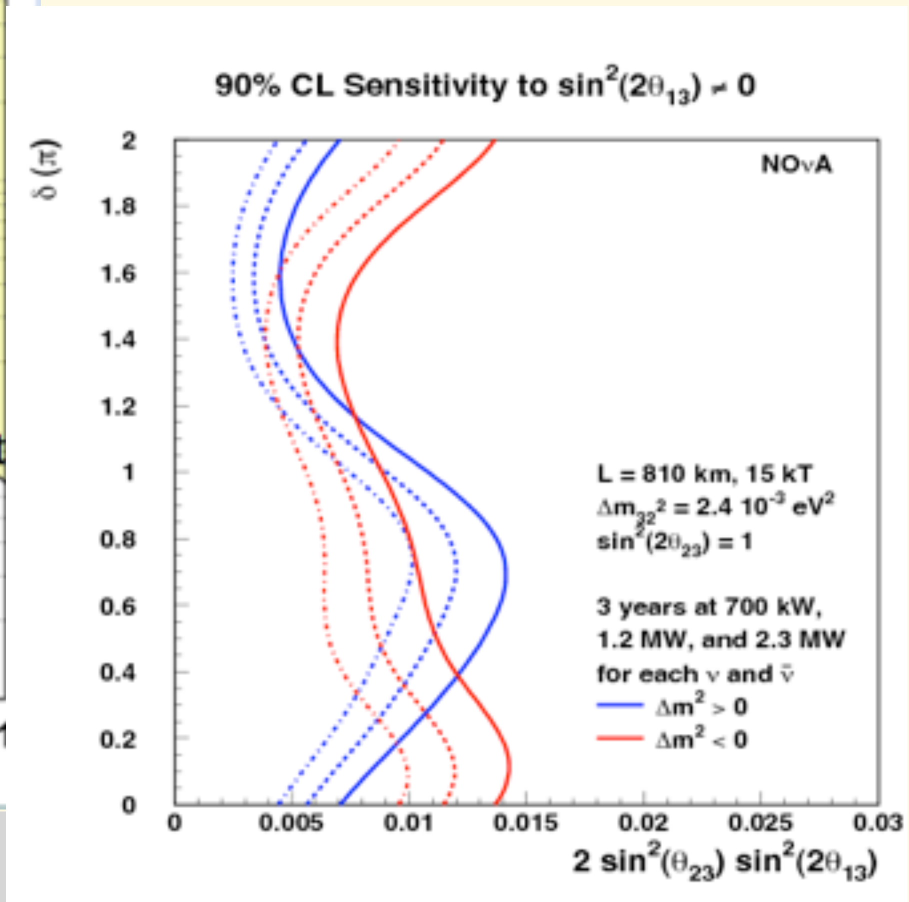
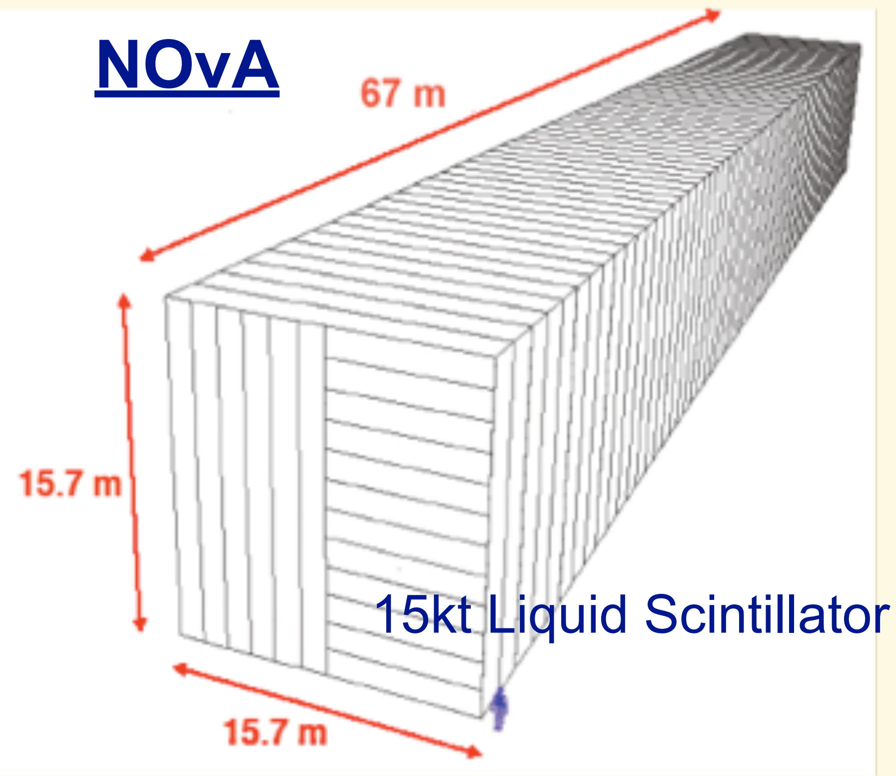
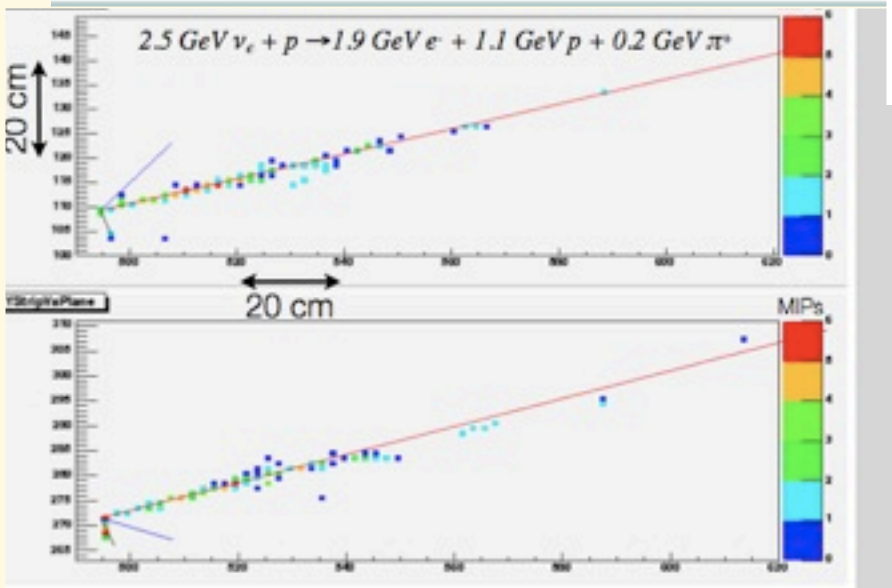


NOvA: Assumes 3 years ν + 3 years anti-ν, 10% systematic, at 700kW







The long distance (810 km) gives it some sensitivity to mass hierarchy

Summary

- Much progress in neutrino oscillations since their discovery in 1998
  - Two mixing angles and the two Δm^2's are now known at a level of few percent
  - The big remaining questions are values of θ_{13} and δ_{CP} and the mass hierarchy
- The experiments on the horizon might provide the answers if θ_{13} is large enough
- The LSND effect and possible $\nu/\overline{\nu}$ differences are issues still to be resolved

Backup Slides

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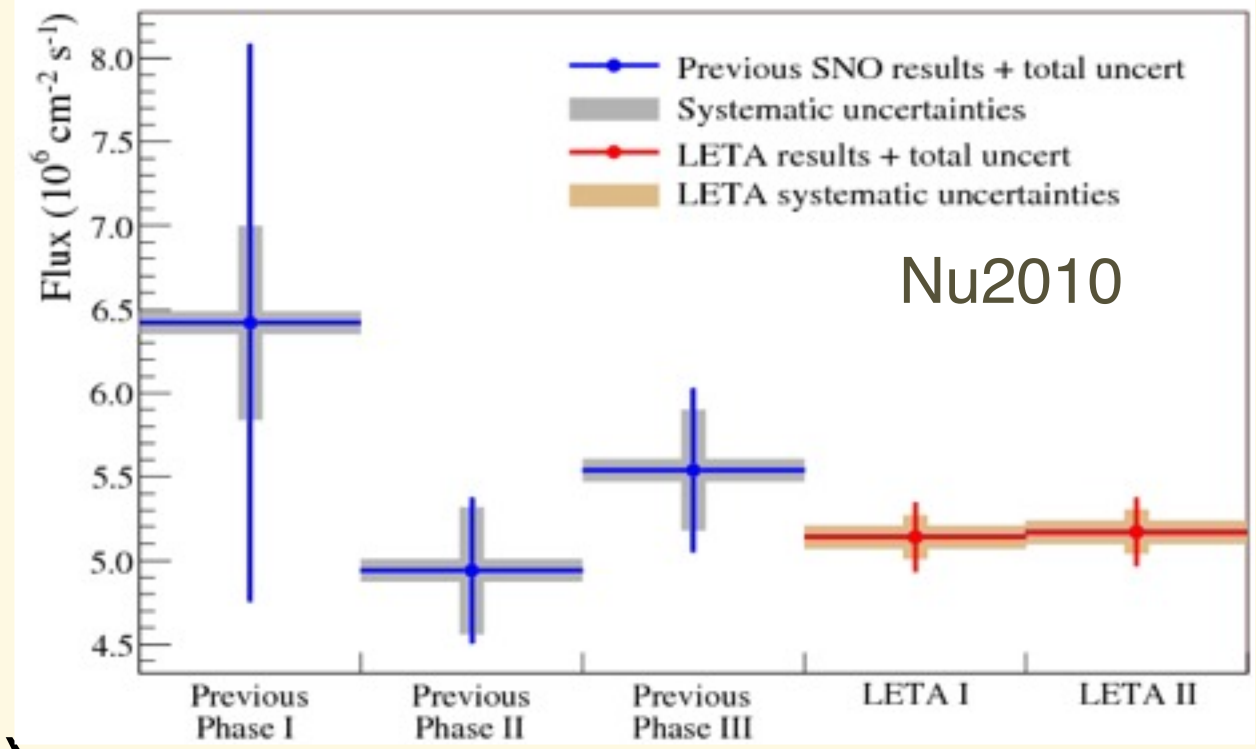

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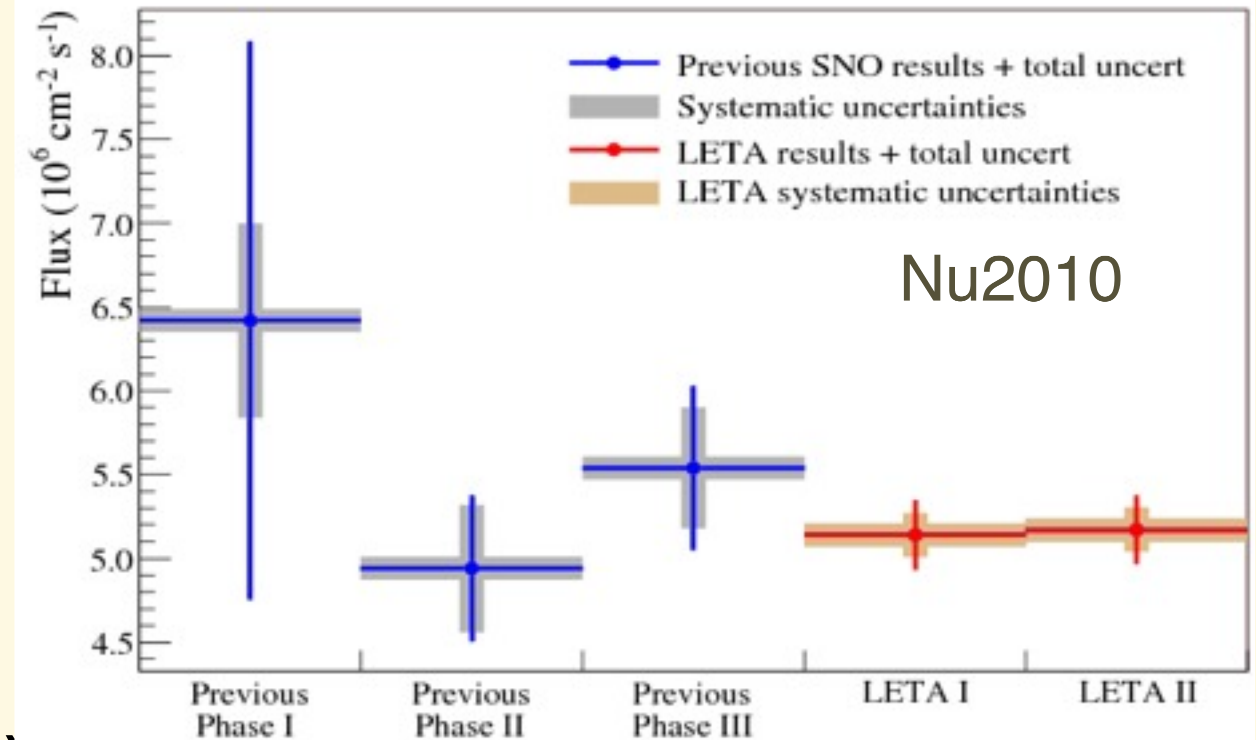

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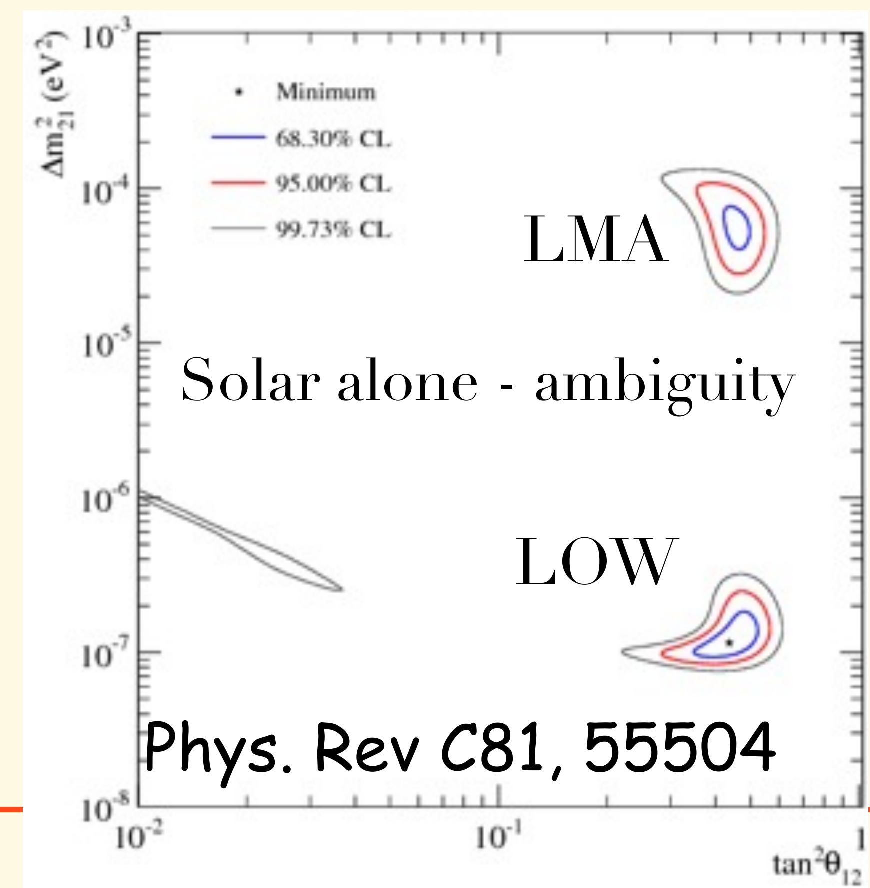

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Magnetic field in its detectors makes MINOS particularly suitable for $\nu_\mu/\bar{\nu}_\mu$ comparison

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In the conventional oscillation picture there should be no depletion of NC events

Summary - Atmospheric sector

Oscillation analysis	$\sin^2 2\theta_{23}$ (90% C.L.)	Δm^2_{31} (eV^2)
SuperK (2v, zenith angle)	>0.96	$2.11^{+0.11}_{-0.19} \times 10^{-3}$
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Neutrino2010

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In their 3 flavor analysis Super K fixes $\sin^2\theta_{12}$ and Δm^2_{21} to 0.304 and 7.66 x 10^{-5} eV^2 respectively

No significant preference on mass hierarchy or CP phase seen in SuperK 3 flavor fit

Neutrino2010

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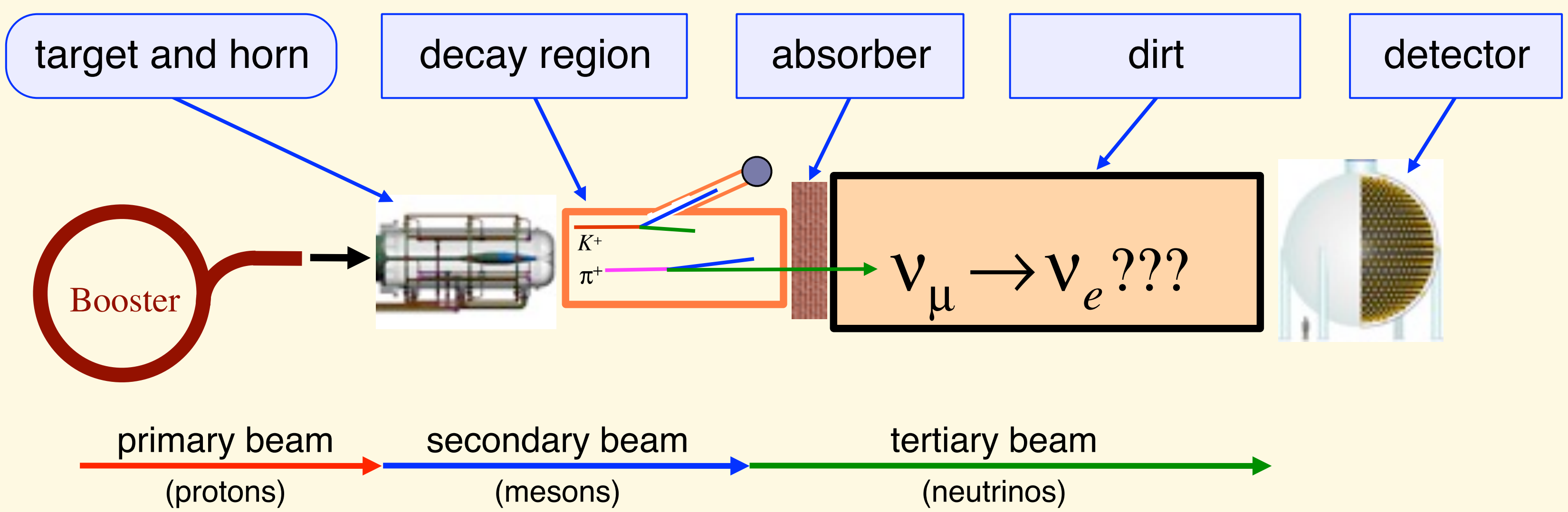

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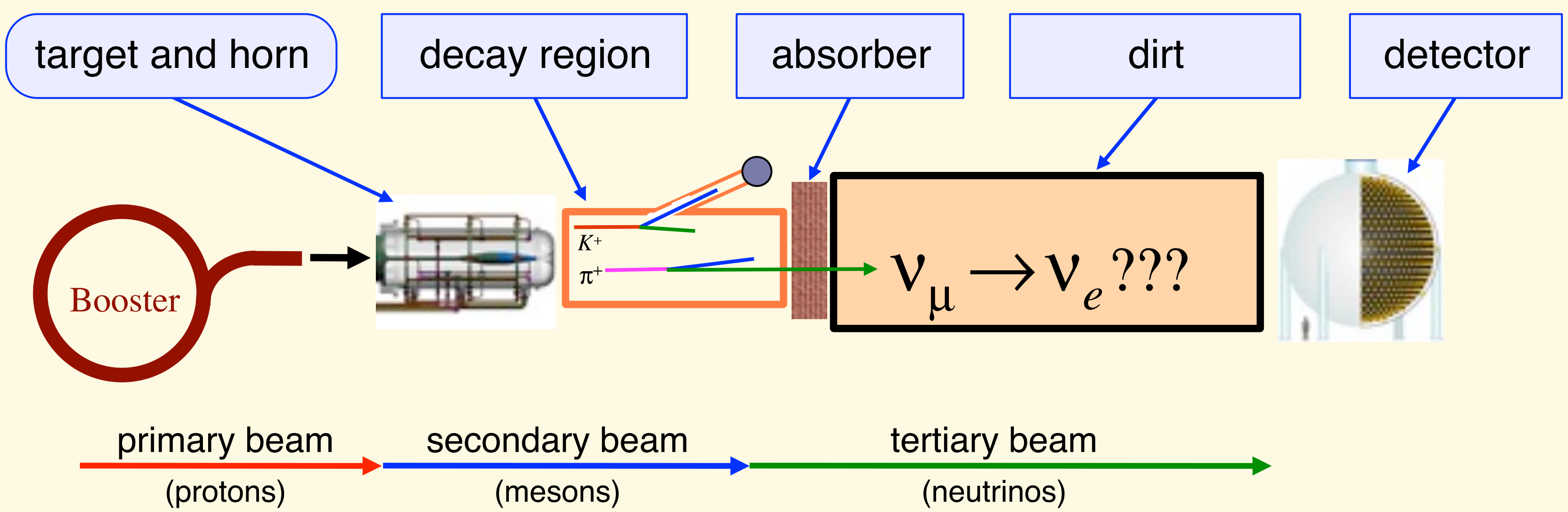

Both neutrino and antineutrino exposures were obtained

Antineutrino run tests the LSND directly

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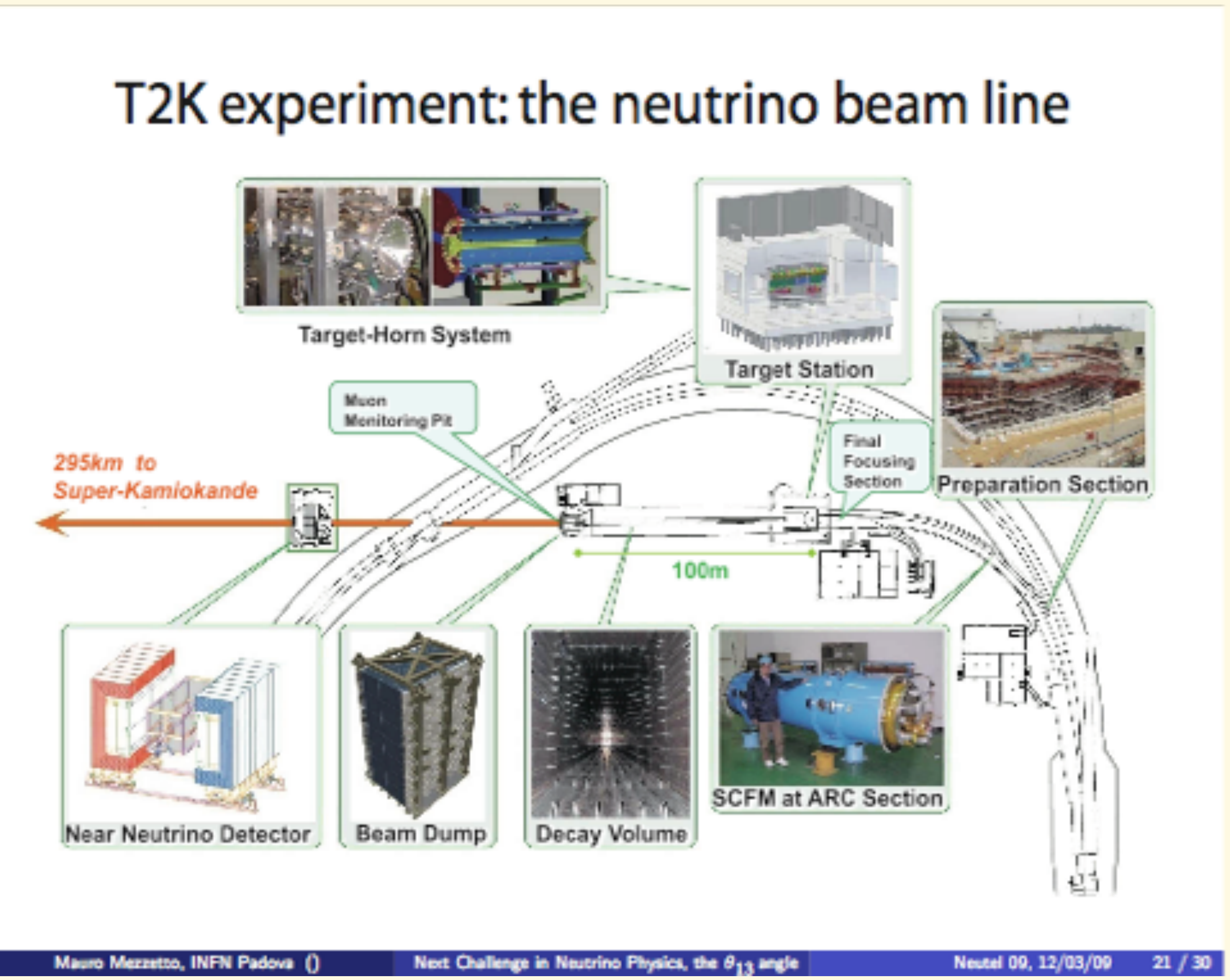

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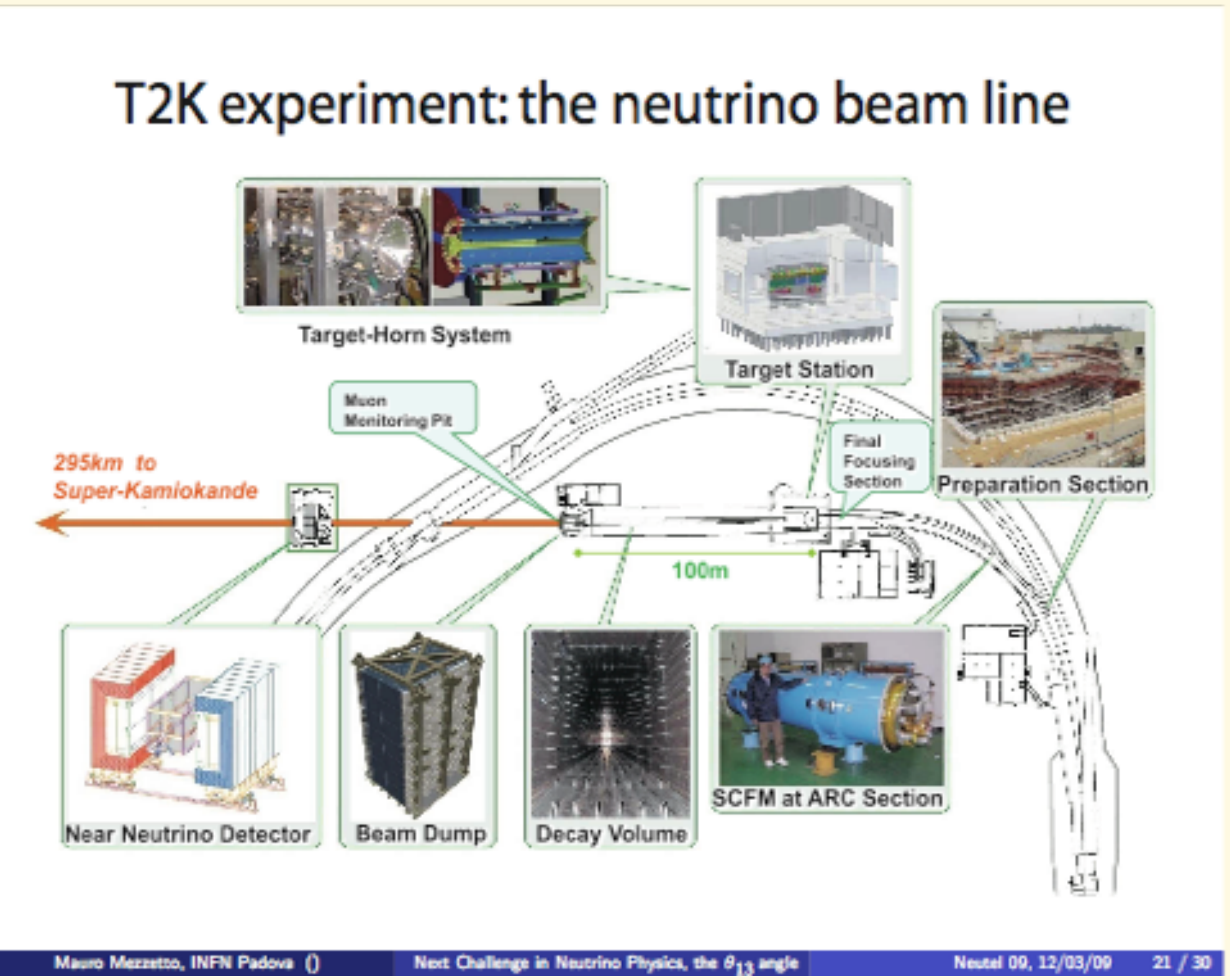

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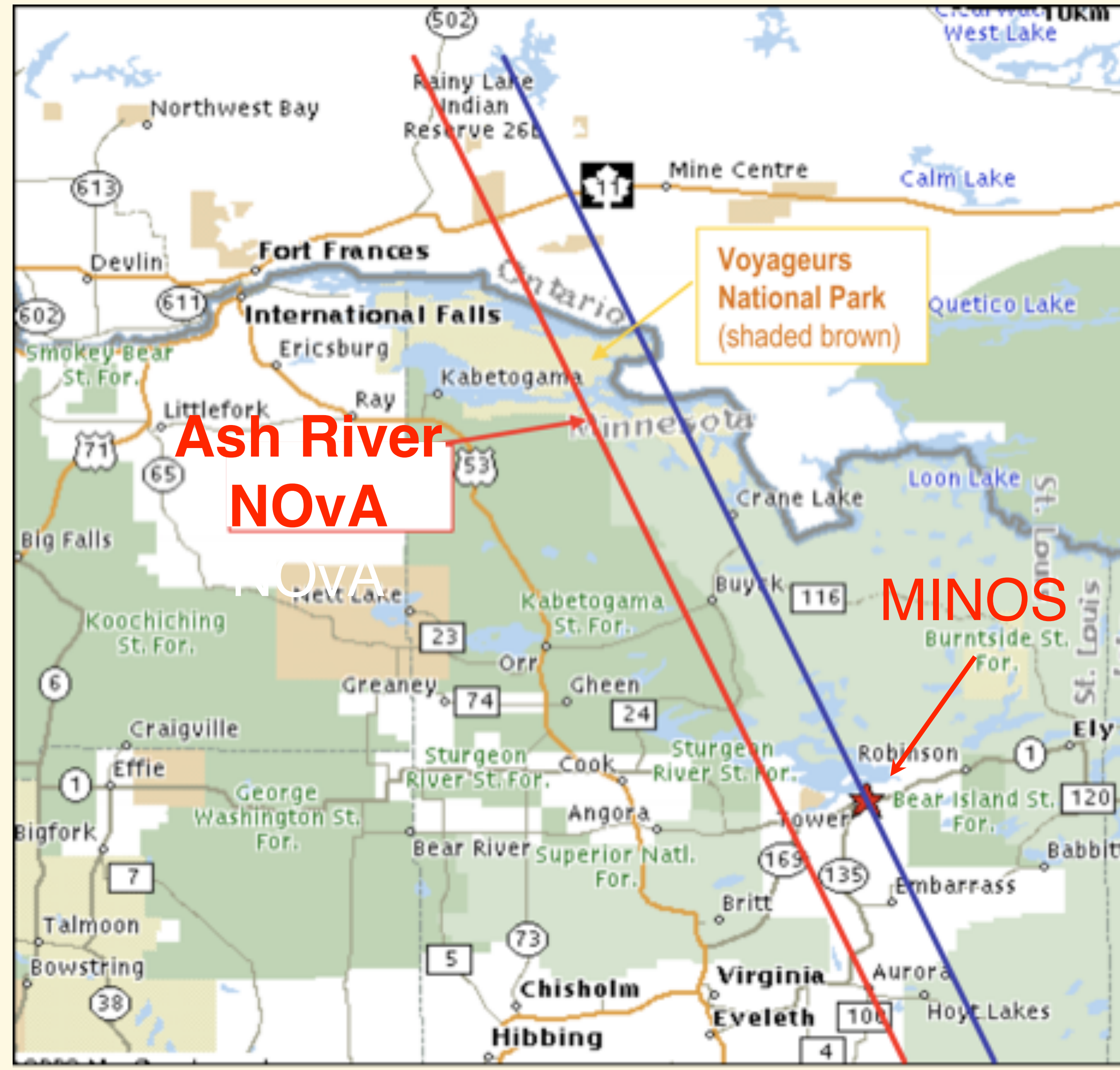

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