Status of three-flavour oscillation parameters from global neutrino data

Mariam Tórtola

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Outline

- Introduction
- The solar neutrino sector: (Δm^2_{21} , θ_{12})
- The atmospheric neutrino sector: (Δm^2_{32} , θ_{23})
- The bound on θ_{13} and indications for $\theta_{13} \neq 0$
- The next generation of neutrino oscillation experiments.
- Summary

If neutrinos are massive …

In general, the flavor eigenstates are an admixture of the mass eigenstates:

$$\nu_{\alpha L} = \sum_{i=1}^{3} U_{\alpha i} \nu_{iL}$$

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$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

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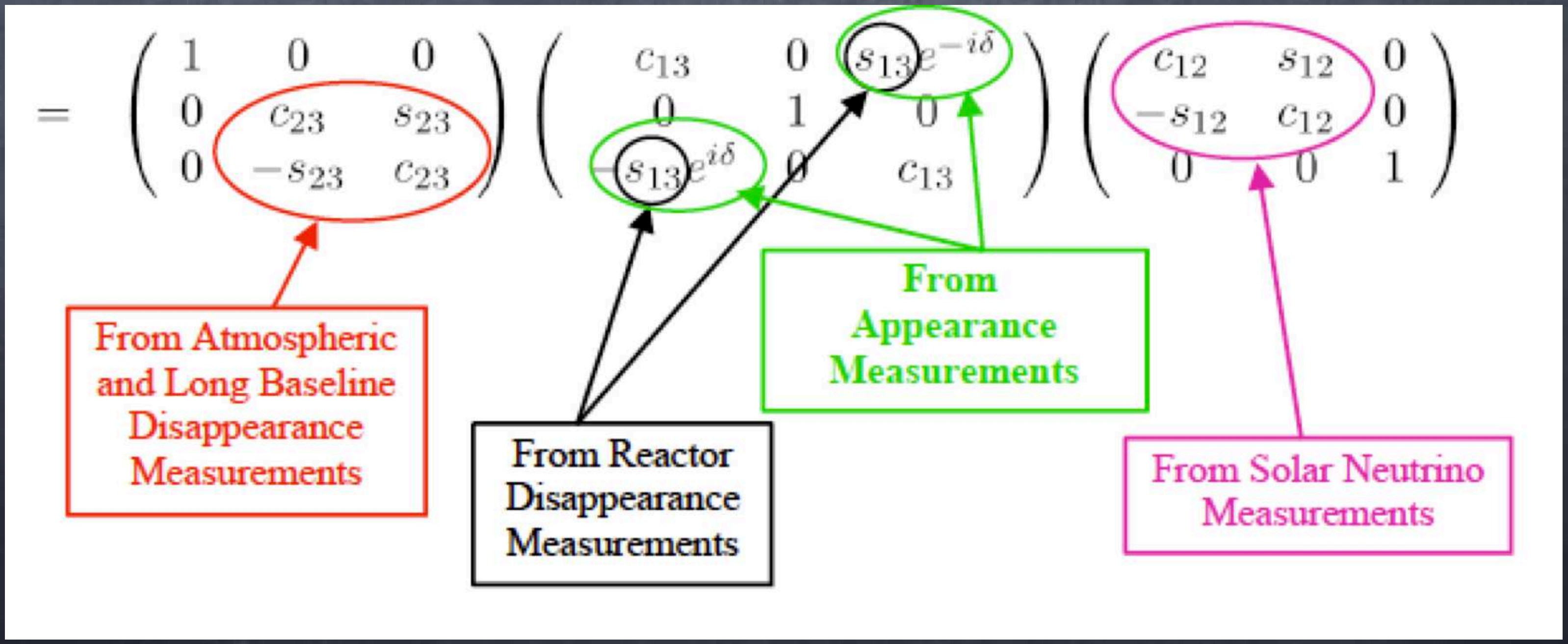
θ_{23}

θ_{13}

θ_{12}

δ



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

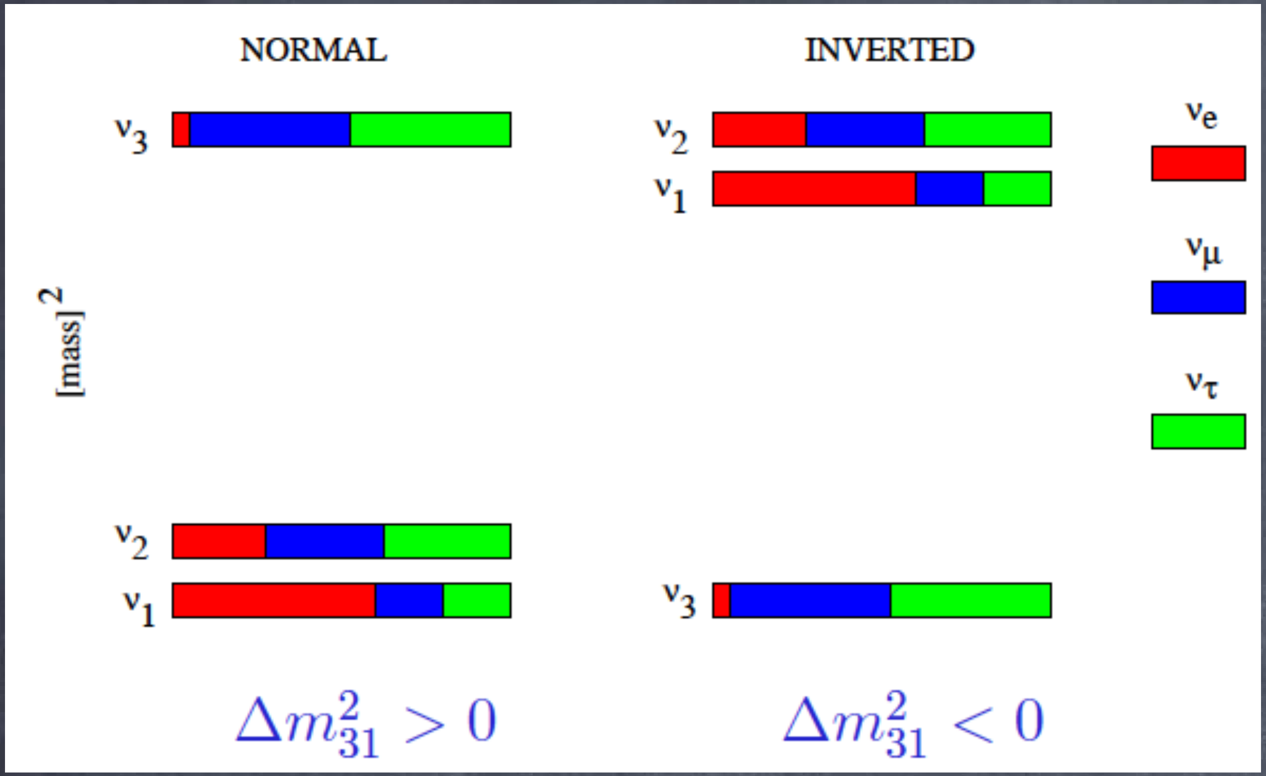
From Atmospheric and Long Baseline Disappearance Measurements

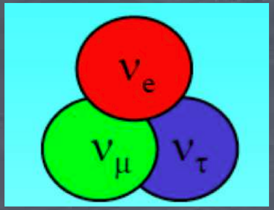
From Reactor Disappearance Measurements

From Appearance Measurements

From Solar Neutrino Measurements

There are two possible mass orderings:





- Neutrino oscillations are sensitive only to Δm^2_{ij}
  - Δm^2_{31} : atmospheric + long-baseline
  - Δm^2_{21} : solar + KamLAND
- absolute scale m_ν ???

Absolute scale of neutrino mass

- Tritium β-decay experiments:

$$m_\beta = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$

→ $m_\beta < 2.05$–2.33 (95%CL) Troitsk, Mainz.

KATRIN sensitivity $m_\beta \sim 0.2$ eV

- Neutrinoless double β-decay:

$$m_{\beta\beta} = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$

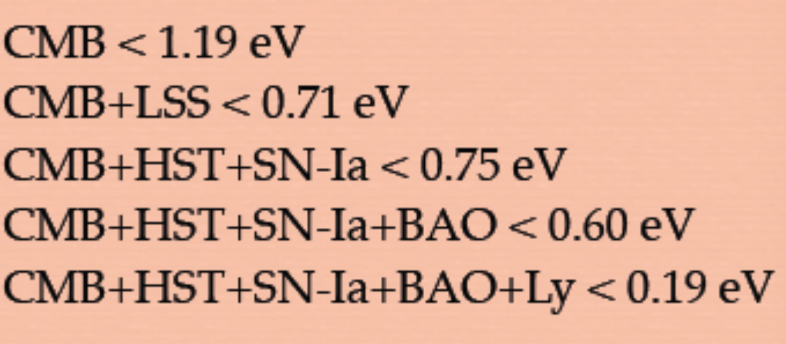
→ claim in ^{76}Ge $m_{\beta\beta} \in [0.16, 0.52]$ eV (2σ)

→ 2σ upper limit from Cuoricino $m_{\beta\beta} < [0.23, 0.85]$ eV

- Cosmology: $\Sigma m_i = m_1 + m_2 + m_3$

95%CL bounds on Σm_i →

Fogli et al.,PRD78 (2008) 033010



CMB < 1.19 eV

CMB+LSS < 0.71 eV

CMB+HST+SN-Ia < 0.75 eV

CMB+HST+SN-Ia+BAO < 0.60 eV

CMB+HST+SN-Ia+BAO+Ly < 0.19 eV

Determination of oscillation parameters from global ν data

two-neutrino approximation:

$\boxed{\Delta m^2_{21} \ll \Delta m^2_{31}}$

$\theta_{12}, \Delta m^2_{21}$

solar + KamLAND

$\theta_{13}, \Delta m^2_{31}$

CHOOZ

$\theta_{23}, \Delta m^2_{31}$

atmospheric + LBL

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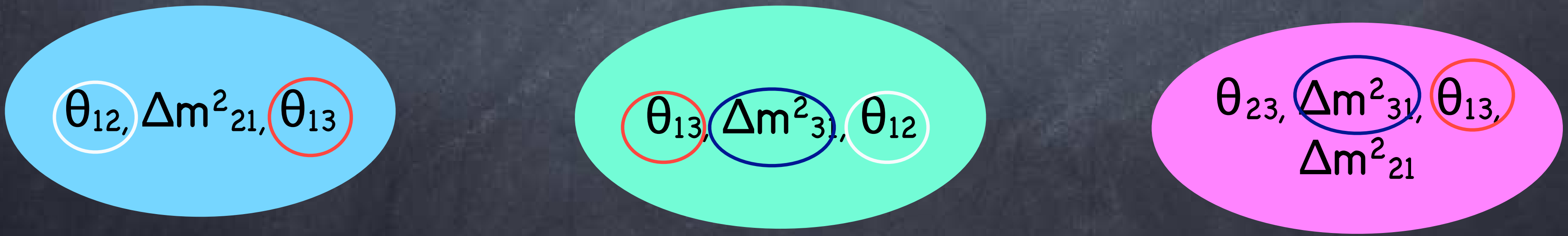

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$\theta_{13}, \Delta m^2_{31}, \theta_{12}$

$\theta_{23}, \Delta m^2_{31}, \theta_{13}, \Delta m^2_{21}$

all data samples are connected → a global 3ν analysis is required.

The solar neutrino sector: $(\Delta m^2_{21}, \sin^2\theta_{12})$

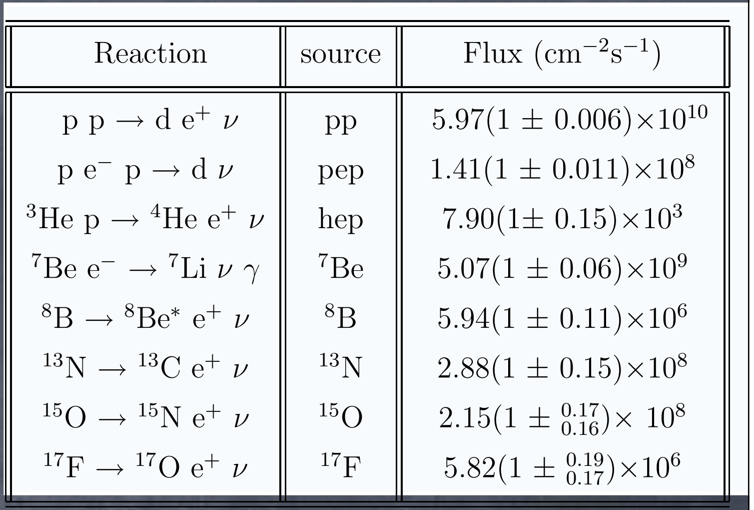
Solar neutrinos

- produced in nuclear reactions in the core of the Sun:

$4p \to {}^4He + 2e^+ + 2\nu_e + \gamma$

pp cycle

CNO

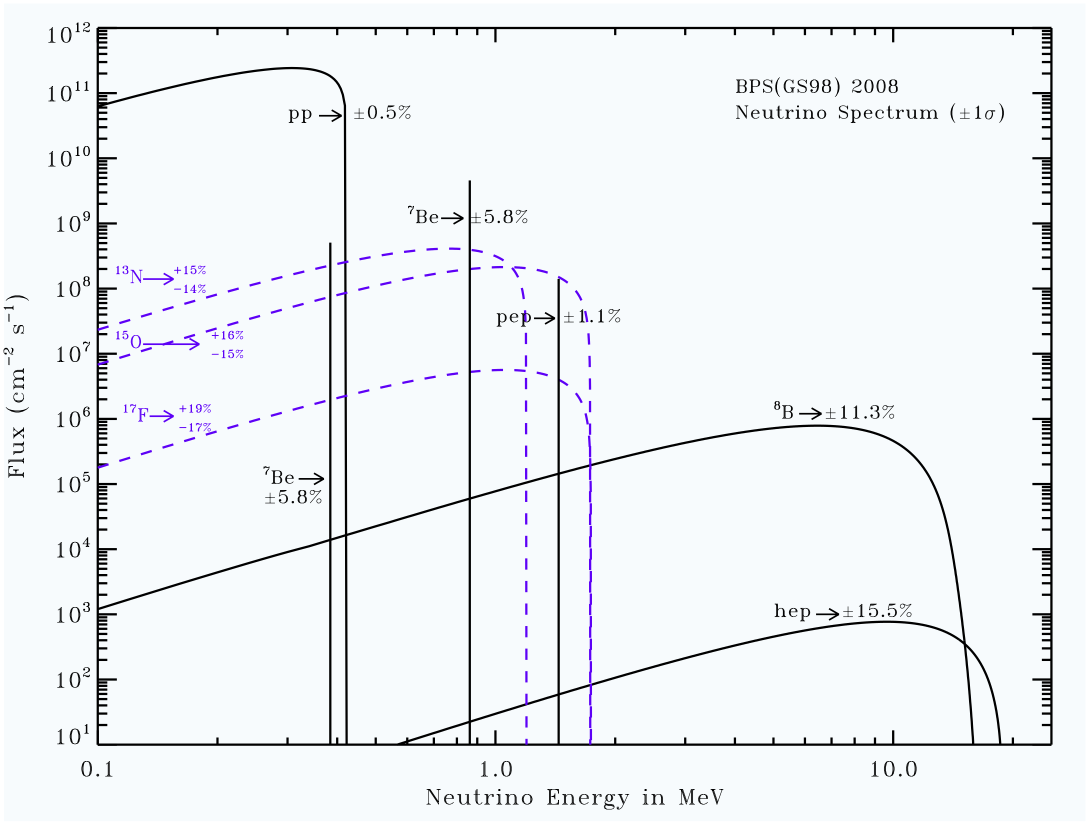


Reaction	source	Flux ($cm^{-2}s^{-1}$)
$p\,p \to d\,e^+\,\nu$	pp	$5.97(1 \pm 0.006)\times 10^{10}$
$p\,e^-\,p \to d\,\nu$	pep	$1.41(1 \pm 0.011)\times 10^{8}$
$^3He\,p \to {}^4He\,e^+\,\nu$	hep	$7.90(1\pm 0.15)\times 10^{3}$
$^7Be\,e^- \to {}^7Li\,\nu\,\gamma$	^7Be	$5.07(1 \pm 0.06)\times 10^{9}$
$^8B \to {}^8Be^*\,e^+\,\nu$	^8B	$5.94(1 \pm 0.11)\times 10^{6}$
$^{13}N \to {}^{13}C\,e^+\,\nu$	^{13}N	$2.88(1 \pm 0.15)\times 10^{8}$
$^{15}O \to {}^{15}N\,e^+\,\nu$	^{15}O	$2.15(1 \pm {}^{0.17}_{0.16})\times 10^{8}$
$^{17}F \to {}^{17}O\,e^+\,\nu$	^{17}F	$5.82(1 \pm {}^{0.19}_{0.17})\times 10^{6}$

ν fluxes

SSM predictions

ν energy spectra



Peña-Garay & Serenelli,arXiv:0811.2424

First solar ν detectors: the radiochemical experiments

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- Chlorine experiment:
  - gold mine in Homestake (South Dakota)
  - 615 tons of perchloro-ethylene (C_2Cl_4)
  - detection process: $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$
  - only 1/3 of SSM prediction detected:

$$R_{Cl}^{SSM} = 8.12 \pm 1.25 \text{ SNU}$$

$$R_{Cl} = 2.56 \pm 0.16 \text{ (stat.)} \pm 0.16 \text{ (syst.) SNU}$$

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- **Gallium** experiments (GALLEX/GNO, SAGE):

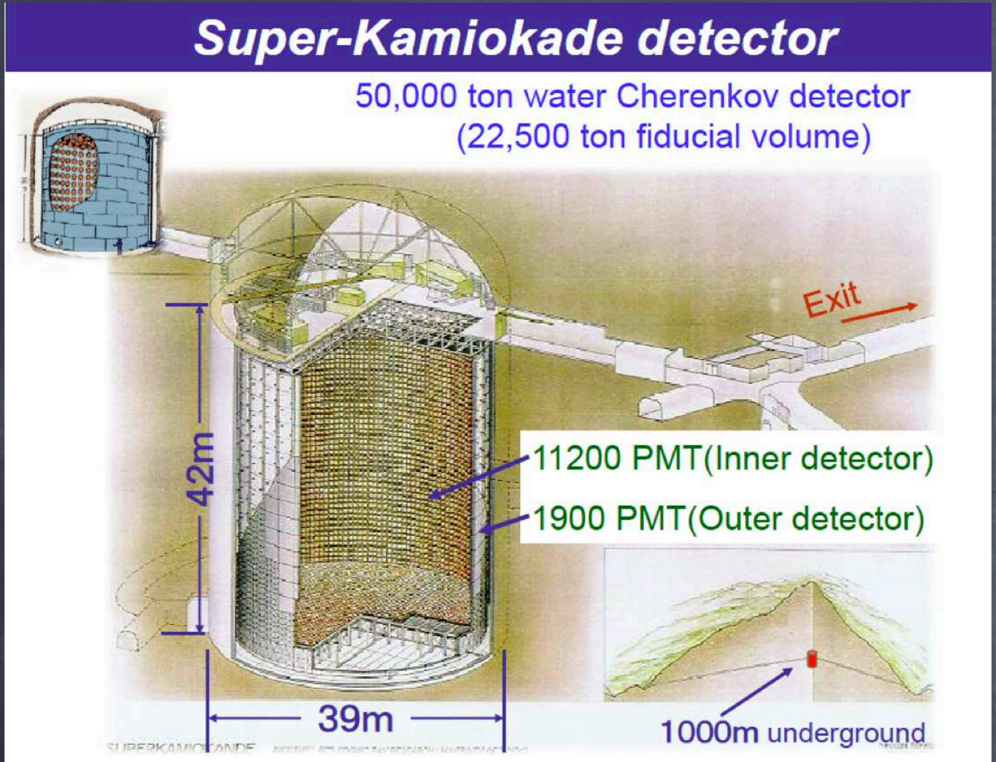
$$R_{GALLEX/GNO} = 69.3 \pm 4.1 \text{ (stat.)} \pm 3.6 \text{ (syst.) SNU}$$

$$R_{SAGE} = 66.9 \pm 3.9 \text{ (stat.)} \pm 3.6 \text{ (syst.) SNU}$$

$$R_{Ga}^{SSM} = 126.2 \pm 8.5 \text{ SNU}$$

→ 50% deficit

Solar neutrinos in Super-Kamiokande



- water cherenkov detector
- sensitive to all neutrino flavors:
  $$\nu_x\, e^- \rightarrow \nu_x\, e^-$$
- threshold energy ~ 4-5 MeV
- real-time detector: (E, t)

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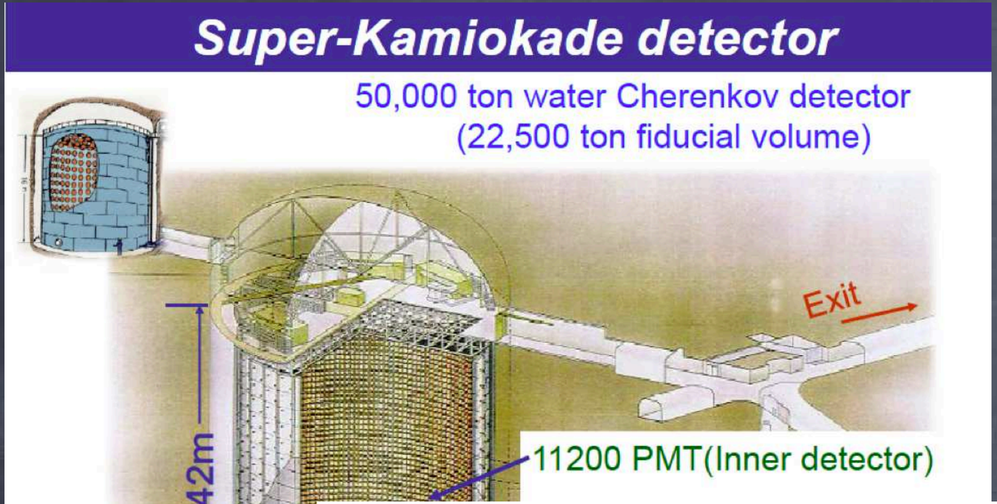

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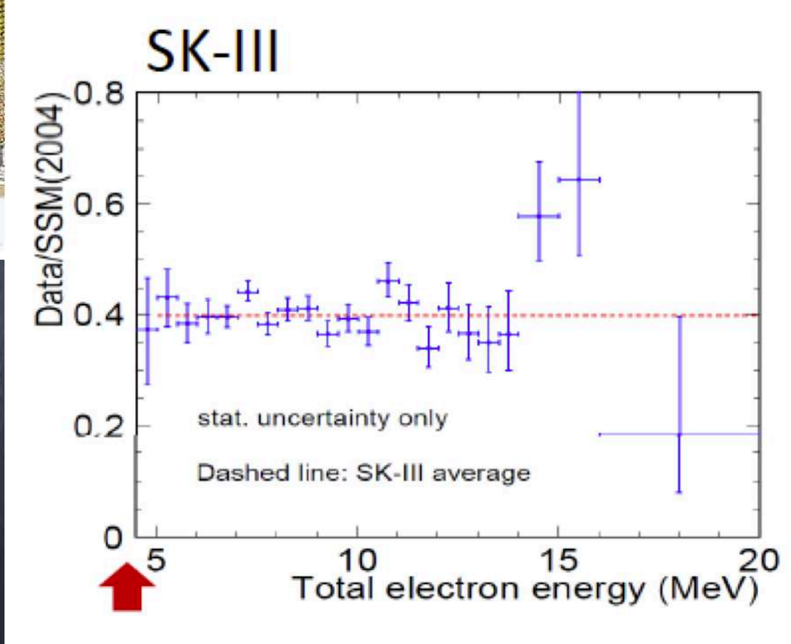

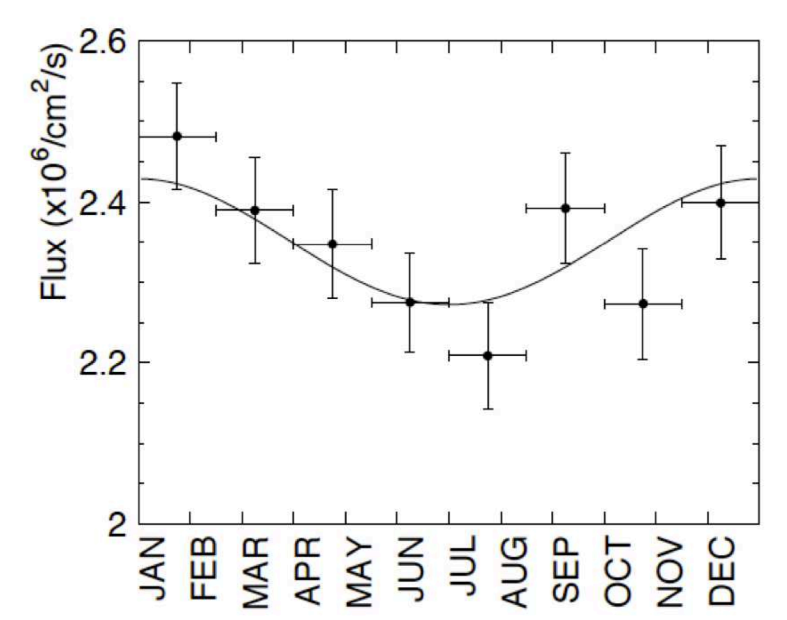

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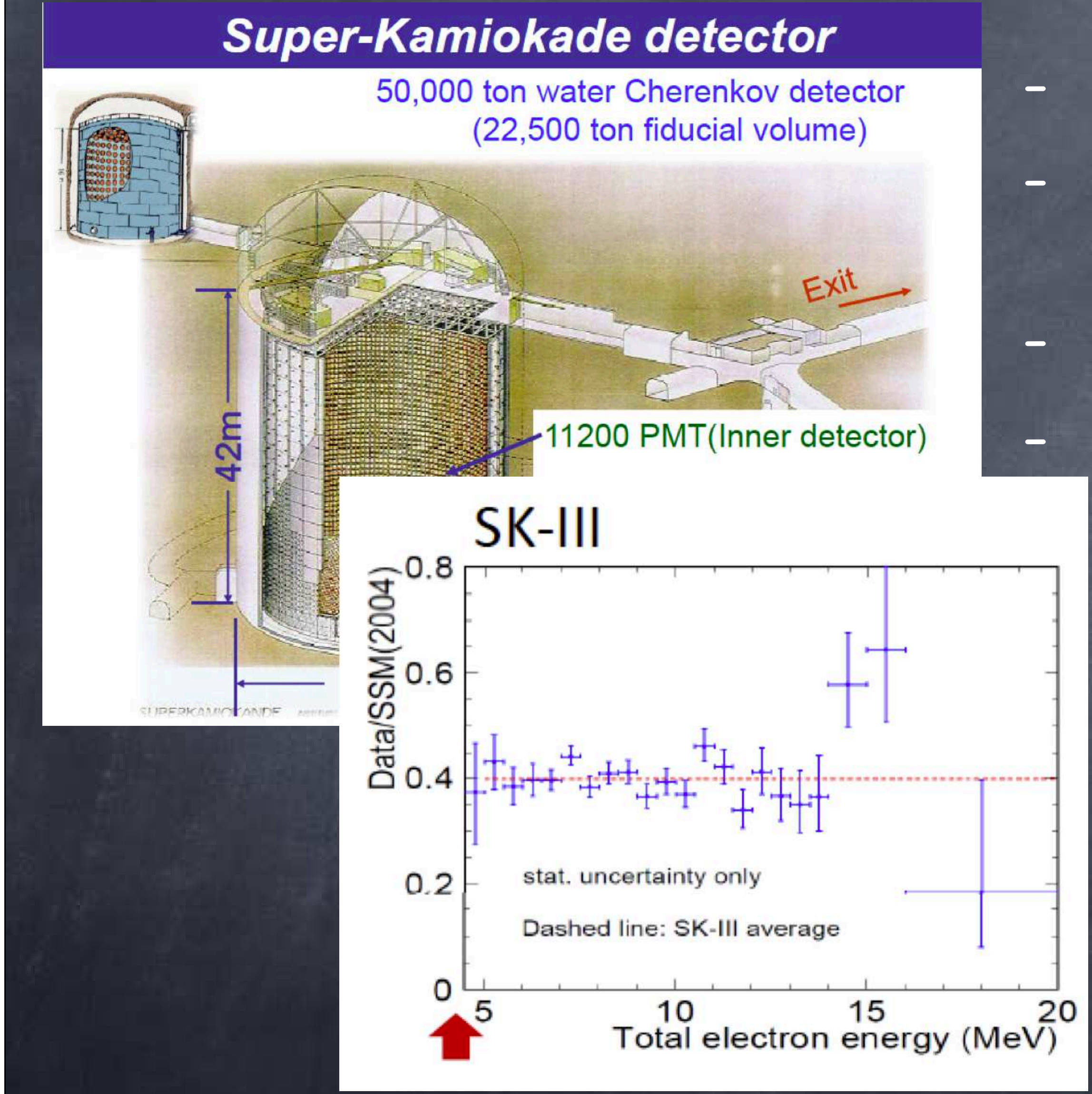

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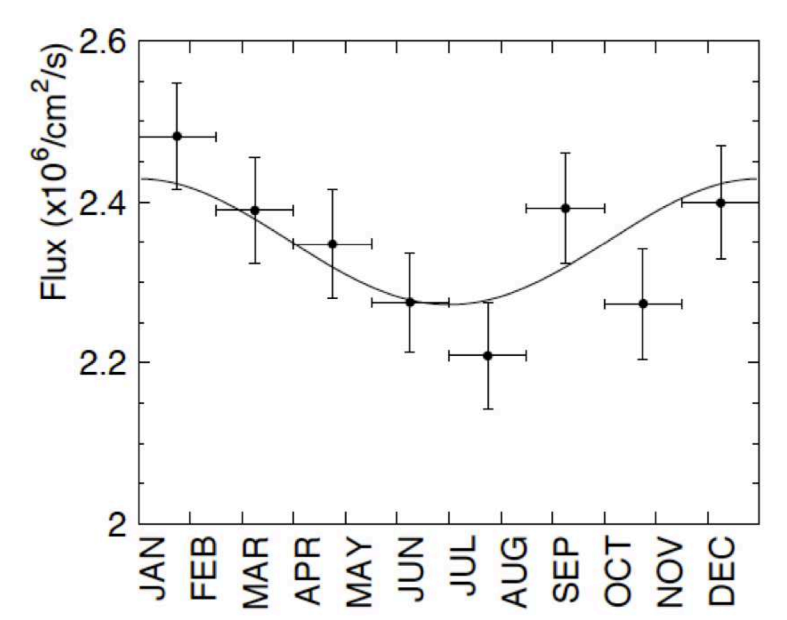
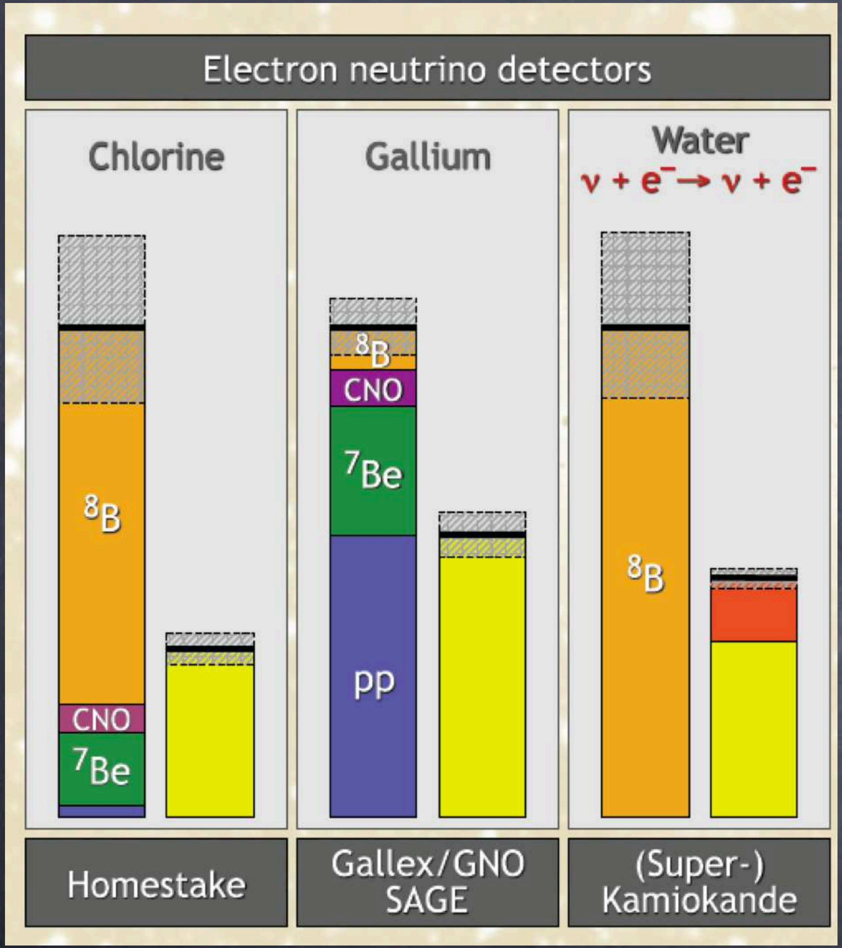


➡ Super-Kamiokande detects less neutrinos than expected according to the SSM (40%)

The solar neutrino problem



~30% ~50% ~40%

➡ All the experiments detect less neutrinos than expected (30-50%)

What is happening?

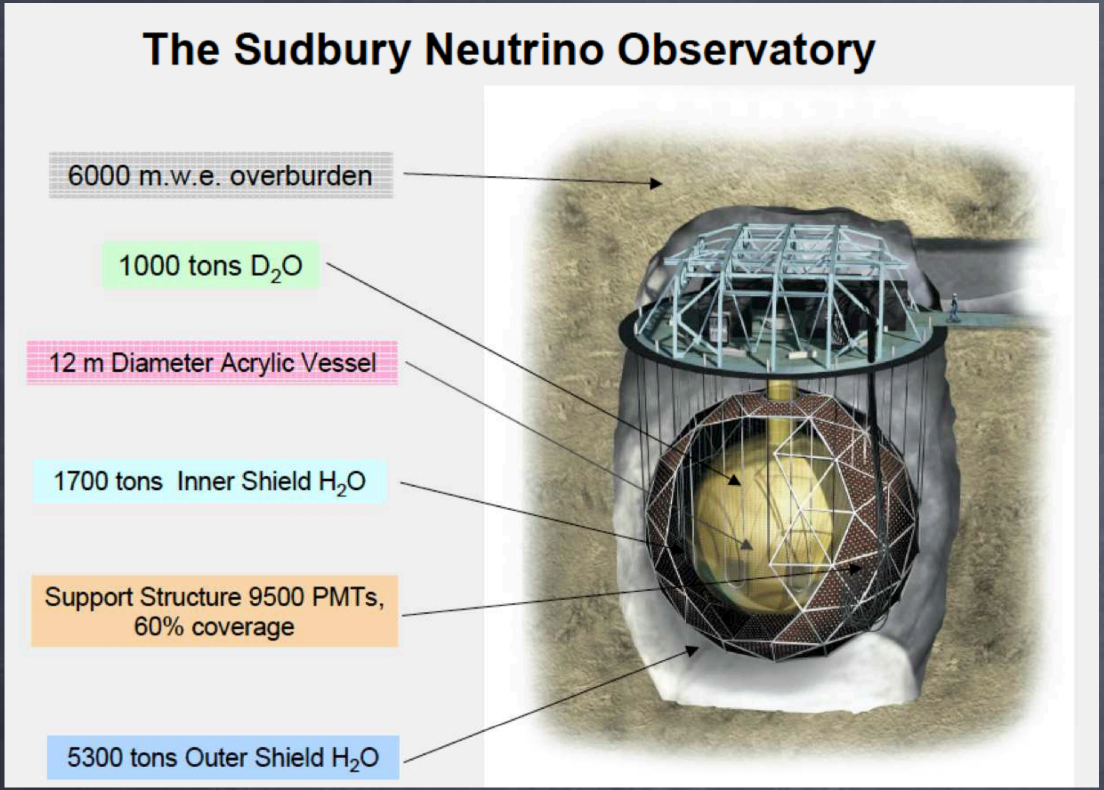
- experimental errors ?
  -> different kinds of experiments.

- errors in the Standard Solar Model?

- something is happening with neutrinos in their way from the Sun to the Earth?

- new particle physics needed ??

The Sudbury Neutrino Observatory, SNO



The Sudbury Neutrino Observatory

6000 m.w.e. overburden

1000 tons D_2O

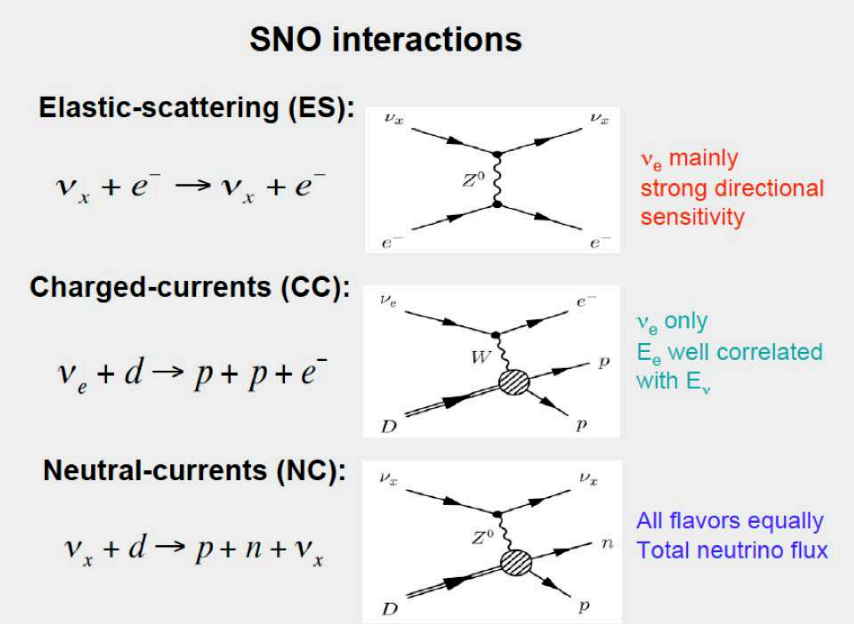
12 m Diameter Acrylic Vessel

1700 tons Inner Shield H_2O

Support Structure 9500 PMTs, 60% coverage

5300 tons Outer Shield H_2O

SNO is sensitive to all ν flavors:



SNO interactions

Elastic-scattering (ES):

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

ν_e mainly
strong directional sensitivity

Charged-currents (CC):

$$\nu_e + d \rightarrow p + p + e^-$$

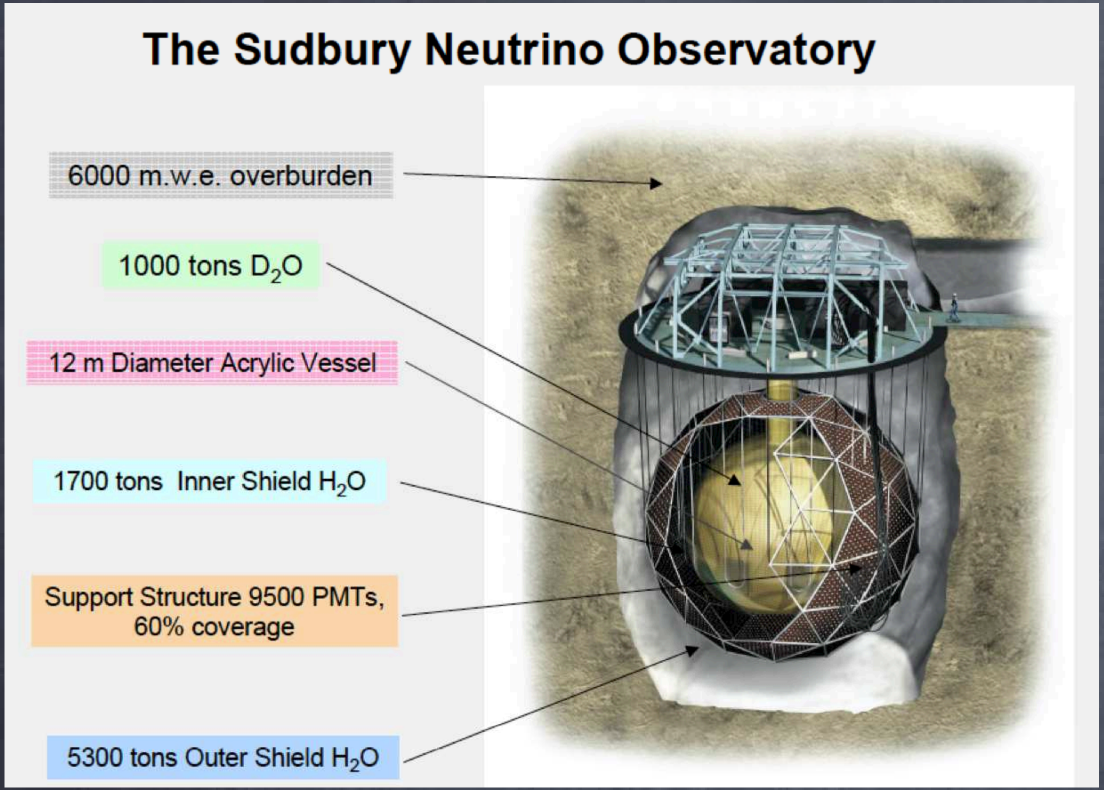
ν_e only
E_e well correlated with E_ν

Neutral-currents (NC):

$$\nu_x + d \rightarrow p + n + \nu_x$$

All flavors equally
Total neutrino flux

The Sudbury Neutrino Observatory, SNO



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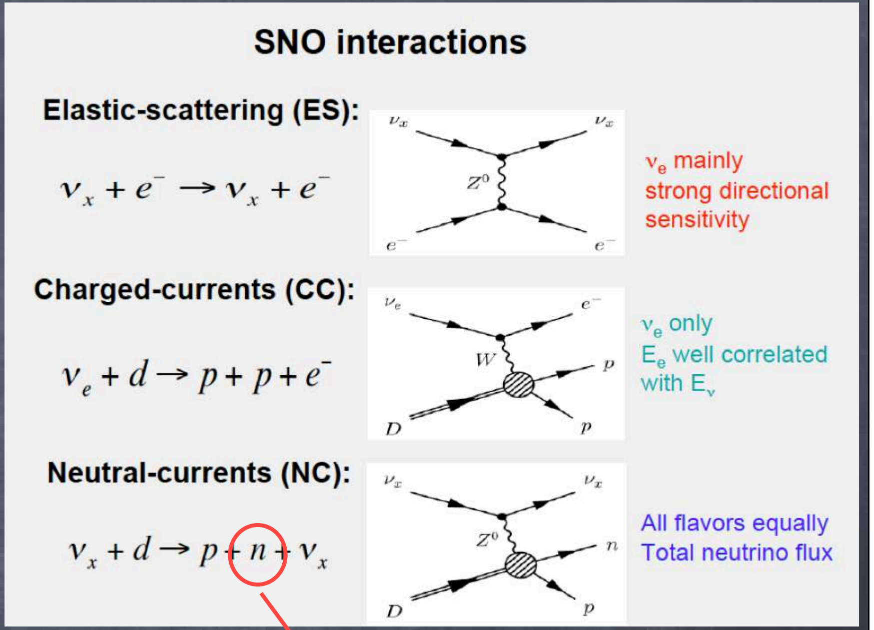

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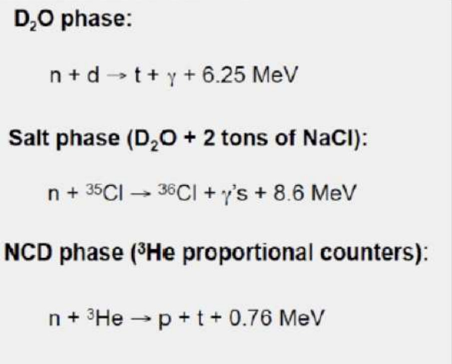
3 phases:



D_2O phase:

$n + d \rightarrow t + \gamma + 6.25$ MeV

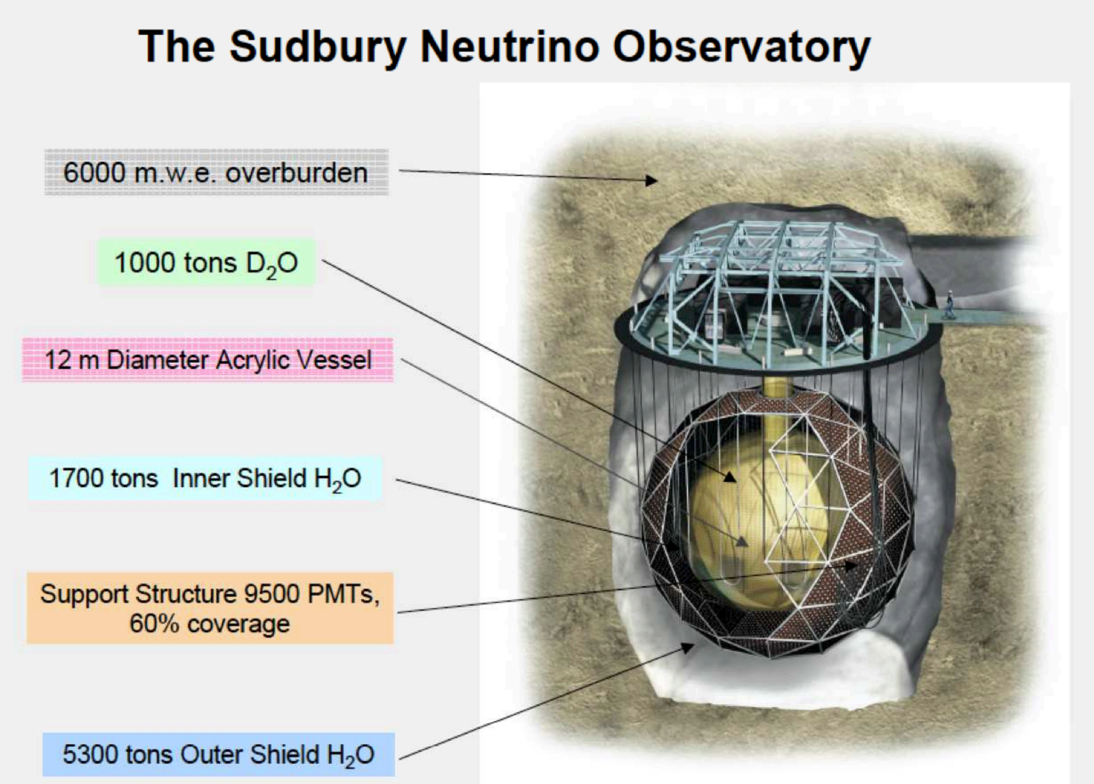
Salt phase (D_2O + 2 tons of NaCl):

$n + {}^{35}Cl \rightarrow {}^{36}Cl + \gamma$'s $+ 8.6$ MeV

NCD phase (${}^3He$ proportional counters):

$n + {}^{3}He \rightarrow p + t + 0.76$ MeV

The Sudbury Neutrino Observatory, SNO



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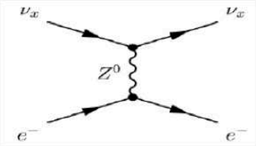

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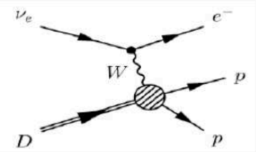

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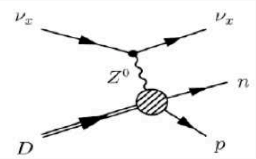

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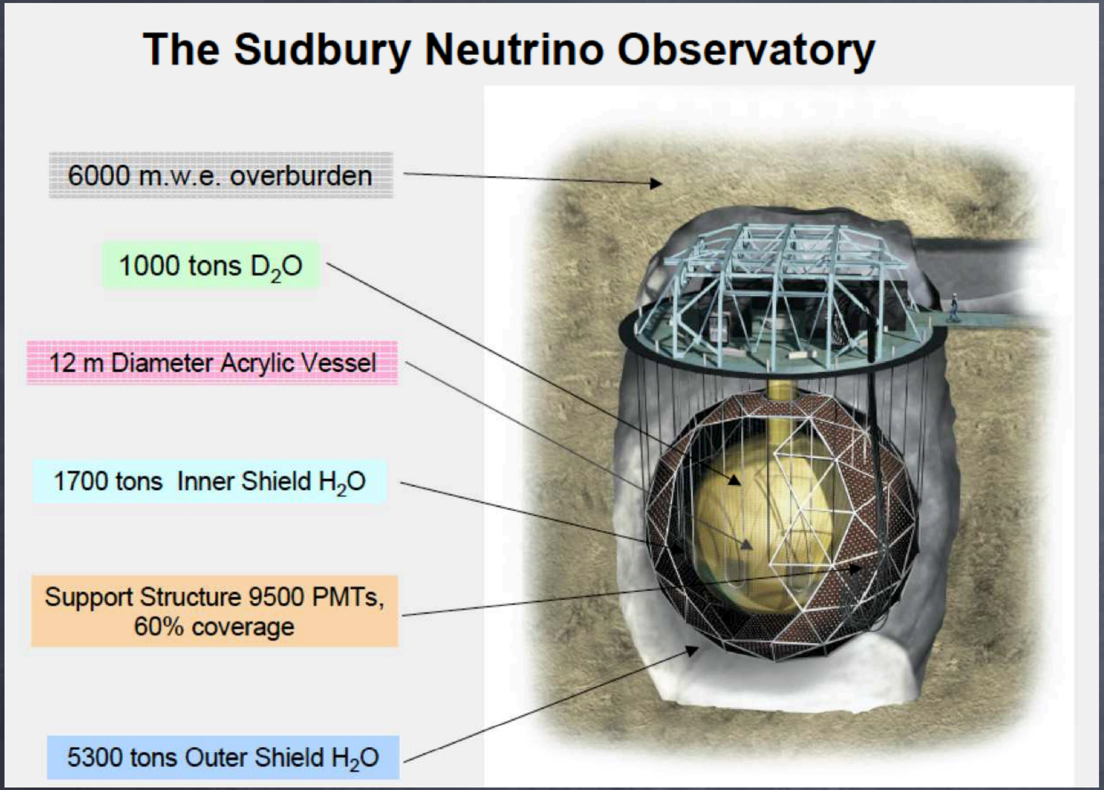
ν_e flux (CC): $$\frac{\phi^{SNO}_{CC}}{\phi^{SNO}_{NC}} = 0.301 \pm 0.033$$

30%

The Sudbury Neutrino Observatory, SNO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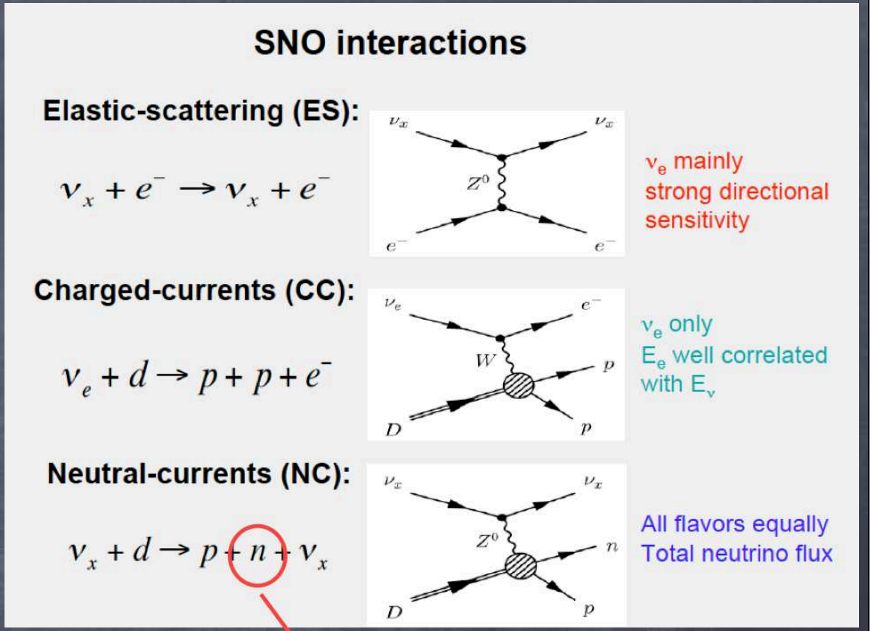
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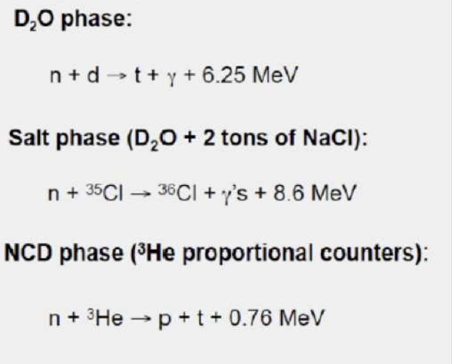
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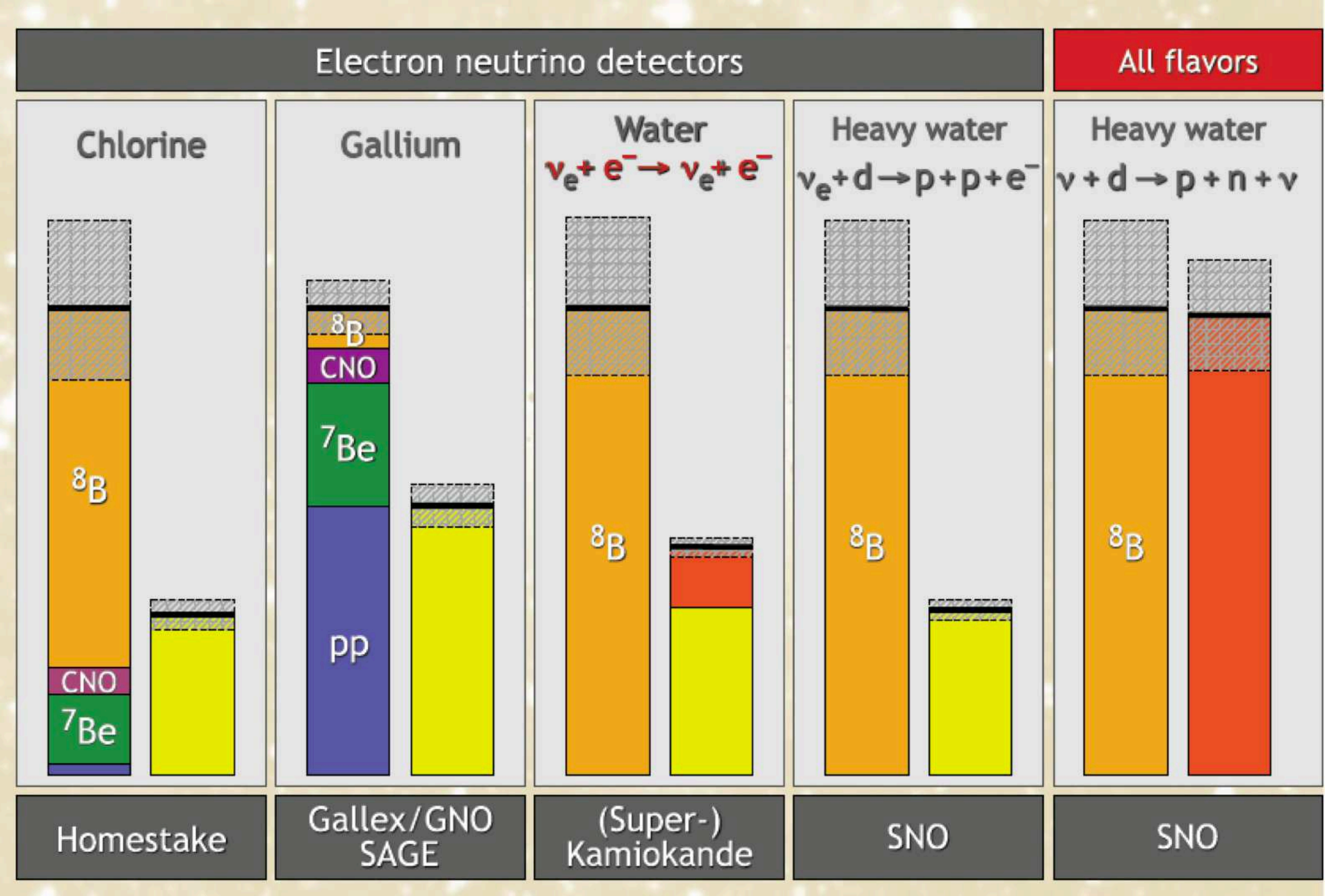
ν_e flux (CC): $$\frac{\phi_{CC}^{SNO}}{\phi_{NC}^{SNO}} = 0.301 \pm 0.033$$

30%

total ν flux (NC): $$\phi_{NC}^{SNO} = 5.54^{+0.33}_{-0.31}(\mathrm{stat})^{+0.36}_{-0.34}(\mathrm{syst})$$

100% !!

The solar neutrino problem

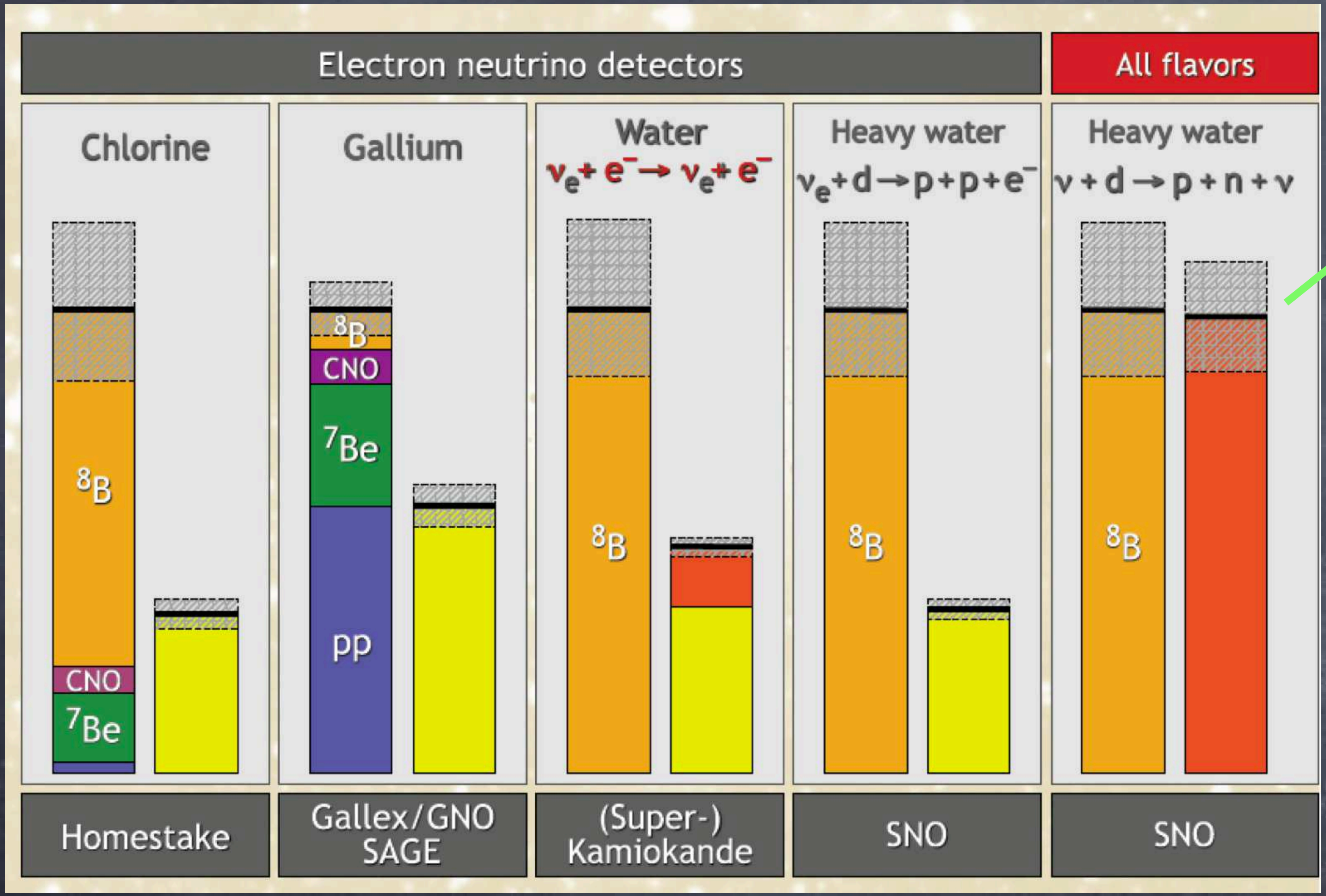


The Sun produces ν_e that arrive to the Earth as 1/3 ν_e + 1/3 ν_μ + 1/3 ν_τ

➡ flavor conversion: $\nu_e \rightarrow \nu_x$

Conversion mechanism ?
Neutrino oscillations ??

The solar neutrino ~~problem~~



All neutrinos
are there!!

The Sun produces ν_e that arrive to the Earth as $1/3\ \nu_e + 1/3\ \nu_\mu + 1/3\ \nu_\tau$

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Conversion mechanism ?
Neutrino oscillations ??

Solar ν oscillation parameters

Homestake ($E_\nu > 0.814$ MeV)

$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$

SAGE/GALLEX-GNO ($E_\nu > 0.233$ MeV)

$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$

Super-Kamiokade ($E_e \gtrsim 5$ MeV)

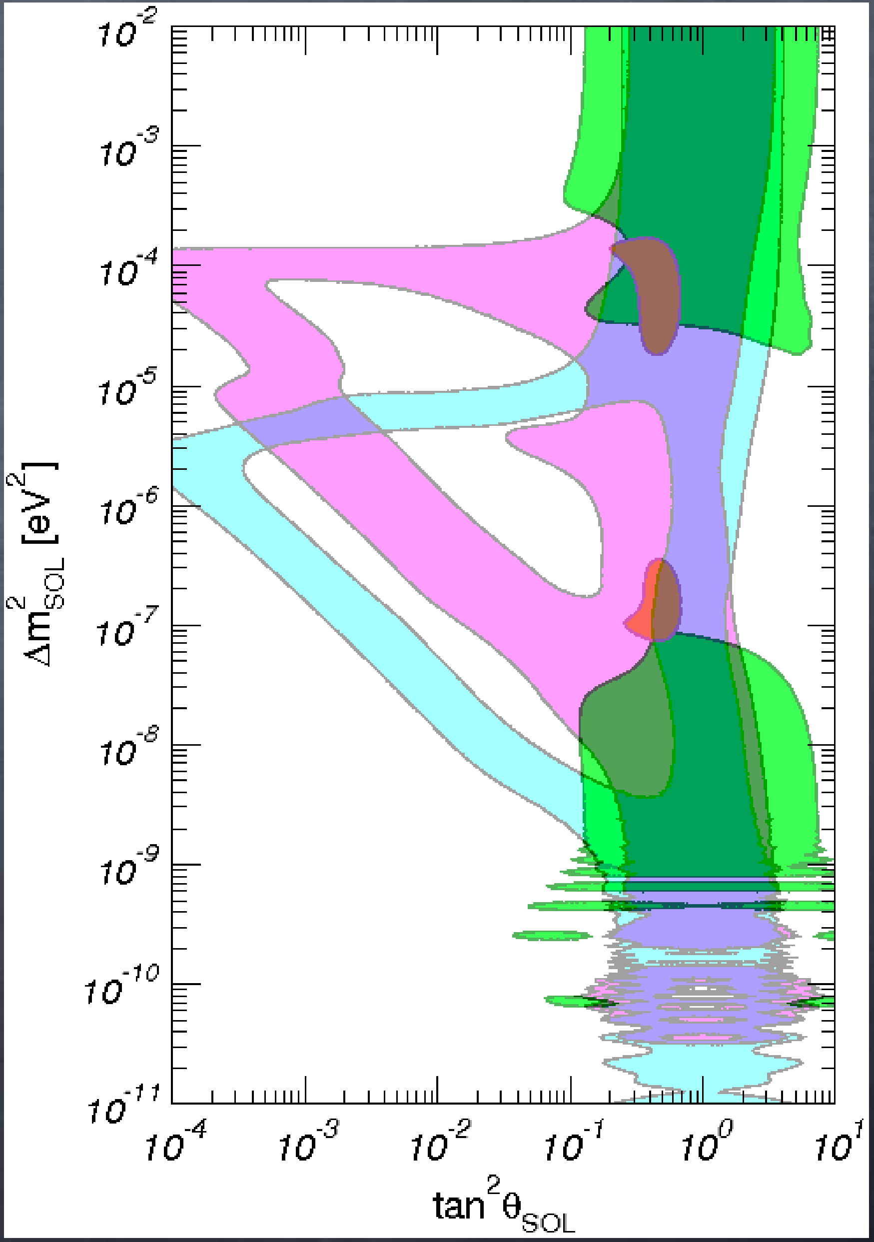
$\nu_x + e^- \rightarrow \nu_x + e^-$

SNO ($E_e \gtrsim 5$ MeV)

[CC] $\nu_e + d \rightarrow p + p + e^-$

[NC] $\nu_x + d \rightarrow \nu_x + n + p$

[ES] $\nu_x + e^- \rightarrow \nu_x + e^-$



Solar ν oscillation parameters

Homestake $(E_\nu > 0.814\ \text{MeV})$

$$\nu_e + {}^{37}\text{Cl} \rightarrow {}^{37}\text{Ar} + e^-$$

SAGE/GALLEX-GNO $(E_\nu > 0.233\ \text{MeV})$

$$\nu_e + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + e^-$$

Super-Kamiokade $(E_e \gtrsim 5\ \text{MeV})$

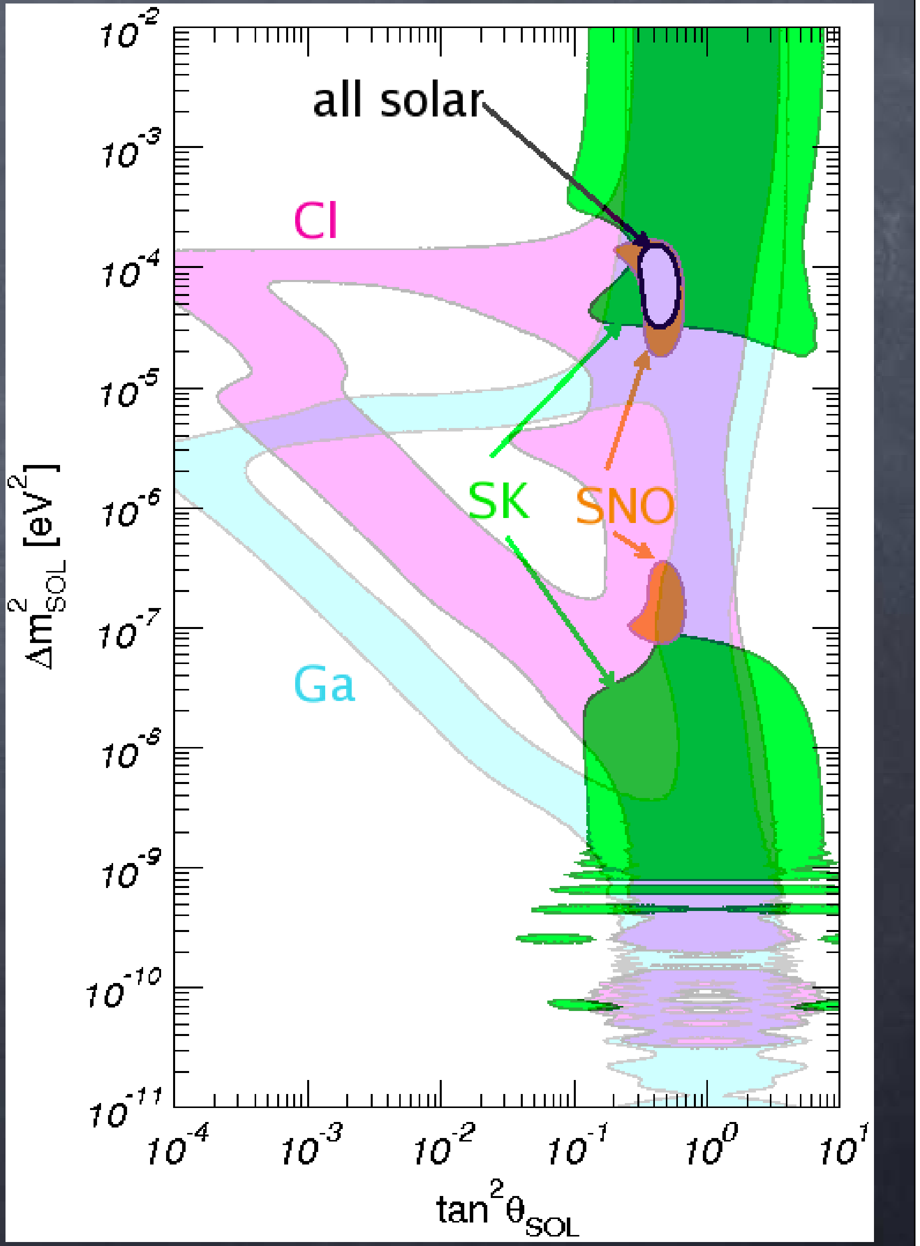
$$\nu_x + e^- \rightarrow \nu_x + e^-$$

SNO $(E_e \gtrsim 5\ \text{MeV})$

[CC] $\nu_e + d \rightarrow p + p + e^-$

[NC] $\nu_x + d \rightarrow \nu_x + n + p$

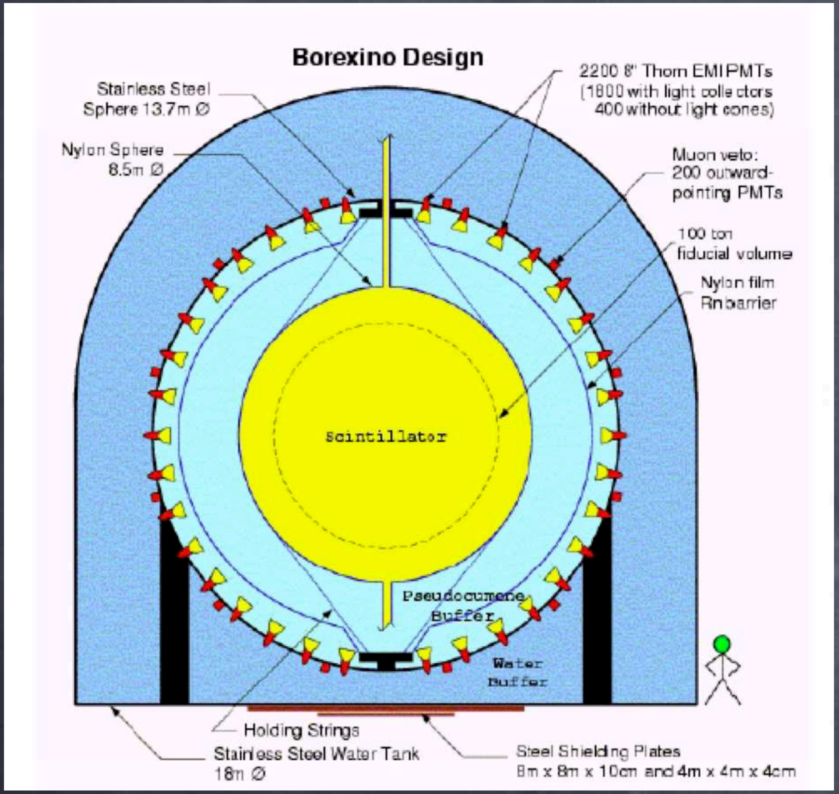
[ES] $\nu_x + e^- \rightarrow \nu_x + e^-$

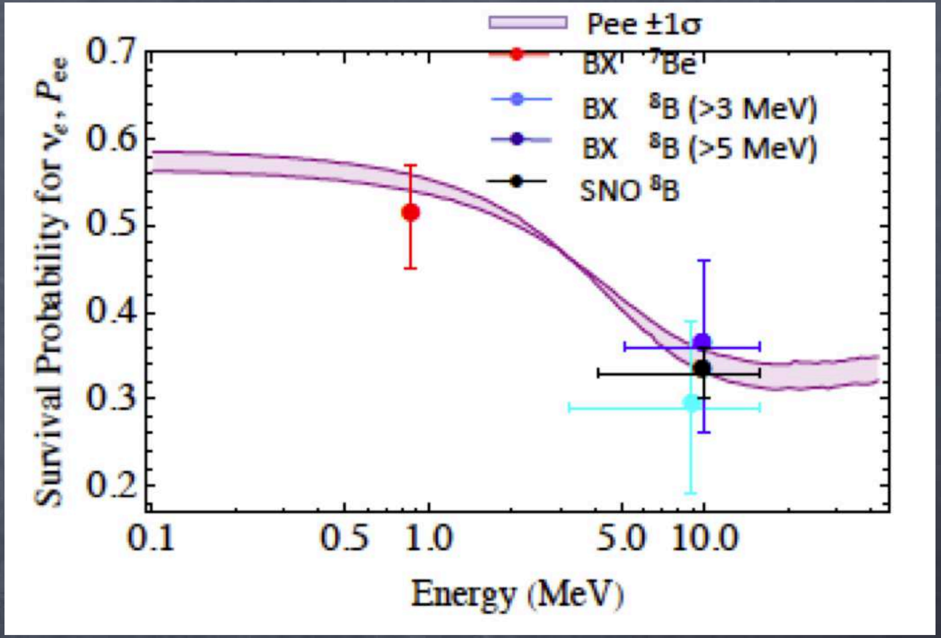


→ only LMA allowed at 3σ

→ max. mixing excluded at 5σ

Borexino: detection of low energy solar neutrinos



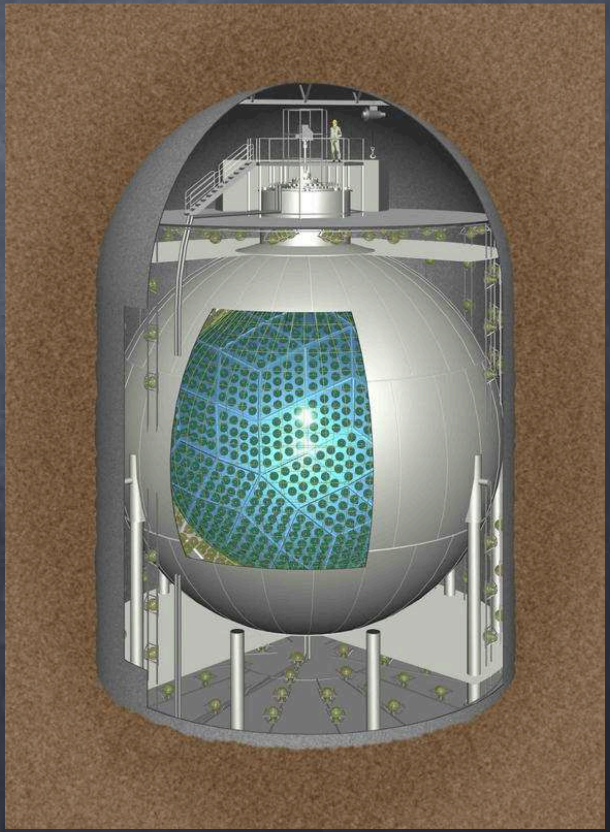


- 300 ton. liquid scintillator
- first real-time measurement of 7Be neutrinos (< 5% error)
- first real-time measurement of 8B flux below 4 MeV

→ consistent with LMA parameters

The KamLAND reactor experiment

- reactor experiment: $\bar{\nu}_e + p \rightarrow e^+ + n$
- CPT invariance: $(\Delta m^2_{21}\,,\ \theta_{12})$



- average distance ~ 180 km

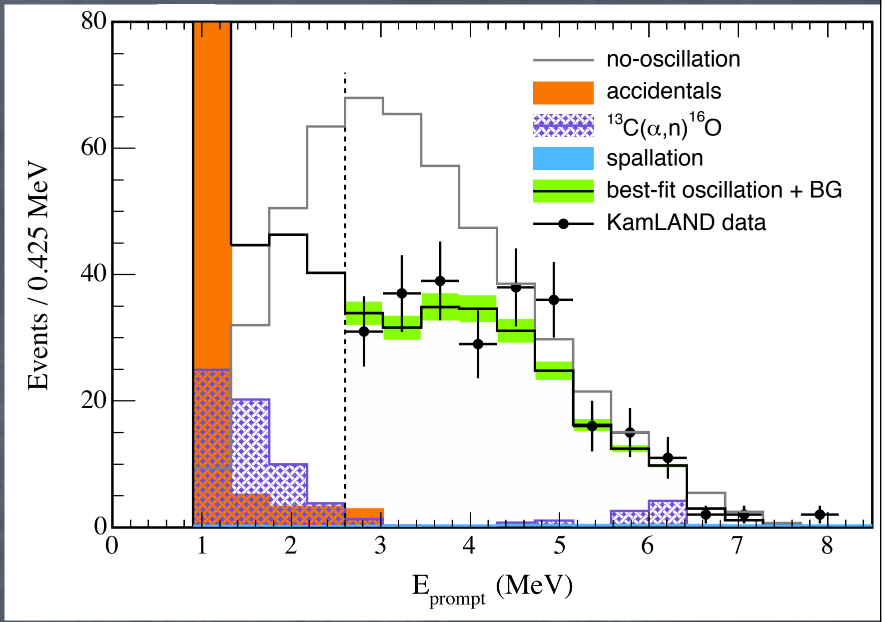
→ sensitive to Δm^2_{21}~few 10^{-5} eV^2 (Δm^2_{LMA})

Results from KamLAND

2002: First evidence $\bar{\nu}_e$ disappearance

→ confirmation of solar LMA ν oscillations

KamLAND Coll, PRL 90 (2003) 021802



Results from KamLAND

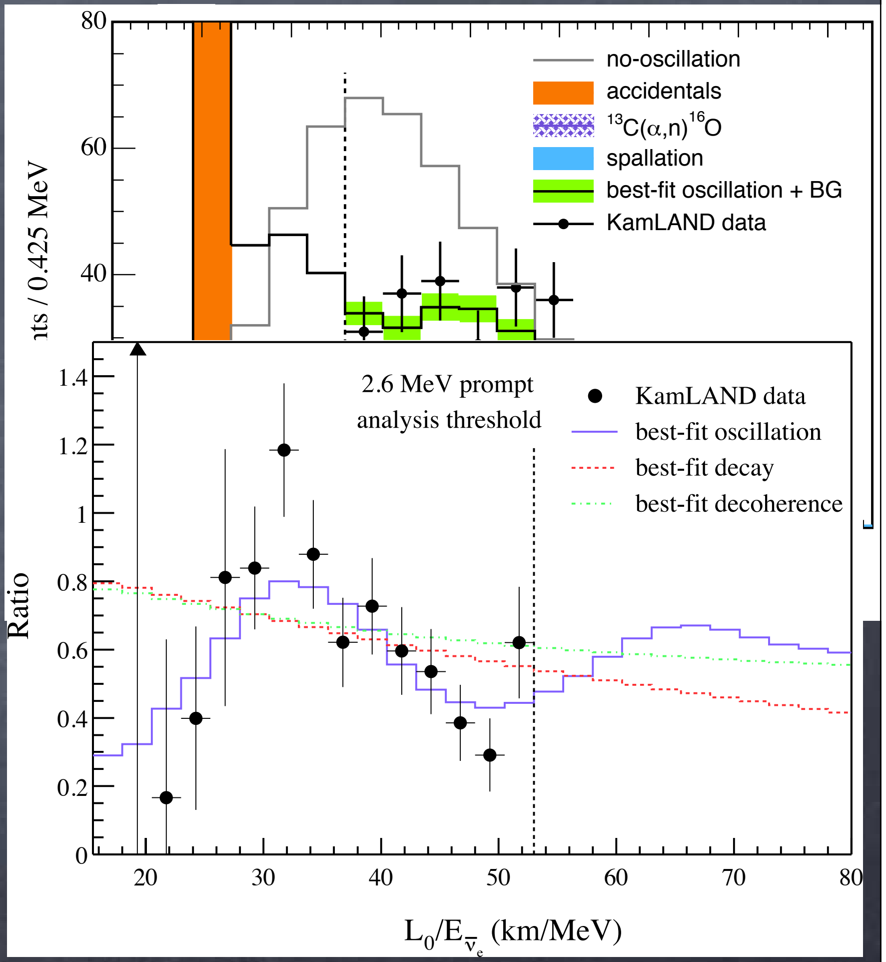
2002: First evidence $\bar{\nu}_e$ disappearance

→ confirmation of solar LMA ν oscillations

KamLAND Coll, PRL 90 (2003) 021802

2004: spectral distortions (L/E)

KamLAND Coll, PRL 94 (2005) 081801



Results from KamLAND

2002: First evidence $\bar{\nu}_e$ disappearance

→ confirmation of solar LMA ν oscillations

KamLAND Coll, PRL 90 (2003) 021802

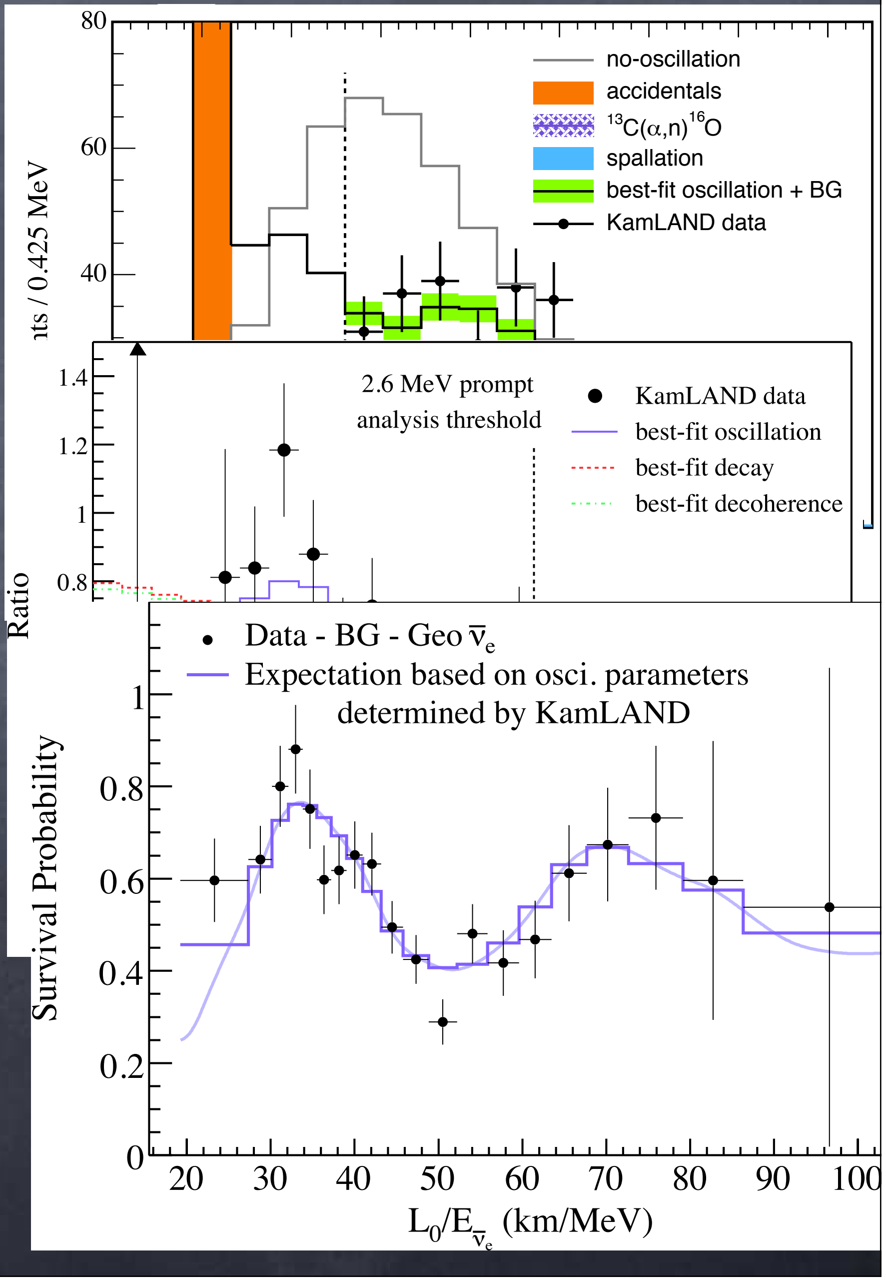
2004: spectral distortions (L/E)

KamLAND Coll, PRL 94 (2005) 081801

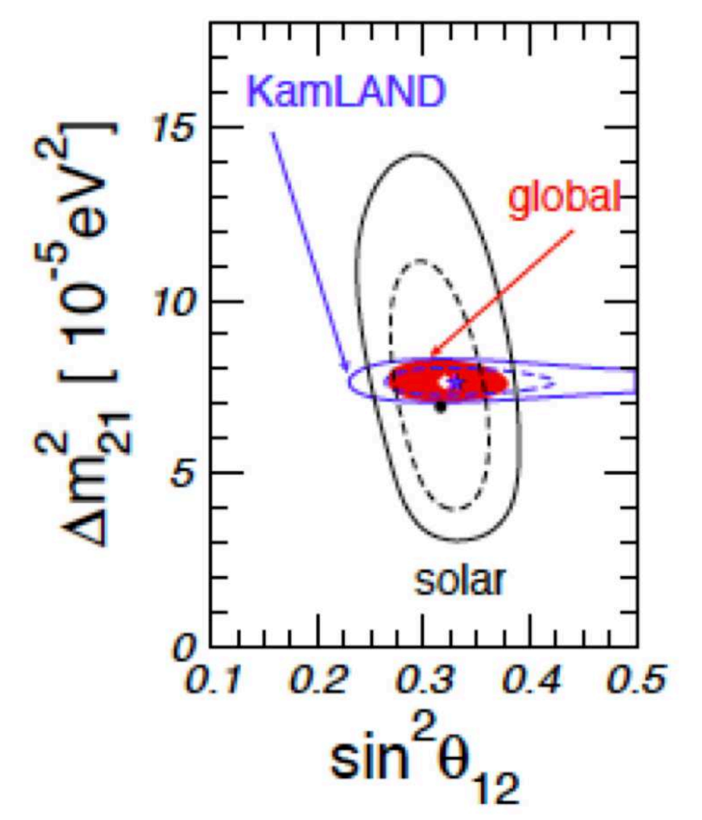
2008: 1-period oscillations observed

→ high precision determination Δm^2_{21}

KamLAND Coll, PRL 100 (2008) 221803



Combined analysis solar + KamLAND data



- KamLAND confirms LMA
- Best fit point:

  $\sin^2\theta_{12} = 0.312\,^{+0.017}_{-0.015}$

  $\Delta m^2_{21} = 7.59\,^{+0.20}_{-0.18} \times 10^{-5}$ eV^2
- max. mixing excluded at more than 7σ

➡ Bound on θ_{12} dominated by solar data.

➡ Bound on Δm^2_{21} dominated by KamLAND.

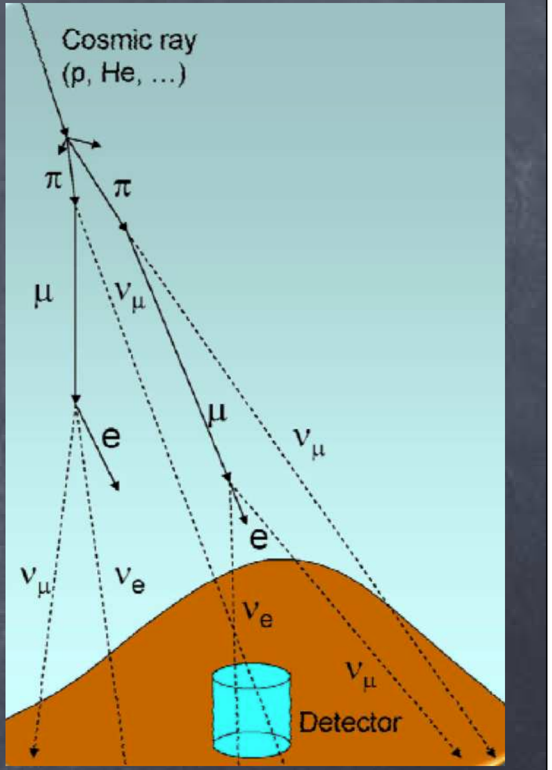
The atmospheric neutrino sector: (Δm^2_{31}, $\sin^2\theta_{23}$)

The atmospheric neutrino anomaly

Cosmic rays interacting with the Earth atmosphere producing pions and kaons, that decay generating neutrinos:

$$\begin{aligned}\pi^- &\to \mu^- + \bar{\nu}_\mu \\ &\quad \mu^- \to e^- + \bar{\nu}_e + \nu_\mu\end{aligned}$$

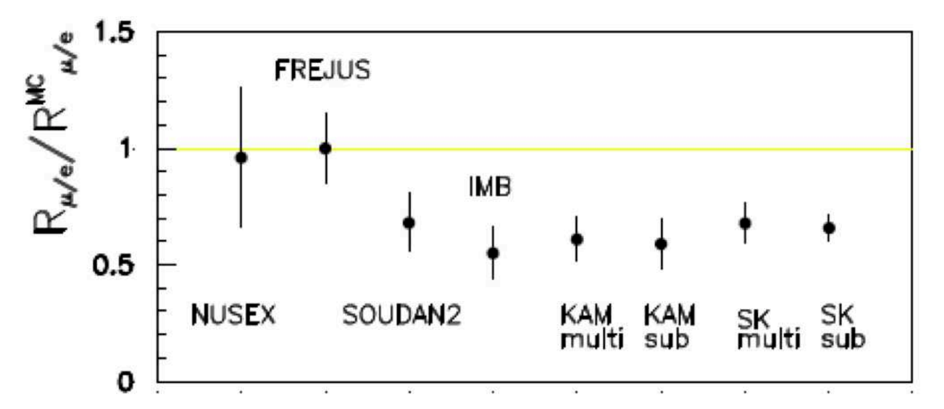
$$\begin{aligned}\pi^+ &\to \mu^+ + \nu_\mu \\ &\quad \mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu\end{aligned}$$



then, one expects:

$$R_{\mu/e} = \frac{N_{\nu_\mu} + N_{\bar{\nu}_\mu}}{N_{\nu_e} + N_{\bar{\nu}_e}} \simeq 2$$

However, this prediction is in disagreement with the experimental results:

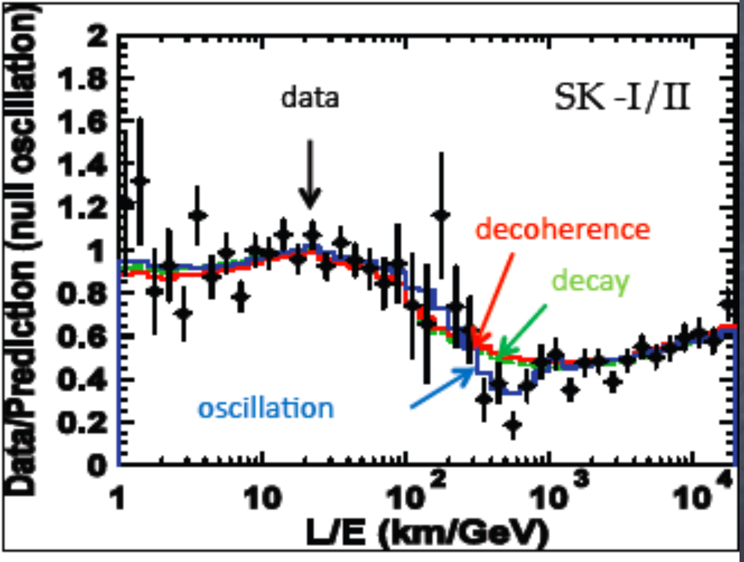


Atmospheric neutrinos

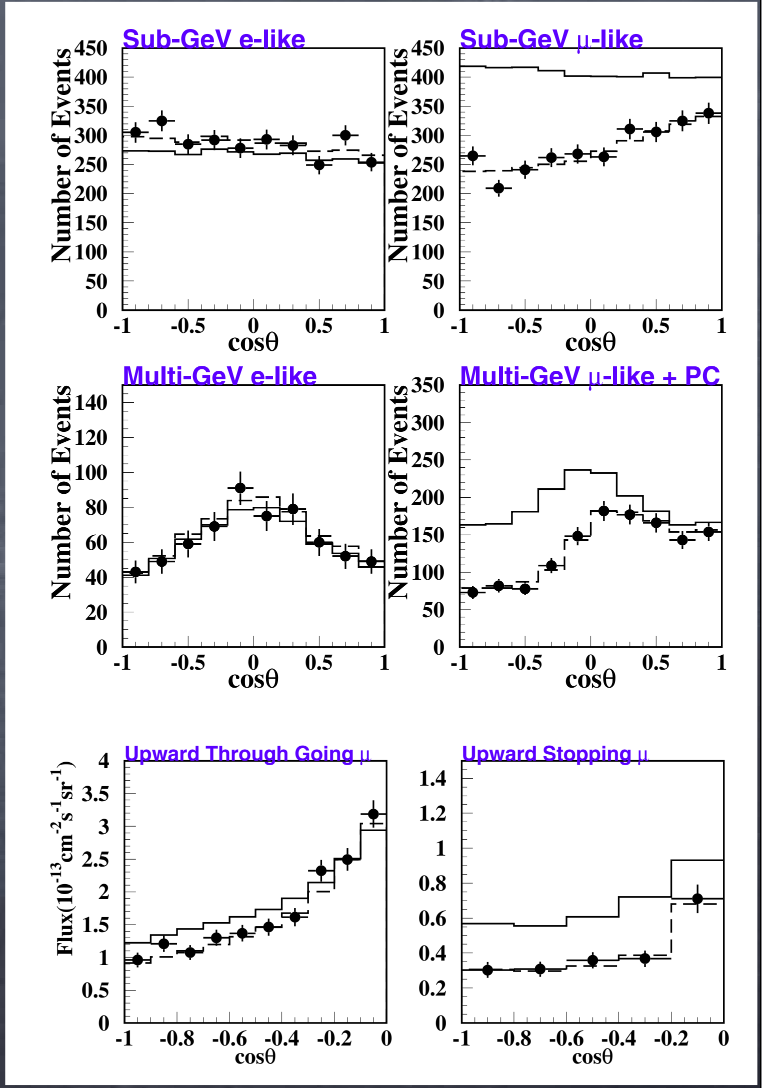
1998: Evidence ν_μ oscillations at Super-K

oscillation channel $\nu_\mu \rightarrow \nu_\tau$

2004: oscillatory L/E pattern



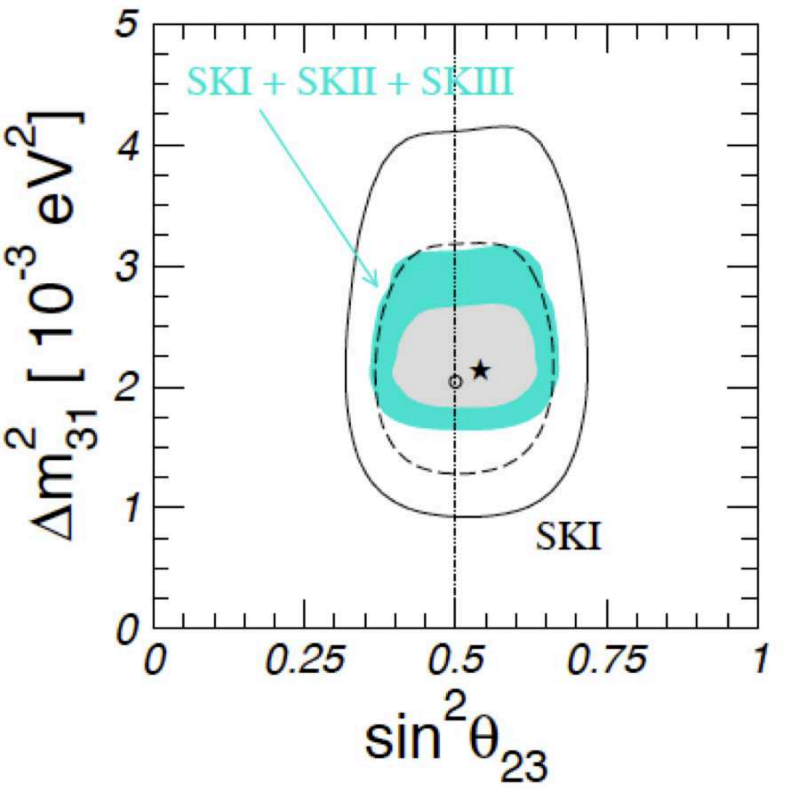
Super-K Coll, PRL93, 101801 (2004)



$$P_{\mu\mu} = 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32}}{4}\frac{L}{E_\nu}\right)$$

Super-K Coll., PRL 8 (1998) 1562.

Determination of atmospheric oscillation parameters



- Three-neutrino analysis using latest Super-Kamiokande data
- 90% C.L. and 3σ regions.
- Best fit point (IH):
  $\sin^2\theta_{23} = 0.54$
  $\Delta m^2_{31} = 2.14 \times 10^{-3}$ eV^2

Long-baseline accelerator experiments

Neutrino beams are generated in accelerators from the decay of pions produced by the scattering of accelerated protons on a fixed target:

$$p + X \rightarrow \pi^{\pm} + Y$$

$$\begin{aligned} \pi^{+} &\rightarrow \mu^{+} + \nu_{\mu} \\ &\quad\ \mu^{+} \rightarrow e^{+} + \nu_{e} + \overline{\nu}_{\mu} \end{aligned}$$

$$\begin{aligned} \pi^{-} &\rightarrow \mu^{-} + \overline{\nu}_{\mu} \\ &\quad\ \mu^{-} \rightarrow e^{-} + \overline{\nu}_{e} + \nu_{\mu} \end{aligned}$$

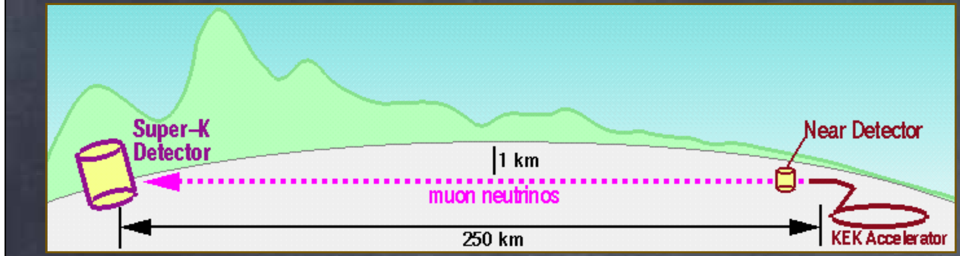
➡ the beam can be focalized to select only neutrinos or antineutrinos.

Goal: to test the atmospheric oscillations and improve parameter determination.

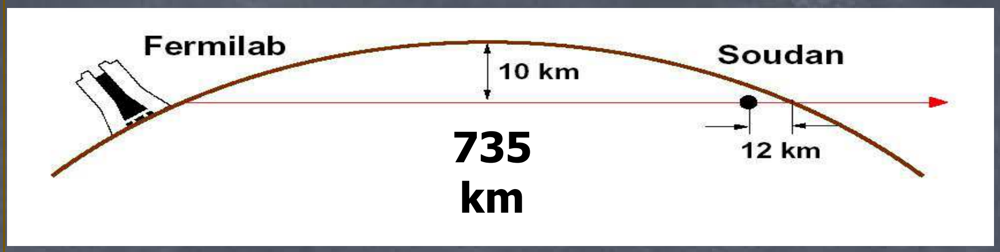
-> the experimental setup must be adjusted to be sensitive to $\Delta m^2 \sim 10^{-3}$ eV^2.

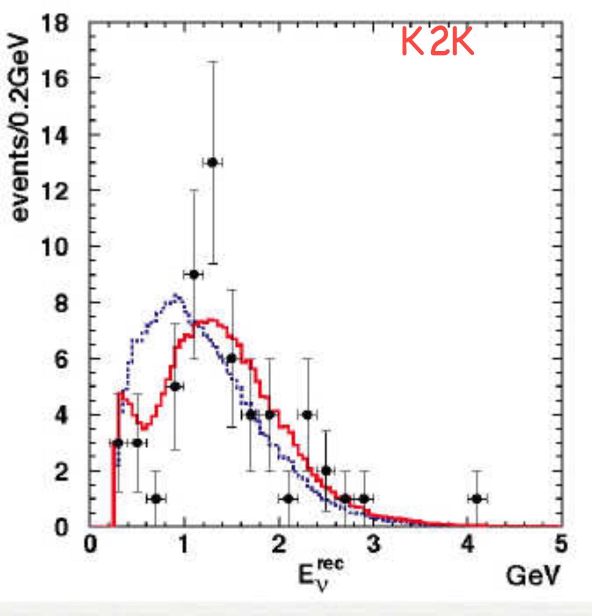
- K2K: $L \approx 250$ km, $E_\nu \approx 1.3$ GeV
- MINOS: $L = 735$ km, $\langle E_\nu \rangle \approx 3$ GeV

K2K: KEK →Kamioka

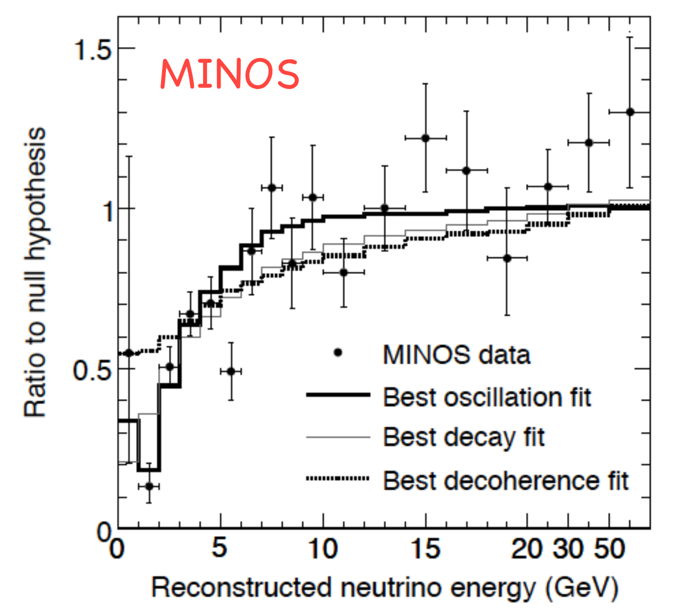


MINOS: Fermilab → Soudan





- ν_μ disappearance
- spectral distortions



→ consistent with atmospheric data

→ atm ν oscillations confirmed by laboratory exps

MINOS results

$\nu_\mu + \bar{\nu}_\mu$ disappearance data

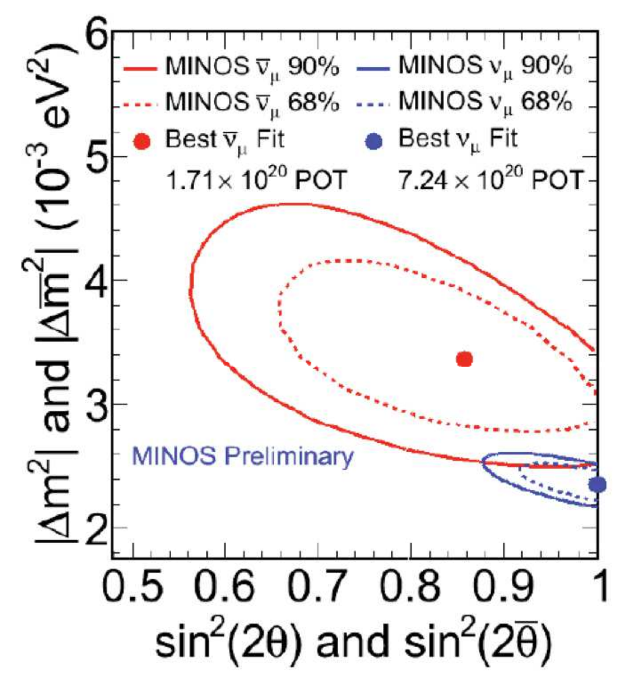
$$P(\nu_\mu \to \nu_\mu) \approx 1 - \boxed{\sin^2(2\theta_{23})}\sin^2\left(\frac{1.27 \times \boxed{\Delta m^2_{32}}/\mathrm{eV} \times L/\mathrm{km}}{E/\mathrm{GeV}}\right)$$

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

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

$$\left|\overline{\Delta m^2}\right| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\,\mathrm{eV}^2$$

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



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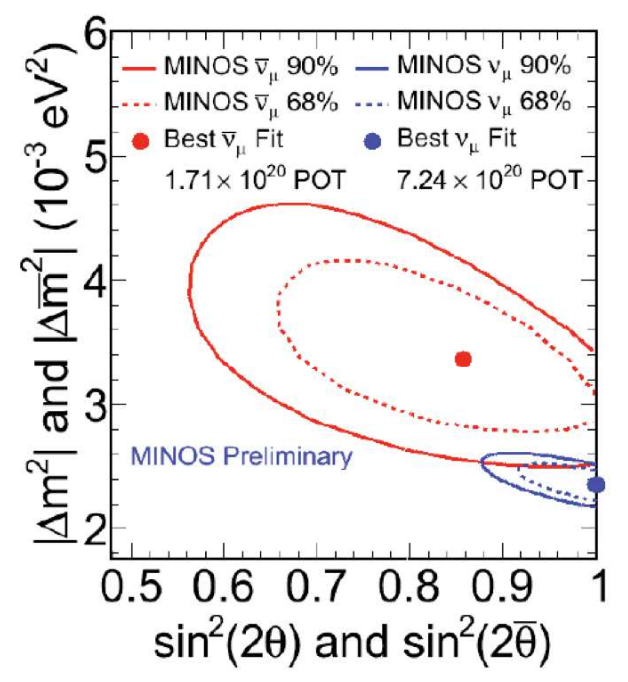
2σ inconsistency



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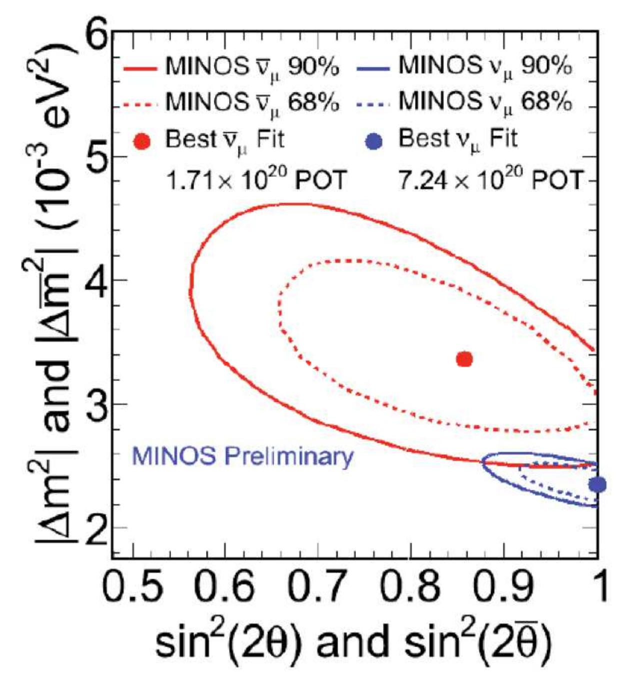
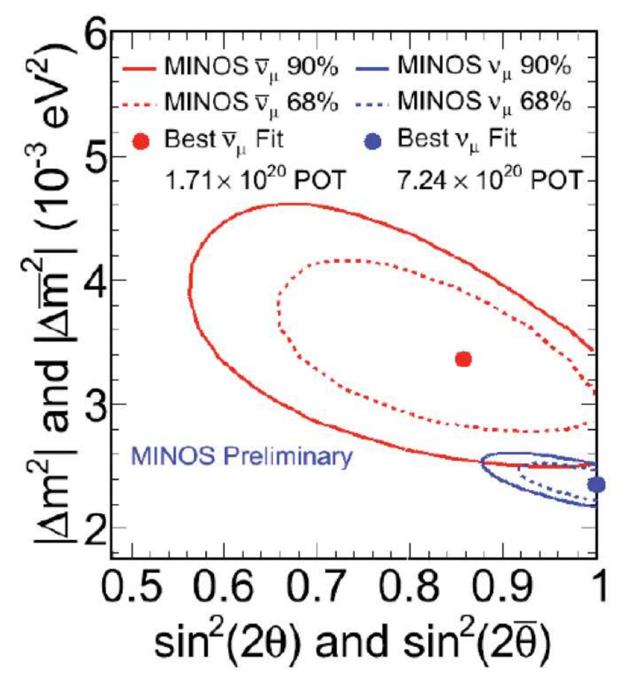
2σ inconsistency → More statistics



MINOS results

$\nu_\mu + \bar{\nu}_\mu$ disappearance data



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2σ inconsistency → More statistics

ν_e appearance data

(7×10^{20} pot)

$$P(\nu_\mu \to \nu_e) \approx \sin^2(\theta_{23})\sin^2(2\boxed{\theta_{13}})\sin^2\left(\frac{1.27\times\Delta m^2_{32}/\text{eV}^2\times L/\text{km}}{E/\text{GeV}}\right)$$

MINOS results

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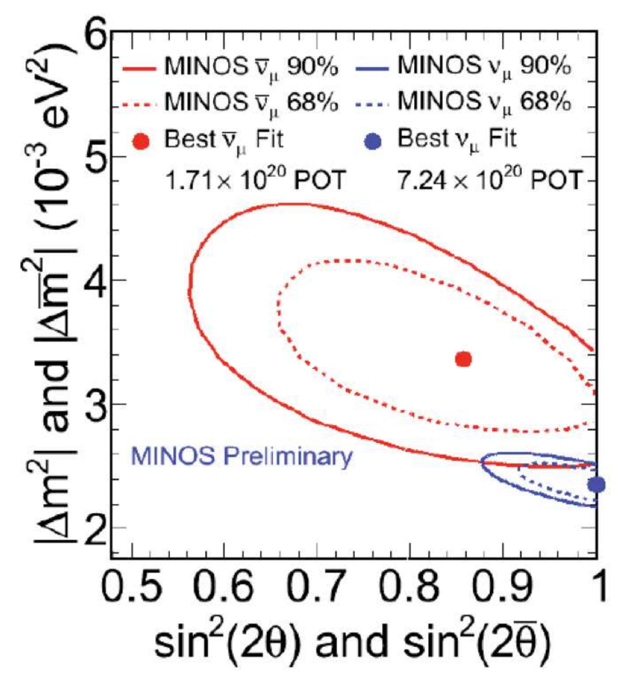
2σ inconsistency → More statistics



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(7×10^{20} pot)

$$P(\nu_\mu \to \nu_e) \approx \sin^2(\theta_{23})\sin^2(2\boxed{\theta_{13}})\sin^2\left(\frac{1.27\times\Delta m^2_{32}/\mathrm{eV}^2\times L/\mathrm{km}}{E/\mathrm{GeV}}\right)$$

- 54 electron events observed
- 49.1 ± 7.0 ± 2.7 expected
  - ➡ 0.7σ excess

MINOS results

$\nu_\mu + \bar{\nu}_\mu$ disappearance data

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \boxed{\sin^2(2\theta_{23})}\sin^2\left(\frac{1.27 \times \boxed{\Delta m^2_{32}}/\mathrm{eV} \times L/\mathrm{km}}{E/\mathrm{GeV}}\right)$$

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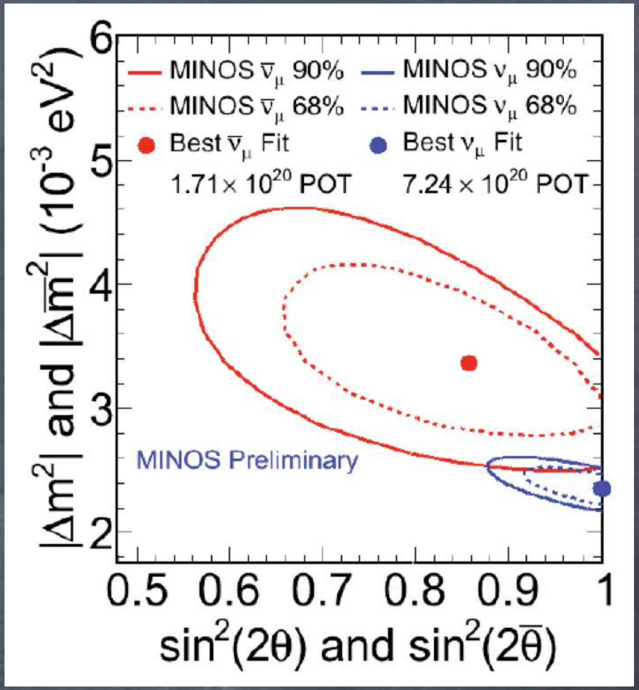


ν_e appearance data

($7\mathrm{x}10^{20}$ pot)

$$P(\nu_\mu \to \nu_e) \approx \sin^2(\theta_{23})\sin^2(2\boxed{\theta_{13}})\sin^2\left(\frac{1.27 \times \Delta m^2_{32}/\mathrm{eV}^2 \times L/\mathrm{km}}{E/\mathrm{GeV}}\right)$$

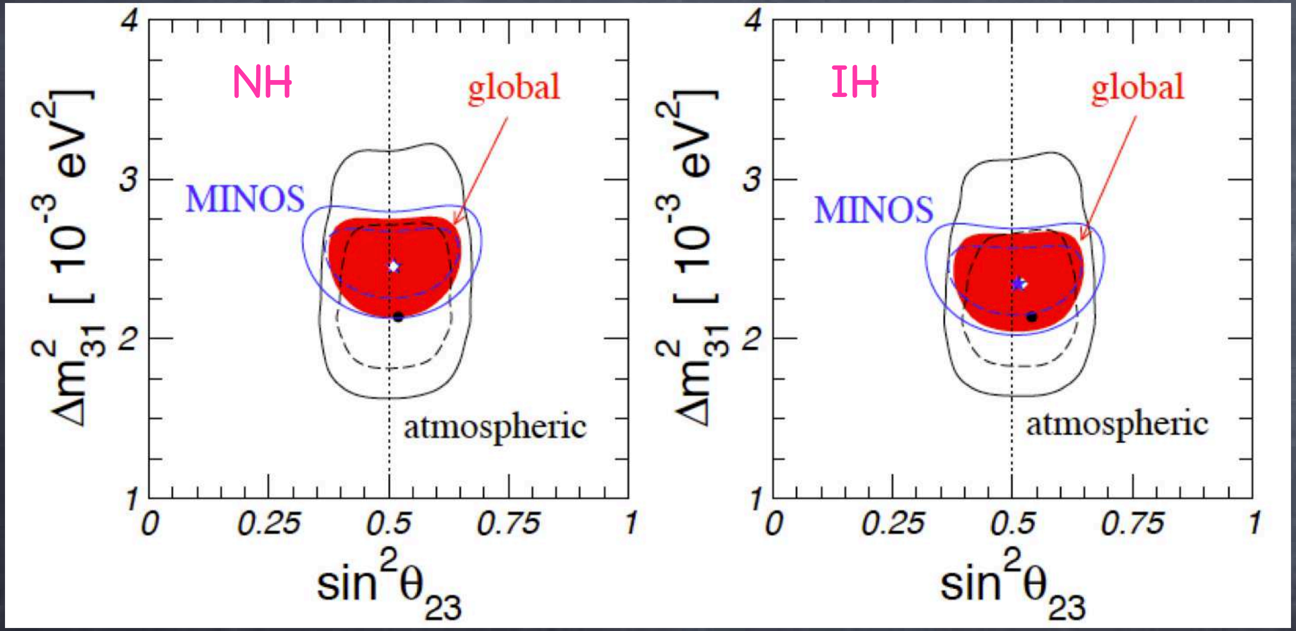
- 54 electron events observed
- 49.1 ± 7.0 ± 2.7 expected
  - ➡ 0.7σ excess

→

NH: $\sin^2(2\theta_{13}) < 0.12$ (90%CL)
IH: $\sin^2(2\theta_{13}) < 0.20$ (90%CL)

Combined analysis atmospheric + LBL data

➡ Combining atmospheric with accelerator K2K and MINOS data we obtain a more precise determination of the oscillation parameters.



➡ Bound on θ_{23} dominated by atmospheric data

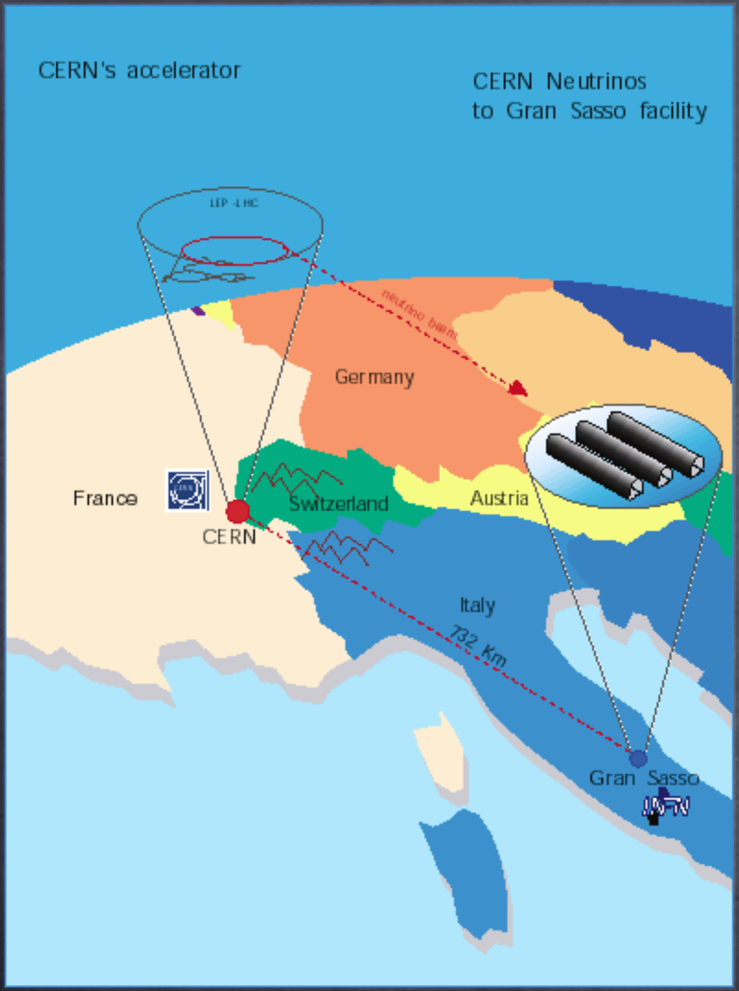
➡ Bound on Δm^2_{32} improved by LBL

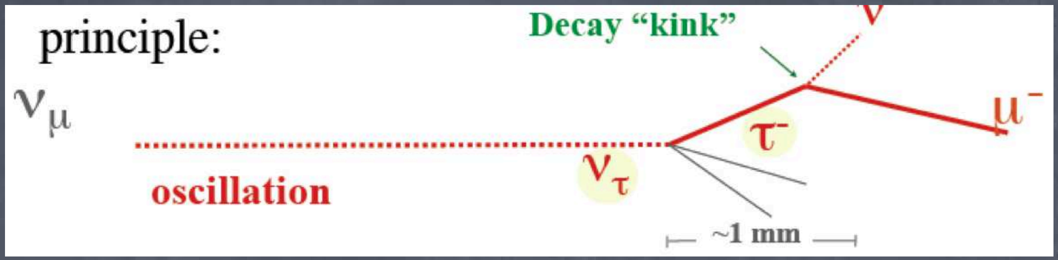
- Best fit point:

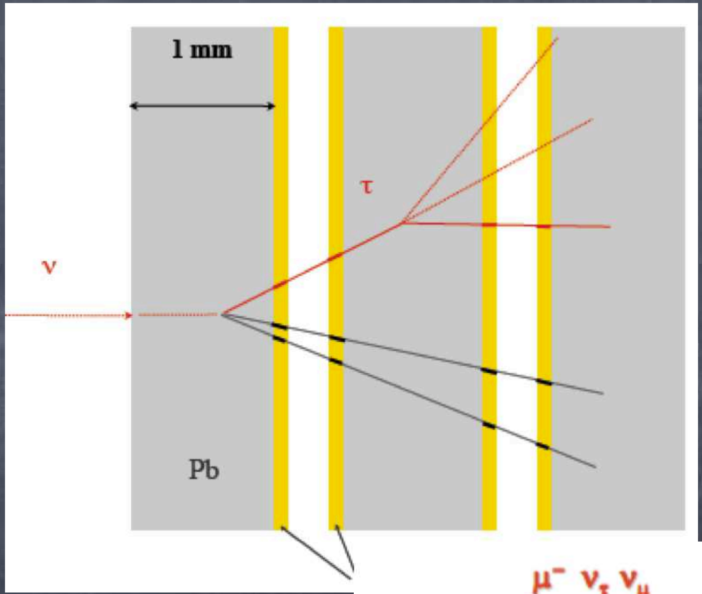
$\sin^2\theta_{23} = 0.51 \pm 0.06$
$\Delta m^2_{31} = 2.45 \pm 0.09 \times 10^{-3}\ \mathrm{eV}^2$

$\sin^2\theta_{23} = 0.52 \pm 0.06$
$\Delta m^2_{31} = -(2.34 \pm 0.10 \times 10^{-3}\ \mathrm{eV}^2)$

OPERA: from CERN to Gran sasso







$\tau \rightarrow$

$\mu^- \; \nu_\tau \; \nu_\mu$	(17.4%)	Kink
$e^- \; \nu_\tau \; \nu_e$	(17.8%)	
$h^- \; \nu_\tau \; n\,\pi^0$	(49.5%)	
$\pi^+ \pi^- \pi^- \nu_\tau \; n\pi^0$	(14.5%)	Multiprong

- L = 732 km.
- < E > ~ 17 GeV
- 2010: first observation of a ν_τ in a ν_μ beam.

The bound on θ_{13}

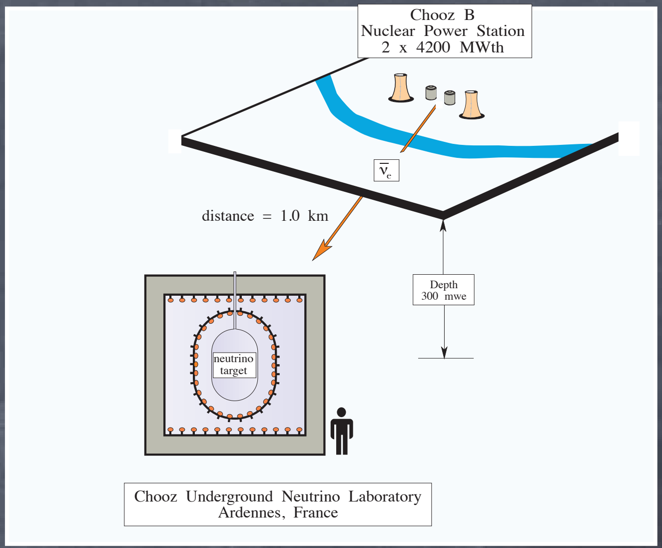
+

indications for $\theta_{13} \neq 0$

The CHOOZ reactor experiment

- disappearance reactor ν_e
- L = 1 km, E~MeV
- 2ν approx: Δm^2_{31} , θ_{13}

$$P_{ee} = 1 - 2\sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$



- non-observation of ν_e disappearance:

$$R = 1.01 \pm 2.8\%(\text{stat}) \pm 2.7\%(\text{syst})$$

The CHOOZ reactor experiment

- disappearance reactor ν_e
- L = 1 km, E~MeV
- 2ν approx: Δm^2_{31} , θ_{13}

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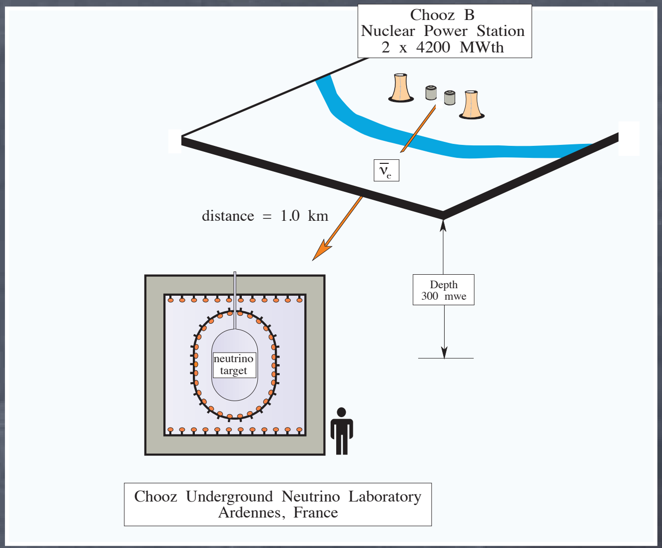
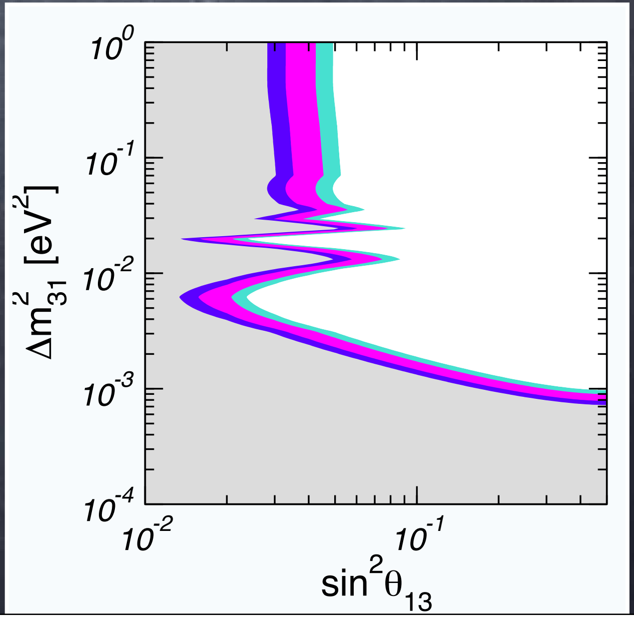


- non-observation of ν_e disappearance:

R = 1.01 ± 2.8%(stat) ± 2.7%(syst)

→ Exclusion plot
(Δm^2_{31} , θ_{13}) plane



The CHOOZ reactor experiment

- disappearance reactor ν_e
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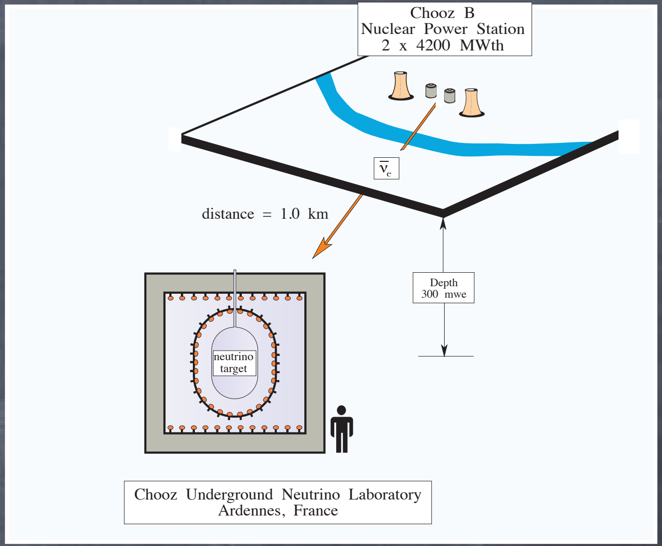
- 2ν approx: Δm^2_{31} , θ_{13}

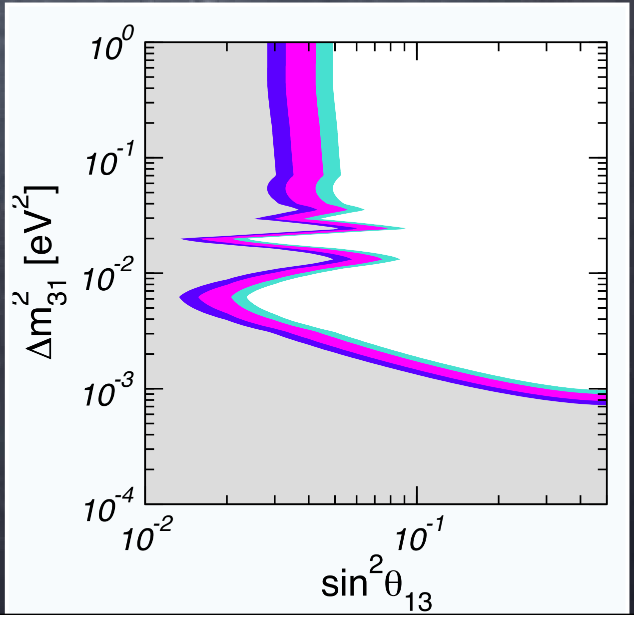
$$P_{ee} = 1 - 2\sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$



- non-observation of ν_e disappearance:

R = 1.01 ± 2.8%(stat) ± 2.7%(syst)

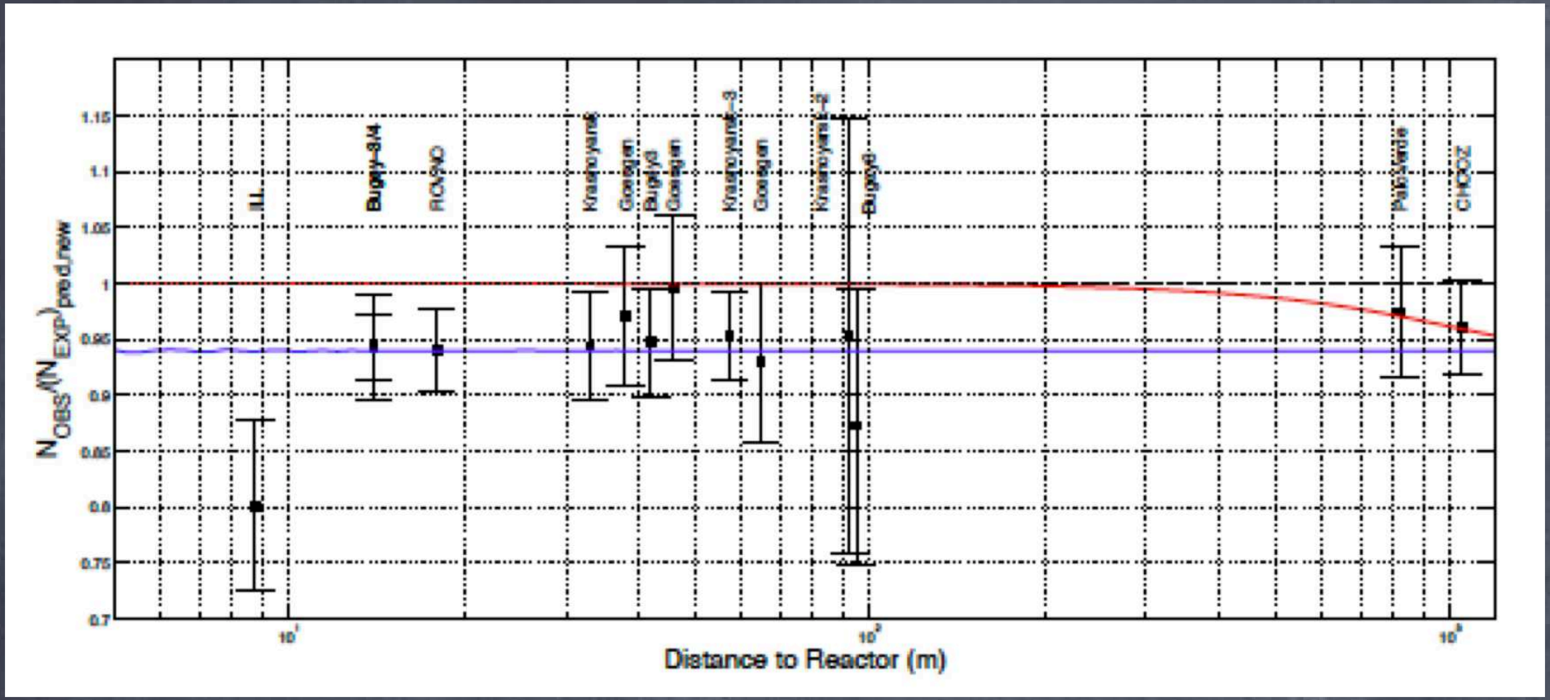
→ Exclusion plot (Δm^2_{31} , θ_{13}) plane



For $\Delta m^2_{31} = 2.5 \cdot 10^{-3}$ eV^2

-> $\sin^2\theta_{13} < 0.039$ (90%CL)

The reactor antineutrino anomaly



Mention et al, arXiv:1101.2755

- increase of 3.5% in the reactor antineutrino fluxes
  - ⇒ SBL reactor experiments show a deficit in the number of detected over expected neutrinos: $R = 0.937 \pm 0.027$
- possible explanations: sterile neutrino(s) with $\Delta m^2 \sim 1$ eV^2
- SBL exps. should be included in a 3ν fit, to account for normalization of reactor exps. (CHOOZ, KamLAND) at short distances.

Reevaluation of the CHOOZ bound after new flux predictions

Old flux predictions:

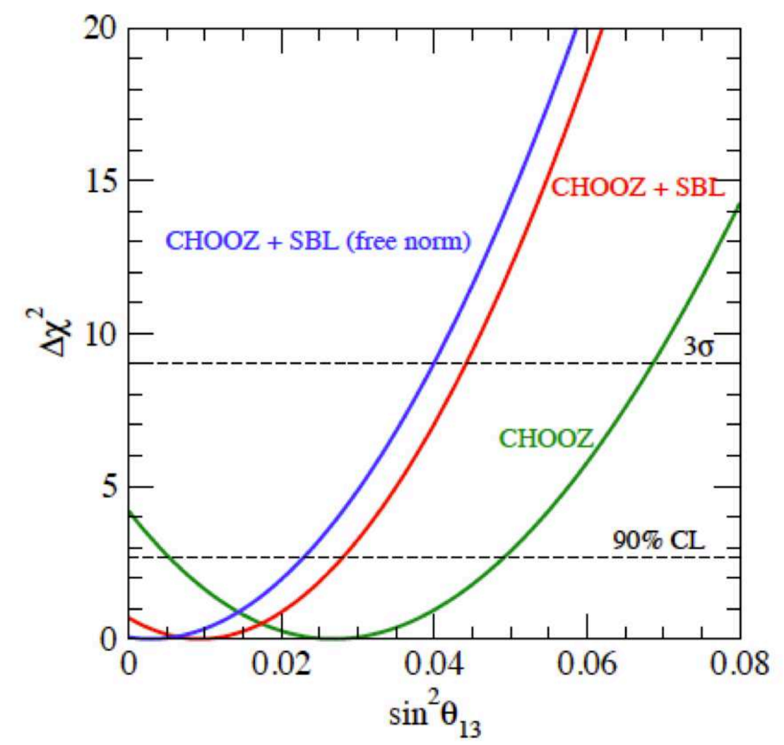
For $\Delta m^2_{31} = 2.5 \cdot 10^{-3}$ eV^2

-> $\sin^2\theta_{13} < 0.039$ (90%CL) ($\sin^2 2\theta_{13} < 0.15$)

New flux predictions:

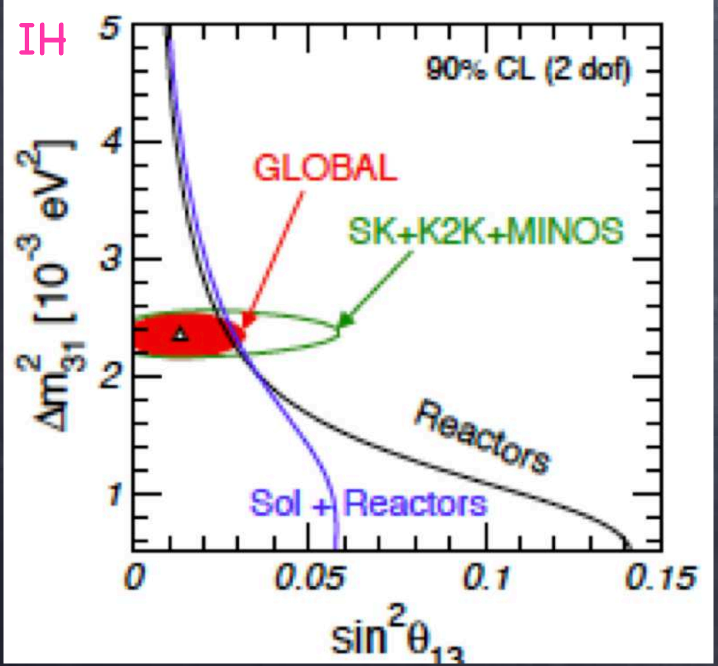
For $\Delta m^2_{31} = 2.5 \cdot 10^{-3}$ eV^2 :

- without SBL: $\sin^2\theta_{13} < 0.049$ (90%CL)
  ($\sin^2 2\theta_{13} < 0.19$)
- with SBL: $\sin^2\theta_{13} < 0.028$ (90%CL)
  ($\sin^2 2\theta_{13} < 0.11$)
- SBL + free norm: $\sin^2\theta_{13} < 0.023$(90%CL)
  ($\sin^2 2\theta_{13} < 0.09$)

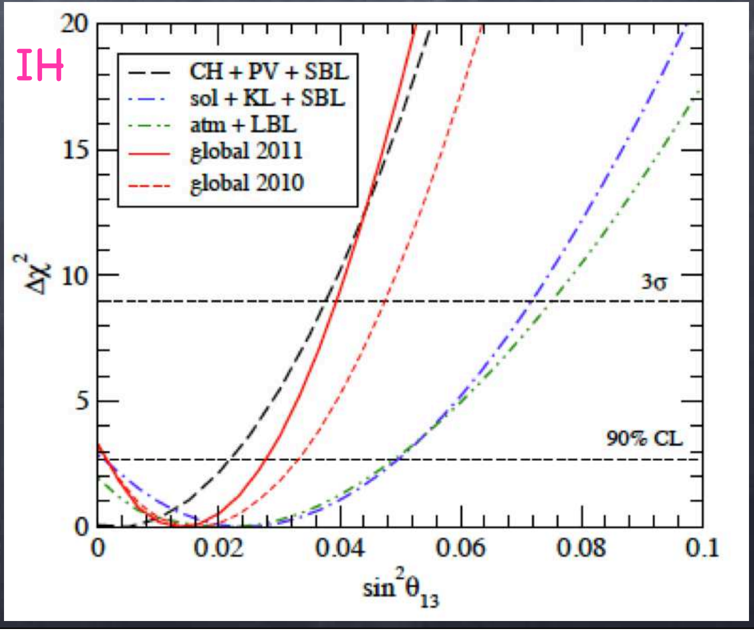


Global bound on θ_{13}

- solar + KamLAND + SBL: $\sin^2\theta_{13} < 0.072$ at 3σ
- atmospheric + LBL : $\sin^2\theta_{13} < 0.057$ (0.075) at 3σ for NH (IH)
- CHOOZ + SBL: $\sin^2\theta_{13} < 0.038$ at 3σ
- Global bound: $\sin^2\theta_{13} < 0.035$ (0.039) at 3σ for NH (IH)

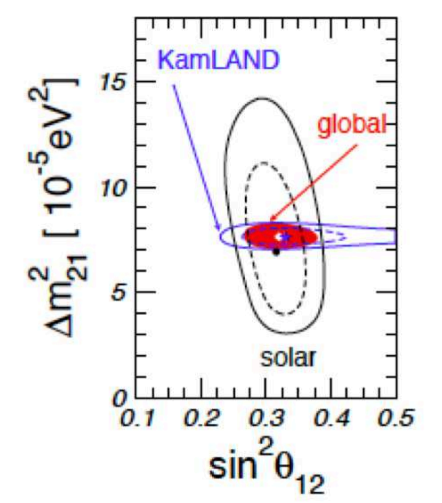


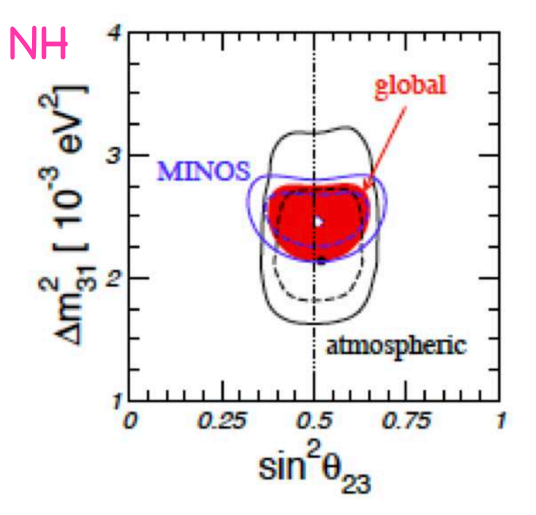
weak indication (1.8σ) for $\theta_{13} \neq 0$:
$\sin^2\theta_{13} = 0.010 \pm^{0.009}_{0.006}$ $(0.013 \pm^{0.009}_{0.007})$ NH (IH)

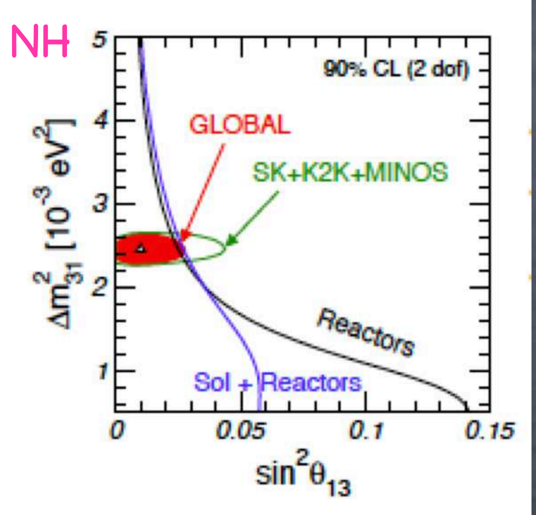


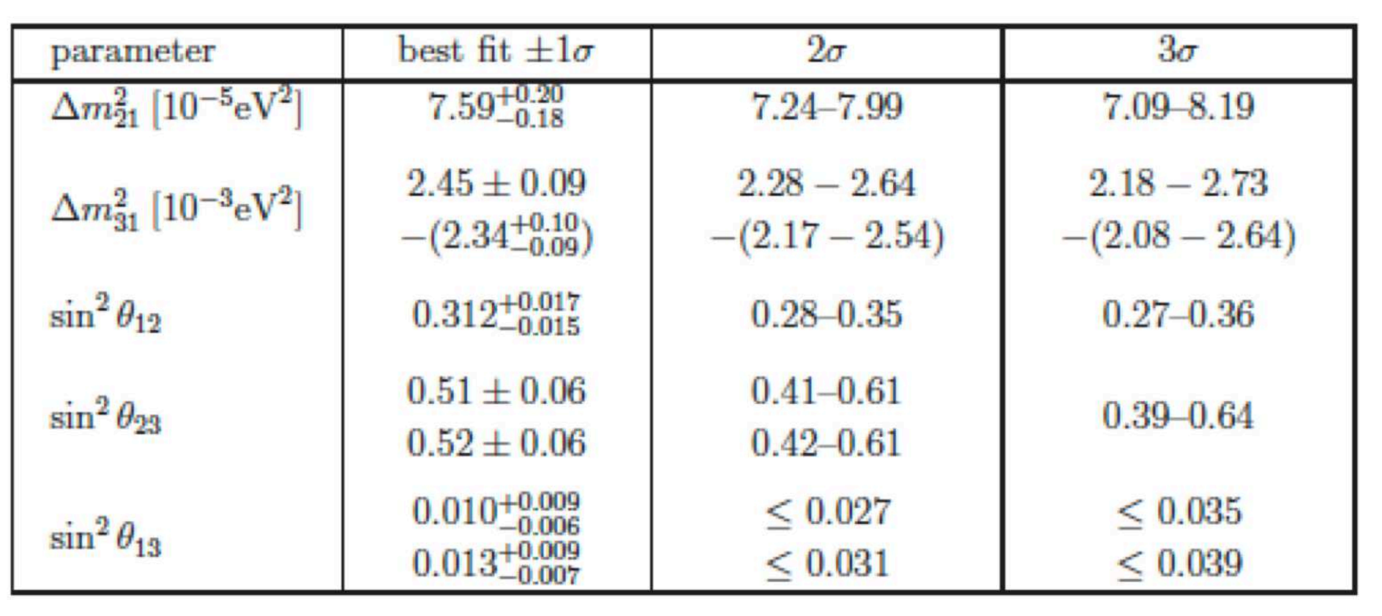
Schwetz, MT, Valle, New J. Phys. 13 (2011) 63004.

3-flavour oscillation parameters









parameter	best fit $\pm 1\sigma$	2σ	3σ
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.59^{+0.20}_{-0.18}$	7.24–7.99	7.09–8.19
Δm^2_{31} $[10^{-3}\text{eV}^2]$	2.45 ± 0.09 $-(2.34^{+0.10}_{-0.09})$	$2.28 - 2.64$ $-(2.17 - 2.54)$	$2.18 - 2.73$ $-(2.08 - 2.64)$
$\sin^2\theta_{12}$	$0.312^{+0.017}_{-0.015}$	0.28–0.35	0.27–0.36
$\sin^2\theta_{23}$	0.51 ± 0.06 0.52 ± 0.06	0.41–0.61 0.42–0.61	0.39–0.64
$\sin^2\theta_{13}$	$0.010^{+0.009}_{-0.006}$ $0.013^{+0.009}_{-0.007}$	≤ 0.027 ≤ 0.031	≤ 0.035 ≤ 0.039

Schwetz, MT, Valle, New J. Phys. 13 (2011) 63004.

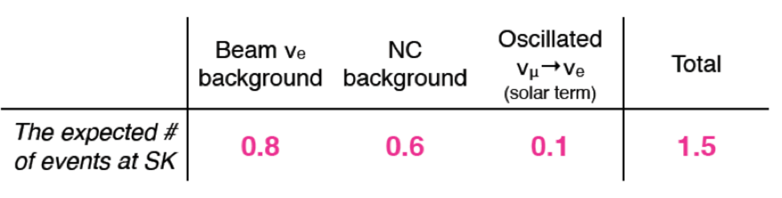
New results from T2K

[T2K Collaboration], arXiv:1106.2822 [hep-ex].

Search for ν_e appearance:

$$P(\nu_\mu \to \nu_e) = \boxed{\sin^2 2\theta_{13}} \sin^2\theta_{23} \sin^2(\Delta m^2_{31} L/4E) + \ldots$$

Expected number of events for $\sin^2 2\theta_{13} = 0$



	Beam ν_e background	NC background	Oscillated $\nu_\mu \to \nu_e$ (solar term)	Total
The expected # of events at SK	0.8	0.6	0.1	1.5

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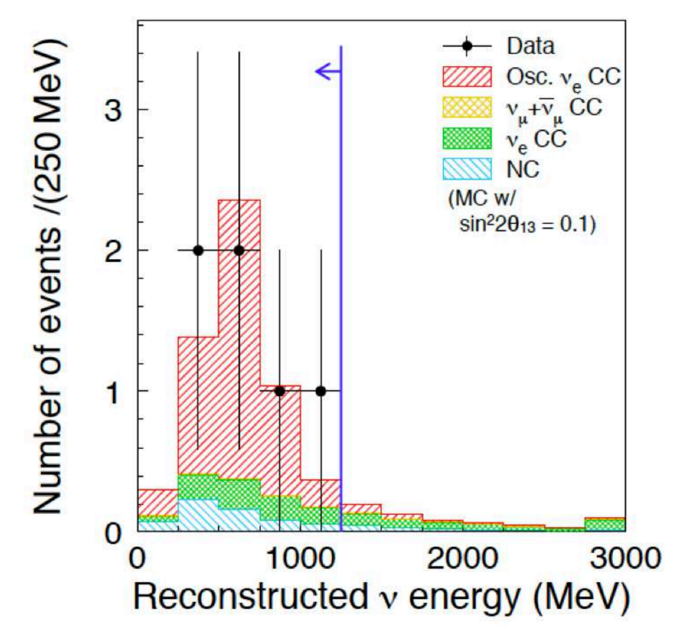

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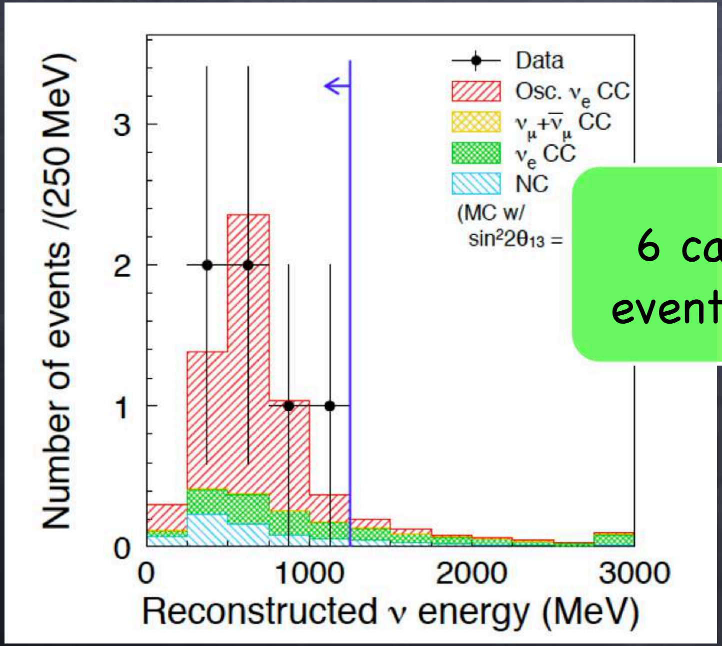

6 candidate events remain

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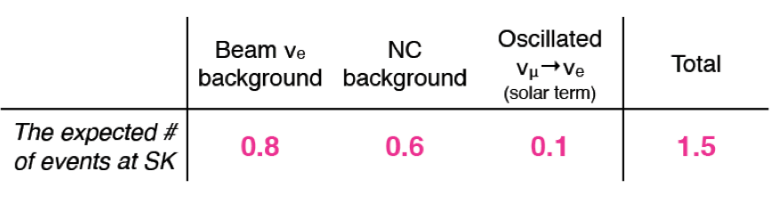

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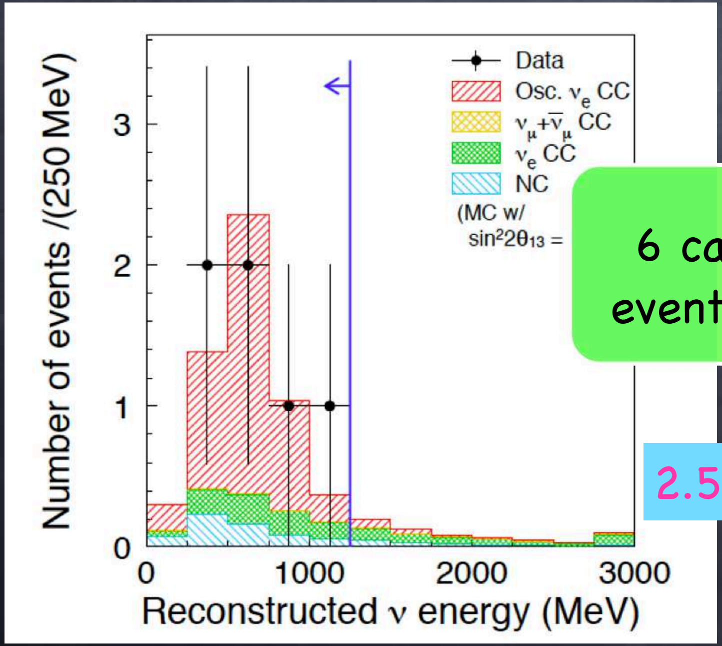

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2.5σ significance

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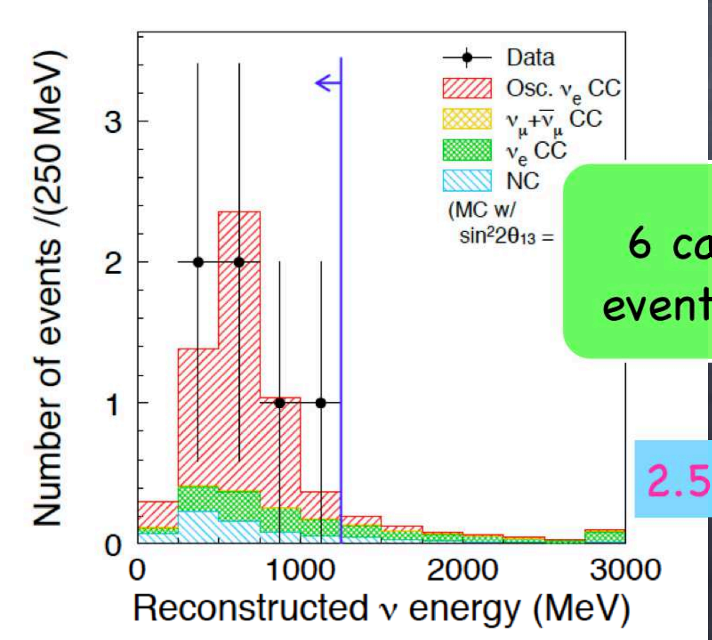

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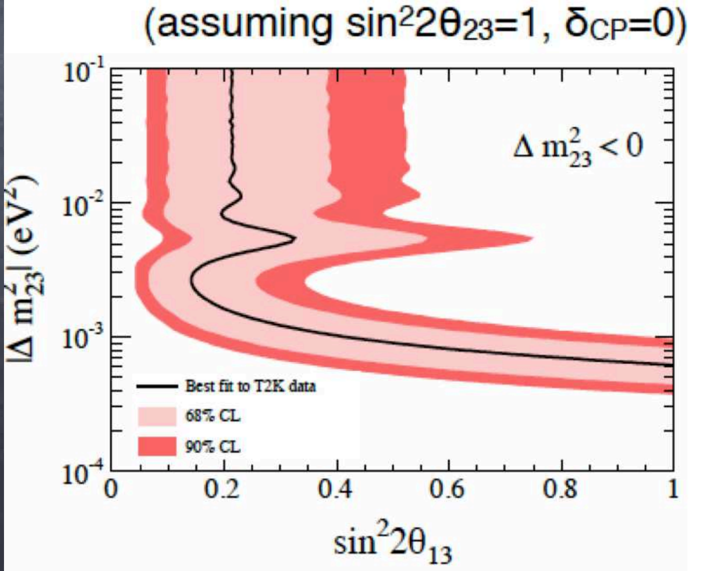
(assuming $\sin^2 2\theta_{23}=1$, $\delta_{CP}=0$)

$0.03\ (0.04) < \sin^2 2\theta_{13} < 0.28\ (0.34)$ at 90% C.L.

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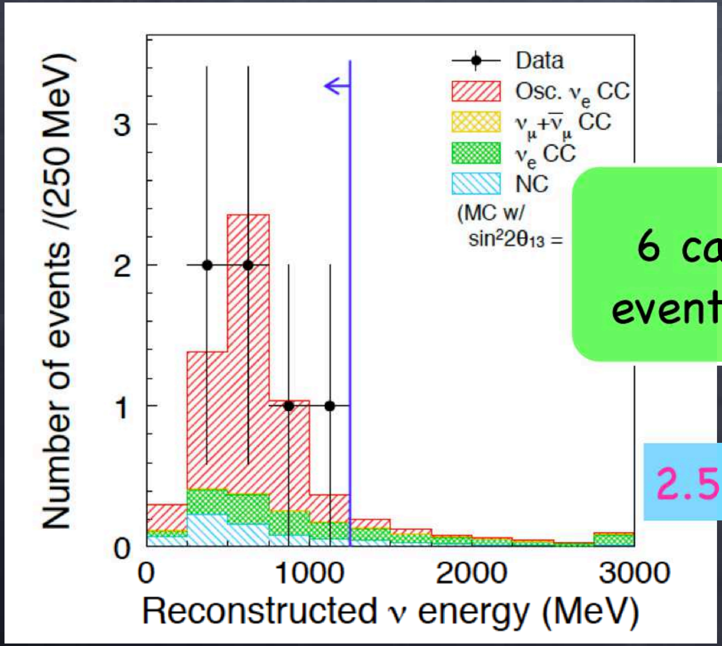

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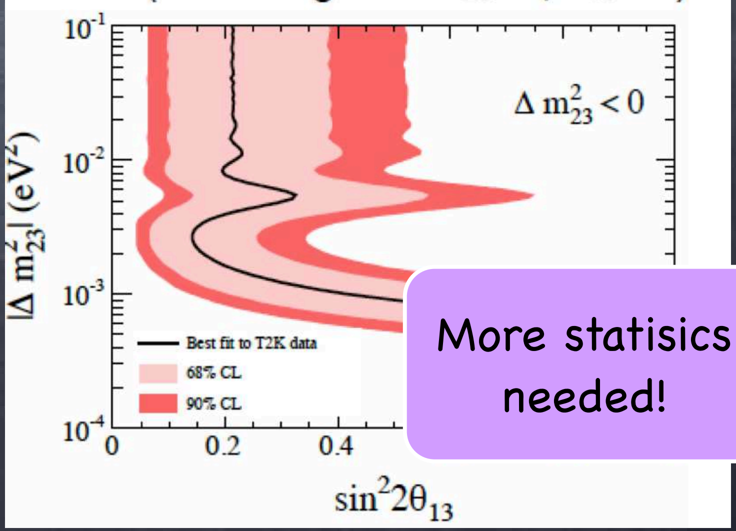

More statisics needed!

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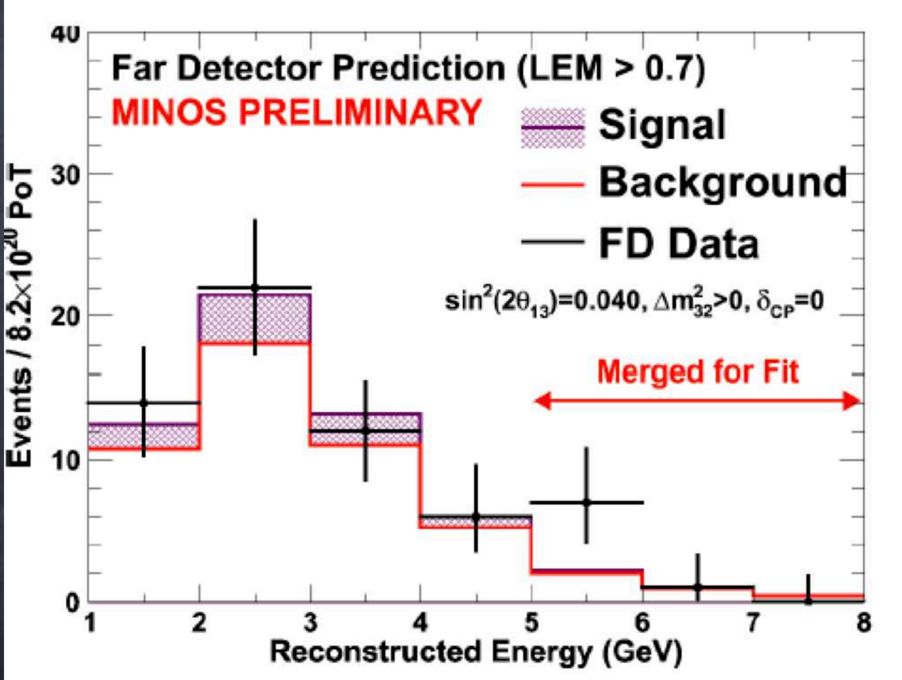
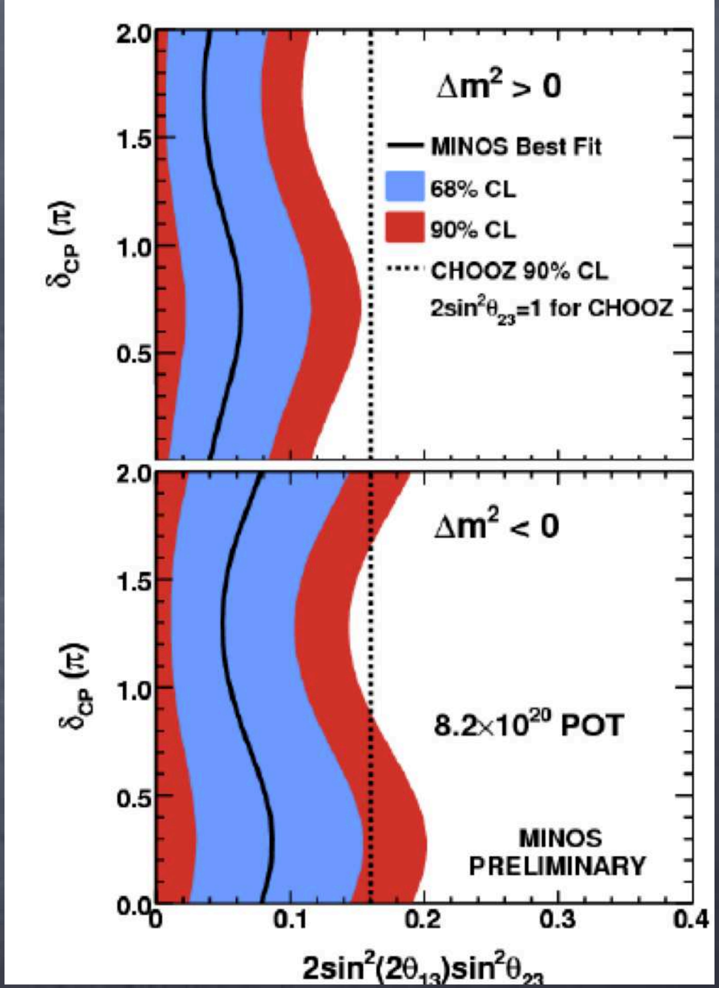
New MINOS appearance results

http://theory.fnal.gov/jetp/talks/MINOSNue_2011June24.pdf

- exposure: 8.2x10^{20} pot
- 30% improved selection sensitivity





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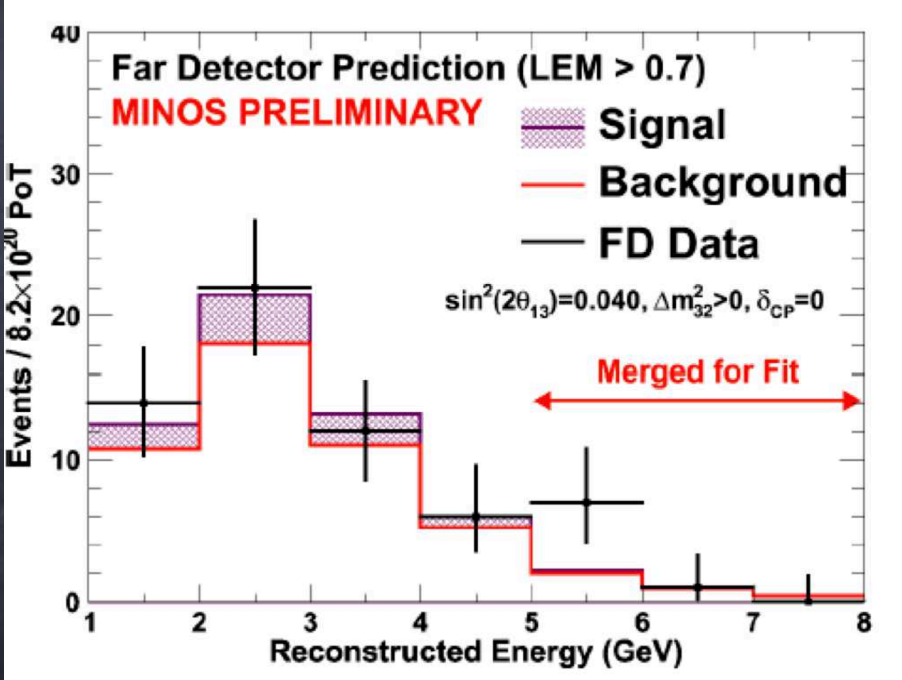

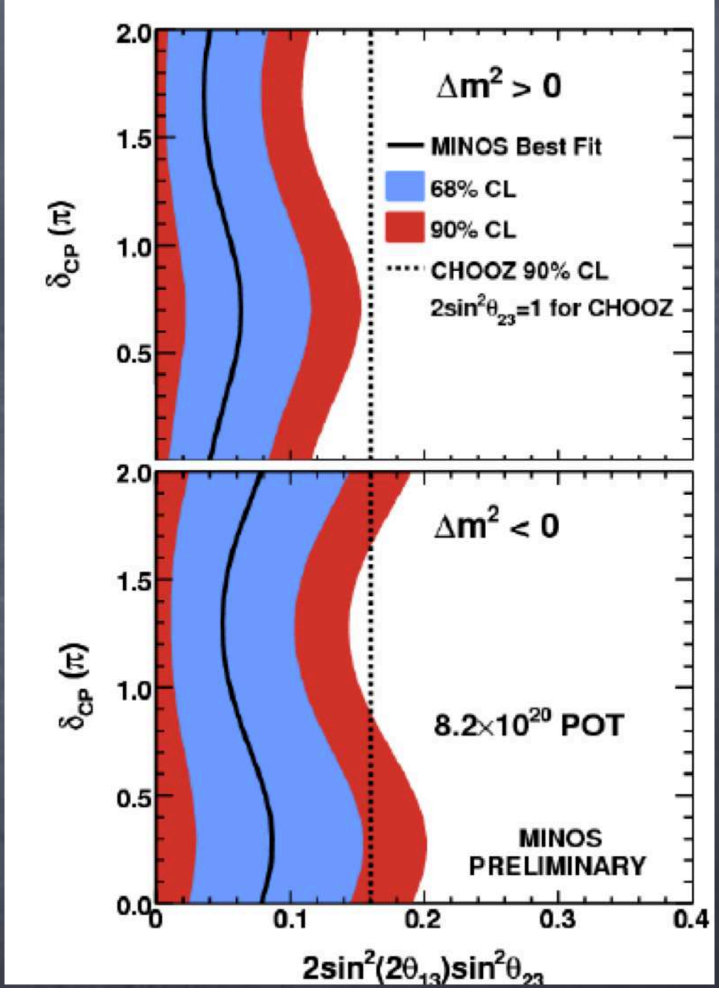

- 62 electron events observed
- 49.5 ± 7.0 (stat) ± 2.8 (syst) expected
  ➡ 1.7σ excess

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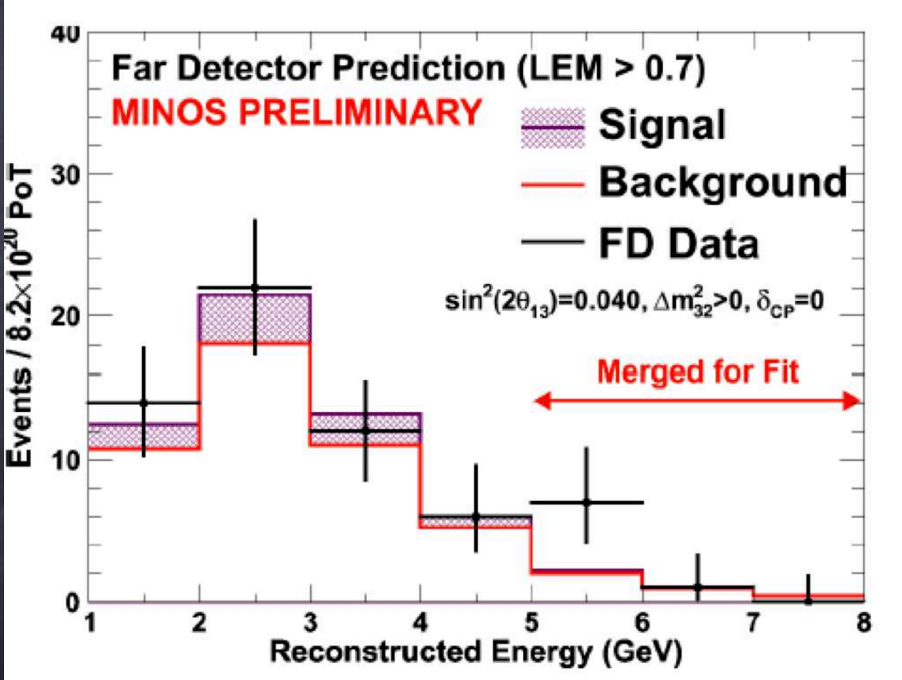

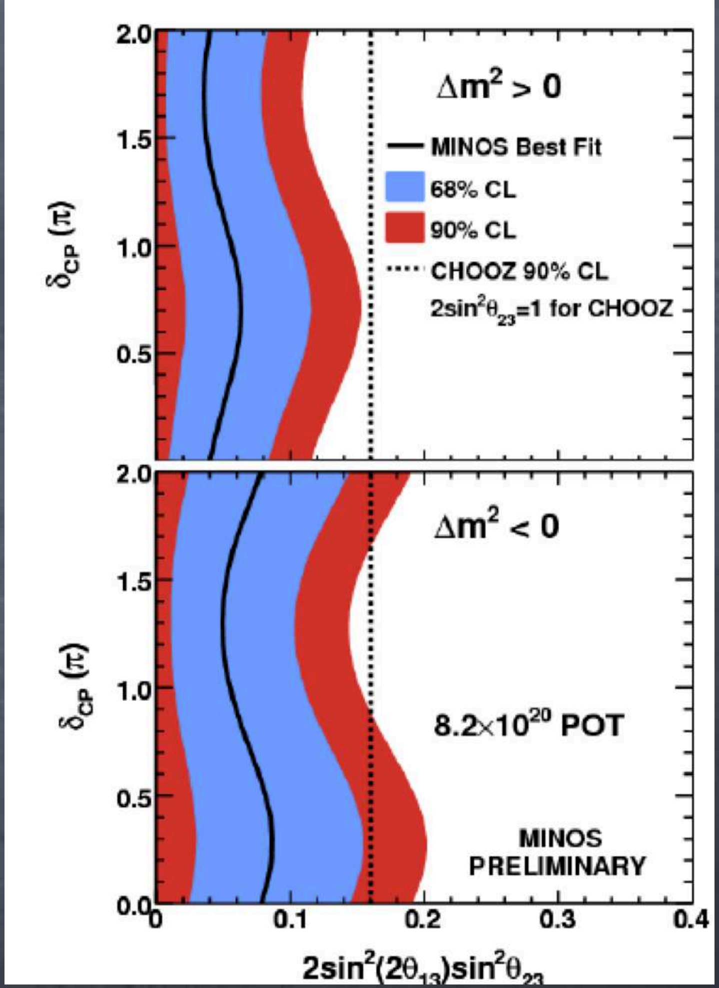

- 62 electron events observed
- 49.5 ± 7.0 (stat) ± 2.8 (syst) expected

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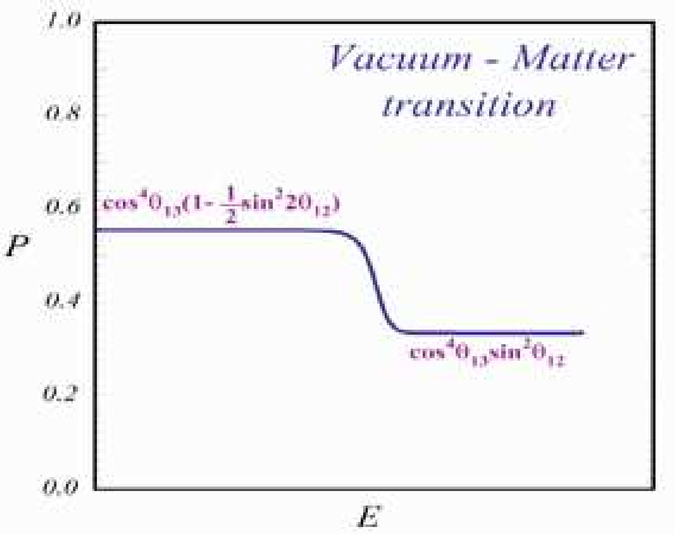
For NH (IH):
$\sin^2(2\theta_{13}) < 0.12$ (0.19) at 90%CL
$\sin^2(2\theta_{13}) = 0.04$ (0.08) best fit
$\sin^2(2\theta_{13}) = 0$ excluded at 89% CL

Next generation of neutrino oscillation experiments

Low energy solar experiments

- real time measurements pp, pep, ^{7}Be fluxes:
  [ES] KamLAND, CLEAN, SNO+
  [CC] LENS, MOON, XMASS

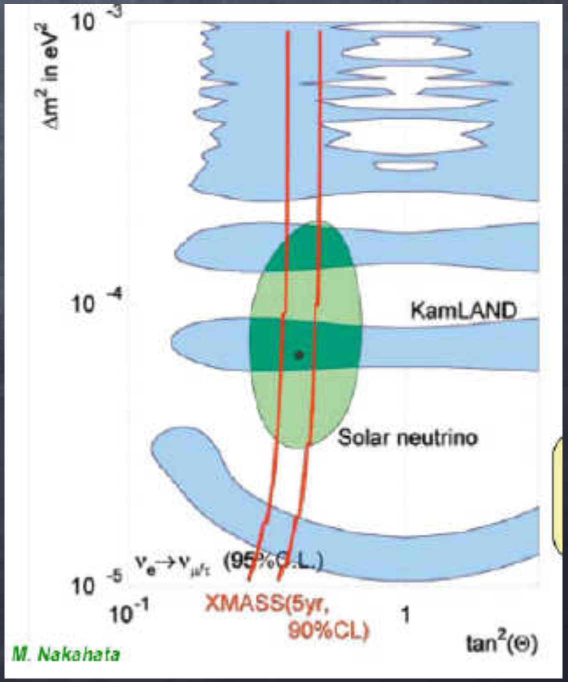


⇒ constrain SSM

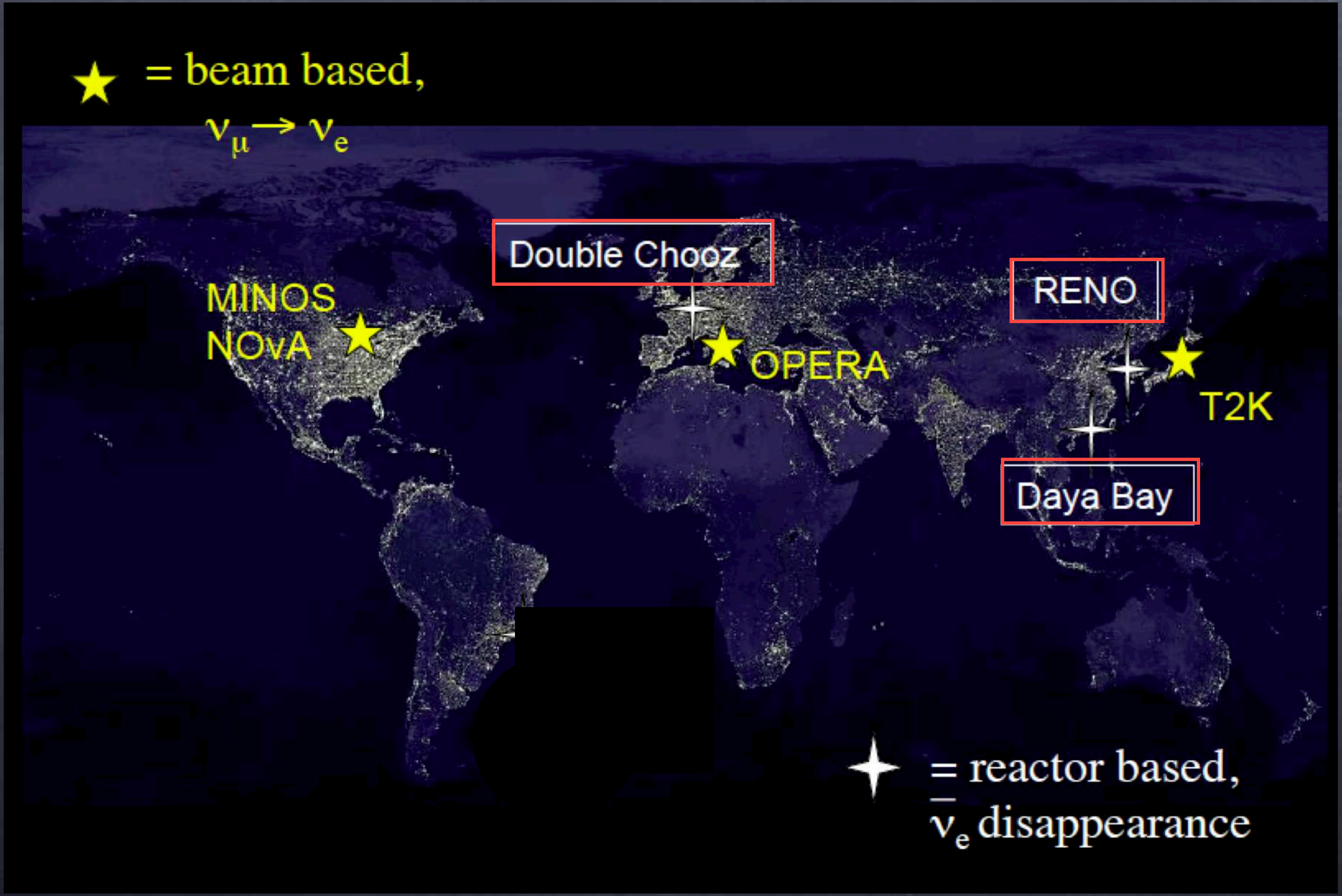
⇒ transition low to high energies

⇒ θ_{12} precision measurements

⇒ signatures of new physics

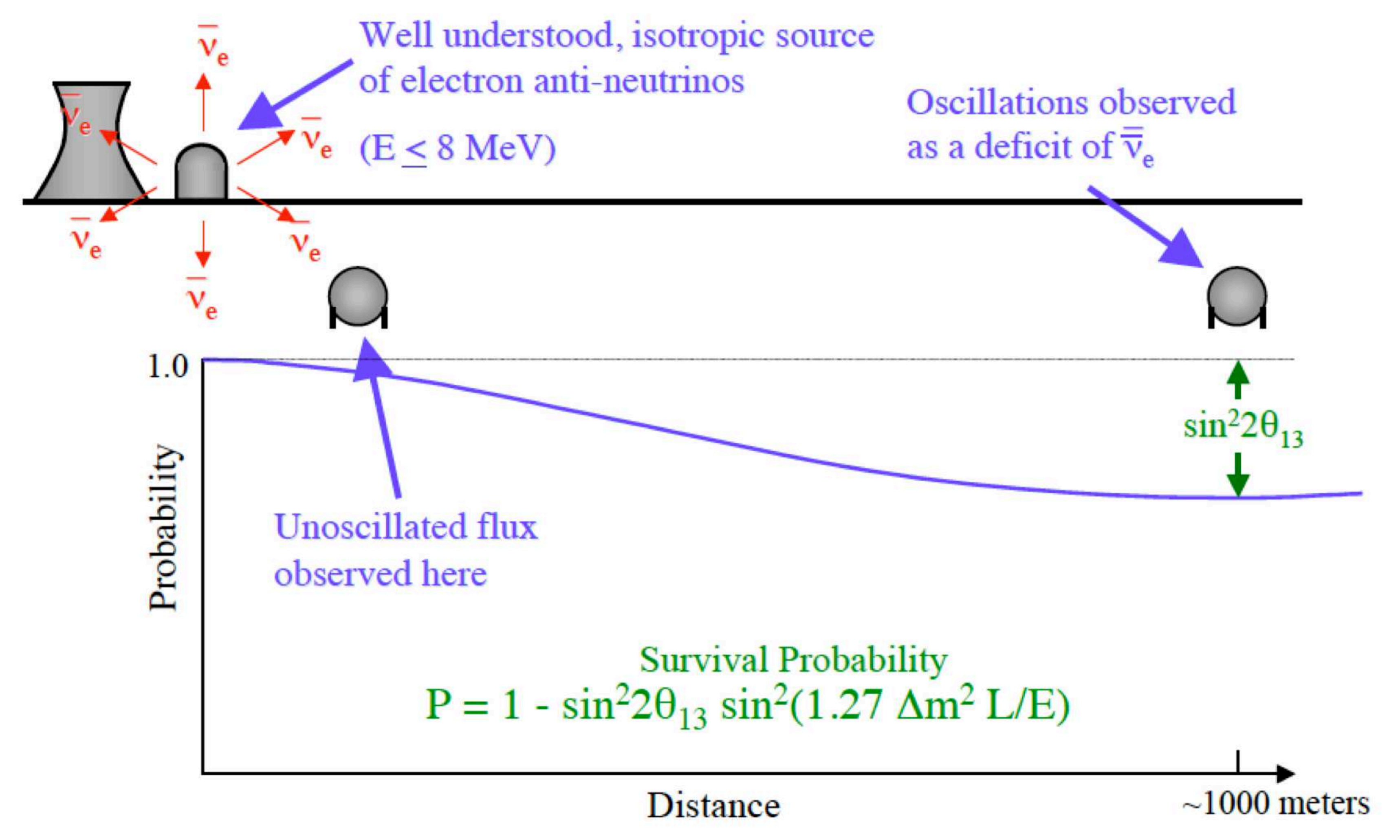


Next generation of reactor experiments



[redacted]

Chasing θ_{13} ...



Well understood, isotropic source of electron anti-neutrinos

($E \le 8$ MeV)

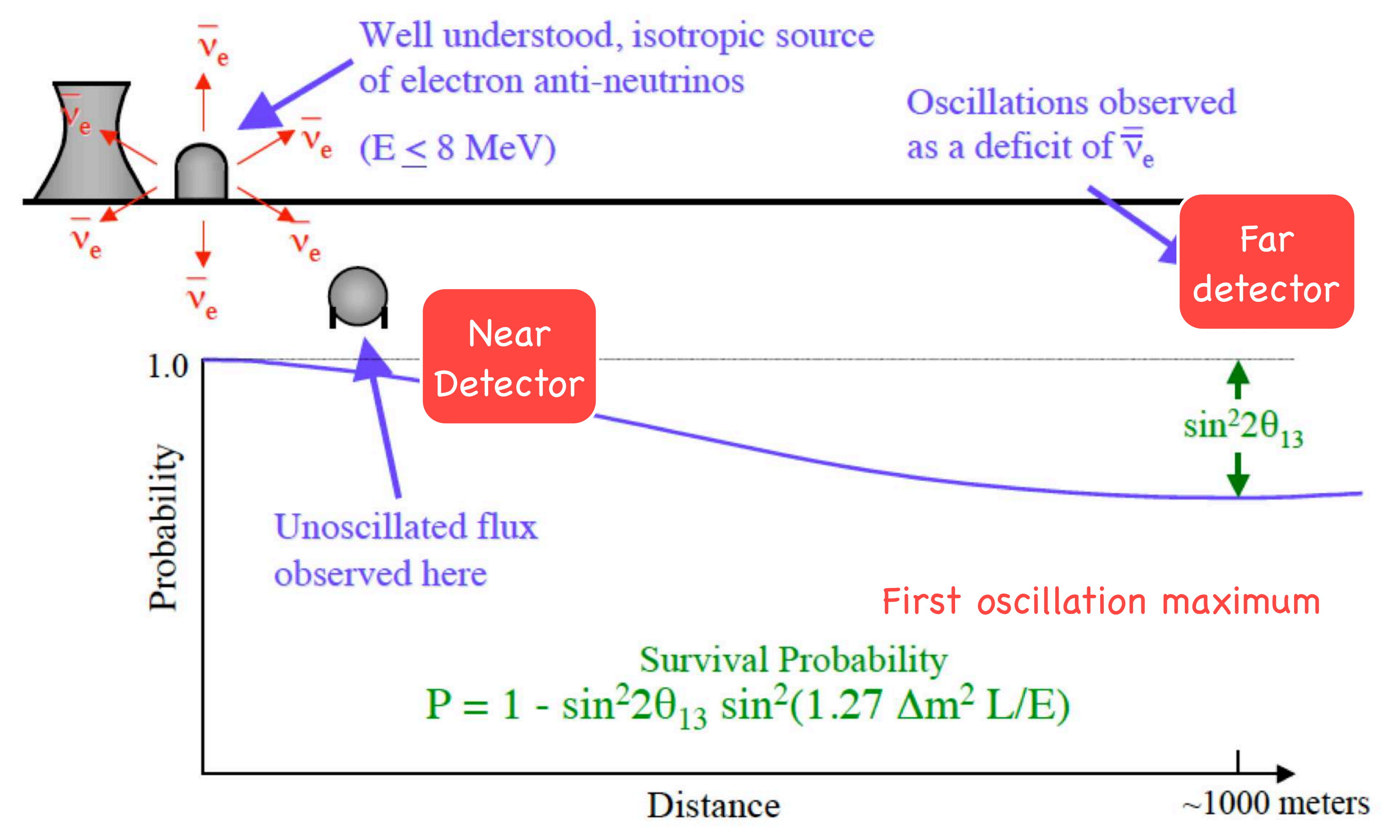
Oscillations observed as a deficit of $\bar{\nu}_e$

Unoscillated flux observed here

Survival Probability

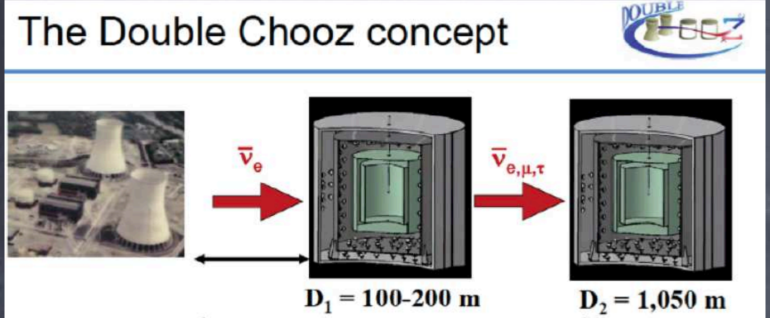
$$P = 1 - \sin^2 2\theta_{13} \sin^2(1.27\, \Delta m^2\, L/E)$$

Chasing θ_{13} ...

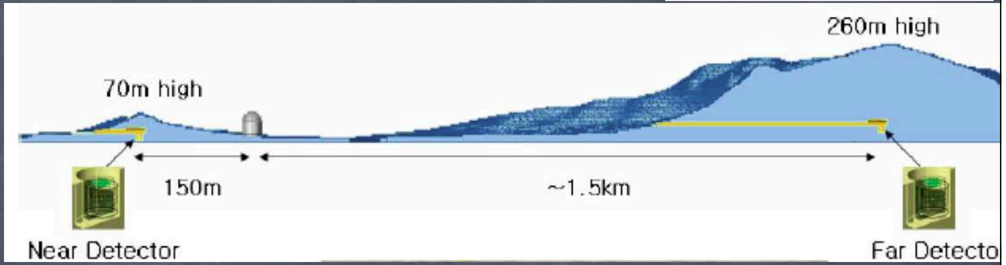


3 proposals...

France


The Double Chooz concept

Korea

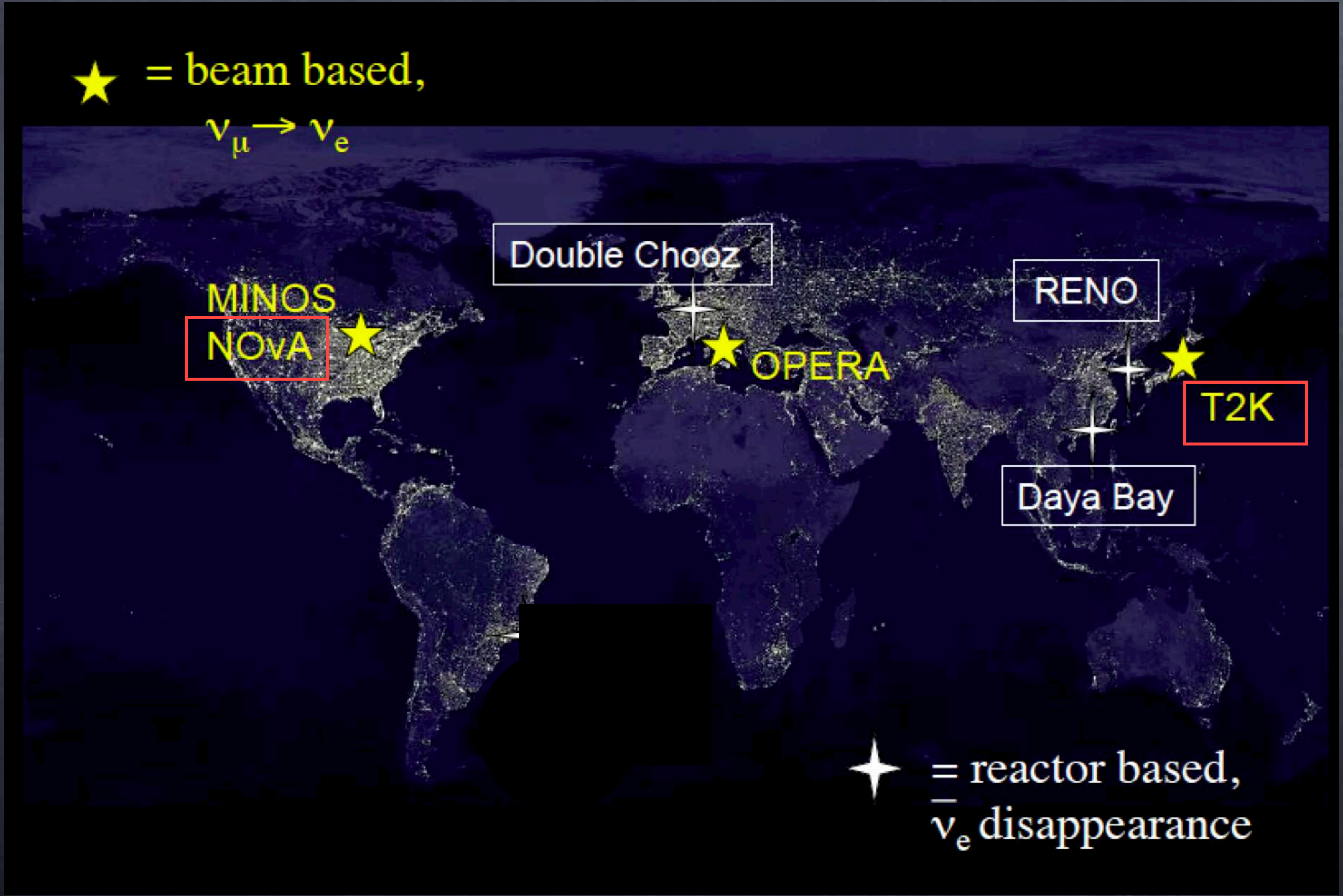


China

- more powerful reactors (multi-core)
- larger detector volume
- 2-3 detectors at 100 m - 1 km.
- sensitivity after 3 years (90% C.L.):

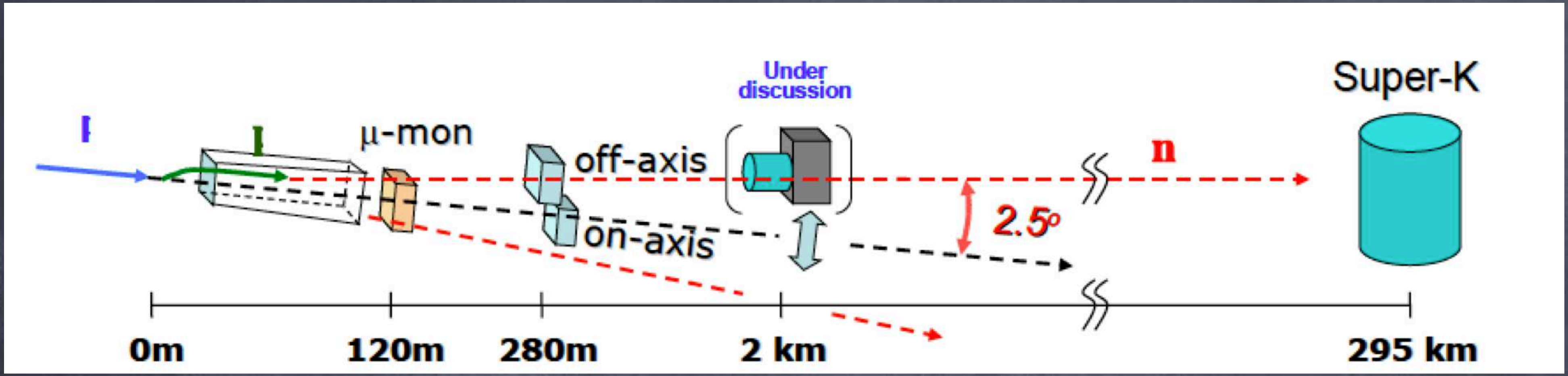
Double-CHOOZ: $\sin^2\theta_{13}$~0.005 – 0.008
RENO: $\sin^2\theta_{13}$~0.005 – 0.008
Daya Bay: $\sin^2\theta_{13}$~0.0025

Next generation of accelerator experiments



[redacted]

LBL off-axis experiments: T2K, NovA



- long-baseline experiments (300 - 800 km)
- "off-axis" technology-> monoenergetic neutrino beam.
- precision measurements of atmospheric oscillation parameters (1%).
- optimized to search for ν_e appearance in a ν_μ beam.
- potentially sensitive to CP violation.

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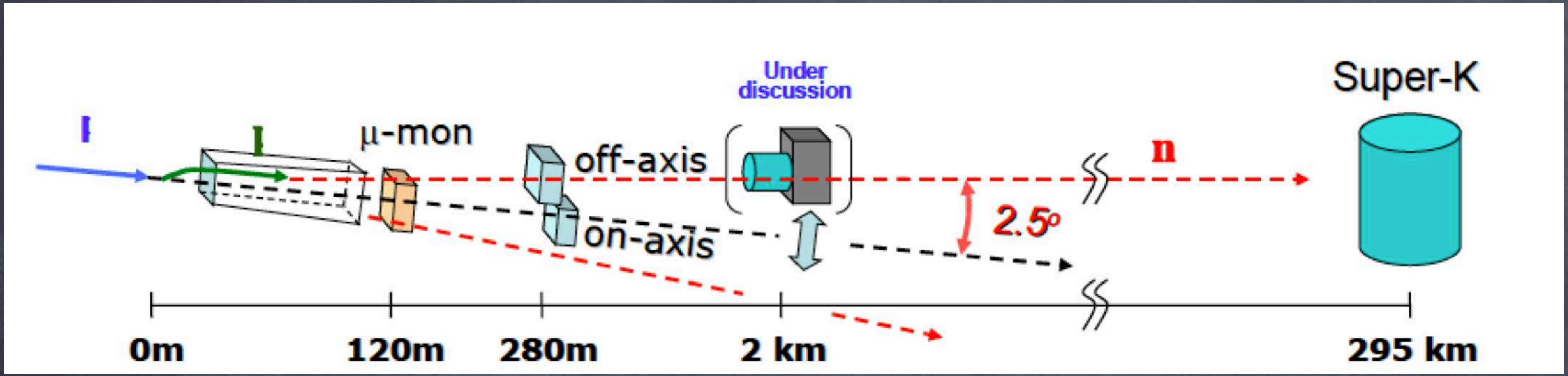

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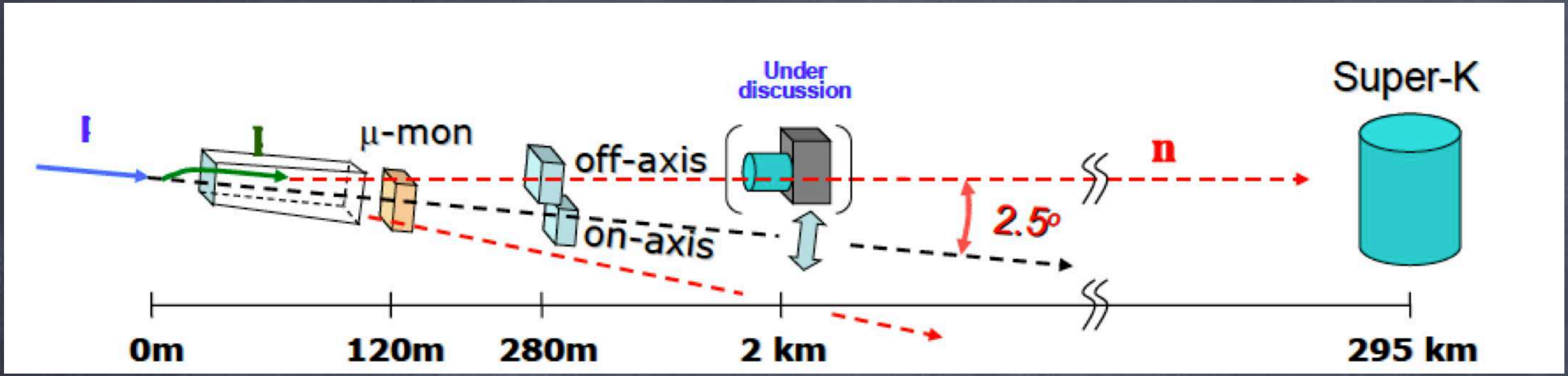
Further in the future...

LBL off-axis experiments: T2K, NovA



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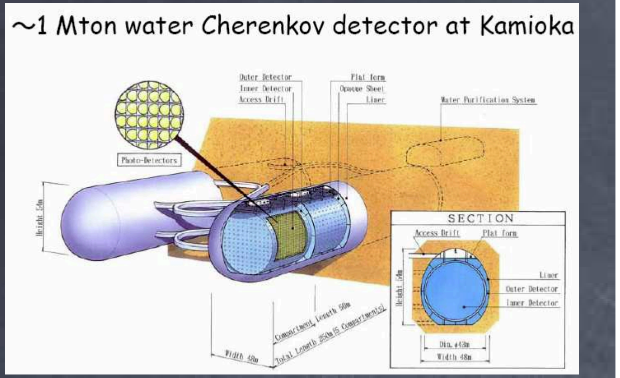
Further in the future...

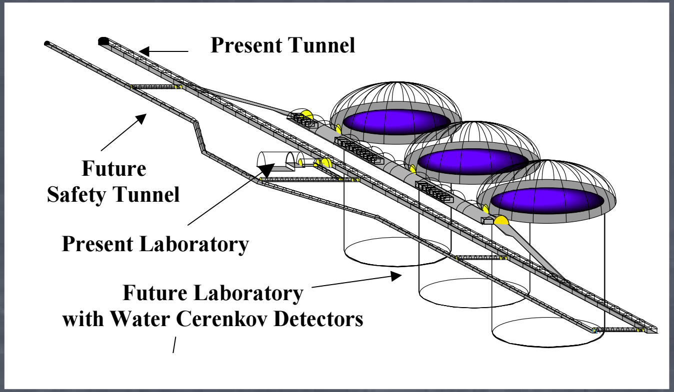
β-beams (2015-2020??):
- improved sensitivity: $\sin^2 2\theta_{13} \lesssim 10^{-3}$
- discovery potential for δ_{CP} and hierarchy if $\theta_{13} \gtrsim 1^{\circ}$

Neutrino Factory (> 2020):
- sensitivity on θ_{13}, δ_{CP}, mass hierarchy.

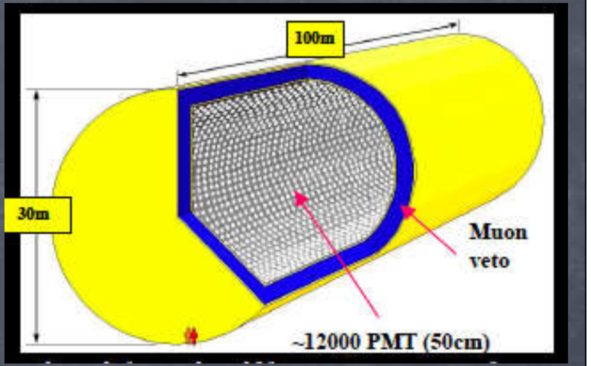
Large underground detectors



Hyper-Kamiokande



MEMPHYS



LENA

- proposals in USA (DUSEL), Europe (LAGUNA) and Japan (Hyper-K).
- detector technology:
  - Mton water Cerenkov: Hyper-Kamiokande, MEMPHYS, UNO
  - liquid scintillator: LENA
  - liquid Argon: GLACIER
- multi-purpose: p decay, supernova, LBL, solar, atmospheric, ...

Summary

- confirmation of neutrino oscillations at different experiments.
- (Δm^2_{32} , θ_{23}), (Δm^2_{21} , θ_{12}) measured accurately ($\lesssim$ 10%) by the combination of different experiments.
- upper bound on θ_{13} coming mainly from reactor experiments.
- recent indications for $\theta_{13} \neq 0$ ⇒ to be confirmed.

- good level of precision: neutrino oscillations can be used to investigate the presence of non-standard physics.
- next generation of neutrino oscillation experiments:
  - ⇒ precision measurements of atm and solar parameters.
  - ⇒ new discoveries: θ_{13}, δ_{CP}, mass hierarchy, new physics...