2nd Vienna Central European Seminar

Neutrino Oscillations: Present status and outlook

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Vienna Convention Bureau

Outline

- Introduction

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- Analysis of global neutrino oscillation data from
  solar (SNO, SK, GNO, SAGE, Homestake),
  atmospheric (SK),
  reactor (KamLAND, CHOOZ),
  accelerator (K2K)

  M. Maltoni, T. Schwetz, M.A. Tortola and J.W.F. Valle, hep-ph/0309130, hep-ph/0405172

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- Outlook for upcoming LBL experiments
  Leading atmospheric parameters
  Sensitivity to θ_{13} and the CP-phase

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- Summary

Introduction

If neutrinos have mass **neutrino mixing** will occure.

In the basis where the charged lepton mass matrix is diagonal:

$$\nu_{\alpha L} = \sum_{i=1}^{3} U_{\alpha i}\, \nu_{iL}\,, \qquad (\alpha = e, \mu, \tau)$$

$\nu_{\alpha L}$: neutrino fields participating in CC interactions (flavour fields)

ν_{iL} : neutrino fields with masses m_i

$U_{\alpha i}$: unitary lepton mixing matrix

Introduction

the oscillation probability in vaccum:

$$P_{\nu_\alpha \to \nu_\beta} = \sum_{jk} U_{\alpha j} U^*_{\beta j} U^*_{\alpha k} U_{\beta k} \exp\left[-i \frac{\Delta m^2_{kj}}{2} \frac{L}{E_\nu}\right]$$

L : distance between neutrino source and detector

E_ν : neutrino energy

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$\longrightarrow$ no information on absolute neutrino masses

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$\longrightarrow$ no information on absolute neutrino masses

holds also for oscillations in matter (MSW effect)

3-flavour oscillation parameters

Δm^2_{31} Δm^2_{21}

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

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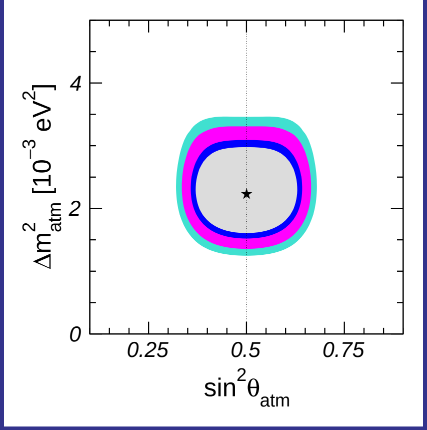
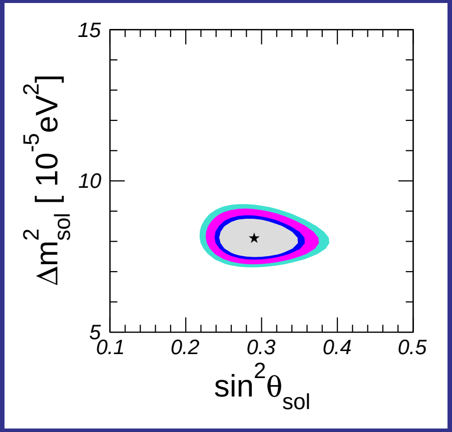


atmospheric + K2K



solar + KamLAND

Maltoni, Schwetz, Tortola, Valle, hep-ph/0405172; Fogli, Lisi, Marrone, Palazzo, hep-ph/0506083; Strumia, Vissani, hep-ph/0503246; Gonzalez-Garcia, Pena-Garay, PRD **68** (2003) 093003; Bahcall, Gonzalez-Garcia, Pena-Garay, JHEP **0408** (2004) 016; de Holanda, Smirnov, Astropart. Phys. **21** (2004) 287; Bandyopadhyay, Choubey, Goswami, Petcov, Roy, hep-ph/0406328.

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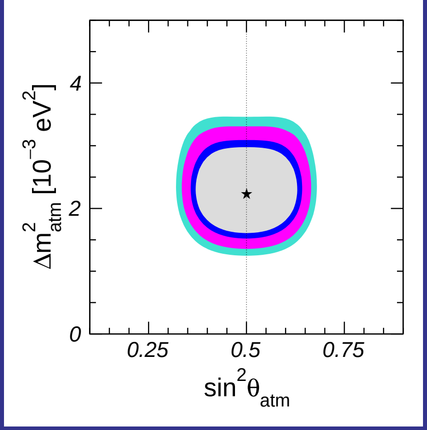

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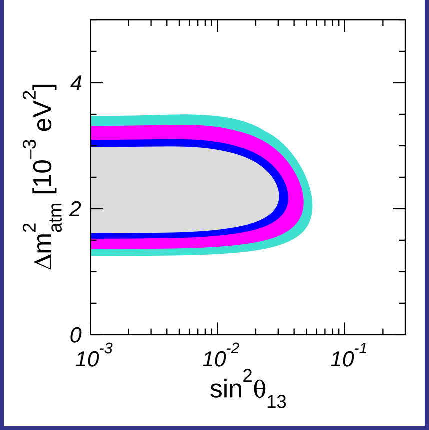
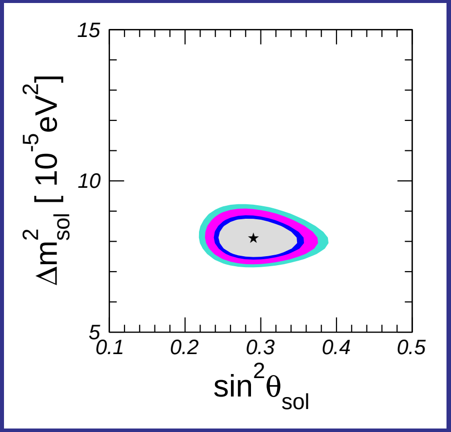


CHOOZ



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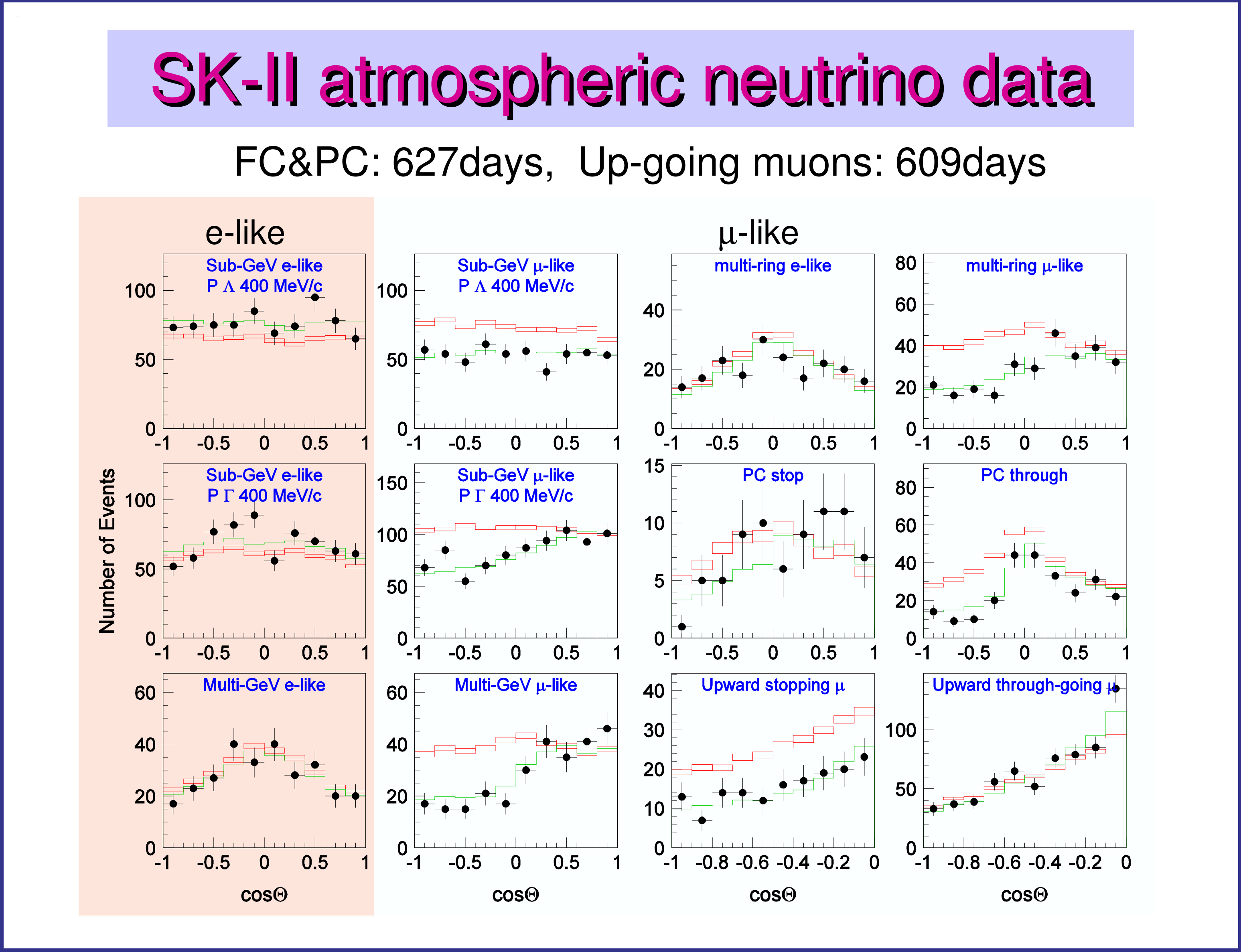
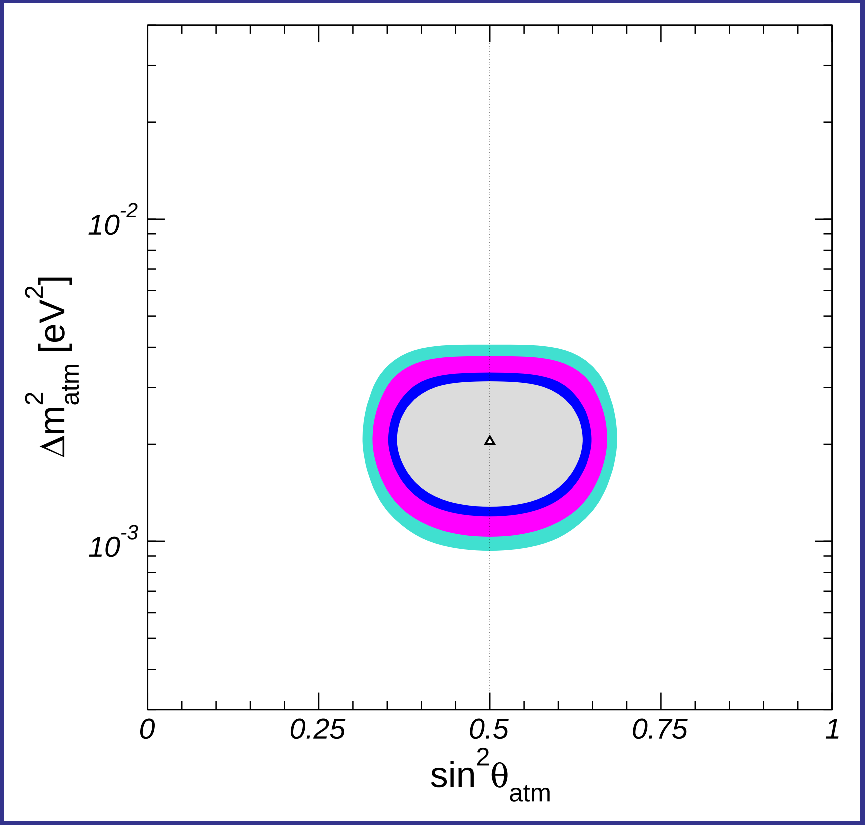
The ’atmospheric’ parameters Δm^2_{31}, θ_{23}

’Atmospheric’ parameters



T. Kajita, Super-K Coll., talk at NuFact05

’Atmospheric’ parameters



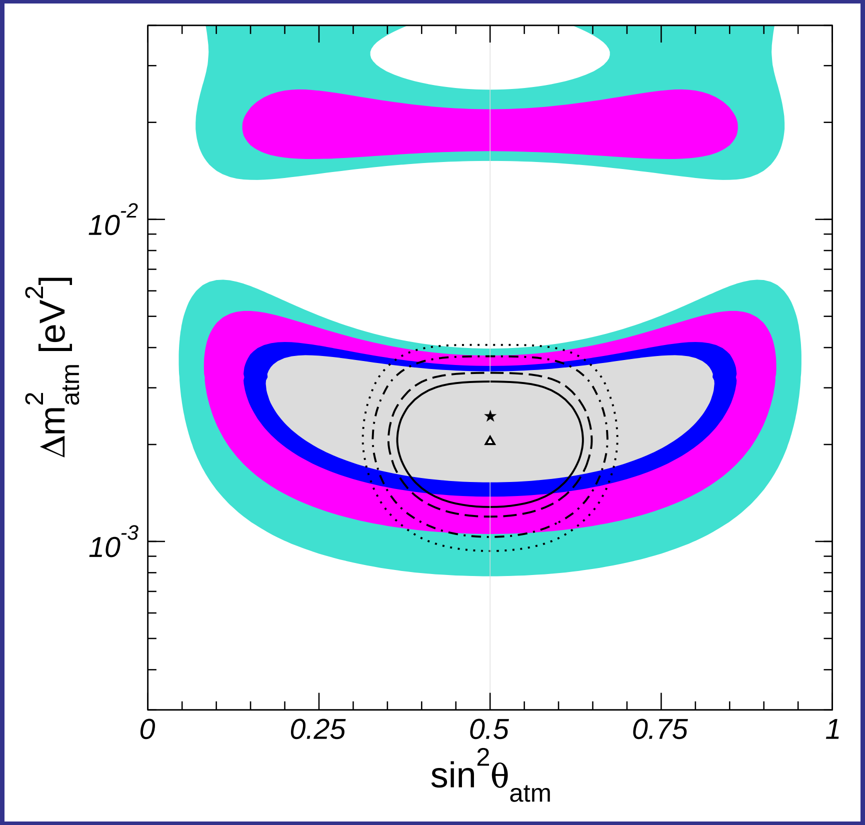
best fit:

$\Delta m^2_{32} = 2.0 \times 10^{-3}$ eV^2

$\sin^2\theta_{23} = 0.5$

Atmospheric neutrino data from SK-I

’Atmospheric’ parameters



best fi t:

$\Delta m^2_{32} = 2.2 \times 10^{-3}$ eV^2

$\sin^2\theta_{23} = 0.5$

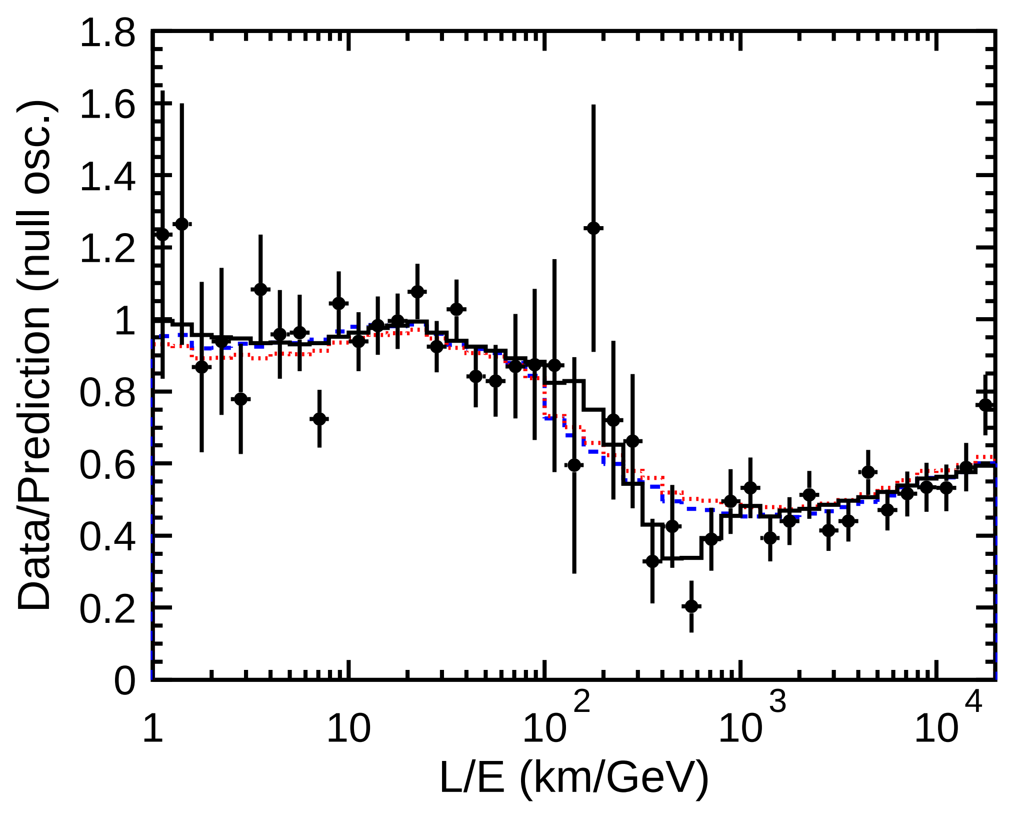
(K2K spectral analysis with 56 1-ring μ-like events)

K2K: 250 km from KEK to SK, 1.3 GeV neutrinos

108 events observed, $150.9^{+11.6}_{-10.0}$ expected for no osc

Oscillatory signal in atmospheric neutrinos

Super-K Coll., Phys. Rev. Lett. **93** (2004) 101801



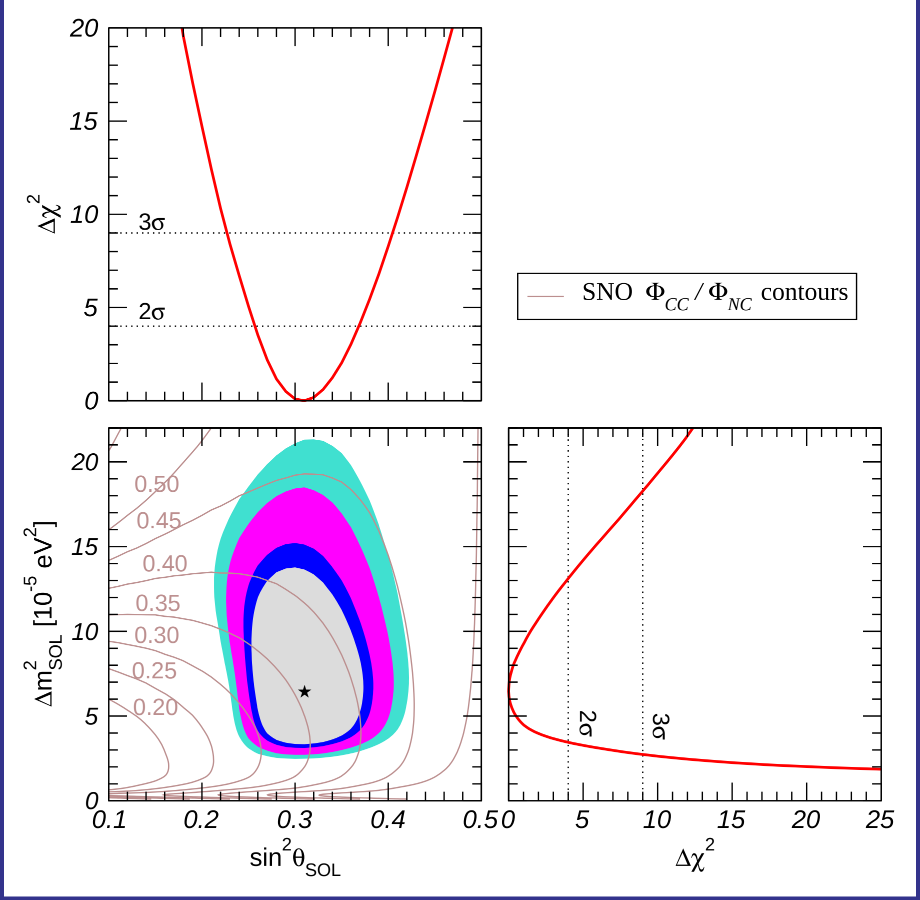
$$P_{2\nu} = 1 - \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2}{4}\frac{L}{E_\nu}\right)$$

The ’solar’ parameters Δm^2_{21}, θ_{12}

'Solar' parameters

global solar neutrino data:

Homestake,SAGE,GNO,SK,SNO



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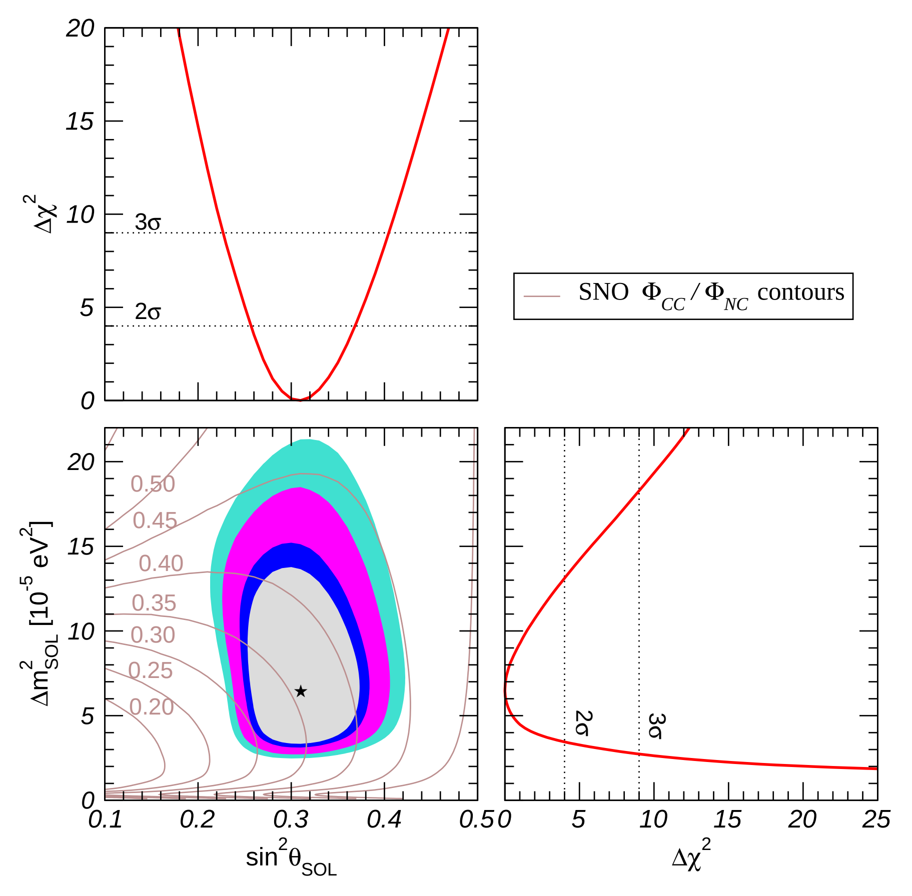


The SNO experiment:

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

$$\nu_x + d \to p + n + \nu_x$$

SNO-II 391d nucl-ex/0502021

$$\frac{\phi_{CC}}{\phi_{NC}} = 0.340 \pm 0.023 \pm 0.030$$

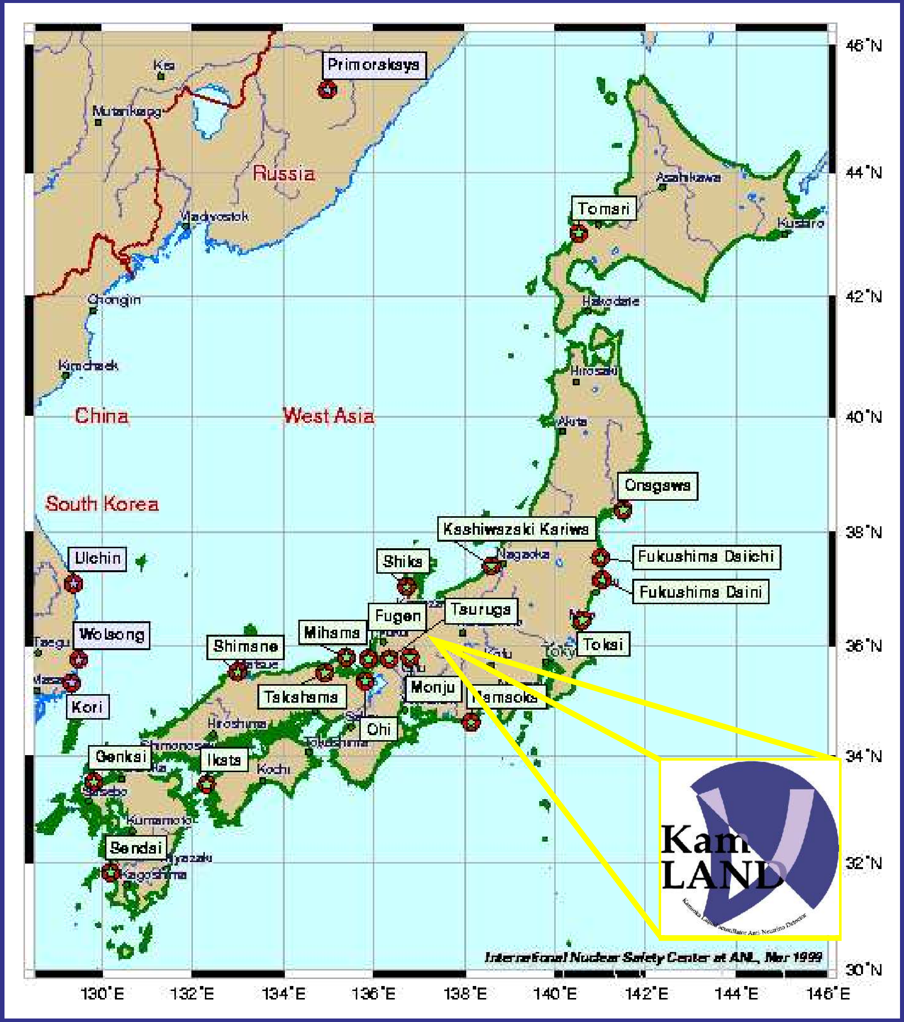
7σ evidence for a non-zero $\nu_{\mu,\tau}$ flux from the sun

constraint on θ_{12}:

$$\frac{\phi_{CC}}{\phi_{NC}} \approx P_{ee}^{\rm SNO} \approx \sin^2\theta_{12}$$

The KamLAND reactor neutrino experiment

Kamioka Liquid scinitillator Anti-Neutrino Detector

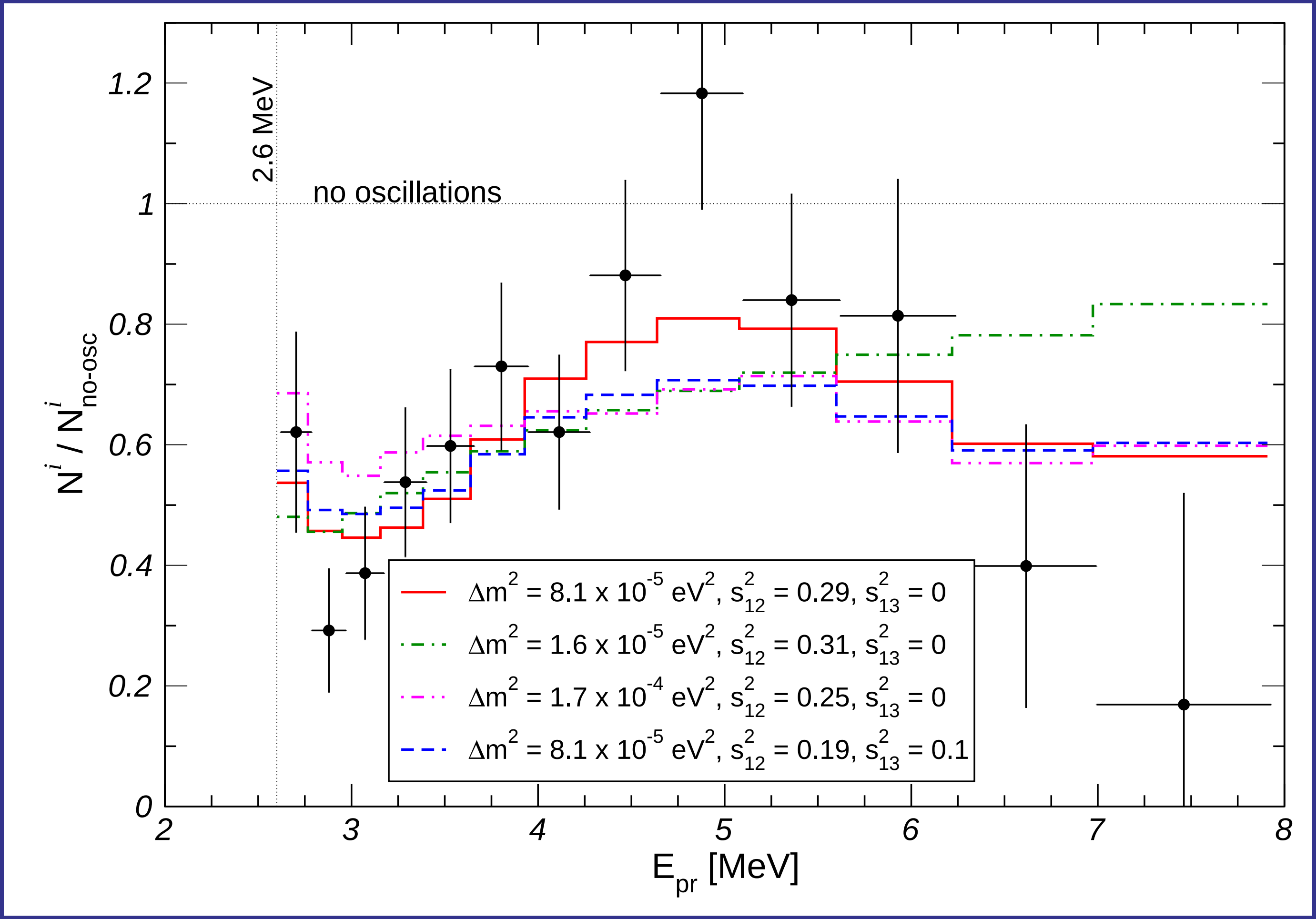


detection of $\bar{\nu}_e$ produced in surrounding nuclear power plants

70 GW of nuclear power (7% of world total) is generated at a distance 175 ± 30 km from Kamioka

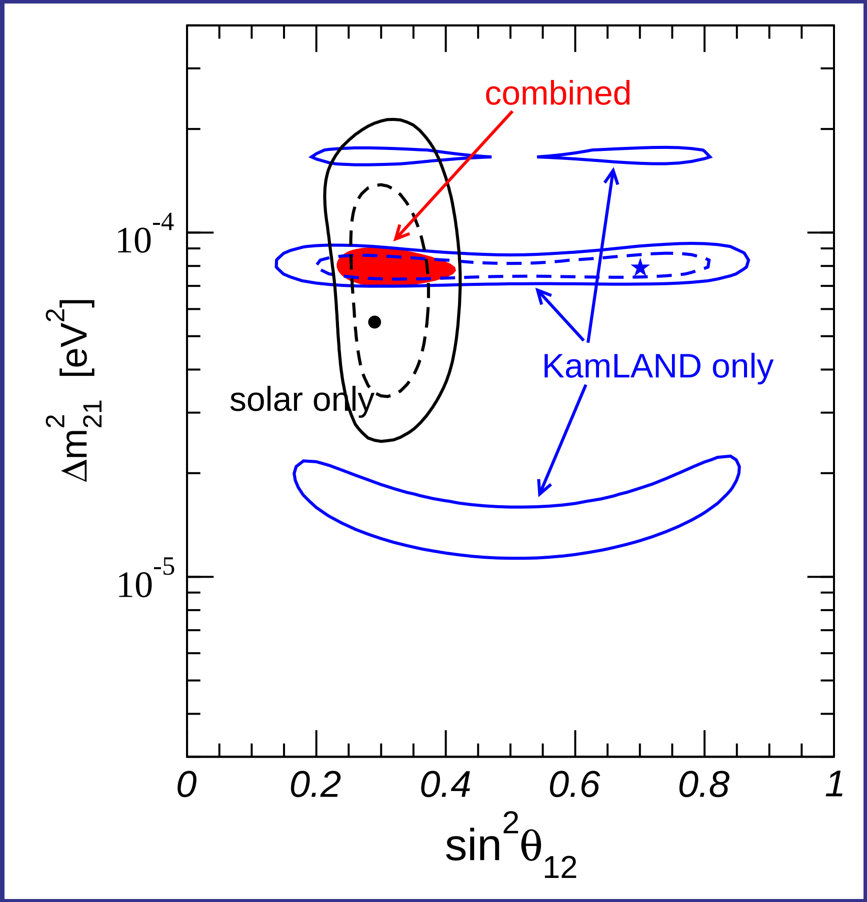
258 events are observed, 365.2 ± 23.7 expected for no disappearance

The KamLAND energy spectrum



evidence for flux suppression and spectral distortion

KamLAND vs solar data



$$\Delta m^2 = 7.9 \pm 0.3 \times 10^{-5}\ \text{eV}^2,\ \sin^2\theta_{12} = 0.31^{+0.02}_{-0.03}$$

The bound on θ_{13}

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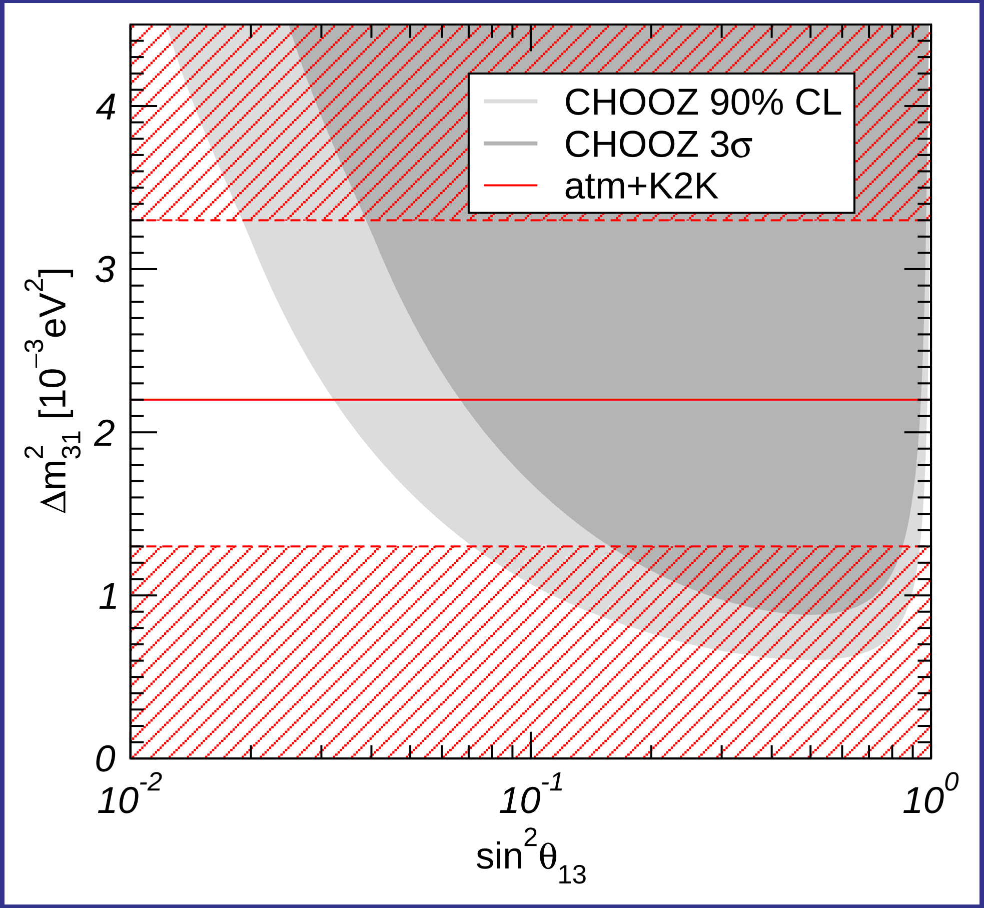
CHOOZ bound depends on the value of Δm^2_{13}

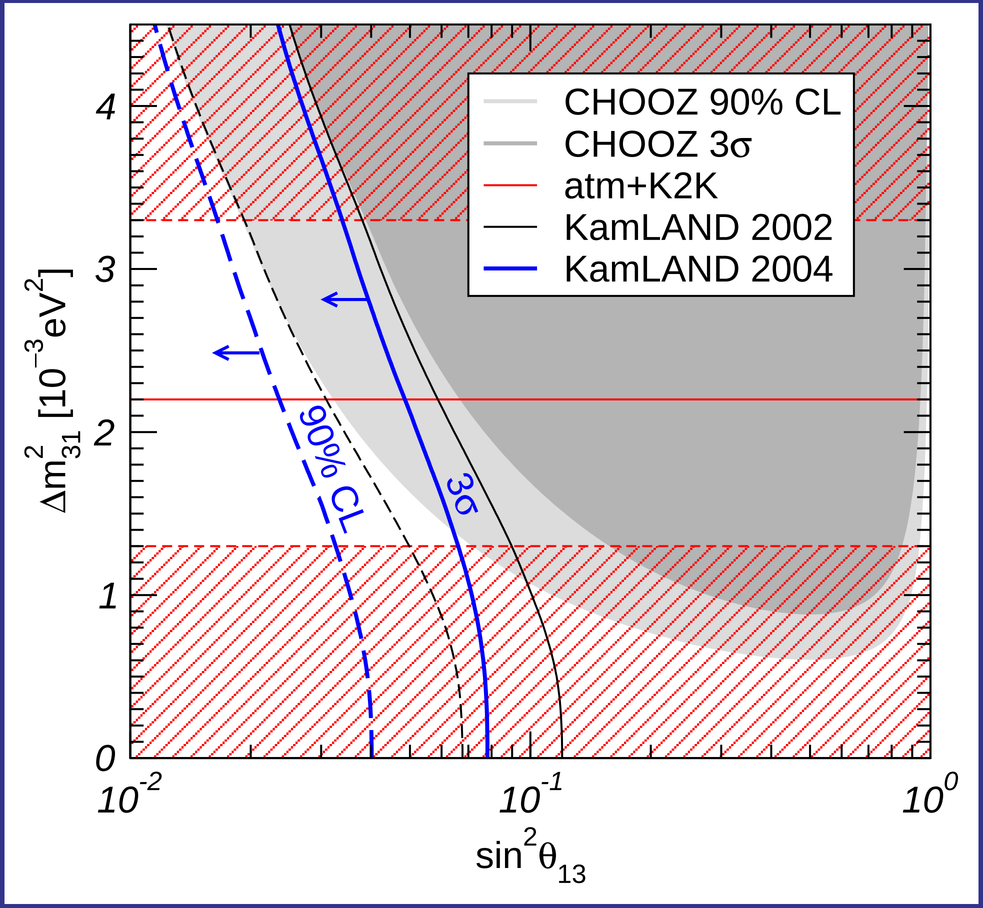


CHOOZ+atm+K2K:

$\sin^2\theta_{13} < 0.029\ (0.067)$

The bound on θ_{13}

solar data contribute for low Δm^2_{13}



CHOOZ+atm+K2K:

$\sin^2\theta_{13} < 0.029\,(0.067)$

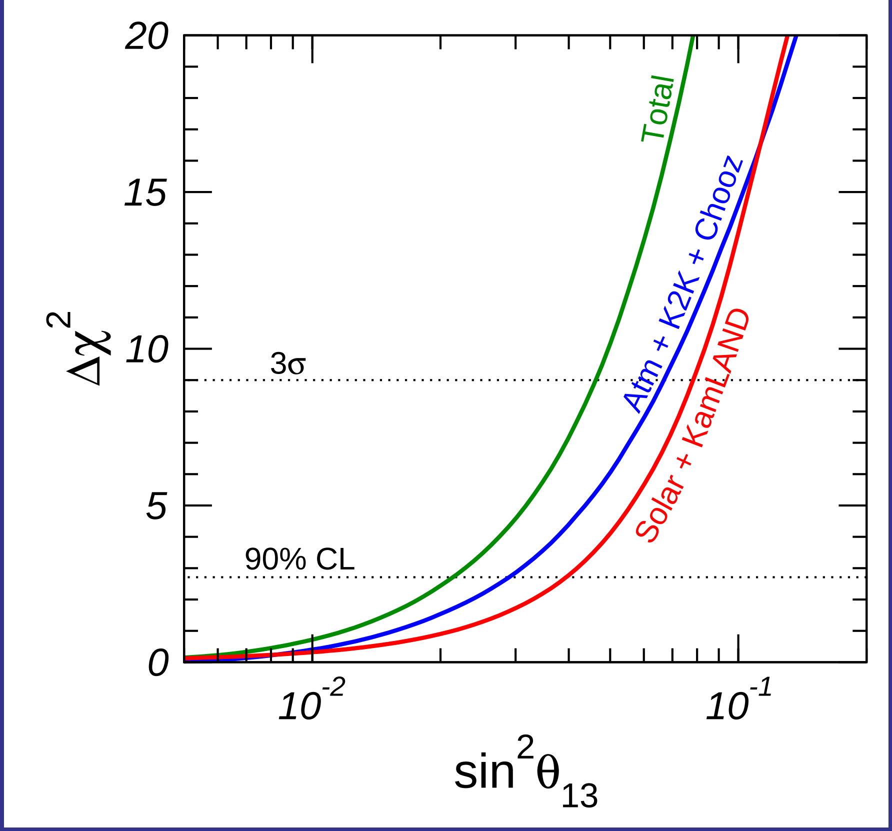
solar+KamL:

$\sin^2\theta_{13} < 0.041\,(0.079)$

global:

$\sin^2\theta_{13} < 0.021\,(0.046)$

The global bound on θ_{13}



$\sin^2\theta_{13} < 0.021\,(0.046)$ at 90% CL (3σ)

3-flavour oscillation parameters - Summary

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mass-squared differences:

parameter	bf$\pm 1\sigma$	1σ acc.	3σ range
Δm^2_{21} $[10^{-5}\text{eV}^2]$	7.9 ± 0.3	4%	$7.1 - 8.9$
$\|\Delta m^2_{31}\|$ $[10^{-3}\text{eV}^2]$	$2.2^{+0.37}_{-0.27}$	14%	$1.4 - 3.3$

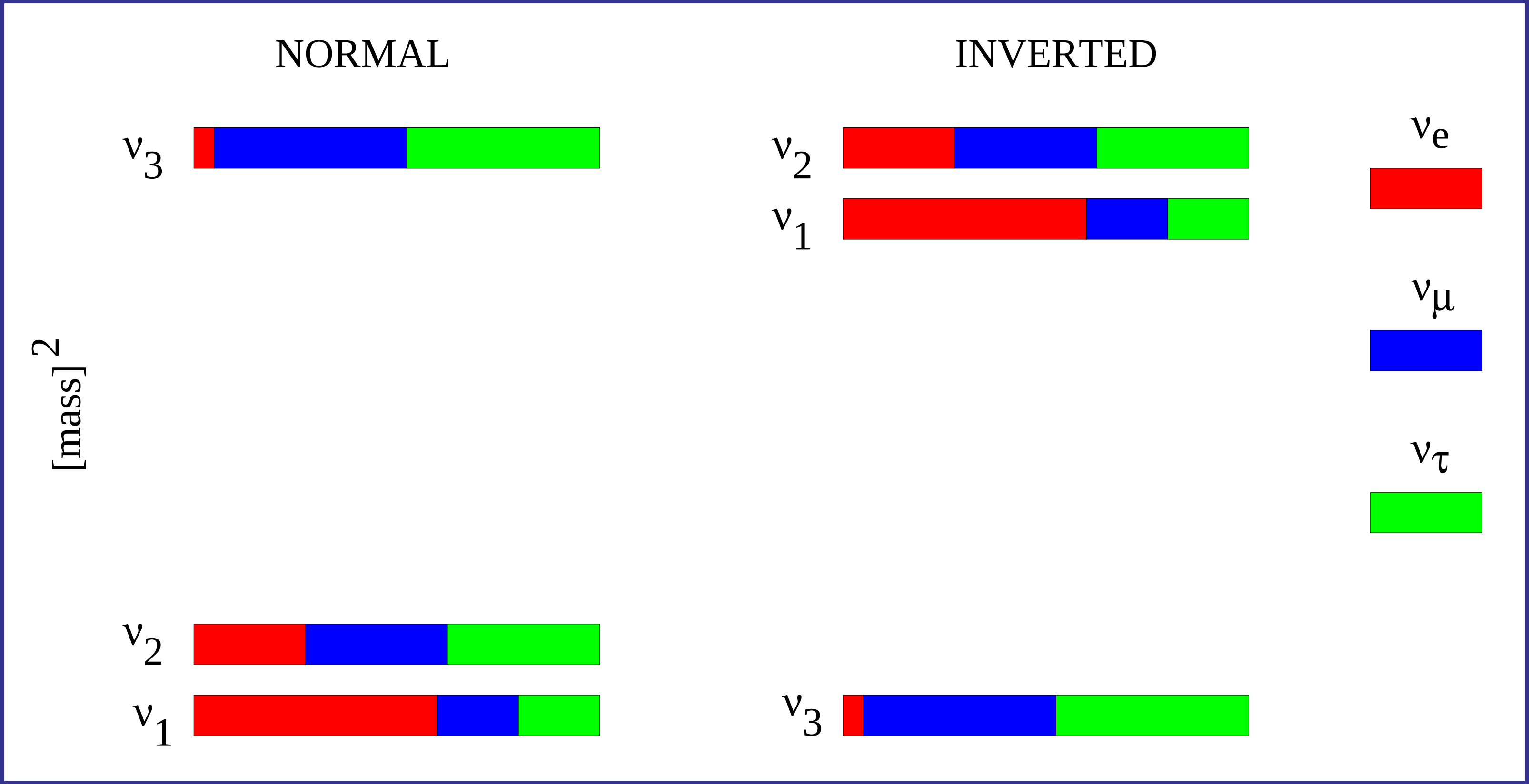
mixing angles:

parameter	bf$\pm 1\sigma$	1σ acc.	3σ range
$\sin^2\theta_{12}$	$0.31^{+0.02}_{-0.03}$	9%	$0.24 - 0.40$
$\sin^2\theta_{23}$	$0.50^{+0.06}_{-0.05}$	11%	$0.34 - 0.68$
$\sin^2\theta_{13}$	–	–	≤ 0.046

M. Maltoni, T. Schwetz, M.A. Tortola and J.W.F. Valle, hep-ph/0405172

3-flavour oscillation parameters - Summary

Two possibilities for the neutrino mass spectrum:



$\Delta m^2_{31} > 0$ $\Delta m^2_{31} < 0$

3-flavour oscillation parameters - Summary

Open questions:

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- Increase the precision on solar and atmospheric parameters (e.g. Is θ_{23} exactly 45°?)

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- What is the value of the CP phase δ?

3-flavour oscillation parameters - Summary

Open questions:

- Increase the precision on solar and atmospheric parameters (e.g. Is θ_{23} exactly 45°?)
- How small is θ_{13}?
- What is the value of the CP phase δ?
- Type of the neutrino mass ordering (sign of Δm^2_{31})

Outlook for upcoming experiments

coming ~ 10 years

LBL experiments in the next ten years

Conventional beam experiments:

Reactor experiments with near and far detectors:

Off-axis superbeams:

LBL experiments in the next ten years

Label	L	$\langle E_\nu \rangle$	$t_{\rm run}$	channel
Conventional beam experiments:				
MINOS	$735\,\mathrm{km}$	$3\,\mathrm{GeV}$	$5\,\mathrm{yr}$	$\nu_\mu \to \nu_\mu, \nu_e$
Reactor experiments with near and far detectors:				
Off-axis superbeams:				

MINOS:
Fermilab to Soudan mine, 5.4 kt magnetized iron calorimeter

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MINOS	$735\,\rm km$	$3\,\rm GeV$	$5\,\rm yr$	$\nu_\mu \to \nu_\mu, \nu_e$
ICARUS	$732\,\rm km$	$17\,\rm GeV$	$5\,\rm yr$	$\nu_\mu \to \nu_e, \nu_\mu, \nu_\tau$
OPERA	$732\,\rm km$	$17\,\rm GeV$	$5\,\rm yr$	$\nu_\mu \to \nu_e, \nu_\mu, \nu_\tau$
Reactor experiments with near and far detectors:				
Off-axis superbeams:				

CNGS: CERN to Gran Sasso, ν_τ appearance

ICARUS: 2.35 kt liquid argon TPC

OPERA: 1.65 kt emulsion cloud chamber

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Reactor experiments with near and far detectors:				
D-Chooz	$1.05\,\text{km}$	$\sim 4\,\text{MeV}$	$3\,\text{yr}$	$\bar\nu_e \longrightarrow \bar\nu_e$
Reactor-II	$1.70\,\text{km}$	$\sim 4\,\text{MeV}$	$5\,\text{yr}$	$\bar\nu_e \longrightarrow \bar\nu_e$
Off-axis superbeams:				

D-Chooz: new experiment at Chooz site (60 000 events)

Reactor-II: optimized reactor experiment (630 000 events)

LBL experiments in the next ten years

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Off-axis superbeams:				
T2K	$295\,\rm km$	$0.76\,\rm GeV$	$5\,\rm yr$	$\nu_\mu \longrightarrow \nu_e, \nu_\mu$
NOνA	$812\,\rm km$	$2.22\,\rm GeV$	$5\,\rm yr$	$\nu_\mu \longrightarrow \nu_e, \nu_\mu$

T2K: Tokai (JPARC) to Kamioka (SK) 22.5 kt water Cherenkov

NOνA: 50 kt low-Z-calorimeter, off-axis angle of 0.72°

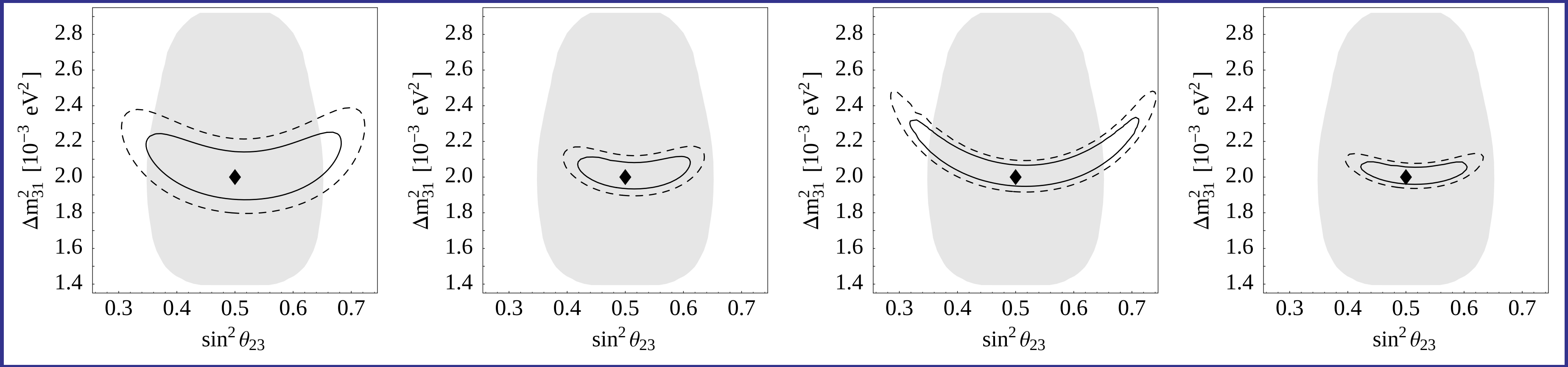
Improving on the ‘atmospheric’ parameters

θ_{23} and $|\Delta m^2_{31}|$

Atmospheric parameters $|\Delta m^2_{13}|$ *and* θ_{23}

ν_μ-disappearance in LBL accelerator experiments

MINOS+CNGS **T2K** **NOνA** combined



Atmospheric parameters $|\Delta m^2_{13}|$ *and* θ_{23}

precision at $3\sigma \equiv \frac{\text{upper}^{(3\sigma)} - \text{lower}^{(3\sigma)}}{\text{true value}}$

for true values $|\Delta m^2_{31}| = 2 \cdot 10^{-3}$eV^2 and $\sin^2\theta_{23} = 0.5$:

	$\lvert\Delta m^2_{31}\rvert$	$\sin^2\theta_{23}$
current	86%	68%
MINOS+CNGS	26%	78%
T2K	12%	46%
NOνA	25%	86%
Combination	9%	42%

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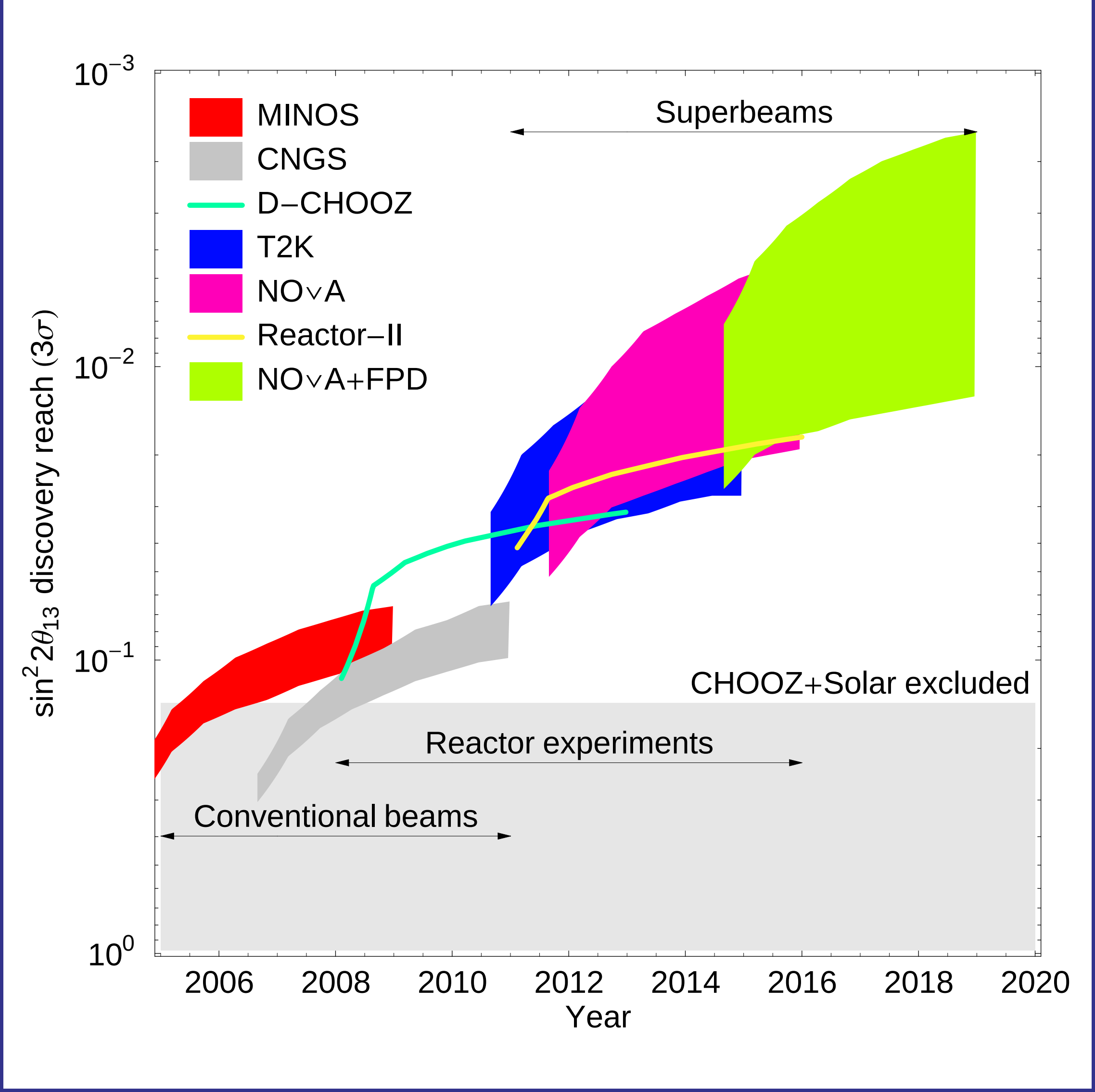
- naively one would expect $\theta_{12} \sim \theta_{23} \sim \theta_{13}$
  $\rightarrow \theta_{13}$ around the corner
- $\theta_{13} \ll 1$ hint for some symmetry
- relatively large θ_{13} opens the possibilty to observe generic 3-flavour effects (CP-violation)

Measuring θ_{13}

- reactor experiments with near and far detectors
  D-Chooz, KASKA, Daya Bay, Angra, Braidwood, RENO

- LBL $\nu_\mu \to \nu_e$ appearance experiments
  MINOS, CNGS, T2K, NOνA
  correlation with CP-phase δ

$\sin^2 2\theta_{13}$ *discovery reach evolution*

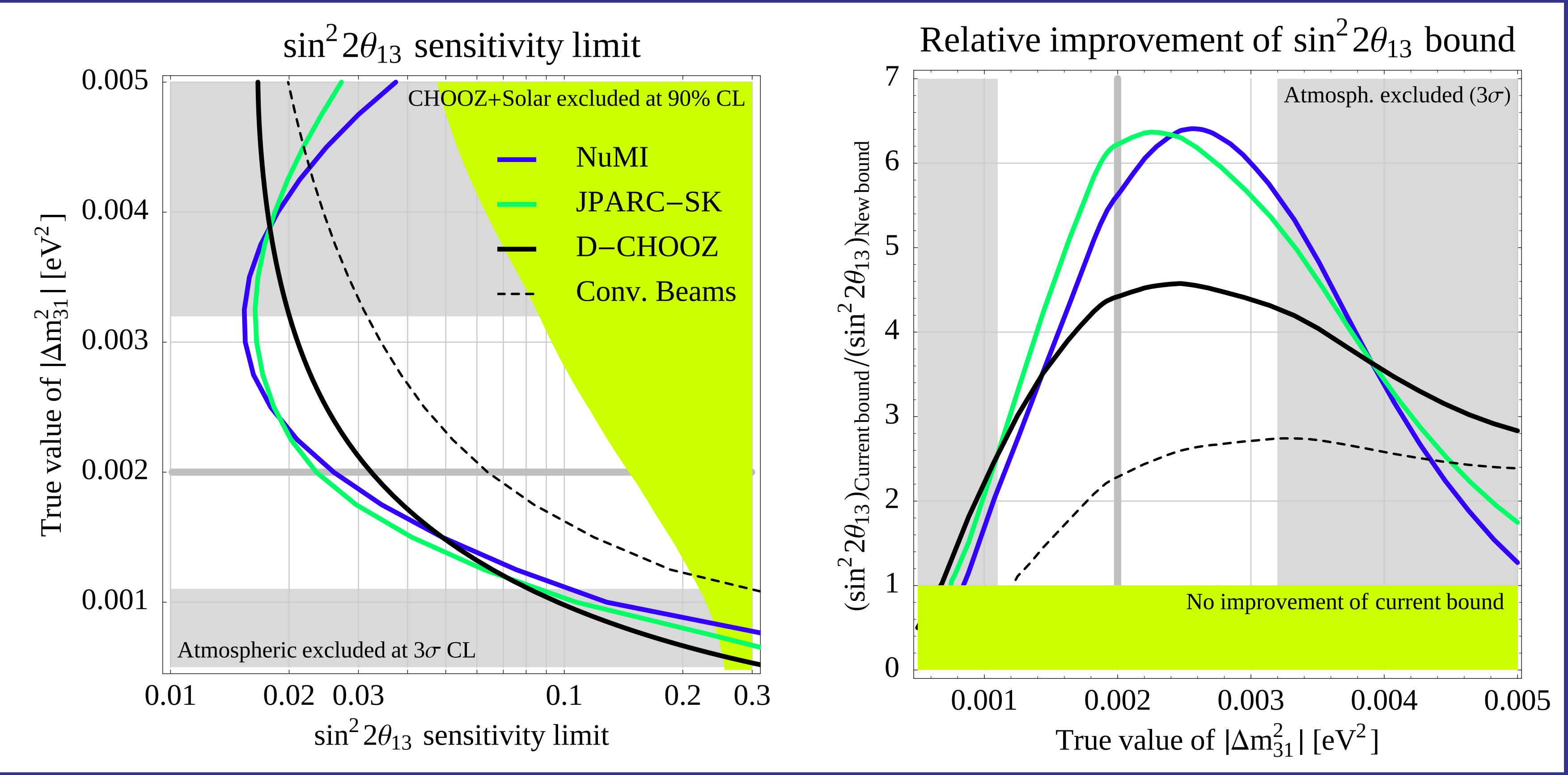


plot by W. Winter from
Albrow et al., hep-ex/0509019

$\Delta m^2_{31} = +2.5 \times 10^{-3}$ eV^2
$\sin^2 2\theta_{23} = 1$

FPD = Fermilab Proton Driver
LBL exps.: neutrinos only

$\sin^2 2\theta_{13}$-*limit within the next ten years*

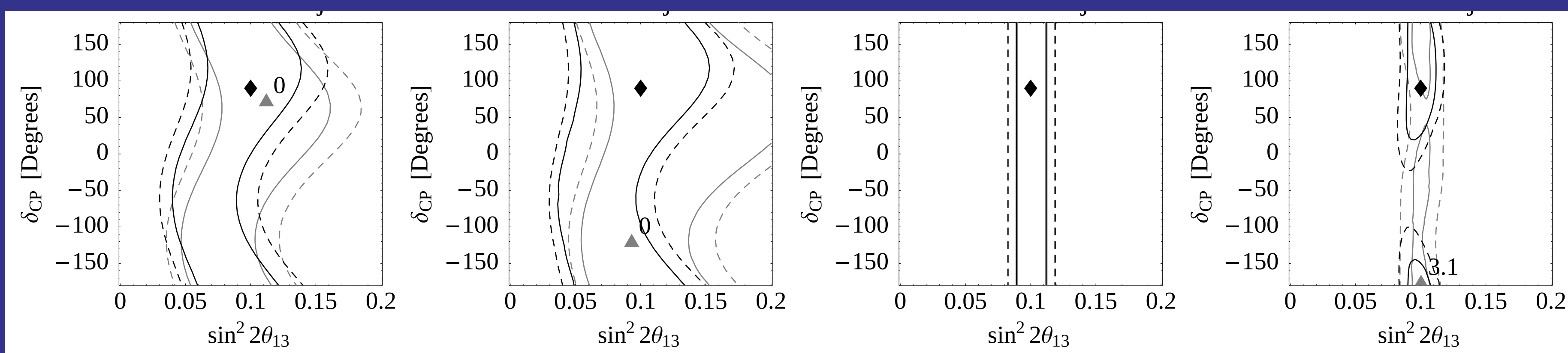


Huber, Lindner, Rolinec, Schwetz, Winter, hep-ph/0403068

Potential if $\sin^2 2\theta_{13}$ turns out to be large

assume $\sin^2 2\theta_{13} = 0.1$

T2K **NOνA** **Reactor-II** combined



Summary

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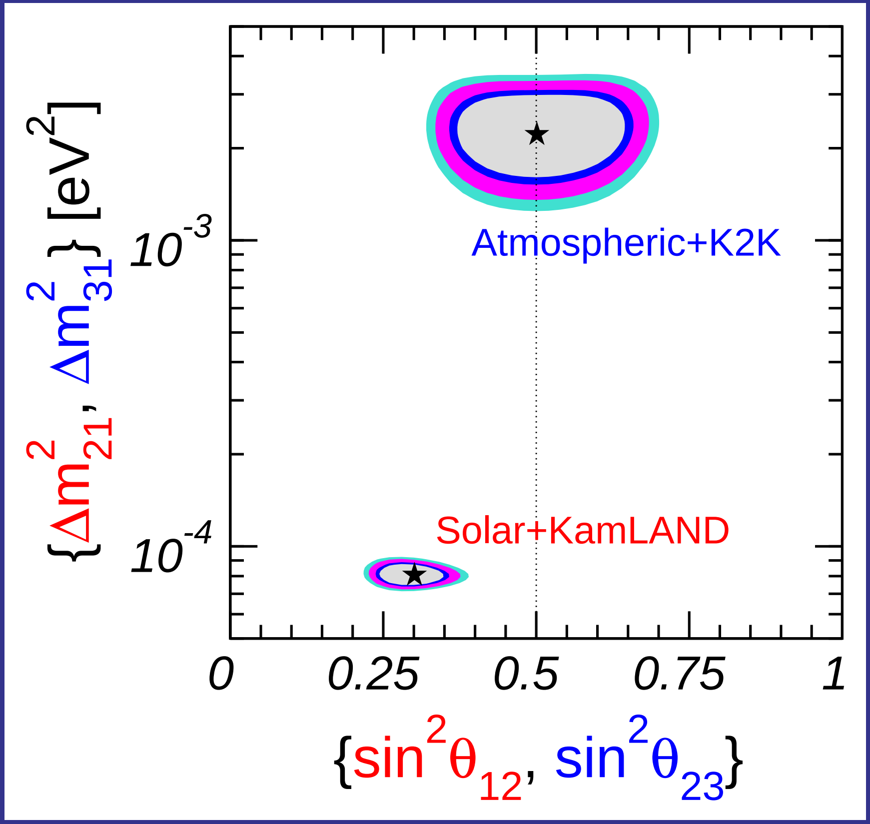
present



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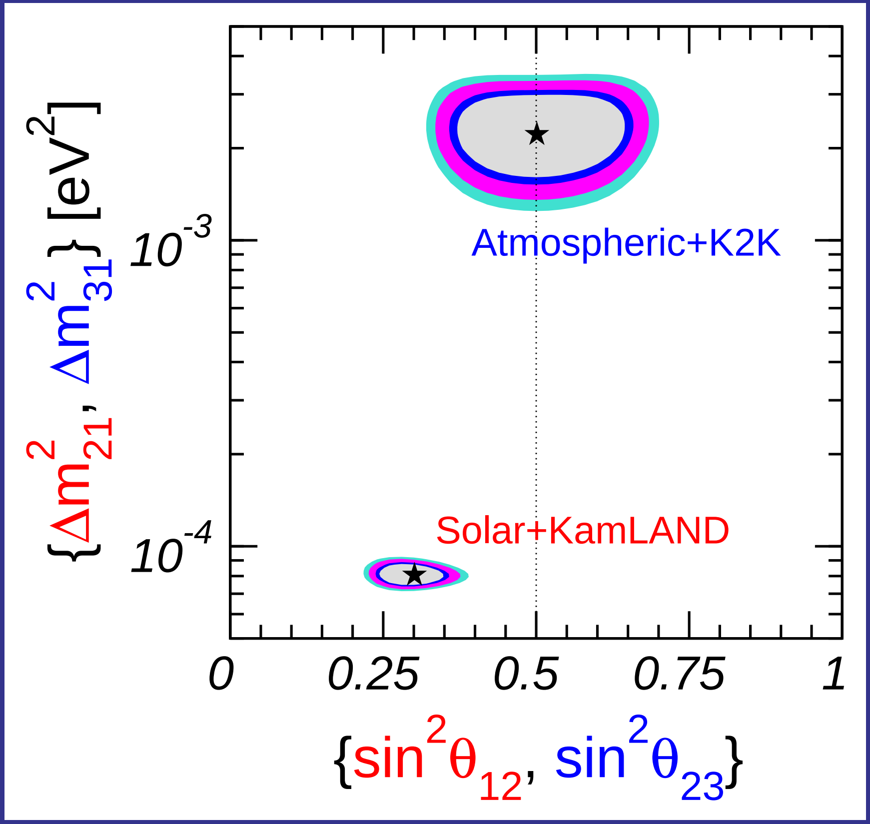
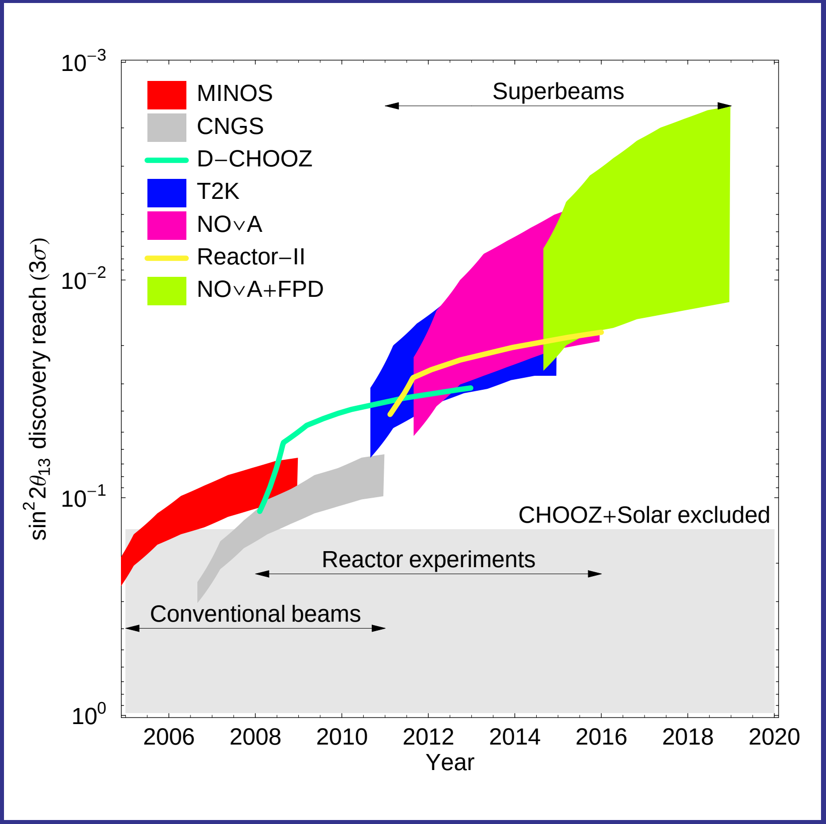
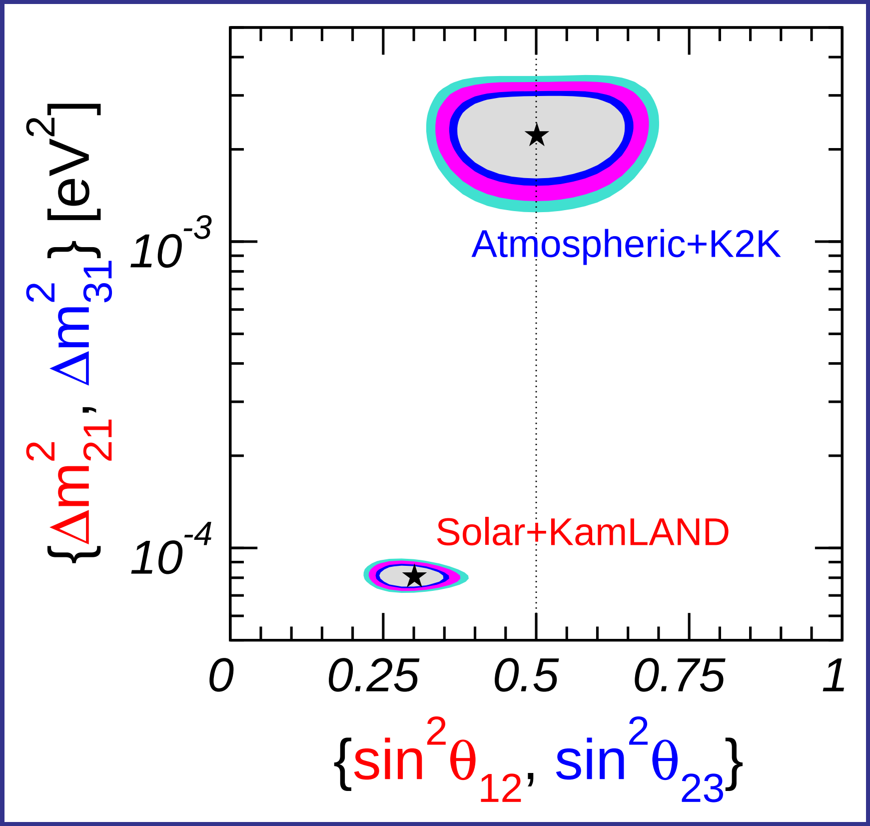


future

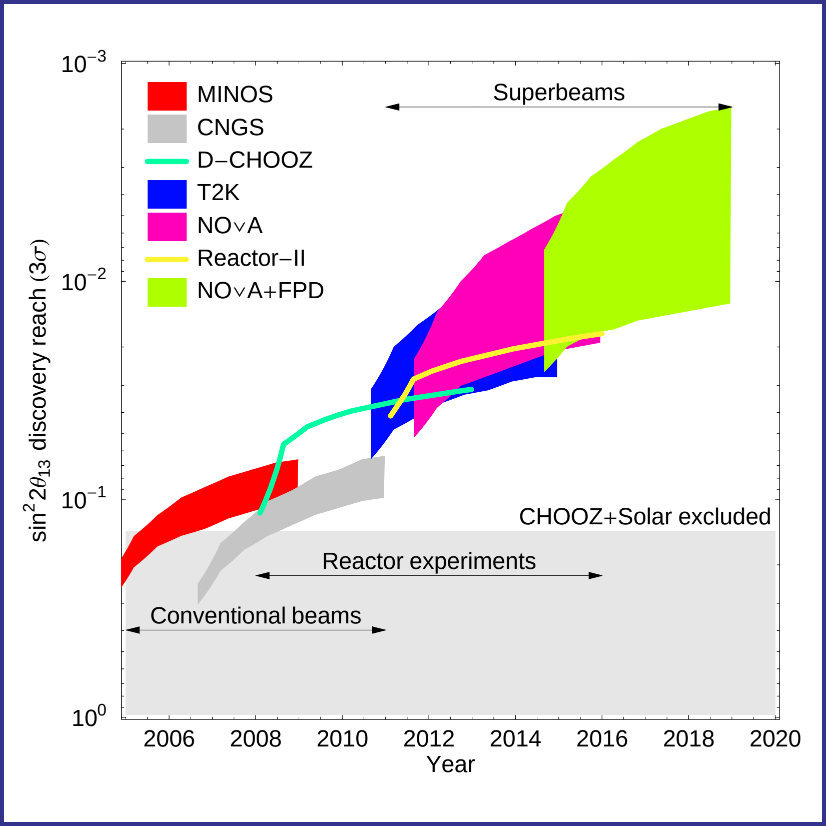


Summary

present



future

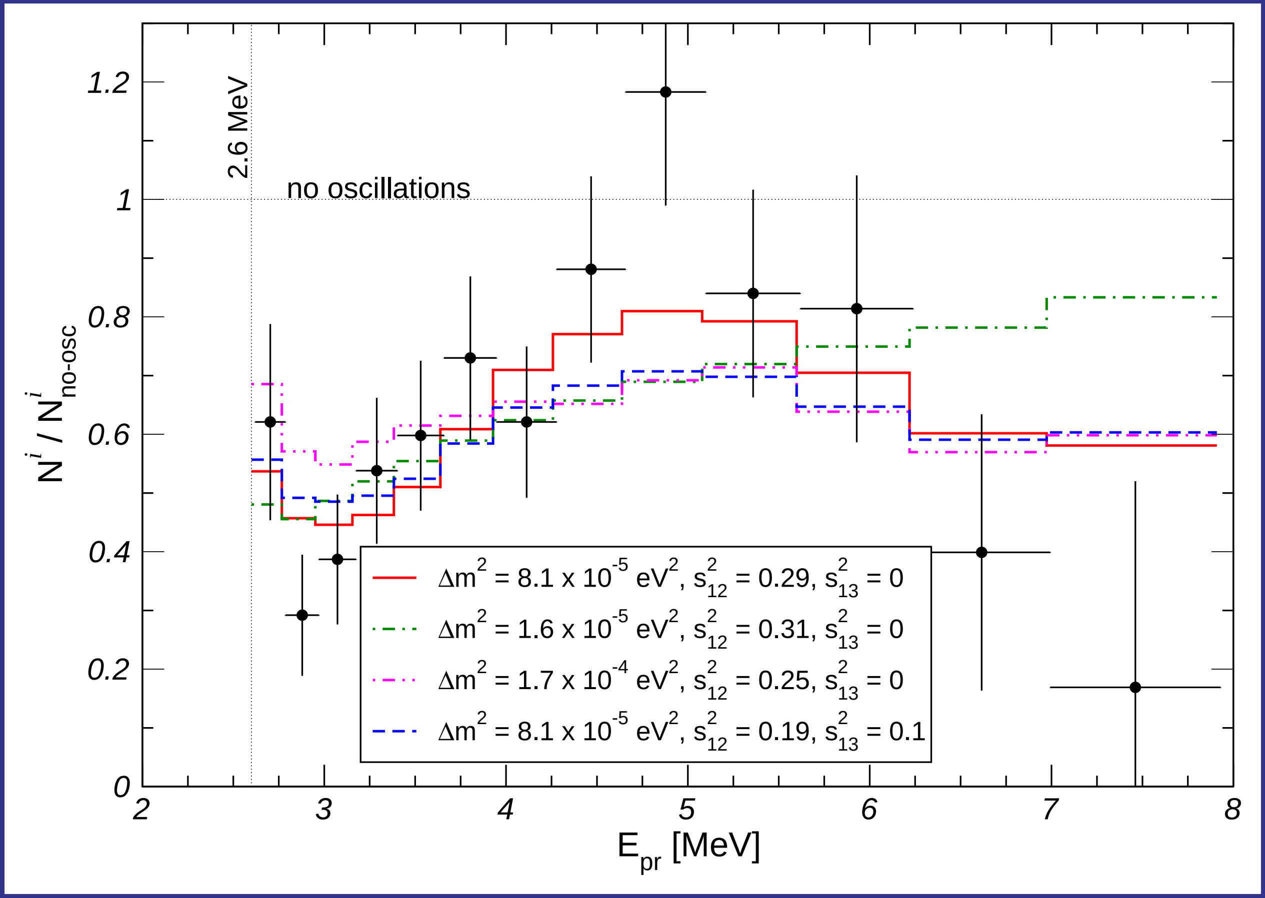


Thank you for your attention!

additional slides

The θ_{13} bound from KamLAND and solar

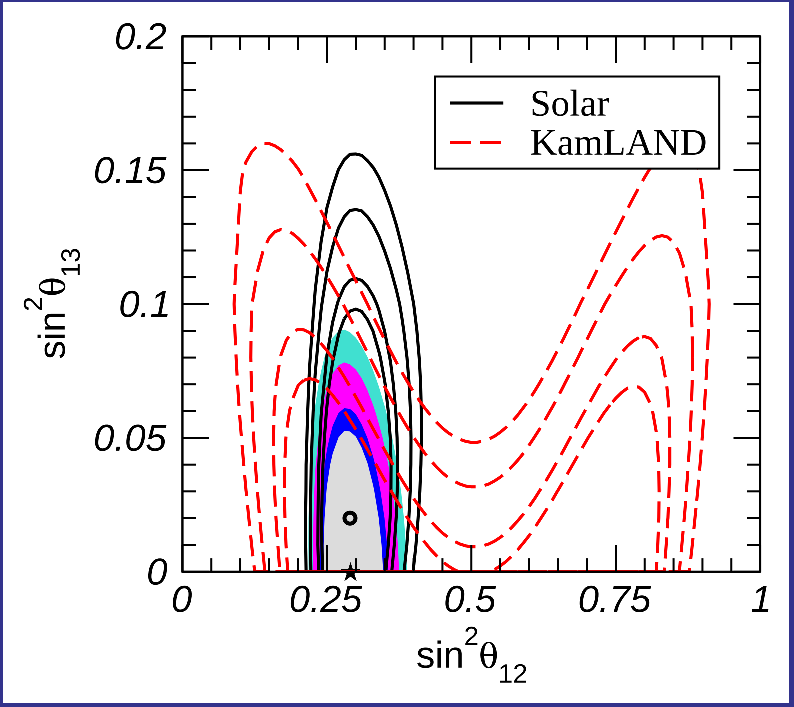
KamLAND energy spectrum



$$P_{\rm KL} = \left(1 - 2\sin^2\theta_{13}\right)\left(1 - \sin^2 2\theta_{12}\,\sin^2\frac{\Delta m^2_{21} L}{4E_\nu}\right)$$

The θ_{13} bound from KamLAND and solar

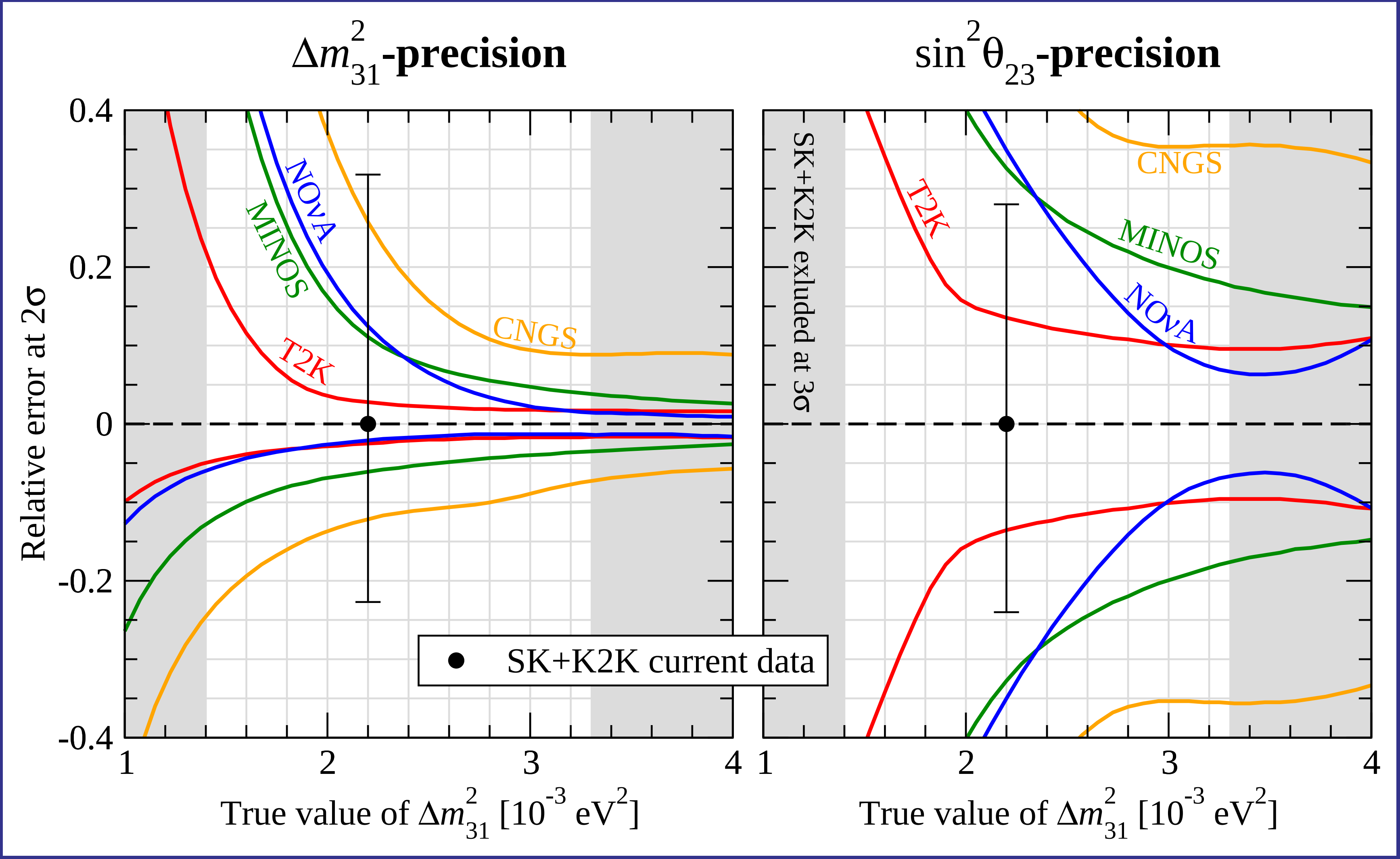
complementarity between solar and KamLAND data



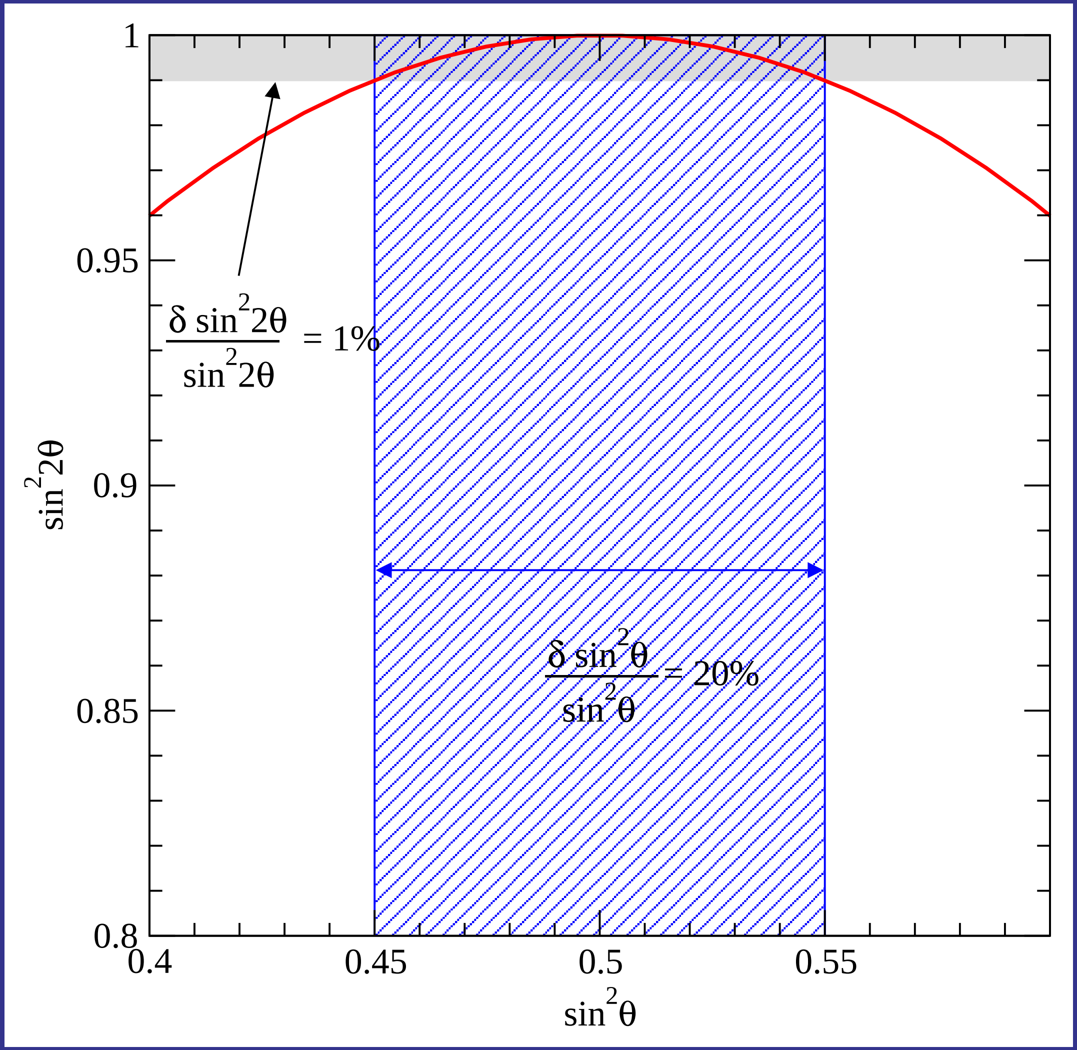
$$P_{\rm KL} = \left(1 - 2\sin^2\theta_{13}\right)\left(1 - \sin^2 2\theta_{12}\,\sin^2\frac{\Delta m^2_{21} L}{4E_\nu}\right)$$

$$P_{\rm Sol} \approx \left(1 - 2\sin^2\theta_{13}\right)\begin{cases} \sin^2\theta_{12} & \text{high } E_\nu \\ \left(1 - 0.5\sin^2 2\theta_{12}\right) & \text{low } E_\nu \end{cases}$$

Atmospheric parameters $|\Delta m^2_{13}|$ *and* θ_{23}

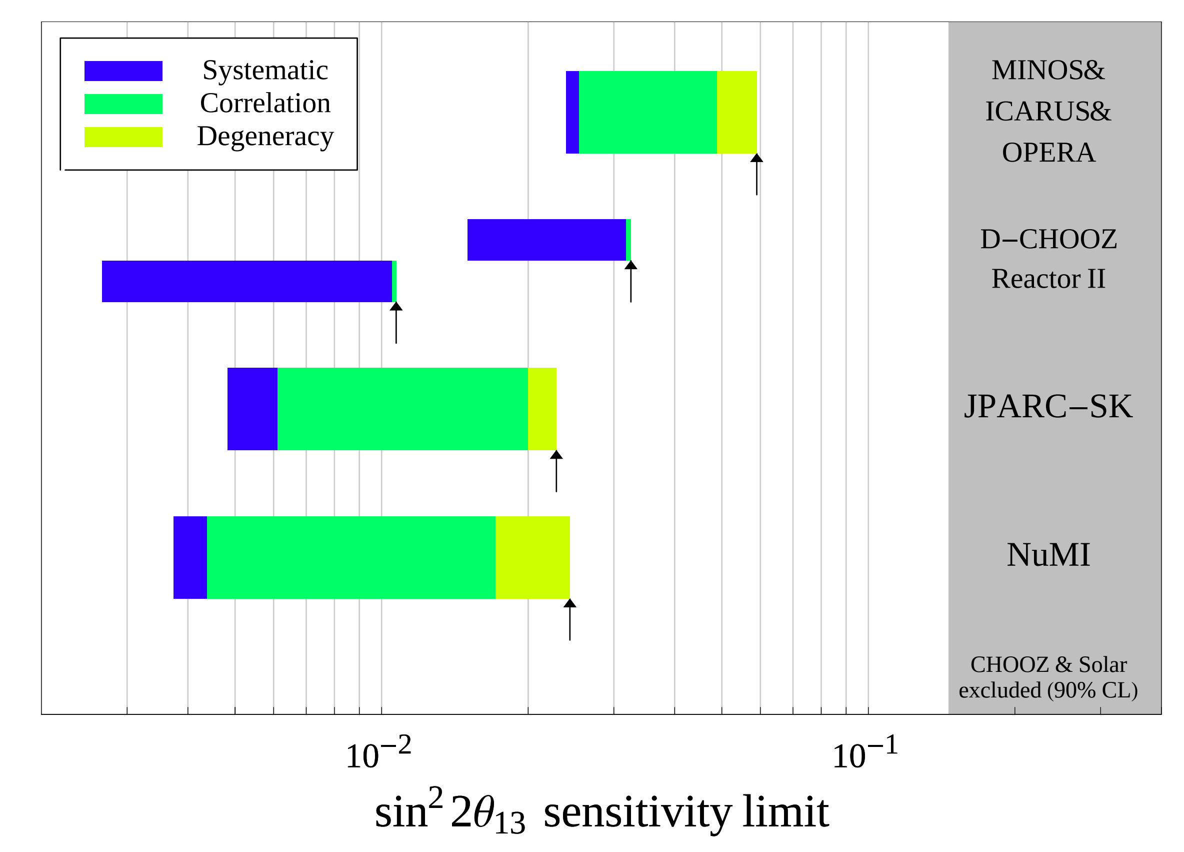


Atmospheric parameters $|\Delta m^2_{13}|$ and θ_{23}



H. Minakata, M. Sonoyama and H. Sugiyama, hep-ph/0406073

$\sin^2 2\theta_{13}$-*limit within the next ten years*



true values:

$$\sin^2 2\theta_{12} = 0.8$$
$$\sin^2 2\theta_{23} = 1.0$$
$$\sin^2 2\theta_{13} = 0.0$$
$$\Delta m^2_{21} = 7.0 \cdot 10^{-5}\ \text{eV}^2$$
$$\Delta m^2_{31} = 2.0 \cdot 10^{-3}\ \text{eV}^2$$

Huber, Lindner, Rolinec, Schwetz, Winter, hep-ph/0403068

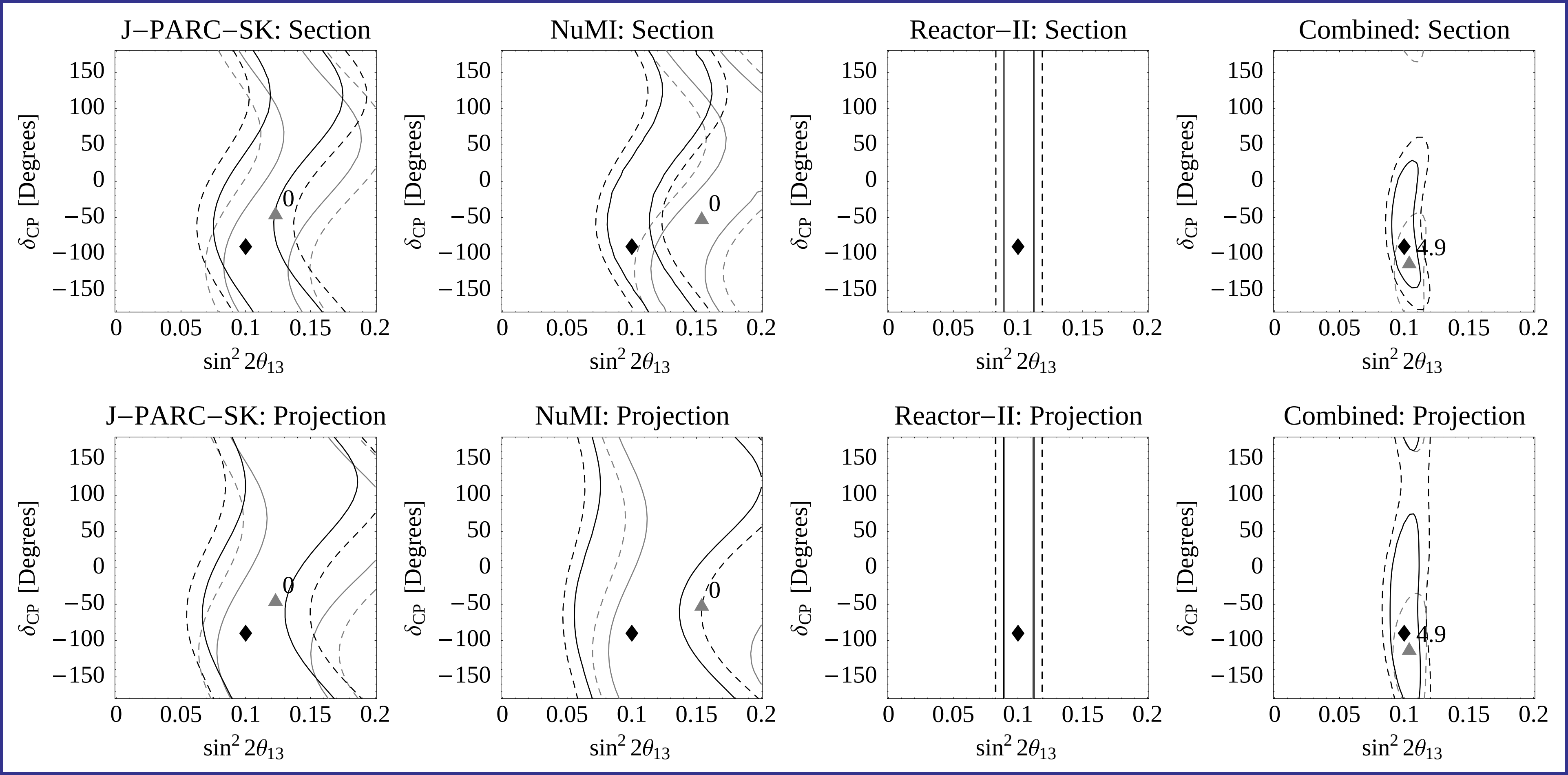
Accuracy on $\sin^2 2\theta_{13}$

$\sin^2 2\theta_{13}$-precision at 90% CL:

MINOS+CNGS	160%
NOνA	130%
T2K	100%
D-Chooz	67%
Reactor-II	18%

true values: $\sin^2 2\theta_{12} = 0.8$ $\Delta m^2_{21} = 7.0 \cdot 10^{-5}$ eV^2
$\sin^2 2\theta_{23} = 1.0$ $\Delta m^2_{31} = 2.0 \cdot 10^{-3}$ eV^2
$\sin^2 2\theta_{13} = 0.1$

Potential if $\sin^2 2\theta_{13}$ turns out to be large



Potential if $\sin^2 2\theta_{13}$ turns out to be large

Superbeam anti-neutrino running vs reactor experiments