GDR Neutrino Meeting

Present and future challenges in neutrino oscillations

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SISSA, Trieste

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Outline

- Introduction
  status of three-flavour neutrino oscillations

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- Determination of neutrino oscillation parameters by future experiments

  leading solar and atmospheric parameters

  determination of θ_{13}, the CP-phase, and the mass hierarchy

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- Summary

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- tritium beta decay experiments
- neutrino-less double-beta decay experiments
- cosmological observations

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but I stress that **such experiments are an important part of the neutrino program, and provide complementary information to oscillation experiments**

Introduction

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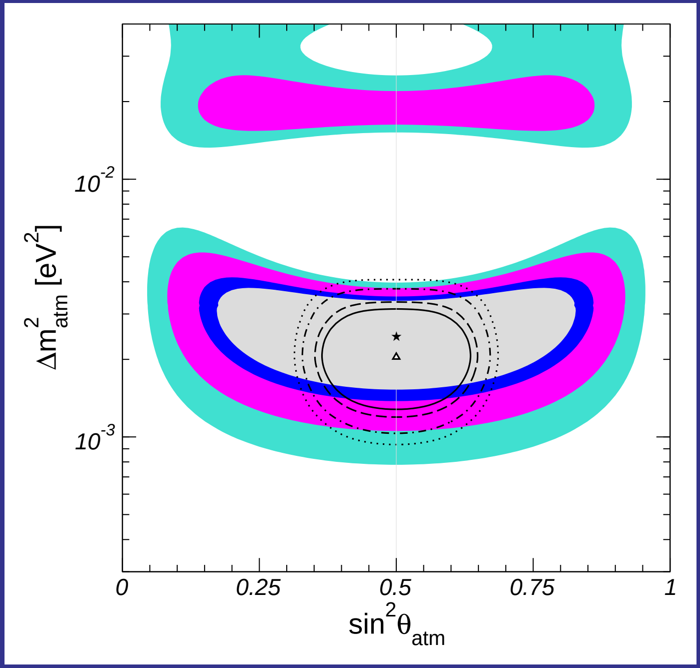
- atmospheric (SK, MACRO, Soudan) and accelerator (K2K) neutrinos



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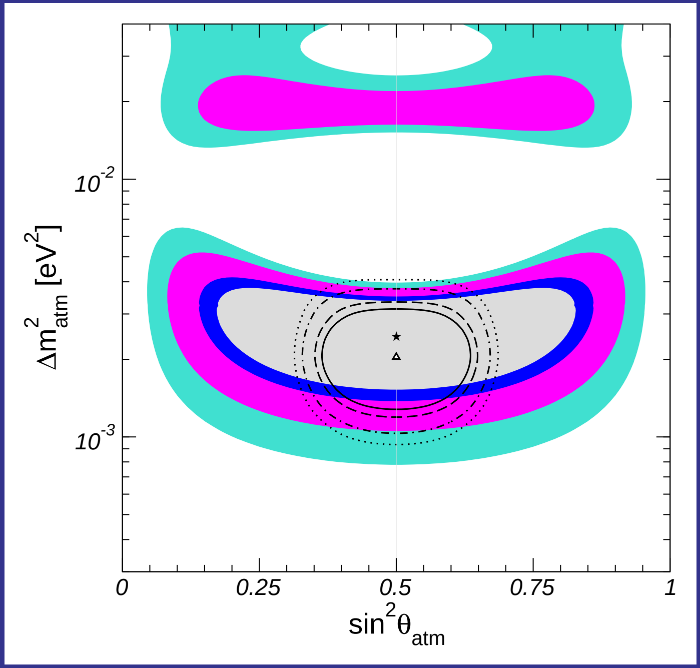

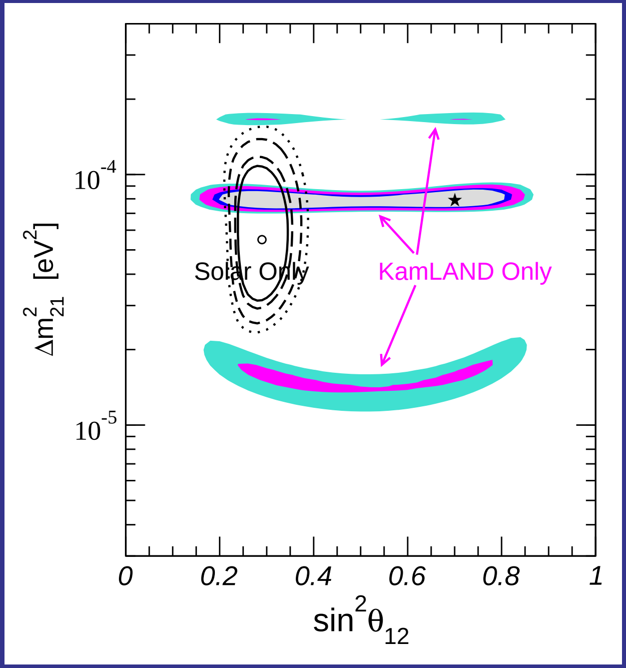

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natural explanation in three-flavour framework

3-flavour oscillation parameters

$$\Delta m^2_{31} \qquad \qquad \qquad \qquad \Delta m^2_{21}$$

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

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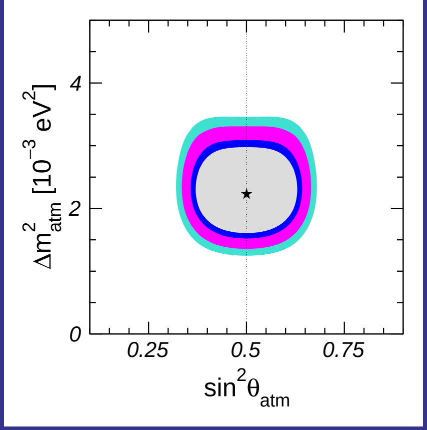
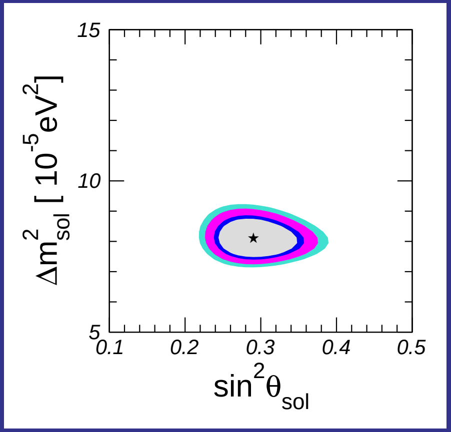


atmospheric + K2K



solar + KamLAND

Maltoni, Schwetz, Tortola, Valle, hep-ph/0405172; Fogli, Lisi, Marrone, Palazzo, hep-ph/0506083; 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; Strumia, Vissani, hep-ph/0503246.

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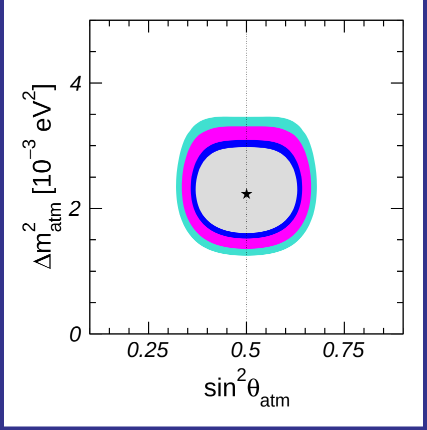

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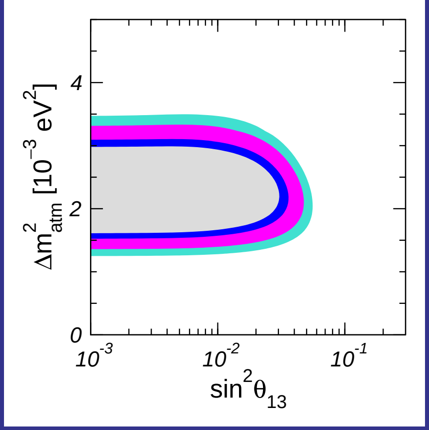
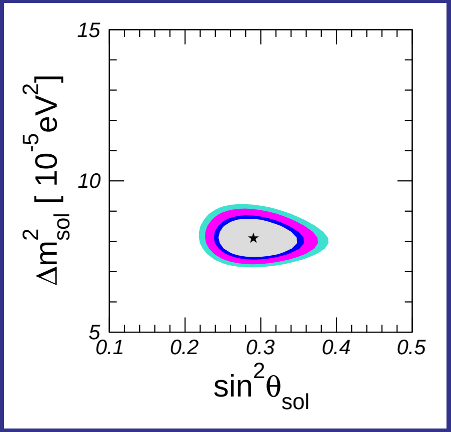


CHOOZ



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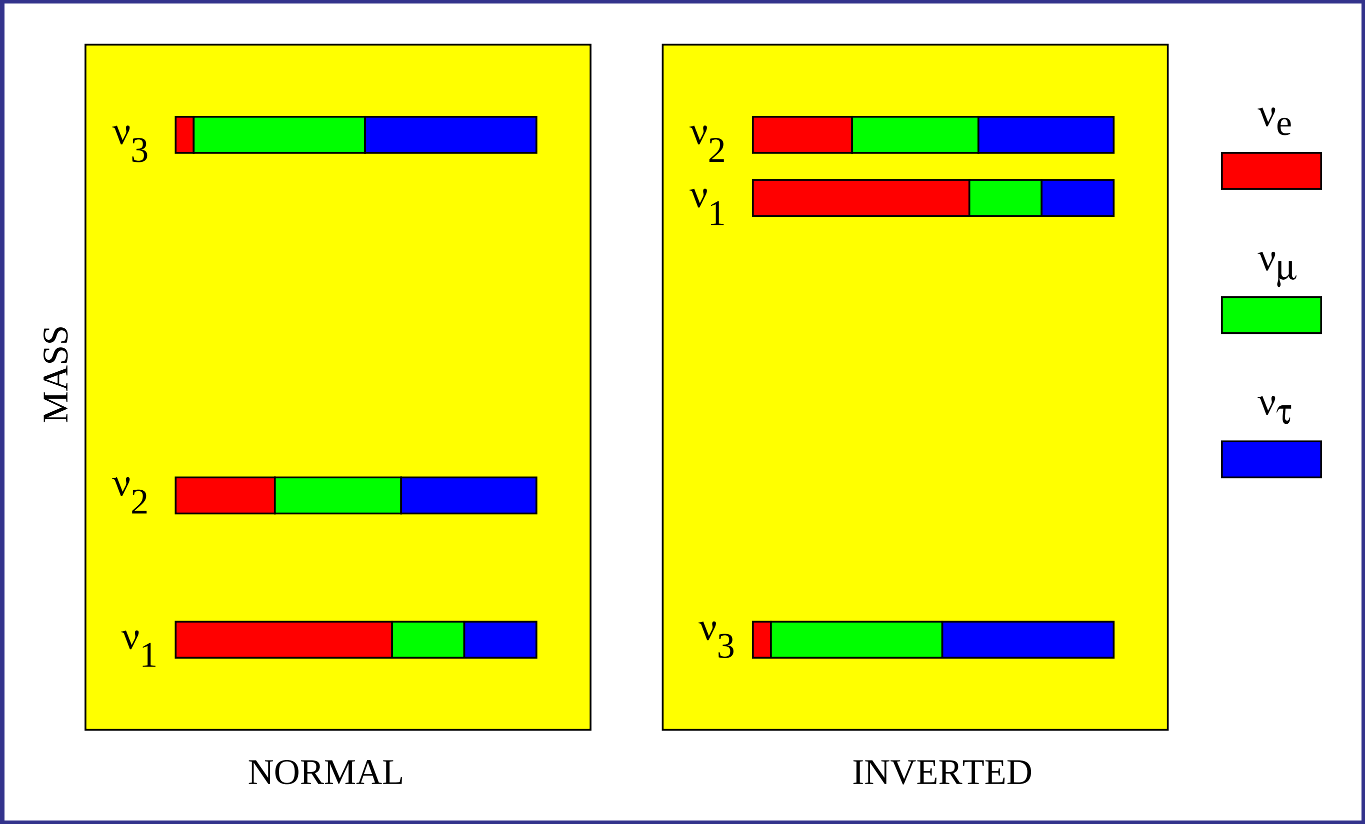
3-flavour oscillation parameters

Two possibilities for the neutrino mass spectrum:



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

3-flavour oscillation parameters

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%	$7.1 - 8.9$
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$	$2.2^{+0.37}_{-0.27}$	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

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

The LSND puzzle

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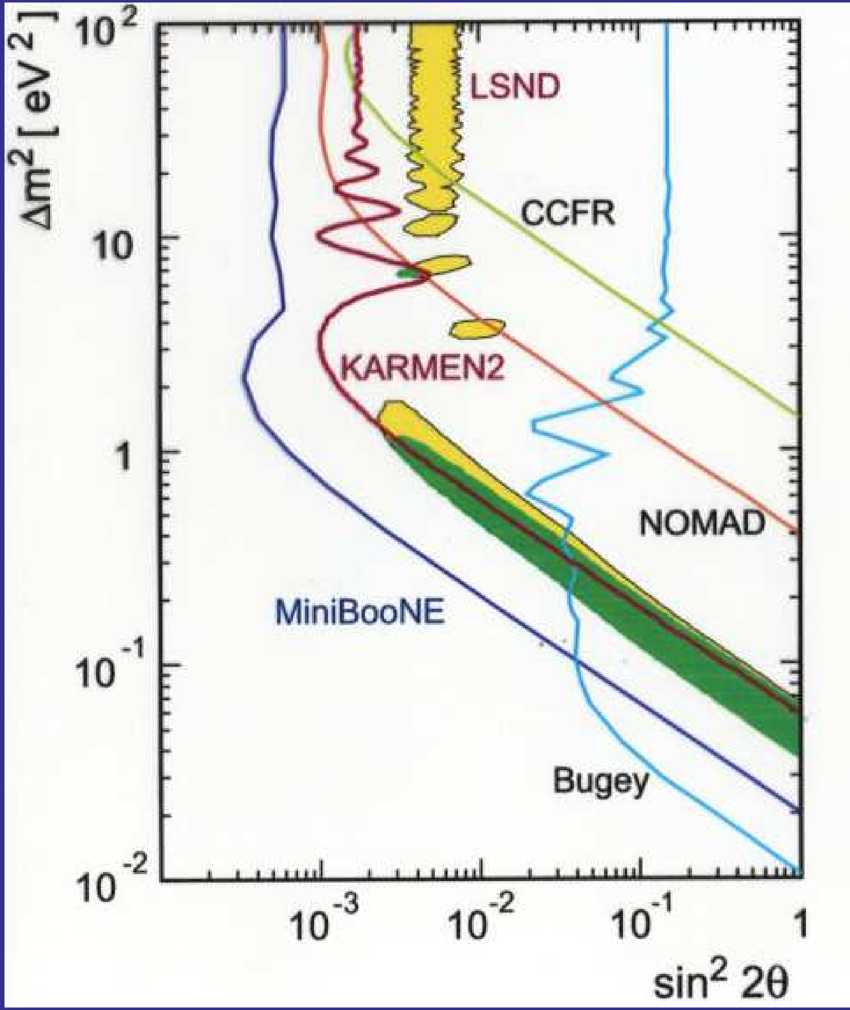
evidence for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations

A. Aguilar *et al.*, PRD 64 (2001) 112007

$87.9 \pm 22.4 \pm 6.0$ excess events

$P = (0.264 \pm 0.067 \pm 0.045)\%$

$\sim 3.3\sigma$ away from zero



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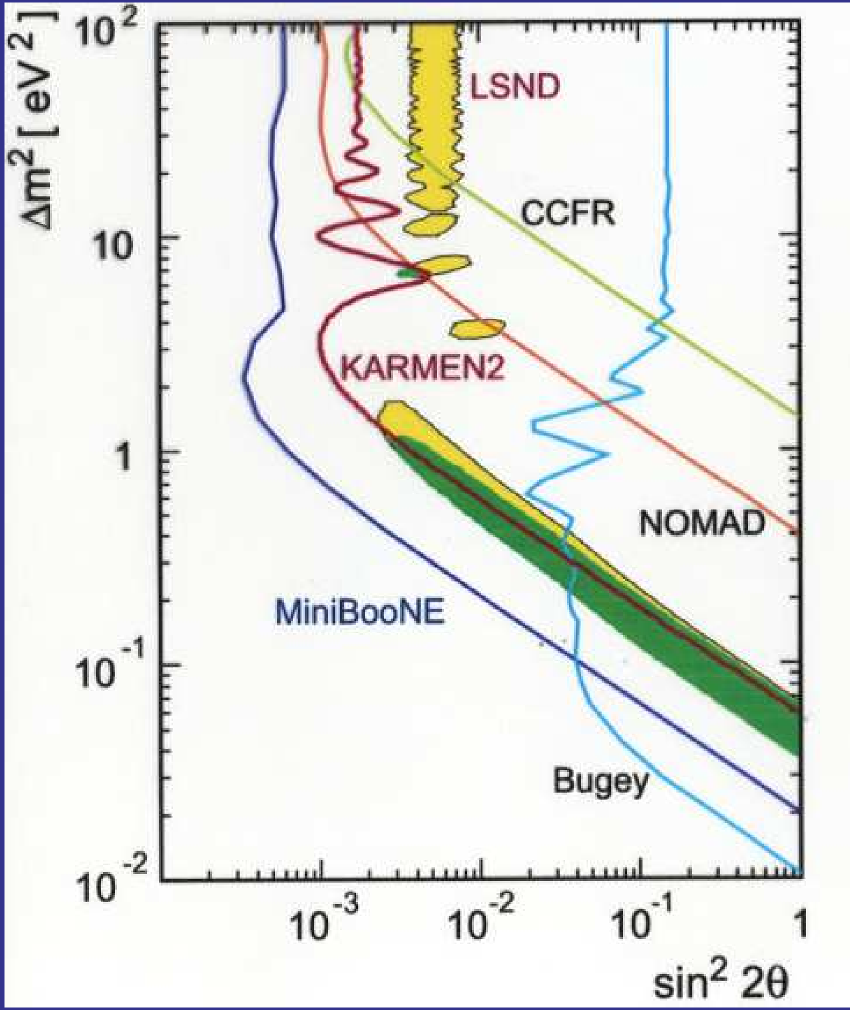

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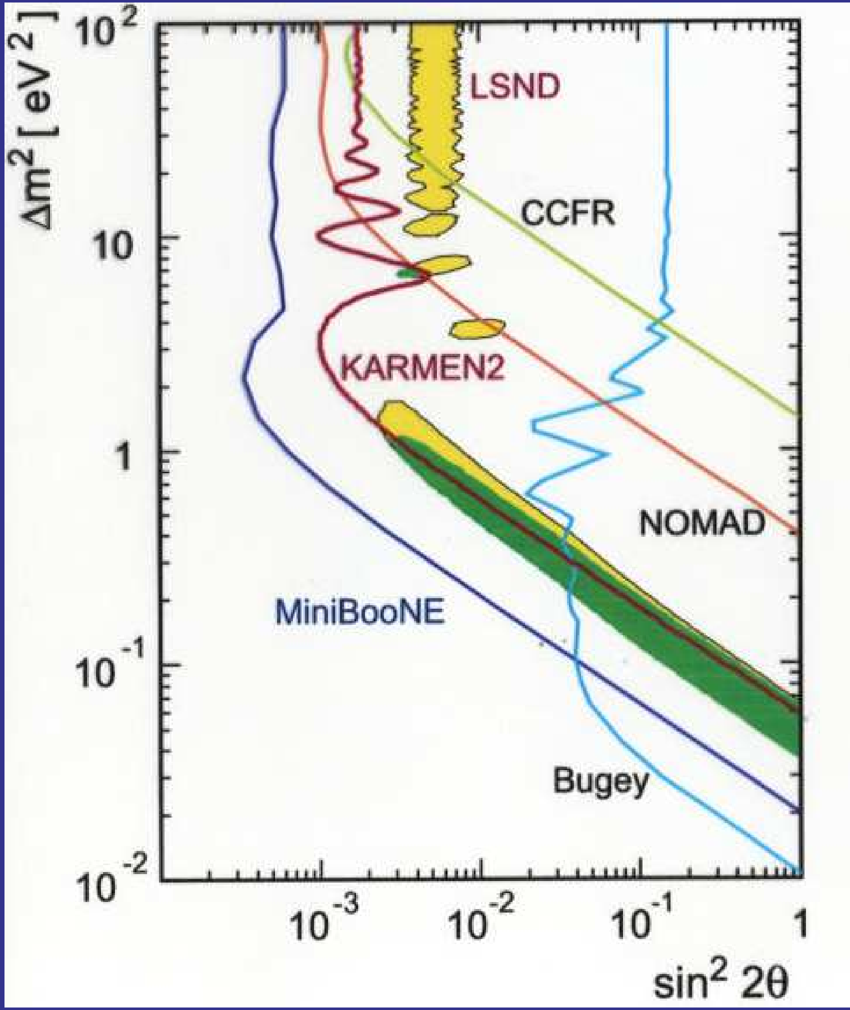
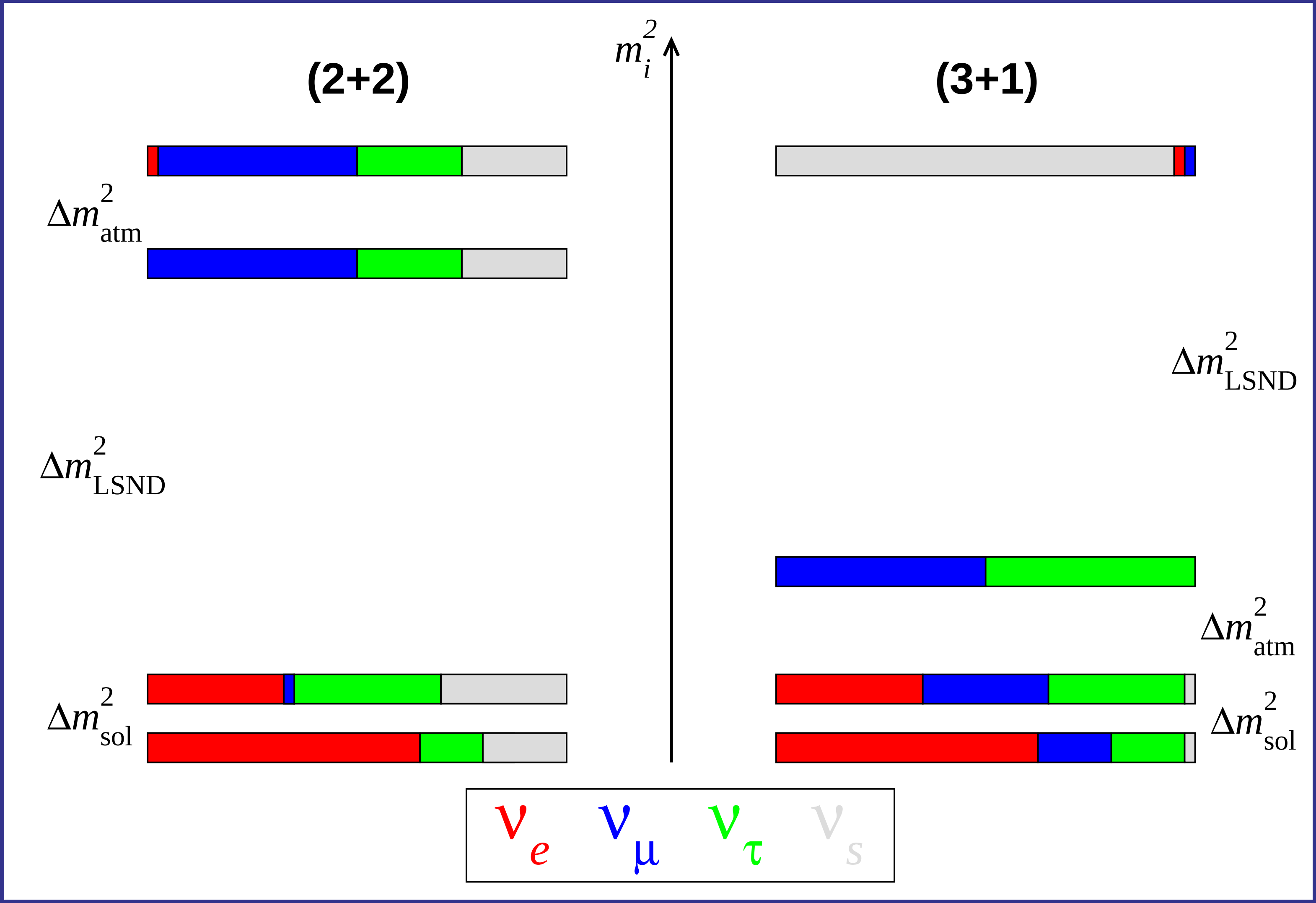
$\longrightarrow$ MiniBooNE

results: 2005/2006?



Adding a sterile neutrino



Four-neutrino oscillation data

- solar+KamLAND data
- atmospheric+K2K data
- LSND

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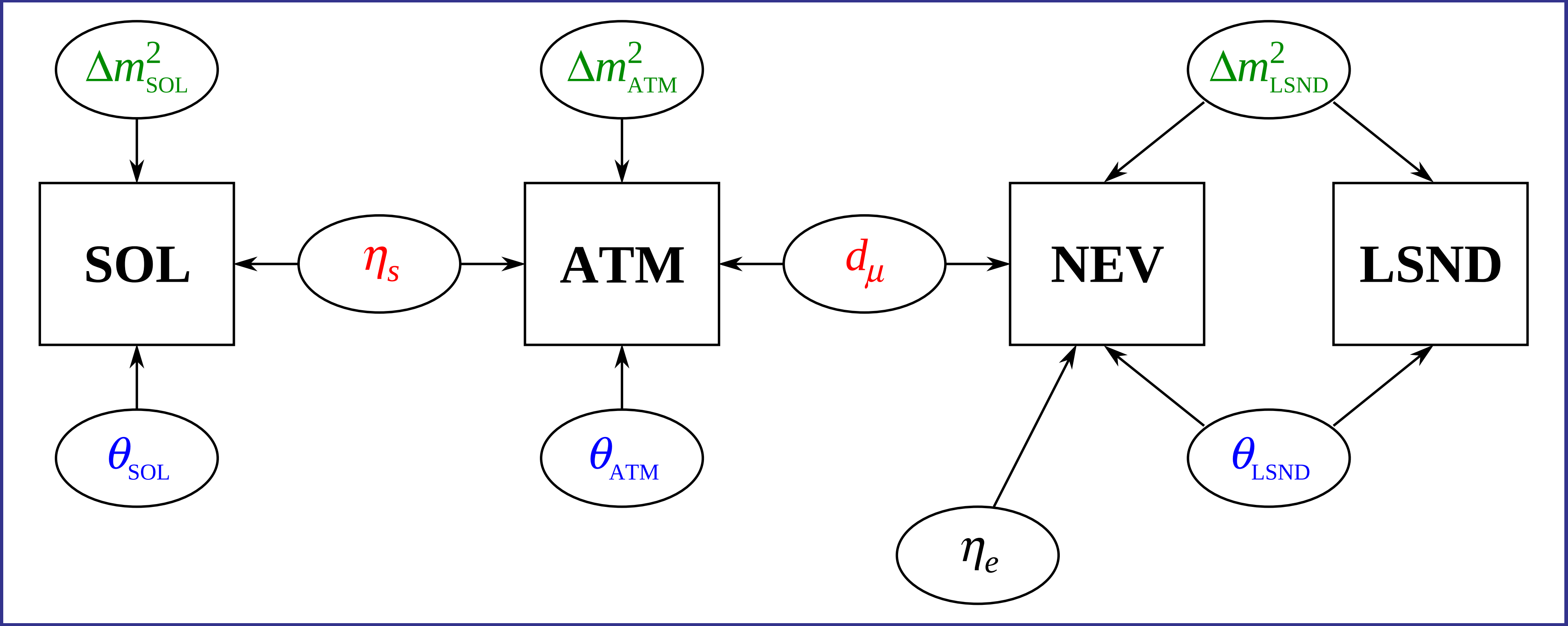
- no-evidence short-baseline data (NEV)
  (KARMEN, Bugey, CDHS)
  provide strong constraints on neutrino mixing
  in the ~ 1 eV^2 range

Coupling of the data sets



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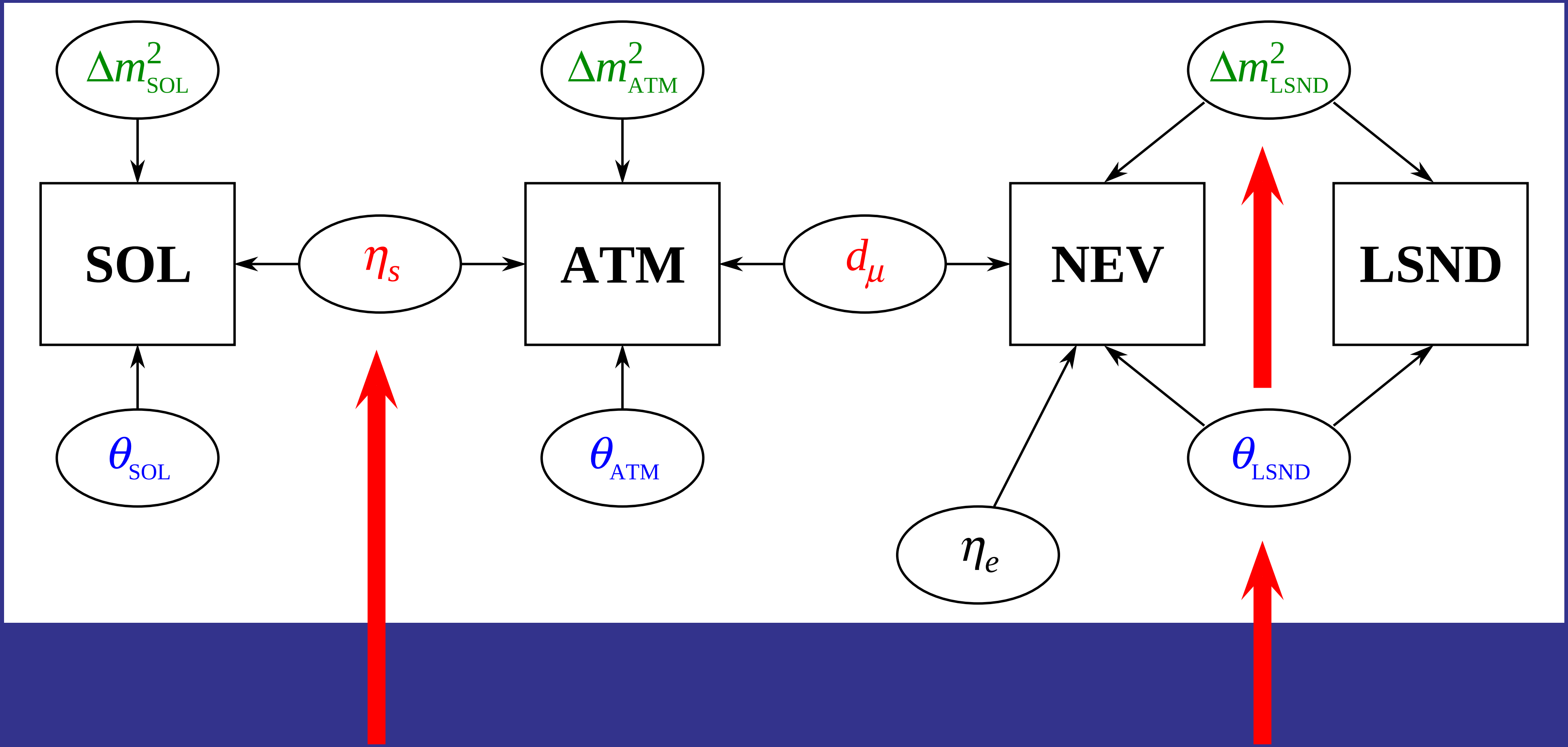


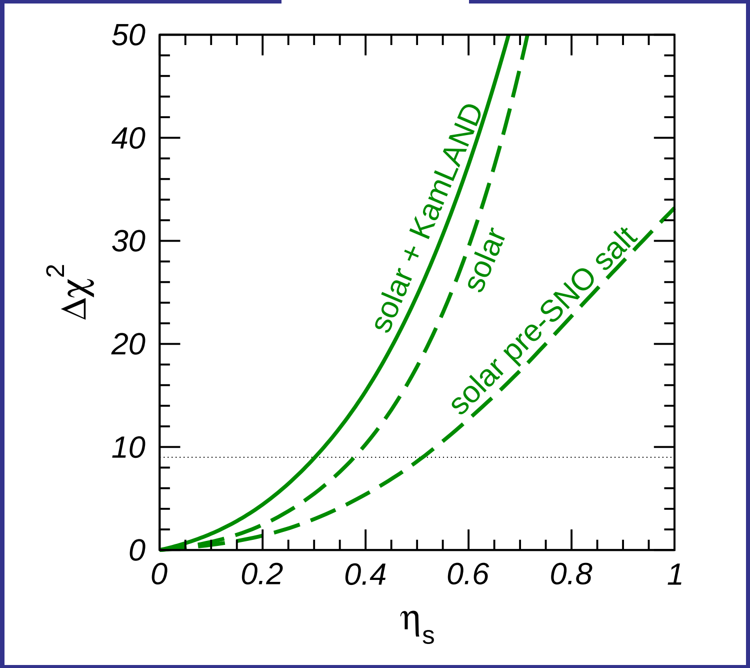
important for (2+2)

important for (3+1)

Global 4-neutrino analysis

Maltoni, Schwetz, Tortola, Valle, hep-ph/0207157, hep-ph/0405172

(2+2)



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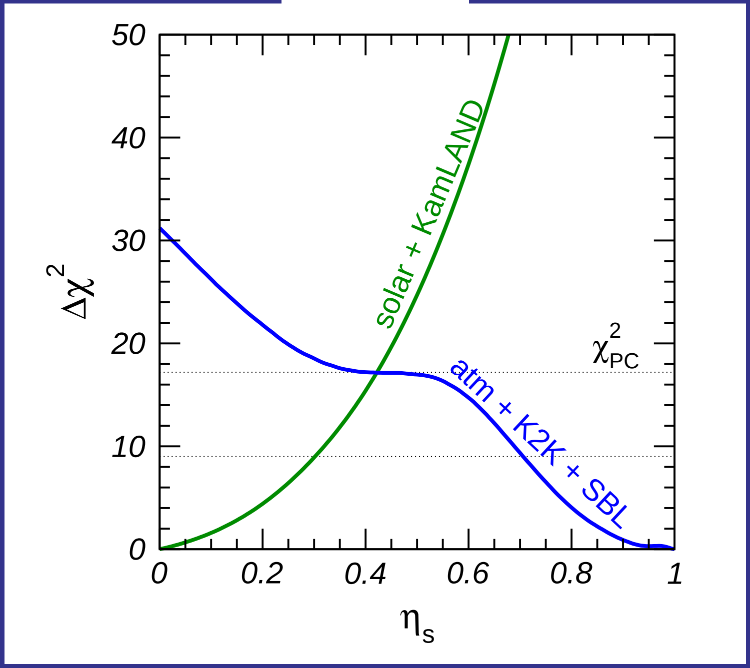

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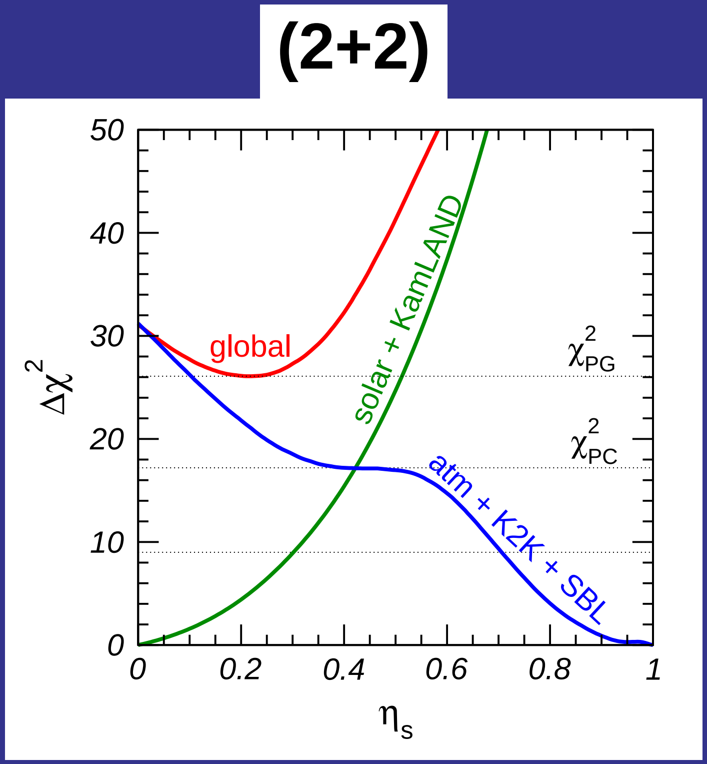

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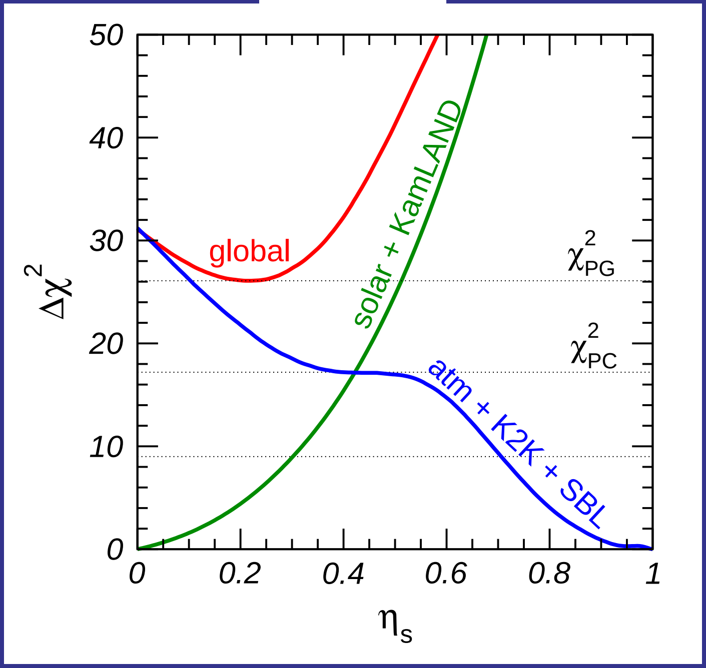

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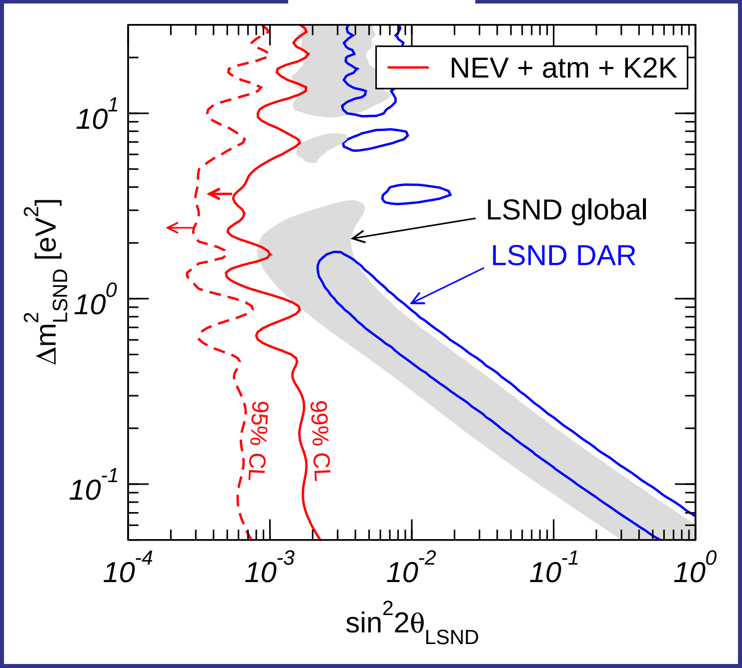

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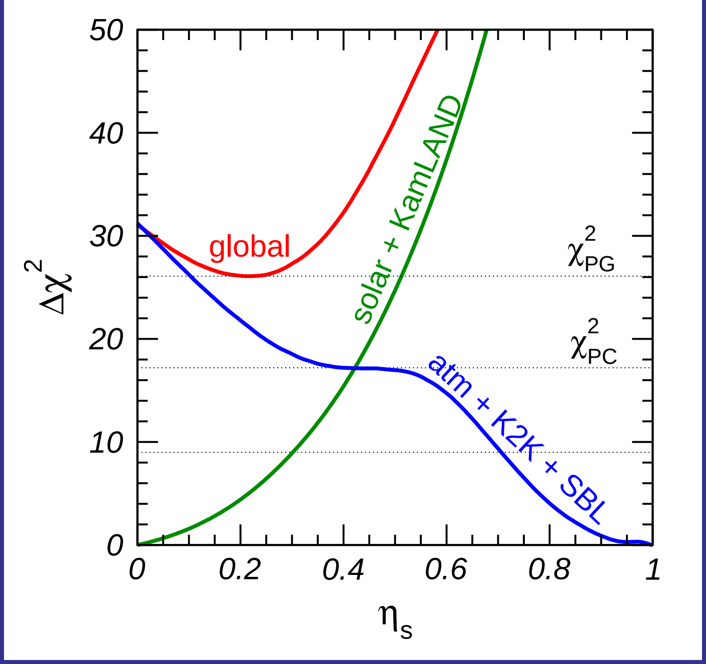

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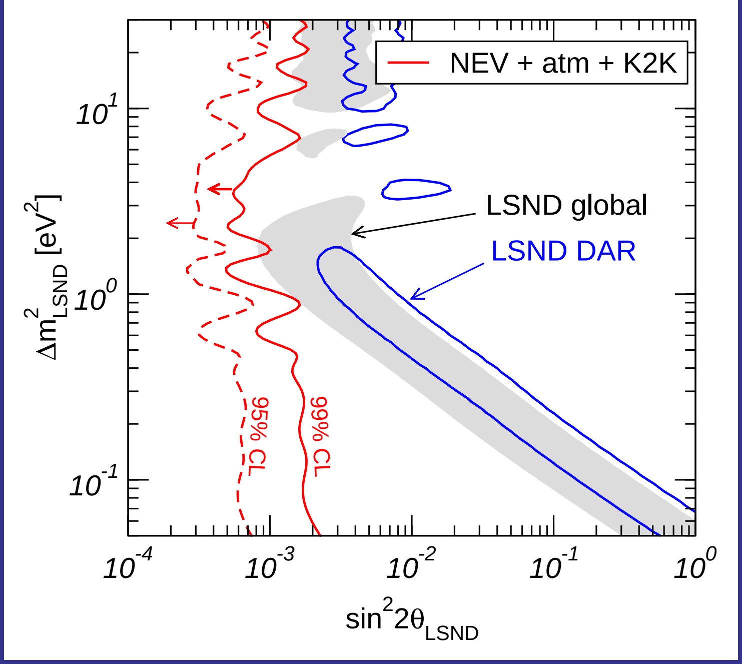

	SOL	ATM	LSND	NEV	χ^2_{PG}	parameter GOF (PG)	
(3+1)	0.0	0.4	5.7	10.9	17.0	1.9×10^{-3}	3.1σ
(2+2)	5.3	20.8	0.6	7.3	33.9	7.8×10^{-7}	4.9σ

5-neutrino oscillations

(3+2) mass schemes, Sorel, Conrad, Shaevitz, hep-ph/0305255

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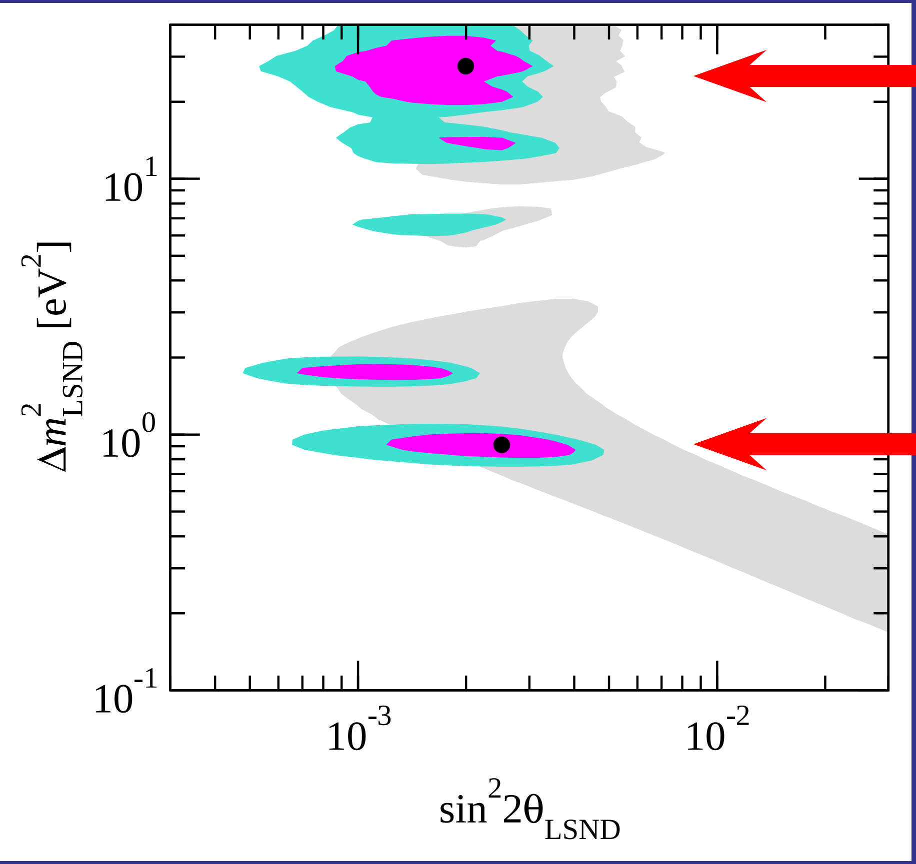

$\Delta m^2_{51} \sim 20$ eV^2

$\Delta m^2_{41} \sim 0.9$ eV^2

$\mathrm{PG}_{(3+2)} = 2.1\%$ $\mathrm{PG}_{(3+1)} = 0.032\%$

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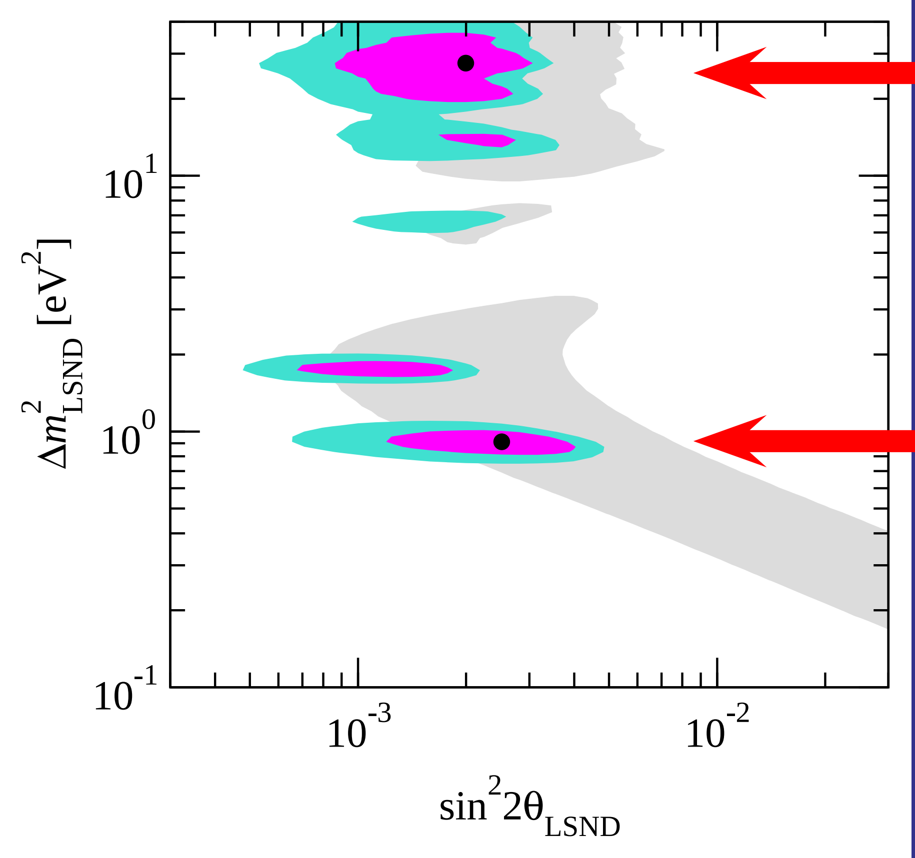

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cosmology?

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- 4-neutrinos and CPT violation Barger, Marfatia, Whisnant 03
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LSND and a decaying sterile neutrino

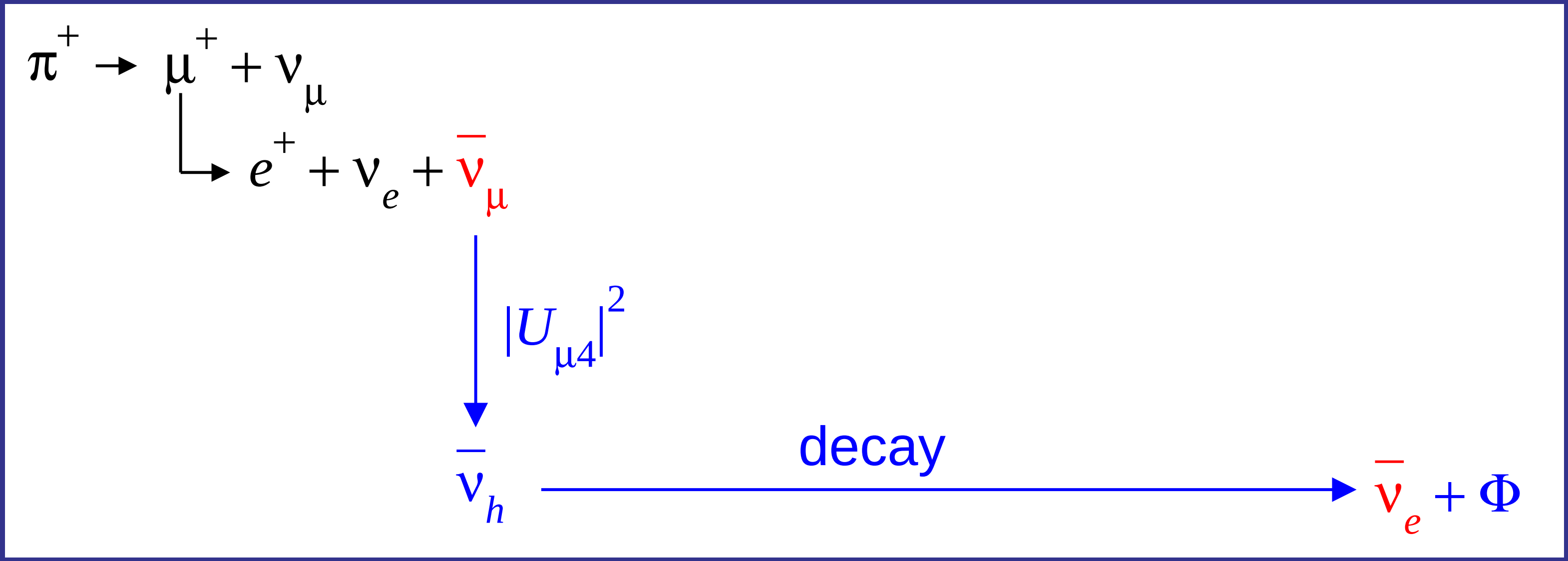
oscillation interpretation

$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu \xrightarrow{\text{oscillations}} \bar{\nu}_e$$

LSND and a decaying sterile neutrino

Palomares-Riuz, Pascoli, Schwetz, hep-ph/0505216



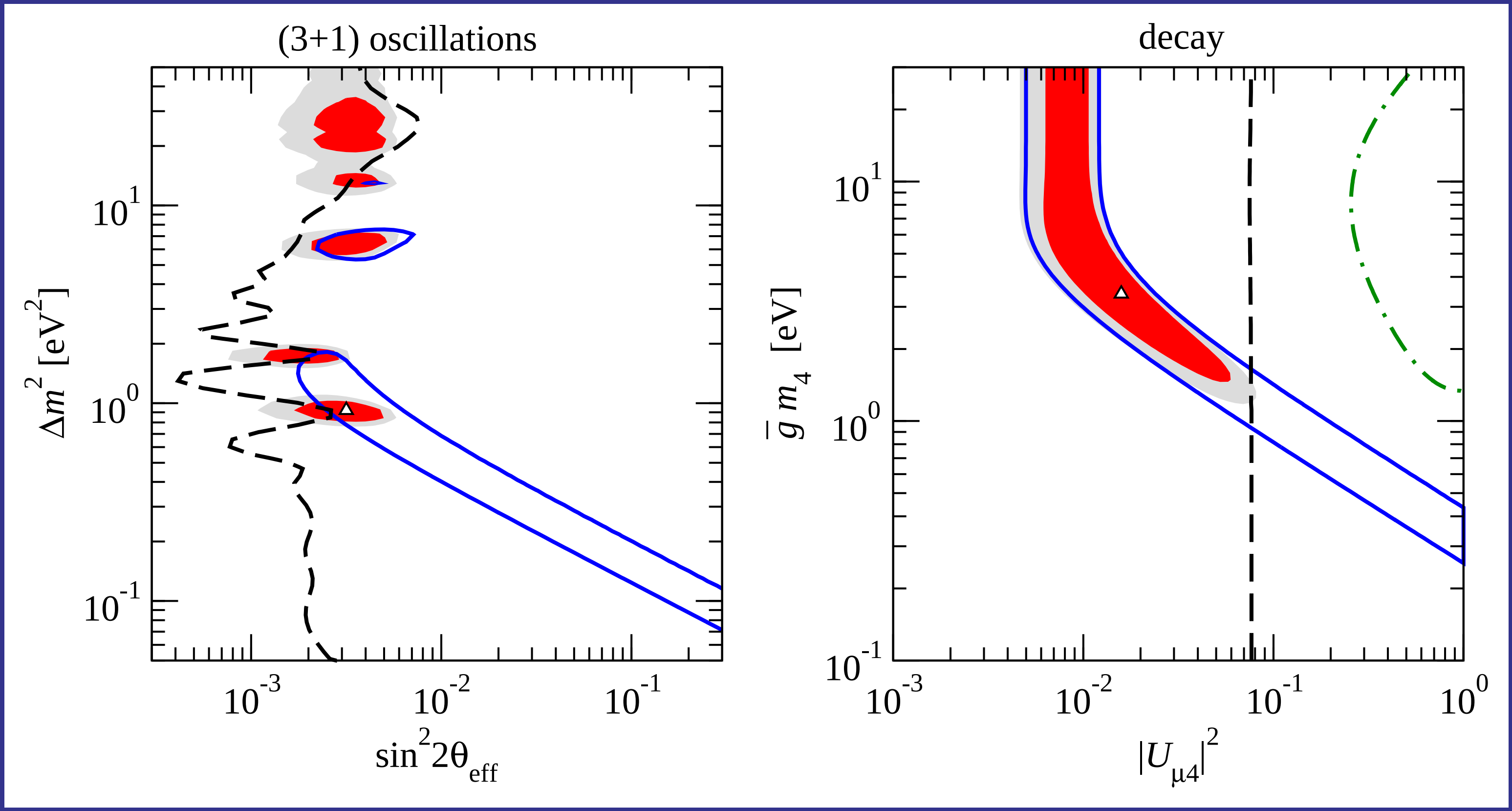
postulate decay of heavy neutrino ν_h into ν_l and a scalar Φ

$$\mathcal{L} = -g\,\bar{\nu}_{lL}\nu_{hR}\,\Phi + \text{h.c.}$$

need $g\,m_h \sim$ eV and $|U_{\mu 4}|^2 \sim 10^{-2}$ (e.g., $g \sim 10^{-6} - 10^{-3}$, $m_h \sim \text{keV} - \text{MeV}$)

LSND and a decaying sterile neutrino

Palomares-Riuz, Pascoli, Schwetz, hep-ph/0505216



$\mathrm{PG}_{(3+1)} = 0.002\%$, $\mathrm{PG}_{(3+2)} = 2.1\%$ $\quad$ $\mathrm{PG}_{\rm decay} = 4.6\%$

for the rest of the talk I assume that

- MiniBooNE does not see a signal, and
- LSND finds some explanation not related to neutrinos

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$\longrightarrow$ Standard three-neutrino oscillation framework

3-flavour oscillation

Open questions:

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Open questions:

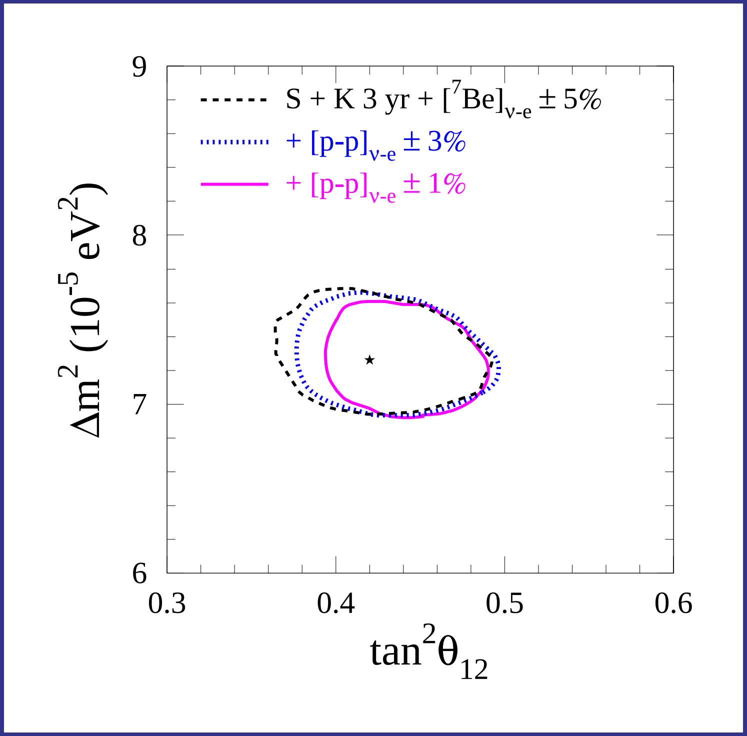
- Increase the precision on solar and atmospheric parameters (e.g. Is θ_{23} exactly 45°?)
- How small is θ_{13}?
- What is the value of the CP phase δ?
- Type of the neutrino mass ordering (sign of Δm^2_{31})

Improving on the ‘solar’ parameters

θ_{12} and Δm^2_{21}

Low energy solar neutrino experiments

J.N. Bahcall, Pena-Garay, hep-ph/0305159



- Solar neutrino data 2003
- 3 years simulated KamLAND data
- 5% measurement (1σ) of the ^{7}Be flux
- 3% and 1% measurement (1σ) of the pp flux

see also S. Choubey, S.T. Petcov, hep-ph/0410283

Long-baseline reactor neutrino experiment

S. Choubey, S.T. Petcov, hep-ph/0404103

99% CL	range	spread	range	spread
Data set	$\Delta m^2_{21}/10^{-5}$eV^2	Δm^2_{21}	$\sin^2\theta_{12}$	$\sin^2\theta_{12}$
only solar	$3.2 - 14.9$	65%	$0.22 - 0.37$	25%
solar+1 kTy KL	$6.5 - 8.0$	10%	$0.23 - 0.37$	23%
solar+2.6 kTy KL	$6.7 - 7.7$	7%	$0.23 - 0.36$	22%

$$\text{spread}(x) = \frac{x^{\text{upper}} - x^{\text{lower}}}{x^{\text{upper}} + x^{\text{lower}}}$$

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solar+2.6 kTy KL	$6.7 - 7.7$	7%	$0.23 - 0.36$	22%
3 yrs SK-Gd	$7.0 - 7.4$	3%	$0.25 - 0.37$	19%
5 yrs SK-Gd	$7.0 - 7.3$	2%	$0.26 - 0.35$	15%

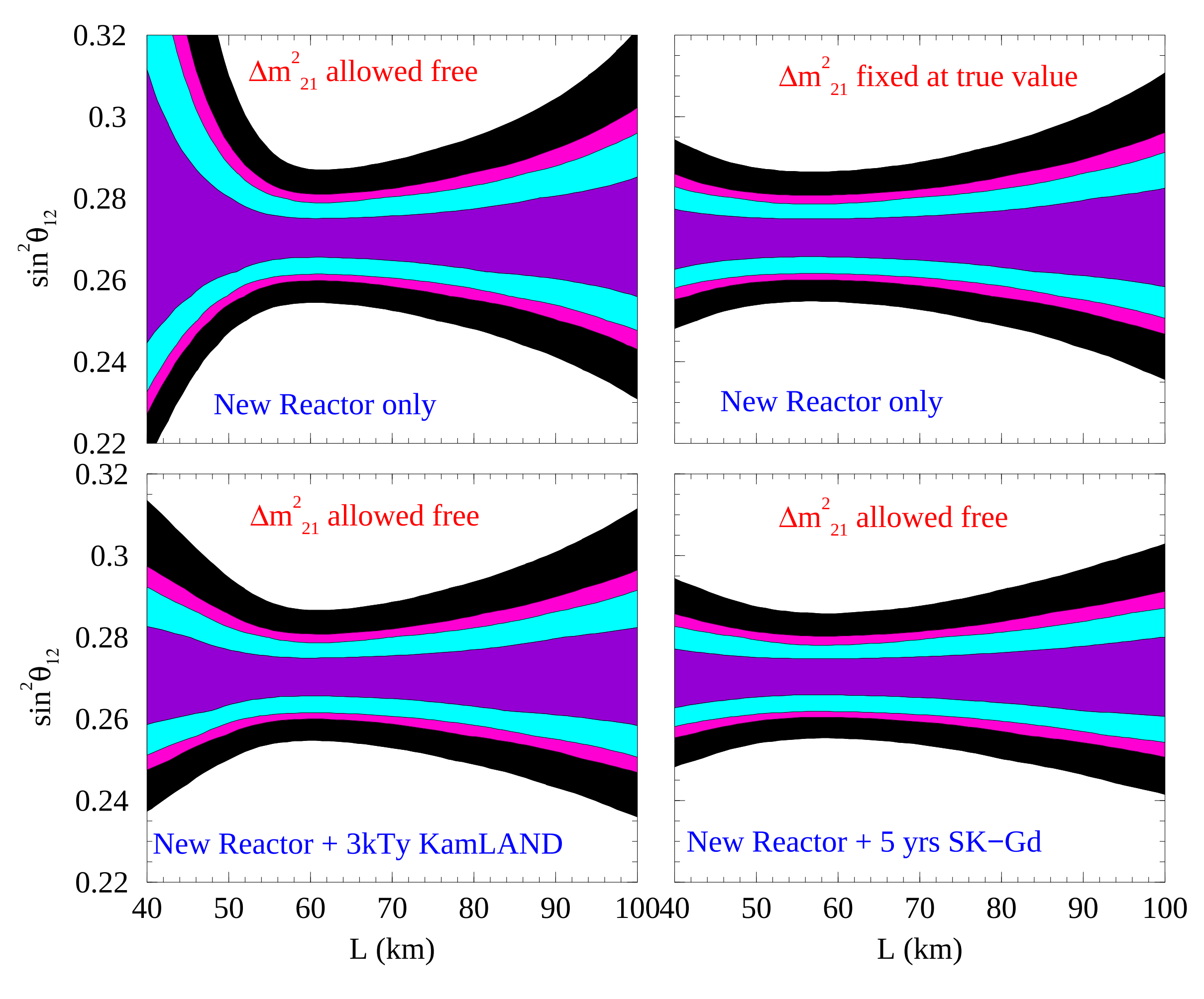
J.F. Beacom, M.R. Vagins, hep-ph/0309300

SK doped with 0.2% Gadolinium (GADZOOKS!)

tag neutrons from the reaction $\bar{\nu}_e + p \rightarrow e^+ + n$

Long-baseline reactor neutrino experiment

%-level determination of θ_{12}: dedicated reactor exp. at $\sim$60 km



S. Choubey, S.T. Petcov, hep-ph/0410283

73 GW kt yr

2% syst. uncert.

$\rightarrow \sin^2\theta_{12}$ with 2% (6%) at 1σ (3σ)

see also J. Bouchiat, hep-ph/0304253; Minakata et al., hep-ph/0407326

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

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

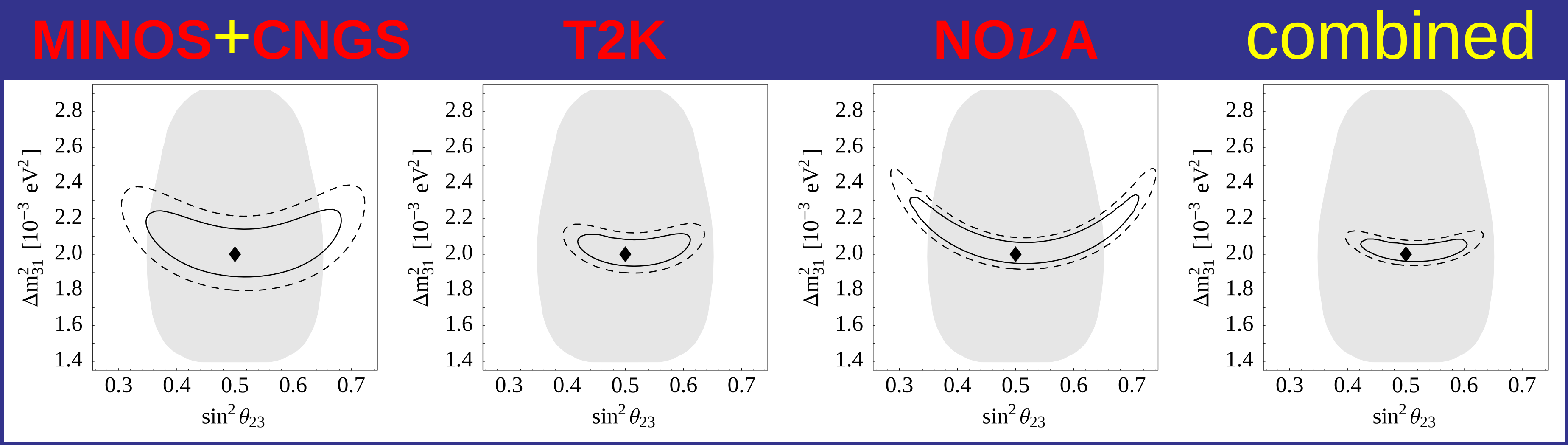
ν_μ-disappearance in LBL accelerator experiments

upcoming experiments:

- conventional beam experiments
  MINOS, CNGS
- superbeam experiments
  T2K, NOνA

assume 5 yrs of running in neutrino mode

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



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

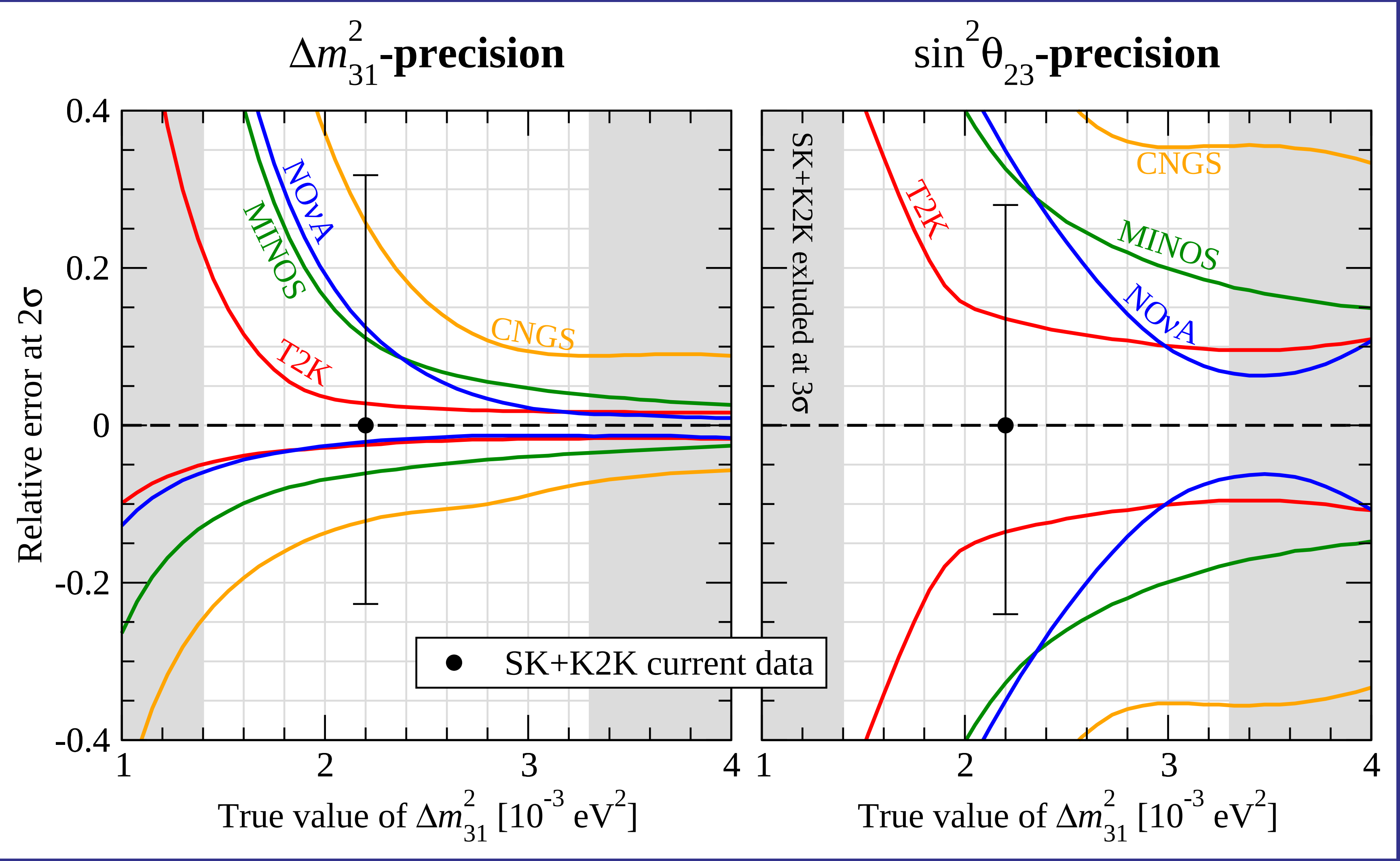
Atmospheric parameters $|\Delta m^2_{13}|$ *and* θ_{23}

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%

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



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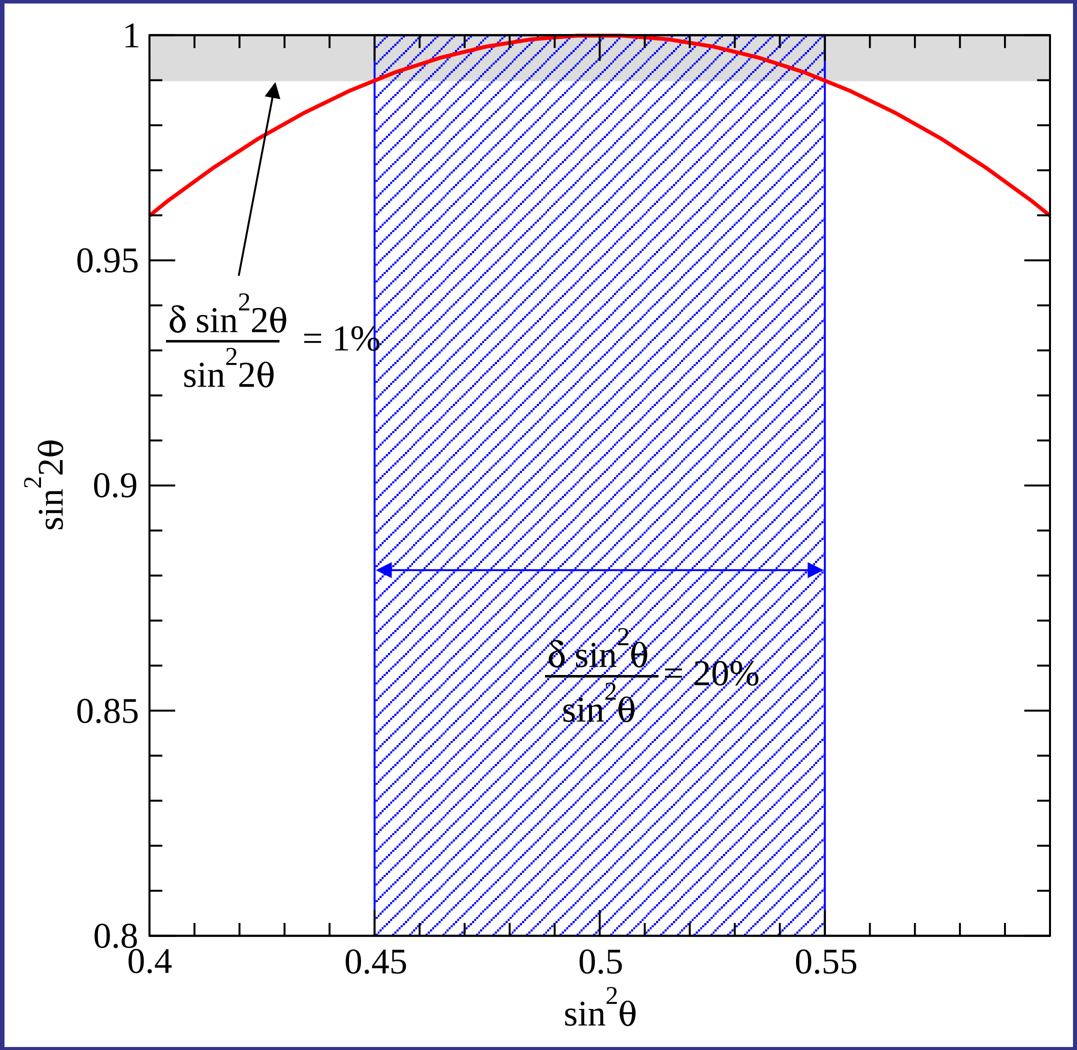

H. Minakata, M. Sonoyama and H. Sugiyama, hep-ph/0406073

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

subsequent generation of LBL experiments like

T2HK, CERN-Frejus exps (**SPL**, **BB**), **NuFact**

will provide a
sub-percent determination of $|\Delta m^2|$ and $\sin^2 2\theta_{23}$!

What is the value of θ_{13}?

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  $\rightarrow \theta_{13}$ around the corner

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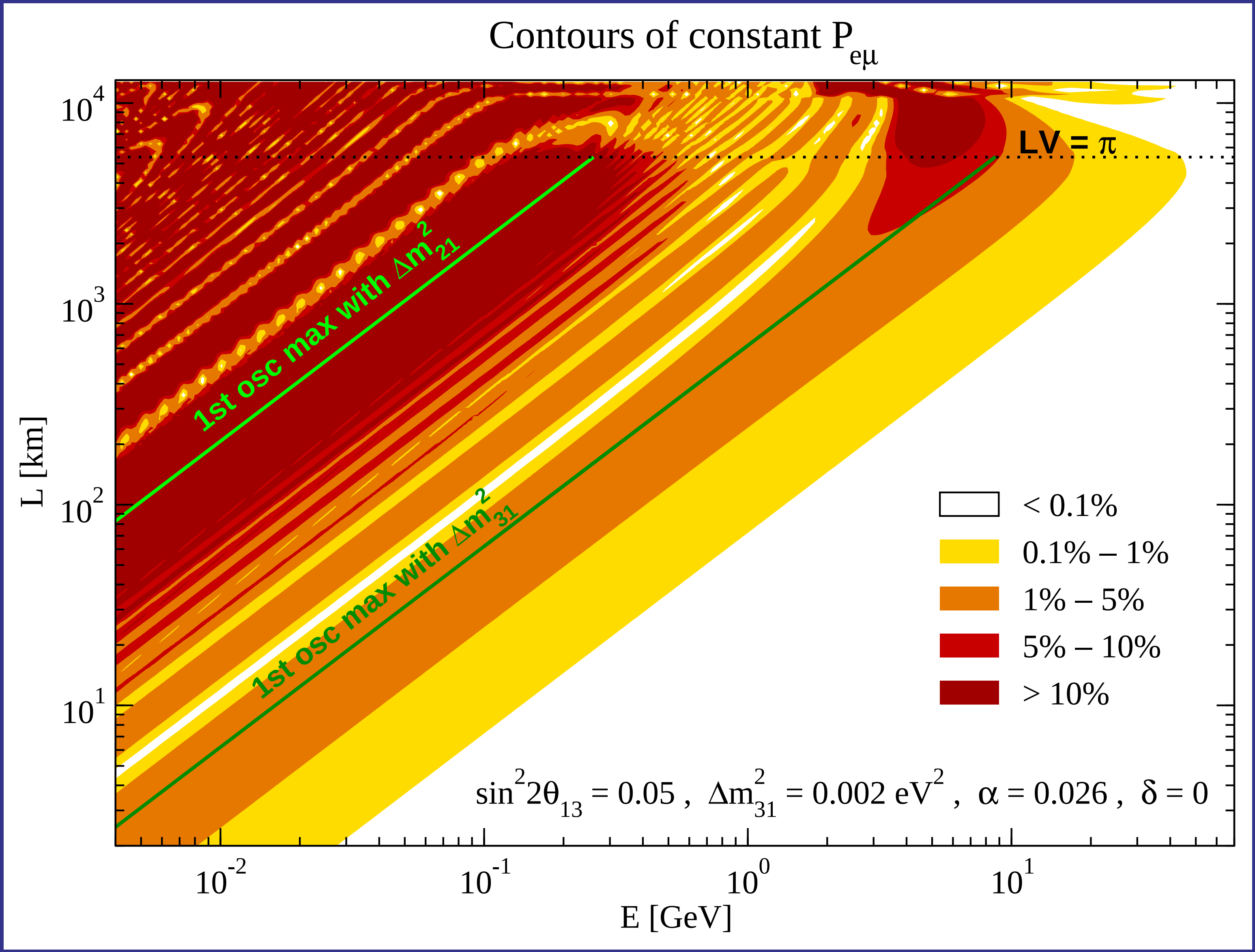
  $\rightarrow \theta_{13}$ around the corner
- $\theta_{13} \ll 1$ hint for some symmetry
- relatively large θ_{13} opens the possibilty to observe generic 3-flavour effects (CP-violation)

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, T2HK, SPL, BB, NuFact

Measuring θ_{13}



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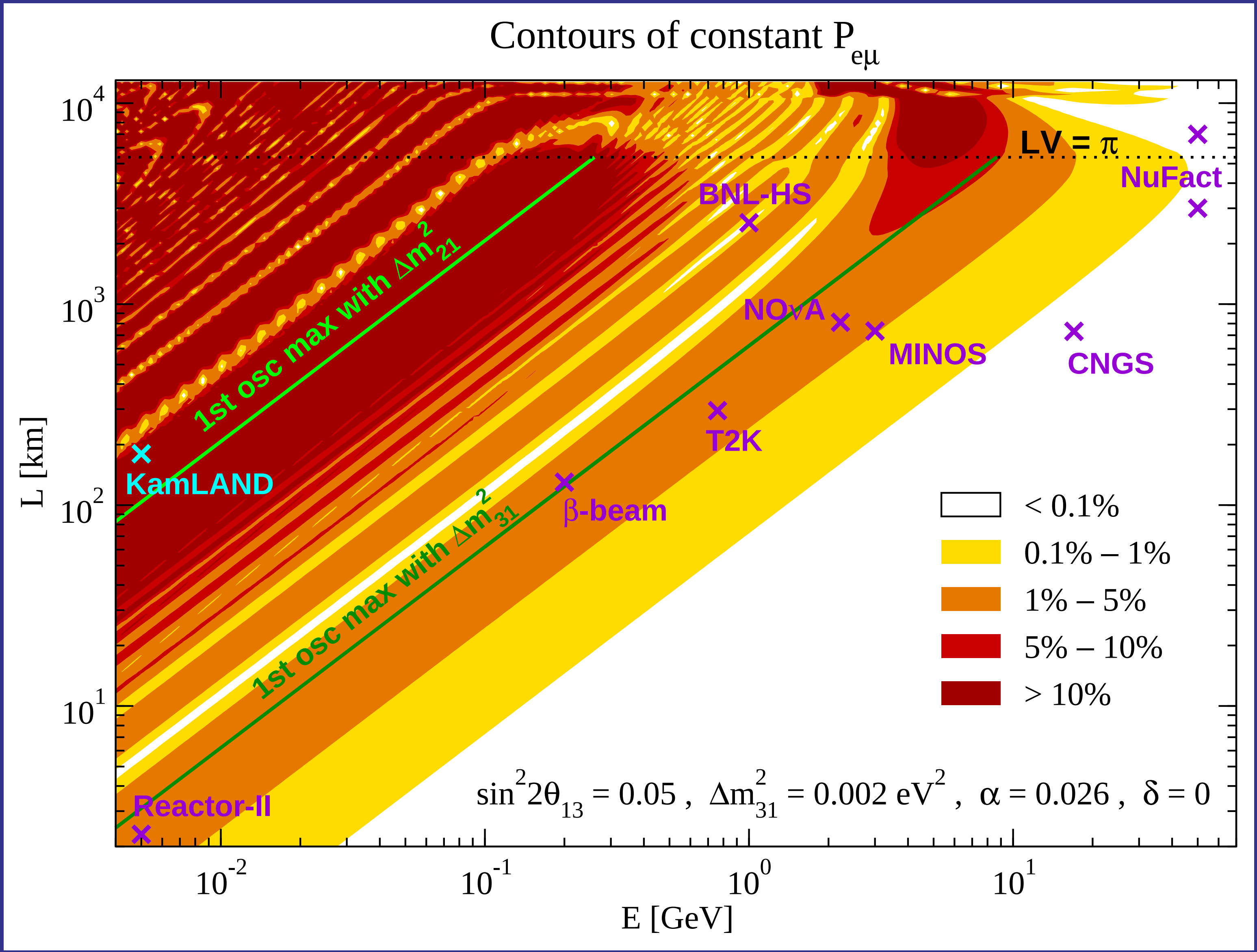


Measuring θ_{13} *by* $\nu_\mu \to \nu_e$ *at beams*

The measurement of θ_{13} with the $\nu_\mu \to \nu_e$ appearance channel suffers from correlations and degeneracies:

G.L. Fogli, E. Lisi, Phys. Rev. D54 (1996) 3667
J. Burguet-Castell et al., Nucl. Phys. B608 (2001) 301
H. Minakata, H. Nunokawa, JHEP 10 (2001) 001
V.Barger, D.Marfatia, K.Whisnant, Phys. Rev. D65 (2002) 073023; D66 (2002) 053007
P.Huber, M.Lindner, W.Winter, Nucl. Phys. B645 (2002) 3; Nucl. Phys. B654 (2003) 3
and many more

Not $\sin^2 2\theta_{13}$, but only a specific parameter combination is measured very accurately

The $\nu_\mu \to \nu_e$ oscillation probability in vacuum

$$
\begin{aligned}
P_{\mu e} \;\simeq\;& \sin^2 2\theta_{13}\, \sin^2\theta_{23} \sin^2\Delta_{31} \\
\mp\;& \alpha\, \sin 2\theta_{12}\, \sin 2\theta_{13}\, \sin\delta\, \cos\theta_{13} \sin 2\theta_{23} \sin^3\Delta_{31} \\
-\;& \alpha\, \sin 2\theta_{12}\, \sin 2\theta_{13}\, \cos\delta\, \cos\theta_{13} \sin 2\theta_{23} \cos\Delta_{31} \sin^2\Delta_{31} \\
+\;& \alpha^2\, \sin^2 2\theta_{12}\, \cos^2\theta_{23} \sin^2\Delta_{31} ,
\end{aligned}
$$

with

$$
\Delta_{31} \equiv \frac{\Delta m^2_{31} L}{4E_\nu} , \qquad \alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}} = 0.035^{+0.009}_{-0.004}
$$

Measuring $\sin^2 2\theta_{13}$ *at reactors*

"Clean" measurement of $\sin^2 2\theta_{13}$:

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E_\nu} + \left(\frac{\Delta m^2_{21} L}{4E_\nu} \right)^2 \cos^4 \theta_{13} \sin^2 2\theta_{12}$$

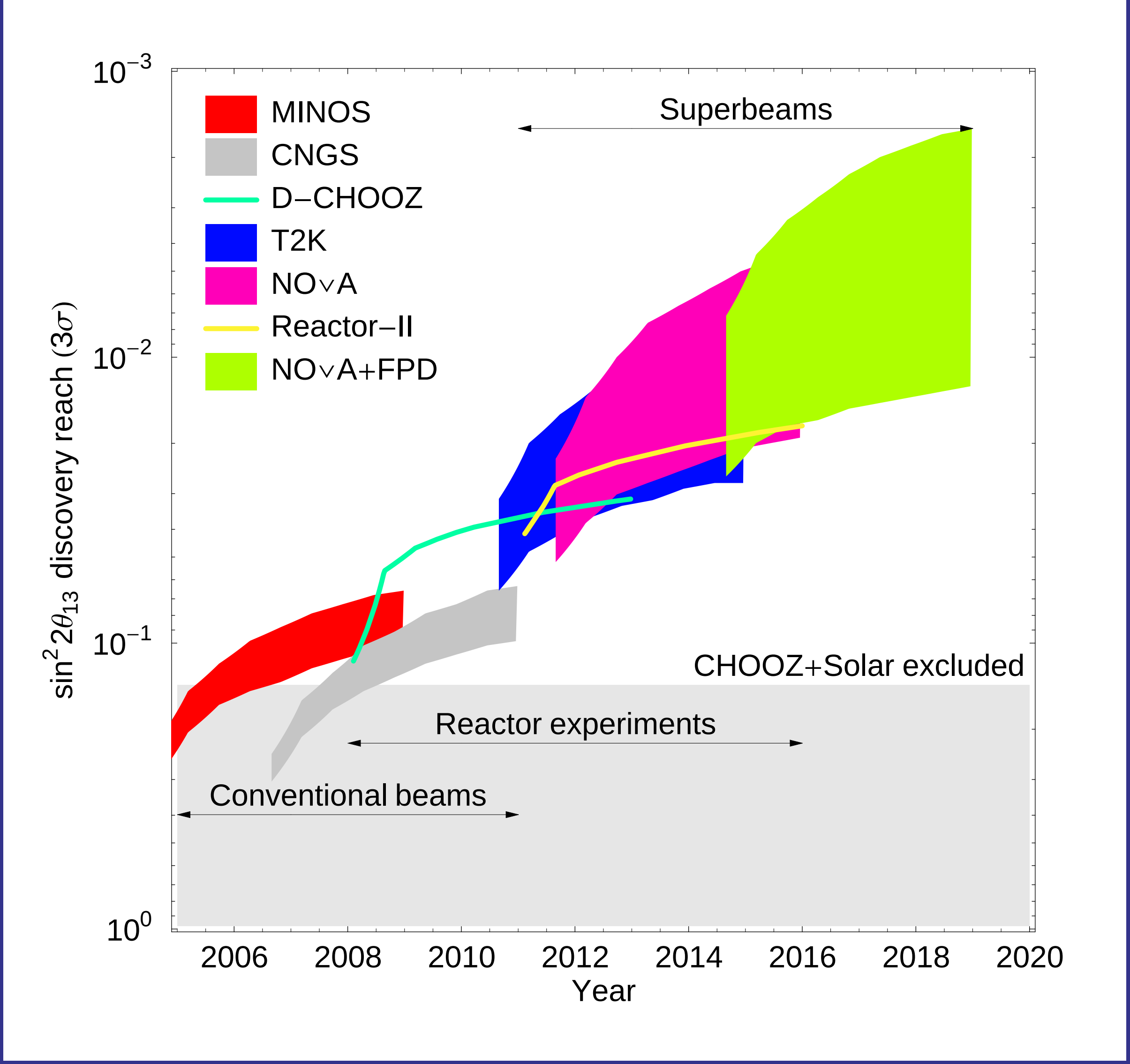
last term negligible for $\frac{\Delta m^2_{31} L}{4E_\nu} \sim \pi/2$ and $\sin^2 2\theta_{13} \gtrsim 10^{-3}$

determination of θ_{13} is free of correlations and degeneracies

P. Huber, M. Lindner, T. Schwetz and W. Winter, Nucl. Phys. B **665** (2003) 487 [hep-ph/0303232]

H. Minakata, H. Sugiyama, O. Yasuda, K. Inoue and F. Suekane, Phys. Rev. D **68** (2003) 033017

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

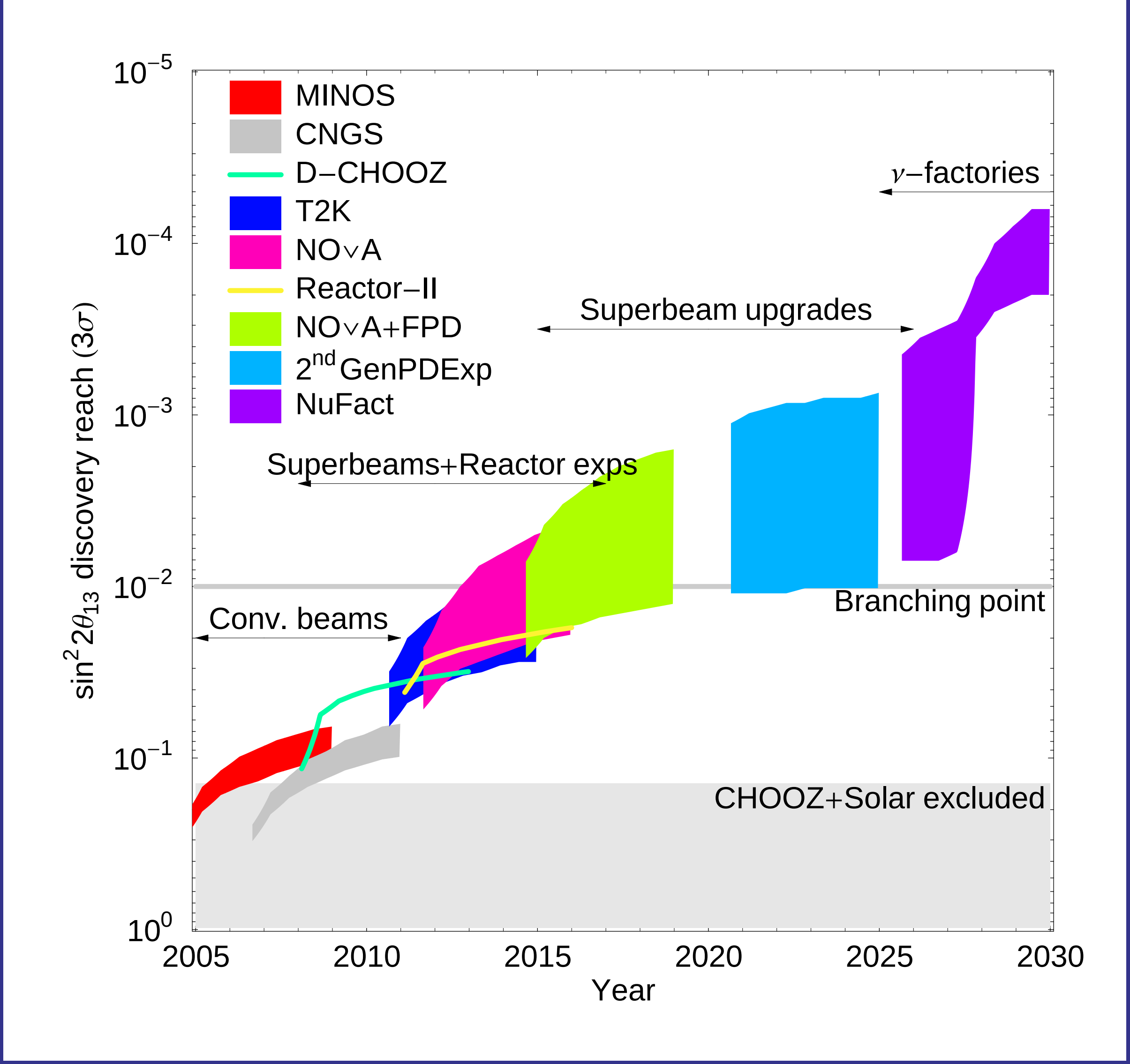


plot by W. Winter from Albrow et al., hep-ex/0509019

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

FPD = Fermilab Proton Driver
LBL exps.: neutrinos only

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



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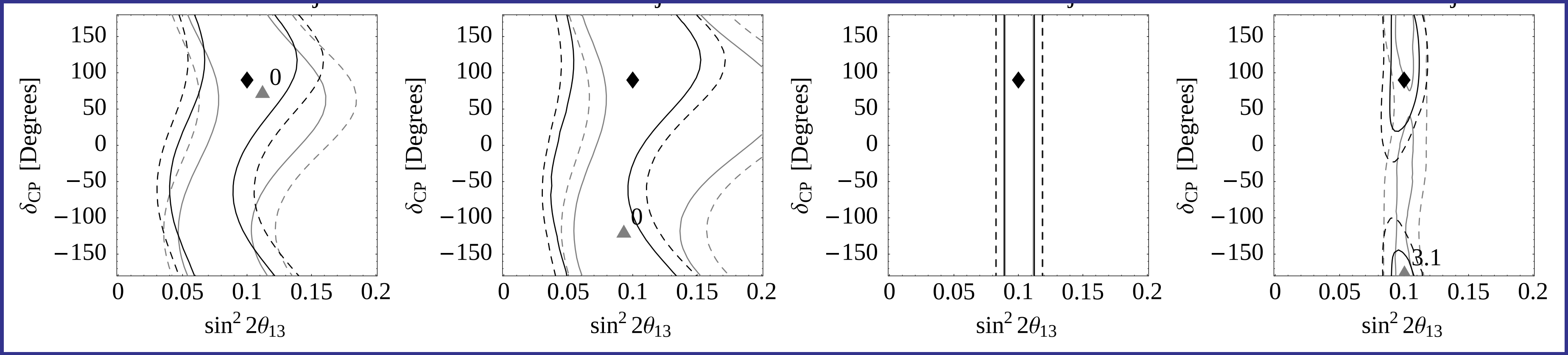
LBL exps.: neutrinos only
$2^{\rm nd}$GenPDExp = T2HK
NuFact anti-ν after 2.5 yr

The CP-phase δ and the type of the mass hierarchy

CP-phase and hierarchy within ten years

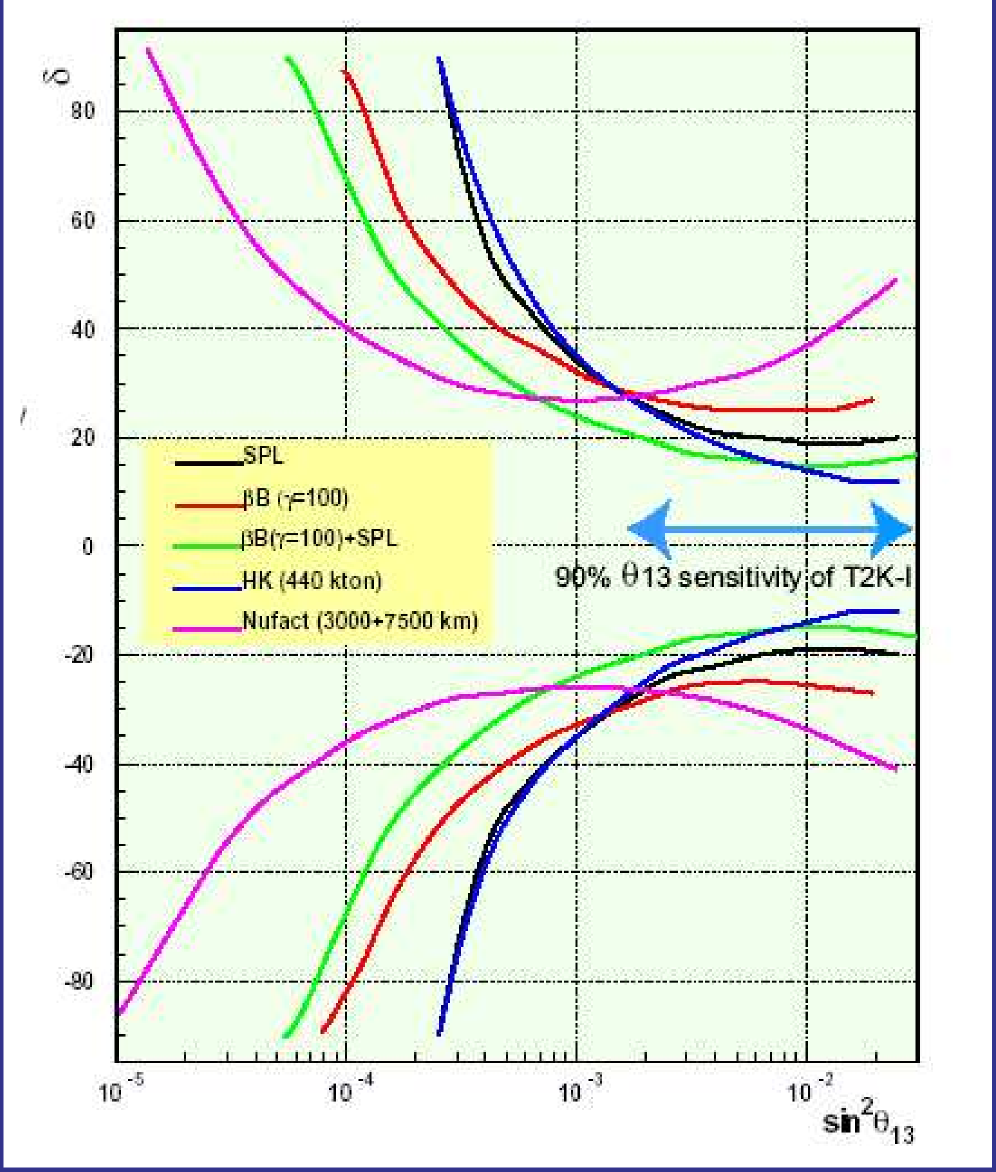
assume $\sin^2 2\theta_{13} = 0.1$

T2K | **NOνA** | **Reactor-II** | combined



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

Sensitivity to CP-violation at 3σ



M.Mezzetto, talk at NuFact 2006

SPL: 2ν+$8\bar{\nu}$ yr, 440 kton

βB: 5ν+$5\bar{\nu}$ yr, 440 kton

βB + SPL

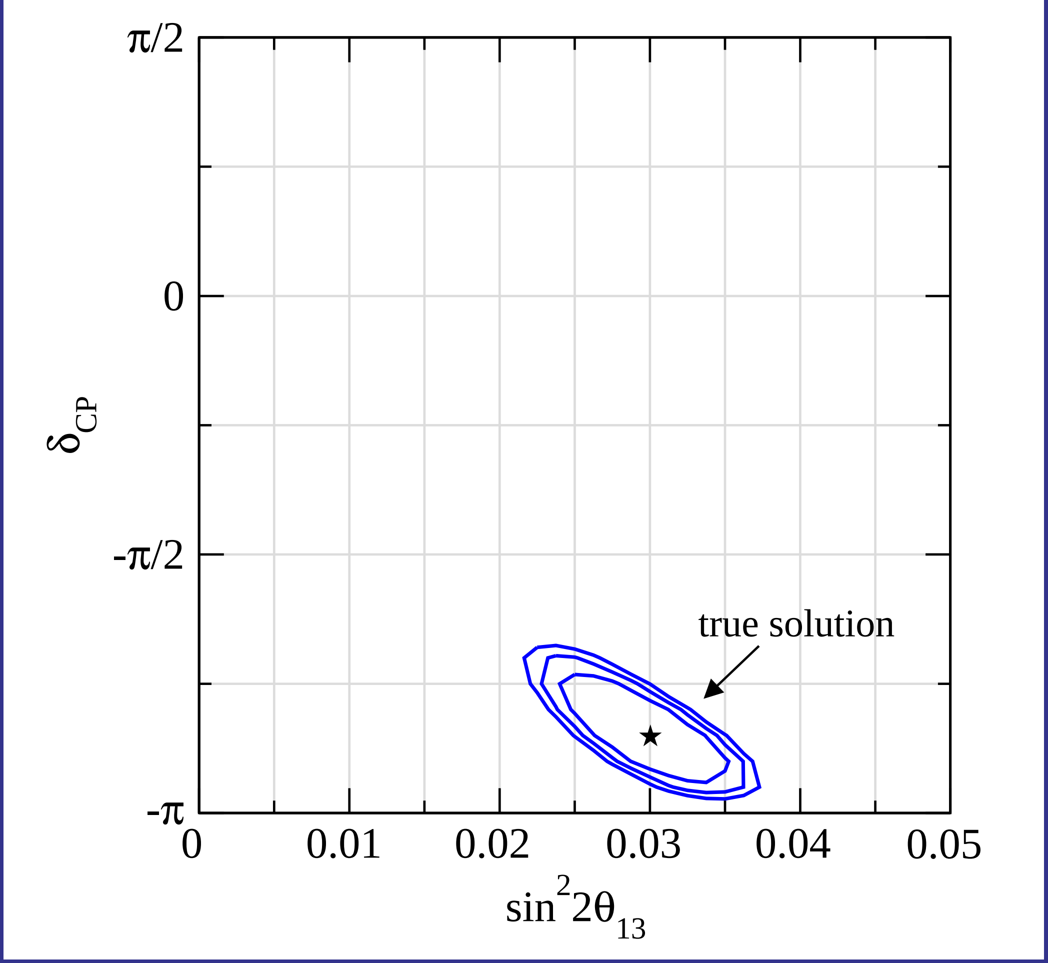
T2HK: 2ν+$8\bar{\nu}$ yr, 440 kton

NuFact: 5ν+$5\bar{\nu}$ yr, 2×50 kton at 3500 and 7000 km

The problem of degeneracies

Parameter degeneracies in LBL experiments provide a severe limitation for the determination of θ_{13}, the CP phase δ and the hierarchy!

Degeneracies and T2HK



allowed regions at 2σ, 99%, 3σ CL

true values:

$\sin^2 2\theta_{13} = 0.03$

$\delta = -0.85\pi$

$\sin^2 \theta_{23} = 0.4$

$\Delta m^2_{31} = 2.2 \times 10^{-3}\text{eV}^2$

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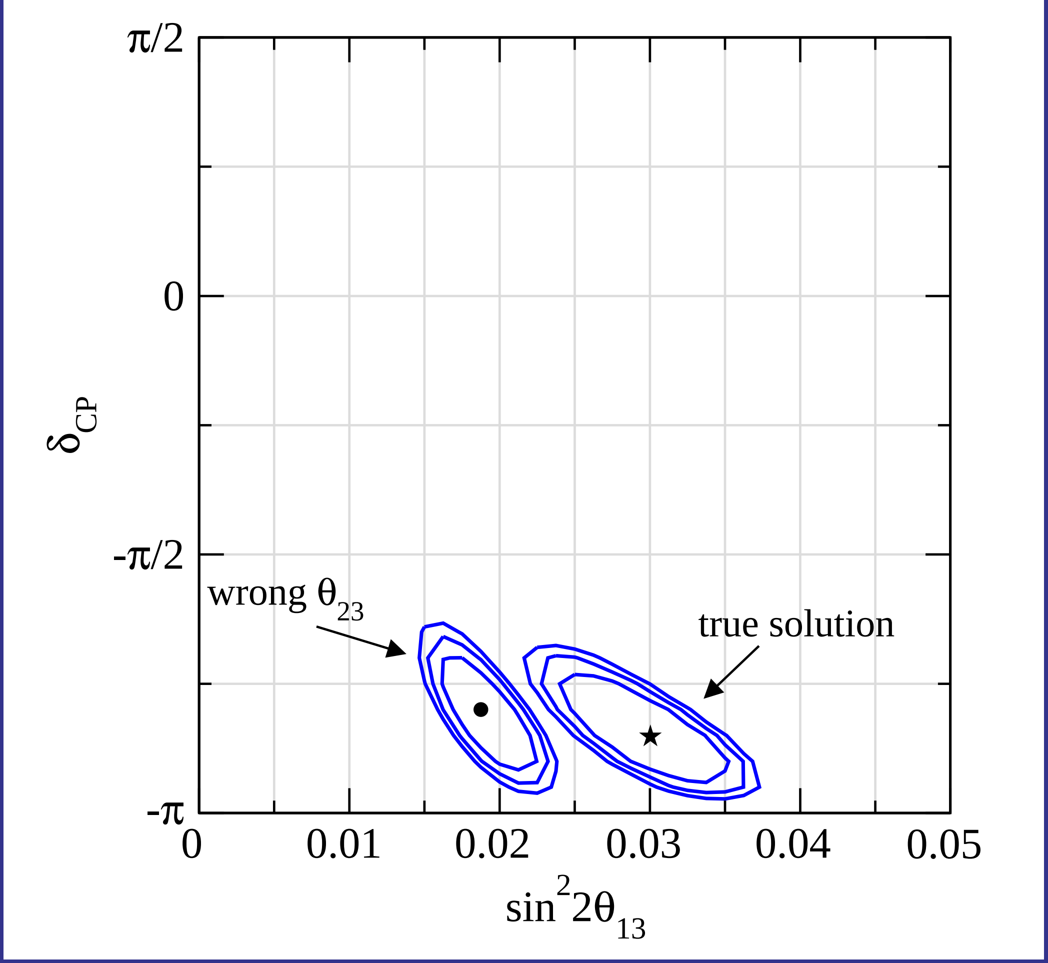

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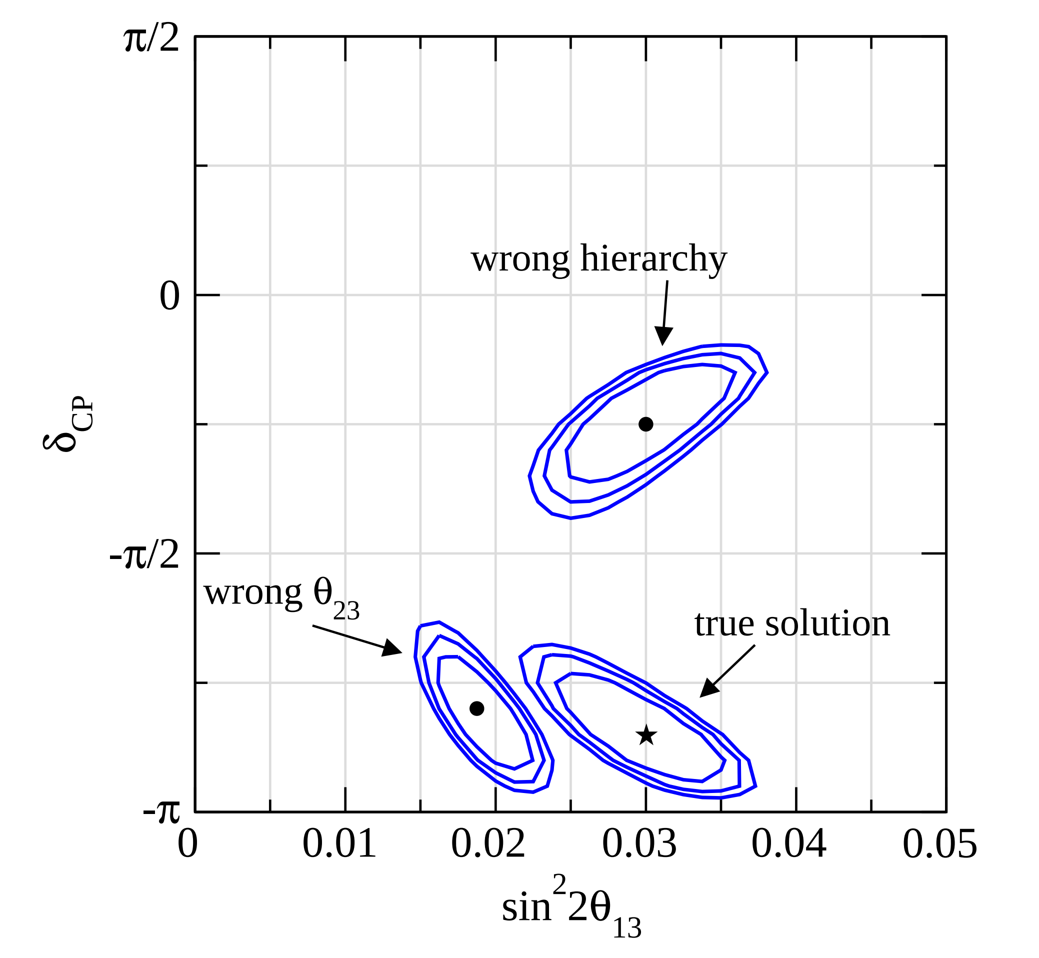

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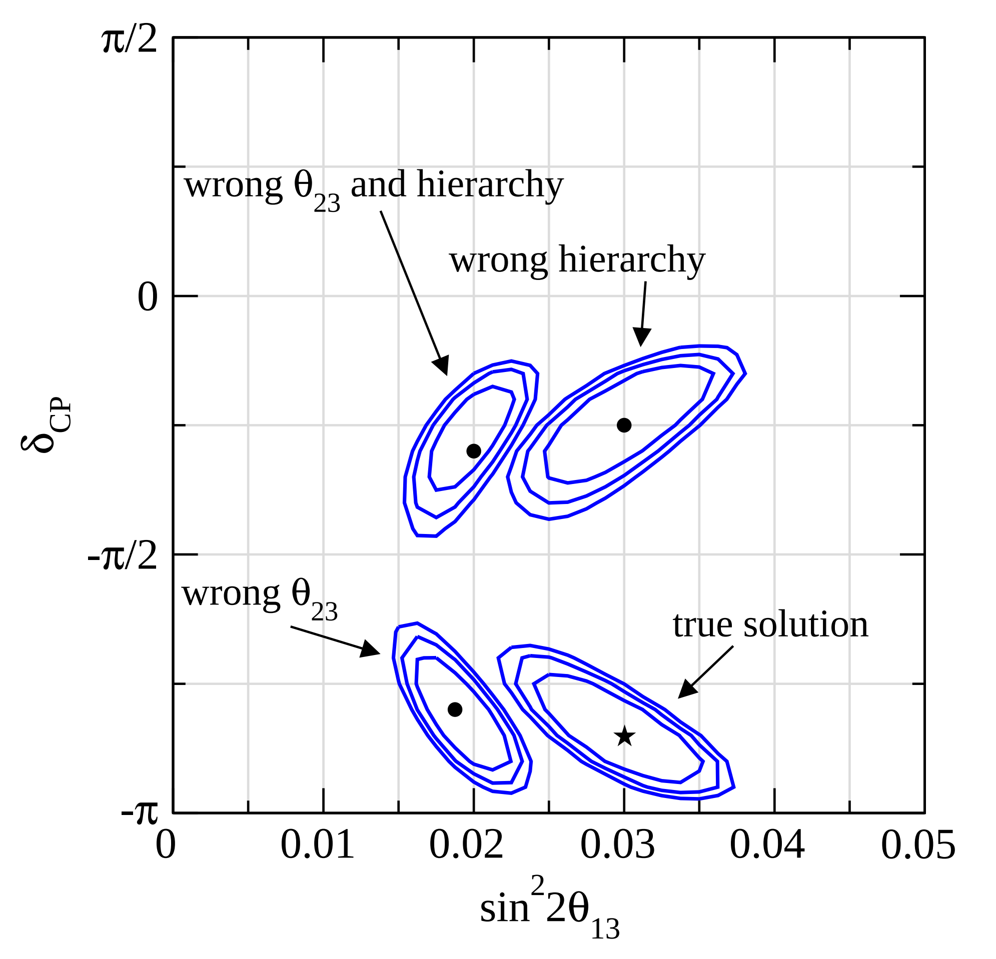

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ambiguities in θ_{13} and δ

no information on the hierarchy

Resolving the degeneracies

several possibilities to resolve the degeneracies are known:

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- combing data from LBL and atmospheric neutrino experiments

Some comments on the hierarchy determination

Determining the neutrino mass hierarchy

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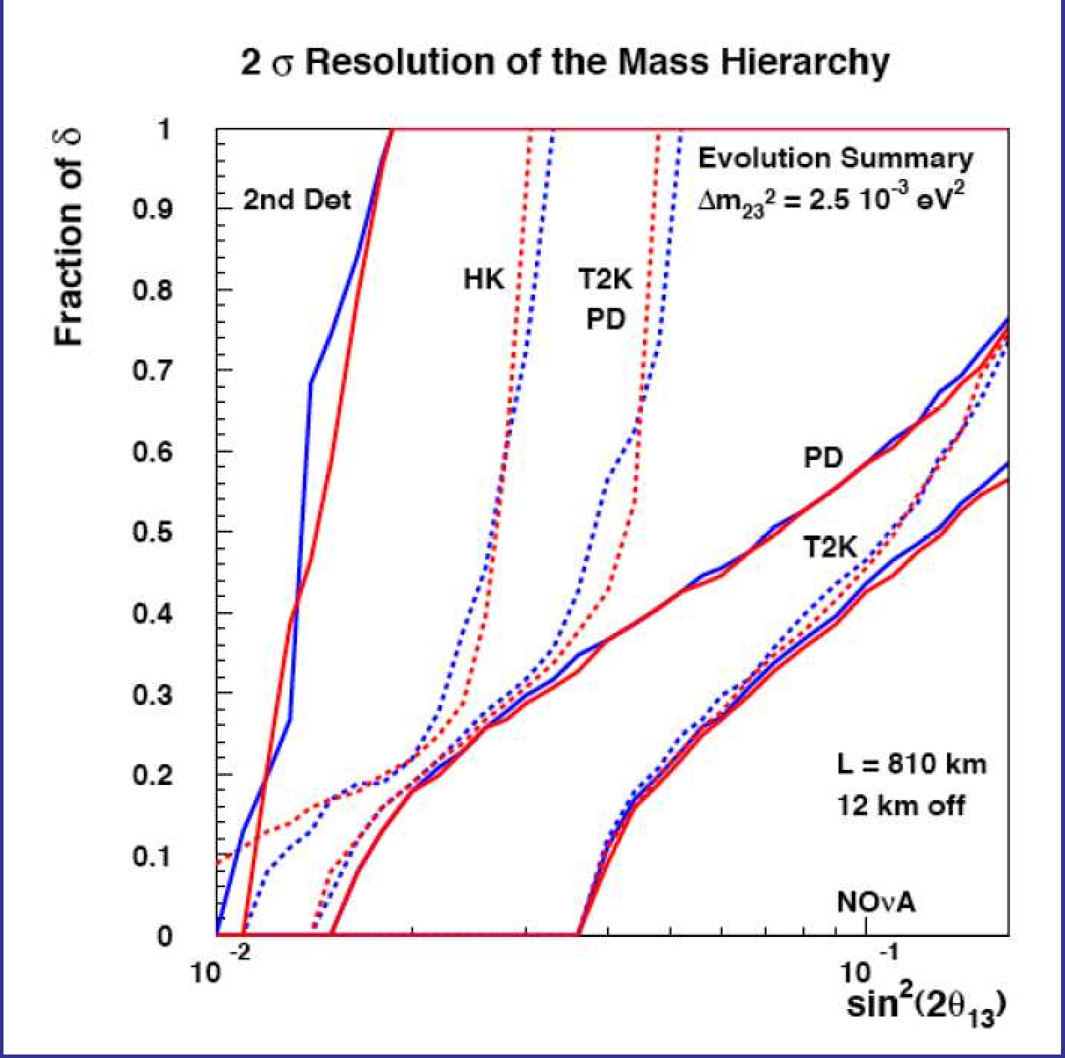
- needs matter effects
  - very long baseline ($\gtrsim 700$ km) in beam exps.
  - atmospheric neutrinos
  - supernova neutrinos

Determining the neutrino mass hierarchy



NOνA proposal, hep-ex/0503053

NOνA: 30 kt at 810 km

3ν+3$\bar{\nu}$ yrs

PD = proton driver

2$^{\rm nd}$ Det: 50 kt detector

at 710 km, 30 km off-axis

3ν+3$\bar{\nu}$ yrs NOνA+PD +

3ν+3$\bar{\nu}$ yrs NOνA+PD+2$^{\rm nd}$ Det

= 12 yrs total

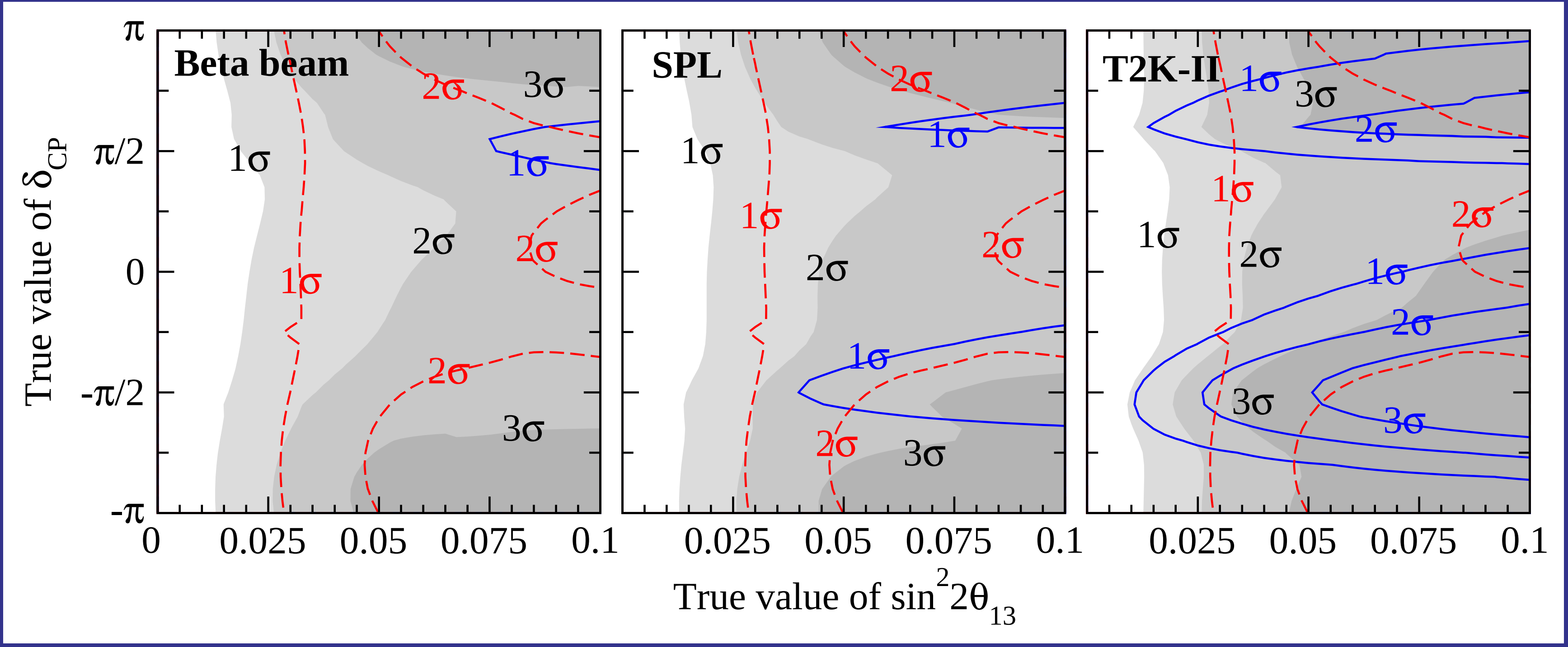
Determining the neutrino mass hierarchy

Combining LBL and atmospheric neutrino data

Determining the neutrino mass hierarchy

Combining LBL and atmospheric neutrino data

Huber, Maltoni, Schwetz, PRD71, 053006 (2005) [hep-ph/0501037]



blue: LBL only, red: ATM only, shading: LBL+ATM

450 kton, 2ν+$8\bar{\nu}$ yrs LBL data, 50 present SK ATM data

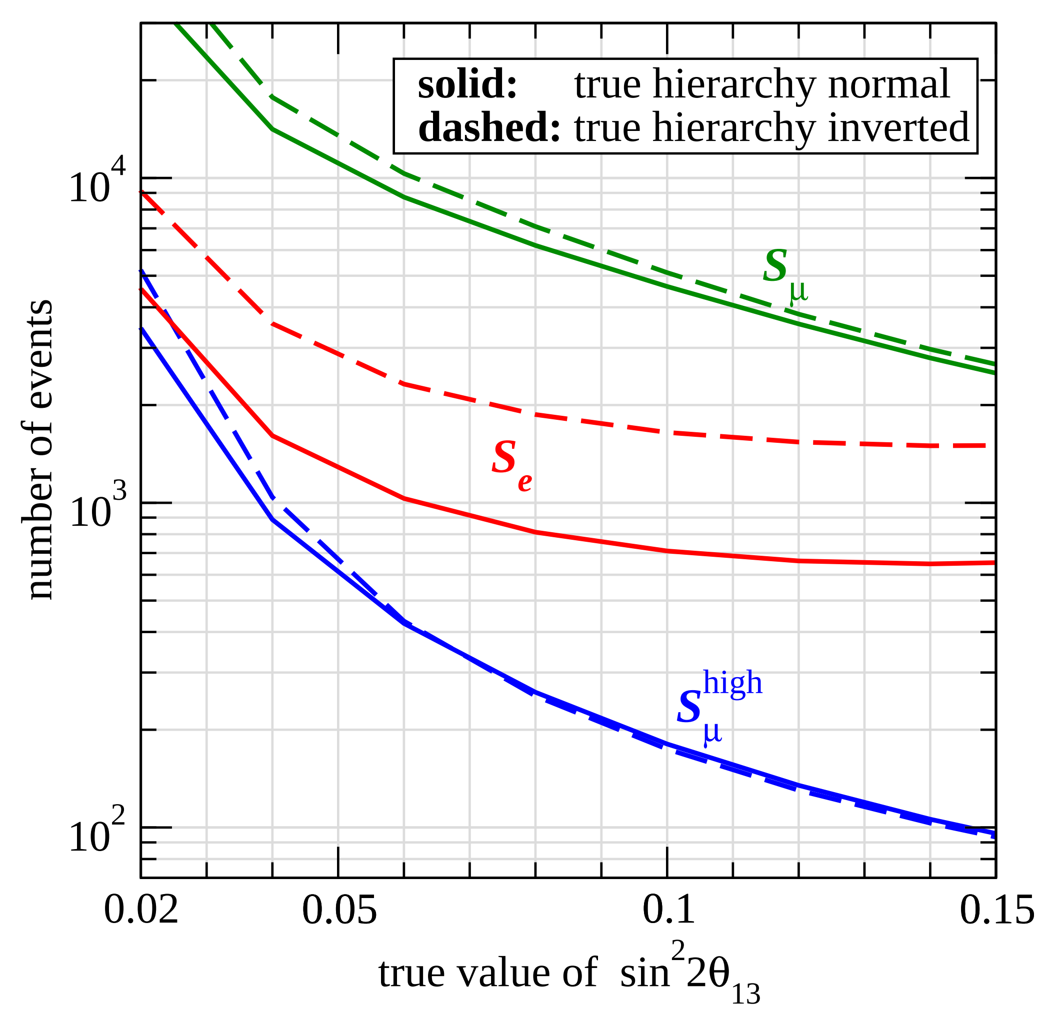
Determining the neutrino mass hierarchy

atmospheric νs with a magnetized iron detector (INO)

Determining the neutrino mass hierarchy

atmospheric νs with a magnetized iron detector (INO)

of events needed for a 2σ hierarchy determination



Petcov, Schwetz, in preparation

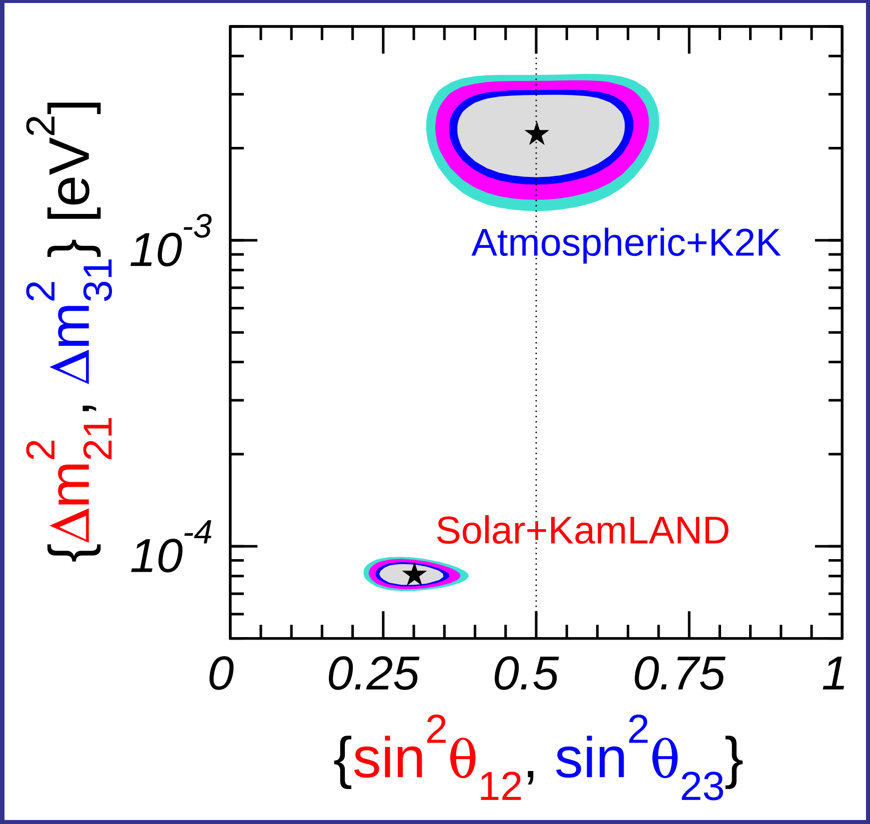
S_μ (S_μ^{high}): μ-like data with
15% (5%) energy,
15° (5°) direction resolution
S_e: e-like data with
85% charge identifi cation

30 kt, 10 yrs $\longrightarrow$
$\sim$ 1200 μ-events

Summary

Summary

present



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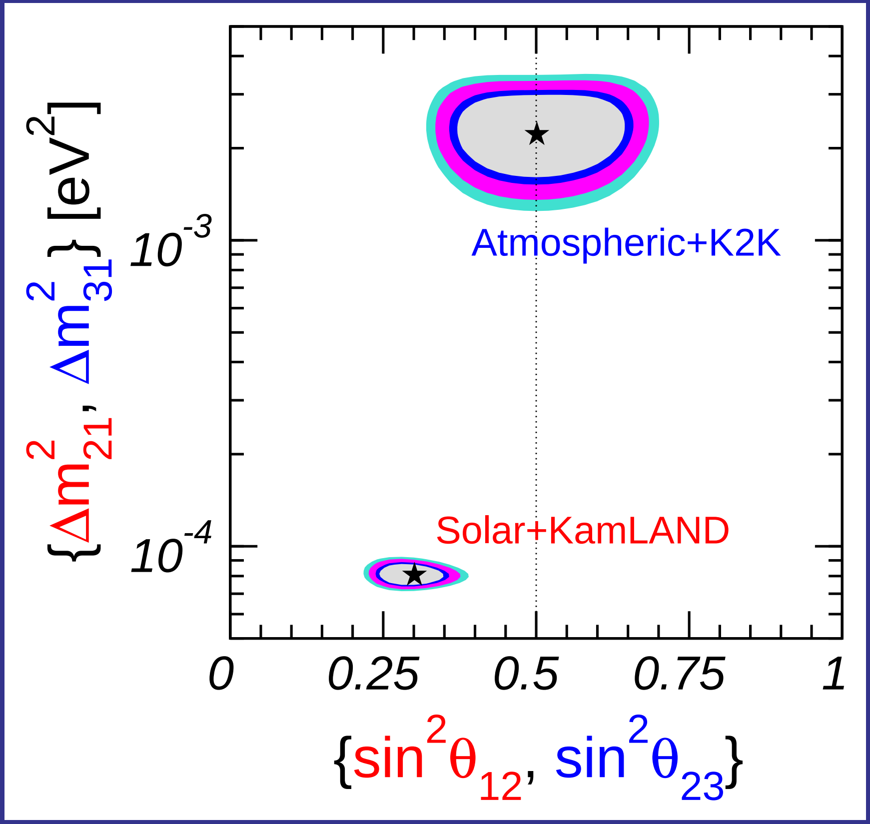
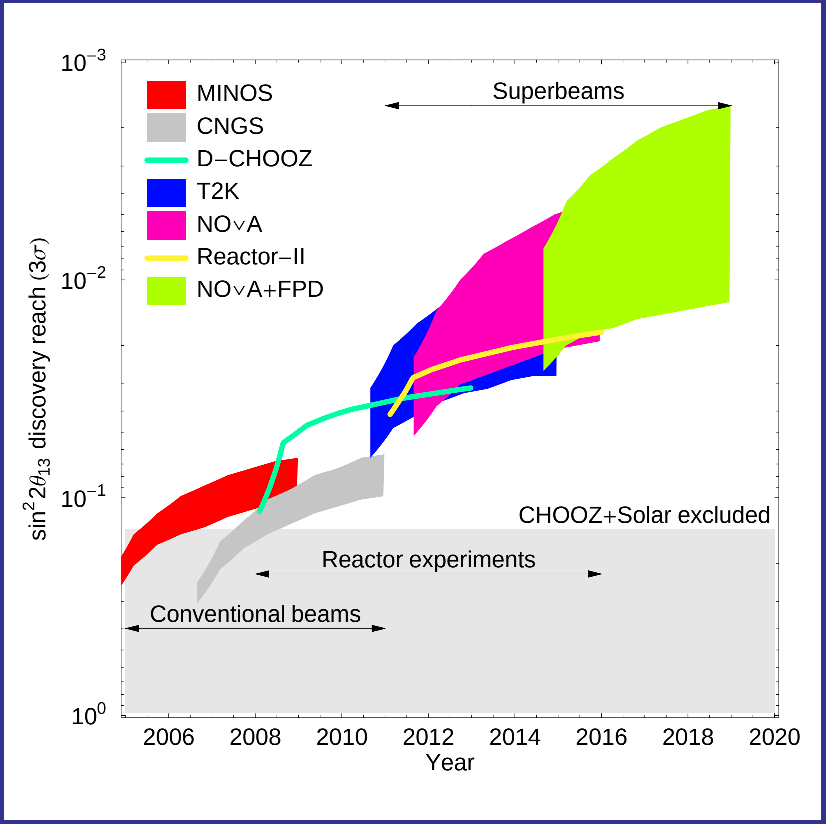


future



Summary

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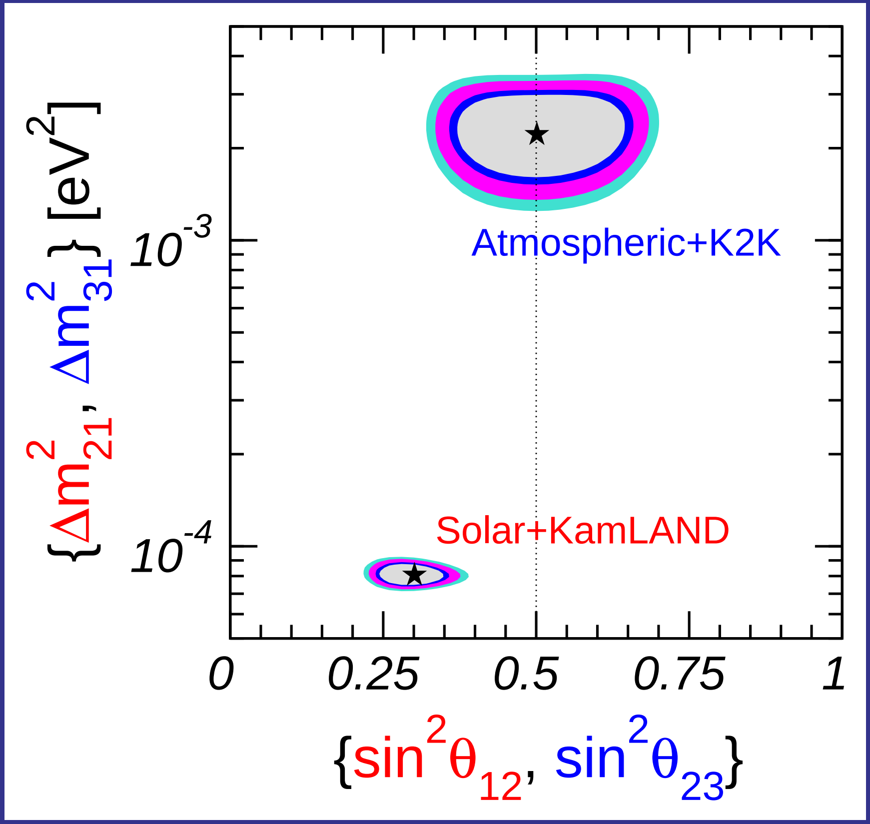

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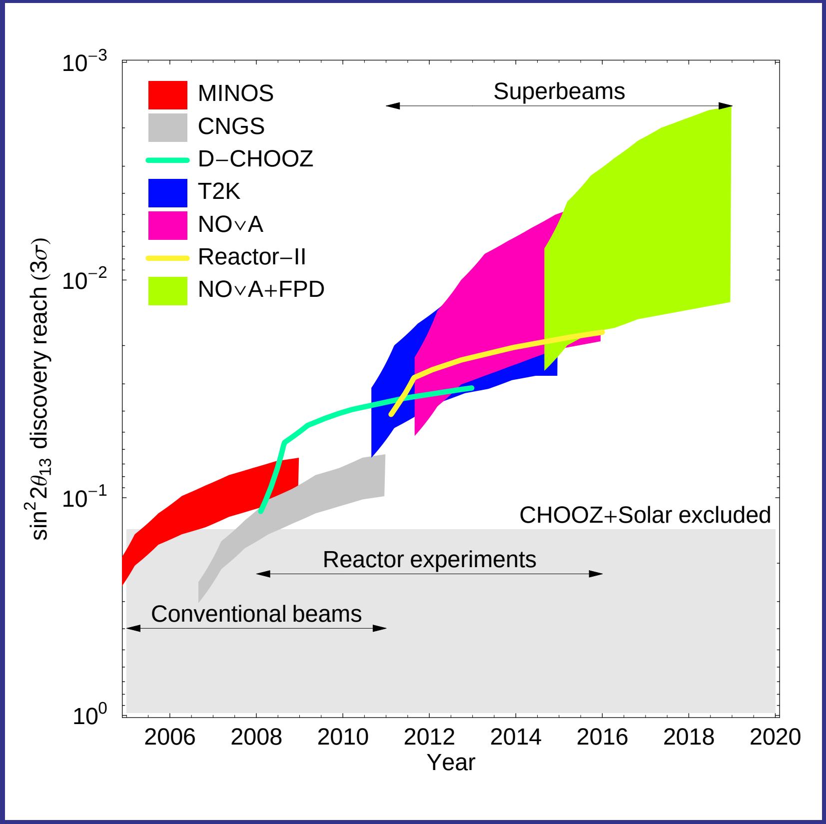
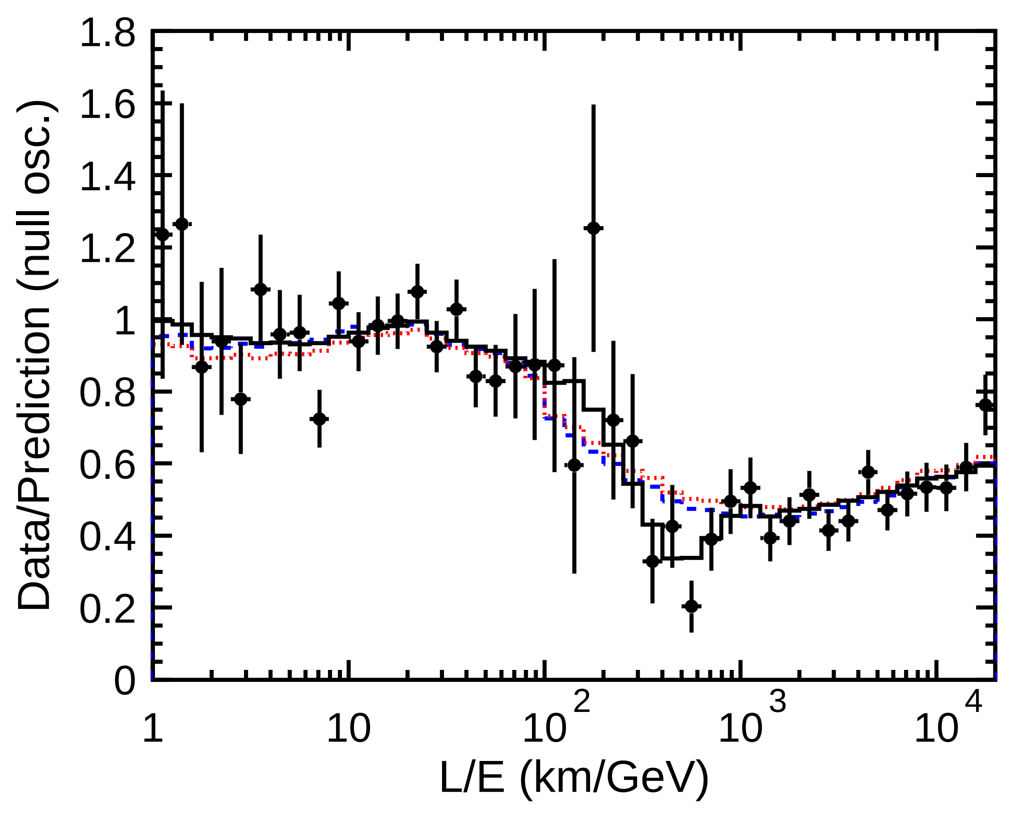


be prepared for surprises: **MiniBooNE**

additional slides

Oscillatory signal in atmospheric neutrinos

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

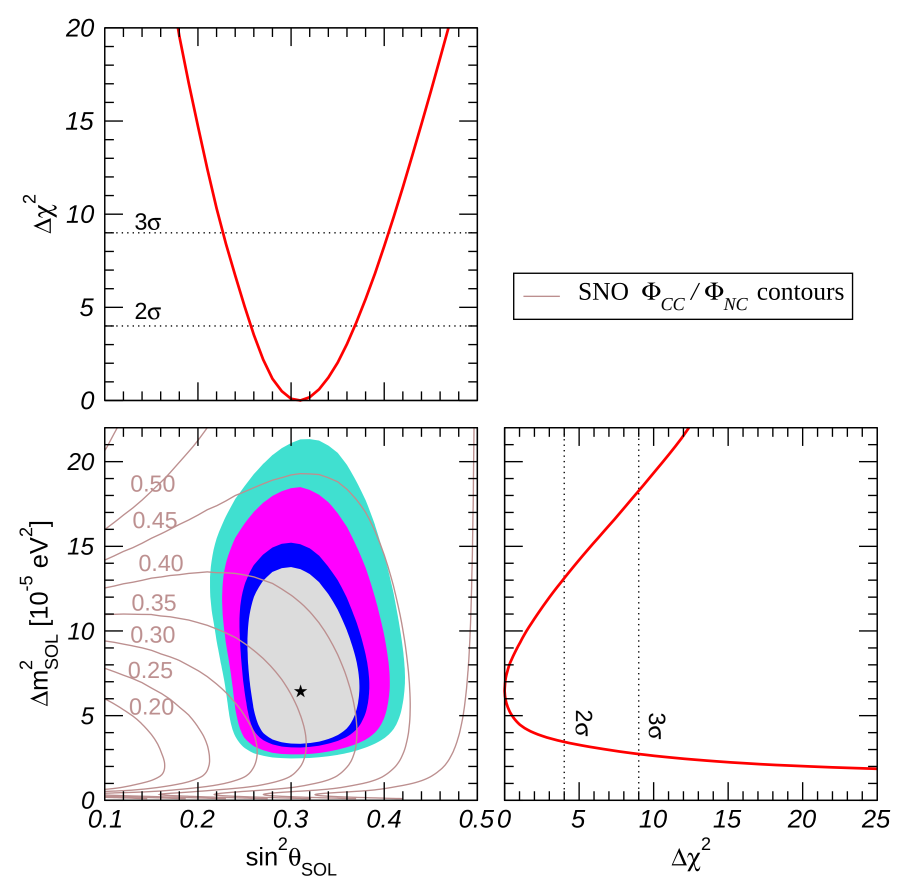


$$P_{2\nu} = 1 - \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2}{4}\frac{L}{E_\nu}\right)$$

’Solar’ parameters

global solar neutrino data:

Homestake,SAGE,GNO,SK,SNO



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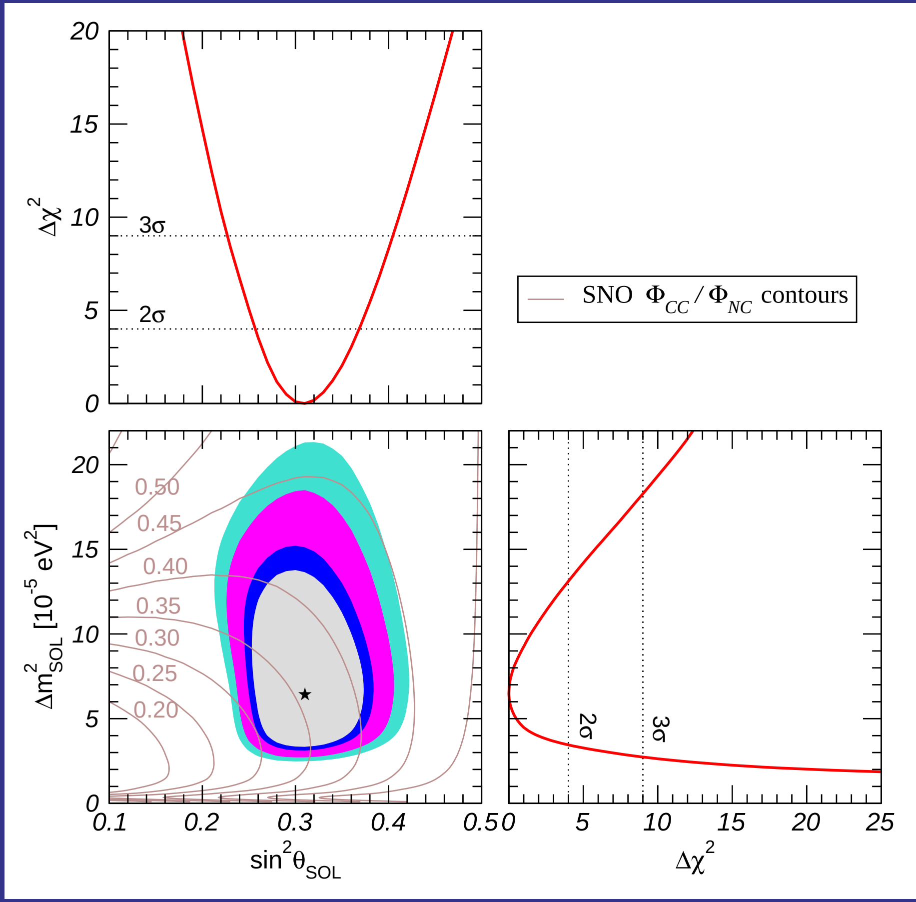


The SNO experiment:

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

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

SNO-II 391d nucl-ex/0502021

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

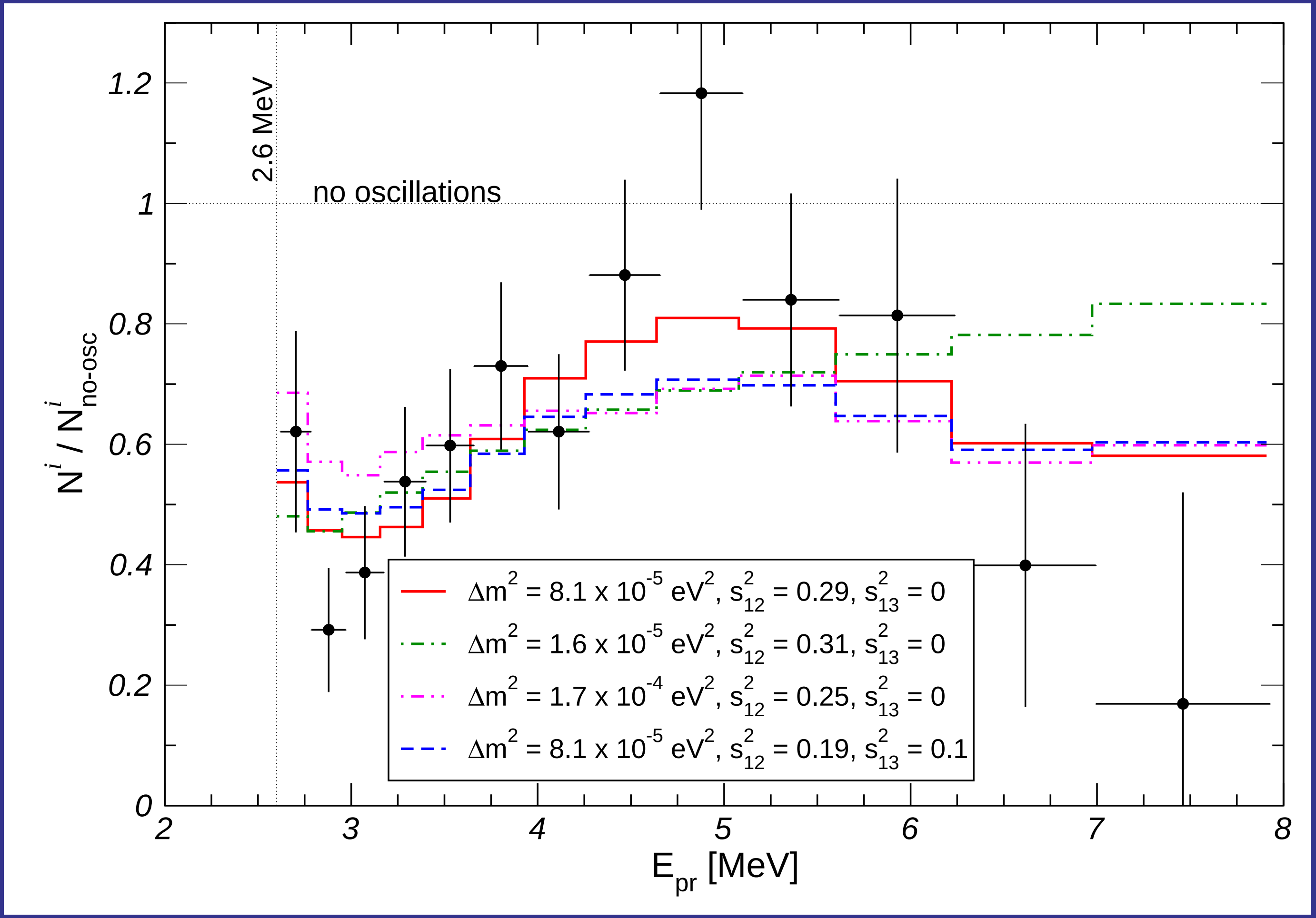
7σ evidence for a non-zero $\nu_{\mu,\tau}$ flux from the sun

constraint on θ_{12}:

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

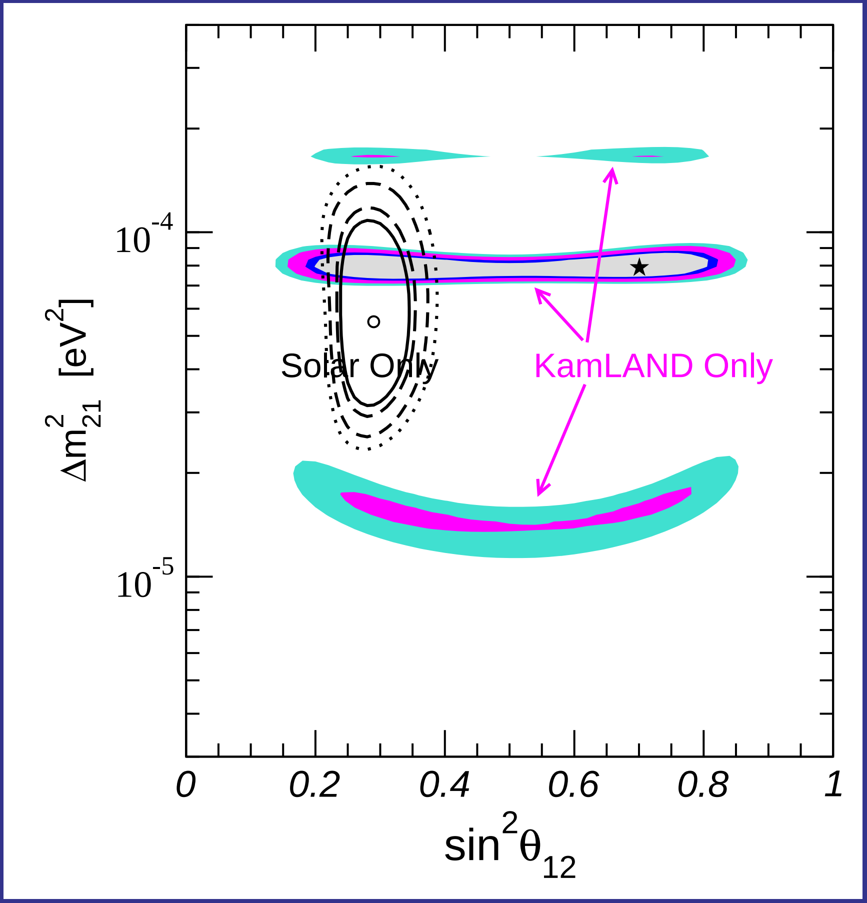
$$\sin^2\theta_{12} = 0.30^{+0.02}_{-0.03} \to 0.31^{+0.02}_{-0.03}$$

The KamLAND energy spectrum

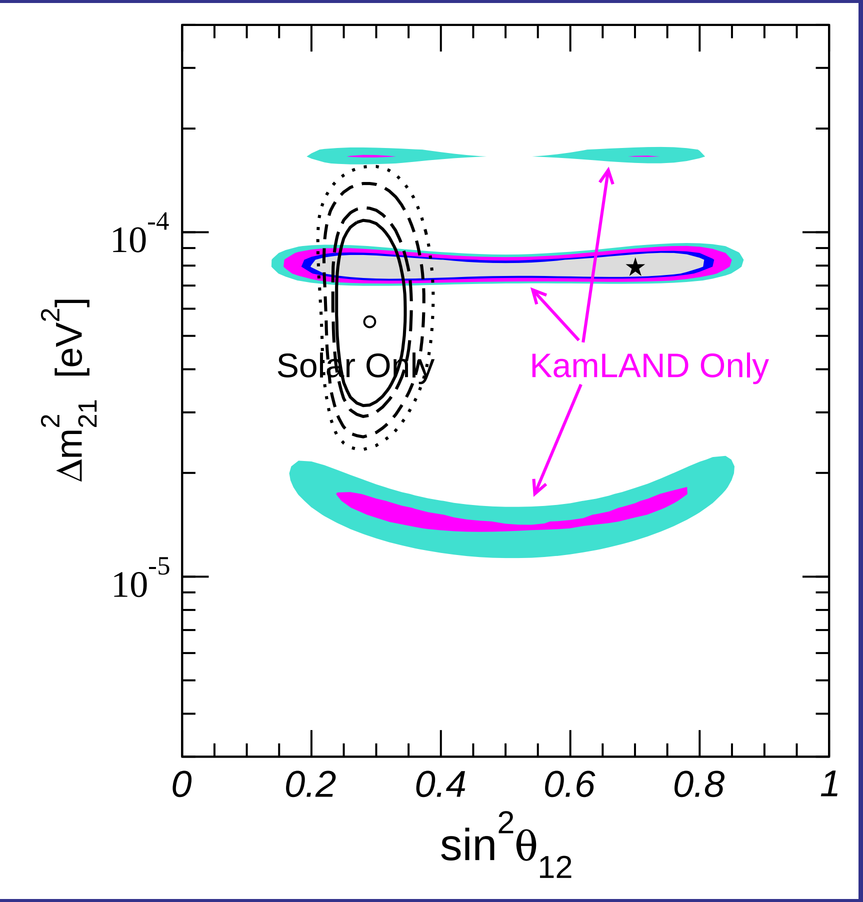


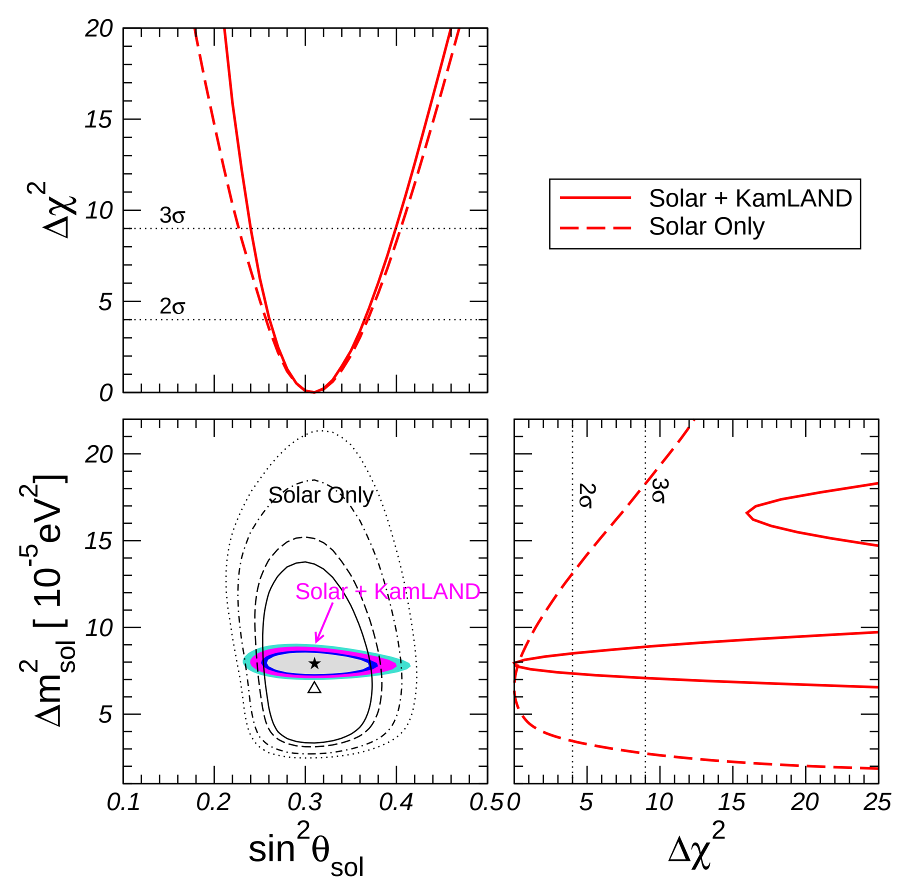
evidence for flux suppression and spectral distortion

KamLAND vs solar data



KamLAND vs solar data

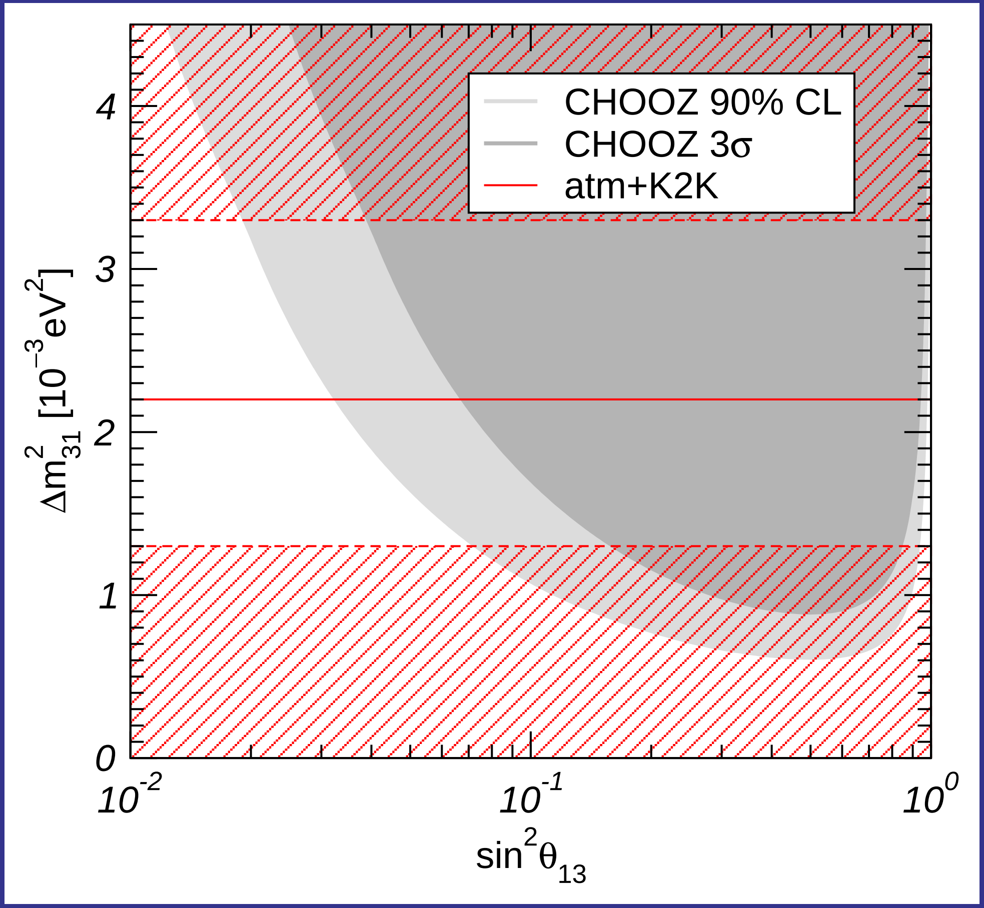




$$\Delta m^2 = 7.9 \pm 0.3 \times 10^{-5}\ \text{eV}^2,\ \sin^2\theta_{12} = 0.31^{+0.02}_{-0.03}$$

The bound on θ_{13}

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

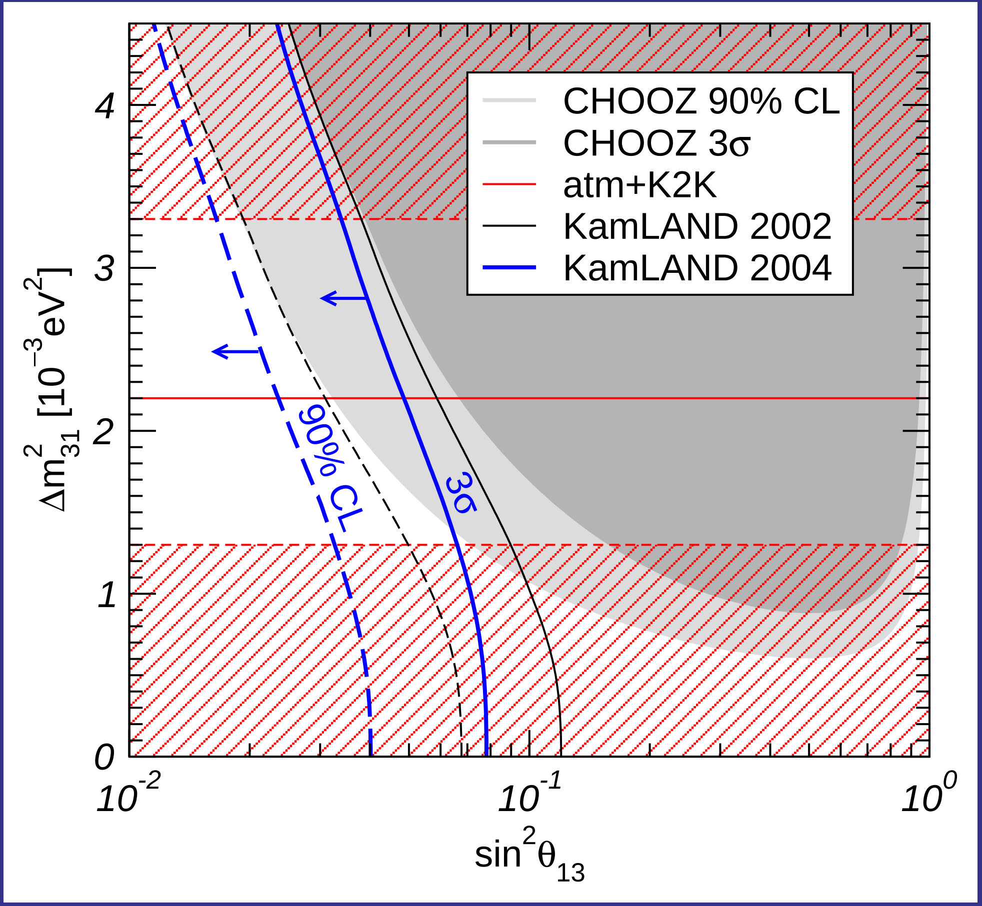


CHOOZ+atm+K2K:

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

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:

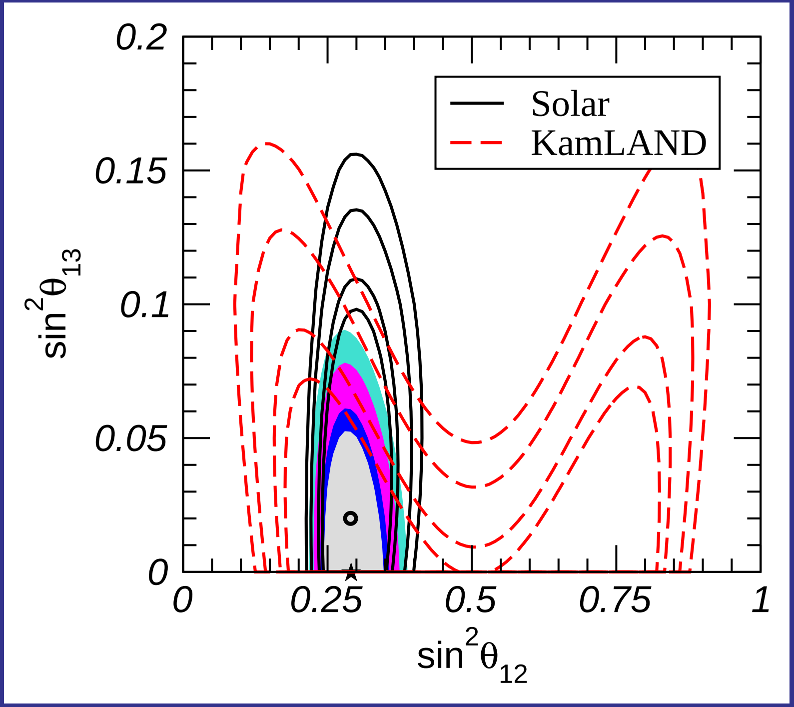
$\sin^2\theta_{13} < 0.041\,(0.079)$

global:

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

The θ_{13} bound from KamLAND and solar

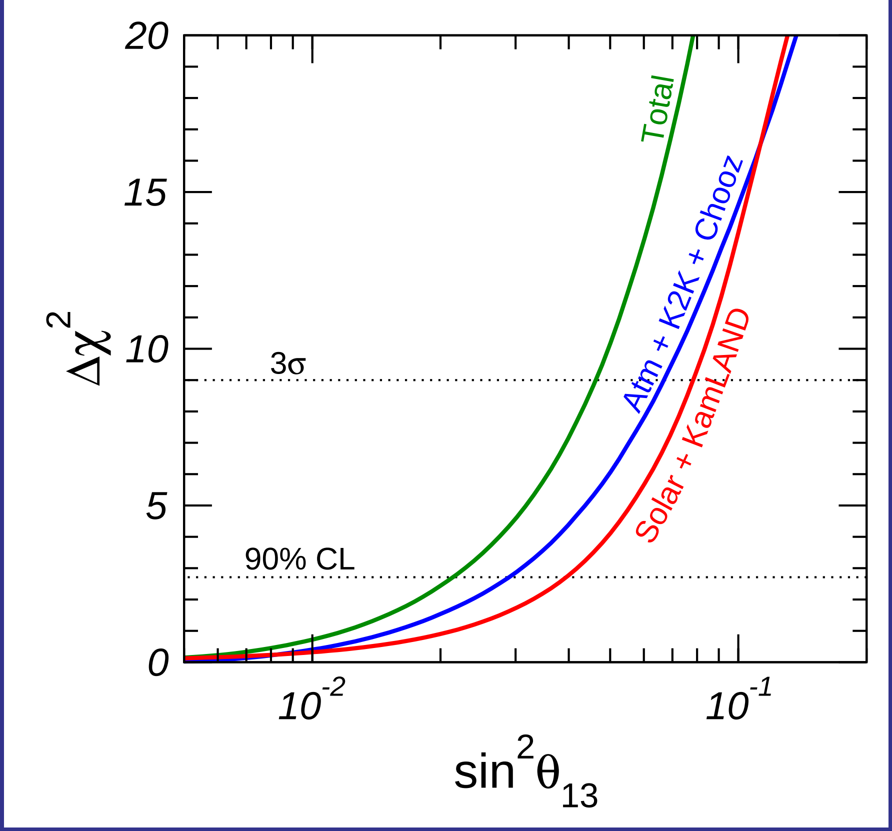
complementarity between solar and KamLAND data



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

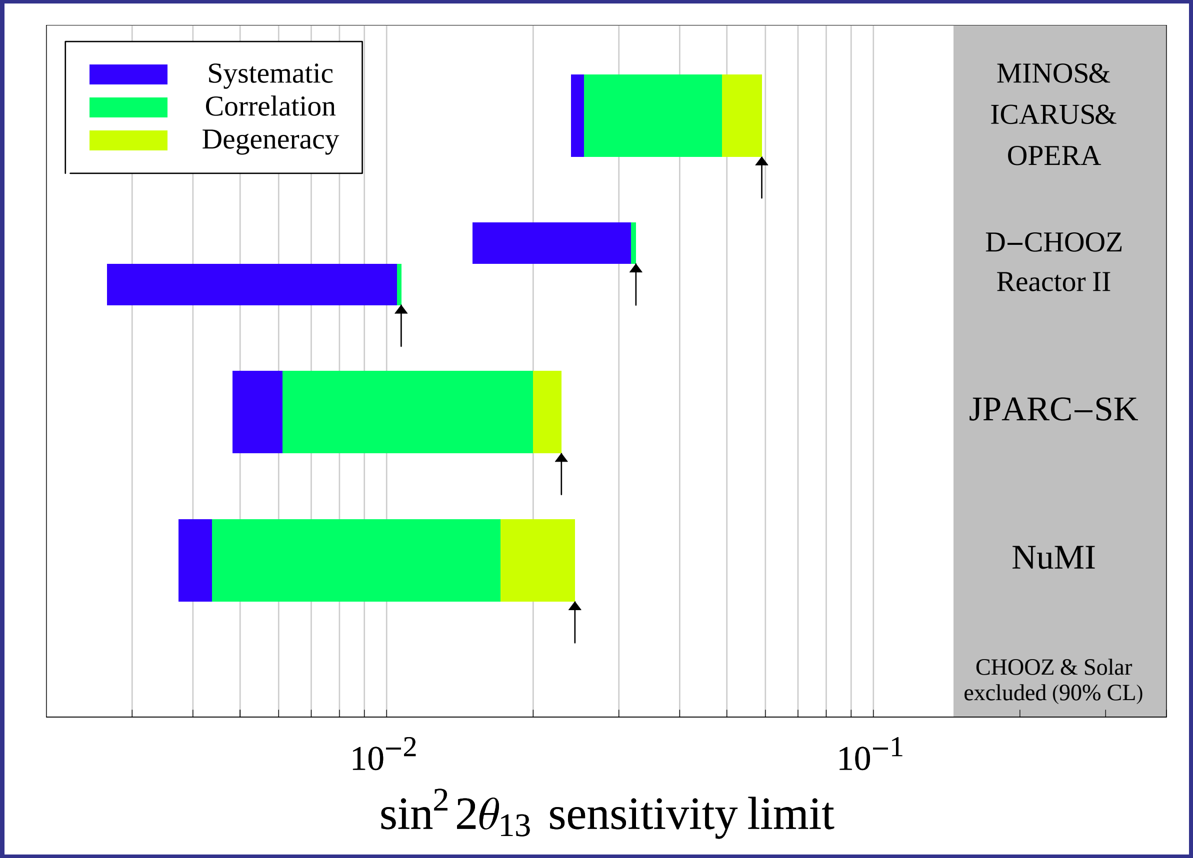
$$P_{\rm Sol} \approx \left(1 - 2\sin^2\theta_{13}\right)\begin{cases} \sin^2\theta_{12} & \text{high } E_\nu \\ \left(1 - 0.5\sin^2 2\theta_{12}\right) & \text{low } E_\nu \end{cases}$$

The global bound on θ_{13}



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

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

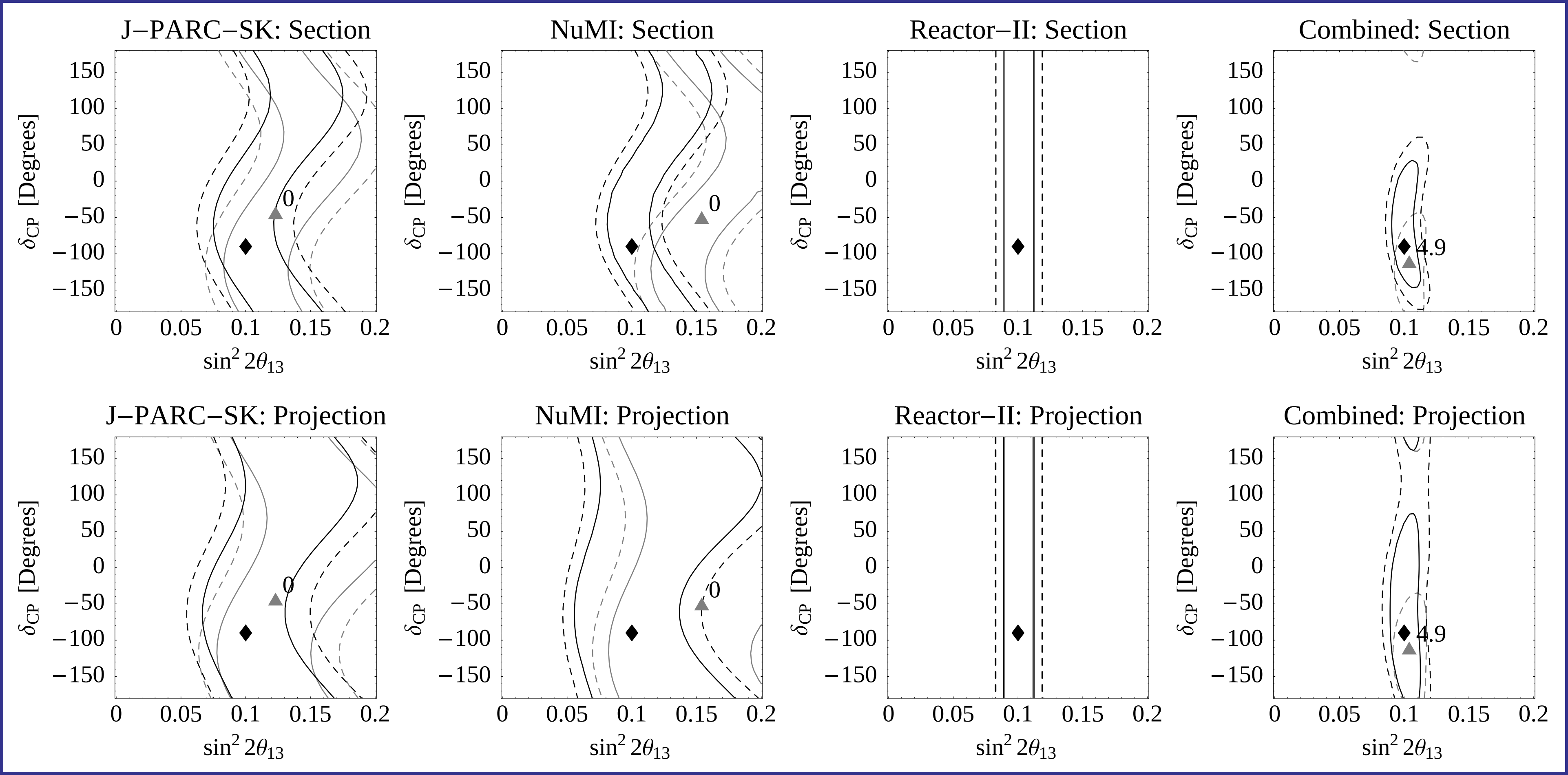


true values:

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

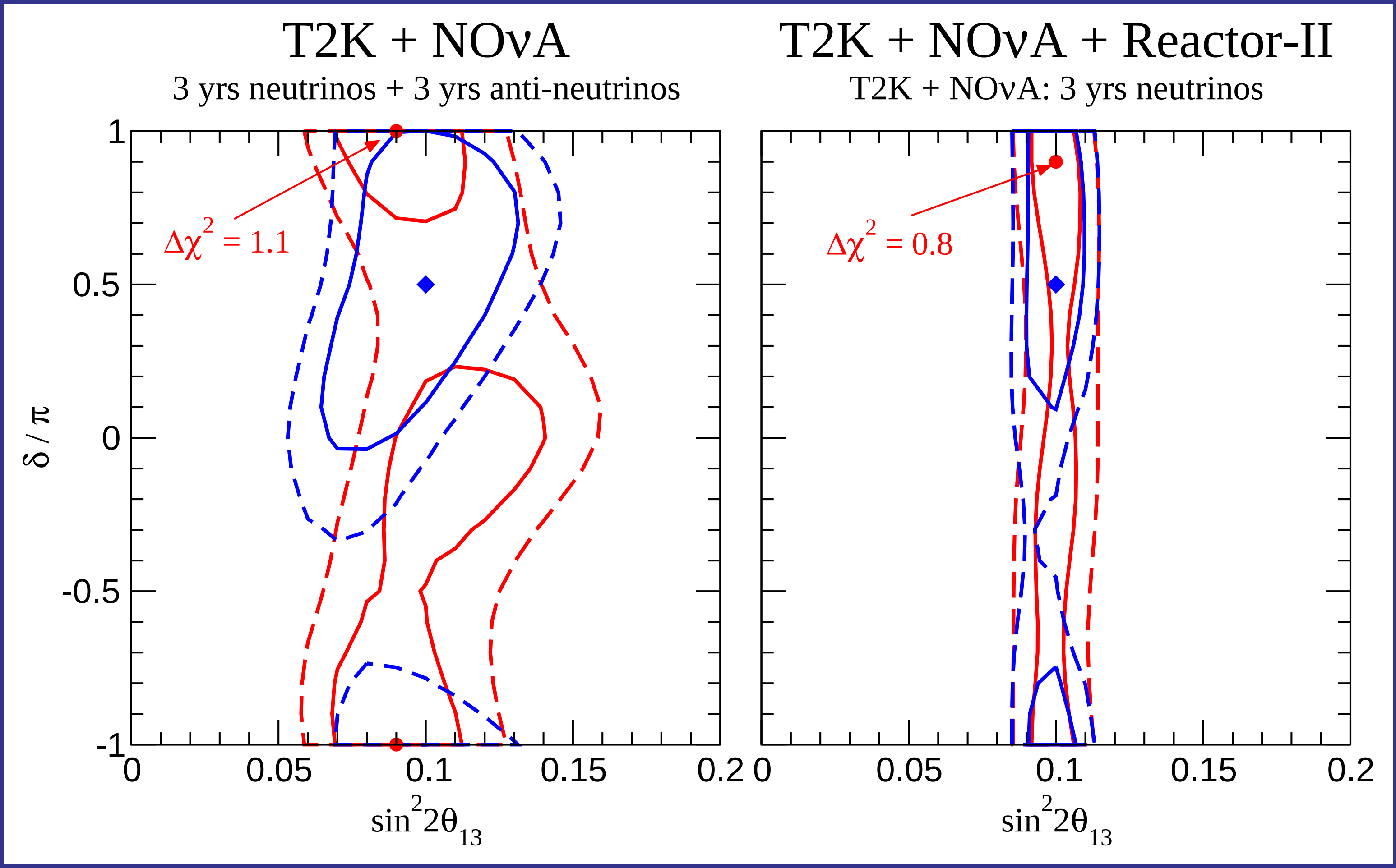
Huber, Lindner, Rolinec, Schwetz, Winter, hep-ph/0403068

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



θ_{13} *limit*