Status of the PMNS Matrix

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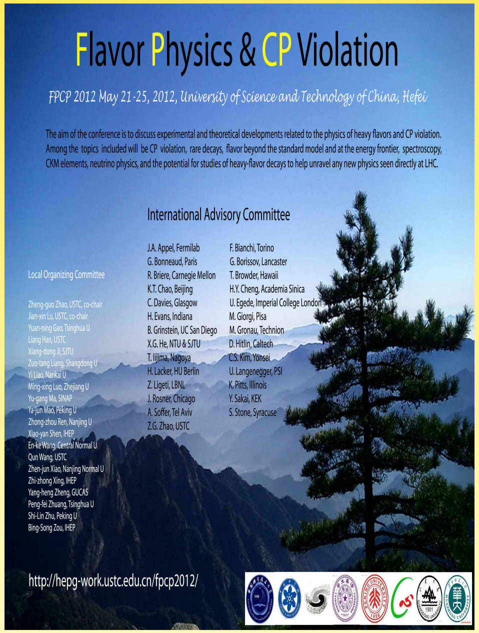
24/05/12

$$m_\nu = m_L - m_D^T M_R^{-1} m_D$$

MANITOP
Massive Neutrinos: Investigating their Theoretical Origin and Phenomenology

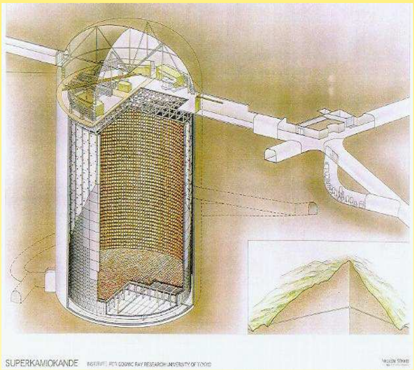


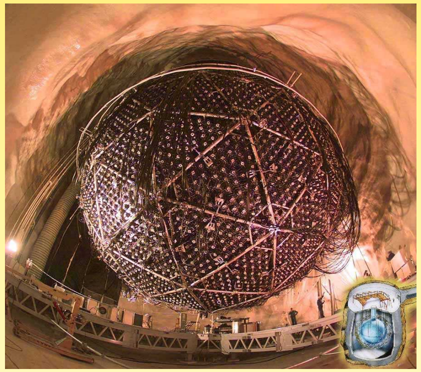
Status of the PMNS Matrix

- What are the parameters of U?
  - θ_{12}
  - θ_{23}
  - θ_{13}
- Impact on θ_{13} on Phenomenology and Models

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

$$\underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\substack{\text{atmospheric and} \\ \text{LBL accelerator}}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}\,e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}\,e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{SBL reactor}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\substack{\text{solar and} \\ \text{LBL reactor}}}$$





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

$$\underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{atmospheric and LBL accelerator}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}\,e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}\,e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{SBL reactor}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar and LBL reactor}}$$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \sqrt{\frac{1}{2}} & -\sqrt{\frac{1}{2}} \\ 0 & \sqrt{\frac{1}{2}} & \sqrt{\frac{1}{2}} \end{pmatrix} \qquad \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ -\sqrt{\frac{1}{3}} & \sqrt{\frac{2}{3}} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$(\sin^2\theta_{23} = \tfrac{1}{2}) \qquad (\sin^2\theta_{13} = 0) \qquad (\sin^2\theta_{12} = \tfrac{1}{3})$$

$$\Delta m^2_{\mathrm{A}} \qquad \Delta m^2_{\mathrm{A}} \qquad \Delta m^2_{\odot}$$

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

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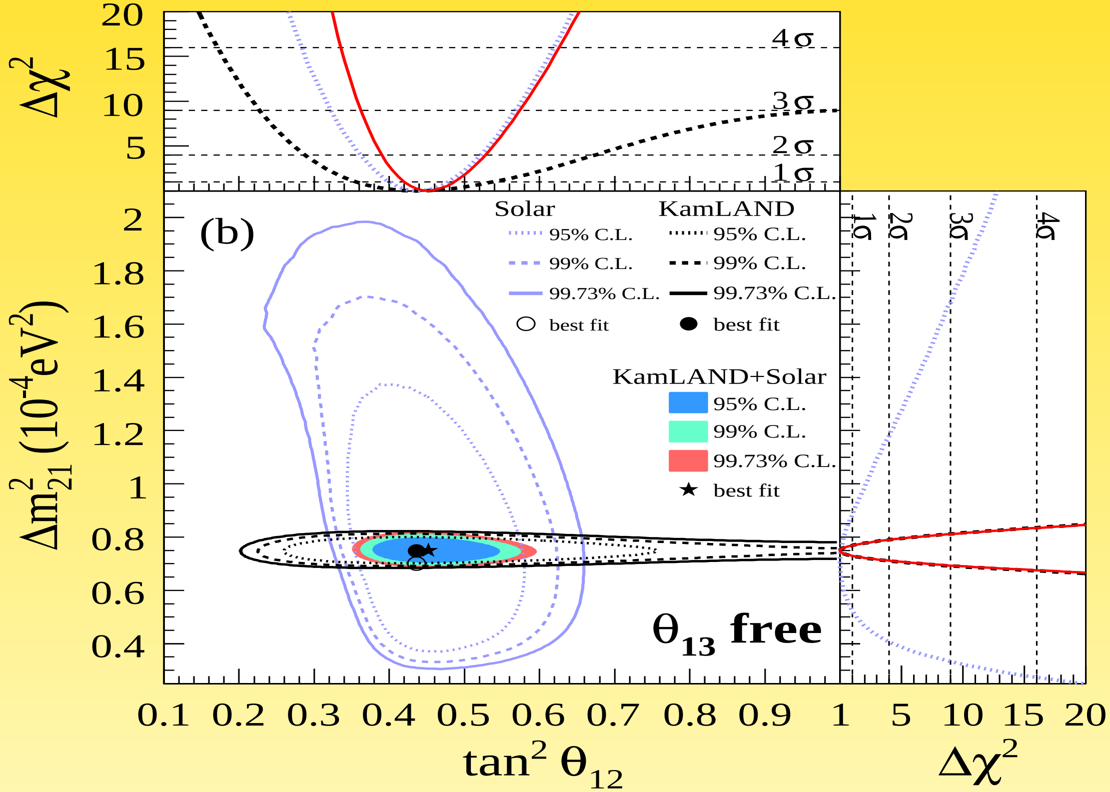
$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \sqrt{\frac{1}{2}} & -\sqrt{\frac{1}{2}} \\ 0 & \sqrt{\frac{1}{2}} & \sqrt{\frac{1}{2}} \end{pmatrix} \qquad \begin{pmatrix} 1 & 0 & \epsilon\,e^{-i\delta} \\ 0 & 1 & 0 \\ -\epsilon\,e^{i\delta} & 0 & 1 \end{pmatrix} \qquad \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ -\sqrt{\frac{1}{3}} & \sqrt{\frac{2}{3}} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$(\sin^2\theta_{23} = \tfrac{1}{2}) \qquad (\sin^2\theta_{13} = \epsilon^2) \qquad (\sin^2\theta_{12} = \tfrac{1}{3})$$

$$\Delta m^2_{\mathrm{A}} \qquad \Delta m^2_{\mathrm{A}} \qquad \Delta m^2_{\odot}$$

θ_{12}: status

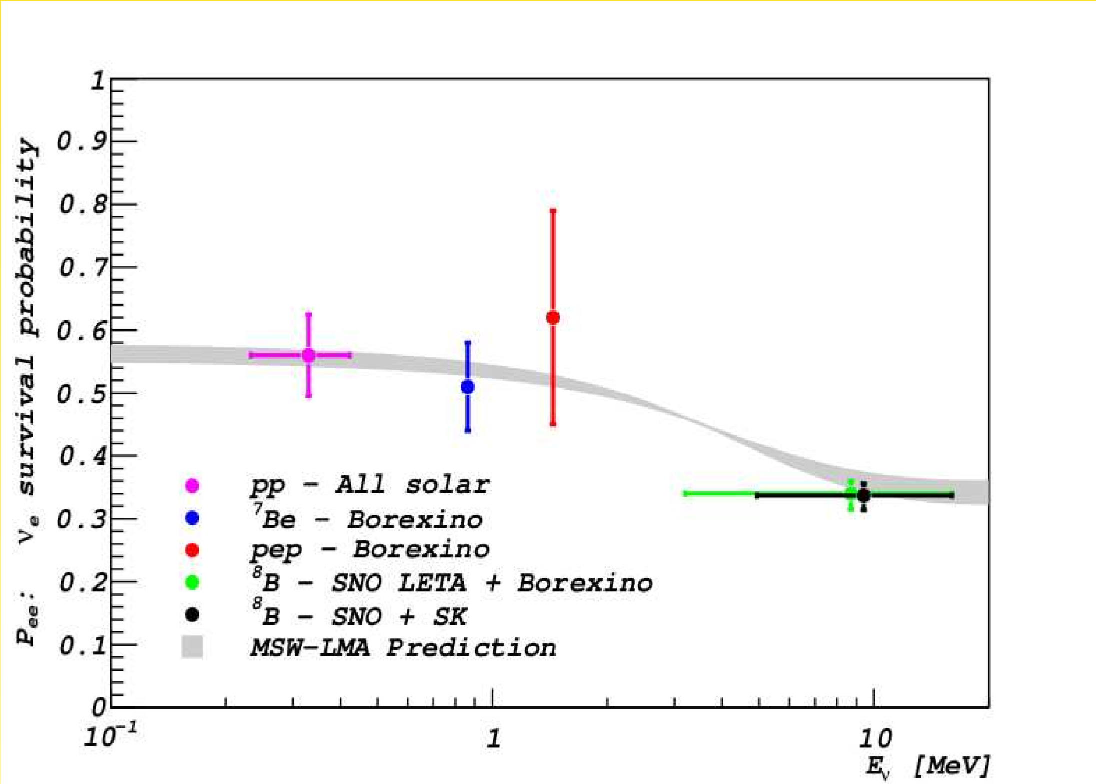
P_{ee} tested in solar and long baseline reactor (KamLAND) experiments



KamLAND

θ_{12}: status

no sign of new physics so far $\leftrightarrow$ consistent with LMA



transition from $1 - \frac{1}{2}\sin^2 2\theta_{12}$ to $\sin^2\theta_{12}$

Borexino

θ_{12}: status

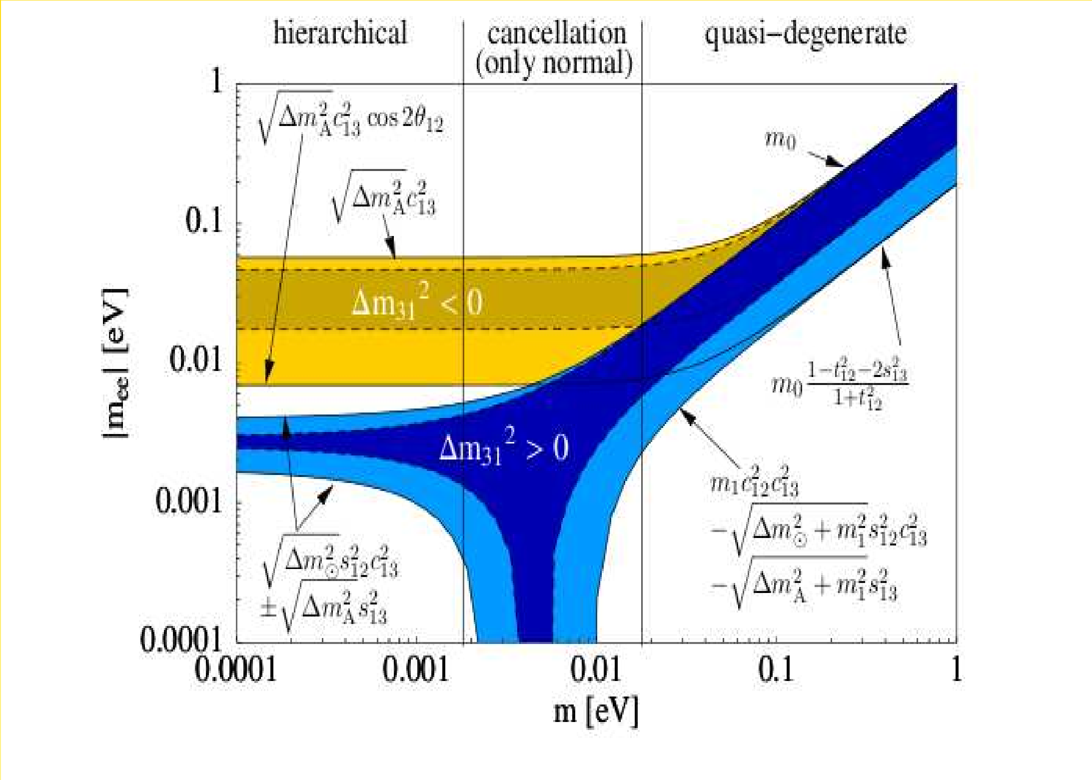
$$\sin^2\theta_{12} = 0.320^{+0.015\ (0.05)}_{-0.017\ (0.05)}$$ Tortola, Valle, Vanegas

$$\sin^2\theta_{12} = 0.312^{+0.019\ (0.063)}_{-0.018\ (0.049)}$$ Fogli, Lisi *et al.*

$$\sin^2\theta_{12} = 0.321^{+0.016\ (0.062)}_{-0.016\ (0.045)}$$ Gonzalez-Garcia *et al.*

- remarkably stable
- 3σ-precision about 15 %
- tri-bimaximal value: $\sin^2\theta_{12} = \frac{1}{3}$ marginally within 1σ
- hexagonal value: $\sin^2\theta_{12} = \frac{1}{4}$ a bit outside 3σ
- golden ratio values: $\cot\theta_{12} = \varphi$ and $\cos\theta_{12} = \varphi/2$ marginally within 3σ
- QLC value: $\sin^2(\pi/4 - \theta_C)$ marginally within 3σ
- no improvement in sight

θ_{12}: a phenomenological aspect



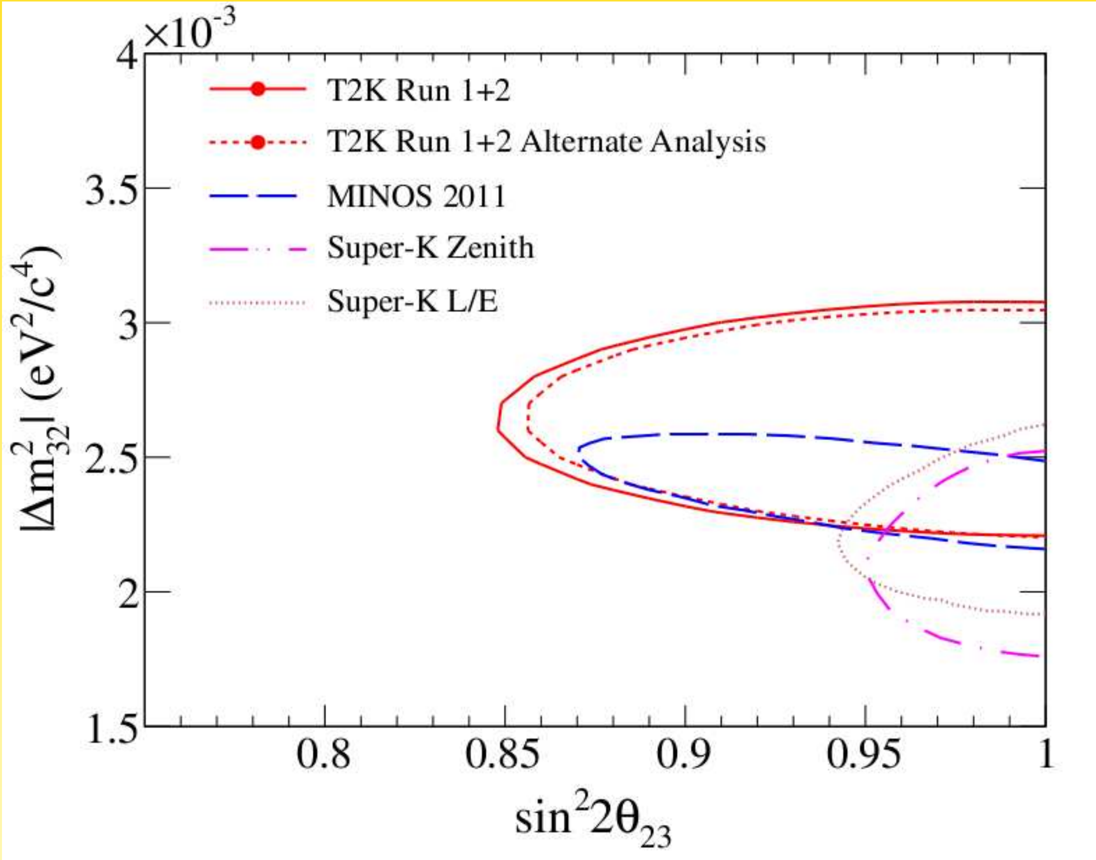
Ruling out the inverted hierarchy: go below

$$|m_{ee}|^{\rm IH}_{\rm min} = \left(1 - |U_{e3}|^2\right) \sqrt{|\Delta m^2_{\rm A}|}\ \left(1 - 2\sin^2\theta_{12}\right)$$

θ_{12}-uncertainty introduces factor 3 uncertainty in lifetime...

θ_{23}: status

$P_{\mu\mu}$ or $P_{\mu\tau}$ tested in atmospheric and long baseline accelerator (K2K, T2K, MINOS) experiments



T2K

θ_{23}: status

Signs of new physics:

- different Δm^2 for neutrinos and anti-neutrinos. . .
- faster than light OPERA neutrinos. . .

. . .all went away. . .

θ_{23}: status

$$\sin^2\theta_{23} = 0.49^{+0.08\ (0.15)}_{-0.05\ (0.10)}$$ Tortola, Valle, Vanegas

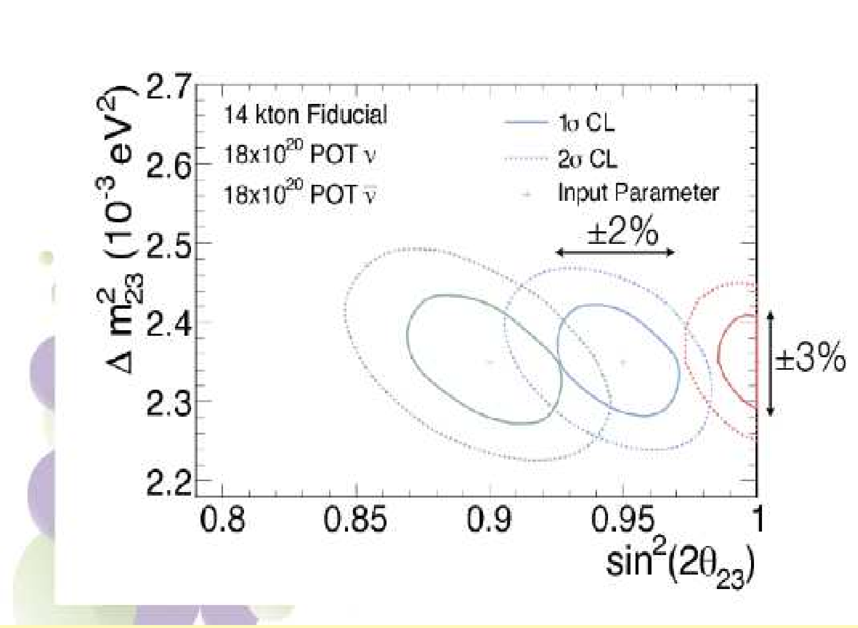
$$\sin^2\theta_{23} = 0.466^{+0.073\ (0.178)}_{-0.058\ (0.135)}$$ Fogli, Lisi *et al.*

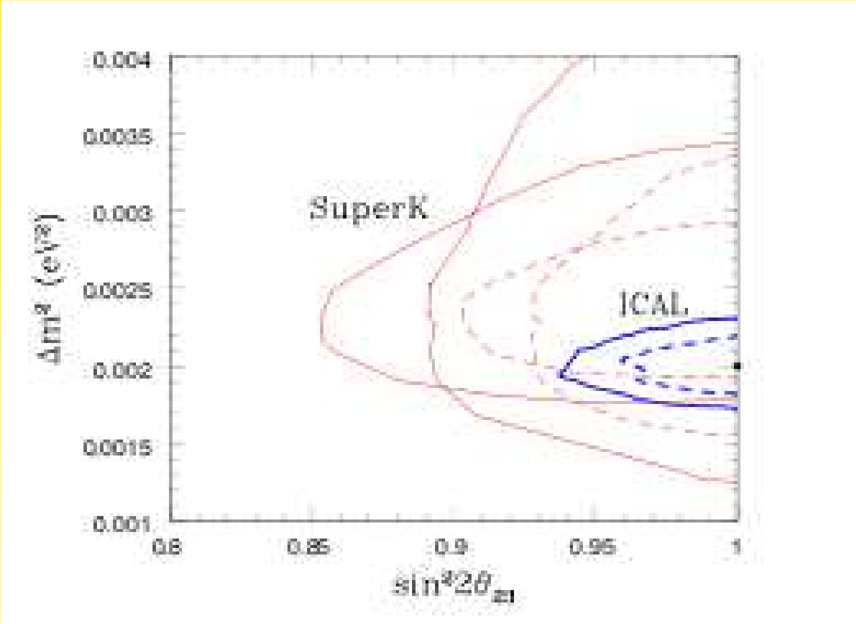
$$\sin^2\theta_{23} = 0.462^{+0.08\ (0.18)}_{-0.05\ (0.13)}$$ Gonzalez-Garcia *et al.*

- somewhat stable
- 3σ-precision about 30 %
- at 1σ: some sensitivity to mass hierarchy (fragile)
- at 1σ: some sensitivity to octant (fragile)
- maximal mixing: $\sin^2\theta_{23} = \frac{1}{2}$ within 1σ
- improvement in sight

θ_{23}: perspectives

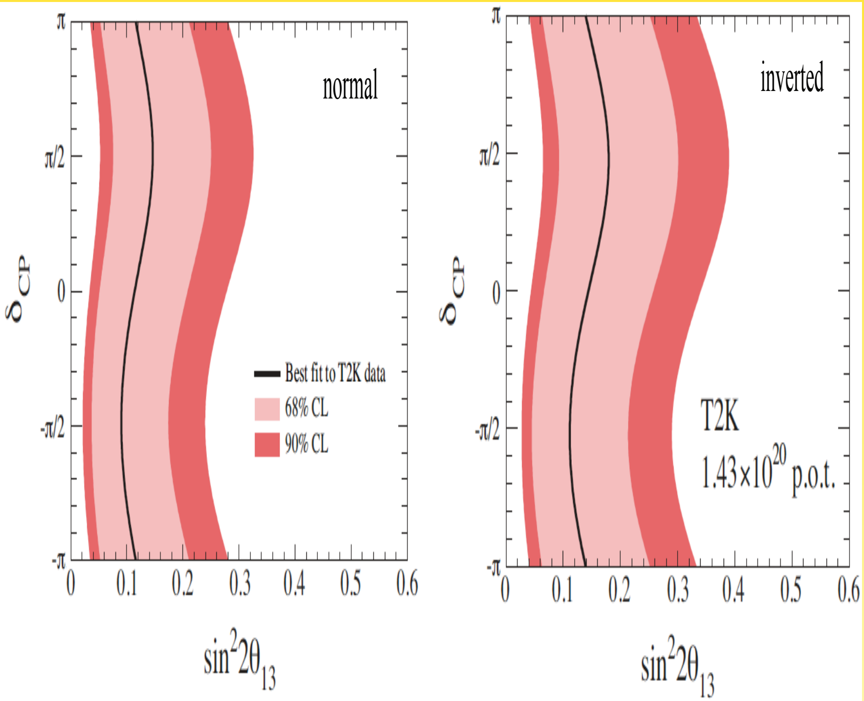
- 2-flavor analysis in vacuum goes with $\sin^2 2\theta_{23}$, hence octant and hierarchy determination needs necessarily 3-flavor and long-baseline analysis
- June, Neutrino2012 in Kyoto: updates of MINOS, T2K, IceCube
- future projects: NoνA, LBNE, LBNO, T2HK, INO,...



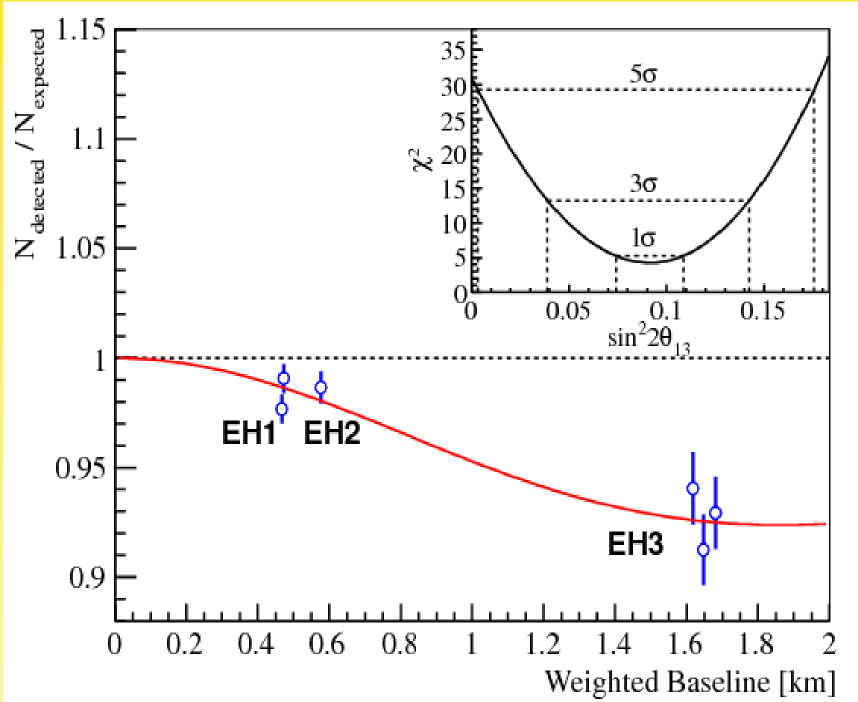


θ_{13}: status

P_{ee} or $P_{\mu e}$ tested in long baseline accelerator (T2K, MINOS) and reactor (Double Chooz, Reno, Daya Bay) experiments



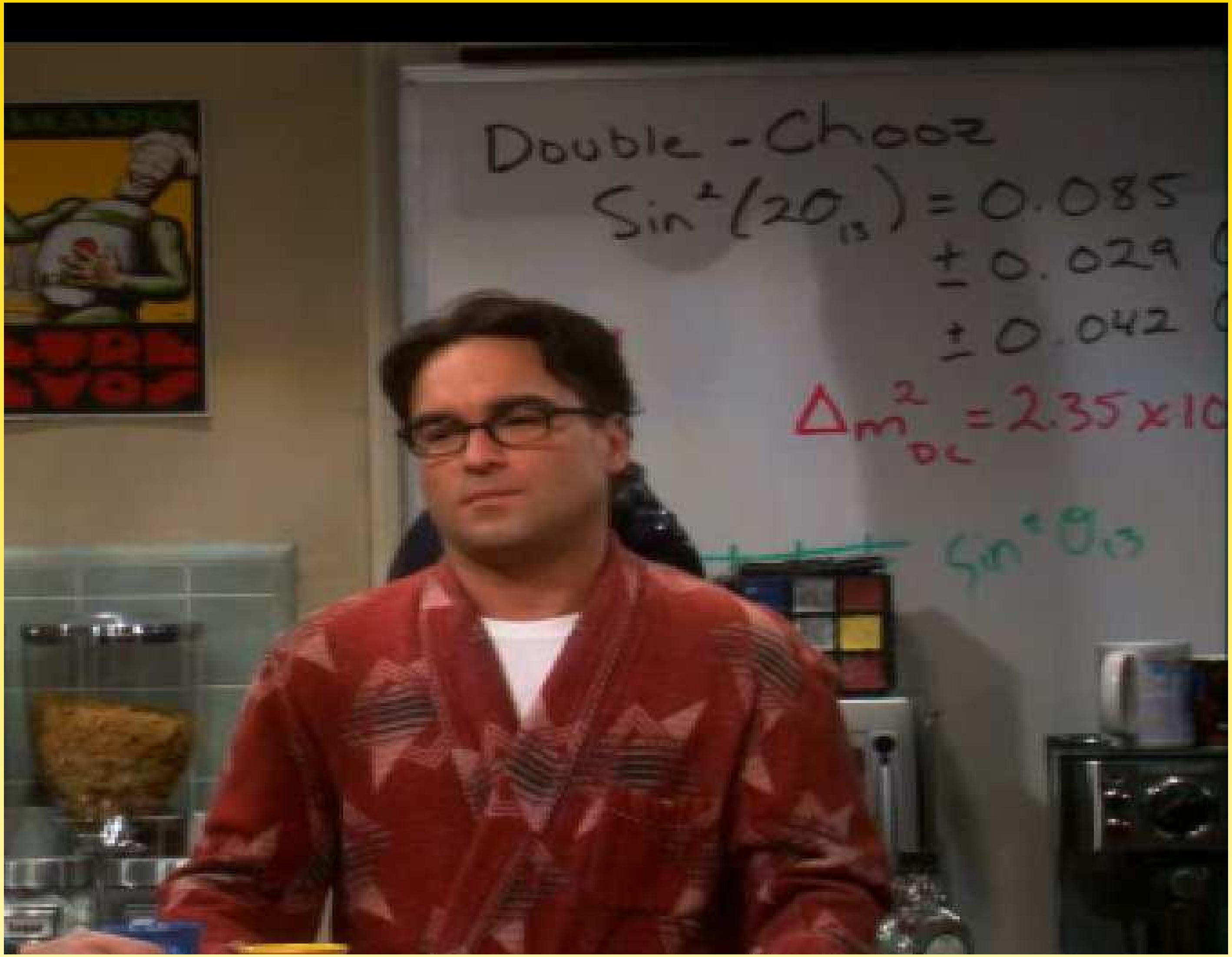
T2K



Daya Bay

θ_{13}: status

Double Chooz:	$\sin^2 2\theta_{13} = 0.086 \pm 0.051$	$\neq 0$ at 1.9σ
Daya Bay:	$\sin^2 2\theta_{13} = 0.092 \pm 0.017$	$\neq 0$ at 5.2σ
RENO:	$\sin^2 2\theta_{13} = 0.113 \pm 0.023$	$\neq 0$ at 4.9σ

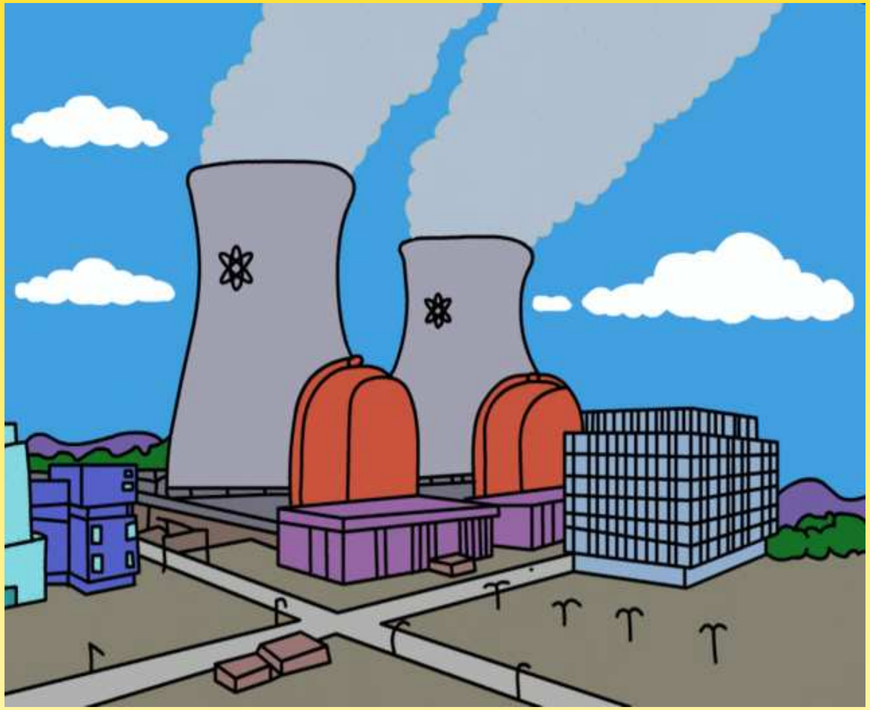


at least, Double Chooz are the only ones who made it to Big Bang Theory...

Year of the dragon

should rather be. . .

. . . Year of the reactor!



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statistics experts, please close your eyes:

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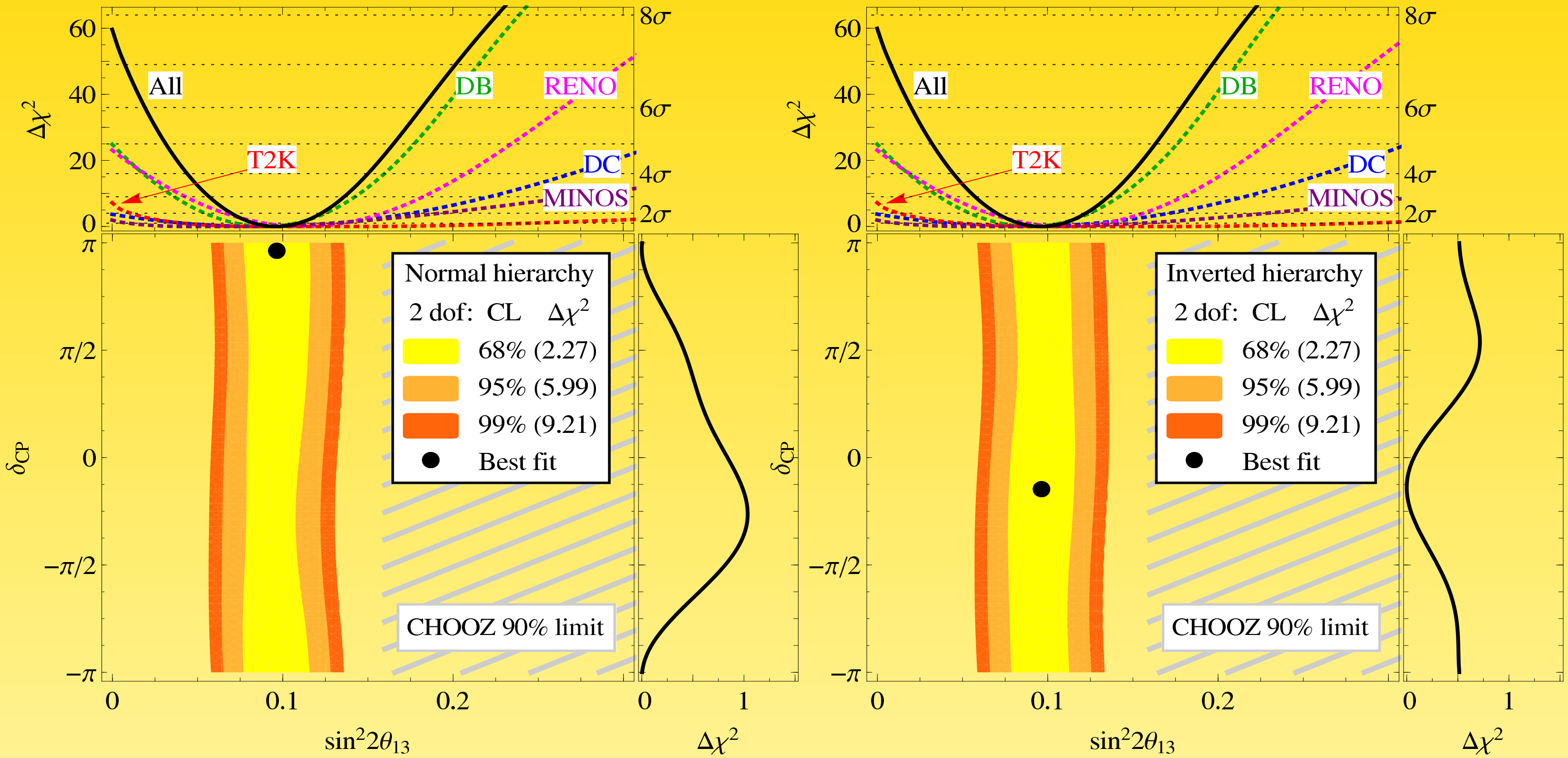
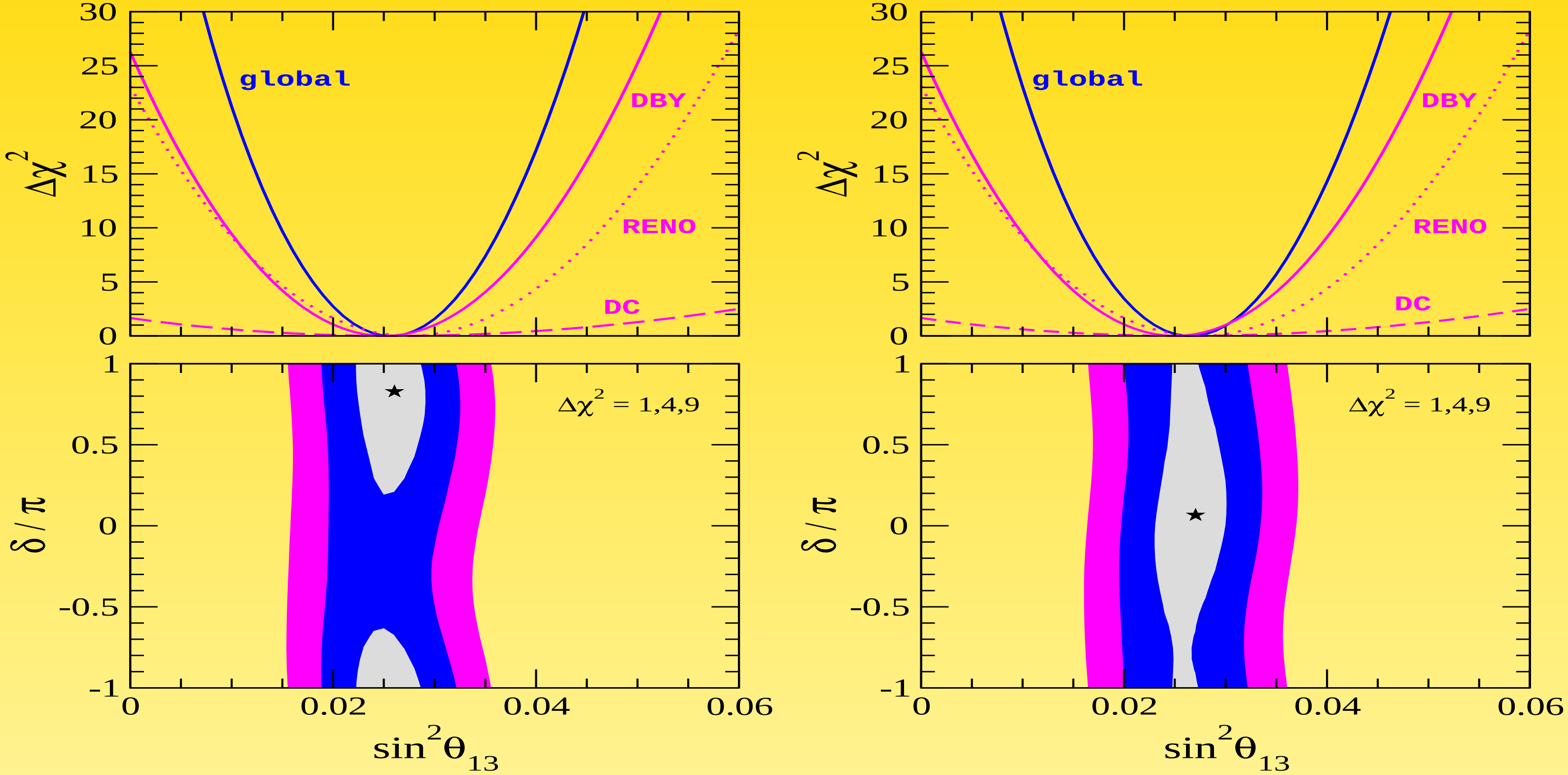
statistics experts, please close your eyes:

$$\sqrt{1.9^2 + 5.2^2 + 4.9^2} \simeq 7.4$$



non-zero θ_{13} ruled out at 7.7σ

Machado, Minakata, Nunokawa, Zukanovich Funchal



non-zero θ_{13} ruled out at 8σ

Tortola, Valle, Vanegas

θ_{13} is large!

with SBL data:

$$\sin^2\theta_{13} = 0.022^{+0.0033}_{-0.0030}$$
$$\sin^2 2\theta_{13} = 0.086 \pm 0.012$$
$$\theta_{13} = (8.5^{+0.62}_{-0.61})^\circ$$

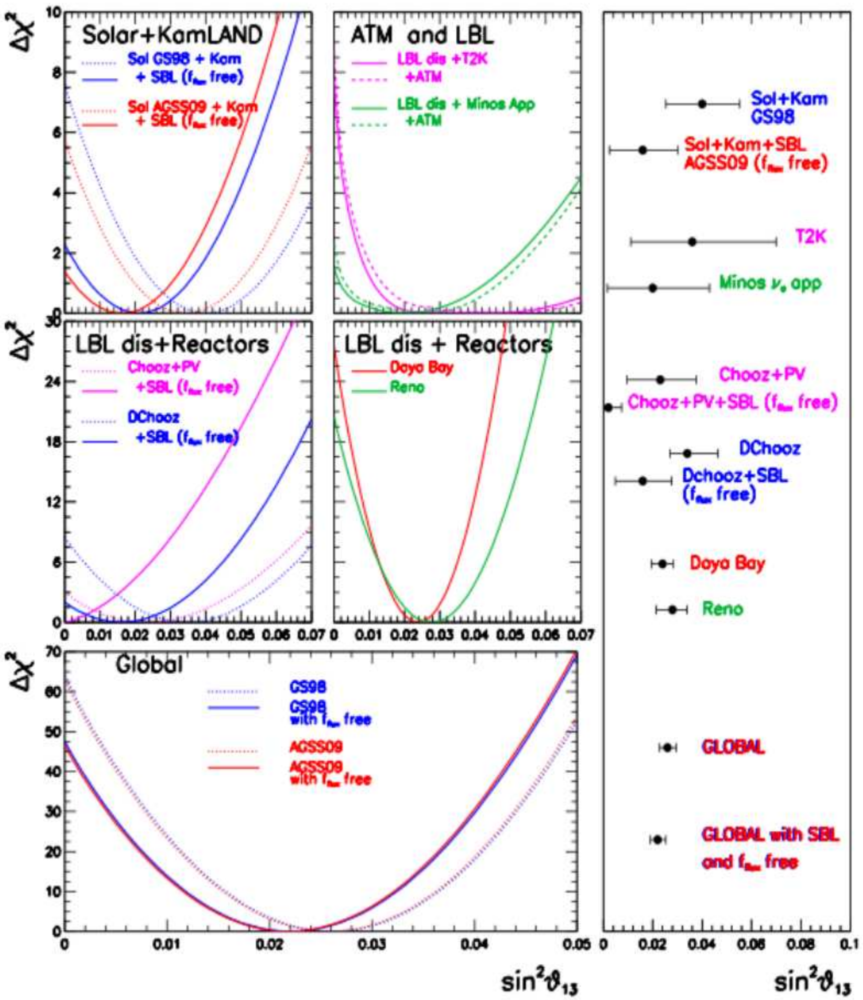
6.9σ significance

without SBL data using 2011 flux pred.:

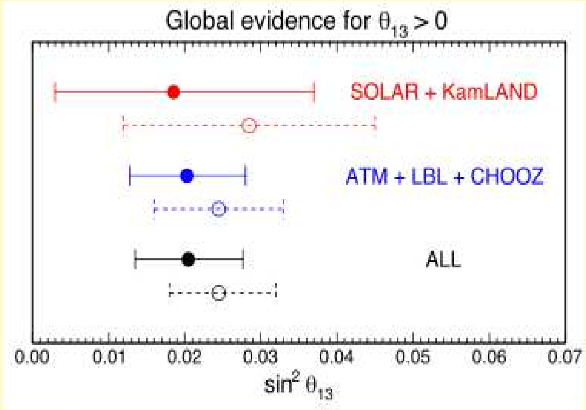
$$\sin^2\theta_{13} = 0.026^{+0.0034}_{-0.0032}$$
$$\sin^2 2\theta_{13} = 0.101^{+0.013}_{-0.012}$$
$$\theta_{13} = (9.3 \pm 0.59)^\circ$$

8.0σ significance

Gonzalez-Garcia, Maltoni, Salvado, TS, in prep.



Comparing 2011 evidence for $\sin^2\theta_{13} > 0$ ...



$\sin^2\theta_{13} = 0.021 \pm 0.007$ (old reactor fluxes)

$\sin^2\theta_{13} = 0.025 \pm 0.007$ (new reactor fluxes)

... with new (2012) SBL reactor data:

Double Chooz (far detector):	$\sin^2\theta_{13} = 0.022 \pm 0.013$
Daya Bay (near + far detectors):	$\sin^2\theta_{13} = 0.024 \pm 0.004$
RENO (near + far detectors):	$\sin^2\theta_{13} = 0.029 \pm 0.006$

we find a spectacular agreement!

θ_{13}: status

$$\sin^2 2\theta_{13} = 0.096 \pm 0.040 \qquad \text{Minakata } et\ al.$$

$$\sin^2 2\theta_{13} = 0.094 \pm 0.046 \qquad \text{Fogli, Lisi } et\ al.$$

$$\sin^2 2\theta_{13} = 0.086 \pm 0.036 \qquad \text{Gonzalez-Garcia } et\ al.$$

$$\sin^2 2\theta_{13} = 0.103 \pm 0.060 \qquad \text{Tortola } et\ al.$$

- 3σ-precision about 40 %
- mean is $\theta_{13} = 8.8^\circ$ 
- astonishingly close to $\sin\theta_C/\sqrt{2}$!
- astonishingly close to $\sqrt{m_s/m_b}$?
- $\sin^2\theta_{13} = 0$ ruled out by $\gtrsim 7\sigma$
- precision dominated by reactors

Remarks

- open questions:
  - θ_{23}: non-maximal? octant?
  - mass ordering: normal? inverted?
  - CP phase(s): δ? Majorana phases?
  - neutrino mass scale?
  - neutrino nature?
- hierarchy seems possible within $1 - 2$ decades
- full CP coverage not without new facilities (not necessarily easier with large θ_{13})
- next generation experiments presumably not able to do it individually
- far future: β-beams? neutrino factory?

θ_{13}: phenomenological aspects

minimal flavor violation in the lepton sector

(Cirigliano, Grinstein, Isidori, Wise)

$$\mathrm{BR}(\mu \to e\gamma) \propto |(m_\nu m_\nu^\dagger)_{e\mu}|^2$$

this quantity can be zero if and only if CP conservation and

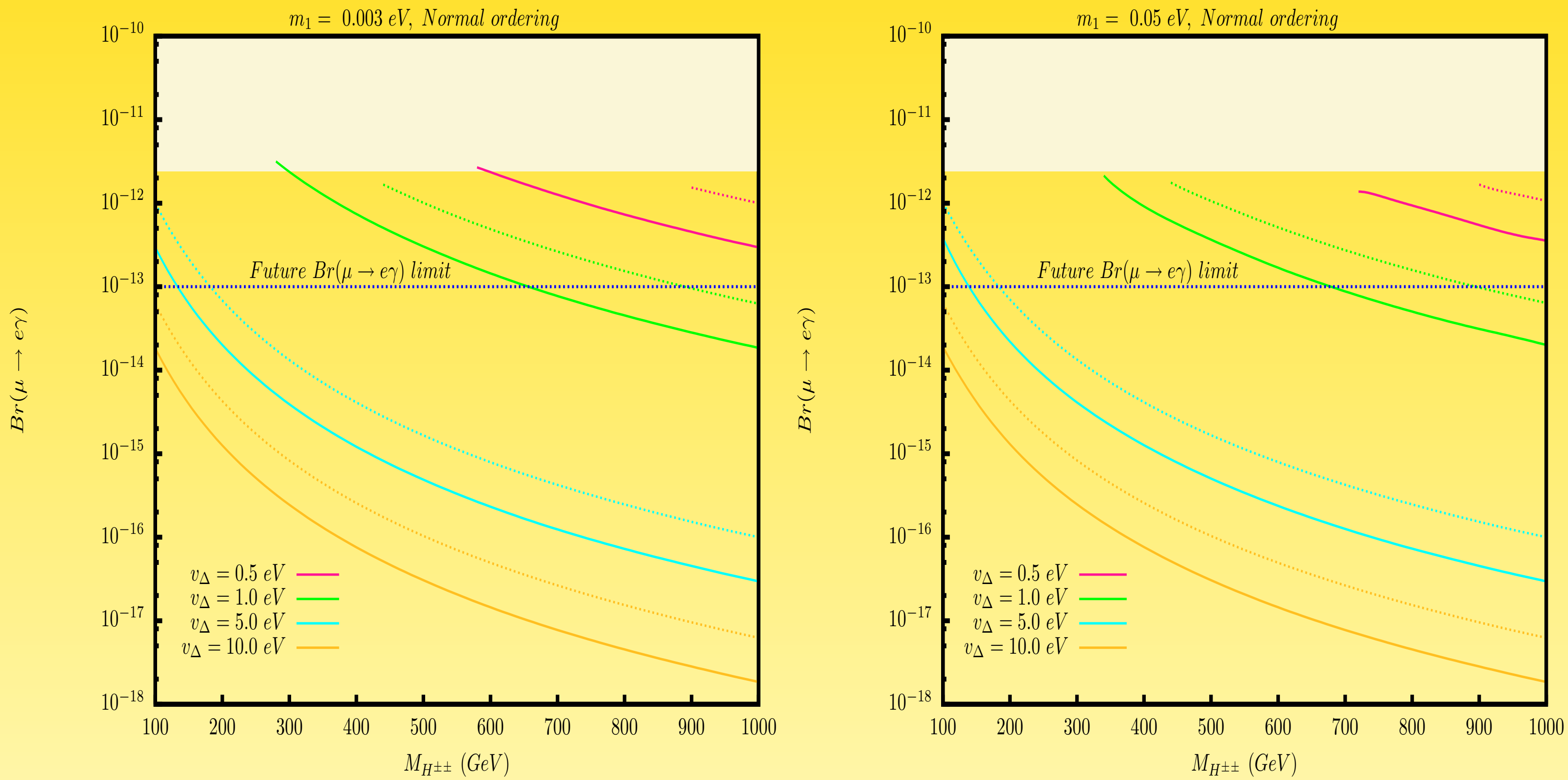
$$|U_{e3}| = \frac{1}{2} \frac{R \sin 2\theta_{12} \cot \theta_{23}}{1 \mp R \sin^2 \theta_{12}} \simeq 0.014$$

With large θ_{13}, the decay is guaranteed!

Chakrabortty, Ghosh, W.R.

Lower limit on $\mu \to e\gamma$

explicitly realized in type II seesaw with Higgs triplet

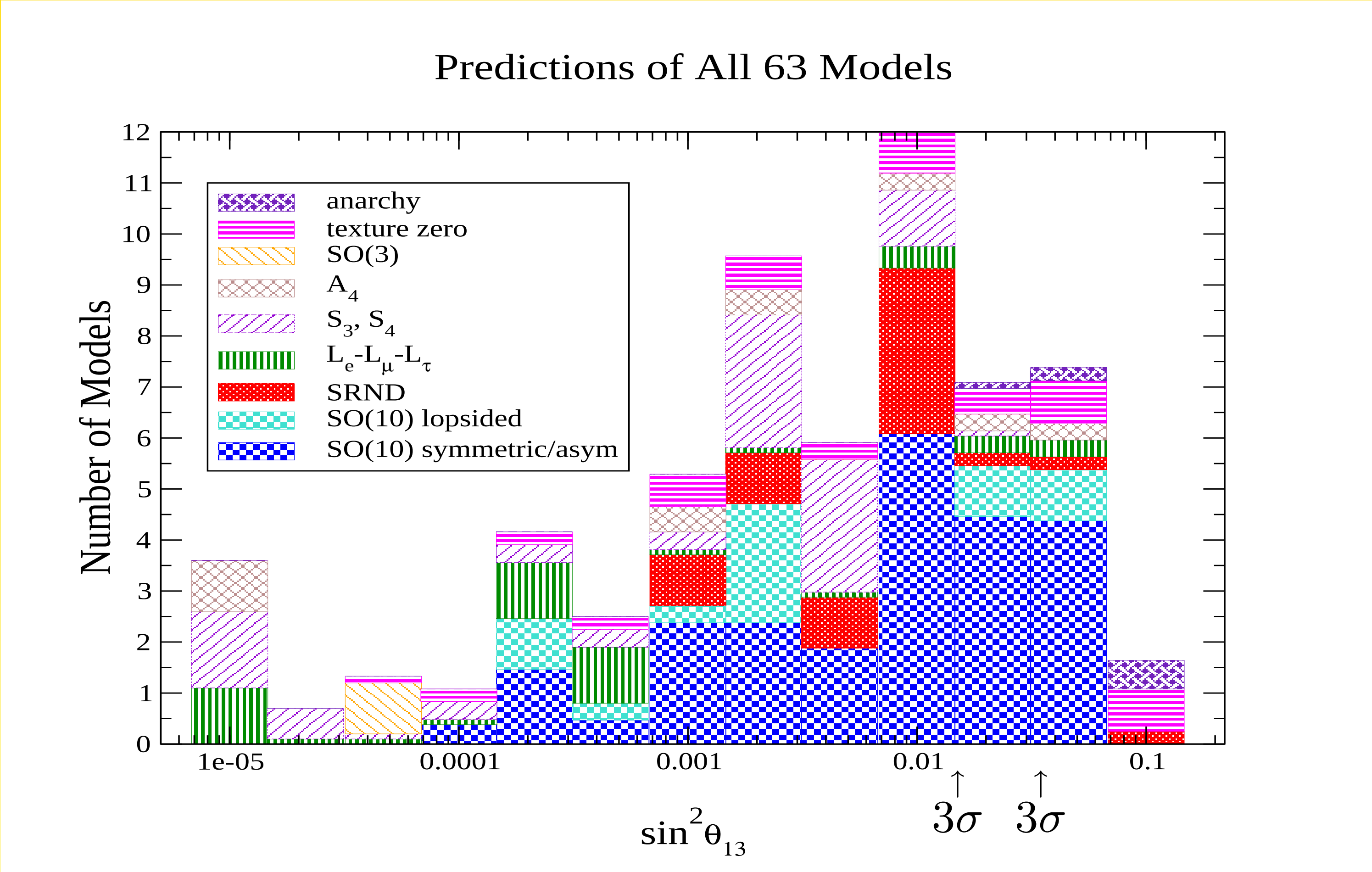


Chakrabortty, Ghosh, W.R.

Model impact...

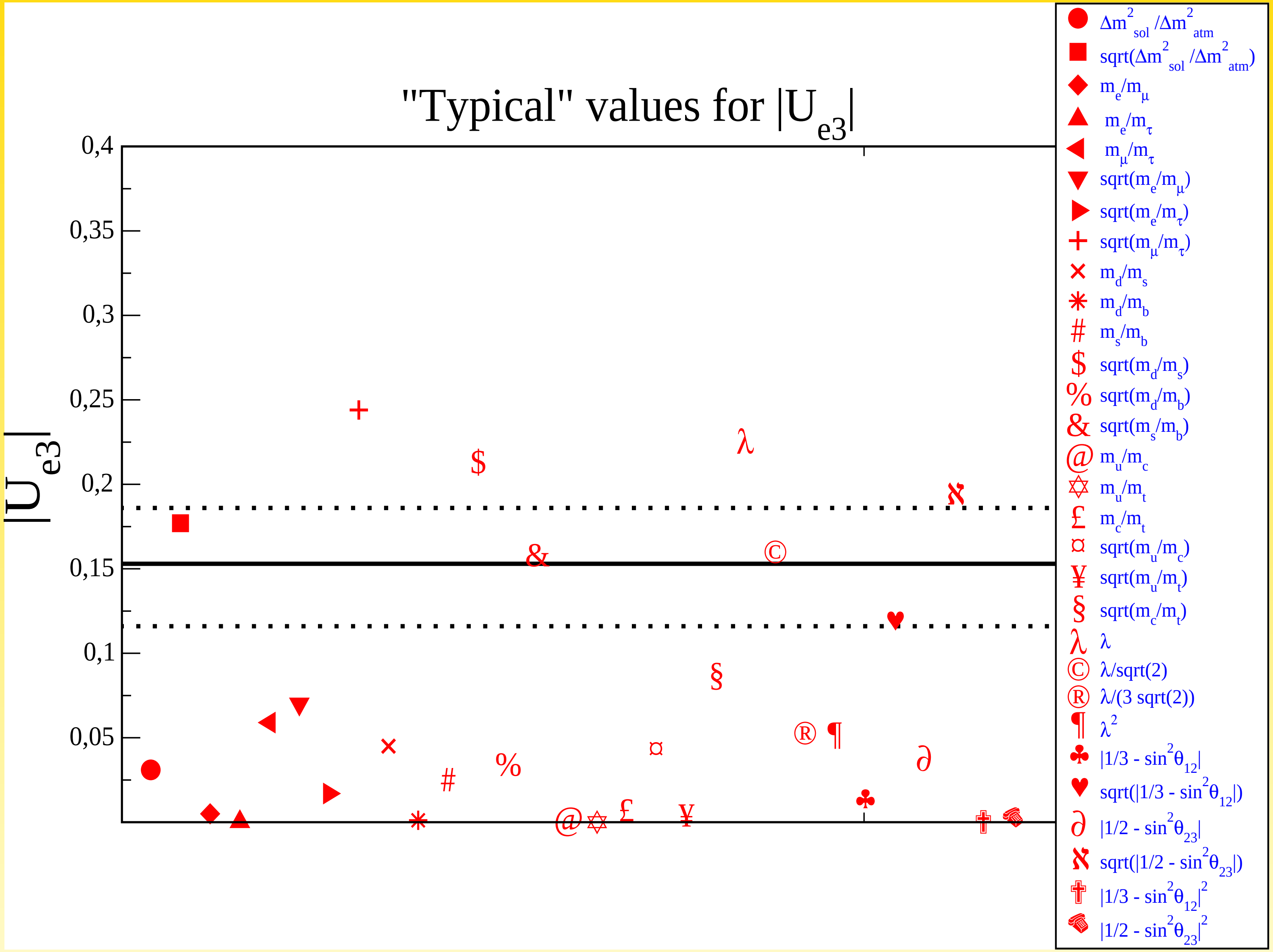
Xing, 1106.3244; Qui, Ma, 1106.3284; He, Zee, 1106.4359; Zheng, Ma, 1106.4040; Zhou, 1106.4808; Araki, 1106.5211; Haba, Takahashi, 1106.5926; Morisi, Patel, Peinado, 1107.0696, Chao, Zheng, 1107.0738; Zhang, Zhou, 1107.1097; Chu, Dhen, Hambye, 1107.1589; Toorop, Feruglio, Hagedorn, 1107.3486; Antusch, Maurer, 1107.3728; Rodejohann, Zhang, Zhou, 1107.3970; Ahn, Cheng, Oh, 1107.4549; Marzocca, Petcov, Romanino, Spinrath, 1108.0614; Ge, Dicus, Repko, 1108.0964; Riazuddin, 1108.1469; Ludl, Morisi, Peinado, 1109.3393; Verma, 1109.4228; Meloni, 1110.5210; Kitabayashi, Yasue, 1110.5162; He, Majee, 1111.2293; Rashed, 1111.3072; Buchmuller, Domcke, Schmitz, 1111.3872; King, Luhn, 1112.1959; Eby, Frampton, 1112.2675; Heeck, Rodejohann, 1112.3628; Gupta, Joshipura, Patel, 1112.6113; Damanik, arXiv:1201.2747; Ding, 1201.3279; Ishimori, Kobayashi, 1201.3429; Dev, Gautam, Singh, 1201.3755; Ahn, Okada, 1201.4436; Rodejohann, Tanimoto, Watanabe, 1201.4936; Dev, Dutta, Mohapatra, Severson, 1202.4012; BenTov, Zee, 1202.4234; Zhang, Ma, 1202.4258; Dorame, Morisi, Peinado, Valle, Rojas, 1203.0155; Dev, Kumar, Verma, Gupta, Gautam, 1203.1403; Cooper, King, Luhn, 1203.1324; Zhang, Zheng, Ma, 1203.1563; Siyeon, 1203.1593; Xing, 1203.1672; Wu, 1203.2382; Branco, Felipe, Joaquim, Serodio, 1203.2646; He, Xu, 1203.2908; Zhang, Ma, 1203.2906; Meloni, 1203.3126; Ahn, Kang, 1203.4185; Fritzsch, 1203.4460; Varzielas, Ross, 1203.6636; de Gouvea, Murayama, 1204.1249; Fukugita, Shimizu, Tanimoto, Yanagida, 1204.2389; Ishimori, Khalil, Ma, 1204.2705; Meloni, Blankenburg, 1204.2706; Minkowski, 1204.4376; Kitabayashi, Yasue, 1204.4523; Zhang, Ma, 1204.6604; King, 1205.0506; Zhou, 1205.0761; Ma, 1205.0766; Antusch, Gross, Maurer, Sluka, 1205.1051; Adhikary, Chakraborty, Ghosal, 1205.1355; Harigaya, Ibe, Yanagida, 1205.2198; Hagedorn, King, Luhn, 1205.3114...

What's that good for?



Albright, Chen

θ_{13}: status



Impact on flavor symmetry models

Almost all models, $\mathcal{O}(500)$, were designed to generate tri-bimaximal mixing:

$$U_{\rm TBM} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & -\sqrt{\frac{1}{2}} \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \end{pmatrix}$$

Harrison, Perkins, Scott (2002)

corresponding to

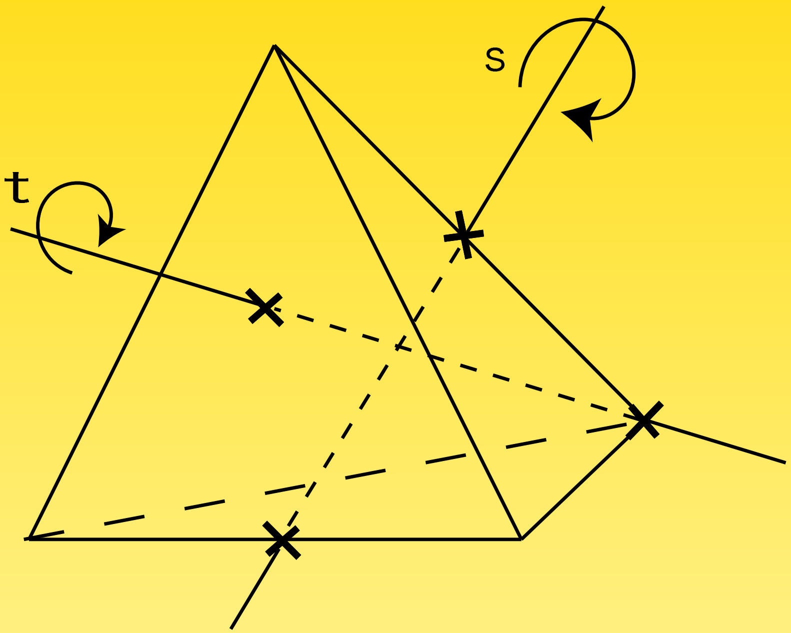
$\sin^2\theta_{12} = \frac{1}{3}$ a bit outside 1σ

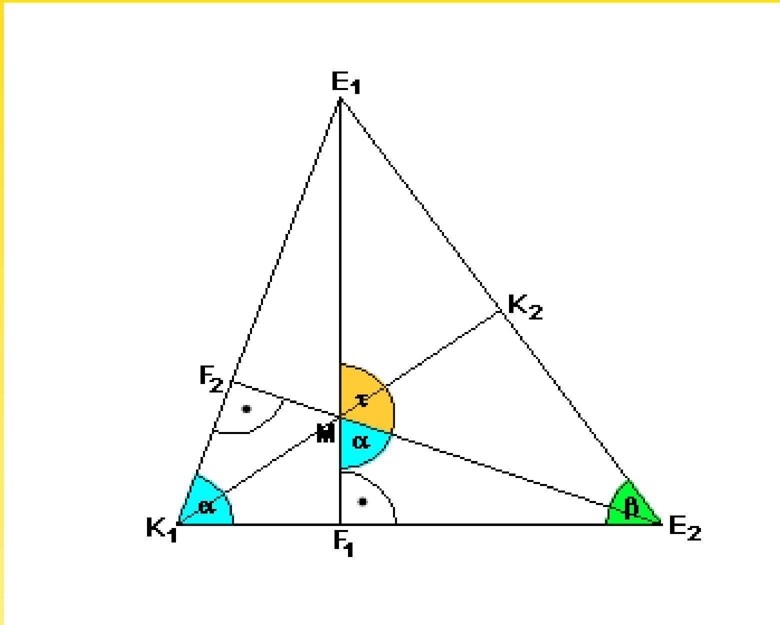
$\sin^2\theta_{23} = \frac{1}{2}$ well within 1σ

$\sin^2\theta_{13} = 0$ wrong by $\gtrsim 7\sigma$

those models typically base on A_4

A_4 is isomorphic to rotation group of tetrahedron:





- smallest group with 3-dim irrep.
- has 3 one-dimensional irreps. 1, $1'$, $1''$
- angle between two faces: $\alpha = 2\,\theta_{\rm TBM}$, where $\sin^2\theta_{\rm TBM} = \frac{1}{3}$

The Zoo (of A_4 models)

Type	L_i	ℓ_i^c	ν_i^c	Δ	References
A1				-	[1–14] [15]$^{\#}$
A2	$\underline{3}$	$\underline{1}, \underline{1}', \underline{1}''$	-	$\underline{1}, \underline{1}', \underline{1}'', \underline{3}$	[16–18]
A3				$\underline{1}, \underline{3}$	[19]
B1	$\underline{3}$	$\underline{1}, \underline{1}', \underline{1}''$	$\underline{3}$	-	[4, 20–27]$^{\#}$ [28–30]* [31–45]
B2				$\underline{1}, \underline{3}$	[46]$^{\#}$
C1				-	[2, 47, 48]
C2	$\underline{3}$	$\underline{3}$	-	$\underline{1}$	[49, 50] [51]$^{\#}$
C3				$\underline{1}, \underline{3}$	[52]
C4				$\underline{1}, \underline{1}', \underline{1}'', \underline{3}$	[53]
D1				-	[54, 55]$^{\#}$ [56, 57]* [58]
D2	$\underline{3}$	$\underline{3}$	$\underline{3}$	$\underline{1}$	[59] [60]*
D3				$\underline{1}'$	[61]*
D4				$\underline{1}', \underline{3}$	[62]*
E	$\underline{3}$	$\underline{3}$	$\underline{1}, \underline{1}', \underline{1}''$	-	[63, 64]
F	$\underline{1}, \underline{1}', \underline{1}''$	$\underline{3}$	$\underline{3}$	$\underline{1}$ or $\underline{1}'$	[65]
G	$\underline{3}$	$\underline{1}, \underline{1}', \underline{1}''$	$\underline{1}, \underline{1}', \underline{1}''$	-	[66]
H	$\underline{3}$	$\underline{1}, \underline{1}, \underline{1}$	-	-	[67]
I	$\underline{3}$	$\underline{1}, \underline{1}, \underline{1}$	$\underline{1}, \underline{1}, \underline{1}$	-	[68]*
J	$\underline{3}$	$\underline{1}, \underline{1}, \underline{1}$	$\underline{3}$	-	[12, 39, 69, 70]
K	$\underline{3}$	$\underline{1}, \underline{1}, \underline{1}$	$\underline{1}, \underline{1}$	$\underline{1}$	[71]*
L	$\underline{3}$	$\underline{1}, \underline{1}, \underline{1}$	$\underline{1}$	-	[72]*
M	$\underline{1}, \underline{1}', \underline{1}''$	$\underline{1}, \underline{1}'', \underline{1}'$	$\underline{3}, \underline{1}$	-	[73, 74]
N	$\underline{1}, \underline{1}', \underline{1}''$	$\underline{1}, \underline{1}'', \underline{1}'$	$\underline{3}, \underline{1}', \underline{1}''$	-	[75]

Barry, W.R., updated regularly on

http://www.mpi-hd.mpg.de/personalhomes/jamesb/Table_A4.pdf

In a model one has to decide which fermions transform as what:

Field	l	e^c	μ^c	τ^c	$h_{u,d}$	φ	φ'	ξ	φ_0	φ'_0	ξ_0	θ
A_4	3	1	$1''$	$1'$	1	3	3	1	3	3	1	1
Z_3	ω	ω^2	ω^2	ω^2	1	1	ω	ω	1	ω	ω	1
$U(1)_{\mathrm{FN}}$	0	4	2	0	0	0	0	0	0	0	0	-1
$U(1)_R$	1	1	1	1	0	0	0	0	2	2	2	0

Altarelli, Feruglio

Due to VEV alignment, A_4 is broken to

- Z_2 in m_ν from $\varphi' = (v', v', v')$
- Z_3 in m_ℓ from $\varphi = (v, 0, 0)$
- accidental μ–τ symmetry $\Rightarrow$ two Z_2 fix m_ν completely

Impact on flavor symmetry models

now θ_{13} is non-zero and large!

- corrections to TBM are naturally occurring in flavor symmetry models
- but: give similar corrections to ALL ANGLES...
- possibilities:
  - tune them to have $\delta\theta_{13} \gg \delta\theta_{12}$
  - start with non-zero θ_{13}

Alternative I: flavor symmetries and non-zero U_{e3}

$G_f = \Delta(96)$, generated by $S^2 = (ST)^3 = T^8 = (ST^{-1}ST)^3 = \mathbb{1}$ with

$$S = \frac{1}{2}\begin{pmatrix} 0 & \sqrt{2} & \sqrt{2} \\ \cdot & -1 & 1 \\ \cdot & \cdot & -1 \end{pmatrix} \text{ and } T = \begin{pmatrix} e^{6i\pi/4} & 0 & 0 \\ \cdot & e^{7i\pi/4} & 0 \\ \cdot & \cdot & e^{3i\pi/4} \end{pmatrix}$$

assumption (1): charged leptons invariant under $G_e = Z_3$; neutrinos under $G_\nu = Z_2 \times Z_2$

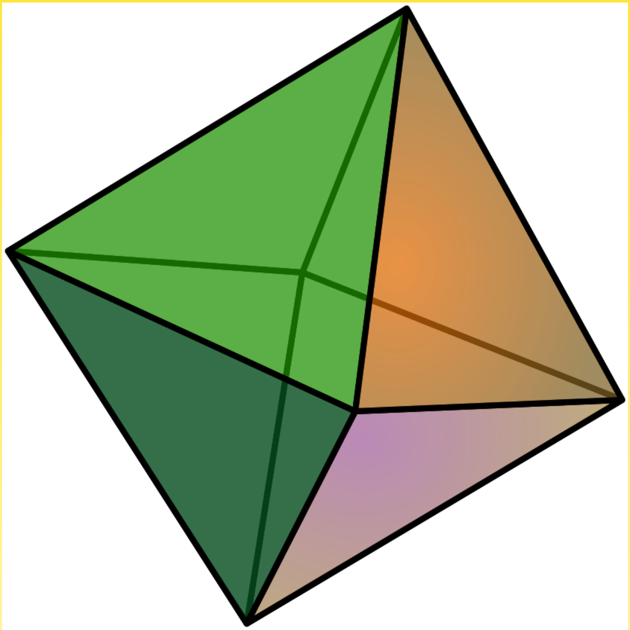
assumption (2): $G_e = ST$ and $G_\nu = \left\{S, ST^4ST^4\right\}$

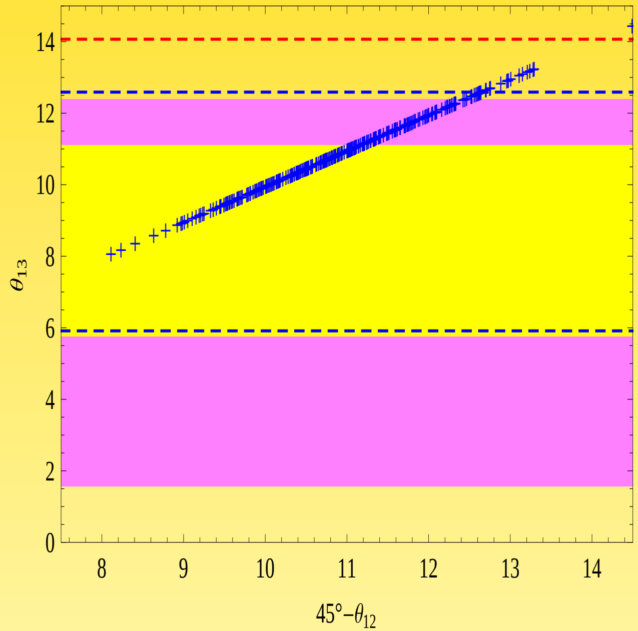
$$|U| = \sqrt{\frac{1}{3}}\begin{pmatrix} \frac{1}{2}(\sqrt{3}+1) & 1 & \frac{1}{2}(\sqrt{3}-1) \\ \frac{1}{2}(\sqrt{3}-1) & 1 & \frac{1}{2}(\sqrt{3}+1) \\ 1 & 1 & 1 \end{pmatrix}$$

Toorop, Feruglio, Hagedorn

Alternative I: flavor symmetries and non-zero U_{e3}

octahedral group O_h, isomorphic to $S_4 \times Z_2$





He, Xu

Alternative II: $|U_{e3}| = \theta_C/\sqrt{2}$ from GUTs

$$U_\nu = \begin{pmatrix} * & * & 0 \\ * & * & \sqrt{\frac{1}{2}} \\ * & * & \sqrt{\frac{1}{2}} \end{pmatrix} \text{ and } U_\ell = \begin{pmatrix} 1 & \lambda & 0 \\ -\lambda & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \Rightarrow |U_{e3}| = \frac{\lambda}{\sqrt{2}}$$

natural framework: $m_{\rm up} \simeq$ diag and relate down quarks to charged leptons

$$Y_d = \begin{pmatrix} d & b \\ a & c \end{pmatrix} \Rightarrow \begin{cases} m_\ell = \begin{pmatrix} c_d\, d & c_b\, b \\ c_a\, a & c_c\, c \end{pmatrix} & \text{Pati-Salam} \quad \Rightarrow |U_{e3}| = \left|\frac{c_c}{c_b}\right| \frac{\theta_C}{\sqrt{2}} \\ m_\ell = \begin{pmatrix} c_d\, d & c_a\, a \\ c_b\, b & c_c\, c \end{pmatrix} & SU(5) \quad \Rightarrow |U_{e3}| = \left|\frac{c_a}{c_b}\right| \frac{\theta_C}{\sqrt{2}} \end{cases}$$

Clebsch-Gordan factors depending on GUT breaking

Antusch *et al.*

Alternative III: Gatto-Sartori-Tonin for leptons

$$\sqrt{\frac{\Delta m_{\odot}^2}{\Delta m_{\rm A}^2}} = 0.160 \ldots 0.190 \quad \leftrightarrow \quad |U_{e3}| = 0.122 \ldots 0.190$$

can be arranged in flavor symmetry models, e.g. S_3

	$(\overline{L_1}, \overline{L_2})$	$\overline{L_3}$	(ν_{R_1}, ν_{R_2})	e_R	μ_R	τ_R	(ϕ_1, ϕ_2)	χ
S_3	2^*	$1_{\rm S}$	2	$1_{\rm S}$	$1_{\rm S}$	$1_{\rm S}$	2	$1_{\rm S}$
Z_3	ω	ω	ω	ω	1	ω^2	ω	ω

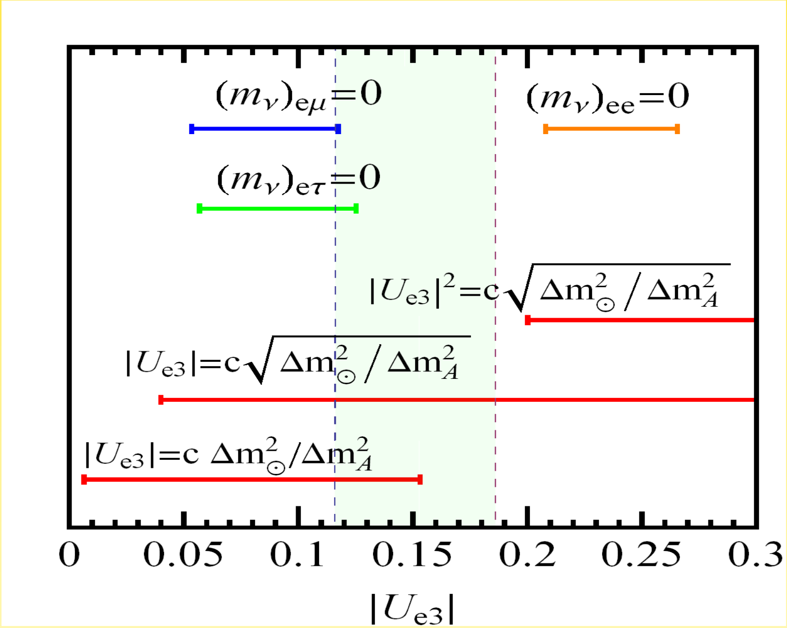
	$(\overline{L_1}, \overline{L_2})$	$\overline{L_3}$	(ν_{R_1}, ν_{R_2})	(e_R, μ_R)	τ_R	η_1^-	η_2^+	η_3^+	η_4^-	(ξ_1^+, ξ_2^+)
D_4	2	1_1	2	2	1_1	1_1	1_2	1_3	1_4	2
Z_2	$+$	$+$	$+$	$-$	$+$	$-$	$+$	$+$	$-$	$+$

W.R., Tanimoto, Watanabe

in 3-flavor framework: relations receive order one factors

Example, $m_1 = 0$ and $(m_\nu)_{e\tau} = 0$:

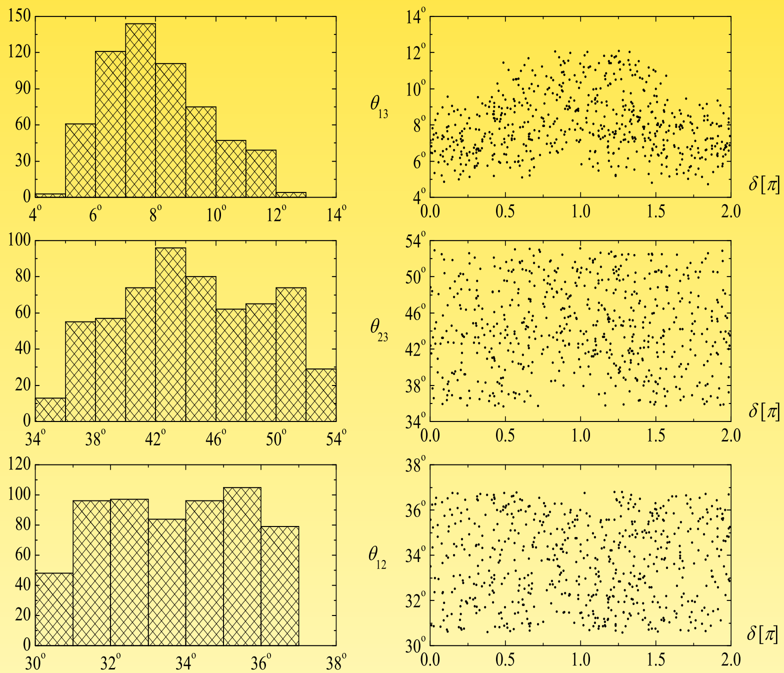
$$|U_{e3}| \simeq \frac{1}{2}\sqrt{\frac{\Delta m^2_\odot}{\Delta m^2_{\rm A}}}\,\sin 2\theta_{12}\tan\theta_{23} = 0.084^{+0.041}_{-0.027}$$



W.R., Tanimoto, Watanabe

Alternative IV: texture zeros

$$m_\nu = \begin{pmatrix} 0 & 0 & * \\ 0 & * & * \\ * & * & * \end{pmatrix} \Rightarrow |U_{e3}|^2 \simeq \frac{1}{4} \frac{\sin^2 2\theta_{12}}{\tan^2 \theta_{23} \, \cos 2\theta_{12}} \frac{\Delta m^2_\odot}{\Delta m^2_{\rm A}}$$



Fritzsch, Xing, Zhou

Summary

$$|U| = \begin{pmatrix} 0.779\ldots0.848 & 0.510\ldots0.604 & 0.122\ldots0.190 \\ 0.183\ldots0.568 & 0.385\ldots0.728 & 0.613\ldots0.794 \\ 0.200\ldots0.576 & 0.408\ldots0.742 & 0.589\ldots0.775 \end{pmatrix}$$

$$|V| = \begin{pmatrix} 0.97428 \pm 0.00015 & 0.2253 \pm 0.0007 & 0.00347^{+0.00016}_{-0.00012} \\ 0.2252 \pm 0.0007 & 0.97345^{+0.00015}_{-0.00016} & 0.0410^{+0.0011}_{-0.0007} \\ 0.00862^{+0.00026}_{-0.00020} & 0.0403^{+0.0011}_{-0.0007} & 0.999152^{+0.000030}_{-0.000045} \end{pmatrix}$$

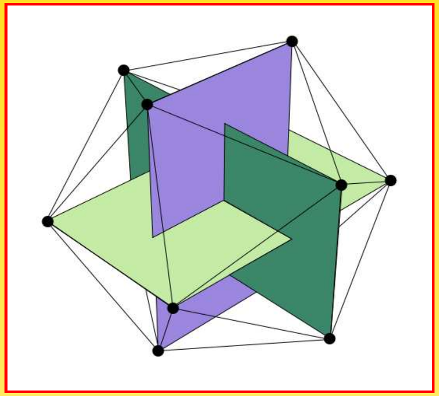
- precision
- unitarity
- CP
- test all elements directly

Summary

- $\theta_{13} \neq 0$ at $\gtrsim 7\sigma$
- factor $\lesssim 2$ below Chooz limit
- makes it possible to test:
  - mass ordering
  - CP violation
  - impact on planing of next generation experiments
  - impact on model building
- no sign new physics (except for sterile neutrinos)

Alternatives to TBM: focus on θ_{12}

- Golden Ratio 1: $\cot\theta_{12} = \varphi = (1+\sqrt{5})/2 \Rightarrow \sin^2\theta_{12} \simeq 0.276$ $\leftrightarrow A_5$



Cartesian coordinates of 12 icosahedron vertices:

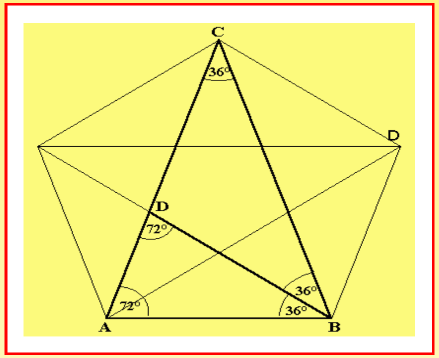
$$(0,\, \pm 1,\, \pm\varphi)$$

$$(\pm 1,\, \pm\varphi,\, 0)$$

$$(\pm\varphi,\, 0,\, \pm 1)$$

(Datta, Ling, Ramond; Kajiyama, Raidal, Strumia; Everett, Stuart)

- Golden Ratio 2: $\cos\theta_{12} = \varphi/2 \Rightarrow \sin^2\theta_{12} = \sin^2\pi/5 \simeq 0.345$ $\leftrightarrow D_{10}$



$$\overline{\mathrm{AD}} = \varphi\,\overline{\mathrm{AB}}$$

(W.R., Adulpravitchai, Blum, W.R.)

Degeneracies

Expand *3 flavor* oscillation probabilities in terms of $R = \Delta m^2_\odot / \Delta m^2_{\rm A}$ and $|U_{e3}|$:

$$P(\nu_e \to \nu_\mu) \simeq \sin^2 2\theta_{13} \, \sin^2\theta_{23} \, \frac{\sin^2 (1-\hat{A})\Delta}{(1-\hat{A})^2} + R^2 \, \sin^2 2\theta_{12} \, \cos^2\theta_{23} \frac{\sin^2 \hat{A}\Delta}{\hat{A}^2}$$

$$+ \sin\delta \sin 2\theta_{13} \, R \, \sin 2\theta_{12} \, \cos\theta_{13} \, \sin 2\theta_{23} \sin\Delta \, \frac{\sin\hat{A}\Delta \, \sin(1-\hat{A})\Delta}{\hat{A}(1-\hat{A})}$$

$$+ \cos\delta \sin 2\theta_{13} \, R \, \sin 2\theta_{12} \, \cos\theta_{13} \, \sin 2\theta_{23} \, \cos\Delta \frac{\sin\hat{A}\Delta \, \sin(1-\hat{A})\Delta}{\hat{A}(1-\hat{A})}$$

with $\hat{A} = 2\sqrt{2}\, G_F \, n_e \, E / \Delta m^2_{\rm A}$ and $\Delta = \dfrac{\Delta m^2_{\rm A}}{4\,E}\, L$

- $\theta_{23} \leftrightarrow \pi/2 - \theta_{23}$ degeneracy
- θ_{13}-δ degeneracy
- δ-sgn$(\Delta m^2_{\rm A})$ degeneracy

Solutions: more channels, different L/E, high precision,...

Is the PMNS matrix 4×4?

Which one is sterile?

Motivation

- particle physics
  - LSND/MiniBooNE
  - Gallium experiments
  - reactor anomaly
- cosmology
  - CMB
  - BBN
- astrophysics
  - r-process nucleosynthesis in supernovae

arXiv:1204.5379v1 [hep-ph] 18 Apr 2012

Light Sterile Neutrinos: A White Paper

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Remarks

- majority of experiments does not require sterile neutrinos
- oscillation experiments: $\Delta m^2 \simeq 1$ eV^2 vs. cosmology: $m_s \lesssim 1$ eV
- appearance-disappearance tension
- all anomalies explained by the same thing?
- are they all real?

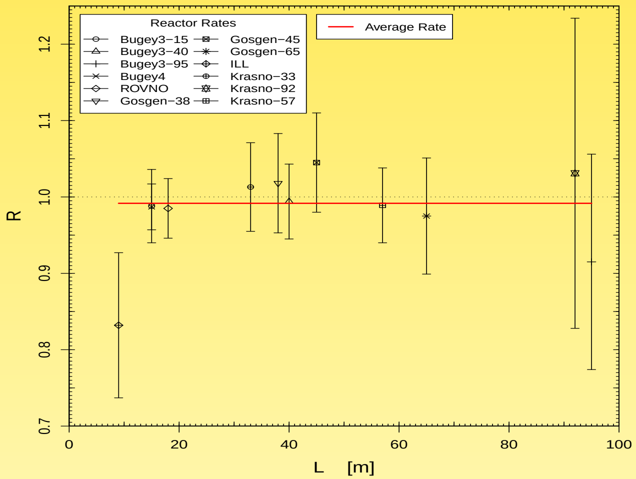
	$\Delta m^2_{41}\,[\mathrm{eV}^2]$	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	$\Delta m^2_{51}\,[\mathrm{eV}^2]$	$\lvert U_{e5}\rvert$	$\lvert U_{\mu 5}\rvert$
3+2/2+3	0.47	0.128	0.165	0.87	0.138	0.148
1+3+1	0.47	0.129	0.154	0.87	0.142	0.163

or $\Delta m^2_{41} = 1.78$ eV^2 and $|U_{e4}|^2 = 0.151$

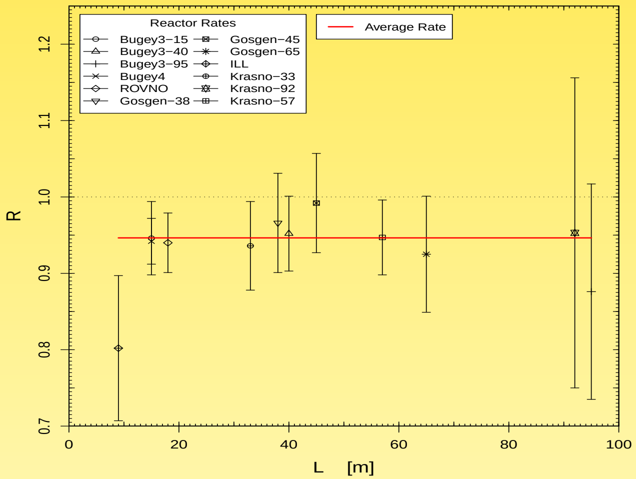
Kopp, Maltoni, Schwetz

Reactor anomaly

- fission yield per isotope
- β decay branching ratios (allowed, forbidden)
- β shape (corrections: QED, weak magnetism, Coulomb)
- extraction from electron spectra



$$R_{\text{old}} = 0.992 \pm 0.024$$



$$R_{\text{new}} = 0.946 \pm 0.024$$

θ_{13}: phenomenological aspects

possibility to distinguish normal vs. inverted with supernovas

Fluxes arriving at the Earth

$$F_{\nu_e} = p\, F^0_{\nu_e} + (1-p)\, F^0_{\nu_x}\,, \qquad F_{\bar{\nu}_e} = \bar{p}\, F^0_{\bar{\nu}_e} + (1-\bar{p})\, F^0_{\nu_x}$$

p at low, intermediate, high energies

		Phase A ($L_{\nu_e} \gtrsim L_{\nu_x}$)			Phase C ($L_{\nu_e} \gtrsim L_{\nu_x}$)		
NH	$\sin^2\theta_{13} \gtrsim 10^{-3}$	0	0	0	0	0	s^2
	$\sin^2\theta_{13} \lesssim 10^{-5}$	s^2	s^2	s^2	s^2	s^2	0
IH	$\sin^2\theta_{13} \gtrsim 10^{-3}$	s^2	0	0	s^2	0	c^2 (s^2)
	$\sin^2\theta_{13} \lesssim 10^{-5}$	s^2	0	0	s^2	0	c^2 (s^2)

$\bar{p}$ at low, intermediate, high energies

		Phase A ($L_{\nu_e} \gtrsim L_{\nu_x}$)			Phase C ($L_{\nu_e} \gtrsim L_{\nu_x}$)		
NH	$\sin^2\theta_{13} \gtrsim 10^{-3}$	c^2	c^2	c^2	c^2	c^2	0
	$\sin^2\theta_{13} \lesssim 10^{-5}$	c^2	c^2	c^2	c^2	c^2	0
IH	$\sin^2\theta_{13} \gtrsim 10^{-3}$	0	c^2	c^2	0	c^2 [0]	s^2 (0)
	$\sin^2\theta_{13} \lesssim 10^{-5}$	c^2	0	0	c^2	0 [c^2]	s^2 (c^2)

$s^2 \equiv \sin^2\theta_{12}$, $c^2 \equiv \cos^2\theta_{12}$ ( ), [ ] : non-adiabatic swaps