Venice, 18 March ‘11

Perspectives in Neutrino Physics

Guido Altarelli
Universita' di Roma Tre/CERN

Concluding Talk at NeuTel11

This is not a summary of the Conference!!

Just a few comments on some of the highlights that particularly impressed me

A very subjective choice

Experimental results

Recently the main development was the coming back of sterile neutrinos
(one also talks of CPT violation and of non standard interactions)

Maltoni

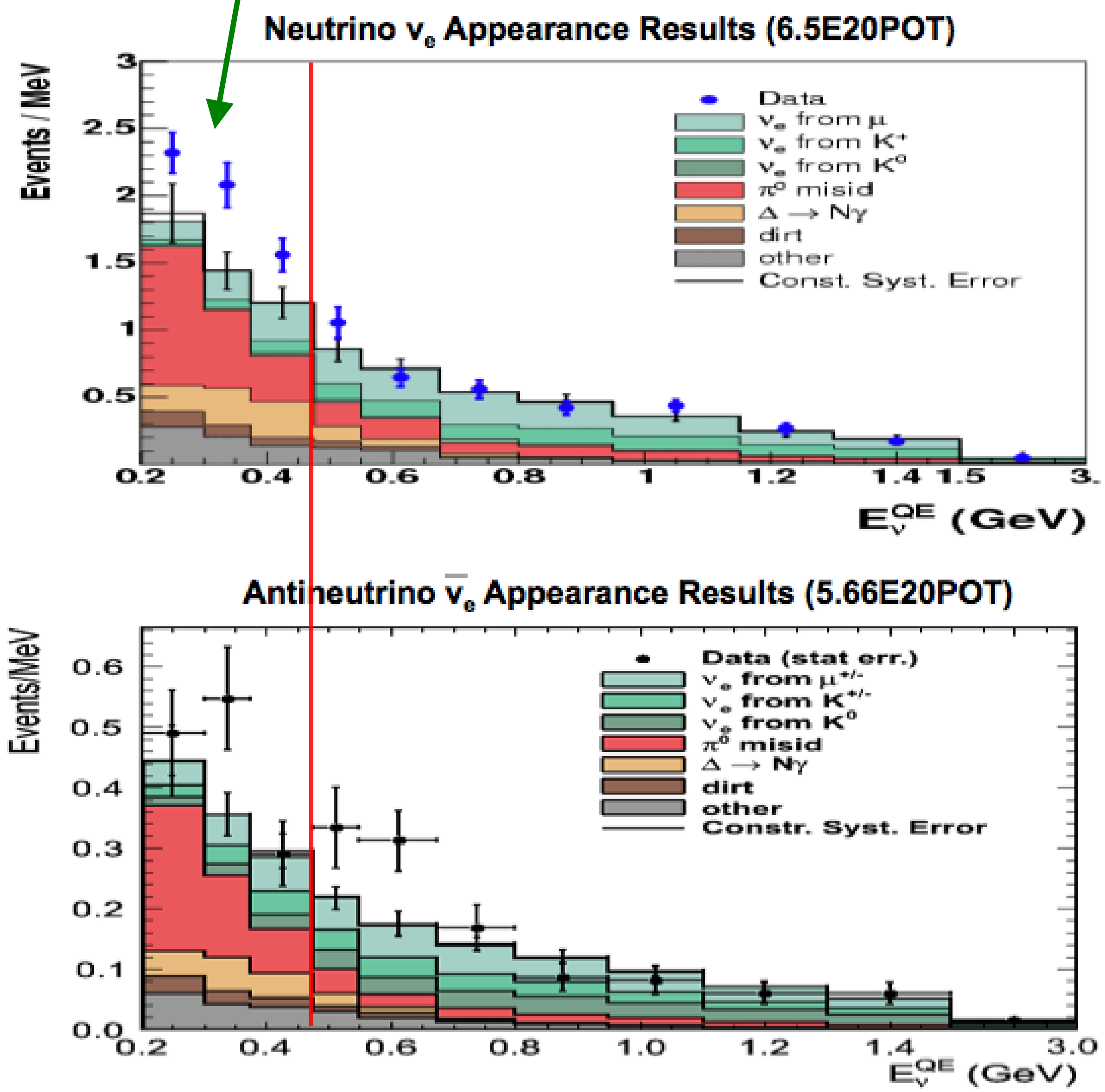
A number of "hints" (they do not make an evidence but pose an experimental problem that needs clarification)

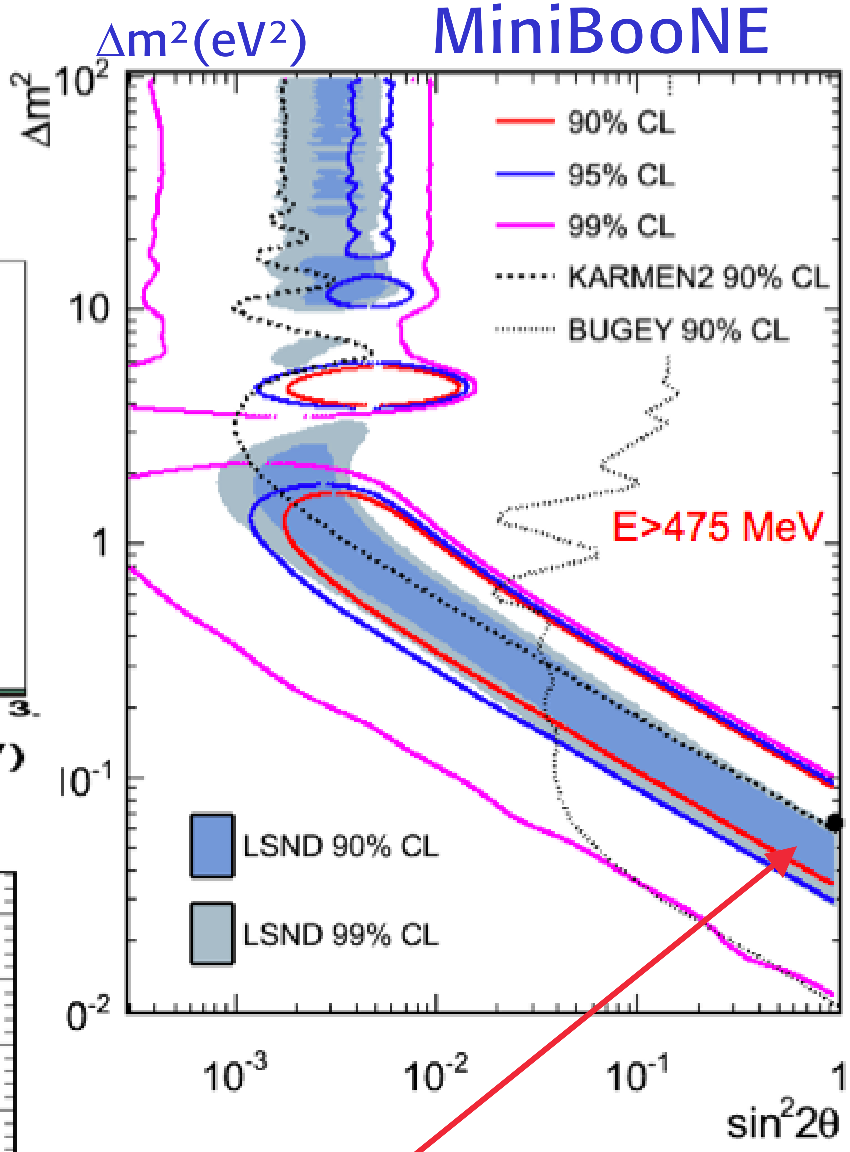
- LSND and MiniBoone
- Reactor flux & anomaly
- Gallium ν_e disappearance vs ν_e^{bar} reactor limits
- Neutrino counting from cosmology

Unidentified excess at low energy

Mills

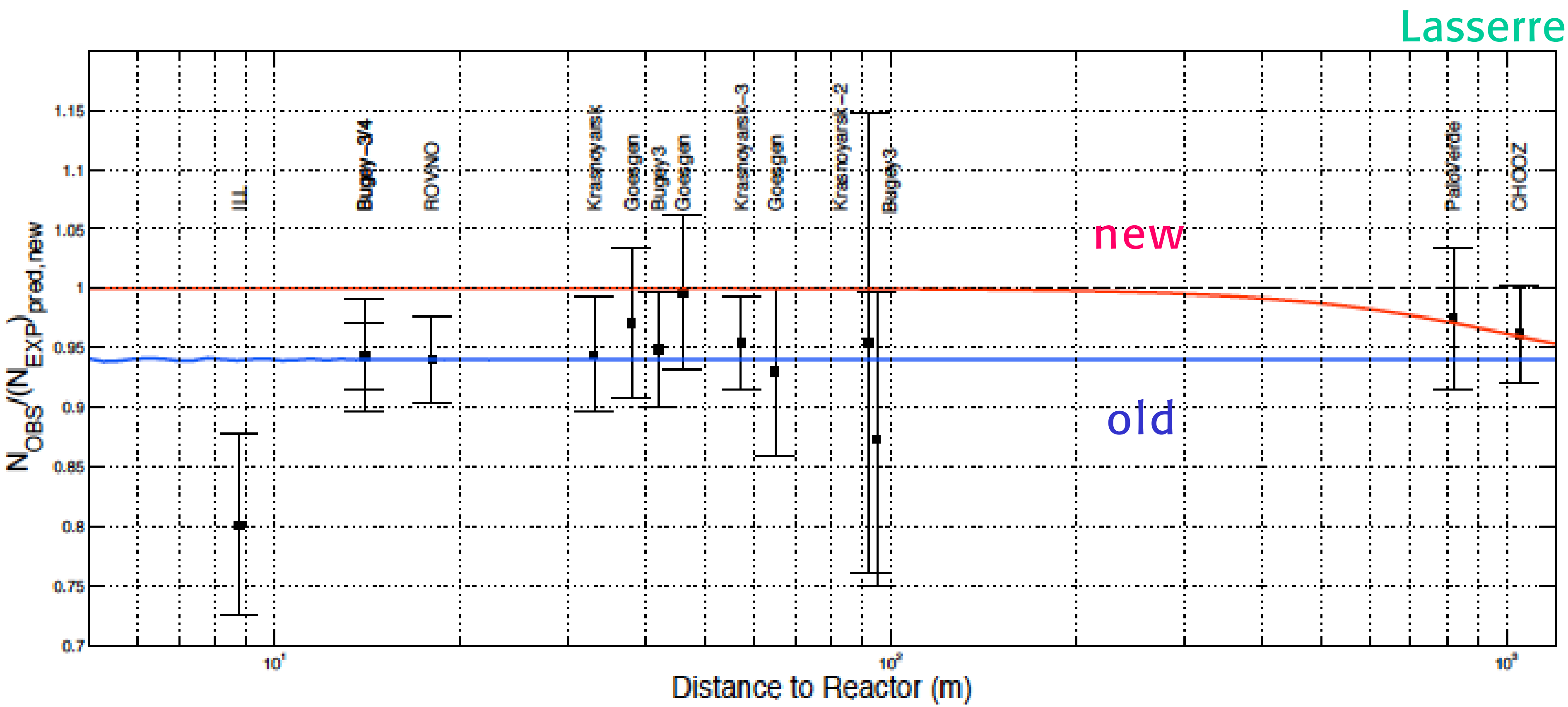
MiniBooNE





Best fit point in Bugey excluded area

The reactor anomaly

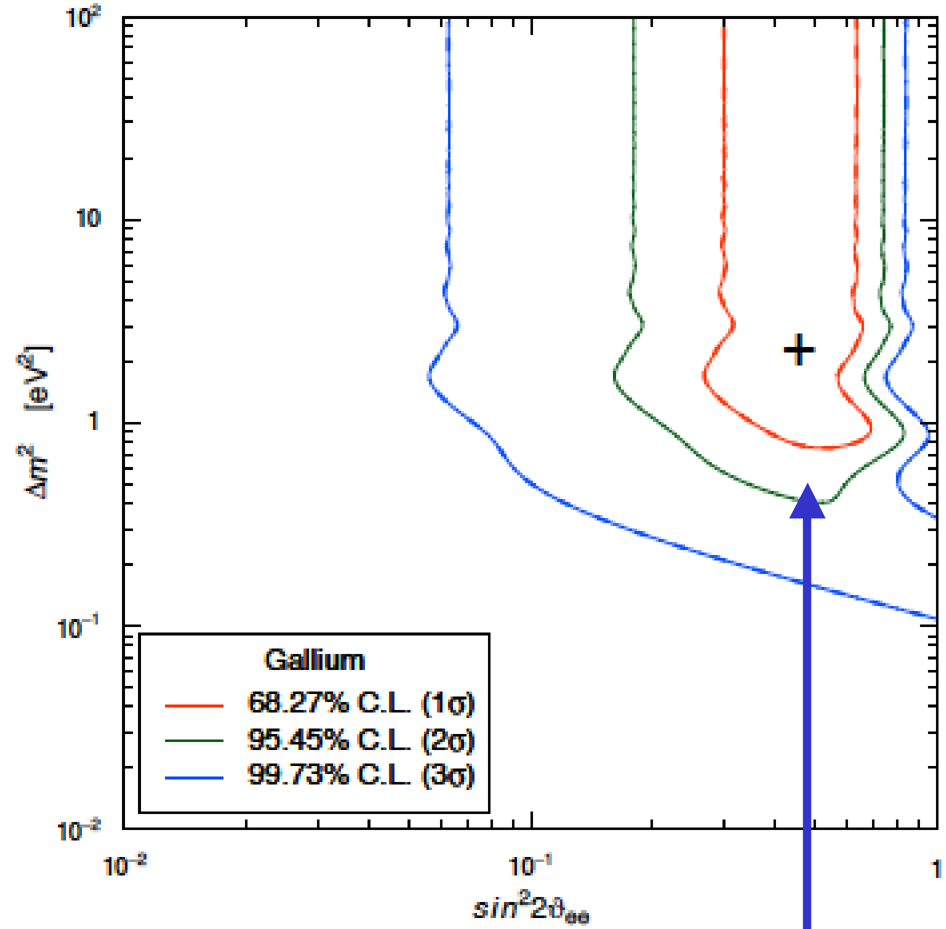


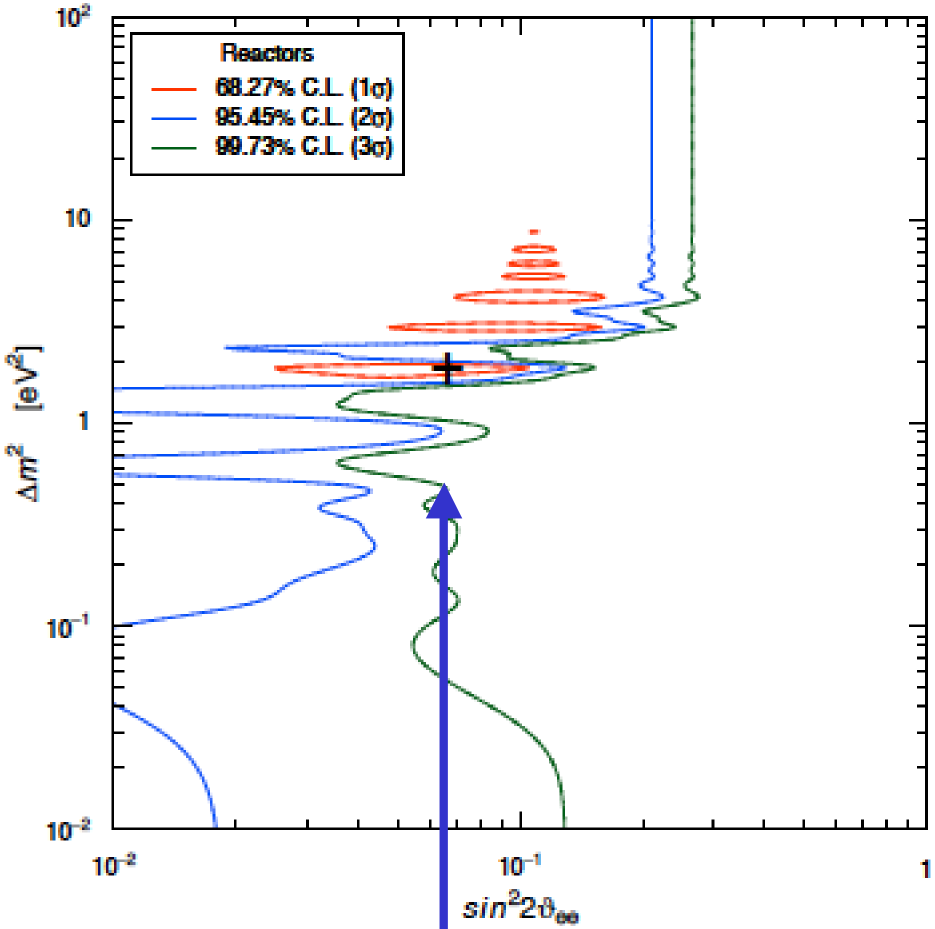
Systematic errors not shown!
Certainly of the same order of the shift.
They could well be larger than estimated

Depends on assumed cross section!

Gallium Anomaly

Reactor Anomaly



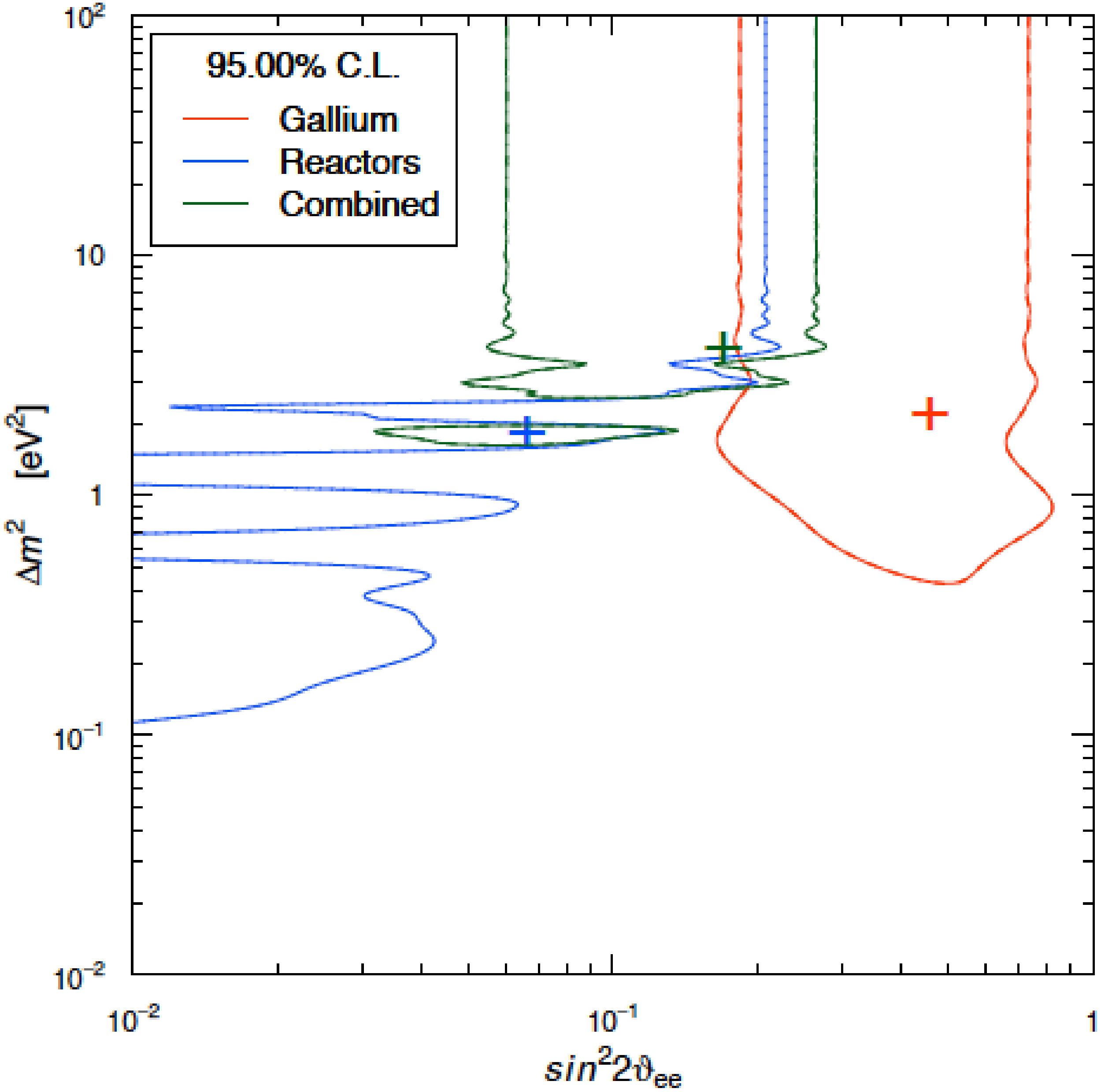


Do not really agree!

large angle

small angle

This is the compromise realized in the fit



$\chi^2_{\text{min}} = 59.8$

$\text{NdF} = 65$

$\text{GoF} = 66\%$

$\sin^2 2\vartheta = 0.17$

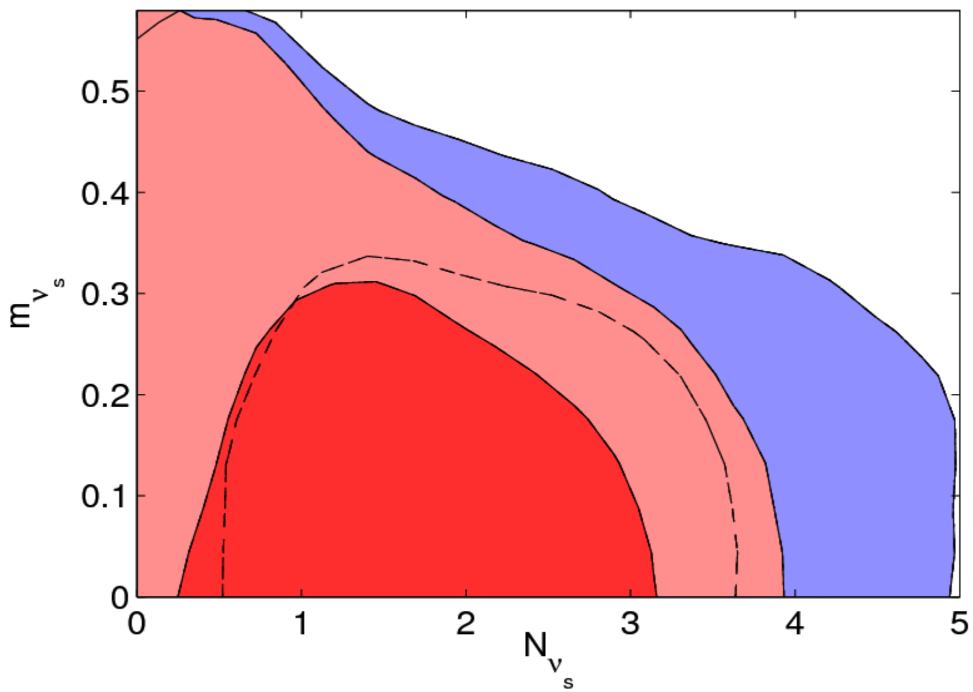
$\Delta m^2 = 4.17\,\text{eV}^2$

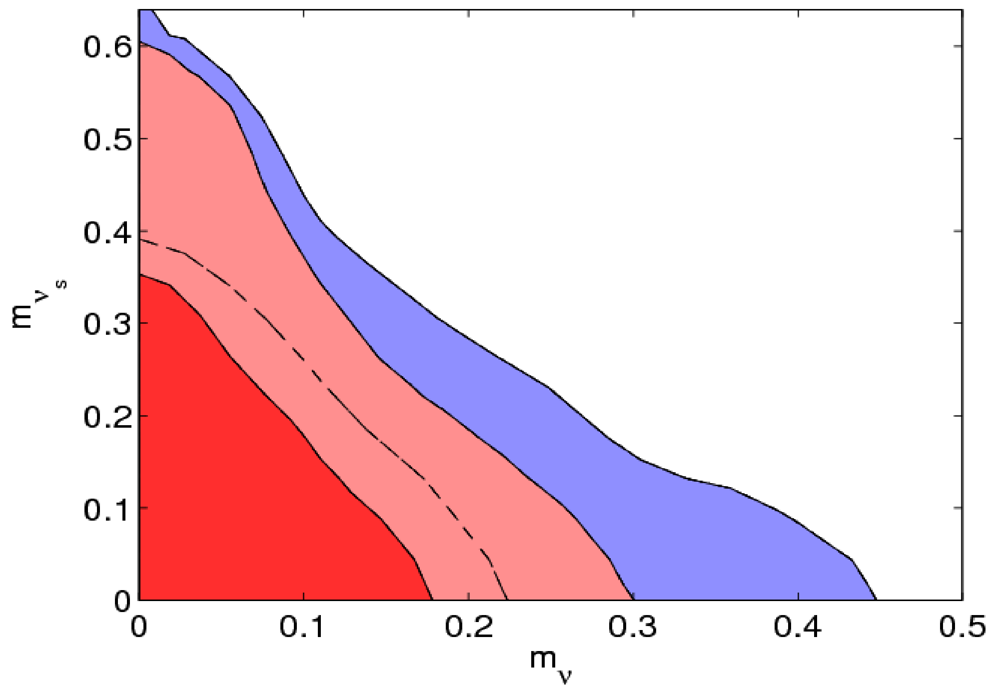
$\text{PGoF} = 1.1\%$

Hints for sterile neutrinos from cosmology

Giusarma et al., 2011 includes masses both in active and sterile Neutrinos.

Melchiorri





Blue: CMB+HST+SDSS

Red: CMB+HST+SDSS+SN-Ia

The bound from nucleosynthesis is more stringent

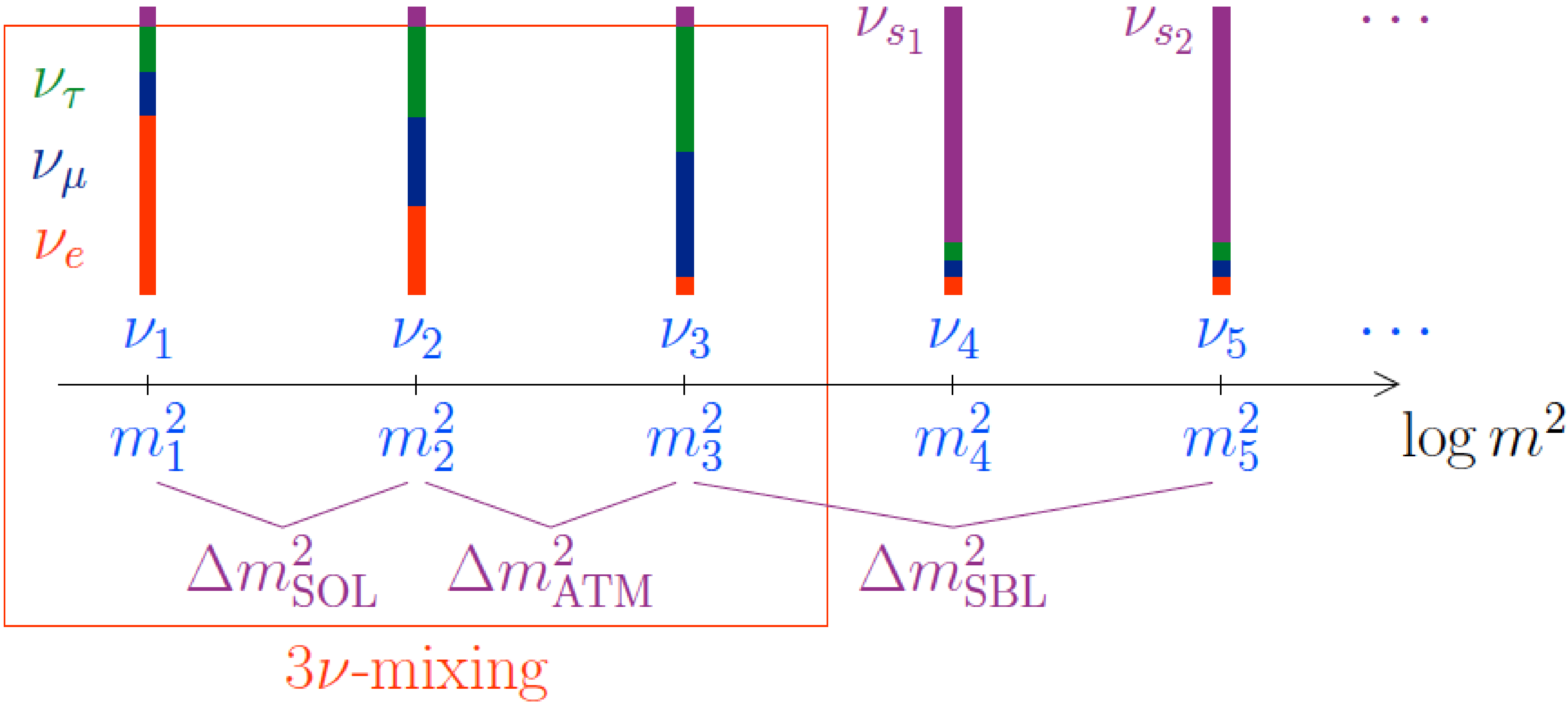
- BBN:
  $N_s = 0.22 \pm 0.59$ [Cyburt, Fields, Olive, Skillman, AP 23 (2005) 313, astro-ph/0408033]
  $N_s = 0.64^{+0.40}_{-0.35}$ [Izotov, Thuan, ApJL 710 (2010) L67, arXiv:1001.4440]

N_s

- BBN: $N_s < 1.2$ (95% CL) Mangano, Serpico, 1103.1261

Only a small leakage from active to sterile neutrinos is allowed by present data

Giunti



We do not need them.
But a sterile neutrino would probably be a remnant of some really hidden sector. So would be a great discovery.

Best fit of sterile neutrinos: at least two

Giunti

- CPT-invariant 3+1 Four-Neutrino Mixing is strongly disfavored (no CP violation and tension between appearance and disappearance)
- 3+2 Five-Neutrino Mixing can explain CP violation but tension between appearance and disappearance persists (reduced by NSI)

Schwetz

3+2 model with two eV-scale neutrinos gives good fit to global data

3+2 global fit

Δm^2_{41}	$\|U_{e4}\|$	$\|U_{\mu 4}\|$	Δm^2_{51}	$\|U_{e5}\|$	$\|U_{\mu 5}\|$	δ/π	χ^2/dof
0.47	0.131	0.170	0.93	0.135	0.142	1.62	105.9/130

New and better experimental data are badly needed!

Mills

MiniBooNE will present new results in the summer

from 5.66 to 8 10^{20} pot

Icarus proposes a new experiment at CERN with 2 argon detectors 150 t and 600 t at 150 m and 800 m resp.

Pietropaolo

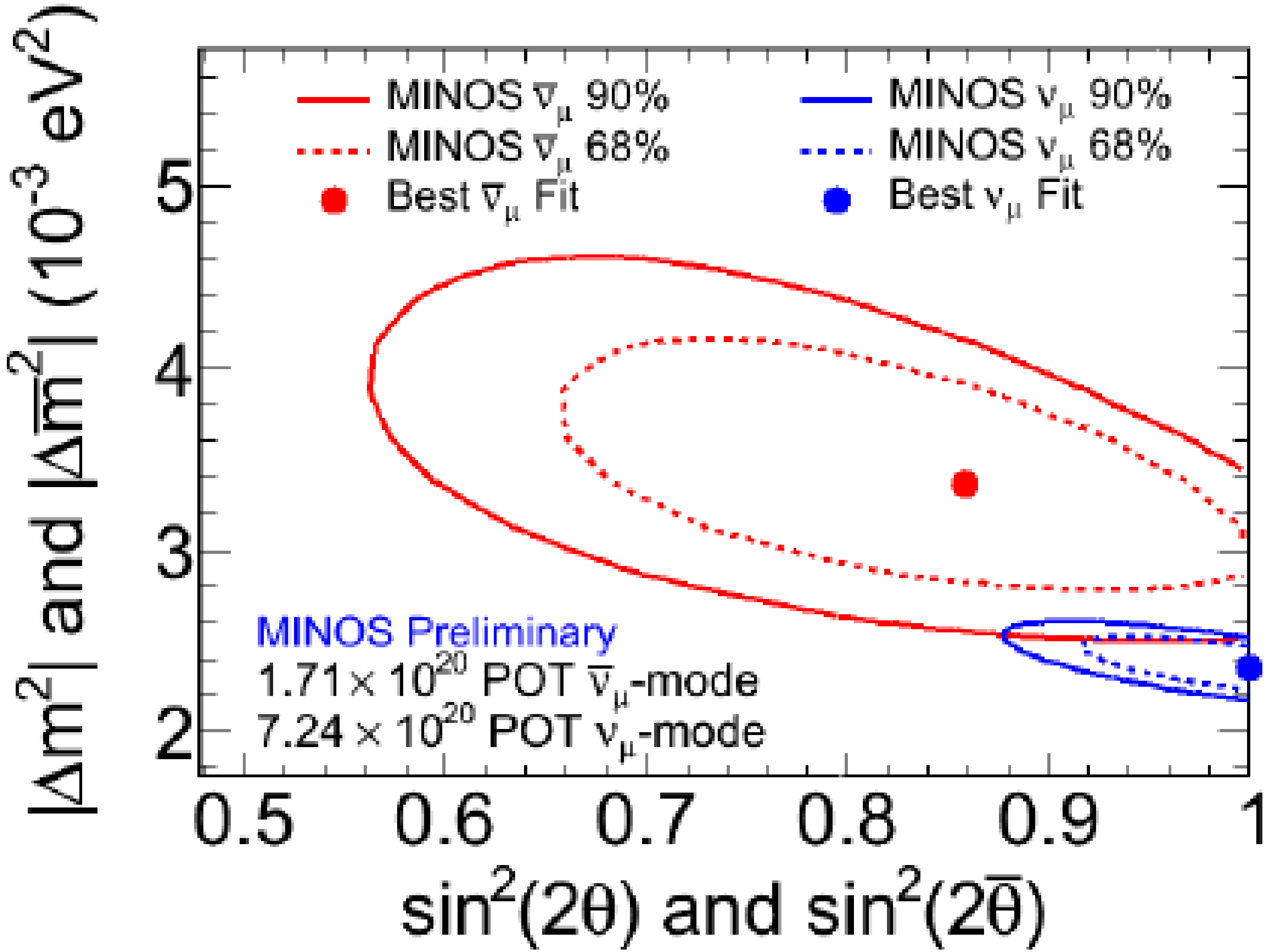
from CNGS

C. Rubbia

a dream experiment for sterile neutrinos!

•••••••

A not yet significant hint of difference between ν's and anti-ν's is also reported by MINOS. CPT viol? Will probably go away.

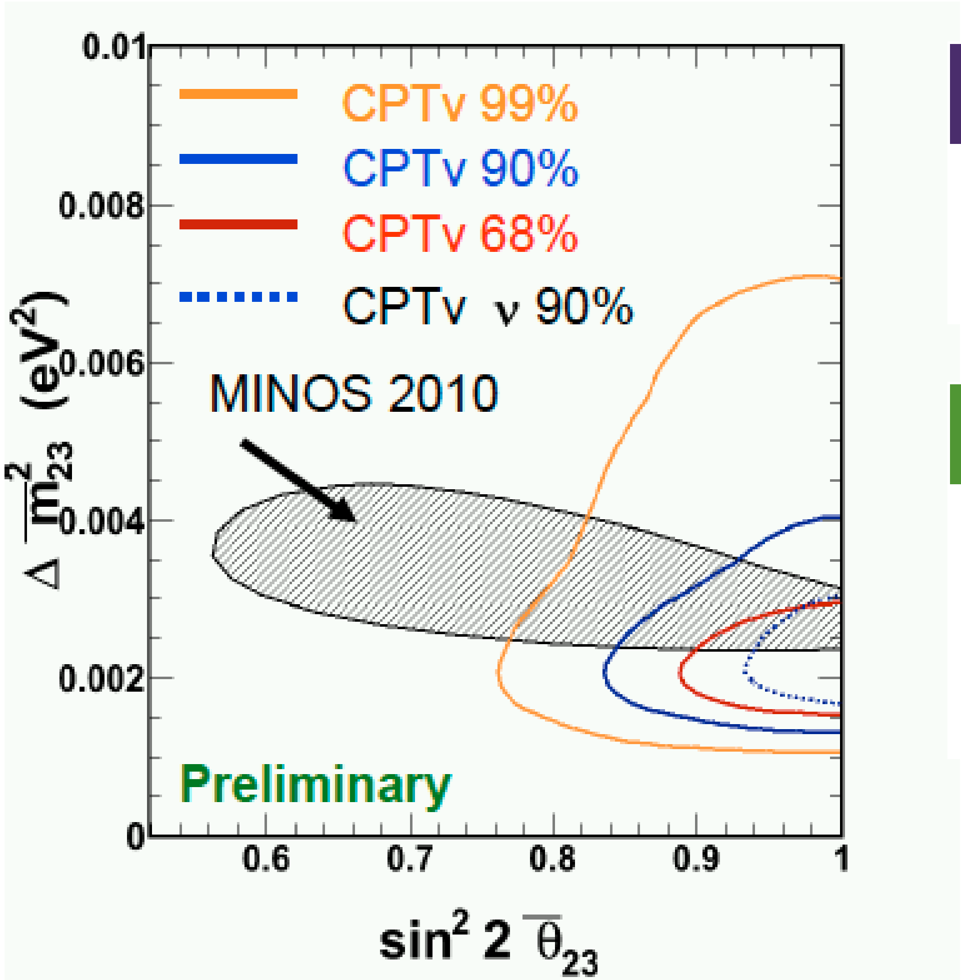


Corwin

Not supported by SuperKamiokande
(strong constraints also on sterile neutrinos)

Wilkes

- Test ν oscillation or $\bar{\nu}$ oscillation separately.



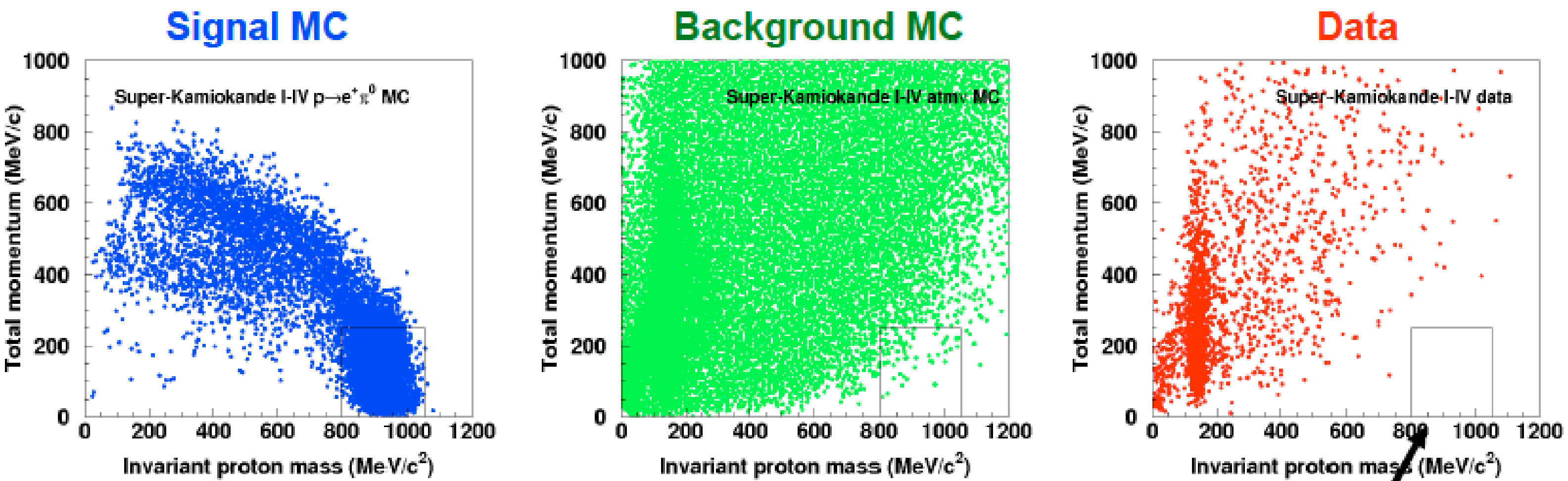
SK 2806 Days

		Best Fit
Δm^2	neutrino	2.1×10^{-3} eV^2
$\sin^2 2\theta$		1.0
		Best Fit
Δm^2	antineutrino	2.0×10^{-3} eV^2
$\sin^2 2\theta$		1.0
χ^2		468.8 / 416 D.O.F

Equal neutrino and antineutrino mixing favored by the data

» No evidence for CPT violation in SK atmospheric data

Search for $p \rightarrow e^+ + \pi^0$, SK-I+II+III+IV Preliminary



p ✹ e+ + ◘ Cut	efficiency (%)	SK4 MC 535.2d	Data
2 or 3 Rings	73.6	1193	1117
All e-like	65.5	708.5	674
85 < ◘$_{mass}$ < 185 MeV	63.5	590.7	575
0 Decay electron	62.5	409.6	386
Total Mass Cut	45.0 ± 19.0	0.05	0

Still no Candidates!

Into the next decade!

SK-IV Only $\tau / B > 1.9 \times 10^{33}$ yr (32.9 kton yr)

SK-I-IV combined $\tau / B > 1.21 \times 10^{34}$ yr (205.7 kton yr)

The 3-neutrino paradigm is still the reference framework

Giunti

Solar $\nu_e \to \nu_\mu, \nu_\tau$	Homestake, Kamiokande, GALLEX/GNO & SAGE, Super-Kamiokande, SNO, BOREXino	$\to$	$\Delta m^2_{\text{SOL}} \simeq 7.6 \times 10^{-5}\,\text{eV}^2$
Reactor $\bar{\nu}_e$ disappearance	(KamLAND)		$\sin^2 \vartheta_{\text{SOL}} \simeq 0.32$
Atmospheric $\nu_\mu \to \nu_\tau$	Kamiokande, IMB, Super-Kamiokande, MACRO, Soudan-2	$\to$	$\Delta m^2_{\text{ATM}} \simeq 2.4 \times 10^{-3}\,\text{eV}^2$
Accelerator ν_μ disappearance	(K2K & MINOS)		$\sin^2 \vartheta_{\text{ATM}} \simeq 0.50$

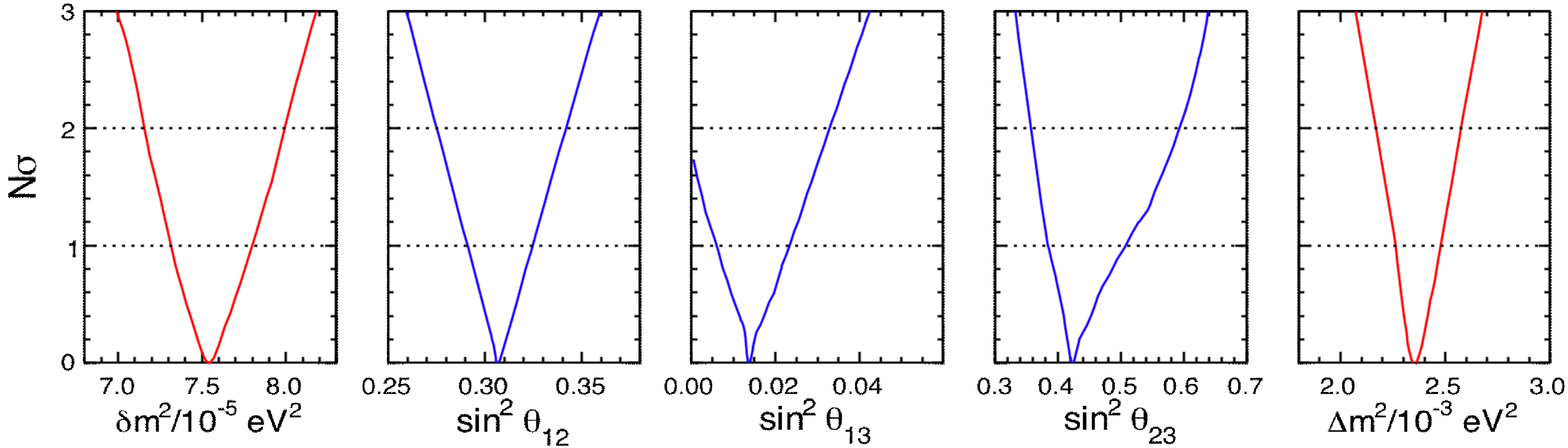
Two scales of $\Delta m^2 \Longleftrightarrow$ Three-Neutrino Mixing

$$\Delta m^2_{\text{SOL}} = \Delta m^2_{21} \simeq 7.6 \times 10^{-5}\,\text{eV}^2$$

$$\Delta m^2_{\text{ATM}} \simeq |\Delta m^2_{31}| \simeq |\Delta m^2_{32}| \simeq 2.4 \times 10^{-3}\,\text{eV}^2$$

OPERA Patrizii
Borexino Meroni

2011 Status: our update of [Fogli et al. arXiv:0805.2517], in preparation* Lisi



Parameter	$\delta m^2/10^{-5}$ eV^2	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	$\Delta m^2/10^{-3}$ eV^2
Best fit	7.54	0.307	0.014	0.42	2.36
1σ range	7.32 – 7.79	0.291 – 0.325	0.006 – 0.023	0.38 – 0.51	2.26 – 2.48
2σ range	7.14 – 7.99	0.275 – 0.342	< 0.033	0.36 – 0.59	2.17 – 2.57
3σ range	6.98 – 8.17	0.259 – 0.360	< 0.042	0.33 – 0.64	2.07 – 2.67

*Includes SK-I+II+III, MINOS app.+disapp., latest KamLAND and solar data.

Other recent global analyses: Gonzalez-Garcia et al, arXiv:1006.3795;
Schwetz et al., arXiv:1103.0734 (includes new evaluation of reactor fluxes)

θ_{13}

Lisi

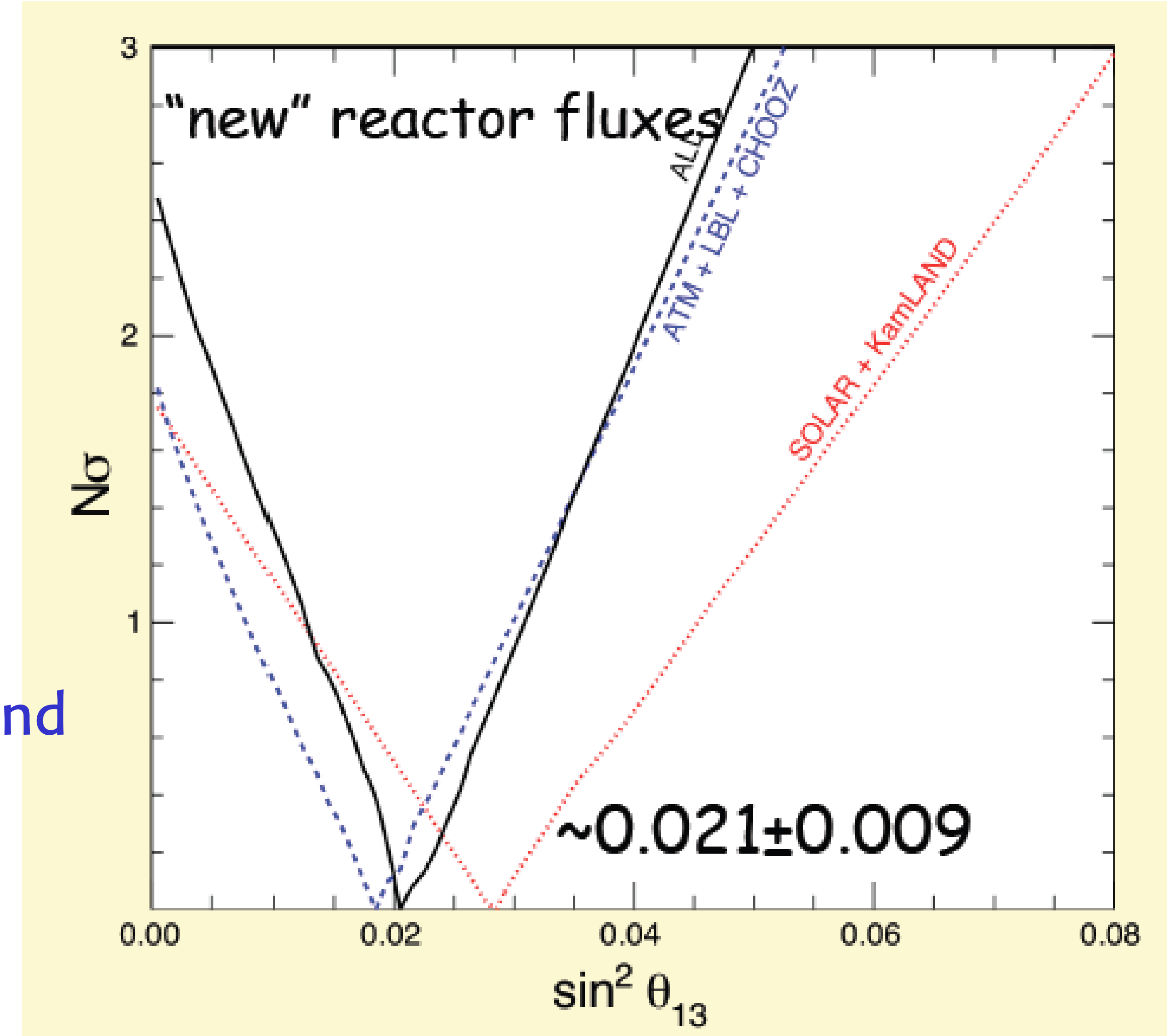
Fogli et al

$\sin^2\theta_{13}=0.021\pm0.009$

At 3σ's:

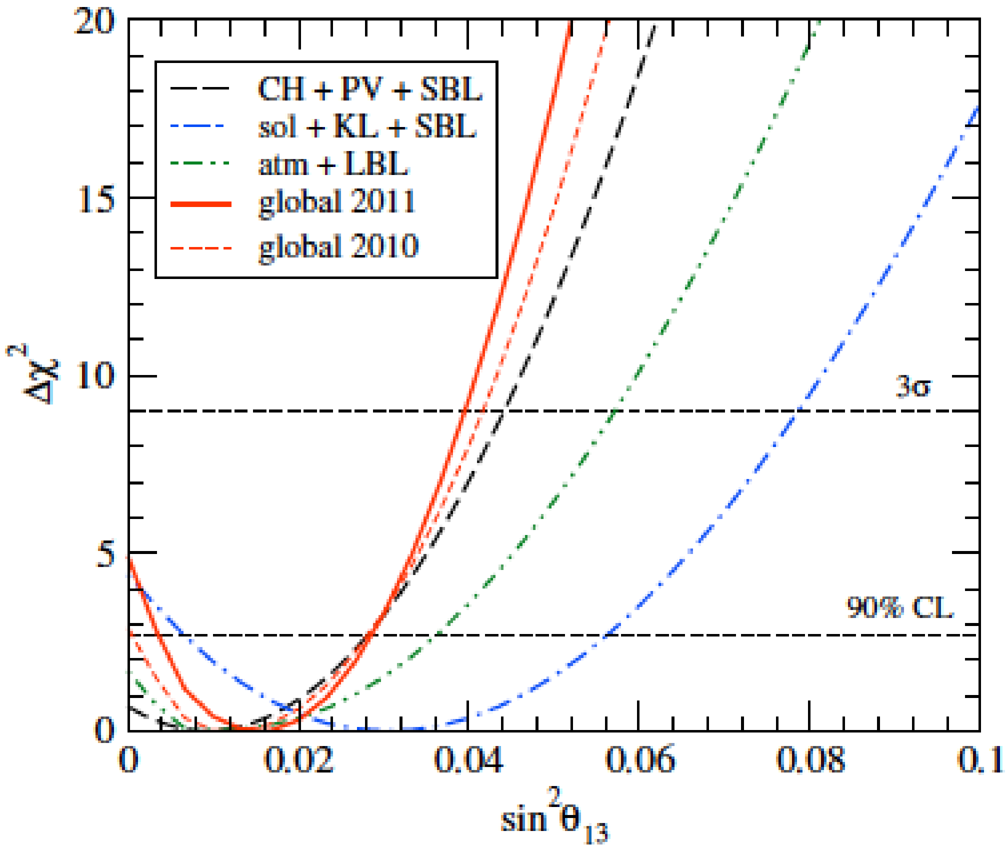
$\sin^2\theta_{13} < 0.05 \sim \theta_C^2$

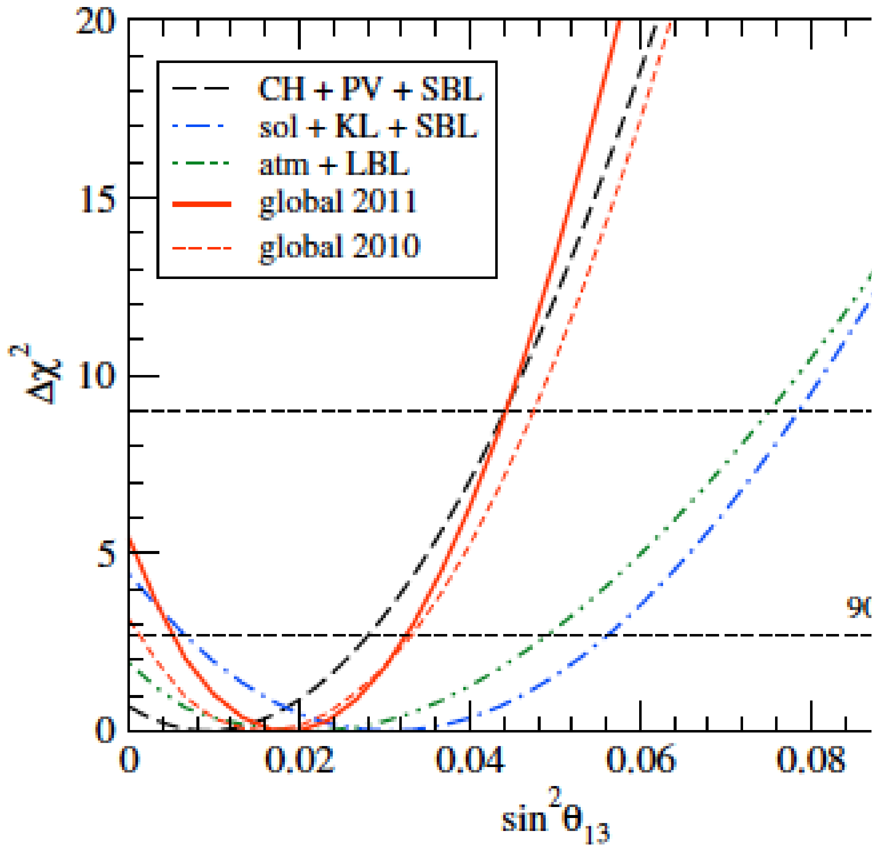
The Cabibbo angle
is a robust upper bound



Global data on θ_{13}

Schwetz





	$\sin^2\theta_{13}$	$\Delta\chi^2(\theta_{13}=0)$	3σ bound
NH	$0.017^{+0.007}_{-0.009}$	4.9 (2.2σ)	0.040
IH	$0.020^{+0.008}_{-0.009}$	5.4 (2.3σ)	0.044

θ_{13} depends on SBL reactor treatment

Schwetz

	$\sin^2\theta_{13}$	$\Delta\chi^2(\theta_{13}=0)$	3σ bound
solar + KamLAND + SBL	$0.030^{+0.015}_{-0.016}$	4.4 (2.1σ)	0.079
Chooz + Palo Verde + SBL	$0.009^{+0.012}_{-0.011}$	0.7 (0.8σ)	0.044
atmospheric + MINOS	$0.010^{+0.016}_{-0.008}$ $0.020^{+0.018}_{-0.015}$	1.7 (1.3σ) 1.9 (1.4σ)	0.057 0.075
atmos + MINOS + solar	$0.013^{+0.014}_{-0.009}$ $0.020^{+0.015}_{-0.012}$	2.3 (1.5σ) 2.7 (1.6σ)	0.053 0.065
global with SBL	$0.017^{+0.007}_{-0.009}$ $0.020^{+0.008}_{-0.009}$	4.9 (2.2σ) 5.4 (2.3σ)	0.040 0.044
global with SBL (free norm)	$0.010^{+0.009}_{-0.006}$ $0.013^{+0.010}_{-0.007}$	3.1 (1.8σ) 3.3 (1.8σ)	0.036 0.041
global w/o SBL	$0.023^{+0.010}_{-0.008}$ 0.030 ± 0.010	9.0 (3.0σ) 10.3 (3.2σ)	0.052 0.058
global w/o SBL (old fluxes)	$0.012^{+0.010}_{-0.007}$ 0.017 ± 0.010	2.9 (1.7σ) 3.2 (1.8σ)	0.042 0.048

θ_{13} depends on SBL reactor treatment

Schwetz

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global w/o SBL (old fluxes)	$0.012^{+0.010}_{-0.007}$ 0.017 ± 0.010	2.9 (1.7σ) 3.2 (1.8σ)	0.042 0.048

NEW!!

The first T2K results presented at this Conference!!

A. Rubbia

T2K preliminary (2010a)

Assuming $\Delta m^2_{23} = 2.4 \cdot 10^{-3} eV^2$ and $\sin^2 2\theta_{23} = 1.0$, $\delta_{CP} = 0$:

(A) Feldman-Cousins	Normal Hierarchy : $\sin^2(2\theta_{13}) < 0.50$ (90%C.L.) Inverted Hierarchy : $\sin^2(2\theta_{13}) < 0.59$ (90%C.L.)
(B) Classical one-sided	Normal Hierarchy : $\sin^2(2\theta_{13}) < 0.44$ (90%C.L.) Inverted Hierarchy : $\sin^2(2\theta_{13}) < 0.53$ (90%C.L.)

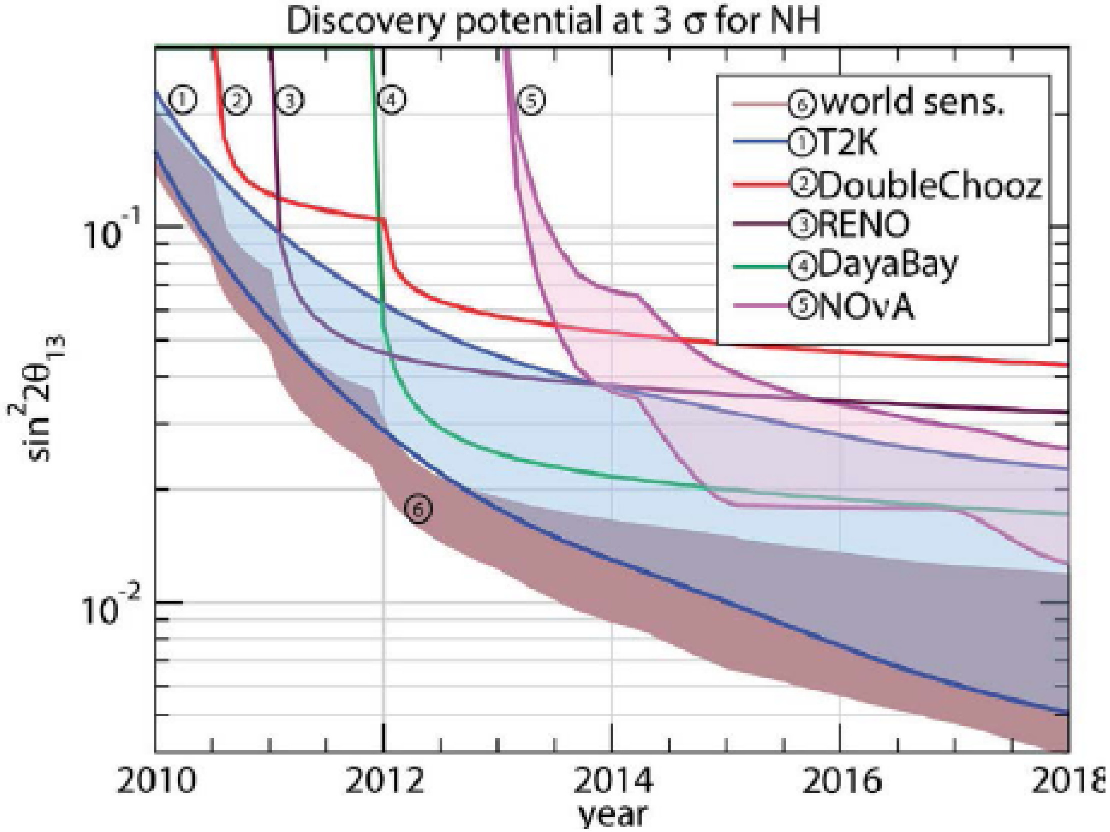
The T2K running was interrupted by the earthquake.
We hope it can be repaired fast.

The future of θ_{13}

Mc Donald
A. Rubbia
Sousa
Cabrera Serra
Wang
Kim

FUTURE

Huber, Lindner, Schwetz, Winter, 2009
Mezzetto, Schwetz, 2010



Soon we will know!

More difficult tasks

- Absolute scale of neutrino mass
- Shift from maximal of θ_{23}
- Sign of Δm^2_{23} (normal or inverse hierarchy)
- CP violation in ν oscillations
- Proof that neutrinos are Majorana fermions
- •••••

Paolone
Efthymiopoulos
Parke

Wildner
Long
A.Rubbia
Bishal

Many projects:

From T2K, NOνA....... to DUSEL, ProjectX, LAGUNA.....
neutrino factories......

ν oscillations measure Δm^2. What is m^2?

$\Delta m^2_{atm} \sim 2.5\ 10^{-3}\ eV^2 = (0.05\ eV)^2$; $\Delta m^2_{sun} \sim 8\ 10^{-5}\ eV^2 = (0.009\ eV)^2$

- Direct limits

$m_{"\nu e"} < 2.2$ eV

$m_{"\nu\mu"} < 170$ KeV

$m_{"\nu\tau"} < 18.2$ MeV

End-point tritium β decay (Mainz, Troitsk)
Future: Katrin
0.2 eV sensitivity
(Karsruhe)

$m_{ee} = |\sum U_{ei}^2\ m_i|$

- $0\nu\beta\beta$ $m_{ee} < 0.2 - 0.7 - ?$ eV (nucl. matrix elmnts)

Evidence of signal? Klapdor-Kleingrothaus

- Cosmology $\Omega_\nu\ h^2 \sim \Sigma_i m_i\ /94eV$ $(h^2 \sim 1/2)$

$\Sigma_i m_i < 0.2\text{-}0.7$ eV (dep. on data&priors)

WMAP, SDSS, 2dFGRS, Ly-α

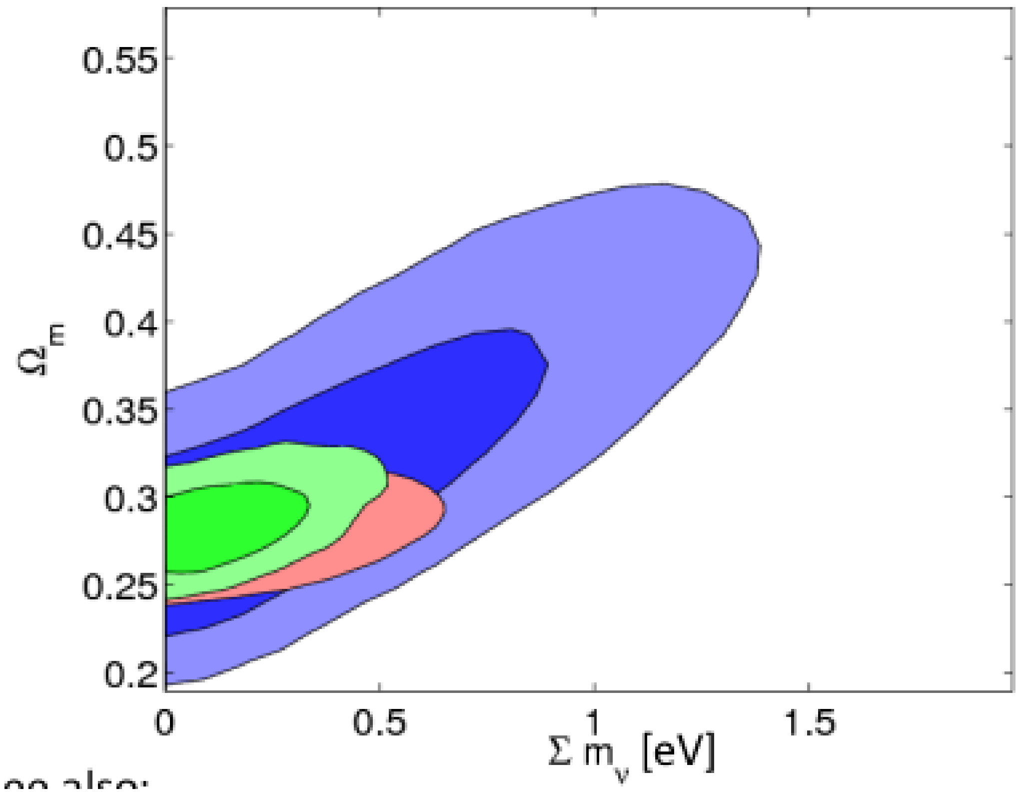
→ Any ν mass $< 0.06 - 0.23 - \sim 1$ eV

depending on your weight on cosmology

Current constraints on neutrino mass from Cosmology

Fogli et al, 2011 in preparation

Melchiorri



Blue: WMAP-7

Red: w7+SN+Bao+H0

Green: w7+CMBsuborb+SN+LRG+H0

Current constraints (assuming ΛCDM):

Σm_ν<1.3 [eV] CMB

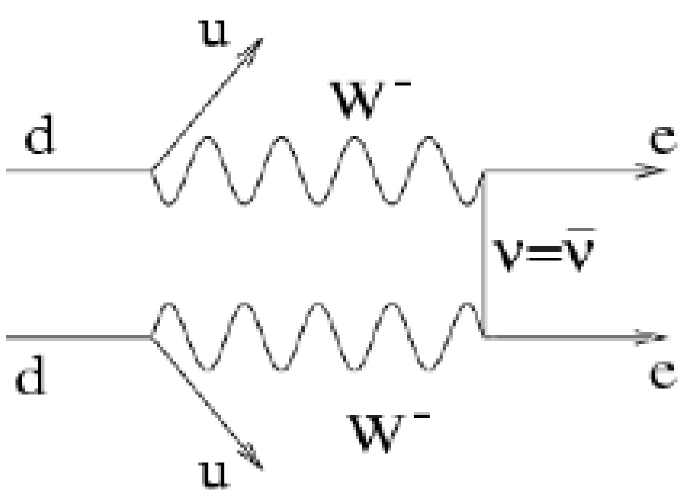
Σm_ν<0.7-0.5 [eV] CMB+other

Σm_ν<0.3 [eV] CMB+LSS (extreme)

See also:

All we know from experiment on ν masses strongly indicates that ν's are Majorana particles and that L is not conserved (but a direct proof still does not exist).

Detection of 0νββ would be a proof of L non conservation. Thus a big effort is devoted to improving present limits and possibly to find a signal.



$0\nu\beta\beta = dd \to uue^-e^-$

Heidelberg-Moscow
IGEX
Cuoricino-Cuore
GERDA
.....

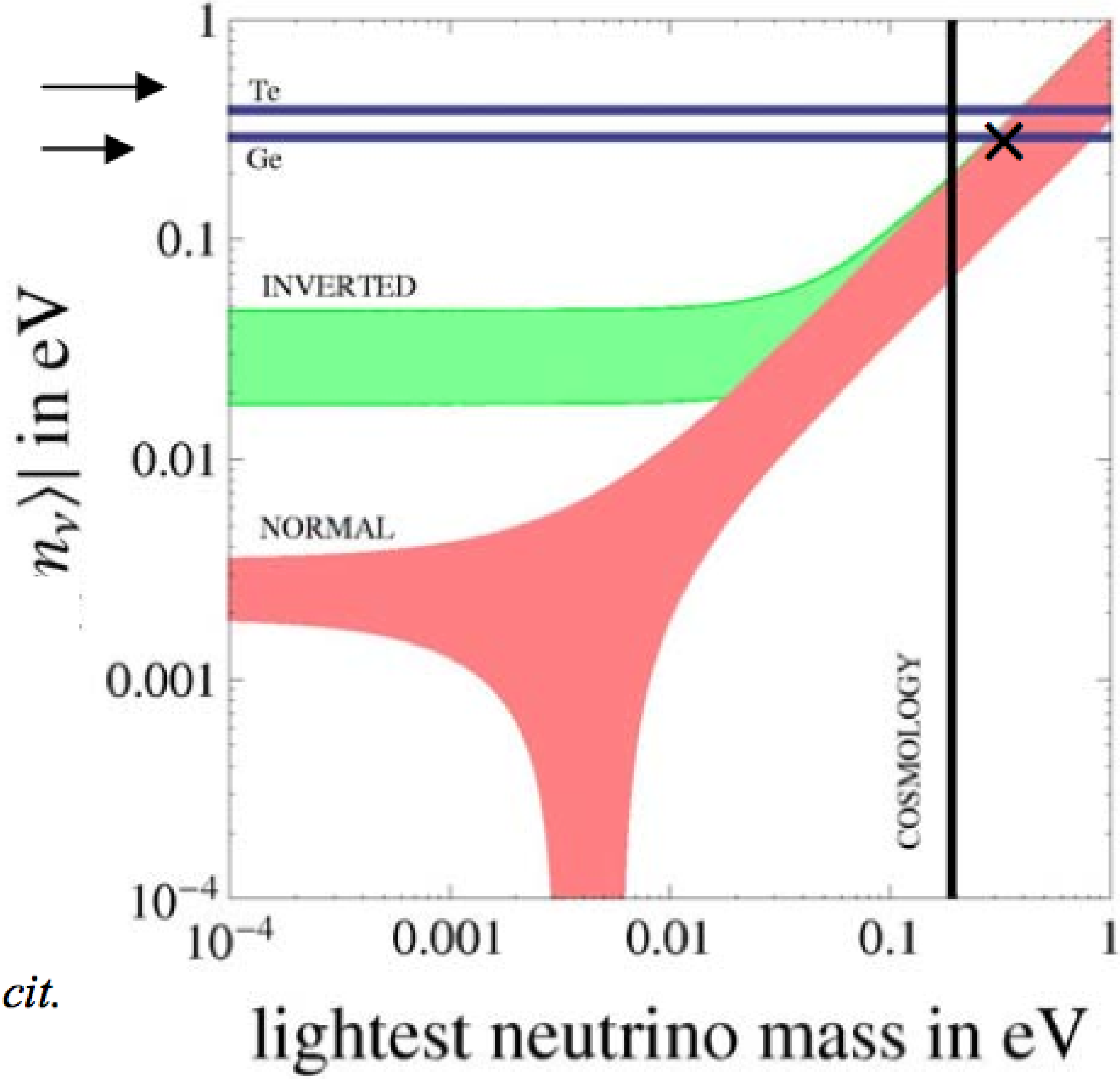
Great role of LNGS

Iachello
Gomez-Cadenas
Brofferio
Schonert

Iachello

CUORICINO
IGEX

+IBM-2



Cosmological constraint from G.L. Fogli, E. Lisi, *et al, loc.cit.*

$$\Sigma = m_1 + m_2 + m_3 < 0.19 eV$$

× H.V. Klapdor *et al, loc. cit.*

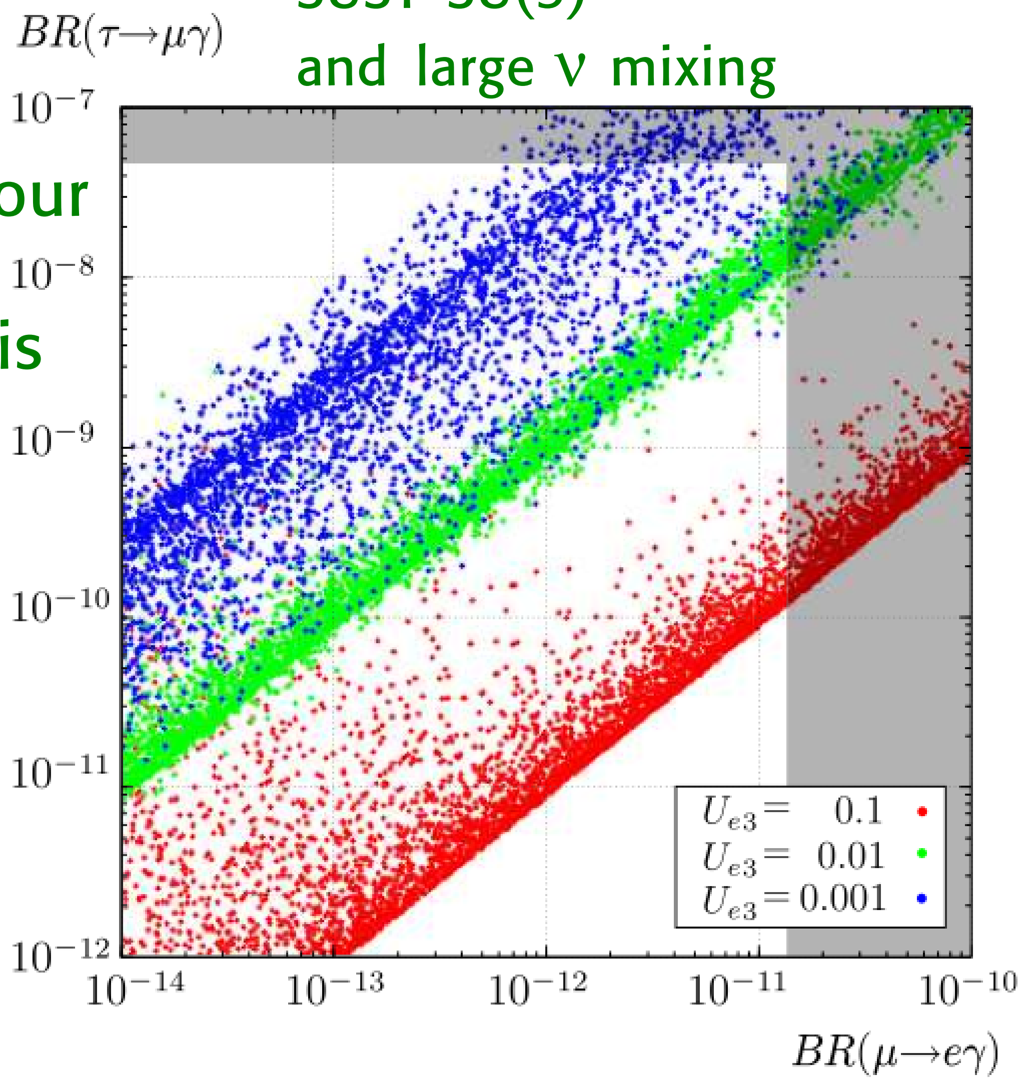
The $\mu \to e\gamma$ search is extremely interesting

Baldini
Paradisi

SUSY SU(5)
and large ν mixing

In general: lepton flavour violation, leptogenesis is a very promising domain

Di Bari



Present $\mu \to e\gamma$ limit

BR < 1.2 10^{-11}
MEGA

Present MEG result

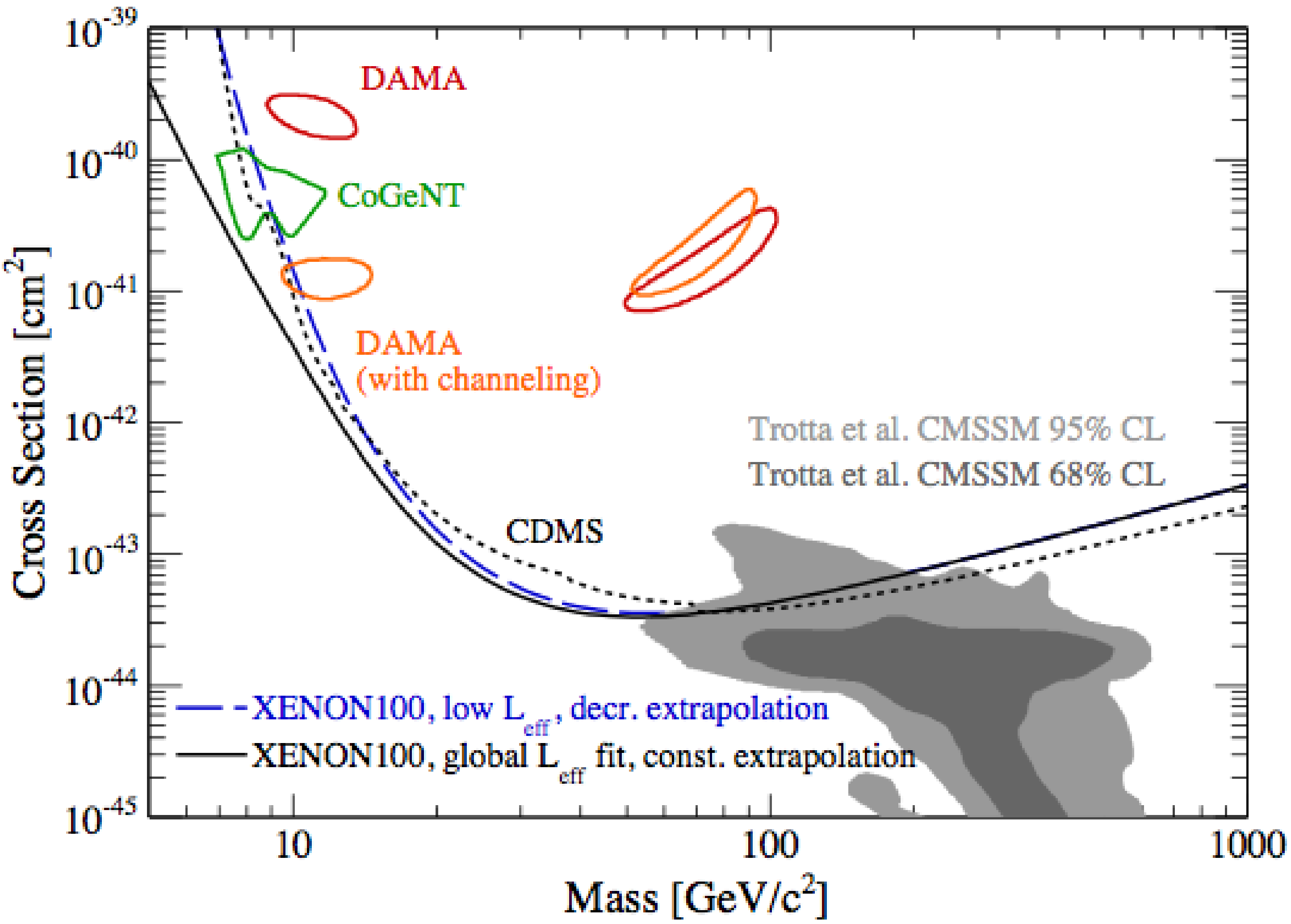
BR < 1.5 10^{-11}
90%

MEG goal 10^{-13}

A highly likely place for new physics within reach

The non accelerator search for Dark Matter is an important complement to the LHC search

Gelmini
Aprile



In this case also LNGS is playing a great role

Main theoretical lessons from ν masses and mixings

- ν's are not all massless but their masses are very small

- probably masses are small because ν's are Majorana particles

- then masses are inv. prop. to the large scale M of L n. viol.

- $M \sim m_{\nu R}$ is empirically close to 10^{14}-10^{15} GeV ~ M_{GUT}
  -> ν masses fit well in the SUSY GUT picture

- decays of ν_R with CP & L violation can produce a B-L asymm.
  -> baryogenesis via leptogenesis

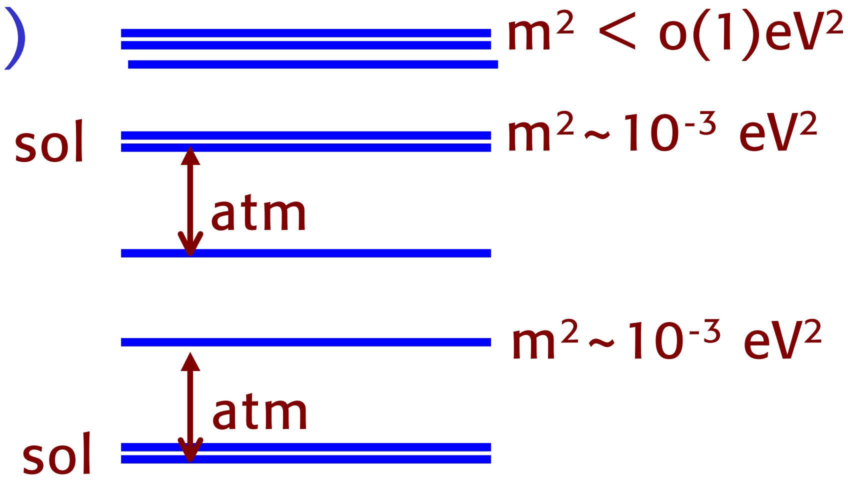
- detecting 0νββ would prove ν's are Majorana and L is viol.

- ν's are not a significant component of dark matter in Universe

The current experimental situation on ν masses and mixings has much improved but is still incomplete

- what is the absolute scale of ν masses?
- value of θ_{13}, more precise angles, phase of CP violation
- pattern of spectrum (sign of Δm^2_{atm})

- Degenerate ($m^2 >> \Delta m^2$)
- Inverse hierarchy
- Normal hierarchy



- no detection of $0\nu\beta\beta$ (i.e. no proof that ν's are Majorana)
  see-saw?
- are 3 light ν's OK? (are the sterile neutrinos)

→ Different classes of models are still possible

General remarks

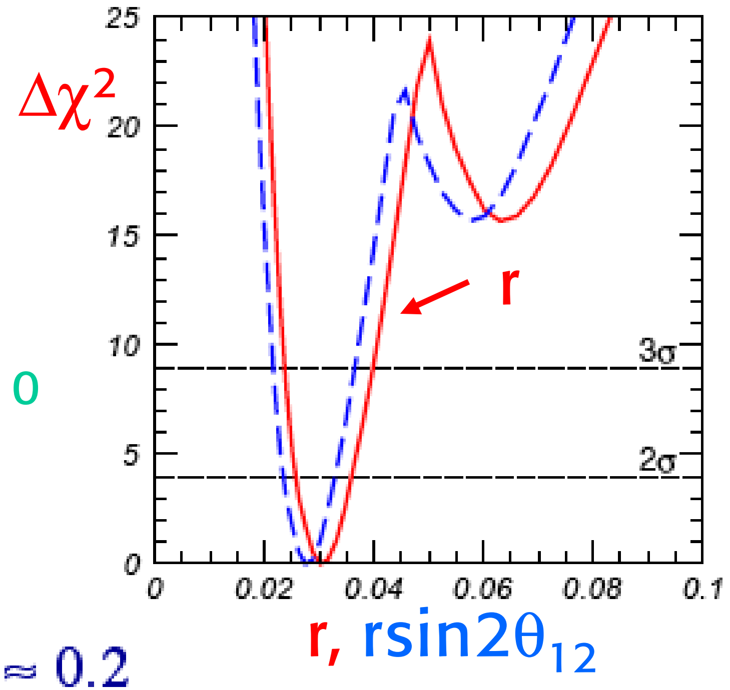
• After KamLAND, SNO .... and Cosmology not too much hierarchy is found in ν masses:

$$r \sim \Delta m^2_{sol}/\Delta m^2_{atm} \sim 1/30$$

Only a few years ago could be as small as 10^{-8}!

Precisely at 3σ: $0.025 < r < 0.039$

Schwetz et al '10



or

$m_{heaviest} < 0.2$ - 0.7 eV
$m_{next} > \sim 8\ 10^{-3}$ eV

For a hierarchical spectrum: $\frac{m_2}{m_3} \approx \sqrt{r} \approx 0.2$

Comparable to $\lambda_C = \sin\theta_C$: $\lambda_C \approx 0.22$ or $\sqrt{\frac{m_\mu}{m_\tau}} \approx 0.24$

Suggests the same "hierarchy" parameters for q, l, ν (small powers of λ_C) ⟶ e.g. θ_{13} not too small!

- θ_{13} not necessarily too small
  probably accessible to exp.

Very small θ_{13} theoretically hard [typically $\theta_{13} > 0.01$]

- Still large space for non maximal 23 mixing

2-σ interval $0.39 < \sin^2\theta_{23} < 0.63$ Schwetz et al '10

Maximal θ_{23} theoretically hard

- θ_{12} is at present the best measured angle
  $\Delta\sin^2\theta_{12}/\sin^2\theta_{12} \sim 6\%$

For constructing models we need the data but also to decide which feature of the data is really relevant

Examples:

Is Tri-Bimaximal (TB) mixing really a significant feature or just an accident?

Is lepton-quark complementarity (LQC) a significant feature or just an accident?

TB Mixing

$$U = \begin{bmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ \frac{-1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{-1}{\sqrt{2}} \\ \frac{-1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{bmatrix}$$

A coincidence or a hint?

TB mixing agrees with data at ~ 1σ

At 1σ:

Schwetz et al '10

$\sin^2\theta_{12} = 1/3$: 0.302-0.337

$\sin^2\theta_{23} = 1/2$: 0.44-0.57

$\sin^2\theta_{13} = 0$: $<$ ~0.026

Called:
Tri-Bimaximal mixing

Harrison, Perkins, Scott '02

$$\nu_3 = \frac{1}{\sqrt{2}}(-\nu_\mu + \nu_\tau)$$

$$\nu_2 = \frac{1}{\sqrt{3}}(\nu_e + \nu_\mu + \nu_\tau)$$

LQC: Lepton Quark Complementarity

$\theta_{12} + \theta_C = (47.0 \pm 1.2)^o \sim \pi/4$

Raidal'04

Suggests Bimaximal mixing corrected by diagonalisation of charged leptons

$$U_{BM} = \begin{pmatrix} \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \\ \frac{1}{2} & \frac{1}{2} & -\frac{1}{\sqrt{2}} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

A coincidence or a hint?

Golden Ratio

Feruglio, Paris'11

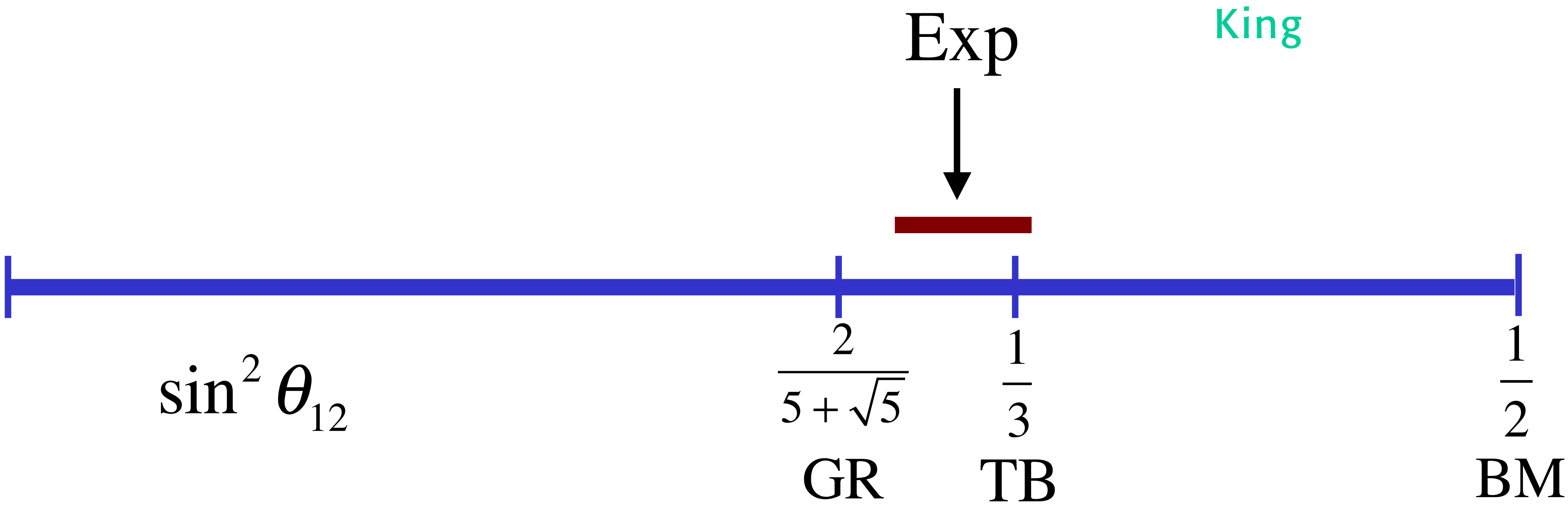
$$\sin^2\theta_{12} = \frac{1}{\sqrt{5}\phi} = \frac{2}{5+\sqrt{5}} \approx 0.276$$

$$U_{GR} = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ \frac{\sin\theta_{12}}{\sqrt{2}} & -\frac{\cos\theta_{12}}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{\sin\theta_{12}}{\sqrt{2}} & -\frac{\cos\theta_{12}}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \end{pmatrix}$$

A coincidence or a hint?

⊕ Cannot be all true hints, perhaps none

King



TB: Group A4, S4..... A vast literature

GR: Golden Ratio - Group A5 Feruglio, Paris '11

} $\theta_{13} \sim o(\theta_C^2)$

BM: Group S4 GA, Feruglio, Merlo '09 $\theta_{13} \sim o(\theta_C)$

A recent review: GA, F. Feruglio, ArXiv:1002.0211
(Review of Modern Physics)

For constructing models we need the data but also to decide which feature of the data is really relevant

Examples:

Is Tri-Bimaximal (TB) mixing really a significant feature or just an accident?

Is lepton-quark complementarity (LQC) a significant feature or just an accident?

Here we already see different classes of models that can fit the data: TB, GR & LQC are all accidents or one of them is relevant

Accidents: a wide spectrum of (mostly old) models

Anarchy, Anarchy in 2-3 sector, Lopsided models, $U(1)_{FN}$, ...

GUT versions exist [SU(5), SO(10)]

Typically there are free parameters fitted to the angles

In lepton sector TB or GR or BM mixing point to discrete flavor groups

What about quarks?

A problem for GUT models is how to reconcile the quark with the lepton mixings

quarks: small angles, strongly hierarchical masses
abelian flavour symm. [e.g. $U(1)_{FN}$]
neutrinos: large angles, perhaps TB or BM
non abelian discrete symm. [e.g. A4]

From experiment:

a good first approximation for quarks

$\lambda = \sin\theta_C$

$$V_{CKM} \sim \begin{pmatrix} 1 & \lambda & 0 \\ -\lambda & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + o(\lambda^2)$$

$V_{CKM} = U_u^+ U_d$

and for neutrinos

$$U = \begin{bmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ \frac{-1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{-1}{\sqrt{2}} \\ \frac{-1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{bmatrix} + o(\lambda^2)\,?$$

Current research

- Larger discrete flavour groups for quark mixings (no GUT's)

Carr, Frampton
Feruglio et al
Frampton, Kephart
....

- GUT models with approximate TB mixing

  it is indeed possible, also for A4, but not easy!
  [SU(5) less difficult than SO(10)]

Ma, Sawanaka, Tanimoto; Ma; GA, Feruglio, Hagedorn 0802.0090
Morisi, Picarello, Torrente Lujan; Bazzocchi et al;
de Madeiros Verzielas, King, Ross [$\Delta(27)$];
King, Malinsky [$SU(4)_C xSU(2)_L xSU(2)_R$]; Antusch et al;
Chen, Mahanthappa [T']; Bazzocchi et al [$\Delta(27)$];
King, Luhn [$PSL_2(7)$]; Dutta, Mimura, Mohapatra [S4];
....

- ν mixing angles are large except for θ_{13} that is small

- The measured values of ν mixing angles are compatible with TB or GR or BM

- If not a coincidence, this points to discrete flavour groups

- In principle there is no contradiction between large ν mixings and small q mixings, even in GUT's

- But quarks offer no new supporting evidence for discrete flavour groups

- Natural GUT models describing all fermion masses with TB, GR, BM mixing in the lepton sector are difficult to construct, in particular for SO(10)

GA, G. Blankenburg '10

As a last speaker, on behalf of all partecipants I would like to most warmly thank the Organisers of this Conference

I am sorry that this is my first NeuTel without the charming presence of Milla Baldo Ceolin who has always been the Queen of the place

So I extend our best greetings to Milla and our warmest wishes of a prompt recovery

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THANK YOU