St. Andrews, August '06

Models of Neutrino Masses & Mixings

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Some recent work by our group

G.A., F. Feruglio, I. Masina, hep-ph/0402155,
G.A., F. Feruglio, hep-ph/0504165,hep-ph/0512103
G.A, R. Franceschini, hep-ph/0512202.

Reviews:

G.A., F. Feruglio, New J.Phys.6:106,2004 [hep-ph/0405048];
G.A., hep-ph/0410101; F. Feruglio, hep-ph/0410131

For ν masses and mixings we do not have so far a Standard Model: many possibilities are still open.

In fact this is the case also for quark and charged leptons; we do not have a theory of flavour that explains the observed spectrum, mixings and CP violation.

ν's are interesting because they can provide new clues on this important problem

In my lectures I will review what we have learnt and the ideas that are being used in model building.

Lecture 1: Basic concepts and experimental facts.
Lecture 2,3: A survey of different classes of models

Lecture 1

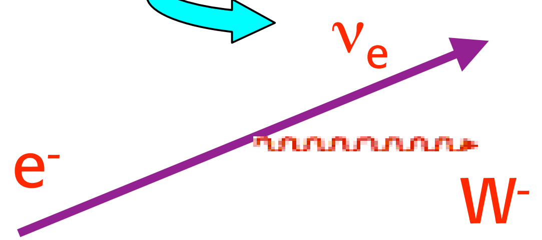
Summary of basic concepts and experimental facts.

Also, a number of assumptions to restrict the subject of my lectures:

e.g. no exotic interpretation of data
only 3 active ν's
CPT invariance
•••••

ν Oscillations Imply Different ν Masses

ν_e: same weak isospin doublet as e^-



flavour mass

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

U: mixing matrix

$U = U_{P\text{-}MNS}$

Pontecorvo
Maki, Nakagawa, Sakata

$\nu_e = \cos\theta\ \nu_1 + \sin\theta\ \nu_2$
$\nu_\mu = -\sin\theta\ \nu_1 + \cos\theta\ \nu_2$

e.g 2 flav.

Stationary source:

Stodolsky

$\nu_{1,2}$: different mass, different x-dep:

$\nu_a(x) = e^{ip_a x}\,\nu_a \qquad p_a^2 = E^2 - m_a^2$

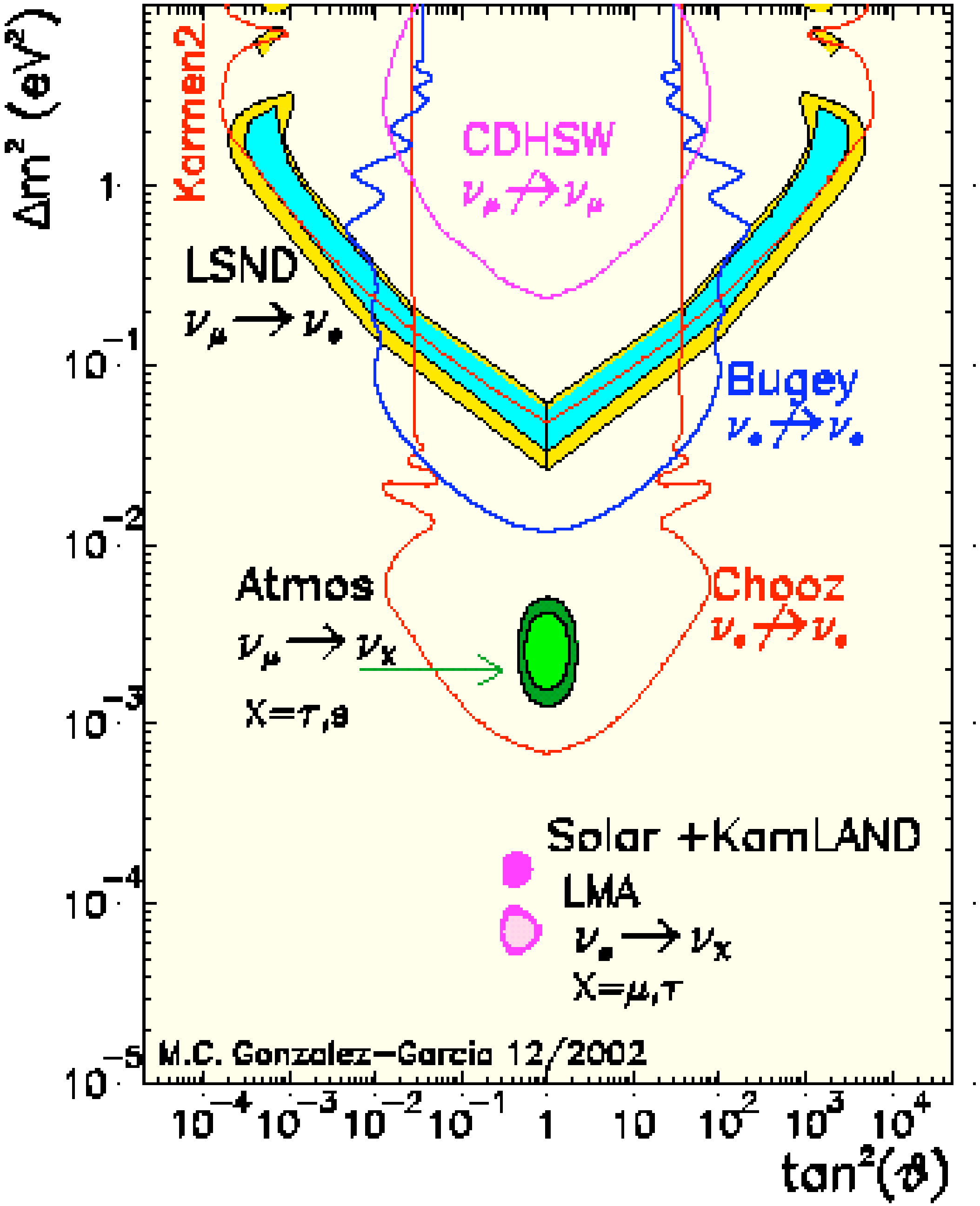
$$P(\nu_e <-> \nu_\mu) = |<\nu_\mu(L)|\,\nu_e>|^2 = \sin^2(2\theta)\cdot\sin^2(\Delta m^2 L/4E)$$

At a distance L, ν_μ from μ^- decay can produce e^- via charged weak interact's

Solid evidence for solar and atmosph. ν oscillations (+LSND unclear)

Δm^2 values fixed:
$\Delta m^2_{atm} \sim 2.5\ 10^{-3}\ eV^2$,
$\Delta m^2_{sol} \sim 8\ 10^{-5}\ eV^2$
($\Delta m^2_{LSND} \sim 1\ eV^2$)

mixing angles:
θ_{12} (solar) large
θ_{23} (atm) large,~maximal
θ_{13} (CHOOZ) small



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

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

- Direct limits

$m_{"\nu e"} < 2.2$ eV — End-point tritium β decay (Mainz, Troitsk)

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

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

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

- $0\nu\beta\beta$ $m_{ee} < 0.3 - 0.7 - ?$ eV (nucl. matrix elmnts)

Evidence of signal? Klapdor-Kleingrothaus

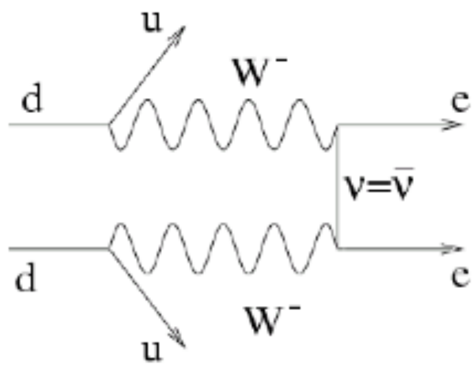
- Cosmology $\Omega_\nu\, h^2 \sim \Sigma_i m_i\, /94eV$ ($h^2 \sim 1/2$)

$\Sigma_i m_i < 0.17$-0.68-2.1 eV (dep. on data&priors)

→ Any ν mass < 0.06-0.23-0.7 eV

WMAP,
2dFGRS,
Ly-α

$0\nu\beta\beta$ experiments



$$\langle m_\nu \rangle^2 = \frac{1}{G(Q,Z)\, |M_{nucl}|^2\, \tau}$$

phase space

matrix elmnt
large uncrtnts

Pavan

Experiment	Isotope	$\tau_{1/2}^{0\nu}$ > [y]	range $\langle m_\nu \rangle$ [eV]
Heidelberg Moscow 2001	^{76}Ge	1.9 10^{25}	0.3-2.5
IGEX 2002	^{76}Ge	1.57 10^{25}	0.3-2.5
Cuoricino 2005	^{130}Te	2 10^{24}	0.3-0.7
NEMO 2005	^{100}Mo	4.6 10^{23}	0.6-1.0

claimed evidence only by a part of the collaboration

started in 2003

$$m_{ee} = |\Sigma\, U_{ej}^2\, m_j\, e^{i\alpha j}|$$

Future: a factor ~ 10 improvement in next decade

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

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Any ν mass $< 0.06\text{-}0.23\text{-}0.7$eV

WMAP, SDSS, 2dFGRS, Ly-α

By itself CMB (eg WMAP) is only mildly sensitive to $\Sigma_i m_i$

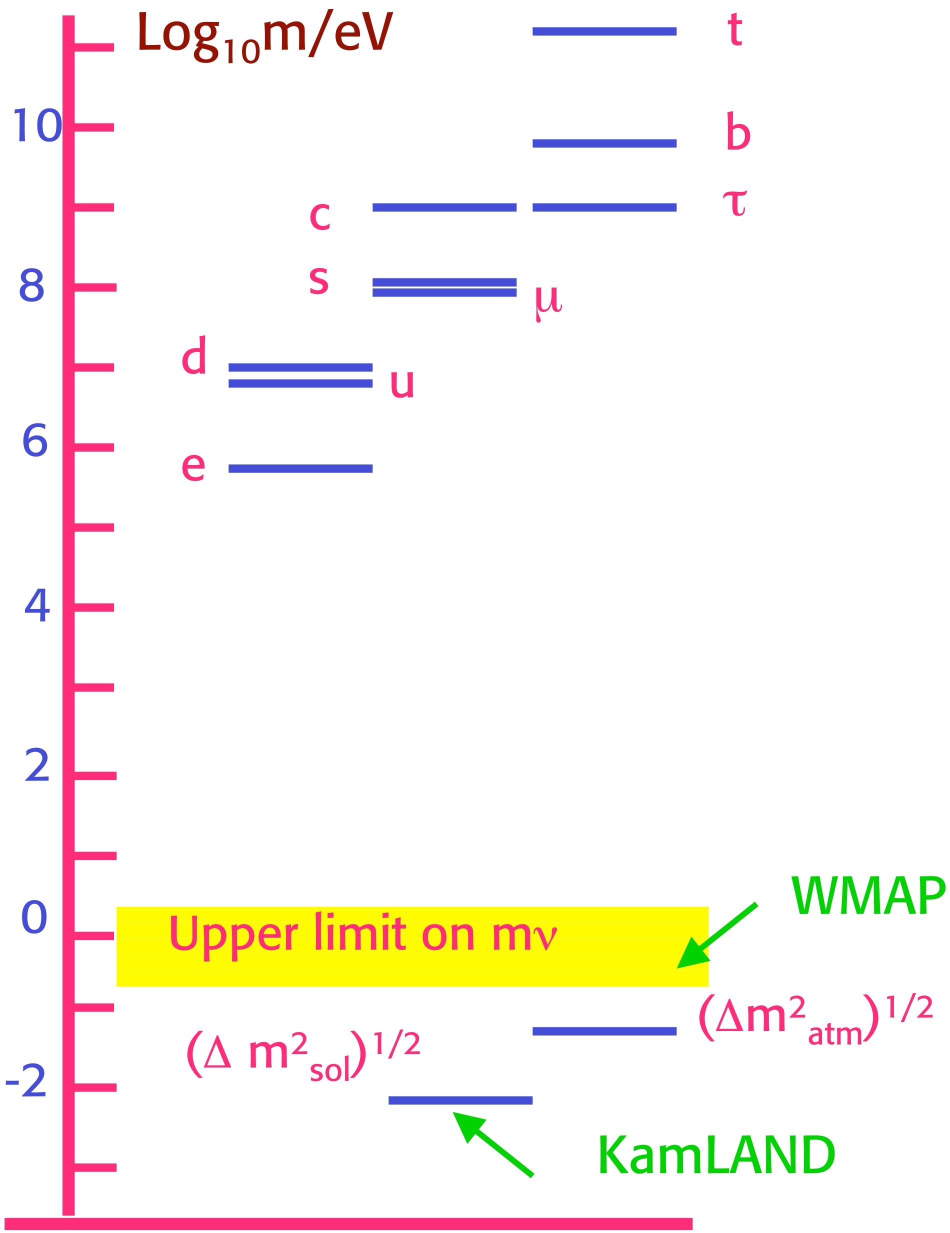
Only in combination with Large Scale Structure (2dFGRS, SDSS) the limit becomes stronger.

And even stronger by adding the Lyman alpha forest data (but some tension among the data).

95%cl

CMB only	(CMB +) LSS	+ Ly-α
$\sum m_{\nu_i} < 2.11$ eV	$\sum m_{\nu_i} < 0.68$ eV	$\sum m_{\nu_i} < 0.17$ eV

Seljac et al '06



Neutrino masses are really special!

$m_t/(\Delta m^2_{atm})^{1/2} \sim 10^{12}$

Massless ν's?

- no ν_R
- L conserved

Small ν masses?

- ν_R very heavy
- L not conserved

How to guarantee a massless neutrino?

1) ν_R does not exist

→ No Dirac mass

$$\overline{\nu}_L \nu_R + \nu_R \overline{\nu}_L$$

and

2) Lepton Number is conserved

→ No Majorana mass

$$\overline{\nu}^c \nu \rightarrow \nu^T{}_R C \nu_R \text{ or } \nu^T{}_L C \nu_L$$

$C = i\gamma^0\gamma^2$

Neutrinos: Dirac mass: $\overline{\nu}_L \nu_R + \overline{\nu}_R \nu_L$

(needs ν_R)

ν's have no electric charge. Their only charge is lepton number L.

IF L is not conserved (not a good quantum number)

ν and $\overline{\nu}$ are not really different

TCP, "Lorentz"

$|\nu, h = -1/2\rangle \longrightarrow |\overline{\nu}, h = +1/2\rangle$

Majorana mass: $\nu^T_R \nu_R$ or $\nu^T_L \nu_L$

(we omit the charge conj. matrix C)

Violates L, B-L by $|\Delta L| = 2$

Weak isospin I

ν_L => $I = 1/2, I_3 = 1/2$

ν_R => $I = 0, I_3 = 0$

Dirac Mass:

$$\bar{\nu}_L \nu_R + \bar{\nu}_R \nu_L \qquad |\Delta I| = 1/2$$

Can be obtained from Higgs doublets: $\nu_L \bar{\nu}_R H$

Majorana Mass:

- $\nu^T{}_L \nu_L \qquad |\Delta I| = 1$

Non ren., dim. 5 operator: $\nu^T{}_L \nu_L HH$

- $\nu^T{}_R \nu_R \qquad |\Delta I| = 0$

Directly compatible with SU(2)xU(1)!

See-Saw Mechanism

Minkowski;
Yanagida; Gell-Mann, Ramond , Slansky;
Glashow; Mohapatra, Senjanovic…..

$M\nu^T_R\nu_R$ allowed by SU(2)xU(1)

Large Majorana mass M (as large as the cut-off)

$m_D\bar{\nu}_L\nu_R$ Dirac mass m from Higgs doublet(s)

$$\begin{array}{c|cc} & \nu_L & \nu_R \\ \hline \nu_L & 0 & m_D \\ \nu_R & m_D & M \end{array}$$

$M \gg m_D$

Eigenvalues

$$\nu_{light} = \frac{-m_D^2}{M}\ , \qquad \nu_{heavy} = M$$

sign conventional
for fermions

In general ν mass terms are:

$$\mathcal{L}_\nu = \bar{L} h \nu_R H + \text{h.c.} + \nu_R^T M_R \nu_R + \nu_L^T \frac{\lambda}{M_L} \nu_L H H$$

Dirac
$m_D = hv$
$v = \langle 0|H|0\rangle$

Majorana

$$m = \frac{\lambda v^2}{M_L}$$

More general see-saw mechanism:

	ν_L	ν_R
ν_L	$\lambda v^2/M_L$	m_D
ν_R	m_D	M_R

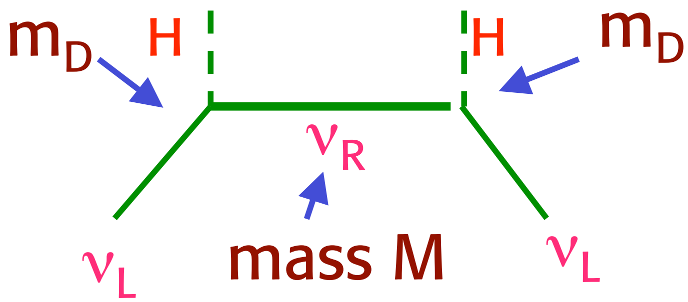
$$m_{light} \sim \frac{m_D^2}{M_R} \quad \text{and/or} \quad \frac{\lambda v^2}{M_L}$$

$m_{heavy} \sim M_R$

$m_{eff} = \nu^T{}_L m_{light} \nu_L$

Neutrinos are (probably) Majorana particles: $\nu_L^T m_\nu \nu_L$

See-saw

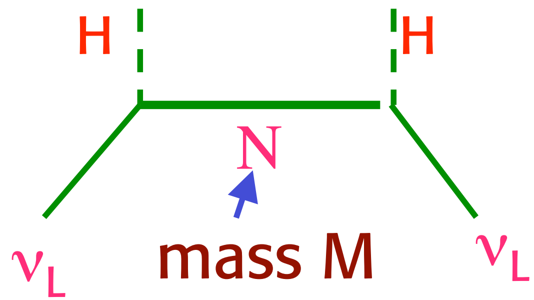


$m_\nu = m_D^T M^{-1} m_D$

connection with m_D

More in general: non ren. O_5 operator $O_5 = \lambda/M \; L^T H H^T L$

e.g from



N: new particle I_w=0,1

Whatever the underlying dynamics O_5 is a more general effective description of light Majorana neutrino masses

ν oscillations point to very large values of M

A very natural and appealing explanation:

ν's are nearly massless because they are Majorana particles and get masses through L non conserving interactions suppressed by a large scale $M \sim M_{GUT}$

$$m_\nu \sim \frac{m^2}{M}$$

$m: \leq m_t \sim v \sim 200$ GeV

M: scale of L non cons.

Note:

$m_\nu \sim (\Delta m^2_{atm})^{1/2} \sim 0.05$ eV

$m \sim v \sim 200$ GeV

$M \sim 10^{15}$ GeV

Neutrino masses are a probe of physics at M_{GUT} !

The current experimental situation is still unclear

- LSND: true or false? -> MiniBooNE soon will tell
- what is the absolute scale of ν masses?
- no detection of $0\nu\beta\beta$ (proof that ν's are Majorana) ••••••

Different classes of models are still possible:

If LSND true

sterile ν(s)??

CPT violat'n??

"3-1" or "3-n"

$m^2 \sim 1\text{-}2\ eV^2$

$\nu_{sterile}$

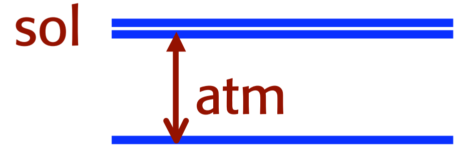
If LSND false → 3 light ν's are OK

We assume this case here

- Degenerate ($m^2 >> \Delta m^2$)

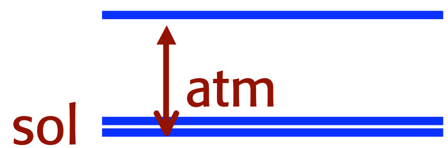
$m^2 < o(1) eV^2$

- Inverse hierarchy



$m^2 \sim 10^{-3}\ eV^2$

- Normal hierarchy

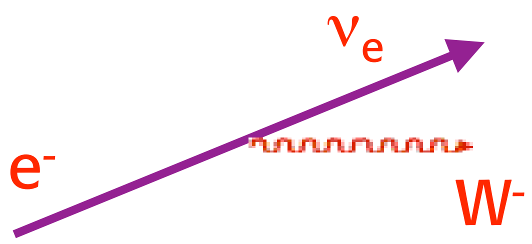


$m^2 \sim 10^{-3}\ eV^2$

3-ν Models

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

flavour mass



$U = U_{P\text{-}MNS}$

Pontecorvo
Maki, Nakagawa, Sakata

In basis where e^-, μ^-, τ^- are diagonal:

δ: CP violation

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

s = solar: large

CHOOZ: $|s_{13}| <\sim 0.2$

$$\sim \begin{bmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ \cdots & \cdots & c_{13}s_{23} \\ \cdots & \cdots & c_{13}c_{23} \end{bmatrix}$$

atm.: ~ max

$$U \simeq \begin{bmatrix} c & -s & 0 \\ \frac{s}{\sqrt{2}} & \frac{c}{\sqrt{2}} & \frac{-1}{\sqrt{2}} \\ \frac{s}{\sqrt{2}} & \frac{c}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}$$

(some signs are conventional)

In general: $U = U^+_e U_\nu$

$$m_\nu \sim U^* \begin{pmatrix} e^{i\alpha_1} m_1 & 0 & 0 \\ 0 & e^{i\alpha_2} m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix} U^+$$

$L^T m_\nu L$

In general 9 parameters:
3 masses, 3 angles,
3 phases

For $s_{13} \sim 0$: $0\nu\beta\beta$

$$m_\nu \sim \begin{pmatrix} m_1c^2+m_2s^2 & (m_1-m_2)cs/\sqrt{2} & (m_1-m_2)cs/\sqrt{2} \\ \ldots & (m_1s^2+m_2c^2+m_3)/2 & (m_1s^2+m_2c^2-m_3)/2 \\ \ldots & \ldots & (m_1s^2+m_2c^2+m_3)/2 \end{pmatrix}$$

Note:
- m_ν is symmetric
- phases included in m_i

Relation between masses and frequencies:

$P(\nu_e \leftrightarrow \nu_\mu) = P(\nu_e \leftrightarrow \nu_\tau) = 1/2 \sin^2 2\theta_{12} \cdot \sin^2\Delta_{sun}$
$P(\nu_\mu \leftrightarrow \nu_\tau) = \sin^2\Delta_{atm} - 1/4 \sin^2 2\theta_{12} \cdot \sin^2\Delta_{sun}$

$$\Delta_{sun} = \frac{m_2^2 - m_1^2}{4E} L \quad ; \quad \Delta_{atm} = \frac{m_3^2 - m_{1,2}^2}{4E} L$$

In our def.: $\Delta_{sun} > 0$, $\Delta_{atm} >$ or < 0

Defining:

$$\Delta m^2_{atm} = m_3^2 - m_2^2 > \text{or} < 0$$

$$\Delta m^2_{sol} = m_2^2 - m_1^2 > 0$$

one has:

$$m_3^2 = \overline{m^2} + \frac{2}{3}\Delta m^2_{atm} + \frac{1}{3}\Delta m^2_{sol}$$

$$m_2^2 = \overline{m^2} - \frac{1}{3}\Delta m^2_{atm} + \frac{1}{3}\Delta m^2_{sol}$$

$$m_1^2 = \overline{m^2} - \frac{1}{3}\Delta m^2_{atm} - \frac{2}{3}\Delta m^2_{sol}$$

and

$$\overline{m^2} >> \left|\Delta m^2_{atm}\right| > \Delta m^2_{sol} \qquad \text{degenerate}$$

$$\Delta m^2_{atm} < 0 \qquad \text{inverse hierarchy}$$

$$\Delta m^2_{atm} > 0 \qquad \text{normal hierarchy}$$

Parameters in the lepton sector

Romanino

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

$$(0 \le \theta_{12}, \theta_{23}, \theta_{13} \le \pi/2, \quad 0 \le \delta \le 2\pi)$$

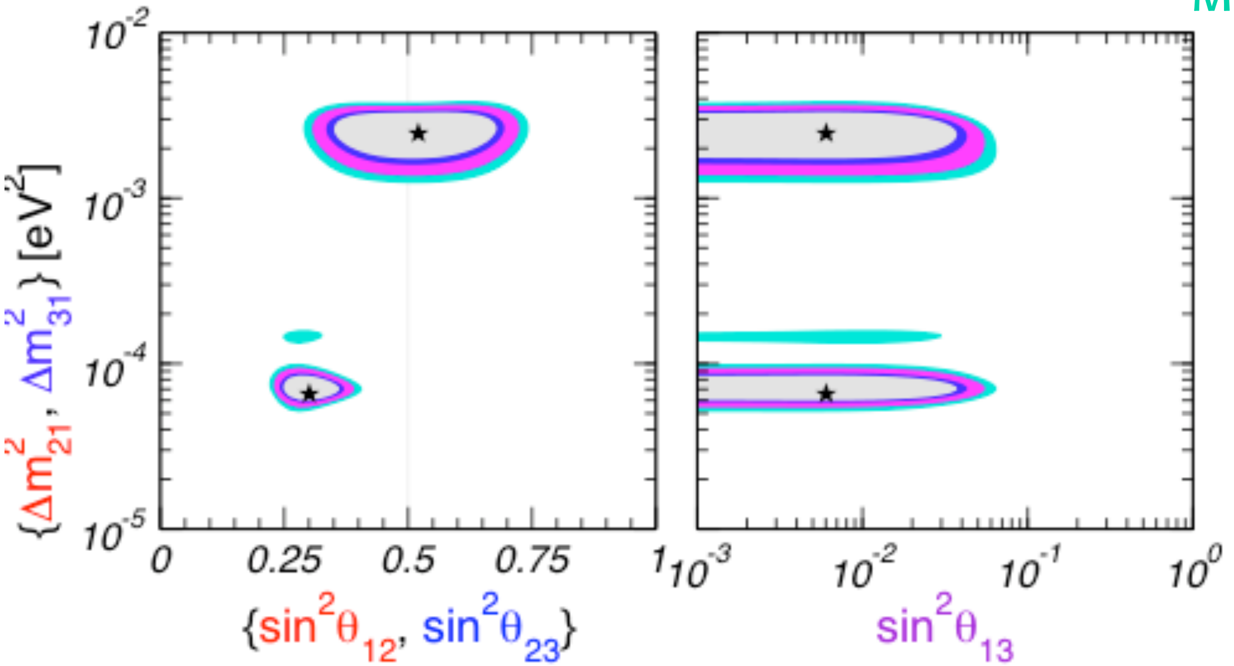
	Δm^2_{21}	m_{lightest}
$m_{e,\mu,\tau}$	$\lvert \Delta m^2_{32} \rvert$	α
	$\text{sign}(\Delta m^2_{32})$	β
	$\theta_{12}, \theta_{23}, \theta_{13}, \delta$	

Neutrino oscillation parameters

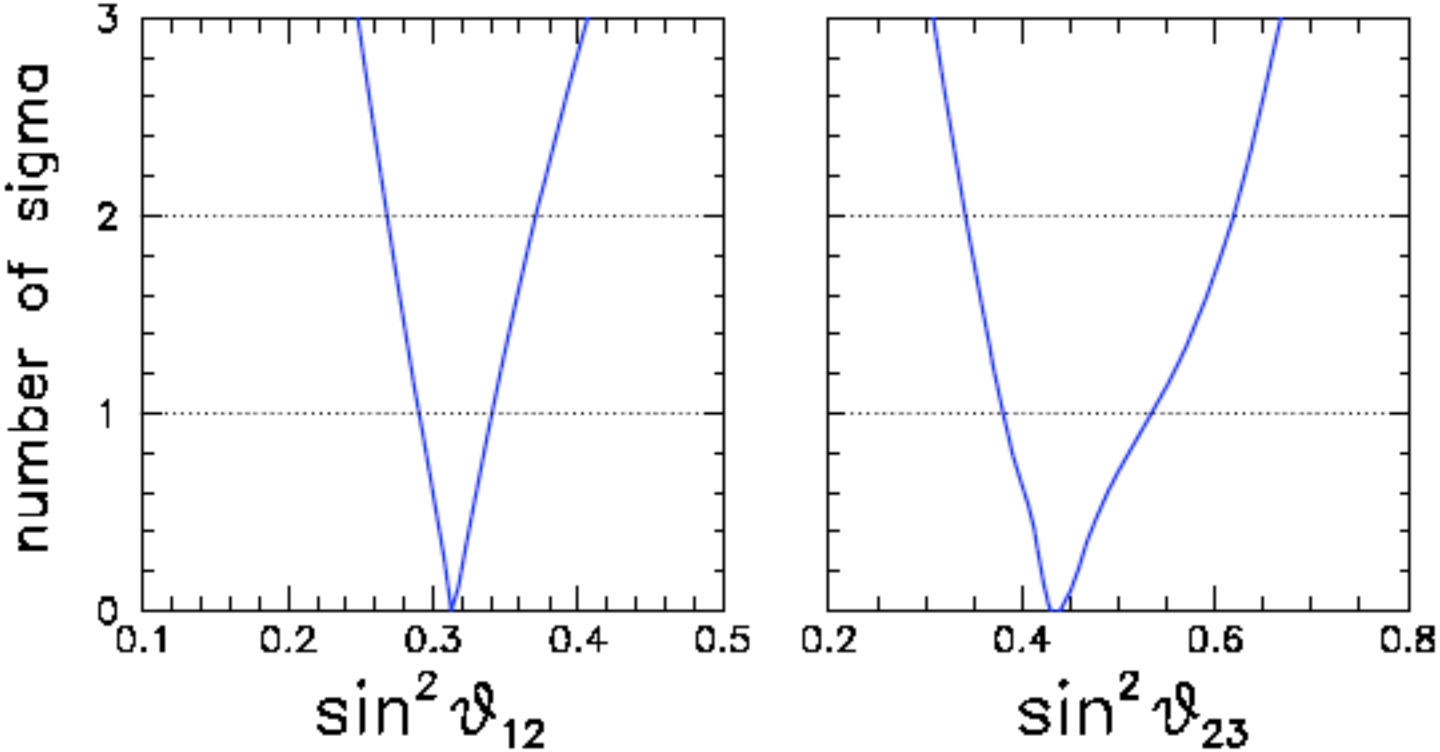
- 2 distinct frequencies
- 2 large angles, 1 small

parameter	best fit	2σ	3σ	5σ
Δm^2_{21} $[10^{-5}\text{eV}^2]$	6.9	6.0–8.4	5.4–9.5	2.1–28
Δm^2_{31} $[10^{-3}\text{eV}^2]$	2.6	1.8–3.3	1.4–3.7	0.77–4.8
$\sin^2\theta_{12}$	0.30	0.25–0.36	0.23–0.39	0.17–0.48
$\sin^2\theta_{23}$	0.52	0.36–0.67	0.31–0.72	0.22–0.81
$\sin^2\theta_{13}$	0.006	$\lesssim 0.035$	$\lesssim 0.054$	$\lesssim 0.11$

Maltoni et al ‘04



Fogli et al '05



$$\delta m^2 = 7.92\,(1^{+0.09}_{-0.09}) \times 10^{-5}\ \mathrm{eV}^2$$

$$\Delta m^2 = 2.4\,(1^{+0.21}_{-0.26}) \times 10^{-3}\ \mathrm{eV}^2$$

$$\sin^2\theta_{12} = 0.314\,(1^{+0.18}_{-0.15})$$

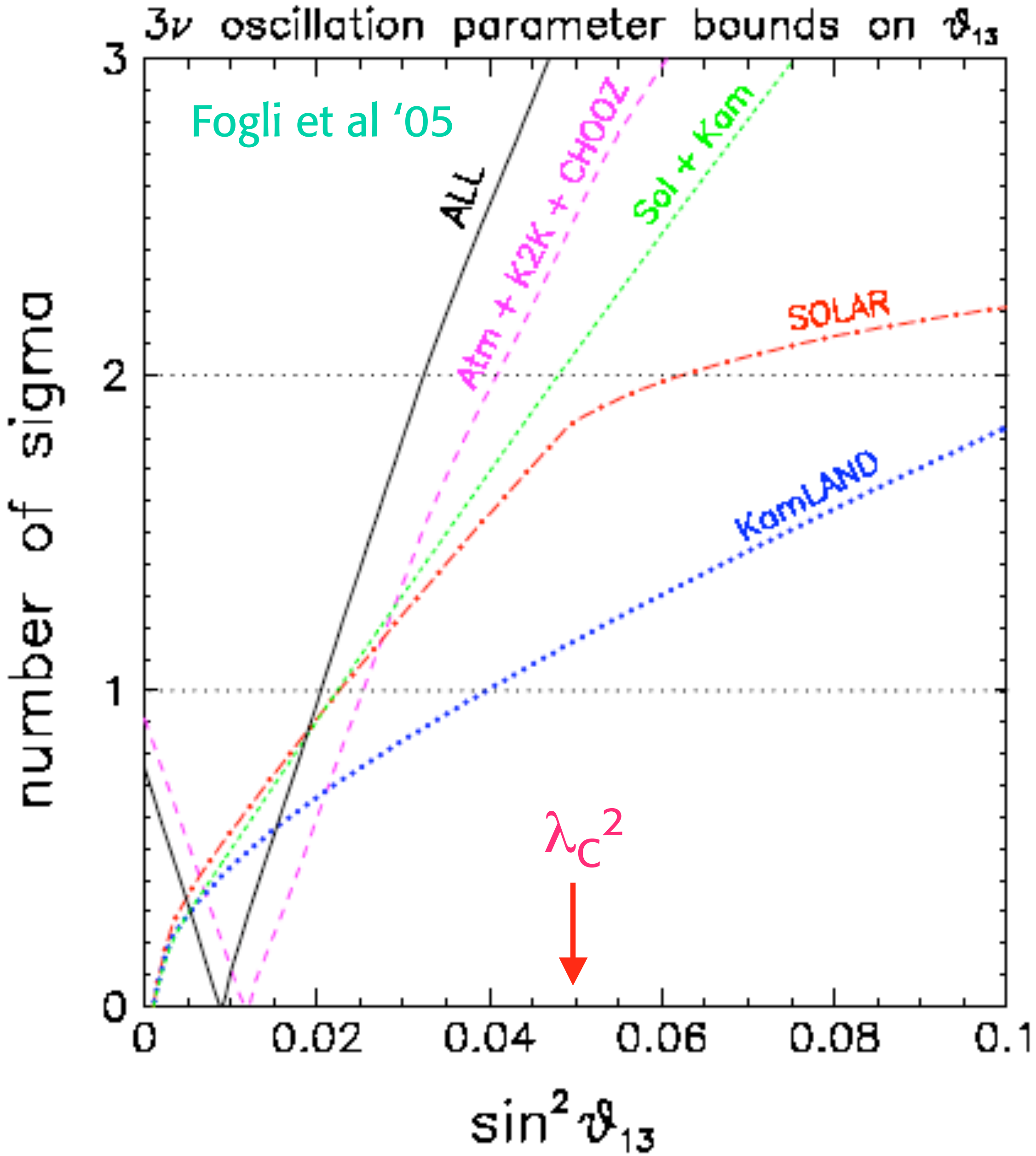
$$\sin^2\theta_{23} = 0.44\,(1^{+0.41}_{-0.22})$$

$$\sin^2\theta_{13} < 3.2 \times 10^{-2}$$

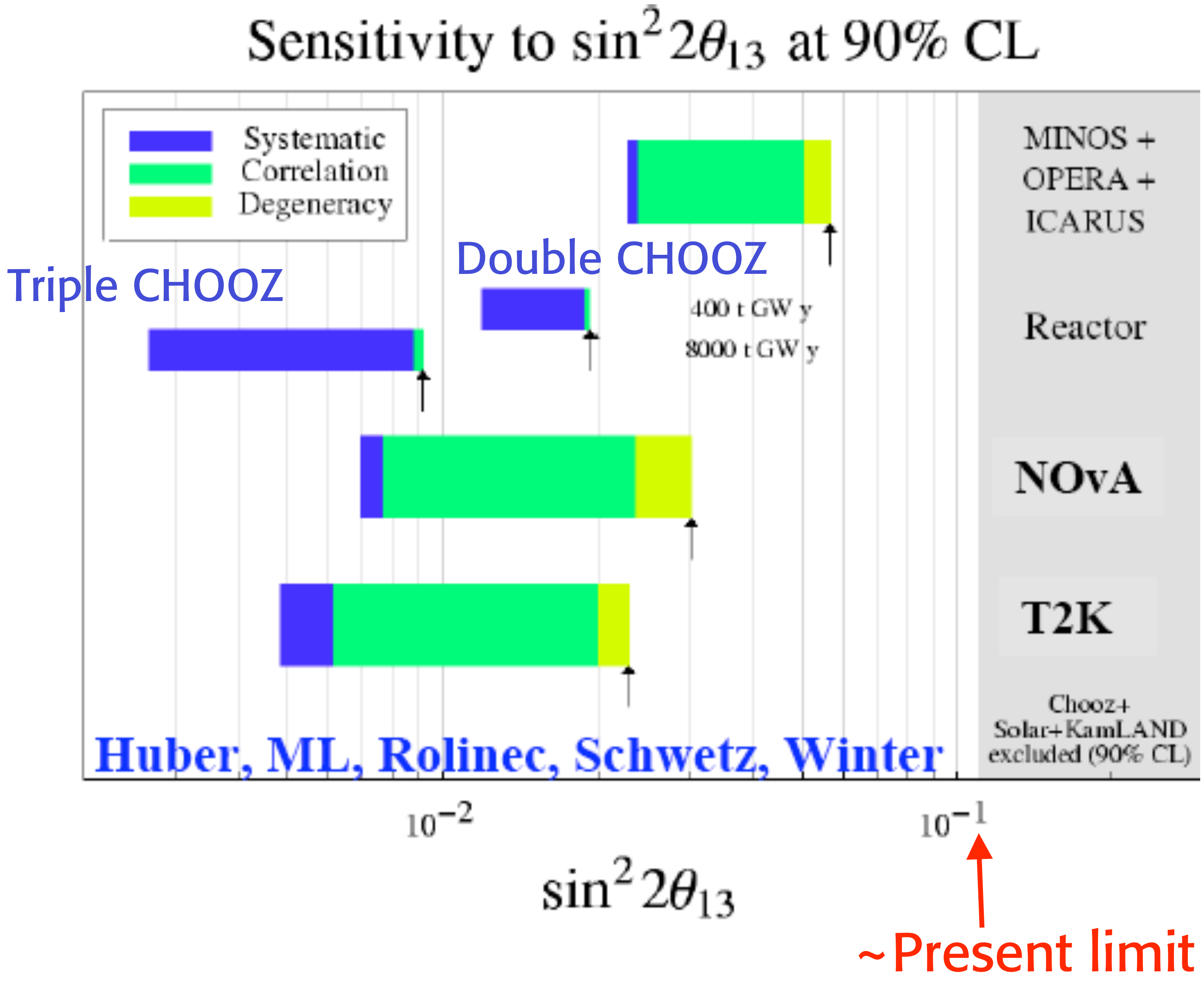
2σ ranges 95%

very precise (KamLAND)
very close to 1/3

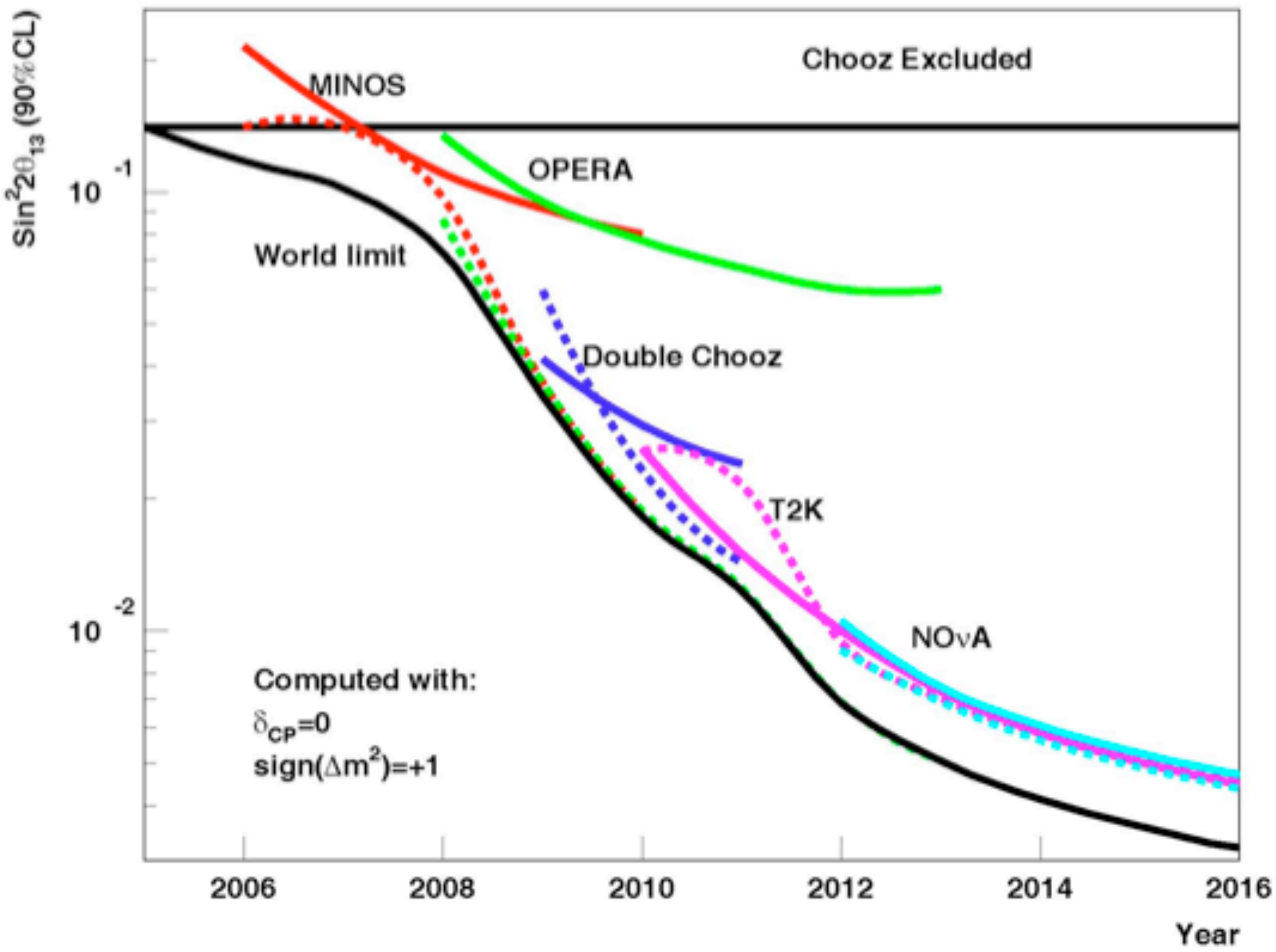
θ_{13} bounds



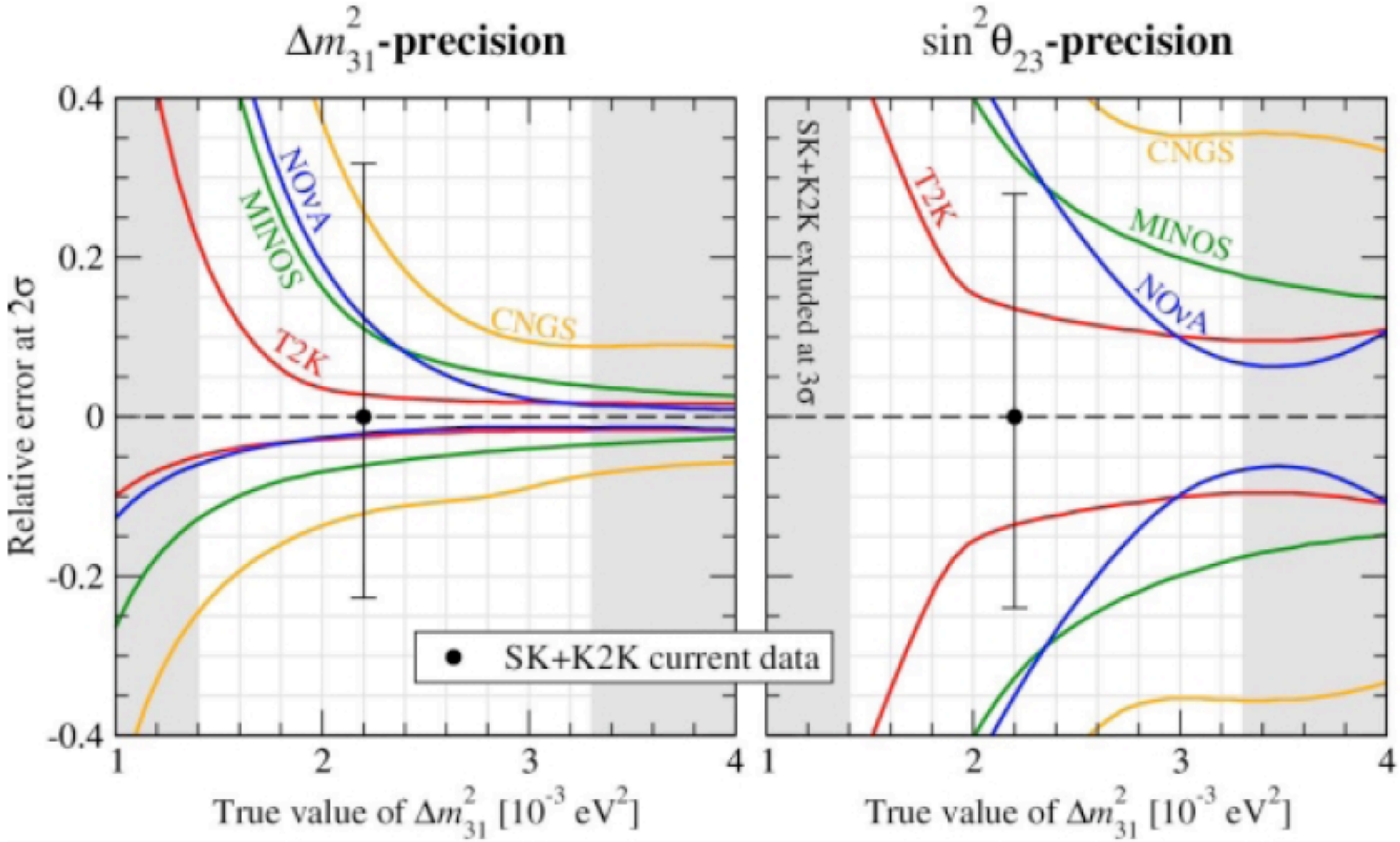
Measuring θ_{13} is crucial for future ν-oscill's experiments (eg CP violation)



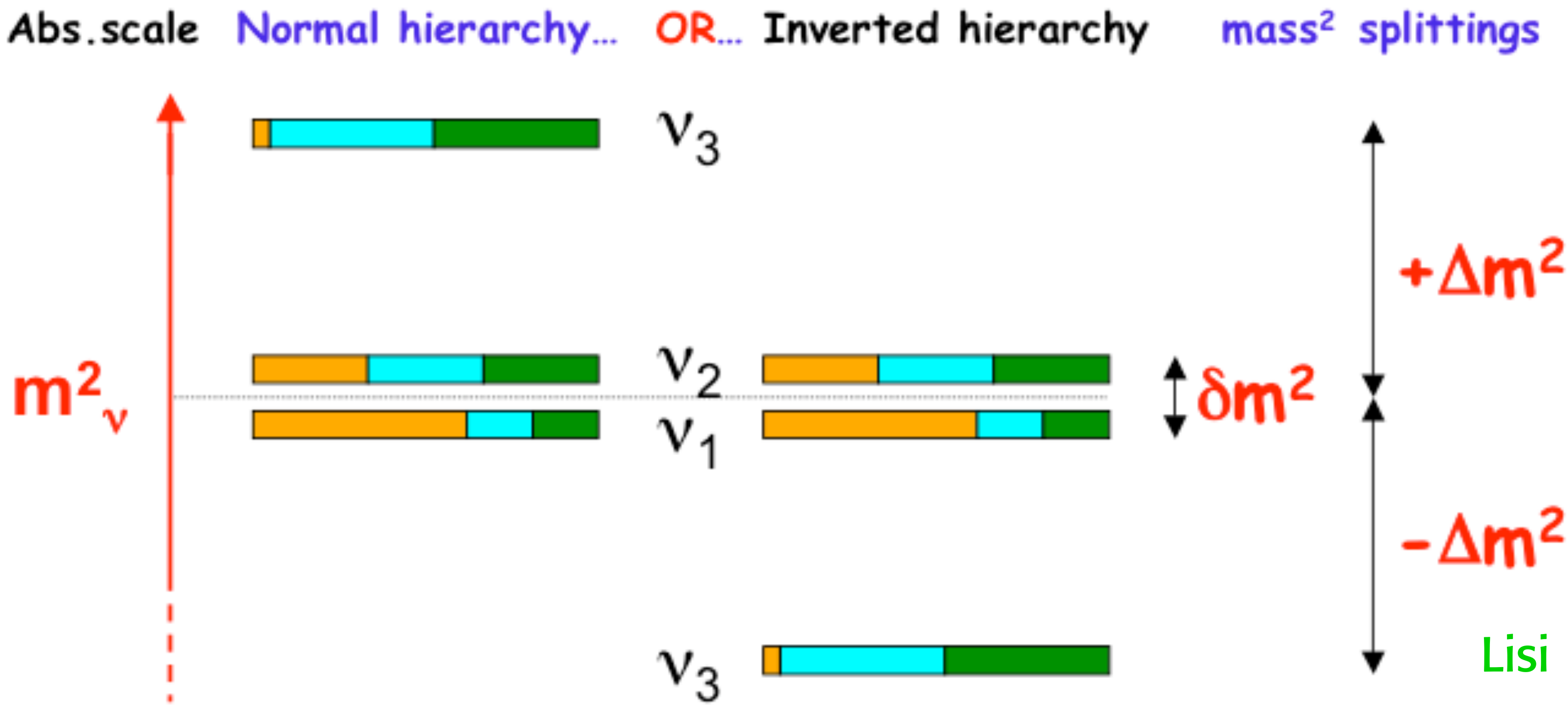
A possible time map for $\sin^2 2\theta_{13}$



Improvement of Δm^2_{31} and $\sin^2\theta_{23}$



Lindner



$\delta m^2 \sim 8 \times 10^{-5}\ \mathrm{eV}^2$

$\Delta m^2 \sim 3 \times 10^{-3}\ \mathrm{eV}^2$

$\sin^2\theta_{12} \sim 0.3$

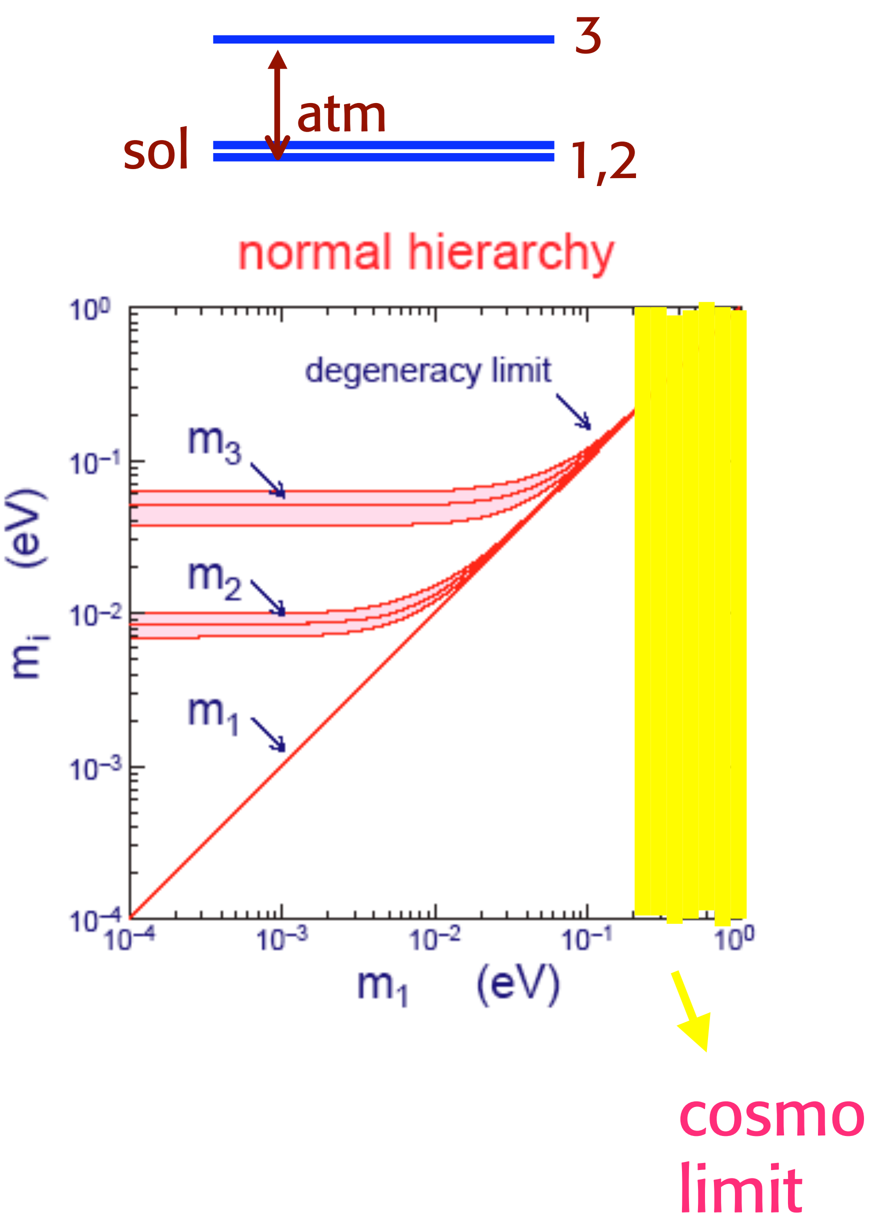
$\sin^2\theta_{23} \sim 0.5$

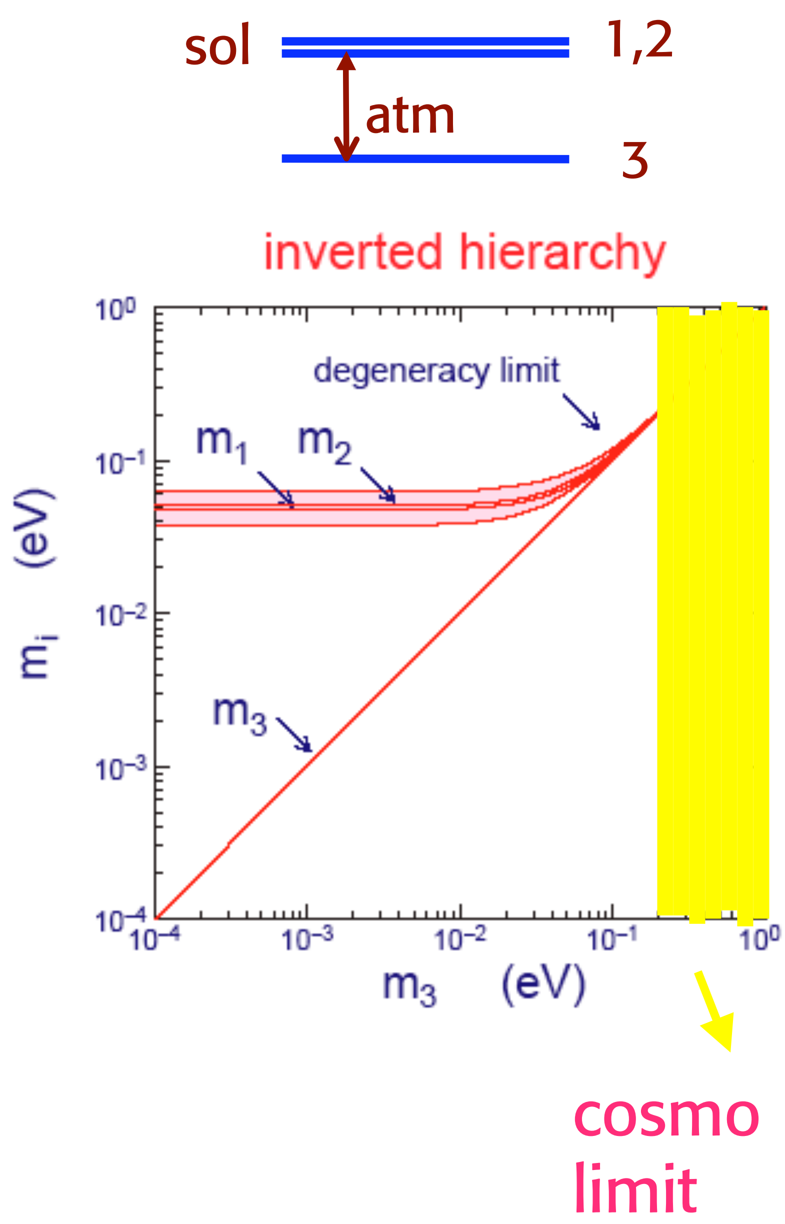
$m_\nu < O(1)\ \mathrm{eV}$

$\sin^2\theta_{13} <$ few%

sign($\pm\Delta m^2$) unknown

δ (CP) unknown





Only moderate degeneracy allowed

$0\nu\beta\beta$ would prove that L is not conserved and ν's are Majorana
Also can tell degenerate, inverted or normal hierarchy

$|m_{ee}| = c_{13}^2\,[m_1 c_{12}^2 + e^{i\alpha} m_2 s_{12}^2] + m_3 e^{i\beta} s_{13}^2$

Degenerate: $\sim |m||c_{12}^2 + e^{i\alpha} s_{12}^2| \sim |m|(0.3\text{-}1)$

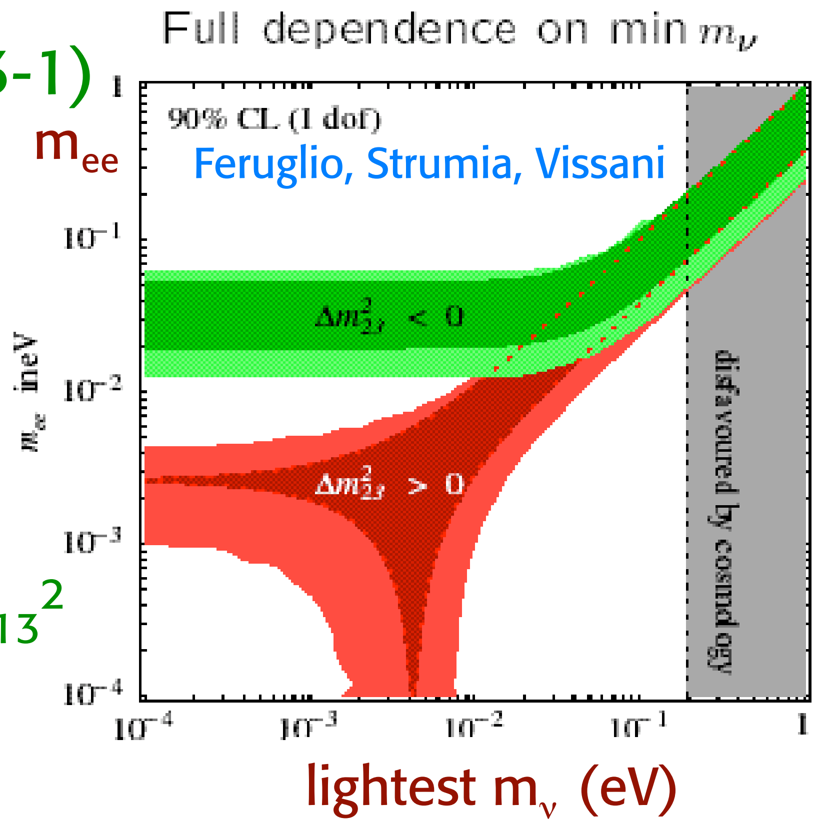
$|m_{ee}| \sim |m|\ (0.3\ \text{-}1) \leq< 0.23\text{-}1$ eV

IH: $\sim (\Delta m^2_{atm})^{1/2} |c_{12}^2 + e^{i\alpha} s_{12}^2|$

$|m_{ee}| \sim (1.6\text{-}5)\ 10^{-2}$ eV

NH: $\sim (\Delta m^2_{sol})^{1/2} s_{12}^2 + (\Delta m^2_{atm})^{1/2} e^{i\beta} s_{13}^2$

$|m_{ee}| \sim$ (few) 10^{-3} eV



Present exp. limit: $m_{ee} < 0.3\text{-}0.5$ eV
(and a hint of signal????? Klapdor Kleingrothaus)

A most attractive possibility:

BG via Leptogenesis near the GUT scale

$T \sim 10^{12\pm3}$ GeV (after inflation)

Buchmuller,Yanagida, Plumacher, Ellis, Lola, Giudice et al, Fujii et al .....

Only survives if $\Delta(B\text{-}L)\neq$is not zero

(otherwise is washed out at T_{ew} by instantons)

Main candidate: decay of lightest ν_R ($M \sim 10^{12}$ GeV)

L non conserv. in ν_R out-of-equilibrium decay:

B-L excess survives at T_{ew} and gives the obs. B asymmetry.

Quantitative studies confirm that the range of m_i from ν oscill's is compatible with BG via (thermal) LG

In particular the bound was derived for hierarchy

$m_i < 10^{-1}$ eV

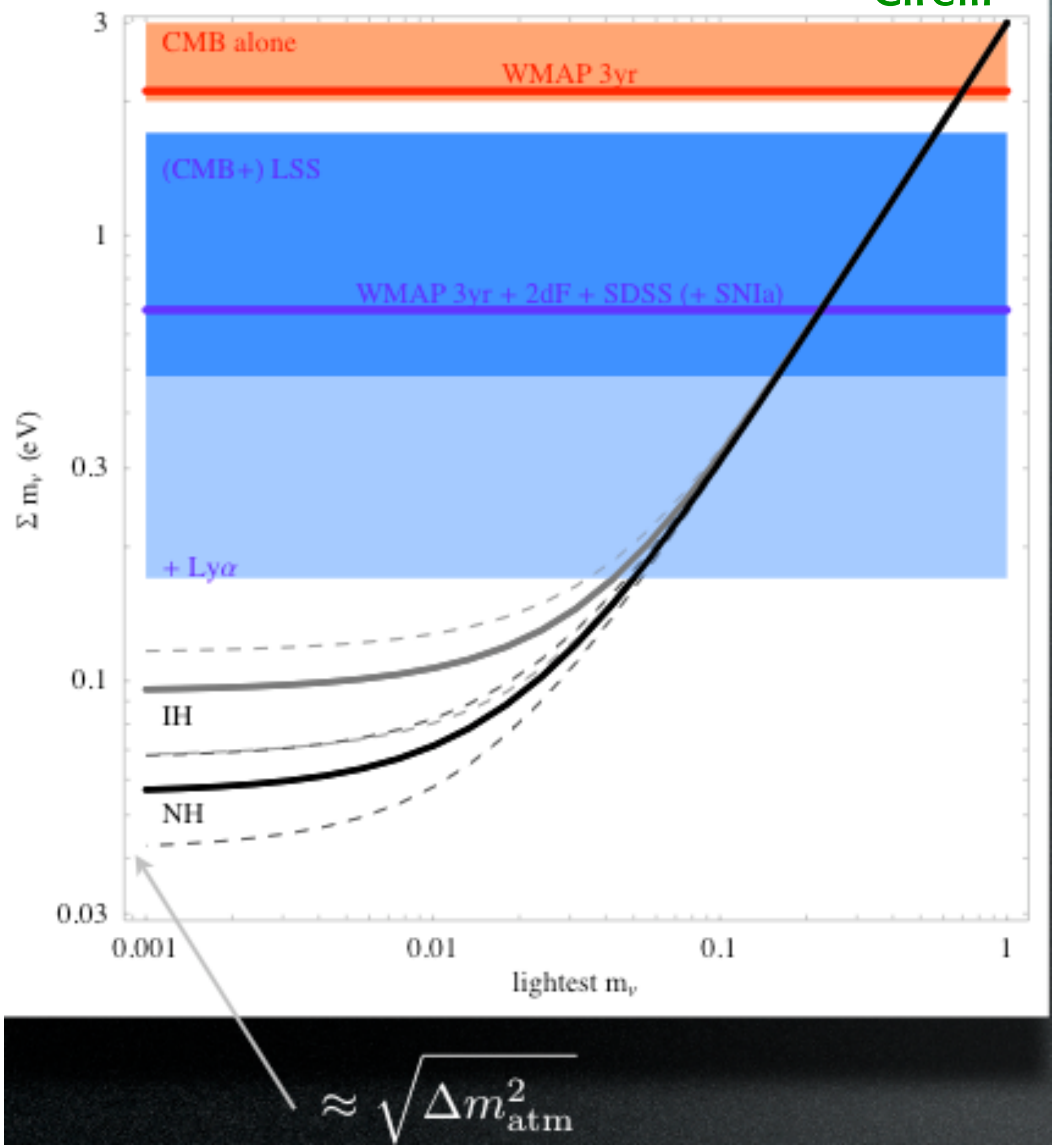
Buchmuller, Di Bari, Plumacher; Giudice et al; Pilaftsis et al; Hambye et al

Can be relaxed for degenerate neutrinos

So fully compatible with oscill'n data!!

Summary

Cirelli



Model building

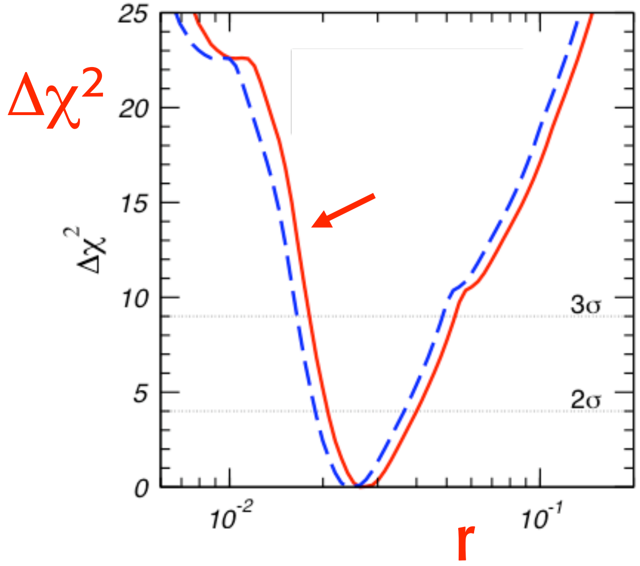
Quality factors for models:

- Based on the most general lagrangian compatible with some simple symmetry or dynamical principle
- Should be complete: address at least charged leptons and neutrinos ($U_{P\text{-}NMS} = U^{+}_{e} U_{\nu}$, and the gauge symmetry connects ch. leptons and LH neutrinos)
- As many as possible small parameters (masses and mixings) should be naturally explained as a consequence.
- The necessary vev configuration should be a minimum of the most general potential for a region of parameter space
- The stability under radiative corrections and higher dim operators must be checked
- Simplicity, economy of fields and parameters, predictivity

General remarks

- After KamLAND, SNO and WMAP.... not too much hierarchy is needed for ν masses:

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



Precisely at 2σ: $0.025 < r < 0.049$

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: $\lambda_C \approx 0.22$ or $\sqrt{\frac{m_\mu}{m_\tau}} \approx 0.24$

Suggests the same "hierarchy" parameters for q, l, ν

$\longrightarrow$ e.g. θ_{13} not too small!

- Still large space for non maximal 23 mixing

2-σ interval $0.32 < \sin^2\theta_{23} < 0.62$

Maximal θ_{23} theoretically hard

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

Very small θ_{13} theoretically hard

"Normal" models: θ_{23} large but not maximal,
θ_{13} not too small (θ_{13} of order λ_C or $\lambda_C{}^2$)

"Exceptional" models: θ_{23} very close to maximal and/or θ_{13} very small
or: a special value for θ_{12}....

Natural models of the "normal" type are not too difficult to build up

It is reasonable to attribute hierarchies in masses and mixings to differences in some flavour quantum number(s).

A simplest flavour (or horizontal) symmetry is $U(1)_F$

For example, some simple models based on see-saw and $U(1)_F$ work for all quark and lepton masses and mixings, are natural and compatible with (SUSY) GUT's, e.g SU(5)x$U(1)_F$.

Larger flavour symmetry groups have been studied.
They are more predictive but less flexible.
The problem of the "best" flavour group is still open.

The most ambitious models try to combine (SUSY) SO(10) GUT's with a suitable flavour group

Hierarchy for masses and mixings via horizontal $U(1)_F$ charges.

Froggatt, Nielsen '79

Principle: A generic mass term

$\bar{R}_1 m_{12} L_2 H$

is forbidden by U(1)

if $q_1+q_2+q_H$ not 0

q_1, q_2, q_H:
U(1) charges of
$\bar{R}_1, L_2, H$

U(1) broken by vev of "flavon" field θ with U(1) charge $q_\theta = -1$.
If vev $\theta = w$, and $w/M = \lambda$ we get for a generic interaction:

Δ_{charge}

$\bar{R}_1 m_{12} L_2 H \; (\theta/M)^{q1+q2+qH}$ $\quad m_{12} \rightarrow m_{12}\, \lambda^{q1+q2+qH}$

Hierarchy: More Δ_{charge} -> more suppression (λ small)

One can have more flavons (λ, λ', ...)
with different charges (>0 or <0) etc -> many versions