neutrino oscillations and the problem of neutrino masses a status report

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Plan

1. Recent issues in neutrino physics
-- active neutrinos [see Fogli's talk]
-- sterile neutrinos

2. Theoretical framework for neutrino masses
-- purely Dirac neutrino masses
-- neutrino masses from D=5 operator
-- the see-saw mechanism
-- tests of D=5 operator

some conservative possibilities

3. Flavour symmetries
-- any pattern behind data?
-- natural setup for a KeV WDM ν candidate

very speculative territory

Part 1.
recent issues in neutrino physics

2011/2012 breakthrough

-- LBL experiments searching for $\nu_\mu \to \nu_e$ conversion [see Fogli's talk]
-- SBL reactor experiments searching for anti-ν_e disappearance

	Lisi [NeuTel 2013]	[1209.3023] [G-Garcia, Maltoni, Salvado, Schwetz]
$\sin^2\vartheta_{13}$	$0.0241^{+0.0025}_{-0.0025}\ (NO)$ $0.0244^{+0.0023}_{-0.0025}\ (IO)$	$0.0227^{+0.0023}_{-0.0024}$
$\sin^2\vartheta_{23}$	$0.386^{+0.024}_{-0.021}\ (NO)$ $0.392^{+0.039}_{-0.022}\ (IO)$	$0.413^{+0.037}_{-0.025} \oplus 0.594^{+0.021}_{-0.022}$

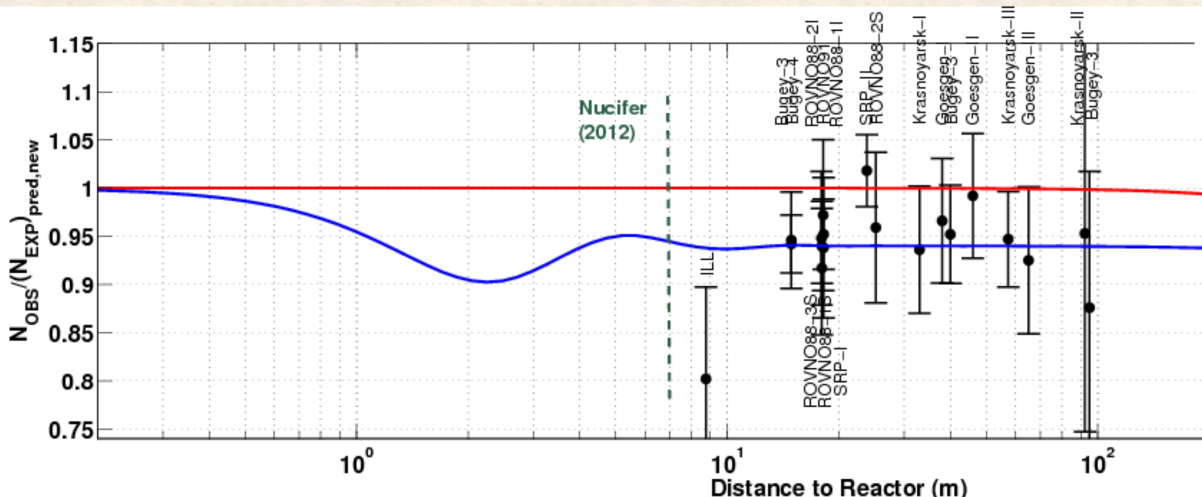
→ 10σ away from 0 — impact on flavor symmetry (part 3)

→ hint for non maximal ϑ_{23}

sterile neutrinos coming back

1 reactor anomaly (anti-ν_e disappearance)

re-evaluation of reactor anti-ν_e flux: new estimate 3.5% higher than old one



$$(\Phi_{exp} - \Phi_{th})/\Phi_{th} \approx -6\%$$

[th. uncertainty?]

very SBL L ≲ 100 m

$$\vartheta_{es} \approx 0.2$$

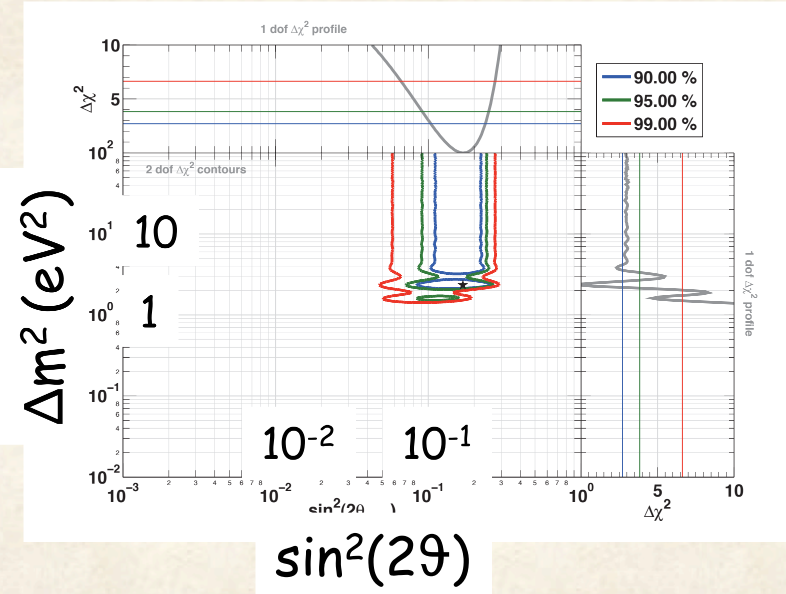
$$\Delta m^2 \approx m_s^2 \geq 1\,eV^2$$

supported by the Gallium anomaly

ν_e flux measured from high intensity radioactive sources in Gallex, Sage exp

$$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$$

[error on σ or on Ge extraction efficiency]



most recent cosmological limits

[depending on assumed cosmological model, data set included,...]

relativistic degrees of freedom at recombination epoch

$$N_{eff} = 3.30 \pm 0.27$$

[Planck, WMAP, BAO, high multiple CMB data]

fully thermalized non relativistic ν

$$N_{eff} < 3.80 \quad (95\%\ CL)$$

$$m_s < 0.42\, eV \quad (95\%\ CL)$$

2 long-standing claim

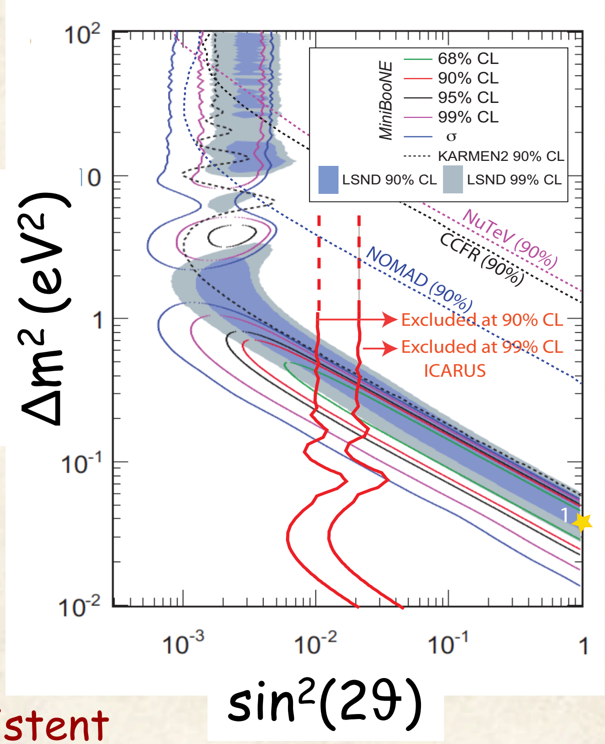
evidence for $\nu_\mu \to \nu_e$ appearance in accelerator experiments

exp		$E(MeV)$	$L(m)$	
LSND	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	$10 \div 50$	30	3.8σ
MiniBoone	$\nu_\mu \rightarrow \nu_e$ $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	$300 \div 3000$	541	3.8σ [signal from low-energy region]

parameter space limited by negative results from Karmen and ICARUS

$$\vartheta_{e\mu} \approx 0.035$$

$$\Delta m^2 \approx 0.5\, eV^2$$

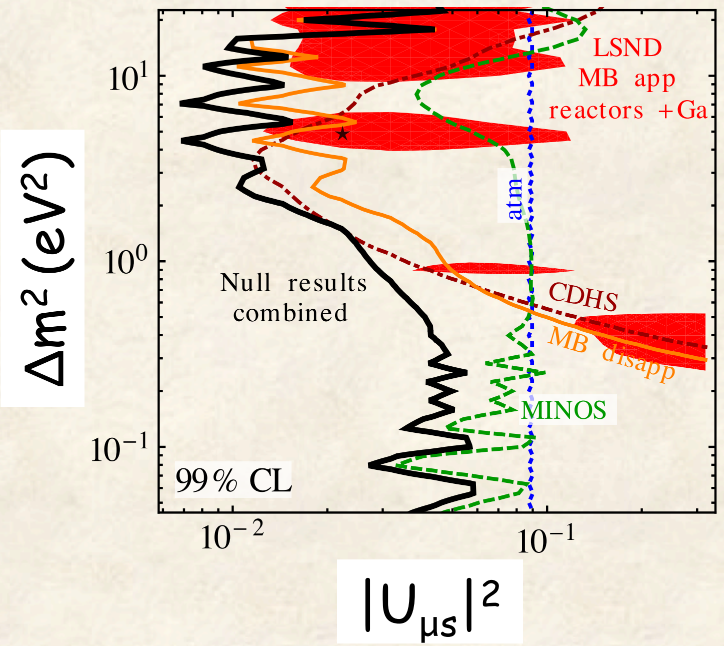


3 interpretation in 3+1 scheme: inconsistent (more than 1s disfavored by cosmology)

$$\underbrace{\vartheta_{e\mu}}_{0.035} \approx \underbrace{\vartheta_{es}}_{0.2} \times \vartheta_{\mu s} \quad \Rightarrow \quad \vartheta_{\mu s} \approx 0.2$$

predicted suppression in ν_μ disappearance experiments: undetected

by ignoring LSND/Miniboone data the reactor anomaly can be accommodated by $m_s \geq 1$ eV and $\vartheta_{es} \approx 0.2$ [not suitable for WDM, more on this later]

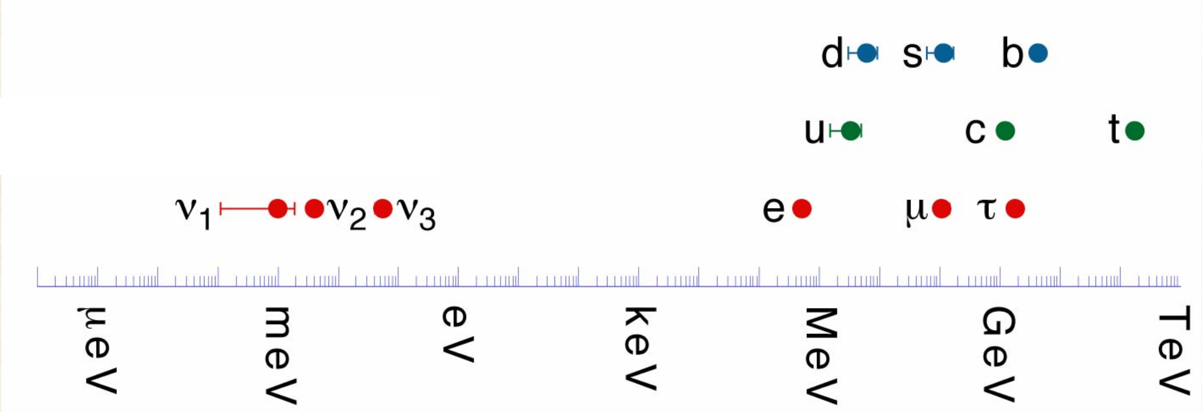


Part 2.
theoretical framework for neutrino masses

a non-vanishing neutrino mass is evidence of the incompleteness of the SM

Questions

- how to extend the SM in order to accommodate neutrino masses?
- why neutrino masses are so small, compared with the charged fermion masses?



- why lepton mixing angles are so different from those of the quark sector?

$$|U_{PMNS}| \approx \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.6 \\ 0.4 & 0.6 & 0.8 \end{pmatrix}$$

$$V_{CKM} \approx \begin{pmatrix} 1 & O(\lambda) & O(\lambda^4 \div \lambda^3) \\ O(\lambda) & 1 & O(\lambda^2) \\ O(\lambda^4 \div \lambda^3) & O(\lambda^2) & 1 \end{pmatrix}$$

$\lambda \approx 0.22$

How to modify the SM?

(I) modify the particle content

Example 1

- add (three copies of) right-handed neutrinos $\nu^c \equiv (1,1,0)$ full singlet under G=SU(3)xSU(2)xU(1)
- ask for (global) invariance under B-L (no more automatically conserved as in the SM)

gauge invariant Yukawa interactions

$$L_Y = d^c y_d (\Phi^+ q) + u^c y_u (\tilde{\Phi}^+ q) + e^c y_e (\Phi^+ l) + \nu^c y_\nu (\tilde{\Phi}^+ l) + h.c.$$

$$m_f = \frac{y_f}{\sqrt{2}} v \qquad f = u,d,e,\nu$$

$$-\frac{g}{\sqrt{2}} W_\mu^- \bar{e} \sigma^\mu U_{PMNS} \nu + h.c.$$

U_{PMNS} has three mixing angles and one phase, like V_{CKM}

a generic problem of this approach

the particle content can be modified in several different ways in order to account for non-vanishing neutrino masses (additional right-handed neutrinos, new SU(2) fermion triplets, additional SU(2) scalar triplet(s), SUSY particles,…). Which is the correct one?

a problem of the above example

if neutrinos are so similar to the other fermions, why are so light?
[right-handed neutrinos have access to an extra spatial dimension?]

$$\frac{y_\nu}{y_{top}} \le 10^{-12}$$

(II) abandon renormalizability

and work with an effective field theory valid up to a cut-off Λ

$$L_{SM} \to L_{SM} + \frac{L_5}{\Lambda} + \frac{L_6}{\Lambda^2} + \ldots$$

$$\frac{L_5}{\Lambda} = \frac{\left(\tilde{\Phi}^+ l\right)\left(\tilde{\Phi}^+ l\right)}{\Lambda} = \frac{v}{2}\left(\frac{v}{\Lambda}\right)\nu\nu + \ldots$$

a unique operator!
[up to flavour combinations]
it violates (B-L) by two units

suppressed by a factor (v/Λ) with respect to the neutrino mass term of Example 1

$$\frac{m_\nu}{m_{top}} \approx 10^{-12}$$

$$\updownarrow$$

$$\Lambda \approx 10^{15}\, GeV$$

L_5 represents the effective, low-energy description of several extensions of the SM

Example 2: see-saw

add (three copies of) $\nu^c \equiv (1,1,0)$

full singlet under G=SU(3)xSU(2)xU(1)

this is like Example 1, but without enforcing (B-L) conservation

$$L(\nu^c, l) = \nu^c y_\nu (\tilde{\Phi}^+ l) + \frac{1}{2}\nu^c M \nu^c + h.c.$$

mass term for right-handed neutrinos: gauge invariant, violates (B-L) by two units.

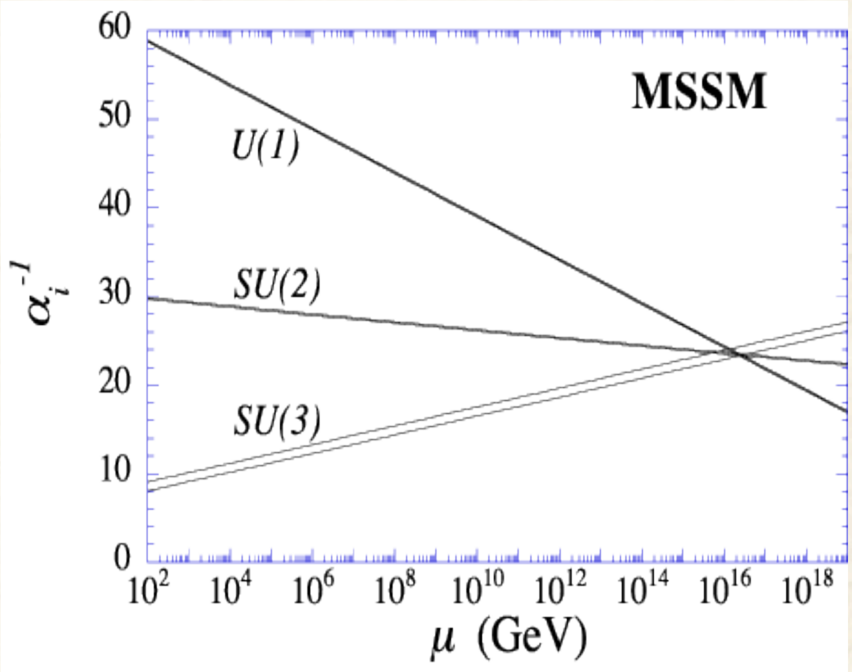
for E<<M

$$L_{eff}(l) = -\frac{1}{2}(\tilde{\Phi}^+ l)\left[y_\nu^T M^{-1} y_\nu\right](\tilde{\Phi}^+ l) + h.c. + \ldots$$

this reproduces L_5, with M playing the role of Λ
(type I) see-saw

Theoretical motivations for the see-saw

- an independent evidence for $\Lambda \approx 10^{15}$ GeV comes from the unification of the gauge coupling constants in (SUSY extensions of) the SM.



such unification is a generic prediction of Grand Unified Theories (GUTs): the SM gauge group G is embedded into a simple group such as SU(5), SO(10),…

Particle classification: it is possible to unify all SM fermions (1 generation) into a single irreducible representation of the GUT gauge group. Simplest example: G_{GUT}=SO(10)

$$16 = (q, d^c, u^c, l, e^c, \nu^c)$$

a whole family plus a right-handed neutrino!

no experimental evidence so far! Look for proton decay (model dependent rates and decay channels)

- 2 additional virtues of the see-saw

the see-saw mechanism can enhance small mixing angles into large ones

the (out-of equilibrium, CP-violating) decay of heavy right-handed neutrinos in the early universe might generate a net asymmetry between leptons and anti-leptons, partially converted into the observed baryon asymmetry

weak point of the see-saw

full high-energy theory is difficult to test

$$L(\nu^c,l)=\nu^c y_\nu(\tilde{\Phi}^+ l)+\frac{1}{2}\nu^c M\nu^c + h.c.$$

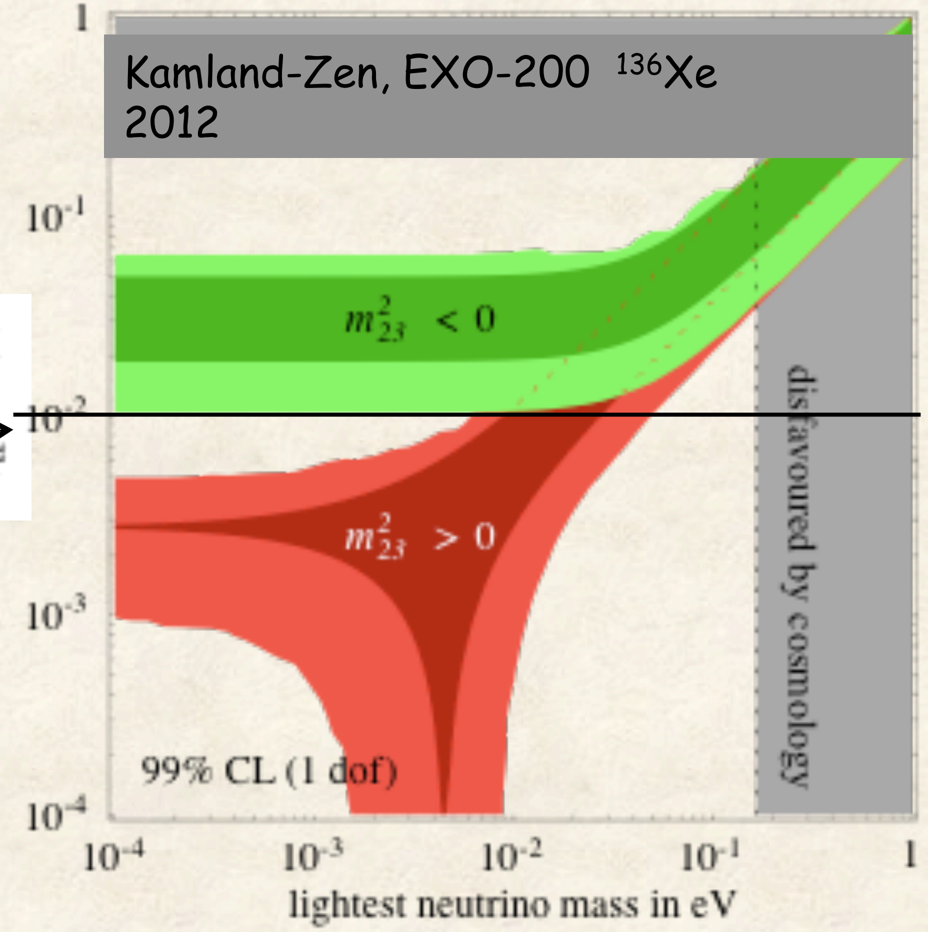
depends on 18 physical parameters, the double of those describing (L_{SM})+L_5:

few observables to pin down the extra parameters: η,... [additional possibilities exist under special conditions, e.g. Lepton Flavor Violation at observable rates]

easier to test the low-energy remnant L_5

[which however is "universal" and does not implies the specific see-saw mechanism of Example 2]

look for a process where B-L is violated by 2 units. The best candidate is 0νββ decay (A,Z)->(A,Z+2)+2e$^-$ this would discriminate L_5 from other possibilities, such as Example 1.



future expected sensitivity on $|m_{ee}|$ is 10 meV

from the current knowledge of $(\Delta m^2_{ij}, \vartheta_{ij})$ we can estimate the expected range of $|m_{ee}|$

part 3.
flavor symmetries

Flavor symmetries

can we constrain Yukawa couplings (and Majorana masses) by some flavour symmetry?

largest possible flavour symmetry is obtained in the limit $y = 0 \quad (M = 0)$

$$G_{MFV} = \begin{cases} SU(3)^5 & \text{SM} \\ SU(3)^6 & \text{SM + 3 } \nu^c \end{cases}$$

observed fermion masses and mixing angles break G_{MFV} completely
(only possible exact symmetry beyond Gauge x Lorentz x CPT is B-L)

flavour symmetry should be spontaneously broken (explicit breaking is not predictive)

$$G_{MFV} \supseteq G_f \to H_f$$

by a set of scalar fields

$\varphi \to \varphi_g$ under G_f

<φ> determined by minimizing an energy functional V(φ) invariant under G_f

$$V(\varphi_g) = V(\varphi)$$

<φ>, absolute minimum of V(φ), breaks G_f down to H_f

Yukawas promoted to dynamical variables

$$y(\varphi / \Lambda_f)$$

observed Yukawa couplings

$$y(<\varphi> / \Lambda_f)$$

huge number of possibilities: choice of G_f (global, local, continuous, discrete,...)
choice of representations for scalars φ and fermions

any empirical evidence for G_f and H_f ?

example I: $G_f = U(1)_{FN}$

[Froggatt,Nielsen 1979]

lessons from the quark sector: mass ratios and mixing angles are small, hierarchical parameters

$$\frac{m_u}{m_t} << \frac{m_c}{m_t} << 1 \qquad \frac{m_d}{m_b} << \frac{m_s}{m_b} << 1 \qquad |V_{ub}| << |V_{cb}| << |V_{us}| \equiv \lambda < 1$$

easily reproduced by $G_f = U(1)_{FN}$ and $H_f = \{1\}$

mass ratios and mixing angles are powers of a small SB parameter λ

flavon	Q_{FN}
φ	-1

$U(1)_{FN}$ broken by

$$\lambda = \frac{<\varphi>}{\Lambda_f} \approx 0.2$$

$$\frac{\varphi^4}{\Lambda_f^4} v\, d^c d$$

assign decreasing, non-negative, charges to fermions of increasing generations

field	Q_{FN}
q, u^c	$(3,2,0)$
d^c	$(1,0,0)$

$$y_d = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 1 \end{pmatrix}$$

unbroken $U(1)_{FN}$

entries up to unknown O(1) coefficients

$$y_d = \begin{pmatrix} \lambda^4 & \lambda^3 & \lambda \\ \lambda^3 & \lambda^2 & 1 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

broken $U(1)_{FN}$

order of magnitude of most mass ratios and mixing angles correctly reproduced can be extended to the lepton sector where evidence for hierarchy mainly comes from charged leptons

field	Q_{FN}
e^c	(3,2,0)
l	(1,0,0)

$$y_e \approx y_d^T$$

$$m_\nu \propto \begin{pmatrix} \lambda^2 & \lambda & \lambda \\ \lambda & 1 & 1 \\ \lambda & 1 & 1 \end{pmatrix}$$

ϑ_{23}	ϑ_{13}	ϑ_{12}	$\Delta m^2_{12} / \Delta m^2_{23}$
1	λ	λ	1
1	λ	1	λ^2

if det(23)≈λ

Anarchy (neutrino sector is structure-less)

[Hall, Murayama, Weiner 1999]

field	Q_{FN}
l	(0,0,0)

$$m_\nu \propto \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

mixing angles and mass ratios are random O(1) quantities

$$|U_{PMNS}| \approx \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.6 \\ 0.4 & 0.6 & 0.8 \end{pmatrix}$$

ϑ_{13} not tiny and ϑ_{23} not maximal predicted consistent with data

$G_f = U(1)_{FN}$

- compatible with SU(5) grand unification
- compatible with known solutions to the gauge hierarchy problem (SUSY, RS,…)
- large number of independent O(1) parameters
- no testable predictions beyond order-of-magnitude accuracy

ν_1^c KeV sterile neutrino as WDM candidate

[reviews by Merle 1302.2615 and Abazajian et al 1204.5186]

two small parameters

$$\underbrace{M_1}_{KeV} \ll \underbrace{M_{2,3}}_{\text{up to } 10^{15}\ GeV}$$

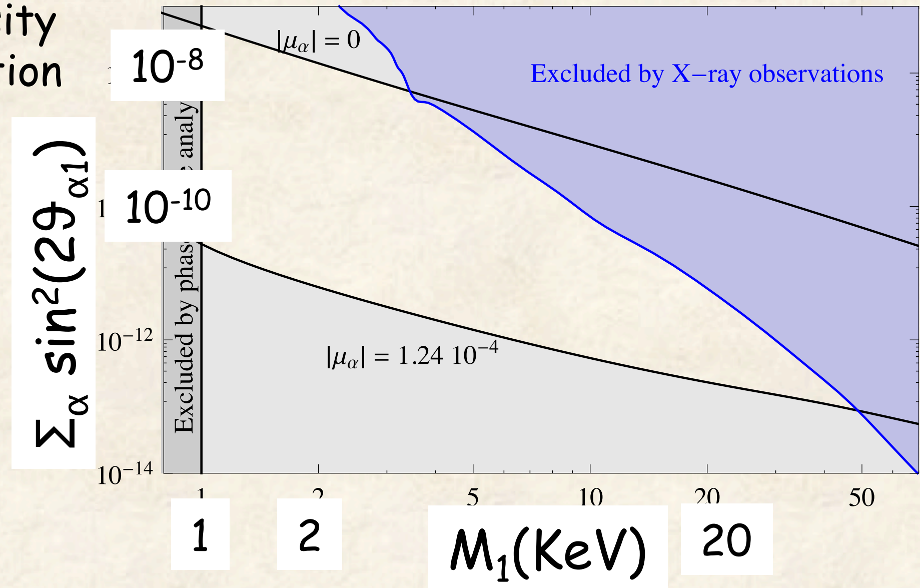
- phase space density
- structure formation

$$\vartheta_1^2 \equiv \sum_\alpha |\vartheta_{1\alpha}|^2 < 10^{-7}$$

active-sterile mixing

- DM-abundance
- X-ray limits
- SN cooling
- $\tau_1 < \tau_U$

[Canetti, Drewes, Frossard, Shaposhnikov 1208.4607]



can both be explained by $U(1)_{FN}$?

field	Q_{FN}
ν^c	$(X,0,0)$
l	$(0,0,0)$

$X \geq 0$

in the unbroken phase:
- $M_1=0$
- ν_1^c decoupled from ν_α

after $U(1)_{FN}$ breaking

$$\xi \equiv \lambda^X$$

$$m_D = \begin{pmatrix} \xi & \xi & \xi \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} m_0 \qquad M = \begin{pmatrix} \xi^2 & \xi & \xi \\ \xi & 1 & 1 \\ \xi & 1 & 1 \end{pmatrix} M_0$$

$$m_i \approx \frac{m_0^2}{M_0} \approx (0.01 \div 0.1)\, eV$$

$$M_1 \approx \xi^2 M_0 \qquad M_{2,3} \approx M_0$$

$$\vartheta_1^2 \approx \frac{m_i}{M_1} \approx (10^{-5} \div 10^{-4}) \left(\frac{1\, KeV}{M_1} \right)$$

not sufficient to match correct DM abundance and X-ray limits

to further suppress ϑ_1^2

- tuning
  stretch unknown O(1) coefficients to produce an extra suppression factor
- additional flavour symmetry
  extra suppression of $m_{1\alpha}$ matrix elements, e.g. by a discrete symmetry

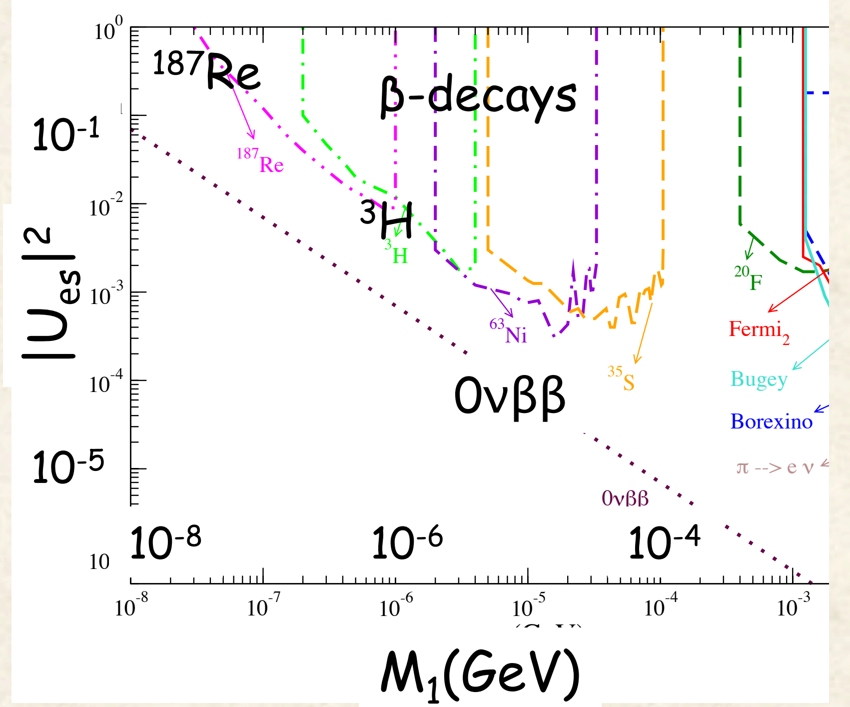
$$Z_2 : \quad \nu_1^c \to -\nu_1^c \qquad \vartheta' \to -\vartheta'$$

$$m_D = \begin{pmatrix} \xi\xi' & \xi\xi' & \xi\xi' \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} m_0 \qquad \xi' \equiv \frac{<\vartheta'>}{\Lambda_f}$$

$$M = \begin{pmatrix} \xi^2 & \xi\xi' & \xi\xi' \\ \xi\xi' & 1 & 1 \\ \xi\xi' & 1 & 1 \end{pmatrix} M_0 \qquad \vartheta_1^2 \approx \xi'^2 \frac{m_i}{M_1}$$

[Merle, Niro 1302.2032
De Vega, Moreno, Moya de Guerra, Ramon Medrano, Sanchez 1109.3452]

lab searches [Abazajian 1204.5186]



example II: G_f = discrete flavor symmetry

$$U_{PMNS} = U^0_{PMNS} + \text{corrections}$$

some simple pattern, exactly reproduced by a flavor symmetry

- well motivated before 2012

$$U^0_{PMNS} = U_{TB} \equiv \begin{pmatrix} 2/\sqrt{6} & 1/\sqrt{3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{3} & -1/\sqrt{2} \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

Tribimaximal Mixing

discrete flavor symmetries showed very efficient to reproduce U^0_{PMNS}

- still justified today?

$$U_{TB} \approx \begin{pmatrix} 0.82 & 0.58 & 0 \\ -0.41 & 0.58 & -0.71 \\ -0.41 & 0.58 & 0.71 \end{pmatrix}$$

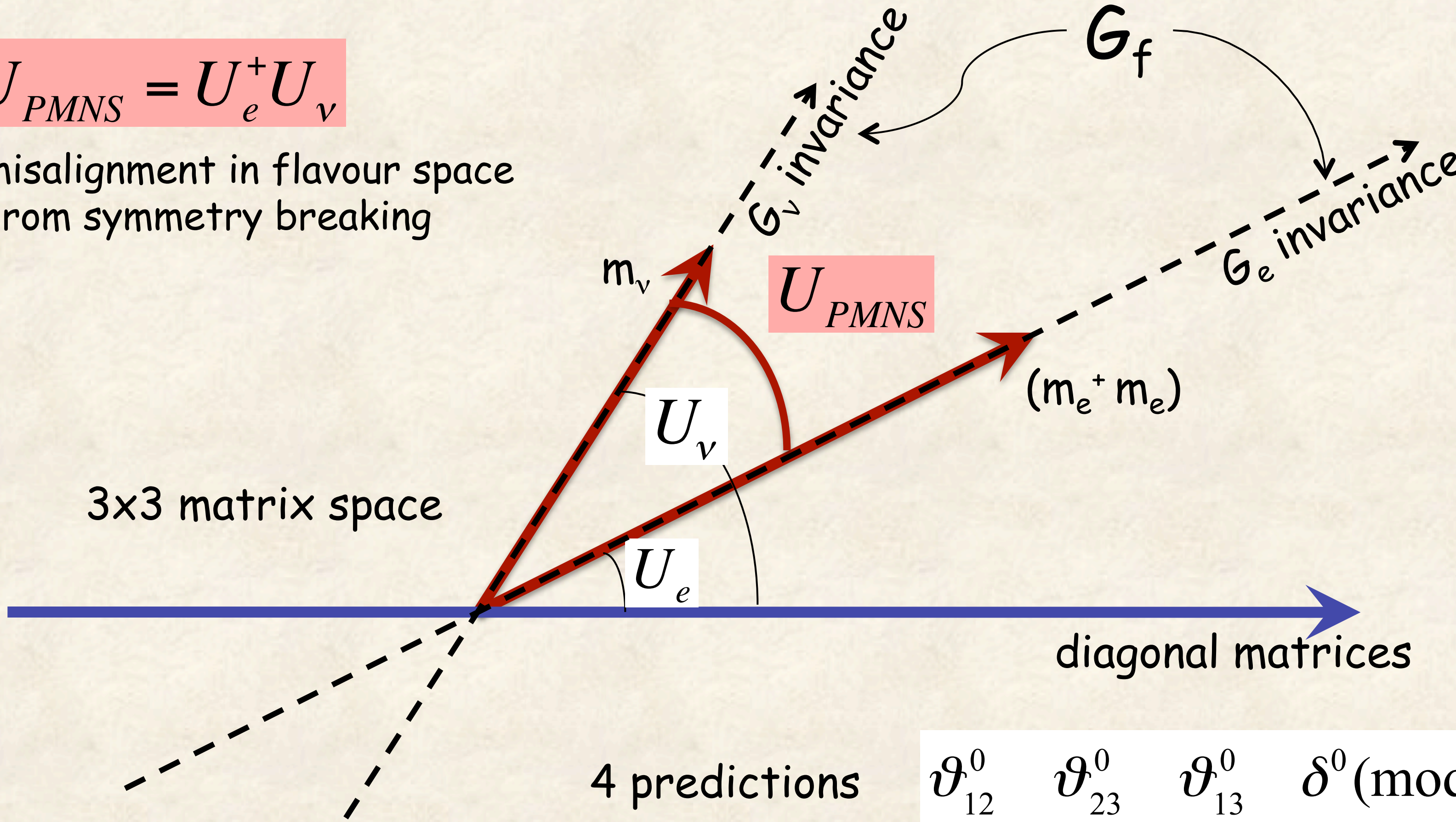
$$|U_{PMNS}| = \begin{pmatrix} 0.80 \div 0.85 & 0.51 \div 0.59 & 0.13 \div 0.18 \\ 0.21 \div 0.54 & 0.42 \div 0.73 & 0.58 \div 0.81 \\ 0.22 \div 0.55 & 0.41 \div 0.73 & 0.57 \div 0.80 \end{pmatrix}$$

[3σ ranges from Gonzalez-Garcia, Maltoni, Salvado, Schwetz 1209.3023]

Mixing patterns U^0_{PMNS} from discrete symmetries

$$U_{PMNS} = U_e^+ U_\nu$$

misalignment in flavour space
from symmetry breaking



4 predictions ϑ^0_{12} ϑ^0_{23} ϑ^0_{13} $\delta^0 (\mathrm{mod}\ \pi)$

- the most general group leaving $\nu^T m_\nu \nu$ invariant, and m_i unconstrained

$$G_\nu = Z_2 \times Z_2$$

Majorana neutrinos imply G_ν discrete!

- G_e can be continuous but the simplest choice is G_e discrete

$$G_e = \begin{cases} Z_2 \times Z_2 \\ Z_n \quad n \geq 3 \end{cases}$$

Some mixing patterns

$G_\nu = Z_2 \times Z_2$

G_f	G_e	U_{PMNS}	$\sin^2\vartheta_{23}$	$\sin\vartheta_{13}$	$\sin^2\vartheta_{12}$	
A_4	Z_3	[M]	$1/2$	$1/\sqrt{3}$	$1/2$	
S_4	Z_3	[TB]	$1/2$	0	$1/3$	
	Z_4 $(Z_2\times Z_2)'$	[BM]	$1/2$	0	$1/2$	
A_5	Z_3	$[GR_1]$	$1/2$	0	0.127	
	Z_5	$[GR_2]$	$1/2$	0	0.276	
	$(Z_2\times Z_2)'$	$[GR_3]$	0.276	0.309	0.276	
		[Exp 3σ]	$0.34\div0.67$	$0.13\div0.17$	$0.27\div0.34$	

[Lam 1104.0055
F., Hagedorn, Toroop]

[TB <->Harrison, Perkins and Scott]

[GR_2<-> Kajiyama, Raidal, Strumia 2007]

-- a long way to promote a candidate pattern to a complete model

-- general feature $U_{PMNS} = U^0_{PMNS} + O(u) \quad u \equiv \frac{\langle\varphi\rangle}{\Lambda} < 1$

-- neutrino masses fitted, not predicted.

expectation for $U^0_{PMNS}=U_{TB}$

$$\begin{cases}\vartheta^0_{13}=0\\ \vartheta^0_{23}=\dfrac{\pi}{4}\end{cases} \Rightarrow \begin{cases}\vartheta_{13}=\mathrm{O}(\text{few degrees})\\ \vartheta_{23}=\text{close to }\dfrac{\pi}{4}\end{cases}$$

not to spoil the agreement with ϑ_{12}

wrong!

possibilities

1 add large corrections $O(\vartheta_{13})\approx 0.2$

- predictability is lost since in general correction terms are many
- new dangerous sources of FC/CPV if NP is at the TeV scale

2 change discrete group G_f

- solutions exist
  special forms of Trimaximal mixing

$$U^0 = U_{TB}\times\begin{pmatrix}\cos\alpha & 0 & e^{i\delta}\sin\alpha\\ 0 & 1 & 0\\ -e^{-i\delta}\sin\alpha & 0 & \cos\alpha\end{pmatrix}$$

G_f	$\Delta(96)$	$\Delta(384)$	$\Delta(600)$
α	$\pm\pi/12$	$\pm\pi/24$	$\pm\pi/15$
$\sin^2\vartheta^0_{13}$	0.045	0.011	0.029

$\delta^0=0,\pi$ (no CP violation) and
α "quantized" by group theory

F.F., C. Hagedorn, R. de A.Toroop
hep-ph/1107.3486 and hep-ph/1112.1340
Lam 1208.5527 and 1301.1736
Holthausen1, Lim and Lindner 1212.2411
Neder, King, Stuart 1305.3200

too big groups?

3 relax symmetry requirements

[Hernandez,Smirnov 1204.0445]

G_e as before

$G_\nu = Z_2$

2 predictions:
2 combinations of ϑ^0_{12} ϑ^0_{23} ϑ^0_{13}

leads to testable sum rules

$$\sin^2\vartheta_{23} = \frac{1}{2} + \frac{1}{\sqrt{2}}\sin\vartheta_{13}\cos\delta_{CP} + O(\sin^2\vartheta_{13})$$

[He, Zee 2007 and 2011, Grimus, Lavoura 2008, Grimus, Lavoura, Singraber 2009, Albright, Rodejohann 2009, Antusch, King, Luhn, Spinrath 2011, King, Luhn 2011, G. Altarelli, F.F., L. Merlo and E. Stamou hep-ph/1205.4670]

4 include CP in the SB pattern

$$G_{CP} = G_f \rtimes CP$$

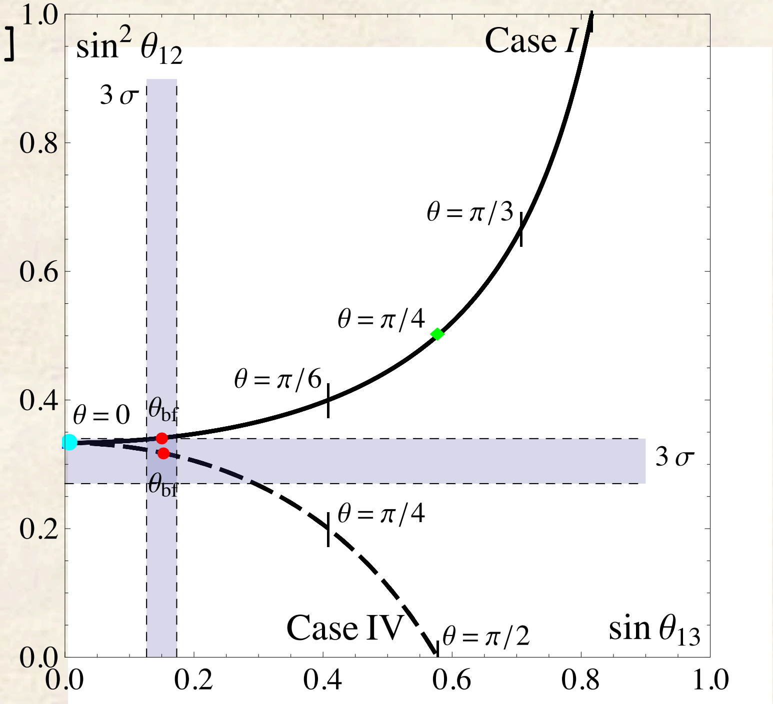
$$G_e \qquad G_\nu = Z_2 \times CP$$

[F. F, C. Hagedorn and R. Ziegler 1211.5560, 1303.7178 Ding,King,Luhn,Stuart 1303.6180]

$\sin^2\vartheta^0_{23} = \frac{1}{2}$ $\quad |\sin\delta^0| = 1$

$\sin\alpha^0 = 0$

$\sin\beta^0 = 0$



mixing angles and CP violating phases

$$(\vartheta^0_{12}, \vartheta^0_{23}, \vartheta^0_{13}, \delta^0, \alpha^0, \beta^0)$$

predicted in terms of a single real parameter $0 \le \vartheta \le 2\pi$

2 examples with $G_f=S_4$ $G_e=Z_3$

Conclusion

- big progress on the experimental side:
  -- precisely measured ϑ_{13}: many σ away from zero!
  -- potentially interesting implications on ϑ_{23}
  -- sterile neutrinos waiting for exp. checks

- on the theory side:
  neutrino masses represent a unique window on high-energy physics (such as GUTs, B-L violation, leptogenesis,…) but the fundamental theory is hard to identify.

  flavour symmetries: a useful tool but
  no compelling and unique picture have emerged so far
  present data can be described within widely different frameworks

- models based on "anarchy" and/or its variants - $U(1)_{FN}$ models - in good shape:
  neutrino mass ratios and mixing angles just random $O(1)$ quantities

- models based on discrete symmetries are less supported by data now and modifications of simplest realizations are required
  -- add large corrections $O(\vartheta_{13})\approx 0.2$
  -- move to large discrete symmetry groups G_f such as $\Delta(96)$ $\Delta(384)$ …
  -- relax symmetry requirements
  -- include CP in the SB pattern

Backup slides

example III: $G_f = G_{MFV} = SU(3)_L \times SU(3)_R \times \ldots$

(relevant for charged lepton masses)

$$L_Y = -e^c \frac{\varphi}{\Lambda_f}\left(\Phi^+ l\right) + h.c. + \ldots$$

$$l \sim (3,1) \quad e^c \sim (1,\bar{3}) \quad \varphi \sim (\bar{3},3)$$

the most general invariant $V(\varphi)$ admits several natural stationary points
closest to the real world is

$$<\varphi> = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & a \end{pmatrix}$$

$$H_f = SU(2)_L \times SU(2)_R \times U(1) \times \ldots$$

hierarchical spectrum: $m_\tau \neq 0$ $m_e = m_\mu = 0$: good starting point but difficult to turn into a realistic model

- ad hoc breaking terms?
- more SB fields?

some recent progress: Espinosa, Fong, Nardi 1211.6428
Alonso, Gavela, Isidori, Maiani 1306.5927

Mixing matrix $U = U_{PMNS}$ (Pontecorvo,Maki,Nakagawa,Sakata)

neutrino interaction eigenstates

$$\nu_f = \sum_{i=1}^{3} U_{fi} \nu_i$$

$$(f = e, \mu, \tau)$$

neutrino mass eigenstates

U is a 3 x 3 unitary matrix
standard parametrization

$$U_{PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{-i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{-i\delta} & c_{13}s_{23} \\ -c_{12}s_{13}c_{23}e^{-i\delta} + s_{12}s_{23} & -s_{12}s_{13}c_{23}e^{-i\delta} - c_{12}s_{23} & c_{13}c_{23} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix}$$

$$c_{12} \equiv \cos\vartheta_{12}, \ldots$$

three mixing angles $\vartheta_{12}, \quad \vartheta_{13}, \quad \vartheta_{23}$

three phases (in the most general case) δ $\underbrace{\alpha, \quad \beta}_{\text{do not enter}}$ $P_{ff'} = P(\nu_f \to \nu_{f'})$

oscillations can only test 6 combinations

$\Delta m_{21}^2, \Delta m_{32}^2,$ $\vartheta_{12}, \quad \vartheta_{13}, \quad \vartheta_{23}$ δ

2011/2012 breakthrough

- from LBL experiments searching for $\nu_\mu \to \nu_e$ conversion

T2K: muon neutrino beam produced at JPARC [Tokai] E=0.6 GeV and sent to SK 295 Km apart [1106.2822]

MINOS: muon neutrino beam produced at Fermilab [E=3 GeV] sent to Soudan Lab 735 Km apart [1108.0015]

$$P(\nu_\mu \to \nu_e) = \sin^2\vartheta_{23}\sin^2 2\vartheta_{13}\sin^2\frac{\Delta m^2_{32}L}{4E} + \ldots$$

both experiments favor $\sin^2\vartheta_{13} \sim$ few %

- from SBL reactor experiments searching for anti-ν_e disappearance

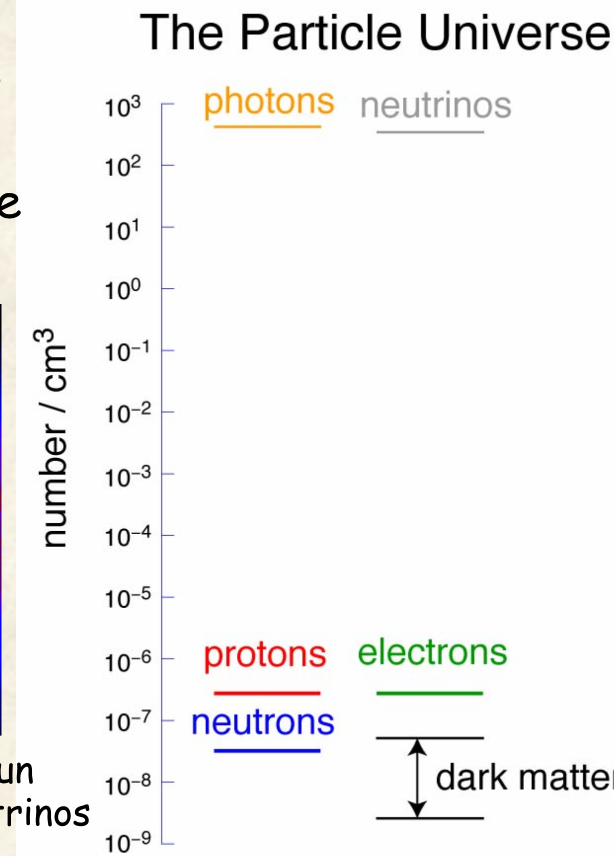
Double Chooz (far detector):	$\sin^2 2\vartheta_{13} = 0.109 \pm 0.039$
Daya Bay (near + far detectors):	$\sin^2\vartheta_{13} = 0.089 \pm 0.011$
RENO (near + far detectors):	$\sin^2\vartheta_{13} = 0.113 \pm 0.023$

$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\vartheta_{13}\sin^2\frac{\Delta m^2_{32}L}{4E} + \ldots$$

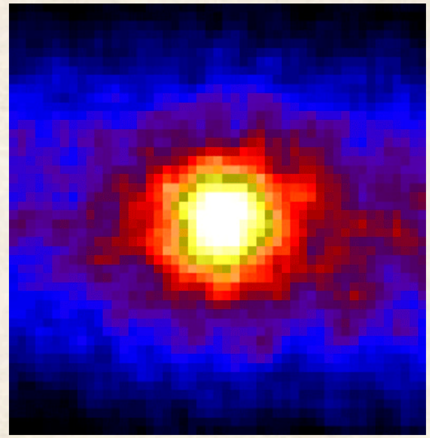
- SBL reactors are sensitive to ϑ_{13} only
  LBL experiments anti-correlate $\sin^2 2\vartheta_{13}$ and $\sin^2\vartheta_{23}$
  also breaking the octant degeneracy $\vartheta_{23} \leftrightarrow (\pi-\vartheta_{23})$

General remarks on neutrinos

the more abundant particles in the universe after the photons: about 300 neutrinos per cm^3



produced by stars: about 3% of the sun energy emitted in neutrinos. As I speak more than 1 000 000 000 000 solar neutrinos go through your bodies each second.

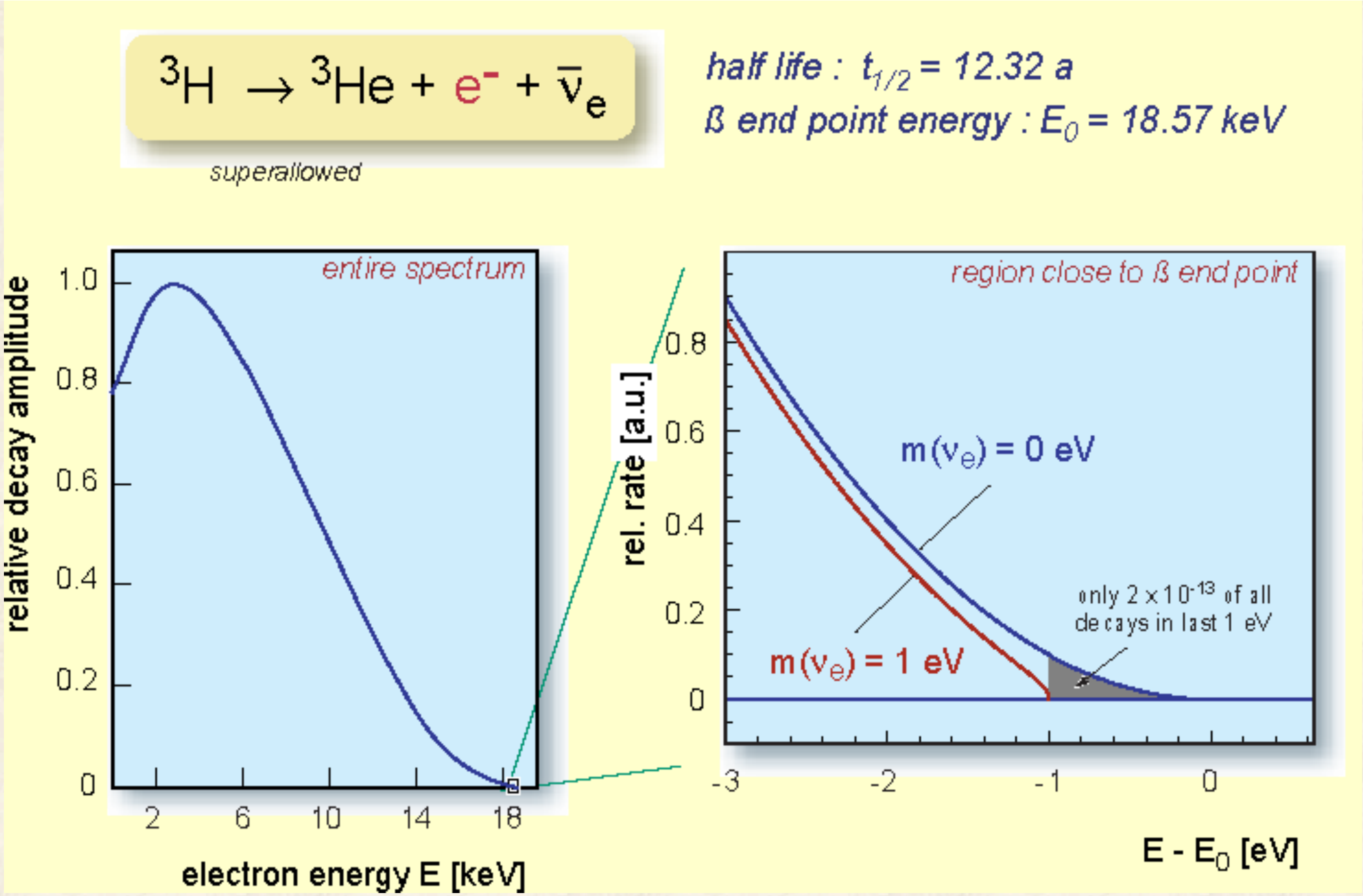


this is a picture of the sun reconstructed from neutrinos

electrically neutral and extremely light:
they can carry information about extremely large length scales
e.g. a probe of supernovae dynamics: neutrino events from a supernova explosion first observed 23 years ago

in particle physics:
they have a tiny mass (1 000 000 times smaller than the electron's mass)
the discovery that they are massive (twelve anniversary now!) allows us to explore, at least in principle, extremely high energy scales, otherwise inaccessible to present laboratory experiments (more on this later on…)

Upper limit on neutrino mass (laboratory)



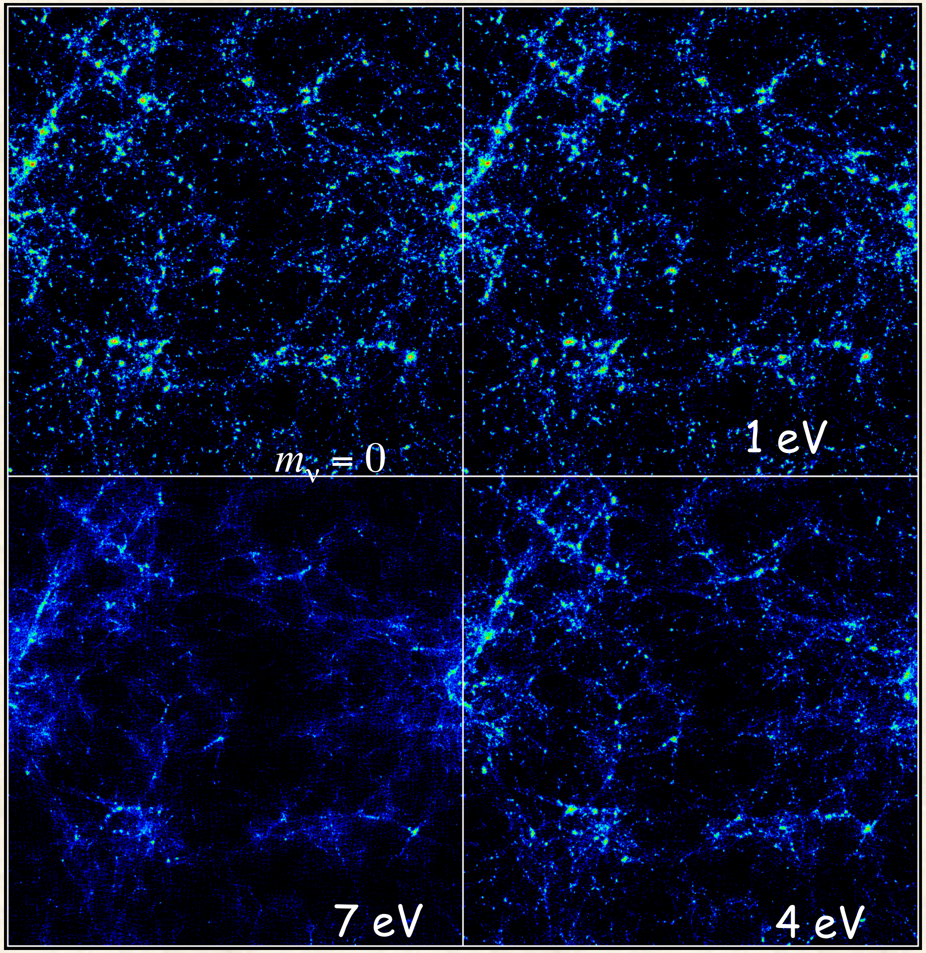
$$m_\nu < 2.2\, eV \quad (95\%\ CL)$$

Upper limit on neutrino mass (cosmology)

massive ν suppress the formation of small scale structures

$$\sum_i m_i < 0.2 \div 1 \quad eV$$

depending on
- assumed cosmological model
- set of data included
- how data are analyzed



$$k_{\rm nr} \approx 0.026 \left(\frac{m_\nu}{1\,{\rm eV}}\right)^{1/2} \Omega_m^{1/2} h\,{\rm Mpc}^{-1}.$$

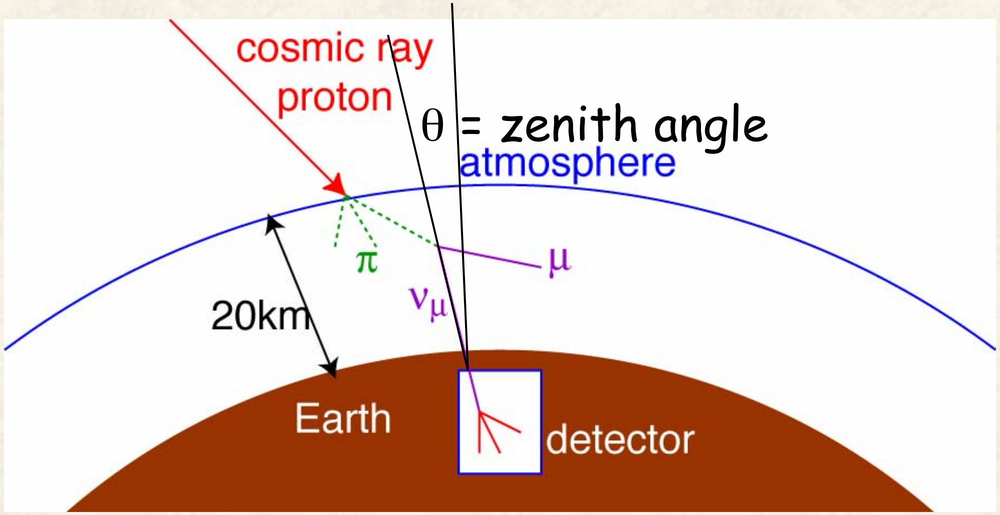
The small-scale suppression is given by

$$\left(\frac{\Delta P}{P}\right) \approx -8\frac{\Omega_\nu}{\Omega_m} \approx -0.8 \left(\frac{m_\nu}{1\,{\rm eV}}\right) \left(\frac{0.1N}{\Omega_m h^2}\right)$$

$$\delta(\vec{x}) \equiv \frac{\rho(\vec{x}) - \bar{\rho}}{\bar{\rho}}$$

$$\langle \delta(\vec{x}_1)\delta(\vec{x}_2) \rangle = \int \frac{d^3k}{(2\pi)^3} e^{i\vec{k}\cdot(\vec{x}_1 - \vec{x}_2)} P(\vec{k})$$

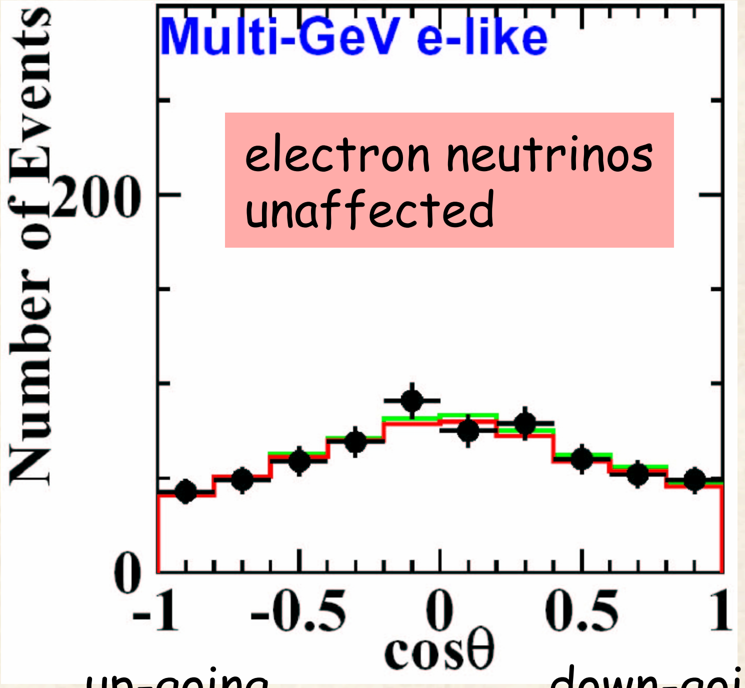
Atmospheric neutrino oscillations



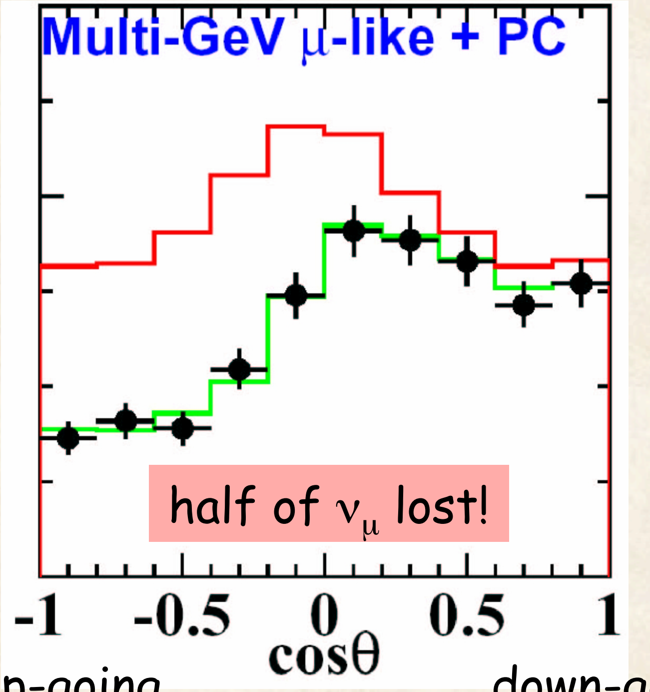
[this year: 10th anniversary]

Electron and muon neutrinos (and antineutrinos) produced by the collision of cosmic ray particles on the atmosphere

Experiment:
SuperKamiokande (Japan)



up-going down-going



up-going down-going

electron neutrinos do not oscillate

by working in the approximation $\Delta m^2_{21} = 0$

$$P_{ee} = 1 - \underbrace{4|U_{e3}|^2(1-|U_{e3}|^2)}_{\sin^2 2\vartheta_{13}} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) \approx 1$$

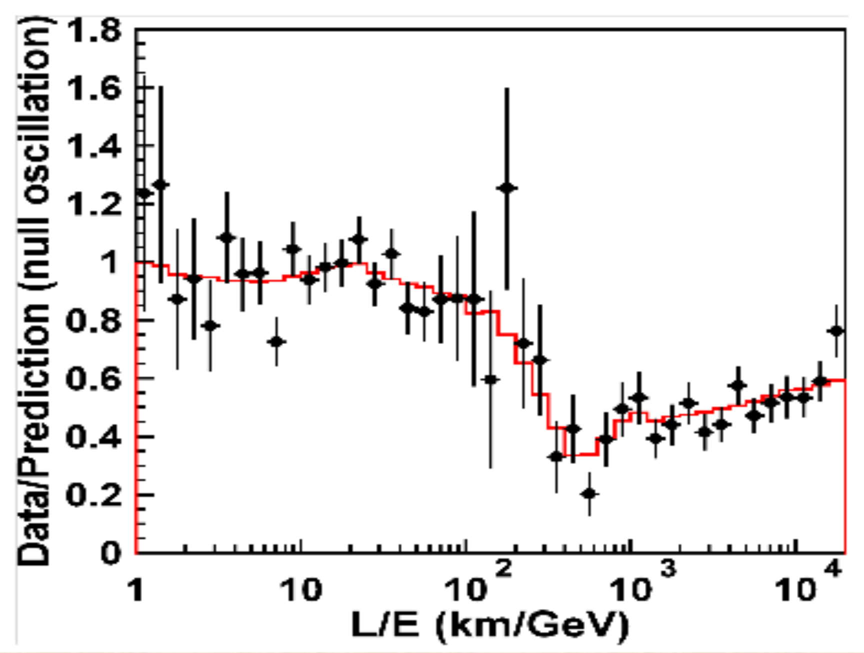
for $U_{e3} = \sin\vartheta_{13} \approx 0$

muon neutrinos oscillate

$$P_{\mu\mu} = 1 - \underbrace{4|U_{\mu 3}|^2(1-|U_{\mu 3}|^2)}_{\sin^2 2\vartheta_{23}} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

$$|\Delta m^2_{32}| \approx 2 \cdot 10^{-3} \quad eV^2$$

$$\sin^2\vartheta_{23} \approx \frac{1}{2}$$



$$U_{PMNS} = \begin{pmatrix} \cdot & \cdot & 0 \\ \cdot & \cdot & -\frac{1}{\sqrt{2}} \\ \cdot & \cdot & \frac{1}{\sqrt{2}} \end{pmatrix} + (\text{small corrections})$$

maximal mixing!
not a replica of the quark mixing pattern

this picture is supported by other terrestrial esperiments such as
K2K (Japan, from KEK to Kamioka mine L ≈ 250 Km E ≈ 1 GeV)
and MINOS (USA, from Fermilab to Soudan mine L ≈ 735 Km E ≈ 5 GeV)
that are sensitive to Δm_{32}^2 close to 10^{-3} eV^2,

KamLAND

previous experiments were sensitive to Δm^2 close to 10^{-3} eV^2
to explore smaller Δm^2 we need larger L and/or smaller E

KamLAND experiment exploits the low-energy electron anti-neutrinos (E≈3 MeV) produced by Japanese and Korean reactors at an average distance of L≈180 Km from the detector and is potentially sensitive to Δm^2 down to 10^{-5} eV^2

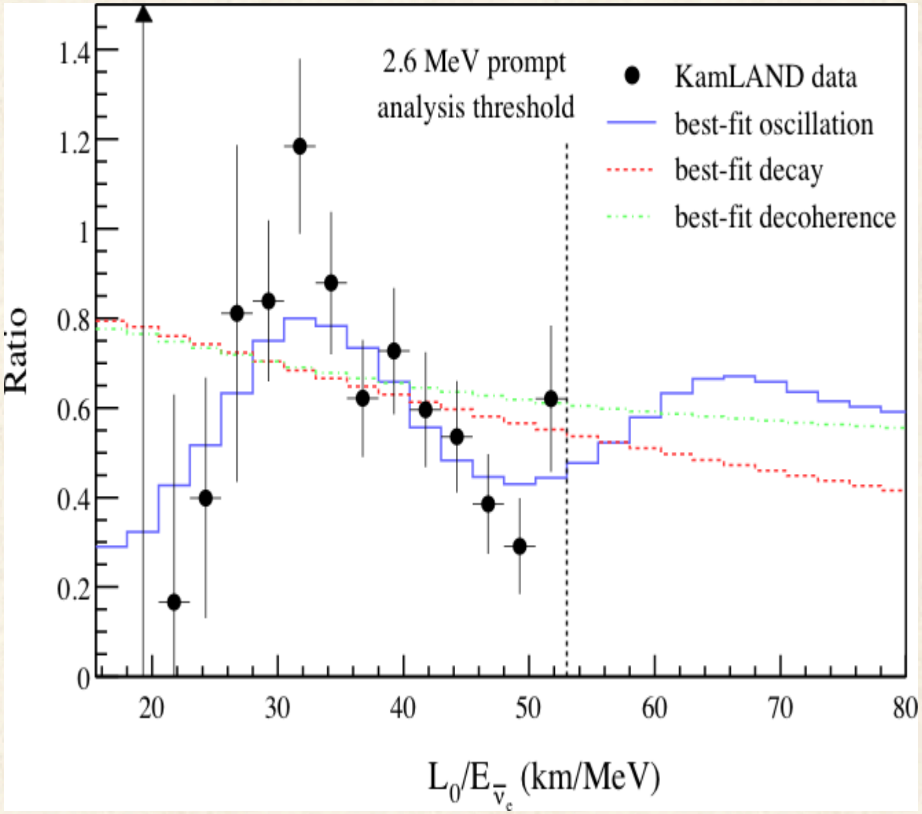
by working in the approximation

$U_{e3} = \sin\vartheta_{13} = 0$ we get

$$P_{ee} = 1 - \underbrace{4|U_{e1}|^2|U_{e2}|^2}_{\sin^2 2\vartheta_{12}} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

$$\Delta m_{21}^2 \approx 8\cdot 10^{-5} \quad eV^2$$

$$\sin^2\vartheta_{12} \approx \frac{1}{3}$$



TB mixing from symmetry breaking

it is easy to find a symmetry that forces $(m_e^+ m_e)$ to be diagonal;
a ''minimal'' example (there are many other possibilities) is

$$G_T=\{1,T,T^2\}$$

$$T=\begin{pmatrix}1 & 0 & 0\\ 0 & \omega^2 & 0\\ 0 & 0 & \omega\end{pmatrix} \qquad \omega = e^{i\frac{2\pi}{3}}$$

[$T^3=1$ and mathematicians call a group with this property Z_3]

$$T^+ (m_e^+ m_e)\, T = (m_e^+ m_e) \quad \Rightarrow \quad (m_e^+ m_e) = \begin{pmatrix} m_e^2 & 0 & 0\\ 0 & m_\mu^2 & 0\\ 0 & 0 & m_\tau^2\end{pmatrix}$$

in such a framework TB mixing should arise entirely from m_ν

$$m_\nu(TB) \equiv \frac{m_3}{2}\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & -1 \\ 0 & -1 & 1 \end{pmatrix} + \frac{m_2}{3}\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} + \frac{m_1}{6}\begin{pmatrix} 4 & -2 & -2 \\ -2 & 1 & 1 \\ -2 & 1 & 1 \end{pmatrix}$$

most general neutrino mass matrix giving rise to TB mixing

easy to construct from the eigenvectors:

$$m_3 \leftrightarrow \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ -1 \\ 1 \end{pmatrix} \qquad m_2 \leftrightarrow \frac{1}{\sqrt{3}}\begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} \qquad m_1 \leftrightarrow \frac{1}{\sqrt{6}}\begin{pmatrix} 2 \\ -1 \\ -1 \end{pmatrix}$$

a ''minimal'' symmetry guaranteeing such a pattern [C.S. Lam 0804.2622]

$G_S \times G_U$ $G_S=\{1,S\}$ $G_U=\{1,U\}$

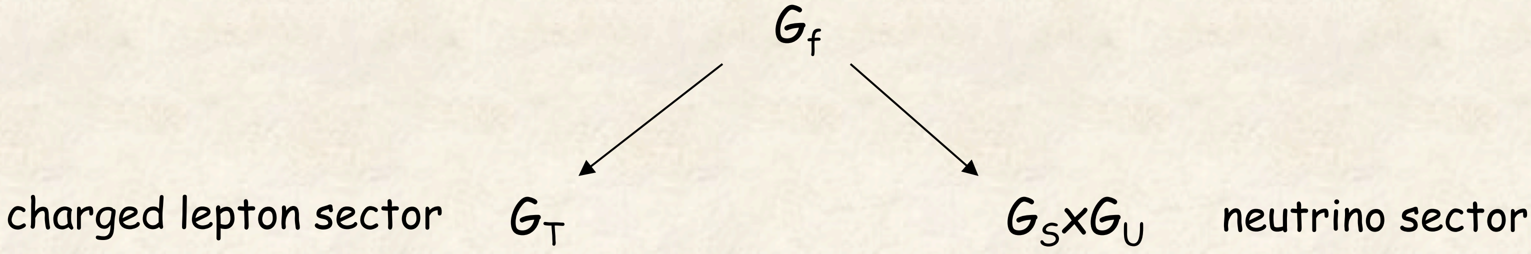
$$S = \frac{1}{3}\begin{pmatrix} -1 & 2 & 2 \\ 2 & -1 & 2 \\ 2 & 2 & -1 \end{pmatrix} \qquad U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

[this group corresponds to $Z_2 \times Z_2$ since $S^2=U^2=1$]

$$S^T m_\nu S = m_\nu \qquad U^T m_\nu U = m_\nu \quad \Rightarrow \quad m_\nu = m_\nu(TB)$$

Algorithm to generate TB mixing

- start from a flavour symmetry group G_f containing G_T, G_S, G_U
- arrange appropriate symmetry breaking



if the breaking is spontaneous, induced by $\langle\varphi_T\rangle$,$\langle\varphi_S\rangle$,… there is a vacuum alignment problem

$\sin^2\theta_{23}$

$\delta(\sin^2\theta_{23})$ reduced by future LBL experiments from $\nu_\mu \rightarrow \nu_\mu$ disappearance channel

$$\vartheta_{23} \approx \frac{\pi}{4}$$

$$P_{\mu\mu} \approx 1 - \sin^2 2\vartheta_{23} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

$$\delta\vartheta_{23} \approx \frac{\sqrt{\delta P_{\mu\mu}}}{2}$$

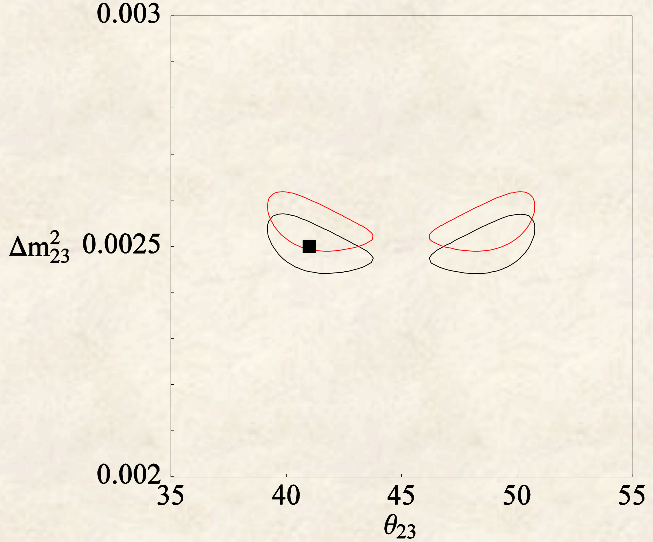
i.e. a small uncertainty on $P_{\mu\mu}$ leads to a large uncertainty on θ_{23}

- no substantial improvements from conventional beams
- superbeams (e.g. T2K in 5 yr of run)

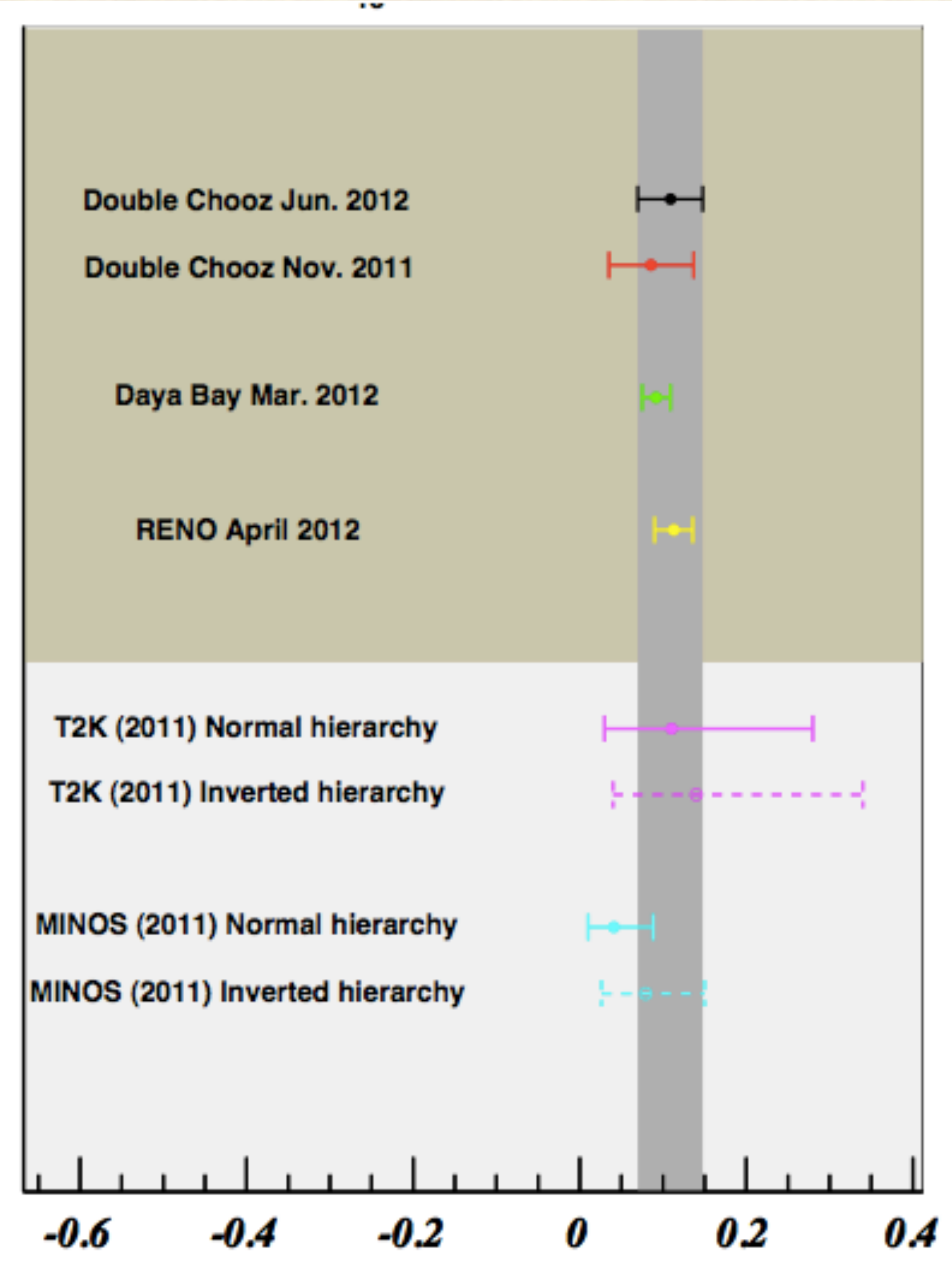
$$\delta P_{\mu\mu} \approx 0.01$$

$$\delta\vartheta_{23} \approx 0.05\,\text{rad} \leftrightarrow 2.9^0$$

improvement by about a factor 2



T2K-1
90% CL
black = normal hierarchy
red = inverted hierarchy
true value 41^0
[courtesy by Enrique Fernandez]



Double Chooz Jun. 2012
Double Chooz Nov. 2011
Daya Bay Mar. 2012
RENO April 2012
T2K (2011) Normal hierarchy
T2K (2011) Inverted hierarchy
MINOS (2011) Normal hierarchy
MINOS (2011) Inverted hierarchy
-0.6
-0.4
-0.2
0
0.2
0.4