Neutrino Mass, Flavour and CP Violation

- Introduction (neutrino masses,mixings,oscillation formulae)
- Cosmological limits on neutrino mass
- CP violation at a neutrino factory
- Theory of neutrino mass (Majorana,Dirac,See-saw,Majorana matrices)
- Natural hierarchy (sequential right-handed neutrino dominance)
- Relation between neutrino factory CP violation and leptogenesis?
- SUSY and lepton flavour violation

Steve King

University of Southampton

Solar neutrino oscillations

- **Energy of solar neutrinos is quite low (MeV).**
- **85% of the 40 billion solar neutrinos per cm^2 per sec reaching earth come from:**

$$p + p \rightarrow d + e^{+} + \nu_e$$

SNO

(Sudbury Neutrino Observatory)

Charged current:

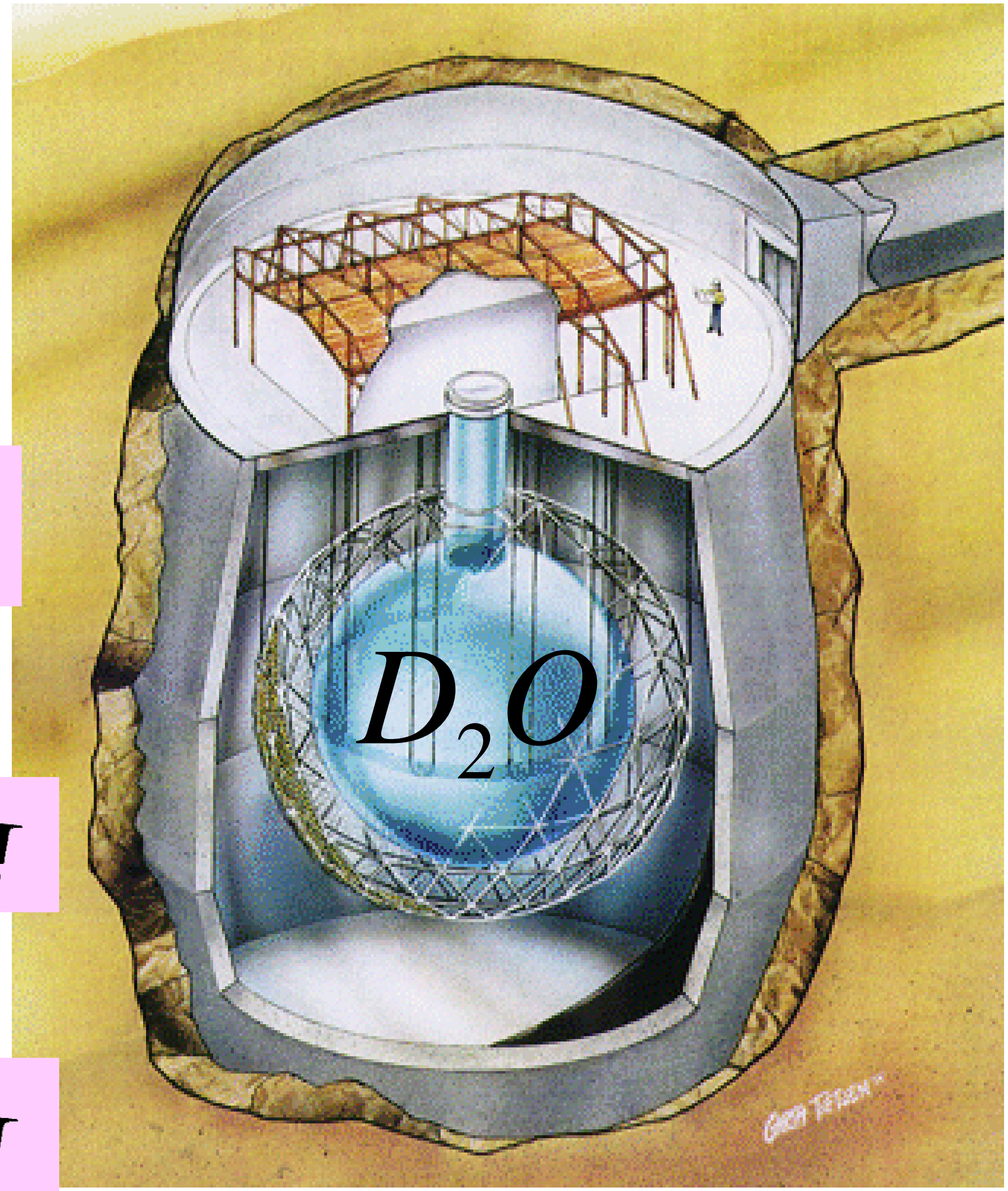
[illegible]

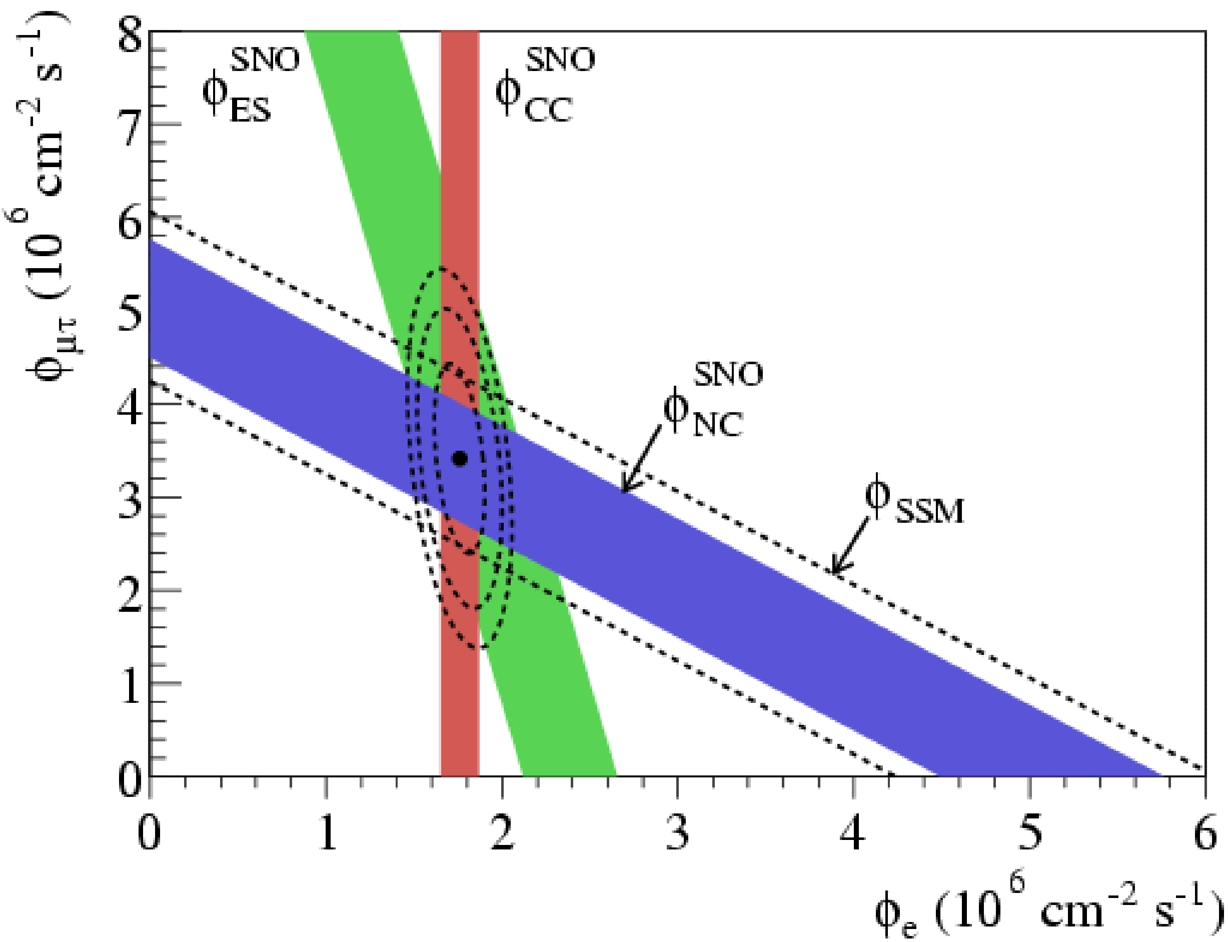
Neutral current:

[illegible]

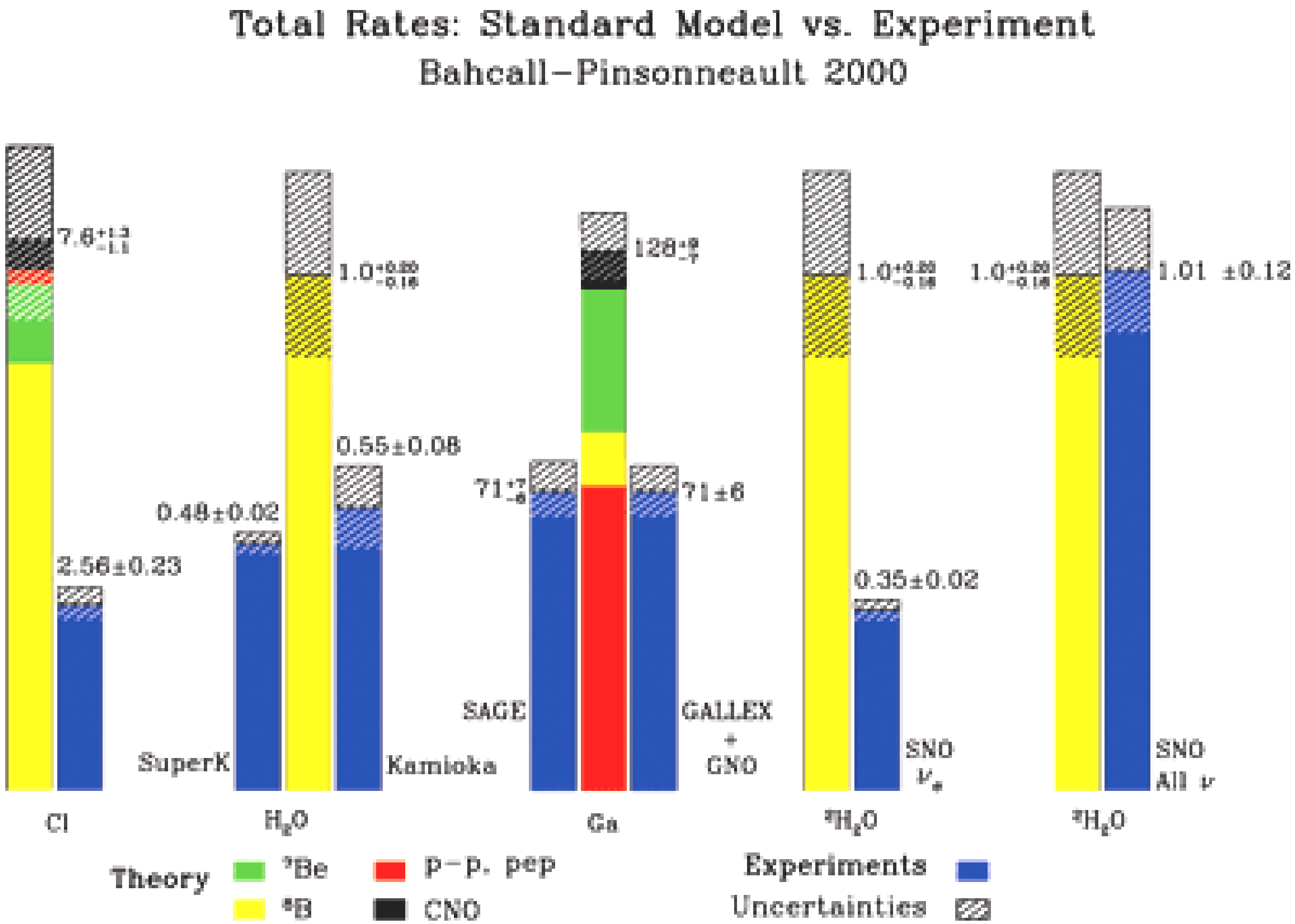
Elastic scattering:

[illegible]

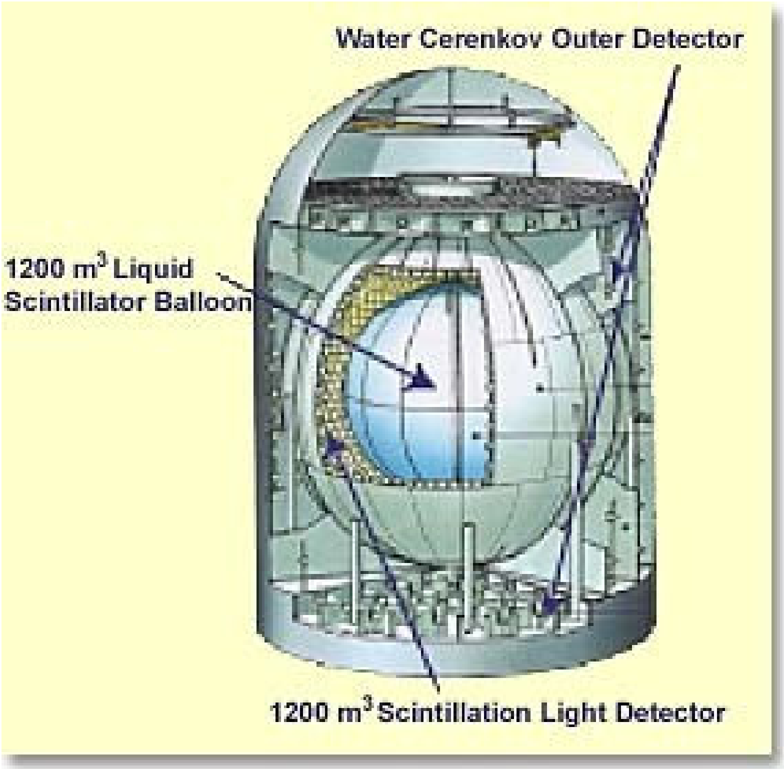




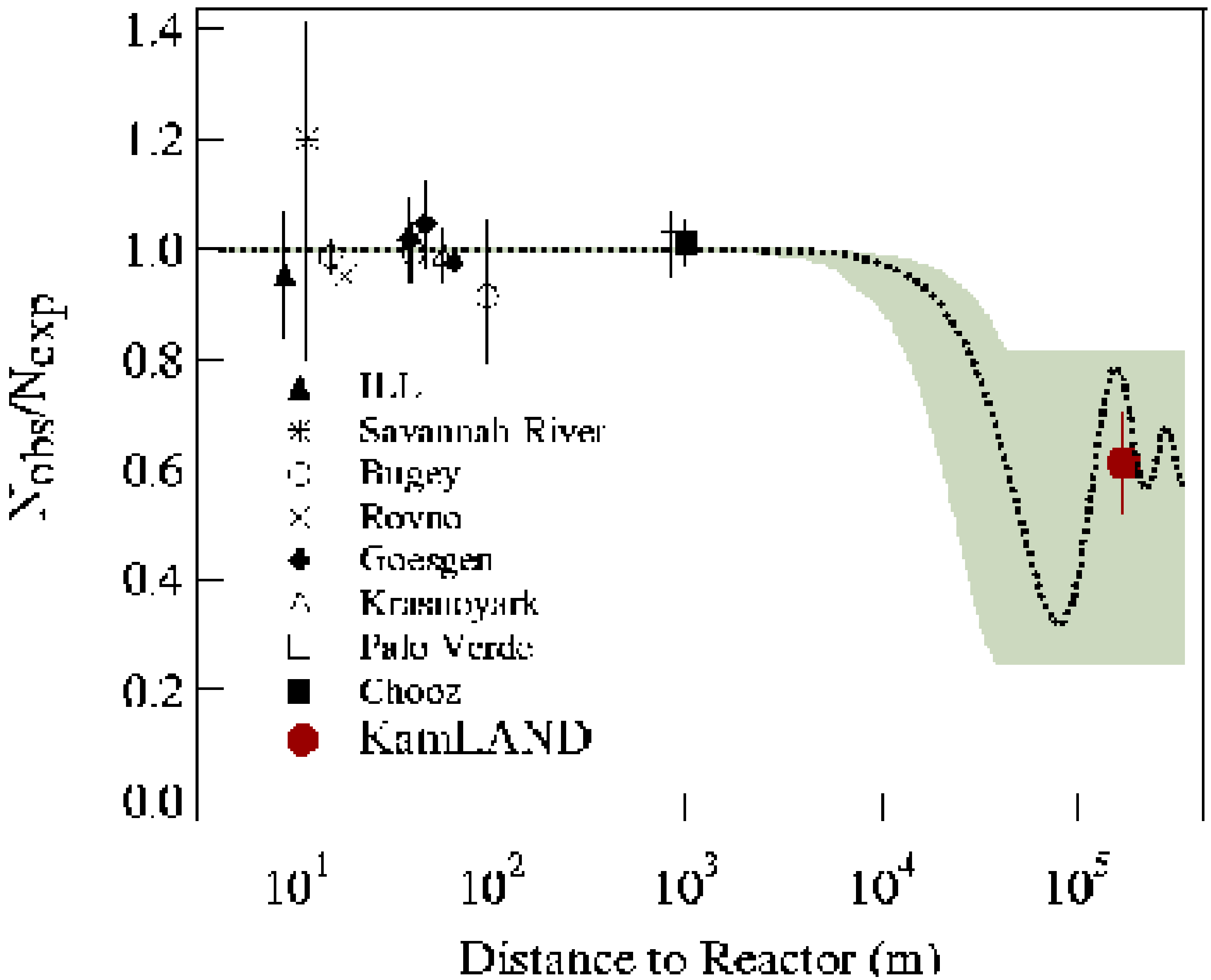
ϕ_{ES}^{SNO}
ϕ_{CC}^{SNO}
ϕ_{NC}^{SNO}
ϕ_{SSM}
$\phi_{\mu\tau}$ (10^6 cm^{-2} s^{-1})
ϕ_e (10^6 cm^{-2} s^{-1})
0
1
2
3
4
5
6
7
8


Total Rates: Standard Model vs. Experiment
Bahcall-Pinsonneault 2000
2.56±0.23
0.48±0.02
0.55±0.08
SuperK
Kamioka
SAGE
GALLEX
+
GNO
71±6
0.35±0.02
1.01 ±0.12
SNO
SNO
All ν
Cl
Ga
Theory
⁷Be
⁸B
p-p, pep
CNO
Experiments
Uncertainties

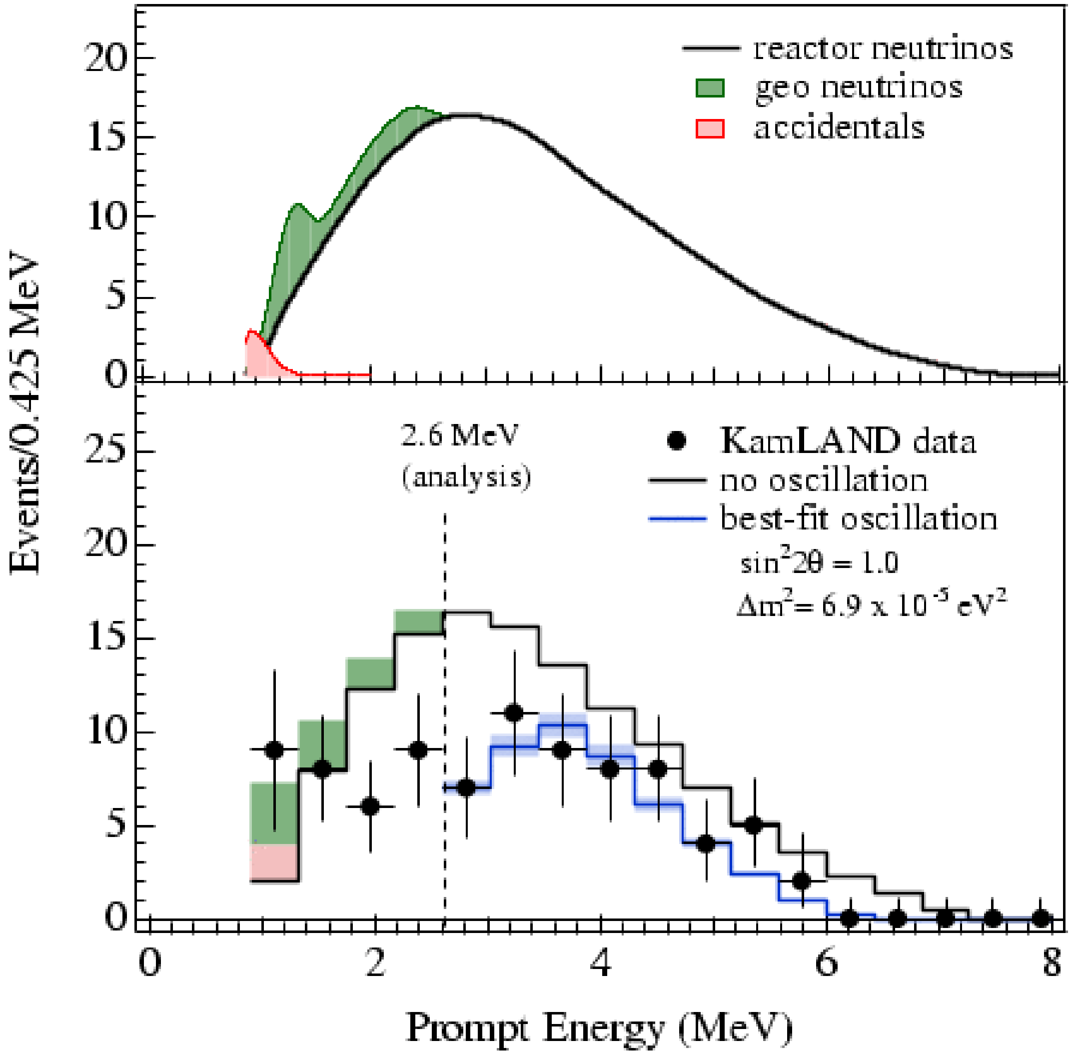
KamLAND

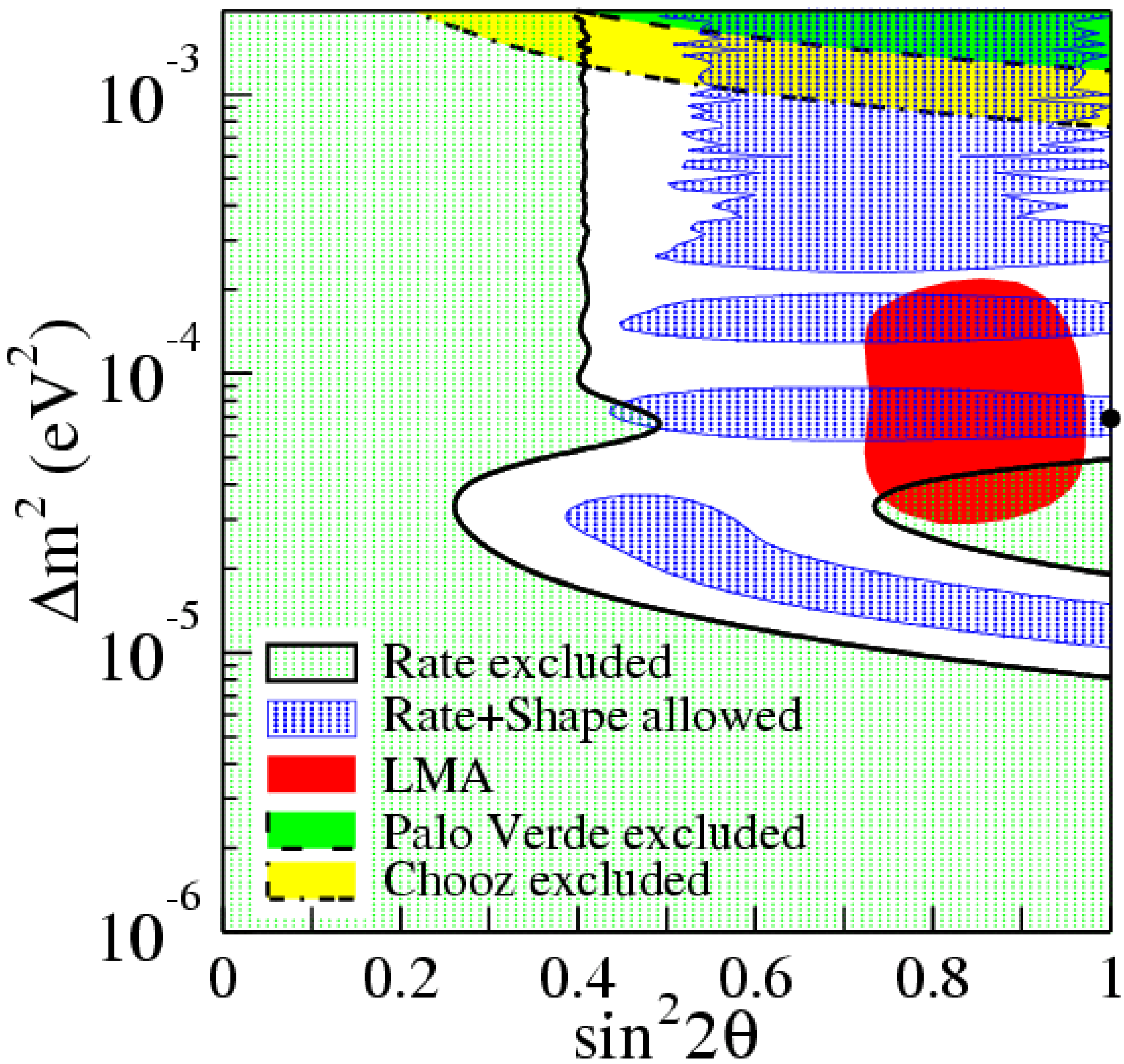


Water Cerenkov Outer Detector
1200 m^3 Liquid Scintillator Balloon
1200 m^3 Scintillation Light Detector



Nobs/Nexp
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
ILL
Savannah River
Bugey
Rovno
Goesgen
Krasnoyark
Palo Verde
Chooz
KamLAND
10^1
10^2
10^3
10^4
10^5
Distance to Reactor (m)

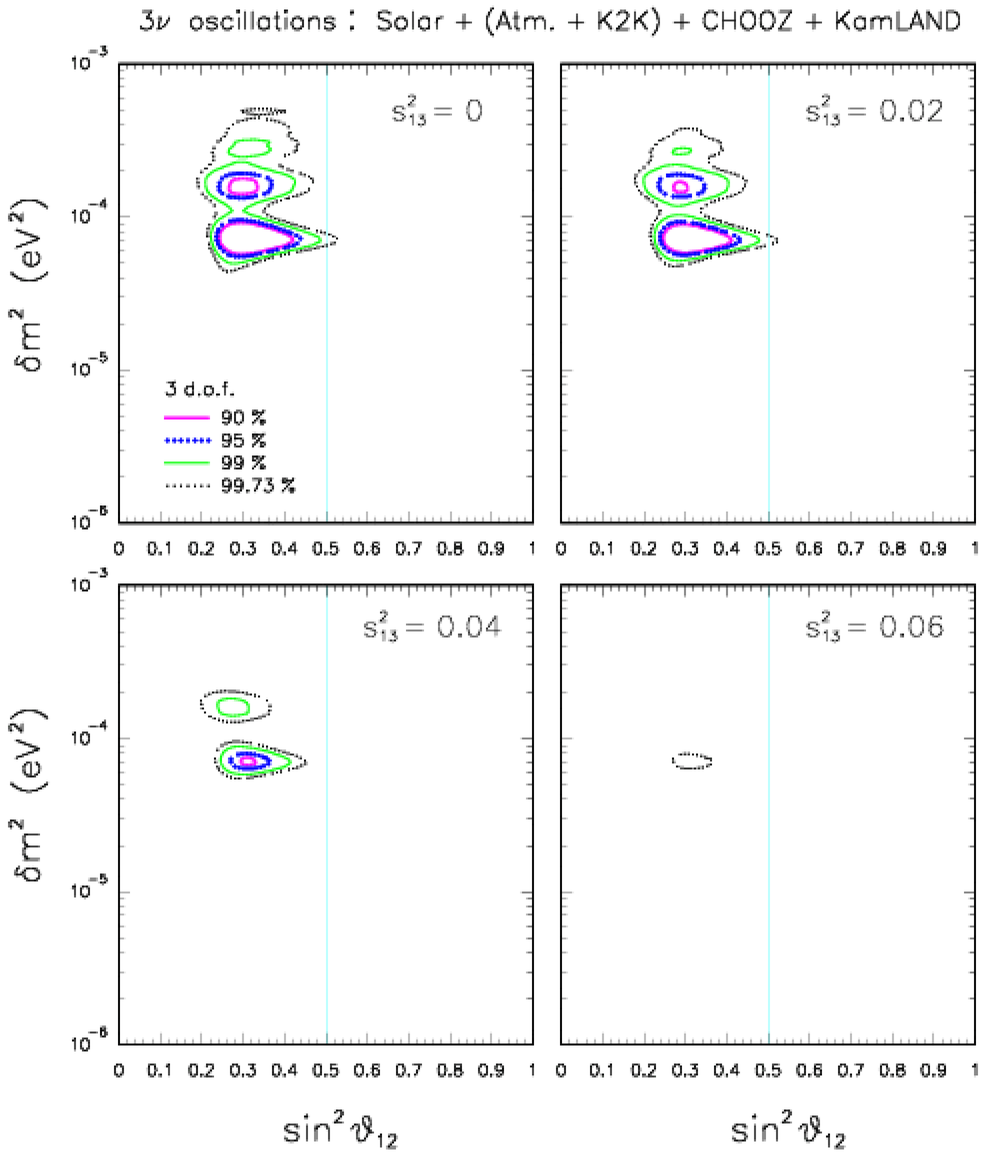

reactor neutrinos
geo neutrinos
accidentals
Events/0.425 MeV
2.6 MeV
(analysis)
KamLAND data
no oscillation
best-fit oscillation
$\sin^2 2\theta = 1.0$
$\Delta m^2 = 6.9 \times 10^{-5}\ eV^2$
Prompt Energy (MeV)



Δm^2 (eV^2)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0
0.2
0.4
0.6
0.8
1
$\sin^2 2\theta$
Rate excluded
Rate+Shape allowed
LMA
Palo Verde excluded
Chooz excluded

Global 3 neutrino analysis

Fogli et al hep-ph/0212127



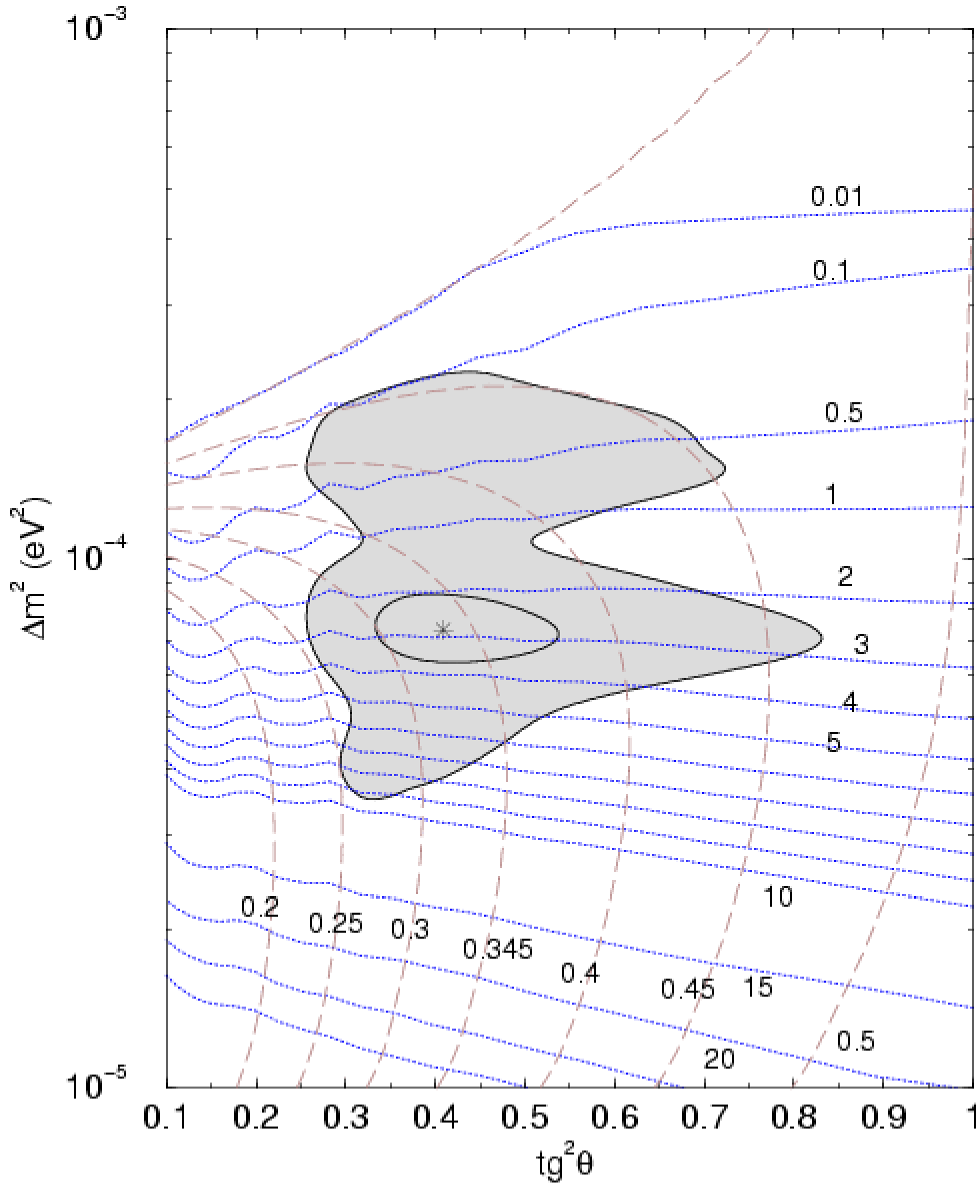
From Holanda and Smirnov
hep-ph/0212270

Impact of Future SNO Measurements

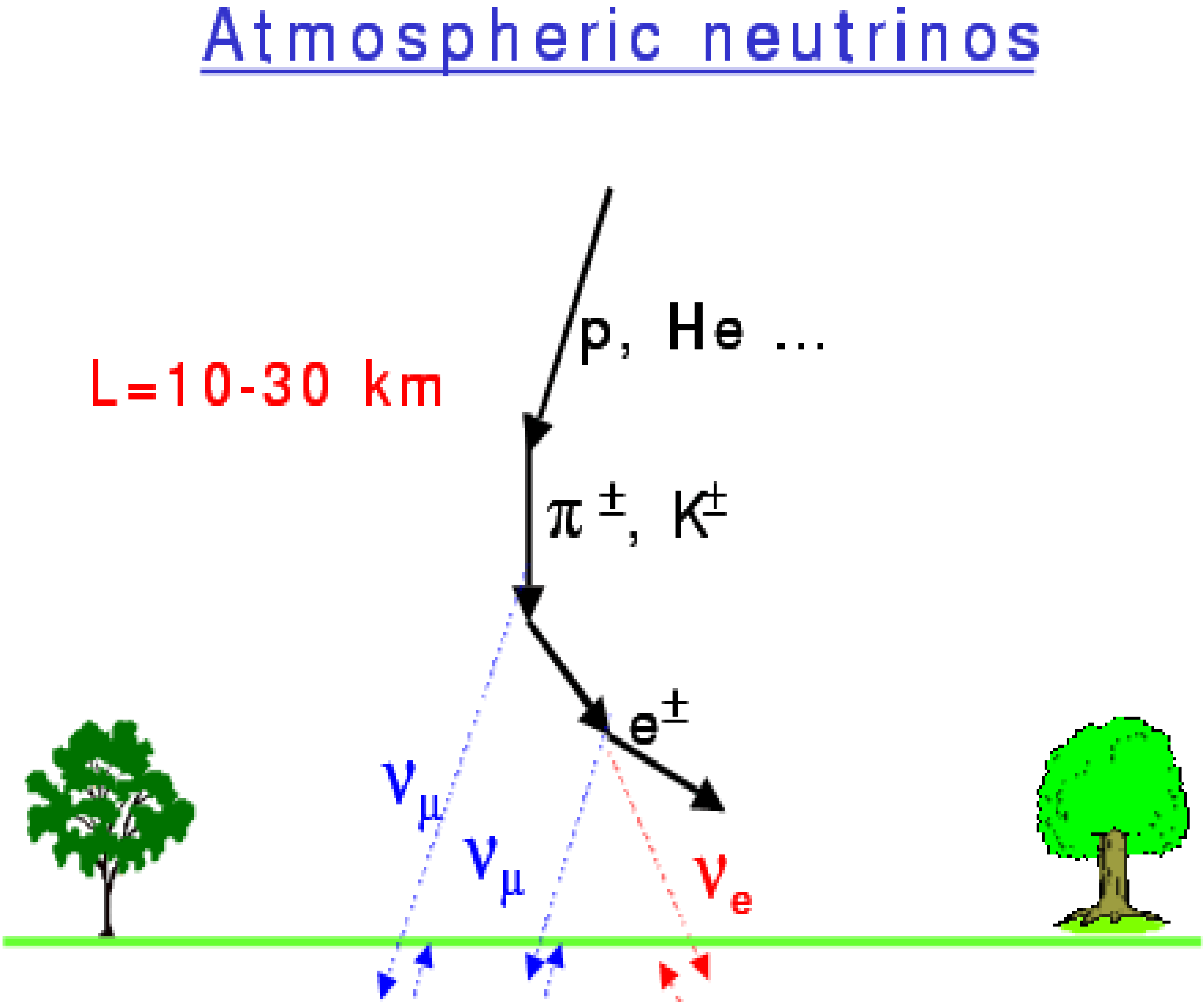
Dashed lines are SNO CC/NC

Dotted lines are SNO N/D %

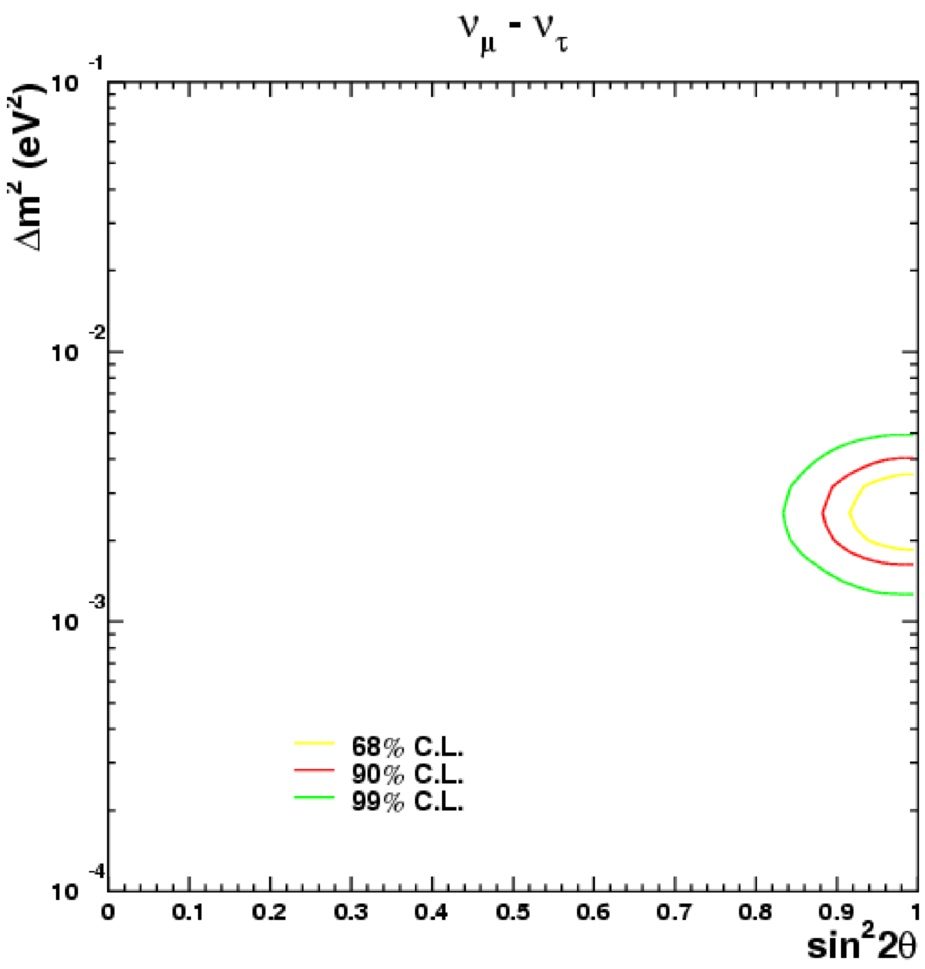
Shaded region is 1sigma and 3 sigma fits



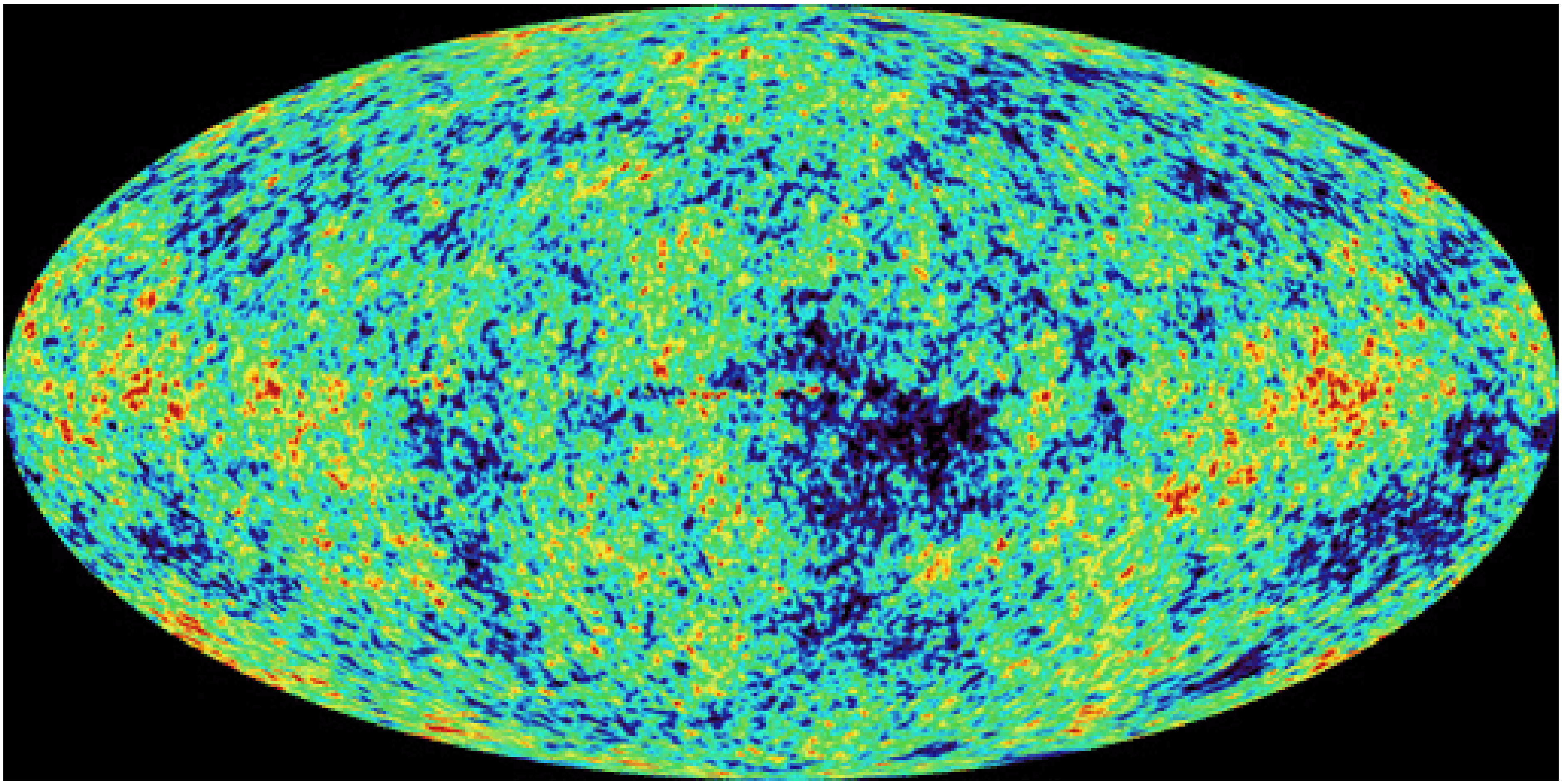
Totsuka, Neutrino Houches, 2001



Atmospheric Neutrino Oscillations

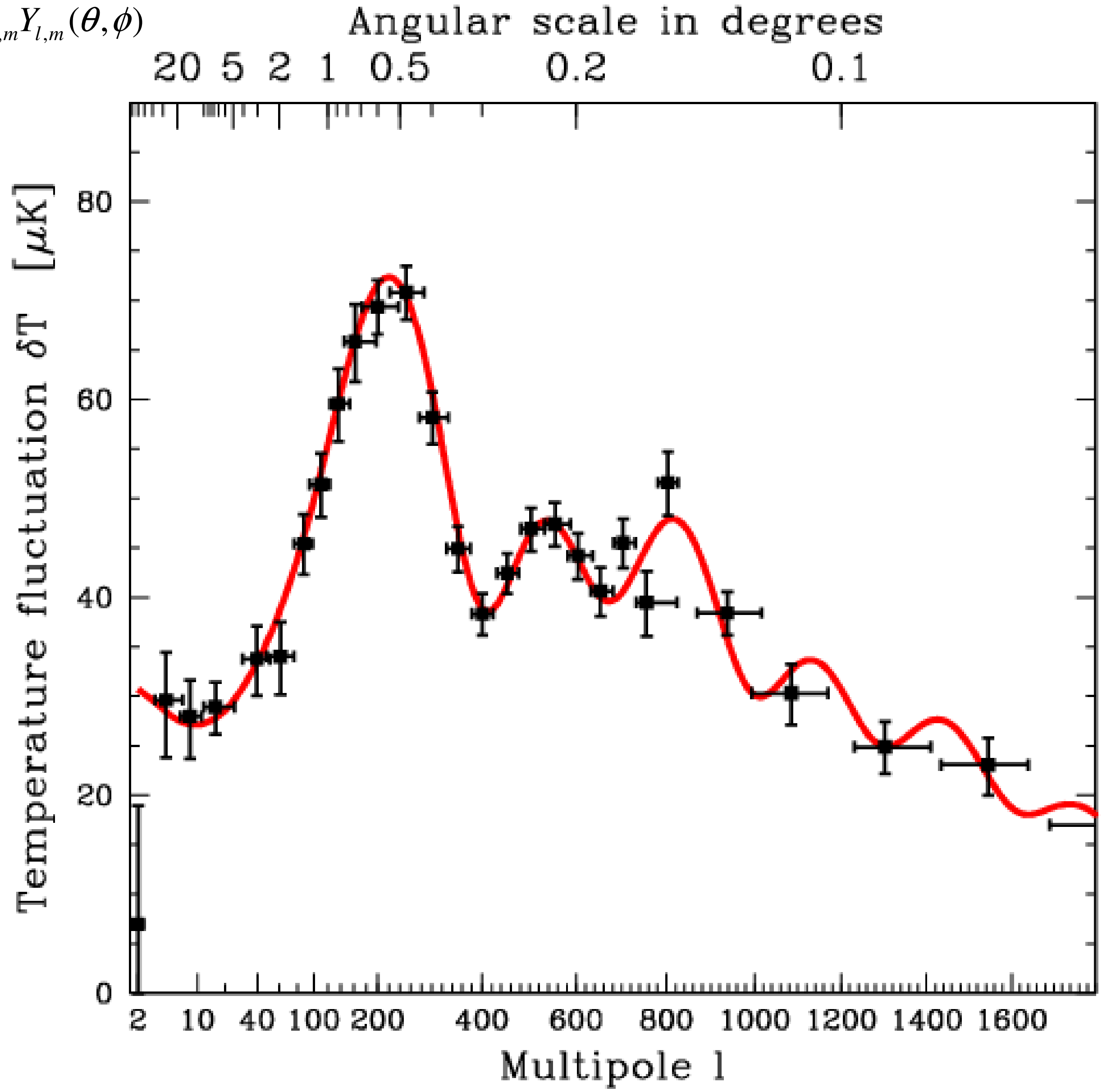


WMAP



$$\frac{\delta T}{T}(\theta,\phi) = \sum_{l,m} a_{l,m} Y_{l,m}(\theta,\phi)$$

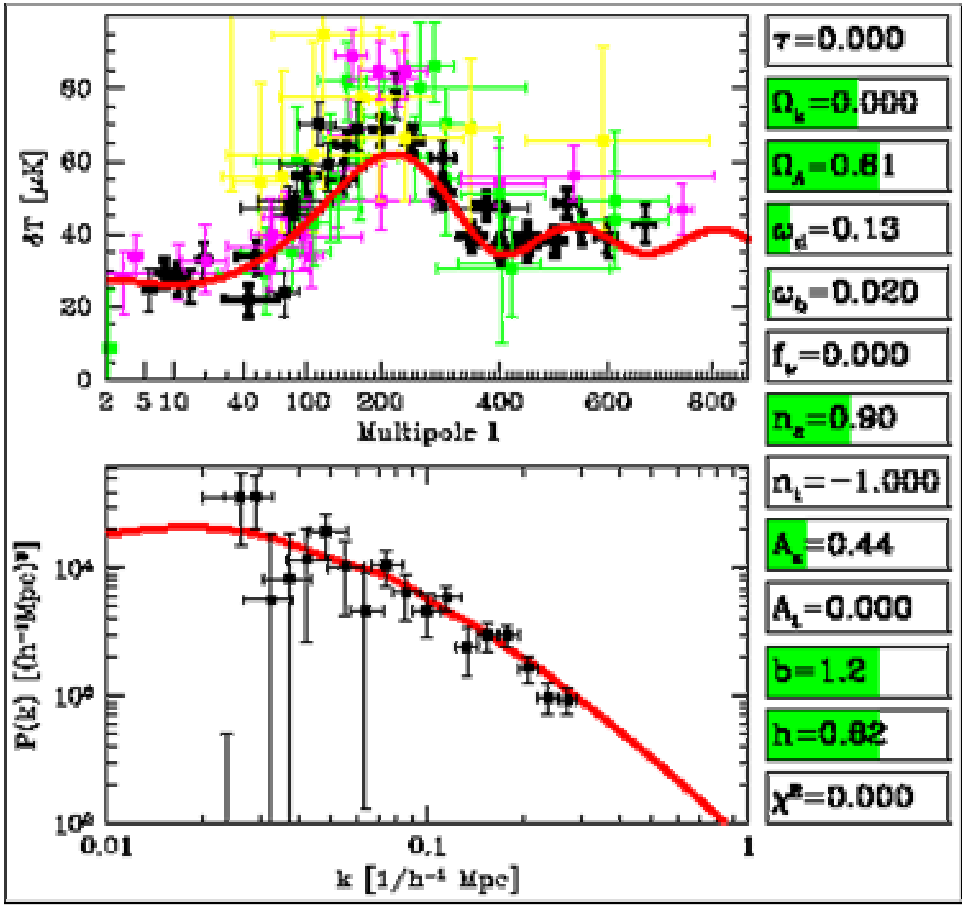
$$C_l \equiv \left\langle \left| a_{l,m} \right|^2 \right\rangle$$



Cosmological limits on neutrino mass

CMB power spectrum

Galaxy power spectrum



Animations due to Tegmark

2dF Galaxy Redshift survey astro-ph/0204152

And WMAP implies

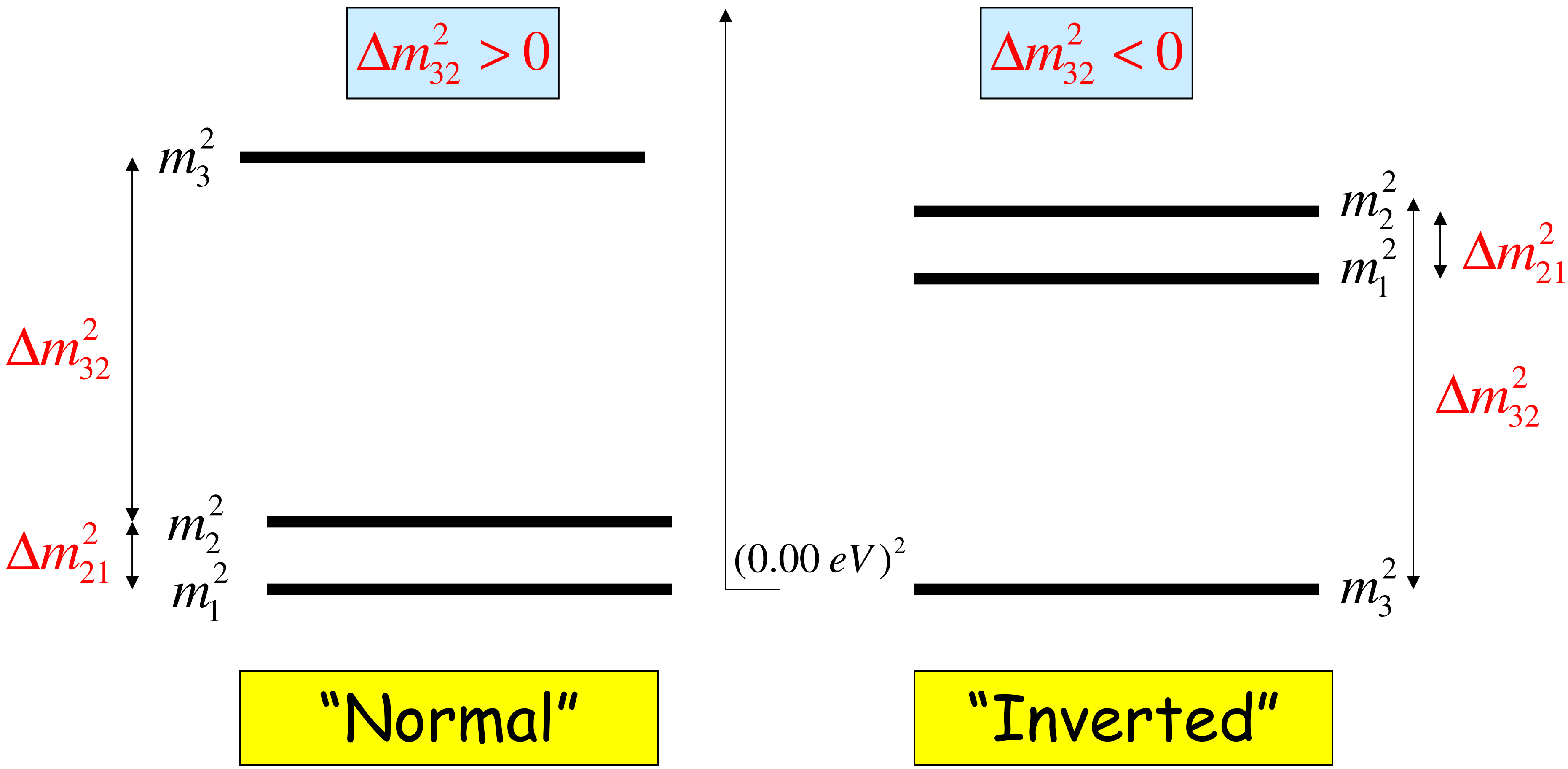
$$\sum_i m_{\nu_i} < 0.69\, eV$$

Neutrino oscillations then imply

$$m_{\nu_i} < 0.23\, eV$$

Per neutrino species

Possible three neutrino mass patterns with LMA $\Delta m^2_{21} = (0.008\, eV)^2$ and $|\Delta m^2_{32}| = (0.05\, eV)^2$.



Large Mixing Angles

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = R_{23} R_{13} R_{12} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

solar LMA MSW

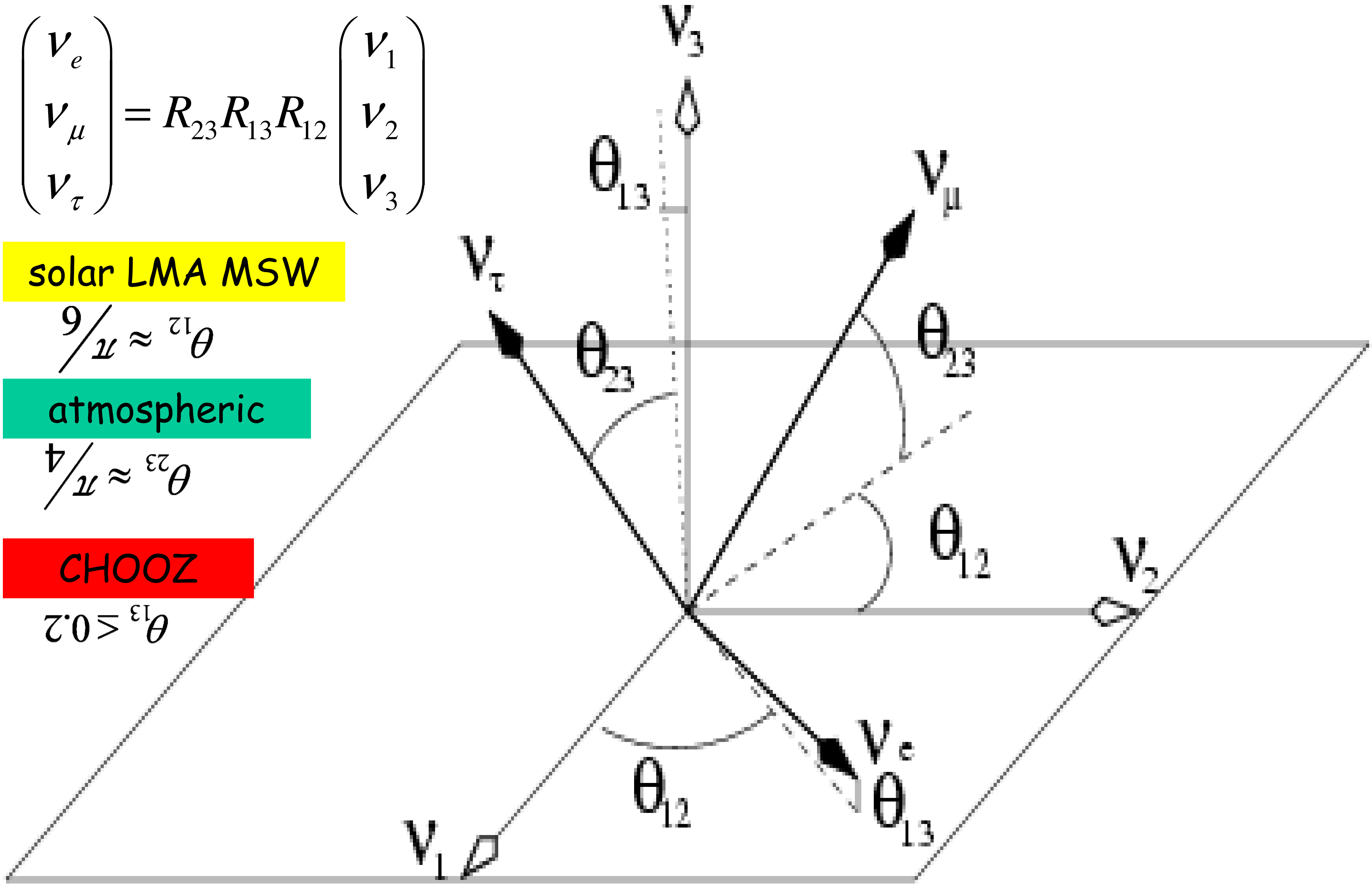
$\theta_{12} \approx \pi/6$

atmospheric

$\theta_{23} \approx \pi/4$

CHOOZ

$\theta_{13} \leq 0.2$



The Neutrino Mixing Matrix U

$$V^{E_L} m^E_{LR} V^{E_R \dagger} = \begin{pmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{pmatrix}$$

Majorana matrix ↓

$$V^{\nu_L} m^\nu_{LL} V^{\nu_L T} = \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix}$$

Constructing ⇒

$$U = V^{E_L} V^{\nu_L \dagger}$$

Parametrising ⇒

$$U = R_{23} U_{13} R_{12} P_{12}$$

$$P_{12} = \begin{pmatrix} e^{i\beta_1} & 0 & 0 \\ 0 & e^{i\beta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

Three Family Oscillation formulae in vacuum

$$P(\nu_e \to \nu_\mu) = P^+(\nu_e \to \nu_\mu) + P^-(\nu_e \to \nu_\mu)$$

$$P(\bar{\nu}_e \to \bar{\nu}_\mu) = P^+(\bar{\nu}_e \to \bar{\nu}_\mu) + P^-(\bar{\nu}_e \to \bar{\nu}_\mu)$$

CP even $\quad P^+(\bar{\nu}_e \to \bar{\nu}_\mu) = P^+(\nu_e \to \nu_\mu)$

CP odd $\quad P^-(\bar{\nu}_e \to \bar{\nu}_\mu) = -P^-(\nu_e \to \nu_\mu)$

$$\begin{aligned} P^+(\nu_e \to \nu_\mu) = &-4\,\mathrm{Re}(U_{e1}U^*_{\mu 1}U^*_{e2}U_{\mu 2})\sin^2(1.27\Delta m^2_{21}L/E) \\ &-4\,\mathrm{Re}(U_{e1}U^*_{\mu 1}U^*_{e3}U_{\mu 3})\sin^2(1.27\Delta m^2_{31}L/E) \\ &-4\,\mathrm{Re}(U_{e2}U^*_{\mu 2}U^*_{e3}U_{\mu 3})\sin^2(1.27\Delta m^2_{32}L/E) \end{aligned}$$

$$P^-(\nu_e \to \nu_\mu) = -c_{13}\sin 2\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin\delta$$

$$\times\sin(1.27\Delta m^2_{21}L/E)\sin(1.27\Delta m^2_{31}L/E)\sin(1.27\Delta m^2_{32}L/E)$$

CP odd part is large for LMA and large θ_{13} and large δ

.

CP Violation at a Neutrino Factory

e.g.Neutrino factory Golden Signature of “wrong sign” muons

$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$$

$\bar{\nu}_\mu \to \mu^+$ “right sign muons”

$\nu_\mu \to \mu^-$ “wrong sign muons” → $P(\nu_e \to \nu_\mu)$

$$\mu^- \to e^- \bar{\nu}_e \nu_\mu$$

$\nu_\mu \to \mu^-$ “right sign muons”

$\bar{\nu}_\mu \to \mu^+$ “wrong sign muons” → $P(\bar{\nu}_e \to \bar{\nu}_\mu)$

$P(\nu_e \to \nu_\mu) - P(\bar{\nu}_e \to \bar{\nu}_\mu) \propto P^-(\nu_e \to \nu_\mu)$ CP odd → δ

Origin of neutrino mass

In the Standard Model neutrinos are massless, and a neutrino and anti-neutrino are distinguished by a (total) conserved lepton number L.

Majorana or Dirac?

Majorana mass

(violates L)

$$m_{LL}\overline{\nu}_L \nu_L^c$$

CP conjugate of left-handed neutrino

$$M_{RR}\overline{\nu}_R \nu_R^c$$

Right-handed neutrinos

Dirac mass

(conserves L)

$$m_{LR}\overline{\nu}_L \nu_R$$

from Yukawa couplings

See-saw mechanism

Diracmatrix

$$\begin{pmatrix} \overline{\nu_L} & \overline{\nu_R^c} \end{pmatrix} \begin{pmatrix} 0 & m_{LR} \\ m_{LR}^T & M_{RR} \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

Heavy Majorana matrix

Diagonalise $\rightarrow m_{LL} \bar{\nu}_L \nu_L^c$

Light Majorana matrix $\rightarrow$

$$m_{LL} = m_{LR} M_{RR}^{-1} m_{LR}^T$$

Leading order m_{LL} consistent with LMA MSW

Barbieri,Hall,Smith,Strumia,Weiner;Altarelli,Feruglio;…

Natural cases: SFK hep-ph/0204360

	Type A (zero in 11)	Type B (non-zero 11)
Hierarchy $m_1^2 \square\ m_2^2 \square\ m_3^2$	$m_{LL}^{HI} \approx \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix} \frac{m}{2}$	Large neutrinoless double beta decay
Inverted hierarchy $m_1^2 \square\ m_2^2 \square\ m_3^2$	$m_{LL}^{IH(A)} \approx \begin{pmatrix} 0 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \frac{m}{\sqrt{2}}$	$m_{LL}^{IH(B)} \approx \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1/2 & 1/2 \\ 0 & 1/2 & 1/2 \end{pmatrix} m$
Degenerate $m_1^2 \approx m_2^2 \approx m_3^2$	$m_{LL}^{DEG(A)} \approx \begin{pmatrix} 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & \frac{1}{2} & \frac{1}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{2} & \frac{1}{2} \end{pmatrix} m$	$m_{LL}^{DEG(B1)} \approx \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} m$; $m_{LL}^{DEG(B2)} \approx \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} m$

Pseudo-Dirac

Natural Neutrino Hierarchy?

$$m_{LL}^{HI} \approx \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix} \frac{m}{2}$$

Natural eigenvalues are $m_2^2 \approx m_3^2$ why $m_2^2 \ll m_3^2$?

Technically need a small 23 sub-determinant:

$$\det \begin{pmatrix} m_{22} & m_{23} \\ m_{23} & m_{33} \end{pmatrix} << m^{2} \qquad \rightarrow m_2 << m_3$$

- But why should the sub-determinant be small ?
- How can we get this from the see-saw mechanism?

See-saw with diagonal heavy Majorana matrix

Columns can be re-ordered without loss of generality

$$M_{RR} = \begin{pmatrix} X' & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & Y \end{pmatrix} \qquad m_{LR} = \begin{pmatrix} a' & a & d \\ b' & b & e \\ c' & c & f \end{pmatrix}$$

$$M_{RR} = \begin{pmatrix} Y & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X' \end{pmatrix} \qquad m_{LR} = \begin{pmatrix} d & a & a' \\ e & b & b' \\ f & c & c' \end{pmatrix}$$

$$m_{LL} = m_{LR} M_{RR}^{-1} m_{LR}^{T} = \begin{pmatrix} \left(\frac{a'^2}{X'}+\frac{a^2}{X}+\frac{d^2}{Y}\right) & \left(\frac{a'b'}{X'}+\frac{ab}{X}+\frac{de}{Y}\right) & \left(\frac{a'c'}{X'}+\frac{ac}{X}+\frac{df}{Y}\right) \\ . & \left(\frac{b'^2}{X'}+\frac{b^2}{X}+\frac{e^2}{Y}\right) & \left(\frac{b'c'}{X'}+\frac{bc}{X}+\frac{ef}{Y}\right) \\ . & . & \left(\frac{c'^2}{X'}+\frac{c^2}{X}+\frac{f^2}{Y}\right) \end{pmatrix}$$

If one right-handed neutrino of mass Y dominates then sub-determinant is naturally small: single right-handed neutrino dominance (SFK PLB 98, NPB 99)

$$\frac{|e|^2, |f|^2, |ef|}{Y} \gg \frac{|xy|}{X} \gg \frac{|x'y'|}{X'},$$

$$x, y \in a, b, c, \quad x', y' \in a', b', c'$$

Sequential dominance
(SFK NPB2000)

Analytic estimates for neutrino masses and mixing angles (valid for sequential dominance)

SFK hep-ph/0204360

Sequential dominance

Mass hierarchy and large mixing angles naturally!

$$\frac{|e|^2,|f|^2,|ef|}{Y} \gg \frac{|xy|}{X} \gg \frac{|x'y'|}{X'}, \qquad |d| \ll |e| \approx |f|$$

$$x, y \in a, b, c, \quad x', y' \in a', b', c'$$

(set d=0 below)

$$m_1 \ll m_2 \ll m_3 \quad \begin{cases} m_1 \sim O(\frac{x'y'}{X'}) \\ m_2 \approx \frac{|a|^2}{X s_{12}^2} \\ m_3 \approx \frac{|e|^2+|f|^2}{Y} \end{cases}$$

$$\tan\theta_{23} \approx \frac{|e|}{|f|}$$

$$\tan\theta_{12} \approx \frac{|a|}{c_{23}|b|\cos(\tilde{\phi}_b) - s_{23}|c|\cos(\tilde{\phi}_c)}$$

$$\theta_{13} \approx e^{i(\tilde{\phi}+\phi_a-\phi_e)} \frac{|a|(e^*b+f^*c)Y}{\left[|e|^2+|f|^2\right]^{3/2} X}$$

Phases fixed by real 12 angle condition $c_{23}|b|\sin(\tilde{\phi}_b) \approx s_{23}|c|\sin(\tilde{\phi}_c)$

where $\tilde{\phi}_b \equiv \phi_b - \phi_a - \tilde{\phi} + \delta$ $\qquad \tilde{\phi}_c \equiv \phi_c - \phi_a + \phi_e - \phi_f - \tilde{\phi} + \delta$

and $\tilde{\phi}$ is fixed by the real 13 angle condition $\tilde{\phi} \equiv \phi_e - \phi_a - \arg(e^*b + f^*c)$

Light or Heavy Sequential Dominance?

Heavy Sequential Dominance (HSD) $X' \ll X \ll Y$

$$M_{RR} = \begin{pmatrix} X' & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & Y \end{pmatrix} \qquad Y^{\nu}_{LR} = \begin{pmatrix} a' & a & d \\ b' & b & e \\ c' & c & f \end{pmatrix} \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 1 \end{pmatrix}$$

"Lop-sided"
(large 23 element)

Light Sequential Dominance (LSD) $Y \ll X \ll X'$

$$M_{RR} = \begin{pmatrix} Y & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X' \end{pmatrix} \qquad Y^{\nu}_{LR} = \begin{pmatrix} d & a & a' \\ e & b & b' \\ f & c & c' \end{pmatrix} \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

"Quark-like"
(no large off-diagonal entries)

Note that X' is irrelevent for neutrino masses, mixings (and leptogenesis-see later), and the model reduces to an effective 2 right-handed neutrino model

SFK 2000; Frampton,Glashow,Yanagida 2002; Raidal,Strumia 2002.

Leptogenesis

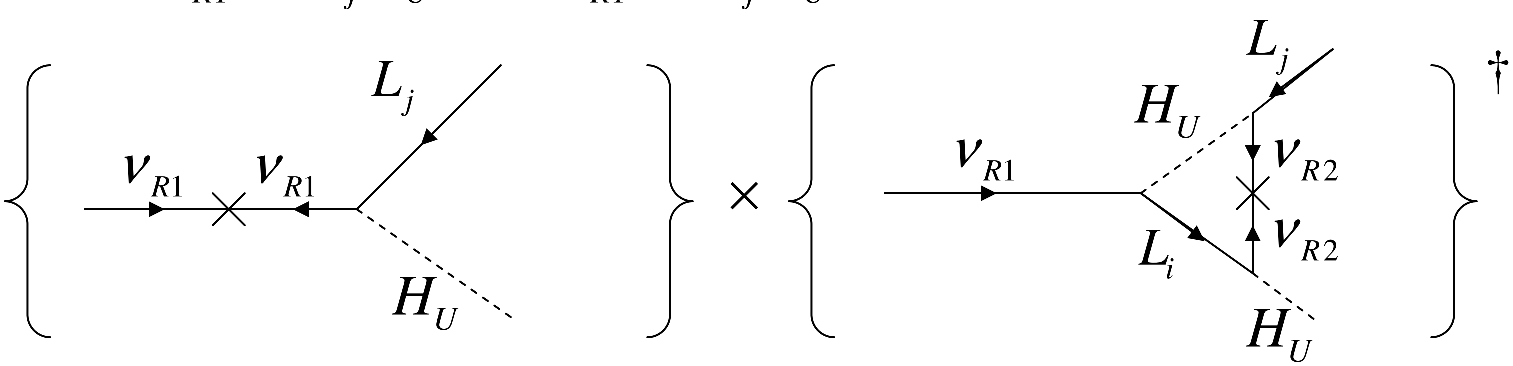
Fukugita,Yanagida; Buchmuller,Plumacher; Di Bari,…

- Right-handed neutrinos are produced in early universe and decay out of equilibrium giving net lepton number L
- CP violation from complex Yukawa couplings
- L is processed into B via B-L conserving sphalerons

$$Y_B = \frac{baryons}{photons} \approx 10^{-10} \approx -d\varepsilon_1 / g^*$$

$$\varepsilon_1 \approx \frac{\Gamma(\nu_{R1} \to L_j \bar{H}_U) - \Gamma(\bar{\nu}_{R1} \to \bar{L}_j H_U)}{\Gamma(\nu_{R1} \to L_j \bar{H}_U) + \Gamma(\bar{\nu}_{R1} \to \bar{L}_j H_U)}$$

$$\varepsilon_1 \approx -\frac{3}{8\pi} \frac{M_1}{M_2} \frac{\mathrm{Im}\{[(Y_{LR}^\dagger Y_{LR})_{12}]^2\}}{(Y_{LR}^\dagger Y_{LR})_{11}}$$



Relation between CP violation at a neutrino factory and in leptogenesis for LSD SFK hep-ph/0211228

LSD

$X' \ll X \ll Y \approx 10^{12}\, GeV$

Di Bari,Buchmuller,Plumacher

$$M_{RR} = \begin{pmatrix} Y & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X' \end{pmatrix}$$

Assume 11 texture zero (common in many models)

$$Y_{LR}^{\nu} = \begin{pmatrix} 0 & a & a' \\ e & b & b' \\ f & c & 1 \end{pmatrix}$$

In LSD the heavy RH neutrino of mass X' is irrelevant for both leptogenesis and neutrino masses, mixings

$$Y_B \propto +\mathrm{Im}\{[(Y_{LR}^{\dagger} Y_{LR})_{12}]^2\} \propto +\sin 2\phi_{COSMO} \qquad \phi_{COSMO} = \arg(e^* b + f^* c)$$

$$\tan(\phi_{COSMO}) \approx \frac{|b| s_{23} \sin\eta_2 + |c| c_{23} \sin\eta_3}{|b| s_{23} \cos\eta_2 + |c| c_{23} \cos\eta_3} \qquad \tan(\phi_{COSMO} + \delta) \approx \frac{|b| c_{23} \sin\eta_2 - |c| s_{23} \sin\eta_3}{-|b| c_{23} \cos\eta_2 + |c| s_{23} \cos\eta_3}$$

Neutrino factory phase and leptogenesis phase are linked in terms of two invariant see-saw phases $\eta_2 \equiv \phi_b - \phi_e, \quad \eta_3 \equiv \phi_c - \phi_f$

Remarkably the leptogenesis phase is equal to the phase which enters neutrinoless double beta decay ! $|\phi_{COSMO}| = |\phi_{\beta\beta 0\nu}|$

In HSD $Y \ll X \ll X' \approx 10^{9}\, GeV$ (Hirsch,SFK) and gravitino bound may be respected. In this case there is no leptogenesis-MNS link since X' couplings are relevant for leptogenesis but not neutrino masses, mixings.

Borzumati, Masiero; Hisano, Moroi, Tobe, Yamaguchi; SFK, Oliveira; Casas, Ibarra; Lavignac, Masina, Savoy; …

SUSY and Lepton Flavour Violation

If SUSY is present then neutrino masses inevitably lead to lepton flavour violation due to radiatively generated off-diagonal slepton masses

$$BR(\tau \to \mu\gamma) \approx \frac{\alpha^3}{G_F^2} f_{32}(M_2, \mu, m_{\tilde{\nu}}) \,|\, m^2_{\tilde{L}_{32}} \,|^2 \tan^2\beta$$

$$\frac{dm^2_{\tilde{L}}}{dt} \approx \left(\frac{dm^2_{\tilde{L}}}{dt}\right)_{Y_{LR}=0} - \frac{(3m_0^2 + A_0^2)}{16\pi^2}\left[Y_{LR}Y_{LR}^\dagger\right] \Rightarrow m^{2(LLA)}_{\tilde{L}_{32}} \approx -\frac{(3m_0^2 + A_0^2)}{8\pi^2} C_{32}$$

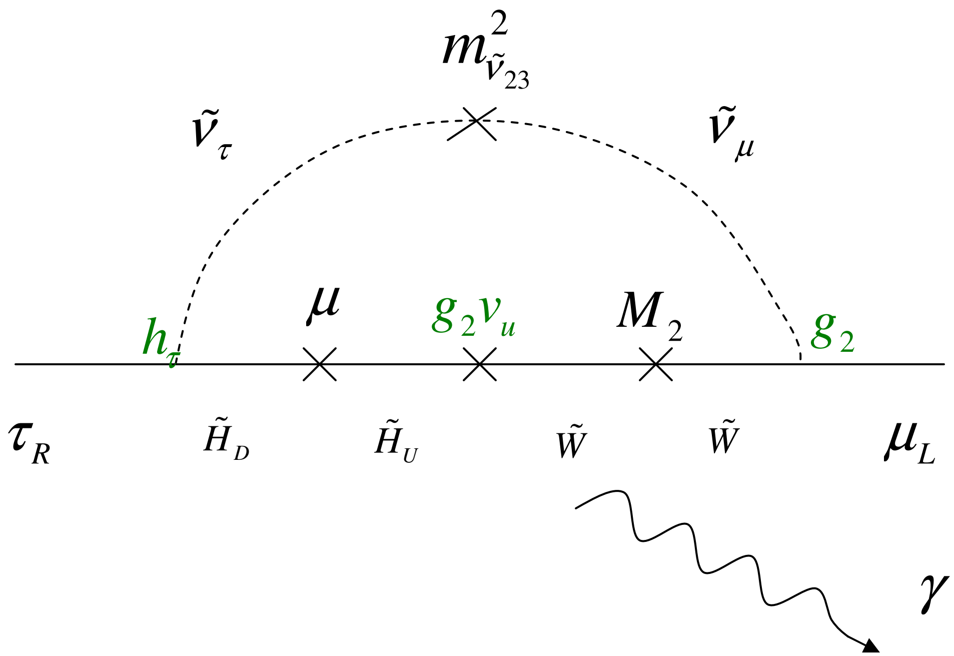
$$C_{32} \approx b'c' \ln\left(\frac{M_{GUT}}{X'}\right) + bc \ln\left(\frac{M_{GUT}}{X}\right) + ef \ln\left(\frac{M_{GUT}}{Y}\right)$$

$$M_{RR} = \begin{pmatrix} X' & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & Y \end{pmatrix} \qquad Y^{\nu}_{LR} = \begin{pmatrix} a' & a & d \\ b' & b & e \\ c' & c & f \end{pmatrix} \approx \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 1 \end{pmatrix}$$

HSD/lopsided will lead to large $BR(\tau \to \mu\gamma)$ due to large 23 Yukawa.

Blazek, SFK

$$\tau \to \mu\gamma$$



Lepton Flavour Violation in Constrained Minimal Supersymmetric Standard Model

Blazek,SFK hep-ph/0211368

HSD parametrisation with dominant heaviest RH neutrino in 33 position

$$M_{RR} = \begin{pmatrix} \sim 1 & 0 & 0 \\ 0 & A\lambda^{2n-1} & 0 \\ 0 & 0 & 1 \end{pmatrix} 3.10^{14}\,GeV$$

$$Y_{LR} = \begin{pmatrix} - & a_{12}\lambda^n & 0 \\ - & a_{22}\lambda^n & a_{23} \\ - & a_{32}\lambda^n & 1 \end{pmatrix} h_t$$

Large 23 element (lop-sided)

$$a_{ij} = O(1)$$

$$\lambda = \sqrt{\frac{\Delta m_{21}^2}{\Delta m_{32}^2}} \approx 0.15$$

$$n > 0$$

LSD parametrisation with dominant lightest RH neutrino in 11 position

$$M_{RR} = \begin{pmatrix} f^2 & 0 & 0 \\ 0 & A\lambda^{2n-1} f^2 & 0 \\ 0 & 0 & \sim 1 \end{pmatrix} 3.10^{14}\,GeV$$

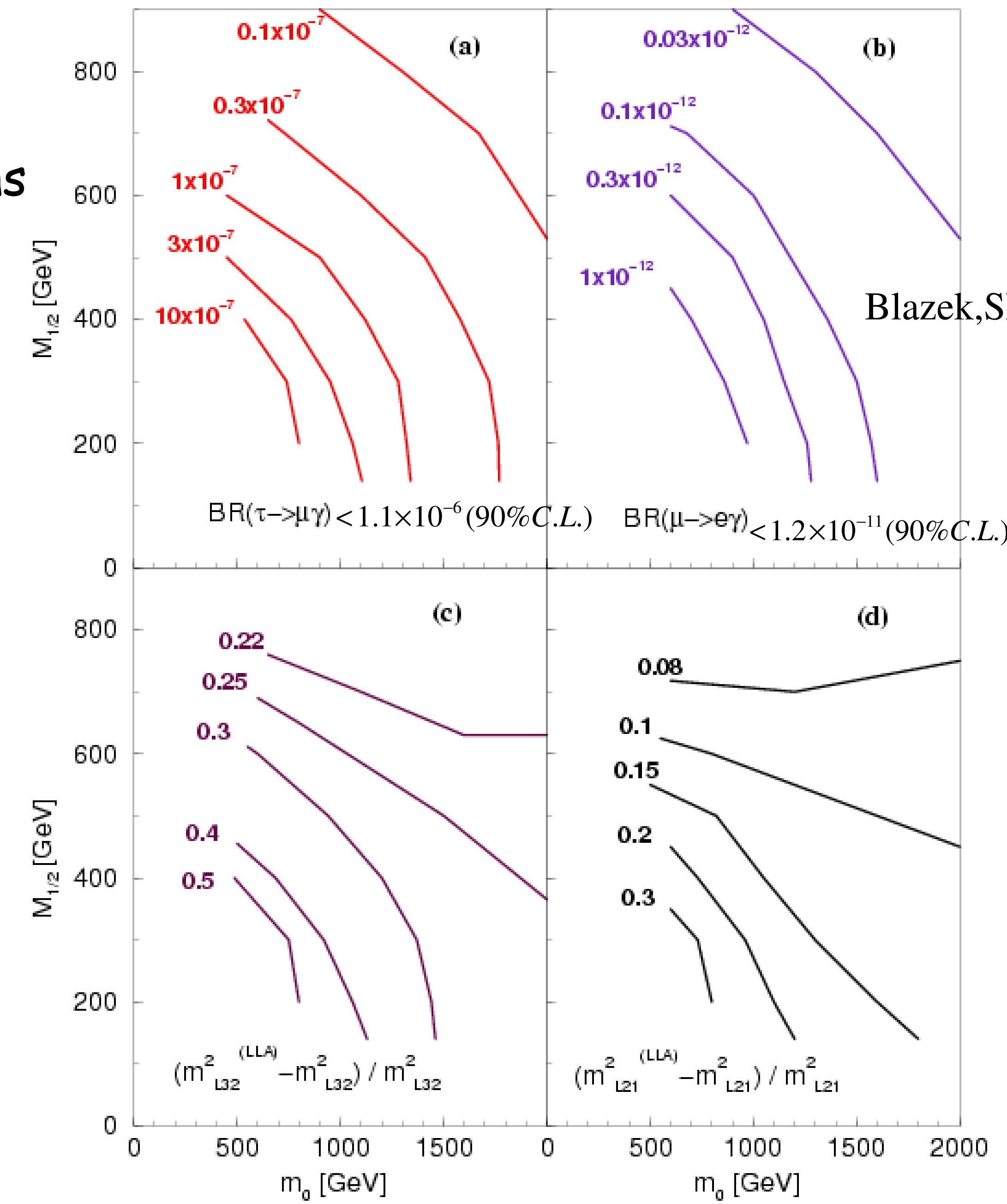
$$Y_{LR} = \begin{pmatrix} 0 & a_{12}\lambda^n f & - \\ a_{23} f & a_{22}\lambda^n f & - \\ f & a_{32}\lambda^n f & 1 \end{pmatrix} h_t$$

$$f = a_{31}\lambda^p$$

$$n < 0 < p$$

HSD predictions

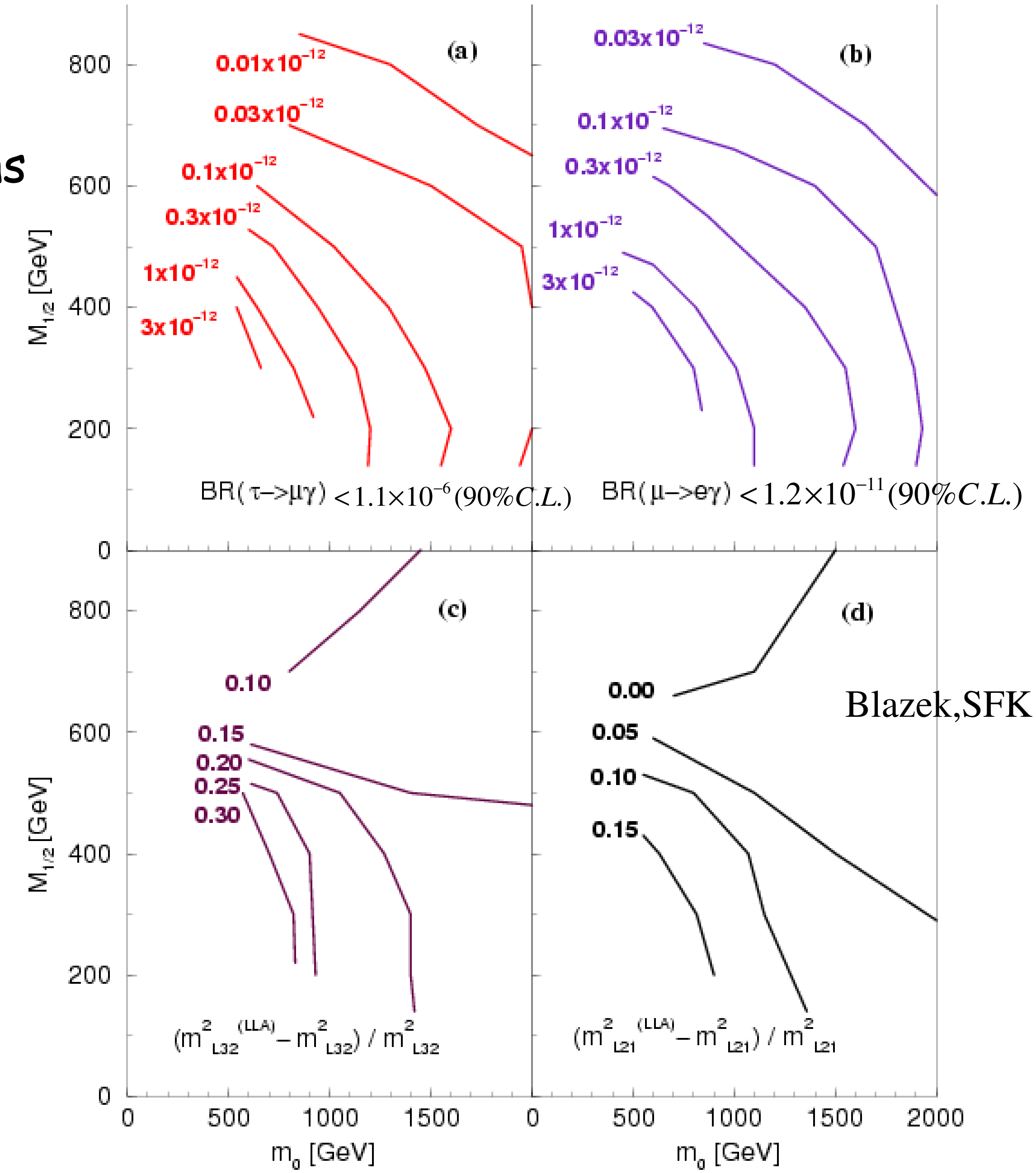
$$\tan\beta = 50,$$
$$n = 2,$$
$$r = \frac{a_{32}}{a_{22}} = -1.$$



Blazek,SFK hep-ph/0211368

LSD predictions

$$\tan\beta = 50,$$
$$p + n = 2,$$
$$n = -1,$$
$$r = \frac{a_{32}}{a_{22}} = -1.$$



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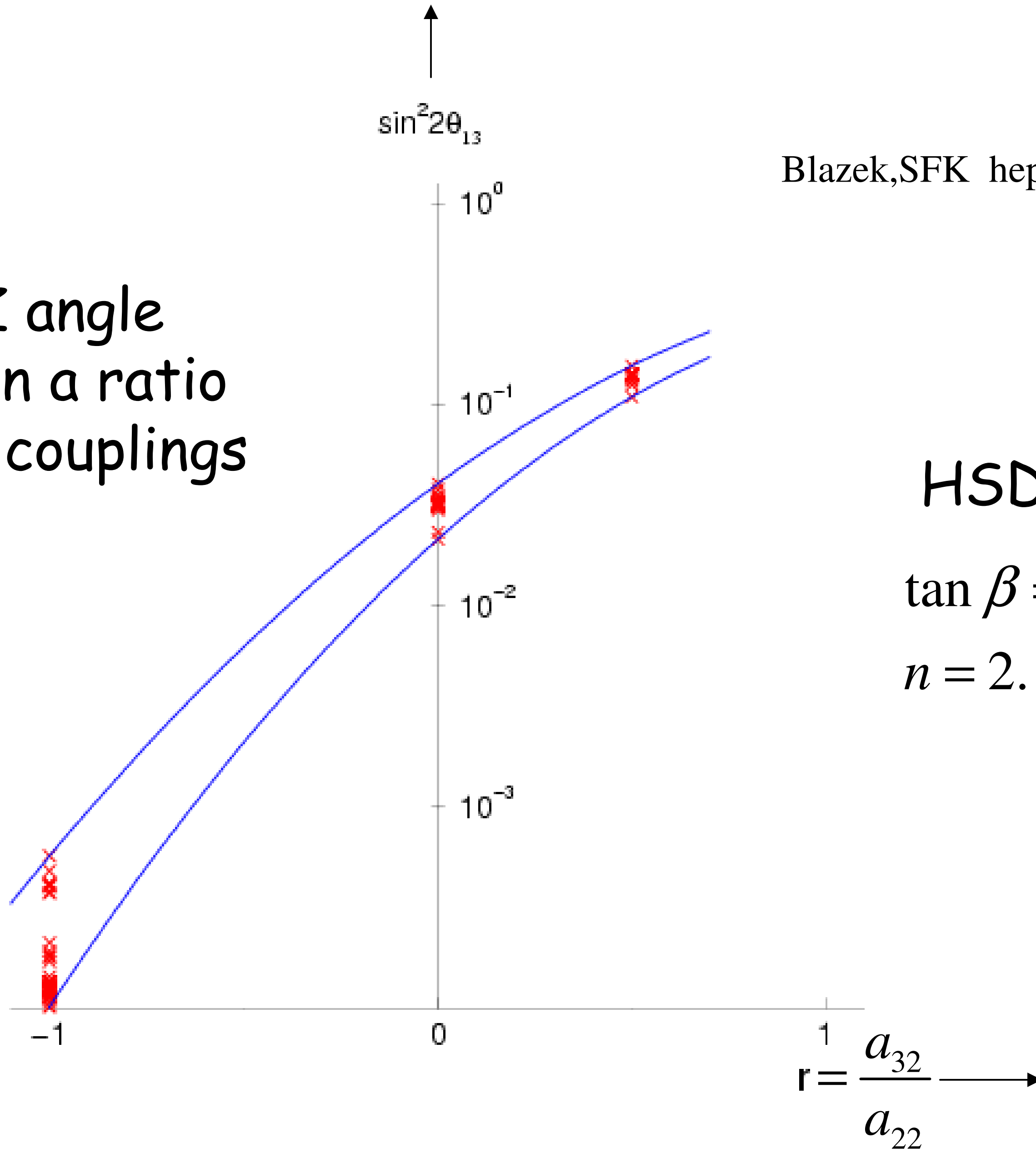
CHOOZ angle depends on a ratio of Yukawa couplings



θ_{13}	$\sin^2 2\theta_{13}$
10^o	0.12
5^o	3.0×10^{-2}
1^o	1.2×10^{-3}
$.5^o$	3.0×10^{-4}

HSD

$\tan\beta = 50,$

$n = 2.$

Conclusion

- LMA MSW is established, along with atmospheric neutrino mixing
  $\theta_{12} \approx 30^o, \quad \theta_{23} \approx 45^o, \quad \theta_{13} \le 10^o \quad |\Delta m^2_{32}| \approx (0.05\, eV)^2 \quad \Delta m^2_{21} \approx (0.008\, eV)^2$
- Heaviest neutrino mass from cosmology and osc. $0.05\, eV < m_\nu^{heaviest} < 0.23\, eV$
- LMA MSW allows CP phase to be measured (maybe) at neutrino factory
- Small neutrino masses can be elegantly explained by the see-saw
- Sequential dominance then provides a natural explanation of a neutrino mass hierarchy and large mixing angles
- The dominant right-handed neutrino may be either the heaviest (HSD) or the lightest one (LSD)
- LSD links leptogenesis phase and the CP phase which is measurable at a neutrino factory, but is inconsistent with SUSY models
- HSD has no such link, but may be consistent with SUSY models
- SUSY leads to lepton flavour violating processes such as mu→e+gamma and especially tau →mu+gamma which can discriminate HSD from LSD.