LNF Spring School, May '05

Neutrinos 2005

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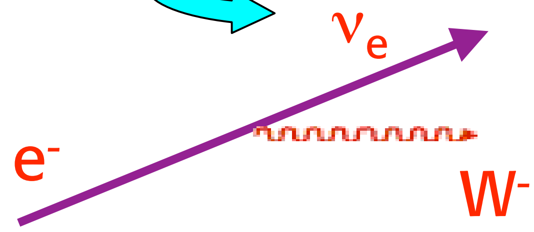
Some recent work by our group
G.A., F. Feruglio, I. Masina, hep-ph/0402155,
G.A., F. Feruglio, hep-ph/0504165
Reviews:
G.A., F. Feruglio, New J.Phys.6:106,2004 [hep-ph/0405048];
G.A., hep-ph/0410101; F. Feruglio, hep-ph/0410131

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

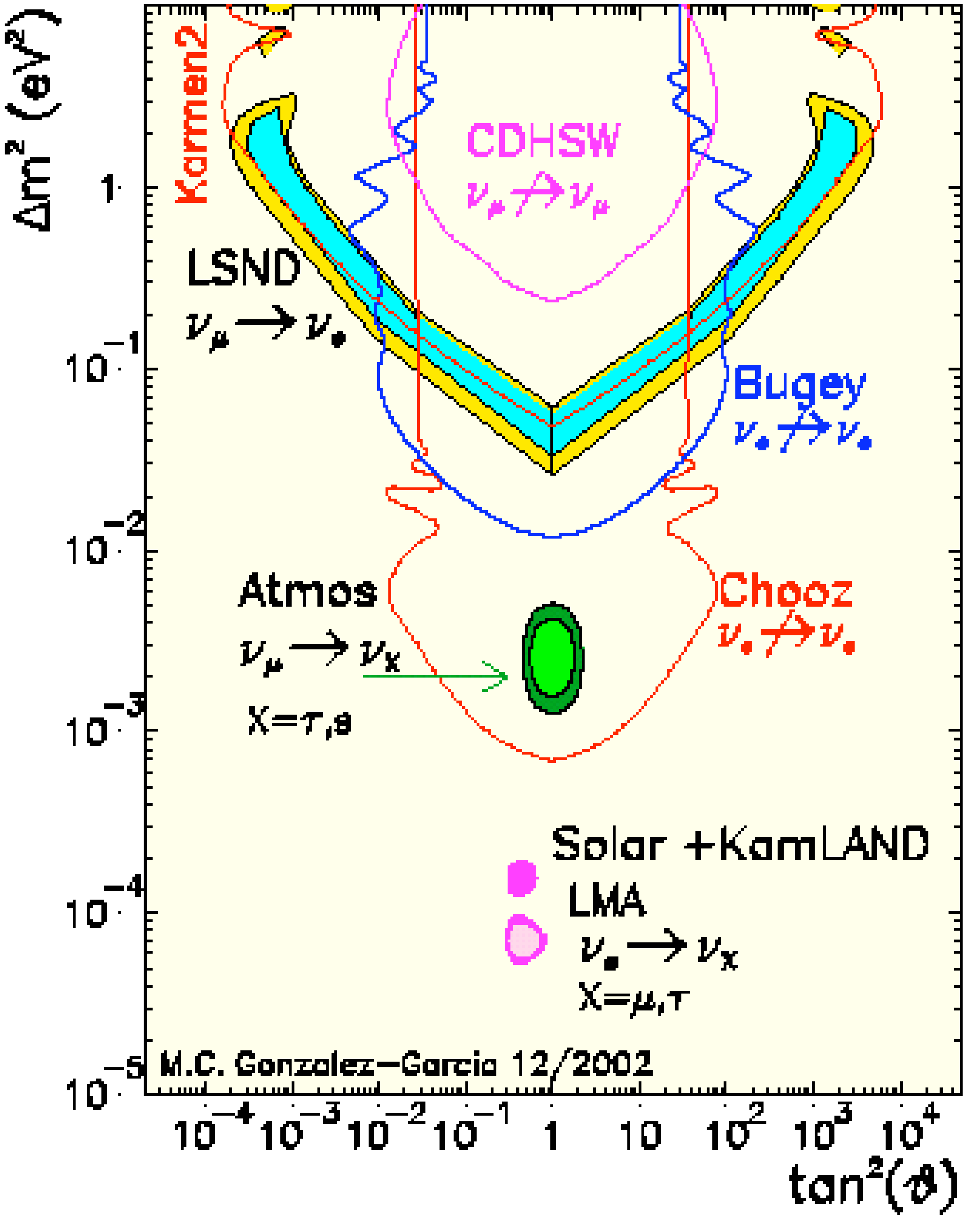
$\nu_{1,2}$: different mass, different x-dep:

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

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

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

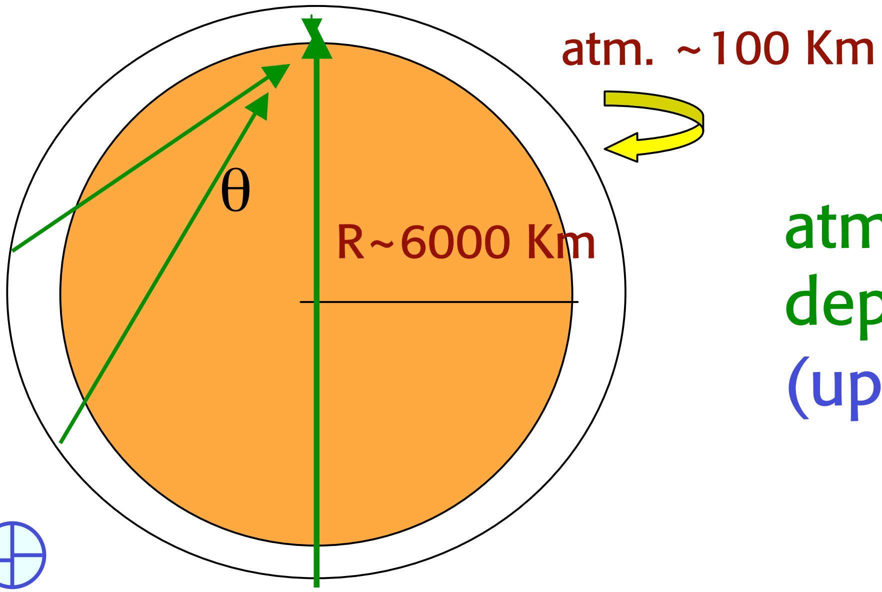
Solar ν's

$\nu_e \to \nu_{\mu,\tau}$

The data imply that the oscill's occur inside the sun thru the MSW effect (resonant oscillation induced by matter)

Mikhaev and Smirnov; Wolfenstein

Atmospheric ν's



$\nu_\mu \to \nu_\tau$

atmospheric ν's traverse different L depending on azimuth θ

(up-down asymm.)

Evolution in vacuum and in matter

$\nu_e = \cos\theta\, \nu_1 + \sin\theta\, \nu_2$

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

$\Delta m^2 = m_2^2 - m_1^2 > 0$

$$i\frac{d}{dt}\begin{bmatrix}\nu_e\\ \nu_\mu\end{bmatrix} = H_{eff}\begin{bmatrix}\nu_e\\ \nu_\mu\end{bmatrix}$$

$$H_{eff} = \frac{\Delta m^2}{4E}\begin{bmatrix}-\cos 2\theta & \sin 2\theta\\ \sin 2\theta & \cos 2\theta\end{bmatrix}$$

In vacuum, for 2 flavours, apart from multiples of the identity

In matter CC int's on electrons introduce a flavour dep.
(coherent forward scattering on electrons)

$$H_{eff} = \frac{\Delta m^2}{4E}\begin{bmatrix}-\cos 2\theta & \sin 2\theta\\ \sin 2\theta & \cos 2\theta\end{bmatrix} + \begin{bmatrix}\sqrt{2}G_F N_e & 0\\ 0 & 0\end{bmatrix}$$

N_e: n. of e per unit V

The mixing angle is changed
A resonance can appear (MSW)

$$\tan 2\theta_m = \frac{\tan 2\theta}{1 - \dfrac{2\sqrt{2}E G_F N_e}{\Delta m^2 \cos 2\theta}}$$

Mikhaev and Smirnov; Wolfenstein

Solar neutrinos

"Classic" exp's: Homestake, Gallex, (Super)Kamiokande,……
pointed to a deficit based on solar model flux calculations.

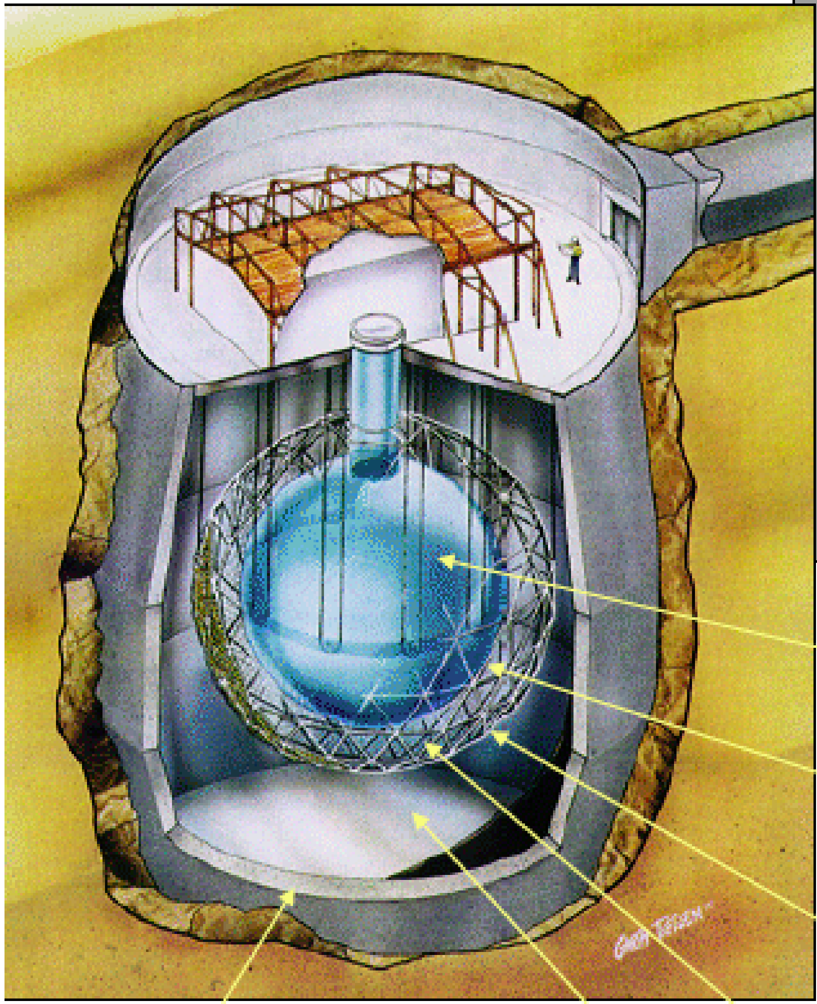
Ongoing experiments, SNO and KamLAND, proved that the effect has to do with ν physics and not with sun physics

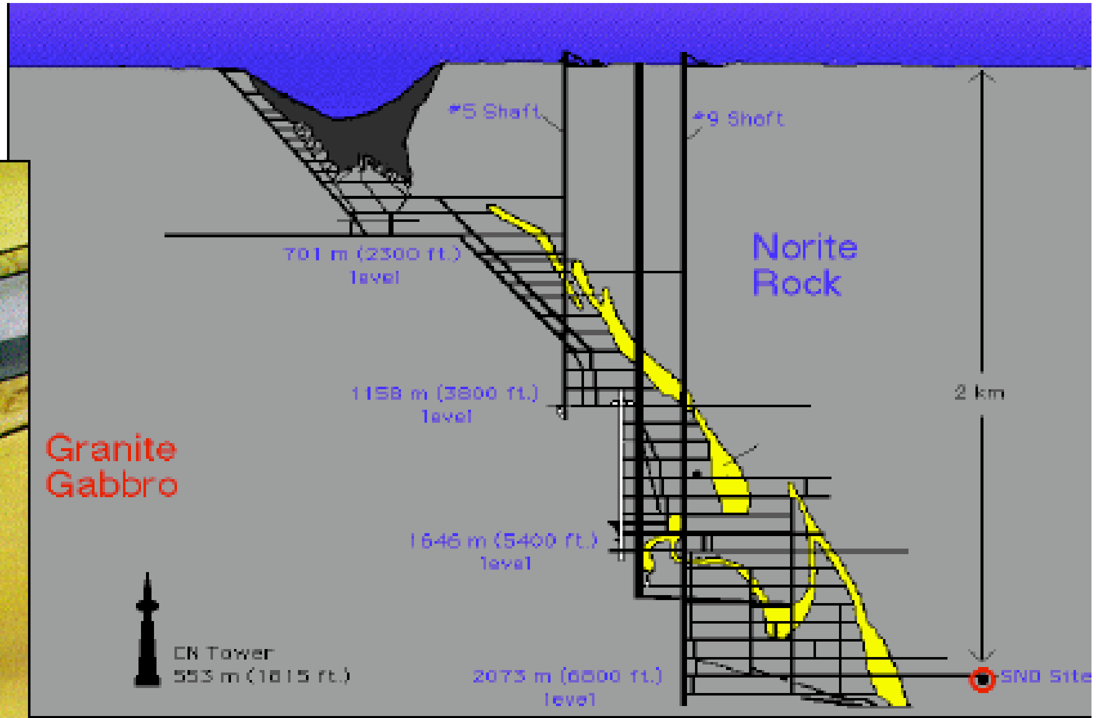
SNO: Proved that the total ν flux from the sun is in agreement with expectations but only ~1/3 is ν_e and ~2/3 is from active ν's, ie not sterile, $(\nu_\mu+\nu_\tau)$

active: with weak int.s, sterile: no weak int.s

KamLAND: Reproduced the oscillations on earth and precisely fixed Δm^2

SNO





1000 tonnes D_2O

12m Diameter Acrylic Vessel

Support Structure for 9500 PMTs, 60% coverage

Urylon Liner and Radon Seal

5300 tonnes Outer Shield H_2O

1700 tonnes Inner Shielding H_2O

CC: $\nu_e + d \rightarrow p + p + e^-$

NC: $\nu_x + d \rightarrow p + n + \nu_x$

ES: $\nu_x + e^- \rightarrow \nu_x + e^-$

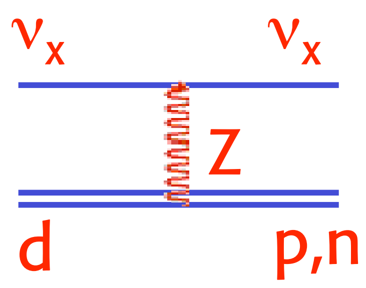
ν Reactions in SNO

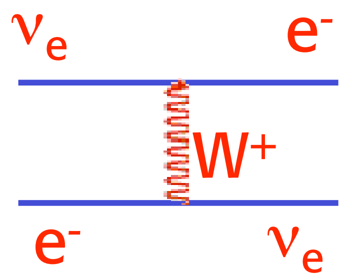
CC $\quad \nu_e + d \Rightarrow p + p + e^-$

- Good measurement of ν_e energy spectrum
- Weak directional sensitivity $\propto 1-1/3\cos(\theta)$
- ν_e only.

NC $\quad \nu_x + d \Rightarrow p + n + \nu_x$

- Equal cross section for all ν types
- Measure total ^8B ν flux from the sun.





ES $\quad \nu_x + e^- \Rightarrow \nu_x + e^-$

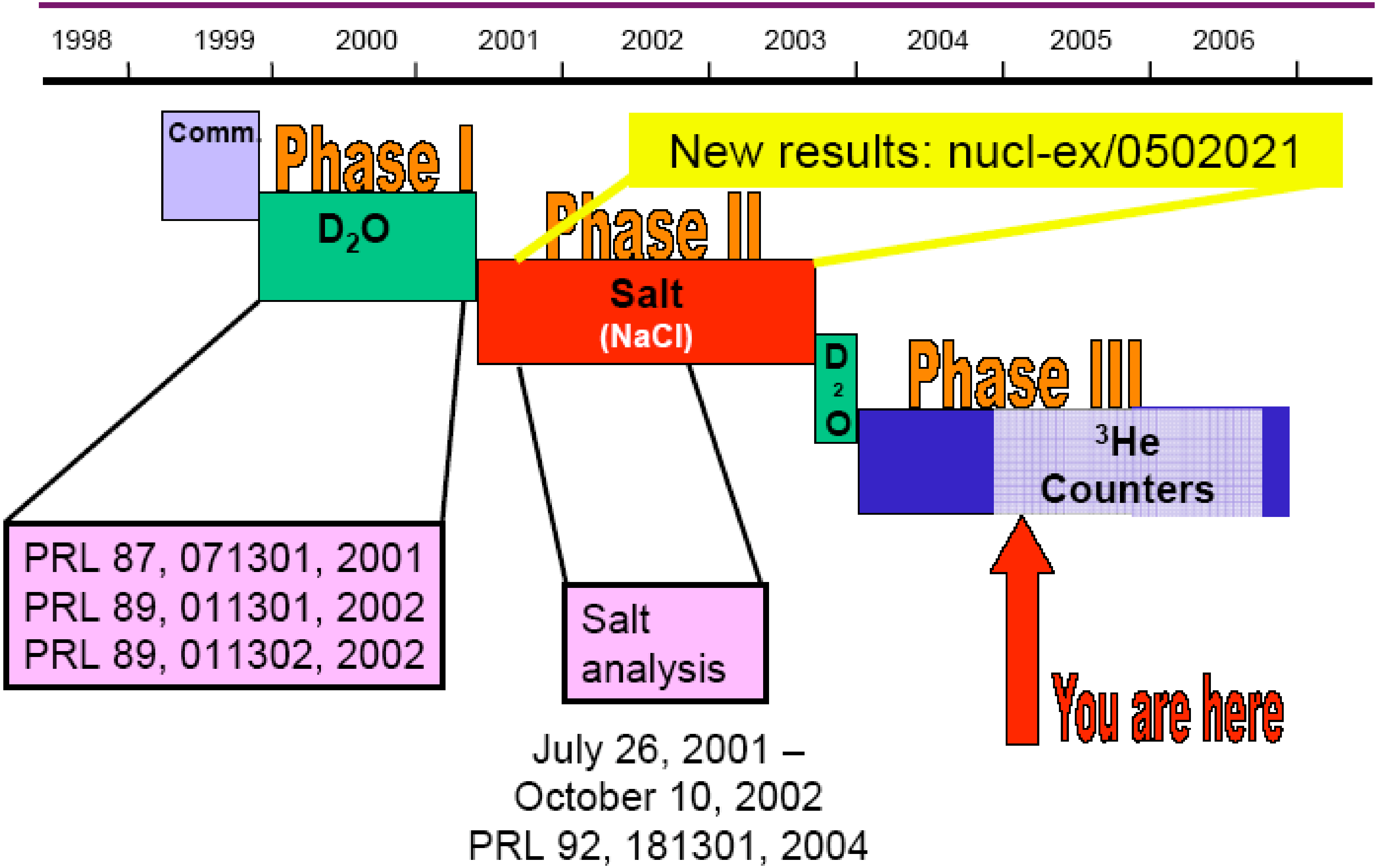
- Low Statistics
- Mainly sensitive to ν_e, some sensitivity to ν_μ and ν_τ
- Strong directional sensitivity

$$\frac{\Phi_{cc}}{\Phi_{es}} = \frac{\nu_e}{\nu_e + 0.154(\nu_\mu + \nu_\tau)} = 1\ ?$$

$$\frac{\Phi_{cc}}{\Phi_{nc}} = \frac{\nu_e}{\nu_e + \nu_\mu + \nu_\tau} = 1\ ?$$

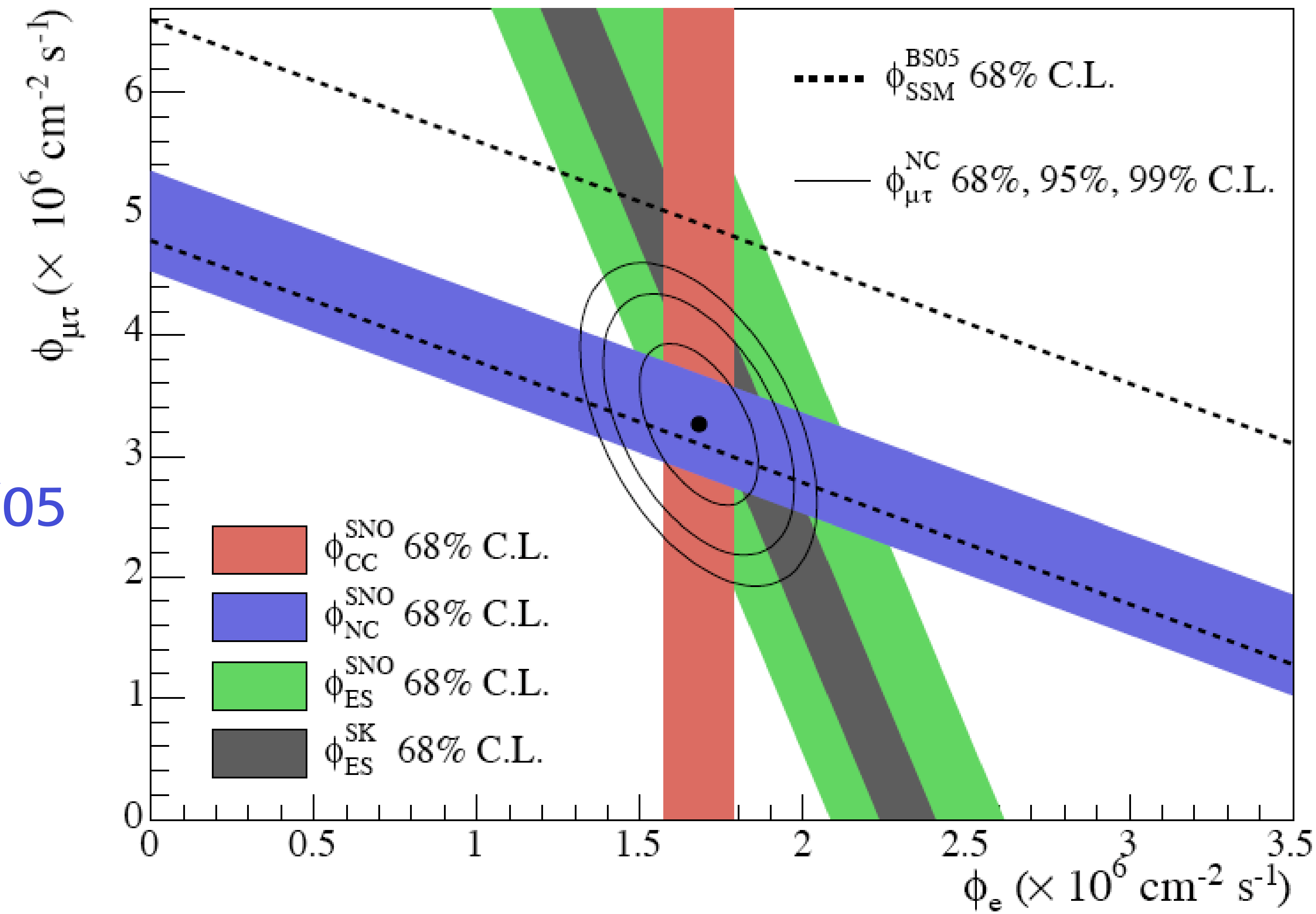
Wilson

SNO Program



The measured total ν flux is in perfect agreement with the Solar Standard Model!! But: $\Phi_e \sim 1/3\ (\Phi_e + \Phi_\mu + \Phi_\tau)$

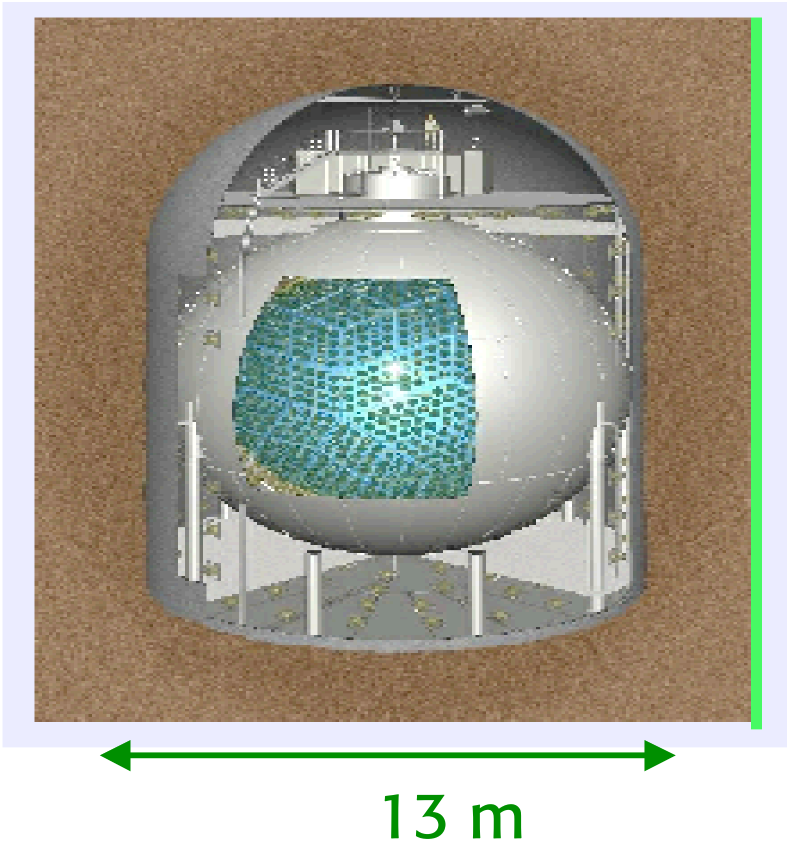
SNO'05



Direct evidence for $\nu_e \rightarrow \nu_{\mu,\tau}$ oscill's as solution of the solar ν_e deficit!

KamLAND

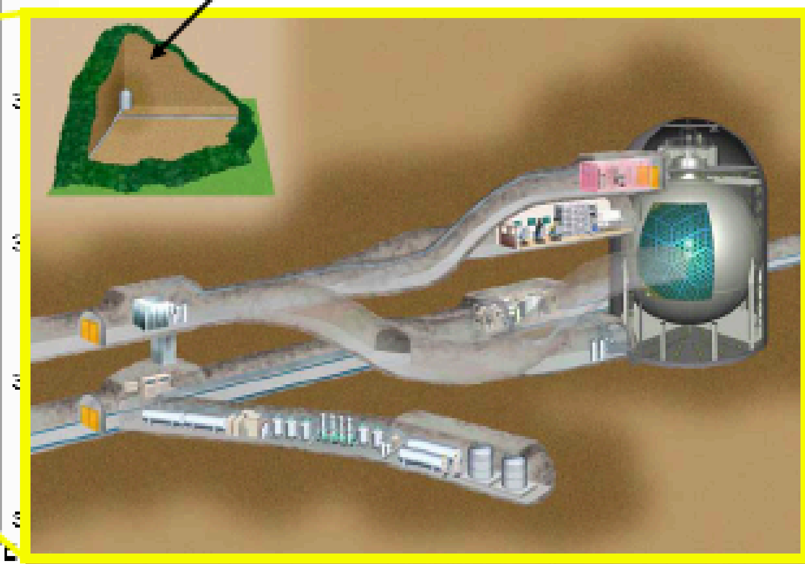
Kamioka
Liquid
scintillator
AntiNeutrino
Detector



Reactor $\bar{\nu}_e$ (E>2.6 MeV) detected ~180 Km away at Kamiokande site

e-antineutrinos
from many
reactors

~1 km high
Mt Ikenoyama



First results from KamLAND

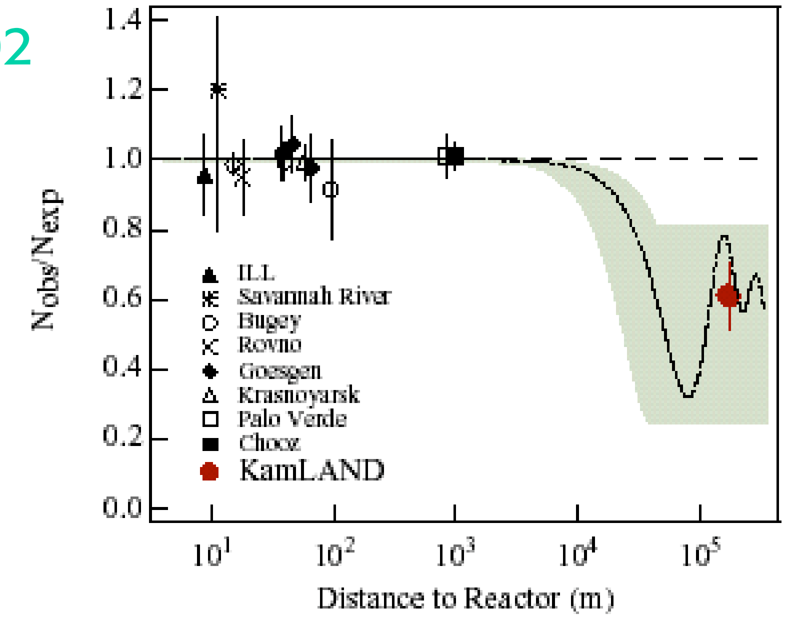
2002

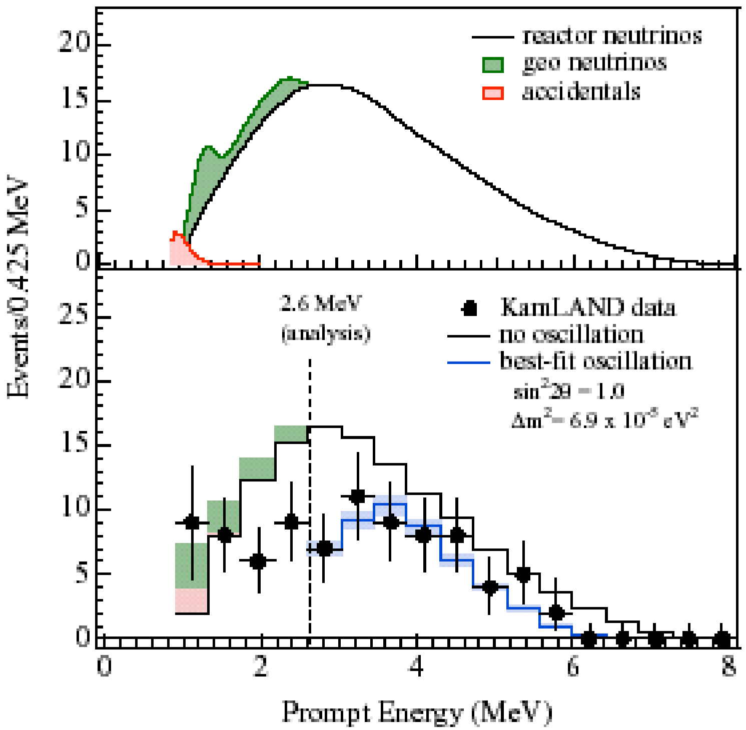
- Solar oscill.'s confirmed on earth
- Large angle sol. established

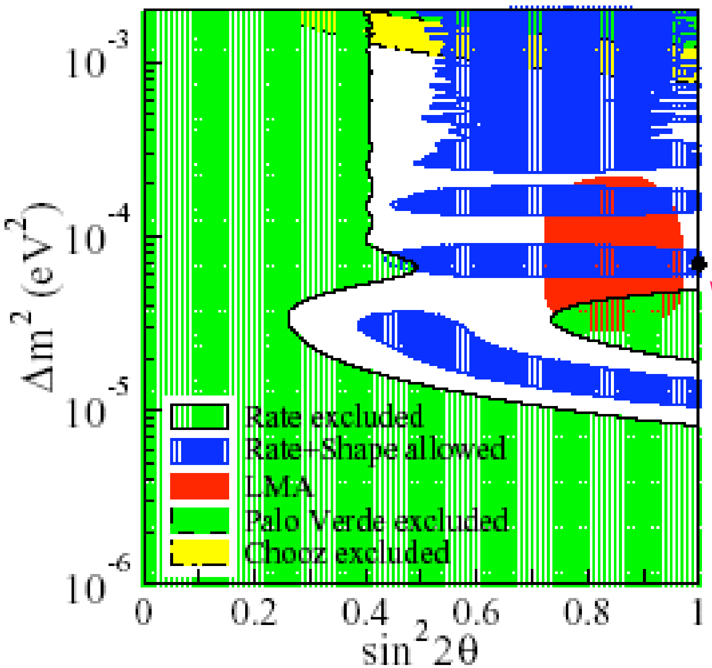
Best fit: $\Delta m^2 \sim 7.10^{-5}$ eV^2, $\sin^2 2\theta = 1$

- $\overline{\nu}_e$ from reactors behave as ν_e from sun:

Constraint on ~~CPT~~ models







Best fit

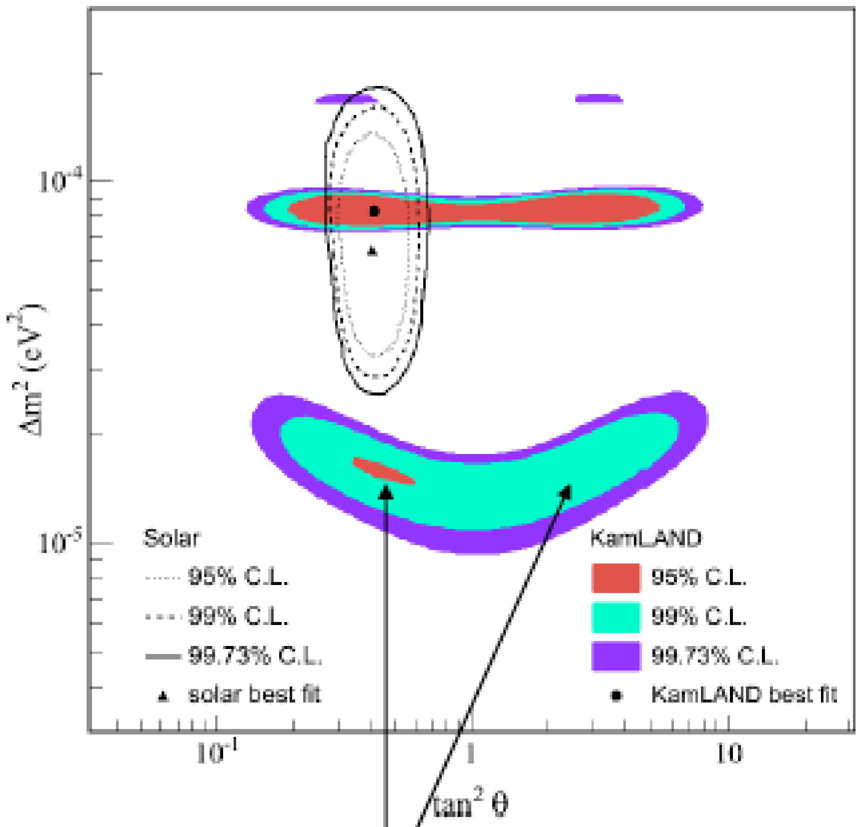
KamLAND brings $\Delta\nu_{solar}$ down to earth!

Combined solar ν - KamLAND 2-flavor analysis

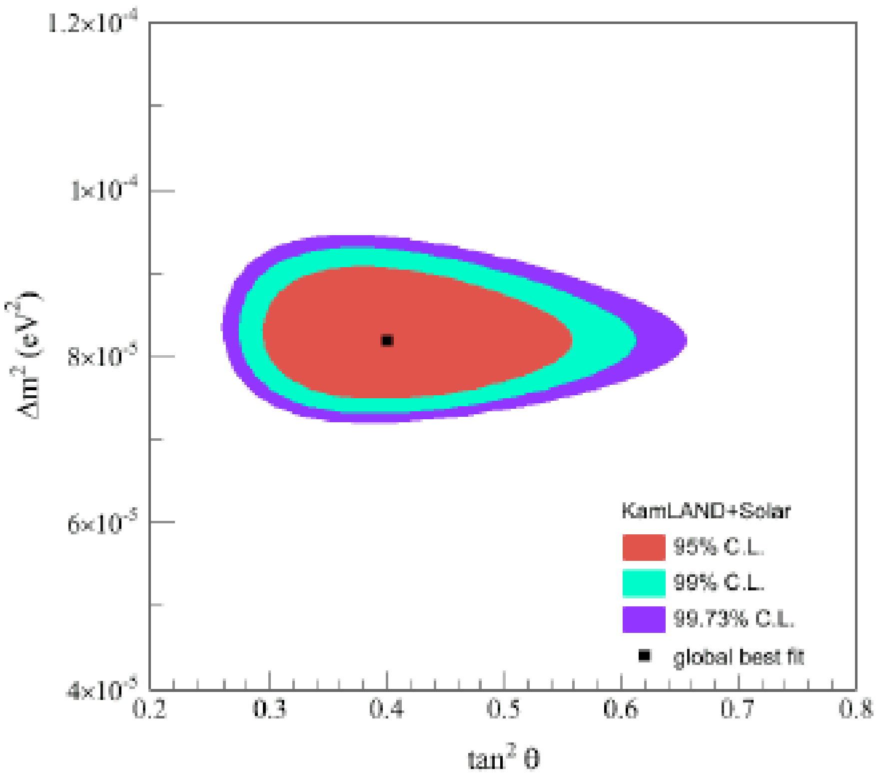
June'04

$$\Delta m_{12}^2 = 8.2^{+0.6}_{-0.5} \times 10^{-5}\, eV^2$$

$$\tan^2\theta_{12} = 0.40^{+0.09}_{-0.07}$$



Includes (small) matter effects



- KamLAND has tremendous sensitivity to Δm^2_{21}
- Does not constrain θ_{12} much better than the current set of solar experiments

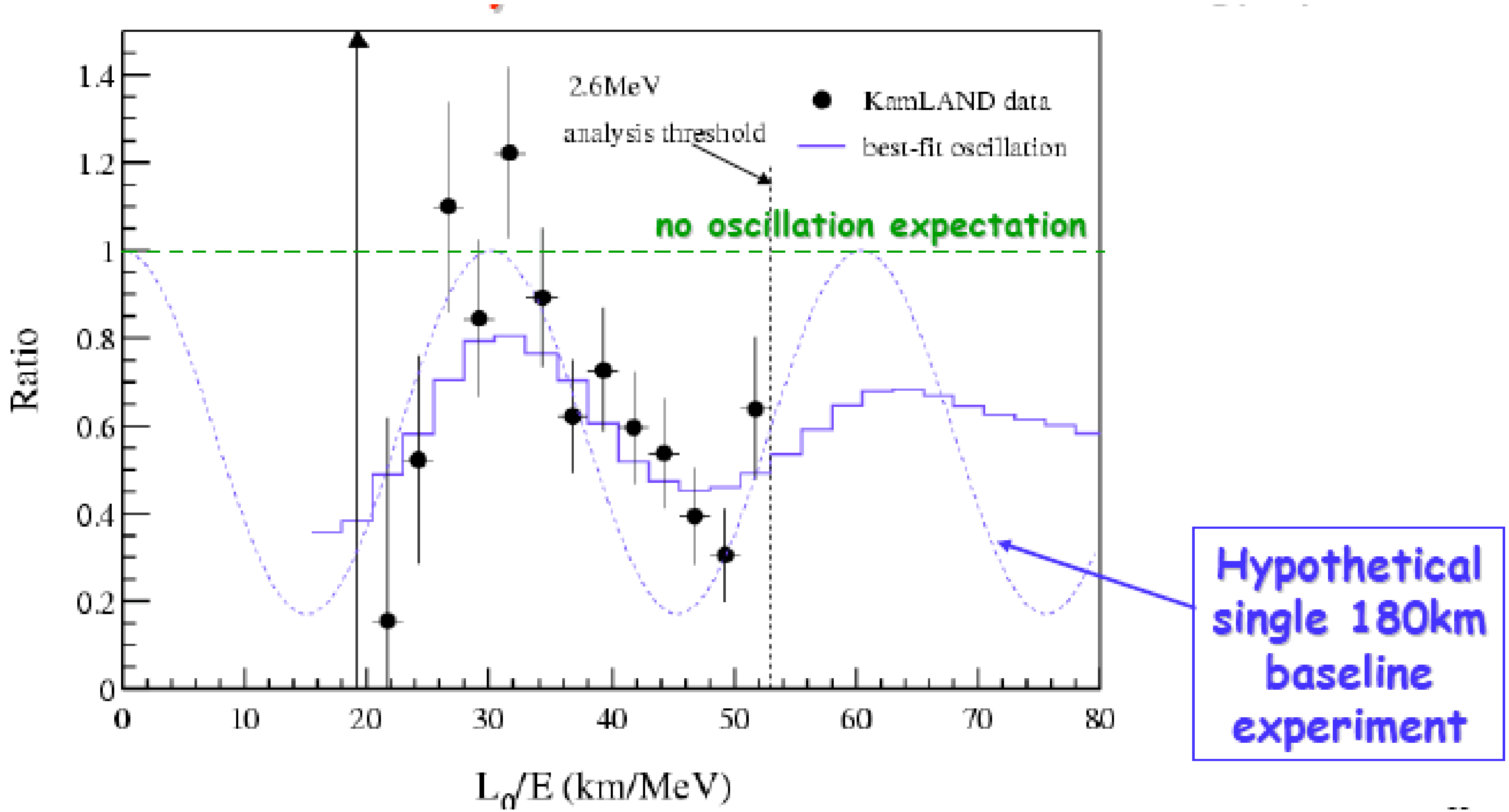
Data set used	Range* of $\Delta m^2_{21} \times 10^{-5}$ eV^2	spread in Δm^2_{21}
only sol	3.2 - 14.9	65%
sol+162 Ty KL	5.2 - 9.8	31%
NOW sol+ 766.3 Ty KL	7.3 - 9.4	13%
future sol+1.3 kTy KL	6.7 - 7.8	8%

* 99% C.L.

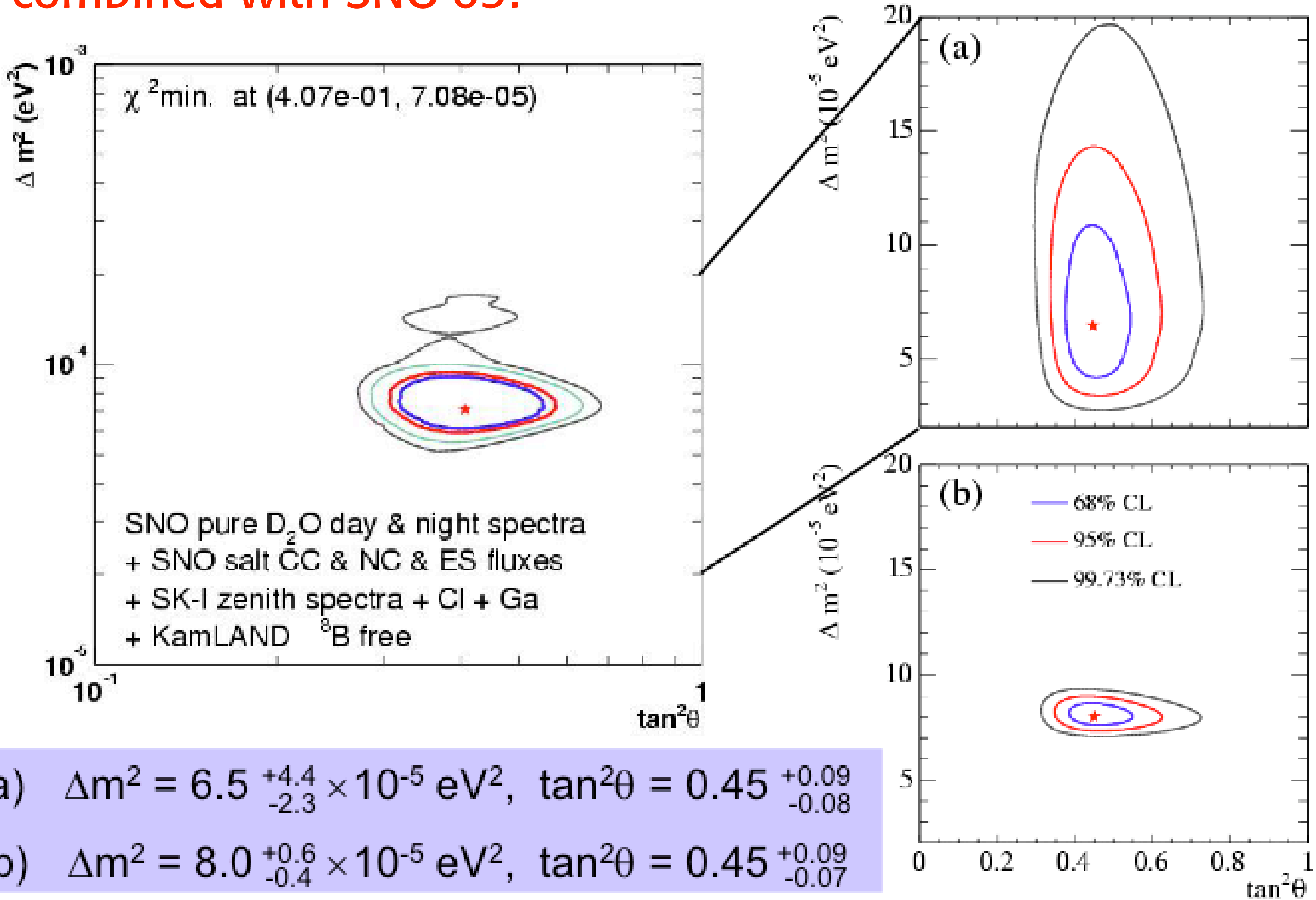
Goswami

KamLAND "L"/E distribution:

The oscillation pattern starts emerging!



"L" is in quote because it is only the average among many contributing reactors combined with SNO'05:



a) $\Delta m^2 = 6.5\,^{+4.4}_{-2.3} \times 10^{-5}$ eV^2, $\tan^2\theta = 0.45\,^{+0.09}_{-0.08}$

b) $\Delta m^2 = 8.0\,^{+0.6}_{-0.4} \times 10^{-5}$ eV^2, $\tan^2\theta = 0.45\,^{+0.09}_{-0.07}$

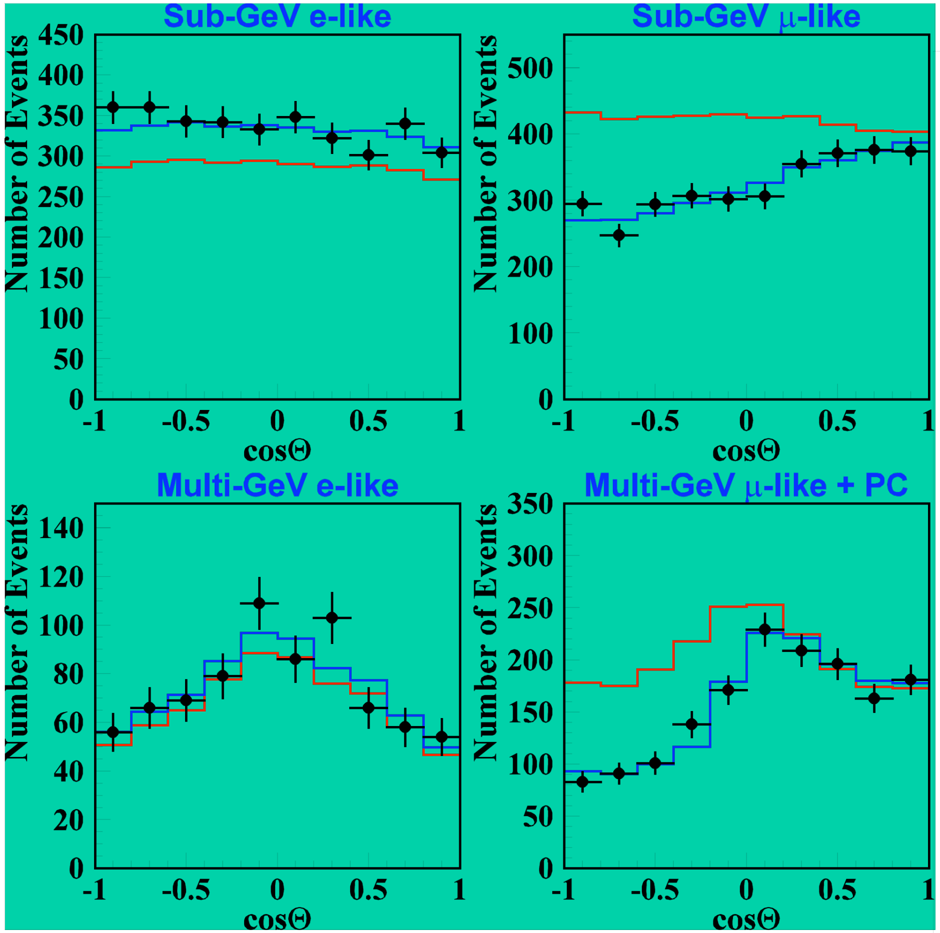
SNO + all other data

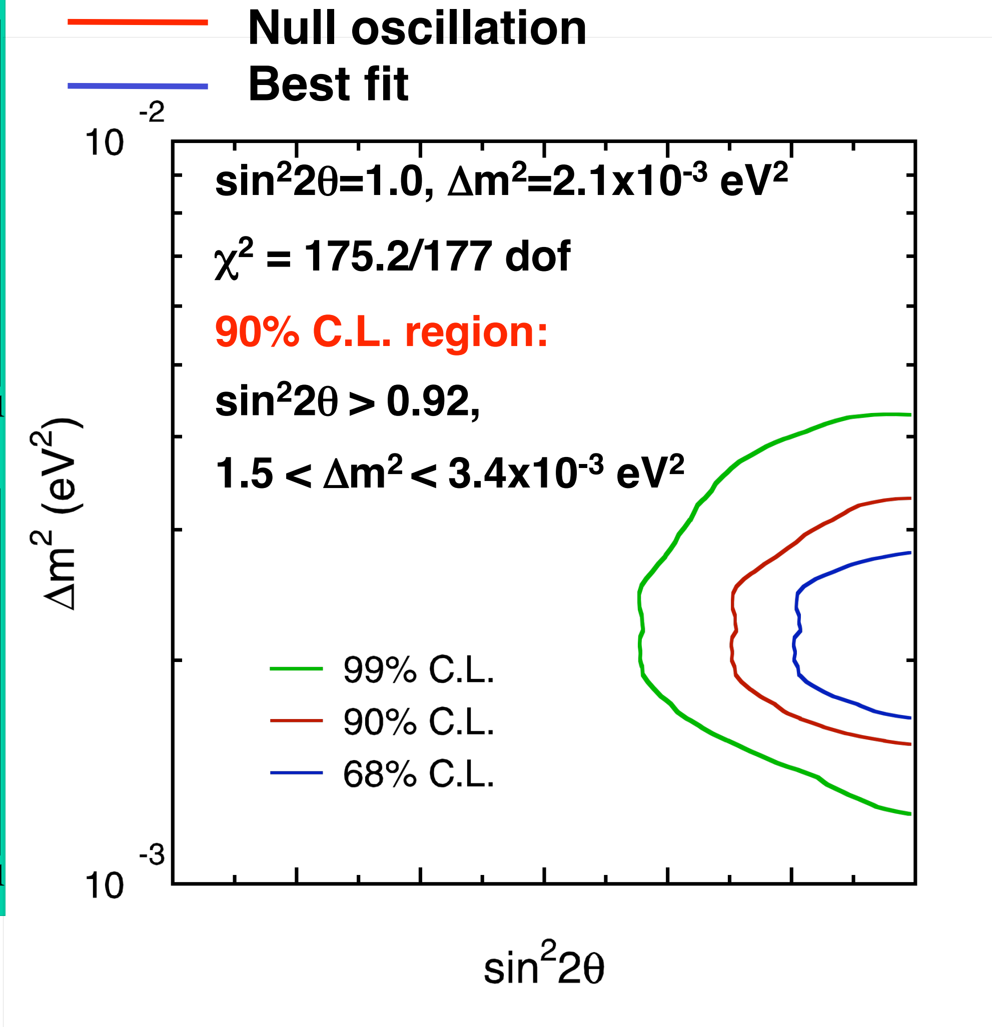
Atmospheric neutrinos

SuperKamiokande

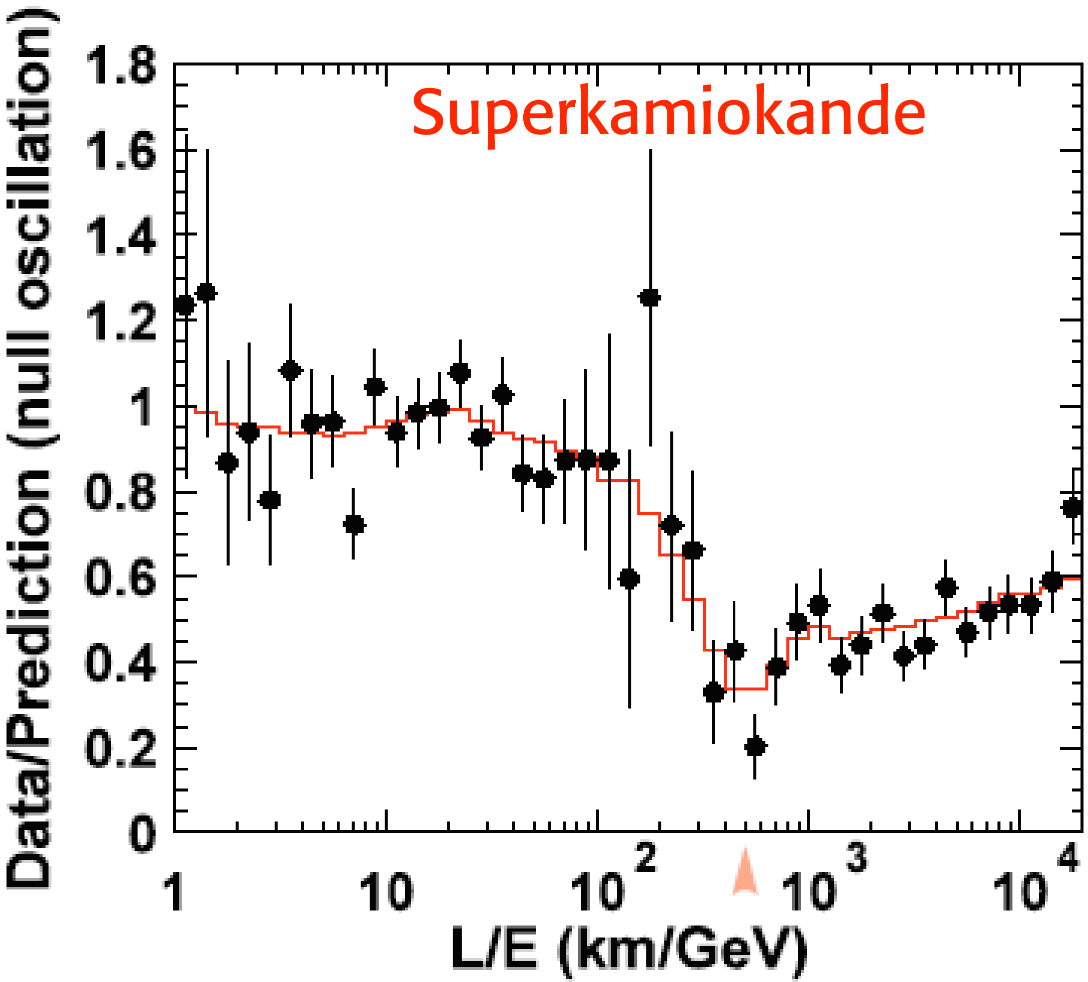
$\nu_\mu \leftrightarrow \nu_\tau$

2-flavor oscillations





Atmospheric neutrinos: SuperKamiokande L/E analysis



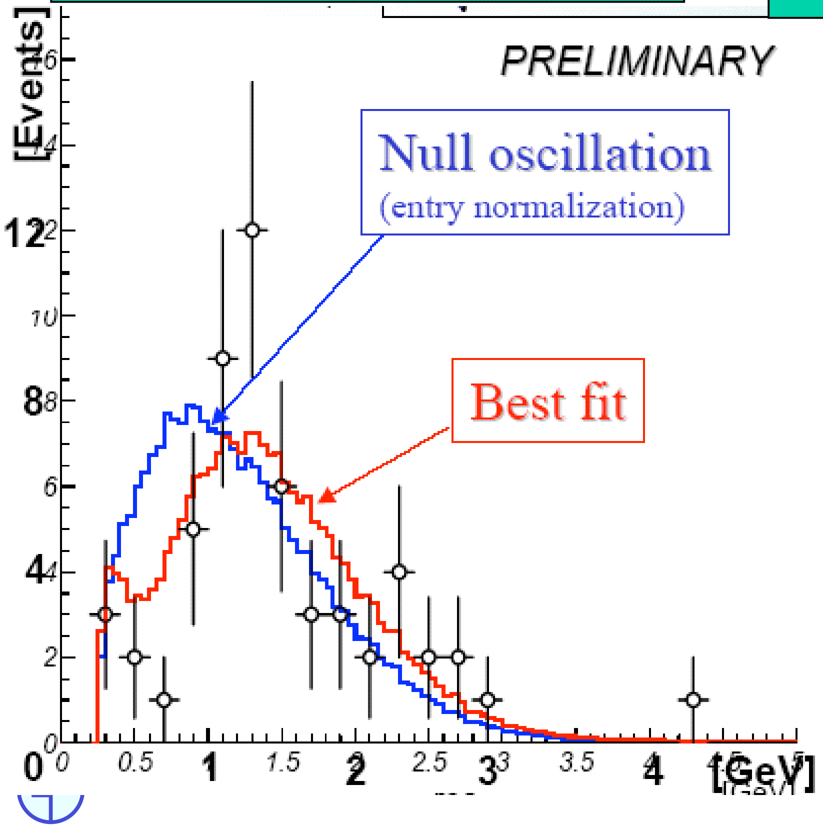
A hint towards direct evidence of oscill's for atm ν also

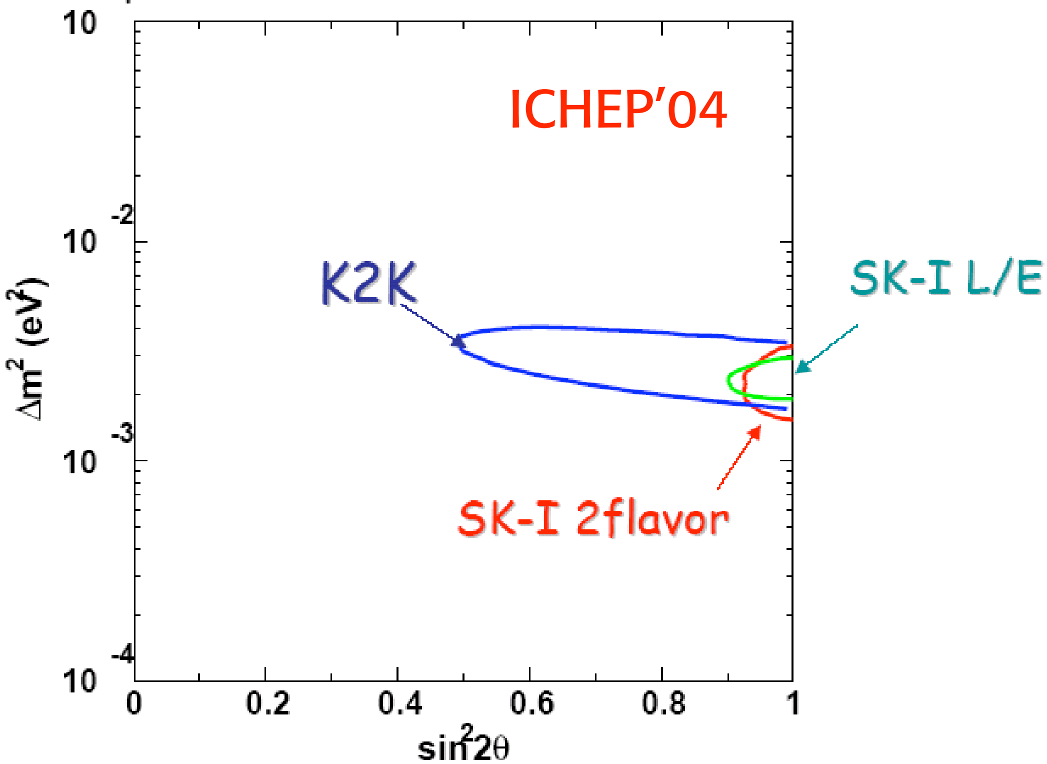
oscillation dip seen at ~500 km/GeV

K2K confirms SK in accelerator exp.

K2K Rate suppression
and
spectral distortion …

… agree with SK azimuthal distributions
and
L/E analysis

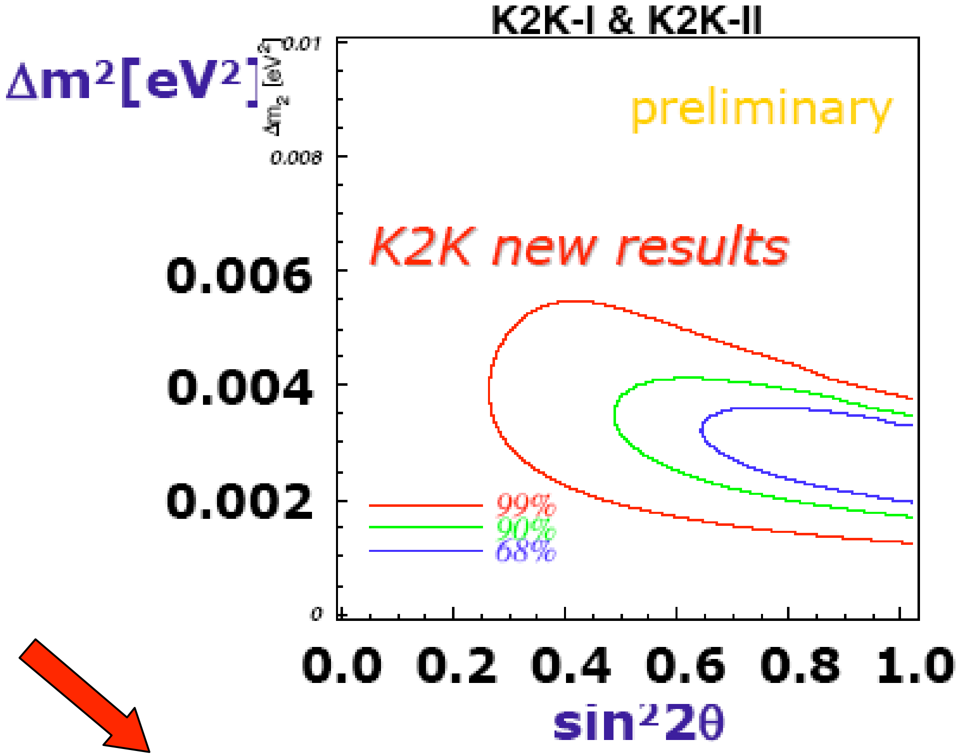




Important progress by K2K (bringing $\Delta\nu_{atm}$ down to earth)

Nakaya

- With 8.9×10^{19} POT, K2K *has confirmed* neutrino oscillations at **3.9σ.**
  - Disappearance of ν_μ **2.9σ**
  - Distortion of E_ν spectrum **2.5σ**



$$N_{SK}^{exp} = 150.9^{+11.6}_{-10.0}$$

$$N_{SK}^{obs} = 108$$

- $\sin^2 2\theta =$ **1.00**
- Δm^2 [eV²] = **2.73×10^{-3}**

K2K now finished (broken hardware)

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

End-point tritium β decay (Mainz, Troitsk)

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

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

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

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

- $0\nu\beta\beta$ $m_{ee} < 0.2 - 0.5 - ?$ eV (nucl. matrix elmnts)

Evidence of signal?   Klapdor-Kleingrothaus

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

$\Sigma_i m_i < 0.7$-1.8-? eV (dep. on priors)

WMAP, 2dFGRS...

Any ν mass < 0.23-0.6-? eV

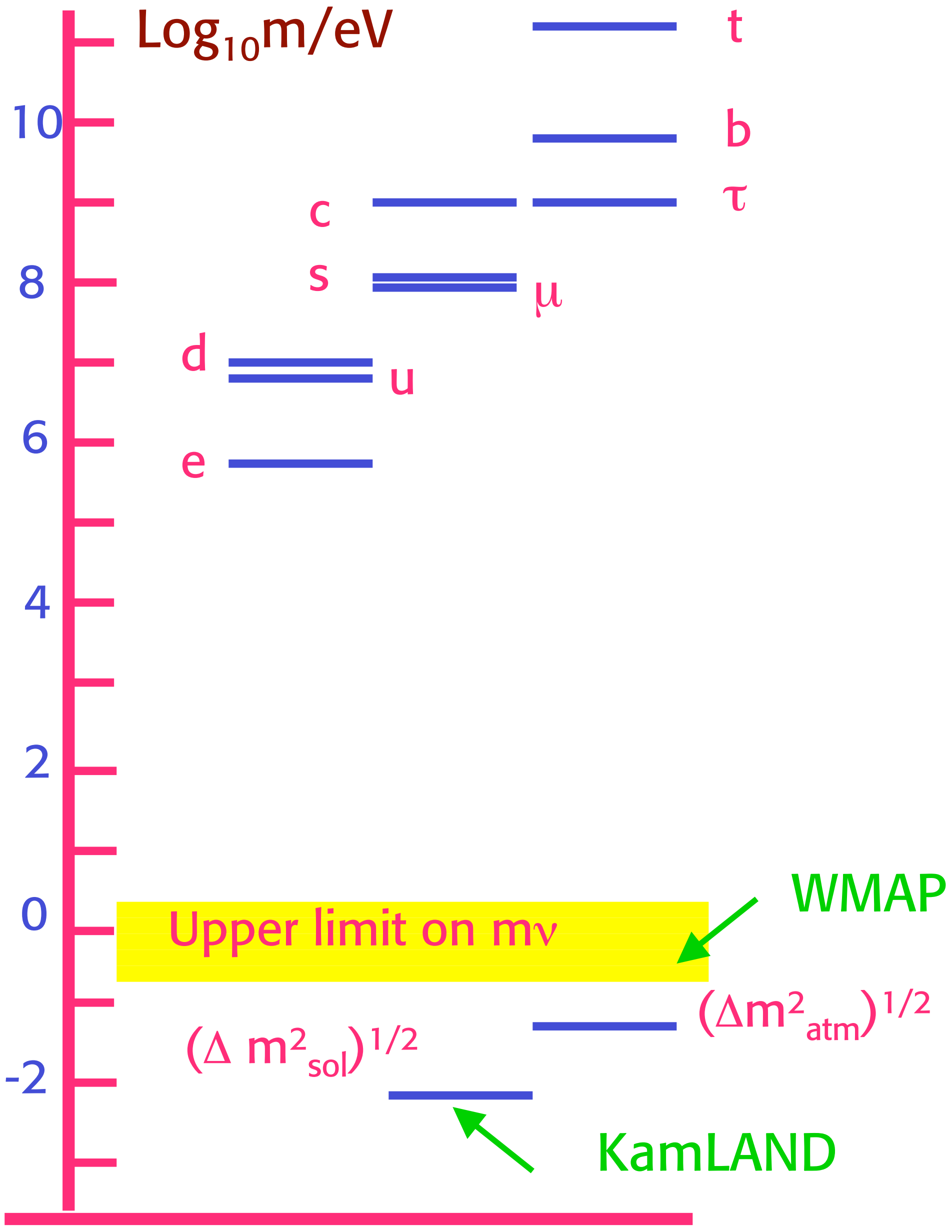
Why ν's so much lighter than quarks and leptons?
Because ν's are Majorana particles: $m_\nu \sim m^2/M$

Lahav

Neutrino mass from Cosmology

Data	Authors	$M_\nu = \Sigma m_i$ 95%cl
2dFGRS	Elgaroy et al. 02	< 1.8 eV
WMAP+2dF+…	Spergel et al. 03	< 0.7 eV
WMAP+2dF	Hannestad 03	< 1.0 eV
SDSS+WMAP	Tegmark et al. 04	< 1.7 eV
WMAP+2dF+ SDSS	Crotty et al. 04	< 1.0 eV

By itself CMB (WMAP, ACBAR) do not fix M_ν
Only in combination with galaxy power spectrum (2dFGRS, SDSS) become sensitive.



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

$\Rightarrow$ No Dirac mass

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

and

2) Lepton Number is conserved

$\Rightarrow$ No Majorana mass

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

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

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

$\nu_L \Rightarrow I = 1/2,\ I_3 = 1/2$

$\nu_R \Rightarrow I = 0,\ I_3 = 0$

Dirac Mass:

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

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

Majorana Mass:

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

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

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

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)

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

$M \gg m_D$

Eigenvalues

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

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:

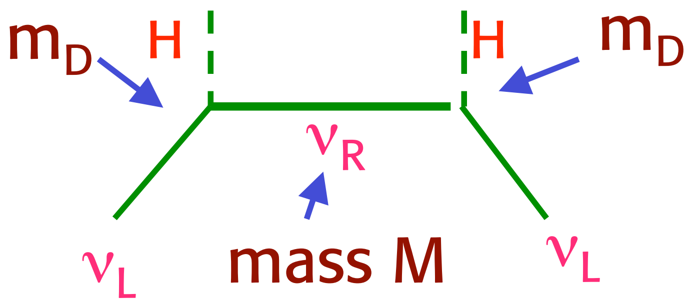
$$\begin{array}{ccc} & \nu_L & \nu_R \\ \begin{array}{c}\nu_L \\ \nu_R\end{array} & \multicolumn{2}{c}{\begin{bmatrix} \lambda v^2/M_L & m_D \\ m_D & M_R \end{bmatrix}} \end{array}$$

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

$$m_{heavy} \sim M_R \qquad m_{eff} = \nu^T_L m_{light} \nu_L$$

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

See-saw

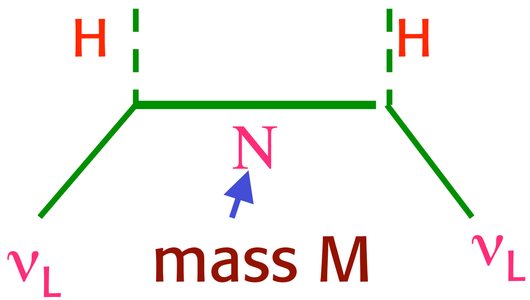


$m_\nu = m_D^T M^{-1} m_D$

connection with m_D

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

e.g from



N: new particle I_w=0,1

Whatever the underlying dynamics O_5 is a 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 $M \sim M_{GUT}$

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

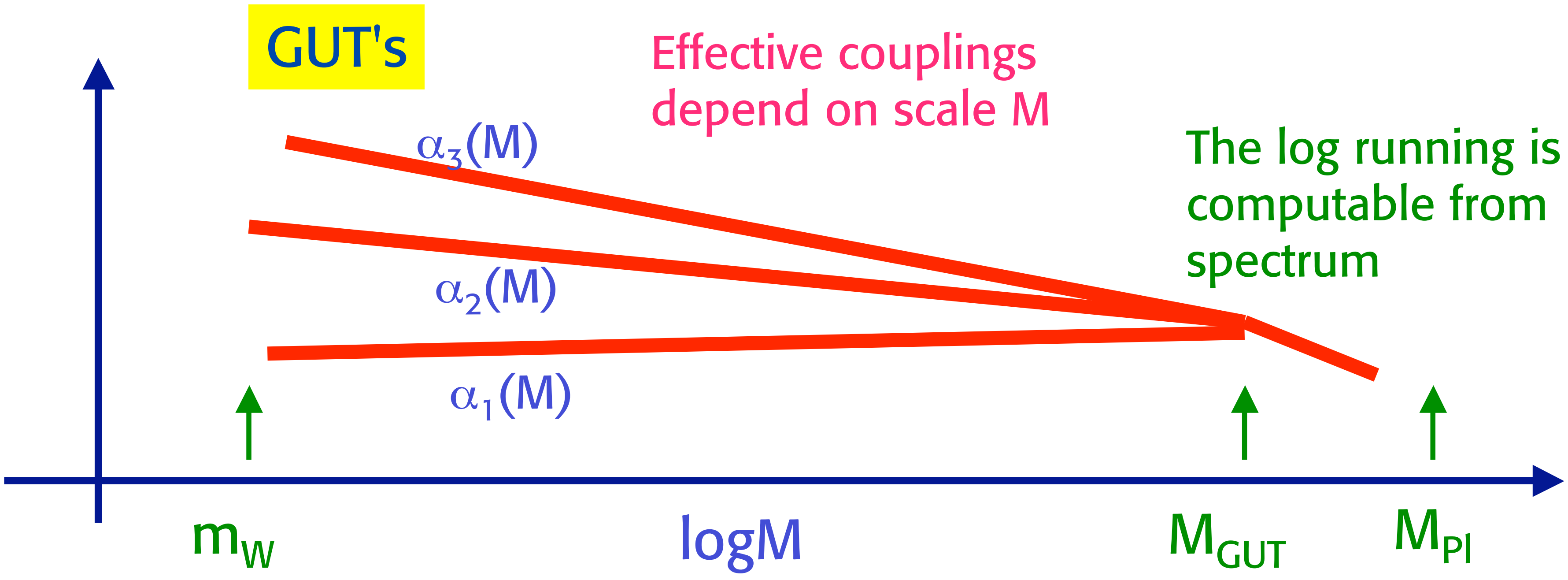
m: $m_t \sim v \sim 200$ GeV
M: scale of L non cons.

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 large scale structure of particle physics:

- (SUSY) $SU(3) \otimes SU(2) \otimes U(1)$ unify at M_{GUT}
- at M_{Pl}: quantum gravity

$$G_{Newton} = \frac{\hbar c}{M_{Pl}^2}$$

$r \sim 10^{-33}$ cm

Superstring theory:
a 10-dimensional non-local, unified theory of all interact's

The really fundamental level

By now GUT's are part of our culture in particle physics

- Unity of forces: $G \supset SU(3) \otimes SU(2) \otimes U(1)$

  unification of couplings
- Unity of quarks and leptons

  different "directions" in G
- Family Q-numbers

  e.g. in SO(10) a whole family in 16
- Charge quantisation: $Q_d = -1/3 \to -1/N_{colour}$
- B and L non conservation

  ->p-decay, baryogenesis, ν masses

• • • • •

Most of us believe that Grand Unification must be a feature of the final theory!

B and L conservation in SM:

"Accidental" symmetries: in SM there is no dim.4 gauge invariant operator that violates B and/or L (if no ν_R, otherwise $M\, \nu^T_R\, \nu_R$ is dim-3 $|\Delta L|=2$)

The same is true in SUSY with R-parity cons.

e. g. for the $\Delta B = \Delta L = -1$ transition $u + u \to e^+ + \bar{d}$

all good quantum numbers are conserved:

e.g. colour $u \sim 3$, $\bar{d} \sim 3$ and $3 \times 3 = 6 + \bar{3}$ but

$$\frac{\lambda}{M^2}\, \overline{d^c}\Gamma u\ \overline{e^c}\Gamma u \longrightarrow \text{dim-6}$$

SU(5): $p \to e^+ \pi^0$

Once ν_R is introduced (Dirac mass) large Majorana mass is naturally induced $\longrightarrow$ see-saw

Neutrinos and Cosmology

More and more unity of particle physics and cosmology

The role of ν's in nucleosynthesis, determining the relative fractions of light elements, has been known since a long time ($N_\nu < \sim 4$)

Recently much progress on:

- Dark Matter
- Dark Energy
- Baryogenesis
- • • •

Dark Matter

At the end of the XIX century J. J. Thompson proved the necessity of new physics (beyond em and gravity) proving that the energy from the sun and the stars cannot be obtained from chemistry

Today the clearest evidence for new physics comes from dark matter and dark energy

Most of the Universe is not made up of atoms: $\Omega_{tot} \sim 1$, $\Omega_b \sim 0.044$, $\Omega_m \sim 0.27$
Most is Dark Matter and Dark Energy

WMAP

Most Dark Matter is Cold (non relativistic at freeze out)
Significant Hot Dark matter is disfavoured
Neutrinos are not much cosmo-relevant: $\Omega_\nu < 0.015$

SUSY has excellent DM candidates: Neutralinos (--> LHC)
Also Axions are still viable
(in a mass window around m $\sim 10^{-4}$ eV and $f_a \sim 10^{11}$ GeV
but these values are simply a-posteriori)

Identification of Dark Matter is a task of enormous importance for particle physics and cosmology

LHC?

LHC has good chances because it can reach any kind of WIMP:

WIMP: weakly interacting particle with m ~ 10^1-10^3 GeV

For WIMP's in thermal equilibrium after inflation the density is:

$$\boxed{\Omega_\chi h^2 \simeq const. \cdot \frac{T_0^3}{M_{\mathrm{Pl}}^3 \langle \sigma_A v \rangle} \simeq \frac{0.1\ \mathrm{pb} \cdot c}{\langle \sigma_A v \rangle}}$$

can work for typical weak cross-sections!!!

This "coincidence" is a good indication in favour of a WIMP explanation of Dark Matter

The scale of the cosmological constant is a big mystery.

$\Omega_\Lambda \sim 0.65 \rightarrow \rho_\Lambda \sim (2\ 10^{-3}\ \text{eV})^4 \sim (0.1\text{mm})^{-4}$

Similar to m_ν!?

In Quantum Field Theory: $\rho_\Lambda \sim (\Lambda_{\text{cutoff}})^4$

If $\Lambda_{\text{cutoff}} \sim M_{\text{Pl}} \rightarrow \rho_\Lambda \sim 10^{123}\ \rho_{\text{obs}}$

Exact SUSY would solve the problem: $\rho_\Lambda = 0$

But SUSY is broken: $\rho_\Lambda \sim (\Lambda_{\text{SUSY}})^4 \sim 10^{59}\ \rho_{\text{obs}}$

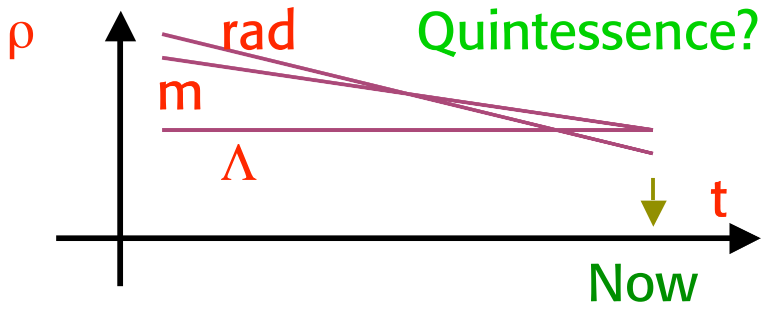
It is interesting that the correct order is $(\rho_\Lambda)^{1/4} \sim (\Lambda_{\text{EW}})^2/M_{\text{Pl}}$

So far no solution:

- A modification of gravity at 0.1mm?(large extra dim.)
- Leak of vac. energy to other universes (wormholes)?

…

Other problem:
Why now?



Quintessence: the cosmological "constant" is actually a vev of a scalar field ϕ which evolves towards the minimum

Could explain smallness, but not "why now?"

A coupling of ν's to Quintessence could explain "why now?"

Fardon, Nelson, Weiner; Peccei....

The Majorana mass M of ν_R could be $M(\phi)$ and the combined evolution could explain "why now?"

Sofar not very appealing: ad hoc potentials and energy scales

A new approach by Barbieri, Hall, Oliver, Strumia

Neutrino masses point to M_{GUT},
well fit into the SUSY-GUT's picture:

indeed add considerable support to
this idea.

Technicolor, Little Higgs, Extra dim....:
nearby cut-off. Problem of suppressing

$$O_5 = \nu_L^T \frac{\lambda}{M} \nu_L HH$$

Another big plus of neutrinos is the elegant
picture of baryogenesis thru leptogenesis
(after LEP has disfavoured BG at the weak scale)

Baryogenesis

$n_B/n_\gamma \sim 10^{-10}$, $n_{Bbar} << n_B$

Conditions for baryogenesis: (Sacharov '67)

- B non conservation (obvious)
- C, CP non conserv'n (B-B^{bar} odd under C, CP)
- No thermal equilib'm ($n=\exp[\mu-E/kT]$; $\mu_B=\mu_{Bbar}$, $m_B=m_{Bbar}$ by CPT

If several phases of BG exist at different scales the asymm. created by one out-of-equilib'm phase could be erased in later equilib'm phases: BG at lowest scale best

Possible epochs and mechanisms for BG:

- At the weak scale in the SM Excluded
- At the weak scale in the MSSM Disfavoured
- Near the GUT scale via Leptogenesis

Very attractive

Possible epochs for baryogenesis

- BG at the weak scale: $T_{EW} \sim 0.1\text{-}\ 10$ TeV

  Rubakov, Shaposhnikov; Cohen, Kaplan, Nelson; Quiros….

In SM:

- B non cons. by instantons ('t Hooft)
  (non pert.; negligible at T=0 but large at $T=T_{EW}$
  B-L conserved!

- CP violation by CKM phase. Enough??
  By general consensus far too small.

- Out of equilibrium during the EW phase trans.
  Needs strong 1st order phase trans. (bubbles)
  Only possible for $m_H <\sim 80$ GeV
  Now excluded by LEP

Is BG at the weak scale possible in MSSM?

- Additional sources of CP violation

  Sofar no signal at beauty factories

- Constraint on m_H modified by presence of extra scalars with strong couplings to Higgs sector (e.g. s-top)

- Requires:
  m_h<80-100 GeV; $m_{s\text{-}topl}<m_t$; $tg\beta \sim 1.2\text{-}5$ preferred

  Espinosa, Quiros, Zwirner; Giudice; Myint; Carena, Quiros, Wagner; Laine; Cline, Kainulainen; Farrar, Losada…..

  Disfavoured by LEP2

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 Δ(B-L)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!!