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ANALYSIS OF OSCILLATIONS OF ATMOSPHERIC NEUTRINOS

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OUTLINE:

- Introduction
- 3ν and 4ν oscillations
- Nonstandard dynamics
- Conclusions

Work done in collaboration with
G.L. Fogli, A. Marrone, D. Montanino, G. Scioscia

INTRODUCTION

The status of two-family oscillations of atmospheric neutrinos is well known:

$\nu_\mu \leftrightarrow \nu_\tau$ Excellent fit to K+SK+Soudan+MACRO ("textbook result" after SK@ν'98)

$\nu_\mu \leftrightarrow \nu_e$ Strongly disfavored by SK and excluded by CHOOZ (+Palo Verde)

$\nu_\mu \leftrightarrow \nu_s$ (Strongly) disfavored by SK (+MACRO), associated matter effects* not observed

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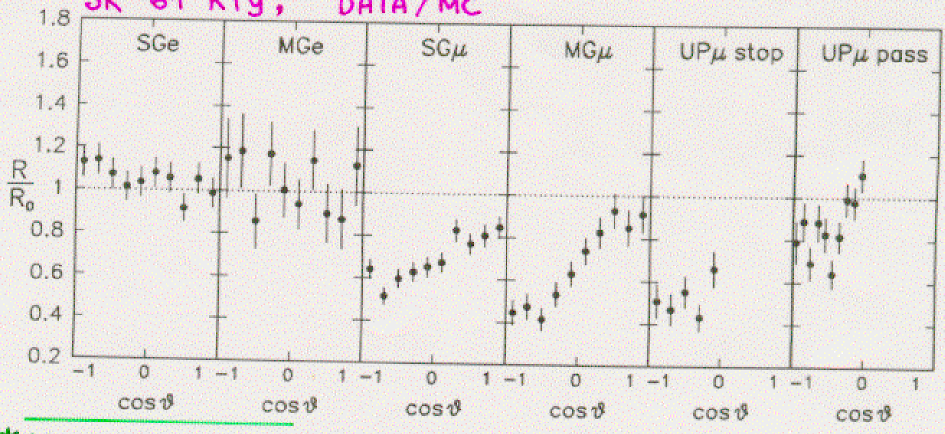
Pure $\nu_\mu \leftrightarrow \nu_\tau$ OK, but two important signatures (τ appearance + periodicity) still missing:

SK 61 KTy, DATA/MC



* Lipari, Lusignoli
Liu, Smirnov
Fornengo, Gonzalez-Garcia, Valle
....

The lack of direct/complete information about flavor ($\equiv \nu$ states) and periodicity ($\equiv \nu$ dynamics) warrants the THEO/EXPT exploration of scenarios beyond standard $\nu_\mu \leftrightarrow \nu_\tau$ oscillations,

either (a) ADDING ν STATES
or (b) MODIFYING ν DYNAMICS

I will focus on the following examples:

(a) ADDING ν_e (3ν mixing)
ADDING ν_s (4ν mixing)

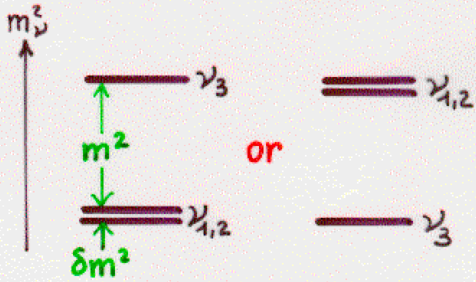
(b) DYNAMICS WITH AND WITHOUT L/E-dependence

and correspondingly discuss

- current constraints from atm. ν data
- tasks for future experiments

3ν (ν_μ, ν_e, ν_τ) OSCILLATIONS

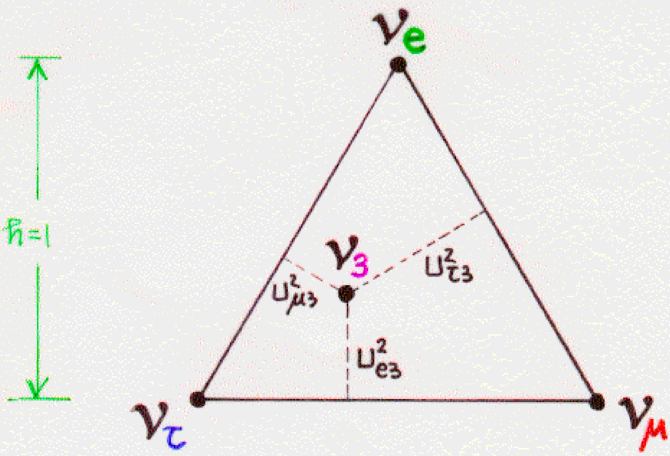
- POSSIBLE SPECTRA
  (absolute values unknown)



- For definiteness, consider normal hierarchy with $\delta m^2 \ll m^2$. Then:
- Physics governed by m^2 and flavor contents of ν_3:

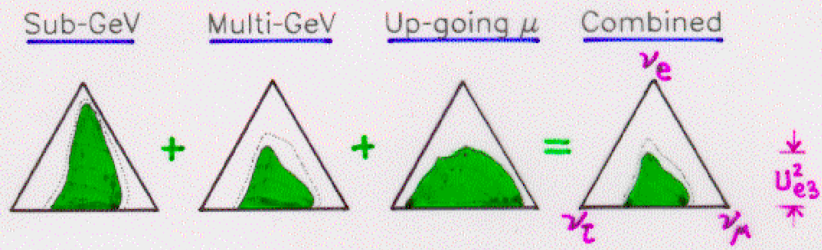
$$\nu_3 = U_{e3}\nu_e + U_{\mu3}\nu_\mu + U_{\tau3}\nu_\tau$$

- Unitarity constraint $U_{e3}^2 + U_{\mu3}^2 + U_{\tau3}^2 = 1$ embedded in triangle (Dalitz-like) plot:

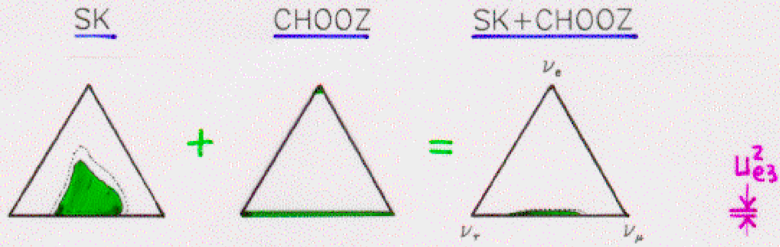


Fogli, E.L., Marrone, Scioscia

- 52 kTy SK data analysis at best-fit value of m^2 ($\sim 3 \times 10^{-3}$ eV^2)



- SK + CHOOZ '99 data analysis :

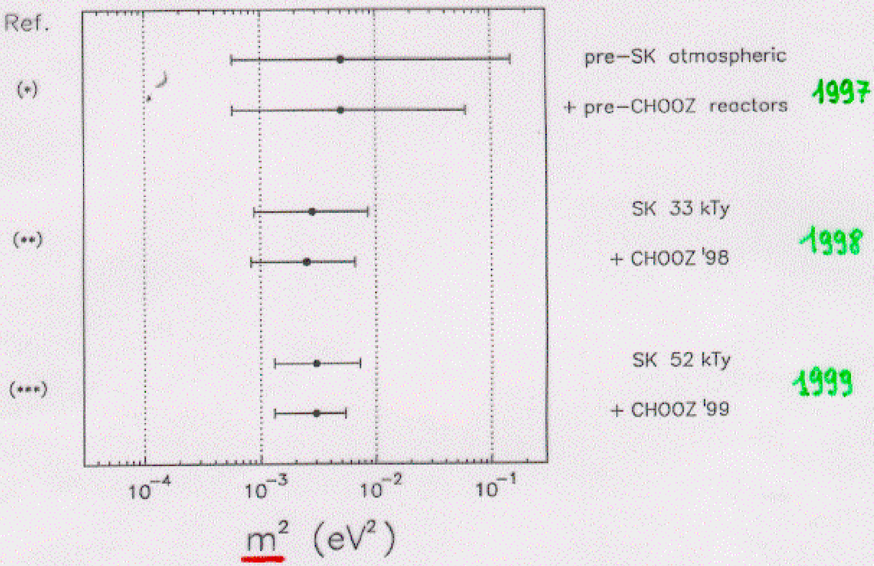


- Compare with situation < 1998 :

→ TREMENDOUS PROGRESS IN 3ν MIXING CONSTRAINTS IN THE LAST COUPLE OF YEARS

- In addition, significant reduction of m^2 range:
(driven by zenith information)

Progress in m^2 bounds for unconstrained 3ν mixing
(90% C.L., $N_{DF} = 3$)



(*) G.L. Fogli, E. Lisi, D. Montanino, and G. Scioscia, Phys. Rev. D 55, 4385 (1997)
(**) G.L. Fogli, E. Lisi, A. Marrone, and G. Scioscia, Phys. Rev. D 59, 033001 (1999)
(***) G.L. Fogli, E. Lisi, A. Marrone, and G. Scioscia Proceedings of TAUP 99

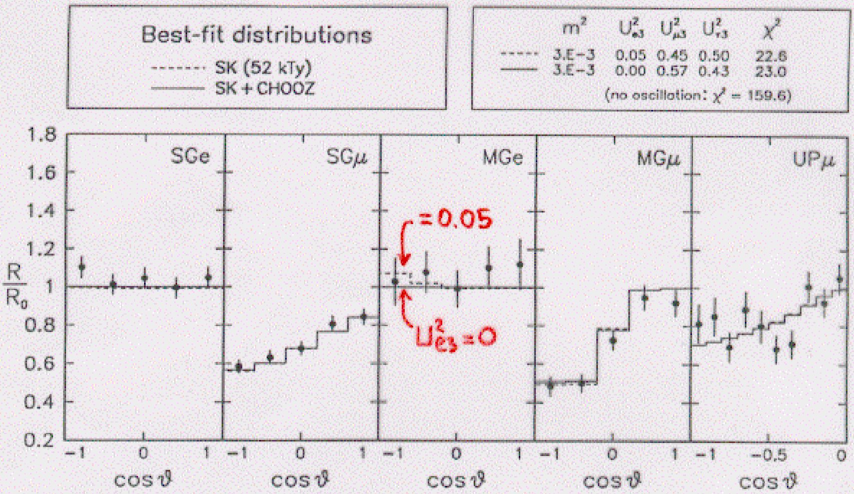
Current summary:

- $m^2 \sim 3 \times 10^{-3}\ eV^2$ within a factor ~2
- $U^2_{\mu 3} \sim U^2_{\tau 3}$ " " "
- $U^2_{e3} \lesssim$ few %

- Missing evidence for $U^2_{e3} \neq 0$

... and no reason for $U^2_{e3} \equiv 0$!

- Cleanest signal of $U^2_{e3} \neq 0$ in SK would be an U/D asymmetry in MGe sample
- However, $U^2_{e3} \lesssim$ few % + large smearing make typical signal smaller than uncertainties

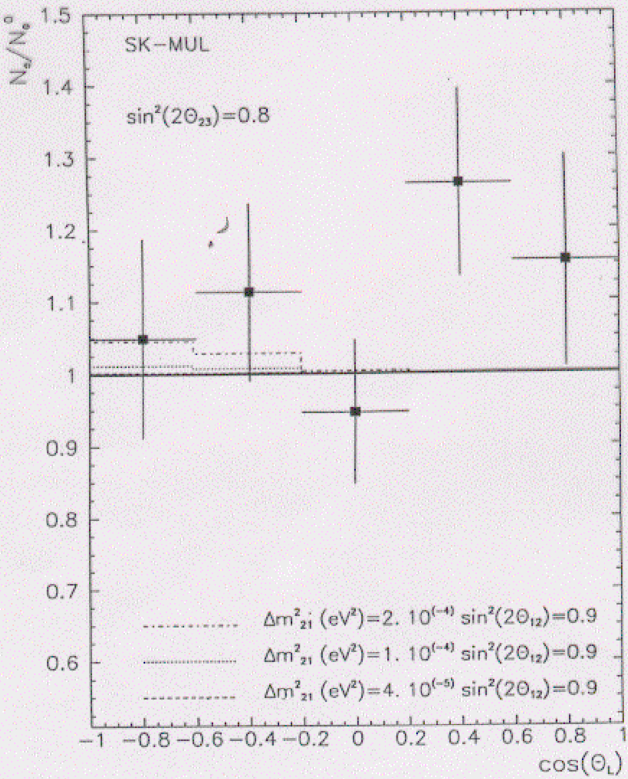


- For $U^2_{e3} \neq 0$, effects of $m^2 \to -m^2$ (inverted hierarchy) are of similar size in SK. Expect hints, not 3σ signals.

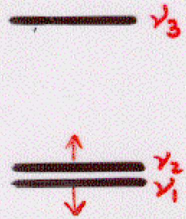
Note: Earth matter effects (MSW resonance, mantle-core interference) are sensitive to $U^2_{e3} \neq 0$ and to $\pm m^2$

FOGLI, E.L., MONTANINO, MARRONE, SCIOSCIA
AKHMEDOV, LIPARI, SMIRNOV
PETCOV ; YASUDA ; BARBIERI & STRUMIA
DE RUJULA, GAVELA, HERNANDEZ
....
....

- Subleading $\nu_\mu \to \nu_e$ effects generated by "solar" (ν_1, ν_2) mass splitting + mixing are also typically small :



← Peres & Smirnov, Strumia



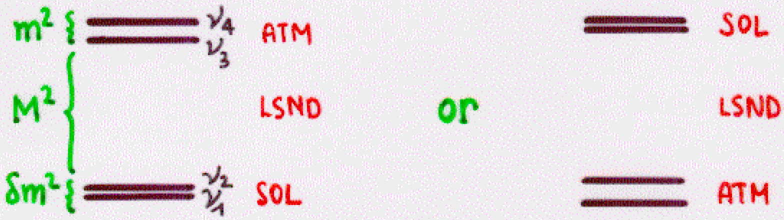
$\delta m^2 \lesssim O(10^{-4})$ for solar LMA

Diagnostics of different 3ν effects ($U^2_{e3} \neq 0$, $\pm m^2$, $\delta m^2 \neq 0$) in atm ν require selection & comparison of event samples in small ranges of E_ν and θ_ν

→ Task for future experiments with improved energy-angle ν reconstruction

4ν $(\nu_e, \nu_\mu, \nu_\tau, \nu_s)$ OSCILLATIONS

- Required to explain solar + atm + LSND *
- Constraints on mass spectrum: two doublets



- Constraints on mixing:

  ν_e mixed mainly with solar doublet (ν_1, ν_2)
  (otherwise, large $\nu_e \to \nu_e$ in reactors)

  ν_μ mixed mainly with atm. doublet (ν_3, ν_4)
  (otherwise, large $\nu_\mu \to \nu_\mu$ in CDHSW)

- Residual (ν_e, ν_μ) inter-doublet mixing (few ‰) needed to explain LSND, but ~negligible (in 1st approx.) for solar or atmospheric ν phenomenology

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* See Bilenky, Giunti, Grimus, PPNP 43, 1 (1999) and refs. therein

Neglect $\nu_\mu \leftrightarrow \nu_e$ inter-doublet mixing (1st approx.) →
Concerning 4ν oscill. channels, one often assumes

either "A"	or "B"
solar $\nu_e \leftrightarrow \nu_\tau$ atm. $\nu_\mu \leftrightarrow \nu_s$	solar $\nu_e \leftrightarrow \nu_s$ atm. $\nu_\mu \leftrightarrow \nu_\tau$
(SK-disfavored)	(SK-favored)

However, smooth interpolations between the above cases are also possible.*

solar $\nu_e \leftrightarrow \nu_-$
atm. $\nu_\mu \leftrightarrow \nu_+$,

$$\nu_- = c_\xi \nu_s - s_\xi \nu_\tau$$
$$\nu_+ = s_\xi \nu_s + c_\xi \nu_\tau$$

"A" ($c_\xi = 0$) ⟶ "B" ($c_\xi = 1$)

For generic ξ, transitions ACTIVE → STERILE occur in addition to ACTIVE → ACTIVE for both solar and atmospheric neutrinos

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* See Dooling, Giunti, Kang, Kim

Recently, solar ν solutions have been found* with large c_ξ^2 (ACTIVE ⊕ STERILE MIXTURE).

E.g., all solutions (SMA, LMA, LOW, VAC) ARE compatible with $c_\xi^2 \sim 1/2$ (50% ν_s + 50% ν_τ)

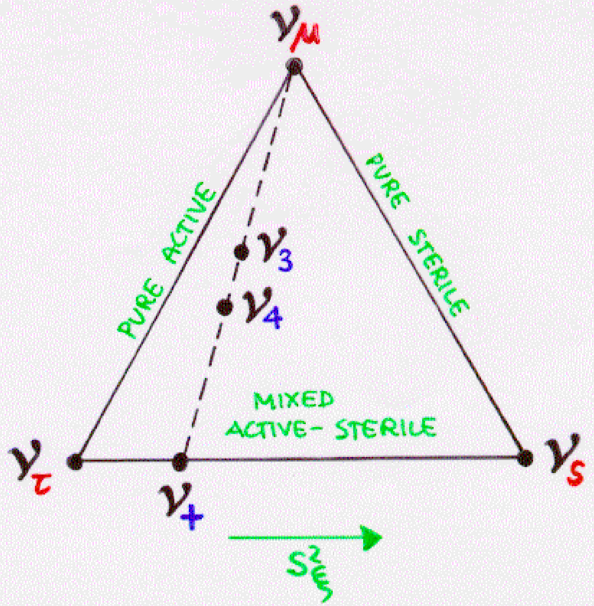
* Giunti, Gonzalez-Garcia, Peña-Garay

- What about atmospheric neutrinos?

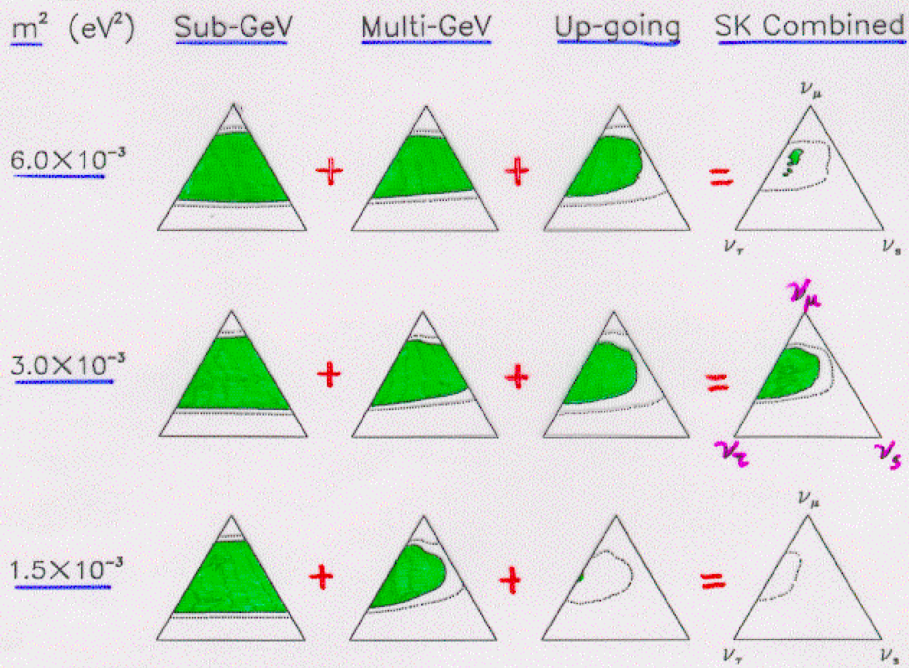
(Fogli, E.L., Marrone, work in progress)

In 4ν scenarios, ν_e is almost decoupled from the atmospheric doublet, and (ν_3, ν_4) are basically mixed with $(\nu_\mu, \nu_\tau, \nu_s)$

→ parameter space can be mapped again in a unitarity triangle (different from 3ν)



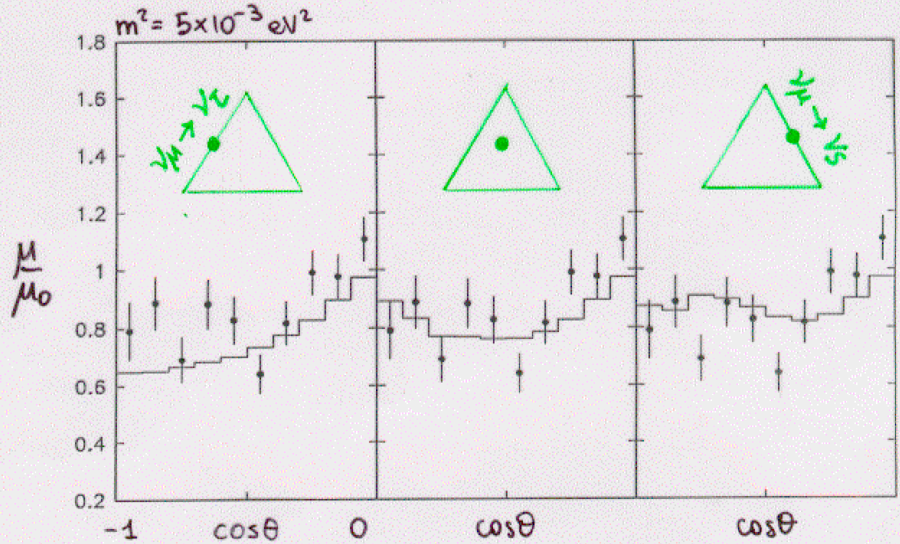
Fogli, E.L., Marrone : PRELIMINARY RESULTS USING 61 KTy SK data (55 bins)



- Best fit at $\sim 3\times10^{-3}\,eV^2$, close to left side ($\sim \nu_\mu\to\nu_\tau$)
- Pure $\nu_\mu\to\nu_s$ (right side) disfavored @ 99% C.L.
- However, large $\nu_\mu\to\nu_s$ oscillations, in addition to $\nu_\mu\to\nu_\tau$, cannot be excluded (e.g., $\nu_\mu\to\frac{1}{\sqrt{2}}(\nu_s+\nu_\tau)$)
- At "high" m^2, nonzero $\nu_\mu\to\nu_s$ favored (reduces large μ suppression)
- Constraints increase with energy and s^2_ξ, due to effective mass term in matter

$$A_{eff} = 2\sqrt{2}\,G_F\,\frac{N_n}{2}\cdot E\cdot s^2_\xi$$

Crucial observable to determine the relative amplitude of $\nu_\mu \to \nu_\tau$ and $\nu_\mu \to \nu_s$:
Upward through-going muon distribution



pure active ⟶ mixed ⟶ pure sterile
increasing matter eff. → increasing modulation

Higher UP_μ statistics would be of great help to (dis)prove the presence of $\nu_\mu \to \nu_s$, in addition to $\nu_\mu \to \nu_\tau$

Fogli, E.L., Marrone
work in progress

A peculiar example of scenario allowed by sol. + atm data :

SOLAR $\nu_{\frac{1}{2}} \simeq \frac{1}{\sqrt{2}}(\nu_e \mp \nu_-)$

ATMOS. $\nu_{\frac{3}{4}} \simeq \frac{1}{\sqrt{2}}(\nu_\mu \mp \nu_+)$

with $\nu_\pm \simeq \frac{1}{\sqrt{2}}(\nu_s \pm \nu_\tau)$

(up to small "LSND corrections")

→ might be dubbed "Fourfold maximal mixing"

4ν summary :

There are allowed scenarios in which ν_s can be an oscillation partner of both solar ν_e's and atmospheric ν_μ's. Solar and atm. ν experiments then probe orthogonal combinations of ν_τ, ν_s.

$(\nu_+ \perp \nu_-)$

DYNAMICS WITH(OUT) L/E-dependence

Let's get back to 2ν ($\nu_\mu \to \nu_\tau$ transitions) with Hamiltonian $\mathcal{H}$ ($\propto \sigma_3$) diagonal in some basis ≠ flavor basis.

- STANDARD CASE: $\mathcal{H} \propto \begin{bmatrix} -E^{-1} & \\ & +E^{-1} \end{bmatrix}$

  → OSCILLATION PHASE: $\propto L/E$ *

- POSSIBLE NON-STD. CASE: $\mathcal{H} \propto \begin{bmatrix} -E^{n} & \\ & E^{n} \end{bmatrix}$

  → OSCILLATION PHASE: $\propto L \cdot E^n$

  ↑ power-law

E.g.:

$n = +1$ Violations of equiv. principle (Gasperini ....)

$n = 0$ Energy-independent ν_μ disappear. (~ FCNC)

$n = -1$ Standard case recovered

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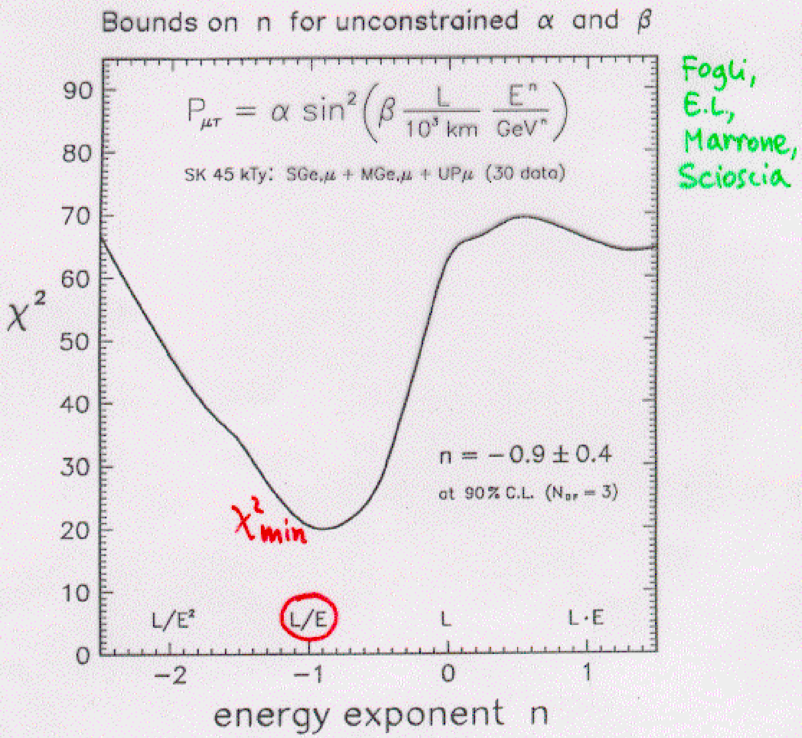
* Standard MSW effects, which spoil exact L/E dependence, are absent for $\nu_\mu \to \nu_\tau$

- Unconstrained fit to SK data strongly favors $n=-1$, and excludes other integers



- Wide energy range probed by SK ($10^{-1} \div 10^3$ GeV) crucial to obtain such results (Lipari & Lusignoli)

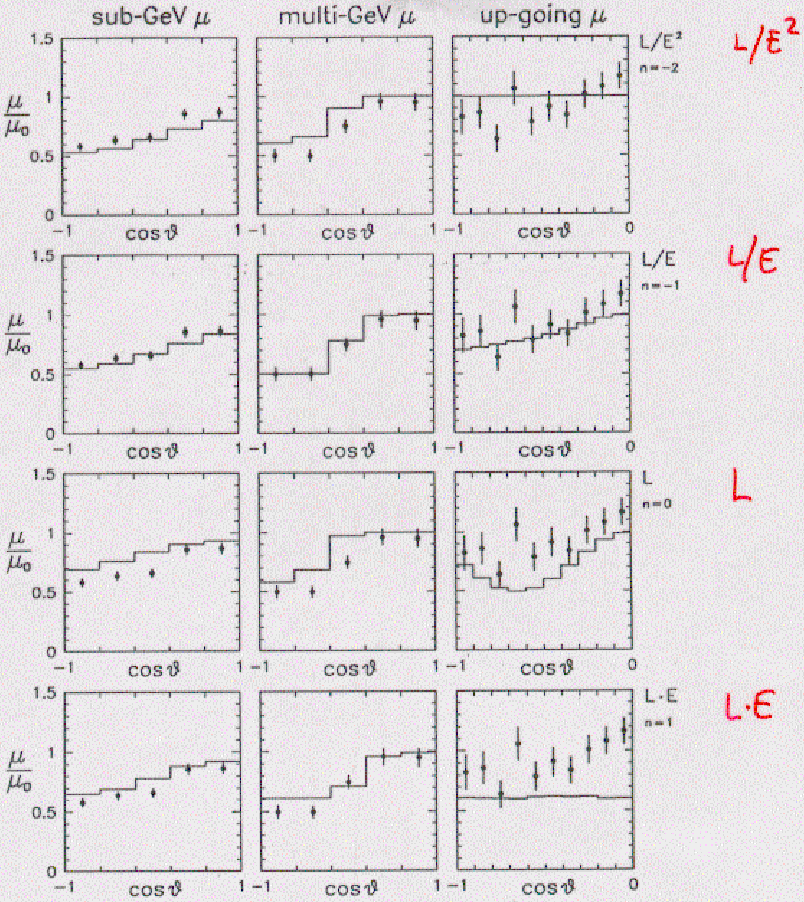
- Oscillation phase dominated by L/E dependence

SK muon distributions

Fogli
E.L.
Marrone
Scioscia

Super-Kamiokande muon distributions at best fit

	L/E^2	L/E	L	$L\cdot E$
$\alpha \rightarrow$	1.00	1.00	0.51	0.78
$\beta \rightarrow$	3.00	3.56	0.19	0.27
$\chi^2 \rightarrow$	47.7	20.3	62.9	66.0



Q. $P_{\mu\mu} = P_{\mu\mu}(L/E)$ OK, but is $P_{\mu\mu}$ necessarily a periodic function ?

A. **NO.**

Three different functional forms for $P_{\mu\mu}(L/E)$, two of which monotonic in L/E, give ~equally good fits to SK data:

(1) $P_{\mu\mu} \simeq 0.5 + 0.5 \cos(+\beta L/E)$

(2) $P_{\mu\mu} \simeq [0.7 + 0.3 \exp(-\beta L/E)]^2$

(3) $P_{\mu\mu} \simeq 0.5 + 0.5 \exp(-\beta L/E)$

all with $\beta \sim 7 \times 10^{-3}$ GeV/km !

Completely different physics involved:

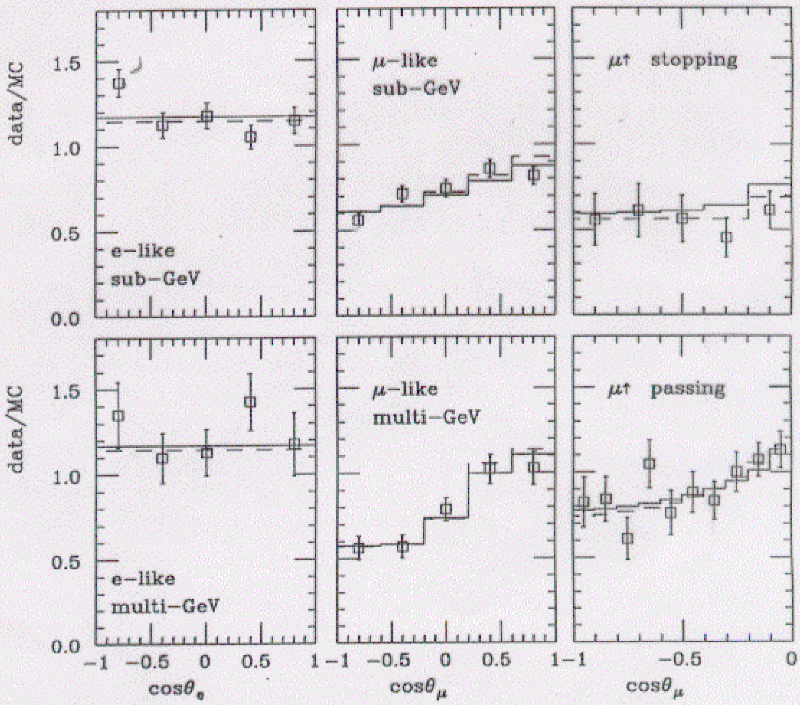
(1) Standard case, $\beta \propto \Delta m^2$

(2) ν decay, $\beta \propto \tau^{-1}$ (Barger et al.)

(3) ν decoherence, $\beta \propto L_{coh}^{-1}$ (E.L., Marrone, Montanino)

Comparison of ν oscillation and ν decay* SK data fits :

Can you tell one from the other?



* Specific model; Barger, Learned, Lipari, Lusignoli, Pakvasa, Weiler

Neutrino decoherence hypothesis

(E.L., Marrone, Montanino, hep-ph/0002053 **v2**)

- If (ν_μ, ν_τ) are a quantum open system,* hypothetically interacting with a dissipative environment, ν-Liouville equation is modified:

$$\underbrace{\dot{\rho} = -i[\mathcal{H}, \rho]}_{\text{Standard Liouville}} - \underbrace{\mathcal{D}[\rho]}_{\substack{\text{Extra term} \\ \text{("Lindblad")}}} \qquad \text{(L)}$$

- Extra-term $\mathcal{D}[\rho]$ (new physics) allows transitions from pure states to mixed states (decoherence)
  E.g.: Environment = Spacetime + Planckian gravity**

- We have specialized (L) to get
  $P_{\mu\mu} = 1 - \frac{1}{2} s^2_{2\theta} (1 - e^{-\gamma x} \cos kx)$, ← oscillations + decoherence
  the standard case being recovered for $\gamma = 0$.

- All very hypothetical, but bonus:
  maximal mixing ≡ maximal entropy
  (intriguing)

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* Benatti & Floreanini

** Hawking; Ellis, Hagelin, Nanopoulos, Srednicki ....

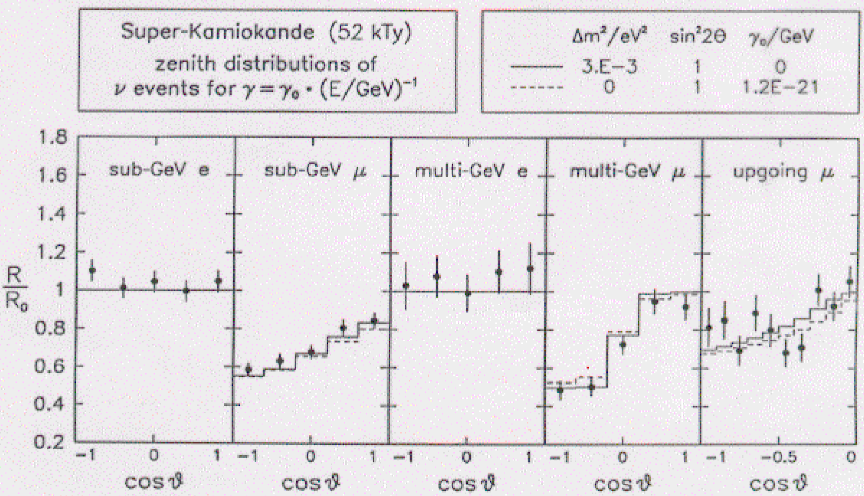
- Simply assume previous $P_{\mu\mu}$ as a phenomenological ansatz
- Fit quality depends on $d\gamma/dE$ (unknown). If $d\gamma/dE \geq 0$, SK data prefer $\gamma=0$ (no decoherence, standard osc.)
- However, if $\gamma \propto 1/E$ (as it should if γ is a Lorentz scalar), then SK data can be fitted for $\Delta m^2=0$! (no oscillation, pure decoherence)

comparison of fits

—— pure oscillations $P_{\mu\mu} \simeq 0.5 + 0.5 \cos(\beta L/E)$

---- pure decoherence $P_{\mu\mu} \simeq 0.5 + 0.5 \exp(-\beta L/E)$

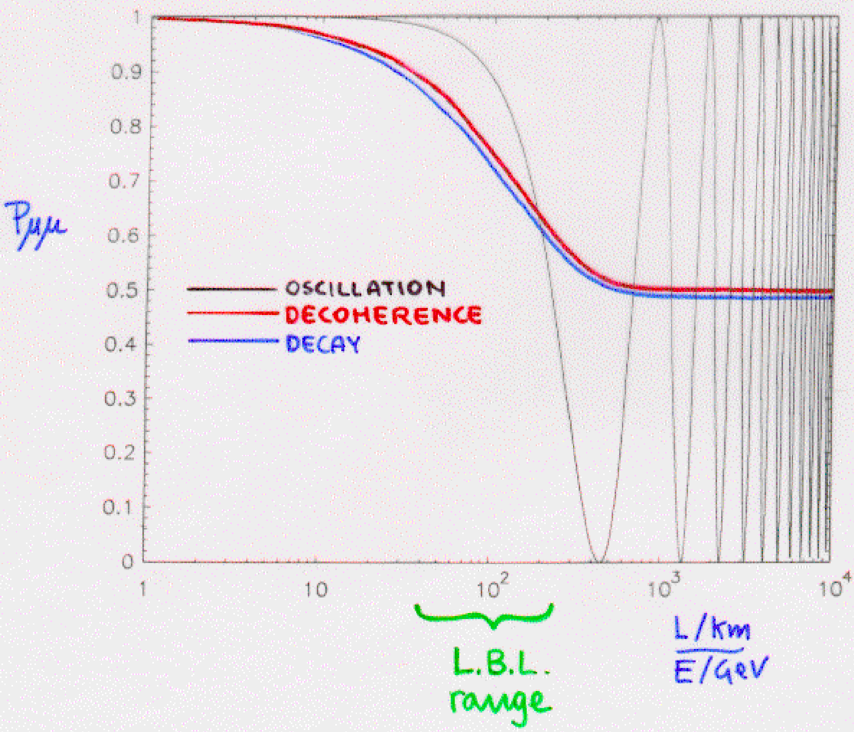
$\beta \sim 7\times10^{-3}$ GeV/Km



E.L., Marrone, Montanino

So, the lack of periodicity in SK μ data can be interpreted in two ways:

- smearing of oscillation pattern
- signal of non-oscillatory new physics (decay, decoherence, ...)*



→ Important to see at least one oscillation cycle (or the lack of it) in the energy and/or pathlength domain (LBL ?)

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* Another example: Barbieri & al., $\nu_\mu \to \nu_{KK}$ in extra-dim. models

CONCLUSIONS

- Standard 2ν oscillations in the $\nu_\mu \to \nu_\tau$ channel are simple and work. Great success of K + SK + Macro + Soudan2

- However, it would be nice to see at least some hints of Earth matter effects, requiring extra states besides ν_μ, ν_τ:

  3ν : $\nu_\mu \to \nu_\tau \oplus \nu_\mu \to \nu_e$ (small)

  4ν : $\nu_\mu \to \nu_\tau \oplus \nu_\mu \to \nu_s$ (may be large)

- Life might become even more interesting, if the nonobservation of periodicity in ν_μ disappearance turns out to be induced by some non-oscillatory new physics, rather than merely by energy-angle smearing

- Better understanding of ν states ($\geq 2\nu$) and of ν dynamics requires, in general:
  - * flavor appearance
  - * better L, E_ν reconstruction