Neutrino Physics After KamLAND

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``Before and After''

The end of era of the neutrino anomalies?

What is left?

Standard and Non-standard

Before and After

After KamLAND → After Confirmation of LMA MSW

CPT

■ ``Neutrino Physics after KamLAND'' started much before announcement of the first results

Since 1998 -1999 most of the papers - in context of the LMA solution (phenomenology, implications etc..)

■ 1998 is the turn point ``Revolution 98'':

- Strong evidence of oscillations of the atmospheric neutrinos
- SMA MSW solution of the solar neutrino problem - disfavored

→ The prejudice of small mixing was destroyed

KamLAND:

Culmination of ~ 40 years of solar neutrino studies

CPT

- has confirmed the LMA MSW solution
  excluded other solutions at least as dominant mechanisms

- further shifted the allowed region and best fit point to larger Δm^2

  $(5 \Rightarrow 7)\ 10^{-5}\ \mathrm{eV}^2$

- The lower bound: $\Delta m^2 > (4 - 5)\ 10^{-5}\ \mathrm{eV}^2$
  looks rather solid

  Mixing is practically unaffected

Confirmation of the whole oscillation picture including oscillations of the atmospheric neutrinos

Neutrino Problems and Anomalies

Driving force of developments in the field

~~Solar Neutrino Problem~~

Real confirmed resolved

~~Atmospheric Neutrino Problem~~

LSND

?

Fake:

ITEP mass
17 kev neutrino
BUGEY oscillations
KARMEN anomaly
Troitzk anomaly
...

Related to neutrinos?

UHE Cosmic Rays
nucleosynthesis
r-processes
pulsar kicks

What is left?

Is the Solar Neutrino Problem Resolved?

- Accepting the first KamLAND result
- CPT

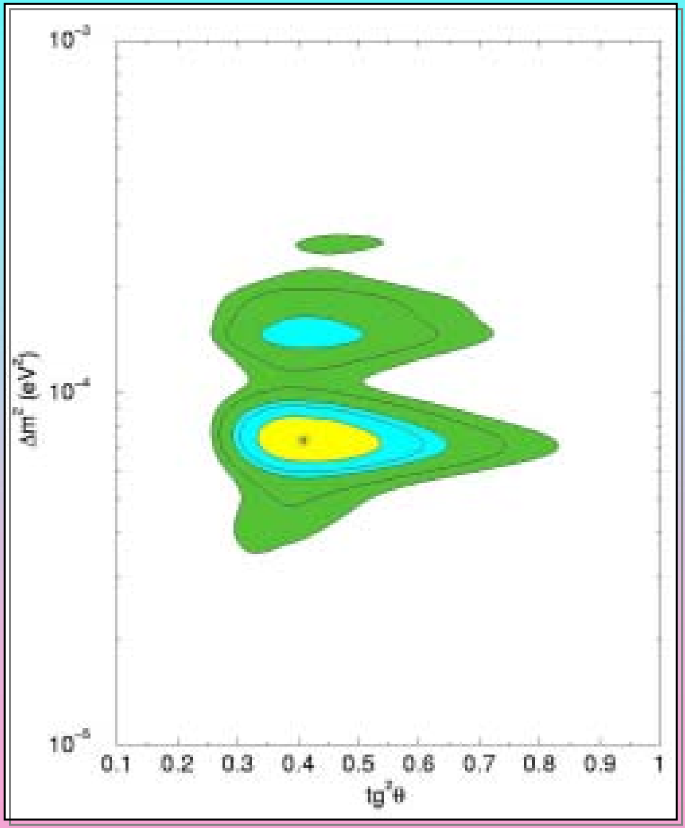
⇒ **LMA**

All other possibilities are excluded as leading effects

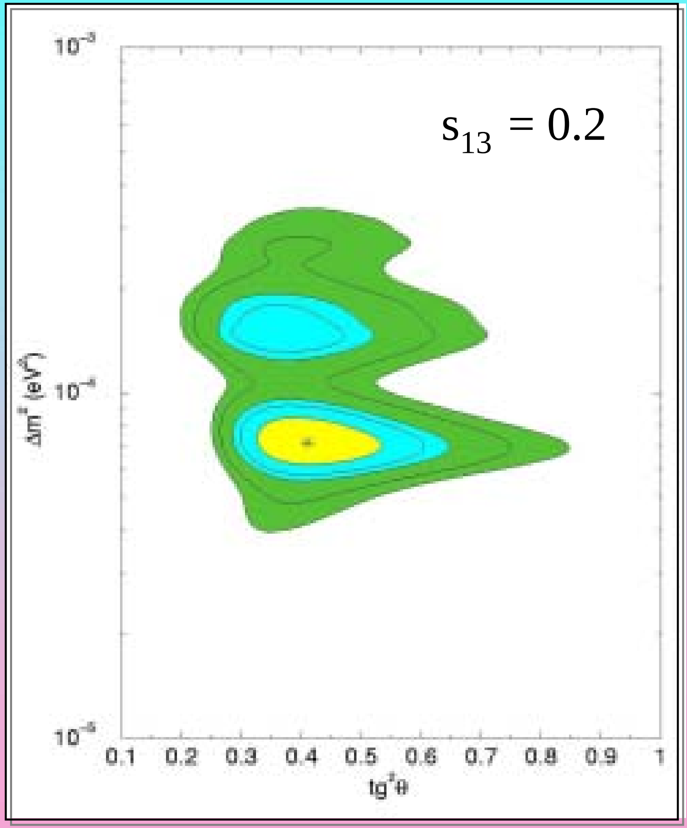
Still the allowed region should be diminished to identify physical processes:

- High Δm^2 — Averaged vacuum oscillations with small matter corrections
- Low Δm^2 — Non-oscillatory adiabatic conversion (for $E > 5$ MeV)
- Small mixing: Resonance description is valid
- Maximal mixing: ``Resonance'' is at zero density

Solar neutrinos and KamLAND



2ν - fit

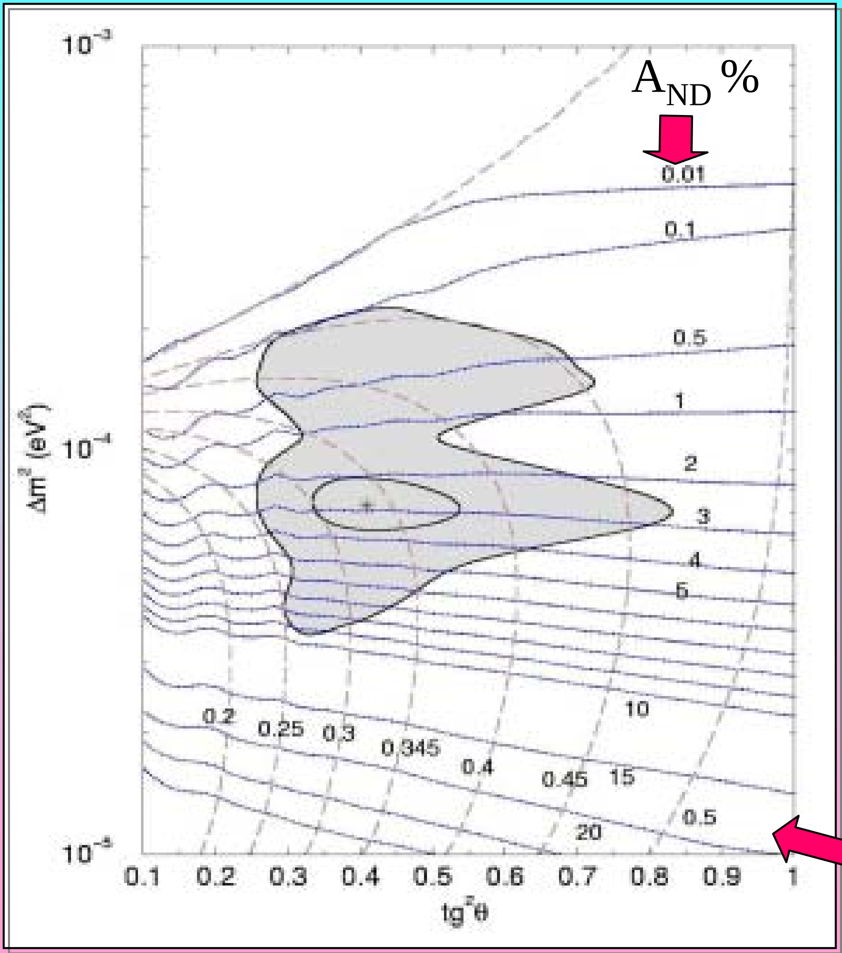


3ν - fit

P.de Holanda, A.S., hep-ph/0212270

Delta m2 and mixing

P.de Holanda, A.S. hep-ph/0212270



$\frac{CC}{NC}$

Lines of constant CC/NC ratio and Day-Night asymmetry at SNO

Two stages

- Identification of the unique region:

  2ν analysis, sub-leading effects (13 -mixing) can be neglected

- Precision measurements:

  Possible sub-leading effects should be included.
  Generic 3ν analysis should be performed.
  Problem of degeneracy of parameters appears

LMA: Consistency Checks

Over determine solution, cross checks

in the b.f. point

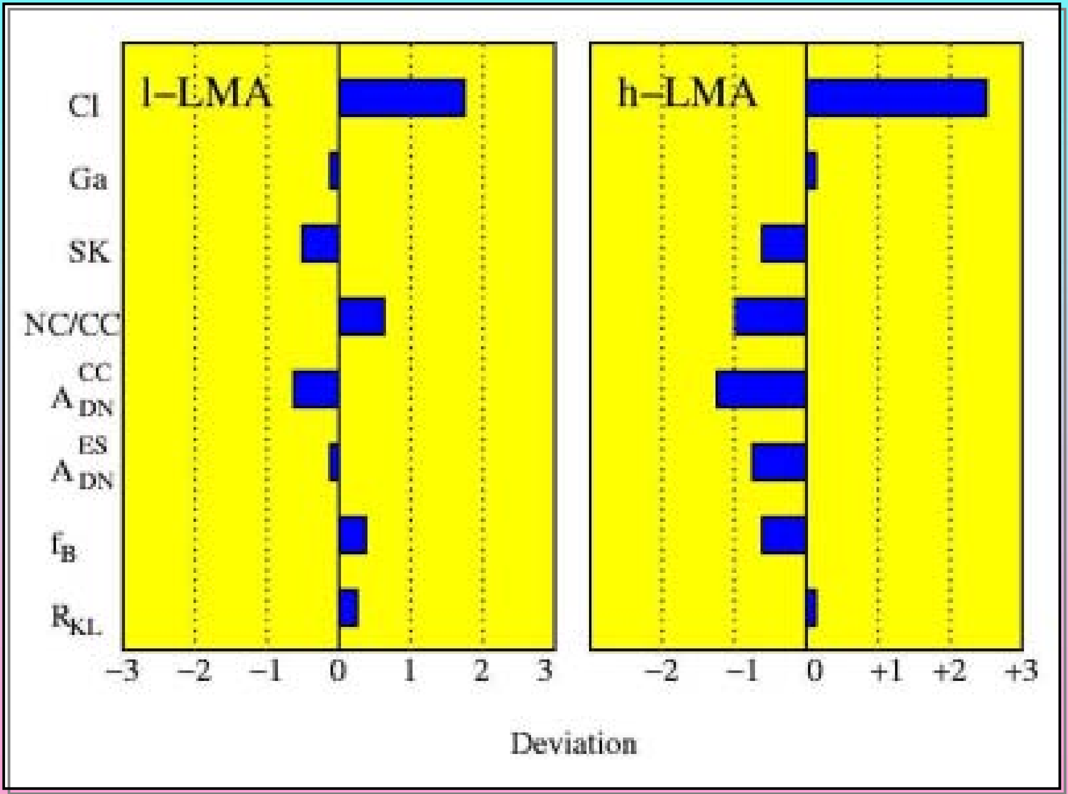
- Day -Night Asymmetries: $A_{ND}(SNO) = 2 - 5\ \%$, $A_{DN}(SK) = 2 - 3\ \%$
- Spectrum distortion: Turn up at low energies: 5 - 10 %
- Rate at the intermediate energies BOREXINO/KamLAND: $R = (0.6 - 0.7)R_{SSM}$
- Seasonal variations: Small (unobservable) effect: $A_{WS} < 0.5\%$
- Low energy experiments

Implications

- further confirmation of LMA
- precise determination of the neutrino parameters
- searches for physics ``beyond the LMA''

Homestake Anomaly?

Pull-off diagrams for the best fit points
of the l- and h- LMA regions



Q_{Ar}(LMA) > Q_{Ar}(Homestake)

(2 - 2.5) σ pull

- Statistical fluctuation ?
- Systematics?
  Related to time variations of rate?
- Neutrino properties: conversion driven by second Δm^2

Additional deep in the suppression pit at E ~ 1 MeV?

Solar Neutrinos versus KamLAND

Parameters from the 2ν analysis:

Solar neutrinos		KamLAND
Δm^2, $\tan^2\theta$	=	Δm^2, $\tan^2\theta$

The equality is satisfied within 1σ

Gives hint that CPT is OK

Further checks of the equality

Possible deviations

(mismatch of parameters if the fit is done in terms of 2ν mixing):

CPT-violation

Physics Beyond the LMA

If some effect influences KamLAND signal it should also show up in the solar neutrinos

Inverse is not correct:

Some effect can influence solar neutrinos but not KamLAND result

Solar neutrinos have much higher sensitivity to Physics Beyond the LMA

- $\Delta m^2 - \theta$ region of sensitivity is much larger for solar neutrinos than for KamLAND

  Additional small Δm^2 or/and θ can strongly influence the solar neutrinos but not KamLAND

- Magnetic moment: the Earth magnetic field is too small

- Non-standard interactions (NSI) of neutrinos do not change the KL signal since the matter effect is small

Even in the CPT conserving case one can find

$$\boxed{\Delta m^2, \theta}\Big|_{\text{solar}} \neq \boxed{\Delta m^2, \theta}\Big|_{\text{KL}}$$

Testing the theory of conversion

Solar neutrinos

- Adiabatic conversion (MSW)
- Matter effect dominates (at least in the HE part)
- Non-oscillatory transition the oscillation phase is irrelevant

KamLAND

- Vacuum oscillations
- Matter effect is very small
- Oscillation phase is crucial for observed effect

Adiabatic conversion formula

Δm^2 , θ

Vacuum oscillation formula

Coincidence of these parameters determined from the solar neutrino data and from KamLAND results testifies for the correctness of the theory (phase of oscillations, matter potential, etc..)

See also F.L. Fogli et al., hep-ph/0211414

Beyond LMA MSW

Physics of sub-leading effects

LMA MSW + ...

Signatures

Implications

+ SFP

- Searches for $\bar{\nu}_e$ flux
- Time variations

Beyond single Δm^2 context

Magnetic moment, magnetic fields inside the Sun

+ nu-sterile

- CC/NC
- Additional distortion of spectrum

+ NSI

(non-standard neutrino interaction)

- Additional contribution to the matter effect

+ VEP

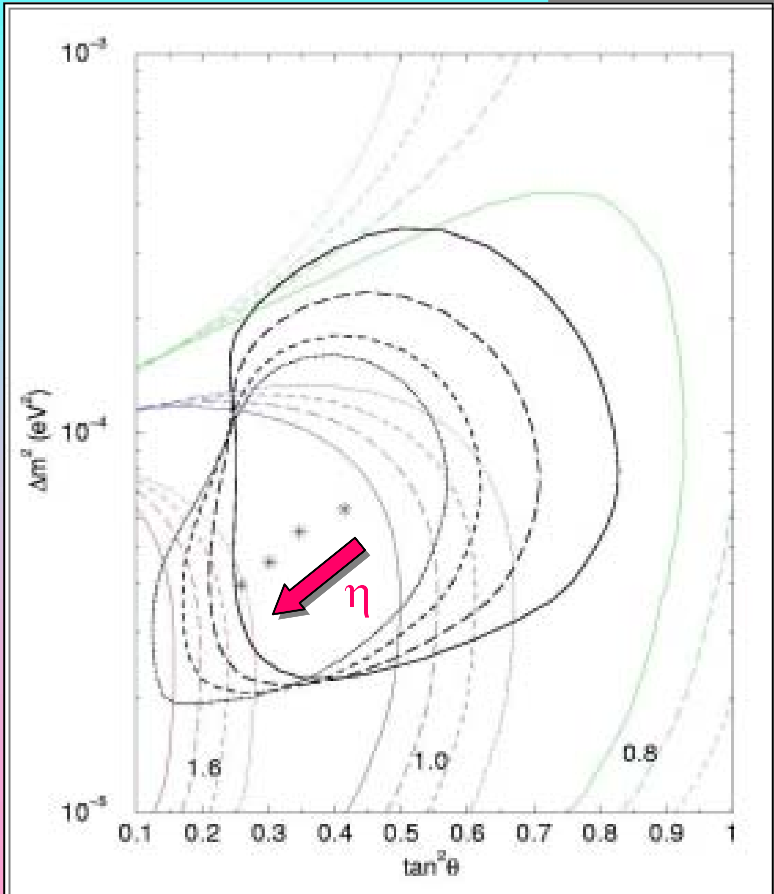
(violation of equivalence principle)

Searches for Nu-sterile

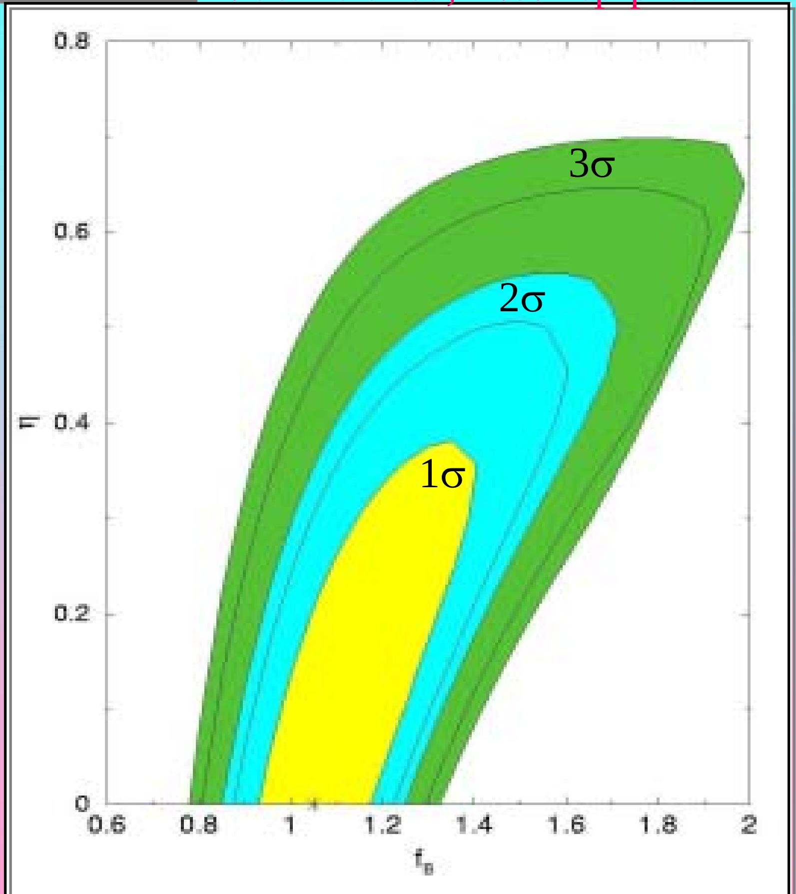
Single Δm^2 context

$$\nu_e \;\rightarrow \sqrt{1-\eta}\;\nu_a \;+\sqrt{\eta}\;\nu_s$$

P. de Holanda, A.S. hep-ph/0211264



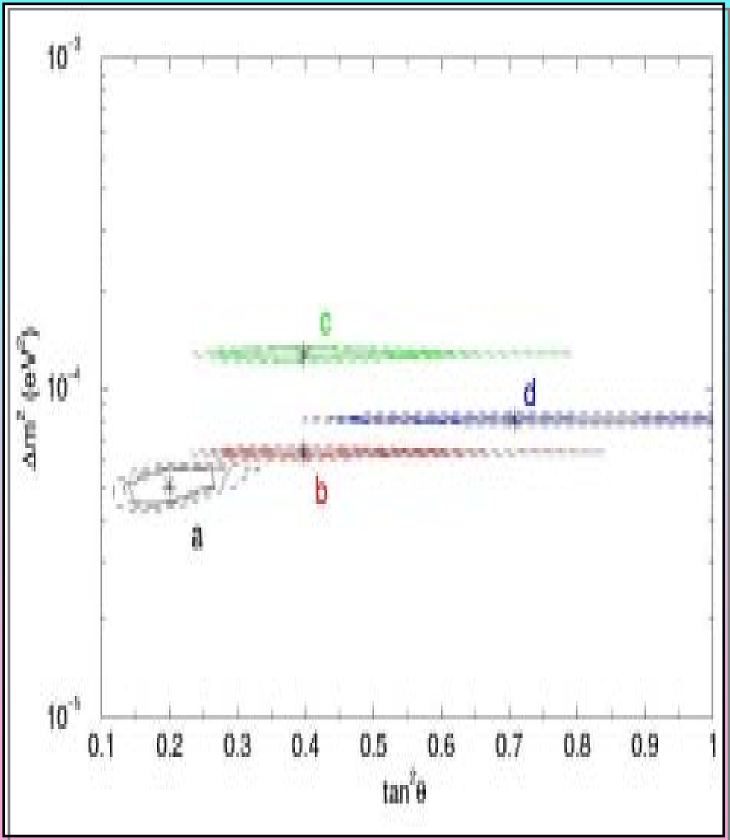
The 3σ allowed region for
$\eta =$ 0.0, 0.2, 0.4, 0.6 (from right to left)



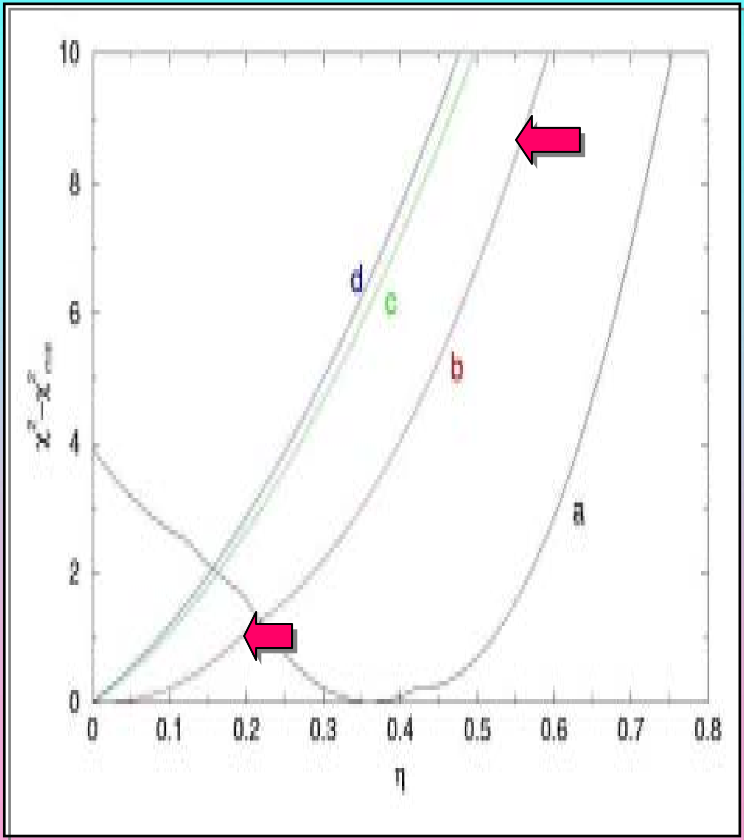
The allowed region in the $\eta - f_B$
(boron neutrino flux) plane for different
confidence levels

...with solar neutrinos and KamLAND

(KamLAND data simulation for 3years, 600 t)



The 1σ, 2σ, 3σ allowed regions from the analysis of 3 years simulated KamLAND data



The dependence of the χ^2 on η from a combined analysis of the solar data and simulated KamLAND results

LMA + SFP

Spin-flavor precession
(resonance, non-resonance

■ ``Post-KamLAND'' study
in the context of single

$$\Delta m^2 = \Delta m^2_{\;LMA}$$

E. Akhmedov, J. Pulido
hep-ph/0209192

■ The effect (neutrino spin flip) is in the central regions
of the Sun (radiative zone)

B > 10 MG

■ Signature: Appearance of the antineutrino $\bar{\nu}_e$ flux

$$\frac{F(\bar{\nu}_e)}{F(\nu_e)} = 1.5\% \left(\frac{\mu_\nu}{10^{-12}\,\mu_B}\right)^2 \left(\frac{B}{100\text{ MG}}\right)^2$$

(for the boron neutrinos)

At the present SK bound

■ Magnetic moment:
(natural* value)

$$\mu_\nu \sim \frac{e}{\Lambda^2}\, m_\nu$$

(unless Voloshin's
cancellation, or polarization
suppression occurs)

For the cut energy Λ = 100 GeV and m_ν = 1 eV: $\mu_\nu \sim 10^{-16}\,\mu_B$ unobservable?

■ Beyond single Δm^2 : if for second $\Delta m^2 \ll \Delta m^2_{\;LMA}$ effect can be much larger

Solar Neutrino Astrophysics

Back to the original task:

J.N.Bahcall
G.T.Zatsepin
V.A. Kuzmin

The spectroscopy of Solar Neutrinos to study interior properties of the Sun

Diagnostics of the Sun

- Determination of the original solar neutrino fluxes

In a sense these fluxes do not exist since neutrino conversion starts already in the neutrino production region

Still we can introduce these fluxes since there is no back influence of neutrino conversion on the solar characteristics and production of neutrinos. Conversion effects can be subtracted

J. N. Bahcall,
M. Gonzalez-Garci
C. Pena-Garay
astro-ph/0212331

- Determine neutrino fluxes from pp- and CNO - cycles
- Searches for time variations of fluxes

Atmospheric Neutrinos: Any problem?

Very compelling evidence that vacuum oscillations ν_μ <–> ν_τ is the dominant mechanism of the atmospheric neutrino conversion

- SuperKamiokande
- K2K
- MACRO
- SOUDAN

KamLAND gives an additional confirmation of the oscillation picture

- confirms oscillations
- large/maximal mixing in the lepton sector

Nothing statistically significant beyond this picture

What is the next?

Searches for

- ν_e oscillations
- sterile neutrinos
- CP-violation
- CPT-violation
- specific oscillation effects

CR physics with atmospheric nu

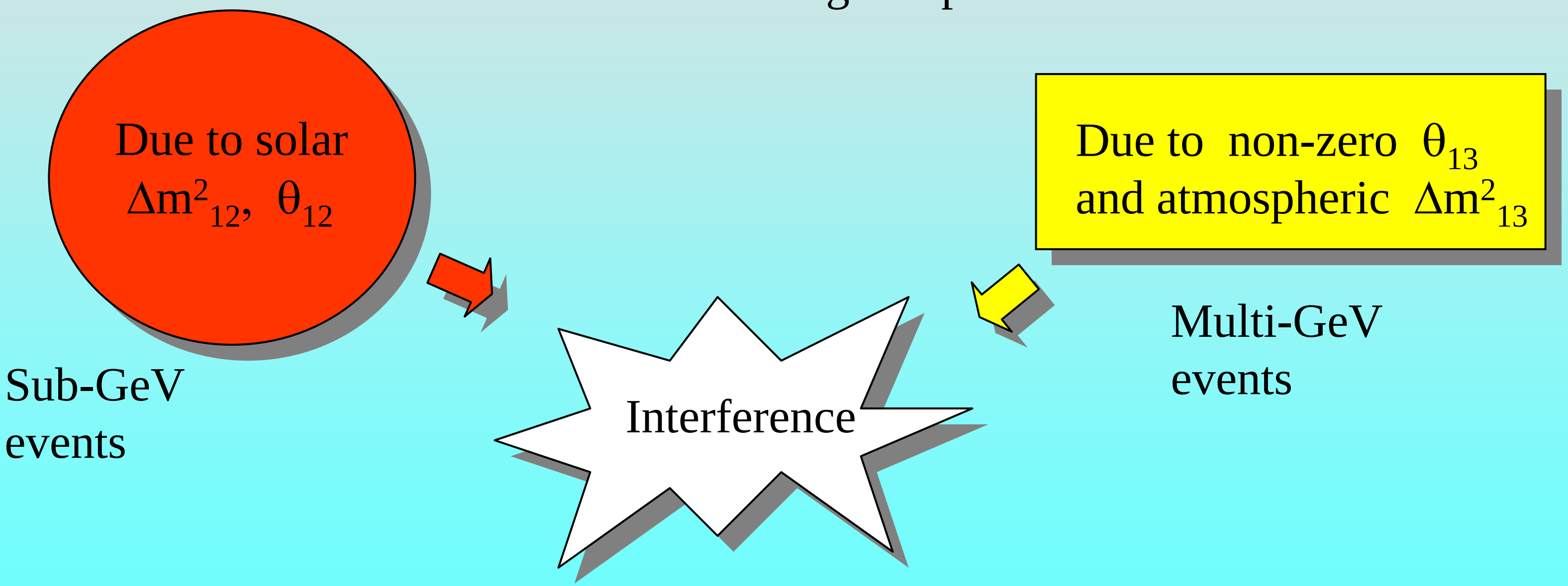
Oscillations of atmospheric nu_e

After KamLAND

Oscillations of electron (anti) neutrino must appear at some level even for $\theta_{13} = 0$ due to the solar oscillation parameters

Signature:

Excess of the e-like events in certain energy range with
- specific energy and
- zenith angle dependence



Oscillations due to solar dm2 and theta

Excess of the e-like events in the sub-GeV

$F_e = F_e^0 (P_{ee} + r P_{\mu e})$

$$\boxed{\frac{F_e}{F_e^0} - 1 = P_2 (r c_{23}^2 - 1)}$$

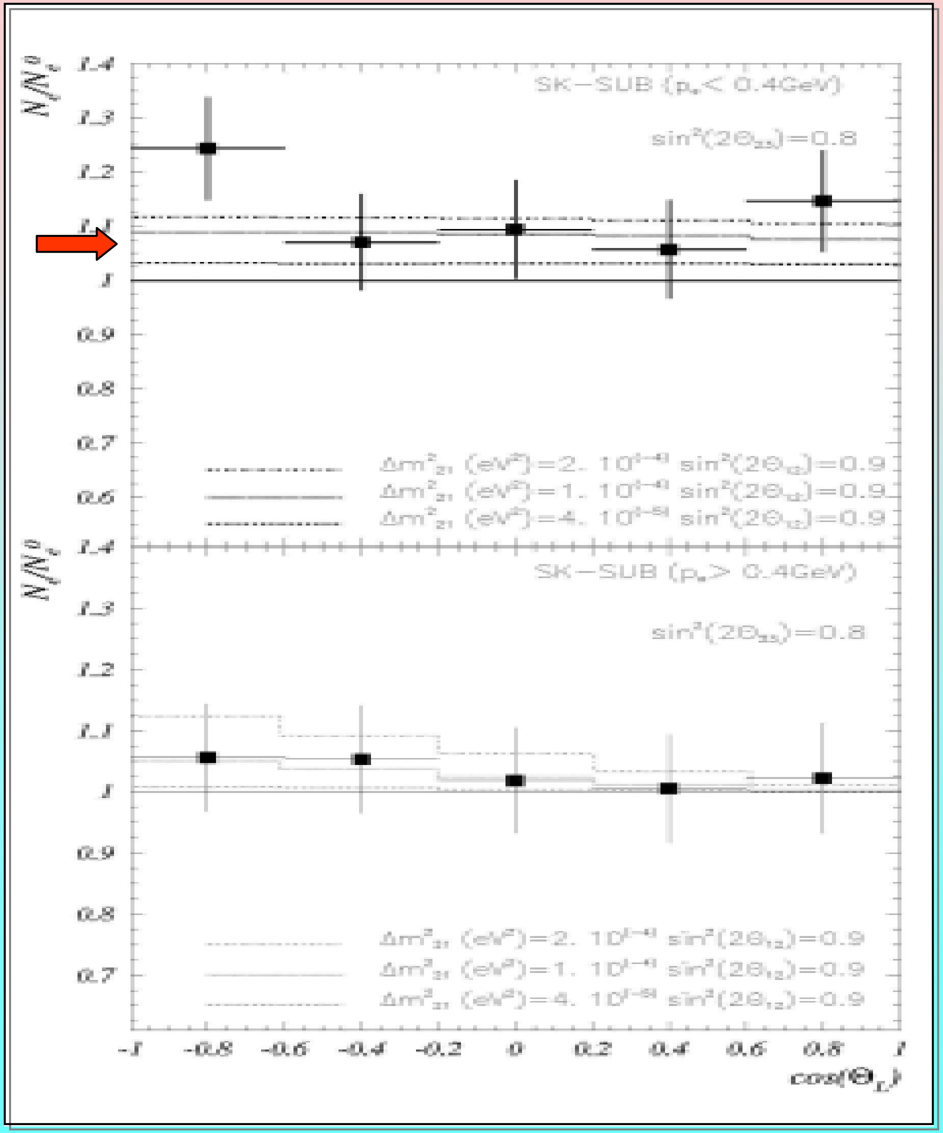
``screening factor''

$P_2 = P(\Delta m^2_{12} , \theta_{12})$ is the 2ν transition probability

In the sub-GeV sample

$r = F_\mu^0 / F_e^0 \sim 2$

The excess is zero for maximal 23- mixing



Zenith angle dependence of the e-like events

0.Peres, A.S., hep-ph/0201069

Excess of the e-like events

$$\varepsilon = \frac{F_e}{F_e^0} - 1$$

In the best fit points of the l- and h- LMA regions

$\sin^2 2\theta_{23}$	ε_l , %	ε_h, %
0.91	2.8	4.8
0.96	1.9	3.2
0.99	0.9	1.6

Excess increases with Δm^2

Once the LMA parameters are known: restrict deviation of 23-mixing from maximal by measuring ε

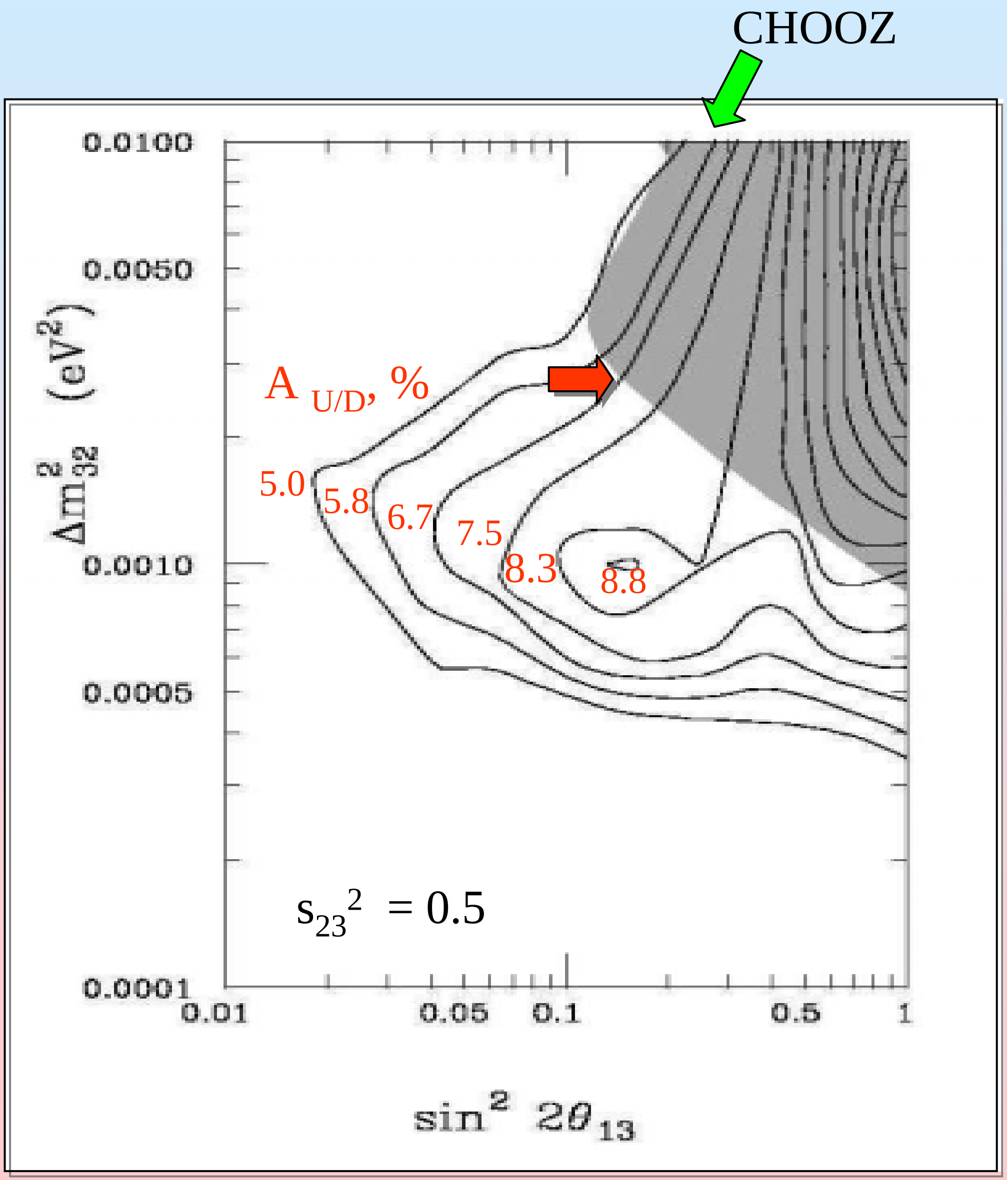
S_13

Excess of the e-like events
in multi-GeV region

$$A_{U/D} = 2\,\frac{U - D}{U + D}$$

U: $\cos\Theta_Z$ = (-1 -- -0.6)

D: $\cos\Theta_Z$ = (0.6 -- 1)



Contours of constant up - down
asymmetry of the e -like events

Akhmedov, A. Dighe,
P. Lipari, A.S.

Induced Interference

Excess of the e-like events in the sub-GeV

$$\frac{F_e}{F_e^0} - 1 = P_2 (r\, c_{23}^2 - 1) - r\, s_{13} \sin 2\theta_{23}\, \mathrm{Re}\, (A^*_{ee} A_{e\mu}) - s^2_{13} [2(1 - r\, s^2_{23}) + P_2\, (r - 2)]$$

$P_2 = |A_{e\mu}|^2$ is the 2ν transition probability

Interference term:

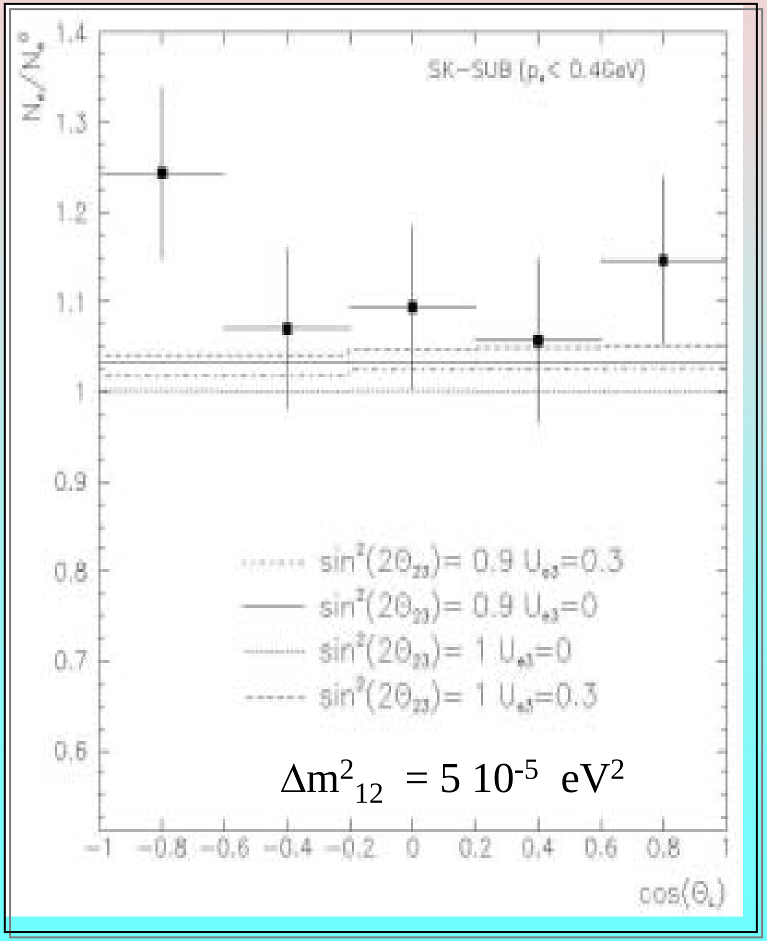
- linear in s_{13}
- no screening effect
- has opposite sign for neutrinos and antineutrinos
- maximal if $\Delta m^2_{12} = 7\ 10^{-5}$ eV^2

Can be dominant if 23-mixing is maximal:

$$\boxed{\varepsilon^{int} \sim 5\% \ \frac{s_{13}}{0.3}}$$

(in maximum)

Zenith angle dependence of the e-like events



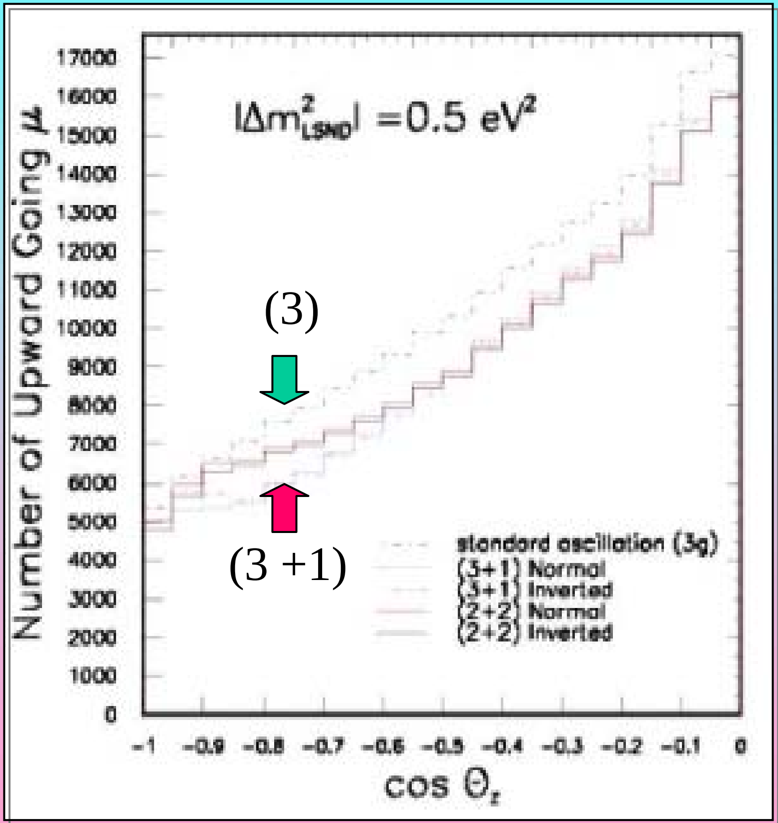
O.Peres, A.S., hep-ph/0201069

Sterile Neutrino

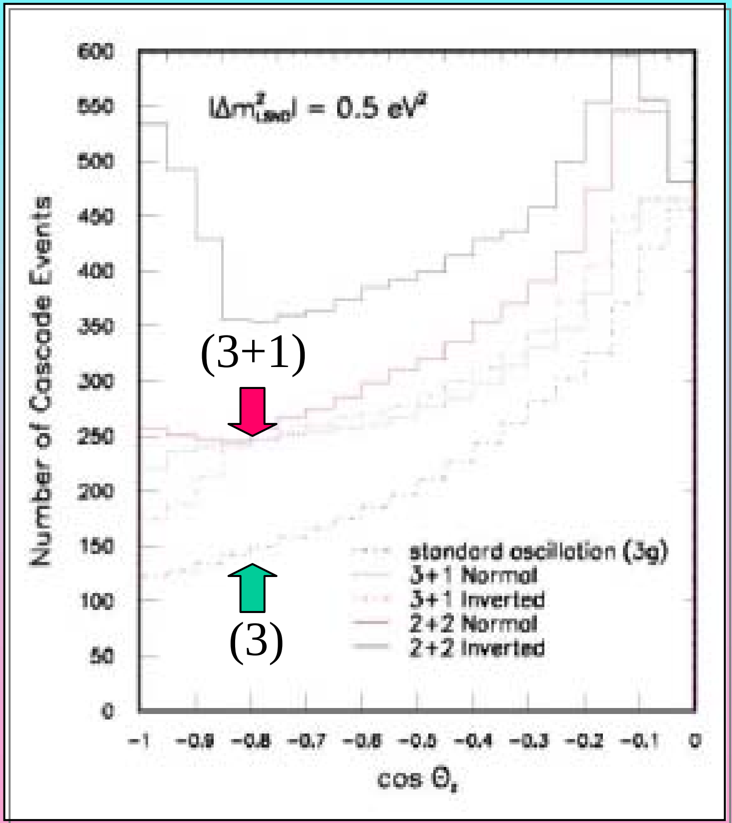
H. Nunokawa, O.L.G.Peres,
R. Zukanovich Funchal, hep-ph/0302039

Fourth neutrino with $\Delta m^2 \sim \Delta m^2_{LSND} \sim 0.5\ eV^2$ resonance in the 0.5 - 1.5 TeV range
For (3+1) scheme resonances are in $\nu_e - \nu_s$, $\overline{\nu}_{\mu/\tau} - \overline{\nu}_s$ channels

IceCube



Upward-going muons



Cascade events (induced by the CC interactions of electron, and tau neutrino and by the NC scattering)

- Searches new neutrino states
- Observation of the parametric effects

Ultimate oscillation
anomaly?

LSND

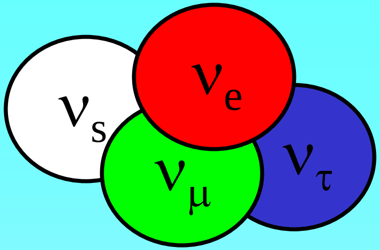
CPT-violation

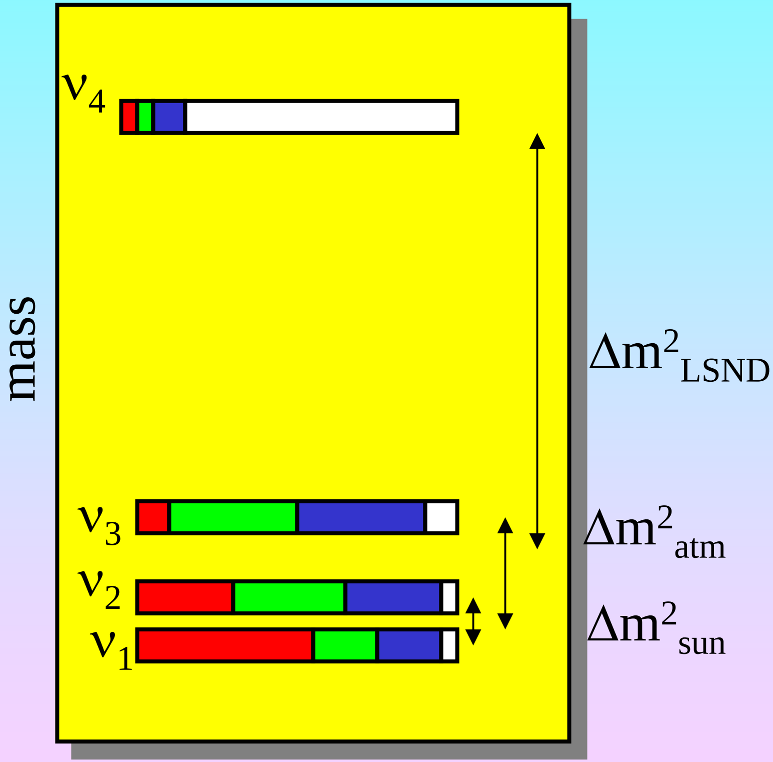
Non-standard Interactions

(3 + 1)-scheme Sterile neutrino

Status after KamLAND

4nu spectrum





Generic possibility of interest even independently of the LSND result

Generation of large mixing of active neutrinos due to small mixing with sterile state

Produces uncertainty in interpretation of results

3 + 1

Non-Standard Interactions

Non-oscillation interpretation

K. S. Babu, and S. Pakvasa
hep-ph/0204226

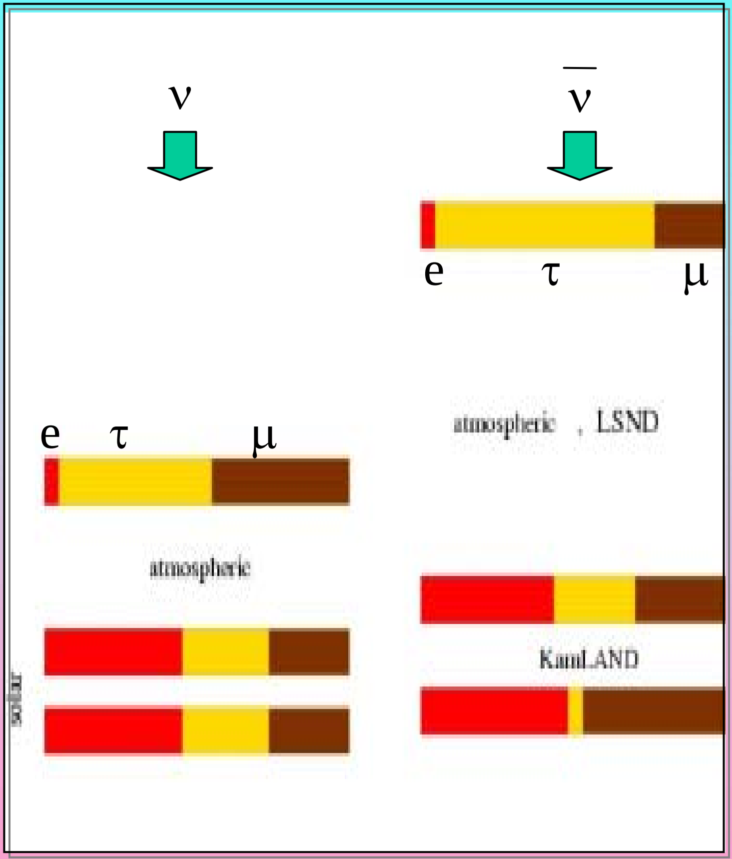
$\mu^+ \longrightarrow e^+ \ \bar{\nu}_e \ \bar{\nu}_i \qquad (e,\ \mu,\ \tau)$

Due to exchange of new neutral scalar bosons with M = 300 - 500 GeV

- $|\Delta L| = 2$ ⇒ key to avoid bounds from $\mu \longrightarrow eee$, etc.
- Michel parameter $\rho = 0$ ⇒ LSND and KARMEN better consistency ??
- No effect for pion decay ⇒ No effect for ``decay in flight'' ⇒ can not explain LSND data for neutrinos
  MiniBOONE can not check even if it will work both in neutrino and antineutrino modes
- Observable effects in ⇒
  $e^+ e^- \to \mu^+ \mu^-$
  $e^+ e^- \to \nu\nu\gamma$
  $Z^0 \to e^+ \mu^- \nu\nu$ with $Br = 10^{-7}$

CPT-violation

G. Barenboim et al, hep-ph/0212116
After KamLAND: ultimate possibility?



Mass spectra of neutrinos and antineutrinos
In original scenario KamLAND
would see very small oscillation effect
G. Barenboim et al., JHEP 0210, 001 (2002)

- Atmospheric antineutrinos: ~10 - 15% averaged oscillation effect
- SuperK analysis of CPT excludes such a possibility?
- Strong oscillation effect for $\bar{\nu}_e$ driven by KamLAND oscillation parameters ~8% excess of the e-like events in the sub-GeV region
- MINOS: checks of oscillations in the neutrino and antineutrino channels
- KamLAND can not check LMA. However, LOW, VO, SFP, etc., are not excluded yet, further check by SNO, BOREXINO… are needed
- MiniBOONE: null result in the neutrino mode positive result in the antineutrino mode

Supernova Neutrinos

``After KamLAND'' we can definitely say that

In 1987 (SN 1987A) the effect of the (anti)neutrino conversion had been observed.

- conversion inside the star
- oscillation in the matter of the Earth
- the Earth matter effect was different for different detectors

With future SN bursts one can test

- $\sin\theta_{13}$
- type of mass hierarchy
- existence of new (sterile) neutrinos

Problem:

Conversion of neutrinos	Original fluxes	Observations
Strong even for very small mixing	all neutrino species are produced, uncertainties	Uncertainties of detection

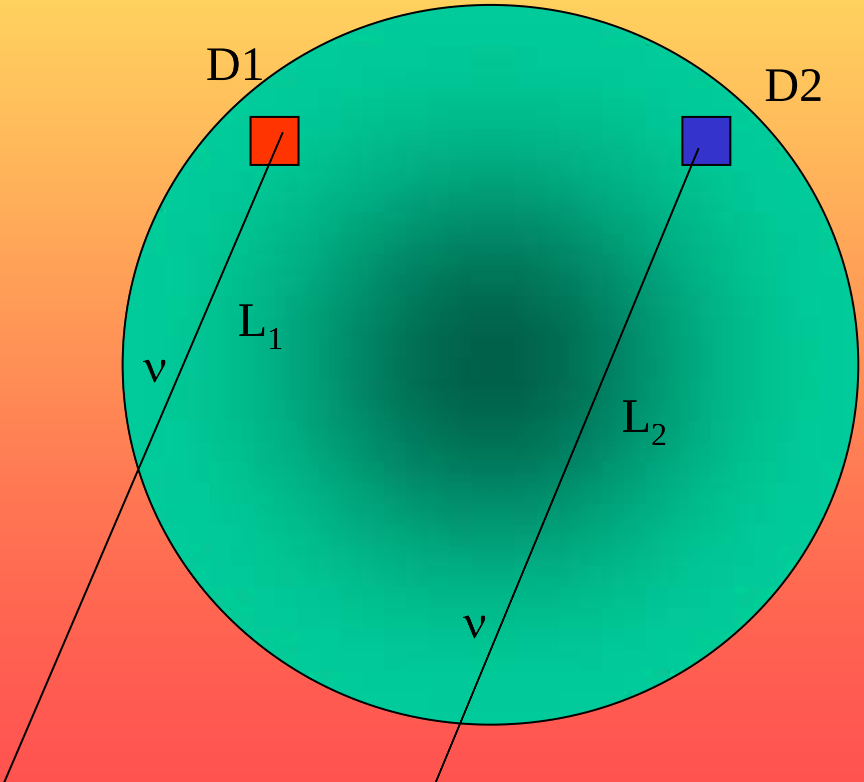
⇨ substantially diminishes observable effect

LBL experiments with SN neutrinos

Beam uncertainties can be controlled if

- Two well separated detectors are used
- Properties of medium are know

⇨ Comparison of signals from the two detectors: oscillation effects between them and also test properties of the original flux



This is realized for oscillations of SN neutrinos inside the Earth:

Fluxes arriving at the surface of the earth are the same for both detectors

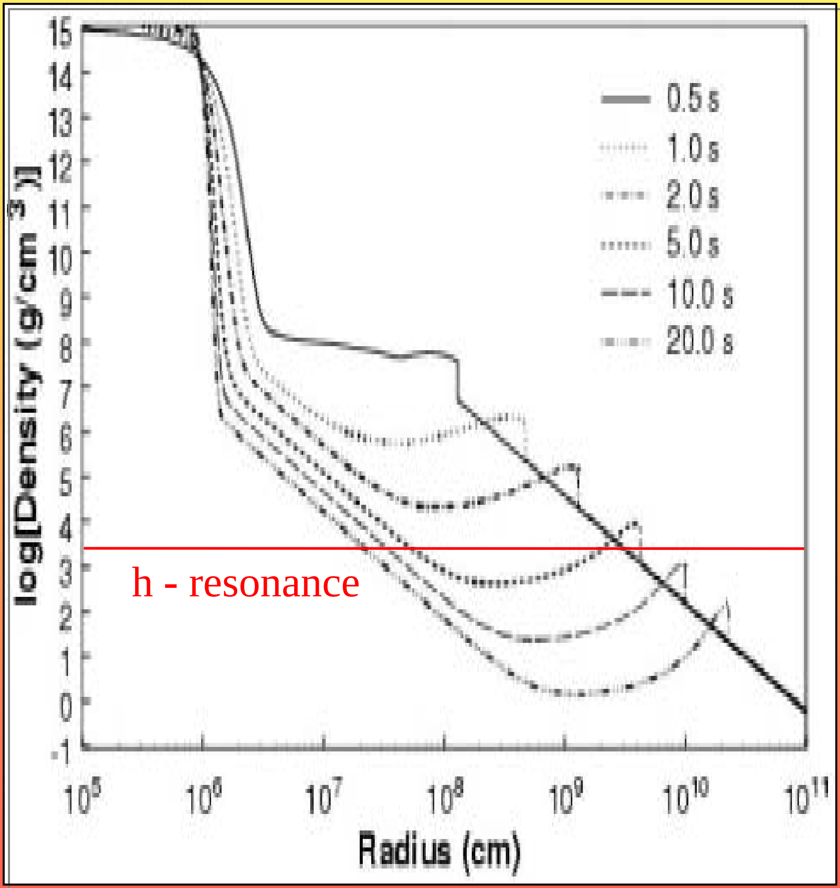
e.g.

If $\sin^2\theta_{13} > 10^{-4}$ an appearance of the Earth matter effect in $\bar{\nu}_e$ or (ν_e) signal will testify for normal (inverted) mass hierarchy of neutrinos

Talk by C. Lunardini

Shock Wave Effect

R.C. Schirato, G.M. Fuller, astro-ph/0205390



Density profile with shock wave propagation at various times post-bounce

The shock wave can reach the region relevant for the neutrino conversion

$\rho \sim 10^4$ g/cc

During 3 - 5 s from the beginning of the burst

Influences neutrino conversion if $\sin^2\theta_{13} > 10^{-5}$

The effects are in the neutrino (antineutrino) for normal (inverted) hierarchy:

- change the number of events
  R.C. Schirato, G.M. Fuller, astro-ph/020539
- ``wave of softening of spectrum''
  K. Takahashi et al, astro-ph/0212195
- delayed Earth matter effect
  C.Lunardini, A.S., hep-ph/0302033

Monitoring shock wave with neutrinos

G. Fuller

Studying effects of the shock wave
on the properties of neutrino burst
one can get (in principle) information on

- time of propagation
- velocity of propagation
- shock wave revival time
- density gradient in the front
- size of the front

Can shed some light on
mechanism of explosion

Standard and Non-Standard

Standard picture

- Three neutrinos
- Massive, m $\lesssim$ 1 eV
- Bi-large or Large-maximal mixing
- Smallness of neutrino mass is related to Majorana nature

Oscillations and matter conversion -- common phenomena

Beyond the Standard

- New neutrino states Sterile neutrinos
- New interactions
- Large anomalous dipole moments

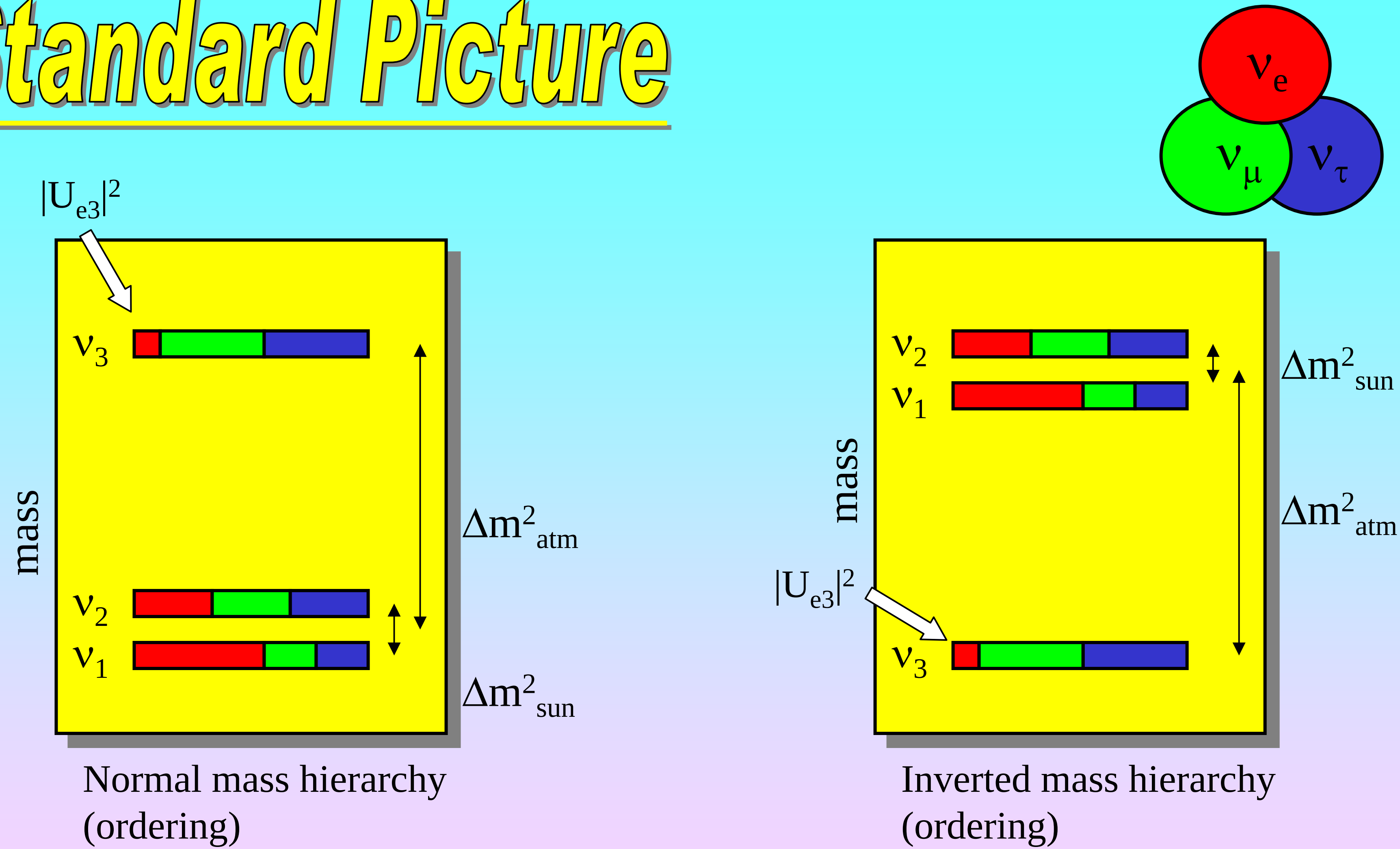
Exotics

Effects of violation of

- Lorentz invariance
- CPT,
- Equivalence principle

...

Standard Picture



- Type of mass spectrum: with Hierarchy, Ordering, Degeneracy ⇒ absolute mass scale
- Type of the mass hierarchy: Normal, Inverted
- $U_{e3} = ?$

Accomplishing Standard Picture

$\sin\theta_{13} = |U_{e3}|$

Type of mass hierarchy or ordering: sign Δm^2_{32}

- Normal
- Inverted

Absolute scale of neutrino mass m_1 → Type of mass spectrum

- hierarchical
- partially degenerate
- quasi-degenerate

Dirac CP-violating phase, δ ↔ Leptonic Unitarity triangle

Nature of neutrinos:

- Dirac
- Majorana → Majorana CP-violating phases, ρ, σ

Precision measurements of oscillation parameters

- Δm^2_{21}
- $\tan^2\theta_{12}$
- Δm^2_{32}
- $\sin^2 2\theta_{23}$

Deviation from maximal mixing

e highest priority

2\beta_0\nu

Absolute mass scale

Nature of Neutrinos

CP phases

Type of mass Spectrum

Type of mass hierarchy

Post -KamLAND, selecting LMA has confirmed

- strong dependence of the effective Majorana mass on CP-violation phases,
- possibility of cancellation of contributions

With $\beta\beta_{0\nu}$ searches it is not possible to fail from scientific point of view
any result - positive or improvement of bound
is of great importance

Can not become irrelevant after further developments

Conclusions

- The main developments in neutrino physics where related to various ``neutrino anomalies’’ (both real and fake).
  The anomalies were driving force of both theoretical and experimental developments

- After KamLAND:
  Are solar and atmospheric neutrino problems solved?
  What is left? LSND?
  New anomalies?

- Does the ``standard picture’’ of neutrino mass and mixing emerge?
  Do neutrinos change their character becoming more predictable?

Perspectives

``Standard picture''

Well defined program characterized by
- further tests
- precision measurements
- searches for /bounds on new physics

LSND confirmed

New perspectives:
- new neutrino states
- new interactions
- CPT-violation
- ???

New anomalies

Lead to something unexpected
- NuTeV
- Z^0 - width
- ???

Some mixture of these scenarios?

Without Anomalies

Warning:
Future High Energy experiments (LHC ...) may have serious impac on this program

Well defined program:

1). Determination of masses, mixings, CP- phases
Precision measurement of parameters

``Technological problems''
absolute scale of neutrino mass, CP-phases - big challenge

2). Searches for new physics beyond ``standard picture''
restrictions of exotics

Non-standard interactions
New neutrino states
Effects of violation of
- CPT
- Lorenz invariance
- Equivalence principle
- Pauli principle

3). Identification of origins of neutrino mass and mixing

Reconstruction of neutrino mass matrix
tests of the see-saw (and other) mechanism
- flavor violation processes
- leptogenesis
- high energy experiments

Applications

Of our knowledge of neutrino mass and mixing

- Geophysics
- Astrophysics
- Cosmology

For details and further developments
See talks at NOON2003