Neutrinos: a phenomenological overview

A. Yu. Smirnov

International Centre for Theoretical Physics, Trieste, Italy
Institute for Nuclear Research, RAS, Moscow, Russia

14th Lomonosov conference
August 19, 2009

Content

1. Status
2. Before and Now
3. Expanding frontiers

Interactions

Gauge interactions are well known (SM) and tested

Yukawa couplings with Higgs boson (s) –
related to existence of the RH neutrinos or new scalars
- unknown; they are relevant for leptogenesis

Open questions:
- axial vector form-factors;
- single pion forward production;
- total invisible width of Z^0

In some cases - neutrinos are unique:
provide axial vector current
interactions of Z, γ, ω

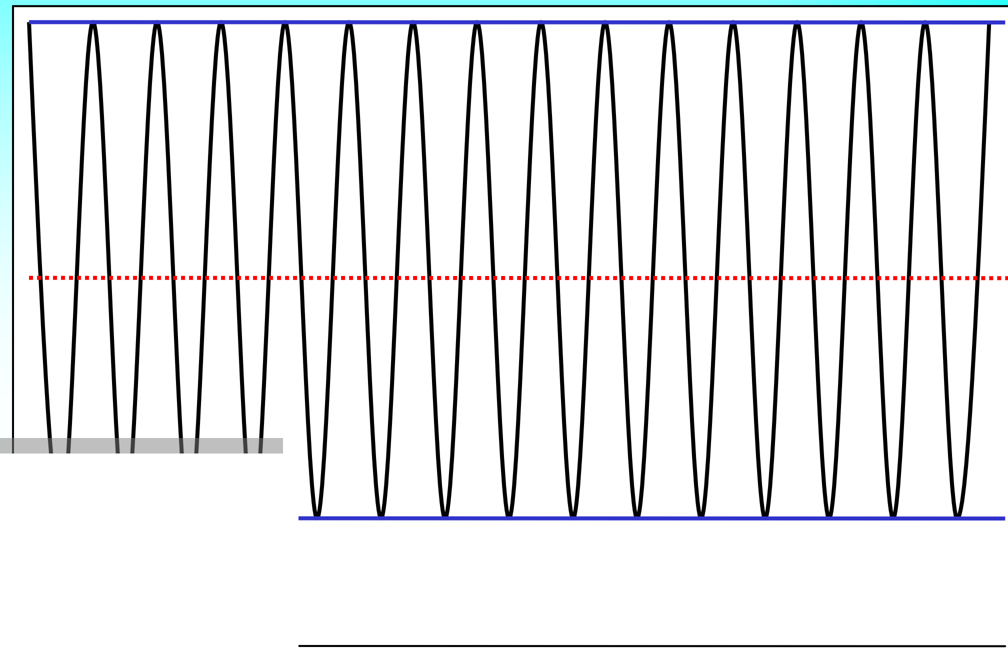
J Harley, C.T. Hill, R. Hill

Studies in the context of search for new neutrino
interactions related to
- various extensions on the SM
- specific mechanisms of neutrino mass generation

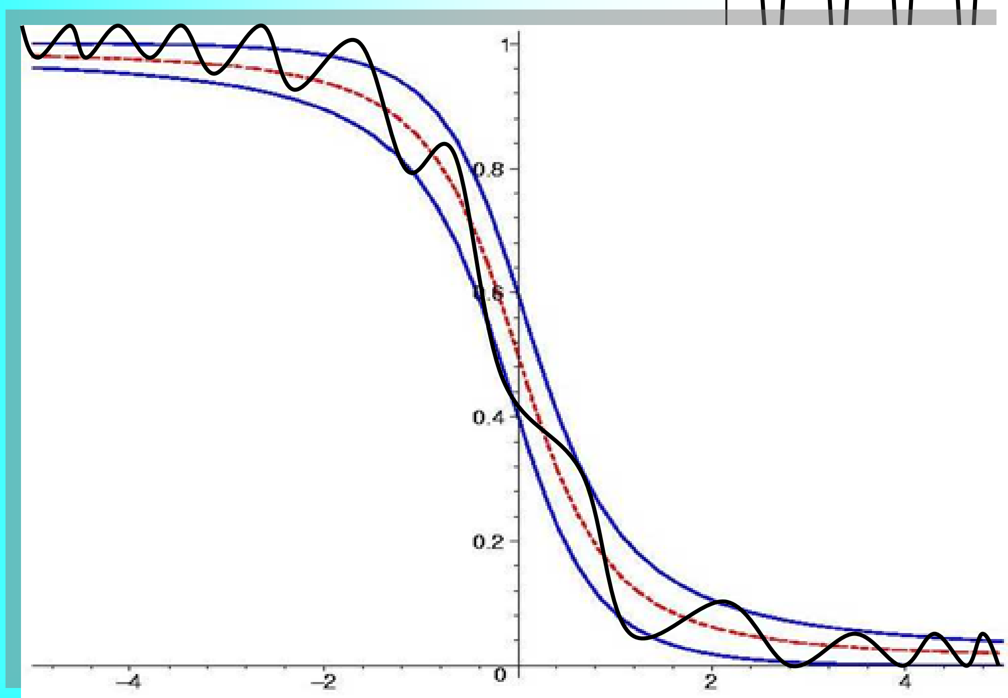
Propagation

Two effects for interpretation of existing data

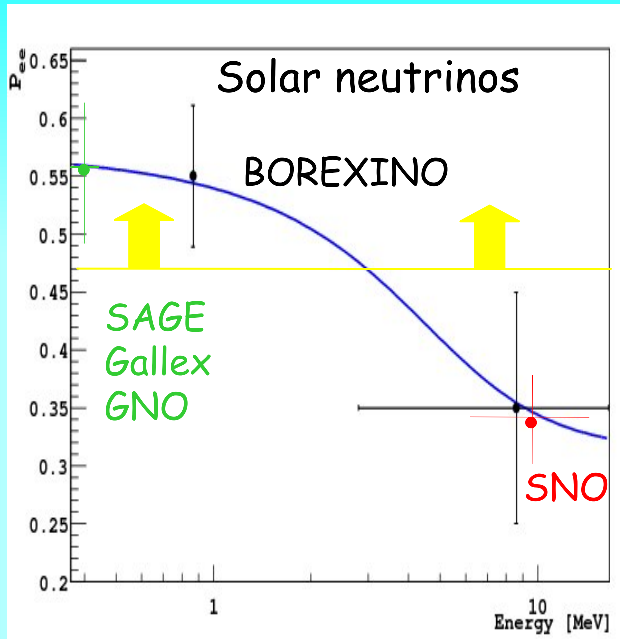
Oscillations

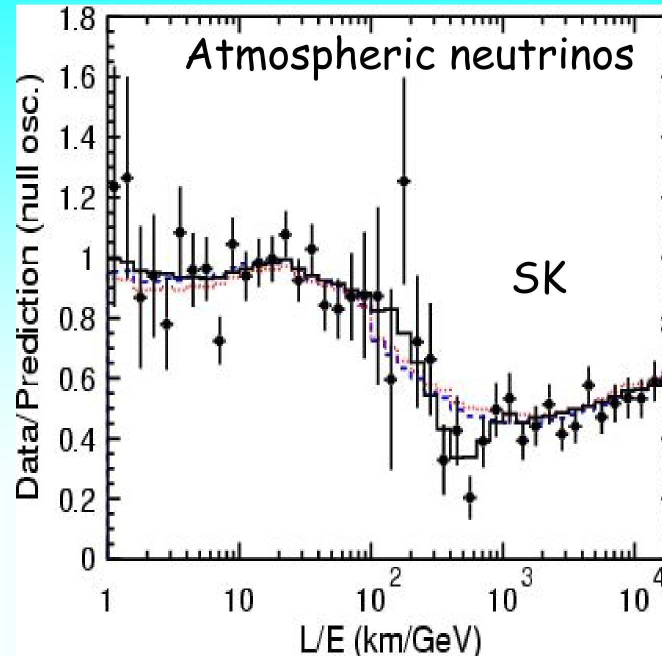


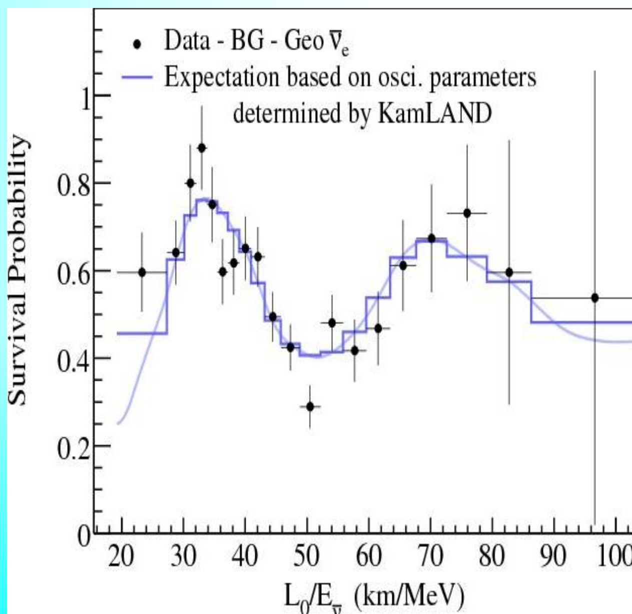
Adiabatic conversion

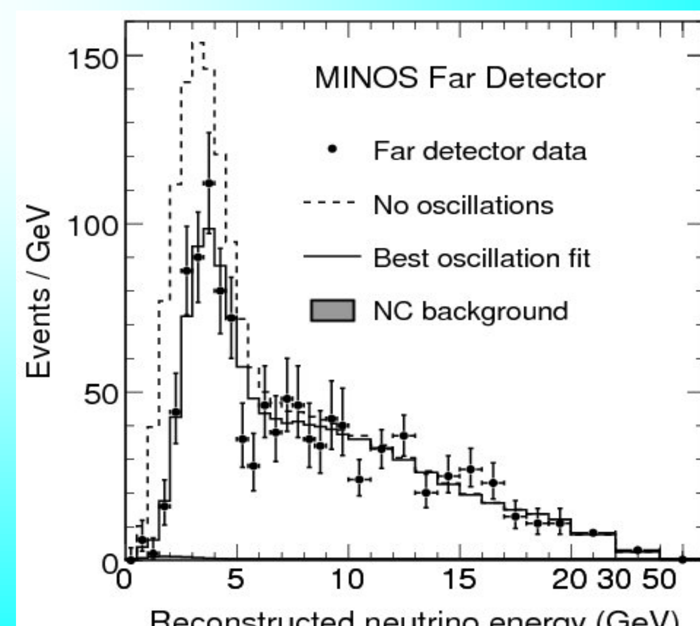


Observations

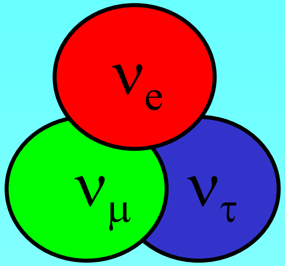


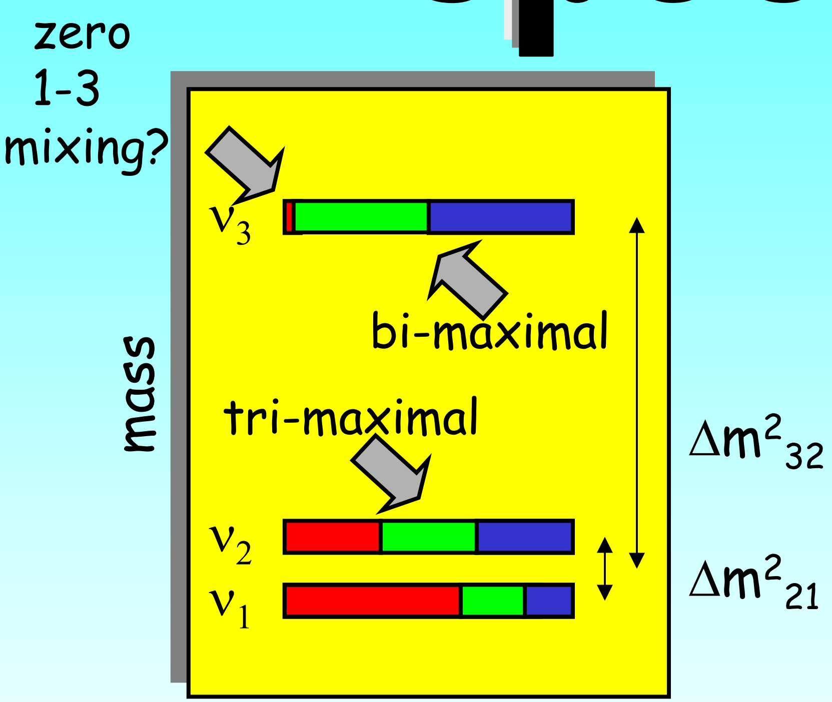






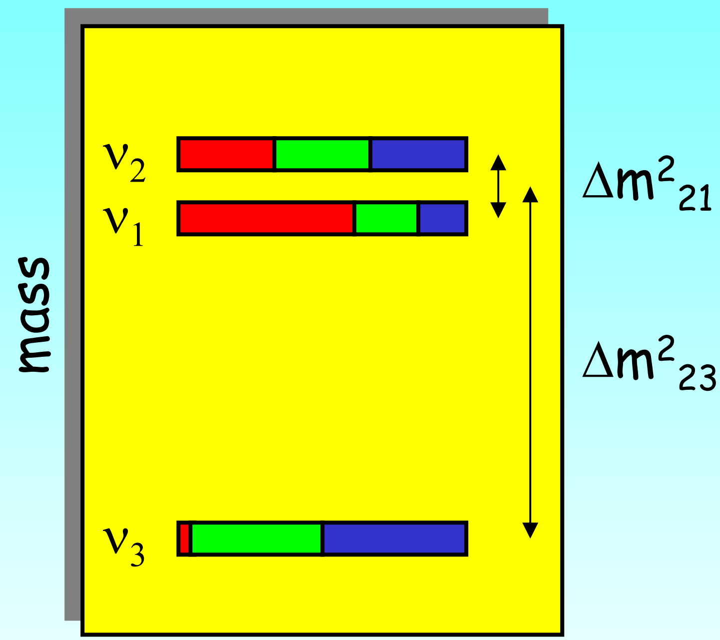
Spectrum





Normal mass hierarchy

?



Inverted mass hierarchy

$$\nu_f = U_{PMNS}\, \nu_{mass}$$

$$U_{PMNS} = U_{23}\; I_\delta\, U_{13}\, I_{-\delta}\, U_{12}$$

Tri-bimaximal mixing if 1-3 mixing is zero

Huge impact of small angle

$\sin^2\theta_{13} = 0.01 - 0.03$

U_{e3}

theoretical implications

symmetry

atmospheric neutrinos

dominant factor for SN neutrinos

door to determination of CP-violation

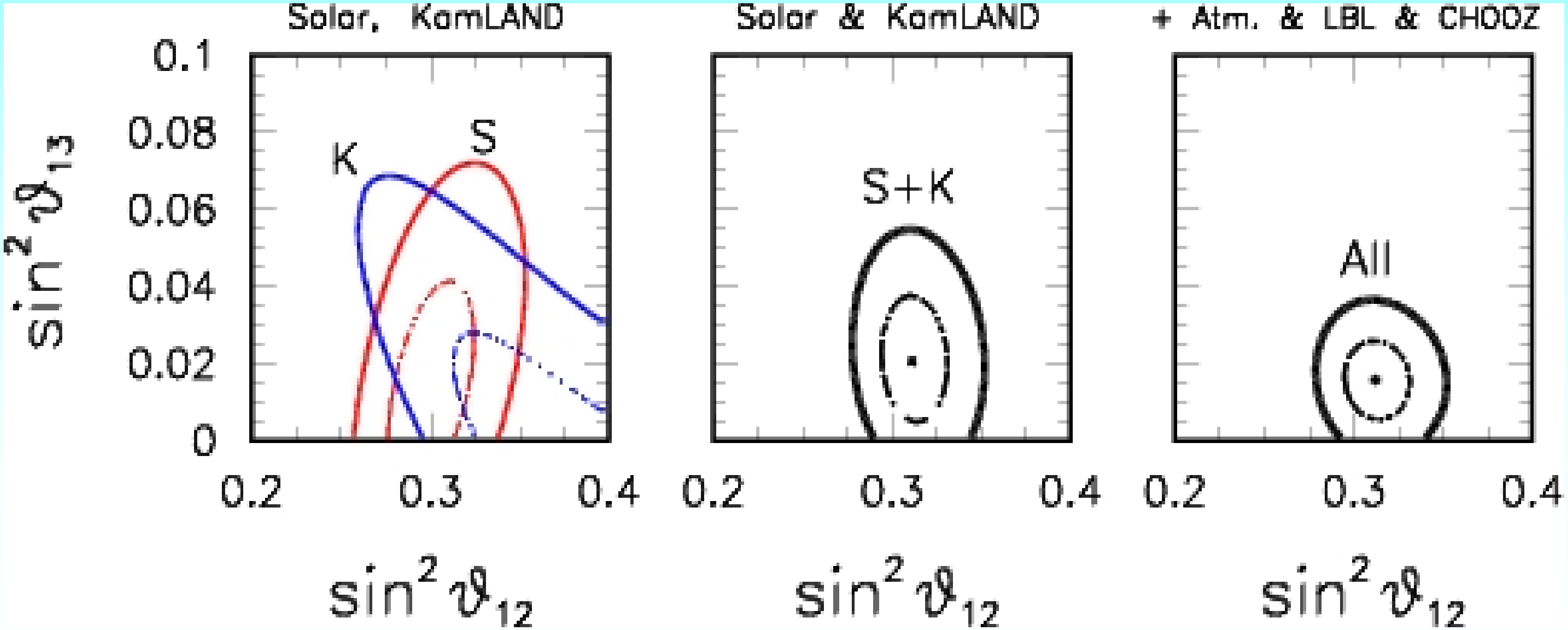
mass hierarchy

Hint of non-zero 1-3 mixing?

Fogli et al., 0806.2649

- difference of 1-2 mixing from solar data and Kamland
- atmospheric: excess of sub-GeV e-like events

$\sin^2\theta_{13} = 0.016 \pm 0.010$



Mass scale & mass spectrum

1. Absolute mass scale:

$$m > \sqrt{\Delta m_{31}^2} > 0.045 \text{ eV}$$

MINOS
Atmospheric
neutrinos

$$m < \Sigma/3 < 0.2 - 0.3 \text{ eV}$$

COSMOLOGY: bound on the sum of neutrino masses

The heaviest neutrino has mass is in the range
(0.045 – 0.30) eV

2. Mass hierarchy:

$$\frac{m_2}{m_3} \gtrsim \sqrt{\frac{\Delta m_{21}^2}{\Delta m_{32}^2}} \sim 0.18$$

Neutrinos have the weakest mass hierarchy (if any) among fermions

Related to the large lepton mixing?

Before and Now

From

Anomalies and Hints,
evidences and
first discoveries

Combined fits

Oscillations and
Adiabatic conversion

Anomalies: what is left?
Unresolved problems?

To

Precision measurements;
searches for New new physics;
studies of sub-leading effects

Confronting high statistics
data from different
experiments

More complicated
phenomena

Looking for mismatch

Determination of the same neutrino parameters from different type of experiments

Δm^2 θ

Low - High energies

Propagation in vacuum - matter

Neutrino-antineutrino

Different flavor channels

Goals:

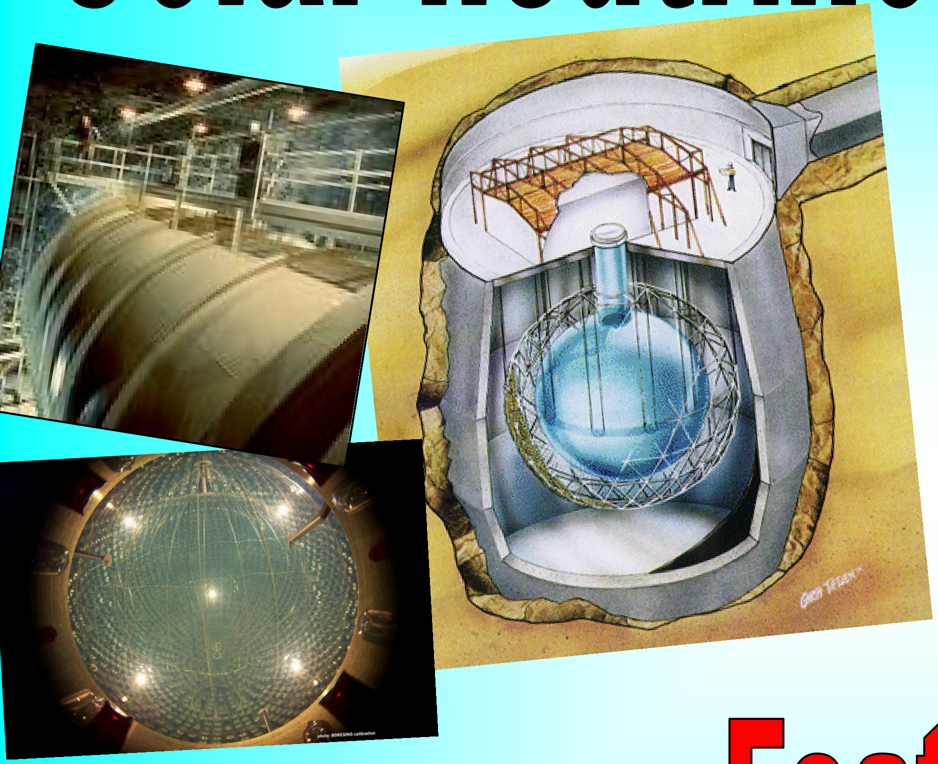
Nature of neutrinos mass: its possible dependence on energy and density

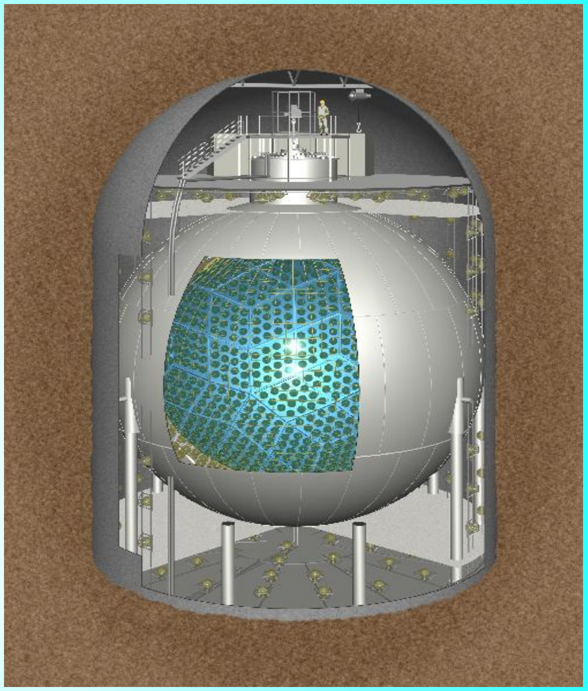
Test of theory of neutrino propagation

Searches for sub-leading effects, e.g. due to 1-3 mixing

Searches for new physics:
- New interactions
- New neutrino states
- Violation of fundamental symmetries (CPT, Lorentz)

Solar neutrinos vs. KamLAND





Features

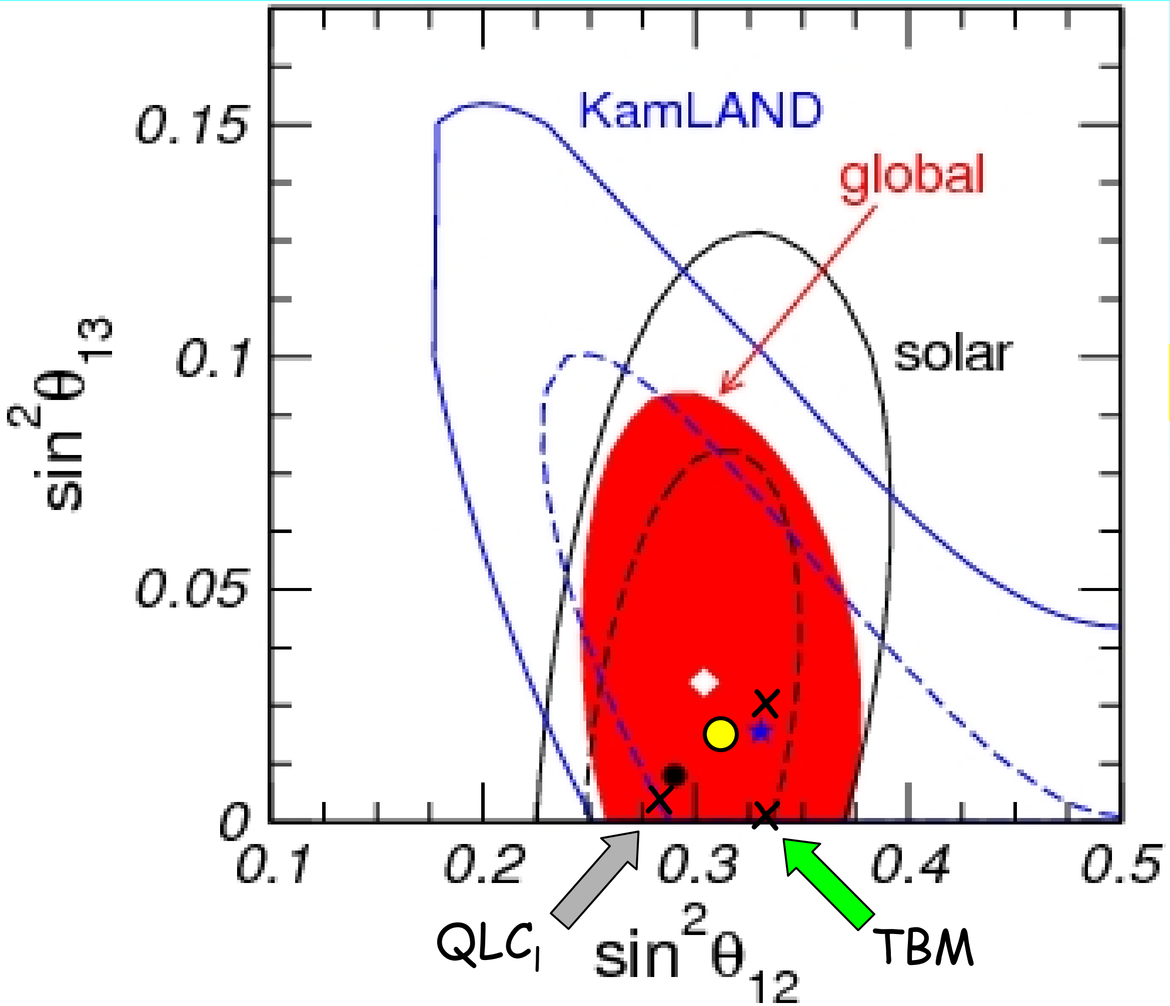
- Electron neutrinos
- Strong matter effect
- Adiabatic conversion
- Averaged oscillations

θ_{12}(solar) < θ_{12}(Kamland)

- Electron antineutrinos
- Non-averaged vacuum oscillations
- Small matter effect
- Phase is crucial

12- and 13- mixings

with some benchmarks



T. Schwetz et al., 0808..2016

○ *G.L. Fogli, et al 0805.2517, v3*

$\sin^2\theta_{13} = 0.016$ +/- 0.010

1σ

$\sin^2 2\theta_{13} \sim 0.06$

+ MINOS: 0.02 +/- 0.1

Solar only SNO vs. Gallium

Vacuum / low energies

$P \sim \cos^4\theta_{13} (1 - \frac{1}{2} \sin^2 2\theta_{12})$

Matter / high energies

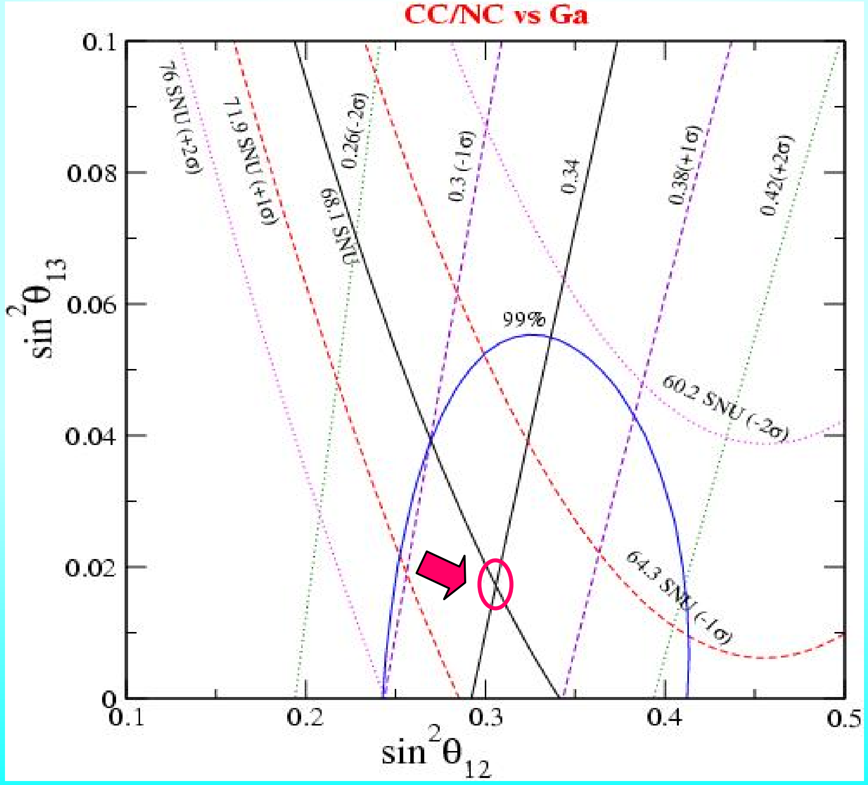
$P \sim \cos^4\theta_{13} \sin^2\theta_{12}$

Lines of
P = const

θ_{13} ↑ θ_{12} ↓

θ_{13} ↑ θ_{12} ↑

Different correlations of 1-2 and 1-3 mixings



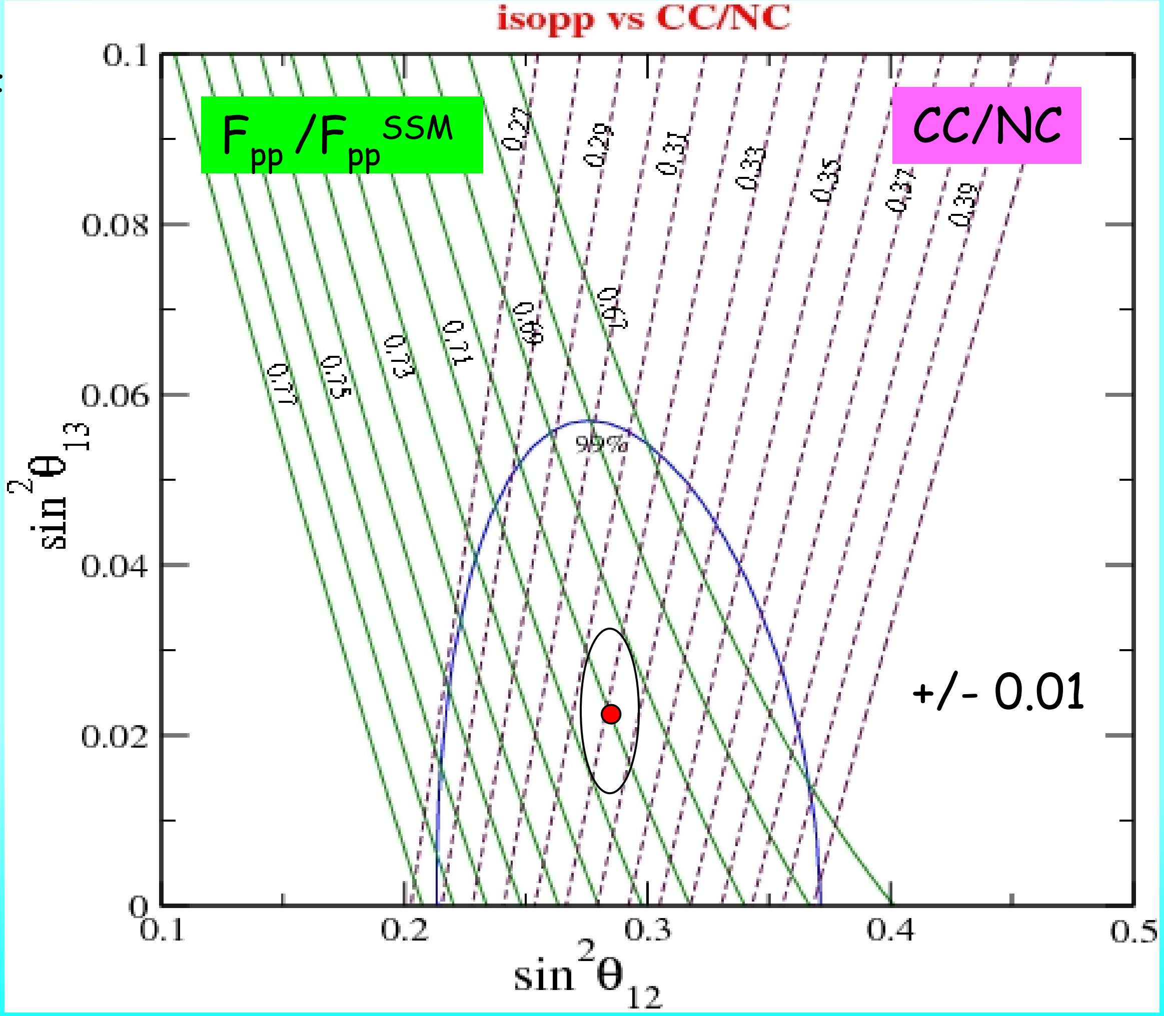
$\sin^2\theta_{13}$ = 0.017+/- 0.26

S. Goswami, A.S.

Future determinations?

Measurements of the pp-neutrino flux

1.5%



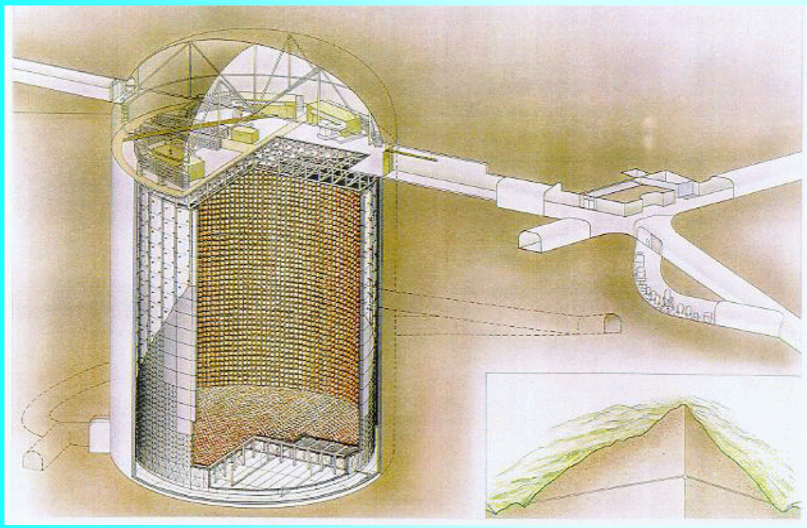
Waiting for final SNO results

CC/NC

3%

S. Goswami, A.S.

Atmospheric neutrinos vs. MINOS K2K



- Muon and electron neutrinos
- Neutrinos and antineutrinos
- Matter effects
- Multilayer medium
- Vacuum - matter
- Large base-lines
- Huge energy range

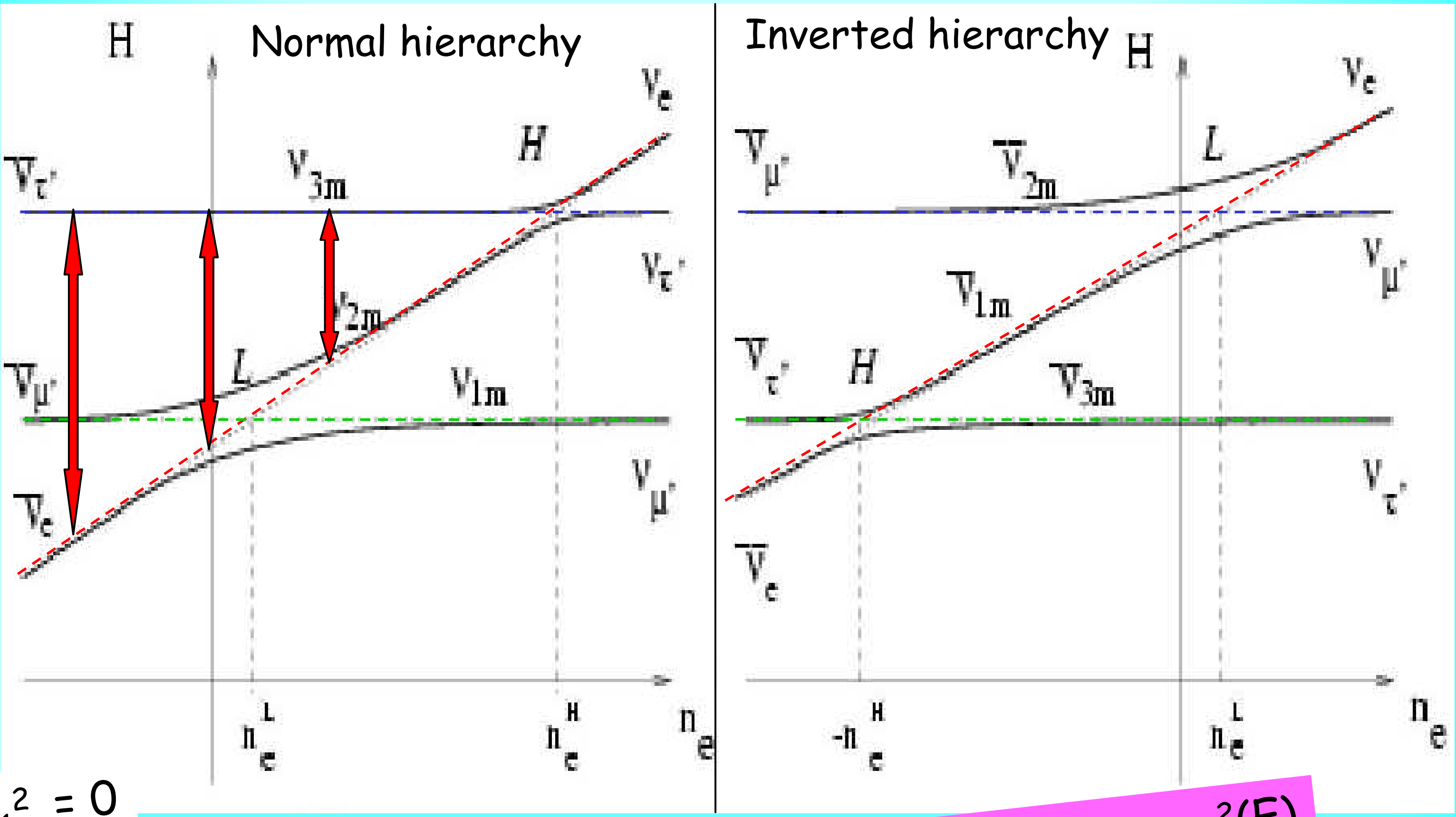
- Muon neutrinos or antineutrinos
- Vacuum mimicking
- Oscillations phase
- E ~ 1 – 10 GeV

Δm_{23}^2 (Atm) < Δm_{23}^2 (MINOS) ?

Matter effect?

Δm_{23}^2 (Atm) = Δm_{23}^2 (effective)

Level crossing scheme



Δm^2 (effective)

SK: $\Delta m_{21}^2 = 0$

Δm_{eff}^2(anti ν) > Δm^2(vac) > $\Delta m_{eff}^2(\nu)$

Δm_{23}^2 (eff) = $\Delta m_{23}^2(E)$

→ extract from different energy ranges

Sub-subGeV neutrinos

Main features:

Two components:
- directly produced by ν_e and $\bar{\nu}_e$
- from invisible muon decay

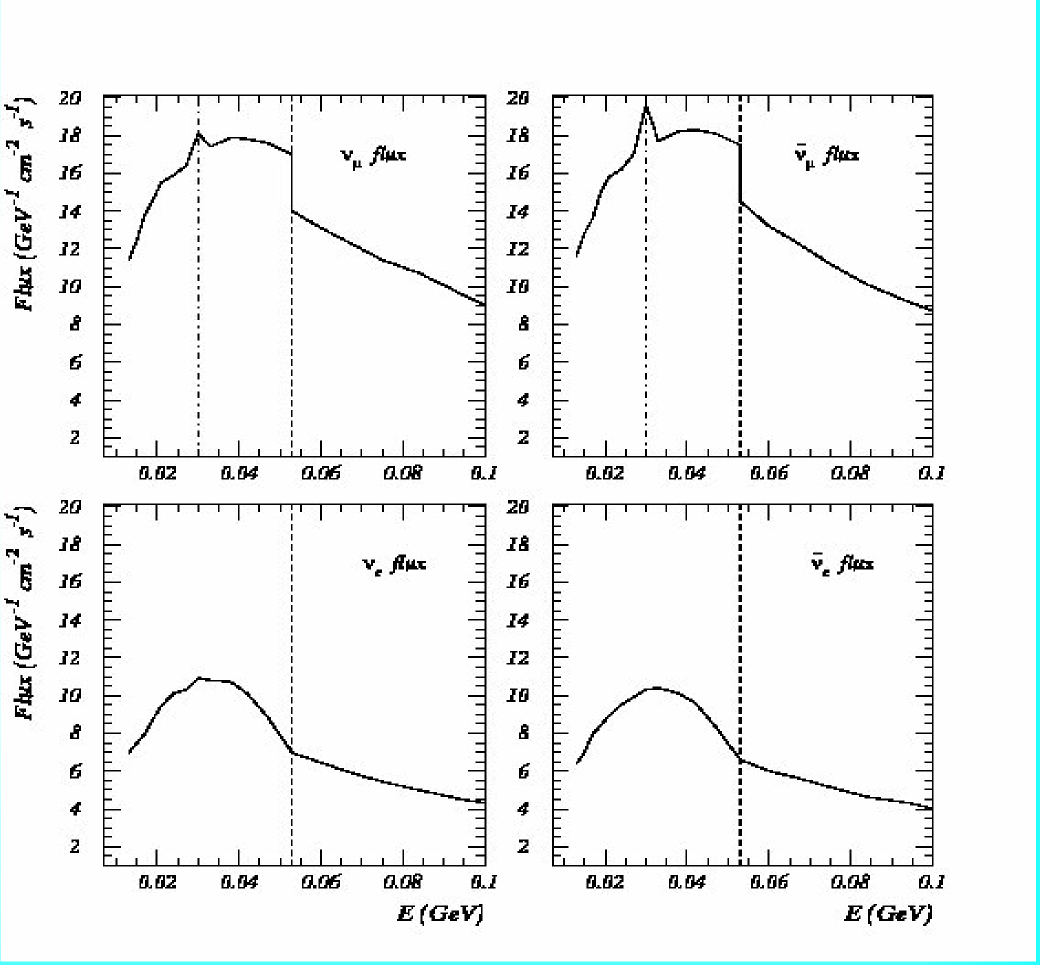
Flavor ratio decrease with energy and deviates from 2
2.1 → 1.6

➡ weaker screening effect

Seasonal variations,
variations with solar activity

Background for diffuse SN fluxes

Enlarging the energy range



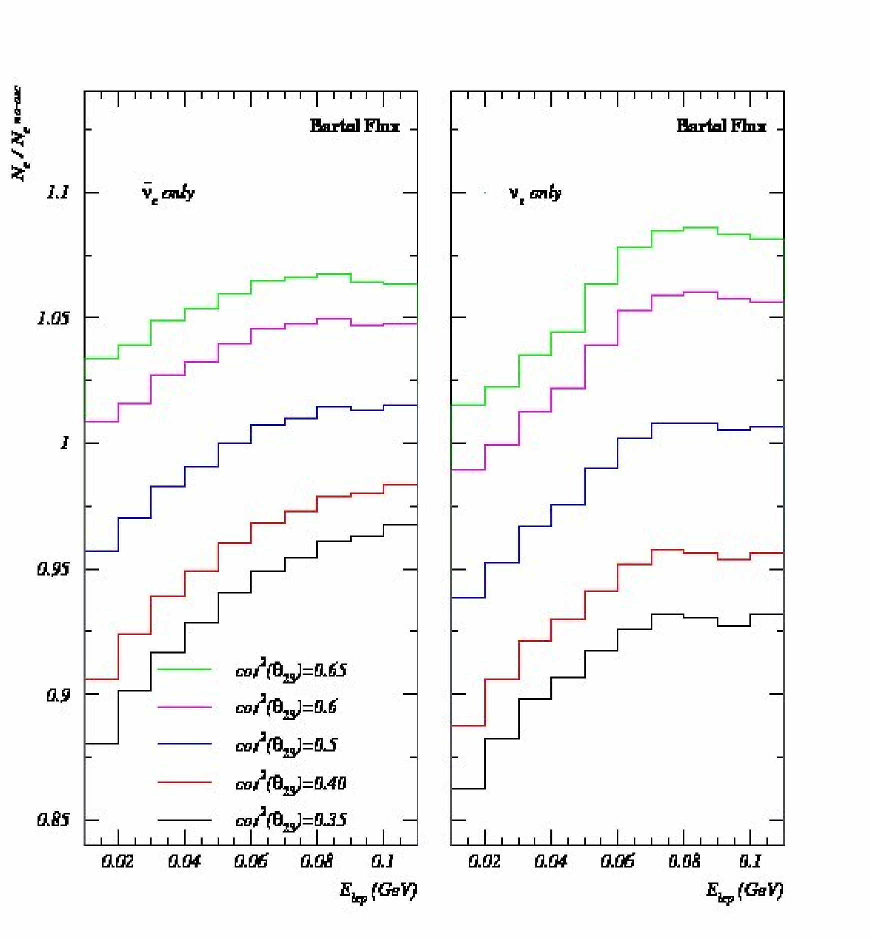
O. Peres, A.S

FLUKA

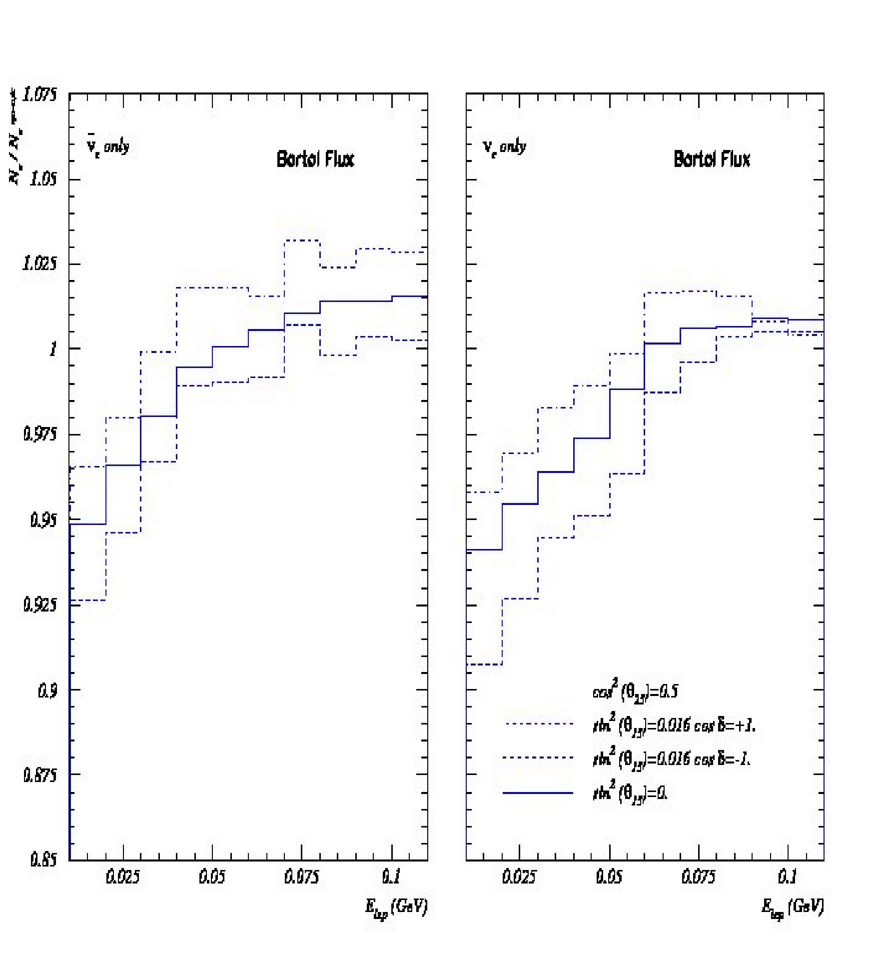
Oscillation effects

O. Peres, A.S

Effect of 2-3 mixing



Effect of 1-3 mixing and CP-phase



Oscillation effects

O. Peres, A.S

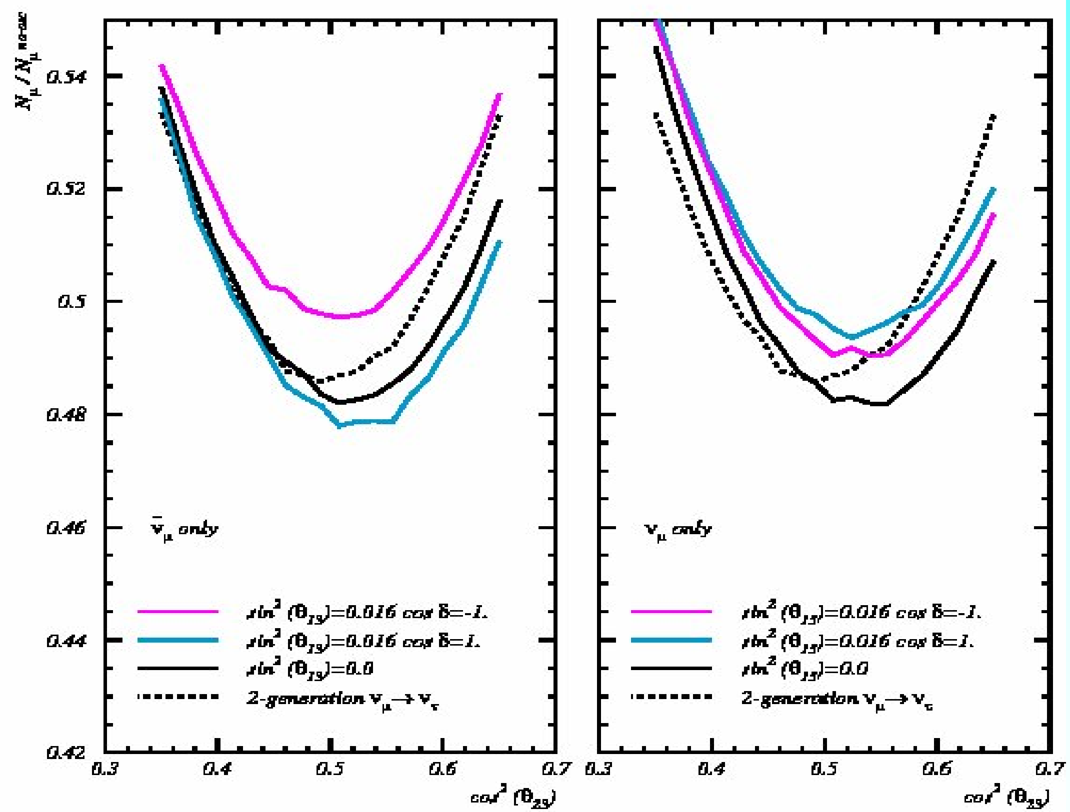
Effects on neutrinos from invisible muon decays

Atmospheric neutrinos with E ~ 150 – 300 MeV produce (in the detector and around it)

$\nu_\mu \rightarrow \mu$

Muon with E < 150 MeV: no Cherenkov lights. They stop in a detector and decays:

$\mu \rightarrow \nu_e$

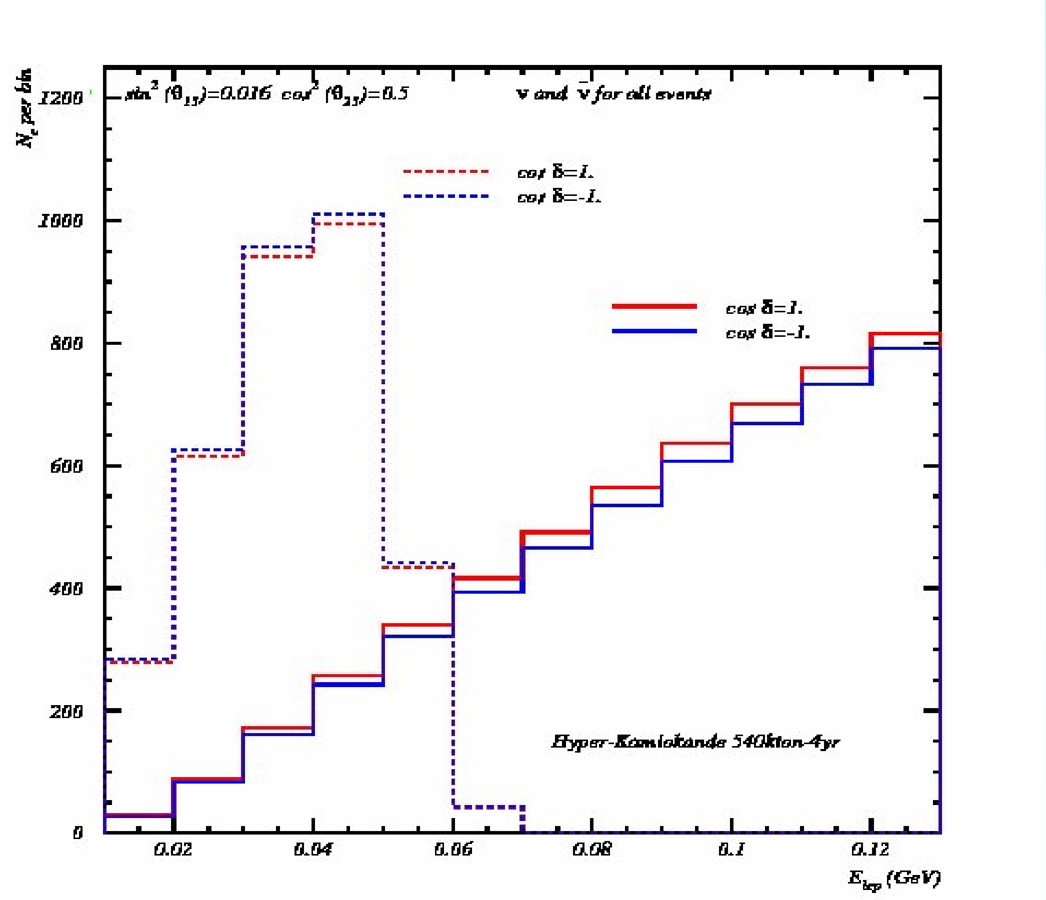


Ratio of total number of events as functions of 2-3 mixing for different values of θ_{13} and δ

Future measurements

Energy spectrum of e-like events in Hyper-Kamiokande (540 kt, 4 years) for two Values of CP-phase

10% effects

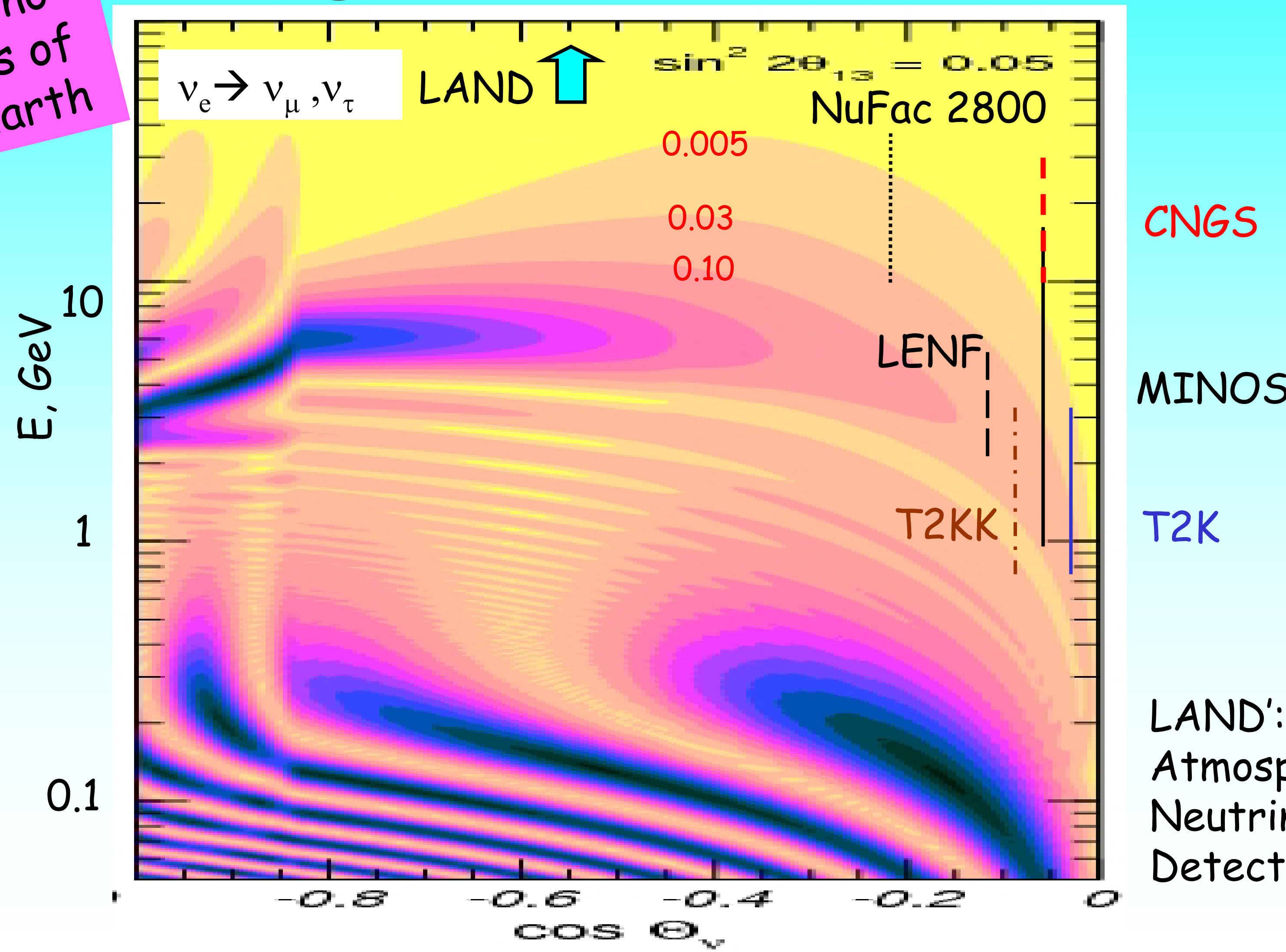


O. Peres, A.S

Oscillograms

contours of constant oscillation probability in energy- nadir (or zenith) angle plane

Neutrino images of the Earth



LAND': Large Atmospheric Neutrino Detector

Measuring oscillograms

$\sin^2 2\theta_{13} = 0.125$

Oscillograms for number of events (no averaging)

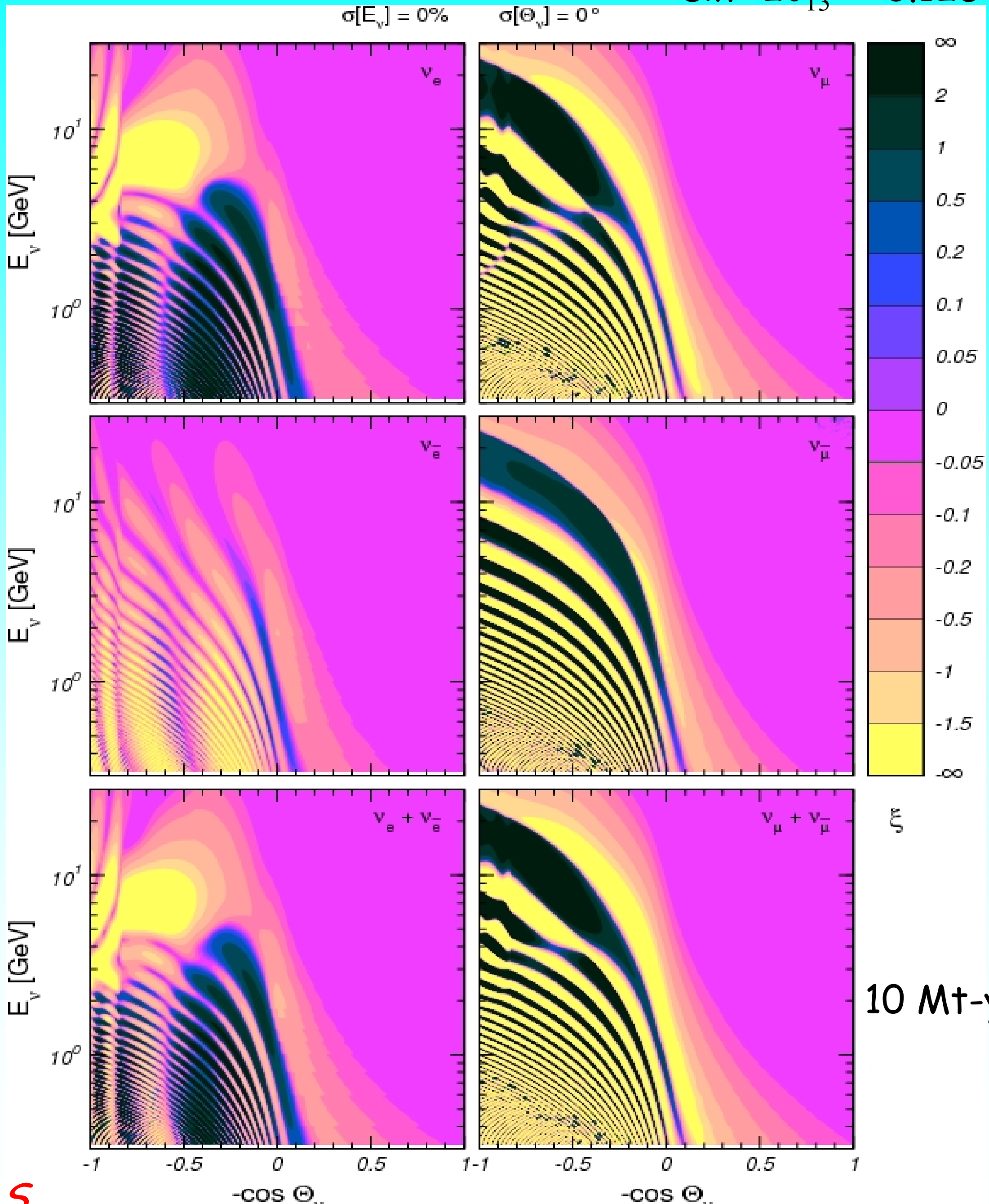
Lines of equal χ^2 for Gaussian:

$\chi^2 = (N - N_0)^2/N_0$

N_0 – number of events for $\theta_{13} = 0$, $\Delta m_{12}^2 = 0$

In contrast to P:

- original fluxes contain ν_e and ν_μ
- neutrinos and antineutrinos
- no exact reconstruction E_ν and θ_ν is possible



10 Mt-y

Akhmedov, Maltoni, AS

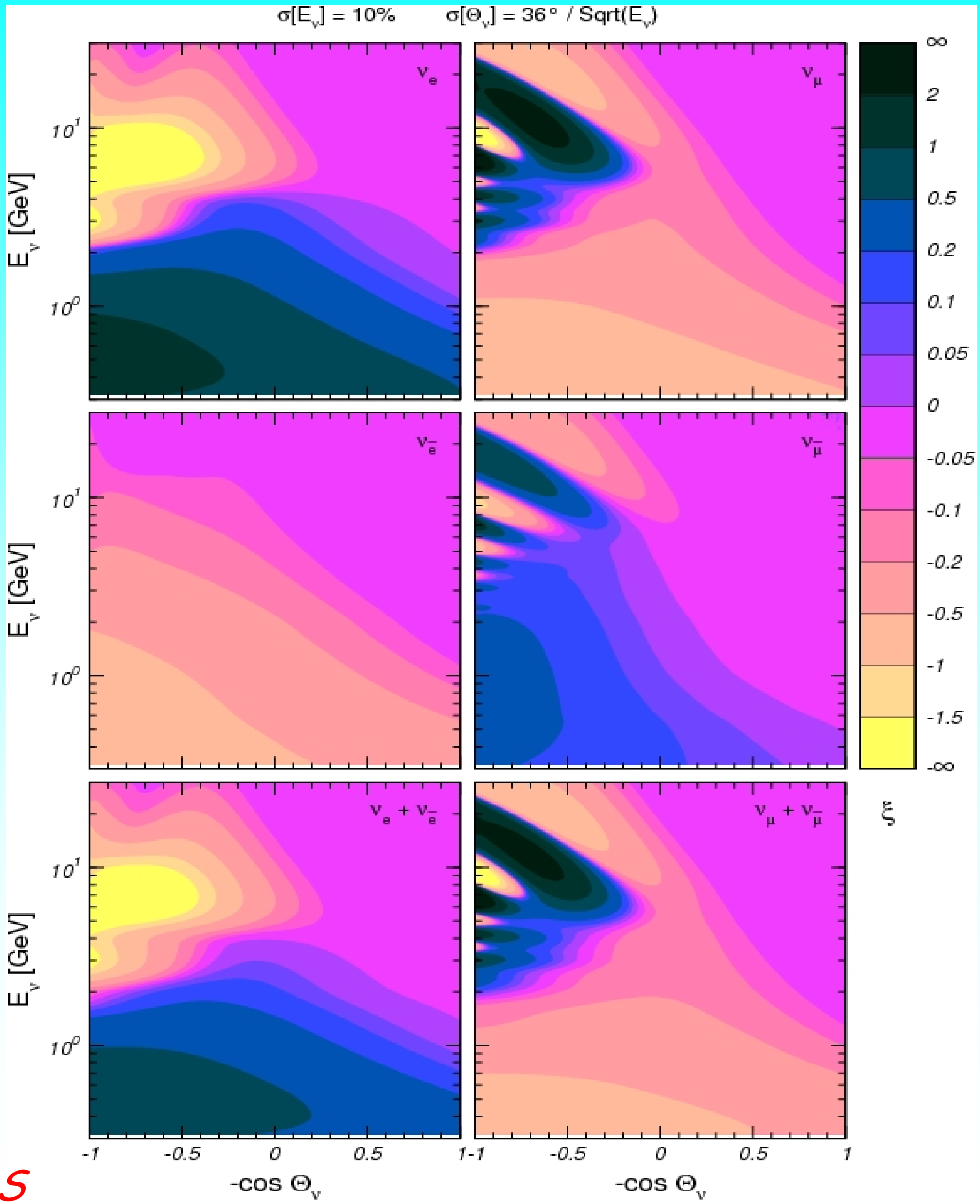
smoothing

Goals:

- 1-3 mixing;
- neutrino mass hierarchy;
- CP–phase;
- oscillation tomography of the Earth;
- searches for new physics effects

Tools:

Multi-Megaton water (ice) Cherenkov detectors TITAND - type



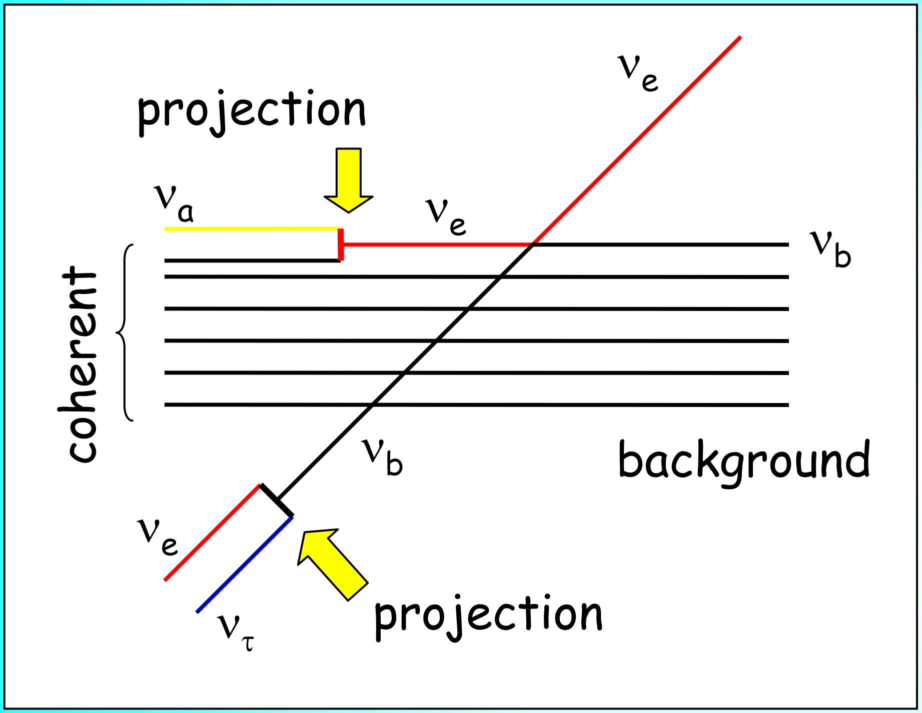
Akhmedov, Maltoni, AS

Expanding frontiers

New energy frontiers	Low energies	Coherent scattering
	High energies	Cosmic neutrinos Accelerator atmospheric
Fluxes and densities	High artificial fluxes Dense neutrino gases Engineering of flavors	
At extreme conditions	High matter densities Strong magnetic fields	
Nu-technologies		

Non-linear neutrino physics

J. Pantaleone
S. Samuel
V.A. Kostelecky



$\nu\nu$ – scattering in u-channel due to Z^0 - exchange

Momentum exchange → flavor exchange

If the background is in mixed state:

$$|\nu_{ib}\rangle = \Phi_{ie}\,|\nu_e\rangle + \Phi_{i\tau}\,|\nu_\tau\rangle$$

coherence → refraction → collective flavor transformations

Contribution to the Hamiltonian in the flavor basis

$$H_{\nu\nu} = \sqrt{2}\,G_F\,\Sigma_i\,(1 - v_e\,v_{ib})\begin{pmatrix} |\Phi_{ie}|^2 & \Phi_{ie}^*\Phi_{i\tau} \\ \Phi_{ie}\Phi_{i\tau}^* & |\Phi_{i\tau}|^2 \end{pmatrix}$$

A. Friedland
C. Lunardini

Evolution equation

Ensemble of neutrino polarization vectors $\mathbf{P}_\omega$

$$d_t \mathbf{P}_\omega = (\omega \mathbf{B} + \mu \mathbf{P}) \times \mathbf{P}_\omega$$

Negative frequencies for antineutrinos

$$\mathbf{B} = (\sin 2\theta,\ 0,\ \cos 2\theta)$$

$\omega = \Delta m^2/2E$

$\mu = \sqrt{2}\, G_F n_\nu$

Collective vector:

$$\mathbf{P} = \int_{-\inf}^{+\inf} d\omega\ \mathbf{P}_\omega$$

Equation of motion for **P**: integrating equation of motion

$$d_t \mathbf{P} = \mathbf{B} \times \mathbf{M}$$

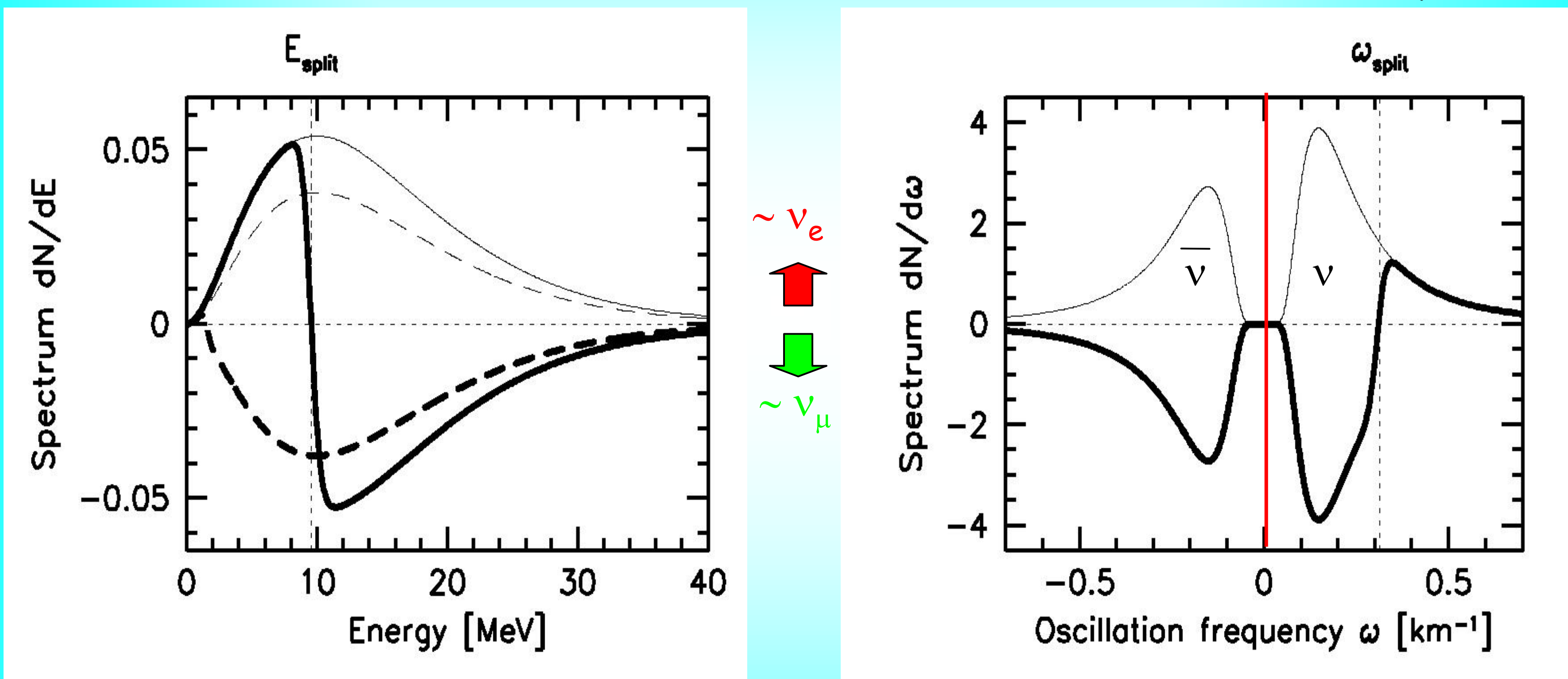
where

$$\mathbf{M} = \int_{-\inf}^{\inf} d\omega\ \omega\ \mathbf{P}_\omega$$

Spectral split

H. Duan, G. Fuller, J. Carlson,
Y. Z. Qian
G. G. Raffelt, A.S.

thin lines – initial spectrum
thick lines – after split



G. Raffelt, A.Yu. S.

$\omega = \Delta m^2/2E$

—— neutrinos
– – – – antineutrinos

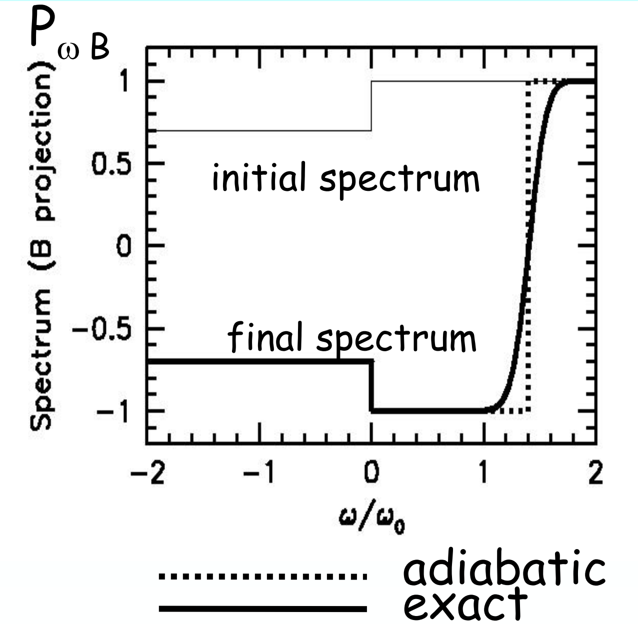
Can be observed!

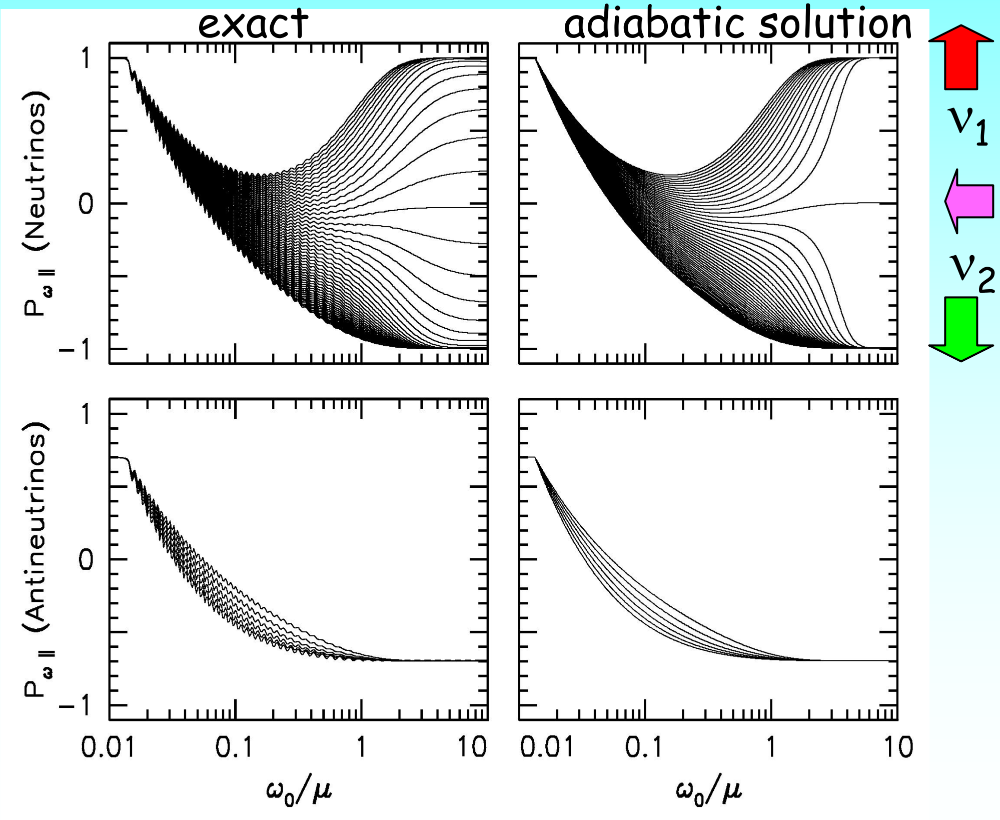
spectral split

Result of the adiabatic evolution in certain co-rotating frame (formed by the collective vector and vector **B**)

$\mu = \sqrt{2}\, G_F n_\nu$ $\omega = \Delta m^2/2E$

can change whole picture of conversion of Supernova neutrinos





G. Raffelt, A.S.

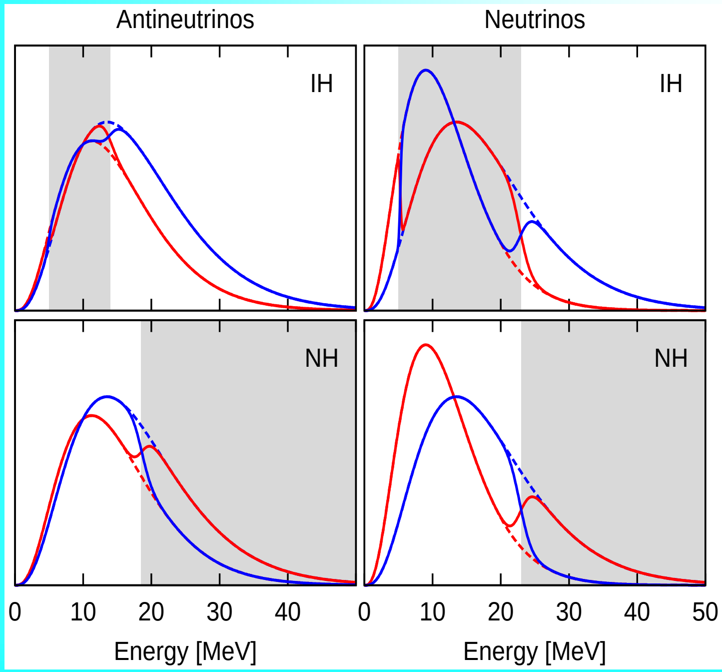
Multiple splits & swaps

Spectral splits – part of more general phenomenon: multiple splits – flavor swaps in certain energy regions bounded by spectral splits

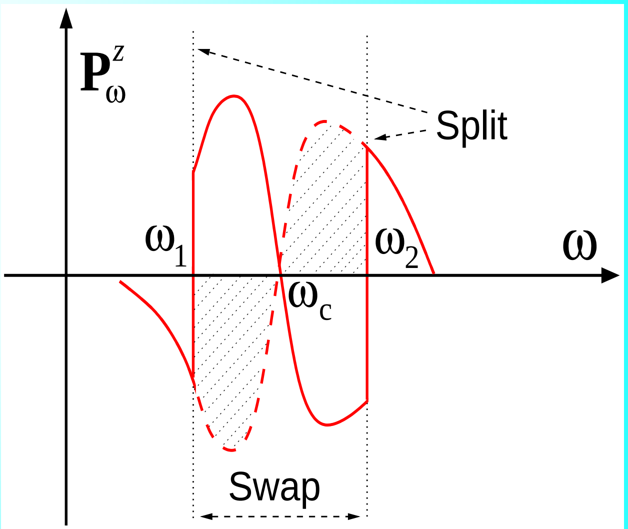
B. Dasgupta, A Dighe, G. Raffelt, A.S.

Swaps develop around unstable spectral crossings: energies where $F_e(E) = F_x(E)$, and flux difference changes in a certain way.

E → infty should be considered as crossings



$P_\omega^z = F_e(\omega) - F_x(\omega)$

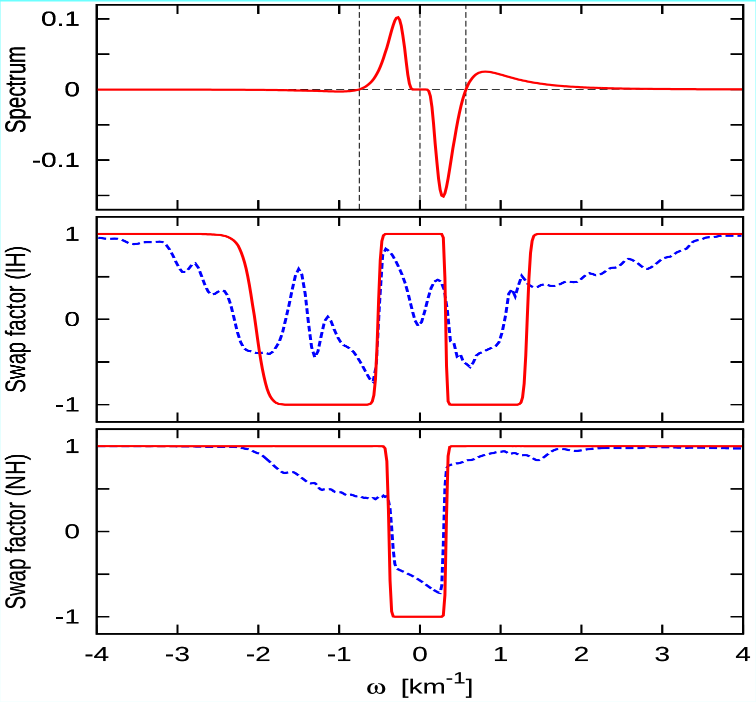


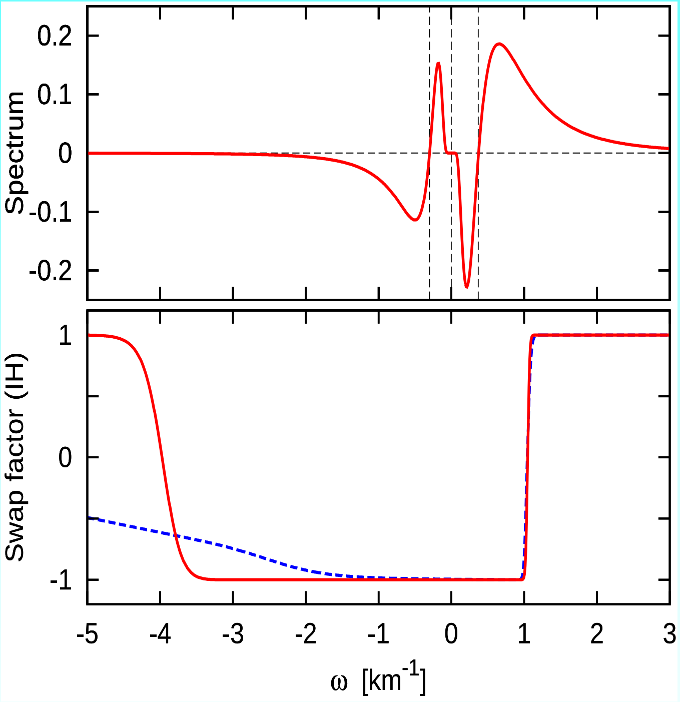
In simplest version swaps are related to existence of two co-rotating planes for polarization vectors above and below crossings

Two examples

$P_\omega^z = F_e(\omega) - F_x(\omega)$

Swap factor: $P_\omega^z(\text{final}) = S_e(\omega)\, P_\omega^z(\text{initial})$





Dashed – after integration over the angle of neutrino trajectory propagation

Real evolution
- number of crossings
- form of spectra,
- total neutrino fluxes

Mutual influence, merging....

Conclusions

More consistent and coherent picture of neutrino properties: masses and mixing

New trend: from combined fits to confronting data from different experiments, looking for mismatch

Phenomenology: complex neutrino phenomena, Energy frontiers, extreme conditions

Developments related to identification of nature and origins of neutrino mass

Neutrinos and LHC

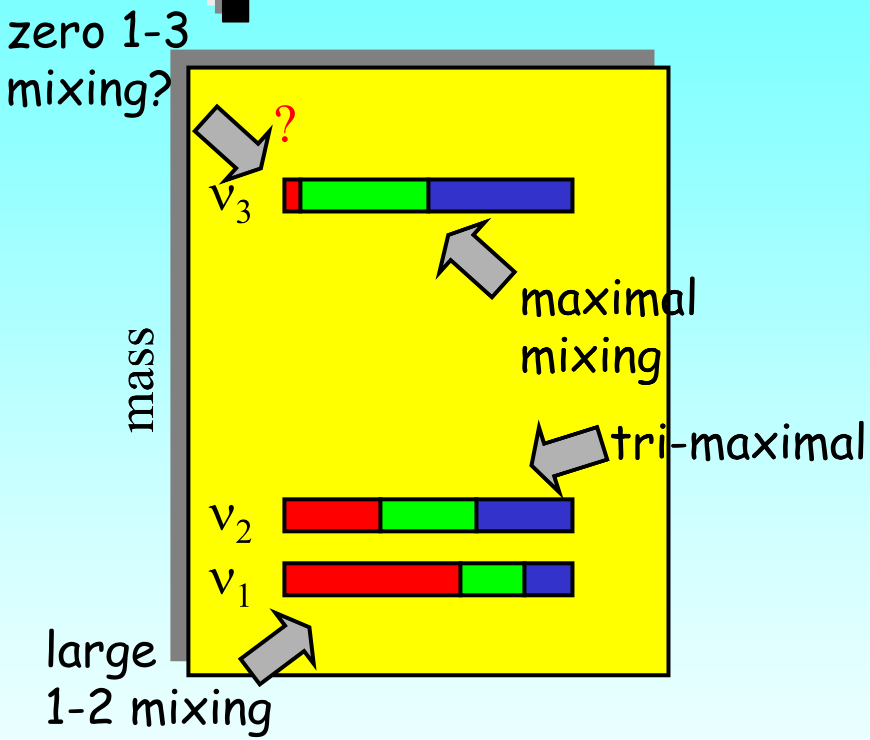
Unclear implications of results to fundamental theory
- origin of neutrino mass and mixing
- existence of flavor symmetries, unification etc.

The question what should be done to have progress in understanding neutrino mass and mixing is already and will be a driving force of future developments

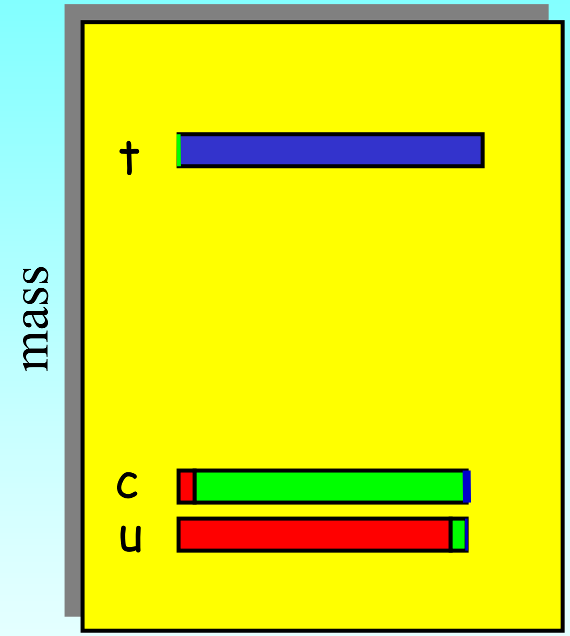
LHC and other HE experiments may clarify the situation

In spite of these problems we can start to think seriously about applications of neutrinos and neutrino technologies

Leptons versus quarks



Leptons



Quarks

small mixing

$\nu_f = U_{PMNS}\, \nu_{mass}$

$U_d = U_{CKM}^{+}\, U$ $U = (u, c, t)$

combination of upper-quarks produced with a given down quark

Non-standard interactions

Motivation: new physics
at the EW and terascale;
various extensions of SM
Z', SUSY, KK, light particles

Rich phenomenology
- propagation
- detections

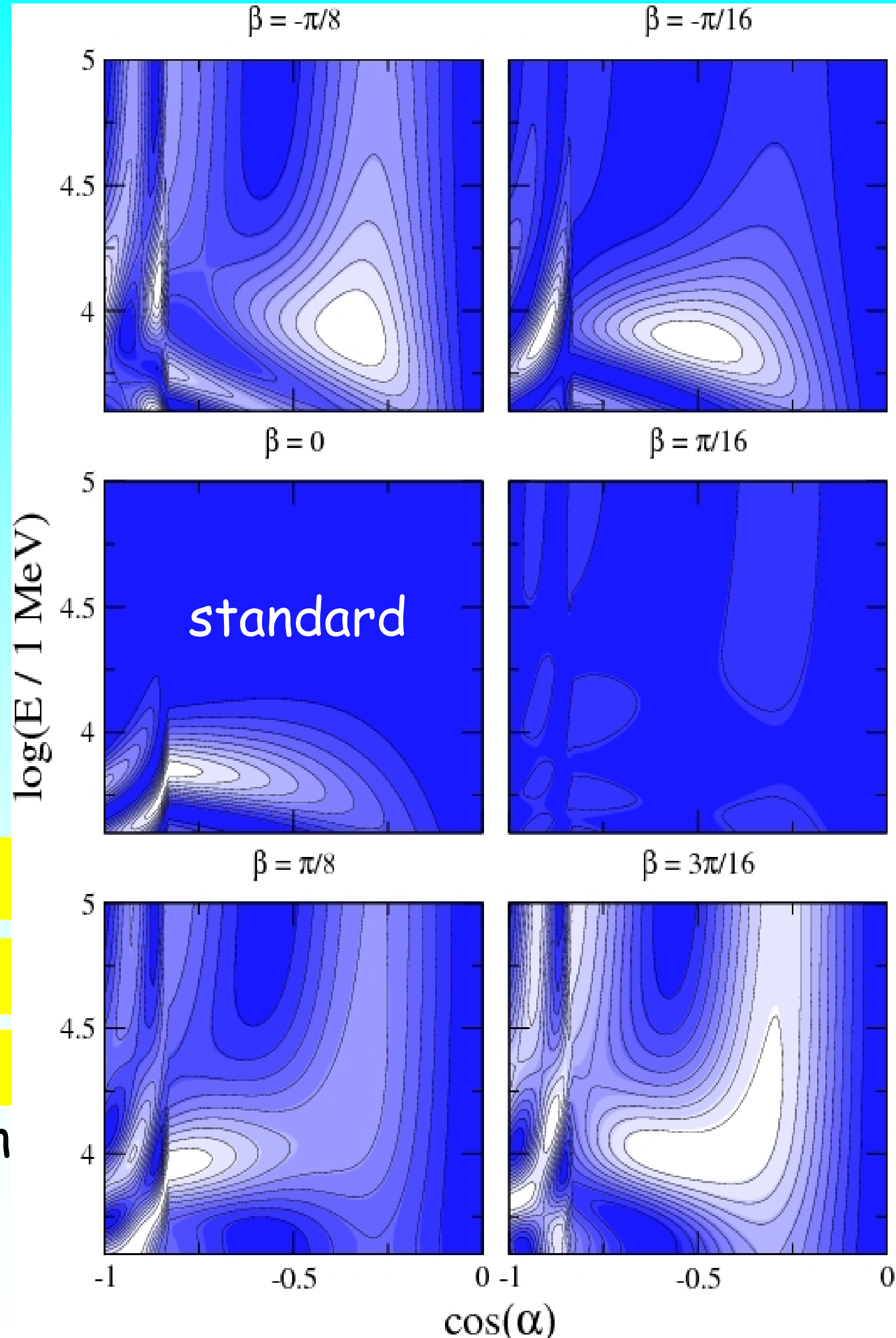
High energies where usual
mixing is suppressed ...

P_{ee}

θ_{13} = 8°

$\varepsilon_{e\tau}$ ~ - 0.5 sin2β

white: strong transition



Checks at LHC,
Rare processes with L-violation

M. Blennow, T. Ohlsson, 0805.2301

What is beyond?

LSND

Excess of e-like events

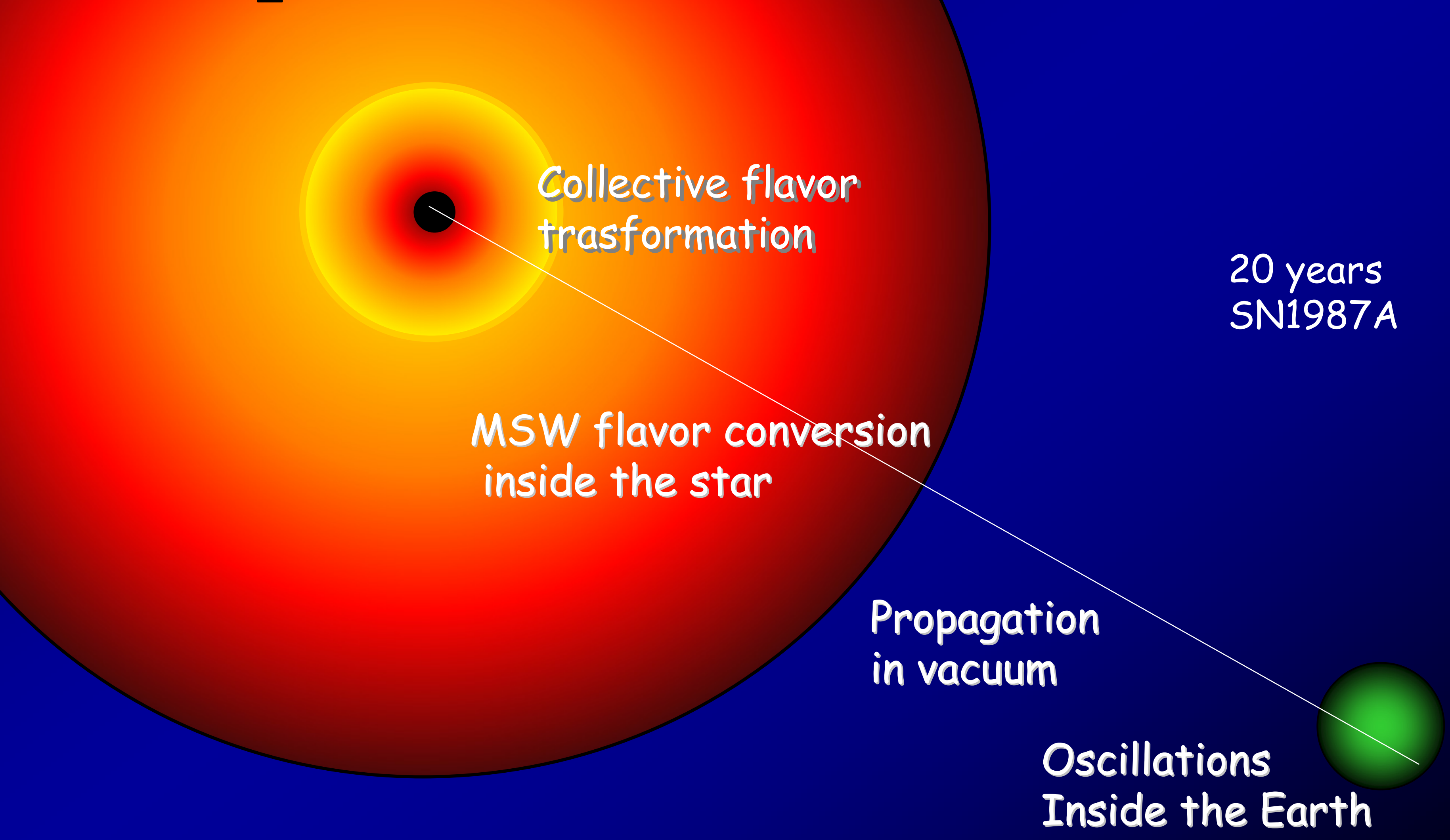
MiniBooNE

Excess of
Low energy events
in the neutrino channel

SAGE
GNO Gallex
calibration experiments

Smaller measured sigmnal

Supernova neutrinos



20 years
SN1987A

Phenomenology

Solar neutrinos

Long baseline experiments

Atmospheric neutrinos

Supernova neutrinos

Cosmic neutrinos

Relic neutrinos

Reactor neutrinos