MSW

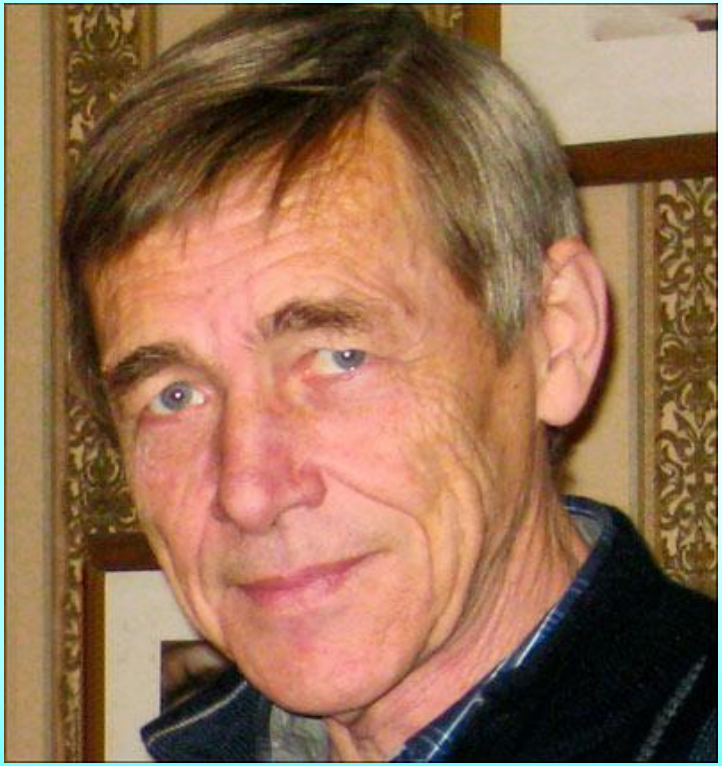
Now & 30 years ago

A. Y. Smirnov

MAX-PLANCK-GESELLSCHAFT

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

"M" Stas Mikheyev

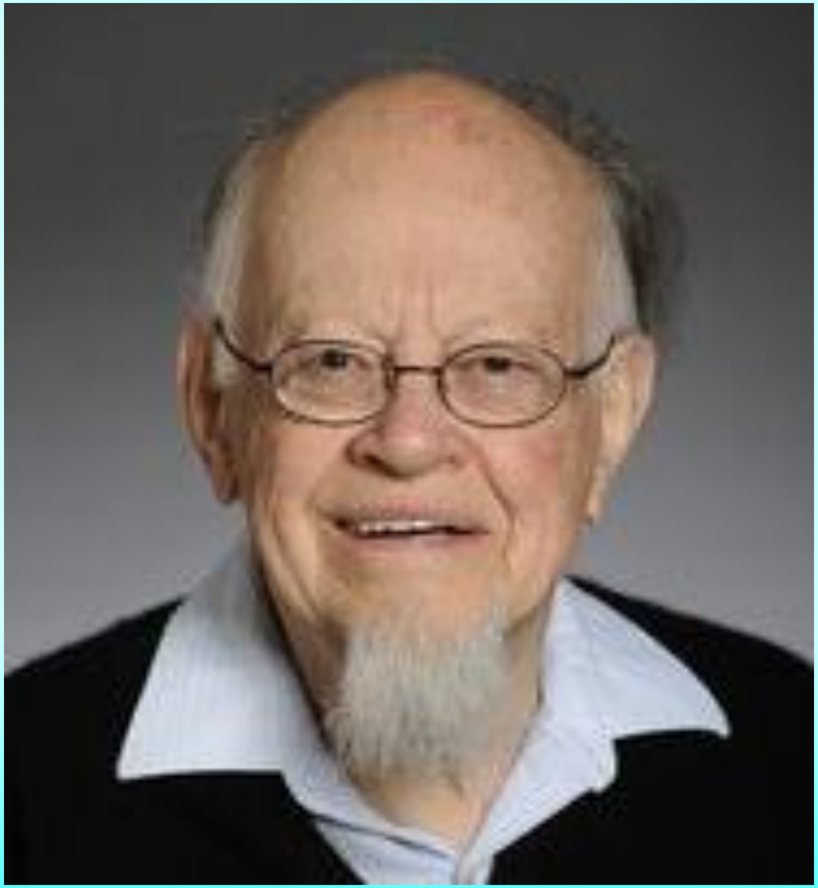


1940 - 2011

Experimentalist

Baksan telescope
MACRO
K2K
Baikal neutrino telescope

"W" Lincoln Wolfenstein



1923 - 2015

March 27

M “S” W

Pre-excursion talk

Between physics program and entertainment

Time ordering:

30 years ago

A bit history but more about physics and some personalities

Looks like abituary

WIN-1985

The Tenth International workshop on Weak Interactions and Neutrinos, Savonlinna, Finland, June 16 - 22, 1985

350 km from Helsinki

The first presentation at international meeting

"Resonance amplification of neutrino oscillations in matter and spectroscopy of solar neutrinos"

Became part of MSW

triggered wide interest to the field

first references were to the Savonlinna talk

The paper was published in Yad. Fiz. in December 1985

Chairman:

Matts Roos

Particle physicist

painter

Cosmologist

Now professor emeritus of Helsinki University

Particle physicist, Cosmologist, Painter

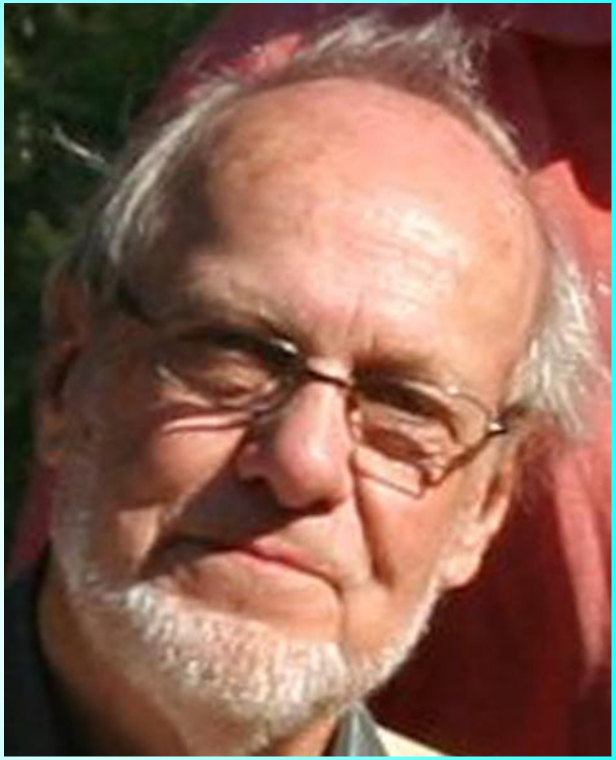
- PDG
- σ meson
- Determination of CKM element
- Minuit, errors correlations

Matts Roos:

From our email exchange

We were unexperienced conference organizers in those days, so I am afraid that there are very few records, if any.

At the Institute I have changed office many times since then, usually to a smaller one, so I have also got rid of a lot of material. But I shall look ...



And then,

The only document I found was the enclosed list of invited speakers. Some of the talks were certainly published as such, try to locate Cabibbo!

Invited and not invited speakers

80 participants, 16 invited speakers

A. Szalay (Fermilab)	Astrophysics and Cosmology
F. Scheck (Mainz)	Charged weak interactions at low energies and family number changing processes
K. E. Bergkvist (Stockholm)	Tritium beta-spectrum
J. Schacher (Bern)	pp-collider; W, Z, exotics and new particles
W. Marciano (BNL)	Electroweak theory
G. Altarelli (Rome)	SUSY-phenomenology
R. Peccei (DESY)	Composite models
A. Bohm (RWTH)	Neutral current experiments with e^+ e beams
D. Haid (DESY)	Other neutral current experiments
A. I. Sanda (Cen-Saclay)	CP-violation
D. O. Caldwell (California)	Neutrinoless double beta decay, experiment
S Stone (Cornell)	Charged currents: new flavors
Some more names...	

Matts Roos: You and Mikheyev were not invited with your names, one Russian professor (I forgot who) proposed you as participants.

A. A. Pomansky

Gianni Conforto

(CERN & Florence)

"Neutrino oscillations"

organizer of parallel session

1938 - 2003

Gargamelle, Crystal Ball
NOMAD, L3

Cecilia Jarlskog

(Stockholm)

"Status of electroweak theory"

Serguey Petcov

(Bulgarian Acad. of Science)

Review talk:

"Massive neutrinos,
neutrino oscillations
and
neutrinoless double beta decay"

I met him before in Dubna

Explained in some details

- Resonance
- adiabaticity
- new solution of the solar neutrino problem

Well, interesting... but unfortunately no time is available

Suddenly things changed:

We have found a slot for your presentation at Neutrino oscillation session

I don't remember who told me this, may be Conforto

but I suspect one person played crucial role

Excursion

Sauna,
Swimming
in a lake

Nicola Cabibbo

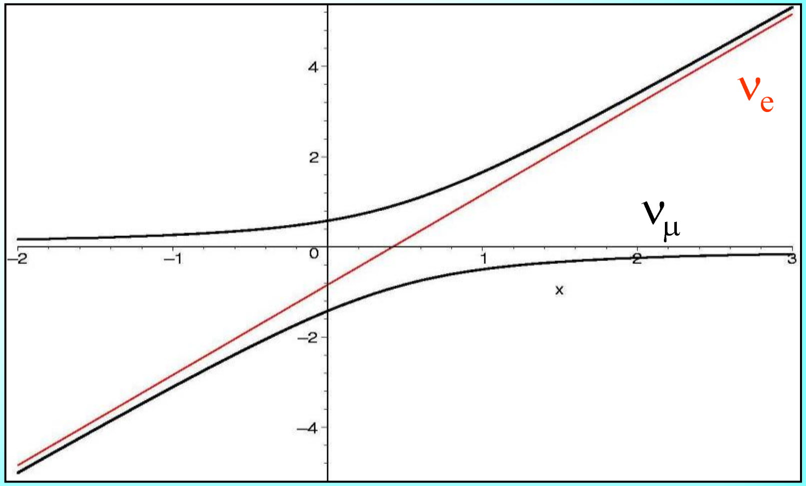
Univ. of Rome

Concluding talk

1935 - 2010

During excursion

Serguey Petcov told me about your paper and I would like to include your result in my talk. I think the effects can be understood as the level crossing processes



Do you agree with this?

Yes

Half a year later: in Hans Bethe paper PRL 65 (1986) 1305

Valery Rubakov

Superheavy Magnetic Monopoles and Proton Decay, 1981

In spring 1985:

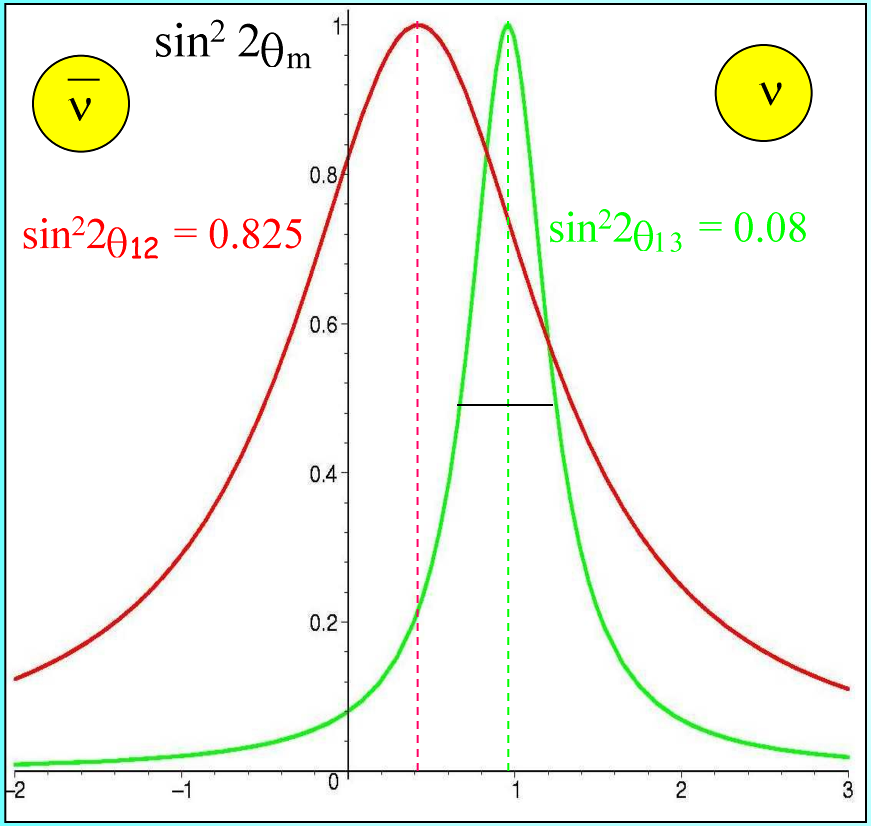
"Your transition has some similarity with catalysis of proton decay when monopole propagates near nucleon . This has interpretation as the level crossing phenomenon"

Complementary description in terms of the Eigenvalues of the system.
I was happy with description in terms of the Eigenstates

I missed Cabibbo talk – we left one day before

In my talk:

Resonance



$l_\nu / l_0 \sim n E$

Resonance condition

$\sin^2 2\theta_m = 1$

Flavor mixing is maximal

$l_\nu = l_0 \cos 2\theta$

Vacuum oscillation length $\approx$ Refraction length

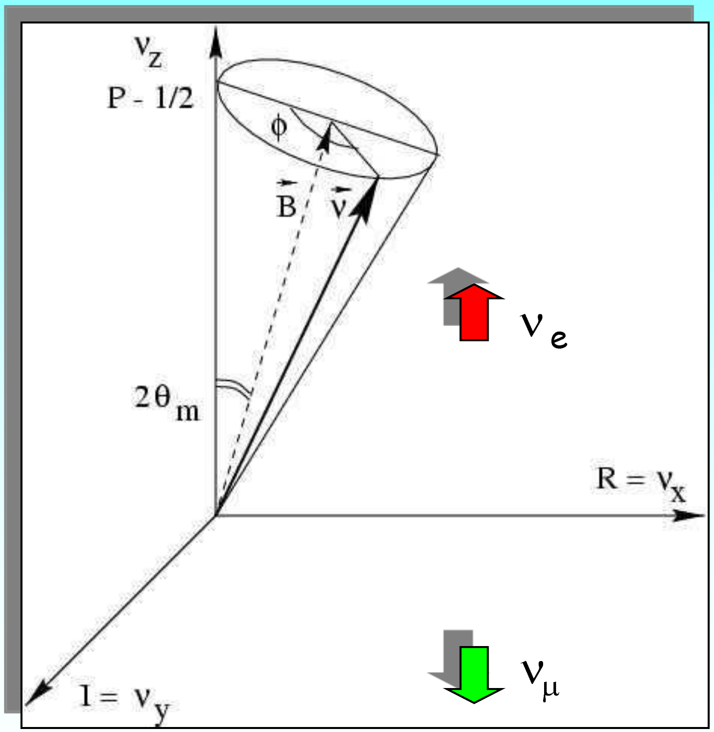
$$V = \frac{\Delta m^2}{2E} \cos 2\theta$$

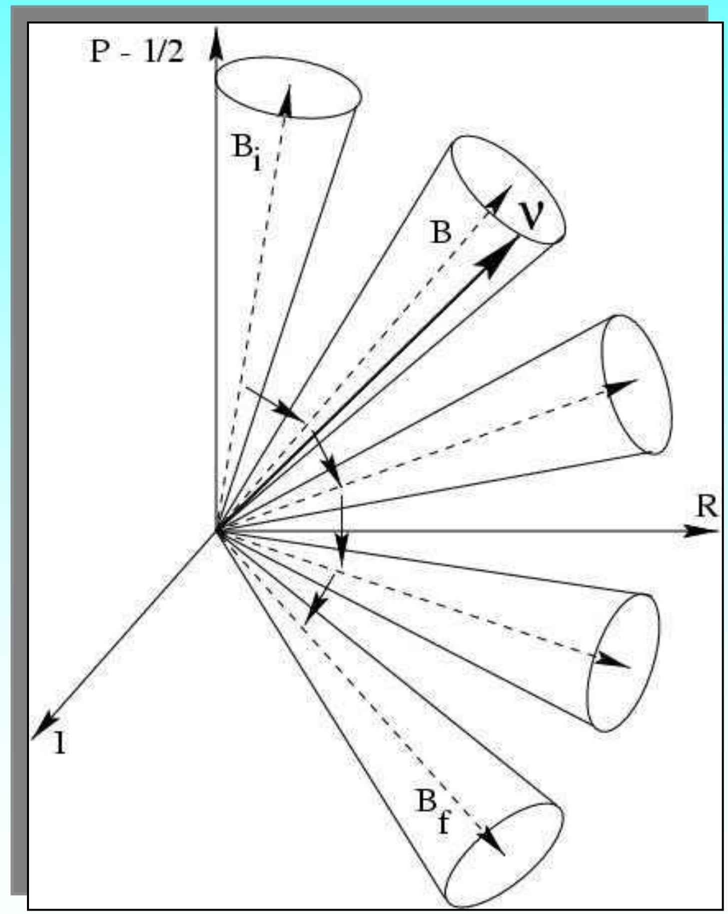
Resonance width: $\Delta n_R = 2 n_R \tan 2\theta$

Resonance layer: $n = n_R +/- \Delta n_R$

Graphic representation

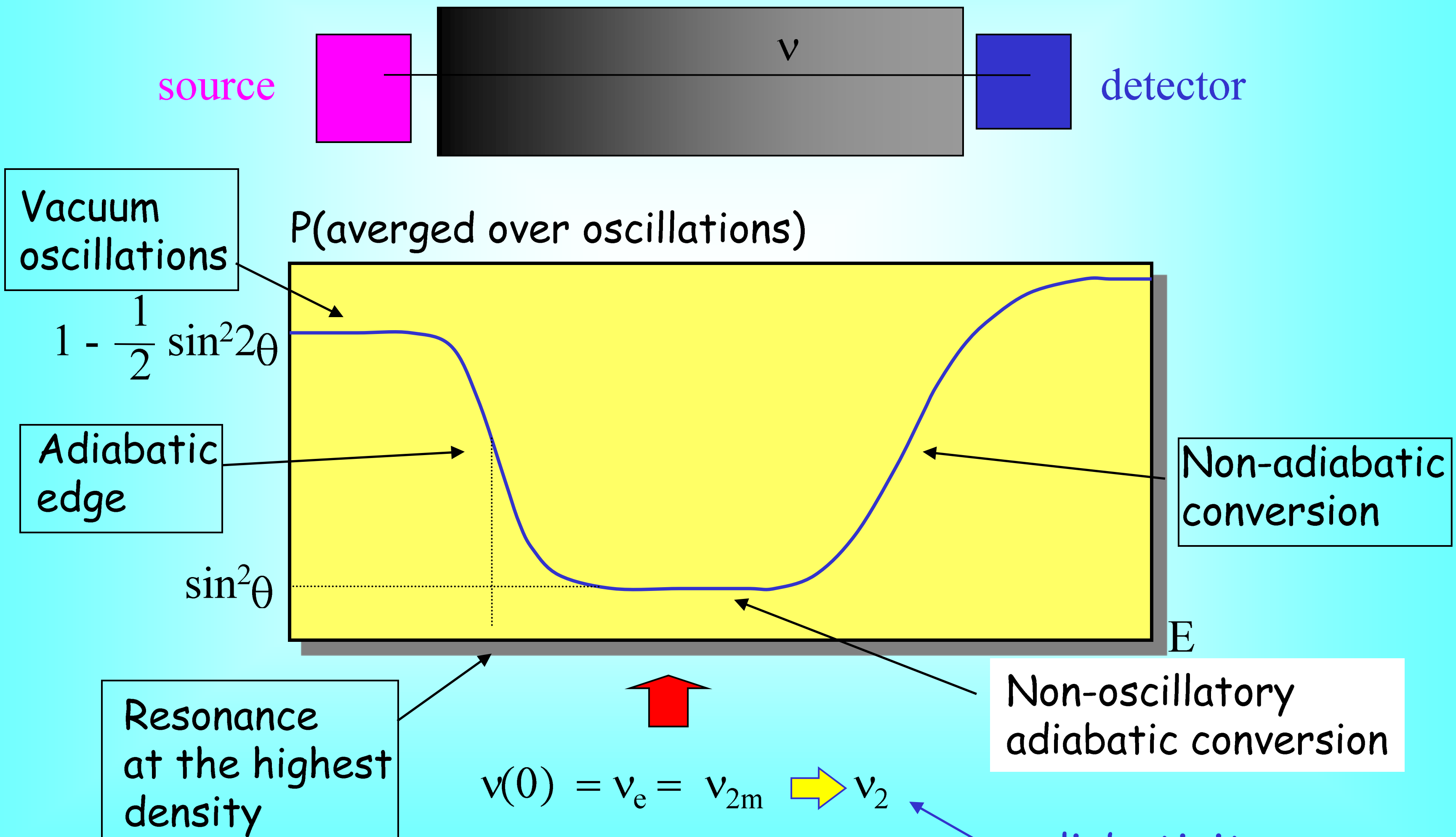
Adiabaticity





Survival probability

"Suppression bath"



$$\nu(0) = \nu_e = \nu_{2m} \Rightarrow \nu_2$$

$$P = |\langle \nu_e | \nu_2 \rangle|^2 = \sin^2\theta$$

adiabaticity

Actually, everything is not as in reality...

The first MS talk was at INR (Moscow) month before

I used different graphic representation: for the amplitudes not for the elements of density matrix

Actually MSW is not the resonance enhancement of oscillations

There is no significant enhancement of oscillations inside the Sun

There is no even oscillations in the Sun (or oscillations are irrelevant)

No MSW in June 1985

The term has appeared at the end of 1985 – beginning 1986

A. Messiah Jan, 1986:

I do not understand why you call it resonant enhancement
I will call it simply the MSW effect.
Unfortunately, there no way to correct terminology ....

History is tricky thing

In fact,

MSW: two effects

Both are related to modification of mixing in mater
But different dynamics
Different degrees of freedom involved

Resonance enhancement of oscillations

uniform medium with constant parameters

Phase difference increase between the eigenstates

$\phi(t)$

θ_m (E)

Mixing does not change but depends on energy

Adiabatic conversion

Non-uniform medium or/and medium with varying in time parameters

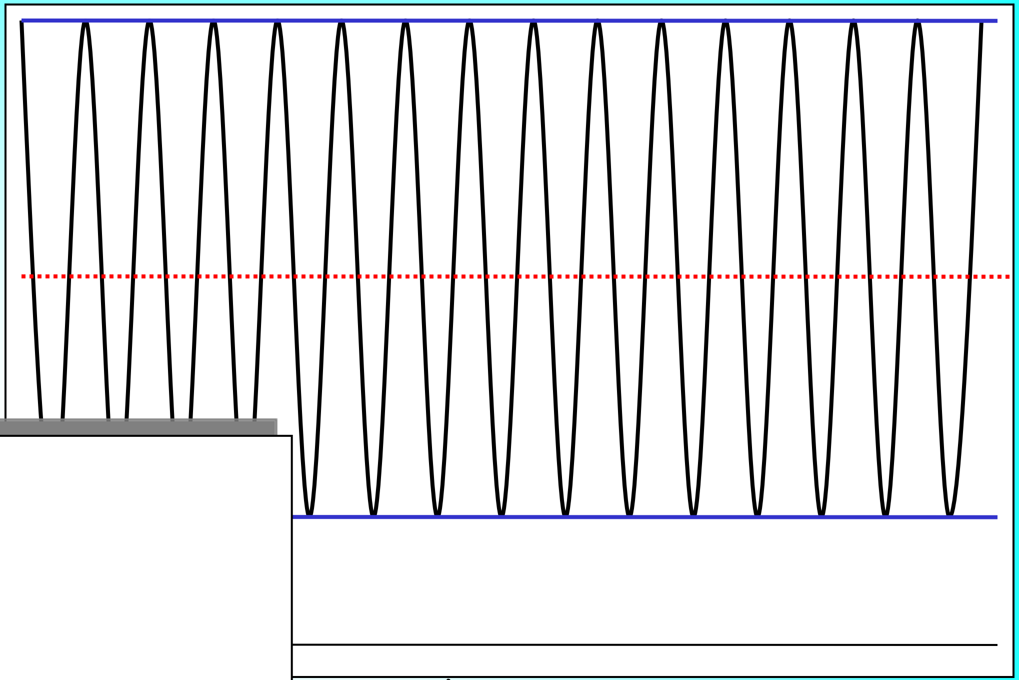
Change of mixing in medium → change of flavor of the eigenstates

θ_m (t)

Phase is irrelevant

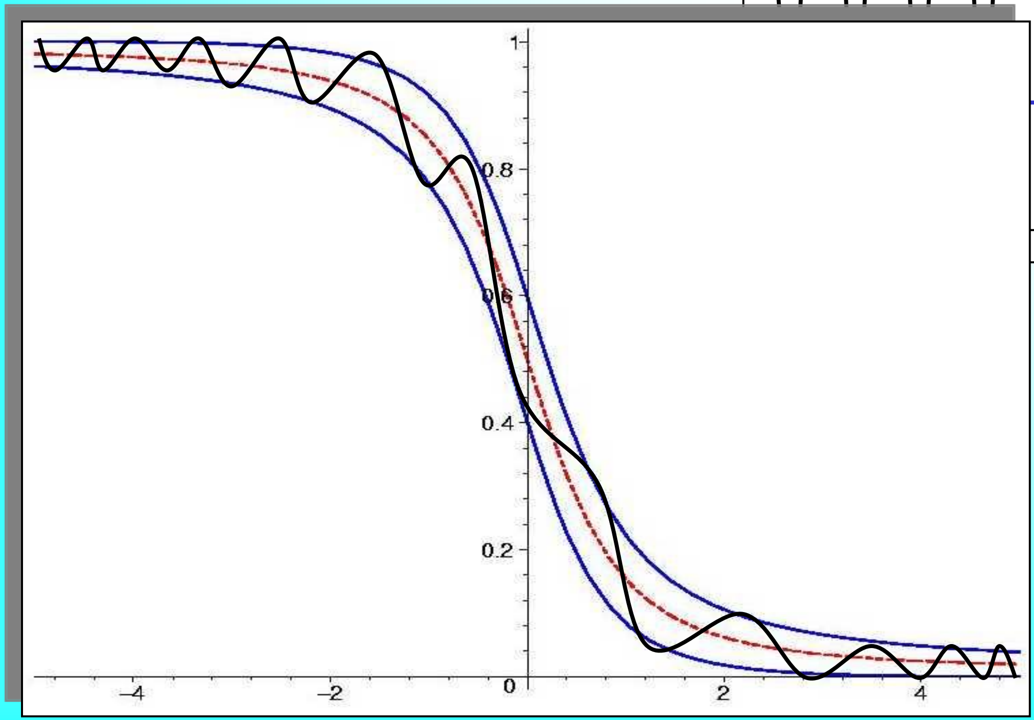
Spatial picture

Oscillations



distance

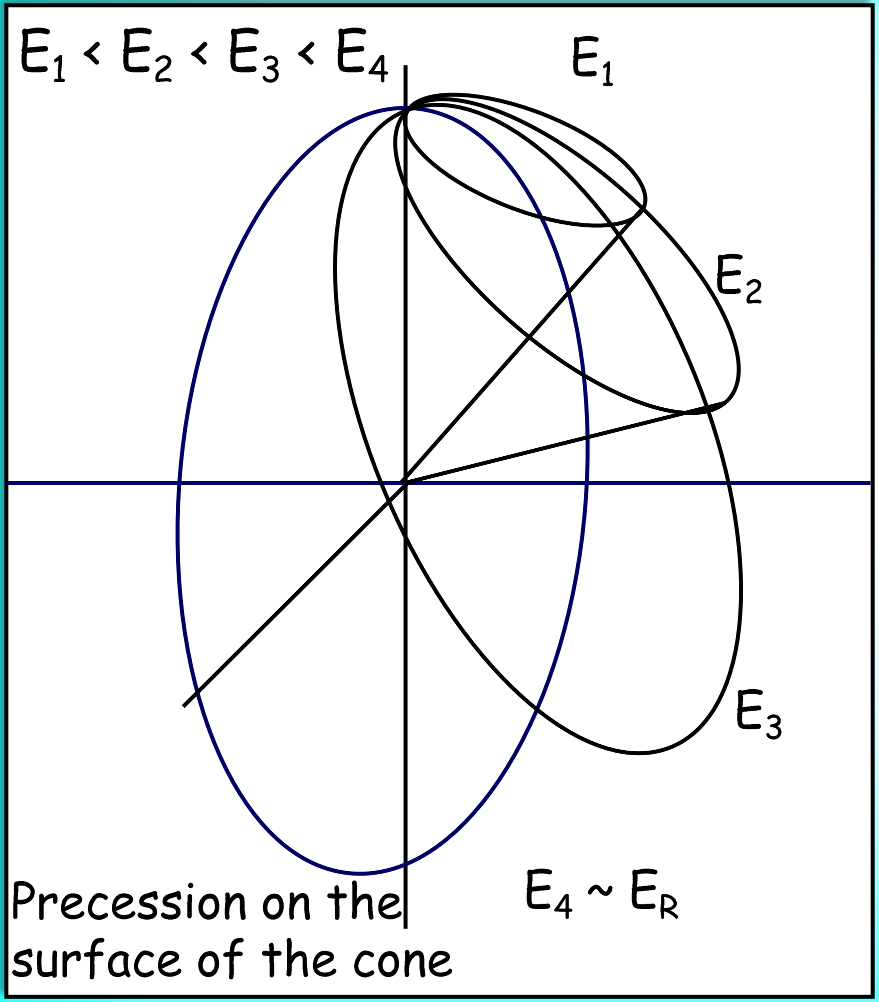
Adiabatic conversion

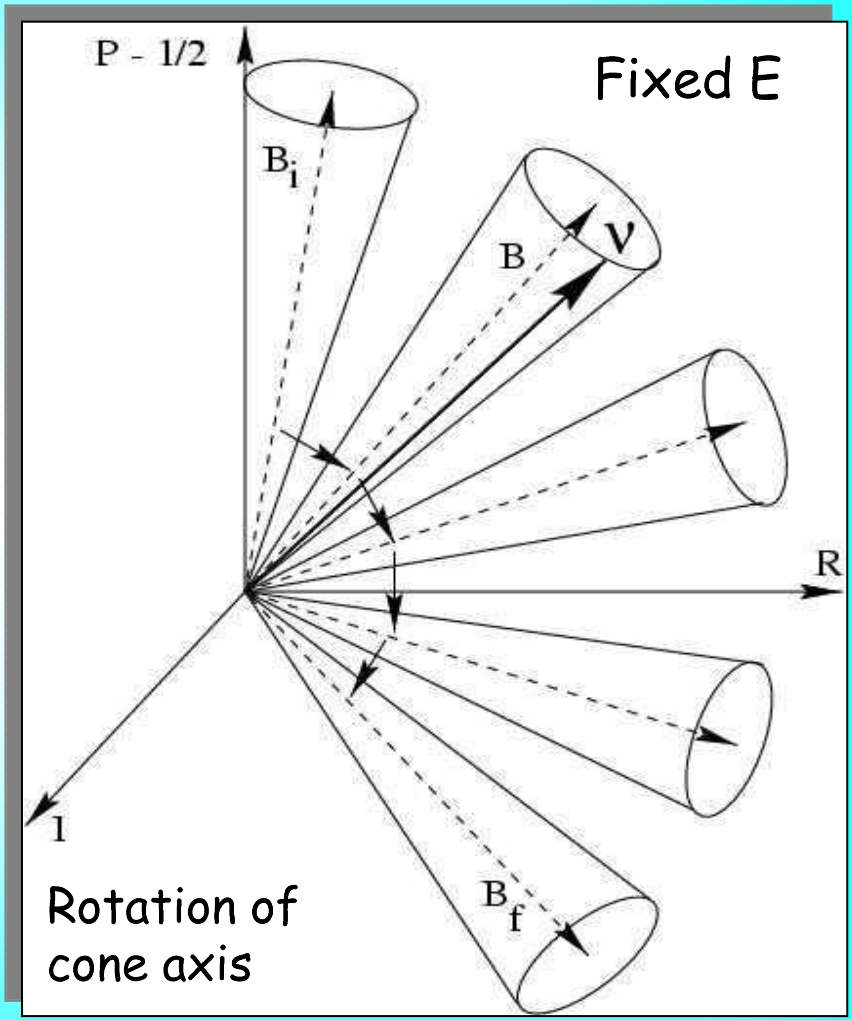


distance

A Yu Smirnov

Graphic representation



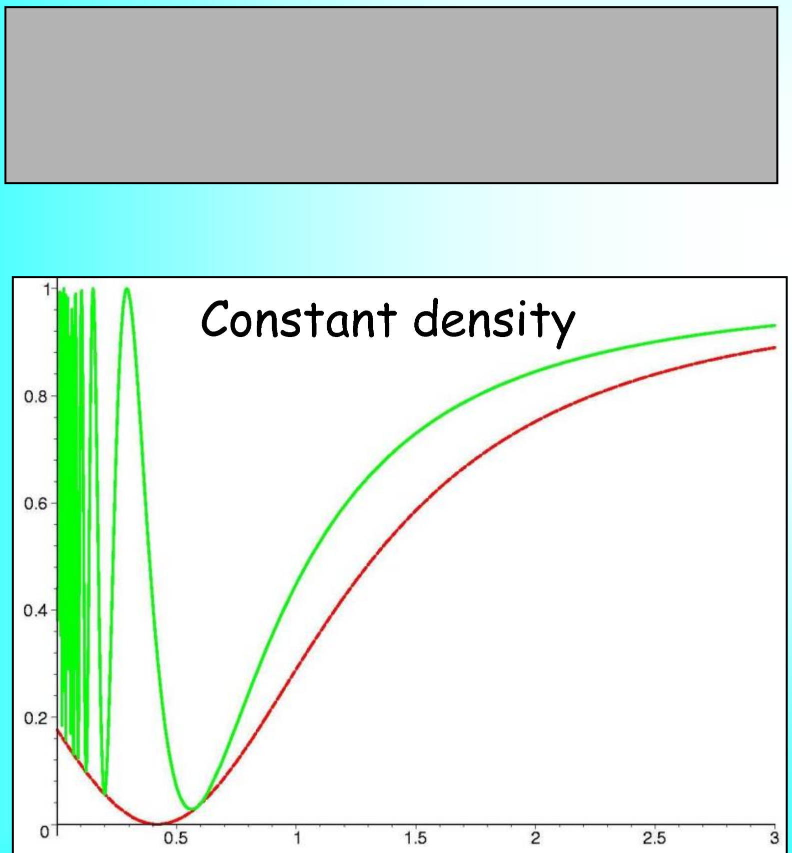


Resonance enhancement **Adiabatic conversion**

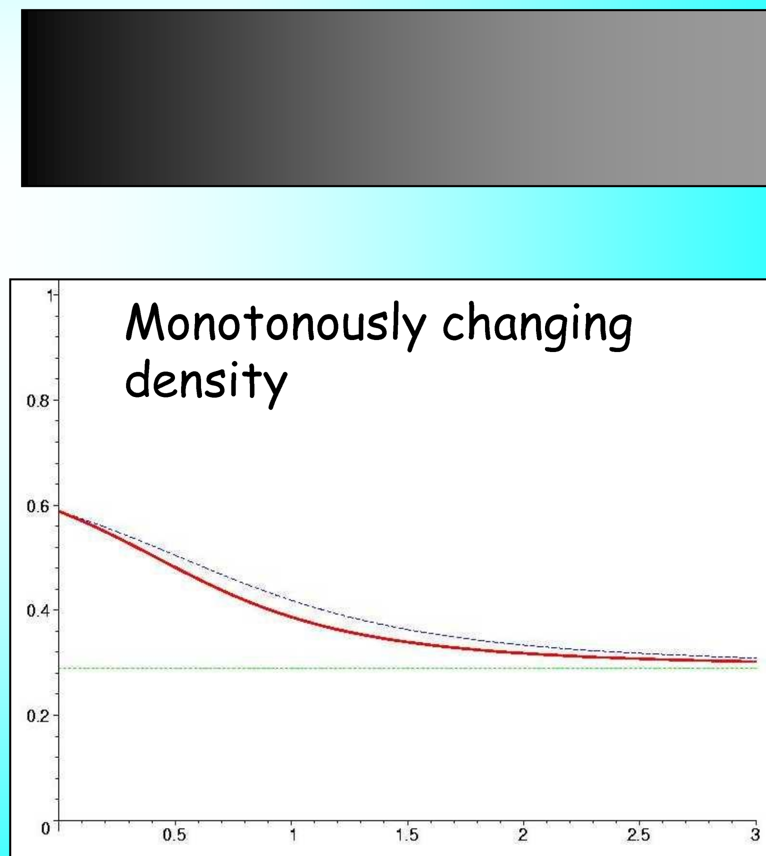
Energy dependence

Resonance enhancement ν Adiabatic conversion

$\frac{F(E)}{F_0(E)}$



E/E_R

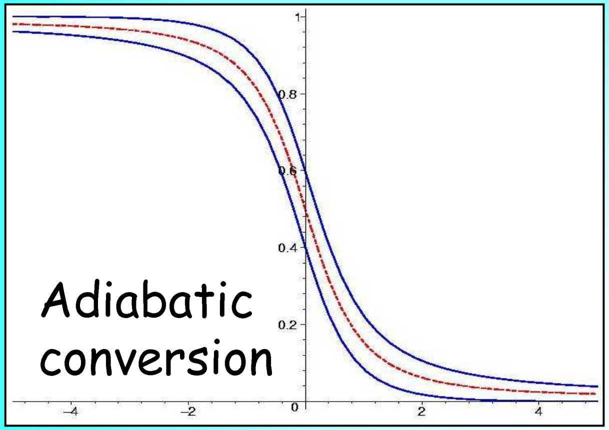


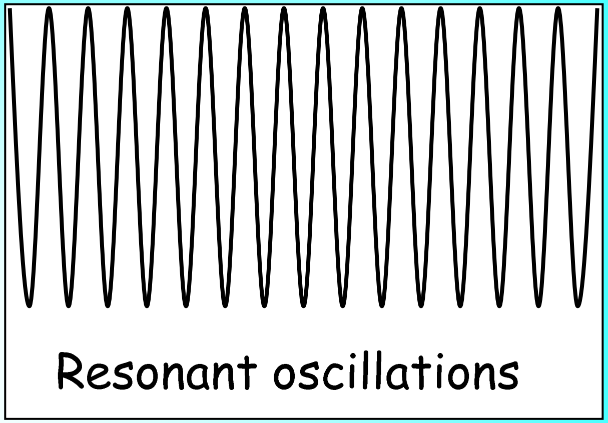
E/E_R

… and Now

Generalizations and

Realizations



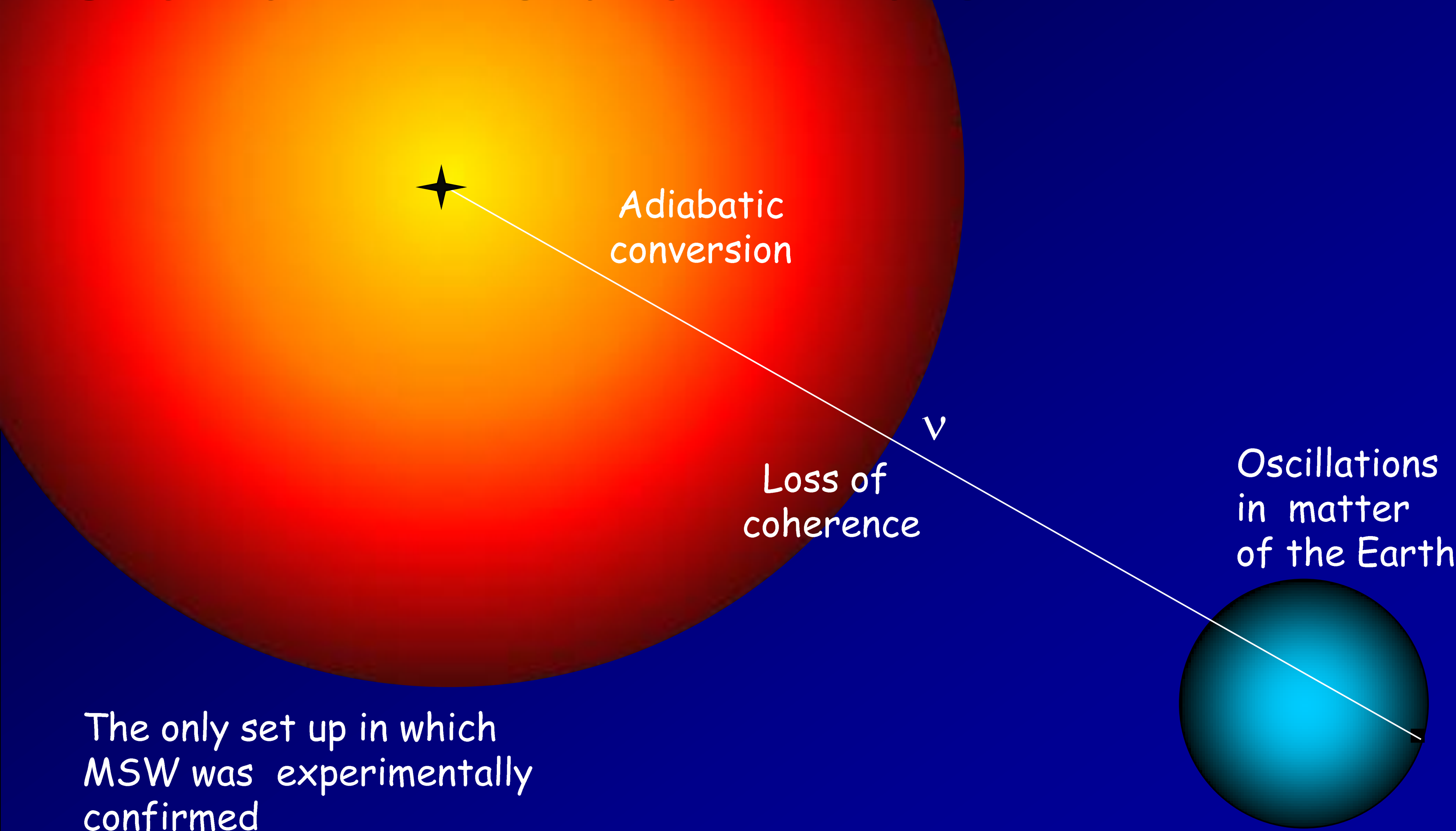


the Sun
Supernovae
Early Universe
CR sources

Atmospheric
Accelerator
Supernova
neutrinos
propagating in
the Earth

Many others if physics
beyond 3nu paradigm
(e.g. sterile neutrinos exists)

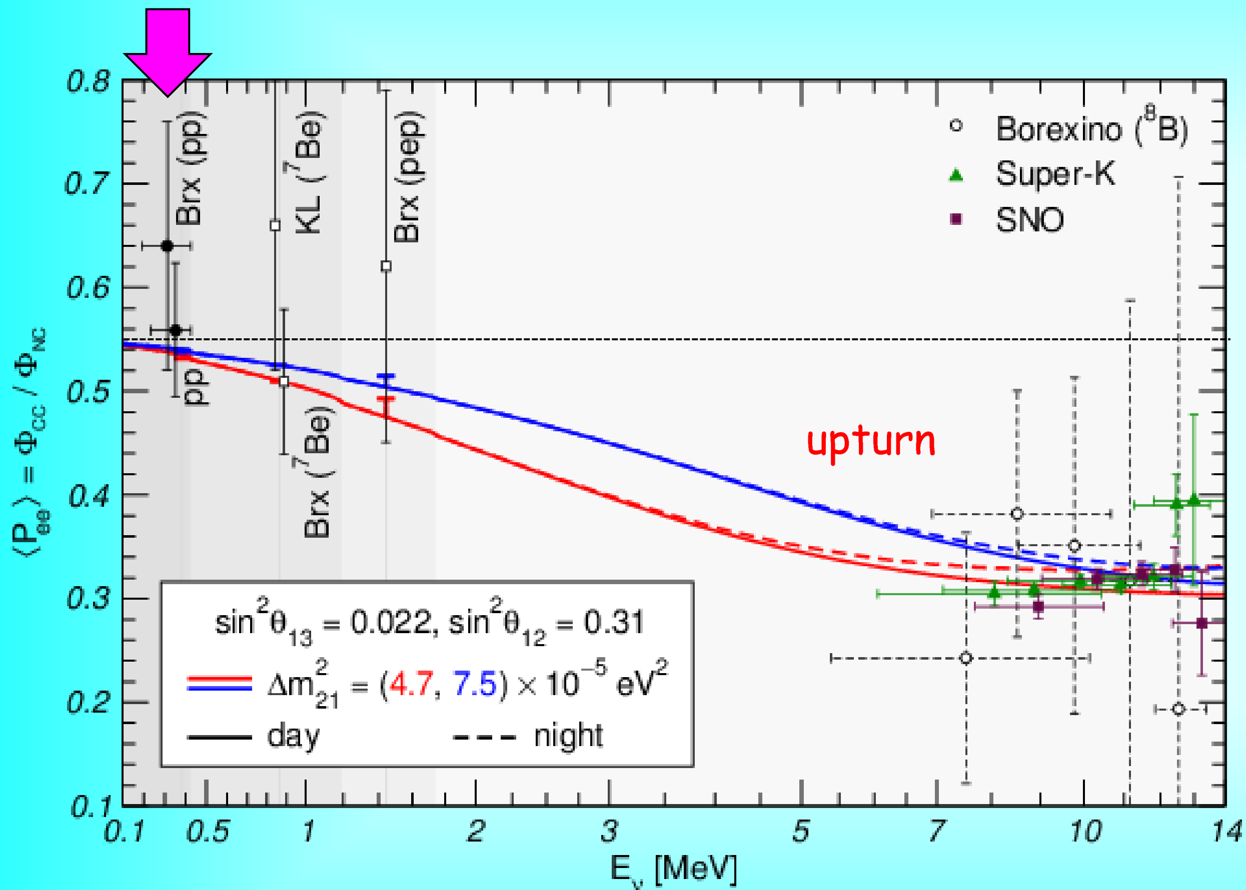
Solar neutrinos



The only set up in which
MSW was experimentally
confirmed

Profile of the effect

M. Maltoni, A.Y.S. to appear



for two different values of Δm_{21}^2

best fit value from solar data

best global fit

Vacuum dominated

Transition region resonance turn on

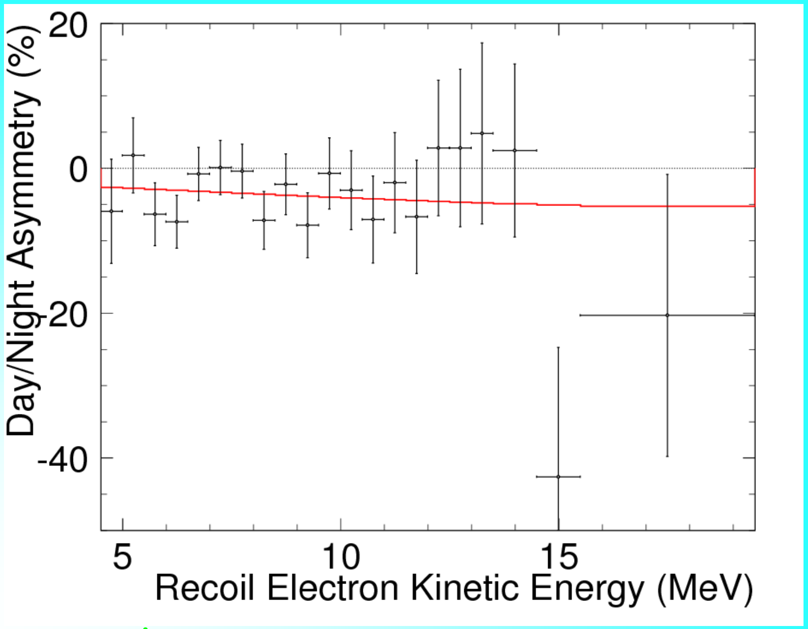
Matter dominated region

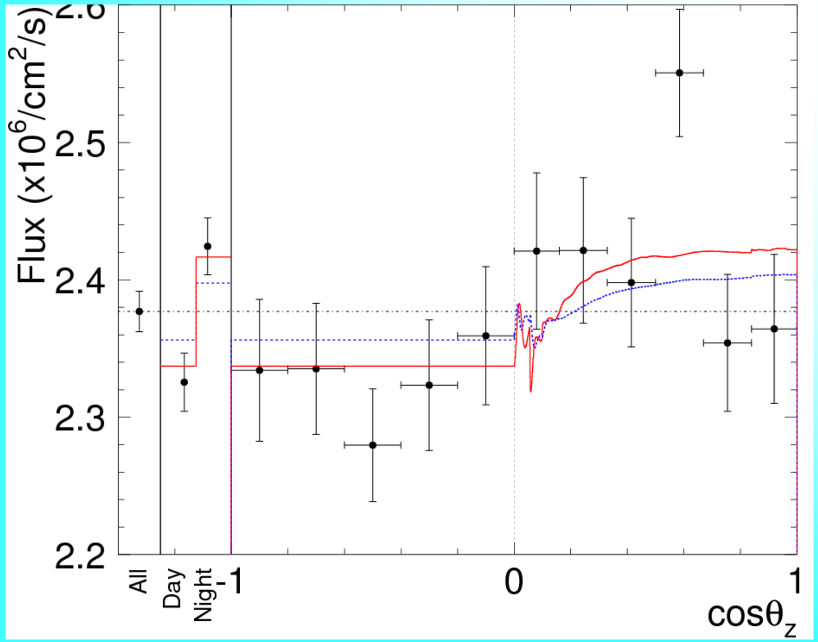
Reconstructed exp. points for SK, SNO and BOREXINO at high energies

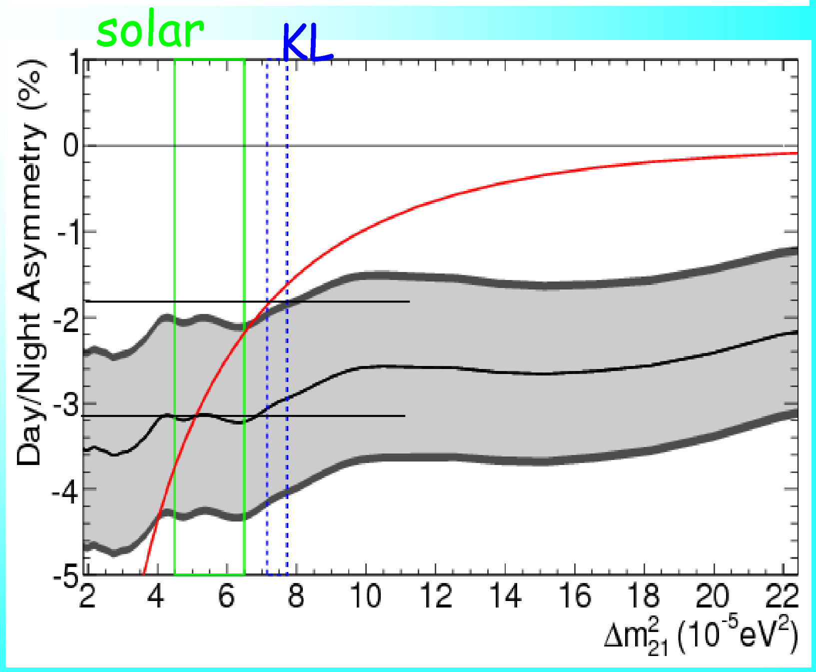
Day-Night effect

First Indication of Terrestrial Matter Effects on Solar Neutrino Oscillation

Super-Kamiokande collaboration
(Renshaw, A. et al.)
Phys.Rev.Lett. 112 (2014) 091805
arXiv:1312.5176

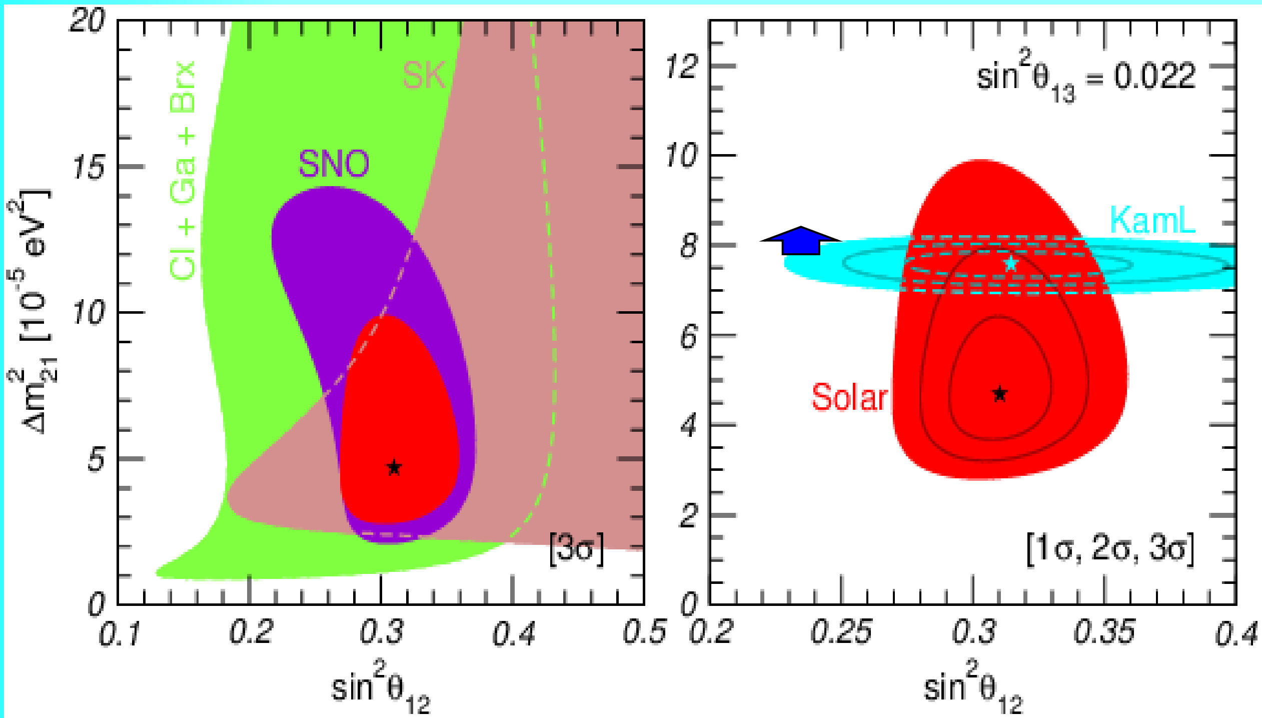






Neutrino parameters

Solar neutrinos
Vs. KamLAND



M. Maltoni, A.Y.S. to appear

Δm^2_{21} : about 2σ descrepancy of the KL and solar values

Red regions: all solar neutrino data

also restrictions from individual experiments

$\sin^2\theta_{13}$ as fit parameter then marginalized

b.f.: $\sin^2\theta_{13} = 0.017$

$\sin^2\theta_{13}$ fixed by reactor experiments

KamLAND data reanalized in view of reactor anomaly (no front detector) bump at 4 -6 MeV

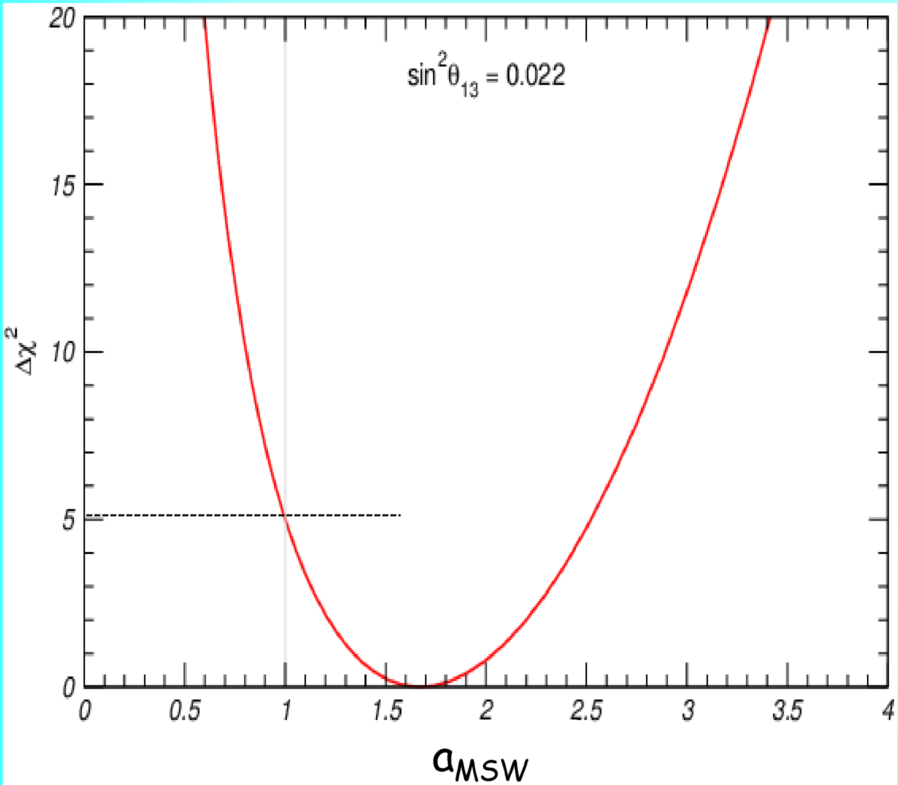
Δm^2_{21} increases by 0.5 10^{-5} eV^2

Matter potential

G. L Fogli et al hep-ph/0309100

C. Pena-Garay, H. Minakata, hep-ph 1009.4869 [hep-ph]

M. Maltoni, A.Y.S. to appear



$V = a_{MSW} V_{stand}$

$a_{MSW} = 0$ is disfavoured by > 15 σ

the best fit value $a_{MSW} = 1.66$

$a_{MSW} = 1.0$ is disfavoured by > 2 σ

related to discrepancy of Δm^2_{21} from solar and KamLAND:

$$\frac{\Delta m^2_{21}\,(KL)}{\Delta m^2_{21}\,(Sun)} = 1.6$$

Determination of the matter potential from the solar plus KamLAND data using a_{MSW} as free parameter

Potential enters the probability in combination

$$\frac{V}{\Delta m^2_{21}}$$

Open issues

at about
3σ - level

Absence of upturn of the spectrum

Large D-N asymmetry

Difference of values of Δm^2_{21} extracted from solar and KamLAND data

Large value of matter potential extracted from global fit

KamLAND

another reactor anomaly?

Solar data alone have very good and consistent description at small Δm^2_{21}

Reactor anomaly should affect KamLAND result

New physics

in solar neutrinos?

Non-standard Neutrino interaction

Very light Sterile neutrinos

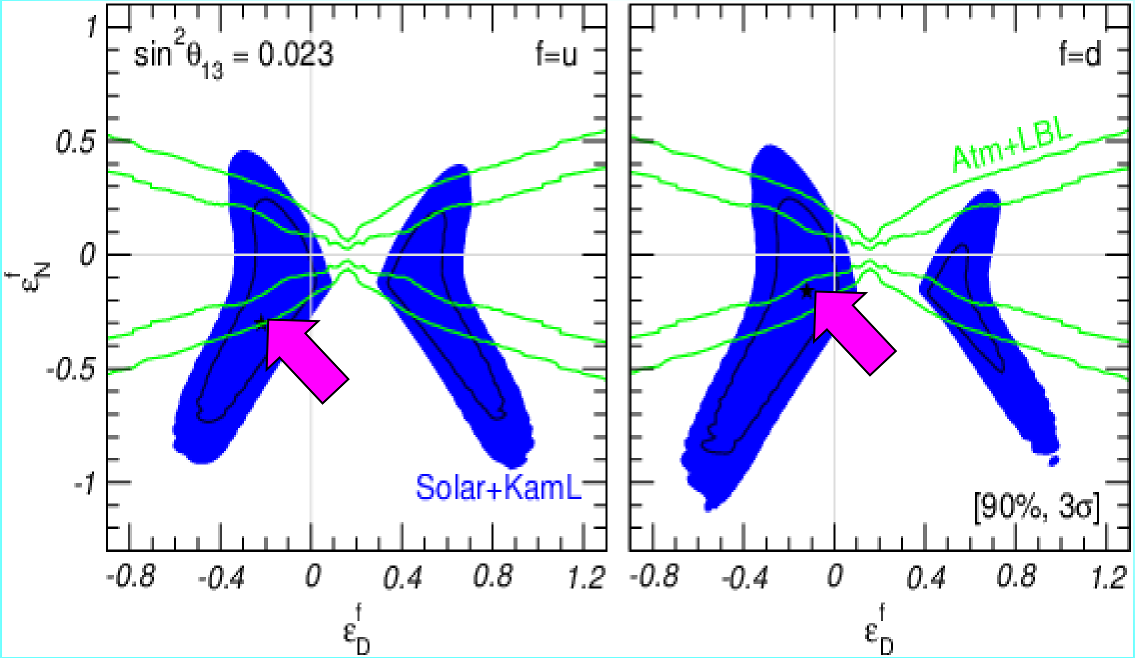
New sub-leading effects

Non-standard interactions

M C. Gonzalez-Garcia ,
M. Maltoni
arXiv 1307.3092

Additional contribution
to the matrix of potentials
in the Hamiltonian

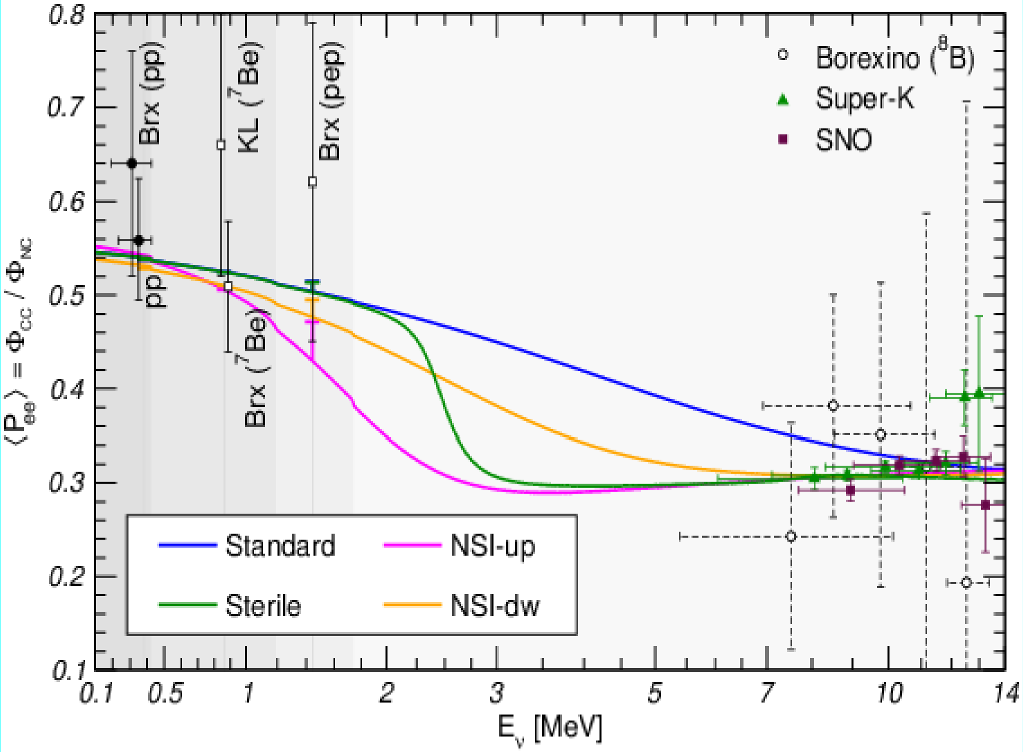
$$V_{NSI} = \sqrt{2}\, G_F\, n_f \begin{pmatrix} \varepsilon^f_D & \varepsilon^f_N \\ \varepsilon^f_N & \varepsilon^f_D \end{pmatrix} \qquad f = e, u, d$$



In the best fit
points the D-N
asymmetry is 5%

Allowed regions of parameters of NSI

New physics effects

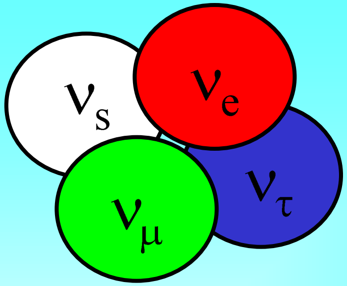


M. Maltoni, A.Y.S. to appear

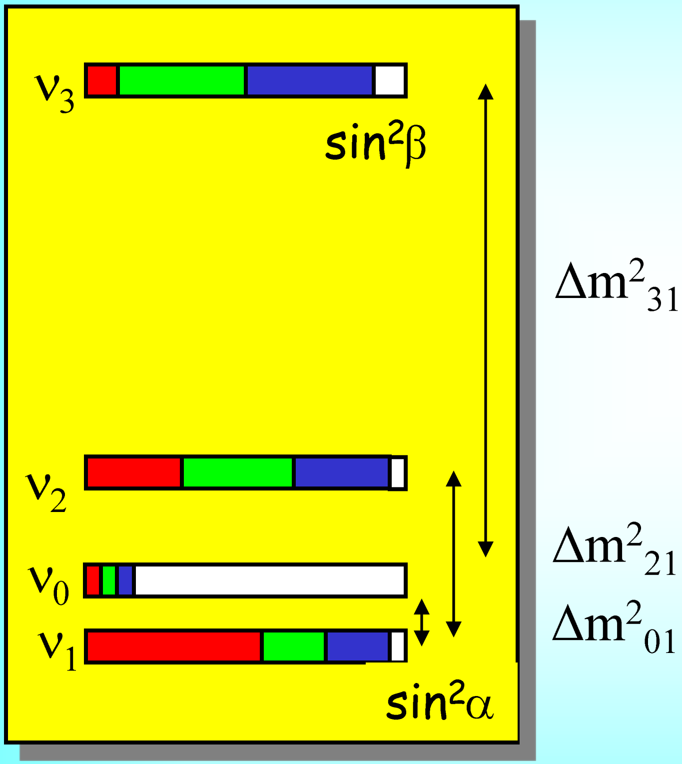
Extra sterile neutrino with $\Delta m^2_{01} = 1.2 \times 10^{-5}$ eV^2, and $\sin^2 2\alpha = 0.005$

Non-standard interactions with
$\varepsilon^u_D = -0.22$, $\varepsilon^u_N = -0.30$
$\varepsilon^d_D = -0.12$, $\varepsilon^d_N = -0.16$

meV physics



sterile neutrino $m_0 \sim 0.003$ eV



Adiabatic conversion
for small mixing angle
Adiabaticity violation

- additional radiation in the Universe if mixed in ν_3

For solar nu: $\sin^2 2\alpha \sim 10^{-3}$

For dark radiation
$\sin^2 2\beta \sim 10^{-3}$ (NH)
$\sin^2 2\beta \sim 10^{-1}$ (IH)

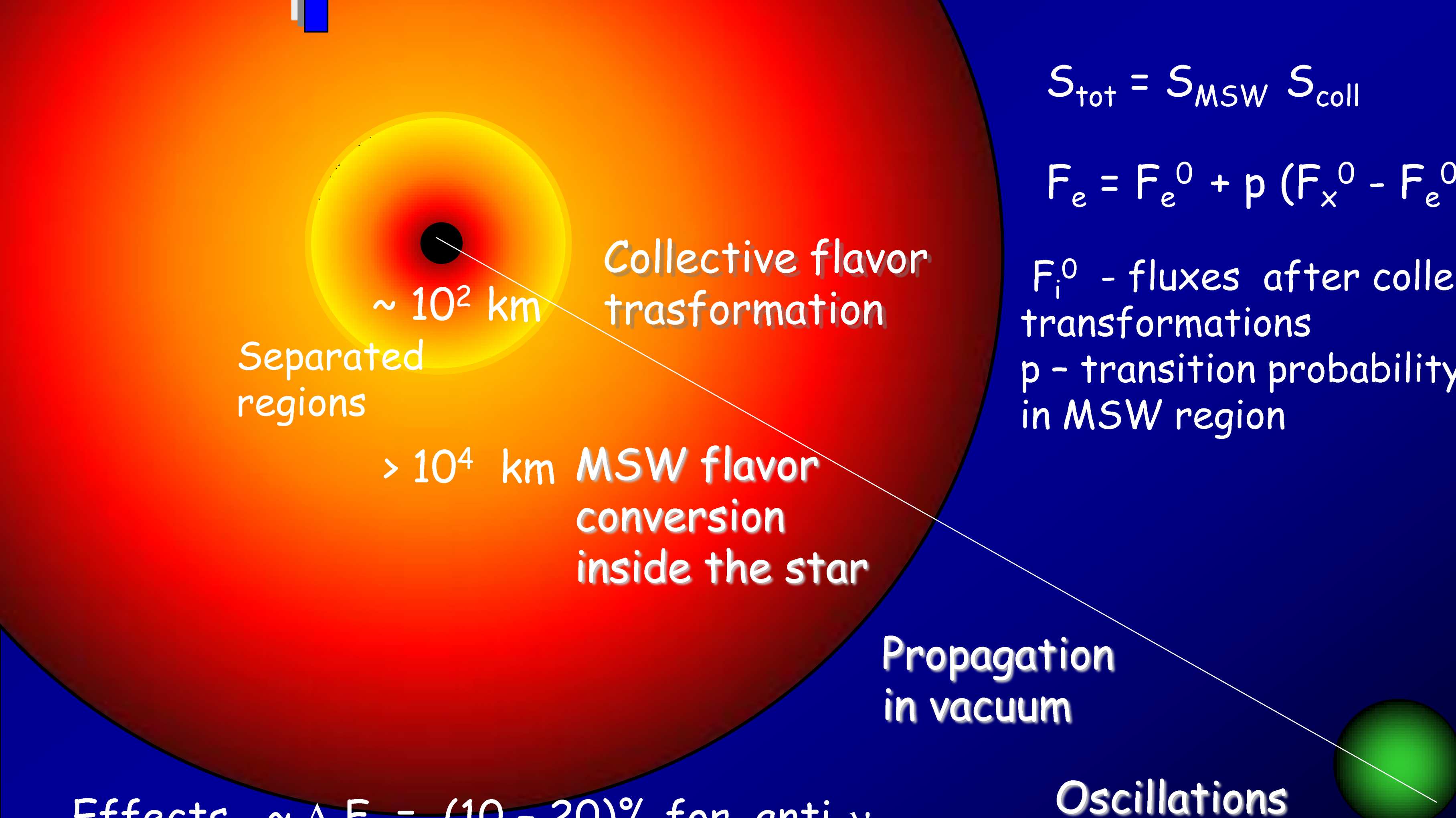
no problem with LSS
bound on neutrino mass

Supernova neutrinos

$S_{tot} = S_{MSW} \; S_{coll}$

$F_e = F_e^0 + p\,(F_x^0 - F_e^0)$

F_i^0 - fluxes after collective transformations
p – transition probability in MSW region



Effects ~ Δ F = (10 – 20)% for anti-ν

SN1987A: 19 events, anti-ν

Effects

Flavor evolution
of neutrino states
In the MSW region
is highly adiabatic

Strong suppression of
the neutronization peak:

NH
$\nu_e \rightarrow \nu_3$

Permutation of the electron and
non-electron neutrino spectra

Earth matter effects

Normal mass hierarchy:
in the antineutrino channel only

Inverted mass hierarchy:
in the neutrino channel only

This does not depend on
presence of collective effects

Shock wave effect

Adiabaticity is broken in shock front
if the relative width of the front:

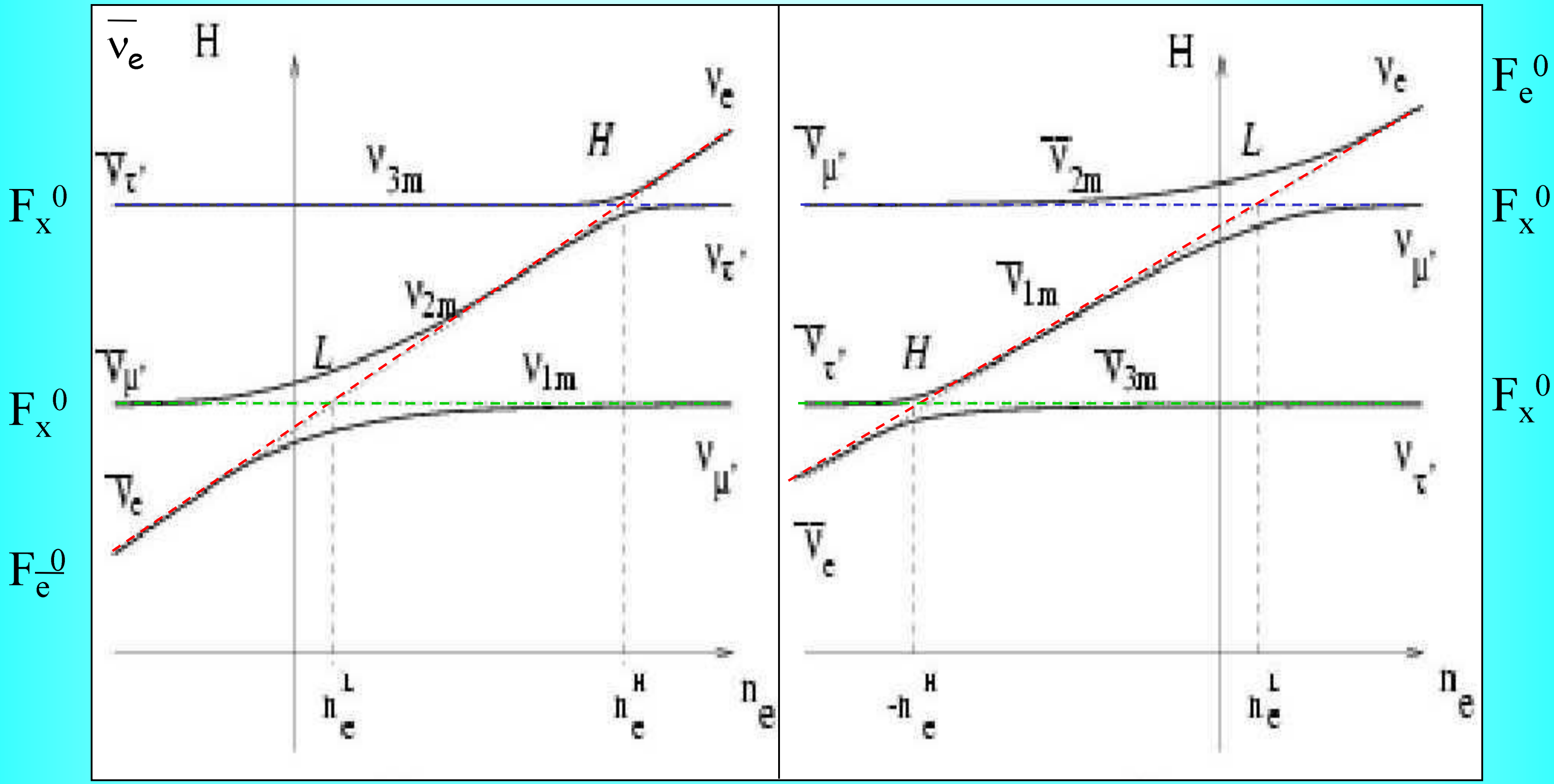
$\Delta R/R < 10^{-4} \rightarrow 10$ km

Level crossing scheme

Two resonances

and even ν_μ - ν_τ resonance

Normal hierarchy | Inverted hierarchy



Both resonances are in the neutrino channel

1-3 resonance is in the antineutrino channnel

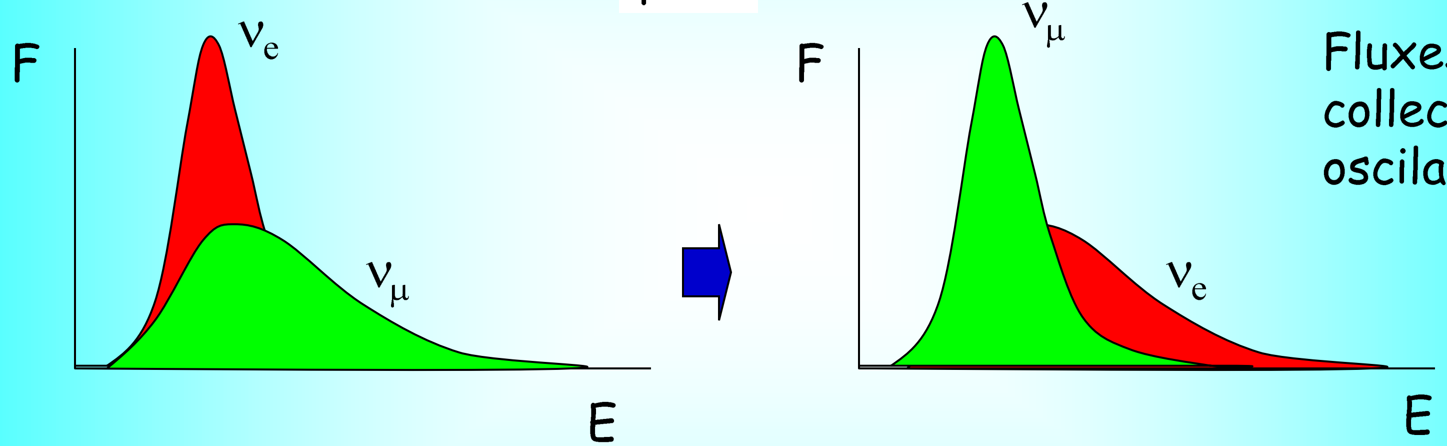
Permutation of spectra

$$F_e = (1 - p)\, F_e^0 + p\, F_x^0$$

$p = 1 - P_{ee}$

Permutation parameter

$p = 1$



Fluxes after collective oscilations

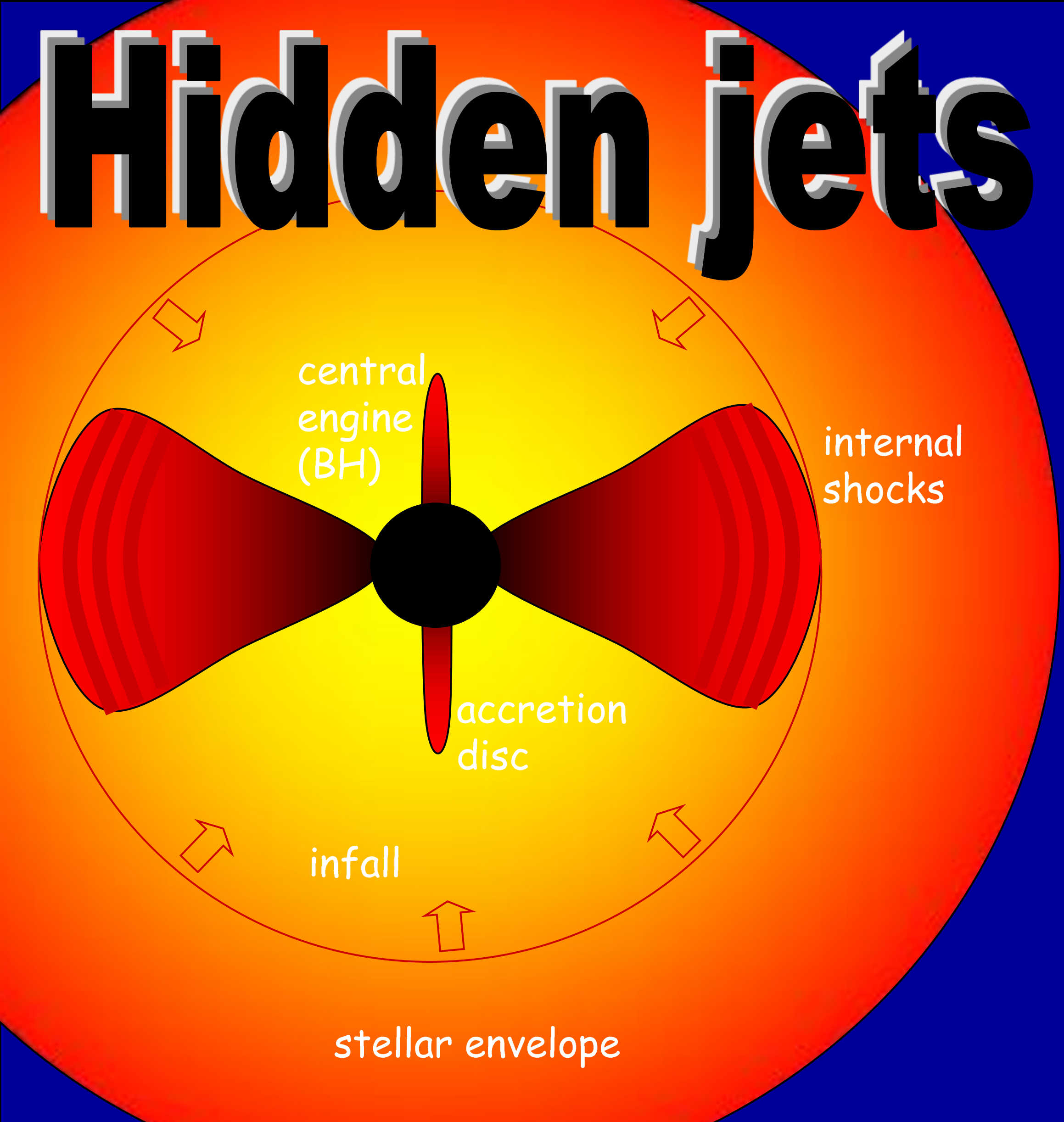
Partial permutation → composite (mixed) spectra

H – hard spectrum

MS – mixed-soft spectrum: 2/3 of the original spectrum

MH – mixed-hard spectrum: with 1/3 part of original spectrum

Hidden jets



Type Ib/c , II SNe

$M_* < 30\ M_{sun}$

Helium ($r < 10^{11}$ cm) and Hydrogen envelope

$R_* = 3\ 10^{12}$ cm

parameters of jet:

bulk jet Lorentz factor: $\Gamma_b \sim 3 - 10$

jet duration: $t \sim 10$ sec

$r_{jet} = 6\ 10^{10}$ cm

half-angle of jet: $\sim 1/\Gamma_b$

$n = 3\ 10^{20}\ cm^{-1}$

shocks:

Variability time scale: 0.1 sec

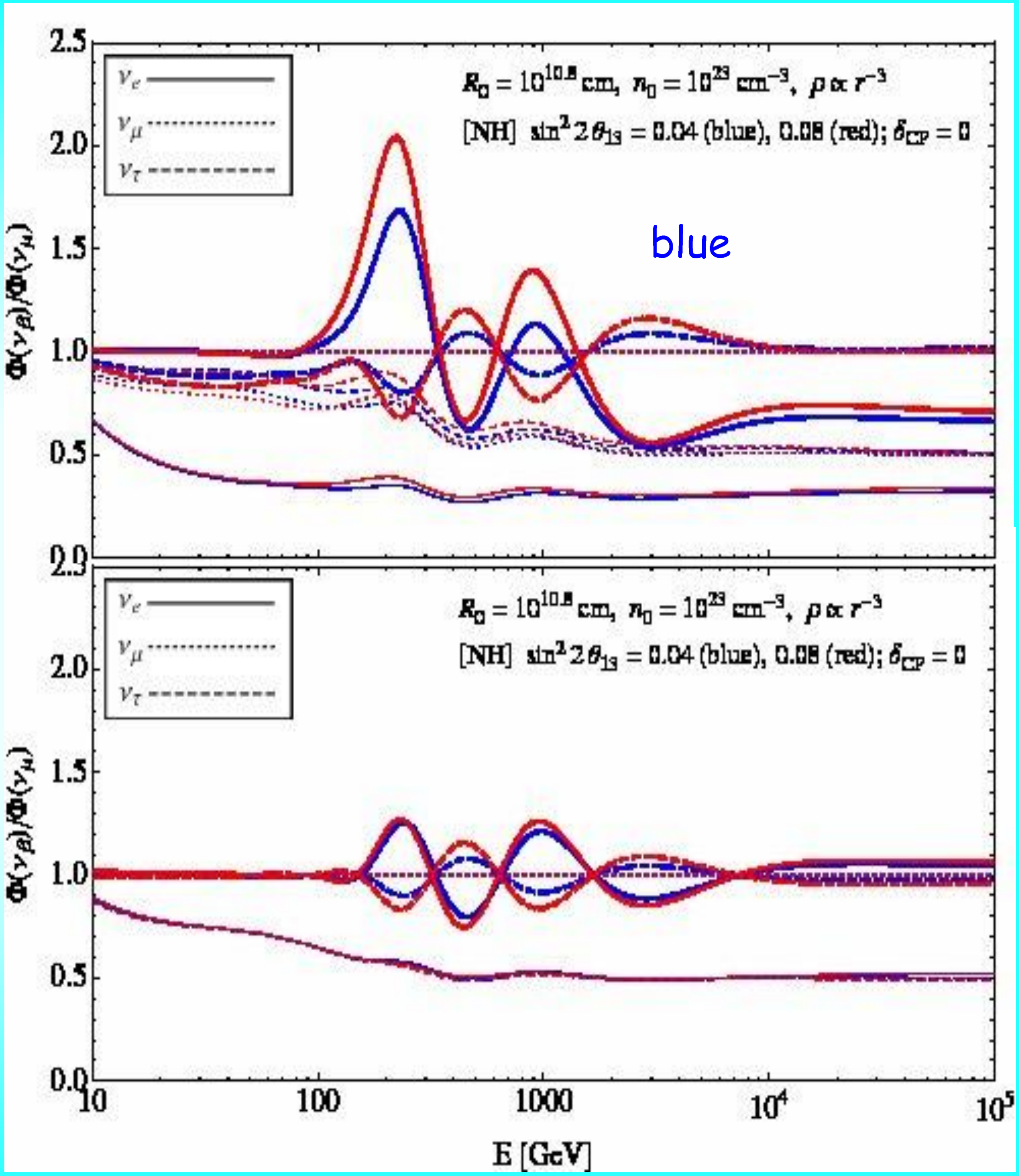
~50 internal shocks

$B \sim 10^8$ Gauss

S. Razzaque, P. Meszaros, E. Waxman

Slow jets which do not break through the envelope

Flavor ratios



Probabilities as functions of neutrino energy for different values of 1-3 mixing and two different initial flavor contents:

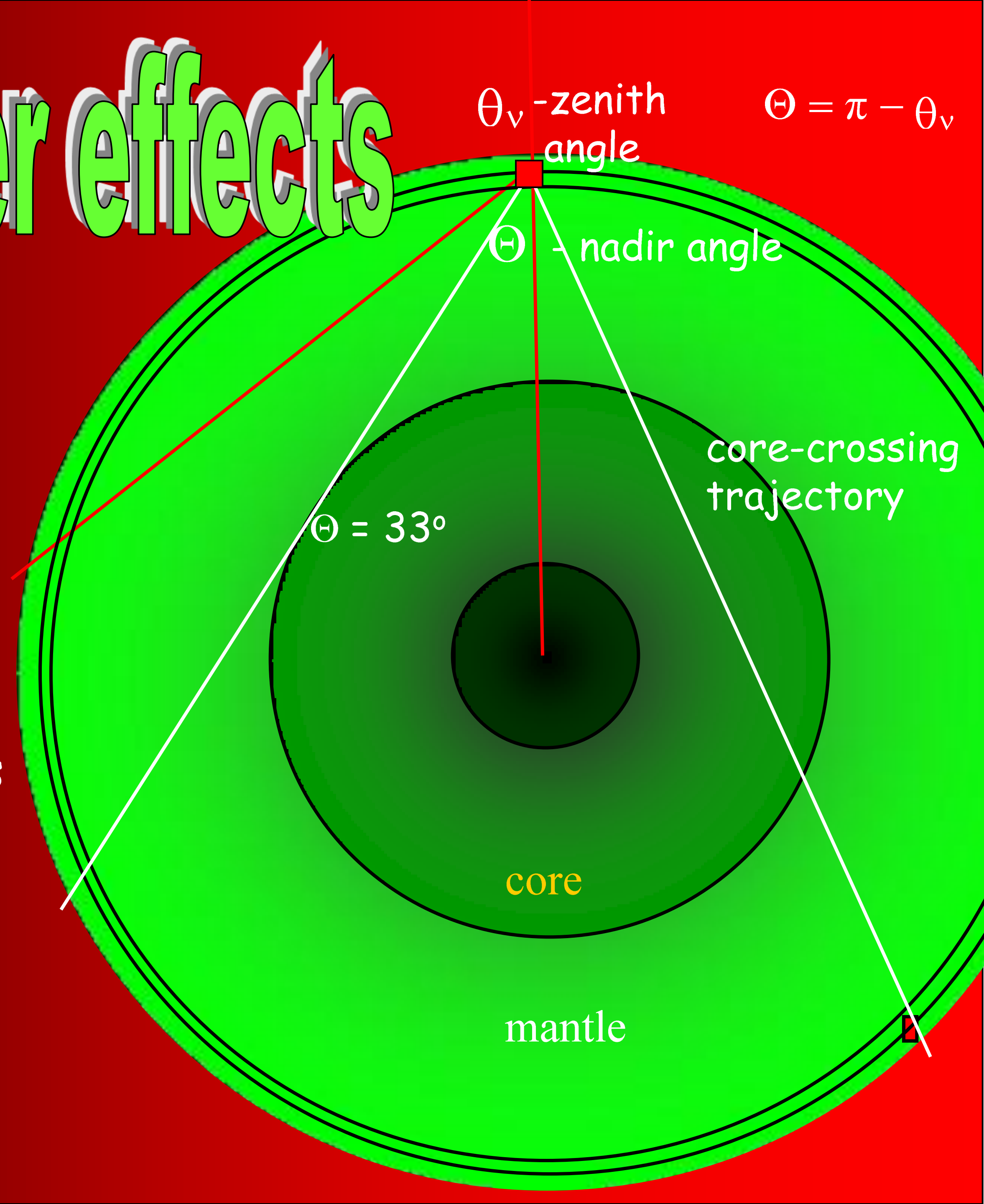
ε : 1 : 0 (upper panel)

1 : 2 : 0 (bottom panel)

S. Razzaque, A.S.

"Earth matter effects

Oscillations in
multilayer medium



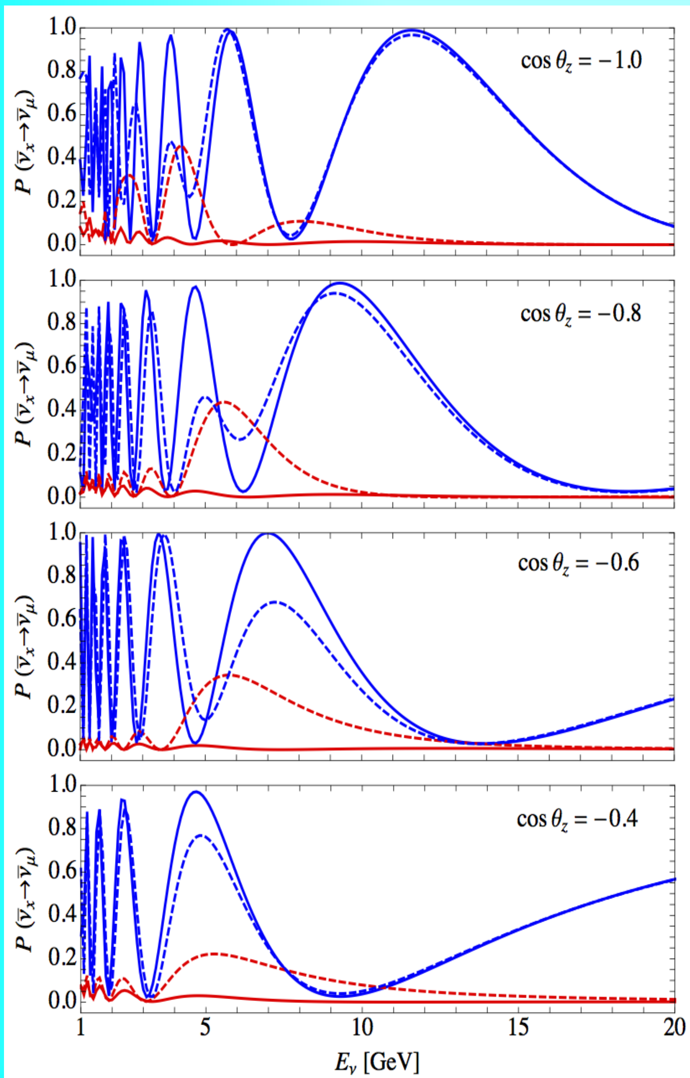
Applications:

flavor-to-flavor transitions

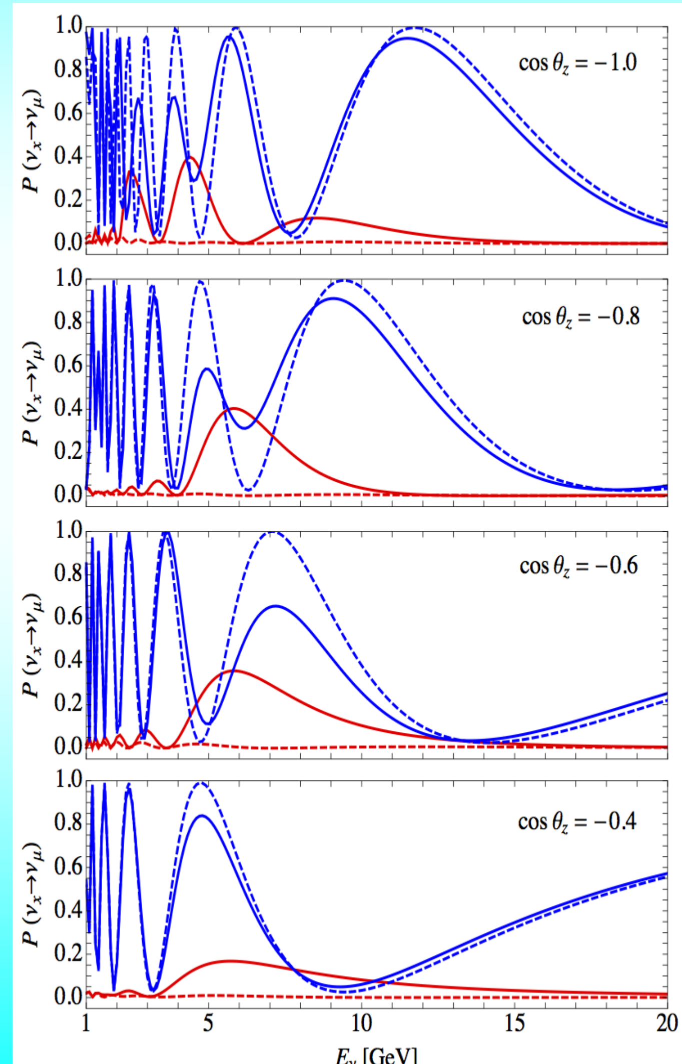
- accelerator
- atmospheric
- cosmic neutrinos

Probabilities

neutrinos



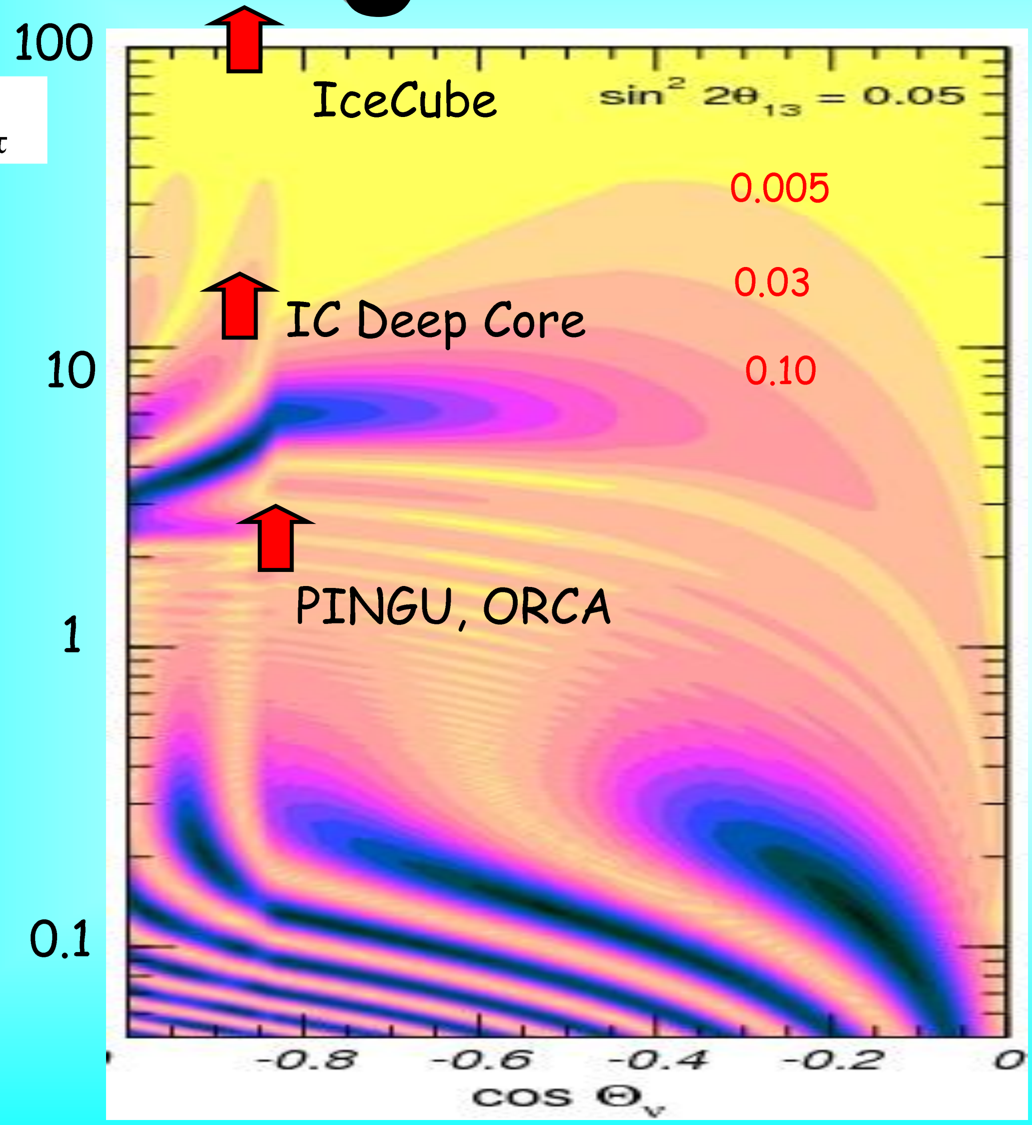
antineutrinos



NH - solid
IH - dashed
$x = \mu$ - blue
$x = e$ - red

Oscillograms

$\nu_e \rightarrow \nu_\mu , \nu_\tau$



1-3 resonance

Determination of mass hierarchy with atmospheric neutrinos

MSW and Physics BSM

Other realizations

eV scale sterile neutrinos

Resonance production in the Early Universe

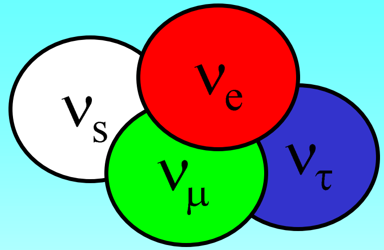
Conversion in SN Resonances due to change of Y_e

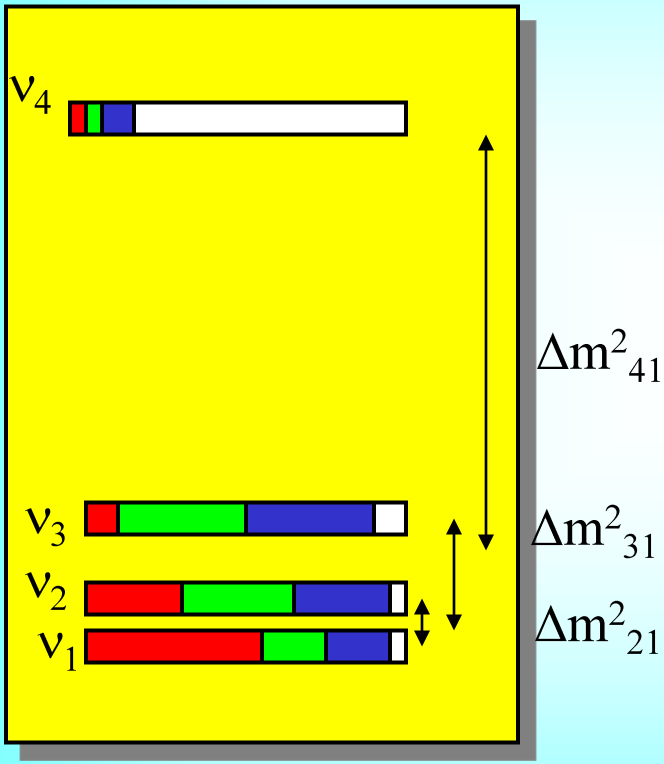
Resonance enhancement of $\nu_\mu \rightarrow \nu_s$ oscillation in the Earth

Resonance production of the 7 - 10 keV neutrinos in the Early Universe in presence of large lepton asymmetry

Conversion of GeV scale neutrinos from annihilation of DM particles in the Matter of the Sun

(3 + 1) scheme





LSND/MiniBooNE: vacuum oscillations

$$P \sim 4|U_{e4}|^2|U_{\mu 4}|^2$$

restricted by short baseline exp.
BUGEY, CHOOZ, CDHS, NOMAD

For reactor and source experiments

$$P \sim 4|U_{e4}|^2(1 - |U_{e4}|^2)$$

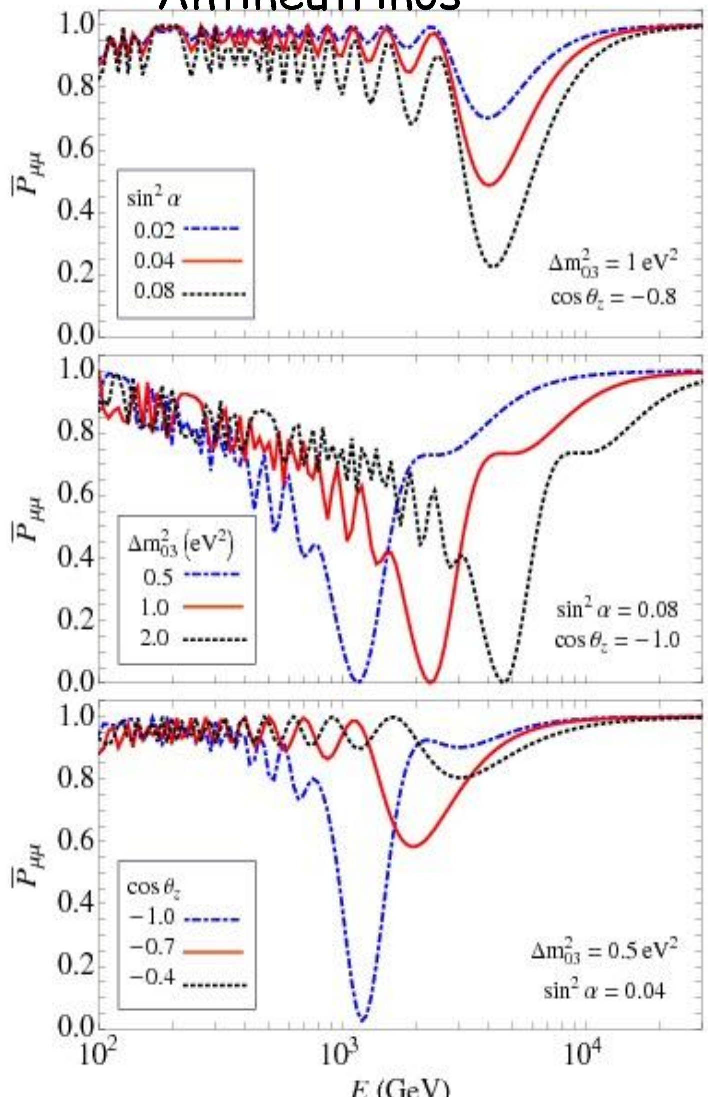
1-4 resonance in the matter of the Earth

Resonance in the Earth at ....

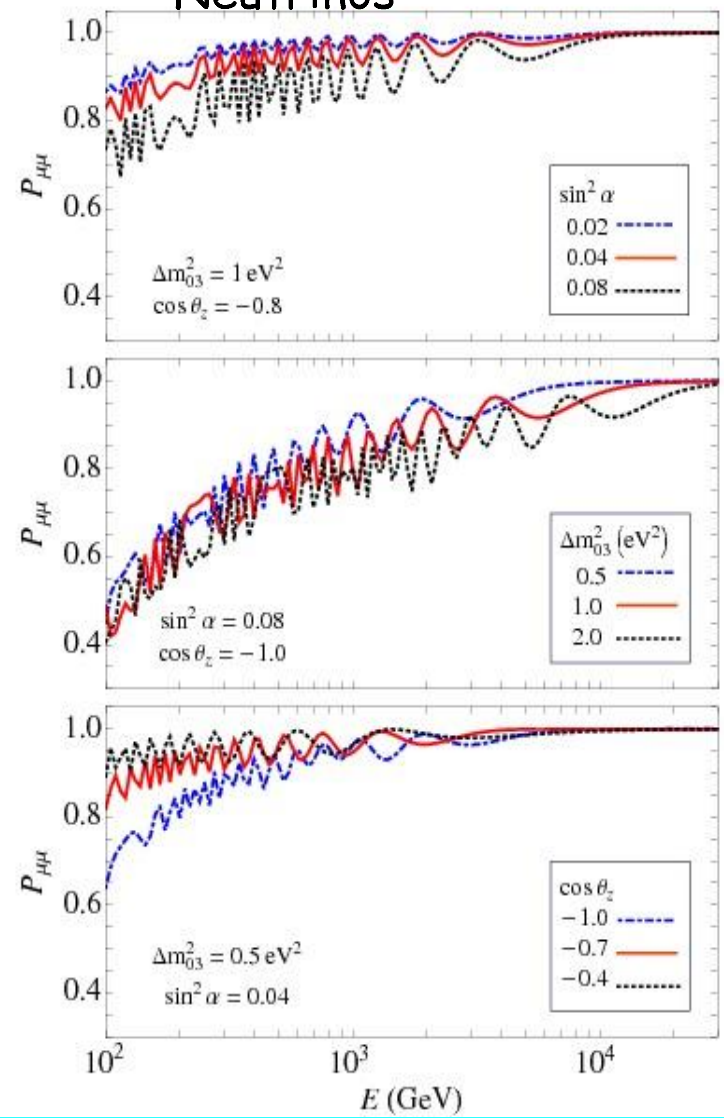
O. Yasuda,
O. Peres et al
S. Razzaque, A.S.....

Survival probability

Antineutrinos



Neutrinos

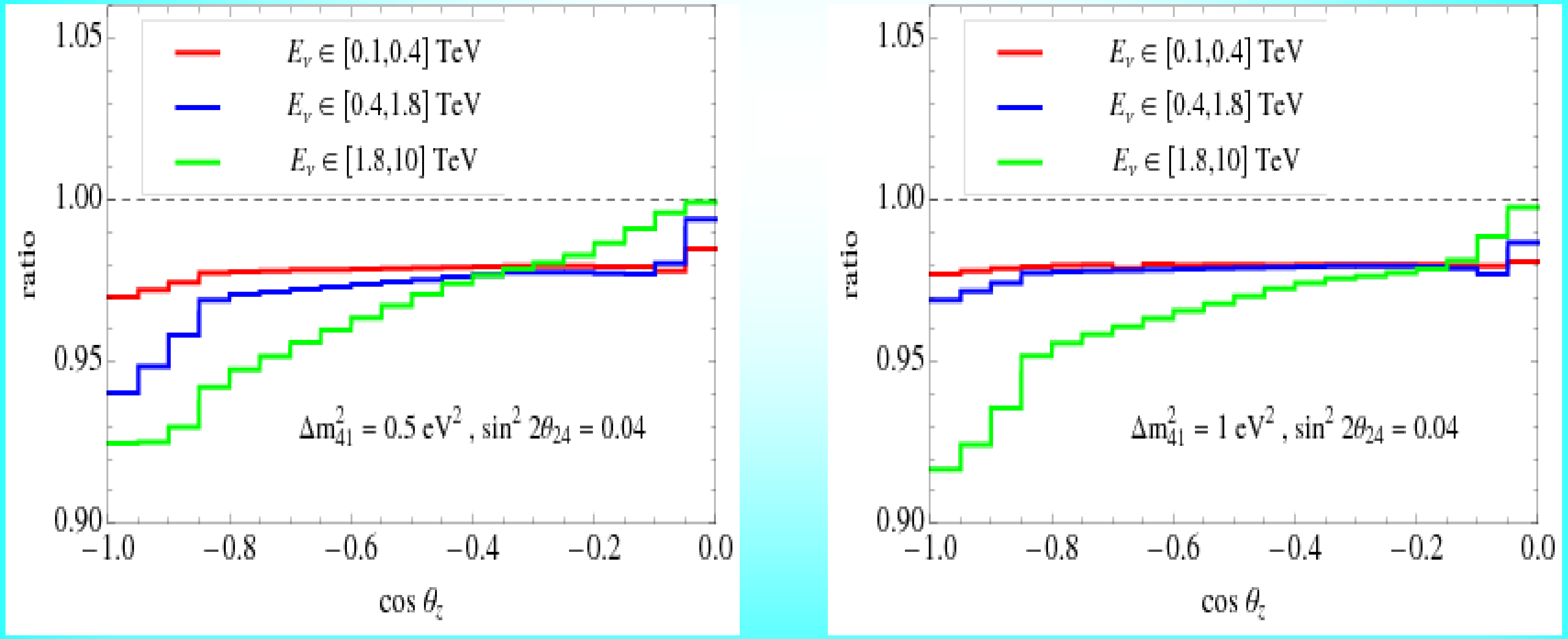


MSW resonance dip

Zenith angle distributions

Substantial improvement of sensitivity if energy information is used

A Esmaili, A Y S,
arXiv: 1307.6824 [hep-ph]




Outlook

Summary

Solar neutrinos: the only place where existence of the MSW conversion was experimentally confirmed

D-N effect is the first evidence of the matter effect in oscillations

Weak manifestations of the matter effects in sub-GeV atmospheric neutrino events

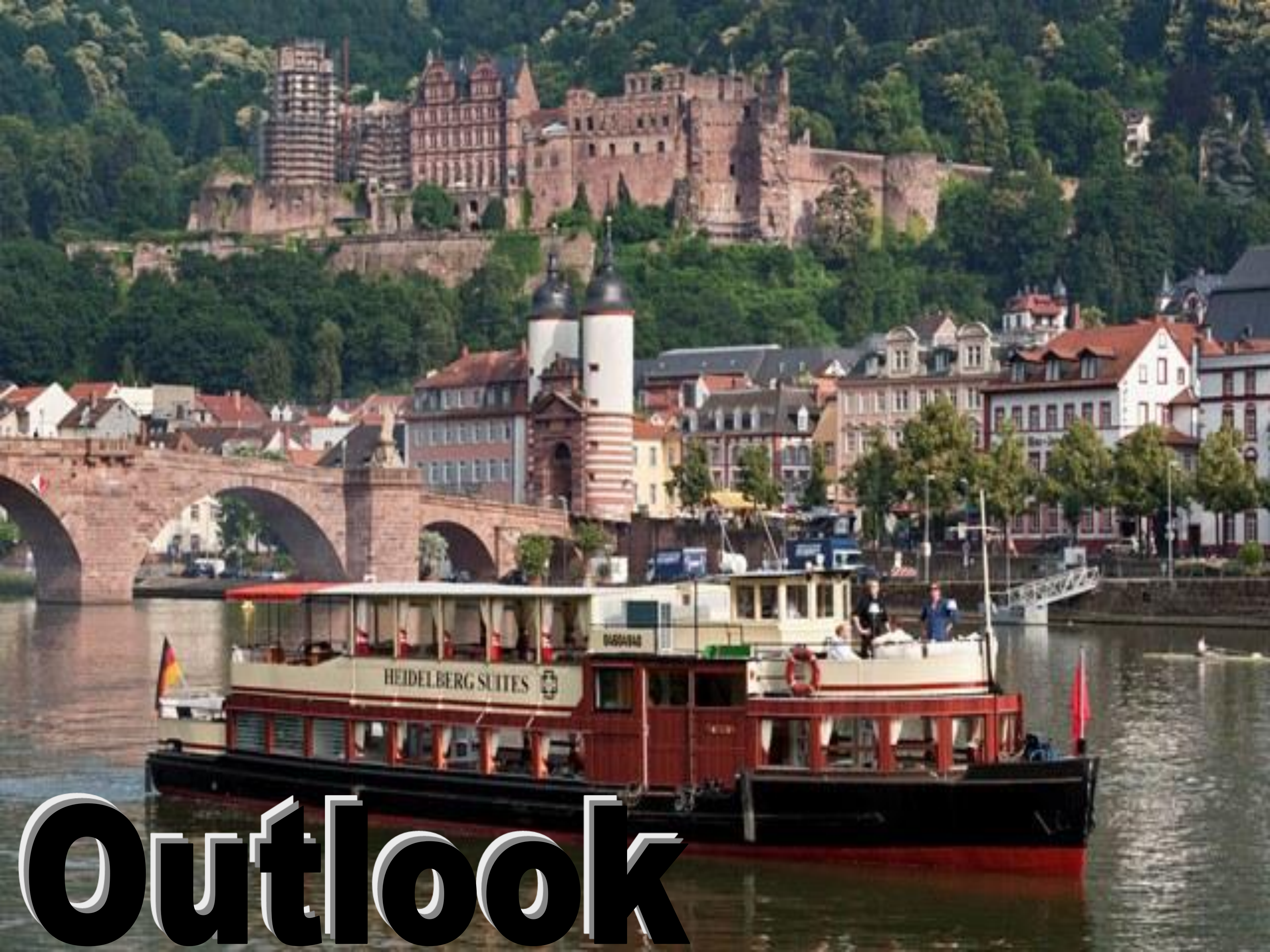
Supernova neutrinos: realization of both 1-3 and 1-2 resonances adiabatic conversion in complete 3nu scheme

Resonance enhancement in the mantle of Earth at & GeV

PINGU, ORCA should see 1-3 resonance in the matter of the Earth using atmospheric neutrinos → establishing mass hierarchy

Various other realizations tool to look for sterile neutrinos NSI, etc

Outlook



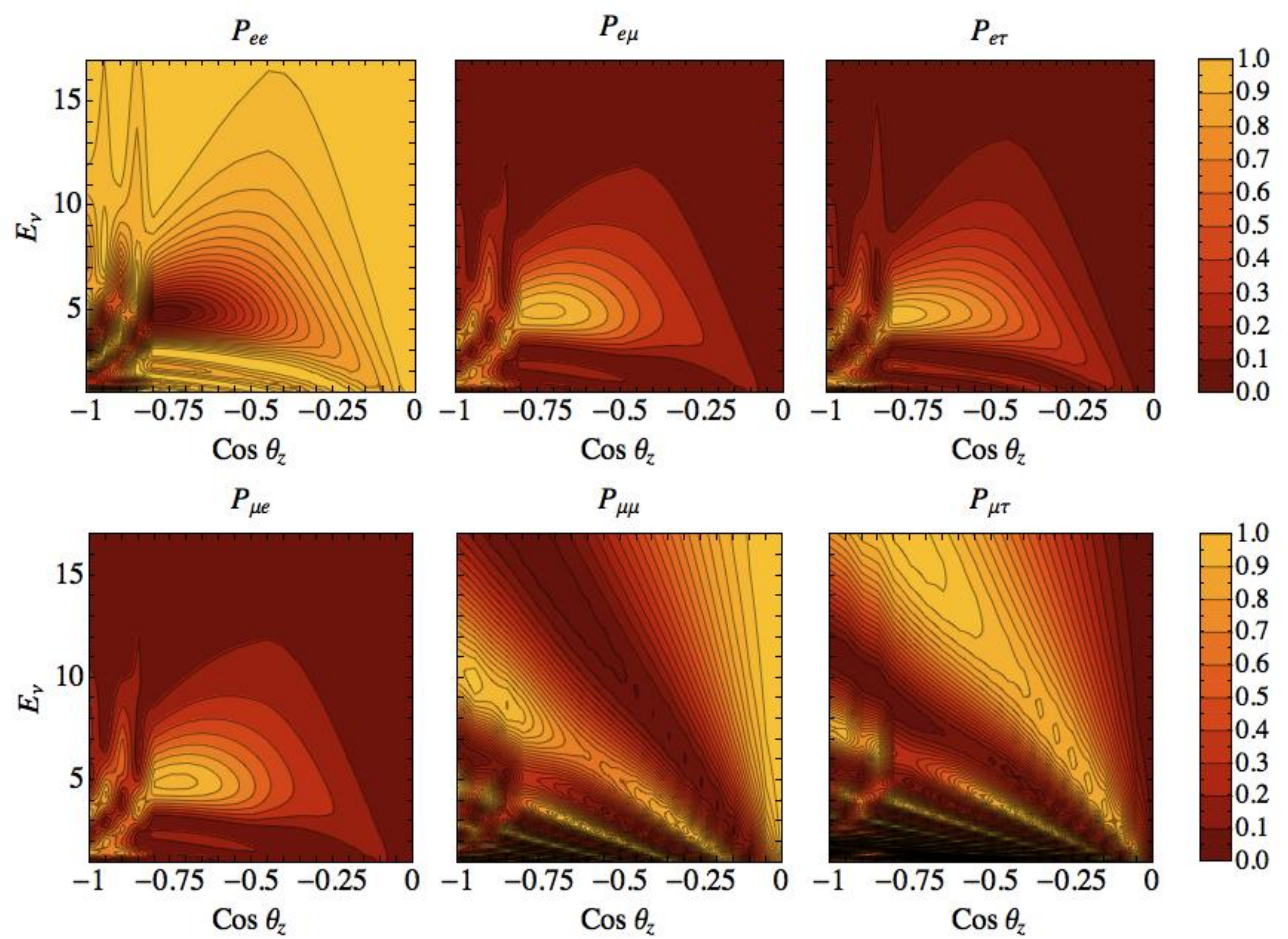
Conclusion:

Adiabatic conversion is effect of change of
mixing angle in matter in medium with slowly enough
density change on the way of neutrino propagation

Resonance enhancement of oscillations occures
in certain energy range in matter with constant density

nearly constant

Oscillograms of the Earth



E. Kh. Akhmedov,
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