Neutrinos

A. Yu. Smirnov

Max-Planck Institute for Nuclear Physics, Heidelberg, Germany

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Bethe Forum, Bonn, Germany
March 6 - 10, 2017

3ν – oscillations

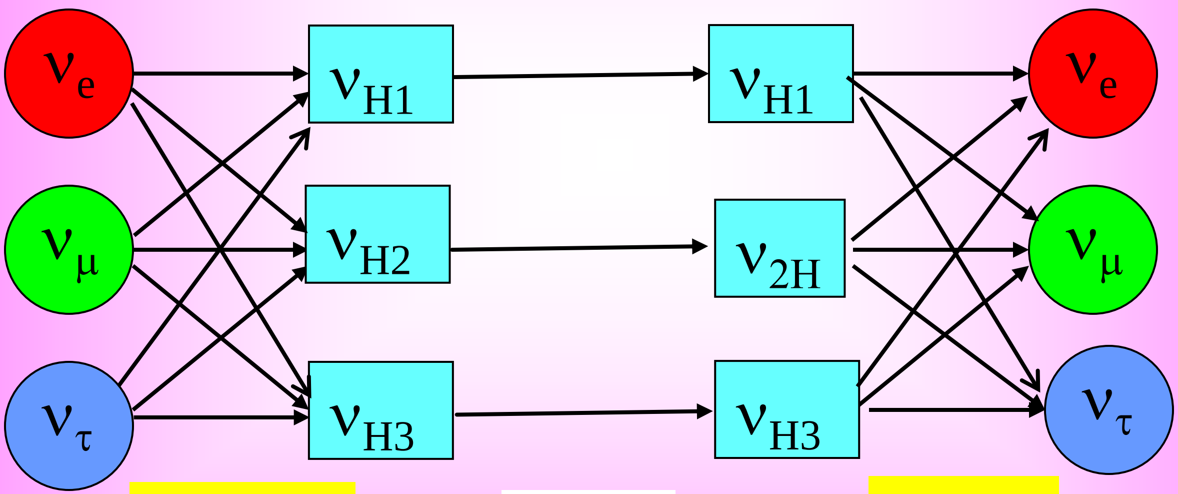
Vacuum, constant density medium

Interference of different channels

Decoupling of one state

Freeze out subsystem

projection propagation projection



$U_{\alpha j}^{H+}$ $e^{-i\phi_j}$ $U_{\beta j}^{H}$

$$P(\nu_\alpha \to \nu_\beta) = |\Sigma_j U_{\beta j}^H e^{-i\phi_j} U_{\alpha j}^{H+}|^2$$

Adiabatic conversion

Hamiltonian for flavor states in matter

In the flavor basis $\nu_f = (\nu_e , \nu_\mu)^T$

$$H_{tot} = \frac{M\,M^+}{2E} + V(t)$$

$$M\,M^+ = U\,M_{diag}^2\,U^+$$

$$M_{diag}^2 = \mathrm{diag}\,(m_1^2,\; m_2^2)$$

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

$$H_{tot} = \frac{\Delta m^2}{4E} \begin{pmatrix} -\cos 2\theta + \xi & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix}$$

$$\xi = \frac{4V_e E}{\Delta m^2} \qquad V_e = \sqrt{2}\,G_F n_e$$

$$\nu_f = U(\theta_m)\,\nu_m$$

Mixing matrix in matter - diagonalizes H_{tot}

Evolution equation for eigenstates

In non-uniform medium the Hamiltonian depends on time: $H_{tot} = H_{tot}(n_e(t))$

$$i \frac{d\nu_f}{dt} = H_{tot}\, \nu_f$$

$$\nu_f = \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} \qquad \nu_m = \begin{pmatrix} \nu_{1m} \\ \nu_{2m} \end{pmatrix}$$

Inserting $\nu_f = U(\theta_m)\, \nu_m$ $\qquad \theta_m = \theta_m(n_e(t))$

$$i \frac{d}{dt} \begin{pmatrix} \nu_{1m} \\ \nu_{2m} \end{pmatrix} = \begin{pmatrix} 0 & i \frac{d\theta_m}{dt} \\ -i \frac{d\theta_m}{dt} & H_{2m} - H_{1m} \end{pmatrix} \begin{pmatrix} \nu_{1m} \\ \nu_{2m} \end{pmatrix}$$

off-diagonal terms imply transitios

$\nu_{1m} \Leftrightarrow \nu_{2m}$

However

if $\left| \frac{d\theta_m}{dt} \right| \ll H_{2m} - H_{1m}$

off-diagonal elements can be neglected
no transitions between eigenstates
propagate independently

Adiabaticity

Adiabaticity condition $\left|\frac{d\theta_m}{dt}\right| \ll H_{2m} - H_{1m}$

External conditions (density) change slowly the system has time to adjust them

transitions between the neutrino eigenstates can be neglected

$\nu_{1m} \not\leftrightarrow \nu_{2m}$ → The eigenstates propagate independently

Shape factors of the eigenstates do not change

Crucial in the resonance layer:
- the mixing changes fast
- level splitting is minimal

Adiabaticity condition $\Delta r_R > l_R$ if vacuum mixing is small

$\Delta r_R = n_R \tan 2\theta / (dn/dx)_R$

width of the resonance layer

$l_R = l_\nu / \sin 2\theta$

oscillation length in resonance

Adiabatic parameter

$$\gamma = \frac{\left|\frac{d\theta_m}{dt}\right|}{H_{2m} - H_{1m}}$$

Adiabaticity condition:
$\gamma << 1$

most crucial in the resonance where
the mixing angle in matter changes fast

$$\gamma_R = \frac{l_R}{2\pi\,\Delta r_R}$$

$\Delta r_R = h_n \tan 2\theta$ is the width of the resonance layer

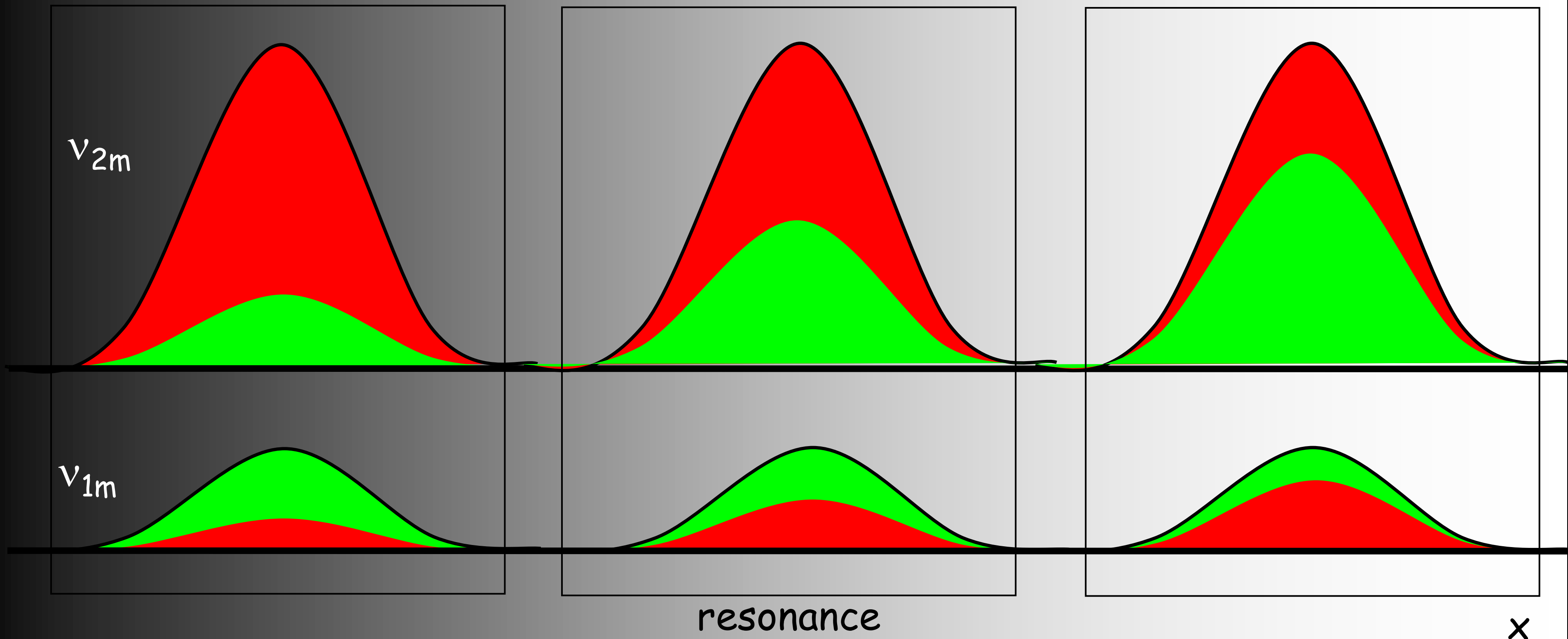
$h_n = \frac{n}{dn/dx}$ is the scale of density change

$l_R = l_\nu / \sin 2\theta$ is the oscillation length in resonance

Explicitly:

$$\gamma_R = \frac{4\pi E \cos 2\theta}{\Delta m^2 \sin^2 2\theta\; h_n}$$

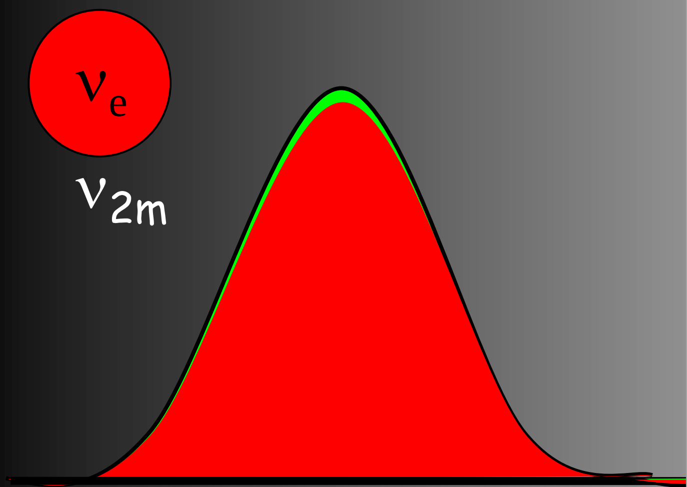
Adiabatic conversion



if density changes slowly

- the amplitudes of the wave packets do not change
-flavors of the eigenstates being determined by mixing angle follow the density change

Non-oscillatory transition

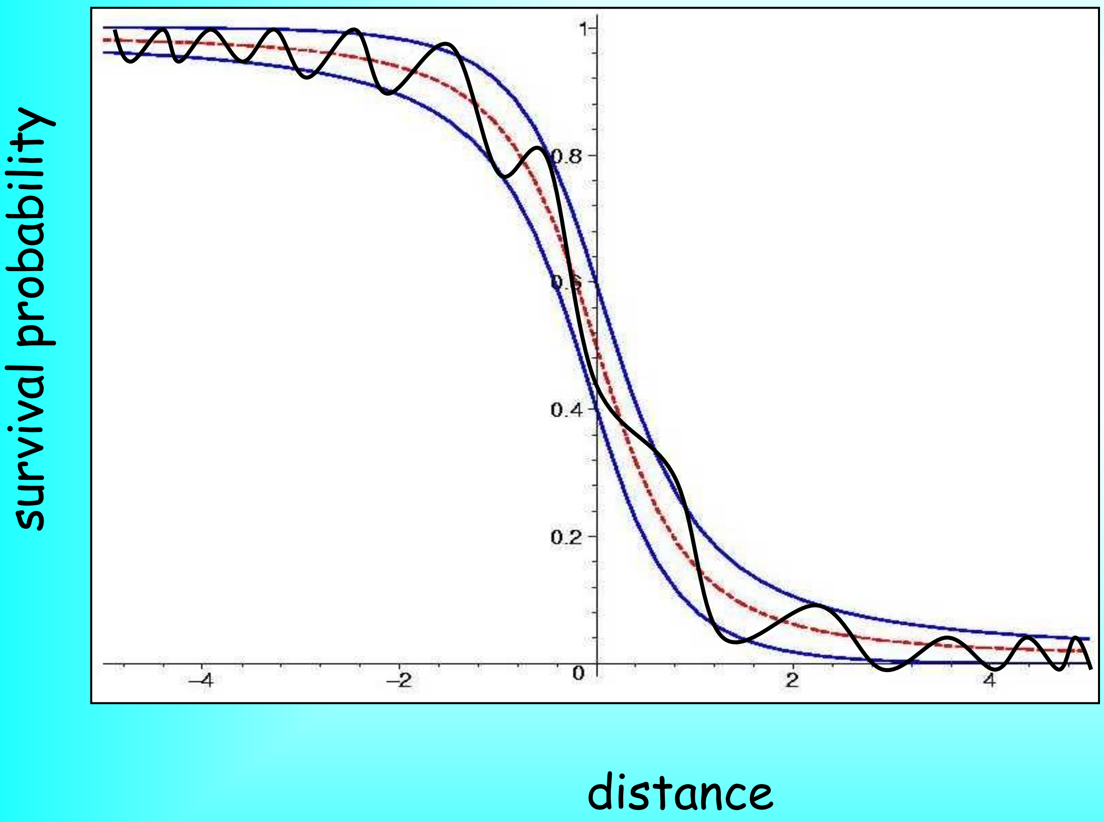


Single eigenstate:
→ no interference
→ no oscillations
→ phase is irrelevant

This happens when mixing is very small in matter with very high density

Spatial picture

Adiabatic conversion

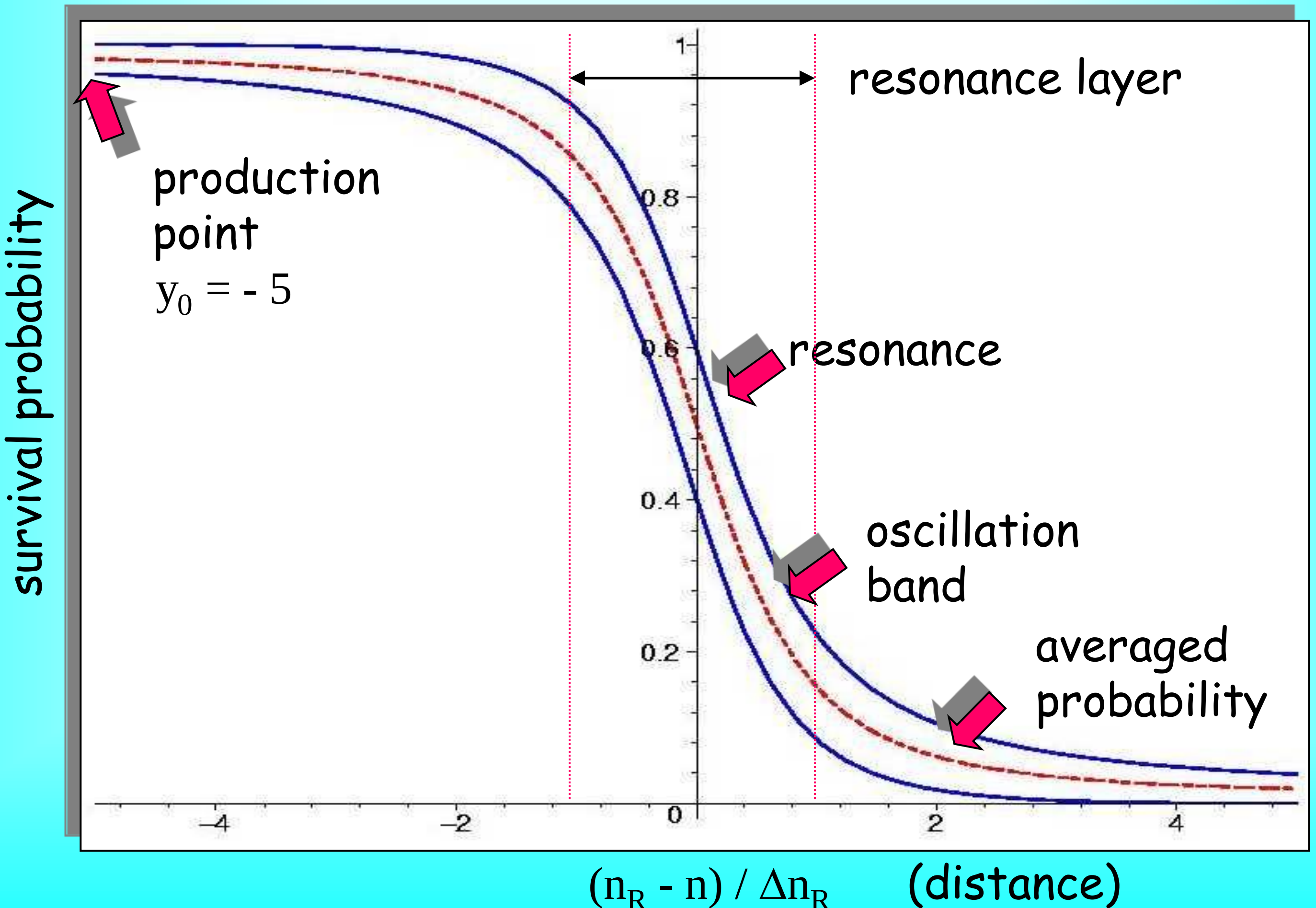


interplay of adiabatic conversion and oscillations

Non-oscillatory transition is modulated by oscillations

Spatial picture

The picture is universal in terms of variable $y = (n_R - n) / \Delta n_R$
no explicit dependence on oscillation parameters, density distribution, etc.
only initial value y_0 matters



A Yu Smirnov

Adiabatic conversion probability

Sun, Supernova

Initial state: $\nu(0) = \nu_e = \cos\theta_m^0\, \nu_{1m}(0) + \sin\theta_m^0\, \nu_{2m}(0)$

Mixing angle in matter in production point

Adiabatic evolution to the surface of the Sun (zero density):

$\nu_{1m}(0) \rightarrow \nu_1$

$\nu_{2m}(0) \rightarrow \nu_2$

Final state: $\nu(f) = \cos\theta_m^0\, \nu_1 + \sin\theta_m^0\, \nu_2\, e^{i\phi}$

Probability to find ν_e averaged over oscillations

$$P_{ee} = |\langle\nu_e|\nu(f)\rangle|^2 = (\cos\theta \cos\theta_m^0)^2 + (\sin\theta \sin\theta_m^0)^2$$

$$= 0.5[\, 1 + \cos 2\theta_m^0 \cos 2\theta \,]$$

or $$P_{ee} = \sin^2\theta + \cos 2\theta \cos^2\theta_m^0$$

Adiabaticity violation

SN shock waves

If sterile neutrinos with small mixing exist

If density $n_e(t)$ changes fast $\left|\frac{d\theta_m}{dt}\right| \sim |H_{2m} - H_{1m}|$

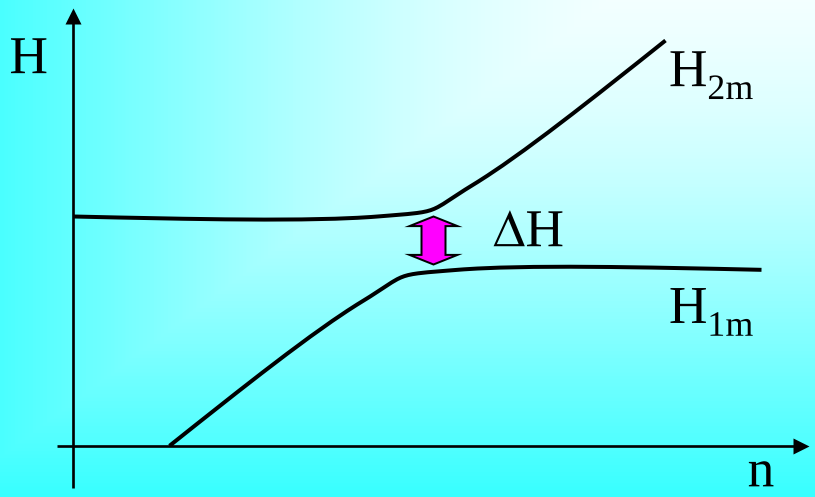
the off-diagonal terms in the Hamiltonian can not be neglected

transitions $\nu_{1m} \Leftrightarrow \nu_{2m}$

Admixtures of ν_{1m} ν_{2m} in a given propagating neutrino state change

``Jump probability" = penetration under barrier:

$$P_{12} = e^{-\frac{\Delta H}{E_n}}$$



$E_n = d\theta_m/dt \sim 1/h_n$

is the energy associated to change of density

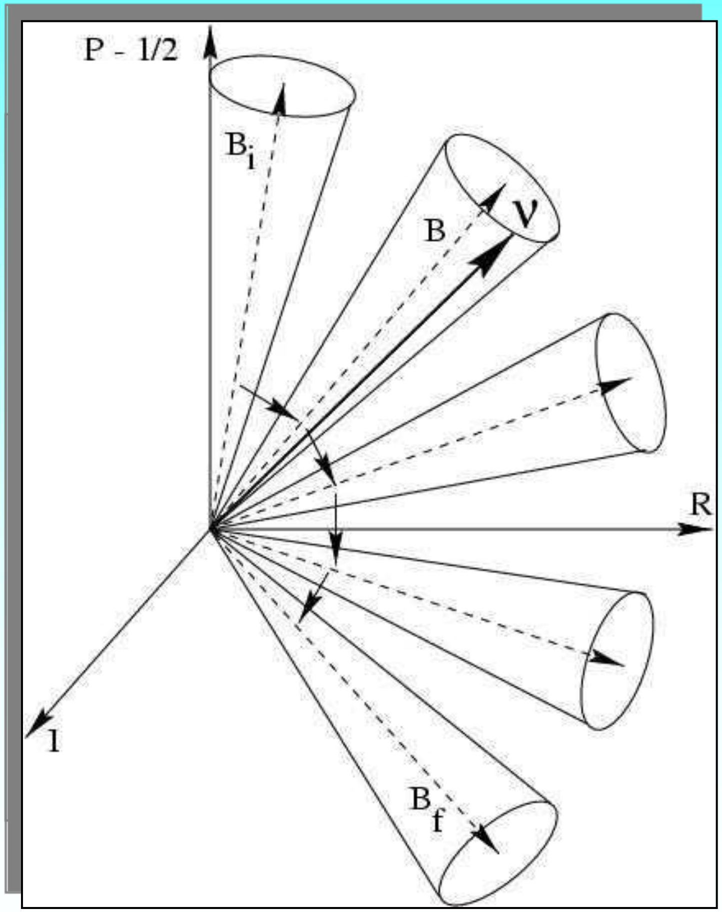
$$P_{12} = e^{-2\pi/\gamma_R}$$

Landau-Zenner

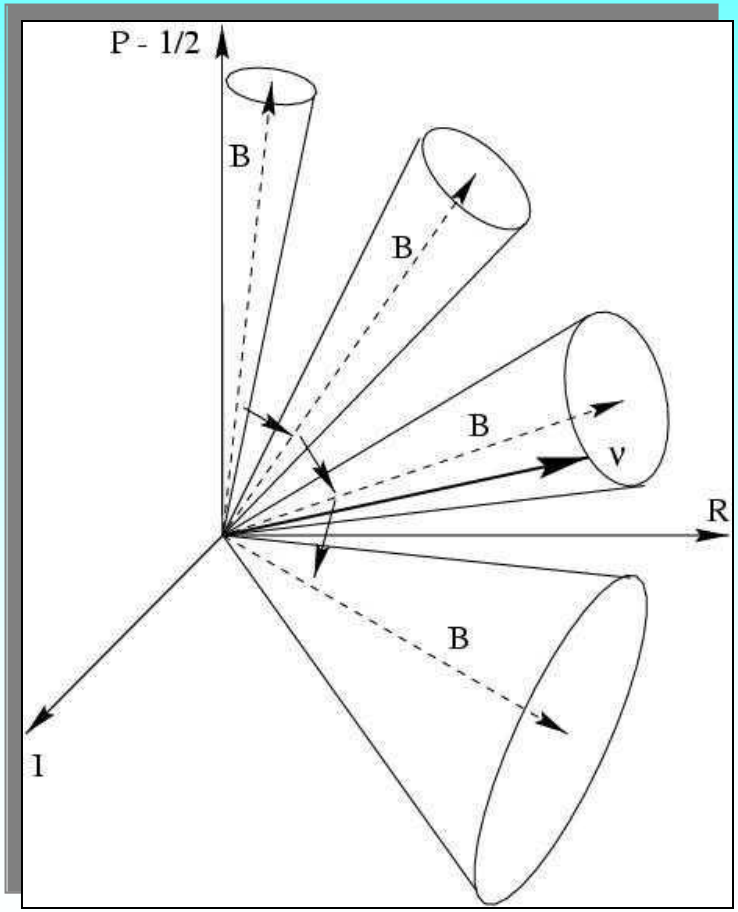
γ_R - adiabaticity parameter

Adiabatic conversion

Pure adiabatic conversion



Partialy adiabatic conversion



Oscillations versus adiabatic conversion

Different degrees of freedom

Oscillations

Vacuum or uniform medium with constant parameters

Phase difference increase between the eigenstates

$\phi(t)$

Mixing does not change

$\theta_m(E)$

Adiabatic conversion

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

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

$\theta_m(t)$

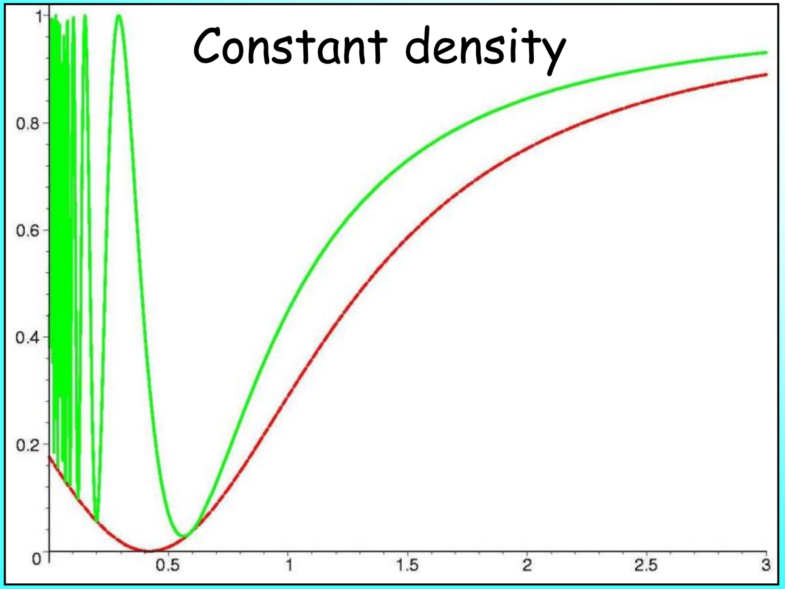
Phase is irrelevant

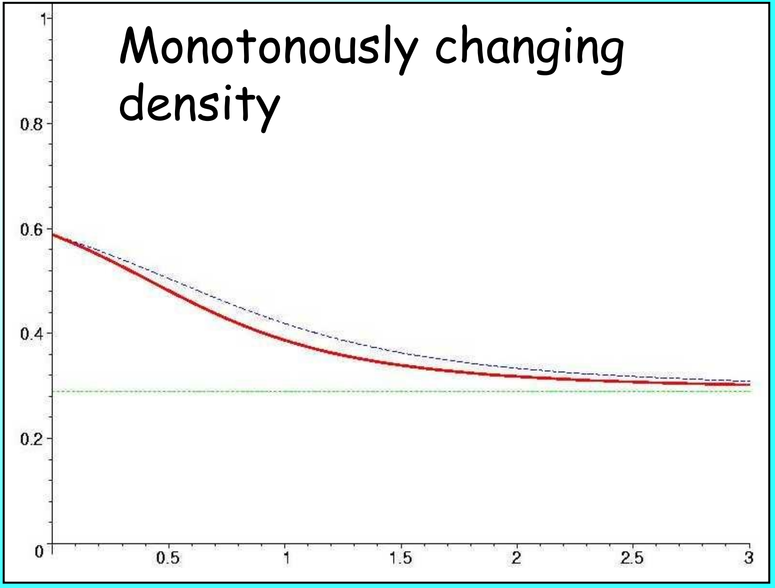
In non-uniform medium: interplay of both processes

Resonance oscillations vs. adiabatic conversion

Passing through the matter filter ν

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



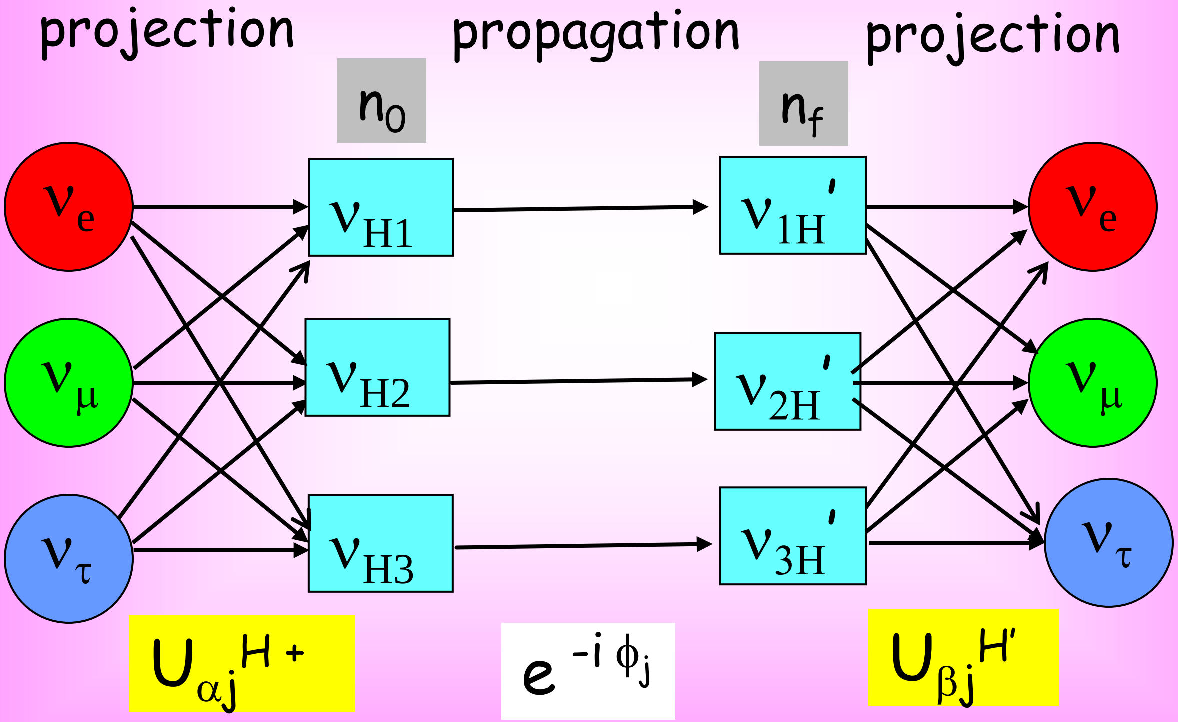


E/E_R

E/E_R

3ν – oscillations

Adiabatic conversion

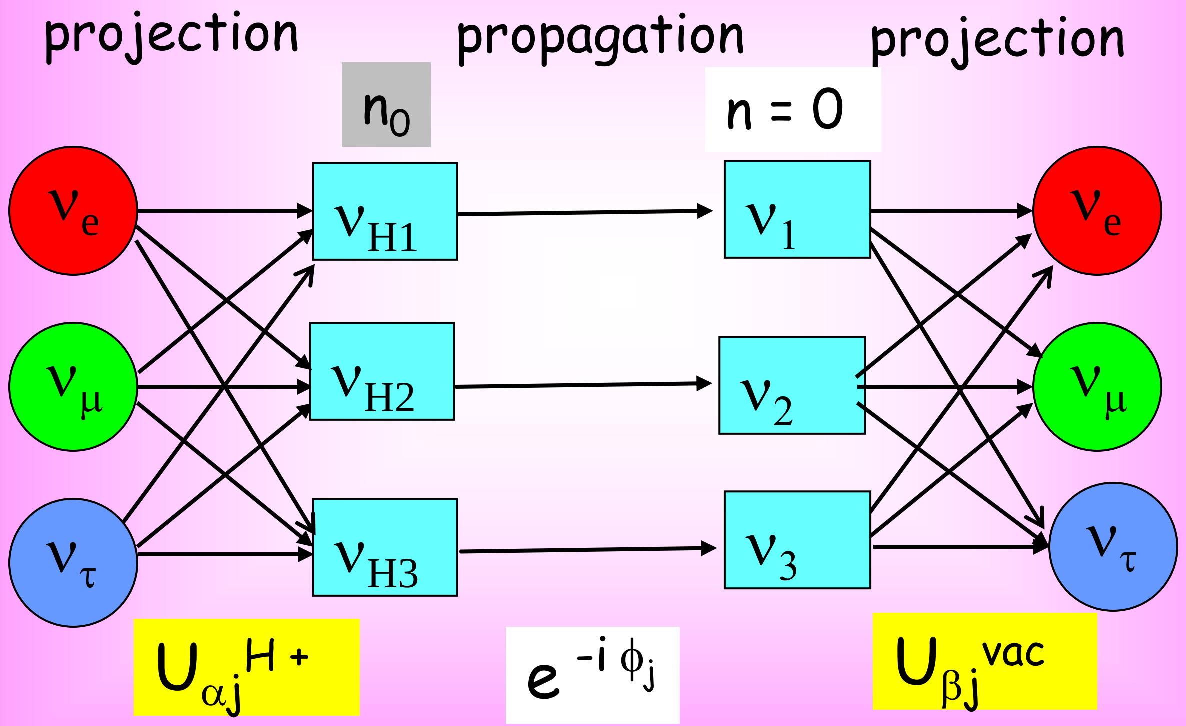


$$P(\nu_\alpha \rightarrow \nu_\beta) = |\Sigma_j U_{\beta j}^{H'} e^{-i\phi_j} U_{\alpha j}^{H+}|^2$$

3ν – oscillations

Adiabatic conversion

Sun, SN



$$P(\nu_\alpha \rightarrow \nu_\beta) = |\Sigma_j U_{\beta j}^{vac} e^{-i\phi_j} U_{\alpha j}^{H+}|^2$$

Parametric effects

Propagation on the Earth

Parametric enhancement

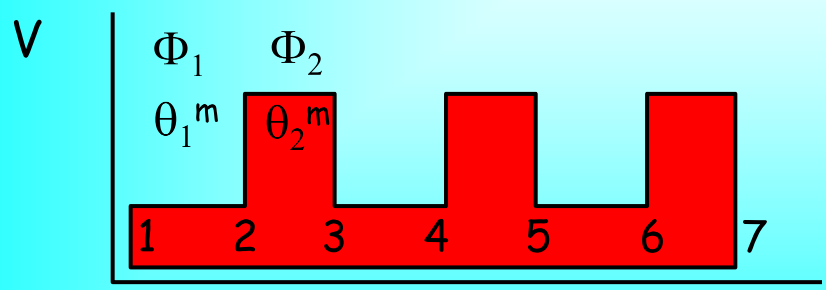
of oscillations

Enhancement associated to certain conditions for the phase of oscillations

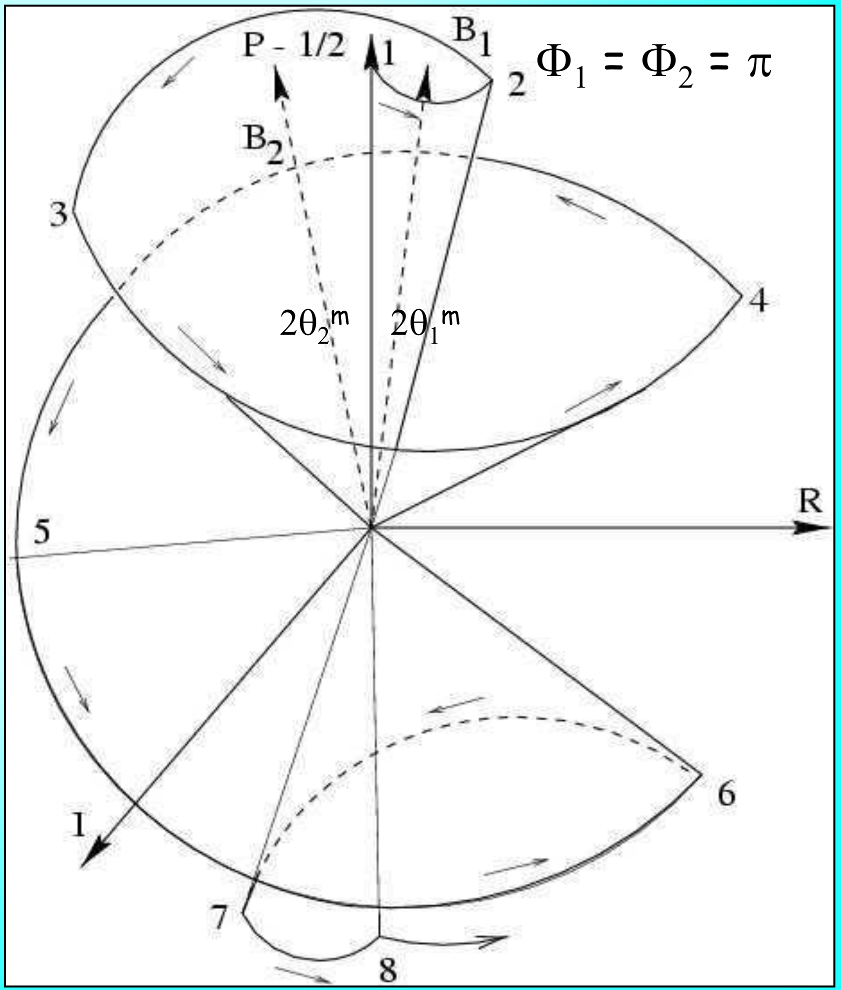
Another way of getting strong transition

No large vacuum mixing and no matter enhancement of mixing or resonance conversion

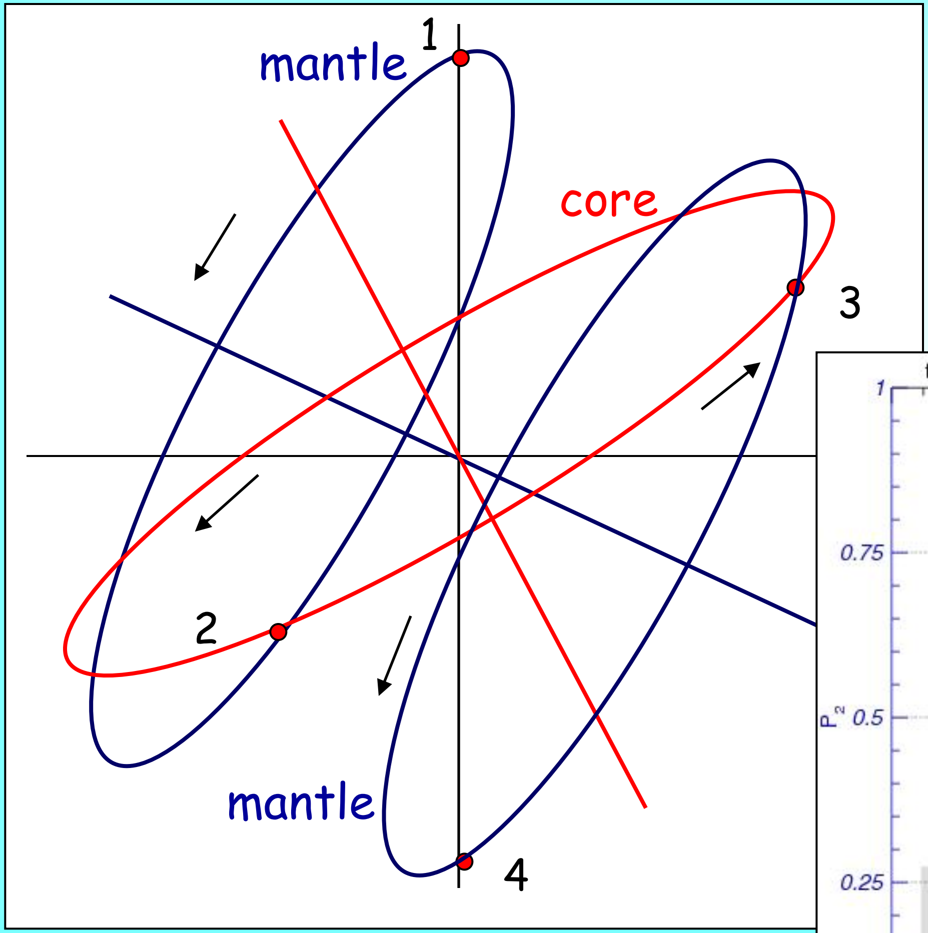
V. Ermilova V. Tsarev, V. Chechin
E. Akhmedov
P. Krastev, A.S., Q. Y. Liu,
S.T. Petcov, M. Chizhov

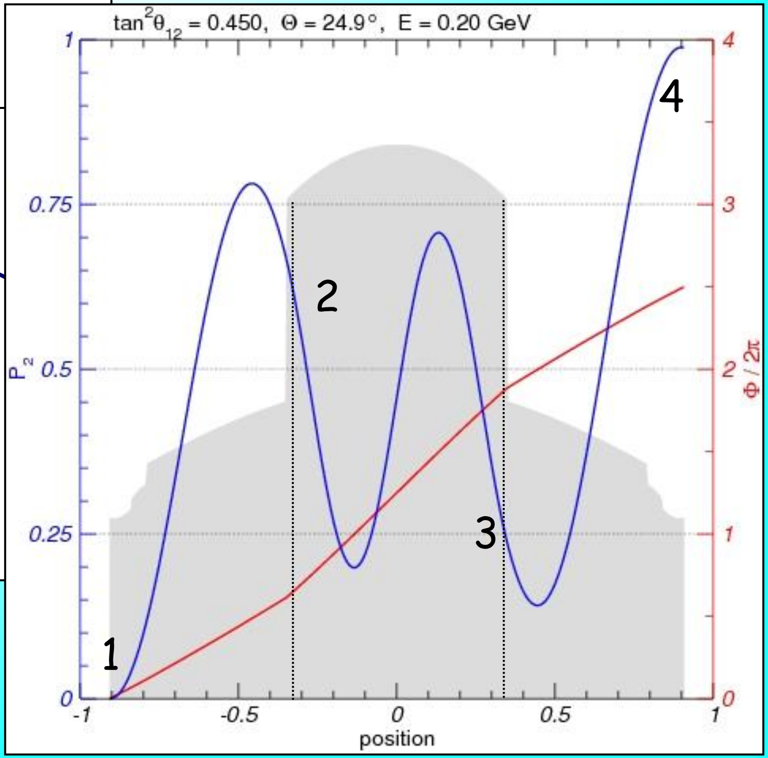


``Castle wall profile"

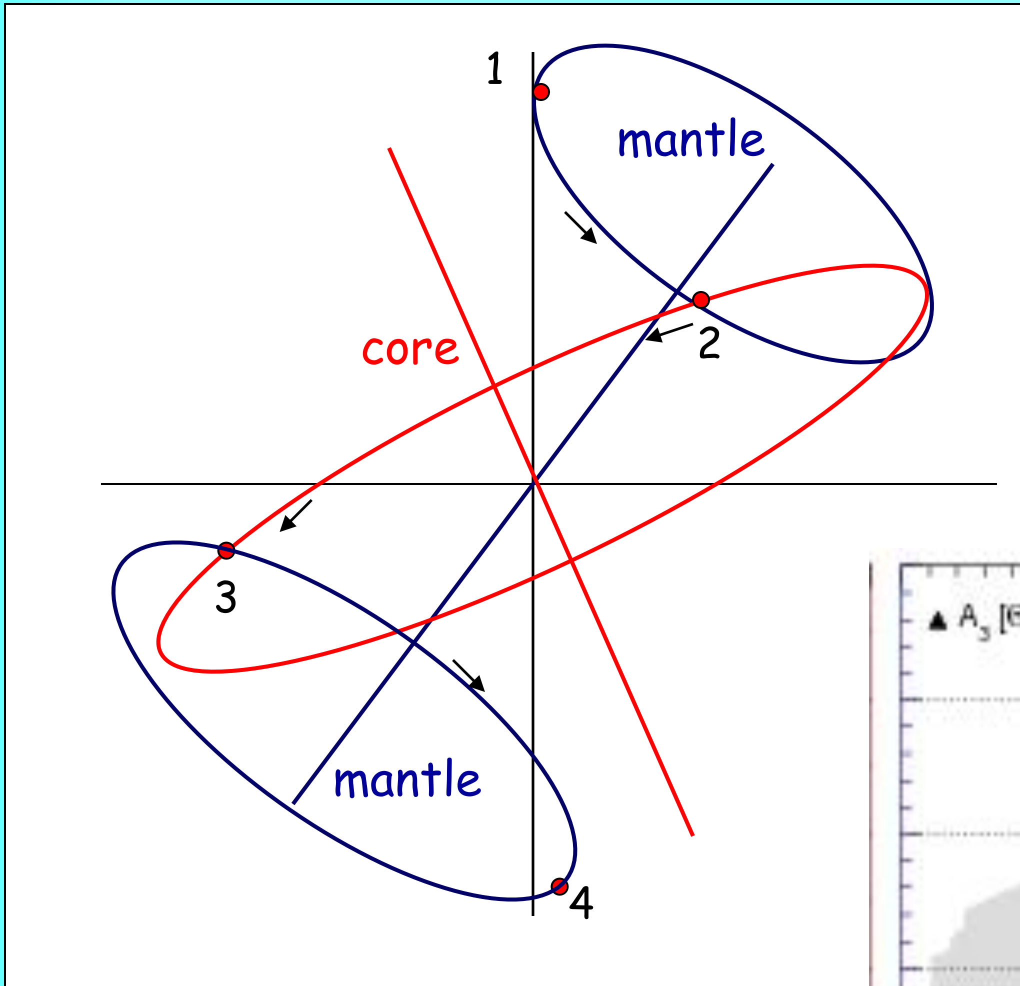


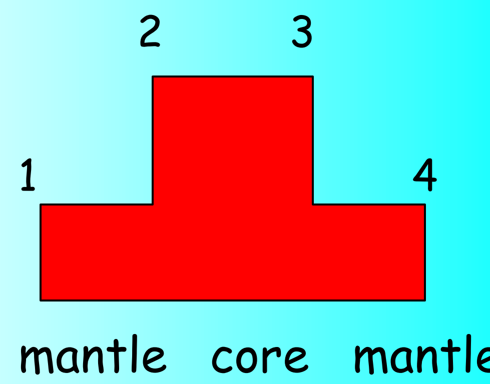
Parametric enhancement of 1-2 mode

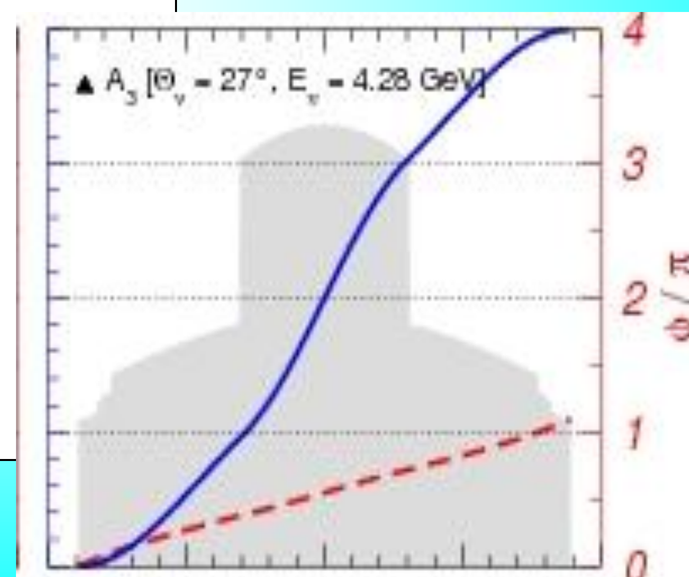




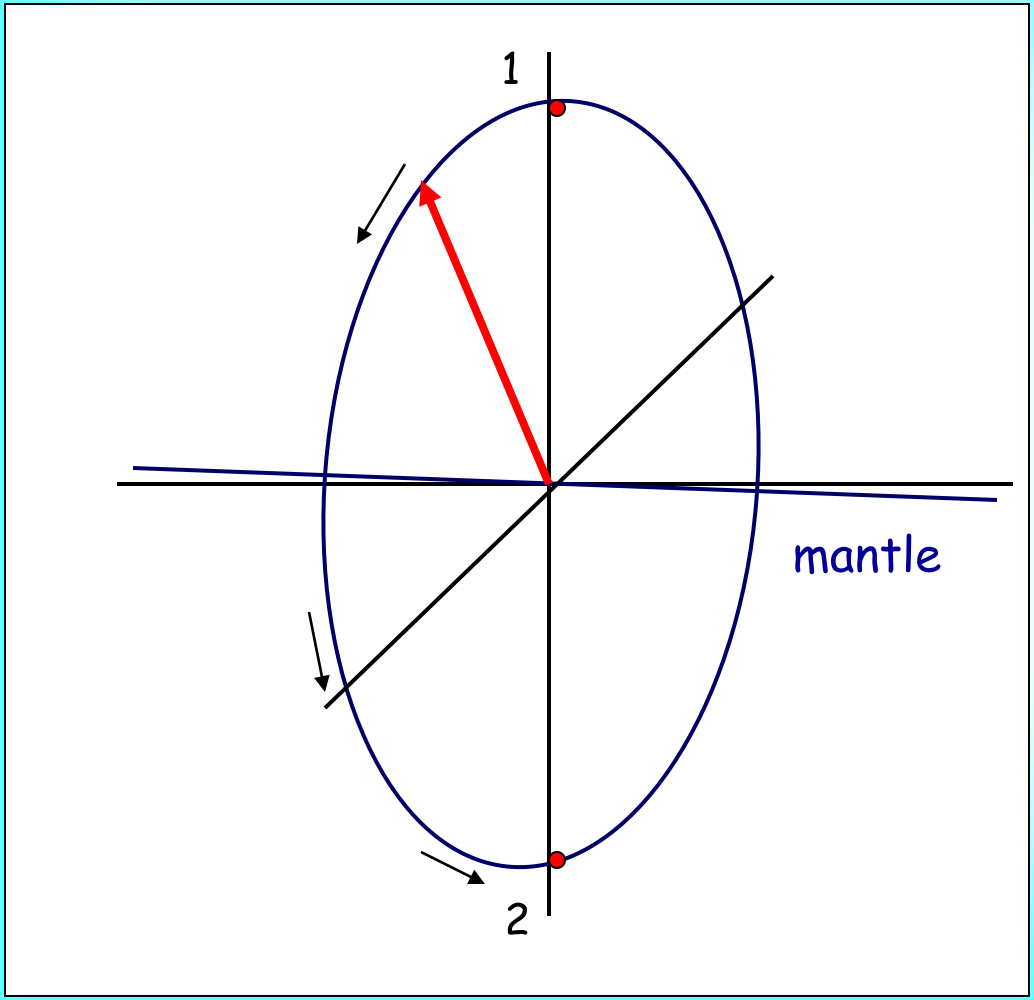
Parametric enhancement

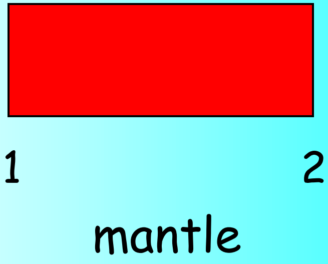




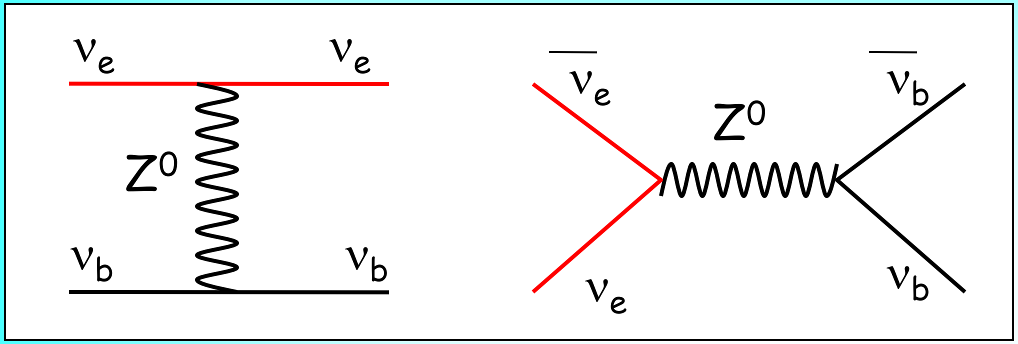


Resonance enhancement in mantle





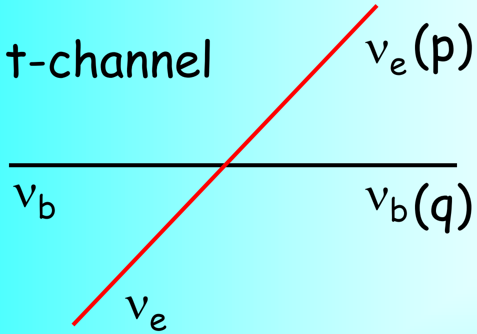
$\nu\nu$-scattering



Refraction in neutrino gases

$$A = \sqrt{2}\, G_F (1 - v_e v_b)$$

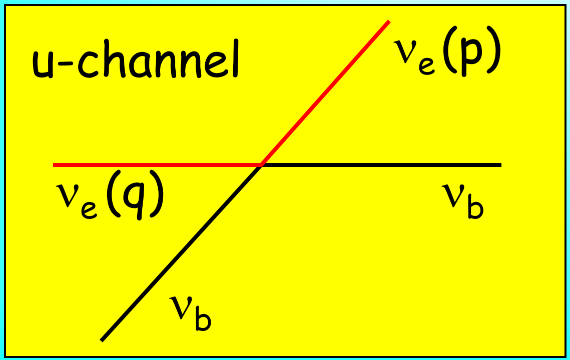
velocities



ν_e

elastic forward scattering

J. Pantaleone



can lead to the coherent effect

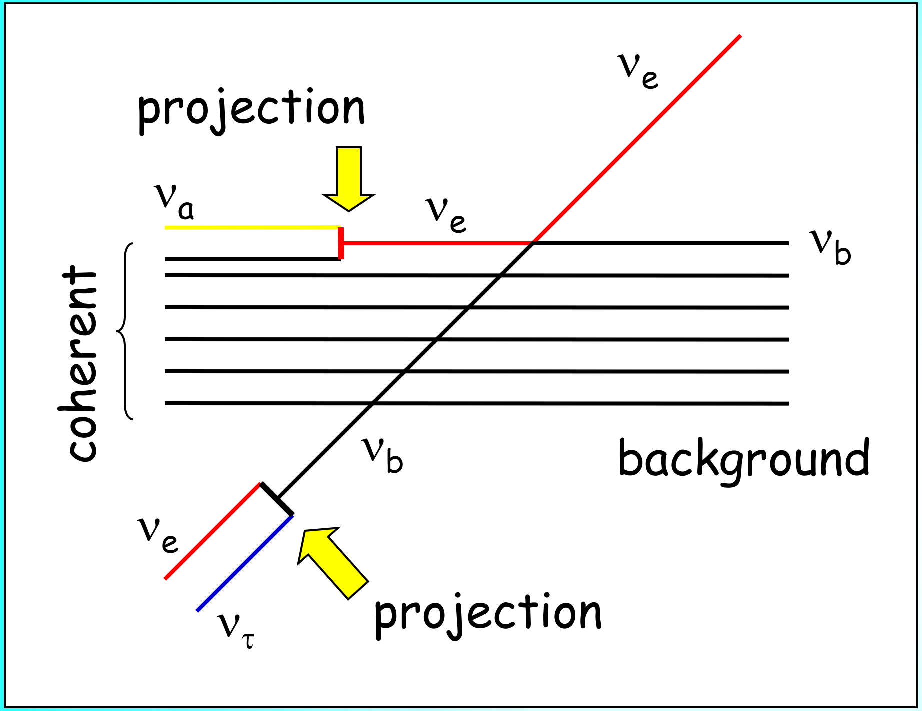
Momentum exchange → flavor exchange

→ flavor mixing

Collective flavor transformations

Flavor exchange

J. Pantaleone
S. Samuel
V.A. Kostelecky



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

1. Momentum exchange → flavor exchange

2. Coherence if the background is in mixed state:

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

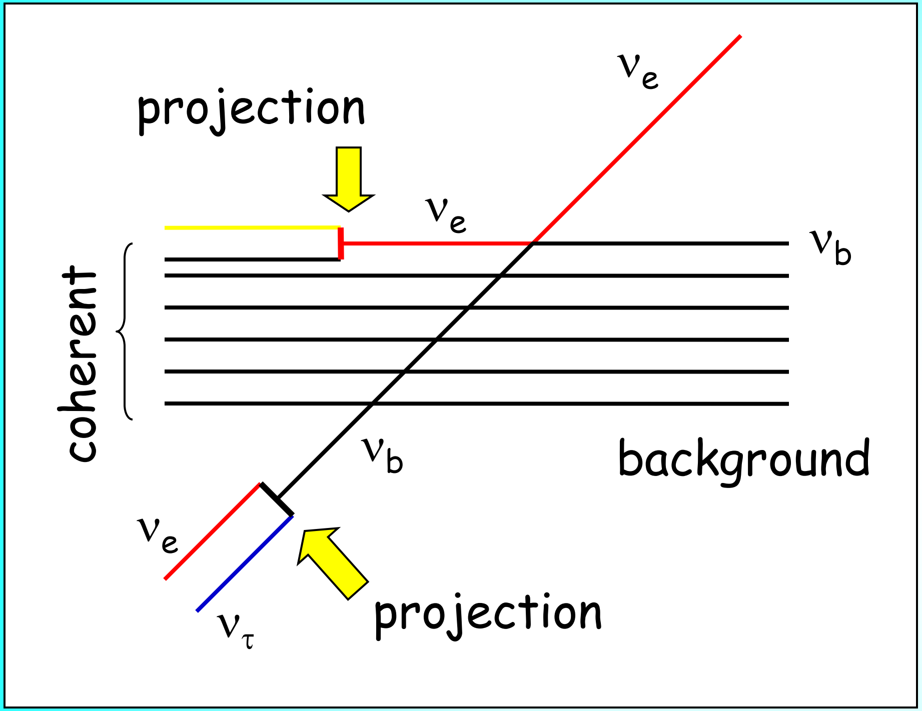
Coherent flavor changing transition

Probe neutrino = background neutrino

Potential depends on transition probability

Flavor exchange

J. Pantaleone
S. Samuel
V.A. Kostelecky



Flavor exchange between the beam (probe) and background neutrinos

If the background is in the mixed state:

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

$$B_{e\tau} \sim \Sigma_i\, \Phi_{ie}^*\Phi_{i\tau}$$

sum over particles of bg.
w.f. give projections

Contribution to the Hamiltonian in the flavor basis

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

Evolution equation

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

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

Negative frequencies for antineutrinos

Vacuum mixing term

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

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

Usual matter potential

$\mathbf{L} = (0,\ 0,\ 1)$

$\lambda = V = \sqrt{2}\, G_F\, n_e$

Collective vector

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

$\mu = \sqrt{2}\, G_F\, n_\nu\, (1 - \cos \theta_{\nu\nu})$

The term describes collective effects

Adiabaticity

Adiabaticity condition $\left| \frac{d\theta_m}{dt} \right| \ll H_{2m} - H_{1m}$

External conditions (density) change slowly the system has time to adjust them

transitions between the neutrino eigenstates can be neglected

$\nu_{1m} \not\leftrightarrow \nu_{2m}$ → The eigenstates propagate independently

Shape factors of the eigenstates do not change

Crucial in the resonance layer:
- the mixing changes fast
- level splitting is minimal

$\Delta r_R > l_R$ if vacuum mixing is small

$l_R = l_\nu / \sin 2\theta$ oscillation length in resonance

$\Delta r_R = n_R / (dn/dx)_R \tan 2\theta$ width of the res. layer

If vacuum mixing is large, the point of maximal adiabaticity violation is shifted to larger densities

$n(a.v.) \to n_R^0 > n_R$

$n_R^0 = \Delta m^2 / 2\sqrt{2}\, G_F E$

Solar neutrinos

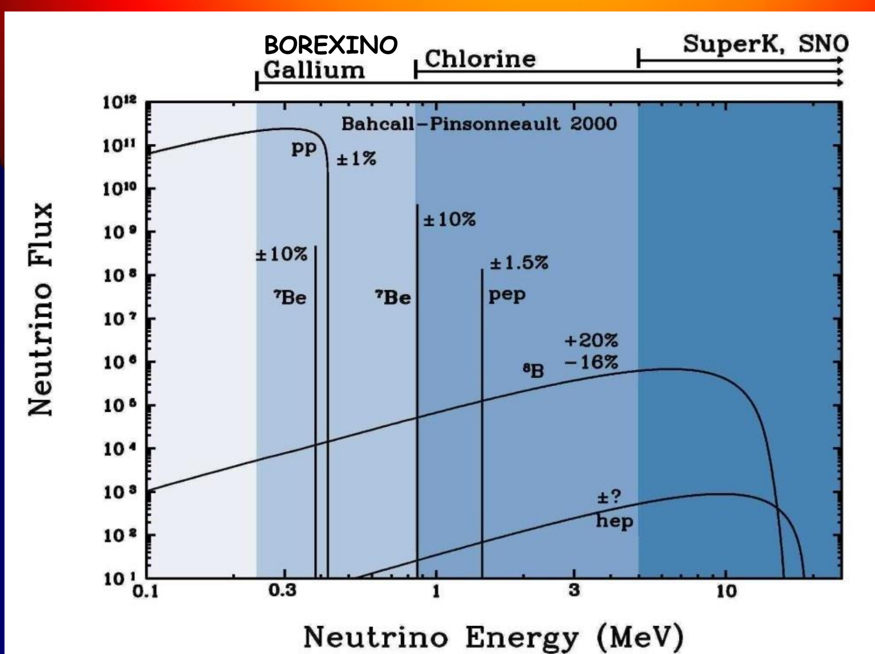
$4p + 2e^{-} \rightarrow {}^{4}He + 2\nu_e + 26.73$ MeV

Adiabatic conversion

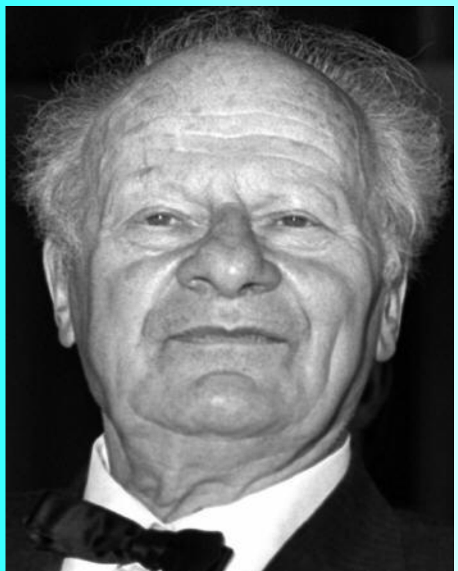
LMA MSW

ν

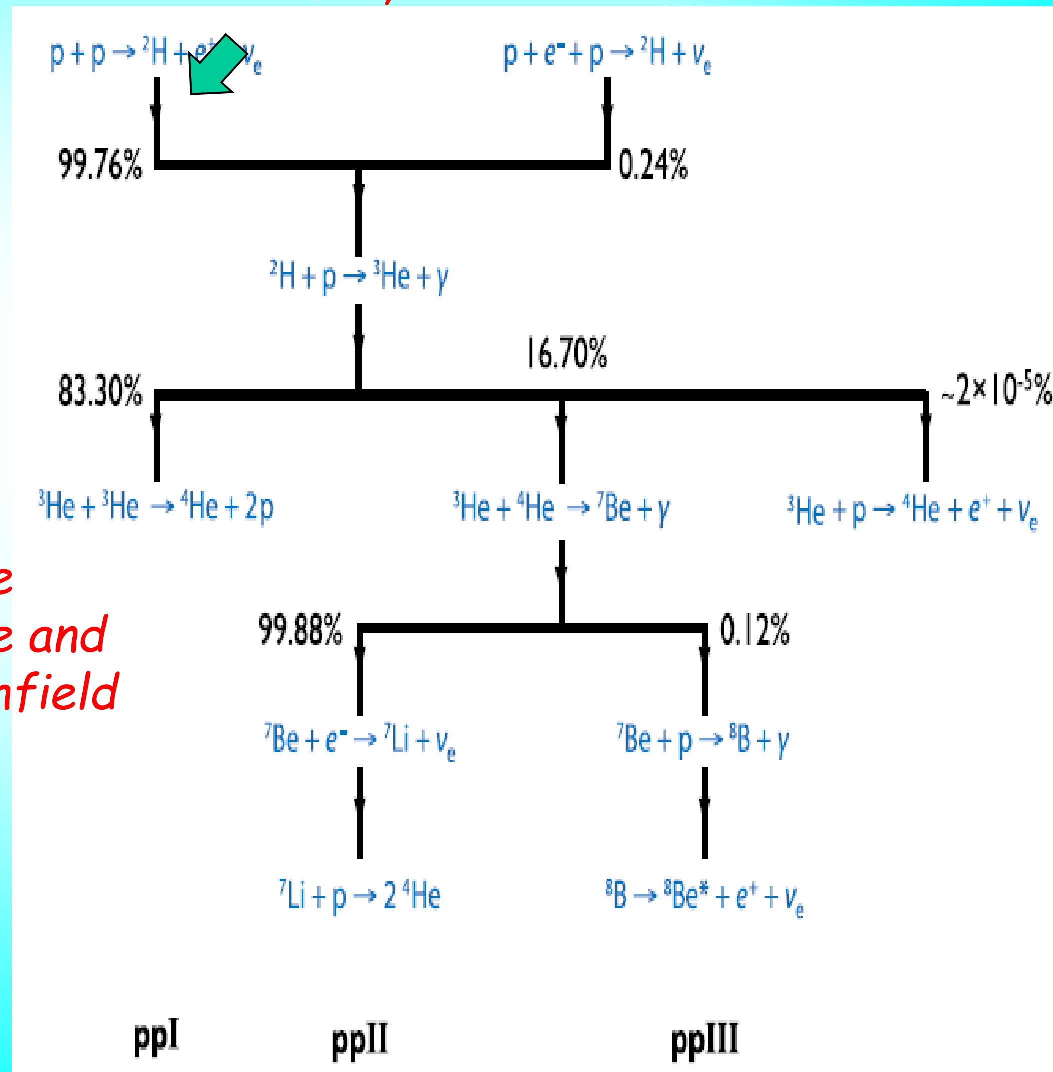
Oscillations in matter of the Earth

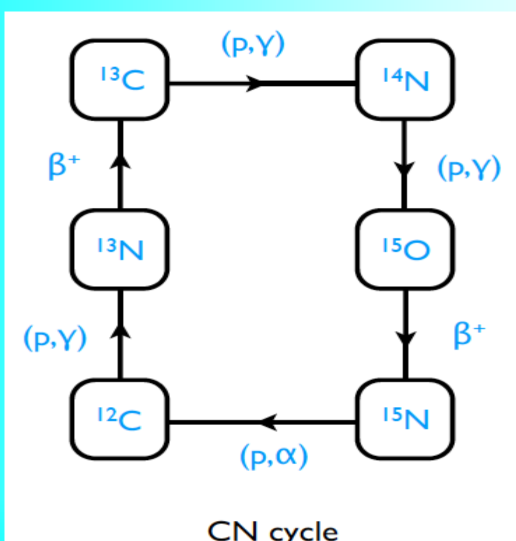


Solar chains and cycles



G. Gamov, V. Weizecker





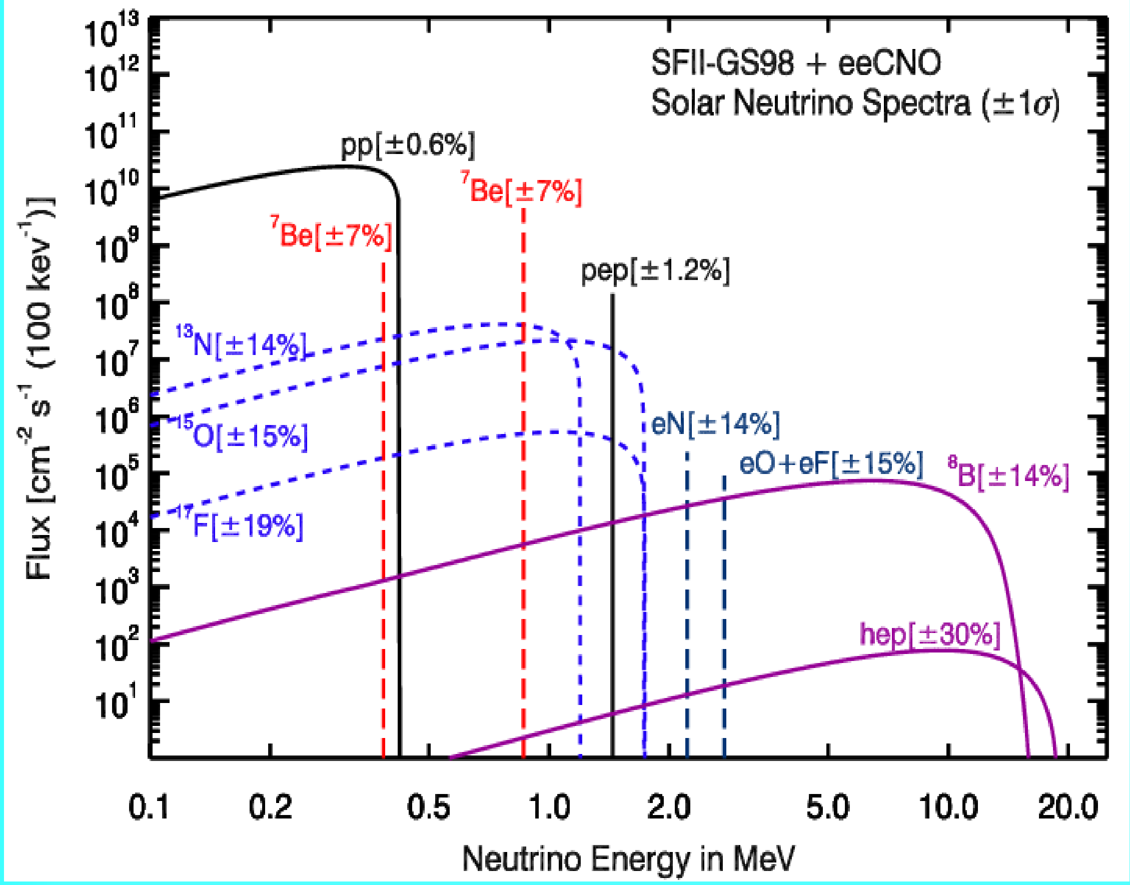
H. Bethe

H. Bethe and

C. Critchfield

Solar neutrino spectrum

A. Serenelly

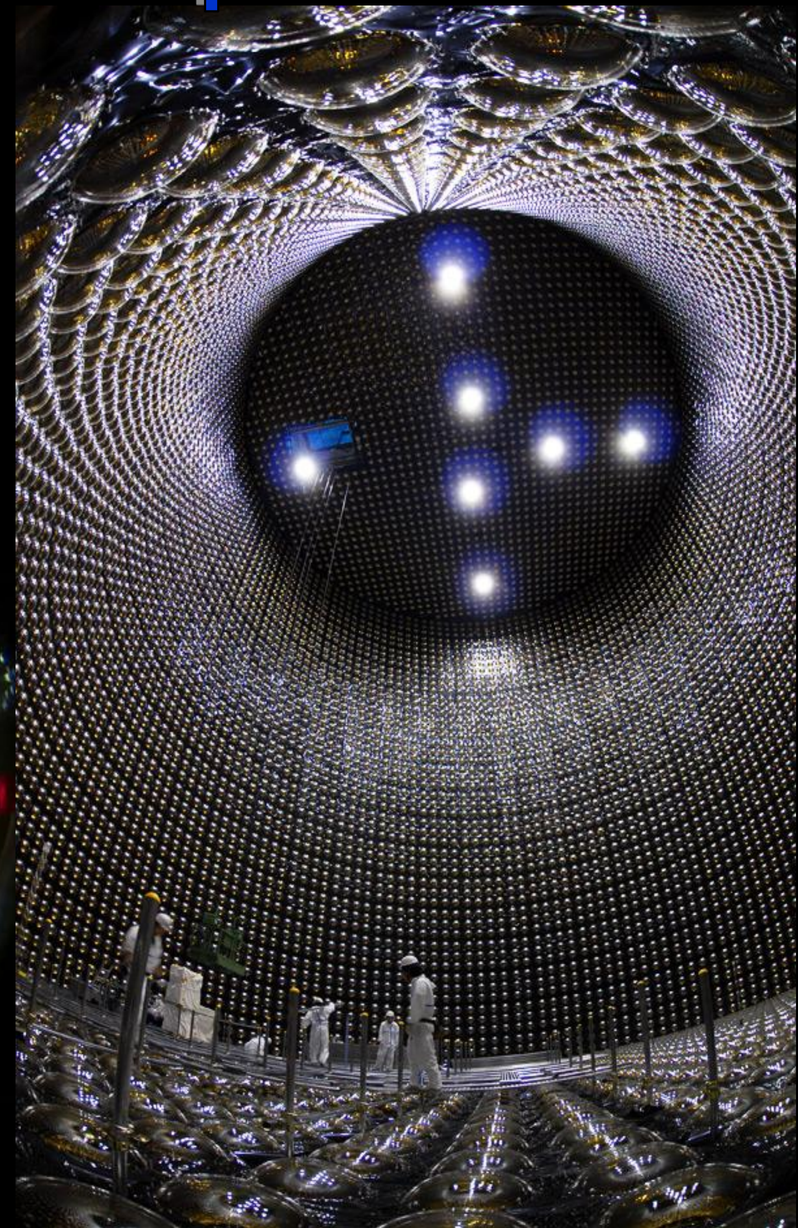


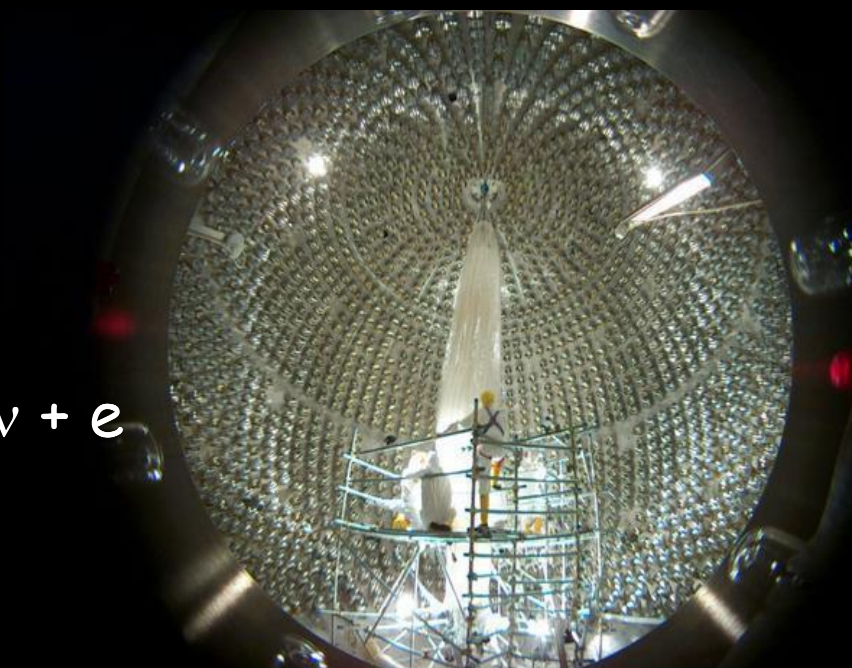
Branches
Terminations

Flux - Luminosity relation and normalization of neutrino flux

Solar neutrinos
Now & in future

SuperKamiokande



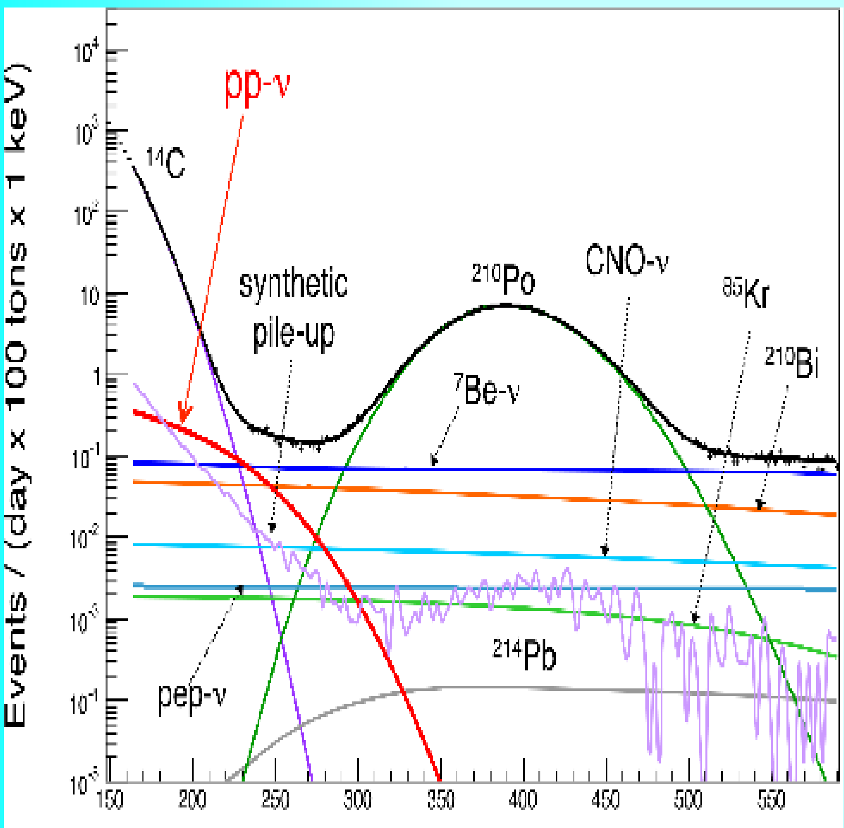


$\nu + e \rightarrow \nu + e$

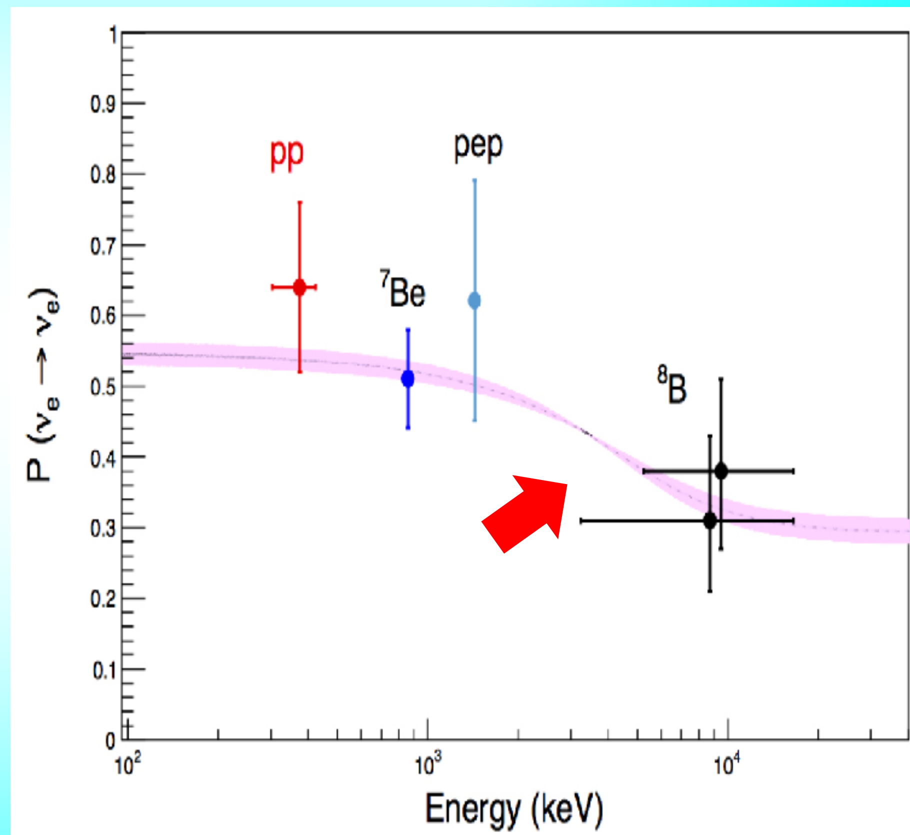
BOREXINO

Solar pp-neutrinos

Neutrinos from the primary pp-reactions in the Sun
BOREXINO Collaboration
(G. Bellini et al.)
***Nature* 512 (2014) 7515, 383**



Energy (keV)

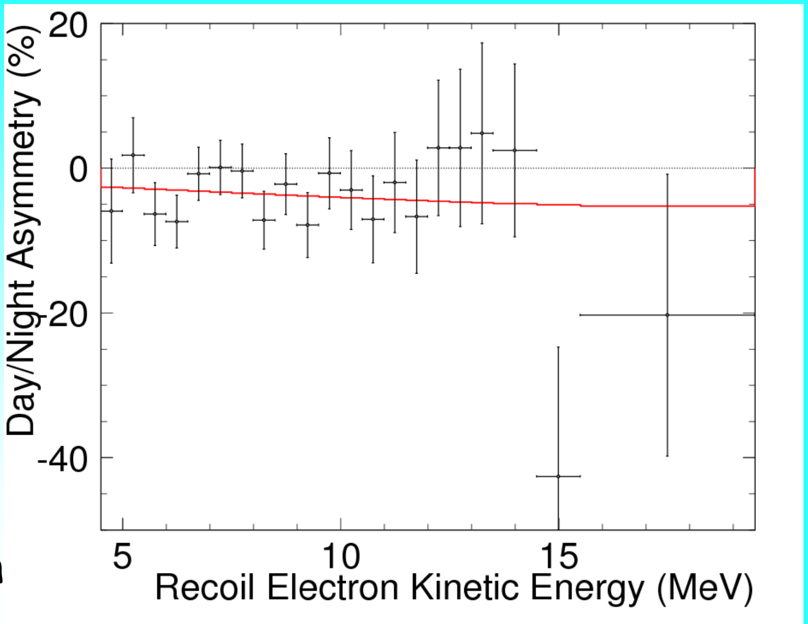


$$\cos^4\theta_{13}\left(1 - \tfrac{1}{2}\sin^2 2\theta_{12}\right) + \sin^4\theta_{13}$$

Day-Night effect

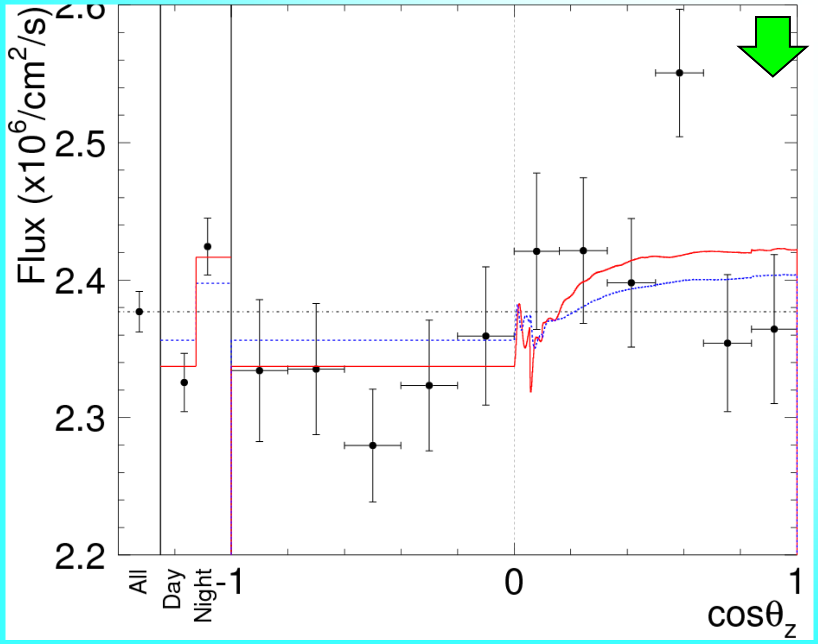
First Indication of Terrestrial Matter Effects on Solar Neutrino Oscillation

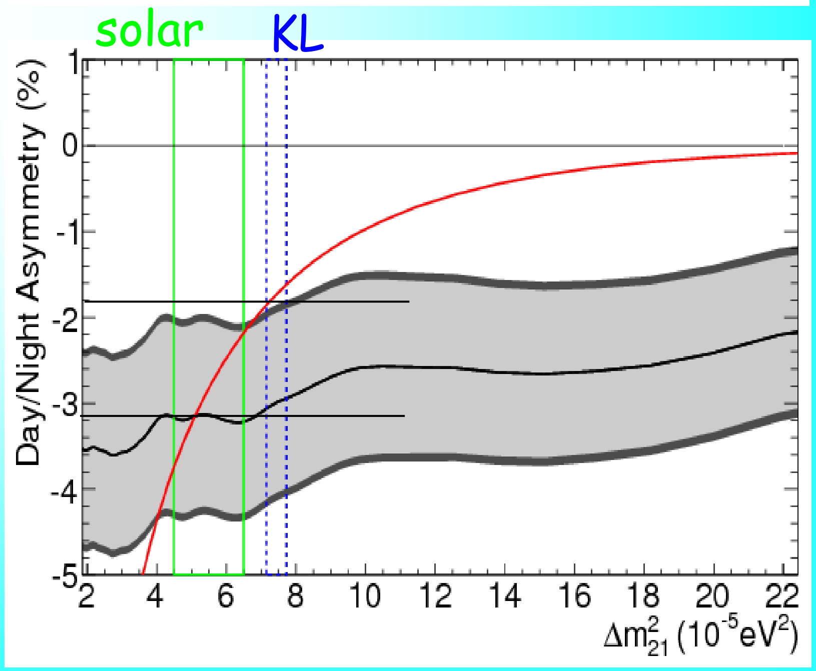
Super-Kamiokande collaboration
(Renshaw, A. et al.)
Phys.Rev.Lett. 112 (2014) 091805
arXiv:1312.5176



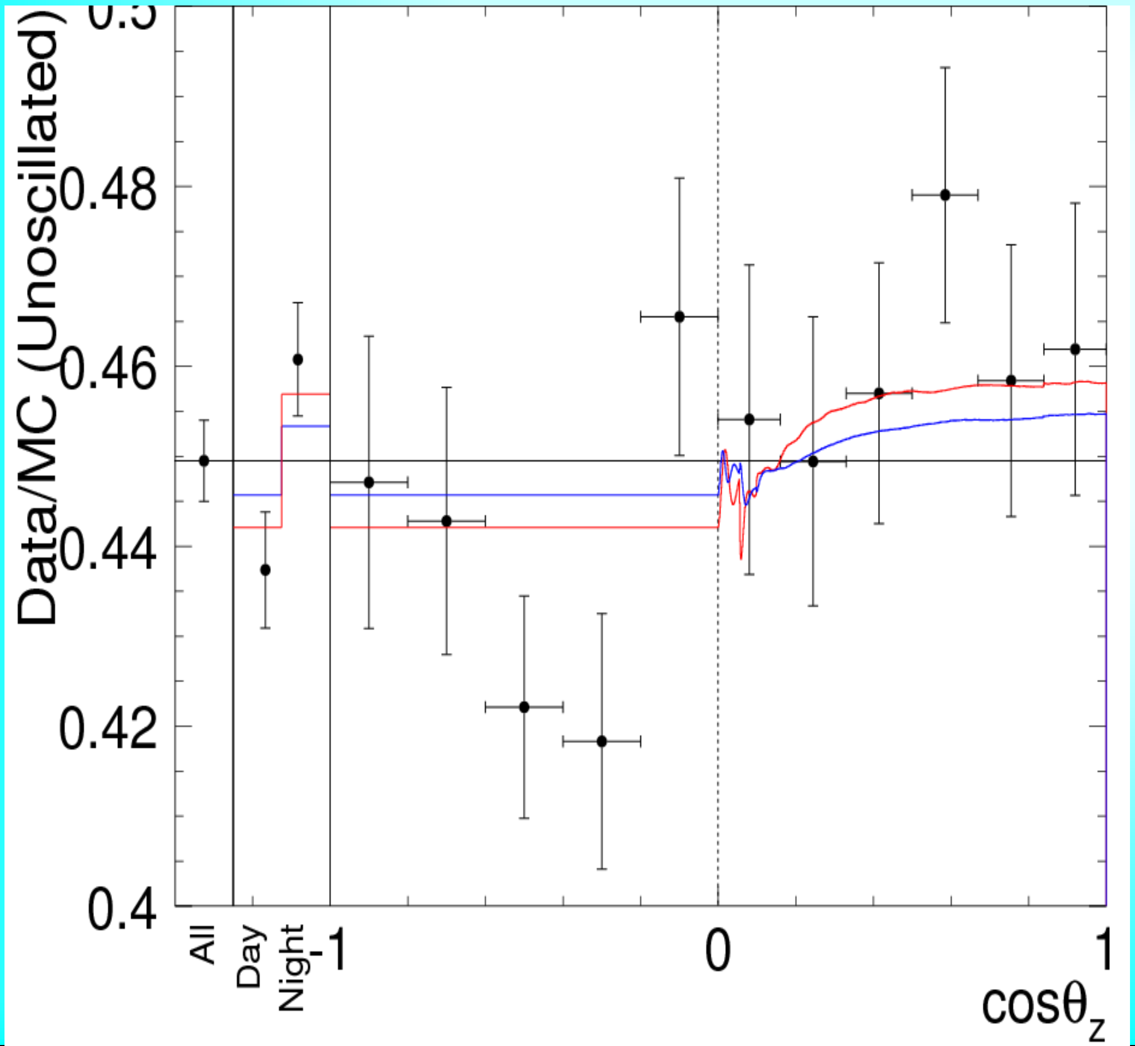
> 3 σ

Attenuation effect





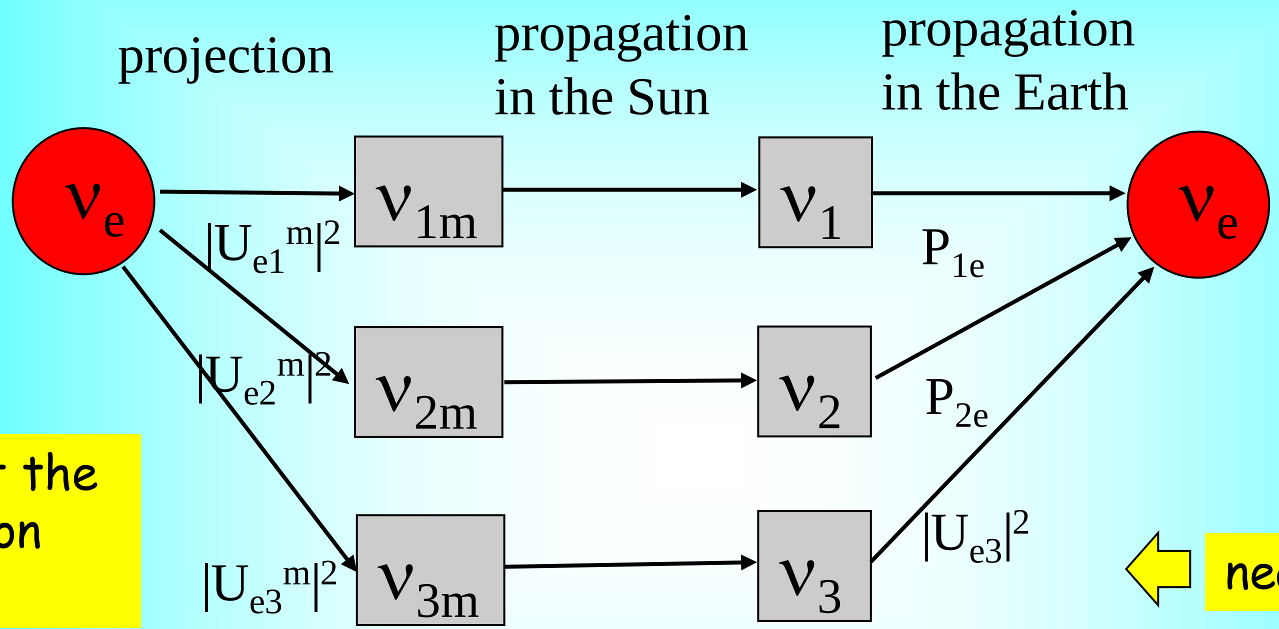
Day-Night asymmetry



SK-IV solar zenith angle dependence of the solar neutrino data/MC (unoscillated) interaction rate ratio (4.49-19.5 MeV). Red (blue) lines are predictions when using the solar neutrino data (solar neutrino data+KamLAND) best-fit oscillation parameters. The error bars are statistical uncertainties only.

Scheme of transitions

and between the Sun and the Earth



mixing at the production point n_0

adiabatic conversion

oscillations in multi-layer medium

nearly decouples

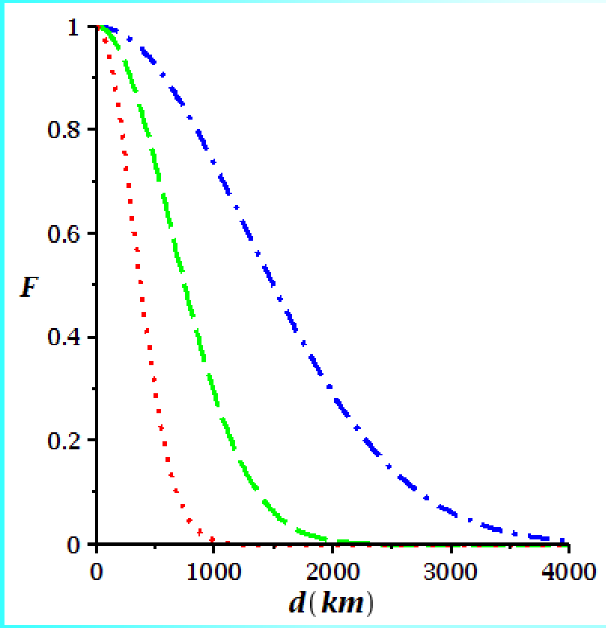
$$P_{ee} = \Sigma_i | U_{ei}^m(n_0)|^2 P_{ie}$$

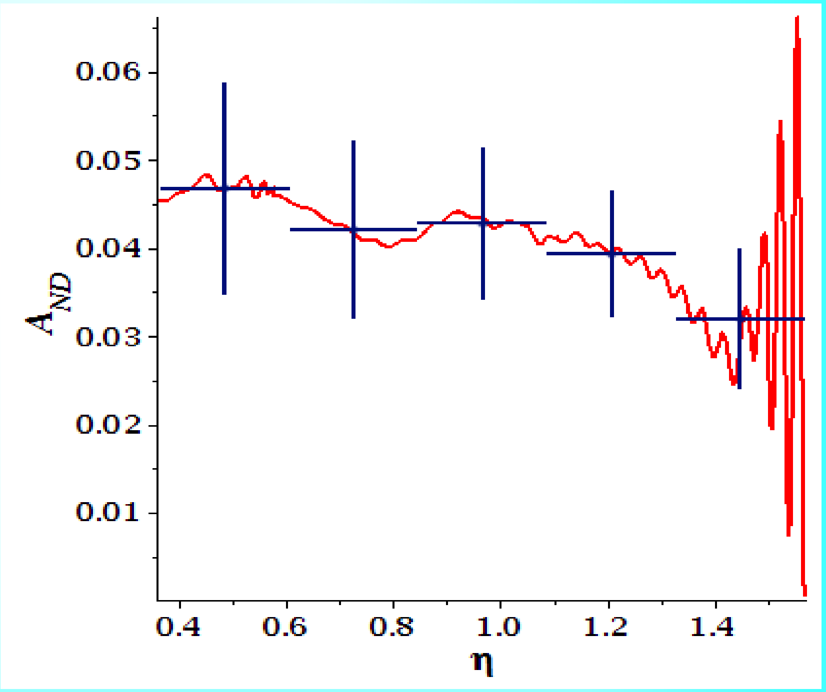
during the day $P_{ie} = | U_{ei}|^2$ scale invariant

Scanning the Earth with solar neutrinos

SNO+

A. Ioannisian, A.Y.S., D. Wyler
1702.06097 [hep-ph]





Attenuation factor for different energy resolutions

Relative excess of the night events Integrated over E > 11 MeV

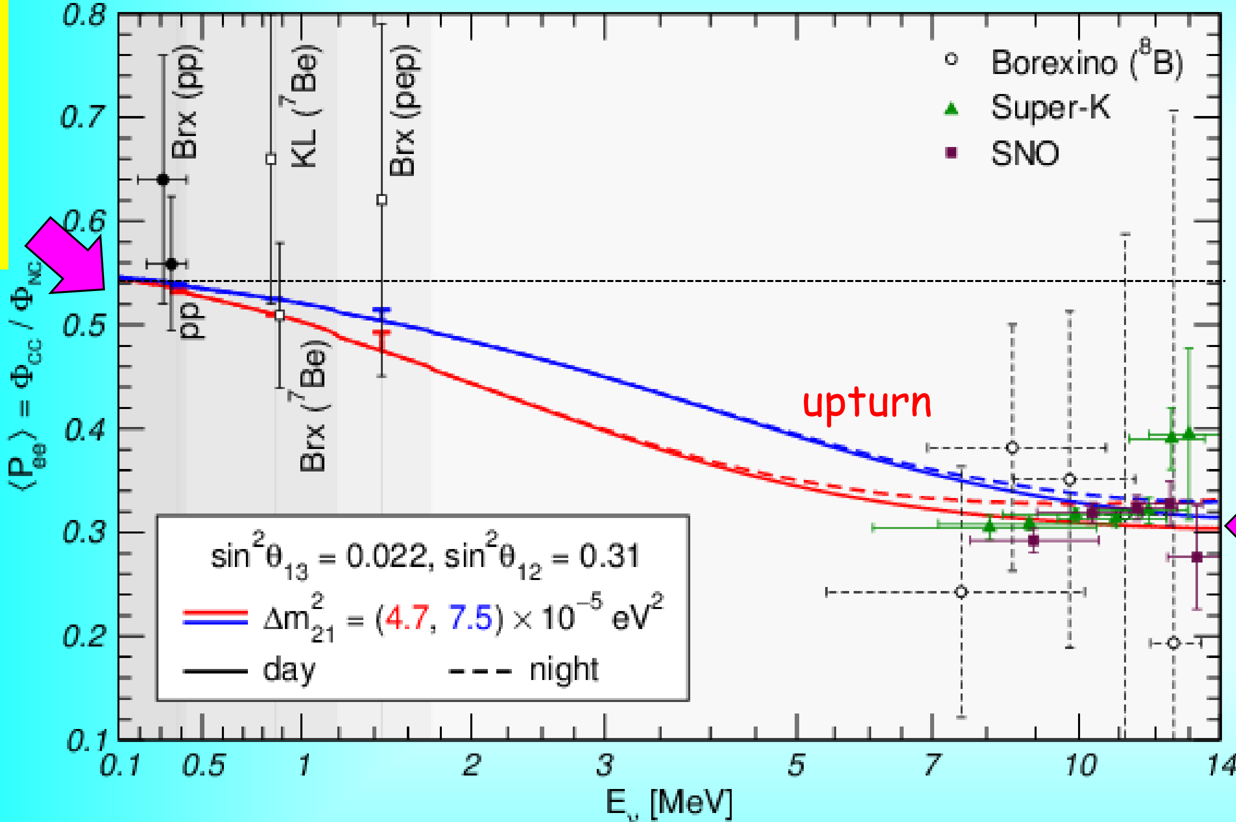
Attenuation effect

Consequence of finite energy resolution /reconstruction function

Solar neutrinos and LMA MSW

M. Maltoni, A.Y.S.
1507.05287 [hep-ph]

$1 - 0.5 \sin^2 2\theta_{12}$



LMA MSW predicion for two different values of Δm_{21}^2

best fit value from solar data

best global fit

$\sin^2 \theta_{12}$

Vacuum dominated

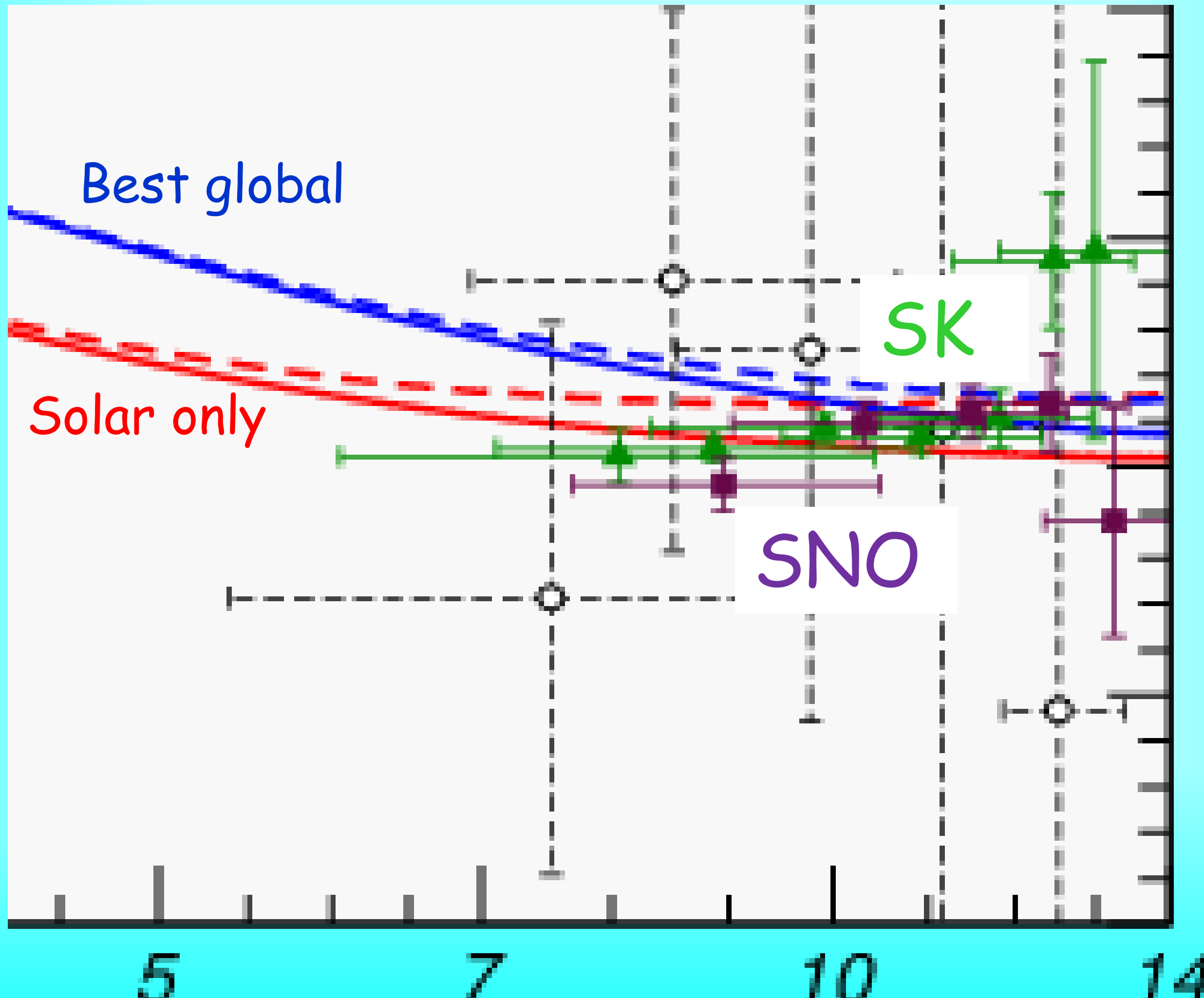
Transition region resonance turn on

Matter dominated region

determined by n_0 and Δm_{21}^2

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

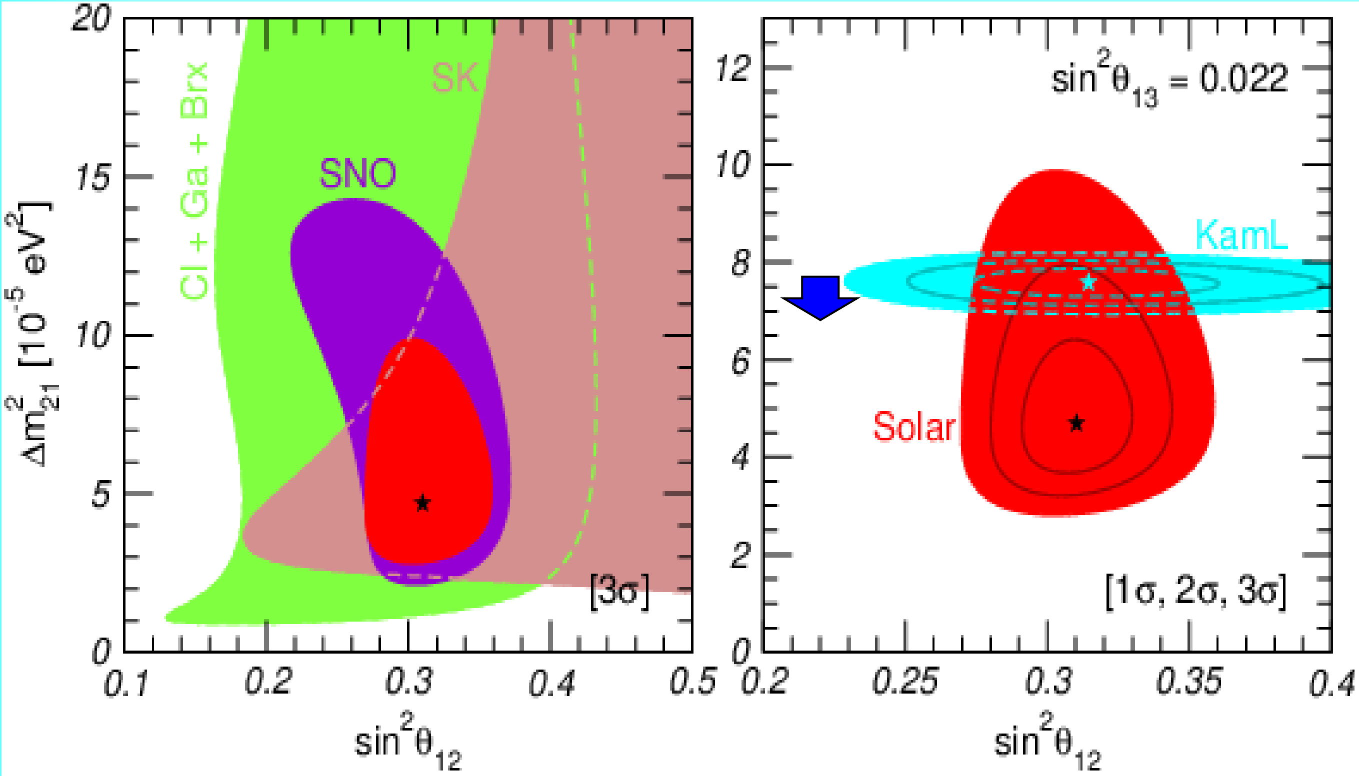
Upturn?



SNO+

Neutrino parameters

M. Maltoni, A.Y.S.
1507.05287 [hep-ph]



Red: all solar neutrino data

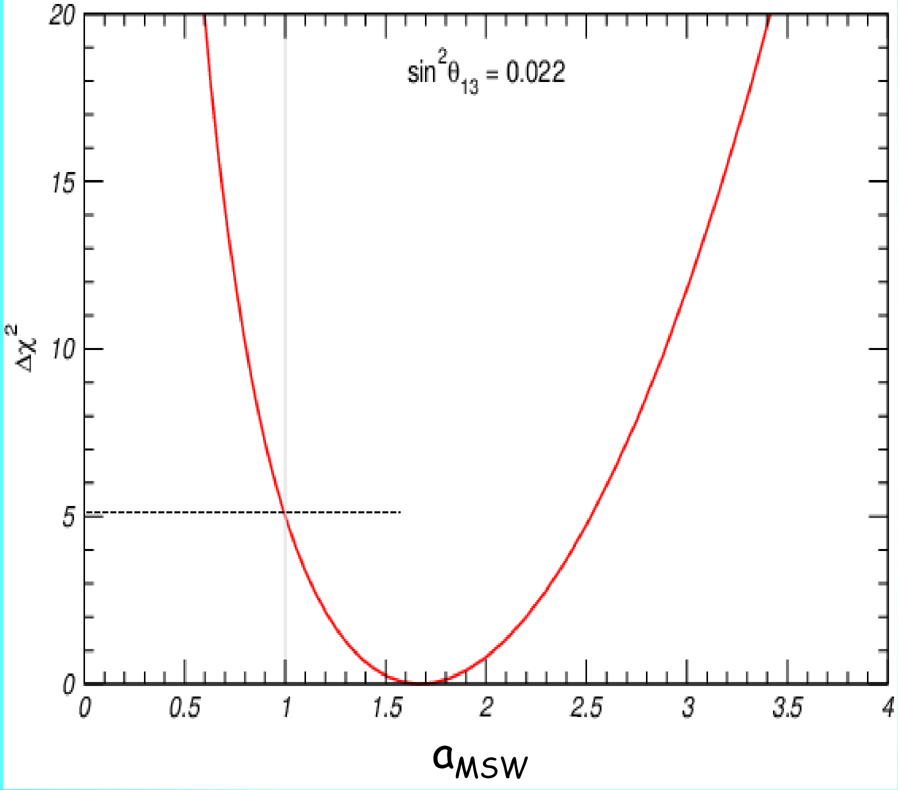
Δm^2_{21} (KL) > Δm^2_{21} (solar) 2 σ

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

Δm^2_{21} decreases by 0.15 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. 1507.05287 [hep-ph]



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

$a_{MSW} = 0$ 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

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

Scaling **

Inside the Sun highly adiabatic conversion →

The averaged survival probability is scale invariant = no dependence on distance, on scales of the density profile, etc.

Function of the combinations

$$\varepsilon_{12} = \frac{2VE}{\Delta m_{21}^2} \qquad \varepsilon_{13} = \frac{2VE}{\Delta m_{31}^2}$$

Very weak dependence

With oscillations in the Earth

$$P_{ee} = P_{ee}(\varepsilon_{12}, \varepsilon_{13}, \phi_E)$$

$$\phi_E = \Delta m_{21}^2 L / 2E$$

L – the length of the trajectory in the Earth

If oscillations in the Earth are averaged

$$P_{ee} = P_{ee}(\varepsilon_{12}, \varepsilon_{13}) = P_{ee}(\varepsilon_{12})$$

Invariance:

$$\Delta m_{ij}^2 \to a\,\Delta m_{ij}^2, \quad V \to a\,V$$

$$\Delta m_{ij}^2 \to b\,\Delta m_{ij}^2, \quad E \to b\,E$$

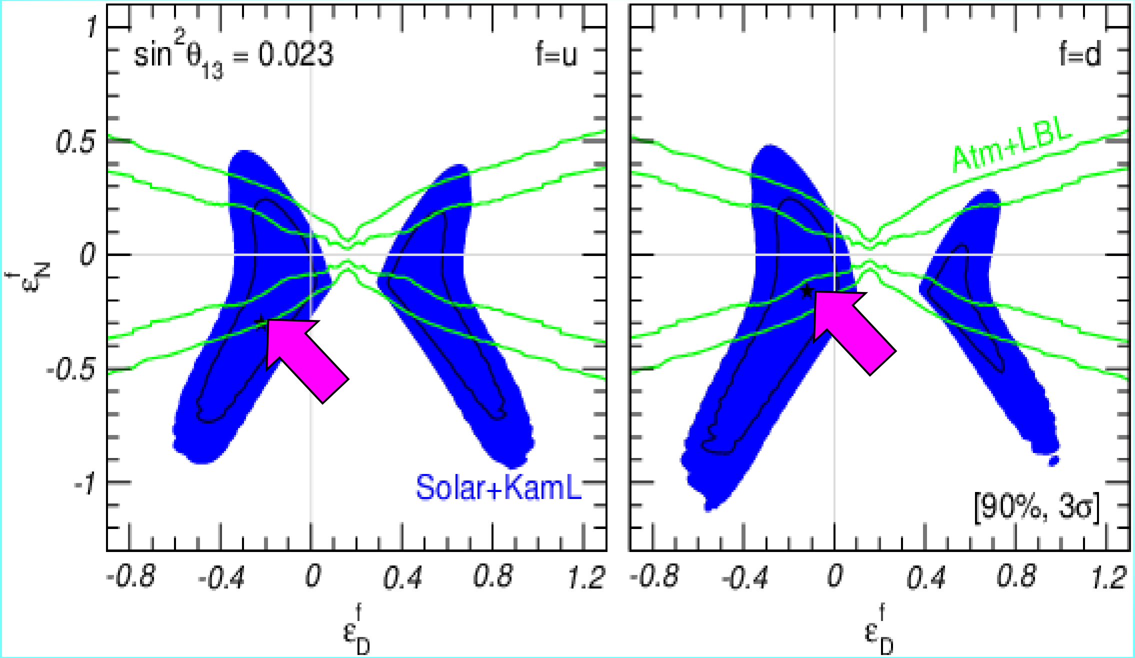
$a = -1$ flip of the mass hierarchy

Non-standard interactions

Additional contribution
to the matrix of potentials
in the Hamiltonian

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

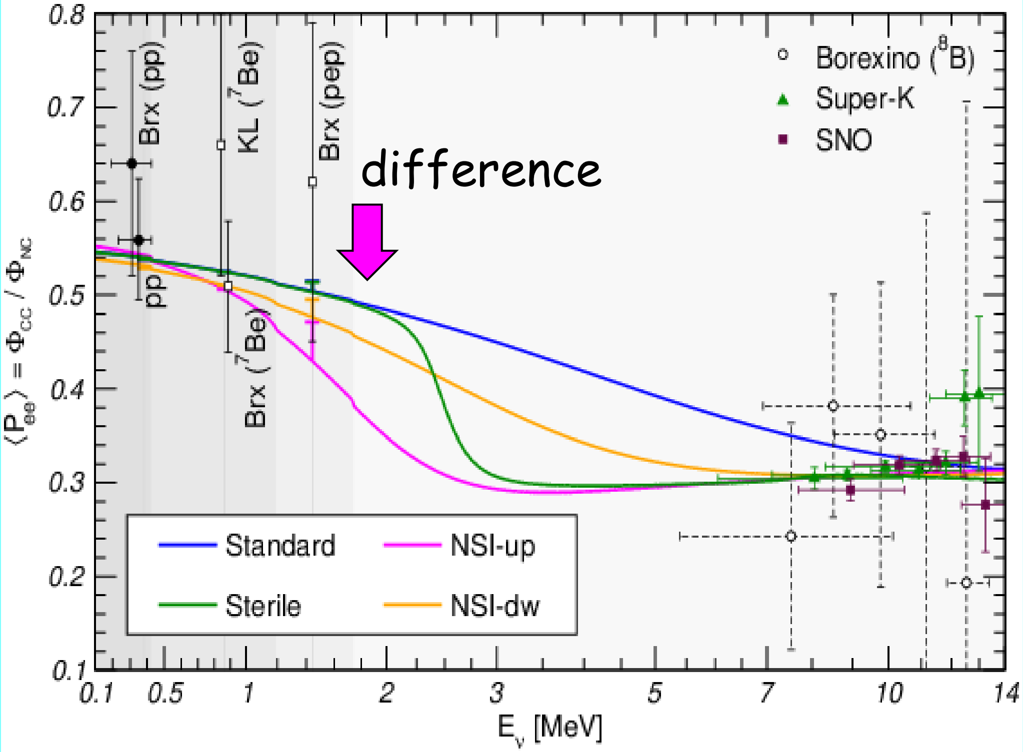
$$V_{NSI} = \sqrt{2}\, G_F\, n_f \begin{pmatrix} \varepsilon^f_D & \varepsilon^f_N \\ \varepsilon^f_N & \varepsilon^f_D \end{pmatrix} \qquad f = e, u, d$$



Allowed regions of parameters of NSI

In the best fit points the D-N asymmetry is 4 - 5%

New physics effects

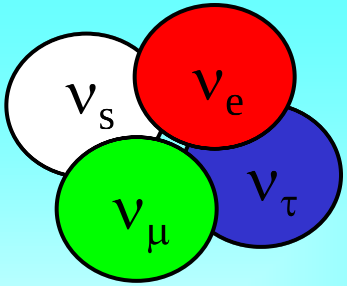


M. Maltoni, A.Y.S.
1507.05287 [hep-ph]

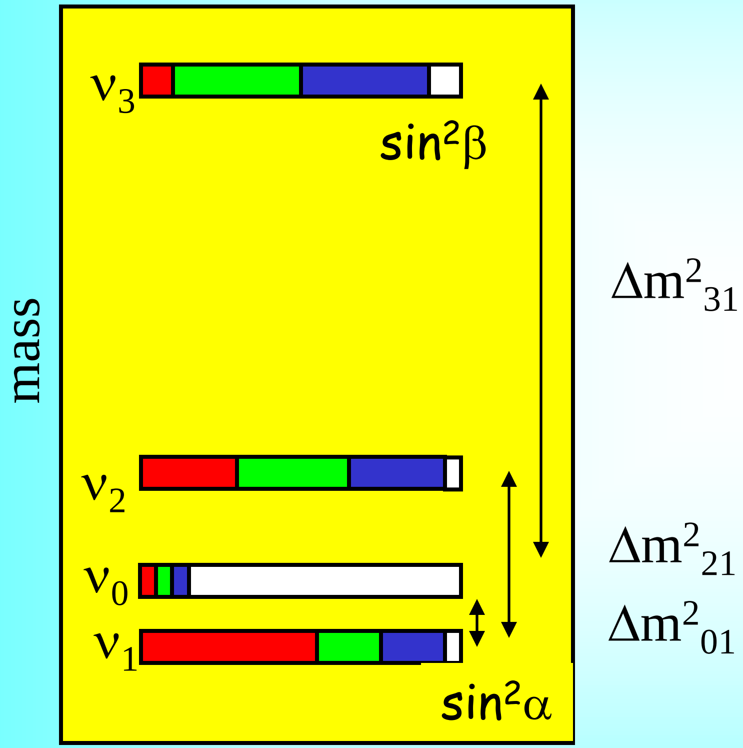
Extra sterile neutrino with
$\Delta m^2_{01} = 1.2 \times 10^{-5}$ eV^2, and
$\sin^2 2\alpha = 0.005$

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

Allows to explain absence
of upturn and reconcile
solar and KAMLAND
mass splitting but not large
DN asymmetry

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)

additional radiation
in the Universe if mixed in ν_3

no problem with LSS
bound on neutrino mass

Problems, future

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

at about 2 -3σ - level

Can be related

Another reactor anomaly or new physics in solar neutrinos?

Detection of CNO neutrinos to shed some light on the problem of SSM: controversy of helioseismology data and abundance of heavy elements

High precision measurements of the pp- and Be- neutrino fluxes

Detailed study of the Earth matter effect

Problems, future

Intermediate energy range upturn, D-N asymmetry

Detection of CNO neutrinos to shed some light on the problem of the SSM: controversy of helioseismology data and metallicity

High precision measurements of the pp- and Be- neutrino fluxes
Checks of flux- luminosity relations

Detailed study of the Earth matter effect
Oscillation tomography

Experiments:

DARWIN

SK

JUNO

JinPing

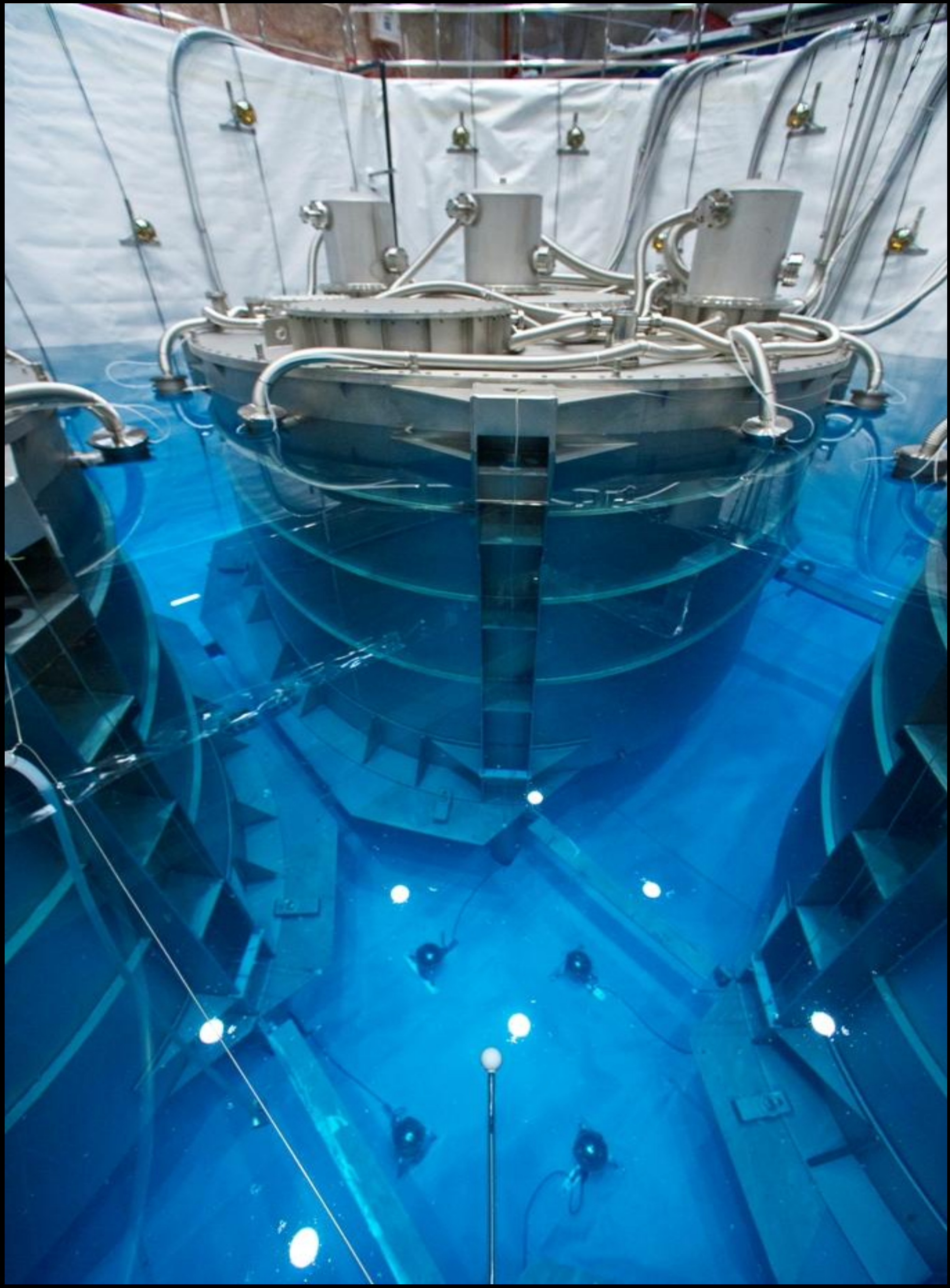
ASDC Theia (WbLS)

SNO+

Hyper-K

DUNE

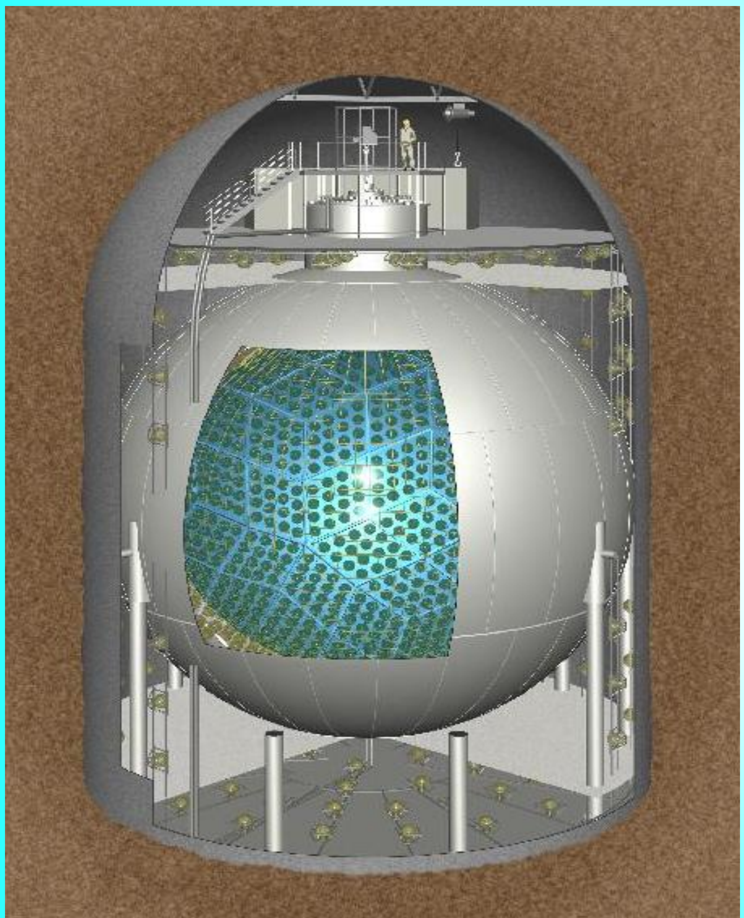
Reactor experiments



$\overline{\nu_e} + p \rightarrow e^+ + n$

KamLAND

scintillator

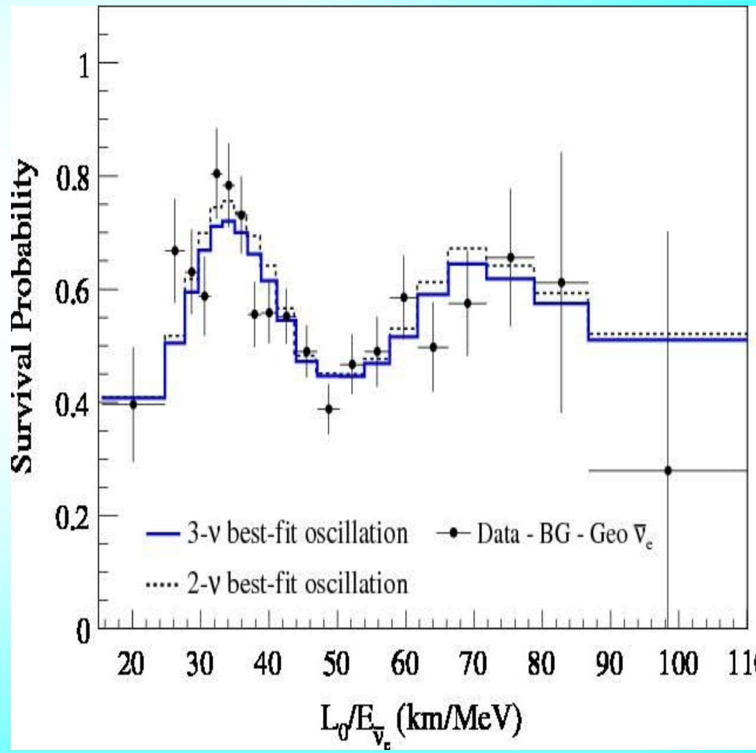


$\overline{\nu}_e + p \rightarrow e^+ + n$

Decisive experiment

reactors

<L> ~ 180 km



Measuring U_{e3}

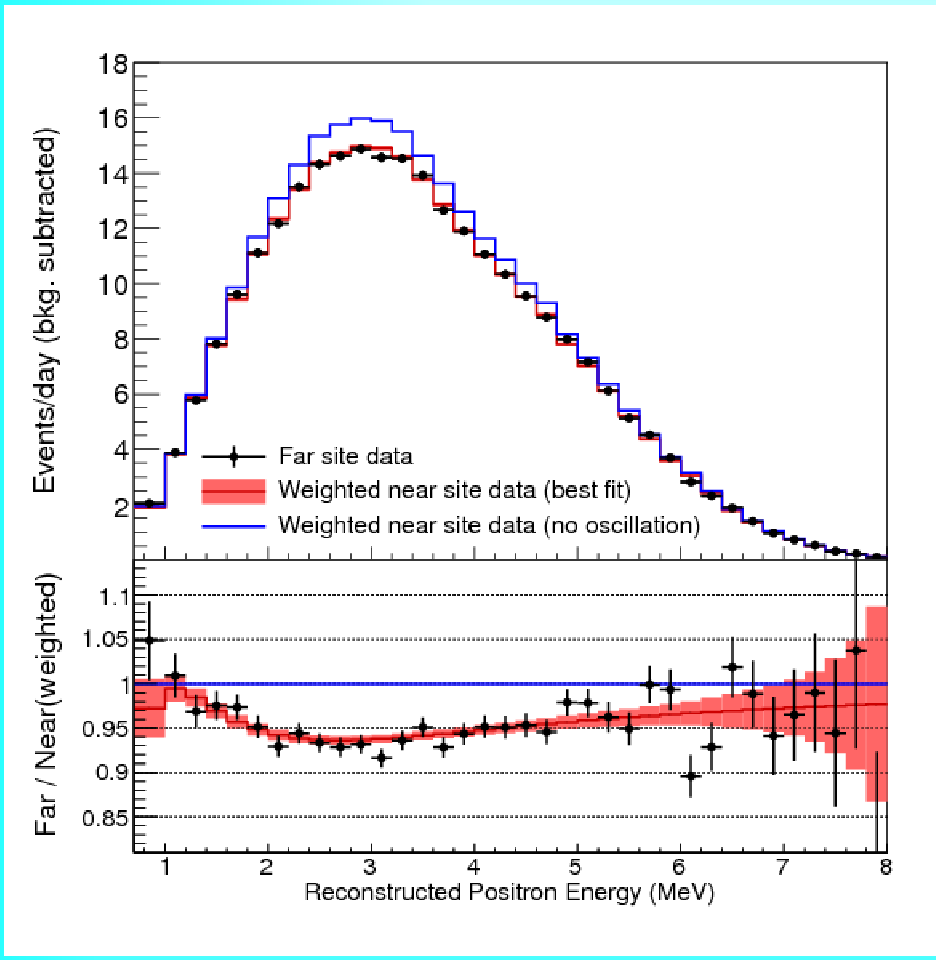
Daya Bay

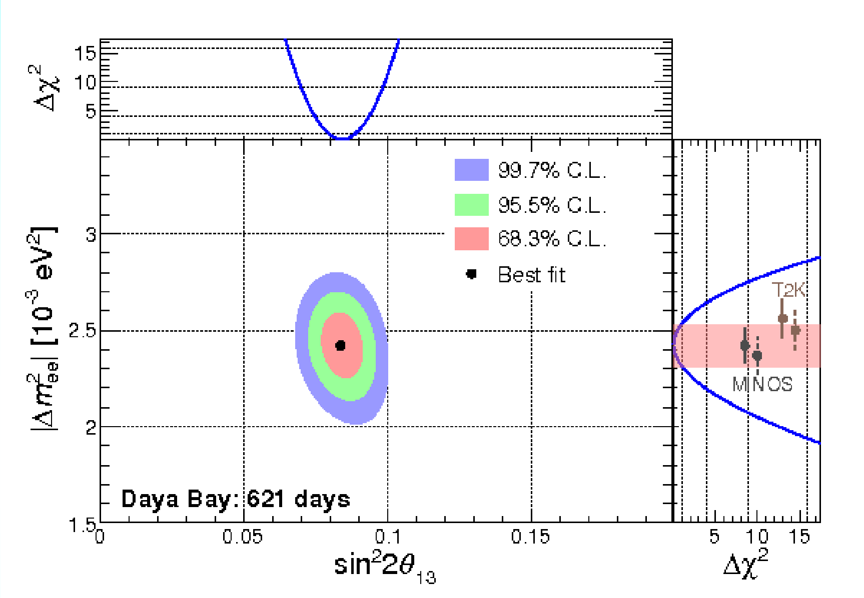
RENO

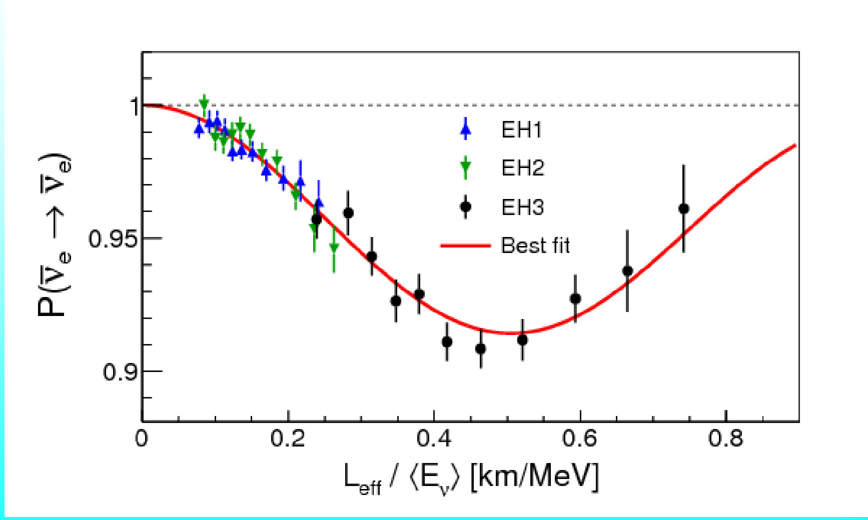
Double-CHOOZ

Daya Bay result

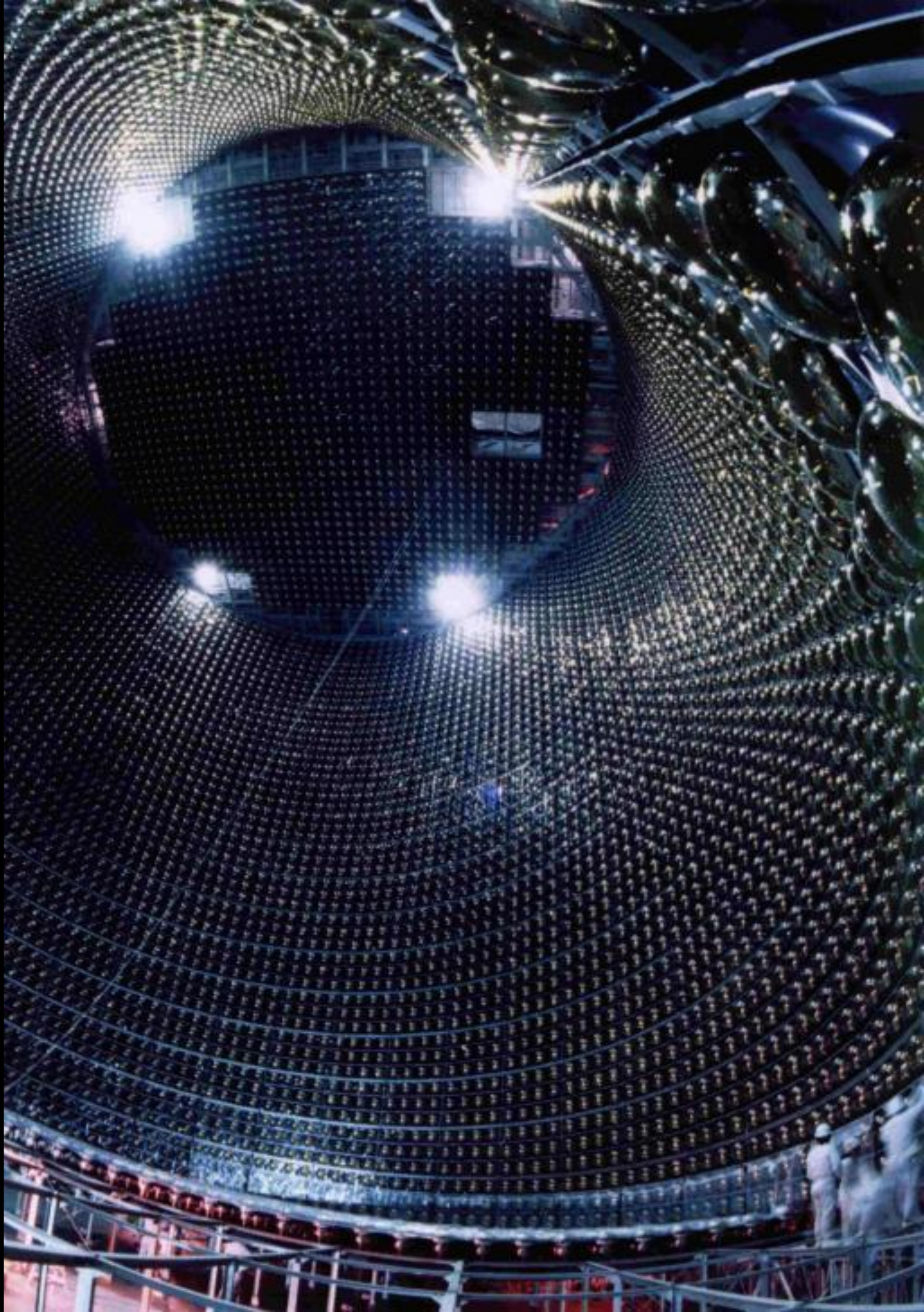
Daya Bay Collaboration
(An, F.P. et al.)
arXiv:1505.03456 [hep-ex]





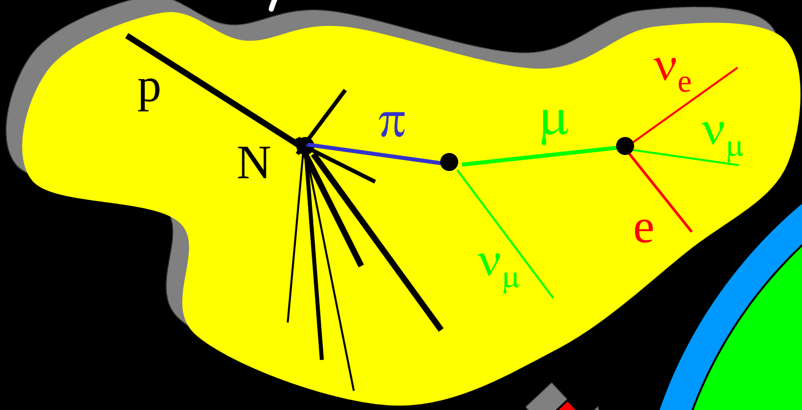


Atmospheric Neutrinos



Atmospheric neutrinos

cosmic rays



$\pi \rightarrow \mu + \nu_\mu$

$\mu \rightarrow e + \nu_\mu + \nu_e$

at low energies:

$F_\mu / F_e = 2$

$K \rightarrow \mu + \nu_\mu$

$K \rightarrow \pi + \mu + \nu_\mu$

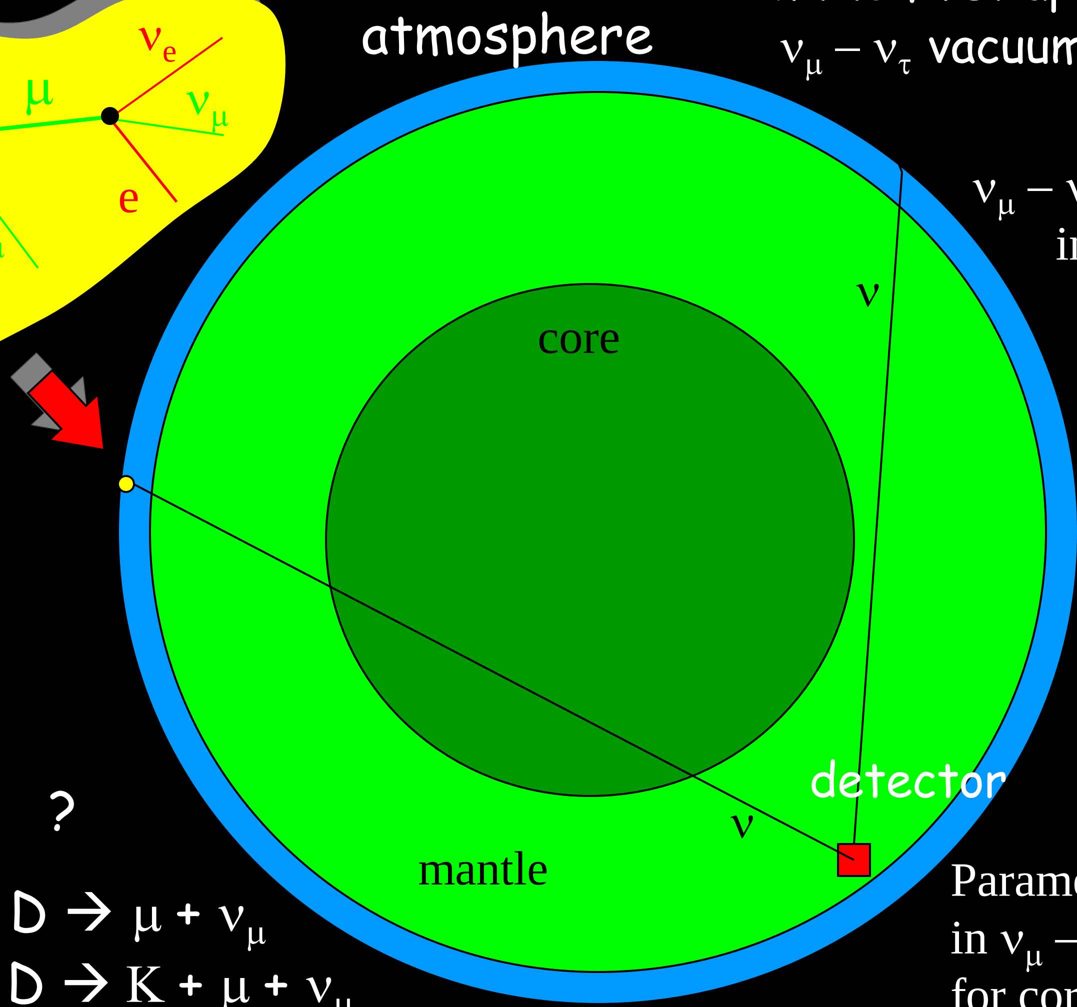
$K \rightarrow \pi + e + \nu_e$

?

$D \rightarrow \mu + \nu_\mu$

$D \rightarrow K + \mu + \nu_\mu$

$D \rightarrow K + e + \nu_e$



in the first approximation $\nu_\mu - \nu_\tau$ vacuum oscillations

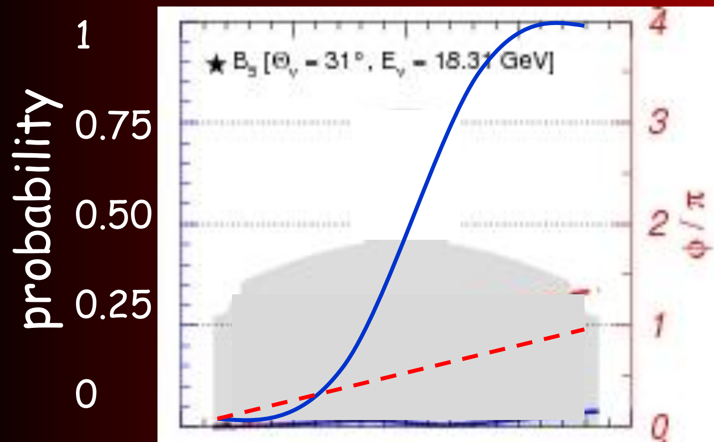
$\nu_\mu - \nu_e$ oscillations in matter

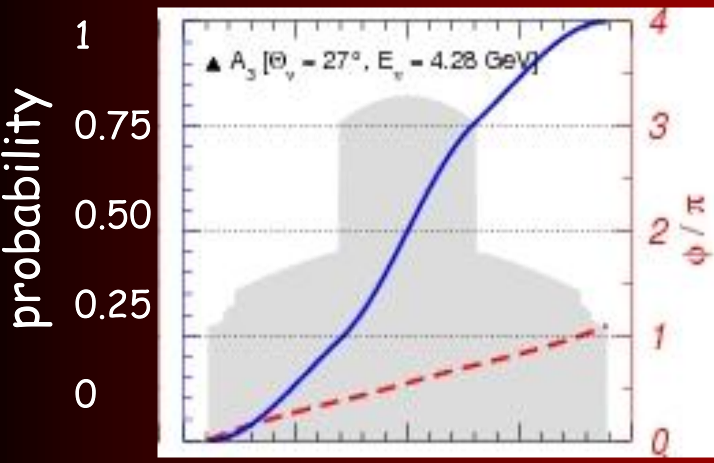
Parametric effects in $\nu_\mu - \nu_e$ oscillations for core crossing trajectories

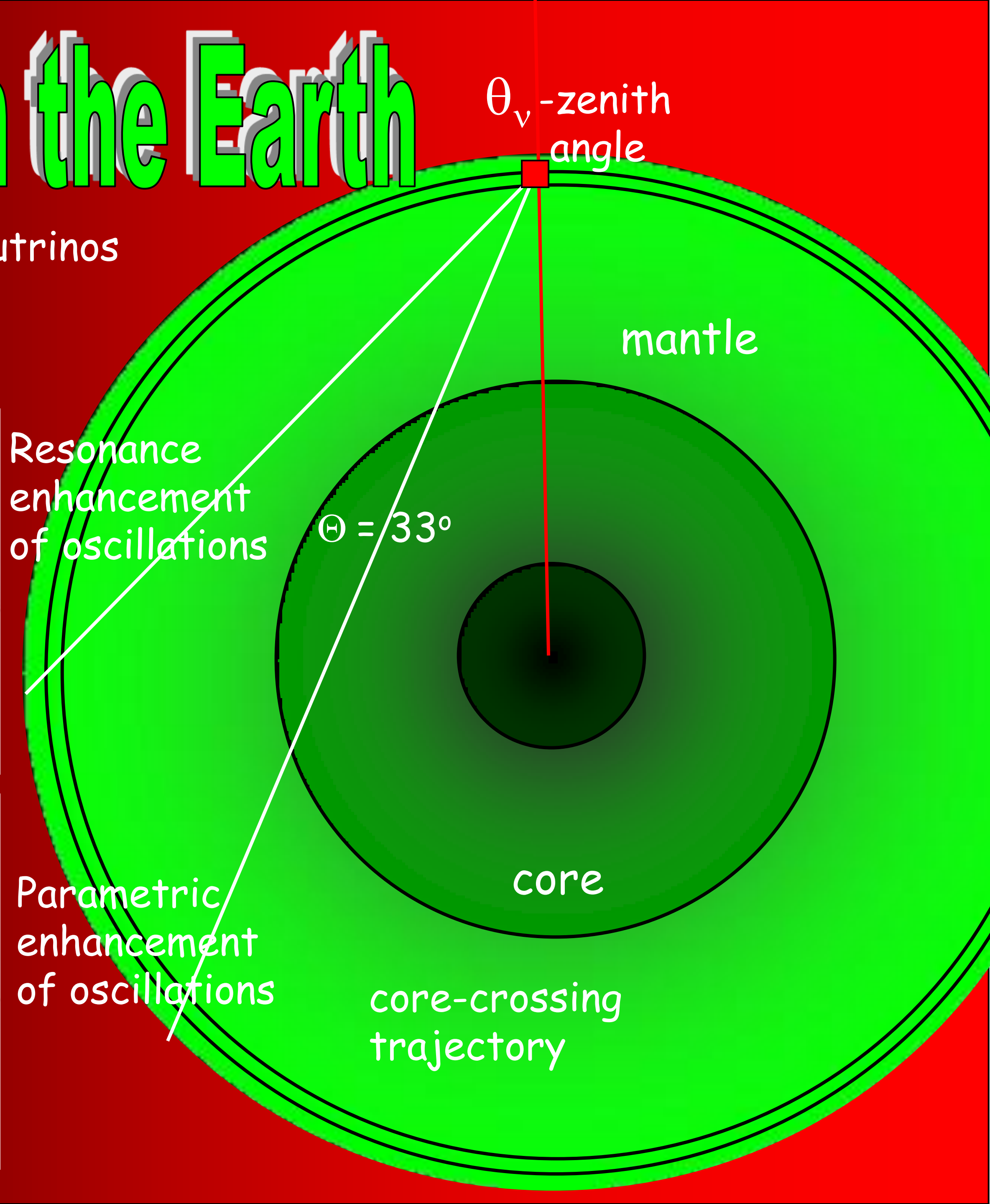
Oscillations in the Earth

Atmospheric, accelerator neutrinos

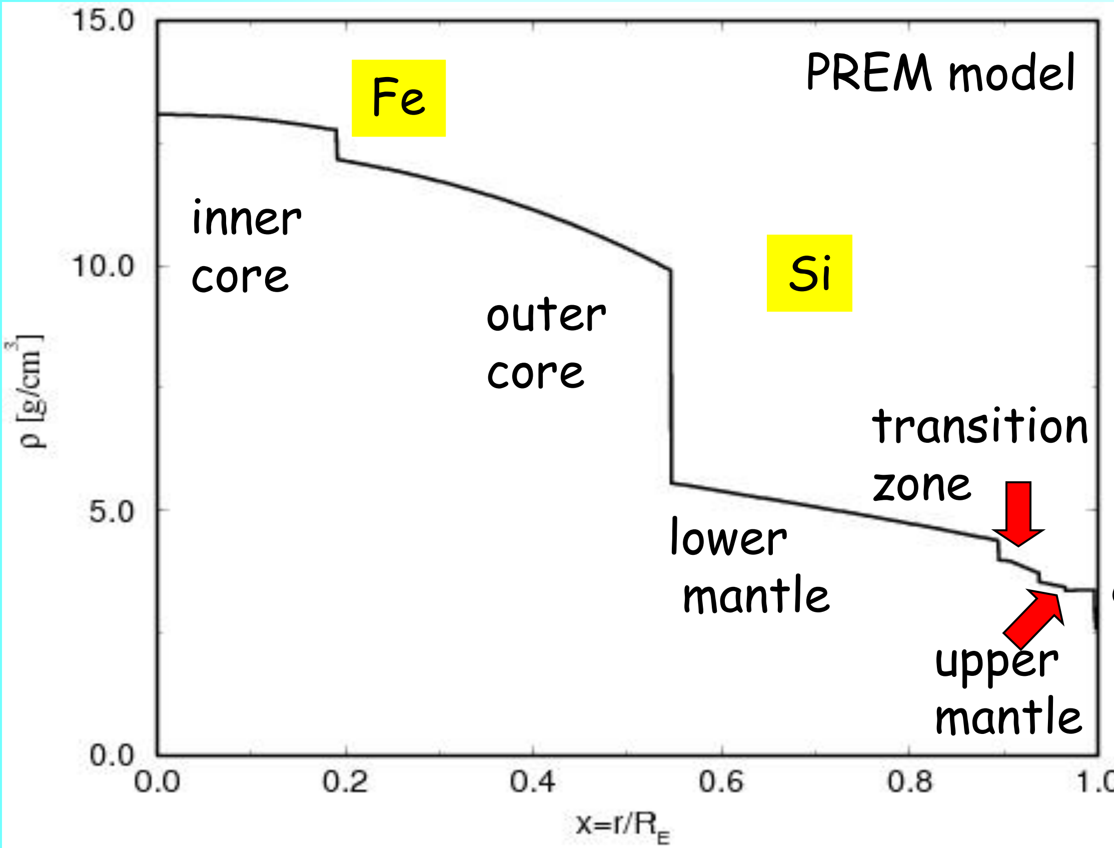
$\nu_e \rightarrow \nu_\mu \, , \nu_\tau$







The earth density profile



A.M. Dziewonski
D.L Anderson 1981

(phase transitions in silicate minerals)

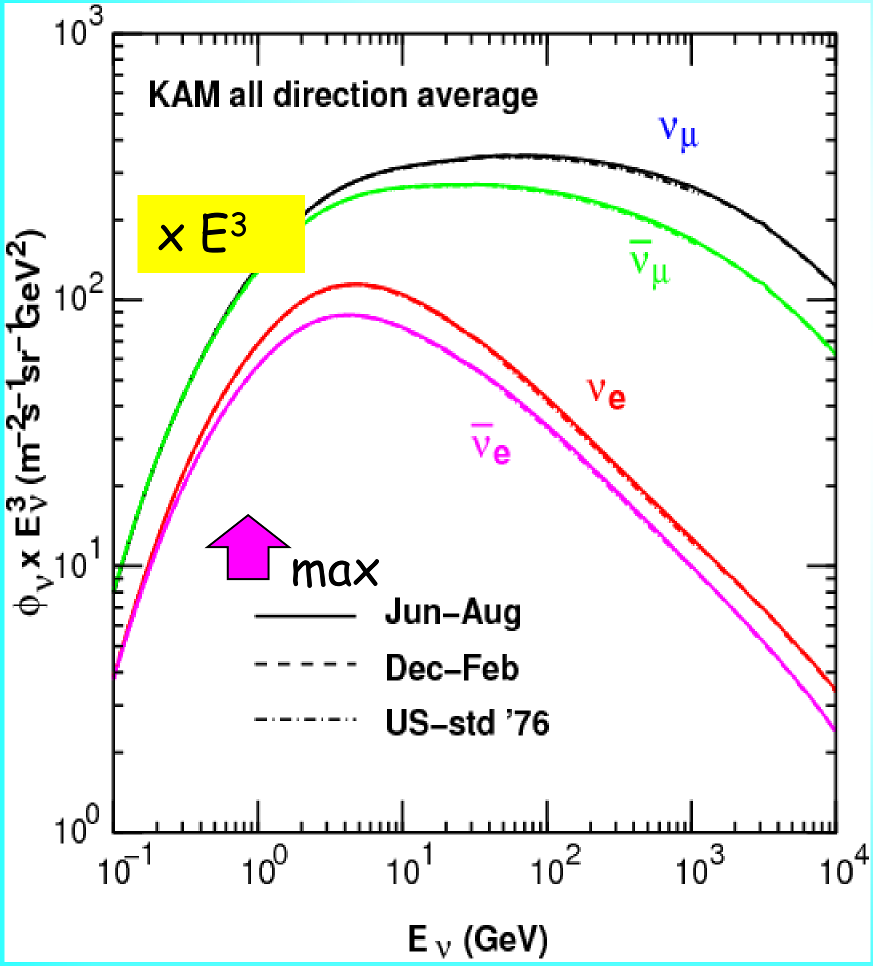
R_e = 6371 km

solid

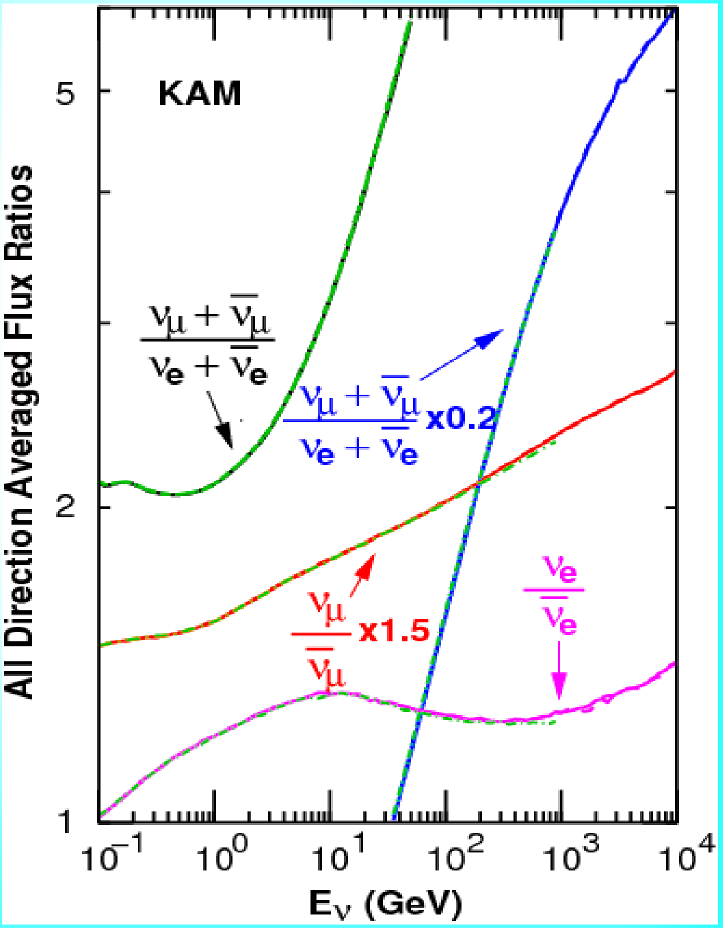
liquid

Atmospheric neutrino fluxes

M. Honda et al., arXiv: 1502.03916



Energy spectra



Flavor ratios

Enormous physics potential

Energy range: 0.01 – 10^5 GeV

Baselines: 0 – 13000 km

Matter effects: 3 – 15 g/cm^3

Flavor content nue, numu

Lepton number nu - antinu

which is not completely explored and largely unused

which change with energy and zenith angle

Achievements:

Discovery of neutrino oscillations

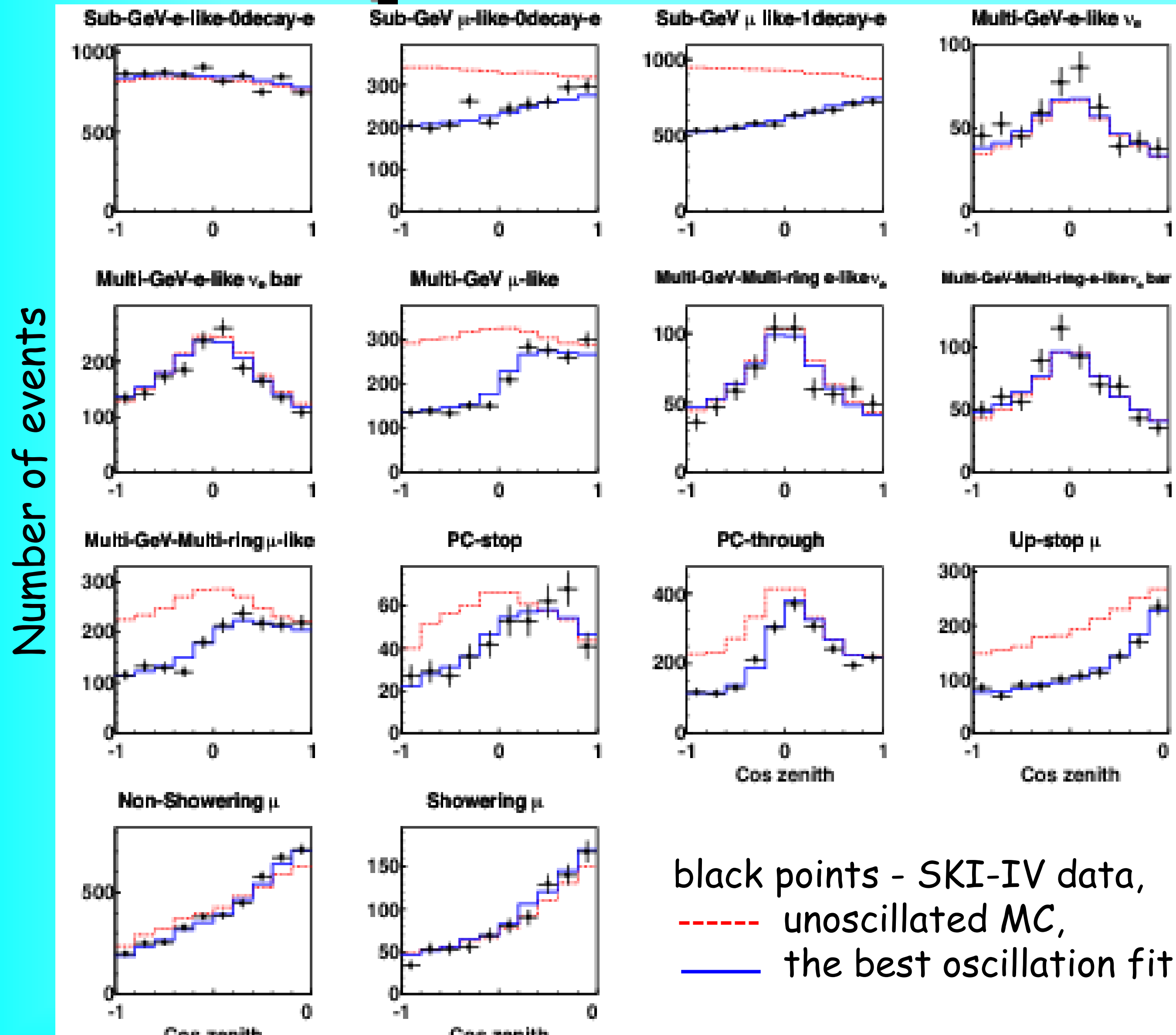
Measurements of 2-3 mixing and mass splitting

Bounds on new physics
- sterile neutrinos
- non-standards interaction
- violation of fundamental symmetries, CPT

BAKSAN
Kamiokande
MACRO ...

Atmospheric neutrino results

Super-Kamiokande Collaboration (Alexander Himmel) arXiv:1310.6677 [hep-ex]

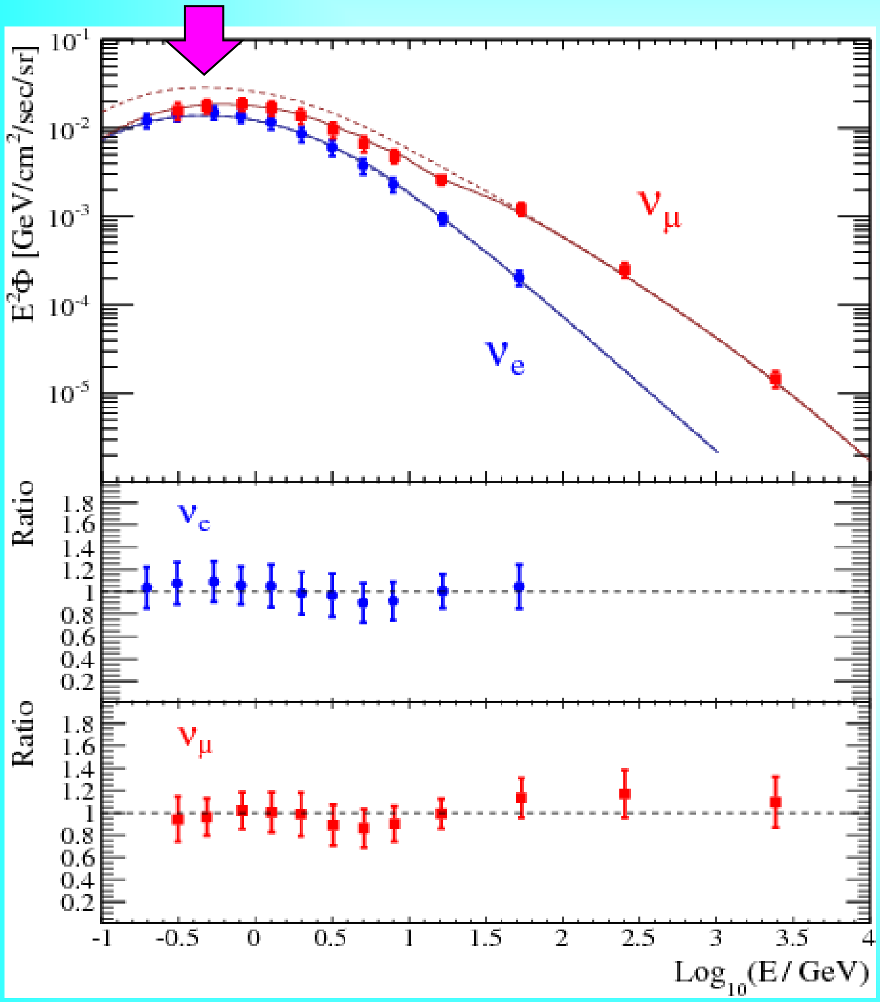


black points - SKI-IV data,
------ unoscillated MC,
—— the best oscillation fit

Zenith angle distributions of different type of events in different energy intervals

Atmospheric neutrinos

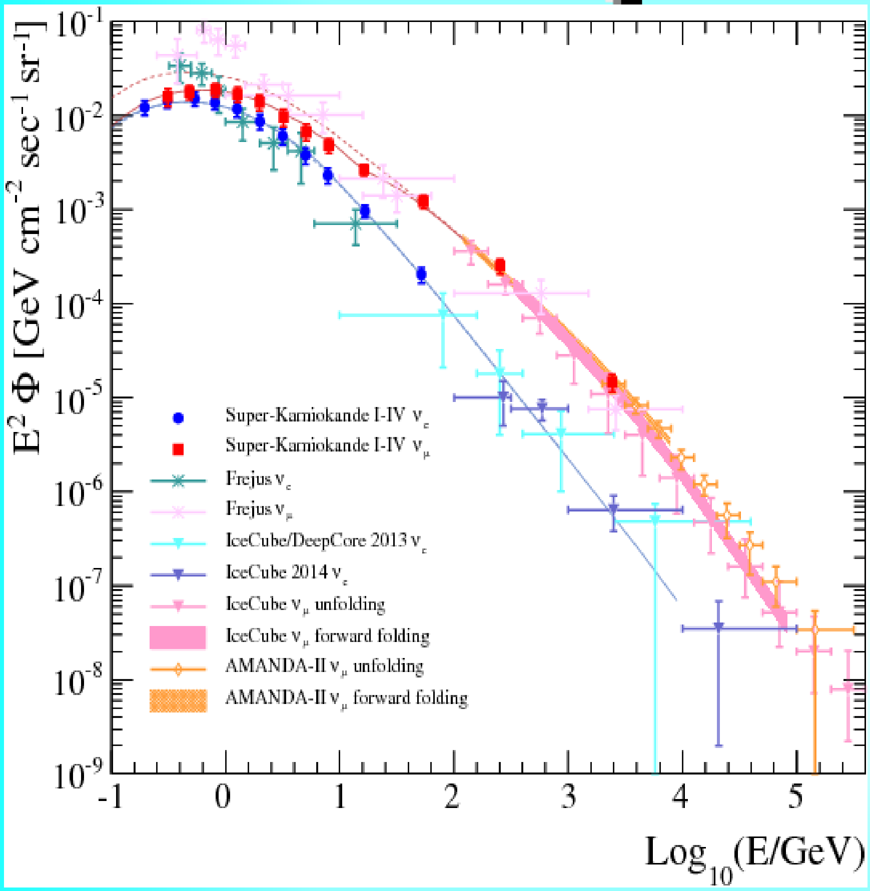
Oscillation effects

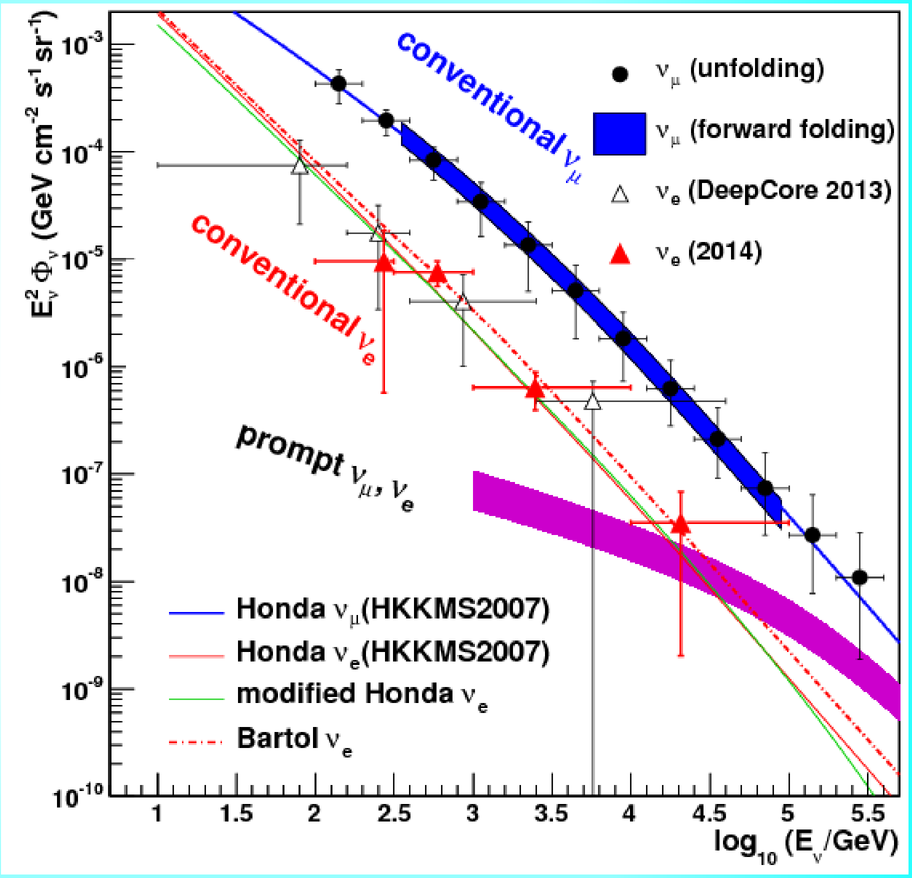


Energy dependence (integrated over the zenith angles)

Measured flux spectra, using all SK I-IV data, Error bars include all statistical and systematic errors.
Lines: the HKKM11 (Honda, et al 2011) model with (solid) and without (dashed) neutrino oscillation.

Atmospheric neutrinos





IceCube Collaboration (Aartsen, M.G. et al.) Phys.Rev. D91 (2015) 122004 arXiv:1504.03753 [astro-ph.HE]

3ν – oscillations

$\nu_f = U_{23} I_\delta U_{13} U_{12} \nu_{mass}$

$U_{13} U_{12} \nu_{mass} = \tilde{\nu}$

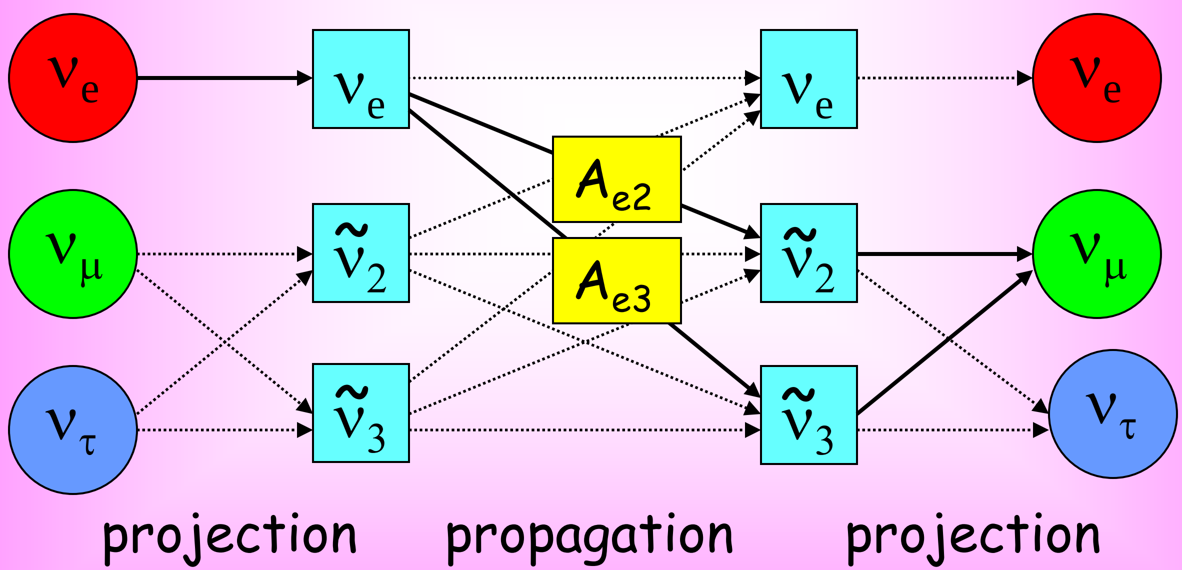
CP-violation and 2-3 mixing are excluded from dynamics of propagation

Propagation basis

$\nu_f = U_{23} I_\delta \tilde{\nu}$

$I_\delta = \mathrm{diag}(1, 1, e^{i\delta})$

Matter potential is unchanged in new basis



A_{22} A_{33} A_{23}

CP appears in projection only

For instance: $A(\nu_e \to \nu_\mu) = \cos\theta_{23} A_{e2} e^{-i\delta} + \sin\theta_{23} A_{e3}$

3ν probabilities

$$P(\nu_e \rightarrow \nu_\mu) = |\cos\theta_{23} A_{e2} e^{-i\delta} + \sin\theta_{23} A_{e3}|^2$$
$$= |\ \cos\theta_{23}\, |A_{e2}|\, e^{\,i(-\delta+\phi)} + \sin\theta_{23}\, |A_{e3}|\ |^2$$

$\phi = \arg(A_{e2} A_{e3}^*)$

$P_{int} = 2 s_{23} c_{23} |A_{e2}||A_{e3}| \cos(\phi - \delta)$

For constant density and E > 0.5 GeV

$|A_{e2}| \sim \cos\theta_{13} \sin 2\theta_{12}^m\ \sin\phi_{12}^m$

$|A_{e3}| \sim \sin 2\theta_{13}^m\ \sin\phi_{13}^m$

Below 1-3 resonance and above 1-2 resonance $\xi_{12} \gg 1 \gg \xi_{13}$

$\xi_{ij} = 2EV/\Delta m_{ij}^2$

$\sin 2\theta_{13}^m \sim \sin 2\theta_{13} / (1 - \xi_{13})$
$\phi_{13}^m \sim \phi_{13} (1 - \xi_{13})$

small matter corrections

$\sin 2\theta_{12}^m \sim \sin 2\theta_{12} / \xi_{12}$
$\phi_{12}^m \sim \phi_{12}\, \xi_{12} = VL/2$

matter dominated limit
If phase is small - vacuum mimicking

gives formula which appears in all Long baseline experiment papers

Probabilities

E Kh Akhmedov,
S Razzaque,
A. Y.S.

for hierarchy determination
high energies

$$P(\nu_e \to \nu_\mu) = s_{23}^2 |A_{e3}|^2$$

$$P(\nu_\mu \to \nu_\mu) = 1 - \tfrac{1}{2} \sin^2 2\theta_{23} - s_{23}^4 |A_{e3}|^2 + \tfrac{1}{2} \sin^2 2\theta_{23} (1 - |A_{e3}|^2)^{\frac{1}{2}} \cos\phi$$

Reduces the average probability

Reduces the depth of oscillations interference

Modifies phase

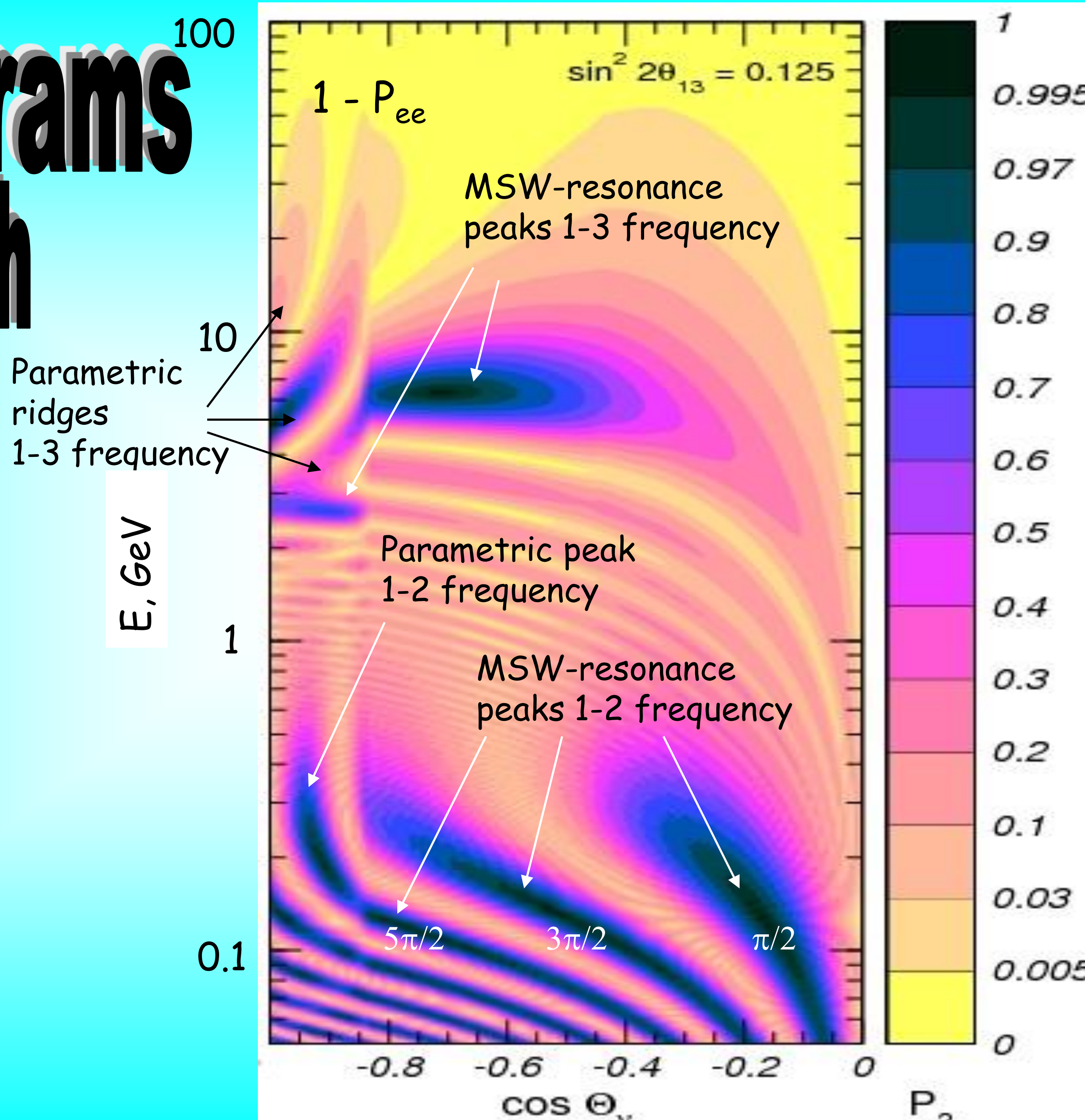
$$\phi = \arg (A_{22} A_{33}^*)$$

$$P(\nu_\mu \to \nu_\tau) = \tfrac{1}{2} \sin^2 2\theta_{23} - s_{23}^2 c_{23}^2 |A_{e3}|^2 - \tfrac{1}{2} \sin^2 2\theta_{23} (1 - |A_{e3}|^2)^{\frac{1}{2}} \cos\phi$$

Oscillograms of the Earth

Lines of equal Probability in the $E - \theta_z$ plane

$\nu_e \rightarrow \nu_\mu + \nu_\tau$

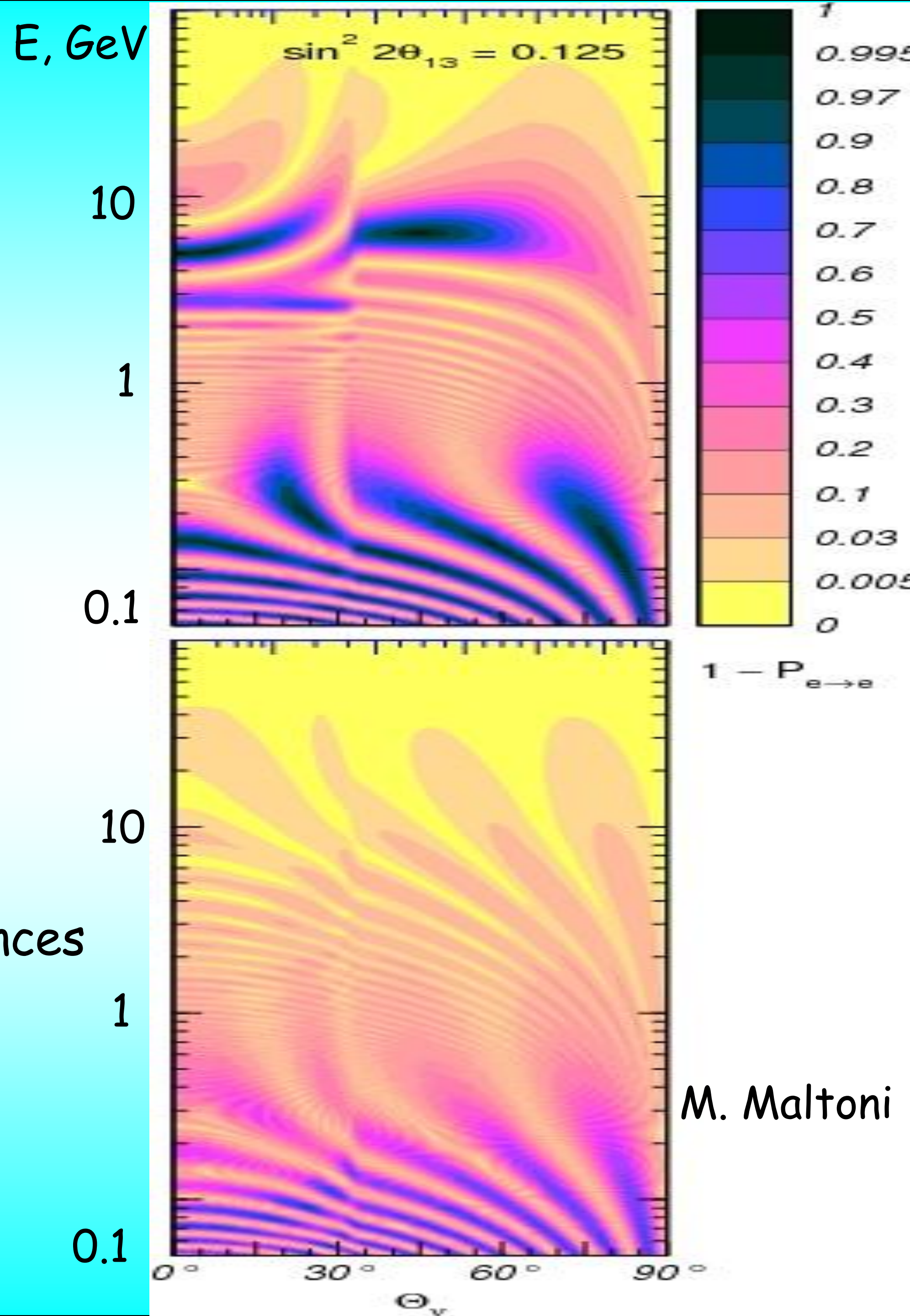


Neutrinos and antineutrinos

Normal mass hierarchy

For inverted mass hierarchy the high energy parts of the diagrams E > 1 GeV interchange

No resonances



M. Maltoni

Probabilities

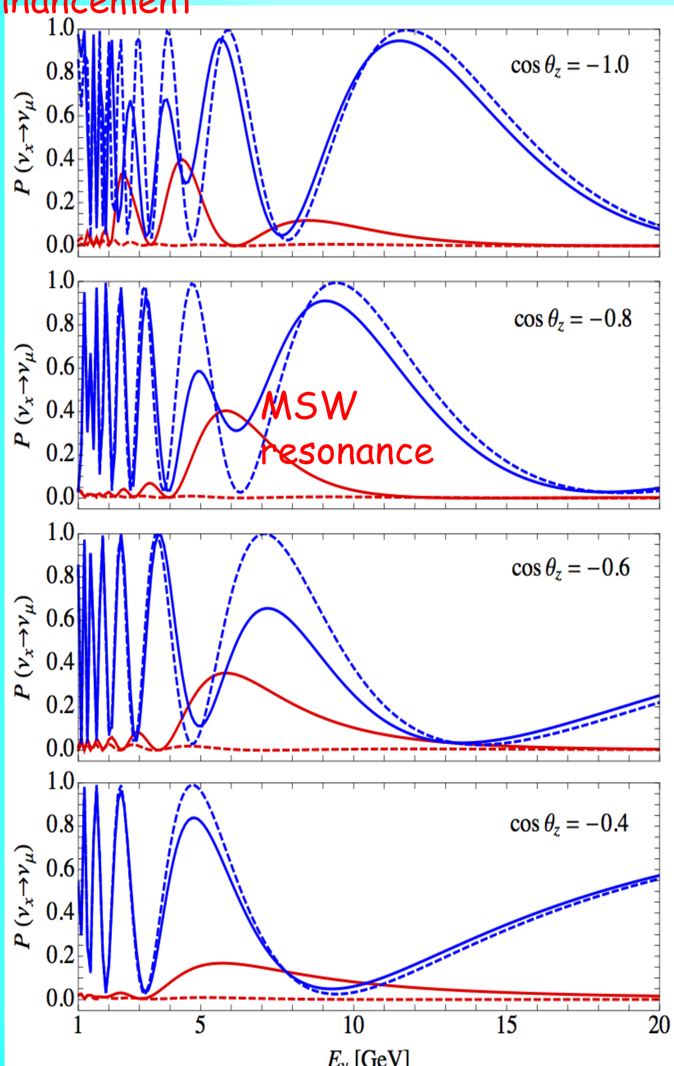
NH – solid, IH – dashed
x = μ - blue, x = e - red

Paramentric enhancement

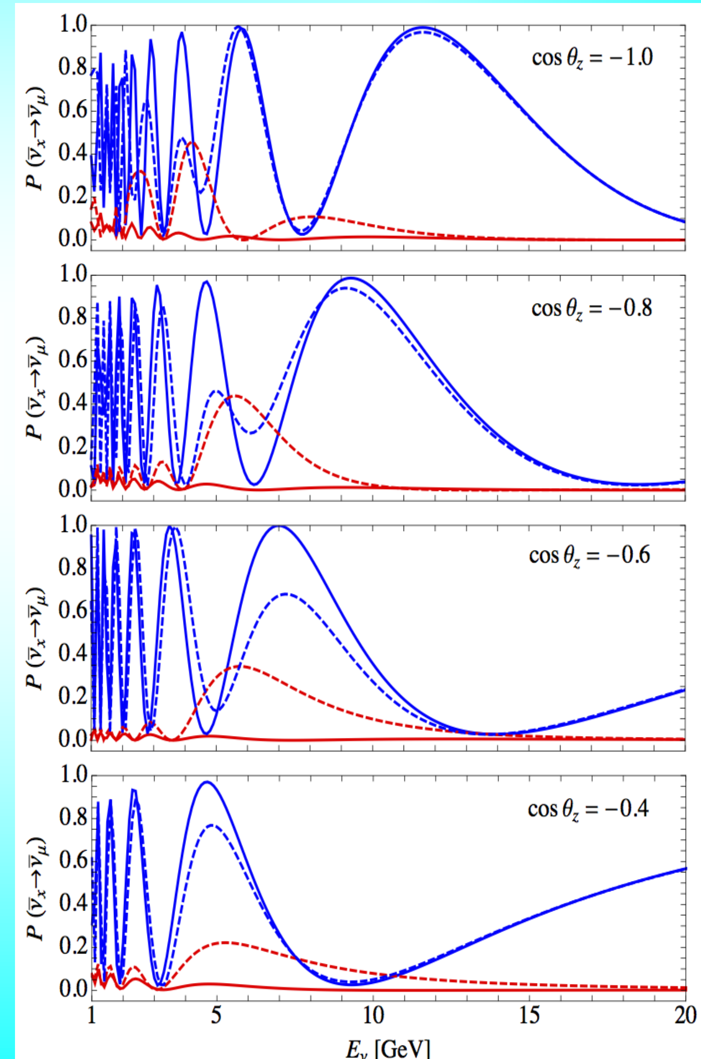
core

mantle only

neutrinos



antineutrinos



Ice Cube

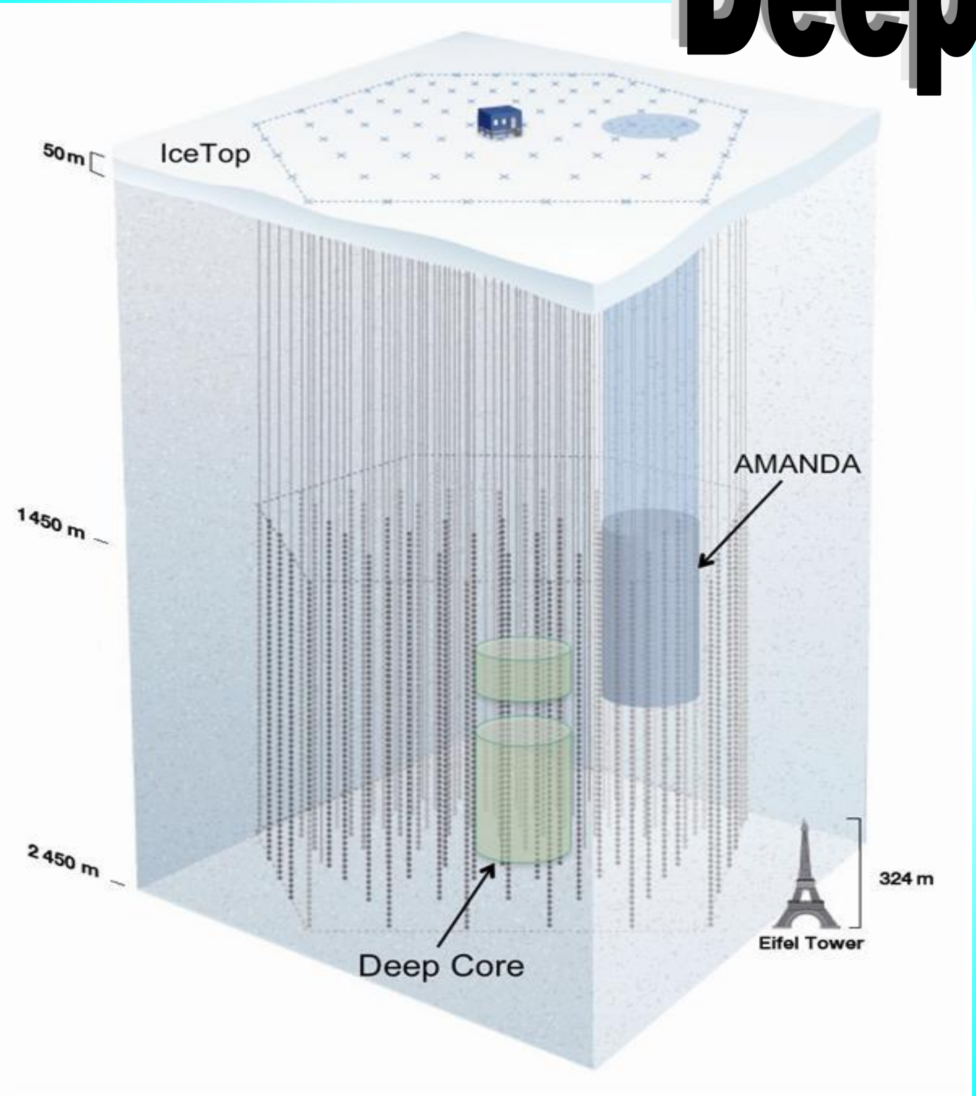
New players in the field

100 GeV

Deep Core

10 - 15 GeV

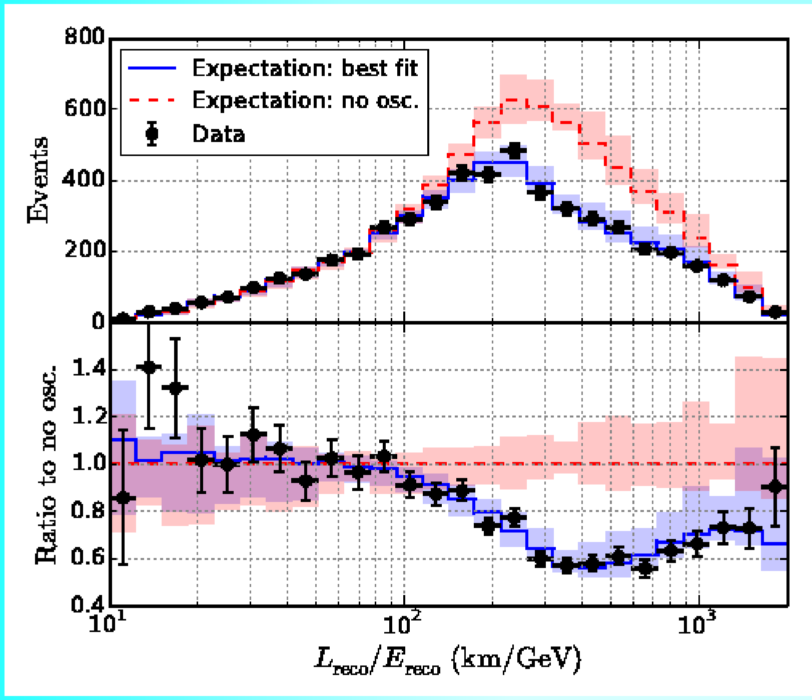
Antares

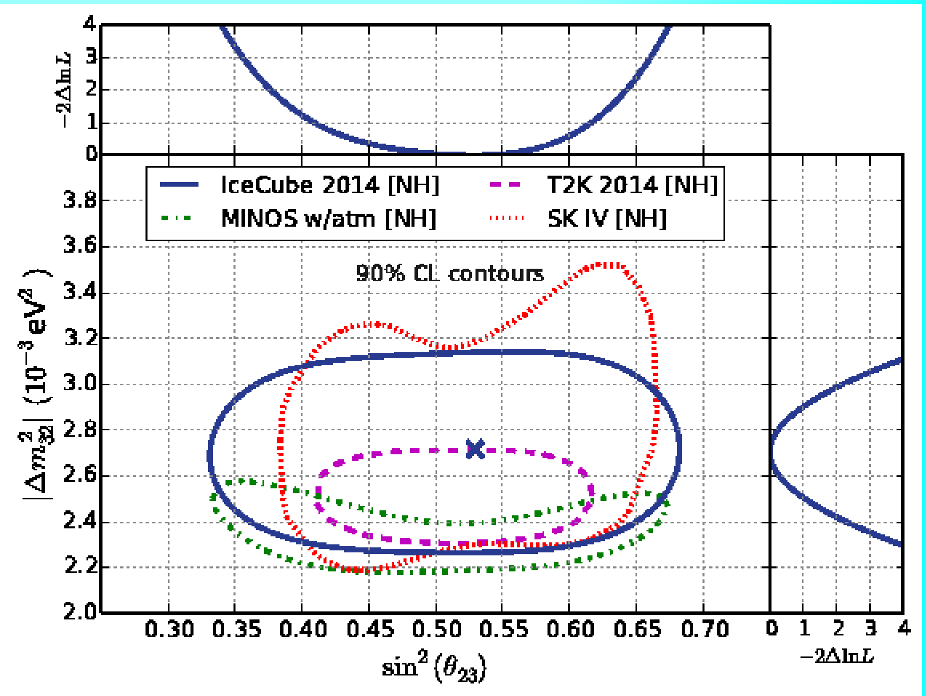


1 - 3 GeV

Precision
IceCube
Next
Generation
Upgrade

DeepCore oscillation result





atmospheric ν_μ disappearance,
3 years of data

similar to SK

IceCube Collaboration (M.G. Aartsen et al.).
arXiv:1410.7227 [hep-ex] |

$\Delta m_{32}{}^2$ = (2.72 +0.19/−0.20) 10^{-3} eV^2
$\sin^2\theta_{23}$ = 0.53 +0.09/−0.12 (NO)

compatible and comparable in precision with accelerator experiments

Problems, future

No inconsistencies, problems

Where are Matter effects?

Experiments:

Ice Cube

Deep Core

SK

ICAL INO

MINOS

PINGU

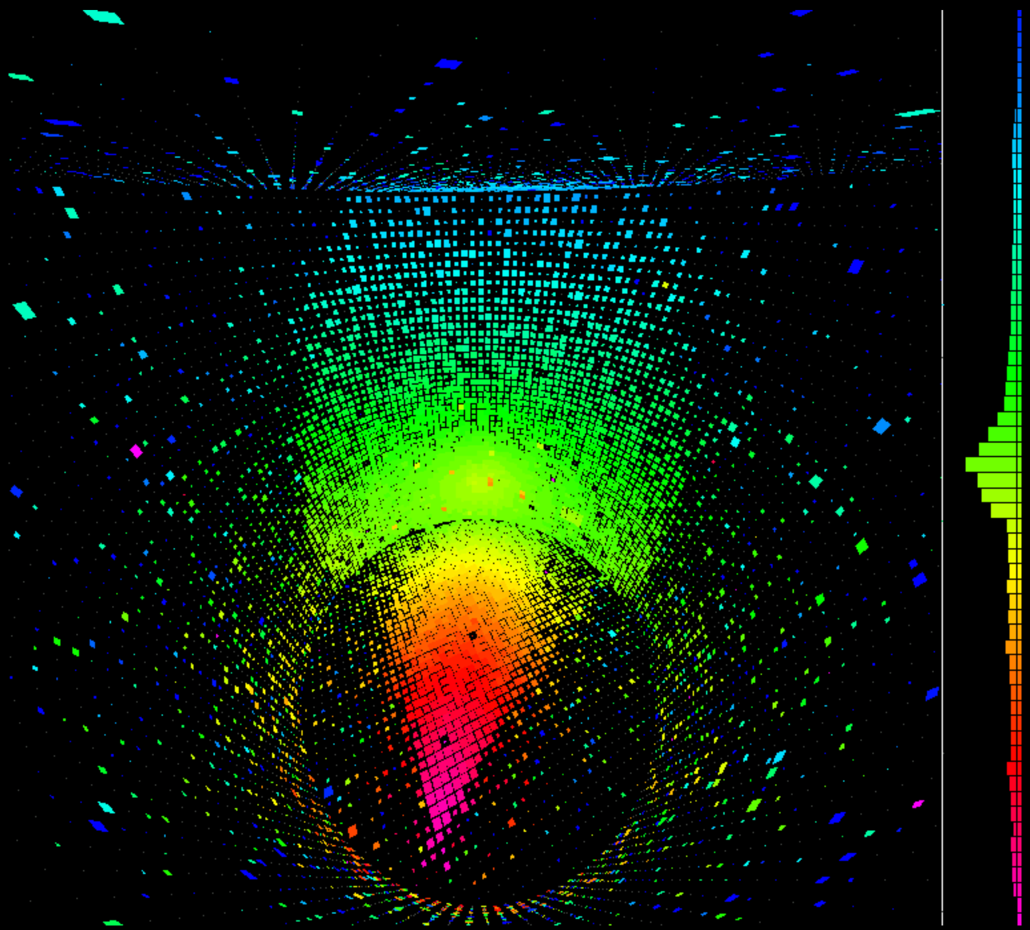
HyperKamiokande

DUNE

ORCA

Super-PINGU/ORCA

Accelerator Neutrinos



Accelerator neutrinos

Sources

p-N collisions

$\pi \rightarrow \mu + \nu_\mu$

$K \rightarrow \mu + \nu_\mu$

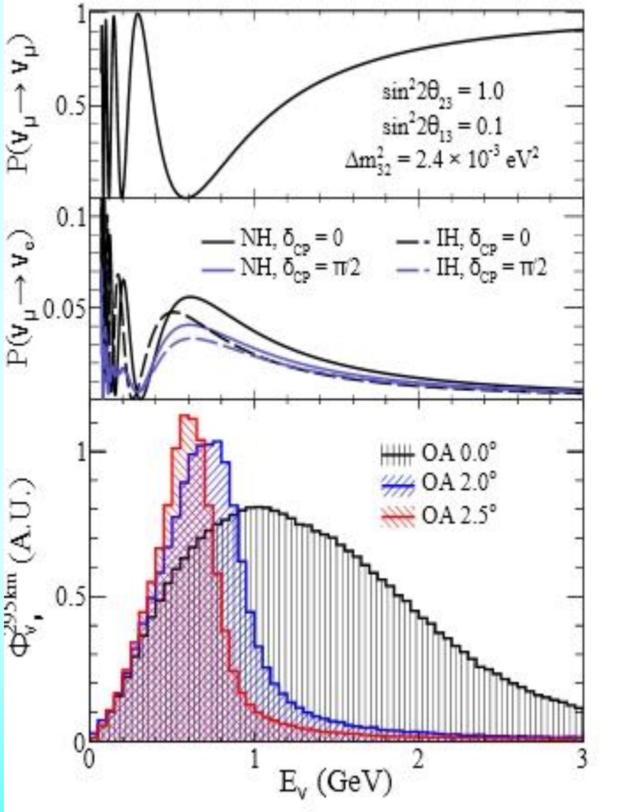
$K \rightarrow \pi + \mu + \nu_\mu$

$K \rightarrow \pi + e + \nu_e$

Also charm meson decays in the beam dump experiments

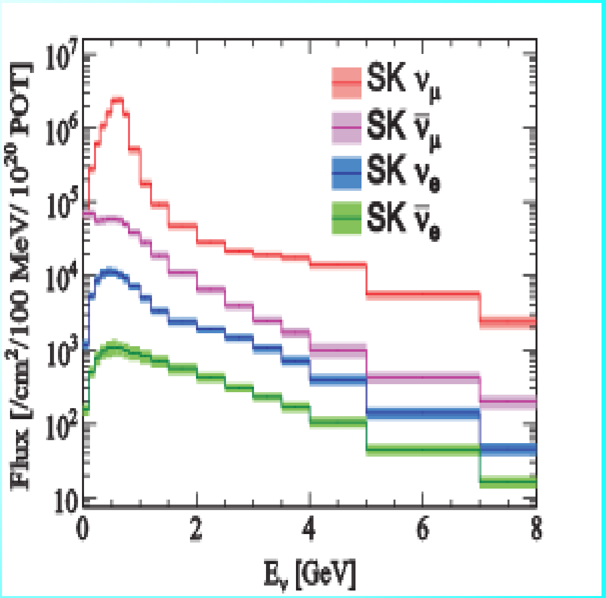
Superbeams
Beta beams
Neutrino factories
$\mu \rightarrow e + \nu_\mu + \nu_e$

off-axis



Detectors

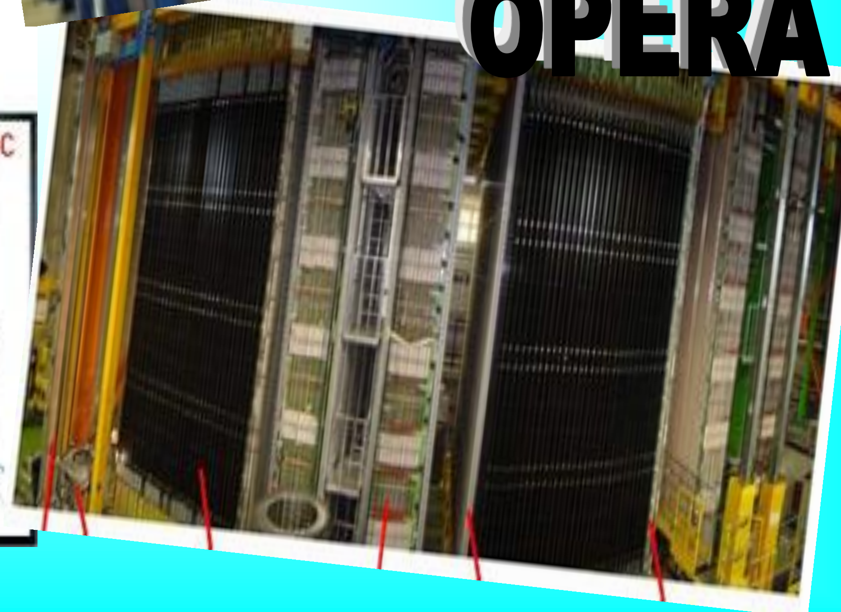
The same as for atmospheric

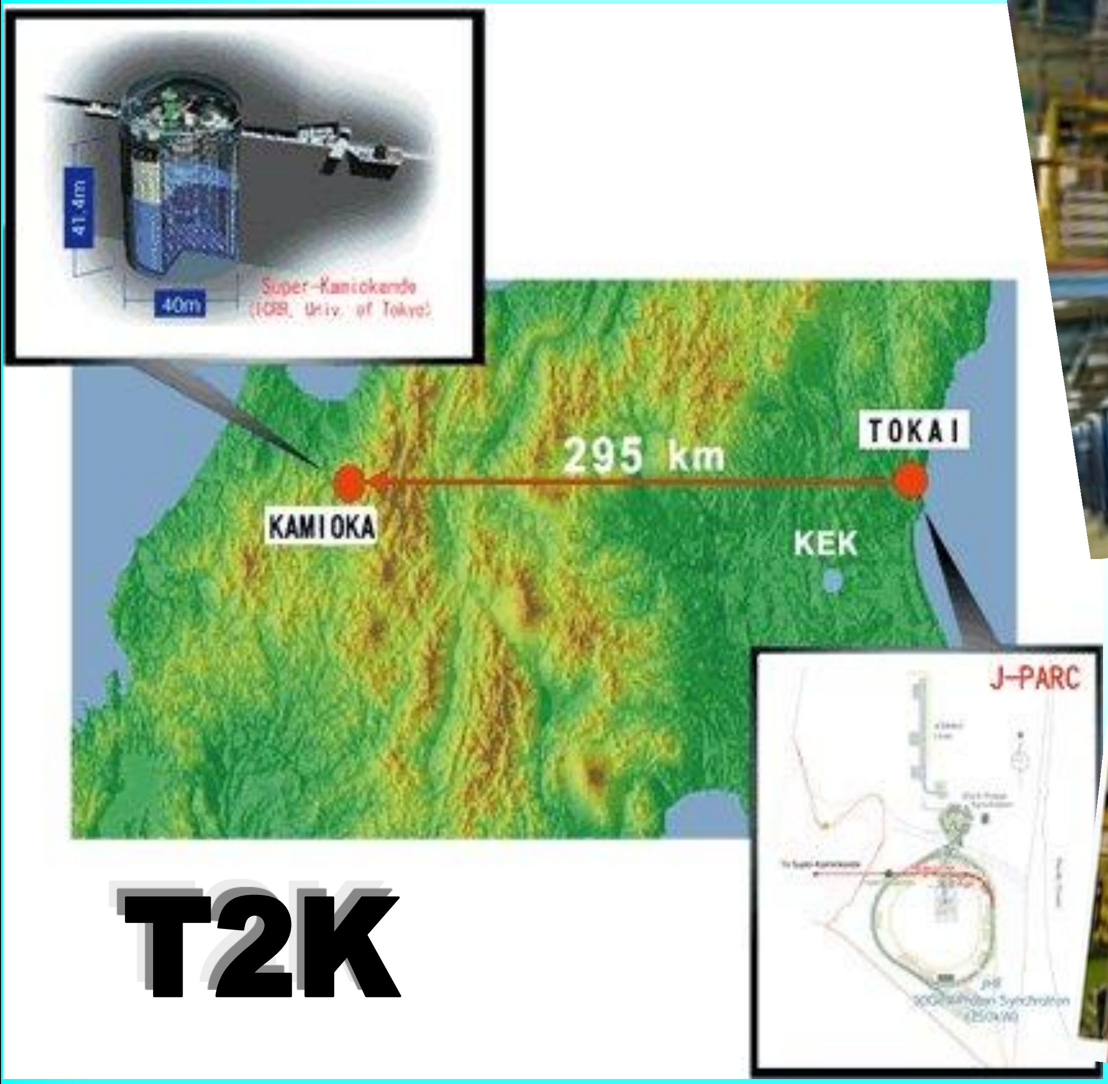


Accelerator experiments

MINOS

OPERA

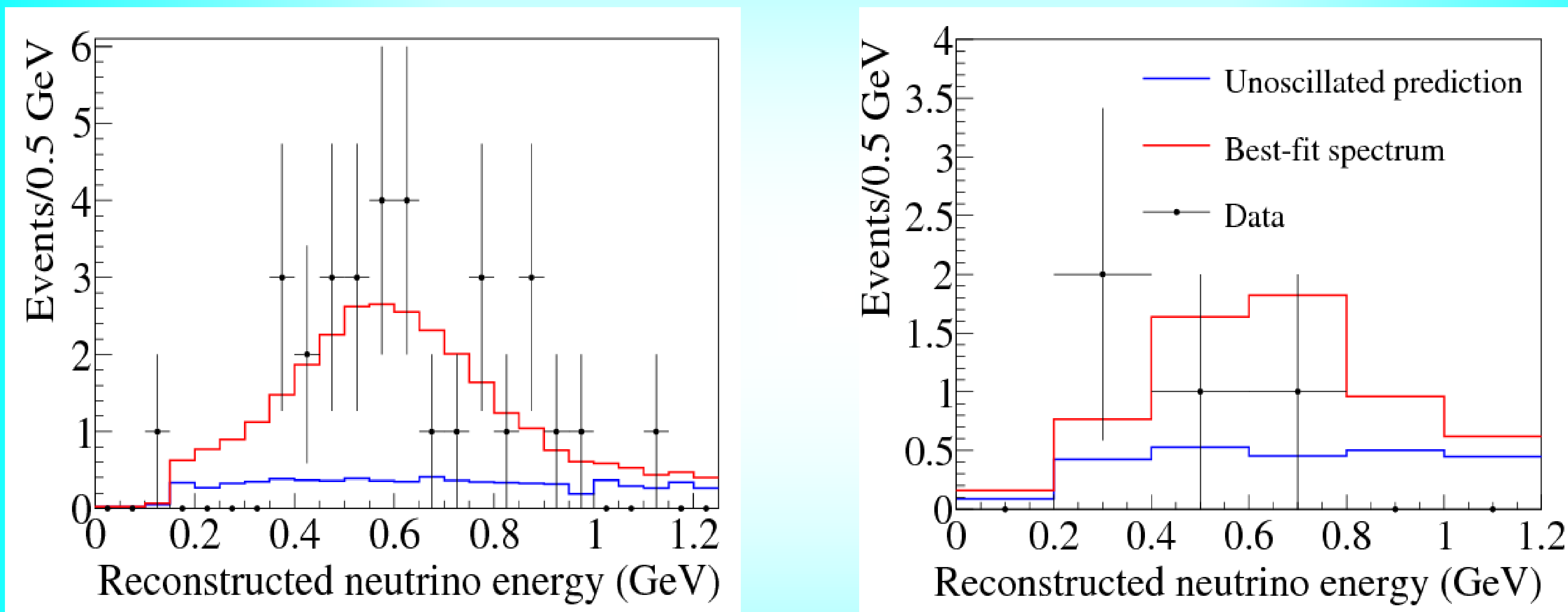




T2K

T2K appearance signal

T2K Collaboration (Abe, K. et al.) arXiv:1701.00432 [hep-ex]

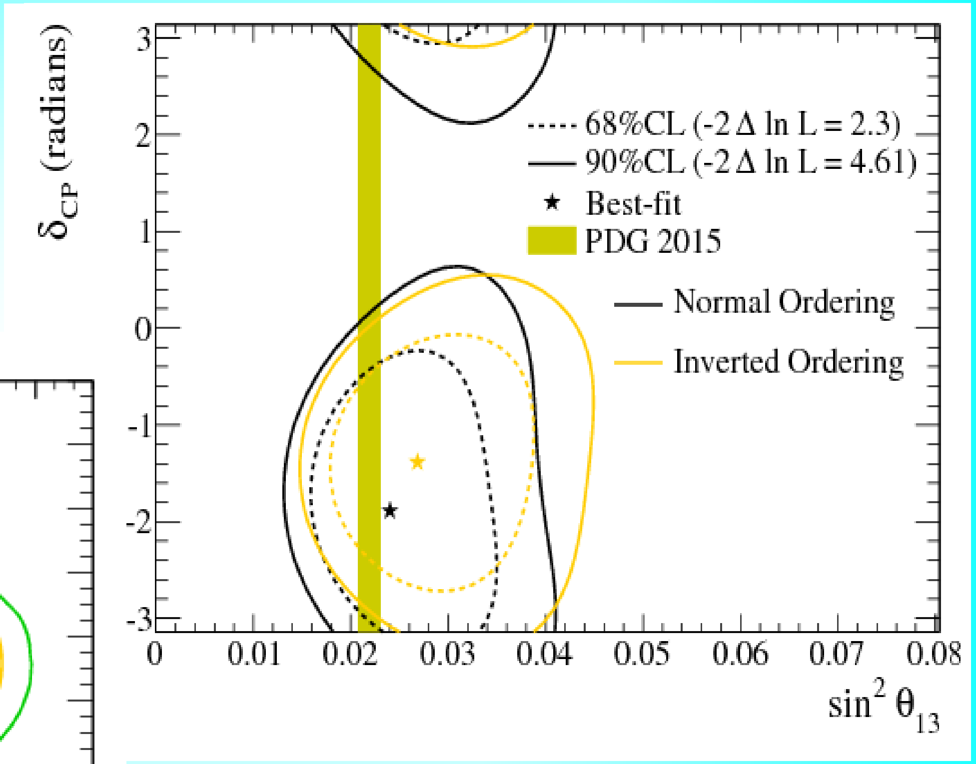


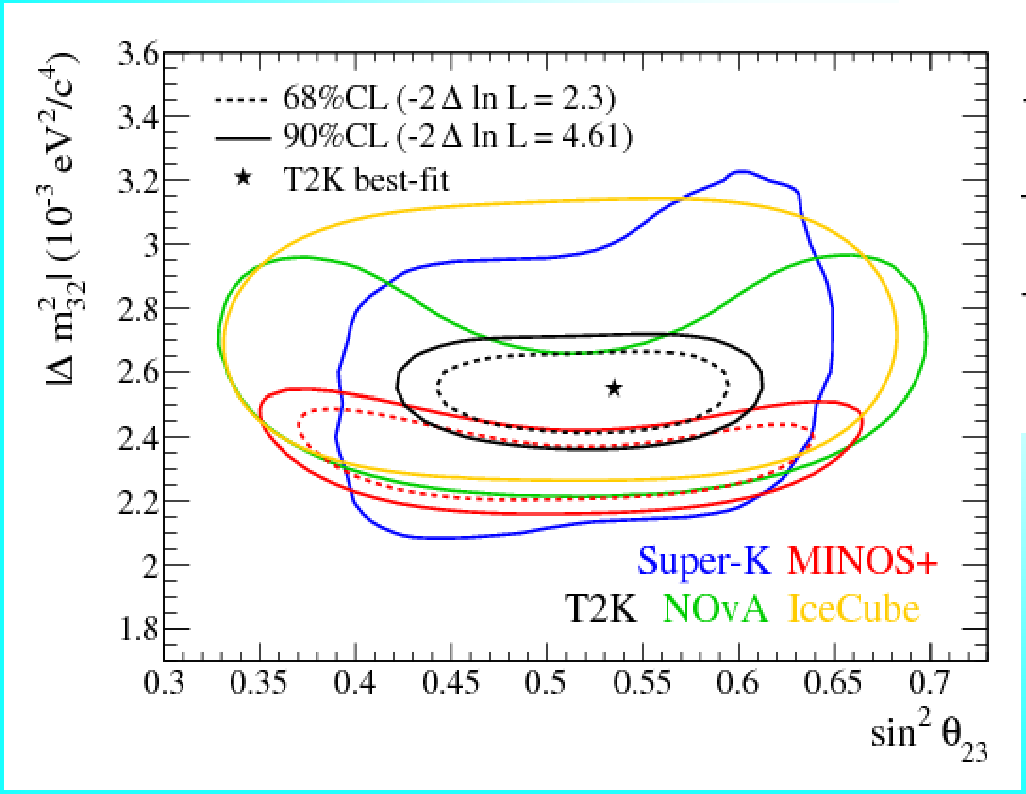
The reconstructed neutrino energy at the far detector for the νe (left) and νe (right) candidate samples . The expected distribution without oscillation (blue histogram) and the best fit (red histogram).

T2K results

T2K Collaboration (Abe, K. et al.) arXiv:1701.00432 [hep-ex]

2-3 mixing (disappearance)
CP-phase



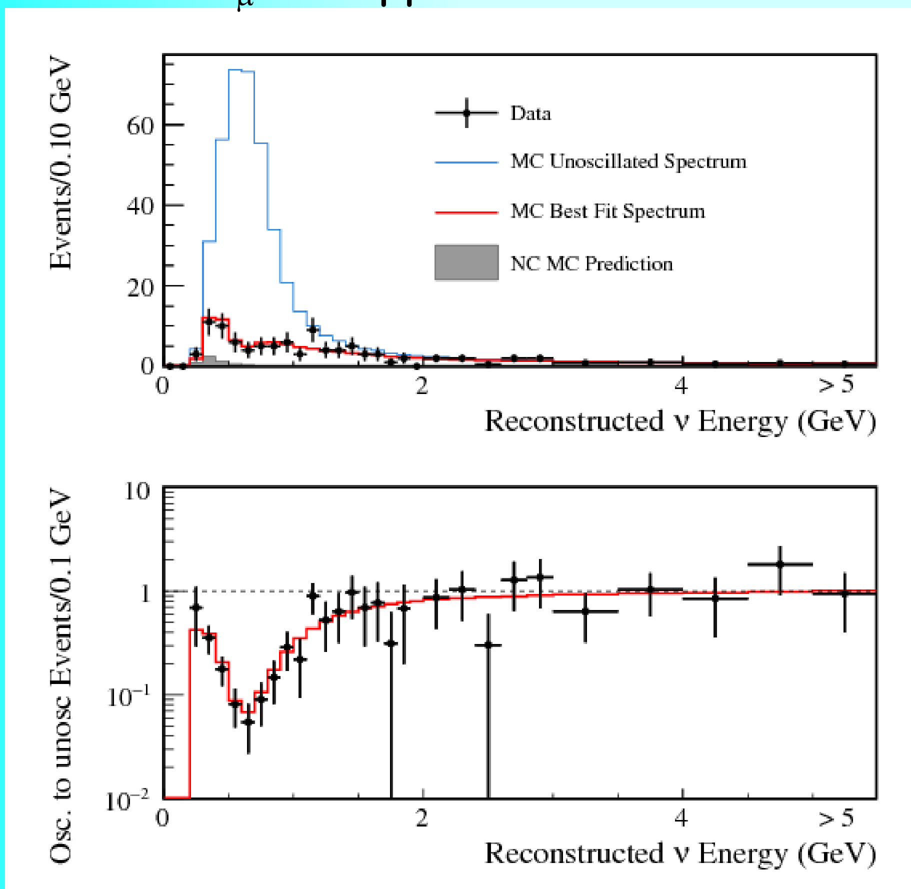


T2K

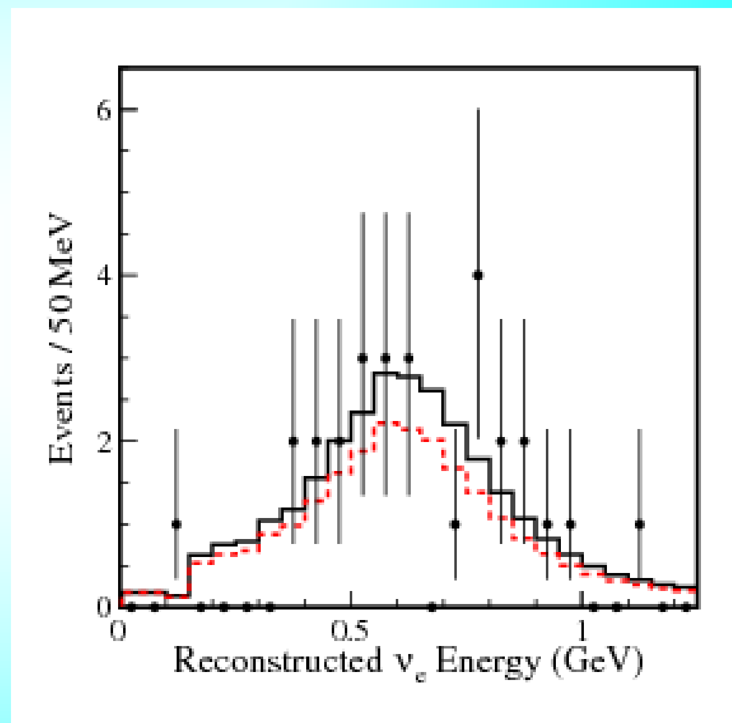
T2K Collaboration (K. Abe et al.).
Phys.Rev. D91 (2015) 7, 072010
arXiv:1502.01550 [hep-ex]

6.6×10^20 POT

ν_μ -disappearance

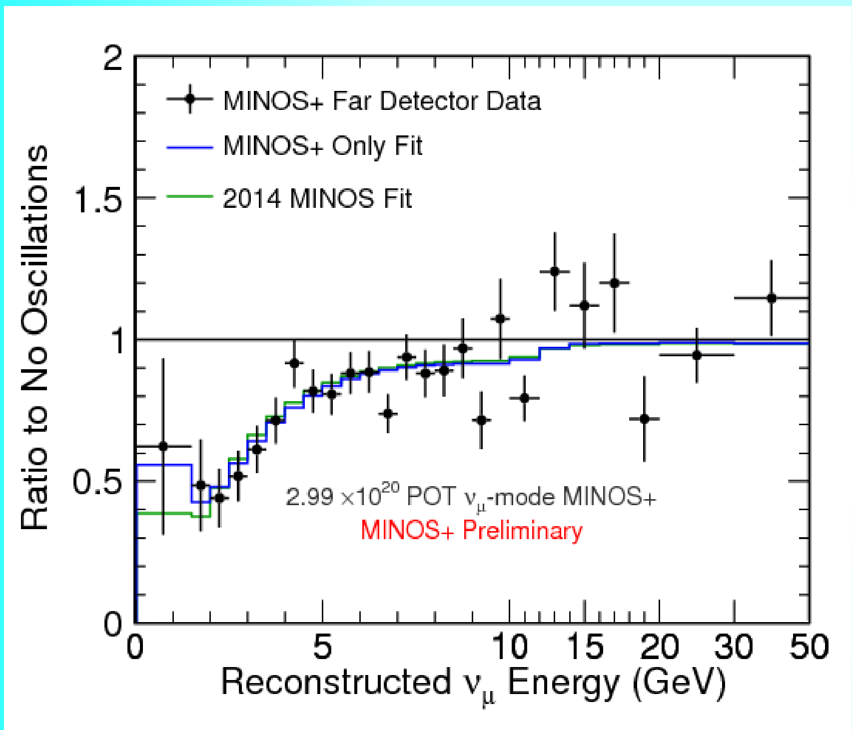


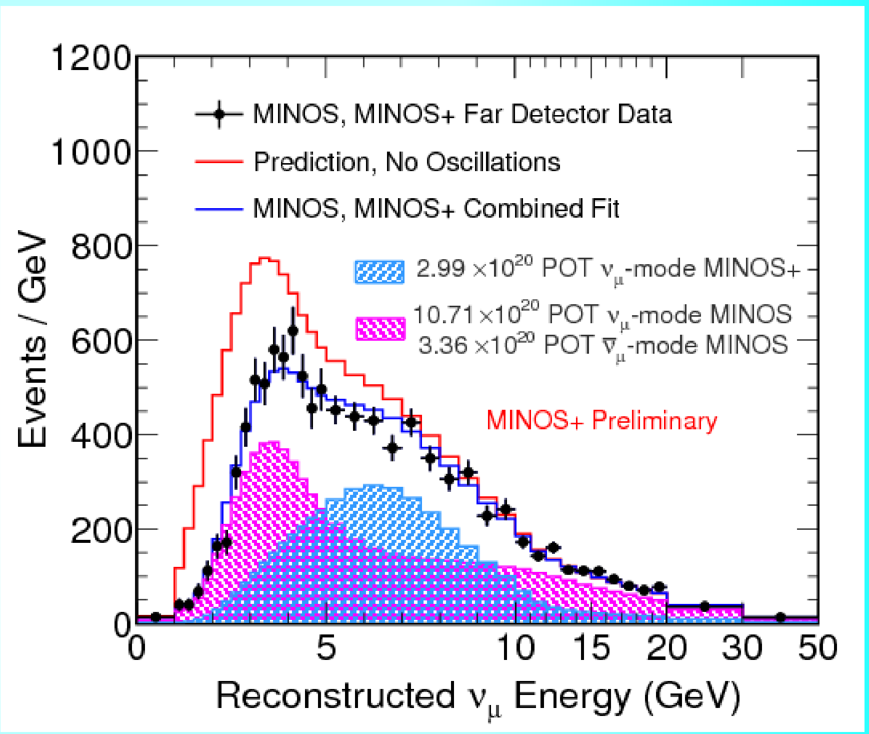
ν_e - appearance



MINOS and MINOS+

MINOS Collaboration (Whitehead, Leigh H. for the collaboration) arXiv:1601.05233 [hep-ex]

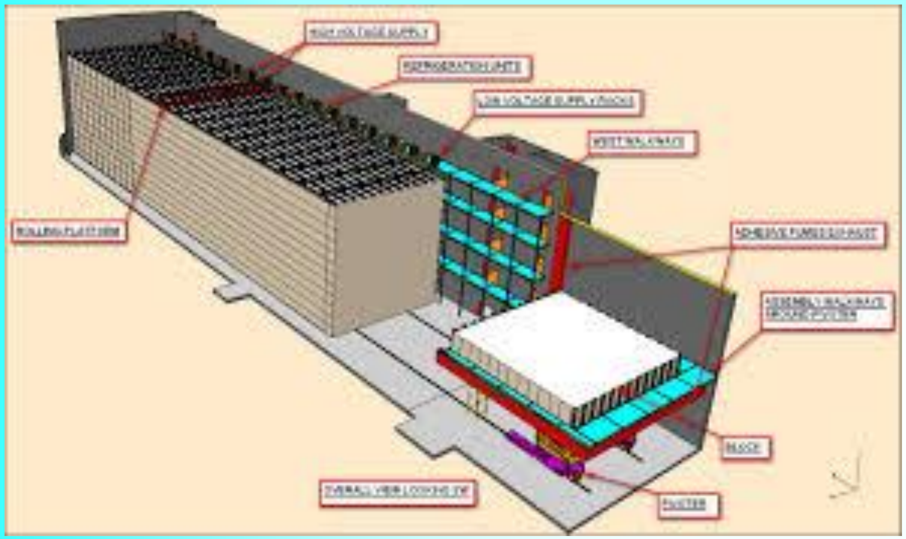


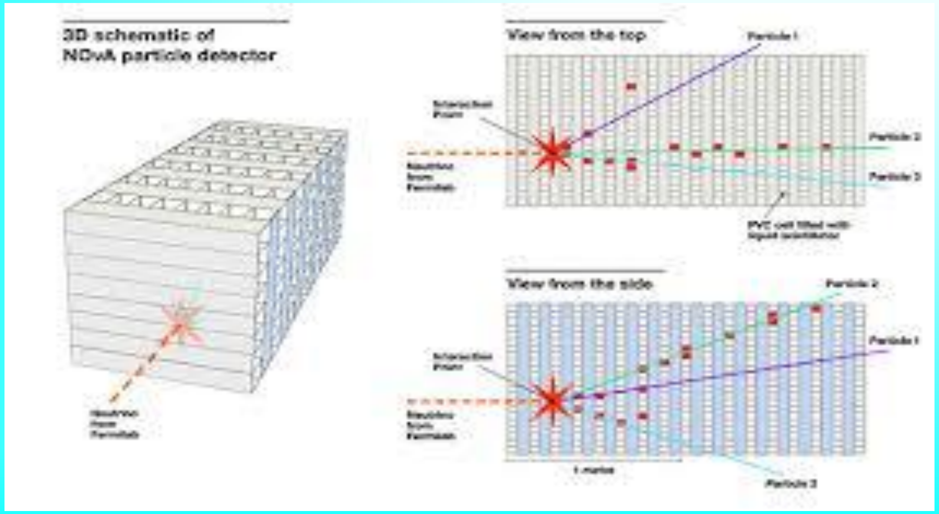


The reconstructed CC numu energy spectrum for beam neutrinos for MINOS+

The reconstructed CC numu energy spectrum for beam neutrinos in MINOS and MINOS+.

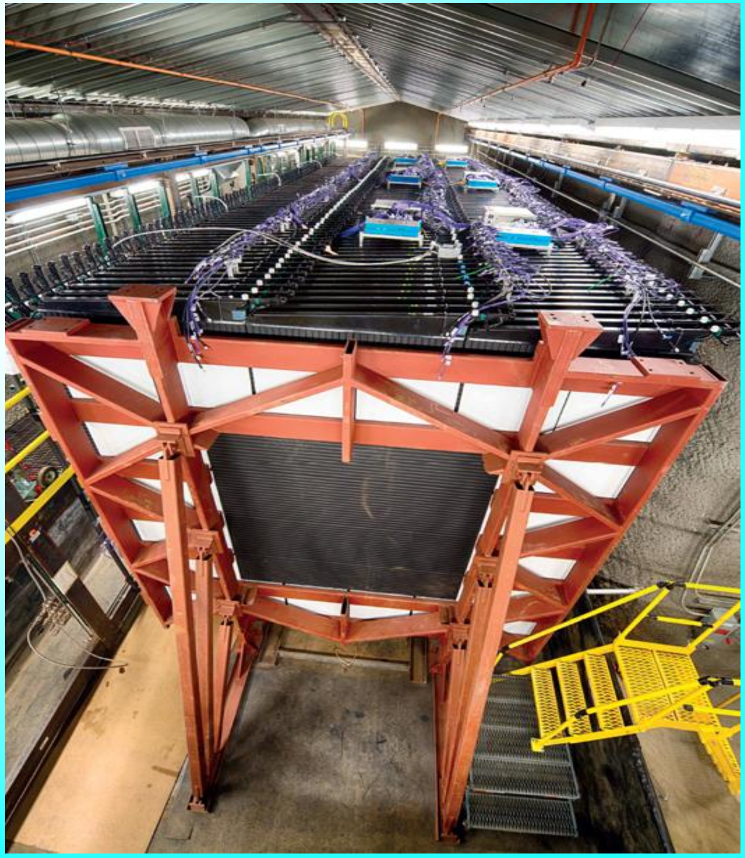
NOvA





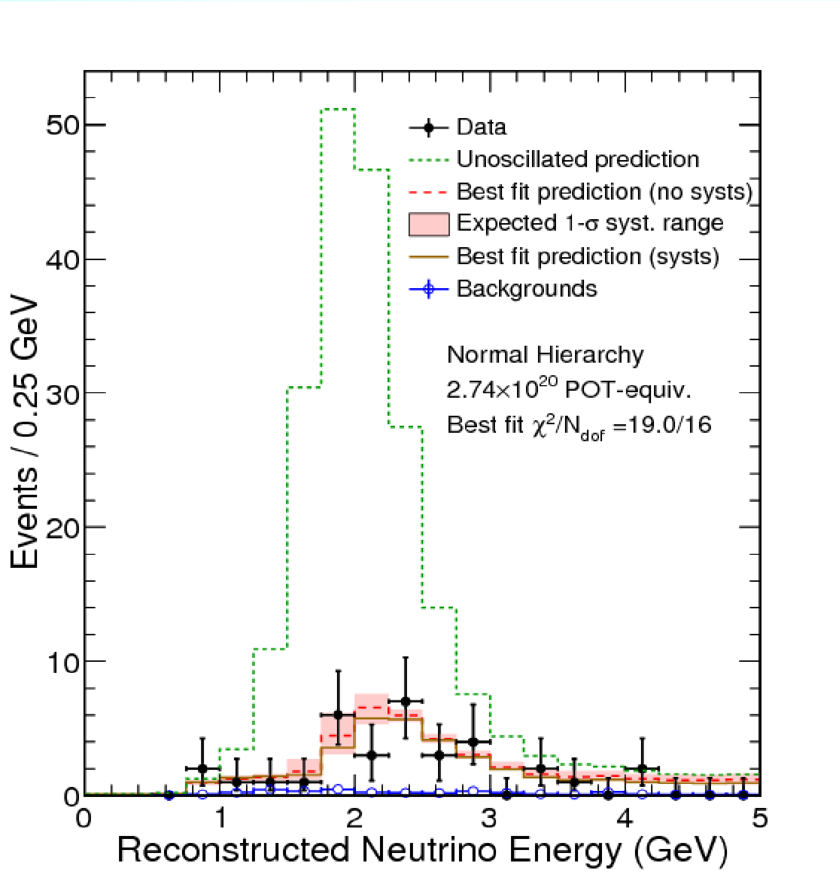
FNAL – Ash River
L = 810 km, 14 kton
off axis 3.3°
E = 1 - 3 GeV

$\nu_\mu - \nu_e$ oscillations in matter



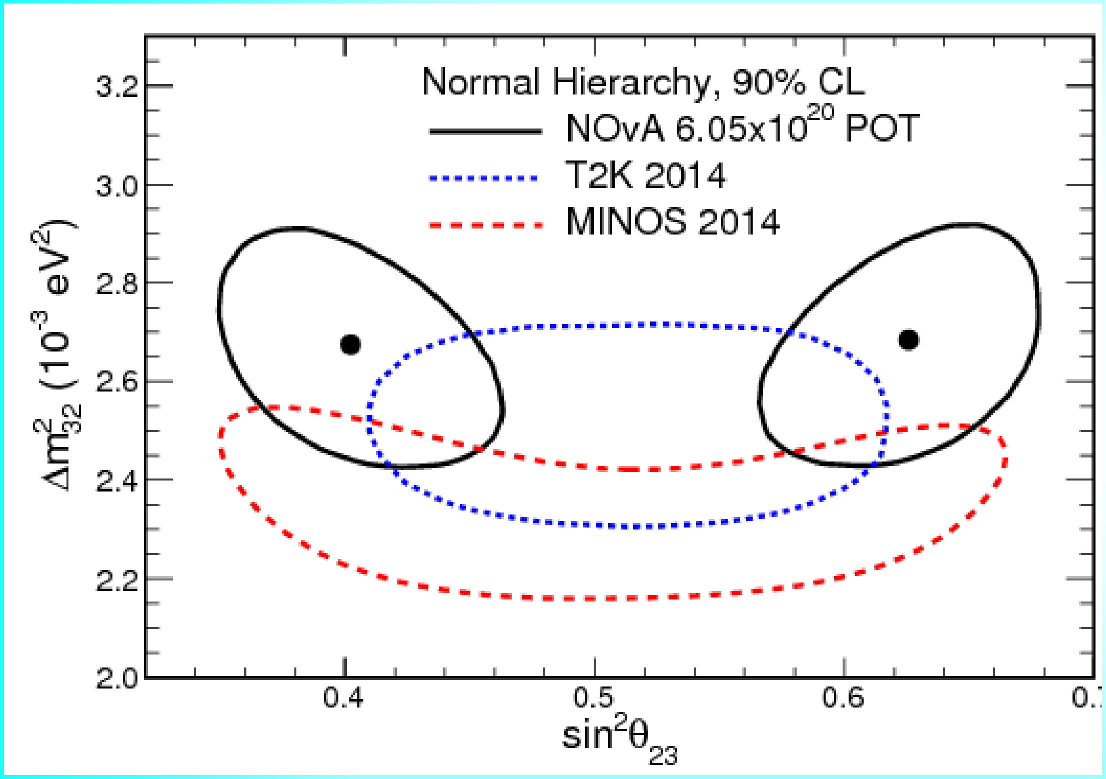
NOvA results

NOvA Collaboration (P. Adamson)
1601.05037 [hep-ex]



NOvA: 2-3 mixing

NOvA Collaboration
(Adamson, P. et al.)
arXiv:1701.05891 [hep-ex]



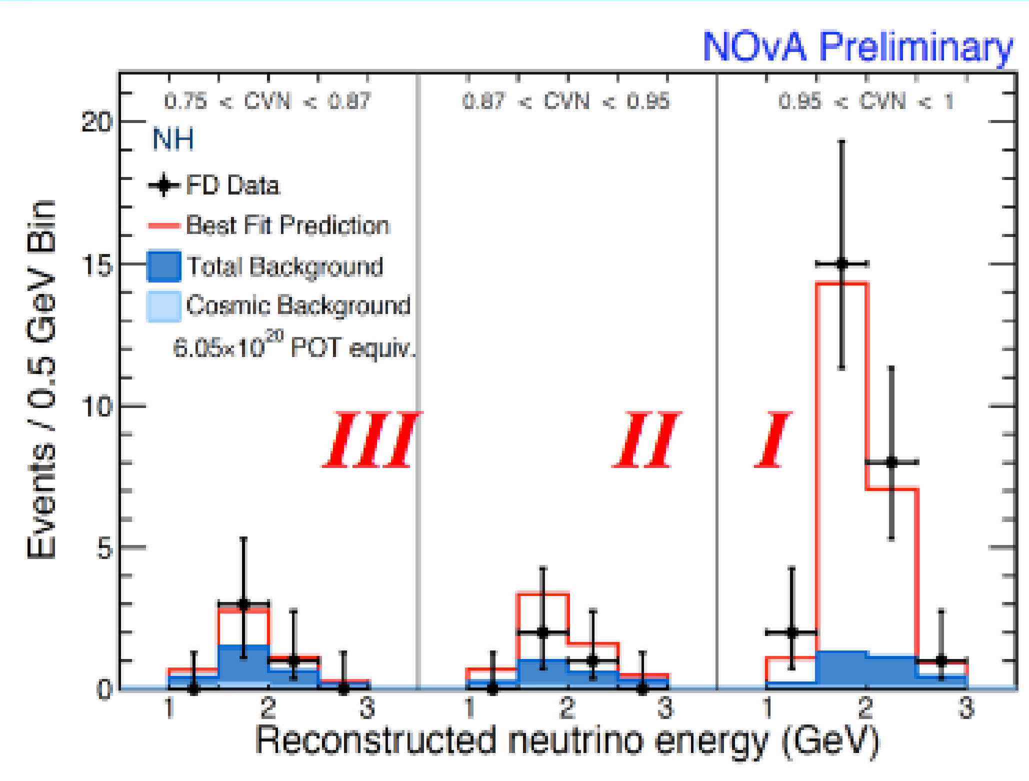
$\Delta m^2 = (2.67 \pm 0.11) \times 10^{-3}\ eV^2$

$\sin^2 \theta_{23}$ =
0.404+0.030/−0.022 and
0.624+0.022−0.030, at 68% CL.

Maximal mixing is disfavored with 2.6 σ

NOvA 2 years data

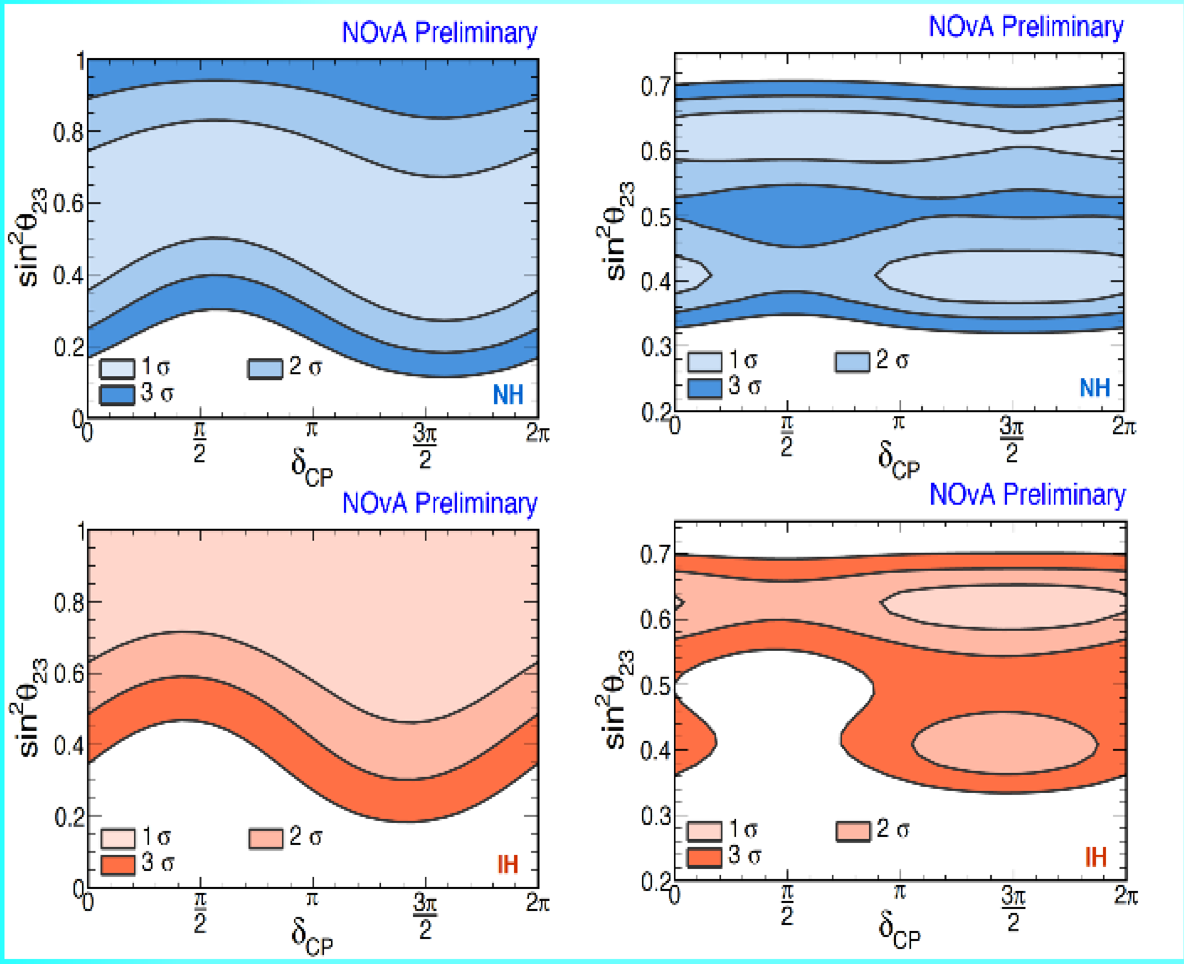
Jianming Bian, arXiv:1611.07480 [hep-ex]



The reconstructed energy spectrum of νe CC selected events in the far detector. Black points: FD data, red histogram: the best fit prediction, blue shaded histograms: background MC.

NOvA 2 years data

Jianming Bian,
arXiv:1611.07480 [hep-ex]



Allowed regions of The 2-3 mixing and CP phase at 1, 2, and 3σ: (left) results from νe appearance data and (right) results from the combination of νe appearance and $\nu\mu$ disappearance data.

appearance + disappearance

Non-standard interactions?

2-3 mixing: 2.5 σ tension

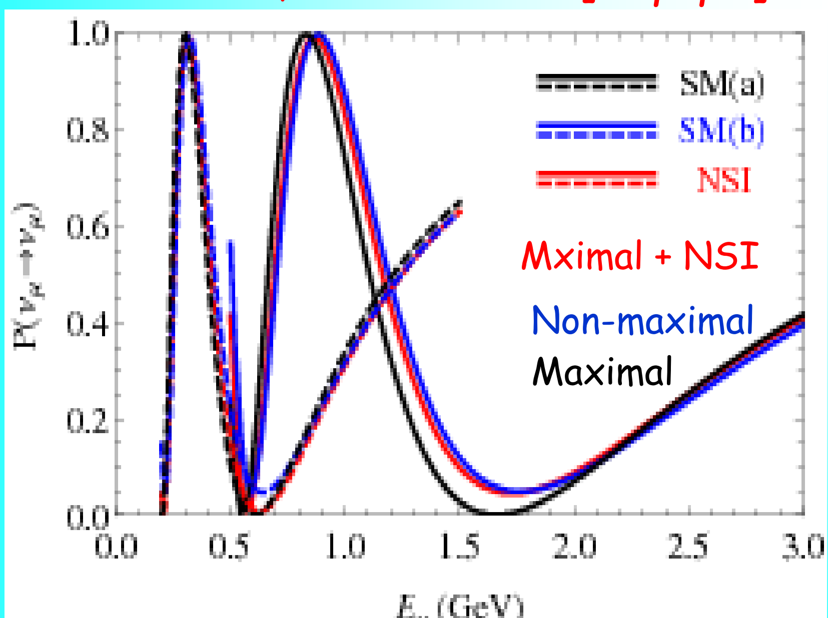
Maximal: T2K,
SK atmospheric, Deep Core

Non-maximal: NOvA, MINOS
more matter

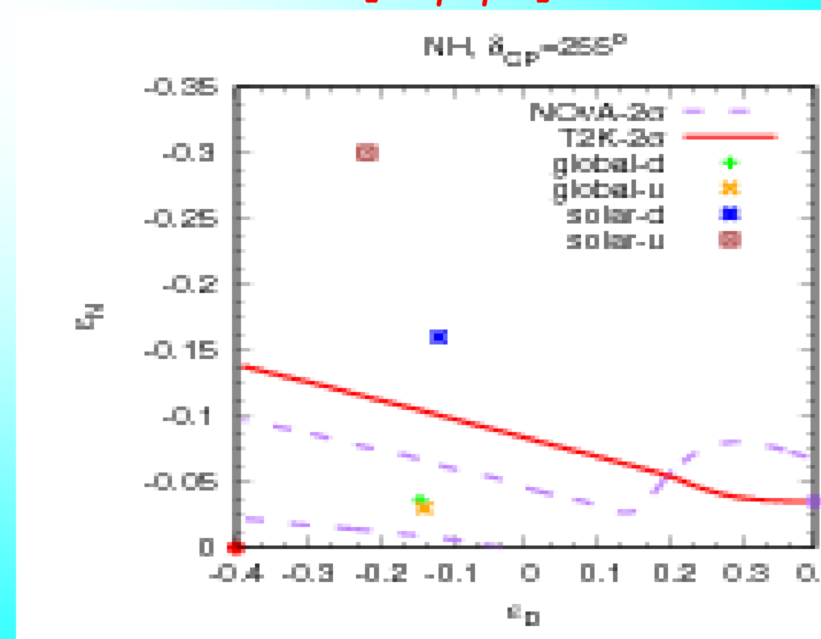
Standard interactions do not help → Non-standard interactions

J. Liao, D Marfatia, K .Whisnant, 1609.01786 [hep-ph]

S. Fukasawa, M. Ghosh O. Yasuda 160904204 [hep-ph]

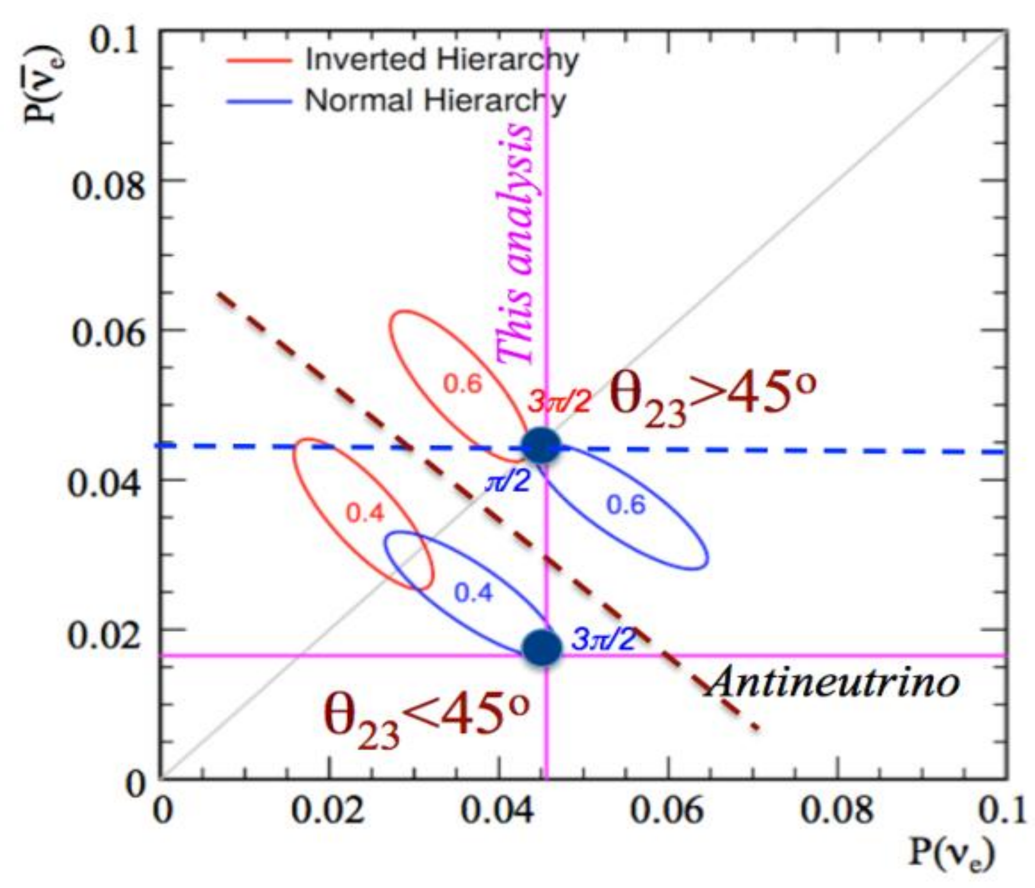


$\varepsilon_{\tau\tau}$ = 1.4



NOvA 2 years data

Jianming Bian,
arXiv:1611.07480 [hep-ex]



The principle of the NOvA *νe* (ν‾ *e*) appearance measurements. All possible values of probabilities of *νμ*→*νe* vs. *ν‾ μ*→*ν‾ e* are on the ellipses. The solid blue (red) ellipses correspond to the normal (inverse) hierarchy with *δCP* varying as one moves around each ellipse.