2.

Determination of mass & mixing

Two effects

Solar neutrinos

KamLAND

Atmospheric neutrinos

Double Chooz

Daya Bay

MINOS

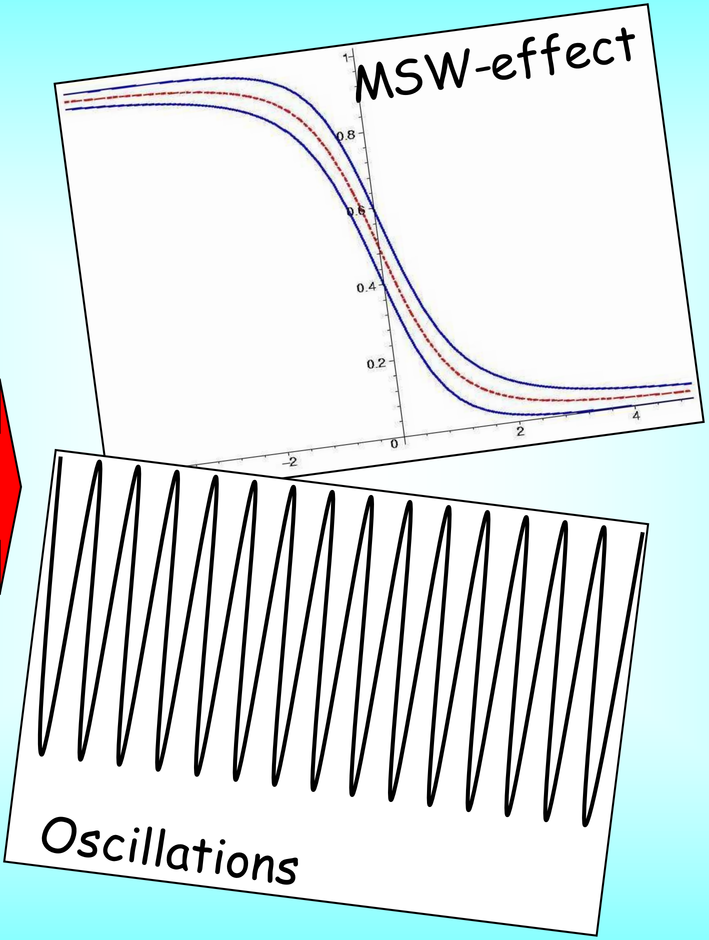
K2K

RENO

T2K

Antares

DeepCore



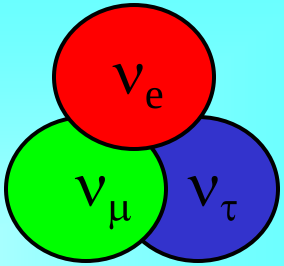
Δm^2

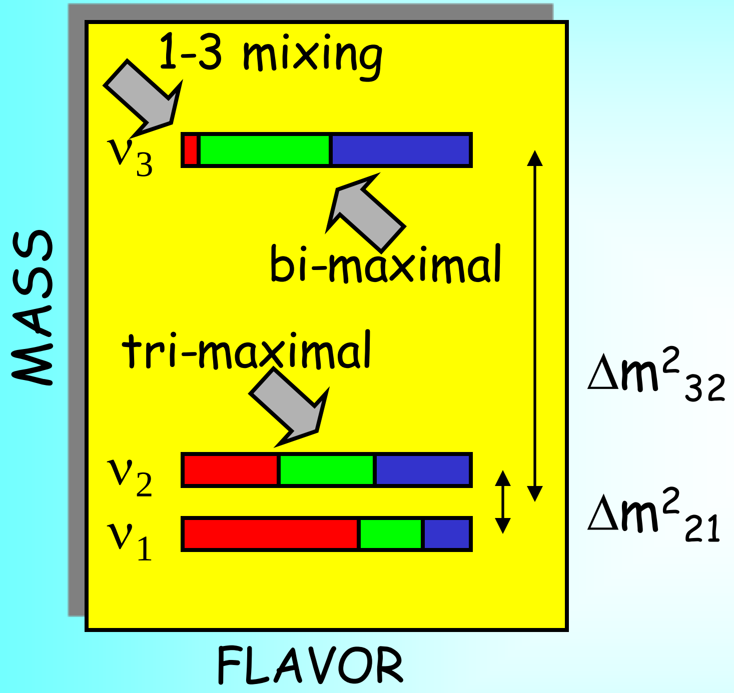
θ

Can be resonantly
enhanced in matter

			Dominant mode
Solar neutrinos	ν_e - ν_e	MSW-effect (HE) Av. oscillations (LE)	1 - 2
KamLAND	ν_e - ν_e	Vacuum oscillations	1 - 2
Atmospheric neutrinos SK	ν_μ - ν_μ ν_μ - ν_τ	~ Vacuum oscillations	1 - 3
Antares DeepCore	ν_μ - ν_μ		
MINOS	ν_μ - ν_μ ν_μ - ν_e	~ Vacuum oscillations	1 - 3
K2K	ν_μ - ν_μ		
Double Chooz Daya Bay RENO	ν_e - ν_e	Vacuum oscillations	1 - 3
T2K	ν_μ - ν_e ν_μ - ν_μ	~ Vacuum oscillations	1 - 3

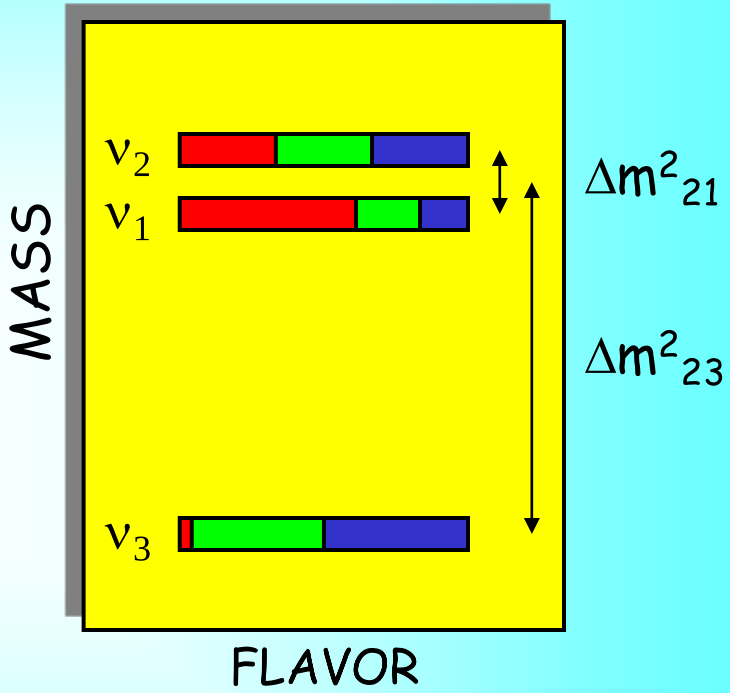
Mixing & masses





Normal mass hierarchy

?



Inverted mass hierarchy

Two large mixings

~ Tri-bimaximal mixing

Symmetry?

ν_μ - ν_τ symmetry

Invariance under U, S transformations in the flavor basis

$\Delta m^2_{32} = 2.3 \times 10^{-3}\ \mathrm{eV}^2$

$\Delta m^2_{21} = 8 \times 10^{-5}\ \mathrm{eV}^2$

Tri-bimaximal mixing

L. Wolfenstein

P. F. Harrison
D. H. Perkins
W. G. Scott

In the first approximation

$$U_{tbm} = \begin{array}{cc} \begin{pmatrix} \sqrt{2/3} & \sqrt{1/3} & 0 \\ -\sqrt{1/6} & \sqrt{1/3} & -\sqrt{1/2} \\ -\sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \end{pmatrix} & \begin{array}{c} 0.15 \\ 0.62 \\ 0.78 \end{array} \end{array}$$

ν_3 is bi-maximally mixed

ν_2 is tri-maximally mixed

$U_{tbm} = U_{23}(\pi/4)\, U_{12}$

- maximal 2-3 mixing
- zero 1-3 mixing
- no CP-violation
- $\sin^2\theta_{12} = 1/3$

Uncertainty related to sign of 2-3 mixing:

$\theta_{23} = \pi/4 \rightarrow -\pi/4$

Symmetry from mixing matrix

Huge impact of small angle

U_{e3}

theoretical implications

symmetry

atmospheric neutrinos

dominant factor
for SN neutrinos

door to determination of
CP-violation
mass hierarchy

Discovering U_{e3}

Global fit
Solar vs KamLAND

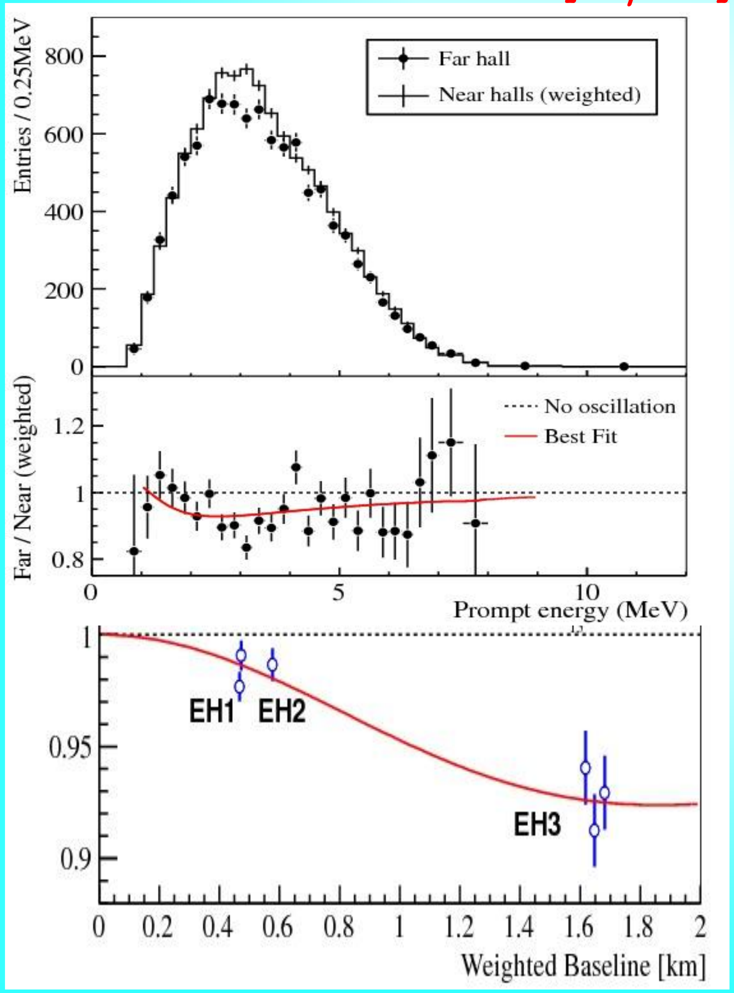
MINOS

T2K

Double-CHOOZ

Daya Bay

arXiv:1203.1669 [hep-ex]

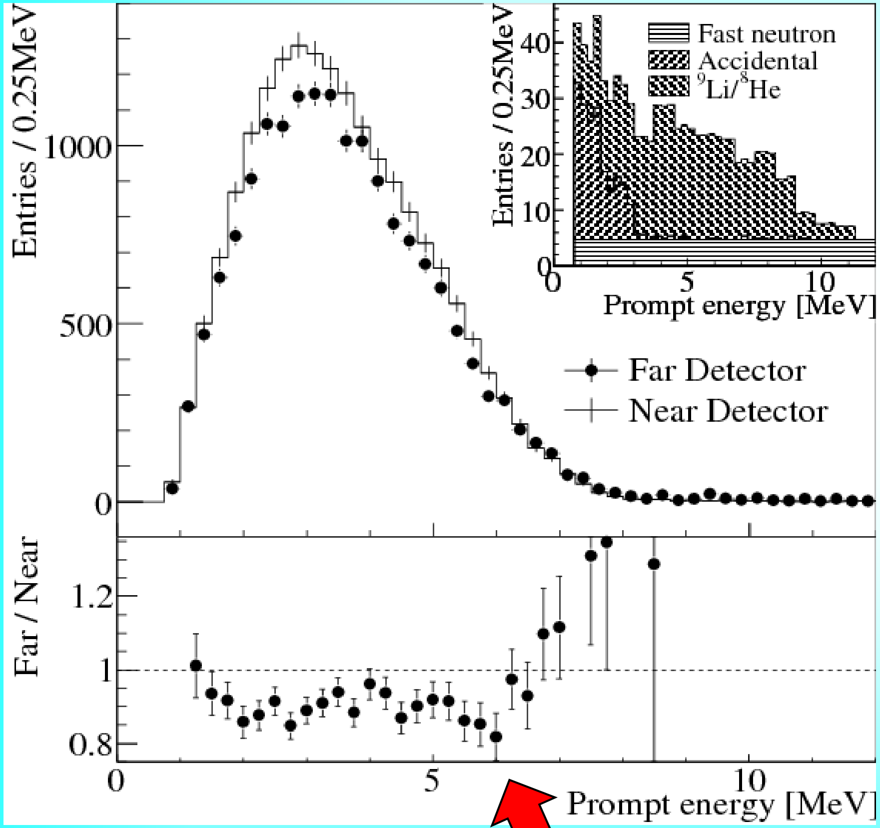


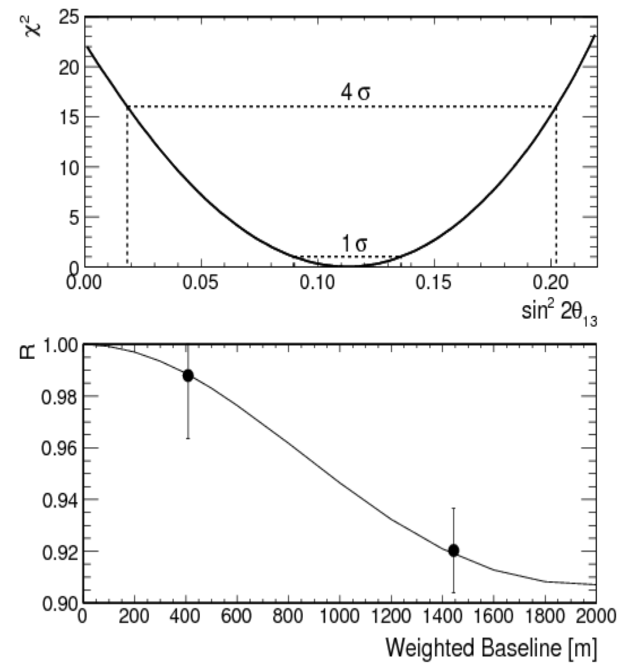
W = 2.9 GW (each of 6 reactor)

AD (antineutrino detectors)

EH (experimental halls)

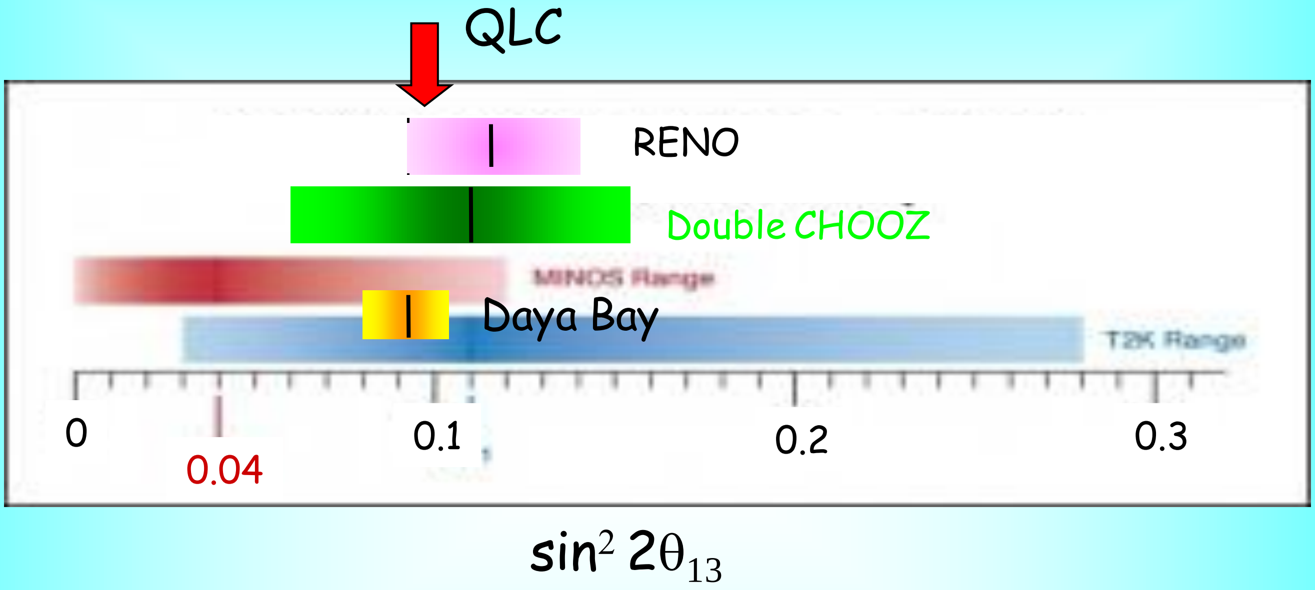
RENO


Entries / 0.25MeV
1000
500
0
Far / Near
1.2
1
0.8
0
5
10
Prompt energy [MeV]
Far Detector
Near Detector
Entries / 0.25MeV
40
30
20
10
0
0
5
10
Prompt energy [MeV]
Fast neutron
Accidental
^{9}Li/^{8}He


χ^2
25
20
15
10
5
0
4 σ
1 σ
0.00
0.05
0.10
0.15
0.20
$\sin^2 2\theta_{13}$
R
1.00
0.98
0.96
0.94
0.92
0.90
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Weighted Baseline [m]

???

Direct measurements of 13 mixing



Daya Bay: 0.092 +/- 0.012

RENO: 0.116 +/- 0.024

> 6σ from 0

Important: Daya Bay, RENO and T2K
(different energies, setups..) give the same value of the angle

Deviation of 2-3 mixing from maximal

$d_{23} = \frac{1}{2} - \sin^2\theta_{23}$

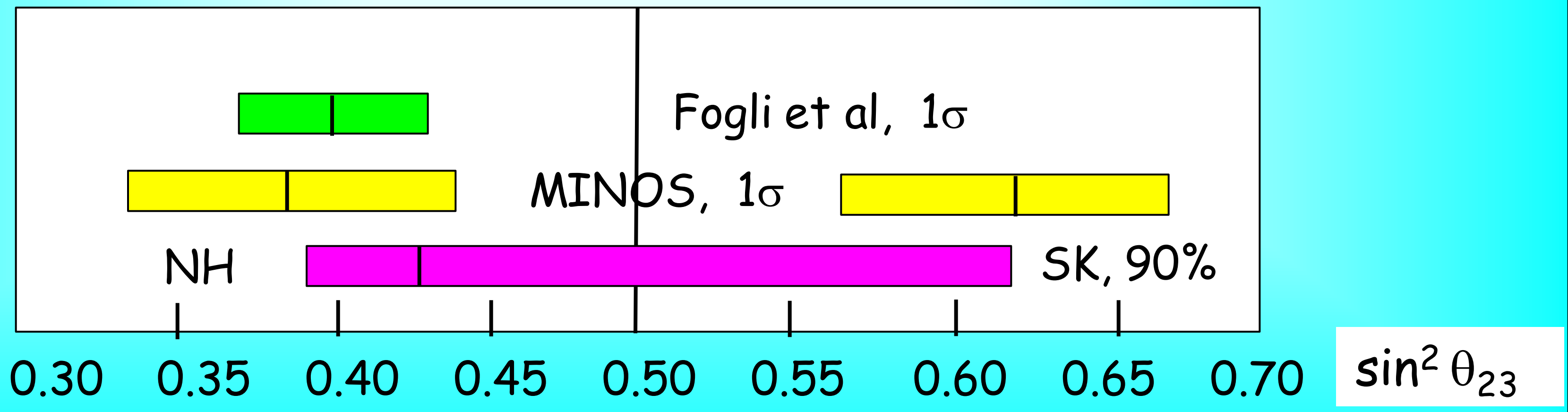
the key to (probe)
understand the
underlying physics

$\nu_\mu - \nu_\tau$ symmetry violation

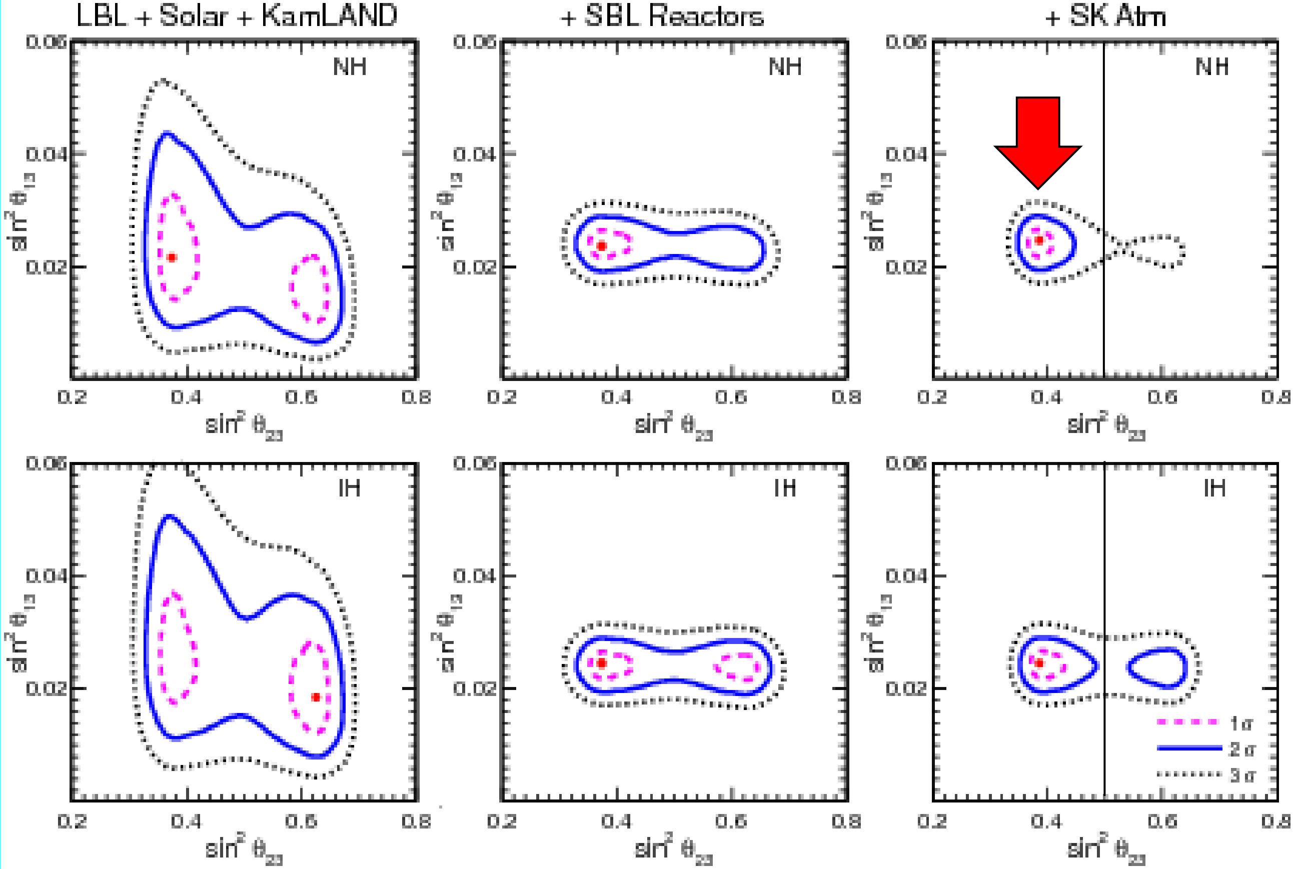
Connection to 1-3 mixing

Quark -Lepton Complementarity

$\theta_{23} \sim \pi/2 - V_{cb}$

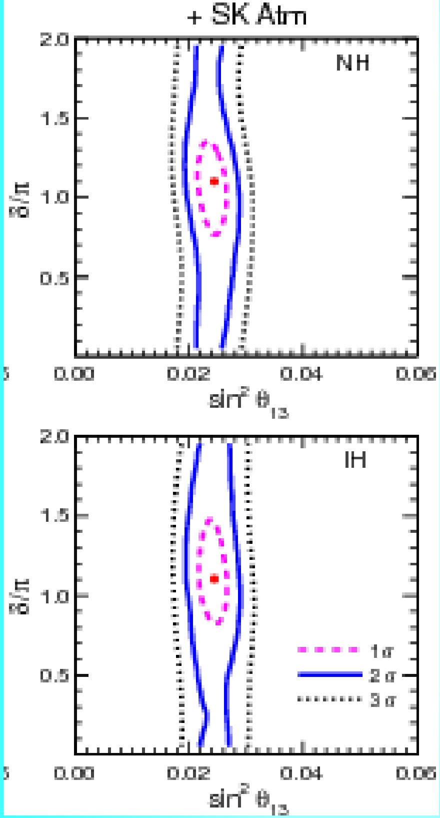


2-3 deviation and quadrant



Global fit of oscillation data

CP-phase: measurements and predictions



G. L. Fogli

Third way

Neutrino-antineutrino asymmery

Dependence of probabilities on energy in wide range

Reconstruction of unitarity triangle

Key measurement: amplitudes of the ν_μ - ν_μ oscillations due to solar and atmospheric mass splittings

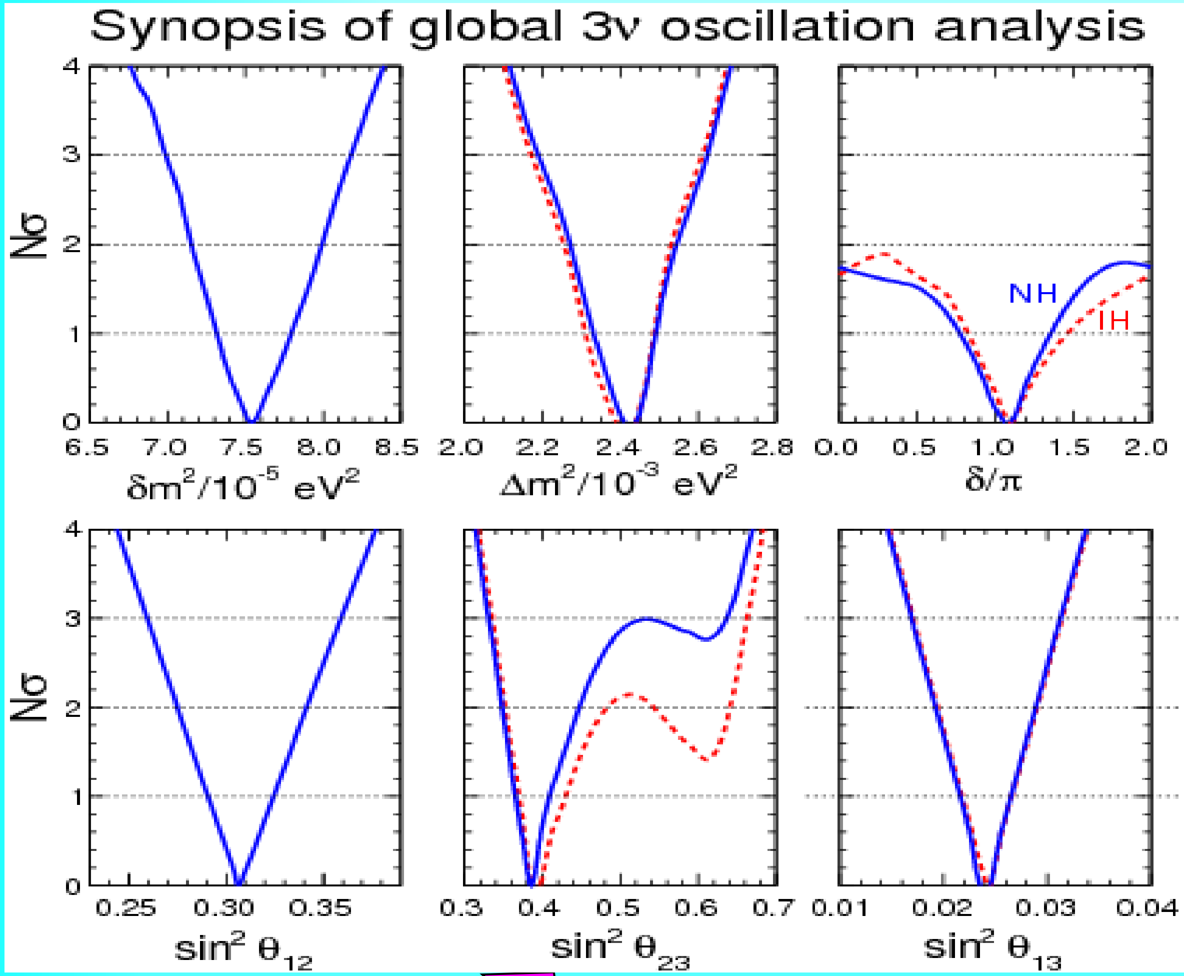
Do we have predictions for the phase in quark sector?
Why do we think that we can predict leptonic mixing?
Again because of neutrinos are special ? Symmetries?

First glimpses?

T. Yanagida δ_{CP} ~ $\pi/2$ +/- 0.02

Synopsis

G. L. Fogli



Serious implications for theory

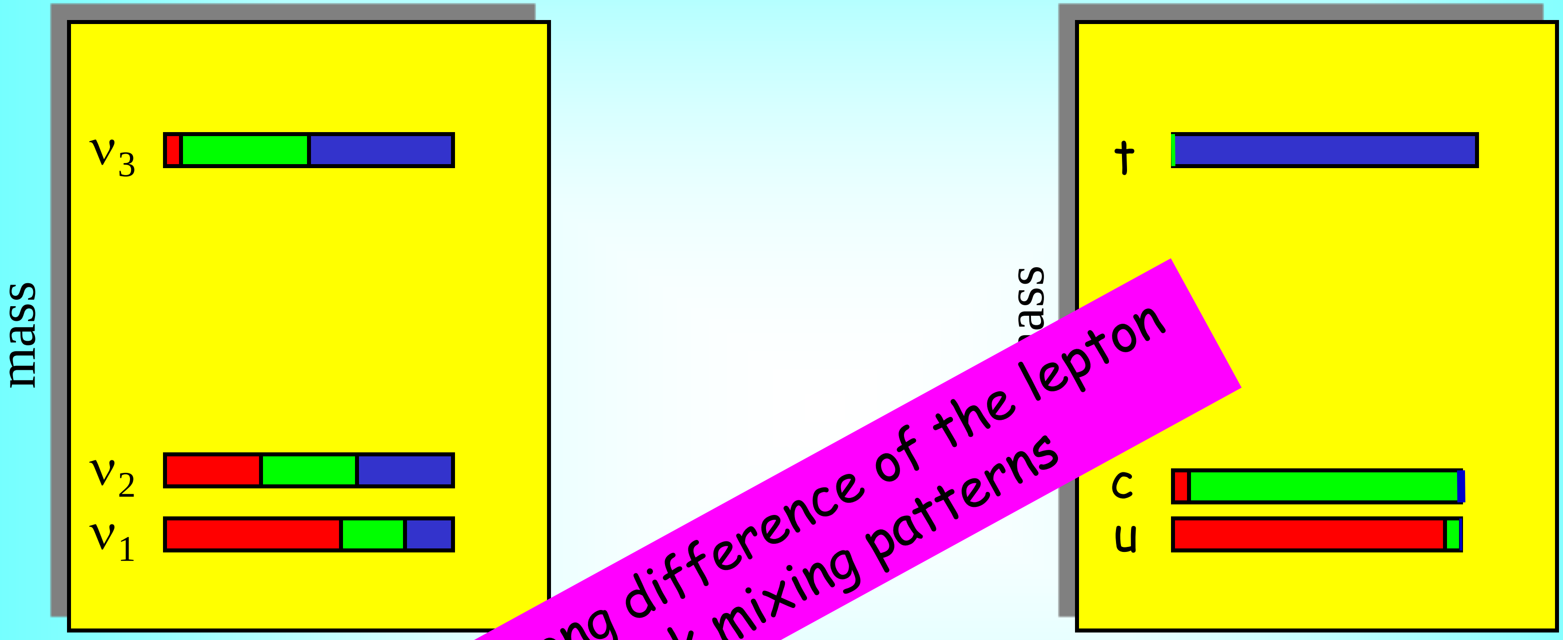
Non-zero, relatively Large 1-3 mixing

Substantial deviation of the 2-3 mixing from maximal

$\delta_{CP} \sim \pi$

Robust ?

Leptons versus quarks



Strong difference of the lepton and quark mixing patterns

Leptons

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

Quarks

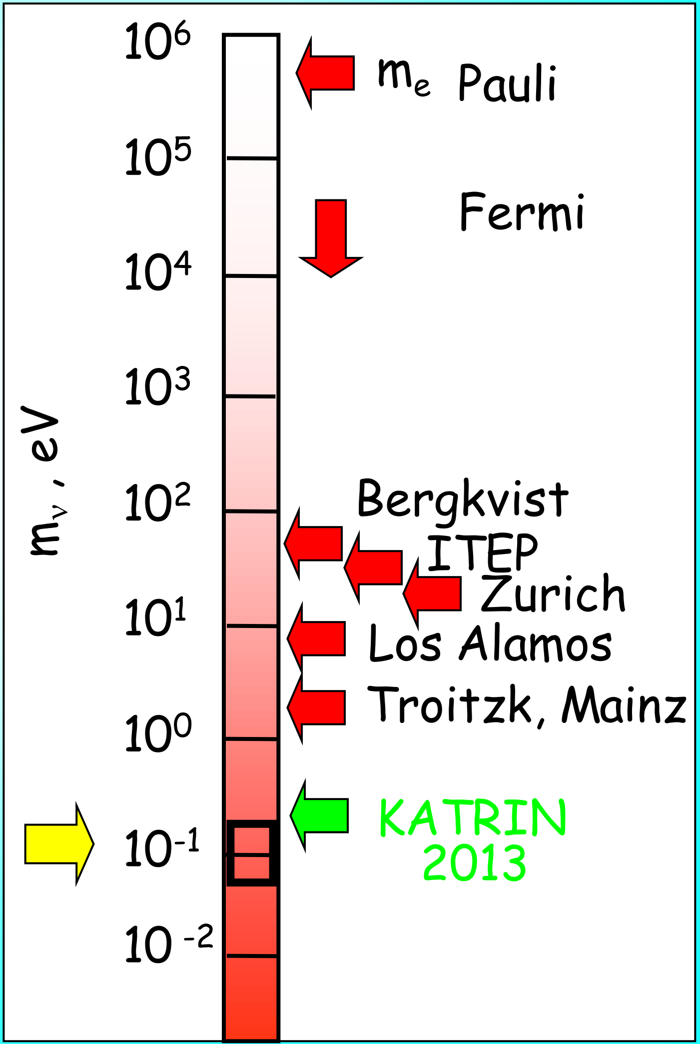
$U_d = U_{CKM}^{+}\, U$

$U = (u, c, t)$

combination of down-quarks
produced with a given up quark

Mass scale

Kinematical methods



Oscillations,
& cosmology

the heaviest neutrino has mass is in the range (0.045 - 0.10) eV

Oscillations: $\frac{m_2}{m_3} \gtrsim 0.18$ the weakest mass hierarchy

Cosmological bounds

ΛCDM

- WMAP 7yr
- SDSS III 8th data release
- Hubble space telescope H

R. De Putter et al, arXiv: 1201.1909 [astro-ph.CO]

$\Sigma m < 0.26$ eV (95 % CL)

Conservative bias

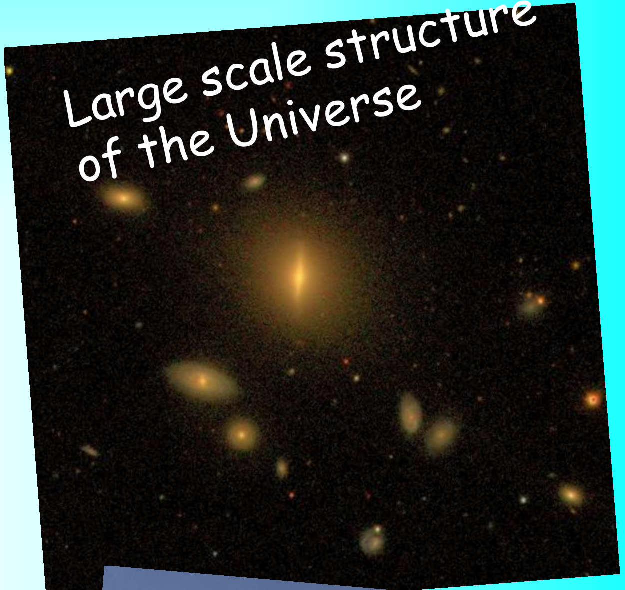
$\Sigma m < 0.36$ eV (95 % CL)

- WMAP 7yr
- Observable Hubble parameter data (OHD)
- H_0 (in correlation with σ_8)

M. Moresco, et al., arXiv:1201.6658 [astro-ph.CO]

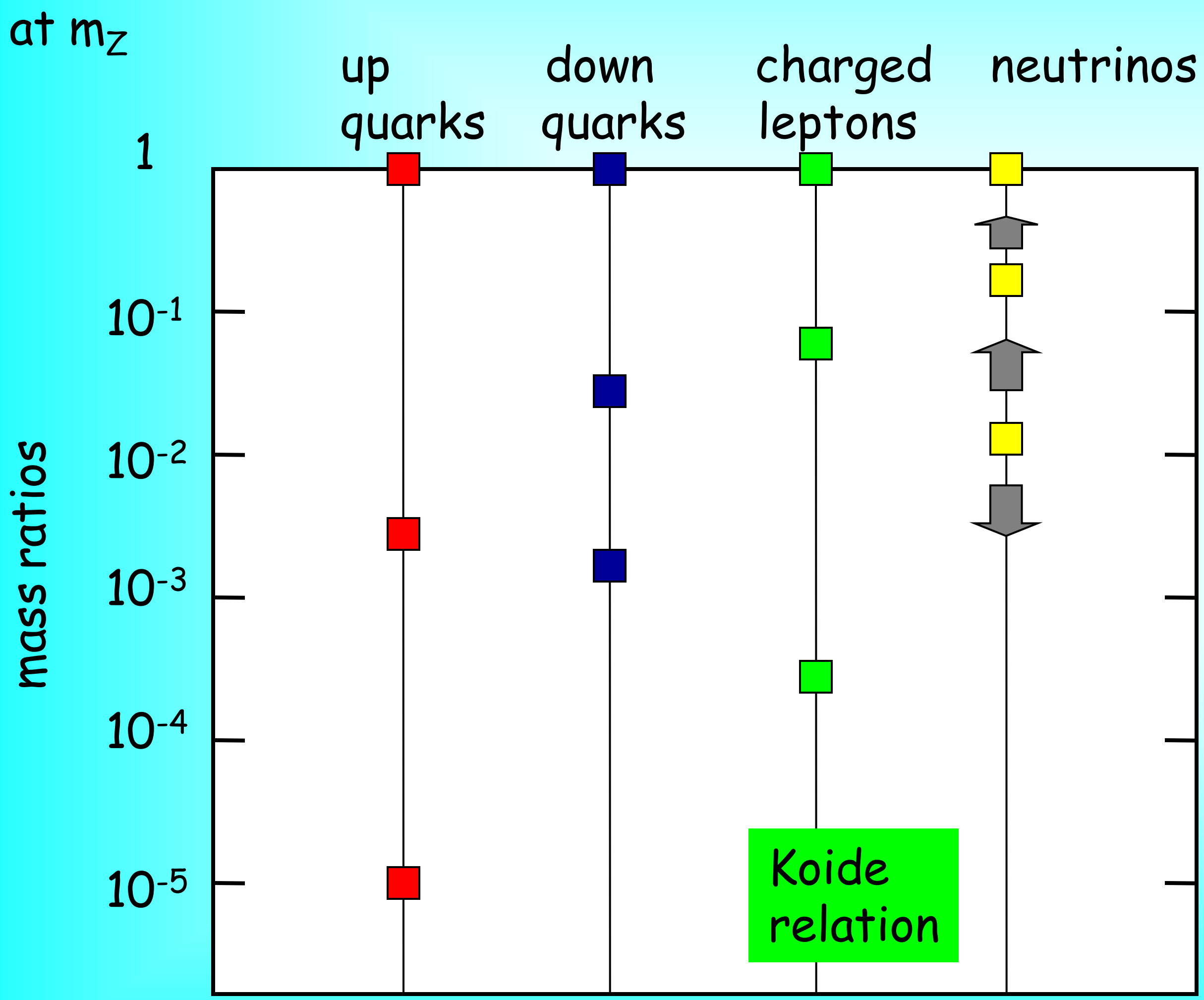
$\Sigma m < 0.24$ eV (68 % CL)

Future: $\Sigma m < 0.08$ eV



Large scale structure of the Universe

Mass hierarchies



Solar, KamLAND

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

~ 0.18

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

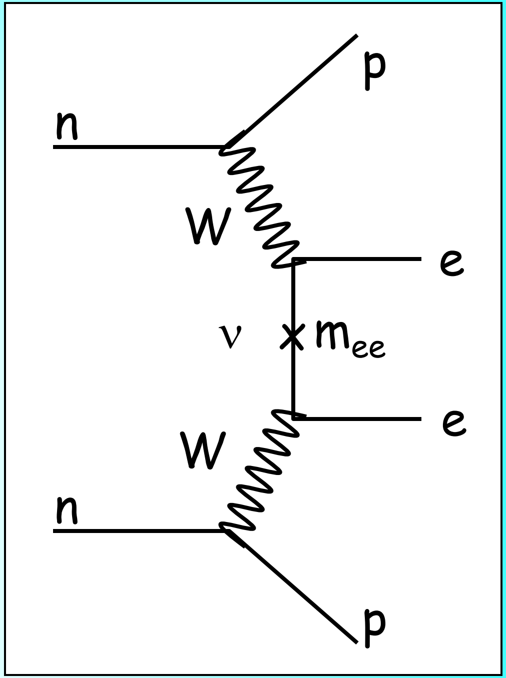
Related to the large lepton mixing?

$m_u\, m_t = m_c^2$

$\sin\theta_C \sim \sqrt{m_d/m_s}$ Gatto-Sartori-Tonin relation

Double beta decay

$$m_{ee} = U_{e1}^2\, m_1 + U_{e2}^2\, m_2\, e^{\iota\alpha} + U_{e3}^2\, m_3\, e^{\iota\beta}$$



$$m_{ee} = \Sigma_k\, U_{ek}^2\, m_k\, e^{i\phi(\kappa)}$$

In terms of the lightest mass eigenstate

$$\begin{aligned} m_{ee} = {} & U_{e1}^2\, m_1 \\ & + U_{e2}^2\, (\Delta m_{21}^2 + m_1^2)^{1/2}\, e^{\iota\alpha} \\ & + U_{e3}^2\, (\Delta m_{31}^2 + m_1^2)^{1/2}\, e^{\iota\beta} \end{aligned}$$

Normal mass hierarchy

$$\begin{aligned} m_{ee} = {} & U_{e1}^2\, (\Delta m_{13}^2 + m_3^2)^{1/2} \\ & + U_{e2}^2\, (\Delta m_{23}^2 + m_3^2)^{1/2}\, e^{\iota\alpha} \\ & + U_{e3}^2\, m_3\, e^{\iota\beta} \end{aligned}$$

Inverted mass hierarchy

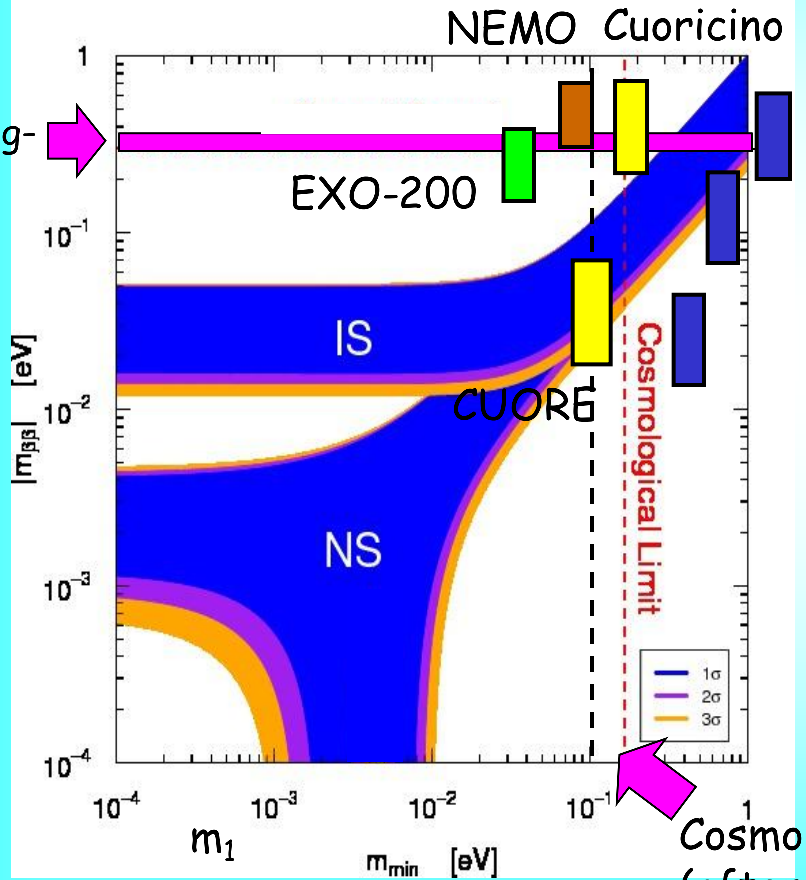
Strong mass hierarchy:

$$m_{ee} \sim U_{e2}^2\, (\Delta m_{21}^2)^{1/2} + U_{e3}^2\, (\Delta m_{31}^2)^{1/2}\, e^{\iota\xi}$$

$$m_{ee} \sim (\Delta m_{31}^2)^{1/2}\, [r\, c_{13}^2\, s_{12}^2 + s_{13}^2\, e^{\iota\xi}]$$

Sensitivity to the Majorana mass

S M Bilenky C Giunti
arXiv:1203.5250 [hep-ph]



Heidelberg-Moscow

GERDA I

GERDA II

GERDA II

Cosmology
(after WMAP-7)

Upper bounds, boxes – uncertainties of NME

H-M: m_{ee} = (0.29 – 0.35) eV

EXO-200: m_{ee} < (0.14 – 0.38) eV

H-M result

$^{76}Ge \rightarrow {}^{76}Se + e^- + e^-$

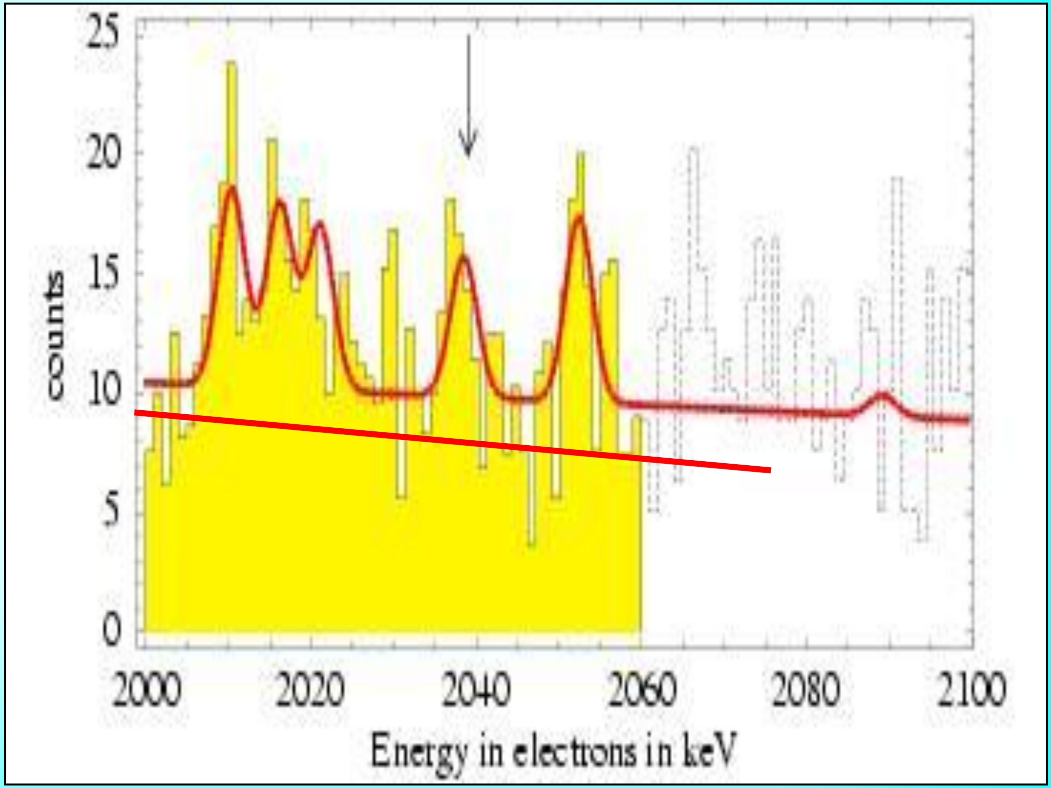
$T_{1/2} = 2.23\,^{+0.44}_{-0.31} \times 10^{25}$ y (1σ)

> 6σ evidence for the observation of 0νββ – decay

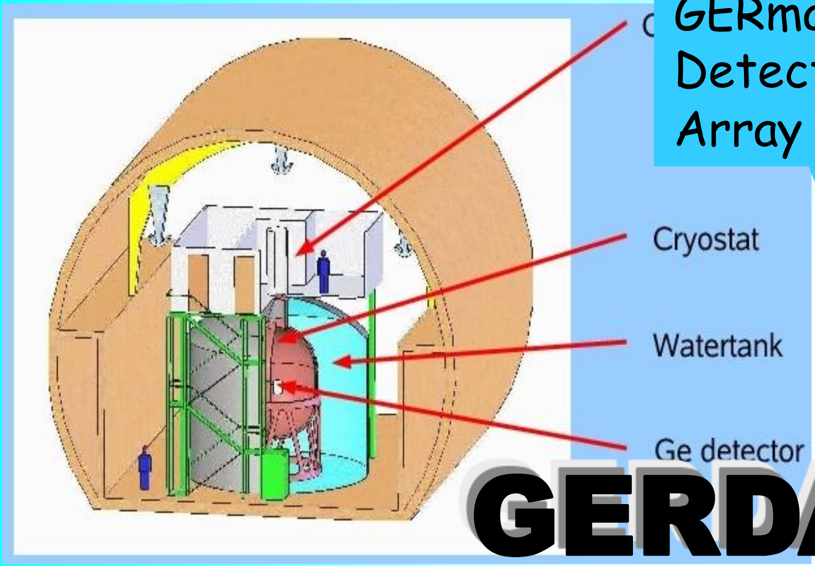
H. V. Klapdor-Kleingrothaus and
I. V. Krivosheina,
Mod. Phys. Lett. A 21 1547 (2006)

m_{ee} = (0.32 +/– 0.03) eV

Spectrum near the end point



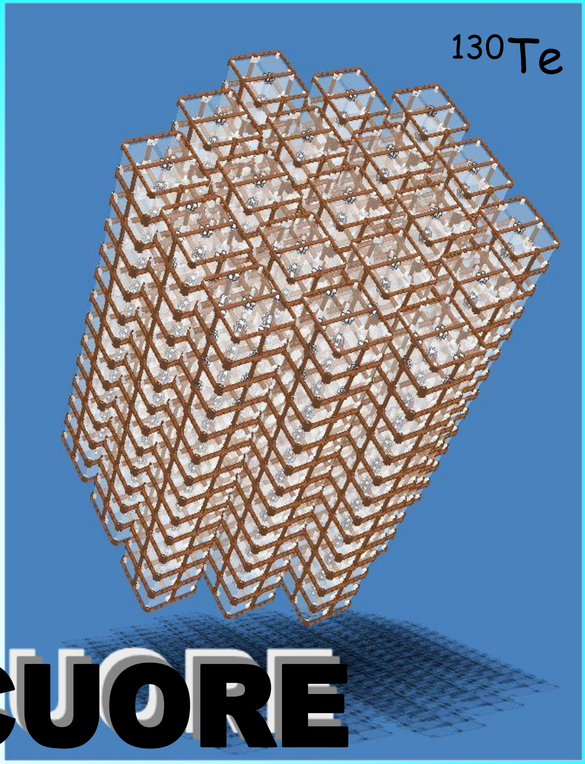
New experiments



GERmanium Detector Array in LAr

GERDA

Phase I:	15 kg y:	0.3 – 0.9 eV
Phase II:	37.5 kg y:	0.09 – 0.29 eV
Phase III:	1 ton	0.01 eV



^{130}Te

CUORE

Cryogenic Underground Observatory for Rare Events

Xe- Observatory

EXO-200

Challenges:

Accomplish reconstruction of neutrino mixing and mass spectrum

Mass hierarchy

CP-violation

Now after establishing relatively large 1-3 mixing can be easy

Deviation of 2-3 mixing from maximal

Precision measurements of mixing angles

Absolute mass scale

Nature of neutrino mass

Dirac vs Majorana

Searches for new neutrino states

3. Race for hierarchy and CP

Mass ordering

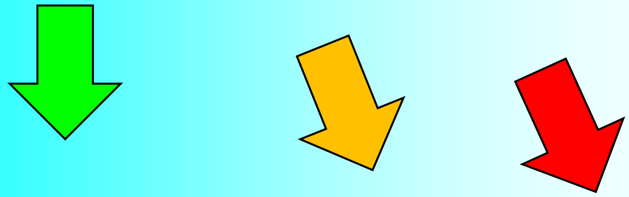
Task for everybody:
* Theory – make predictions
* Phenomenology – find effects whic
depend on mass hierarchy and CP-ph
* Experiment – measure these effect

$\Delta m^2_{31} \rightarrow - \Delta m^2_{31}$

Resonance in the antineutrino channel> V → -V

Race for hierarchy

Matter effect on 1-3 mixing



Precise measurements of Δm^2 at reactors

Cosmology Σm

Atmospheric neutrinos

LBL experiments

Supernova neutrinos

Double beta decay m_{ee}

PINGU

INO

NH ←→ IH
nu ←→ antinu

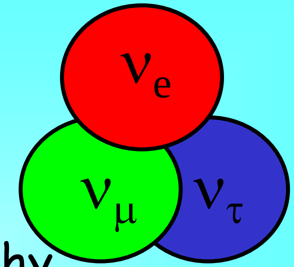
NOvA

Neutrino beam
Fermilab-PINGU(W. Winter)

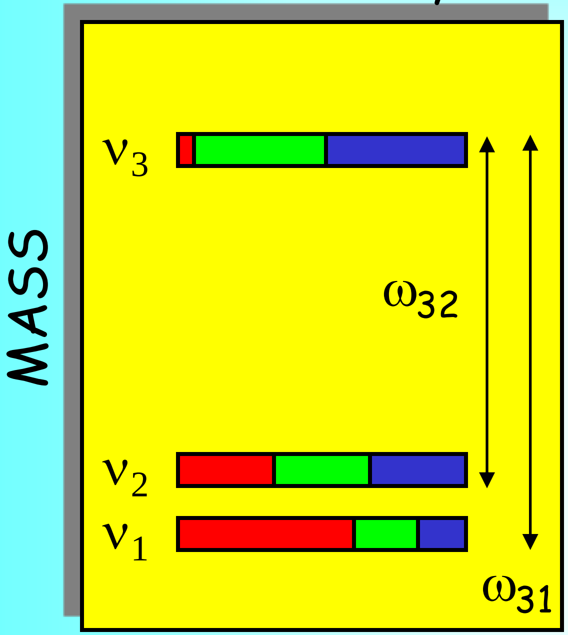
Earth matter effect
Energy spectrs

Sterile neutrinos may help?

Mass hierarchy (ordering)



Normal hierarchy



$\omega_{31} > \omega_{32}$

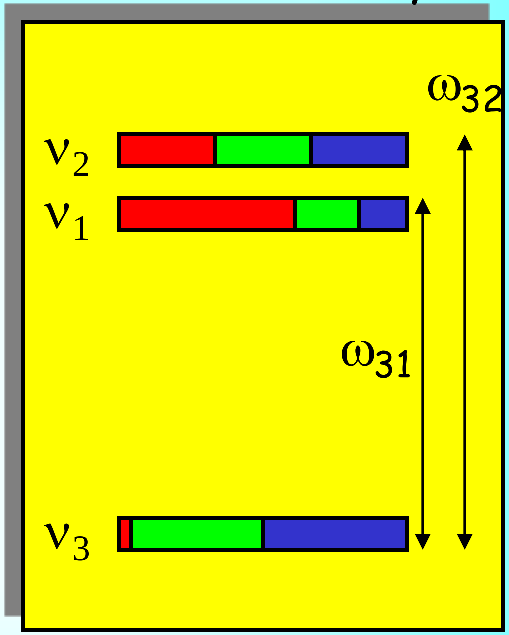
Cosmology

$\beta\beta$-decay

$\omega_{ij} = \Delta m^2_{ij} / 2E$

Mass states can be marked by ν_e - admixtures

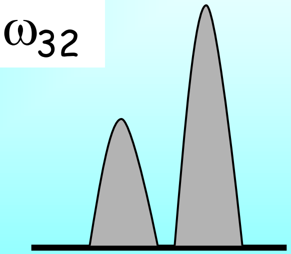
Inverted hierarchy



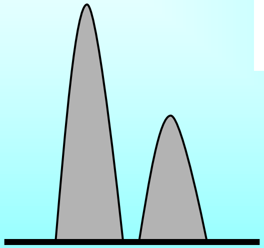
$\omega_{31} < \omega_{32}$

Oscillations

$D_{31} \sim 2D_{32}$



Fourier analysis



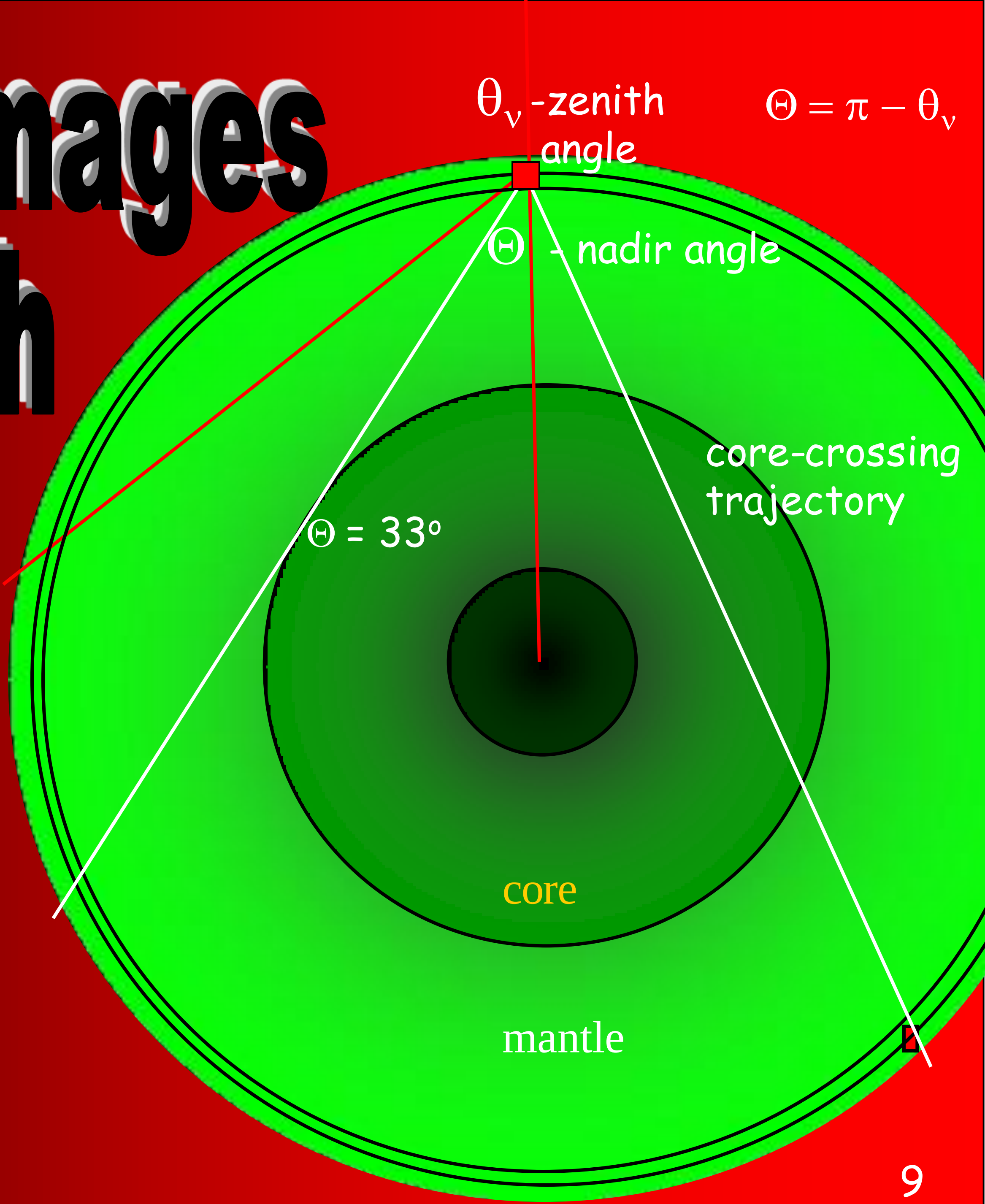
ω

S. Petcov
M. Piai

Matter effect

makes the e-flavor heavier ⇨
changes two spectra differently

Neutrino images of the Earth



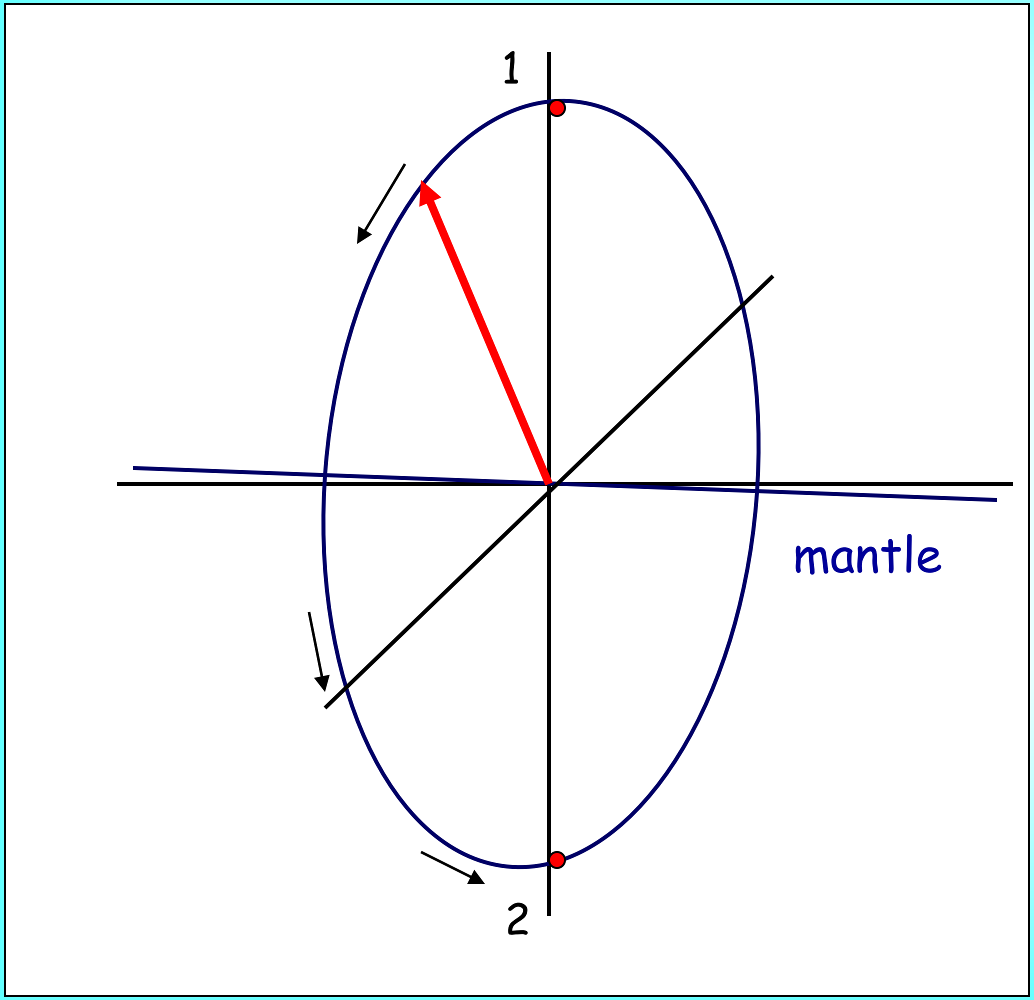
Oscillations in multilayer medium

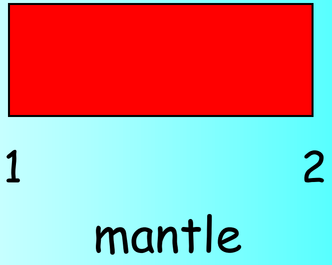
Applications:

flavor-to-flavor transitions

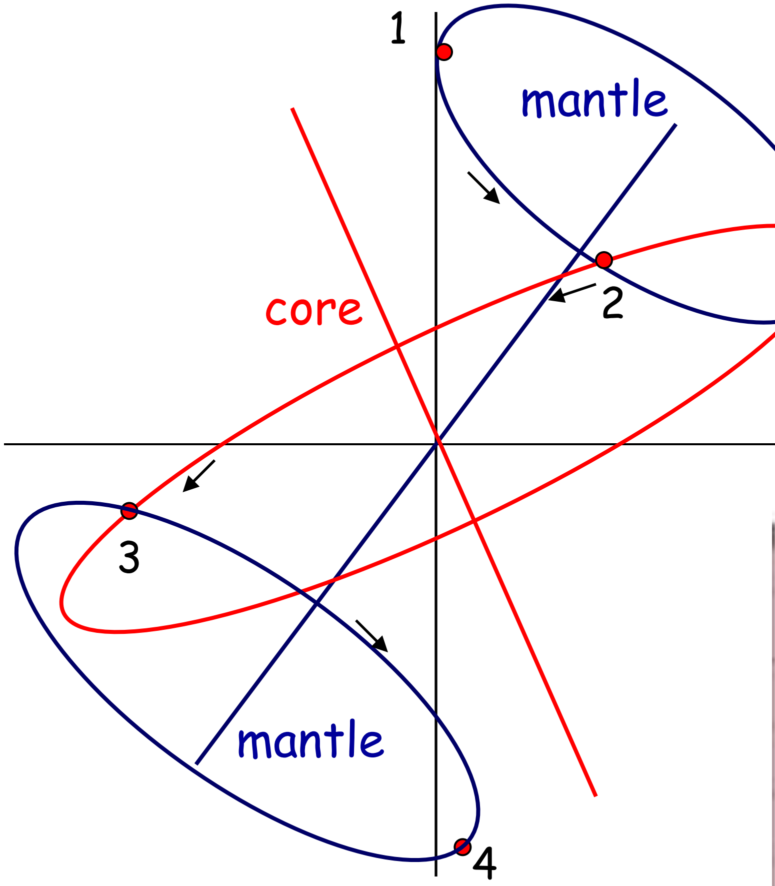
- accelerator
- atmospheric
- cosmic neutrinos

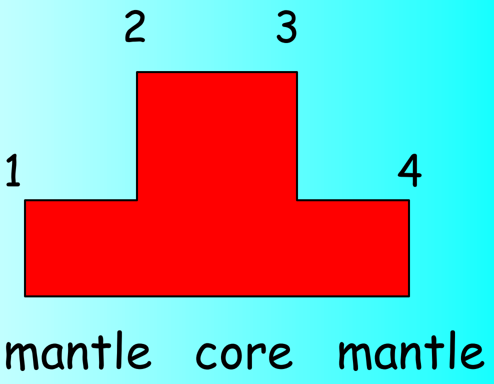
Resonance enhancement in mantle

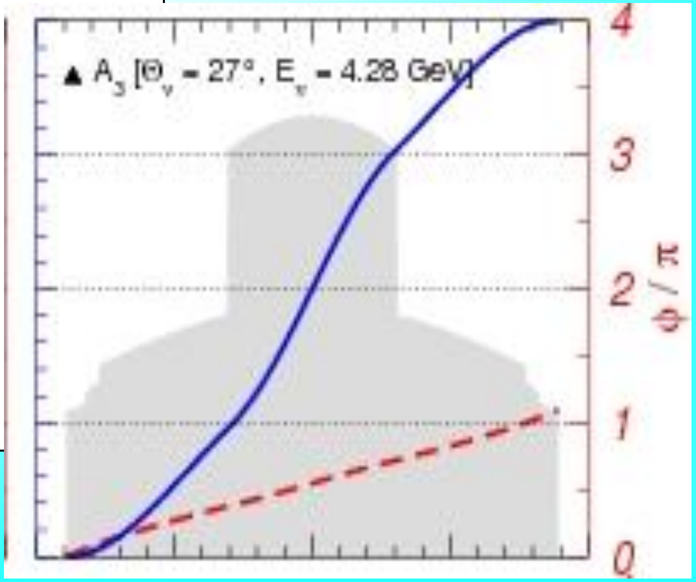




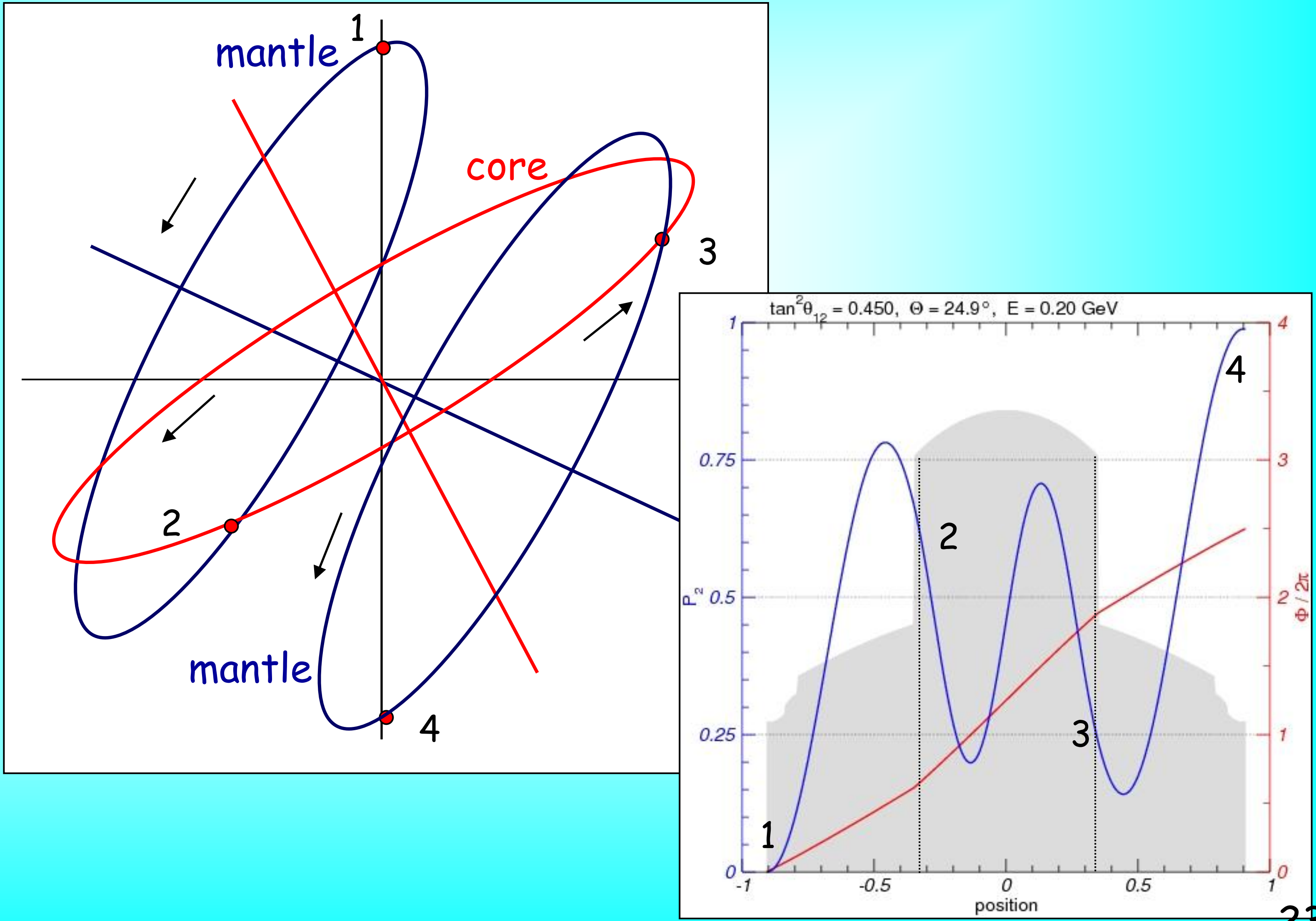
Parametric enhancement





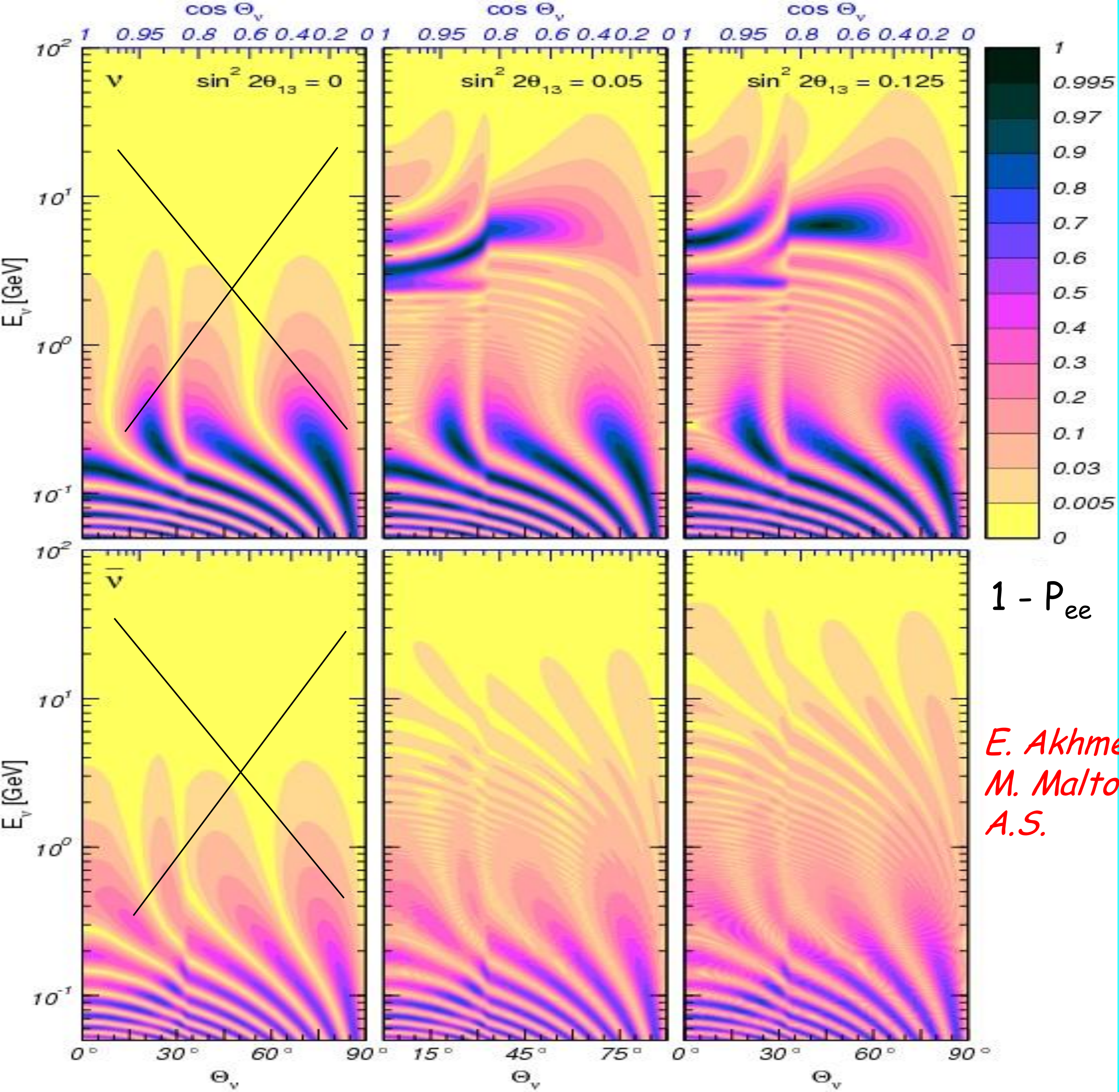


Parametric enhancement of 1-2 mode



Oscillograms of the Earth

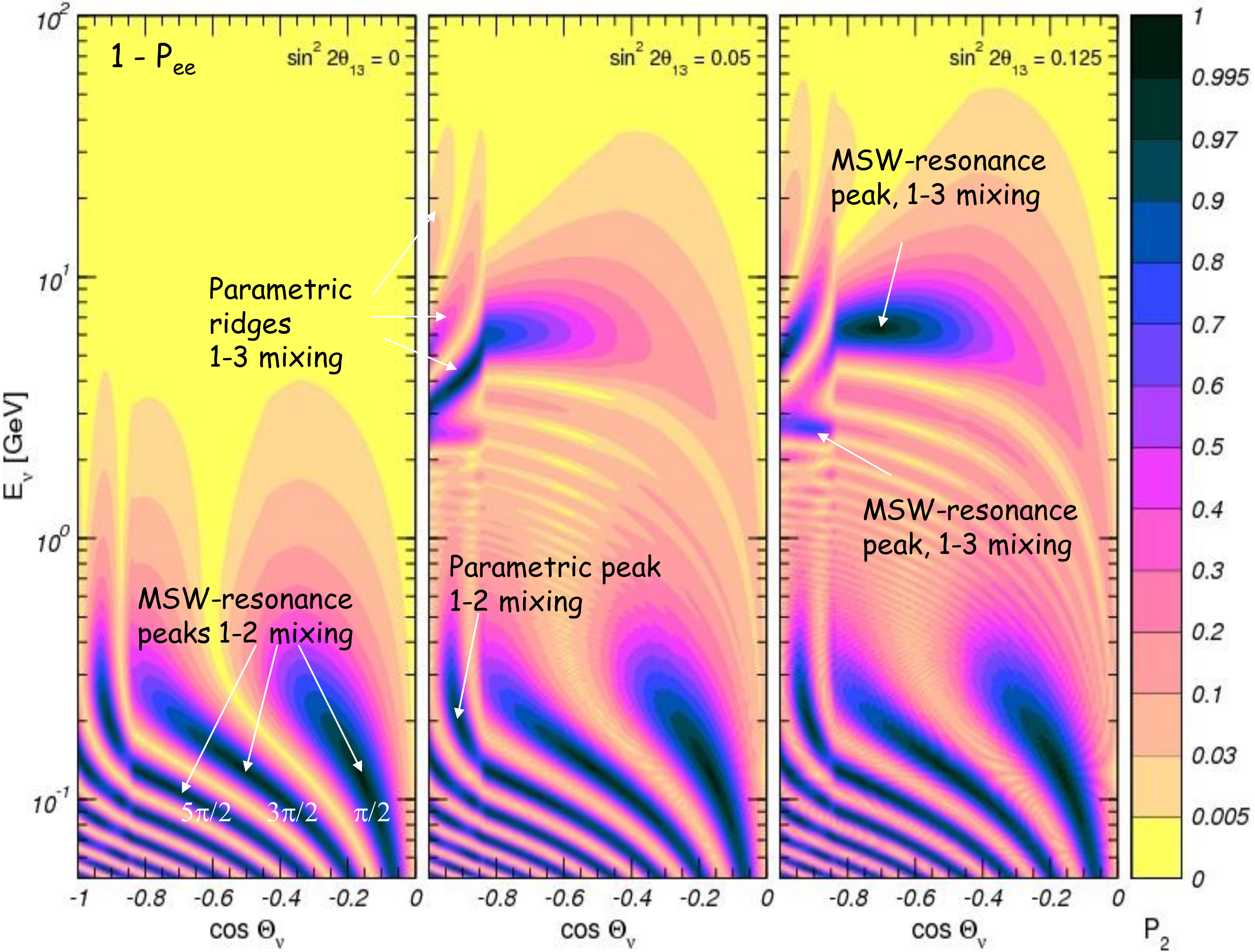
NH



Change of hierarchy

$1 - P_{ee}$

E. Akhmedov
M. Maltoni
A.S.



Parametric ridges 1-3 mixing

MSW-resonance peaks 1-2 mixing

Parametric peak 1-2 mixing

MSW-resonance peak, 1-3 mixing

MSW-resonance peak, 1-3 mixing

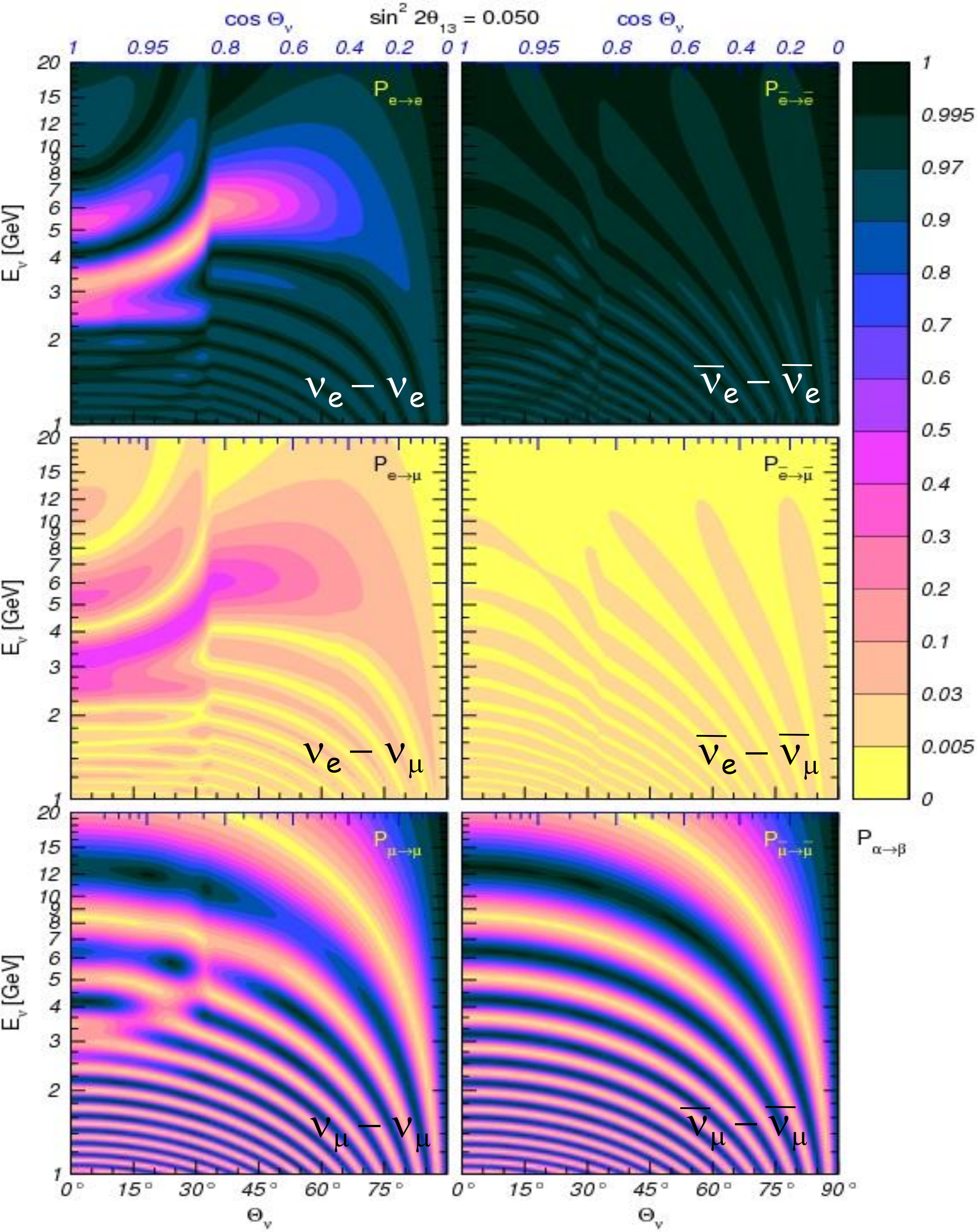
Oscillograms

$\sin^2 2\theta_{13} = 0.050$

Normal mass hierarchy

The Earth in neutrino light

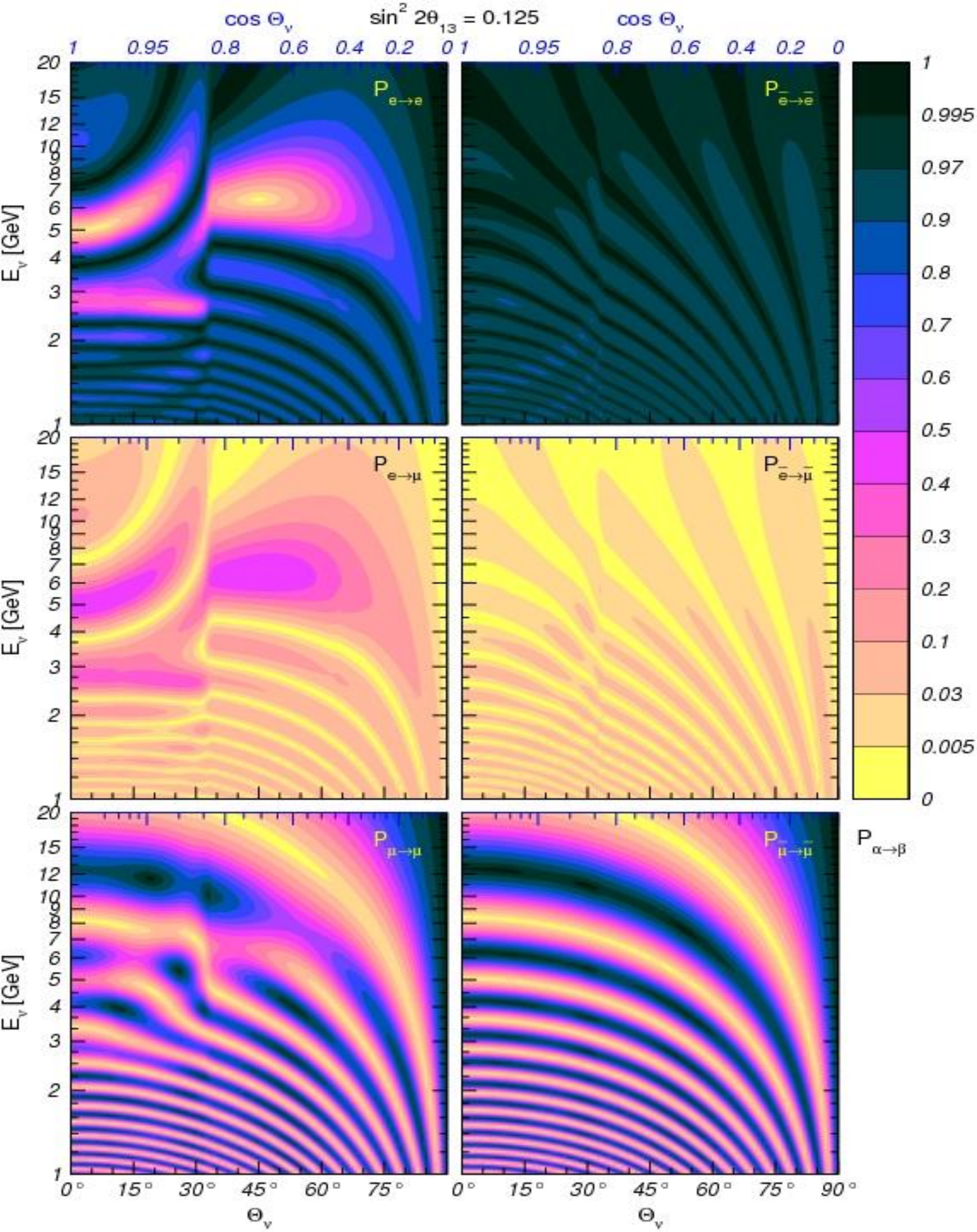
contours of constant
oscillation probability
in the energy- nadir
(or zenith) angle plane



Oscillograms

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

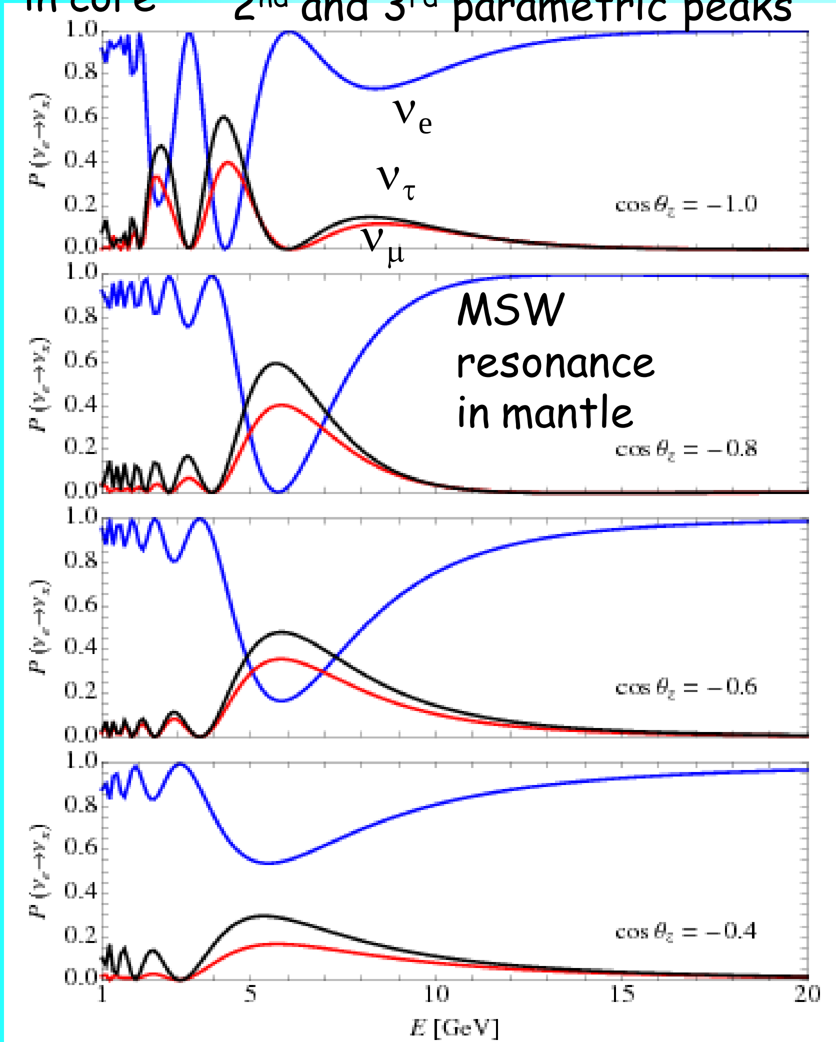
Normal mass hierarchy



Oscillation probabilities

MSW resonance in core

2nd and 3rd parametric peaks

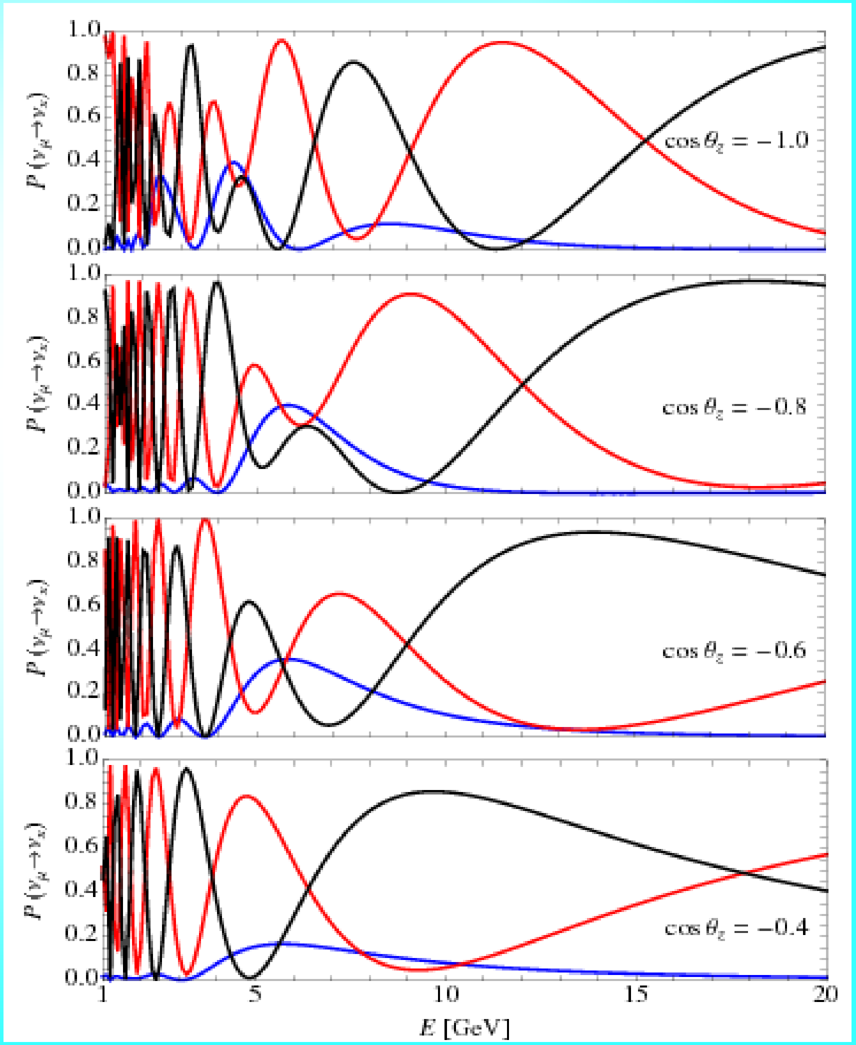


ν_e

ν_τ

ν_μ

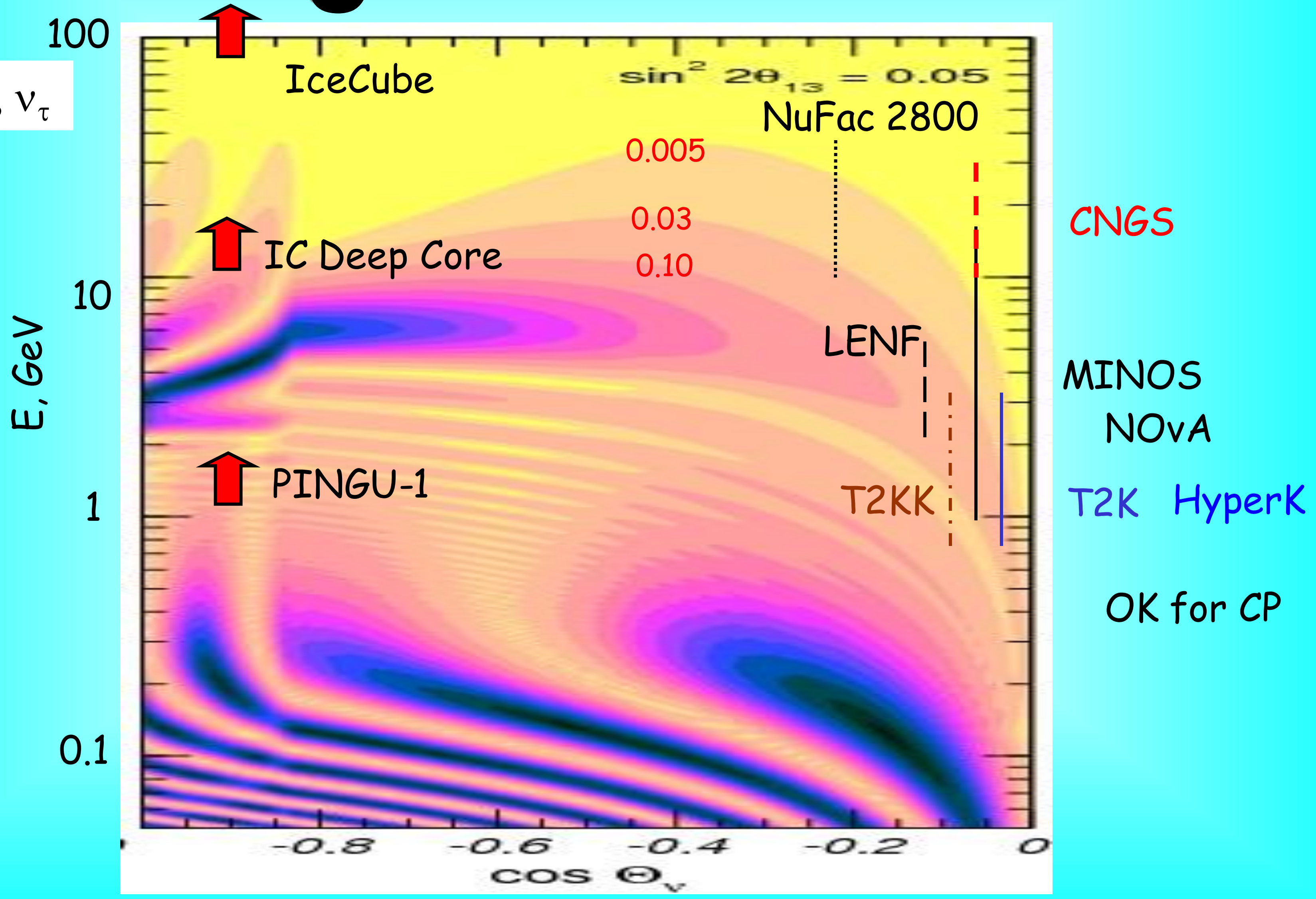
MSW resonance in mantle



Oscillograms

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

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



Atmospheric neutrinos

Oscillation physics with Huge
atmospheric neutrino detectors

P. Coyle

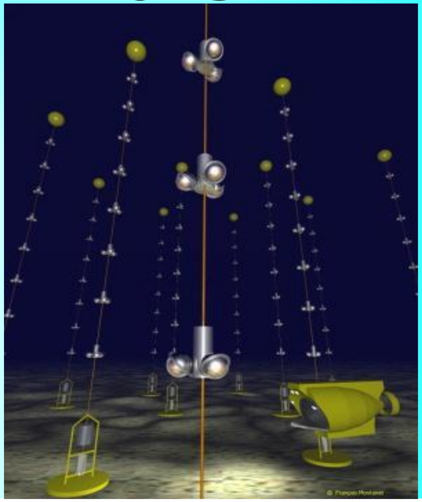
ANTARES Oscillations 2.7σ

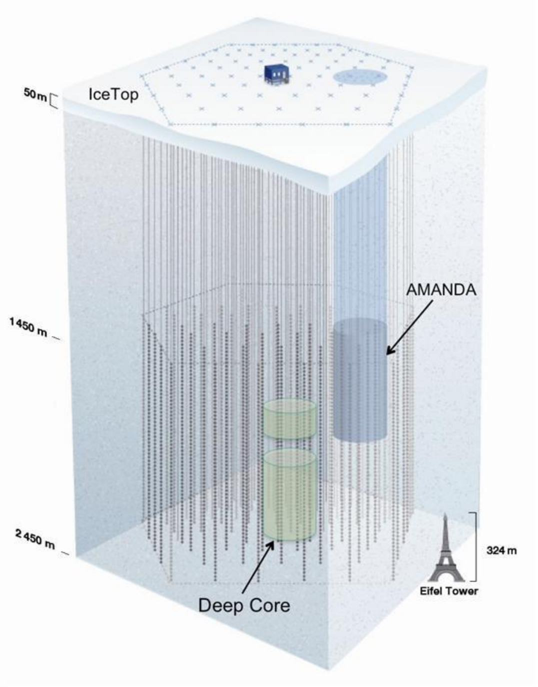
G. Sullivan

DeepCore Oscillations at high energies 10 – 100 GeV in agreement with low energy data

Ice Cube no oscillation effect
at E > 100 GeV

Bounds on non-standard interaction,
Lorentz violation etc





PINGU Geometry

Precision IceCube Next Generation Upgrade

Denser array

20 new strings (~60 DOMs each)
in 30 MTon DeepCore volume

⇩

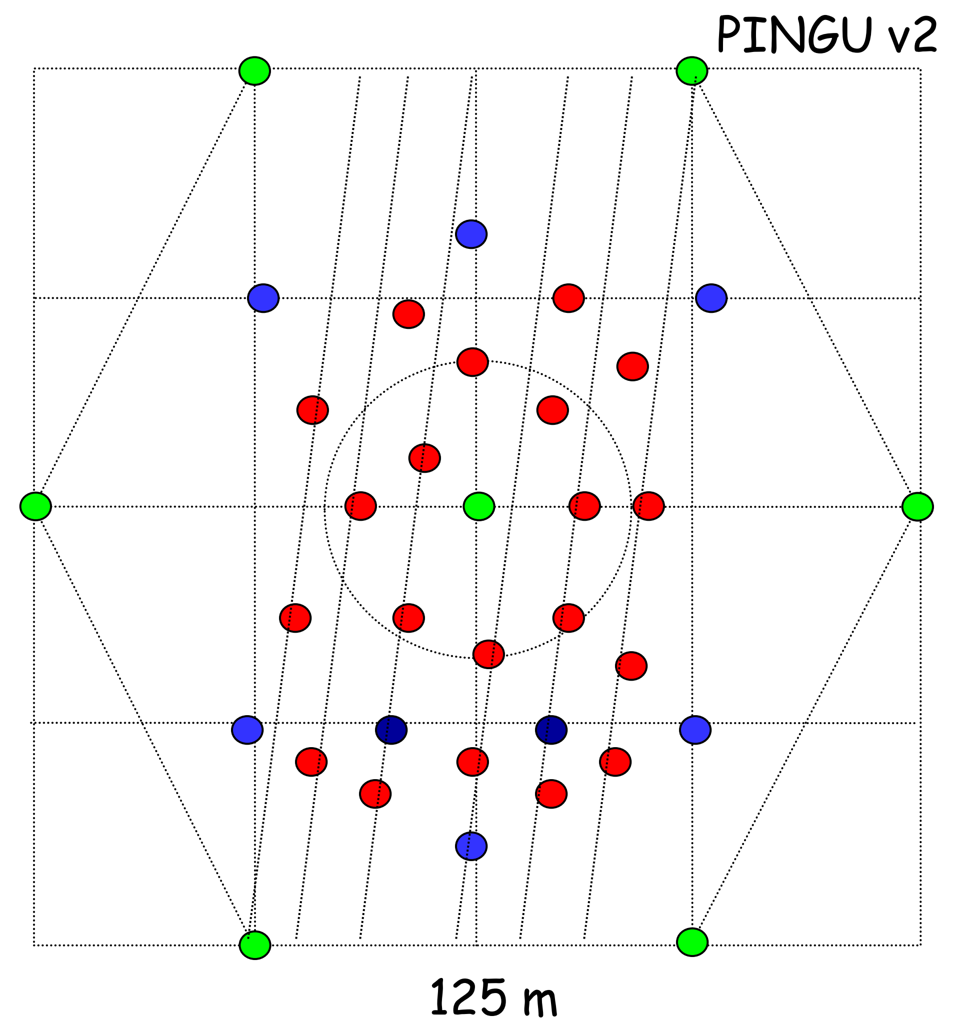
Few GeV threshold in inner
10 Mton volume

Energy resolution ~ 3 GeV

🟢 Existing IceCube strings

🔵 Existing DeepCore strings

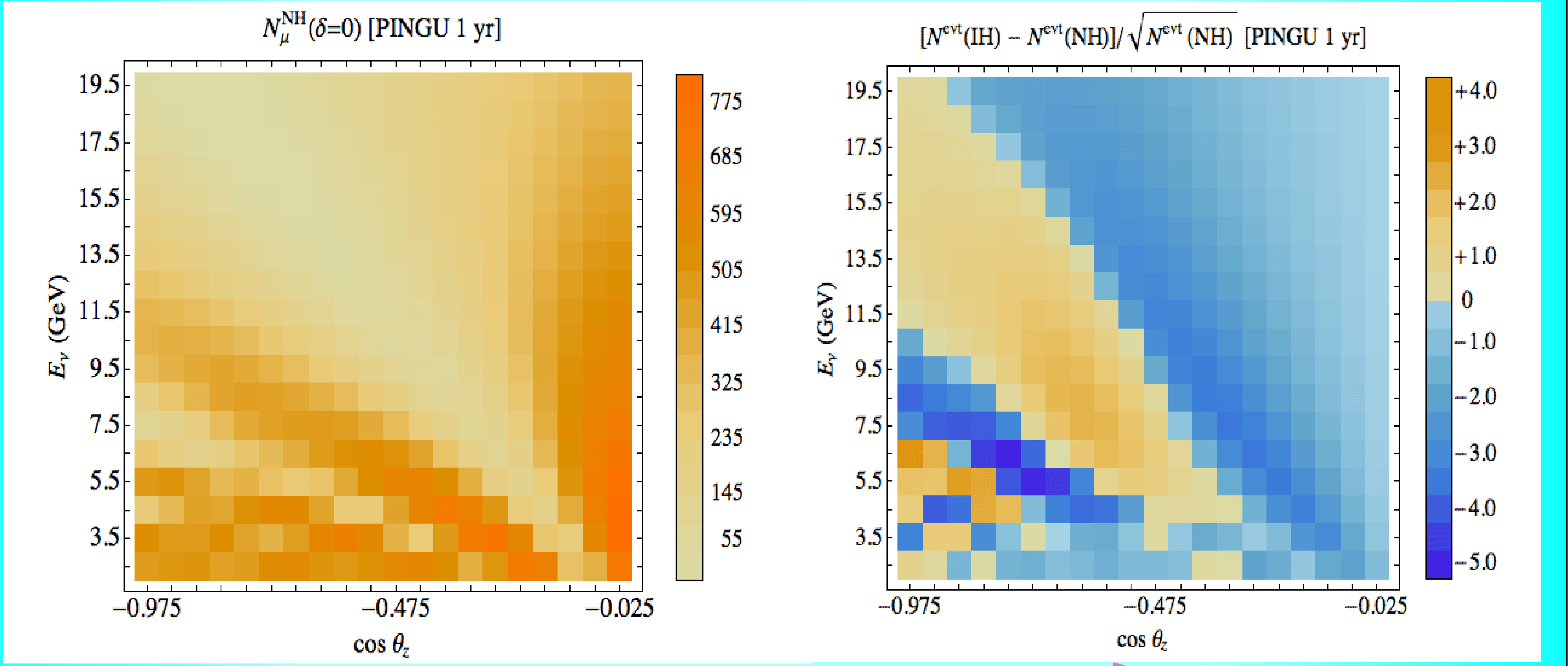
🔴 New PINGU-I strings



PINGU: Tracking events

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

Asymmetry, statistical significance



$S_{tot} \sim s\, n^{1/2}$

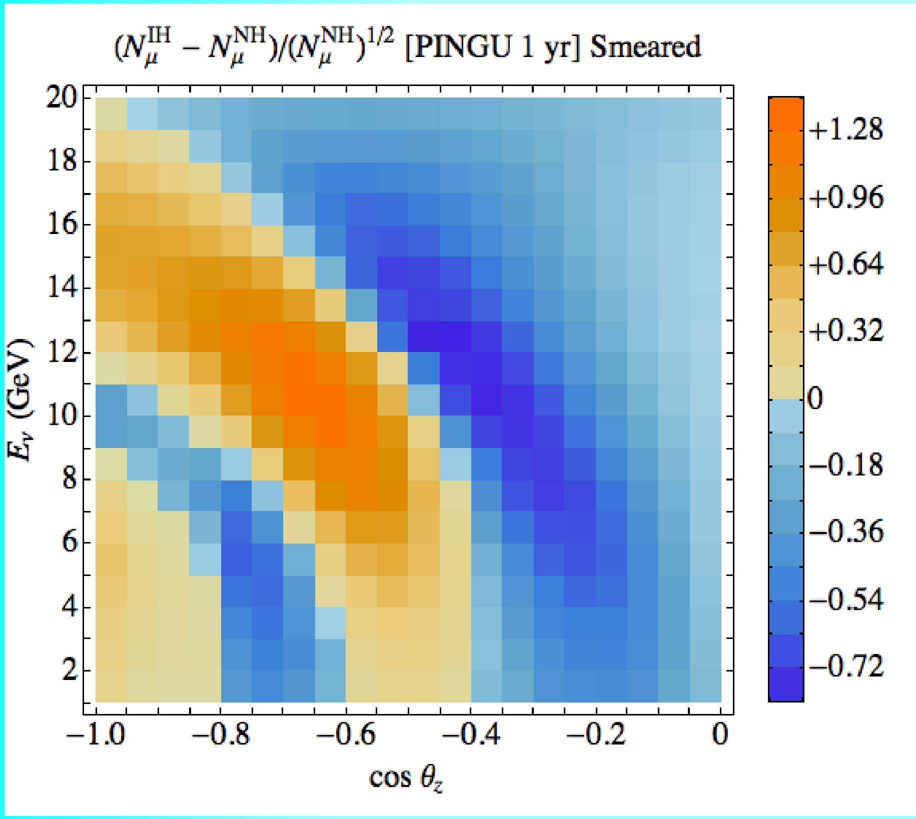
Quick estimation of significance

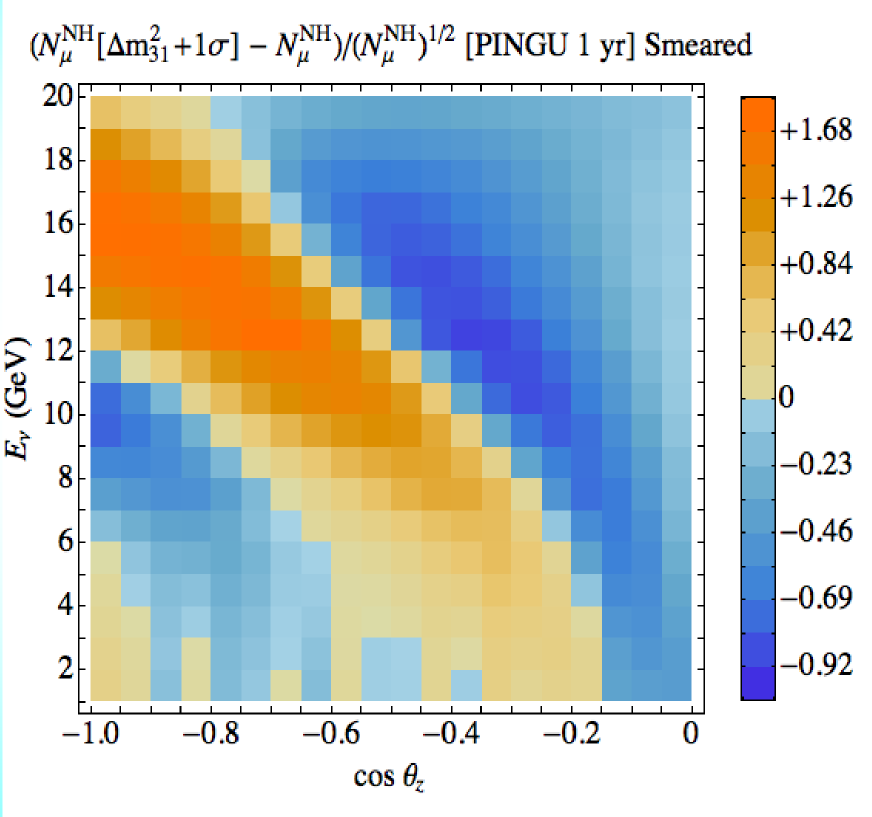
Effective average significance in individual bin

Number of bins in resolution domains

Systematics reduces significance by factor 2

Hierarchy with PINGU


$(N_\mu^{IH} - N_\mu^{NH})/(N_\mu^{NH})^{1/2}$ [PINGU 1 yr] Smeared


$(N_\mu^{NH}[\Delta m^2_{31}+1\sigma] - N_\mu^{NH})/(N_\mu^{NH})^{1/2}$ [PINGU 1 yr] Smeared

$\sigma_E = 0.2E$

$\sigma_\theta \sim 1/E^{0.5}$

Degeneracy

CP- violation

CP-violation

CP- transformations:

$\nu \rightarrow \nu^c$

$\nu^c = i \gamma_0 \gamma_2 \nu^+$

applying to the chiral components

Under CP-transformations:

$U_{PMNS} \rightarrow U_{PMNS}^*$ ⇨ $\delta \rightarrow -\delta$

$V \rightarrow -V$

usual medium is C-asymmetric which leads to CP asymmetry of interactions

Degeneracy of effects:
Matter can imitate CP-violation

Evolution

For E > 0.1 GeV

Propagation basis

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

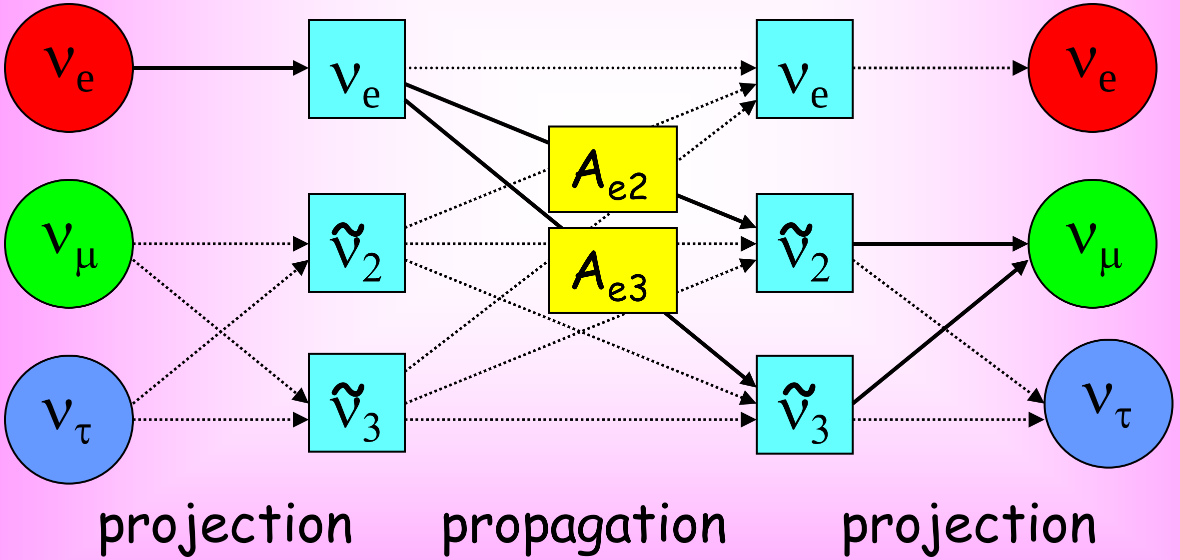
$I_\delta = \mathrm{diag}\,(1, 1, e^{i\delta})$

⇨

$\tilde{H} = U_{13}^T U_{12}^T H^{diag} U_{12} U_{13}$

$H^{diag} = \mathrm{diag}\,(H_{1m}, H_{2m}, H_{3m})$

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



CP appears in projection only

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

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

Interference

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

``solar" amplitude

``atmospheric" amplitude

dependence on
δ and θ_{23} is explicit

<u>``Factorization" approximation:</u>

A_{e2} depends mainly on Δm_{12}^2, θ_{12}
A_{e3} depends mainly on Δm_{13}^2, θ_{13}
corrections of the order $\Delta m_{12}^2 / \Delta m_{13}^2$, s_{13}^2

<u>For constant density:</u>

$$A_{e2} \sim i \sin 2\theta_{12}^m \sin\frac{\pi L}{l_{12}^m}$$

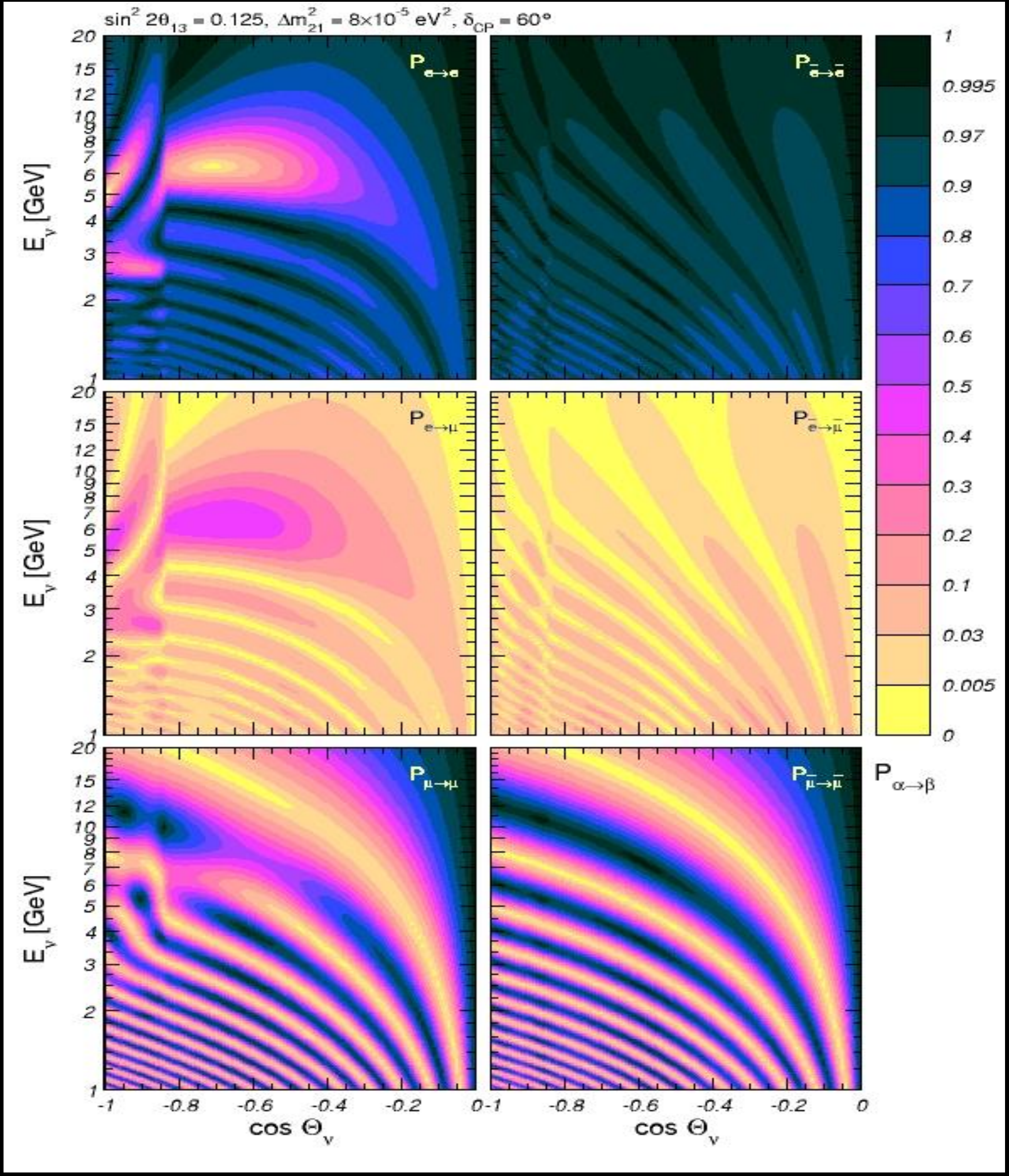
$$A_{e3} \sim i \sin 2\theta_{13}^m \sin\frac{\pi L}{l_{13}^m}$$

up to phase
factors

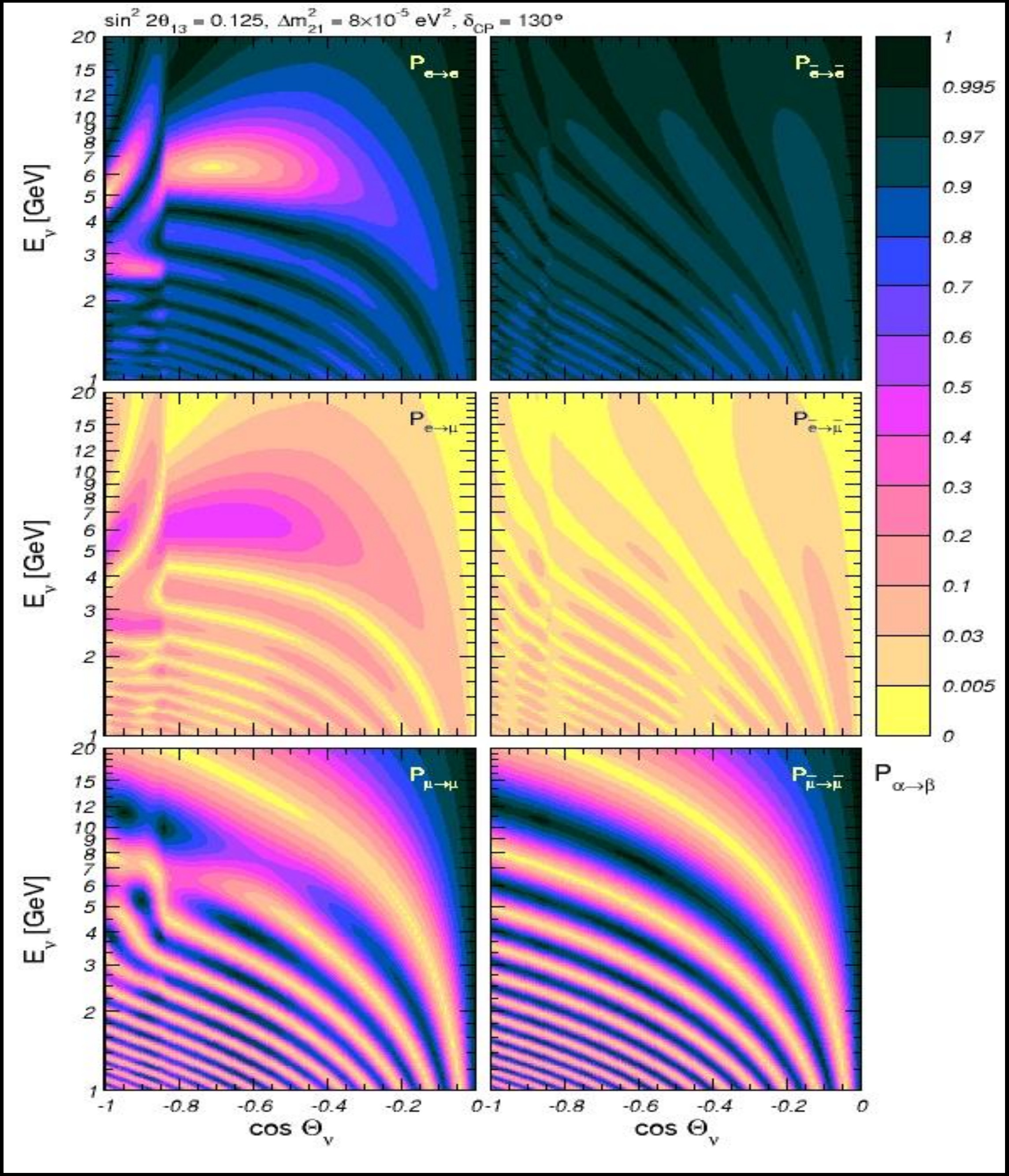
CP-violation

$\delta = 60^{o}$

Standard parameterization

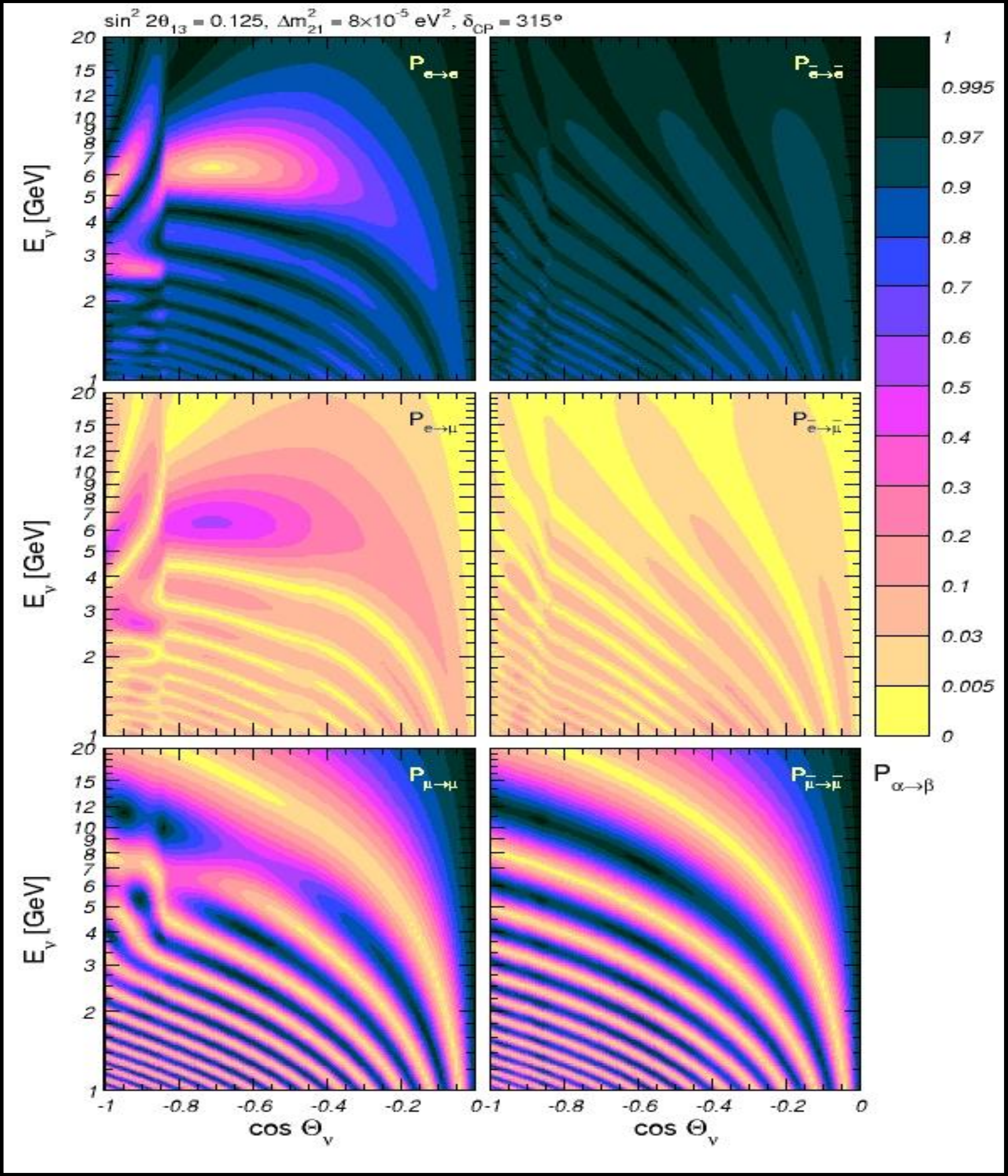


δ = 130°



$\sin^2 2\theta_{13} = 0.125$, $\Delta m^2_{21} = 8\times10^{-5}$ eV^2, $\delta_{CP} = 130°$
$P_{e\to e}$
$P_{\bar{e}\to\bar{e}}$
$P_{e\to\mu}$
$P_{\bar{e}\to\bar{\mu}}$
$P_{\mu\to\mu}$
$P_{\bar{\mu}\to\bar{\mu}}$
E_ν [GeV]
20
15
12
10
9
8
7
6
5
4
3
2
1
cos Θ_ν
-1
-0.8
-0.6
-0.4
-0.2
0
1
0.995
0.97
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.03
0.005
0
$P_{\alpha\to\beta}$

$\delta = 315^{o}$


$\sin^2 2\theta_{13} = 0.125,\ \Delta m^2_{21} = 8\times10^{-5}\ \mathrm{eV}^2,\ \delta_{CP} = 315°$
$P_{e\to e}$
$P_{\bar{e}\to\bar{e}}$
$P_{e\to\mu}$
$P_{\bar{e}\to\bar{\mu}}$
$P_{\mu\to\mu}$
$P_{\bar{\mu}\to\bar{\mu}}$
E_ν [GeV]
20
15
12
10
9
8
7
6
5
4
3
2
1
cos Θ_ν
-1
-0.8
-0.6
-0.4
-0.2
0
1
0.995
0.97
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.03
0.005
0
$P_{\alpha\to\beta}$

CP-violation domains

Three grids of lines:

- Solar magic lines
- Atmospheric magic lines
- Interference phase lines

"Magic lines"

P. Huber, W. Winter
V. Barger, D. Marfatia,
K Whisnant, A.S.

Explicitly

$$P(\nu_e \rightarrow \nu_\mu) = c_{23}^2|A_{e2}|^2 + s_{23}^2|A_{e3}|^2 + 2s_{23}c_{23}|A_{e2}||A_{e3}|\cos(\phi + \delta)$$

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

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

Dependence on δ disappears, interference term is zero if

$P_{int} = 0$

- $A_{e2} = 0$ - solar magic lines
- $A_{e3} = 0$ - atmospheric magic lines
- $(\phi + \delta) = \pi/2 + 2\pi k$ - interference phase condition

$$\boxed{\phi\,(E, L) = -\delta + \pi/2 + \pi k}$$

depends on δ

"Magic lines"

For $\nu_\mu \rightarrow \nu_\mu$ channel

$$P_{int} \sim 2 s_{23} c_{23} |A_{e2}||A_{e3}| \cos\phi \cos\delta$$

- The survival probabilities is CP-even functions of δ
- no CP-violation
- dependences on phases factorize

Dependence on δ disappears

$P_{int} = 0$

$A_{e2} = 0$

$A_{e3} = 0$

$\phi = \pi/2 + \pi k$

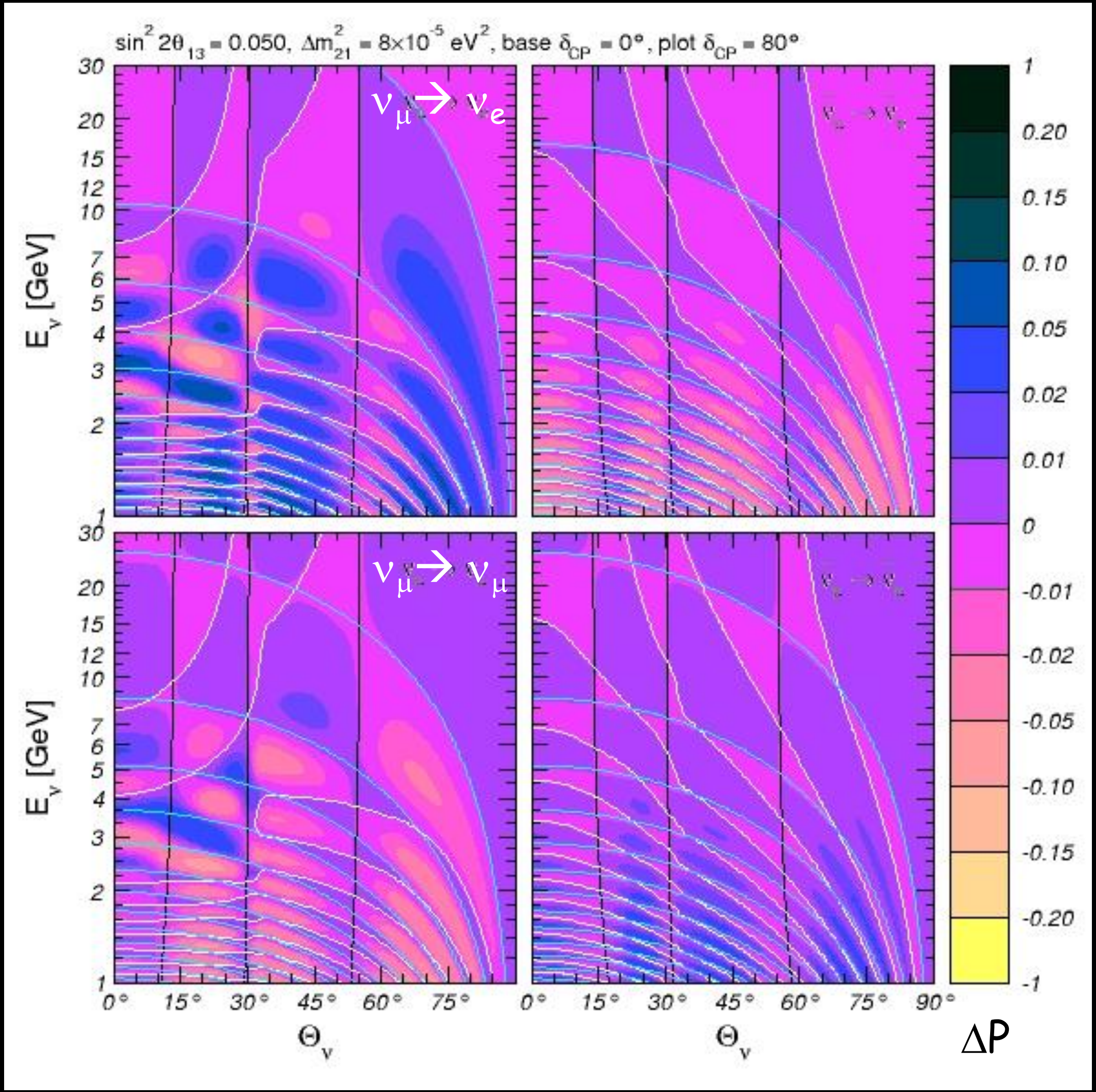
interference phase
does not depends on δ

Form the phase line grid

$$\Delta P = P(\delta) - P(\delta_f) = \text{const}$$

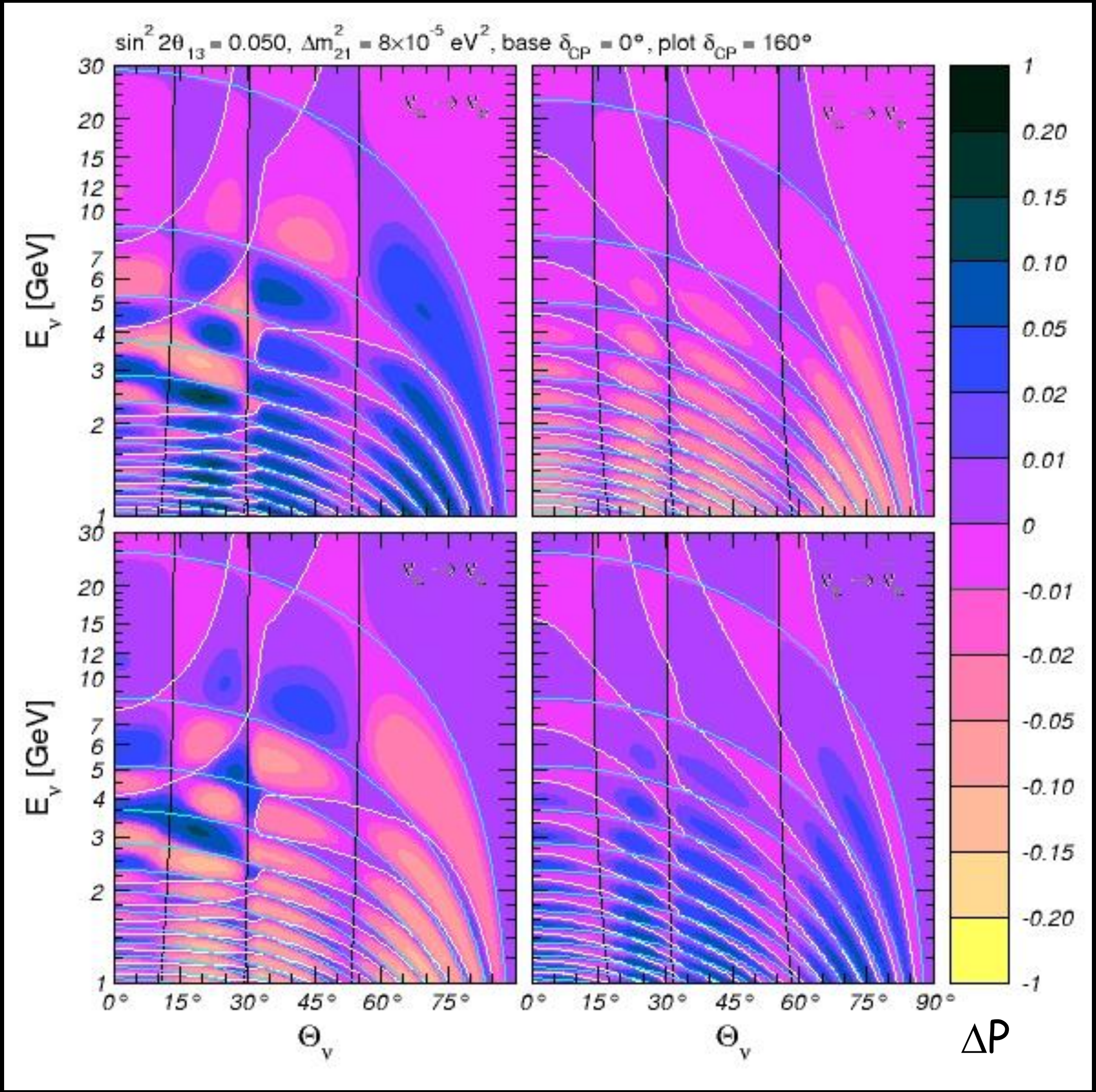
Int. phase line (blue) moves with δ-change

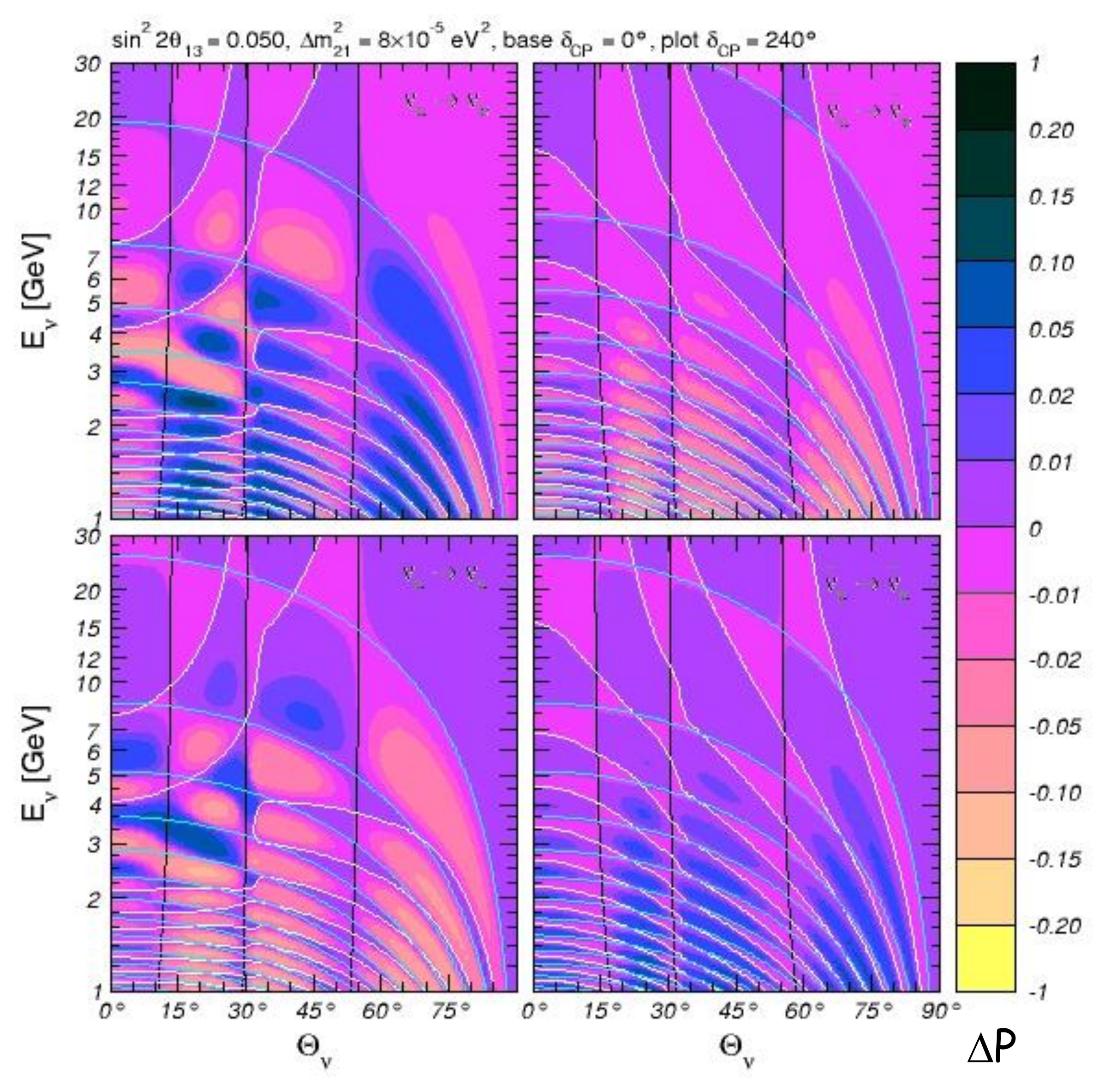
Grids do not change with δ



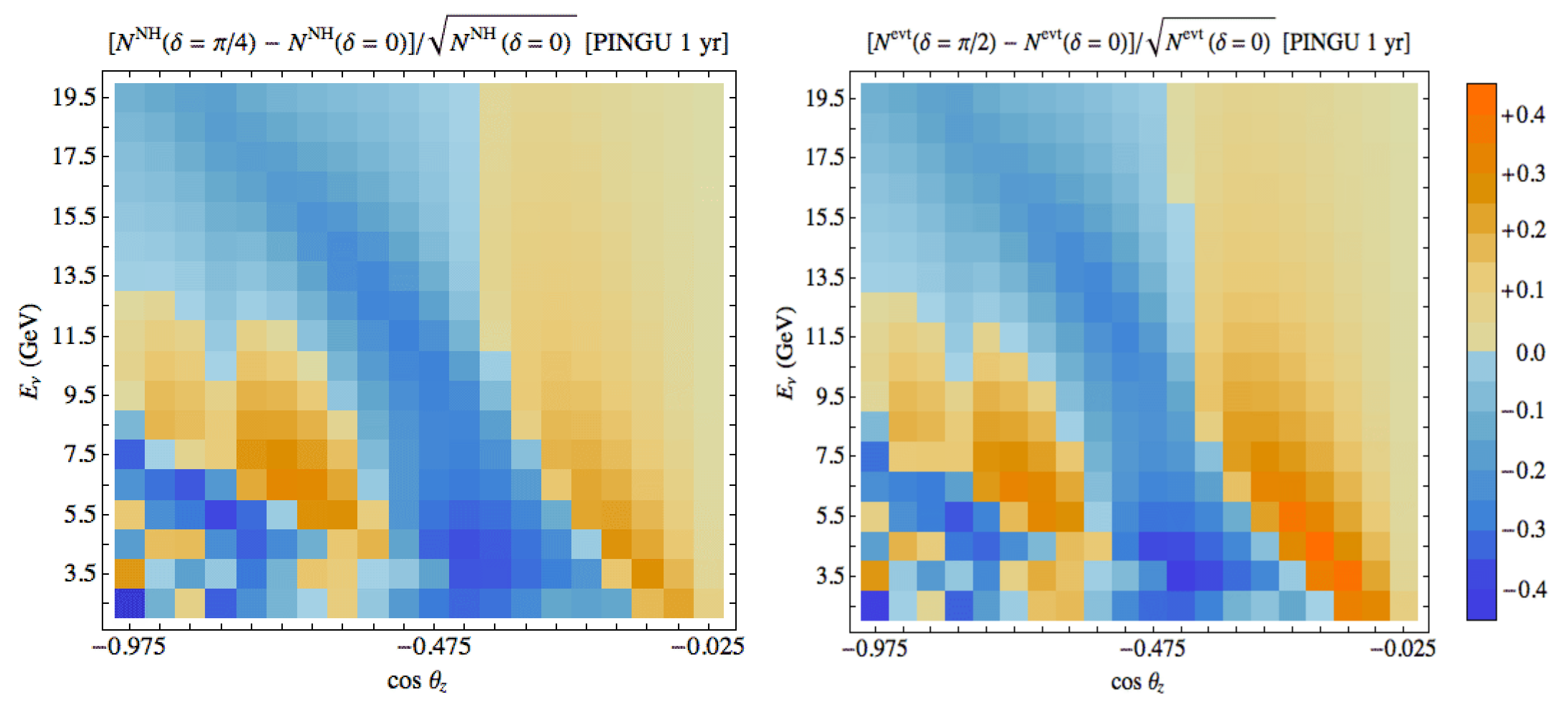
Black: solar
White: atmospheric

Magic grid


sin² 2θ₁₃ = 0.050, Δm²₂₁ = 8×10⁻⁵ eV², base δ_CP = 0°, plot δ_CP = 160°
ν_μ → ν_e
ν̄_μ → ν̄_e
ν_e → ν_μ
ν̄_e → ν̄_μ
E_ν [GeV]
30
20
15
12
10
7
6
5
4
3
2
1
0°
15°
30°
45°
60°
75°
90°
Θ_ν
1
0.20
0.15
0.10
0.05
0.02
0.01
0
-0.01
-0.02
-0.05
-0.10
-0.15
-0.20
-1
ΔP


$\sin^2 2\theta_{13} = 0.050$, $\Delta m^2_{21} = 8\times10^{-5}$ eV^2, base $\delta_{CP} = 0°$, plot $\delta_{CP} = 240°$
$\nu_\mu \to \nu_e$
$\bar{\nu}_\mu \to \bar{\nu}_e$
$\nu_e \to \nu_\mu$
$\bar{\nu}_e \to \bar{\nu}_\mu$
E_ν [GeV]
30
20
15
12
10
7
6
5
4
3
2
1
Θ_ν
0°
15°
30°
45°
60°
75°
90°
1
0.20
0.15
0.10
0.05
0.02
0.01
0
-0.01
-0.02
-0.05
-0.10
-0.15
-0.20
-1
ΔP

CP asymmetry



Summary

All three mixing angles are measured

Determination of 1-3 mixing (which turns out to be not very small) → strong impact on phenomenology , theory and future experimental programs

Indications of significant deviation of the 2-3 mixing from maximal → important implications for theory

Next step: determination of neutrino mass hierarchy and CP-violating phase

Studies of atmospheric neutrinos with huge (multi-megaton scale detectors) can play crucial role

Establishing the absolute neutrino mass scale, and Majorana nature → among main goals