Lecture 4

ICTP 2015 Summer school

Neutrinos
selected topics

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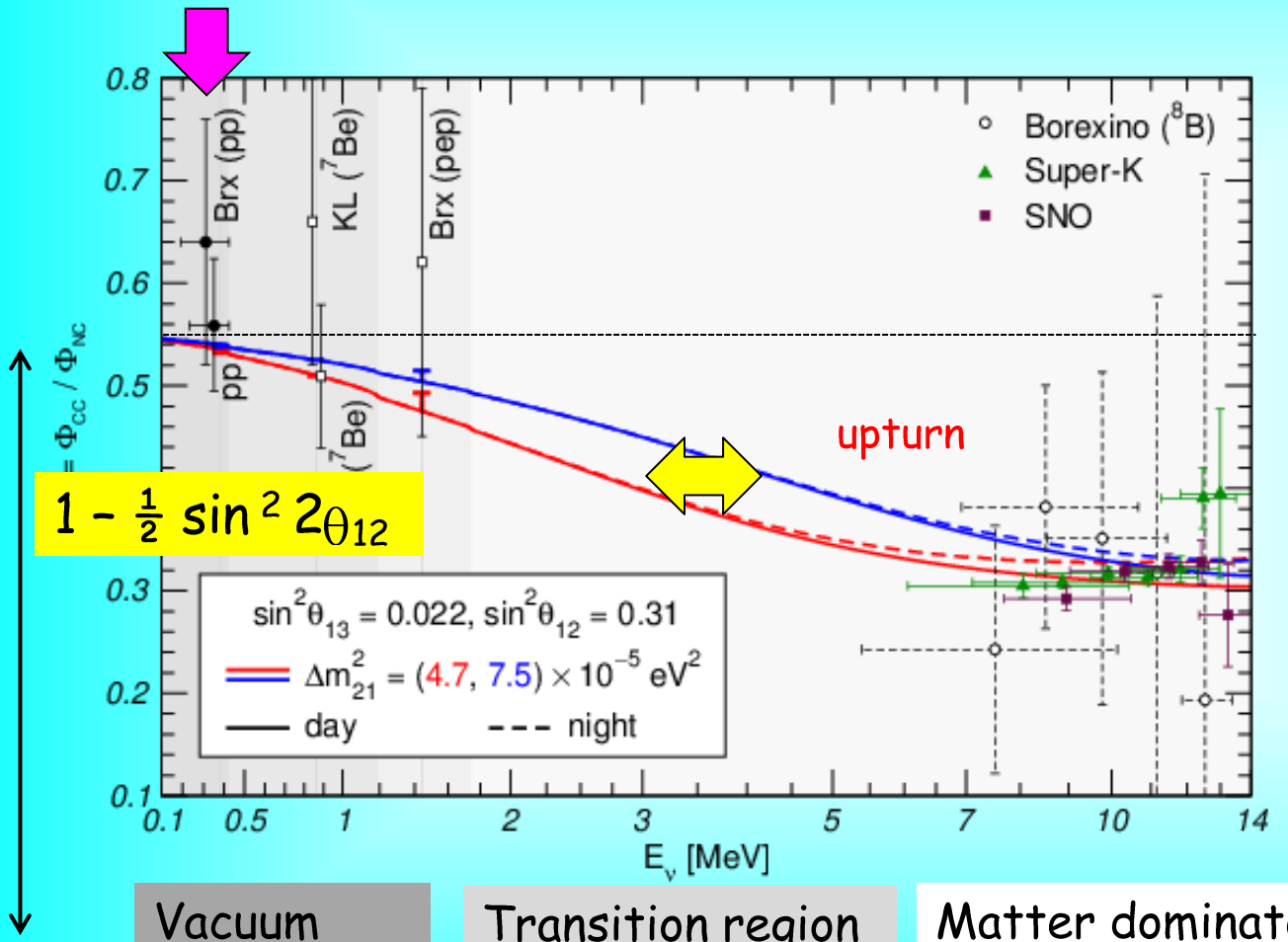
Results

Energy dependent deficit of signal

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



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

$\sin^2\theta_{12}$

for two different values of Δm_{21}^2

best fit value from solar data

best global fit

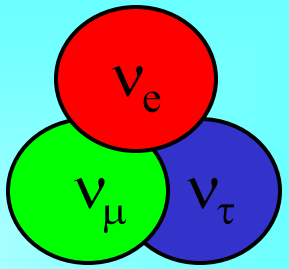
Vacuum dominated

Transition region resonance turn on

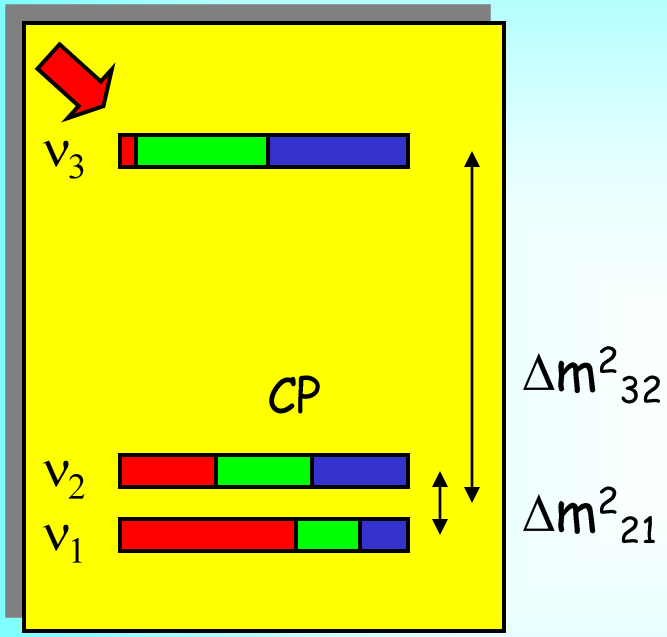
Matter dominated region

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

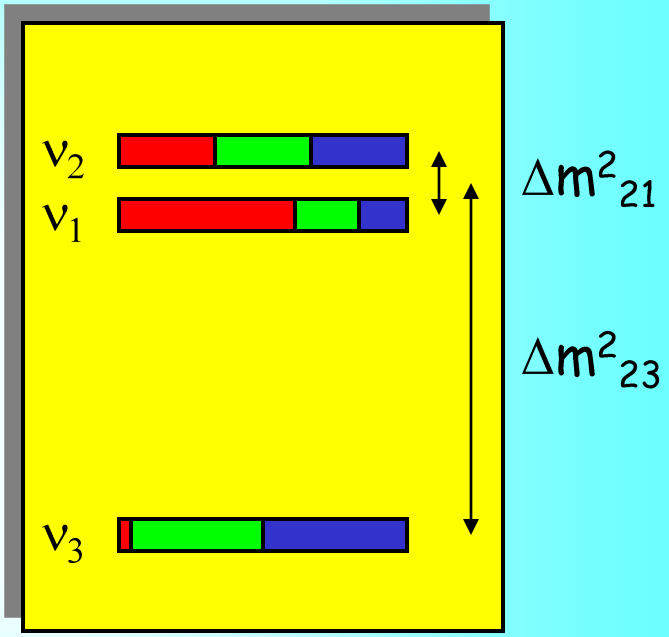
Lepton Mixing



1-3 mixing
2%



Normal mass hierarchy



Inverted mass hierarchy

$\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV^2

$\Delta m^2_{21} = 7.5 \times 10^{-5}$ eV^2

$\sin^2\theta_{12} = 1/3$

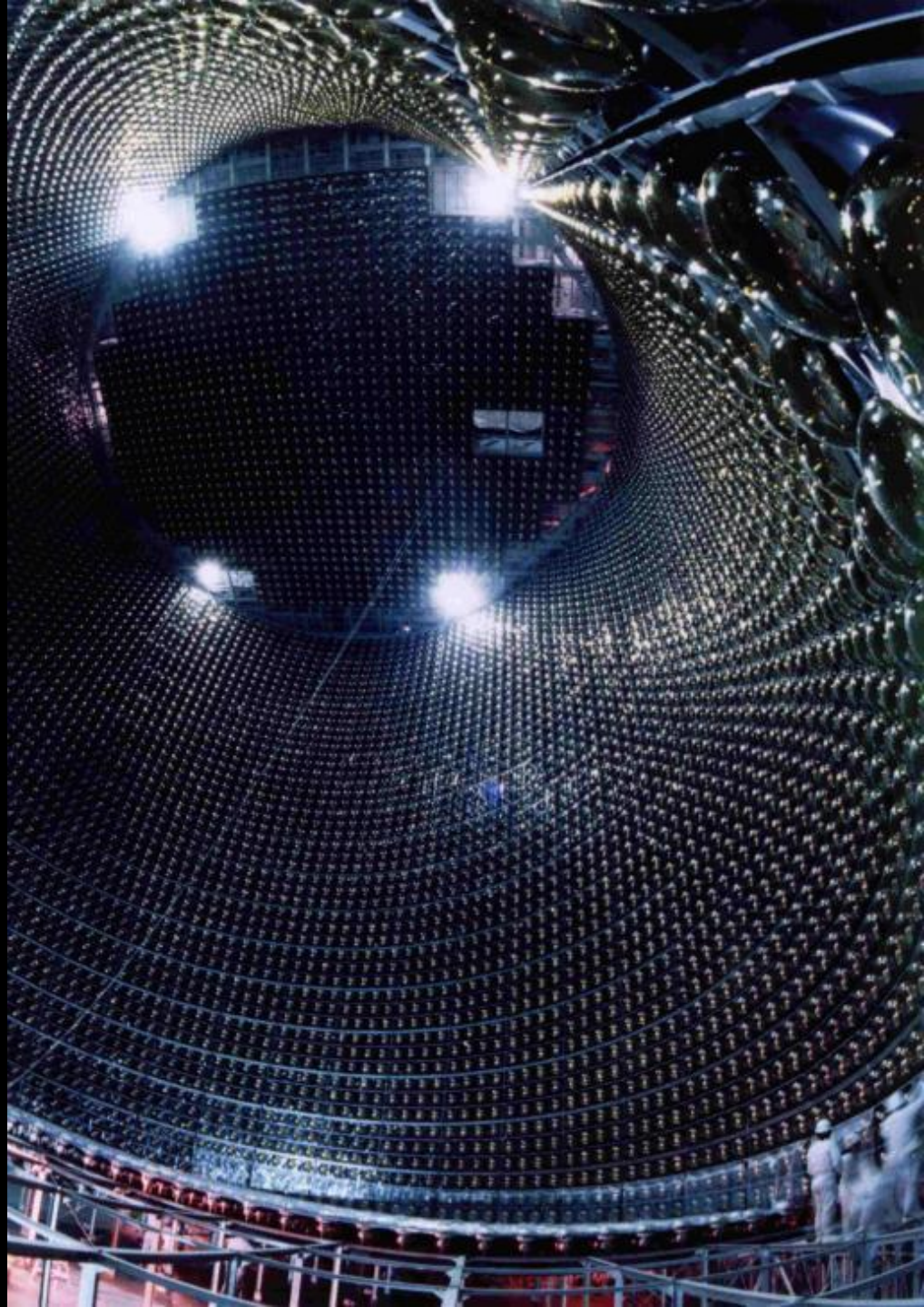
$\sin^2\theta_{23} = 1/2$

$\sin^2\theta_{13} = 0$

Symmetry: TBM?

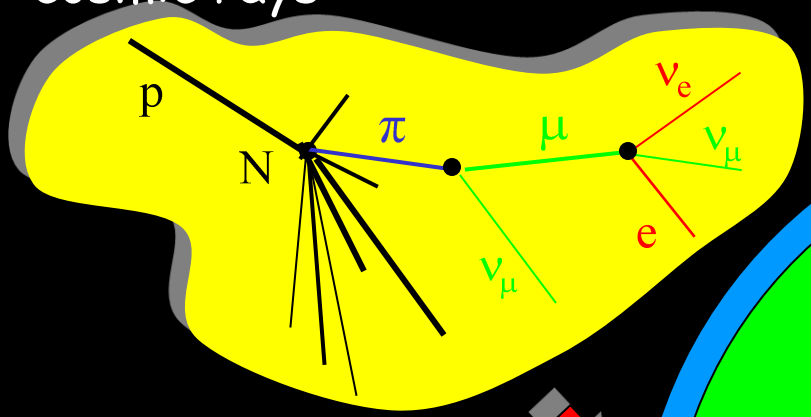
For antineutrinos spectra are different (distribution of the ν_μ and ν_τ - flavors in ν_1 and ν_2) due to possible CP-violation

Atmospheric Neutrinos



Atmospheric neutrinos

cosmic rays



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

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

at low energies:

$F_\mu / F_e = 2$

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

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

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

charm?

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

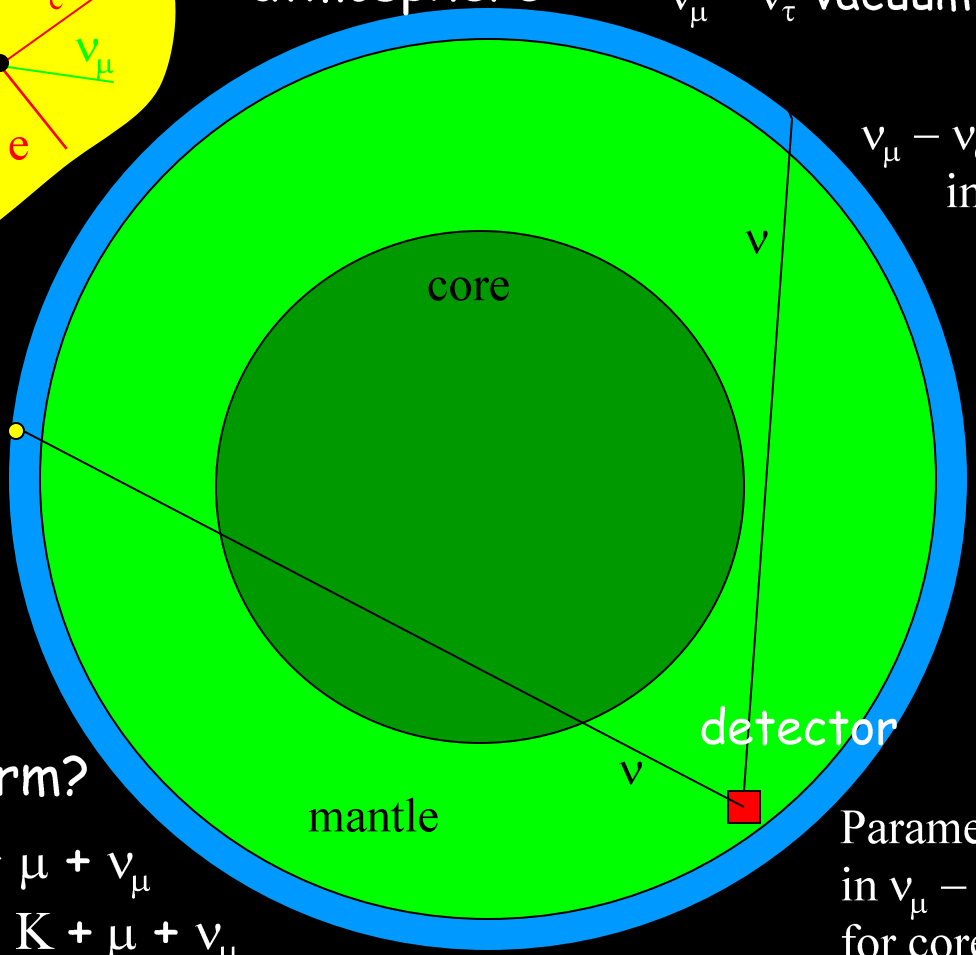
$D \rightarrow K + \mu + \nu_\mu$

$D \rightarrow K + e + \nu_e$

atmosphere

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

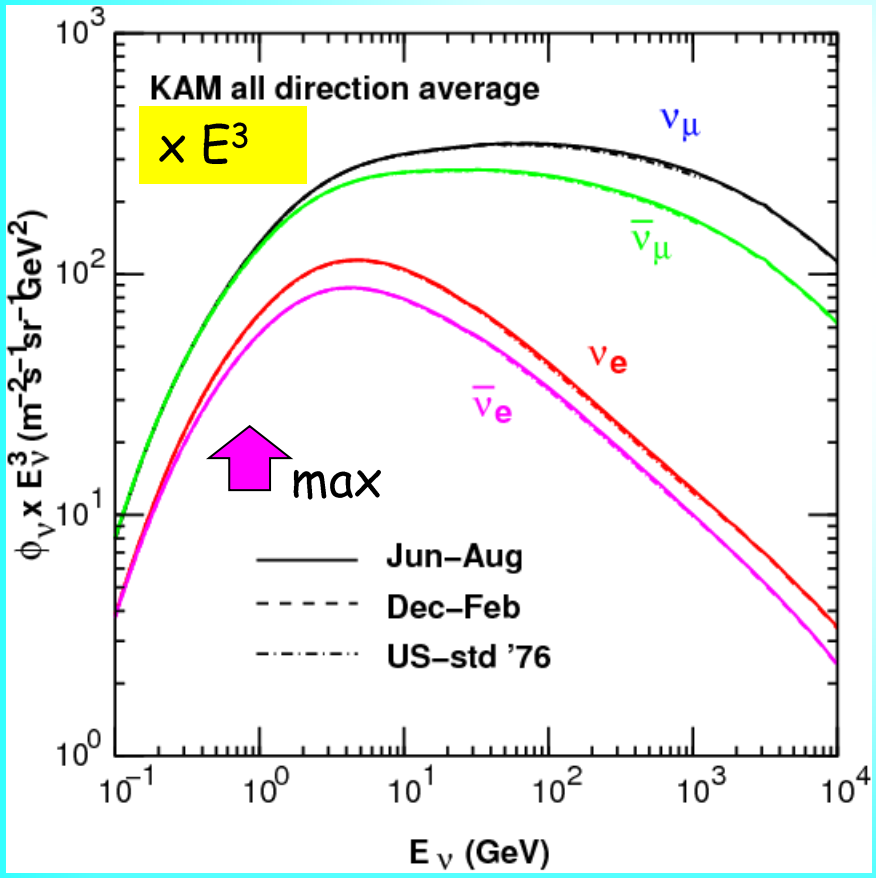
$\nu_\mu - \nu_e$ oscillations in matter

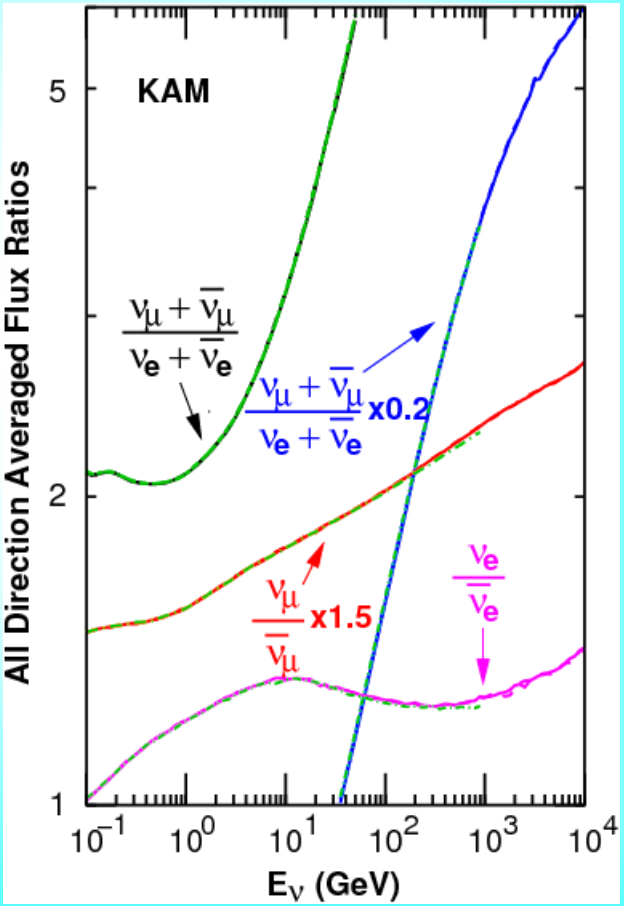


Parametric effects in $\nu_\mu - \nu_e$ oscillations for core crossing trajectories

Atmospheric neutrino fluxes

M. Honda et al.,
arXiv: 1502.03916





Charm contribution

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:

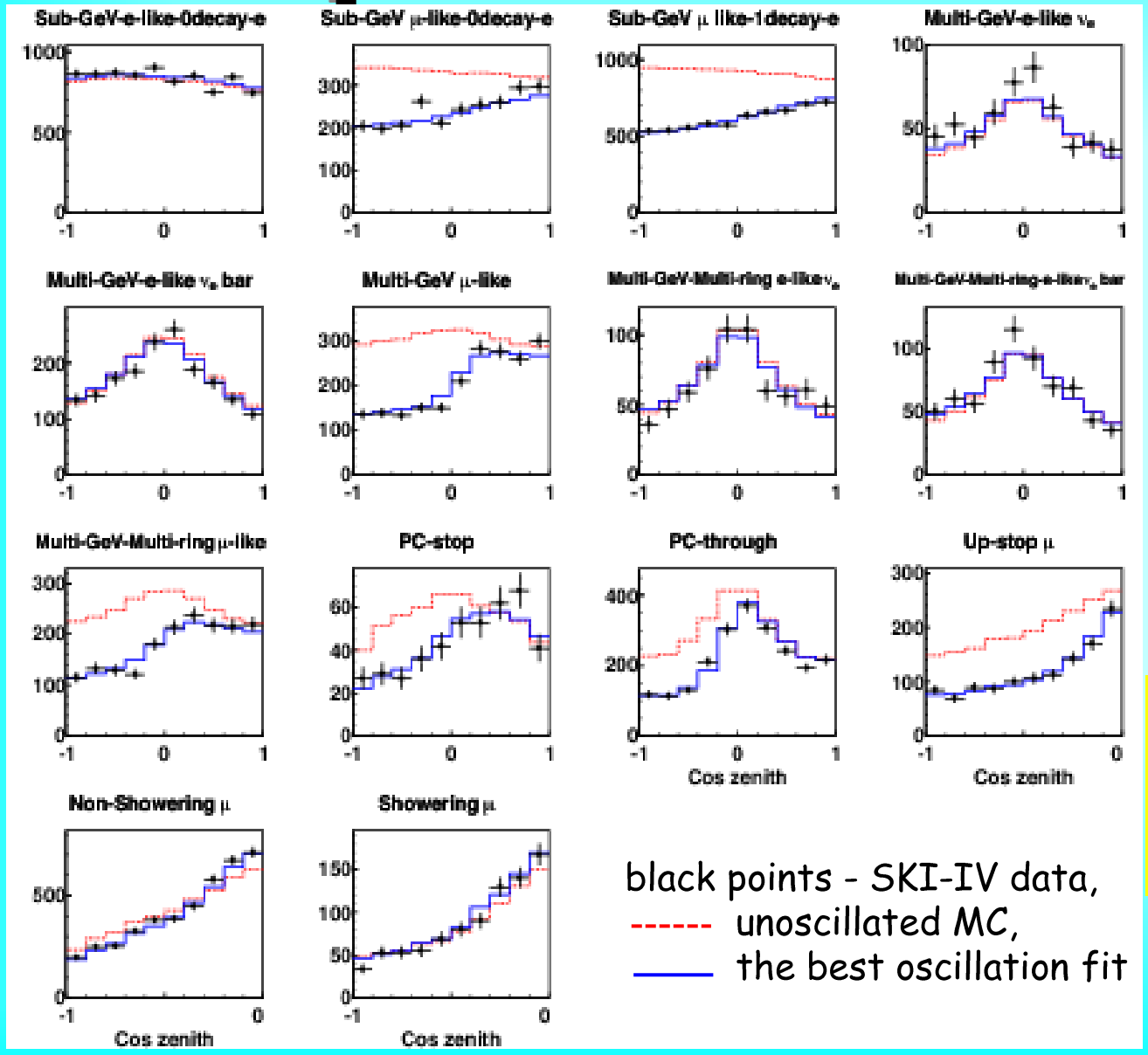
BAKSAN
Kamiokande
MACRO ...

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

Atmospheric neutrino results



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

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

Deficit of signal in mu channel depends zenith angle and energy

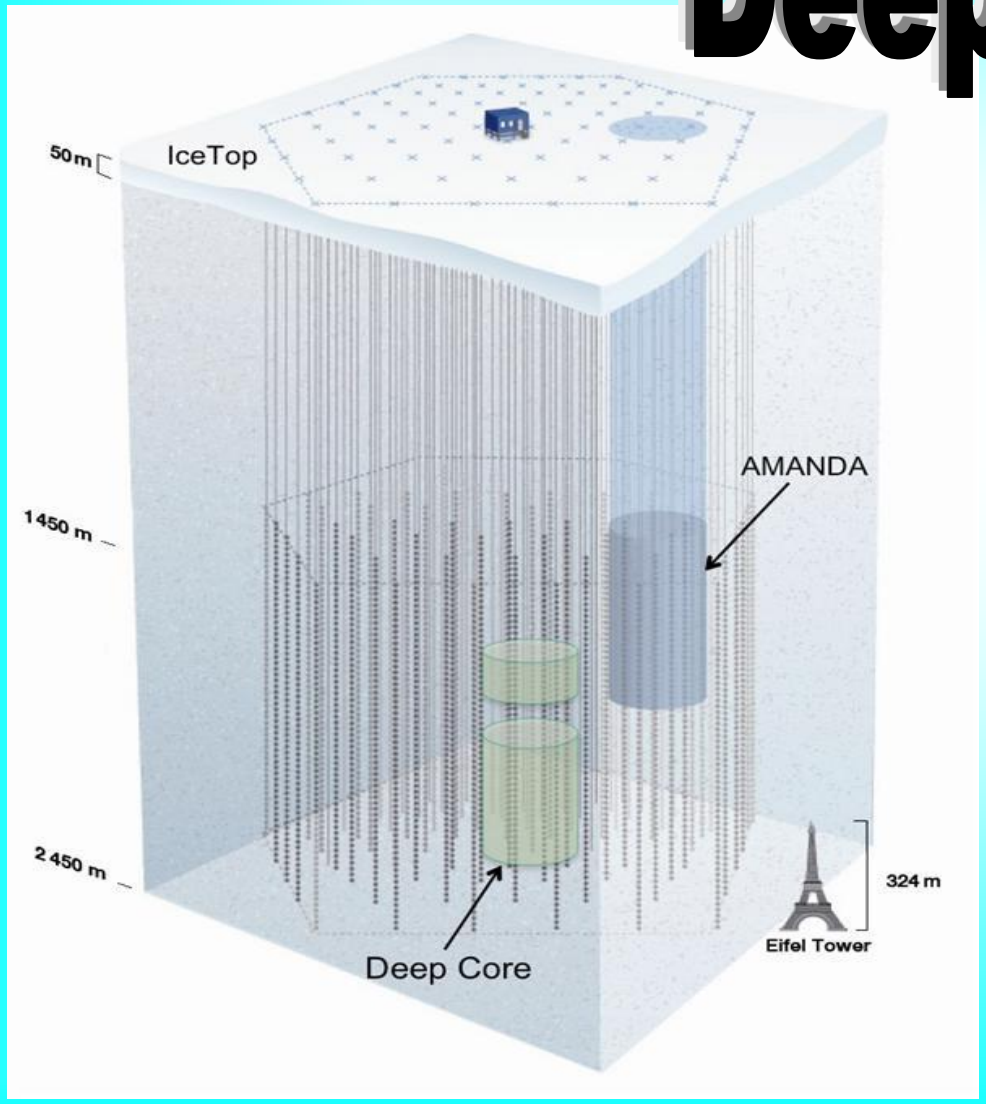
black points - SKI-IV data,
------ unoscillated MC,
——— the best oscillation fit

Ice Cube

Deep Core

100 GeV

10 - 15 GeV



PINGU

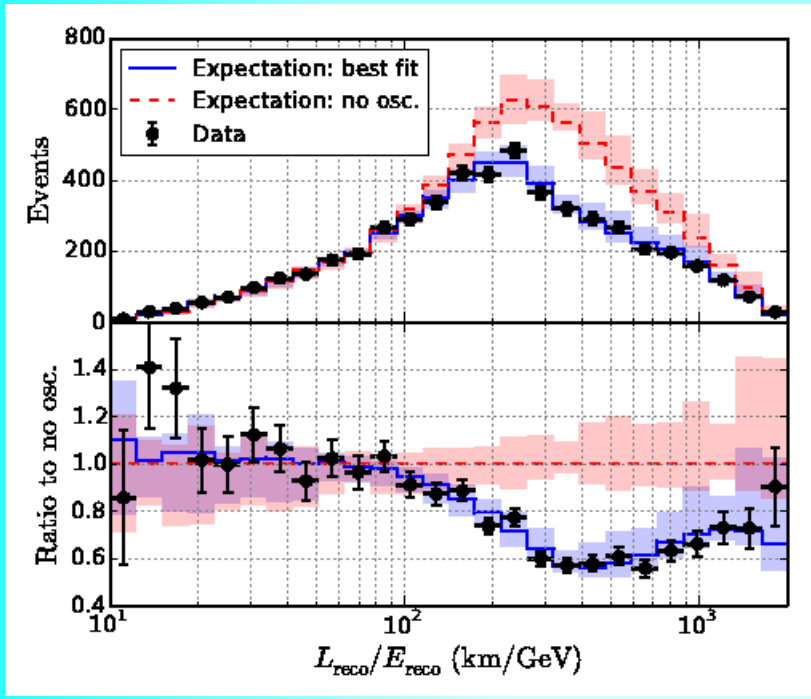
1 - 3 GeV

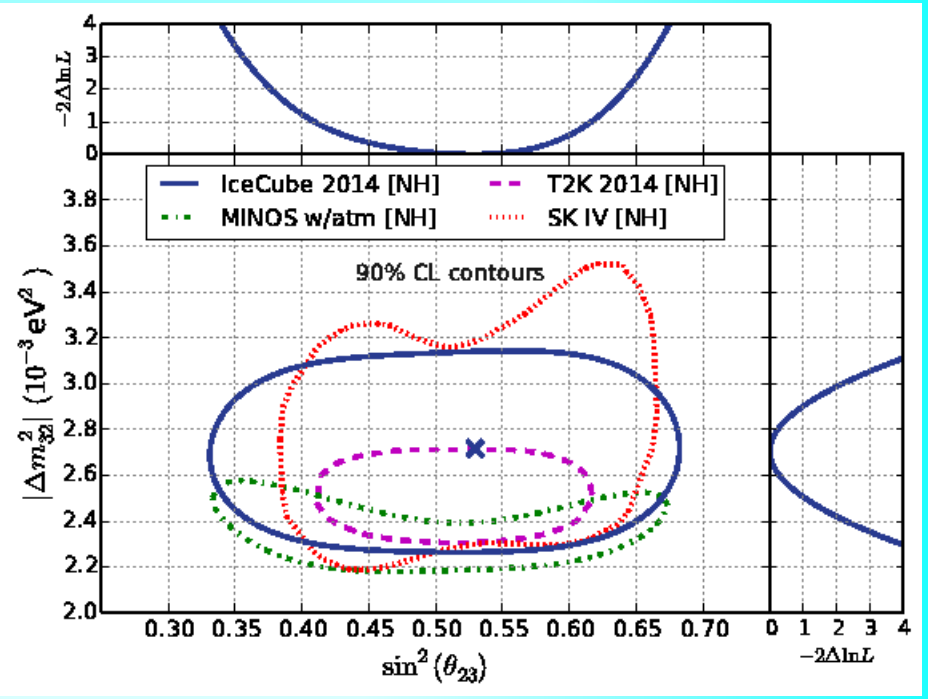
Precision IceCube Next Generation Upgrade

arXiv:1401.2046

Mass hierarchy

DeepCore oscillation result





atmospheric ν_μ disappearance,
3 years of data

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

Precise computations of the atmospheric neutrino flux, dedicated measurements

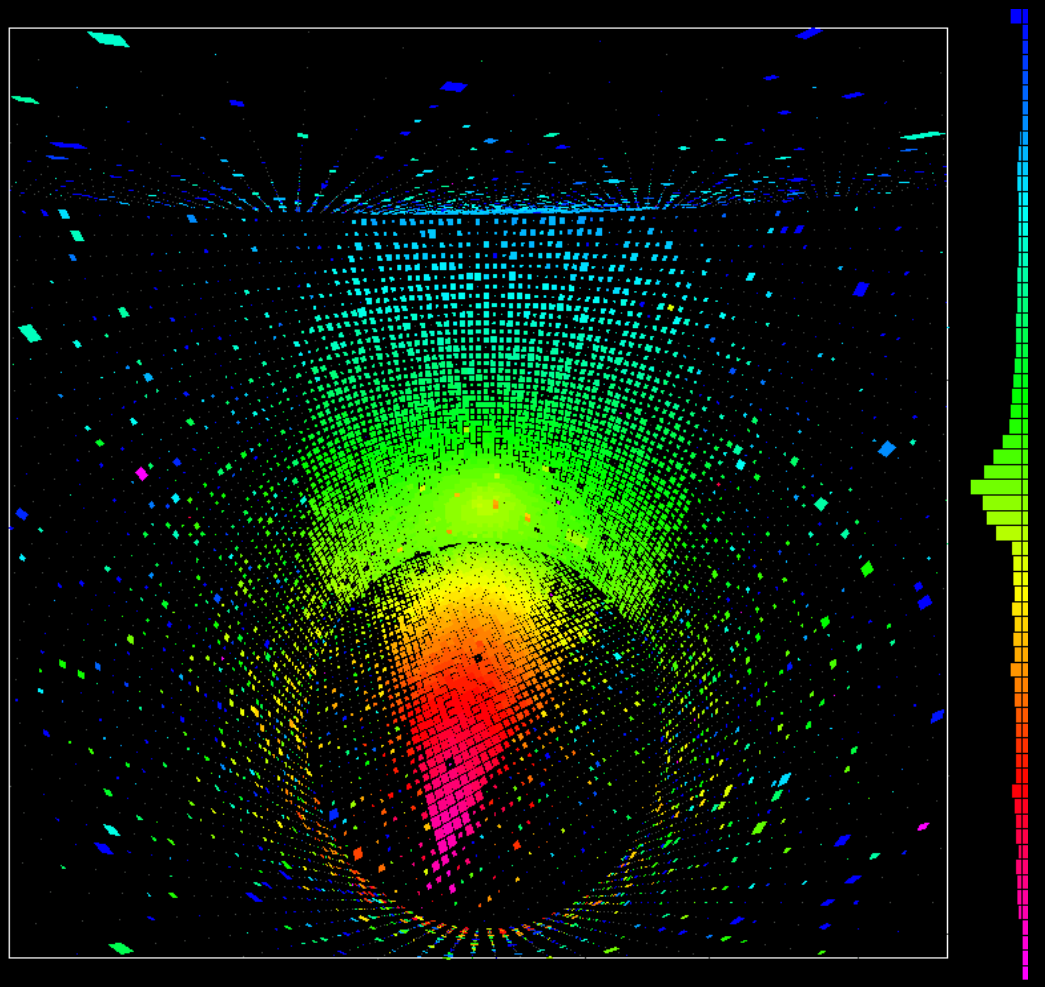
Determination of mass hierarchy

Measurements of the CP-phase

Physics beyond 3ν-paradigm:
- sterile neutrinos,
- non-standard interactions
- effects of violation of fundamental symmetries:

Experiments:

Accelerator Neutrinos



Accelerator neutrinos

Sources

p-N collisions

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

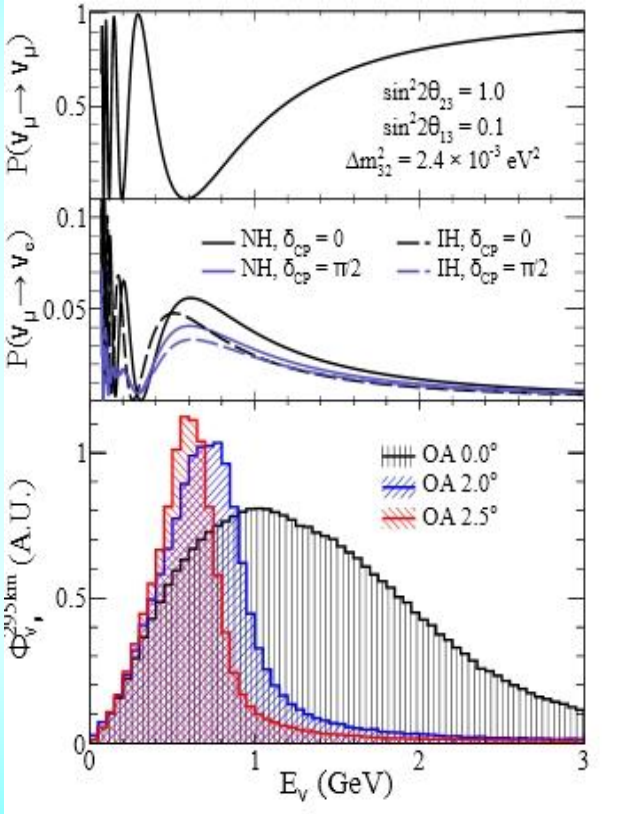
$K \rightarrow \mu + \nu_\mu$

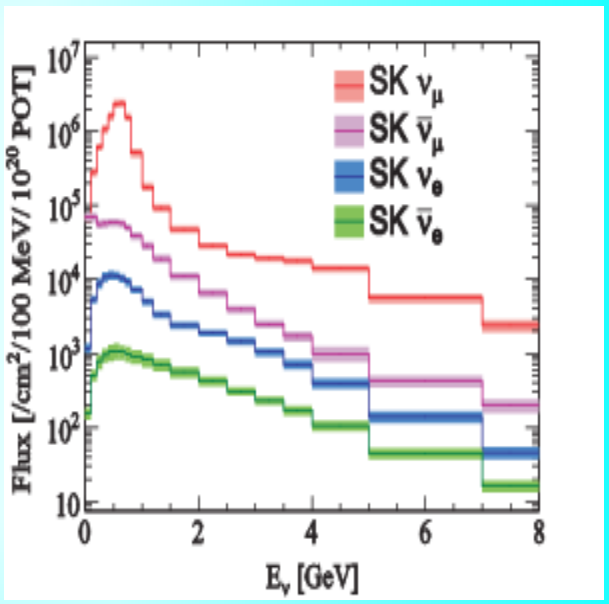
$K \rightarrow \pi + \mu + \nu_\mu$

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

Also charm meson decays in the beam dump experiments

off-axis





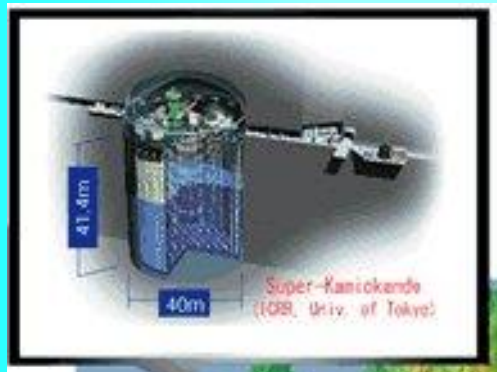
In future:
Beta beams
Neutrino factories

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

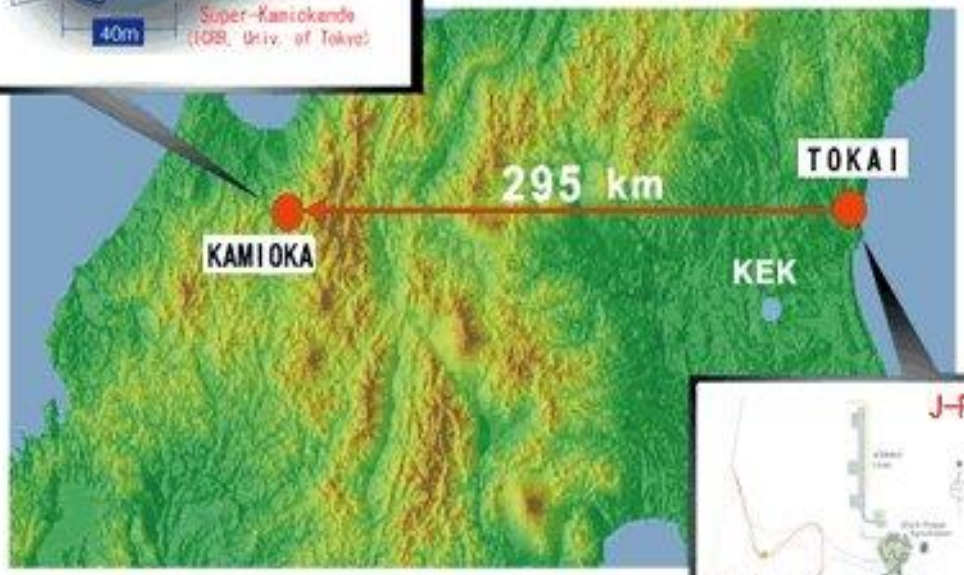
Detectors

Also the same as for atmospheric

Accelerator experiments



T2K



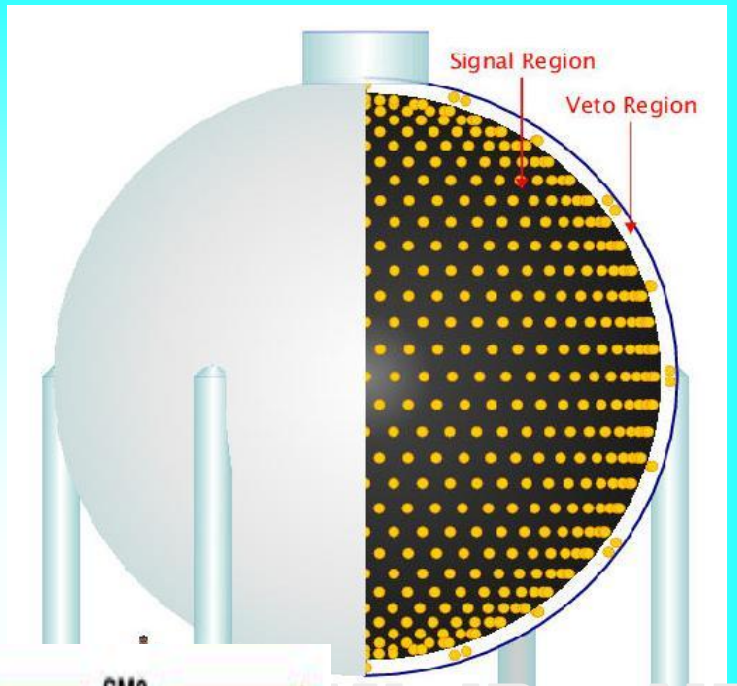
protons 30 GeV
2.5° off-axis →
narrow beam, E = 0.6 GeV
first oscillation maximum

MINOS+

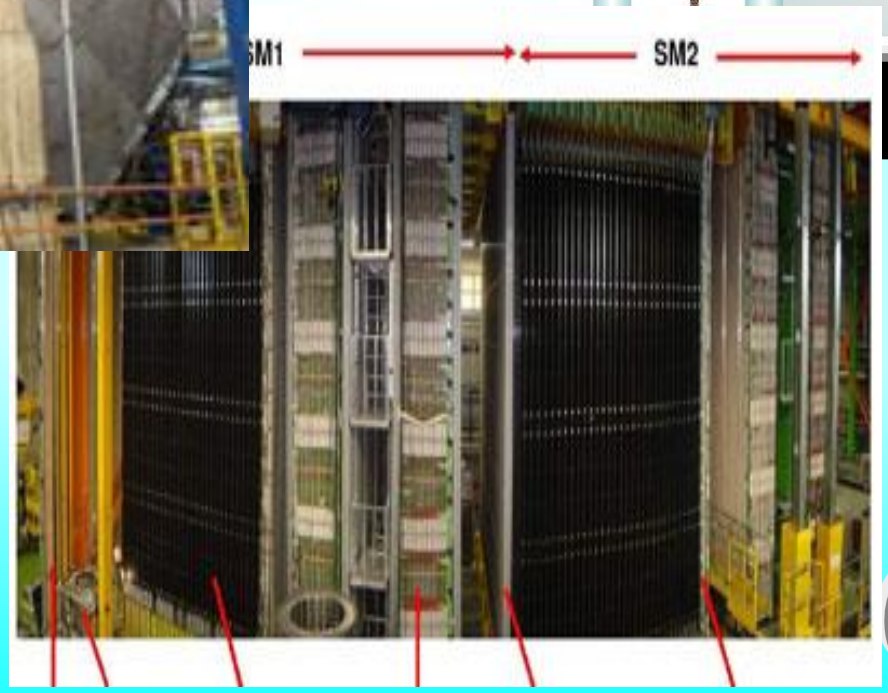
L = 735 km;
wide beam 4 – 10 GeV;
searches for nonstandard physics

Accelerator neutrinos

MINOS



MiniBooNE



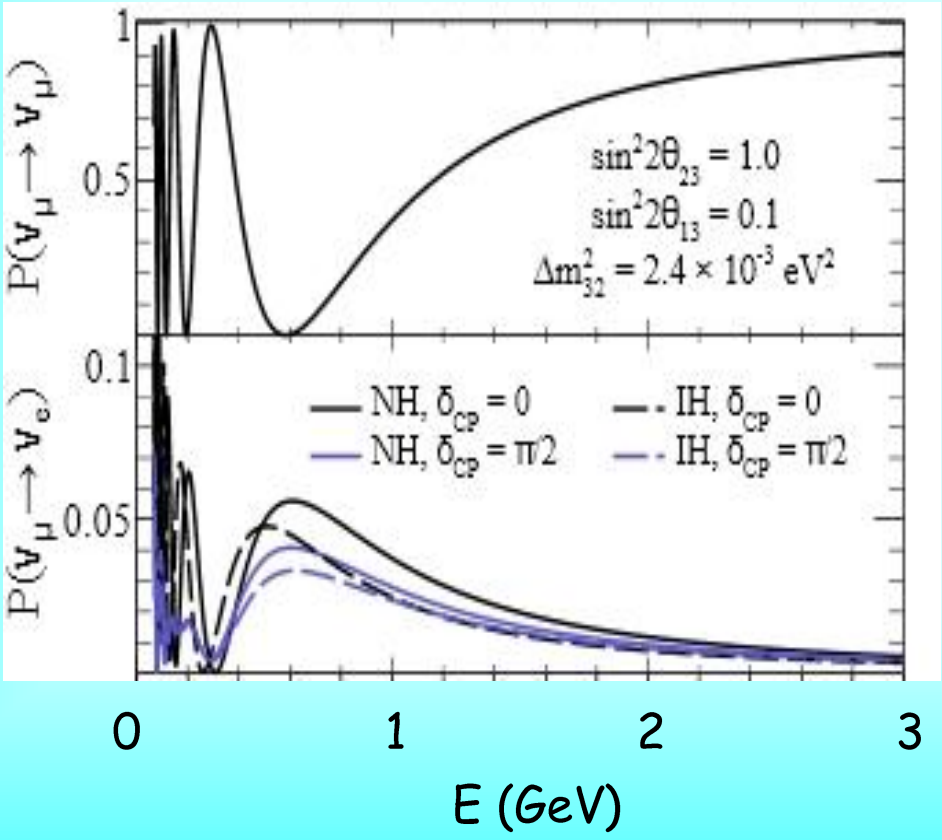
5th ν_τ - event

OPERA

T2K

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

Oscillation probabilities

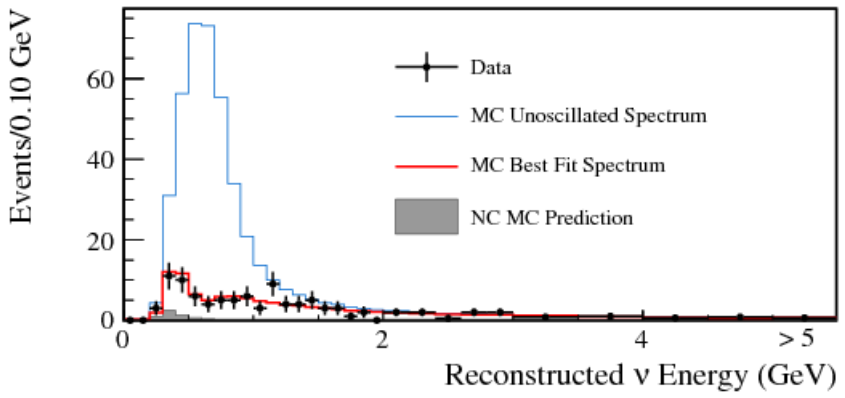


T2K

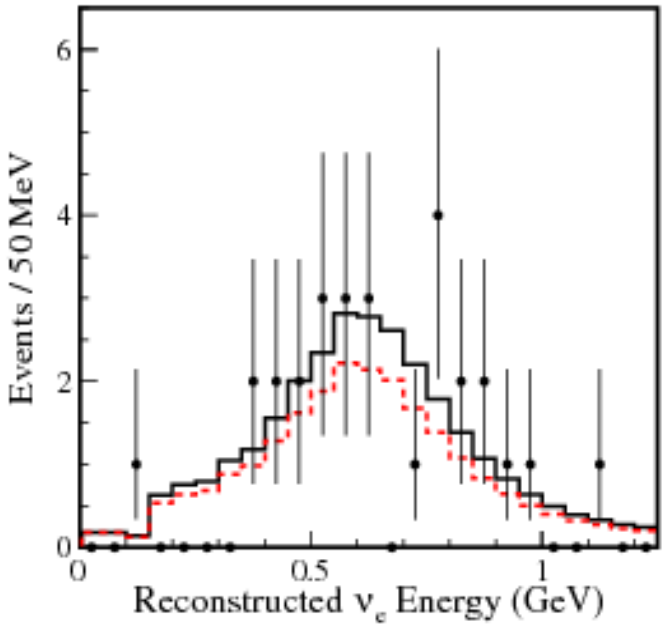
T2K Collaboration (K. Abe et al.).
Phys.Rev. D91 (2015) 7, 072010
arXiv:1502.01550 [hep-ex]

6.6×10^20 POT

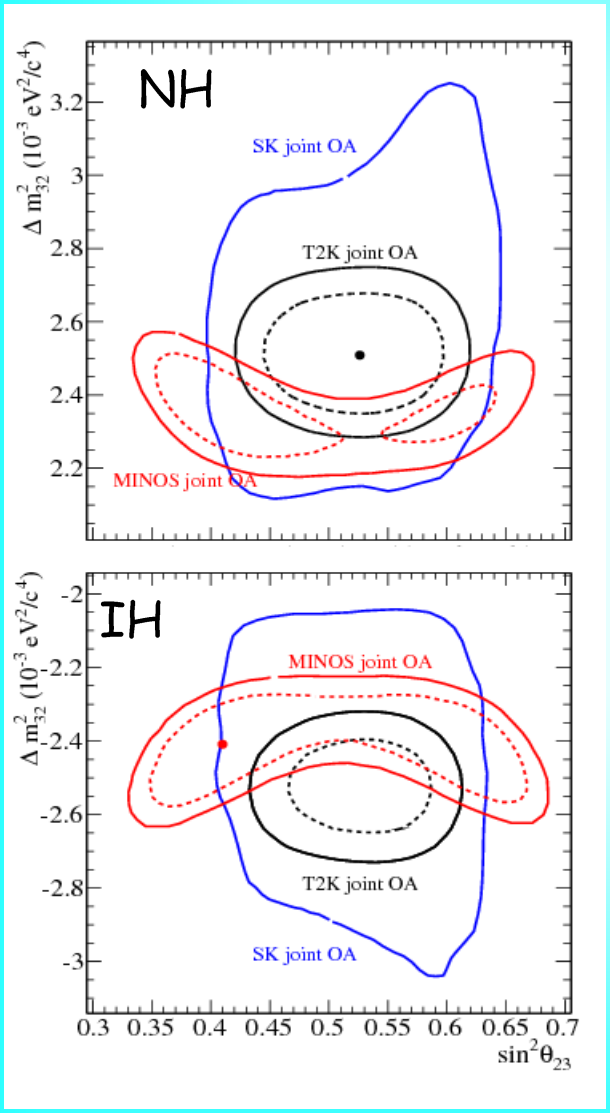
ν_μ -disappearance

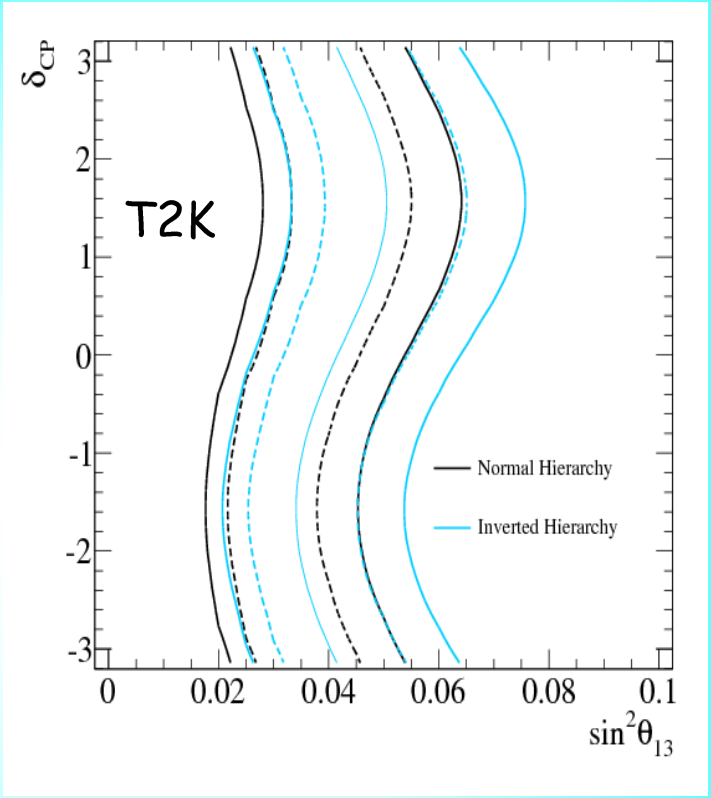


ν_e - appearance



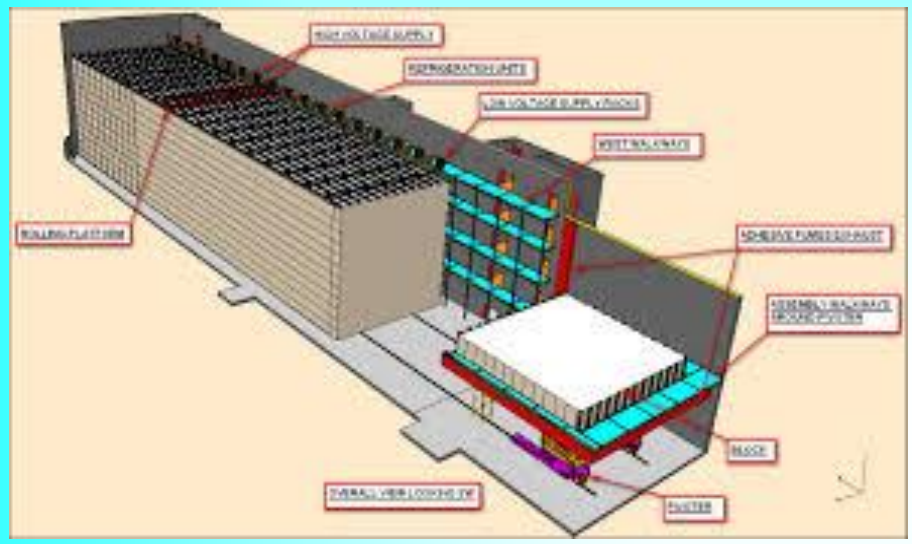
Accelerator experiments results





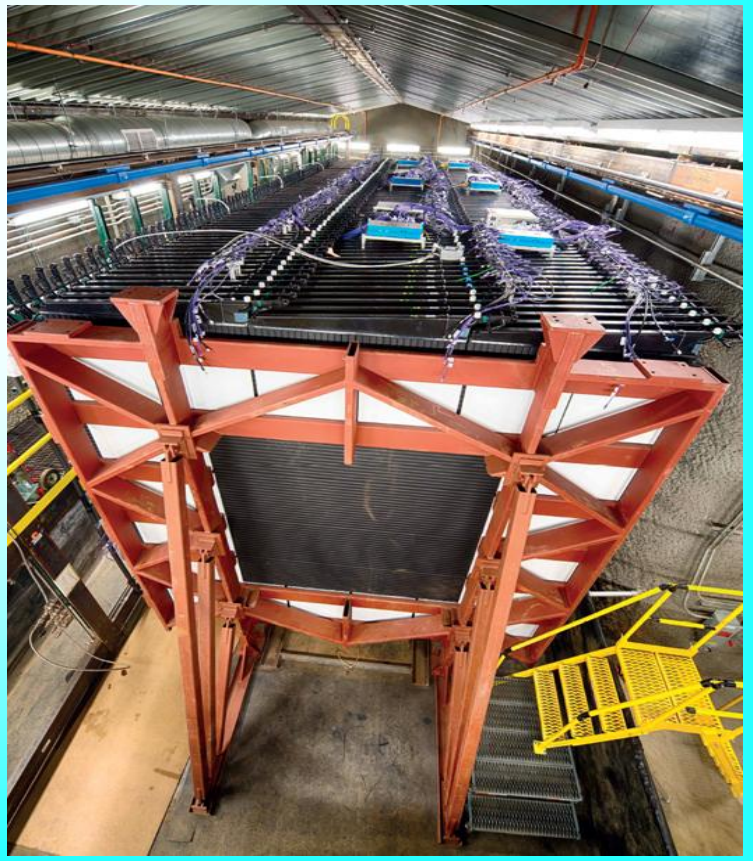
T2K: May 2014 - March 2015
- antineutrino mode: numu events
  59.8 - expected
  17 - observed

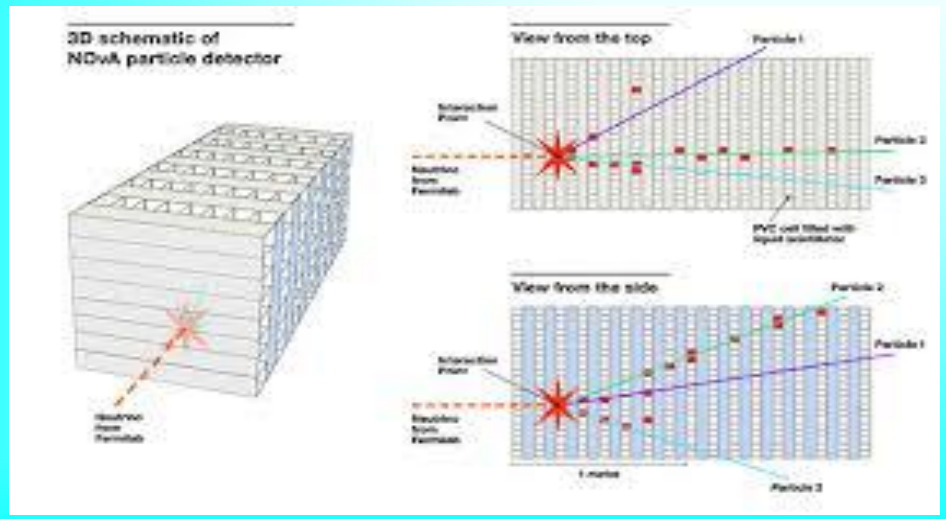
NOVA



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

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

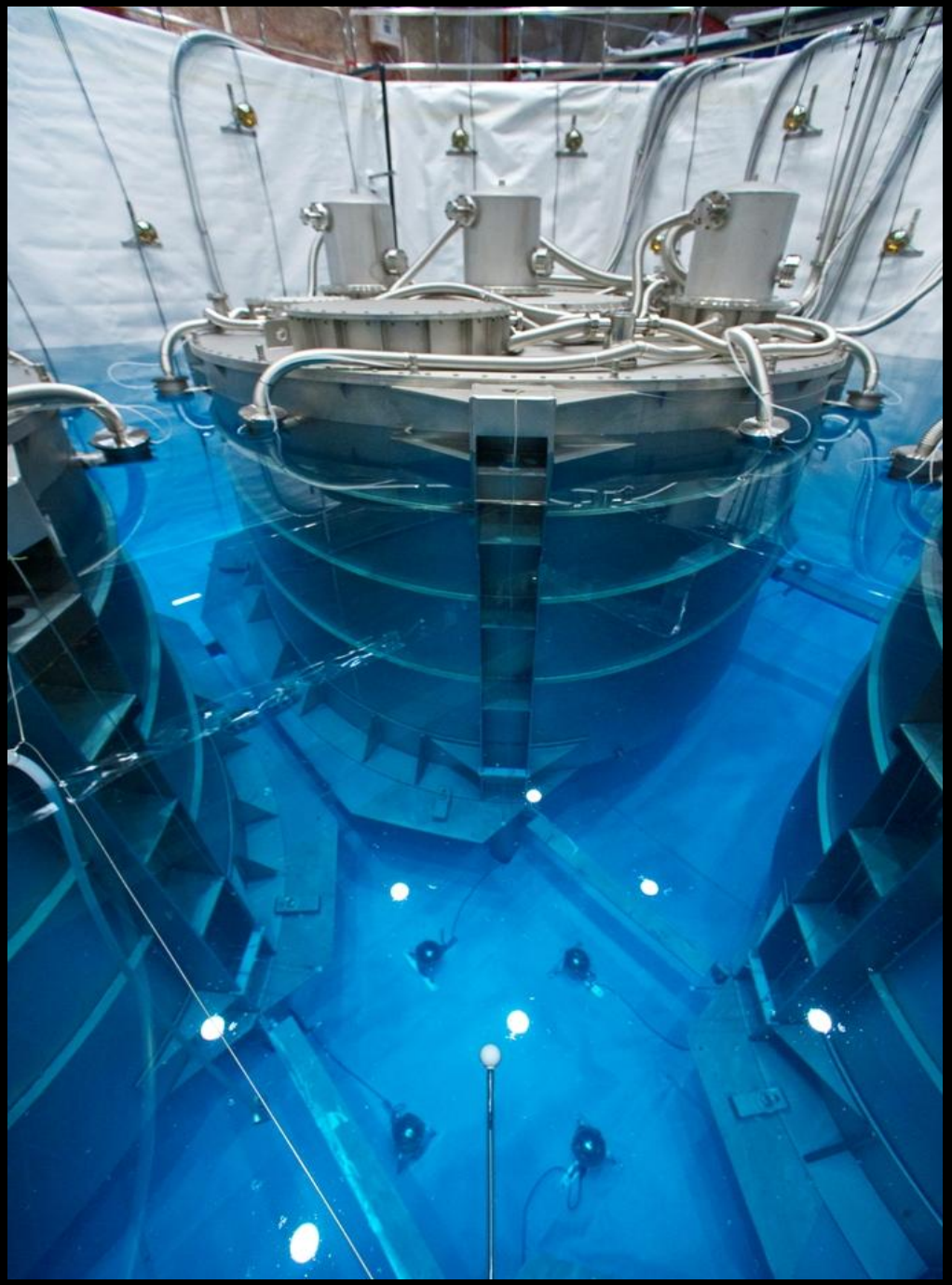




Reactor experiments

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

Gd loaded scintillators



Measuring U_{e3}

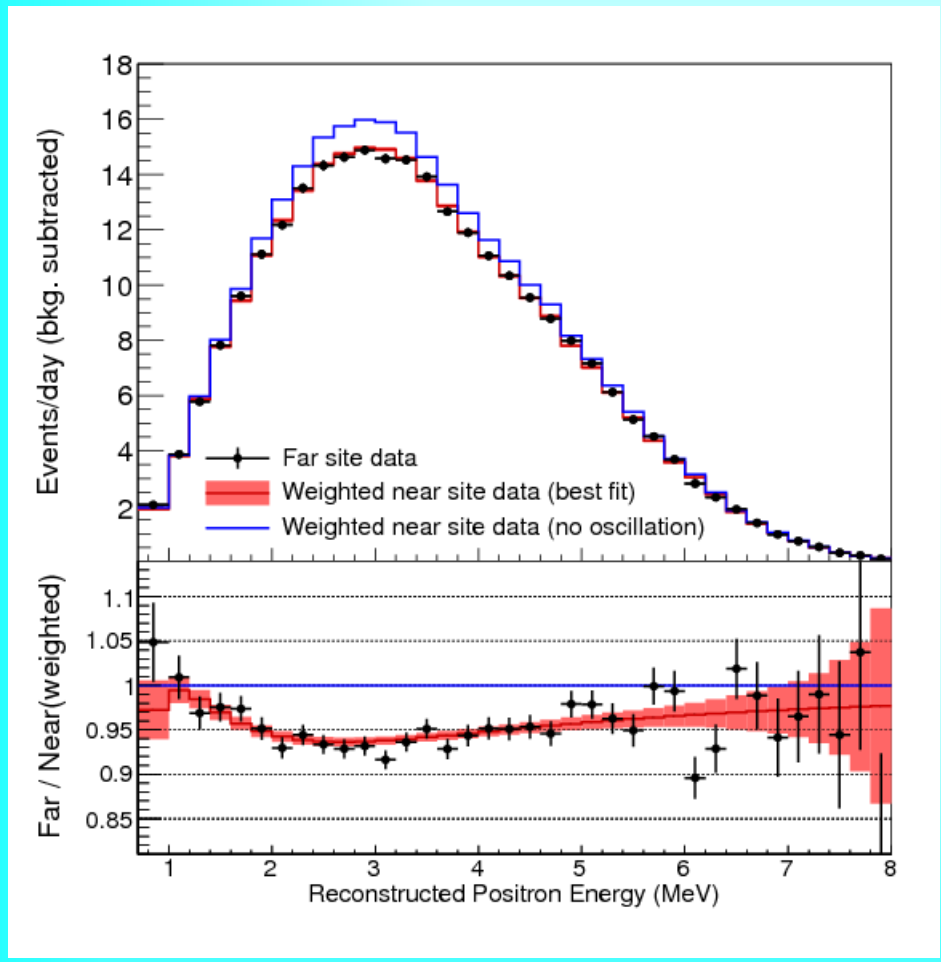
Daya Bay

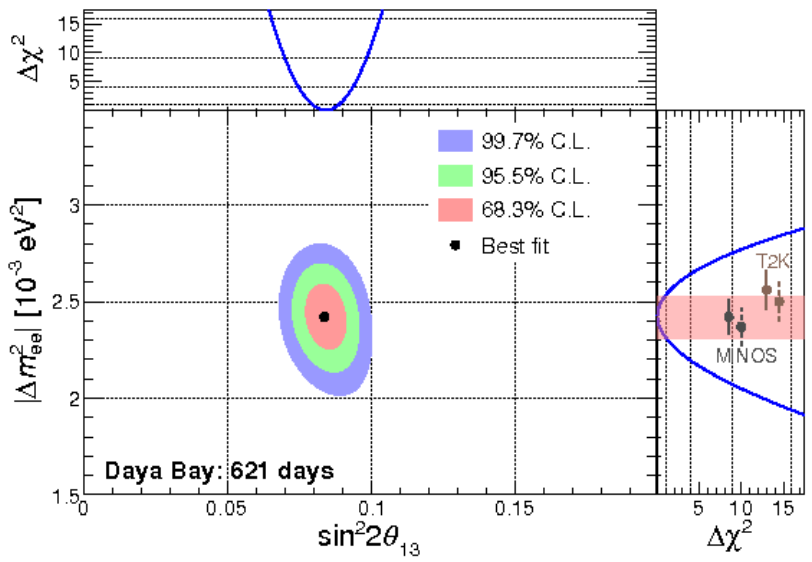
RENO

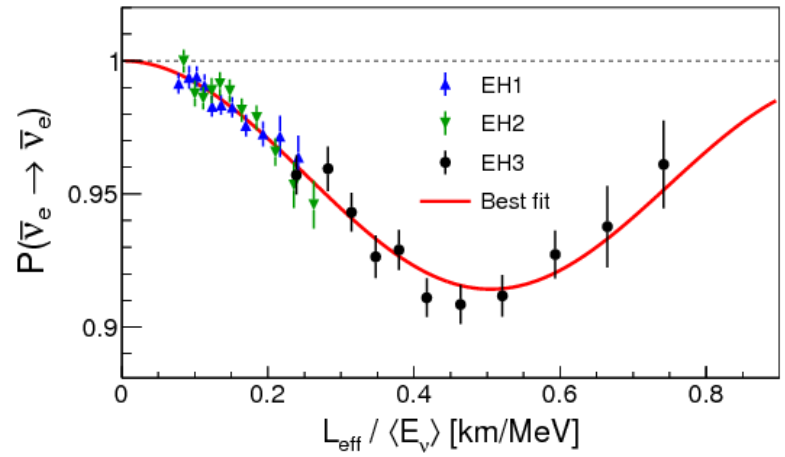
Double-CHOOZ

Daya Bay result

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

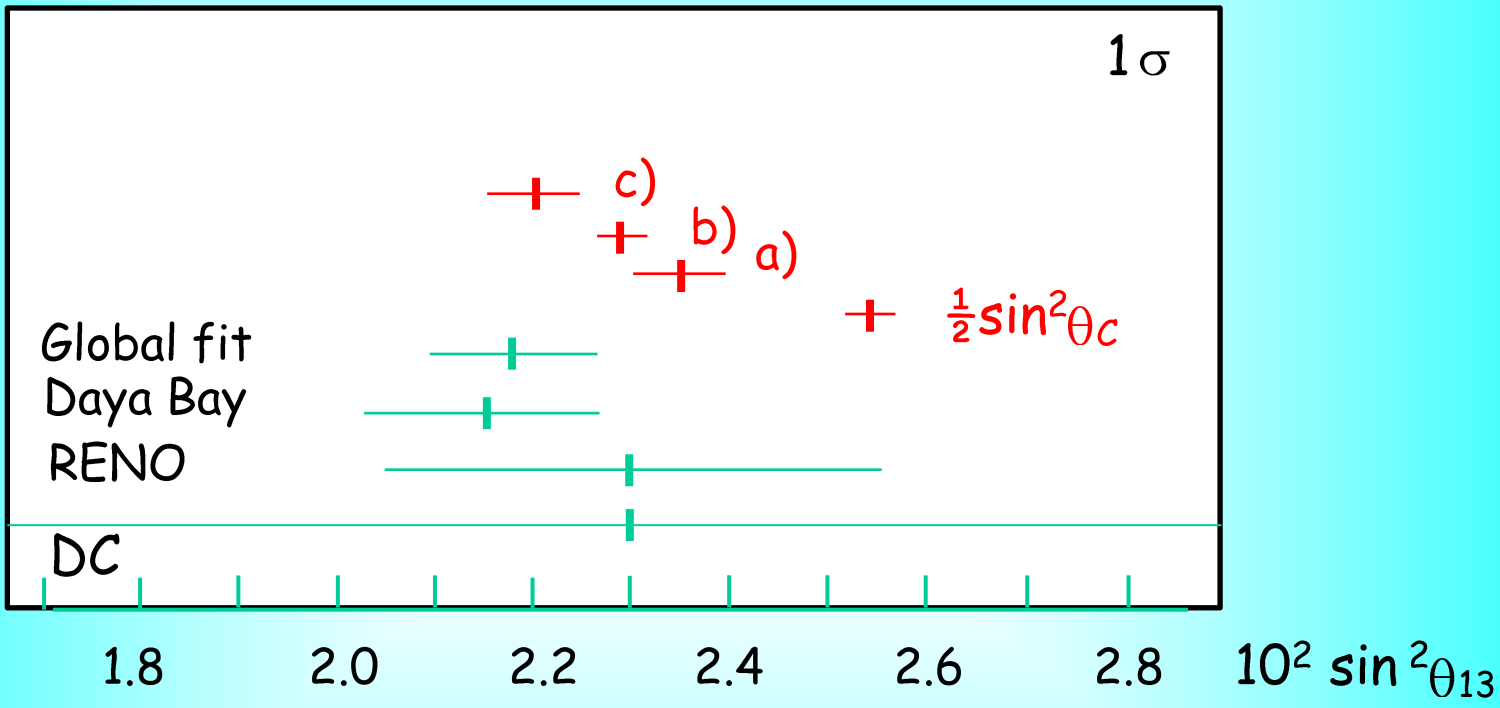






All the data

smaller than from T2K



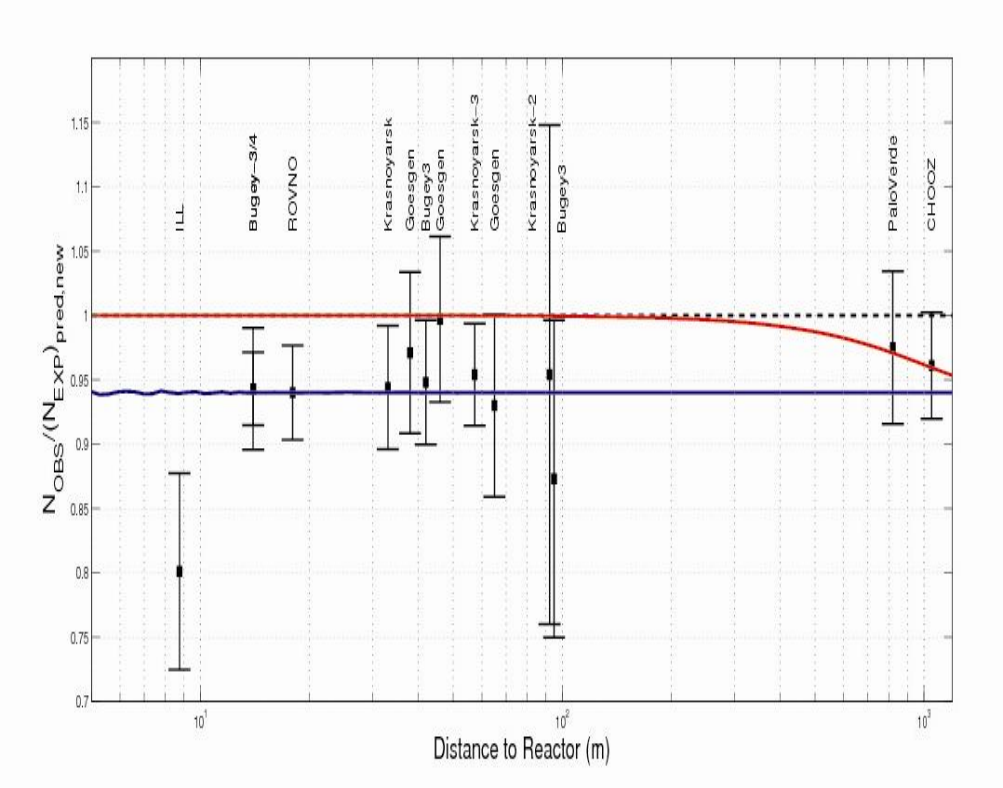
a) CKM -corrections; $\sin^2\theta^x_{23} = 0.50$

b) No CKM corrections, $\sin^2\theta^x_{23} = 0.45$ $(\sin^2\theta_{23} = 0.40)$

c) CKM-corrections, $\sin^2\theta^x_{23} = 0.47$ $(\sin^2\theta_{23} = 0.42)$

$\cos(\alpha - \phi_{td}) = 1$

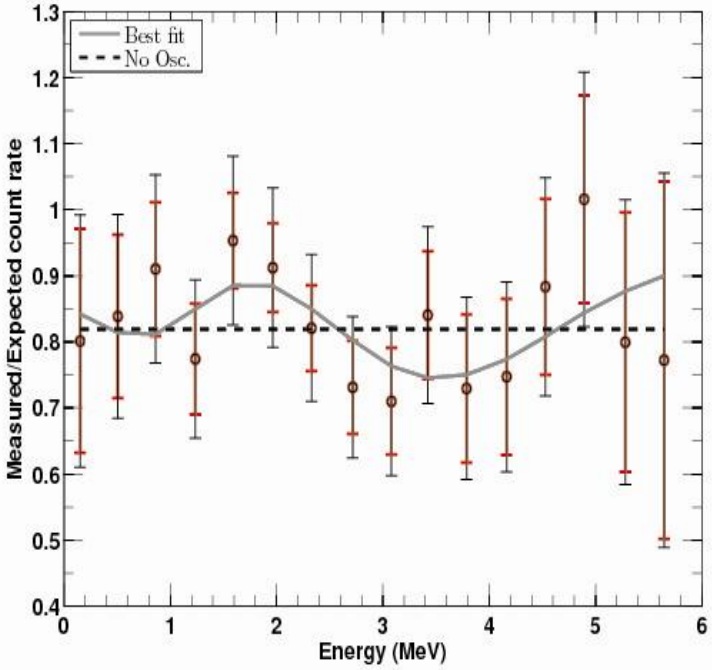
Reactor neutrino anomaly



Sterile neutrinos

$\Delta m^2 > 1.5\ eV^2$

$\sin^2 2\theta = 0.17 +/- 0.1$



G.Mention et al, arXiv: 1101.2755

increase of the mean flux by 3 -6%

Global fit

Solar neutrinos

KamLAND

Atmospheric neutrinos

Double Chooz

Daya Bay

MINOS

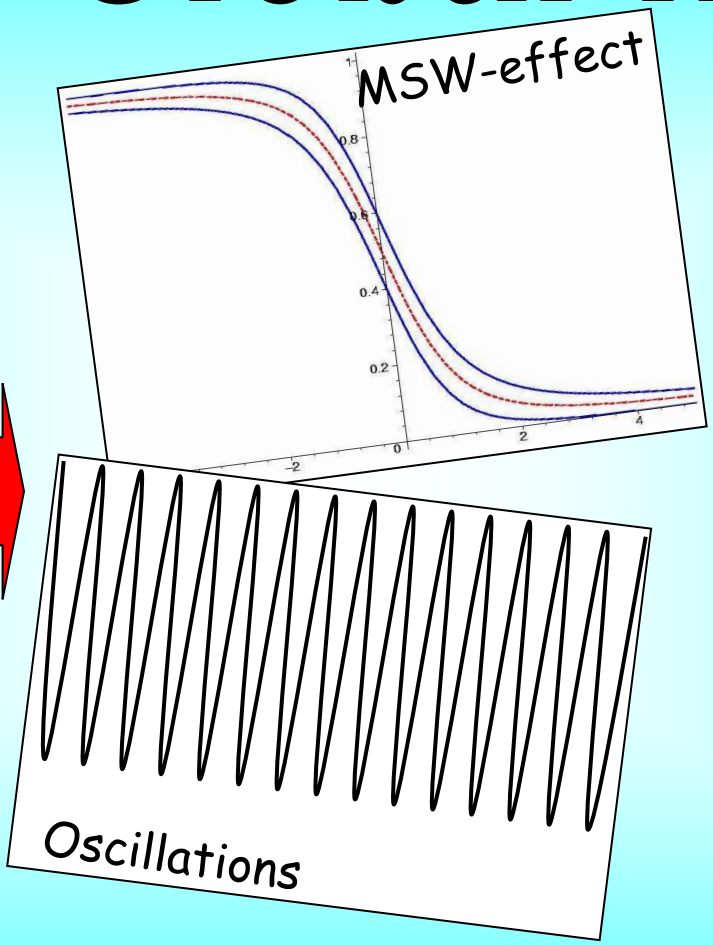
K2K

RENO

T2K

Antares

DeepCore

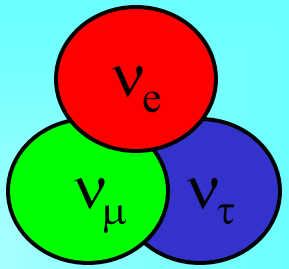


Δm^2

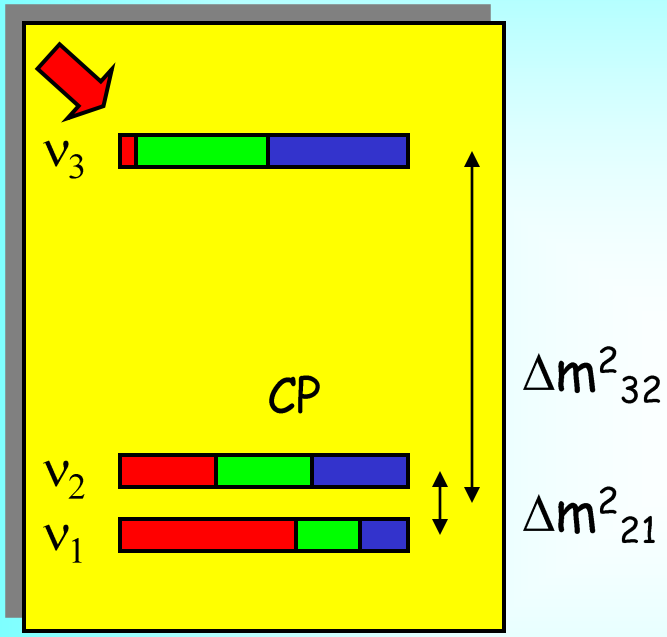
θ

Can be resonantly enhanced in matter

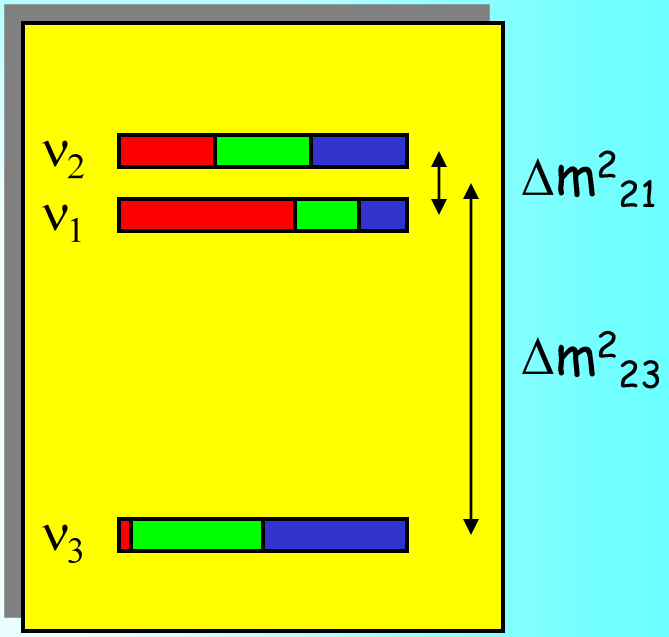
Lepton Mixing



1-3 mixing
2%



Normal mass hierarchy



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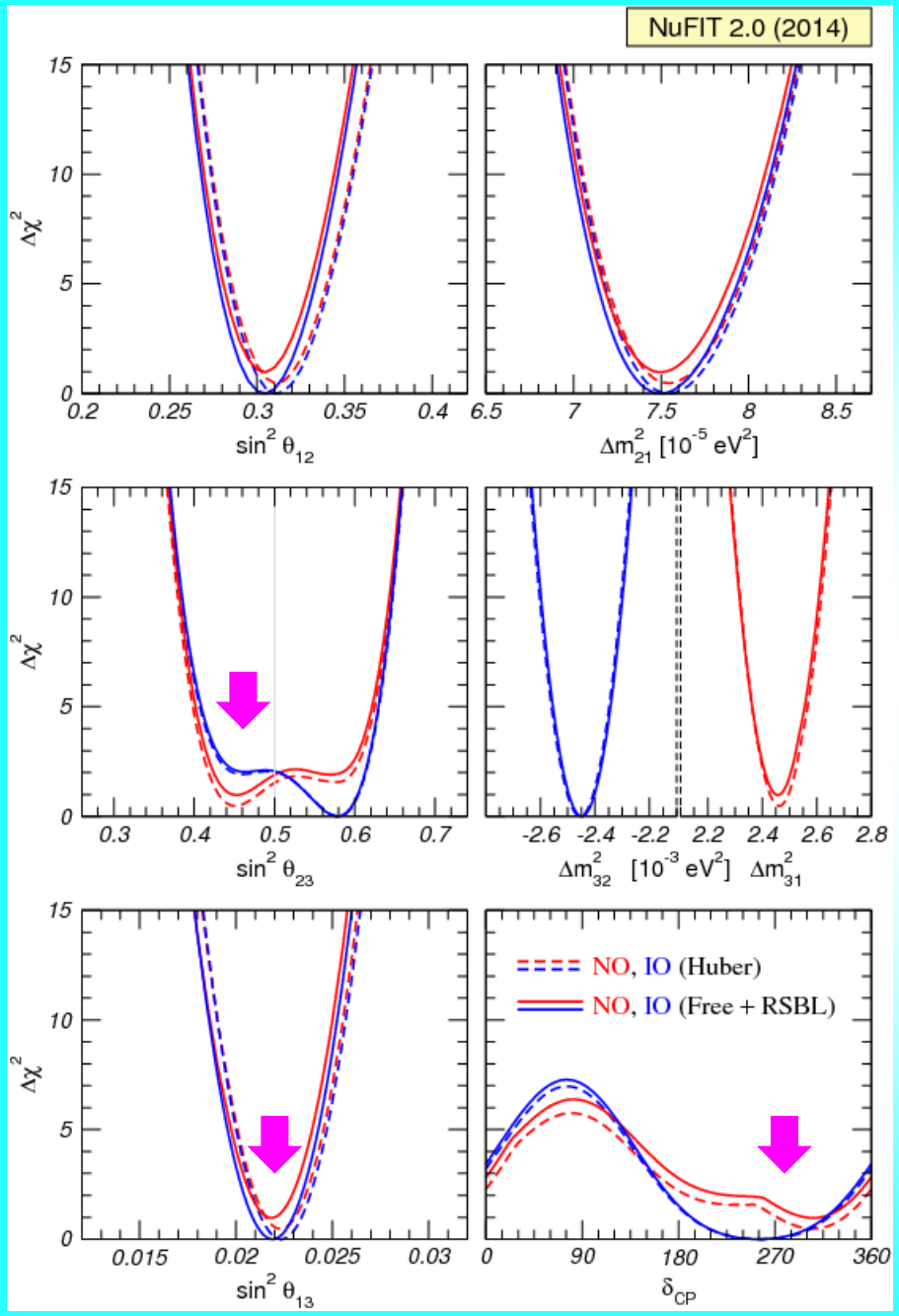
Symmetry: TBM?

For antineutrinos spectra are different (distribution of the ν_μ and ν_τ - flavors in ν_1 and ν_2) due to possible CP-violation



Global 3ν - fit

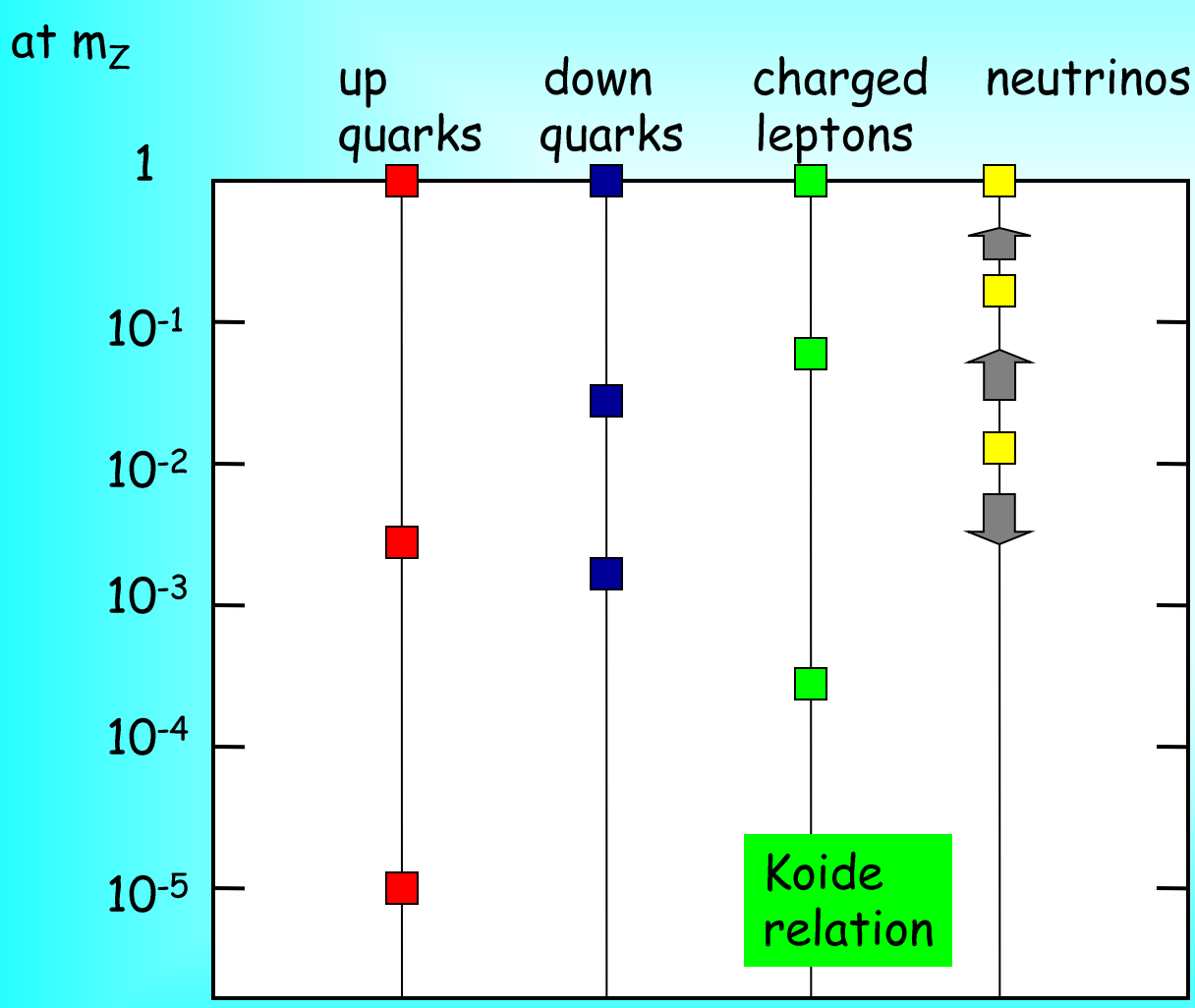
M.C. Gonzalez-Garcia, M. Maltoni, T. Schwetz, JHEP 1411 (2014) 052,1409.5439 [hep-ph]

2-3 mixing:

asymmetric for NO and IO
NO: $\sin^2\theta_{23}$ = 0.45, IO: 0.58

Small preference IO and 2nd quadrant

Mass hierarchies



Solar, KamLAND

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

~ 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

What is Next?

Mass hierarchy / ordering

CP-violation phase

Deviation of 2-3 mixing from maximal

Type of the mass spectrum
(quasi-degeneate, hierarchical)

Absolute mass scale

Nature of neutrino mass (Dirac, Majorana)?

Lepton number violation

New neutrino states (sterile neutrinos)

Symmetry or no symmetry?

Neutrino interactions

Race for hierarchy and CP

Mass ordering

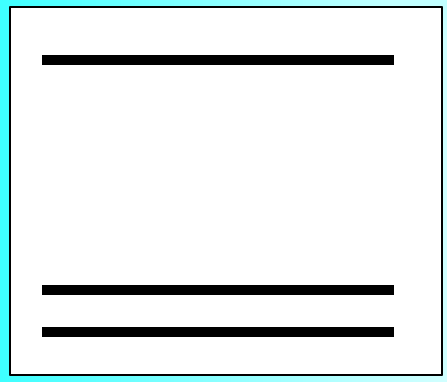
$\Delta m^2_{31} \rightarrow - \Delta m^2_{31}$

Resonance in the antineutrino channel> V → -V

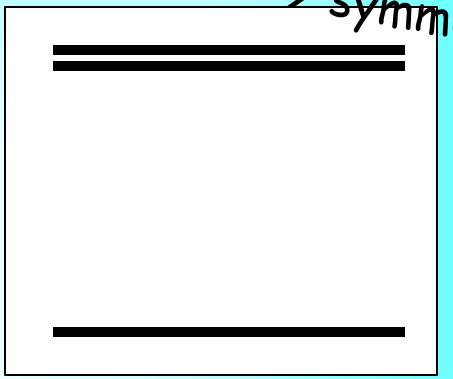
Theoretical implications

generically

Quasi-degenerate
→ symmetry



Normal vs. special



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

$$\theta \sim \sqrt{\frac{m_2}{m_3}}$$

Similar to quark spectrum

rescaling

See-saw

Quark-lepton symmetry

Unification

$$\frac{\Delta m}{m} \sim \frac{\Delta m_{21}^2}{2\,\Delta m_{32}^2} = 1.6\ 10^{-2}$$

but 1-2 mixing strongly deviates from maximal

Pseudo-dirac + 1 Majorana

Flavor symmetries

Broken $L_e - L_\mu - L_\tau$ symmetry

Race for mass hierarchy

Matter effect on 1-3 mixing

Precise measurements of Δm^2 at reactors

Cosmology Σm

Atmospheric neutrinos

PINGU

ORCA

INO

NH ↔ IH
nu ↔ antinu

LBL experiments

NOvA
T2K
LBNE-DUNE

Supernova neutrinos

Earth matter effect
Energy spectra

Double beta decay m_{ee}

Sterile neutrinos may help?

Mass hierarchy

→ Further advance

Step to discover CP

important by itself

↓ Theoretical implications

↘ Phenomenology

Supernova neutrinos

Atmospheric neutrinos

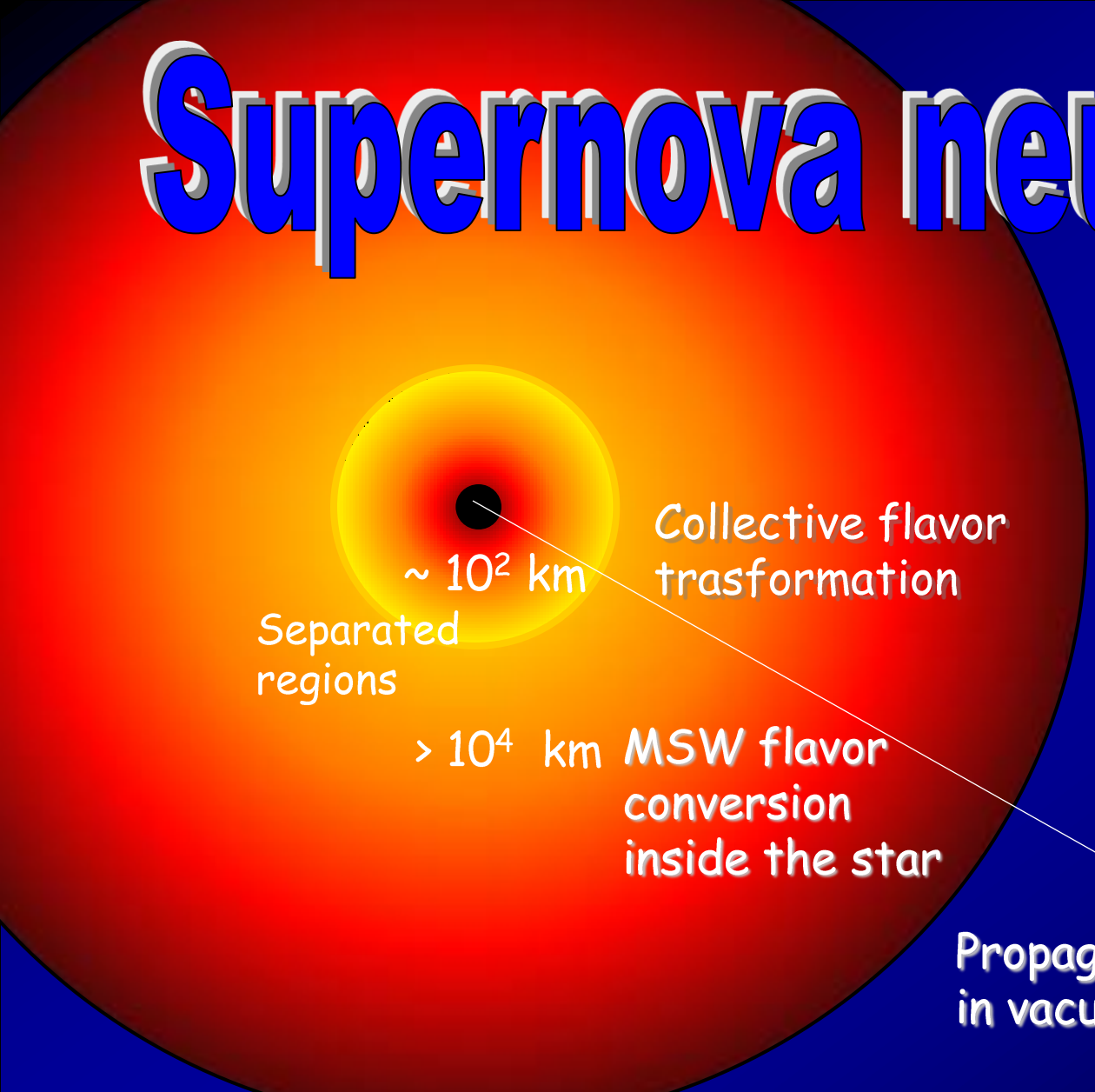
bb0n decay

LBL

Solar neutrinos

Cosmology

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 ~ ΔF = (10 – 20)% for anti-ν

SN1987A: 19 events, anti-ν

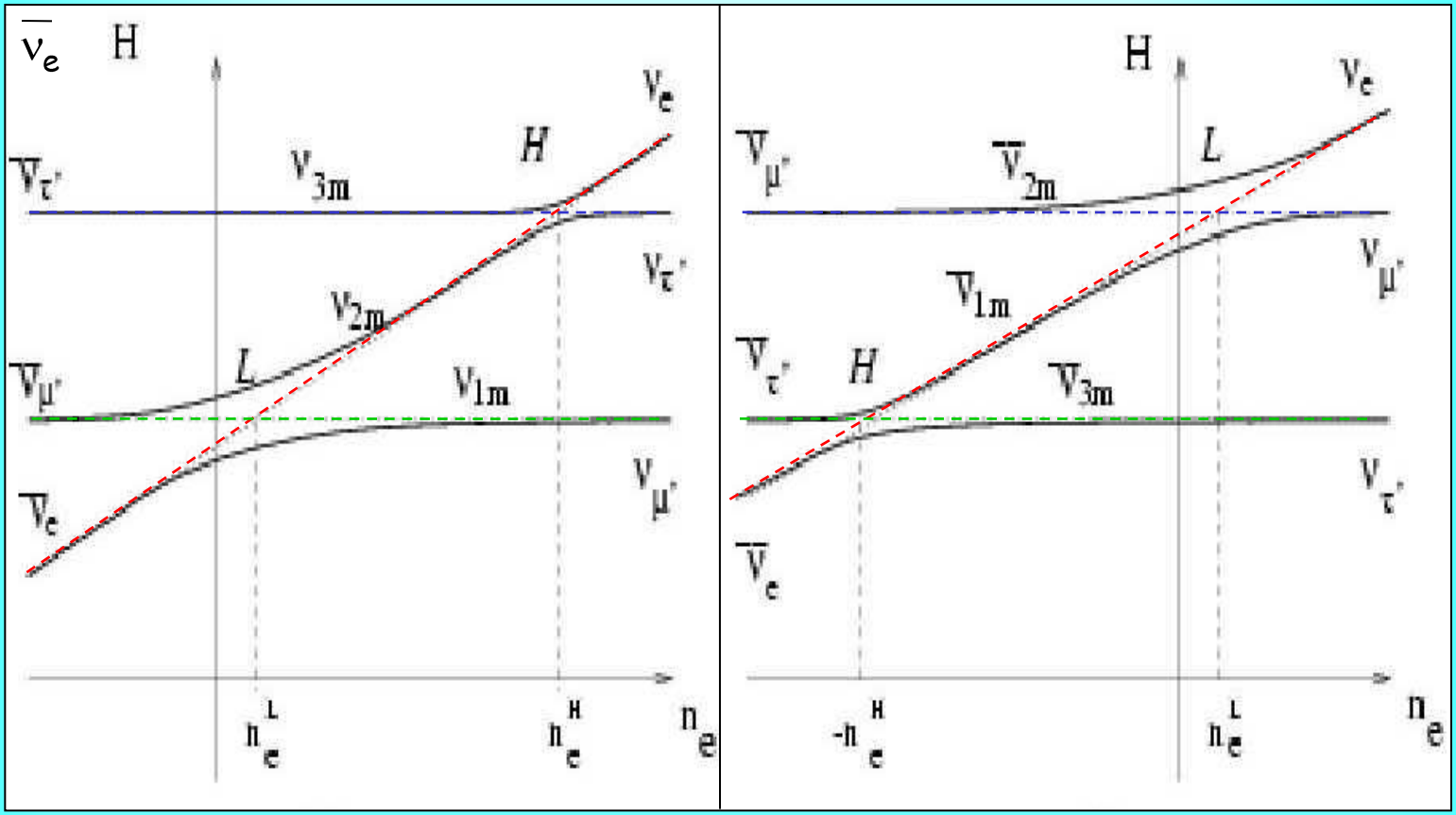
Level crossing scheme

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

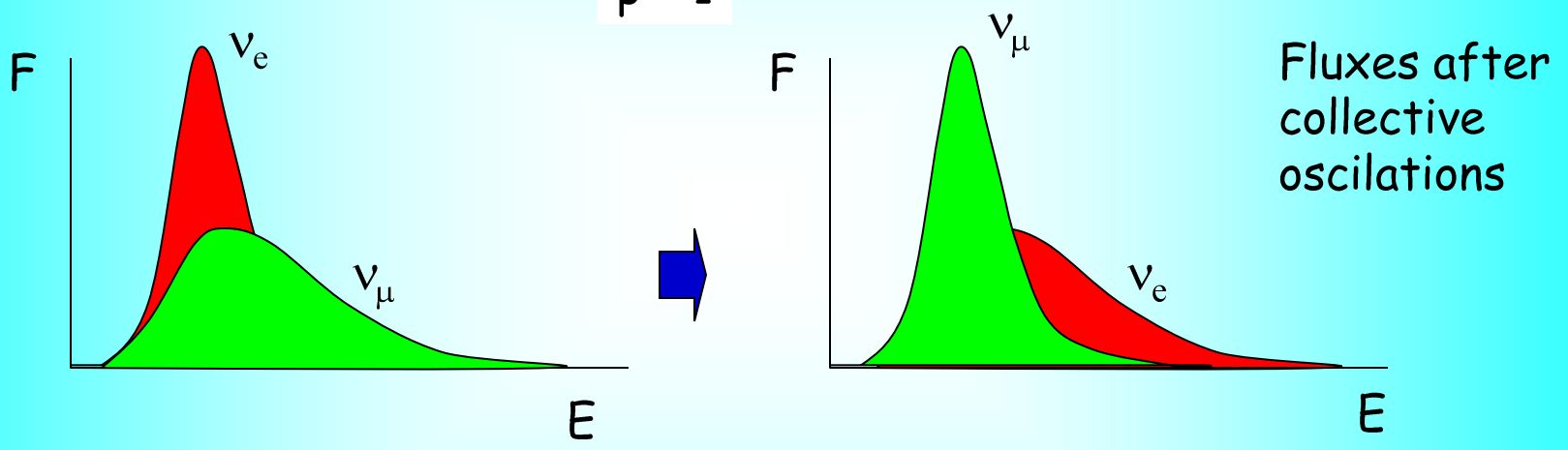
Permutation of spectra

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

$p = 1 - P_{ee}$

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

Hierarchy affects

Time rise of the anti-ν_e burst initial phase → IH

P. Serpico et al

Strong suppression of the ν_e peak → NH

$\nu_e \rightarrow \nu_3$

Permutation of the electron and non-electron neutrino spectra

A. Dighe, A. S. C. Lunardini

Earth matter effects

in the antineutrino channel only → NH

in the neutrino channel only → IH

If the earth matter effect is observed for antineutrinos NH is established!

Shock wave effect

in neutrino channels → NH
in antineutrino → IH

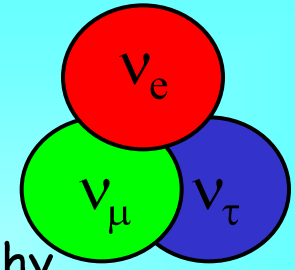
G. Fuller, et al
R. Tomas et al

Neutrino collective effects

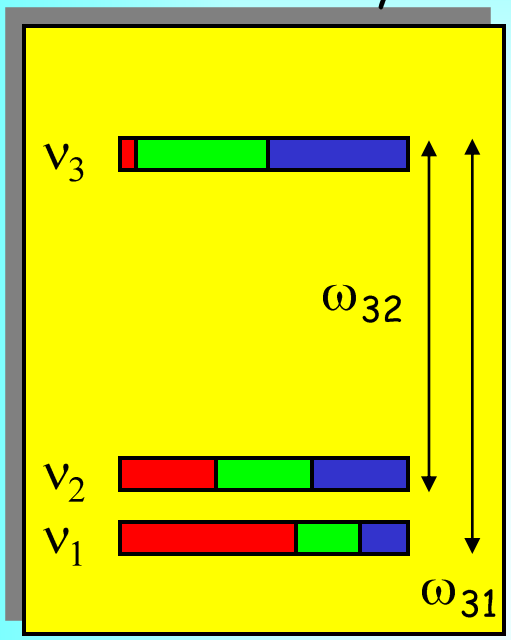
more in IH case
Spectral splits at high energies → IH

G Fuller et al
B Dasgupta et al

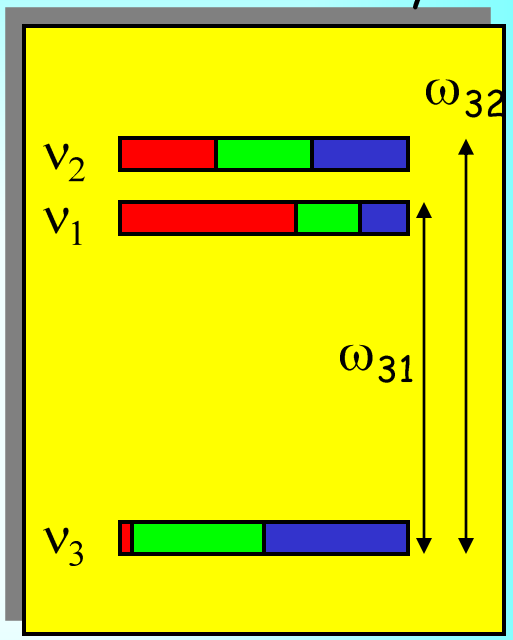
Mass hierarchy (ordering)



Normal hierarchy



Inverted hierarchy



Cosmology

$\beta\beta$-decay

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

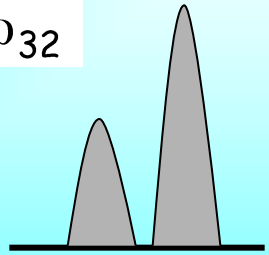
Mass states can be marked by ν_e - admixtures

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

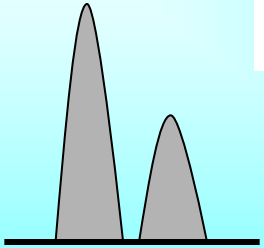
$\omega_{31} < \omega_{32}$

Oscillation depth

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



Fourier analysis



S. Petcov
M. Piai

JUNO

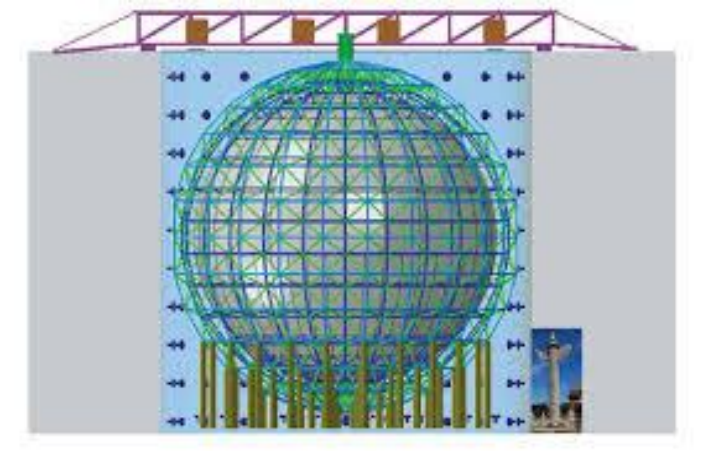
Jiangmen Underground Neutrino Observatory

d = 700 m, L = 53 km, P = 36 GW

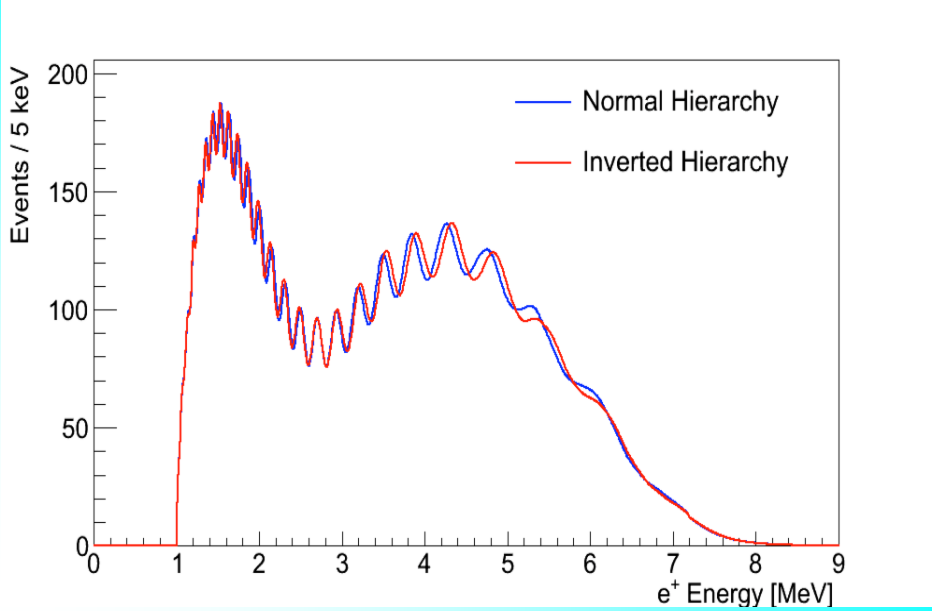
20 kt LAB scintillator

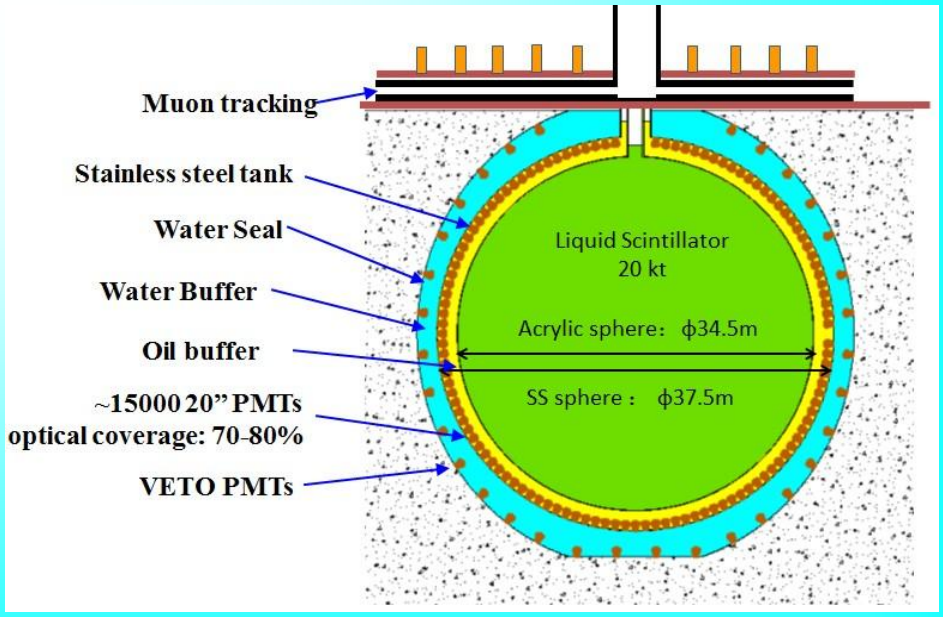
$n + p \rightarrow d + \gamma$

Key requirement:
energy resolution 3% at 1 MeV



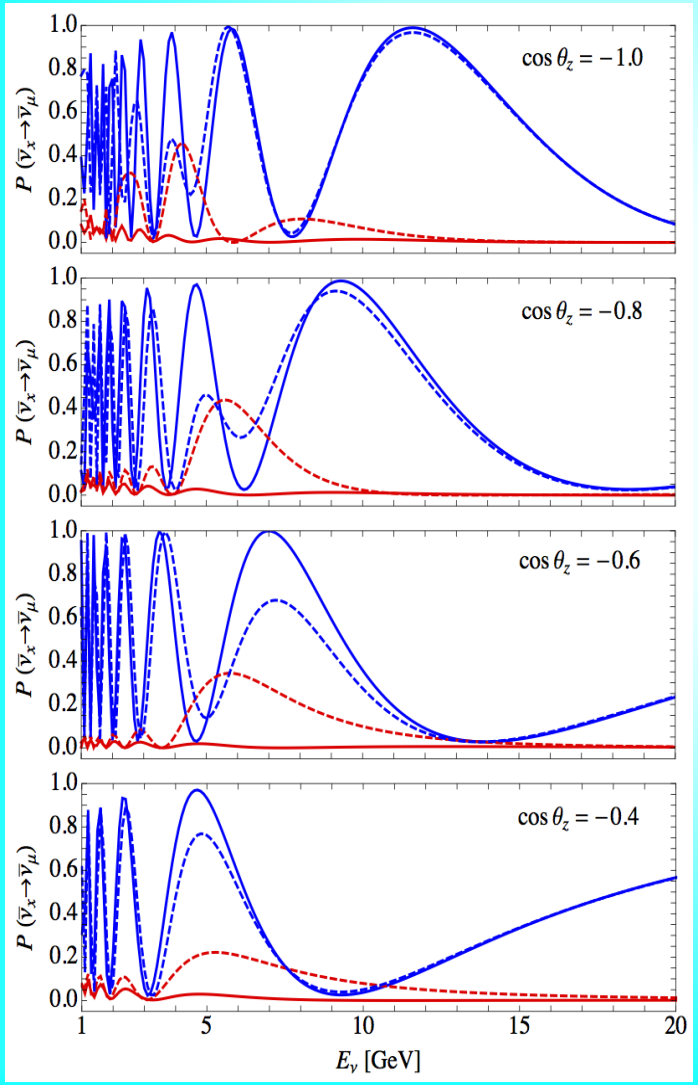
Also RENO-50



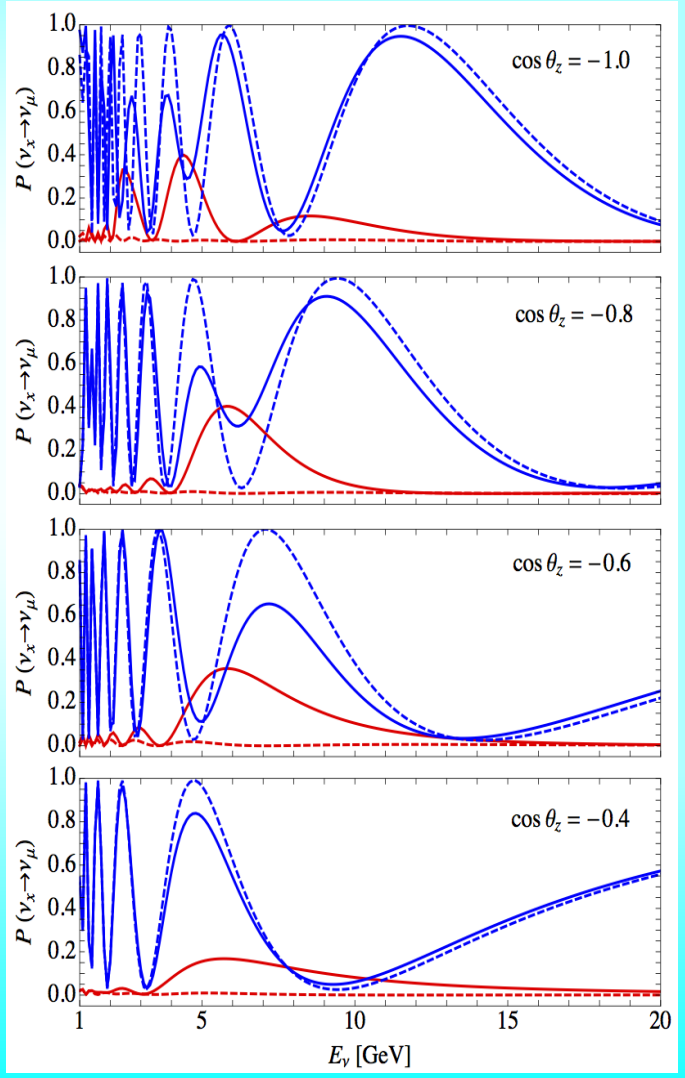


Probabilities

neutrinos



antineutrinos



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

Hierarchy, neutrinos and antineutrinos

Inversion of mass hierarchy is related to neutrino – antineutrino transition

In matter

neutrino → antineutrino

$V \rightarrow -V$

In 2ν approximation

inversion of mass hierarchy

$\Delta m^2 \rightarrow -\Delta m^2$

Under simultaneous transition

NH → IH

nu → antinu

$\frac{2EV}{\Delta m^2}$ is invariant

Mixing does not change

Moduli of the oscillation phase does not change

$P_{NH} = \bar{P}_{IH}$ $P_{IH} = \bar{P}_{NH}$

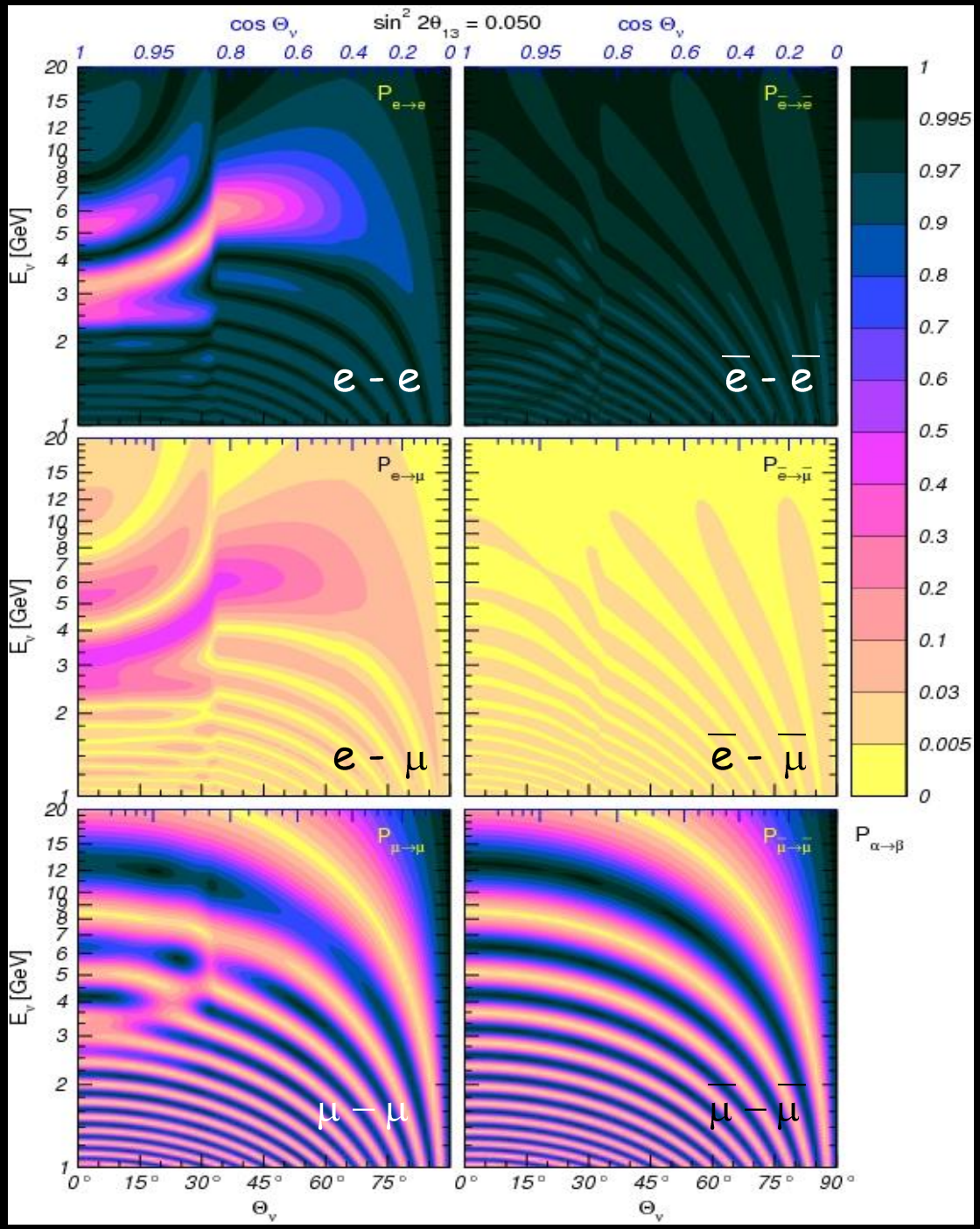
Hierarchy asymmetries for neutrinos and antineutrinos have opposite signs

Mass hierarchy

For 2ν system

normal → inverted

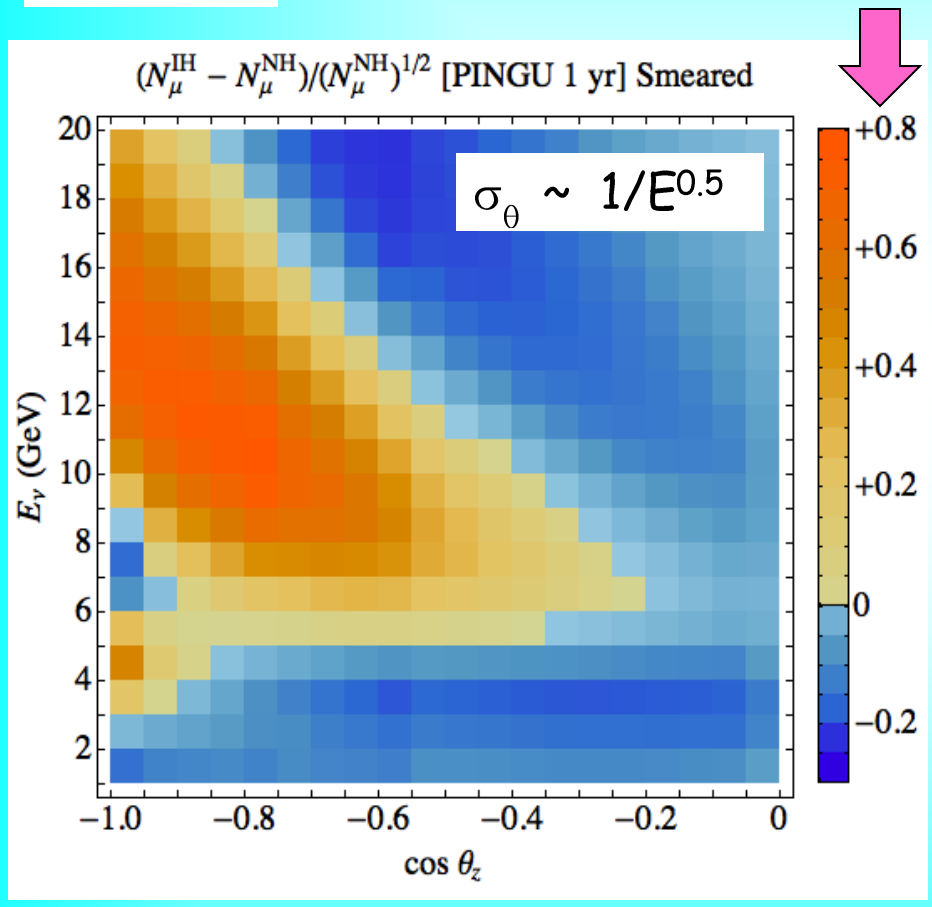
neutrino → antineutrino

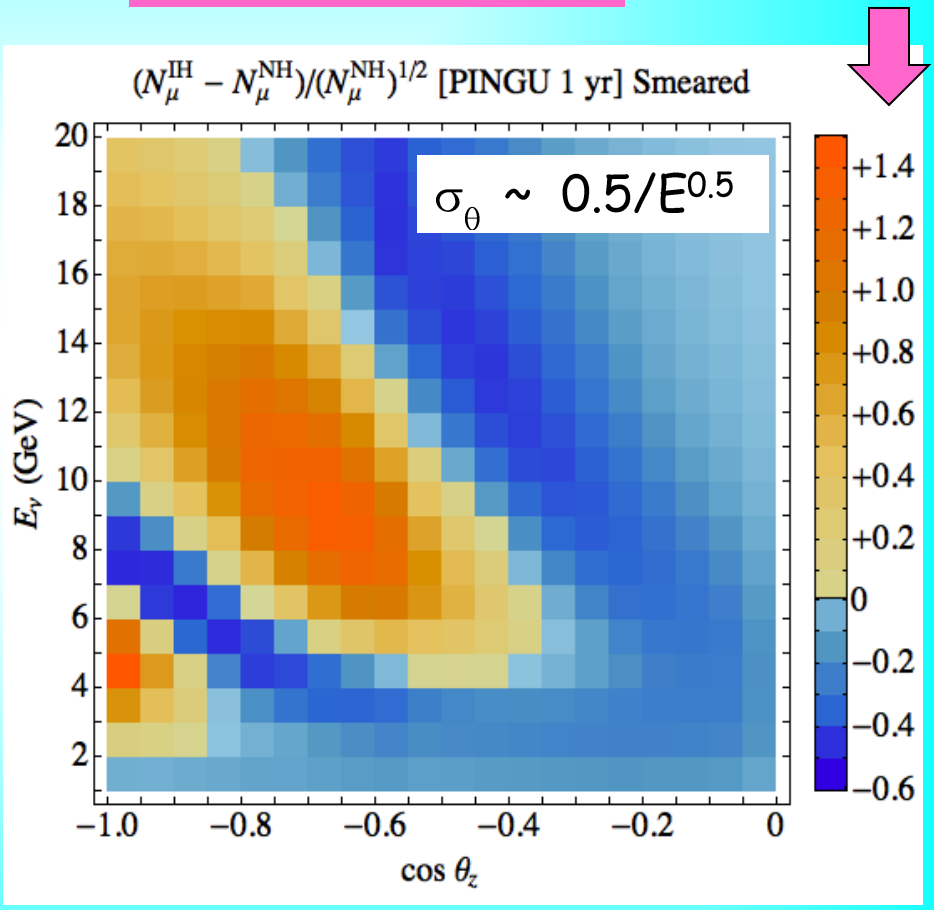


Smeared asymmetries

$\sigma_E = 0.2E$

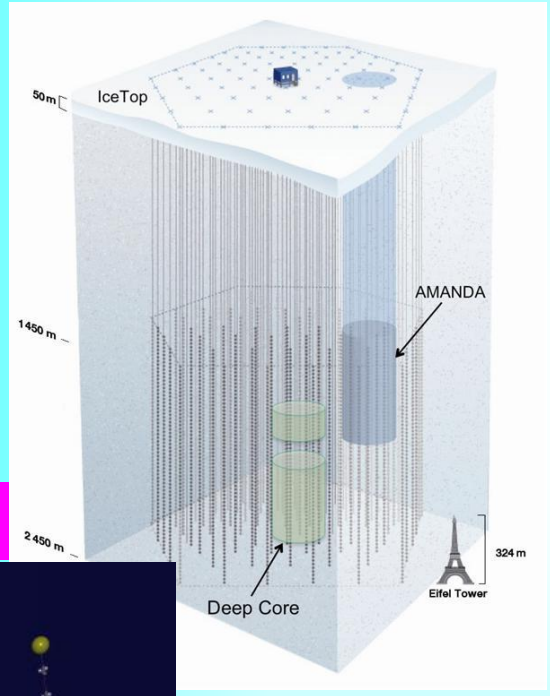
Change of the scale



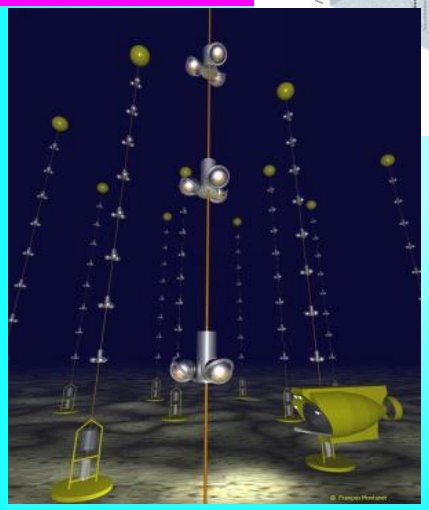


Shift to high energies and vertical directions

HAND's



ANTARES



PINGU

Precision IceCube Next Generation Upgrade

ORCA

Oscillation Research with Cosmics with the Abyss

Expected significance

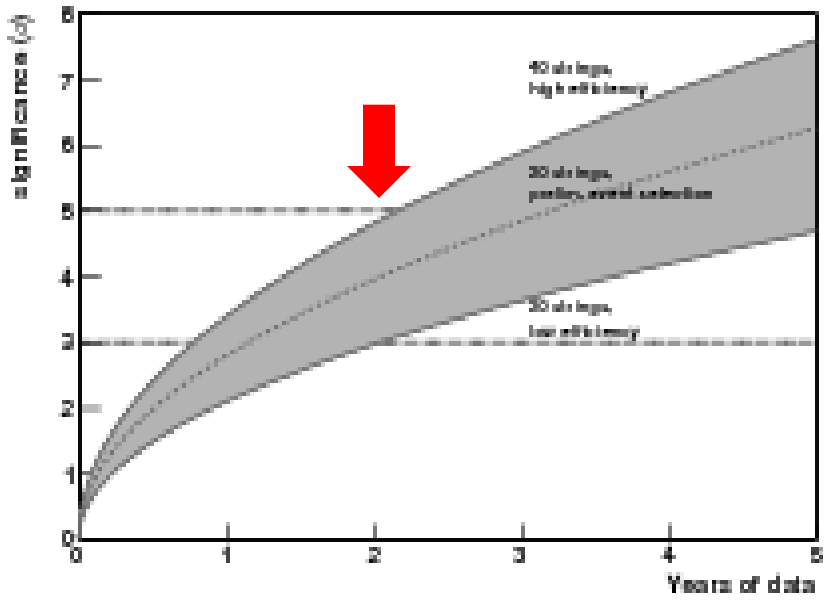


Figure 7: Expected significance for the neutrino mass hierarchy by PINGU as a function of time [20].

5σ in 2 years

With smaller effective volume

Interference

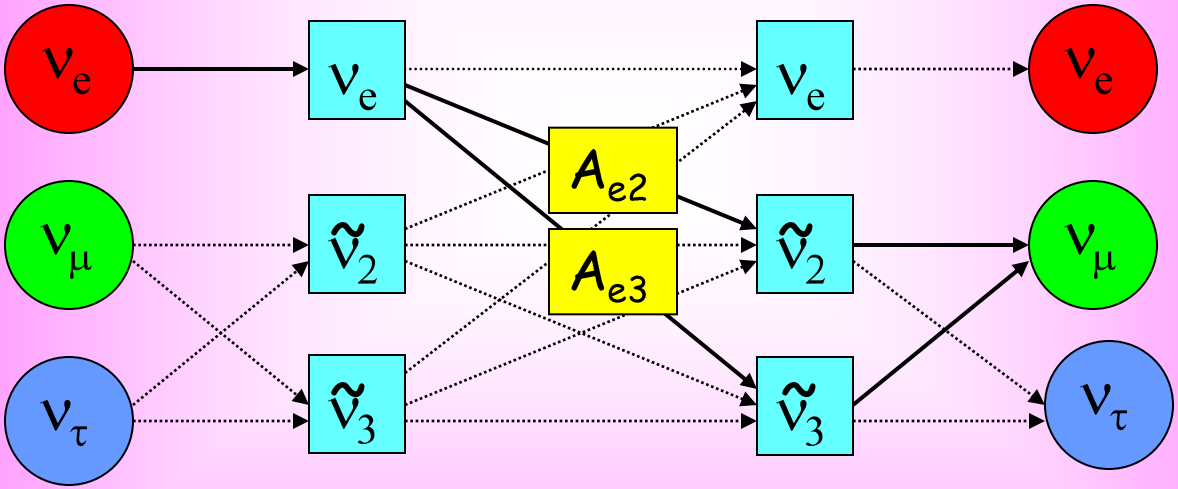
For E > 0.1 GeV

Propagation basis

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

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

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



projection propagation projection

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

CP appears in projection only

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

"Magic lines"

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

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

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

$$\phi = \arg(A_S A_A^*)$$

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

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

depends on δ

Measuring CP-phase

Global fit

T2K + NOvA
+ reactors
J-PARC- SK
750 kw upgrade

$3\pi/2$ from 0
at 3 - ? σ

Dedicated experiments

J-PARC- HK
DUNE - LBNF
ESS European spalation source Lund

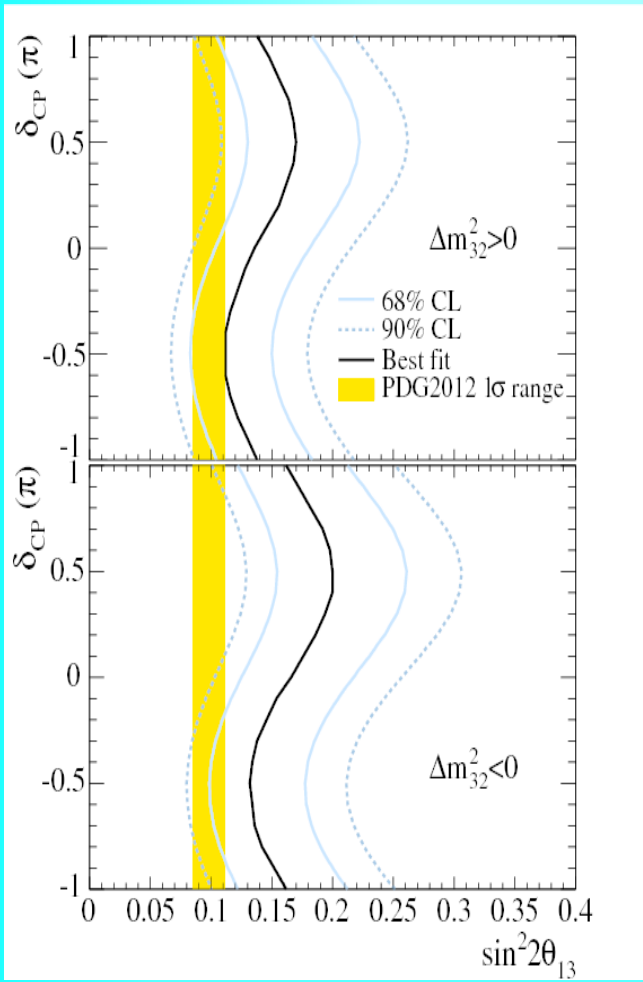
~ 5 - 7 σ

result in 2030 - 2035
O(1) bln US$

Super-PINGU ?

Before dedicated experiments?

Marginalized over 2-3 mixing



PDG (reactors)

J-PARK (beam upgrade)

p.o.t. 6 10^{20} → 7.8 10^{21}

by 2018

Super-Kamiokande

13 times higher statistics in few years

$\nu_\mu \rightarrow \nu_e$ sensitive to both mass splittings

$\sin 2\theta_{13}$ δ

$\sin \theta_{23}$ from $\nu_\mu \rightarrow \nu_\mu$

NOvA

Reactors

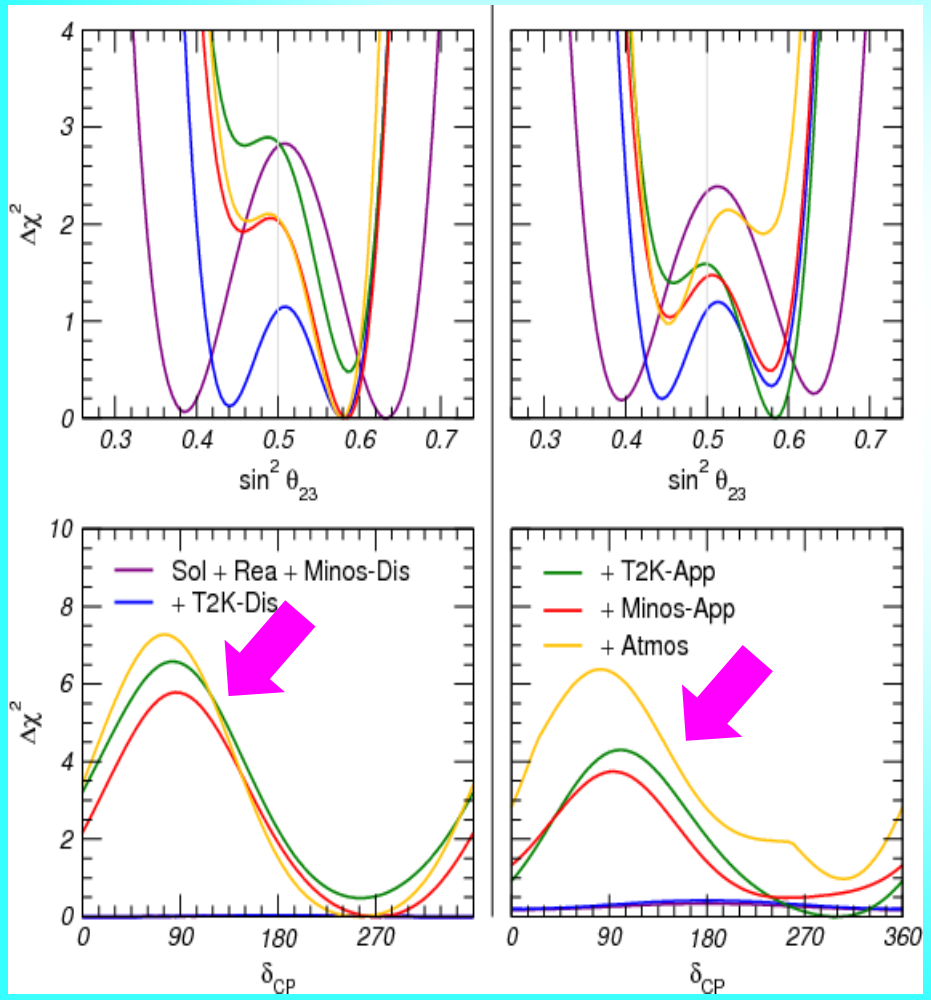
$\sin 2\theta_{13}$

Distinguishing - $\pi/2$ from 0 at > 3σ level?

CP-phase and 2-3 mixing

M.C. Gonzalez-Garcia, M. Maltoni, T. Schwetz, JHEP 1411 (2014) 052,1409.5439 [hep-ph]

Inverted Normal



Contribution of different sets of experimental results to the determination of the mass ordering, the octant of θ_{23} and of the CP violating phase.

Genesis of determination

Solar
Reactors
MINOS dis

\+ T2K - Dis

\+ T2K-App

\+ MINOS-App

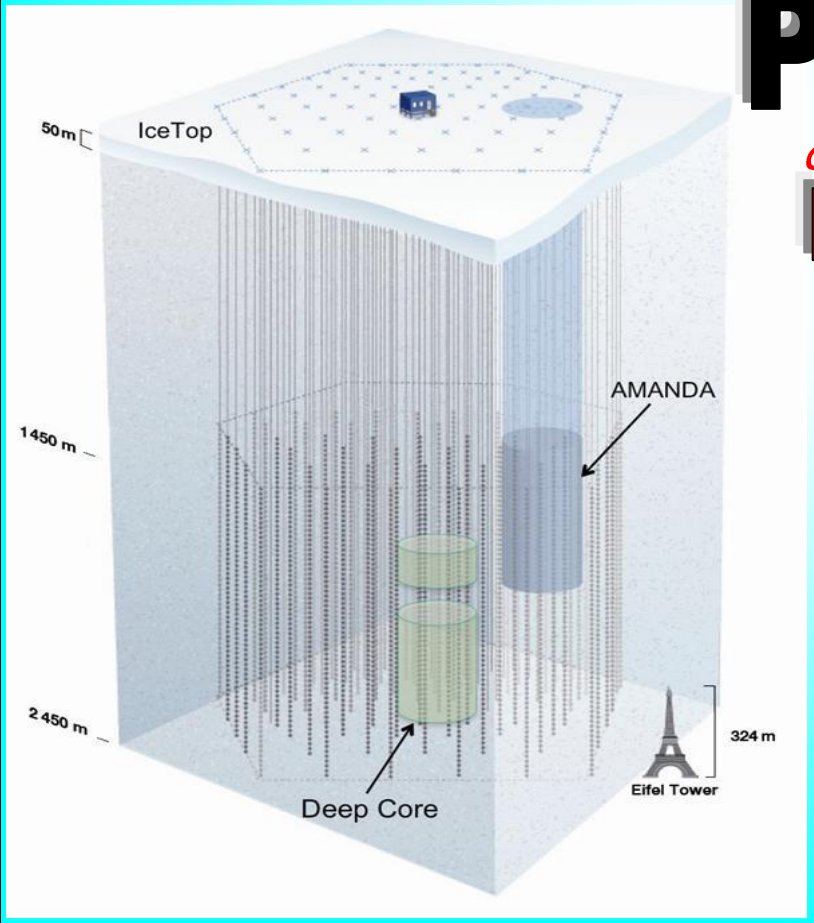
\+ Atmospheric

Ice Cube

Deep Core

100 GeV

10 - 15 GeV



PINGU

arXiv:1401.2046

Mass hierarchy

Precision IceCube Next Generation Upgrade

1 - 3 GeV

Oscillation Research with Cosmics with the Abyss

Super-PINGU -ORCA

0.2 - 0.5 GeV

Few Mtons in sub-GeVrange

S. Razzaque, A.Y.S. 1406.1407 hep-ph

Megaton-scale Ice Cherenkov Array

MICA

0.01 GeV

Distinguishability for CP

Quick estimator (metric) of discovery potential

E. Kh. Akhmedov, S. Razzaque, A. Y. S.
arXiv: 1205.7071

For each energy-zenith angle bin ij relative CP-difference

$$S_{ij} = \frac{N_{ij}^{\delta} - N_{ij}^{\delta=0}}{\sqrt{N_{ij}^{\delta=0}}}$$

no fluctuations

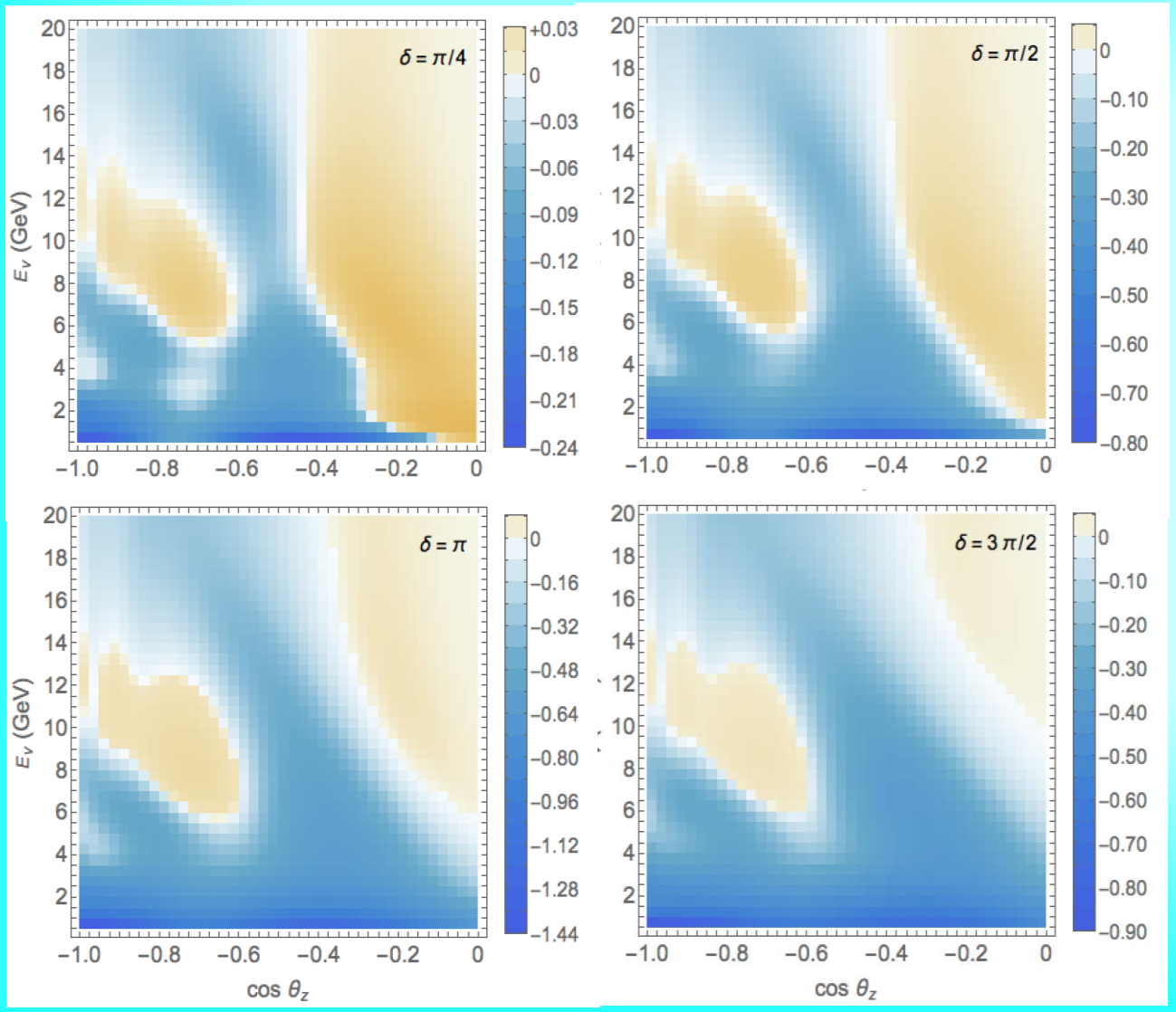
If is true value → N_{ij}^{δ} corresponds to ``true'' value of events
→ $N_{ij}^{\delta=0}$ ``measured'' number of events

$|S_{ij}|$ - distinguishability of different values of CP-phase

Total distinguishability $S^{tot} = [\Sigma_{ij} S_{ij}^2]^{1/2}$

S-distributions

After smearing over neutrino energy and direction



ν_μ- CC events (track + cascade)

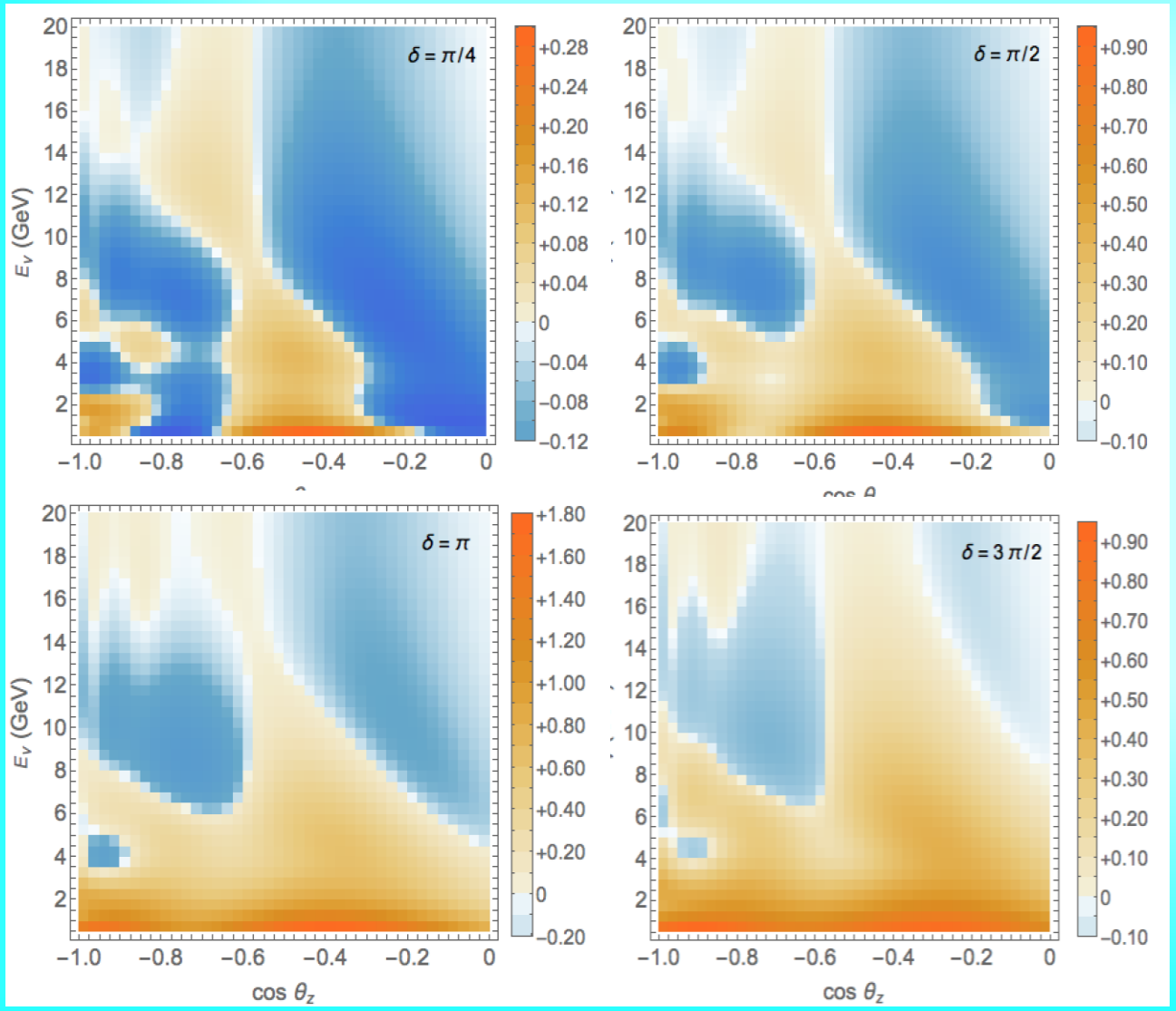
S-distributions for different values of δ

Super PINGU
1 year

S. Razzaque, A.Y.S. arXiv: 1406.1407 v2 hep-ph

S-distributions

After smearing over neutrino energy and direction



ν_e - CC events (cascades)

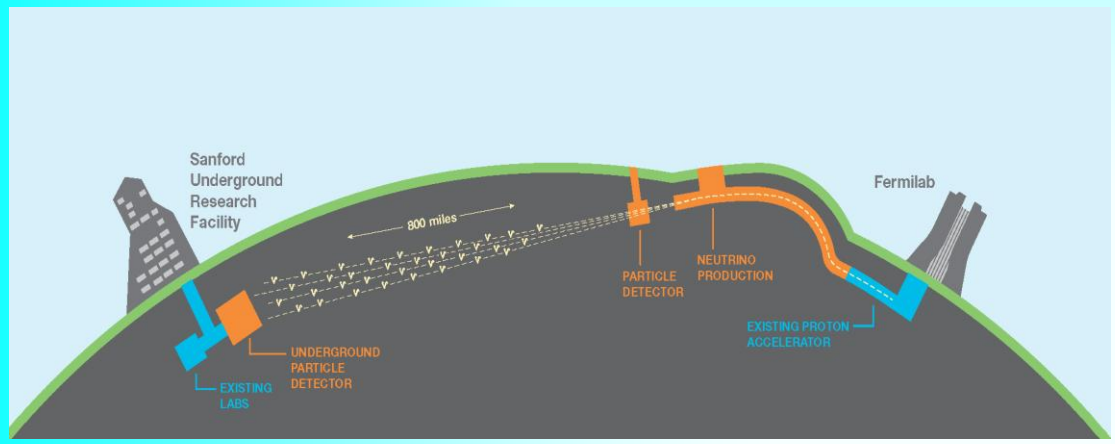
S-distributions for different values of δ

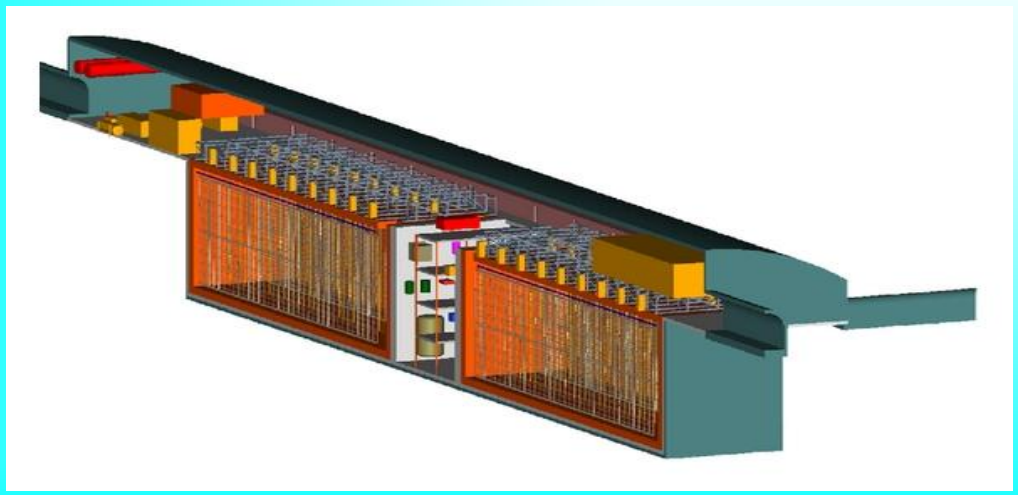
Super PINGU 1 year

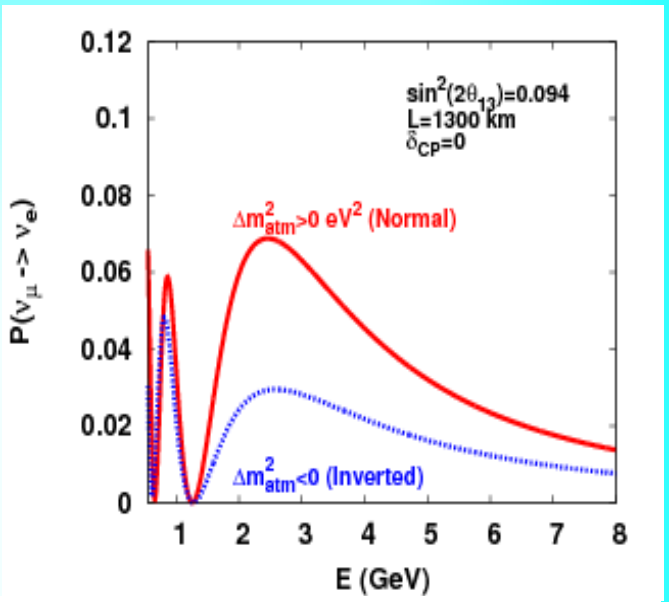
S. Razzaque, A.Y.S. arXiv: 1406.1407 v2 hep-ph

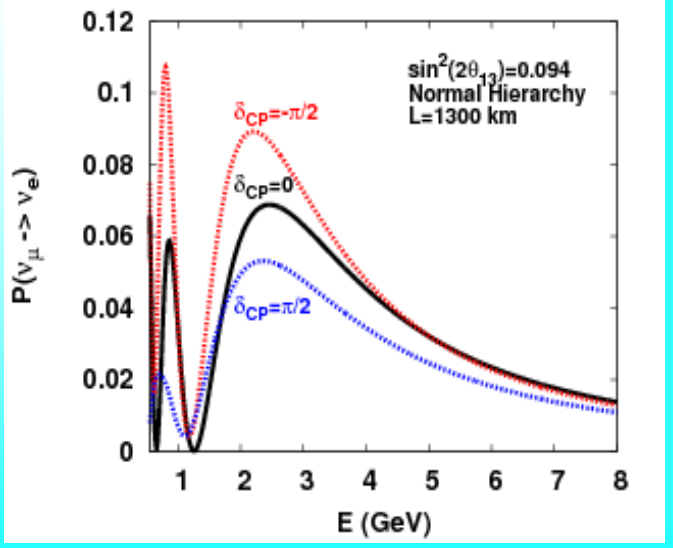
LBNF-DUNE

L = 1300km, LAr TPC 35 kt



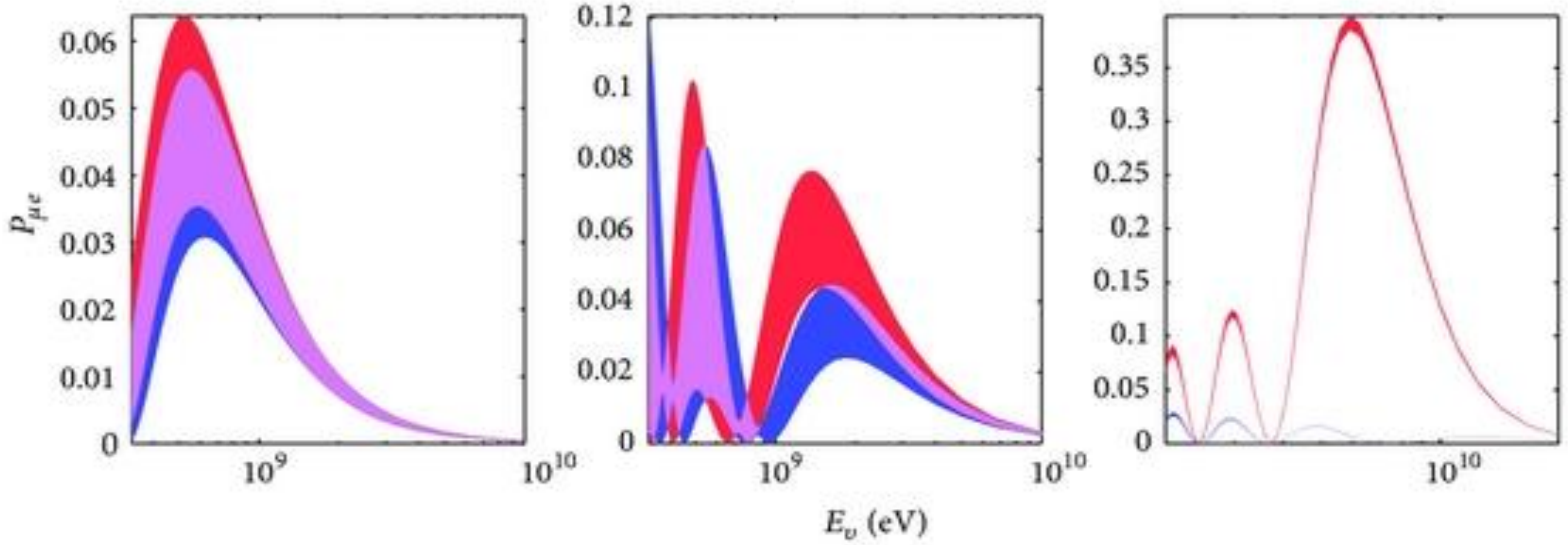






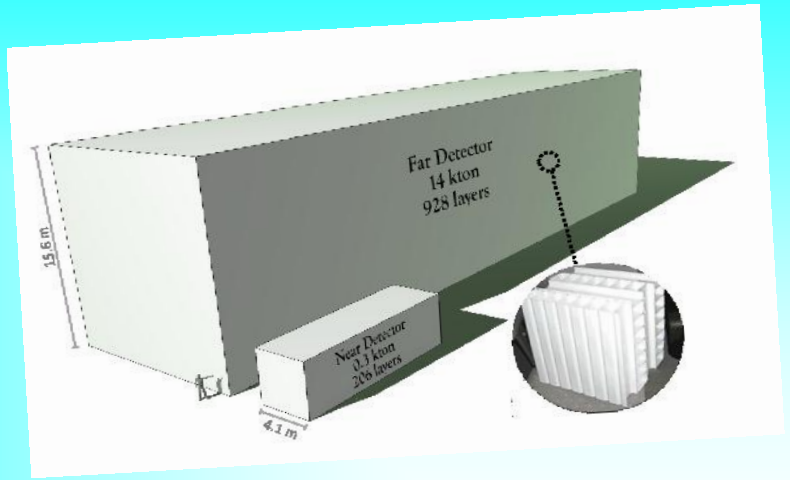
Hierarchy and CP

M. Blennow and A Y Smirnov Advances in High Energy Physics Volume 2013 (2013), Article ID 972485



The neutrino oscillation probability at baselines of 295 (left), 810 (middle), and 7500 km (right) as a function of the neutrino energy. The red (blue) band corresponds to the normal (inverted) mass hierarchy and the band width is obtained by varying the value of . The probabilities for look similar with the hierarchies interchanged. Note the different scales of the axes.

NOvA

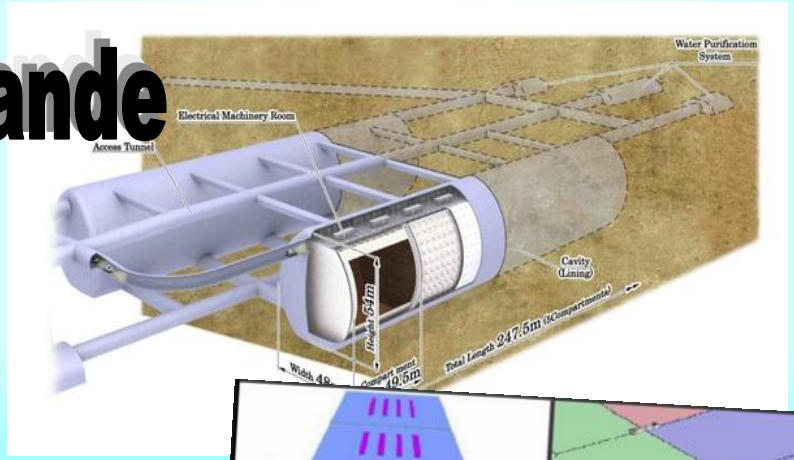


Segmented scimtillator detector 14 kT
NuMI beamoff-axis (14 mrad)
baseline 810 km

CP/MH/osc. parameters

MH: 2 - 3 σ in half δ space

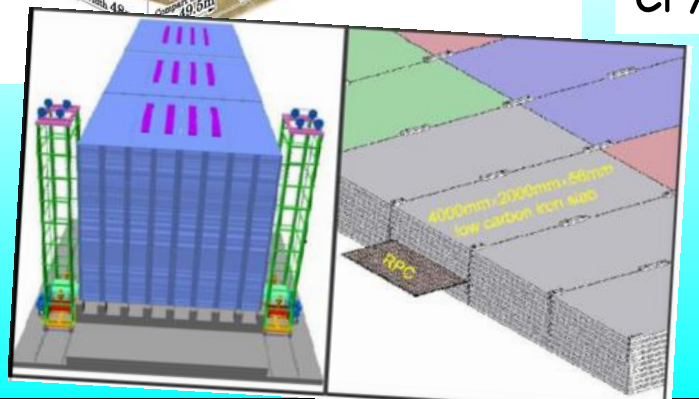
HyperKamiokande



WC, V = 0.99 Mt
Fid. V = 0.56 Mt
99,000, 20 inch PMTs
20% photocoverage
JPARC beam, off-axis
Baseline 295 km

CP/MH/astro

INO



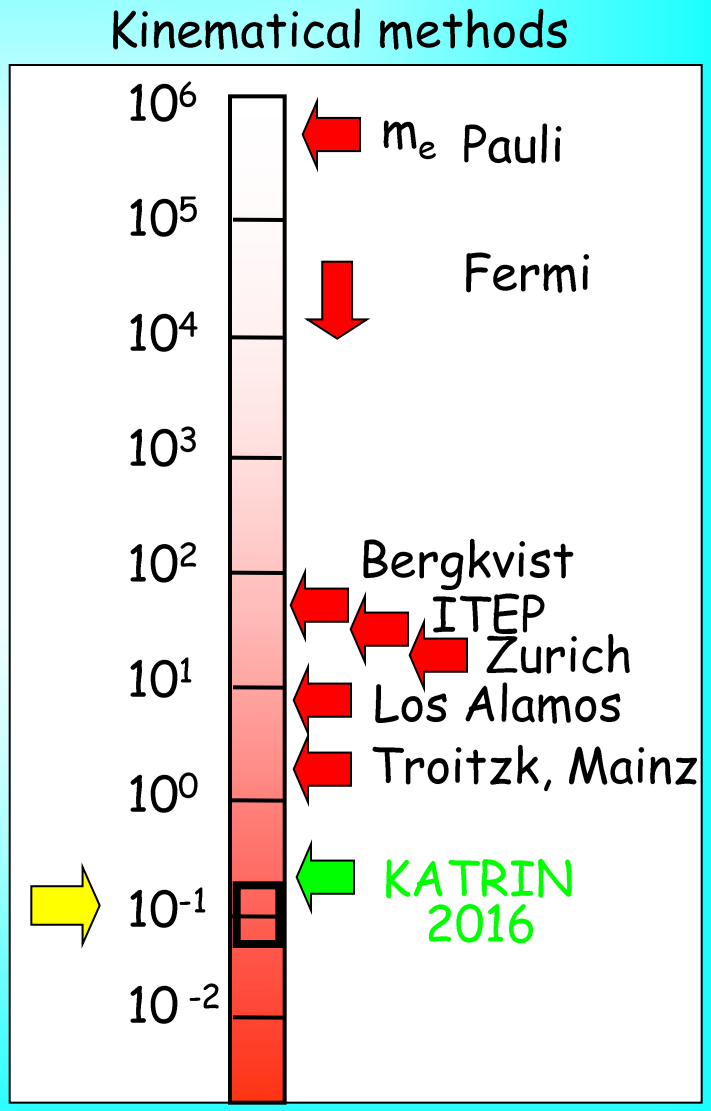
ICAL Iron calorimeter scintillator

MH/astro

Mass scale ~

Bound at the level
0.20 eV
3σ discovery : 0.30 eV

Project-8 cyclotron radiation from electrons



Scales of new physics

28 orders of magnitude

GUT - Planck mass

$$\frac{V_{EW}^2}{m_\nu}$$

High scale seesaw
Quark- lepton symmetry /analogy GUT

Unification

Electroweak - LHC

Looking under the lamp

Low scale seesaw, radiative mechanisms, RPV, high dimensional operators

m_ν

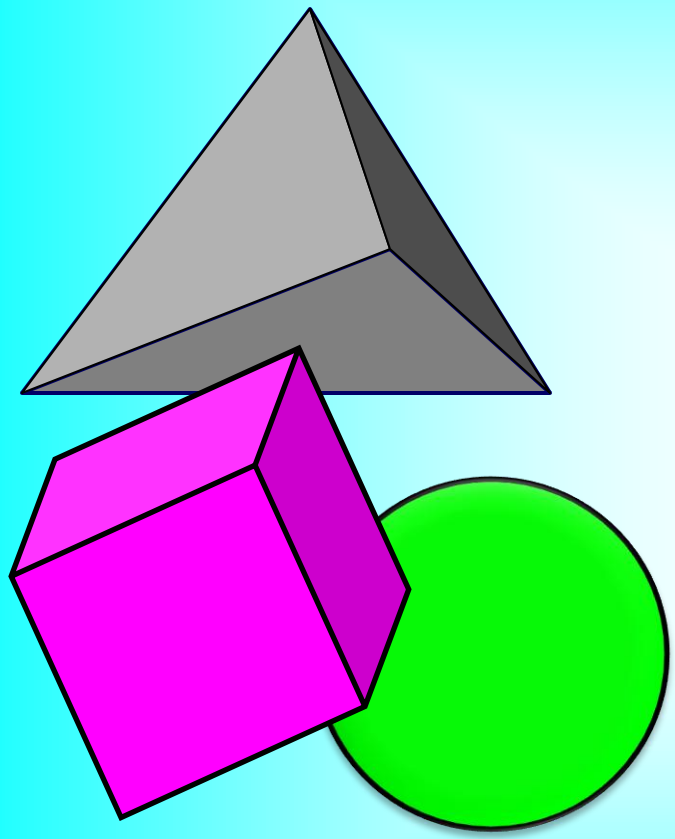
eV-sub-eV

Scale of neutrino masses themselves
Relation to dark energy, MAVAN?

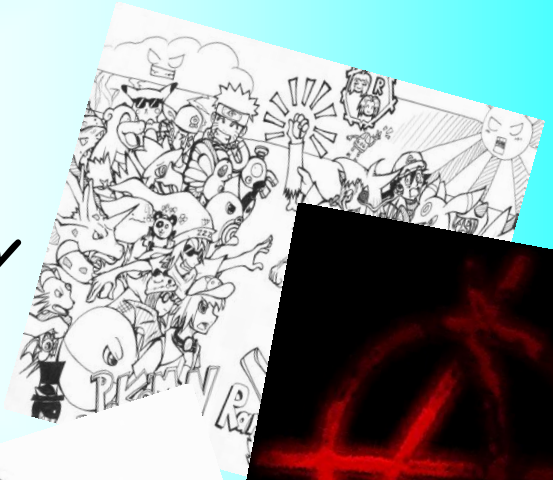
Spurious scale?

Neutrino mass itself is the fundamental scale of new physics

Mixing:



From symmetry
to anarchy
and randomness



Conclusions

No convincing understanding

of mass and mixing pattern although some constructions may have connection to reality.

The problem is to identify correct ones among hundreds ideas, approaches, models

with scepticism: no explanation of quark masses and mixing

Back to bottom

Back to data, search for hints, indications.
Look for connection to other sectors, e.g. Dark sector of the Universe

May be

Solutions of problems of visible sector in the Hidden sector