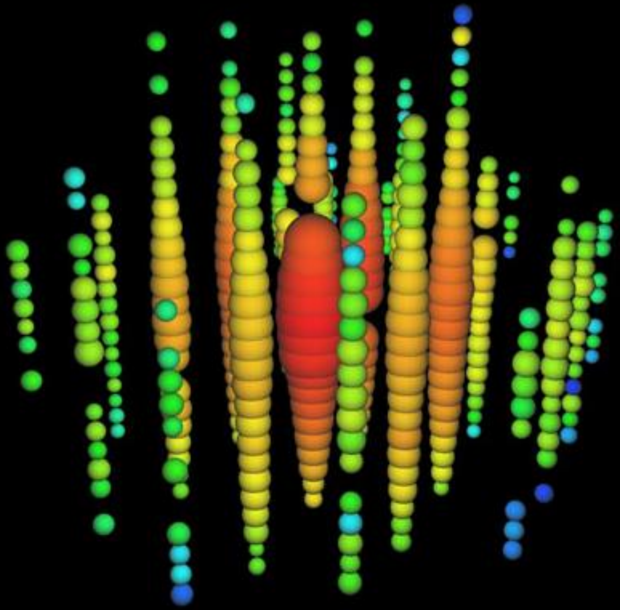
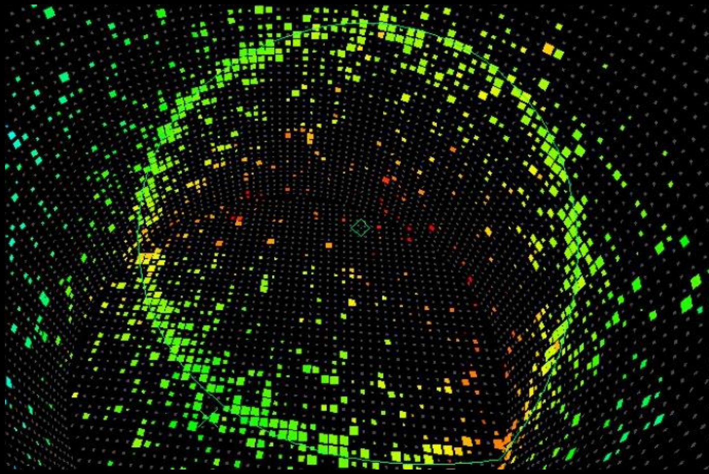
Neutrino properties
Mass hierarchy and CP-violation





A. Yu. Smirnov

Max-Planck Institute for Nuclear Physics,
Heidelberg, Germany
& ICTP

MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK

ICRC , August 5, 2015,
The Hague

Outline

1. Neutrino properties
2. Mass hierarchy
3. CP-violation
4. Summary

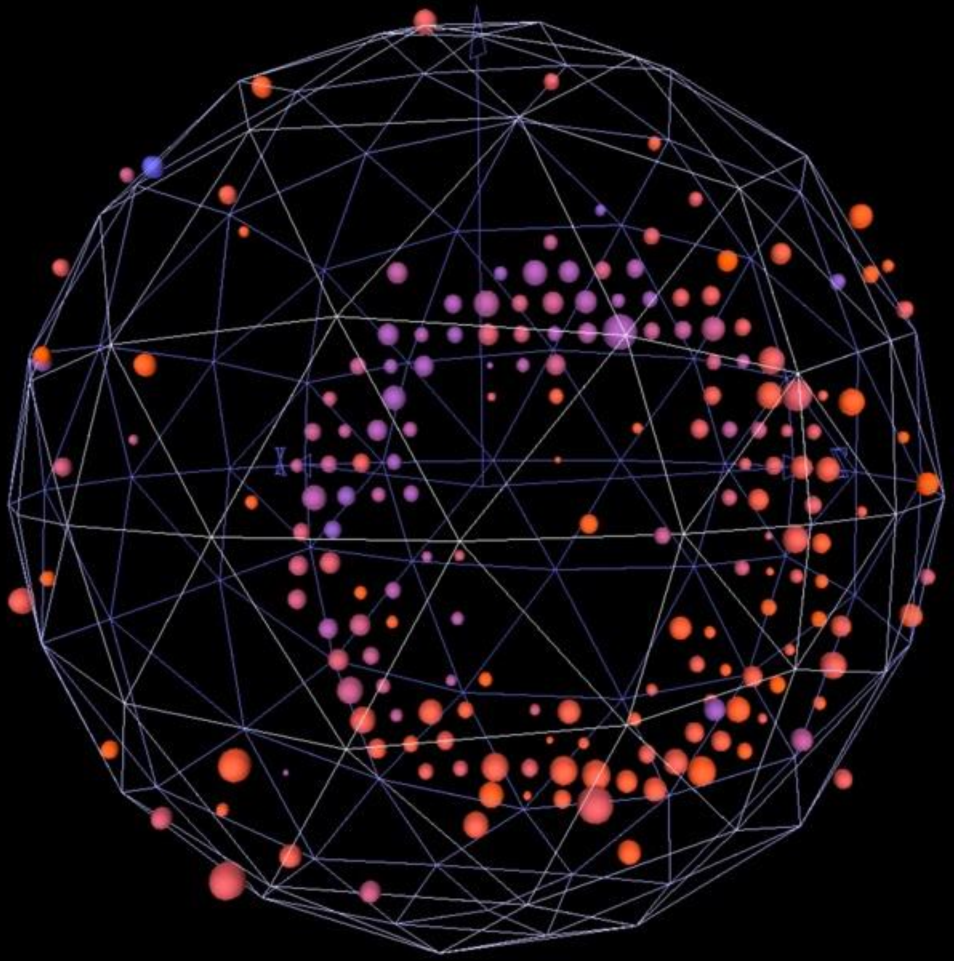
Brief summary of
what we know

Next big in neutrino
physics?

Ultimate goal;
connected to
mass hierarchy
determination

with emphasis on
astrophysical/
astroparticle methods

Neutrino properties

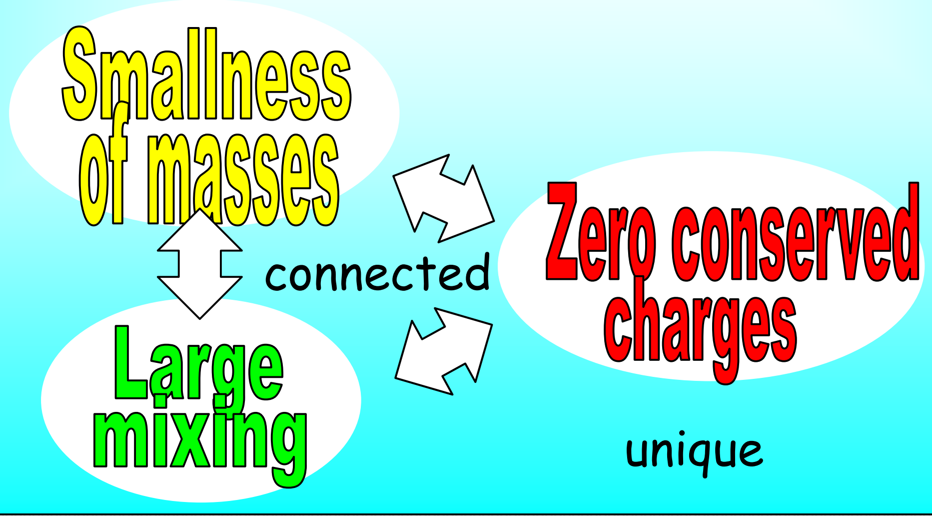


3ν paradigm:

All well established/confirmed results fit well a framework with

- three neutrinos
  - interactions described by the standard model
    - with masses and mixing

It is widely believed that peculiar properties



Smallness of masses

connected

Large mixing

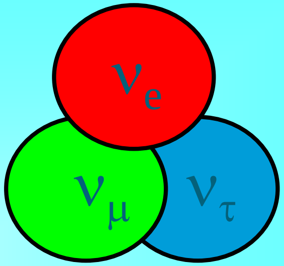
Zero conserved charges

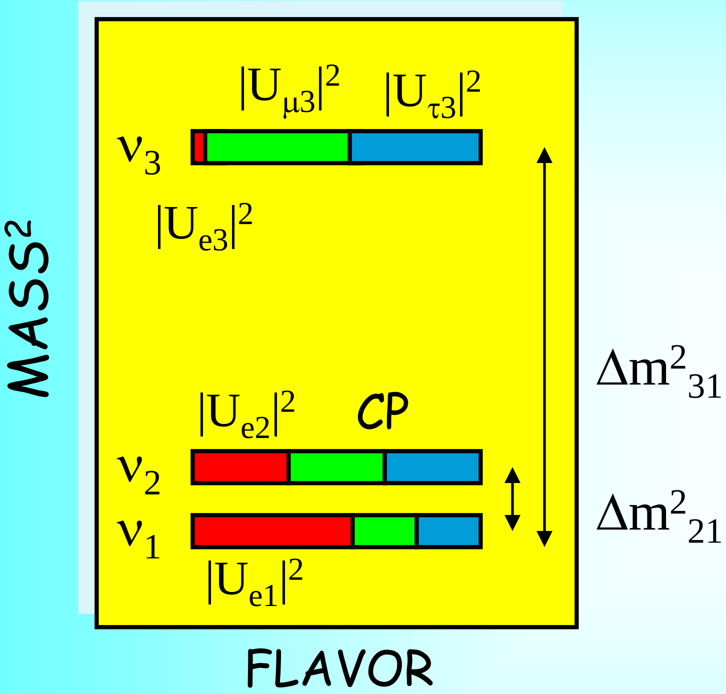
unique

which admits

Majorana nature

Lepton Mixing





Mixing parameters

$\tan^2\theta_{12} = |U_{e2}|^2 / |U_{e1}|^2$ ~ 1/2

$\sin^2\theta_{13} = |U_{e3}|^2$ = 0.022

$\tan^2\theta_{23} = |U_{\mu 3}|^2 / |U_{\tau 3}|^2$ ~ 1.0

TBM,
Symmetry?

Mixing matrix:

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

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Normal mass hierarchy

$\Delta m^2_{ij} = m^2_i - m^2_j$

$\Delta m^2_{32} = 2.5 \times 10^{-3}\ \mathrm{eV}^2$

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

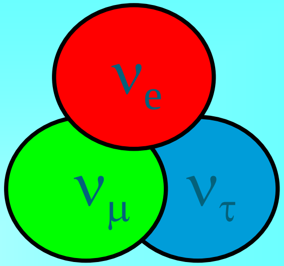
Standard parametrization

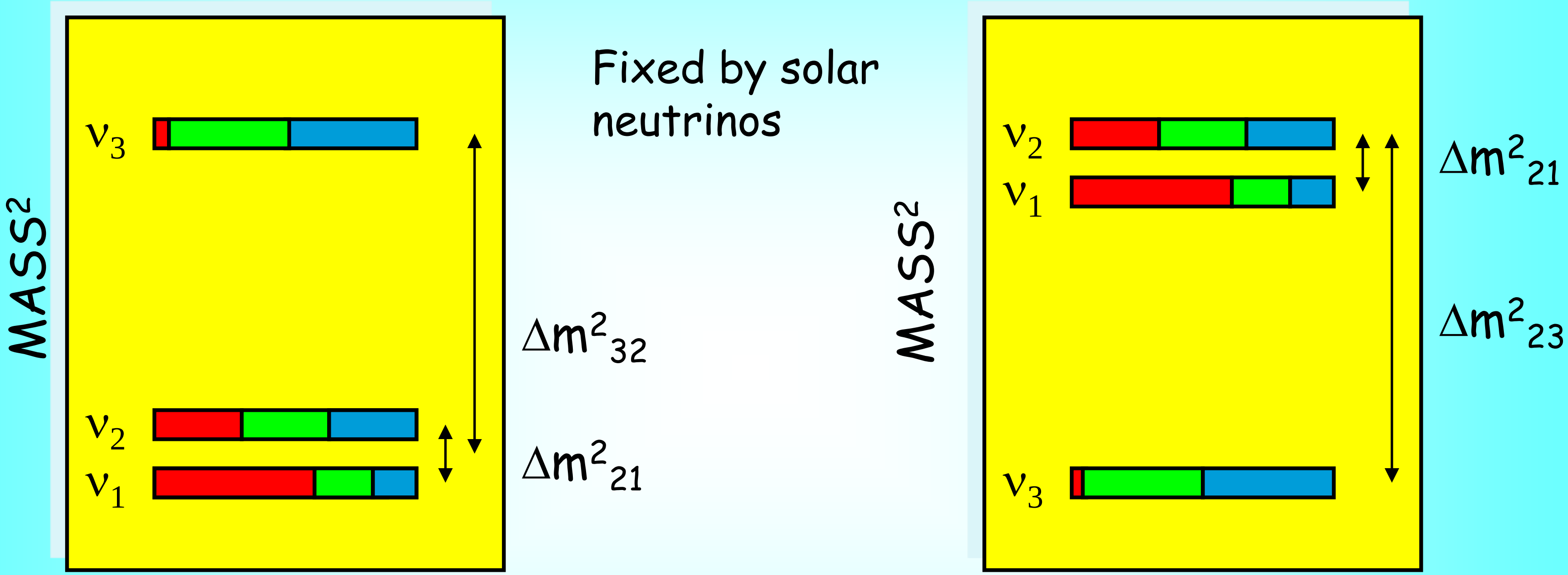
$U_{PMNS} = U_{23} I_\delta U_{13} I_{-\delta} U_{12}$

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

CP-phase

Neutrino mass ordering





Fixed by solar neutrinos

Normal mass hierarchy

$\Sigma m > m_h$

$|\Delta m^2_{31}| = |\Delta m^2_{32}| + |\Delta m^2_{21}|$

Inverted mass hierarchy

$\Sigma m > 2\, m_h$

$|\Delta m^2_{31}| = |\Delta m^2_{32}| - |\Delta m^2_{21}|$

$|\Delta m^2_{ij}| \Leftrightarrow D_{ij} = 4|U_{ei}|^2|U_{ej}|^2$

mass splittings

oscillation depth

TBM Mixing pattern

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

L. Wolfenstein

$$U_{tbm} = \begin{pmatrix} \sqrt{2/3} & \sqrt{1/3} & 0 \\ -\sqrt{1/6} & \sqrt{1/3} & -\sqrt{1/2} \\ -\sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \end{pmatrix}$$

0.15

0.62

0.78

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

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

0.30- 0.31

Accidental, numerology, useful for bookkeeping

Accidental symmetry (still useful)

Not accidental

Lowest order approximation which corresponds to weakly broken (flavor) symmetry of the Lagrangian

with some other physics and structures associated

There is no relation of mixing with masses (mass ratios)

Parameters look like *C-G* coefficients

Global oscillation fit

Solar neutrinos

KamLAND

Atmospheric neutrinos

Double Chooz

Daya Bay

MINOS

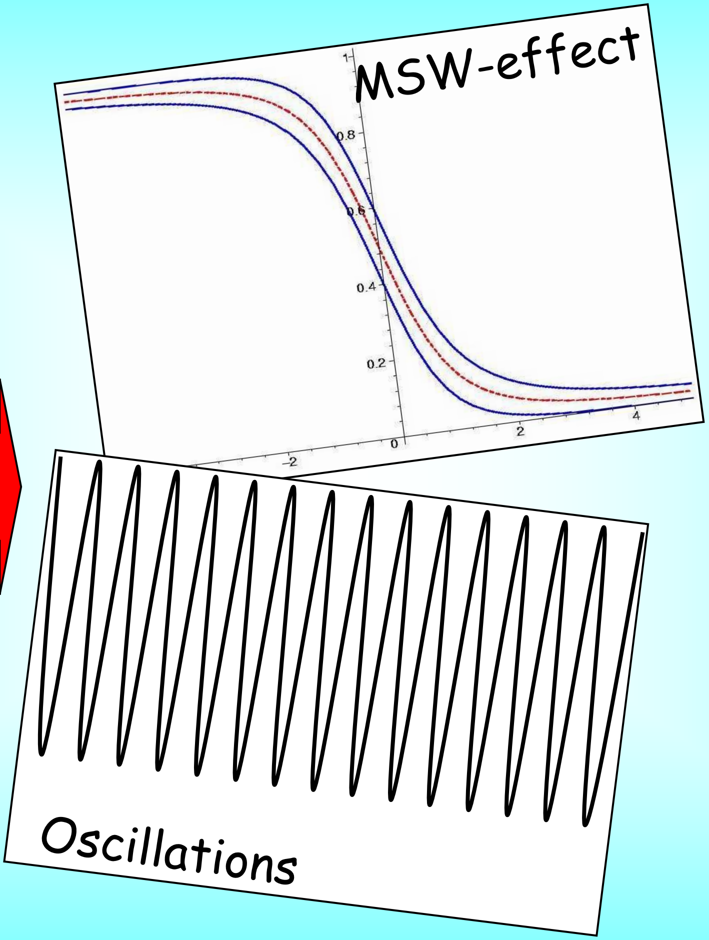
K2K

RENO

T2K

Antares

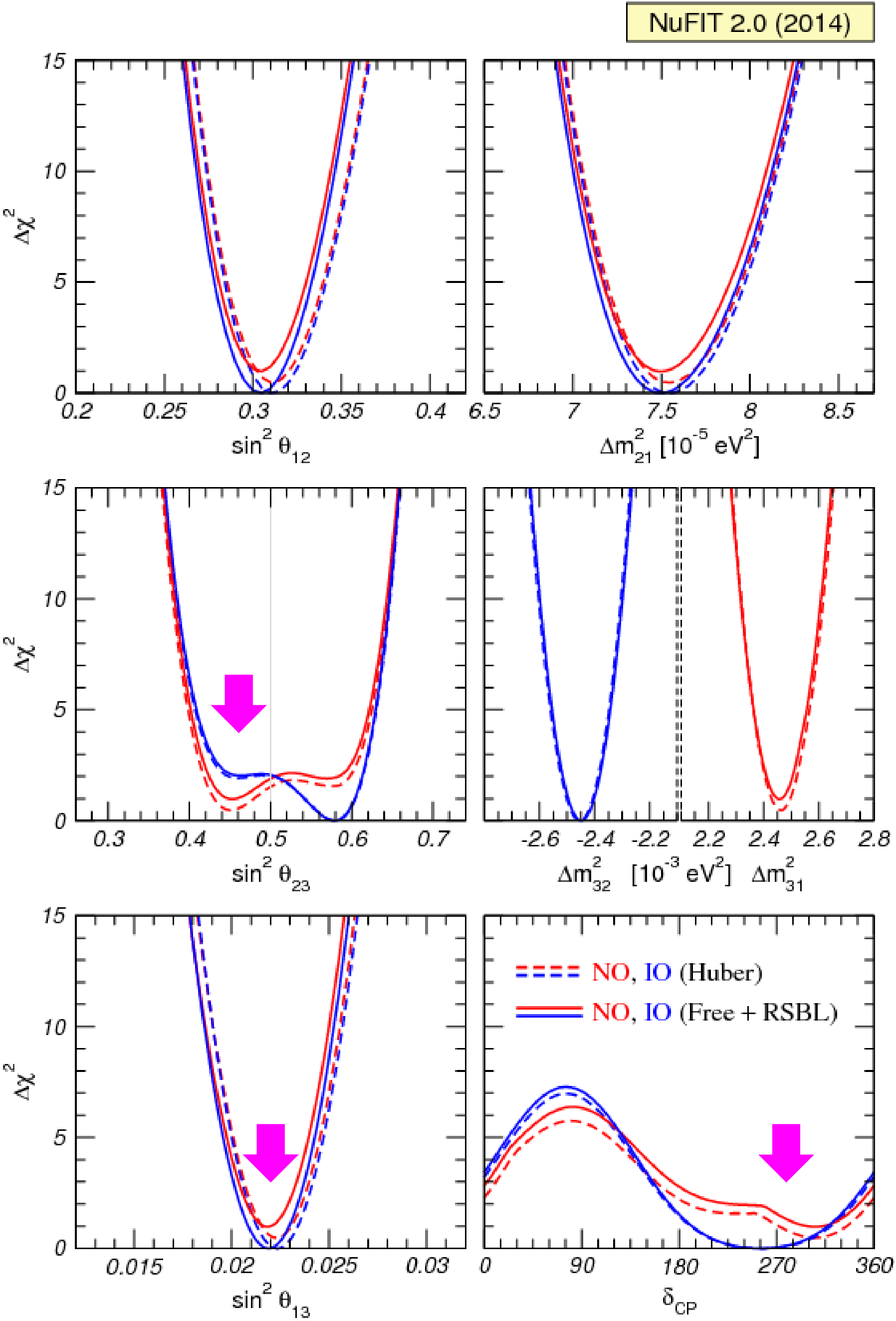
DeepCore



Δm^2

θ

Can be resonantly
enhanced in matter



Global 3ν – fit

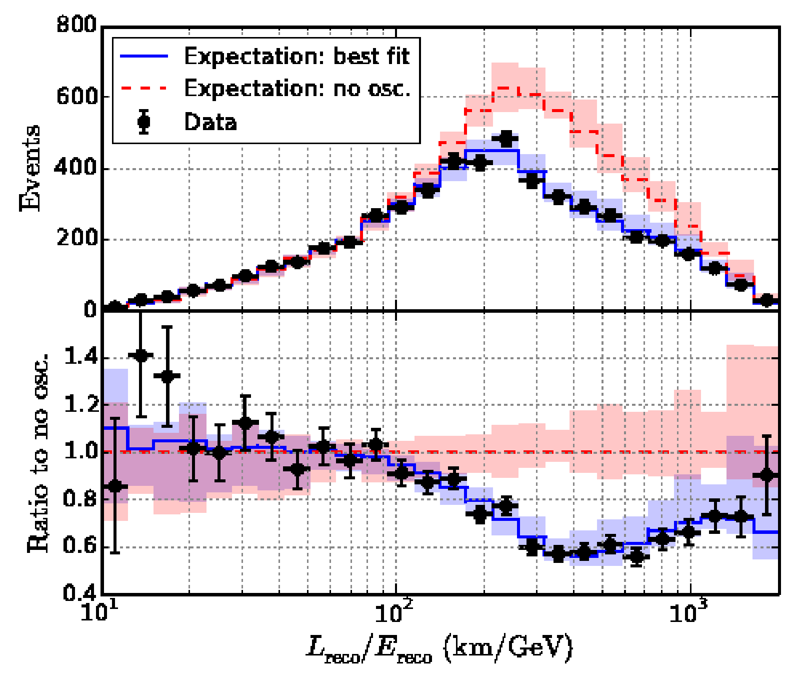
M.C. Gonzalez-Garcia, M. Maltoni, T. Schwetz, **JHEP 1411 (2014) 052,1409.5439 [hep-ph]**

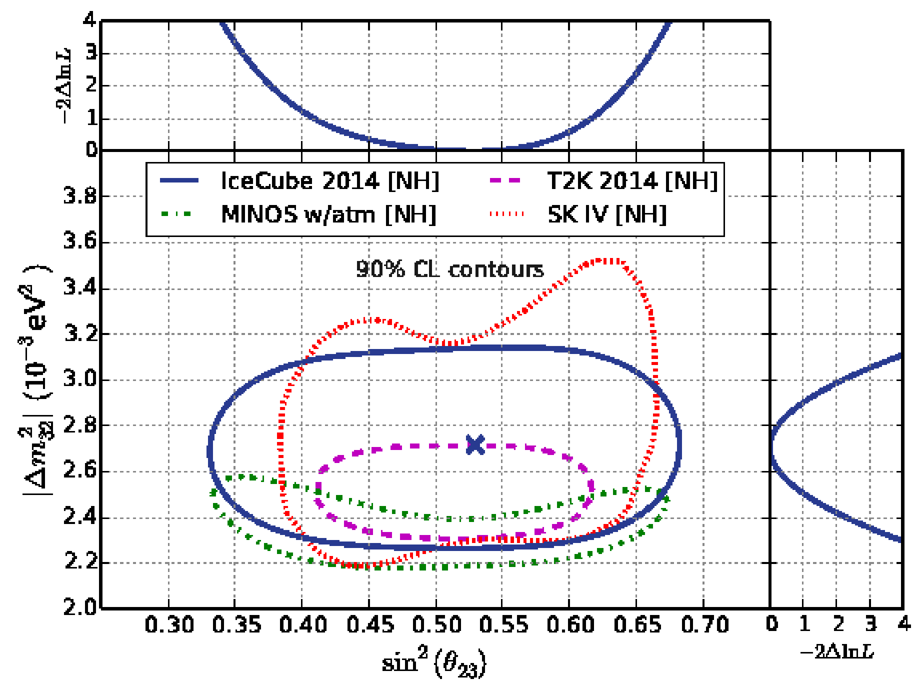
2-3 mixing:

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

Small preference IO and
2nd quadrant

DeepCore oscillation result





atmospheric ν_μ disappearance,
3 years of data

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

Δm_{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

Neutrino mass scale

Kinematical methods
KATRIN

Oscillations:

The heaviest neutrino $m_h \gtrsim \sqrt{\Delta m_{31}^2} > 0.045$ eV

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

the weakest mass hierarchy,
related to large mixing

Cosmology:

$\Sigma m < 0.136$ eV (95 % CL) Planck 2015 + BAO+ HST

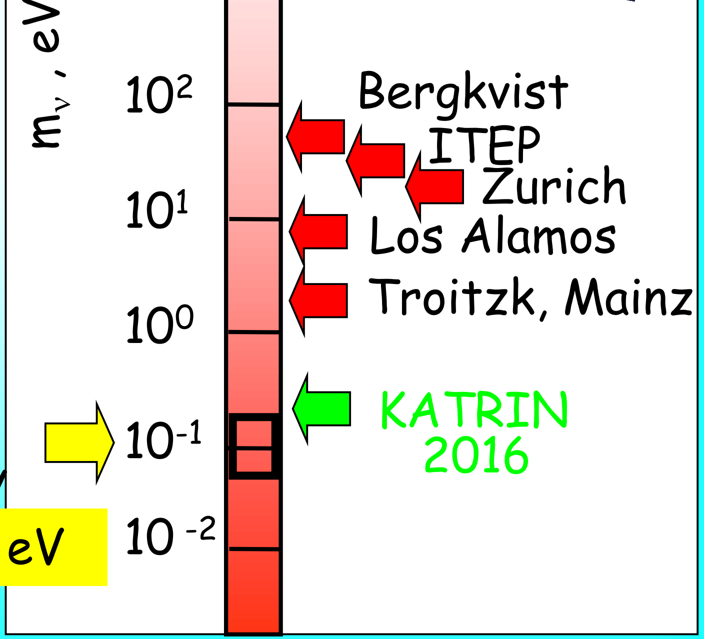
E. Di Valentino, et al
1507.08665 [astro-ph.CO]

$\Sigma m < (0.3 - 0.4)$ eV (95 % CL)

conservative

Oscillations,
& cosmology

$m_h \sim (0.045 - 0.10)$ eV



Scales of new physics

GUT - Planck mass

28 orders of magnitude

High scale seesaw
Quark- lepton symmetry /analogy
GUT

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

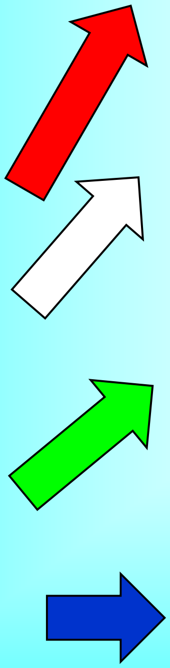
PeV

Electroweak - LHC

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

eV- sub-eV

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

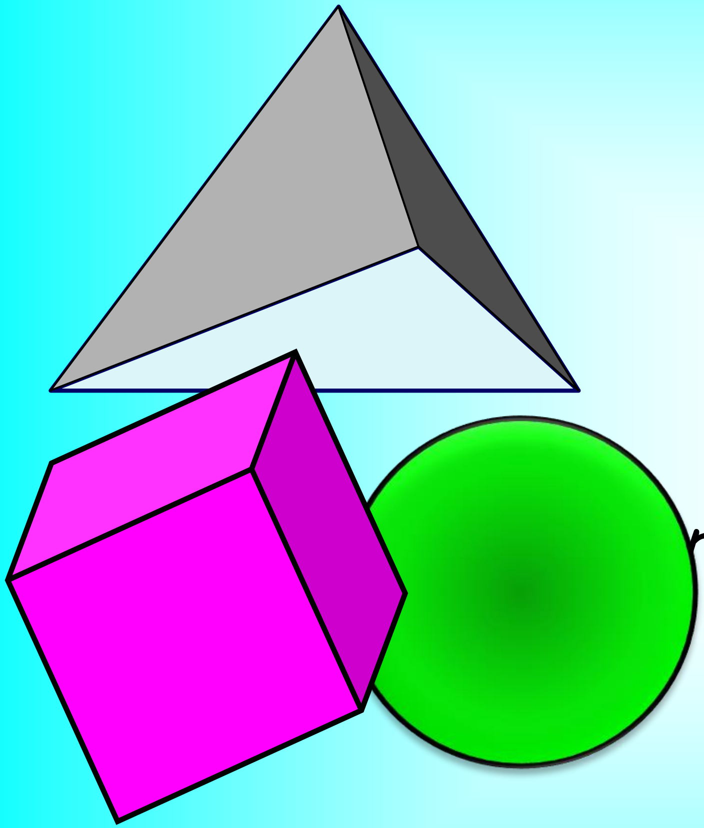


$m\nu$

Spurious scale?

Neutrino mass itself is the fundamental scale of new physics

Mixing



Complicated constructions, especially if quarks are included

from symmetry to anarchy and randomness

Not much to add
- String landscape
- Multiverse?

PMNS & CKM

Quark
mixing

my prejudice

C. Giunti, M. Tanimoto
H. Minakata, A Y S
Z - Z. Xing
J Harada
S Antusch , S. F. King
Y Farzan, A Y S
M Picariello , … .

$$U_{PMNS} = U_{CKM}^{+} U_{X}$$

where $U_{CKM} \sim V_{CKM}$

has similar hierarchical structure determined by powers of

$\lambda = \sin\theta_C$

From the Dirac matrices of charged leptons and neutrinos

U_X has some special form determined by symmetry

related to mechanism that explains smallness of neutrino mass

$U_X \sim U_{23}(\pi/4)\, U_{12}$

Prediction for the 1-3 mixing

$$\sin^2\theta_{13} = \sin^2\theta_{23} \sin^2\theta_C \,(1 + O(\lambda^2))$$

$$\sin^2\theta_{13} \sim \tfrac{1}{2} \sin^2\theta_C$$

in a good agreement with measurements

What does this mean?

if not
accidental

- Quarks and leptons know about each other,
  Q L unification, GUT or/and
  Common flavor symmetries

- Some additional physics is involved in the lepton sector which explains smallness of neutrino mass and difference of the quark and lepton mixing patterns

- Two types of new physics

CKM

Neutrino new physics

Indicates SO(10): no CKM mixing
in the first approximation

Challenges and Anomalies

Determination of unknowns within 3nu paradigm

Mass hierarchy/ordering

Absolute values of masses,
type of spectrum

CP-violation phase(s)

Nature of neutrino mass:
(Majorana-Dirac,
hard – soft (effective))

Checks of Anomalies and their explanations

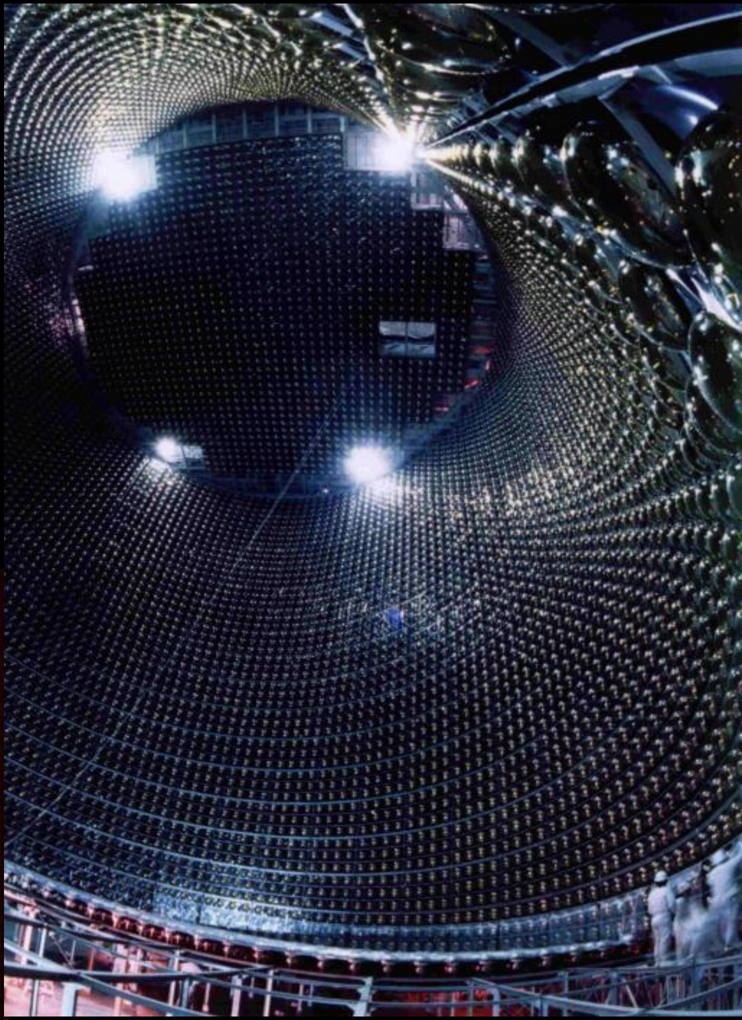
Reactor, Gallium source	Deficit of signal
LSND, MiniBooNE	Excess of signal

1 eV sterile neutrino: not a small perturbation of the 3ν picture

IceCube	High sensitivity to steriles
Solar neutrino anomaly?	Absence of spectral upturn, large DN asymmetry

steriles? NSI?

Mass hierarchy



Mass hierarchy

Further advance

Step to discover CP

important by itself

Theoretical implications

Phenomenology

Supernova neutrinos

Atmospheric neutrinos

bb0n decay

LBL

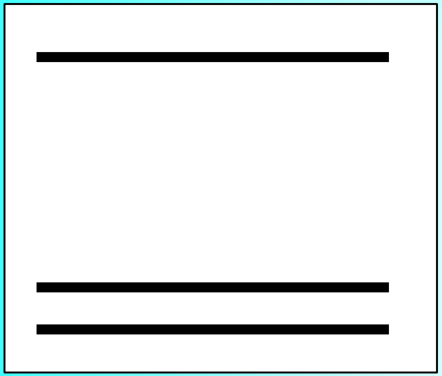
Solar neutrinos

Cosmology

Theoretical implications

generically

Quasi-degenerate → symmetry



Normal vs. special

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

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

the weakest hierarchy

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

Oscillations, conversion

Precise measurements of Δm^2 at reactors

JUNO,
RENO-50

Cosmology
Σm

Double beta decay m_{ee}

Atmospheric neutrinos

PINGU
ORCA
INO

LBL experiments

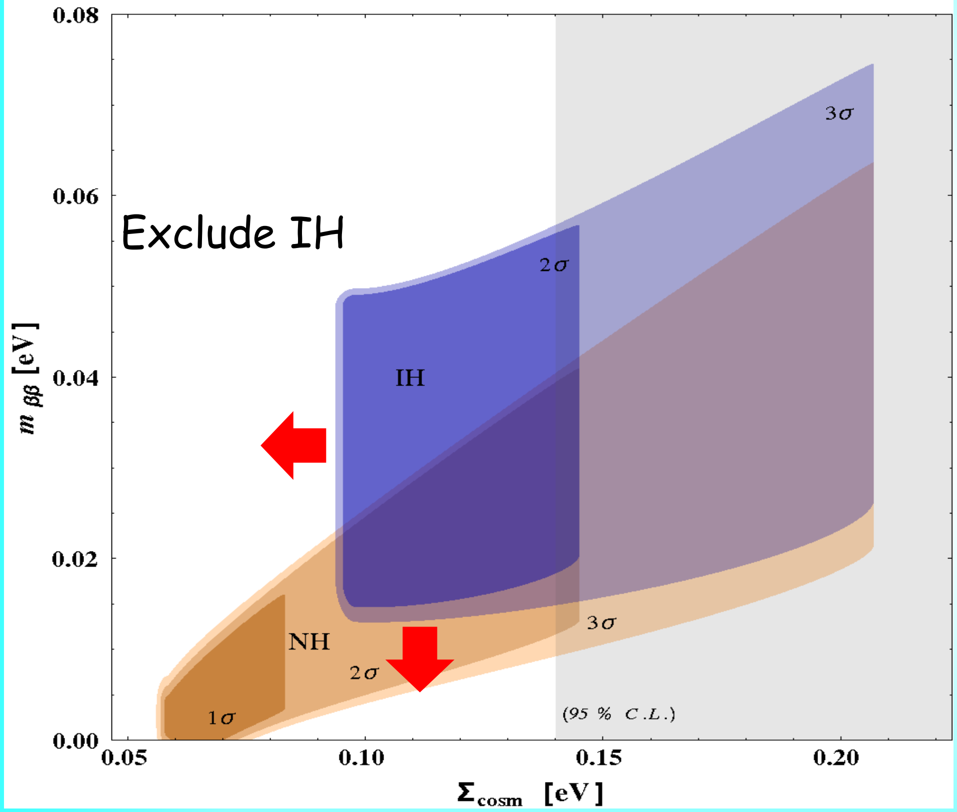
NOvA
LBNF – DUNE
JPARC-HK

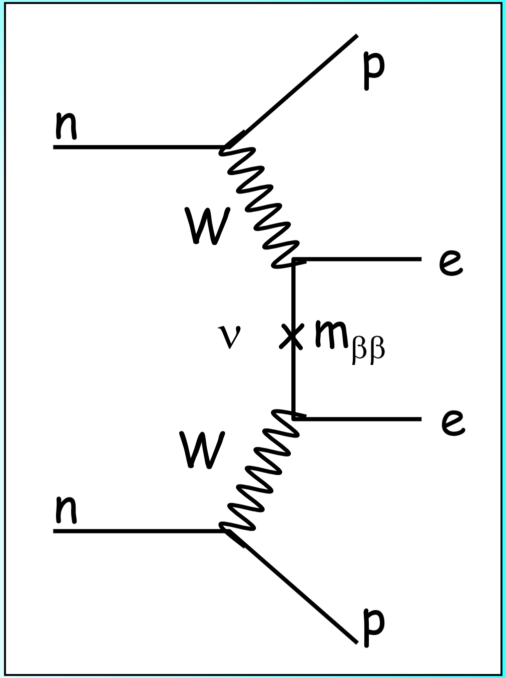
Supernova neutrinos

Earth matter effects,
energy spectra

Double beta decay

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

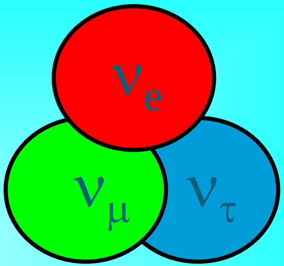




S. Dell'Oro, et al, 1505.02722 [hep-ph]

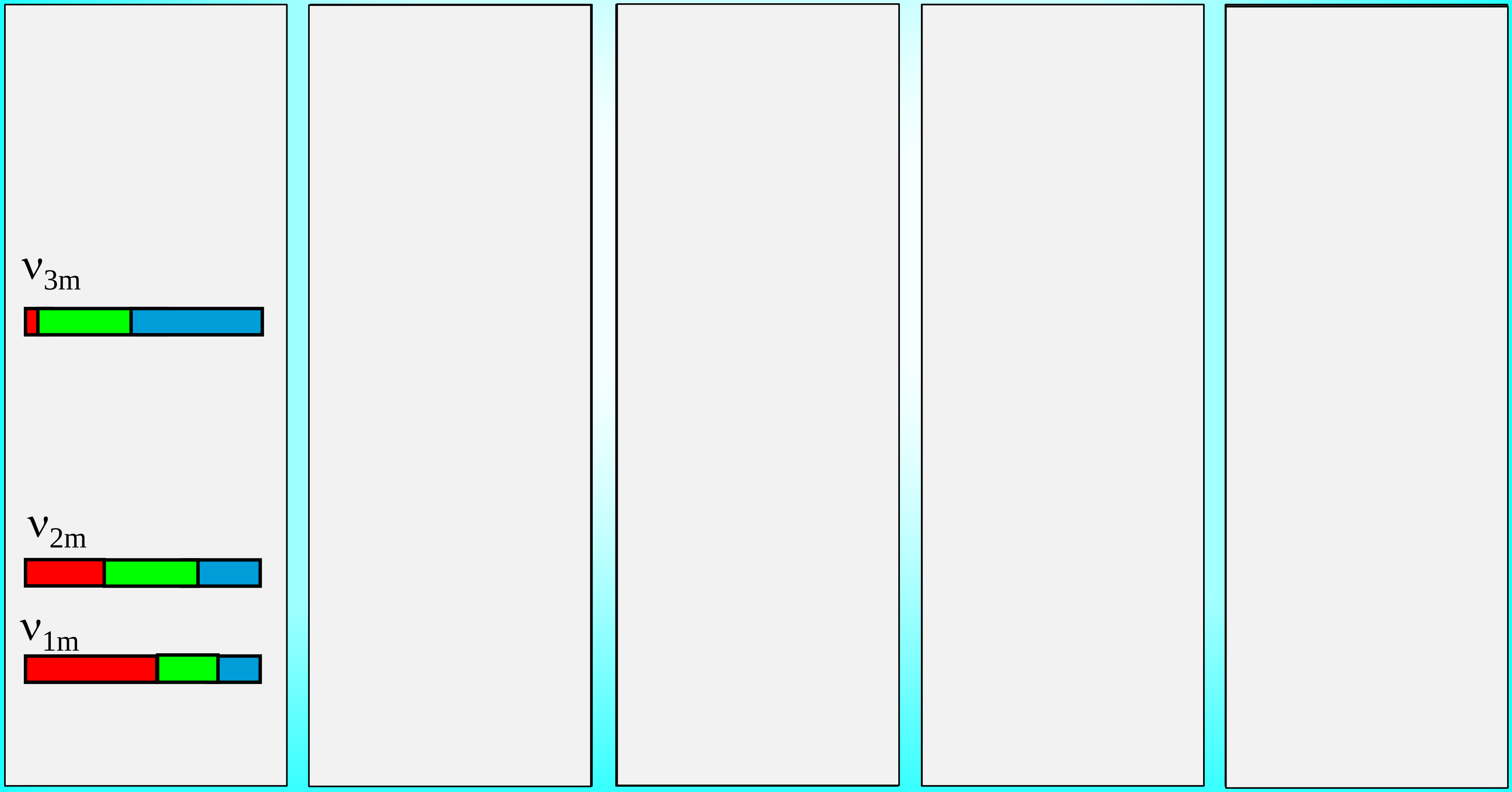
Constraints from cosmological surveys and from oscillations.
The 1σ region for the IH case is not present at this confidence level.
The grey band is the 95% C.L. excluded region coming from Cosmology

Flavor in matter

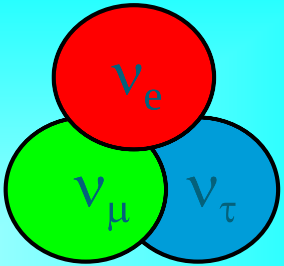


Density increase →

Normal mass hierarchy, neutrinos

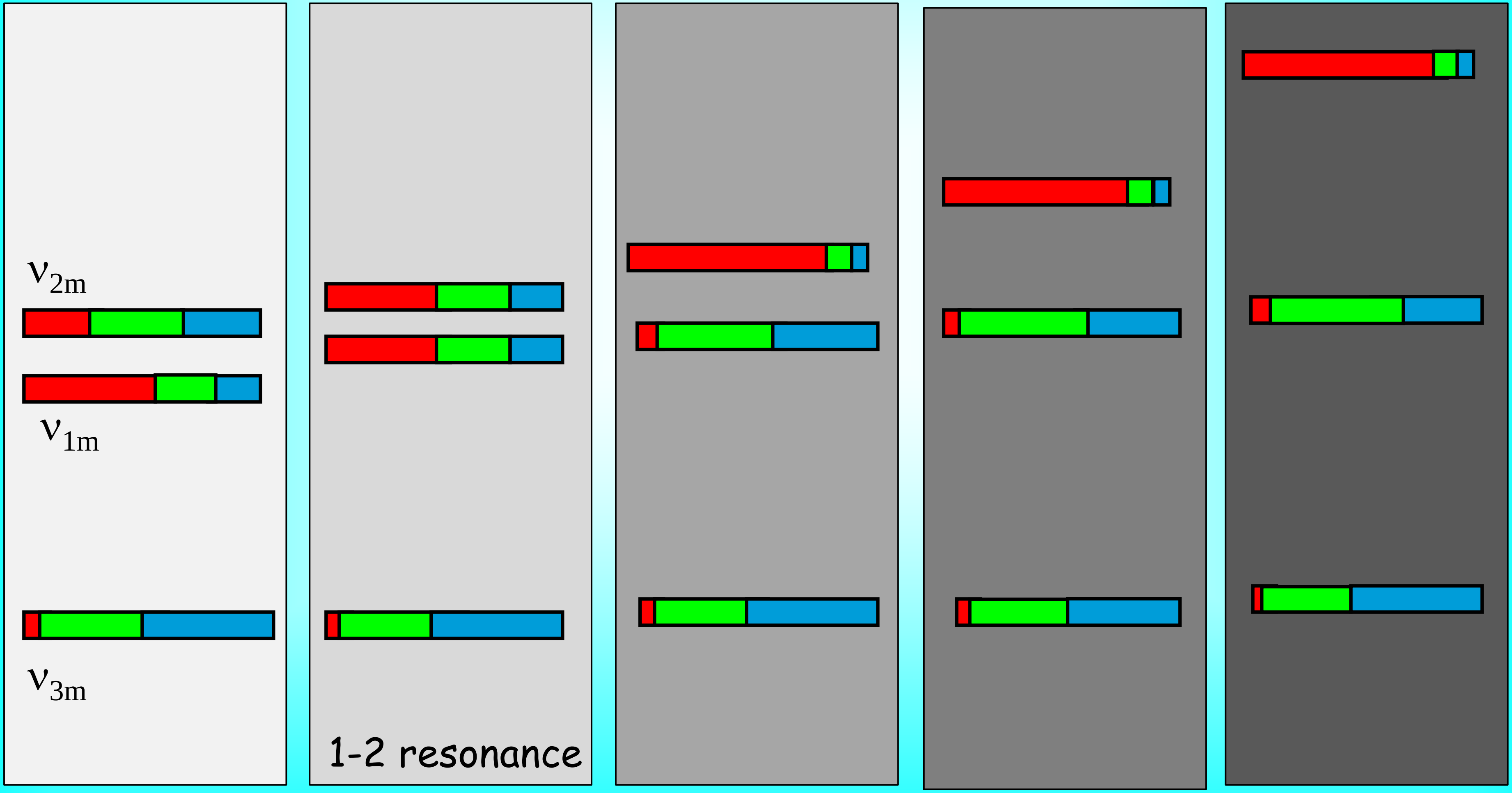


Flavor in matter



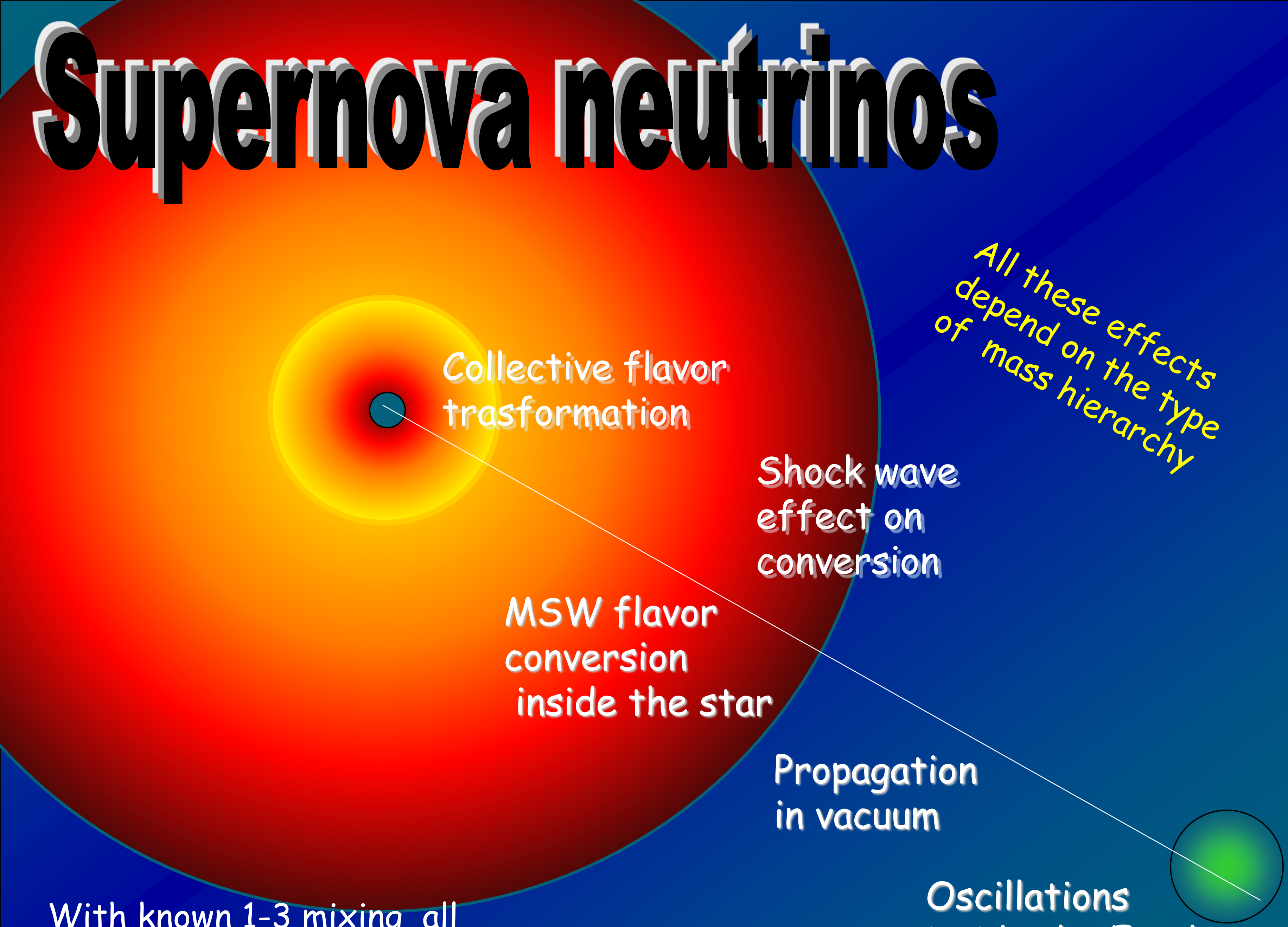
Density increase →

Inverted mass hierarchy, neutrinos



1-2 resonance

Supernova neutrinos



Collective flavor
trasformation

Shock wave
effect on
conversion

MSW flavor
conversion
inside the star

Propagation
in vacuum

Oscillations
inside the Earth

All these effects
depend on the type
of mass hierarchy

With known 1-3 mixing all
MSW transitions are adiabatic

Hierarchy affects

Time rise of the anti-ν_e burst initial phase: fast → 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

Earth matter effects

A. Dighe, A. S.
C. Lunardini

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

Different for IH and NH cases;
spectral splits
at high energies
→ IH

G. Fuller, et al
B. Dasgupta ,et al

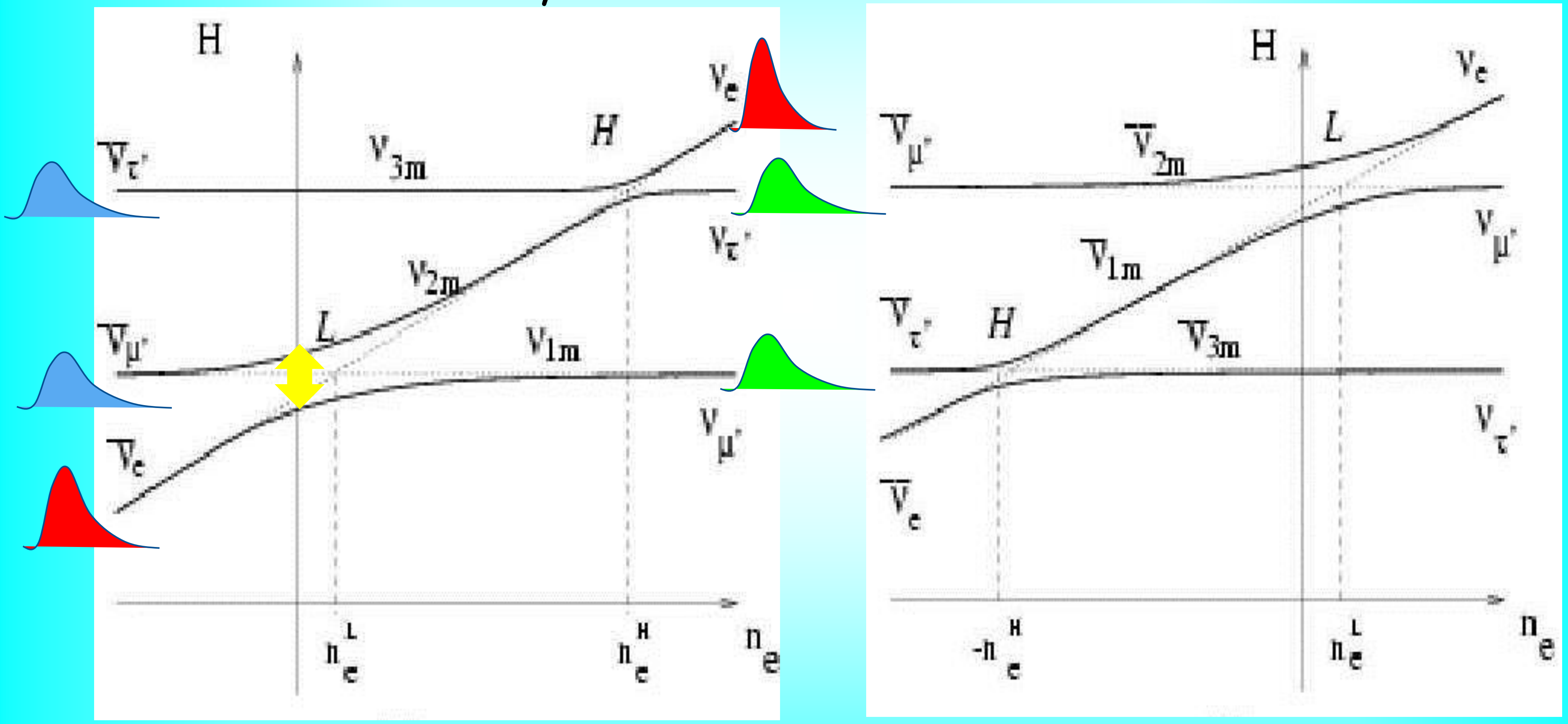
Earth matter effect and hierarchy

Adiabatic evolution

Level crossings

Normal hierarchy

Inverted hierarchy



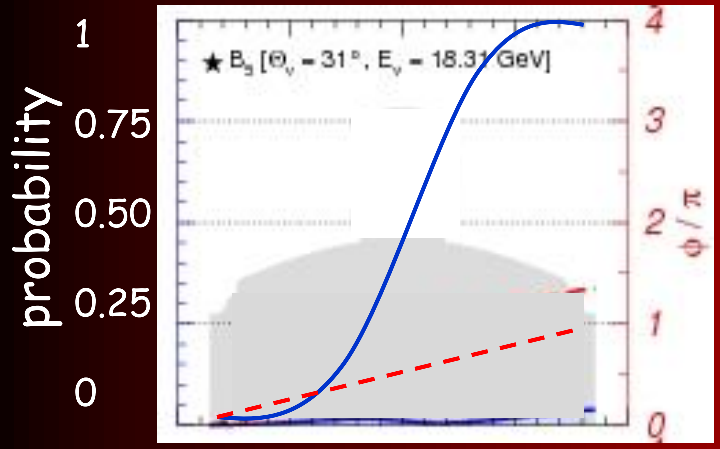
No Earth matter effect provided that initial fluxes of ν_{μ}' and ν_{τ}' are identical

Collective effects and shock waves may change this.

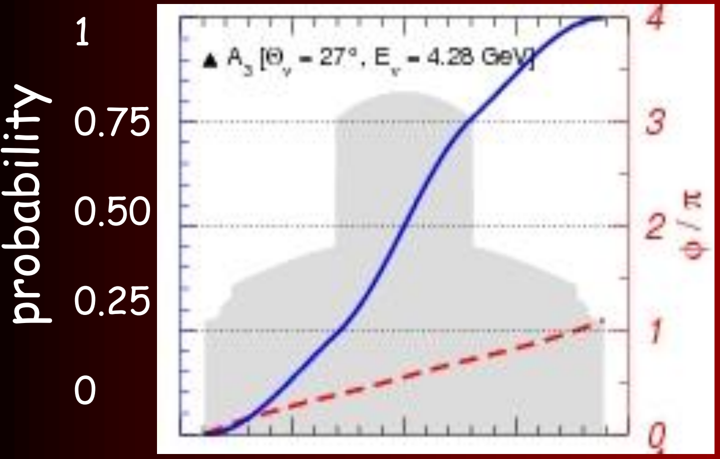
Atmospheric neutrinos

Oscillations in the Earth

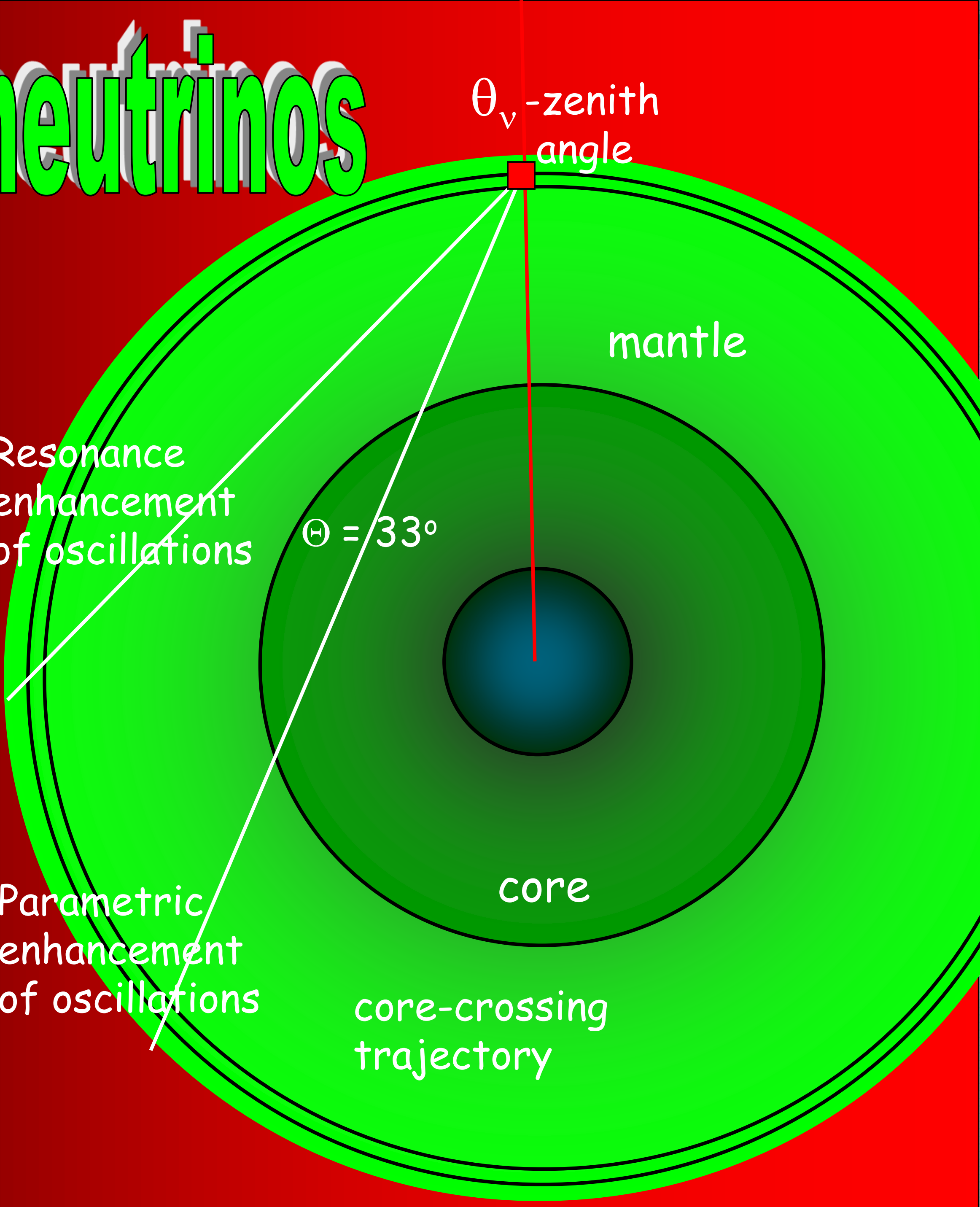
$\nu_e \to \nu_\mu , \nu_\tau$



Resonance enhancement of oscillations

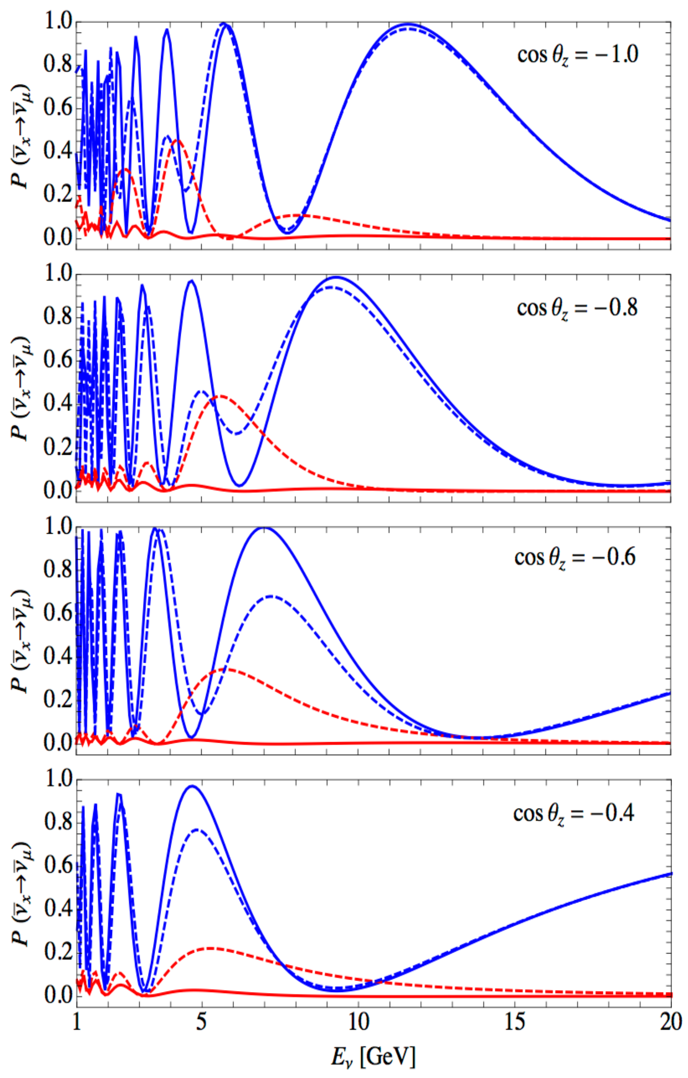


Parametric enhancement of oscillations

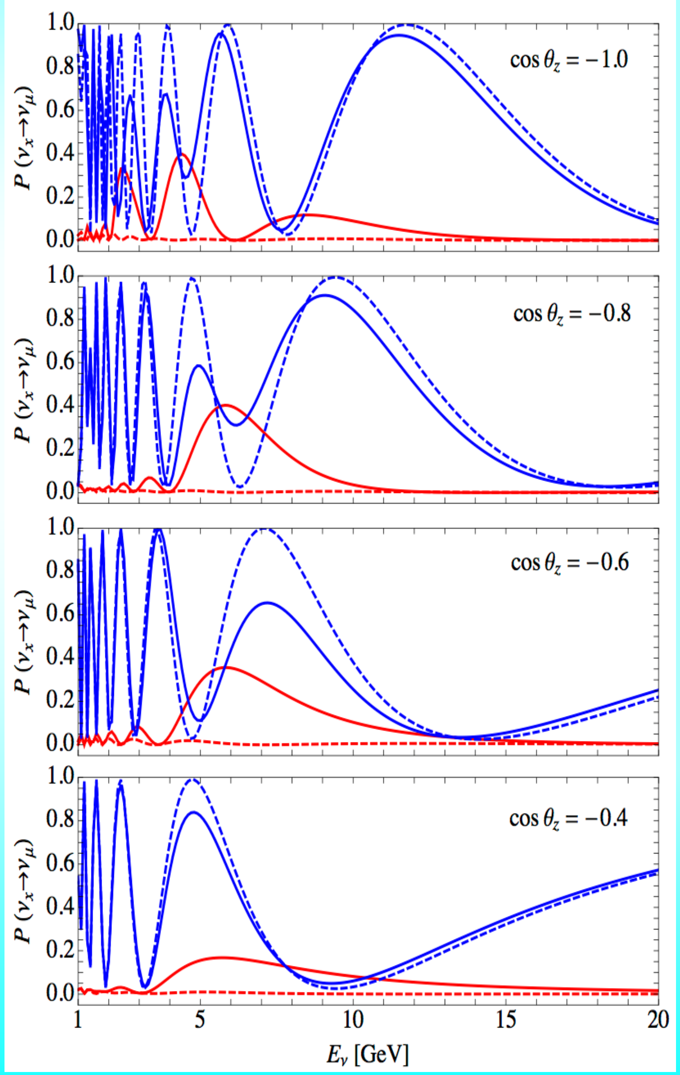


Probabilities

neutrinos



antineutrinos



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

Method

Measurement of $E - \theta$ distributions of different type of events.
Compare events for the normal and inverted orderings

"tracks"

$\nu_\mu + N \rightarrow \mu + h$

$\nu_\tau + N \rightarrow \tau + h$

$\rightarrow \mu + \nu + \nu$

muon track

+ cascade

Measurements

$E_\mu \quad \theta_\mu \quad E_h$ inelasticity

$E_\nu = E_\mu + E_h$

$E_h \quad E_\mu \quad \theta_\mu \rightarrow \theta_\nu$ reconstruction

"cascades"

$\nu_e + N \rightarrow e + h$

$\nu_\alpha + N \rightarrow \nu_\alpha + h$

$\nu_\tau + N \rightarrow \tau + h$

$\rightarrow h + \nu$

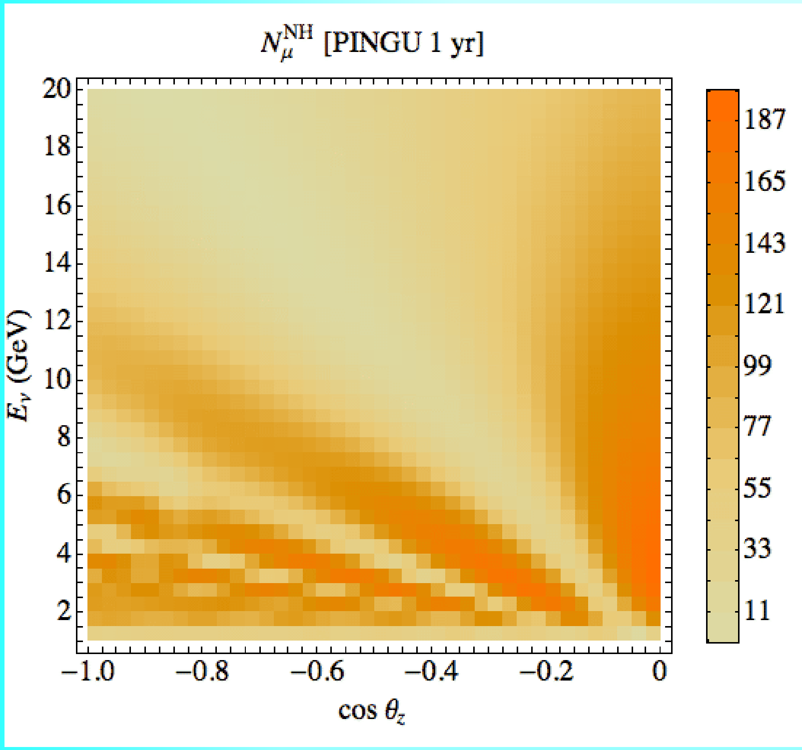
$\rightarrow e + \nu + \nu$

cascades

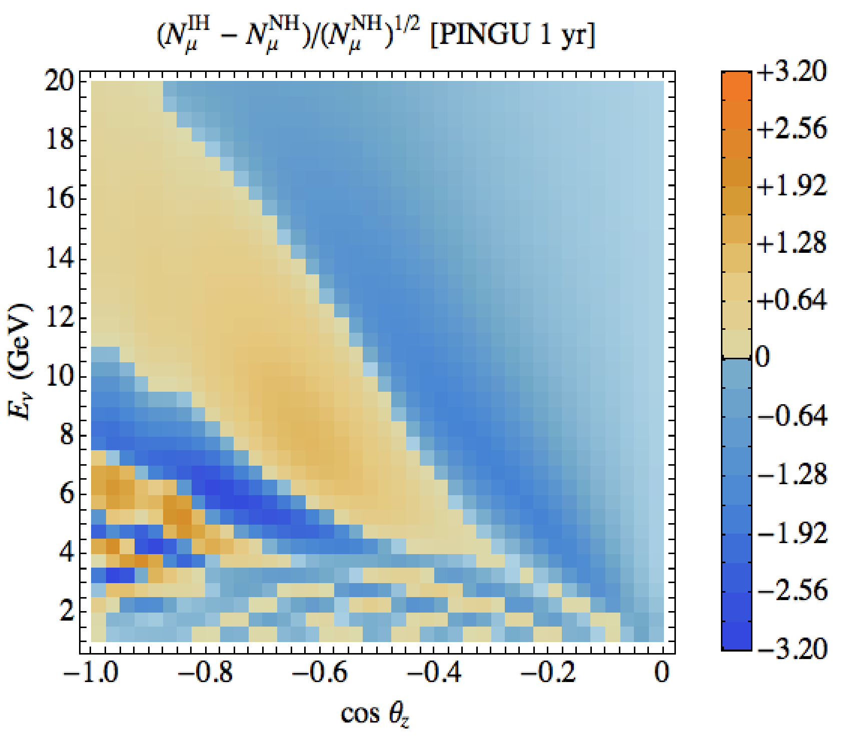
$E_\nu \quad \theta_\nu$ reconstruction

Track events

~ 10^5 events/year



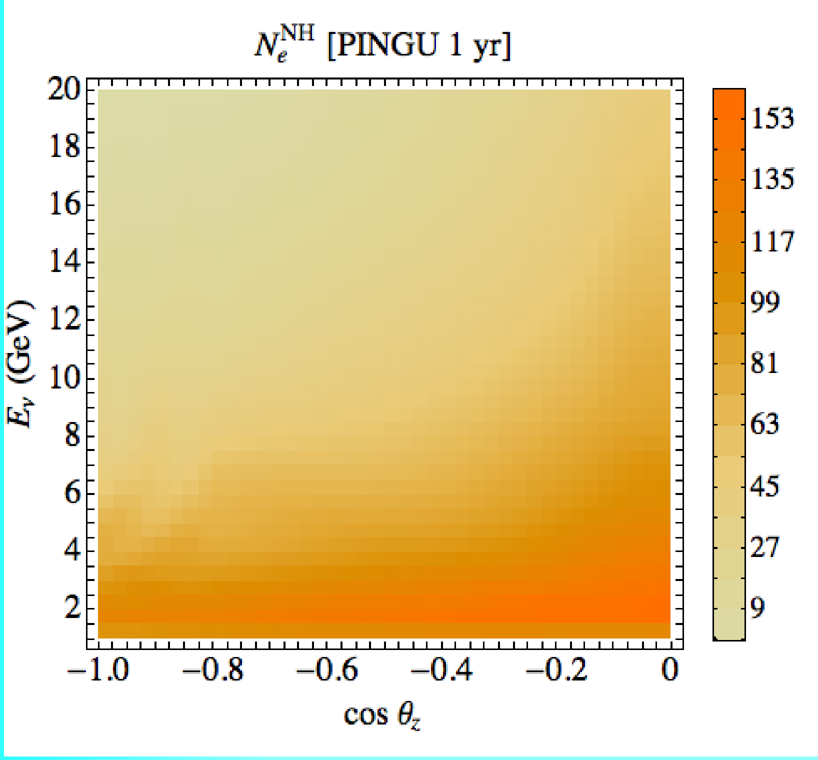
\`\`Distinguishability"

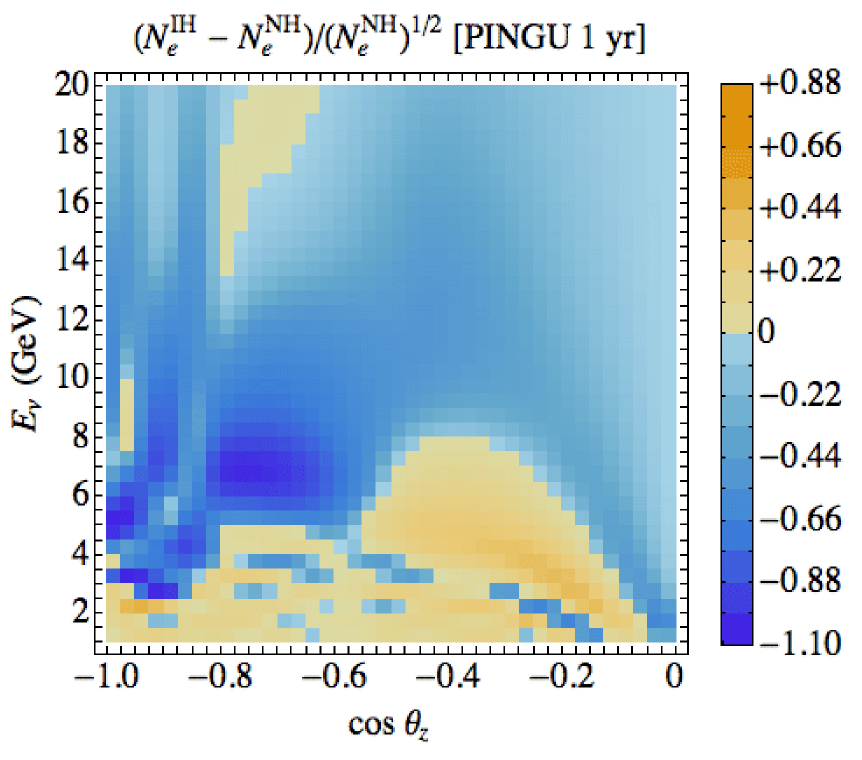


Estimator of sensitivity
S – asymmetry
|S| - significance

Cascade events

``Distinguishability"





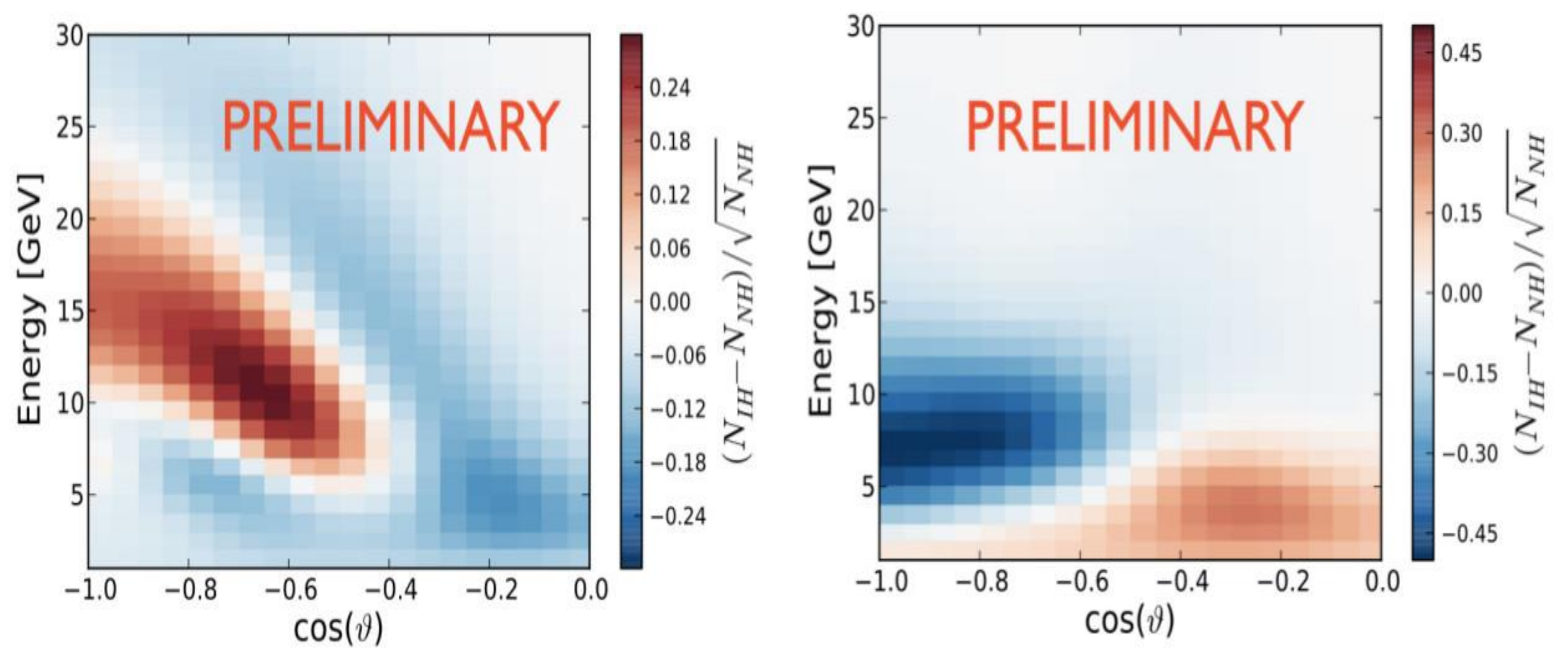
Statistical significance

Smeared distributions

Ken Clark

Over energy and angle
resolution functions

PINGU



tracks

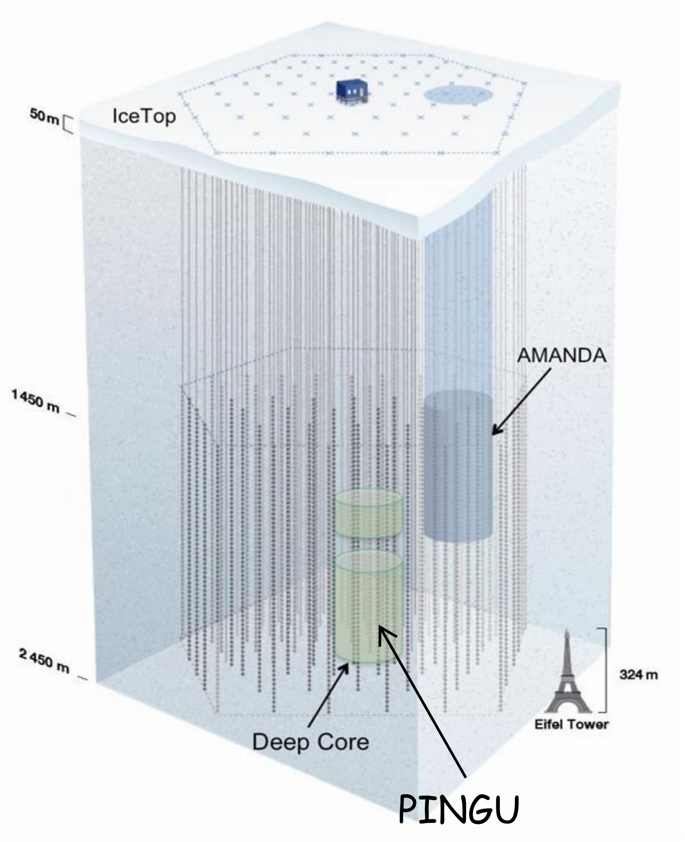
cascades

distinguishability

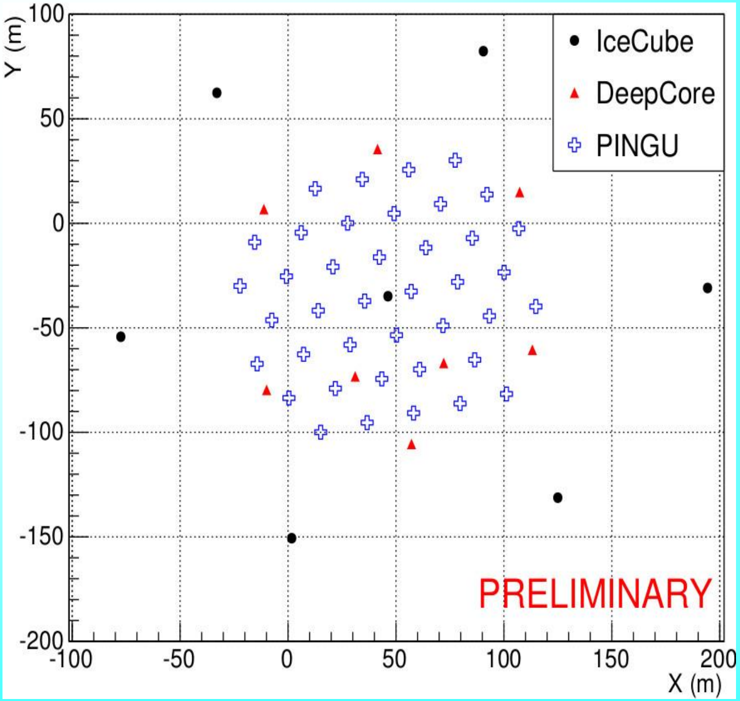
PINGU

Precision IceCube
Next Generation
Upgrade

K. Clark



40 strings
96 DOM's per string

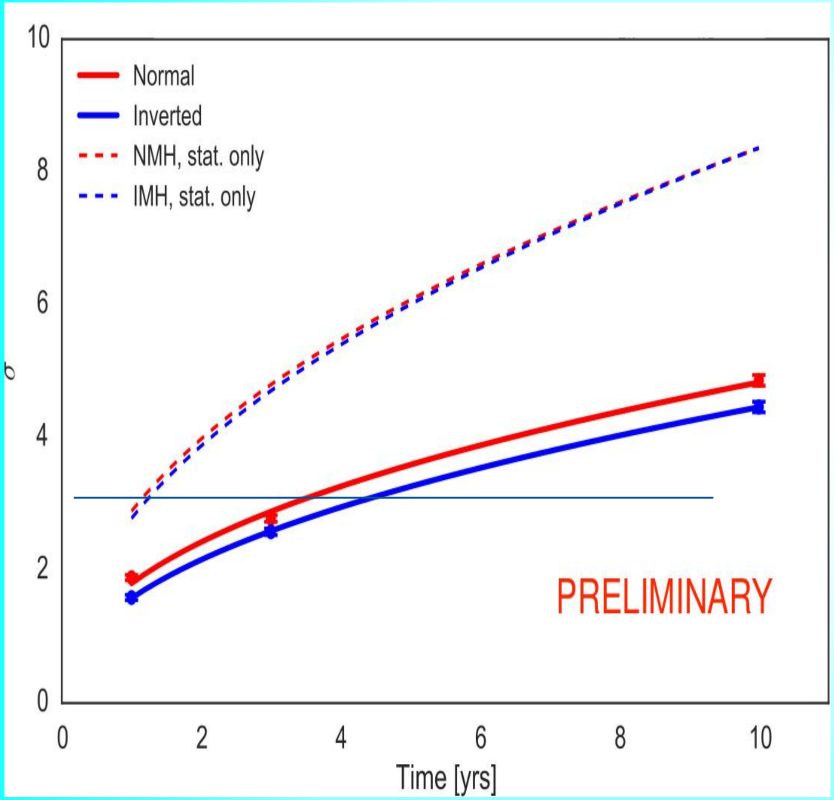


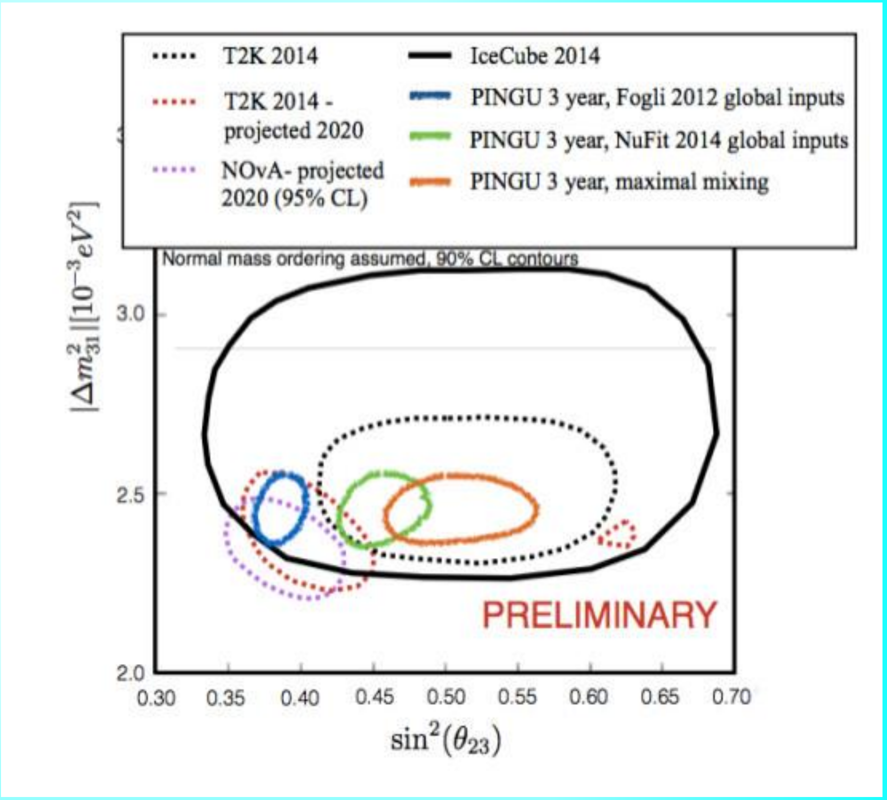
Sensitivity

K. Clark

Mass hierarchy

Parameters of the 2-3 sector





Deviation from maximal:
symmetry or no symmetry, Quadrant
Sensitivity to MH depends on

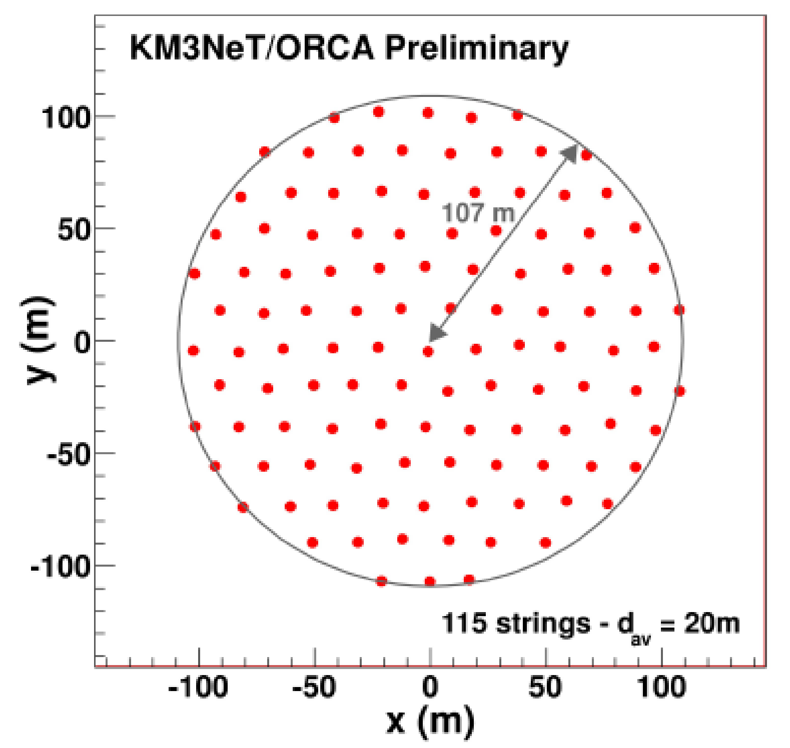
ORCA

Oscillation Research with
Cosmics in the Abyss

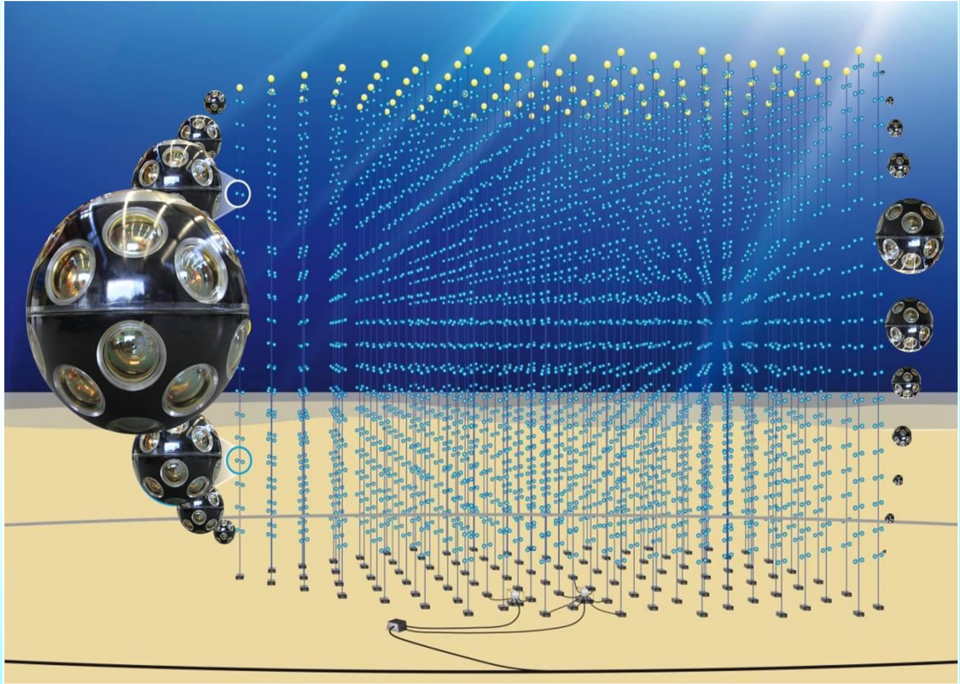
J. Brunner
Highlight talk: C. James

115 lines, 20m spaced,
18 DOMs/line, 6m spaced
Instrumented volume ~3.8 Mt,
2070 OM

450 m



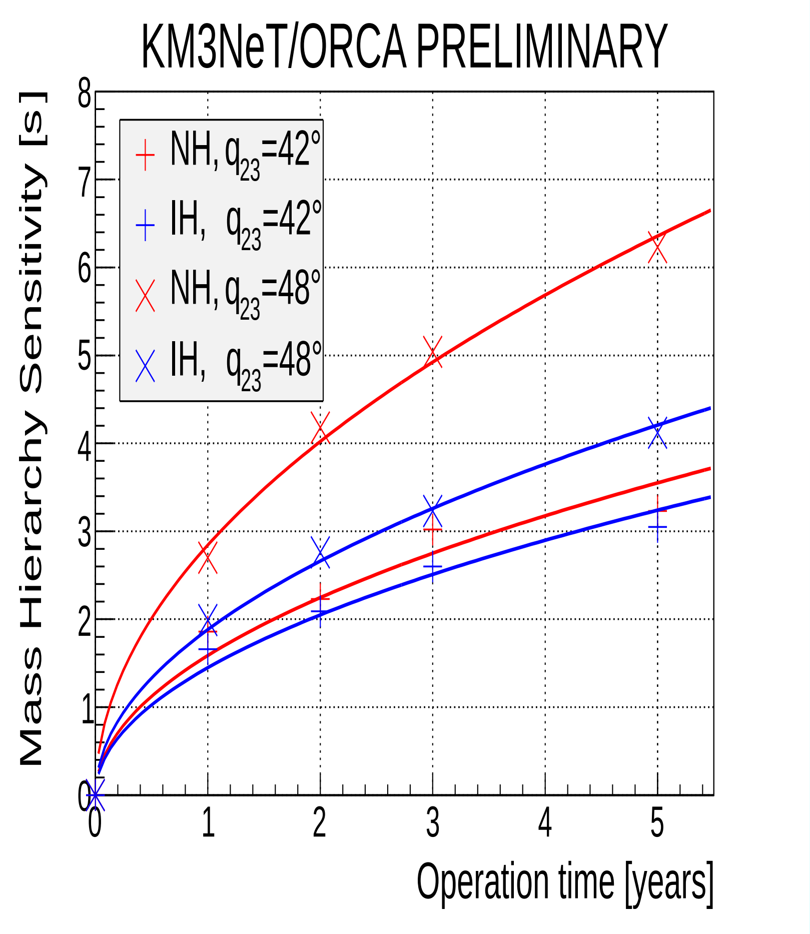
Poster : Ronald Bruijn



- 31 3" PMTs
- Digital photon counting
- Directional information
- Wide angle view

Sensitivity to MH

J. Brunner



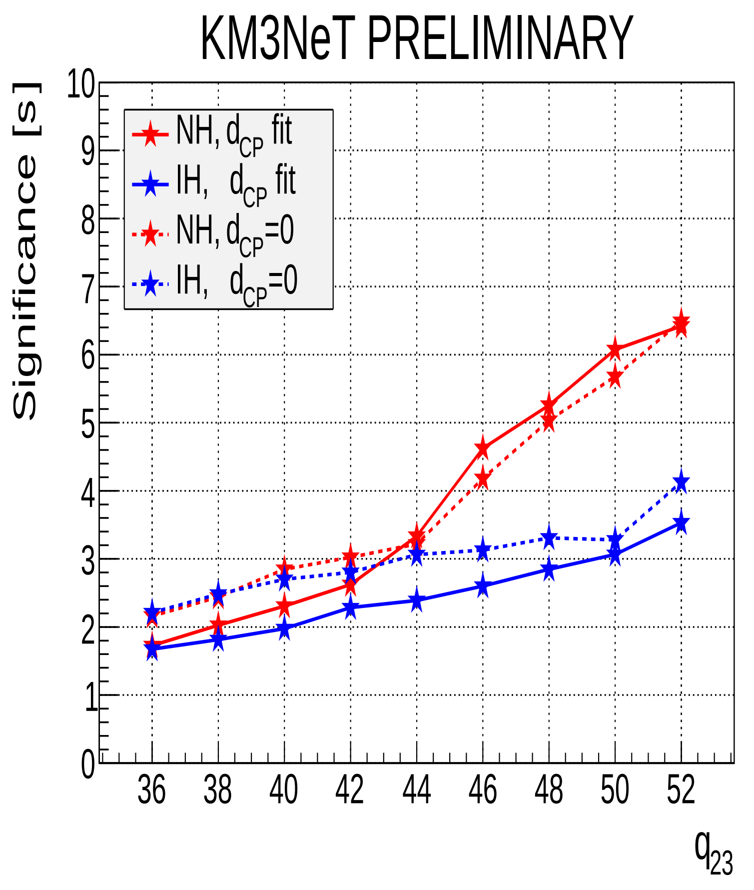
Dependence of sensitivity on time for fixed θ_{23} values and δ_{CP} fixed to zero

- Track vs shower event classification
- Full MC detector response matrices including misidentified and NC events
- Atmospheric muon contamination
- Neutral current event contamination
- Various Systematic uncertainties

Poster : Martijn Jongen

Sensitivity to mass hierarchy

3 years



J. Brunner

Dependence of sensitivity on θ_{23} .
Higher for NH than IH.

Second octant easier than first octant.

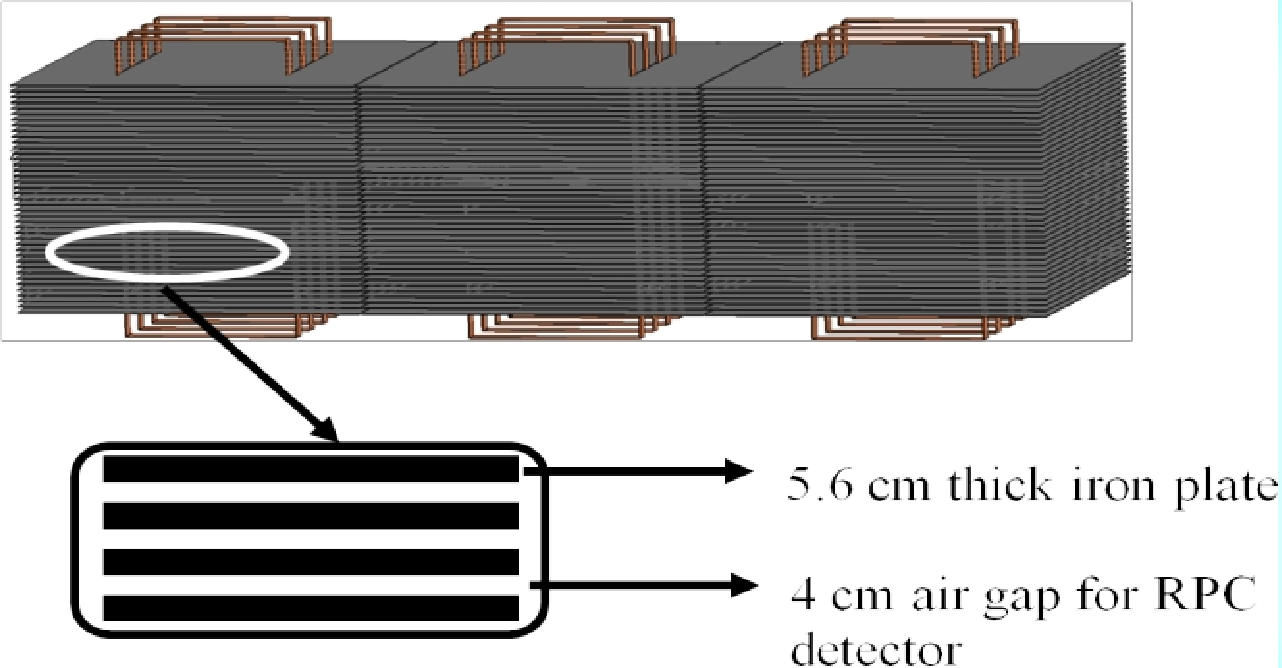
When fixing δ_{CP} to zero sensitivity increases by ~0.5σ

Martijn JONGEN
Poster 935

INO-ICAL

ICAL Collaboration (Ahmed Shakeel et al.)
arXiv:1505.07380 [physics.ins-det]

The 50 kt magnetized iron calorimeter (ICAL) detector at the India-based Neutrino Observatory (INO)



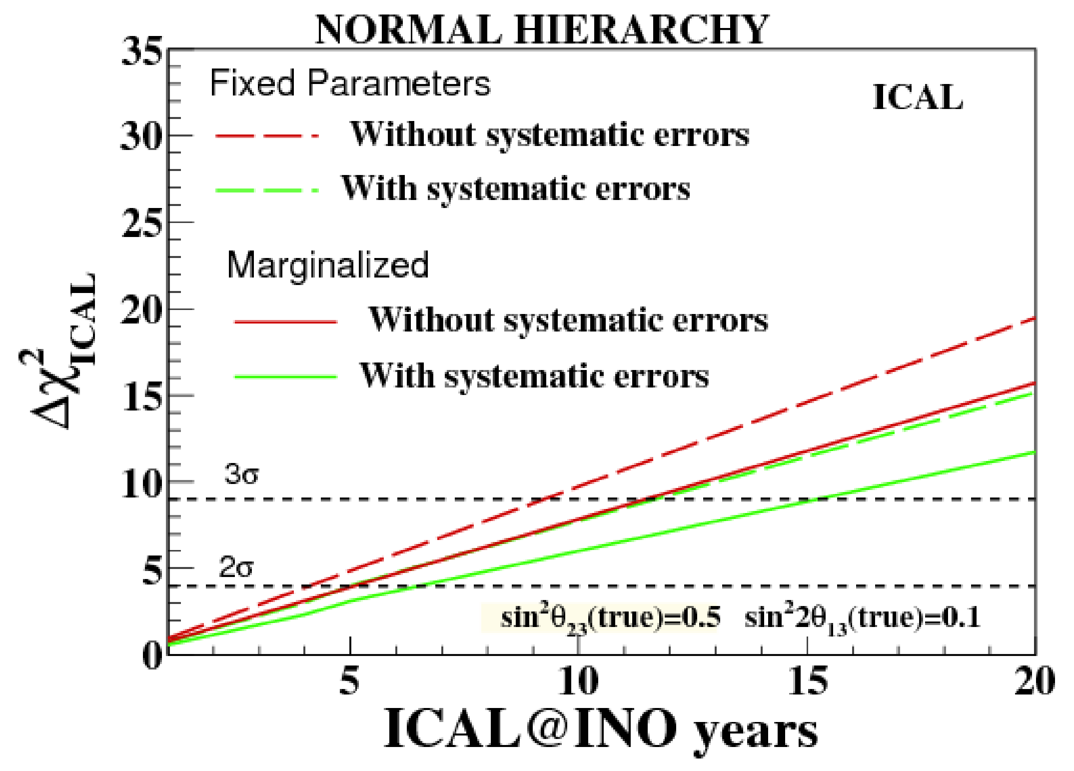
Resistive plate chambers

Energy and direction of the muons; energy of multi-GeV hadrons; charge of muon

The energy and zenith angle dependence of the atmospheric neutrinos in the multi-GeV range.

Sensitivity to hierarchy

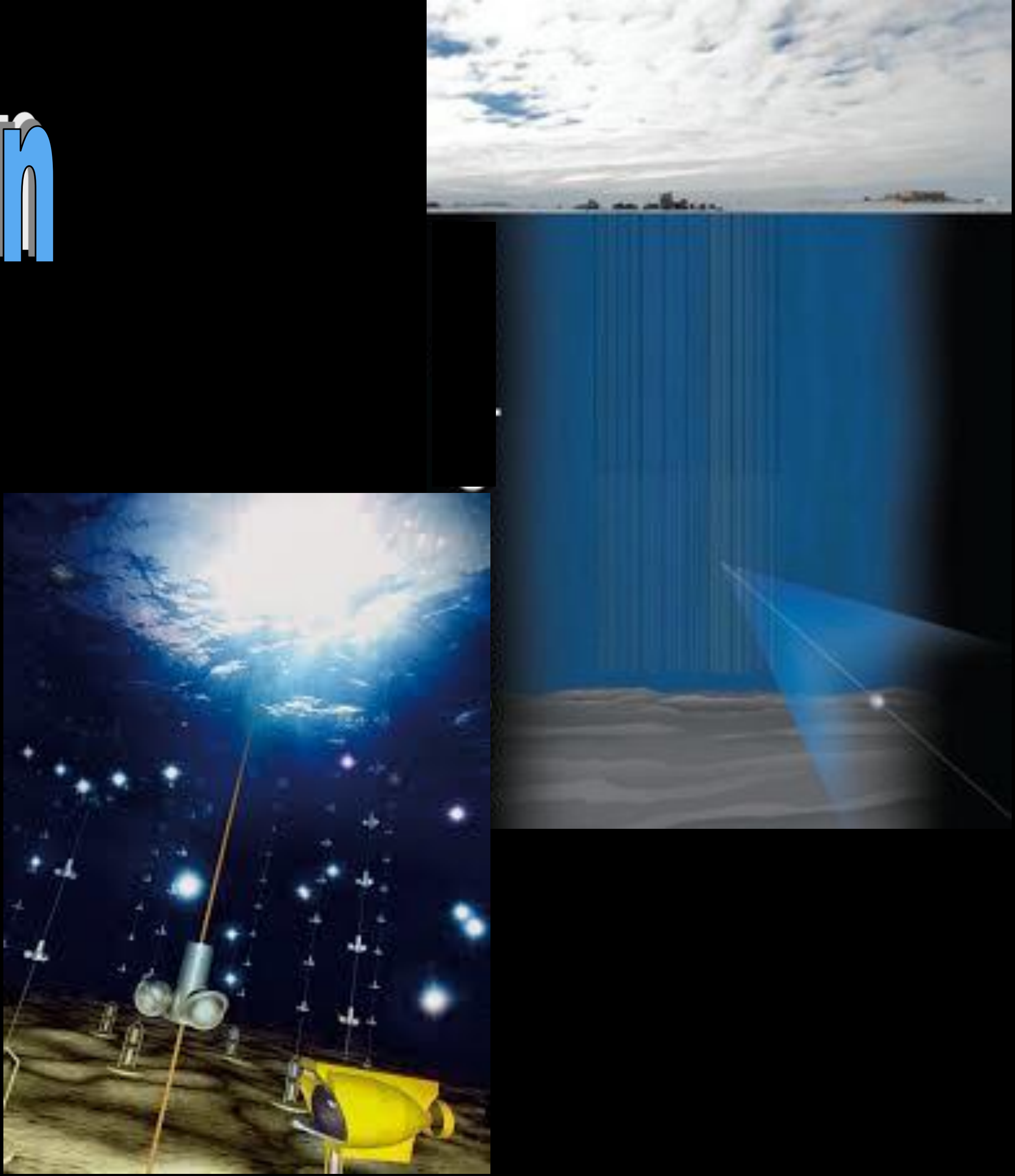
ICAL Collaboration
(Ahmed Shakeel et al.)
arXiv:1505.07380 [physics.ins-det]



10 -15 years

The impact of systematic uncertainties on mass hierarchy sensitivity.
The red (green) lines – without (with) systematic uncertainties
Long-dashed lines are for fixed values of parameters (1-3 mixing, 2-3 mixing, mass splitting), solid -marginalized

CP-violation



Measuring CP-phase

Global fit

T2K + NOvA + reactors

J-PARC- SK

750 kw upgrade

at 2- 3 σ

Dedicated experiments

J-PARC- HK

DUNE LBNF

ESS

Europeanspalation source Lund

$3\pi/2$ from 0

~ 5 - 7 σ

result in 2030 - 2035

~ 2 bln US$

Long term and expensive commitment

Alternative?

All possible alternatives must be explored and scenarios of developments in the next 20 years should be considered

Ice Cube

100 GeV

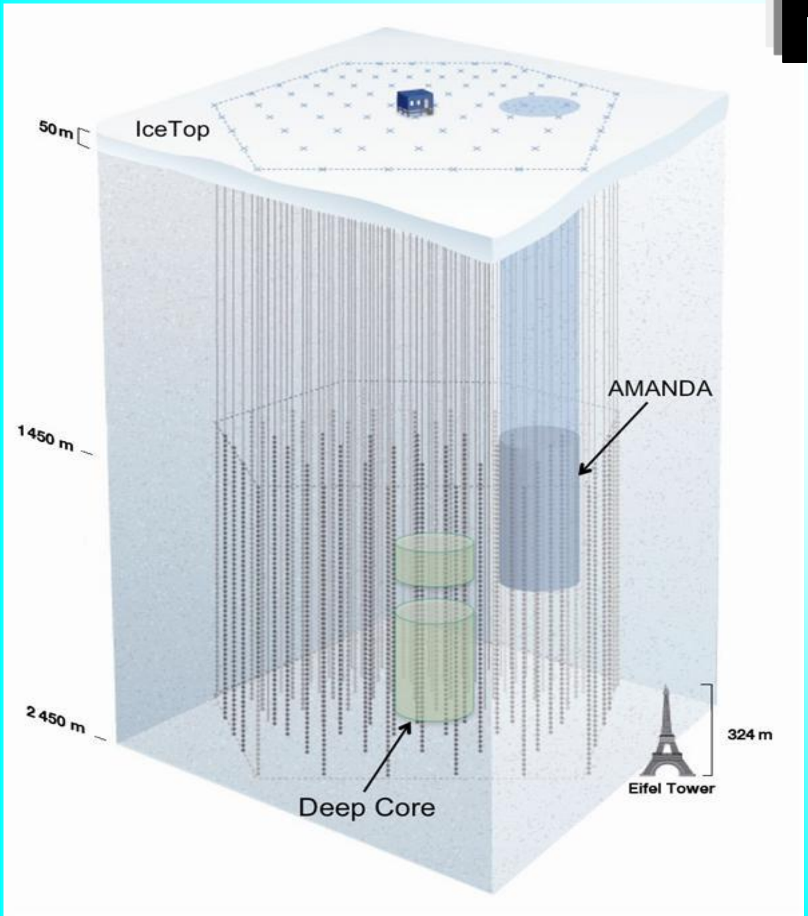
Deep Core

10 - 15 GeV

PINGU
ORCA

Mass hierarchy

3 GeV



Super-PINGU
.ORCA

3 times denser
array than PINGU

0.5 – 1 GeV

Few Mtons in
sub-GeVrange

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

Megaton-scale
Ice
Cherenkov
Array

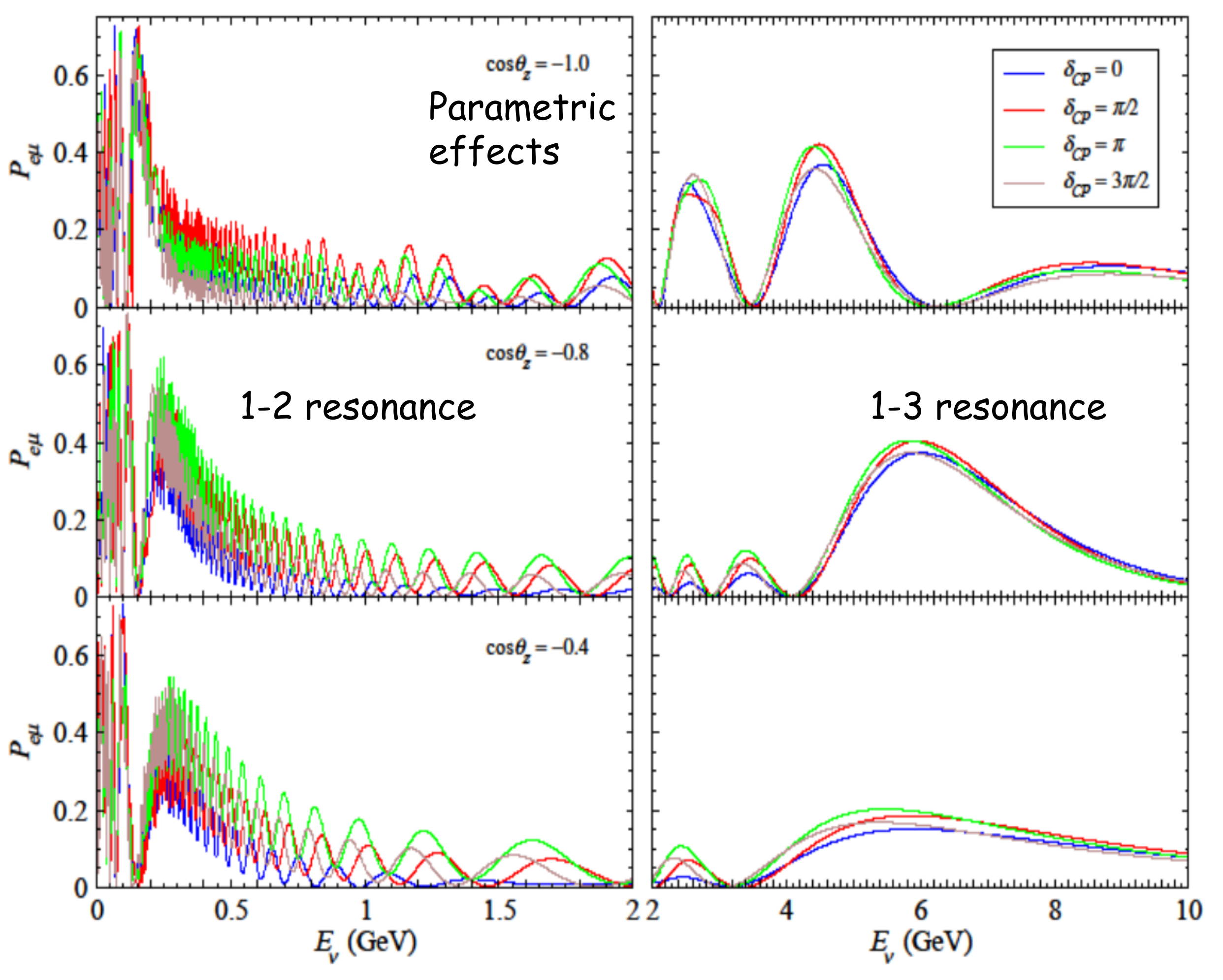
MICA

0.01 GeV

Probabilities

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

$\nu_e \rightarrow \nu_\mu$ NH



Parametric effects

1-2 resonance

1-3 resonance

Large (10%) effect
at E ~ (0.5 – 1.5) GeV

The key: with
change of the phase

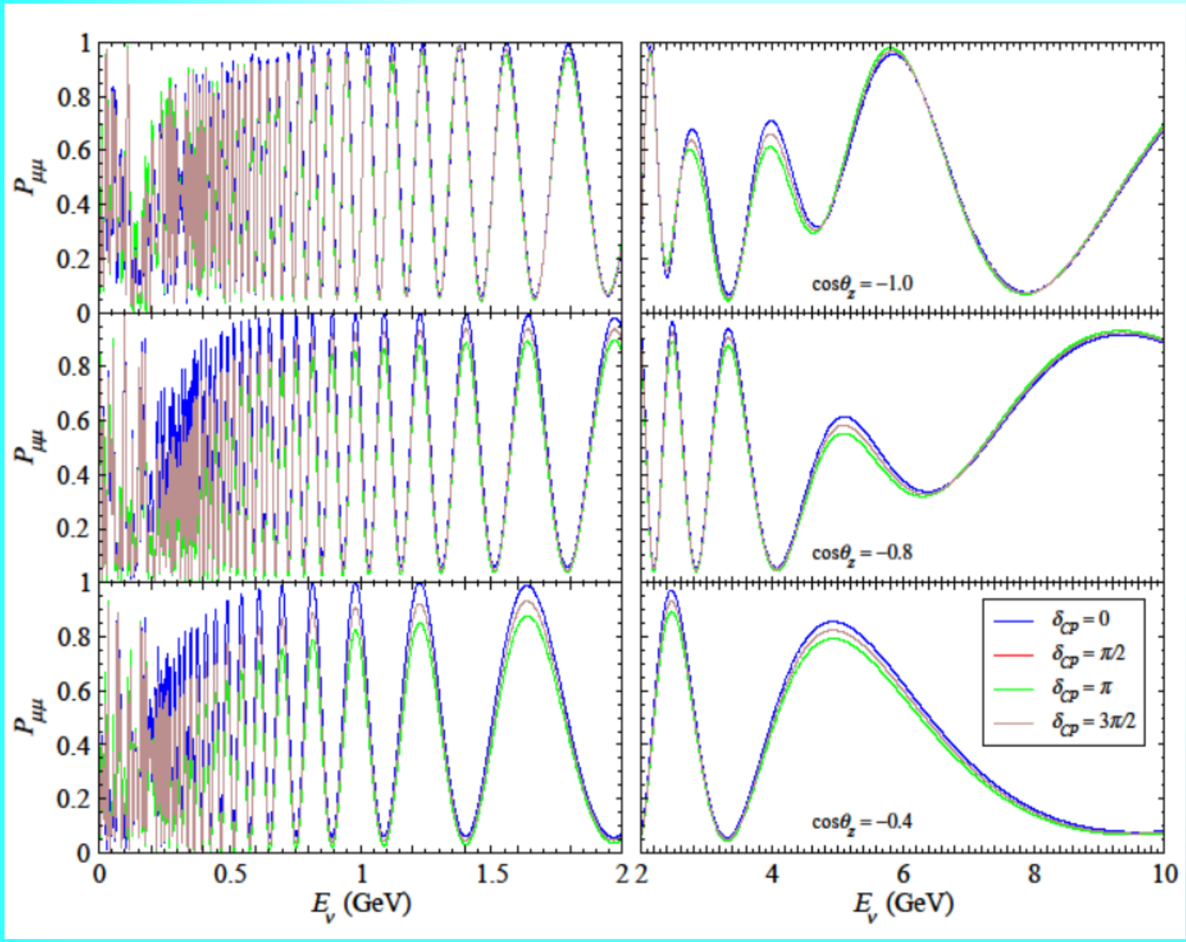
systematic shift
of curves,
the same for all zenith
angles in mantle

Averaging over
fast oscillations
and integration over
zenith angle does
not wash out CP
phase effect

Probabilities

S. Razzaque A Y S

ν_μ → ν_μ



No phase shift

Effect is opposite to ν_e → ν_μ with change of δ

Flavor suppression of effects for ν_μ events

Flavor identification is crucial

Distinguishability for CP

Quick estimator (metric) of discovery potential

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

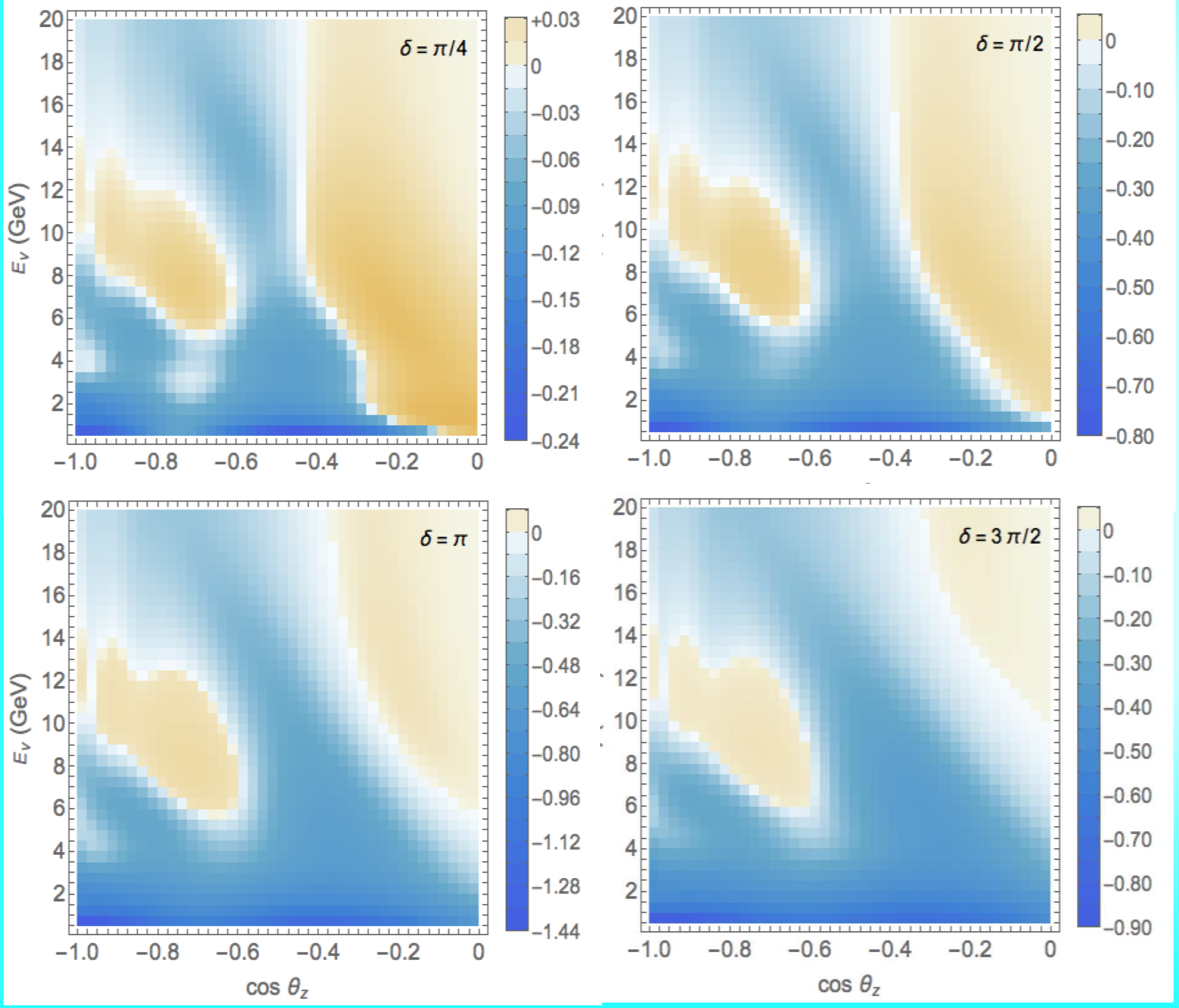
$|S_{ij}|$ - distinguishability of different values of CP-phase

Total distinguishability

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

Neutrino images of the Earth

For different values of CP phase



ν_μ- CC events
(track + cascade)

S-distributions
for different
values of δ

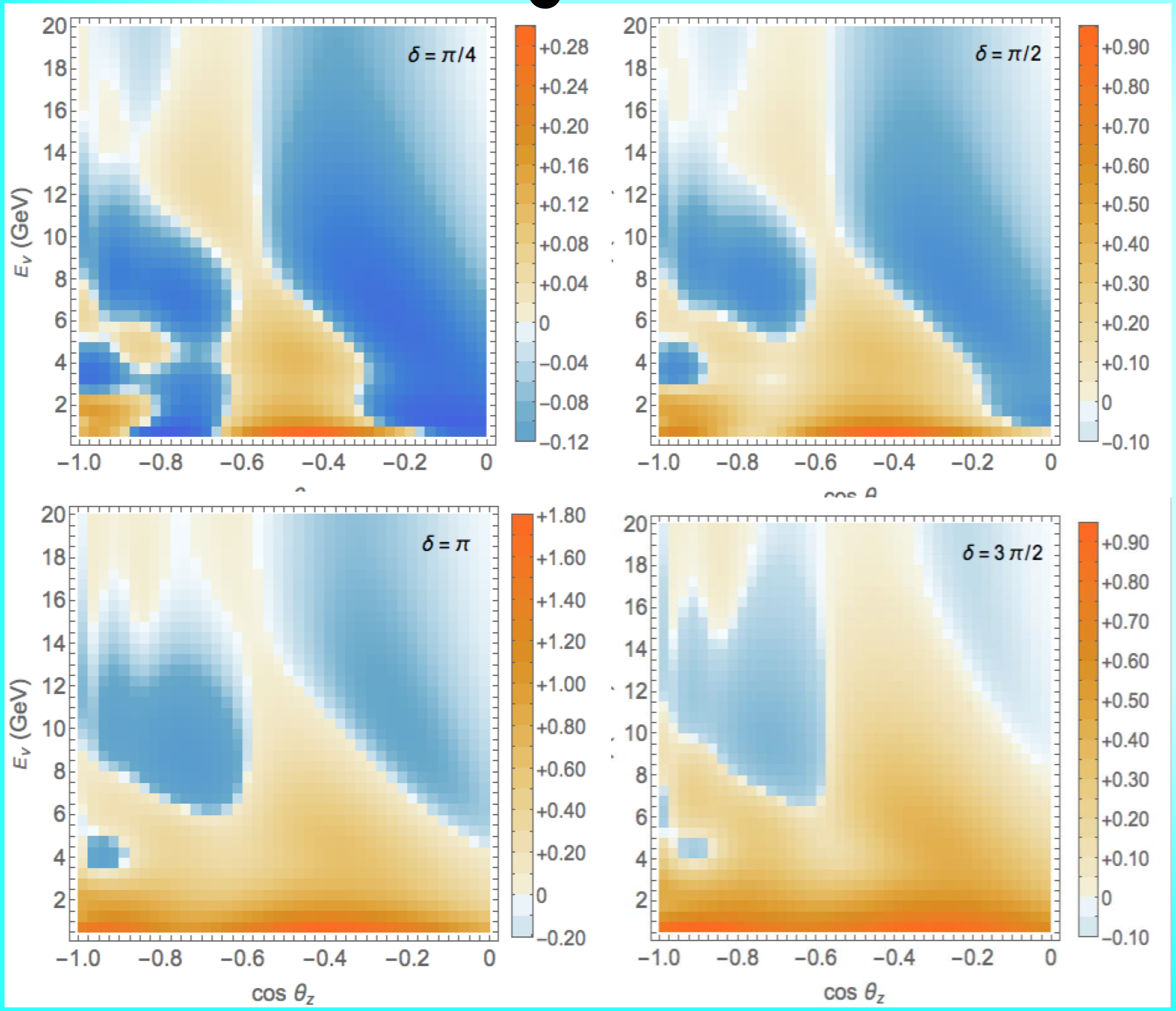
Super PINGU
1 year

After smearing over neutrino energy and direction

S distributions

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

Neutrino images of the Earth



ν_e - CC events
(cascades)

S-distributions
for different
values of δ

Super PINGU
1 year

After smearing over neutrino energy and direction

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

Can we measure this?

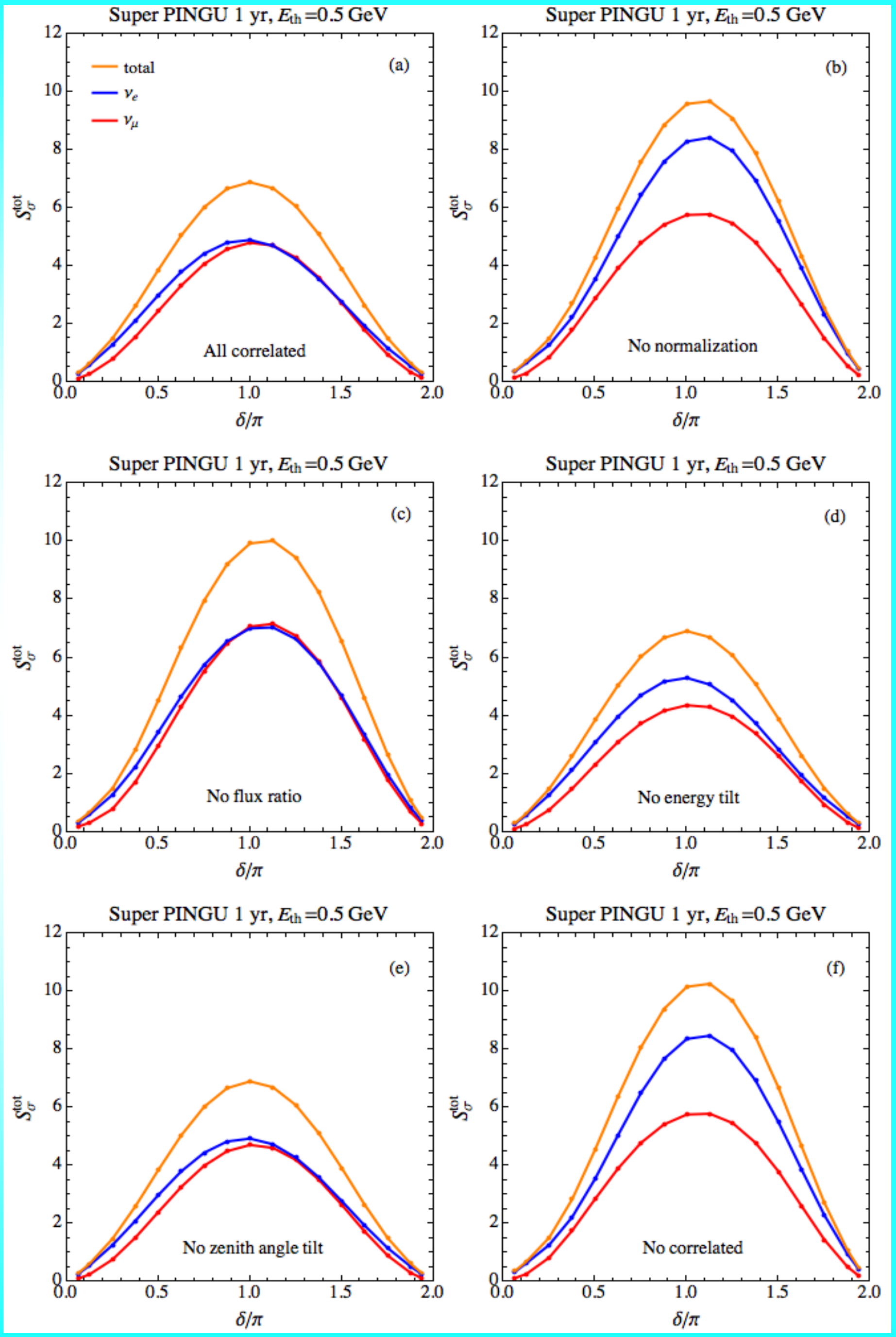
Sensitivity of SuperPINGU

Effect of correlated systematic errors

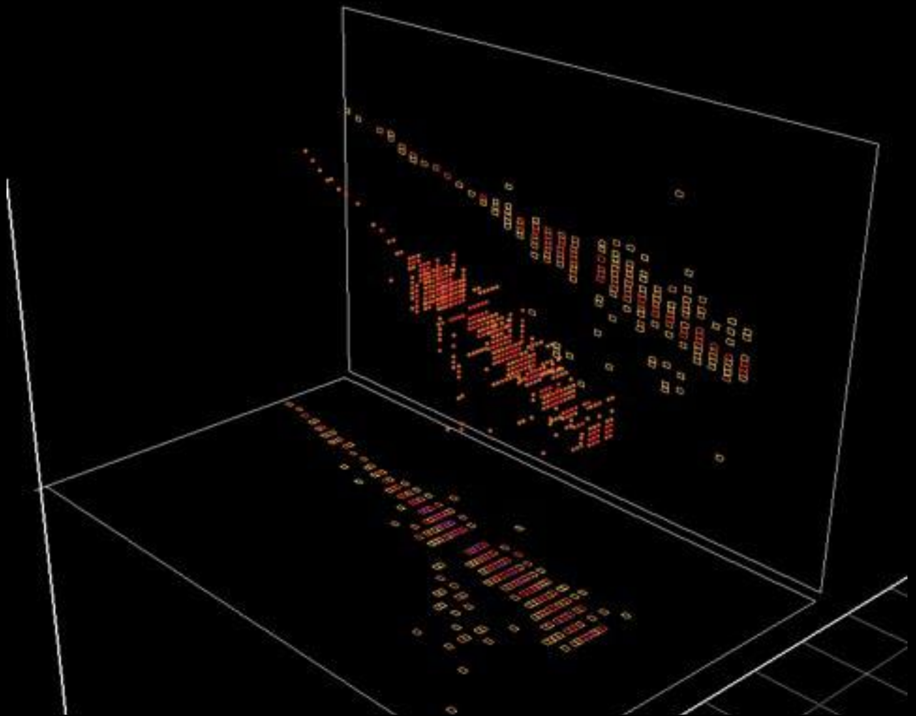
Flavor misidentification can further reduce distinguishability by factor 1.5 - 2

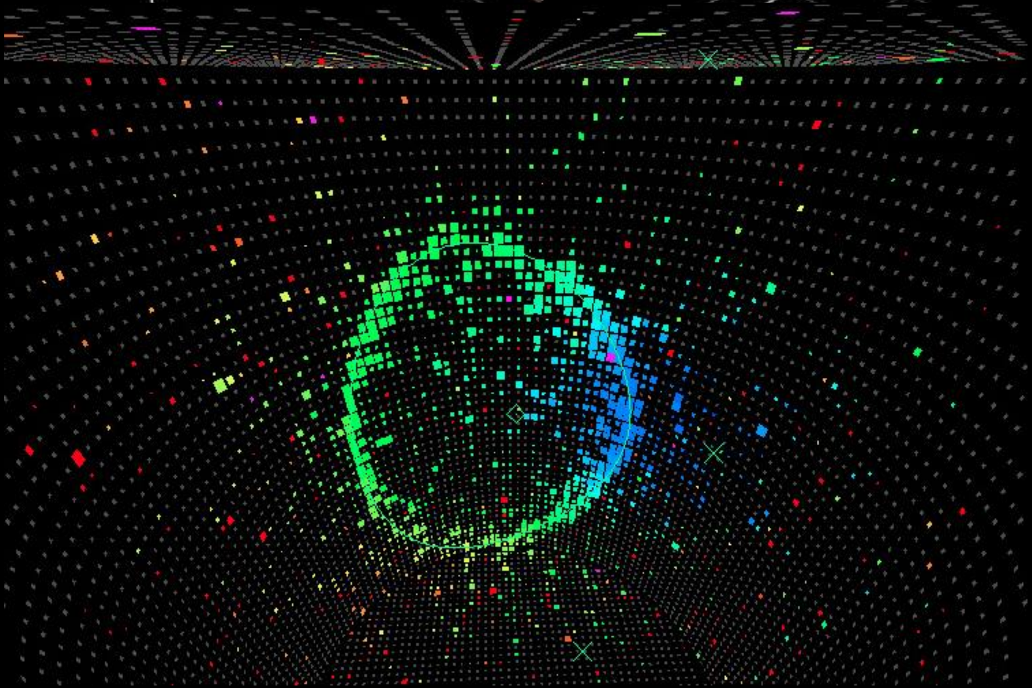
Still $S_\sigma \sim 3\text{-}4$ for $\delta = \pi$

after 4 years of exposure



Summary





Enormous progress all mixing angles and mass splittings in 3ν framework are measured

Still physics behind neutrino mass and mixing is not yet identified

Few challenges imply existence of new neutrino states- sterile neutrinos

Measurements of missing parameters of the 3ν paradigm
- mass hierarchy,
- CP phase, as well as
- searches physics beyond 3ν paradigm
  may lead to breakthrough in the field.

Identification of the neutrino mass ordering – next big in neutrino physics

Large atmospheric neutrino detectors with low (few GeV) energy threshold PINGU, ORCA may be first in this race.

Measurements of the Dirac CP-phase ultimate in oscillation neutrino experiments

A possibility to use further upgrade of PINGU, ORCA detectors to measure the CP phase should be explored

Race for mass hierarchy:
PINGU, ORCA
JUNO, RENO 50
T2K , NOvA
Supernova neutrino bursts
Cosmology

2022 – 2026 ?

Tomorrow? But require better understanding collective effects

Fast developments of techniques of detection of low energy (atmospheric) neutrinos in multi Megaton detectors

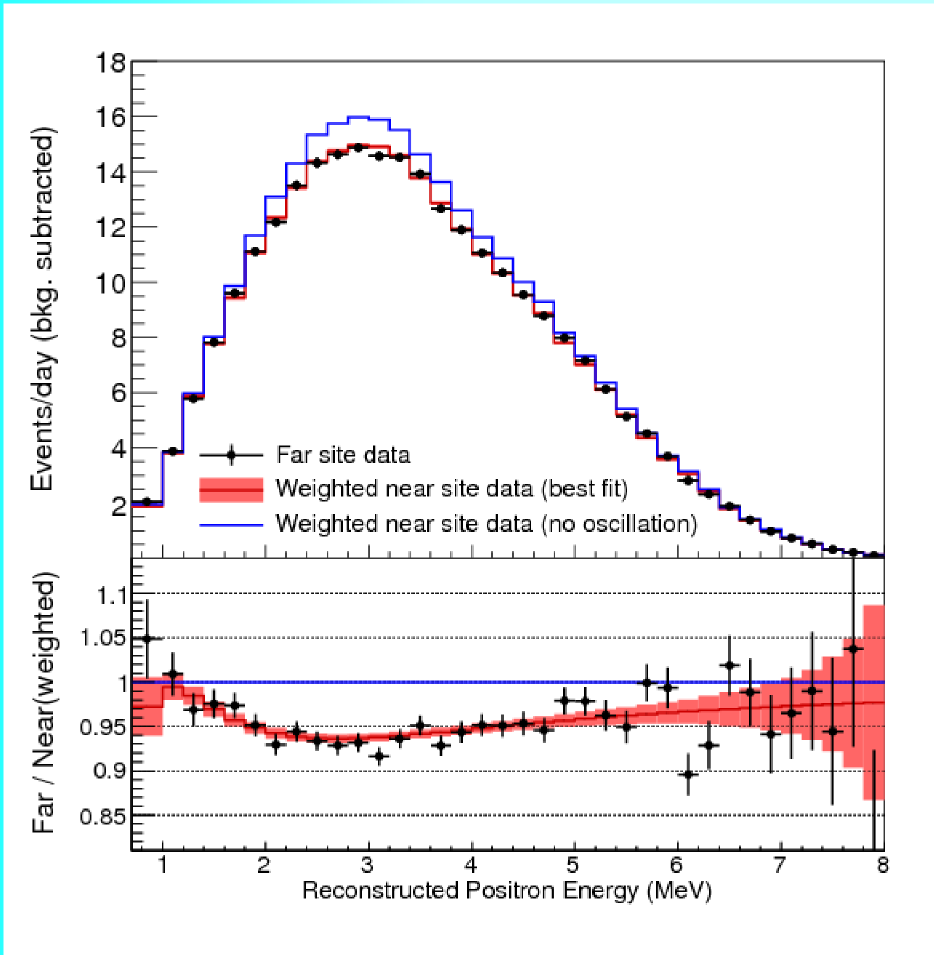
Can address crucial issues in particle, neutrino physics:
- establishing neutrino mass ordering
- determination of the CP-phase
- searches for sterile neutrinos, and tests of existing hints
- searches for non-standard neutrino interactions, etc.

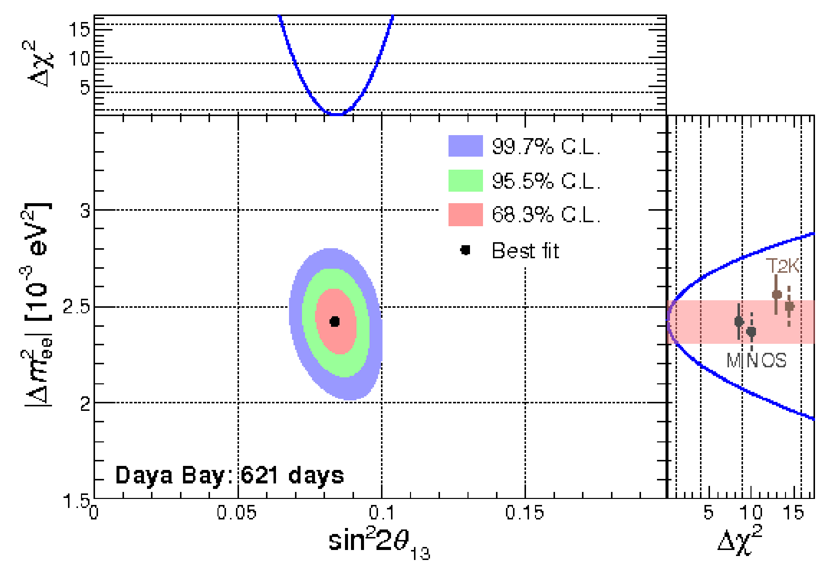
This may lead to major developments in the field

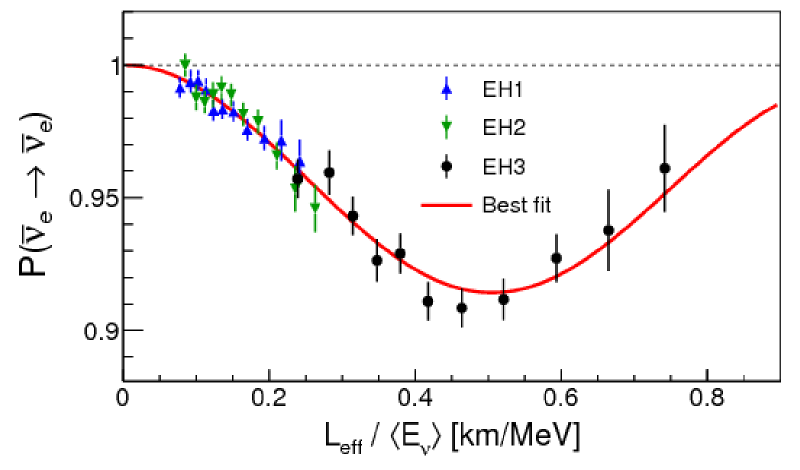
Backup slides

Daya Bay result

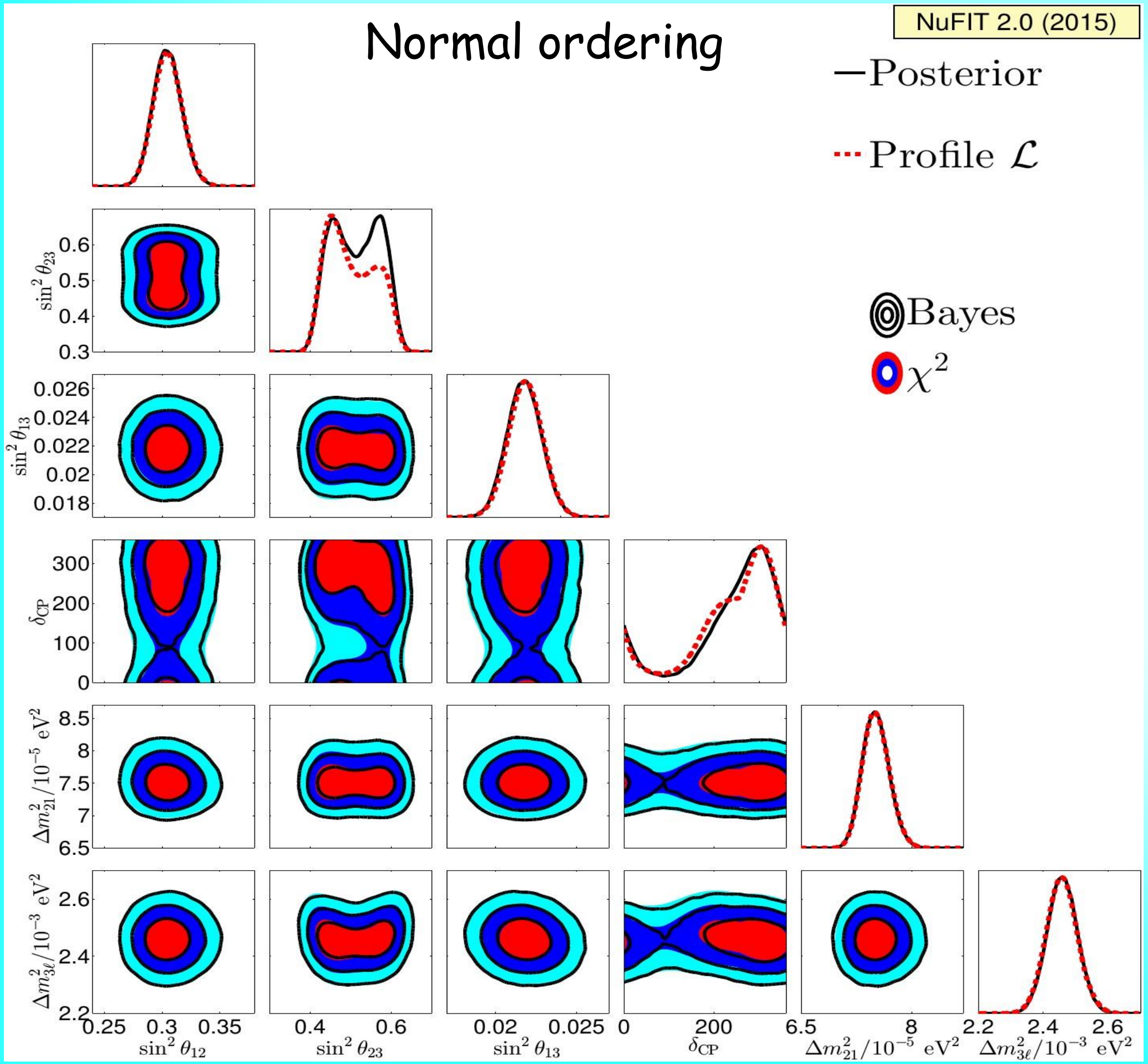
Daya Bay Collaboration
(An, F.P. et al.)
arXiv:1505.03456 [hep-ex]





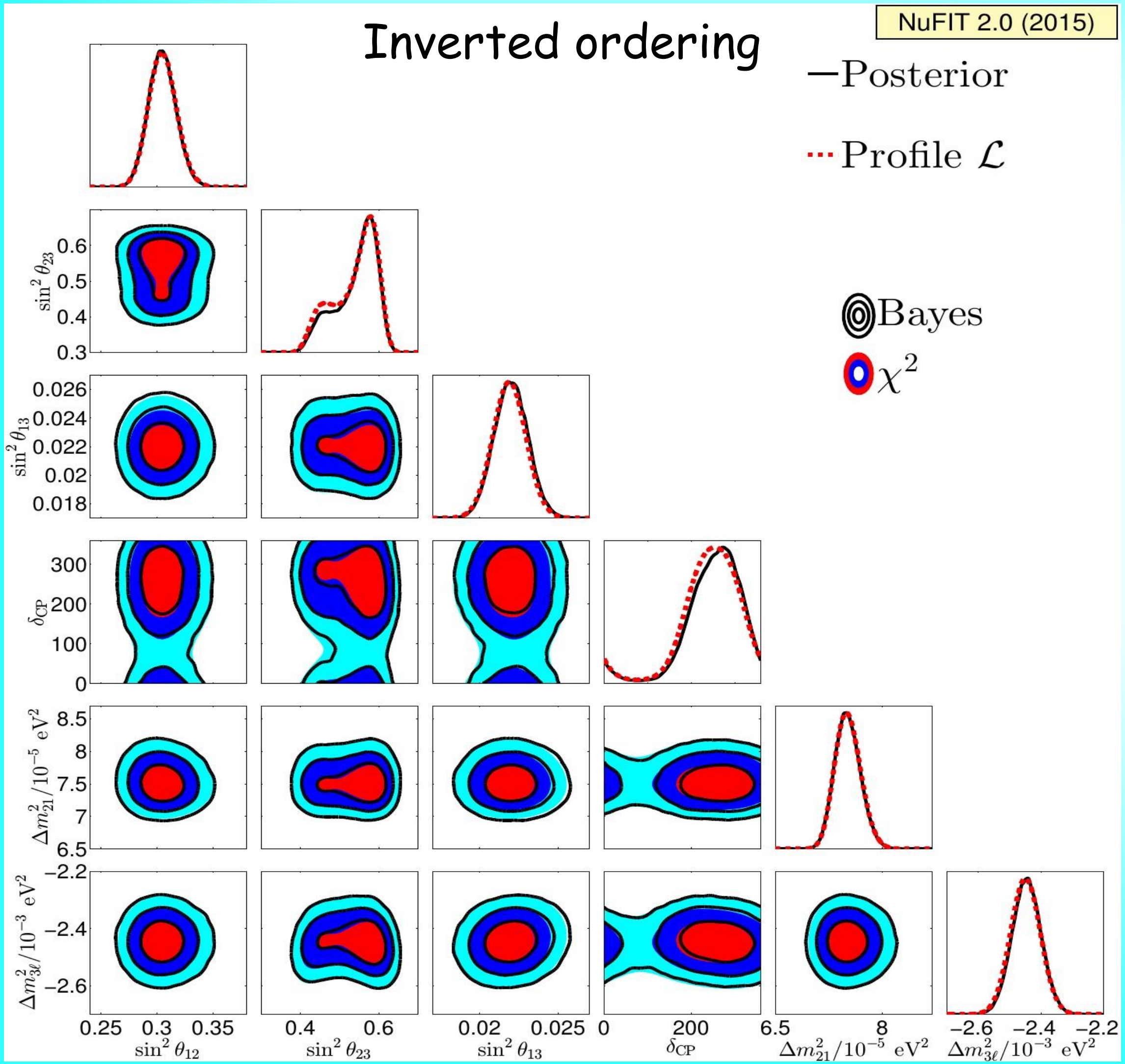


Global fit results



J. Bergstrom, et al, 1507.0436 [hep-ph]

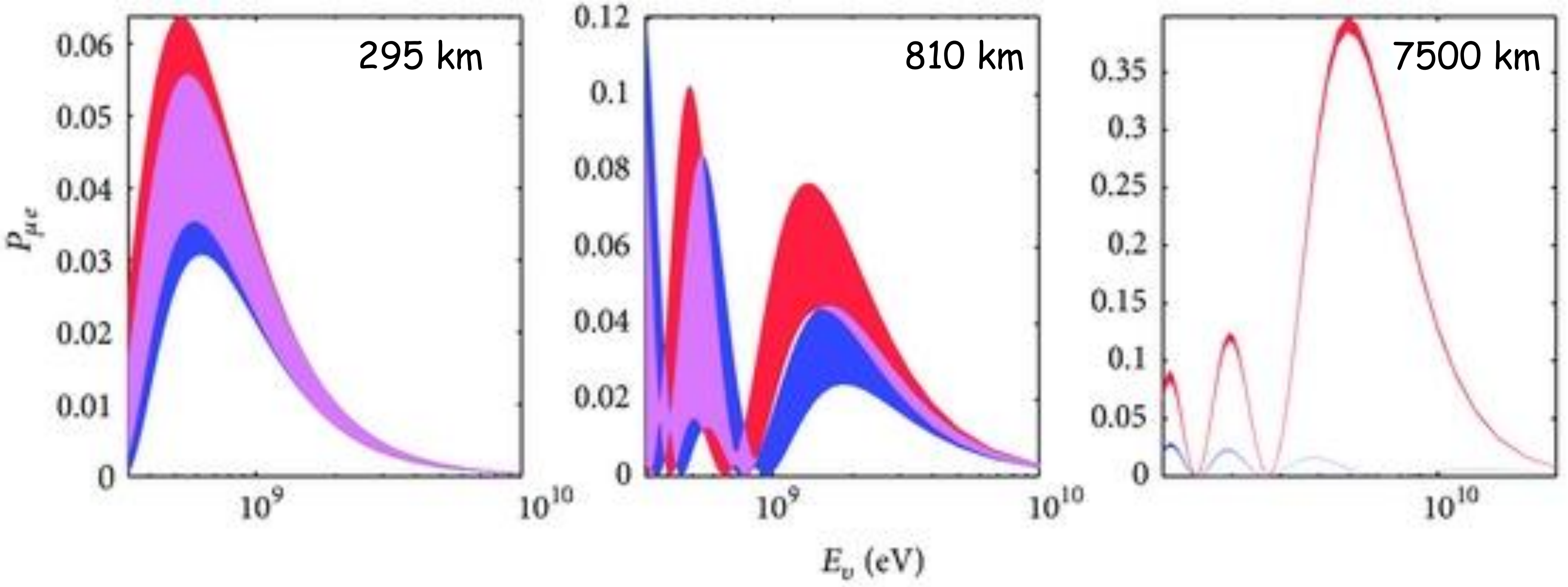
Global fit results



Hierarchy and CP

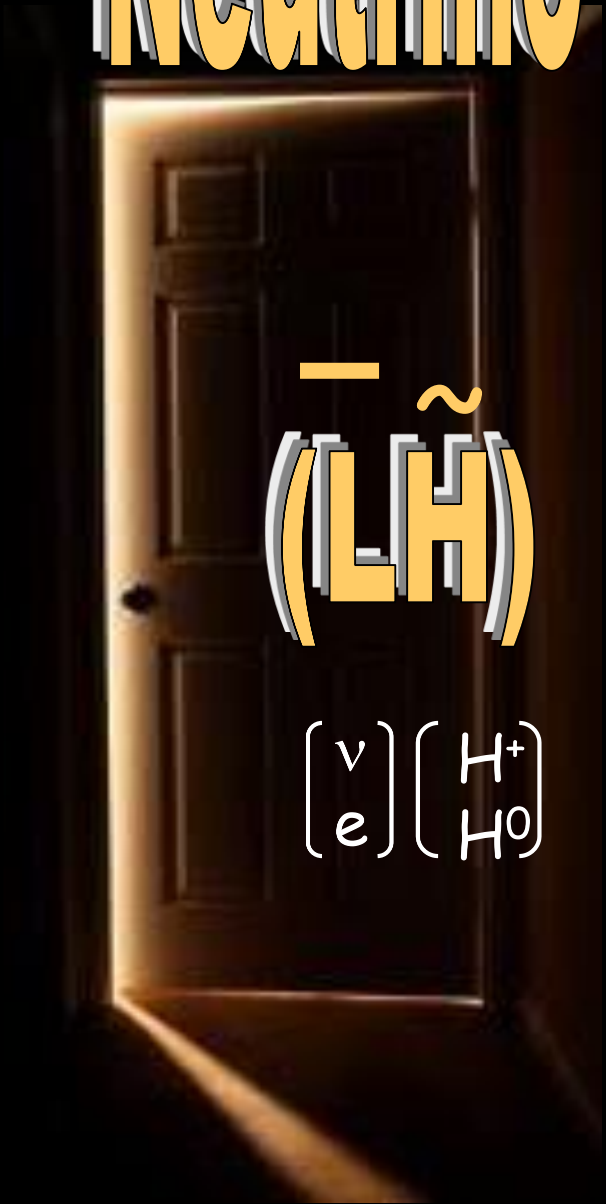
degeneracy

M. Blennow and A Y S, Advances in High Energy Physics , v. 2013 (2013), 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 delta . The probabilities for antineutrinos look similar with the hierarchies interchanged. Note the different scales of the axes.

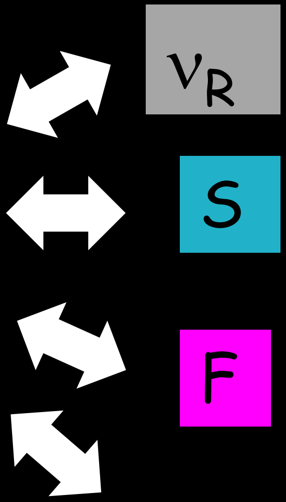
Neutrino Portal



$$(\bar{L}\tilde{H})$$

$$\begin{pmatrix}\nu\\ e\end{pmatrix}\begin{pmatrix}H^+\\ H^0\end{pmatrix}$$

Singlet of SM
symmetry group
SU(3)xSU(2) XU(1



ν_R

S

F

F is composite fermionic operator

singlet of symmetry group of hidden sector

Non-local interactions which violate fundamental symmetries eg CPT

H-asymmetry and significance

Quick estimator (metric) of discovery potential

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

For each ij- bin
Hierarchy asymmetry
H-asymmetry

$$S_{ij} = \frac{[N_{ij}^{IH} - N_{ij}^{NH}]}{\sqrt{N_{ij}^{NH}}}$$

``Distinguishability"

If NH is true hierarchy → N_{ij}^{NH} ``experimental" number of events
→ N_{ij}^{IH} ``fit" number of events

$|S_{ij}|$ statistical significance of establishing true hierarchy

Uncorrelated systematic error

$$N_{ij}^{NH} \rightarrow \sigma_{ij}^2 = N_{ij}^{NH} + (f N_{ij}^{NH})^2$$

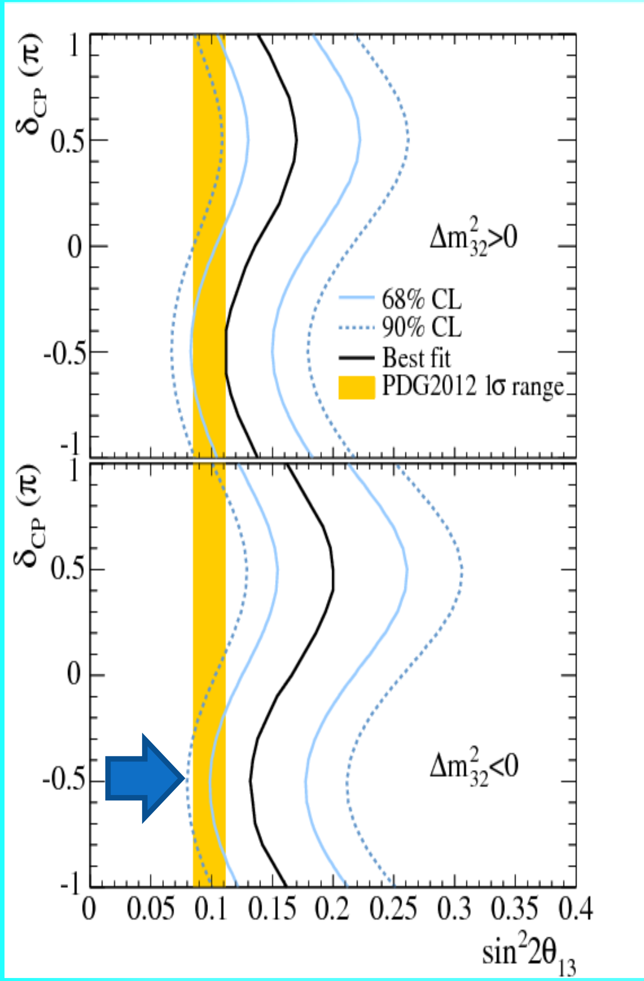
in denominator

Total distinguishability

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

Status and hint

Marginalized over 2-3 mixing



PDG (reactors)

J-PARC (beam upgrade) Super Kamiokande

p.o.t. $6\ 10^{20}$ → $7.8\ \ 10^{21}$ by 2018

i.e. 13 times higher statistics

sensitivity to the phase δ_{CP} at 90% C.L. or better over

$-115^\circ < \delta_{CP} < -60^\circ$ for NH

$+50^\circ < \delta_{CP} < +130^\circ$ for IH.

if $\theta_{23} = 45^\circ$

T2K Collaboration (K. Abe, et al.).
arXiv:1409.7469 [hep-ex]

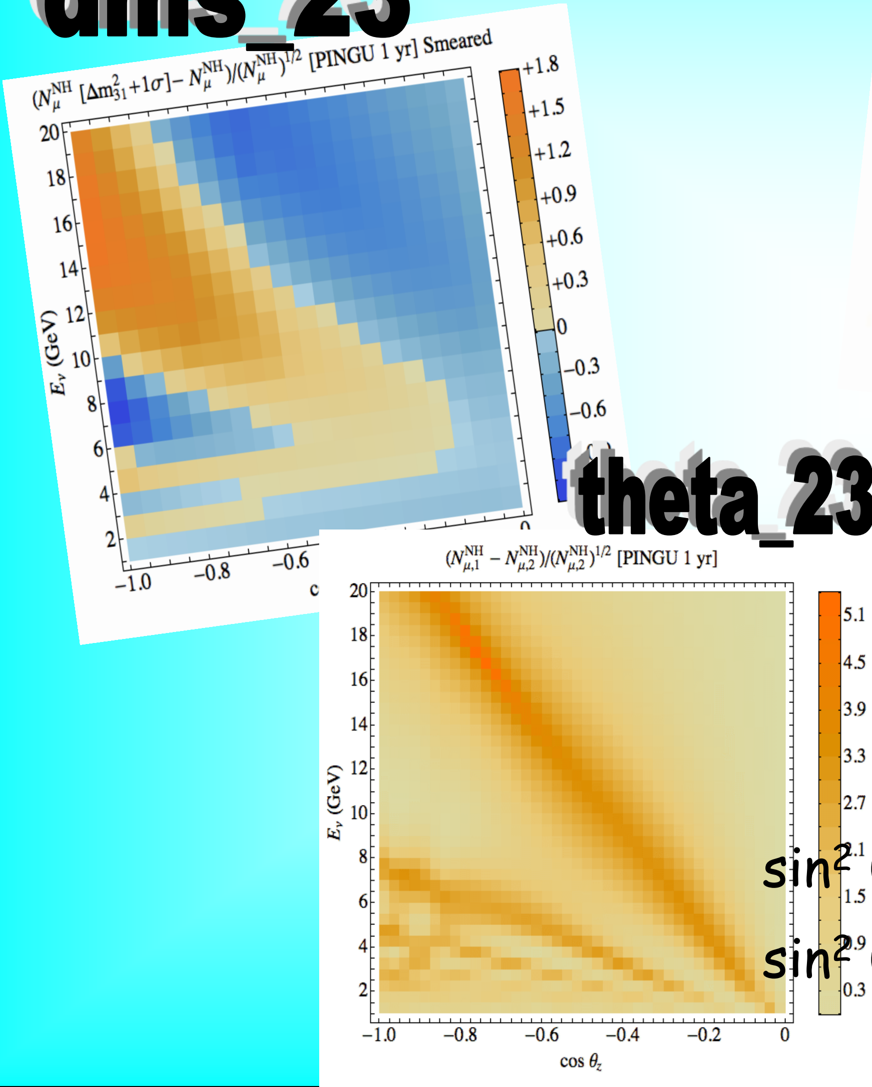
NOvA further substantial improvements

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

Other physics

dms_23

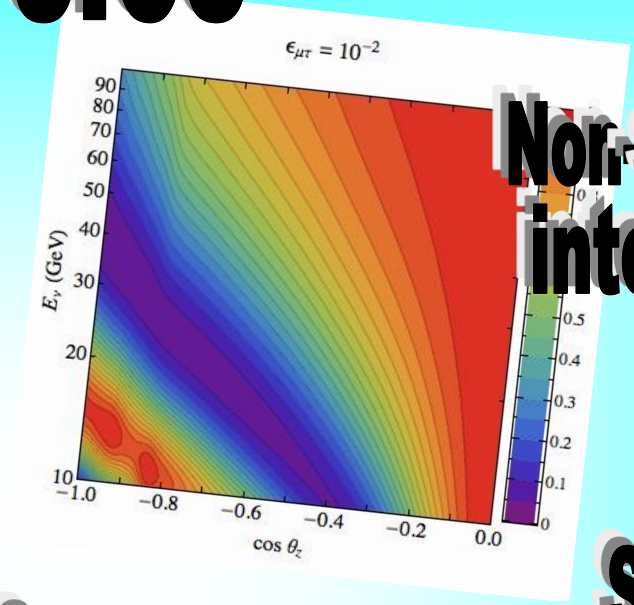
theta_23



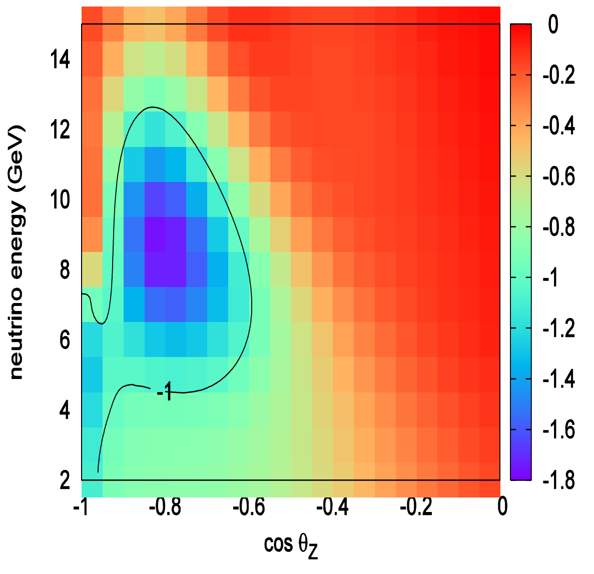
$\sin^2\theta_{32,\,\text{fit}} = 0.50$

$\sin^2\theta_{32,\,\text{true}} = 0.42$

Non-standard interactions

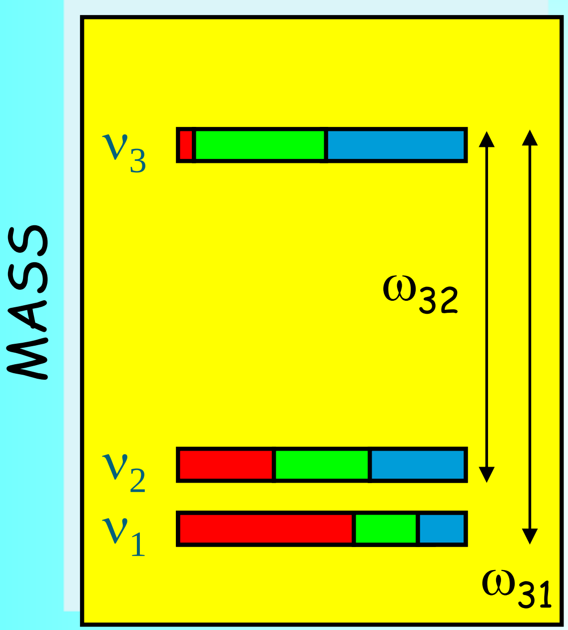


Sterile nu



Mass ordering with reactors

Normal hierarchy



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

Oscillation frequency

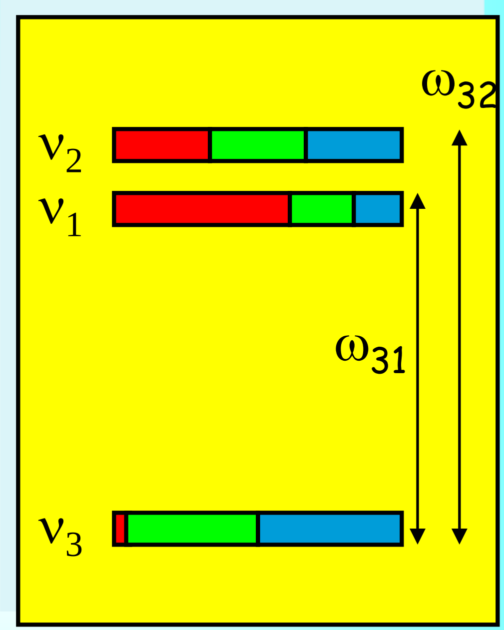
$\omega_{ij} = \Delta m^2_{ij} / 2E$

Oscillation depth:

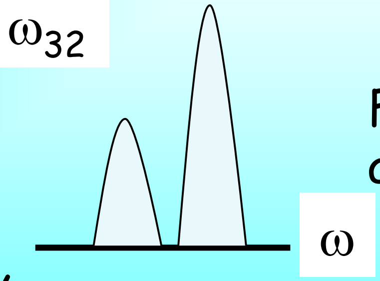
$D_{31} = 4|U_{e1}|^2|U_{e3}|^2$

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

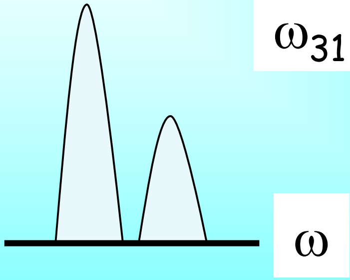
Inverted hierarchy



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



Fourier analysis



S. Petcov
M. Piai

Higher frequency - larger depth

Higher frequency – smaller depth

$D_{32} = 4|U_{e2}|^2|U_{e3}|^2$

JUNO

Also RENO-50

Jiangmen Underground Neutrino Observatory

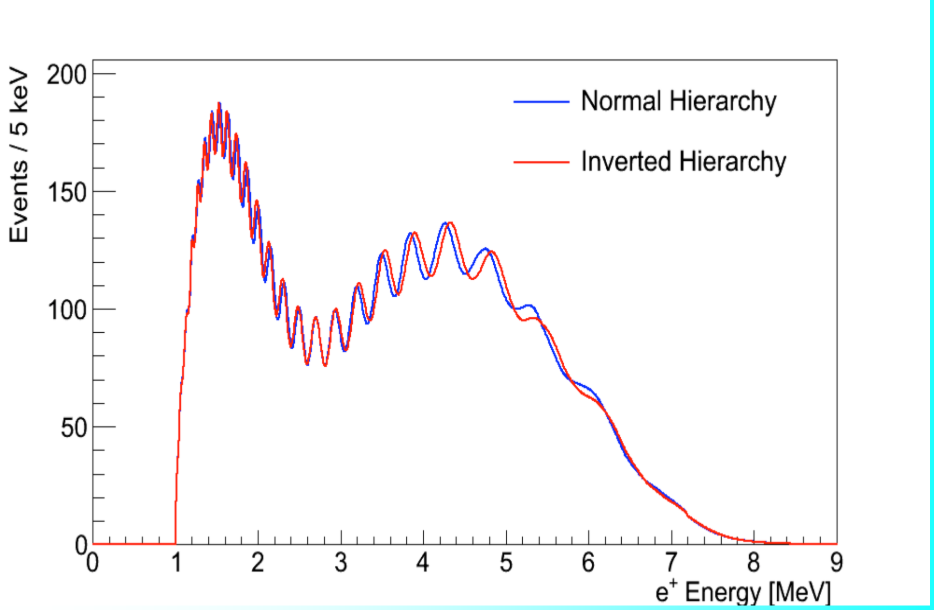
d = 700 m, L = 53 km, P = 36 GW

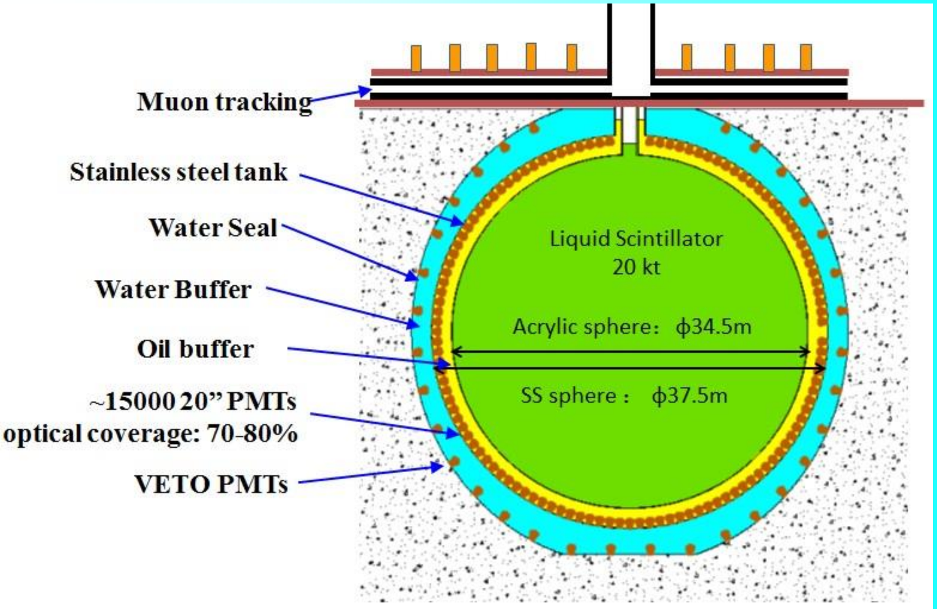
20 kt LAB scintillator

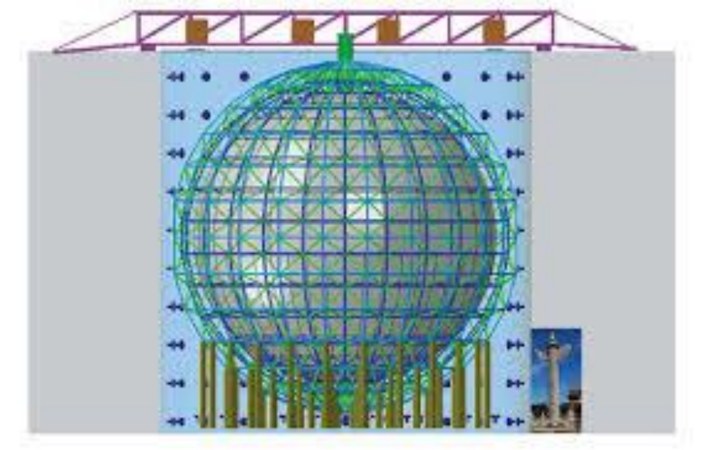
$n + p \rightarrow d + \gamma$

Key requirement:
energy resolution 3% at 1 MeV

Operation in 2020
(3 - 4)σ in 6 years

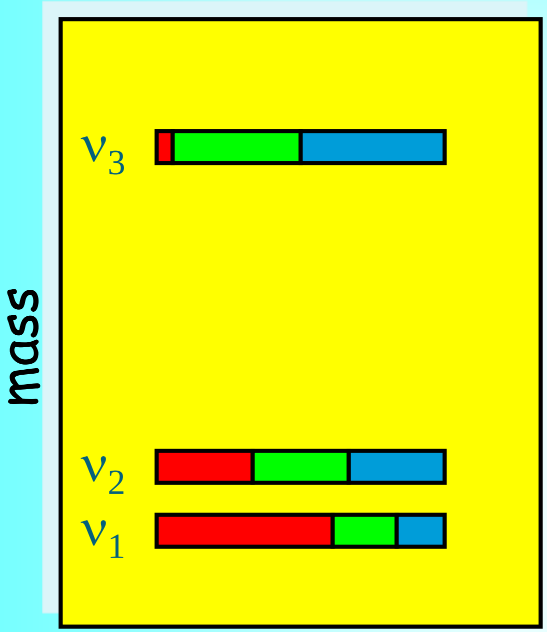






Leptons versus quarks

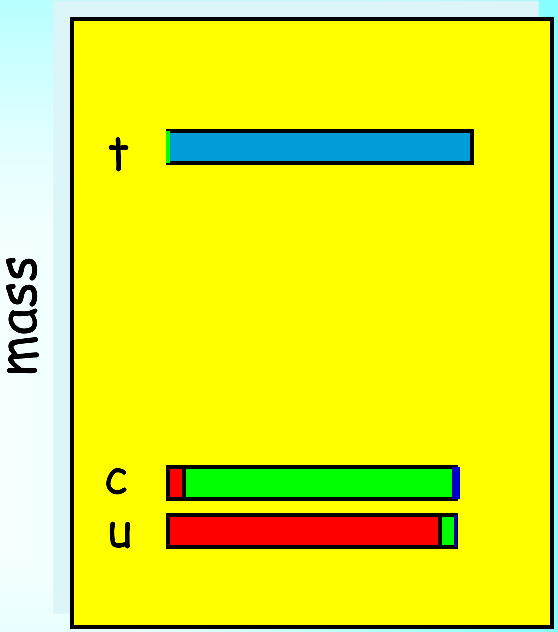
special



Leptons

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

normal



Quarks

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

$U = (u, c, t)$

combination of down-quarks
produced with a given up quark

Solar neutrinos: 1-2 normal ordering

Determined with matter effects
on the solar neutrinos

suppression at high energies
is smaller than at low energies

$$P_{ee} = \begin{cases} |U_{e2}|^2 \sim \sin^2\theta_{12} \sim 0.3 & \text{for NH} \\ |U_{e1}|^2 \sim \cos^2\theta_{12} \sim 0.7 & \text{for IH} \end{cases}$$

The problem is to determine the 1-3 or 2-3 ordering

Solar neutrinos are not sensitive to 1-3 ordering
due to very small matter effect on 1-3 mixing:

$$\sin\theta^m_{13} = \sin\theta_{13}\left(1 +/- \frac{2EV\cos 2\theta_{13}}{\Delta m^2_{31}}\right)$$

NH / IH

few 10^{-2}

Suppression of effects

Original fluxes

different flavors: ν_e and ν_μ

Screening factors $(1 - r\, s_{23}^2)$

neutrinos and antineutrinos

$(1 - \kappa_e)$

$(1 - \kappa_\mu)$

Reduces CP-asymmetry

Integration averaging

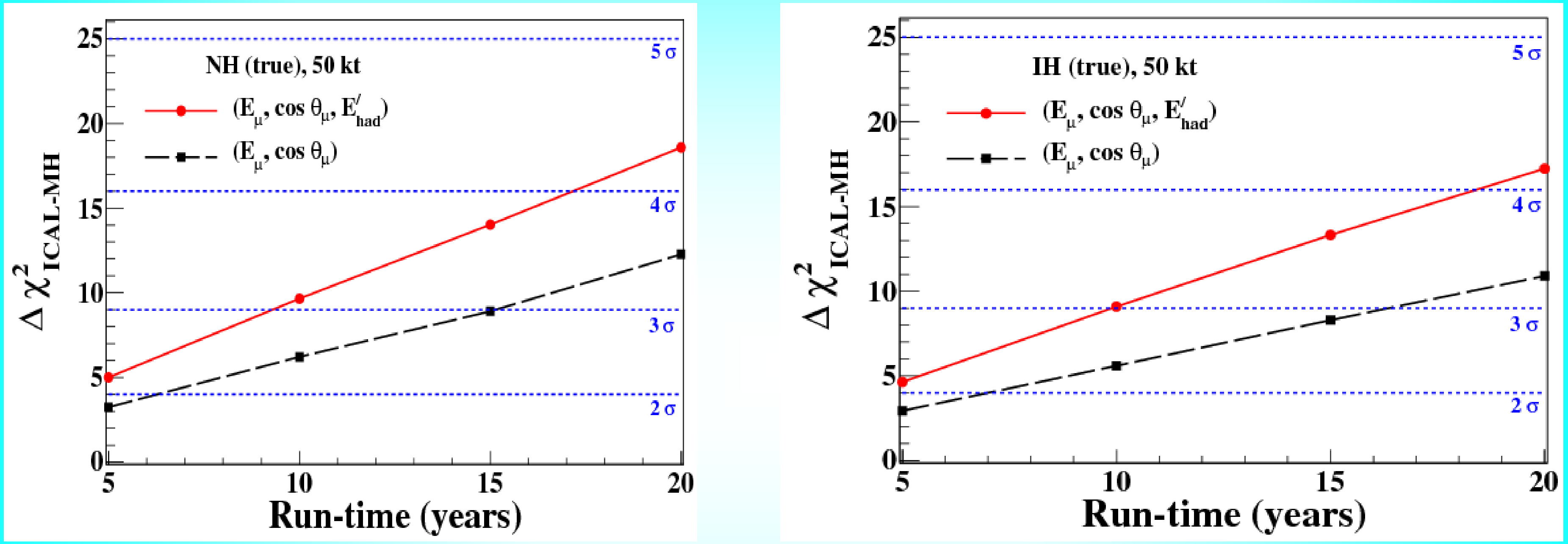
averaging and smoothing effects
reconstruction of neutrino energy
and direction

Detection

identification of flavor

INO-ICAL

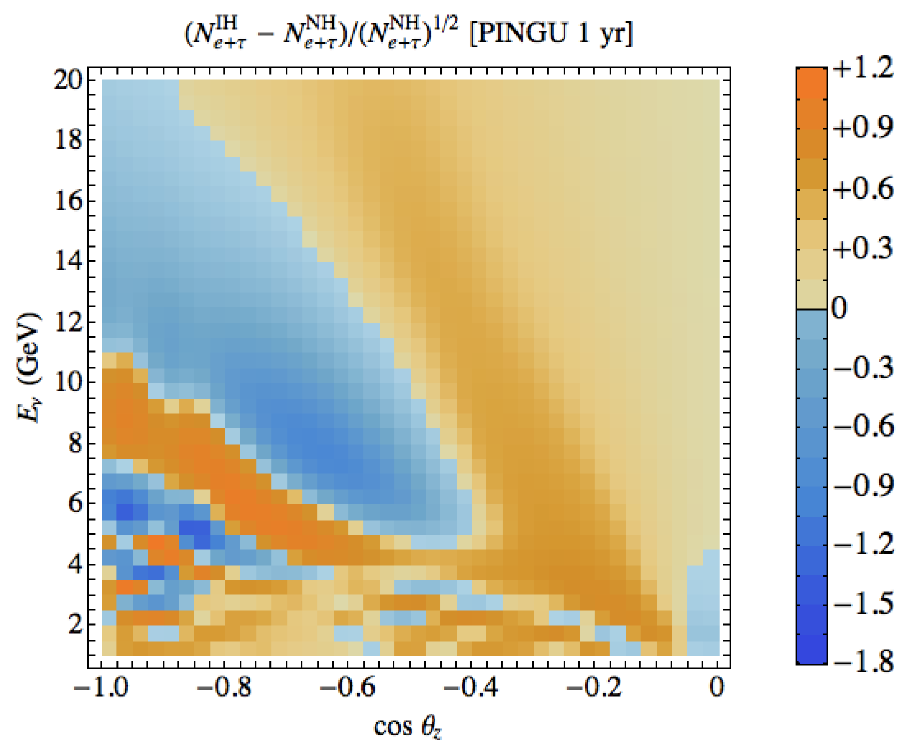
ICAL Collaboration (Ahmed Shakeel et al.)
arXiv:1505.07380 [physics.ins-det]



The hierarchy sensitivity of ICAL with input normal hierarchy including correlated hadron energy information, with |Δ*m*2eff|, sin2*θ*23 and sin22*θ*13 marginalised over their 3*σ* ranges . Improvement with the inclusion of hadron energy is significant.\chisqmh as a function of the exposure assuming NH (left panel) and IH (right panel) as true hierarchy.

Cascade events e + nutau

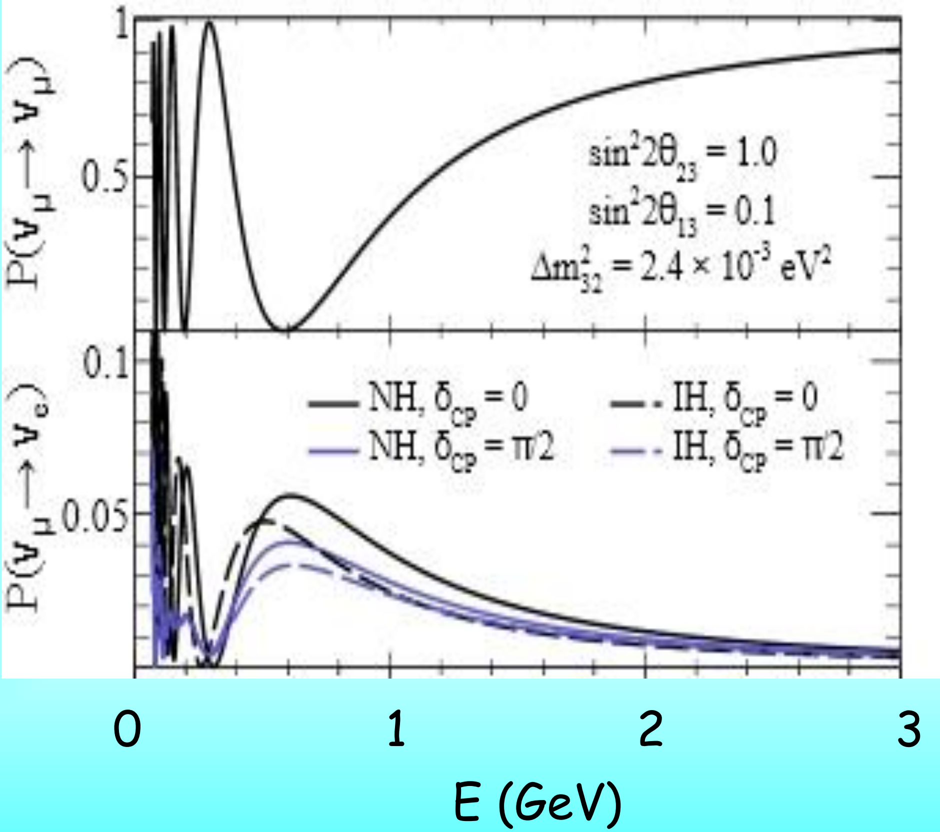
S. Razzque and A.Y.S.,



T2K

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

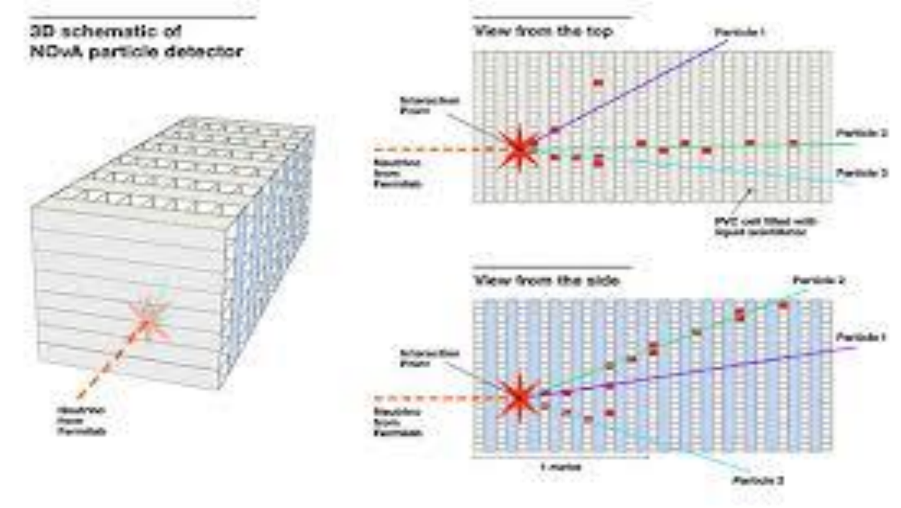
Oscillation probabilities

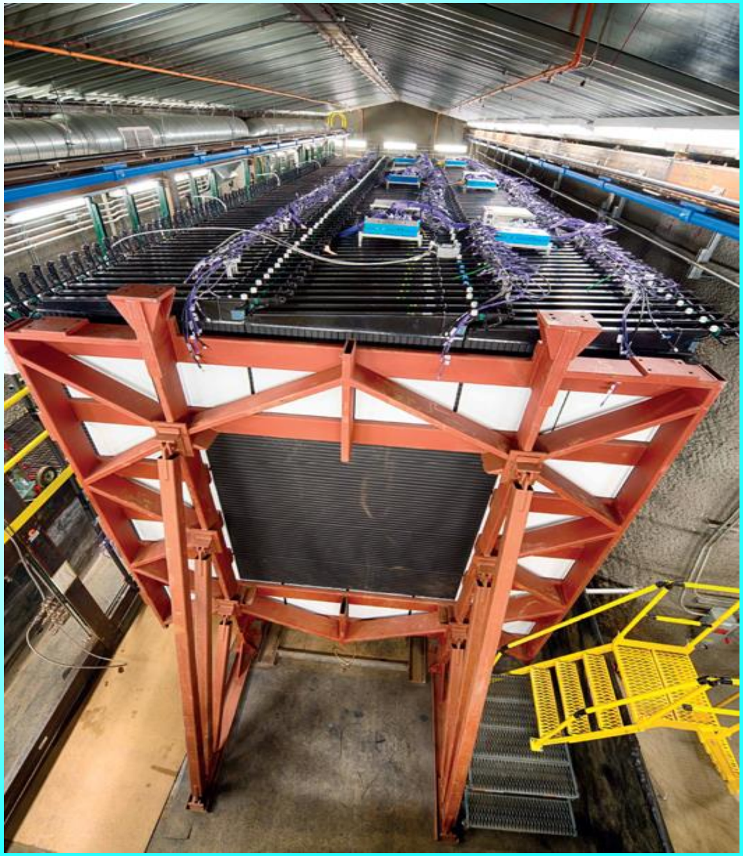


NOVA

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

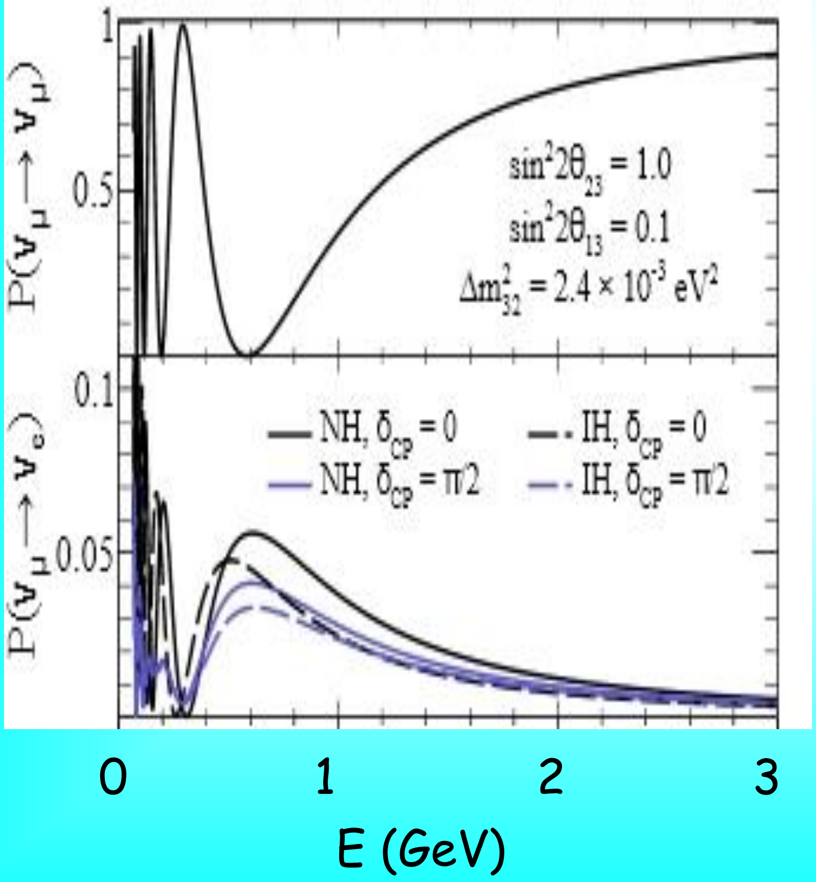
$\nu_\mu - \nu_e$ oscillations in matter

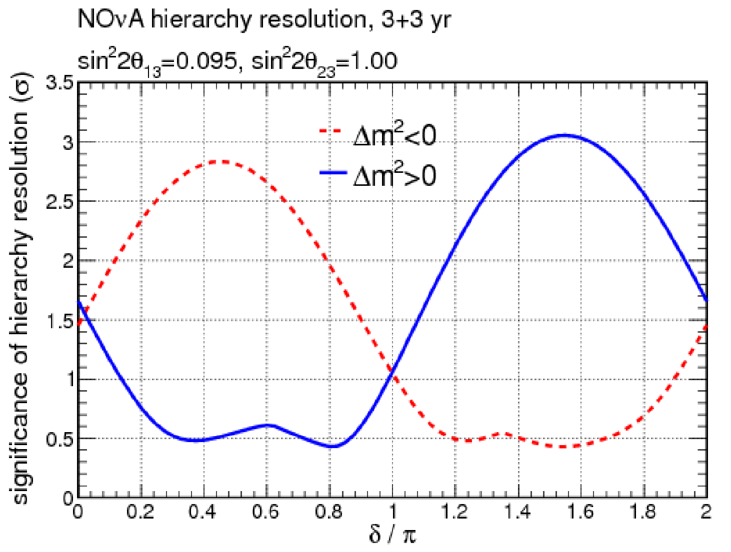


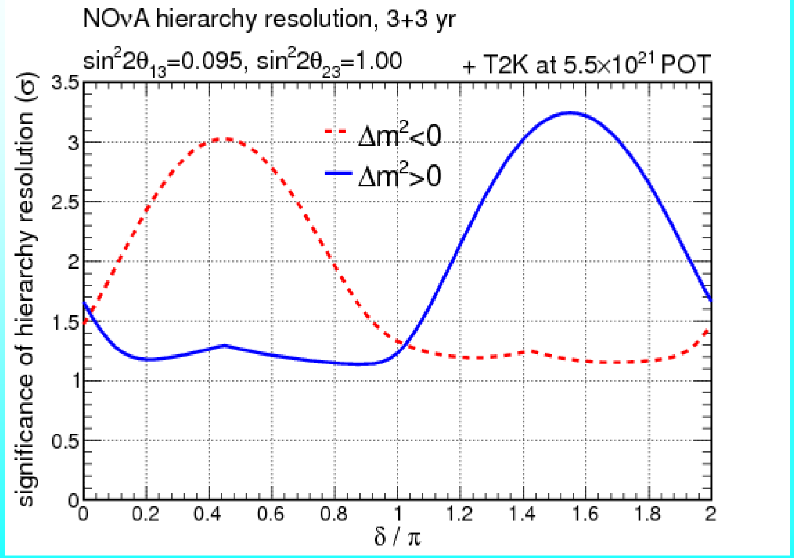


NOvA and T2K sensitivity

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

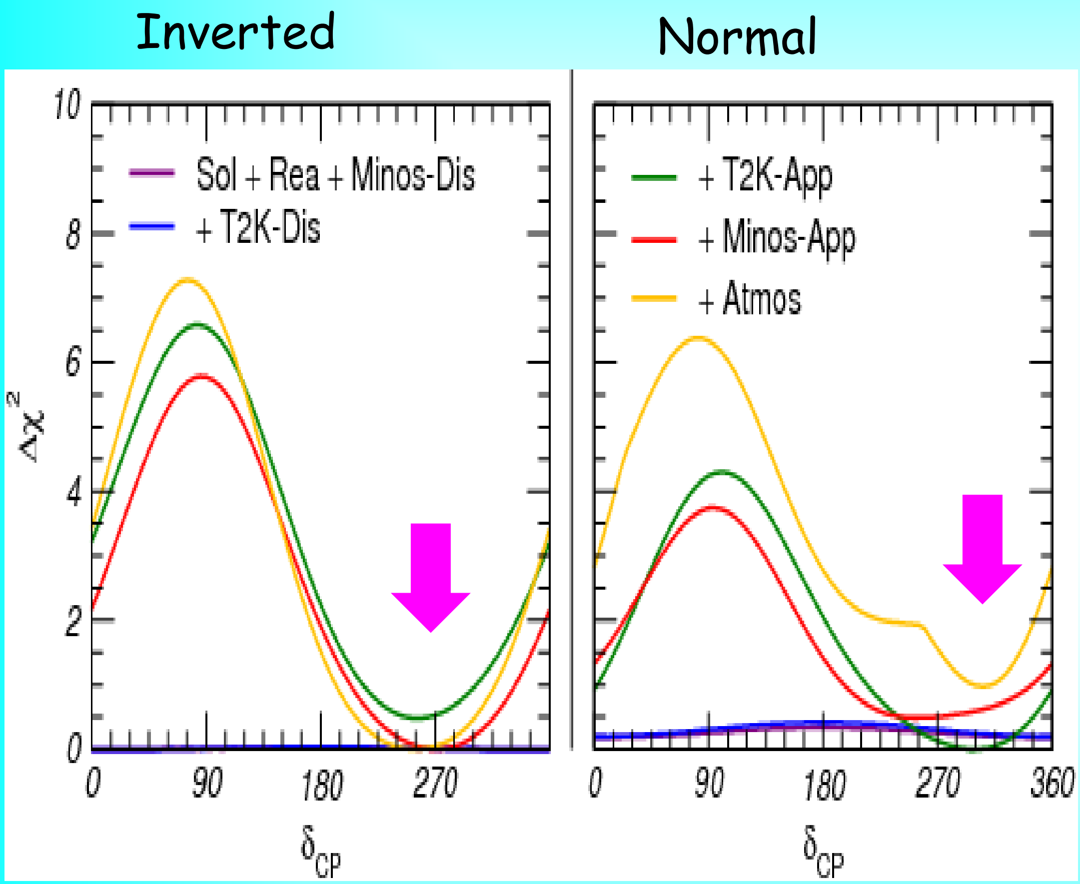






CP-phase from global fit

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



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

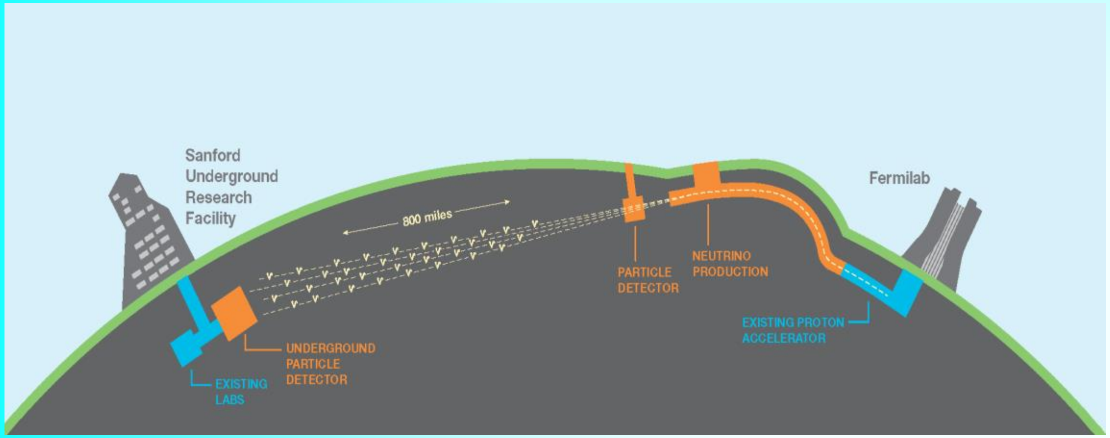
+ MINOS-App

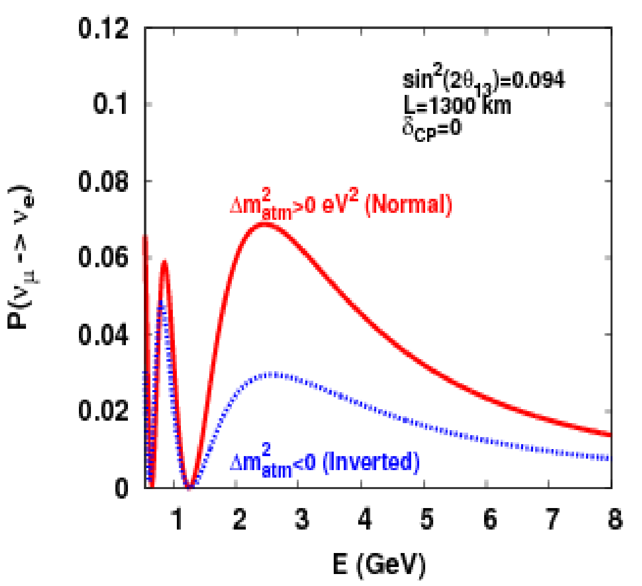
+ Atmospheric

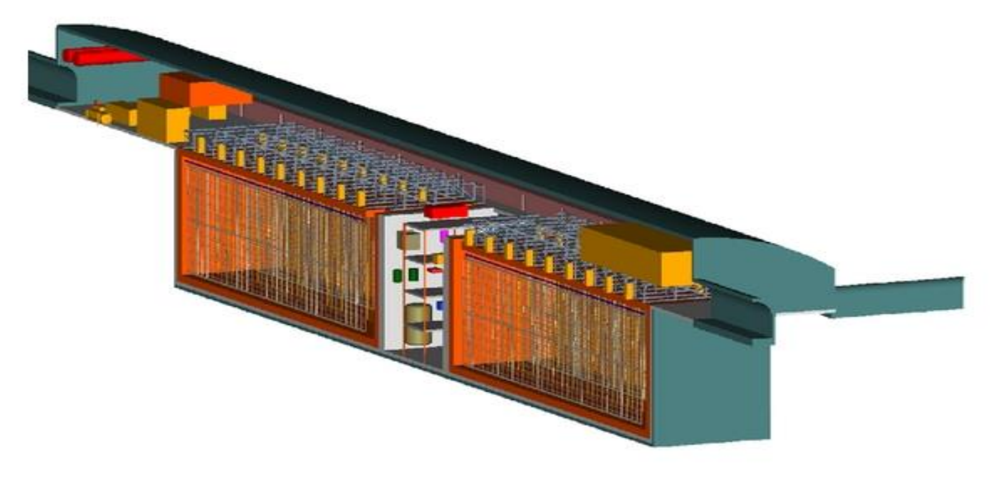
Atm nu contribution: excess of sub GeV nue events

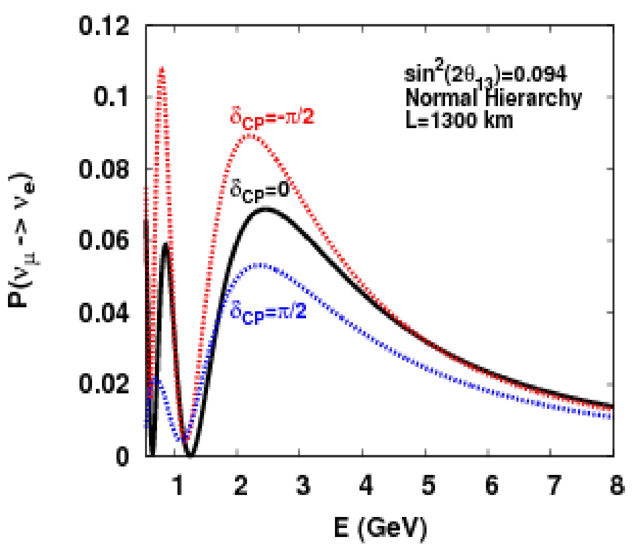
LBNF-DUNE

L = 1300km, LAr TPC 35 kt



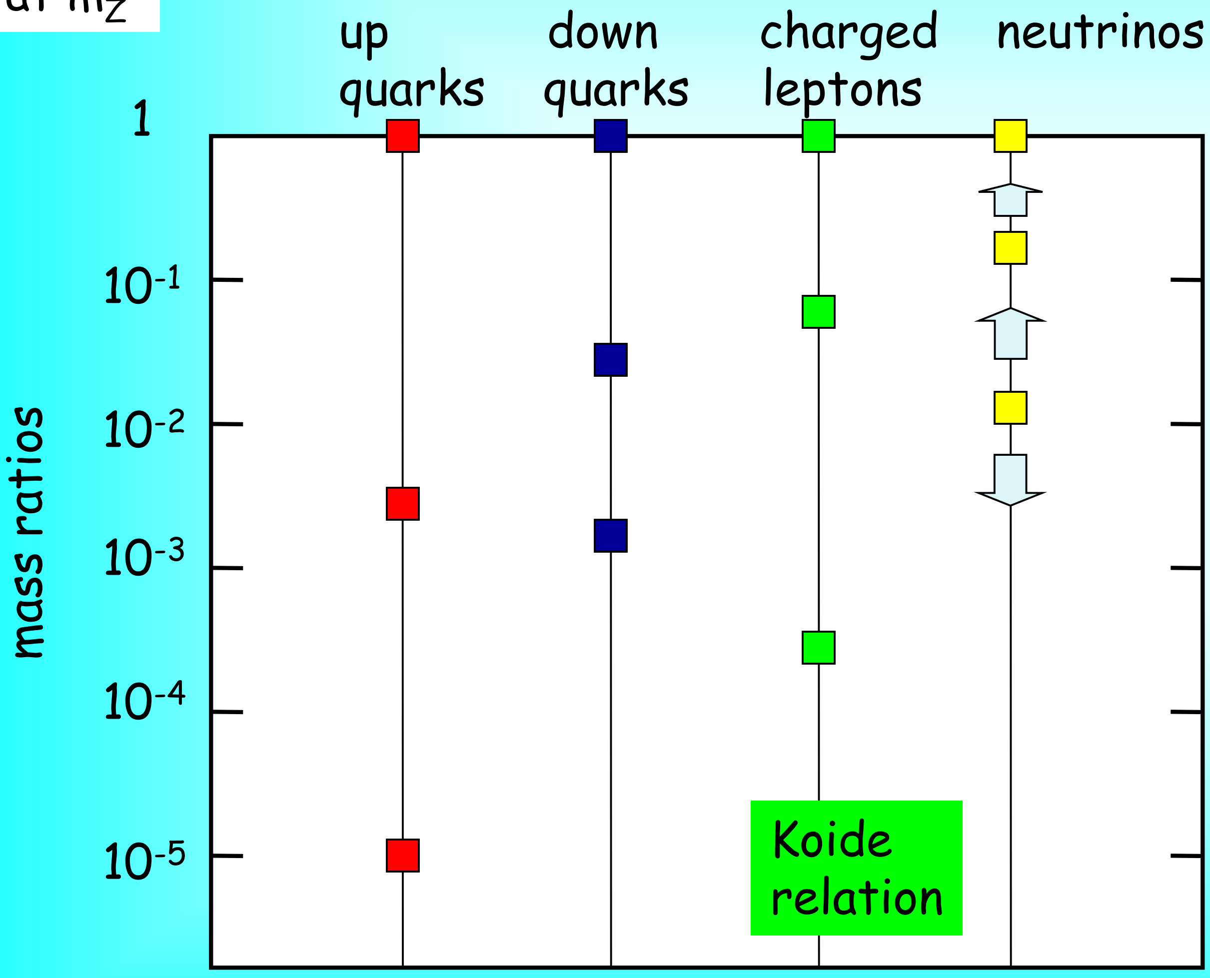






Mass hierarchies

at m_Z



Koide relation

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

~ 0.18

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

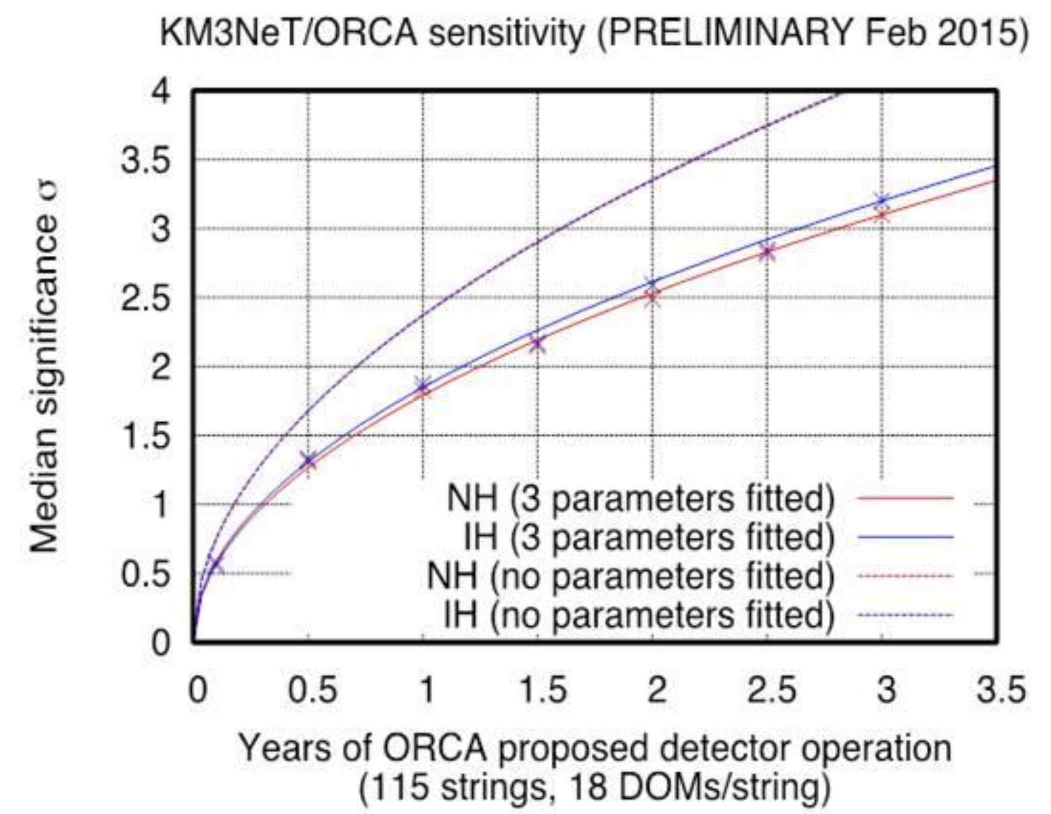
Related to large lepton mixing?

$m_u\, m_t \;=\; m_c^2$

$\sin\theta_C \sim \sqrt{m_d/m_s}$

Gatto-Sartori-Tonin relation

Sensitivity to MH



CP-violation and CP-phase

Dirac CP-phase in the standard parametrization of the PMNS matrix

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

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

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

CP- transformations:

$\nu \rightarrow \nu^c$

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

upto Majorana phase

Under CP-transformations:

Matter potential

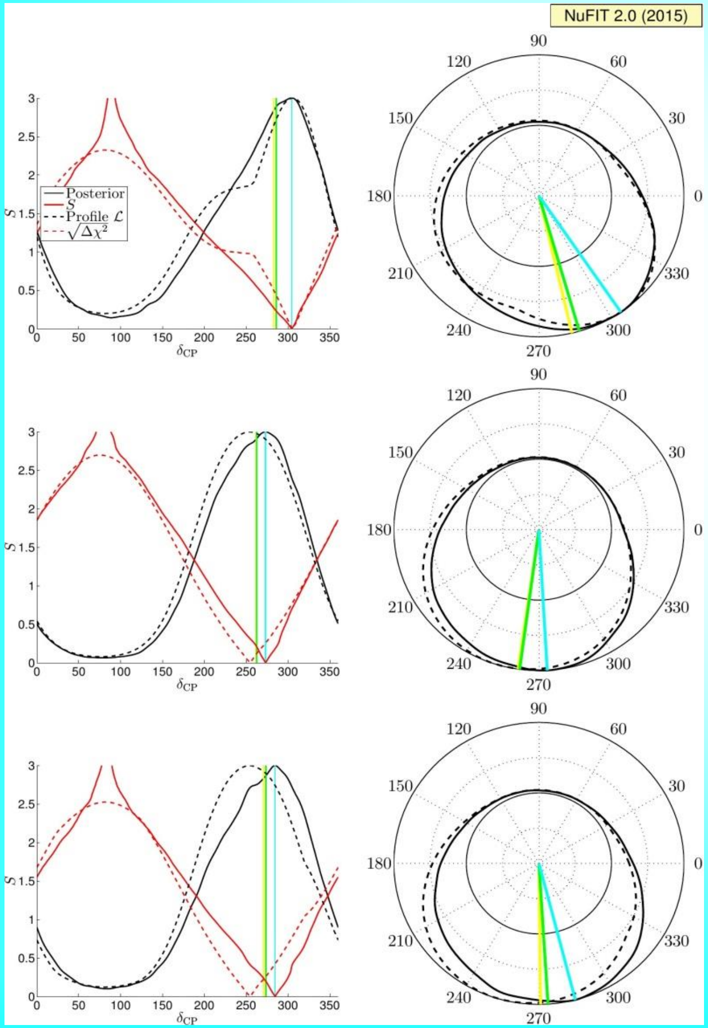
$U_{PMNS} \rightarrow U_{PMNS}^*$ $\Rightarrow$ $\delta \rightarrow -\delta$

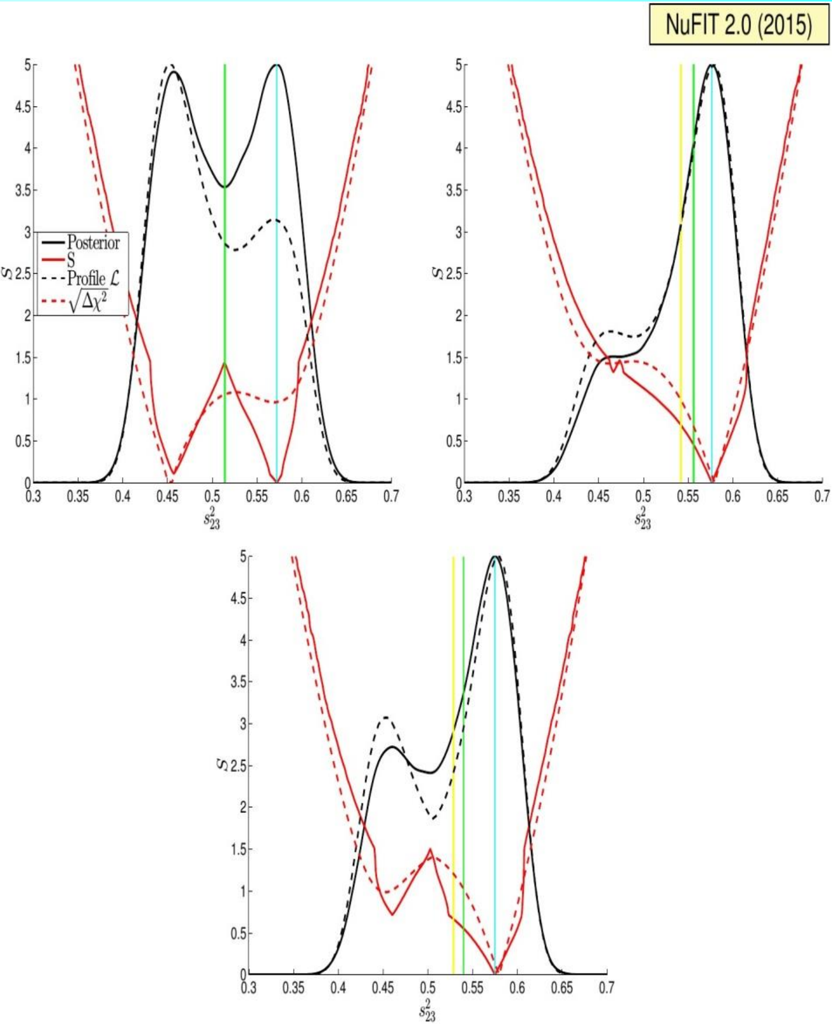
$V \rightarrow -V$

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

Degeneracy of effects:
Matter can imitate CP-violation

Global Fit

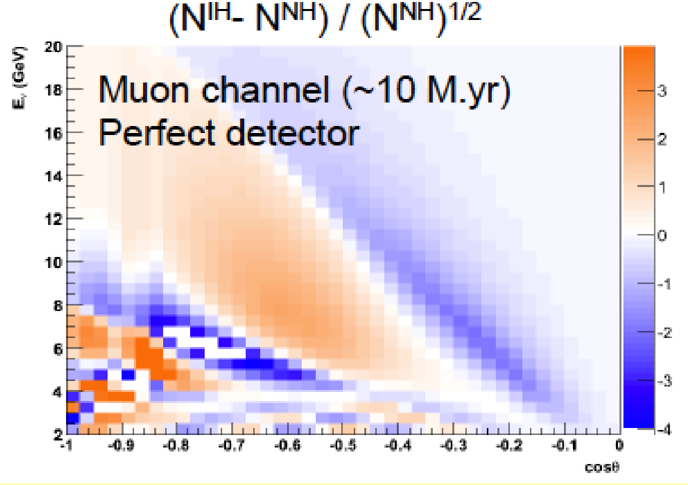

NuFIT 2.0 (2015)
Posterior
S
Profile $\mathcal{L}$
$\sqrt{\Delta\chi^2}$
S
δ_{CP}
0
50
100
150
200
250
300
350
0
0.5
1
1.5
2
2.5
3
90
60
30
0
330
300
270
240
210
180
150
120


NuFIT 2.0 (2015)
Posterior
S
Profile $\mathcal{L}$
$\sqrt{\Delta\chi^2}$
S
s^2_{23}
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.65
0.7
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

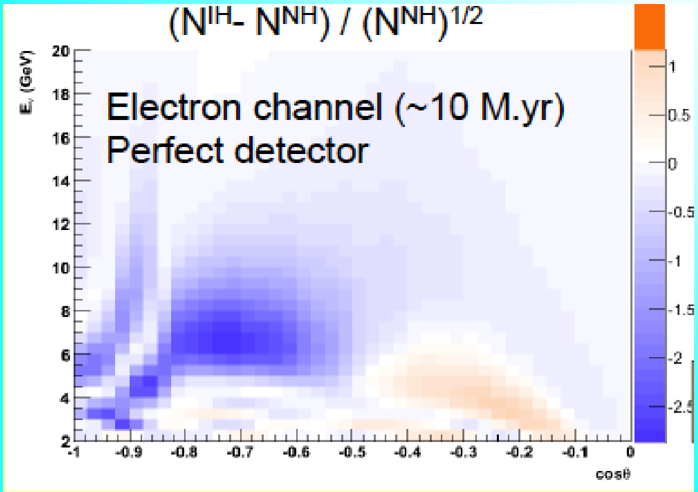
Smeared distributions

J. Brunner [532]

Muon- and electron-channels contribute to net hierarchy asymmetry.
Electron channel more robust against detector resolution effects:

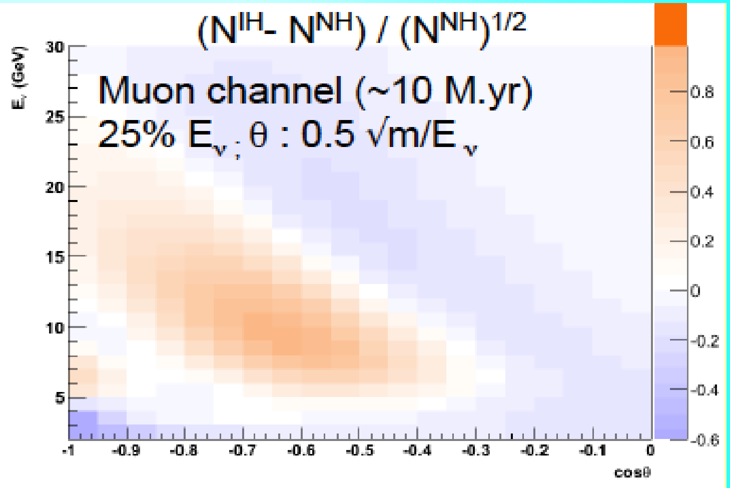

$(N^{IH} - N^{NH}) / (N^{NH})^{1/2}$

Muon channel (~10 M.yr)
Perfect detector

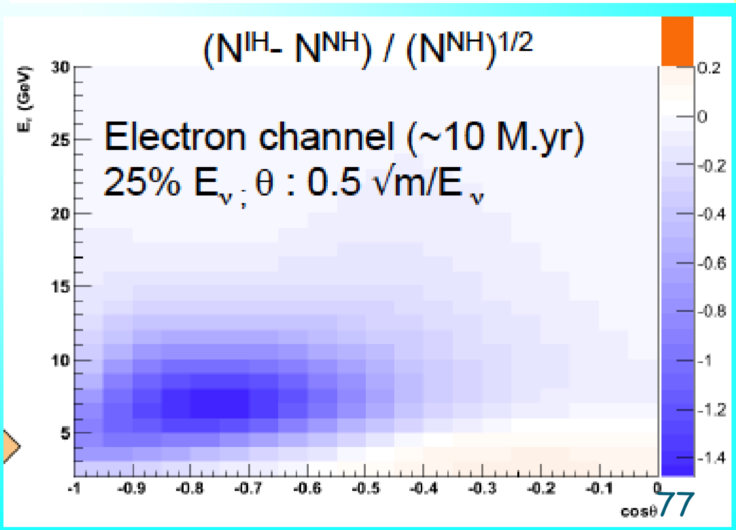

$(N^{IH} - N^{NH}) / (N^{NH})^{1/2}$

Electron channel (~10 M.yr)
Perfect detector

E, θ smearing
(kinematics
+ detector
resolution)


$(N^{IH} - N^{NH}) / (N^{NH})^{1/2}$

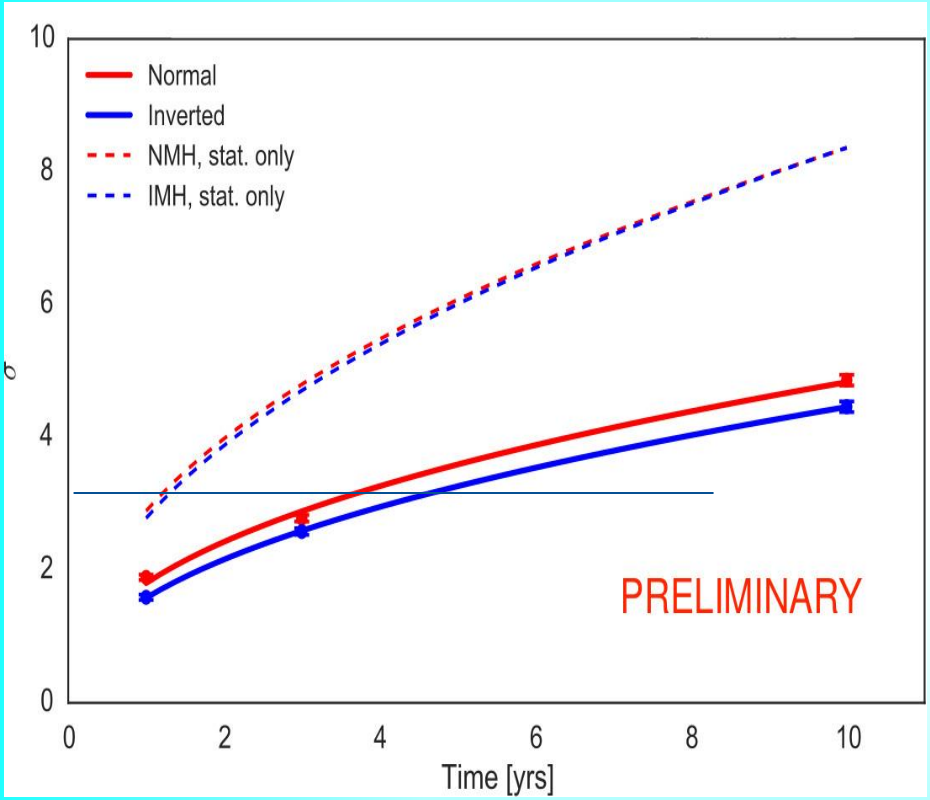
Muon channel (~10 M.yr)
25% E_ν ; θ : 0.5 $\sqrt{m/E_\nu}$

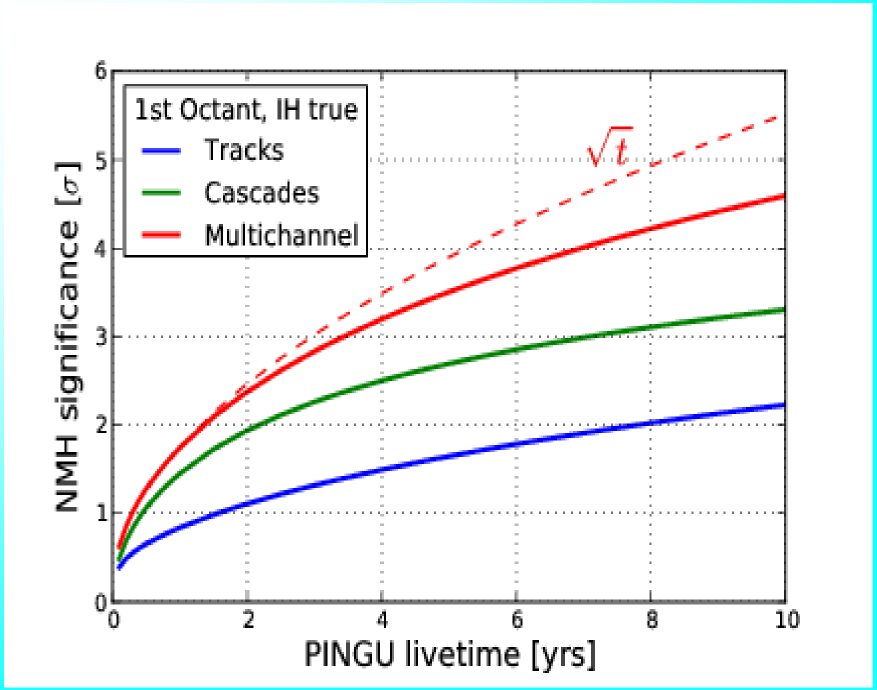

$(N^{IH} - N^{NH}) / (N^{NH})^{1/2}$

Electron channel (~10 M.yr)
25% E_ν ; θ : 0.5 $\sqrt{m/E_\nu}$

Sensitivity

K. Clark



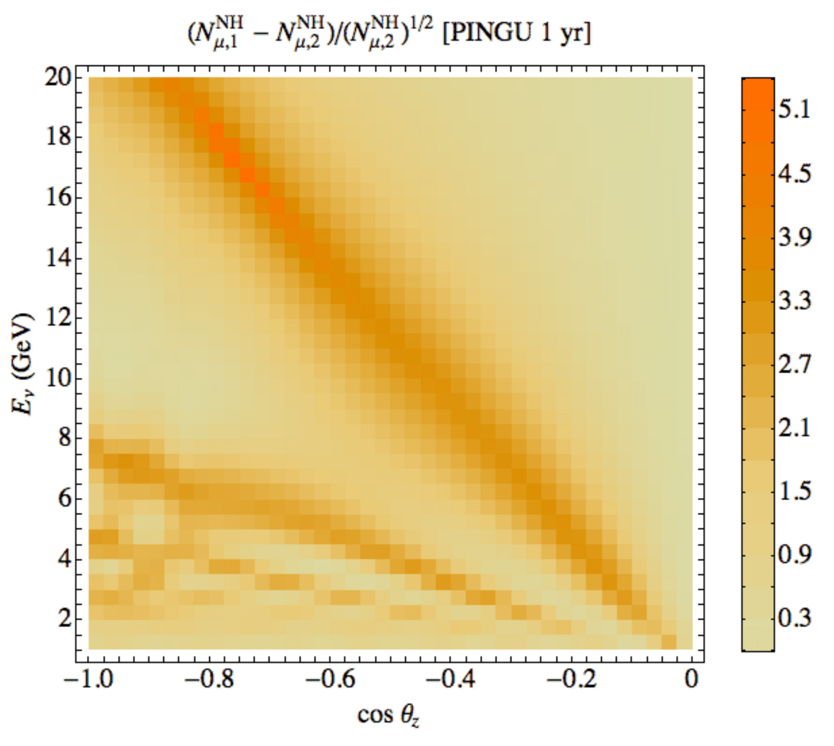


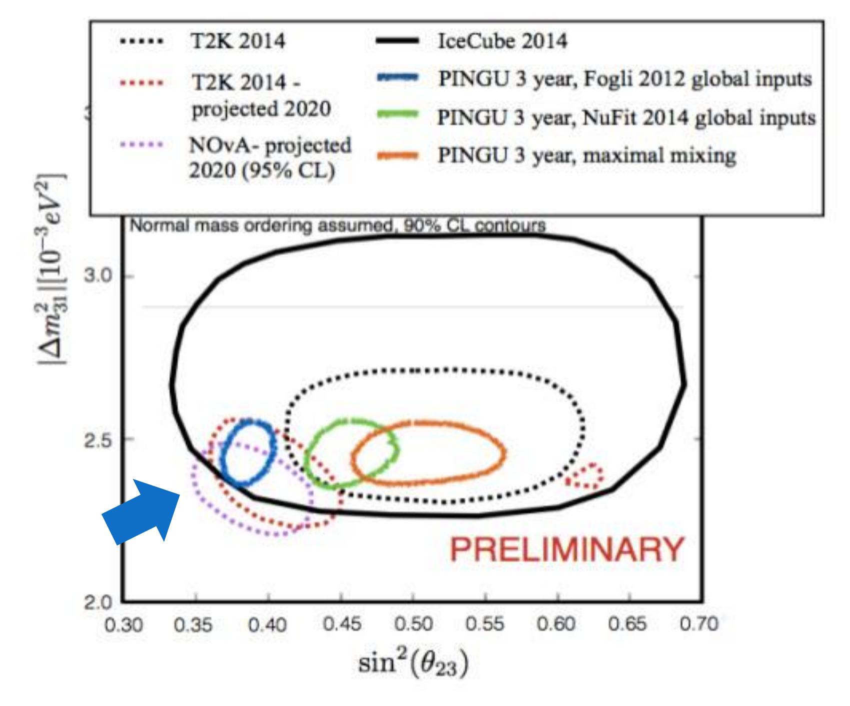
Sensitivity to 2-3 mixing

Deviation from maximal symmetry or no symmetry *K. Clark, [1379]*

Quadrant

Sensitivity to MH depends on



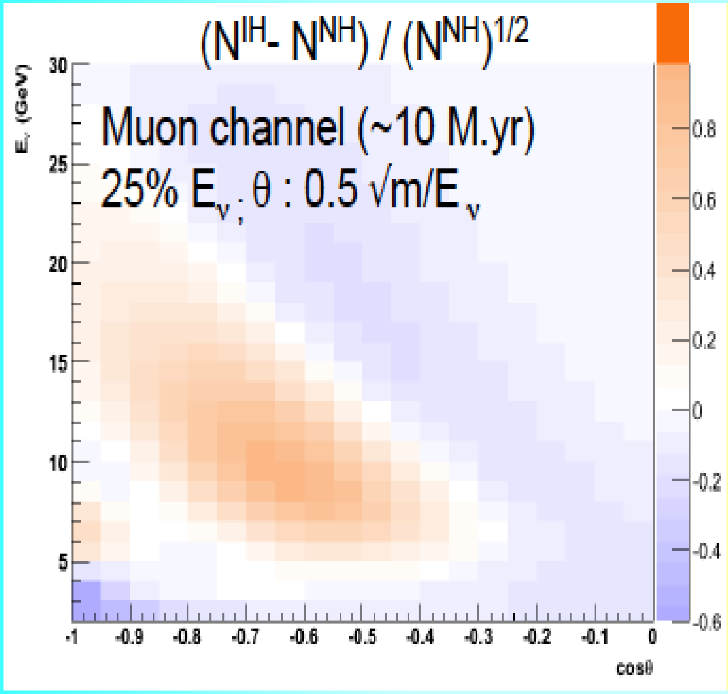


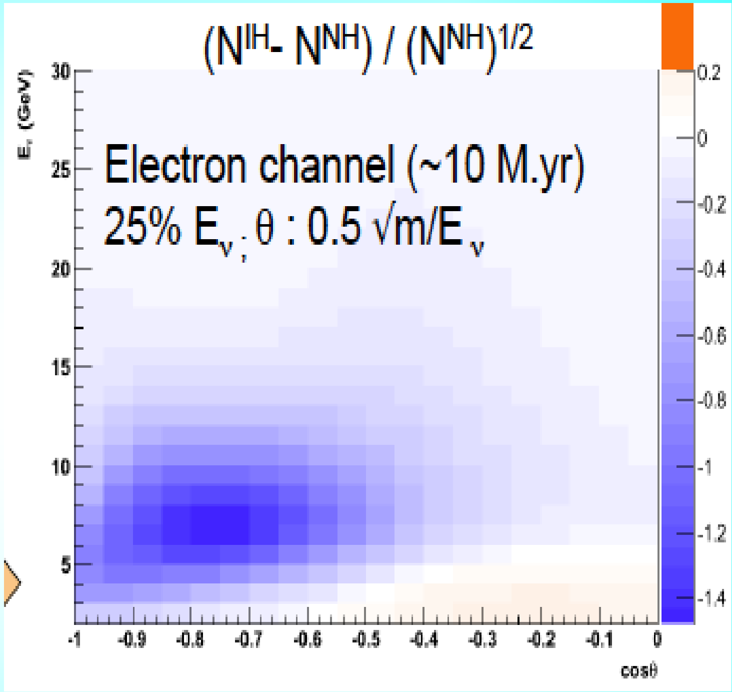
$\sin^2 \theta_{32,\text{ fit}}$ = 0.50

$\sin^2 \theta_{32,\text{ true}}$ = 0.42

Smeared distributions

J. Brunner





Muon- and electron-channels contribute to net hierarchy asymmetry.
Electron channel more robust against detector resolution effects:

Symmetries of Hidden sector