Neutrinos

selected topics

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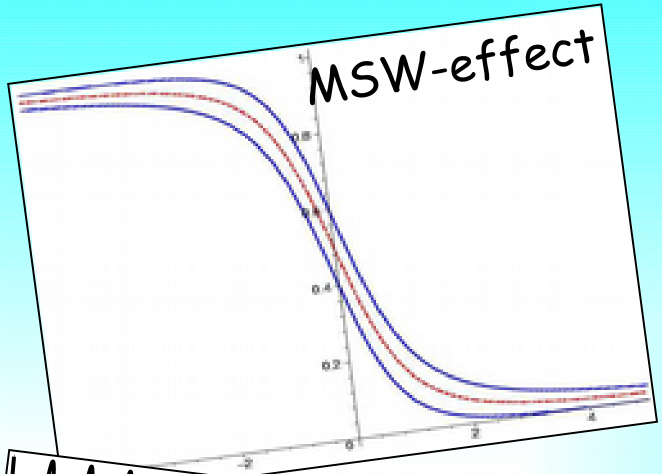
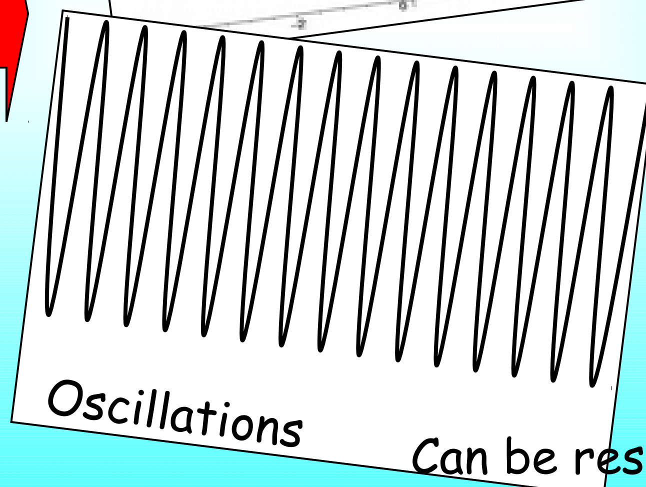
Determination of mass and mix

- MINOS ★
- T2K ★
- NOvA ★★
- Solar neutrinos ★
- KamLAND
- Double Chooz ★
- Daya Bay ★
- RENO ★
- NEOS ★★
- Atmospheric neutrinos
- SK ★
- DeepCore ★





Can be resonantly enhanced in matter

Δm^2

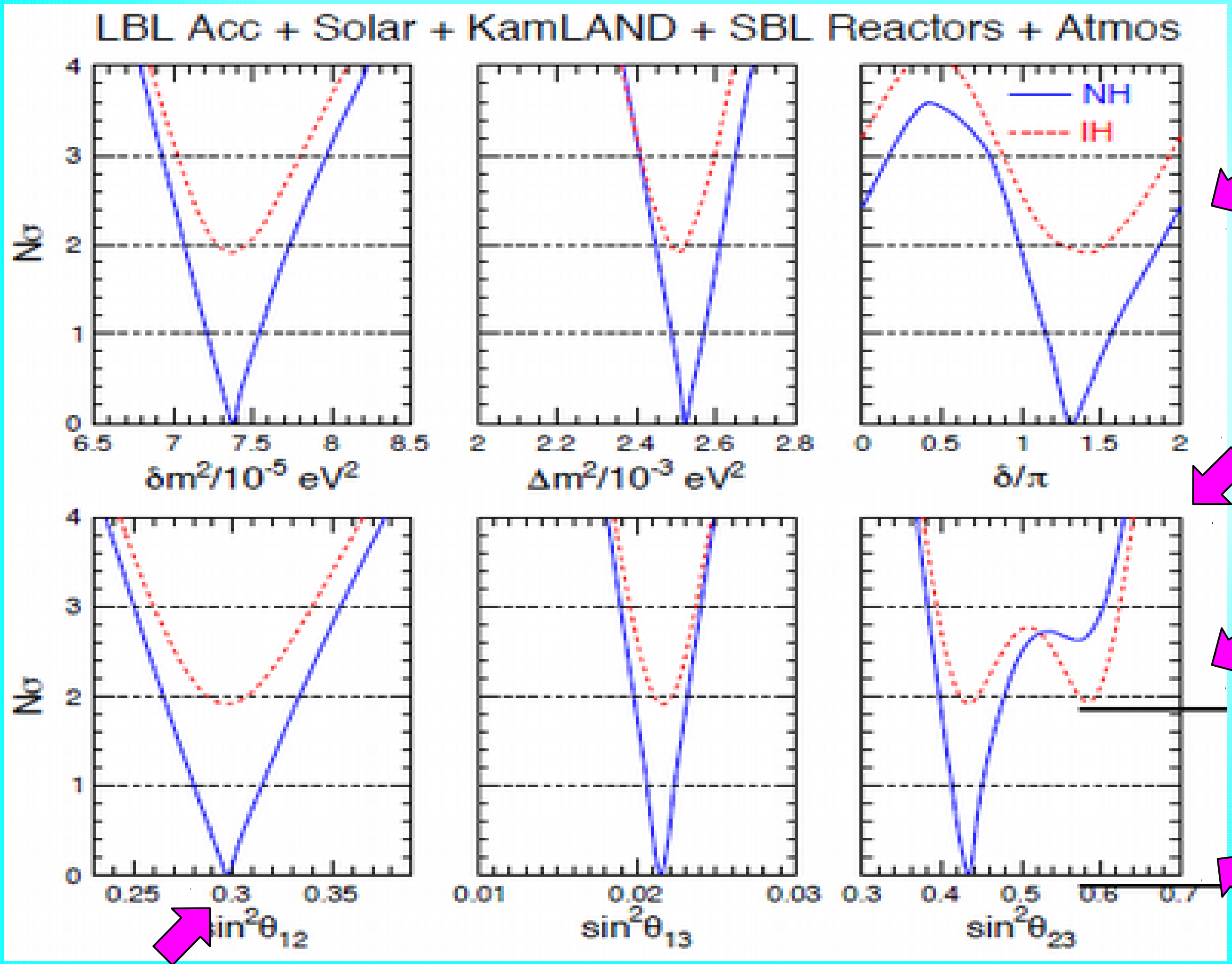
θ

★ New, recent results

Global 3ν– fit

F. Capozzi et al, NOW 2016

With respect to absolute minimum in NH case



CP violation at 2.4 σ consistent with maximal

Maximal 2-3 mixing is disfavoured at 2.8σ

Second octant is disfavoured at 2σ

$\Delta\chi^2 = 3.7$

between NH and IH

IH disfavored at about 2σ

smaller than 0.30

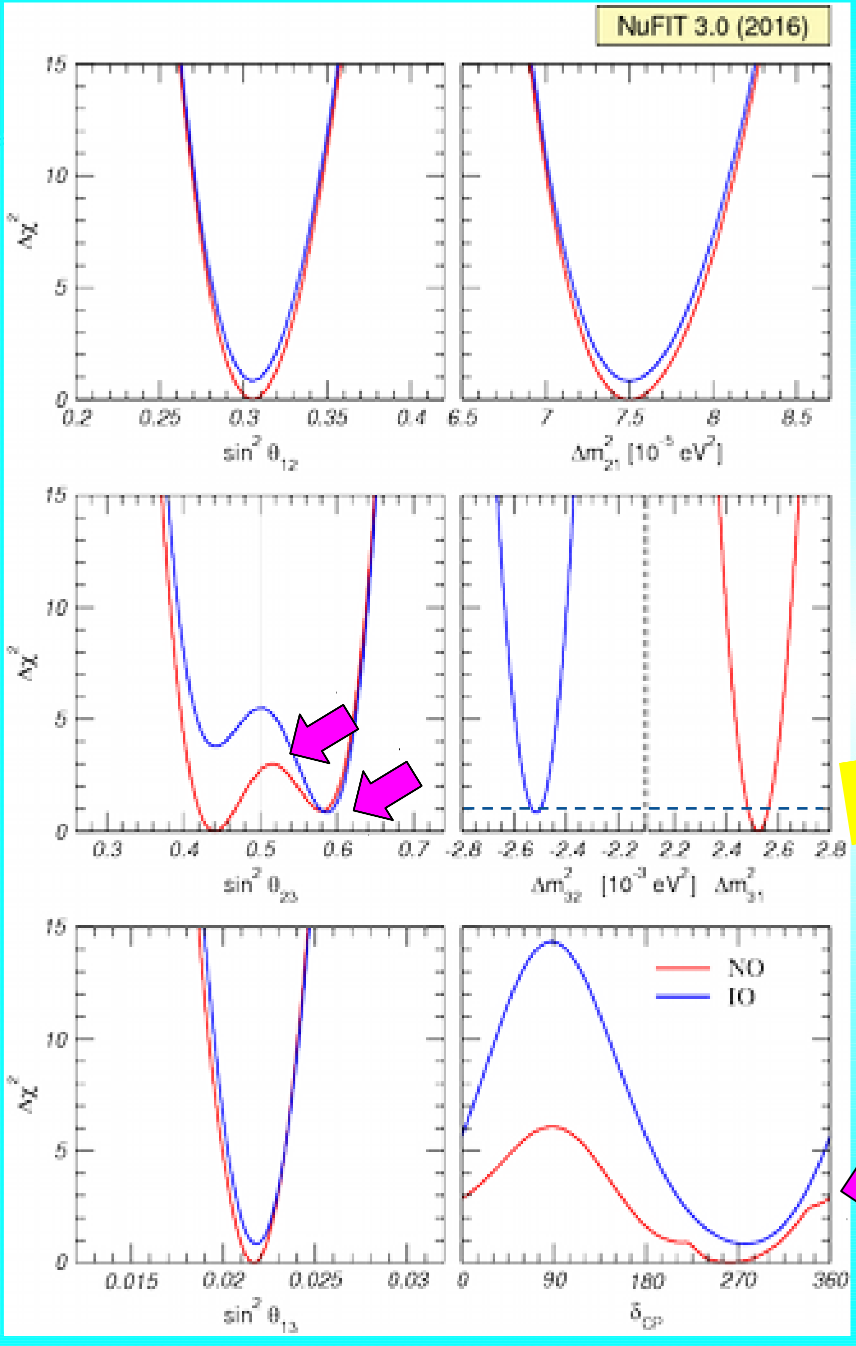
NuFIT 3.0 (2016)

I. Esteban, et al, 1611.01514 [hep-ph]

Similar conclusions but with lower confidence level

SK atmospheric data are not included

Δm^2_{31} from reactor experiments



IH disfavoured at about 1σ

Second octant disfavoured for NO at 1σ

Maximal 2-3 mixing disfavoured at 1.7σ

CP violation at 1.7σ (NO), 2.3σ (IO)
Consistent with maximal

Behind the global fit

Tensions, inconsistencies which can be hidden in the complicated statistical analysis with many degrees of freedom

2-3 mixing

2.5 σ Tension
Maximal: T2K, SK atmospheric, Deep Core
Non-maximal: NOvA, MINOS

In the last case – more matter effect
Non-standard interactions

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

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

1-2 mass splitting

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

NSI (for solar) or
Very light sterile neutrinos

Next Big

ass ordering

ptonic CP violation

irac phase δ_{CP}

correlate in determination

Theoretically related?

Should be in complete theory

Type of spectrum (hierarchical vs. quasi-degenerate)

absolute values of masses

Nature of neutrino mass: (Majorana vs. Dirac)

Majorana phases

Deviation of 2-3 mixing from maximal

Octant

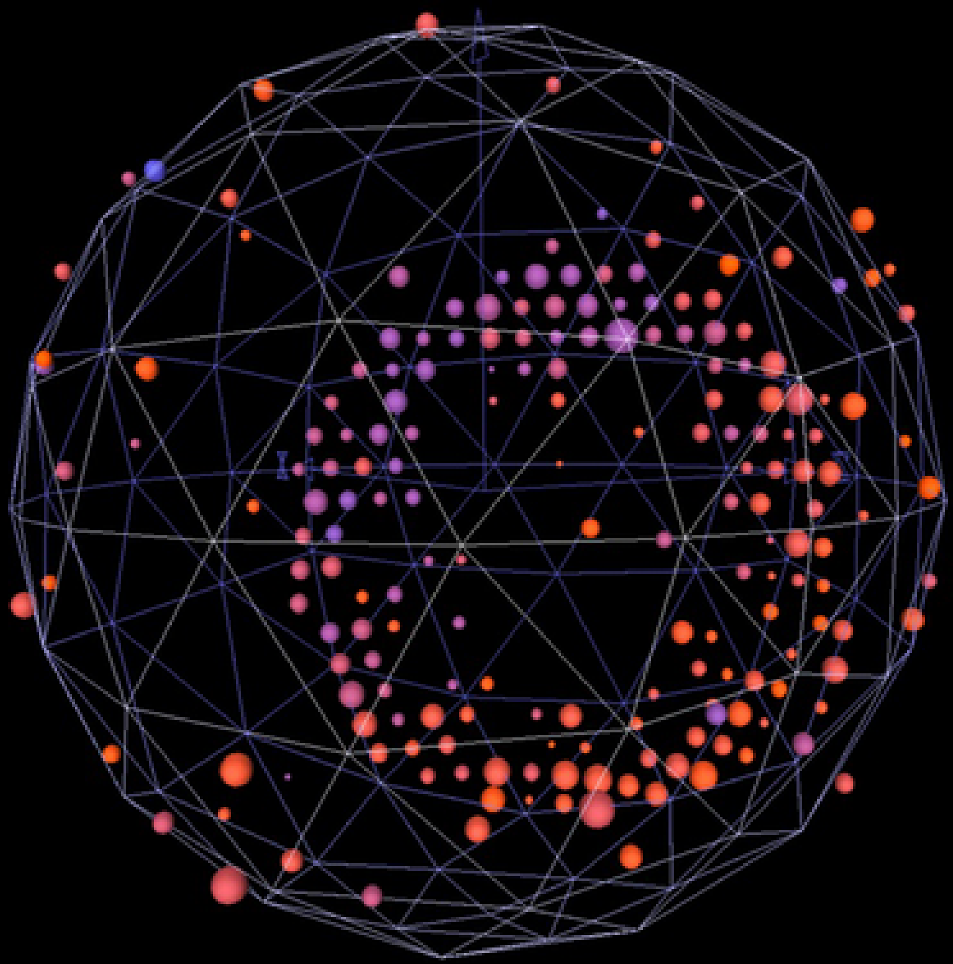
ν_s Sterile neutrinos

1 eV mass scale - not a small perturbation of the 3ν picture

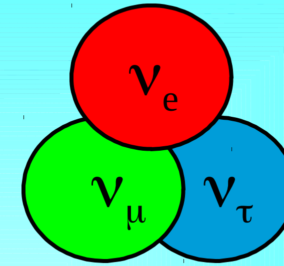
Mass

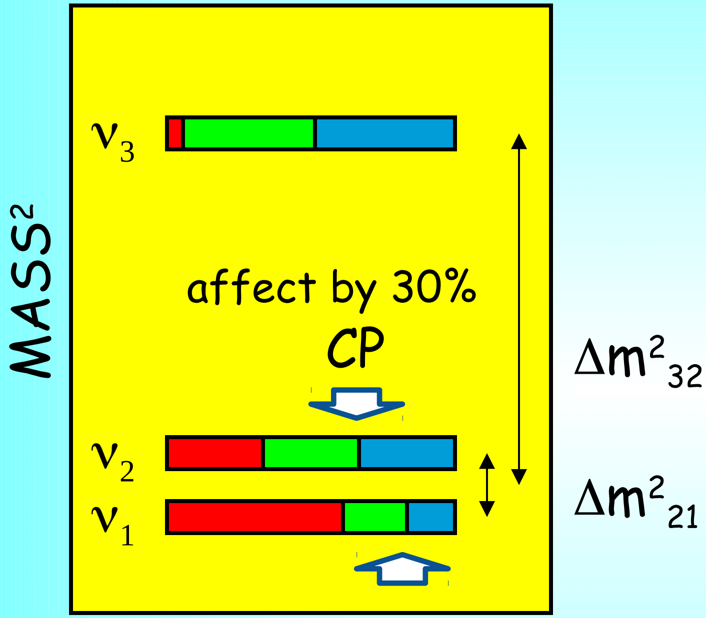
Mass ordering

CP-violation



Ordering and CP violation



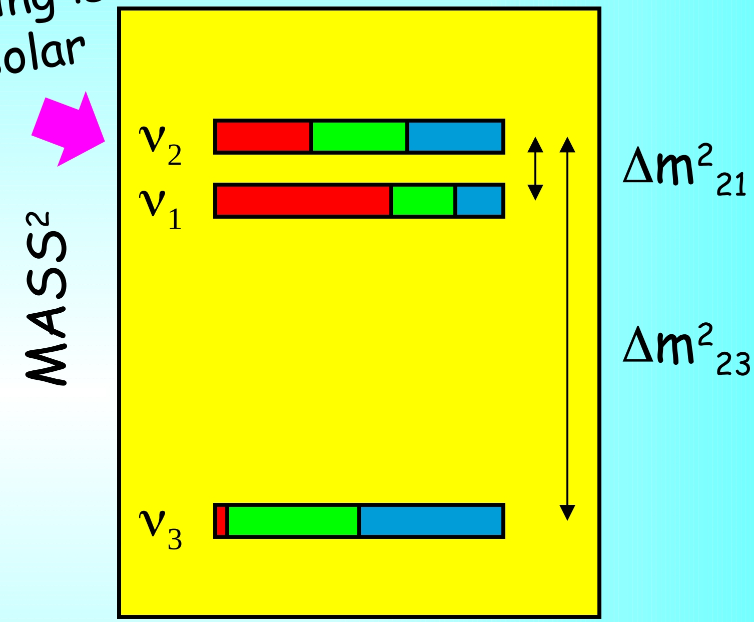


Normal mass hierarchy

$\Sigma m > m_h$

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

1-2 ordering is fixed by solar neutrinos



Inverted mass hierarchy

$\Sigma m > 2\, m_h$

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

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

mass splittings — oscillation depth

in vacuum

Mass hierarchy

Further advance

Step to discover CP

important by itse

Theoretical implications

Phenomenology

Supernova neutrinos

Atmospheric neutrinos

bb0n decay

LBL

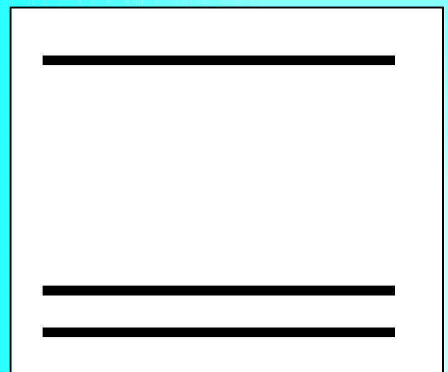
Solar neutrinos

Cosmology

Neutrino Mass hierarchy

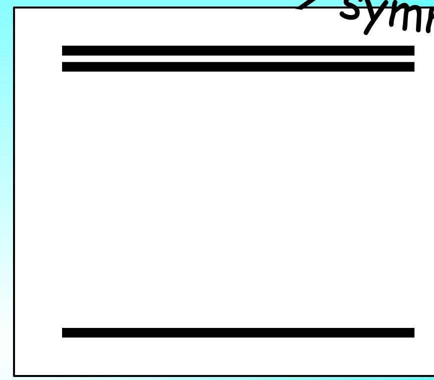
Fundamental:
principle, symmetry

Accidental: selection of
values of parameters



Correlation of masses
of neutrinos and
charged leptons
in weak interactions:
Light likes light,
heavy – likes heavy

Quasi-degenerate
→ symmetry



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

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

the weakest
hierarchy

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

but 1-2 mixing strongly
deviates from maximal

Similar to quark spectrum

rescaling

See-saw

Quark-lepton
symmetry

Unification

Pseudo-Dirac + 1 Majorana

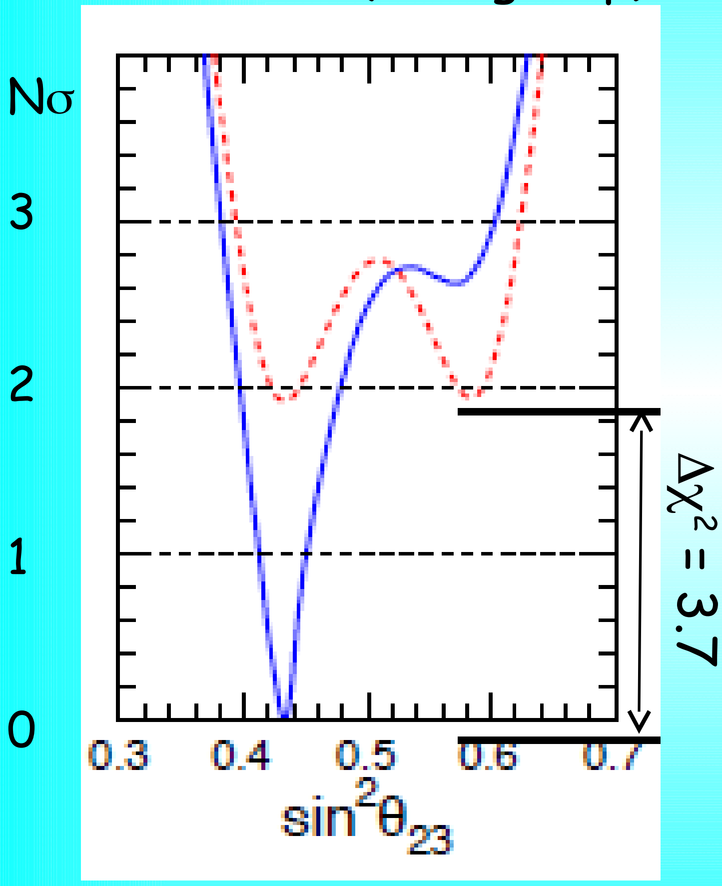
Flavor symmetries

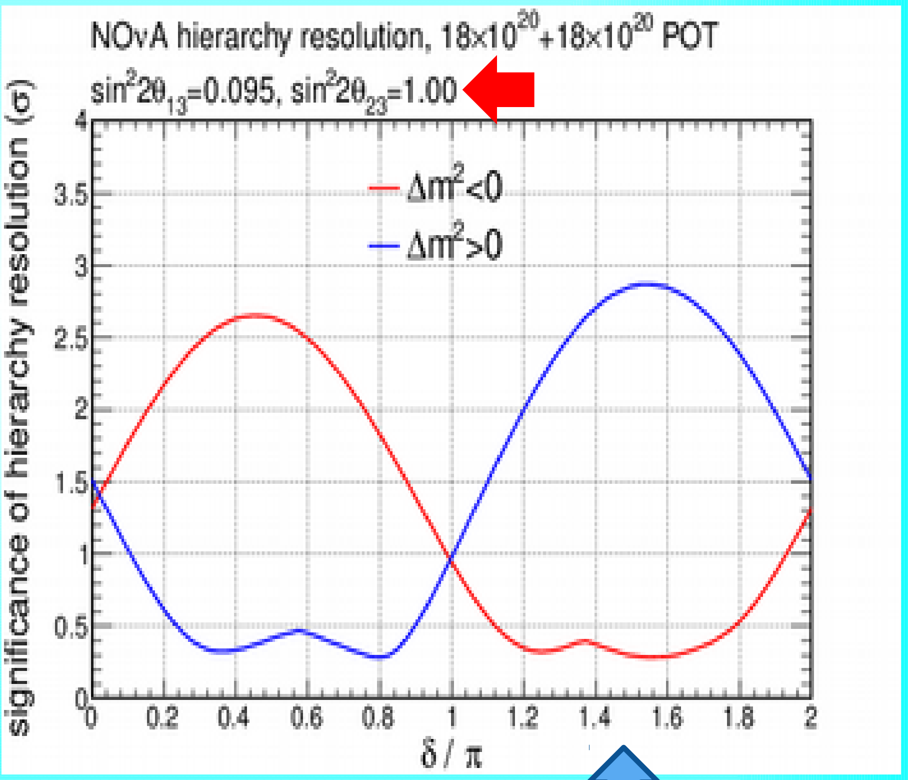
Broken $L_e - L_\mu - L_\tau$ symmetry

Present sensitivity

F. Capozzi et al, NOW 2016

Global fit (Bari group)





2.5σ

6 10^{20} POT

$\Delta\chi^2 = 1$
in NuFIT 2016

Race for mass hierarchy

Matter effect
on 1-3 mixing
ations, conversion

Precise measurements of Δm^2 at reactors

JUNO,
RENO-50

Cosmology
Σm

tmospheric neutrinos

PINGU
ORCA
INO

LBL experiments

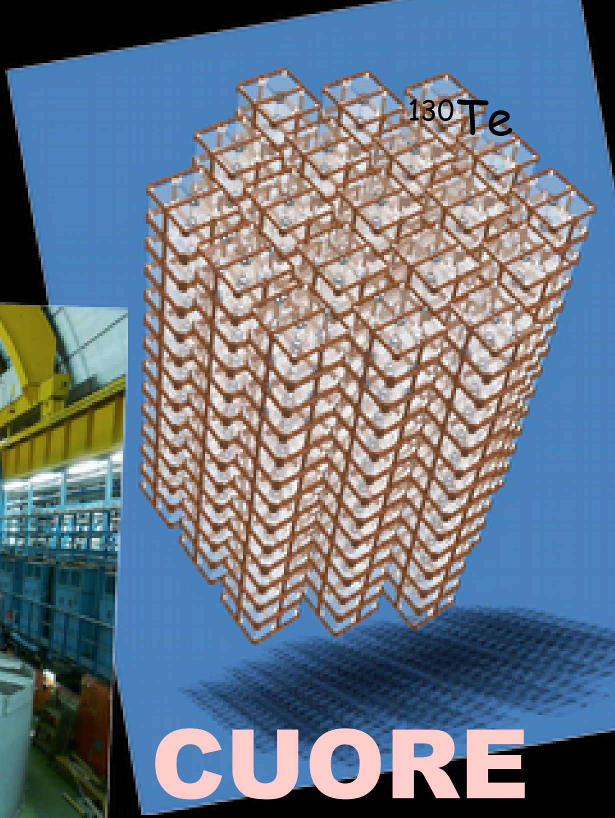
NOvA
LBNF – DUNE
JPARC-HK

Supernova neutrinos

Earth matter
effects,
energy spectra

Double bet
decay
m_{ee}

Neutrinoless $\beta\beta$ – decay & mass hierarchy



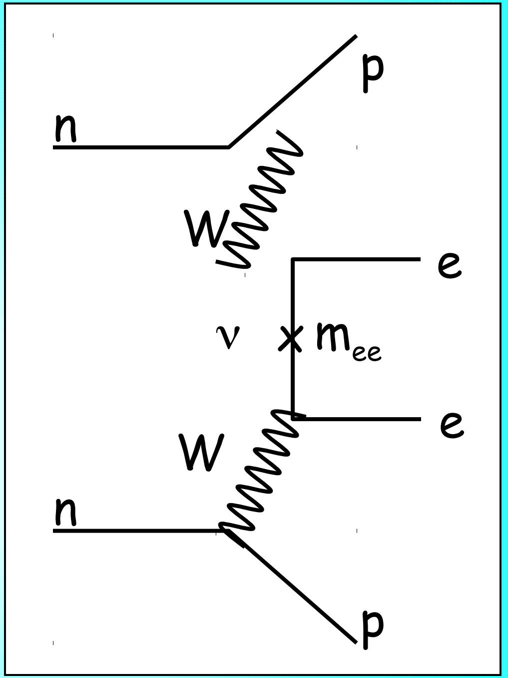
CUORE

GERDA

EXO-200

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

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

Normal mass hierarchy

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

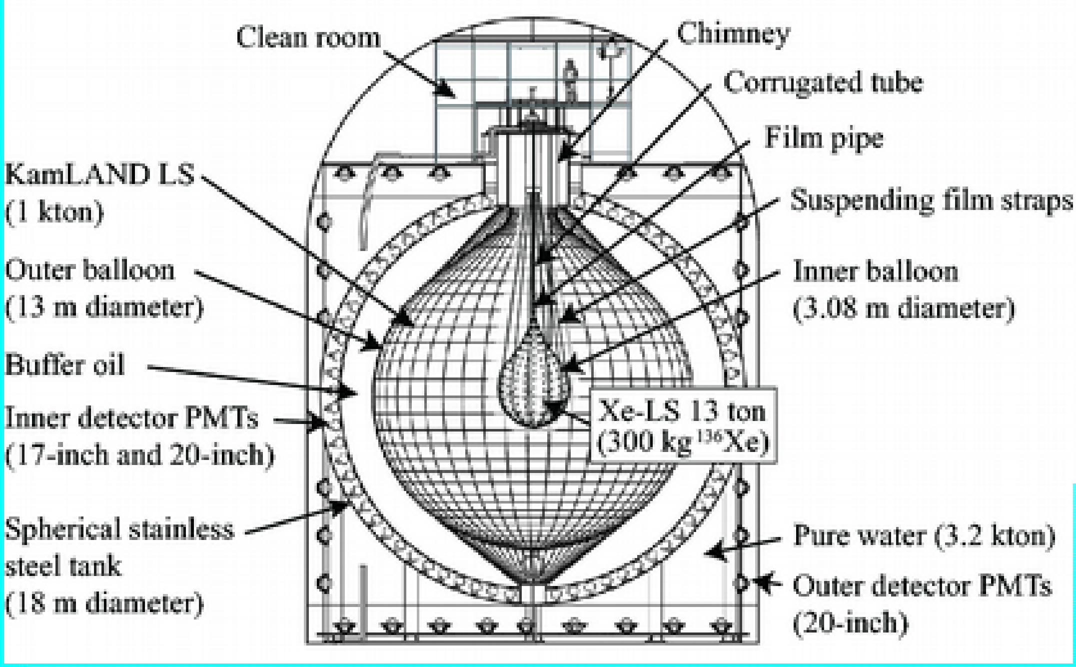
Inverted mass hierarchy

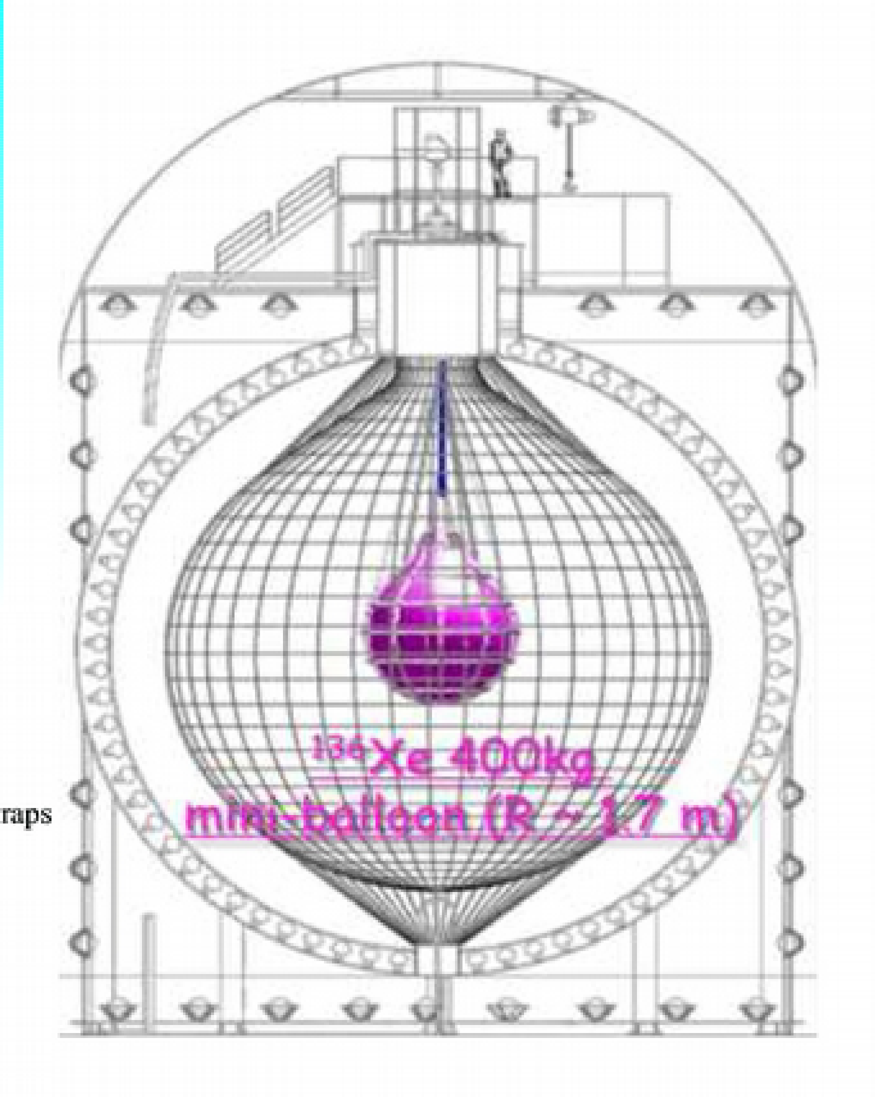
Strong mass hierarchy:

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

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

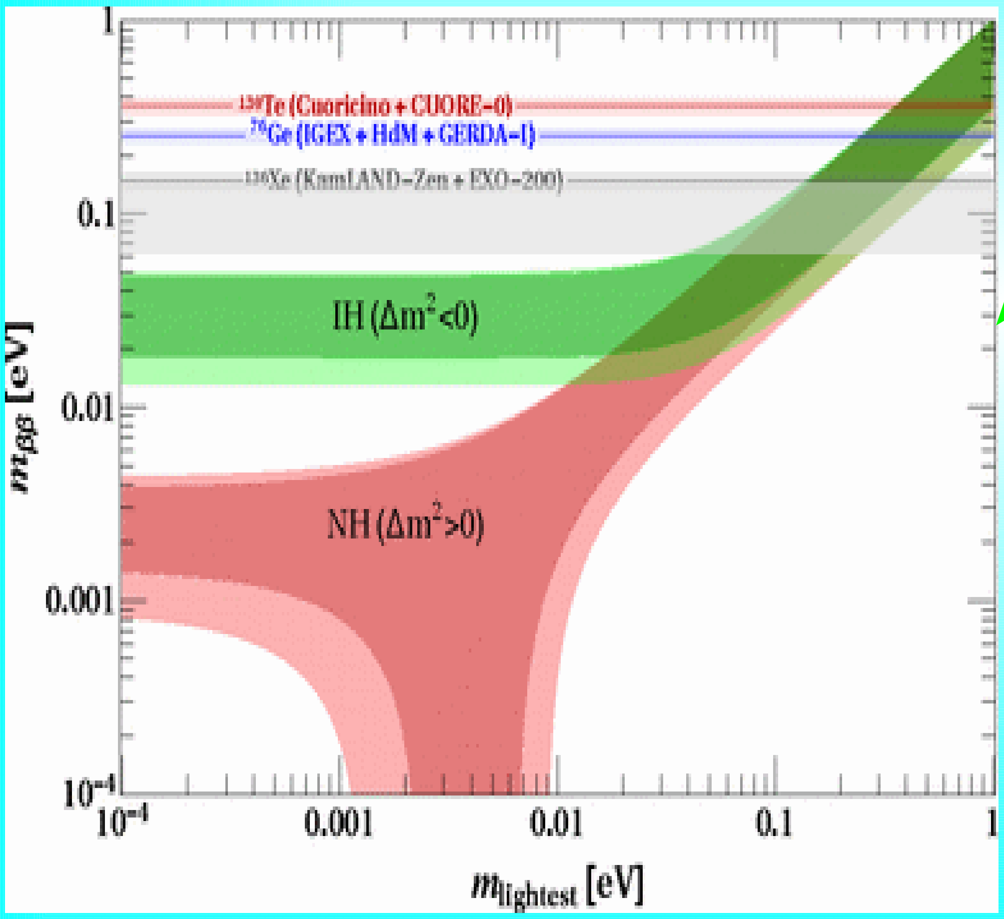
KamLAND-Zen

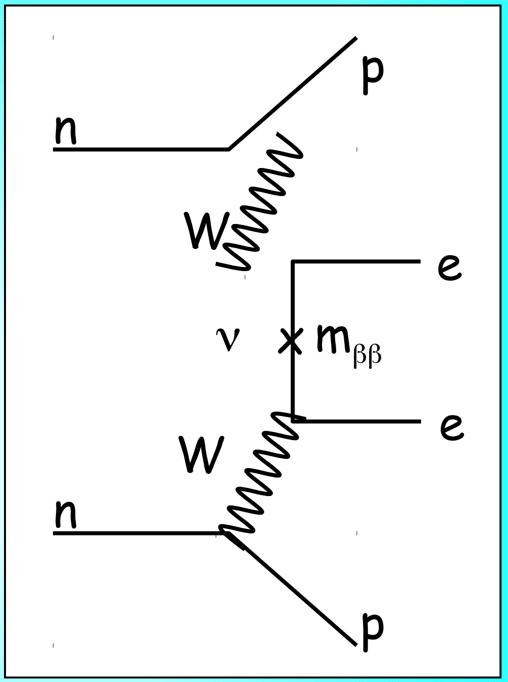

Clean room
Chimney
Corrugated tube
Film pipe
Suspending film straps
KamLAND LS
(1 kton)
Outer balloon
(13 m diameter)
Inner balloon
(3.08 m diameter)
Buffer oil
Inner detector PMTs
(17-inch and 20-inch)
Xe-LS 13 ton
(300 kg ^{136}Xe)
Spherical stainless
steel tank
(18 m diameter)
Pure water (3.2 kton)
Outer detector PMTs
(20-inch)


^{136}Xe 400kg
mini-balloon (R ~ 1.7 m)

Double beta decay

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





KamLAND-Zen

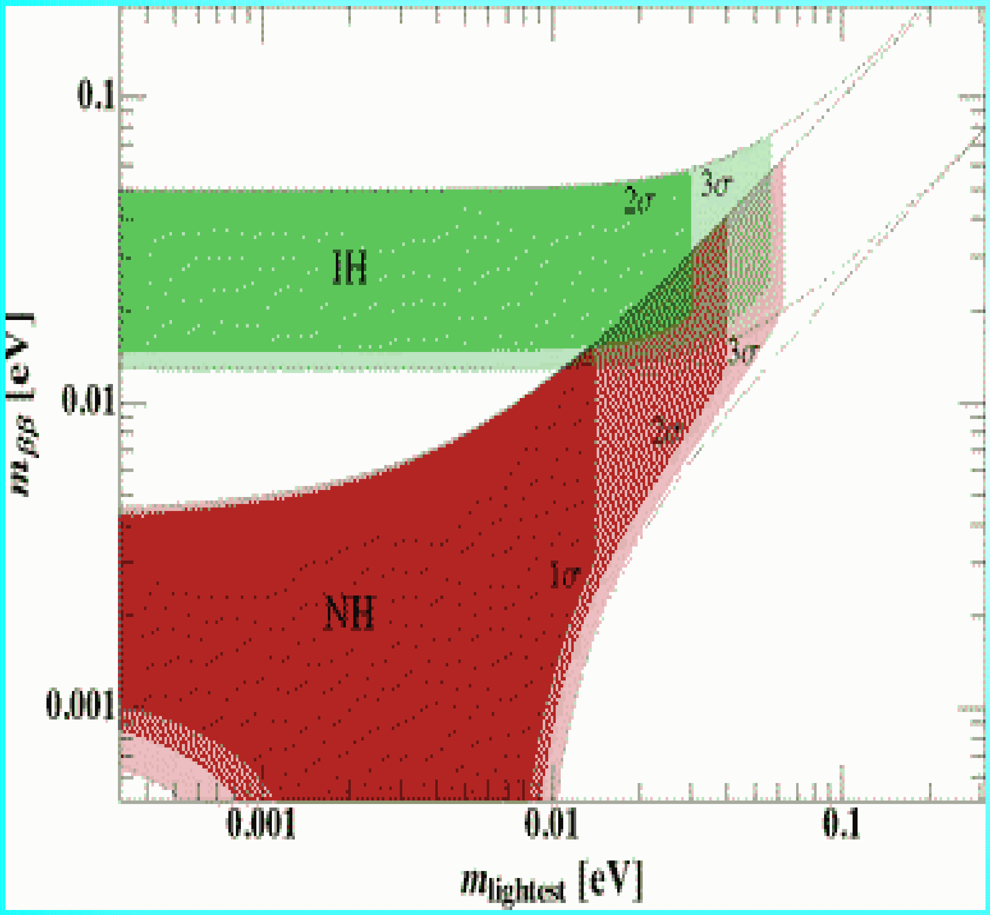
$m_{\beta\beta}$ < (60 – 161) meV, 90% CL

Depending on NME

A.Gando, et al, 1605.02889 [hep-ex]

Approaching IH band

utrinoless ββ – decay and cosmology



S. Dell'Oro, S. Marcocci, M. Viel, F. Vissani
arXiv:1601.07512 [hep-ph]

The shaded areas show the effect of the inclusion of cosmological constraints at different C.L.

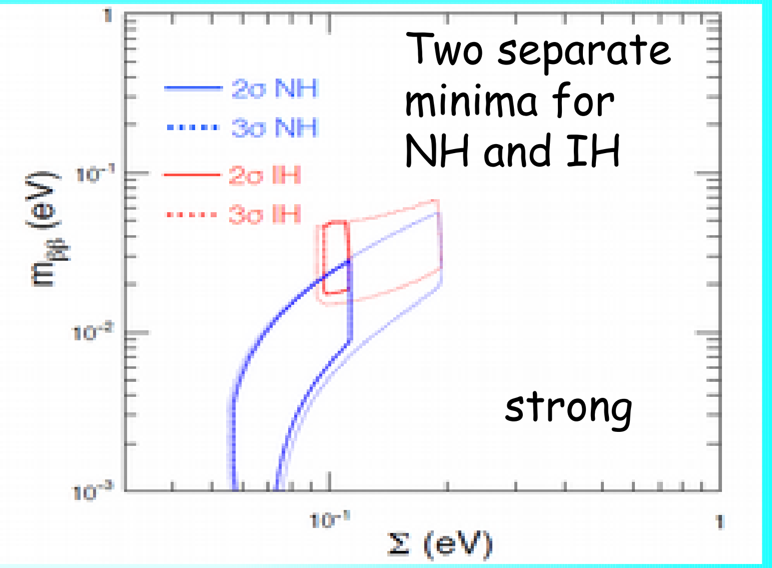
Absolute mass scale

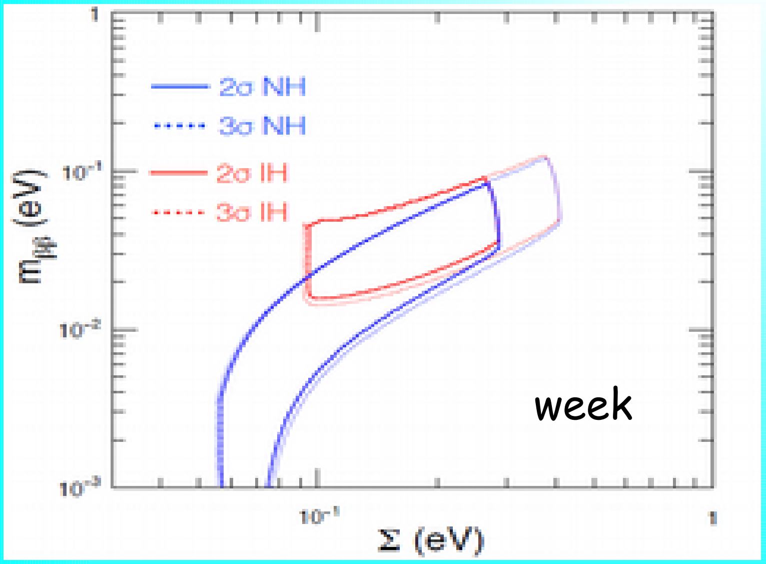
F. Capozzi et al, NOW 2016

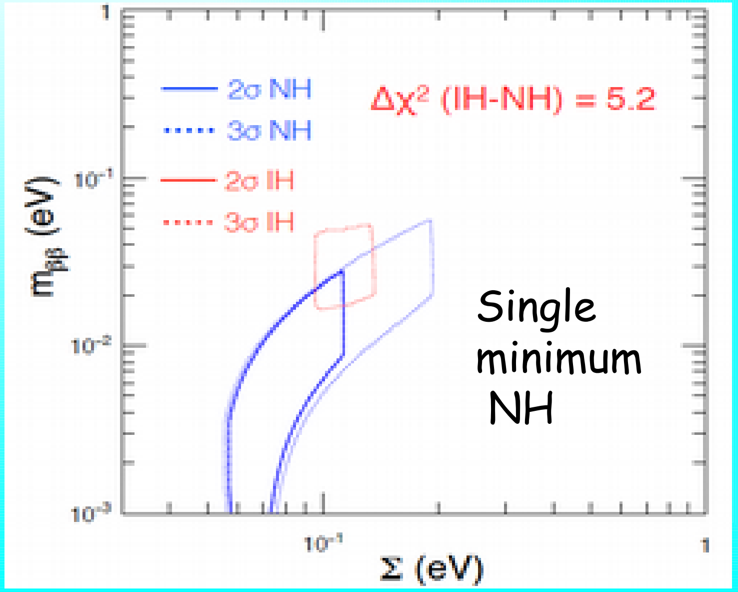
Bounds from oscillations
and cosmology

Cosmology start to restrict IH

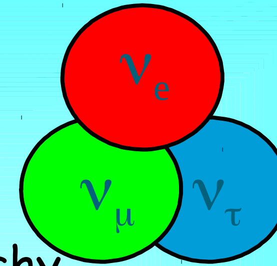
$$m_{\beta\beta} = U_{e1}^2 m_1 + U_{e2}^2 m_2 e^{\iota\alpha} + U_{e3}^2 m_3 e^{\iota\beta}$$



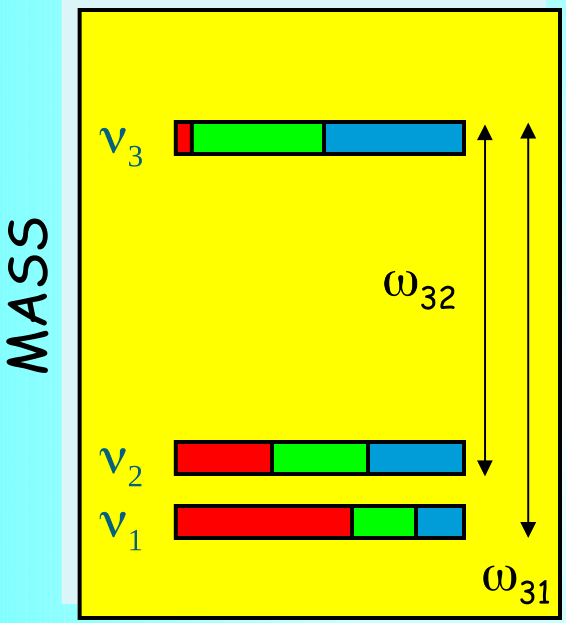




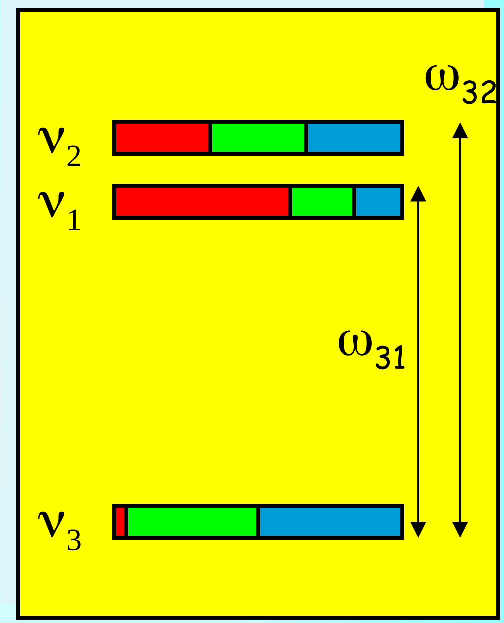
Mass ordering with reactors



Normal hierarchy



Inverted hierarchy



Oscillation frequency

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

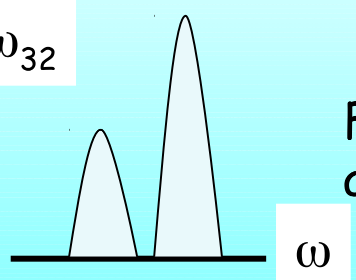
Oscillation depth:

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

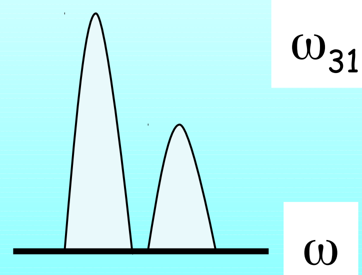
$D_{31} \sim 2D_{32}$

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

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



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

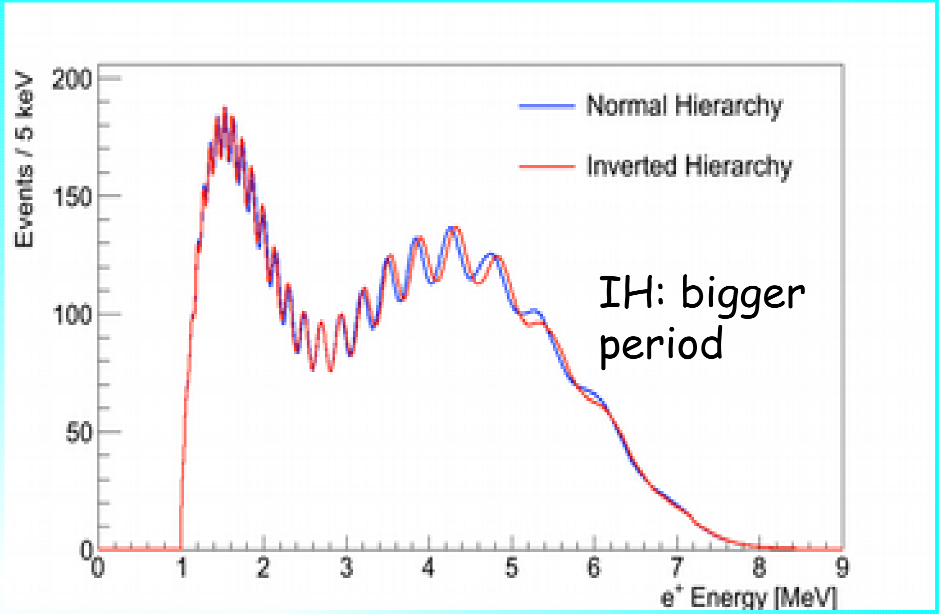
Jiangmen Underground Neutrino Observatory

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

20 kt LAB scintillator

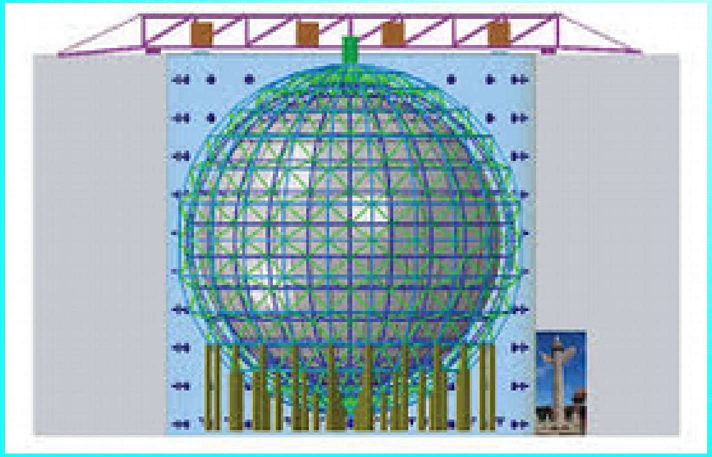
$n + p \rightarrow d + \gamma$

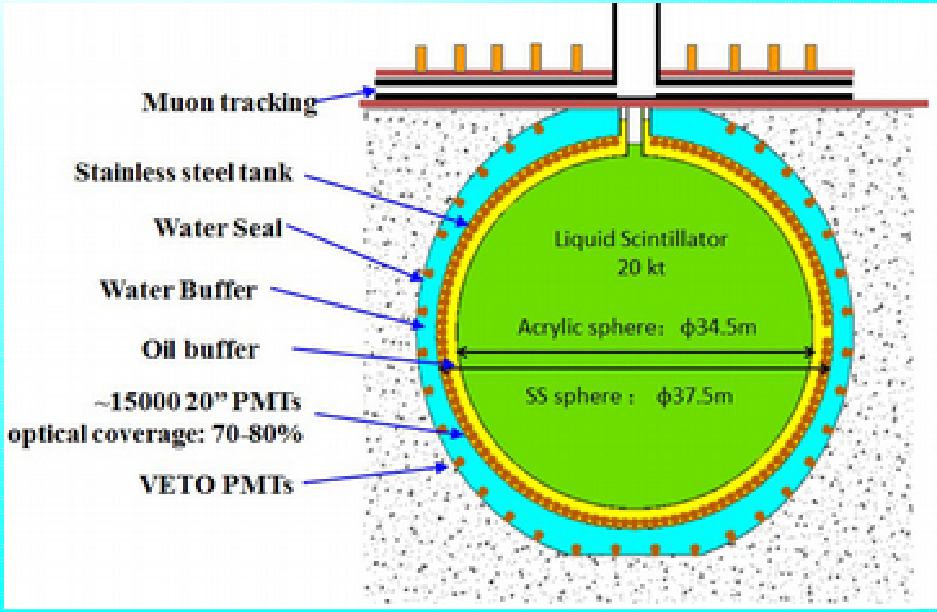
Key requirement:
energy resolution 3% at 1 MeV



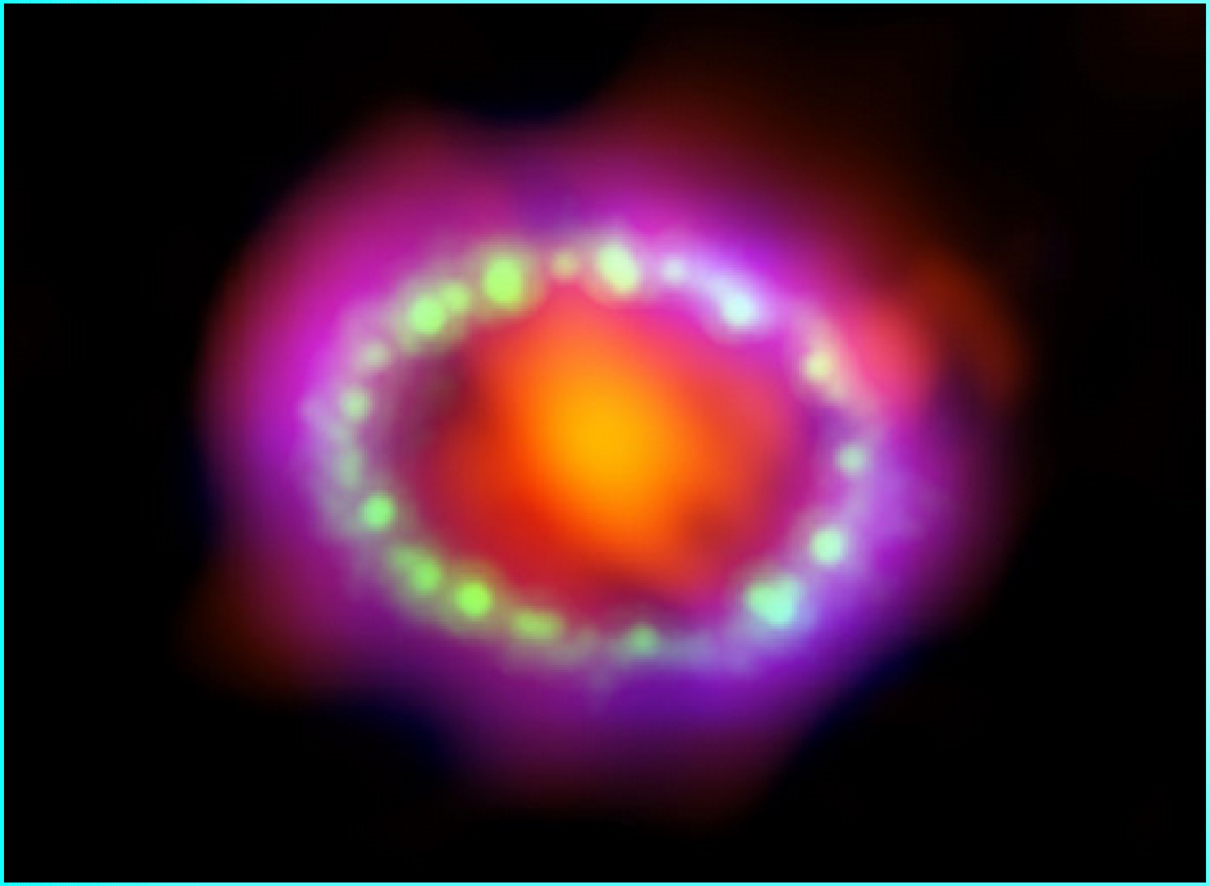
IH: bigger period

Operation in 2020
(3 - 4)σ in 6 years



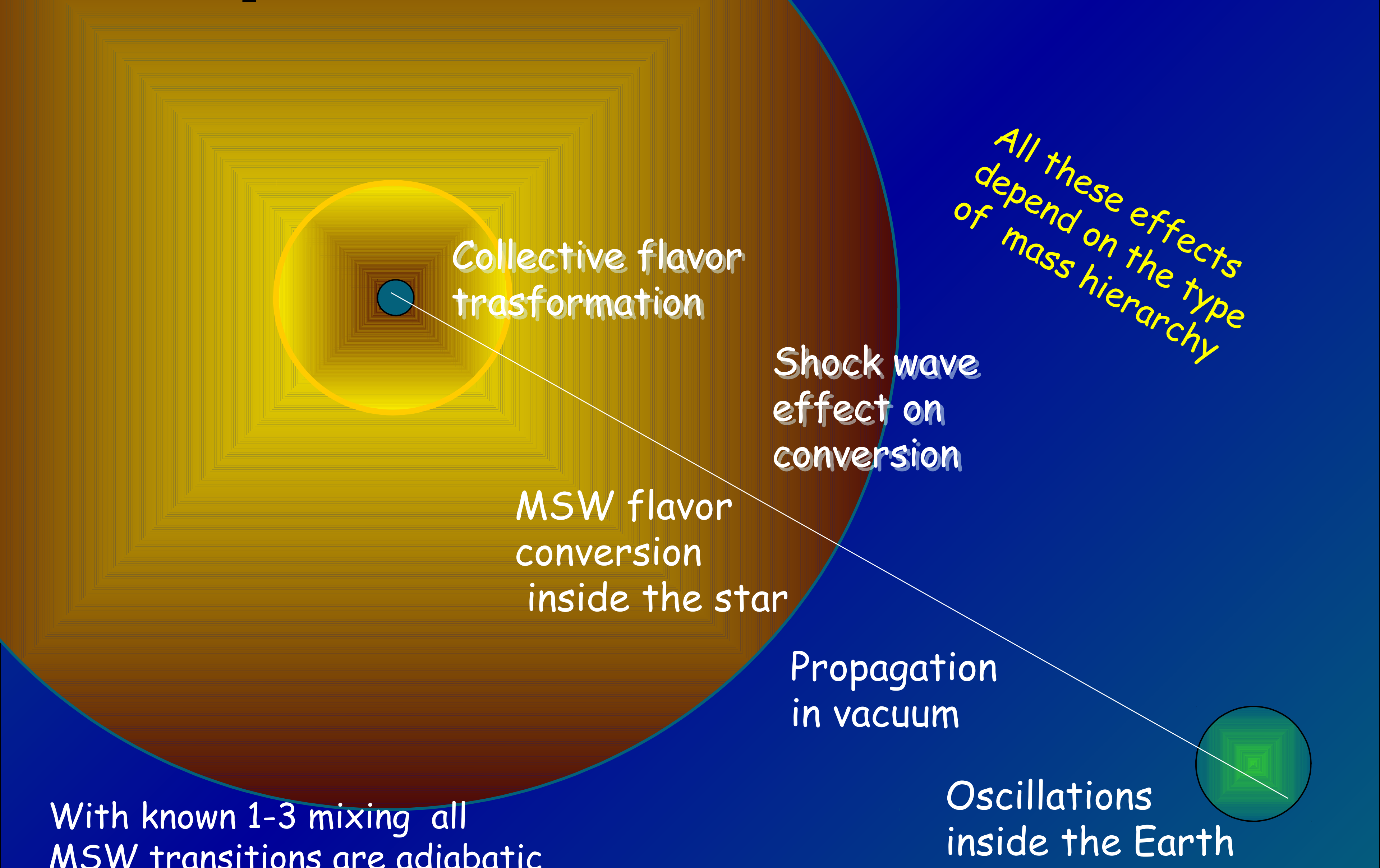


SN 1987A



Composite image of the SN 1987A inner ring shows the fuzzy glow of X-rays seen by ALMA in orange. The green ring is visible light detected by the Hubble Space Telescope and the violet ring is the X-ray signal seen by Chandra. (Courtesy: NASA / ESA / A Angelich (NRAO / AUI / NSF) / R Kirshner (Harvard–Smithsonian CfA / Gordon and Betty Moore Foundation) / ALMA (ESO / NAOJ / NRAO) /

Supernova neutrinos



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

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

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

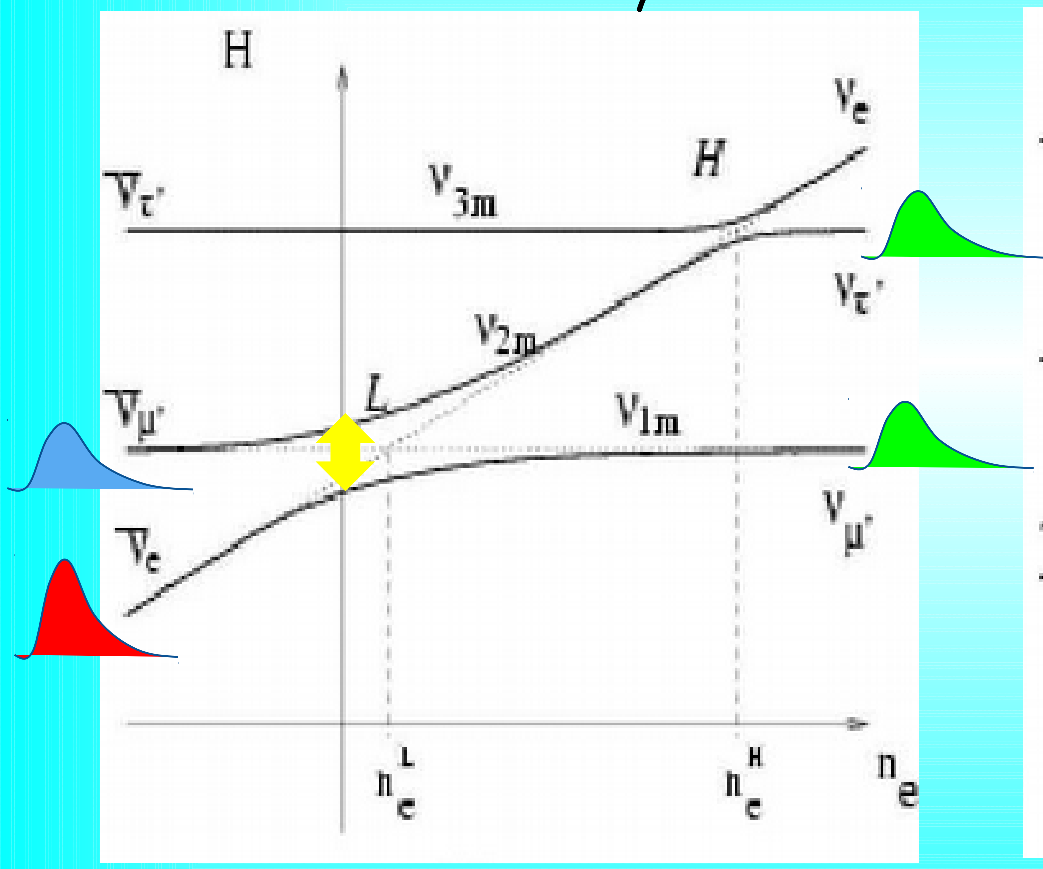
G. Fuller, et al
B. Dasgupta ,et al

rth matter effect and hierarchy

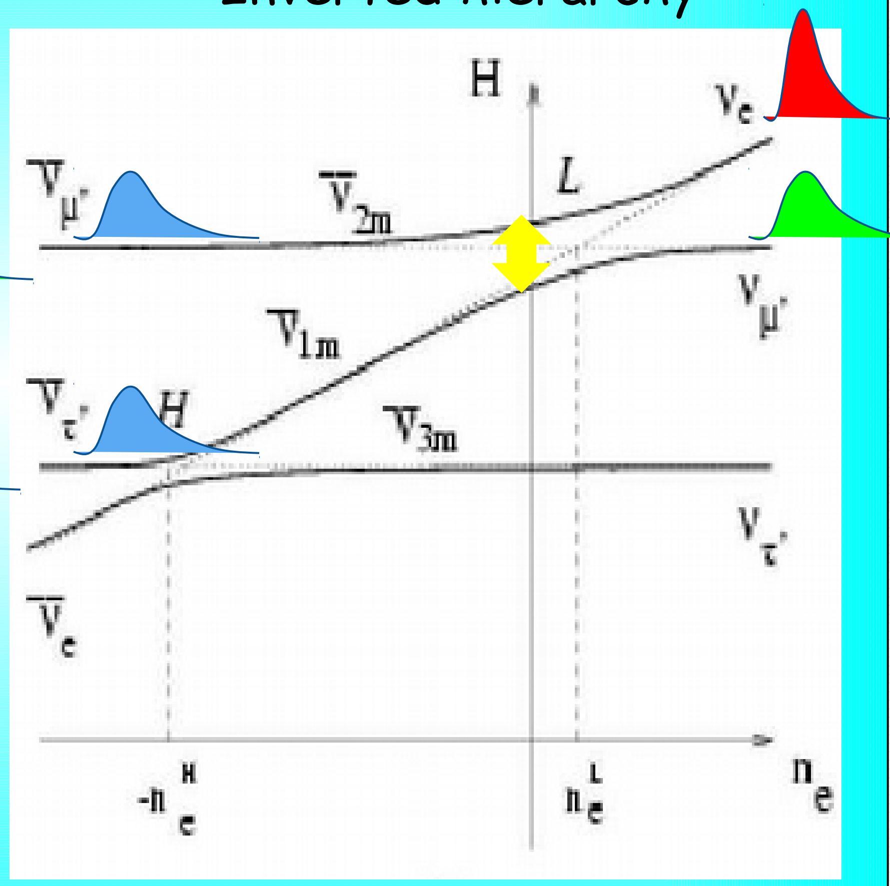
Adiabatic evolution

Level crossings

Normal hierarchy



Inverted hierarchy

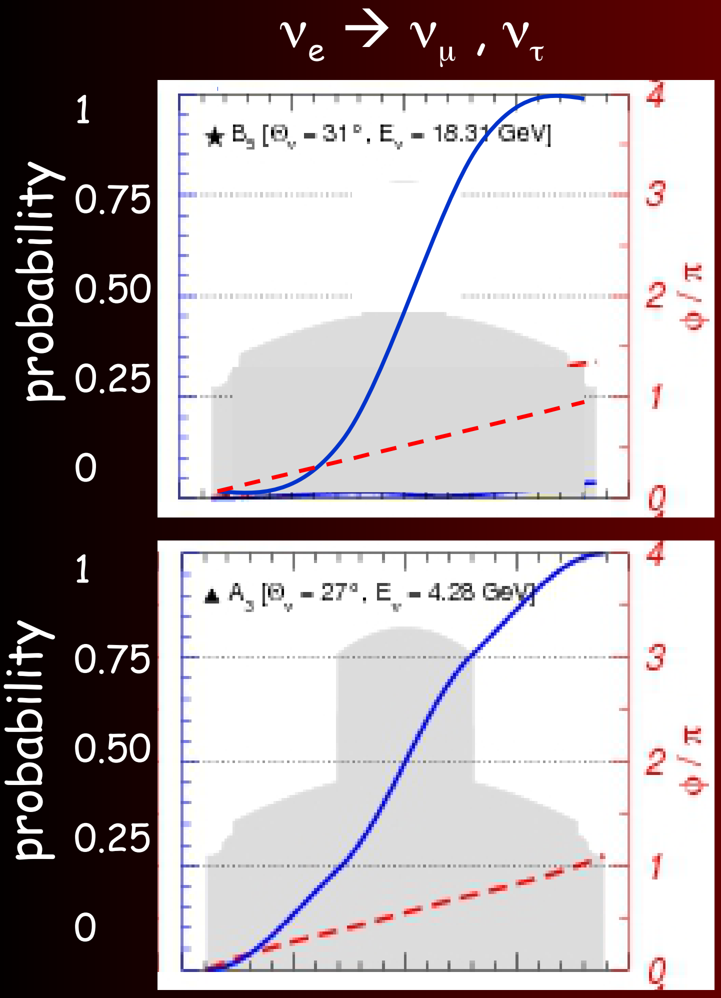


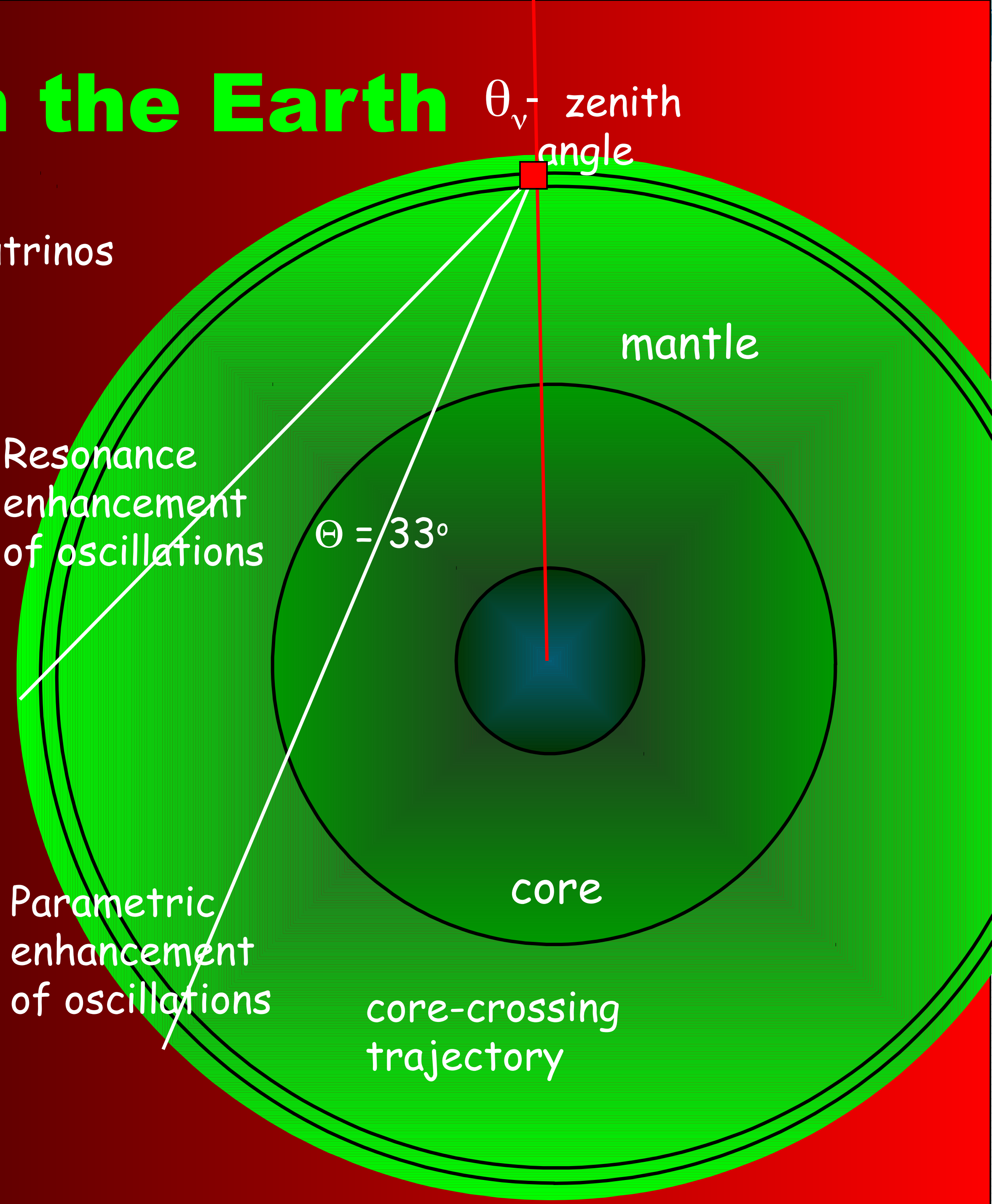
No Earth matter effect provided that initial fluxes of ν_{μ}' and ν_{τ}' are identical

Collective effects and shock waves may change this.

Oscillations in the Earth

Atmospheric, accelerator neutrinos





Probabilities

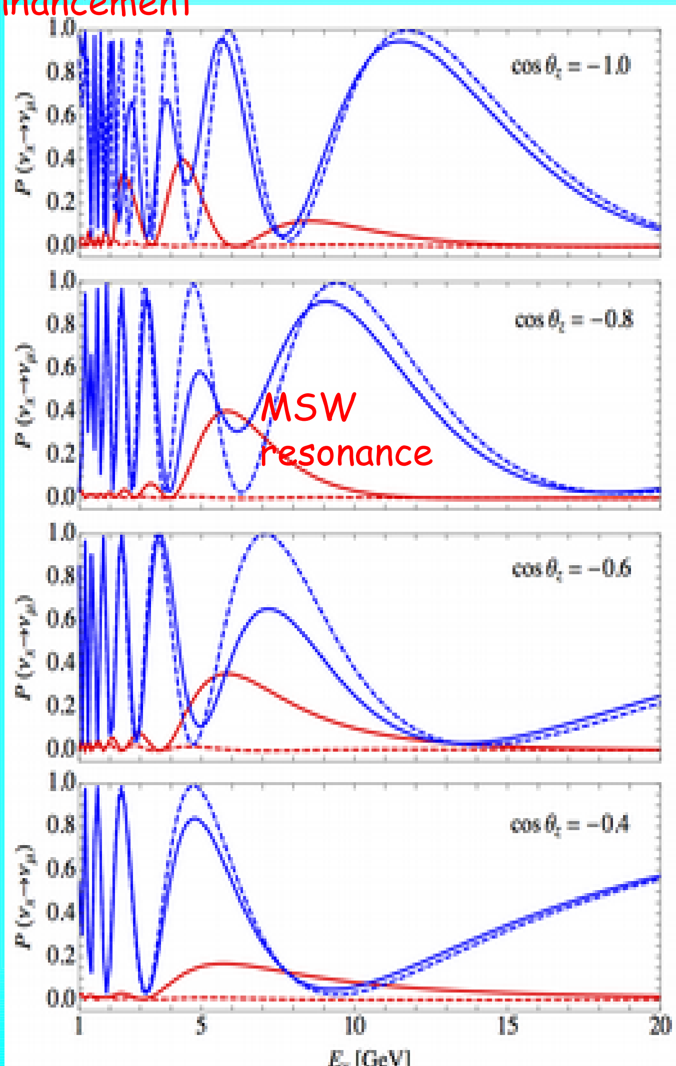
NH – solid, IH – dashed
x = μ - blue, x = e - red

Paramentric enhancement

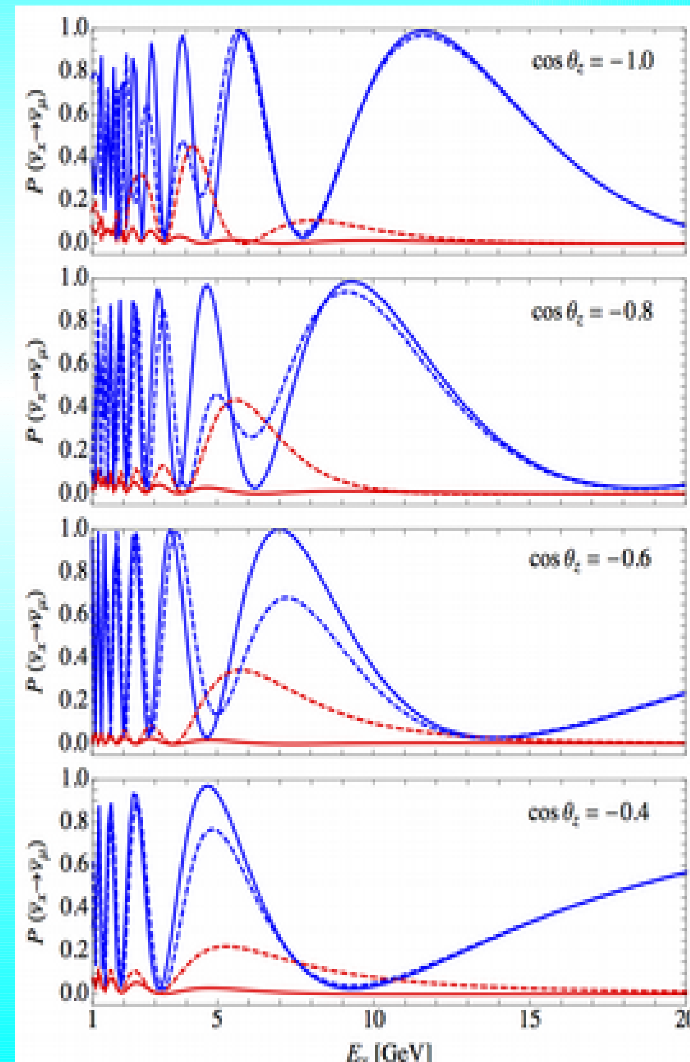
neutrinos

core

mantle only



antineutrinos

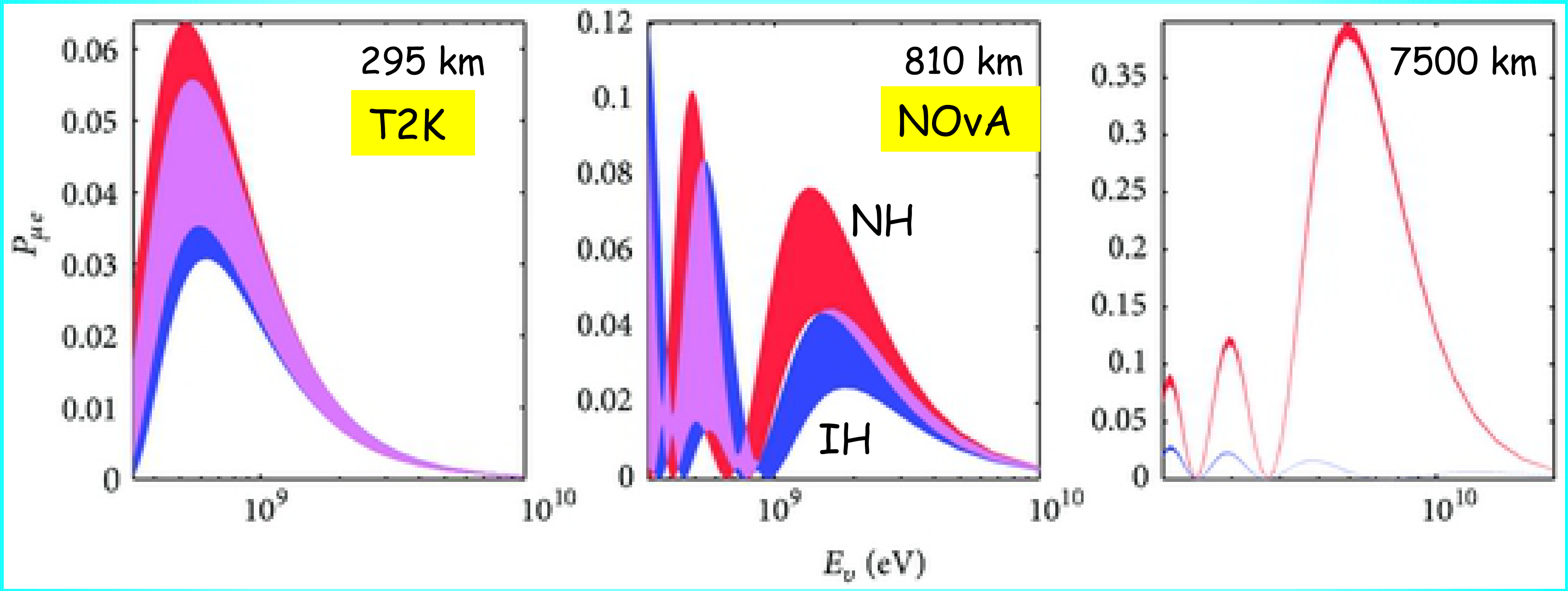


Hierarchy and CP

M. Blennow and A Y S, Advances in High Energy Physics , v. 2013 (2013), ID 972485

degeneracy

neutrinos

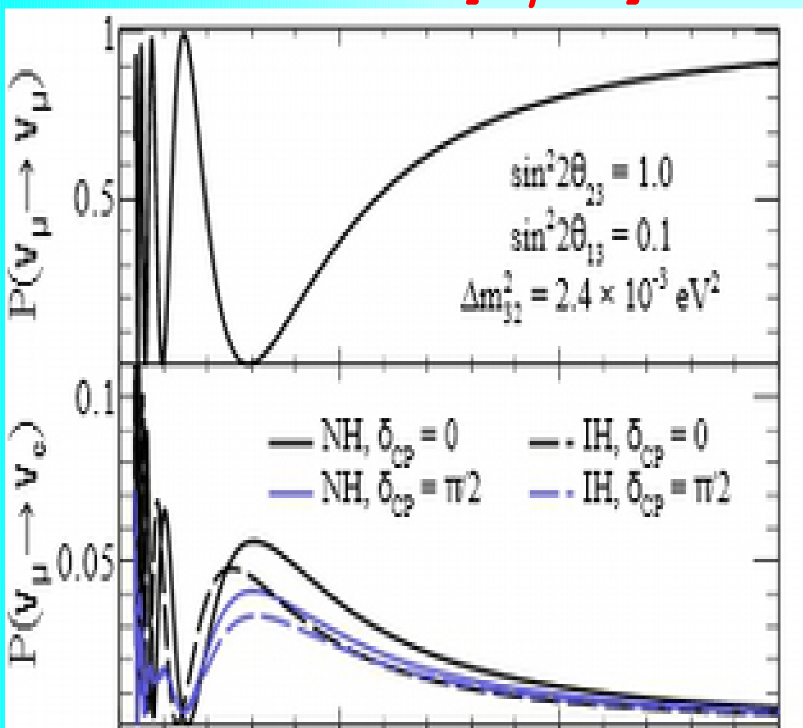


The red (blue) band corresponds to the normal (inverted) mass hierarchy and the band width is obtained by varying the value of delta .
The probabilities for antineutrinos look similar with the hierarchies interchanged.

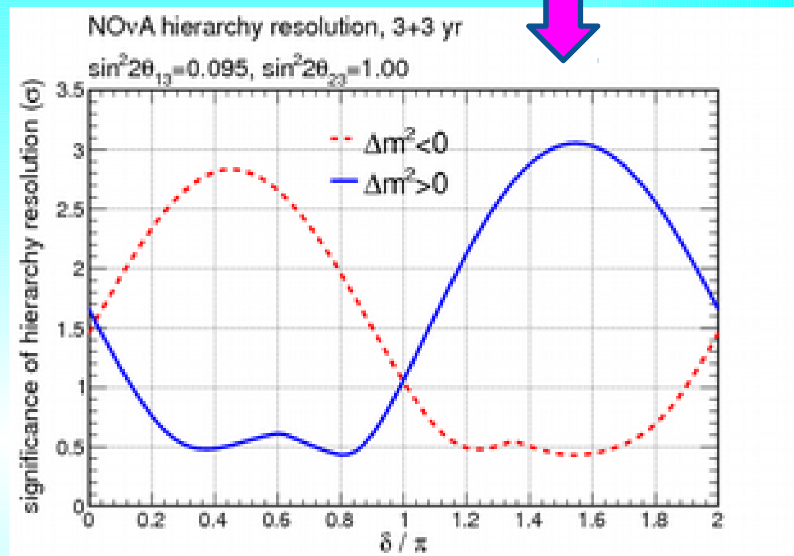
NOvA and T2K sensitivity

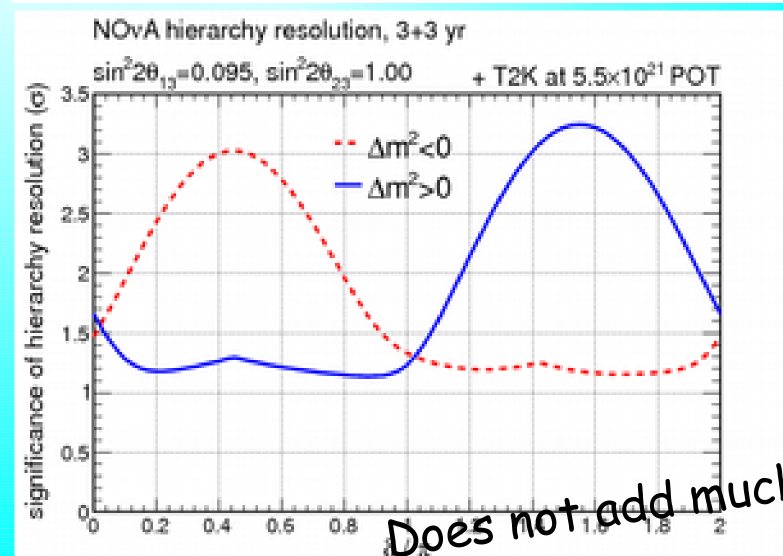
now 90%

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



0 1 2 3
E (GeV)





Does not add much

Atmospheric neutrinos

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"

$\nu_e + N \rightarrow e + h$

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

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

$\rightarrow h + \nu$

$\rightarrow e + \nu + \nu$

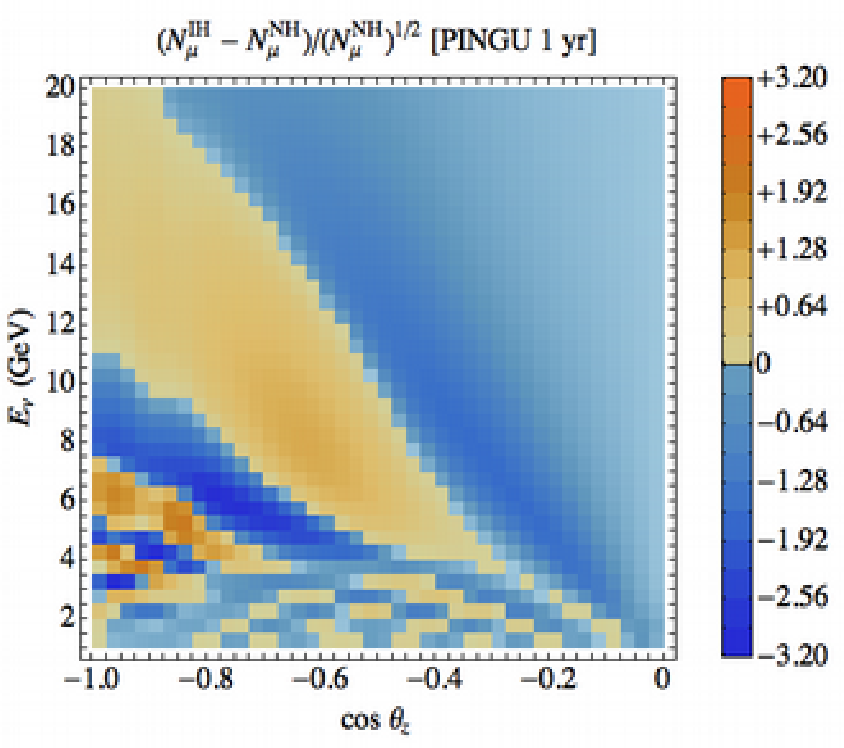
cascades

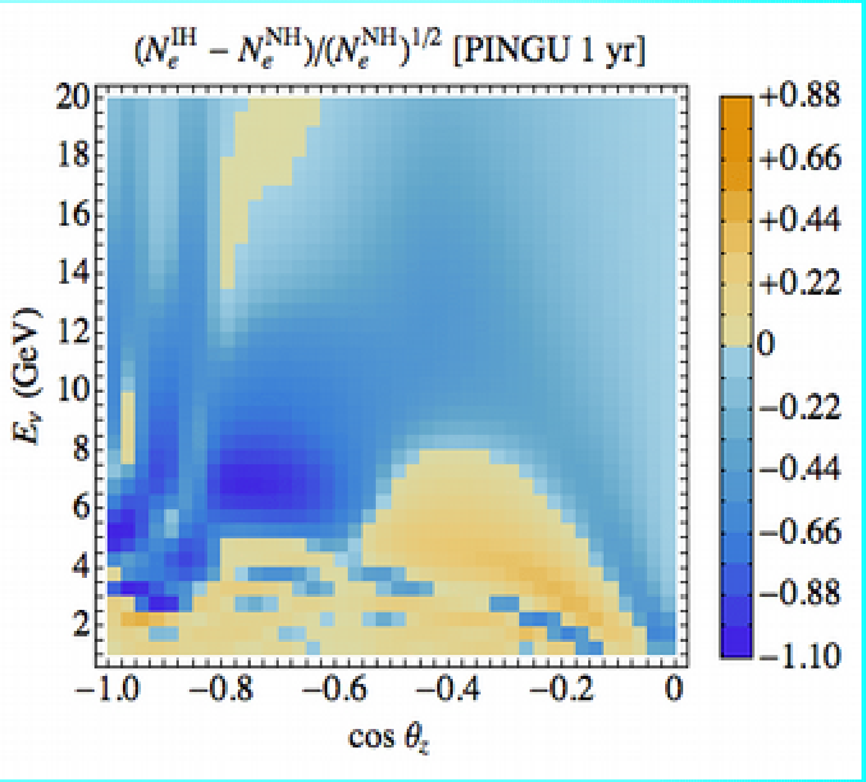
$E_\nu \quad \theta_\nu$ — reconstruction

Tracks

Cascades

``Distinguishability"





~ 10^5 events/year

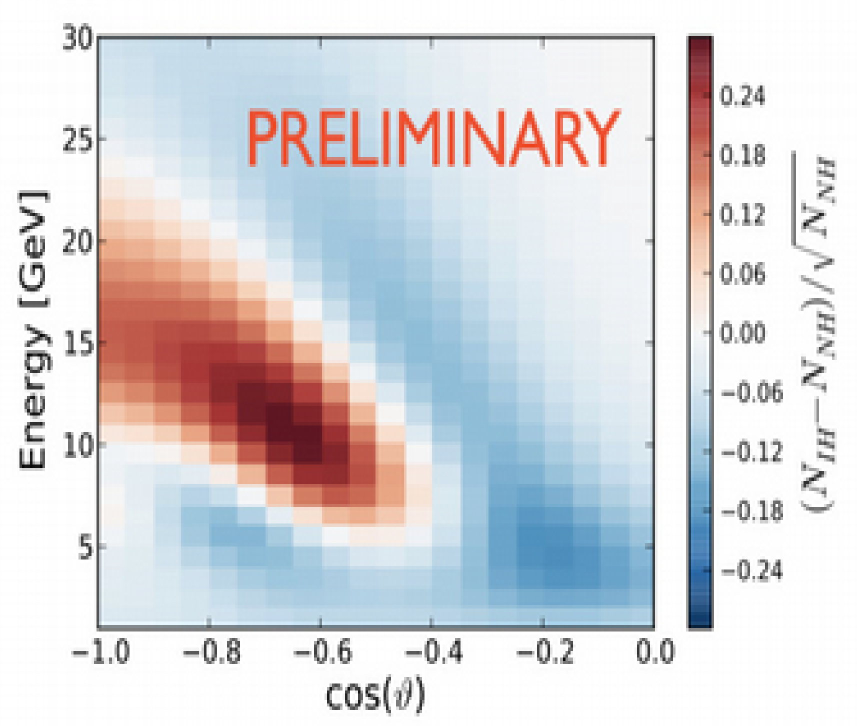
Estimator of sensitivity
S – asymmetry
|S| - significance

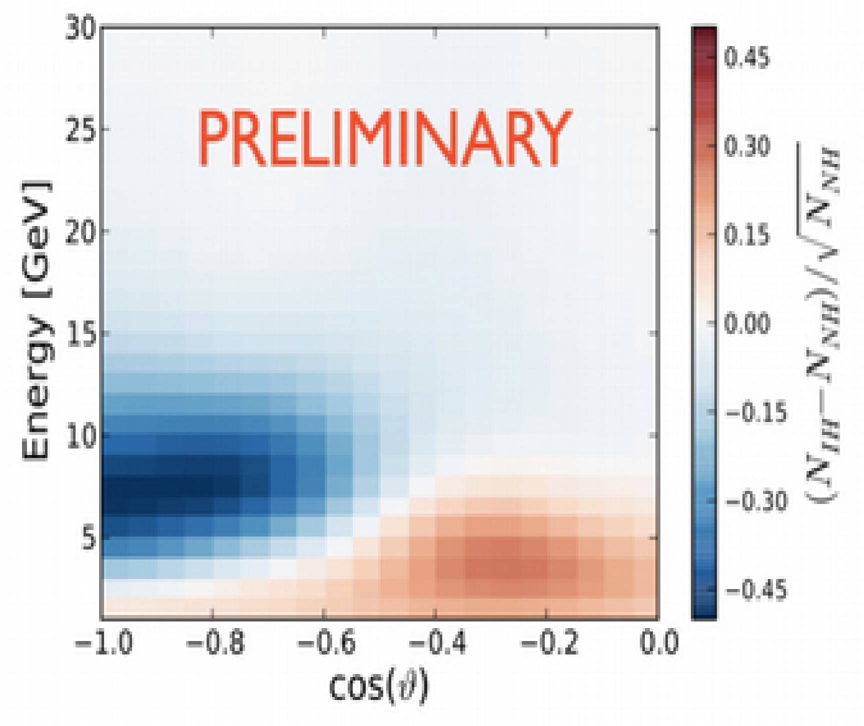
Smeared distributions

Ken Clark

Over energy and angle
resolution functions

PINGU





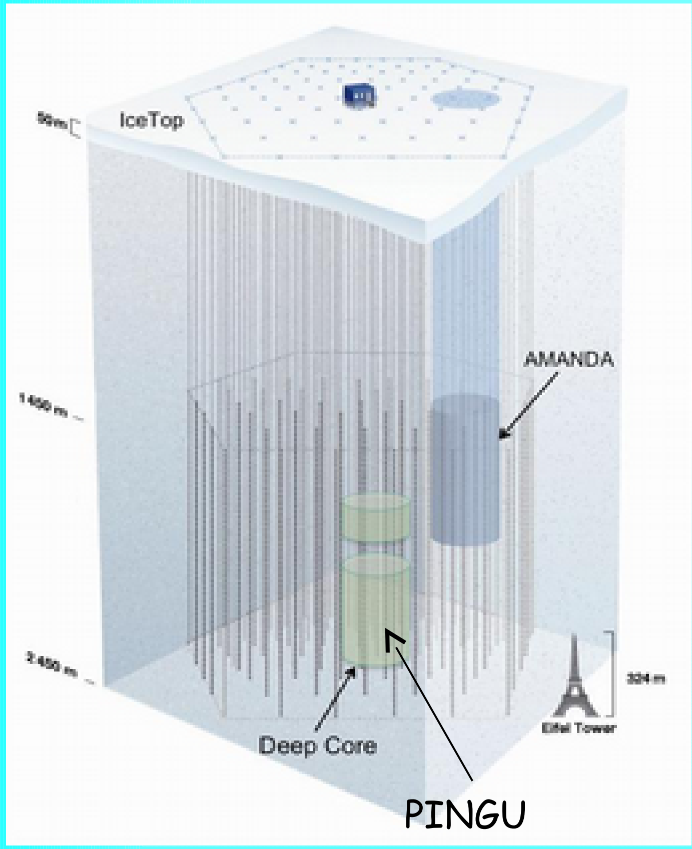
tracks

cascades

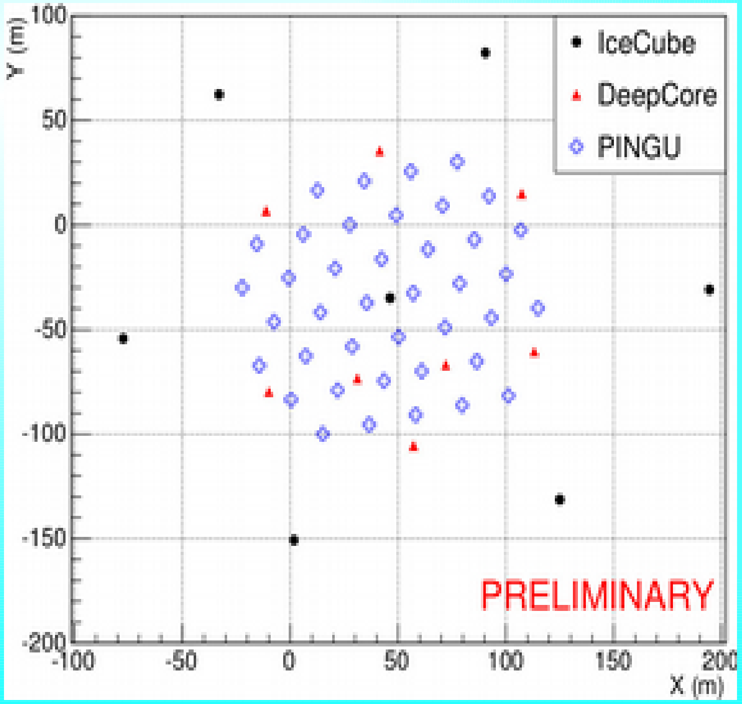
distinguishability

PINGU

Precision IceCube
Next Generation
Upgrade



40 strings
96 DOM's per string

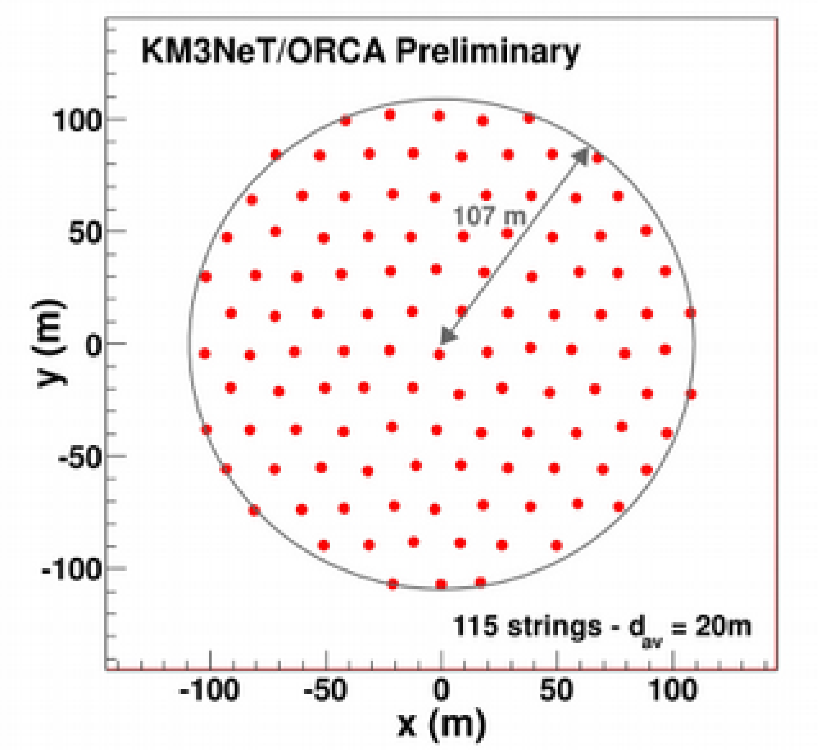


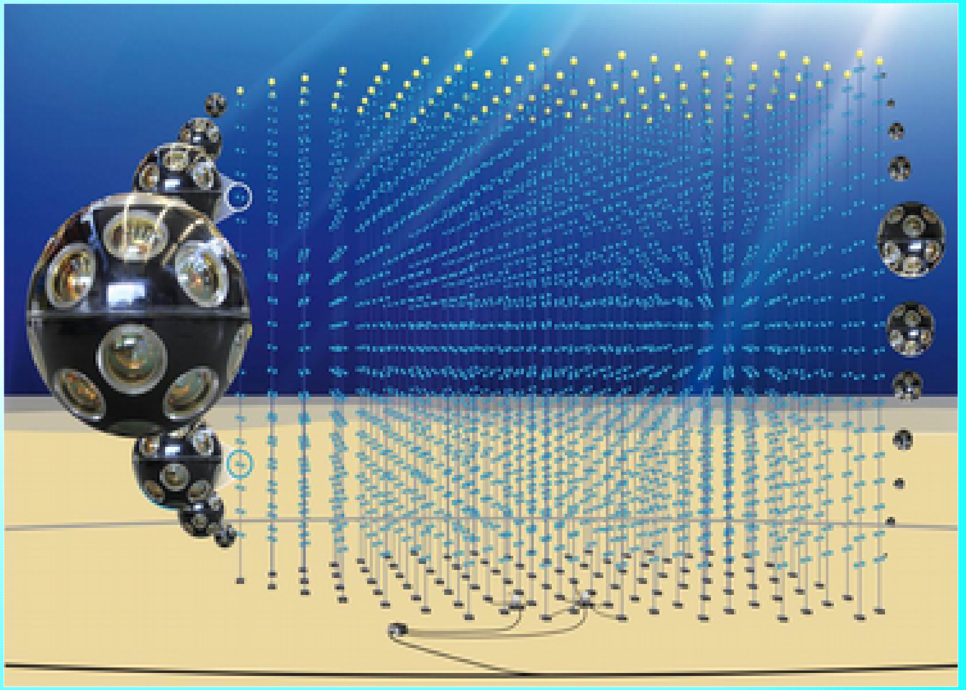
ORCA

Oscillation Research with Cosmics in the Abyss

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

450 m



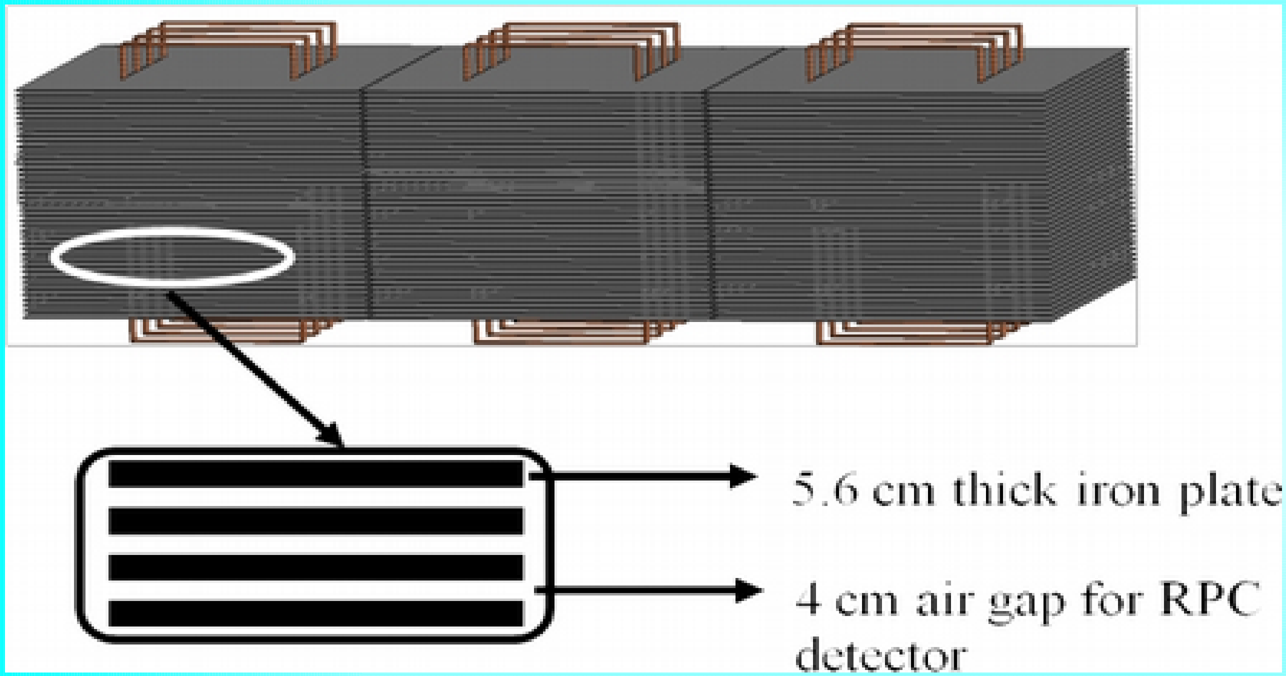


- 31 3" PMTs
- Digital photon counting
- Directional information
- Wide angle view

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)

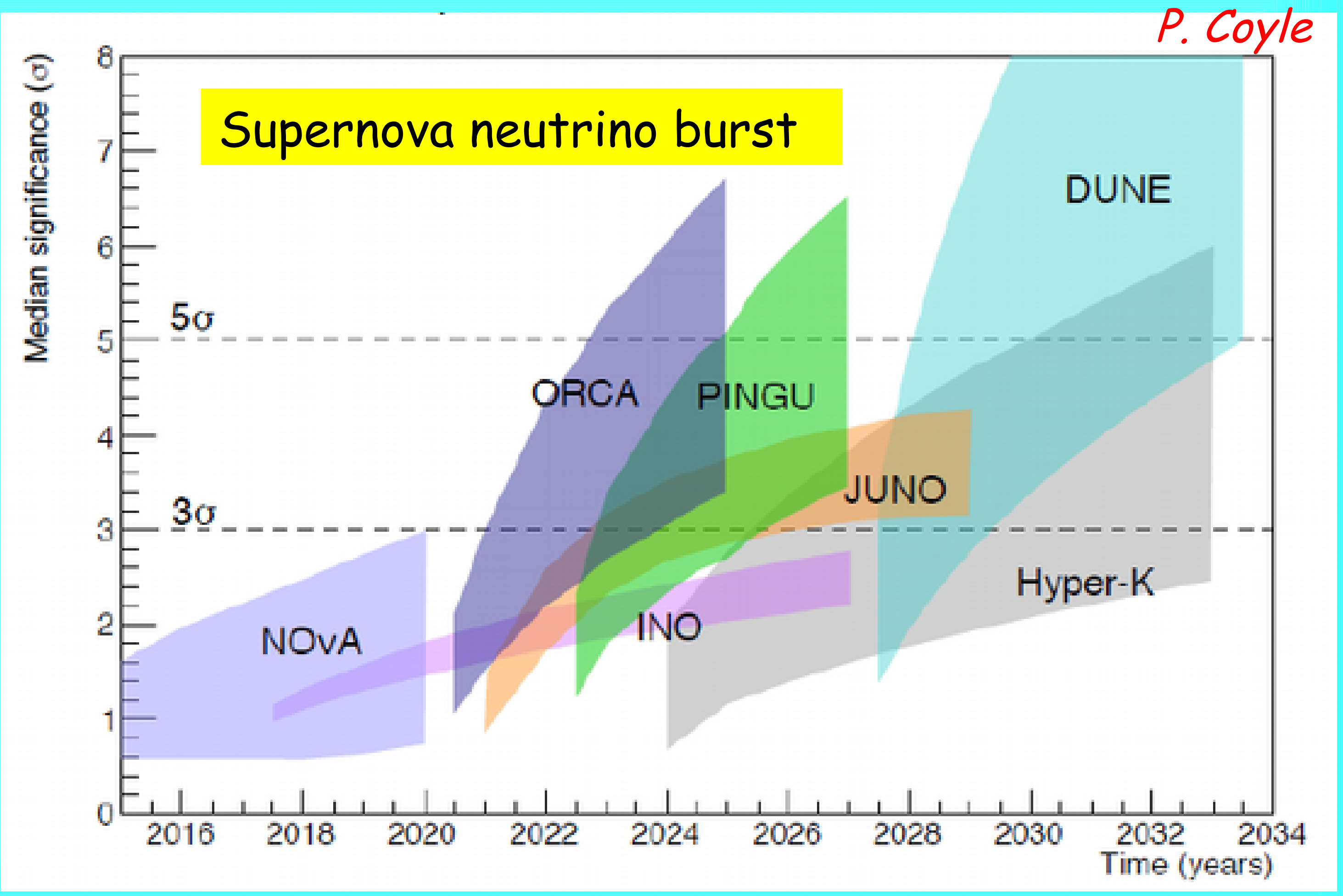


Resistive plate chambers

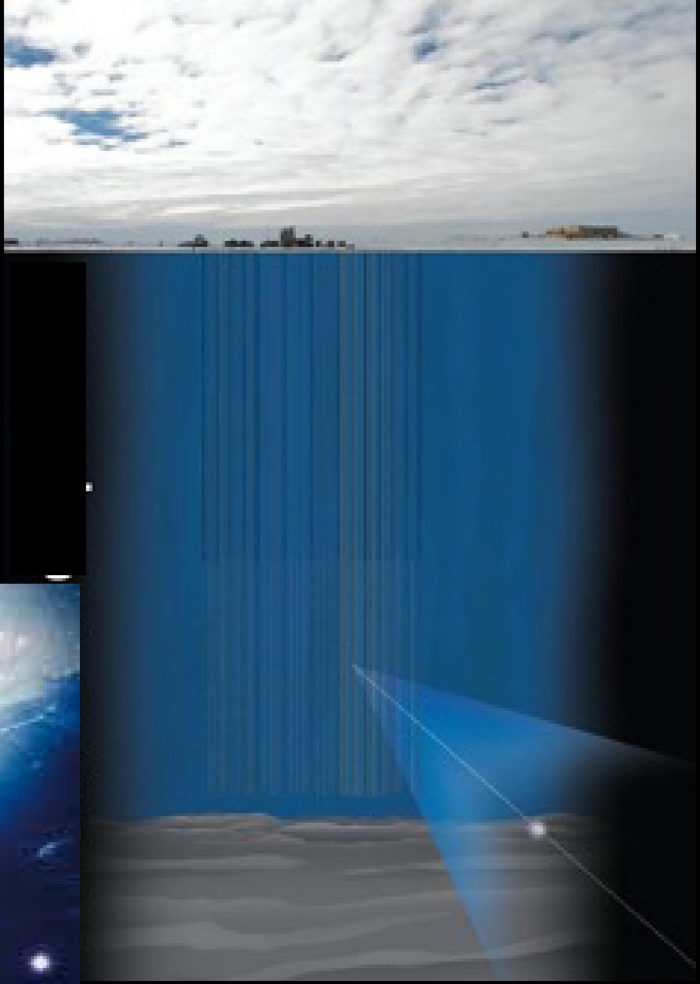
Energy and direction of the muons; energy of multi-GeV hadrons; charge of muon

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

Race for the mass hierarchy



CP-violation



Leptonic

CP-phase

phenomenology

Theory

probe of the underlying physics, enters various test equalities

Cosmic neutrinos

Predicting CP-ph

In quark sector?
Special values of

Long Baseline eutrino beams

Atmospheric neutrinos

The only possible way to measure the phase
bln $, after 20??

0nbb- decay

insensitive to CPV in standard 3nu scenario

Cosmology

Leptogenesis

Lepton asymmetry, oscillations in the Early Universe

Solar neutri

Supernova neutrino

CP-violation and CP-phase

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

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

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

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

CP- transformations: $\nu \rightarrow \nu^c$ $\nu^c = i \gamma_0 \gamma_2 \nu^+$ up to Majorana phase

Under CP-transformations:

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

Matter potential $V \rightarrow -V$

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

Degeneracy of effects: Matter can imitate CP-violation

CP- violation phase

F. Capozzi et al, NOW 2016

Theory

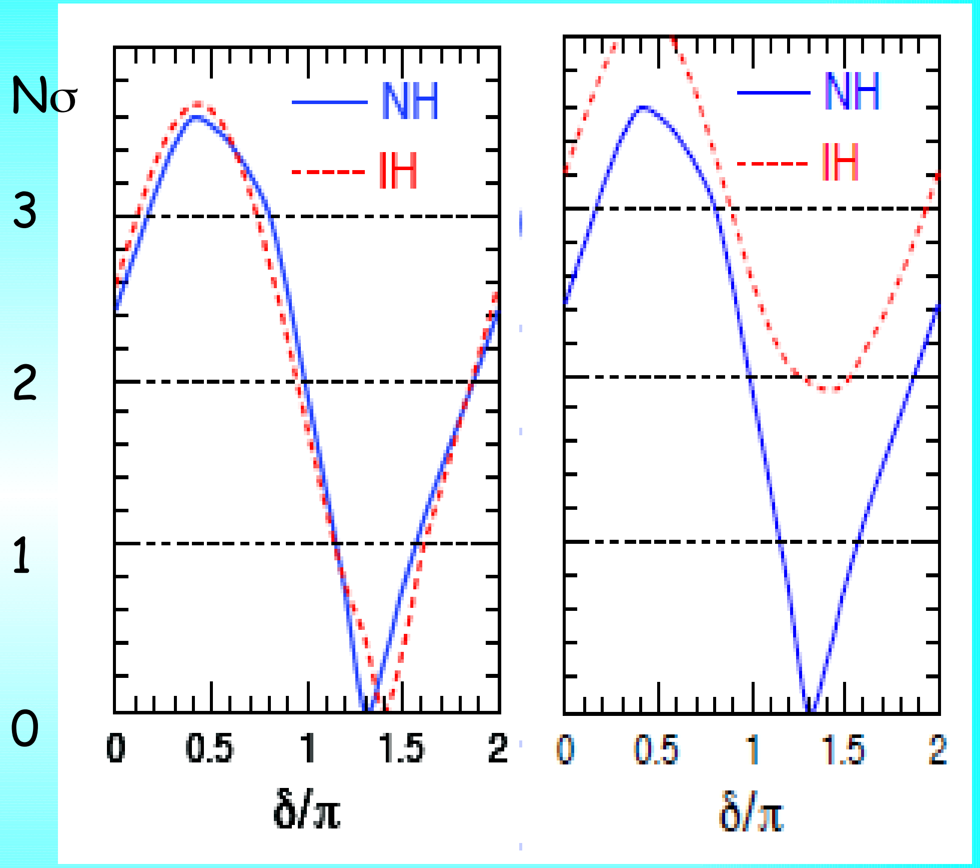
probe of the underlying physics, enters various test equalities

If the same origin as in quark sector : $\delta \sim \lambda^2$ - small

Special values, e.g.

$\delta = -\pi/2$

would testify for symmetry



Single minimum

CPV

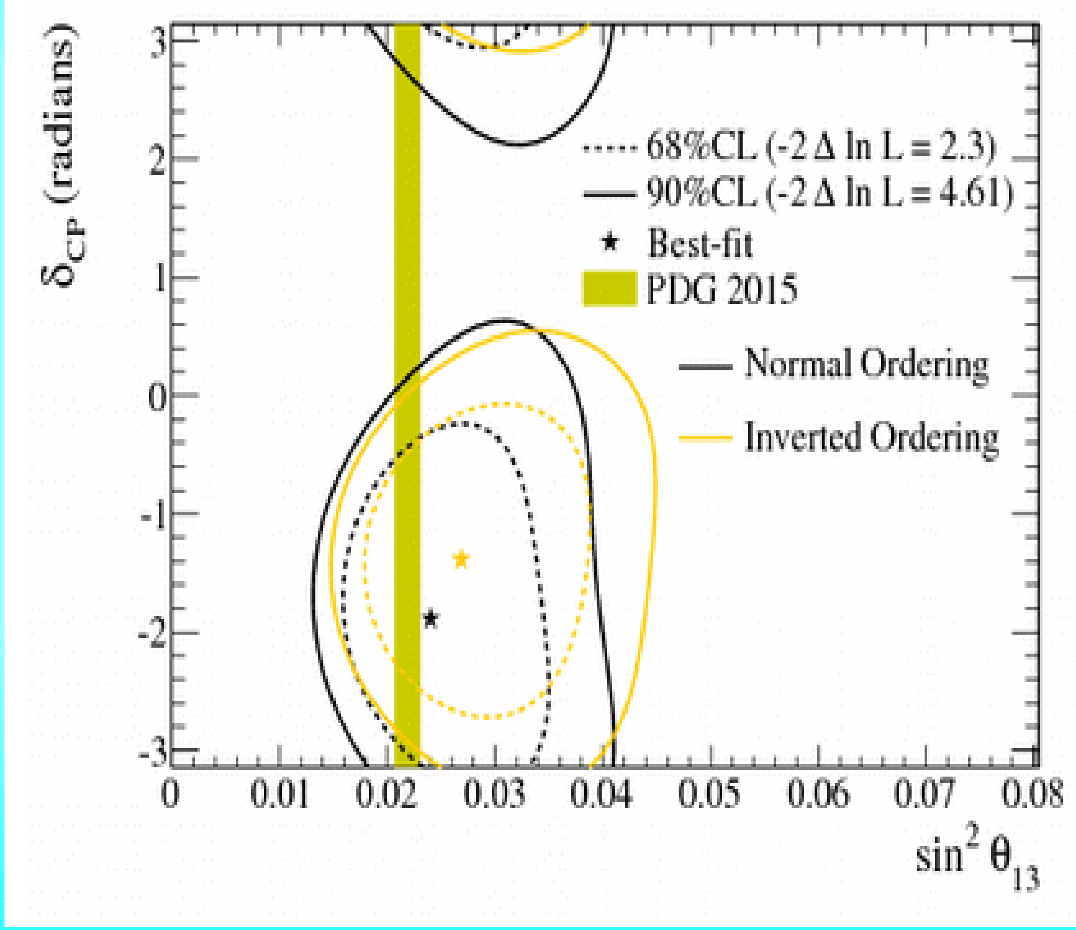
LBL + solar: 1.8 σ

+ reactors: 2.1 σ

+ atmosph: 2.4 σ

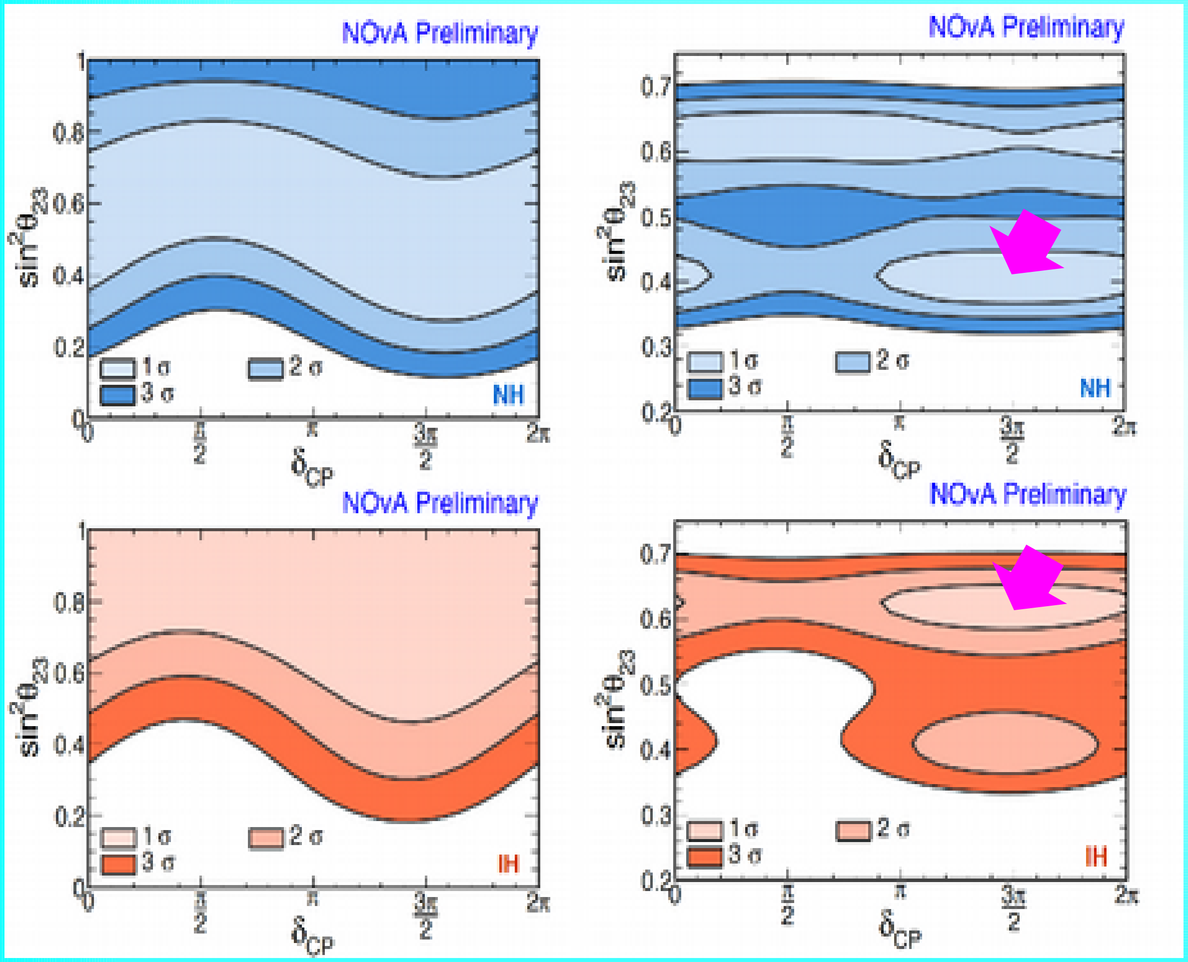
T2K results

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



NOvA 2 years data

Jianming Bian, arXiv:1611.07480 [hep-ex]



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

appearance + disappearance

Measuring CP-phase

Global fit

K + NOvA + reactors

J-PARC- SK

750 kw upgrade

at 2- 3 σ

T2K2: by 2026 further upgrade
→ 1.3 MW, 20 times bigger p.o.t. than now

T2K2 alone establishing CPV
with C.L. > 3 σ before HK,DUNE…

Dedicated experiments

J-PARC- HK

DUNE LBNF

ESS European spalation Source (Lund)

- π/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

3 GeV

Mass hierarchy

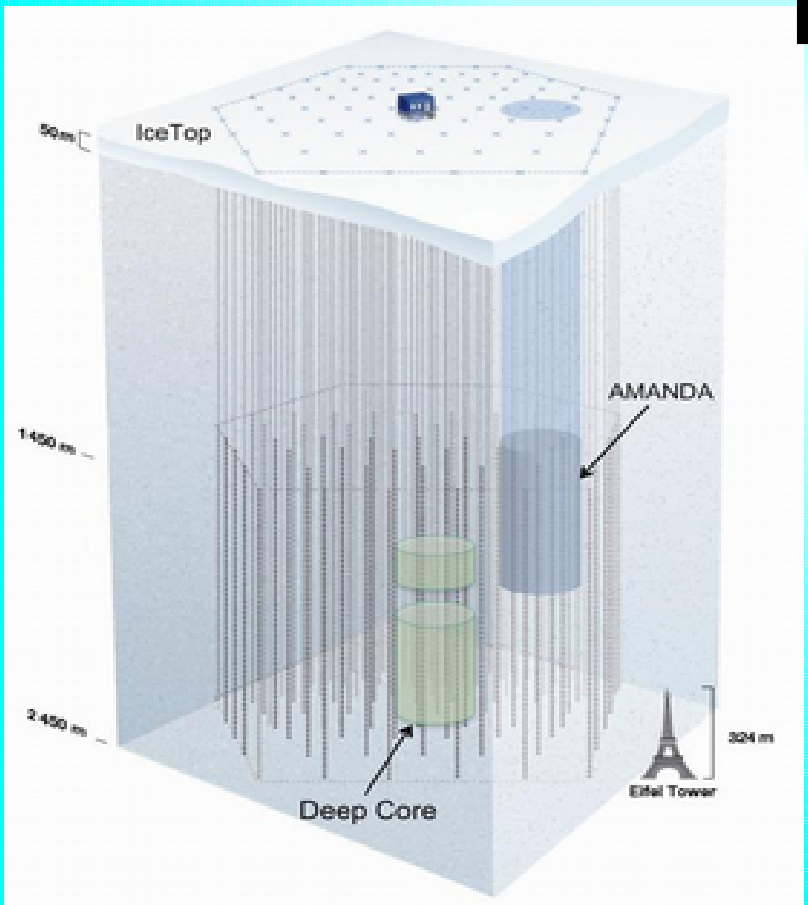
ORCA

3 times denser array than PINGU

Super-PINGU -ORCA

0.5 – 1 GeV

Few Mtons in sub-GeVrange



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

Megaton-scale Ice Cherenkov Array

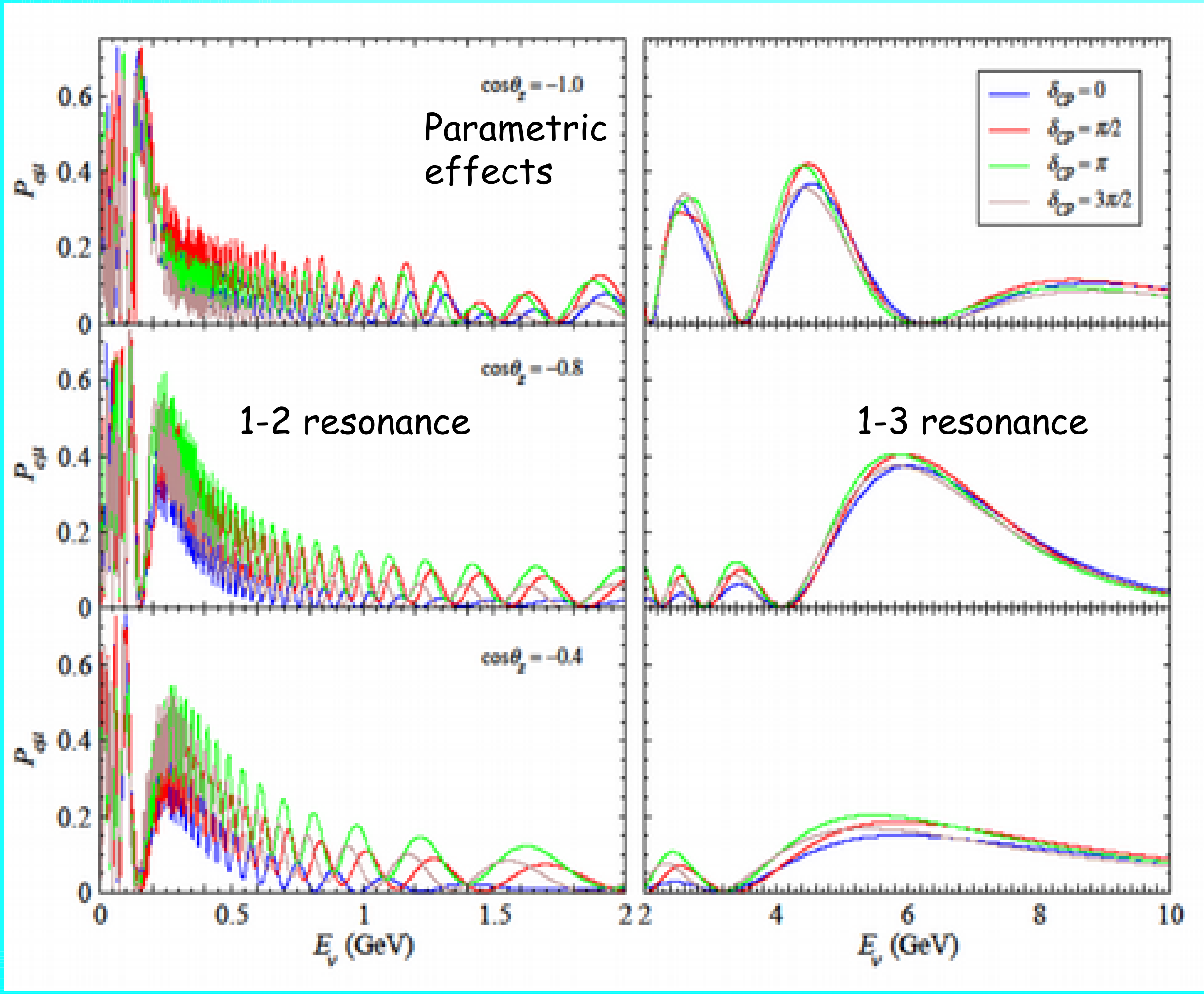
MICA

0.01 GeV

Probabilities

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

$\nu_e \rightarrow \nu_\mu$ NH



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

``Magic lines"

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

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

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

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

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

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

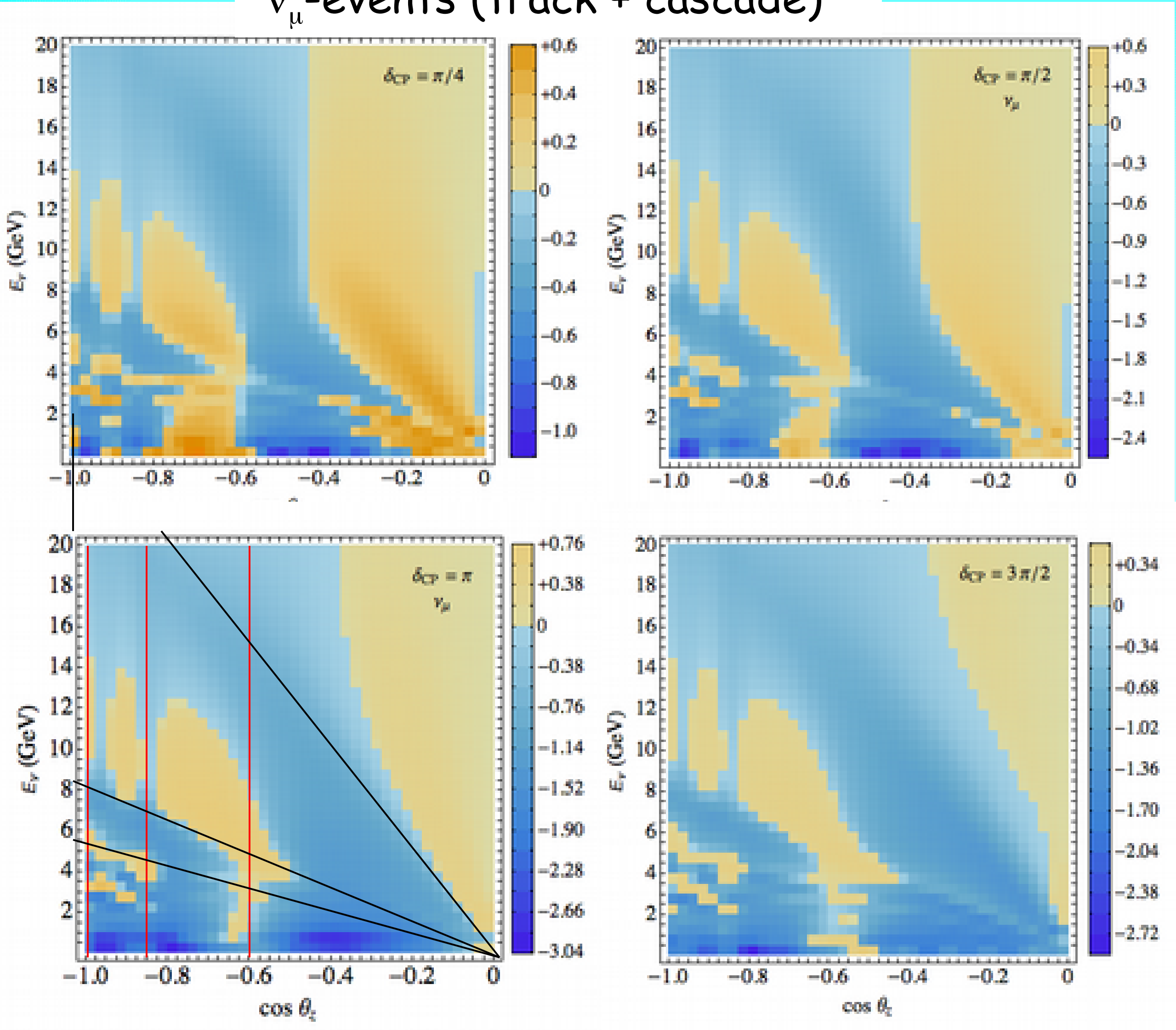
$|S_{ij}|$ - distinguishability of different values of CP-phase

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

CP-domains

S-distributions for different values of δ

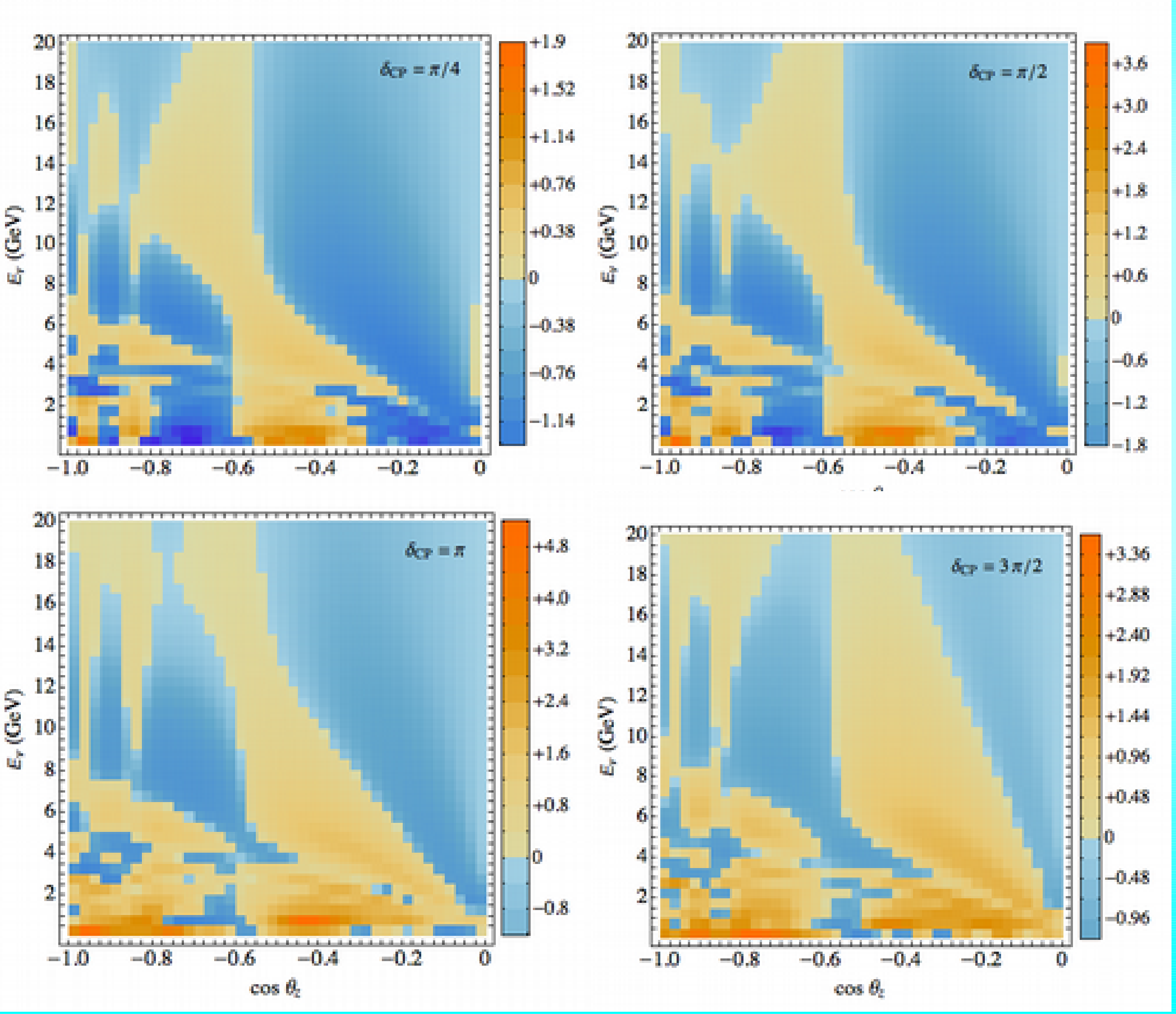
ν_μ-events (track + cascade)



CP-effect:
2 - 5 %
ΔN = 2 – 10 events in each small bin

CP-domains

Cascades (ν_e - events)



S-distributions for different values of δ

Strong asymmetry of CP differences

Have opposite sign at low energies with respect to ν_μ-events

CP violating phase

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

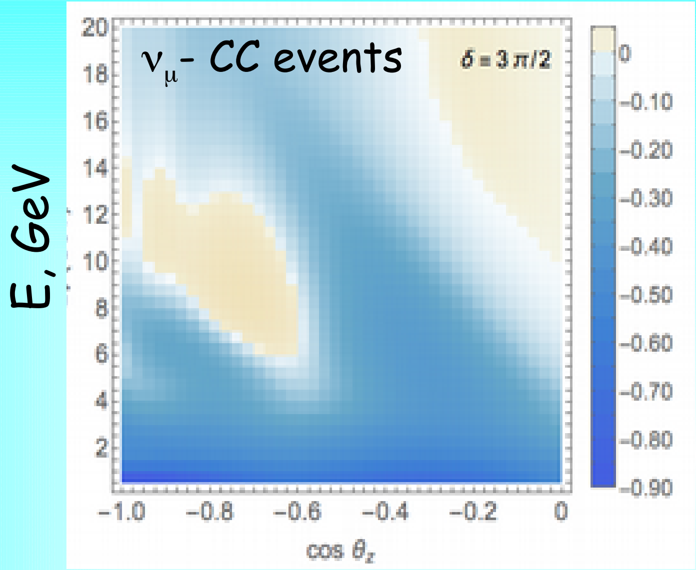
S-distributions for different values of δ

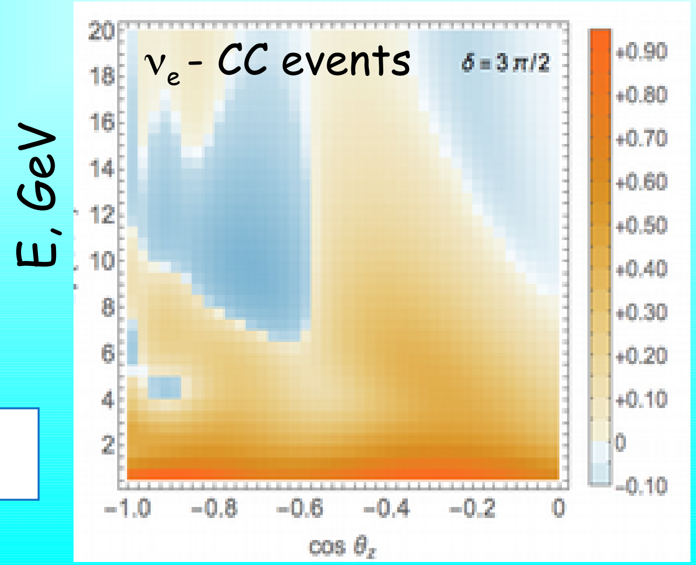
$$S_{ij} = \frac{N_{ij}^{\delta} - N_{ij}^{\delta=0}}{\sqrt{N_{ij}^{\delta=0}}}$$

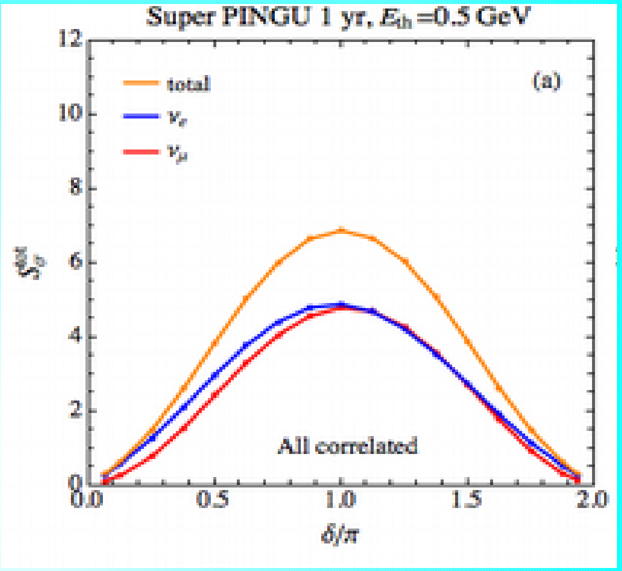
Super PINGU, 1 year

Total distinguishability

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







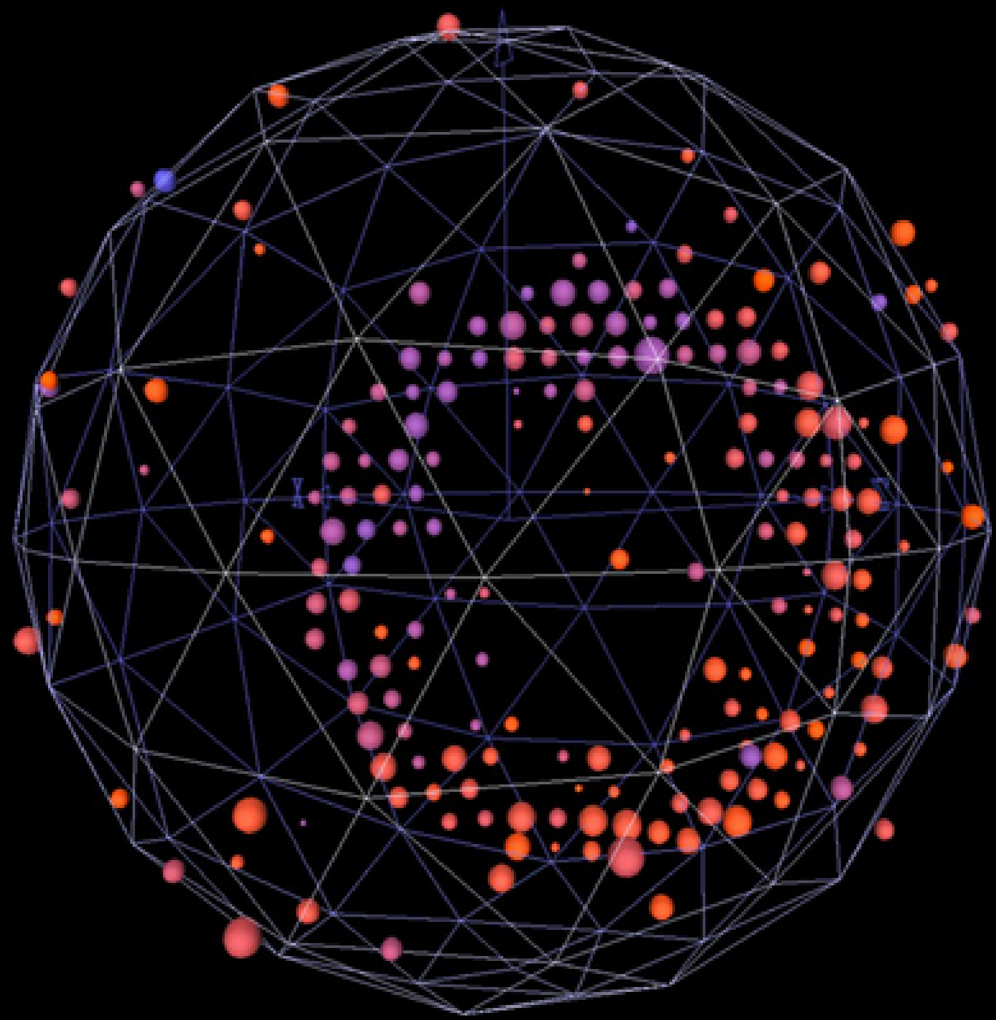
Flavor misidentification reduces distinguishability by factor 1.5 - 2

S_σ ~ 3, for $\delta = 3/2\pi$
4 years of exposure

ORCA: effect of δ_{CP} ~0.5 σ

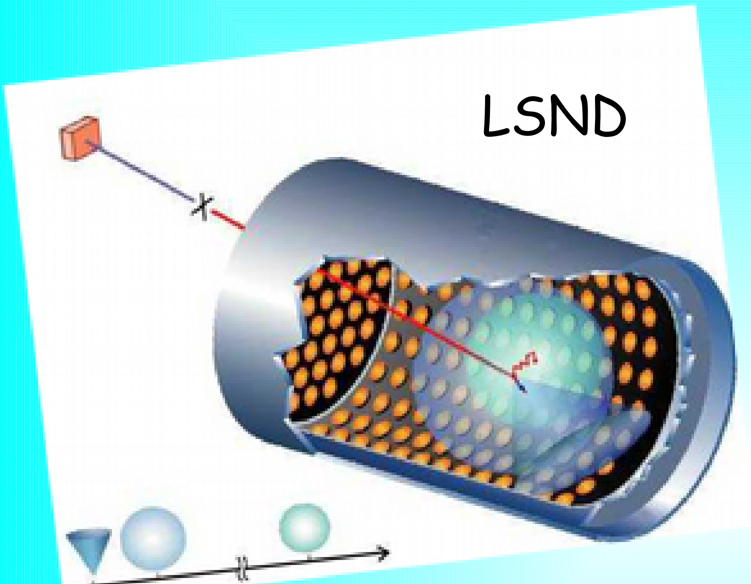
Sterile

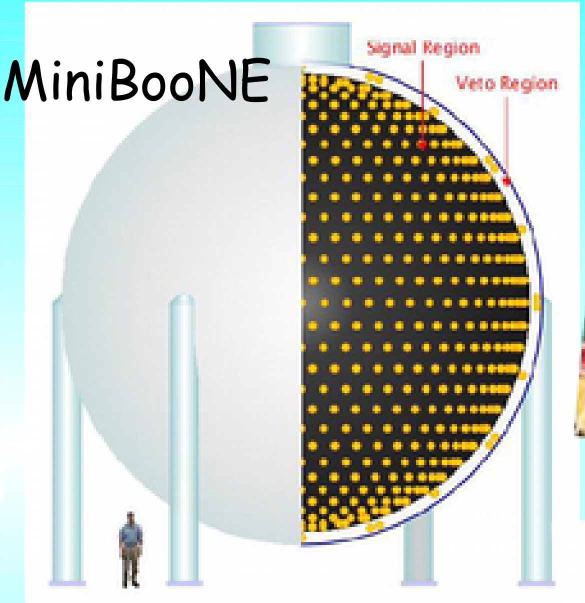
Neutrinos

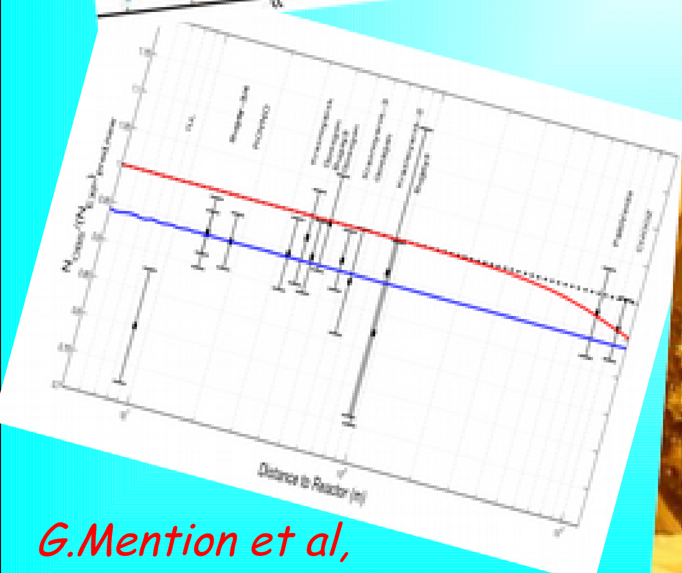


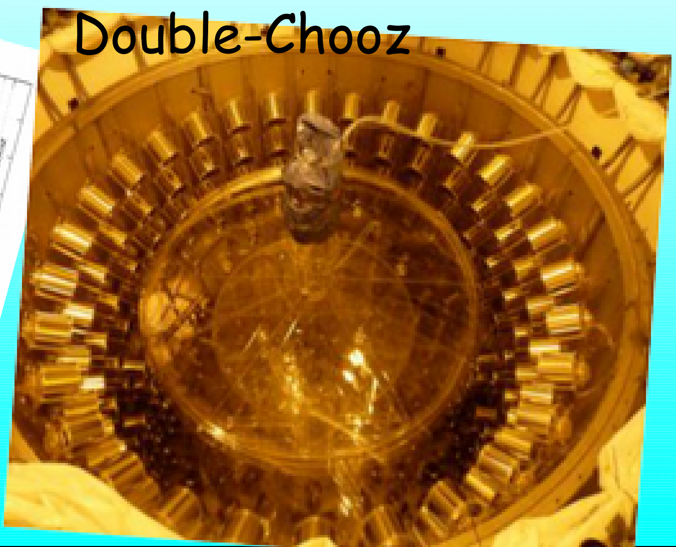
Evidences?

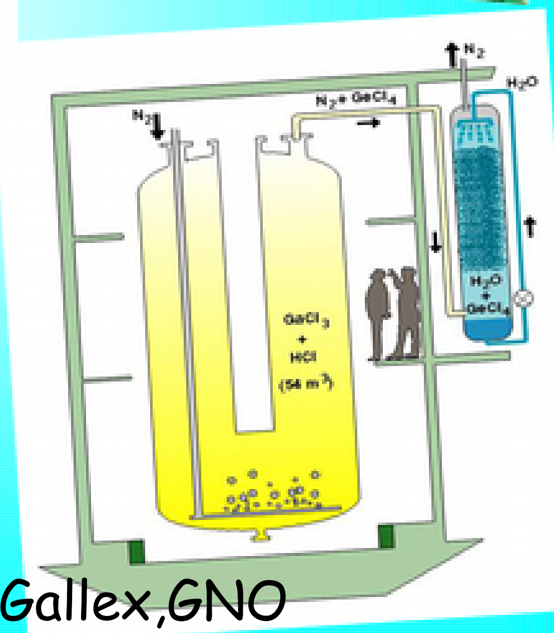
$\Delta m_{41}^2 = 1 - 2\ eV^2$





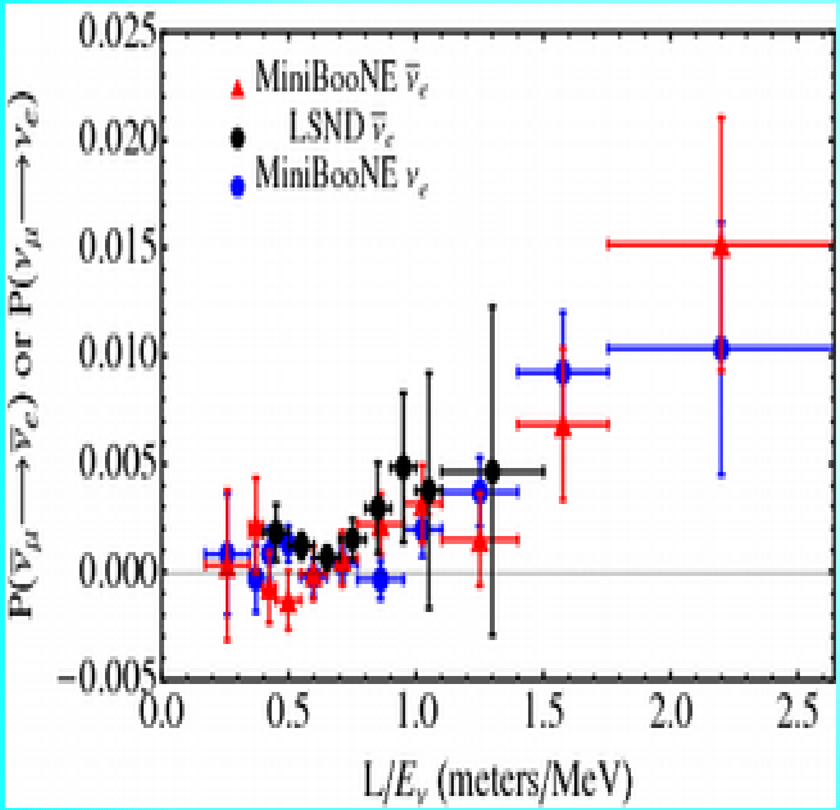


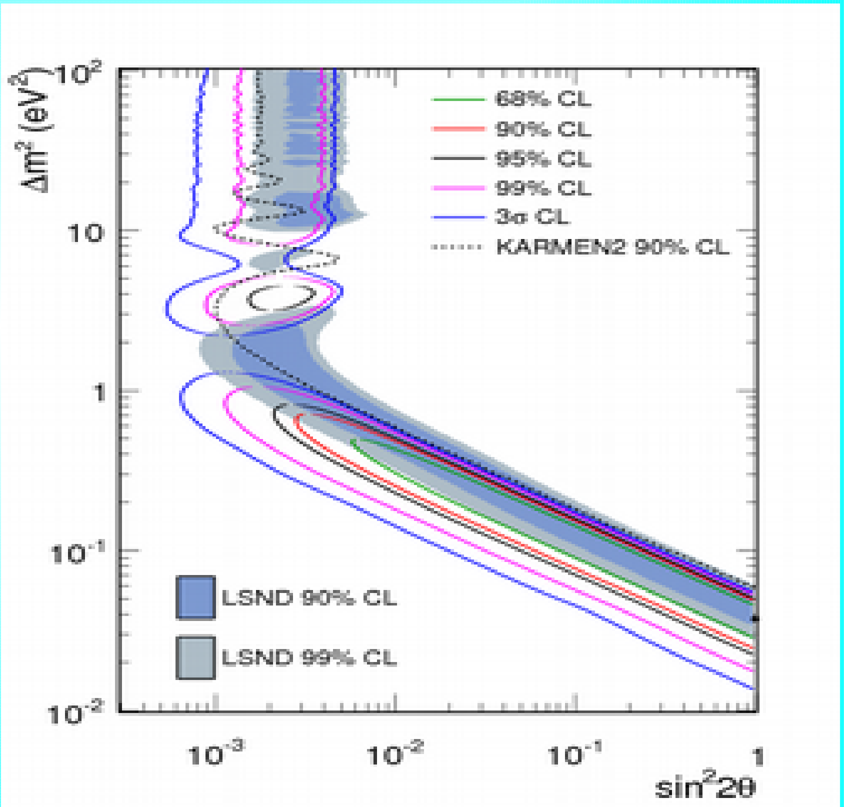




G.Mention et al, arXiv: 1101.2755

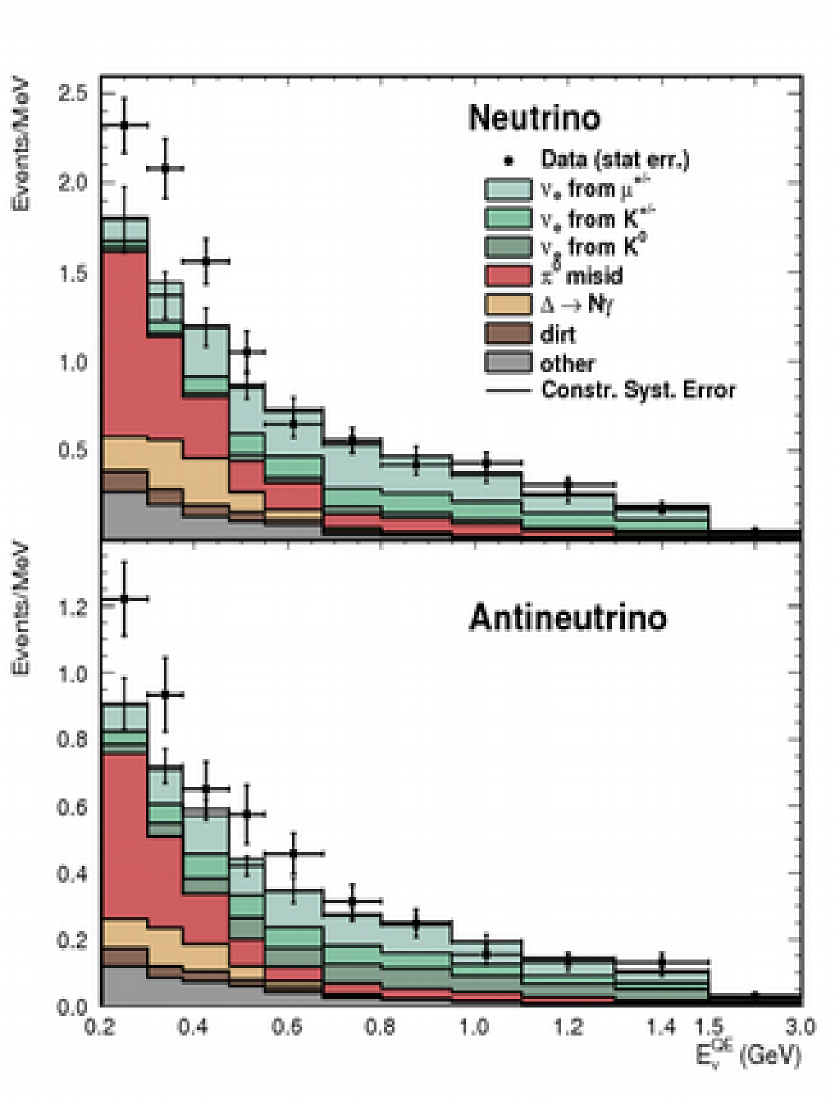
LSND and MiniBooNE

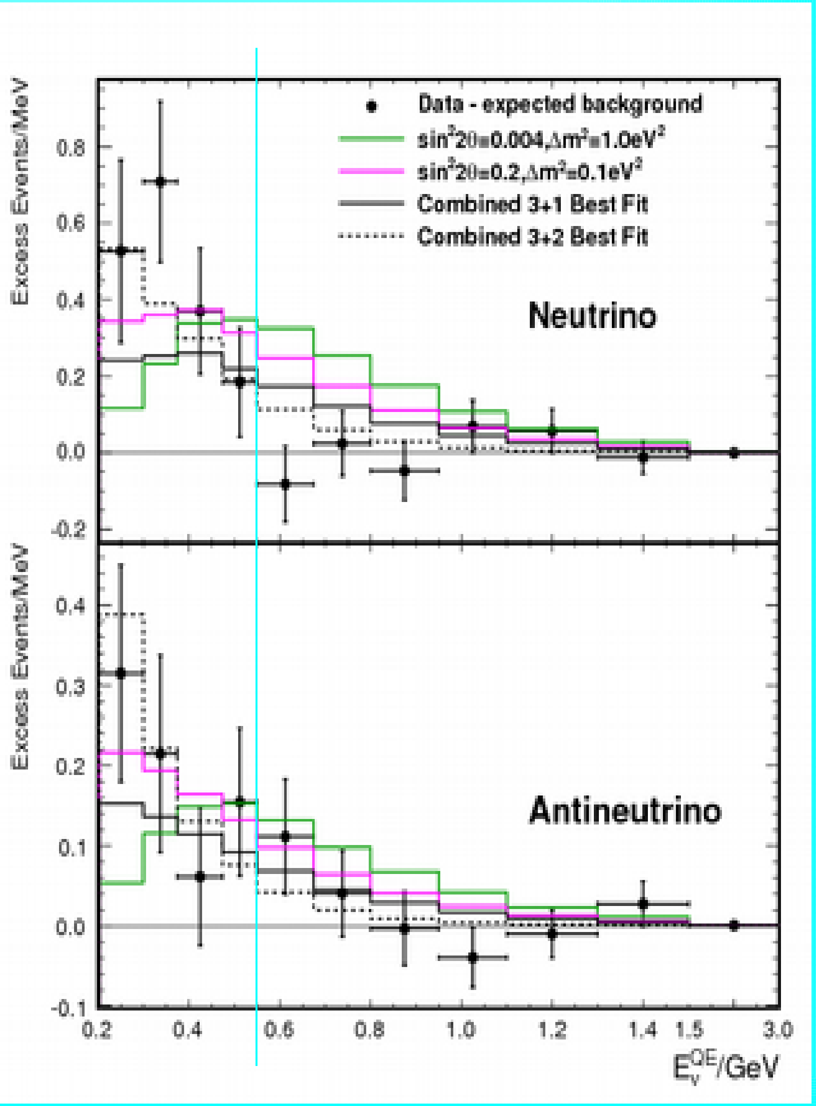




Consistency? Continuation
of the background

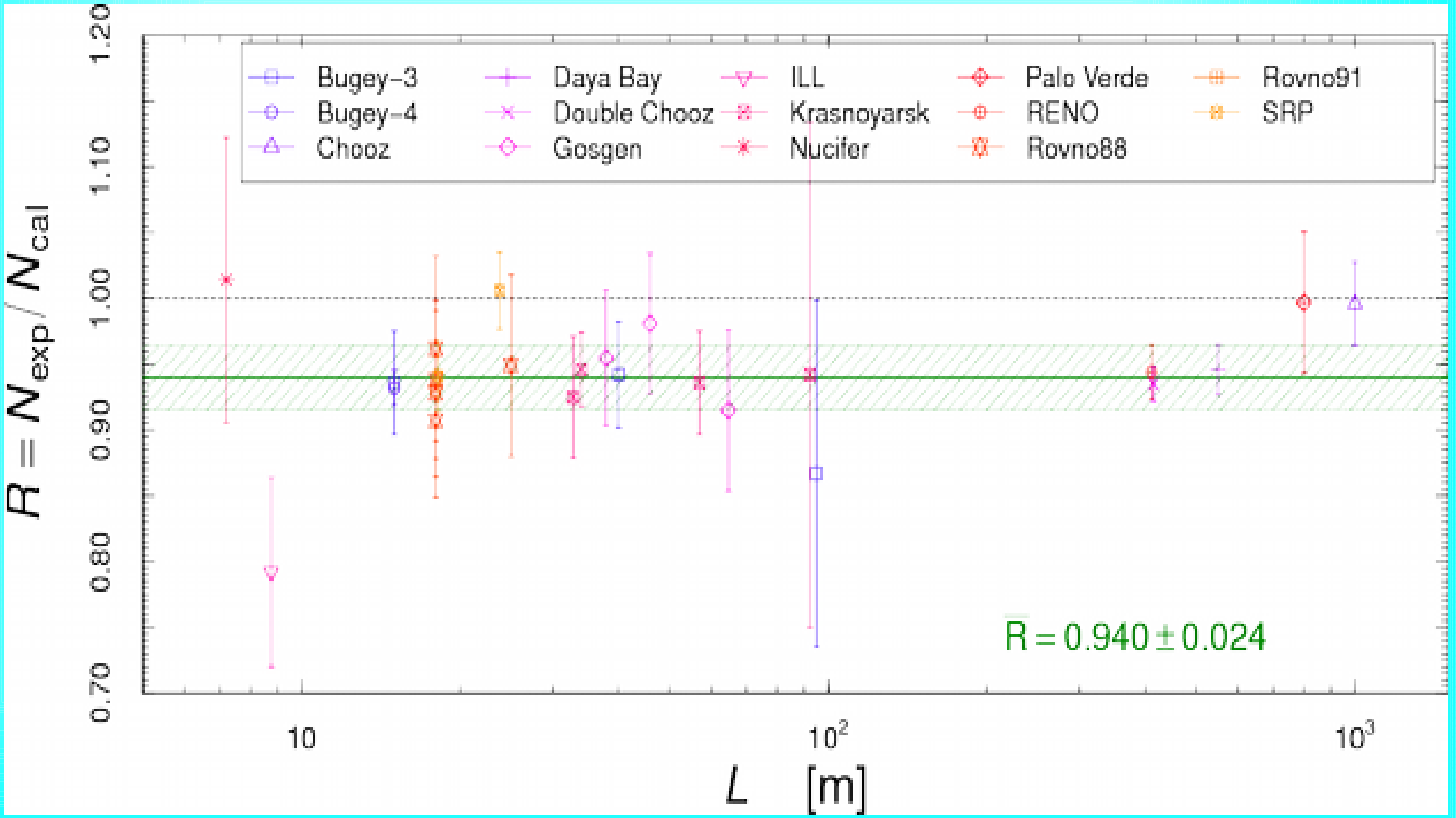
MiniBooNE results



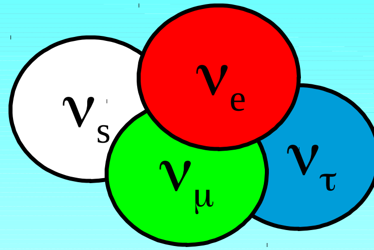


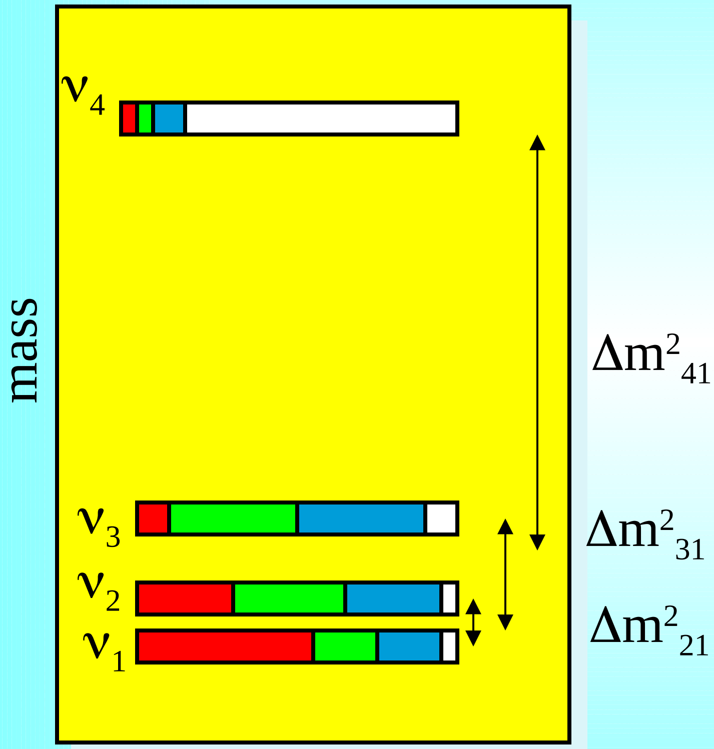
Reactor neutrino anomaly

SNO+



(3 + 1) scheme





LSND/MiniBooNE: vacuum oscillations

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

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

For reactor and source experiments

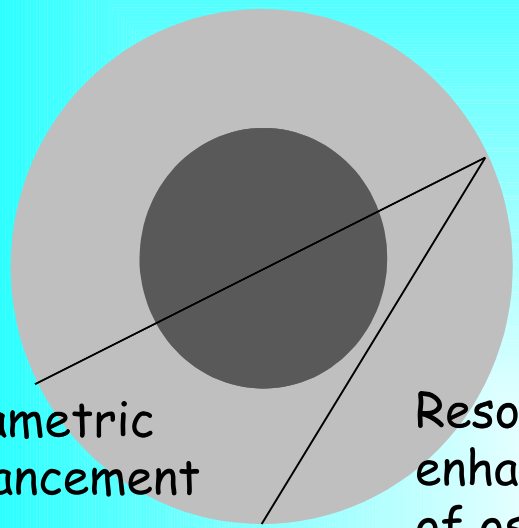
$$P \sim 4|U_{e4}|^2 (1 - |U_{e4}|^2)$$

Strong perturbation of 3ν pattern:

$$\delta m_{\alpha\beta} \sim m_4 U_{\alpha 4} U_{\beta 4} \sim \sqrt{\Delta m_{32}^2}$$

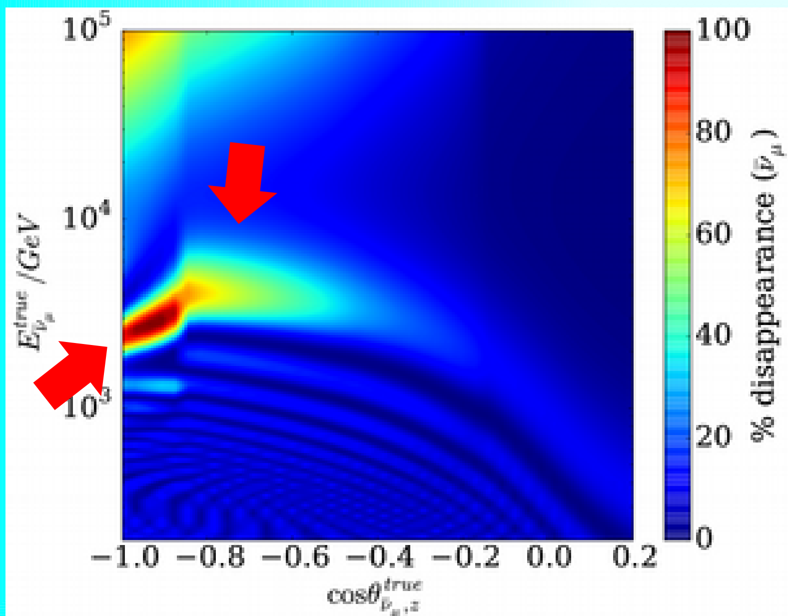
- additional radiation in the Universe
- bound from LSS?

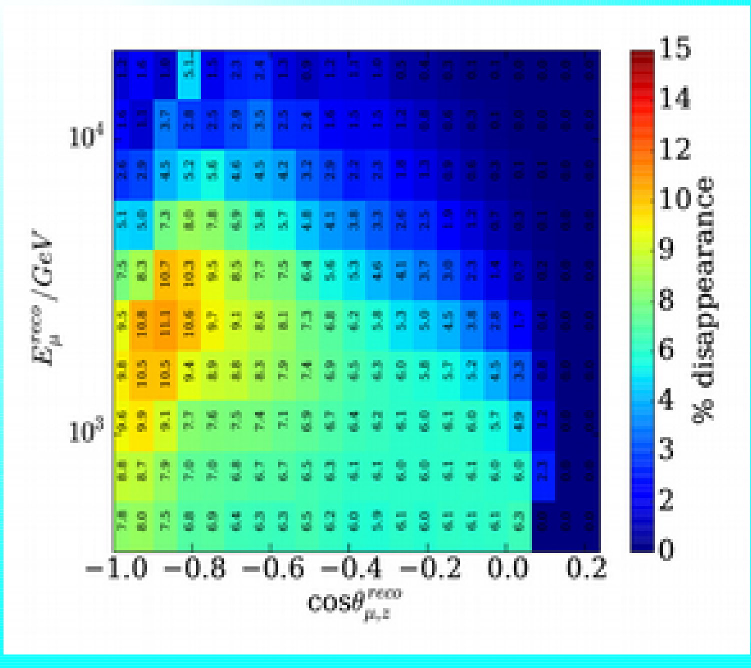
ceCube searches for sterile neutrino



M.G. Aartsen et al,
(IceCube Collaboration)
1605.01990 (hep-ex)

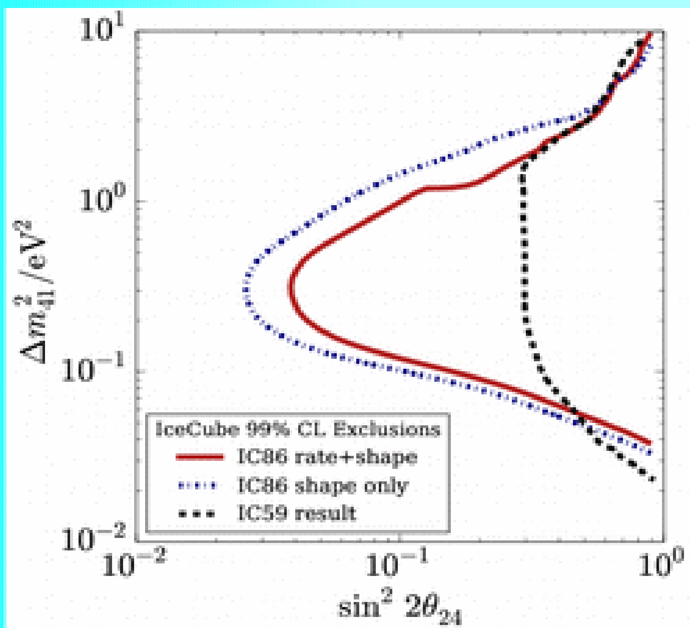
IC86, 2011 – 2012, 343,7 days,
20,145 muon events
(reconstructed tracks) with
E = 320 GeV – 20 TeV



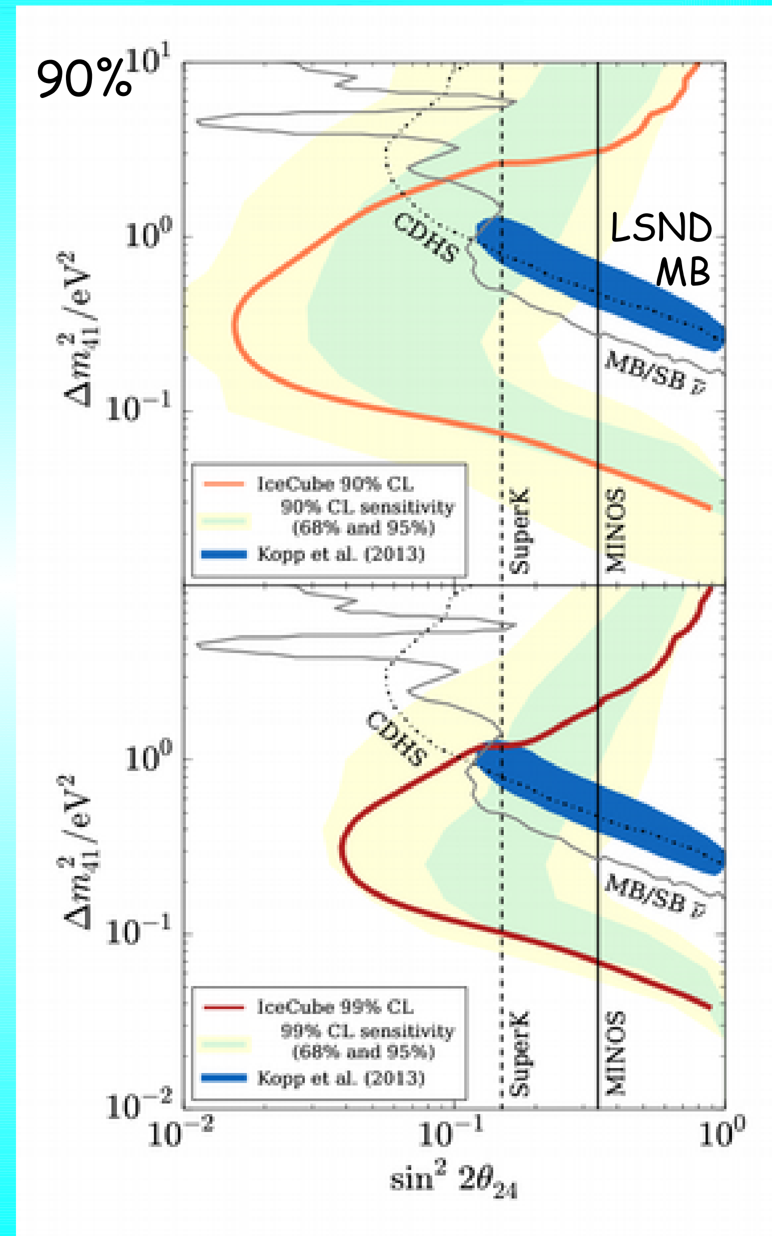


IC bounds

on parameters of sterile neutrinos in 3+1 scheme



Rate and shape



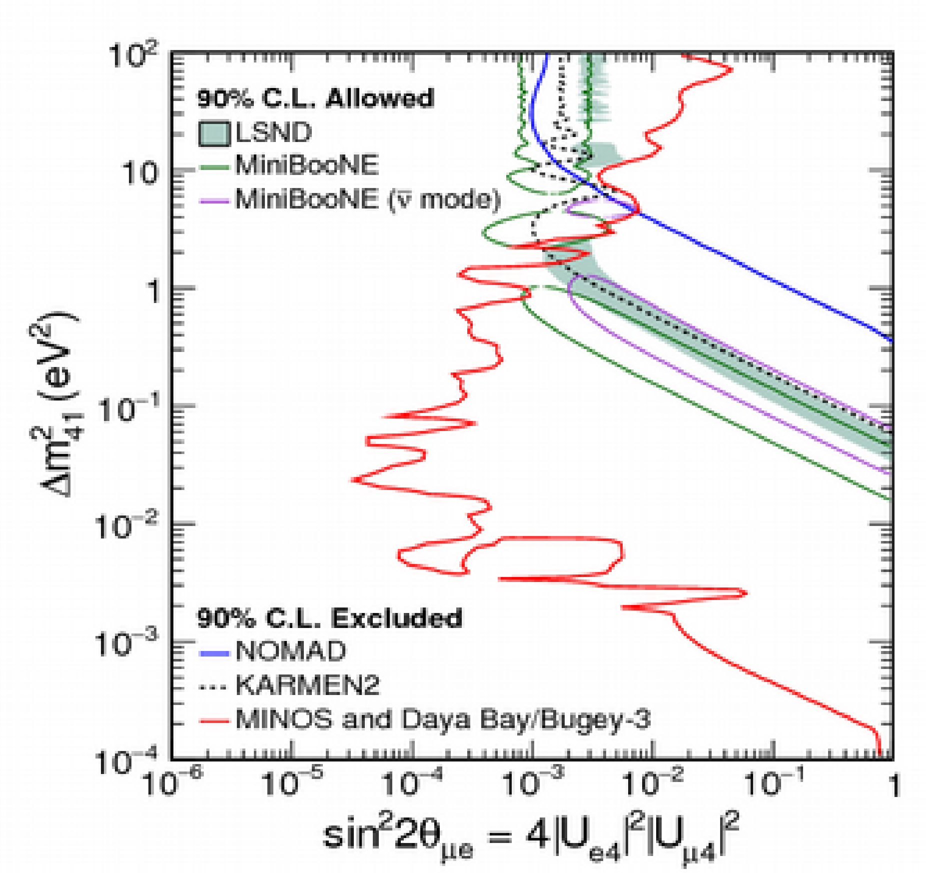
Other experiments results are at 90% CL

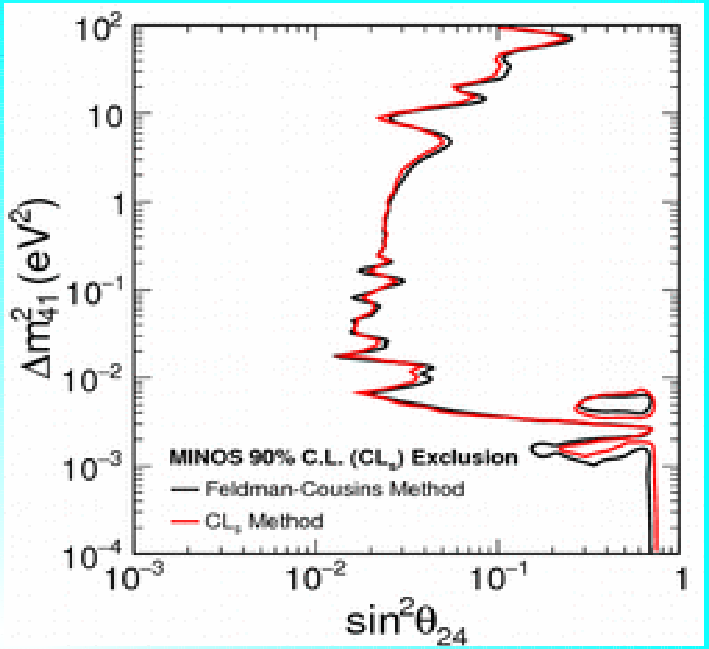
For LSND/MB and SBL

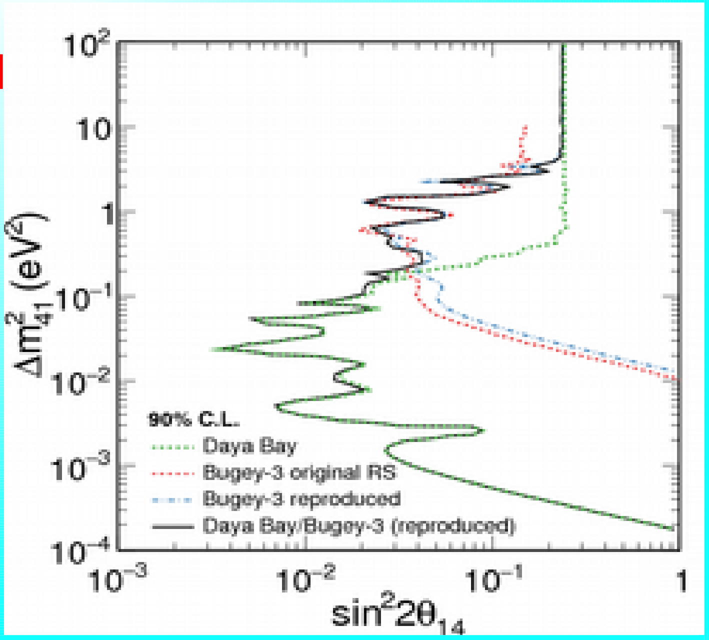
Bounds

from disappearance searches in MINOS, Daya Bay and Bugey-3

Daya Bay and MINOS Collaborations (Adamson, P. et al.) arXiv:1607.01177 [hep-ex]

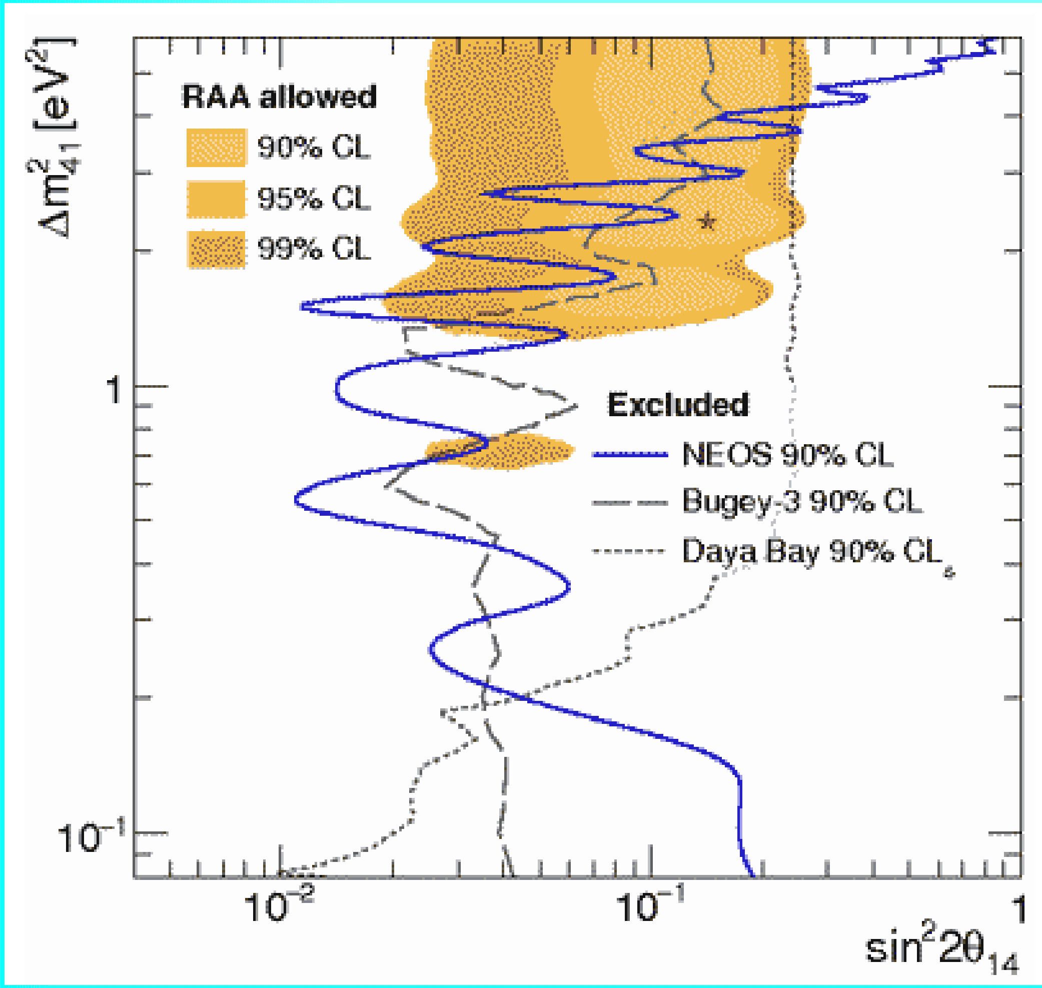






NEOS

Y.J Ko, et al,
arXiv:1610.05134 [hep-ex]

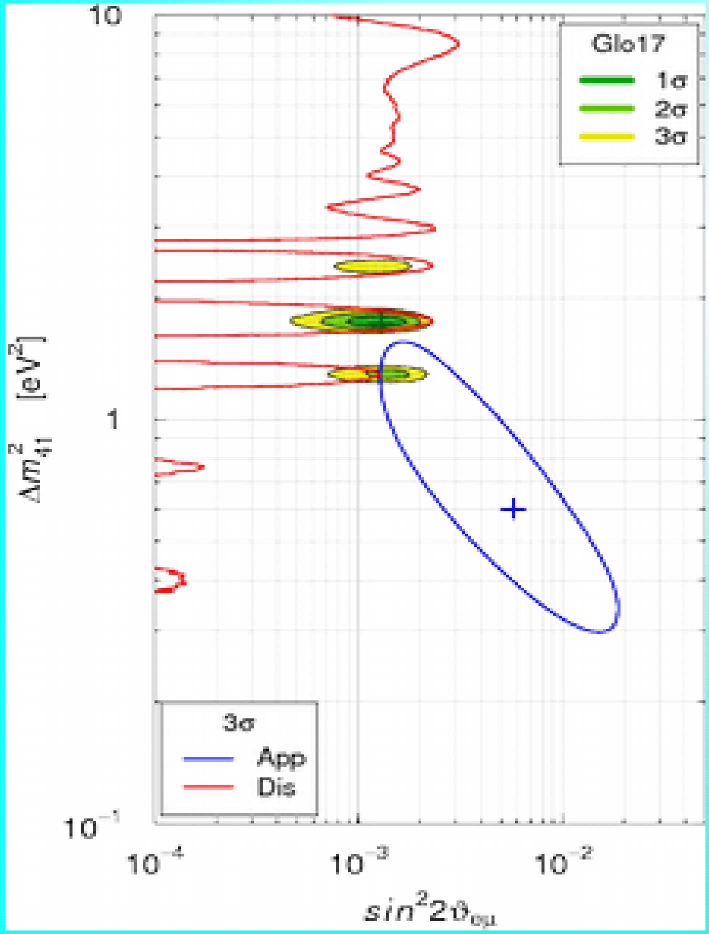


The solid-blue curve is 90% CL exclusion contours based on the comparison with the Daya Bay spectrum,

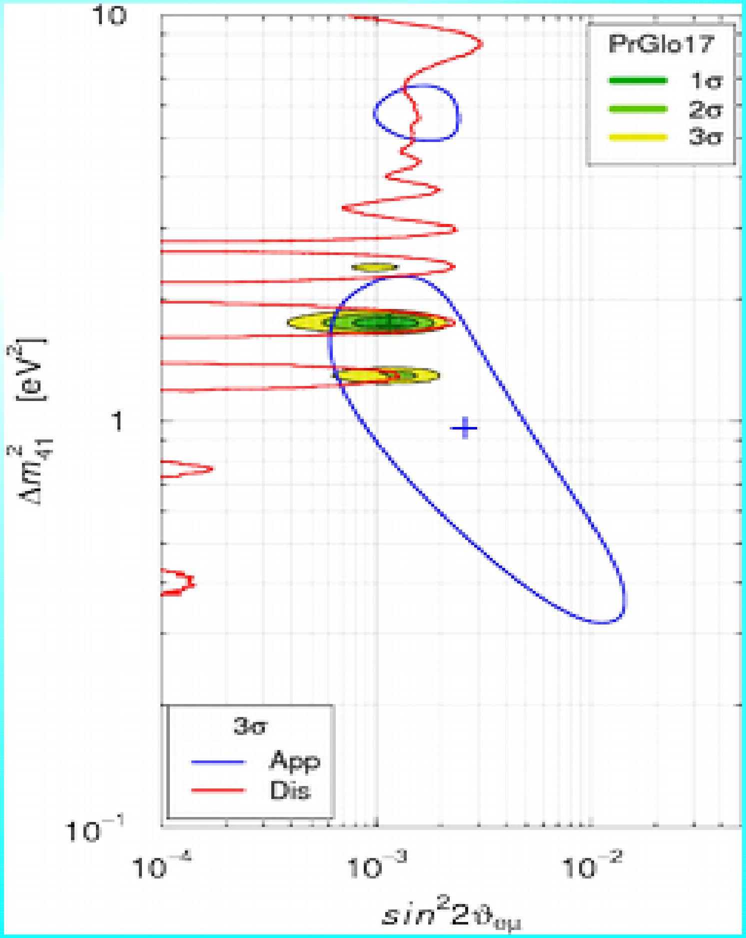
Global fit

S. Gariazzo, C. Giunti, M. Laveder, Y.F. Li, arXiv:1703.00860 [hep-ph]

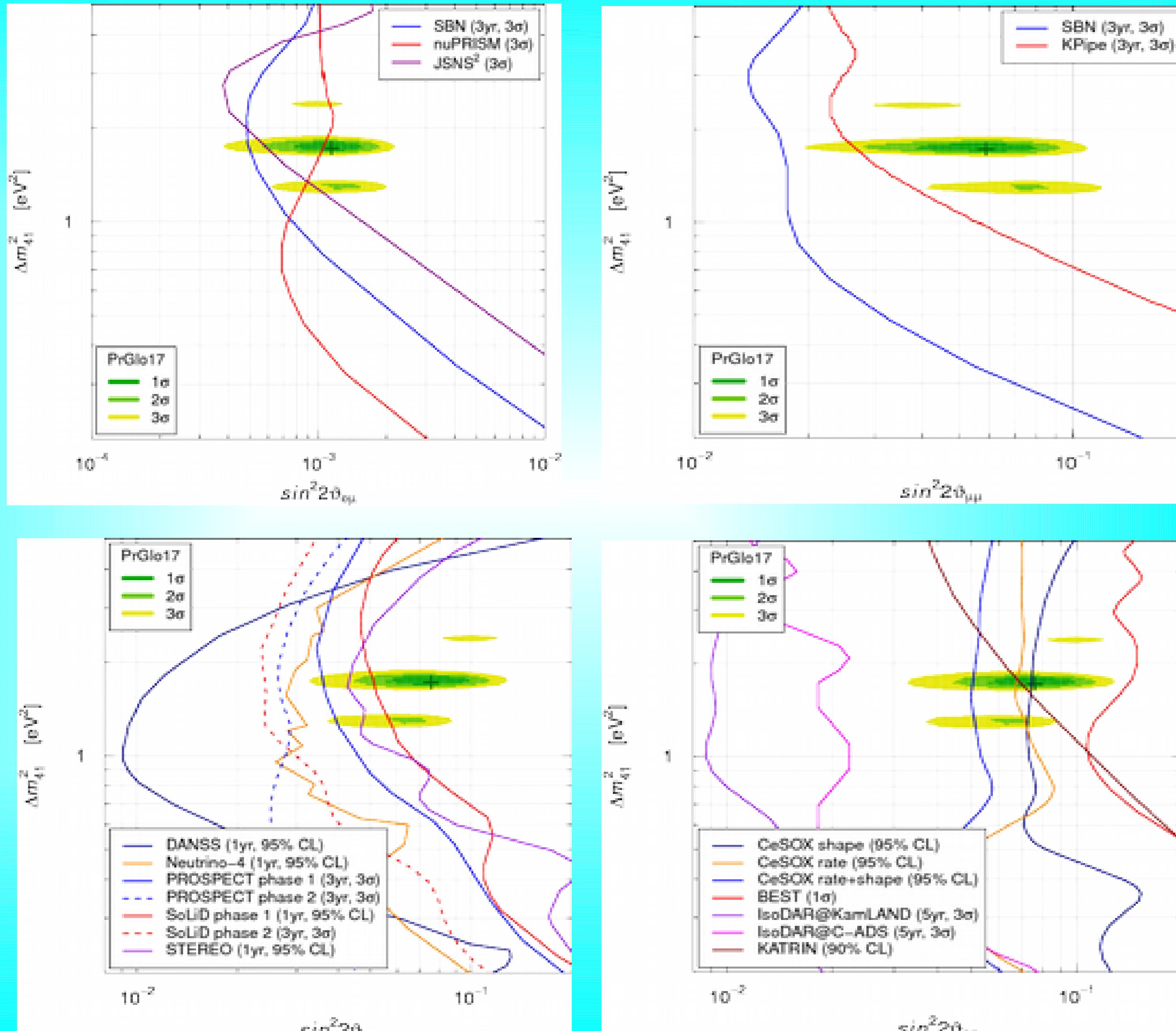
All the data



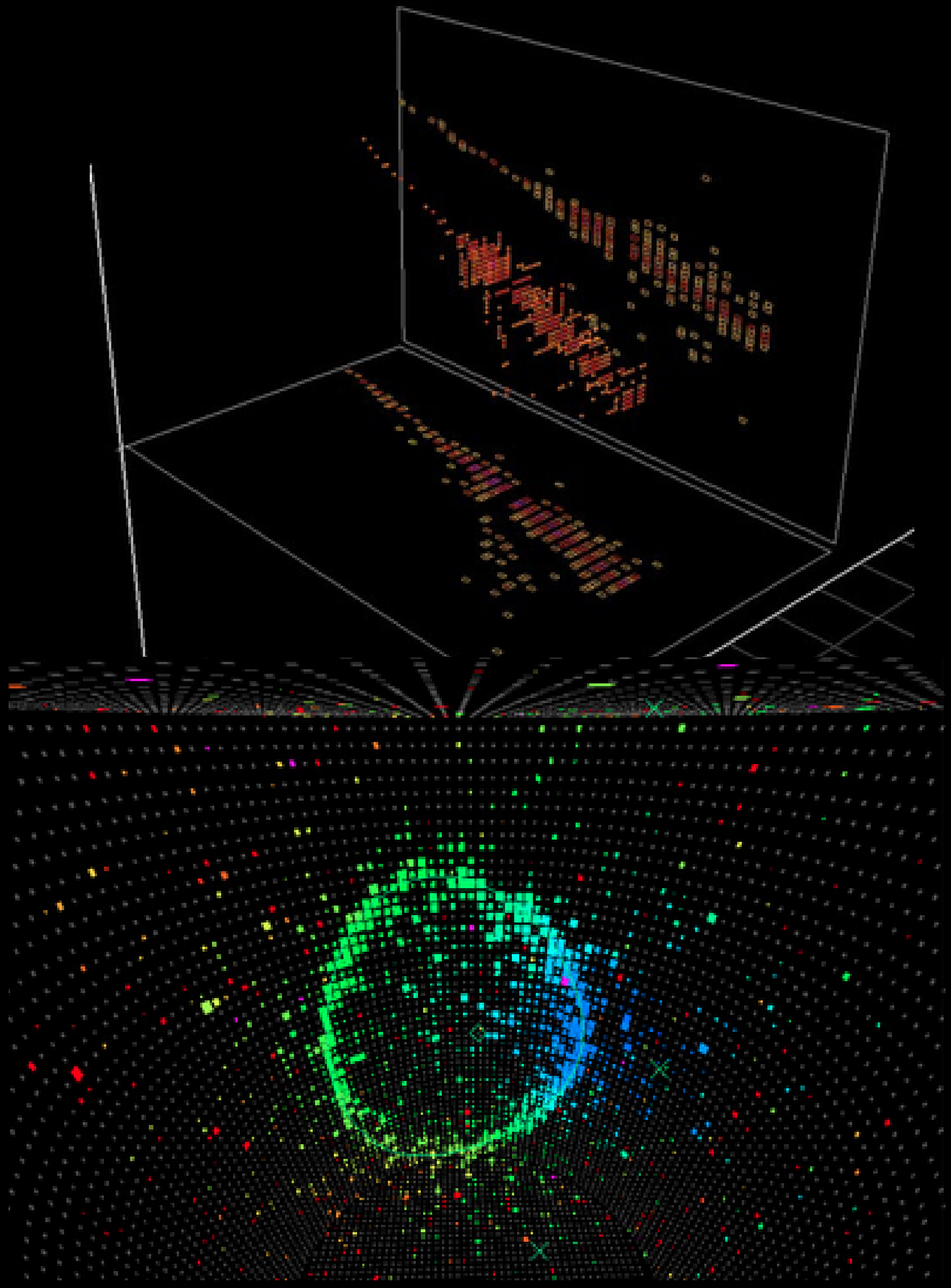
"Pragmatic" global fit (without MiniBooNE low energy excess)



Future experimental bound

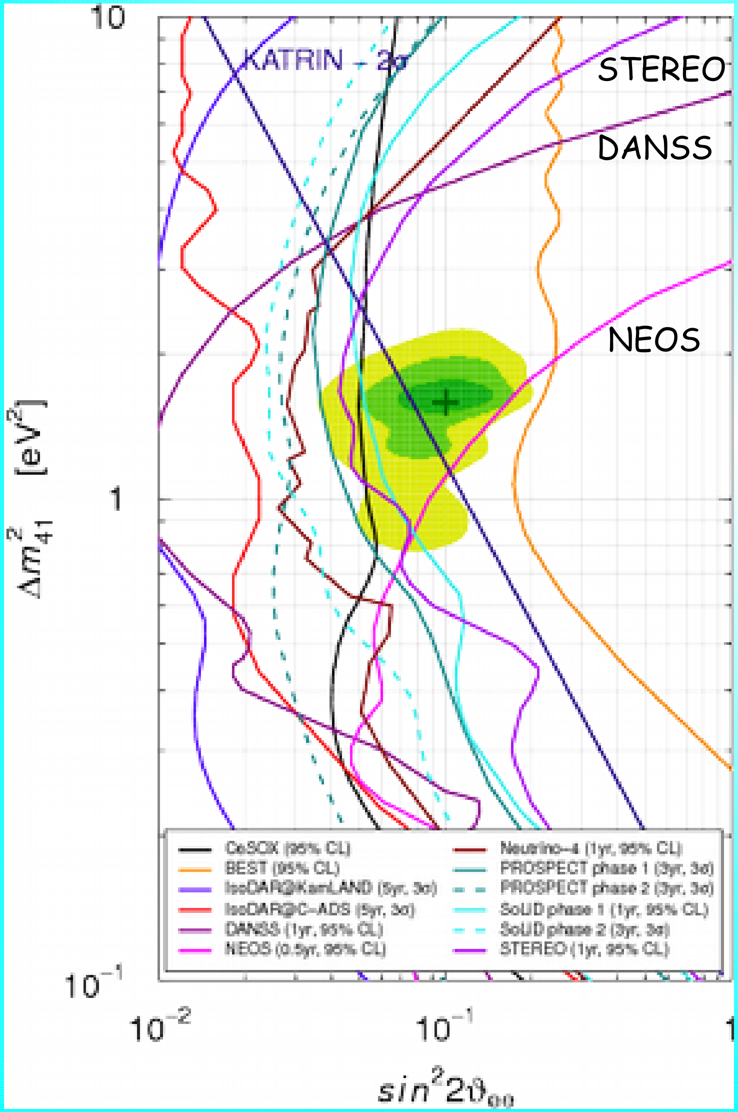


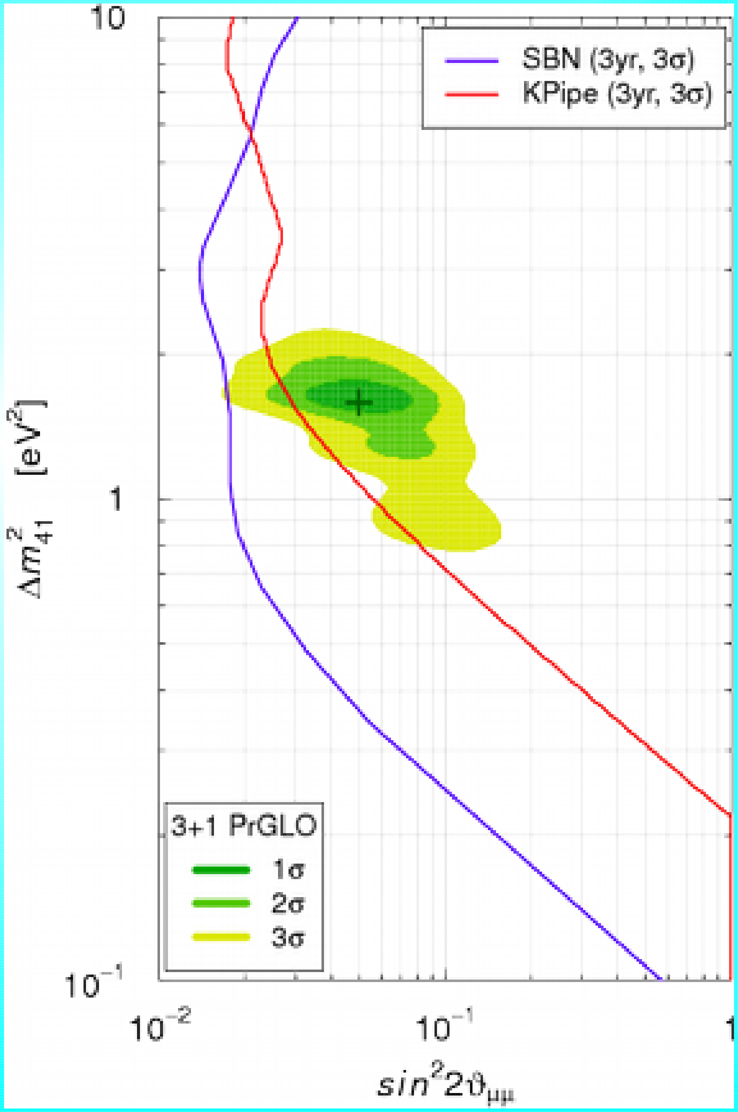
Conclusion



Future

C. Giunti ,
arXiv: 1609.04688 [hep-ph]



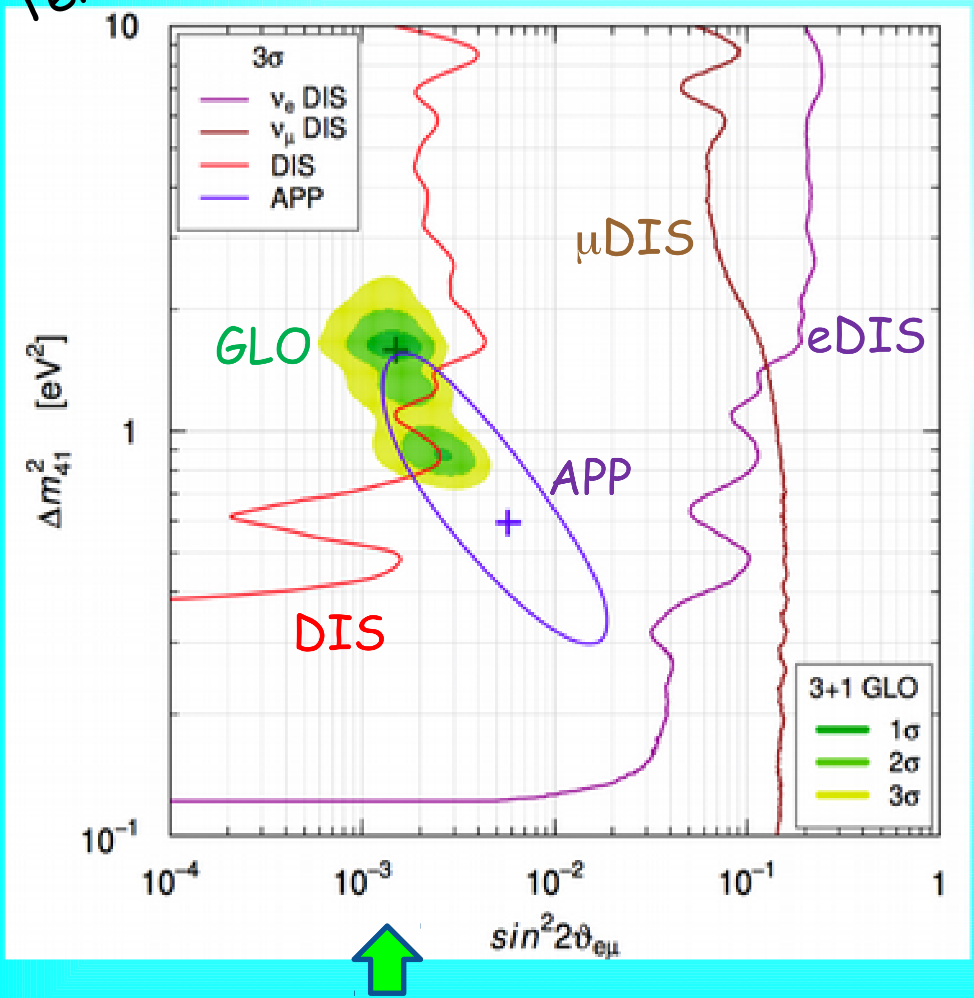


ppearance vs. disappearance

C. Giunti , arXiv: 1609.04688 [hep-ph]

3+1 scheme

Tension



4 - 5 times smaller signal

GLO: allowed regions (at 3σ) from global fit of all short-baseline data

APP: allowed regions from $\nu\mu \rightarrow \nu e$ appearance-only data

eDIS: constraints from νe disappearance –only data

μDIS: $\nu\mu$ disappearance-only data

DIS: combined disappearance data

For the allowed values of parameters sterile neutrinos do not really explain LSND, MiniBooNE excess (3.8σ)

Neutrino mass scale

Oscillations:

The heaviest neutrino

$$m_h \gtrsim \sqrt{\Delta m_{31}^2} > 0.045 \text{ eV}$$

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

the weakest mass hierarchy,
related to large mixing

Cosmology:

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

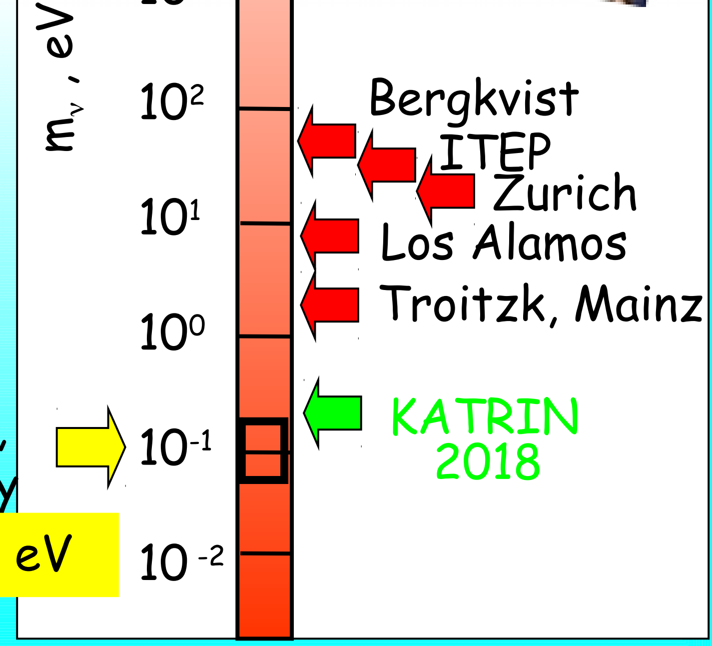
E. Di Valentino, et al
1507.08665 [astro-ph.CO]

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

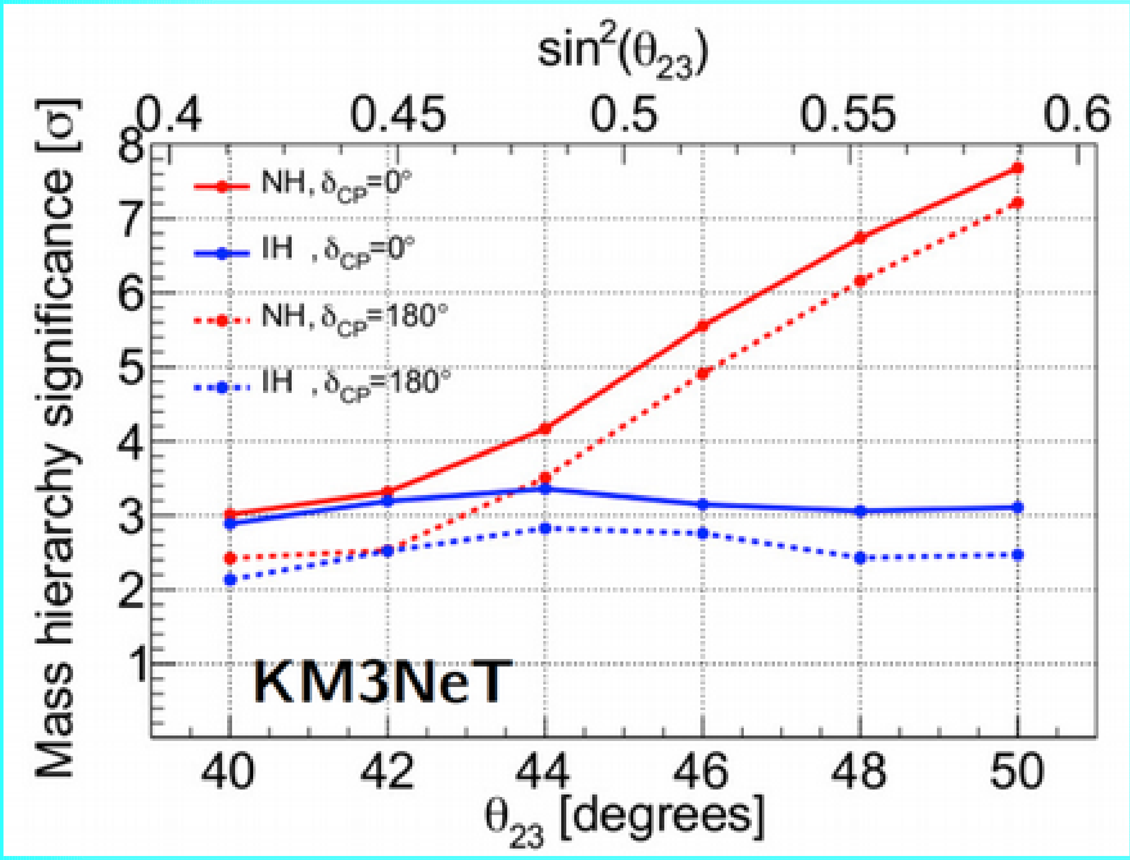
conservative

Oscillations,
& cosmology

$m_h \sim (0.045 - 0.10)$ eV

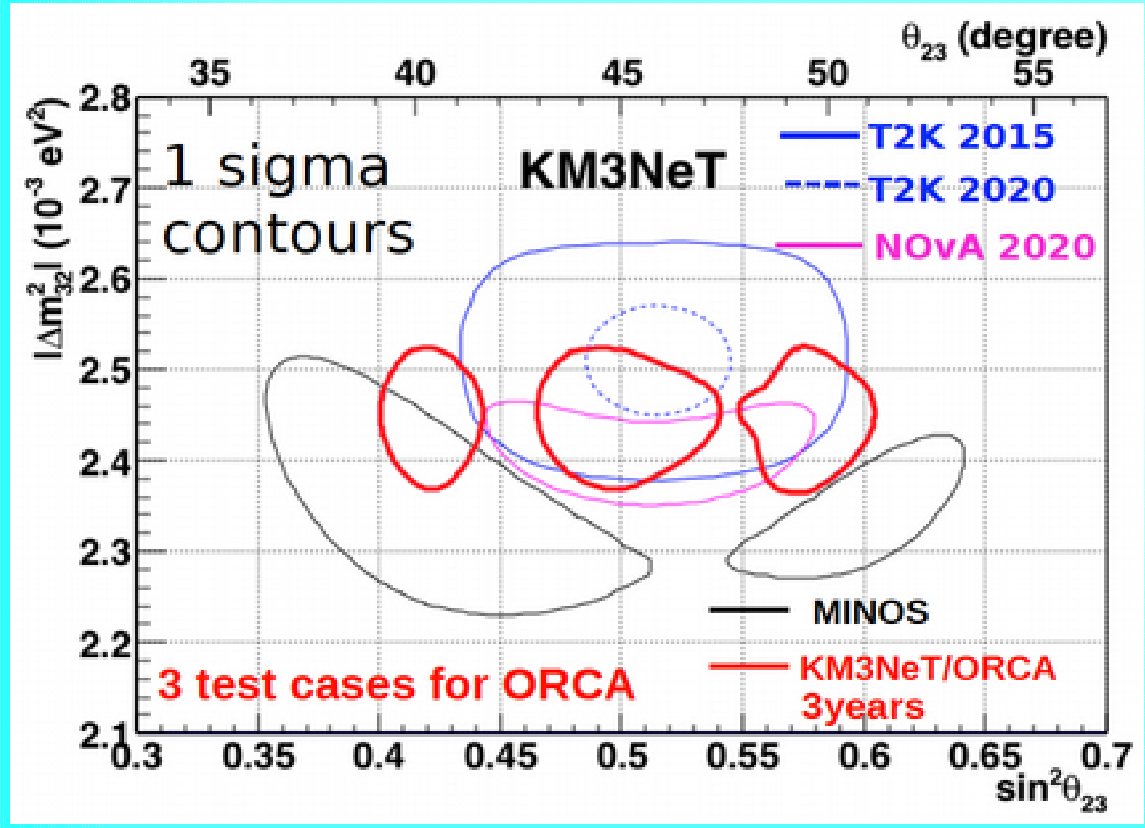


ORCA



sin²(θ23)
0.4
0.45
0.5
0.55
0.6
NH, δCP=0°
IH , δCP=0°
NH, δCP=180°
IH , δCP=180°
KM3NeT
Mass hierarchy significance [σ]
1
2
3
4
5
6
7
8
40
42
44
46
48
50
θ23 [degrees]

ORCA

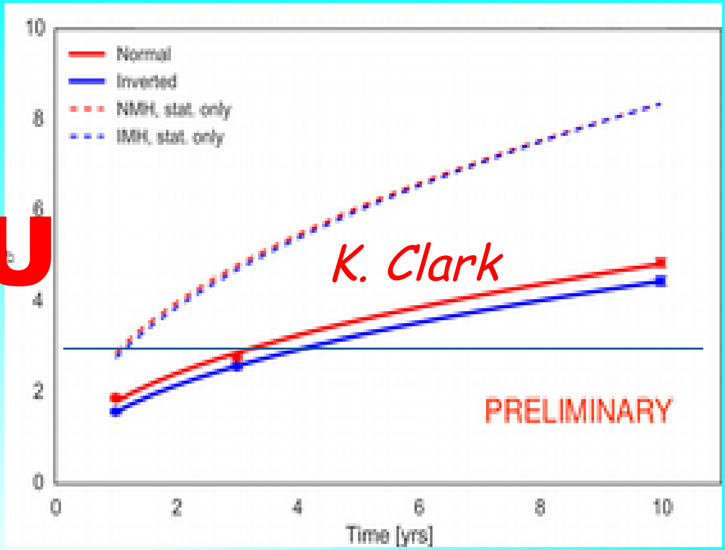


θ23 (degree)
35
40
45
50
55
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
|Δm²32| (10⁻³ eV²)
1 sigma
contours
KM3NeT
T2K 2015
T2K 2020
NOvA 2020
MINOS
KM3NeT/ORCA
3years
3 test cases for ORCA
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.65
0.7
sin²θ23

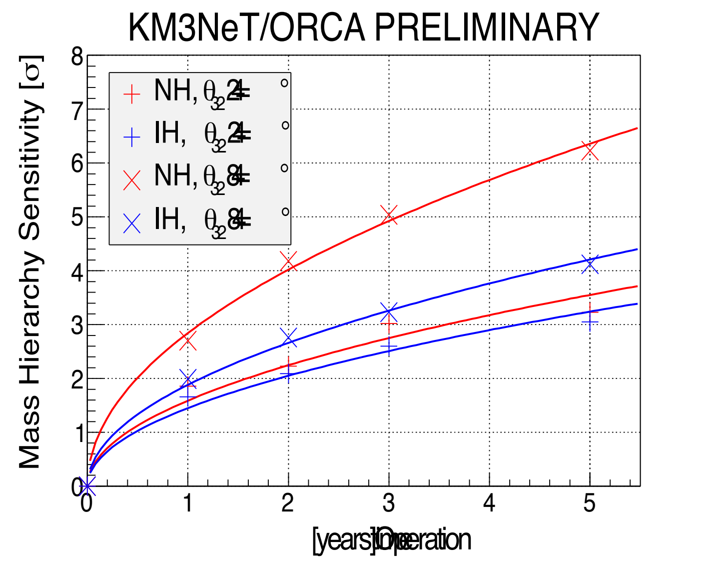
Determination of mass ordering

Crucial developments of detection techniques

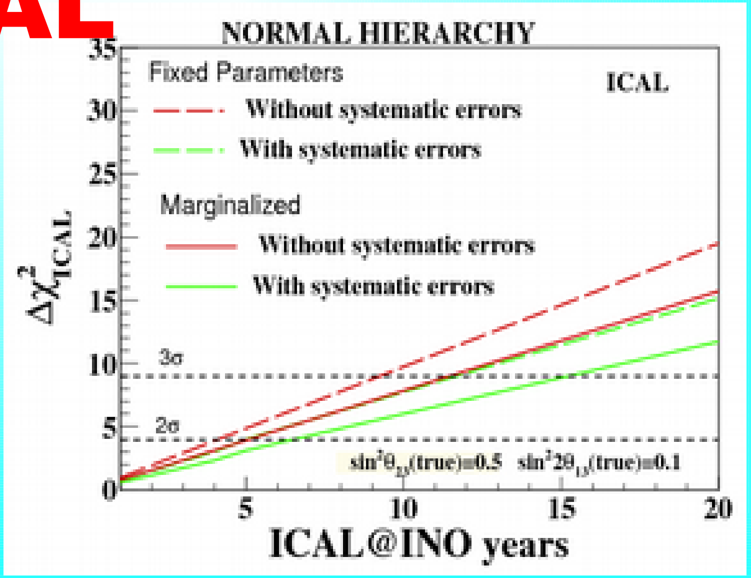
PINGU



ORCA



ICAL



H-asymmetry and distinguishability

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

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

ORCA