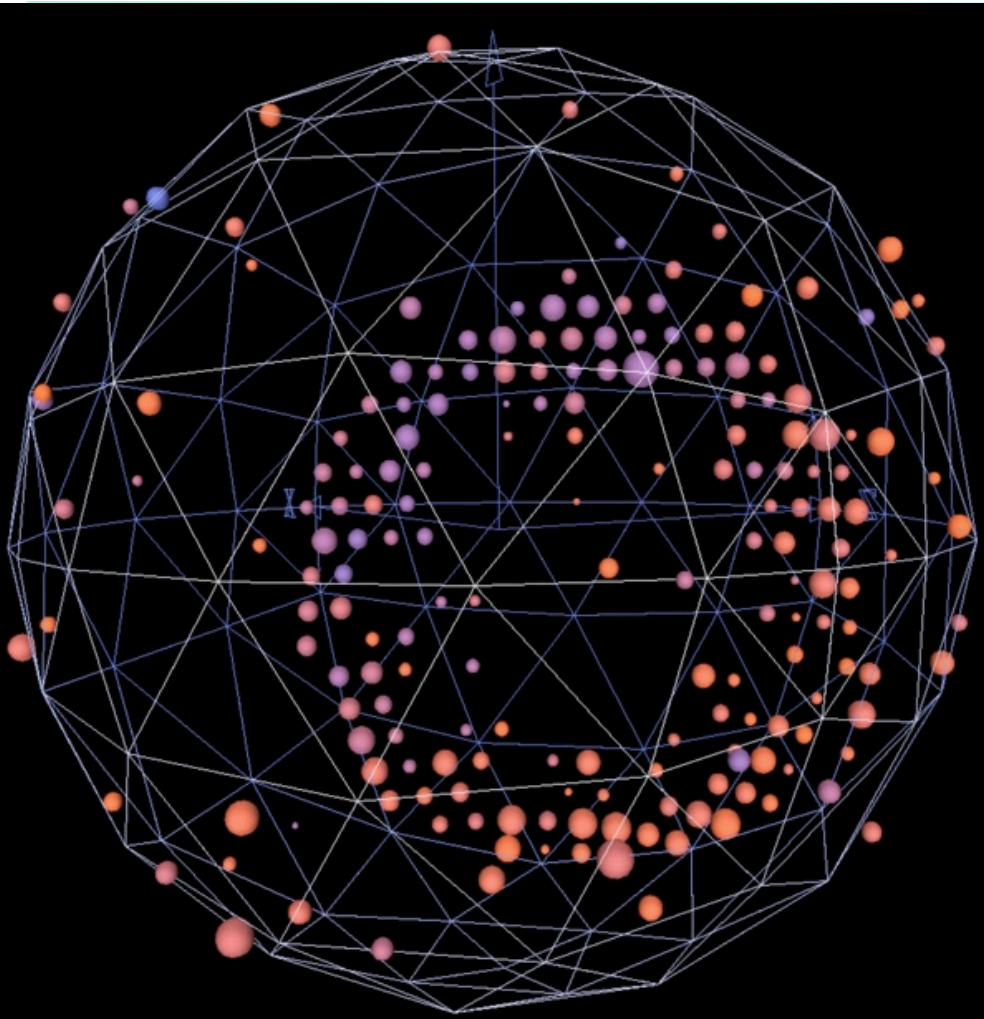
Neutrinos: Projecting into the Future



A. Yu. Smirnov

Max-Planck Institute for Nuclear Physics,
Heidelberg, Germany

Neutrino telescopes, Venice, March 2015

On "predictions"

Unusual discussion between several members of IAC
(which reflects the present situation in the field)
about necessity of the talk on predictions of the CP phase

In the past: bad experience with "predictions" of the 1-3 mixing:
too much theory emphasis on zero (or very small) θ_{13}

Predictions were largely misleading

Concerning CP: one can not say "model" predicts the phase.
Already now all possible values of δ_{CP} from 0 to 2π are predicted

Theorists should wait (20 years ?) till of δ_{CP} is measured with
good enough precision , this may help them to construct a model
which may predict something new...

Complete failure of THEORY, its uselessness !

δ_{CP} is one of few unknown yet parameters for which
predictions still can be done.

What then we will understand prove?

...continued

Zero (small) 1-3 was supported by TBM and flavor symmetries

This was appreciated/supported by large EXPERIMENTAL community that wanted to do neutrino factories

Even in the past there were a spectrum of predictions (see compilation in C. Albright, Mu Chum Chen hep-ph/0608137).

Then discussion went to philosophical and moral issues of

What is the meaning of predictions
What is the role of input, assumptions
What is the role of theory in general etc. etc.

Quality and number of assumptions, honesty...

Input → **Model** → **Predictions**

- Assumptions
- measured values of parameters

Concepts, principles
Symmetries, etc

Projecting into the Future

Extrapolate progress and advances we made in recent years
previous experience, lessons, etc.

Starting point also to check if I can trust myself

Neutrino -2008: Where are we?
Where are we going?

XXIII Int conference on
Neutrino physics and Astrophysics,
Christchurch, New Zealand, May 2008

0810.2668 [hep-ph]

7 years later
a number of statements are still valid

Content:

1. 1-3 mixing. Impact
2. Solar neutrinos
3. CP violation
4. Projecting into the future

Three stories
and some guesses

Neutrino map

Cosmology

Dark matter

LBNF

ESS

RENO50

JUNO

HyperKamiokande

IC HEX

PIN

NOvA SNO+

LH

SN 20XX

IET

INO

MICA

Great
Achevements
after 2008

J-PARC SK

1-3 mixing

MINOS+

IC: cosmic neutrinos

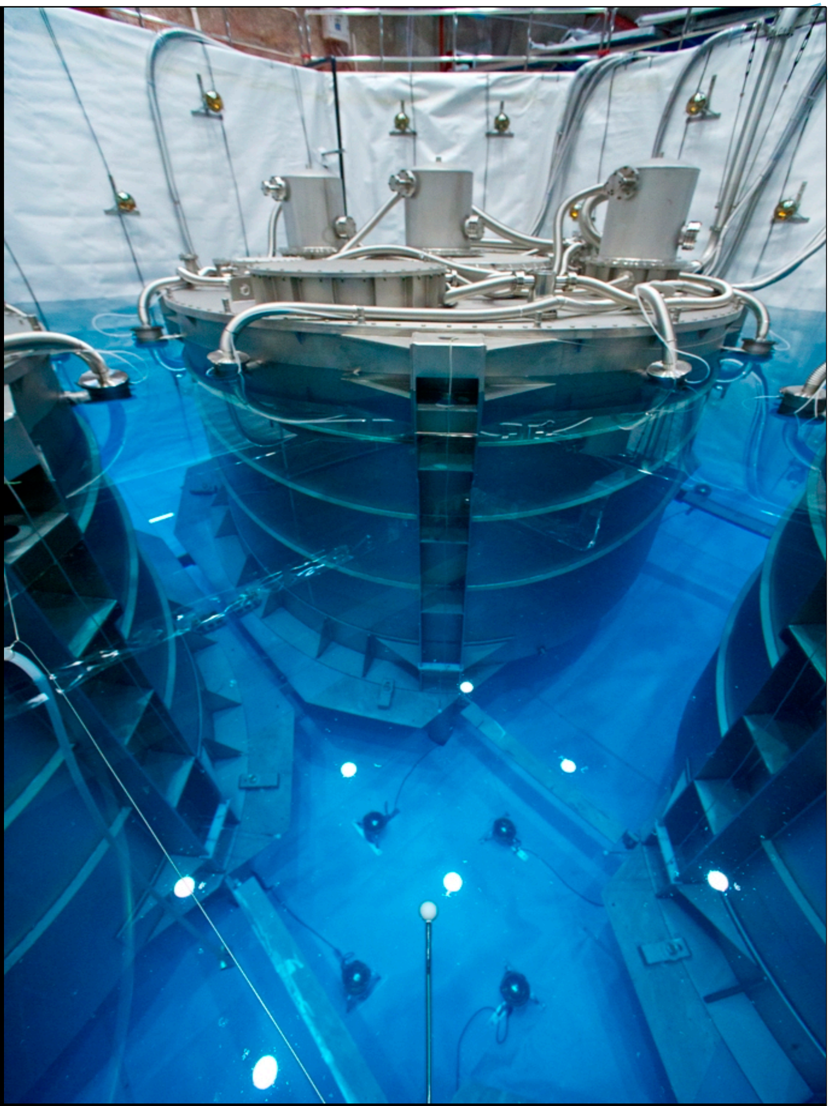
Double beta decay experiments

BOREXINO: pp-, pep-neutrinos

Sterile Neutrino searches

SK: DN-effect

1-3 mixing Impact



My (successful?) story of the 1-3 mixing

end of 90ies

L. A. Mikaelyan: any chance/reason that θ_{13} is close to the CHOOZ upper bound?

A.S.: Yes, this is very plausible

Reference to $\sin^2\theta_{13} = \underset{0.75}{O(1)}\frac{\Delta m_{21}^2}{\Delta m_{32}^2}$

E. K. Akhmedov, G.C. Branco, M.N. Rebelo Phys.Rev.Lett. 84 (2000) 3535, [hep-ph /9912205]

``Naturalness'' : absence of fine tuning of mass matrix

Connecting solar and atmospheric neutrino sectors

Very small 1-3 mixing would be something special (symmetry)

Dilemma: usual versus special

supported by almost the same relation in the quark and lepton sectors

$$\sin^2\theta_{13} = q \sin^2\theta_{12}\sin^2\theta_{23}$$

K. Patel, A. Y. S.

Prediction from QLC

H. Minakata, A. Yu. S., Phys.Rev. D70 (2004) 073009
hep-ph/0405088

Quark-Lepton Complementarity

$$\sin\theta_{13} = -\sqrt{\tfrac{1}{2}}\,\sin\theta_C(1 - |V_{cb}|\cos\alpha) + V_{ub}$$

in general: $\sin\theta_{23}$

CP-phase

$\frac{1}{2}\sin^2\theta_C = 2.54 +/- 0.02$ $\times 10^{-2}$

C. Giunti, M. Tanimoto

$\sin^2\theta_{13} = 2.18 +/- 0.10$ Global fit, C. Gonzalez-Garcia et al

2.15 +/- 0.13 Daya Bay (15% smaller, 3σ)

Reducing predicted value

1. correction from V_{CKM}^+ 2.54 → 2.11
2. Non-maximal 2-3 mixing

2.54 → 2.28 for $\sin^2\theta_{23} = 0.45$

Framework

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 ,etc.

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

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

has similar hierarchical structure determined (as in Wolfenstein parametrization) by powers of

$\lambda = \sin \theta_C$

U_X should be fixed to reproduce correct lepton mixing angles

$U_{CKM} \sim I \Rightarrow U_X \sim U_{TBM}$

can be always written

Deeper sense: reflects

Quarks and leptons know about each other, Q L unification
Some additional physics is involved in the lepton sector related to neutrino properties

PMNS & CKM

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

From the Dirac matrices of charged leptons and neutrinos

Related to (any) mechanism that explains smallness of neutrino mass

New neutrino structure

Neutrino portal

Two types of new physics and partial relations

CKM type new physics

Neutrino new physics

Can be realized in seesaw I

Another interpretation

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

$U_{CKM} = V_{corr}$

Correction due to flavor symmetry breaking

Mixing matrix in the flavor symmetry limit

e.g. $U_X = U_{TBM}$

Corrections of the order

$\lambda = \sin \theta_C$

Realized in the residual discrete symmetry approach

"Sum rules" predictions

Connection to quark sector is more complicated

In general: no relations to masses

Prediction:

C. Giunti, M. Tanimoto

H. Minakata, A Y S

……………………………

If $U_X = U_{23}(\pi/2)\, U_{12}$ no 1-3 rotation (or very small)

$$U_{PMNS} = U_{CKM}^{+}\, U_{23}(\pi/2)\, U_{12}$$

$$= U_{12}\,(\theta_c)^{+}\, U_{23}(\pi/2)\, U_{12}$$

permutation - to reduce the lepton mixing matrix to the standard form

$$\sin^2\theta_{13} \sim \tfrac{1}{2}\sin^2\theta_C \qquad \theta_{13} \sim \sqrt{\tfrac{1}{2}}\;\theta_c$$

can be obtained e.g. in the context of

$$U_X = \begin{cases} U_{BM} & \text{QLC (Quark-Lepton Complementarity)} \\ U_{TBM} & \text{TBM-Cabibbo scheme} \\ U_{GR} & \text{Golden ratio (for 12 mixing)} \end{cases}$$

S. F. King et al

Agrees well with data – in favor of the approach

Leptons & quarks

There is no convincing explanation of quark masses and mixing

Can we solve the neutrino mass and mixing problem?
Do efforts make sense?

Yes, if

neutrino mass generation and charged lepton and quark mass generation are independent

we will try to explain the difference of masses and mixing of neutrino and quarks, and not masses and mixing completely

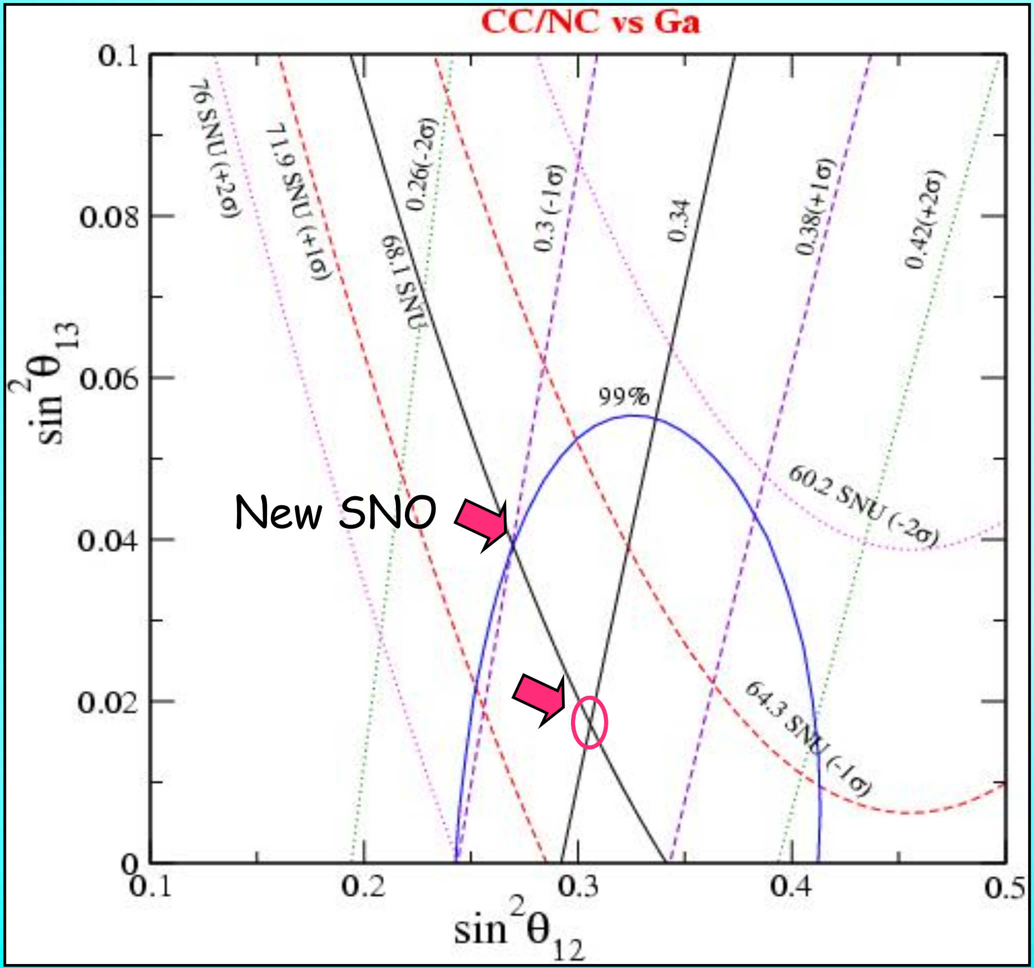
we still hope (as it was before) that neutrinos will uncover something simple and insightful which will allow to solve the quark mass riddle

Theta 1-3 and solar neutrinos

S. Goswami, A. Yu. S.:
hep-ph/0411359
Phys.Rev. D72 (2005)
053011

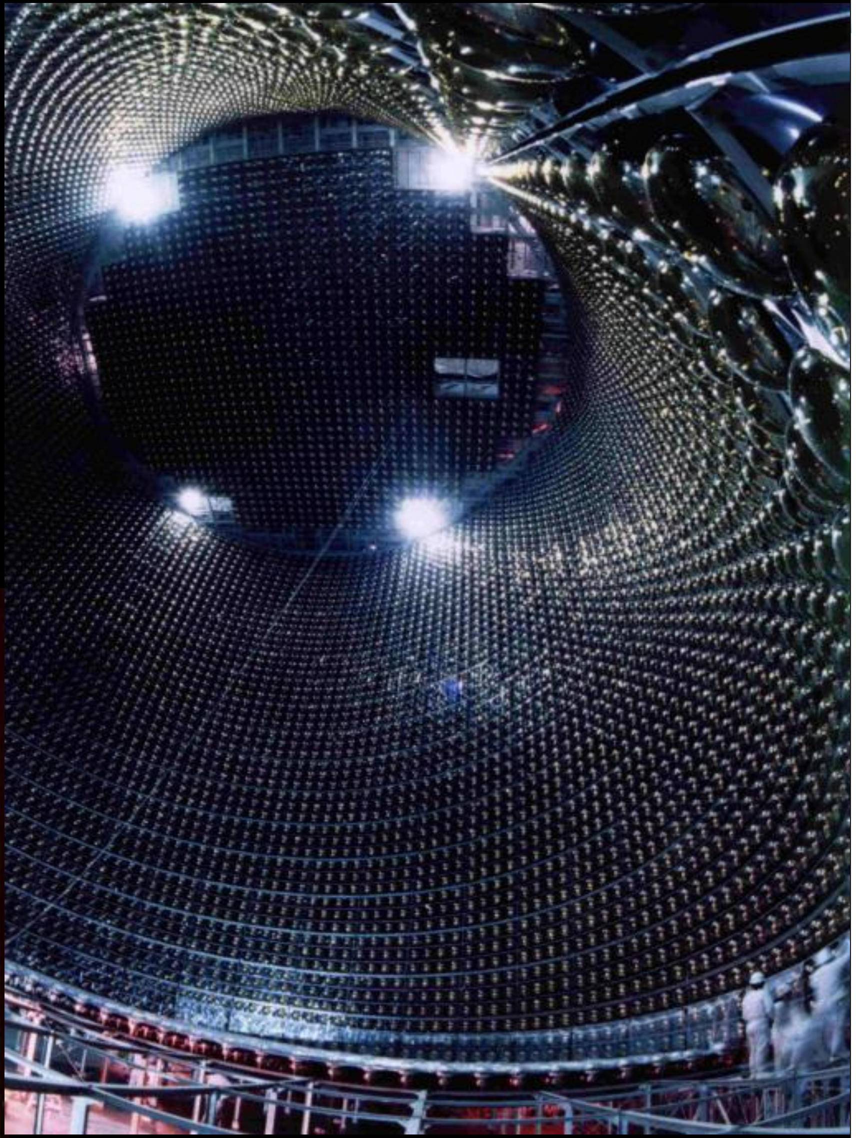
Effect is not just overall normalization of the flux

Measuring 1-2 and 1-3 mixings



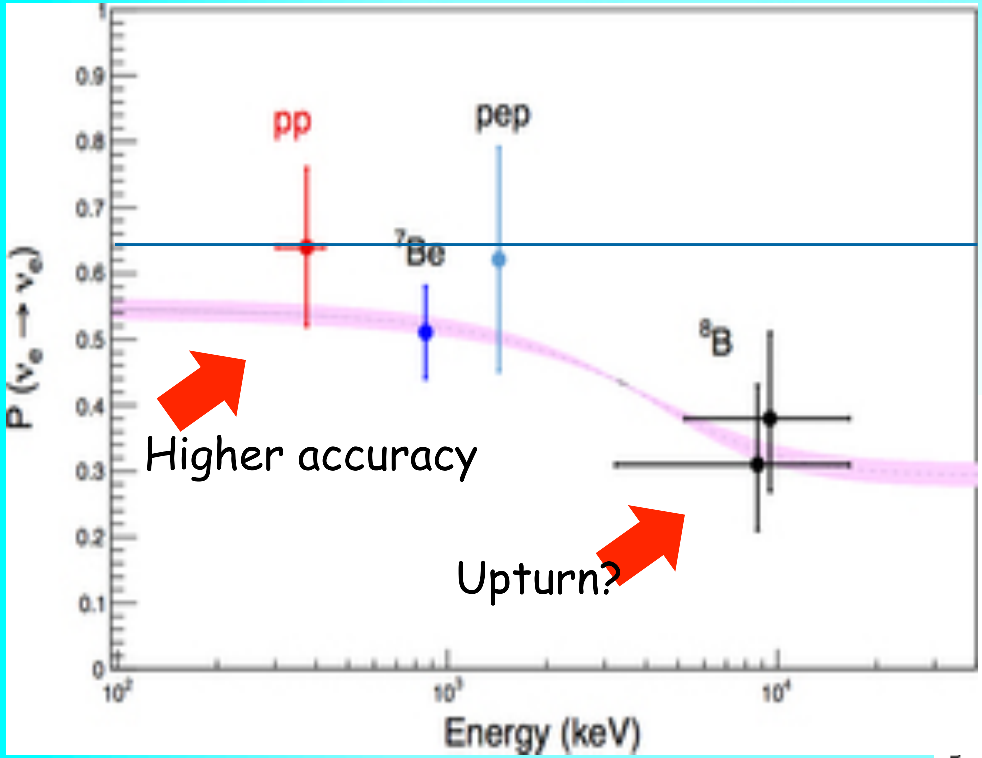
$\sin^2\theta_{13}$ = 0.017+/- 0.26

Solar Neutrinos



Solar pp-neutrinos

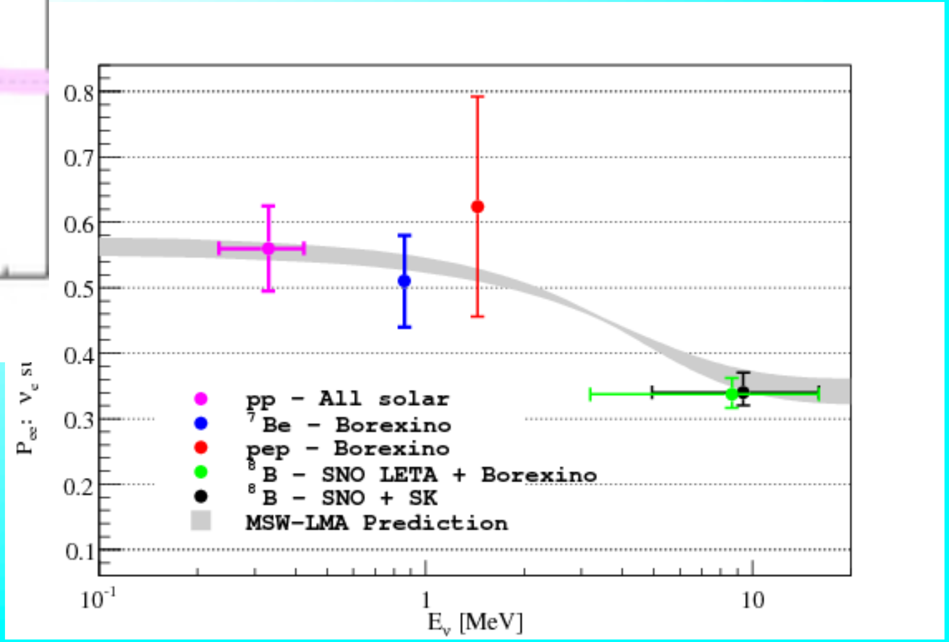
Neutrinos from the primary pp-reactions in the Sun
BOREXINO Collaboration
(G. Bellini et al.)
Nature 512 (2014) 7515, 383



Higher accuracy

Upturn?

Before direct pp -measurements



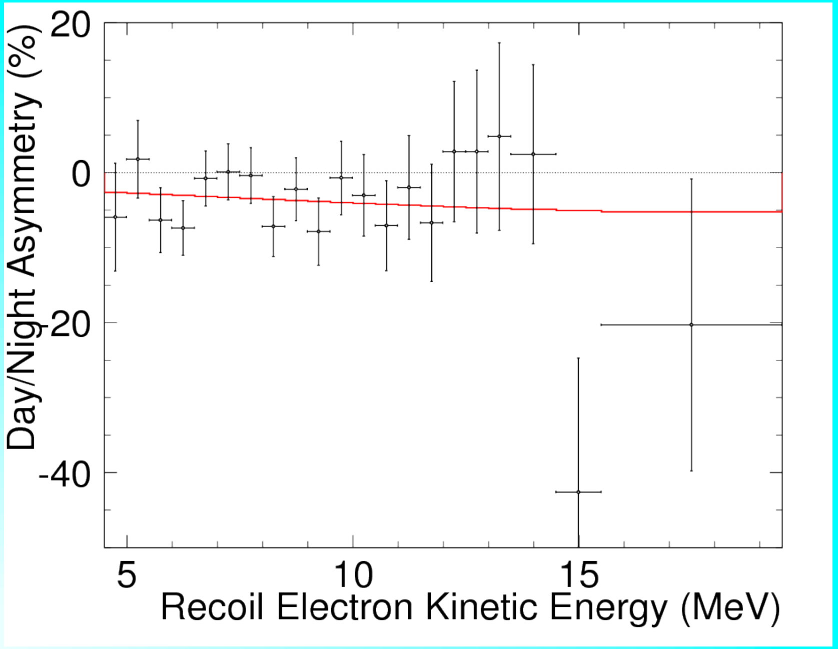
$\frac{1}{2}\cos^4\theta_{13}\ \sin^2 2\theta_{12}$

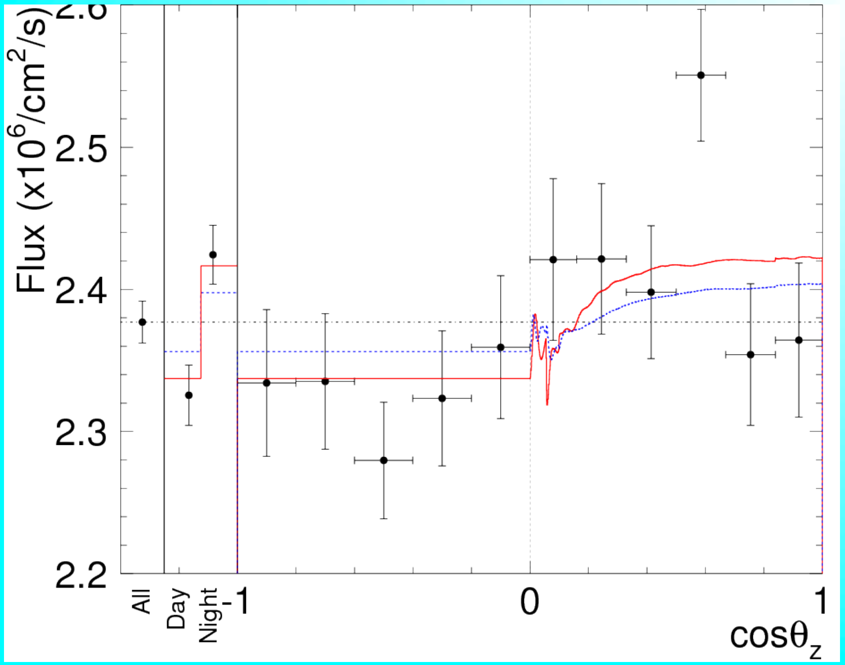
Day-Night effect

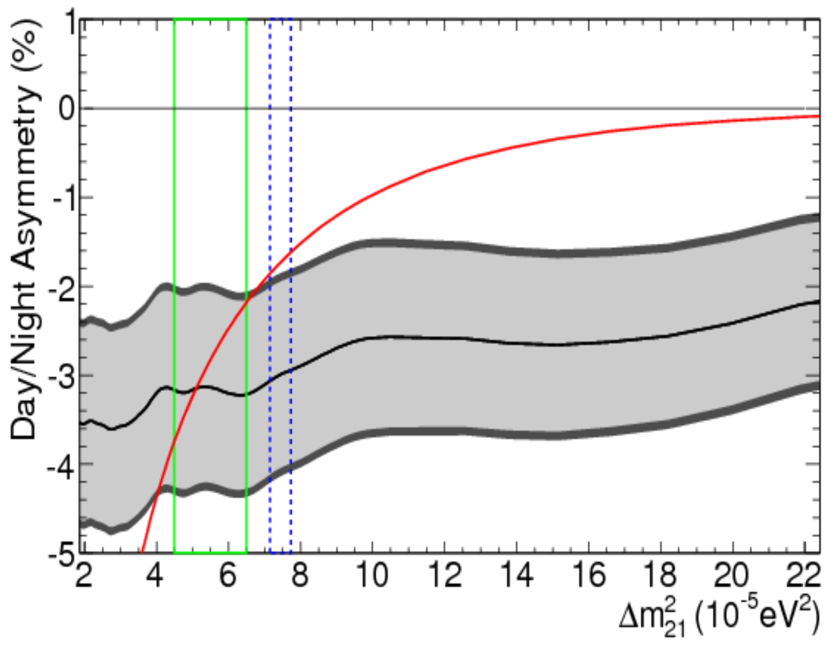
First Indication of Terrestrial Matter Effects on Solar Neutrino Oscillation

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

fluctuations?



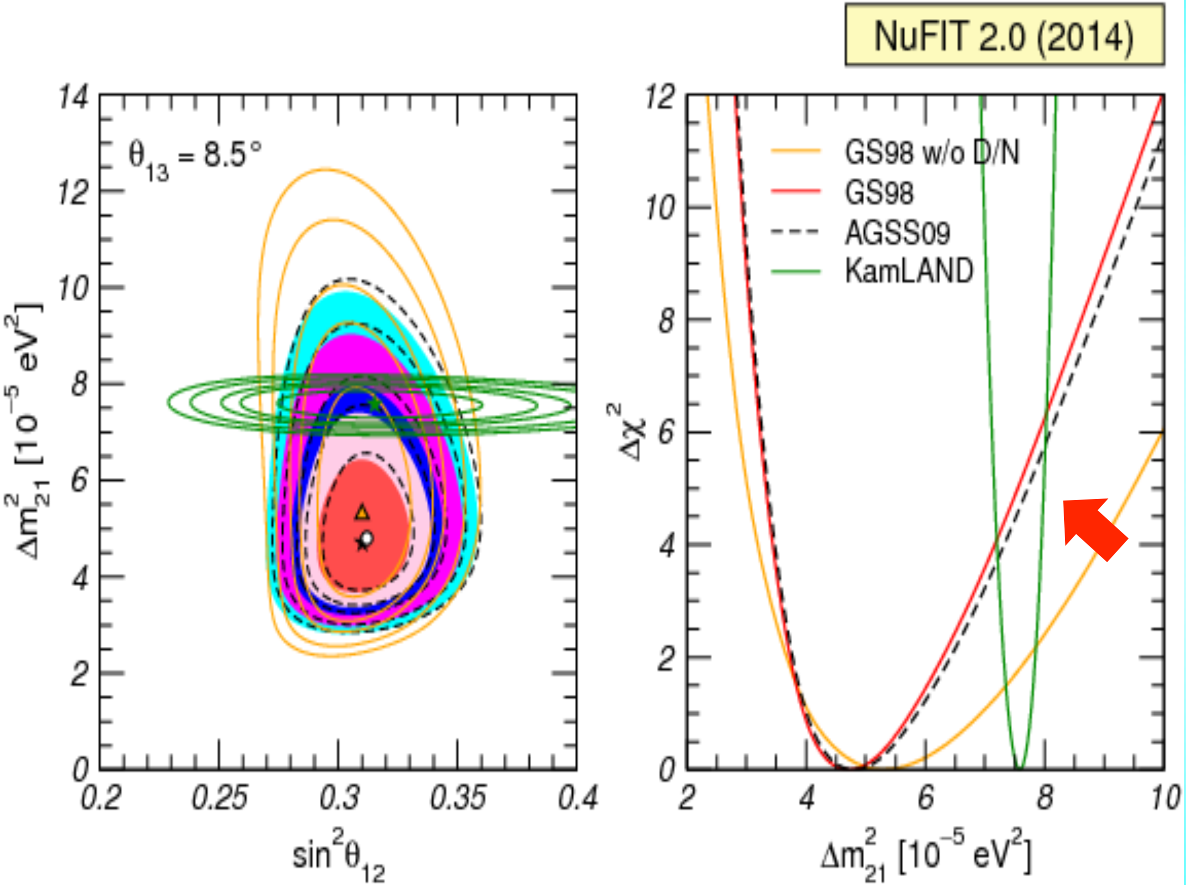




Consistency

Solar data vs KamLAND

About 2σ discrepancy



1σ, 90 %, 2σ, 99% and 3σ CL (for 2 dof) allowed regions.

Full - GS98 model,
bf - blackstar;
Dashed - AGSS09 model
(bf - white dot),
Green - KamLAND ;
Orange - GS98 model,
without the D-N from SK .

$\Delta\chi 2$ dependence on Δm_{21}^2 for the same four analysis after marginalizing over θ_{12}.

fixed $\theta_{13} = 8.5°$

Very light sterile neutrino? P de Holanda, AYS

A. Suzuki: CPT violation? K. Fujikawa, A. Tureanu, 1409.8023 [hep-ph]

Non-local interactions in Nu portal → CPT violation → nu-antinu mass splitting

Oscillations of Be neutrinos in the Earth

A. N . Ioannisian, A.Y.S. ,
D. Wyler, to appear

Γ_{Be} = 1.6 kev   E = 862.27 kev

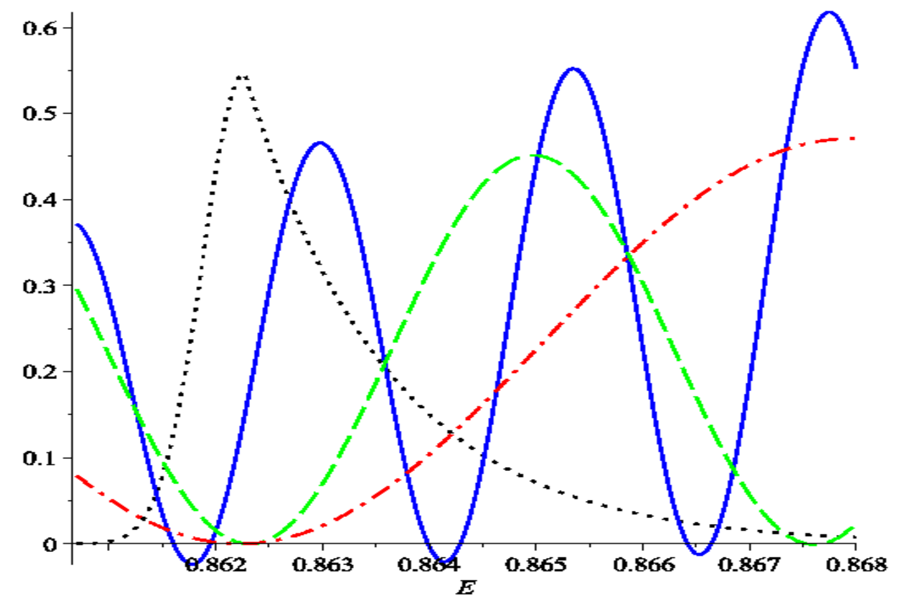
Γ_{Be} /E = 1.86 10^{-3}

$\Gamma_{Be} \sim \Delta E_T$

Oscillatory period in the energy scale

$$\Delta E_T = E\, l_\nu / L = E \frac{l_\nu}{2 R_E \cos \eta}$$

Depending on nadir angle η level of averaging changes



BOREXINO:

A_{DN} = 0.001 +/- 0.012 (stat) +/- 0.007 (syst)

Main features

Oscillations of mass eigenstates – pure matter effect

$l_m \; = \; l_\nu = 28.5$ km

$$\varepsilon = \frac{2VE}{\Delta m_{21}^2} = 2.4 \;\; 10^{-3} \;\; (\rho/2.7g\ cm^{-3})$$

$$l_m = l_\nu \, [\, 1 + c_{13}^2 \cos 2\theta_{12}\, \varepsilon \; + \; ...] \; = 28.5 \text{ km}$$

Variations

$$A_P = (P - P_D)/P_D = - \, c_{13}^2 \, f(\Delta m_{21}^2, \theta_{12} \, , \theta_{13}) \, \tfrac{1}{2} \int_0^L dx \, V(x) \sin \phi^m_{x \to L}$$

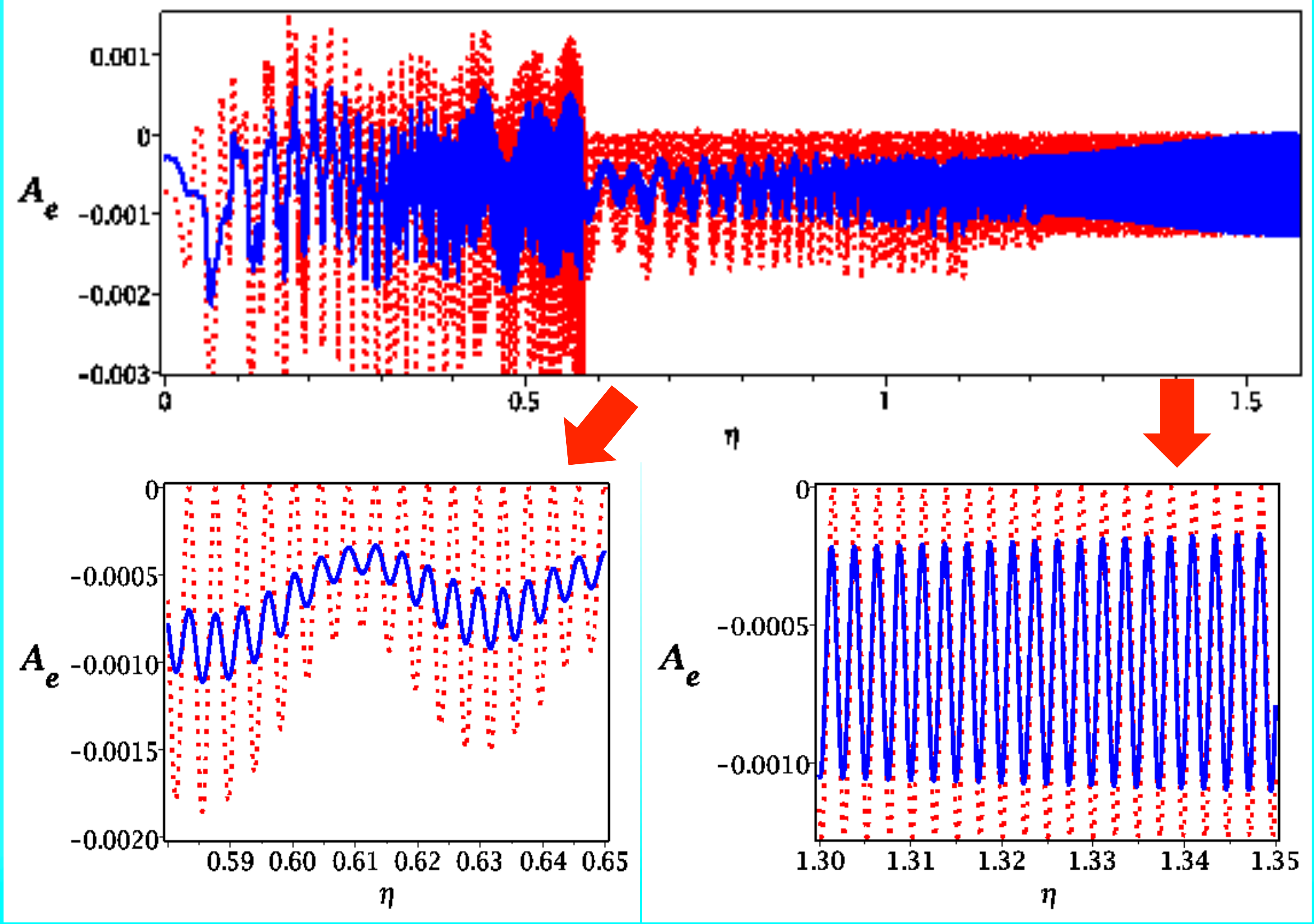
$f = 0.43$

Constant density

$$A_P = - \, c_{13}^2 \, \varepsilon \, f \sin^2 \tfrac{1}{2} \, \Delta_m L$$

$$\Delta_m \; = 2\pi \, / \, l_m$$

Variations of the Be flux



Measurements

Establishing oscillations, matter effect

Quasi- periodic variations during night

Determination of the line width

Precision measurements of Δm_{21}^2

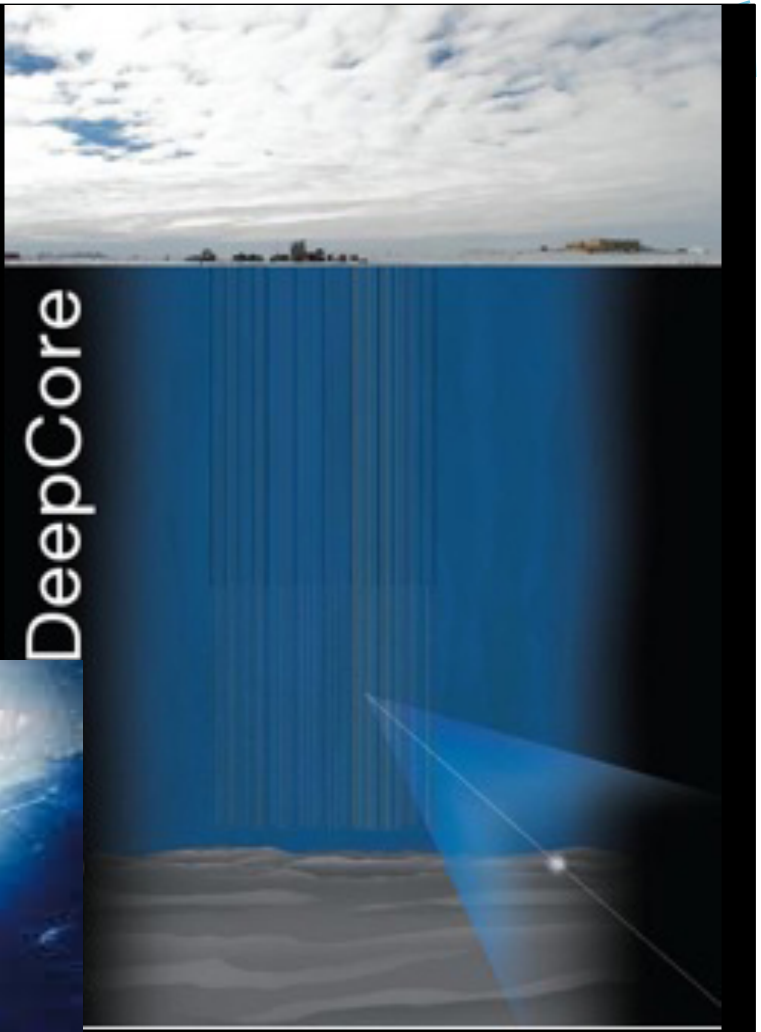
Tomography of the Earth interior

- Small scale structures, at the surface (mountains, oceans, ..)
- Non-sphericity of the Earth
- Density jumps in the mantle,
- Shape of the core,,,

Searches for sterile neutrinos

especially for $\Delta m_{10}^2 \sim 10^{-7}$ eV^2 $\sin^2 2\theta_s \sim 10^{-2}$

CP-violation



Leptonic unitarity triangle

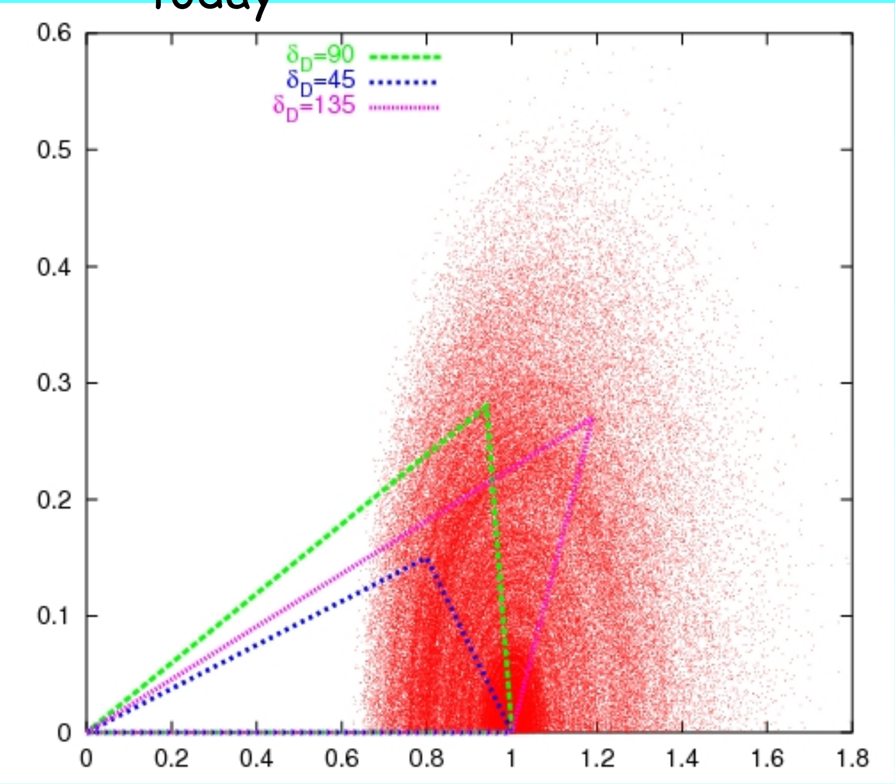
eμ - triangle

$\sin\theta_{13} = 0.15$

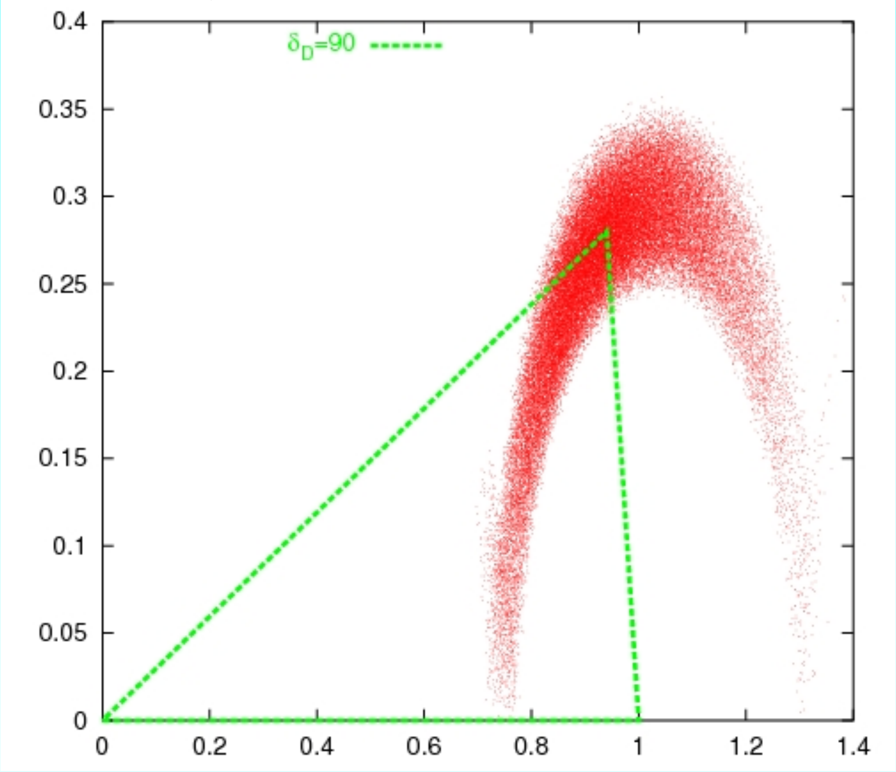
after Double Chooze, Daya Bay, JPARK T2K, NOvA

Neutrino 2008 *Y. Farzan ,AYS*

today



in future



- illustration
- method to measure δ , test of unitarity?

CP-phase and the framework

$U_{PMNS} \sim V_{CKM}^{+} U_X$

If the only source of CP violation

No CPV

B. Dasgupta, A.S.

$\sin\theta_{13} \sin \delta_{CP} = (-\cos \theta_{23}) \sin\theta_{13}^{q} \sin\delta_q$

λ λ^3 $\delta_q = 1.2 +/- 0.08$ rad

$\sin \delta_{CP} \sim \lambda^3/s_{13} \sim \lambda^2 \sim 0.046$

$\delta_{CP} \sim - \delta$ or $\pi + \delta$

where $\delta = (s_{13}^{q} / s_{13})\, c_{23} \sin \delta_q$

Implications

If the phase δ_{CP} deviates substantially from 0 or π, new sources of CPV beyond CKM

New sources may have specific symmetries which lead to particular values of δ_{CP} e.g. $-\pi /2$

In general

B. Dasgupta, A Y.S. ,
Nucl.Phys. B884 (2014) 357
1404.0272 [hep-ph]

any value of the phase can be obtained

Also taking U_X from seesaw

In contrast to quarks for Majorana neutrinos the RH rotation that diagonalizes m_D becomes relevant and contributes to PMNS

CPV from U_R

In the LR symmetric basis

minimal extension is the L- R symmetry:

$$U_R = U_L \sim V_{CKM}^*$$

and no CPV in M_R

Seesaw can enhance this small CPV effect, so that resulting phase in PMNS is large

Measuring CP-phase

Global fit

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

Dedicated experiments

J-PARC- HK
LBNF
ESS European spalation source Lund

$3\pi/2$ from 0

at 2- 3 σ

~ 5 - 7 σ

result in 2030 - 2035

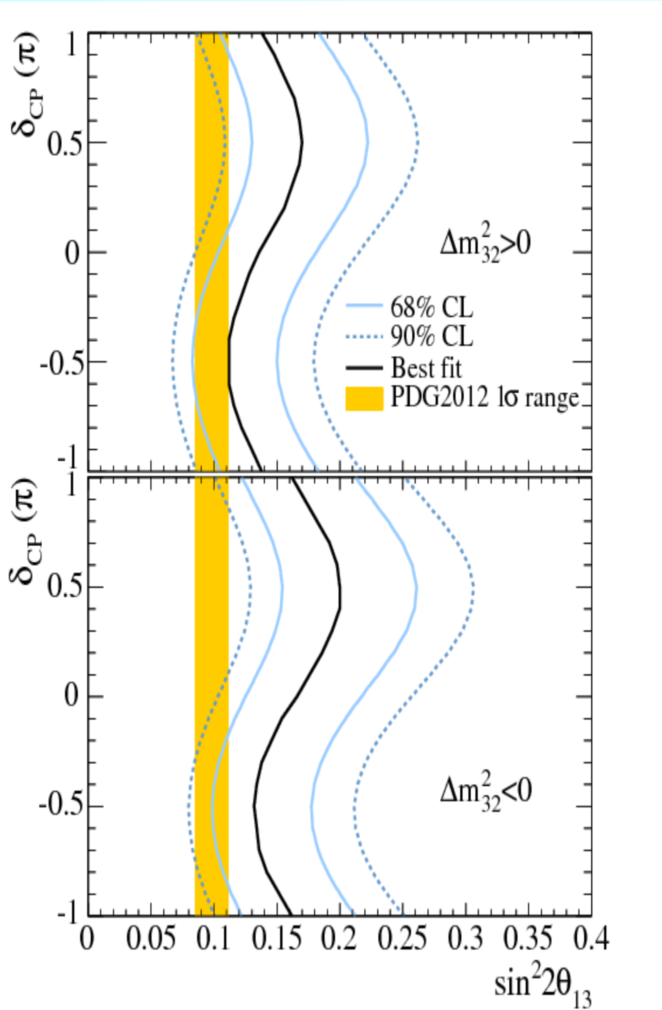
O(1) bln US$

In this connection

DETAILS

Before dedicated experiments?

Marginalized over 2-3 mixing



PDG (reactors)

J-PARK (beam upgrade)

Super-Kamiokande

p.o.t. $6\ 10^{20} \rightarrow 7.8\ 10^{21}$

by 2018 → 13 times higher statistics in few years

sensitivity to the CP-violating 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]

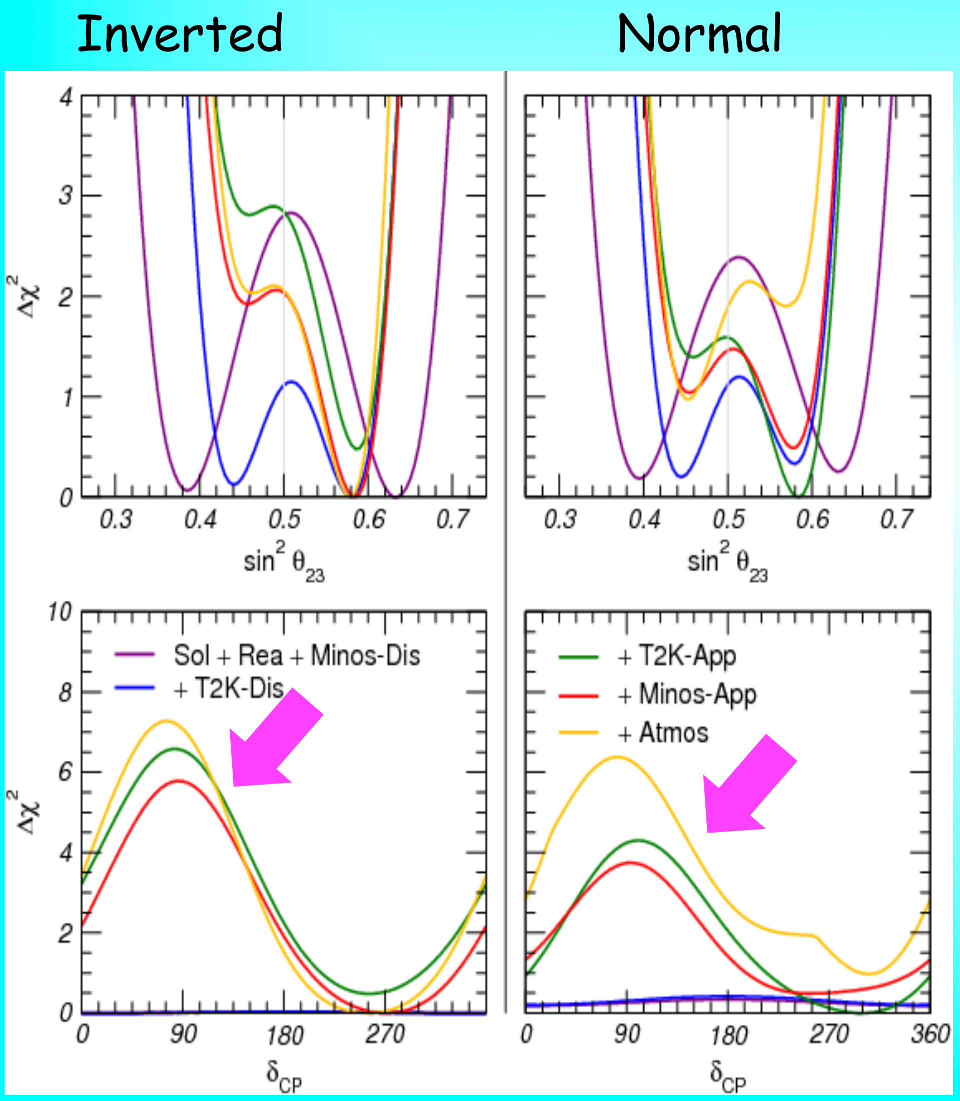
NOvA

further substantial improvements

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

CP-phase and 2-3 mixing

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

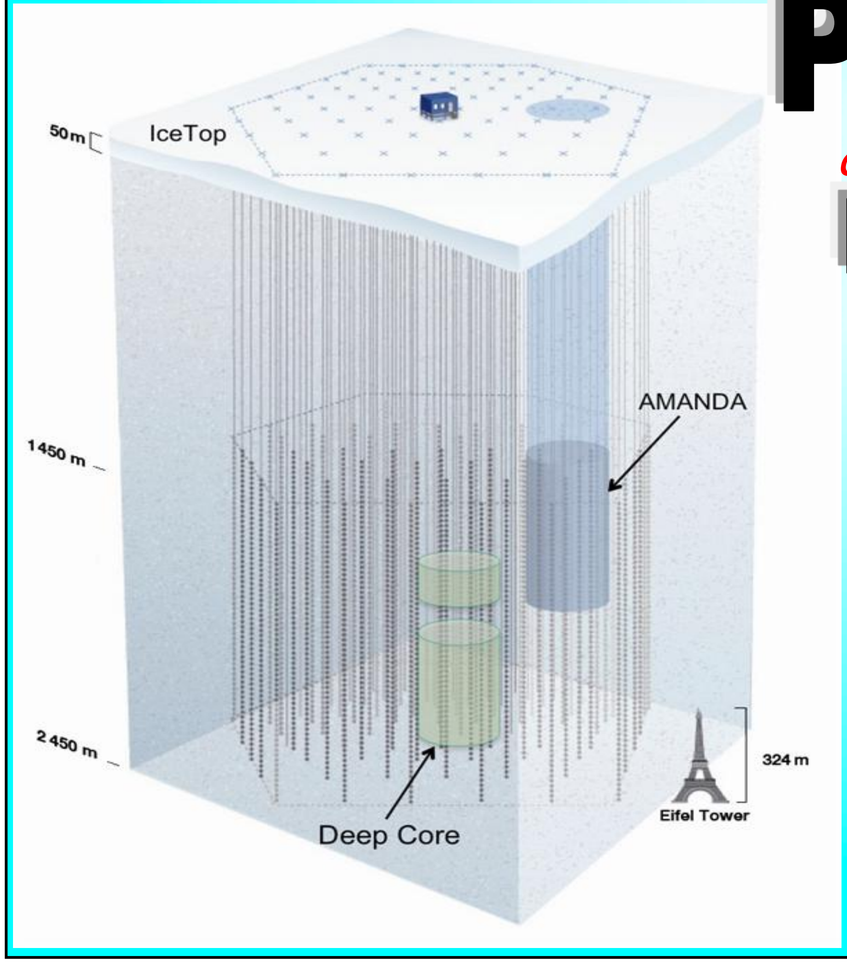
\+ Atmospheric

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

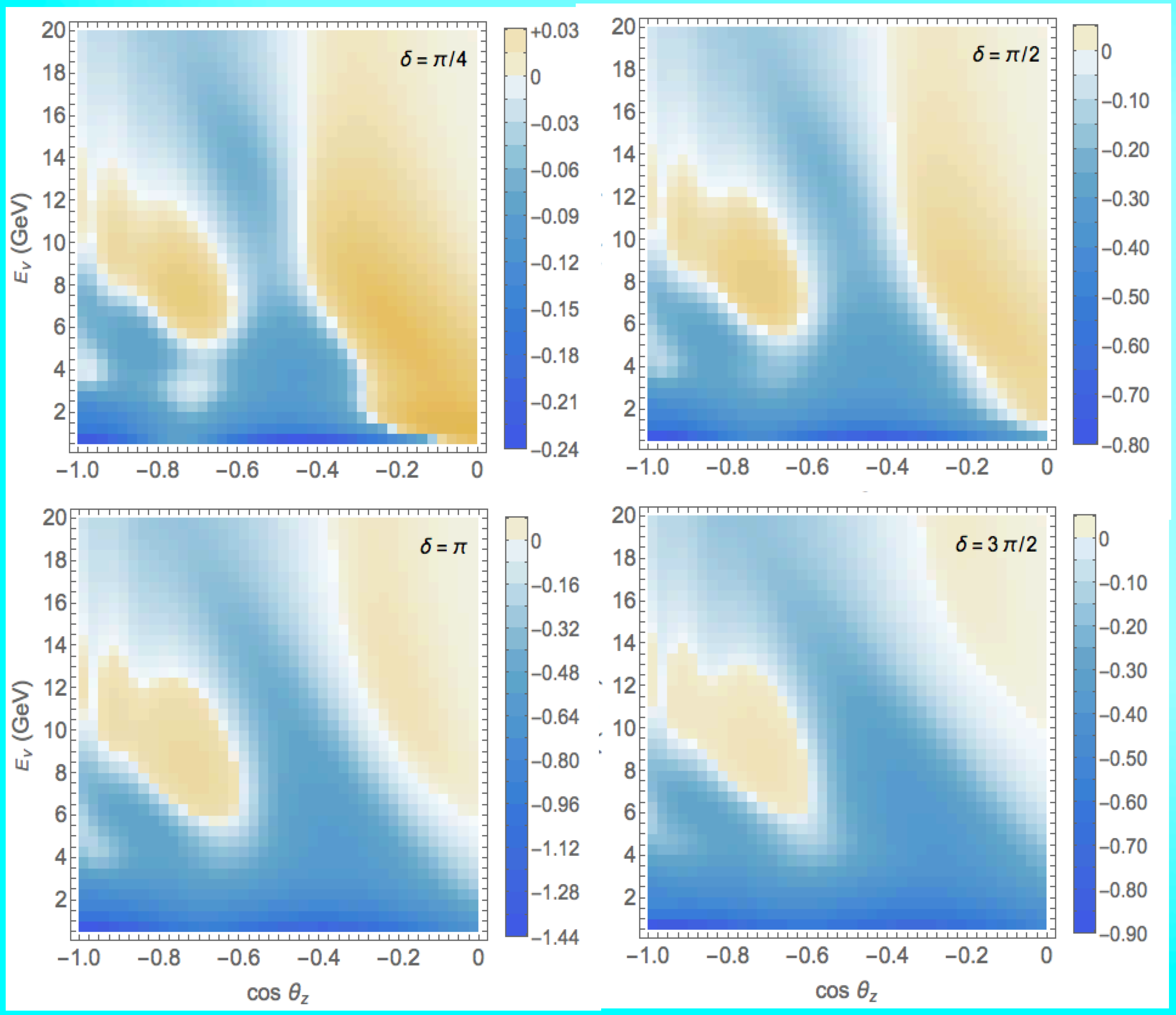
If is true value → N_{ij}^{δ} corresponds to ``true" value of events
→ $N_{ij}^{\delta = 0}$ ``measured" number of events

$|S_{ij}|$ - 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)

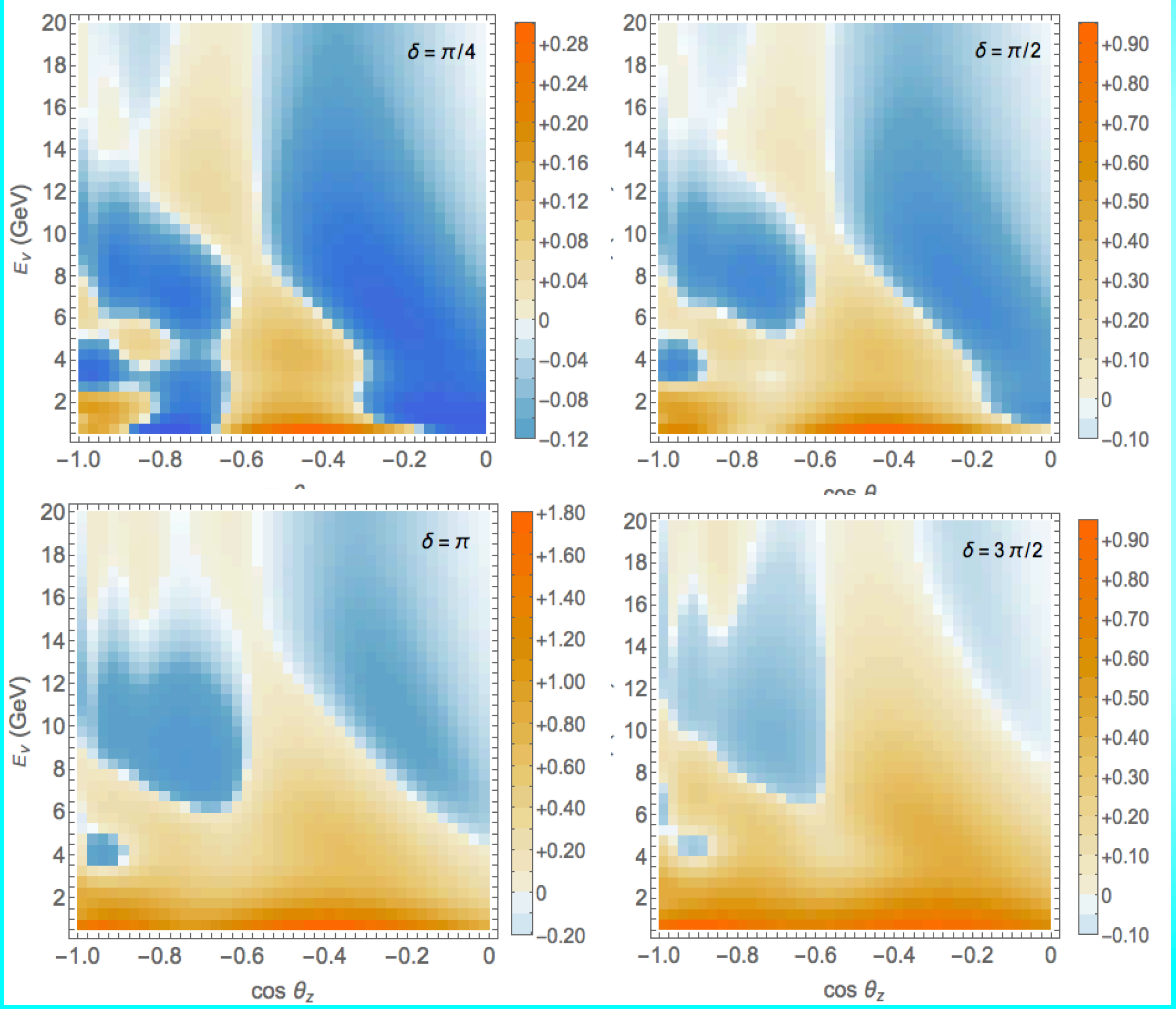
S-distributions
for different
values of δ

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

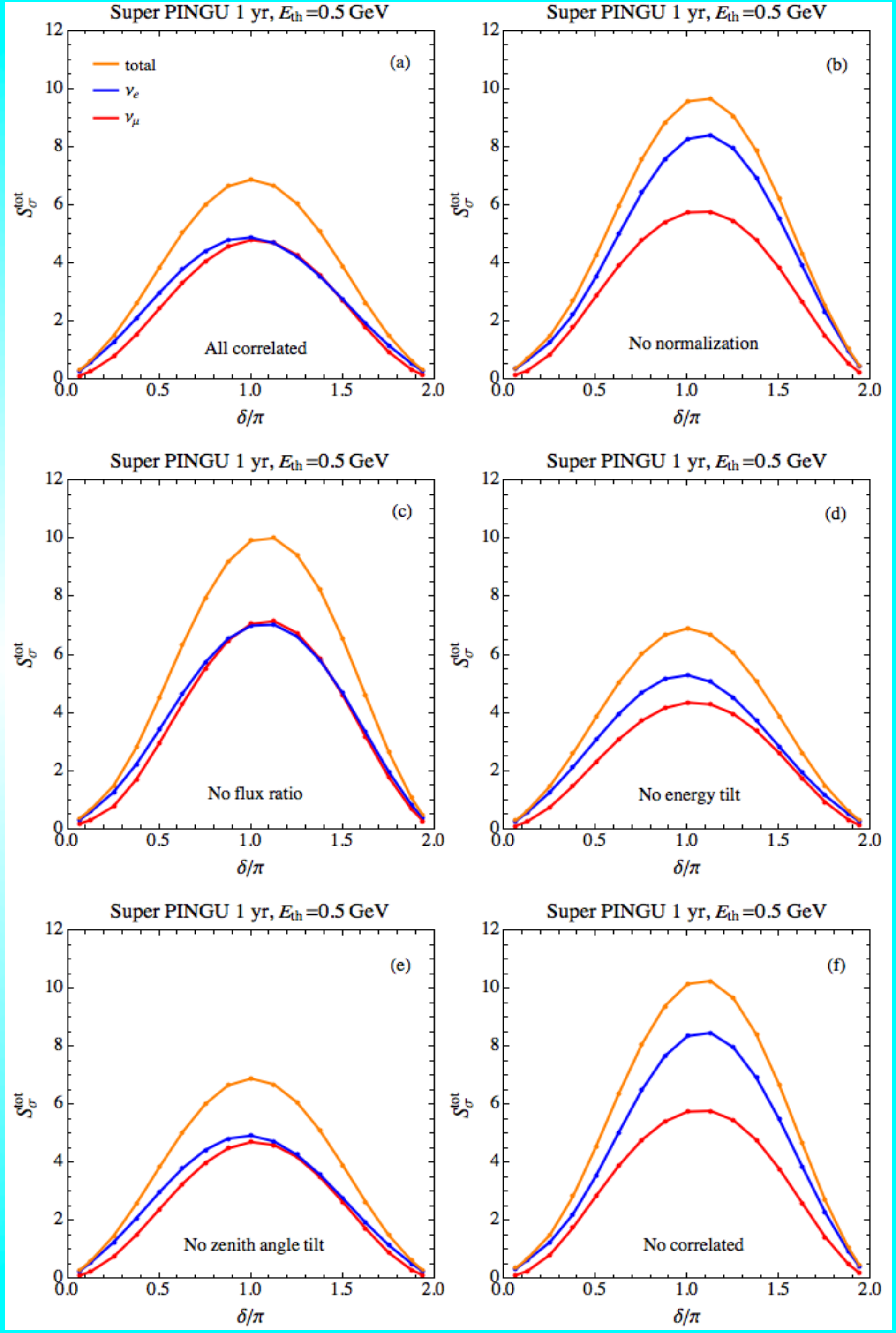
Super PINGU 1 year

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

Sensitivity of SuperPINGU

Effect of correlated systematic errors

Flavor misidentification can further reduce distinguishability by factor 1.5 - 2



Still S_σ ~ 3-4 for $\delta = \pi$

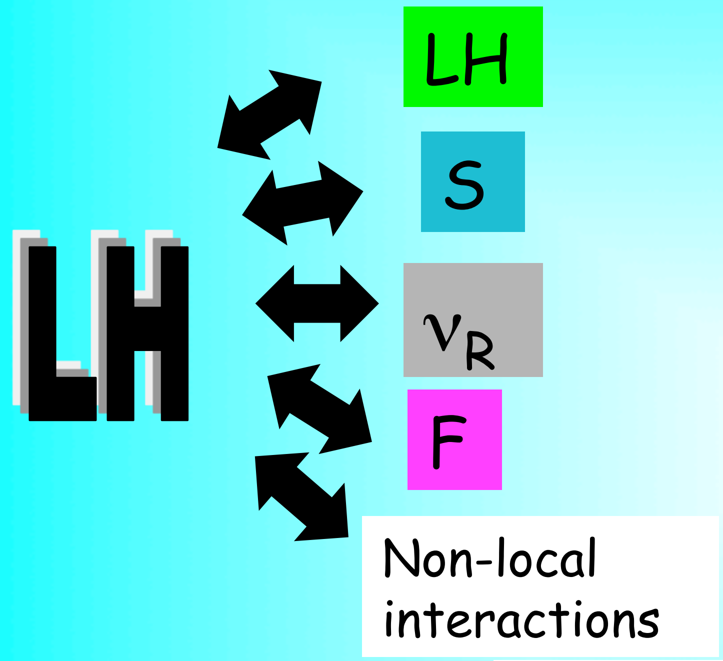
after 4 years of exposure

Neutrino Portal

Prospects
in theory

LH

Neutrino Portal



LH

LH

S

ν_R

F

Non-local interactions

$$\frac{1}{\Lambda^{n(F)\ -\ 3/2}}\ L\ H\ F$$

F is the fermionic operator

Singlet of symmetry group of hidden sector

Interactions which violated fundamental symmetries

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

A GUT scenario

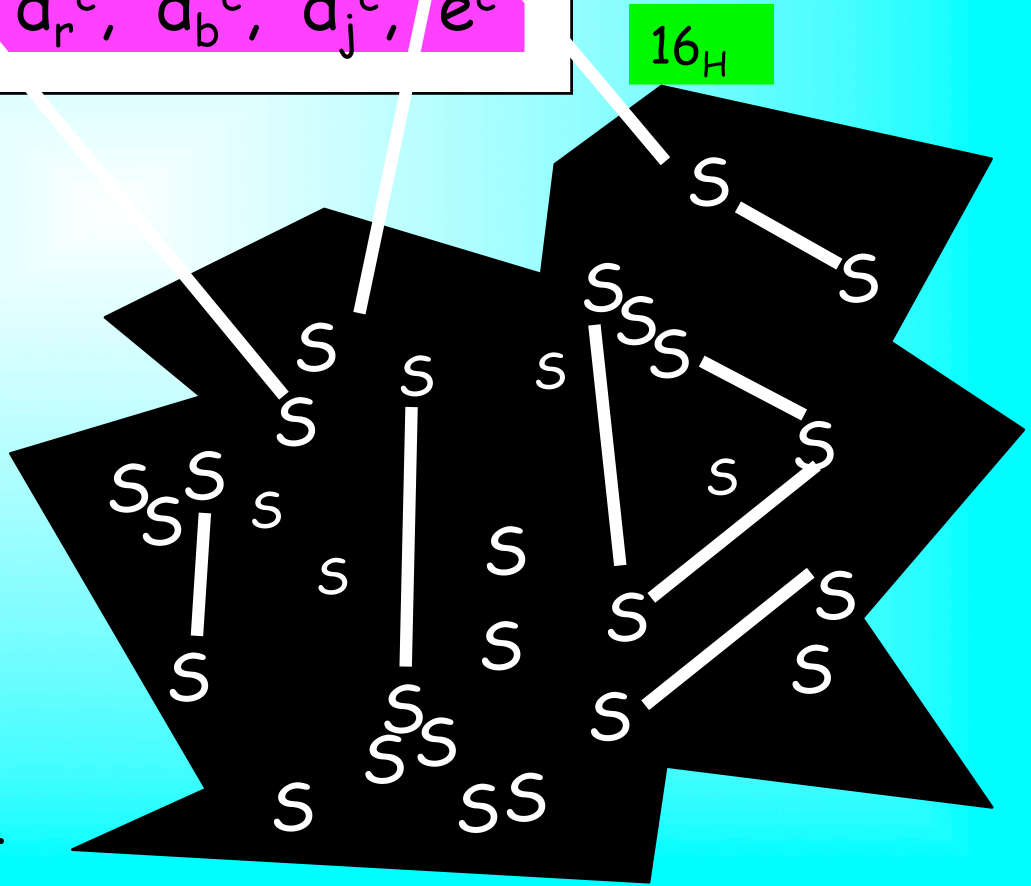
SO(10) GUT + hidden sector + flavor symmetries

16

u_r , u_b , u_j , ν
d_r , d_b , d_j , e

u_r^c, u_b^c, u_j^c, ν^c
d_r^c, d_b^c, d_j^c, e^c

RH-neutrino



(Double) seesaw → smallness of neutrino mass, can realize framework

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

Flavor symmetries at very high scales, above GUT
Symmetries in S-sector

Proton decay...

Projecting into the Future

Sterile Neutrinos

Checks of existence of 1 eV steriles is the must.
... May be by smaller prize, smaller numbers of experiments.
If results are negative?
Where are the IceCube results on sterile?

Searches for new neutrino states (sterile, partially sterile) will continue anyway. Goal –upper bounds on mixing as function of mass. For 1 eV bound on mixing at the level $\sin^2 \theta_{aS} < 10^{-3}$ is important to exclude substantial influence on the the 3ν picture .

7 kev sterile : further checks of the 3.5 kev line,
Does not play any role in generation of masses of light neutrinos.
Probably not a right handed component but some new fermion on the top of 3 RH neutrinos

LHC 14

Tests of the low scale mechanisms of neutrino mass generation

Discovery of almost any kind on new physics will have impact on neutrino physics

No new physics result is possible

LFV-processes

Chance to see something ?

Dedicated experiments

like SHiP

Double beta decay searches

Are and will be of the highest priority

Neutrinos and Dark Universe

Active are of research

Connection: Neutrinos - Dark matter

will be further explored

Also possible connections to Dark radiation, Dark energy

Neutrinos as probe of Dark Universe:
High energy cosmic neutrinos,
Relic supernova neutrinos

Very light sector which may include

- new scalar bosons, majoron, axions,
- new fermions (sterile neutrinos, partially sterile),
- new gauge bosons (e.g. Dark photons)
- gravitinos

Neutrinos and Hidden/Dark Sector

Interaction via neutrino portal

New experimental techniques for low energy physics

Mass hierarchy

Should not miss chance with PINGU, ORCA,
probably with JUNO, RENO50

Implications for SN neutrinos and $\beta\beta0\nu$ decay,
for cosmology and atmospheric neutrinos
for theory.

Knowledge of H facilitates determination of δ

2-3 mixing

Accuracy of $\sin^2\theta_{23}$ better than 0.05 to
test various relation is required

Multimegaton atmospheric neutrino detectors with low threshold

Enormous physics/discovery potential

Also searches for sterile neutrinos, non-standard
interactions, violation of fundamental symmetries

CP violation

J-PARK-SK, NOvA: accumulation of evidence for -90 deg.?

Next: LBNF, ESS?

A possibility to measure the phase using multi- megaton scale atmospheric neutrino detectors should be explored

Specific values like 0, π , $\pi/2$ may have more straightforward implications (still not unique)

+/- $\pi/2$ can be related (by symmetry) with maximal 2-3 mixing, quasi-degeneracy of mass states ...

Majorana vs. Dirac

Comparison with quark phase will be interesting
Even in unification approach they can be very different.
Substantial deviation of δ_{CP} from 0, π ,
will testify for new sources of CP in lepton sector

Solar Neutrinos

Day-night asymmetry

To be further studied

Upturn of spectrum

Precise measurements of the pp-neutrino flux

CNO neutrinos

Earth matter effect on Be neutrinos

Seasonal variations of Boron neutrinos in Antarctica (MICA)

Supernova neutrinos

Hopefully a signal will arrive soon

Partially... although knowledge of 1-3 mixing simplifies many things

Still role collective effects in neutrino oscillations is not completely understood...
Lepton asymmetry in emission ?

Theory

After 1-3 symmetry or no symmetry behind the lepton mixing and masses. Symmetry: accidental or real with new structures?

Inverted mass hierarchy, degenerate spectrum, special values of CP phase would testify for symmetry

Some new realizations of flavor symmetries?

Grand Unification, high (GUT) scale seesaw, additional hidden sector (at GUT-Planck scale) flavor symmetries at high scales – still appealing scenario

Other possibilities: scales on new physics, mechanisms of neutrino mass generation, etc. are possible

No simple solution is expected and different type of new physics (e.g. CKM new physics and neutrino new physics) can be involved

New experimental input is needed for further progress!

Backup