Aspects of Neutrino physics

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TPC's and Topics

cover a number of
important topics
in neutrino physics

T2K ND
WA105
LArTPC DUNE
ProtoDUNE DP
LArIAT
MicroBooNE
NEXT
Spherical LXe
HARPO
LUX
MIMAC
XENON
NEWS-LSM
PANDA-X
TREX-DM

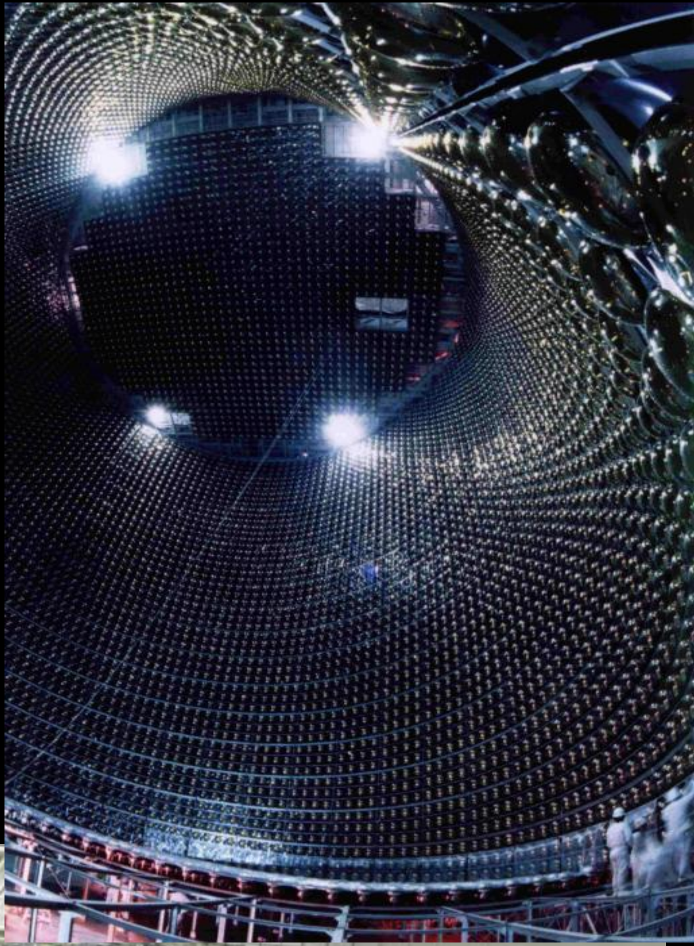
Neutrino mass hierarchy
CP-violation
Sterile neutrinos
Double beta decay
Solar neutrinos
Supernova neutrinos
Geo-neutrinos
Neutrinos and dark sector
Neutrinos and axions

Outline:

1. Global view with global fits
2. Mass hierarchy and CP-violation
3. Nature and Mass scale
4. Sterile neutrinos
5. Neutrinos and Dark matter
6. Neutrinos and the Hidden world

Global view and global fits

T2K



Daya-Bay, RENO updates
Double CHOOZ with front detector

T2K anti-nu

MINOS +

New players:
DeepCore, Antares

NOvA

3ν - paradigm

All well established/confirmed results fit well a framework

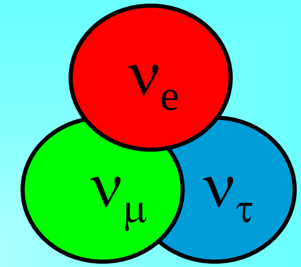
- three neutrinos
  - with interactions described by the standard model
    - with masses and mixing

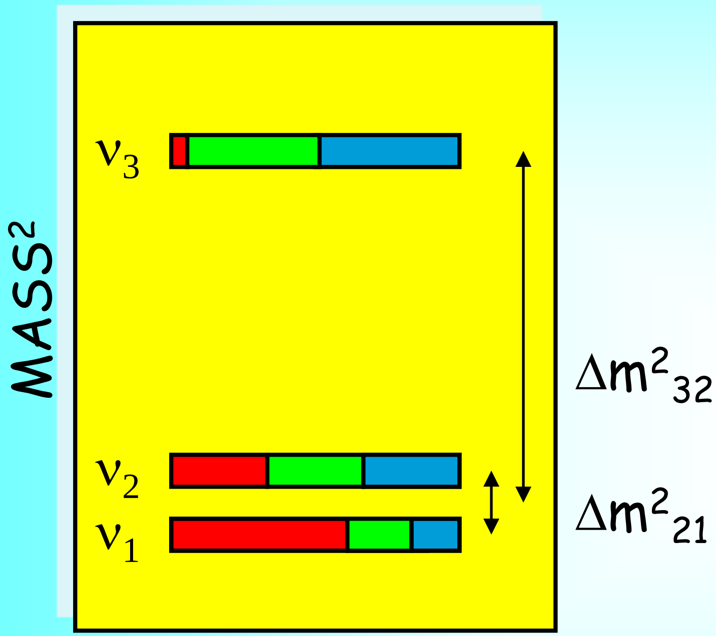
New physics BSM behind ν_R

Mechanism of neutrino mass generation has negligible effect (feedback) on Standard model structures and interaction

Higgs properties?

Mass and Mixing

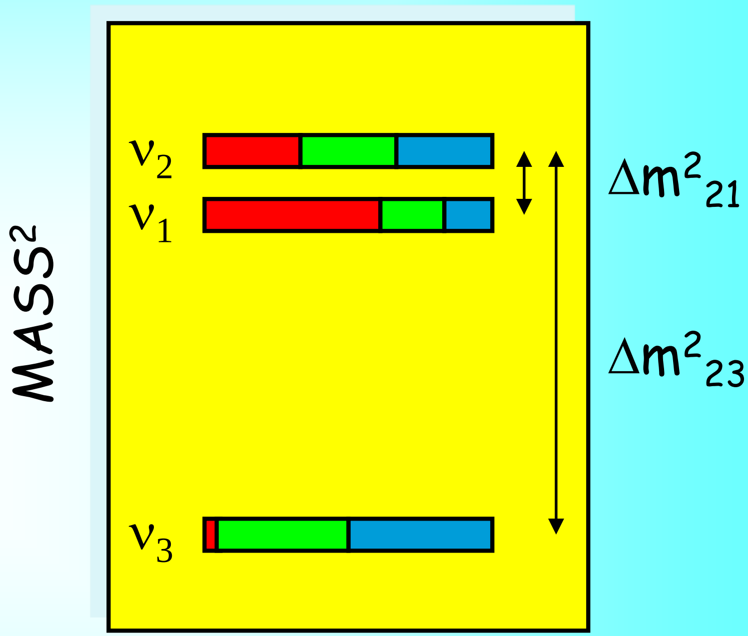




Normal mass hierarchy

$\Sigma\, m > m_h$

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



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

Landscape of studies

Phenomenology

Supernova neutrinos collective oscillations

Solar neutrinos D-N, ...

Connections

Higgs
Dark matter
axions

3ν paradigm

Neutrinos as tool and probe

Sterile neutrinos
Non-standard interactions
Non-unitarity, non-universality
Violation of fundamental symmetries

Anomalies tensions

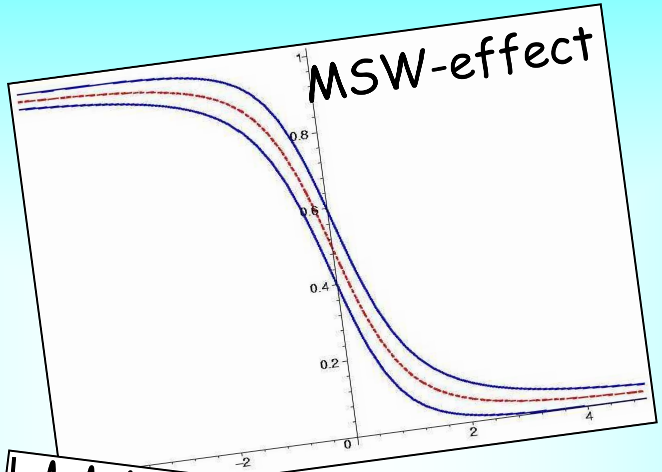
LSND,
MiniBooNE
Reactors
Gallium

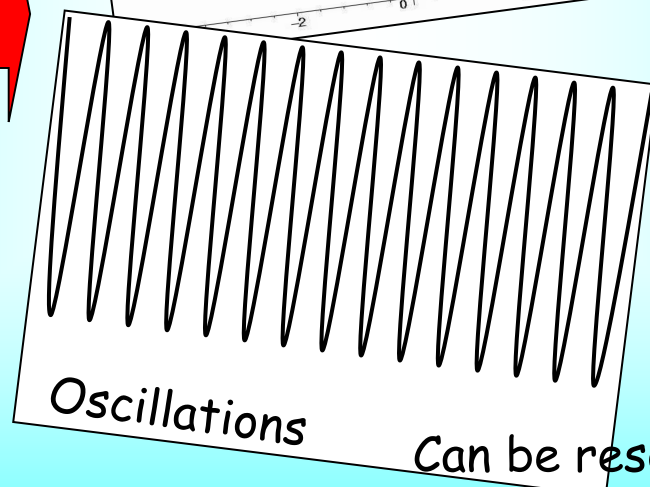
Theory

Masses, mixing, connection to physics BSM

Determination of mass and mixing

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





Can be resonantly enhanced in matter

Δm^2

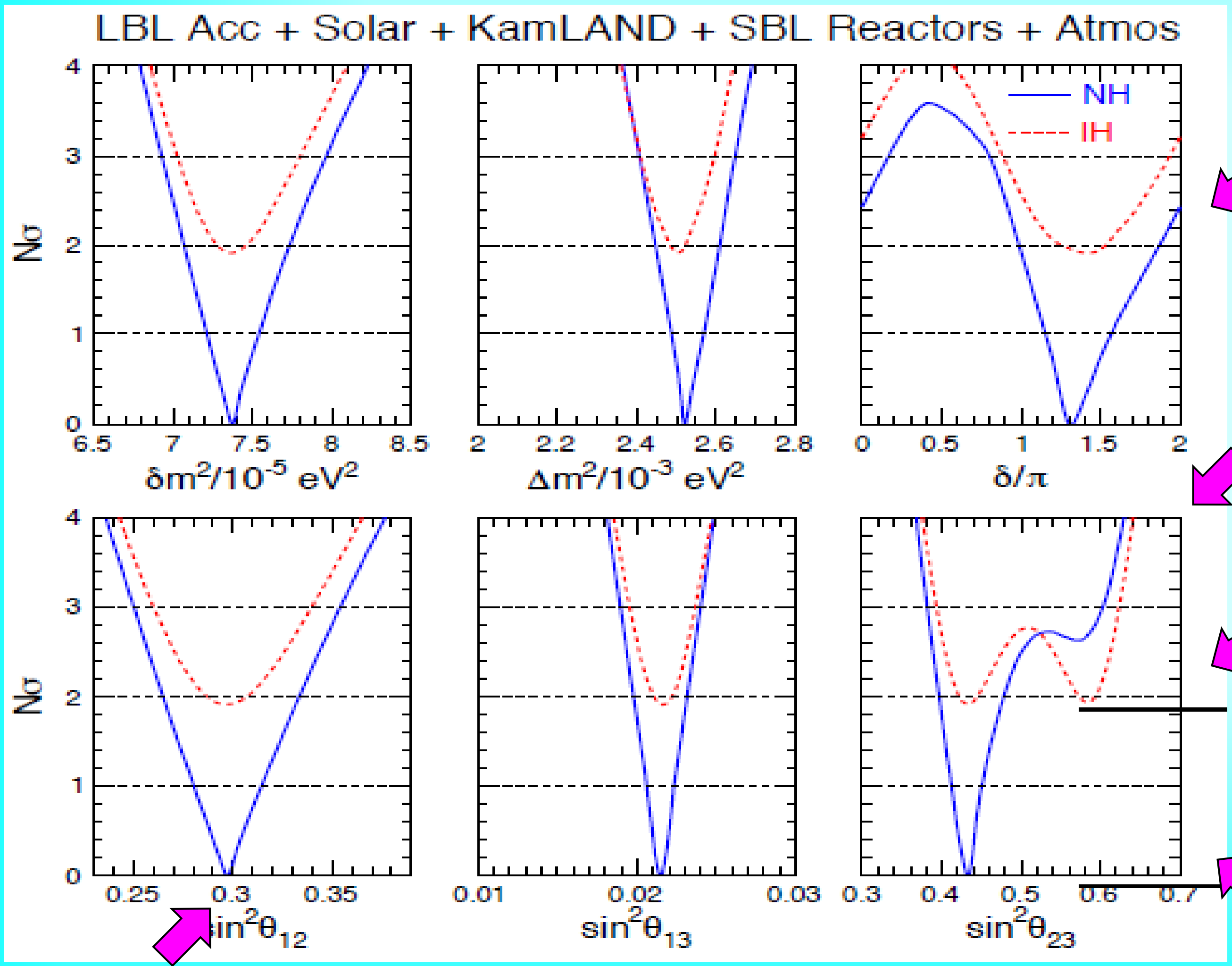
θ

★ 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

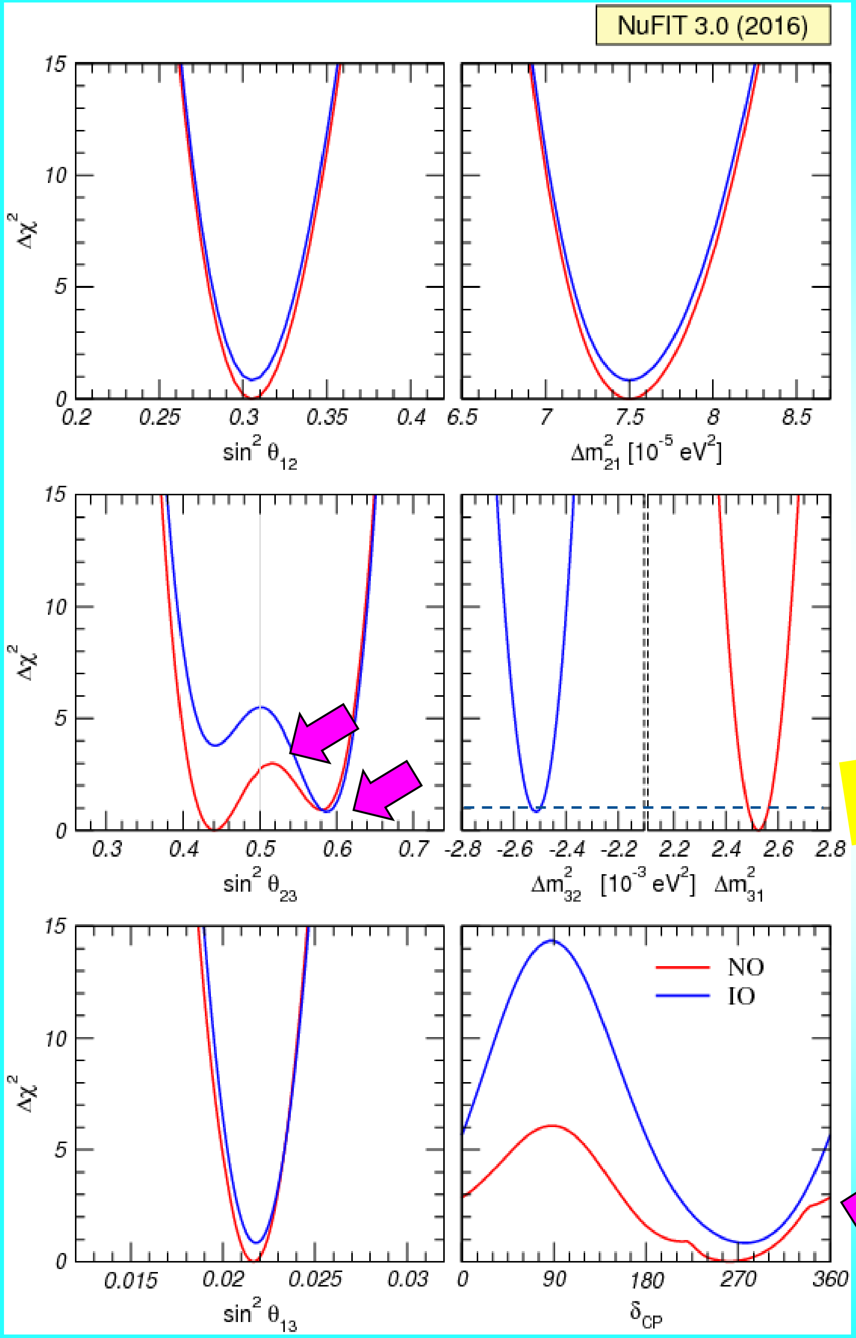
Second octant is disfavoured at 2σ

$\Delta\chi^2 = 3.7$ between NH and IH

IH disfavored at about 2σ

smaller than 0.30

NuFIT 3.0 (2016)



*I. Esteban, M.C. Gonzalez-Garcia
M. Maltoni, I. Martinez-Soler,
T. Schwetz, 1611.01514 [hep-ph]*

Similar conclusions but with lower confidence level

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]

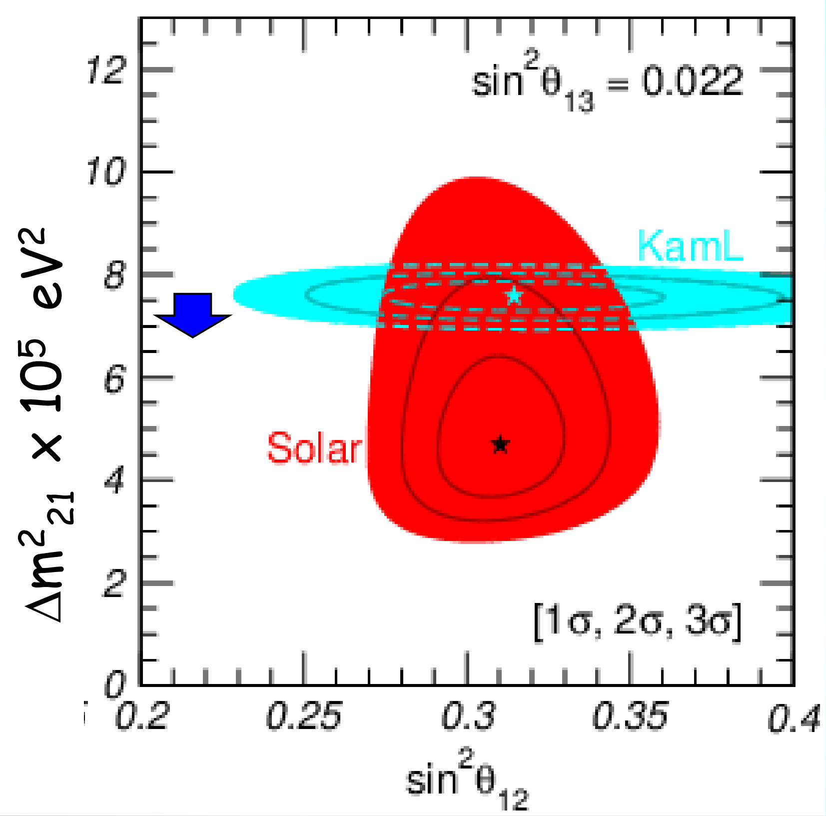
1-2 mass splitting

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

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

NSI (for solar) or
Very light sterile neutrinos

Solar vs. KamLAND



M. Maltoni, A.Y.S.
1507.05287 [hep-ph]

Two reasons:

Absense of the upturn of solar neutrino spectrum,

Large Day-Night asymmetry

See also F. Capozzi et al, 1601.07777 [hep-ph]

Red: all solar neutrino data

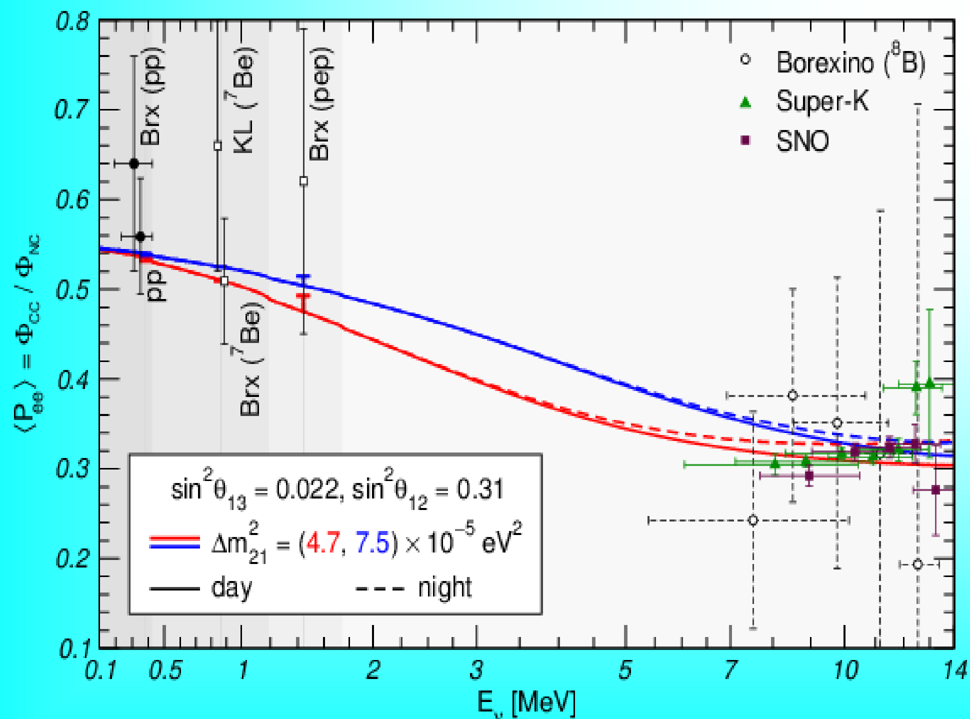
Δm^2_{21} (KL) > Δm^2_{21} (solar) 2 σ

Two reasons:

For smaller
solar split

Absence of upturn of
the energy spectrum

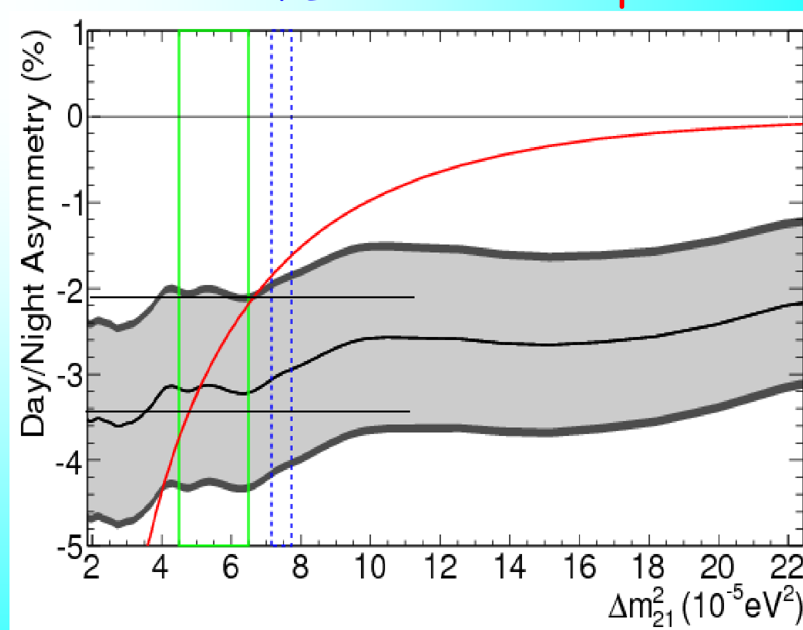
M. Maltoni, A.Y.S.
1507.05287 [hep-ph]



Large DM asymmetry at SK

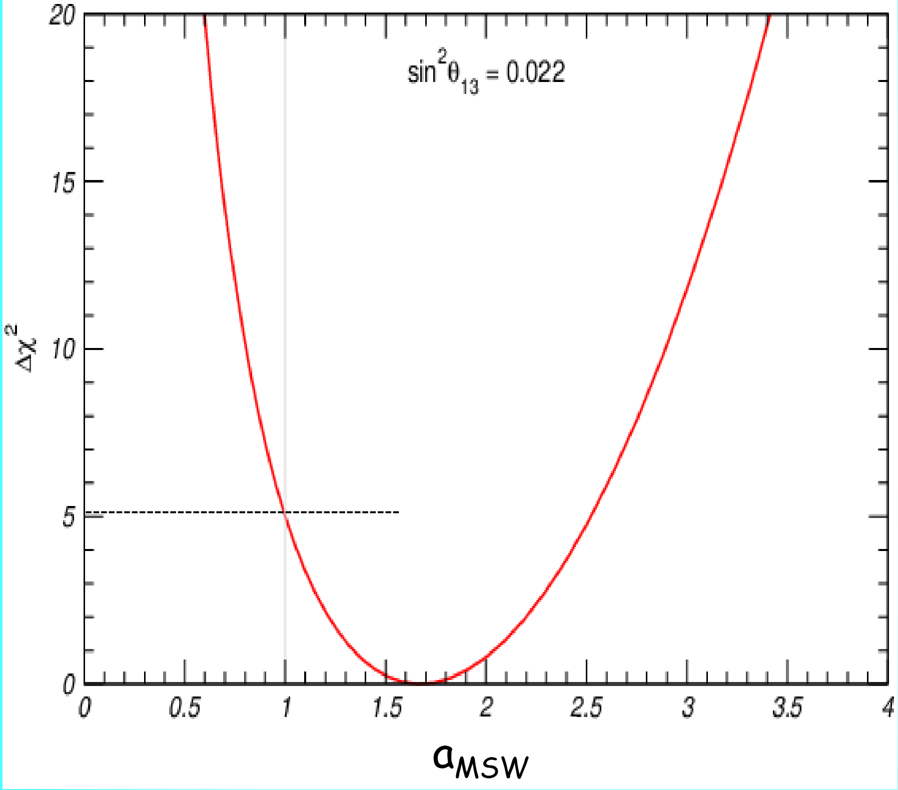
Super-Kamiokande collaboration
(Renshaw, A. et al.)
Phys.Rev.Lett. 112 (2014) 091805
arXiv:1312.5176

solar KL LMA expected



Another way to see...

Matter potential



G. L Fogli et al hep-ph/0309100

C. Pena-Garay, H. Minakata, hep-ph 1009.4869 [hep-ph]

M. Maltoni, A.Y.S. 1507.05287 [hep-ph]

$V = a_{MSW} V_{stand}$

the best fit value $a_{MSW} = 1.66$

$a_{MSW} = 1.0$ is disfavoured by > 2 σ

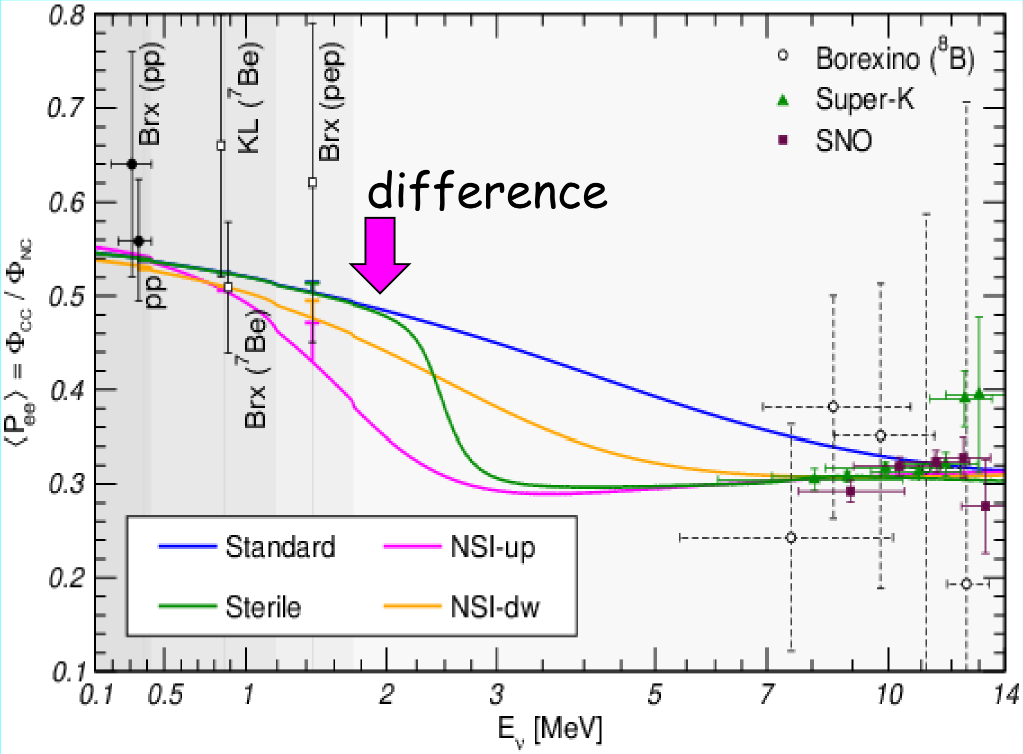
$$\frac{\Delta m^2_{21}\,(KL)}{\Delta m^2_{21}\,(Sun)} = 1.6$$

Determination of the matter potential from the solar plus KamLAND data using a_{MSW} as free parameter

Potential enters the probability in combination

$$\frac{V}{\Delta m^2_{21}}$$

New physics effects



M. Maltoni, A.Y.S.

Extra sterile neutrino with
$\Delta m^2_{01} = 1.2 \times 10^{-5}$ eV^2, and
$\sin^2 2\alpha = 0.005$

Non-standard interactions with
$\varepsilon^u_D = -0.22$, $\varepsilon^u_N = -0.30$
$\varepsilon^d_D = -0.12$, $\varepsilon^d_N = -0.16$

NSI due exchange by light (MeV scale mass) mediators
with small couplings allow to avoid existing bounds

M. Pospelov
Y. Farzan

Solar neutrinos

SuperKamiokande

BOREXINO II

SNO+

E > 3 MeV, upturn later pep- CNO- later

JUNO

Δm^2_{21} from reactor

HyperKamiokande

E > 7 MeV 5σ D-N in 10 years

JinPing

DARWIN

J Aalbers, 1606.07001 [astro-ph.IM]

Dark matter detector for solar neutrinos

LXe TPC 50 kt

1% accuracy of pp- neutrino flux

DUNE

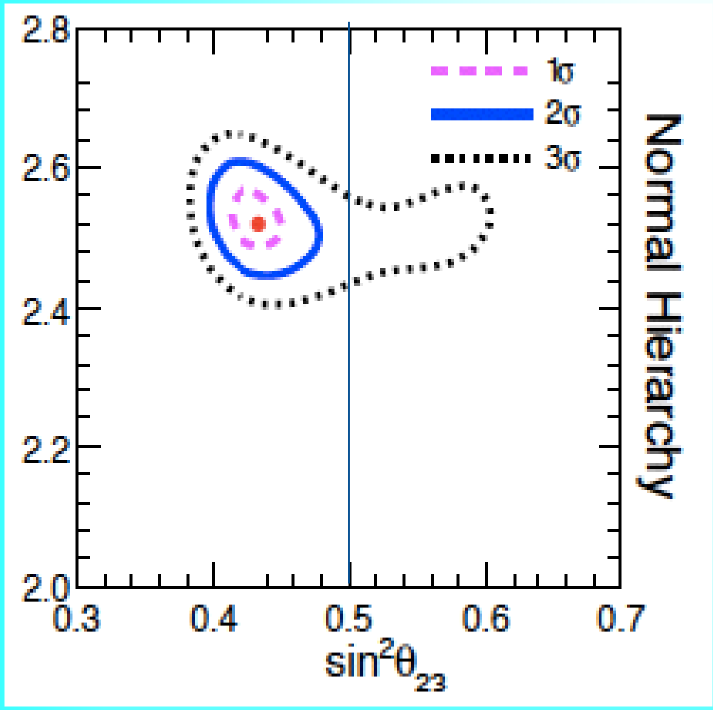
ν + Ar

energy determination, DN ?

2-3 mixing

Deviation from maximal, octant

NOvA, T2K, MINOS



F. Capozzi et al, NOW 2016

IMPLICATIONS

THEORY:

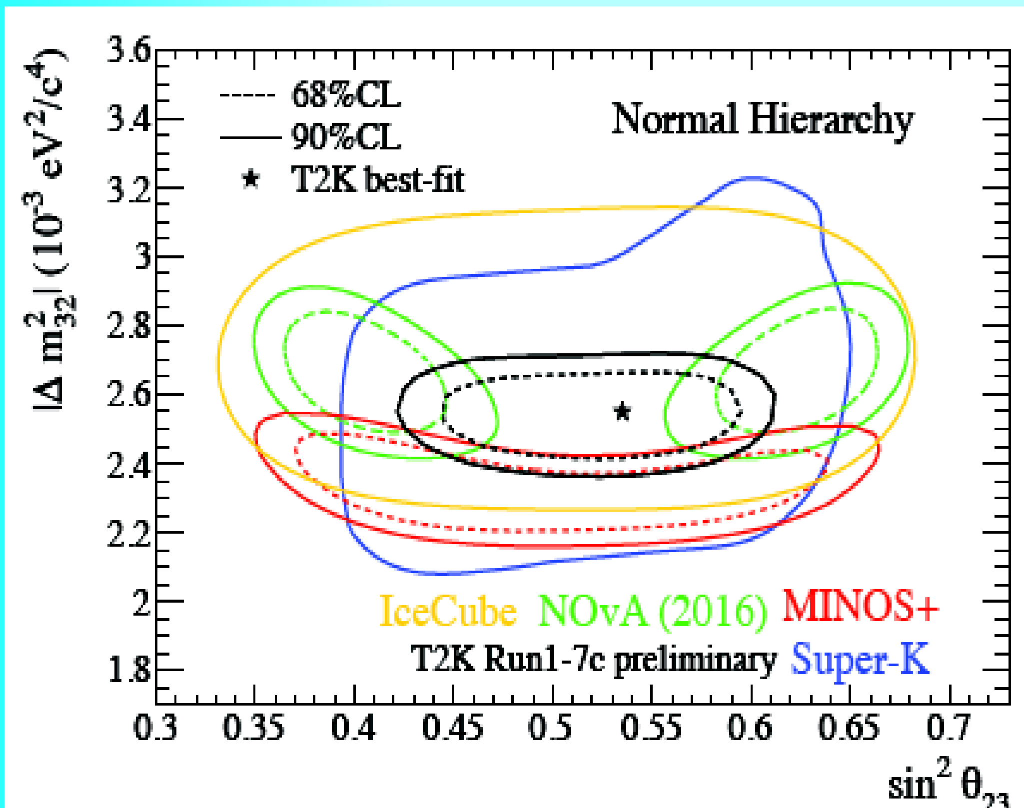
- Crucial for existence of symmetry behind the mixing pattern

- Possible relation between the deviation and non-zero 1-3 mixing – both can originate from violation of the 2-3 symmetry

PHENOMENOLOGY:

Affect sensitivity to CP-phase: Higher in 2nd octant

2-3 mixing: geography vs. new physics



US vs Japan or
New physics?

J. Hartnell, NOW2016

NOvA:

$\sin^2\theta_{23} = 0.40\ +0.03/-\ 0.02$

Maximal mixing
excluded at 2.5 σ

T2K + SK atmospheric
are consistent
with maximal mixing

Non-standard interactions?

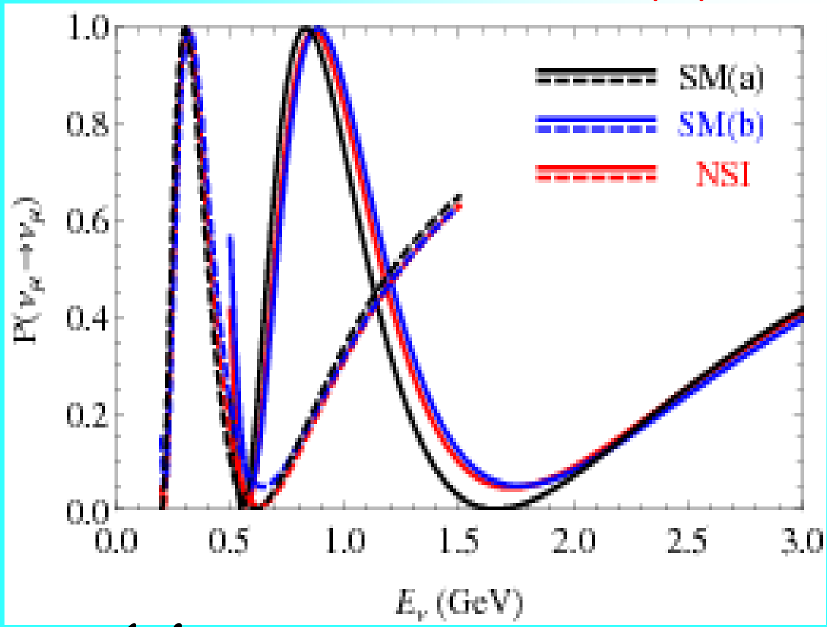
2-3 mixing: 2.5 σ tension

Maximal: T2K,
SK atmospheric, Deep Core

Non-maximal: NOvA, MINOS
more matter

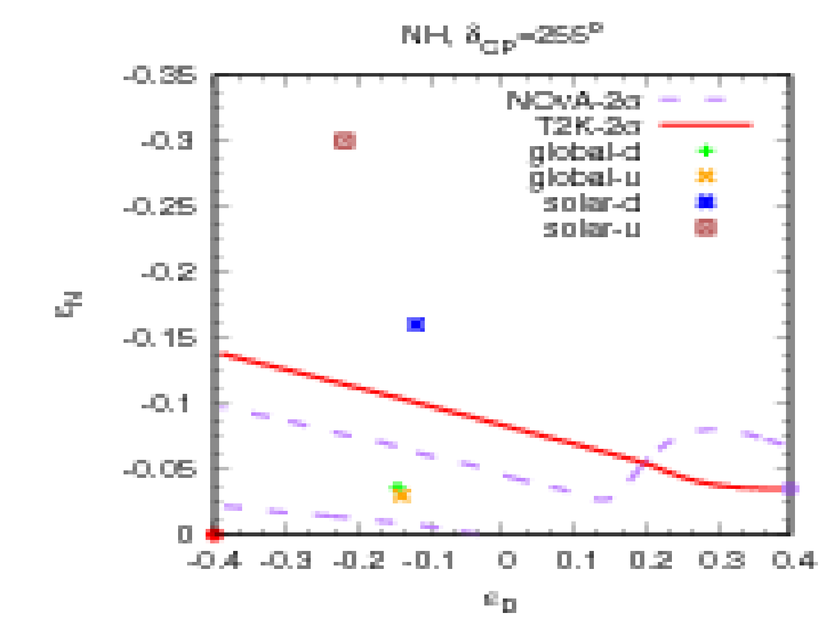
Standard interactions do not help → Non-standard interactions

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

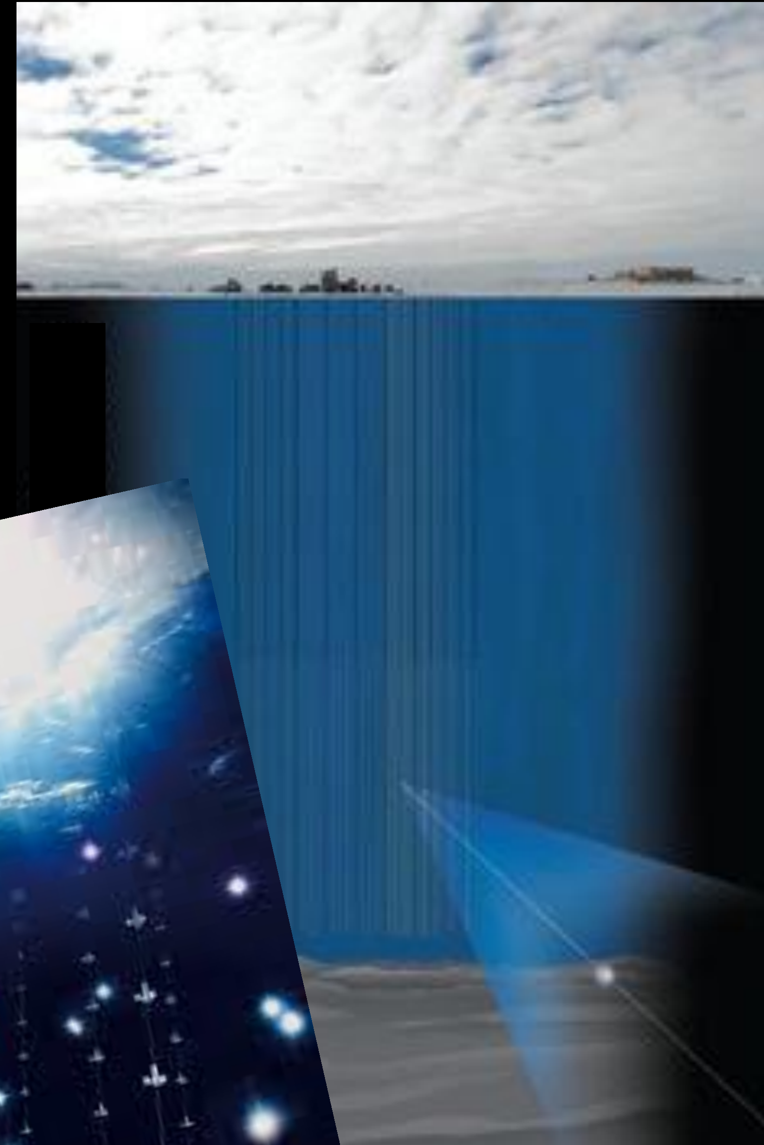


$\varepsilon_{\tau\tau}$ = 1.4

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



Mass hierarchy CP-violation



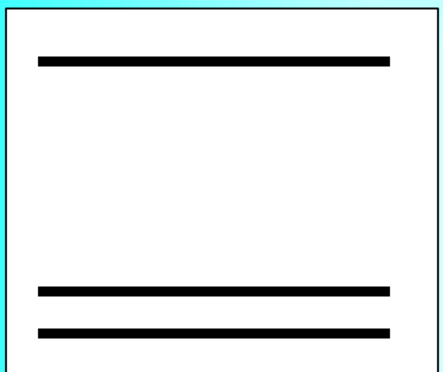
The first glimpses?

Neutrino Mass hierarchy

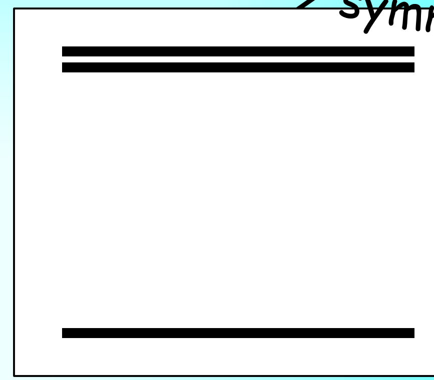
Fundamental:
principle, symmetry

Accidental: selection of
values of parameters

Quasi-degenerate
→ symmetry



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



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

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

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

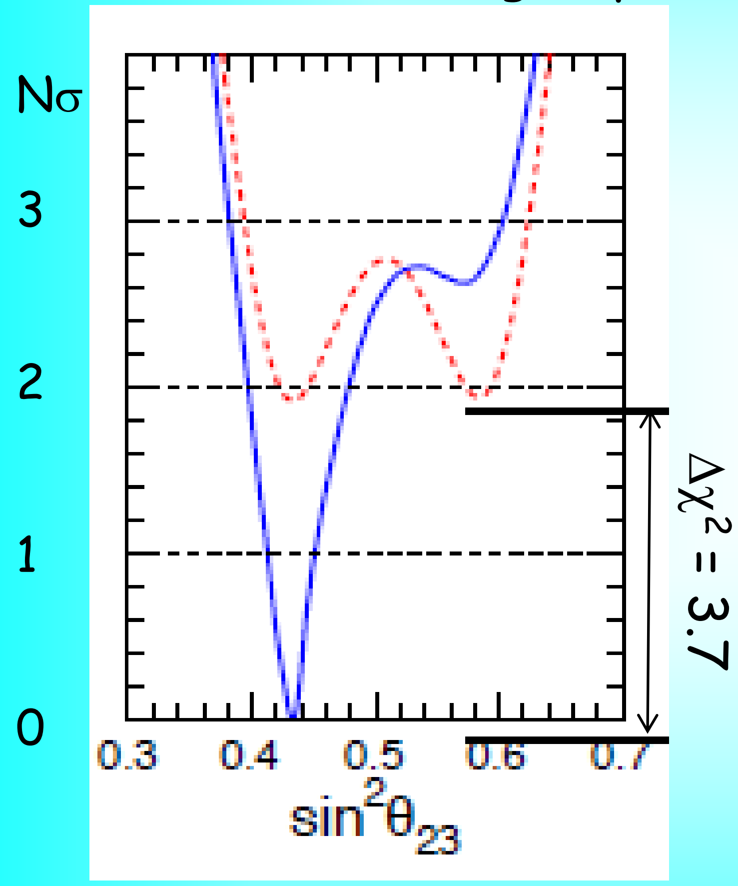
Flavor symmetries

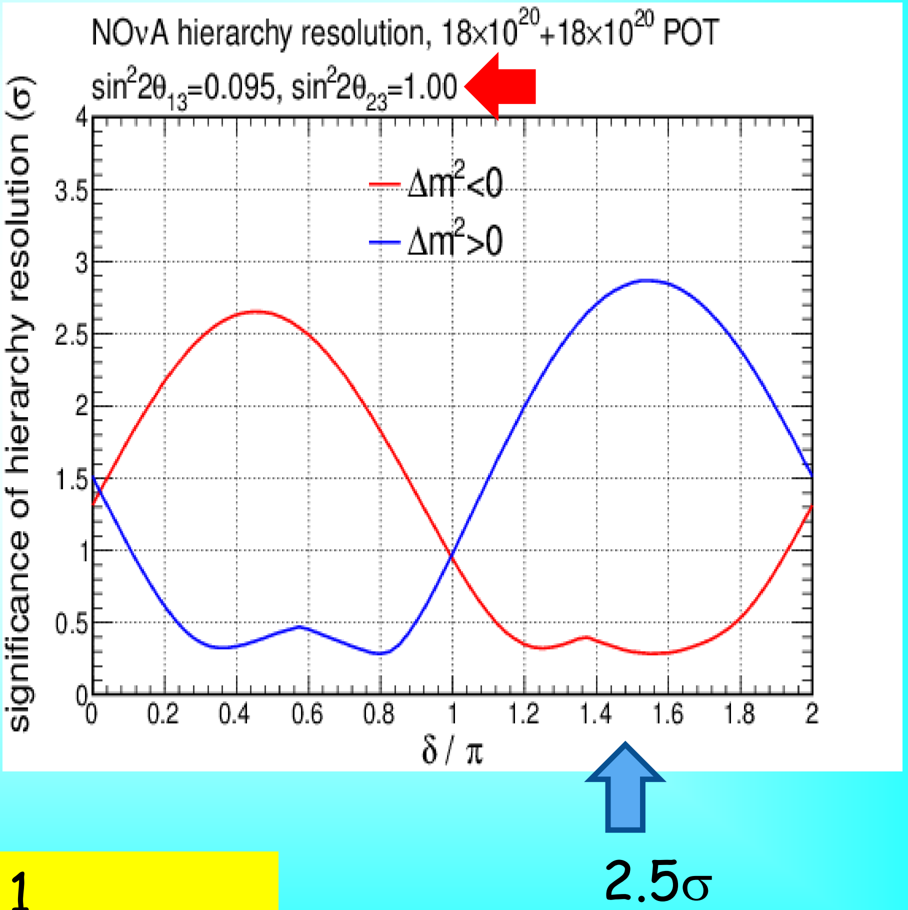
Broken $L_e - L_\mu - L_\tau$ symmetry

Present sensitivity

F. Capozzi et al, NOW 2016

Global fit (Bari group)

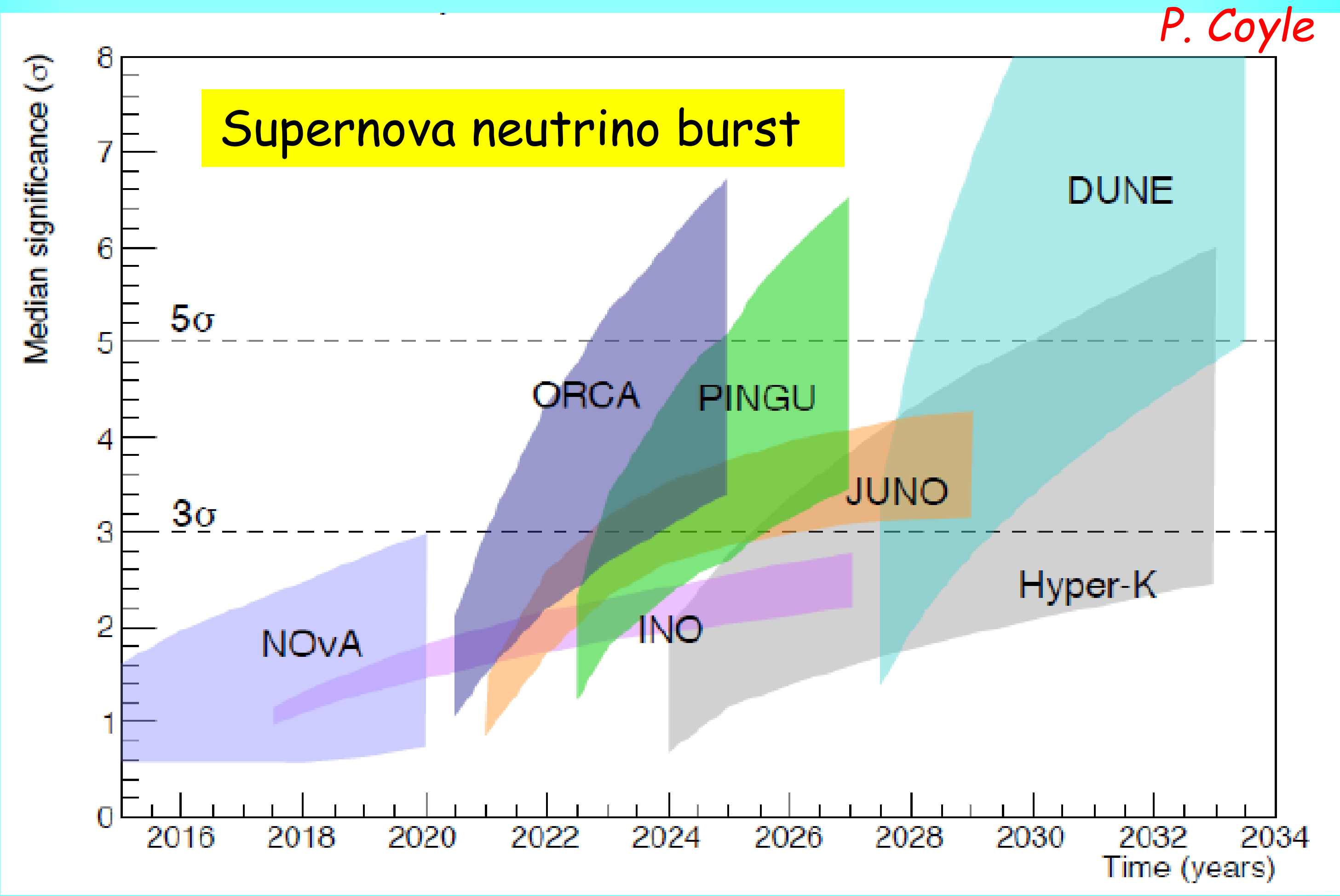




$6\ 10^{20}$ POT

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

Race for the mass hierarchy



CP- violation phase

F. Capozzi et al,
NOW 2016

Theory

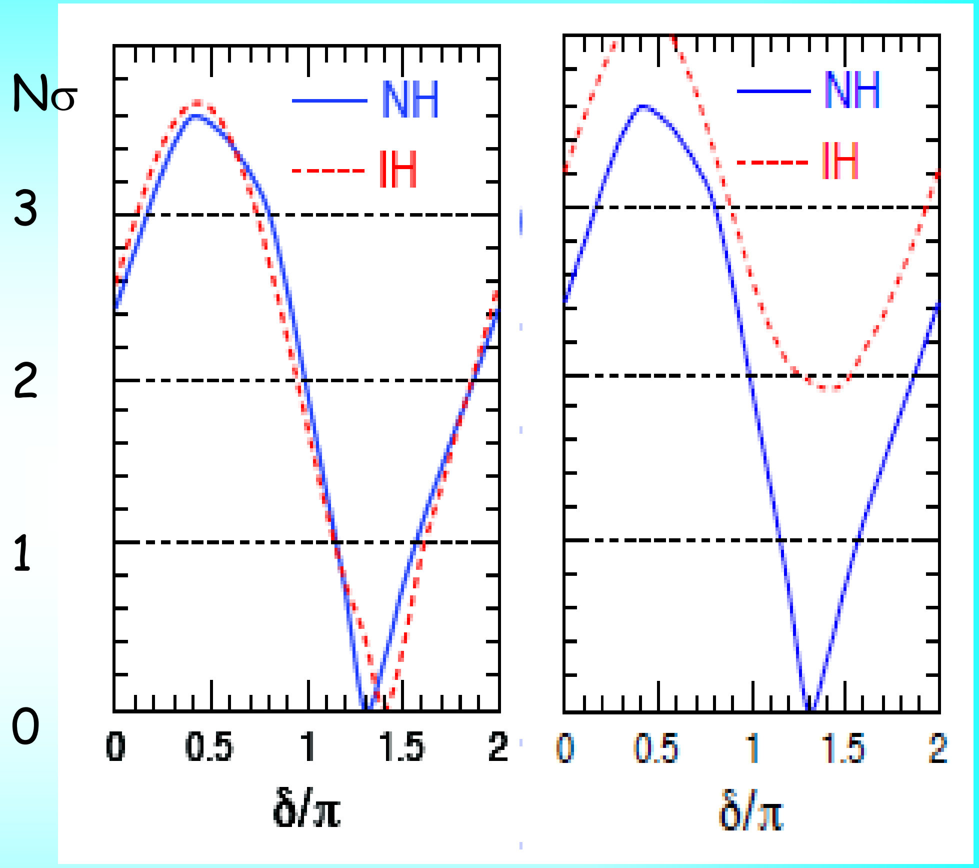
probe of the underlying physics, enters various test equalities

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

Measuring CP-phase

Global fit

T2K + 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)

- $\pi/2$ 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

Neutrino masses: Scales and nature

KATRIN 2016

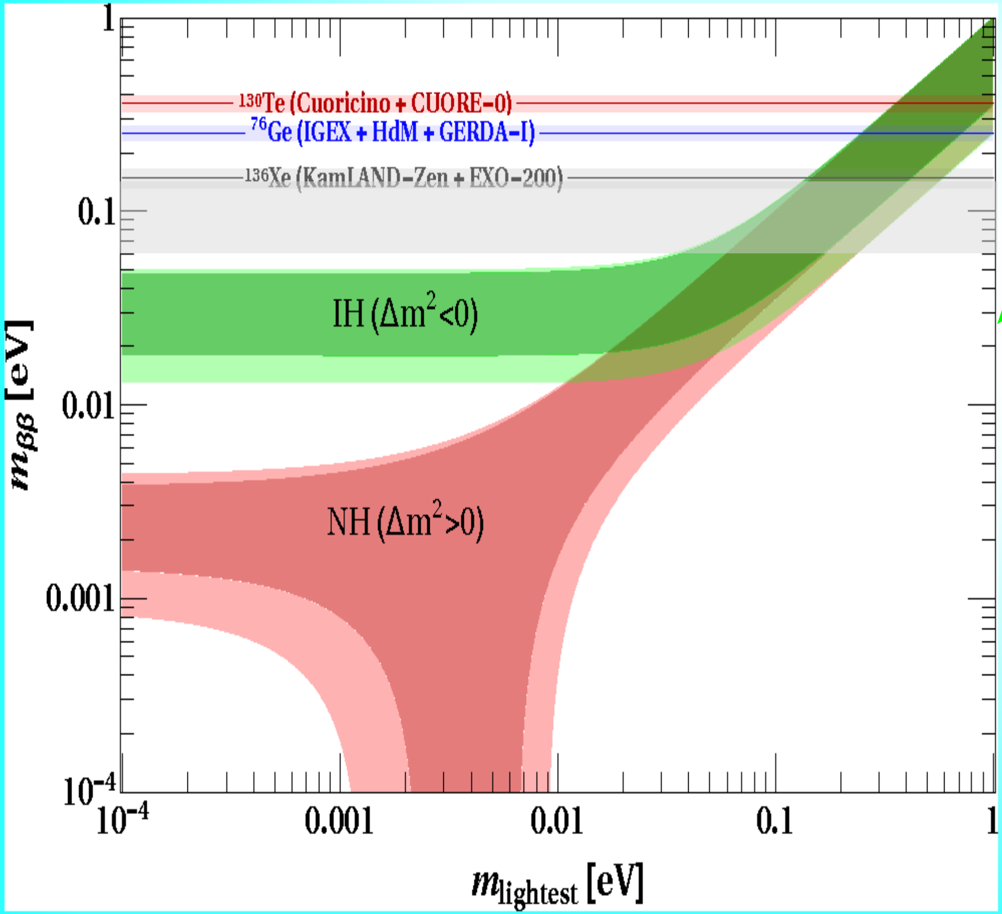
Cosmology

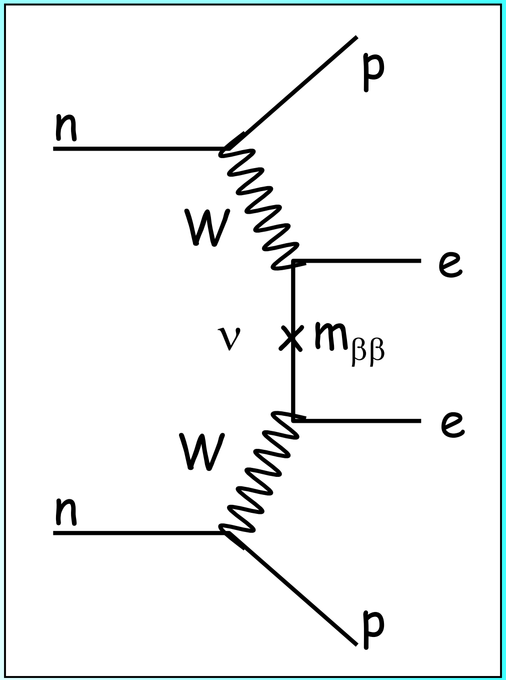
KamLAND Zen

If LHC see will see nothing....

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

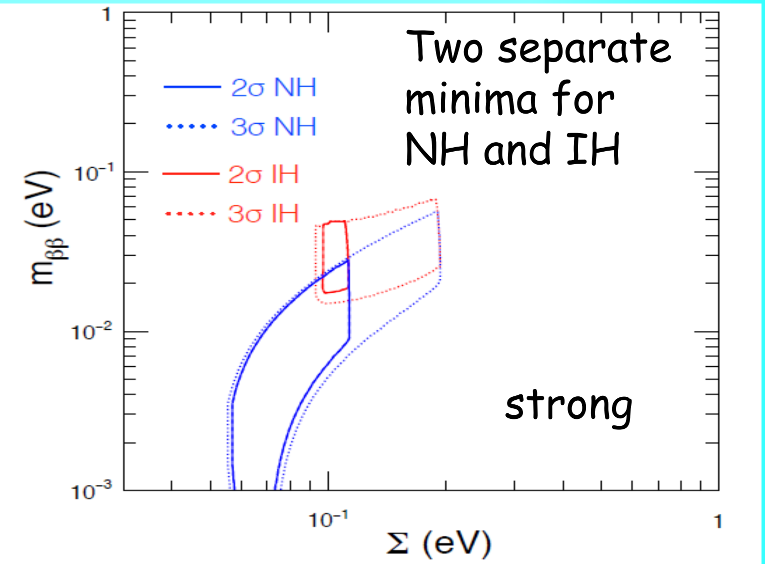
Absolute mass scale

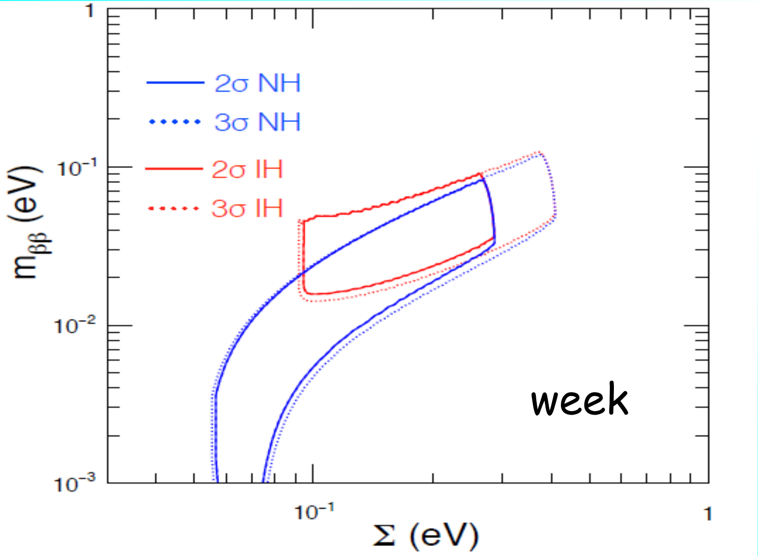
F. Capozzi et al, NOW 2016

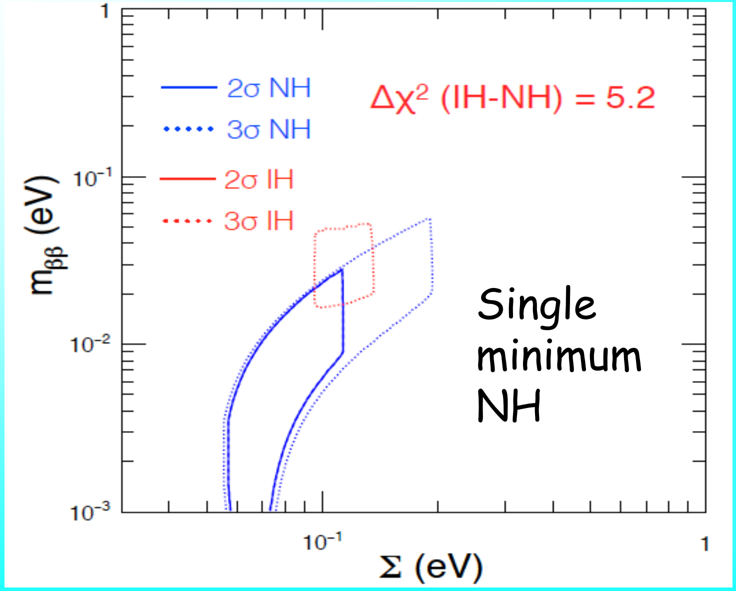
Bounds from oscillations and cosmology

Cosmology start to restrict IH

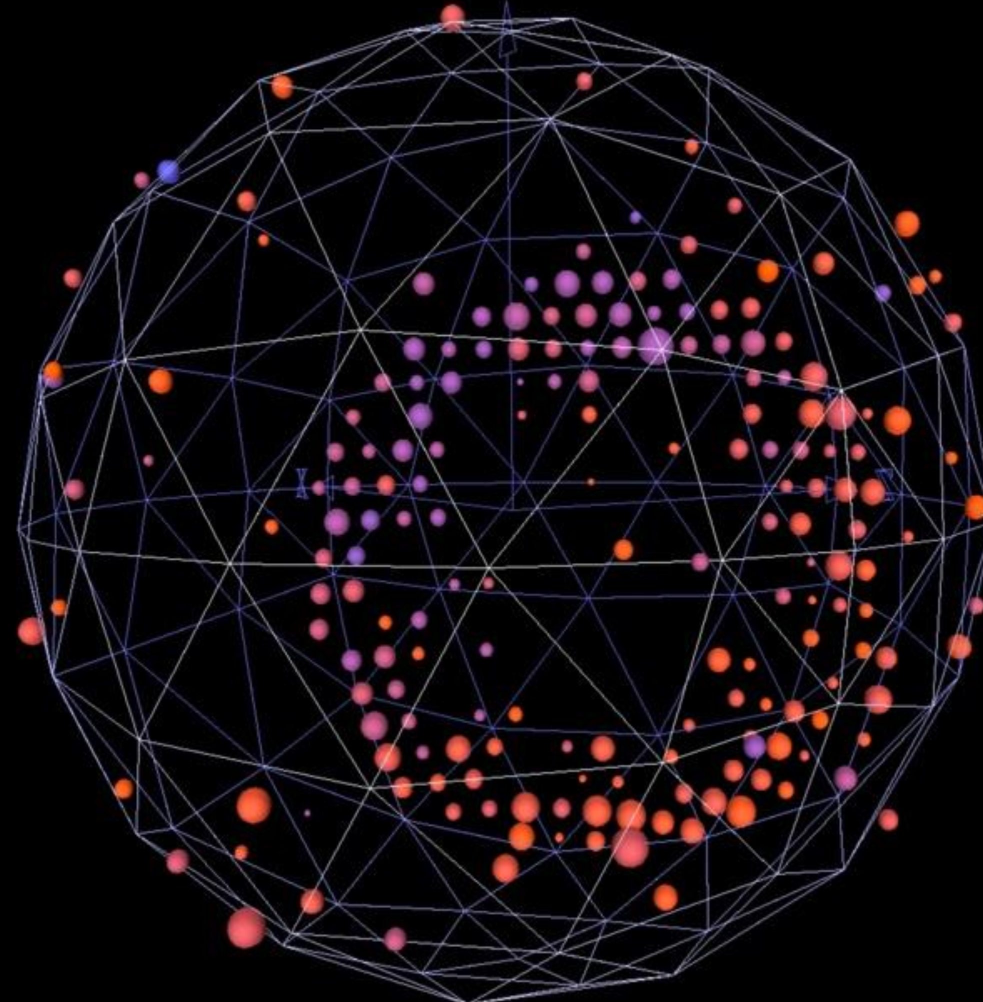
$$m_{\beta\beta} = U_{e1}^2 m_1 + U_{e2}^2 m_2 e^{i\alpha} + U_{e3}^2 m_3 e^{i\beta}$$



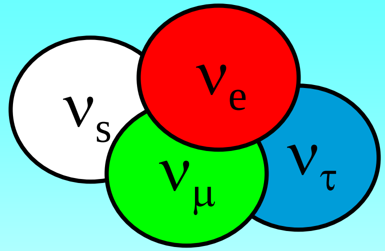


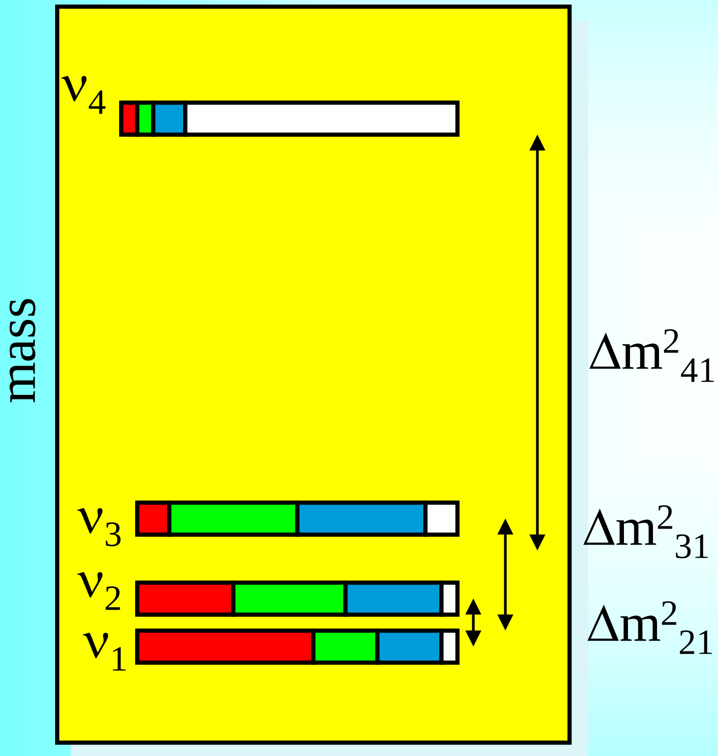


Sterile Neutrinos



(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

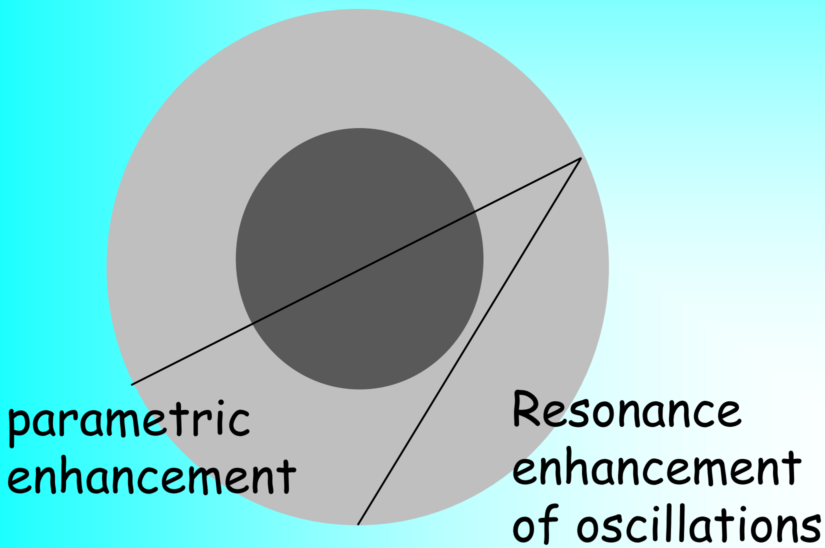
$$P \sim 4|U_{e4}|^2 (1 - |U_{e4}|^2)$$

Strong perturbation of 3ν pattern:

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

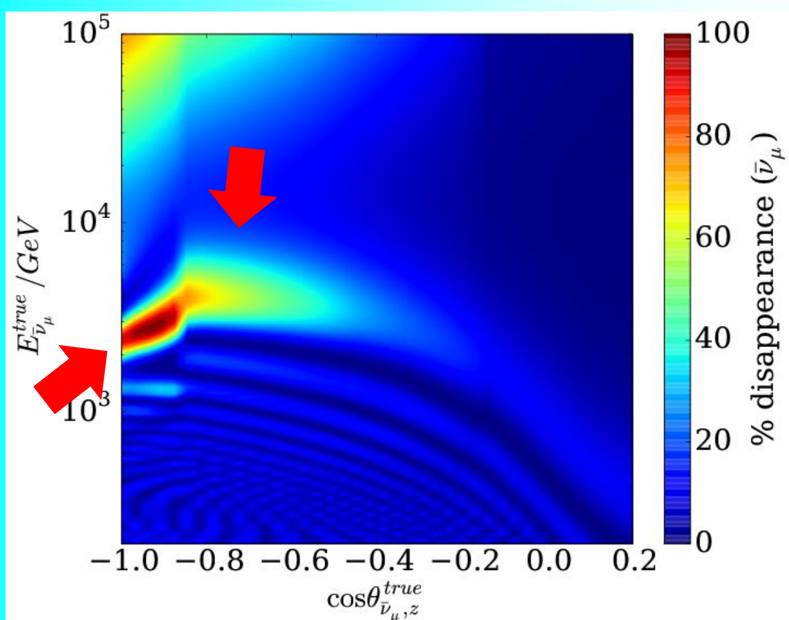
- additional radiation in the Universe
- bound from LSS?

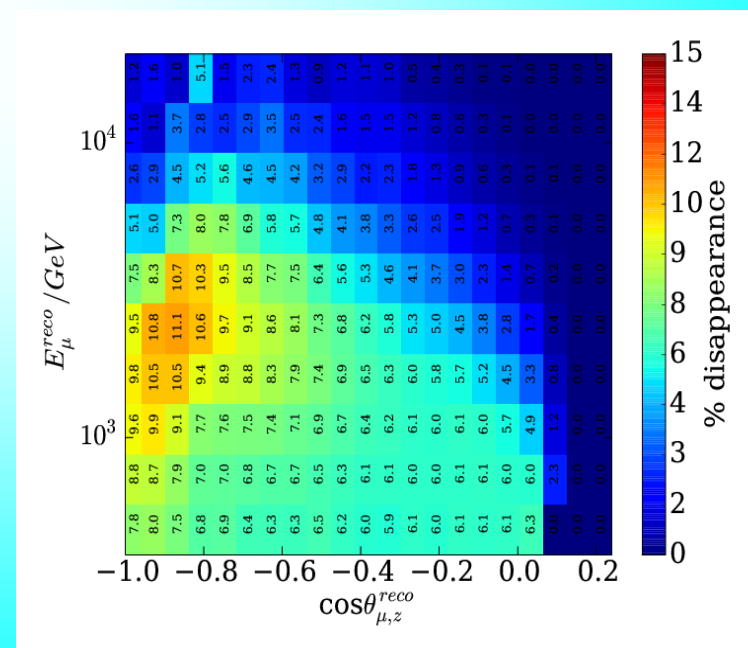
IceCube searches for sterile neutrinos



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

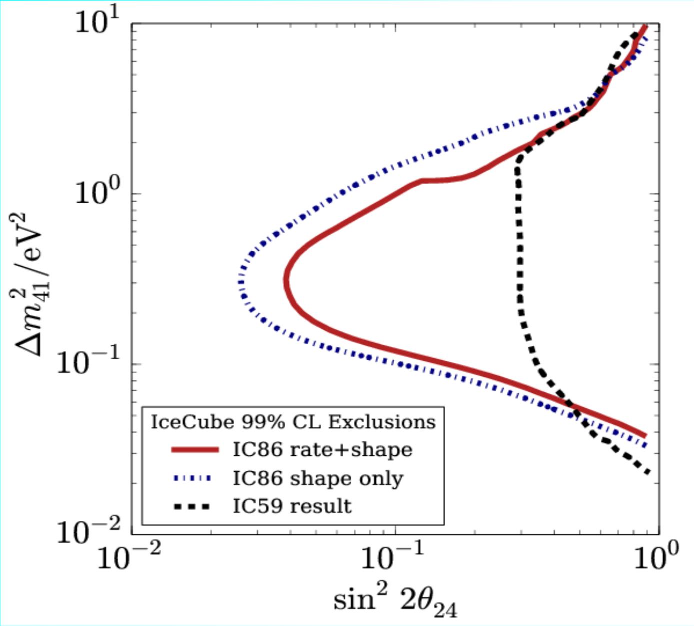


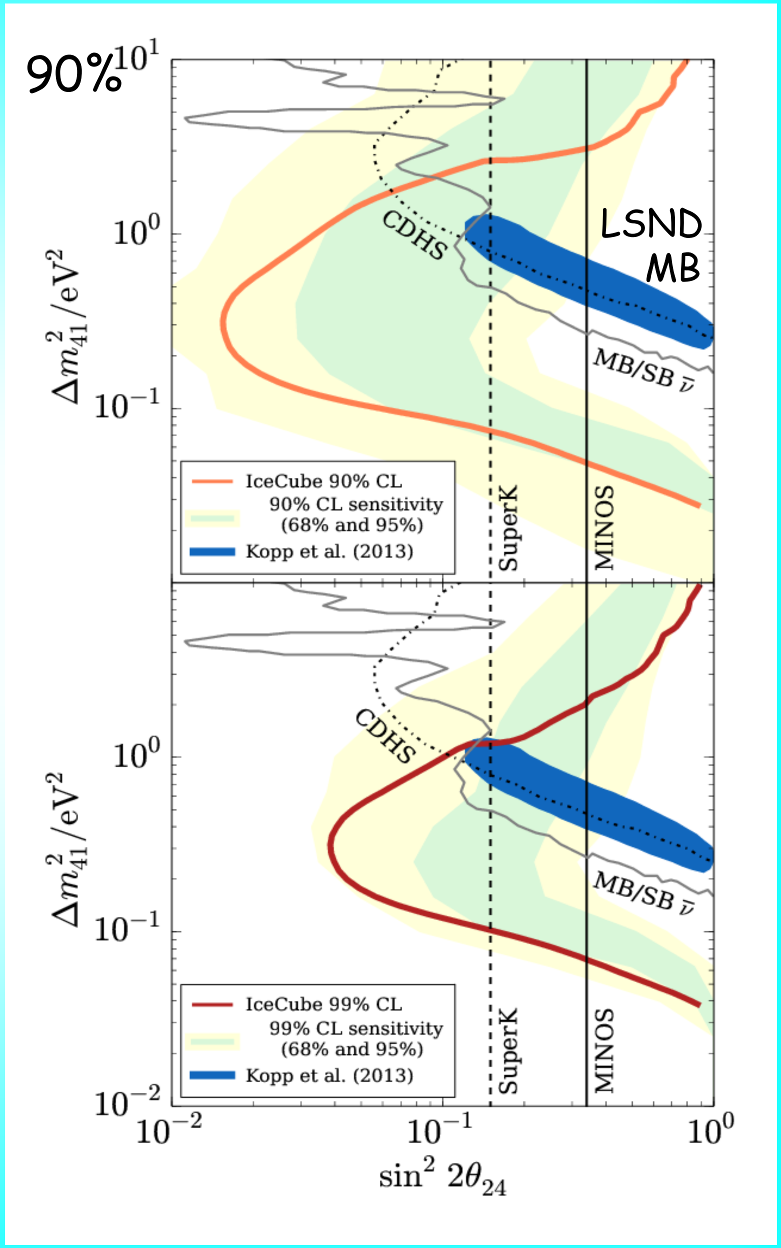


IC bounds

Rate and shape

on parameters of sterile neutrinos in 3+1 scheme



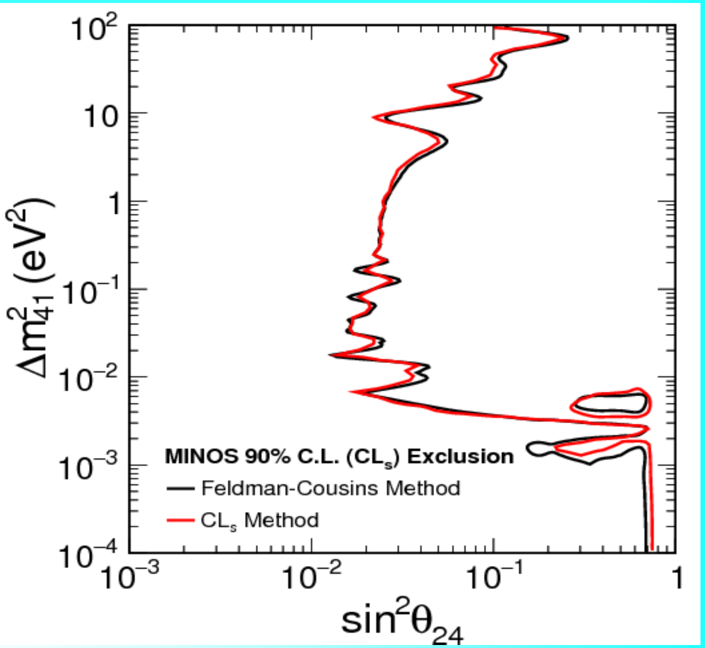


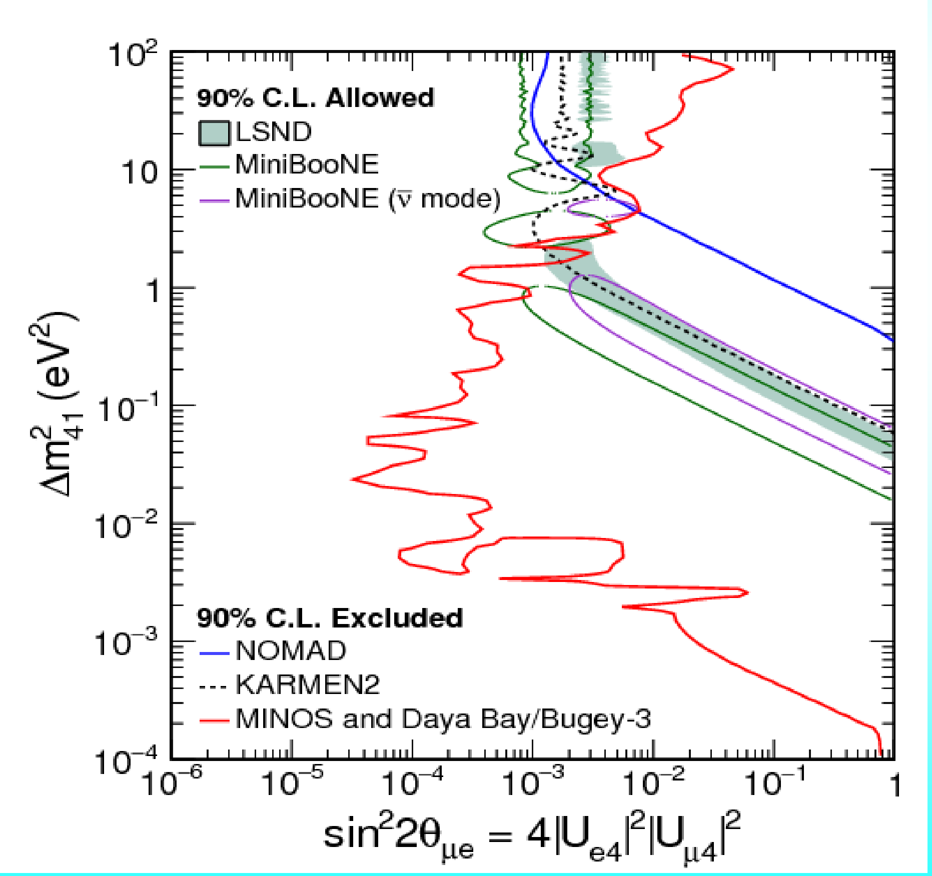
Other experiments results are at 90% CL

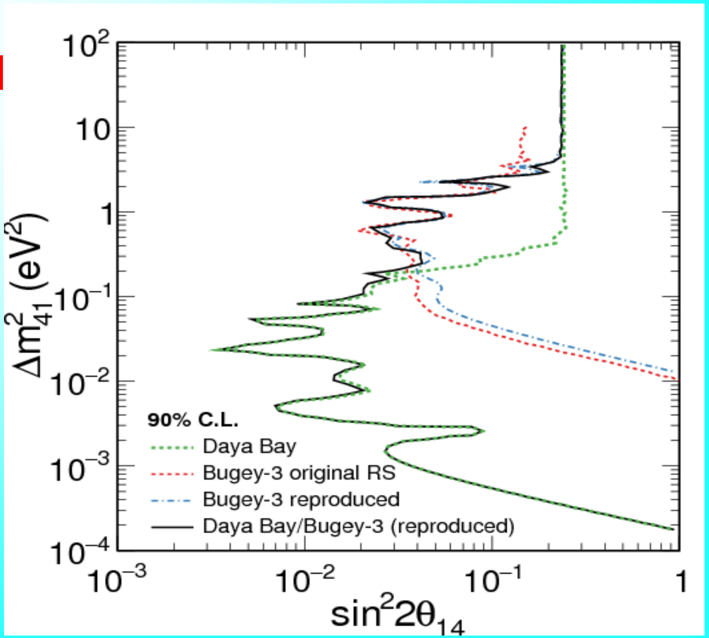
For LSND/MB and SBL $|U_{e4}|^2 = 0.023$ is taken

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]





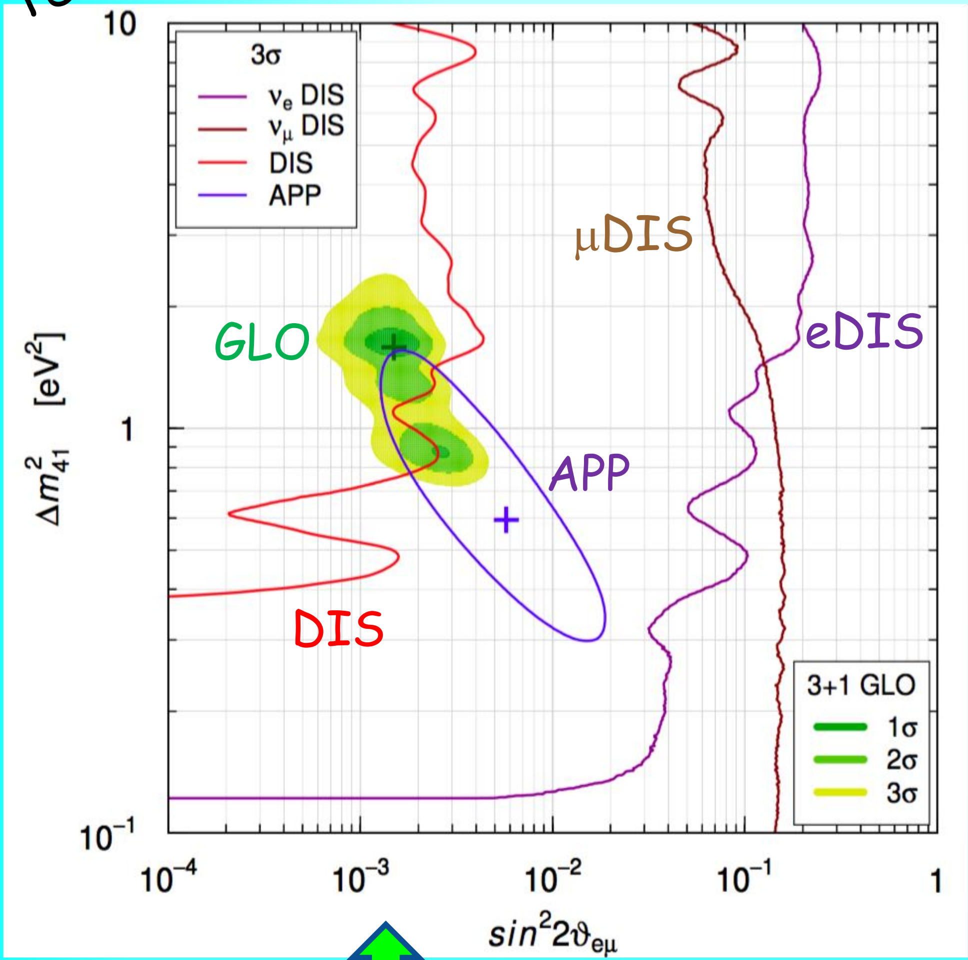


Appearance vs. disappearance

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

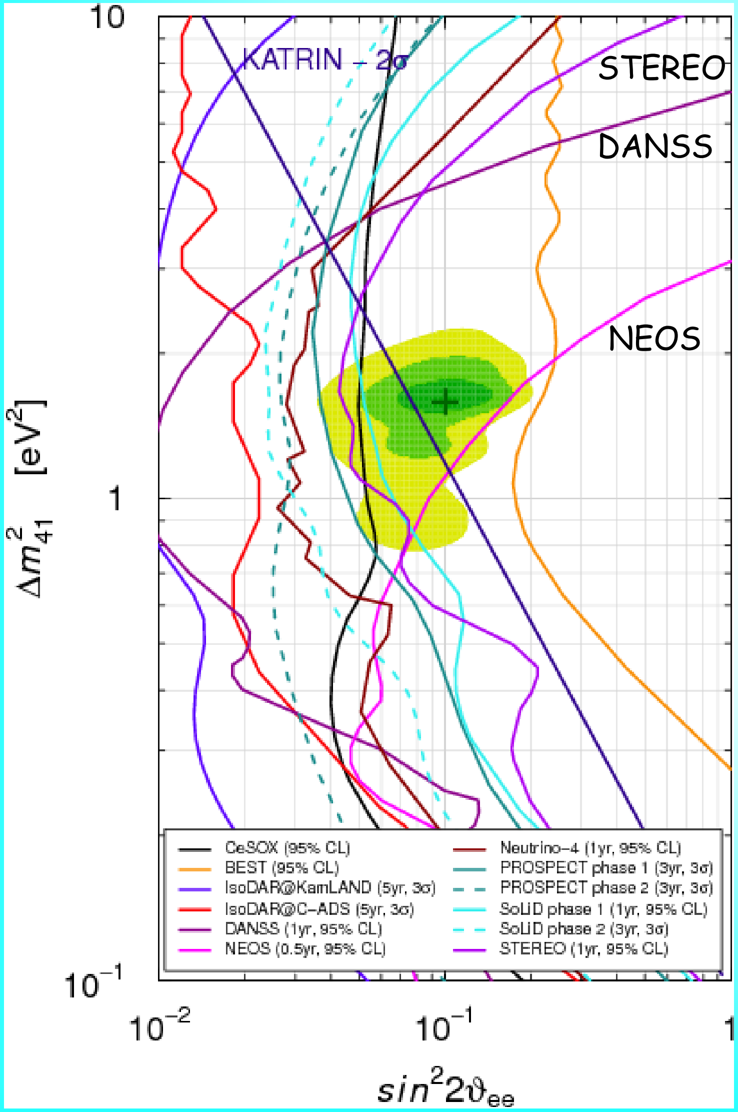
μDIS: $\nu\mu$ disappearance-only data

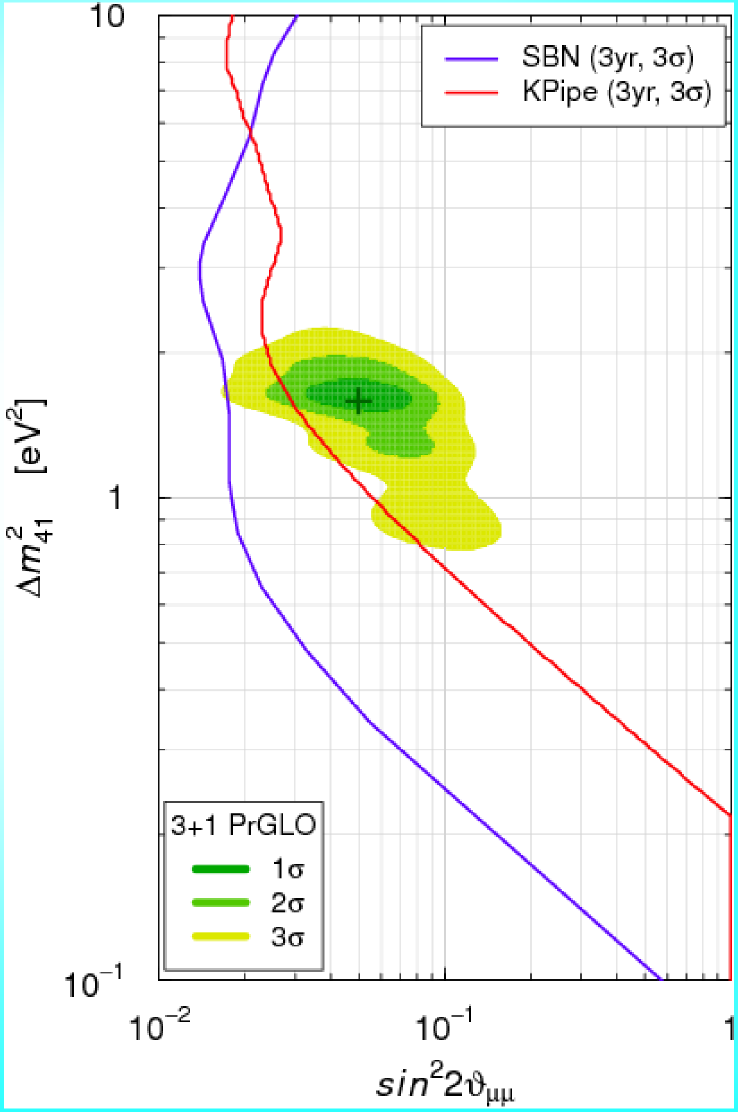
DIS: combined disappearance data

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

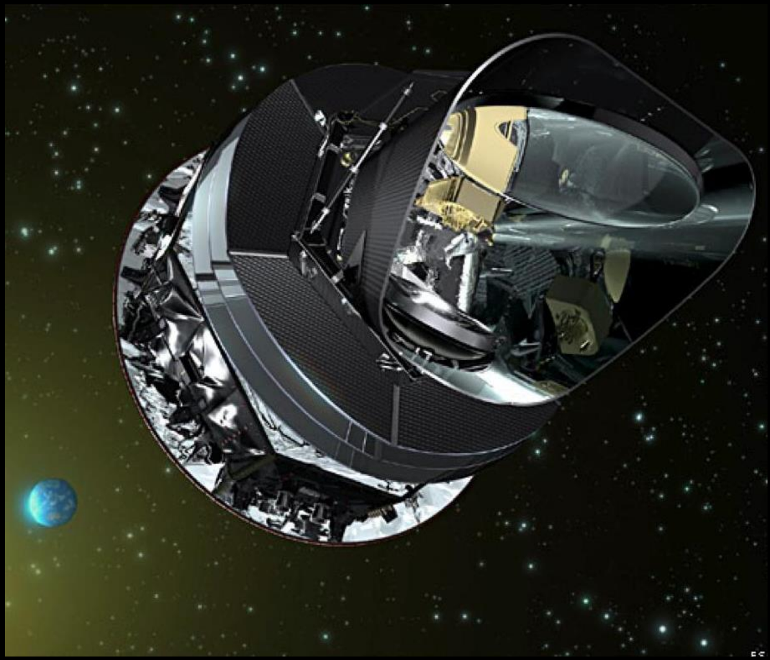
Future

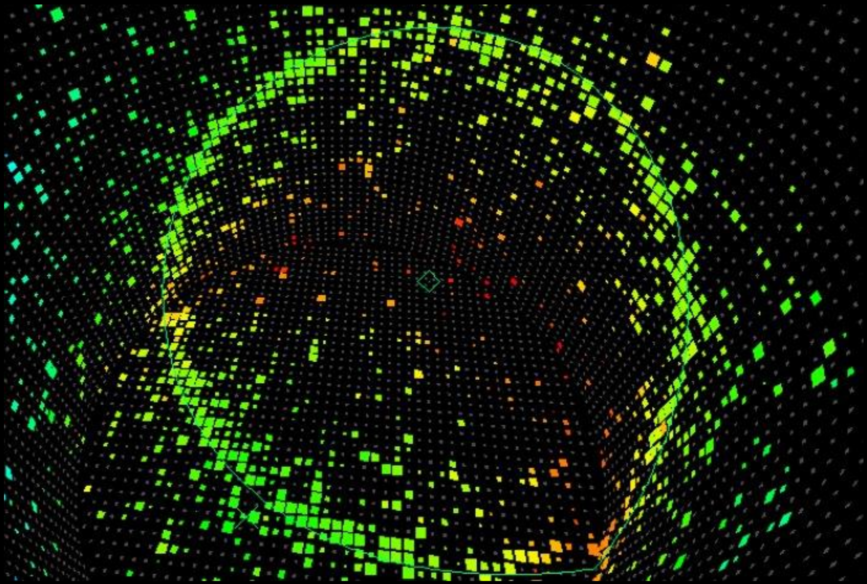
C. Giunti ,
arXiv: 1609.04688 [hep-ph]





Neutrinos and Dark matter





Neutrinos - Dark matter

Is the (hot) component of the DM

Mechanism of generation of small neutrino masses is related to DM

RH neutrinos as DM particles

Neutrino portal connects DM and neutrinos

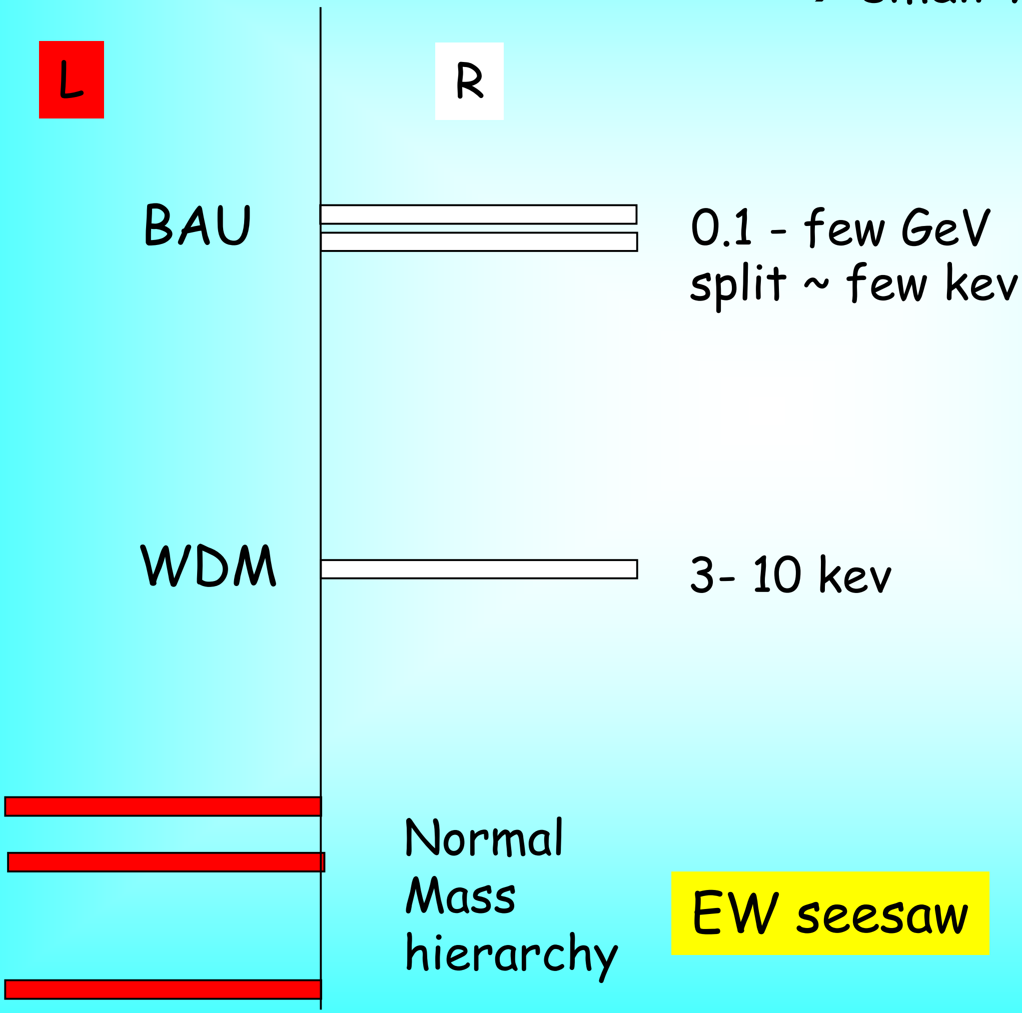
DM particles participate (appear in loops) in generation of neutrino mass

The same symmetry is responsible for smallness of neutrino mass and stability of the DM

νMSM

M. Shaposhnikov et al

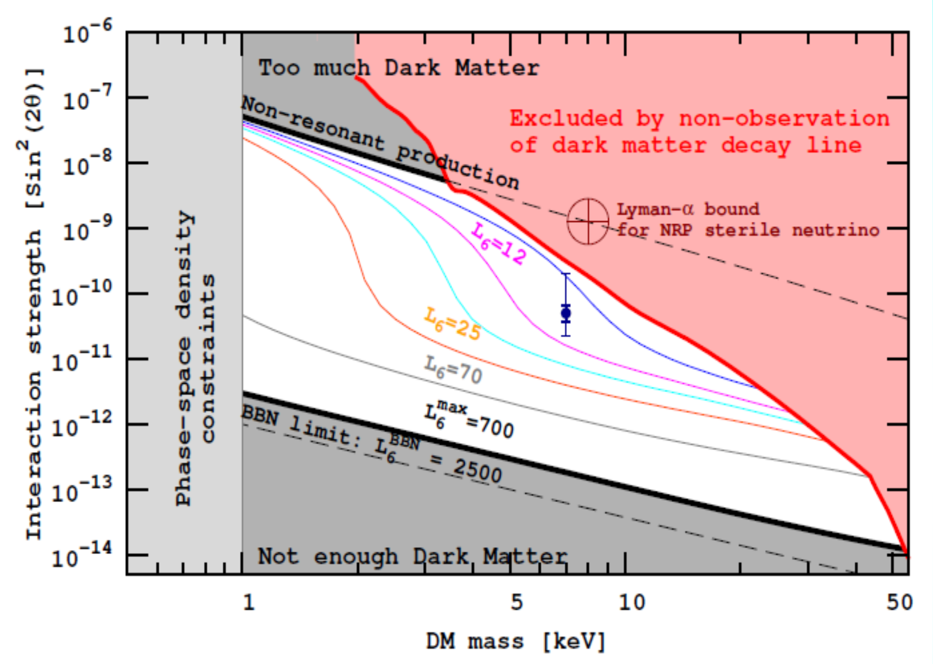
Everything below EW scale
→ small Yukawa couplings

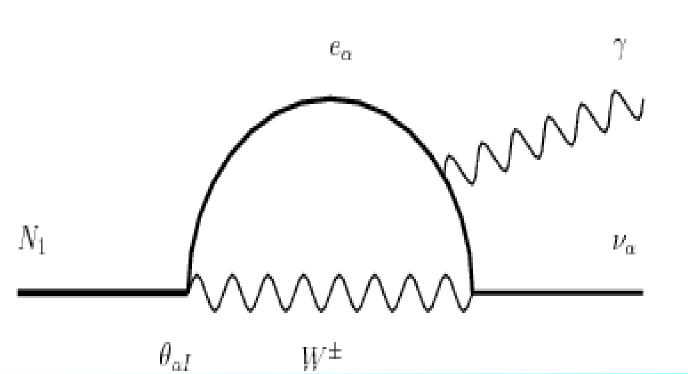


- small neutrino mass
- generate lepton asymmetry in the Universe via oscillations
- can be produced in B-decays (BR ~ 10^{-10}) etc, SHiP

- warm dark matter
- radiative decays → X-rays

WDM sterile neutrino ?





3.5 kev X ray line

$\theta_{aS}^2 \sim 2\ 10^{-11}$

$\delta m \sim \theta_{aS}^2\ m \sim (1 - 2)\ 10^{-7}$ eV

→ does not participate in neutrino mass generation

→ is not RH, but some singlet from HS beside 3 ν_R

The blue point: the best-fit value from M31 (Andromeda galaxy). Thick error bars are ±1σ limits on the flux. Thin error bars correspond to the uncertainty in the DM distribution in the center of M31.

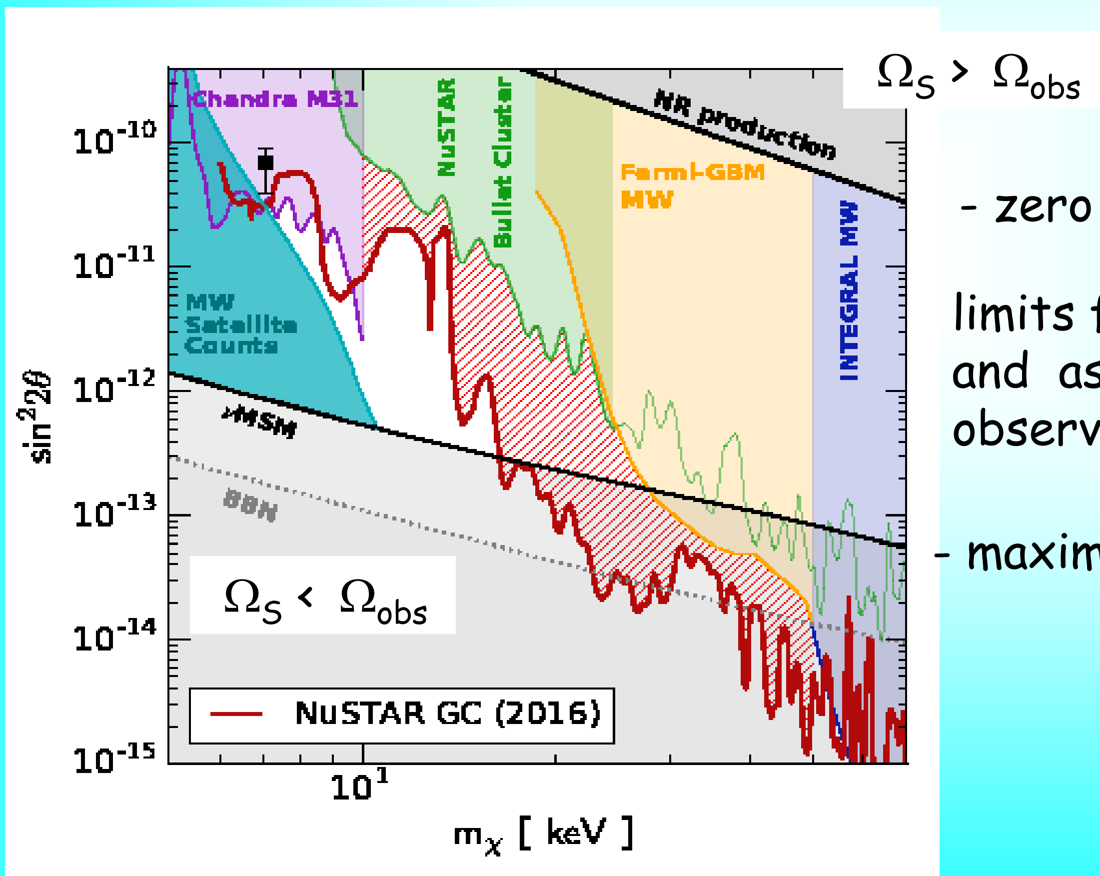
A Boyarsky et al, 1402.4119

Sterile Neutrinos as Dark matter

(Almost) Closing the Sterile Neutrino Dark Matter Window with NuSTAR

K. Perez, et al.
arXiv:1609.00667 [astro-ph.HE]

Nuclear Spectroscopic Telescope Array, Galactic Center



- zero lepton asymmetry

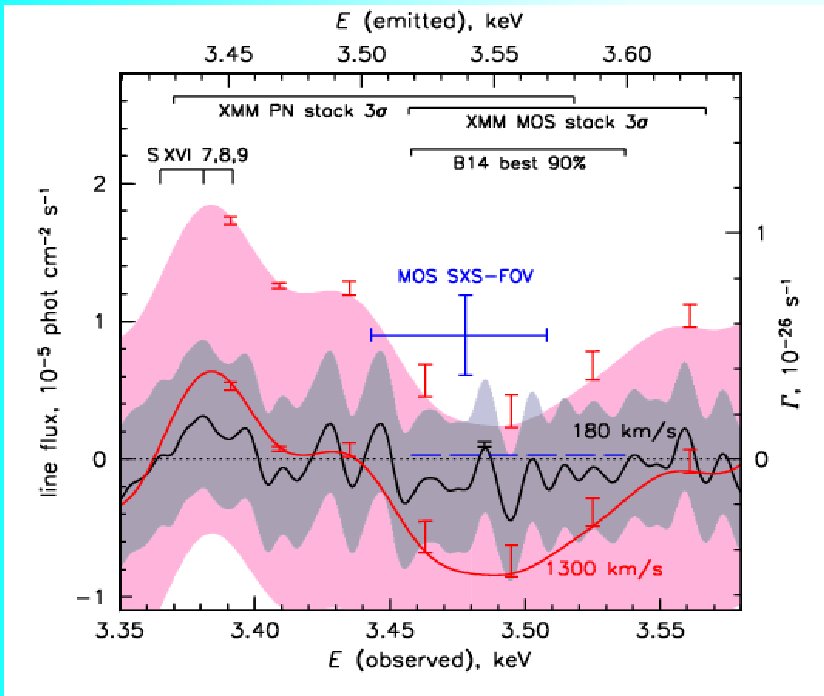
limits from structure formation and astrophysical X-ray observations the colored, regions.

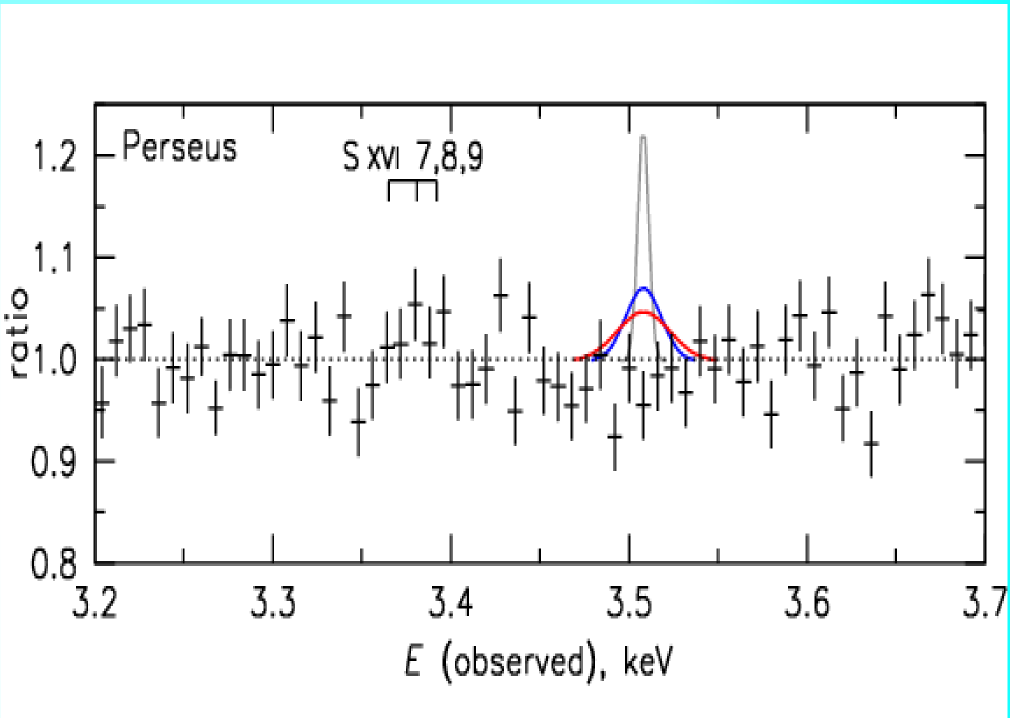
- maximal lepton asymmetry

Hitomi constraints

on the 3.5 keV line in
the Perseus galaxy cluster

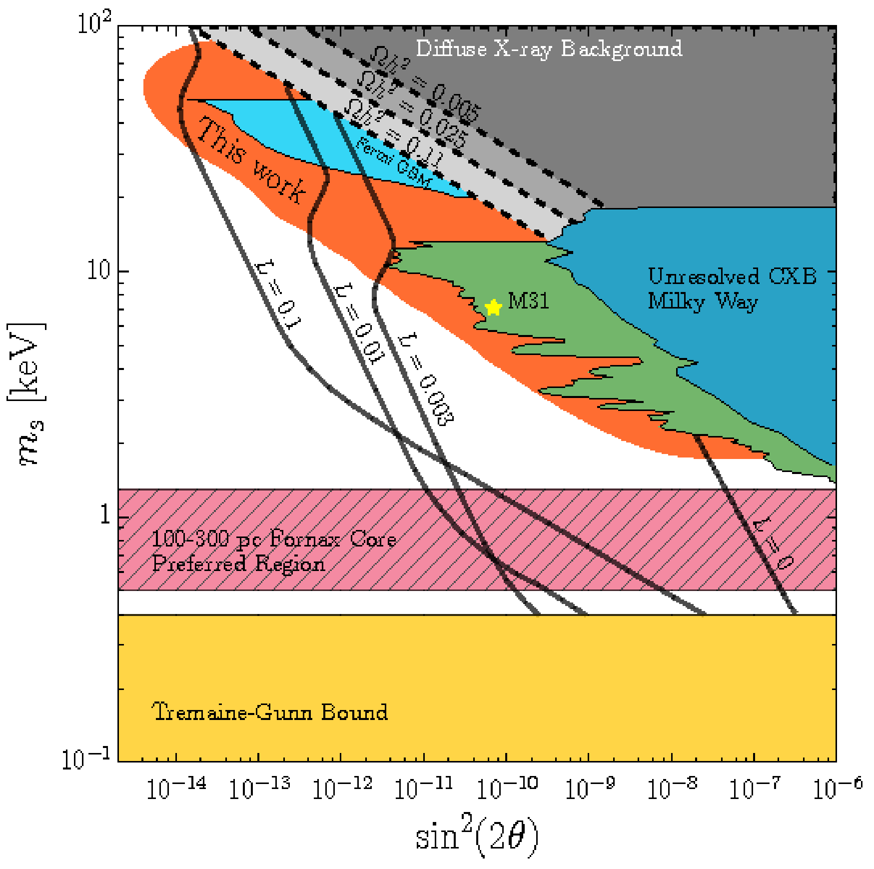
Hitomi Collaboration
(F. Aharonian, et al.)
arXiv:1607.07420 [astro-ph.HE]





Ratio of data to best-fit model .
A line at 3.57 keV (rest-frame) with a flux derived in the SXS FOV is shown with curves of different colors, which denote different l.o.s. velocity dispersions (gray: 180 km/s, blue: 800 km/s, red: 1300 km/s.
Position of S feature is marked.

Bounds from Supernova



C. A. Argüelles, et al.
arXiv:1605.00654 [hep-ph]

Similar bound from SN1987A from the condition that the flux of antinu_e is not suppressed stronger than by factor 10, otherwise no signal could be observe

S.P. Mikheev, A.Yu. S.
JETP Lett. 46 (1987) 10-14

Supernova bounds on the sterile neutrino parameters from cooling effect $E_S < E^{tot}$

Modification of the production mechanism

via decay

$\phi \to S + S$

A.Merle, NOW2016

$y\, SS\, \phi + \lambda\, H^+ H\, \phi\, \phi$

$y\,,\ \lambda \sim 10^{-8}$

via decreasing mixing

A Berlin, D. Hooper, 1610.03849

"axion assisted ...

Large mixing in earlier epoch during production of S

Small mixing later, to suppress X ray production

$$g_a \frac{a}{f_a} S\, LH + \tfrac{1}{2} m_S\, SS \Rightarrow \sin^2 2\theta \sim \frac{g_a{}^2\, v^2 \rho_a}{m_S}$$

a - axion

$f_a \sim 10^9$ GeV - scale of PQ symmetry breaking $g_a \sim 10^{-9}$

ρ_a - axion energy density decreases with expansion of the Universe

Neutrinos and Hidden world

Theoretical perspective

with
Borut Bajc
Patric Ludl
Xiaoyong Chu,
Daniel Hernandez

Trends and implications

No new physics is found

No new physics at LHC in particular new physics which could be associated to low scale mechanisms of neutrino mass generation

- right Handed neutrinos, new heavy leptons
- right handed gauge bosons of the L-R symmetric models
- double charged scalars (of seesaw type II), etc
- new fermions and scalars which can participate in the radiative mechanism of neutrino mass generation

→ Bounds on masses / couplings of these new particles

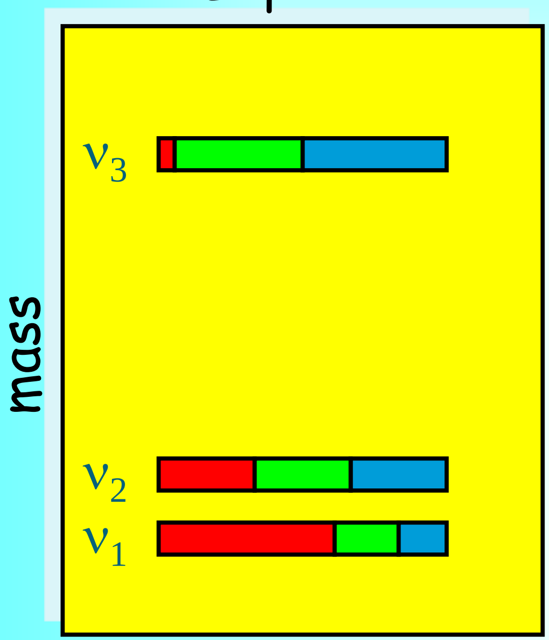
No Lepton number violation, MEG, ….

Nothing yet at well motivated TeV-scale.
The next motivated scales are intermediate and then GUT

Observation:

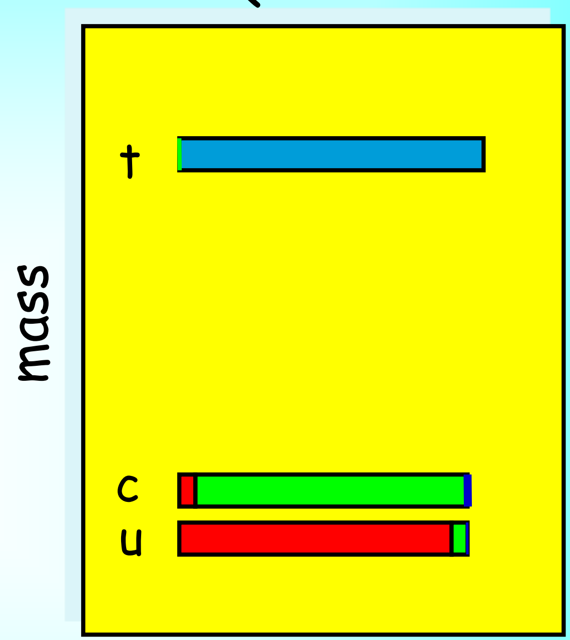
Mixings of quarks and leptons are strongly different but still can be related

Leptons



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

Quarks



$U_d \;=\; V_{CKM}^{+}\, U$ $\quad U = (u, c, t)$

Observation:

$\theta_{12}^{l} + \theta_{12}^{q} \sim \pi/4$

$\theta_{23}^{l} + \theta_{23}^{q} \sim \pi/4$

Sum up to maximal mixing angle
kind of complementarity

In general

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.

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

U_X special matrix close to bi-maximal or TBM matrix:

$$U_X = \begin{cases} U_{BM} = U_{23}(\pi/4)\, U_{12}(\pi/4) \\ U_{TBM} = U_{23}(\pi/4)\, U_{12}(\theta_{TBM}) \end{cases}$$

Prediction:
if $U_X = U_{23}(\pi/4)\, U_{12}$ $\theta_{13}^X \sim 0$

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

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

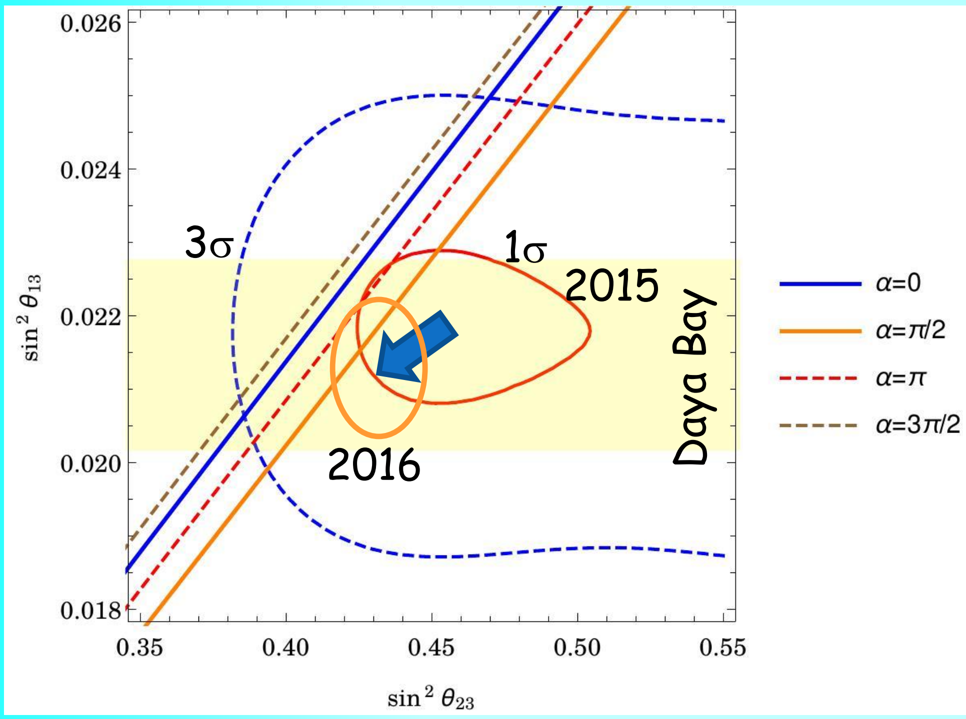
Now more than 3σ off

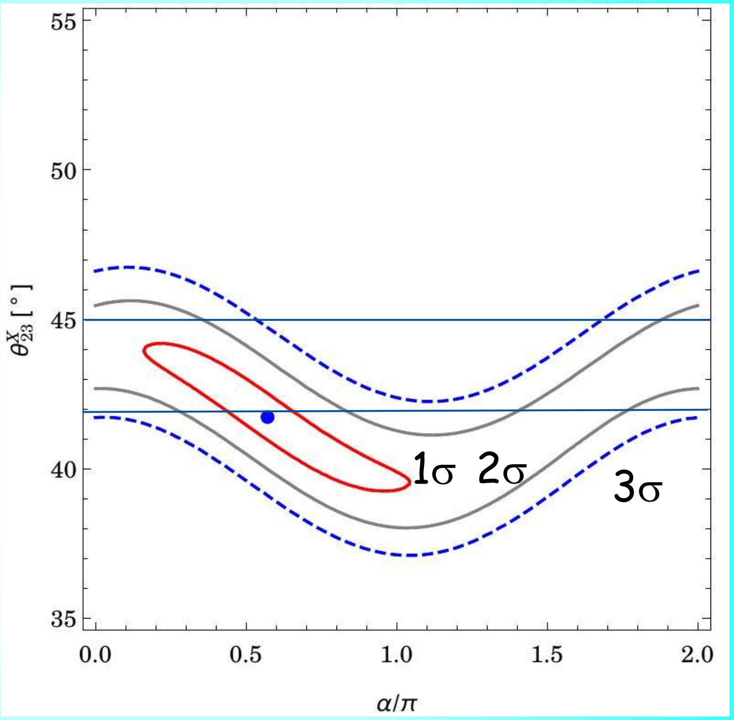
General relation

Normal mass ordering

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

$\lambda = \sin \theta_C$





Dependence of 1-3 mixing on 2-3 mixing for different values of the phase α. Allowed regions from the global fit NuFIT 2015

Allowed values of parameters of U_X

Best fit value: $\theta^x_{23} = 42^0$

RGE effect from maximal mixing value at high scale

What does this mean?

- 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

PMNS & CKM

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

From the Dirac matrices of charged leptons and neutrinos

Related to mechanism that explains smallness of neutrino mass

New neutrino structure

Two types of new physics ?

CKM type new physics

Neutrino new physics

Can be naturally realized in the seesaw type I which after all is the most appealing mechanism of explanation of smallness of neutrino mass

See-saw and GUT

See-saw

$$m_\nu = - m_D \frac{1}{M_R} m_D^T$$

Dirac mass matrix

Majorana mass matrix of RH neutrinos

$M_R \sim 2\ 10^{14}$ GeV

new scale ?

GUT:

$m_D \sim m_u \sim$ diag

$m_l \sim m_d$

produce CKM mixing in both sectors

$m_D \sim m_u$ strong mass hierarchy should be compensated by M_R

M_R itself get mass from seesaw → double seesaw

Double Seesaw

R.N. Mohapatra
J. Valle

Three additional singlets S which couple with RH neutrinos

$$\begin{pmatrix} 0 & m_D^T & 0 \\ m_D & 0 & M_D^T \\ 0 & M_D & M_S \end{pmatrix} \begin{pmatrix} \nu \\ N \\ S \end{pmatrix}$$

M_S - scale of B-L violation

$M_S \sim M_{Pl}$, $M_D \sim M_{GU}$

$M_S >> M_D$

$$M_R = M_D^T \frac{1}{M_S} M_D$$

$$m_\nu = m_D^T M_D^{-1T} M_S M_D^{-1} m_D$$

if $M_D = A\, m_D$

→ hierarchical Dirac structures cancel

→ CKM and neutrino new physics - disentangled

A.Y.S

M. Lindner, M.A. Schmidt A.Y.S

can be achieved due to symmetry

$$m_\nu \sim M_S$$

Screening of the Dirac structure

Origins of S:

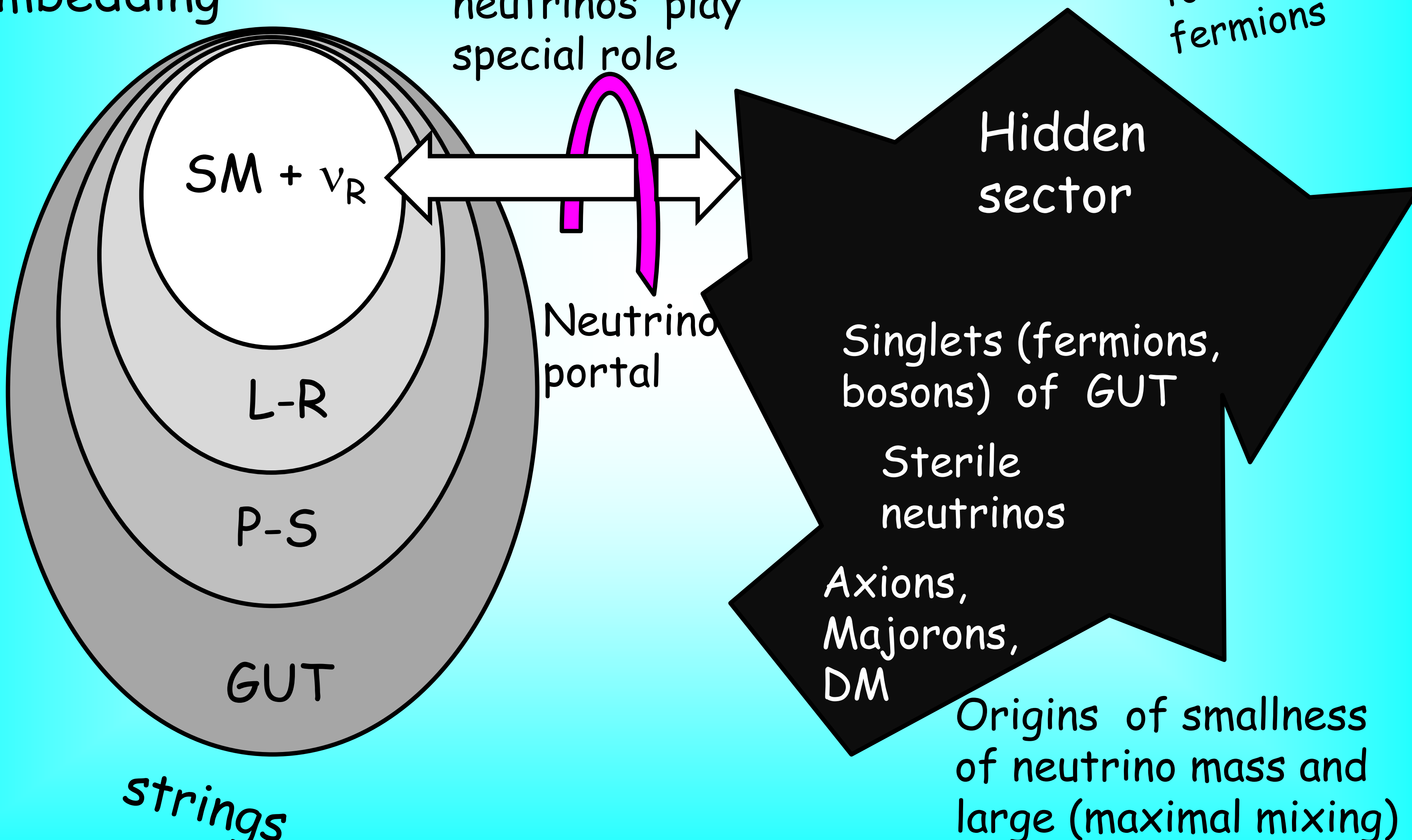
extended GUT , E_6

the Hidden sector

symmetry properties of S differ from toseof other fermions

Embedding

due to neutrality neutrinos play special role



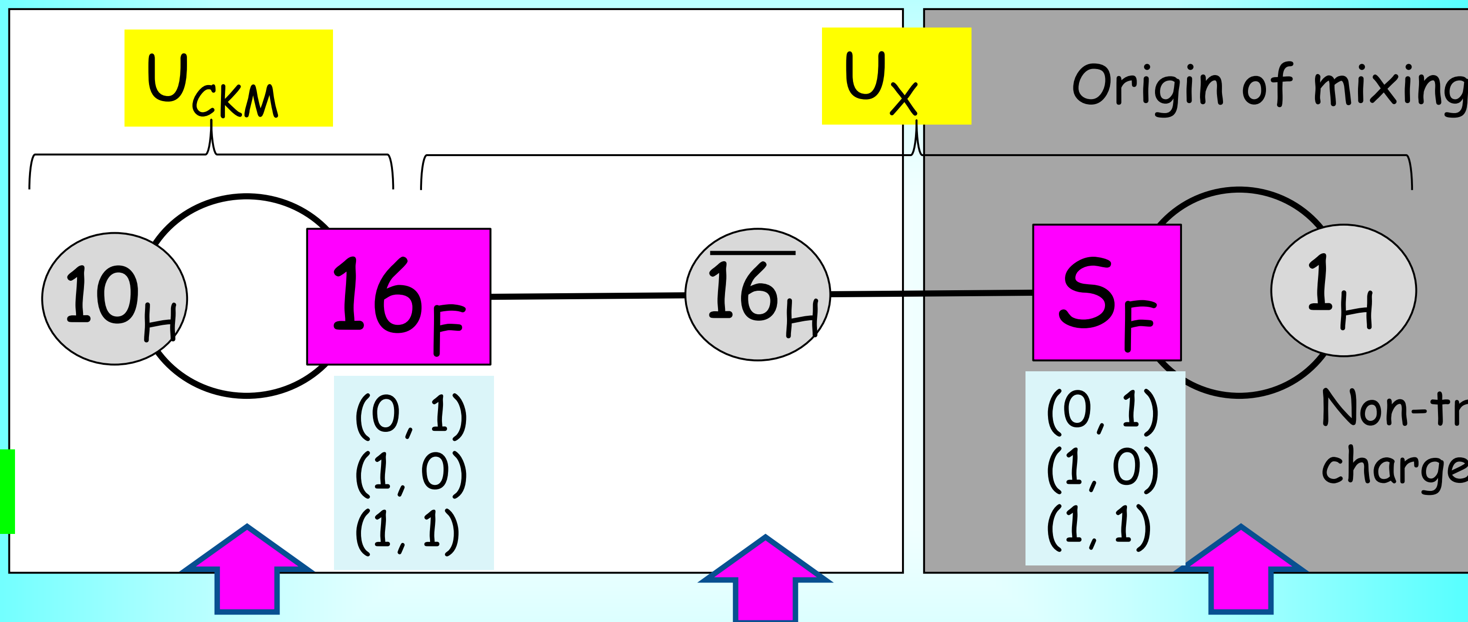
Origins of smallness of neutrino mass and large (maximal mixing)

Scheme

Patrick Ludl, A.S
arXiv:1507.03494 [hep-ph]

SO(10)

with basis symmetry $Z_2 \times Z_2$



$Z_2 \times Z_2$

Basis fixing symmetry
Part of intrinsic symmetry of SO(10) Yukawa couplings

mass hierarchy

No mixing

Mixing by S-S

$m_D \sim M_D$ = diag

$M_X = d^T M_S d$

due to non-trivial $Z_2 \times Z_2$ charges of 1_H

M_S ~ non-diagonal, can be further structured by additional hidden symmetries

How to test?

Hopeless?

Further precise measurements of the 1-3 and 2-3 mixings (octant)

Nothing should be observed at LHC which is responsible for neutrino masses

If something is observed against (excludes) framework

Proton decay

Special value of CP-phases

Light sterile neutrinos

Dark matter

May or may not help

Inflation

Leptogenesis

Conclusion

3ν -paradigm further confirmations

Progress in determination of neutrino parameters

First glimpses of certain mass hierarchy and CP-violation

Flavour symmetry behind mixing pattern?

Tension: 1-2 mass splitting (solar vs KamLAND), 2-3 mixing maximal – non-maximal ?

NSI with light mediators?

eV scale sterile neutrinos – further disfavored

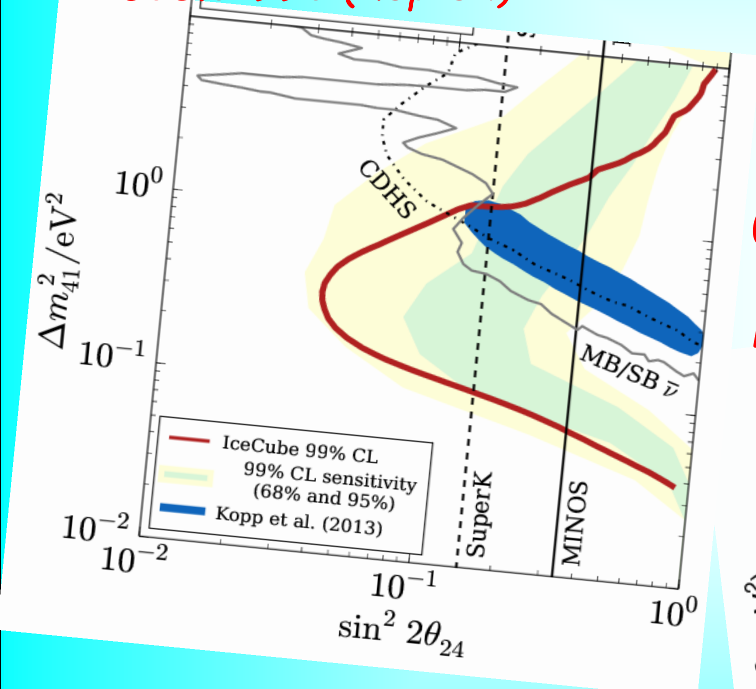
3.5 keV line - DM? other mechanisms of S production

Relation between l- and q- mixings $U_{PMNS} = V_{CKM}^{+} U_X$ indicate (can be realized) to seesaw, GUT, Hidden sector with certain symmetries

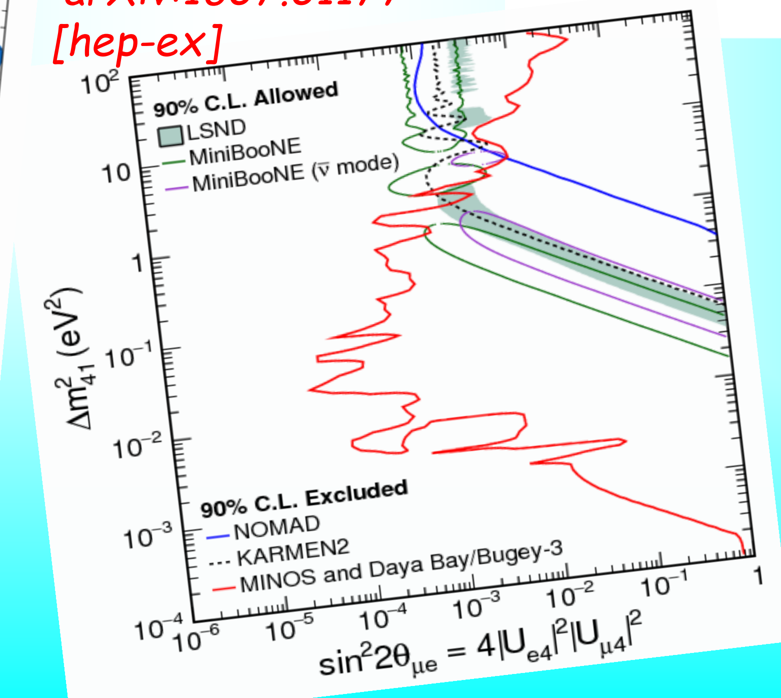
Backup slides

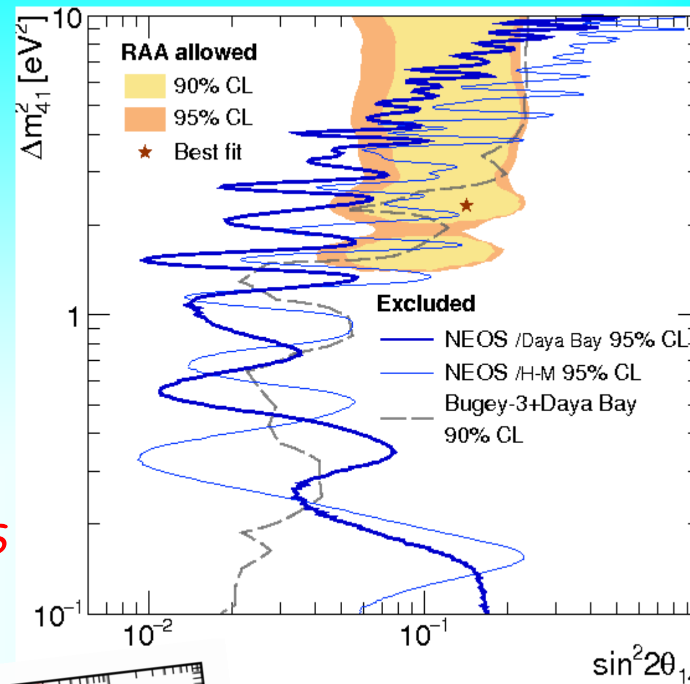
New bounds on steriles

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



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





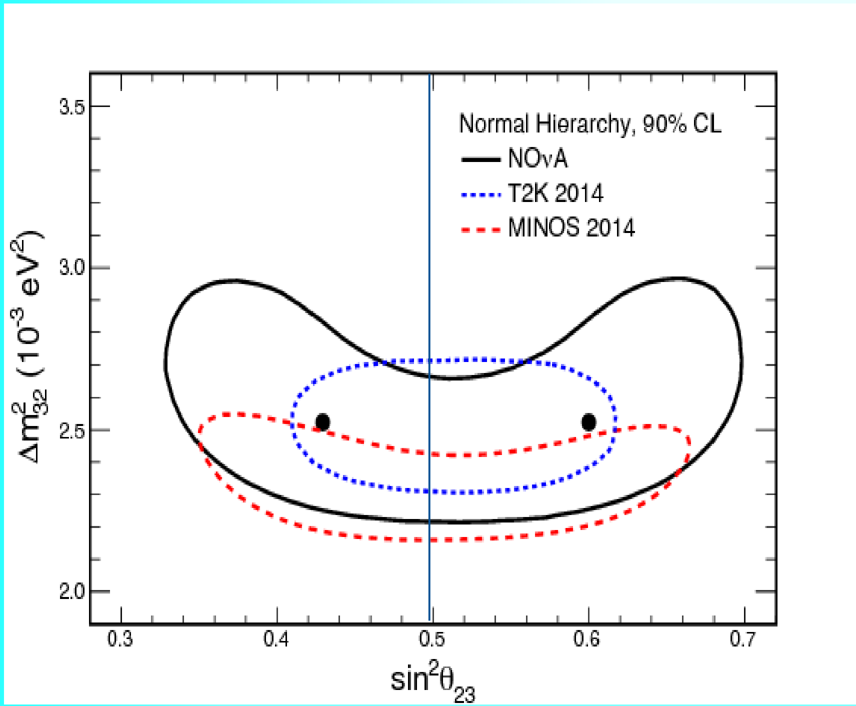
NEOS Experiment Y.J. Ko, et al., arXiv:1610.05134 [hep-ex]

For LSND/MB and SBL $|U_{e4}|^2 = 0.023$ is taken

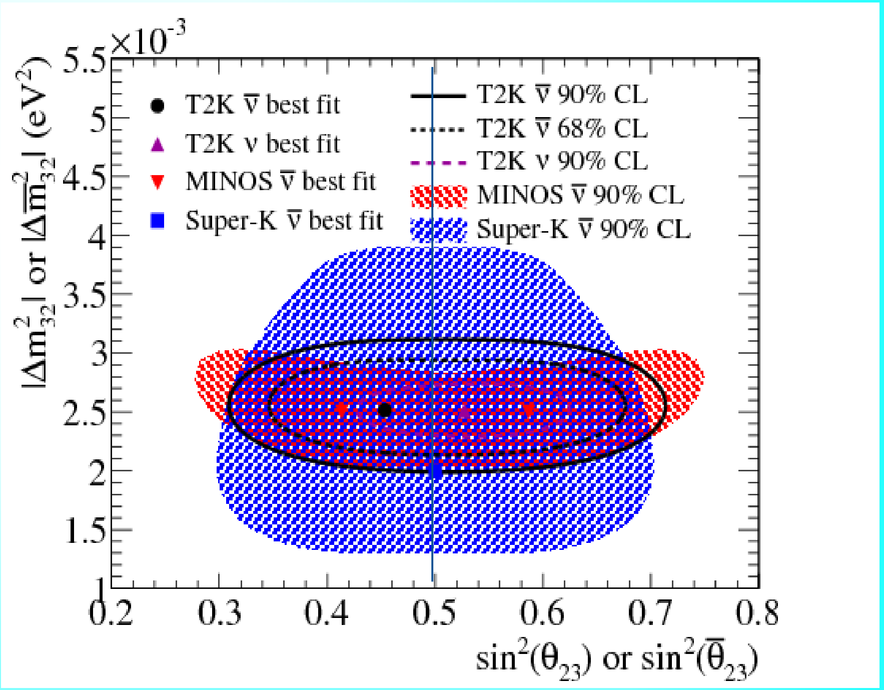
2-3 mixing

Deviation from maximal: octant symmetry or no symmetry

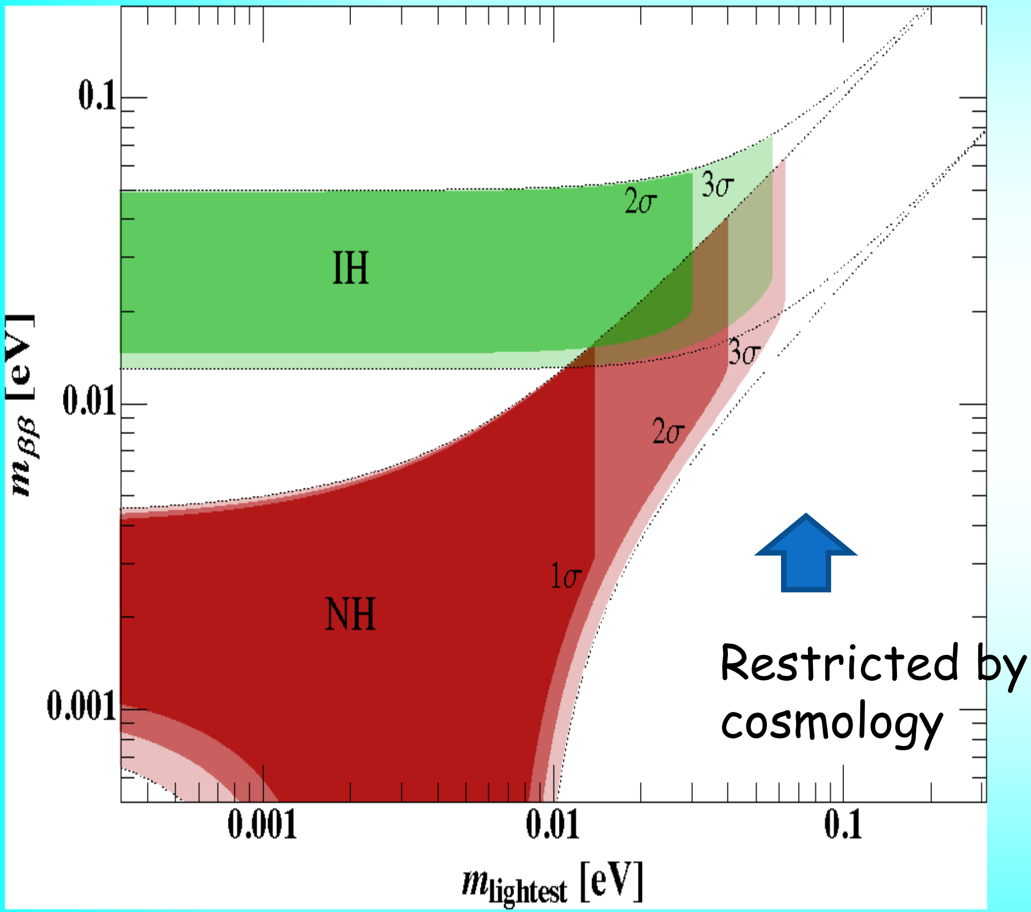
NOvA, T2K, MINOS



T2K bound on antineutrino parameters



Neutrinoless ββ - decay and cosmology



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

$\Sigma m < 0.136$ eV (95 % CL)

Constraints from cosmological surveys and from oscillations. The 1σ region for the IH case is not present at this confidence level.

$\Sigma m < 0.176$ eV (95 % CL)

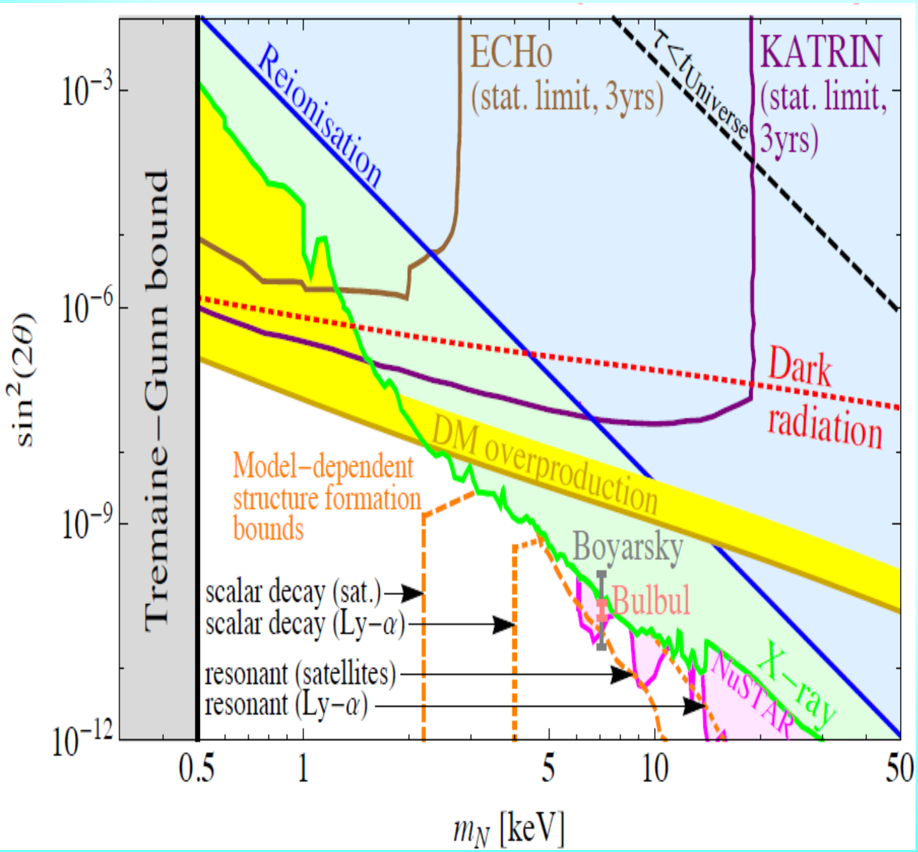
E. Giusarma, et al, 1605.04320 [astro-ph.CO]

$\Sigma m < 0.12$ eV (95 % CL)

A.J. Cuesta et al, 1511.05983 [astro-ph. CO]

Bounds

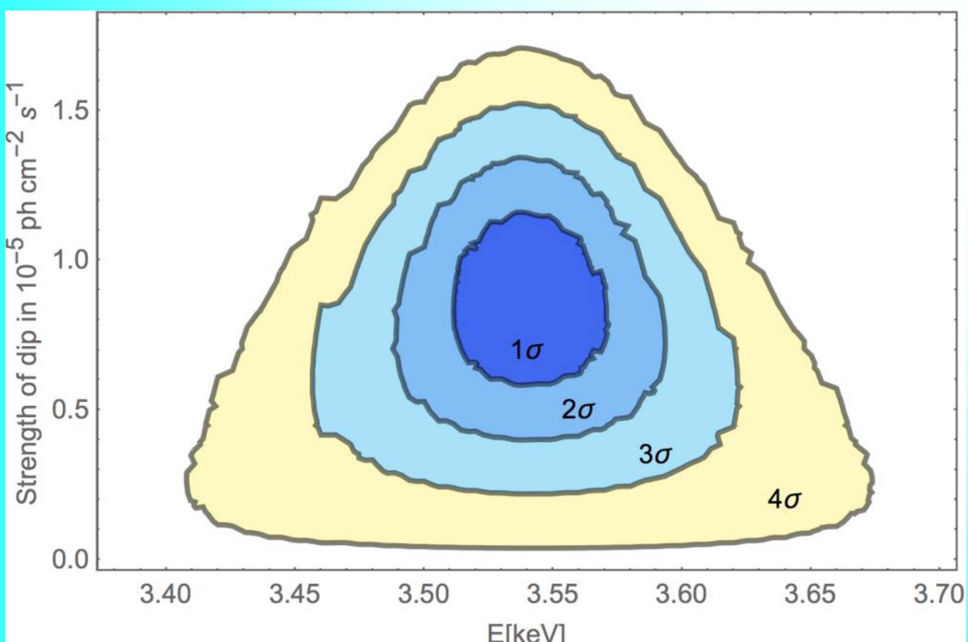
A. Merle, NOW 2016



Consistency of data from Perseus?

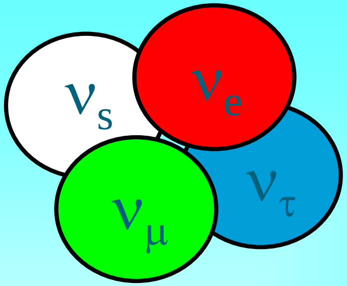
Consistency of Hitomi, XMM-Newton and Chandra 3.5 keV data from Perseus

Conlon, Joseph P. et al.
arXiv:1608.01684 [astro-ph.HE]

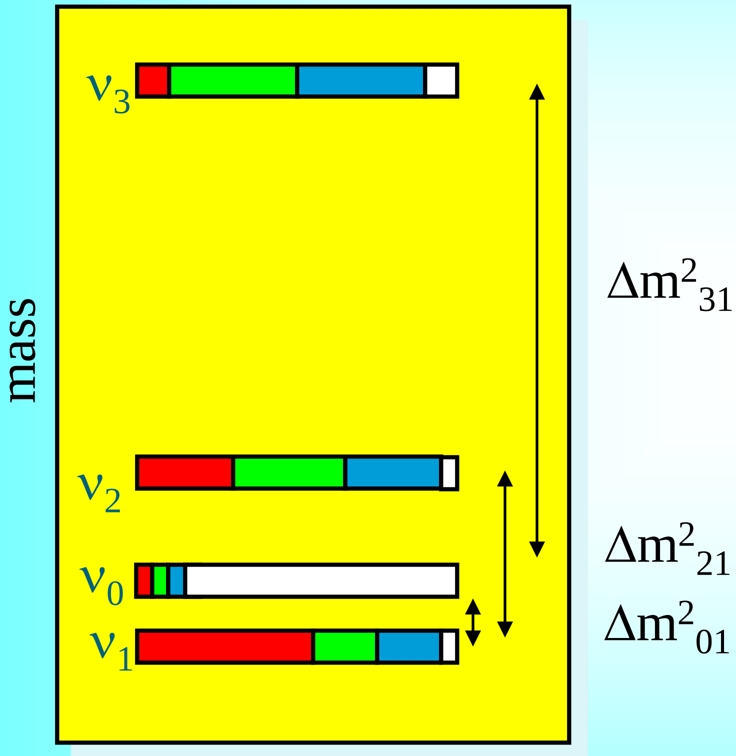


The location and strength of the best-fit dip in the AGN spectrum, derived from stacked Chandra observations 11713, 12025, 12033 and 12036.

meV physics



Very light sterile neutrino $m_0 \sim 0.003$ eV



Motivated by

Solar neutrino data
- absence of upturn of spectrum

- additional radiation in the Universe if mixed in ν_3

no problem with LSS bound on neutrino mass

$$m_0 \sim \frac{M^2}{M_{Planck}} \qquad M \sim 2 - 3 \text{ TeV}$$

$\alpha \sim v / M$

$\sin^2 2\alpha \sim 10^{-3}$

$\sin^2 2\beta \sim 10^{-1}$

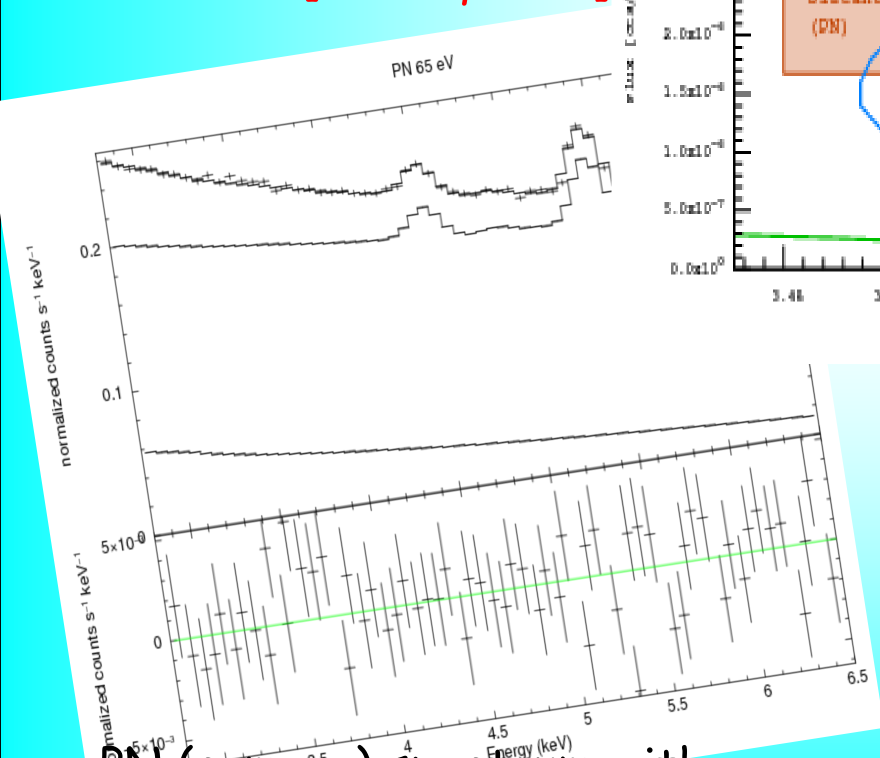
DE scale?

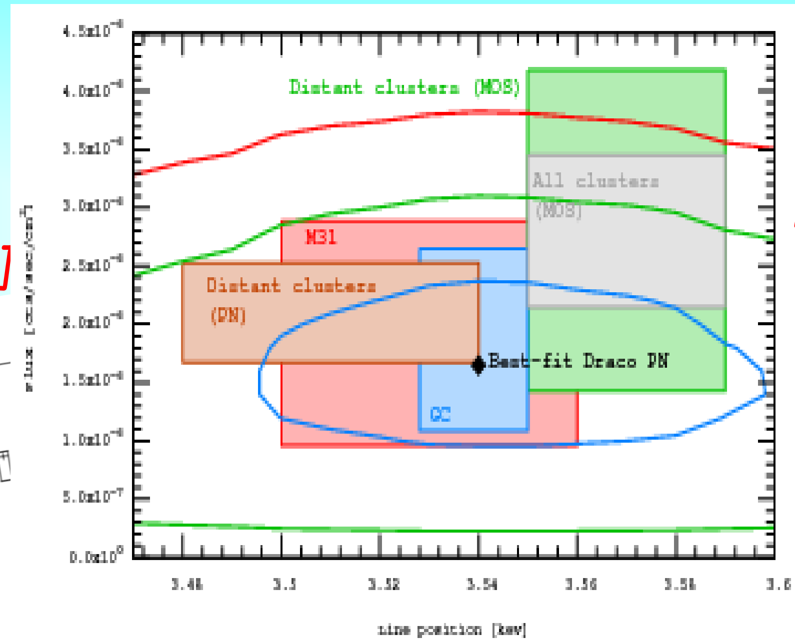
3.5 kev γ–line

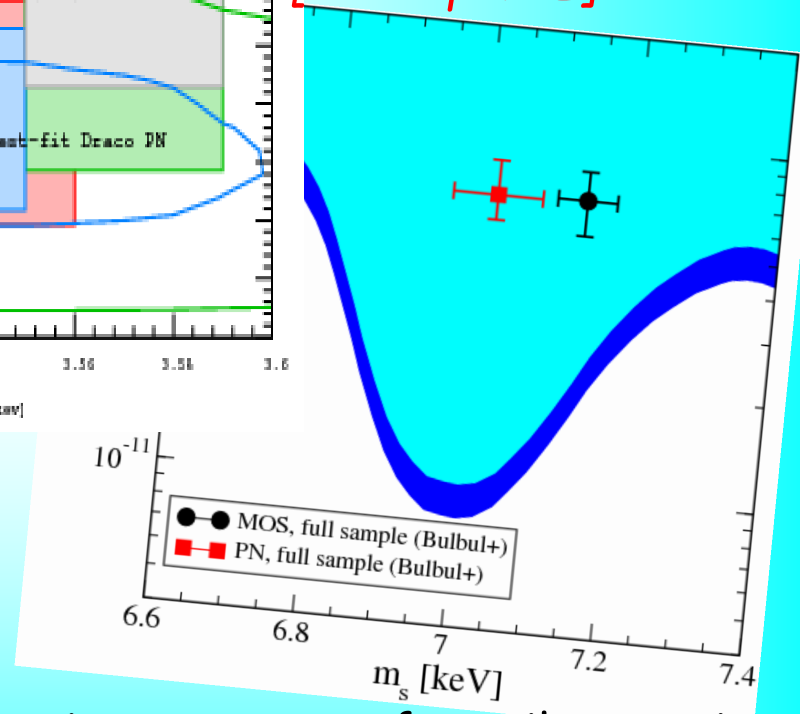
From Draco dwarf galaxy

O. Ruchayskiy et al, 1512.07217 [astro-ph.HE]

T. Jeltema and S Profumo, 1512.01239 [astro-ph.HE]





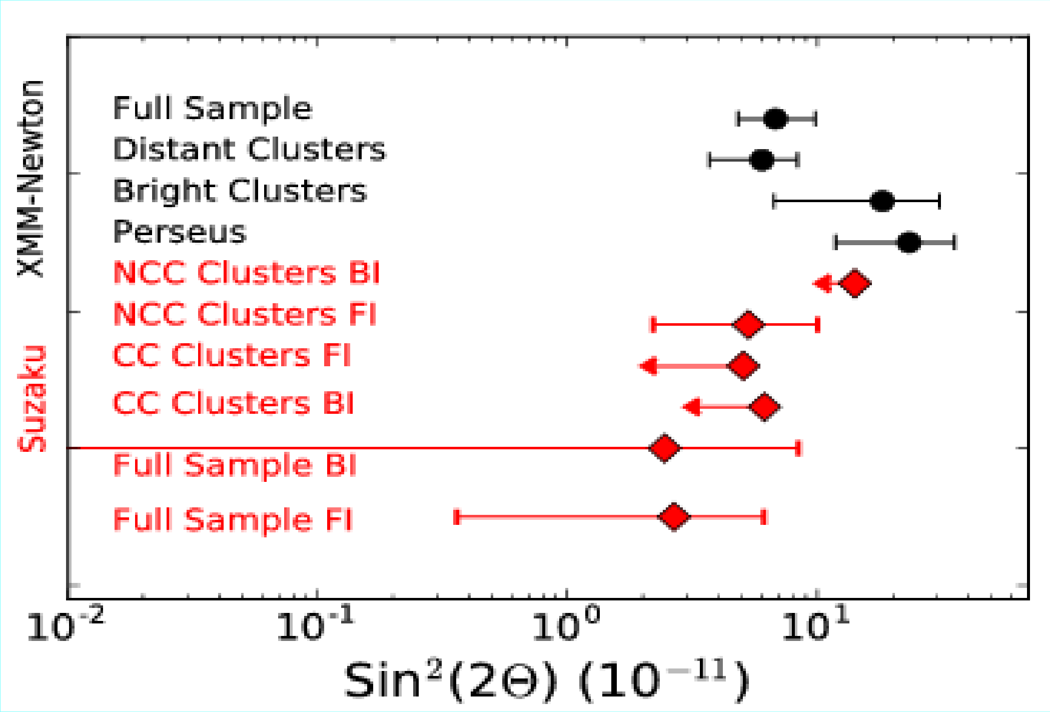


PN (camera) spectrum with unmodeled feature at 3.54 keV.

Constraints on mass of sterile neutrino and its mixing angle with active neutrinos from Draco MOS observations.

More bounds

E. Bulbul, et al. arXiv:1605.02034 [astro-ph.HE]



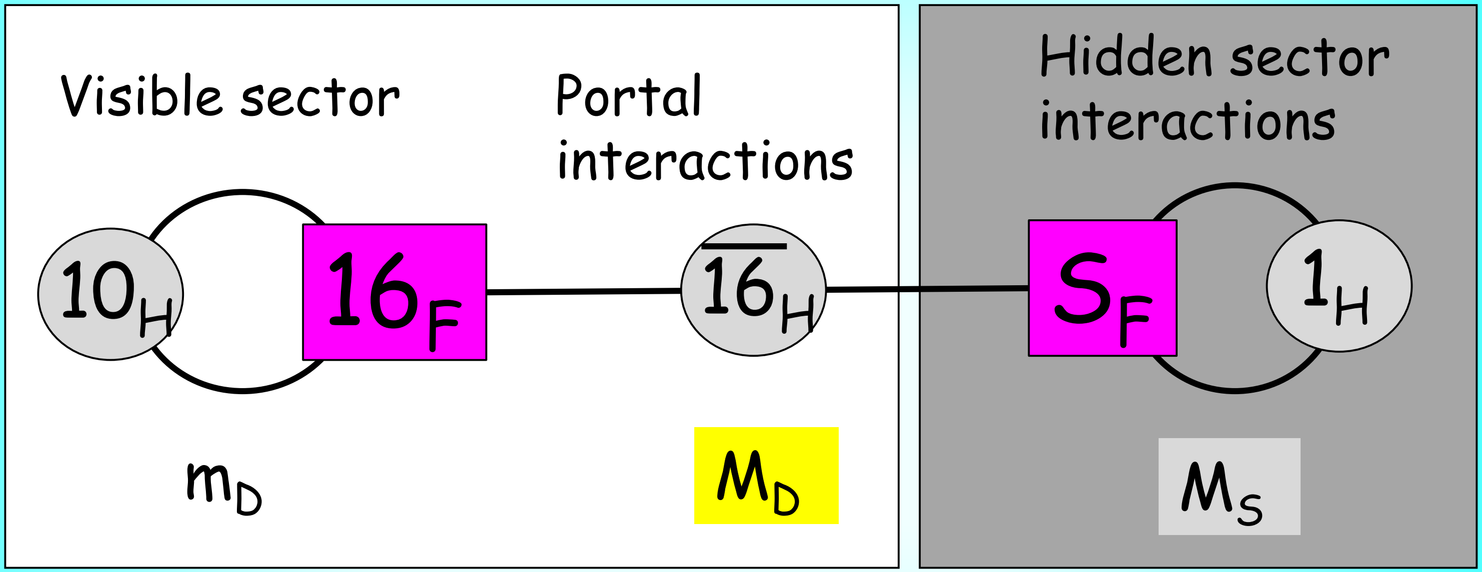
Bound from stacking analysis of Suzaku Observations of Galaxy Clusters 90% CL.

Yukawa interactions

Patrick Ludl, A.S

1507.03494 [hep-ph]

SO(10)



$Y_{ij}\ 16_F{}^i\ 16_F{}^j\ 10_H{}^u$

$Y_{ij}'\ 16_F{}^i\ S^j\ \overline{16}_H$

$h_{ijk}\ S^i\ S^j\ 1_H{}^k$

$Y \sim y\ (\langle\phi\rangle / \Lambda)^n$

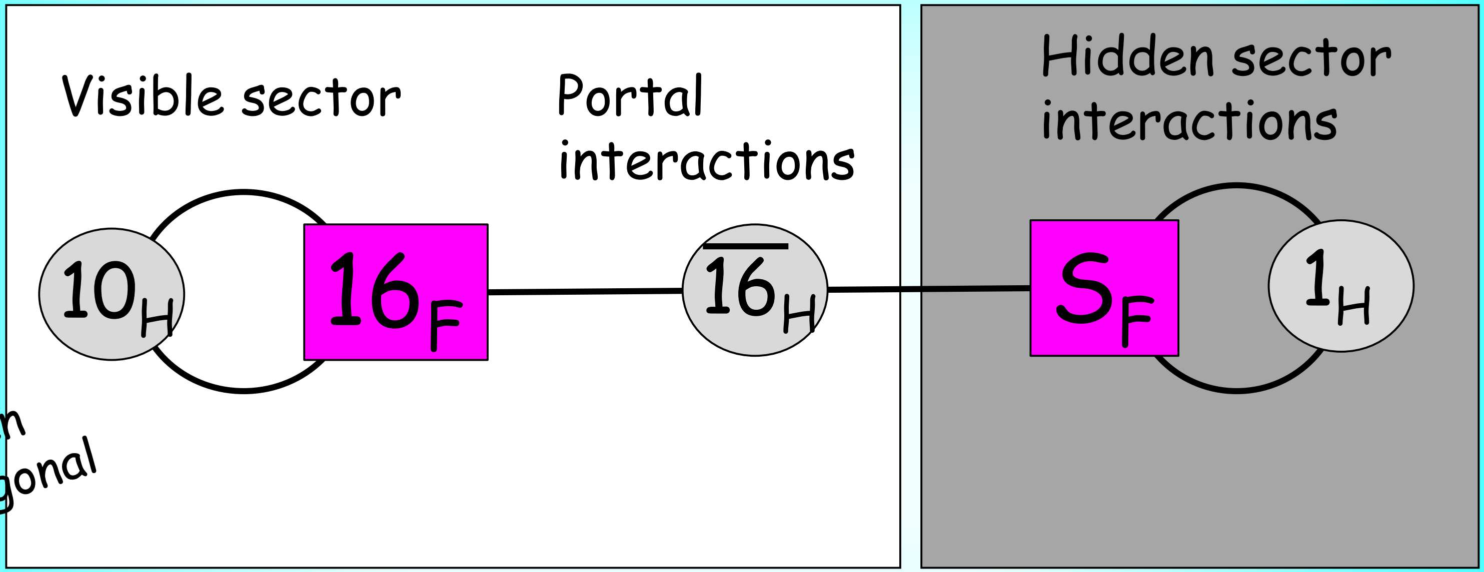
For third generation: $n = 0$, the mass is generated at the renormalizable level

Second Higgs 10-plet should be introduced to produce the CKM mixing

Intrinsic symmetries

of SO(10)

C.S.Lam
1403.7835 [hep-ph]
B. Bajc, AS
1507.03494 [hep-ph]



better seen in the diagonal basis

$Y_{ii}\ 16_F{}^i\ 16_F{}^i\ 10_H{}^u$

$[\,Z_2\,]^3$

$16_F{}^i \rightarrow -16_F{}^i$

$Y_{jj}'\ 16_F{}^j\ S^j\ \overline{16}_H$

$[\,U(1)\,]^3$

$h_{ijk}\ S^i\ S^j\ 1_H{}^k$

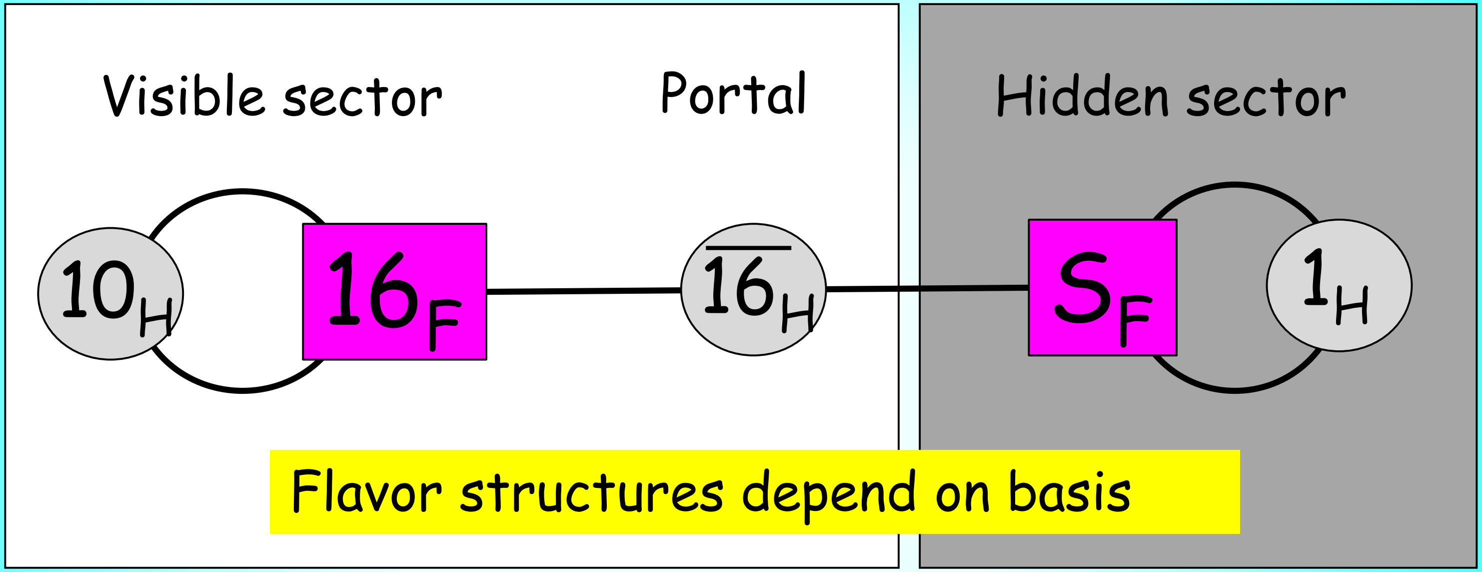
$[\,Z_2\,]^3$

For the mass matrix in the diagonal basis

Communication to the Hidden world

Patrick Ludl, A.S
1507.03494 [hep-ph]

Information about flavor structures in the hidden sector should be communicated (transferred) to the observable sector



Minimal way – to communicate info about bases we use in the Hidden (S) and visible sectors (16)

Introduce the same basis symmetry for F and S and prescribe certain charges for them

G_{basis}

$G_{basis} = G_{intrinsic} = Z_2 \times Z_2$ (subgroup)

Seesaw and PMNS-CKM relation

Right handed components of neutrinos N
Neutrinos get usual Dirac mass terms $m_D = Y\langle H\rangle$
N have large Majorana masses $M_R \gg m_D$

P. Minkowski
T. Yanagida
M. Gell-Mann,
P. Ramond,
R. Slansky
S. L. Glashow
R.N. Mohapatra,
G. Senjanovic

$$\begin{array}{c|cc} & \nu & N \\ \hline \nu & 0 & m_D \\ N & m_D^T & M_R \end{array}$$

diagonalization

$$m_\nu = - m_D (M_R)^{-1} m_D^T$$

$$m_D = U_L (m_D^{diag}) U_R^+$$

If $U_L = V_{CKM}^*$ -- realized in the simplest SO(10)

$$m_\nu = - U_L \underbrace{(m_D^{diag}) U_R^+ (M_R)^{-1} U_R^* (m_D^{diag})}_{\text{produces } U_X} U_L^T$$

produces U_X - we realize the connection

so U_X should diagonalize

$$M_X = - m_D^{diag} U_R^+ (M_R)^{-1} U_R^* m_D^{diag}$$

that is

$$M_X = U_X M_X^{diag} U_X^T = U_X m_\nu^{diag} U_X^T \sim m_{TBM}$$

See-saw and GUT

Scale of see-saw

$$M_R = - m_D^T \frac{1}{m_\nu} m_D$$

q – l similarity: $m_D \sim m_q \sim m_l$

for one third generations $M_R \sim 2\ 10^{14}$ GeV

new scale ?

M_R - hierarchy

$$M_R = - m_D^{diag} (m_{TBM})^{-1} m_D^{diag}$$

Quadratic hierarchy

Flavor structure

Difficult to reproduce

Can be explained in the framework of double seesaw

From GUT to Planck

Features of M_R

Scale

$$M_R = - m_D^T \frac{1}{m_\nu} m_D$$

new scale?

q – l similarity: $m_D \sim m_q \sim m_l$

→ for third generations $M_R \sim 2\ 10^{14}$ GeV

Correlation

$$- m_D^{diag} U_R^+ (M_R)^{-1} U_R^* m_D^{diag} \sim m_{TBM}$$

should correlate to get

Mass hierarchy

$$M_R \sim - m_D^{diag} (m_{TBM})^{-1} m_D^{diag}$$

quadratic hierarchy

in the basis where $U_R = I$

All these features can be explained if (imply) masses of RH neutrinos themselves are generated by seesaw

$$M_R \sim \frac{M_{GUT}^2}{M_S}$$

$M_S \sim (1 - 3)\ 10^{18}$ GeV

$M_S / M_{Pl} \sim 0.1$ string scale?

→ double seesaw

Double Seesaw

R.N. Mohapatra
J. Valle

Three additional singlets S which couple with RH neutrinos

$$\begin{pmatrix} 0 & m_D^T & 0 \\ m_D & 0 & M_D^T \\ 0 & M_D & M_S \end{pmatrix} \begin{pmatrix} \nu \\ \nu^c \\ S \end{pmatrix}$$

$M_S >> M_D$

M_S - scale of B-L violation

RH neutrinos get mass via see-saw

$$M_R = M_D^T M_S^{-1} M_D$$

This explains

1. strong mass hierarchy $M_D \sim m_D$ and M_S has no strong hierarchy
2. intermediate scale of masses if $M_S \sim M_{Pl}$, $M_D \sim M_{GU}$
3. Flavor structure:

$$m_\nu = m_D^T M_D^{-1T} M_S M_D^{-1} m_D$$

if $m_D = A M_D$ ➡ $m_\nu \sim M_S$

Screening of the Dirac structure

may have certain symmetries

A.Y.S
M. Lindner,
M.A. Schmidt
A.Y.S

Behind neutrino mass

with
Borut Bajc
Patric Ludl
Xiaoyong Chu,
Daniel Hernandez

Theoretical perspectives

Testability with the present facilities is not the problem of NATURE

Unified description of quarks and leptons, GUT?

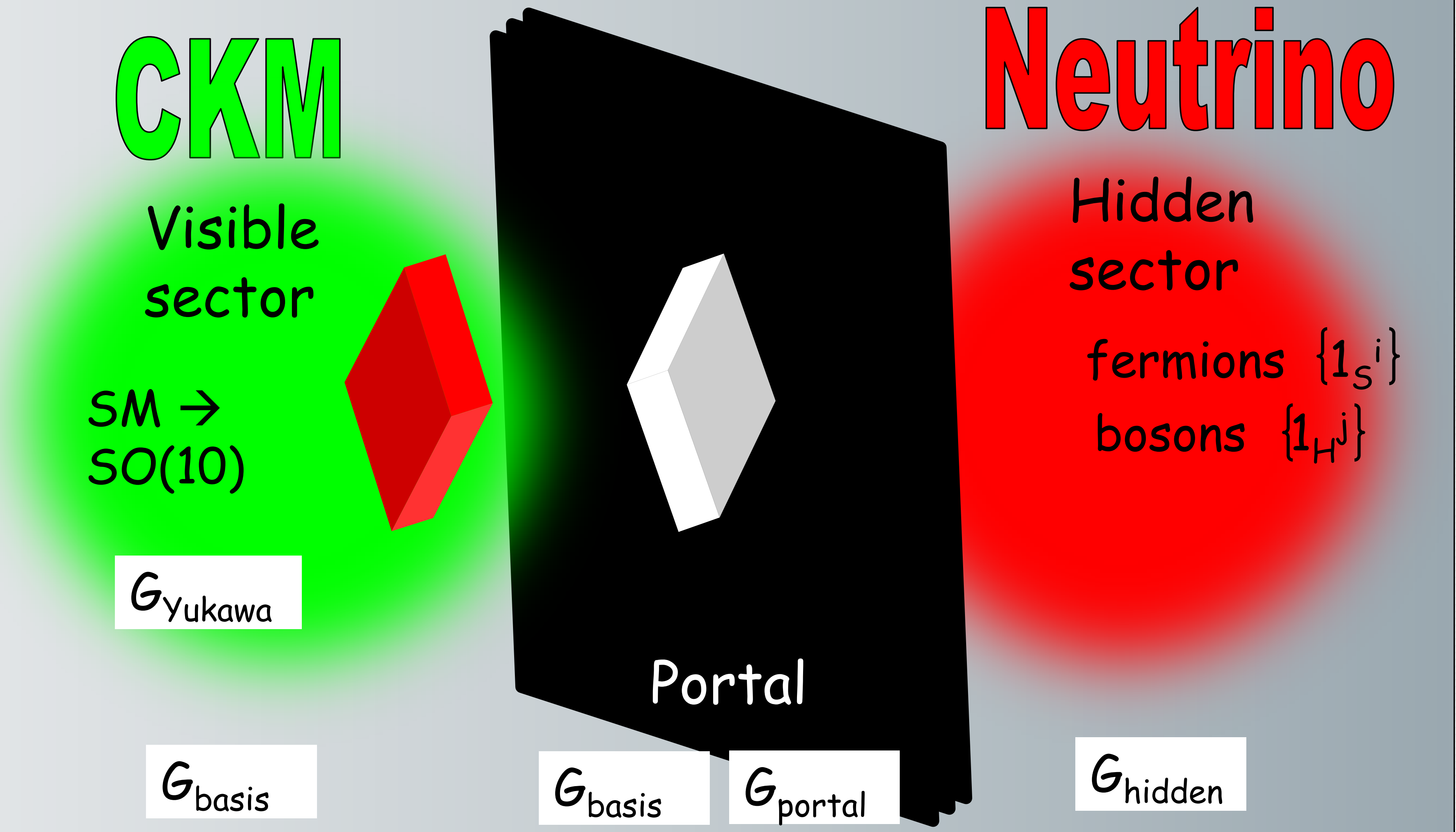
Solutions of the problems of the Visible sector can be in the Hidden sector

Simplicity, minimality

Old does not mean wrong

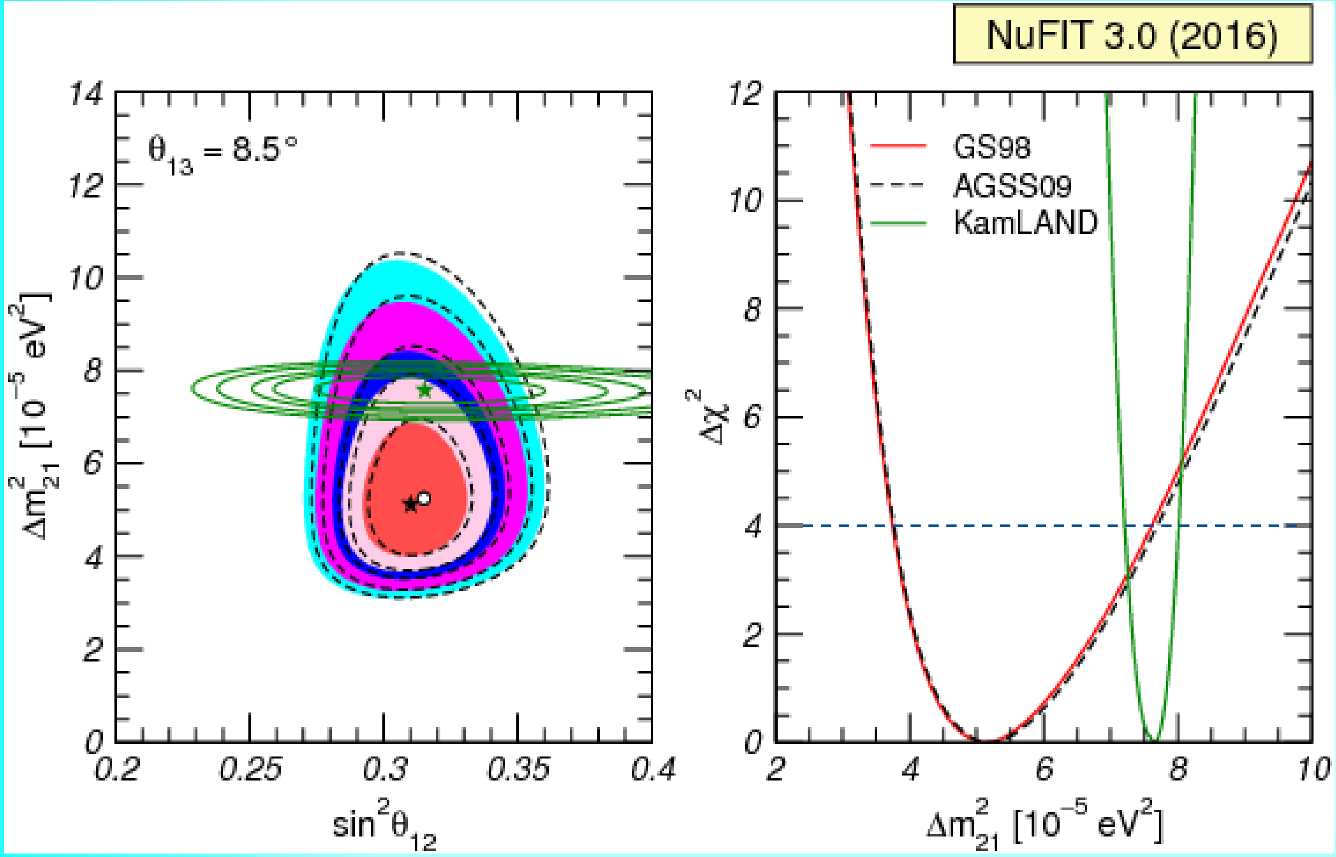
Symmetries and set-up

Patrick Ludl A.S



Solar vs. KamLAND

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



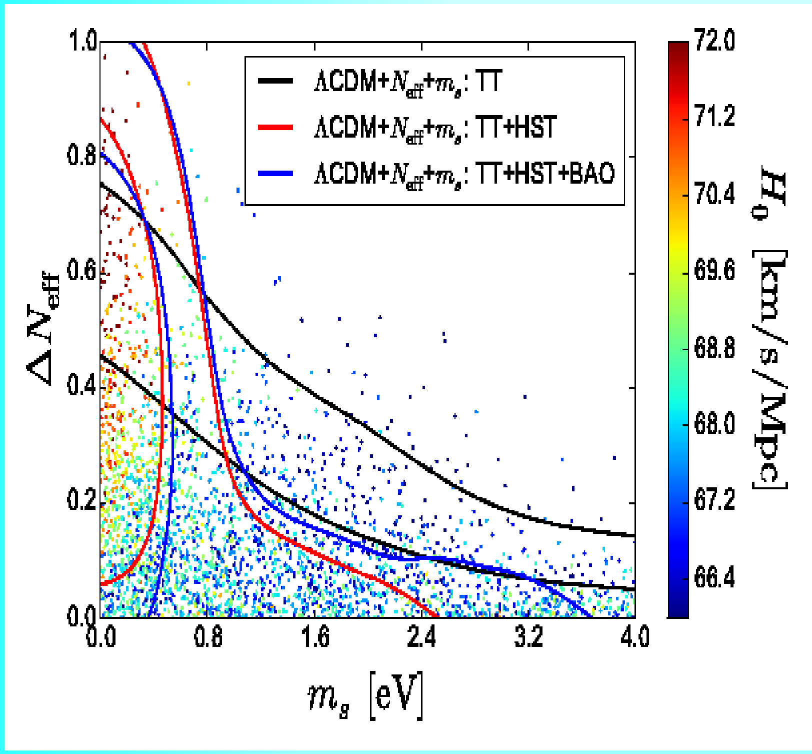
Δm^2_{21} (solar) = 5.2 10^{-5} eV^2

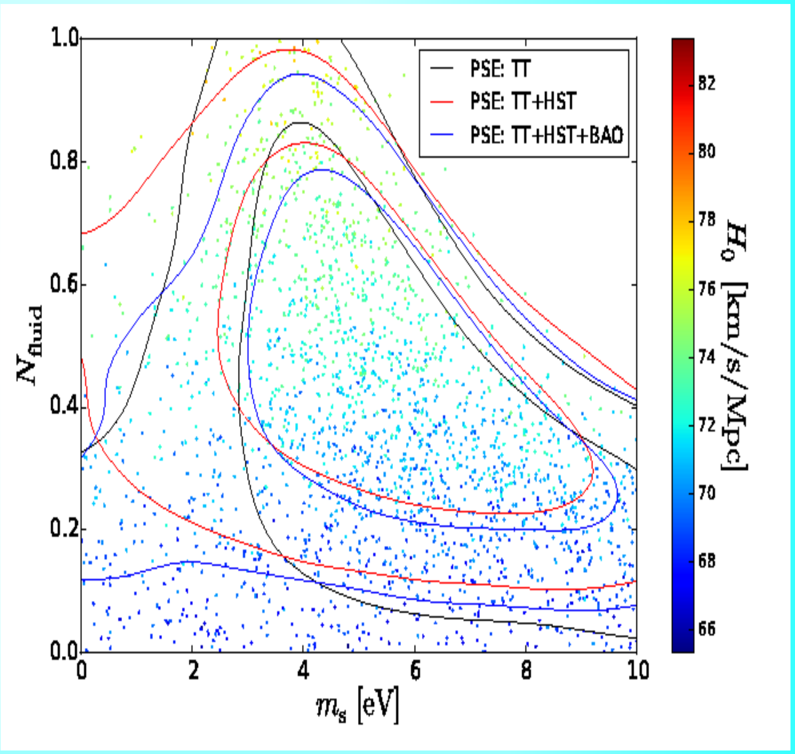
shifted slightly up

Allowed parameter regions (at 1s, 90%, 2s, 99% and 3s CL for 2~dof) from solar data for GS98 model (full regions with b.f. - black star) and AGSS09 model (dashed contours with b. f. - white dot), and from KamLAND data (solid, green) for fixed θ_{13} = 8.5°.
Right: after marginalizing over 12 mixing.

Cosmological bounds on steriles

M. Archidiacono, et al.,
arXiv:1606.07673 [astro-ph.CO]



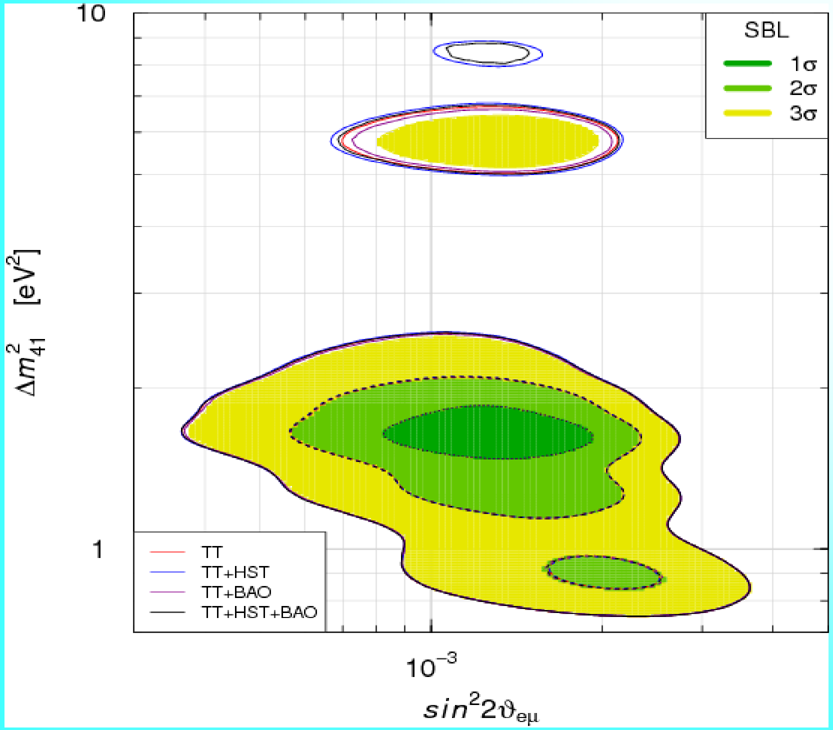


Constraints on mass and effective number from different combinations of cosmological data without (left) and with (right) pseudo-scalar interactions. The points are color coded by the corresponding value of the Hubble parameter *H*0.

Reconciling with cosmology

Pseudoscalar—sterile neutrino interactions: reconciling the cosmos with neutrino oscillations

M. Archidiacono, et al., arXiv:1606.07673 [astro-ph.CO]



Interactions of sterile neutrinos mediated by new nearly massless pseudoscalar boson

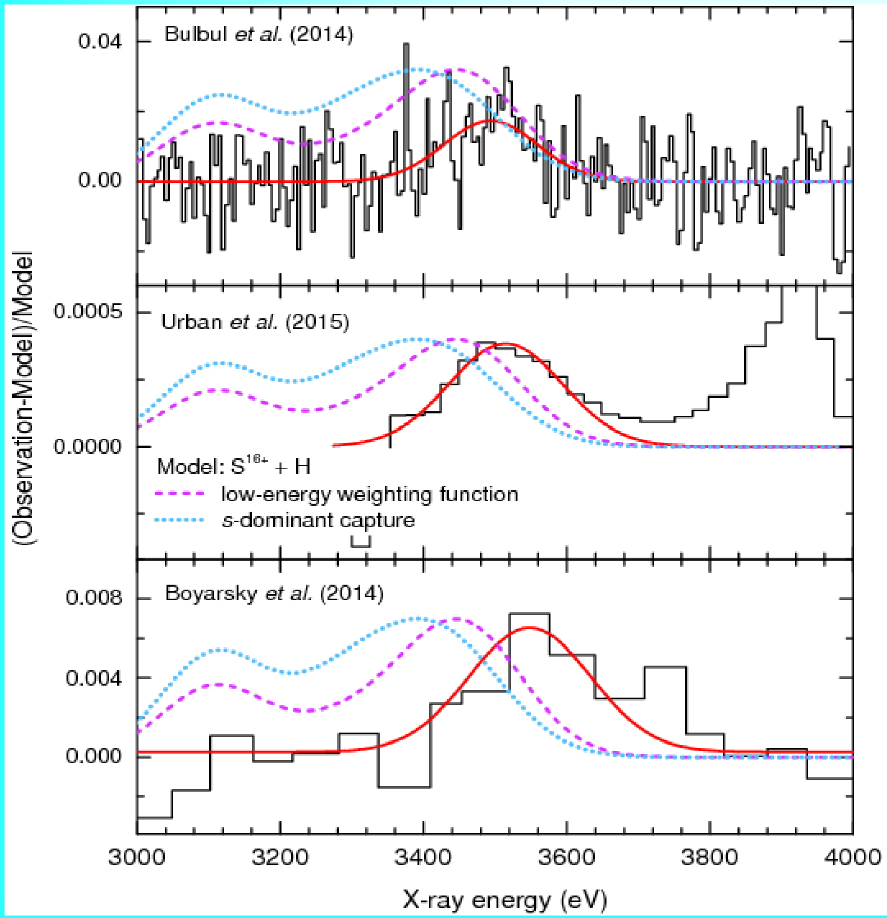
Oscilations in the Early Universe are suppressed by the matter effect driven by the pseudoscalar fluid.

Results of the SBL analysis alone (filled regions) compared with the joint SBL + cosmological data analyses (colored contours)

3.5 keV and atomic lines

Laboratory measurements compellingly support charge-exchange mechanism for the 'dark matter' 3.5 keV X-ray line.

Chintan Shah et al, arXiv:1608.04751 [astro-ph.HE]



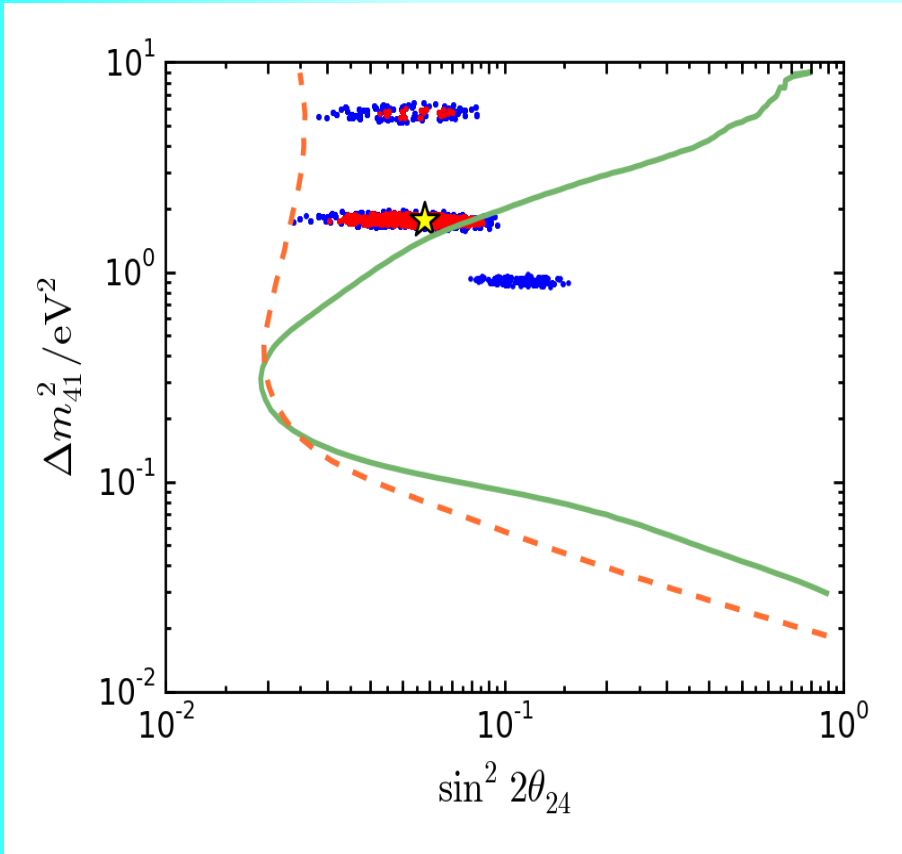
Astrophysical observations reported The red solid curves - the Gaussian line with the energies fixed to the reported values (Bulbul, Boyarsky).

Synthetic spectra (S16++H) using low-energy weighting (dashed line) and with s-dominant capture (dotted line) .

Hitomi observed S feature

Global fit vs. Ice Cube

J. Conrad et al



The 90% C.L. IceCube limit for $\theta_{34} = 0$ (solid) and $\theta_{34} = 15^0$ (dashed)

The SBL+IC global fit:
Red - 90% CL; blue - 99% CL.

$\Delta m_{41}{}^2 =$ 1.75 eV^2

$|U_{e4}|^2 = 0.027$

$|U_{\mu 4}|^2 = 0.014$

keV steriles and RH neutrinos

Too small mixing to participate in generation of neutrino masses –
Decouples from generation of light neutrino masses

$$m = \sin^2\theta_{aS}\, m_S = (1 - 2)\, 10^{-7}\ \text{eV} \ll \sqrt{\Delta m_{21}^2} = 8\, 10^{-3}\ \text{eV}$$

Not the RH neutrino but some new singlet from the Hidden sector

Standard high scale see-saw mechanism with three heavy RH neutrinos plus additional singles and one S is of them

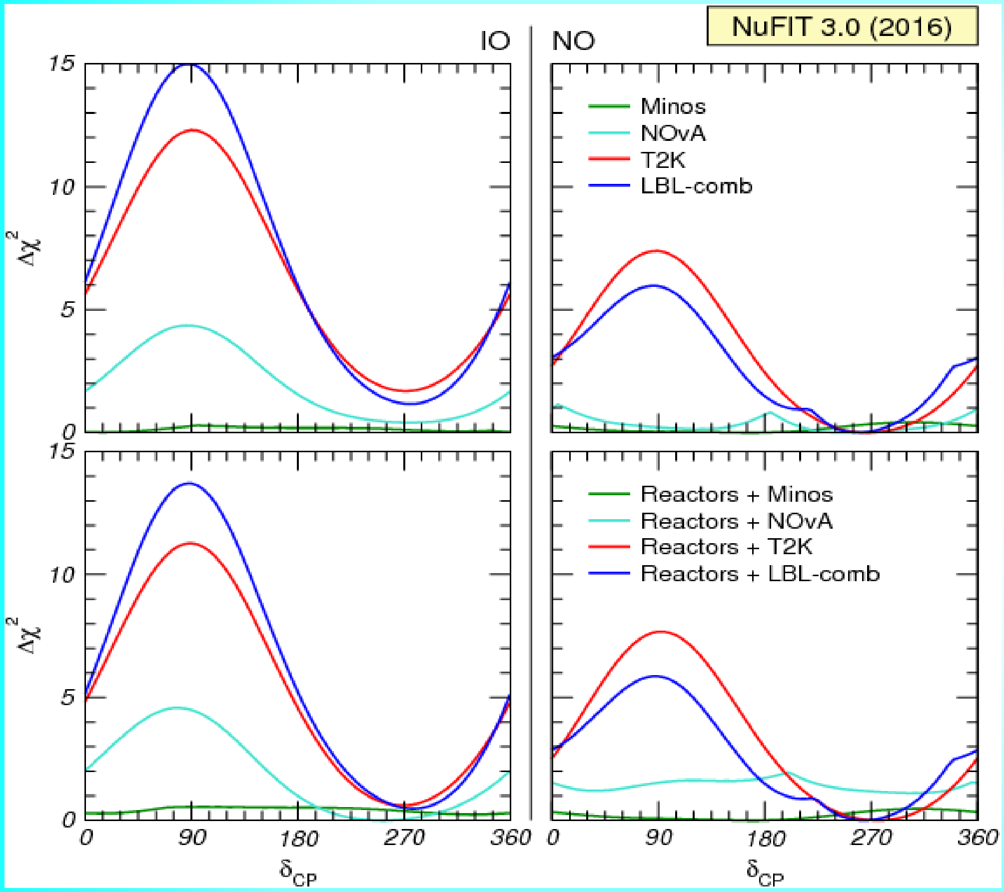
7 kev scale appears in framework of the double seesaw

$$m(7\ \text{keV}) = \frac{M_{LHC}^2}{m_D^2}\, m_3$$

$$M_{LHC} = 7\ \text{TeV}$$

Determination of CP phase

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



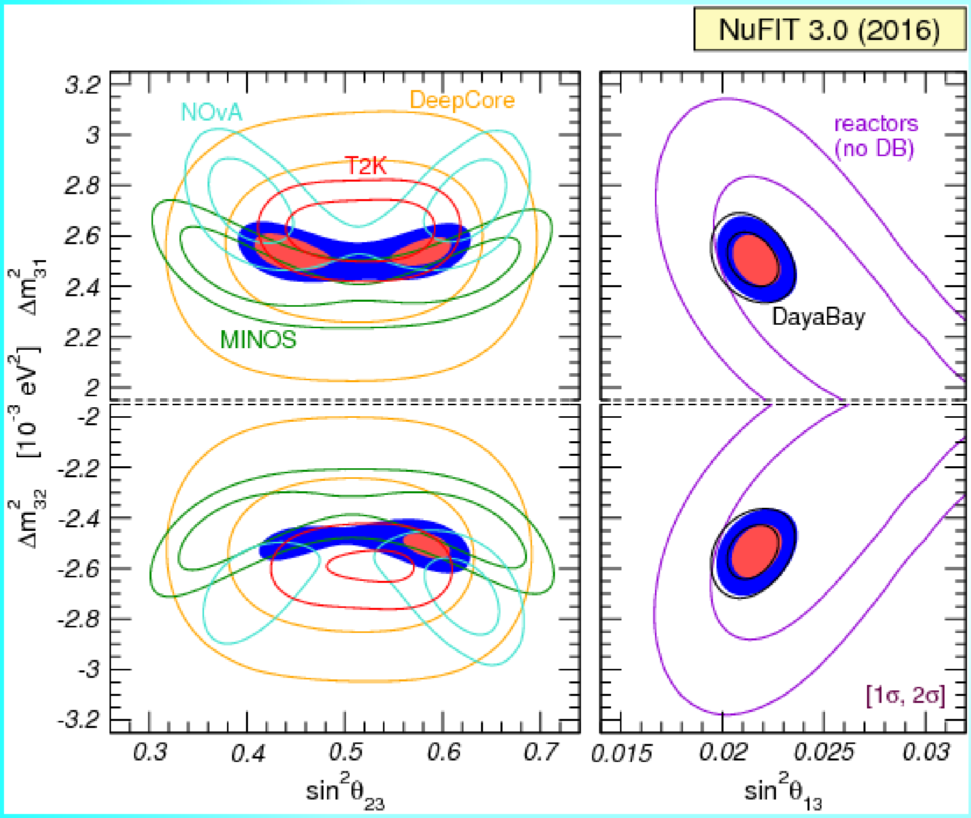
δ from LBL, reactor and their combination.
Upper panels: 1D $\Delta\chi 2$ from LBL experiments after constraining $\theta 13$ only from reactor exp.

$\delta\chi 2$ is defined with respect to the global minimum of the two orderings.

The lower panels - corresponding determination when the full information of LBL accelerator and reactor experiments is used in the combination.

2-3 mixing

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



1σ and 2σ regions using both appearance and disappearance data from MINOS (green line), T2K (red lines), NOvA (light blue lines), as well as IceCube DeepCore (orange lines), and the combination of them (colored regions).

The right panels allowed regions using only Daya-Bay (black lines), reactor data without Daya-Bay (violet lines), and their combination (colored regions).
Solar and KamLAND data are included to constrain Dmq21 and θ 12.