Neutrinos: experiment & theory

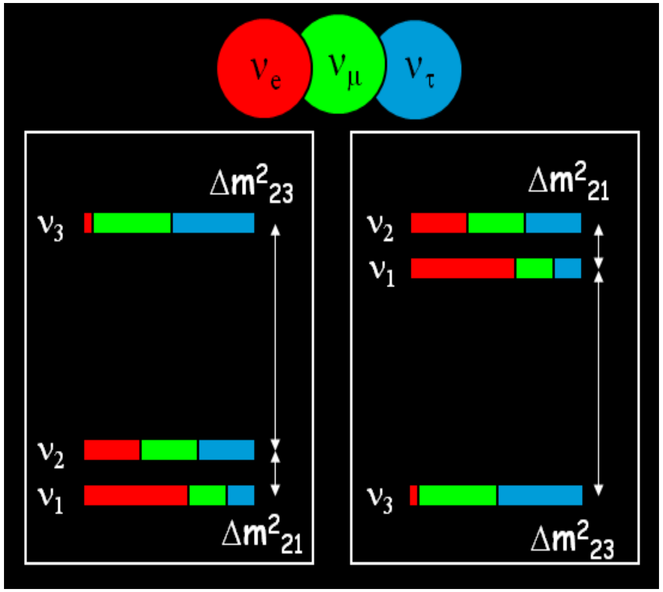
A. Yu. Smirnov

MPIK, Heidelberg

PASCOS 2019,
Manchester, July 3, 2019

3ν paradigm

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



With still unknown:
- Mass ordering
- deviation of 2-3 mixing from maximal
- CP-violation phase

- Dirac vs. Majorana nature

and related:
- existence and mass of the RH neutrinos

works well - starting and ... final point of the talk

Precision and benchmark points

$\frac{1}{2} - \sin^2\theta_{23}$ → $\frac{1}{2}\sin^2\theta_{13} \sim 0.01$; $\sqrt{\frac{1}{2}}\sin\theta_{13} \sim 0.1$

Important probe of the underlying physics

$\theta_{23} \sim \pi/4 - \theta_{cb}$ QLC

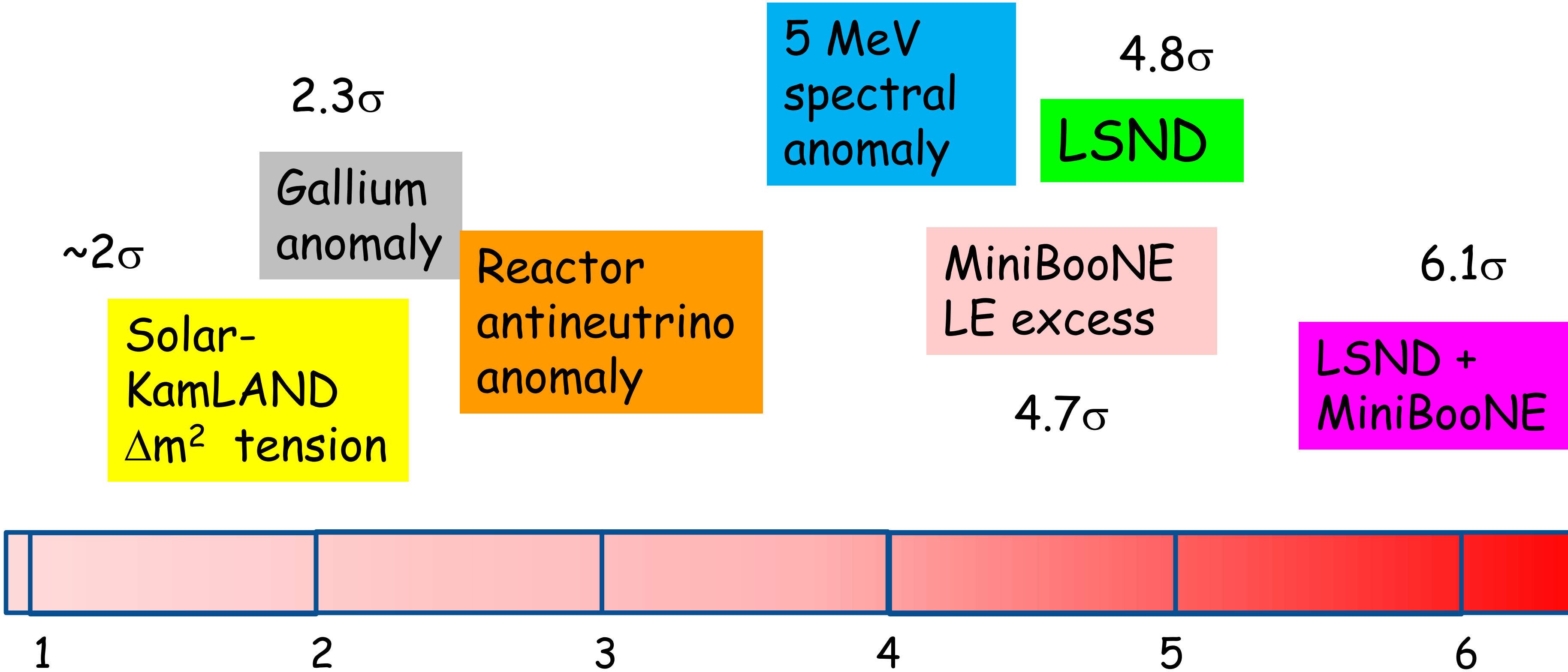
δ_{CP} → $-\pi/2$; π ; 0

$\theta_{12} \sim \pi/4 - \theta_C$

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

Various more complicated relations (sum rules)

Challenging the 3ν paradigm: anomalies and tensions



Possible connection of neutrinos
connection to other hints BSM

B- anomalies
Be-anomaly

Grand unification of anomalies

Beyond 3 paradigm

``Standard set"

New neutrino states- sterile neutrinos

Non-standard interactions (NSI)

Non-unitarity, non-universality

Violation of fundamental symmetries

New dynamics

Connections & portals

standard & non-standard
Nu-option...

Outline

- 3ν paradigm: experimental results and implications
- Sterile neutrinos
- Neutrinos and light Dark sector
- Towards the underlying theory

Conclusion

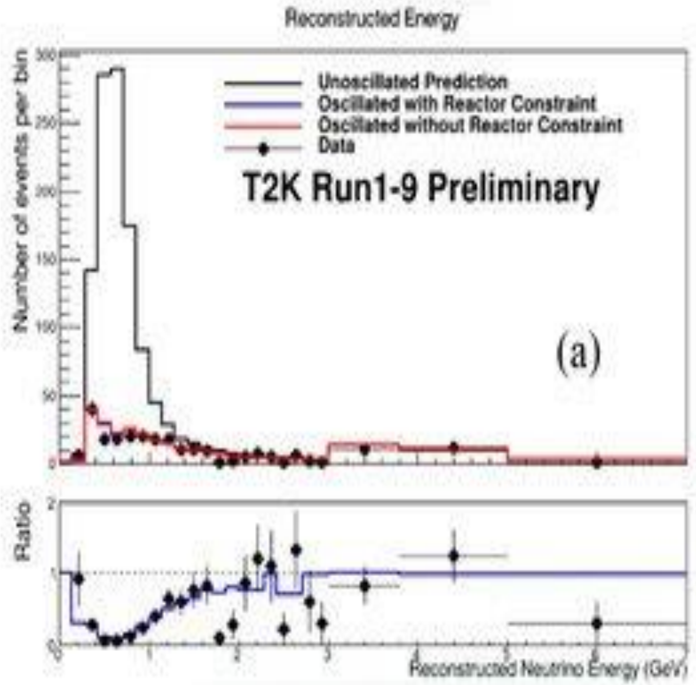
3-nu paradigm: experimental results & implications

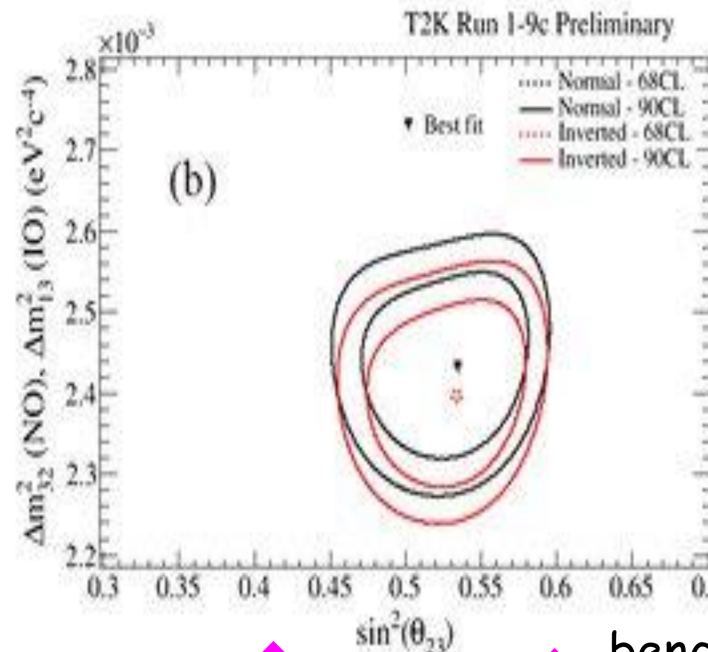
after nu2018,
few initial results,
mostly updates,
trends

T2K results

D. Karlen, (T2K Collaboration)
Universe **2019**, *5*(1), 21.

Update 2.2 → 2.6×10 [21] POT



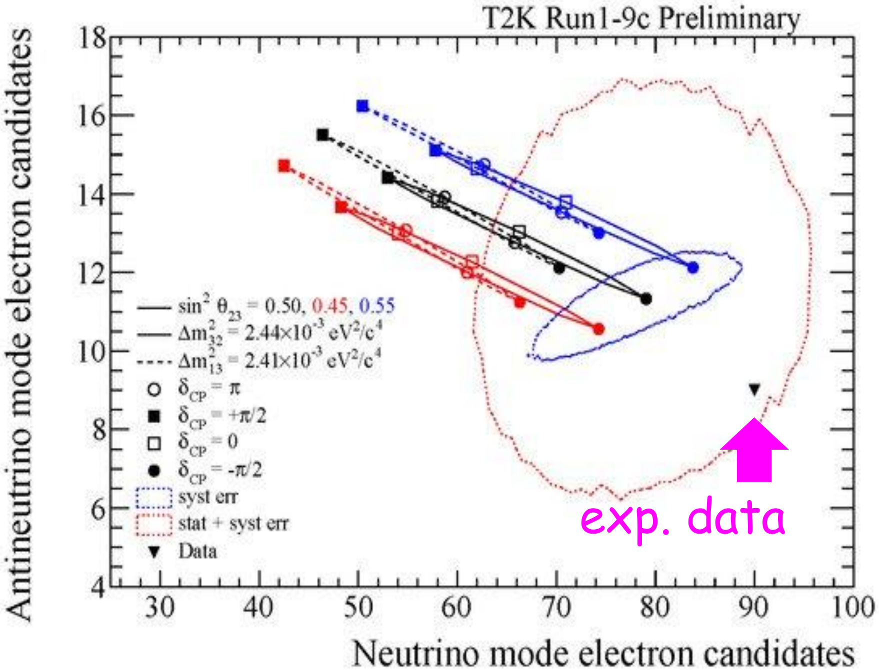


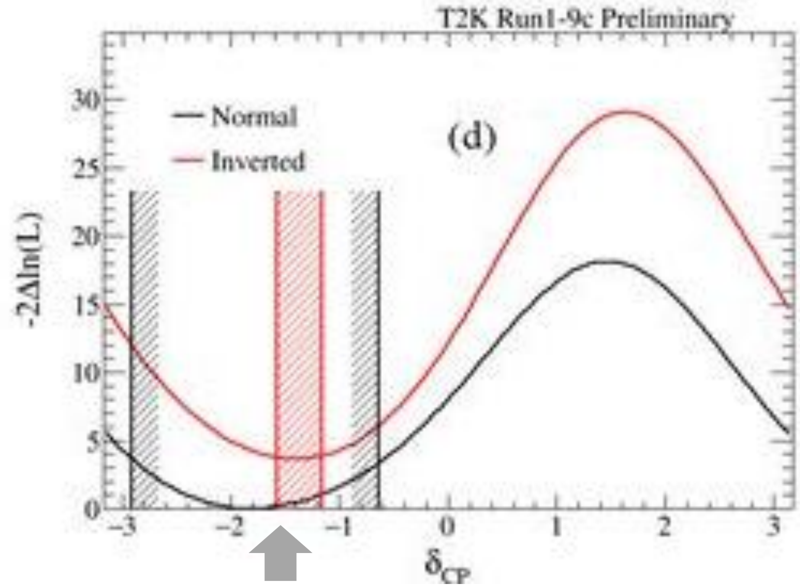
benchmark values

The rate of muon-neutrinos in the far detector. Data vs. expected rate for the best fit oscillation parameters.

Confidence intervals for the atmospheric oscillation parameters for the normal and inverted mass ordering .

T2K results





The frequentist 2σ confidence intervals on δ_{CP}

The expected numbers of ν_e and $\bar{\nu}_e$ events for optimized systematic parameter values. The solid (dashed) ellipses are for NO (IO)

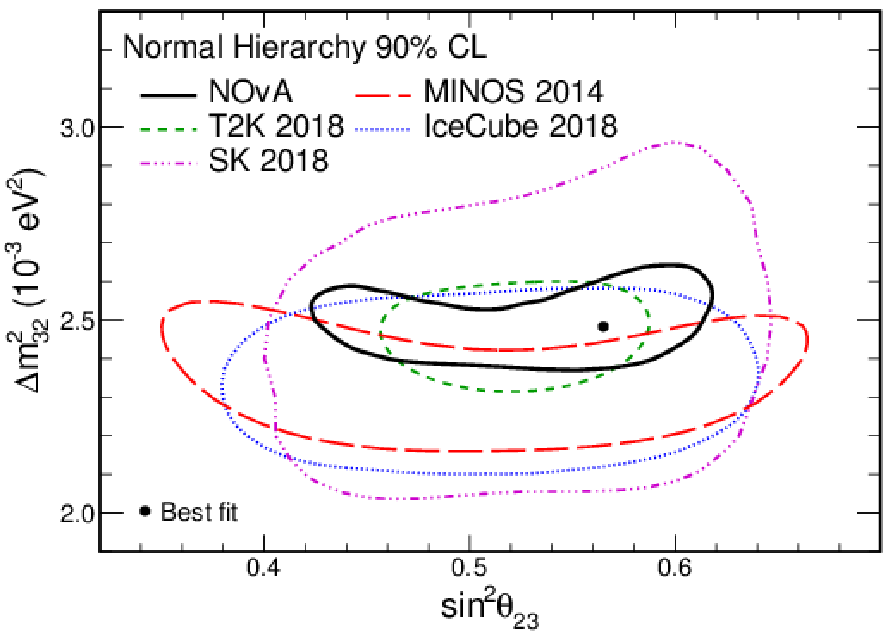
Jagged - expected 1σ regions for $\sin^2\theta_{23} = 0.5$, $\delta_{CP} = -\pi/2$ with different treatment of systematics: random with external data (blue) or Poisson random (red)

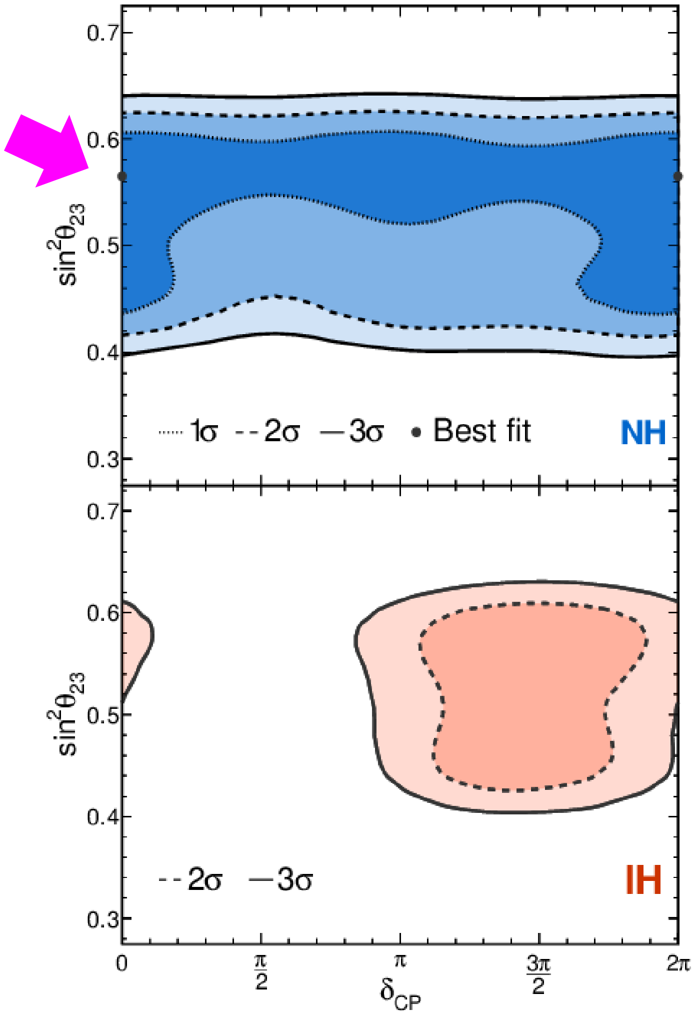
Best fit close to maximal CP violation

NOvA results

NOvA Collaboration (Acero, M.A. et al.) arXiv:1906.04907 [hep-ex]

First measurement of neutrino oscillation parameters using neutrinos and antineutrinos by NOvA

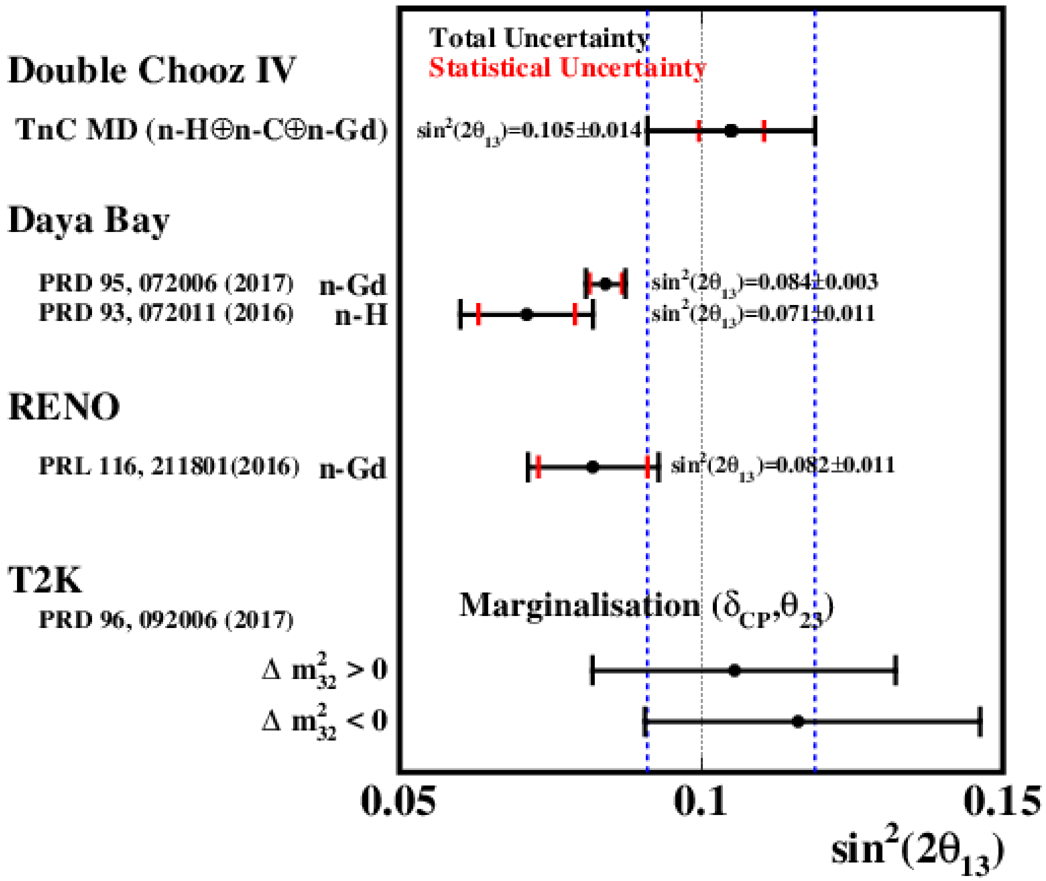




Best fit point (NO):
no CP violation, δ_{CP} = 0.
At 1σ any value is allowed

1-3 mixing from reactors

First Double Chooz θ13 Measurement via Total Neutron Capture Detection - Double Chooz Collaboration (de Kerret, H. et al.) arXiv:1901.09445 [hep-ex]

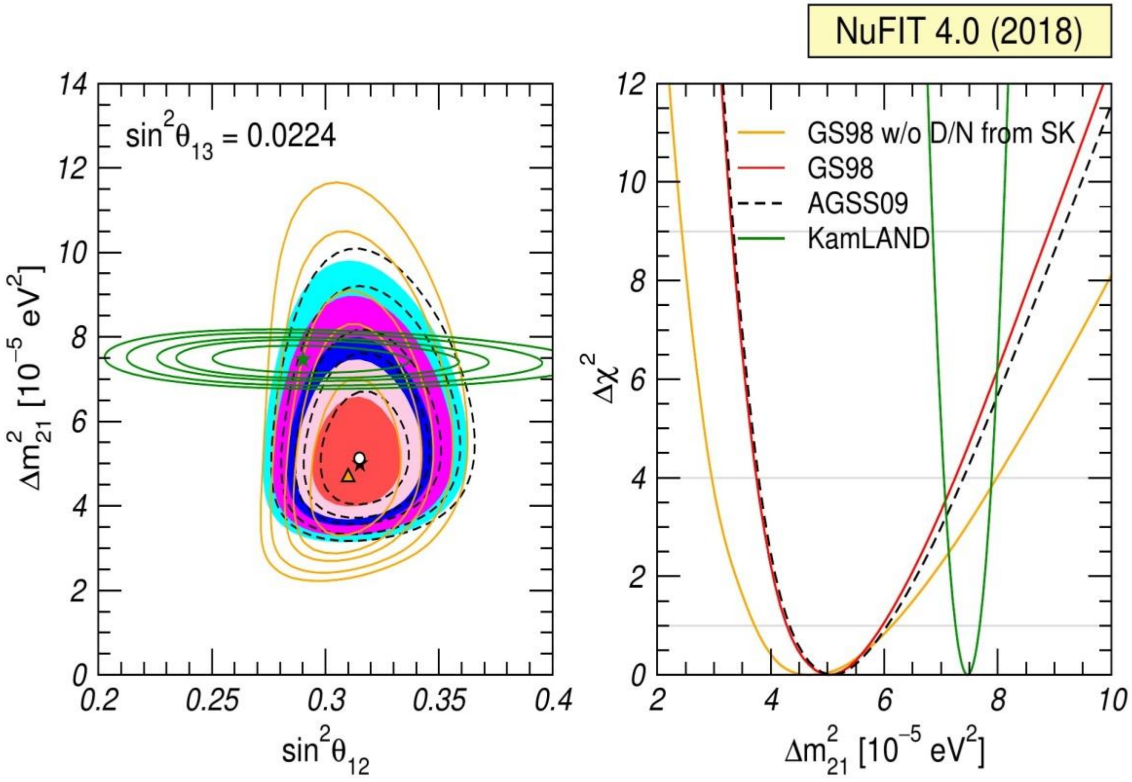


The most precise published reactor measurements of θ_{13} from DC MD TnC , DYB and RENO .

DC result shows a [25,48]% higher central value whose significance ranges [1.3,1,9]σ compared to other reactor measurements.

The T2K larger uncertainty is due to the marginalisation over θ_{23} and CP violation.

Solar neutrinos: Δm_{21}^2 - tension



Origin of tension:
- Absence of the upturn of spectrum (SNO, SK)
- 50% larger than expected D-N asymmetry for the bf Δm_{21}^2

Yellow lines - without the DN effect

68%, 90%, 95%, 99%, 3σ CL contours

Contours for solar models with different metallicity) also with and without DN effect

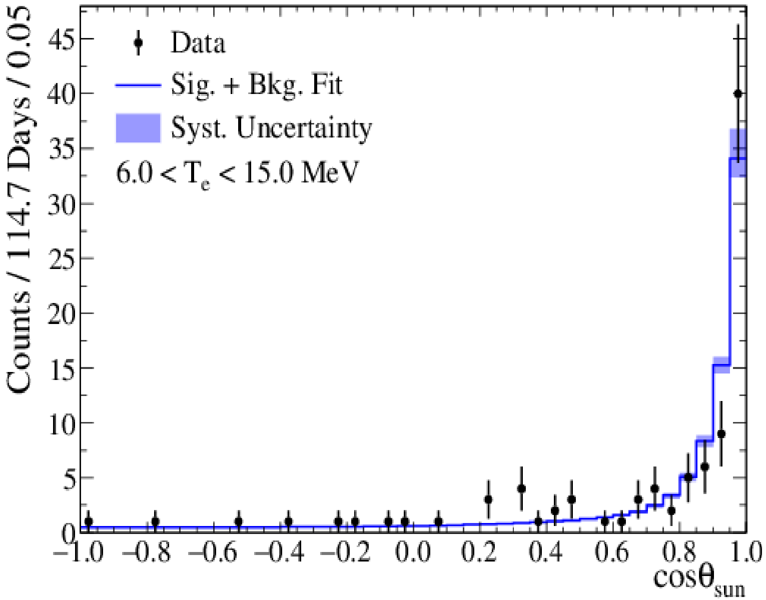
tension starts to disappear?

Solar neutrinos SNO+ results

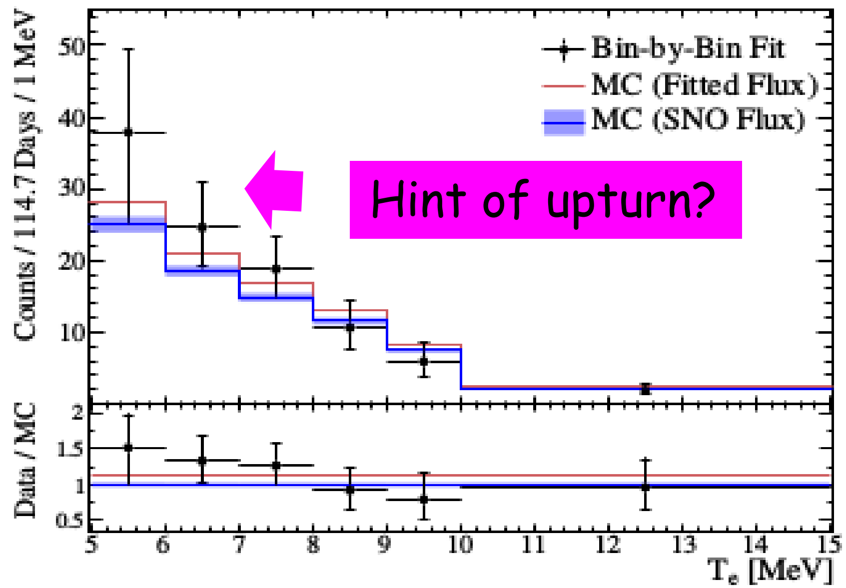
SNO+ Collaboration (Anderson, M. et al.)
Phys.Rev. D99 (2019) no.1, 012012
1812.03355 [hep-ex]

Water phase: Measurement of the 8B solar neutrino flux in SNO+ with very low backgrounds S/B ~ 4, E > 6 MeV

114.7 days of data



Distribution of event directions wrt. solar direction



The extracted event rate as function of reconstructed electron kinetic energy

69.2 kt-day dataset

Flux: 2.53 [-0.28+0.31(stat) -0.10+0.13(syst)] x 10^{-6} cm $^{-2}$ s^{-1}

Atmospheric neutrinos

ANTARES: measurements of 2-3 mass and mixing

IceCube Deep Core: tentative attempts to extract mass hierarchy

ORCA: 2 strings employed

Super-Kamiokande -IV

Super-Kamiokande Collaboration (Jiang, M. et al.) PTEP 2019 (2019) no.5, 053F01, 1901.03230 [hep-ex]

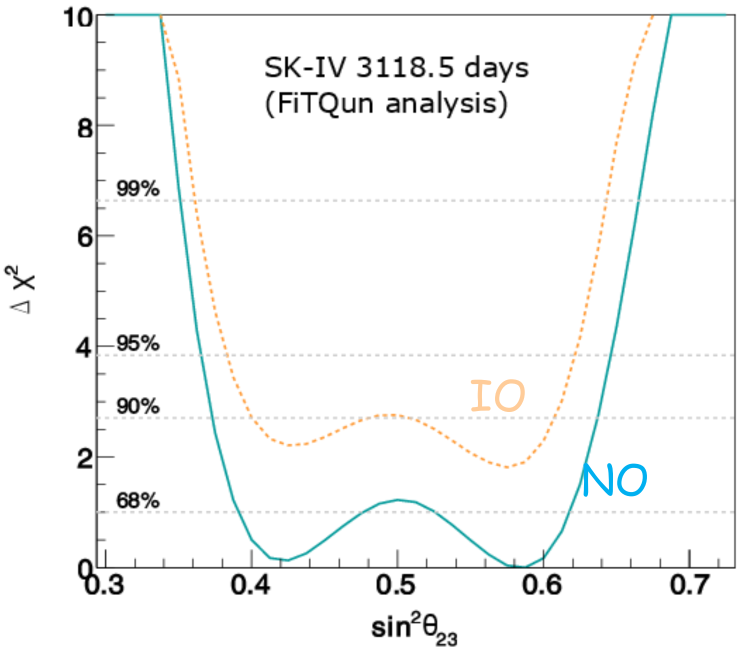
Atmospheric Neutrino Oscillation Analysis With Improved Event Reconstruction

- A new event reconstruction algorithm based on a maximum likelihood method developed .
- Improves kinematic and particle identification capabilities,
- Enable to increase fiducial volume by 32%
- increase the sensitivity to the neutrino mass hierarchy.

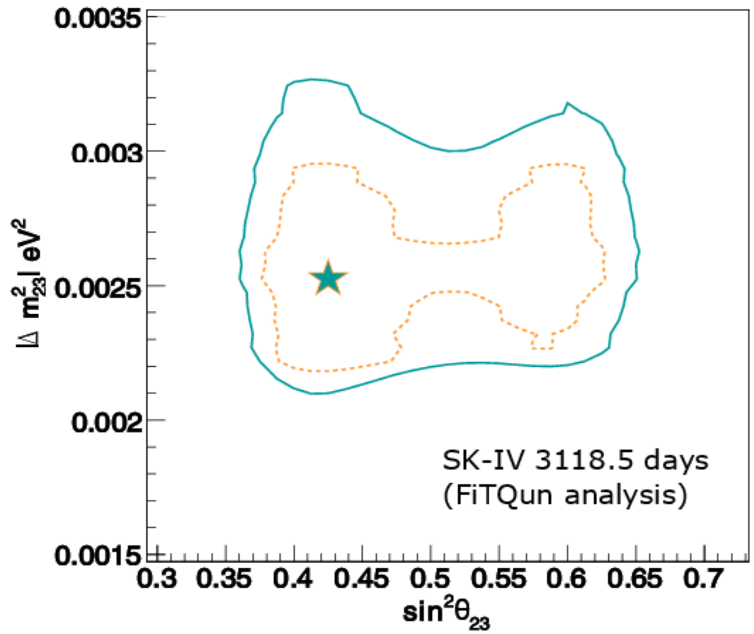
Super-Kamiokande results

Super-Kamiokande Collaboration (Jiang, M. et al.) PTEP 2019 (2019) no.5, 053F01, 1901.03230 [hep-ex]

253.9 kton·year exposure



Super-K constraint with no assumed bounds on 13 mixing

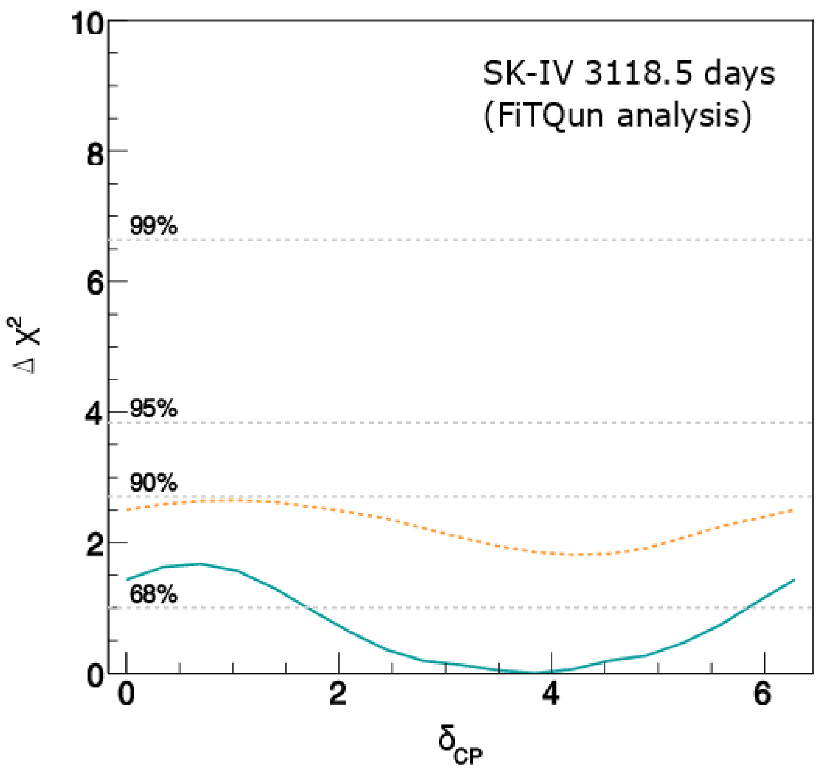


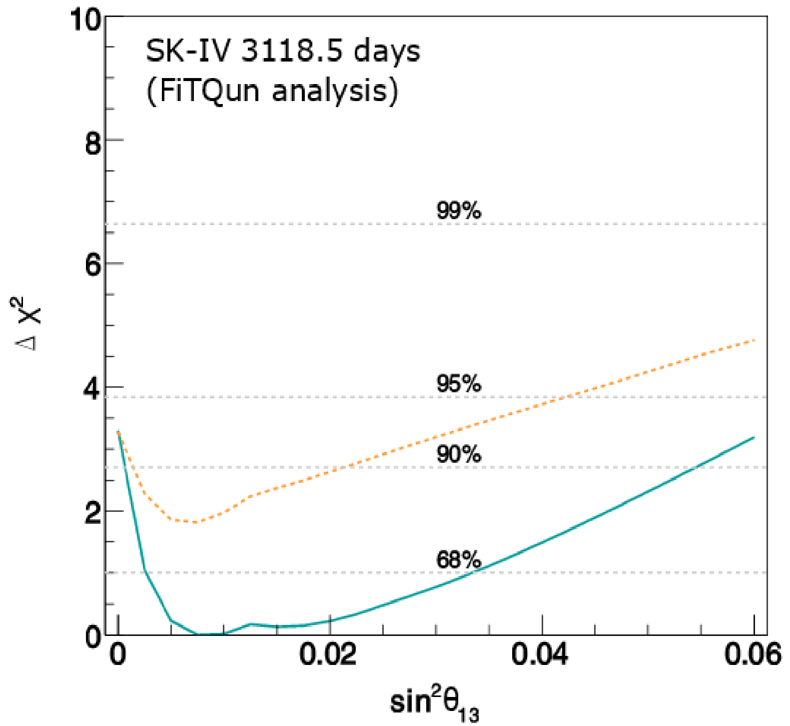
The best-fit value, (star) is the same for NO and IO. $\sin^2\theta_{13}$=0.0210 ± 0.0011. The contours - relative to the global bf.

Weak preference for the NO, disfavoring the IO at 74%

bf – substantial deviation from maximal: $\sin^2\theta_{23}$ = 0.42.
At 1 maximal mixing and high octant are allowed

Atmospheric neutrinos: SK-IV results





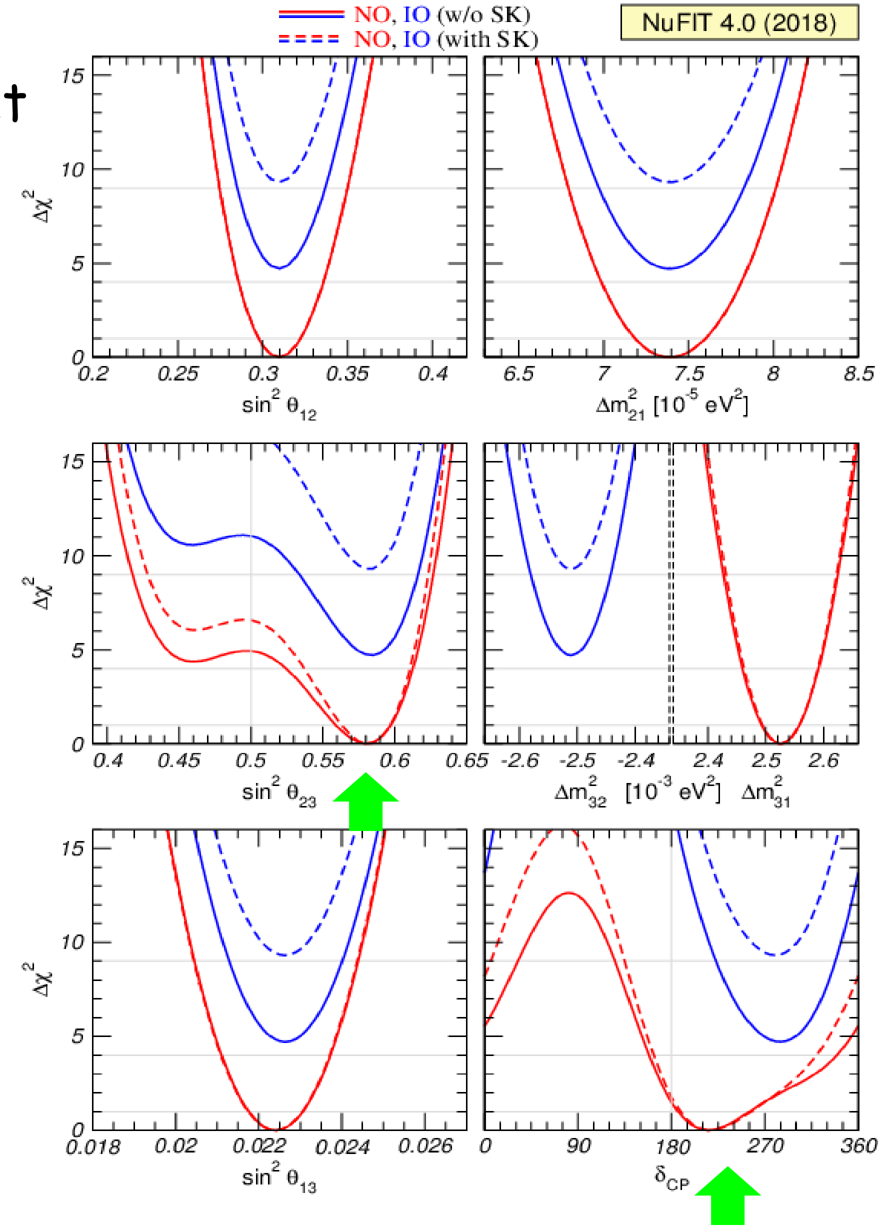
Super-K constraint with no assumed bounds on 13 mixing

Best fit point (NO):
Nearly maximal CP violation, δ_{CP} = 1.9π .
At ~1.2σ any value is allowed

Global 3nu analysis

Esteban, Ivan et al.
arXiv:1811.05487 [hep-ph]

$\Delta\chi 2$ profiles minimized with respect to all undisplayed parameters.

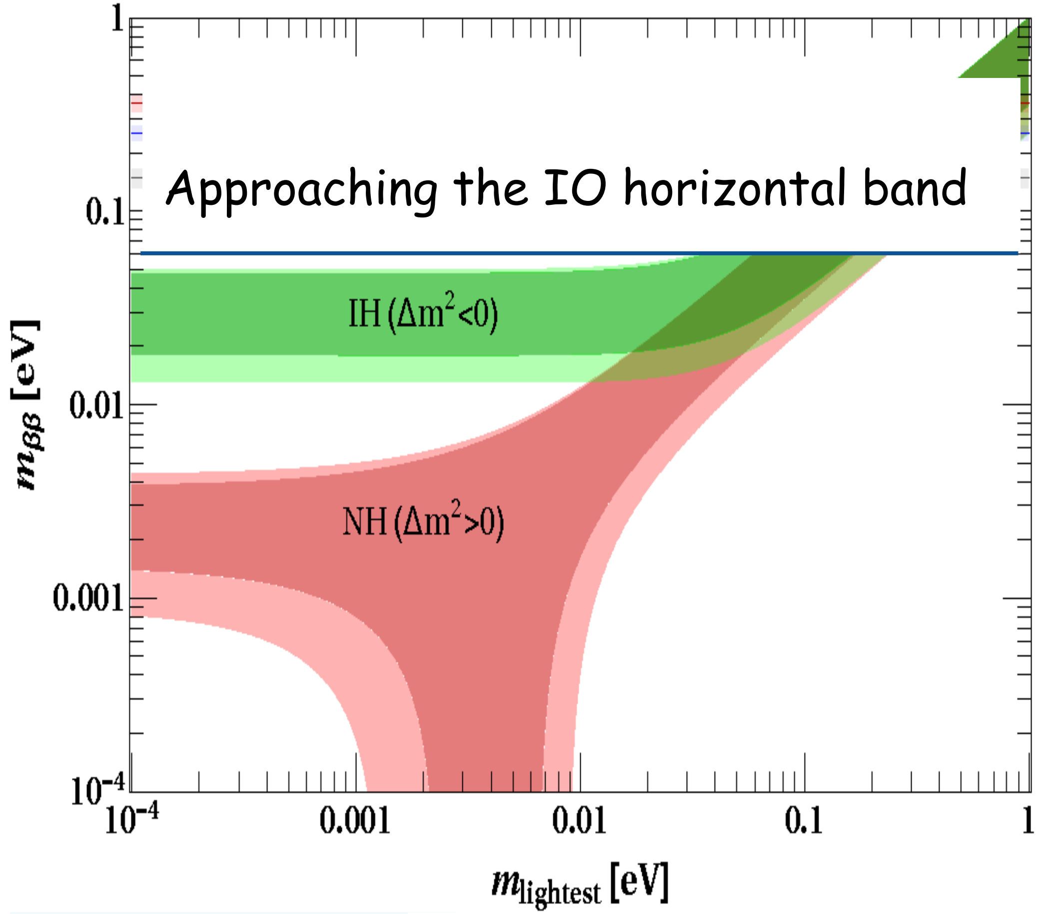


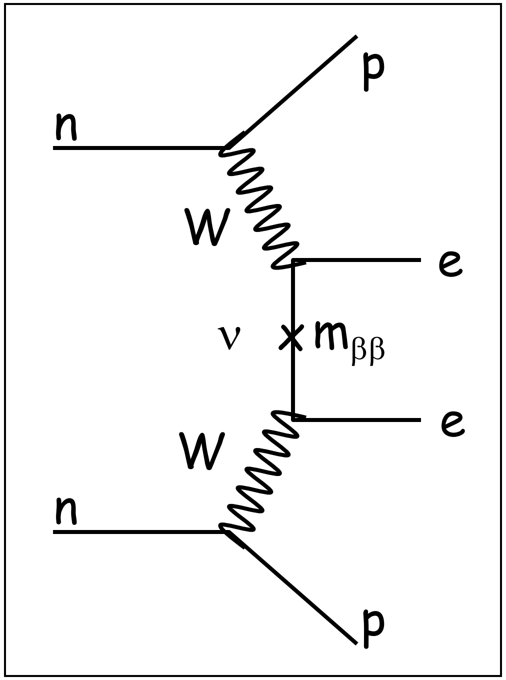
The red (blue) curves correspond to Normal (Inverted) Ordering.
Solid (dashed) curves are without (with) adding the tabulated SK-atm $\Delta\chi 2$.

Mass-squared splitting:
$\Delta m_{31}{}^2$ for NO and $\Delta m_{31}{}^2$ for IO

ββ0ν – decay results

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





90% CL upper bound on $m_{\beta\beta}$ depending on NME

KamLAND-Zen	(61 – 165) meV	*A.Gando, et al, 1605.02889 [hep-ex]*
EXO-200	(93 – 286) meV	*G. Anton et al. 1906.02723 [hep-ex]*
CUORE	(110 – 520) meV	*S. Dell'Oro et al. 1905.07667 [nucl-ex]*
GERDA	(110 – 260) meV	

Towards ultimate $\beta\beta0\nu$ - experiment

The case on normal mass hierarchy

A. Barabash

m_{ee} = 3 meV $T_{1/2}$ = 10^{29} - 10^{30} years

20 time below present bound

10 - 20 t of enriched material → produced in 5 – 10 years

10 years measurements

Background: 0-2 events during measurements

Number of events per 10 t x 10 y	Cost
^{48}Ca – 8.6	
^{76}Ge – 5.5	
^{82}Se – 5.0	800 mln
^{100}Mo – 4.1	
^{116}Cd – 3.6	
^{130}Te – 3.2	200 mln
^{136}Xe – 3.0	50 – 100 mln

The last phenomenological problem?

Coherent flavor exchange → ``Collective oscillations"

Collective flavor trasformation

Bi-polar oscillations
Flavor instabilities
Fast flavor transitions
Fast temporal flavor
Oscillations
Spectral splits

↑

obtained in certain approximations and under simplifications

Effective theory of collective oscillations based on evolution of individual neutrinos in external potential which have non-trivial time (distance) dependence

Sterile neutrinos

Status of Light Sterile Neutrino Searches - Böser, Sebastian et al. 1906.01739 [hep-ex]

Remark

LSND / MiniBooNE
RAA, Gallium

m_S = 0.1 – 10 eV

$\theta_S \sim 0.1$

Adding such a neutrino is not small perturbation of the 3nu picture.
Correction to the mass matrix of active neutrinos

$\delta m \sim \sin^2\theta_S \, m_S \sim (2\text{-}5)\ 10^{-2}$ eV

- at the level of largest elements

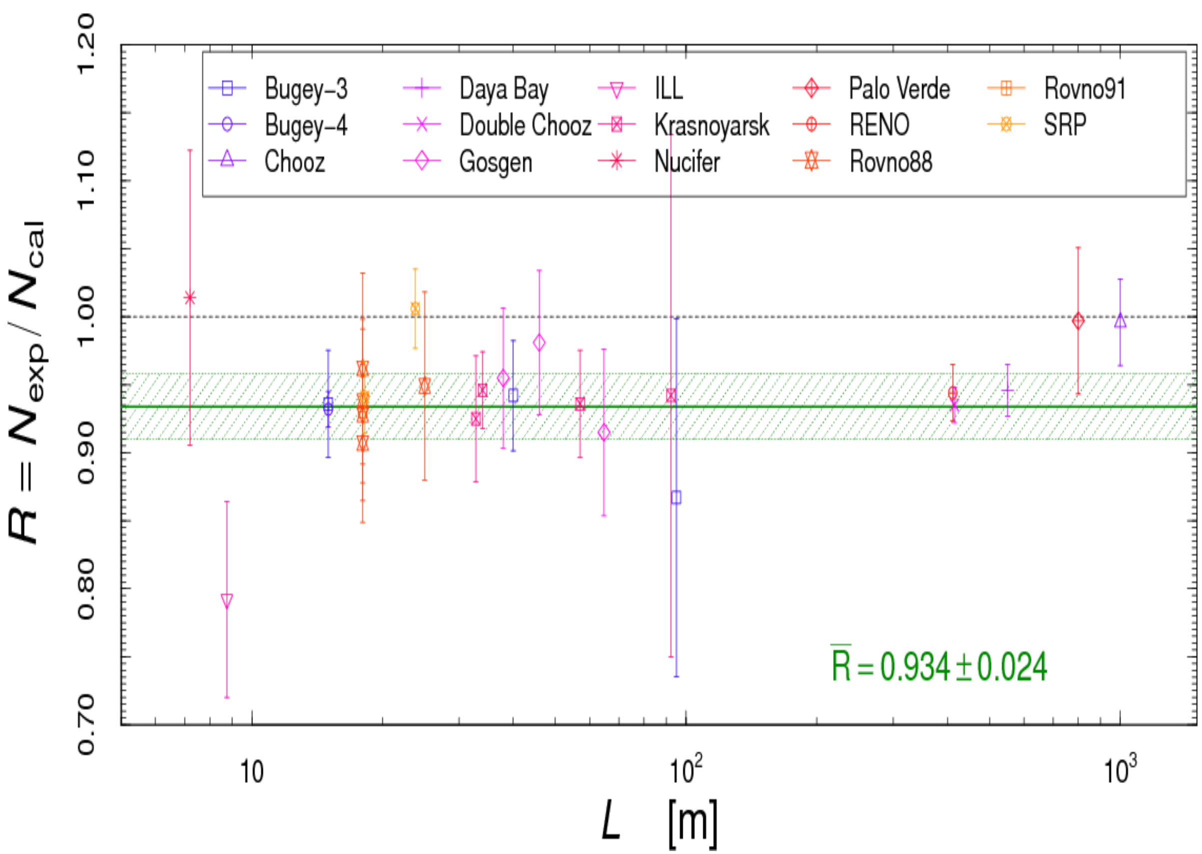
Should be included
in theory construction
in the beginning

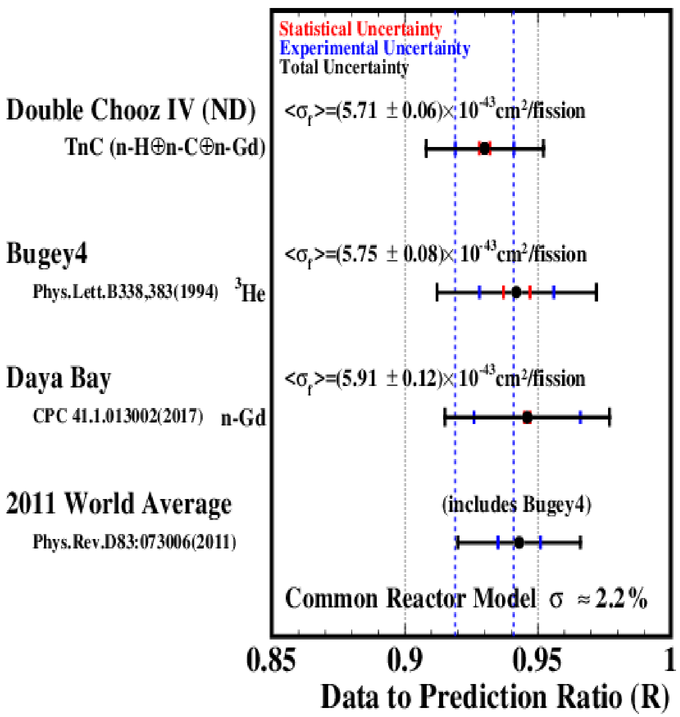
For two and more
steriles cancellation of
their contributions can
be arrangedis possible

Future bound $\sin^2\theta_S < 10^{-3}$ eV / m_S

will allow to consider them as perturbation

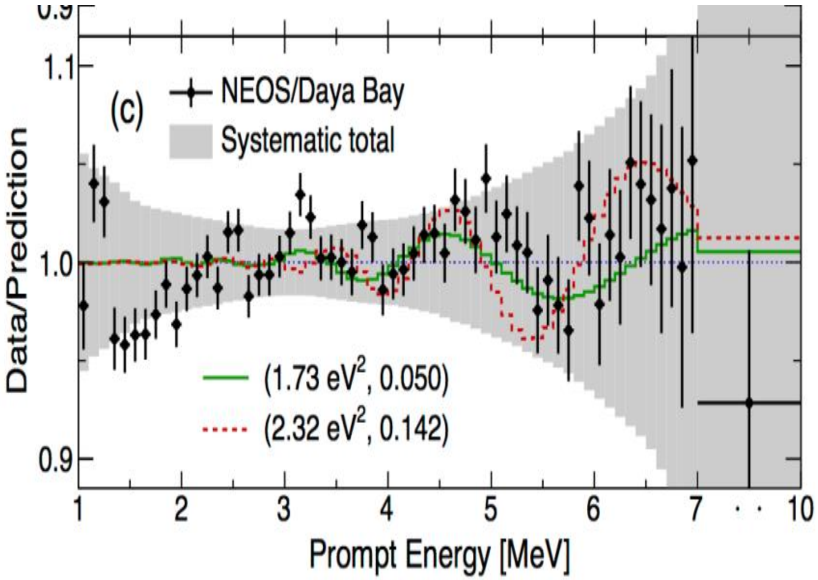
Reactor antineutrino anomaly (RAA)

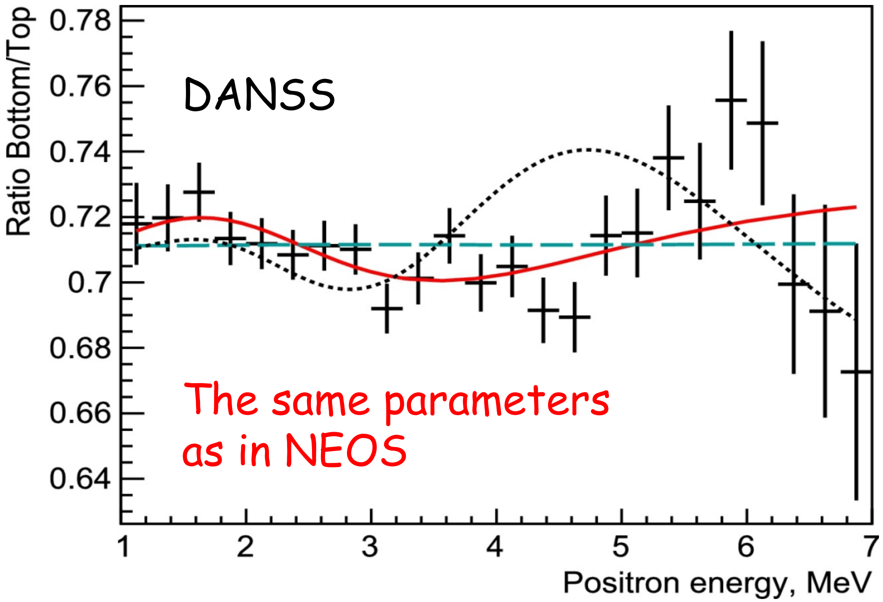




Ratios *R* of reactor data over predicted flux by Mueller and Huber as function of the reactor-detector distance *L*. From Gariazzo et al.

New anomaly? NEOS and DANSS



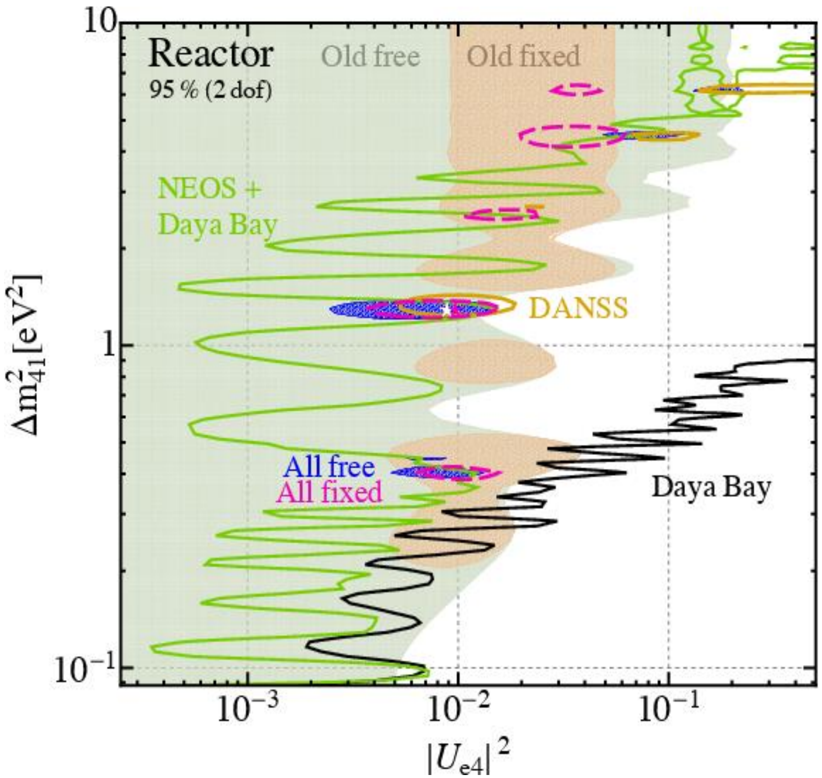


Ratio of the data to the expected Daya Bay spectrum.
The solid green line - the best fit.
The dashed red line corresponds to the RAA best fit parameters Ko:2016, et al.

Ratio of positron energy spectra measured at the bottom and top detector positions (stat. errors only). Dashed curve - the three active neutrino case,
the red solid curve - the best fit in (3+1) case, the black dotted curve is the RAA expectation.

Disappearance bounds

M. Dentler et al, JHEP 08, 010 (2018)



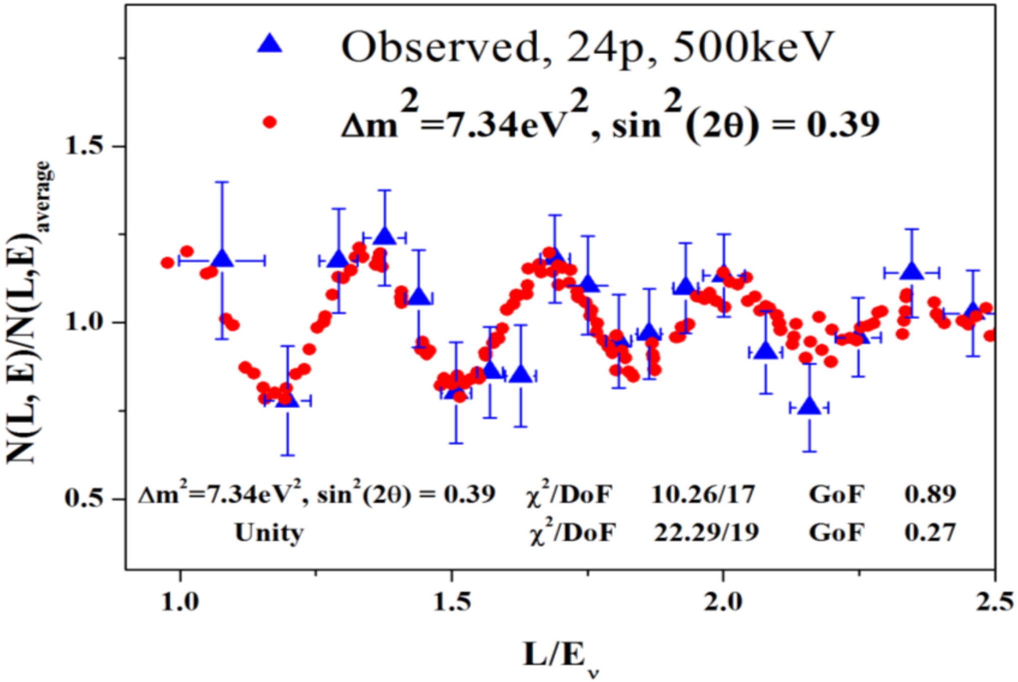
Blue shaded regions - 95% CL allowed by the fit of all reactor data with free fluxes,
White star - best-fit point .

Magenta lines enclose the regions allowed by a fit of all reactor data with the Huber-Mueller fluxes, magenta star - the best-fit point (nearly to white).

Exclusion curves: Daya Bay (black) and NEOS/Daya Bay (green)

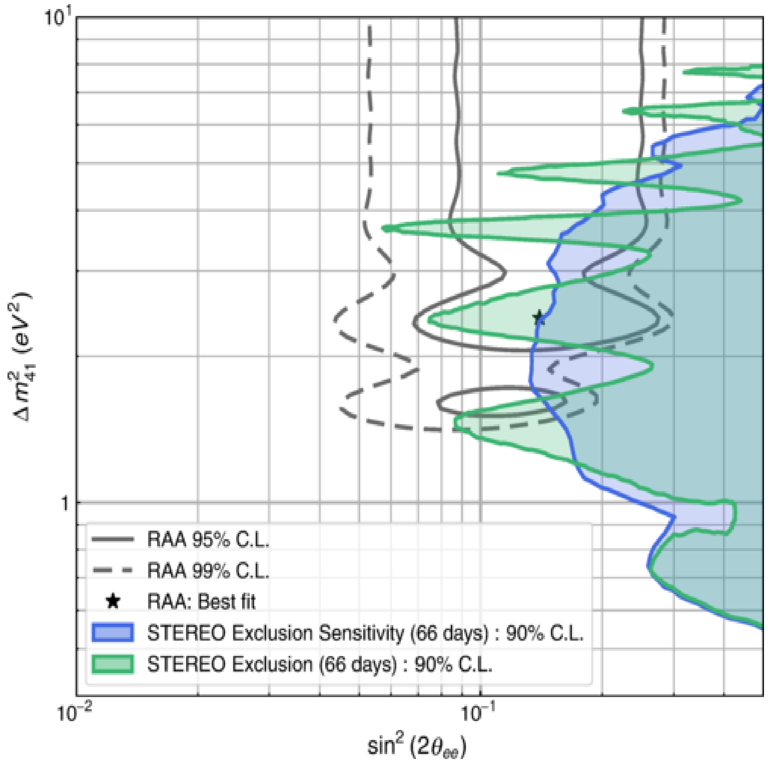
The light-shaded areas are allowed by the ``old'' reactor data (without NEOS, Daya Bay and DANSS) with fixed Huber-Mueller (light orange) and free (light green) fluxes.

Neutrino-4: another anomaly?

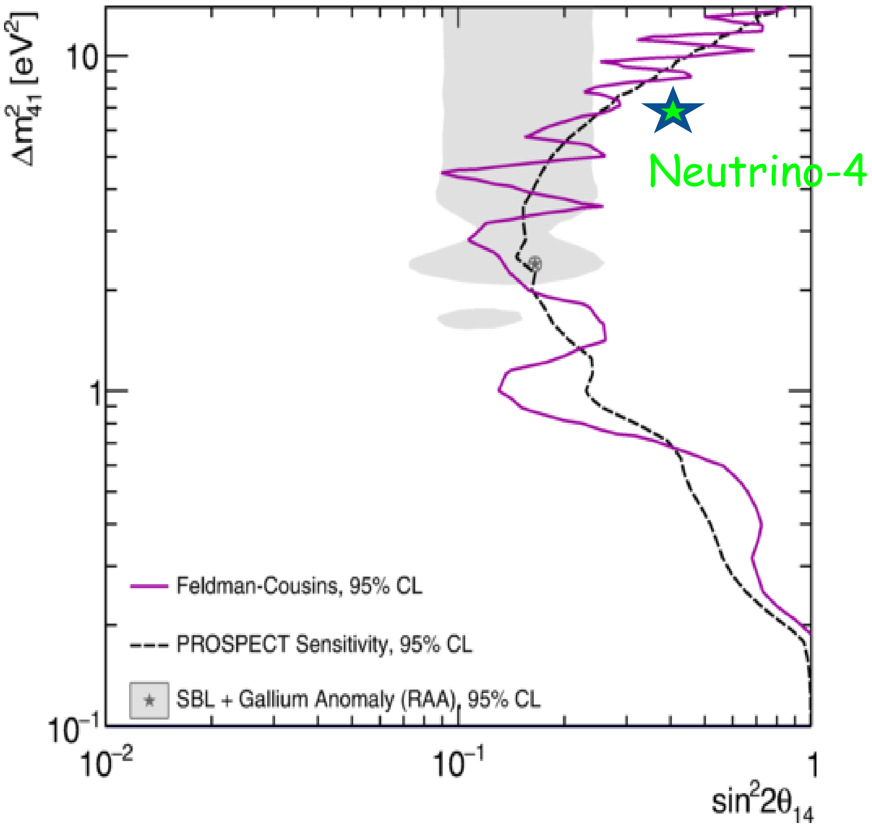


L/E dependence for Neutrino-4 data points vs. expected oscillation signal for the best fit values (red dots), Serebrov 2019.

Prospect and STEREO

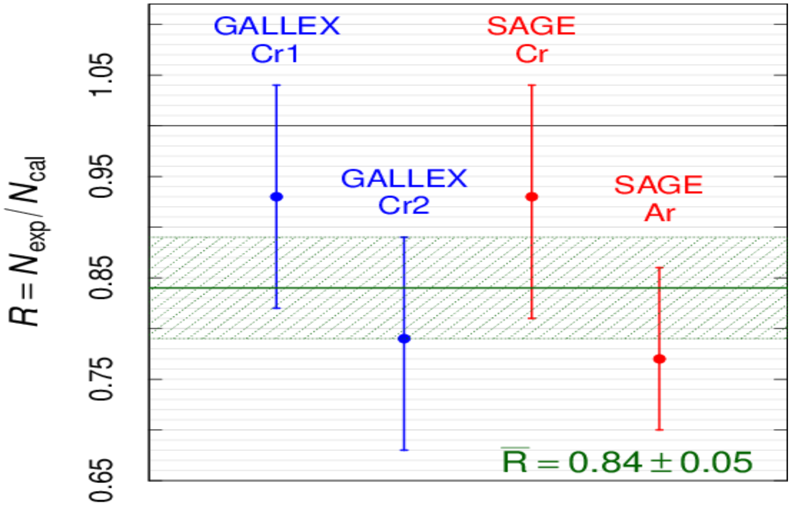


Stereo sensitivity and exclusion contour of the oscillation parameters, Almazan et al.



PROSPECT sensitivity and neutrino oscillation exclusion contour with 33 live-days of reactor-ON data Ashenfelter et al.

Ga-anomaly

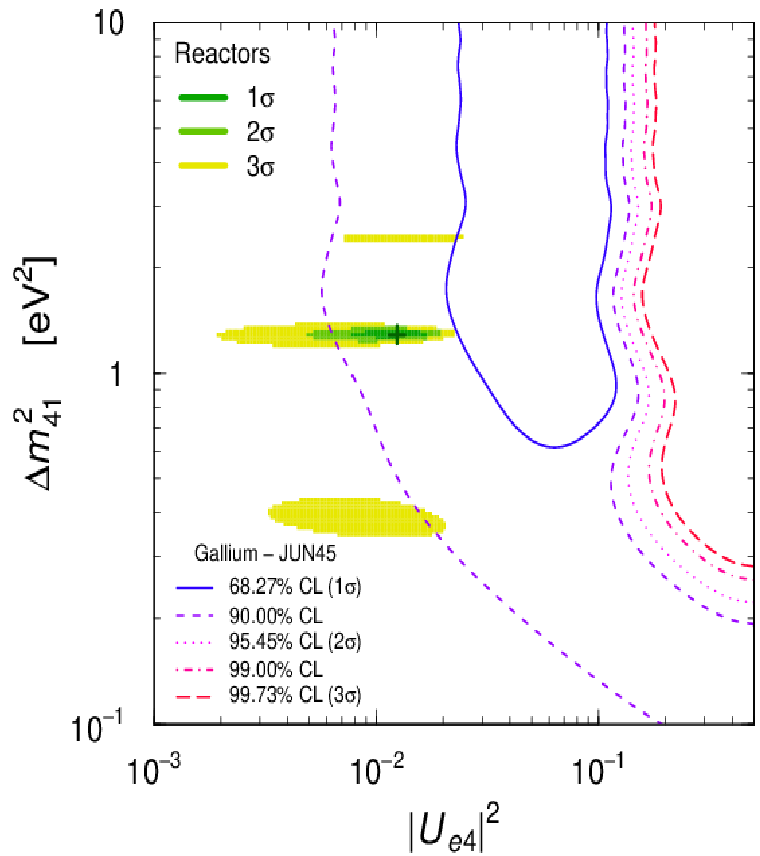


New cross-section calculations using nuclear shell-model wave functions obtained by exploiting recently developed two-nucleon interactions.

The significance of anomaly decreases from 3.0σ to 2.3σ.

The result is compatible with indication of short-baseline *ve* disappearance from NEOS and DANSS data .

Joel Kostensalo et al 1906.10980 [nucl-th]

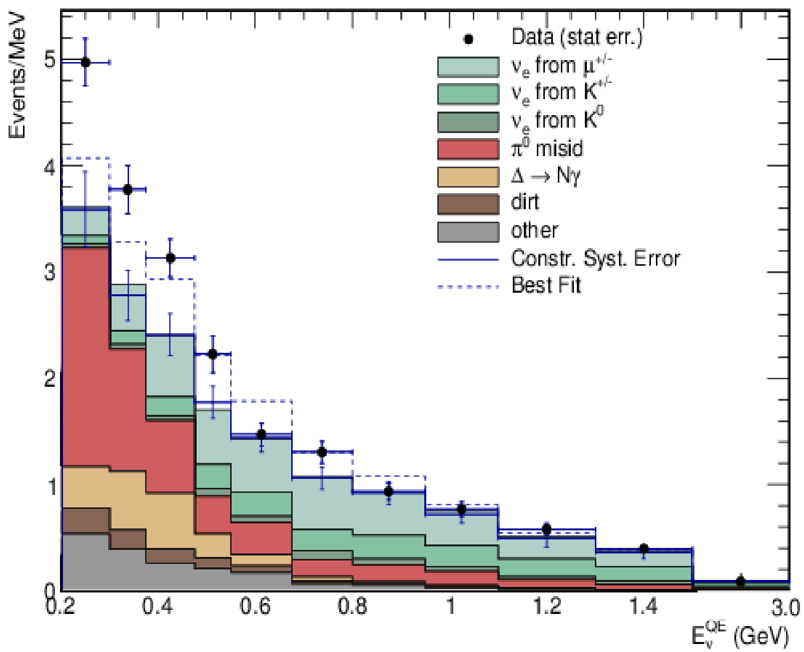


Gallium data with the JUN45 cross sections vs. the allowed regions from NEOS, DANSS and PROSPECT reactor experiments

MiniBooNE excess

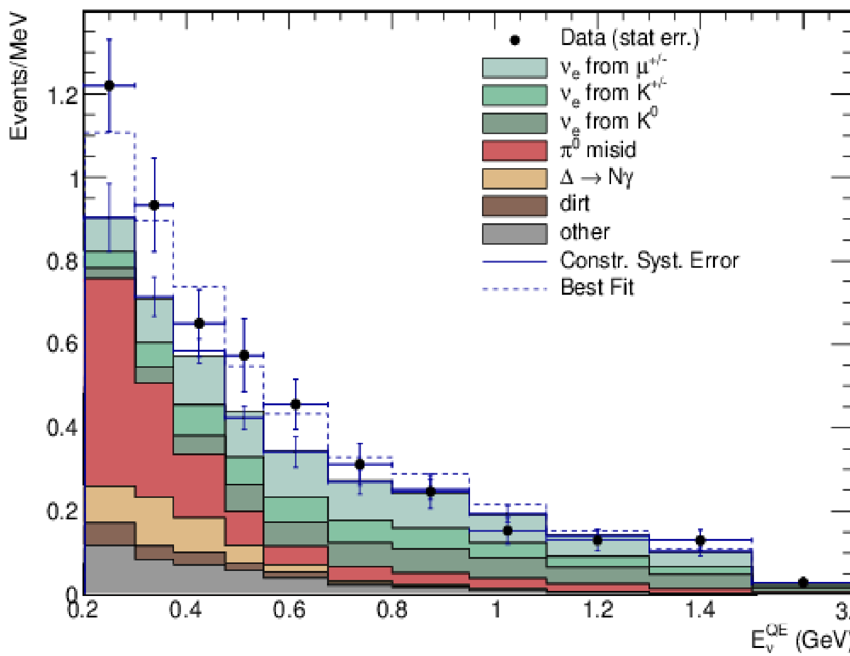
A.A. Aguilar-Arevalo et al
Phys.Rev.Lett. 121 (2018) no.22, 221801)
1805.12028 [hep-ex] |

neutrinos



The neutrino mode *EQEv* distributions, with 12.84×1020 POT data, *ve* CCQE data (points with statistical errors) and background (histogram with systematic errors). The dashed curve shows the best fit to the neutrino mode. The last bin is for the energy interval from 1500-3000 MeV.

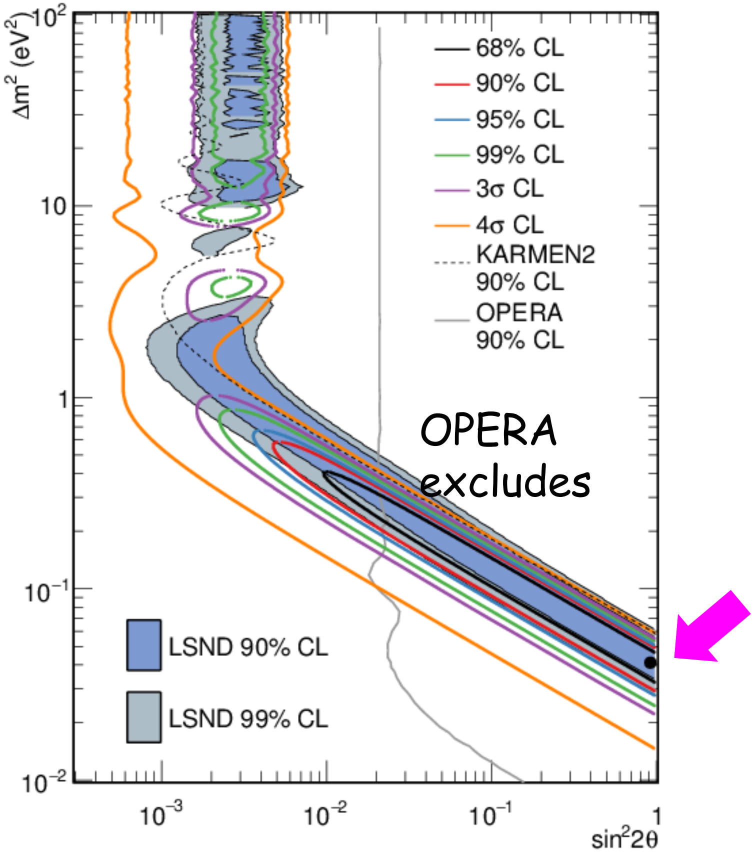
antineutrinos



The antineutrino mode *EQEv* distributions, with 11.27×1020 POT data, *ve* CCQE data (points with statistical errors) and background (histogram with systematic errors).

MiniBooNE excess

A.A. Aguilar-Arevalo et al
Phys.Rev.Lett. 121 (2018) no.22, 221801)
1805.12028 [hep-ex]

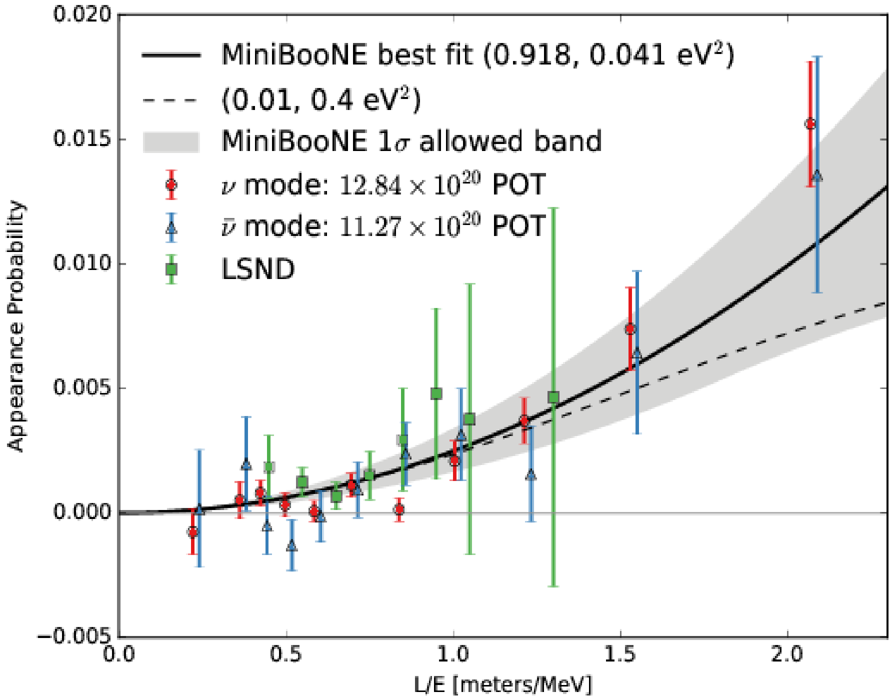


MiniBooNE allowed regions for a combined neutrino mode (12.84×10^{20} POT) and antineutrino mode (11.27×10^{20} POT) data sets for events with 200< E^{QE}_{ν} <3000 MeV. The shaded areas show the 90% and 99% C.L. LSND $\bar{\nu}_\mu\rightarrow\bar{\nu}_e$ allowed regions.

The black point shows the MiniBooNE best fit point. Also shown are 90% C.L. limits from the KARMEN and OPERA experiments.

MiniBooNE and LSND

A.A. Aguilar-Arevalo et al
Phys.Rev.Lett. 121 (2018) no.22, 221801)
1805.12028 [hep-ex] |



A comparison between the *L/EQEv* distributions for the MiniBooNE data excesses in neutrino mode .

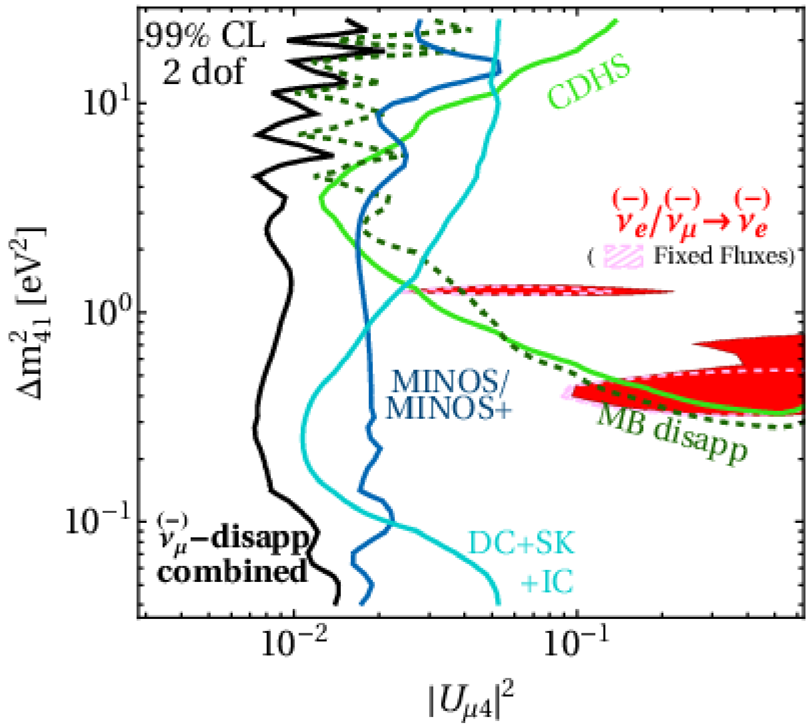
The error bars - statistical uncertainties only. The curves show fits to the MiniBooNE data, the shaded area is the MiniBooNE 1σ allowed band. The dashed curve shows the example 1σ fit point.

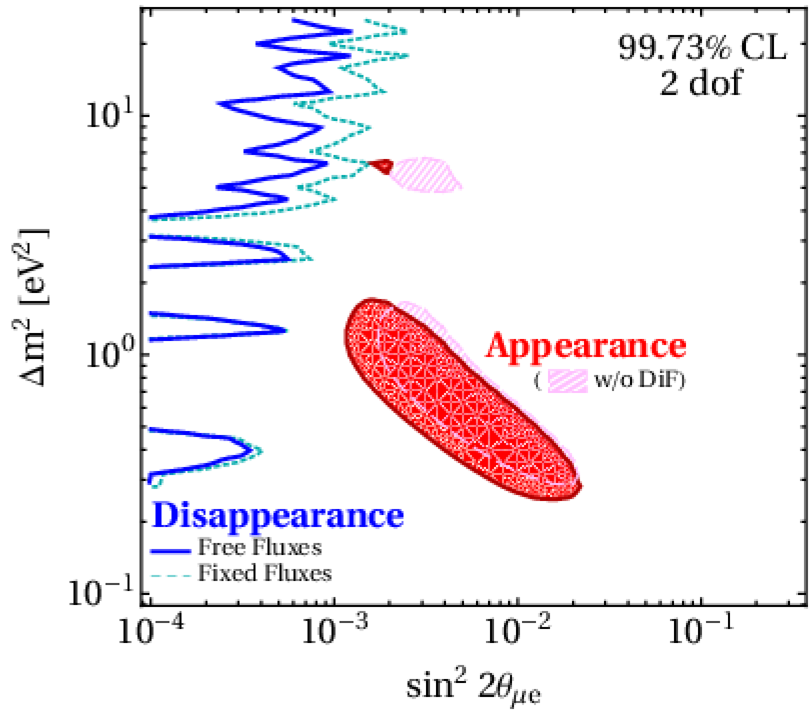
No good agreement in overlapping region

Appearance vs. disappearance tension

M. Dentler et al, JHEP 08, 010 (2018)

from short-baseline ν_μ disappearance and $\nu_\mu \rightarrow \nu_e$ appearance data.





99% CL exclusion curves from various experiments vs. the allowed regions inferred from combination of ν_e (bar) disappearance and $\nu_\mu \rightarrow \nu_e$ appearance data with free (red) and fixed Huber-Mueller (pink) reactor fluxes.

The 3σ allowed region by $\nu_\mu \rightarrow \nu_e$ (bar) appearance data with (red) and without (pink) LSND decay in flight (DIF) data vs. the combined ν_e and ν_μ disappearance exclusion curve with free (blue solid) and fixed (cyan dashed) reactor fluxes.

A prediction

Presently indicated oscillation parameters of sterile neutrinos will be excluded by forthcoming experiments

In turn, the forthcoming experiments will find oscillations with smaller (un excluded) mixing angles.

New experiments will be planned to check new indications, etc.

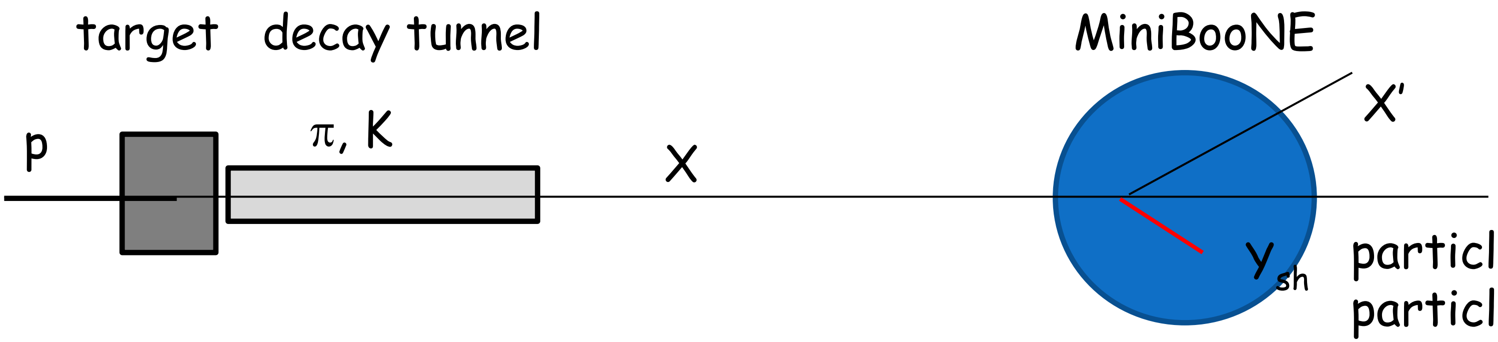
The interest will drop down when we reach

$$\sin^2 \theta_S < 10^{-3} \ (eV/m_S)$$

Neutrinos and light dark sector

Two recent developments:
- Explanaton of MiniBooNE excess
- New refraction efffects

MiniBooNE excess: scanning possibilities



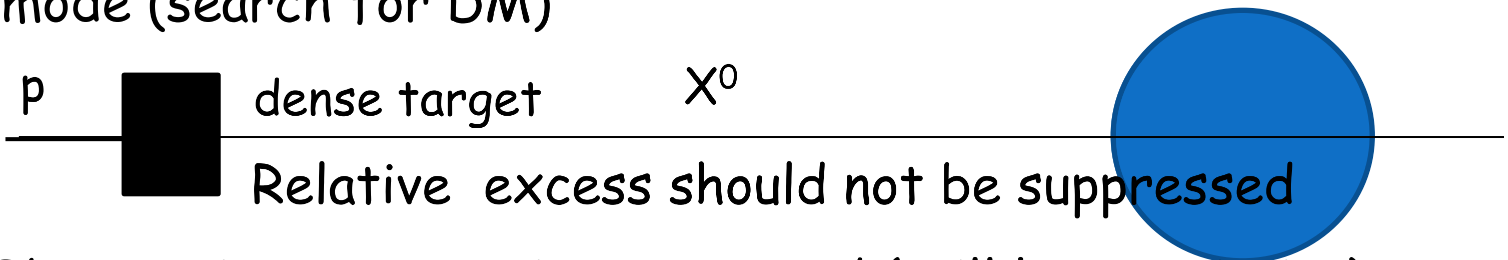
particle or system particles which produce showers

$X = \nu_\mu, X^0$

Y_{sh} = e, γ, $\gamma\gamma$, $e^+ e^-$

m_Y < 30 MeV

X^0 from proton interactions in target restricted by the beam-dump mode (search for DM)



Relative excess should not be suppressed

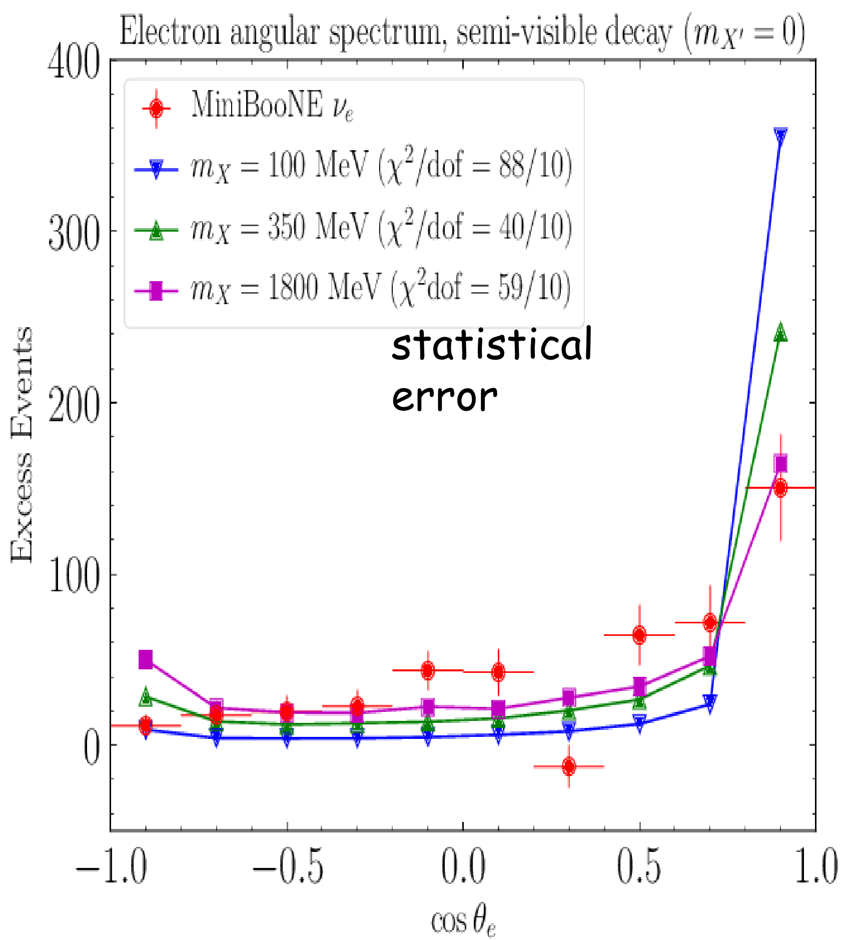
Observations: excess is suppressed (still low statistics)
→ X^0 from π, K decays

But X^0 from π, K - BR is strongly restricted

Constraints on X-decay

J Jordan et al. Phys.Rev.Lett. 122 (2019) no.8, 081801, 1810.07185 [hep-ph]

X (produced outside the detector) decaying in the detector
(already disfavored)



Small masses of X are strongly disfavored

Angular distributions for semi-visibly decaying particles

$X \rightarrow X' + Y_{sh}$

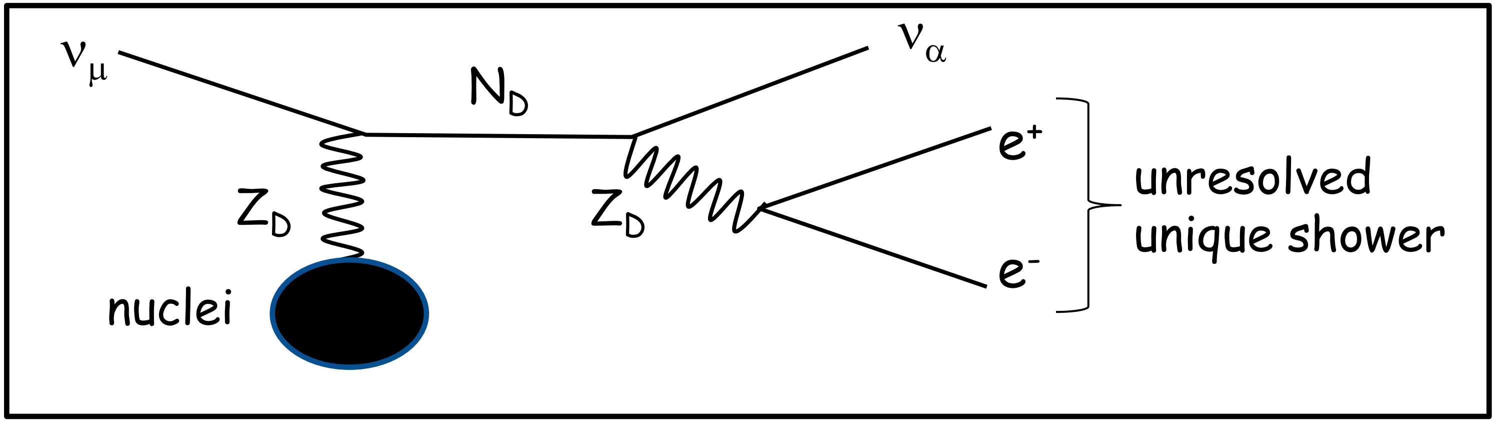
for different masses of X (m X' = 0).

The observed angular distribution of the *excess* - red crosses.

$\chi 2$ values - statistical errors only) .

MiniBooNE: up-scattering in the detector

Two possibilities which use
- dark gauge boson Z_D with kinetic mixing to Z and γ
- dark (sterile) neutrino N_D with mixing to active neutrinos



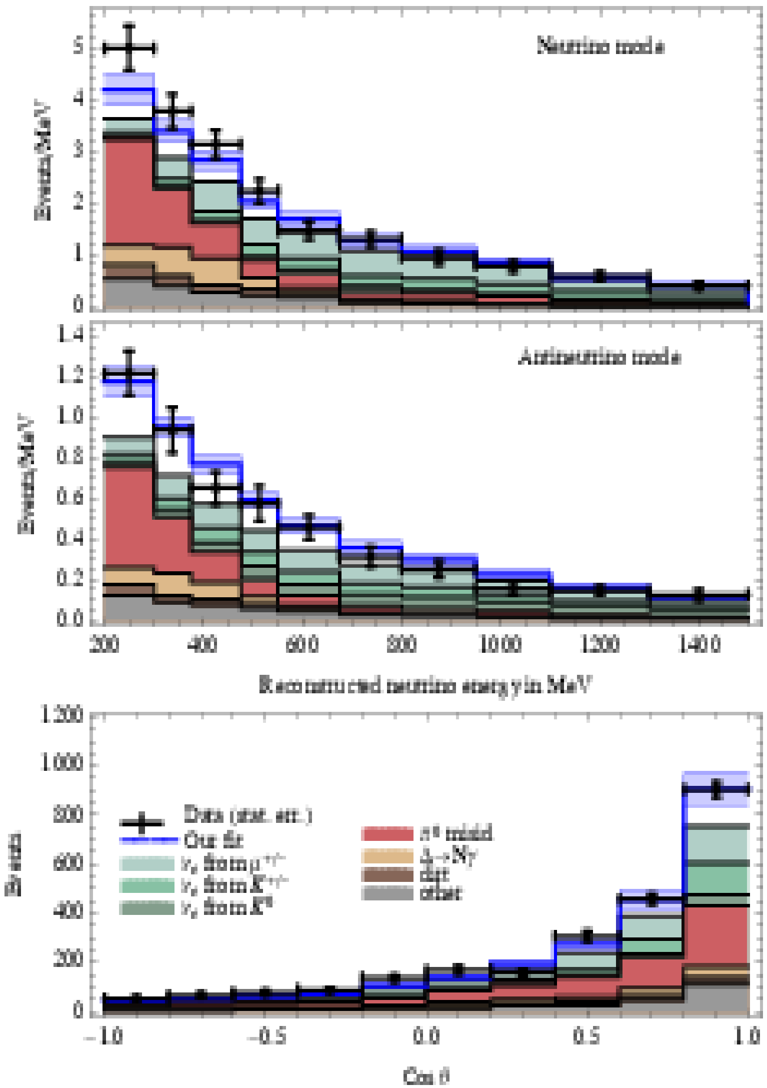
Two realizations

$m_N > m_Z$	$m_Z > m_N$
on shell decay $Z_D \rightarrow e^+ e^-$	on shell decay $N_D \rightarrow \nu_\alpha e^+ e^-$
m_N = 420 MeV, m_Z =30 MeV	m_N = 140 MeV, m_Z = 1.25 GeV
E. Bertuzzo, et al. PRL 121 (2018), 24, 241801, 1807.09877 [hep-ph]	*P. Ballett, et al. PR D99 (2019) 071701 1808.02915 [hep-ph]*

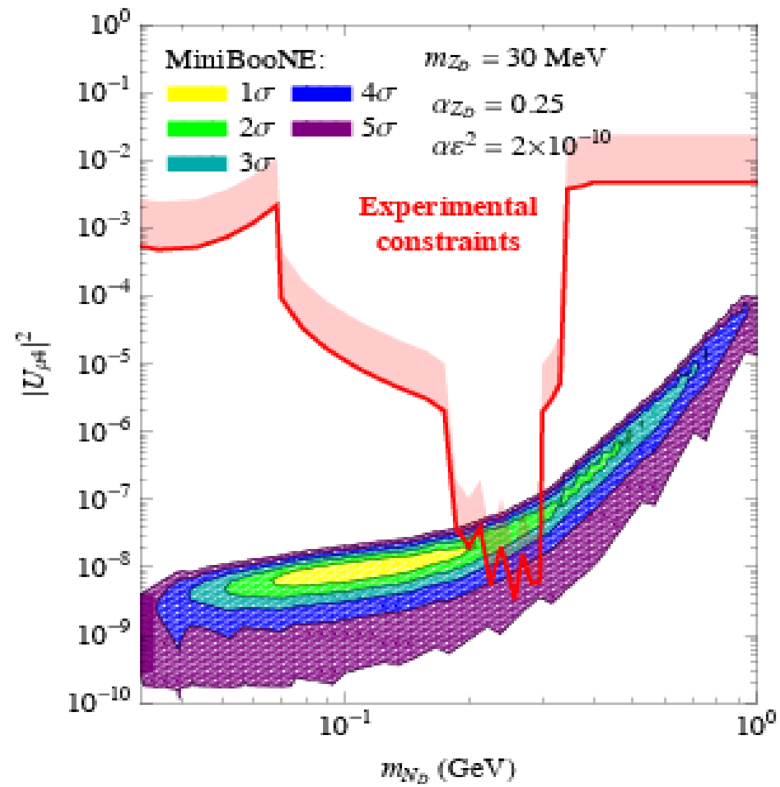
do not explain LSND

Dark photon decay

E. Bertuzzo, et al. Phys.Rev.Lett. 121 (2018) no.24, 241801 1807.09877 [hep-ph]



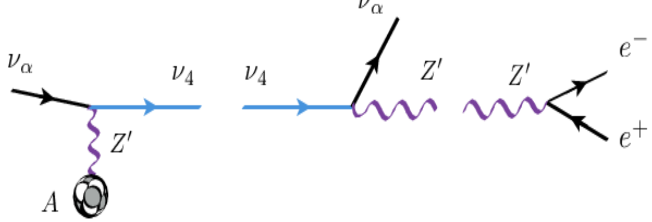
Data points - only statistical uncertainties, the systematic uncertainties of background are encoded in the light blue band.
The predictions of benchmark point (blue line) α_D=0.25 $|U_{\mu 4}|^2$= 9 10^{-7}

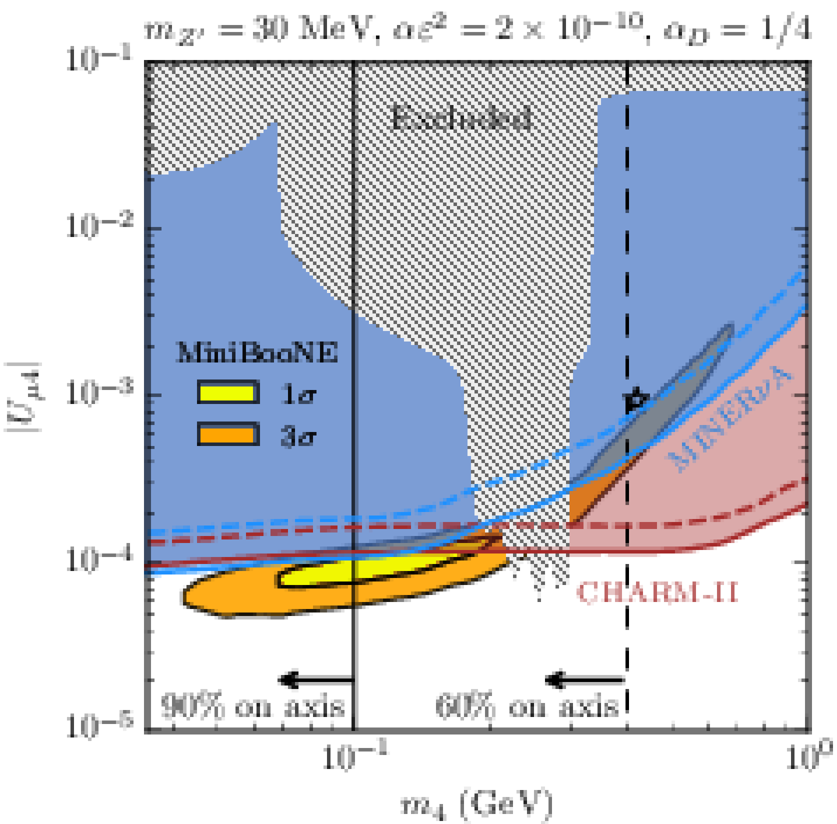


Constraints on dark photon decay

C. Argüelles, et al.
1812.08768 [hep-ph]

from scattering experiments





The benchmark point (black star) provides good angular distribution fit. Exclusion from heavy neutrino searches is shown as a hatched background.

New constraints at 90% C.L. using Minerva - blue for nominal 30% background normalization uncertainty (solid) and conservative case of 100% background uncertainty (dashed).

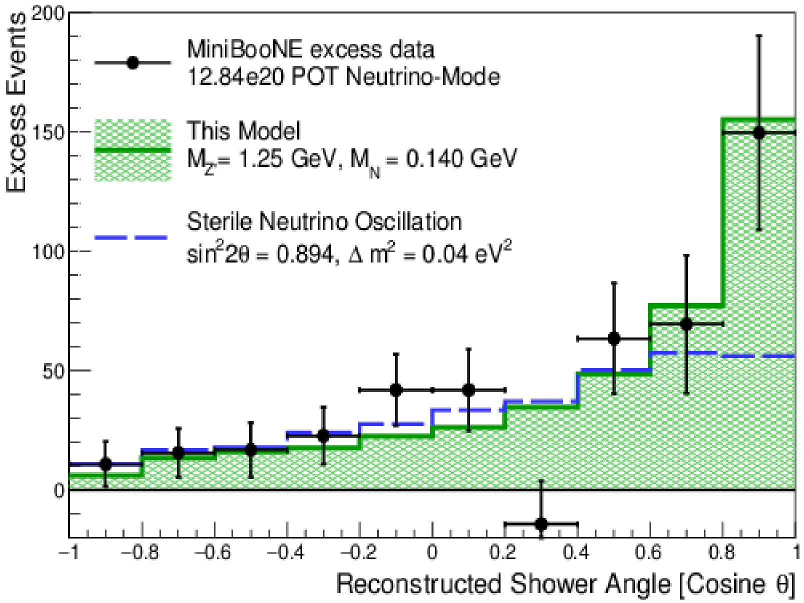
CHARM-II bound - red-cherry,
the 3% background normalization from the sideband is shown as a solid curve and the conservative 10% case as a dashed curve.

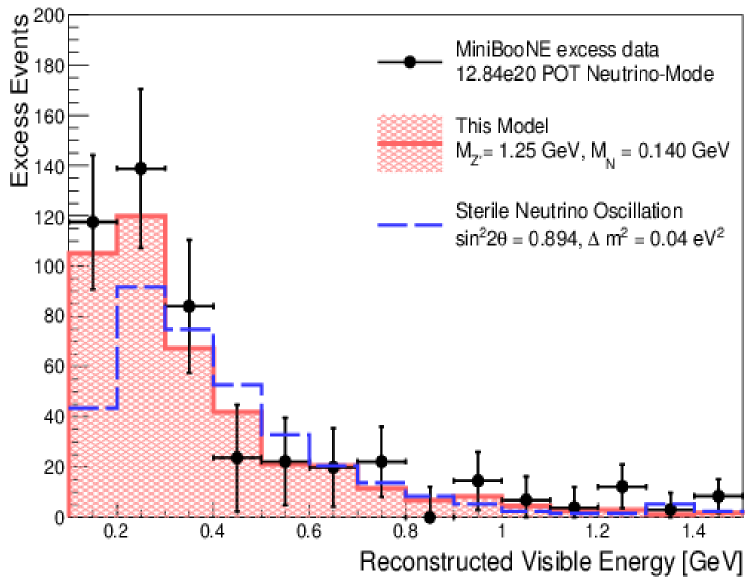
The solid vertical black line at 100 MeV signals the point where 90% of NP events lie in the most forward bin in the MB angular distribution, and the dashed one where 60% of events do so.

CHARM and Minerva exclude region of good angular fit

Heavy sterile decay

P. Ballett, et al. Phys.Rev. D99 (2019) 071701, 1808.02915 [hep-ph]





Reconstructed visible energy (left) and reconstructed shower angle relative to the beam-line (right), for 0.14 GeV sterile neutrino and 1.25 GeV *Z*.

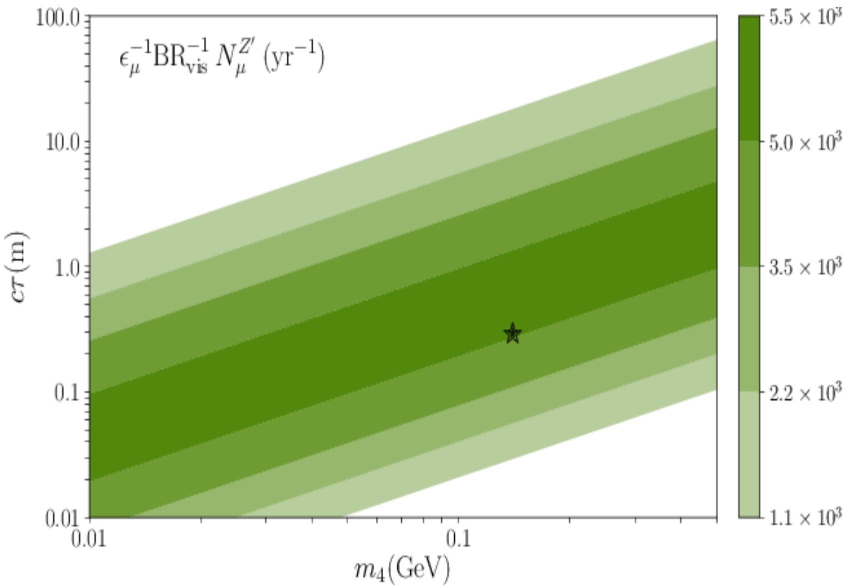
In minimal version: $|U_{\mu 4}|^2 = 1.5\ 10^{-6}$, $|U_{\tau 4}|^2 = 7.8\ 10^{-4}$, kinetic mixing parameter $\chi^2 = 5 \times 10^{-6}$, a total N_D decay length ~ 1 m.

Bounds on heavy neutrino decay explanations

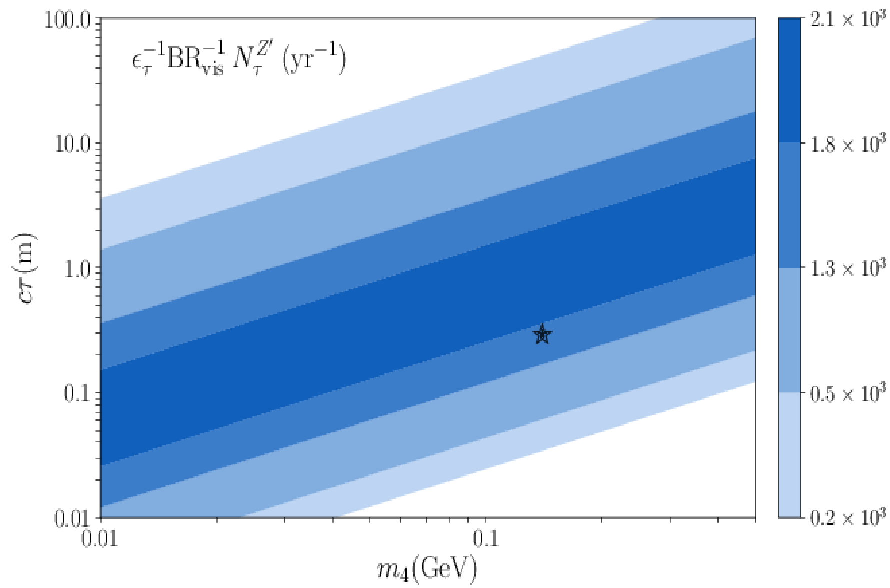
P. Coloma, 1906.02106 [hep-ph]

Double bang events are expected in N_D decay scenario

ν_τ up-scattering



ν_μ up-scattering



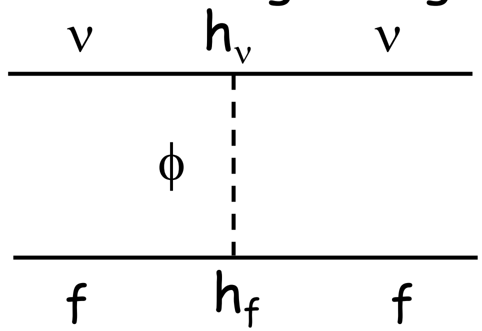
Expected number of DB events per year at Icecube/DeepCore

Black star - representative point of Ballett et al: m_4 = 140 MeV and $c\tau$ ~0.3 m. The benchmark values required by the MiniBooNE excess imply ϵ_τ~0.5 and ϵ_μ~ 10^{-3} assuming $\langle Q^2\rangle$~4 GeV^2.

Refraction due to long range forces

Light dark sector scalars, vectors ...

Scattering via light mediators exchange:



$$A \sim \frac{h_\nu h_f}{q^2 - m_\phi^2}$$

With decrease of m_ϕ and the same decrease of h

refraction $(q^2 = 0) \sim h_\nu h_f / m_\phi^2$ does not change

inelastic scattering is suppressed as $h_\nu h_f / q^2$

Refraction effects dominate at small m_ϕ

Potential $$V = \frac{h_\nu h_f}{m_\phi^2} n_f$$

number density of scatterers

Interactions with fuzzy dark matter

A. Berlin,
B. 1608.01307 [hep-ph]

Ultra-light scalar DM, huge density ρ – as a classical field, solution

$$\phi(t, x) \sim \frac{\sqrt{2\rho(x)}}{m_\phi} \cos(m_\phi t)$$

Coupling to neutrinos $g_\phi \phi \nu_i \nu_j + \ldots$

gives contribution to neutrino mass and modifies mixing

Mass states oscillate

$\delta m(t) = g_\phi \phi(t)$ $\Delta\theta_m(t) = g_\phi \phi(t) / \Delta m_{ij}$

Neutrinos propagating in this field will experience time variations of mixing in time with frequency given by m_ϕ

Period ~ month, bounds from solar neutrinos, lab. experiments

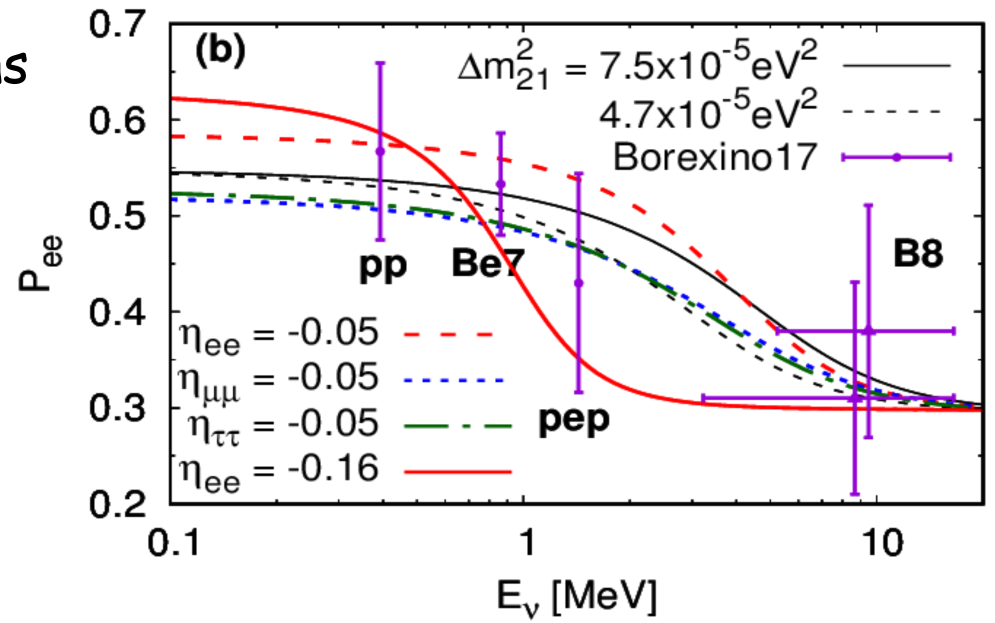
Observable new effects (and not just renormalization of SM Yukawa and VEV) if the field has

- spatial dependence
- different sign for neutrinos and antineutrinos

Refraction due to very light scalar mediator

Shao-Feng Ge, S. Parke,1812.08376 [hep-ph]

Neutrino scattering on electrons via very light scalar exchange



The solar neutrino conversion probabilities with scalar NSIs vs. Borexino results.

To satisfy bounds on h_ν h_e (especially from searches of 5th force:

$$1/m_\phi \gg R_{Earth}$$

→ strong suppression of the potential $V = V_0\, m_\phi R_{Earth}$

To avoid bounds – cancellations in 5th force experiments – not shown if this is possible

Towards underlying theory

A. Yu. S., Xun-Jie Xu
Phys.Rev. D97 (2018) no.9, 095030
[arXiv:1803.07933 [hep-ph]]

V. Brdar, A. Yu S.
arXiv:1809.09115 [hep-ph]

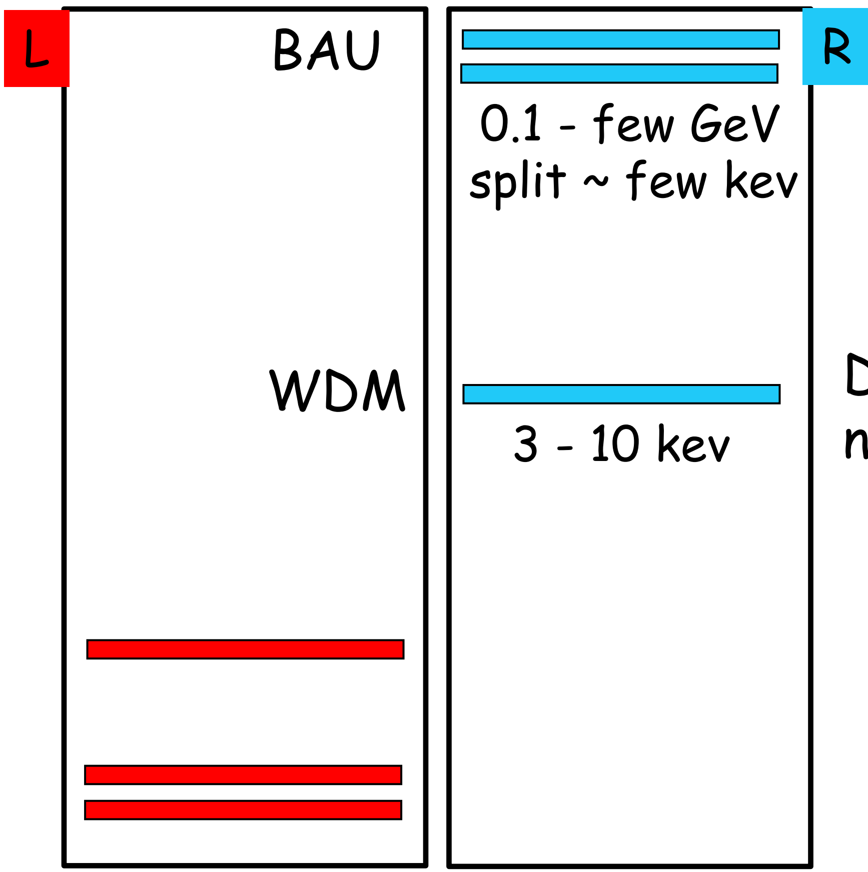
νMSM or no νMSM

nuMSM with UV completion
at the string-Planck scale

Flavor physics, unification, etc.

New physics (particles)
below Planck scale

Flavor physics, scales
in terms of QFT



Decouples from generation of
neutrino mass, RHN?

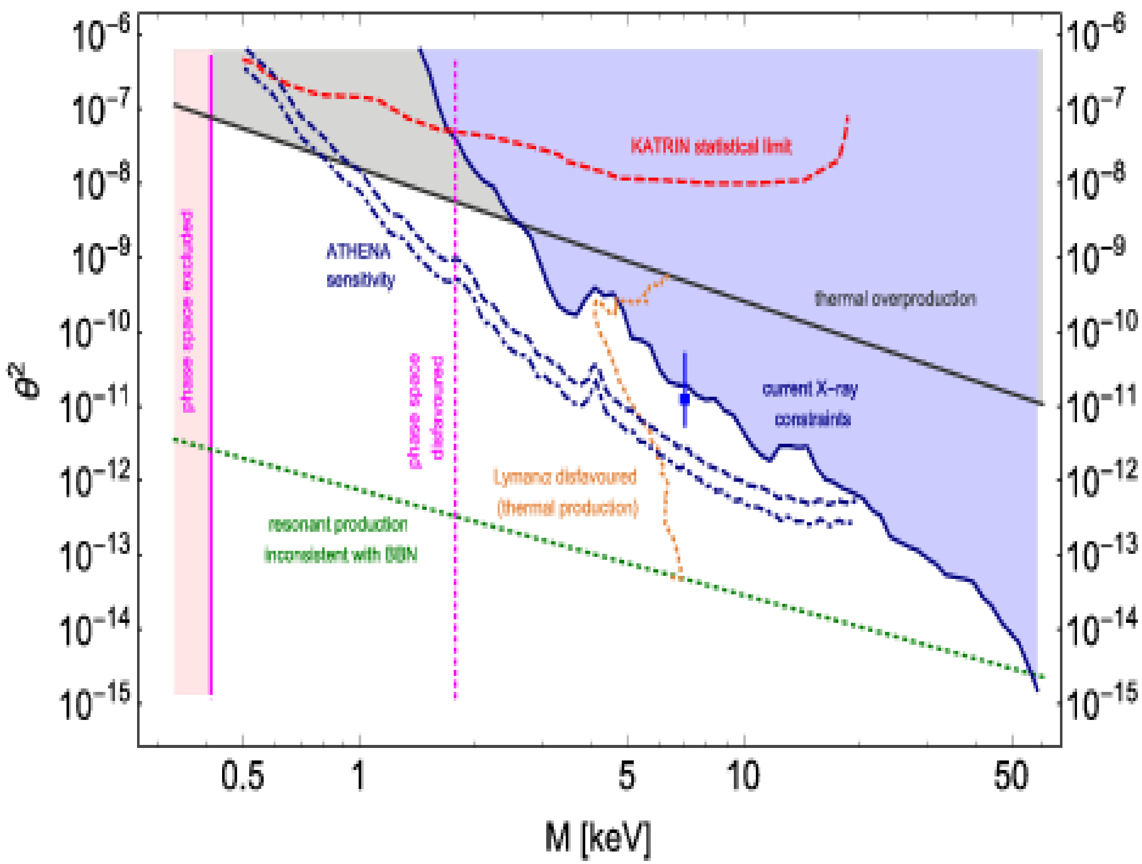
- small neutrino mass
- lepton asymmetry via oscillations
- can be produced in B-decays (BR ~ 10^{-10}) etc., SHiP

- radiative decays → 3.5 keV line?

keV sterile neutrino dark matter

Boyarsky, A. et al.
Prog.Part.Nucl.Phys. 104 (2019) 1,
1807.07938 [hep-ph]

Constraints on sterile neutrino DM parameters



Violet ares - bounds from non-observation of X-rays from the decay $N \to \nu\gamma$ (decay through mixing with the active neutrinos)

overclosure bound

resonance thermal production

lower bound on the mass of r (yelow) is based on the BOSS Lyman-α forest data (structure formation)

Below green dotted the lepton asymmetries required for this mechanism to work are ruled out because they would affect BBN.

A case of non νMSM

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

The data are in a good agreement with

S. Petcov, AYS, 1993

$$U_{PMNS} \sim U_l^{+} U_X$$

$U_l \sim V_{CKM}$ — Quark mixing matrix

Γ_α — diagonal phase matrix

$U_X = U_{BM}\, ,\, U_{TBM}$

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

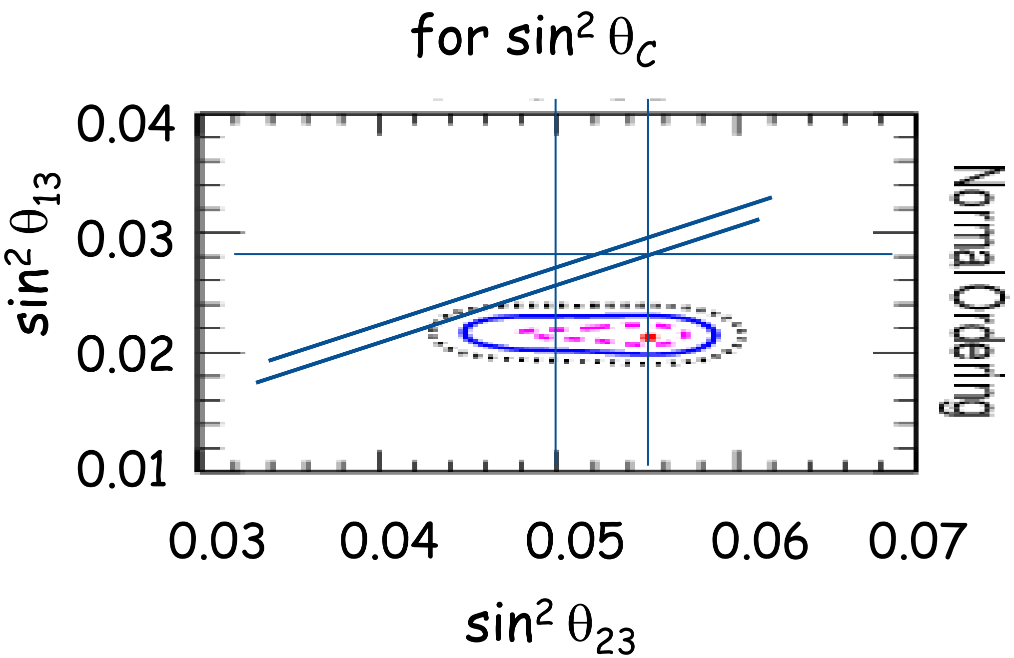
$$\sin^2\theta_{13} \sim \tfrac{1}{2}\sin^2\theta_C$$

In general,

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

Experimental status

From global fit *F. Capozzi, et al. Prog.Part.Nucl.Phys. 102 (2018) 48, arXiv:1804.09678 [hep-ph]*



~ 20% deviation in $\sin^2\theta_{13}$

can be due to deviation of $\theta_{12}{}^l$ from θ_C

Renormalization (RGE) effects from GUT scales to low energies

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

lines: predictions from QLC

Interpretation: two sectors involved:

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

Common sector for quarks and leptons. Implies

$m_l \sim m_d$ $m^D_\nu \sim m_u$

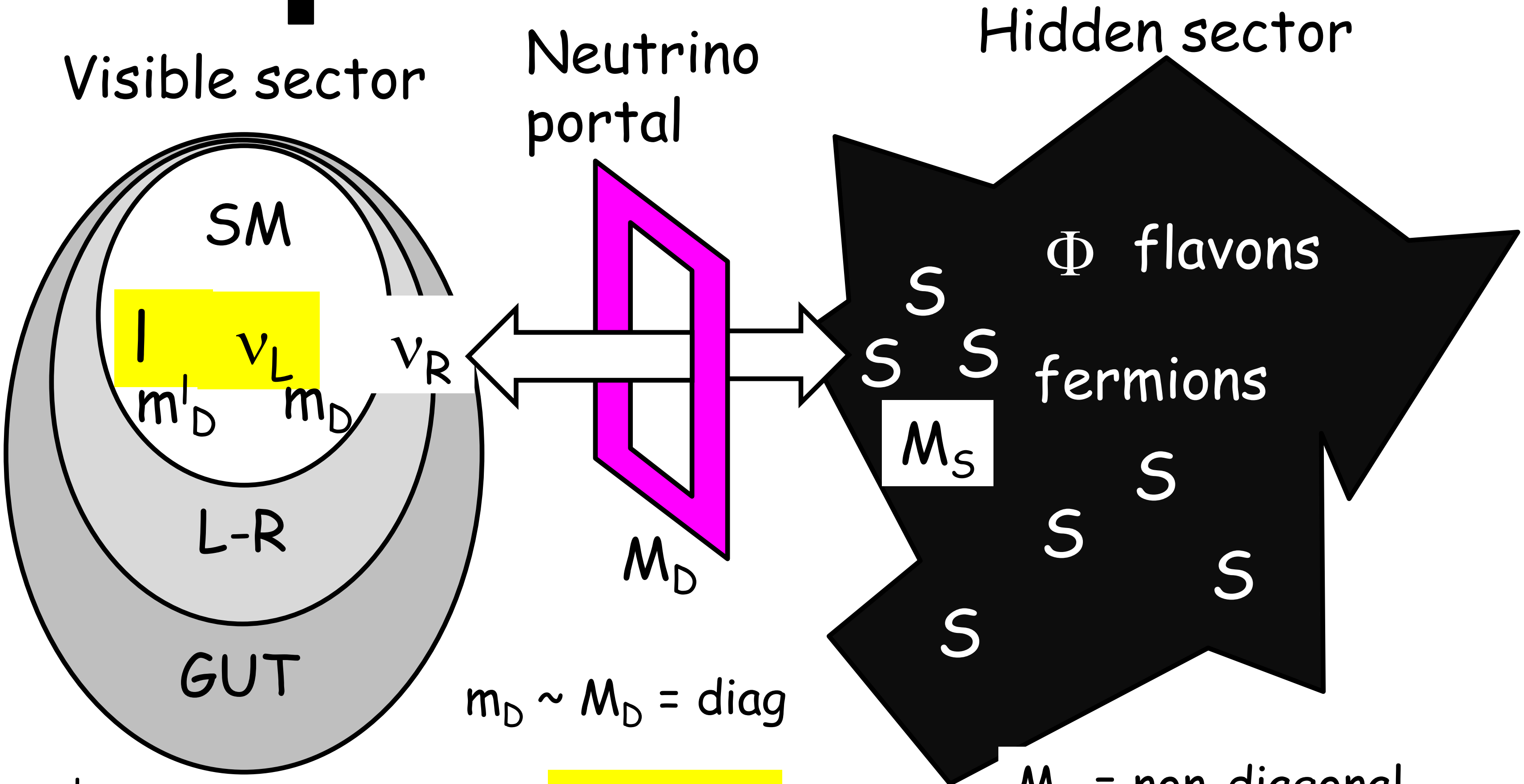
Q - L unification, GUT

CKM physics, hierarchy, of masses and mixings Froggatt-Nielsen (?), relations between masses and mixing

New sector related to neutrinos, responsible for large neutrino mixing smallness of neutrino mass

May have special symmetries which lead to BM or TBM mixing

Set-up



$m_D \sim M_D$ = diag

M_S = non-diagonal

m^l_D

$U_l \sim V_{CKM}$

$m_\nu \sim M_S$

origin of U_X

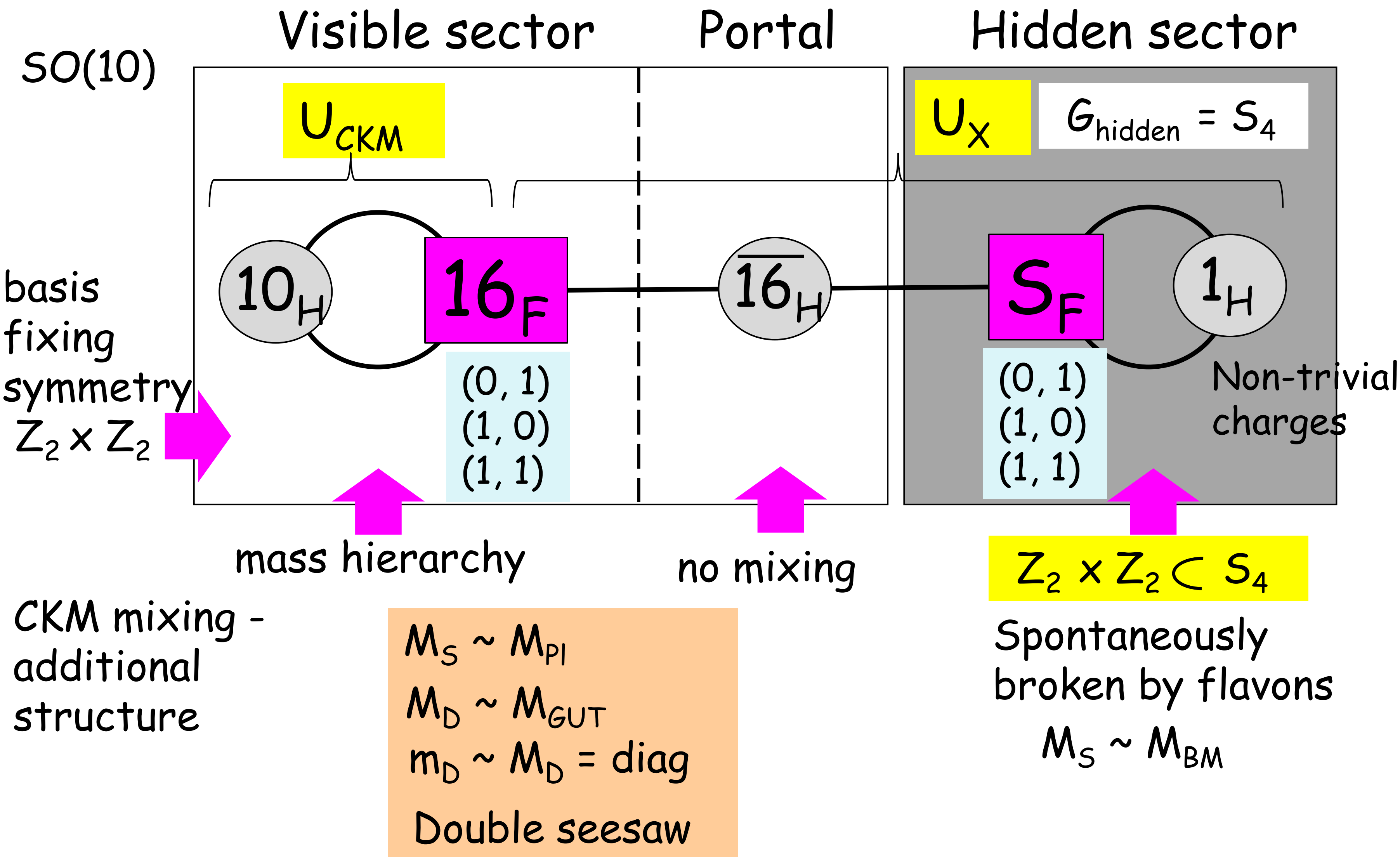
$G_{basis} = Z_2 \times Z_2$

scale M_S ⇄ M_{Pl}

μ = keV - MeV

A GUT scheme with $G_{hidden} = S_4$

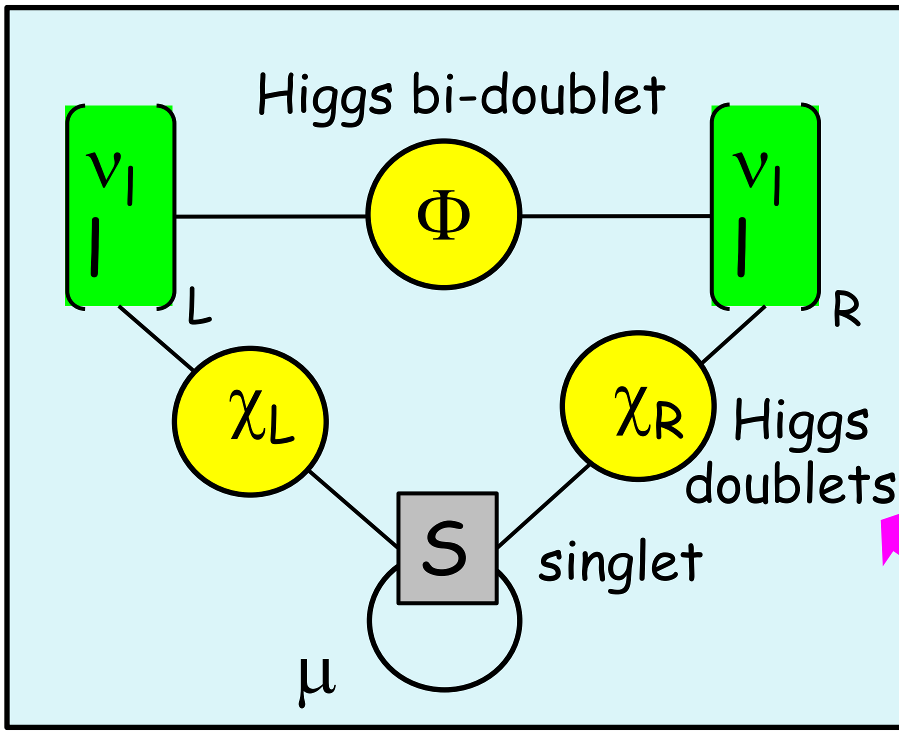
and BM mixing



Low scale Left-right symmetric model

$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \quad \times P$

with q-l similarity $m_q \sim m_l \sim m^D_\nu$ – inverse seesaw



with Majorana mass terms

Fields	L_L	L_R	χ_L	χ_R	S
B – L	-1	-1	1	1	0

$M_D \sim M_R \sim$ PeV

$\mu \sim$ 10 keV

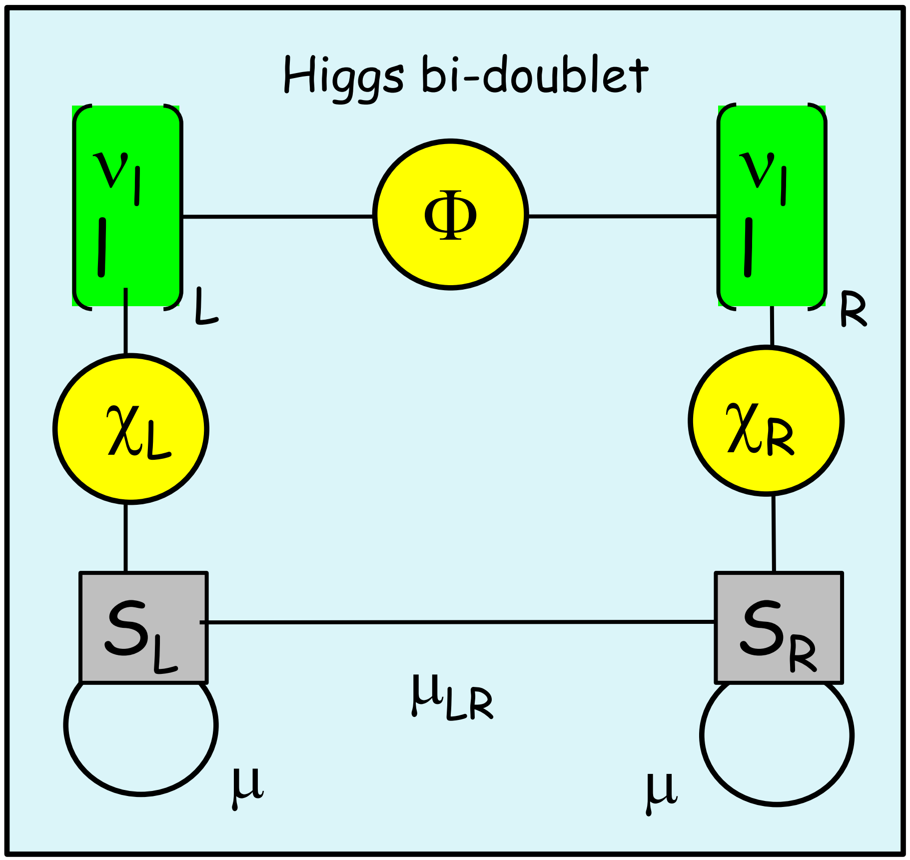
inverse seesaw

flavor symmetry in μ

breaks
L-R symmetry

Model with "left and right" singlets

$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \quad \times P$



invariant under global U(1)

Fields	L_L	L_R	S_L	S_R
L	1	1	- 1	- 1

broken by μ-terms

keV scale sterile neutrino
- DM

Conclusion

3ν - paradigm works well, no significant and well established deviations have been found

Situation with unknowns is rather uncertain: various preferences are at 2-3 σ level and in some cases controversial, hints fragile

The case of eV sterile neutrinos is very weak

Oscillation explanation – strongly disfavored

Non-oscillatory explanations – strongly restricted

Theory of neutrino mass and mixing: nothing is really established and we are not far from the beginning

Neutrino properties from dark sector?

Backup

3ν - paradigm works well, no significant and well established deviations have been found

Situation with unknowns is rather uncertain: various preferences are at 2-3 σ level and in some cases controversial, hints fragile

Normal mass ordering is preferred over inverted at ~ 3σ level (global fit) NOvA, T2K, SK atmospheric

Maximal CP violation is less favored: $\delta_{CP} = \pi$ is possible, NOvA best fit at $\delta_{CP} = 0$, T2K evidence is result of tensions

$\theta_{23} > \pi/4$ is preferred from global fit, but e.g. the best fit of SK atmospheric is at $\theta_{23} < \pi/4$

The case of eV sterile neutrinos is weaker.

Gallium anomaly is weaker. RAA is largely excluded by DANSS and NEOS. In turn, the latter show new anomaly - oscillatory behavior with smaller mixing.

MiniBooNE – non-oscillatory explanations, which strongly restricted by various data and can not reproduce LSND simultaneously.

New developments neutrino interactions with light dark sector (partially motivated by MiniBooNE) , new bounds.

New refraction effects due to neutrino interaction with dark sector

Theory of neutrino mass and mixing: nothing is really established and we are not far from the beginning

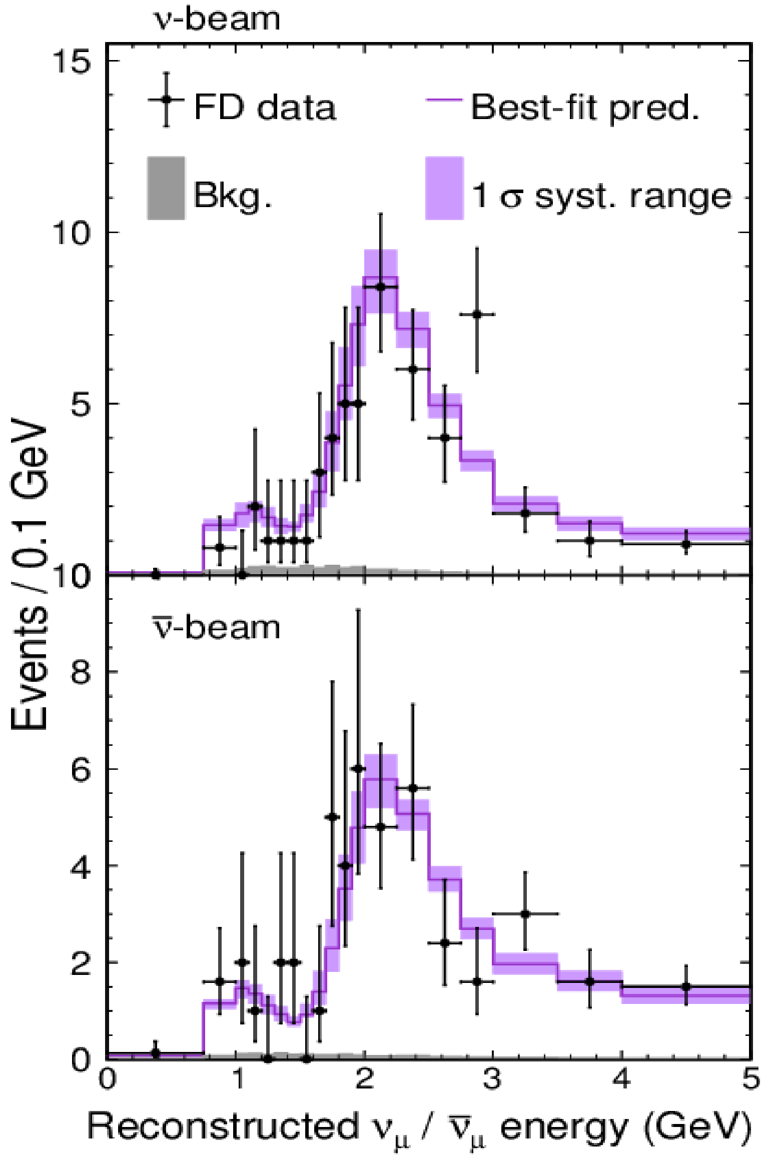
Possibilities range from minimalistic νMSM to very complicated models with sophisticated structure, broken flavor symmetry, etc.

νMSM with Planck/string UV or we still be able to understand features within QFT ?

Neutrino properties from dark sector?

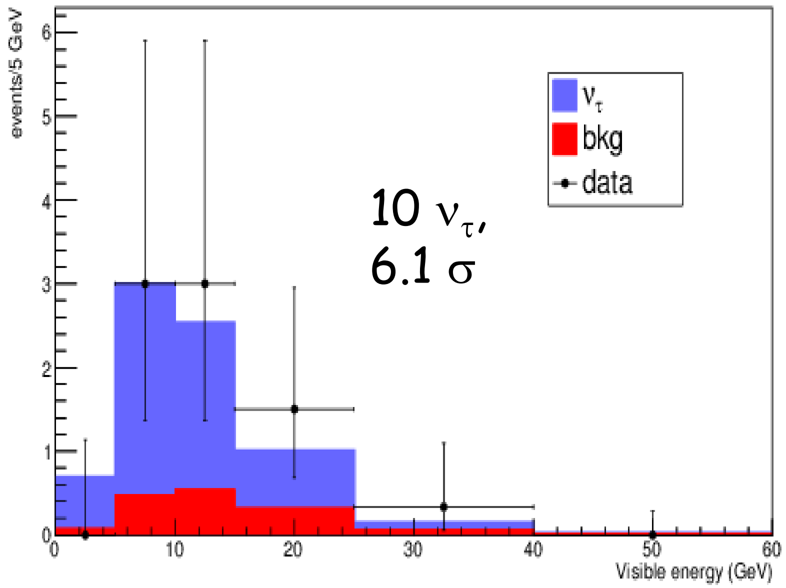
NOvA results

the reconstructed neutrino
energy spectr\numu~CC, FD



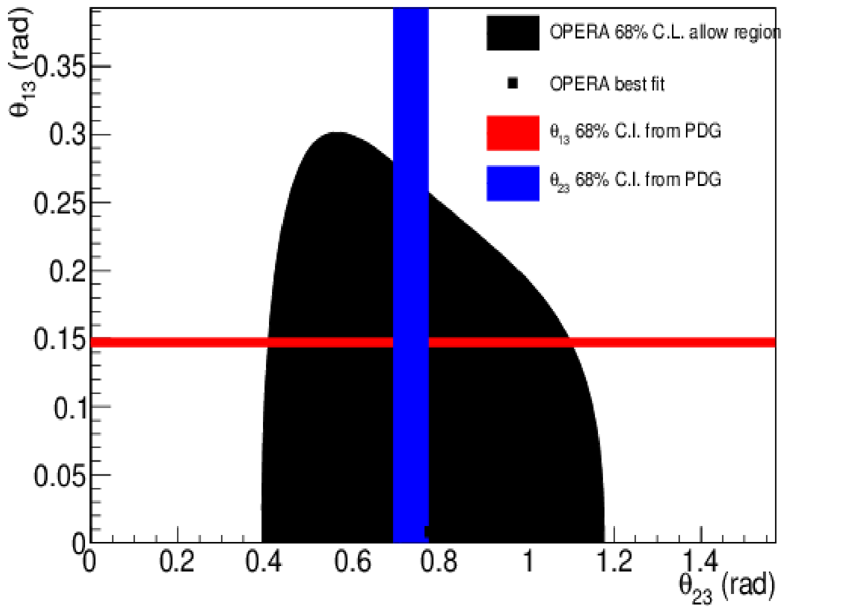
OPERA: final results

Agafonova, N. et al. SciPost Phys.Proc. 1 (2019) 028, 1811.00095 [hep-ex]



Stacked plot of visible energy: data are compared with the expectation. Monte Carlo simulation is normalised to the expected number of events

N. Agafonova , et al. 1904.05686 [hep-ex]



OPERA 68% C.L. allowed region in the θ13 and θ23 plane for NO. Red and blue areas - 1σ confidence interval from the global best fit

Coherent neutrino-nucleus scattering at reactors

xxx

CONUS

Hakenmüller, J. et al.
1903.09269 [physics.ins-det]

Neutron background study

High-purity Germanium (Ge) detectors . The commercial nuclear power plant in Brokdorf, Germany. Very small distance to the reactor core, high flux > 10^{13} $\bar{\nu}$ /(s·cm^2).

1σ Excess of the reactor on/off efents

CONNIE

Aguilar-Arevalo, Alexis et al.
1906.02200 [physics.ins-det]

Active mass of 73.2 g (12 CCDs), silicon nuclei 30 m from the core of the Angra 2 nuclear reactor, with a thermal power of 3.8 GW, reactor on (2.1 kg-day) and reactor off (1.6 kg-day).

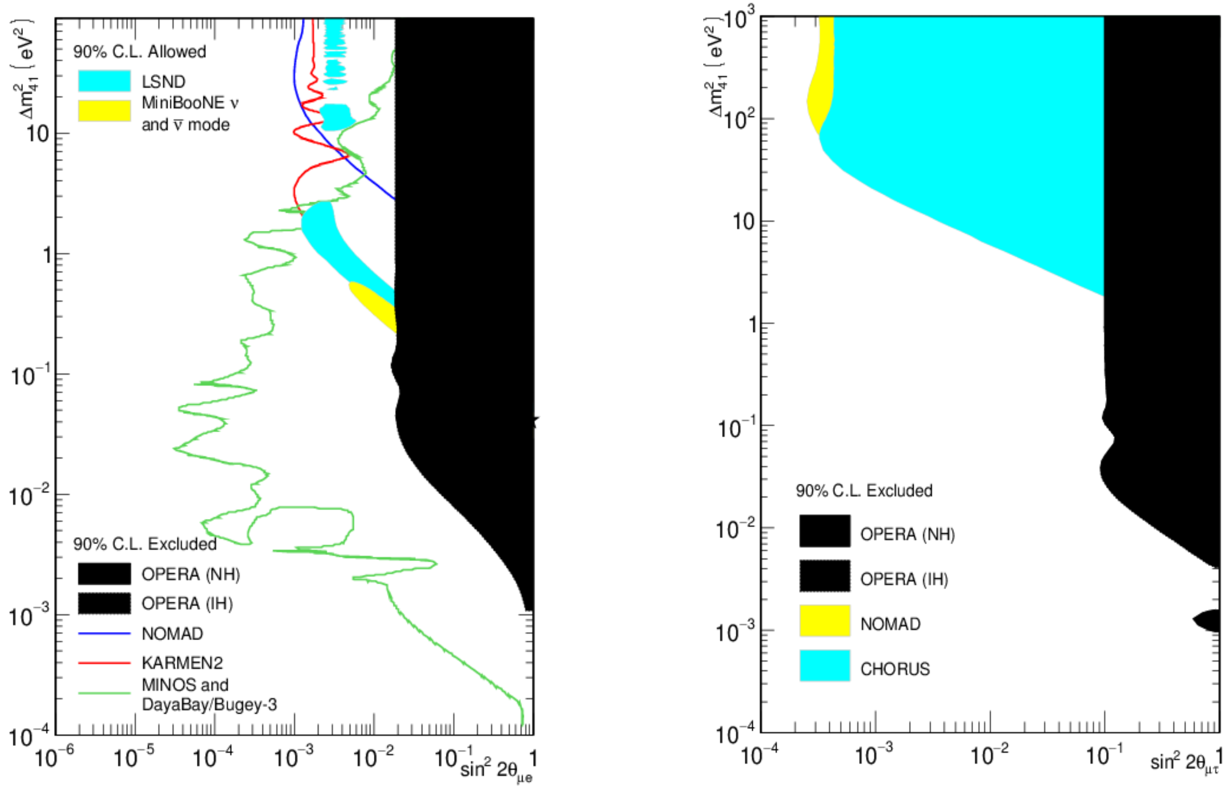
A 95% confidence level limit for new physics is established at an event rate of 40 times the one expected from the standard model at this energy scale.

OPERA: bounds on steriles

OPERA Collaboration
(N. Agafonova , et al.).
1904.05686 [hep-ex]

ν_e - appearance

The 90% C.L. exclusion region in the $\Delta m241$ - sin22$\theta\mu e$ plane (left) and $\Delta m241$ - sin22$\theta\mu\tau$ (right)



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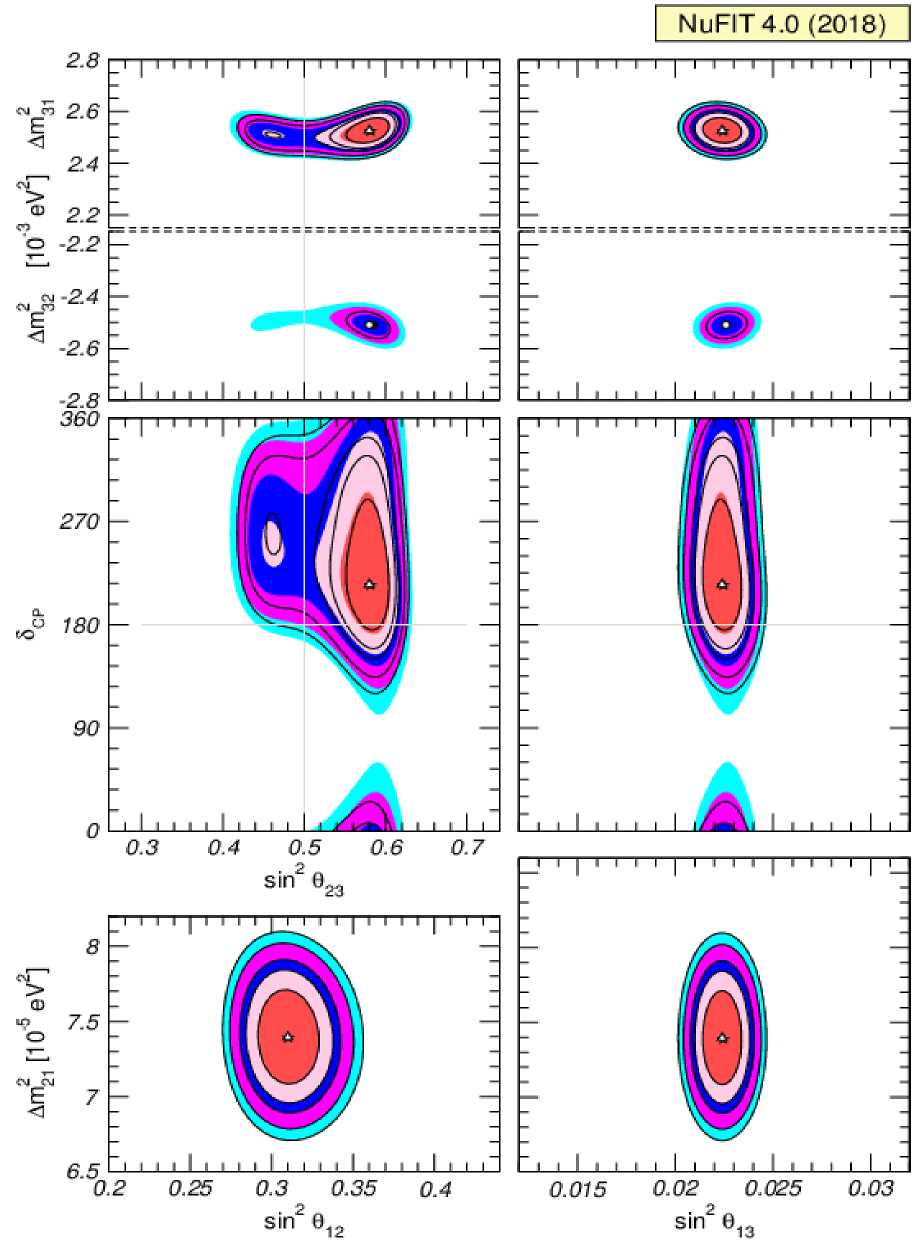
Global 3nu analysis

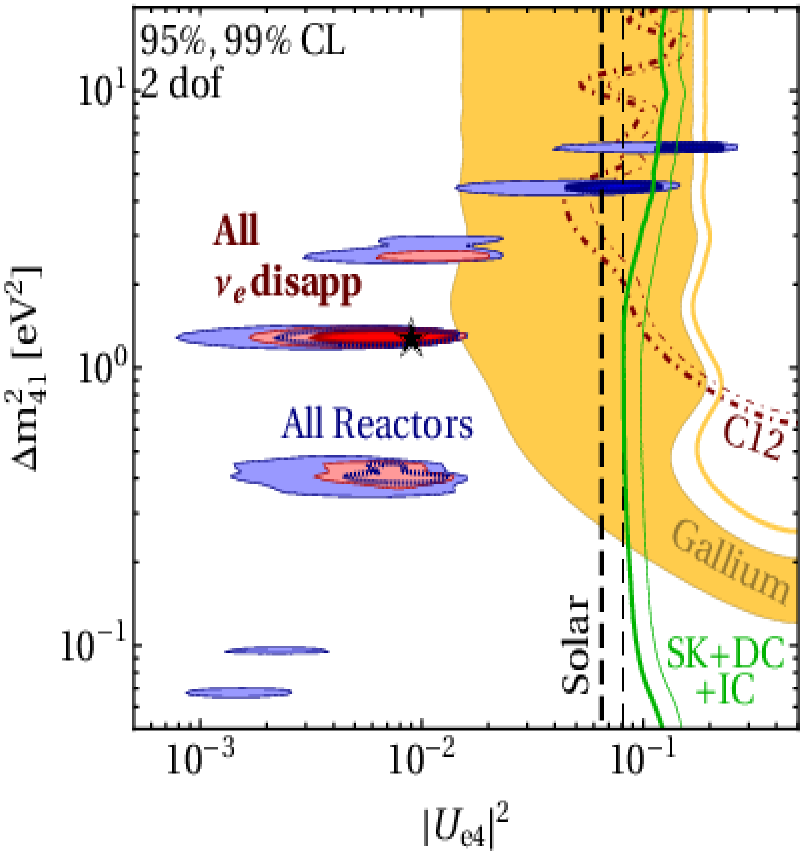
Esteban, Ivan et al. 1811.05487 [hep-ph]

The two-dimensional projection of the allowed six-dimensional region after minimization with respect to the undisplayed parameters.



The regions in the four lower panels are obtained from $\Delta\chi 2$ minimized with respect to the mass ordering. Contours correspond to 1σ, 90%, 2σ, 99%, 3σ CL (2 dof).
Coloured regions (black contour curves) are without (with) adding the tabulated SK-atm $\Delta\chi 2$.

Disappearance bounds



The allowed regions and exclusion curves at 95% (dark shaded regions and thick curves) and 99% (light shaded regions and thin curves) CL.

The blue - allowed by combined fit of all reactor data

Red shaded regions allowed by all nuae disappearance data (the best-fit point - black star).

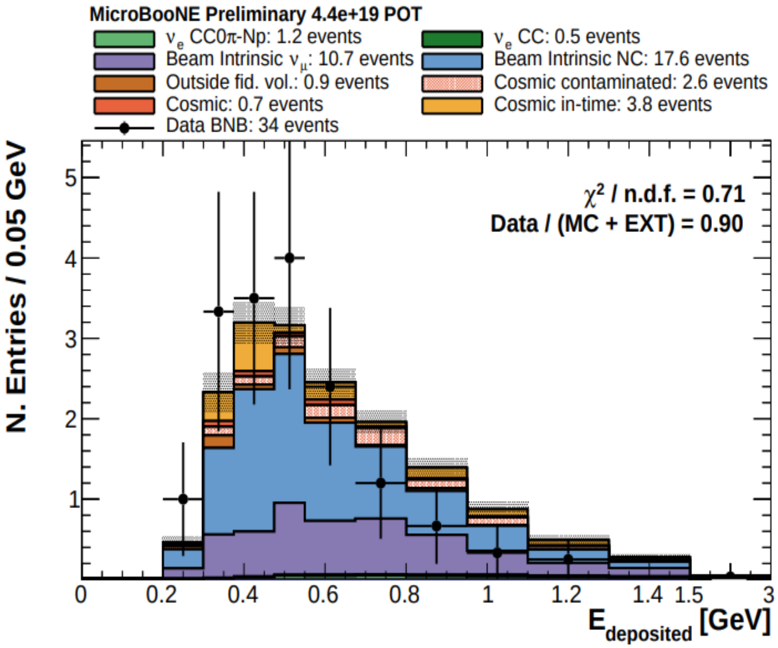
Exclusion curves: solar (black dashed). S-K+DeepCore+IceCube (green solid), the *ve*- 12C scattering (dark red dash-dotted).
Gallium data: the 95% allowed yellow region and the 99% CL yellow exclusion curve.

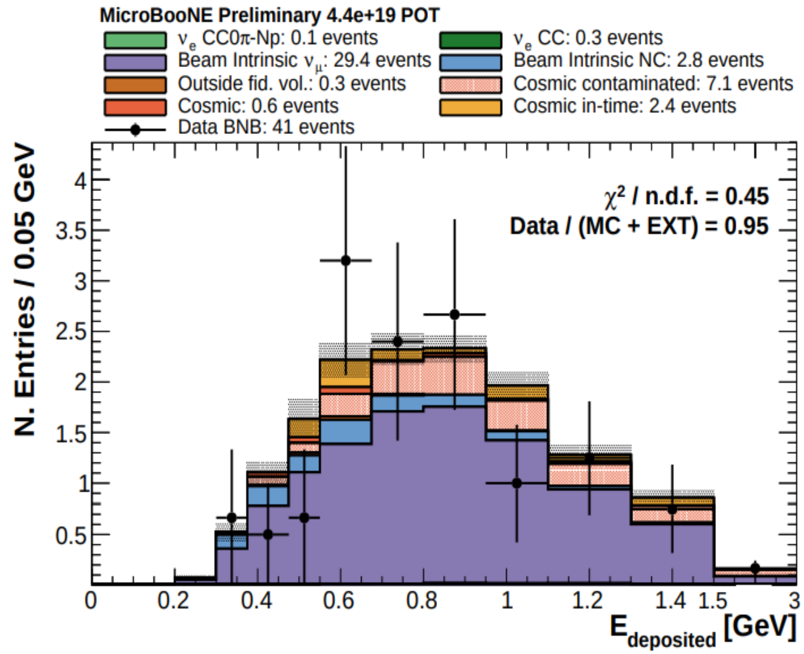
xxx

MicroBooNE

Search for a Low Energy Excess in MicroBooNE - MicroBooNE Collaboration (Foppiani, Nicolò for the collaboration) 1905.05325 [hep-ex]

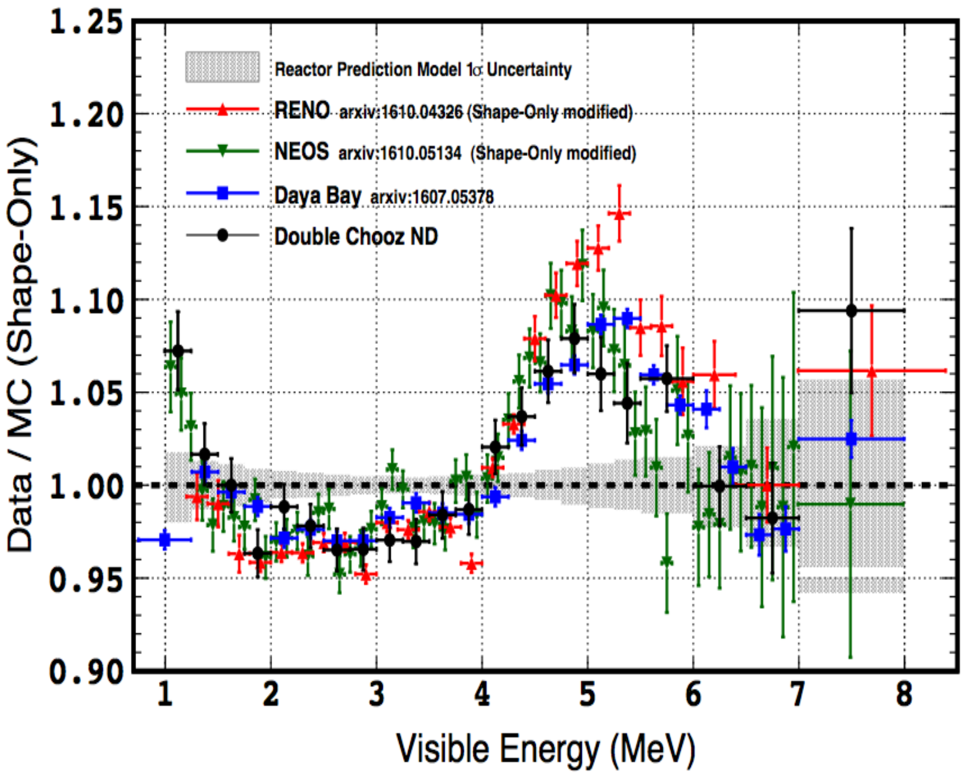
LAr TPC off axis 470 m, 85 t, ~ 10^{21} POT collected
but in this analysis





Distributions of the selected events in the NC π^0 sideband (left) and CC ν_μ sideband (right) of the CCν_e 0π np analysis.

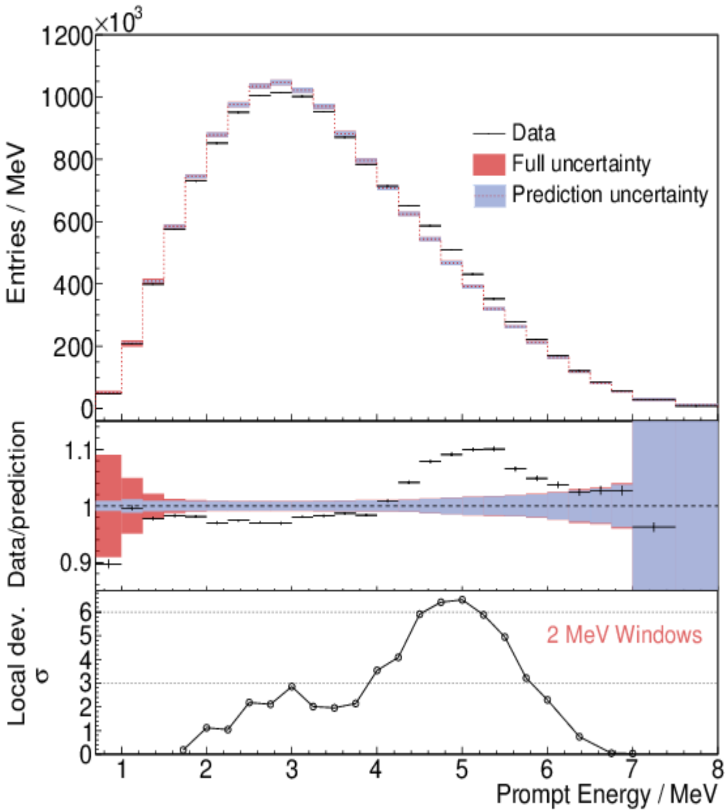
5 MeV bump



The data-to-prediction spectral ratio for several experiments From DoubleChooz:2019qbj}.

5 MeV bump

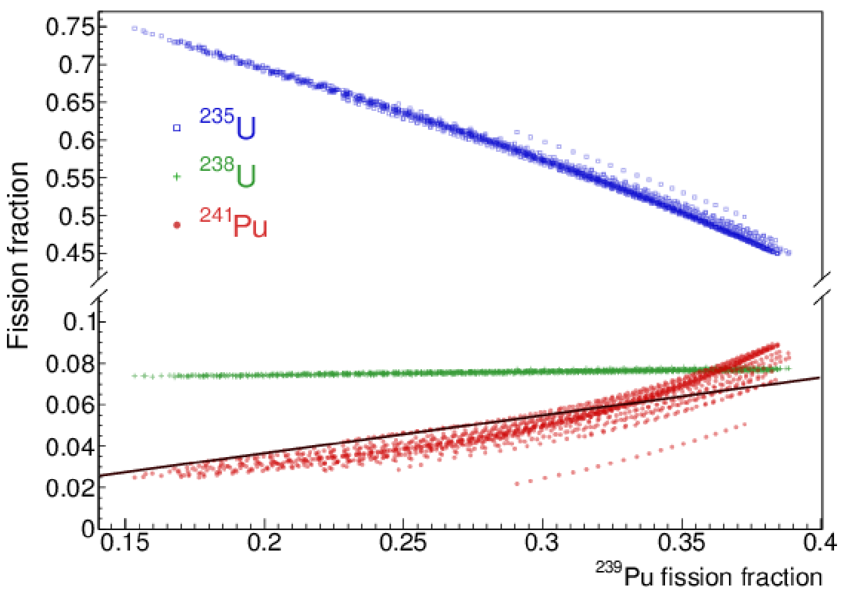
Measurement of Individual Antineutrino Spectra from 235U and 239Pu at Daya Bay - Daya Bay Collaboration (Adey, D. et al.) 1904.07812 [hep-ex]

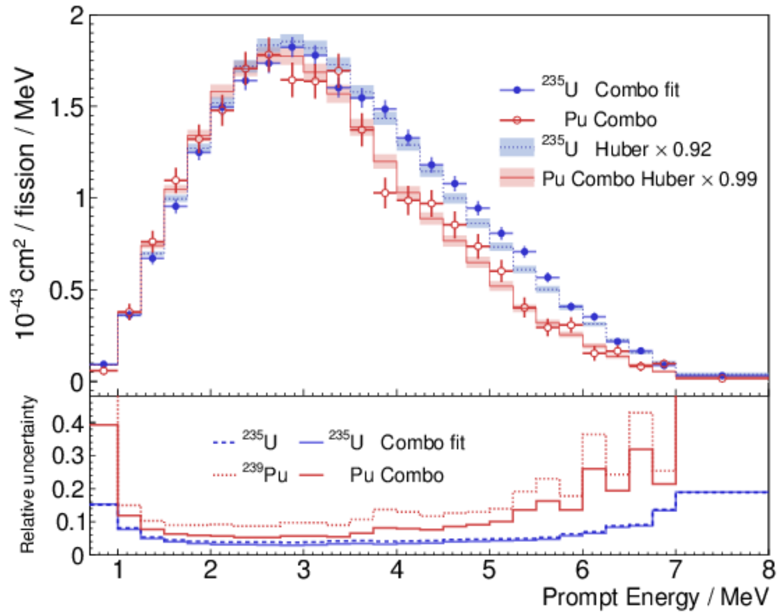


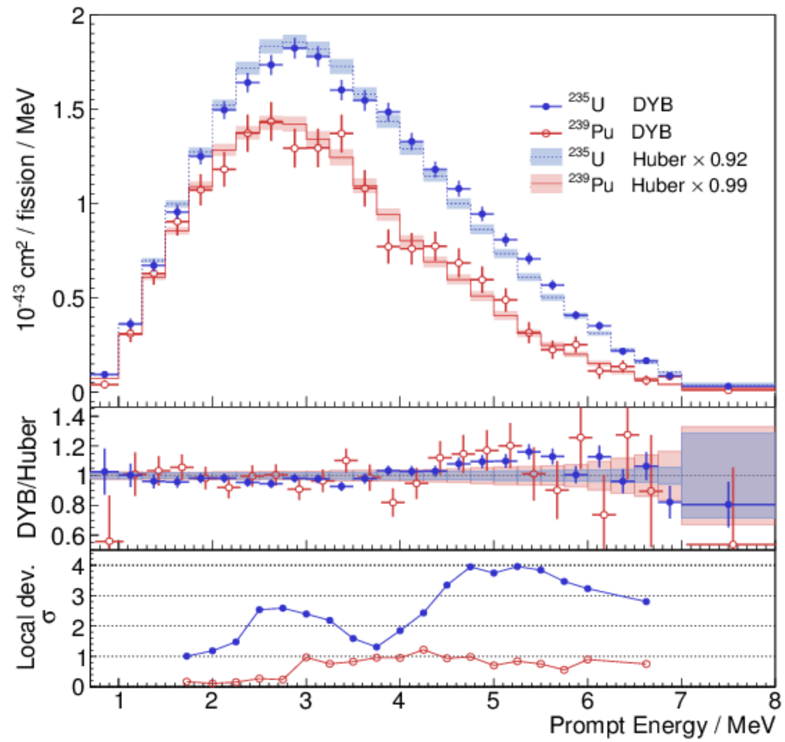
(Top panel) Predicted and measured prompt energy spectra. The prediction is based on the Huber-Mueller model and is normalized to the number of measured events. The blue and red filled bands represent the square-root of diagonal elements of the covariance matrix for the flux prediction and the full systematic uncertainties, respectively. (Middle panel) Ratio of the measured prompt energy spectrum and the normalized predicted spectrum. The error bars on the data points represent the statistical uncertainty. (Bottom panel) The local significance of the shape deviation in a sliding 2-MeV window showing a maximum 6.3σ discrepancy in 4--6~MeV\@.

5 MeV bump

Measurement of Individual Antineutrino Spectra from 235U and 239Pu at Daya Bay Adey, D. et al. 1904.07812 [hep-ex]



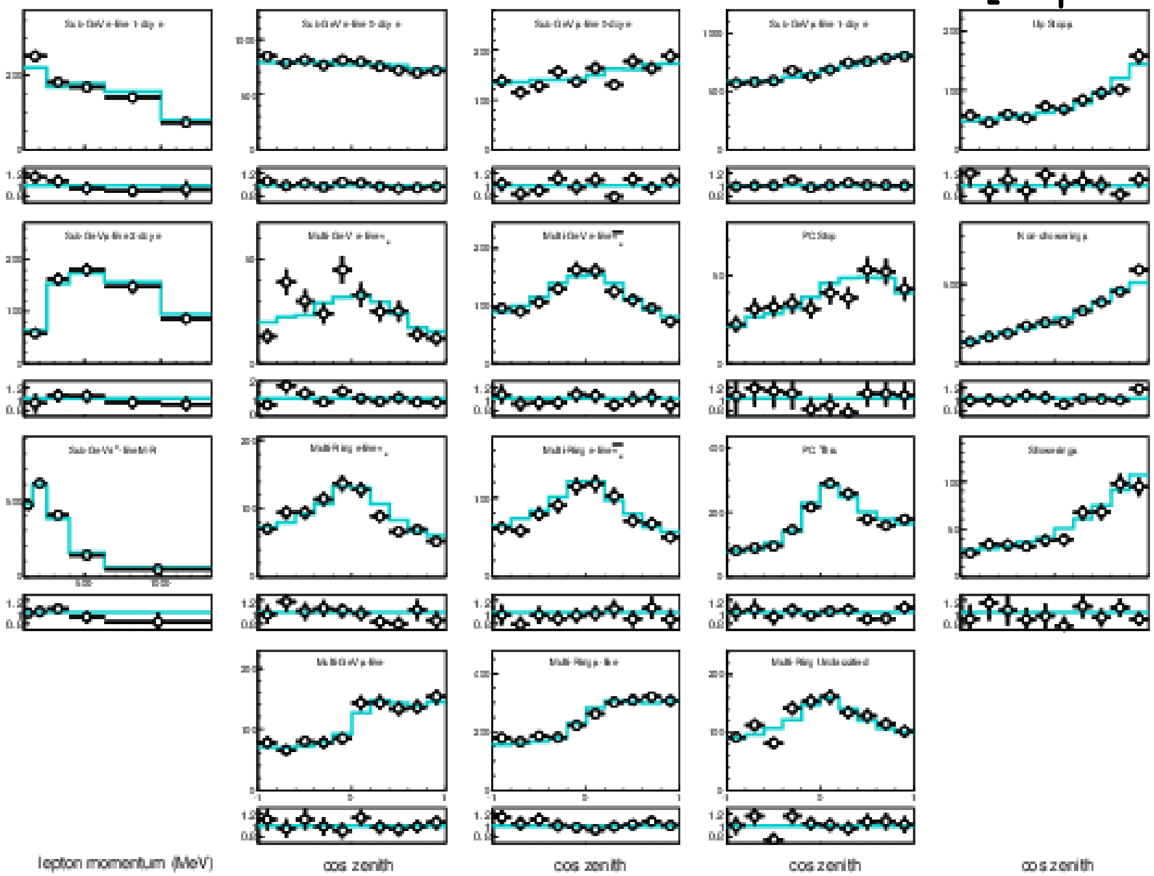




Comparison of the extracted 235U spectrum and *s*combo as a combination of 239Pu and 241Pu with the corresponding Huber-Mueller predicted spectra

Atmospheric neutrinos

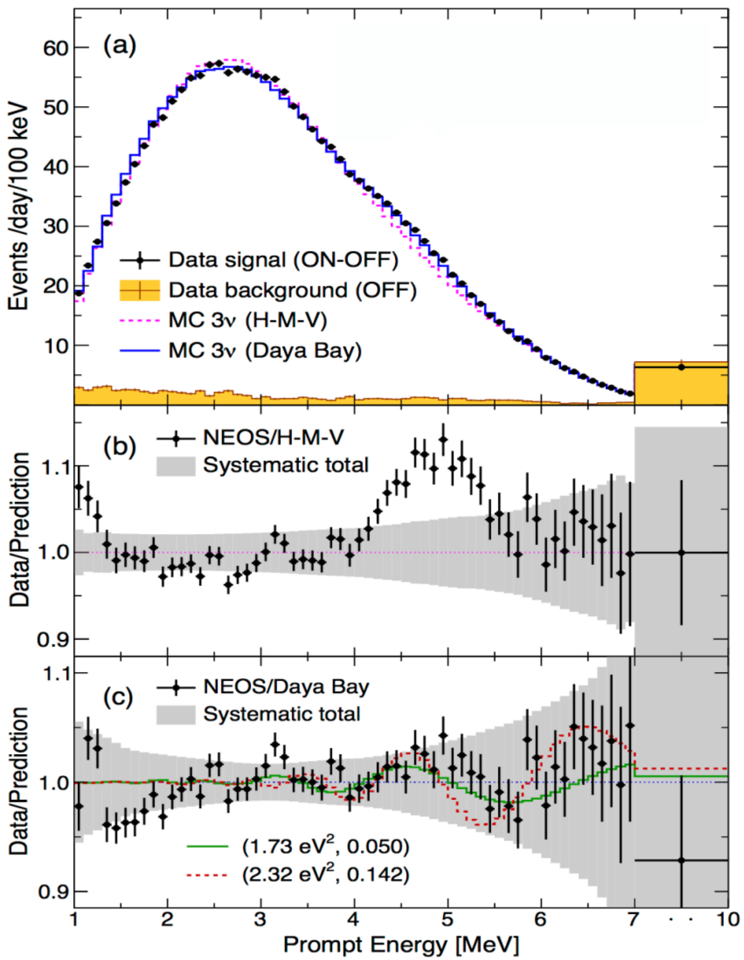
Atmospheric Neutrino Oscillation Analysis With Improved Event Reconstruction in Super-Kamiokande IV - Super-Kamiokande Collaboration (Jiang, M. *et al.*) PTEP 2019 (2019) no.5, 053F01 1901.03230 [hep-ex]



Data and MC comparisons for the SK-IV data divided into 18 analysis samples. The expanded FV, where dwall > 50 cm, is shown here. Cyan lines - the best-fit MC for the normal ordering. Narrow panels - the ratio relative to the normal hierarchy MC. The error bars the statistical uncertainty.

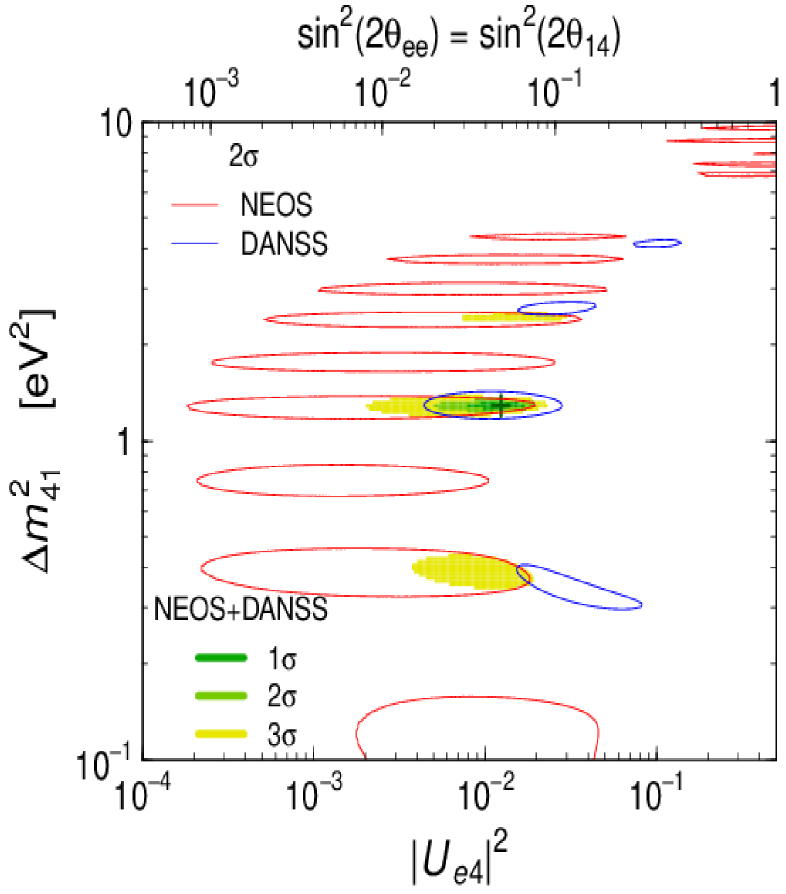
New anomaly: NEOS results

(a) The NEOS IBD prompt energy spectrum and comparison to Daya Bay.
(b) Ratio of the NEOS spectrum to the Huber/Mueller flux prediction assuming no sterile neutrinos. The predicted spectrum is normalized to the data excluding the 5~MeV excess region.
(c) Ratio of the data to the expected Daya Bay spectrum. The solid green line shows the best fit of the data including a 4th neutrino state. The dashed red line corresponds to the RAA best fit parameters~\cite{Ko:2016owz}.



NEOS and DANSS

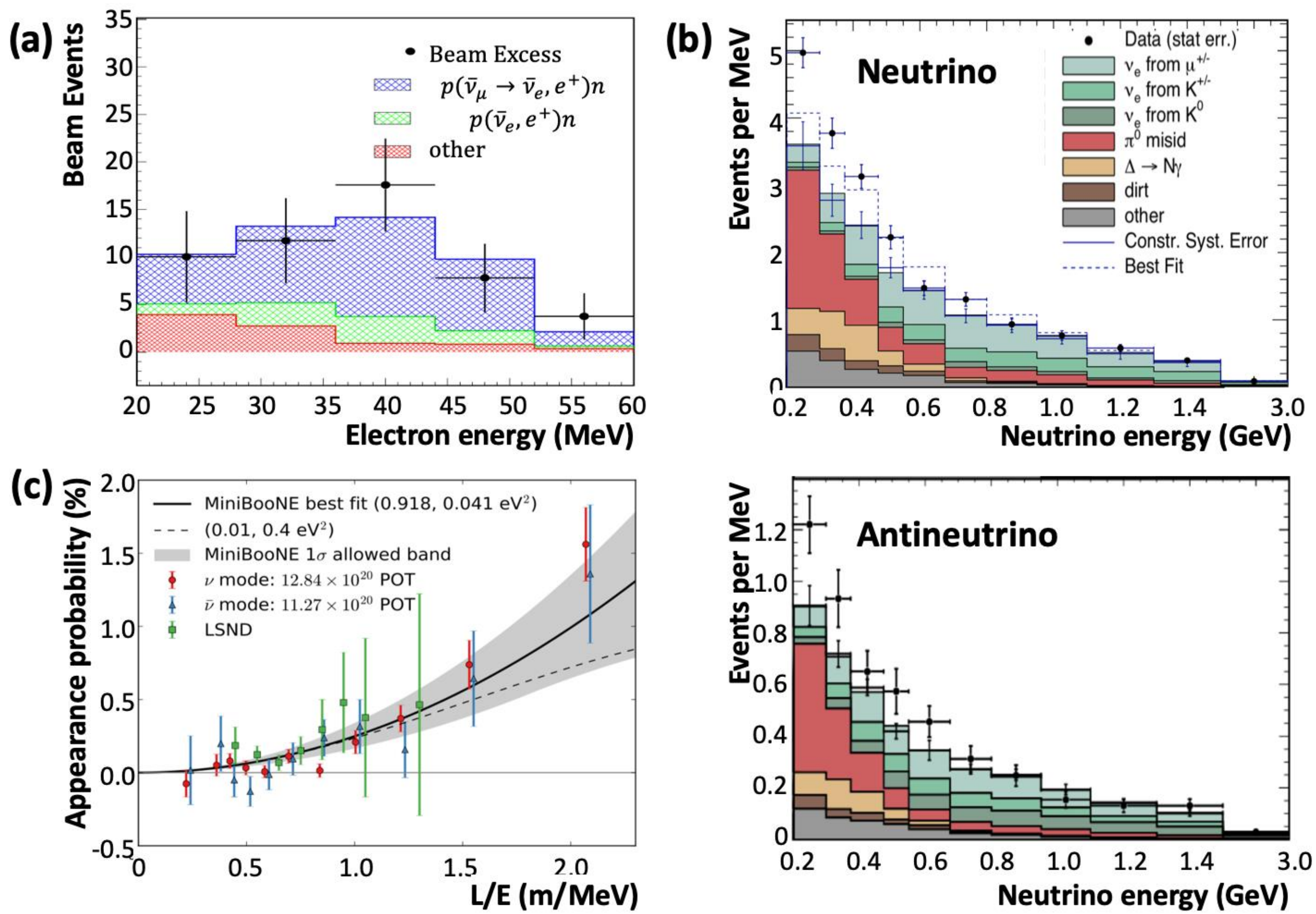
S. Gariazzo et al, PL B782 13, (2018)



The allowed regions by NEOS/DayaBay and DANSS

LSND and MiniBooNE

sss



Double or inverse Seesaw

R.N. Mohapatra
J. Valle

- For three singlets S which couple with RH neutrinos – inverse or double seesaw

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

- RH neutrinos get mass via see-saw $M_R = M_D^T M_S^{-1} M_D$ if $M_S \sim M_{Pl}$, $M_D \sim M_{GUT}$

- For light neutrinos

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

- If $m_D = A M_D$ $m_\nu = A^2 M_S$

Structure of m_ν is determined by M_S, it does not depend on the Dirac mass matrix structure (Dirac screening)

Basis fixing symmetry and mixing

Higgs multiplets of visible sector are singlets of $G_{basis} = Z_2 \times Z_2$
the charges of generations can be selected such that

$$m_D \sim M_D = \text{diagonal}$$

Flavons Φ are charged with respect to G_{basis} and
spontaneously break G_{basis} → non-diagonal M_S → mixing U_X

$G_{basis} = Z_2 \times Z_2$ is a part of intrinsic symmetry of Majorana mass
mass matrix $(Z_2)^3$ which is always present!

For free!

In the basis fixed by G_{basis}: m_D, M_D - diagonal, M_S is non-diagonal.
M_S is diagonalized by U_X and has another unbroken symmetry $(Z_2 \times Z_2)_H$

U_X connects bases determined by $(Z_2 \times Z_2)_H$ and $(Z_2 \times Z_2)_H$

Residual symmetry approach

Mass matrix of neutral leptons

$$M = \begin{pmatrix} 0 & m_D & m_D' & 0 \\ m_D & 0 & 0 & M_D \\ m_D' & 0 & \mu & \mu_{LR} \\ 0 & M_D & \mu_{LR}^T & \mu \end{pmatrix} \begin{pmatrix} \nu_L \\ N \\ S_L \\ S_R^C \end{pmatrix} \qquad N = (\nu_R)^C$$

- Pairs of pseudoDirac heavy leptons formed by N and S_R^C with similar phenomenology as before

- After decoupling these heavy states

$$\begin{pmatrix} \mu\xi^2 & m_D' - \xi\,\mu_{LR} \\ m_D' - \xi\,\mu_{LR} & \mu \end{pmatrix} \begin{pmatrix} \nu_L' \\ S_L \end{pmatrix} \qquad \xi = m_D / M_D$$

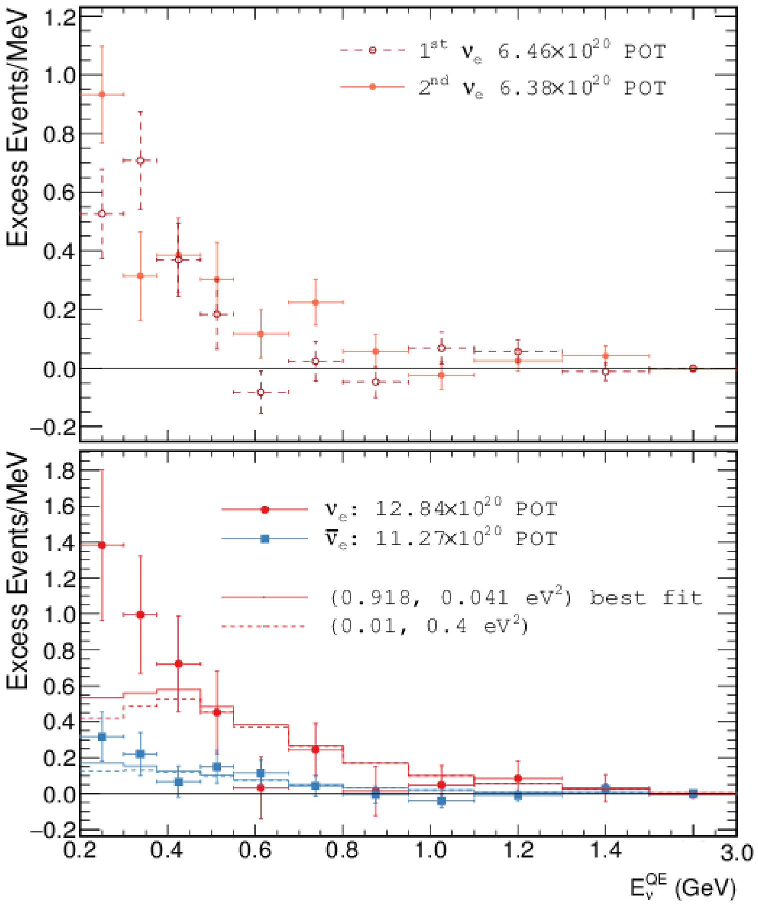
- S_L are the (10 – 100) keV scale Majorana neutrinos, which mix very weakly with usual active neutrinos

$$\sin\theta_s \sim \xi\,\mu_{LR}/\mu \qquad (m_D' = 0)$$

- If $\mu_{LR}/\mu < 10^{-2}$ the lightest S_L can be the Dark matter

MiniBooNE excess

A.A. Aguilar-Arevalo et al
Phys.Rev.Lett. 121 (2018) no.22, 221801)
1805.12028 [hep-ex]



the MiniBooNE event excesses in neutrino mode as a function of *EQEν* from the first 6.46×1020 POT data and the second 6.38×1020 POT data. The bottom plot shows the total event excesses in both neutrino mode and antineutrino mode, corresponding to 12.84×1020 POT and 11.27×1020 POT, respectively. The solid (dashed) curve is the best fit (1σ fit point) to the neutrino-mode and antineutrino-mode data (two-neutrino oscillations). The last bin is for the energy interval from 1500-3000 MeV. Error bars include only statistical uncertainties for the top plot and both statistical and correlated systematic uncertainties for the bottom plot.

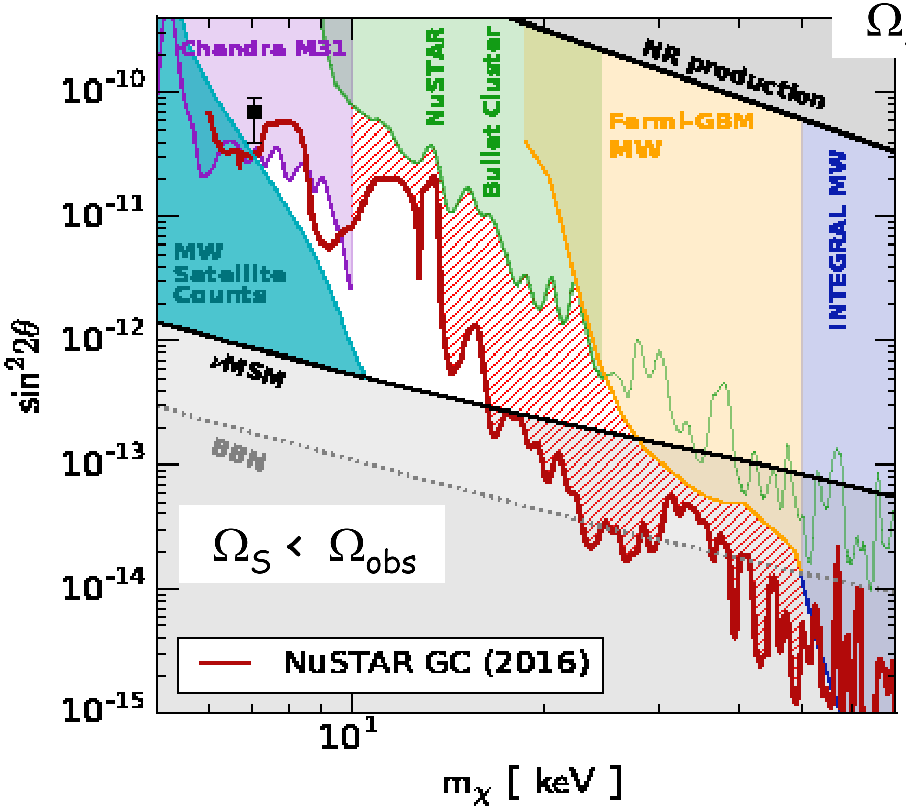
Sterile Neutrinos as Dark matter

(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

$\Omega_S > \Omega_{obs}$



- zero lepton asymmetry

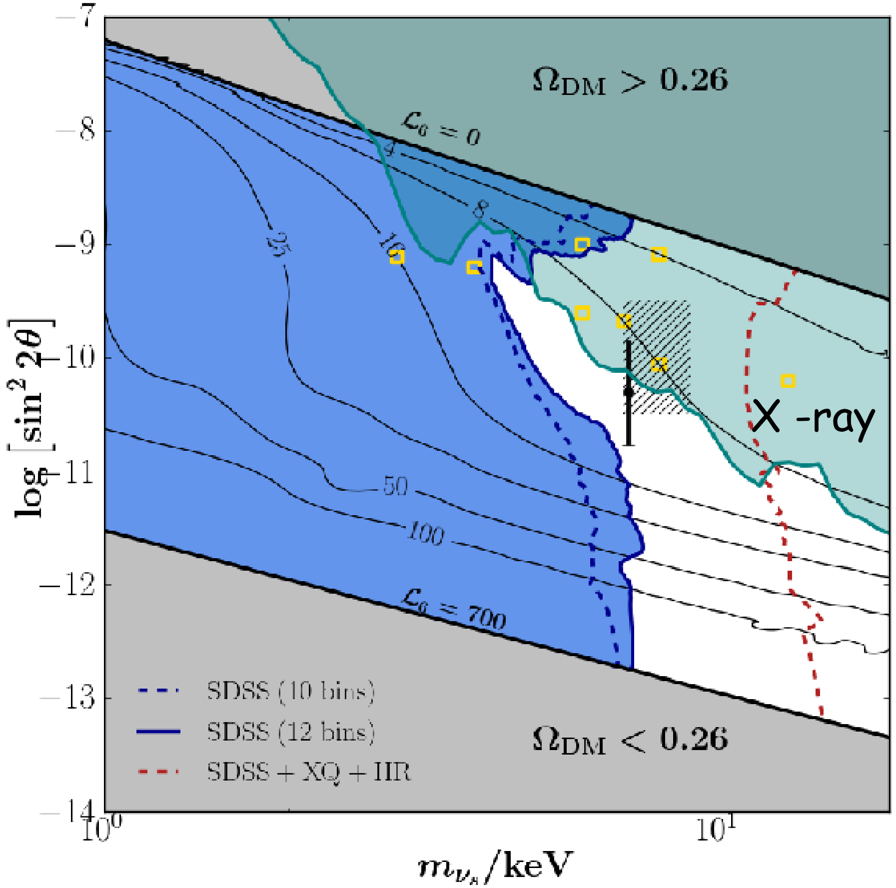
limits from structure formation and astrophysical X-ray observations the colored, regions.

- maximal lepton asymmetry

Deep sky

WDM&Ly-alpha

Julien Baur, et al,
1706.03118 [astro-ph.CO] l,



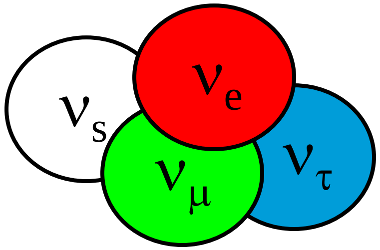
Constraints from Ly-α forest

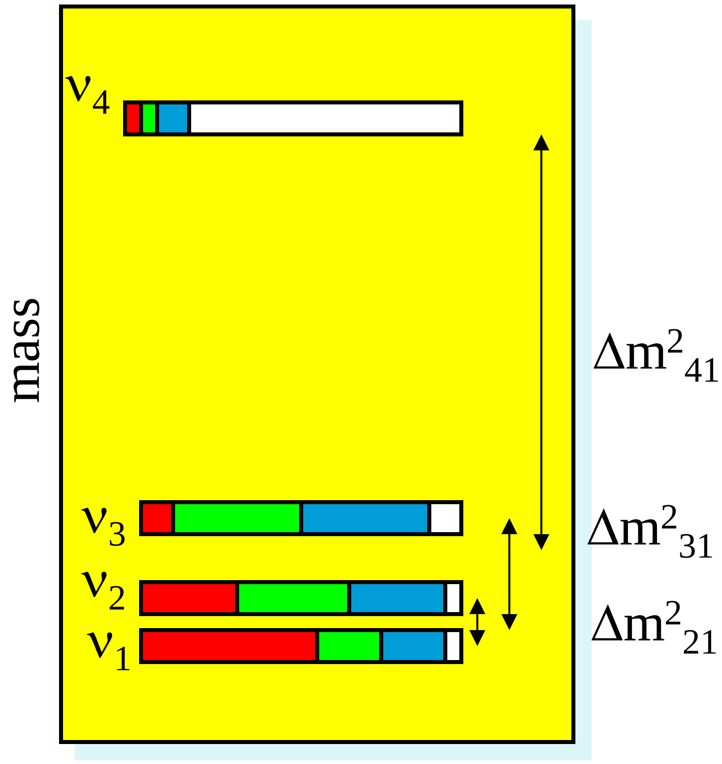
The blue shade - excluded by over 3σ by the Ly-α forest BOSS power spectrum.

The green shade are models inconsistent beyond 3σ with a compilation of X-ray data from the Milky Way, Andromeda and other galaxies.

Red dashed with assumption about temperature of medium

(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:

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

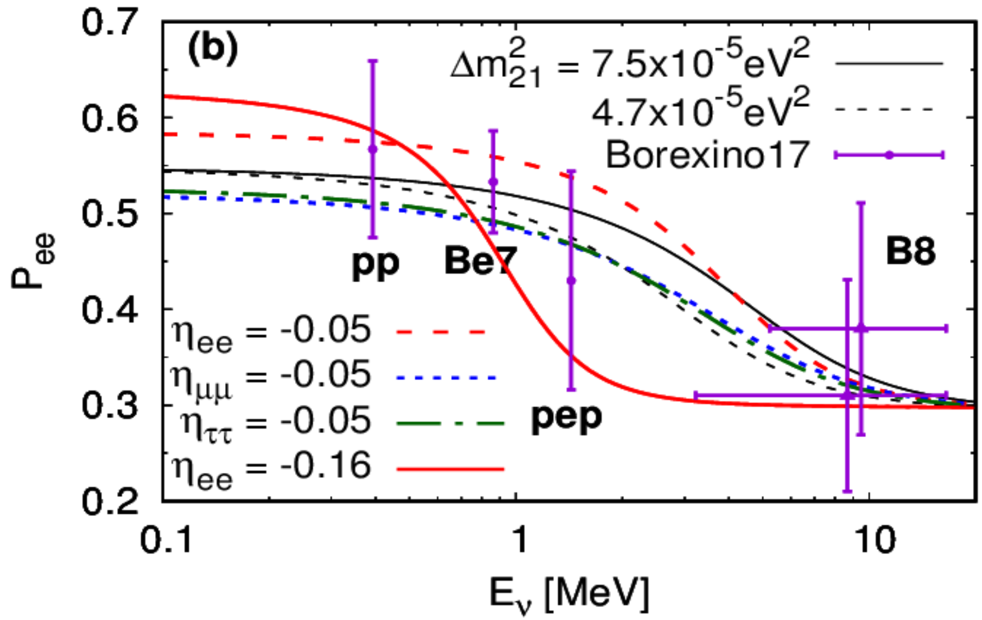
- additional radiation in the Universe
- bound from LSS?

Refraction due to very light scalar mediator

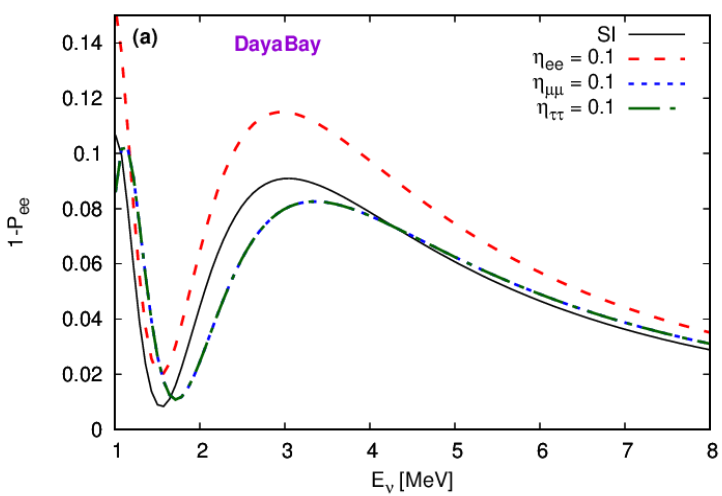
Shao-Feng Ge, S. Parke

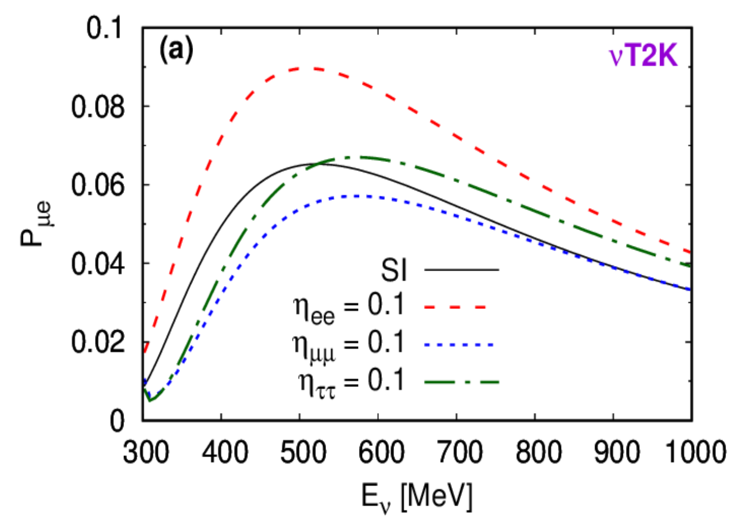
Neutrino scattering on electrons via very light scalar exchange

The solar neutrino conversion probabilities with the scalar NSIs, together with the Borexino measurements.



To satisfy bounds on h_ν h_e (from searches of 5th force $1/m_\phi$





Total Hamiltonian and potentials

$$H = \frac{1}{2}\begin{pmatrix} -\cos 2\theta\,\omega_p + V_e + V_\nu & \sin 2\theta\,\omega_p + 2\bar{V}_\nu e^{i\phi} \\ \sin 2\theta\,\omega_p + 2\bar{V}_\nu e^{-i\phi} & \cos 2\theta\,\omega_p - V_e - V_\nu \end{pmatrix} \quad \begin{pmatrix} \nu_e \\ \nu_\tau \end{pmatrix}$$

Potentials

$$V_\nu \sim V_\nu^0 (1 - P^B_{e\tau})$$

$$\bar{V}_\nu \sim V_\nu^0 \sqrt{P^B_{e\tau}(1 - P^B_{e\tau})}$$

$P^B_{e\tau} = P_{e\tau}$

non-linearity

$P^B_{e\tau}(x)$ – effective transition probability of the background neutrinos

$$V_e \gg V_\nu \gg \omega$$

$H^{diag} \sim V_e$ $\quad H^{non\text{-}diag} \sim V_\nu^0 \sqrt{P^b_{e\tau}} < V_\nu^0$ $\quad \phi \sim \int dt\, \Delta H$

$\Delta H \sim V_e$ $\quad d\phi/dt \sim V_e$

if $\omega \ll V_\nu$, H depends on potentials only – evolution of neutrinos and antineutrinos is the same → bi-polar oscillations

Two effects of enhancement

Phase velocity cancellation

Rotation of the fields that eliminates the phase from the off-diagonal terms leads to appearance of phase velocity in the diagonal terms

$$V^r(t) = V_e + V_\nu - \cos 2\theta\, \omega_p - d\phi/dt$$

if $d\phi/dt \sim V_e + V_\nu$ strong cancellation → matter suppression is removed

Oscillations with maximal depth and frequency $1/V_\nu$

Parametric enhancement

V_ν and $\overline{V}_\nu$ - periodic functions

Parametric resonance if the frequency of modulations of potentials coincides with eigenfrequency of the probe neutrino

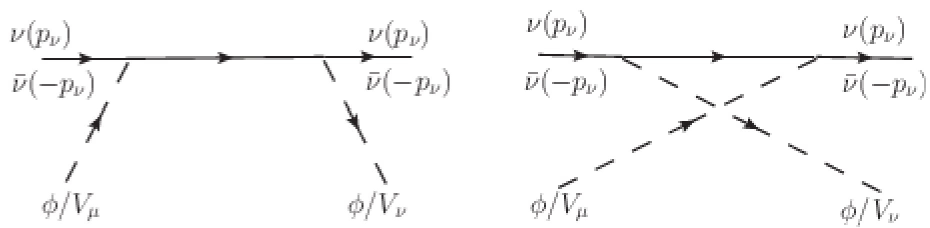
Reinterpretation of collective effects

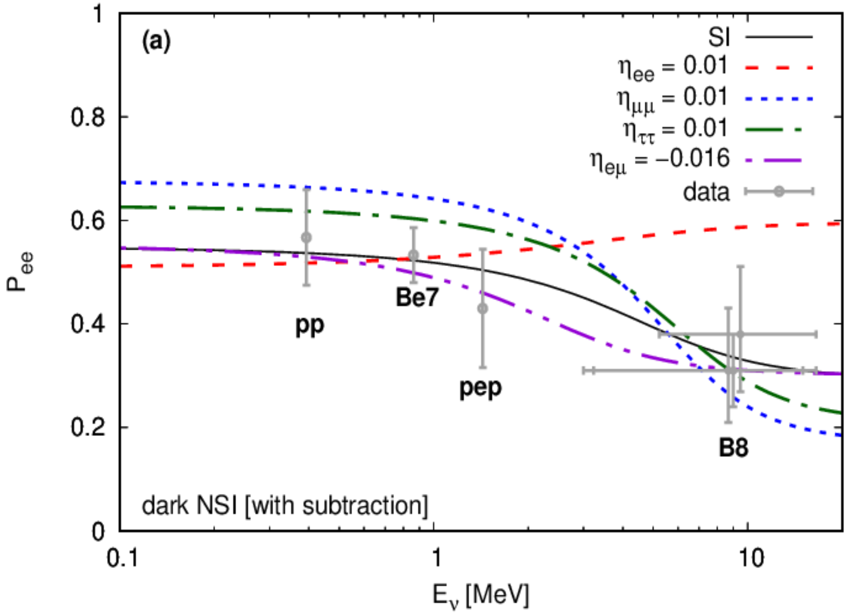
effects which can lead to
strong flavor transformations
Conditions for these effects

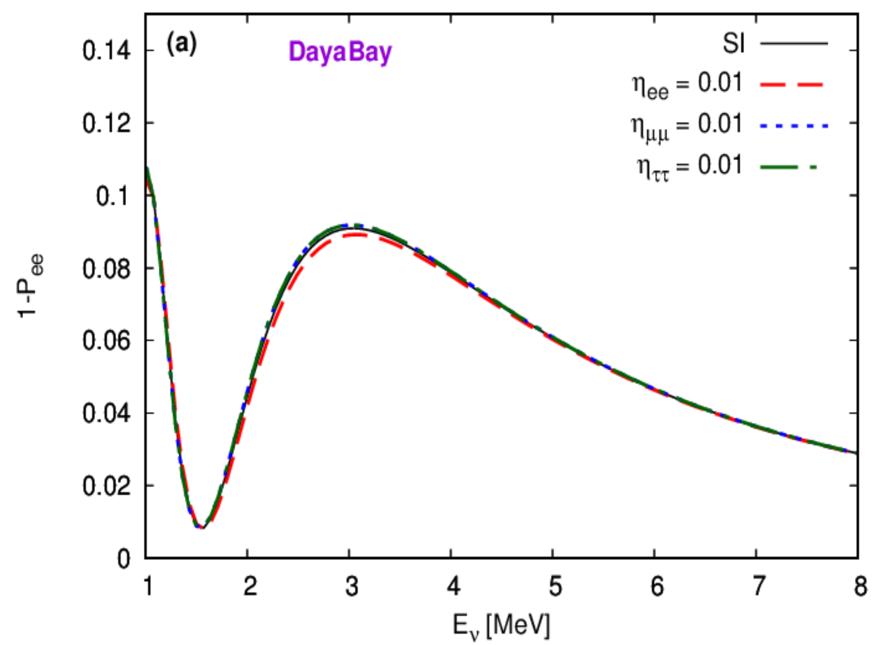
problems of realizations of these conditions in realistic supernova

NSI on DM

Apparent CPT Violation in Neutrino Oscillation from Dark Non-Standard Interactions - Ge, Shao-Feng et al. arXiv:1904.02518 [hep-ph]





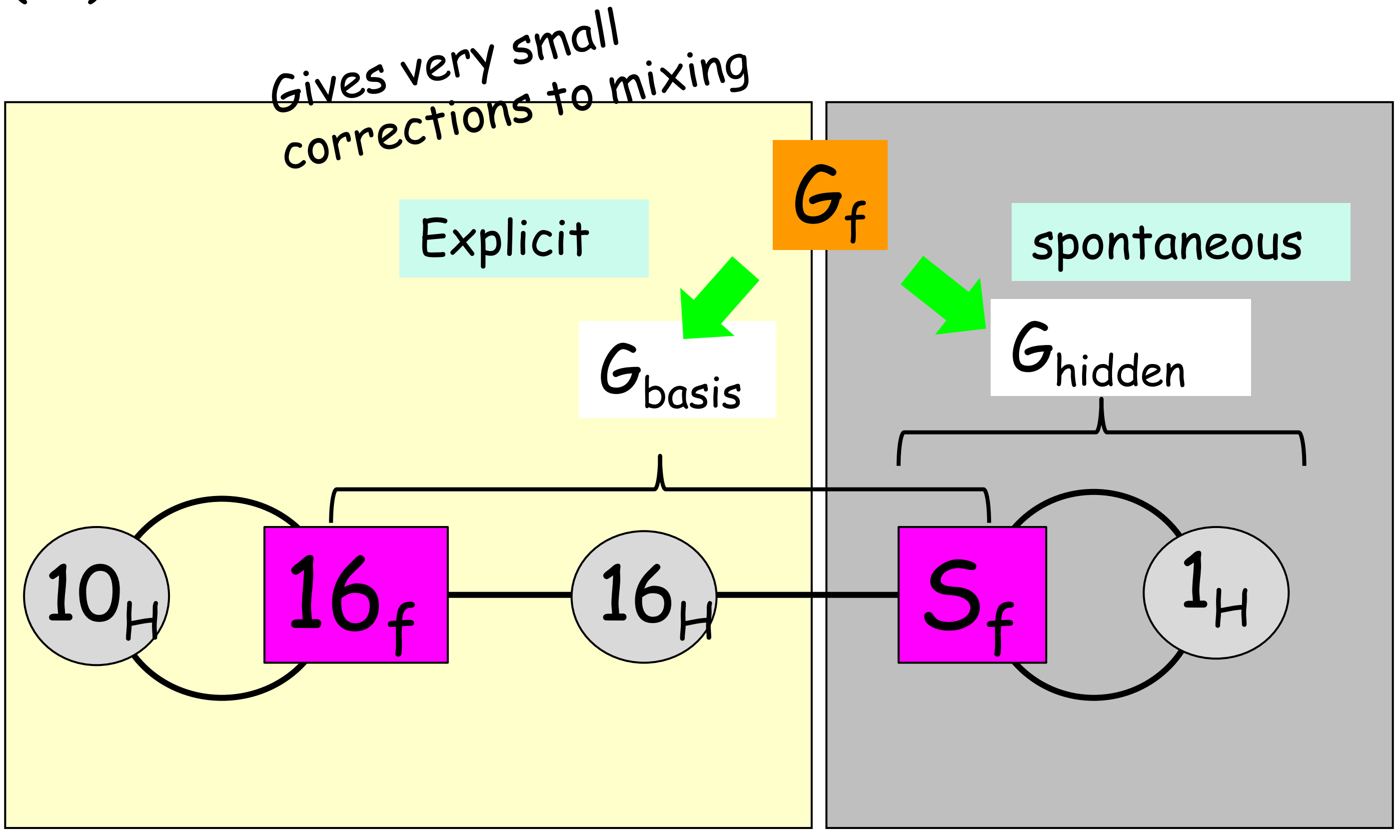


The dark NSI effect on solar neutrino transition probability

The effect of the dark Non-Standard Interactions (NSI) on (a) short-baseline neutrino oscillation at Daya Bay

GUT/Planck realization

SO(10) GUT



$G_{basis} = Z_2 \times Z_2$

$M_S \sim M_{Pl}$

Neutrino-4