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Light sterile neutrinos: the current picture

Conference on Flavour Physics and CP violation (FPCP), 8–12/06/2020 https://www.particlesforjustice.org/

Three Neutrino Oscillations

$$\nu_\alpha = \sum_{k=1}^{3} U_{\alpha k} \nu_k \quad (\alpha = e, \mu, \tau)$$

$U_{\alpha k}$ described by 3 mixing angles θ_{12}, θ_{13}, θ_{23} and one CP phase δ

Current knowledge of the 3 active ν mixing: [in preparation]

NO/NH: Normal Ordering/Hierarchy, $m_1 < m_2 < m_3$

IO/IH: Inverted O/H, $m_3 < m_1 < m_2$

$$\Delta m^2_{21} = (7.50^{+0.22}_{-0.20}) \cdot 10^{-5}\ \mathrm{eV}^2$$

$$|\Delta m^2_{31}| = (2.56^{+0.03}_{-0.04}) \cdot 10^{-3}\ \mathrm{eV}^2 \ (\mathrm{NO})$$

$$= (2.46 \pm 0.03) \cdot 10^{-3}\ \mathrm{eV}^2 \ (\mathrm{IO})$$

$$10 \sin^2(\theta_{12}) = 3.18 \pm 0.16$$

$$10^2 \sin^2(\theta_{13}) = 2.225^{+0.055}_{-0.078} \ (\mathrm{NO})$$

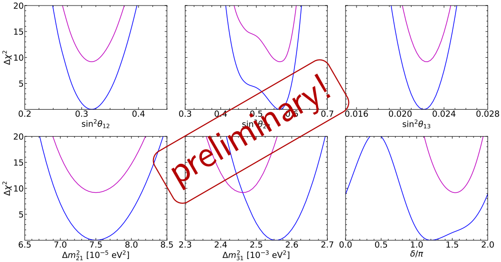
$$= 2.250^{+0.056}_{-0.076} \ (\mathrm{IO})$$

$$10 \sin^2(\theta_{23}) = 5.66^{+0.16}_{-0.22} \ (\mathrm{NO})$$

$$= 5.66^{+0.18}_{-0.23} \ (\mathrm{IO})$$

$$\delta/\pi = 1.20^{+0.23}_{-0.14} \ (\mathrm{NO})$$

$$= 1.54 \pm 0.13 \ (\mathrm{IO})$$



see next talk by I. Esteban

see also: http://globalfit.astroparticles.es

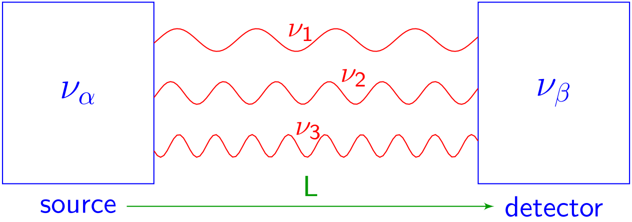
Two neutrino bases

flavor neutrinos ν_α

$|\nu_\alpha\rangle = \sum_k U_{\alpha k}|\nu_k\rangle$

massive neutrinos ν_k

$$|\nu(t=0)\rangle = |\nu_\alpha\rangle = U_{\alpha 1}|\nu_1\rangle + U_{\alpha 2}|\nu_2\rangle + U_{\alpha 3}|\nu_3\rangle$$



$$|\nu(t>0)\rangle = |\nu_\beta\rangle = U_{\alpha 1}\, e^{-iE_1 t}|\nu_1\rangle + U_{\alpha 2}\, e^{-iE_2 t}|\nu_2\rangle + U_{\alpha 3}\, e^{-iE_3 t}|\nu_3\rangle \neq |\nu_\alpha\rangle$$

$E_k^2 = p^2 + m_k^2$ ⟵ define ⟶ $t = L$

$$P_{\nu_\alpha \to \nu_\beta}(L) = |\langle \nu_\alpha | \nu(L) \rangle|^2 = \sum_{k,j} U_{\beta k} U^*_{\alpha k} U^*_{\beta j} U_{\alpha j} \exp\left(-i \frac{\Delta m^2_{kj} L}{2E}\right)$$

$$\Delta m^2_{ij} = m_i^2 - m_j^2$$

A large family

In principle, previous discussion is valid for N neutrinos

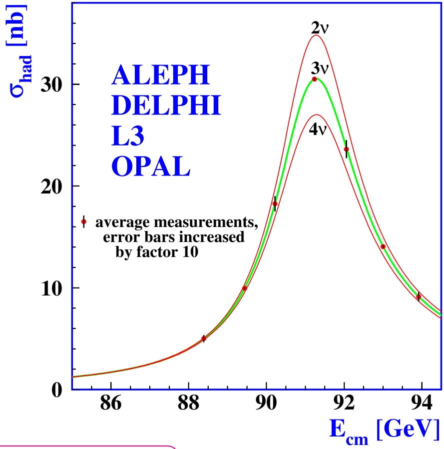
only constraint: there are exactly three flavor neutrinos in the SM

[LEP, Phys. Rept. 427 (2006) 257, arXiv:hep-ex/0509008]

$$N_\nu^{(Z)} = 2.9840 \pm 0.0082$$

through the measurement of the Z resonance

$$e^+e^- \longrightarrow Z \longrightarrow \sum_{a=e,\mu,\tau} \nu_a \bar{\nu}_a$$



neutrinos $\alpha > 3$ must be sterile

sterile neutrino = SM singlet: no couplings with other SM particles

A large family

In principle, previous discussion is valid for N neutrinos

$N \times N$ mixing matrix, N flavor neutrinos, N massive neutrinos

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \\ |\nu_{s_1}\rangle \\ \ldots \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \vdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \\ U_{s_1 1} & U_{s_1 2} & U_{s_1 3} & U_{s_1 4} & \\ \ldots & & & & \ddots \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \\ |\nu_4\rangle \\ \ldots \end{pmatrix}$$

A large family

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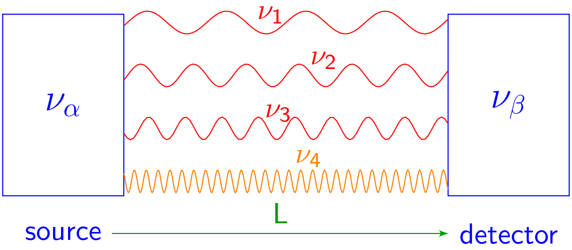
Our case will be 3 (active)+1 (sterile), a perturbation of 3 neutrinos case

$m_4 \gg m_\ell$

$\ell = 1, 2, 3$

$\Delta m^2_{41} \simeq 1\ \text{eV}^2$
$\simeq \Delta m^2_{42}$
$\simeq \Delta m^2_{43}$



6 angles

3 Dirac CP phases

3 Majorana CP phases

Short BaseLine (SBL)

$$P_{\nu_\alpha \to \nu_\beta}(L) = |\langle \nu_\alpha | \nu(L) \rangle|^2 = \sum_{k,j} U_{\beta k} U^*_{\alpha k} U^*_{\beta j} U_{\alpha j} \exp\left(-i \frac{\Delta m^2_{kj} L}{2E}\right)$$

If $m_4 \gg m_\ell$, faster oscillations

ν_4 oscillations are averaged in most neutrino oscillation experiments

Effect of 4th neutrino only visible as global normalization

Short BaseLine (SBL) oscillations: $\frac{\Delta m^2_{41} L}{E} \simeq 1$

At SBL, oscillations due to Δm^2_{21} and $|\Delta m^2_{31}|$ do not develop

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APPearance ($\alpha \neq \beta$)

source of $\overset{(-)}{\nu}_\alpha$

detect different flavor $\overset{(-)}{\nu}_\beta$

Short BaseLine (SBL)

$$P_{\nu_\alpha \to \nu_\beta}(L) = |\langle \nu_\alpha | \nu(L) \rangle|^2 = \sum_{k,j} U_{\beta k} U^*_{\alpha k} U^*_{\beta j} U_{\alpha j} \exp\left(-i \frac{\Delta m^2_{kj} L}{2E} \right)$$

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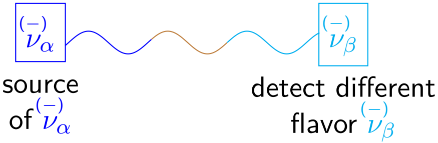
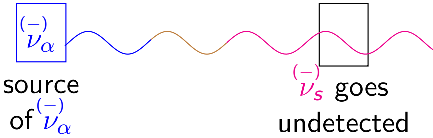
DISappearance





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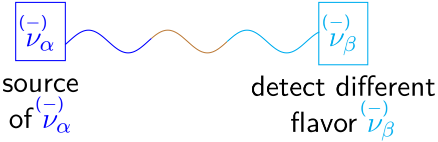
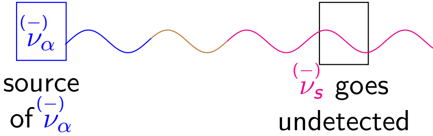


DISappearance



CP violation cannot be observed in SBL experiments!

New mixings in the 3+1 scenario

$$4 \times 4 \text{ mixing matrix: } \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s_1 1} & U_{s_1 2} & U_{s_1 3} & U_{s_1 4} \end{pmatrix}$$

New mixings in the 3+1 scenario

4 × 4 mixing matrix:
$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s_1 1} & U_{s_1 2} & U_{s_1 3} & U_{s_1 4} \end{pmatrix}$$

ϑ_{14}

ϑ_{24}

ϑ_{34}

New mixings in the 3+1 scenario

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DISappearance

$$P^{\mathrm{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} \simeq 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha 4}|^2(1 - |U_{\alpha 4}|^2)$$

$\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_e$ reactor, gallium

$$|U_{e4}|^2 = \sin^2 \vartheta_{14}$$

$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$ accelerator, atmospheric

$$|U_{\mu 4}|^2 = \cos^2 \vartheta_{14} \sin^2 \vartheta_{24}$$

New mixings in the 3+1 scenario

4×4 mixing matrix: $\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s_11} & U_{s_12} & U_{s_13} & U_{s_14} \end{pmatrix}$ ϑ_{14}, ϑ_{24}, ϑ_{34}

DISappearance

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$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$ — accelerator, atmospheric

$$|U_{\mu4}|^2 = \cos^2\vartheta_{14}\sin^2\vartheta_{24}$$

APPearance

$$P^{\mathrm{SBL}}_{\overset{(-)}{\nu}_\alpha\to\overset{(-)}{\nu}_\beta} \simeq \sin^2 2\vartheta_{\alpha\beta}\sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right)$$

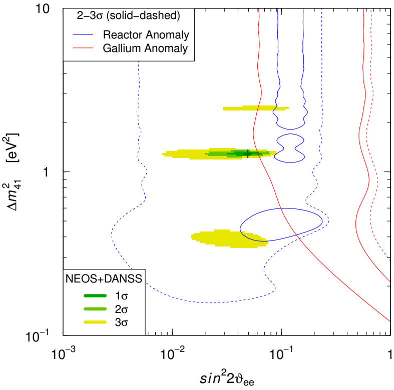
$$\sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha4}|^2|U_{\beta4}|^2$$

$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ — LSND, MiniBooNE, KARMEN, OPERA, ...

$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2$$

quadratically suppressed!

for small $|U_{e4}|^2$, $|U_{\mu4}|^2$


2–3σ (solid–dashed)
Reactor Anomaly
Gallium Anomaly
NEOS+DANSS
1σ
2σ
3σ
Δm^2_{41} [eV^2]
$sin^2 2\vartheta_{ee}$
10
1
10^{-1}
10^{-3}
10^{-2}
10^{-1}
1

Gallium anomaly

[SAGE, 2006][Laveder, 2007][Giunti&Laveder, 2011]

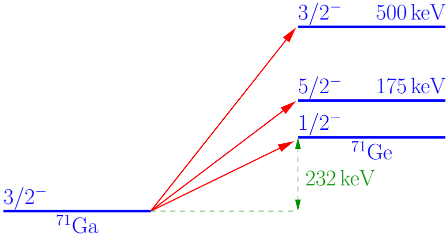
$L \simeq 1.9$ m $\quad L \simeq 0.6$ m

Gallium radioactive source experiments: GALLEX and SAGE

ν_e sources: $e^- + {}^{51}\text{Cr} \to {}^{51}\text{V} + \nu_e$ $\qquad e^- + {}^{37}\text{Ar} \to {}^{37}\text{Cl} + \nu_e$

$E \simeq 0.75$ MeV $\qquad E \simeq 0.81$ MeV

In the detector: $\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$



cross sections of
the transitions from

[Krofcheck et al., PRL 55 (1985) 1051]

[Frekers et al., PLB 706 (2011) 134]

Gallium anomaly

[SAGE, 2006][Laveder, 2007][Giunti&Laveder, 2011]

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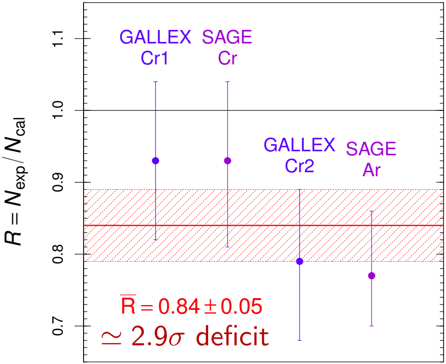
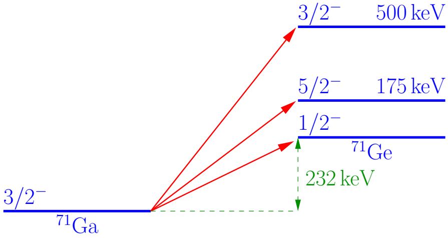
In the detector: $\nu_e + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + e^-$

Test detection of solar ν_e





cross sections of the transitions from

[Krofcheck et al., PRL 55 (1985) 1051]

[Frekers et al., PLB 706 (2011) 134]

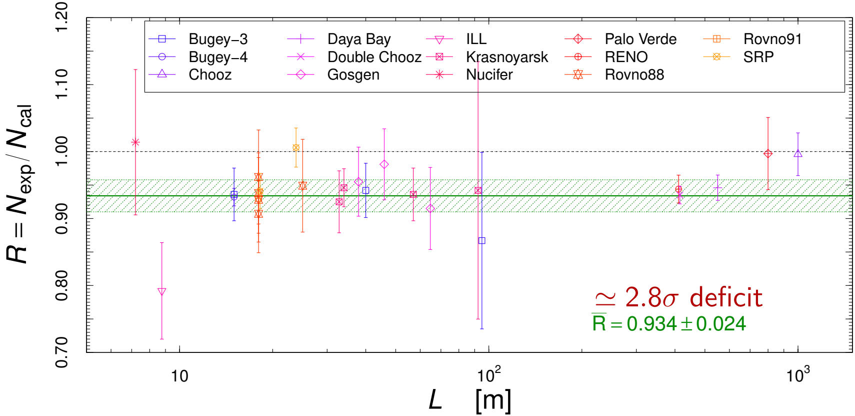
Reactor Antineutrino Anomaly (RAA)

[PRD 83 (2011) 073006]

2011: new reactor $\bar{\nu}_e$ fluxes by Huber and Mueller+ (HM)

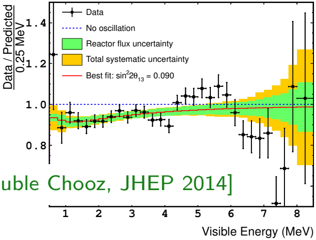
[Huber, PRC 84 (2011) 024617] [Mueller et al., PRC 83 (2011) 054615]

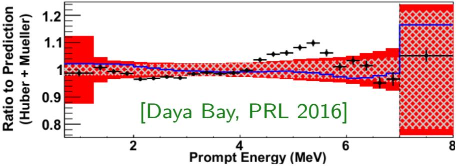
Previous reactor rates evaluated with new fluxes ⇒ deficit

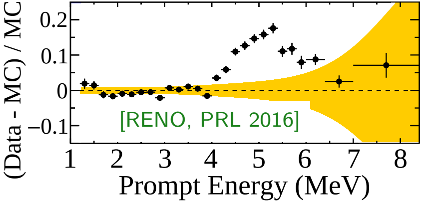


Suppression at detector due to active-sterile oscillations?

Can we trust the HM fluxes?







known since 2014:

bump in the spectrum around 5 MeV!

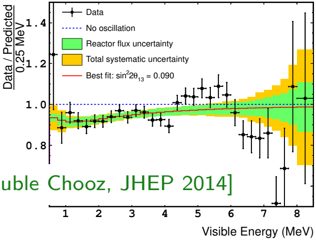
cannot be explained by SBL oscillations

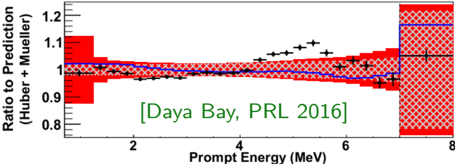
(averaged at the observed distances)

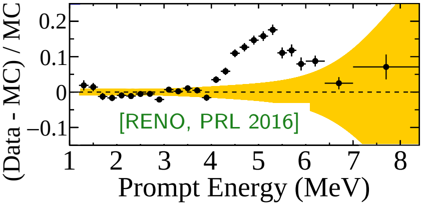
many attempts of possible explanations, how to clarify the issue?

see also talk by B. Roskovec on Friday!

Can we trust the HM fluxes?







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(averaged at the observed distances)

many attempts of possible explanations,

how to clarify the issue?

Model independent information!

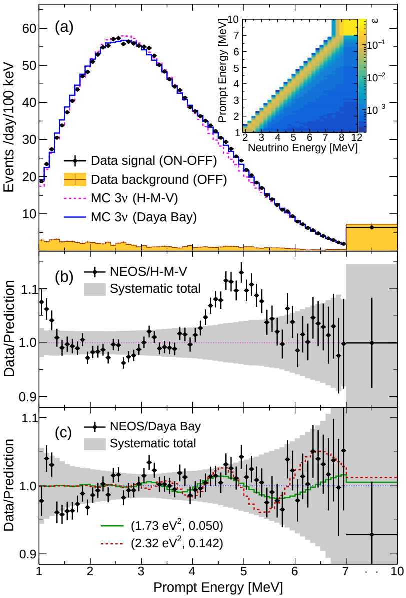
(i.e. take ratio of spectra at different distances)

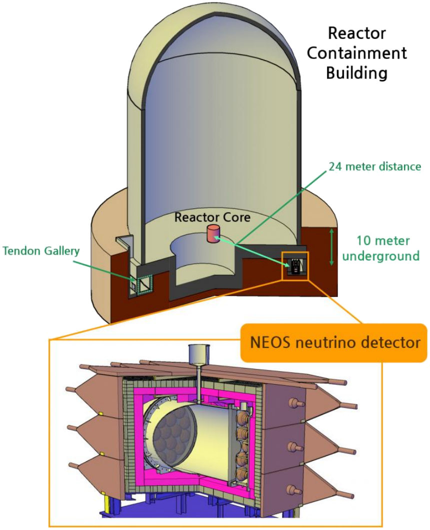
$$\Phi_1 = \Phi_0(E) f(L_1, E) \quad \Phi_2 = \Phi_0(E) f(L_2, E)$$

$$\Phi_1/\Phi_2 = f(L_1, E)/f(L_2, E)$$

[PRL 118 (2017) 121802]

Single detector experiment



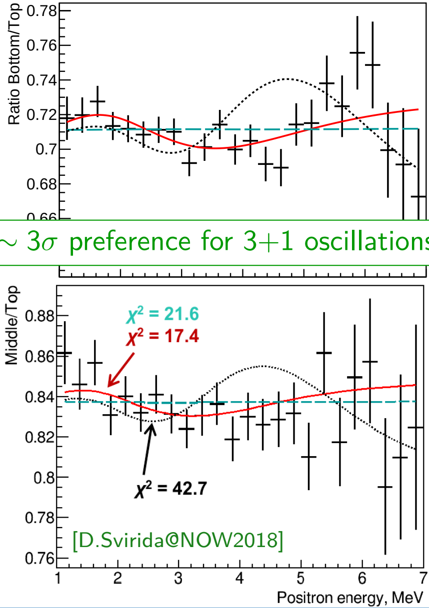


Ratio to DayaBay measurement to be model independent

DANSS

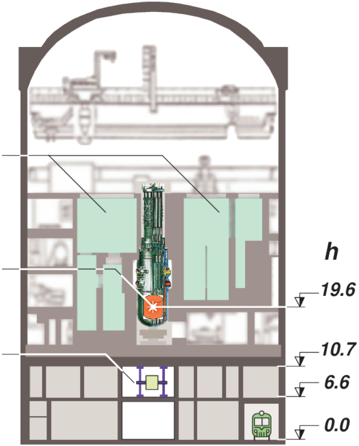
[PLB 787 (2018) 56]

Single movable detector



$\sim 3\sigma$ preference for 3+1 oscillations

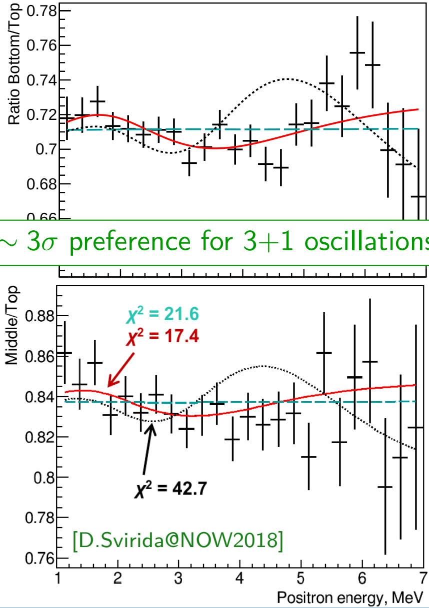
[D.Svirida@NOW2018]



Detector can be at $\sim$ 10.5, $\sim$ 11.5 or $\sim$ 12.5 m from reactor core

DANSS

Single movable detector



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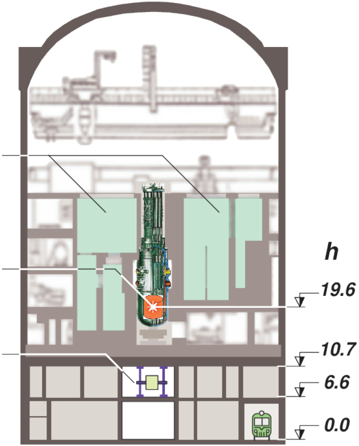


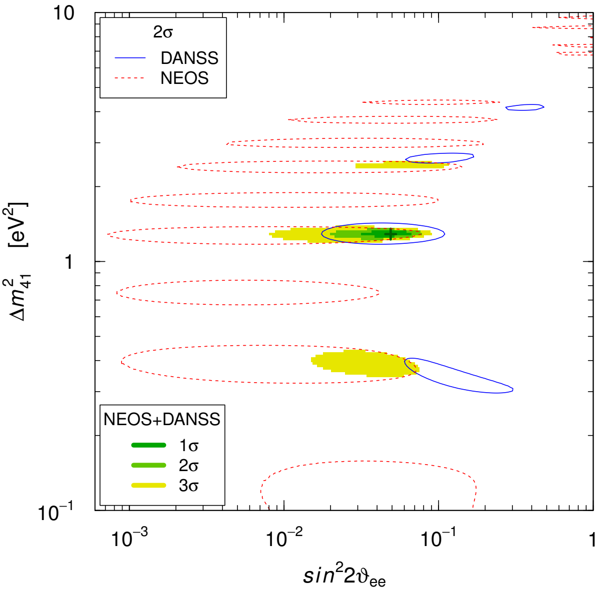
Detector can be at $\sim$ 10.5, $\sim$ 11.5 or $\sim$ 12.5 m from reactor core

see later for 2019 update!

Model-independent fit of $\overset{(-)}{\nu}_e$ DIS (2018)

[SG+, PLB 782 (2018) 13]

NEOS + DANSS



The NEOS and DANSS region perfectly overlap at

$$\Delta m^2_{41} \simeq 1.3 \text{ eV}^2$$

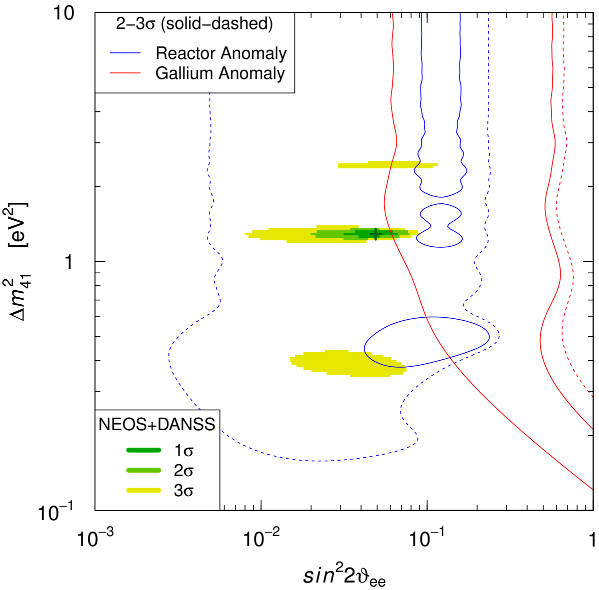
$$\sin^2 2\vartheta_{ee} \simeq 0.05$$

$$\sin^2 \vartheta_{14} \simeq 0.01$$

Model-independent fit of $\overset{(-)}{\nu}_e$ DIS (2018)

[SG+, PLB 782 (2018) 13]

DANSS + NEOS + RAA + Gallium

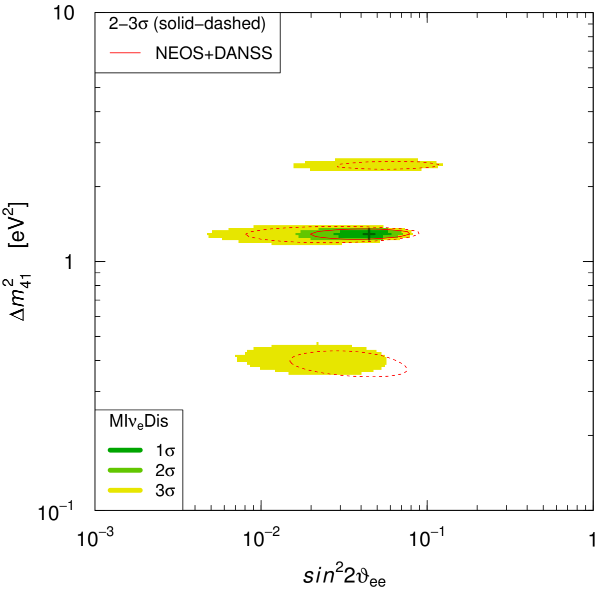


DANSS + NEOS do not agree with Gallium and RAA

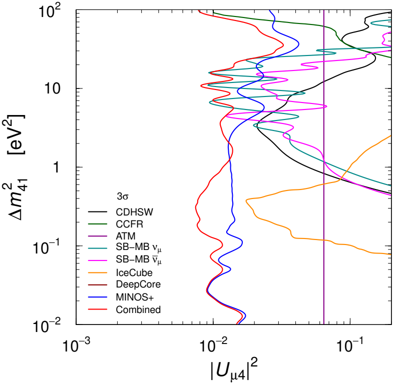
Model-independent fit of $\overset{(-)}{\nu}_e$ DIS (2018)

[SG+, PLB 782 (2018) 13]

All data:



Fit dominated by DANSS + NEOS


10^2
10
1
10^{-1}
10^{-2}
Δm^2_{41} [eV^2]
10^{-3}
10^{-2}
10^{-1}
$|U_{\mu 4}|^2$
3σ
CDHSW
CCFR
ATM
SB–MB ν_μ
SB–MB $\bar{\nu}_\mu$
IceCube
DeepCore
MINOS+
Combined

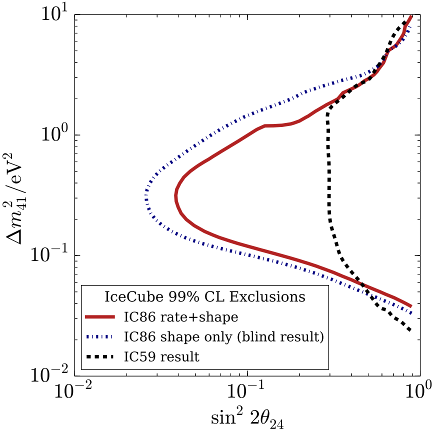
IceCube and DeepCore

IceCube

$\mathcal{O}(10\text{ km}) \lesssim L \lesssim \mathcal{O}(10^4\text{ km})$

$\sim 2 \times 10^4$ High energy μ events

$320\text{ GeV} < E < 20\text{ TeV}$



[PRL 117 (2016) 071801]

IceCube and DeepCore

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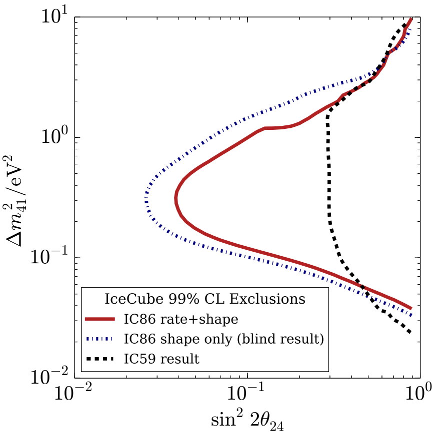
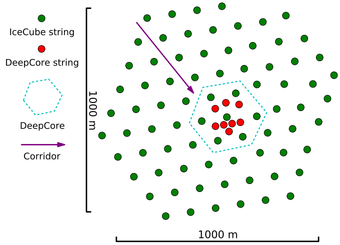
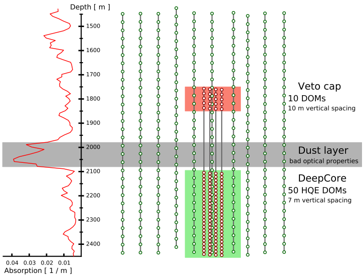


[PRL 117 (2016) 071801]





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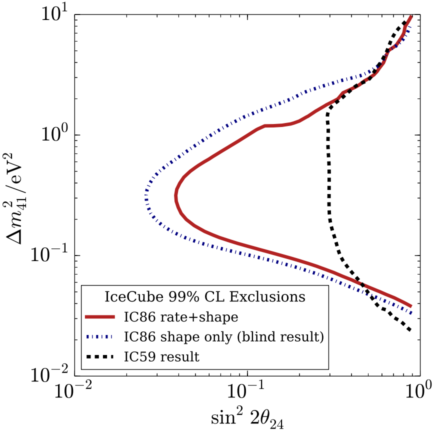
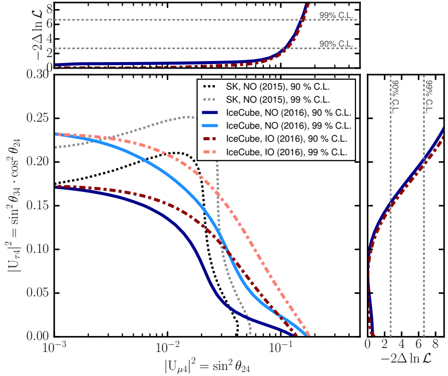


[PRL 117 (2016) 071801]

$\sim 5\times10^3$ tracklike events

$6\text{ GeV} \lesssim E \lesssim 60\text{ GeV}$



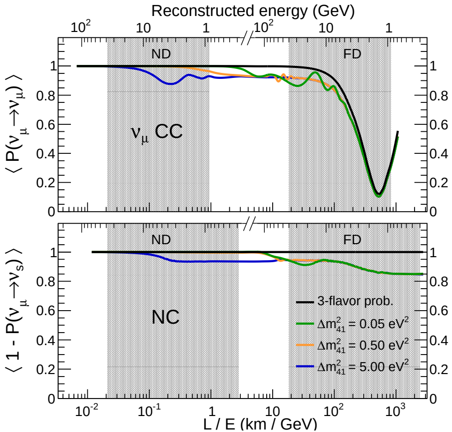
[PRD 95 (2017) 112002]

Both also constrain $|U_{\tau4}|^2$

MINOS & MINOS+

Near (ND, $\simeq$ 500 m) and far (FD, $\simeq$ 800 km) detector

$1\ \text{GeV} \lesssim E \lesssim 40\ \text{GeV}$, peak at 3 GeV



[PRL 117 (2016) 151803]:

far-to-near ratio

[PRL 122 (2019) 091803]:

full two-detectors fit

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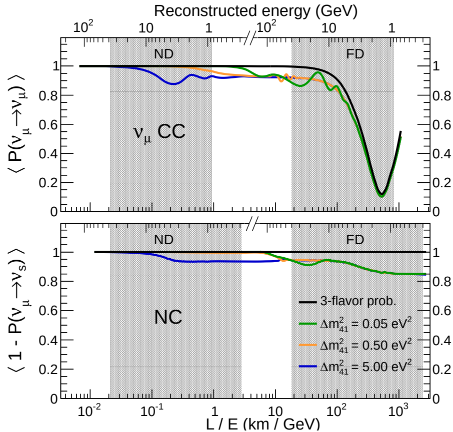
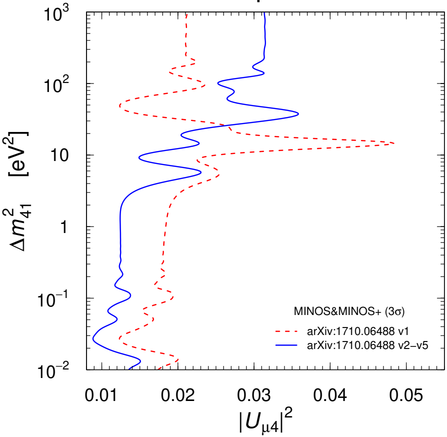


[PRL 117 (2016) 151803]: far-to-near ratio

[PRL 122 (2019) 091803]: full two-detectors fit

MINOS+ update:



[SG+, in preparation]

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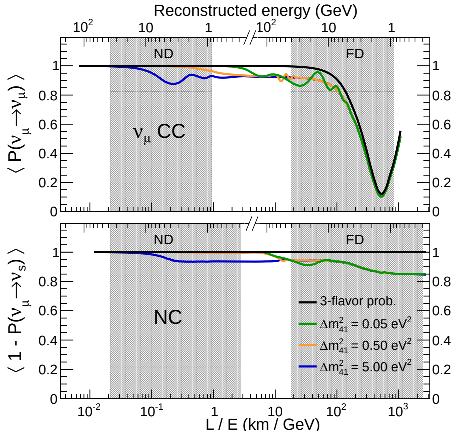
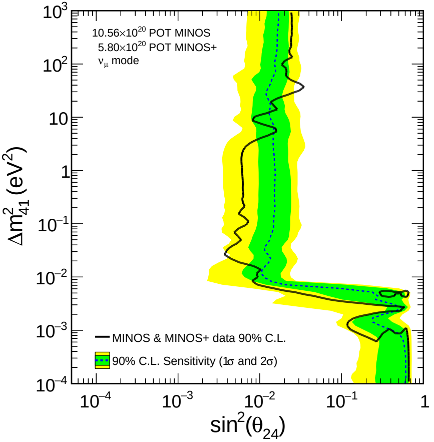


Sensitivity and exclusion limit:



[PRL 117 (2016) 151803]: far-to-near ratio

[PRL 122 (2019) 091803]: full two-detectors fit

[PRL 122 (2019) 091803]

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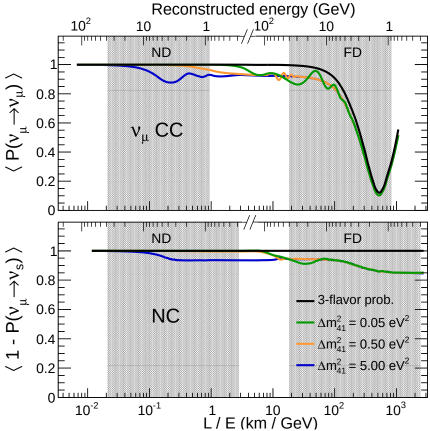
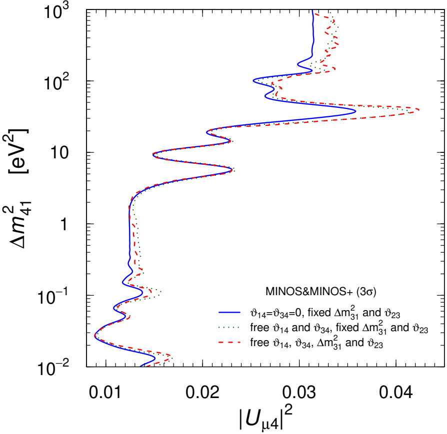


[PRL 117 (2016) 151803]: far-to-near ratio

[PRL 122 (2019) 091803]: full two-detectors fit

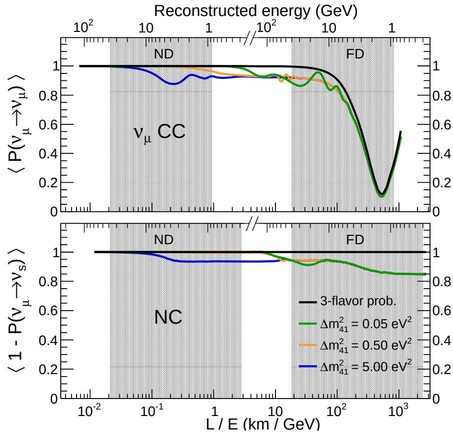
Marginalize over mixing parameters:



[SG+, in preparation]

MINOS & MINOS+

Near (ND, $\simeq$ 500 m) and far (FD, $\simeq$ 800 km) detector

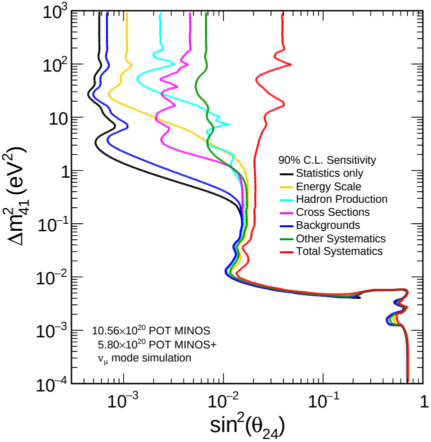


[PRL 117 (2016) 151803]: far-to-near ratio

[PRL 122 (2019) 091803]: full two-detectors fit

1 GeV $\lesssim E \lesssim$ 40 GeV, peak at 3 GeV

Systematics:



[PRL 122 (2019) 091803]

MINOS & MINOS+

Near (ND, $\simeq$ 500 m) and
far (FD, $\simeq$ 800 km) detector

1 GeV $\lesssim E \lesssim$ 40 GeV,
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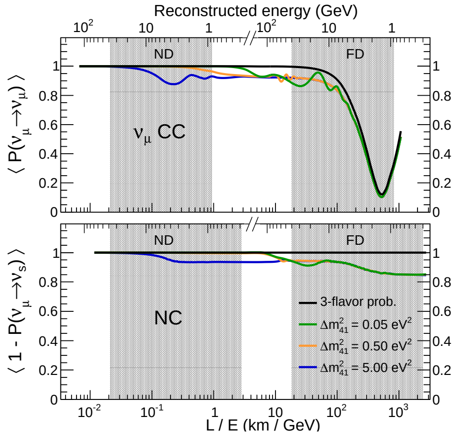


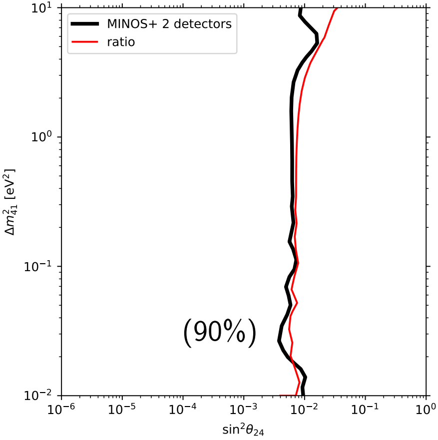
[PRL 117 (2016) 151803]:

far-to-near ratio

[PRL 122 (2019) 091803]:

full two-detectors fit

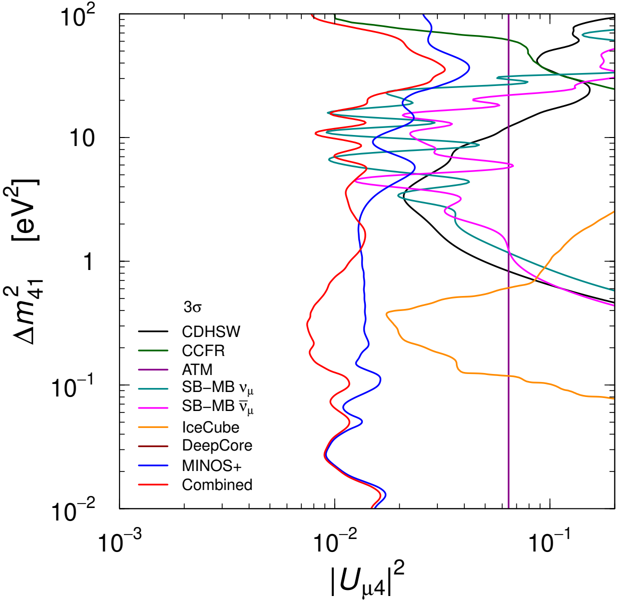
Two detectors vs ratio fit:



[SG+, in preparation]

Global fit of $\overset{(-)}{\nu}_\mu$ DIS

[SG+, in preparation]



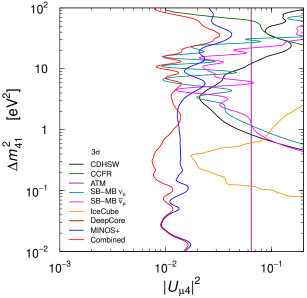
MINOS+ dominates at small Δm^2_{41}

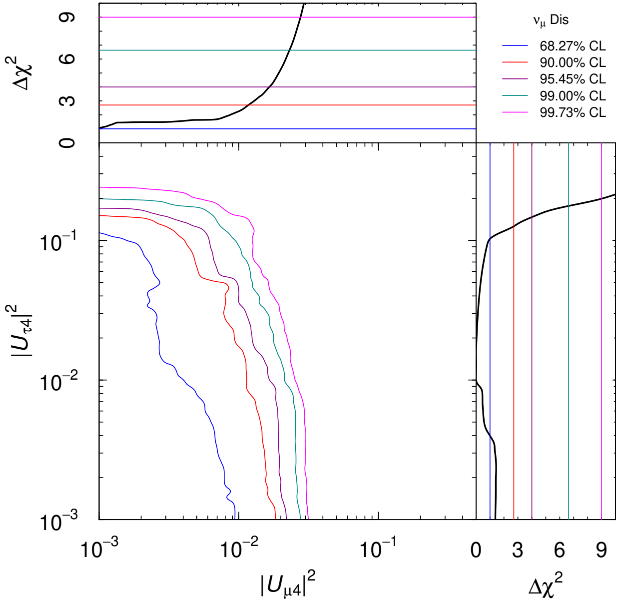
IceCube (1 yr) important at $\Delta m^2_{41} \simeq 0.2$ eV^2

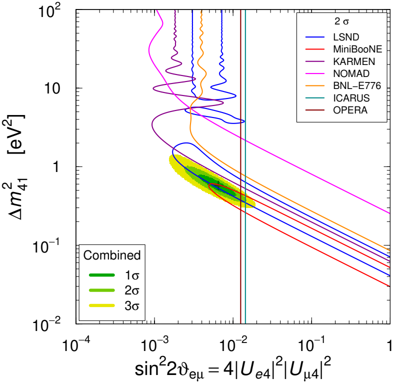
see later for IceCube 8 yr!

Global fit of $\overset{(-)}{\nu}_\mu$ DIS

[SG+, in preparation]

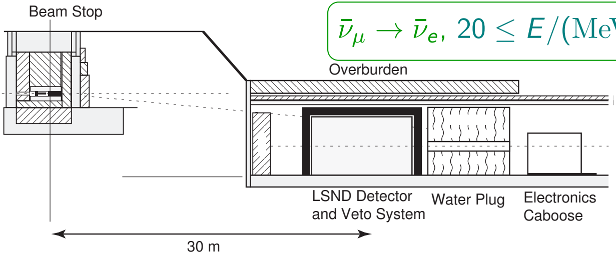





2 σ
LSND
MiniBooNE
KARMEN
NOMAD
BNL–E776
ICARUS
OPERA
Combined
1σ
2σ
3σ
Δm^2_{41} [eV^2]
$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2$
10^2
10
1
10^{-1}
10^{-2}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1

LSND

[PRD 64 (2001) 112007]



$\bar{\nu}_\mu \to \bar{\nu}_e$, $20 \leq E/(\mathrm{MeV}) \leq 52.8$

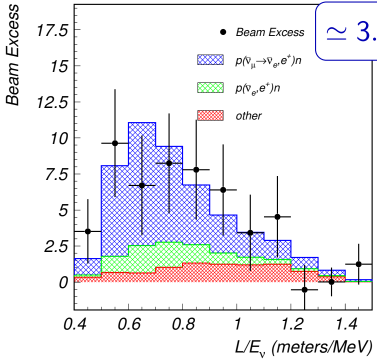
well known source of $\bar{\nu}_\mu$:

$$p + \mathrm{target} \to \pi^+ \xrightarrow{\text{at rest}} \mu^+ + \nu_\mu$$

$$\mu^+ \xrightarrow{\text{at rest}} e^+ + \nu_e + \bar{\nu}_\mu$$

$L \simeq 30$ m

$$\bar{\nu}_e + p \longrightarrow n + e^+$$



$\simeq 3.8\sigma$

No signal seen in KARMEN ($L \simeq 18$ m)

[PRD 65 (2002) 112001]

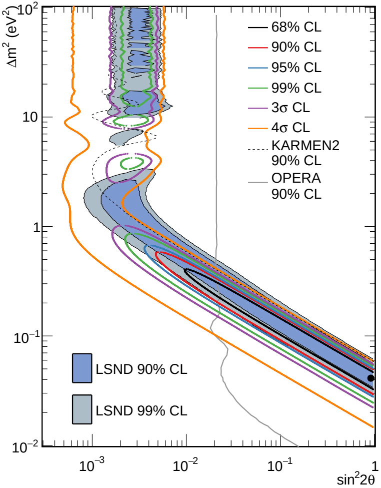
MiniBooNE

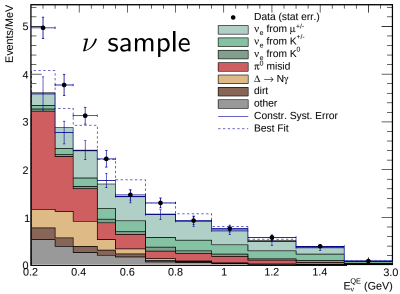
[PRL 121 (2018) 221801]

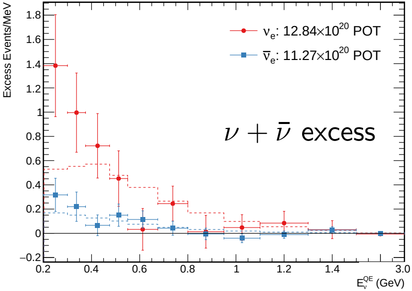
purpose: check LSND signal

$L \simeq 541$ m, 200 MeV $\leq E \lesssim$ 3 GeV

no money, no near detector







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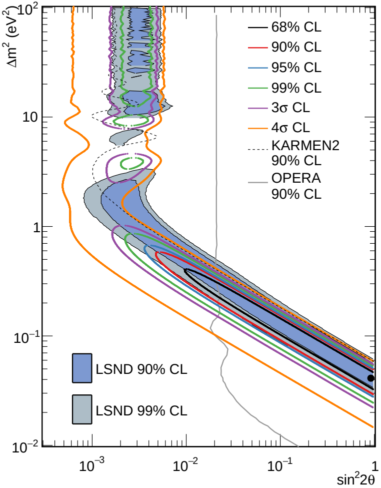
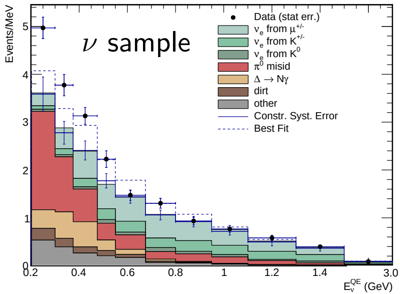
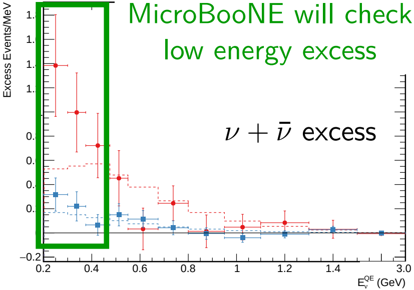


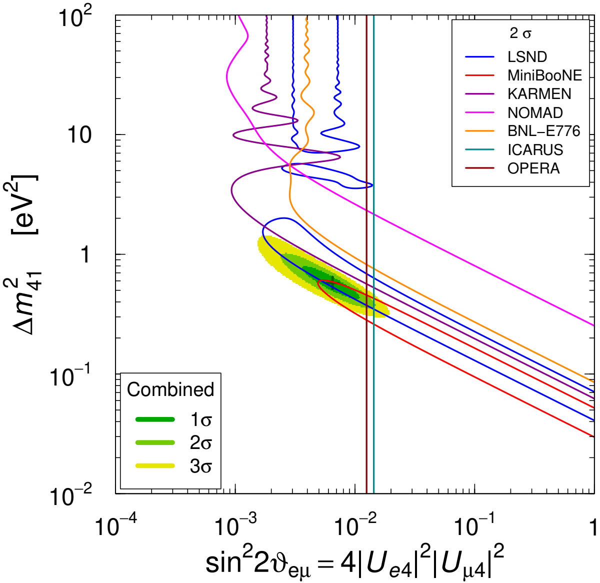




MicroBooNE will check low energy excess

Global fit of $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ APP

[SG+, in preparation]



with full MiniBooNE data

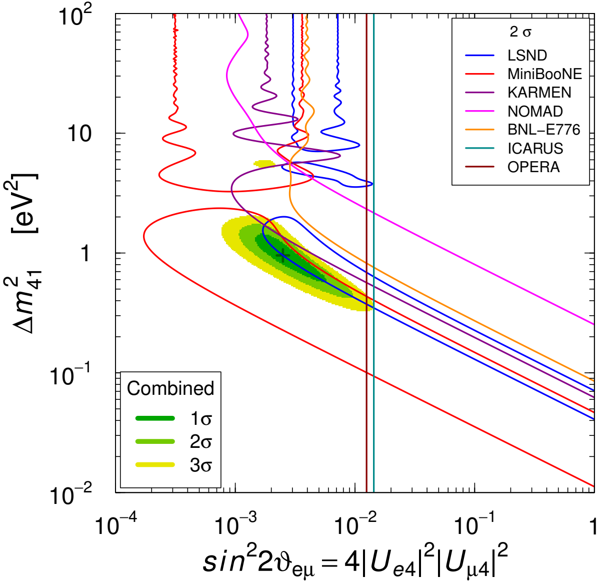
ICARUS and OPERA exclude MiniBooNE best fit

LSND and MiniBooNE only partially in agreement

KARMEN cuts part of LSND region

Global fit of $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ APP

[SG+, in preparation]

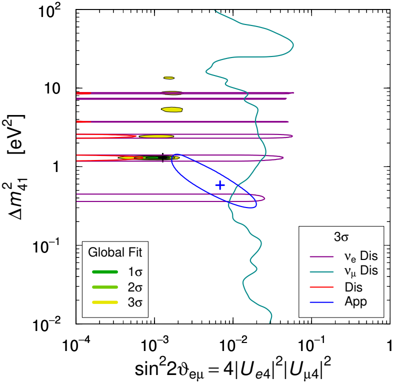


without MiniBooNE low energy bins

ICARUS and OPERA exclude MiniBooNE best fit

LSND and MiniBooNE only partially in agreement

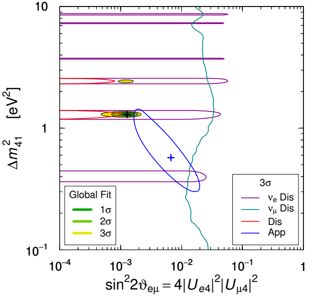
KARMEN cuts part of LSND region


Δm^2_{41} [eV^2]
$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2$
Global Fit
1σ
2σ
3σ
3σ
ν_e Dis
ν_μ Dis
Dis
App

APP – DIS tension in 2019

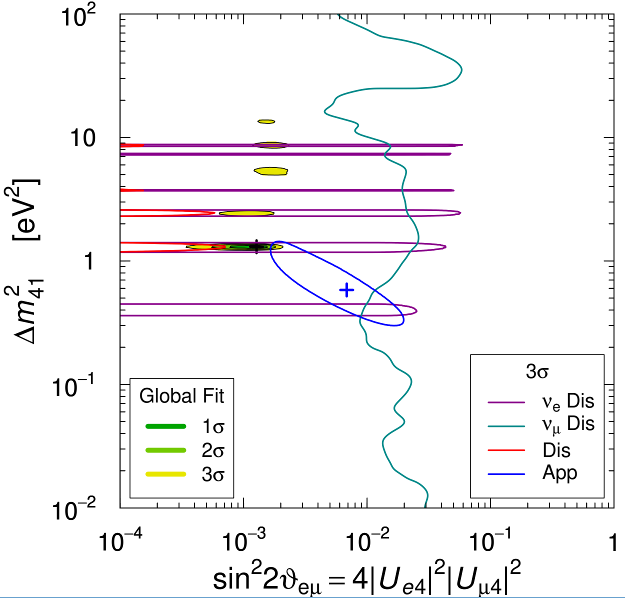
[SG+, in preparation]

Status just after Neutrino 2018:



MINOS+ update, new data including MiniBooNE (all bins)

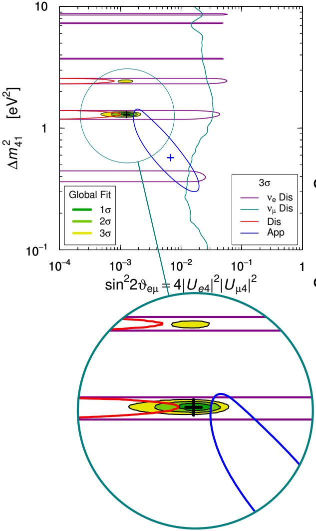
Status in early 2019



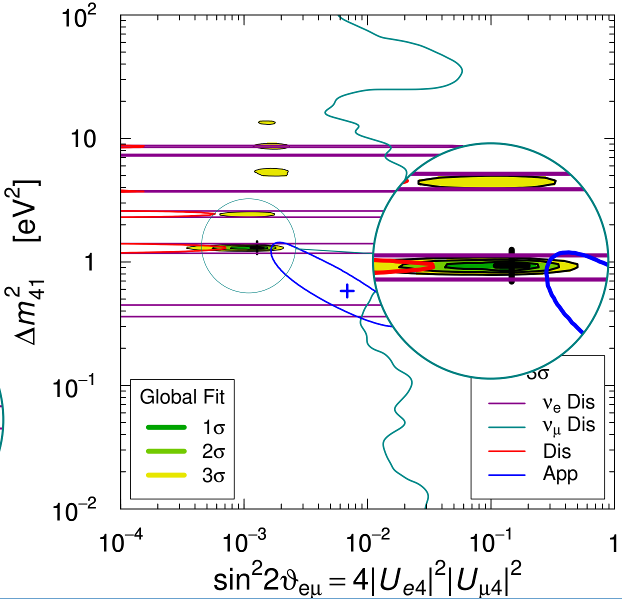
APP – DIS tension in 2019

[SG+, in preparation]

Status just after Neutrino 2018:

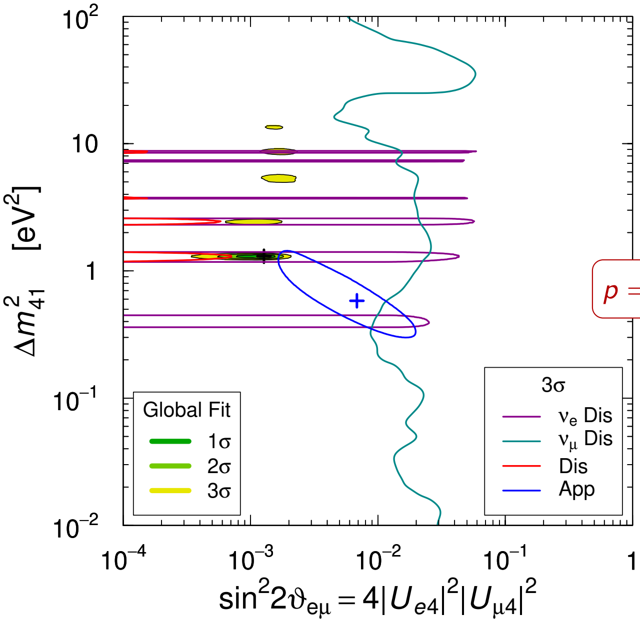


Status in early 2019



APP – DIS tension in 2019

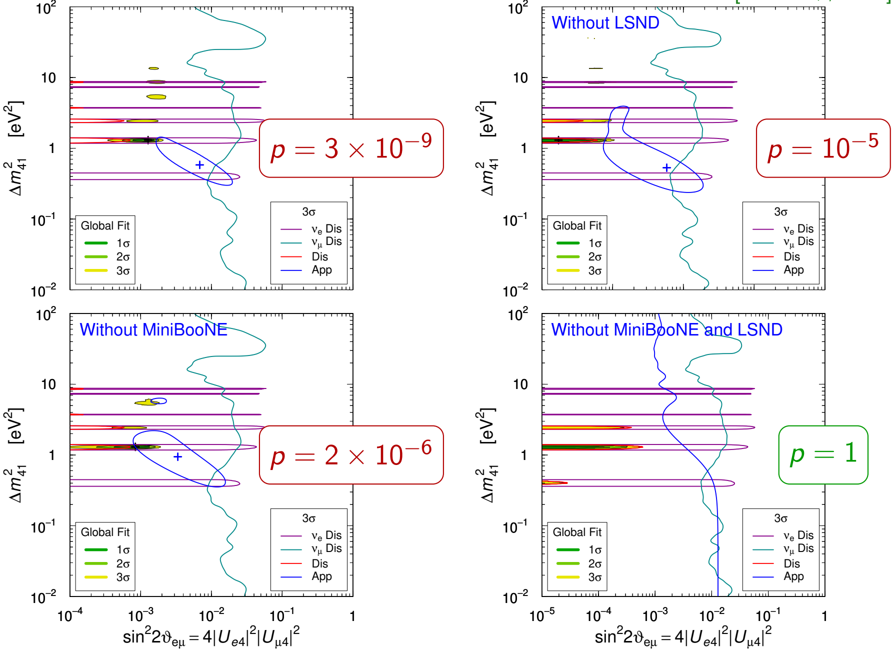
[SG+, in preparation]

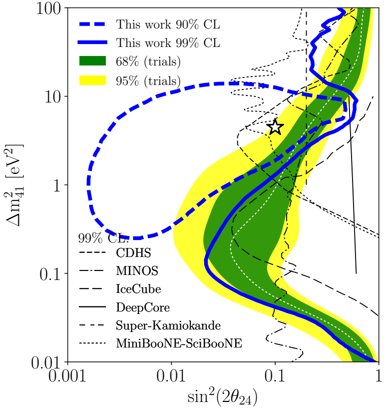


$p = 3 \times 10^{-9}$

APP – DIS tension in 2019

[SG+, in preparation]
see also [Dentler+, 2018]



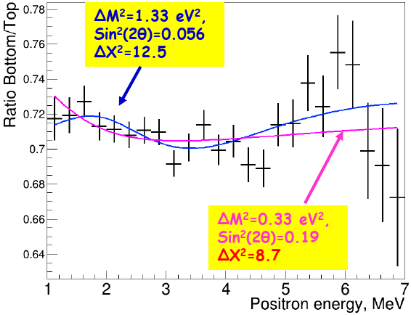


This work 90% CL
This work 99% CL
68% (trials)
95% (trials)
99% CL:
CDHS
MINOS
IceCube
DeepCore
Super-Kamiokande
MiniBooNE-SciBooNE
Δm^2_{41} [eV^2]
$\sin^2(2\theta_{24})$
100
10
1
0.1
0.01
0.001
0.01
0.1
1

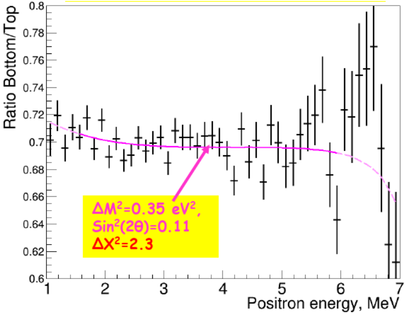
DANSS in 2019

[Danilov@EPS-HEP, 2019]

old data



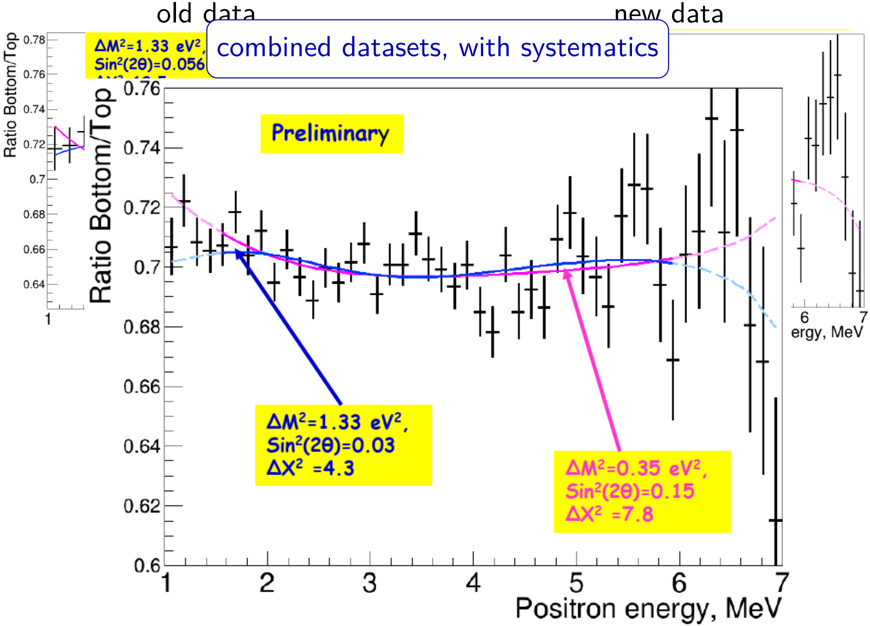
new data



New analysis also considers systematics!

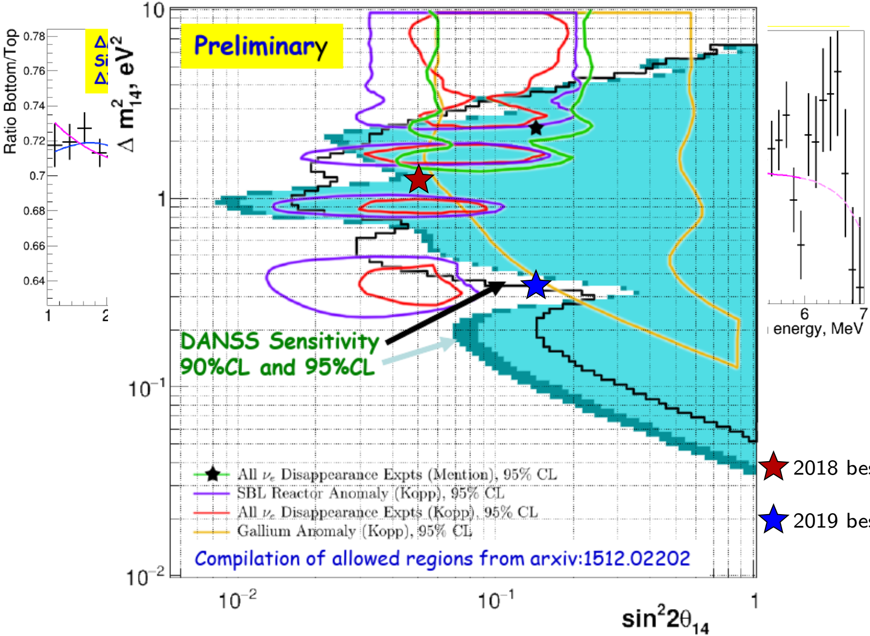
DANSS in 2019

[Danilov@EPS-HEP, 2019]



DANSS in 2019

[Danilov@EPS-HEP, 2019]

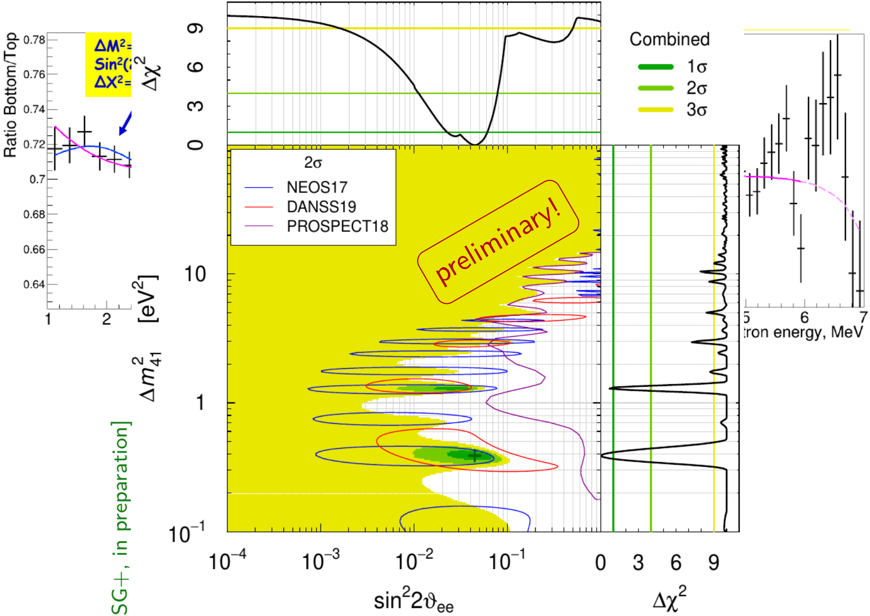


2018 best fit

2019 best fit

DANSS in 2019

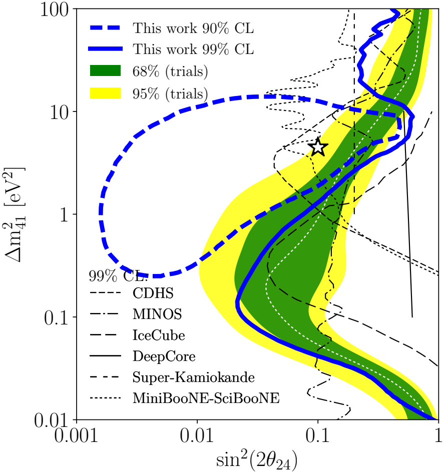
[Danilov@EPS-HEP, 2019]

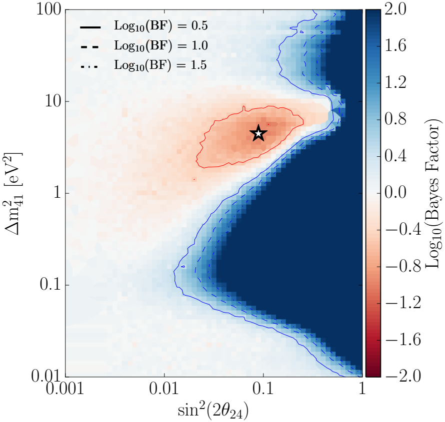


[SG+, in preparation]

IceCube 8 yr update

[IceCube, arxiv:2005.12942]

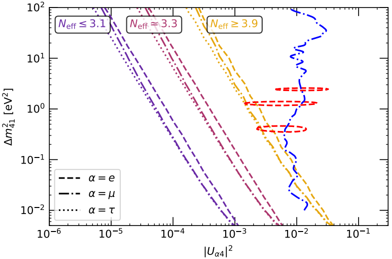




first indication in favor of sterile from ν_μ DIS!

although rather weak: $\log_{10} BF \simeq 1$ (weak preference)

or compatible with no oscillations at p-value of 8%


$N_{\rm eff} \leq 3.1$
$N_{\rm eff} \simeq 3.3$
$N_{\rm eff} \geq 3.9$
$\alpha = e$
$\alpha = \mu$
$\alpha = \tau$
Δm^2_{41} [eV^2]
$|U_{\alpha 4}|^2$
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}

ν oscillations in the early universe

[SG+, JCAP 07 (2019) 014]

comoving coordinates: $a = 1/T \quad x \equiv m_e\, a \quad y \equiv p\, a \quad z \equiv T_\gamma\, a \quad w \equiv T_\nu\, a$

density matrix: $$\varrho(x,y) = \begin{pmatrix} \varrho_{ee} \equiv f_{\nu_e} & \varrho_{e\mu} & \varrho_{e\tau} & \varrho_{es} \\ \varrho_{\mu e} & \varrho_{\mu\mu} \equiv f_{\nu_\mu} & \varrho_{\mu\tau} & \varrho_{\mu s} \\ \varrho_{\tau e} & \varrho_{\tau\mu} & \varrho_{\tau\tau} \equiv f_{\nu_\tau} & \varrho_{\tau s} \\ \varrho_{se} & \varrho_{s\mu} & \varrho_{s\tau} & \varrho_{ss} \equiv f_{\nu_s} \end{pmatrix}$$

$$\frac{\mathrm{d}\varrho(y,x)}{\mathrm{d}x} = \sqrt{\frac{3m_{\mathrm{Pl}}^2}{8\pi\rho_{\mathrm{T}}}} \left\{ -i\frac{x^2}{m_e^3}\left[\frac{\mathbb{M}_{\mathrm{F}}}{2y} - \frac{8\sqrt{2}G_{\mathrm{F}}\, y m_e^6}{3x^6}\left(\frac{\mathbb{E}_\ell}{m_W^2} + \frac{\mathbb{E}_\nu}{m_Z^2} \right), \varrho \right] + \frac{m_e^3 G_{\mathrm{F}}^2}{(2\pi)^3 x^4 y^2}\mathcal{I}(\varrho) \right\}$$

m_{Pl} Planck mass – ρ_T total energy density – $m_{W,Z}$ mass of the W, Z bosons – G_{F} Fermi constant – $[.,.]$ commutator

ν oscillations in the early universe

[SG+, JCAP 07 (2019) 014]

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$m_{\rm Pl}$ Planck mass – ρ_T total energy density – $m_{W,Z}$ mass of the W, Z bosons – $G_{\rm F}$ Fermi constant – $[.,.]$ commutator

$$\mathbb{M}_{\rm F} = U \mathbb{M} U^\dagger$$

$$\mathbb{M} = \mathrm{diag}(m_1^2, \ldots, m_N^2)$$

$$U = R^{34} R^{24} R^{14} R^{23} R^{13} R^{12}$$

e.g. $$R^{14} = \begin{pmatrix} \cos\theta_{14} & 0 & 0 & \sin\theta_{14} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\sin\theta_{14} & 0 & 0 & \cos\theta_{14} \end{pmatrix}$$

$$|U|^2 = \begin{pmatrix} \ldots & \ldots & \ldots & \sin^2\theta_{14} \\ \ldots & \ldots & \ldots & \cos^2\theta_{14}\sin^2\theta_{24} \\ \ldots & \ldots & \ldots & \cos^2\theta_{14}\cos^2\theta_{24}\sin^2\theta_{34} \\ \ldots & \ldots & \ldots & \cos^2\theta_{14}\cos^2\theta_{24}\cos^2\theta_{34} \end{pmatrix}$$

ν oscillations in the early universe

[SG+, JCAP 07 (2019) 014]

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$\mathbb{E}_\ell = \mathrm{diag}(\rho_e, \rho_\mu, 0, 0)$ $\qquad \mathbb{E}_\nu = S_a \left(\int dy y^3 \varrho \right) S_a$ $\quad$ with $S_a = \mathrm{diag}(1,1,1,0)$

lepton densities $\qquad$ neutrino densities $\qquad$ (only for active neutrinos)

take into account matter effects in oscillations

ν oscillations in the early universe

[SG+, JCAP 07 (2019) 014]

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$\mathcal{I}(\varrho)$ collision integrals

take into account neutrino-electron scattering and pair annihilation

2D integrals over the momentum, take most of the computation time

ν oscillations in the early universe

[SG+, JCAP 07 (2019) 014]

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from continuity equation $\dot\rho = -3H(\rho + P)$

$$\frac{\mathrm{d}z}{\mathrm{d}x} = \frac{\displaystyle\sum_{\ell=e,\mu}\left[\frac{r_\ell^2}{r}J(r_\ell)\right] + G_1(r) - \frac{1}{2\pi^2 z^3}\int_0^\infty dy\, y^3 \sum_{\alpha=e}^{s}\frac{\mathrm{d}\varrho_{\alpha\alpha}}{\mathrm{d}x}}{\displaystyle\sum_{\ell=e,\mu}\left[r_\ell^2 J(r_\ell) + Y(r_\ell)\right] + G_2(r) + \frac{2\pi^2}{15}}$$

$r = x/z$, $r_\ell = m_\ell/m_e\, r$ $\quad$ $J(r)$, $Y(r)$ from non-relativistic transition of $e^\pm$, $\mu^\pm$

$G_1(r)$ and $G_2(r)$ from electromagnetic corrections

ν oscillations in the early universe

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neutrino temperature w: same equation as z, but electrons always relativistic

ν oscillations in the early universe

[SG+, JCAP 07 (2019) 014]

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initial conditions: $\varrho_{\alpha\alpha}$ = Fermi-Dirac at $x_{\mathrm{in}} \simeq 0.001$, with $w = z \simeq 1$

ν oscillations in the early universe

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$m_{\rm Pl}$ … commutator

FORTran-Evolved PrimordIAl Neutrino Oscillations (FortEPiaNO)
https://bitbucket.org/ahep_cosmo/fortepiano

from continuity equation
$\dot\rho = -3H(\rho + P)$

will be public soon

$$\frac{\mathrm{d}z}{\mathrm{d}x} = \frac{\sum_{\ell=e,\mu}\left[\,r \ldots\right] \ldots) - \frac{1}{2\pi^2 z^3}\int_0^\infty dy\, y^3 \sum_{\alpha=e}^{s}\frac{\mathrm{d}\varrho_{\alpha\alpha}}{\mathrm{d}x}}{\sum_{\ell=e,\mu}\left[r_\ell^2 J(r_\ell) + Y(r_\ell)\right] + G_2(r) + \frac{2\pi^2}{15}}$$

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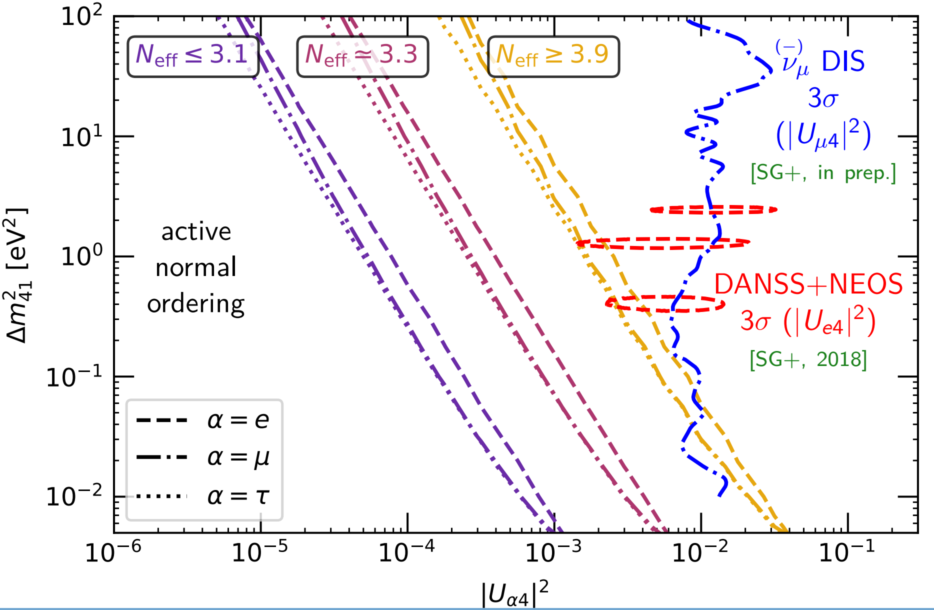
$N_{\rm eff}$ and the new mixing parameters

[SG+, JCAP 07 (2019) 014]

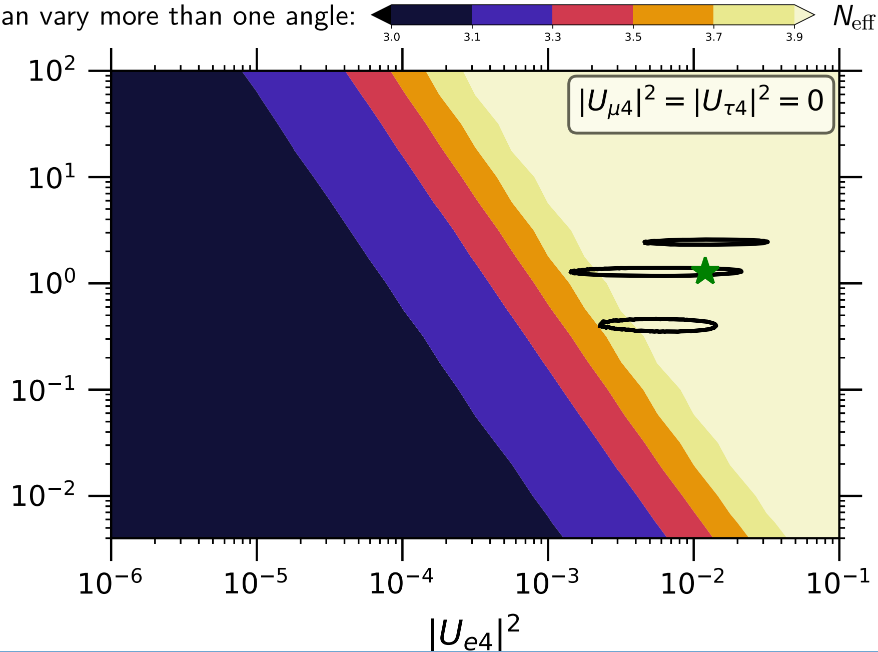
Only vary one angle and fix two to zero: do they have the same effect?



$N_{\rm eff}$ and the new mixing parameters

[SG+, JCAP 07 (2019) 014]

We can vary more than one angle:



N_{eff} and the new mixing parameters

[SG+, JCAP 07 (2019) 014]

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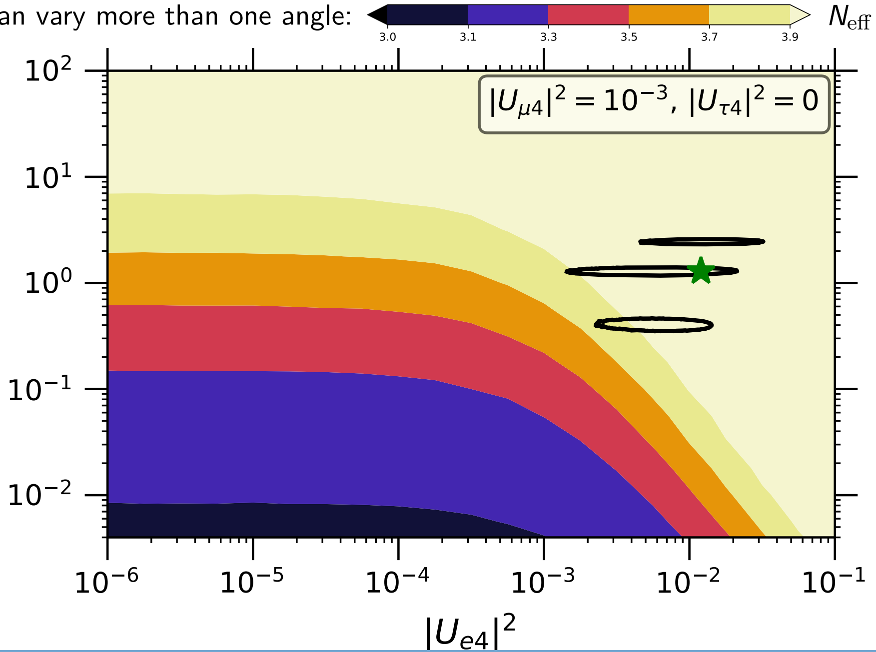

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[SG+, JCAP 07 (2019) 014]

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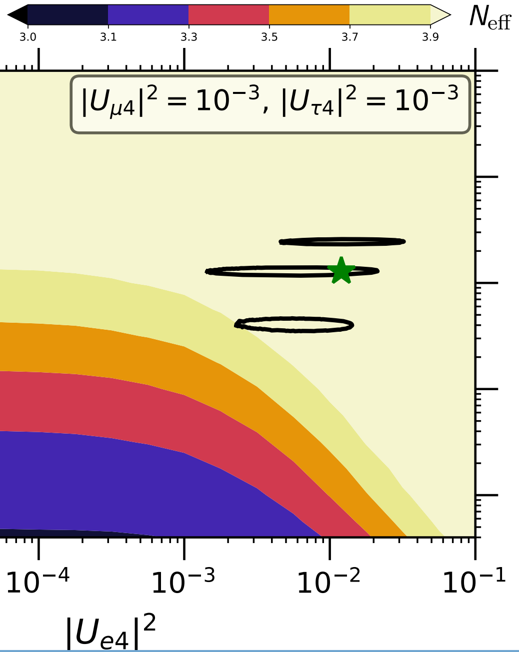
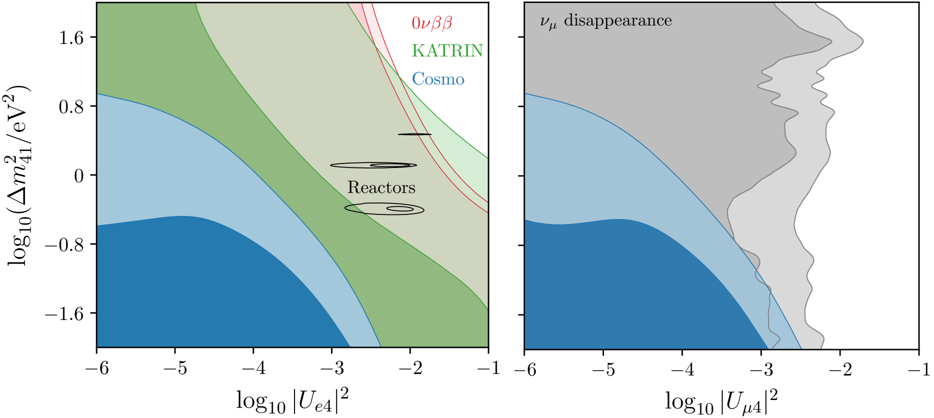


Comparing constraints

[arxiv:2003.02289]

Cosmological constraints are stronger than most other probes

But much more model dependent (as all the cosmological constraints)!



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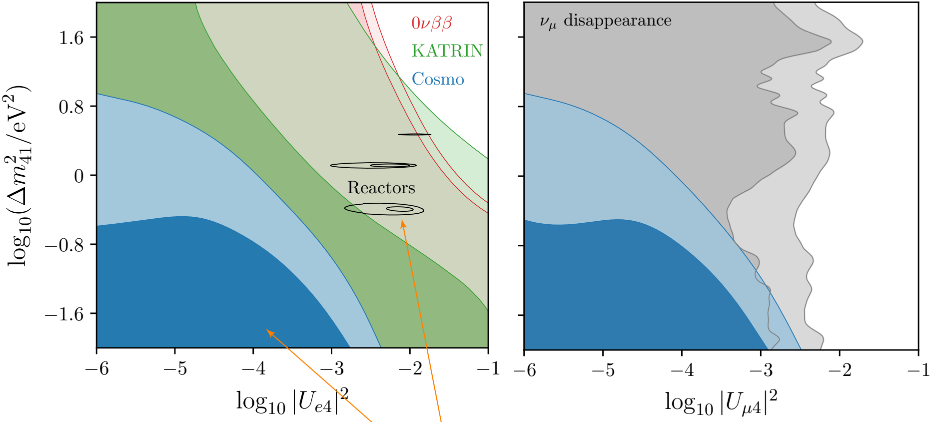


Warning: tension between reactor experiments and CMB bounds!

Conclusions

1

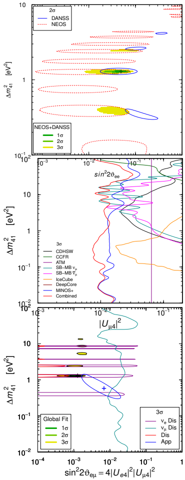
Unclear model-independent results
from $\overset{(-)}{\nu}_e$ DIS, plus discrepancy
with Gallium anomaly and RAA

2

no significant evidence in $\overset{(-)}{\nu}_\mu$ DIS:
rather strong upper bounds on $|U_{\mu 4}|^2$,
but also constraints on $|U_{\tau 4}|^2$

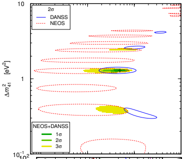
3

strong APP-DIS tension
What are LSND/MiniBooNE observing?
Systematics or LSν or new physics?



Conclusions

1 Unclear model-independent results from $\overset{(-)}{\nu}_e$ DIS, plus discrepancy with Gallium anomaly and RAA



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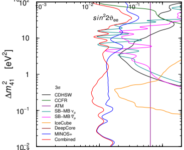

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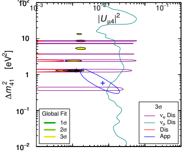
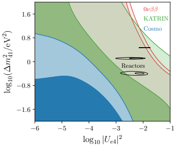


+1 oscillations in the early universe $\rightarrow N_{\rm eff} \simeq 4.05$
Planck constrains $N_{\rm eff} \lesssim 3.3$!
new physics needed? where???



Conclusions

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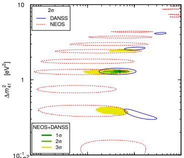
Unclear model-independent results

from $\overset{(-)}{\nu}_e$ DIS, plus discrepancy

with Gallium anomaly and RAA



2

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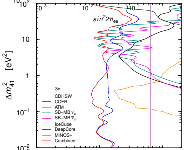

3

strong APP-DIS tension

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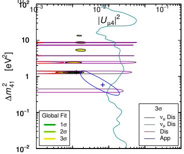
Systematics or LSν or new physics?



+1

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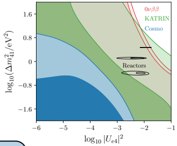

Thank you for the attention!