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Light sterile neutrinos: oscillations and cosmology

Matter to the Deepest, Katowice (PL), 1–6/09/2019

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 $\delta_{\rm CP}$

Current knowledge of the 3 active ν mixing: [de Salas et al. (2018)]

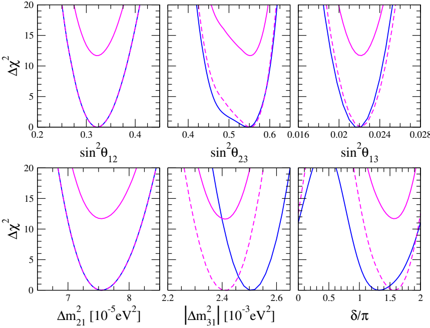
NO: Normal Ordering, $m_1 < m_2 < m_3$

IO: Inverted Ordering, $m_3 < m_1 < m_2$

$$\begin{aligned} \Delta m^2_{21} &= (7.55^{+0.20}_{-0.16}) \cdot 10^{-5}\ \mathrm{eV}^2 \\ |\Delta m^2_{31}| &= (2.50 \pm 0.03) \cdot 10^{-3}\ \mathrm{eV}^2\ (\mathrm{NO}) \\ &= (2.42^{+0.03}_{-0.04}) \cdot 10^{-3}\ \mathrm{eV}^2\ (\mathrm{IO}) \end{aligned}$$

$$\begin{aligned} \sin^2(\theta_{12}) &= 0.320^{+0.020}_{-0.016} \\ \sin^2(\theta_{13}) &= 0.0216^{+0.008}_{-0.007}\ (\mathrm{NO}) \\ &= 0.0222^{+0.007}_{-0.008}\ (\mathrm{IO}) \\ \sin^2(\theta_{23}) &= 0.547^{+0.020}_{-0.030}\ (\mathrm{NO}) \\ &= 0.551^{+0.018}_{-0.030}\ (\mathrm{IO}) \end{aligned}$$

First hints for $\delta_{\rm CP} \simeq 3/2\pi$

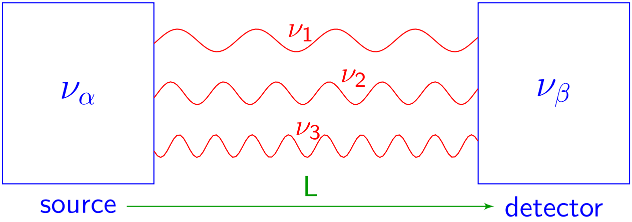


see also: http://globalfit.astroparticles.es

Two types of neutrinos

flavor neutrinos ν_α | $|\nu_\alpha\rangle = U_{\alpha k}|\nu_k\rangle$ | massive neutrinos ν_k

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



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

$E_k^2 = p^2 + m_k^2 \longleftarrow$ define $\longrightarrow t = L$

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

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

A large family

In principle, previous discussion is valid for N neutrinos

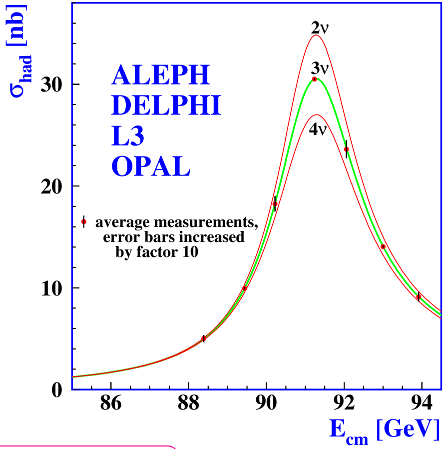
only constraint: there are exactly three flavor neutrinos in the SM

[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

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

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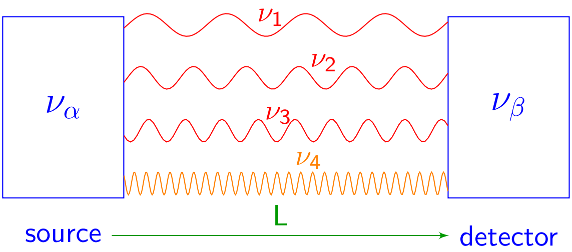
Our case will be 3 (active)+1 (sterile), a perturbation of 3 neutrinos case

$m_4 \gg m_\ell$
$\ell = 1, 2, 3$

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



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: $\dfrac{\Delta m^2_{41} L}{E} \simeq 1$

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 $\overset{(-)}{\nu}_\beta$

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$\overset{(-)}{\nu}_s$ goes undetected

CP violation cannot be observed in SBL experiments!

New mixings in the 3+1 scenario

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

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ϑ_{14}

ϑ_{24}

ϑ_{34}

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

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

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

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

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

APPearance

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

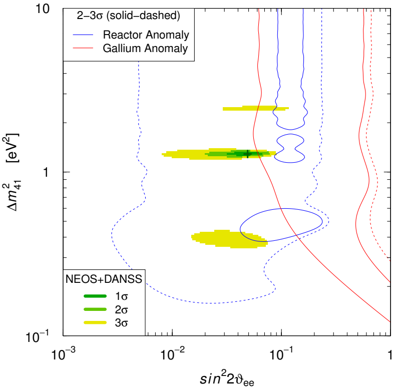
$$\sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha4}|^2|U_{\beta4}|^2$$

$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ — 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
10
1
10^{-1}
10^{-3}
10^{-2}
10^{-1}
1
Δm^2_{41} [eV^2]
$sin^2 2\vartheta_{ee}$

Gallium anomaly

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

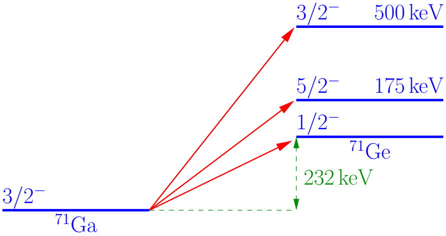
$L \simeq 1.9$ m $\quad L \simeq 0.6$ m

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]

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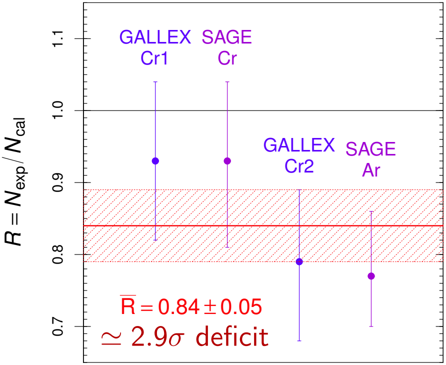
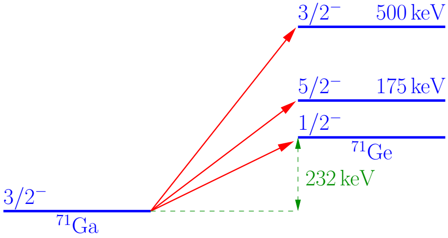
Test detection of solar ν_e





cross sections of the transitions from

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

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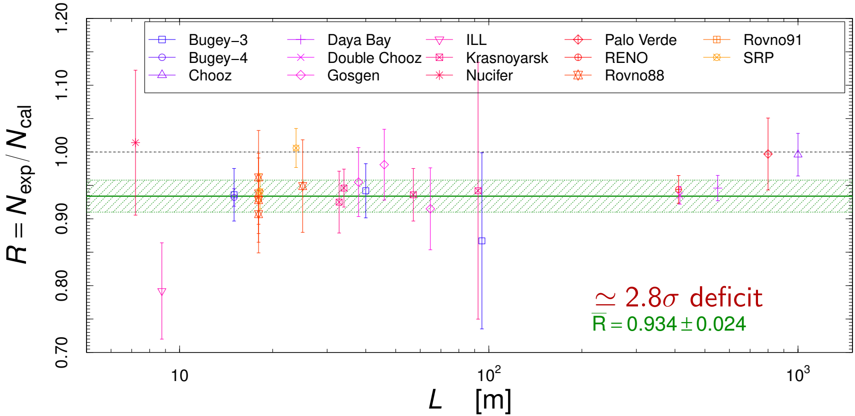
Reactor Antineutrino Anomaly (RAA)

[PRD 83 (2011) 073006]

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

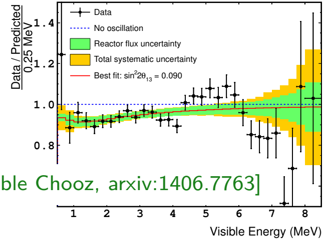
[Huber, PRC 84 (2011) 024617] [Mueller et al., PRC 83 (2011) 054615]

Previous reactor rates evaluated with new fluxes ⇒ deficit

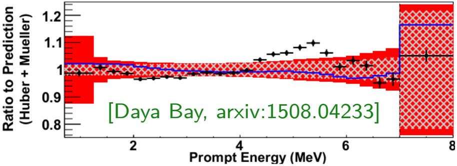


Suppression at detector due to active-sterile oscillations?

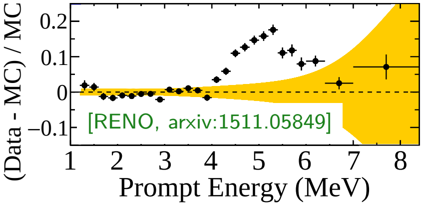
Can we trust the HM fluxes?



[Double Chooz, arxiv:1406.7763]



[Daya Bay, arxiv:1508.04233]



[RENO, arxiv:1511.05849]

2014:

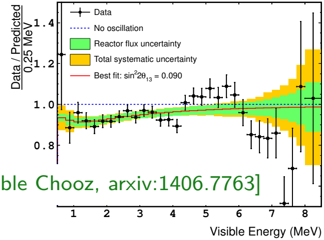
bump in the spectrum around 5 MeV!

cannot be explained by SBL oscillations

(averaged at the observed distances)

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

Can we trust the HM fluxes?



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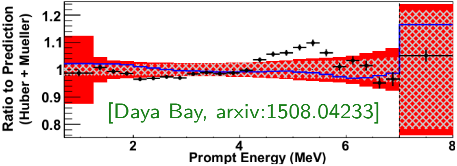

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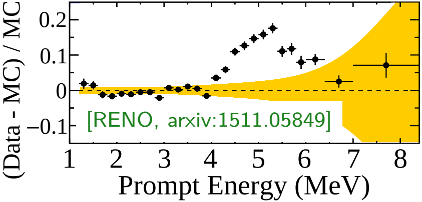

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Model independent information!

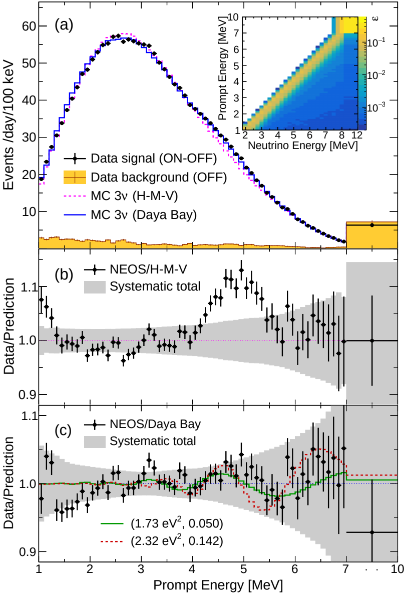
(i.e. take ratio of spectra at different distances)

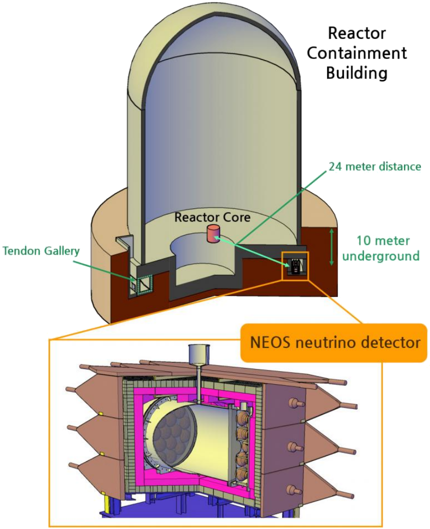
$$\Phi_1 = \Phi_0(E) f(L_1, E) \quad \Phi_2 = \Phi_0(E) f(L_2, E)$$

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

Single detector experiment

[PRL 118 (2017) 121802]



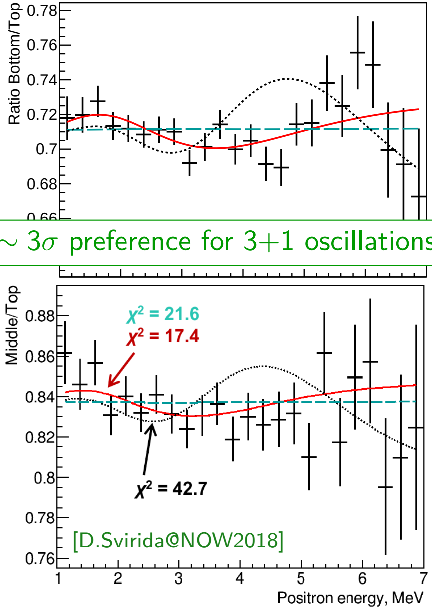


Ratio to DayaBay measurement to be model independent

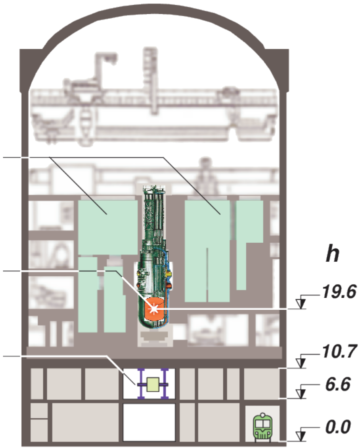
DANSS

[PLB 787 (2018) 56]

Single movable detector



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



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

DANSS

[PLB 787 (2018) 56]

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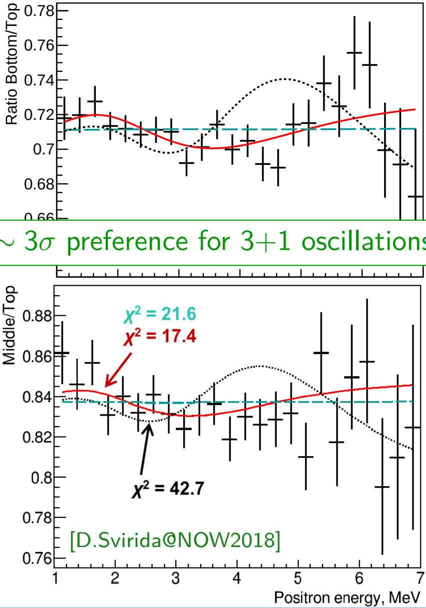

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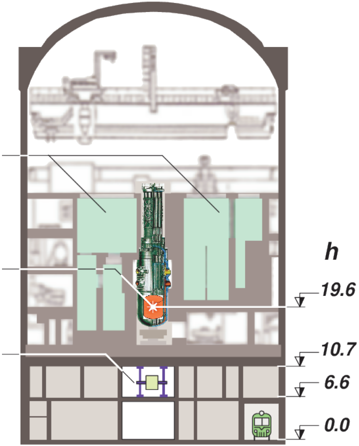

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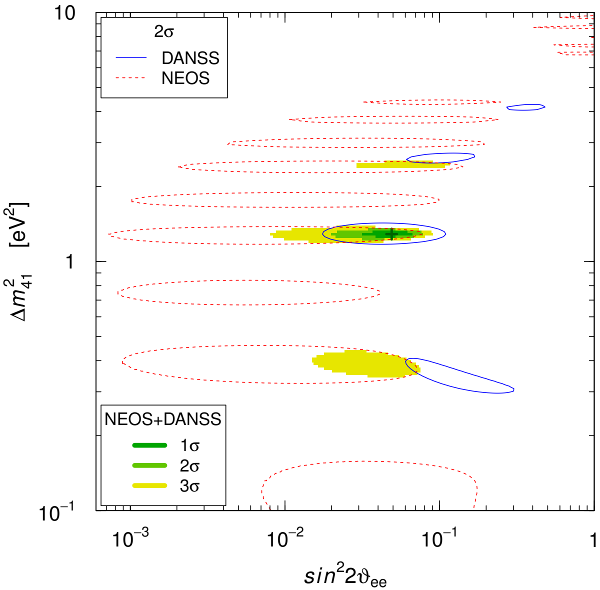
see later for 2019 update!

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

[SG+, PLB 782 (2018) 13]

NEOS + DANSS



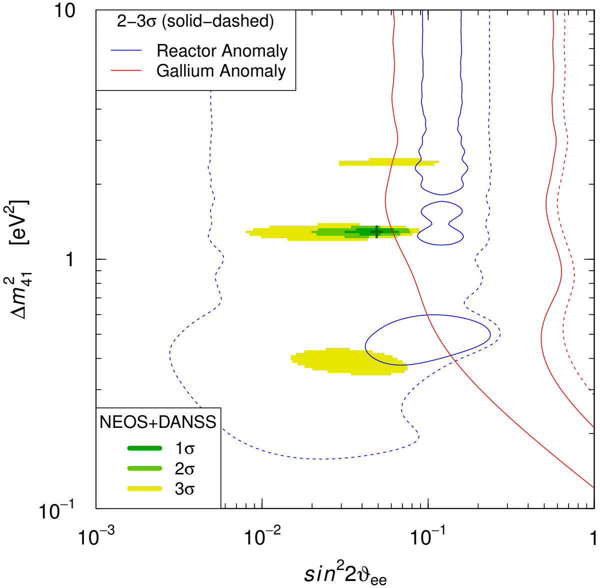
The NEOS and DANSS region perfectly overlap at

$$\Delta m^2_{41} \simeq 1.3 \text{ eV}^2$$
$$\sin^2 2\vartheta_{ee} \simeq 0.05$$
$$\sin^2 \vartheta_{14} \simeq 0.01$$

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

[SG+, PLB 782 (2018) 13]

DANSS + NEOS + RAA + Gallium

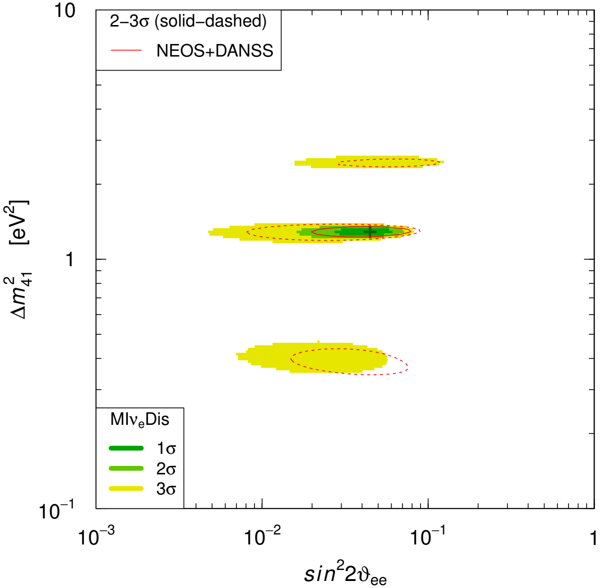


DANSS + NEOS
do not agree with
Gallium and RAA

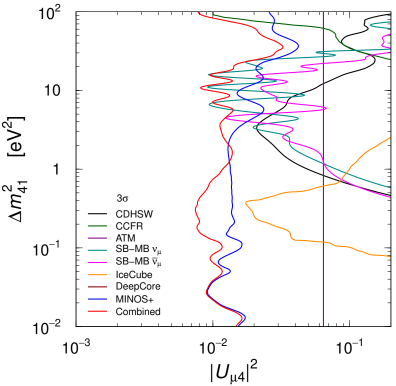
Model-independent fit of $\overset{(-)}{\nu}_e$ DIS (2018)

[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

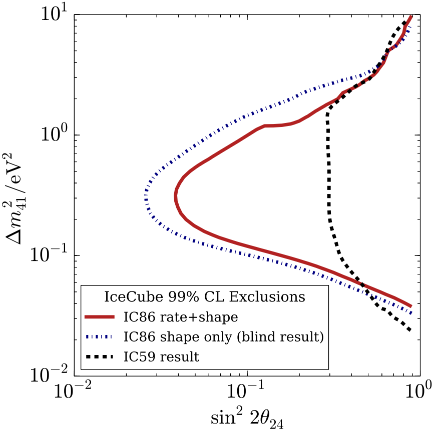
IceCube and DeepCore

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 GeV $< E <$ 20 TeV



[PRL 117 (2016) 071801]

IceCube and DeepCore

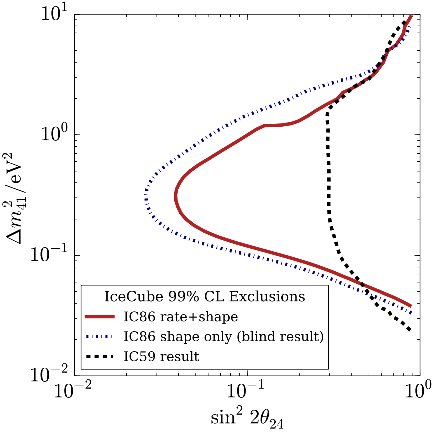
IceCube

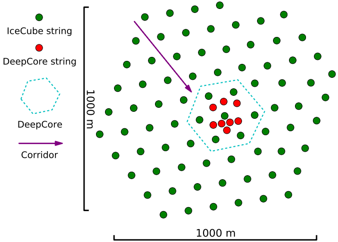
$\mathcal{O}(10\text{ km}) \lesssim L \lesssim \mathcal{O}(10^4\text{ km})$

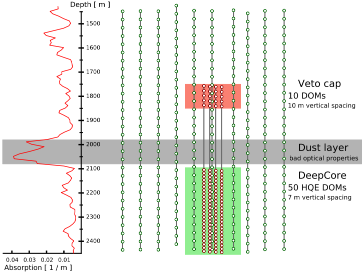
DeepCore

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

320 GeV $< E <$ 20 TeV







[PRL 117 (2016) 071801]

IceCube and DeepCore

IceCube

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

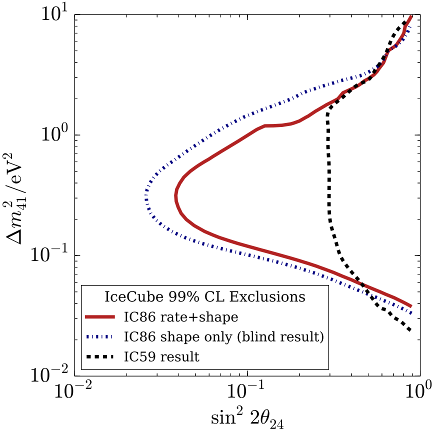
DeepCore

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

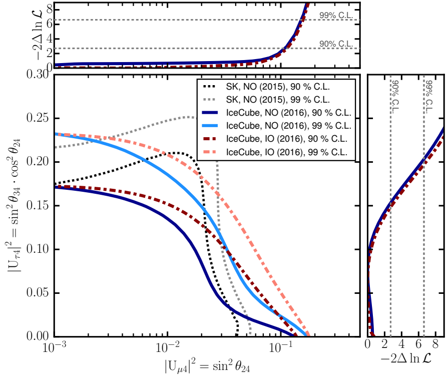
$320\text{ GeV} < E < 20\text{ TeV}$

$\sim 5 \times 10^3$ tracklike events

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



[PRL 117 (2016) 071801]



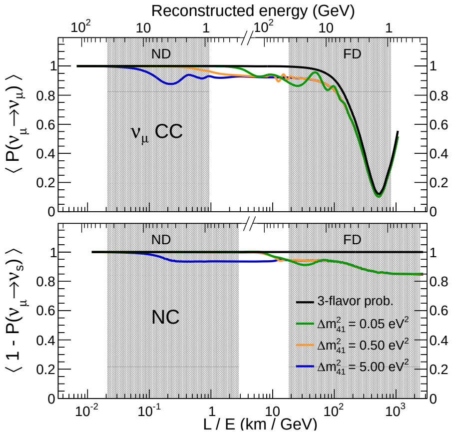
[PRD 95 (2017) 112002]

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



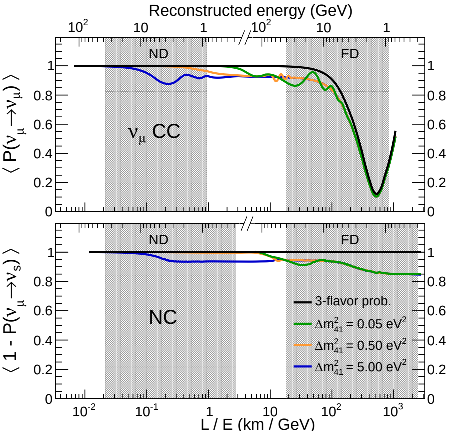
[PRL 117 (2016) 151803]: far-to-near ratio

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

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



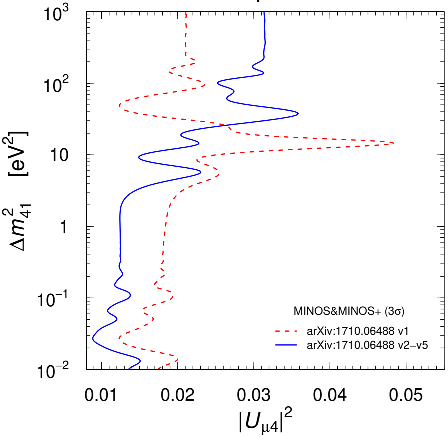
[PRL 117 (2016) 151803]:

far-to-near ratio

[PRL 122 (2019) 091803]:

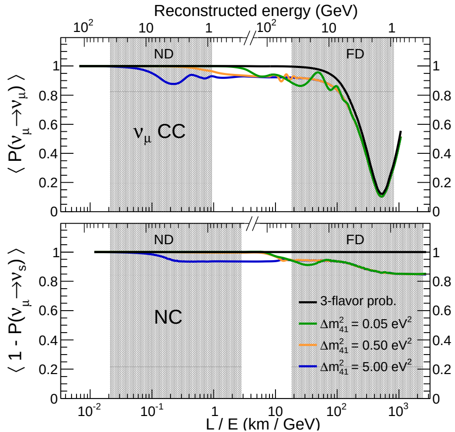
full two-detectors fit

MINOS+ update:



MINOS & MINOS+

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



[PRL 117 (2016) 151803]:

far-to-near ratio

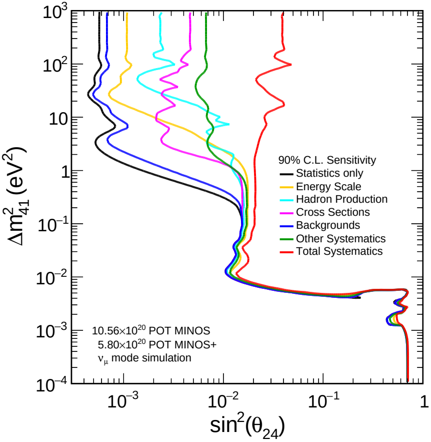
[PRL 122 (2019) 091803]:

full two-detectors fit

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

peak at 3 GeV

Systematics:

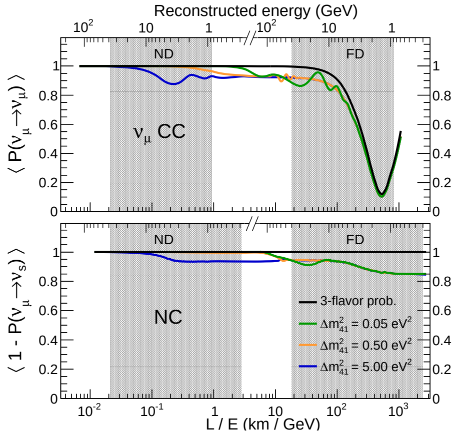


[PRL 122 (2019) 091803]

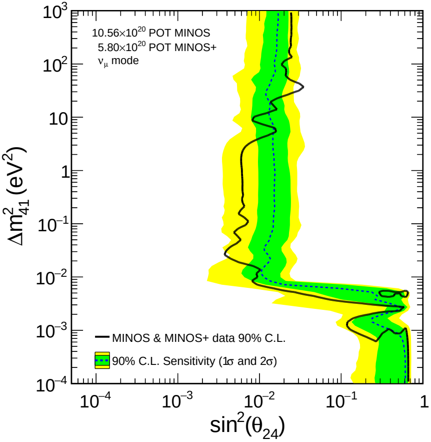
MINOS & MINOS+

Near (ND, ≃ 500 m) and far (FD, ≃ 800 km) detector

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



Sensitivity and exclusion limit:



[PRL 117 (2016) 151803]:

far-to-near ratio

[PRL 122 (2019) 091803]:

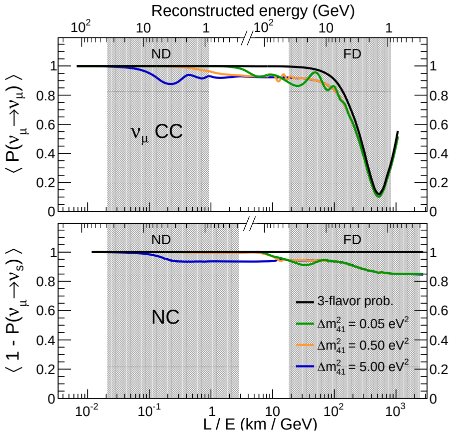
full two-detectors fit

[PRL 122 (2019) 091803]

MINOS & MINOS+

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

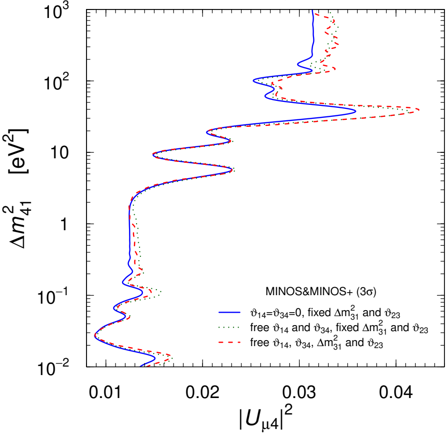
1 GeV $\lesssim E \lesssim$ 40 GeV, peak at 3 GeV



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

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

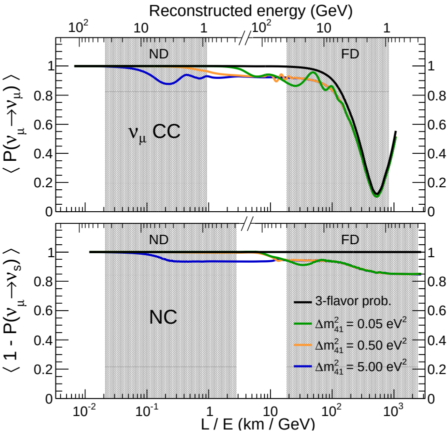
Marginalize over mixing parameters:



[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

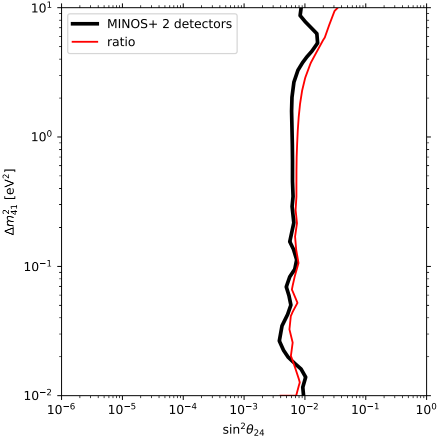
[PRL 122 (2019) 091803]:

full two-detectors fit

$1\ \text{GeV} \lesssim E \lesssim 40\ \text{GeV}$,

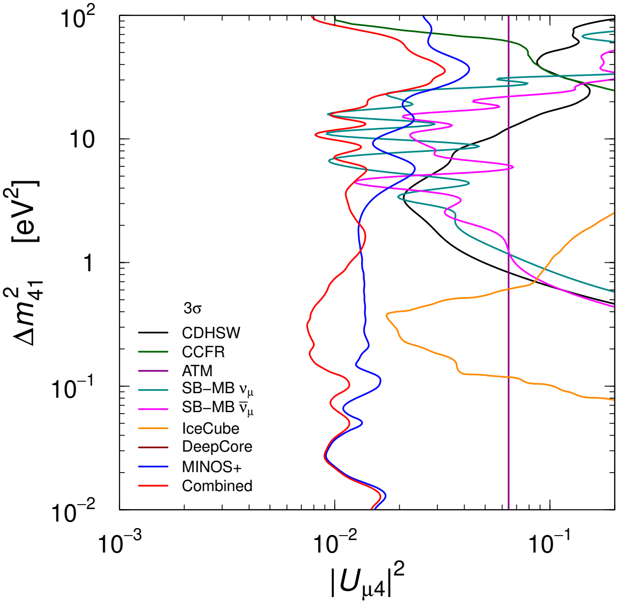
peak at 3 GeV

Two detectors vs ratio fit:



[SG+, in preparation]

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

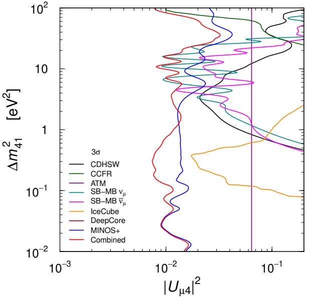


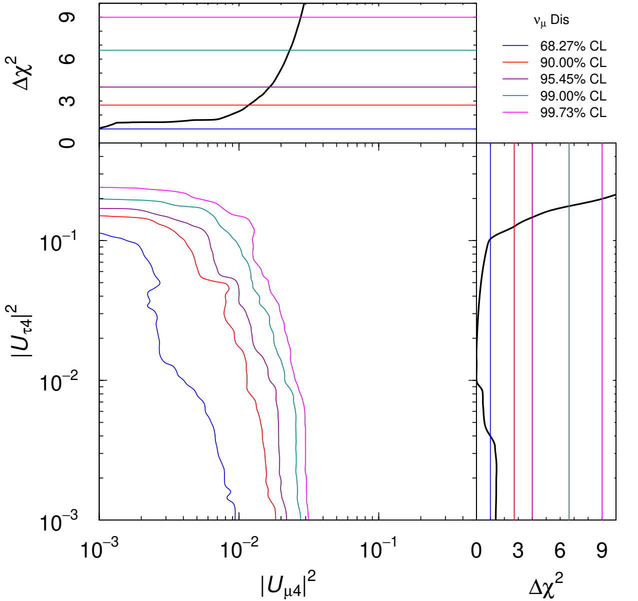
MINOS+
dominates
at small Δm^2_{41}

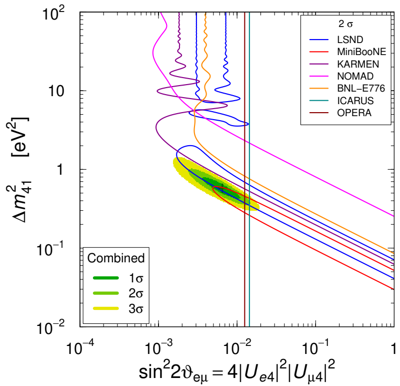
IceCube
important at
$\Delta m^2_{41} \simeq 0.2$ eV^2

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

[SG+, in preparation]



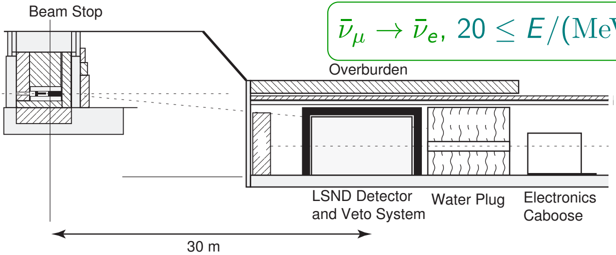



2 σ
LSND
MiniBooNE
KARMEN
NOMAD
BNL–E776
ICARUS
OPERA
Combined
1σ
2σ
3σ
Δm^2_{41} [eV^2]
10^2
10
1
10^{-1}
10^{-2}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2$

LSND

[PRD 64 (2001) 112007]

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



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

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

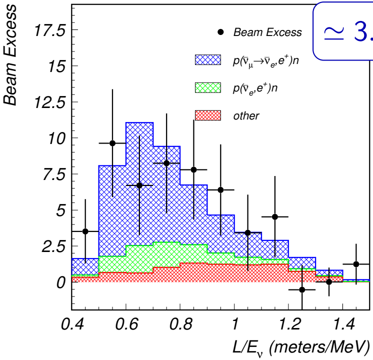
$$\mu^+ \xrightarrow{\mathrm{at\ rest}} e^+ + \nu_e + \bar{\nu}_\mu$$

$L \simeq 30$ m

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

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

[PRD 65 (2002) 112001]



$\simeq 3.8\sigma$

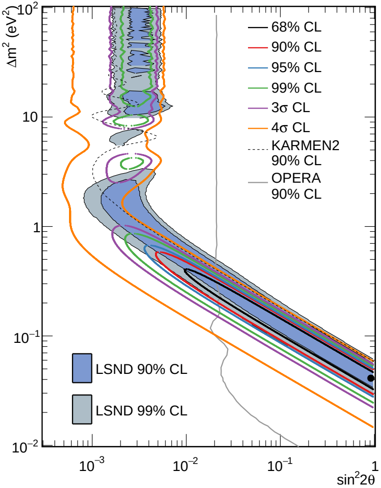
MiniBooNE

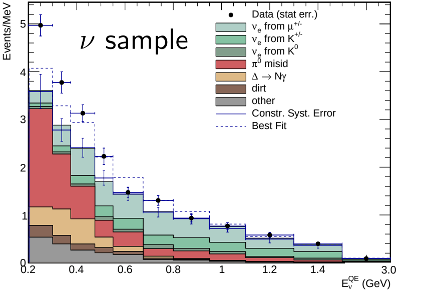
[PRL 121 (2018) 221801]

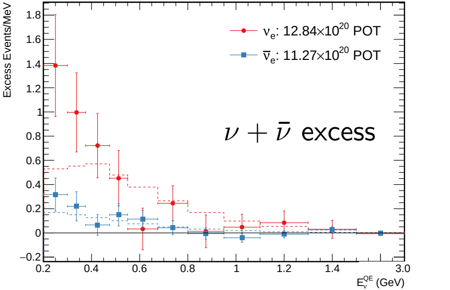
purpose: check LSND signal

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

no money, no near detector







MiniBooNE

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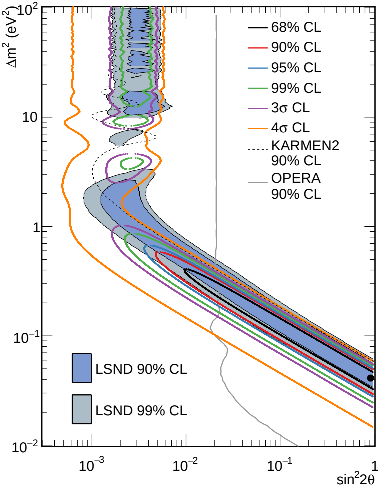
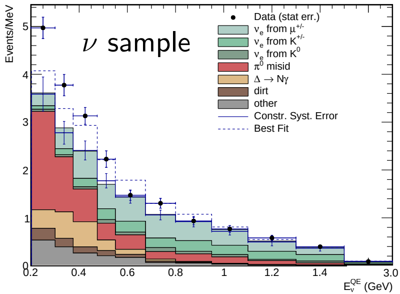
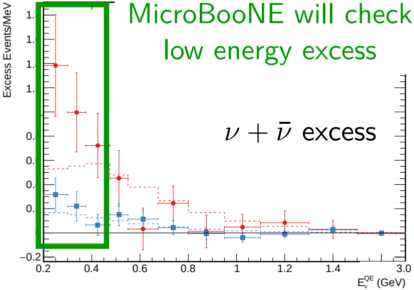
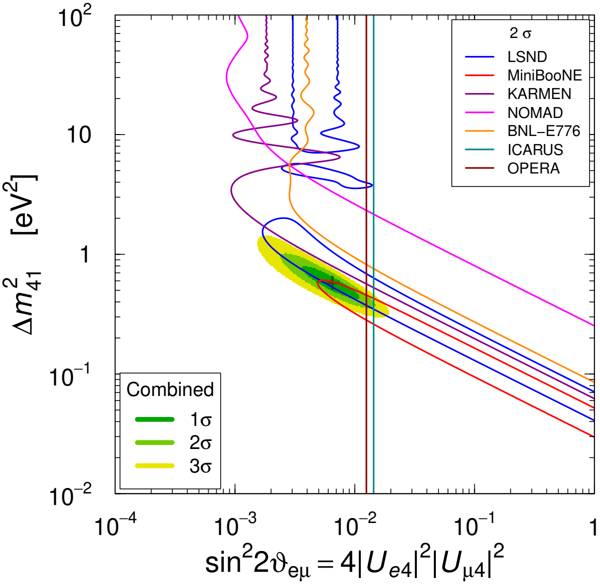






MicroBooNE will check low energy excess

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



with full MiniBooNE data

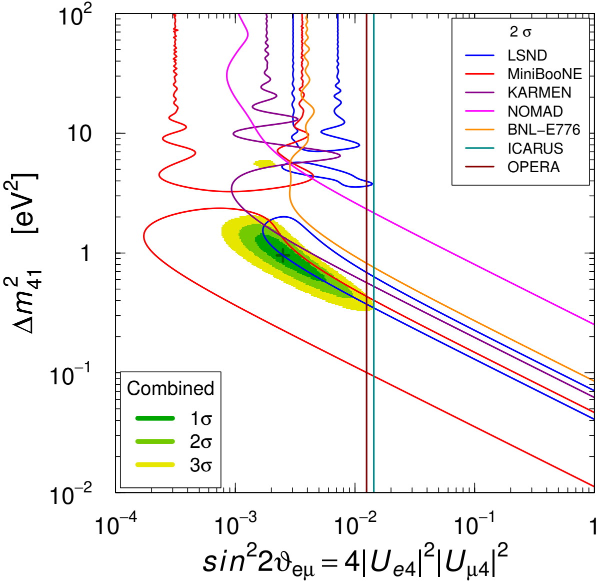
ICARUS and OPERA exclude MiniBooNE best fit

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

1 Neutrino Oscillations - Some theory

2 Electron (anti)neutrino disappearence

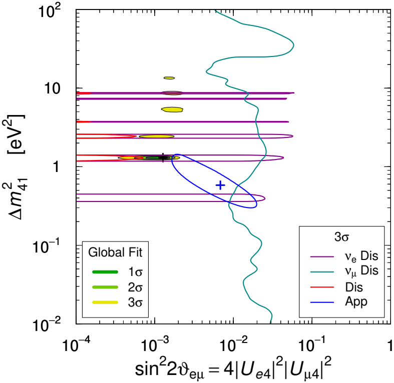
3 Muon (anti)neutrino disappearence

4 Electron (anti)neutrino appearence

5 Global fit

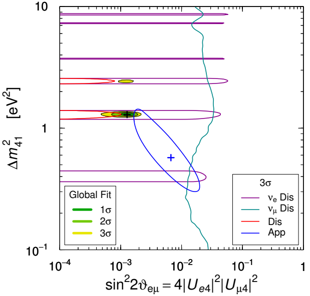
6 Cosmology

7 Conclusions

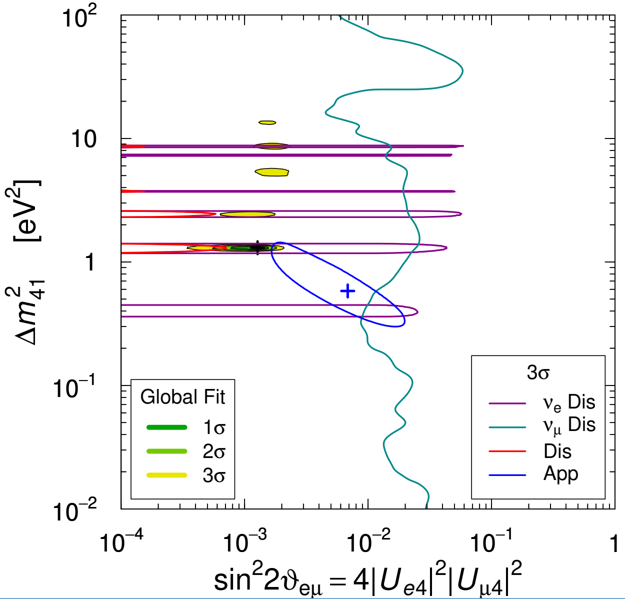


APP – DIS tension in 2019

Status just after Neutrino 2018:



Status in early 2019

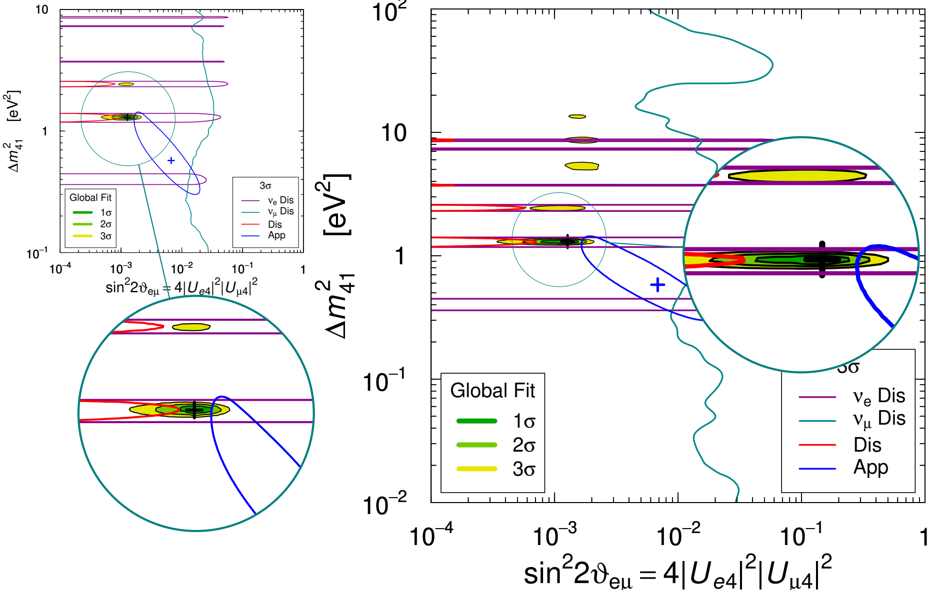


MINOS+ update,
new data
including MiniBooNE
(all bins)

APP – DIS tension in 2019

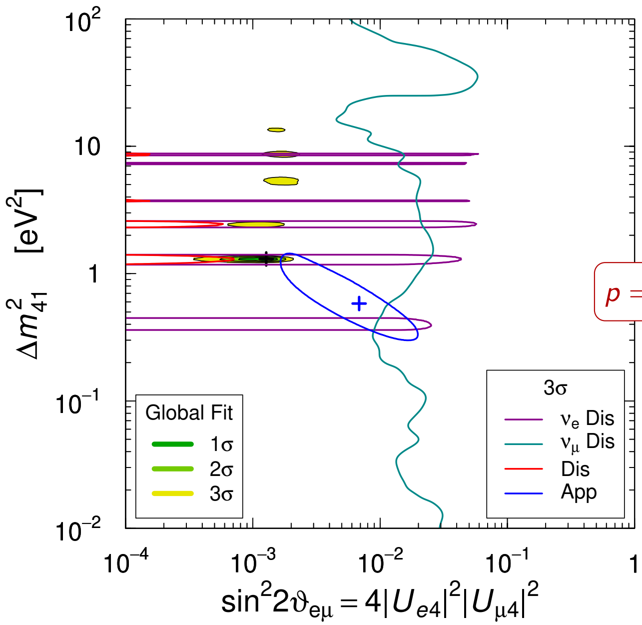
Status just after Neutrino 2018:

Status in early 2019



APP – DIS tension in 2019

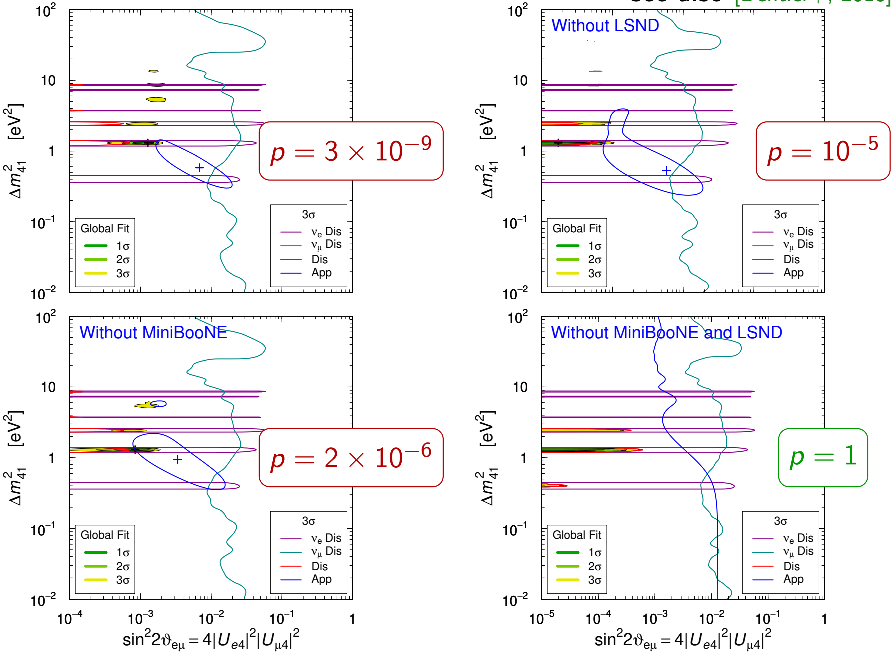
[SG+, in preparation]



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

APP – DIS tension in 2019

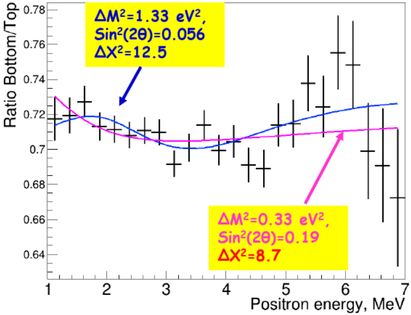
[SG+, in preparation]
see also [Dentler+, 2018]



DANSS in 2019

[Danilov@EPS-HEP, 2019]

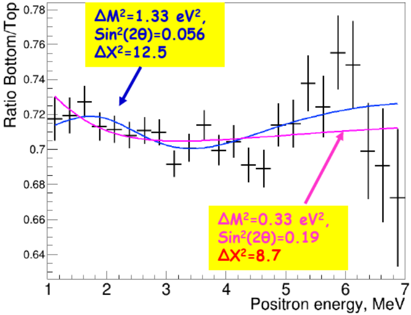
old data



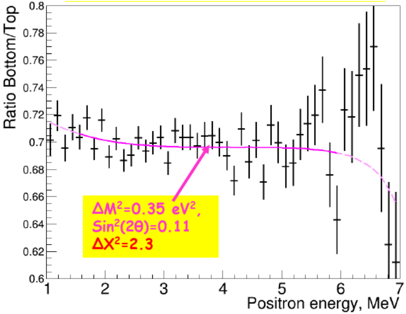
DANSS in 2019

[Danilov@EPS-HEP, 2019]

old data



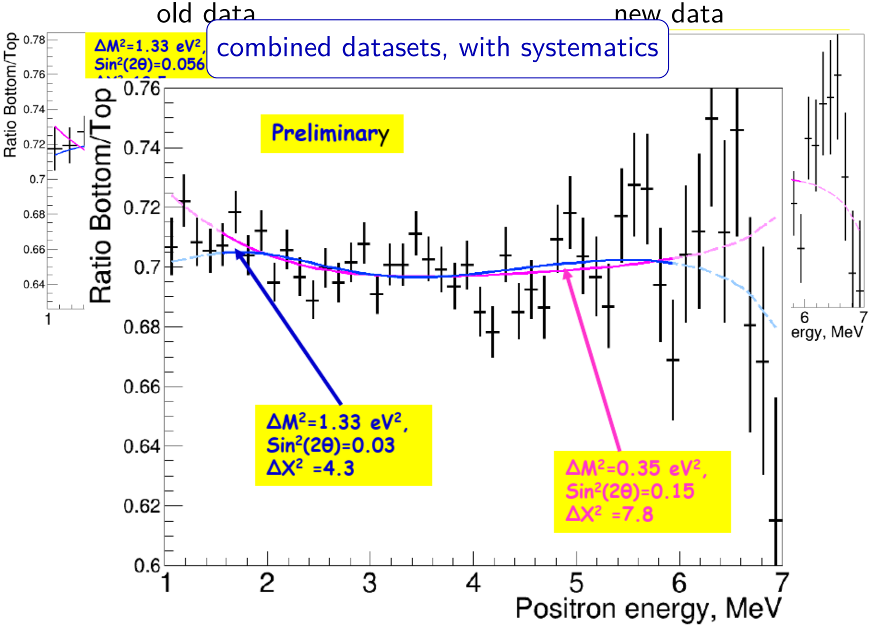
new data



New analysis also considers systematics!

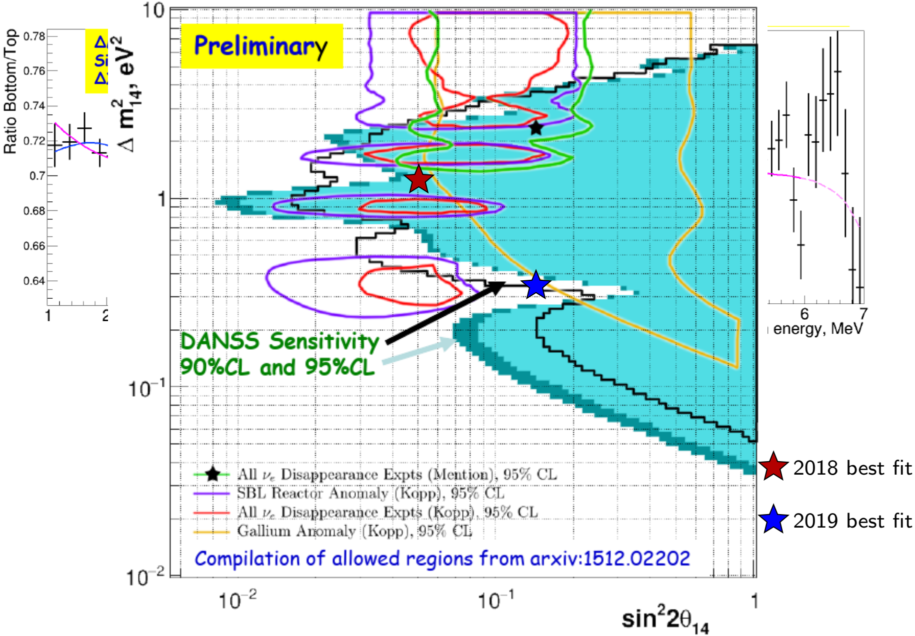
DANSS in 2019

[Danilov@EPS-HEP, 2019]



DANSS in 2019

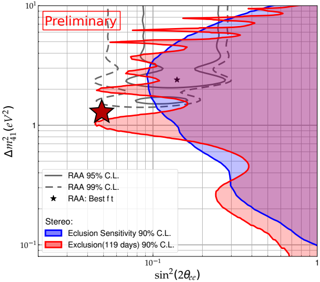
[Danilov@EPS-HEP, 2019]



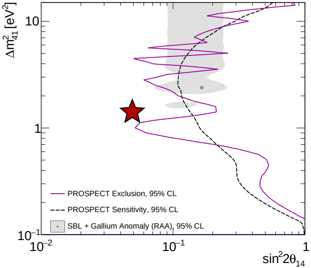
More to come...

★ = 2018 DANSS+NEOS best fit
[SG et al., PLB 782 (2018) 13]

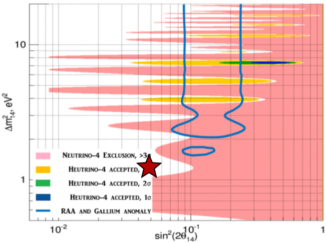
[STEREO, arxiv:1905.11896]



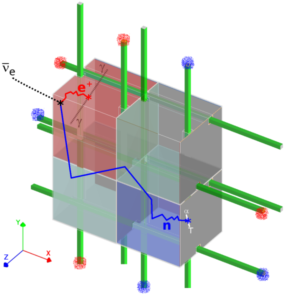
[PROSPECT, PRL 121 (2018) 251802]

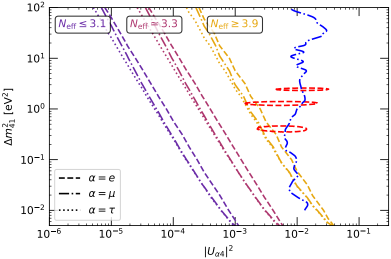


[Neutrino-4, PZETF 109 (2019) 209-218]



[SoLiD, JINST 13 (2018) P09005]





$N_{\rm eff} \leq 3.1$
$N_{\rm eff} \simeq 3.3$
$N_{\rm eff} \geq 3.9$
$\alpha = e$
$\alpha = \mu$
$\alpha = \tau$
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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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

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

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

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

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]

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

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

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

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

lepton densities — neutrino densities — (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

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

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

$r = x/z$, $r_\ell = m_\ell/m_e\, r$ $\quad J(r)$, $Y(r)$ 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

[SG+, JCAP 07 (2019) 014]

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

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

[SG+, JCAP 07 (2019) 014]

ν oscillations in the early universe

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$m_{\rm Pl}$ Planck mass $\quad \rho_{\rm T}$ total energy density $\quad$ [illegible] mass of the W, Z bosons $\quad$ [illegible] Fermi constant $\quad [\,,\,]$ commutator

FORTran-Evolved PrimordIAl Neutrino Oscillations (FortEPiaNO)

https://bitbucket.org/ahep_cosmo/fortepiano

will be public soon

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

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

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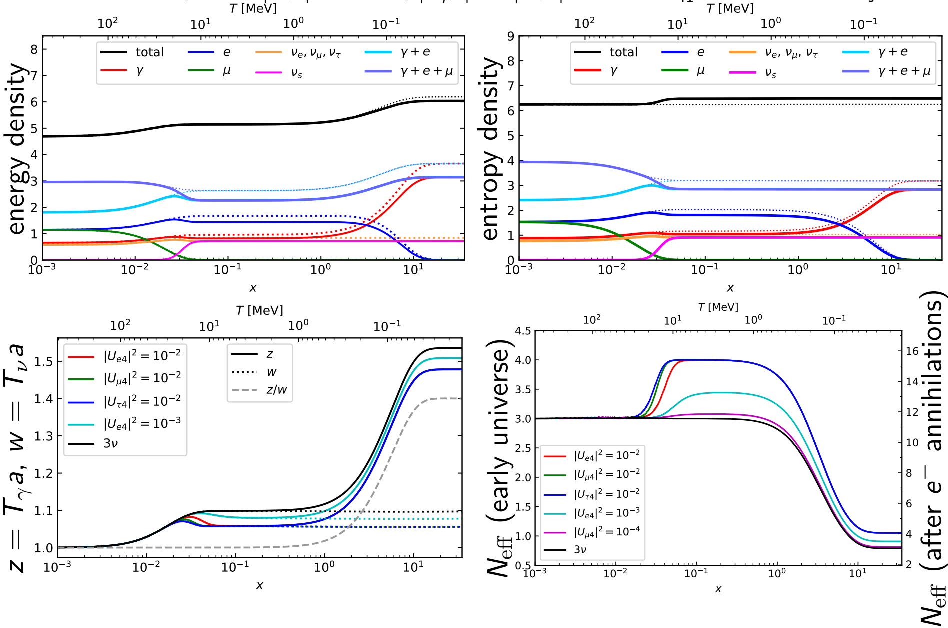
Energy, entropy, temperatures, $N_{\rm eff}$

[SG+, JCAP 07 (2019) 014]

dashed: 3ν, solid: $|U_{e4}|^2 = 10^{-2}$, $|U_{\mu 4}|^2 = |U_{\tau 4}|^2 = 0$. $\Delta m^2_{41} = 1.29$ eV^2 always



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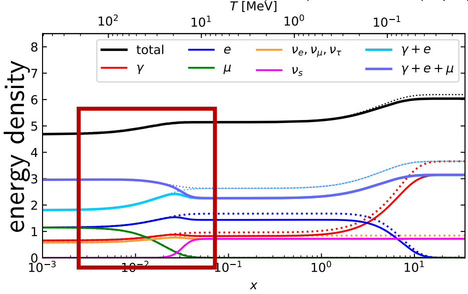

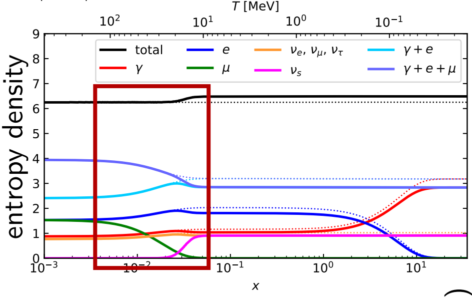

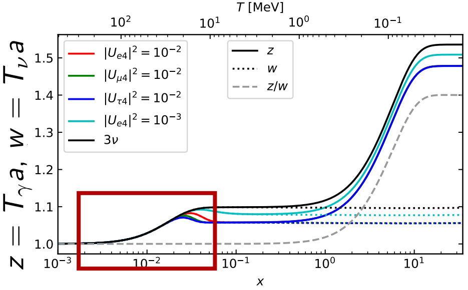

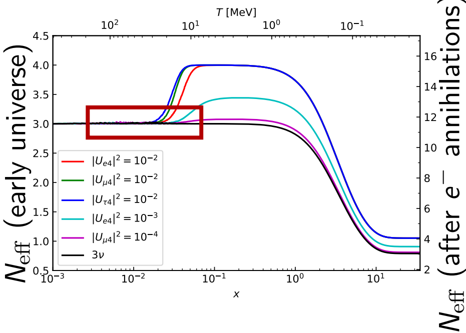

muons annihilate

Energy, entropy, temperatures, $N_{\rm eff}$

[SG+, JCAP 07 (2019) 014]

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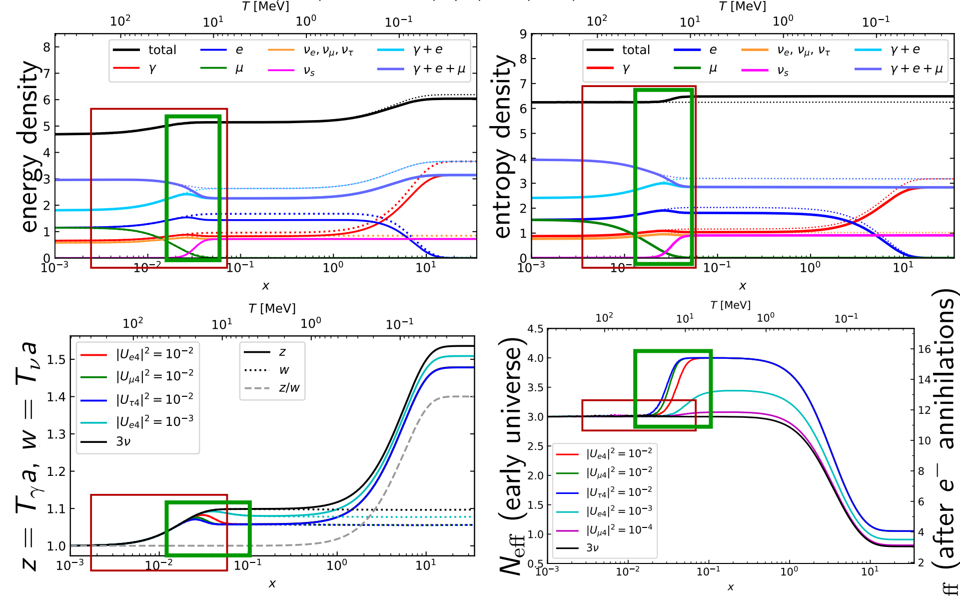

muons annihilate

ν_s thermalizes

Energy, entropy, temperatures, N_{eff}

[SG+, JCAP 07 (2019) 014]

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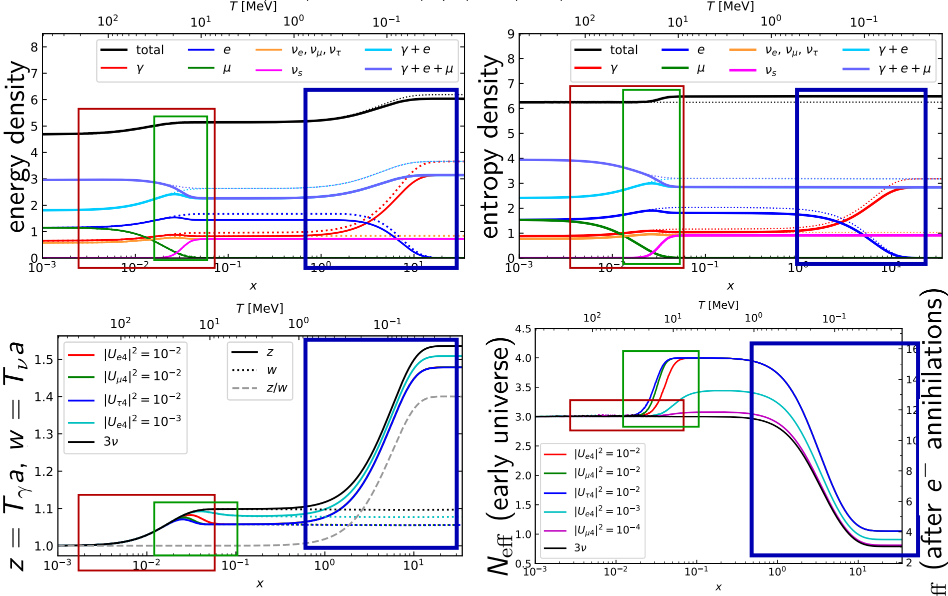
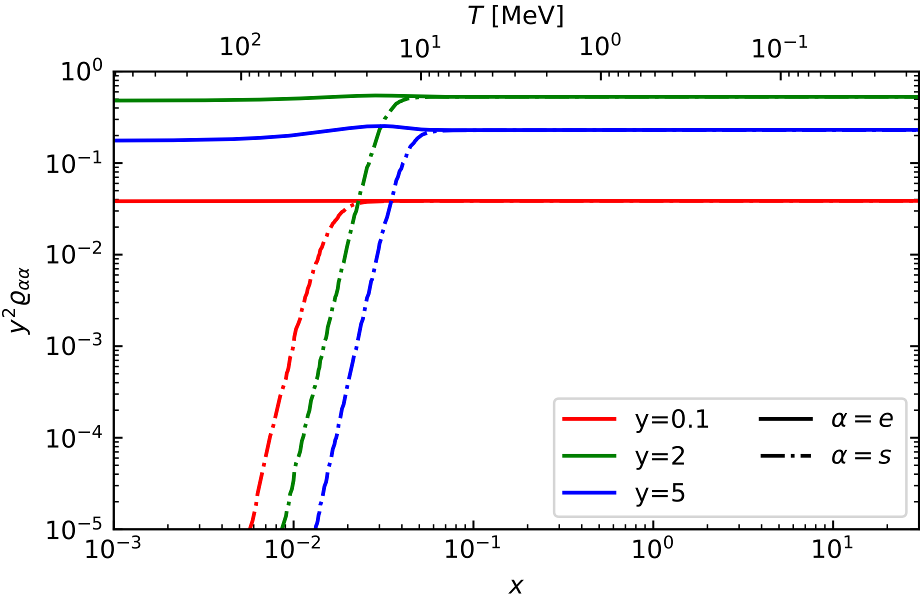


muons annihilate ν_s thermalizes electrons annihilate

Momentum distributions

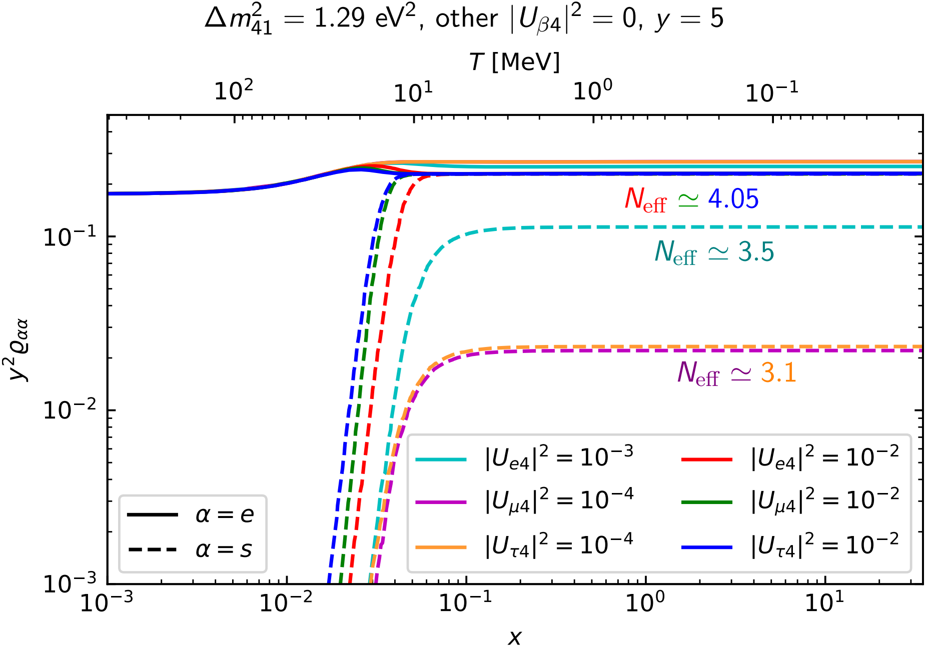
[SG+, JCAP 07 (2019) 014]

$\Delta m^2_{41} = 1.29$ eV^2, $|U_{e4}|^2 = 10^{-2}$, $|U_{\mu 4}|^2 = |U_{\tau 4}|^2 = 0$, $N_{\rm eff} \simeq 4.05$



Momentum distributions

[SG+, JCAP 07 (2019) 014]



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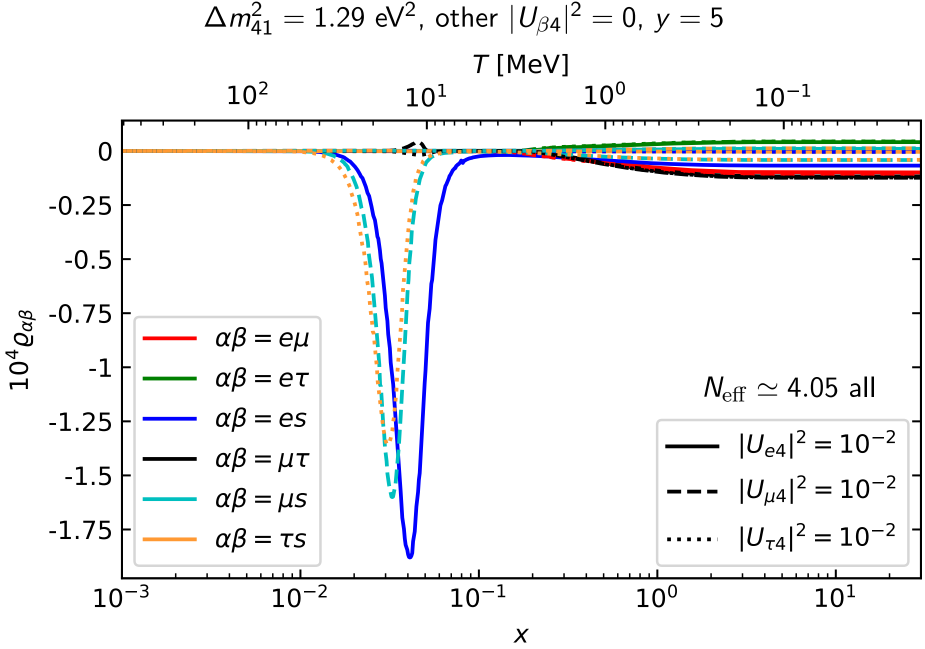
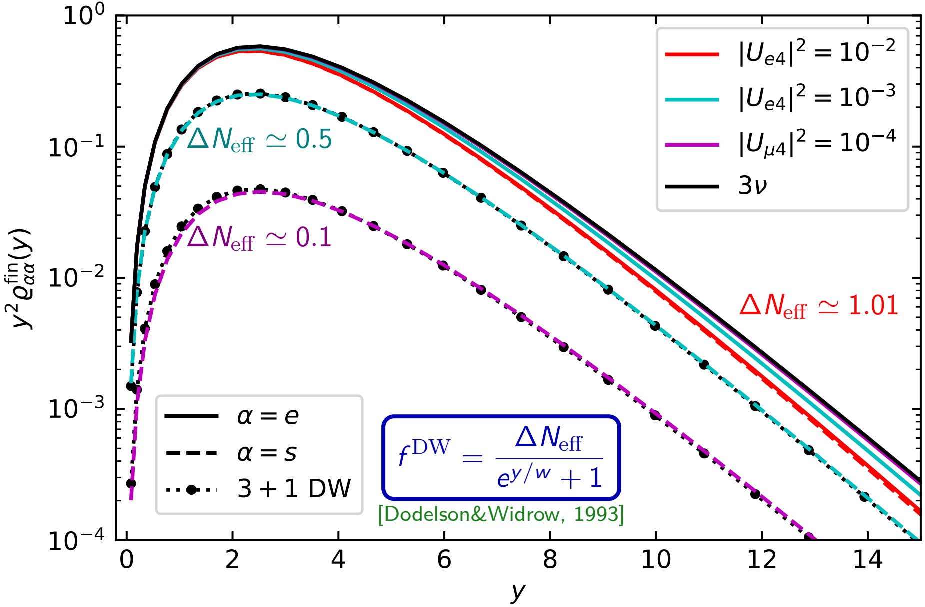
[SG+, JCAP 07 (2019) 014]



Momentum distributions

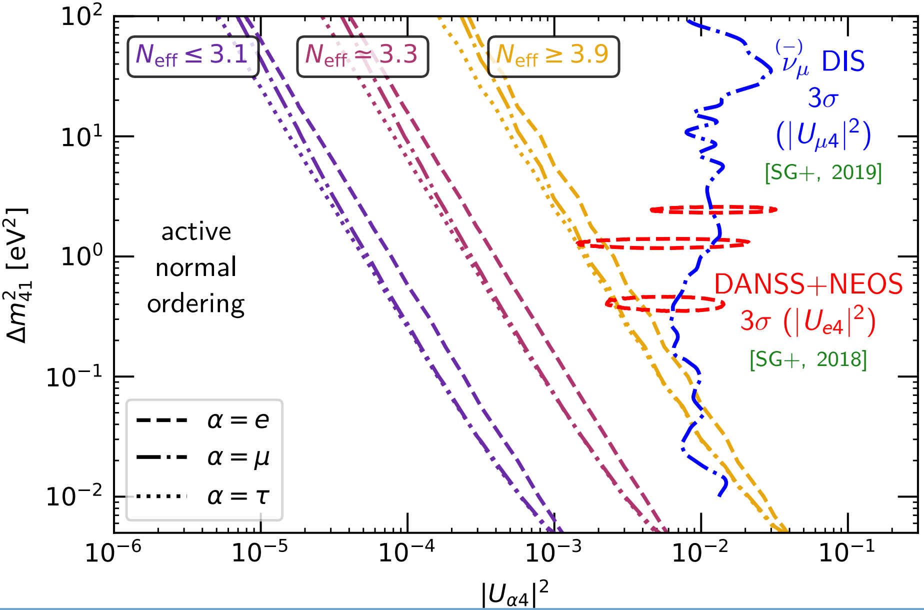
[SG+, JCAP 07 (2019) 014]

$\Delta m^2_{41} = 1.29$ eV^2, other $|U_{\beta 4}|^2 = 0$, $\Delta N_{\rm eff} = N_{\rm eff} - N_{\rm eff}^{\rm active}$



N_{eff} and the new mixing parameters

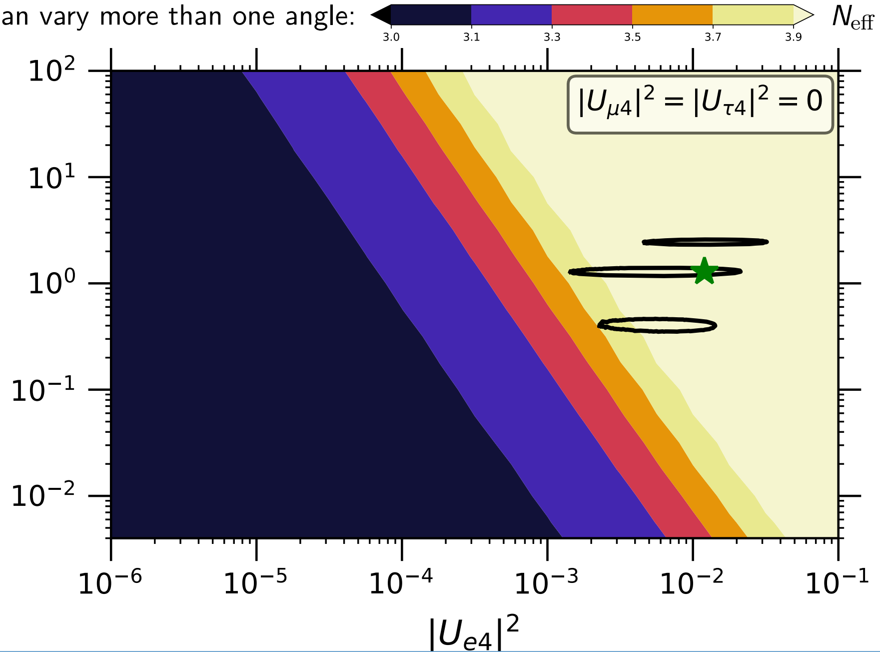
Only vary one angle and fix two to zero: do they have the same effect?



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

[SG+, JCAP 07 (2019) 014]

We can vary more than one angle:



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[SG+, JCAP 07 (2019) 014]

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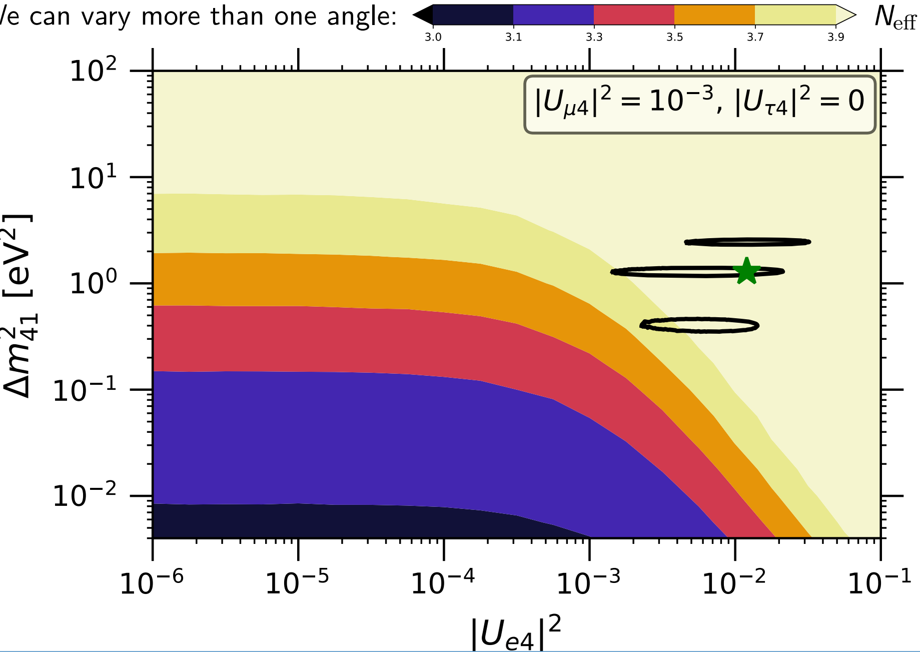

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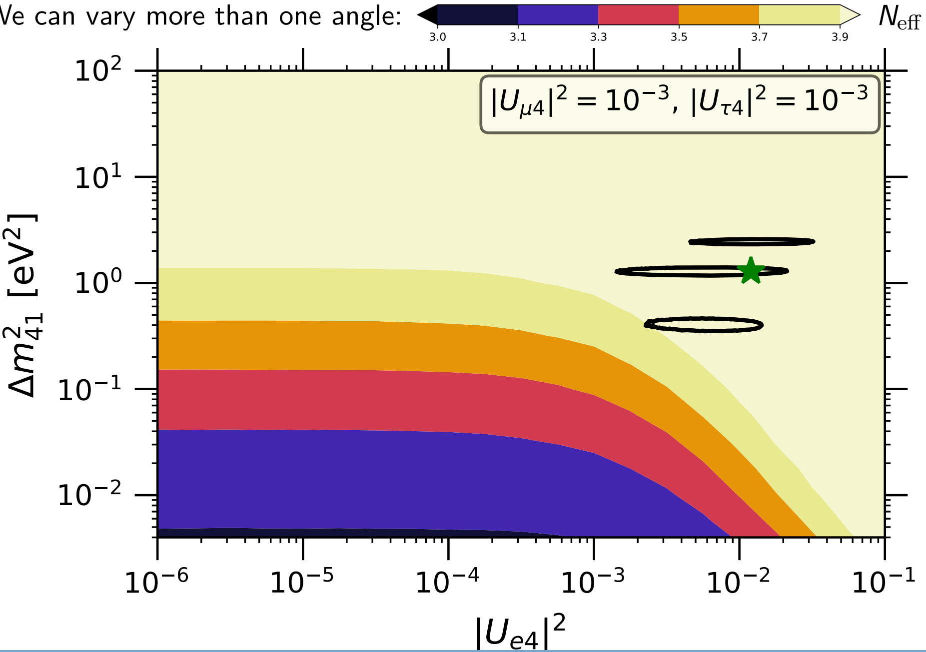
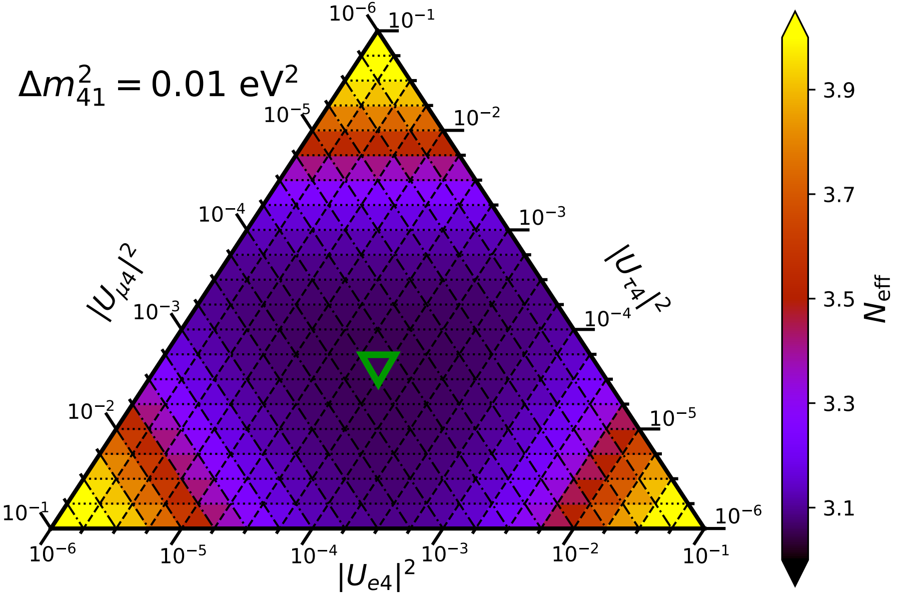


N_{eff} and the new mixing parameters

[SG+, JCAP 07 (2019) 014]

Sort of ternary plot (sum of $|U_{\alpha 4}|^2$ does not add up to 1!):



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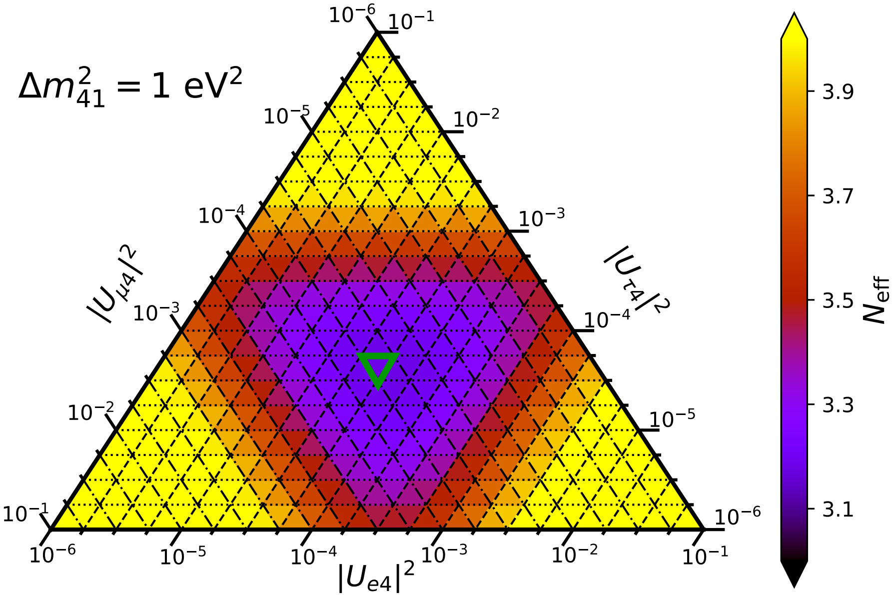

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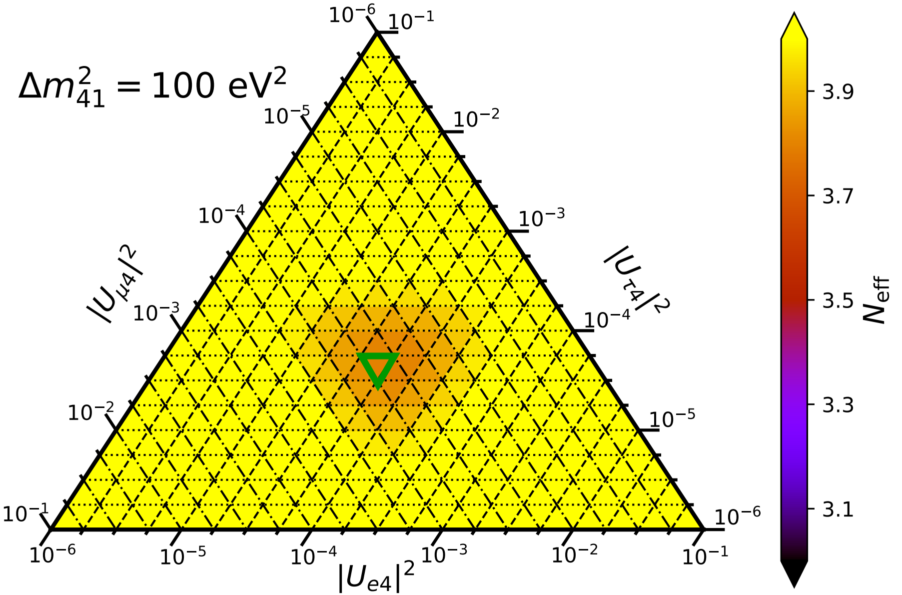
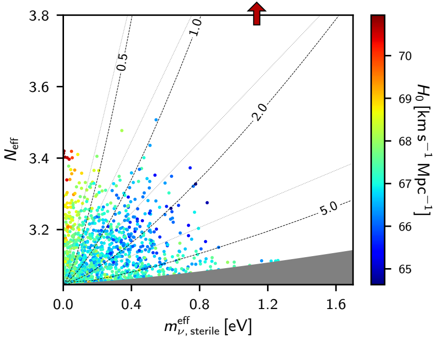
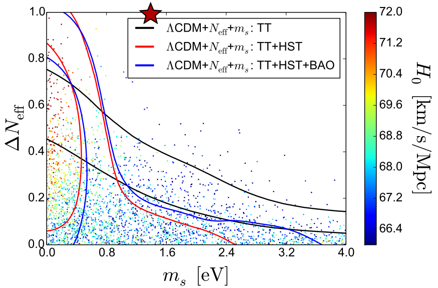


LSν constraints from cosmology

CMB+local: [Planck Collaboration, 2018] [Archidiacono et al., JCAP 08 (2016) 067]





$$\begin{cases} N_{\rm eff} < 3.29 \\ m_s^{\rm eff} < 0.65 \text{ eV} \end{cases}$$ (Planck18+BAO) [$m_s < 10$ eV]

dataset	free $\Delta N_{\rm eff}$ [$m_s < 10$ eV]	$\Delta N_{\rm eff} = 1$
(TT)	$N_{\rm eff} < 3.5$	$m_s < 0.66$ eV
(+H_0)	$N_{\rm eff} < 3.9$	$m_s < 0.55$ eV
(+BAO)	$N_{\rm eff} < 3.8$	$m_s < 0.53$ eV

BBN constraints: $N_{\rm eff} = 2.90 \pm 0.22$ (BBN+Y_p) [Peimbert et al., 2016]

Summary: $\Delta N_{\rm eff} = 1$ from LSν incompatible with CMB and BBN!

Planck18=Planck 2018 TT,TE,EE + lowE + lensing All the constraints are at 2σ CL

Conclusions

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

2. nothing seen in $\overset{(-)}{\nu}_\mu$ DIS
strong upper bounds on $|U_{\mu 4}|^2$,
but also first constraints on $|U_{\tau 4}|^2$

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

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+1 oscillations in the early universe $\rightarrow$ $N_{\rm eff} \simeq 4.05$
Planck constrains $N_{\rm eff} \lesssim 3.3$!
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Thank you for the attention!

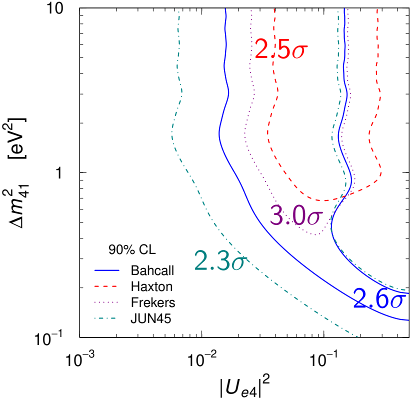
8 ***LSν constraints from oscillation experiments***

9 ***Cosmological constraints***

Gallium anomaly revisited

[Kostensalo+, PLB 795 (2019) 542-547]

New cross section calculations:
(interacting nuclear shell model)



original Gallium anomaly: $\sim 2.9\sigma$

[SAGE, 2006]

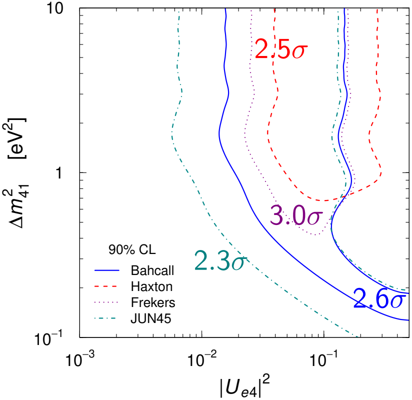
[Laveder, 2007]

[Giunti&Laveder, 2011]

Gallium anomaly revisited

[Kostensalo+, PLB 795 (2019) 542-547]

New cross section calculations:
(interacting nuclear shell model)



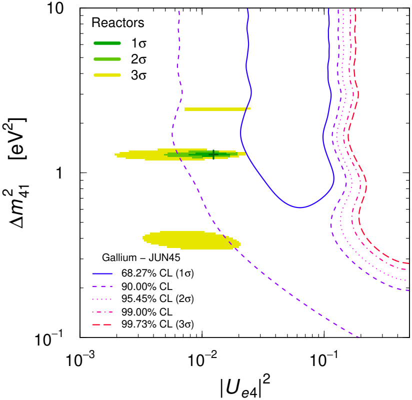
original Gallium anomaly: $\sim 2.9\sigma$

[SAGE, 2006]

[Laveder, 2007]

[Giunti&Laveder, 2011]

Compare with DANSS+NEOS:



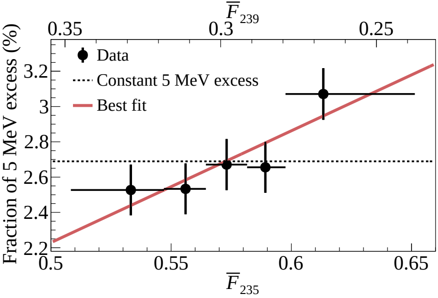
Better compatibility with reactors

Fuel evolution

Reactor fluxes produced
by decay fissions of

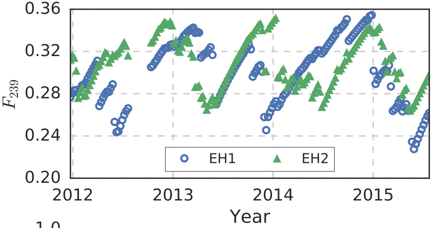
^{235}U ^{238}U ^{239}Pu ^{241}Pu

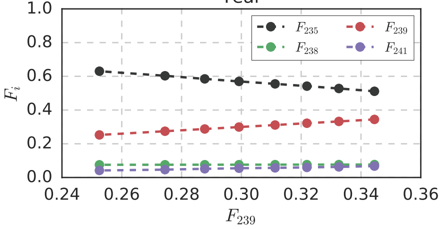
Can we use time evolution to identify source of 5 MeV bump?



[RENO, arxiv:1806.00574]

Fuel fractions in reactors change with time

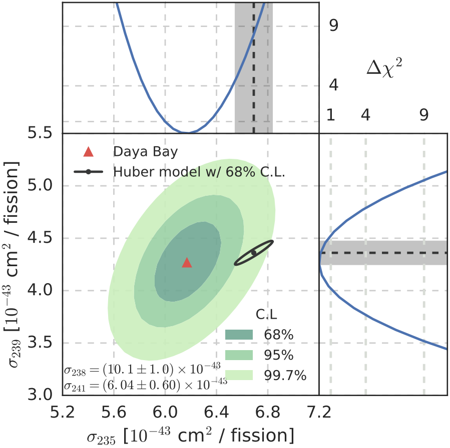




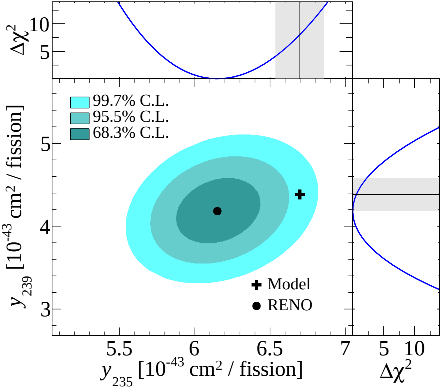
[Daya Bay, PRL 118 (2017) 251801]

Fuel evolution

Fit bump amplitude as a function of flux normalizations → Normalization of ^{235}U flux smaller than prediction!



[Daya Bay, PRL 118 (2017) 251801]



[RENO, arxiv:1806.00574]

Again, we need model-independent information!

take ratios at different distances to avoid normalization dependency

Gallium anomaly and RAA revisited

[SG+, PLB 782 (2018) 13]

fit with free parameters:

detection efficiencies in Gallium experiments

normalization of spectra of reactor fuels

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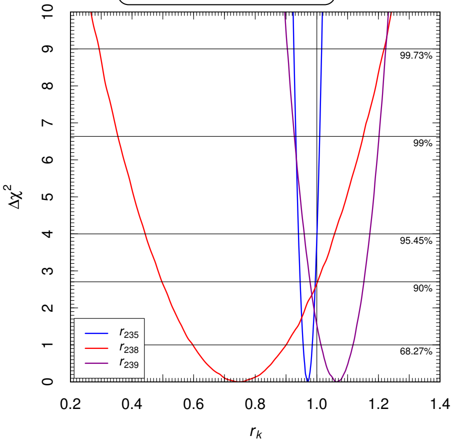
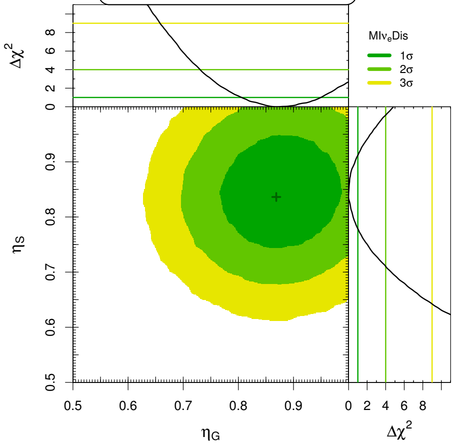
Reactor spectra:



Gallium efficiencies:



^{235}U flux normalization smaller than 1 at $\gtrsim 2\sigma$

SAGE efficiency $\eta_{\rm S}$ smaller than 1 at $\gtrsim 2\sigma$

May something be wrong?

[Dentler+, JHEP 08 (2018) 010]
(2013 data from MiniBooNE, MINOS+ v1!)

Analysis	$\chi^2_{\rm min,global}$	$\chi^2_{\rm min,app}$	$\Delta\chi^2_{\rm app}$	$\chi^2_{\rm min,disapp}$	$\Delta\chi^2_{\rm disapp}$	$\chi^2_{\rm PG}$/dof	PG
Global	1120.9	79.1	11.9	1012.2	17.7	29.6/2	3.71×10^{-7}
Removing anomalous data sets							
w/o LSND	1099.2	86.8	12.8	1012.2	0.1	12.9/2	1.6×10^{-3}
w/o MiniBooNE	1012.2	40.7	8.3	947.2	16.1	24.4/2	5.2×10^{-6}
w/o reactors	925.1	79.1	12.2	833.8	8.1	20.3/2	3.8×10^{-5}
w/o gallium	1116.0	79.1	13.8	1003.1	20.1	33.9/2	4.4×10^{-8}
Removing constraints							
w/o IceCube	920.8	79.1	11.9	812.4	17.5	29.4/2	4.2×10^{-7}
w/o MINOS(+)	1052.1	79.1	15.6	948.6	8.94	24.5/2	4.7×10^{-6}
w/o MB disapp	1054.9	79.1	14.7	947.2	13.9	28.7/2	6.0×10^{-7}
w/o CDHS	1104.8	79.1	11.9	997.5	16.3	28.2/2	7.5×10^{-7}
Removing classes of data							
$\overset{(-)}{\nu}_e$ dis vs app	628.6	79.1	0.8	542.9	5.8	6.6/2	3.6×10^{-2}
$\overset{(-)}{\nu}_\mu$ dis vs app	564.7	79.1	12.0	468.9	4.7	16.7/2	2.3×10^{-4}
$\overset{(-)}{\nu}_\mu$ dis + solar vs app	884.4	79.1	13.9	781.7	9.7	23.6/2	7.4×10^{-6}

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No improvements if MiniBooNE is not considered

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$\overset{(-)}{\nu}_\mu$ DIS also constrain $|U_{e4}|^2$, while $\overset{(-)}{\nu}_e$ DIS do not constrain $|U_{\mu4}|^2$

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Only removing LSND or all $\overset{(-)}{\nu}_\mu$ constraints the fit is almost acceptable

No reason to do so!

Incomplete Thermalization

Active-sterile oscillations in the early Universe:

mixing parameters from SBL data $\Longrightarrow \Delta N_{\rm eff} \simeq 1$

[Hannestad et al., 2012] [Mirizzi et al., 2012]

Many probes constrain $\Delta N_{\rm eff} < 1$. Do we need

- a mechanism to suppress oscillations and full thermalization of ν_s?
- to compensate $\Delta N_{\rm eff} = 1$ with additional mechanisms in Cosmology?

Some ideas (an incomplete list!):

- large lepton asymmetry [Foot et al., 1995; Mirizzi et al., 2012; many more]
- new neutrino interactions [Bento et al., 2001; Dasgupta et al., 2014; Hannestad et al., 2014; Saviano et al., 2014; Archidiacono et al. 2016; many more]
- entropy production after neutrino decoupling [Ho et al., 2013]
- very low reheating temperature [Gelmini et al., 2004; Smirnov et al., 2006]
- time varying dark energy components [Giusarma et al., 2012]
- larger expansion rate at the time of ν_s production [Rehagen et al., 2014]
- freedom in the Primordial Power Spectrum (PPS) of scalar perturbations from inflation compensate damping due to $N_{\rm eff} \neq 3.046$ [SG et al., 2015]