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Light sterile neutrinos

from A to Z

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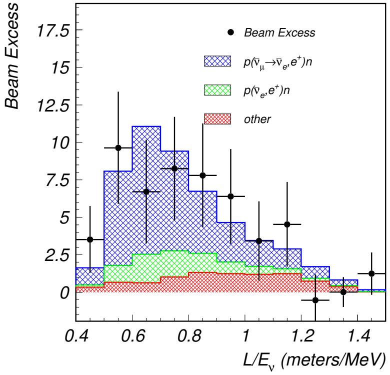
A Anomalies

Why do we need a light sterile neutrino?

Based on:

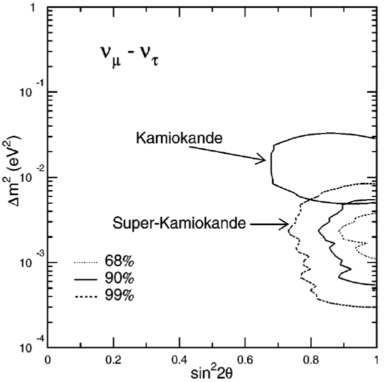
- JHEP 02 (2021) 071
  and update
- JPG 43 (2016) 033001
- LSND
- MiniBooNE



Neutrino oscillations

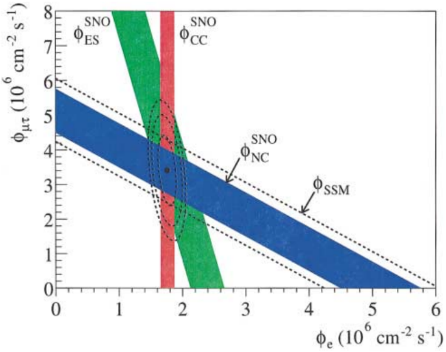
Major discoveries:

[SuperKamiokande, 1998]



first discovery of $\nu_\mu \to \nu_\tau$ oscillations from atmospheric ν

[SNO, 2001-2002]



first discovery of $\nu_e \to \nu_\mu, \nu_\tau$ oscillations from solar ν

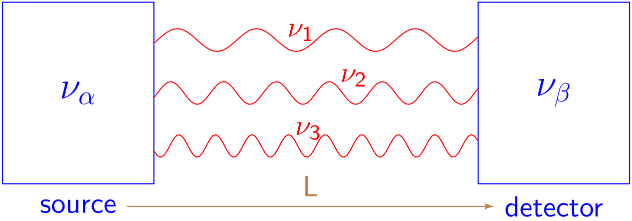
Nobel prize in 2015

Two neutrino bases

interaction — flavor neutrinos ν_α

U mixing matrix — $|\nu_\alpha\rangle = \sum_k U_{\alpha k}|\nu_k\rangle$

propagation — massive neutrinos ν_k



Transition probability between source and detector:

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

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

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: [JHEP 02 (2021) update]

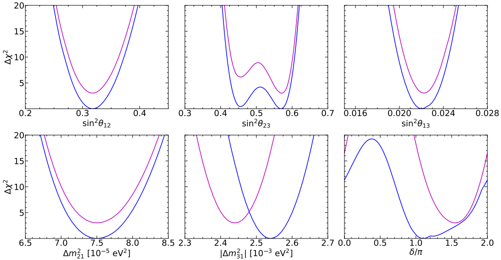
NO/NH: Normal Ordering/Hierarchy, $m_1 < m_2 < m_3$

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

$$\Delta m^2_{21} = (7.50^{+0.22}_{-0.20}) \cdot 10^{-5}\ \mathrm{eV}^2$$
$$|\Delta m^2_{31}| = (2.54 \pm 0.03) \cdot 10^{-3}\ \mathrm{eV}^2\ (\mathrm{NO})$$
$$= (2.44 \pm 0.03) \cdot 10^{-3}\ \mathrm{eV}^2\ (\mathrm{IO})$$

$$10 \sin^2(\theta_{12}) = 3.18 \pm 0.16$$
$$10^2 \sin^2(\theta_{13}) = 2.200^{+0.069}_{-0.062}\ (\mathrm{NO})$$
$$= 2.225^{+0.064}_{-0.070}\ (\mathrm{IO})$$
$$10 \sin^2(\theta_{23}) = 4.55 \pm 0.13 U 5.71 \pm 0.12\ (\mathrm{NO})$$
$$= 5.71^{+0.14}_{-0.17}\ (\mathrm{IO})$$

$$\delta/\pi = 1.10^{+0.27}_{-0.12}\ (\mathrm{NO})$$
$$= 1.54 \pm 0.14\ (\mathrm{IO})$$



mass ordering still unknown

δ still unknown

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

Short Baseline (SBL) anomalies

[SG+, JPG 43 (2016) 033001]

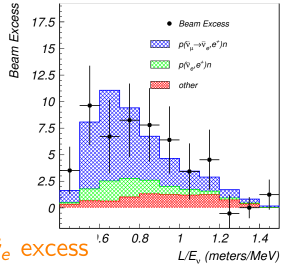
Do three-neutrino oscillations explain all experimental results?

Short Baseline (SBL) anomalies

[SG+, JPG 43 (2016) 033001]

Do three-neutrino oscillations explain all experimental results?

LSND



[Aguilar+, 2001]

3.8σ

$\bar{\nu}_\mu \to \bar{\nu}_e$ excess

Short Baseline (SBL) anomalies

[SG+, JPG 43 (2016) 033001]

Do three-neutrino oscillations explain all experimental results?

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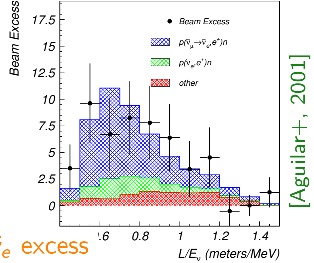
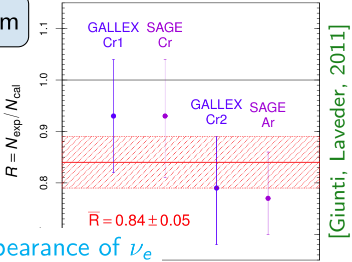


3.8σ

$\bar{\nu}_\mu \to \bar{\nu}_e$ excess

Gallium

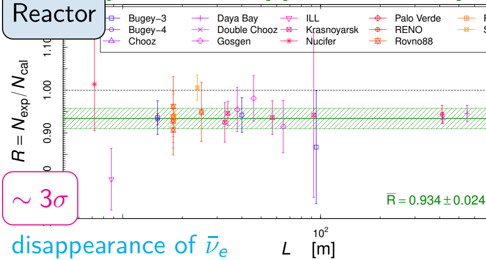


2.7σ

disappearance of ν_e

[Mention+, 2011] [Azabajian+, 2012]

Reactor



$\sim 3\sigma$

disappearance of $\bar{\nu}_e$

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[SG+, JPG 43 (2016) 033001]

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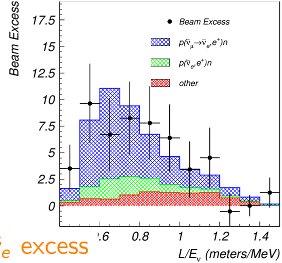

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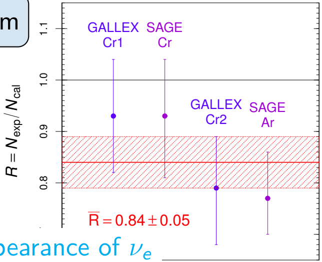

[Giunti, Laveder, 2011]

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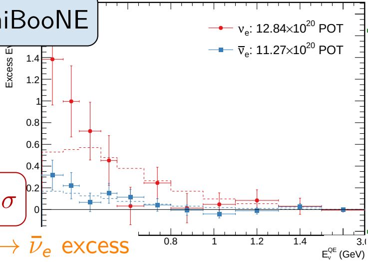
MiniBooNE



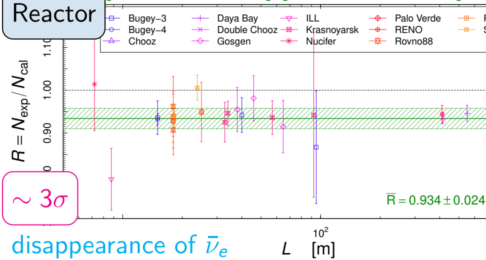
[Aguilar+, 2008-2018]

$\sim 5\sigma$

$\bar{\nu}_\mu \to \bar{\nu}_e$ excess

Reactor

[Mention+, 2011] [Azabajian+, 2012]



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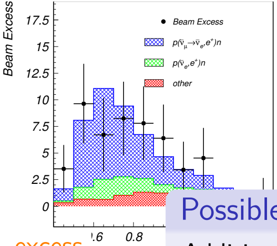

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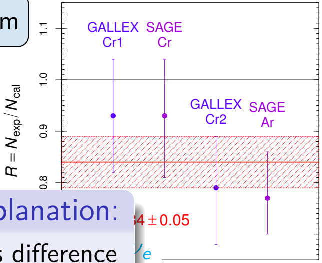
Gallium



[Giunti, Laveder, 2011]

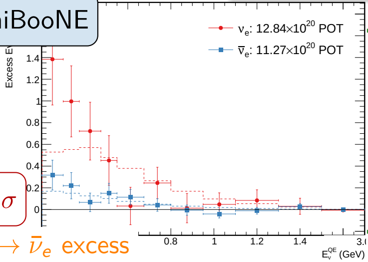
Possible common explanation:

Additional squared mass difference

$\Delta m^2_{\rm SBL} \simeq 1\ {\rm eV}^2$

[Mention+, 2011] [Azabajian+, 2012]

MiniBooNE



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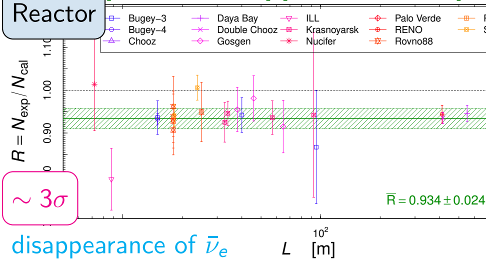


$\sim 3\sigma$

disappearance of $\bar{\nu}_e$

A large family

In principle, previous discussion is valid for N neutrinos

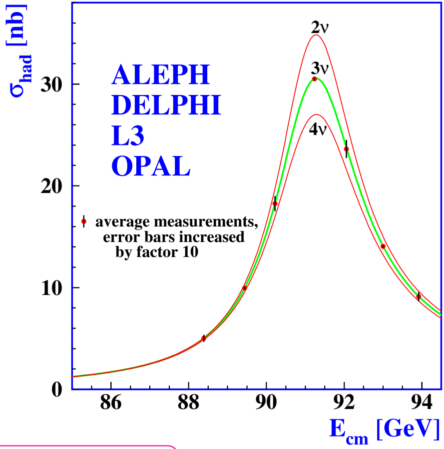
only constraint: there are exactly three flavor neutrinos in the SM

[LEP, Phys. Rept. 427 (2006) 257]
$N_\nu^{(Z)} = 2.9840 \pm 0.0082$

[Janot+, PLB 2020]
$N_\nu^{(Z)} = 2.9963 \pm 0.0074$

from measurement of 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

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

A large family

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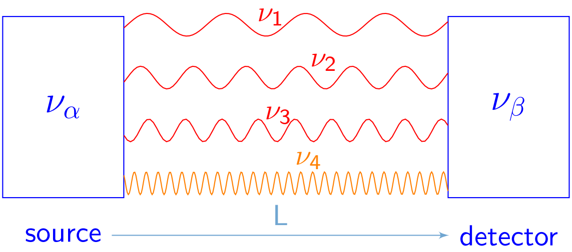
Our case will be 3 (active)+1 (sterile), a perturbation of 3 neutrinos case

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

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



6 angles

3 Dirac CP phases

3 Majorana CP phases

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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DISappearance

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

$$\sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha4}|^2(1 - |U_{\alpha4}|^2)$$

$\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_e$

reactor
gallium

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

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

accelerator
atmospheric

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

New mixings in the 3+1 scenario

4 × 4 mixing matrix: $\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s_1 1} & U_{s_1 2} & U_{s_1 3} & U_{s_1 4} \end{pmatrix}$ ϑ_{14} ϑ_{24} ϑ_{34}

DISappearance

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

$$\sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha4}|^2(1 - |U_{\alpha4}|^2)$$

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

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

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

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

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!

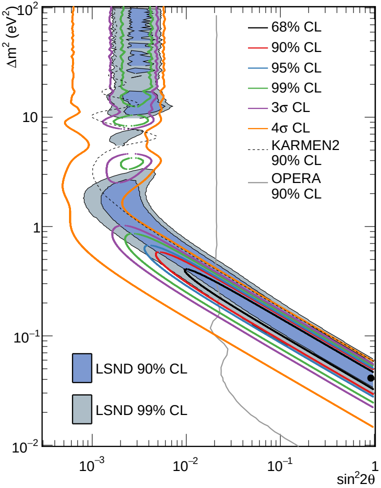
for small $|U_{e4}|^2$, $|U_{\mu4}|^2$

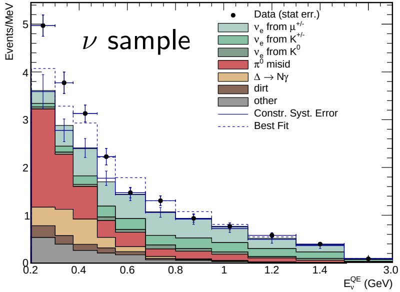
MiniBooNE

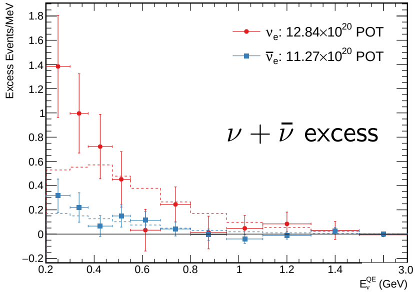
purpose: check LSND signal

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

no money, no near detector







MiniBooNE

[PRL 121 (2018) 221801]

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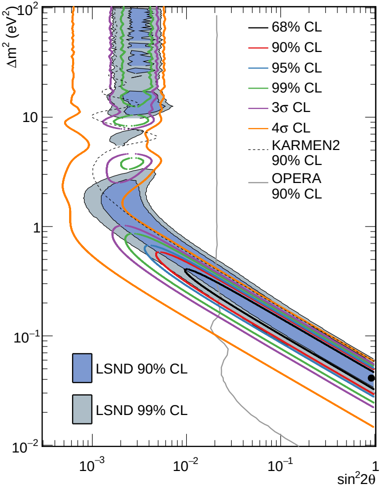
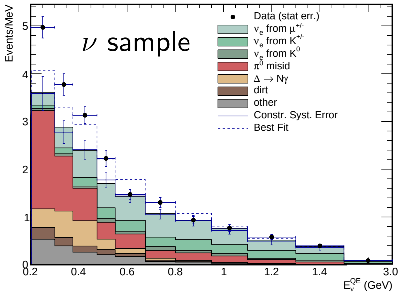
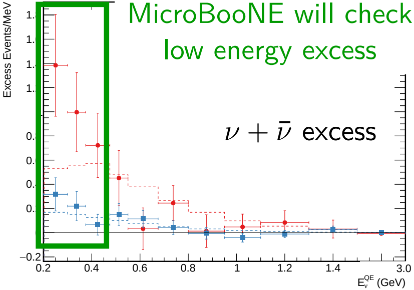




MicroBooNE will check low energy excess

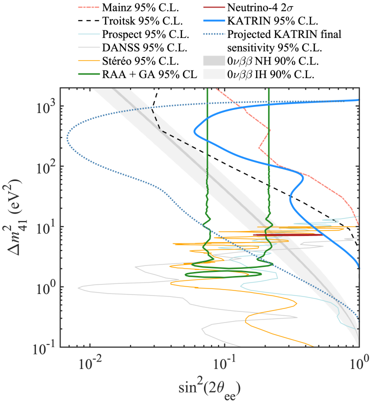


B Beta decay constraints

i.e. non-oscillation probes, first part

Based on:

- KATRIN



β decay

β decay: $\mathcal{N}(A, Z) \longrightarrow \mathcal{N}(A, Z+1) + e^- + \bar{\nu}_e$

$Q_\beta = M_i - M_f - m_e$

total available energy

$E_\nu = Q_\beta - T = Q_\beta - (E_e - m_e)$

neutrino energy

notice that max electron energy is:

$$T_{\rm max} = Q_\beta - m_{\bar{\nu}_e}$$

Kurie function: (degenerate ν masses)

$$K(T) = \left[(Q_\beta - T)\sqrt{(Q_\beta - T)^2 - m^2_{\bar{\nu}_e}}\right]^{1/2}$$

Useful to describe the e^- spectrum near the endpoint

β decay

$$\beta \text{ decay: } \mathcal{N}(A,Z) \longrightarrow \mathcal{N}(A,Z+1) + e^- + \bar{\nu}_e$$

$$Q_\beta = M_i - M_f - m_e$$

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notice: flavor neutrinos have no definite mass!

$$m^2_{\bar{\nu}_e} = \sum |U_{ei}|^2 m_i^2$$

β decay

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Useful to describe the e^- spectrum near the endpoint

notice: flavor neutrinos have no definite mass!

$$m^2_{\bar{\nu}_e} = \sum |U_{ei}|^2 m_i^2$$

Full expression:

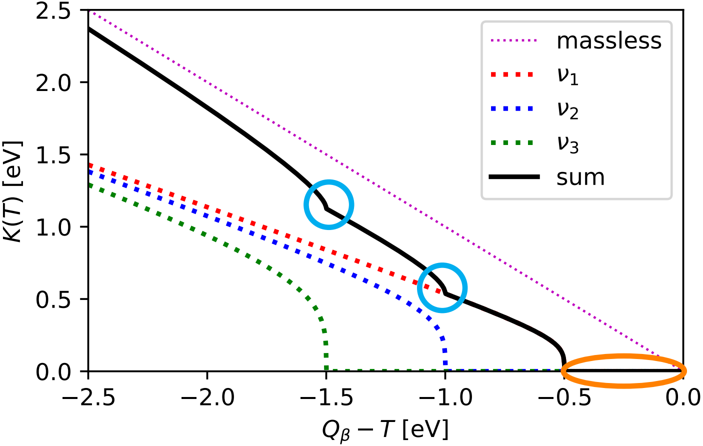
$$K(T) = \left[(Q_\beta - T)\sum_{i=1}^{N_\nu} |U_{ei}|^2 \sqrt{(Q_\beta - T)^2 - m_i^2}\right]^{1/2}$$

N_ν neutrinos with different masses m_i

mixing angles enter ($|U_{ei}|^2$)

β decay

$$K(T) = \left[(Q_\beta - T) \sum_{i=1}^{N_\nu} |U_{ei}|^2 \sqrt{(Q_\beta - T)^2 - m_i^2} \right]^{1/2}$$



Fake case:
3 neutrinos

masses:
$m_i = i \cdot 0.5$ eV,

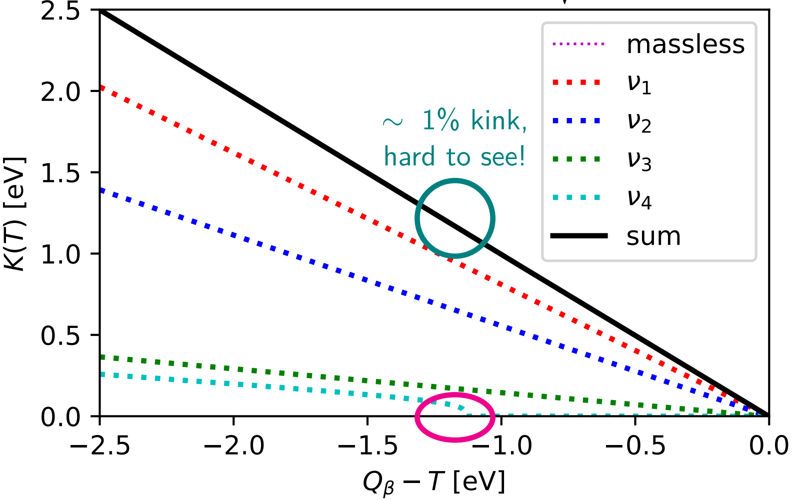
mixings:
$|U_{ei}|^2 = 1/3$

endpoint shifted + one kink for each mass eigenstate

Sterile neutrino in β decay

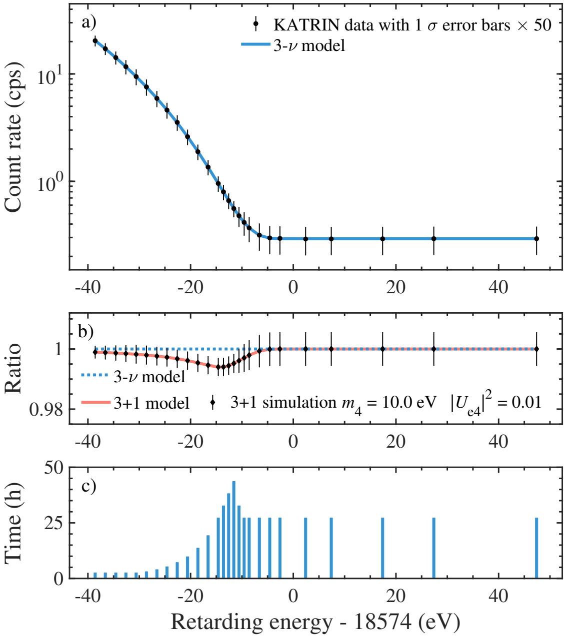
$$K(T) = \left[(Q_\beta - T) \sum_{i=1}^{N_\nu} |U_{ei}|^2 \sqrt{(Q_\beta - T)^2 - m_i^2} \right]^{1/2}$$

$|U_{e4}|^2 \sim 0.01$ $\quad$ $m_4 \sim \sqrt{\Delta m^2_{41}} \simeq 1.15$ eV



Sterile neutrino in β decay

[KATRIN, PRL 126 (2021)]



Sterile neutrino in β decay

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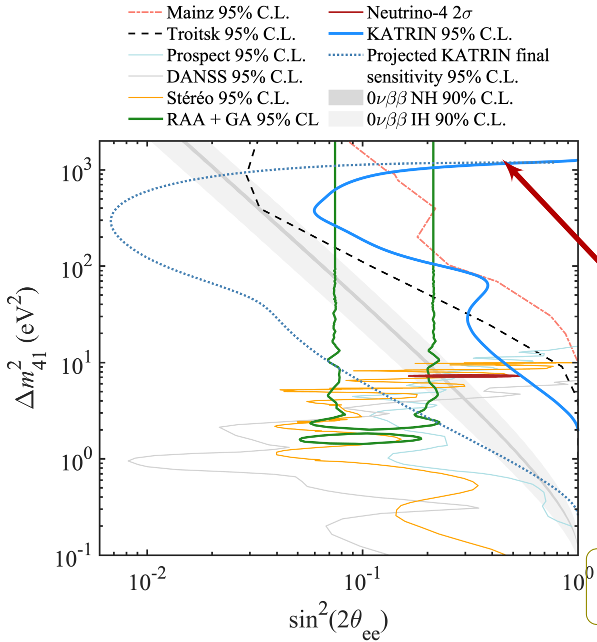


final sensitivity will test several oscillation results!

search for keV states needs to measure the spectrum much further from the endpoint...

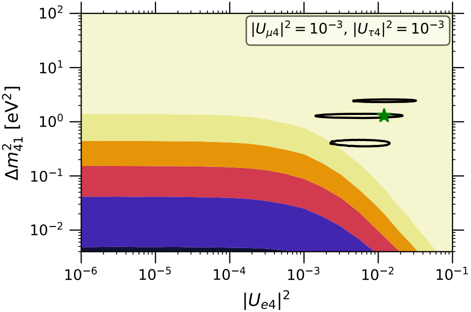
see hot topic by A.Lokhov, tomorrow h13.30

C Cosmology

i.e. non-oscillation probes, second part

Based on:

- JCAP 04 (2021) 073
- JCAP 07 (2019) 014
- Planck
- arxiv:2003.02289



Sterile neutrino in the early universe

[SG+, JCAP 07 (2019) 014]

Four neutrinos $\longrightarrow$ new oscillations in the early Universe

sterile $\Longrightarrow$ no weak/em interactions in the thermal plasma

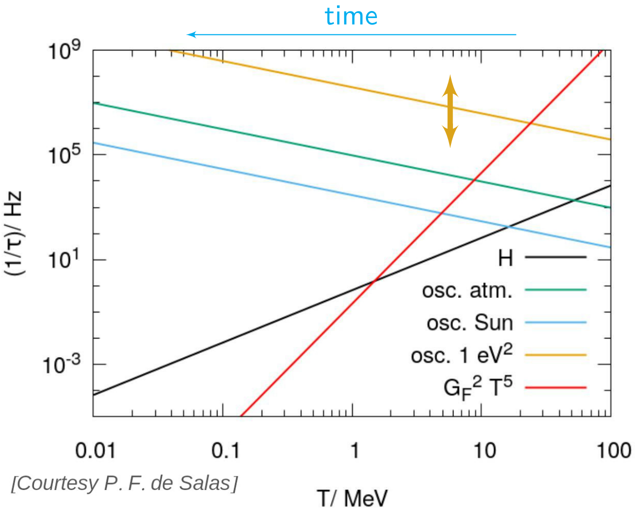
Sterile neutrino in the early universe

[SG+, JCAP 07 (2019) 014]

Four neutrinos $\longrightarrow$ new oscillations in the early Universe

sterile $\Longrightarrow$ no weak/em interactions in the thermal plasma

need to produce it through oscillations, but matter effects may block them



[Courtesy P. F. de Salas]

beginning of oscillations depends on Δm^2_{41}

later oscillations

$\Downarrow$

less time before ν decoupling!

Sterile neutrino in the early universe

[SG+, JCAP 07 (2019) 014]

Four neutrinos $\longrightarrow$ new oscillations in the early Universe

sterile $\Longrightarrow$ no weak/em interactions in the thermal plasma

need to produce it through oscillations, but matter effects may block them

when are they enough to allow full equilibrium of active-sterile states?

$$0 \longleftarrow \Delta N_{\rm eff} = N_{\rm eff}^{4\nu} - N_{\rm eff}^{3\nu} \longrightarrow \simeq 1$$

no sterile production — active&sterile in equilibrium

$$\frac{\Delta m^2_{as}}{\text{eV}^2} \sin^4(2\vartheta_{as}) \simeq 10^{-5} \ln^2(1-\Delta N_{\rm eff}) \qquad \text{(1+1 approx.)}$$

[Dolgov&Villante, 2004]

e.g.: $\Delta m^2_{as} = 1\ \text{eV}^2,\ \sin^2(2\vartheta_{as}) \simeq 10^{-3} \Longrightarrow \Delta N_{\rm eff} \simeq 1$

$N_{\rm eff}^{3\nu} = 3.044$ [SG+, JCAP 2021]

see async talk by J.Froustey

Sterile neutrino in the early universe

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[Dolgov&Villante, 2004]

e.g.: $\Delta m^2_{as} = 1\ \mathrm{eV}^2$, $\sin^2(2\vartheta_{as}) \simeq 10^{-3} \Longrightarrow \Delta N_{\rm eff} \simeq 1$

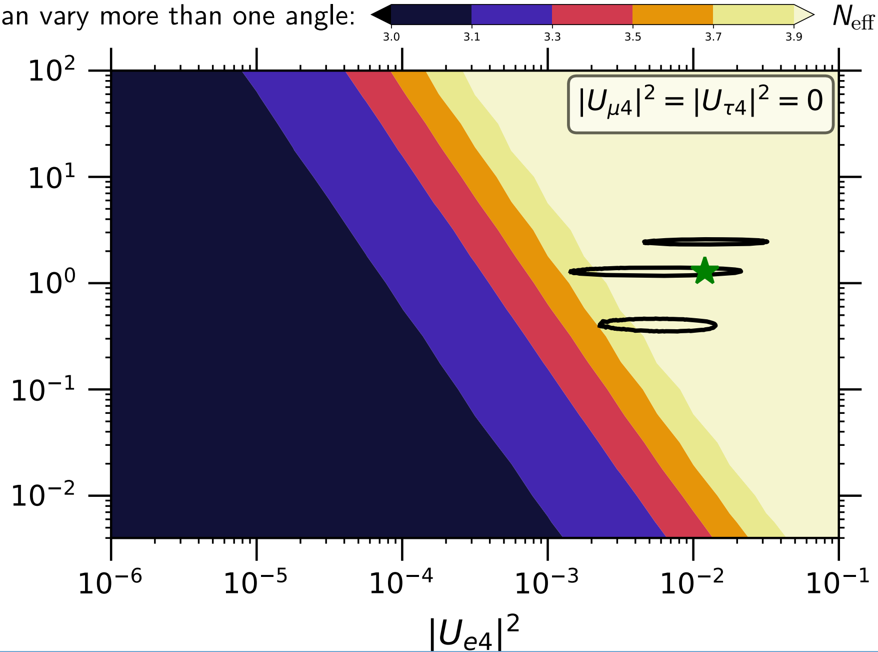
Full calculation: use numerical code!

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

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

[SG+, JCAP 07 (2019) 014]

We can vary more than one angle:



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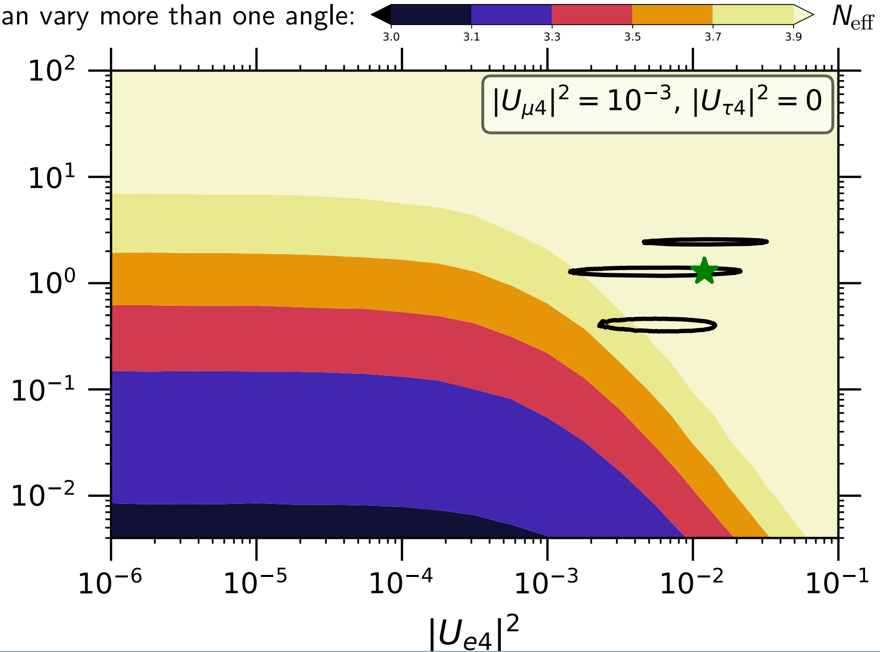

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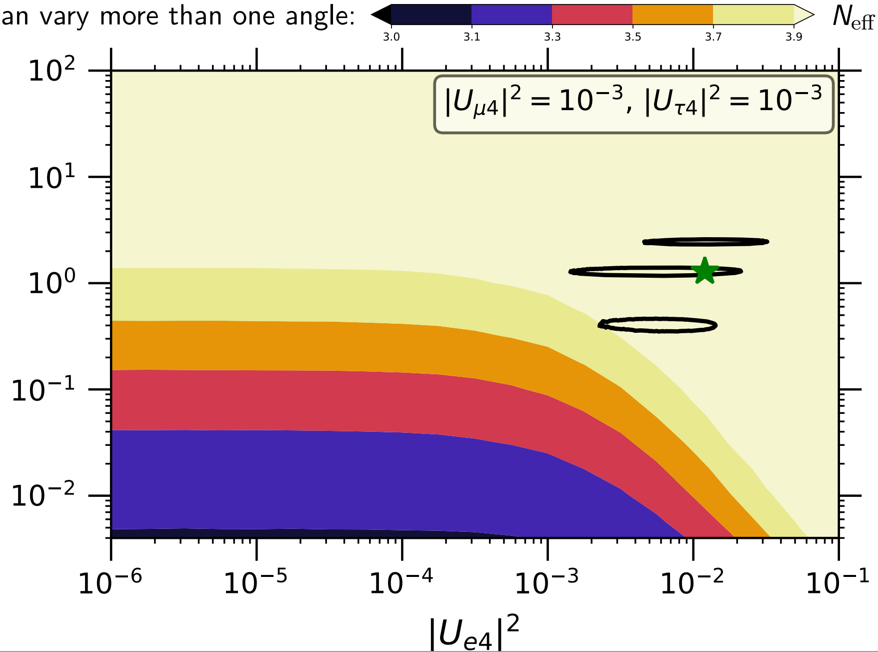
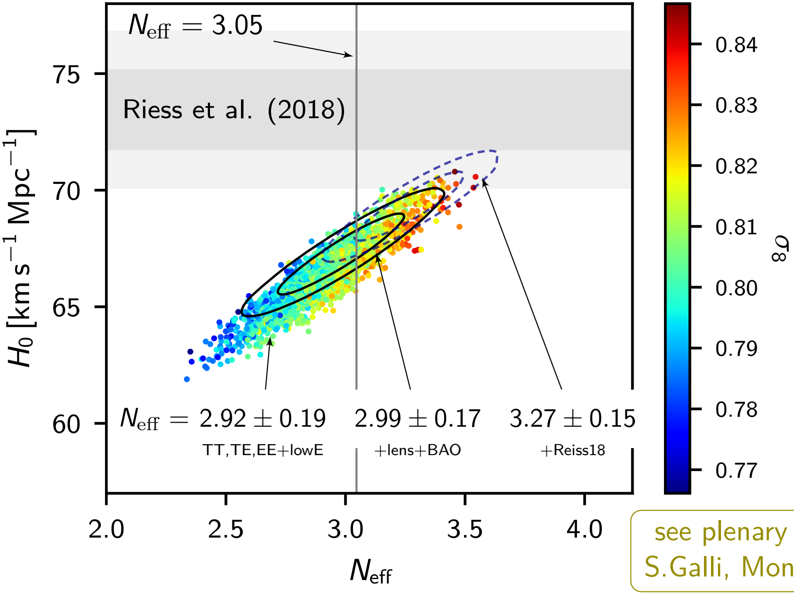


$N_{\rm eff}$ and CMB

[Planck Collaboration, 2018]

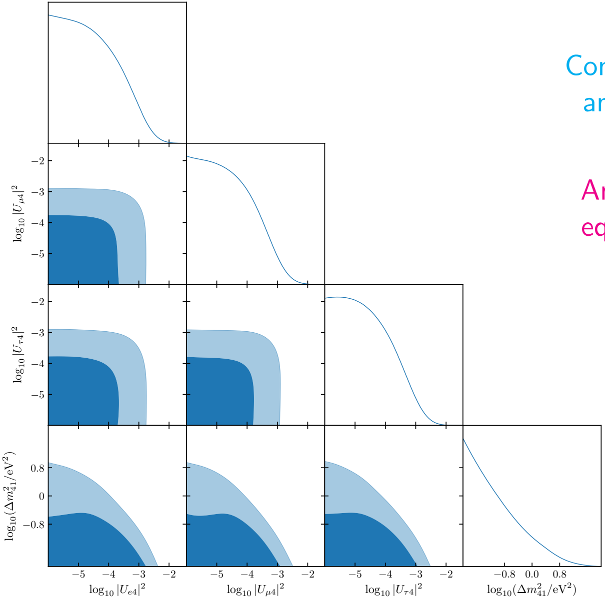


see plenary talk by S.Galli, Monday h15

Cosmological constraints on $|U_{\alpha 4}|^2$

[arxiv:2003.02289]

Use multi-angle results from `FortEPiaNO` to derive constraints on $|U_{\alpha 4}|^2$:



Constraints come from $N_{\rm eff}$ and late-time density Ω_s

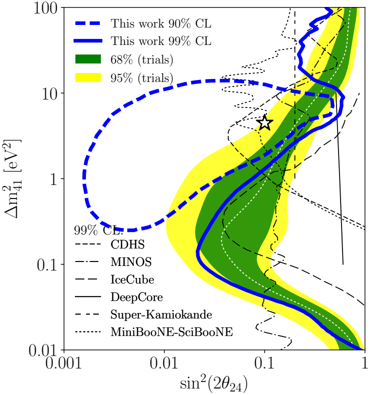
Angles $|U_{\alpha 4}|^2$ are almost equivalent for cosmology

D Disappearance (Muon channel)

strong constraints, and a recent first hint

Based on:

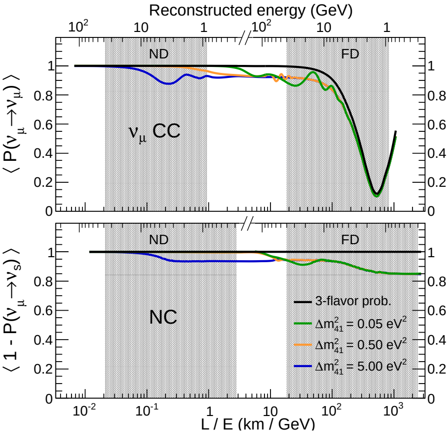
- MINOS/MINOS+
- IceCube 2016
- DeepCore
- IceCube 2020
- NOvA



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+

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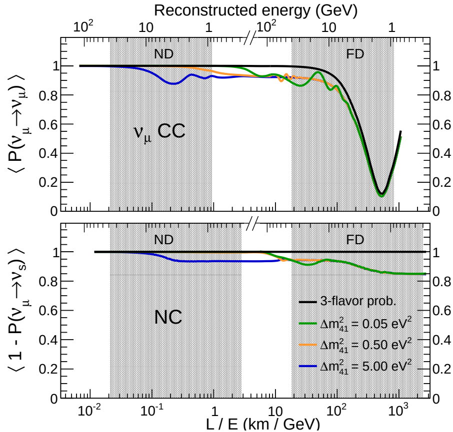
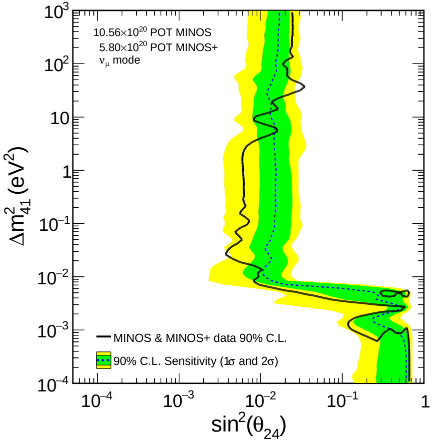


[PRL 117 (2016) 151803]: far-to-near ratio

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

Sensitivity and exclusion limit:



[PRL 122 (2019) 091803]

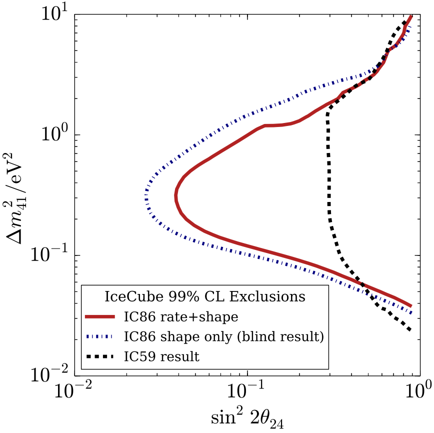
IceCube and DeepCore

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]

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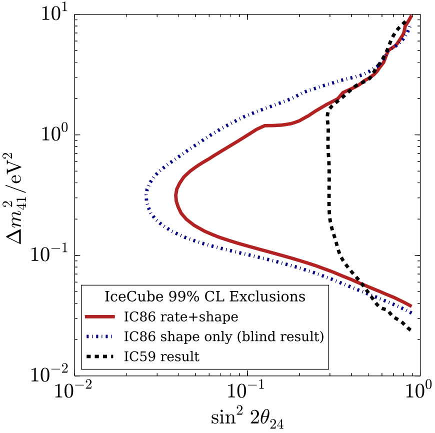

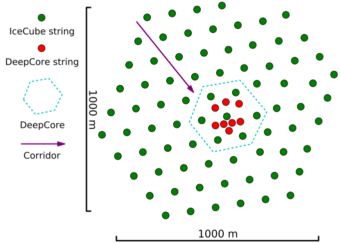

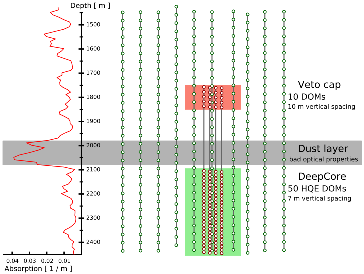

[PRL 117 (2016) 071801]

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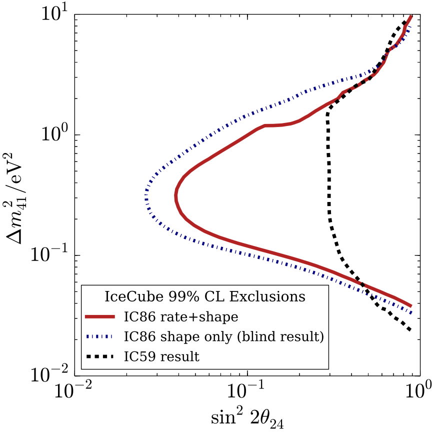
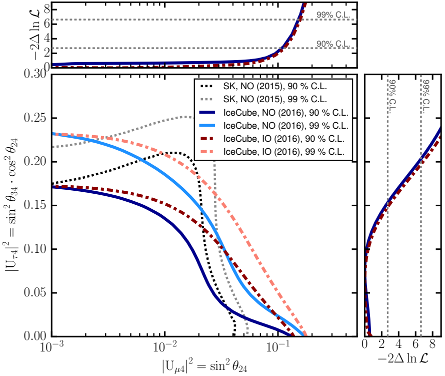


[PRL 117 (2016) 071801]

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

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

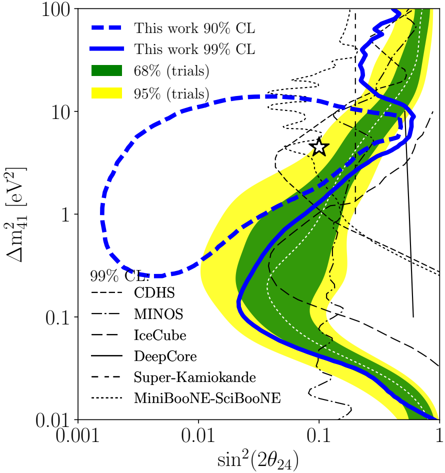


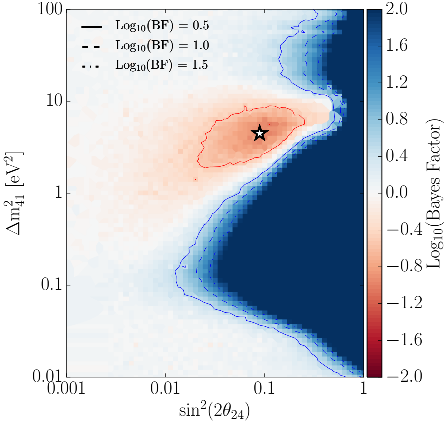
[PRD 95 (2017) 112002]

Both also constrain $|U_{\tau 4}|^2$

IceCube 8 yr update

[IceCube, PRL 2020]





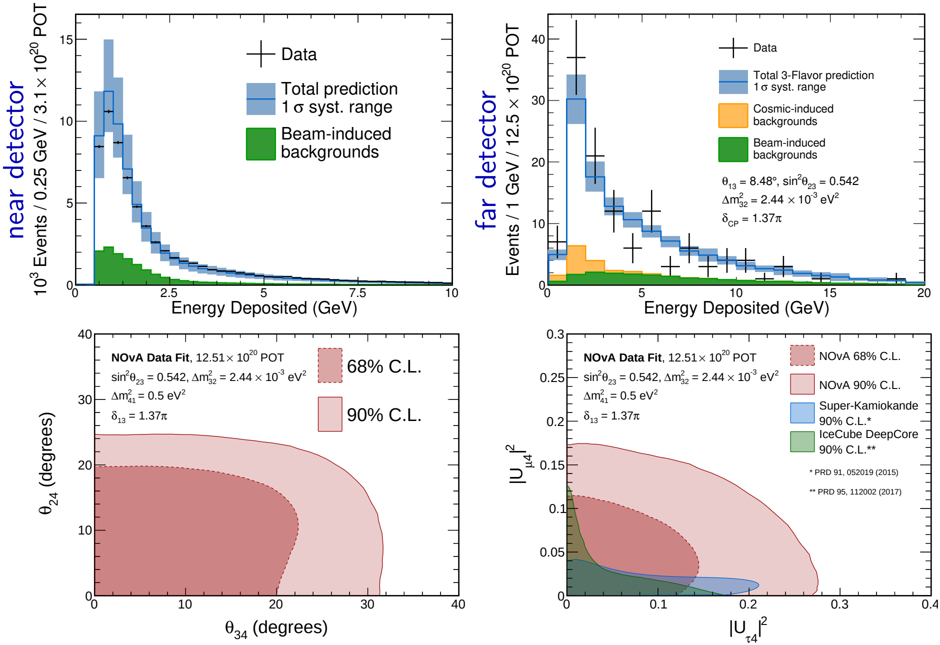
first indication in favor of sterile from ν_μ DIS!

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

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

First LBL constraints from NOvA

[NOvA, arxiv:2106.04673]

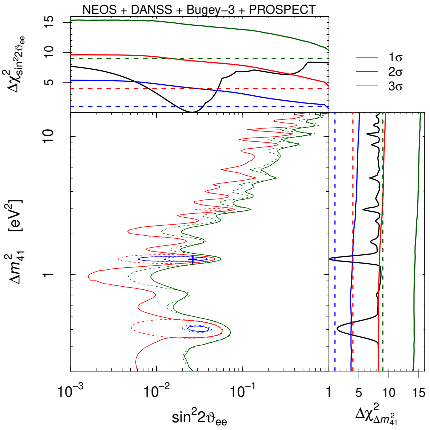


E disappearance (Electron channel)

reactor and Gallium experiments

Based on:

- JPG 43 (2016) 033001
- Kostensalo+ 2019
- Giunti, PRD 101 (2020)
- PROSPECT
- STEREO
- DayaBay
- ...



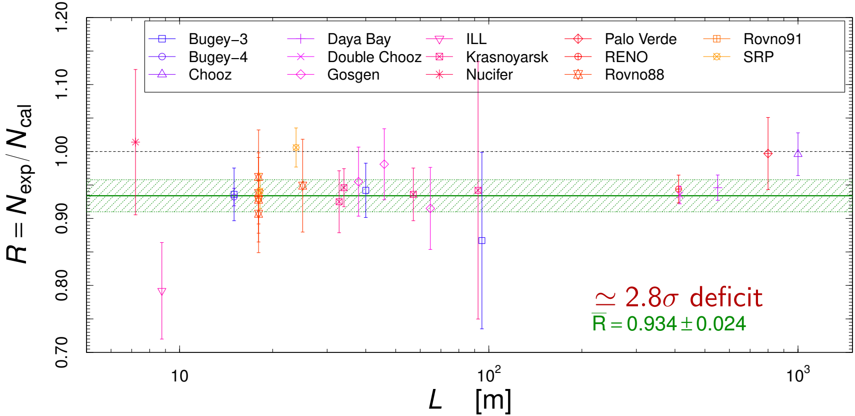
Reactor Antineutrino Anomaly (RAA)

[Mention+, PRD 83 (2011)]

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

[Huber, PRC 84 (2011) 024617] [Mueller+, PRC 83 (2011) 054615]

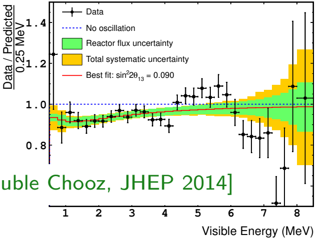
Previous reactor rates evaluated with new fluxes ⇒ deficit

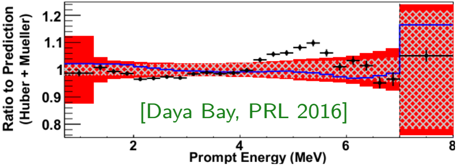


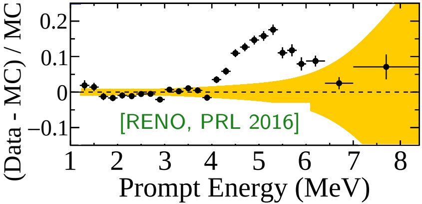
Suppression at detector due to active-sterile oscillations?

see plenary talk by C.Jollet, tomorrow h16.30

Can we trust the HM fluxes?







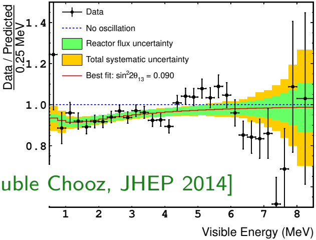
known since 2014:
bump in the spectrum around 5 MeV!

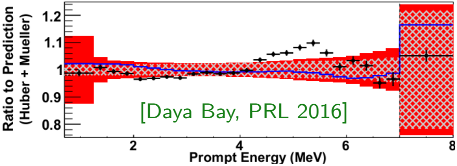
cannot be explained by SBL oscillations

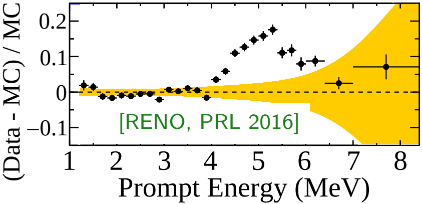
(averaged at the observed distances)

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

Can we trust the HM fluxes?







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

Model independent information!

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

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

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

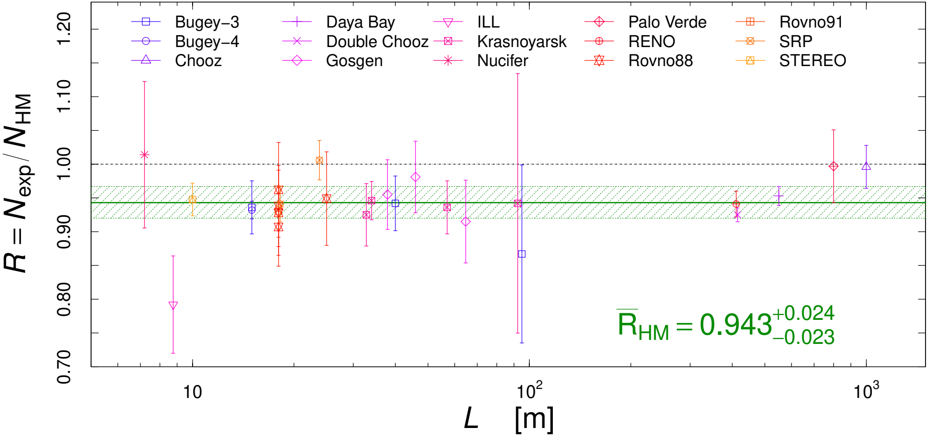
Reactor antineutrino spectrum and RAA

[Courtesy C. Giunti]

When the RAA was discovered:

conversion method (ILL data) and *ab initio* calculations in agreement

[Huber, 2011], [Mueller+, 2011] spectra



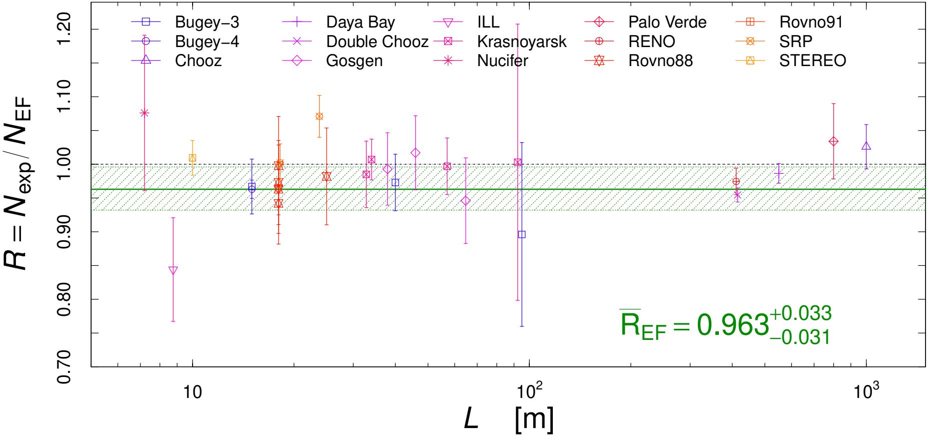
$\sim 2.4\sigma$ deficit $\Longrightarrow$ anomaly!

Reactor antineutrino spectrum and RAA

[Courtesy C. Giunti]

Revised *ab initio* calculation:

[Estienne, Fallot+, PRL 123 (2019)]



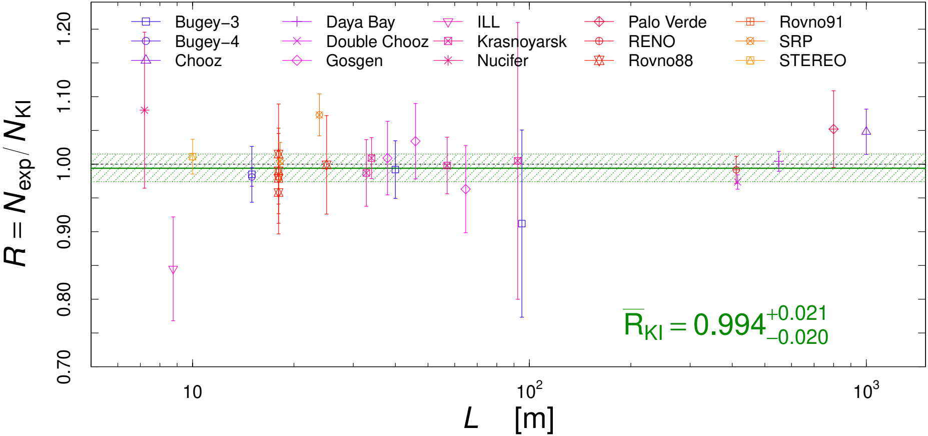
$\sim 1.2\sigma$ deficit $\Longrightarrow$ no anomaly!

Reactor antineutrino spectrum and RAA

[Courtesy C. Giunti]

Conversion method on new measurements of electron spectrum at Kurchatov Institute (KI) (updates ILL measurements from the 80's):

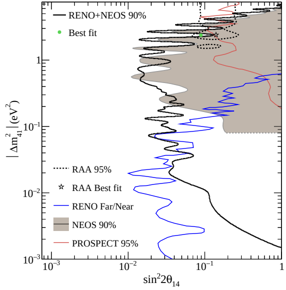
[Kopeikin+, arxiv:2103.01684]



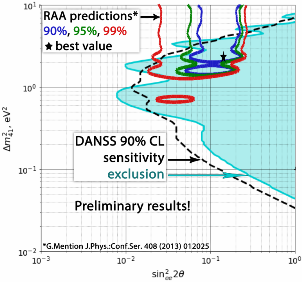
approximate agreement with EF fluxes, no anomaly!

ν_s at reactors in 2020

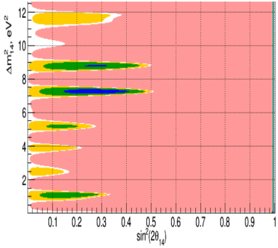
[RENO+NEOS, 2020]



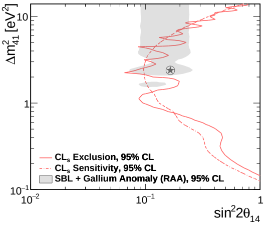
[DANSS, 2020]



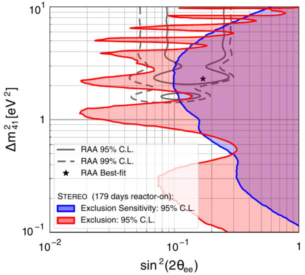
[Neutrino-4, PZETF 2020]



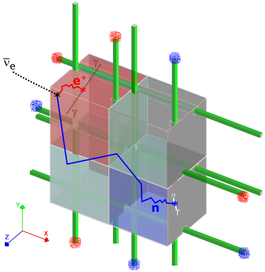
[PROSPECT, PRD 2020]



[STEREO, PRD 2020]



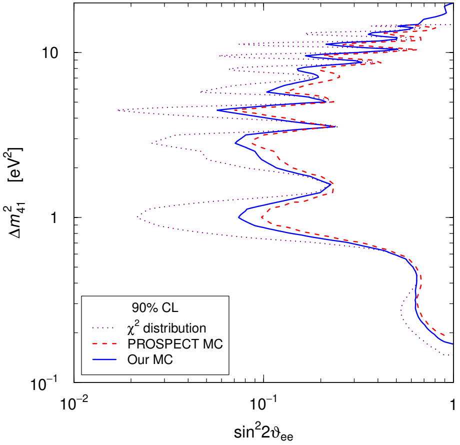
[SoLiD, JINST 2021]



Significance of the preference?

[Giunti, PRD 101 (2020)]

standard χ^2 distribution may be not appropriate to study the significance due to undercoverage at angles below the experiment sensitivity



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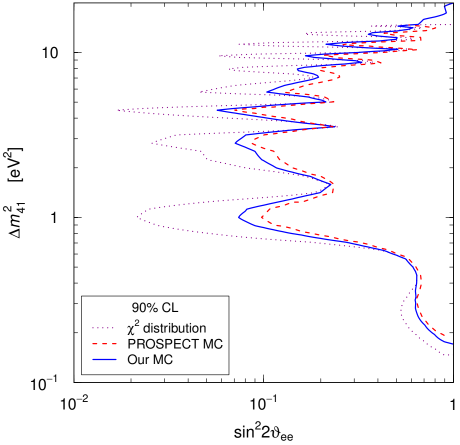
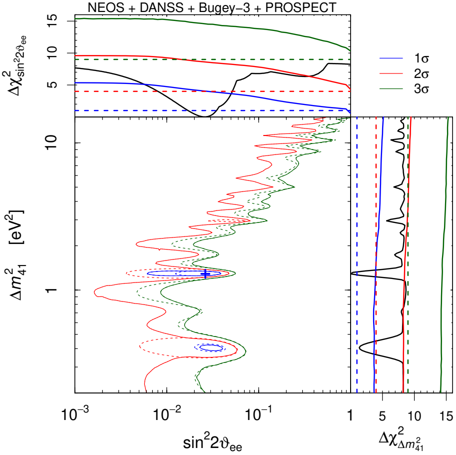




solid: MC, dashed: χ^2

True significance smaller than usually quoted (e.g. $2.4 \rightarrow 1.8\sigma$)

Gallium anomaly

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

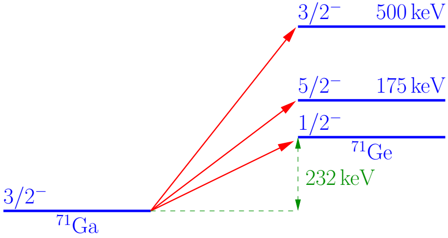
$L \simeq 1.9$ m $\quad L \simeq 0.6$ m

Gallium radioactive source experiments: GALLEX and SAGE

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

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

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



cross sections of
the transitions from

[Krofcheck+, PRL 55 (1985) 1051]

[Frekers+, PLB 706 (2011) 134]

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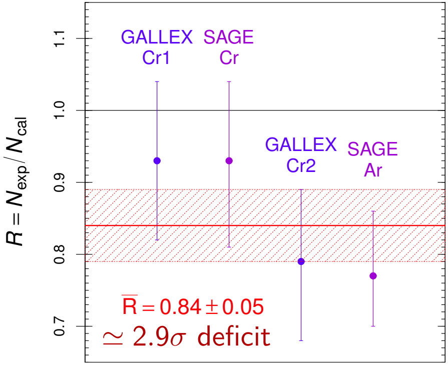
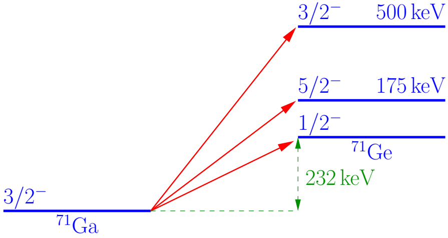
Test detection of solar ν_e





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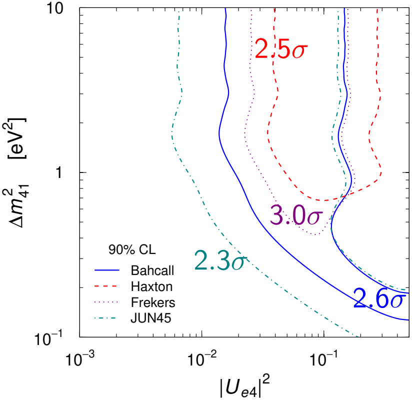
[Krofcheck+, PRL 55 (1985) 1051]

[Frekers+, PLB 706 (2011) 134]

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]

[Giunti&Laveder, 2011]

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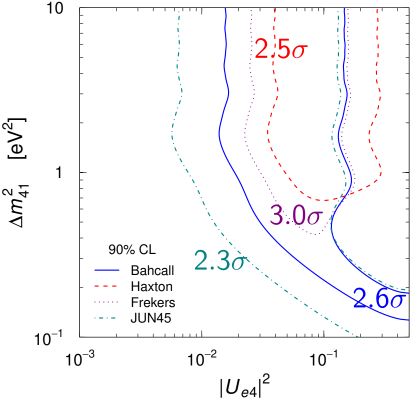

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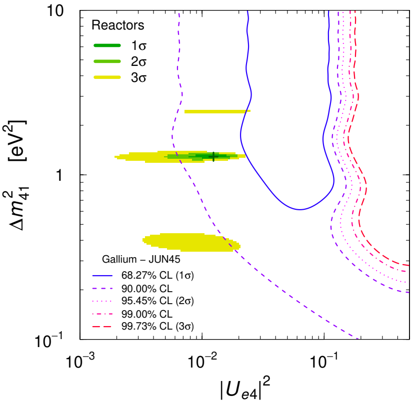
[SAGE, 2006]

[Giunti&Laveder, 2011]

Compare with DANSS+NEOS:

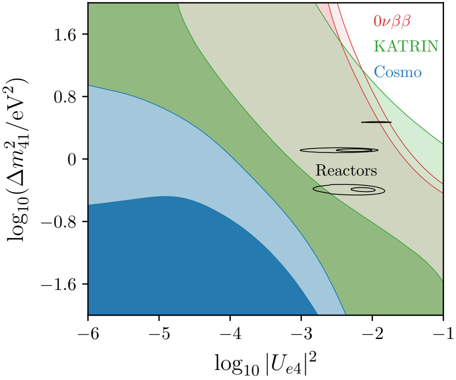


Better compatibility with reactors

F Fit

Based on:

- work in progress
- Dentler+ 2018
- arxiv:2003.02289

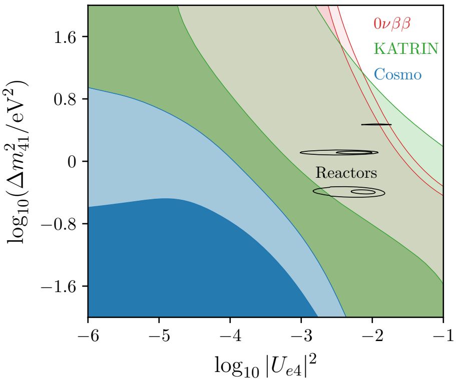


Fit = Global Fit

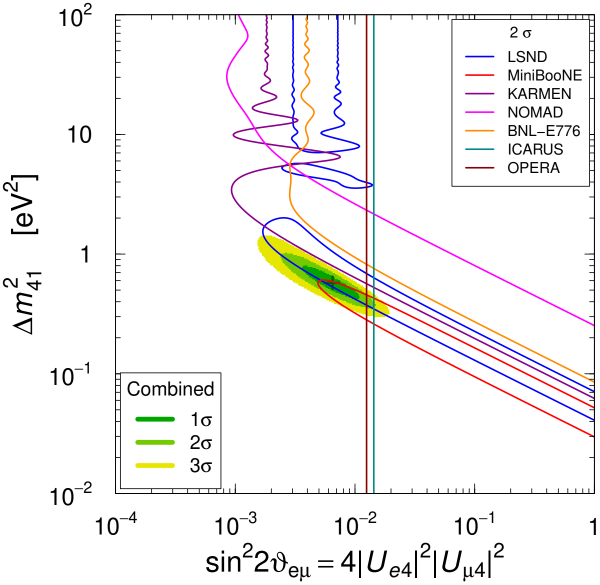
like “Bond, James Bond”

Based on:

- work in progress
- Dentler+ 2018
- arxiv:2003.02289



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



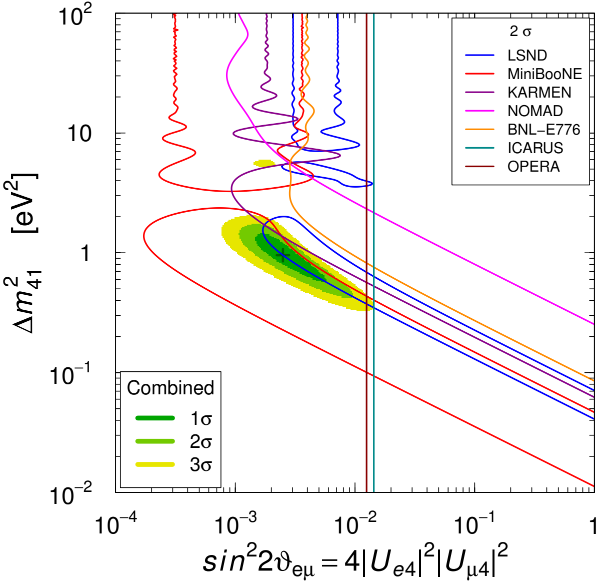
with full MiniBooNE data

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



without MiniBooNE low energy bins

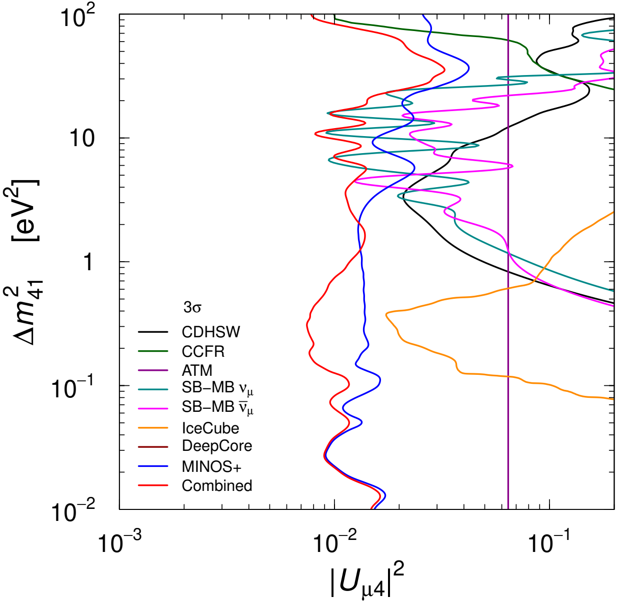
ICARUS and OPERA exclude MiniBooNE best fit

LSND and MiniBooNE only partially in agreement

KARMEN cuts part of LSND region

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

[SG+, in preparation]



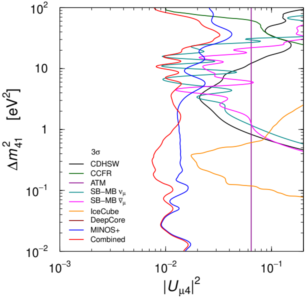
MINOS+ dominates at small Δm^2_{41}

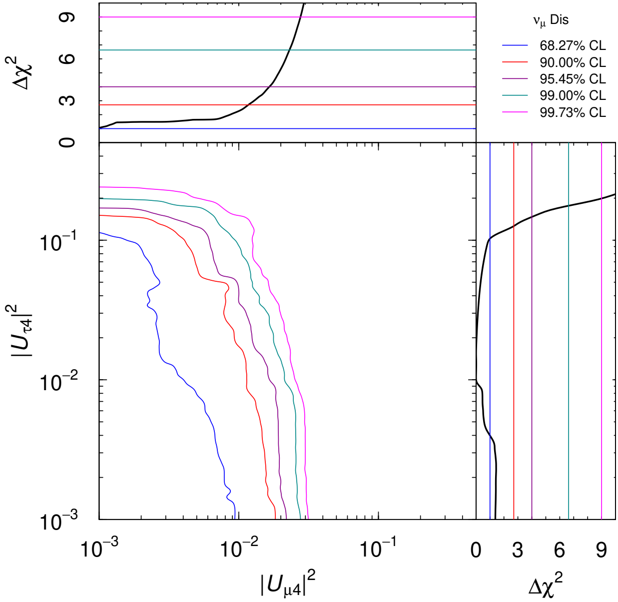
IceCube (1 yr) important at $\Delta m^2_{41} \simeq 0.2$ eV^2

IceCube 8 yr not included!

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

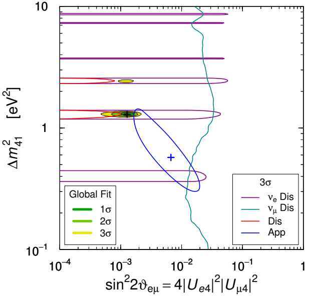
[SG+, in preparation]





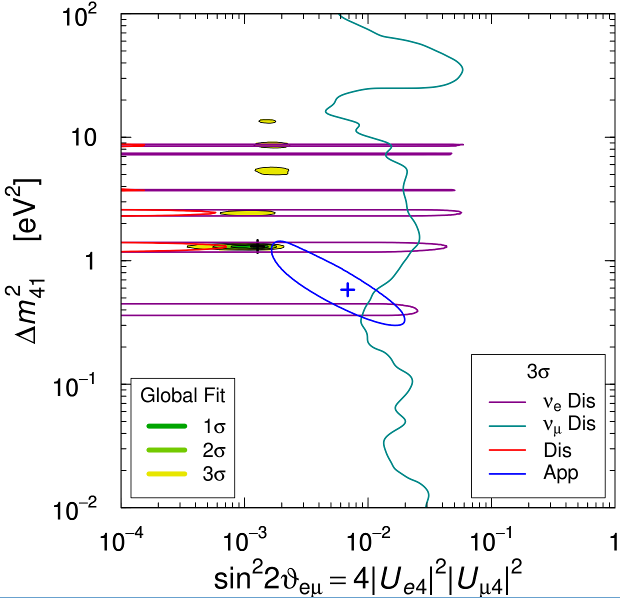
APP – DIS tension in 2019

Status just after Neutrino 2018:



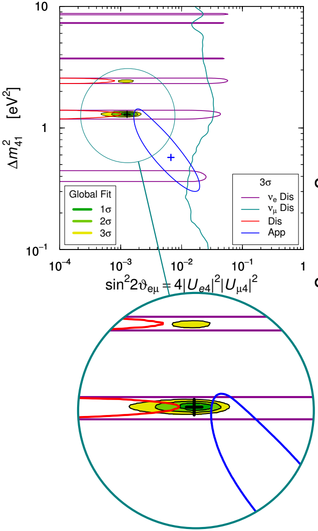
MINOS+ update, new data including MiniBooNE (all bins)

Status in early 2019

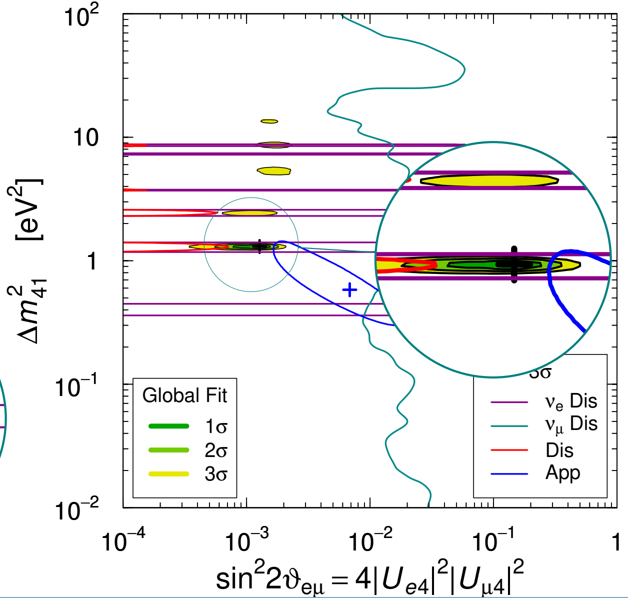


[SG+, in preparation]

Status just after Neutrino 2018:

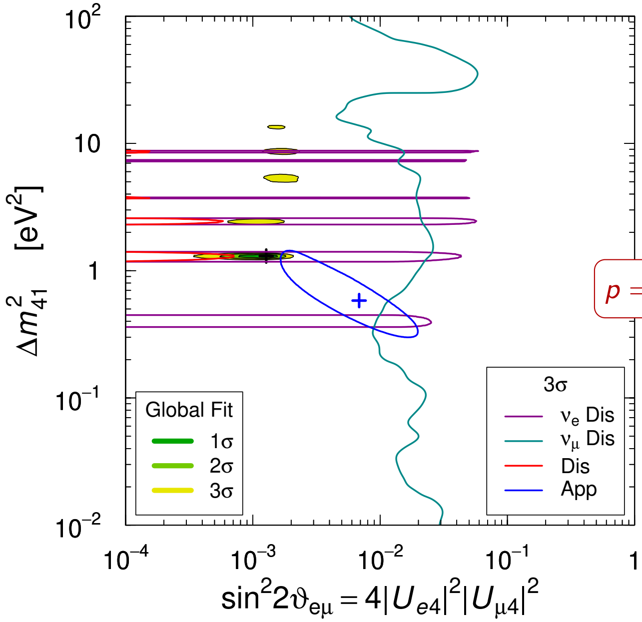


Status in early 2019



APP – DIS tension in 2019

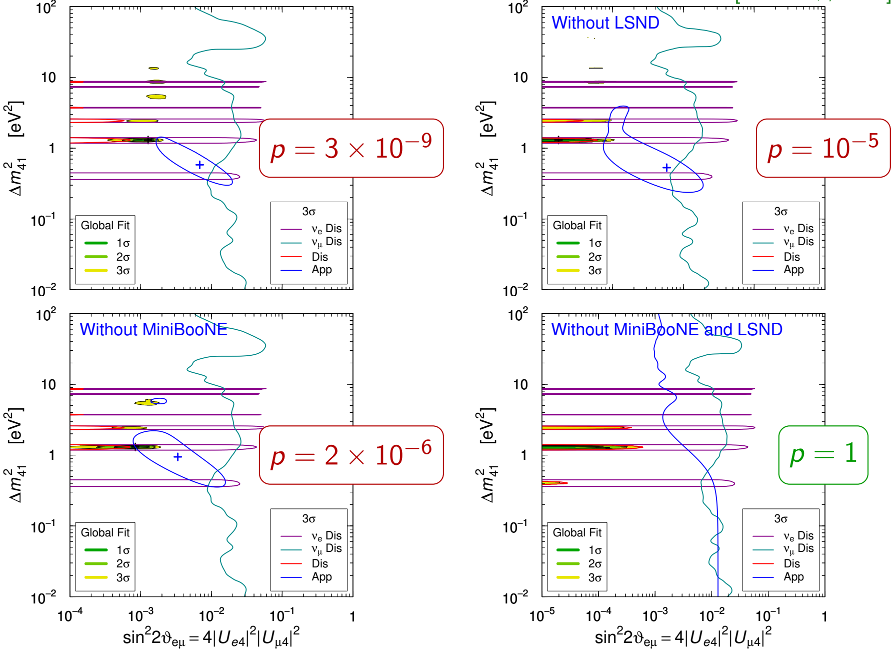
[SG+, in preparation]



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

APP – DIS tension in 2019

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

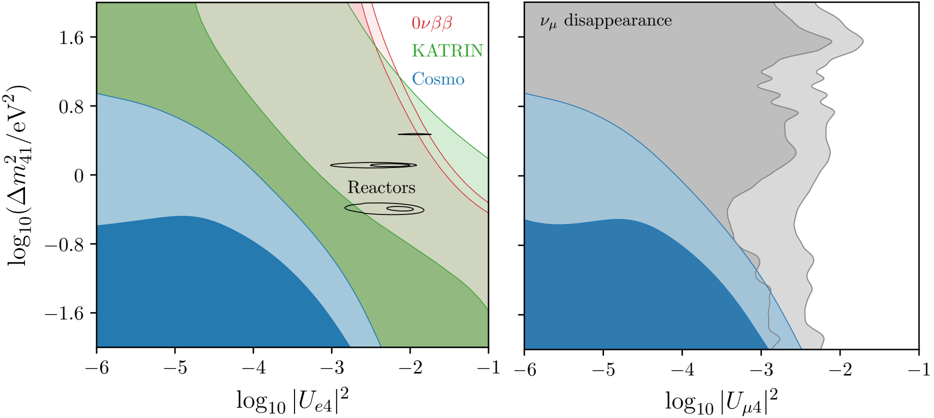


Comparing constraints

[arxiv:2003.02289]

Cosmological constraints are stronger than most other probes

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



Comparing constraints

[arxiv:2003.02289]

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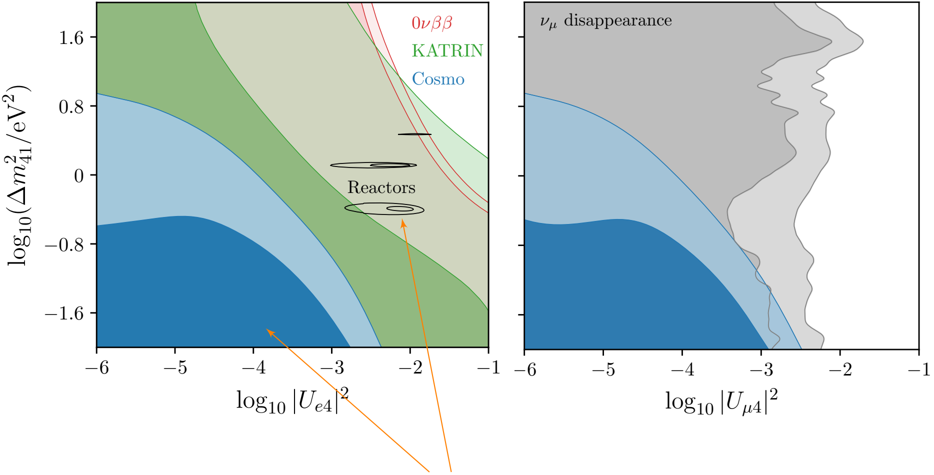


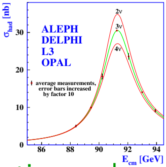
Warning: tension between reactor experiments and CMB bounds!

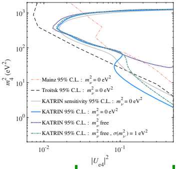
Z Conclusions

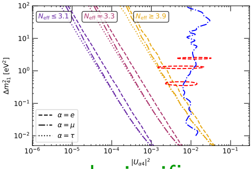
The situation is NOT favorable
for the light sterile neutrino...

What do we learn on sterile neutrinos?

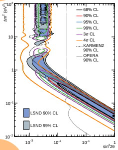
N Non-oscillation probes: no signal, possibly strong constraints

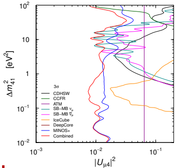


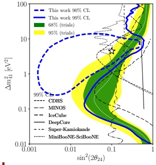


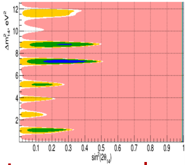


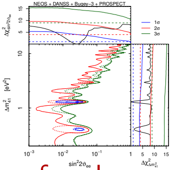
O Oscillation probes: several anomalies, weak significance each



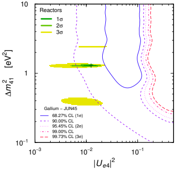


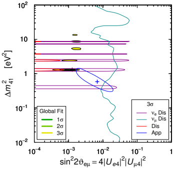


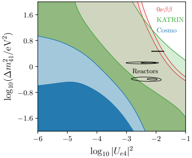


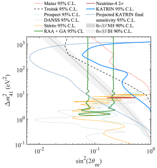


T Tensions! even strong, between experiments or classes of probes



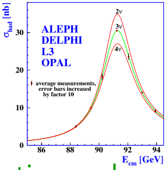


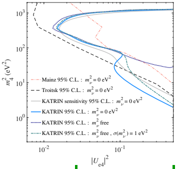


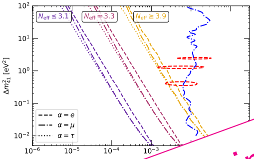


What do we learn on sterile neutrinos?

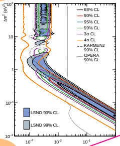
N Non-oscillation probes: no signal, possibly strong constraints

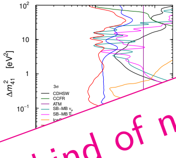


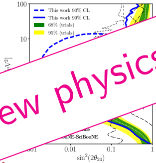


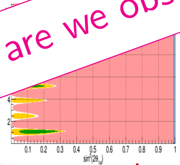


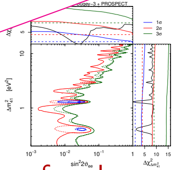
O Oscillation probes: several anomalies, weak



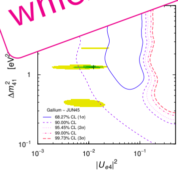


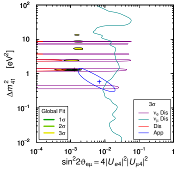


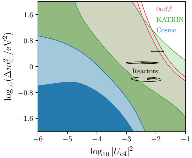


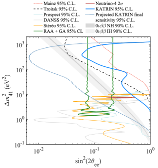


T ng, between experiments or classes of probes





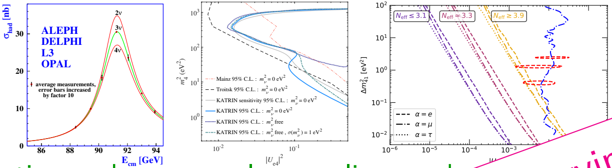




which kind of new physics are we observing?

What do we learn on sterile neutrinos?

N Non-oscillation probes: no signal, possibly strong constraints



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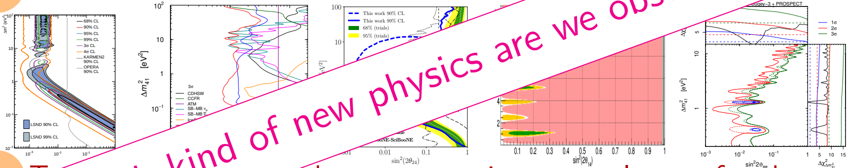

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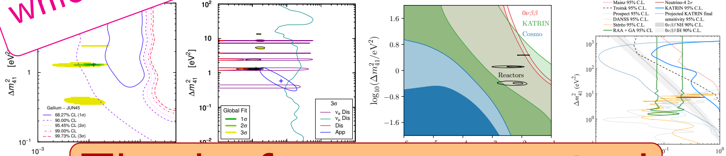


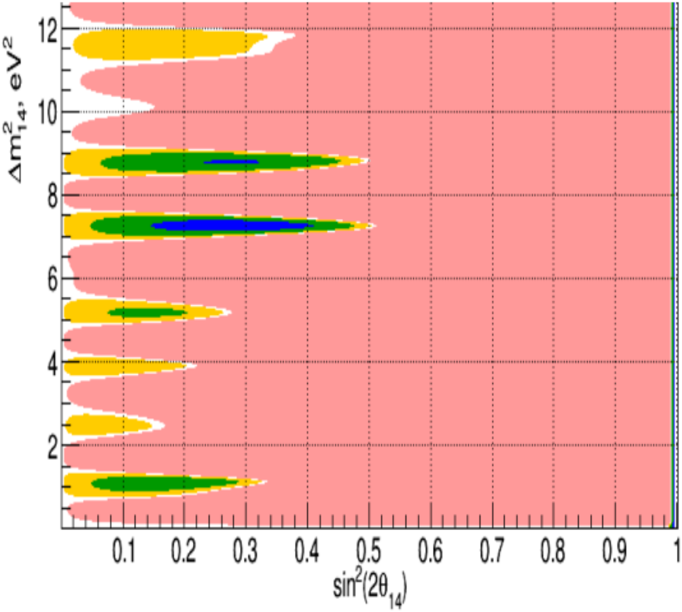
which kind of new physics are we observing?

Thanks for your attention!

Appendix

Neutrino-4

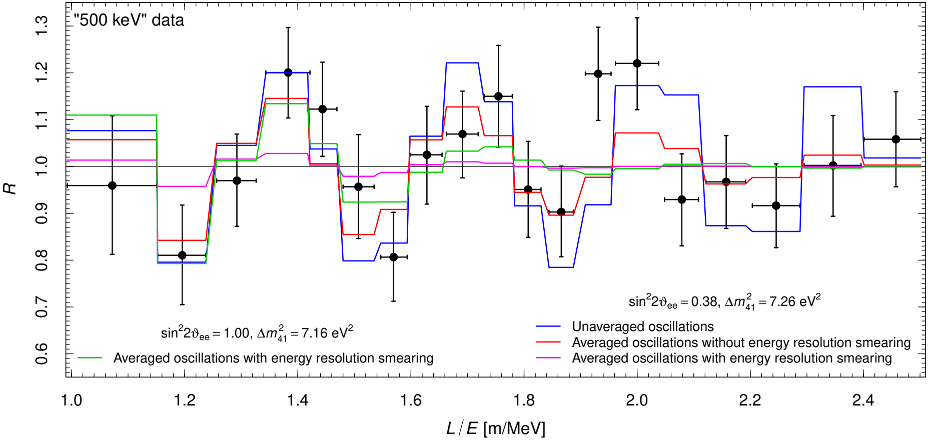
[Neutrino-4 2020]



claimed $> 3\sigma$ preference for $3+1$ over 3ν case

best fit incompatible with other reactor experiments

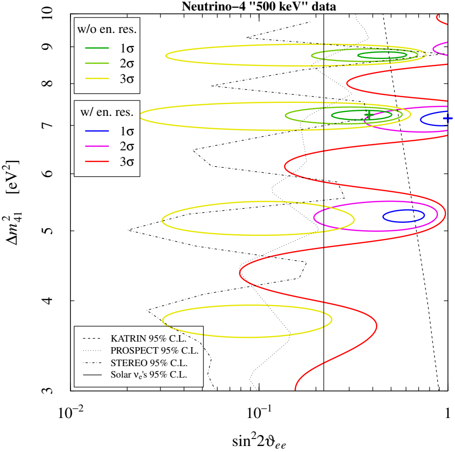
Neutrino-4

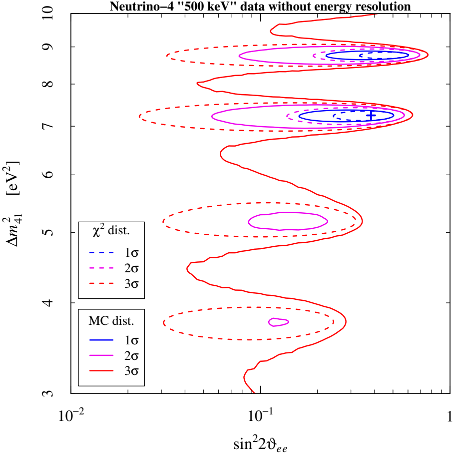


energy resolution smearing not properly taken into account?

Neutrino-4

[Giunti+, PLB 2021]





proper energy resolution treatment moves best-fit $\to$ $\sin^2 2\vartheta \simeq 1$

need to take into account
violation of Wilk's theorem
↓
relaxed constraints