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G.A. 754496

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SEZIONE DI TORINO

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Light sterile neutrinos

i.e. eV-scale mass standard model singlets

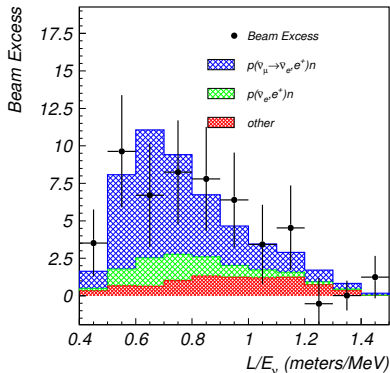
A

Anomalies

Why do we need a light sterile neutrino?

Based on:

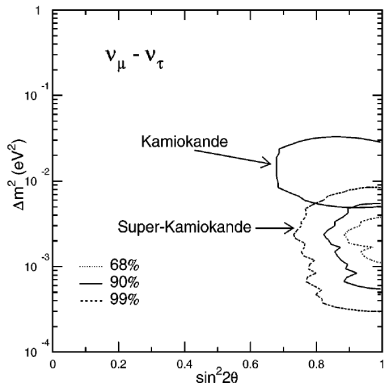
- JHEP 02 (2021) 071 and update
- JPG 43 (2016) 033001
- LSND
- MiniBooNE



Neutrino oscillations

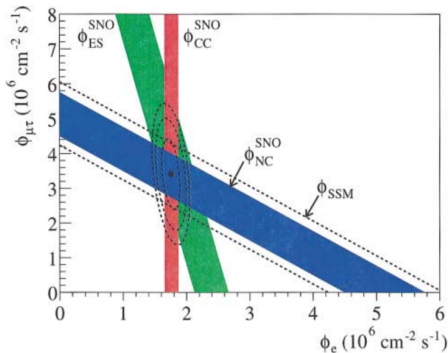
Major discoveries:

[SuperKamiokande, 1998]



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

[SNO, 2001-2002]



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

Nobel prize in 2015

Two neutrino bases

interaction

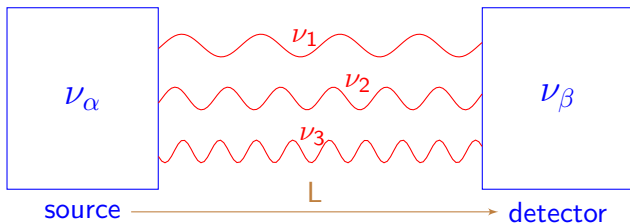
flavor neutrinos ν_α

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:

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

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

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]

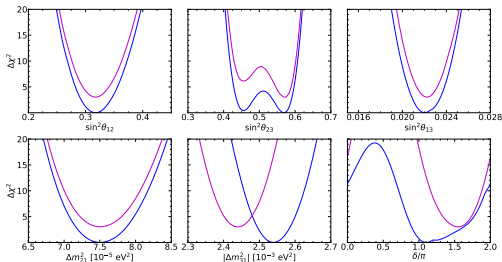
NO/NH: Normal Ordering/Hierarchy, $m_1 < m_2 < m_3$

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

$$\begin{aligned} \Delta m_{21}^2 &= (7.50^{+0.22}_{-0.20}) \cdot 10^{-5} \text{ eV}^2 \\ |\Delta m_{31}^2| &= (2.54 \pm 0.03) \cdot 10^{-3} \text{ eV}^2 \text{ (NO)} \\ &= (2.44 \pm 0.03) \cdot 10^{-3} \text{ eV}^2 \text{ (IO)} \end{aligned}$$

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

$$\begin{aligned} \delta/\pi &= 1.10^{+0.27}_{-0.12} \text{ (NO)} \\ &= 1.54 \pm 0.14 \text{ (IO)} \end{aligned}$$



mass ordering
still unknown

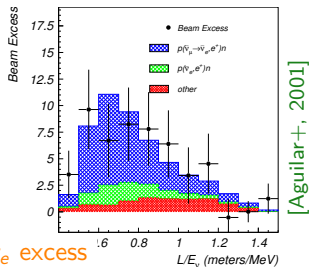
δ still unknown

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

Do three-neutrino oscillations explain all experimental results?

Do three-neutrino oscillations explain all experimental results?

LSND

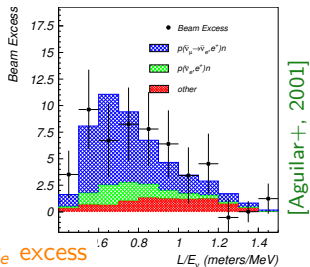


[Aguilar+, 2001]

 3.8σ $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ excess

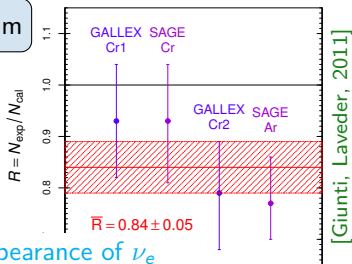
Do three-neutrino oscillations explain all experimental results?

LSND



3.8σ

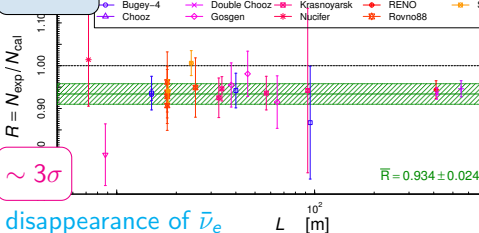
Gallium



2.7σ

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

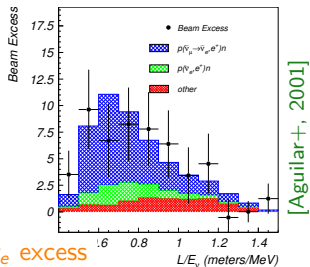
Reactor



$\sim 3\sigma$

Do three-neutrino oscillations explain all experimental results?

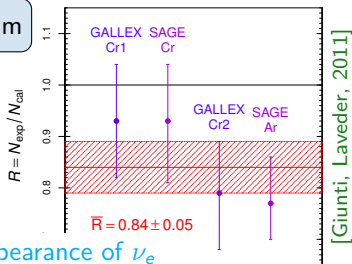
LSND



3.8σ

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

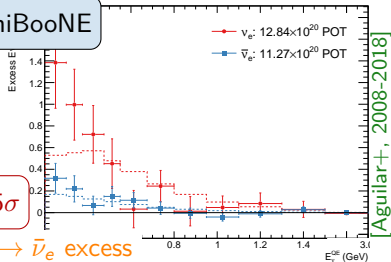
Gallium



2.7σ

disappearance of ν_e

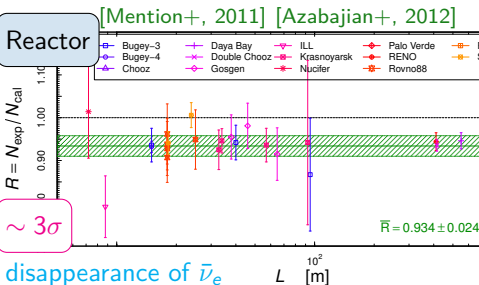
MiniBooNE



$\sim 5\sigma$

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

Reactor

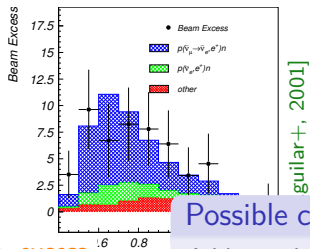


$\sim 3\sigma$

disappearance of $\bar{\nu}_e$

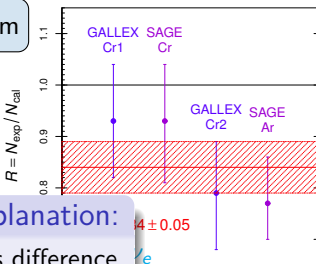
Do three-neutrino oscillations explain all experimental results?

LSND



guilard+, 2001]

Gallium



[Giunti, Laveder, 2011]

3.8σ

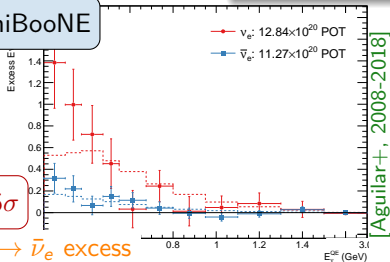
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ excess

Possible common explanation:

Additional squared mass difference

$$\Delta m_{\text{SBL}}^2 \simeq 1 \text{ eV}^2$$

MiniBooNE

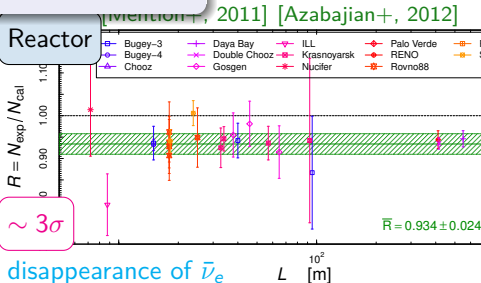


[Aguilar+, 2008-2018]

$\sim 5\sigma$

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

Reactor



[Aguilar+, 2008-2018] [Azabajian+, 2012]

$\sim 3\sigma$

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]

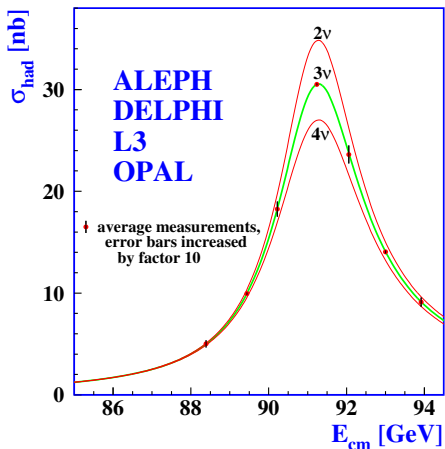
$$N_\nu^{(Z)} = 2.9963 \pm 0.0074$$

from measurement of Z resonance

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

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

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \\ |\nu_{s1}\rangle \\ \dots \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \vdots \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} & \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} & \\ U_{s11} & U_{s12} & U_{s13} & U_{s14} & \\ \dots & & & & \ddots \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \\ |\nu_4\rangle \\ \dots \end{pmatrix}$$

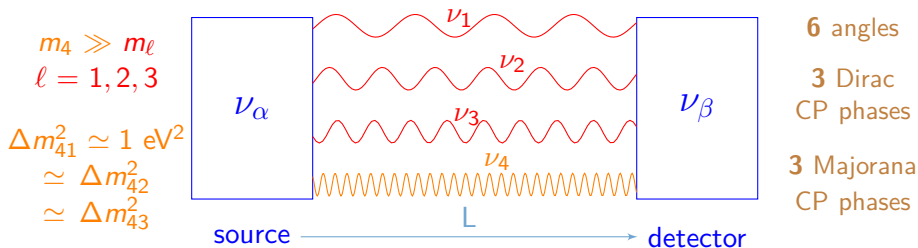
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Our case will be 3 (active)+1 (sterile), a perturbation of 3 neutrinos case



New mixings in the 3+1 scenario

4 × 4 mixing matrix:

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

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New mixings in the 3+1 scenario

4 × 4 mixing matrix:

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{array}{l} \left[\right. \\ \left. \right] \\ \left. \right] \\ \left. \right] \end{array} \begin{array}{l} \vartheta_{14} \\ \vartheta_{24} \\ \vartheta_{34} \end{array}$$

DISappearance

$$P_{\nu_{\alpha}^{(-)} \rightarrow \nu_{\alpha}^{(-)}}^{\text{SBL}} \simeq 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E} \right)$$

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

$\nu_e^{(-)} \rightarrow \nu_e^{(-)}$

reactor
gallium

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

$\nu_{\mu}^{(-)} \rightarrow \nu_{\mu}^{(-)}$

accelerator
atmospheric

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

New mixings in the 3+1 scenario

4 × 4 mixing matrix:

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atmospheric

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APPearence

$$P_{\nu_{\alpha} \rightarrow \nu_{\beta}}^{\text{SBL}(-)} \simeq \sin^2 2\vartheta_{\alpha\beta} \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E} \right)$$

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

$$\nu_{\mu}^{(-)} \rightarrow \nu_e^{(-)}$$

LSND
MiniBooNE
KARMEN
OPERA
...

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

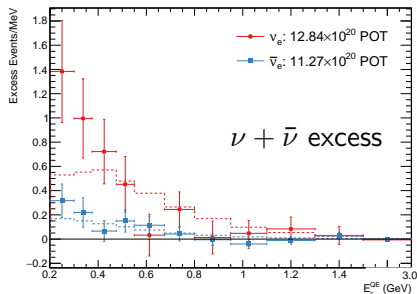
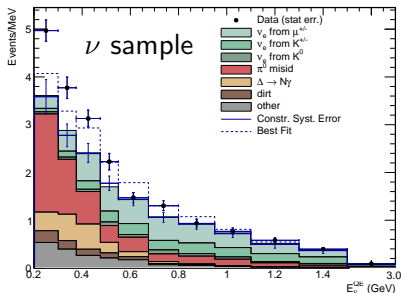
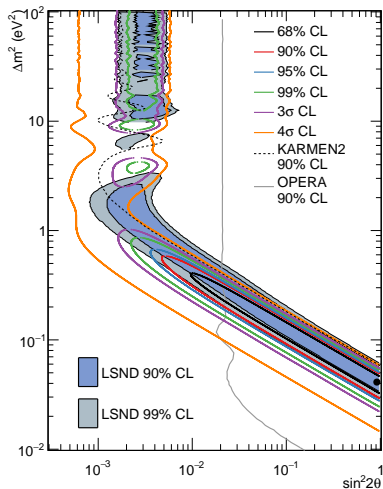
quadratically suppressed!

for small $|U_{e4}|^2$, $|U_{\mu 4}|^2$

purpose: check LSND signal

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

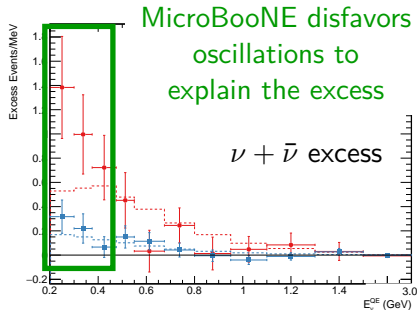
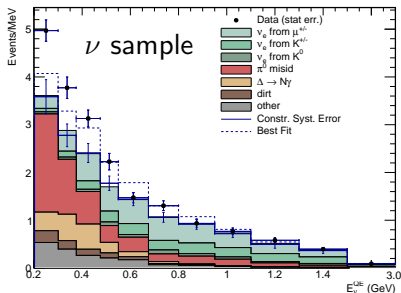
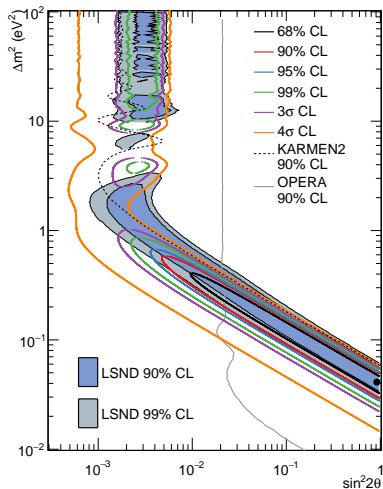
no money, no near detector



purpose: check LSND signal

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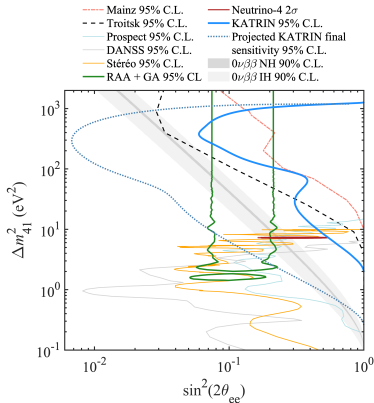
B

Beta decay constraints

i.e. non-oscillation probes, first part

Based on:

- KATRIN



β decay



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

total available energy

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

neutrino energy

notice that max electron energy is:

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

Kurie function: (degenerate ν masses)

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

Useful to describe
the e^- spectrum
near the endpoint

β decay



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total available energy

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notice: flavor neutrinos have no definite mass!

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

β decay



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

Full expression:

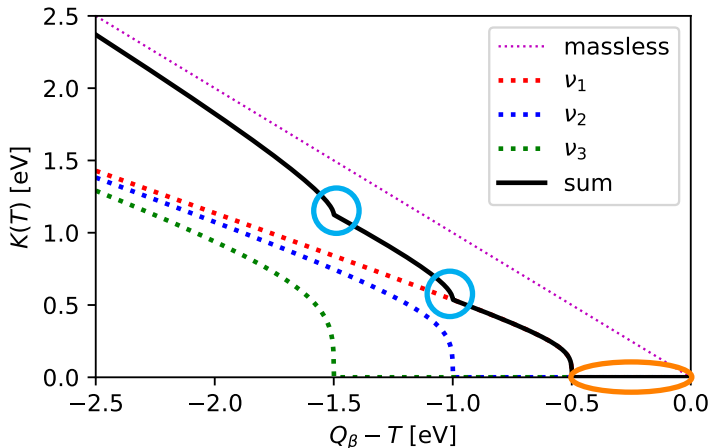
$$K(T) = \left[(Q_\beta - T) \sum_{i=1}^{N_\nu} |U_{ei}|^2 \sqrt{(Q_\beta - T)^2 - m_i^2} \right]^{1/2}$$

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

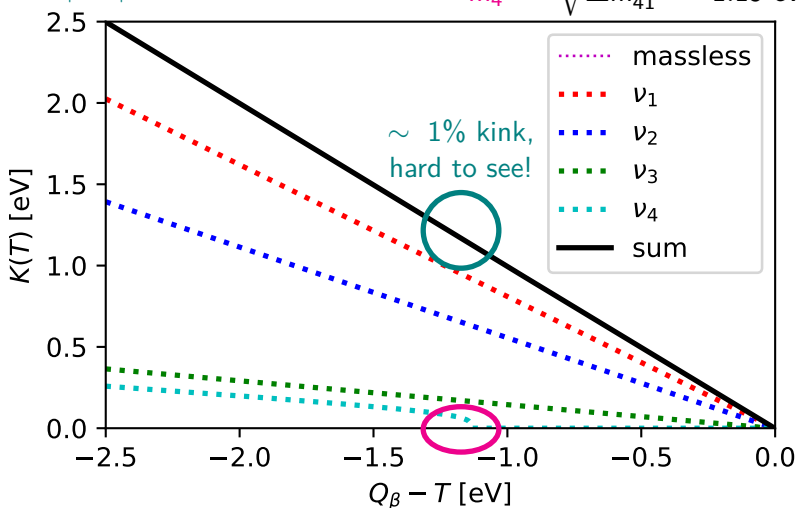
endpoint shifted + one kink for each mass eigenstate

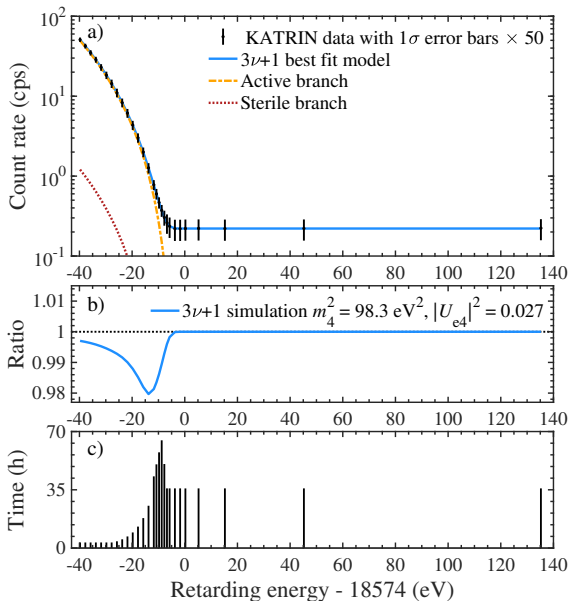
Sterile neutrino in β decay

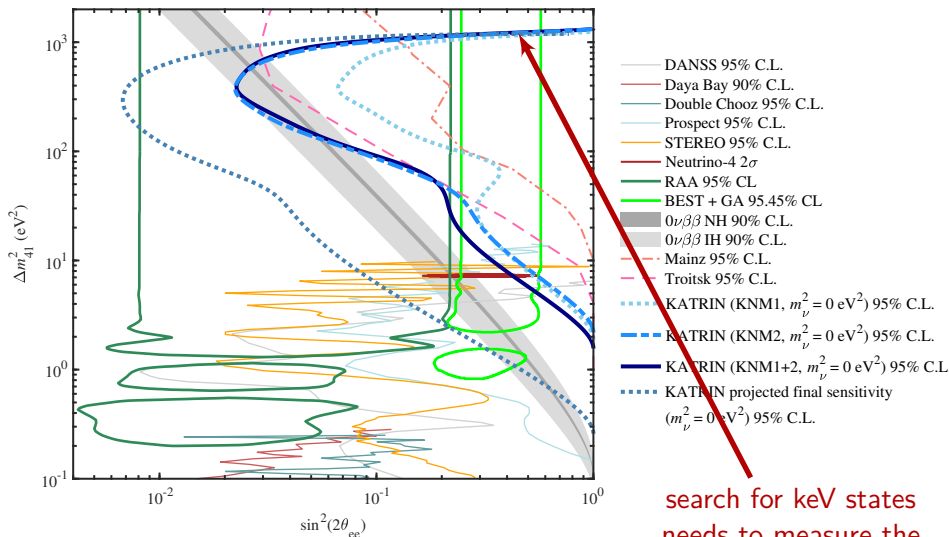
$$K(T) = \left[(Q_\beta - T) \sum_{i=1}^{N_\nu} |U_{ei}|^2 \sqrt{(Q_\beta - T)^2 - m_i^2} \right]^{1/2}$$

$$|U_{e4}|^2 \sim 0.01$$

$$m_4 \sim \sqrt{\Delta m_{41}^2} \simeq 1.15 \text{ eV}$$







final sensitivity will test
several oscillation results!

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

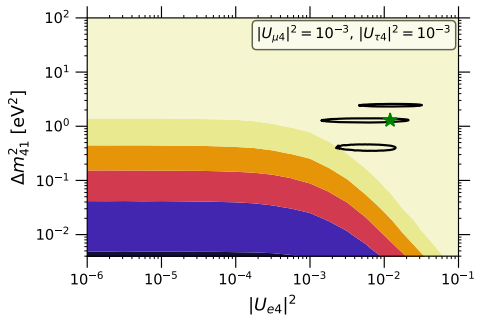


Cosmology

i.e. non-oscillation probes, second part

Based on:

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



Four neutrinos \rightarrow new oscillations in the early Universe

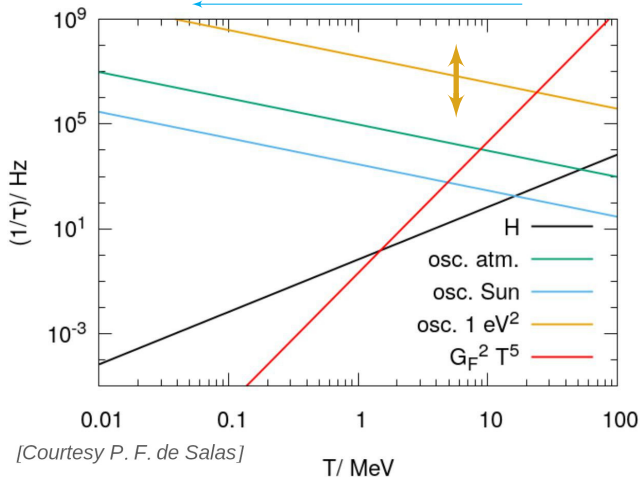
sterile \implies no weak/em interactions in the thermal plasma

Sterile neutrino in the early universe

Four neutrinos \rightarrow new oscillations in the early Universe

sterile \implies no weak/em interactions in the thermal plasma

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



[Courtesy P. F. de Salas]

beginning of
oscillations
depends on Δm_{41}^2

later oscillations
 \Downarrow
less time before
 ν decoupling!

Sterile neutrino in the early universe

Four neutrinos \rightarrow new oscillations in the early Universe

sterile \implies 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?

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

no sterile production active&sterile in equilibrium

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

[Dolgov&Villante, 2004]

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

$$N_{\text{eff}}^{3\nu} = 3.044 \quad [\text{JCAP 2021}]$$

Four neutrinos \rightarrow new oscillations in the early Universe

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[Dolgov&Villante, 2004]

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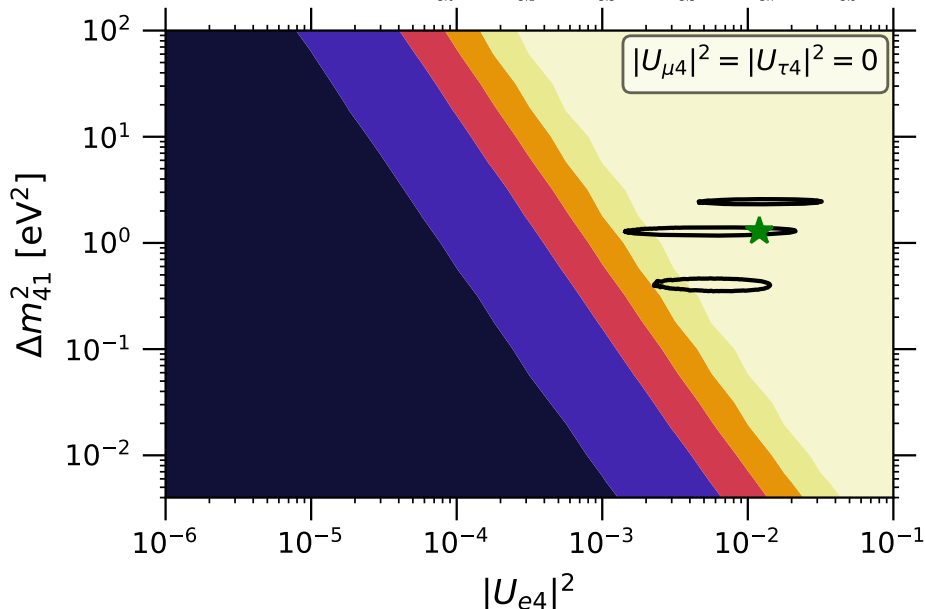
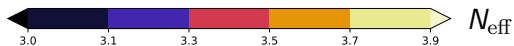
Full calculation: use numerical code!

FORTran-Evolved Primordial Neutrino Oscillations
(FortEPiano)

https://bitbucket.org/ahep_cosmo/fortepiano_public

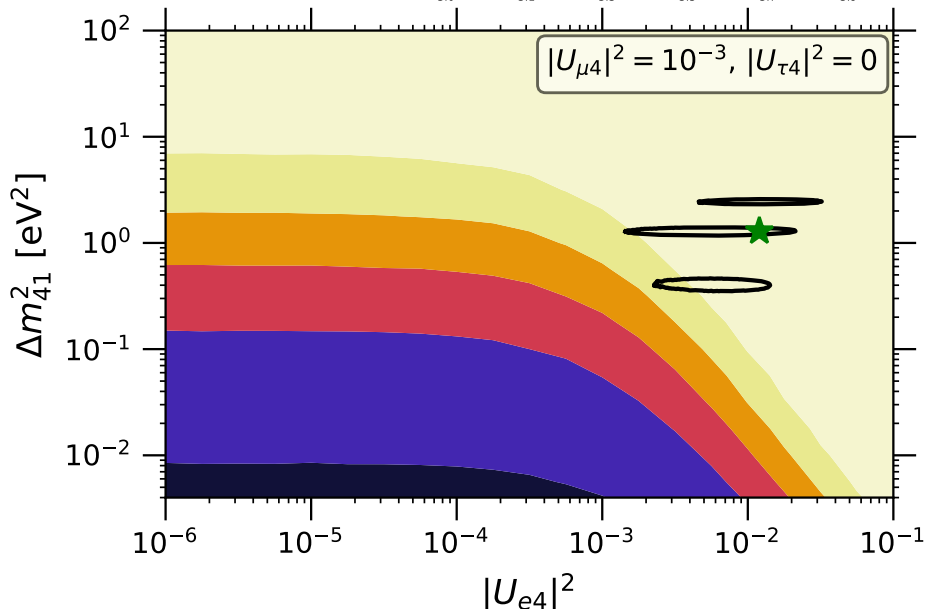
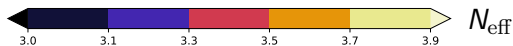
N_{eff} and the new mixing parameters

We can vary more than one angle:

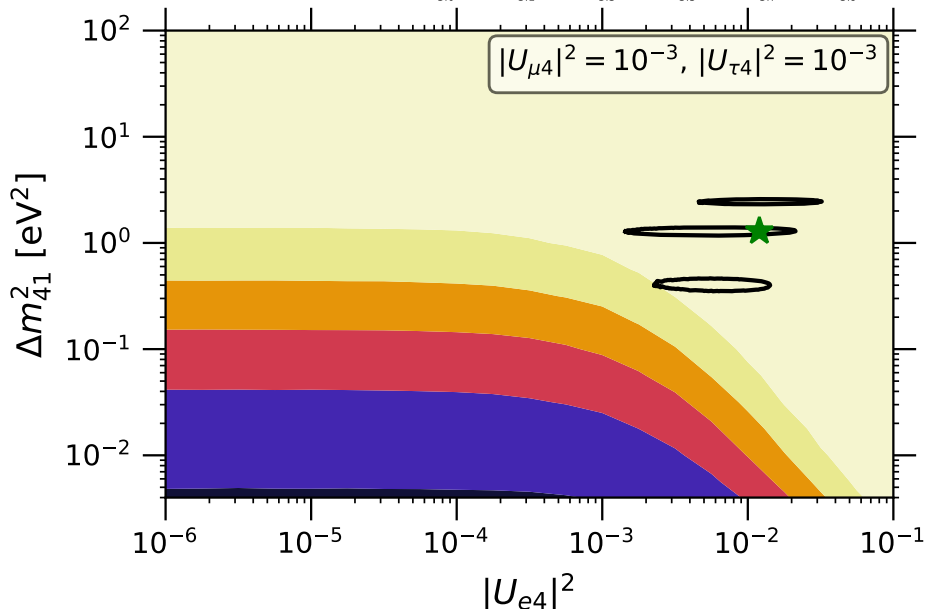
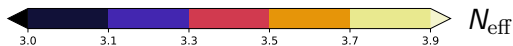


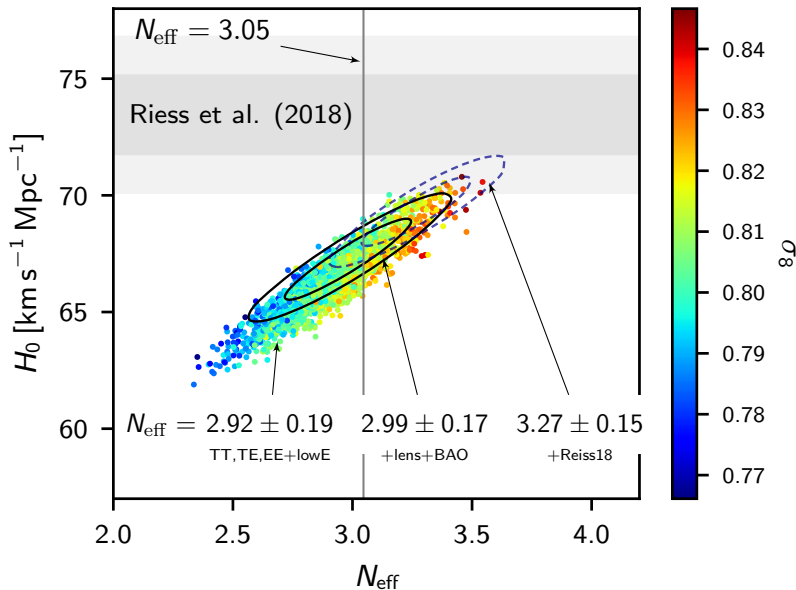
N_{eff} and the new mixing parameters

We can vary more than one angle:



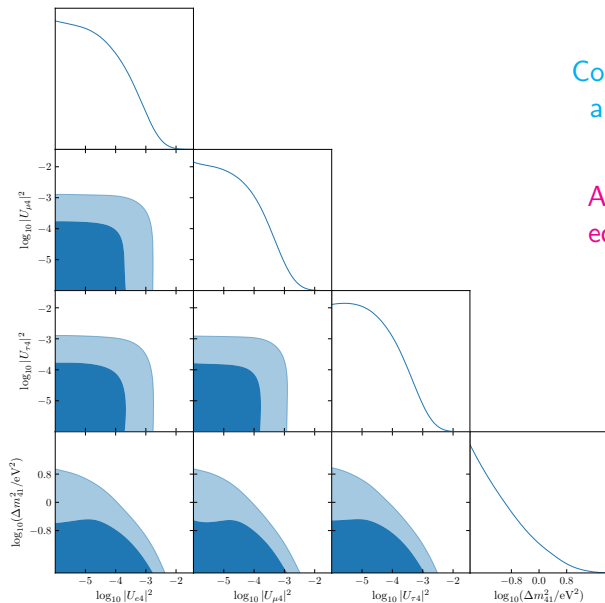
We can vary more than one angle:





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

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



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

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

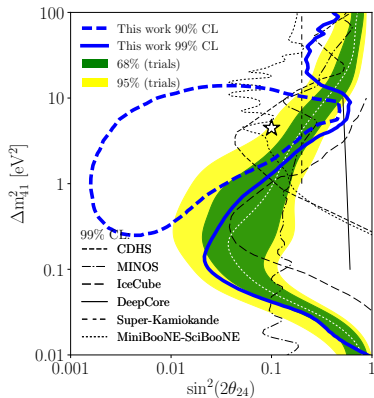
D

Disappearance (Muon channel)

strong constraints, and a recent first hint

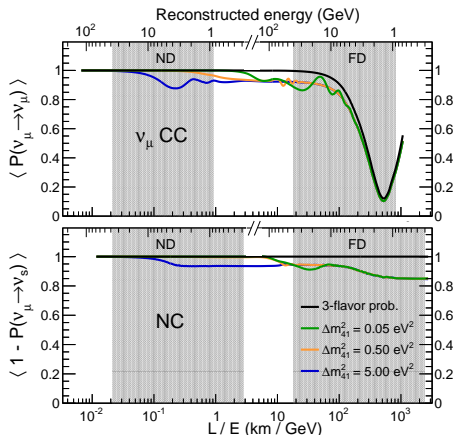
Based on:

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



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]:

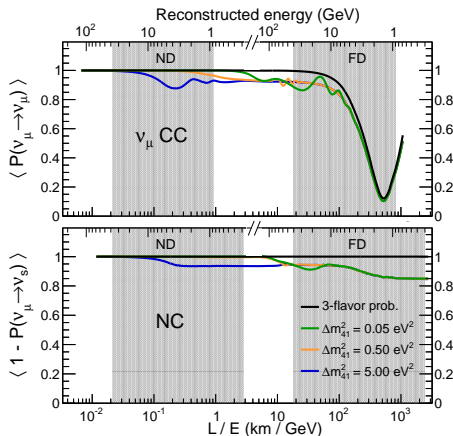
far-to-near ratio

[PRL 122 (2019) 091803]:

full two-detectors fit

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



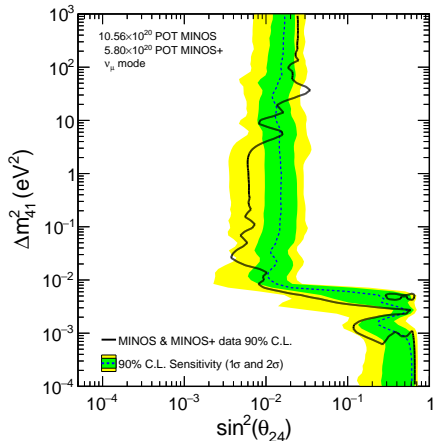
[PRL 117 (2016) 151803]:

far-to-near ratio

[PRL 122 (2019) 091803]:

full two-detectors fit

Sensitivity and exclusion limit:



[PRL 122 (2019) 091803]

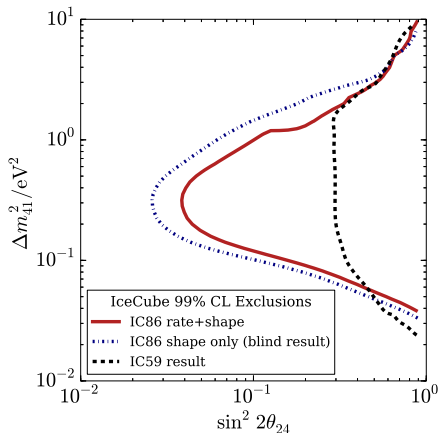
IceCube and DeepCore

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]

IceCube and DeepCore

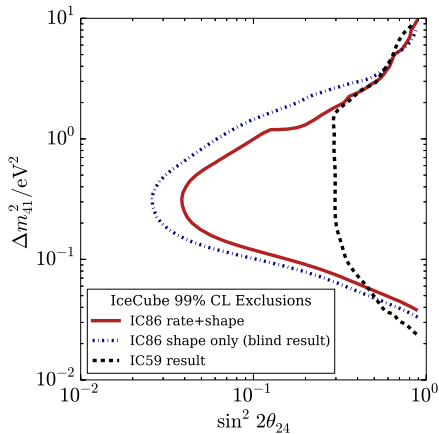
IceCube

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

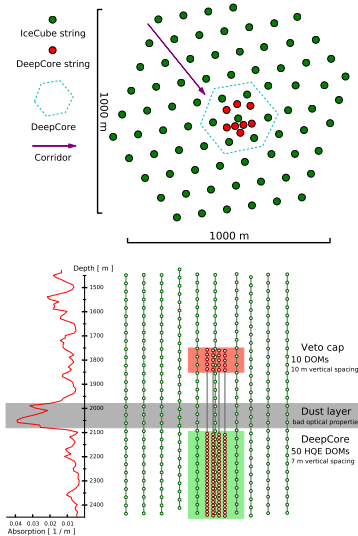
DeepCore

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[PRL 117 (2016) 071801]



IceCube and DeepCore

IceCube

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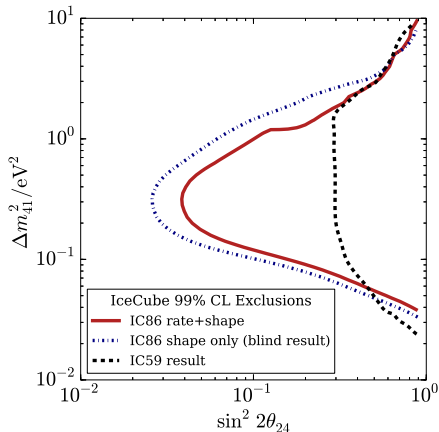
DeepCore

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

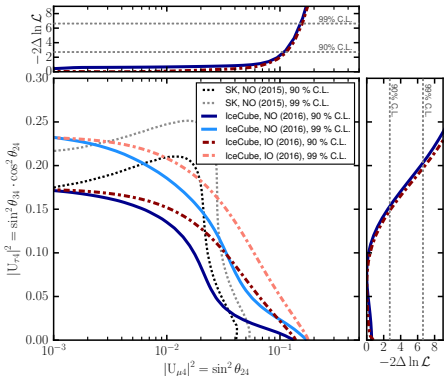
$320 \text{ GeV} < E < 20 \text{ TeV}$

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

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

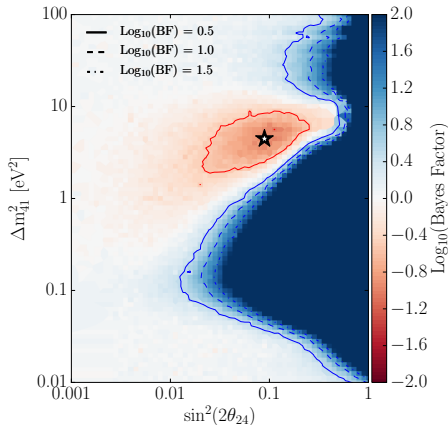
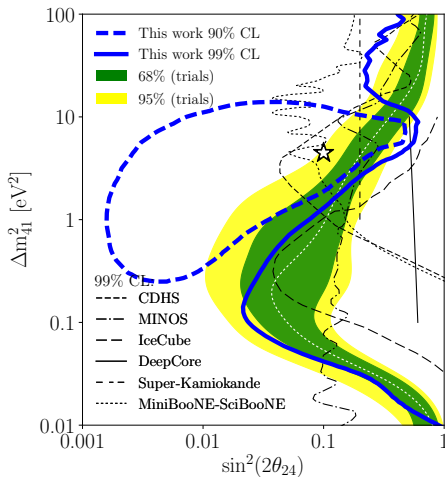


[PRL 117 (2016) 071801]



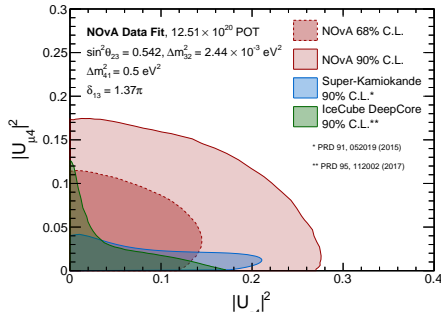
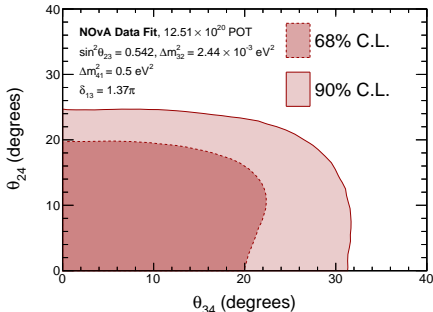
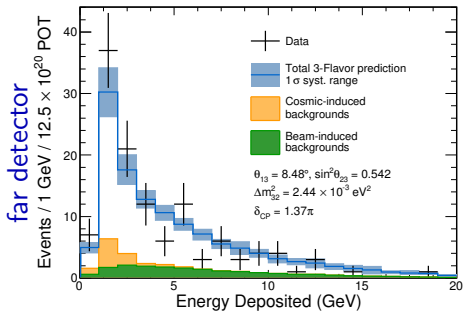
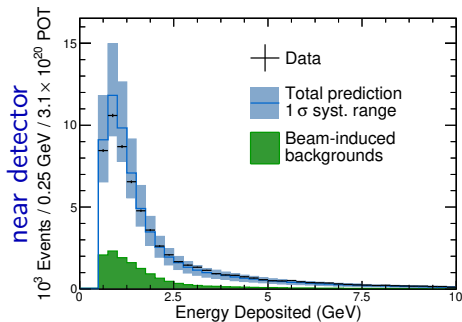
[PRD 95 (2017) 112002]

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



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%



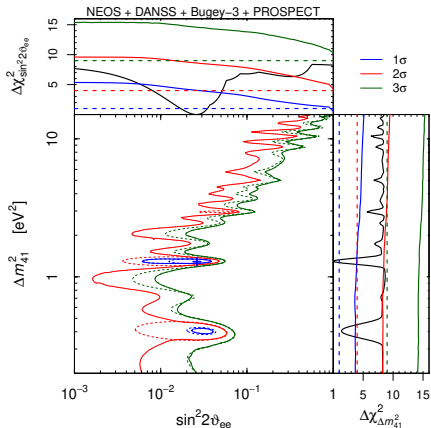
E

disappearance (Electron channel)

reactor and Gallium experiments

Based on:

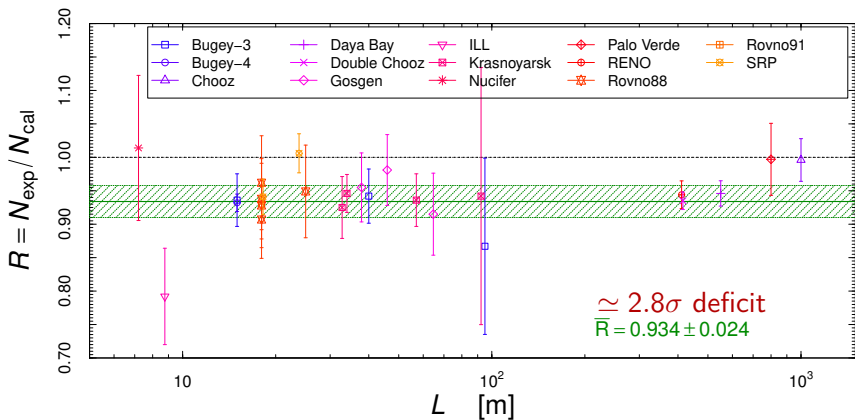
- JPG 43 (2016) 033001
- Kostensalo+ 2019
- Giunti, PRD 101 (2020)
- PROSPECT
- STEREO
- DayaBay
- ...



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

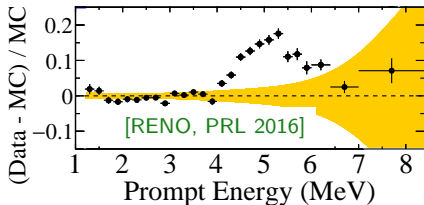
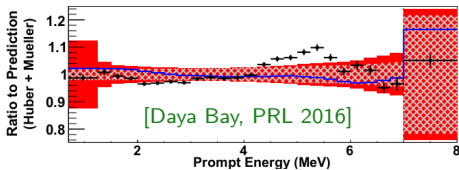
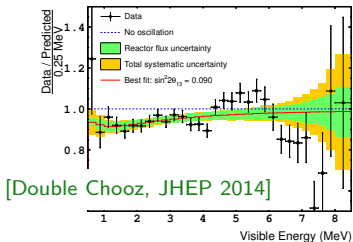
[Huber, PRC 84 (2011) 024617] [Mueller+, PRC 83 (2011) 054615]

Previous reactor rates evaluated with new fluxes \Rightarrow deficit



Suppression at detector due to active-sterile oscillations?

Can we trust the HM fluxes?



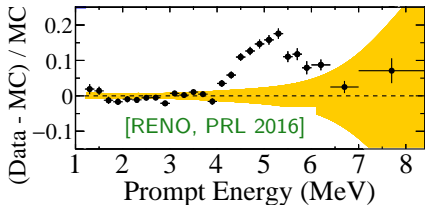
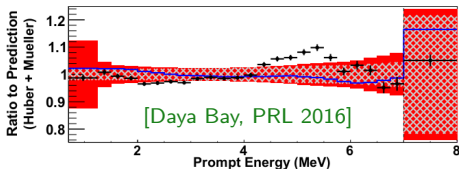
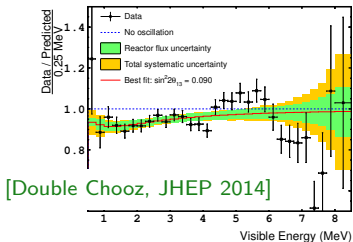
known since 2014:
bump in the spectrum
around 5 MeV!

cannot be explained
by SBL oscillations

(averaged at the ob-
served distances)

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

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 ob-
served distances)

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

Model independent information!

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

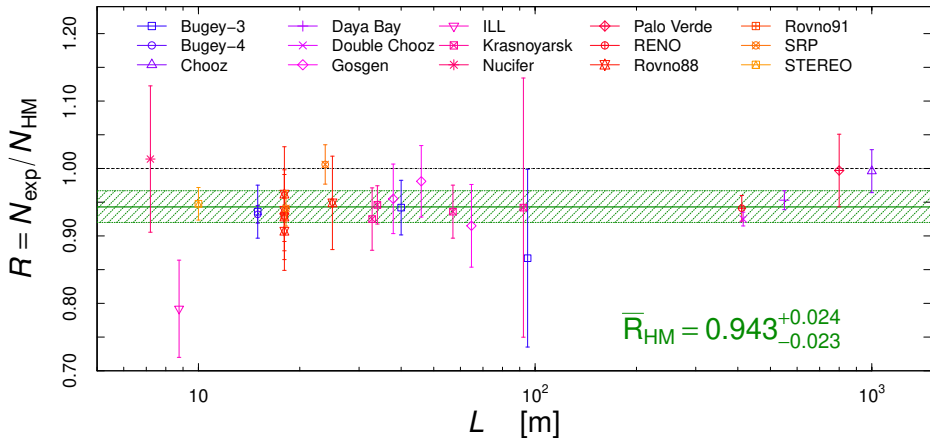
$$\Phi_1 = \Phi_0(E)f(L_1, E) \quad \Phi_2 = \Phi_0(E)f(L_2, E)$$

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

When the RAA was discovered:

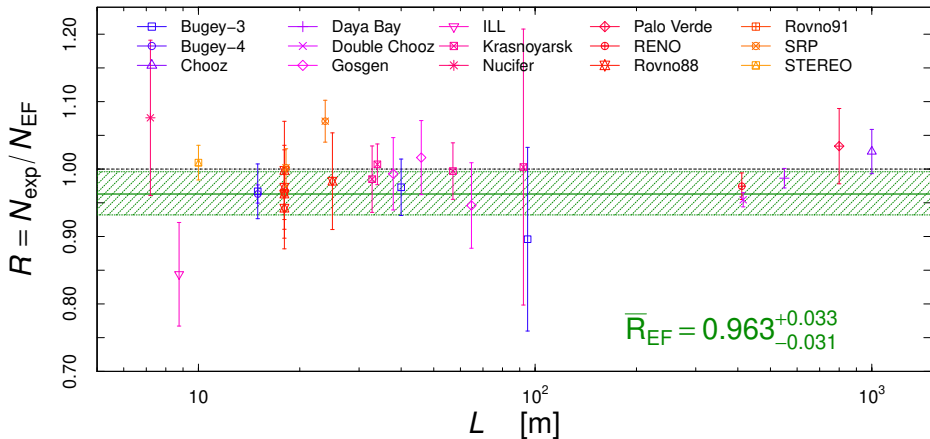
conversion method (ILL data) and *ab initio* calculations in agreement

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



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

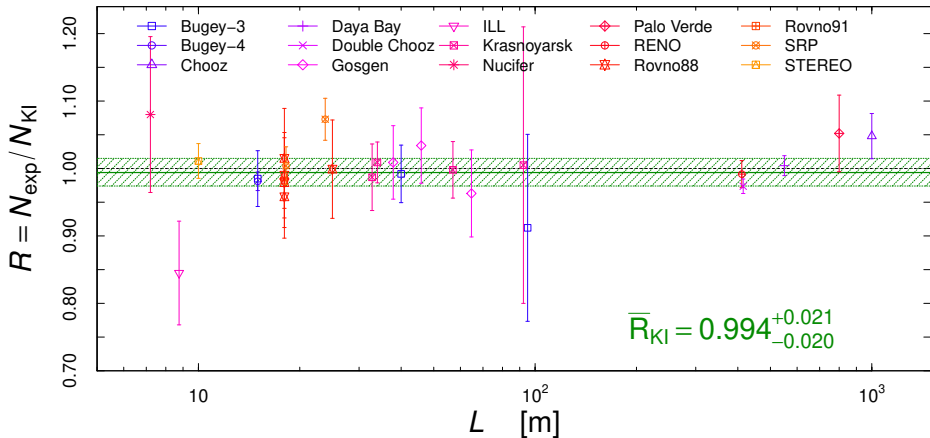
Revised *ab initio* calculation:
 [Estienne, Fallot+, PRL 123 (2019)]



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

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

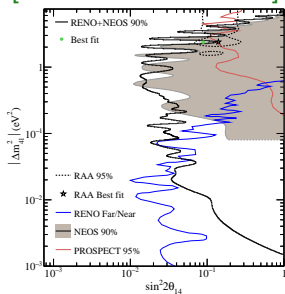
[Kopeikin+, PRD 2021]



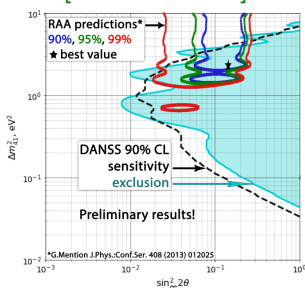
approximate agreement with EF fluxes, no anomaly!

ν_s at reactors in 2020

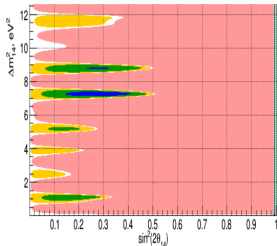
[RENO+NEOS, 2020]



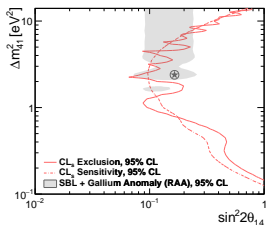
[DANSS, 2020]



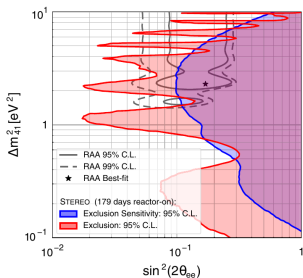
[Neutrino-4, PZETF 2020]



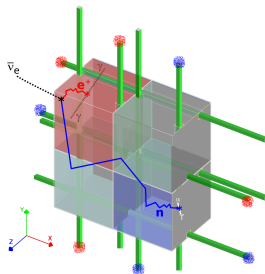
[PROSPECT, PRD 2020]



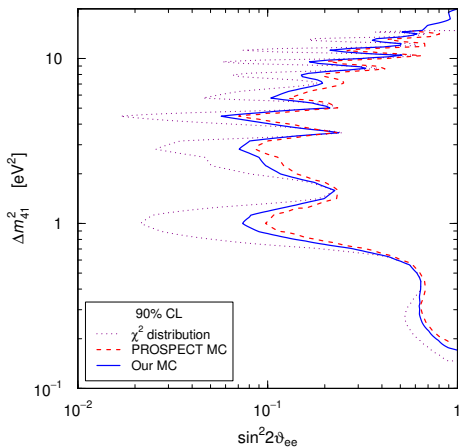
[STEREO, PRD 2020]



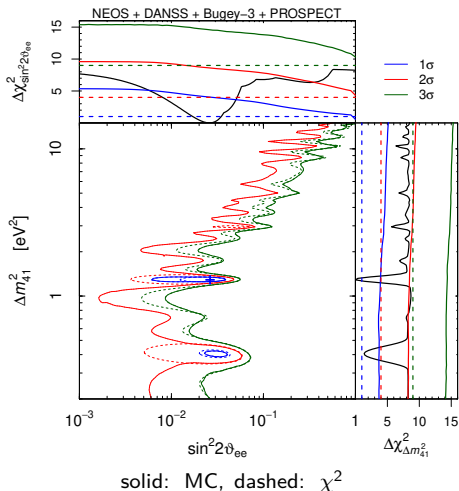
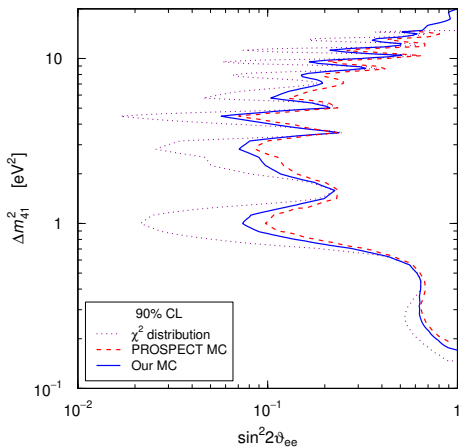
[SoLiD, JINST 2021]



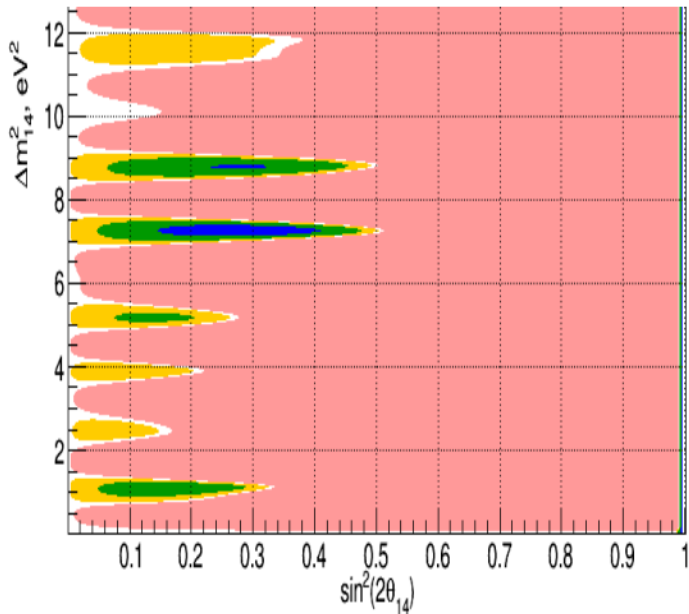
standard χ^2 distribution may be not appropriate to study the significance due to undercoverage at angles below the experiment sensitivity



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

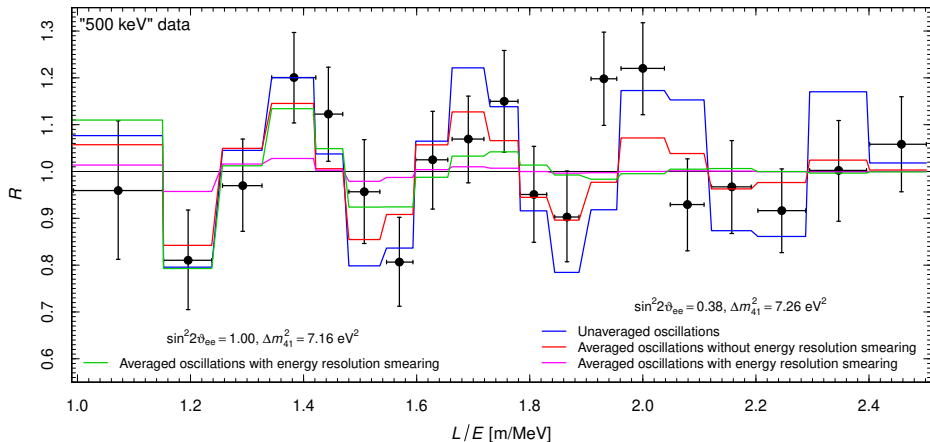


True significance smaller than usually quoted (e.g. $2.4 \rightarrow 1.8\sigma$)

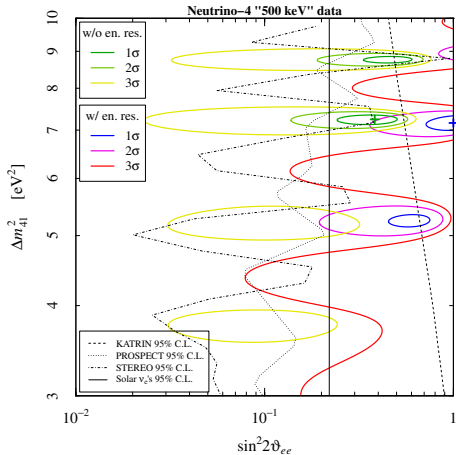


claimed $> 3\sigma$
preference for
 $3+1$ over 3ν case

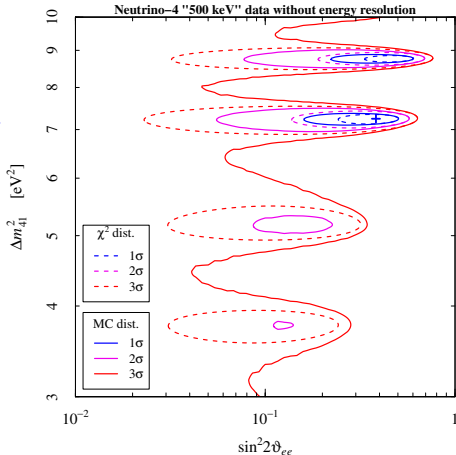
best fit
incompatible
with other
reactor
experiments



energy resolution smearing not properly taken into account?



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



need to take into account
violation of Wilk's theorem

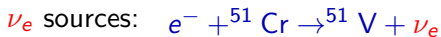
↓
relaxed constraints

Gallium anomaly

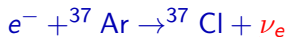
[SAGE, 2006][Giunti&Laveder, 2011]

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

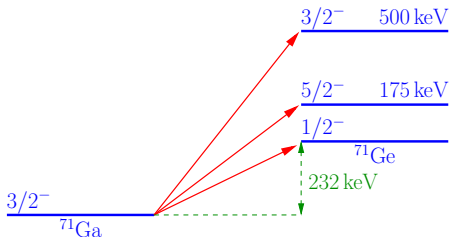
Gallium radioactive source experiments: **GALLEX** and **SAGE**



$E \simeq 0.75$ MeV



$E \simeq 0.81$ MeV



cross sections of
the transitions from

[Krofcheck+, PRL 55 (1985) 1051]

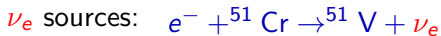
[Frekers+, PLB 706 (2011) 134]

Gallium anomaly

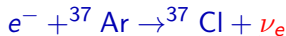
[SAGE, 2006][Giunti&Laveder, 2011]

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

Gallium radioactive source experiments: **GALLEX** and **SAGE**



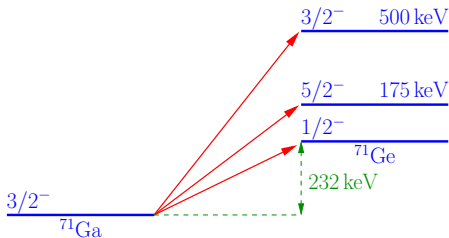
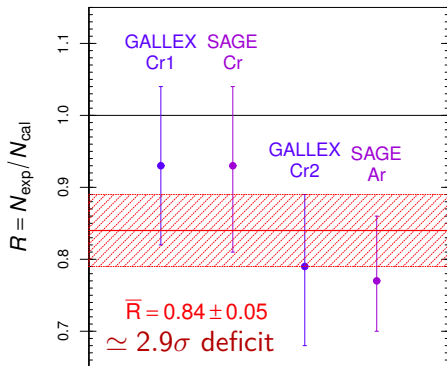
$E \simeq 0.75$ MeV



$E \simeq 0.81$ MeV



Test detection of solar ν_e

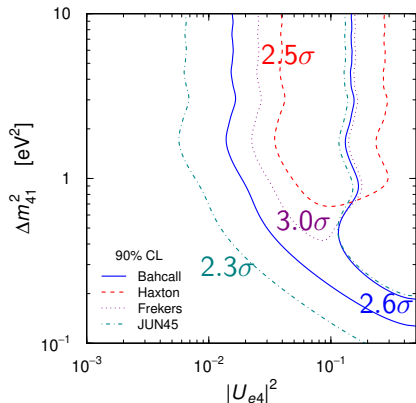


cross sections of the transitions from

[Krofcheck+, PRL 55 (1985) 1051]

[Frekers+, PLB 706 (2011) 134]

New cross section calculations:
(interacting nuclear shell model)



original Gallium anomaly: $\sim 2.9\sigma$

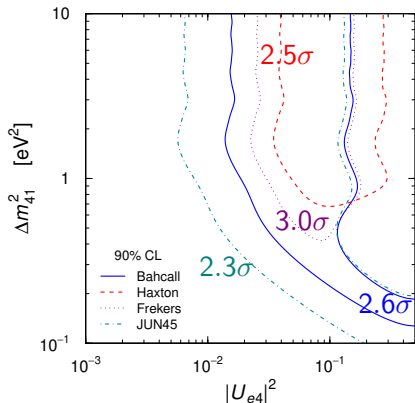
[SAGE, 2006]

[Giunti&Laveder, 2011]

Gallium anomaly revisited

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

New cross section calculations:
(interacting nuclear shell model)

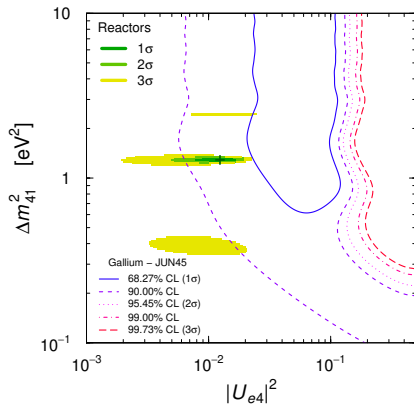


original Gallium anomaly: $\sim 2.9\sigma$

[SAGE, 2006]

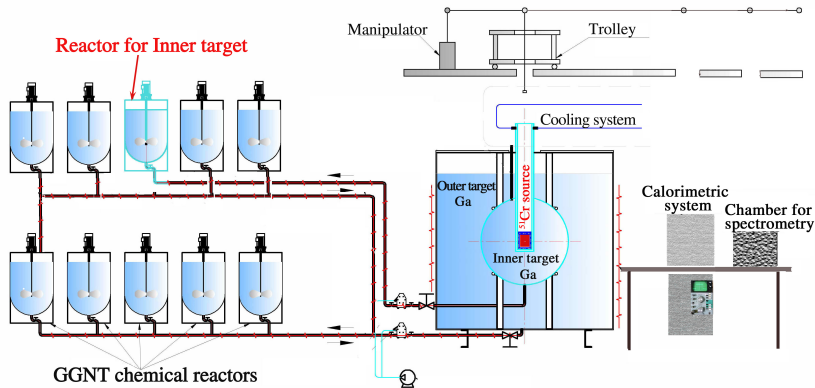
[Giunti&Laveder, 2011]

Compare with DANSS+NEOS:

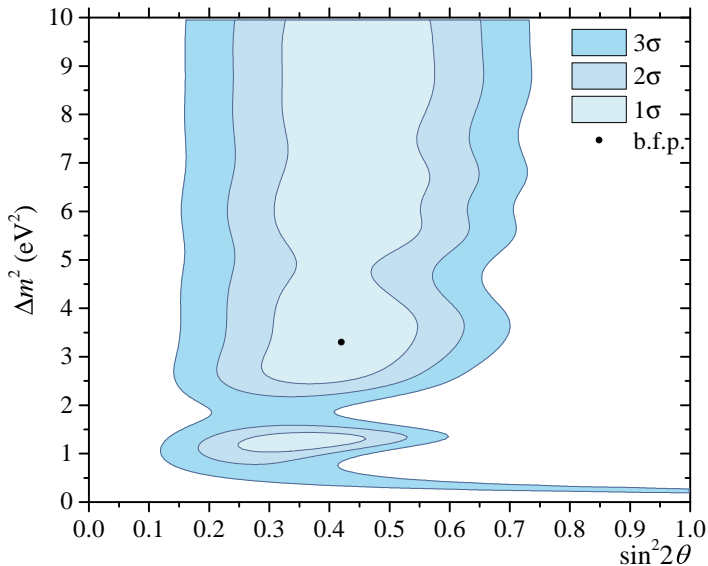


Better compatibility with reactors

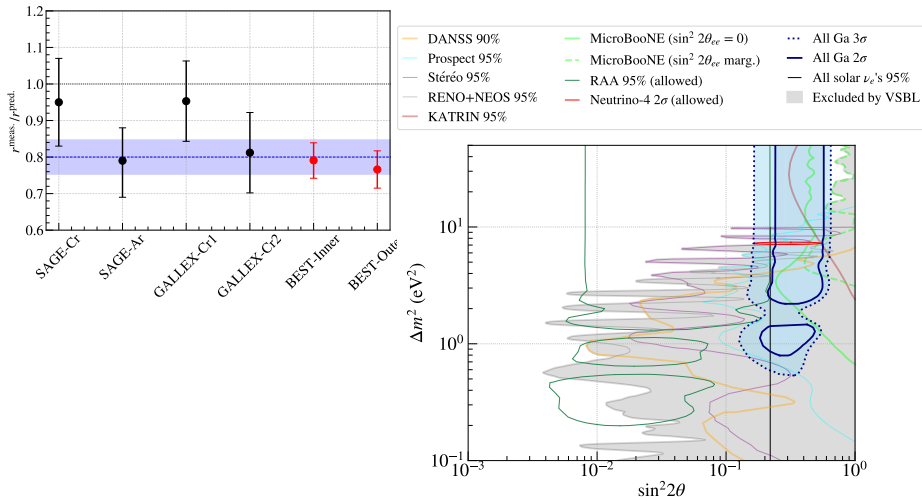
Built to test Gallex and Sage anomalies



Built to test Gallex and Sage anomalies



Built to test Gallex and Sage anomalies



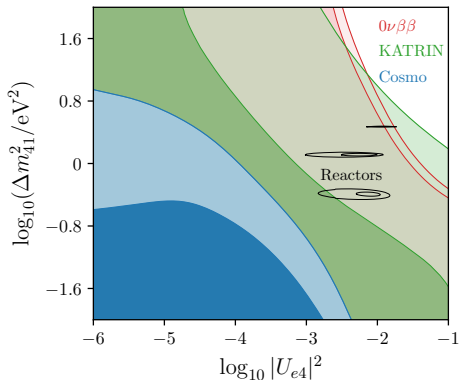
Full agreement with Neutrino-4

Big part of the region excluded by several other reactor experiments

F Fit

Based on:

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



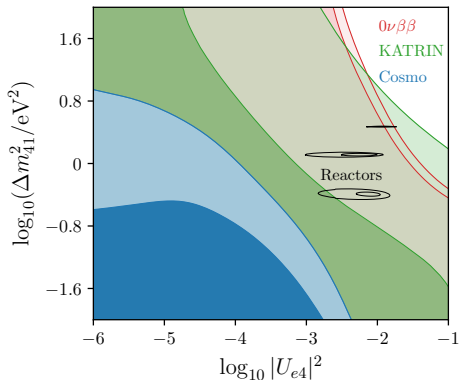
G

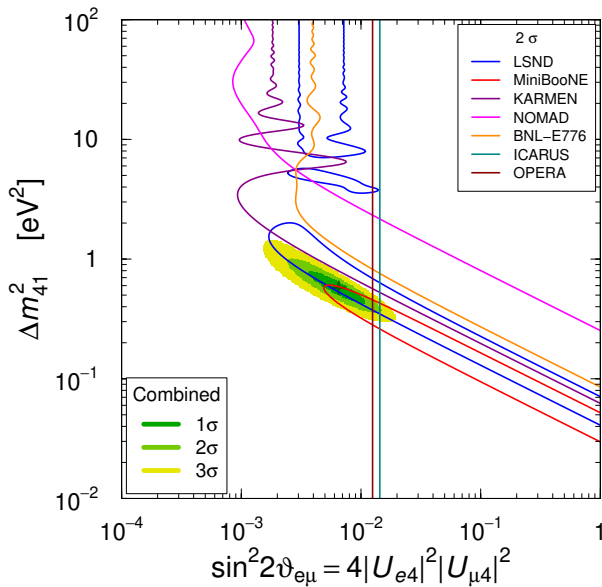
Fit = Global Fit

like “Bond, James Bond”

Based on:

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





with full MiniBooNE data

ICARUS and OPERA

exclude

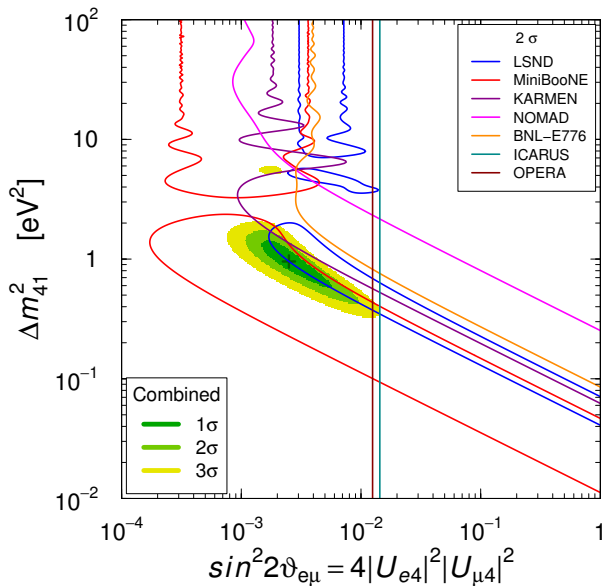
MiniBooNE best fit

LSND and MiniBooNE

only partially
in agreement

KARMEN cuts part

of LSND region



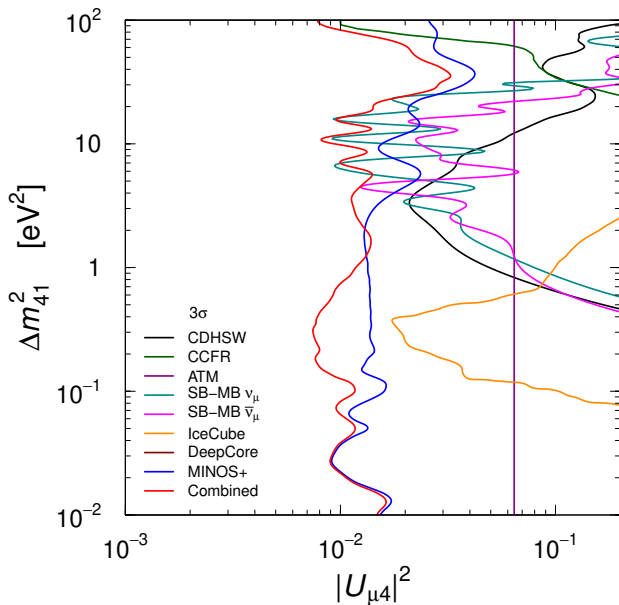
without MiniBooNE low energy bins

ICARUS and OPERA
exclude

MiniBooNE best fit

LSND and MiniBooNE
only partially
in agreement

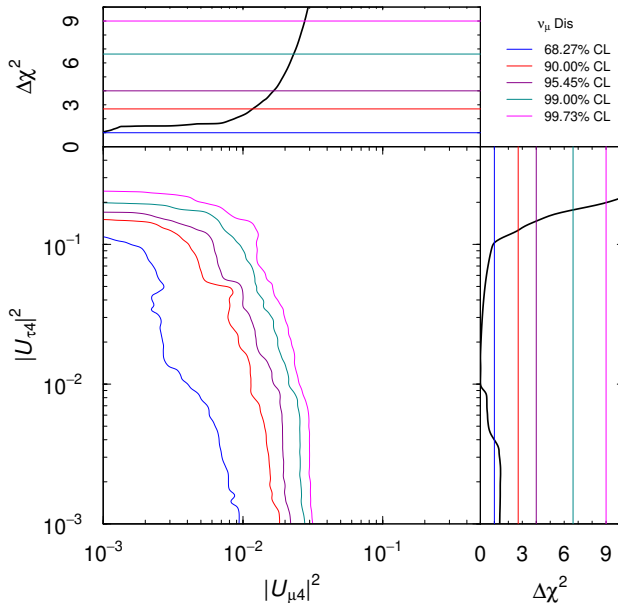
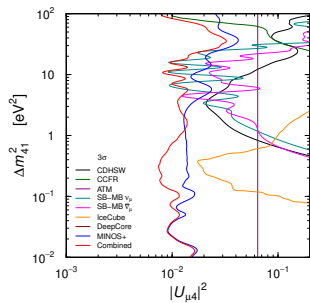
KARMEN cuts part
of LSND region



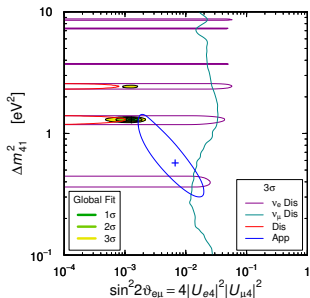
MINOS+
dominates
at small Δm_{41}^2

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

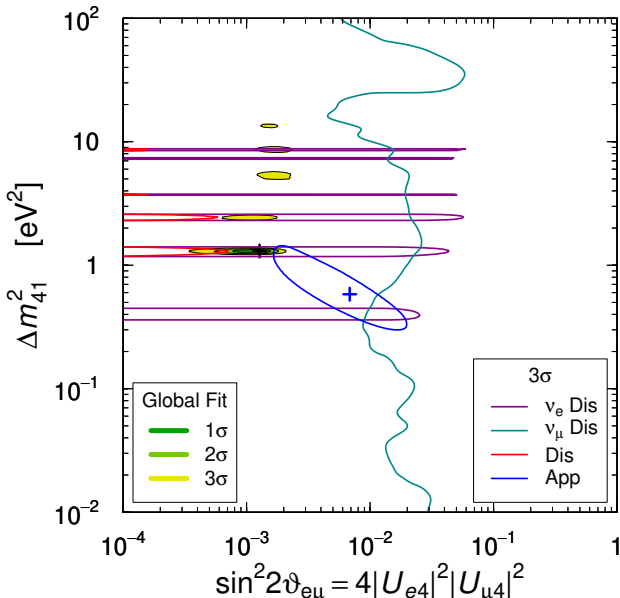
IceCube 8 yr
not included!



Status just after
Neutrino 2018:

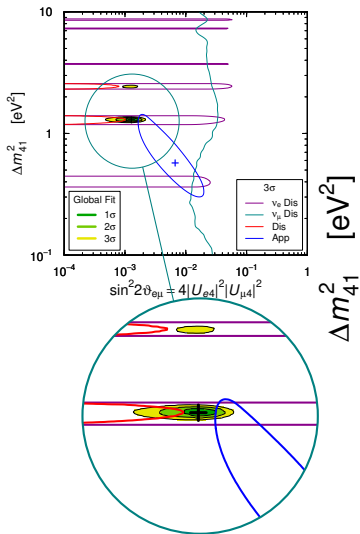


Status in early 2019

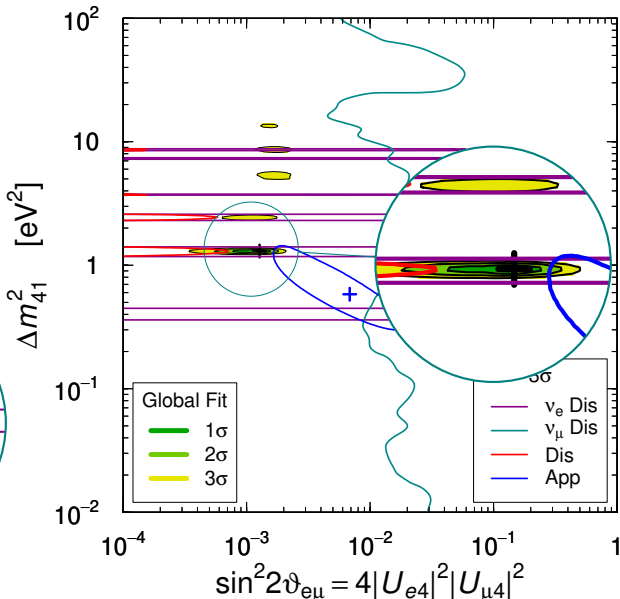


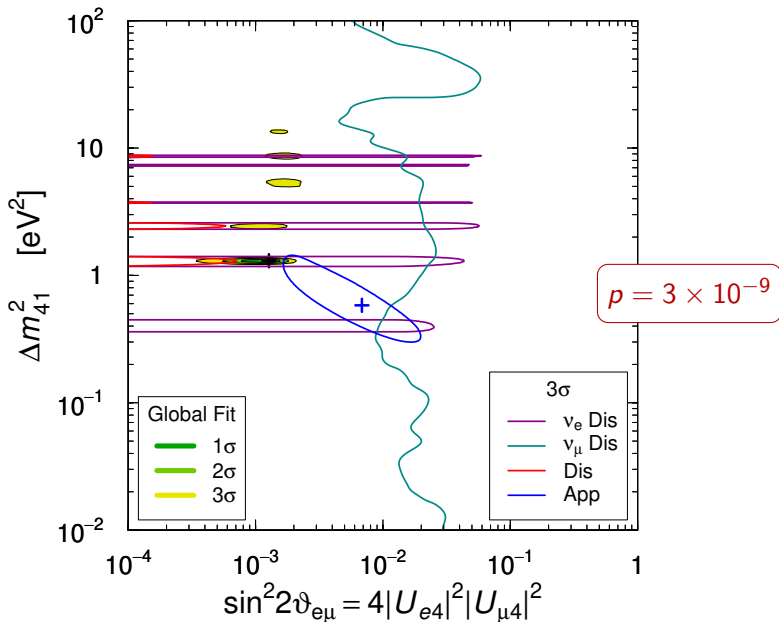
MINOS+ update,
new data
including MiniBooNE
(all bins)

Status just after
Neutrino 2018:



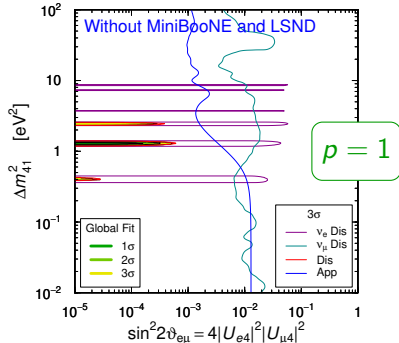
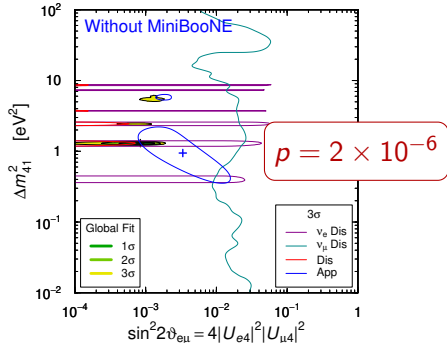
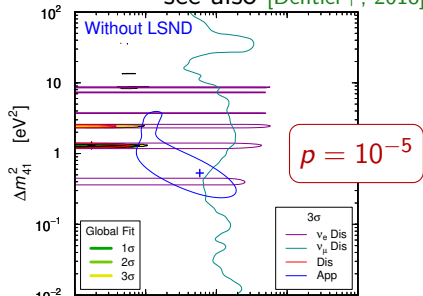
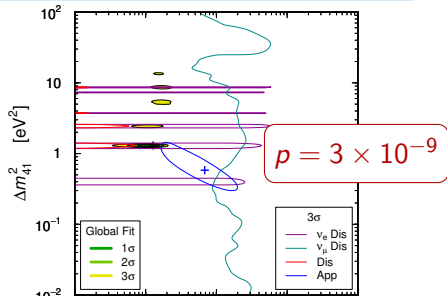
Status in early 2019





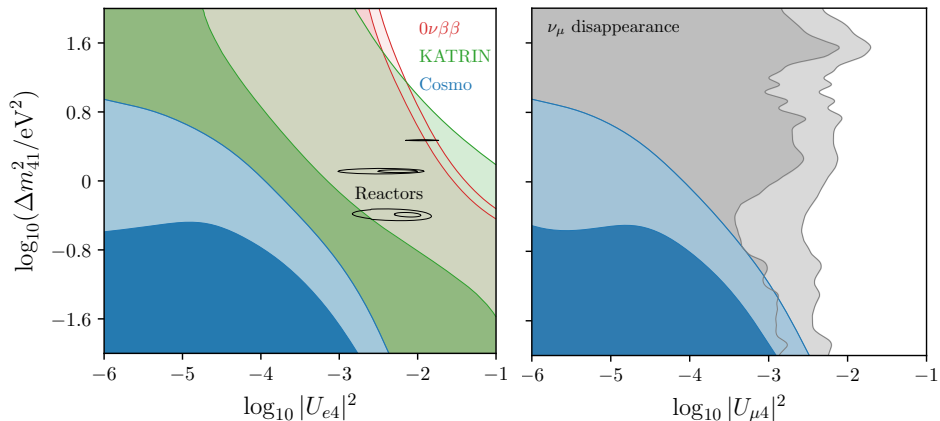
APP – DIS tension in 2019

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



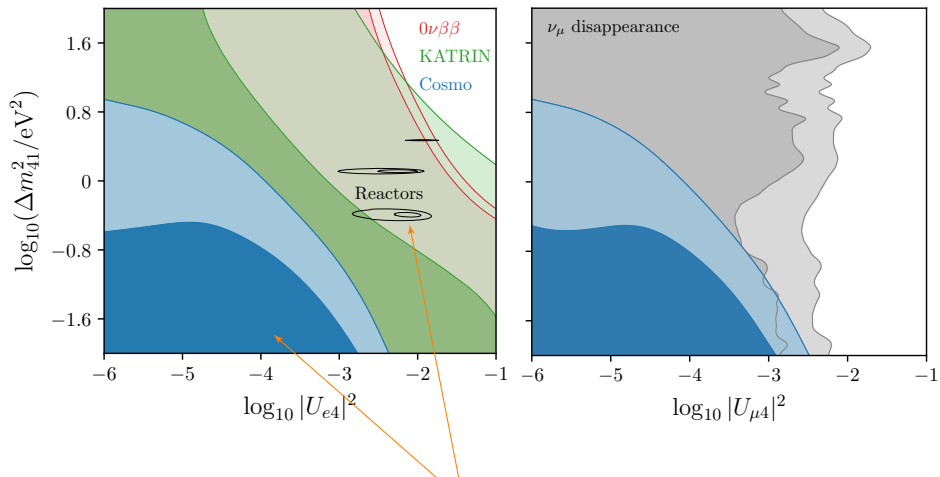
Cosmological constraints are stronger than most other probes

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



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Warning: tension between reactor experiments and CMB bounds!

Z

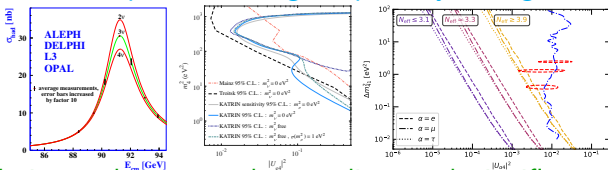
Conclusions

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

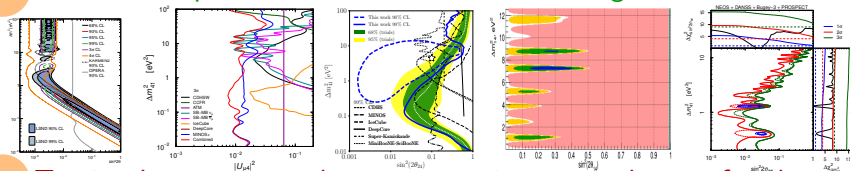


What do we learn on sterile neutrinos?

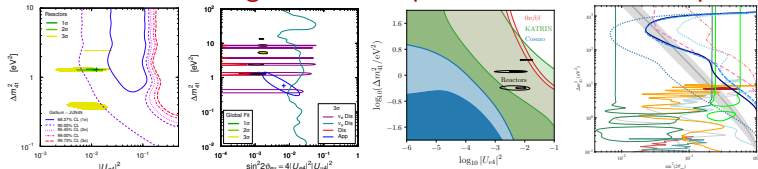
N Non-oscillation probes: no signal, possibly strong constraints



O Oscillation probes: several anomalies, weak significance each

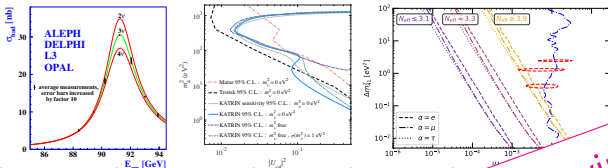


T Tensions! even strong, between experiments or classes of probes

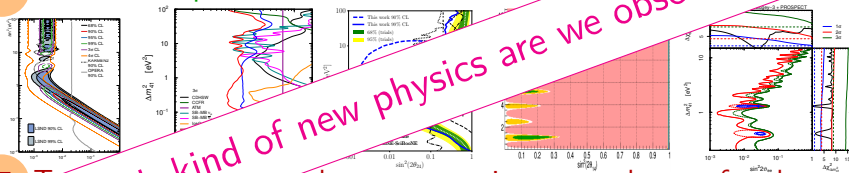


What do we learn on sterile neutrinos?

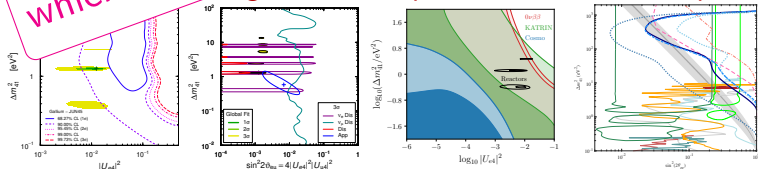
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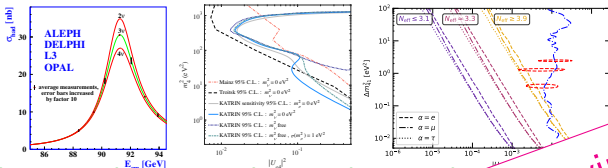


T Tension, between experiments or classes of probes

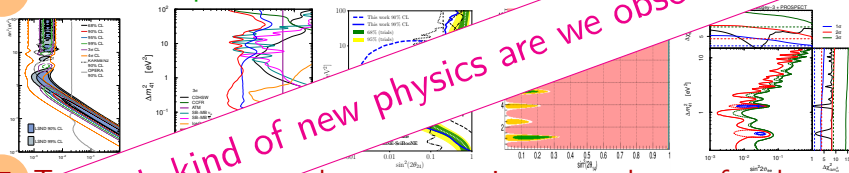


What do we learn on sterile neutrinos?

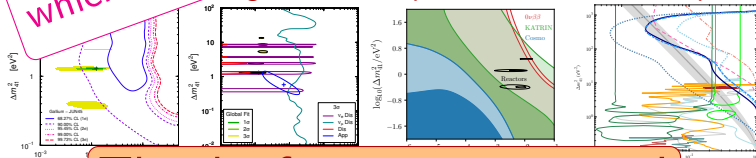
N Non-oscillation probes: no signal, possibly strong constraints



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T Tension, between experiments or classes of probes



Thanks for your attention!