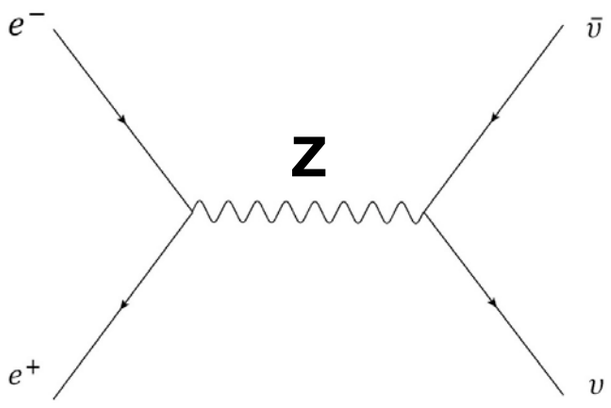
Lecture 4

Neutrino physics beyond the Standard Model

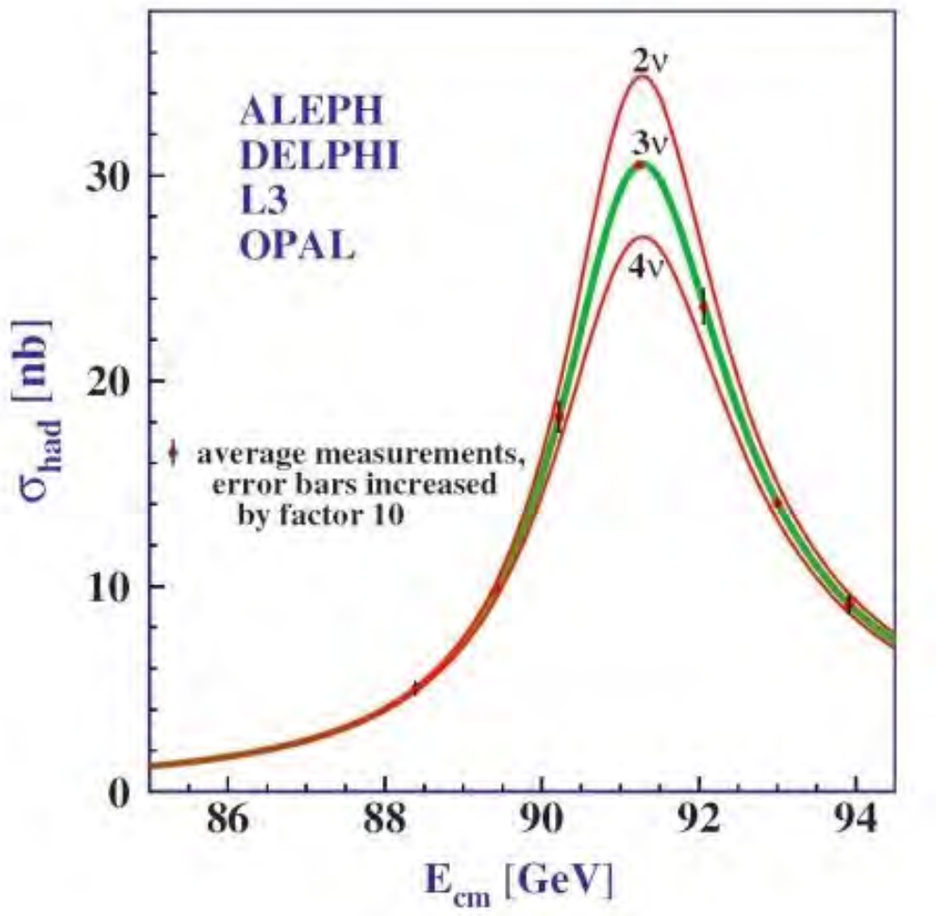
Are there light sterile neutrinos?

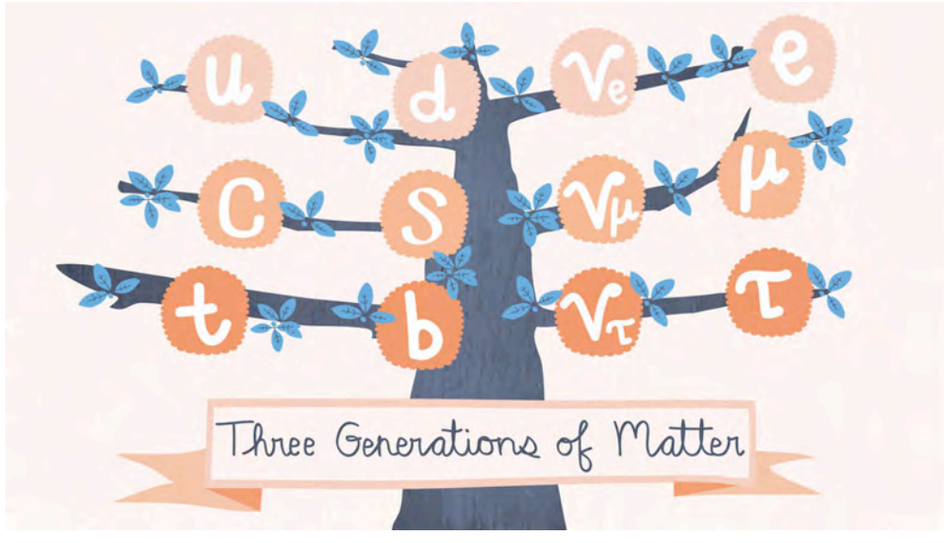
How many neutrinos?

✦ According to LEP measurements of the invisible Z decay width:



$N_\nu = 2.984 \pm 0.008$





→ No evidence of a fourth family of quarks or charged leptons

How many neutrinos?

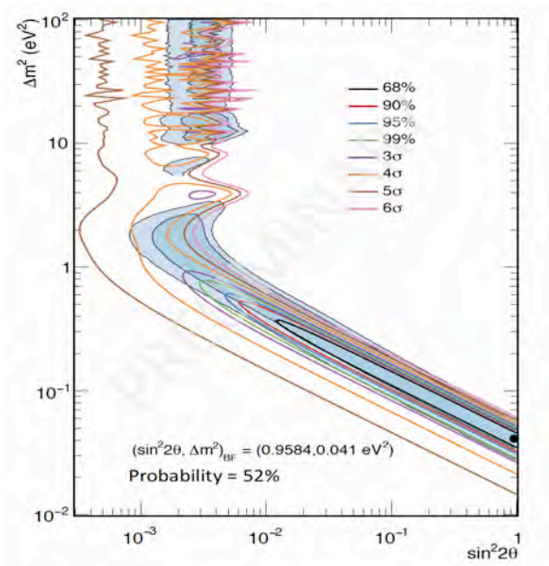
✦ According to LEP measurements of invisible Z decay width:

$\rightarrow N_\nu = 2.984 \pm 0.008$ (light, active neutrinos)

Experimental hints for a 4th sterile neutrino:

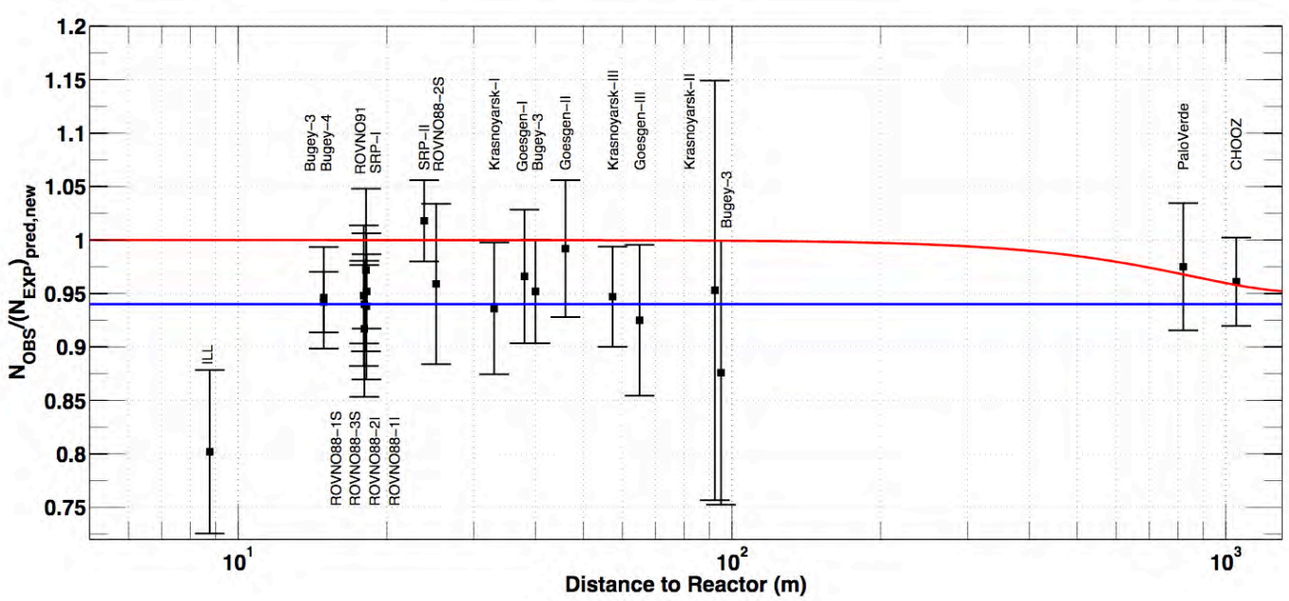
LSND & MiniBooNE

$\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$



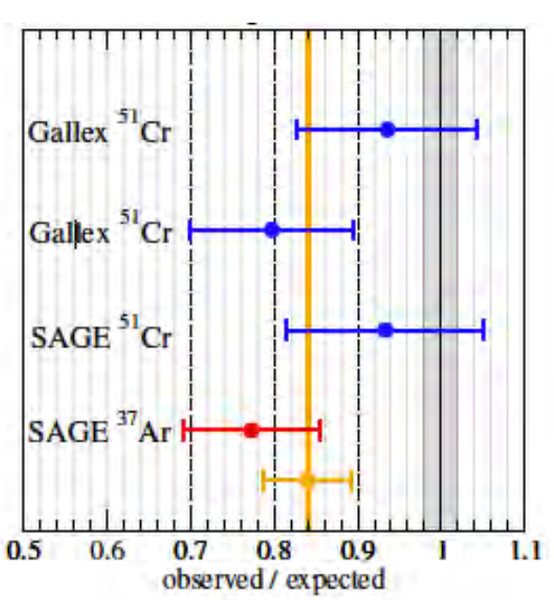
Reactor anomaly

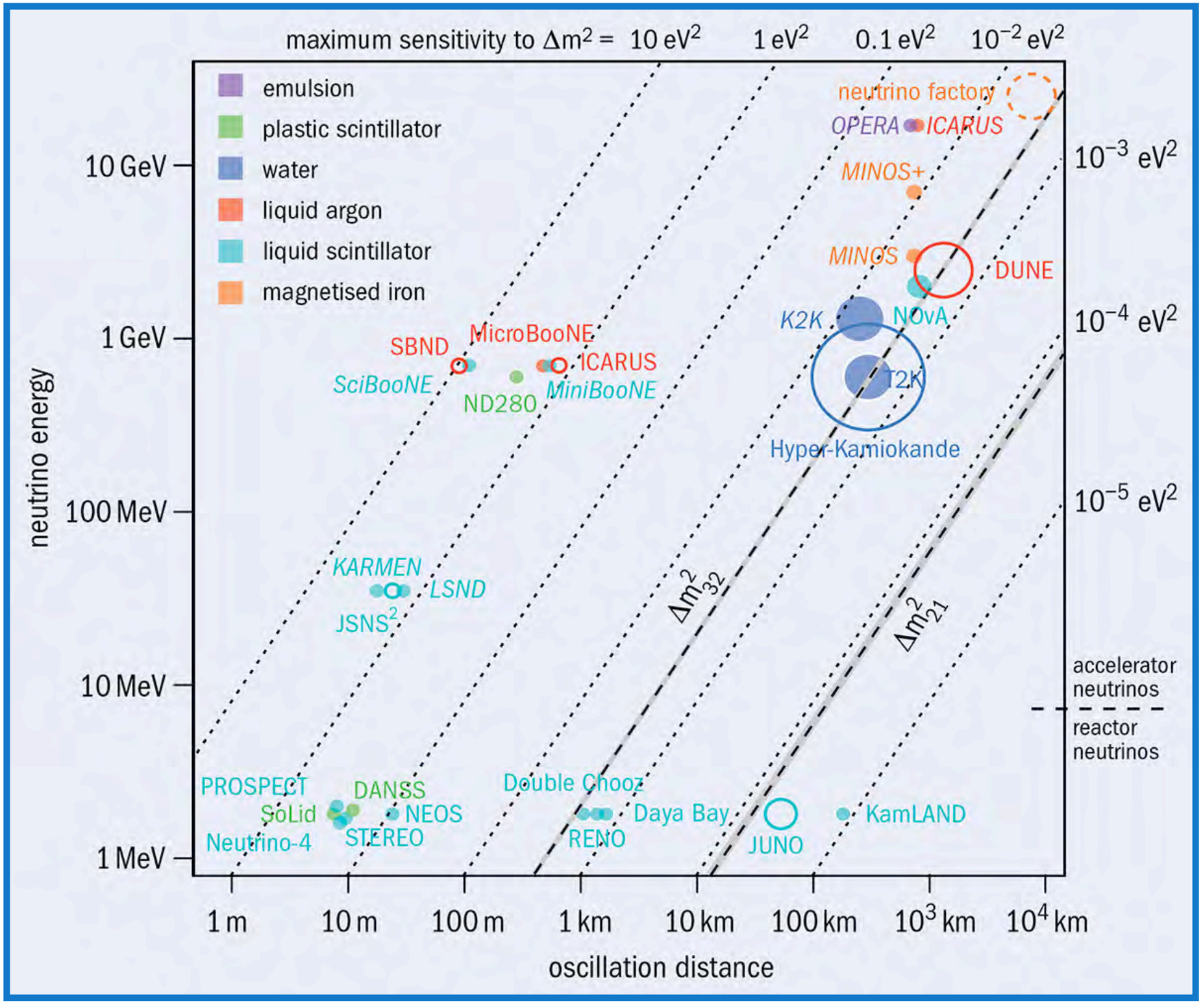
$\overline{\nu}_e \rightarrow \overline{\nu}_e$



Gallium anomaly

$\nu_e \rightarrow \nu_e$



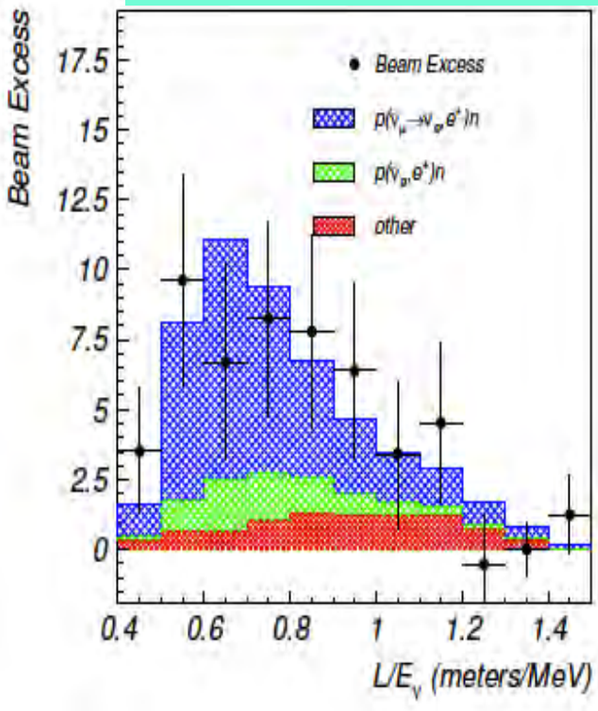


M Rayner, CERN Courier, 2020

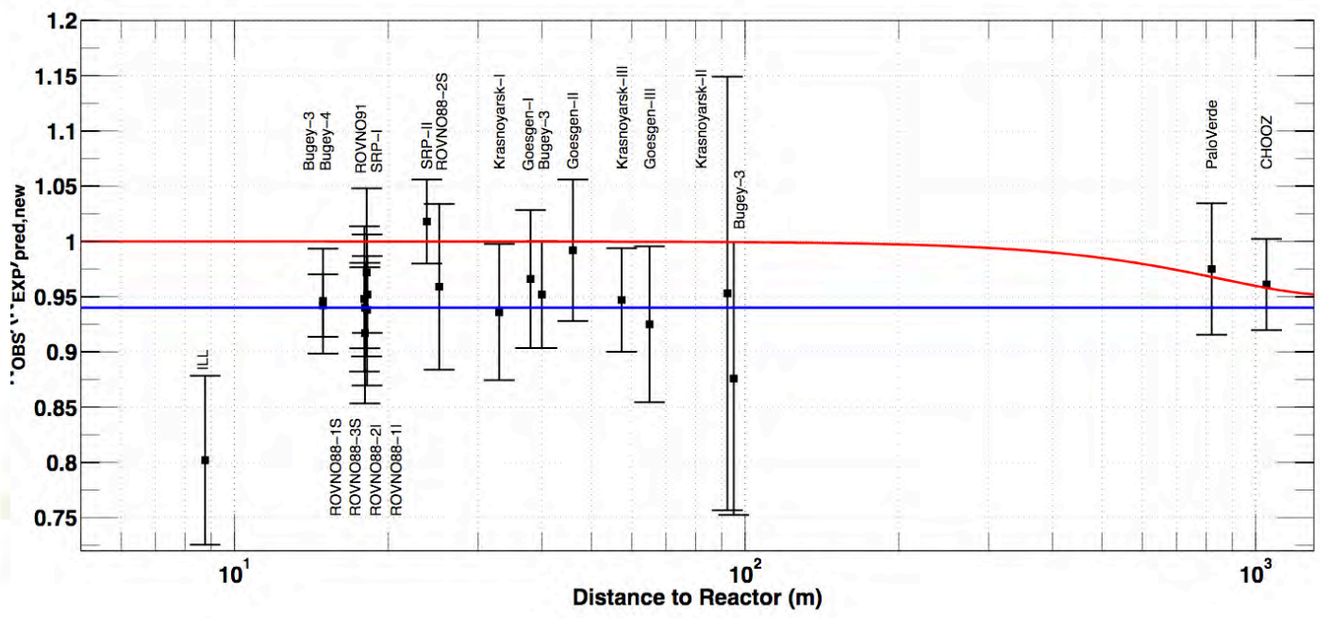
Hints for a light sterile neutrino

Anomalies in neutrino experiments with very short baselines source-detector (10-100 m)

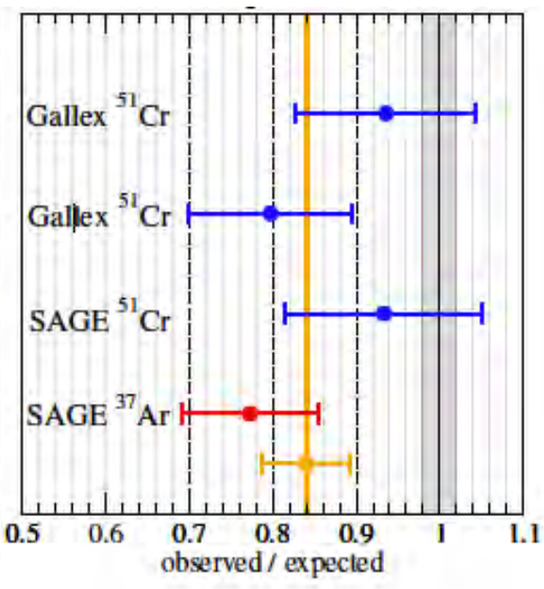
LSND & MiniBooNE



Reactor anomaly



Gallium anomaly



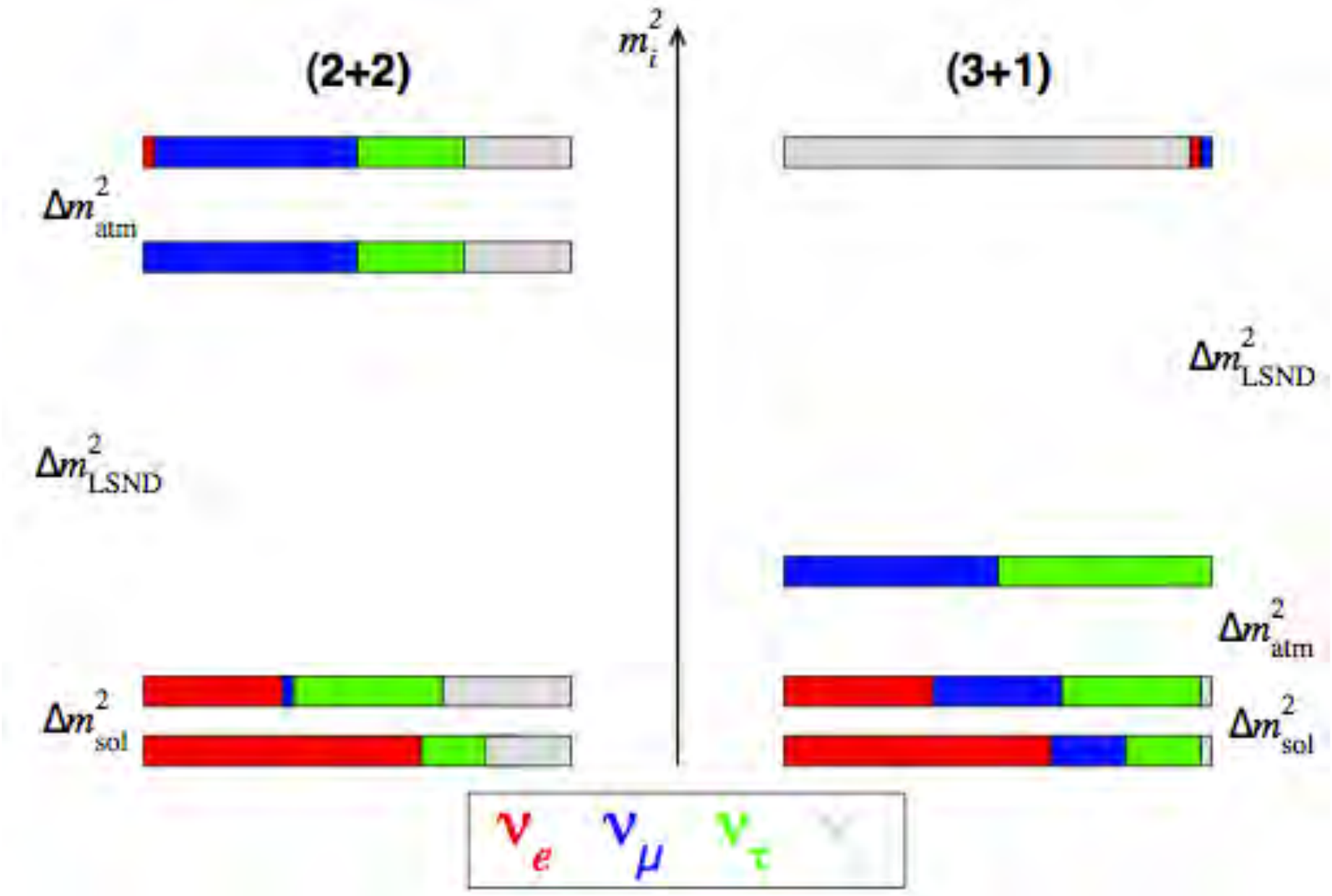
Explained with neutrino oscillations with $\Delta m^2 \sim 1$ eV^2 in the channels:

$$\overline{\nu}_\mu \to \overline{\nu}_e \qquad \overline{\nu}_e \to \overline{\nu}_x \qquad \nu_e \to \nu_x$$

Interpretation of the anomalies

$\Delta m^2_{sol} \sim 8x10^{-5}\,eV^2$ $\Delta m^2_{atm} \sim 2x10^{-3}\,eV^2$ $\Delta m^2_{LSND} \sim 1\,eV^2$

⇒ Can only be accommodated considering four neutrino states



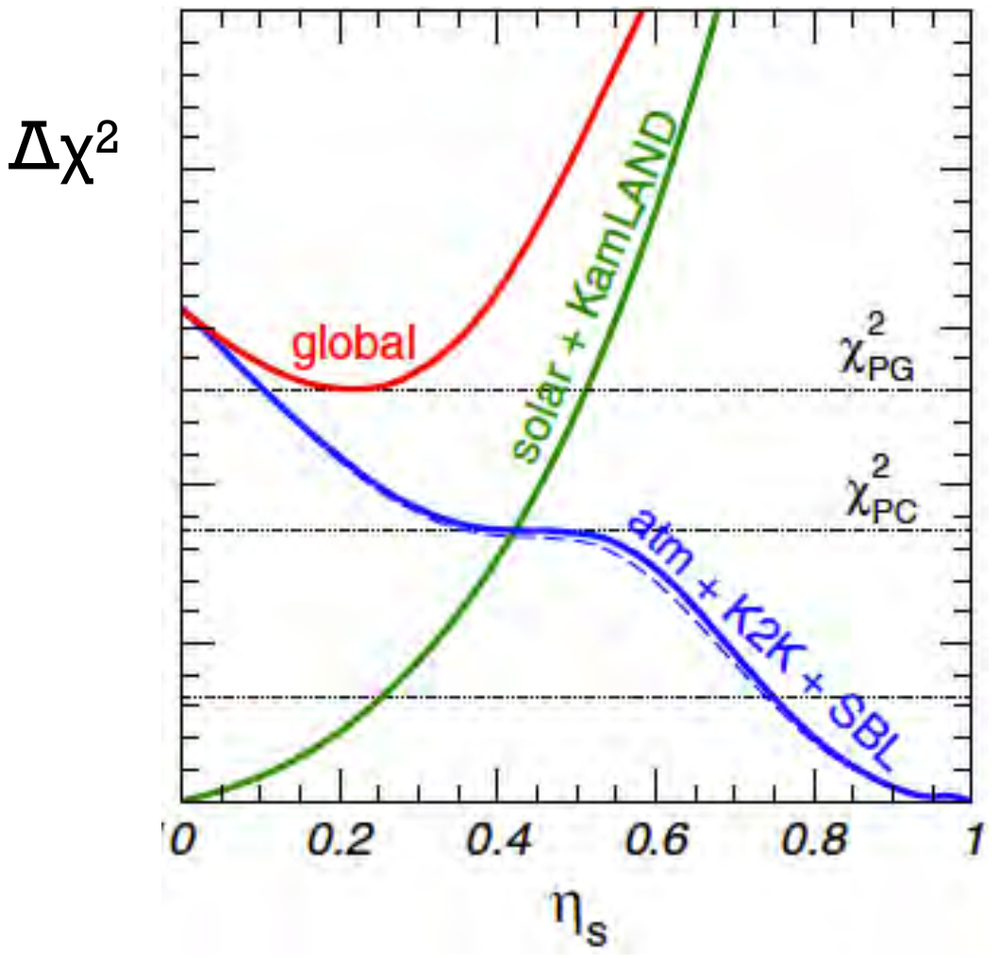
The new neutrino could not be produced at Z decay

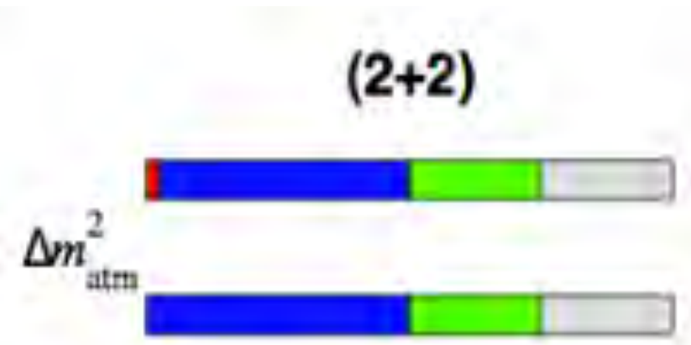
→ Sterile neutirno

2+2 neutrino scheme

✦This scheme requires the presence of sterile neutrinos either in solar or atmospheric neutrinos

✦However, solar and atmospheric data show a strong preference for active oscillations





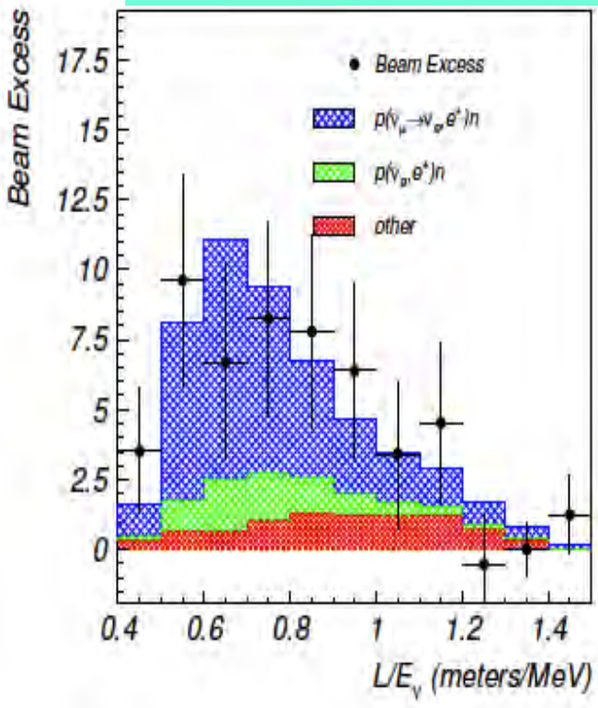
excluded by solar and atmospheric data

Maltoni et al, NPB643 (2003), NJP06 (2004)

Hints for a light sterile neutrino

Anomalies in neutrino experiments with very short baselines source-detector (10-100 m)

LSND & MiniBooNE



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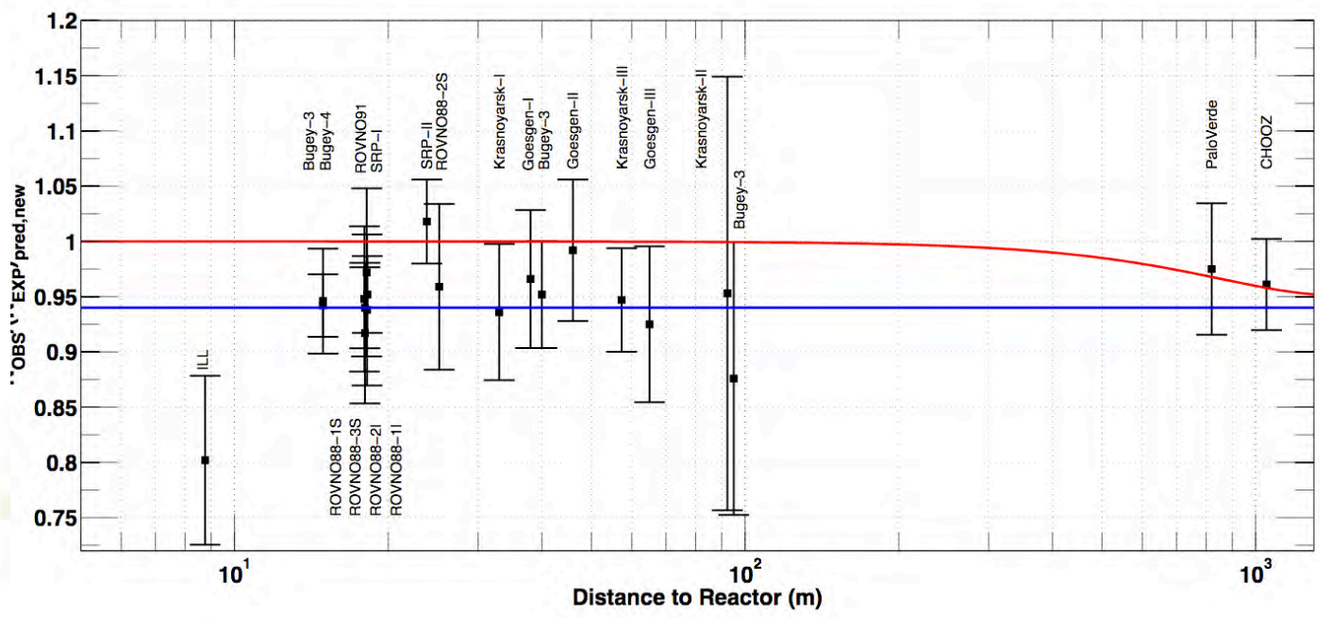
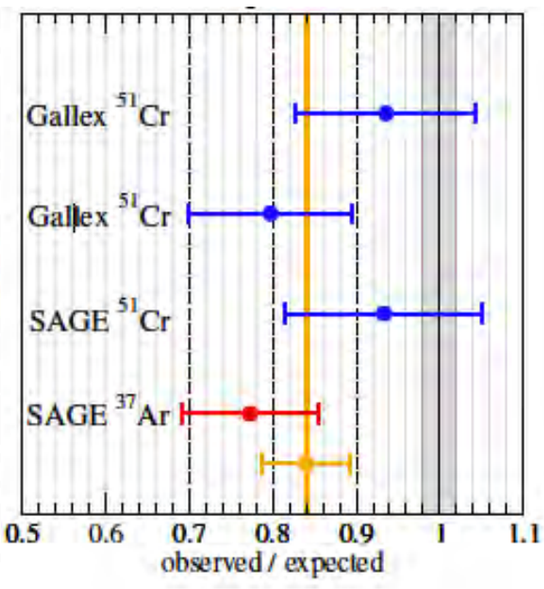


Gallium anomaly



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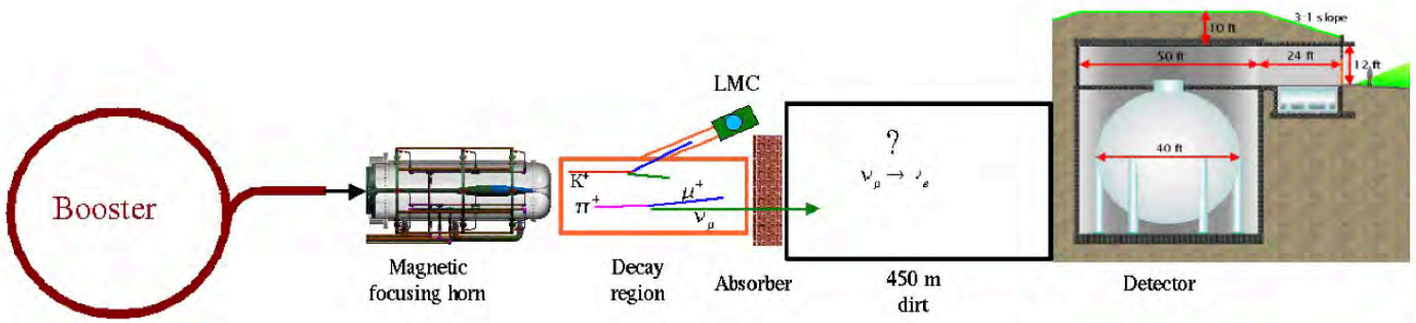
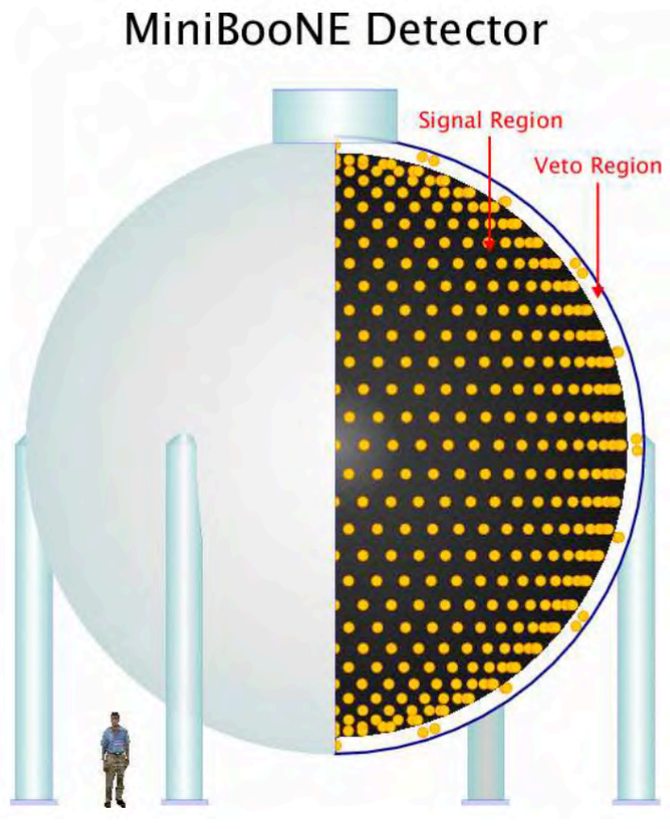
$$\overline{\nu}_\mu \to \overline{\nu}_e \qquad \overline{\nu}_e \to \overline{\nu}_x \qquad \nu_e \to \nu_x$$

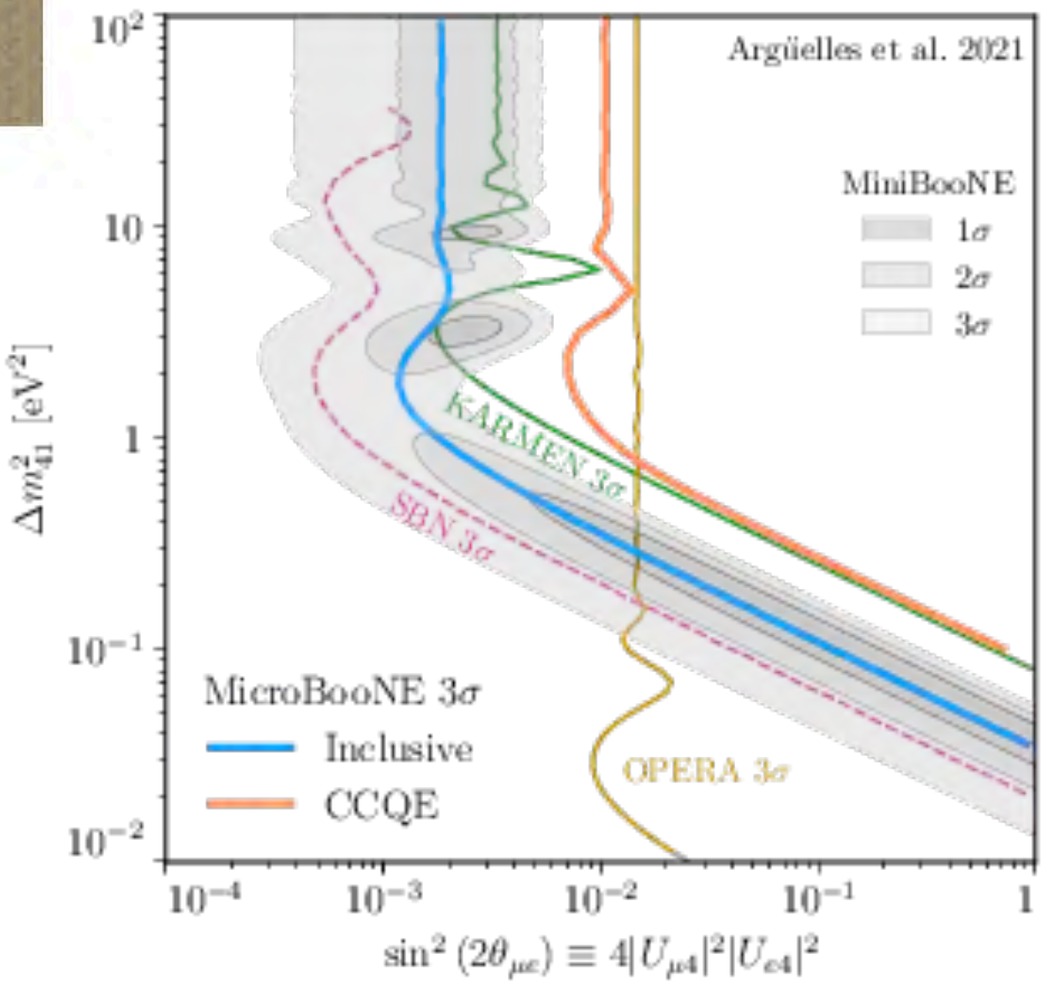
Testing the LSND anomaly

Experiments designed to check LSND signal: **MiniBooNE** & **MicroBooNE**





Argüelles et al, 2021

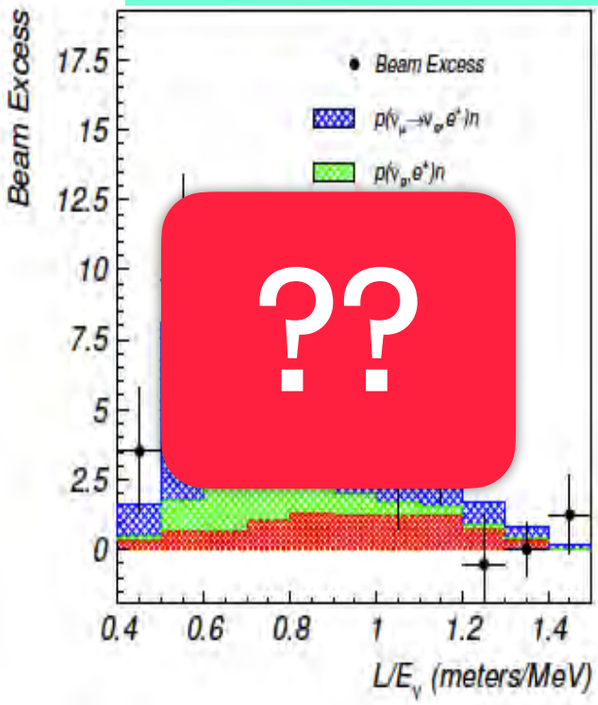


→ Not enough evidences to confirm or rule out the anomaly

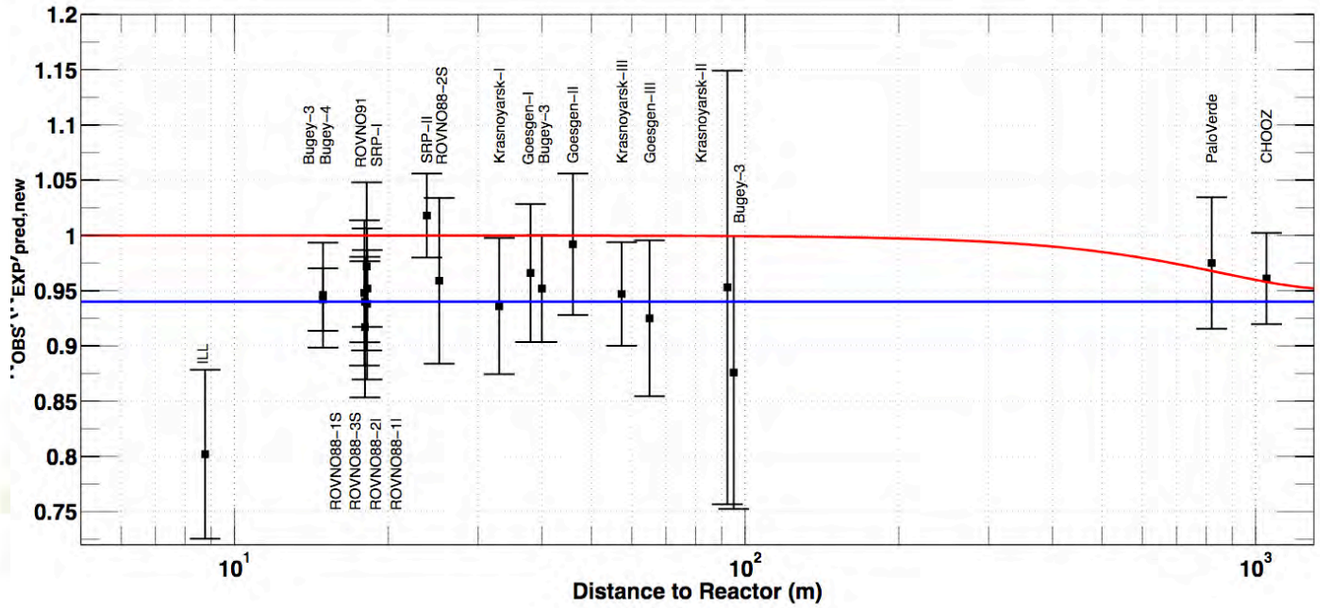
Hints for a light sterile neutrino

Anomalies in neutrino experiments with very short baselines source-detector (10-100 m)

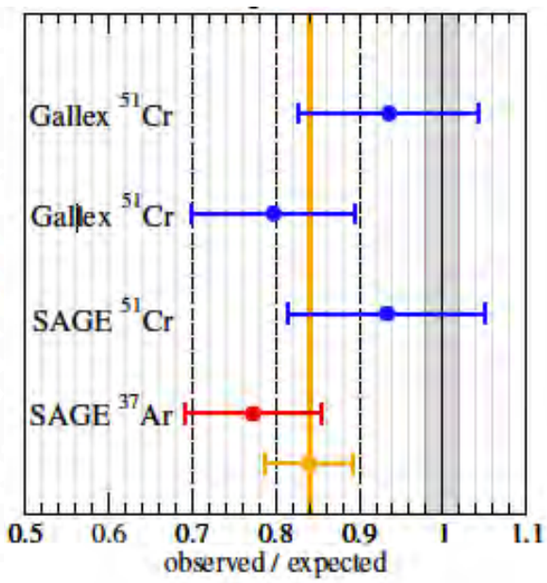
LSND & MiniBooNE



Reactor anomaly



Gallium anomaly



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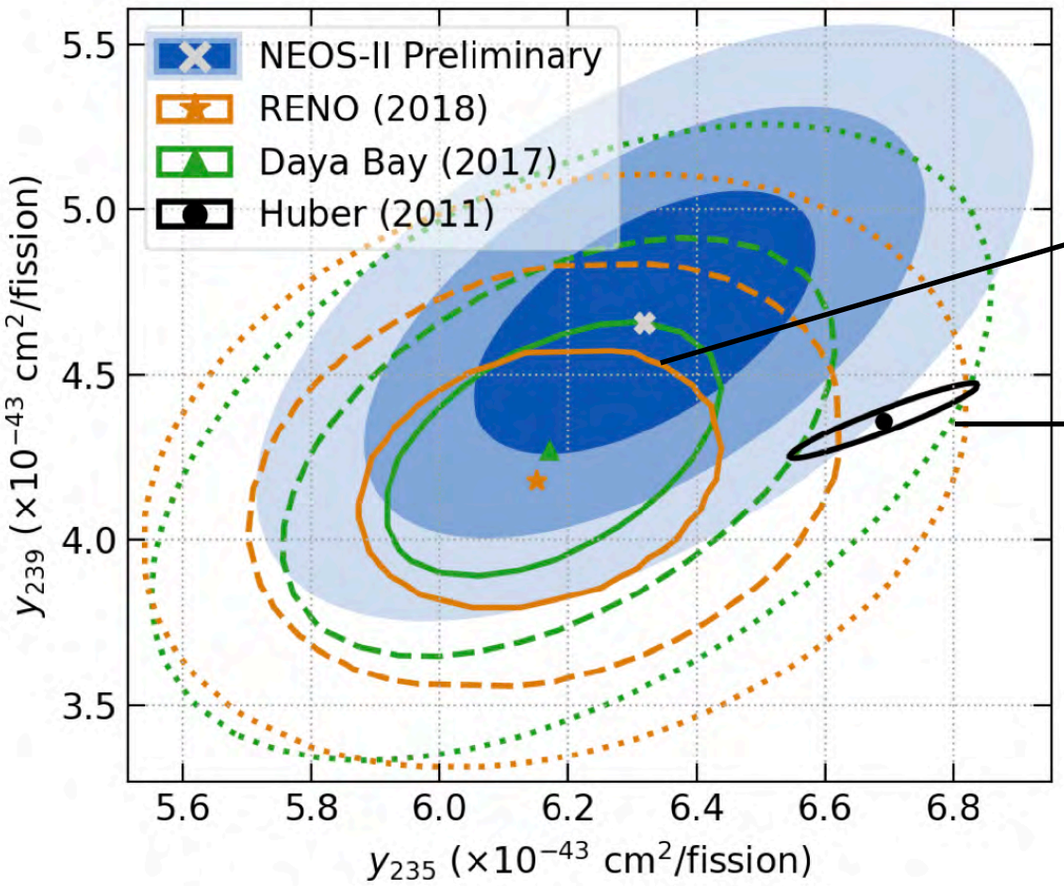
$$\overline{\nu}_\mu \to \overline{\nu}_e \qquad \overline{\nu}_e \to \overline{\nu}_x \qquad \nu_e \to \nu_x$$

The reactor anomaly

New theoretical models and reactor results indicate that the neutrino flux for ^{235}U should be reduced by 5-10 % with respect to previous estimations



Measurements at reactor experiments NEOS, RENO and DayaBay

Previous theoretical predictions

→ this result reconciles experimental data with theoretical predictions, solving the reactor neutrino flux anomaly

P. Vogel, Neutrino 2022

Hints for a light sterile neutrino

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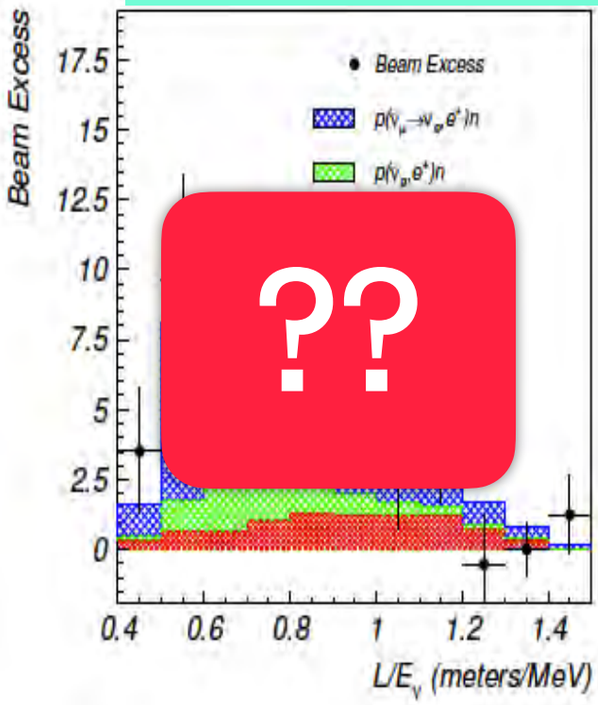

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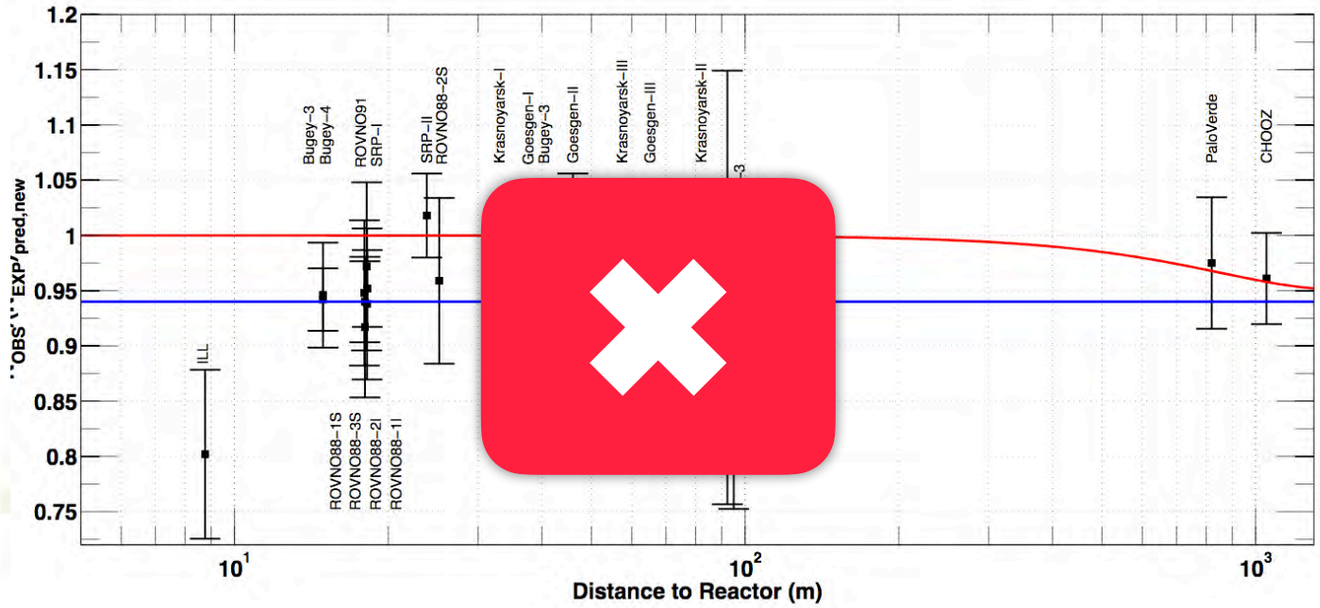
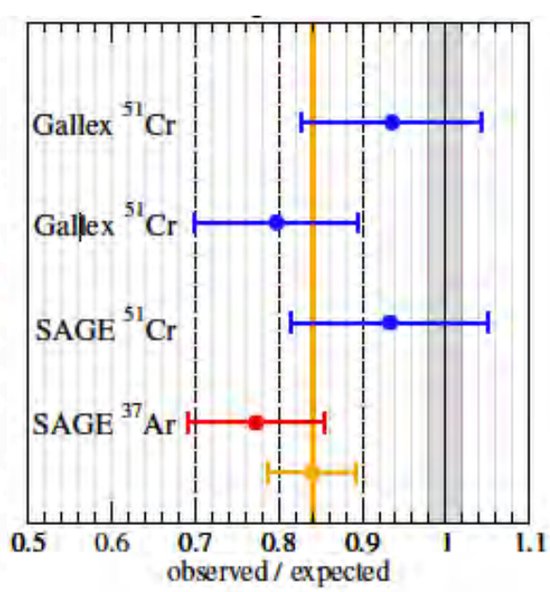
Reactor anomaly



Gallium anomaly



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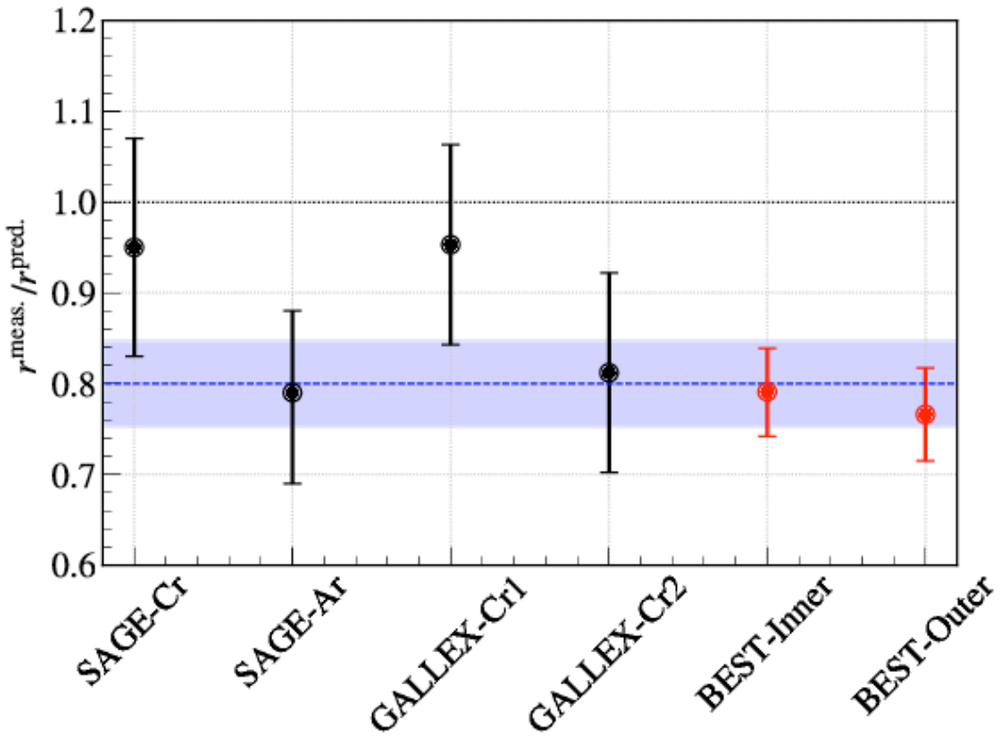
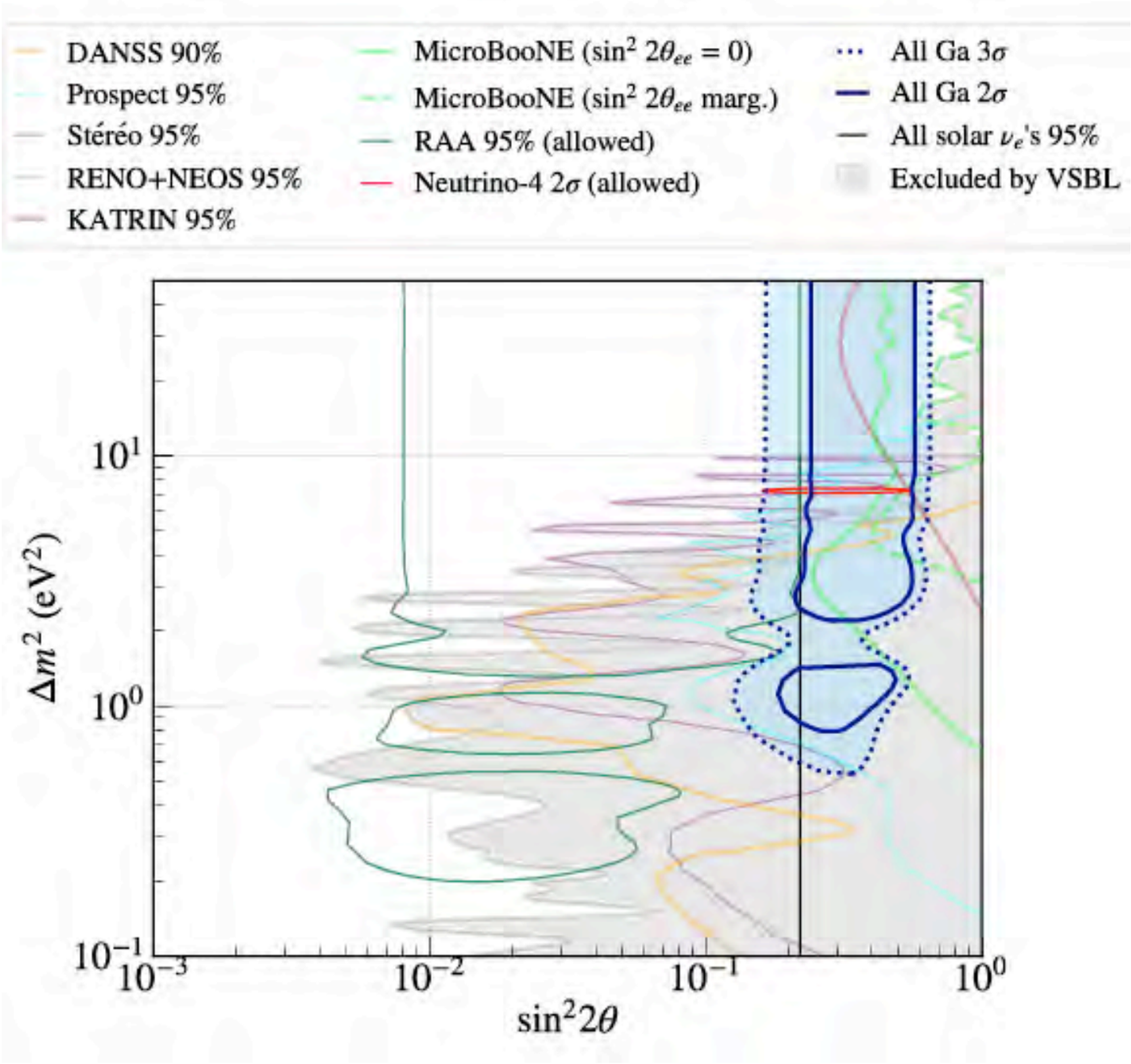
Current status of the Ga anomaly

✦ Recently confirmed by BEST (Baksan Experiment on Sterile Transitions) at 4σ



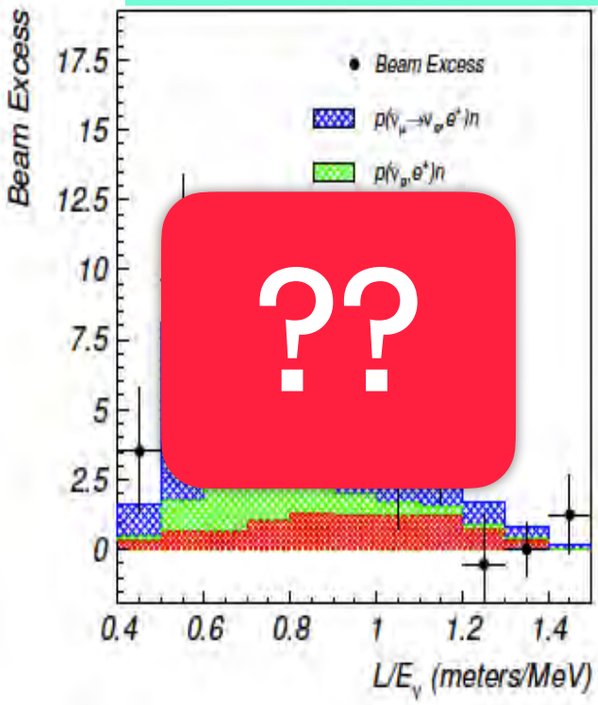


Barinov et al, PRC 2022

Hints for a light sterile neutrino

Anomalies in neutrino experiments with very short baselines source-detector (10-100 m)

LSND & MiniBooNE



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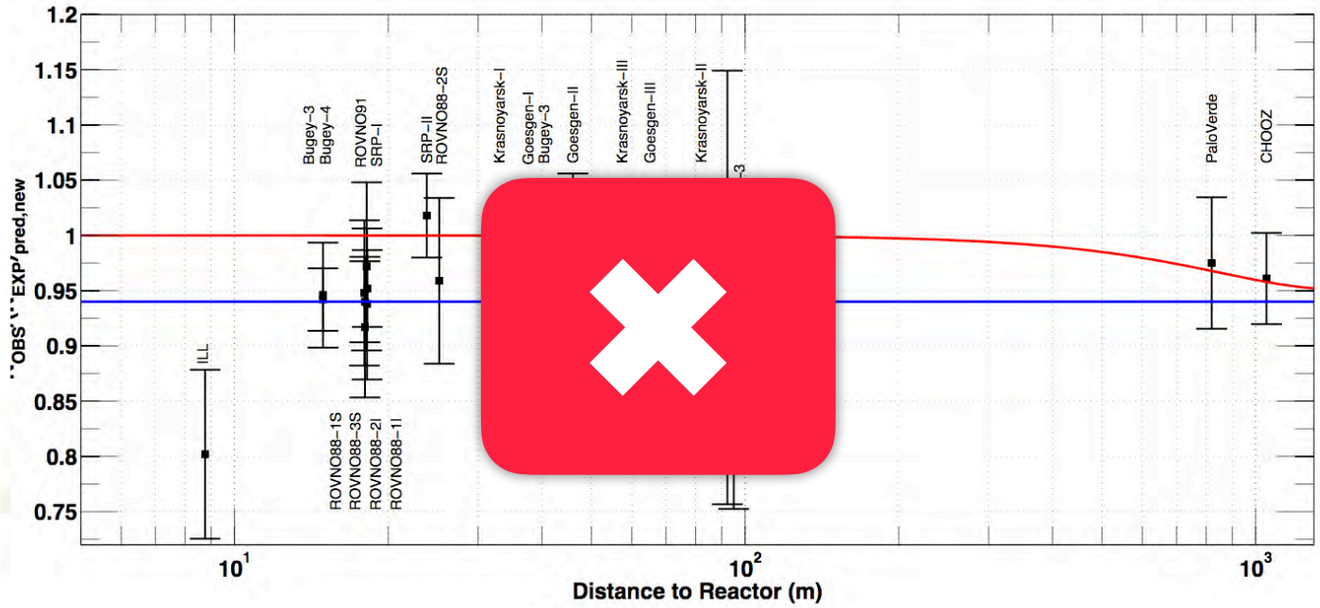
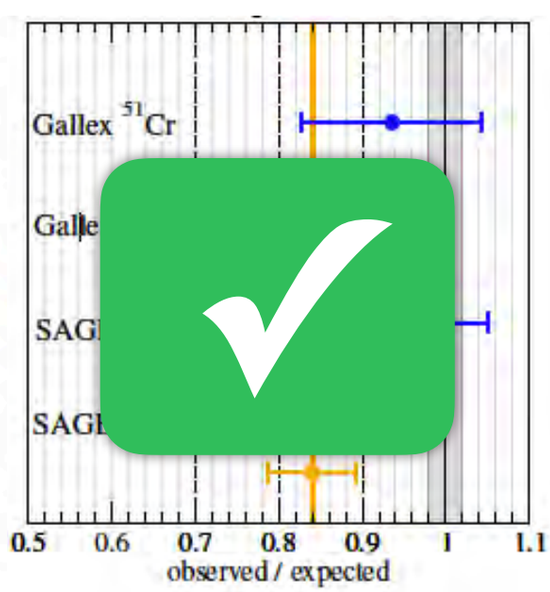
Reactor anomaly



Gallium anomaly



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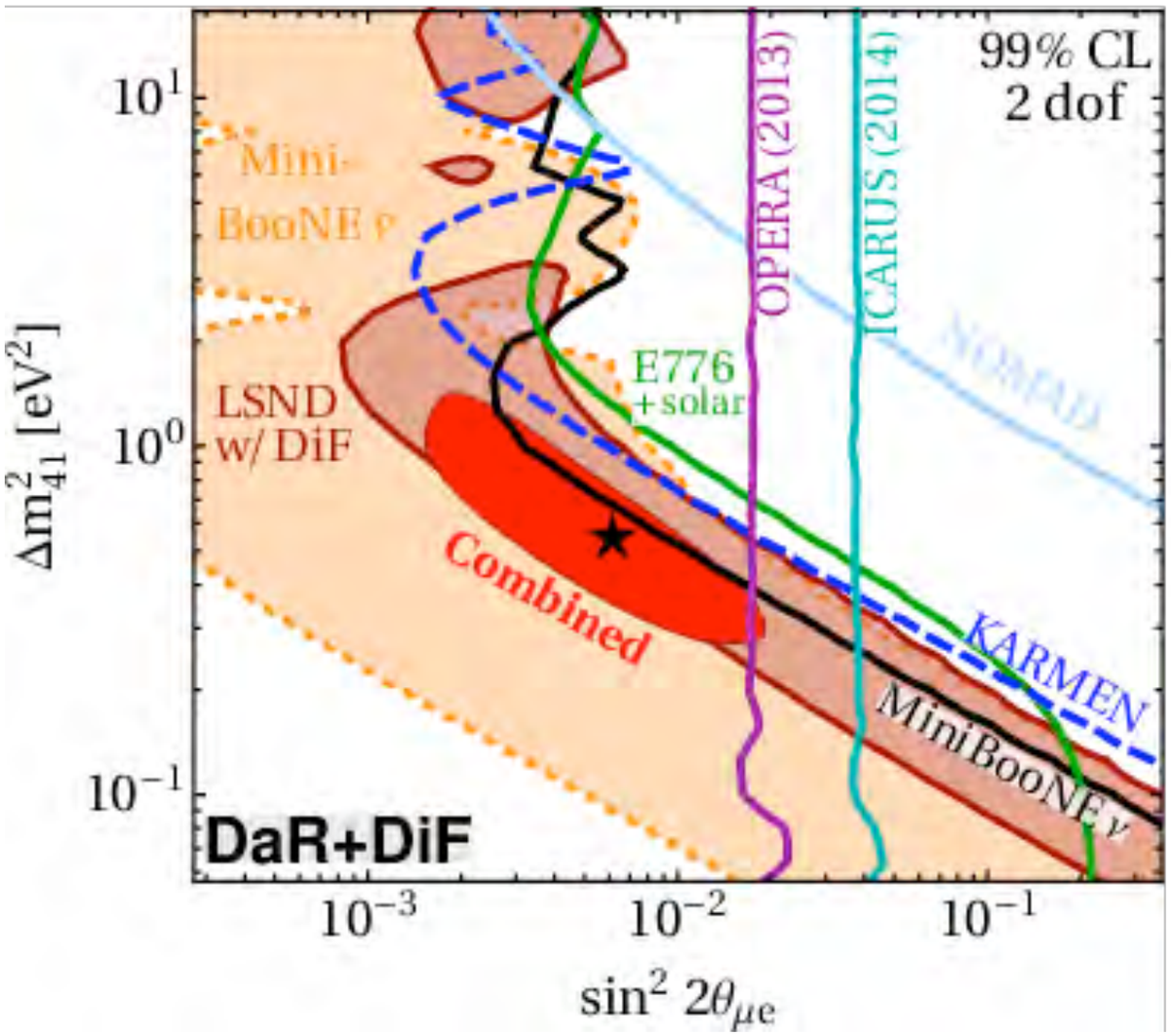
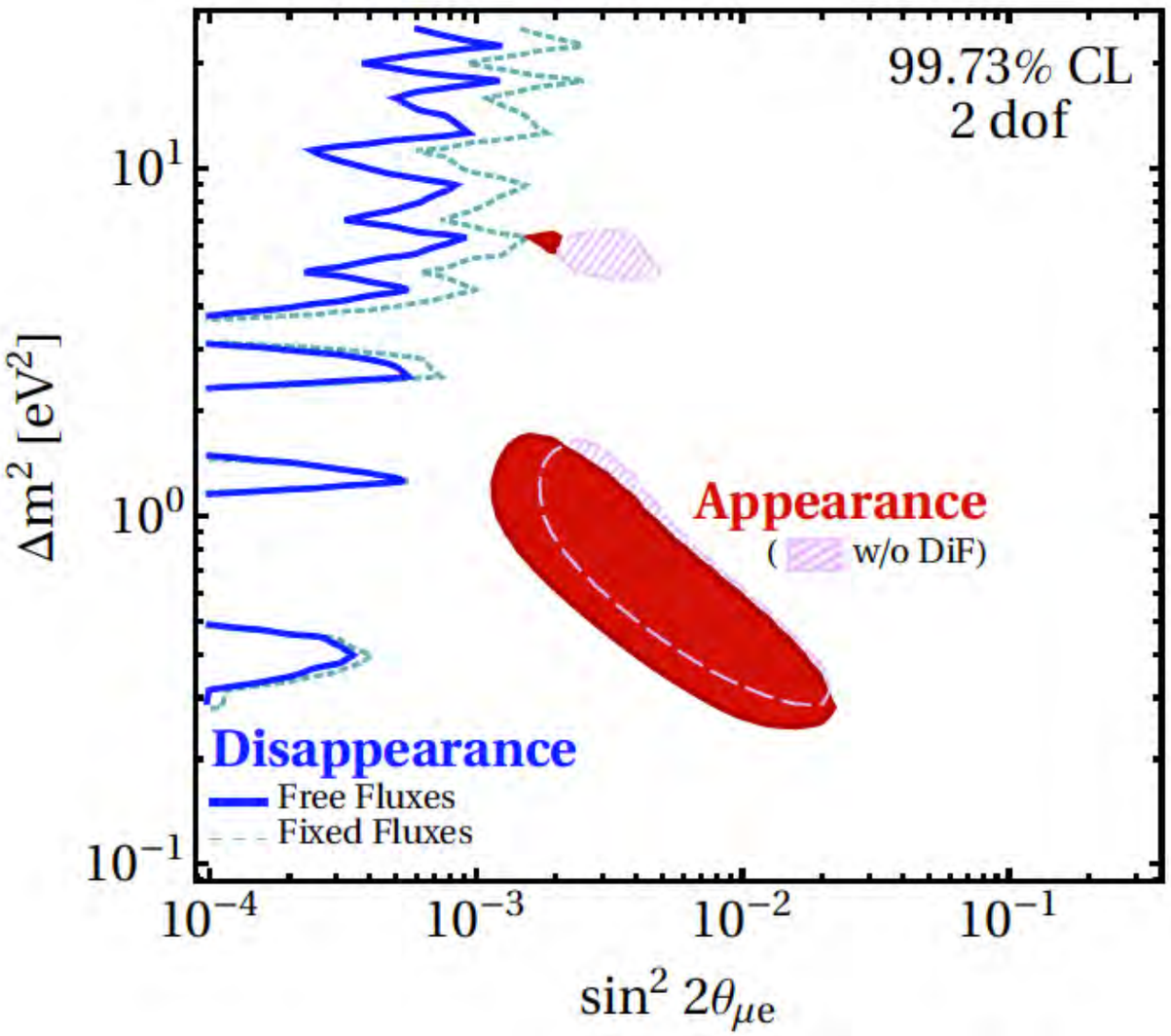
Global fit in 3+1 neutrino scheme

Dentler et al, JHEP 2018 [See also Giunti et al]



⇒ Constraints on short-baseline

$\nu_\mu \to \nu_e$ oscillations



⇒ strong tension between appearance (LSND/MiniBooNE) and disappearance experiments: SK, IceCube, MINOS/+,…

eV-sterile neutrino in Cosmology

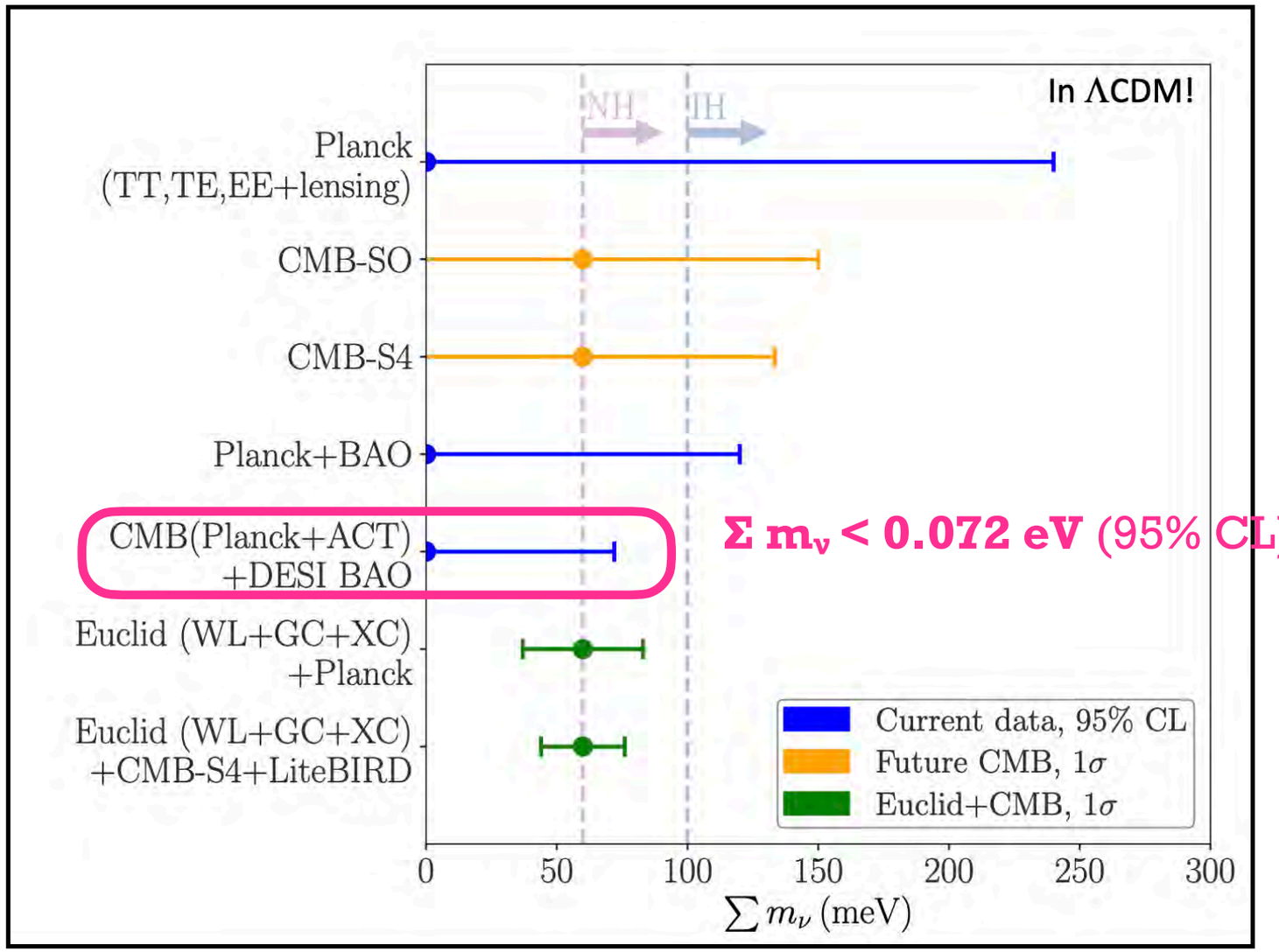
Cosmological constraints on neutrinos

relativistic degrees of freedom

$$N_{\rm eff} = 2.96^{+0.34}_{-0.33}$$

Strong tension between the eV sterile neutrino hypothesis and cosmology

Sum of neutrino masses

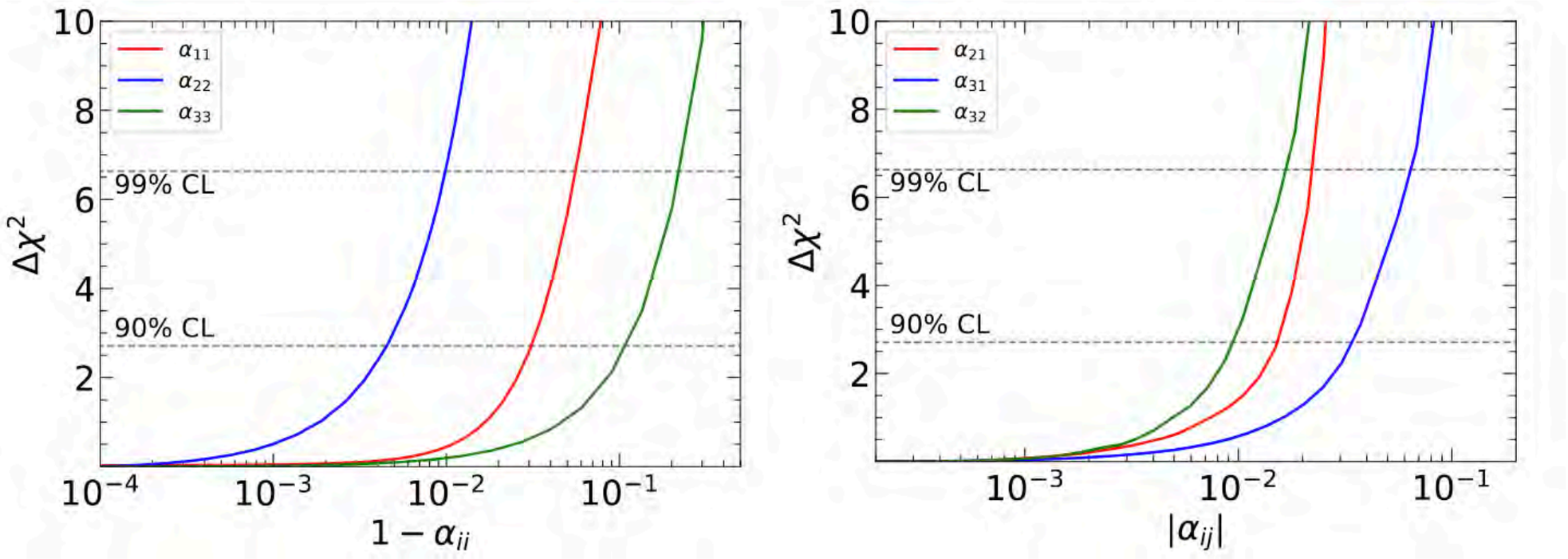


M. Archidiacono @ Neutrino 2024

Non-unitary neutrino mixing

Bounds on neutrino NU mixing

- Analysis of **short-baseline** and **long-baseline** neutrino experiments: NOMAD and NuTeV and MINOS, NOvA and T2K.

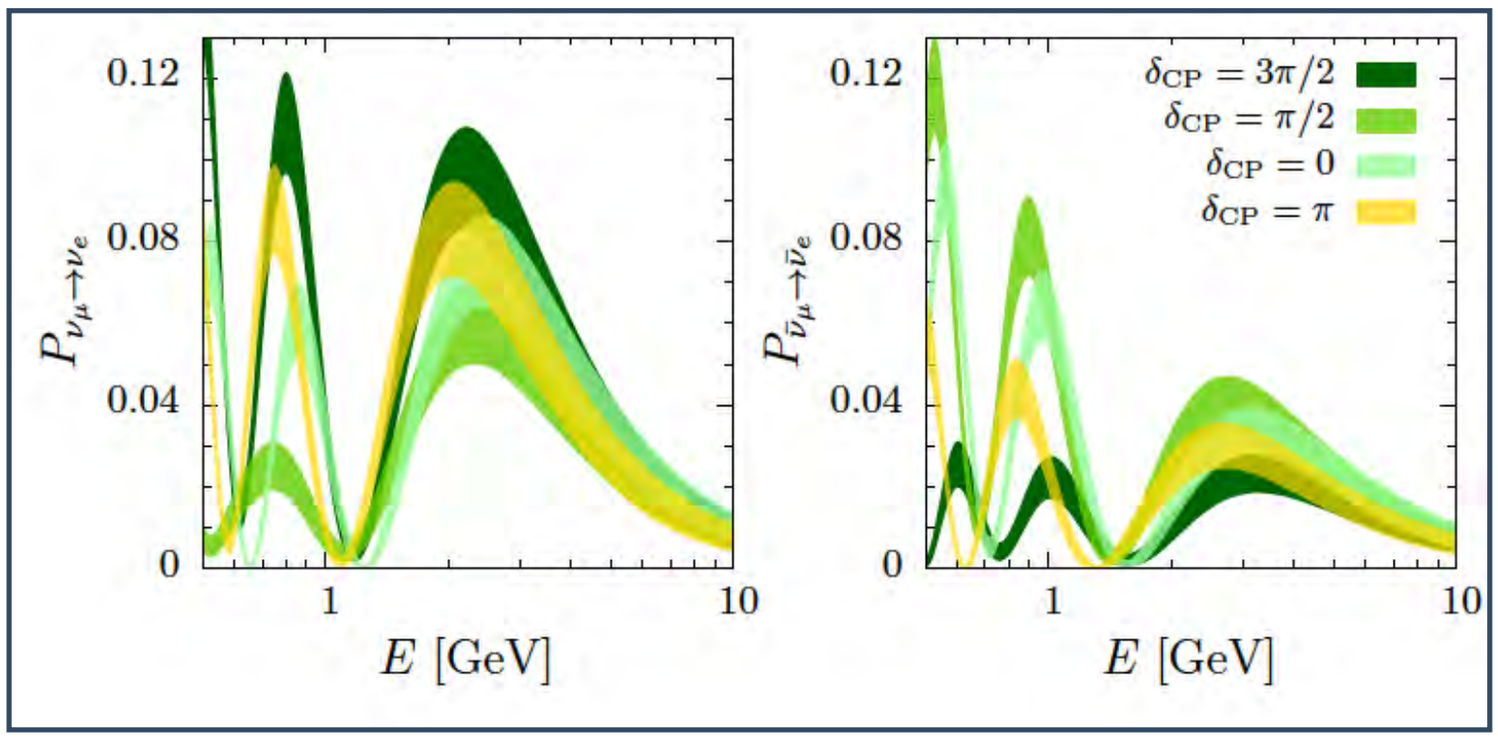


Parameter	90% C.L.	99% C.L.
$1-\alpha_{11}$	< 0.031	< 0.056
$1-\alpha_{22}$	< 0.005	< 0.010
$1-\alpha_{33}$	< 0.110	< 0.220
$\lvert\alpha_{21}\rvert$	< 0.013	< 0.023
$\lvert\alpha_{31}\rvert$	< 0.033	< 0.065
$\lvert\alpha_{32}\rvert$	< 0.009	< 0.017

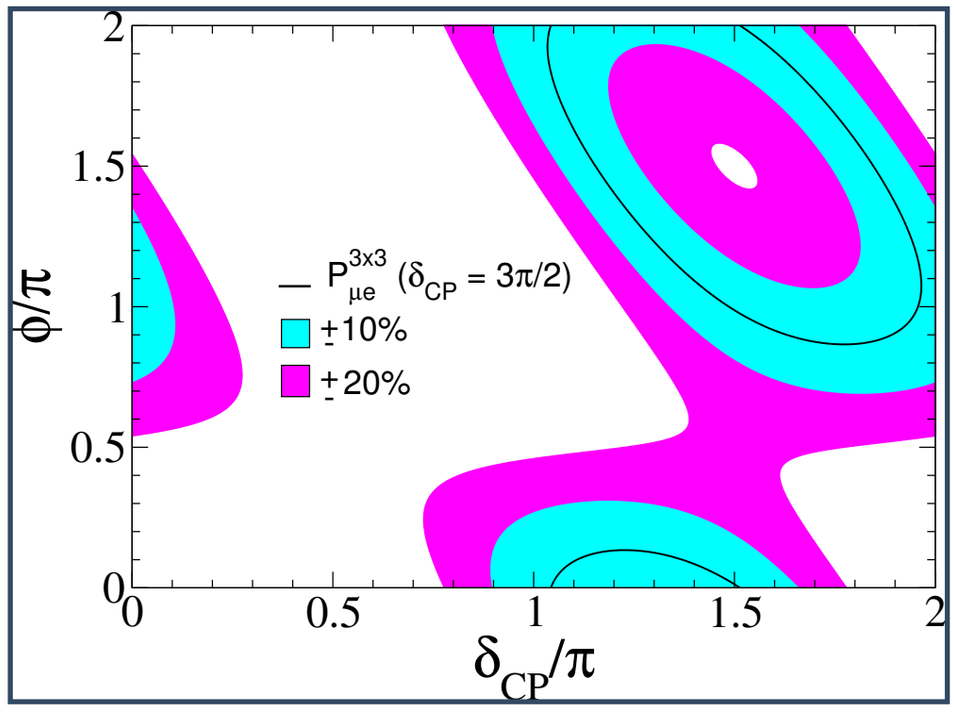
Forero, Giunti, Ternes, Tórtola, PRD 2022

NU neutrino oscillations in DUNE

The new phases associated to the non-unitarity will modify the standard oscillation picture in LBL experiments, such as DUNE



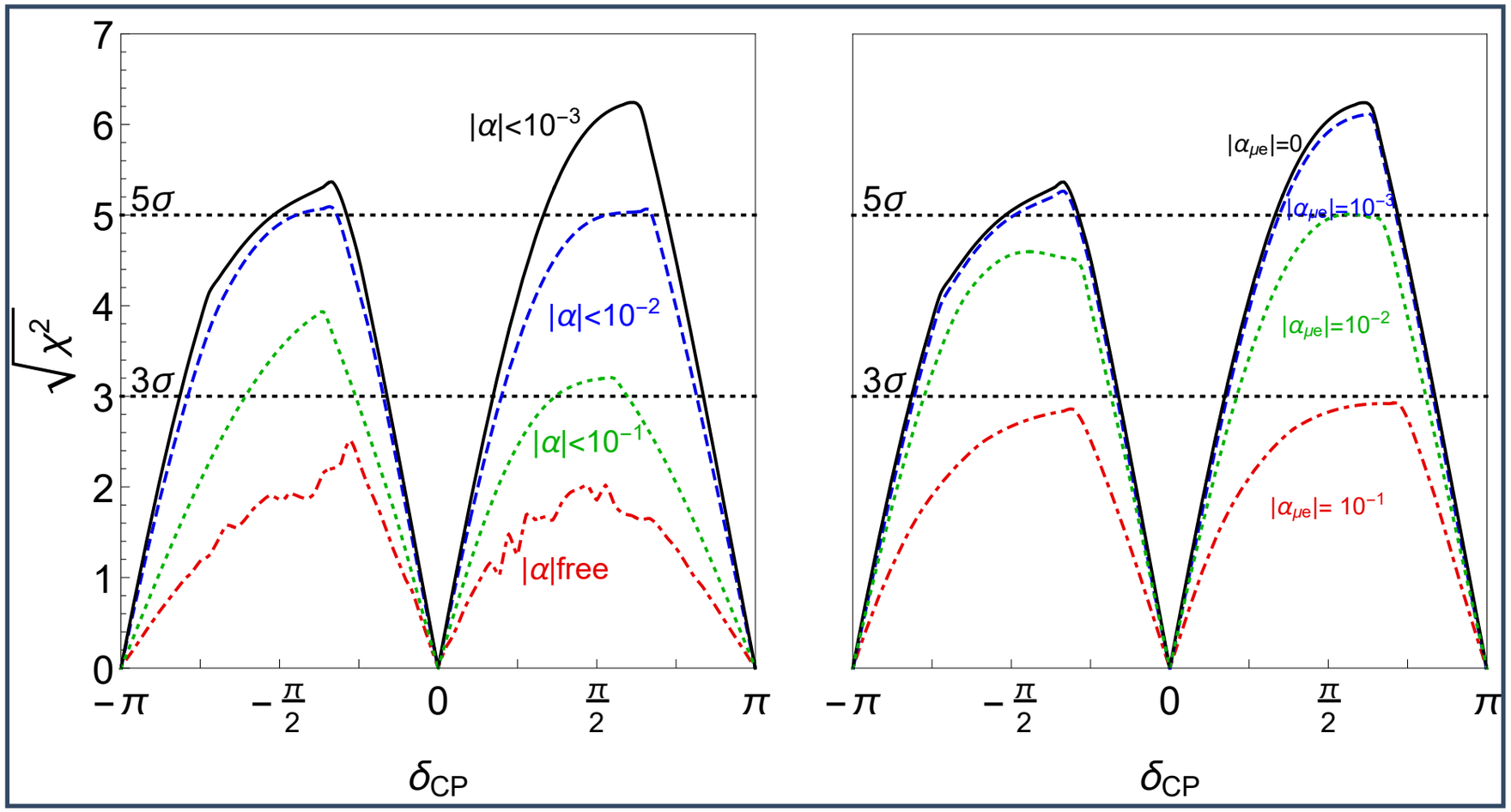
Escrihuela et al, NJP 2017



Miranda, MT, Valle, PRL 117 (2016)

→ (δ, ϕ) degeneracies in $P_{\mu e}$ for E≳ 3 GeV spoil sensitivity to δ

DUNE CP sensitivity with NU



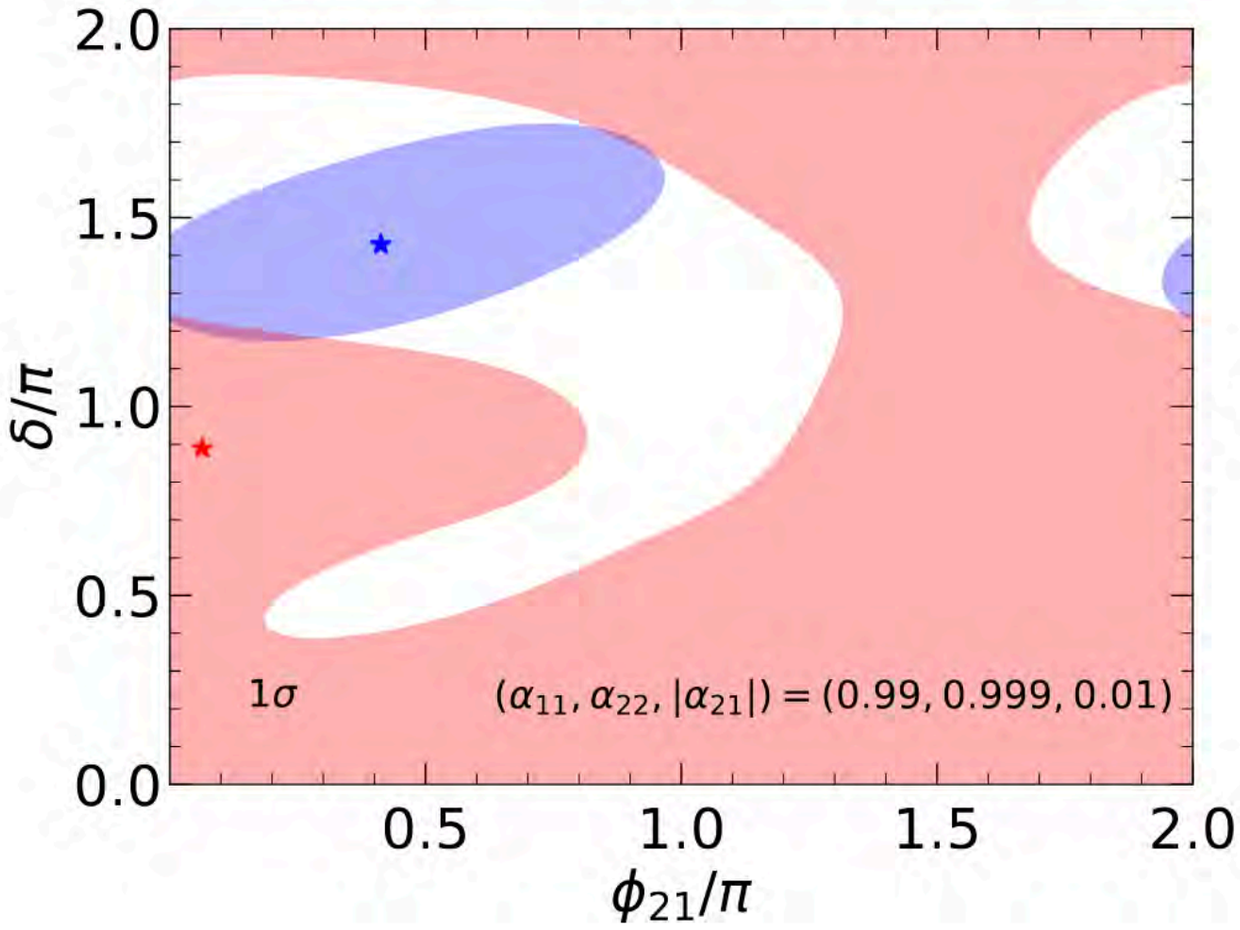
Fernández-Martínez et al (DUNE-BSM Working Group)

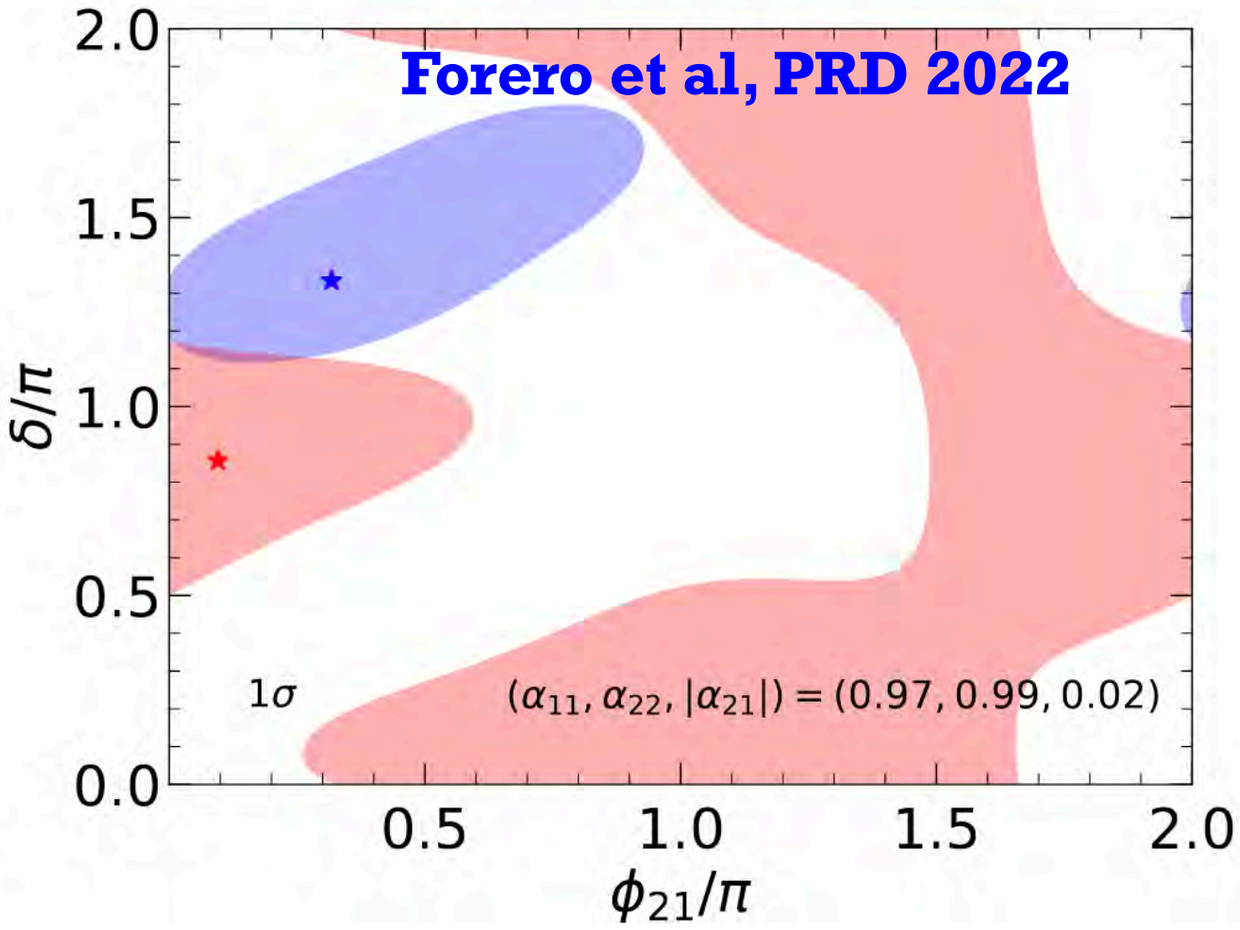
→ The sensitivity to CP violation might be spoiled in the absence of priors on NU

→ With priors based on current bounds (10^{-3}-10^{-2}), the effect is not less dramatic

The T2K-NOvA δ_{CP} tension

Non-unitary mixing analysis of T2K and NOvA (normal ordering)



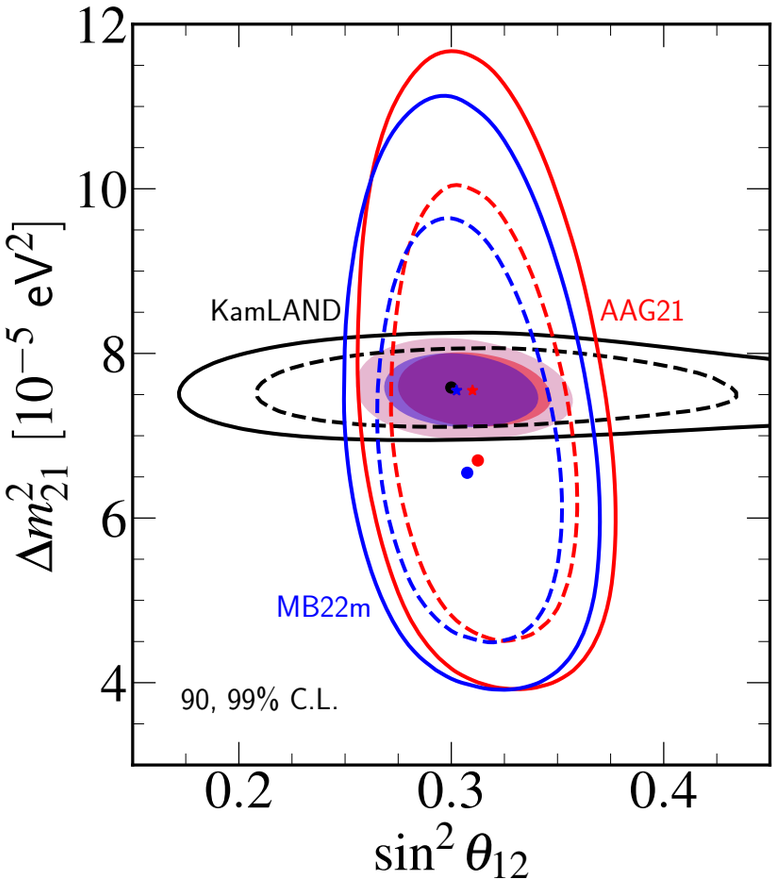


- NU includes additional sources of CP violation.
- No significant deviation from unitary mixing is found: updated bounds with LBL and SBL ⇒MINOS improves current neutrino limits!

⇒ The tension is not alleviated in the context of NU neutrino mixing

Neutrino non-standard interactions (NSI) with matter

NSI in the solar sector



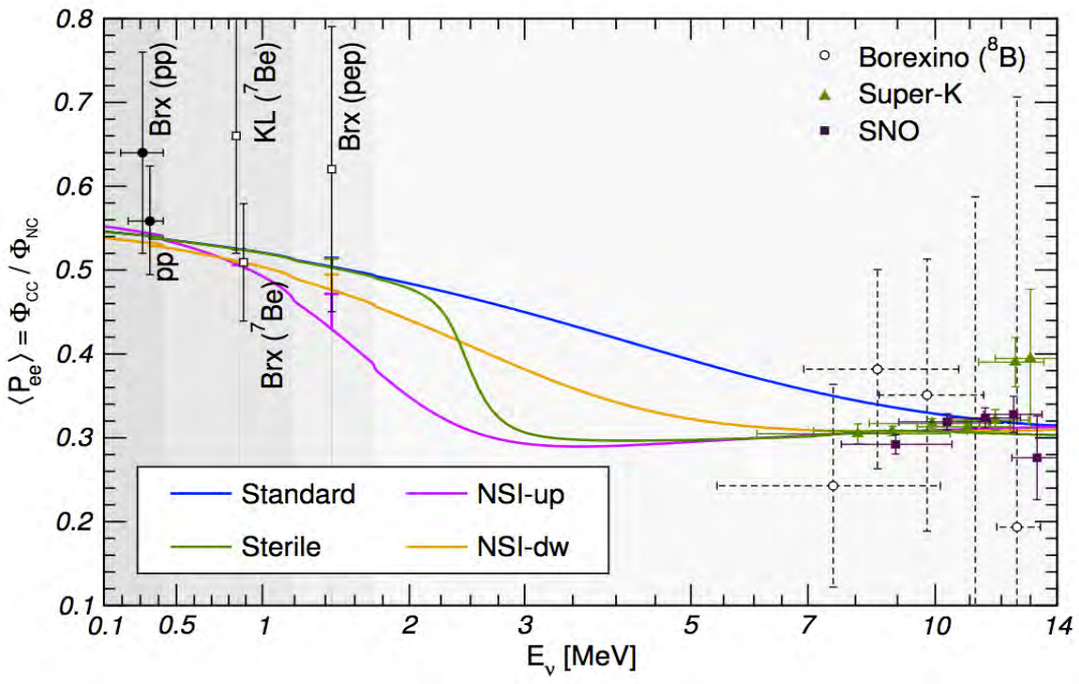
⇒ tension between preferred value of Δm^2_{21} from KamLAND and solar data

⇒ Δm^2_{21} preferred by KamLAND predicts steep upturn and smaller D/N asymmetry

✦ **NSI** (ε ~0.3) can reconcile both results:

⇒ flatter spectrum at intermediate E-region

⇒ larger D/N asymmetries can be expected



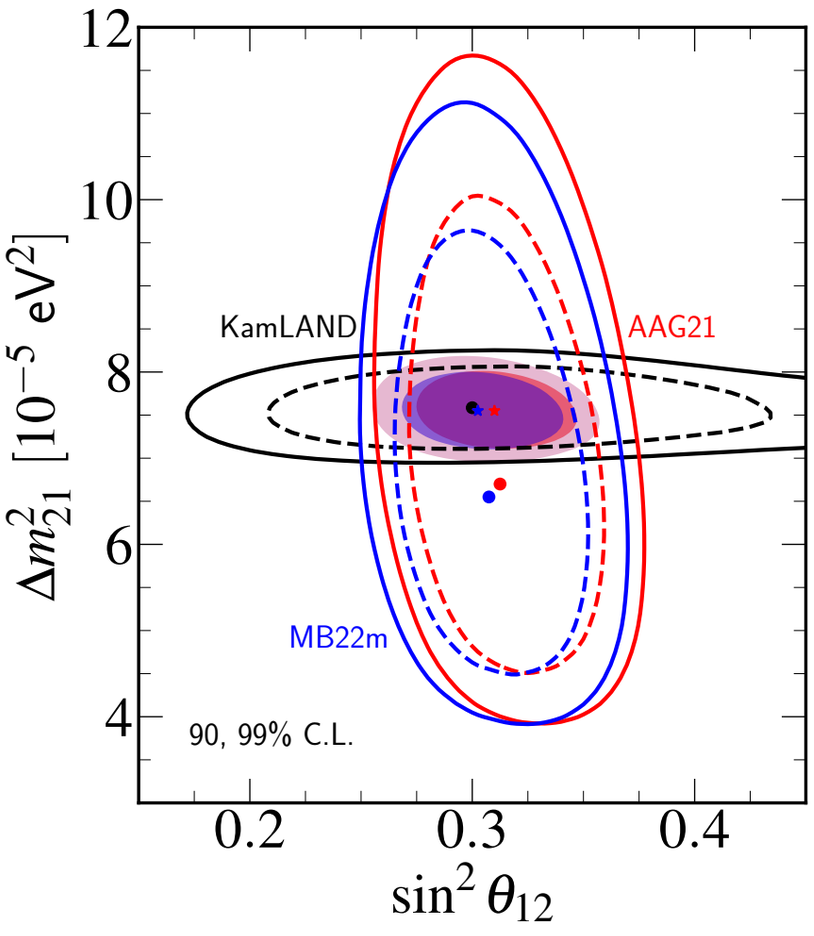
Escrihuela et al, PRD80 (2009); Coloma et al, PRD96 (2017) Maltoni & Smirnov, EPJ 2015

NSI in the solar sector

$$P_{ee} = \frac{1}{2}\left[1 + \cos 2\theta \cos 2\theta_{\rm mat}\right]$$

3ν oscillations

$$\cos 2\theta_m = \frac{\Delta m^2 \cos 2\theta - 2\sqrt{2} E G_F N_e}{\sqrt{(\Delta m^2 \cos 2\theta - 2\sqrt{2} E G_F N_e)^2 + (\Delta m^2 \sin^2 2\theta)^2}}$$

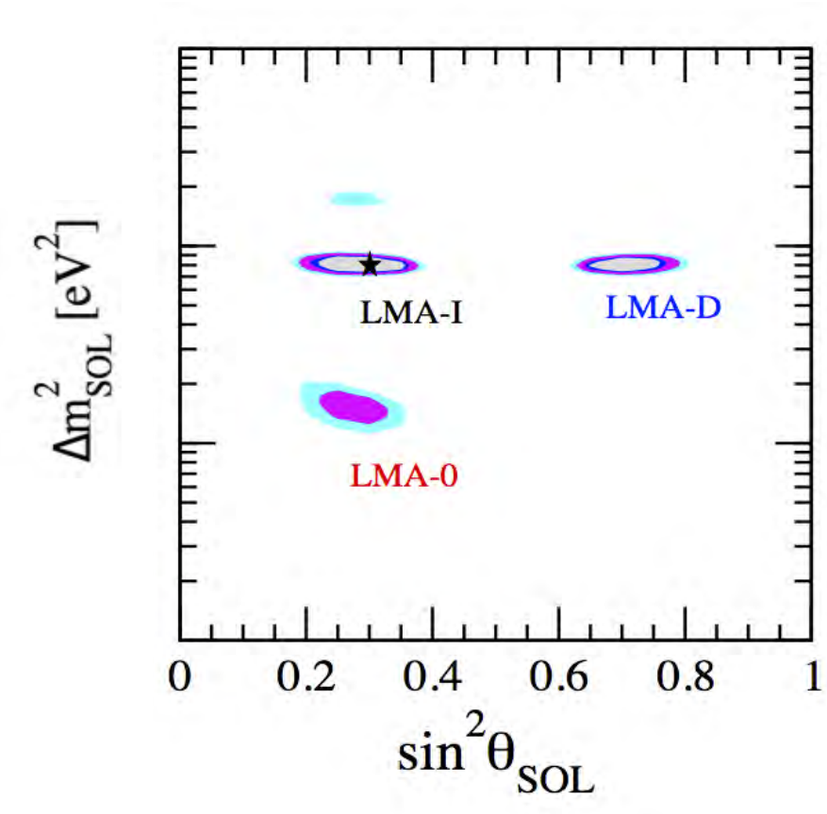


3ν oscillations + NSI:

$$N_e \to N_e + \varepsilon^f_{\alpha\alpha} N_f$$

⇒ **degenerate solution with:**

$$\varepsilon^f_{\alpha\alpha} N_f \to -\varepsilon^f_{\alpha\alpha} N_f - 2N_e\,, \quad \theta \to \pi/2 - \theta$$



Miranda et al, JHEP 2006

	NSI with quarks	
ϵ_{ee}^{dL}	$[-0.3, 0.3]$	CHARM
ϵ_{ee}^{dR}	$[-0.6, 0.5]$	CHARM
ϵ_{ee}^{dV}	$[0.030, 0.55]$	oscillation data + COHERENT
ϵ_{ee}^{uV}	$[0.028, 0.60]$	oscillation data + COHERENT
$\epsilon_{\mu\mu}^{dV}$	$[-0.042, 0.042]$	atmospheric + accelerator
$\epsilon_{\mu\mu}^{uV}$	$[-0.044, 0.044]$	atmospheric + accelerator
$\epsilon_{\mu\mu}^{dA}$	$[-0.072, 0.057]$	atmospheric + accelerator
$\epsilon_{\mu\mu}^{uA}$	$[-0.094, 0.14]$	atmospheric + accelerator
$\epsilon_{\tau\tau}^{dV}$	$[-0.075, 0.33]$	oscillation data + COHERENT
$\epsilon_{\tau\tau}^{uV}$	$[-0.09, 0.38]$	oscillation data + COHERENT
$\epsilon_{\tau\tau}^{qV}$	$[-0.037, 0.037]$	atmospheric
	NSI with electrons	
ϵ_{ee}^{eL}	$[-0.021, 0.052]$	solar + KamLAND
ϵ_{ee}^{eR}	$[-0.07, 0.08]$	TEXONO
$\epsilon_{\mu\mu}^{eL}$, $\epsilon_{\mu\mu}^{eR}$	$[-0.03, 0.03]$	reactor + accelerator
$\epsilon_{\tau\tau}^{eL}$	$[-0.12, 0.06]$	solar + KamLAND
$\epsilon_{\tau\tau}^{eR}$	$[-0.98, 0.23]$ [-0.25, 0.43]	solar + KamLAND and Borexino reactor + accelerator
$\epsilon_{\tau\tau}^{eV}$	$[-0.11, 0.11]$	atmospheric

90% C.L. bounds on NU-NSI

$$\epsilon_{\alpha\alpha}^{fP}$$

[f=u,d,e; P=L,R,V,A]

Farzan, MT, Frontiers in Phys. 6 (2018) 10

NSI with quarks		
$\epsilon^{qL}_{e\mu}$	$[-0.023, 0.023]$	accelerator
$\epsilon^{qR}_{e\mu}$	$[-0.036, 0.036]$	accelerator
$\epsilon^{uV}_{e\mu}$	$[-0.073, 0.044]$	oscillation data + COHERENT
$\epsilon^{dV}_{e\mu}$	$[-0.07, 0.04]$	oscillation data + COHERENT
$\epsilon^{qL}_{e\tau}$, $\epsilon^{qR}_{e\tau}$	$[-0.5, 0.5]$	CHARM
$\epsilon^{uV}_{e\tau}$	$[-0.15, 0.13]$	oscillation data + COHERENT
$\epsilon^{dV}_{e\tau}$	$[-0.13, 0.12]$	oscillation data + COHERENT
$\epsilon^{qL}_{\mu\tau}$	$[-0.023, 0.023]$	accelerator
$\epsilon^{qR}_{\mu\tau}$	$[-0.036, 0.036]$	accelerator
$\epsilon^{qV}_{\mu\tau}$	$[-0.006, 0.0054]$	IceCube
$\epsilon^{qA}_{\mu\tau}$	$[-0.039, 0.039]$	atmospheric + accelerator
NSI with electrons		
$\epsilon^{eL}_{e\mu}$, $\epsilon^{eR}_{e\mu}$	$[-0.13, 0.13]$	reactor + accelerator
$\epsilon^{eL}_{e\tau}$	$[-0.33, 0.33]$	reactor + accelerator
$\epsilon^{eR}_{e\tau}$	$[-0.28, -0.05]$ & $[0.05, 0.28]$ $[-0.19, 0.19]$	reactor + accelerator TEXONO
$\epsilon^{eL}_{\mu\tau}$, $\epsilon^{eR}_{\mu\tau}$	$[-0.10, 0.10]$	reactor + accelerator
$\epsilon^{eV}_{\mu\tau}$	$[-0.018, 0.016]$	IceCube

90% C.L. bounds on FC-NSI

$$\epsilon^{fP}_{\alpha\beta}$$

[f=u,d,e; P=L,R,V,A]

Farzan, MT, Frontiers in Phys. 6 (2018) 10

		semileptonic NSI
ϵ_{ee}^{udP}	$[-0.015, 0.015]$	Daya Bay
$\epsilon_{e\mu}^{udL}$	$[-0.026, 0.026]$	NOMAD
$\epsilon_{e\mu}^{udR}$	$[-0.037, 0.037]$	NOMAD
$\epsilon_{\tau e}^{udL}$	$[-0.087, 0.087]$	NOMAD
$\epsilon_{\tau e}^{udR}$	$[-0.12, 0.12]$	NOMAD
$\epsilon_{\tau\mu}^{udL}$	$[-0.013, 0.013]$	NOMAD
$\epsilon_{\tau\mu}^{udR}$	$[-0.018, 0.018]$	NOMAD
		purely leptonic NSI
$\epsilon_{\alpha e}^{\mu eL}$, $\epsilon_{\alpha e}^{\mu eR}$	$[-0.025, 0.025]$	KARMEN
$\epsilon_{\alpha\beta}^{\mu eL}$, $\epsilon_{\alpha\beta}^{\mu eR}$	$[-0.030, 0.030]$	kinematic G_F

90% C.L. bounds on CC-NSI

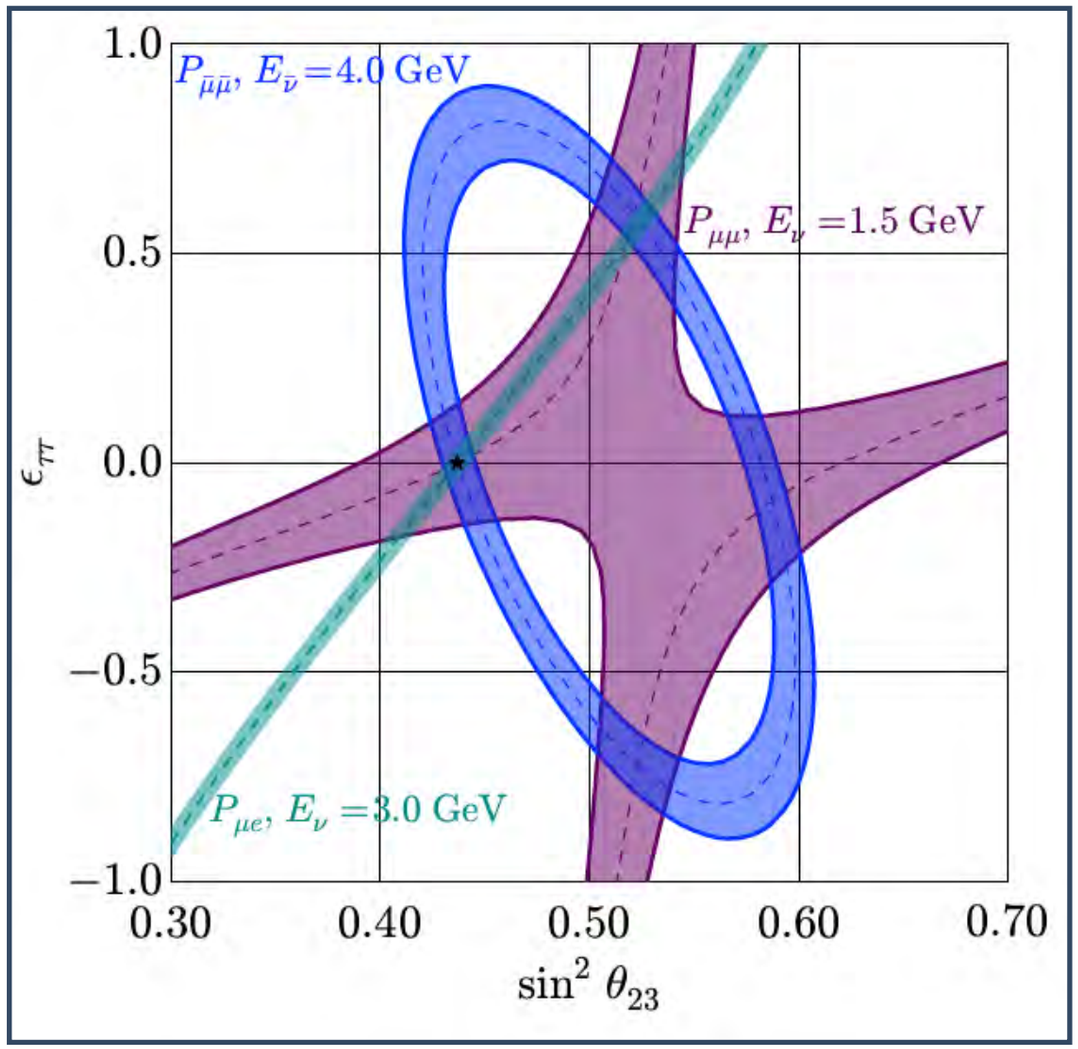
$$\epsilon_{\alpha\beta}^{f f' P}$$

[f,f'=u,d,e; P=L,R,V,A]

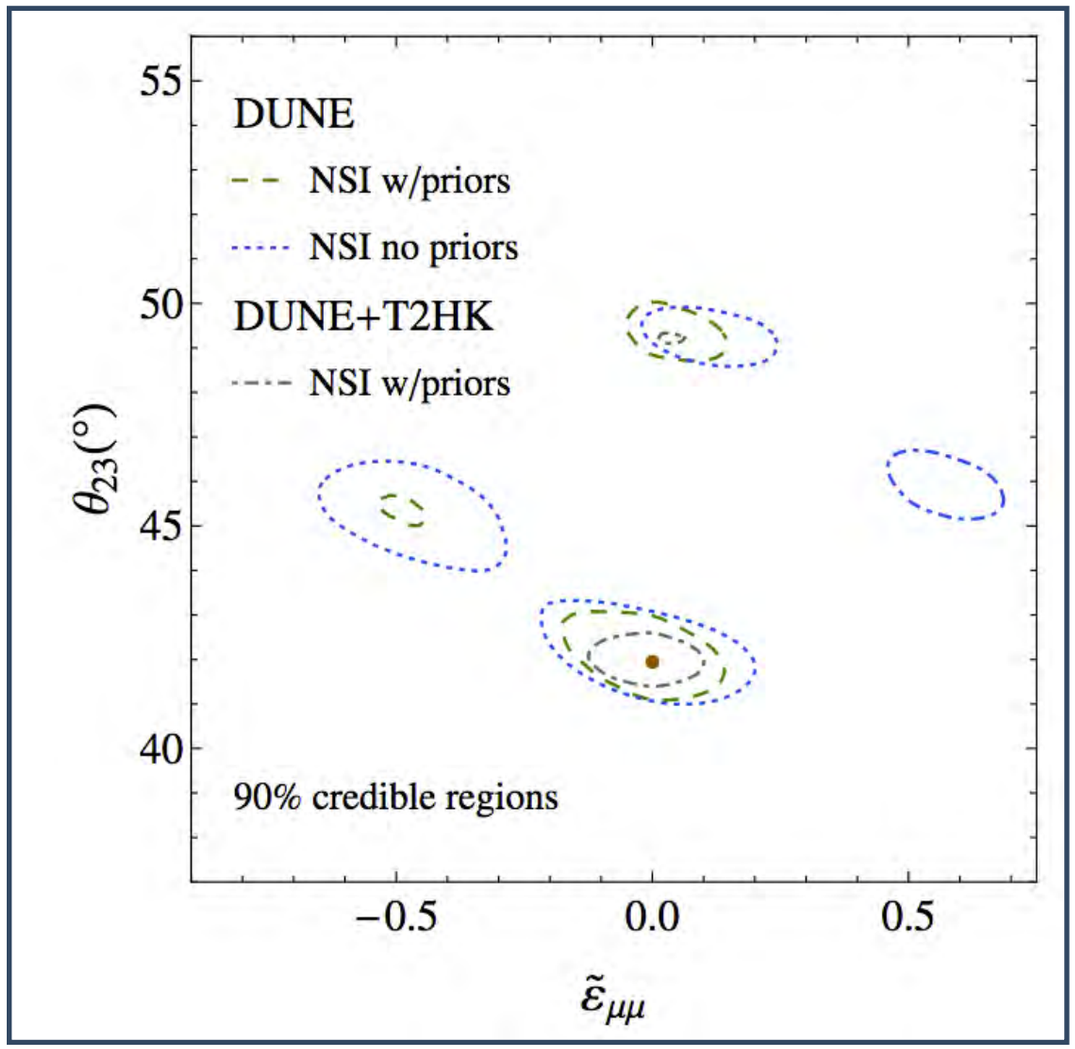
Farzan, MT, Frontiers in Phys. 6 (2018) 10

NSI at future LBL experiments

(θ_{23}-$\epsilon_{\tau\tau}$) degeneracy in DUNE



Gouvea and Kelly, NPB 2016

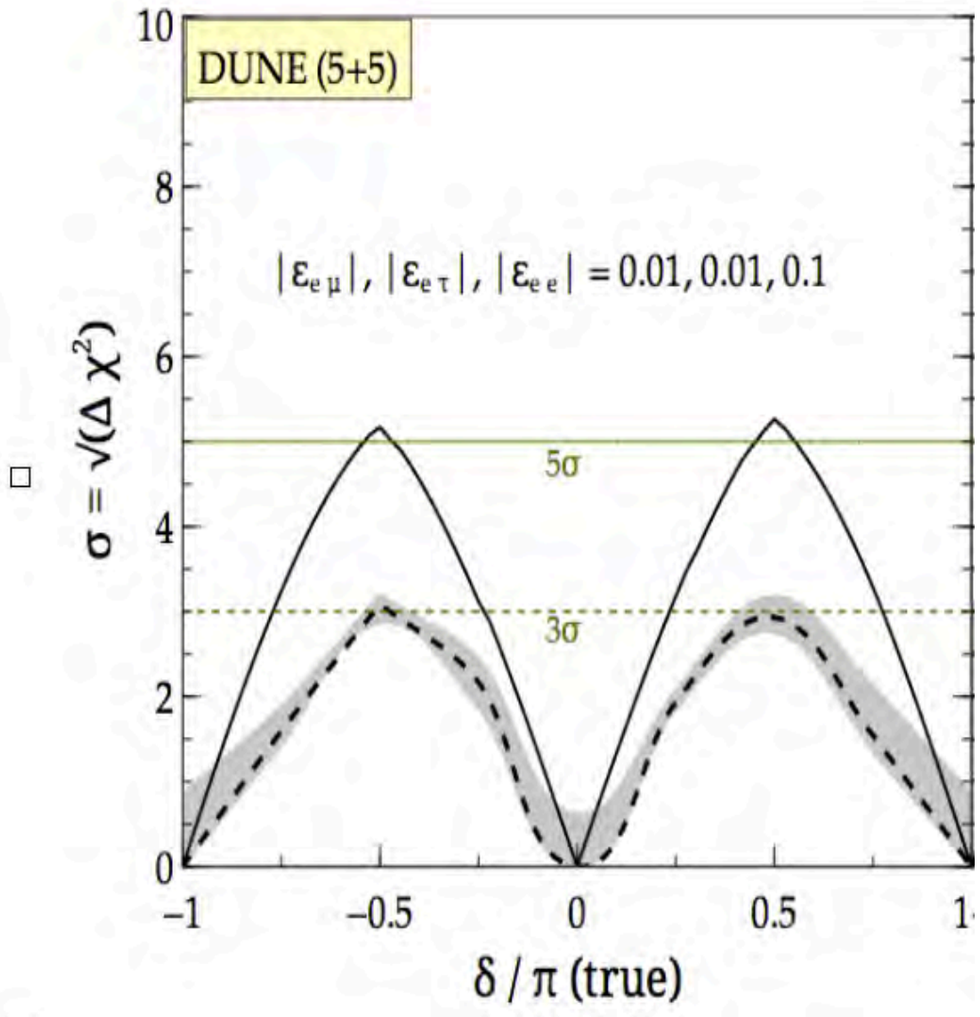


Coloma, JHEP 2016

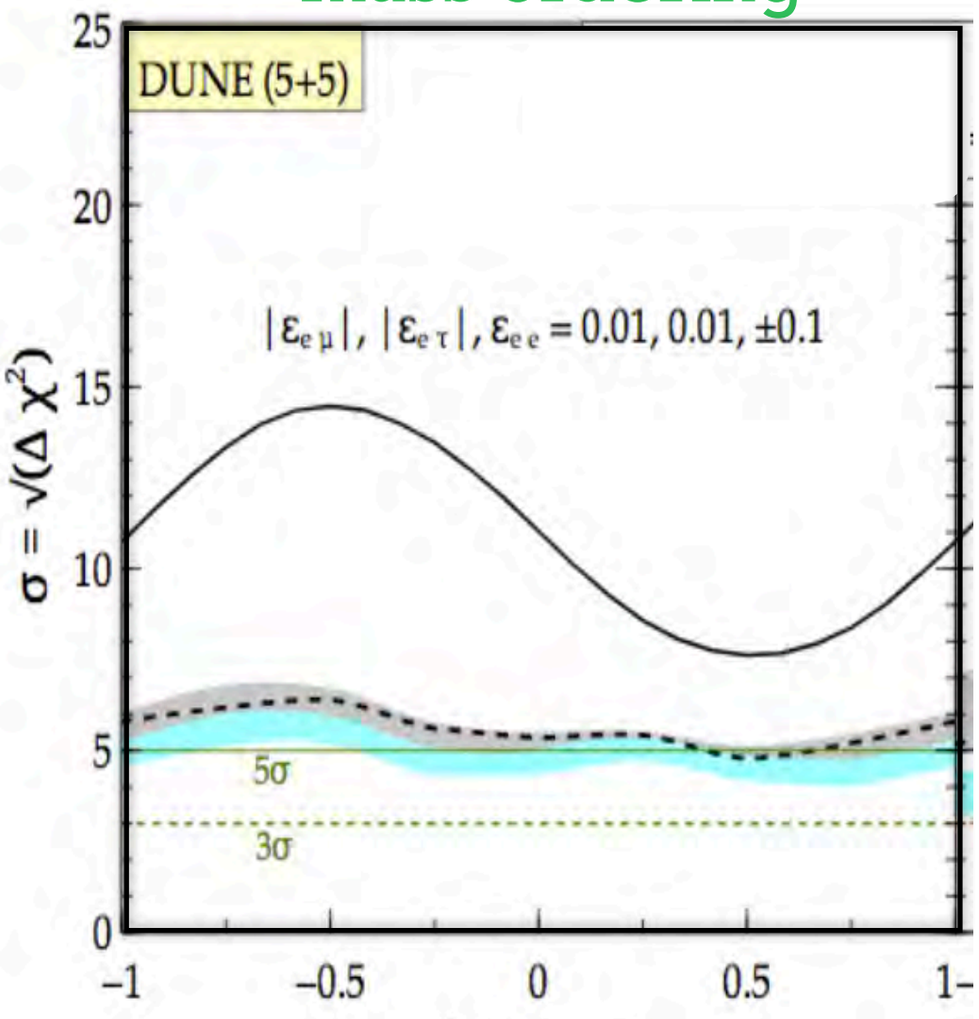
NSI at future LBL experiments

NSI can significantly spoil DUNE's sensitivity to:

CP violation



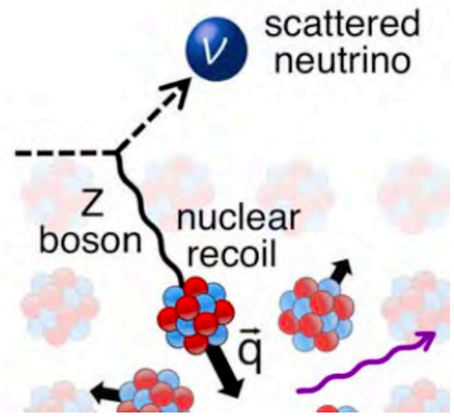
mass ordering



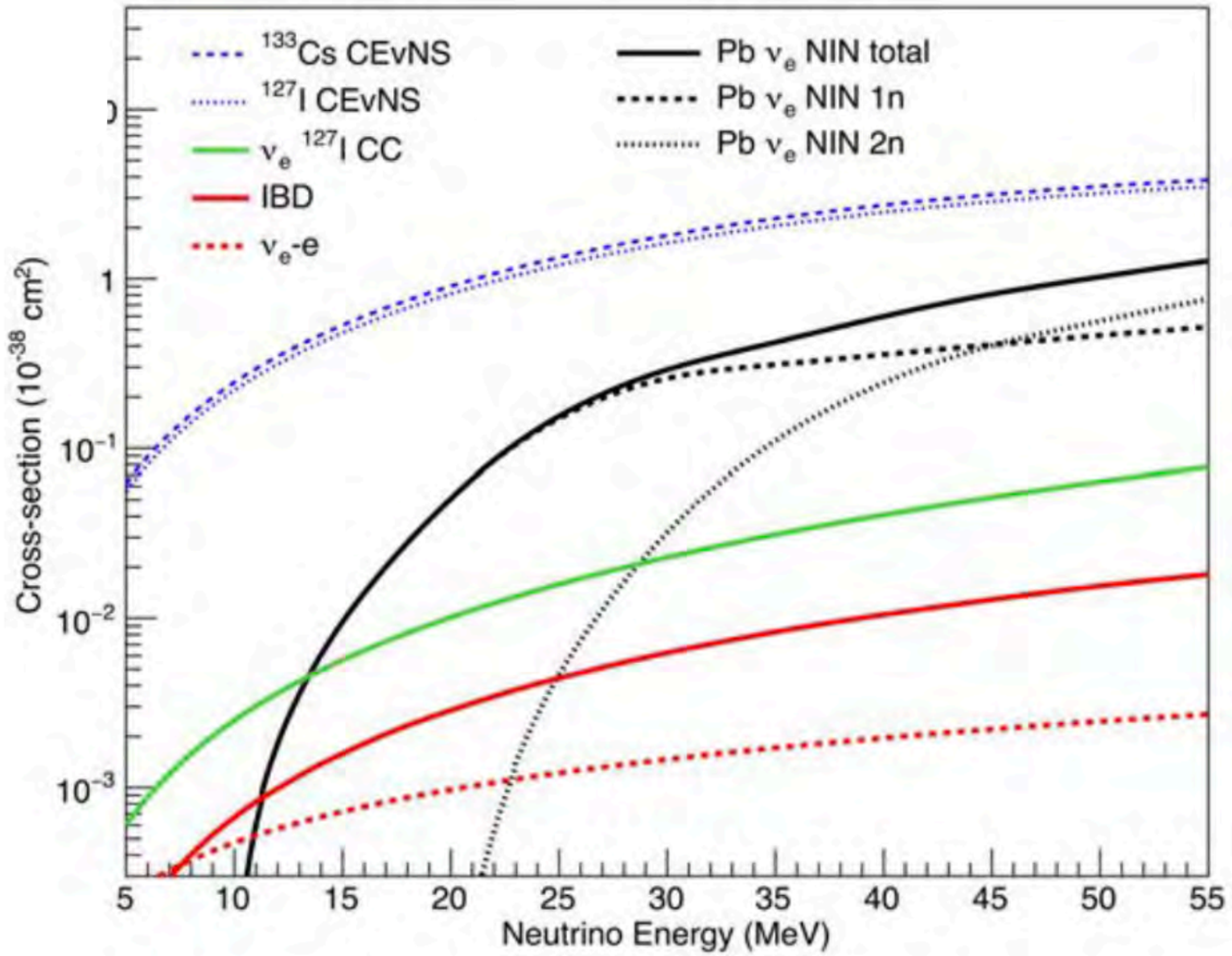
Masud and Mehta, PRD 2016

BSM searches with CEvNS experiments

Coherent Elastic ν Nucleus Scattering (CEvNS)



D. Freedman PRD9 (1974) 1389



First observed at the Spallation Neutron Source (Oak Ridge National Laboratory) in 2017

COHERENT Coll. Science 357 (2017) 1123

What can we learn from CEvNS?

Freedman, PRD 1974

Barranco et al, JHEP 2005

Nuclear form factor

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{4\pi}\left(1 - \frac{MT}{2E_\nu^2} - \frac{T}{E_\nu}\right) Q_w^2 [F_w(q^2)]^2 + \frac{G_F^2 M}{4\pi}\left(1 + \frac{MT}{2E_\nu^2} - \frac{T}{E_\nu}\right) F_A(q^2)$$

Axial contribution: small for most nuclei, it cancels out for nuclei with even number of p and n

Weak nuclear charge

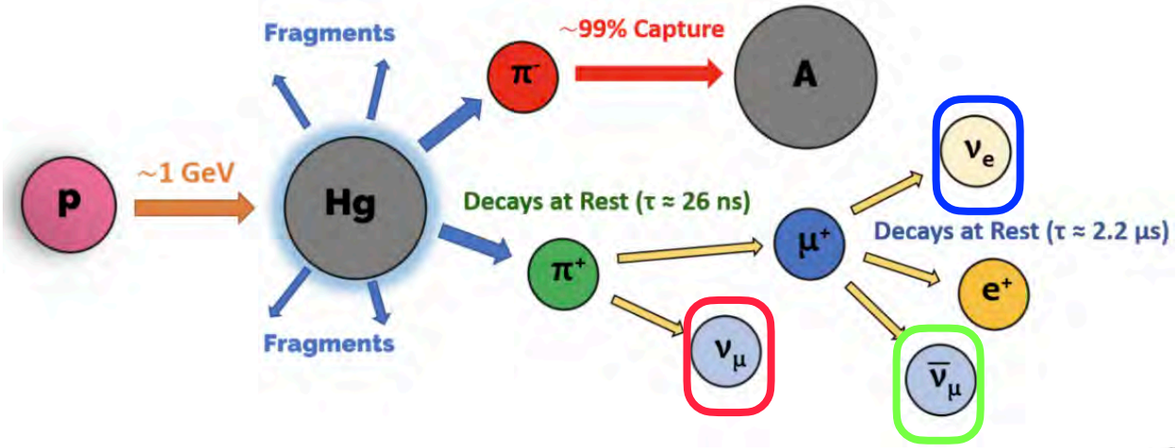
$$Q_W = [Z(1 - 4\sin^2\theta_W) - N]$$

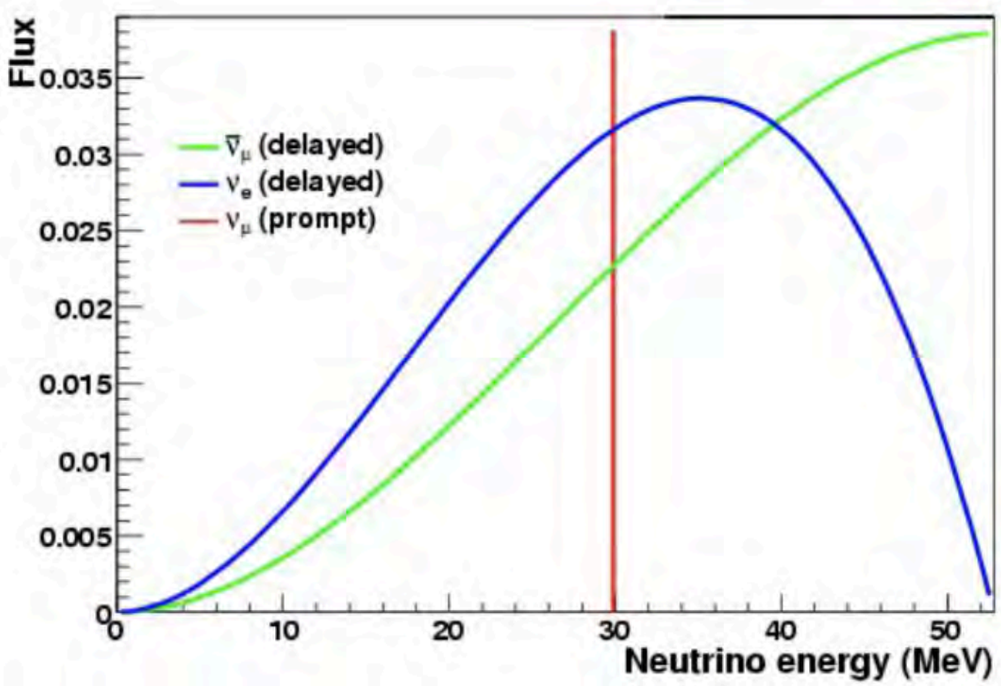
$\sin^2\theta_W \sim 0.23$ → neutron contribution dominates

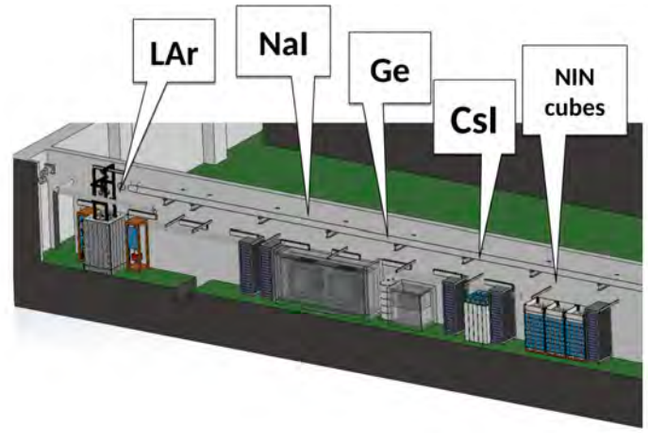
- **Standard Model tests:** nuclear physics, EW measurements (θ_W)
- **BSM searches:** neutrino electromagnetic properties, NSI, couplings with new mediator particles,…

CEvNS data from COHERENT

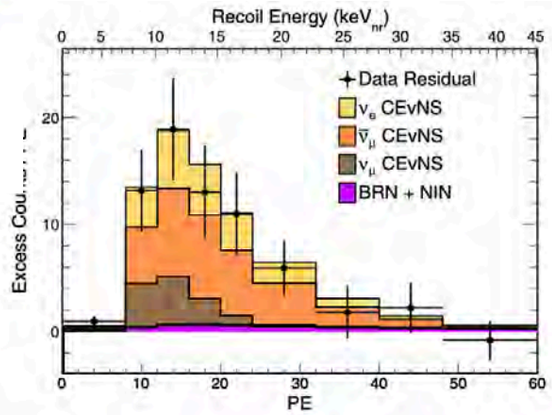
Source: Neutrinos from pion decay at rest

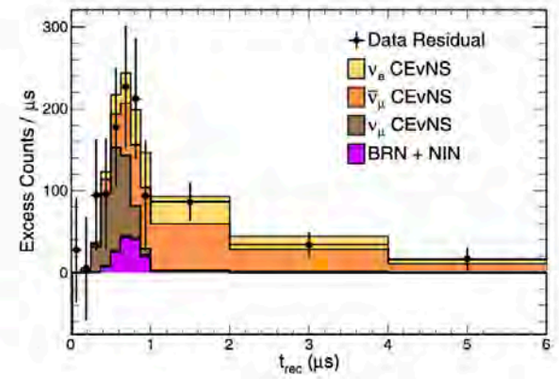




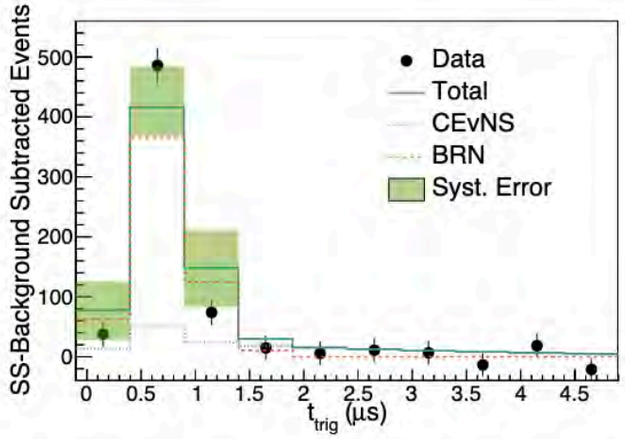


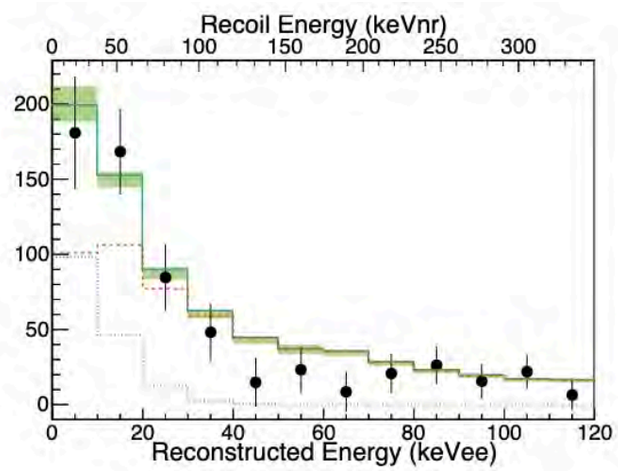
CsI (2021) Akimov et al, PRL 129 (2022) 081801





LAr (2020) Akimov et al, PRL 126 (2021) 012002

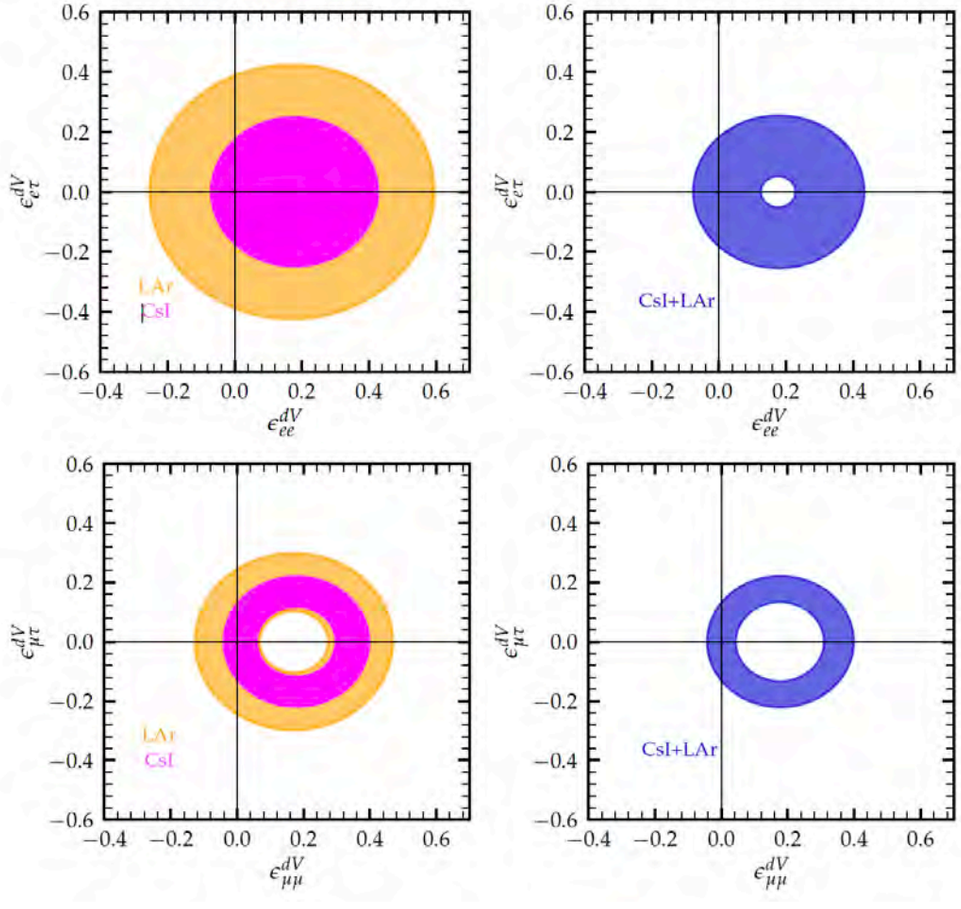




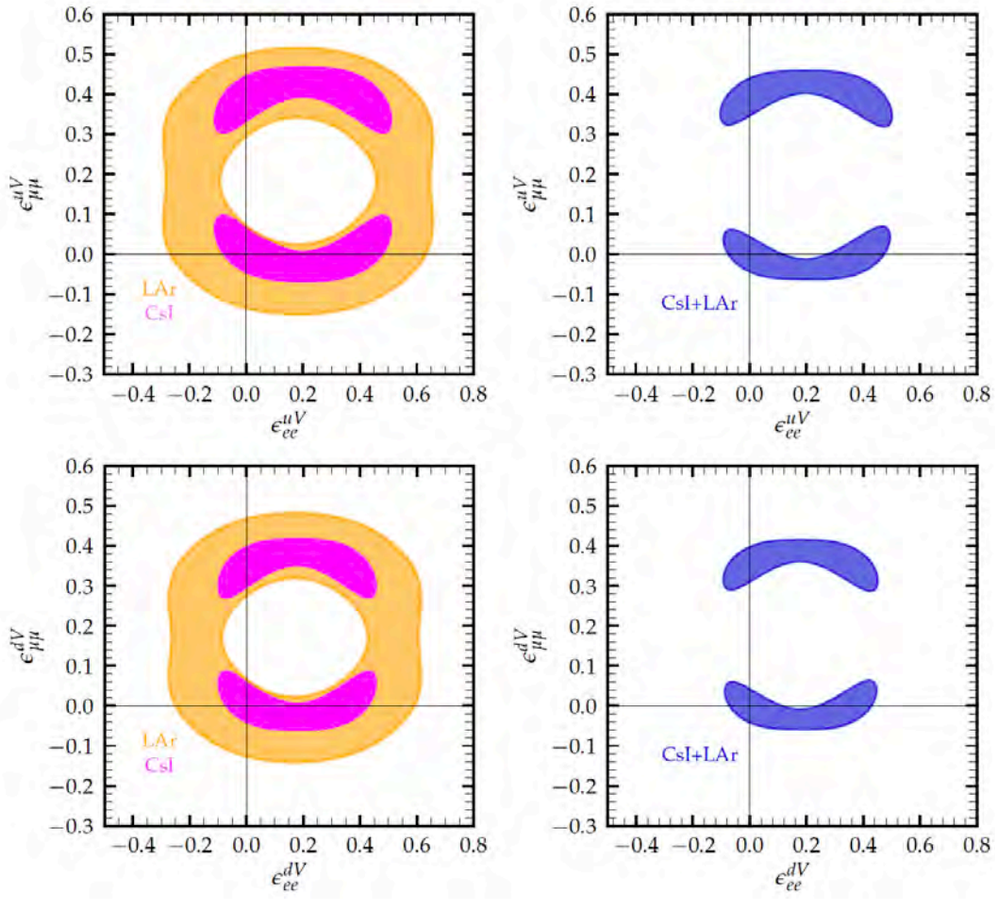
Non-standard interactions

$$Q_V^{\rm NSI} = \left[\left(g_V^p + 2\varepsilon_{\ell\ell}^{uV} + \varepsilon_{\ell\ell}^{dV}\right) Z + \left(g_V^n + \varepsilon_{\ell\ell}^{uV} + 2\varepsilon_{\ell\ell}^{dV}\right) N\right] + \sum_{\ell,\ell'} \left[\left(2\varepsilon_{\ell\ell'}^{uV} + \varepsilon_{\ell\ell'}^{dV}\right) Z + \left(\varepsilon_{\ell\ell'}^{uV} + 2\varepsilon_{\ell\ell'}^{dV}\right) N\right].$$

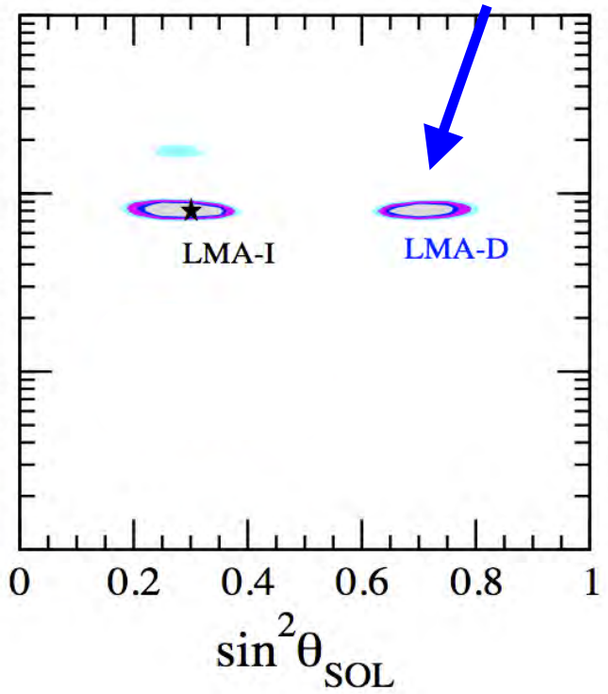
Flavour-changing NSI

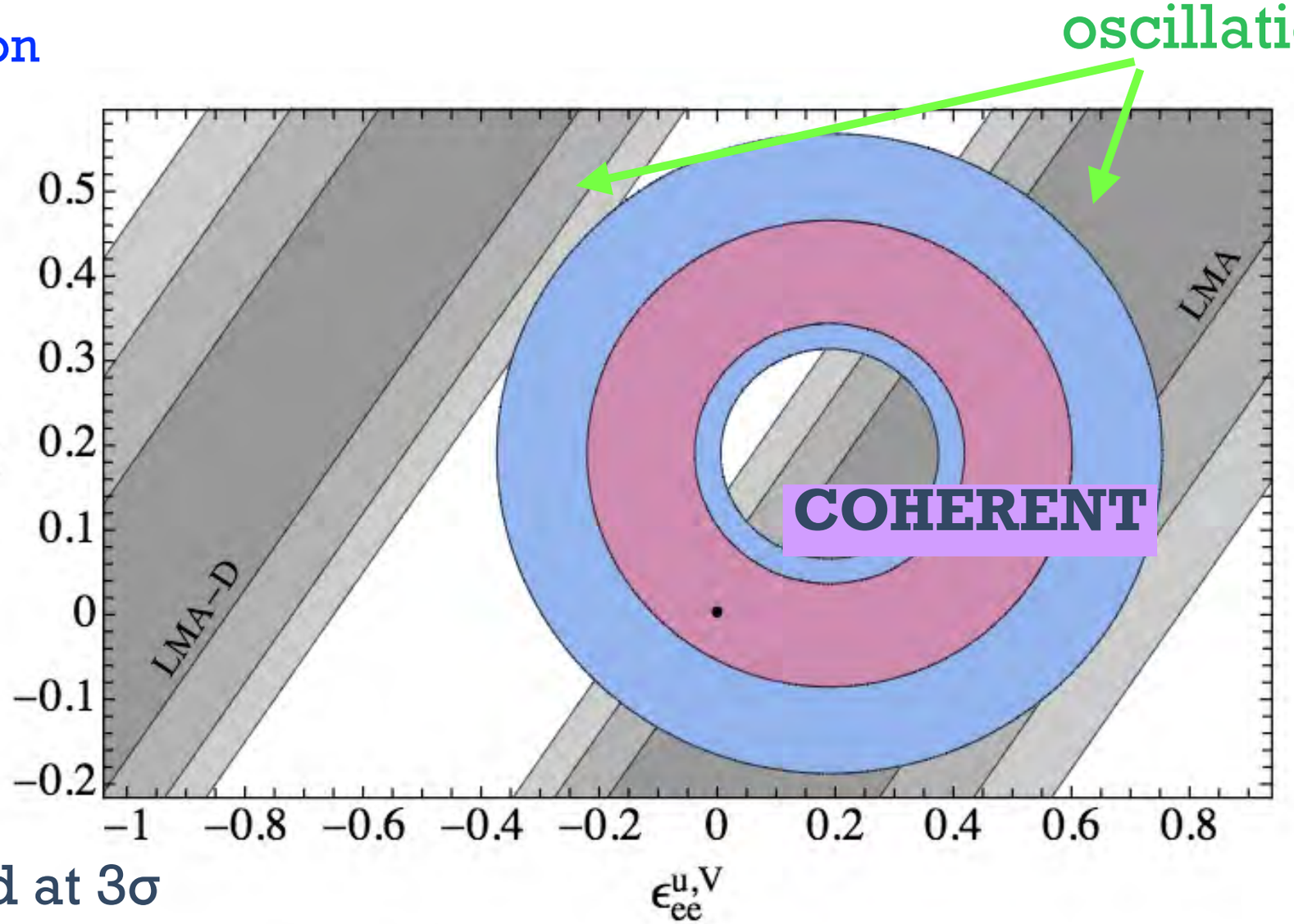


Non-Universal NSI



CEvNS and the LMA-D solution





⇒ **LMA-Dark** excluded at 3σ

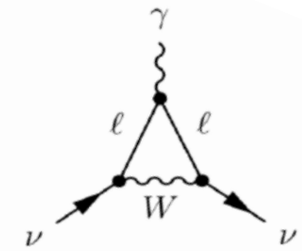
Relaxed if:

- NSI mediator lighter than 50 MeV
- degeneracies in (ε_d, ε_u)

Coloma et al, PRD 2017

Complementarity of CEvNS and oscillation data to constrain BSM physics

Neutrino charge radius



- It is the only EM neutrino parameter that is different from zero in the SM:

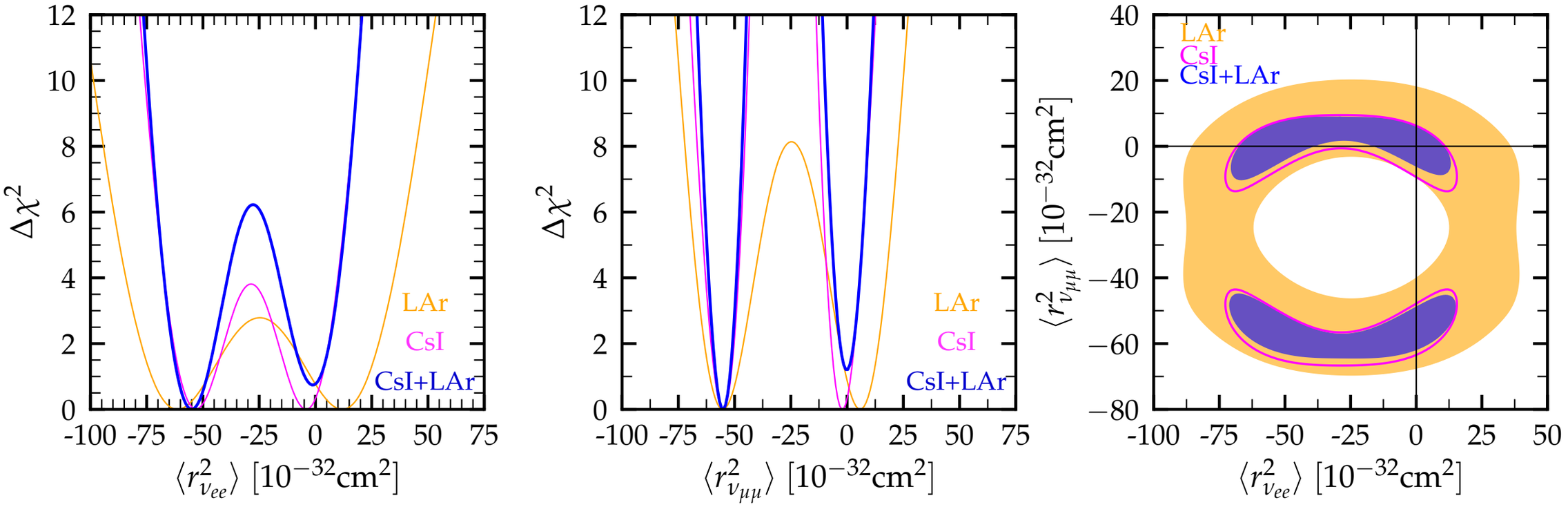
$$\left(\langle r^2_{\nu_{ee}}\rangle, \langle r^2_{\nu_{\mu\mu}}\rangle, \langle r^2_{\nu_{\tau\tau}}\rangle\right) = (-0.83, -0.48, -0.30) \times 10^{-32}\ \text{cm}^2$$ Bernabeu et al NPB 2004

- New contribution to the CEvNS cross section, proportional to

$$Q^{\text{CR}}_{\ell\ell} = \frac{\sqrt{2}\pi\alpha_{\text{EM}}}{3\,G_F}\langle r^2_{\nu_{\ell\ell}}\rangle$$

$$\langle r^2_{\nu_{ee}}\rangle \in [-61.2, -48.2] \cup [-4.7, 2.2] \times 10^{-32}\ \text{cm}^2$$
$$\langle r^2_{\nu_{\mu\mu}}\rangle \in [-58.2, -52.1] \times 10^{-32}\ \text{cm}^2 \quad (1\sigma)$$

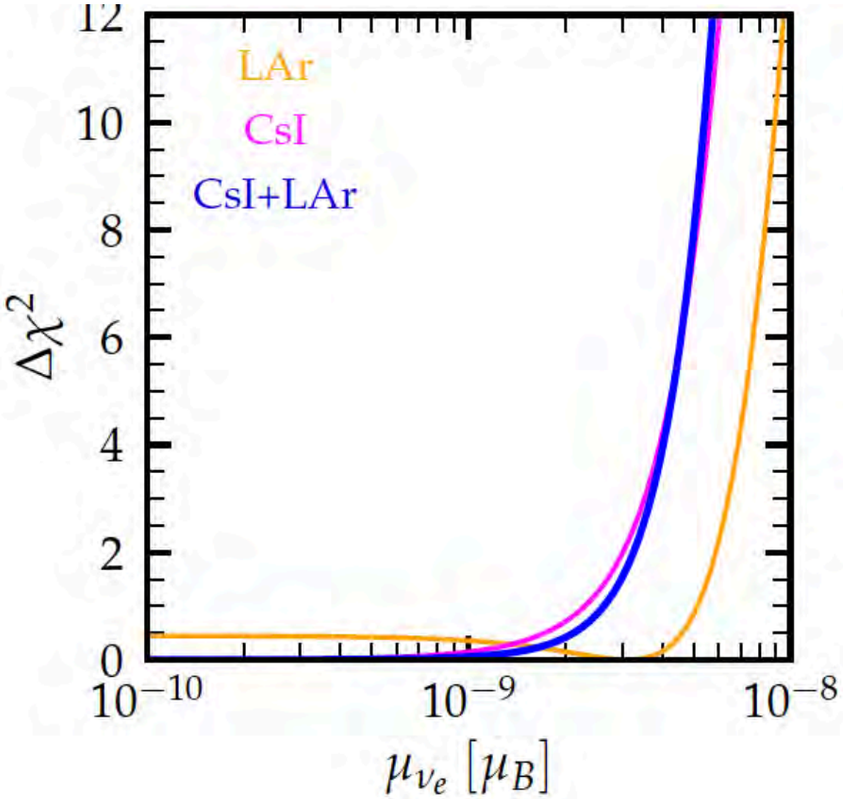
De Romeri et al, JHEP 2023

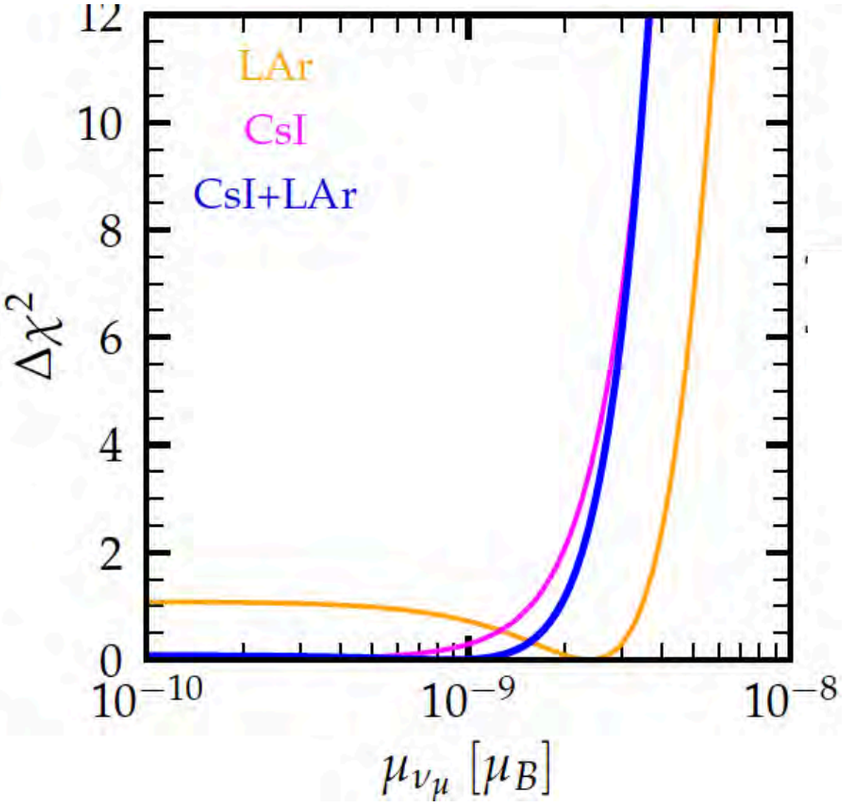


Neutrino magnetic moment

- Minimal SM extension (with m_ν) predicts $\mu_\nu \simeq 3 \times 10^{-19} \left(\frac{m_\nu}{\mathrm{eV}}\right) \mu_B$ ➡ larger in BSM
- The (effective) neutrino magnetic moment gives extra contribution to CEvNS cross section:

$$\left.\frac{d\sigma_{\nu_\ell \mathcal{N}}}{dE_{\mathrm{nr}}}\right|_{\mathrm{CE\nu NS}}^{\mathrm{MM}} = \frac{\pi \alpha_{\mathrm{EM}}^2}{m_e^2}\left(\frac{1}{E_{\mathrm{nr}}} - \frac{1}{E_\nu}\right) Z^2 F_W^2(|\vec{q}|^2) \left|\frac{\mu_{\nu_\ell}}{\mu_{\mathrm{B}}}\right|^2$$





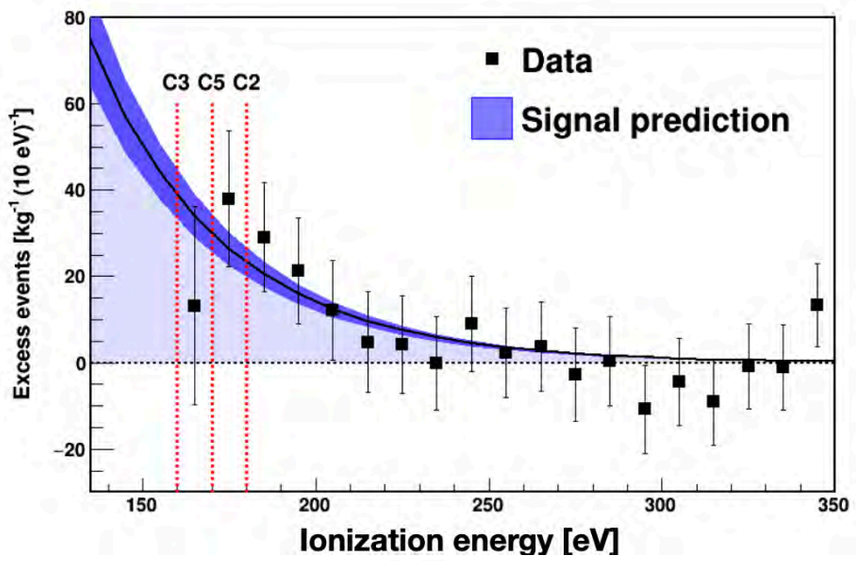
90% C.L. limits

$$\mu_{\nu_e} < 3.6\ (3.8) \times 10^{-9}\ \mu_B$$
$$\mu_{\nu_\mu} < 2.4\ (2.6) \times 10^{-9}\ \mu_B$$

Limits from reactor CEvNS data

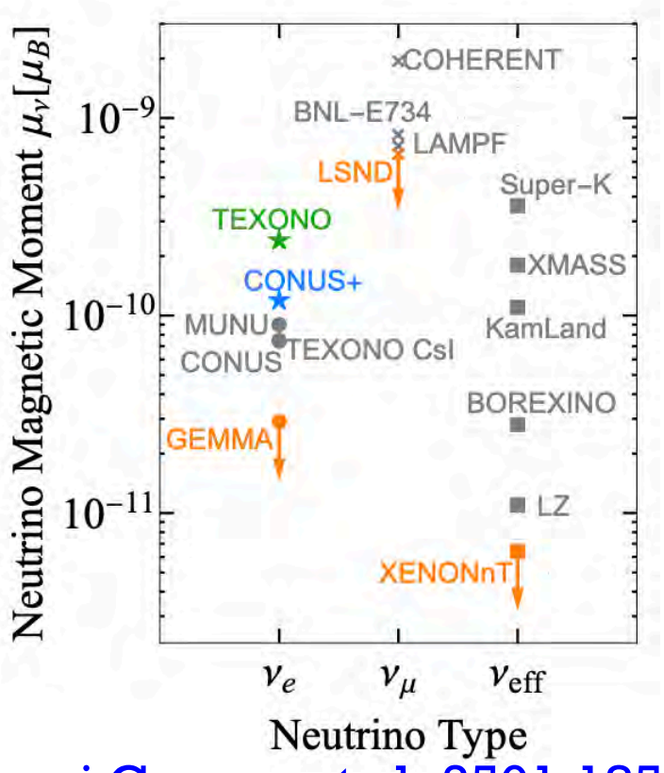
CONUS+

CONUS+ Collaboration, 2501.05206



Bounds on neutrino magnetic moment (90% CL)

$$\mu_{\nu_e}^{\text{eff}} \leq 4.78 \times 10^{-10}\ \mu_B \qquad (\text{CE}\nu\text{NS only})\,,$$
$$\mu_{\nu_e}^{\text{eff}} \leq 1.10 \times 10^{-10}\ \mu_B \qquad (\text{CE}\nu\text{NS} + \text{E}\nu\text{ES})$$

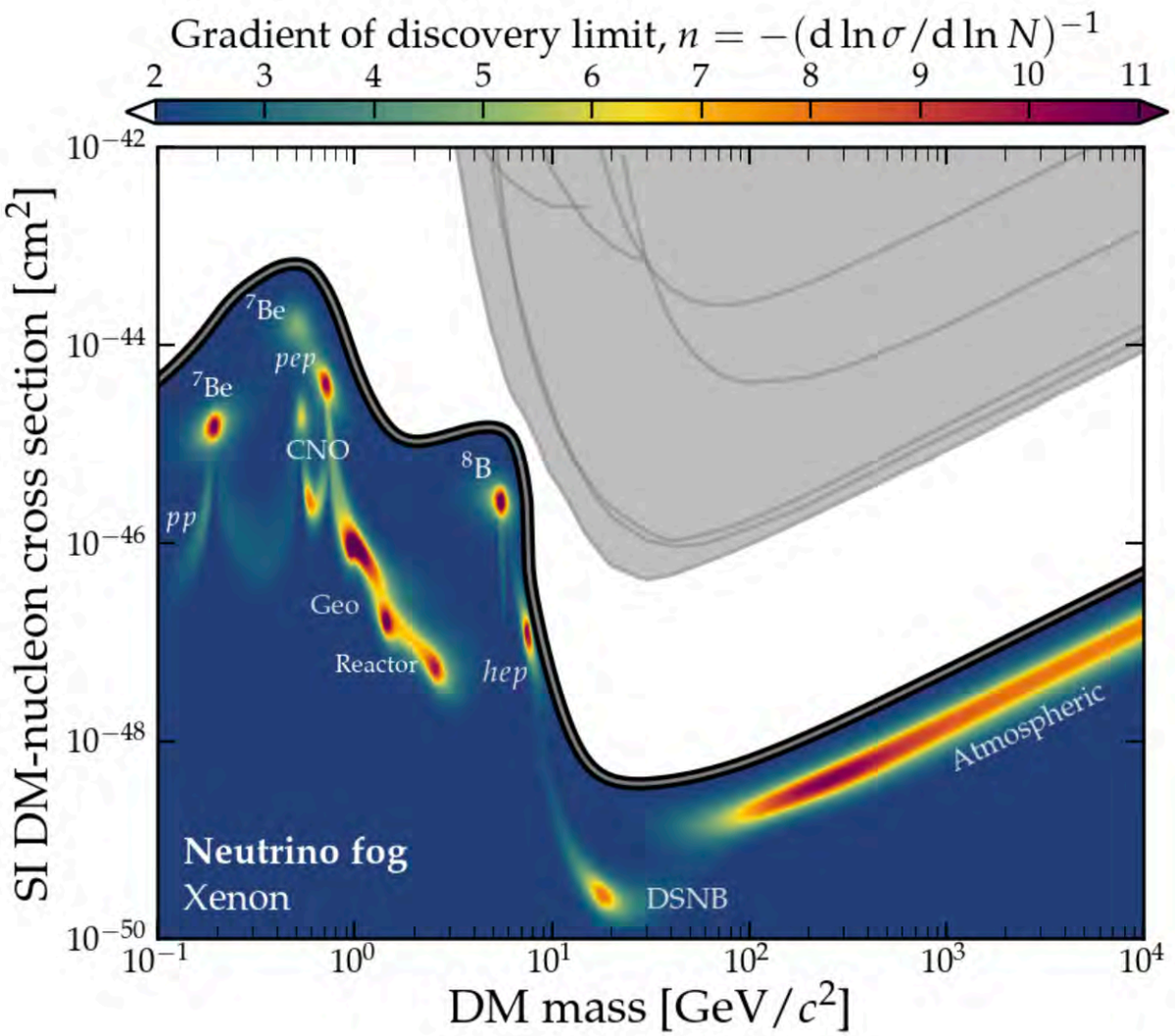


De Romeri et al, 2501.17843

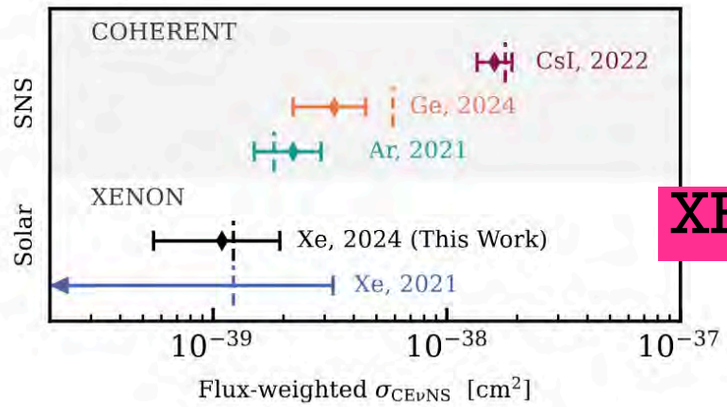
Atzori Corona et al, 2501.18550

Limits from the first solar CEvNS data

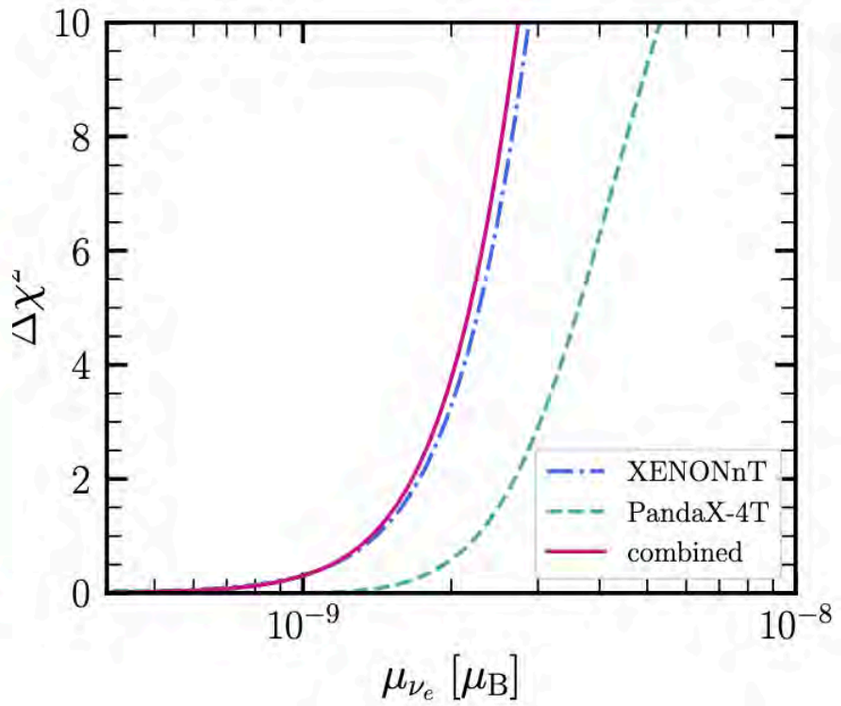
2024: **XENONnT** and **PandaX-4T** have observed CEvNS induced by 8B solar neutrinos scattering off xenon nuclei in their detectors.



O'Hare PRL 127 (2021) 251802



XENONnT



90% C.L. limits

$\mu_{\nu_e} < 1.9 \times 10^{-9} \mu_B$

$\mu_{\nu_\mu} < 1.8 \times 10^{-9} \mu_B$

De Romeri et al, 2412.14991

EvES at Dark Matter Experiments

EvES = elastic neutrino-electron scattering

Experiment	$\lvert\mu_{\nu_e}\rvert$ $[10^{-12}\mu_B]$	$\lvert\mu_{\nu_{\mu/\tau}}\rvert$ $[10^{-12}\mu_B]$	$\lvert\mu_\nu^{eff}\rvert$ $[10^{-12}\mu_B]$
PandaX-4T	< 38.7	< 58.6	< 28.3
LZ	< 17.1	< 25.9	< 12.5
XENONnT	< 11.5	< 17.5	< 8.4
combined	< 10.3	< 15.6	< 7.5

Giunti, Ternes, 2309.17380, PRD 2023

- Previous bounds obtained from solar data in **Borexino**:

$$\mu_{\nu_e} < 3.7 \times 10^{-11}\mu_B\,, \qquad \mu_{\nu_\mu} < 5.0 \times 10^{-11}\mu_B\,, \qquad \mu_{\nu_\tau} < 5.9 \times 10^{-11}\mu_B$$

  - ➡ surpassed by dark matter direct detection experiments.

- Current stronger limit from astrophysical observations:

$$\mu_\nu < 1.5 \times 10^{-12}\mu_B \text{ (95\% CL)}$$

Capozzi, Raffelt, 2007.03694, PRD 2020

CPT violation in ν oscillations ??

Violation of CPT symmetry

- CPT is presently observed as an exact symmetry of nature.

PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1, 1956

Question of Parity Conservation in Weak Interactions*

T. D. LEE, *Columbia University, New York, New York*

AND

C. N. YANG,† *Brookhaven National Laboratory, Upton, New York*

(Received June 22, 1956)

Parity violation in weak interactions?

Experimental Test of Parity Conservation in Beta Decay*

C. S. WU, *Columbia University, New York, New York*

AND

E. AMBLER, R. W. HAYWARD, D. D. HOPPES, AND R. P. HUDSON, *National Bureau of Standards, Washington, D. C.*

(Received January 15, 1957)

→ **P** violated: what about **CP**?

VOLUME 13, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1964

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§

Princeton University, Princeton, New Jersey

(Received 10 July 1964)

→ Evidence for **CP** violation

Is **CPT** conserved?

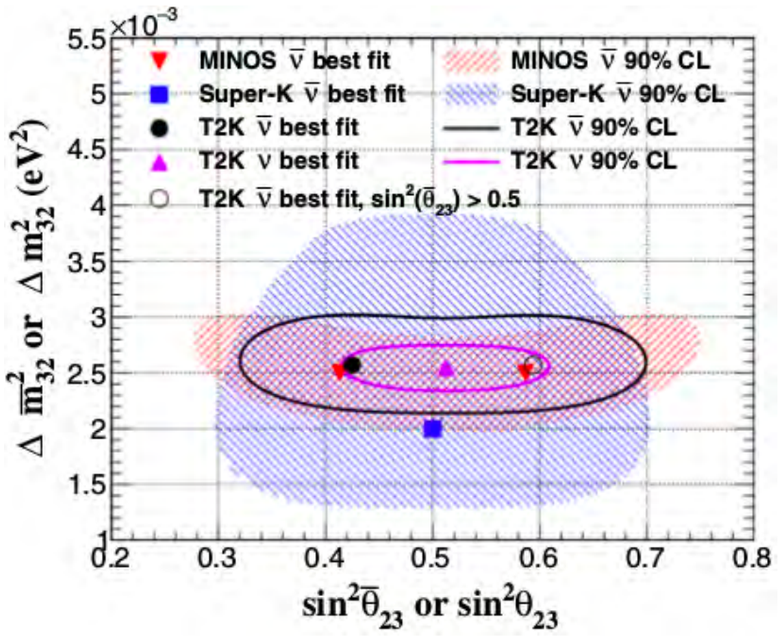
If not: $$P(\nu_\alpha \to \nu_\beta) \neq P(\overline{\nu}_\beta \to \overline{\nu}_\alpha)$$

Neutrino oscillation data can be used to constrain CPT violation at the neutrino sector

CPT in neutrino oscillations

- Test hypothesis: neutrino and antineutrino oscillations are ruled by different parameters: $(\Delta m^2_{ji}, \theta_{ij}, \delta)$ **vs** $(\overline{\Delta m^2_{ji}}, \overline{\theta_{ij}}, \overline{\delta})$

- Separate neutrino and antineutrino analysis in T2K



T2K Coll, PRD2017

$$\sin^2\theta_{23} = 0.51, \quad \Delta m^2_{32} = 2.53 \times 10^{-3}\text{eV}^2$$
$$\sin^2\overline{\theta}_{23} = 0.42, \quad \Delta \overline{m}^2_{32} = 2.55 \times 10^{-3}\text{eV}^2$$

→ different best fit values

→ consistent with CPT conservation

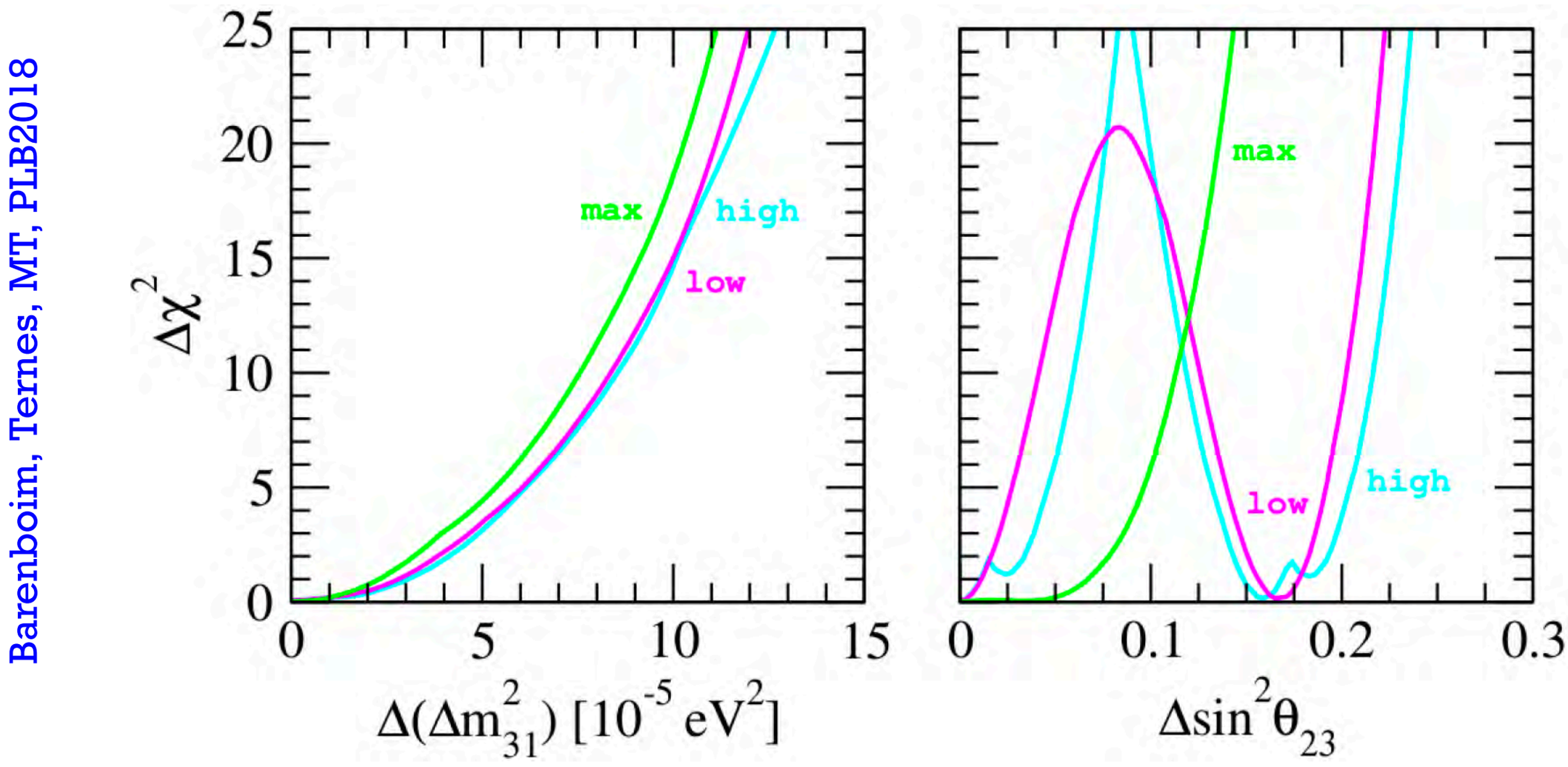
- Current bounds at 3σ:

$$|\Delta m^2_{21} - \Delta\overline{m}^2_{21}| < 3.7 \times 10^{-5}\ \text{eV}^2 \qquad |\sin^2\theta_{12} - \sin^2\overline{\theta}_{12}| < 0.187,$$
$$|\Delta m^2_{31} - \Delta\overline{m}^2_{31}| < 2.5 \times 10^{-4}\ \text{eV}^2 \qquad |\sin^2\theta_{13} - \sin^2\overline{\theta}_{13}| < 0.029,$$
$$|\sin^2\theta_{23} - \sin^2\overline{\theta}_{23}| < 0.19,$$

Barenboim, Ternes, MT, PLB2018 - Barenboim, Martinez-Miravé,Ternes, MT, PRD2023

CPT in neutrino oscillations

- DUNE sensitivity analysis to differences in atmospheric parameters



→ one order of magnitude improvement:

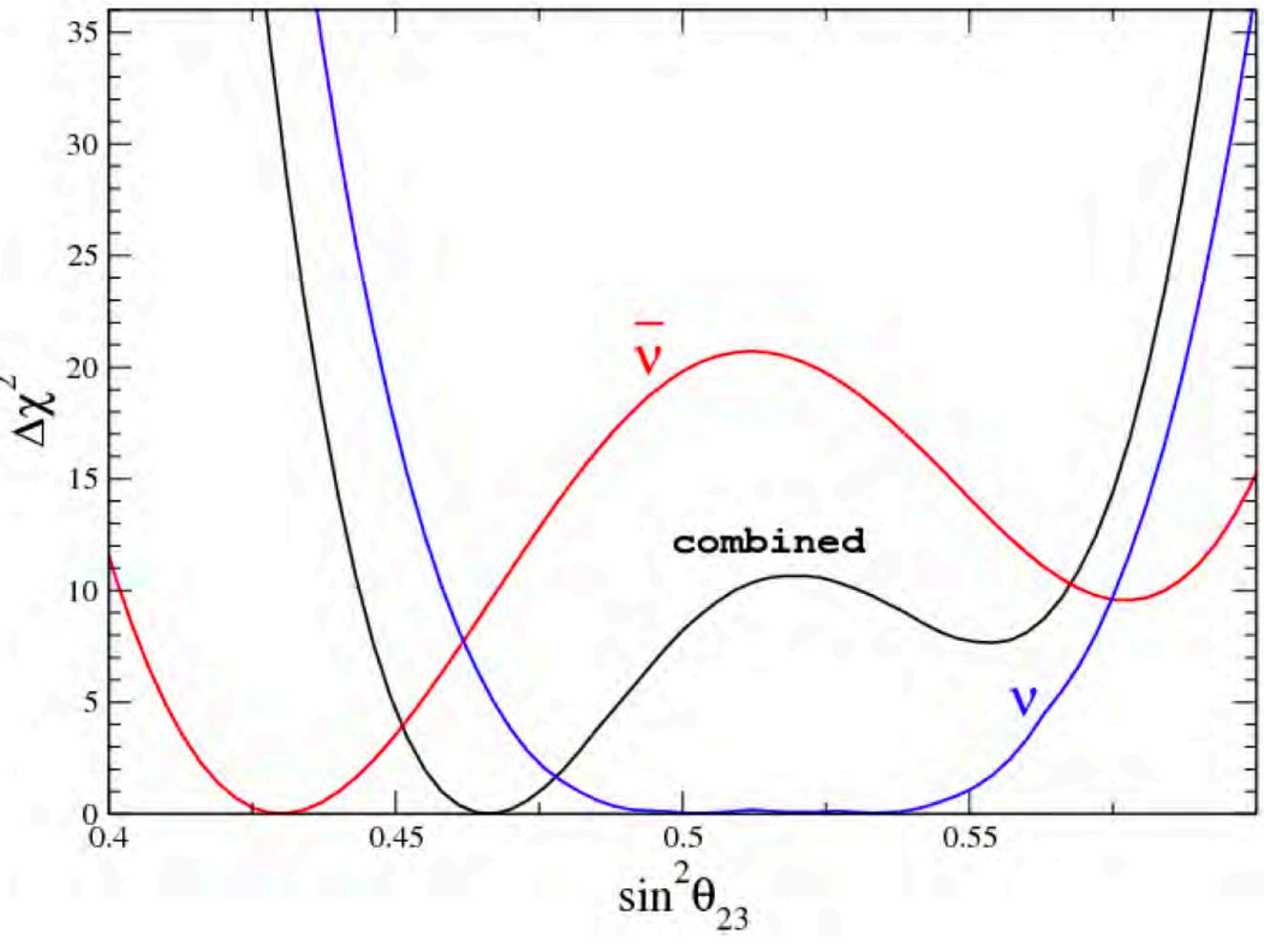
$$\Delta(\Delta m^2_{31}) < 8.1 \times 10^{-5}\text{eV}^2 \quad (3\sigma)$$

→ excellent sensitivity for max mixing

→ oscillating results for high and low octant due to degeneracies

~~CPT~~ oscillations: imposter solutions

- Standard analyses of oscillation data assume CPT conservation
- If CPT is violated one can obtain imposter solutions
- Ex: DUNE neutrino data simulated with $\sin^2\theta_{23} = 0.5\,, \sin^2\overline{\theta}_{23} = 0.43$



→ the combined analysis under CPT conservation gives the best fit value:

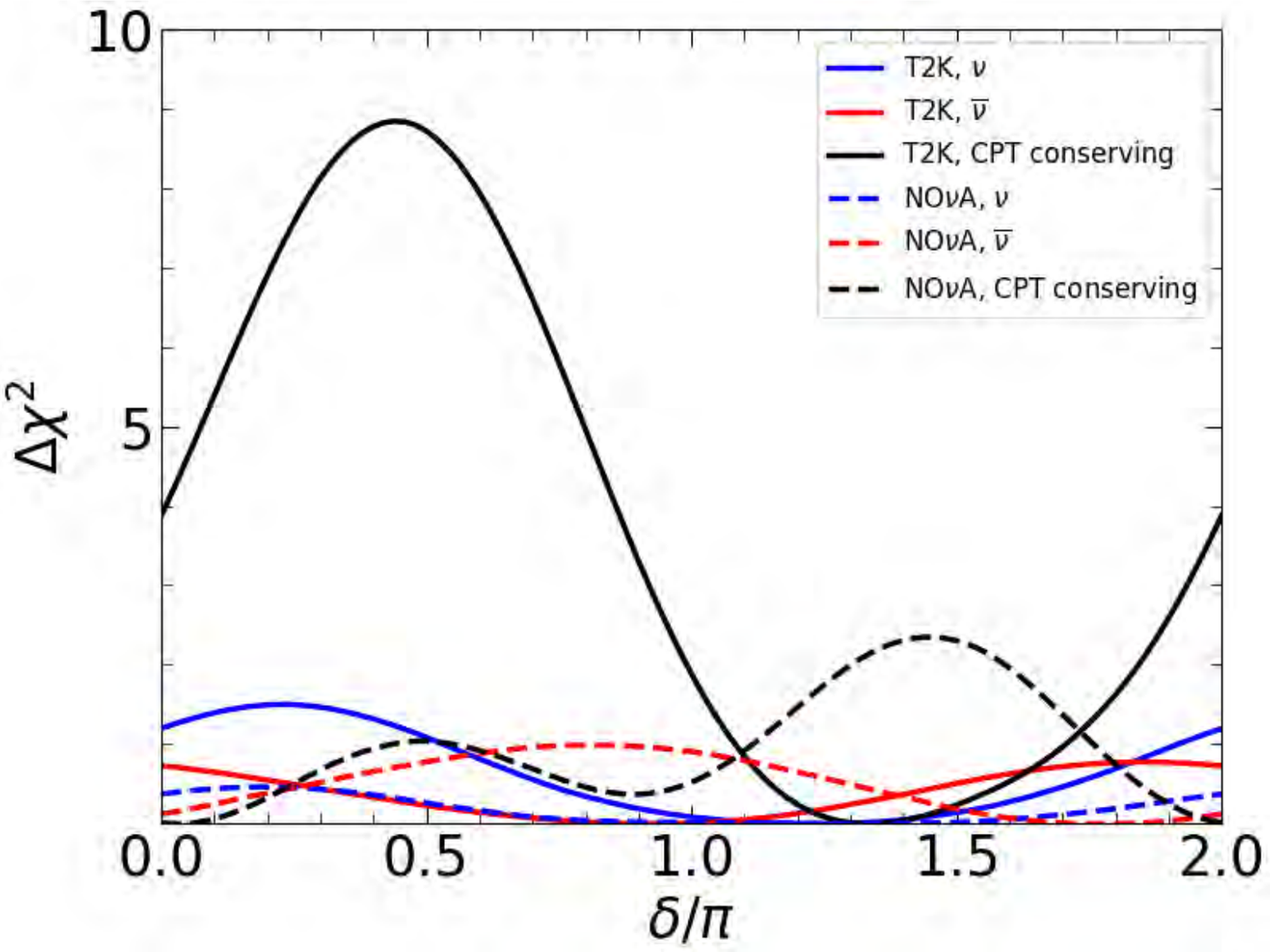
$$\sin^2\theta_{23}^{\rm comb} = 0.467$$

→ real true values disfavored at close to 3σ (neutrino) and more than 5σ (antineutrino)

Barenboim, Ternes, MT, PLB2018

The T2K-NOvA δ_{CP} tension

CPT-violating analysis of T2K and NOvA (normal ordering)



- the tension appears only in the $\bar{\nu}$ channel, with less sensitivity
- all values of δ and $\bar{\delta}$ remain allowed at $\sim 1\sigma$
- $\theta_{13} \neq \bar{\theta}_{13}$ can account for different behavior in neutrino and antineutrino channels

$\Rightarrow$ very poor sensitivity on CP violation compared to CPT-conserving scenario

Barenboim, Ternes, MT, JHEP2020