Review WG4: Low energy neutrino phenomenology

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COST Action CA18108
(QG-MM) meeting

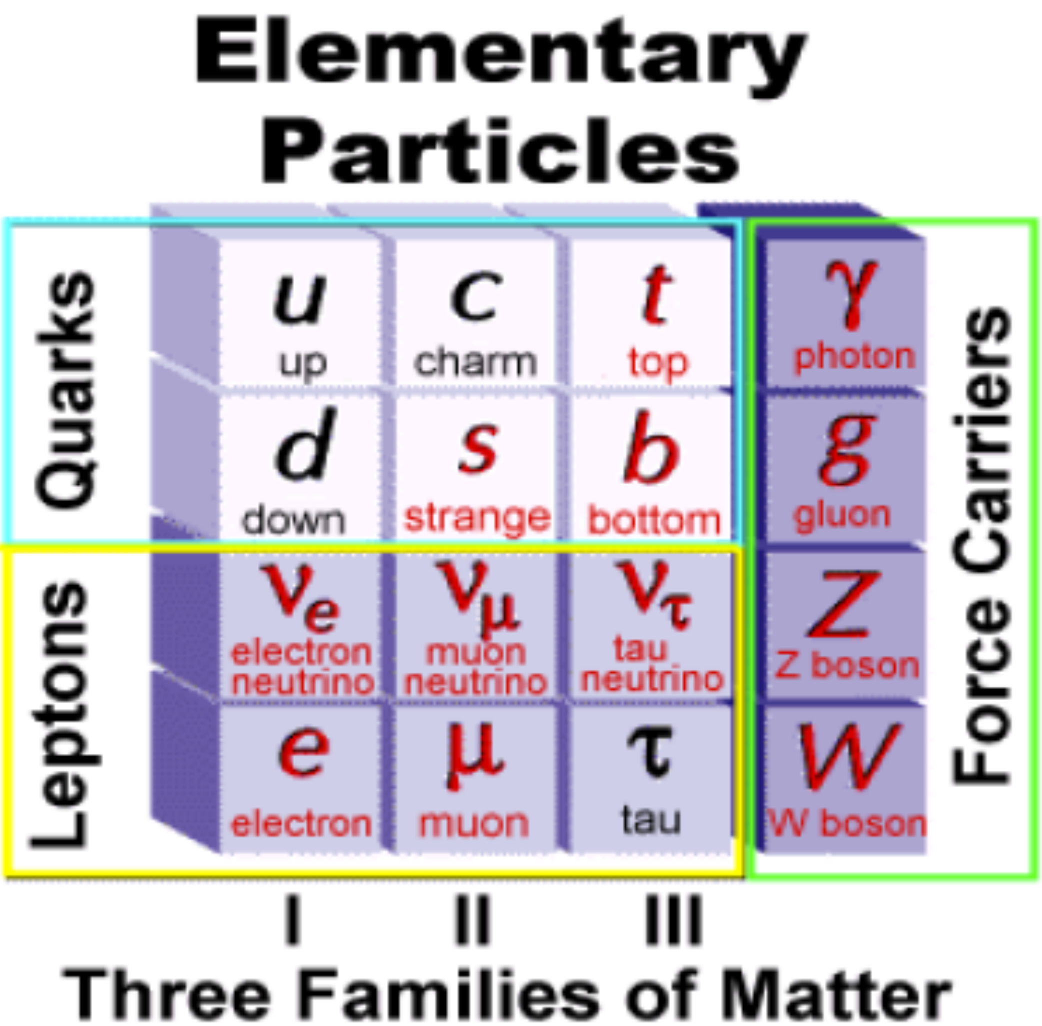
2–4 October 2019
Barcelona, Spain

Outline

- Introduction to neutrino physics
- Three-flavour neutrino oscillations
- Beyond the three-neutrino scenario
- The Standard Model Extension (SME)
  - ✓ Lorentz invariance violation
  - ✓ CPT invariance violation

Introduction to neutrino physics

Neutrinos in the Standard Model



✦ neutrinos come in 3 flavours, corresponding to the charged lepton associated

✦ they belong to SU(2) lepton doublets

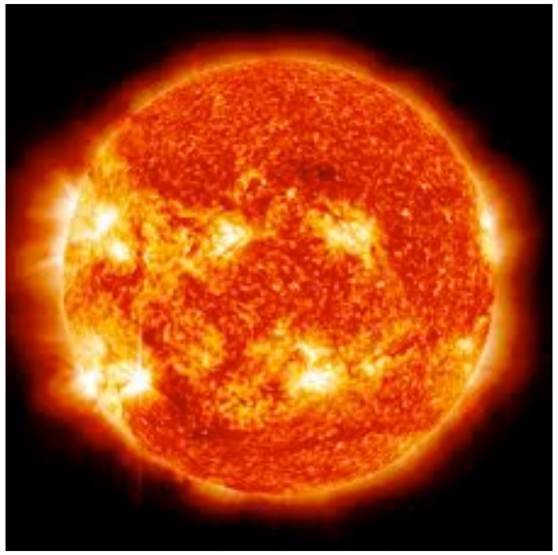
$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L , \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$$

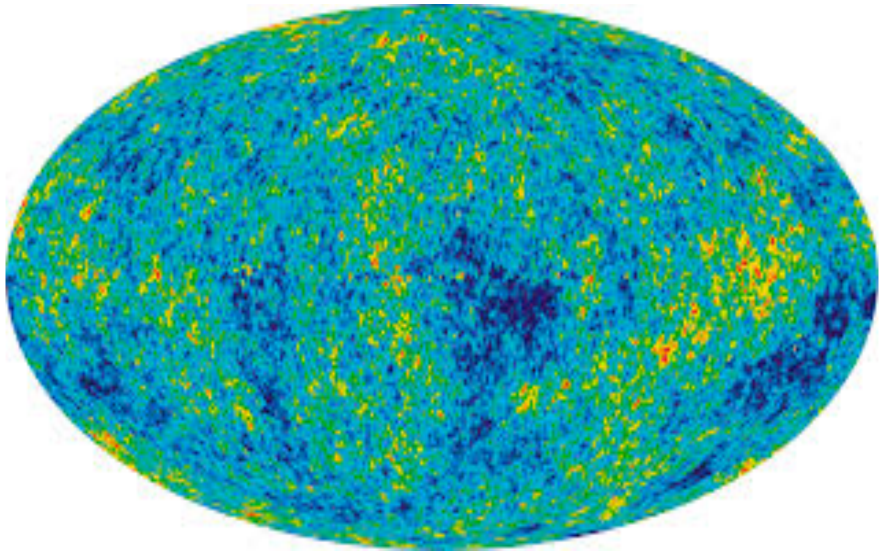
✦ There are no SU(2) neutrino singlets (alike e_R, μ_R, τ_R): neutrinos are left handed and antineutrinos right handed

✦ Neutrinos are massless in the SM: there is no mechanism to implement neutrino masses

Why neutrinos are so important?

- they can probe environments that other techniques cannot: SN explosions, core of the Sun,…
- their role is crucial for the evolution of the universe (Big Bang Nucleosynthesis, structure formation)
- they could help explaining the matter-antimatter asymmetry of the Universe (leptogenesis mechanism)
- they could be a component of the dark matter of the universe.
- they provide the first evidence for physics beyond the SM!!!



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However: there are still many open questions in neutrino physics

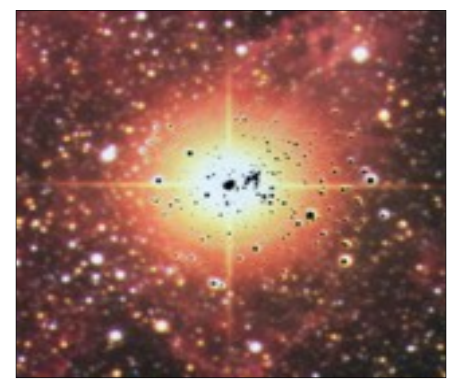
What we know about neutrinos

- We have observed neutrinos from a variety of sources

✓ Nuclear Reactors

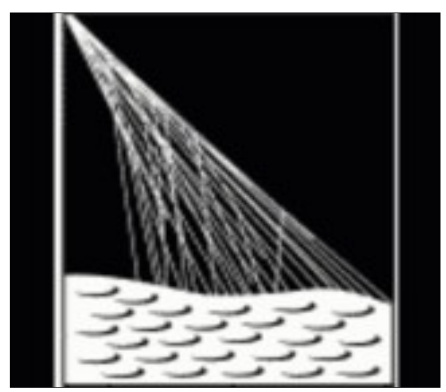
Sun ✓

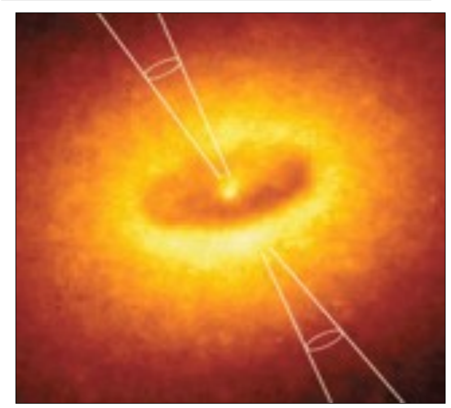
✓ Particle Accelerators



Supernova explosions
SN 1987A ✓

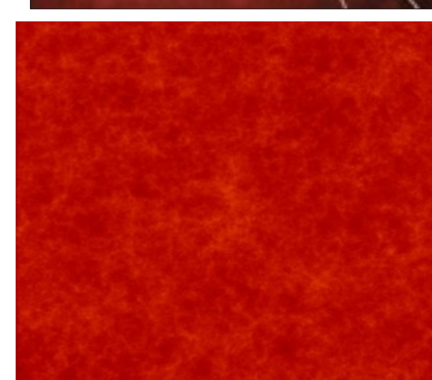
✓ Earth Atmosphere (Comic Rays)





Astrophysical Sources
TXS 0506 + 056 ✓

✓ Earth Crust (Natural Radioactivity)



Origin of Universe
Indirect evidence

What we know about neutrinos

- They are extremely abundant (9 orders of magnitude wrt p, e^-)

10.000 millions

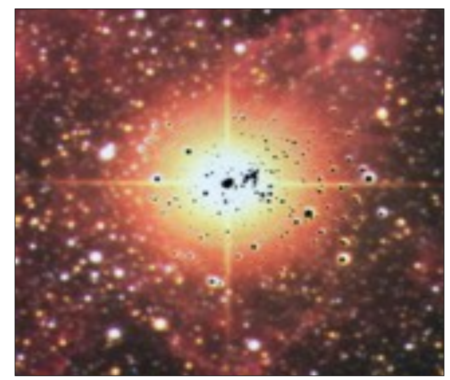
✓ Nuclear Reactors

600 billions

Sun ✓

✓ Particle Accelerators

CERN



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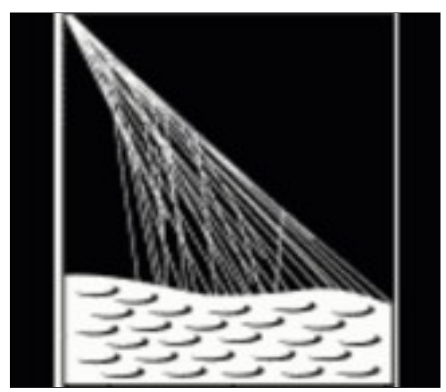

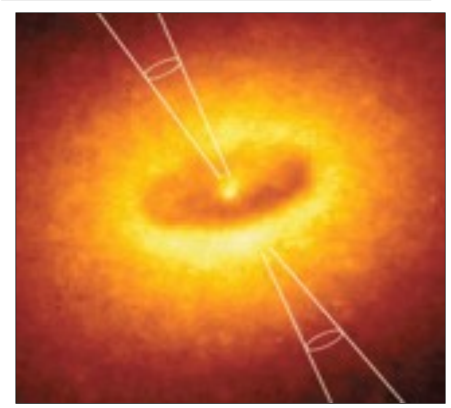

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50.000 millions

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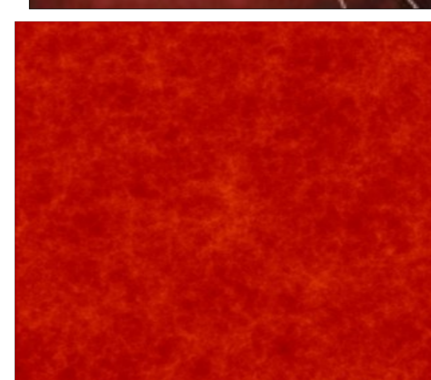

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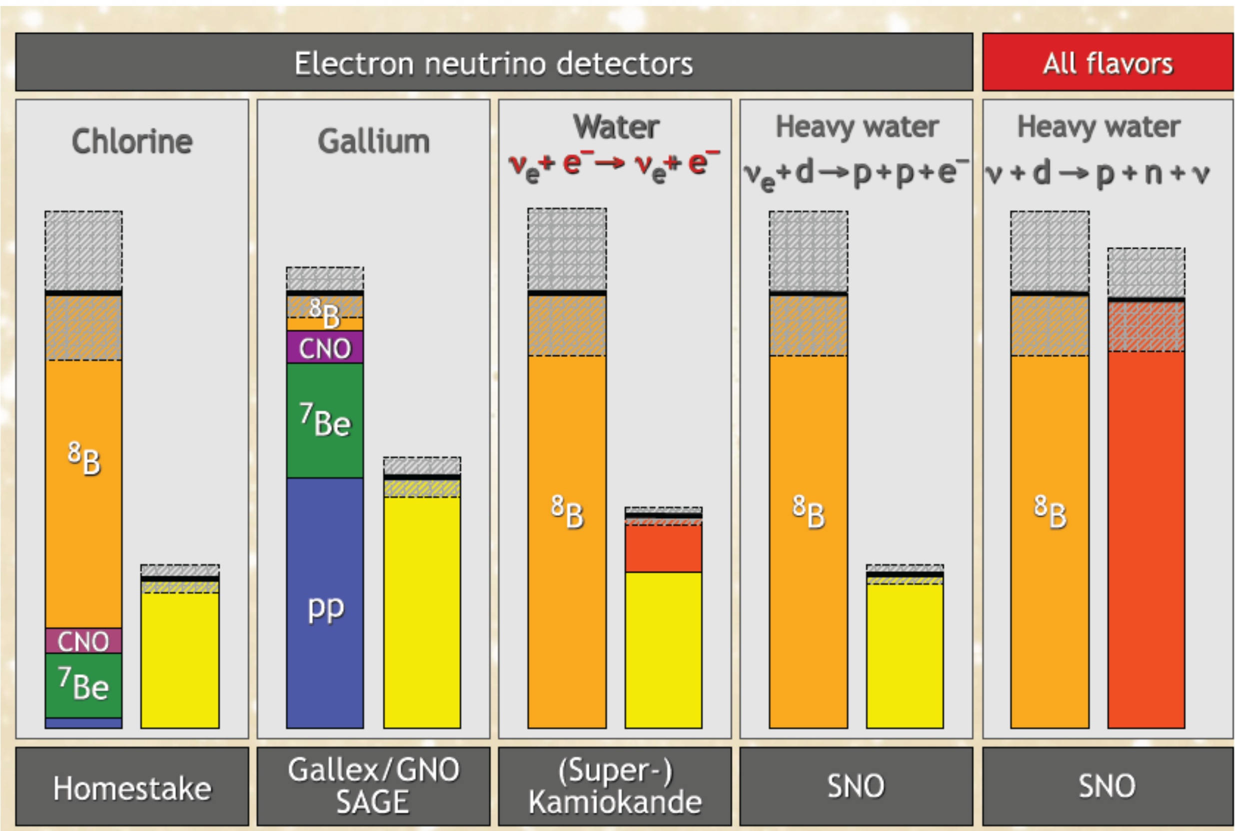
Solar ν anomaly



solar ν_e arrive to Earth as
$1/3\ \nu_e + 1/3\ \nu_\mu + 1/3\ \nu_\tau$

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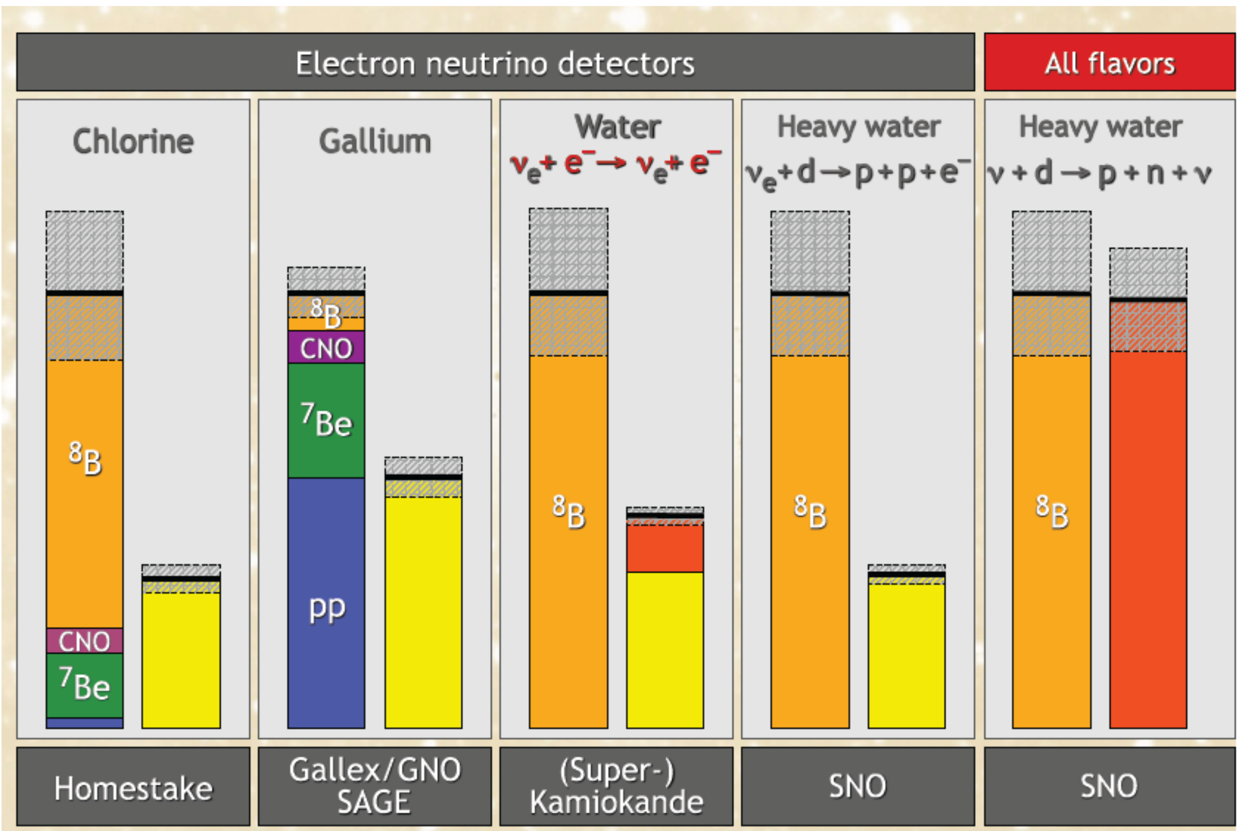

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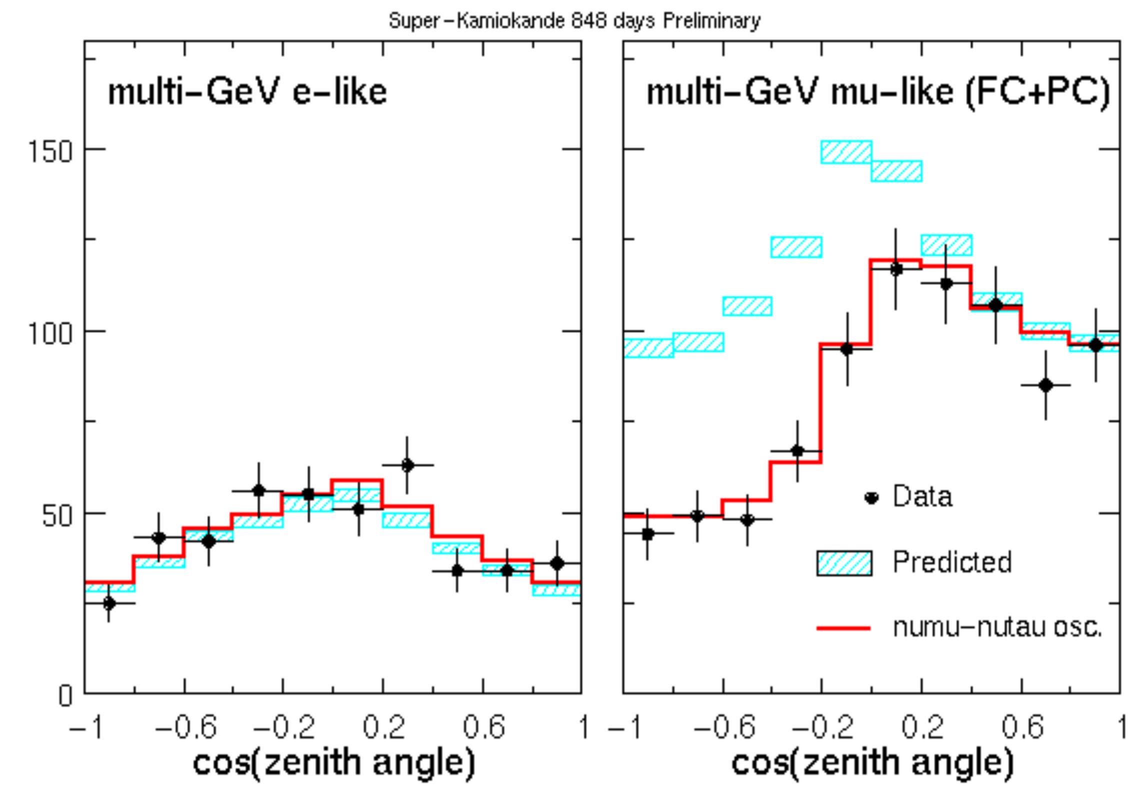

oscillation channel $\nu_\mu \rightarrow \nu_\tau$

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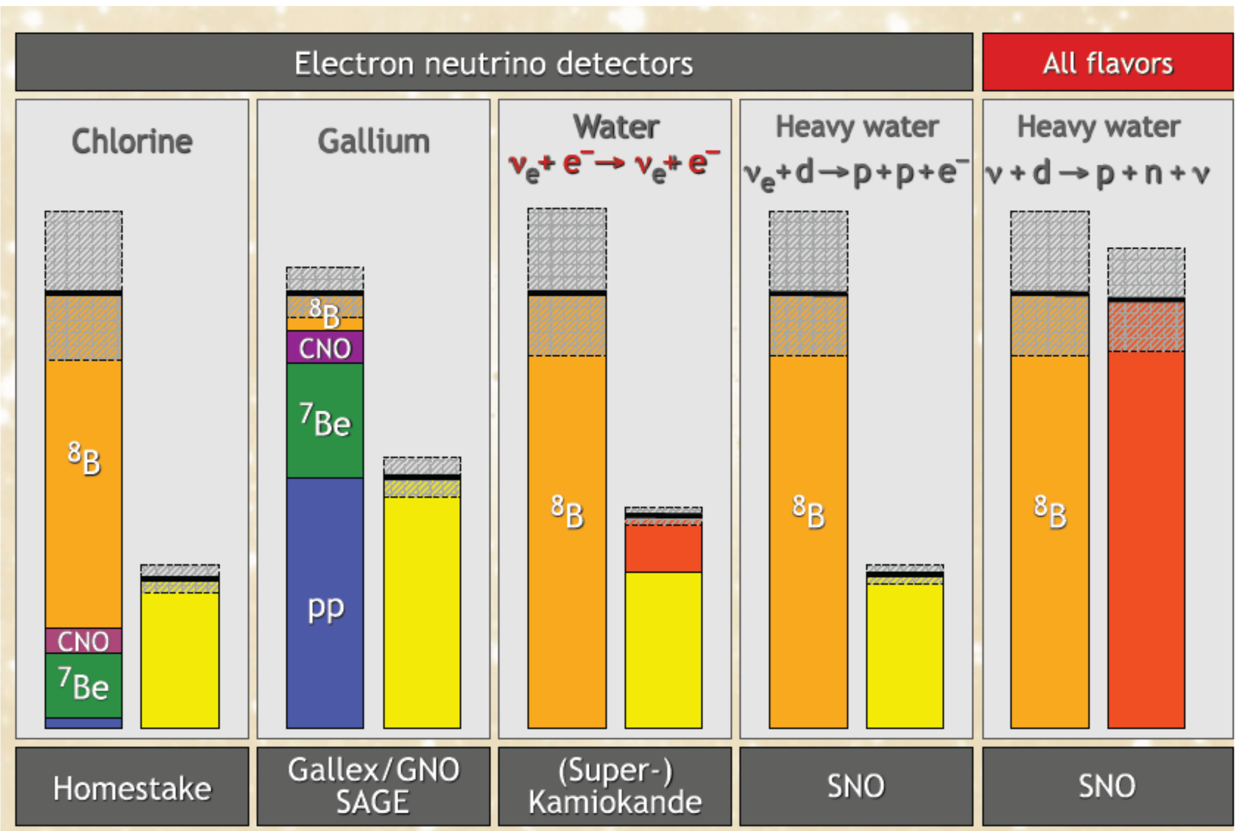

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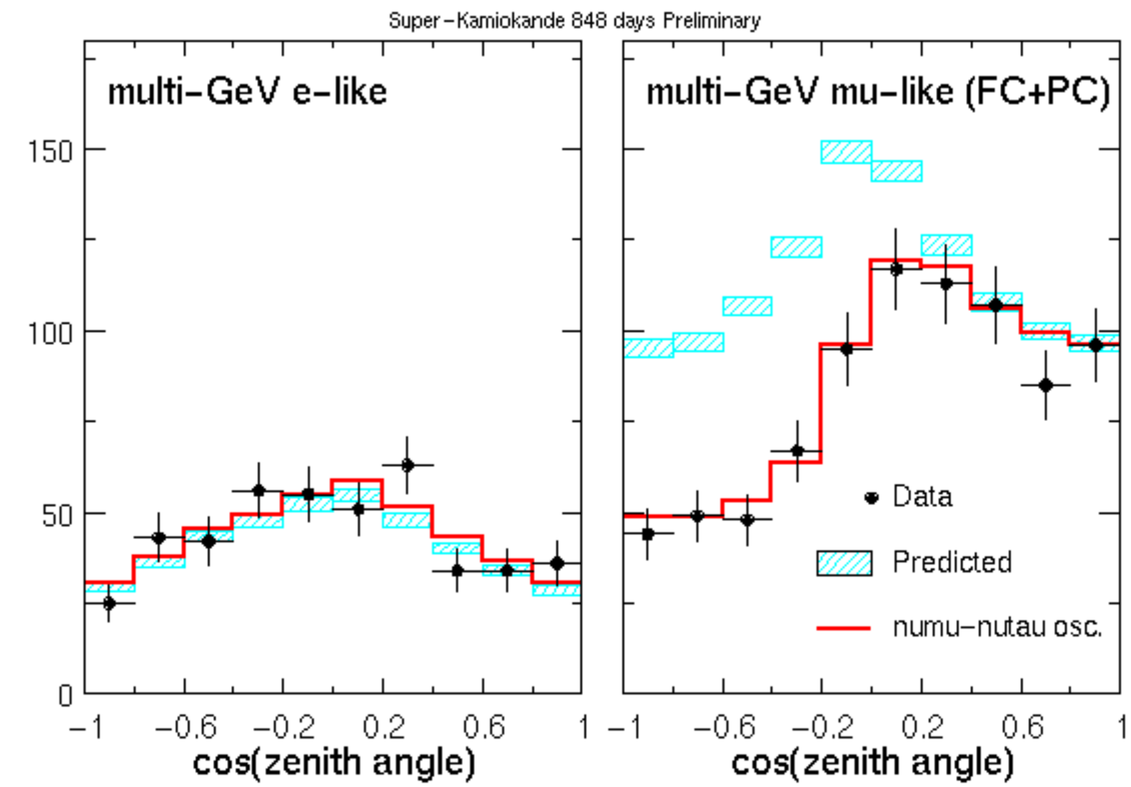

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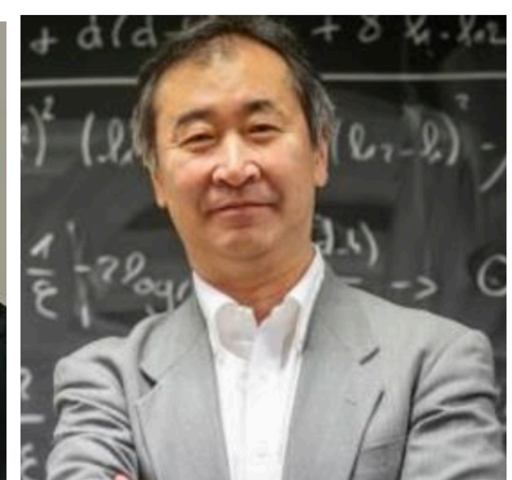

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2015 Nobel Prize in Physics

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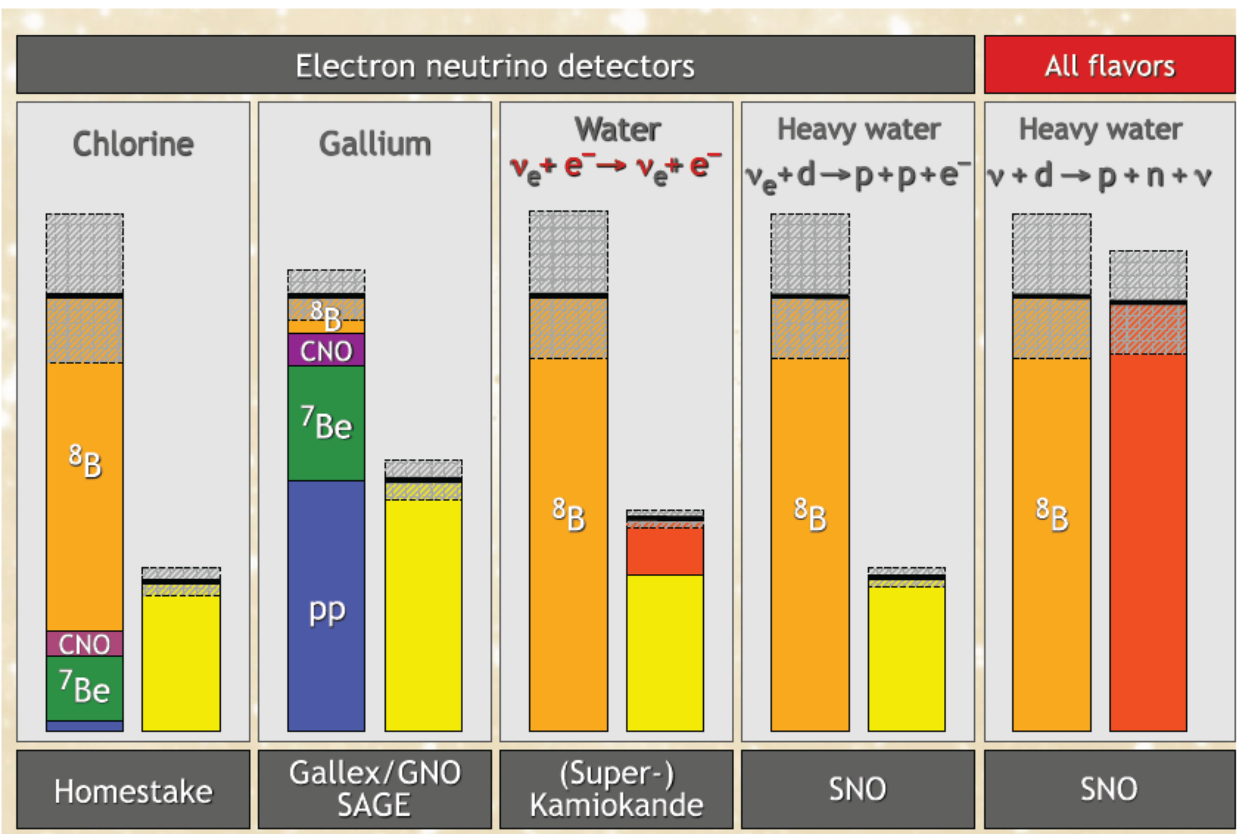

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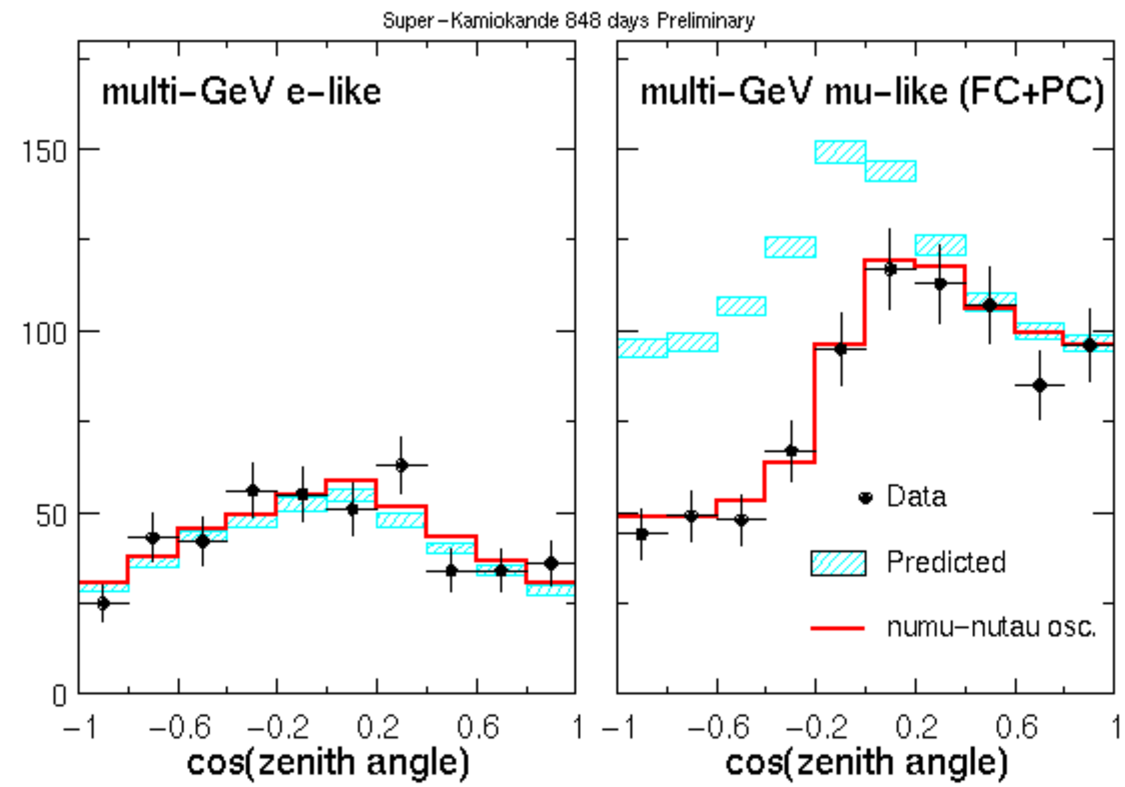

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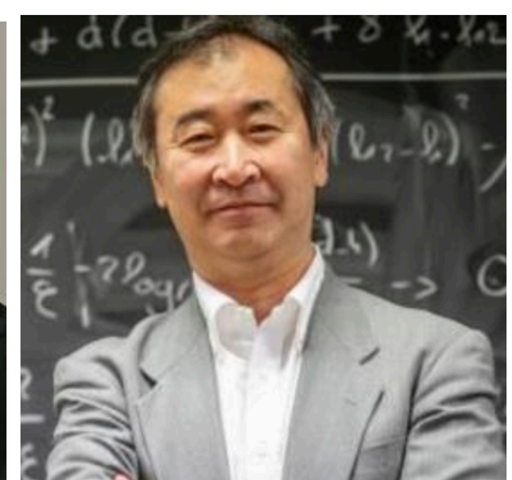

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Confirmed by KamLAND !!

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What we know about neutrinos

- Existence of flavour oscillations imply they are massive.

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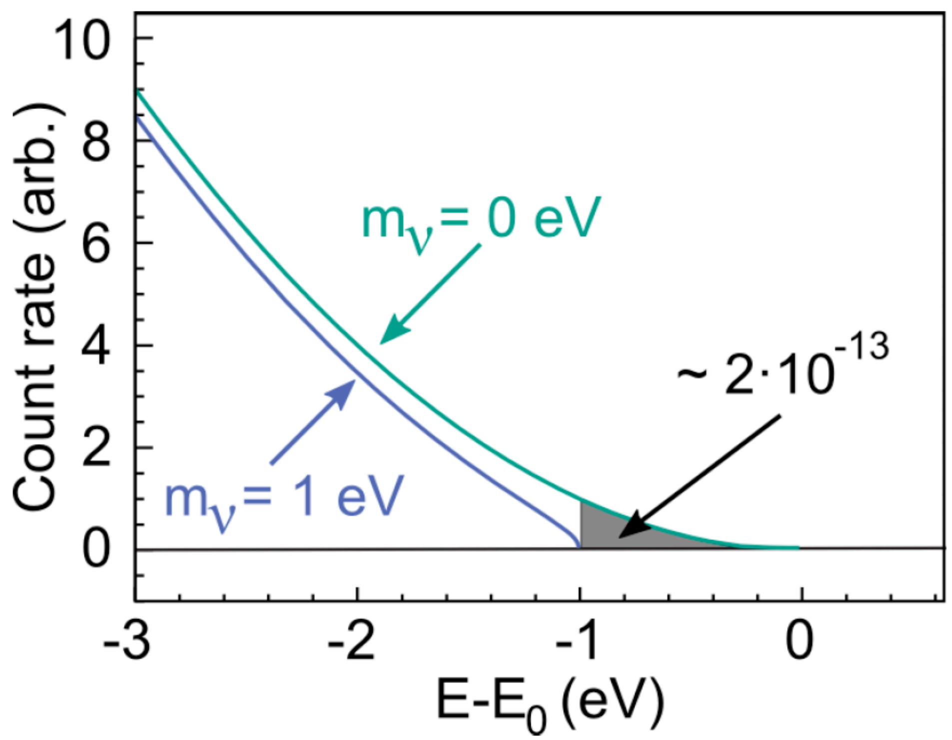
KATRIN (tritium decay)



$m_\nu < 1.1$ eV (90% C.L.)

KATRIN Collab, arXiv:1909.06048

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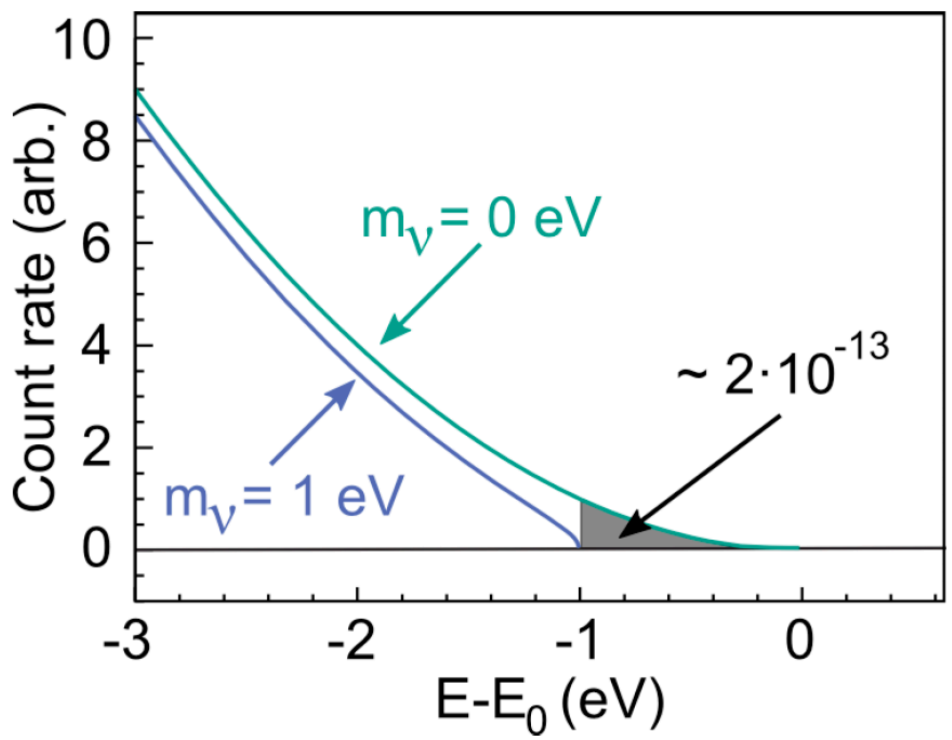

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Cosmological measurements

→ anisotropies in the CMB spectrum

→ Large Scale Structure formation

→ weak gravitational lensing

Fit ΛCDM model + experimental data (WMAP, PLANCK, HST, LSS,...)

$\Sigma\, m_{\nu i} < 0.14$- 0.72 eV (95% C.L.)

Lattanzi & Gerbino, arXiv:1712.07109

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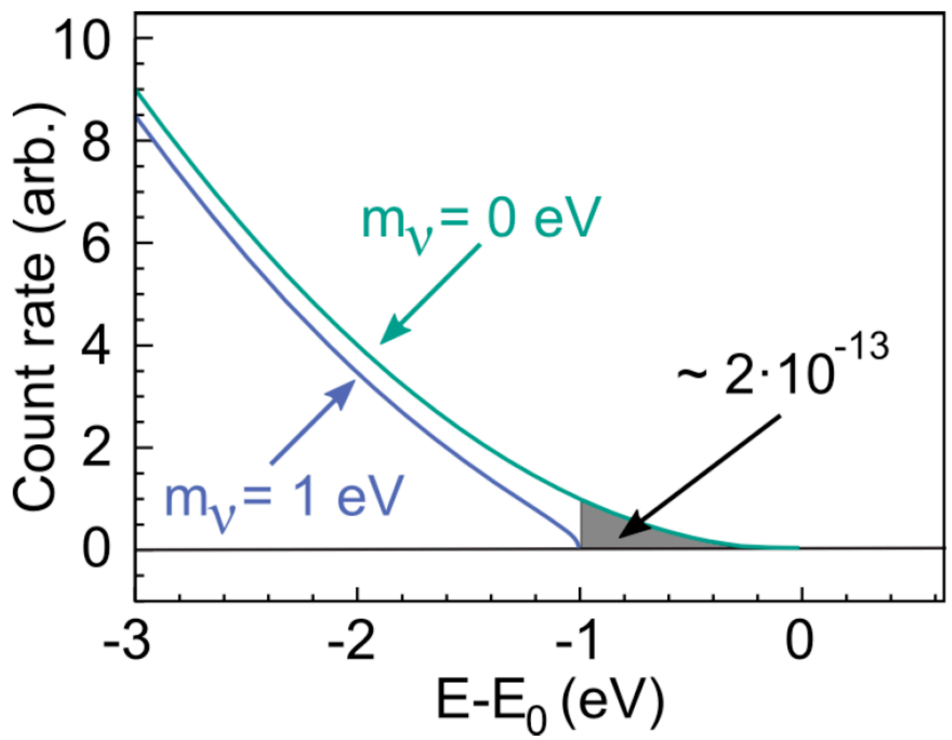

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0νββ decay

[M. Manganaro, Neutrino Exp]
[S. Stoica WG discussion]

Three-flavour neutrino oscillations

The 3-flavour ν picture

neutrino mixing

$$U_{3\times3} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

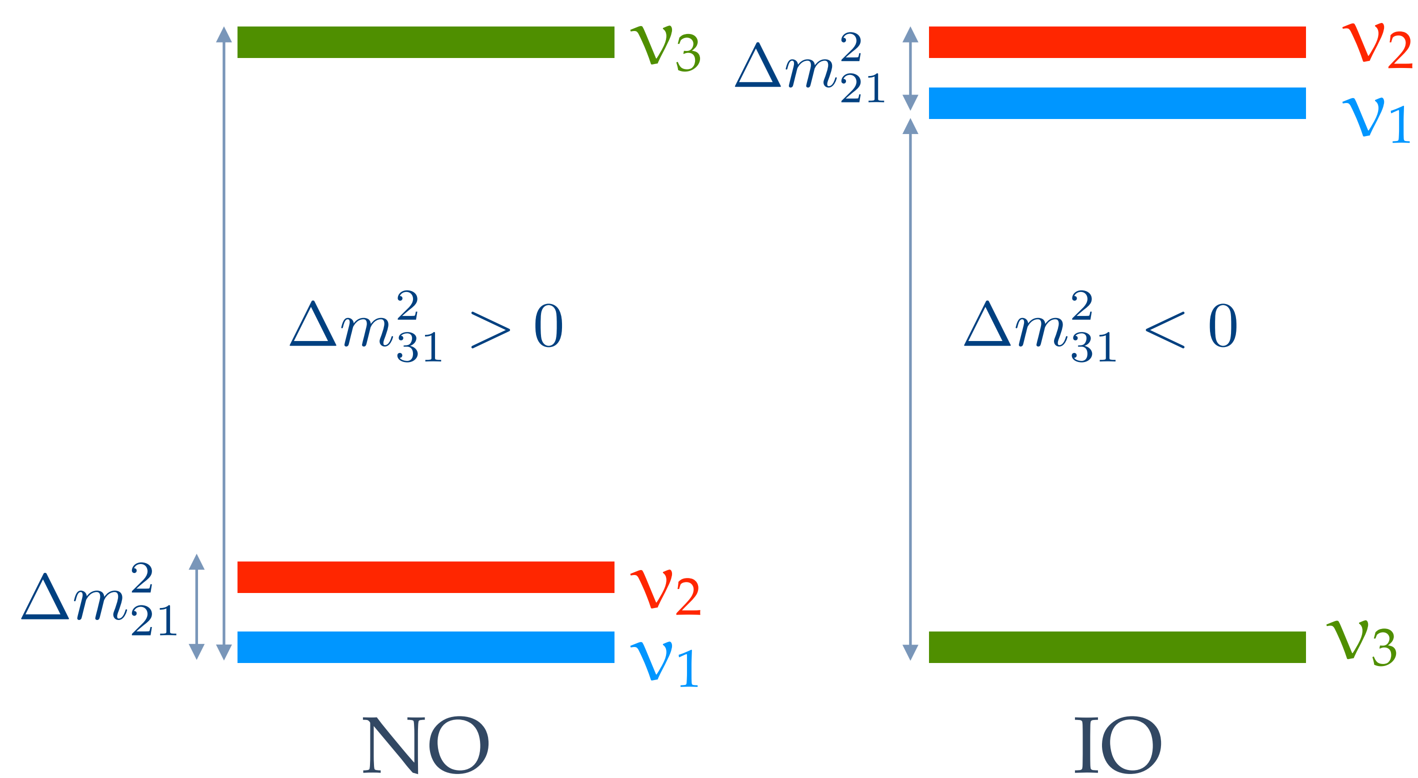
- ✓ 3 mixing angles: θ_{12}, θ_{23}, θ_{13}
- ✓ 3 CP phases: 1 Dirac + 2 Majorana
- ✓ 3 masses: m_1, m_2, m_3

⇒ absolute neutrino mass: m_0

⇒ two mass splittings:

$$\Delta m^2_{21}, \Delta m^2_{31}$$

neutrino mass spectrum



Three-neutrino mixing

✦ Currently, we have evidence for neutrino oscillations in atmospheric, solar, reactor and accelerator experiments

✦ Each experiment is sensitive to different mixing parameters:

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atmospheric + accelerator disapp	SBL reactor + accelerator app	solar + KamLAND
Δm^2_{31}	Δm^2_{31}	Δm^2_{21}

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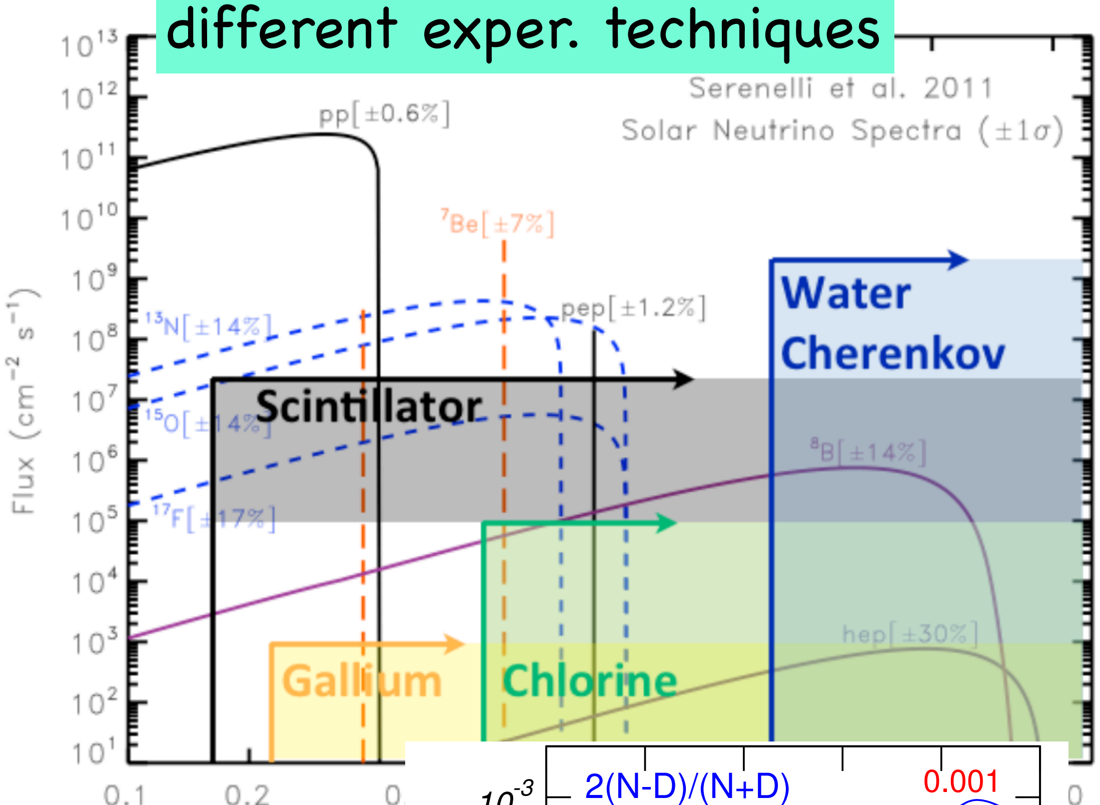
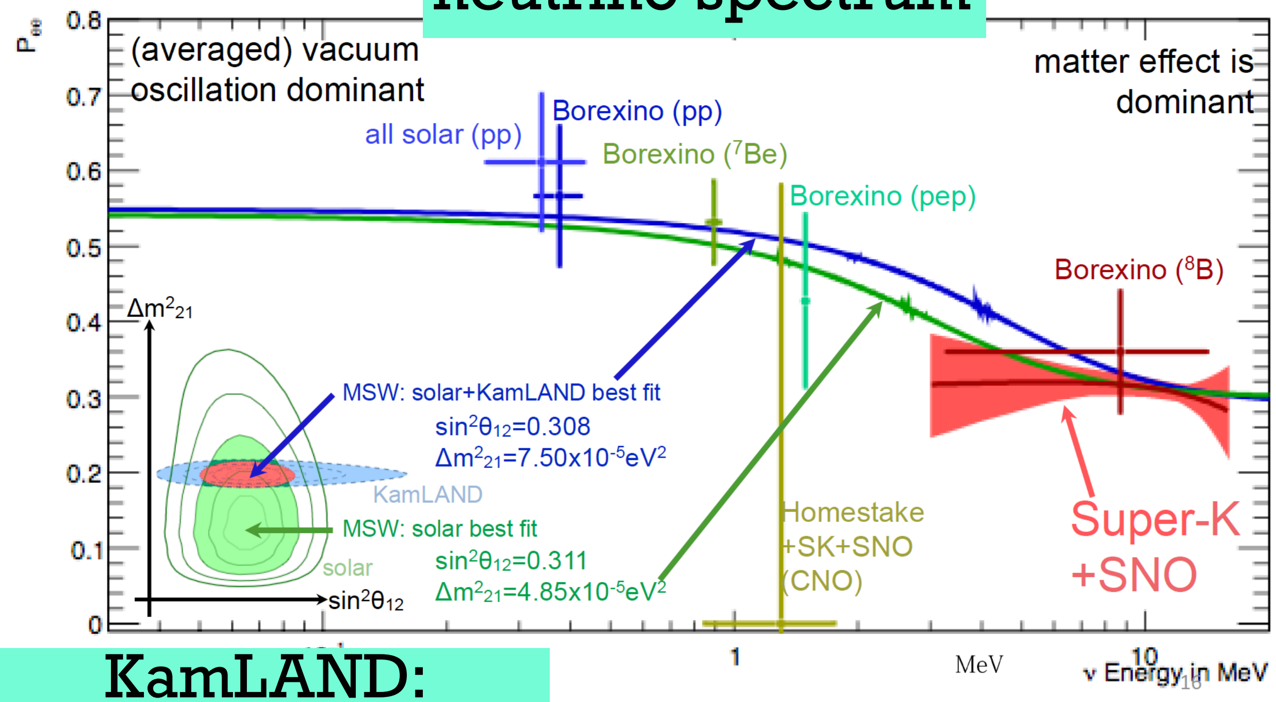
The solar neutrino sector

Solar experiments have measured neutrino disappearance for ~ 50 years

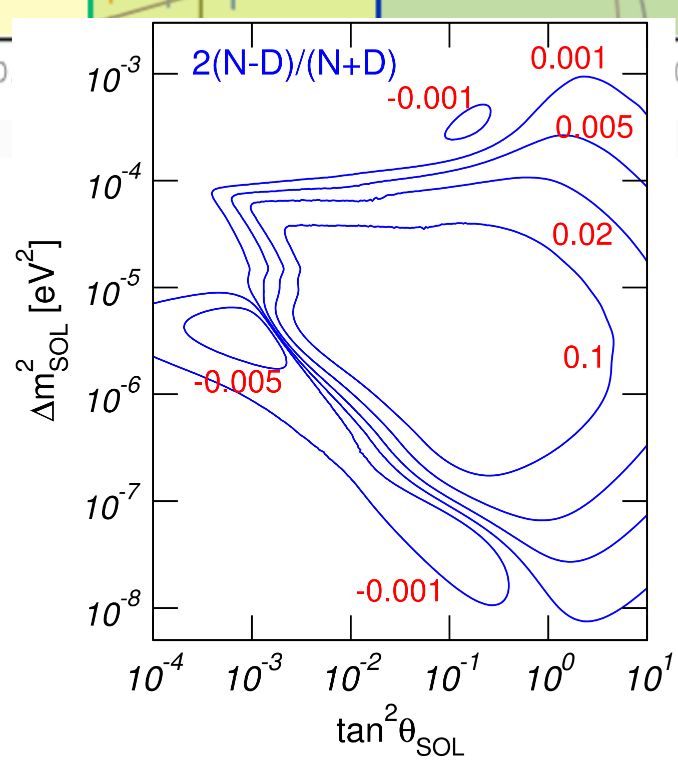
different exper. techniques



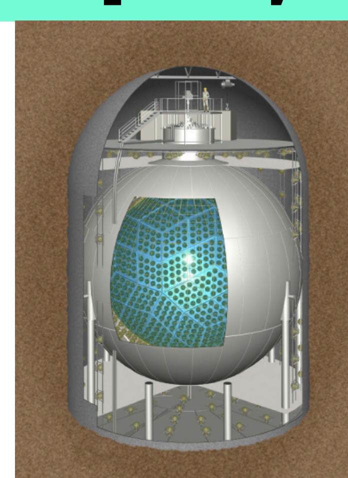
neutrino spectrum

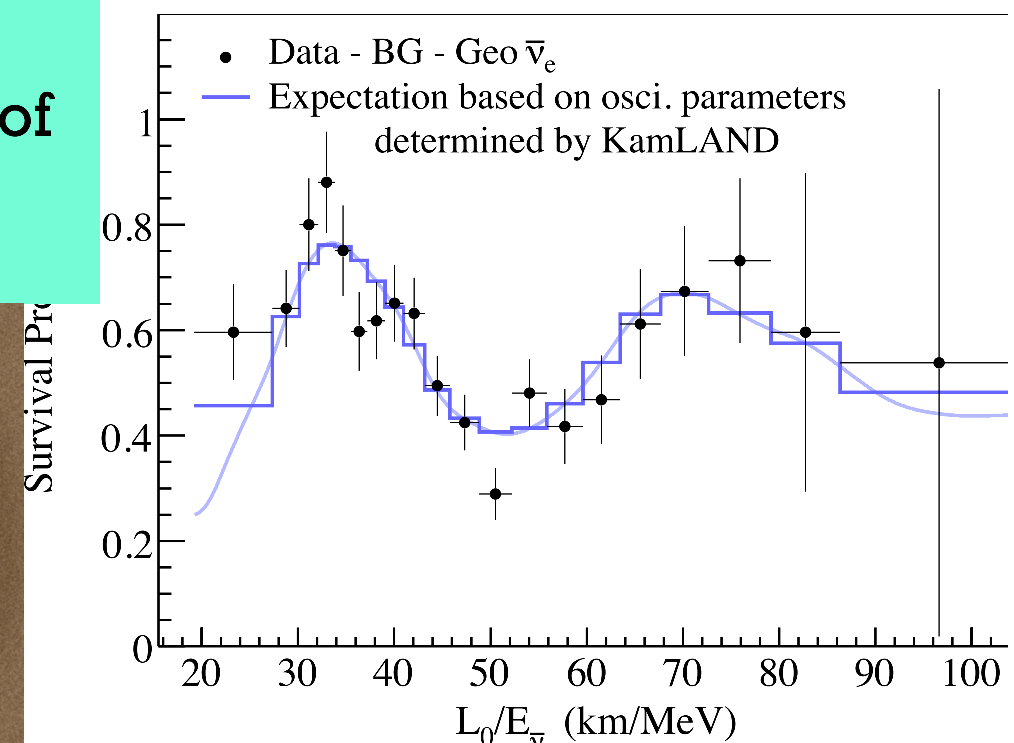


day/night asymmetry

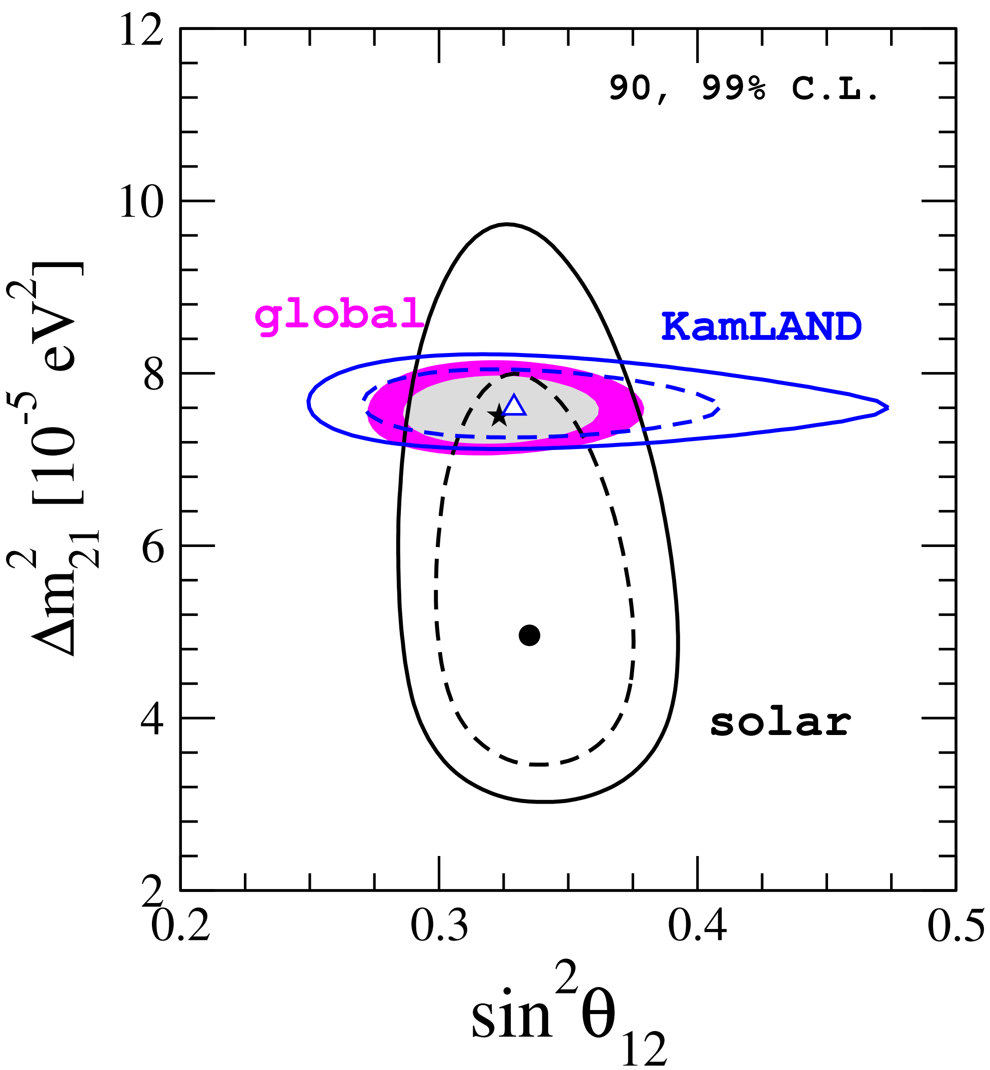


KamLAND: precise measurement of oscillation frequency





Combined analysis solar + KamLAND



- KamLAND confirms solar ν oscillations.
- Best fit point:

$$\sin^2\theta_{12} = 0.321^{+0.018}_{-0.016}$$

$$\Delta m^2_{21} = (7.56 \pm 0.19) \times 10^{-5}\ \mathrm{eV}^2$$

- max. mixing excluded at more than 7σ

de Salas et al, PLB782 (2018) 633

➡ Bound on θ_{12} dominated by solar data.

➡ Bound on Δm^2_{21} dominated by KamLAND.

➡ mismatch between Δm^2_{21} from solar and KamLAND

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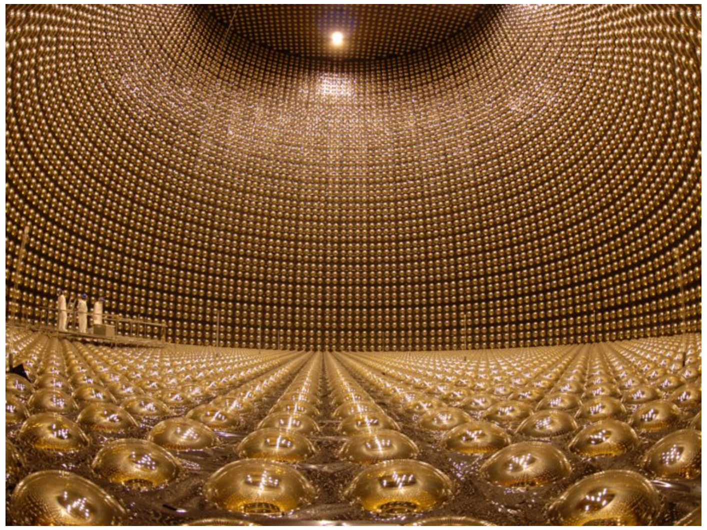
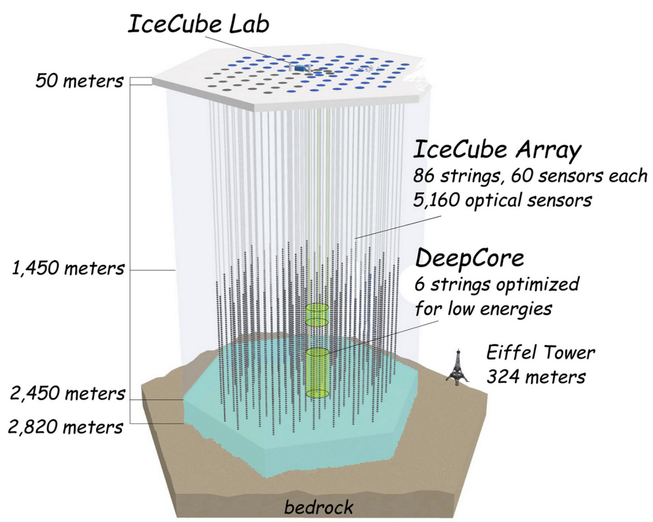
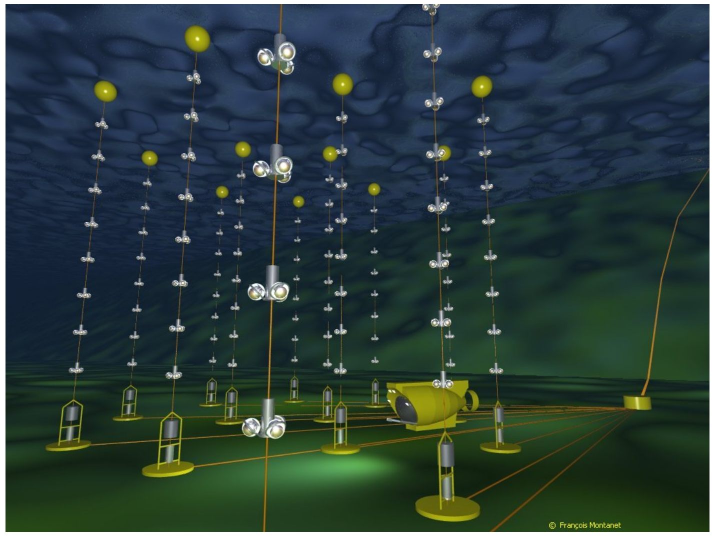
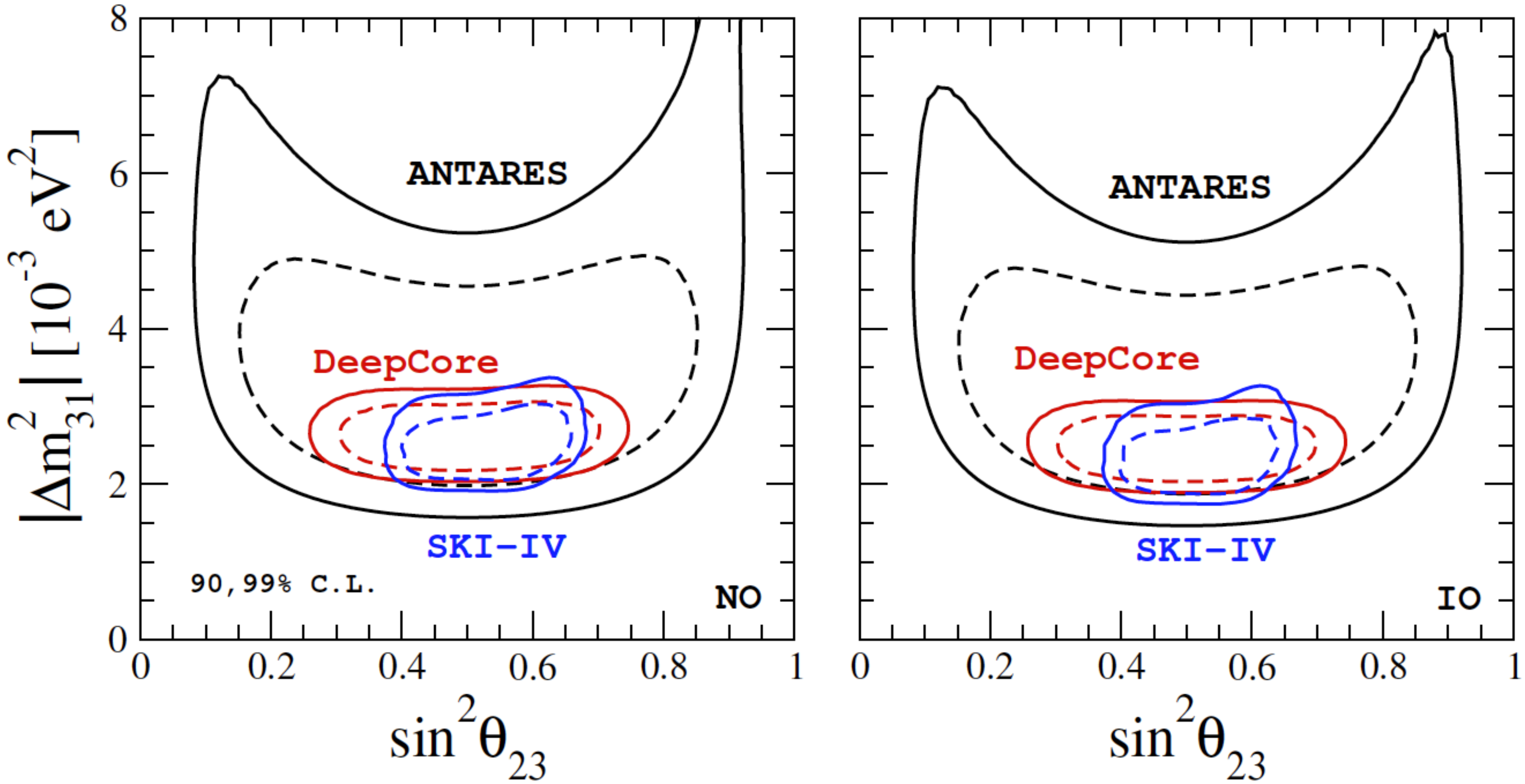
Atmospheric experiments









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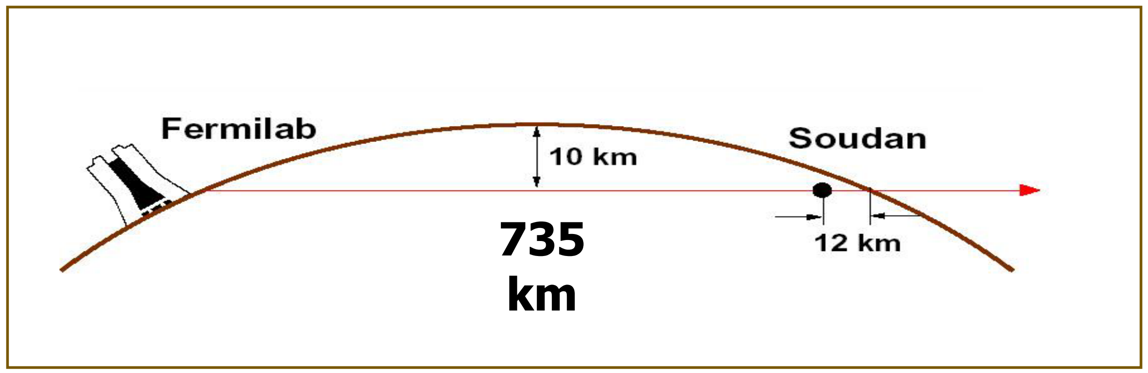
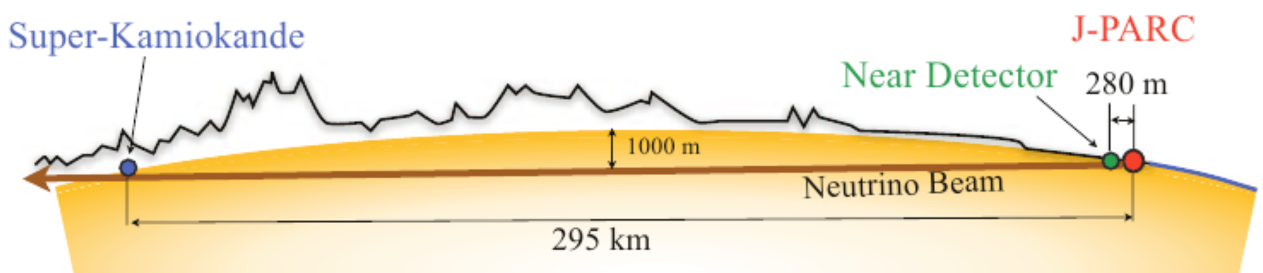
LBL accelerator experiments

MINOS



Feb2005 - Jun2016

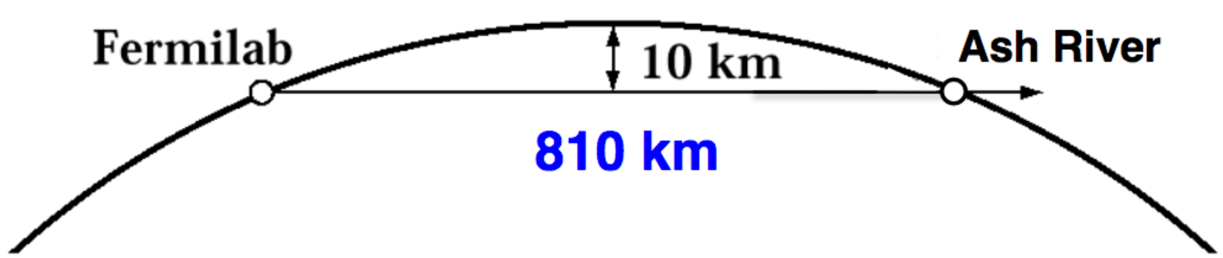
T2K



From Jan2010

now running in antineutrino channel

NOvA



From Oct2014

now running in antineutrino channel

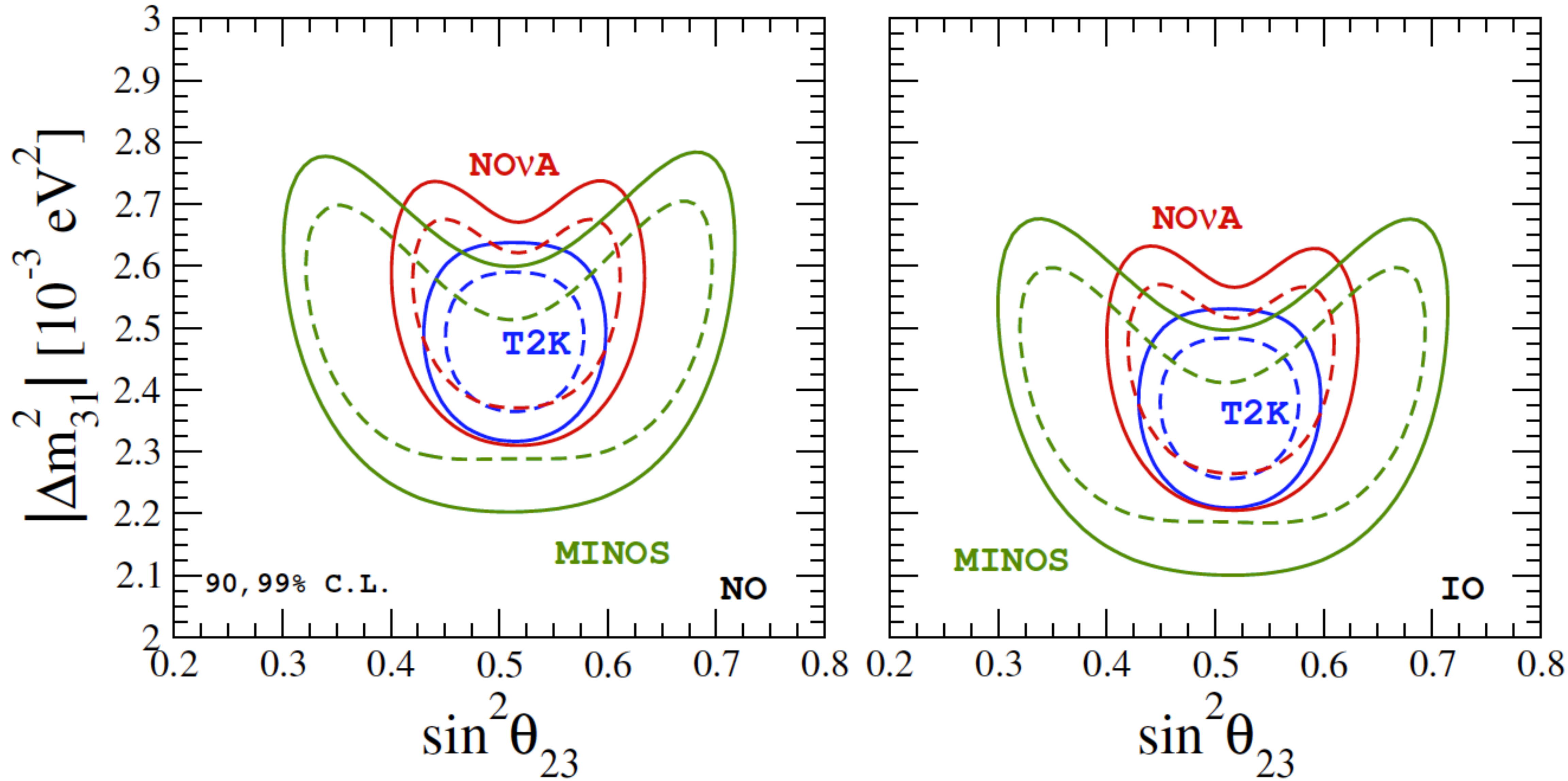
GOAL: observation of ν_μ disappearance, ν_e appearance and spectral distortions expected in the case of neutrino oscillations

→ consistent with atmospheric data
→ atm ν oscillations confirmed by laboratory exps

LBL accelerator experiments

- MINOS neutrino + antineutrino)
- T2K (neutrino + antineutrino)
- NOvA (only neutrino data)

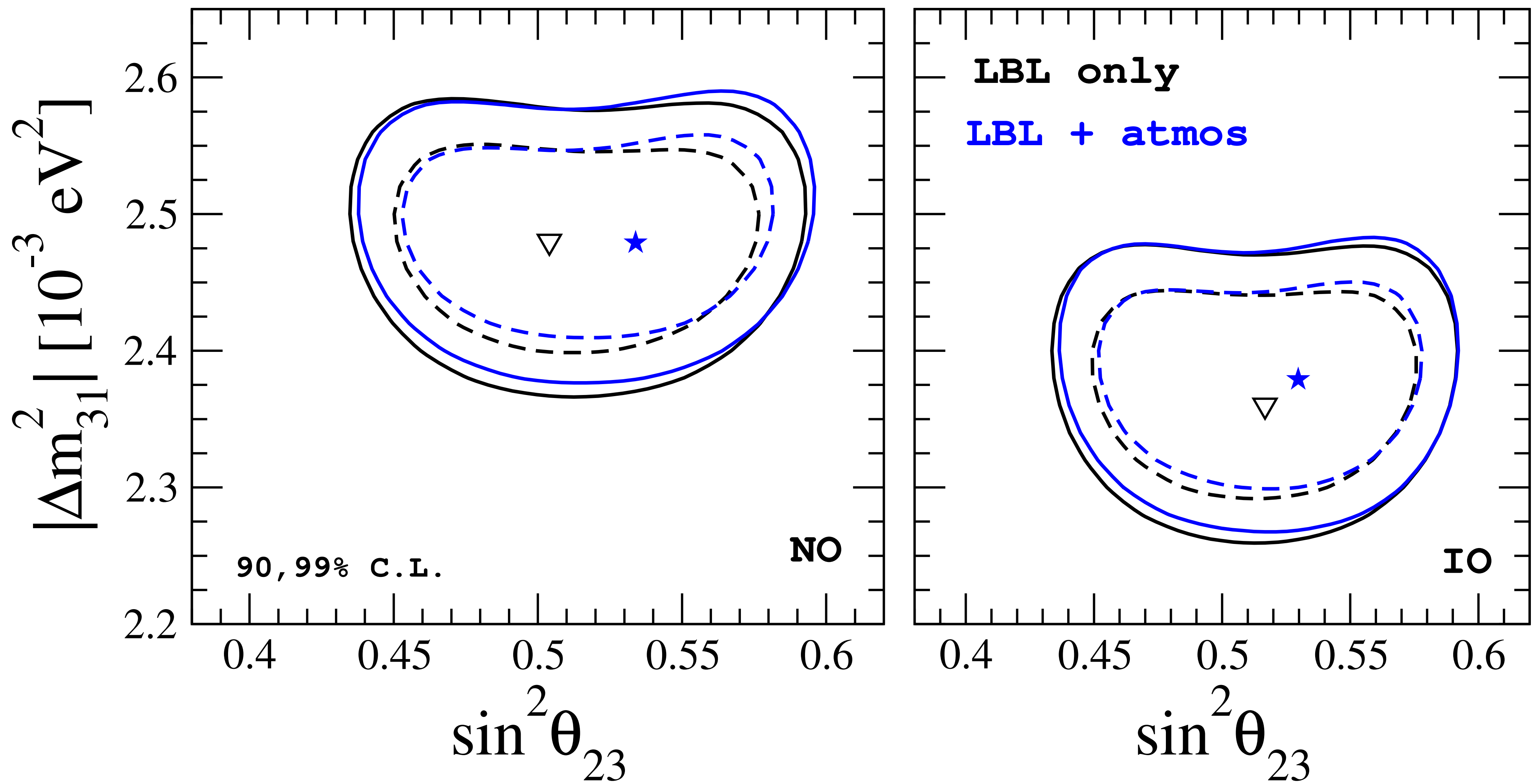
Update in progress



all experiments prefer mixing angle close to maximal

Atmospheric parameters

Combined analysis atmospheric + accelerator data



atmospheric parameters are mostly constrained by LBL data

de Salas et al, PLB 782 (2018) 633

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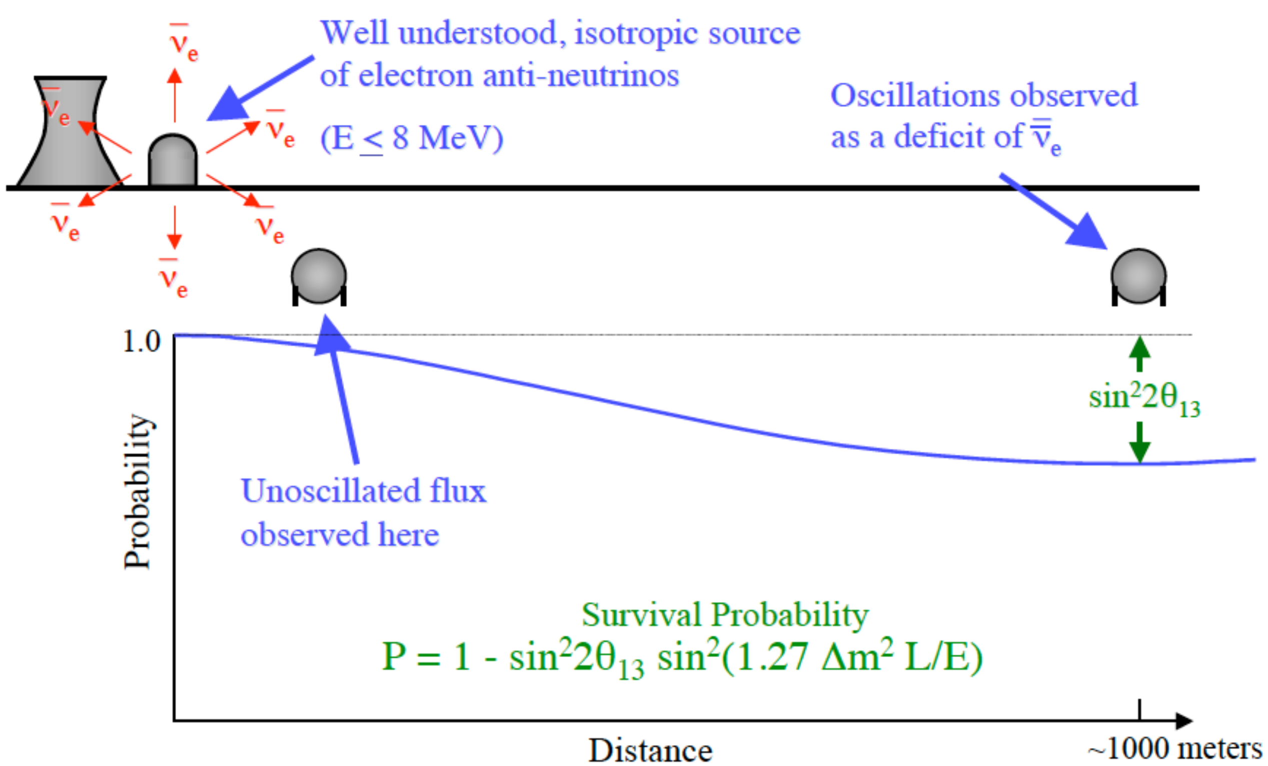
atmospheric + accelerator disapp	SBL reactor + accelerator app	solar + KamLAND
Δm^2_{31}	Δm^2_{31}	Δm^2_{21}

Most recent measurement: 2012 !!

New generation of reactor experiments

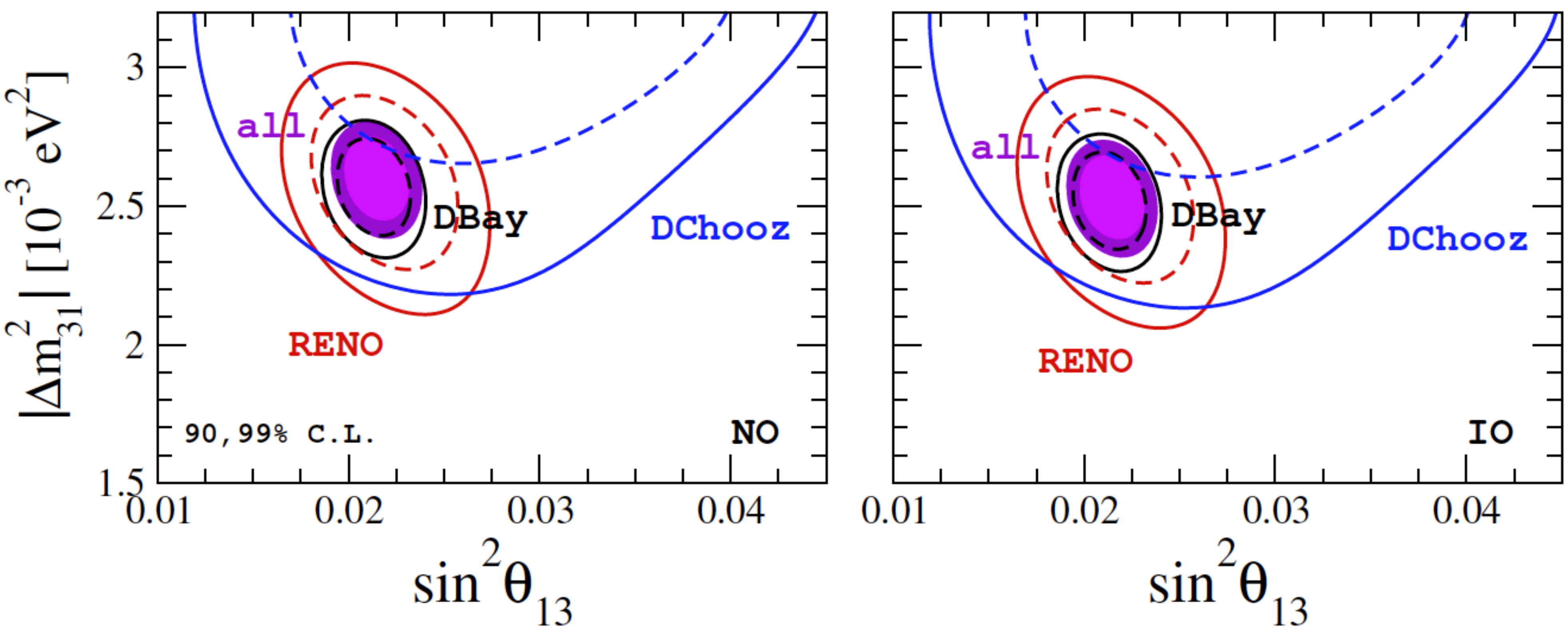
6 cores + 4 ND + 4FD   2 cores + 1 ND + 1 FD   6 cores + 1 ND + 1 FD



- more powerful reactors
- larger detector volume
- 2-8 detectors at 100 m – 1 km

New generation of reactor experiments

de Salas et al, PLB 782 (2018)



Precision dominated by Daya Bay

What we know about neutrinos

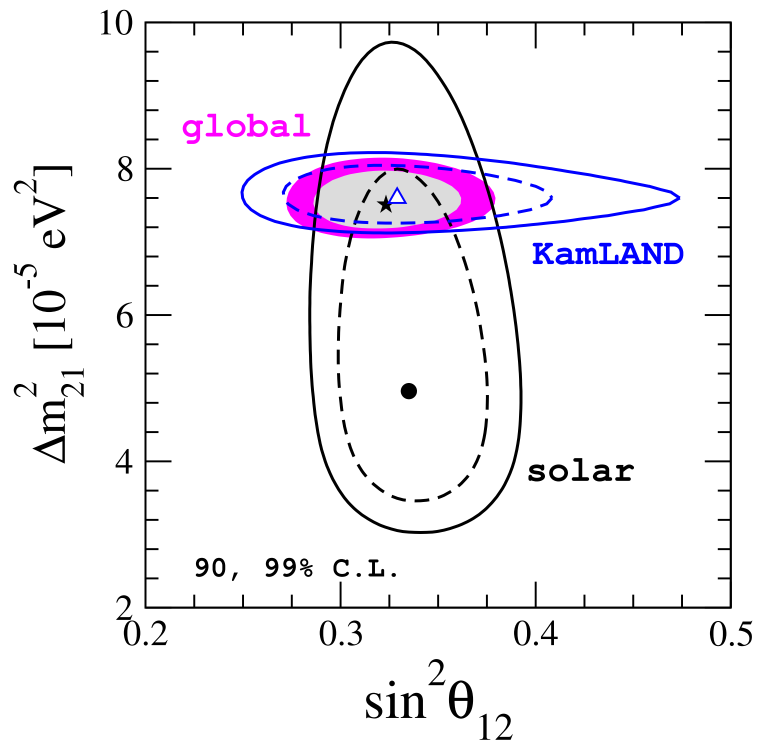
de Salas et al, PLB782 (2018) 633

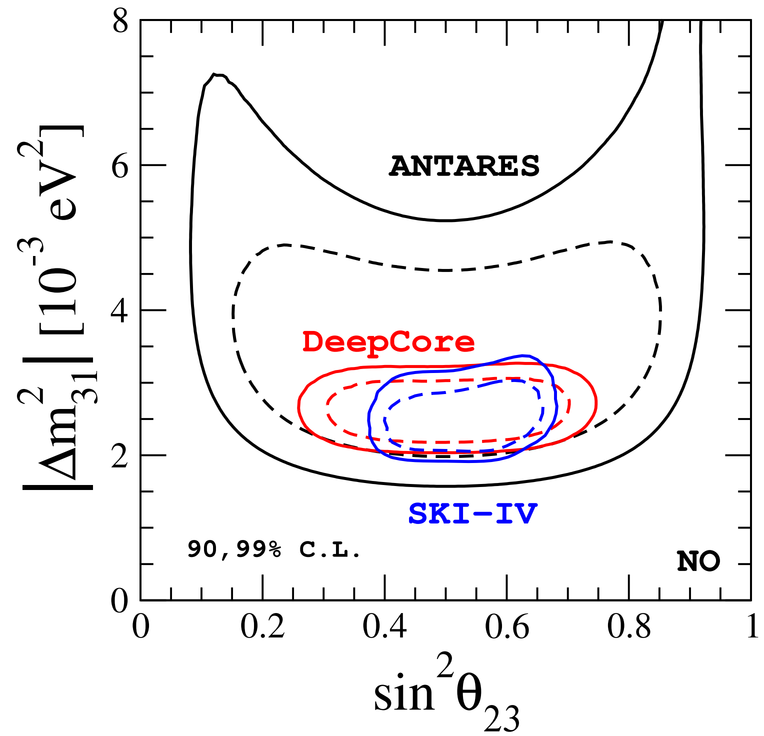
solar sector

Cl, Ga, SK

SNO, Borexino

KamLAND





atmospheric results

SK (official χ^2 maps)

IC-DeepCore

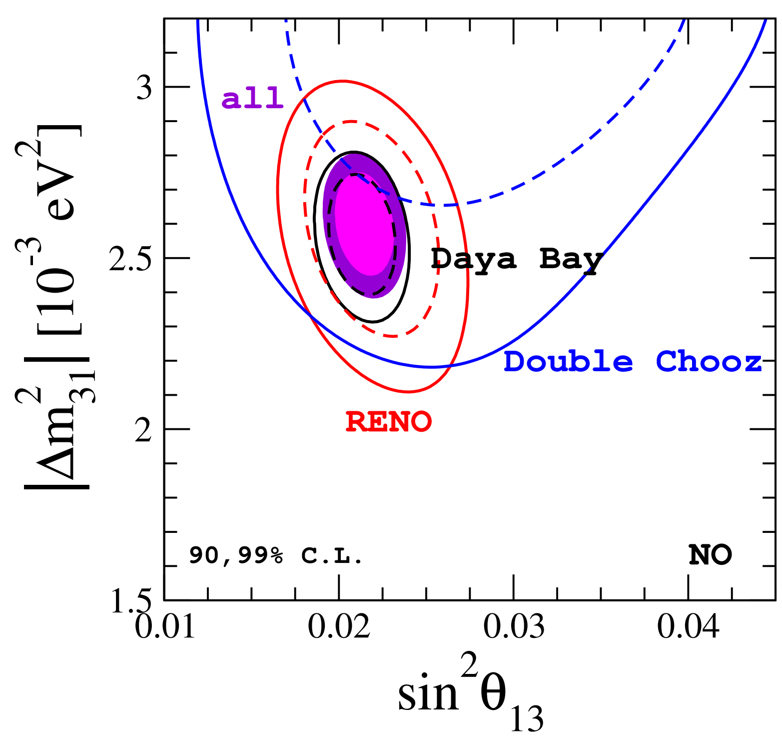
ANTARES

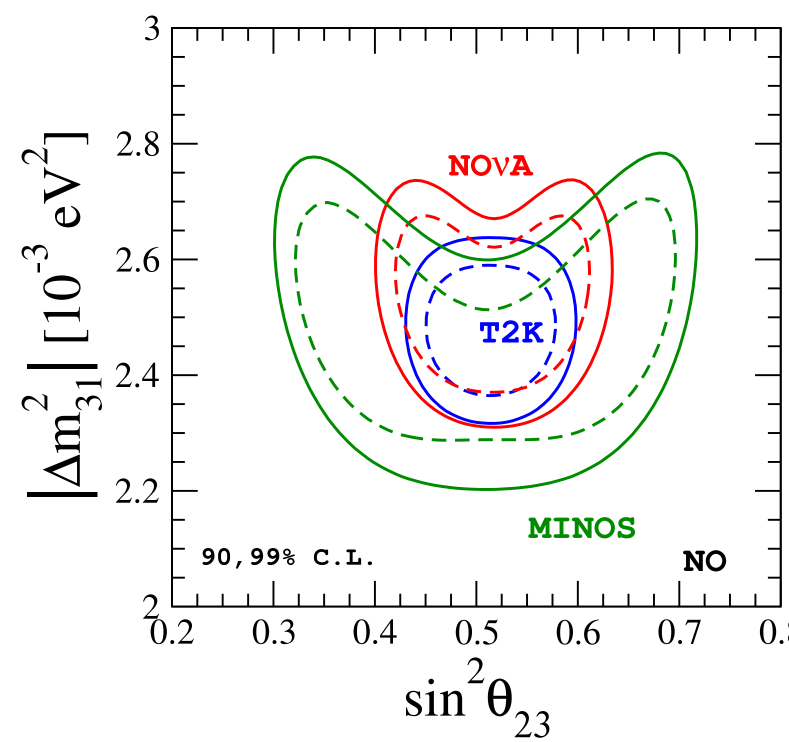
SBL reactors

Daya Bay

RENO

Double Chooz





LBL experiments

MINOS

T2K

NOνA

Neutrino oscillation parameters

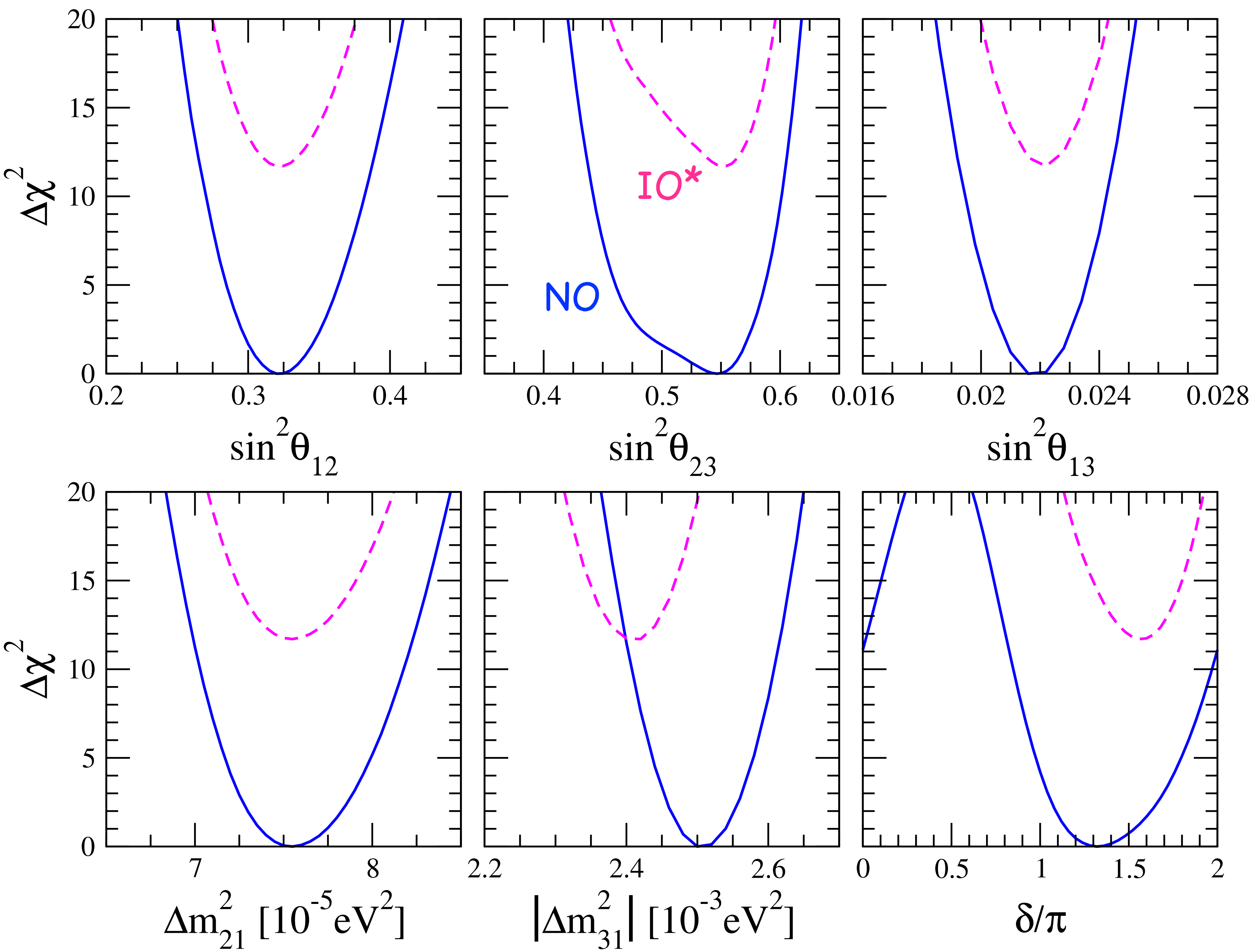
de Salas et al, PLB782 (2018) 633

https://globalfit.astroparticles.es/

parameter	best fit ± 1σ	3σ range	relative 1σ uncertainty
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.55^{+0.20}_{-0.16}$	7.05–8.14	2.4%
$\|\Delta m^2_{31}\|$ $[10^{-3}\text{eV}^2]$ (NO)	2.50±0.03	2.41–2.60	1.3%
$\|\Delta m^2_{31}\|$ $[10^{-3}\text{eV}^2]$ (IO)	$2.42^{+0.03}_{-0.04}$	2.31-2.51	
$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.73–3.79	5.5%
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.45–5.99	4.7%
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.53–5.98	4.4%
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	1.96–2.41	3.5%
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	1.99–2.44	
δ/π (NO)	$1.32^{+0.21}_{-0.15}$	0.87–1.94	10%
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.12–1.94	9%

Neutrino oscillation parameters

de Salas et al, PLB782 (2018) 633



See also

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- Lisi et al.

Neutrino oscillation parameters

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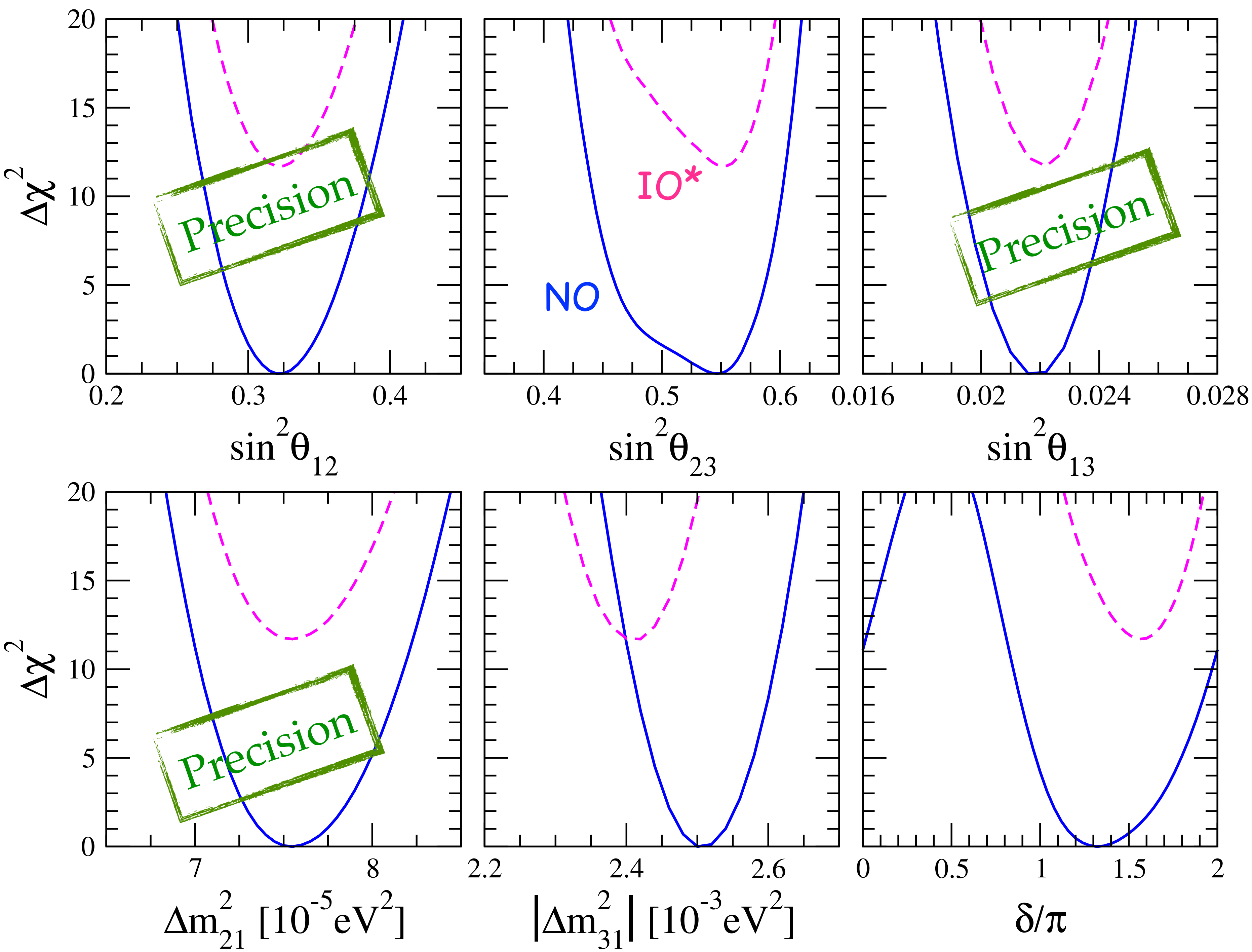

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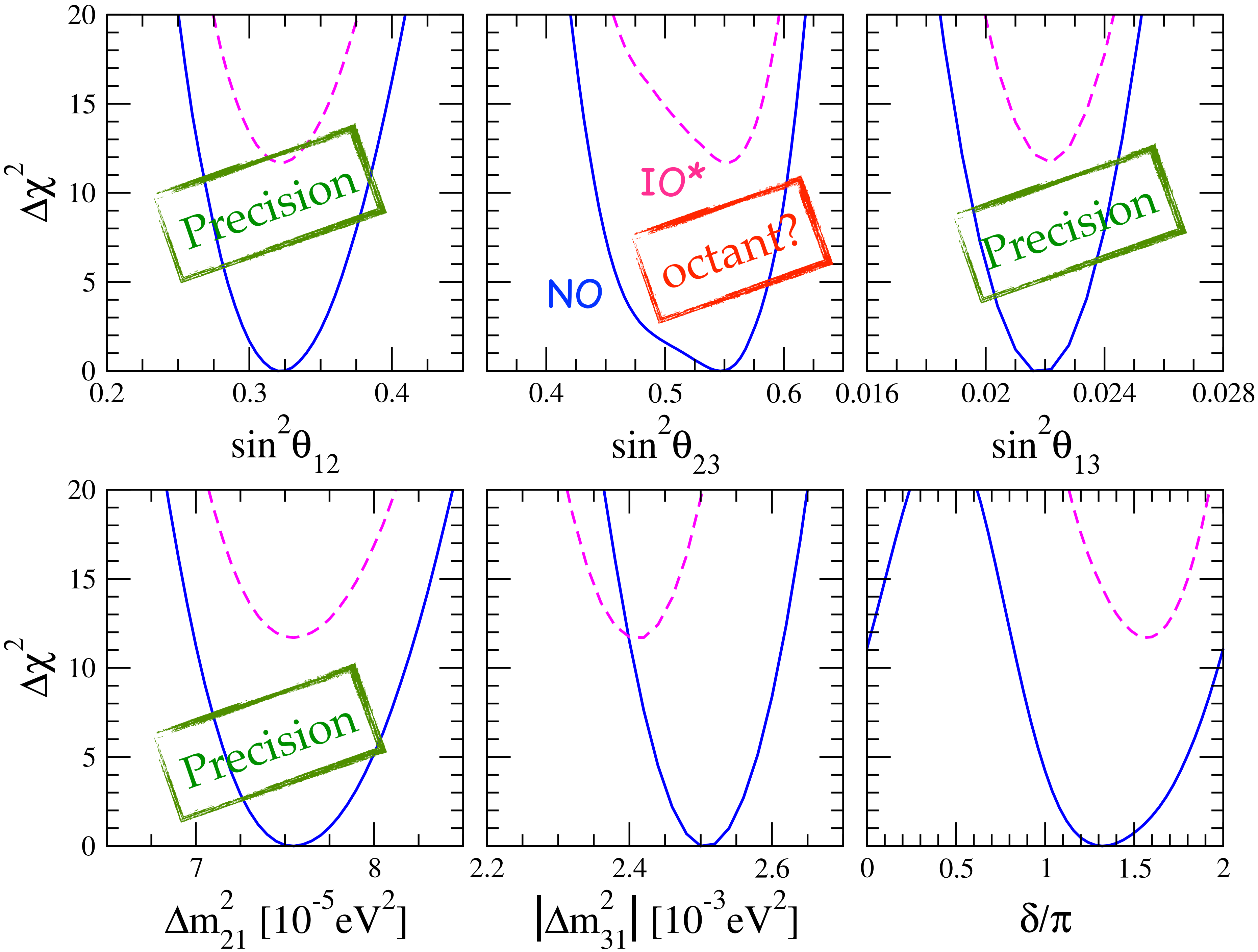

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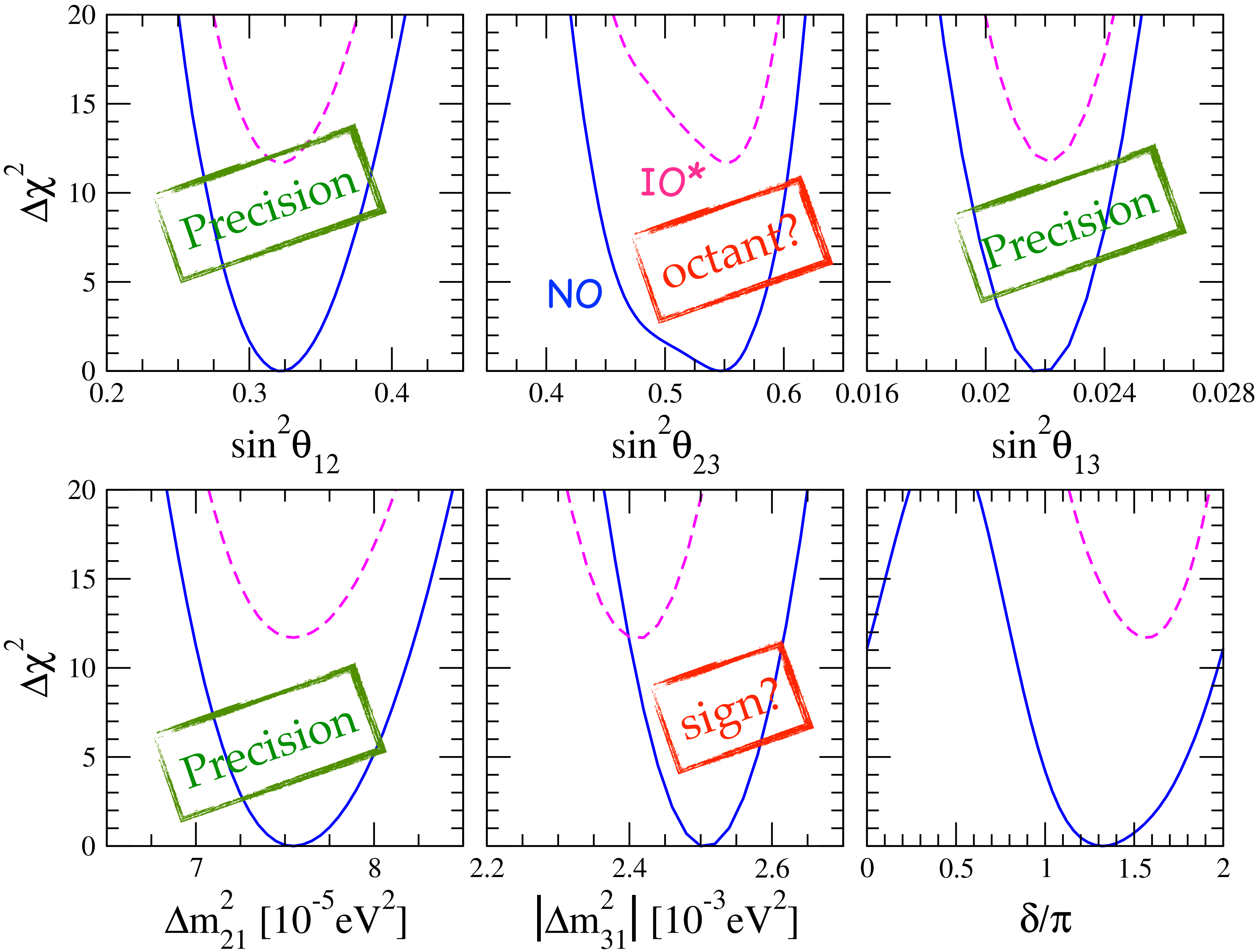

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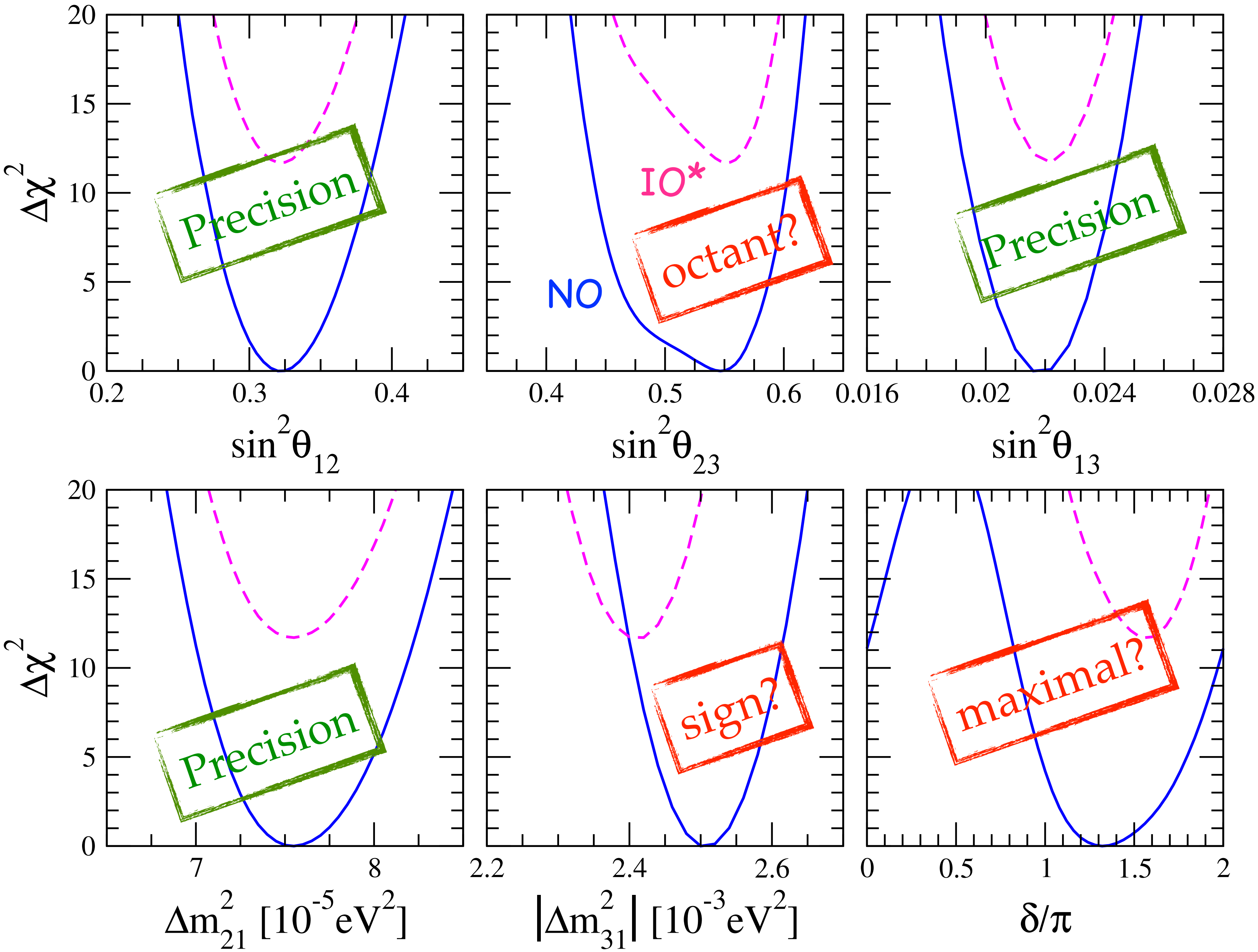

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Beyond the 3-neutrino scenario

Physics Beyond the SM

✦ Neutrino results suggest the presence of **physics BSM** to explain:

- ✓ light neutrino masses (mass generation mechanism?)
- ✓ large neutrino mixing compared to quark sector (flavour problem?)
- ✓ short-distance anomalies

✦ Many different scenarios BSM considered:

- ✓ neutrino non-standard interactions (NSI) with matter
- ✓ exotic neutrino electromagnetic properties
- ✓ presence of light sterile neutrinos
- ✓ mixing with heavy sterile neutrinos: non-unitary neutrino mixing
- ✓ ….

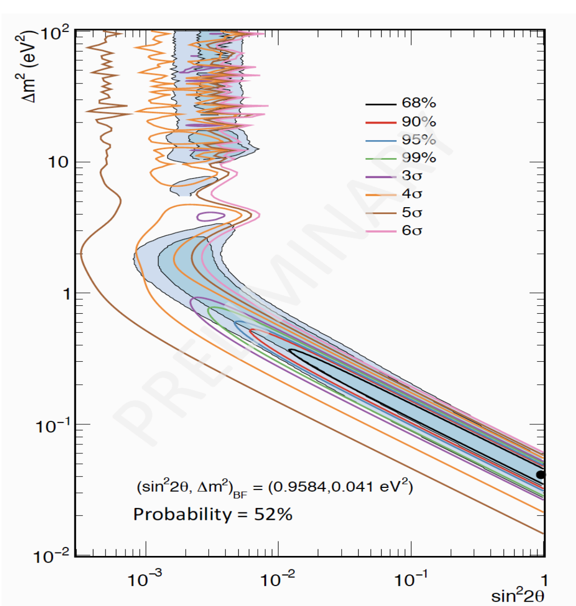
How many neutrinos?

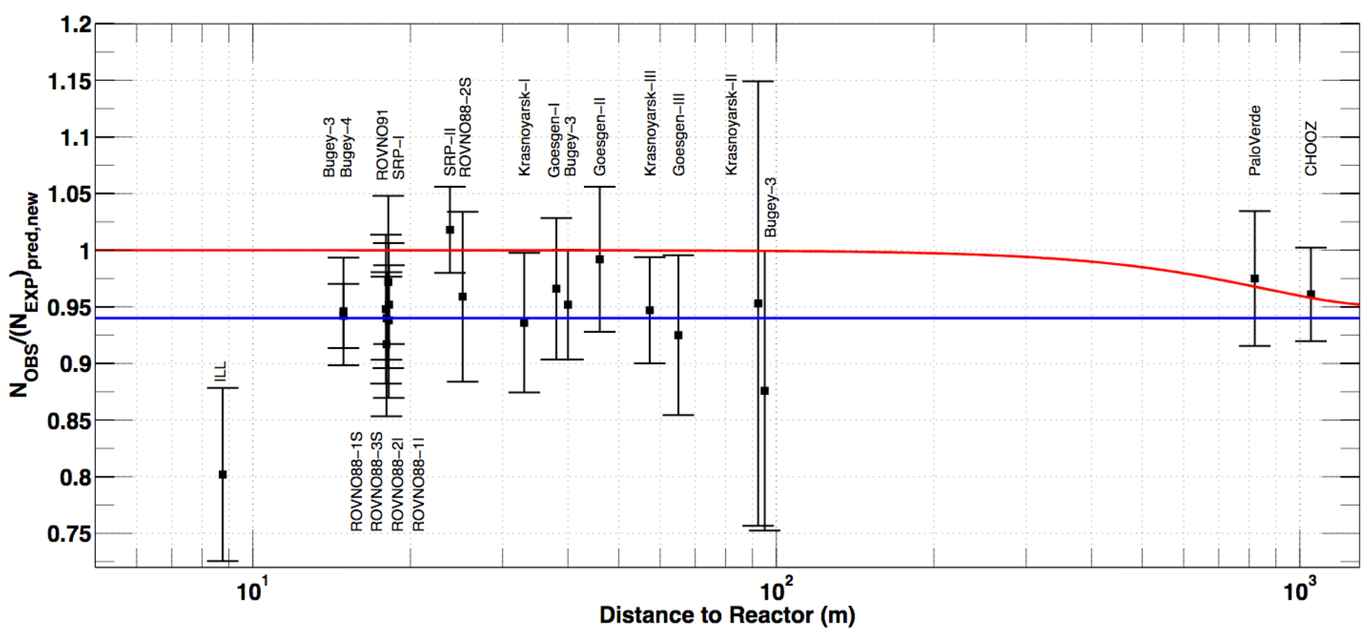
- LEP measurements of invisible Z decay width:

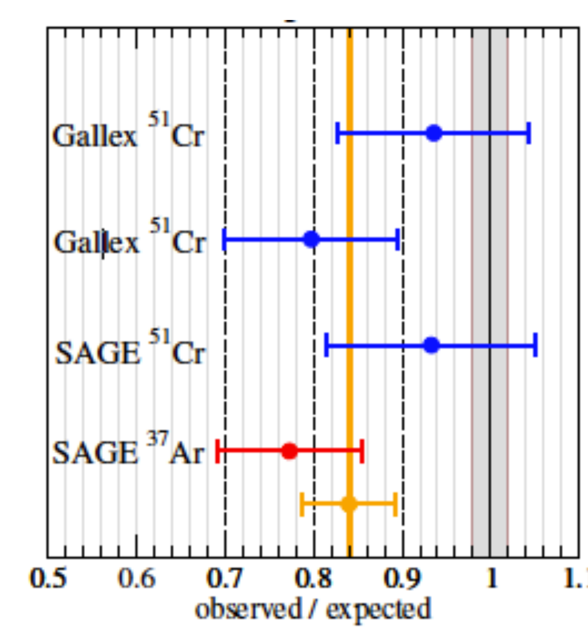
$N_\nu = 2.984 \pm 0.008$ (light, active neutrinos)

Experimental hints for a 4th sterile neutrino:

LSND & MiniBooNE	Reactor anomaly	Gallium anomaly
$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$	$\overline{\nu}_e \to \overline{\nu}_e$	$\nu_e \to \nu_e$



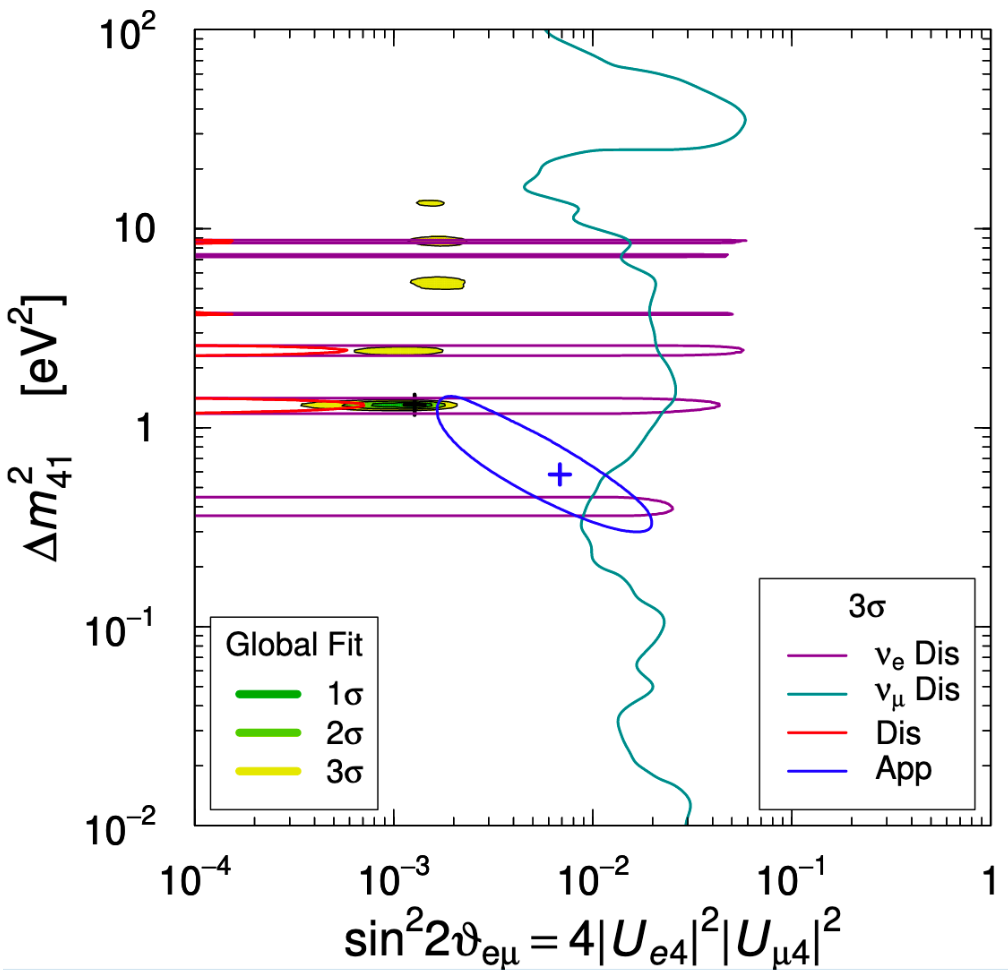




However…

Global 3+1 oscillation analysis

strong tension between appearance (LSND/MB) and disappearance exp. (CDHS, SK, IceCube, MINOS/+)



S. Gariazzo@ TAUP 2019

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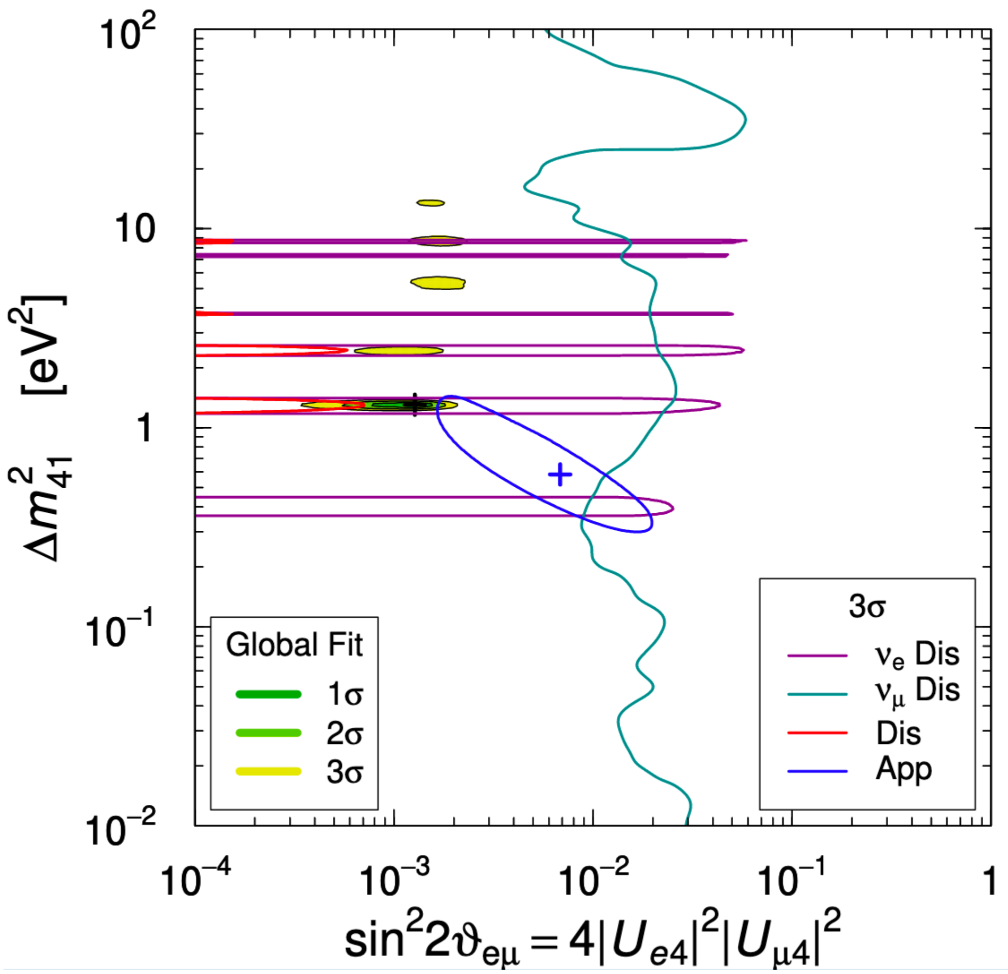

S. Gariazzo@ TAUP 2019

Σm_ν = sum of neutrino masses

N_{eff} = relativistic degrees of freedom

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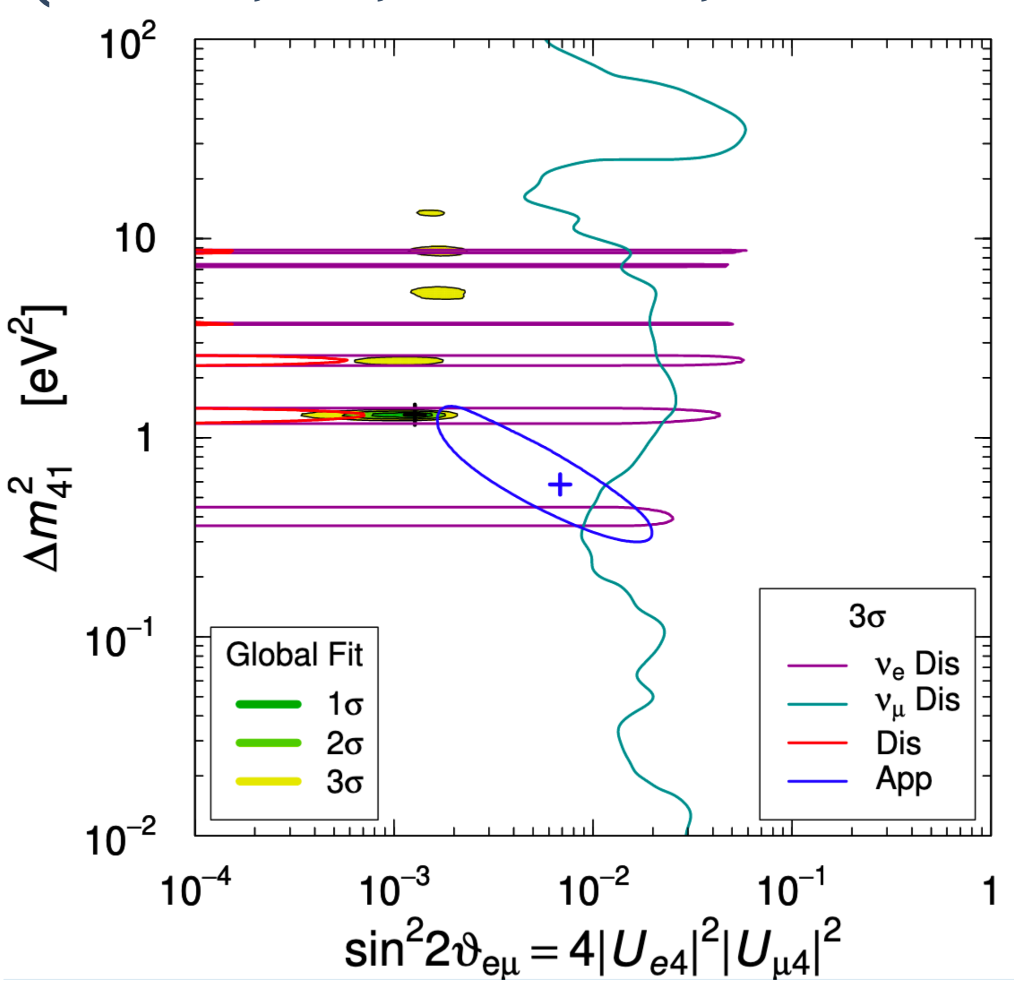

S. Gariazzo@ TAUP 2019

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Σm_ν = sum of neutrino masses

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✦ The sterile hypothesis requires

$$\rightarrow \sum m_\nu \gtrsim 0.05\,\text{eV} + \sqrt{\Delta m^2_{41}} > 1\,\text{eV}$$

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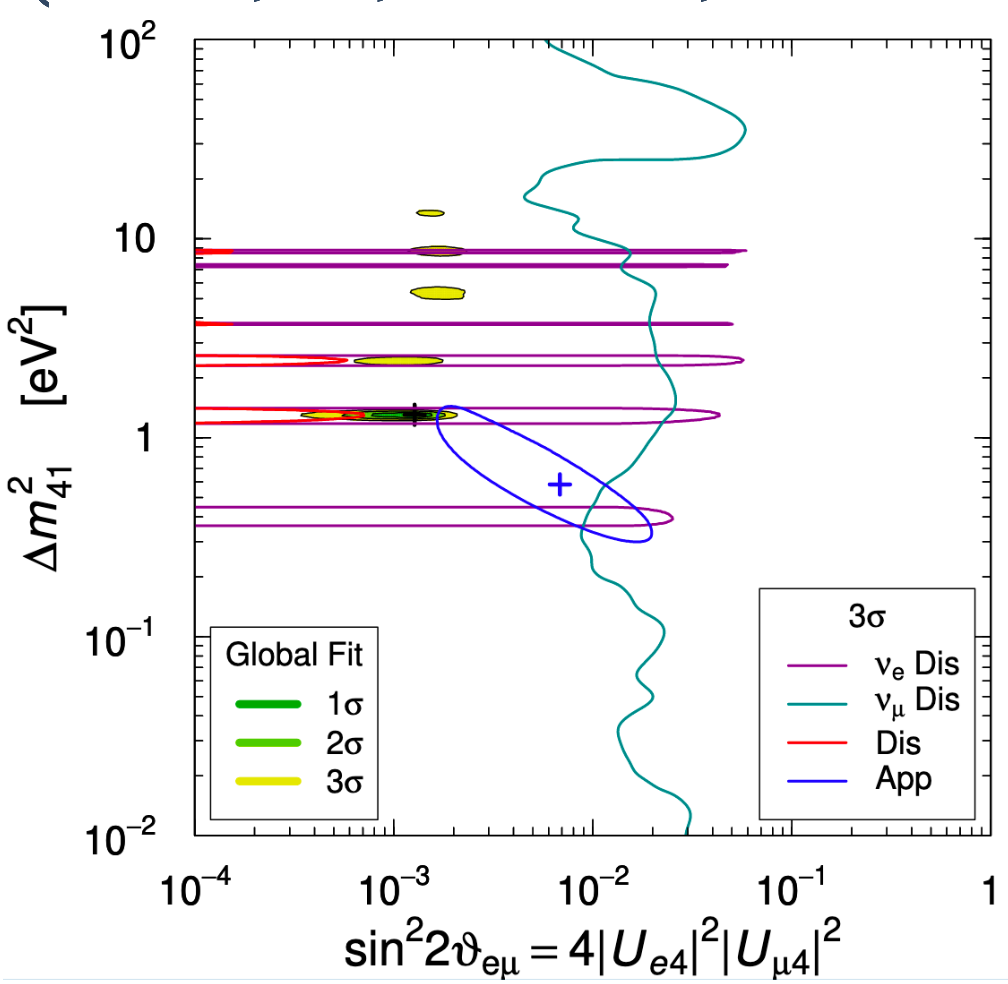

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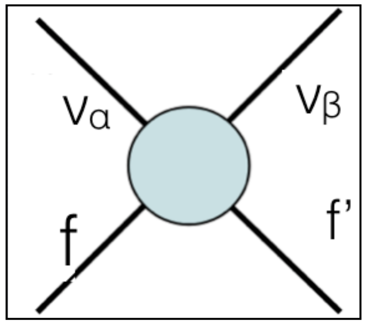
- Recent results:

$\Sigma m_\nu < 0.14 - 0.72$ eV < 1 eV !!!!

$N_{eff} = 3.15 \pm 0.23$ (PLANCK)
$N_{eff} = 3.03 \pm 0.18$ (PLANCK + LSS)

New physics beyond the SM

Non-standard interactions (NSI)



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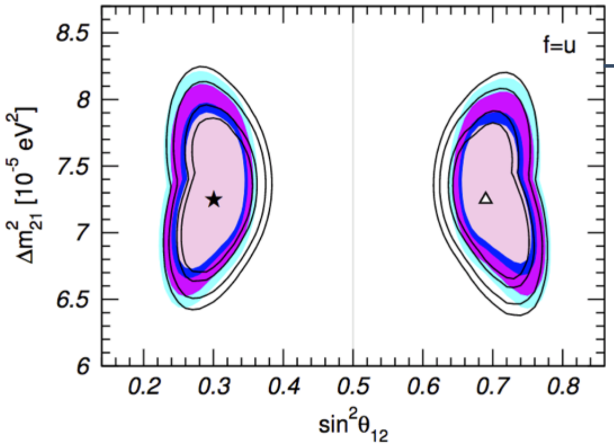
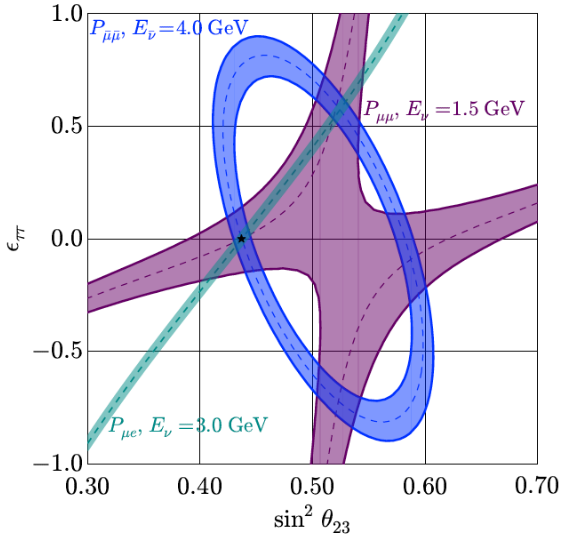
- affect precision on oscillation parameters
- sensitivity reach of upcoming experiments



→ degenerate solution with $\theta_{12} > \pi/4$

Miranda et al, JHEP 2006



→ θ_{23}-degeneracy in DUNE

Gouvea and Kelly, NPB 2016

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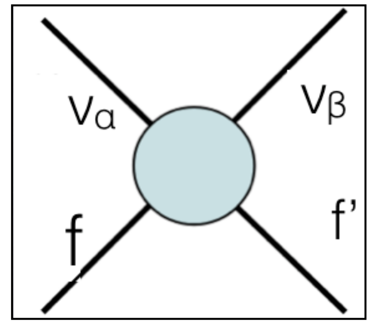

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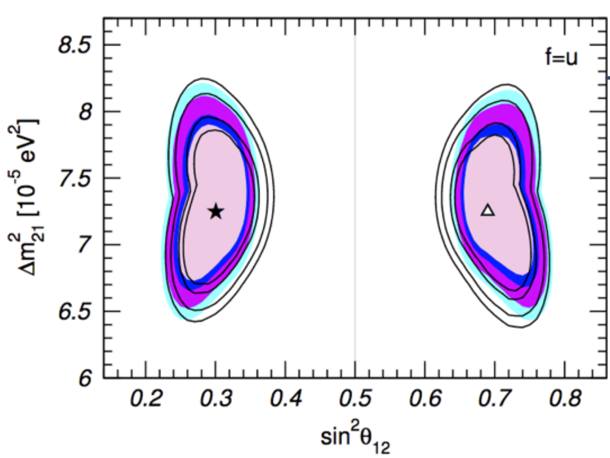

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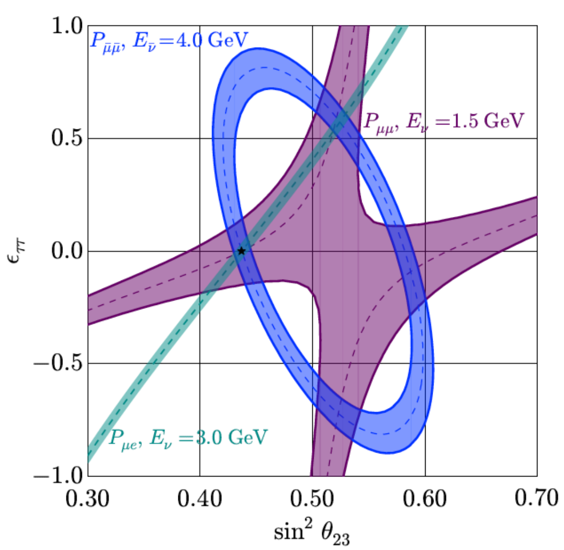

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Gouvea and Kelly, NPB 2016

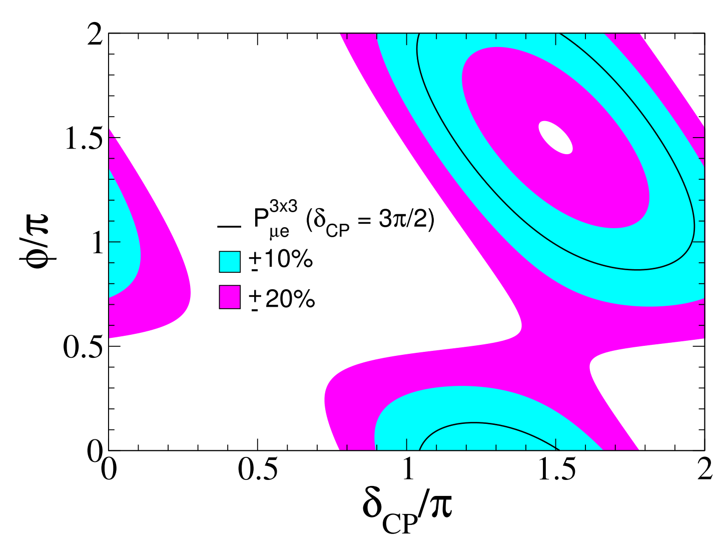
Non-unitary 3ν mixing

- Most models of neutrino masses → extra heavy states

$$\begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix} \quad \begin{pmatrix} 0 & M_D & 0 \\ M_D^T & 0 & M \\ 0 & M^T & \mu \end{pmatrix}$$

- NxN unitary mixing matrix
→ (3x3) mixing matrix non-unitary:

$$N = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U^{3x3}$$



→ degeneracies in δ determination in DUNE

Miranda, MT, Valle, PRL 2016

Lorentz and CPT invariance violation in ν oscillations

The Standard Model Extension

✦ Lorentz and CPT symmetries are the basis for local relativistic quantum field theories.

✦ Motivated by current high-precision experiments, one may try to probe such symmetries: the observation of Lorentz or CPT violation will provide a signal for new physics (Quantum Gravity theories, String Theories)

✦ The SME, developed by Kostelecky and collaborators:

➡ contains all the properties of the SM + General Relativity except that Lorentz and CPT symmetry can be violated.

➡ suggests that breaking of CPT and Lorentz symmetry might be observable at current or near-future experiments

➡ the physical source of Lorentz and CPT violation is spontaneous symmetry breaking, that may happen in complicated theories.

More details in: https://lorentz.sitehost.iu.edu/kostelecky/faq.html

Lorentz violation in ν experiments

- In the SME, the neutrino sector is described by

Kostelecky et al.

$$\mathcal{L} = \frac{1}{2}\overline{\Psi}(i\gamma^\alpha\partial_\alpha - M + \mathcal{Q})\Psi$$ where $\mathcal{Q}$ is the Lorentz-violating operator

- Lorentz-violating lagrangian is parametrized as

$$\mathcal{L}_{\rm LIV} = -\frac{1}{2}\left[a^\mu_{\alpha\beta}\bar{\psi}_\alpha\gamma_\mu\psi_\beta + b^\mu_{\alpha\beta}\bar{\psi}_\alpha\gamma_5\gamma_\mu\psi_\beta - ic^{\mu\nu}_{\alpha\beta}\bar{\psi}_\alpha\gamma_\mu\partial_\nu\psi_\beta - id^{\mu\nu}_{\alpha\beta}\bar{\psi}_\alpha\gamma_5\gamma_\mu\partial_\nu\psi_\beta\right] + h.c.$$

with the observable effect on the left handed neutrinos is controlled by:

$$(a_L)^\mu_{\alpha\beta} = (a+b)^\mu_{\alpha\beta}\,, \qquad (c_L)^{\mu\nu}_{\alpha\beta} = (c+d)^{\mu\nu}_{\alpha\beta}\,,$$

➡ This scenario has been explored in the context of many neutrino experiments: MINOS, IceCube, SNO,…

[M. Manganaro, Neutrino Exp]

Lorentz violation in DUNE

- The effective neutrino Hamiltonian in this scenario is given by

$$H = H_{vac} + H_{mat} + H_{LIV}$$

with

$$H_{\rm LIV} = \begin{pmatrix} a_{ee} & a_{e\mu} & a_{e\tau} \\ a^*_{e\mu} & a_{\mu\mu} & a_{\mu\tau} \\ a^*_{e\tau} & a^*_{\mu\tau} & a_{\tau\tau} \end{pmatrix} - \frac{4}{3} E \begin{pmatrix} c_{ee} & c_{e\mu} & c_{e\tau} \\ c^*_{e\mu} & c_{\mu\mu} & c_{\mu\tau} \\ c^*_{e\tau} & c^*_{\mu\tau} & c_{\tau\tau} \end{pmatrix}$$

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we focus on this matrix (CPT-odd part)

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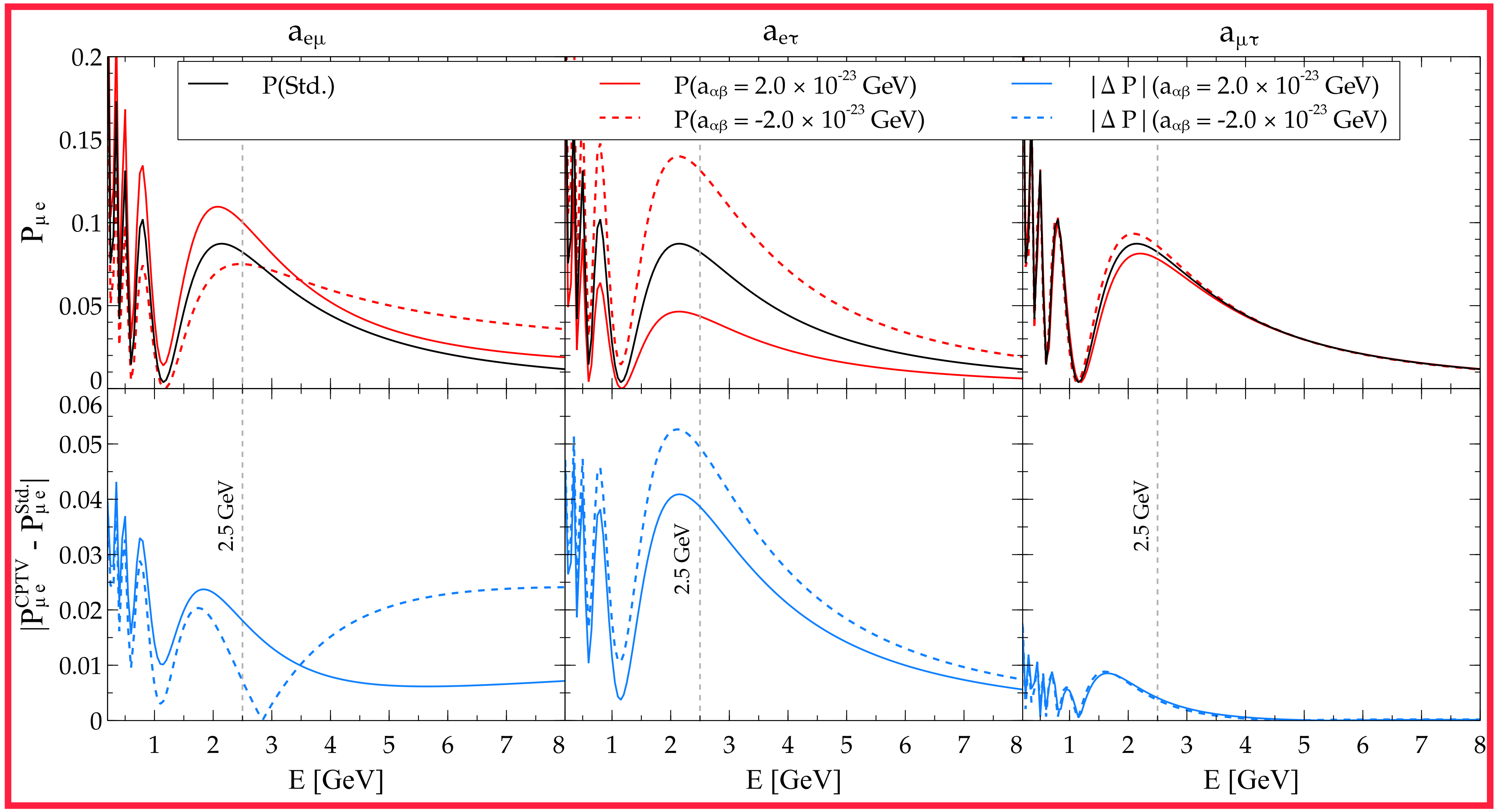
- $P_{\mu e}$ oscillation probabilities in DUNE are modified in presence of Lorentz violation

Barenboim, Masud, Ternes, MT,PLB2019



Lorentz violation in DUNE

- DUNE simulation: → disapp + app channels
  → 3.5 yr neutrino + 3.5 yr antineutrino run

- DUNE's sensitivity to Lorentz-violating parameters

Parameter	Existing Bounds (SK-atm)	This work (DUNE)
$\lvert a_{e\mu} \rvert$ [GeV]	2.5×10^{-23}	7.0×10^{-24}
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Factor 5 improvement

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(SK-atm)

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new bounds

Barenboim, Masud, Ternes, MT,PLB2019

Violation of CPT symmetry

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

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PHYSICAL REVIEW — VOLUME 104, NUMBER 1 — OCTOBER 1, 1956

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

AND

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

(Received June 22, 1956)

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→ **P** violated: what about **CP**?

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→ 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** $(\overline{\Delta m^2_{ji}}, \overline{\theta_{ij}}, \overline{\delta})$

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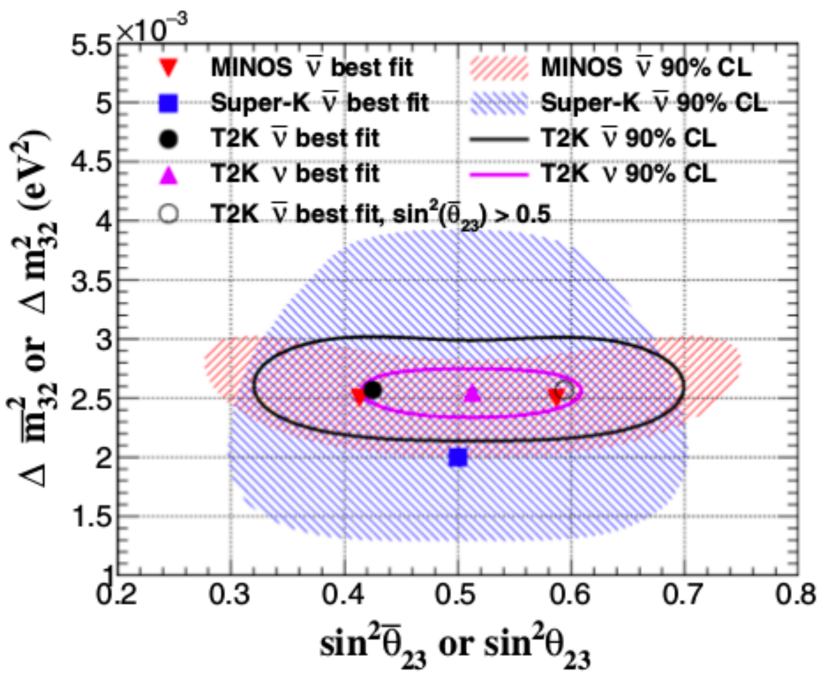
- Separate neutrino and antineutrino analysis in T2K

T2K Coll, PRD2017



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

$\rightarrow$ different best fit values

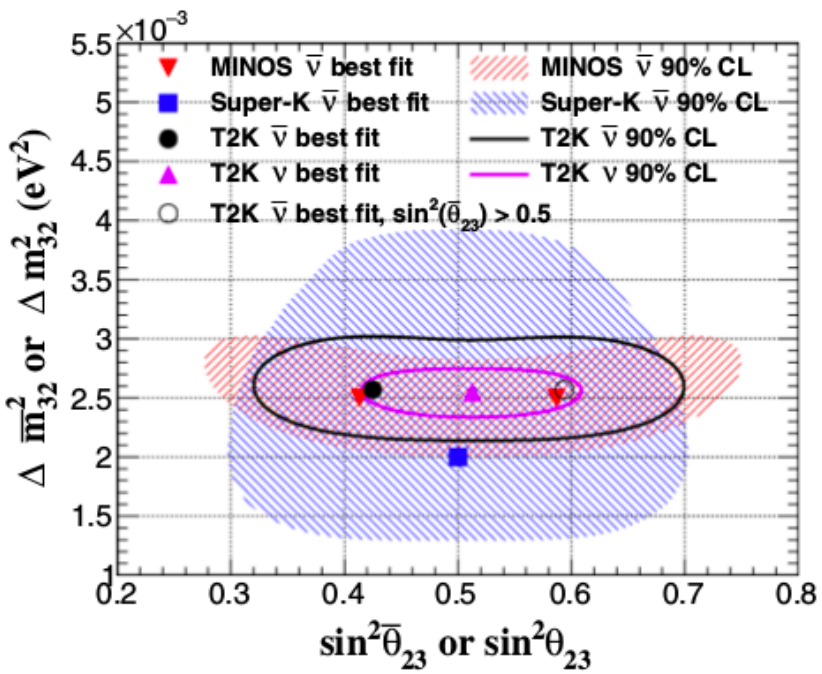
$\rightarrow$ consistent with CPT conservation

~~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



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- Current bounds at 3σ:

$$|\Delta m^2_{21} - \Delta \overline{m}^2_{21}| \quad < 4.7 \times 10^{-5} \mathrm{eV}^2$$
$$|\Delta m^2_{31} - \Delta \overline{m}^2_{31}| \quad < 3.7 \times 10^{-4} \mathrm{eV}^2$$
$$|\sin^2\theta_{12} - \sin^2\overline{\theta}_{12}| \quad < 0.14,$$
$$|\sin^2\theta_{13} - \sin^2\overline{\theta}_{13}| \quad < 0.03,$$
$$|\sin^2\theta_{23} - \sin^2\overline{\theta}_{23}| \quad < 0.32$$

Barenboim, Ternes, MT, PLB2018

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

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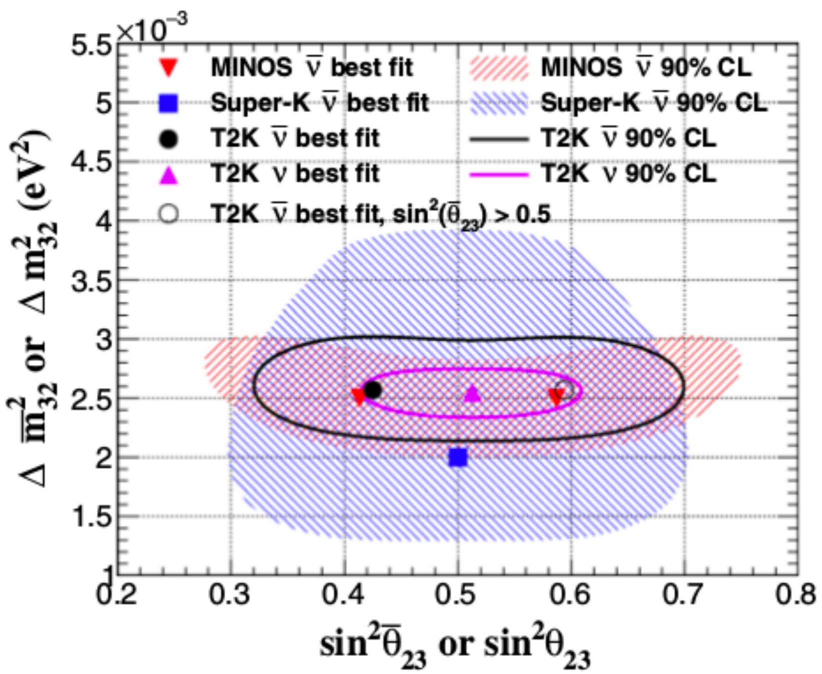
T2K Coll, PRD2017



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$|\sin^2\theta_{12} - \sin^2\overline{\theta}$ ... $.14,$

$|\Delta m_{21}^2 - \Delta\overline{m}_{21}^2| \quad < 4.7 \times 10^{-5}$ ... $03,$

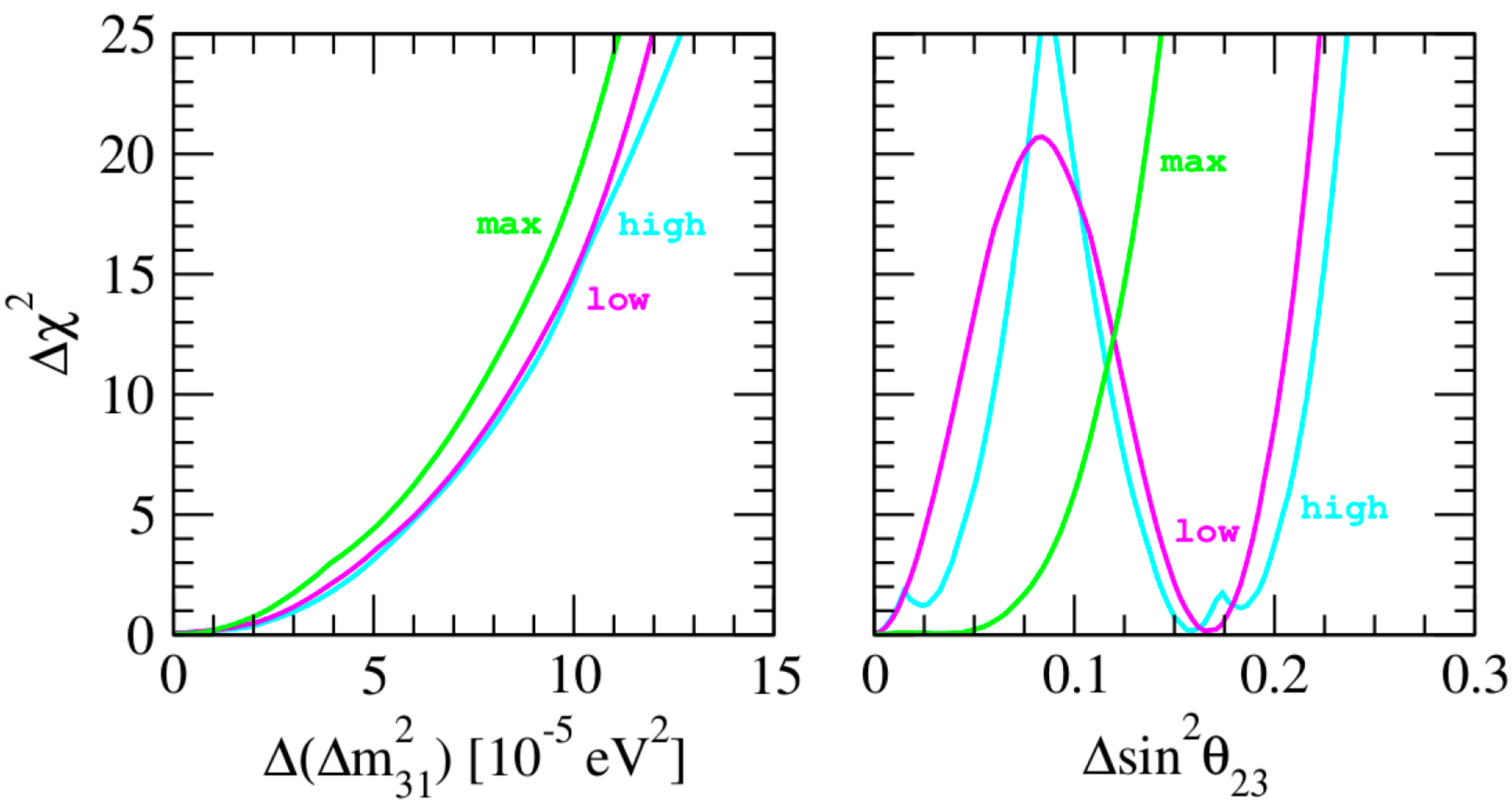
$|\Delta m_{31}^2 - \Delta\overline{m}_{31}^2| \quad < 3.7 \times 10$ ... $_{23}| < 0.32$

Can DUNE improve these bounds?

Barenboim, Ternes, MT, PLB2018

~~CPT~~ sensitivity in DUNE

✦ Very good sensitivity to differences in atmospheric parameters



→ one order of magnitude improvement:

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

→ excellent sensitivity for max mixing

→ oscillating results for high and low octant due to degeneracies

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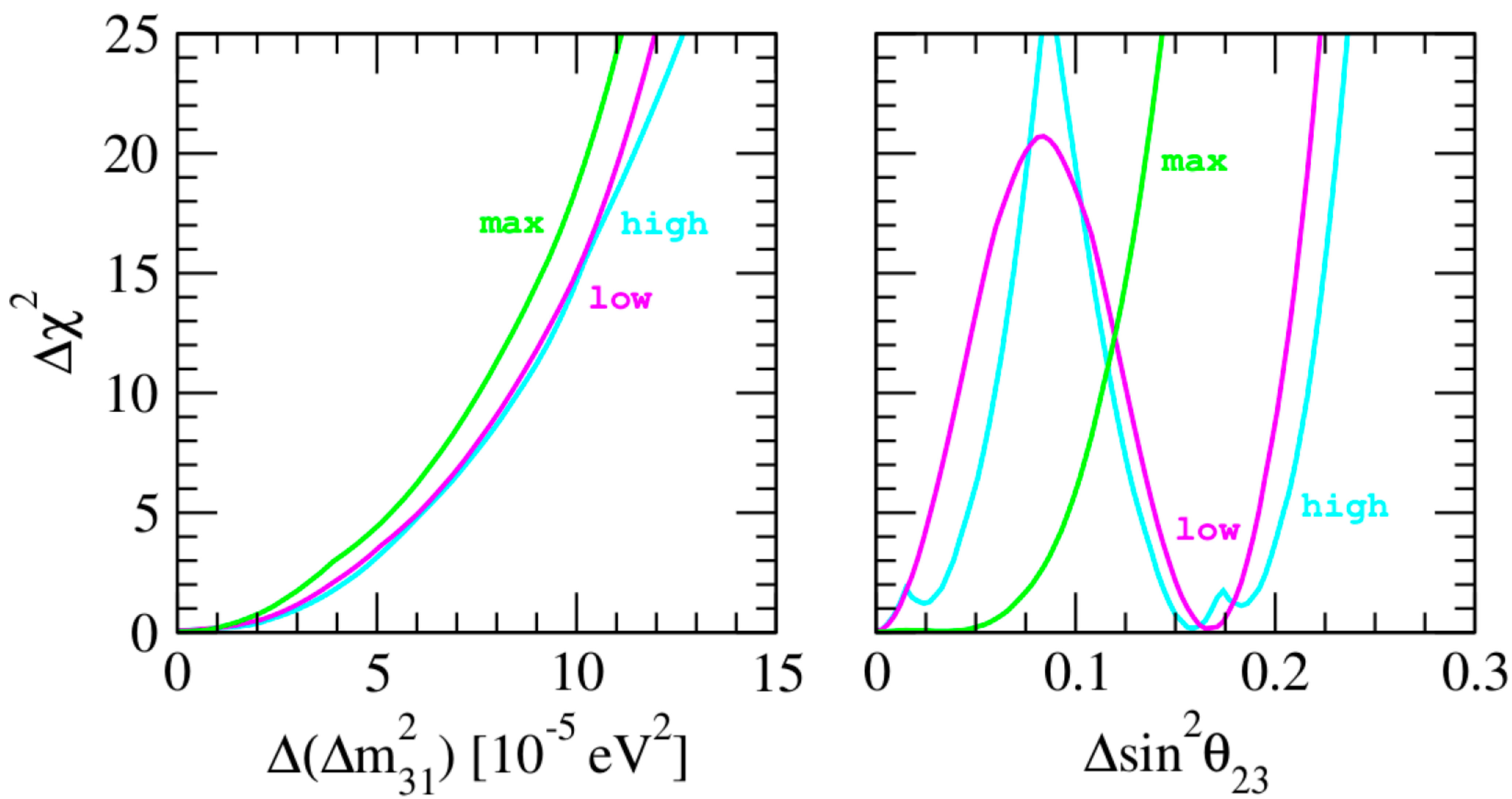
Bareboim, Ternes, MT, PLB2018



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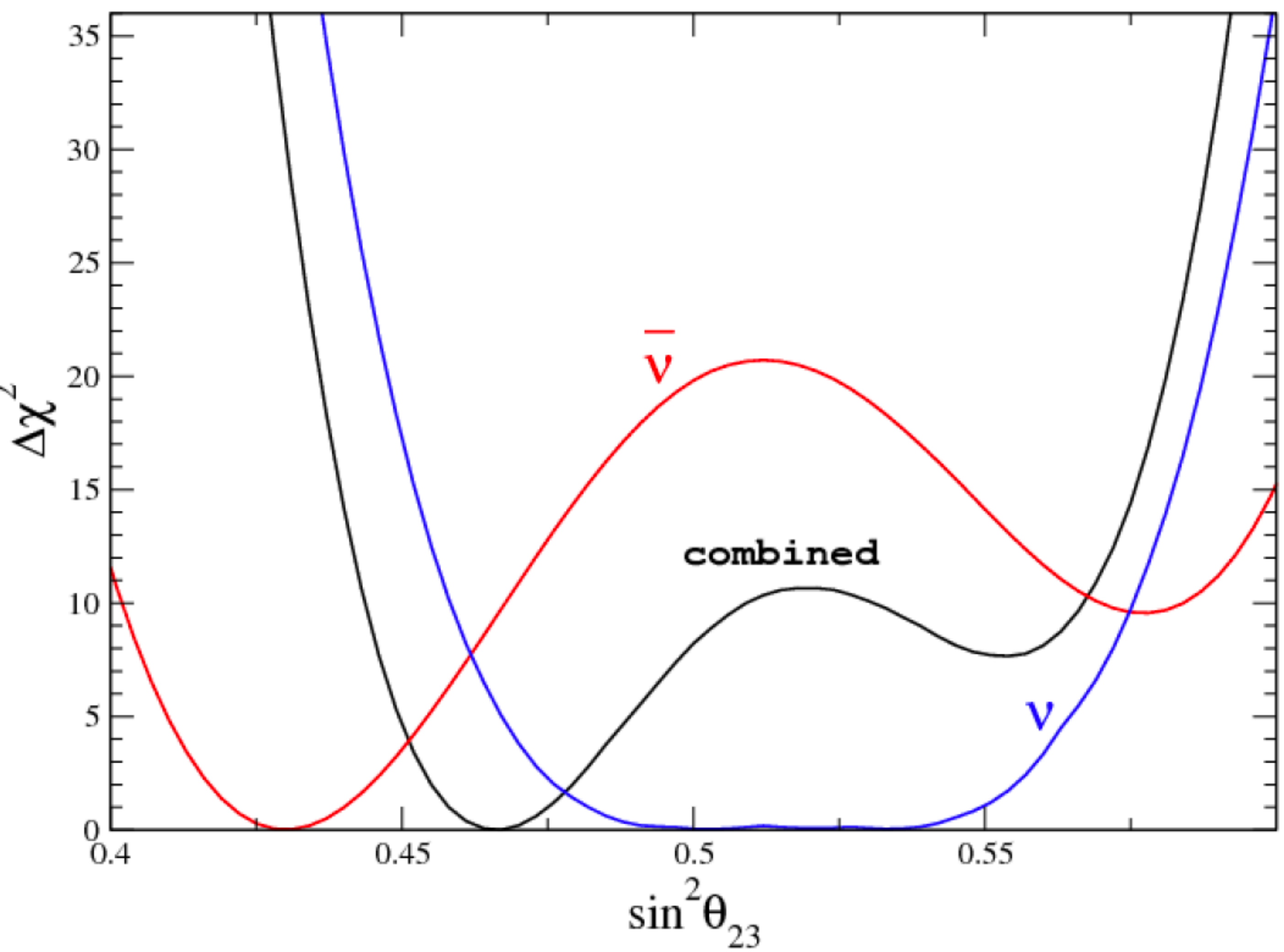
~~CPT~~ oscillations: imposter solutions

- 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

Summary

✦ Important discoveries on neutrino physics along last century have provided the first evidence for physics beyond the Standard Model.

✦ Neutrino oscillations are well stablished with observations in several experiments, with natural and artificial sources.

➡ Oscillation parameters accurately measured ($\lesssim$ 6%) by the combination of different experiments.

➡ First indications for normal mass ordering and maximal CP violation.

✦ Several scenarios of physics BSM motivated by the building of neutrino mass models and the observation of anomalies are being explored (NSI, sterile neutrinos, Non-unitary 3-neutrino mixing).

✦ Scenarios motivated by Quantum Gravity developments may also produce interesting phenomenology in neutrino experiments (violation of CPT and Lorentz invariance symmetries).

Backup slides

~~CPT~~ sensitivity in DUNE

☑ DUNE's simulation:
→ disappearance + appearance channels
→ 3.5 yr neutrino run + 3.5 yr antineutrino run

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- ☑ Sensitivity to the difference between neutrino and antineutrino params.

$$\Delta x = |x - \overline{x}| \quad \text{for} \quad x \equiv \Delta m^2_{31} \, , \theta_{23} \, , \theta_{13} \, , \delta$$

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- DUNE's simulation:
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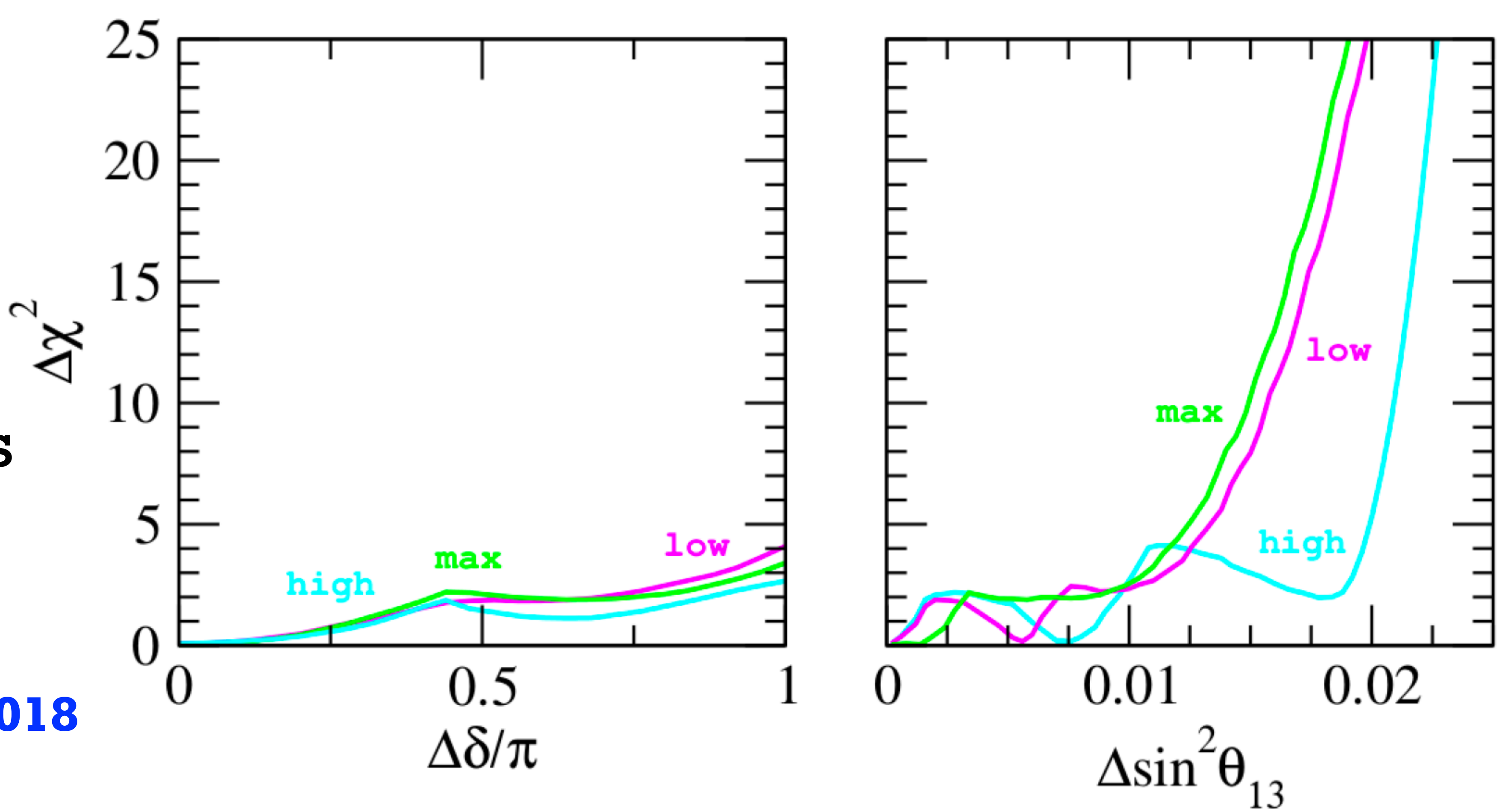
$$\Delta x = |x - \overline{x}| \quad \text{for} \quad x \equiv \Delta m^2_{31}\,, \theta_{23}\,, \theta_{13}\,, \delta$$

- Poor sensitivity to differences in CP phase and reactor angle

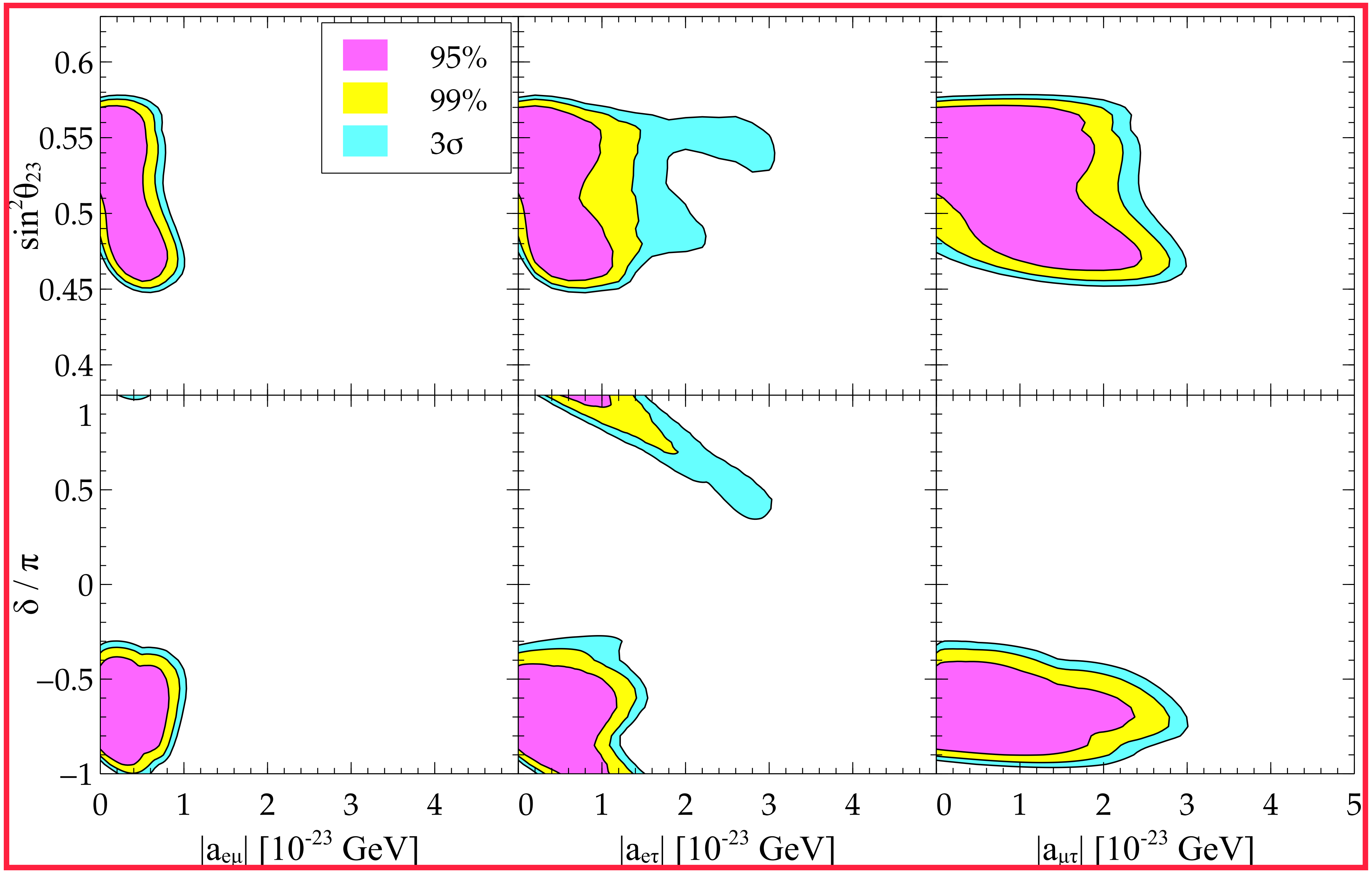
  → three different values of θ_{23} considered



Barenboim, Ternes, MT, PLB2018

Lorentz violation in ν oscillations

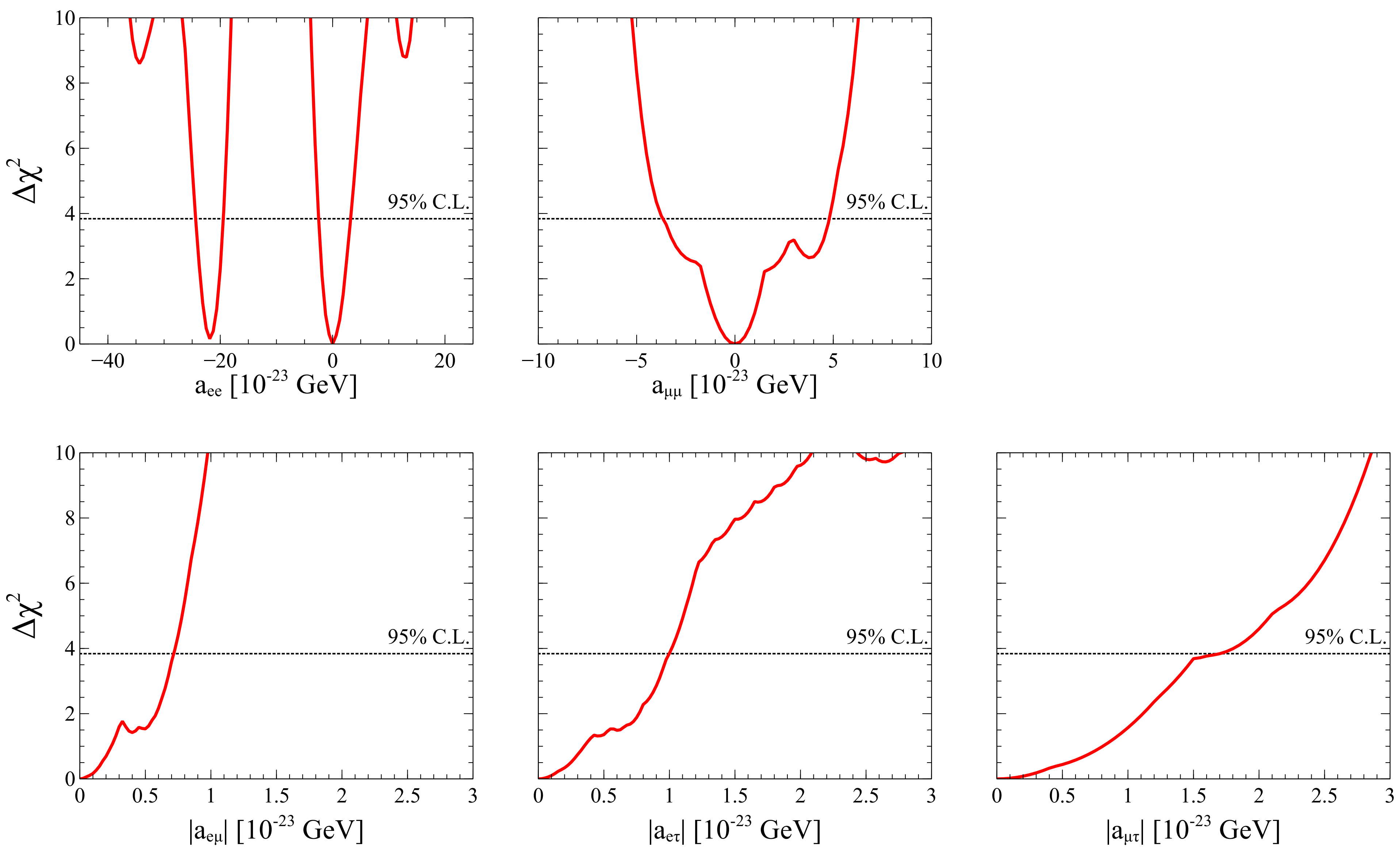
☑ The sensitivity to the standard parameters gets worse



Barenboim, Masud, Ternes, MT,PLB2019

Lorentz violation in ν oscillations

☑ DUNE's sensitivity to Lorentz-violating parameters

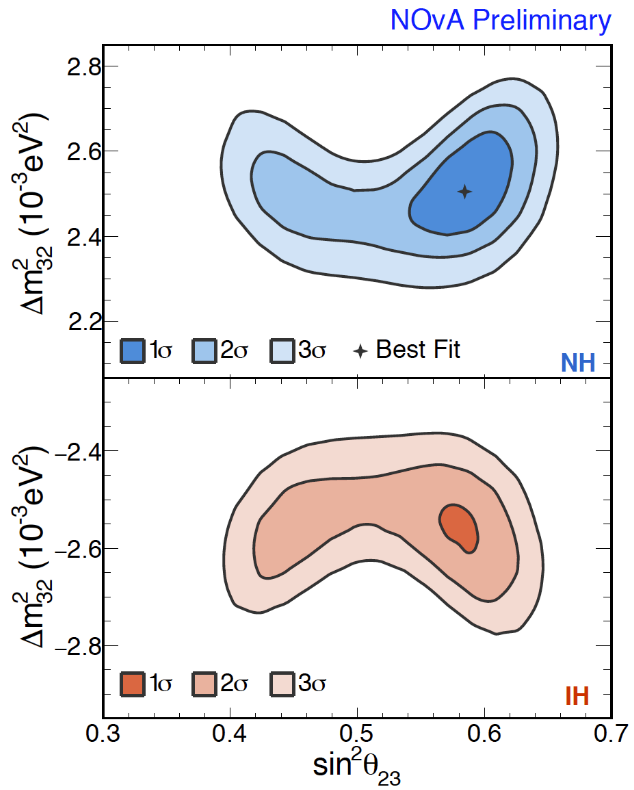


Barenboim, Masud, Ternes, MT,PLB2019

New experimental data

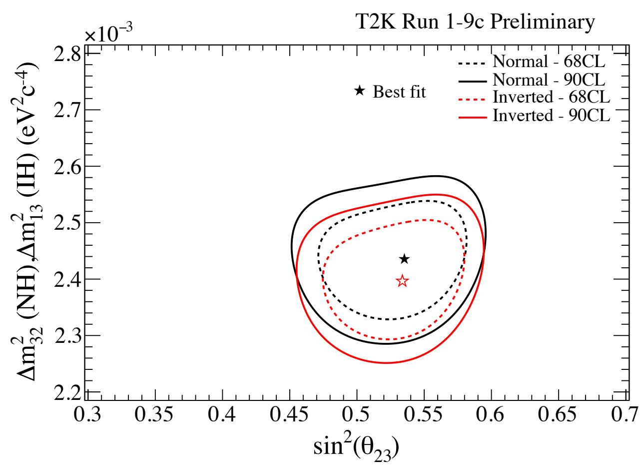
First NOvA antineutrino data

M. Sánchez, Neutrino'18



New T2K antineutrino data

M. Wascko, Neutrino'18



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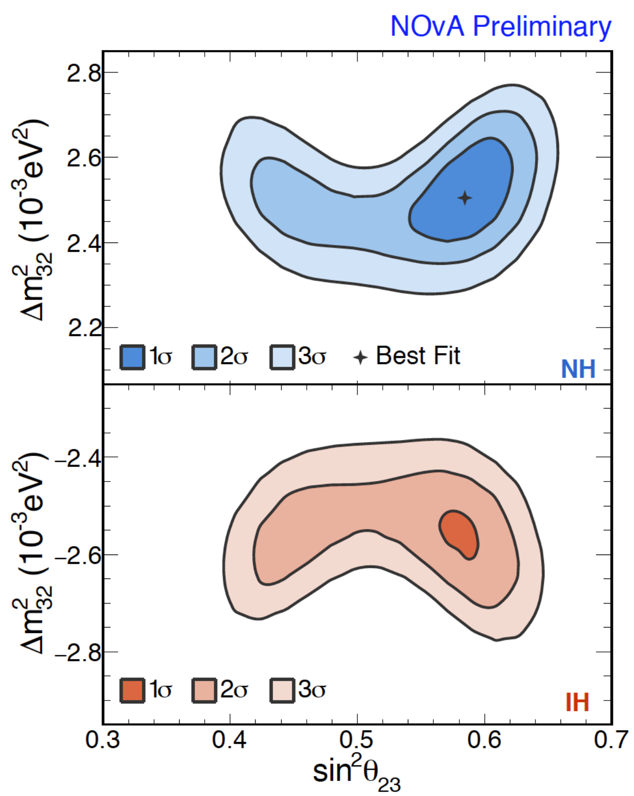

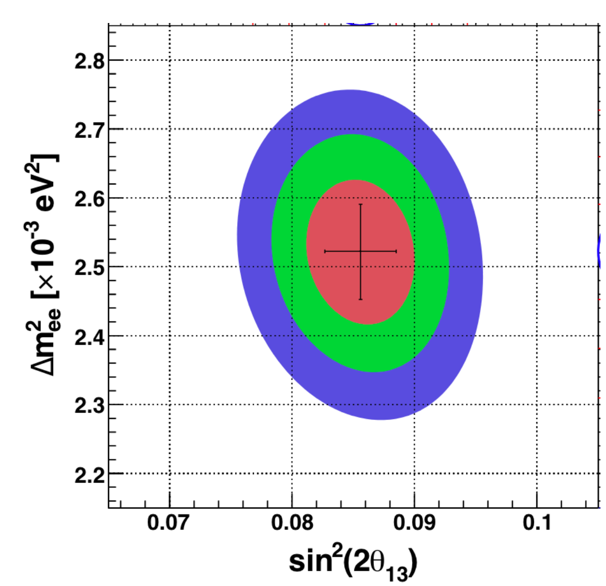

Daya Bay 1958-day data

Adey et al, 1809.02261

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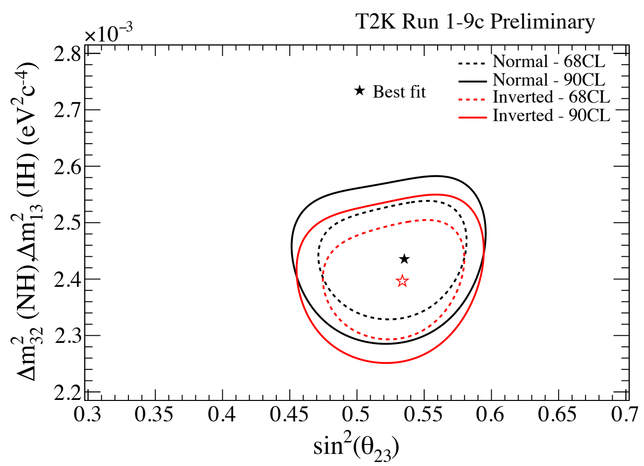

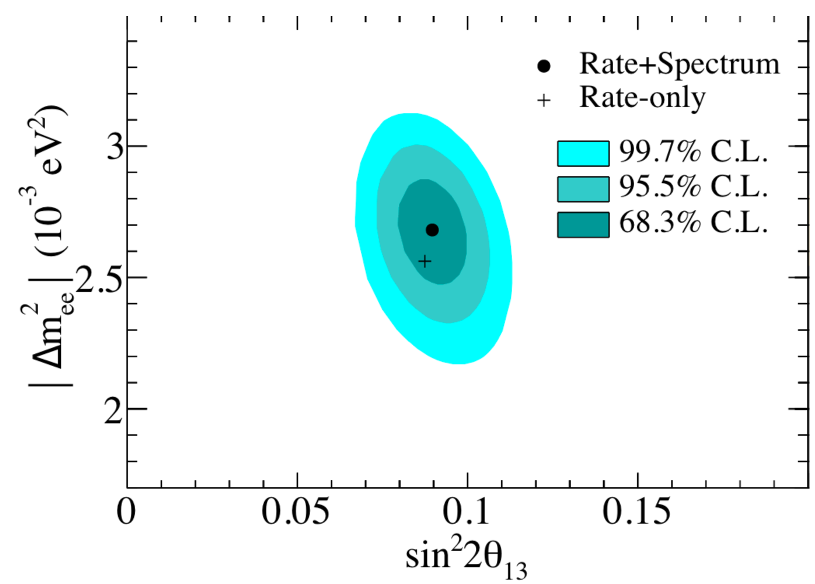

RENO 2200-day data

Bak et al, 1806.00248

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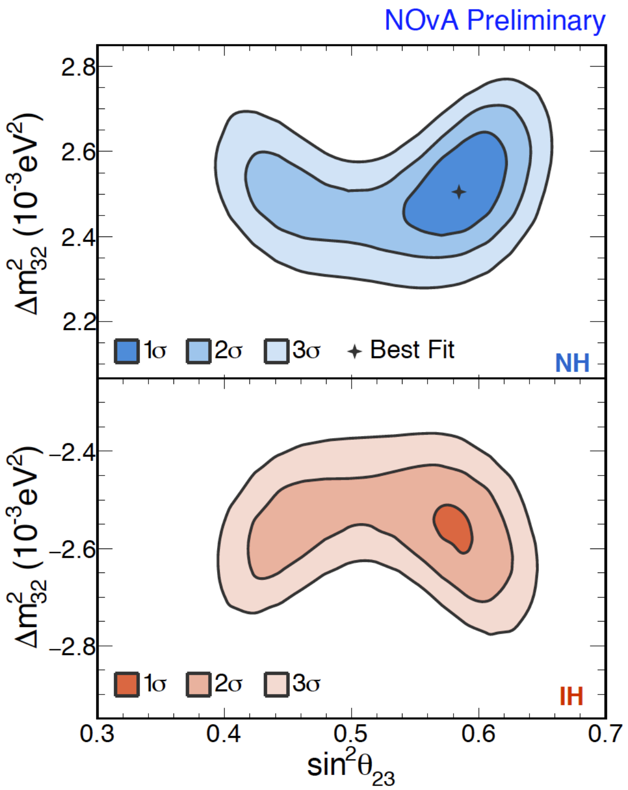

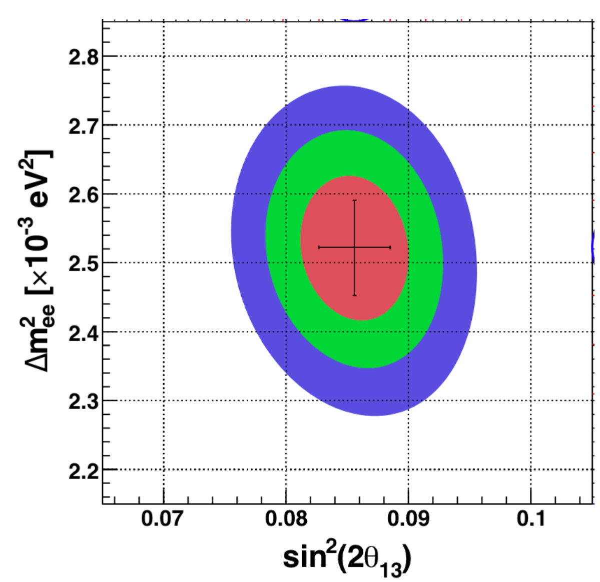

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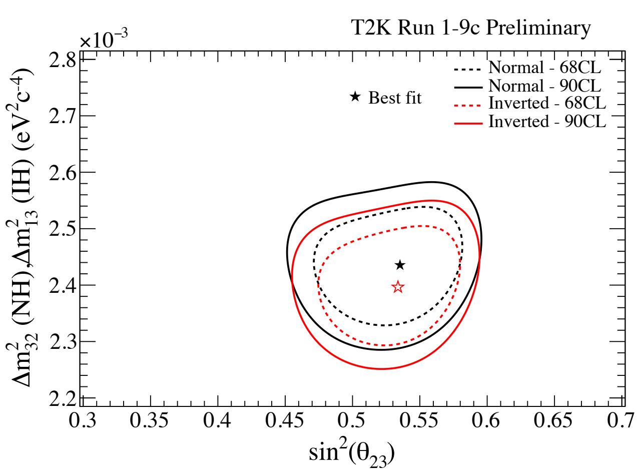
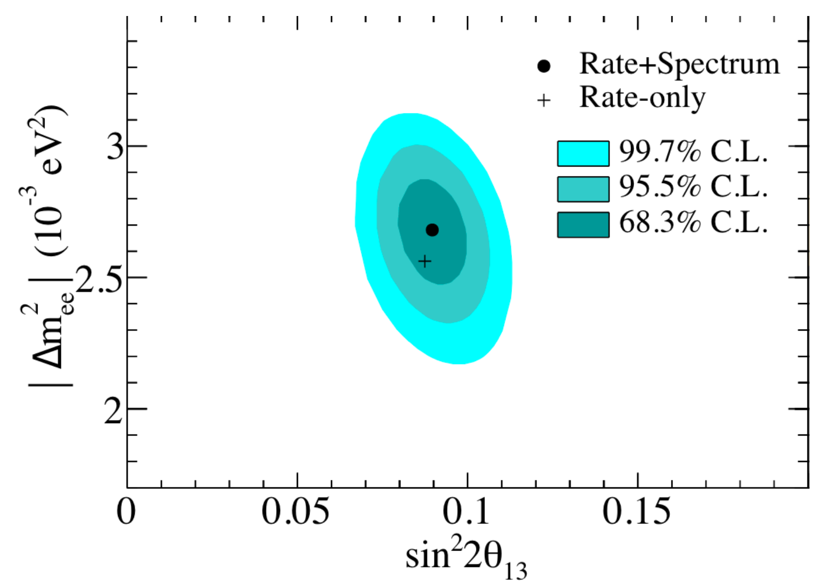




RENO 2200-day data

Bak et al, 1806.00248

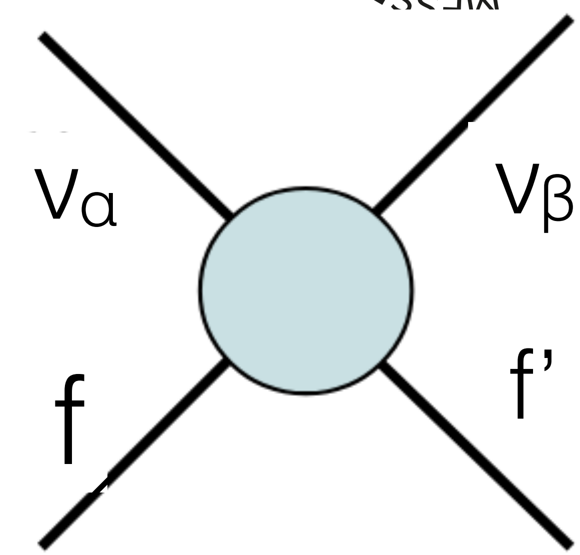
Three-year high-statistics IceCube data

M.G. Aartsen et al., 1902.07771

10 yr ANTARES atmospheric data

Albert et al, 1812.0865

Neutrino NSI with matter



- NSI appear in models of neutrino masses
- Information about the size of NSI could be very useful for neutrino model building
- NSI may affect oscillation parameters

  ⇒ precision measurements at current experiments
  ⇒ sensitivity reach of upcoming experiments(degeneracies)

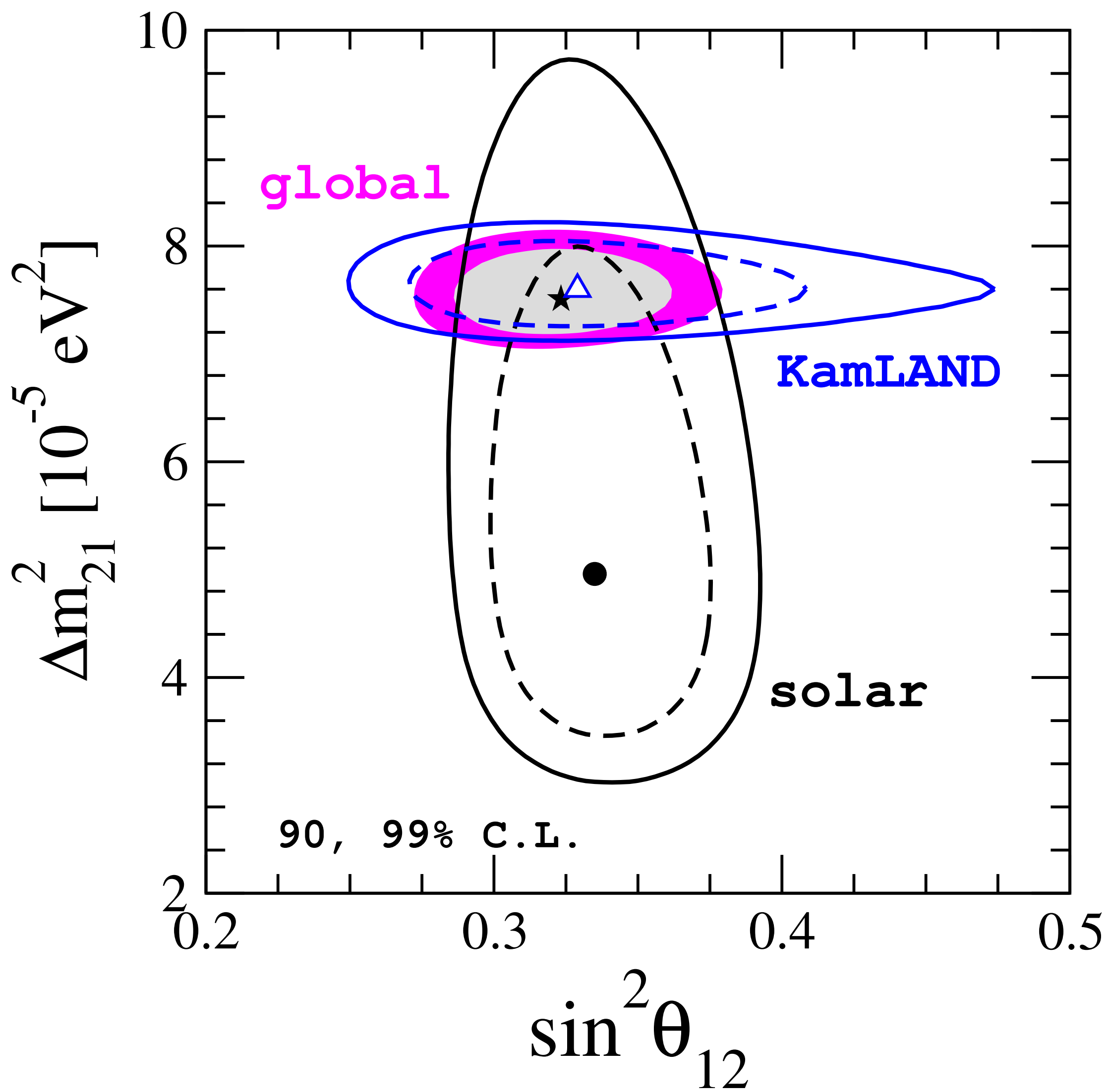
$$\mathcal{L}_{\rm NC-NSI} = -2\sqrt{2} G_F\, \epsilon_{\alpha\beta}^{fX} \left(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta\right) \left(\bar{f} \gamma_\mu P_X f\right)$$

$\epsilon_{\alpha\beta} \neq 0$ → NSI violate lepton flavor (FC-NSI)

$\epsilon_{\alpha\alpha} - \epsilon_{\beta\beta} \neq 0$ → NSI violate lepton universality (NU-NSI)

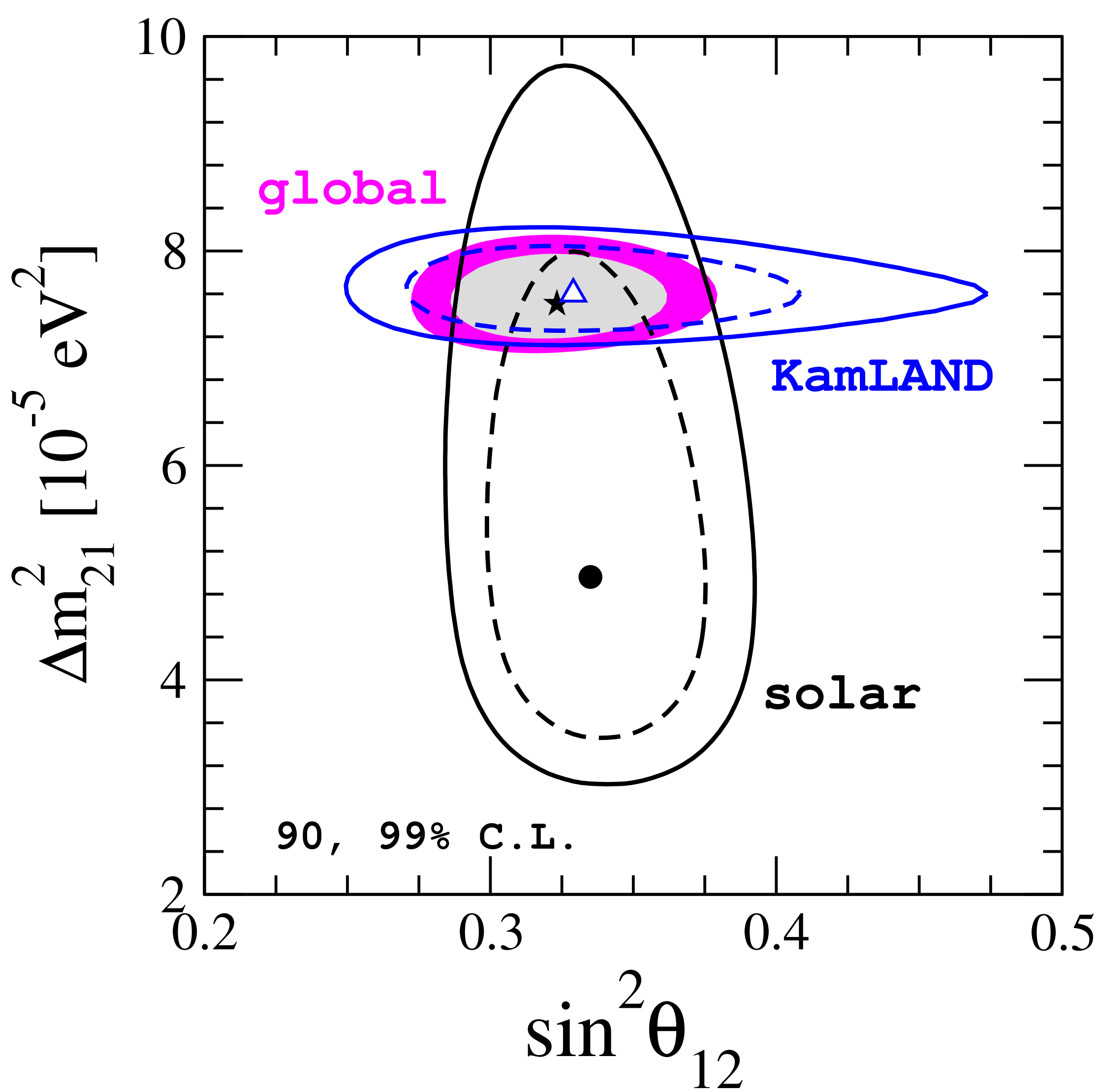
⇒ mainly affecting neutrino propagation in matter (but also detection in Super-K & Borexino)

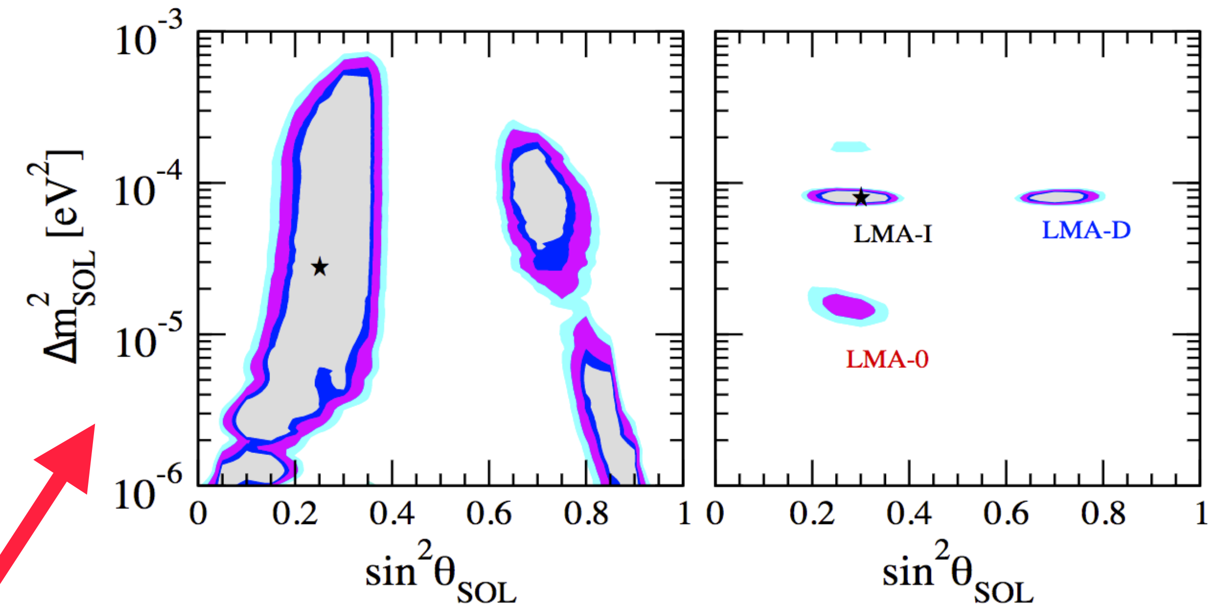
NSI in solar ν sector



de Salas et al, PLB782 (2018) 633

NSI in solar ν sector



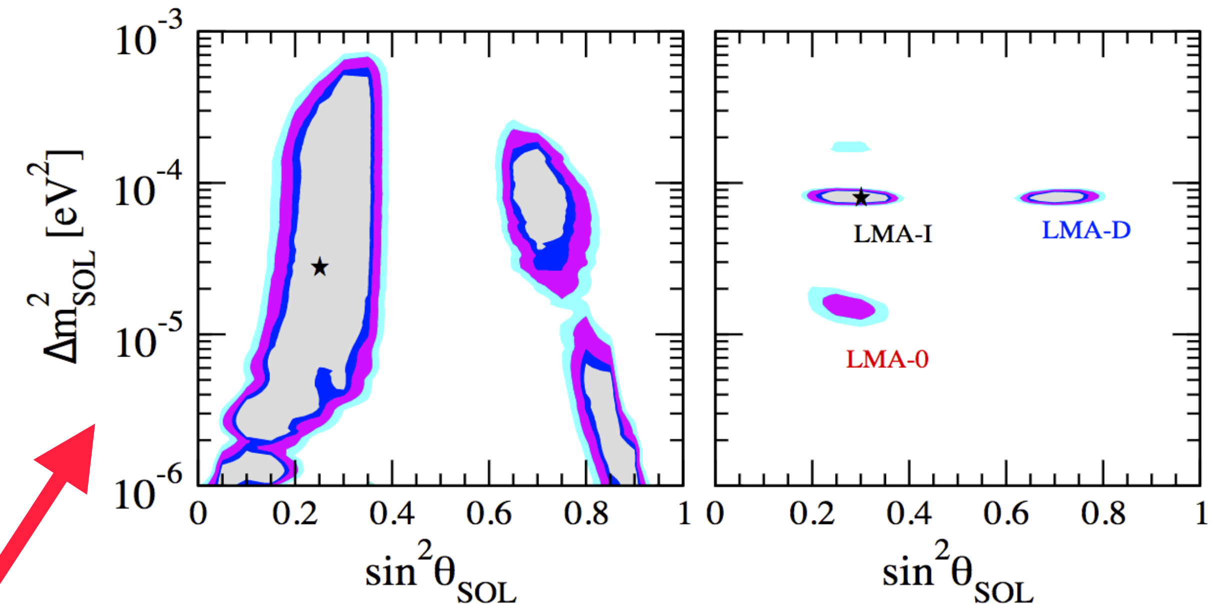


⇒ degenerate solar solution

de Salas et al, PLB782 (2018) 633

NSI in solar ν sector

Miranda et al, JHEP 2006



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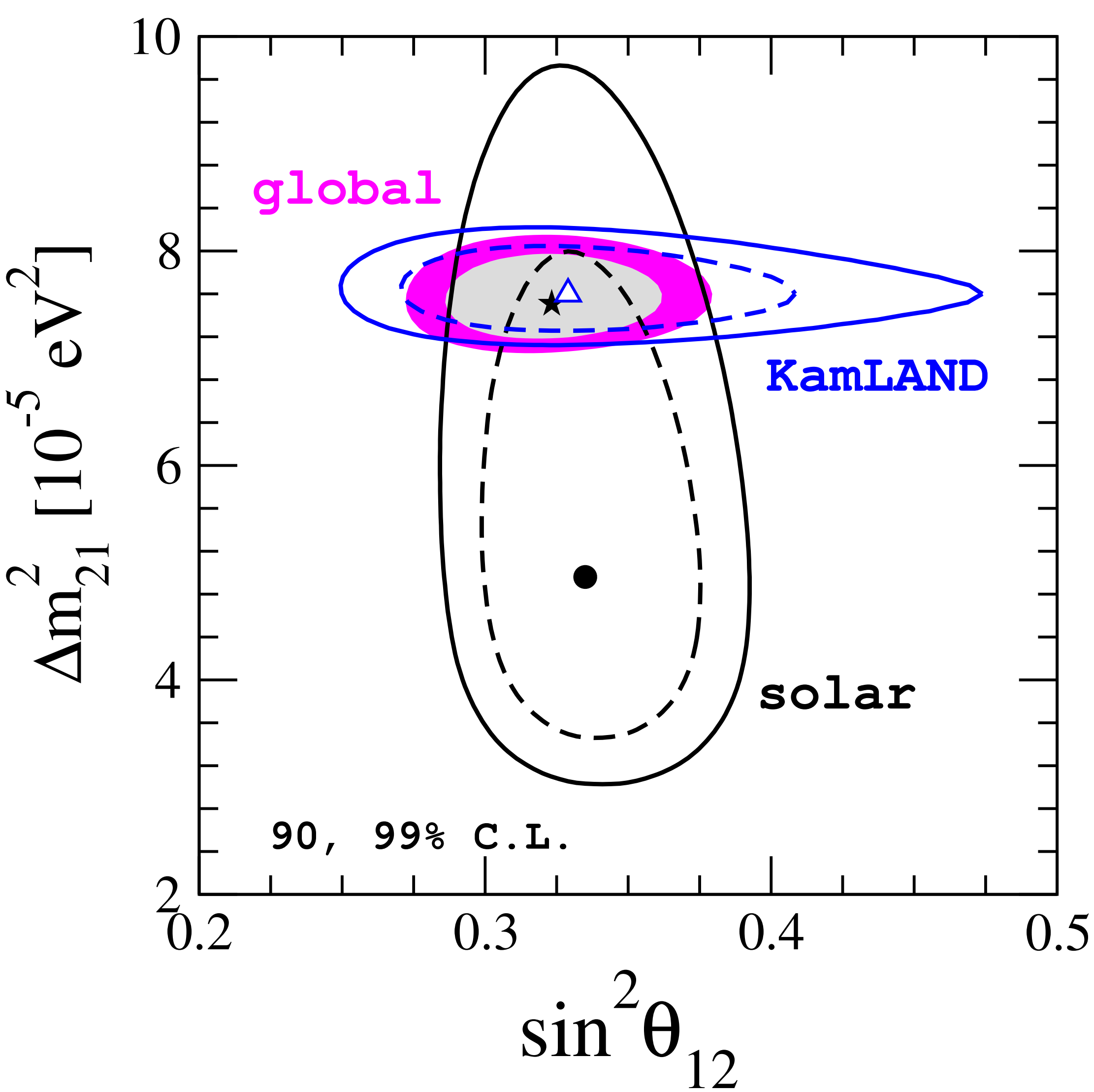
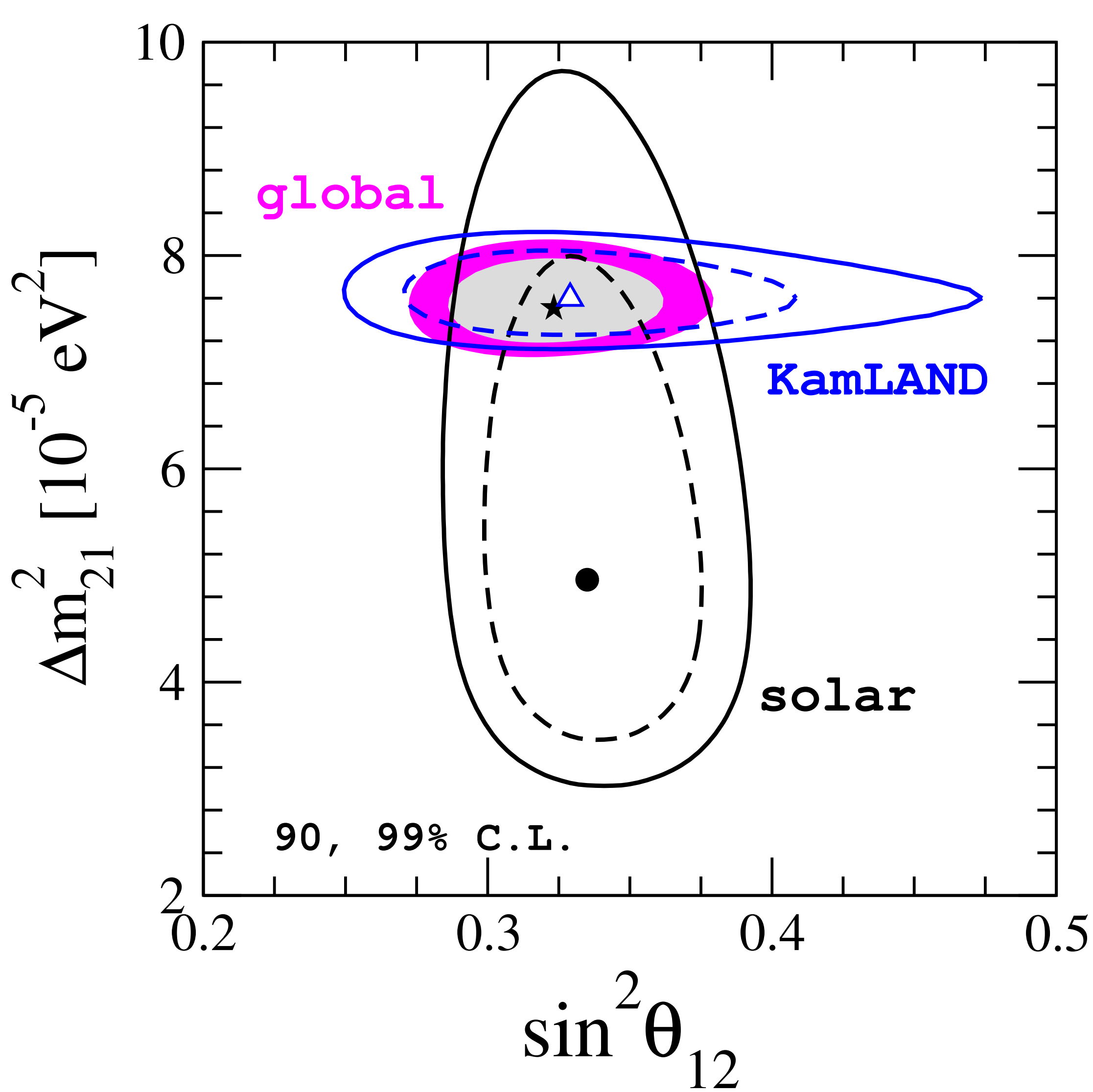


de Salas et al, PLB782 (2018) 633

NSI in solar ν sector

Standard 3ν oscillations



de Salas et al, PLB782 (2018) 633

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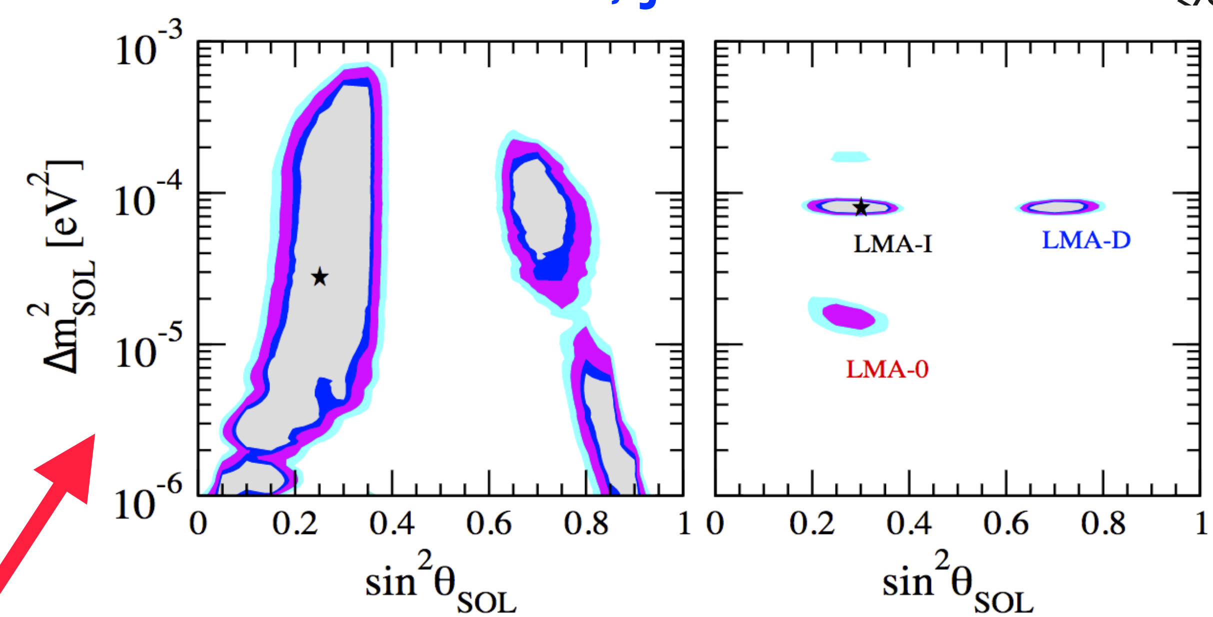

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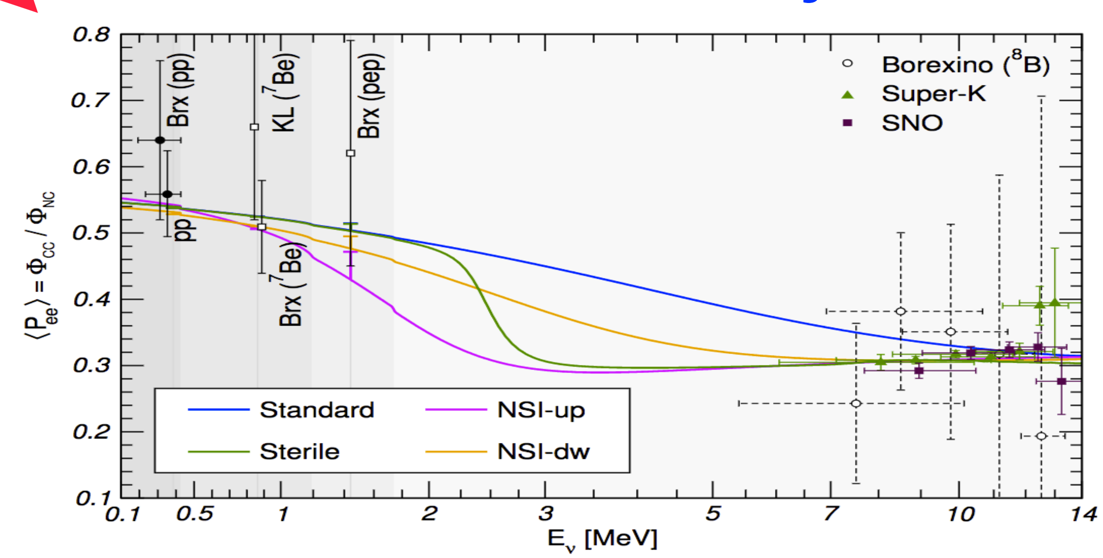
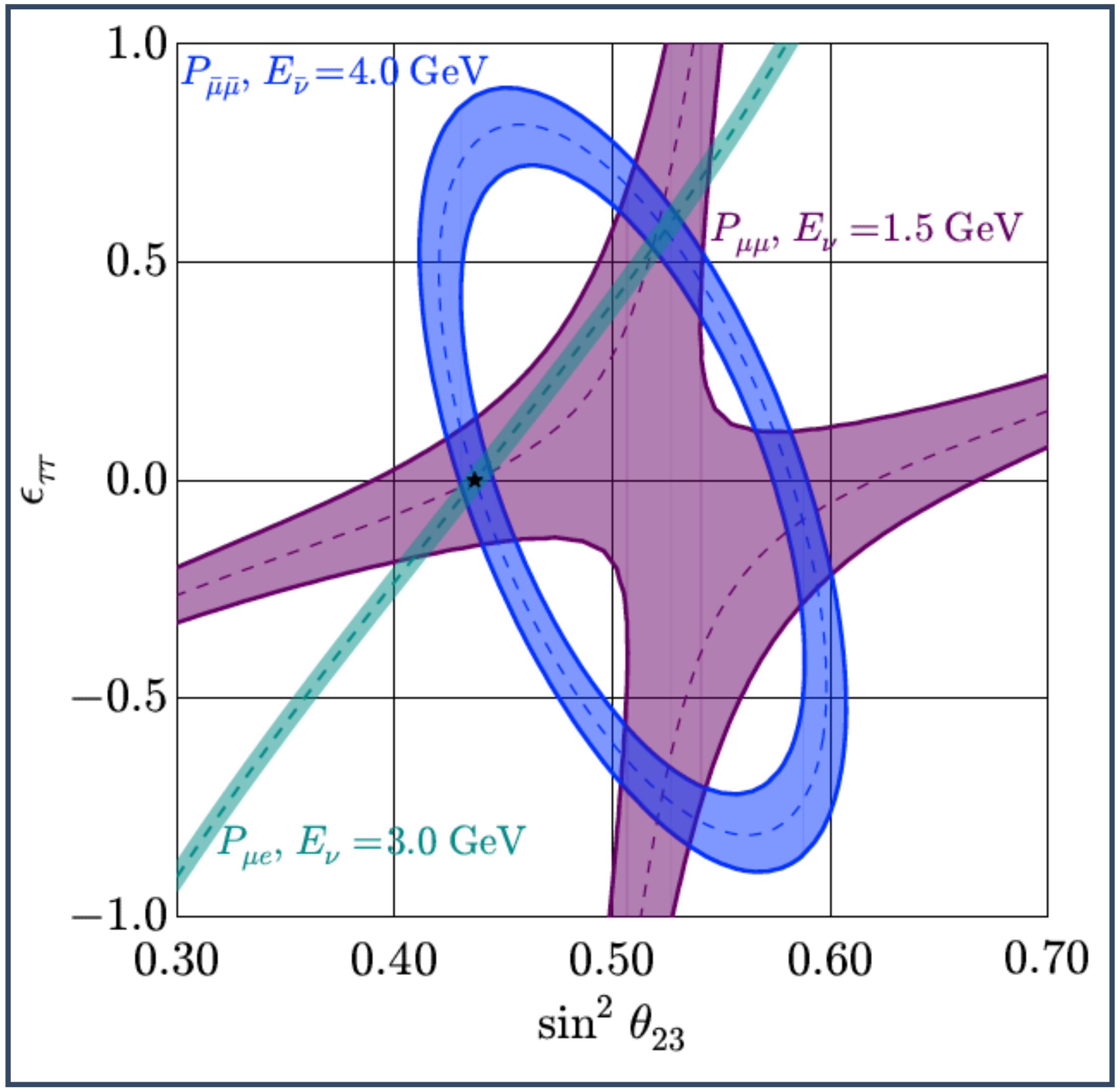
Maltoni & Smirnov, EPJ 2015



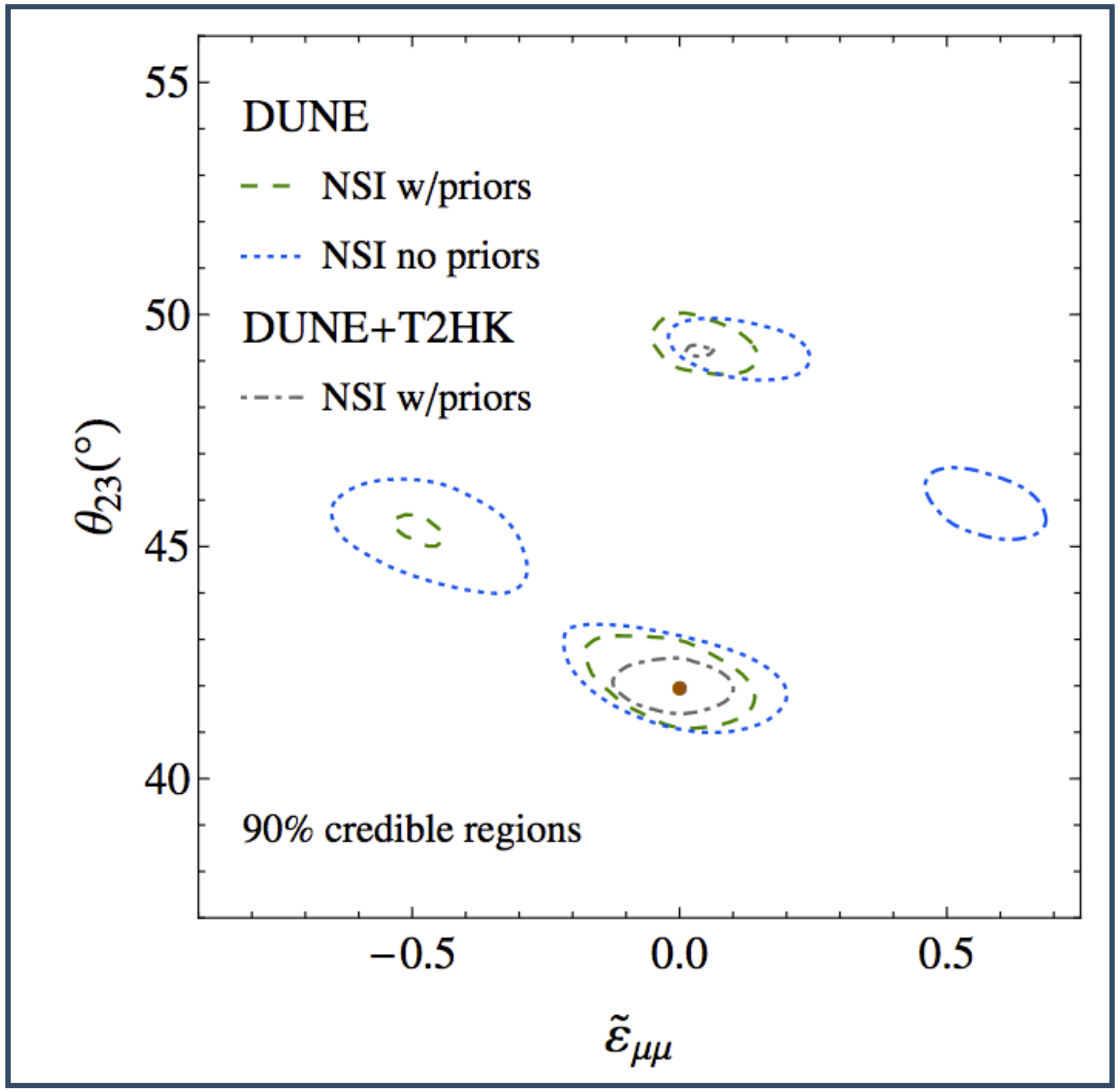
⇒ reconciles tension between Δm^2_{21} @ KamLAND and solar data

NSI at future LBL experiments

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



Gouvea and Kelly, NPB 2016



Coloma, JHEP 2016

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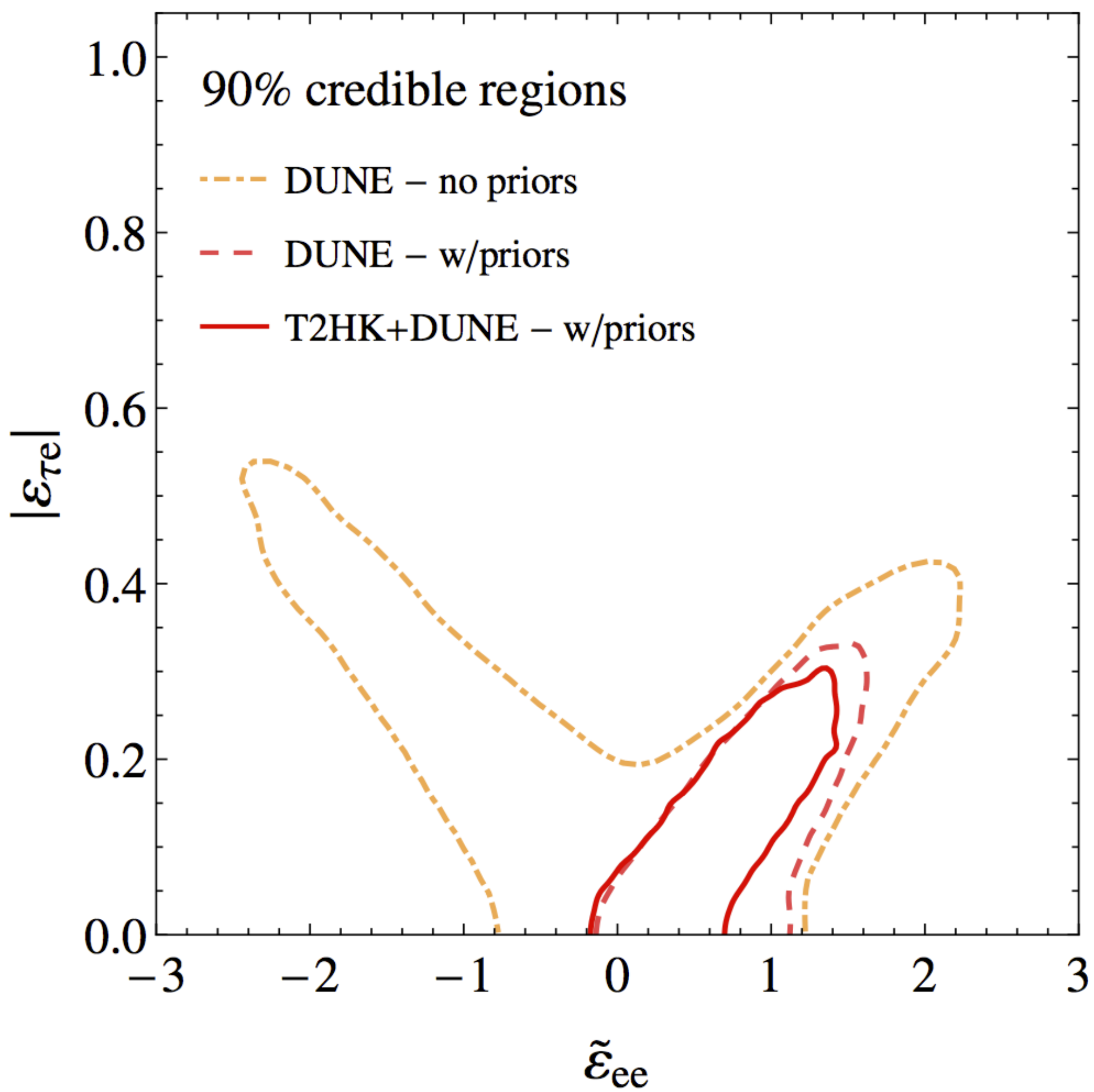

Coloma, JHEP 2016

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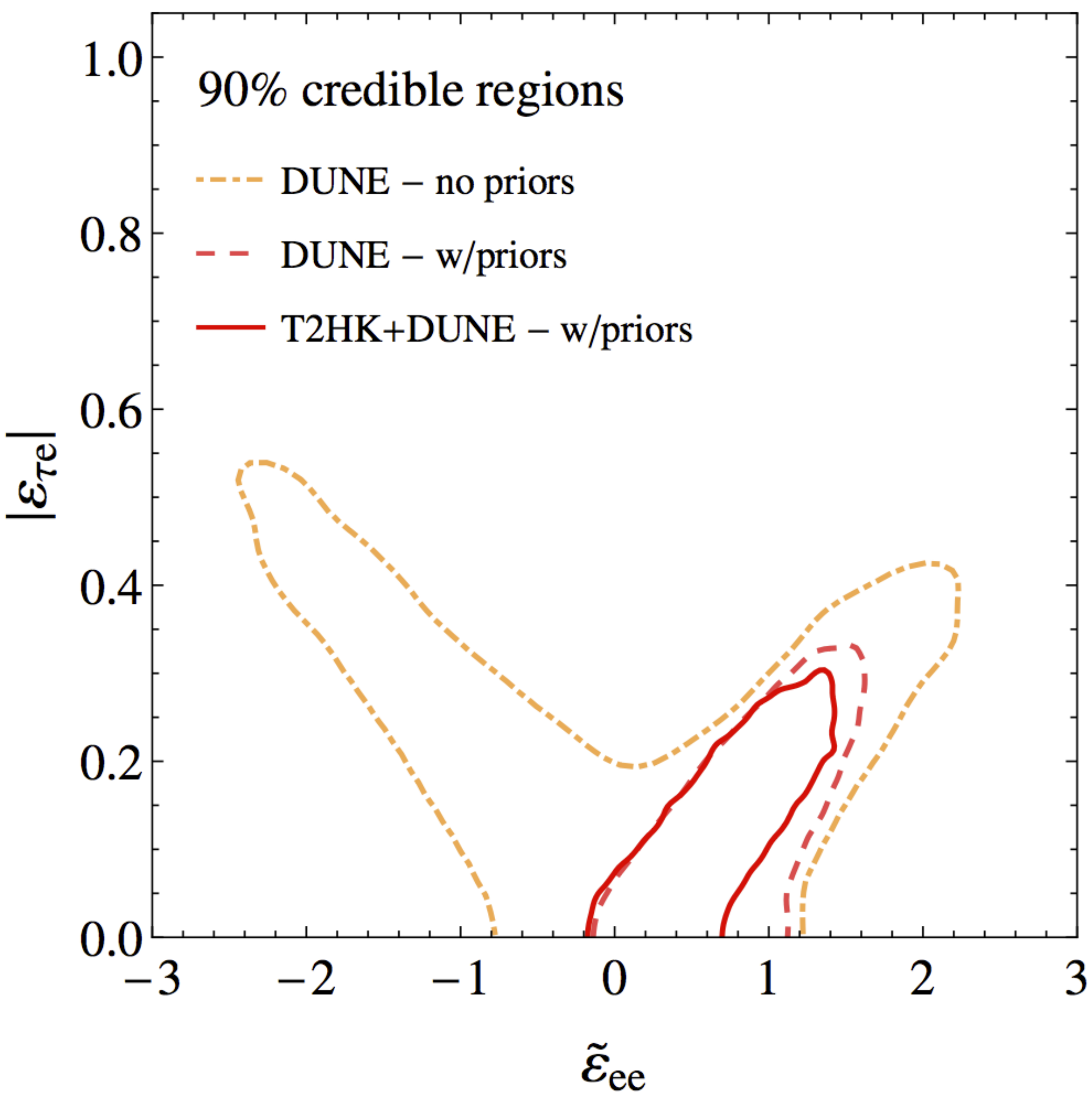
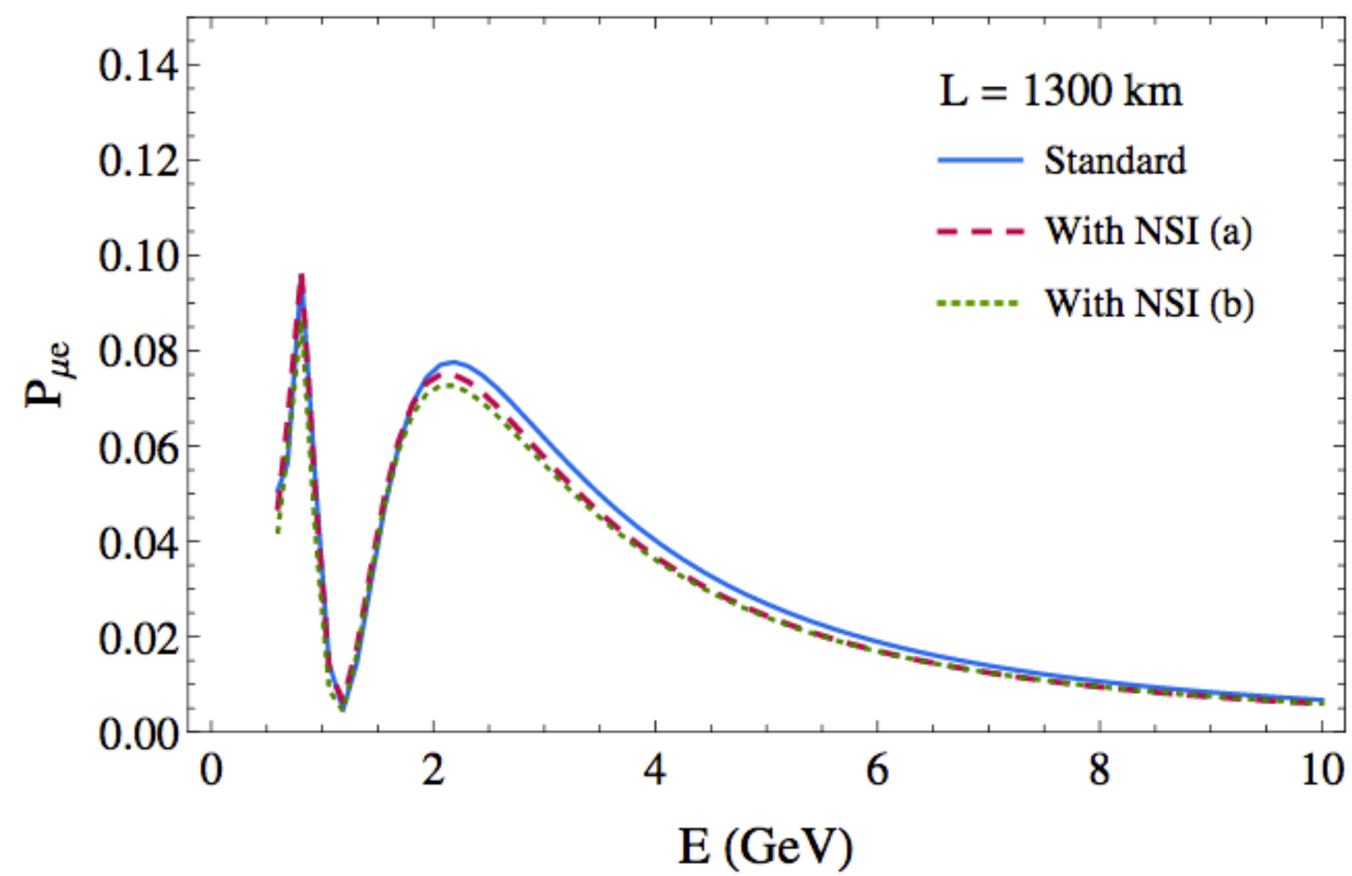


Coloma, JHEP 2016

⇒ it may affect CP-violation sensitivity



NSI: Notation

✓NSI in neutrino propagation in matter:

$$\epsilon_{\alpha\beta}^{fV} = \epsilon_{\alpha\beta}^{fL} + \epsilon_{\alpha\beta}^{fR}$$

(NSI at detection: $\epsilon_{\alpha\beta}^{fL}$, $\epsilon_{\alpha\beta}^{fR}$)

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✓ In ordinary matter (e, p, n) → (e, u ,d)

$$\epsilon_{\alpha\beta} \equiv \epsilon_{\alpha\beta}^{eV} + \frac{N_u}{N_e}\epsilon_{\alpha\beta}^{uV} + \frac{N_d}{N_e}\epsilon_{\alpha\beta}^{dV}$$ with $$V_{\rm NSI} \propto \epsilon_{\alpha\beta} N_e$$

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✓However:

$$\epsilon_{\alpha\beta} = \sum_f \frac{N_f}{N_d}\epsilon_{\alpha\beta}^{fV} \qquad \text{with} \qquad V_{\text{NSI}} \propto \epsilon_{\alpha\beta} N_d$$

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Sun: $N_u/N_e \simeq 2N_d/N_e \simeq 1$

Earth: $N_u/N_e \simeq N_d/N_e \simeq 3$

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Factor 3 difference!!

✓ However:

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with $V_{\rm NSI} \propto \epsilon_{\alpha\beta} N_d$

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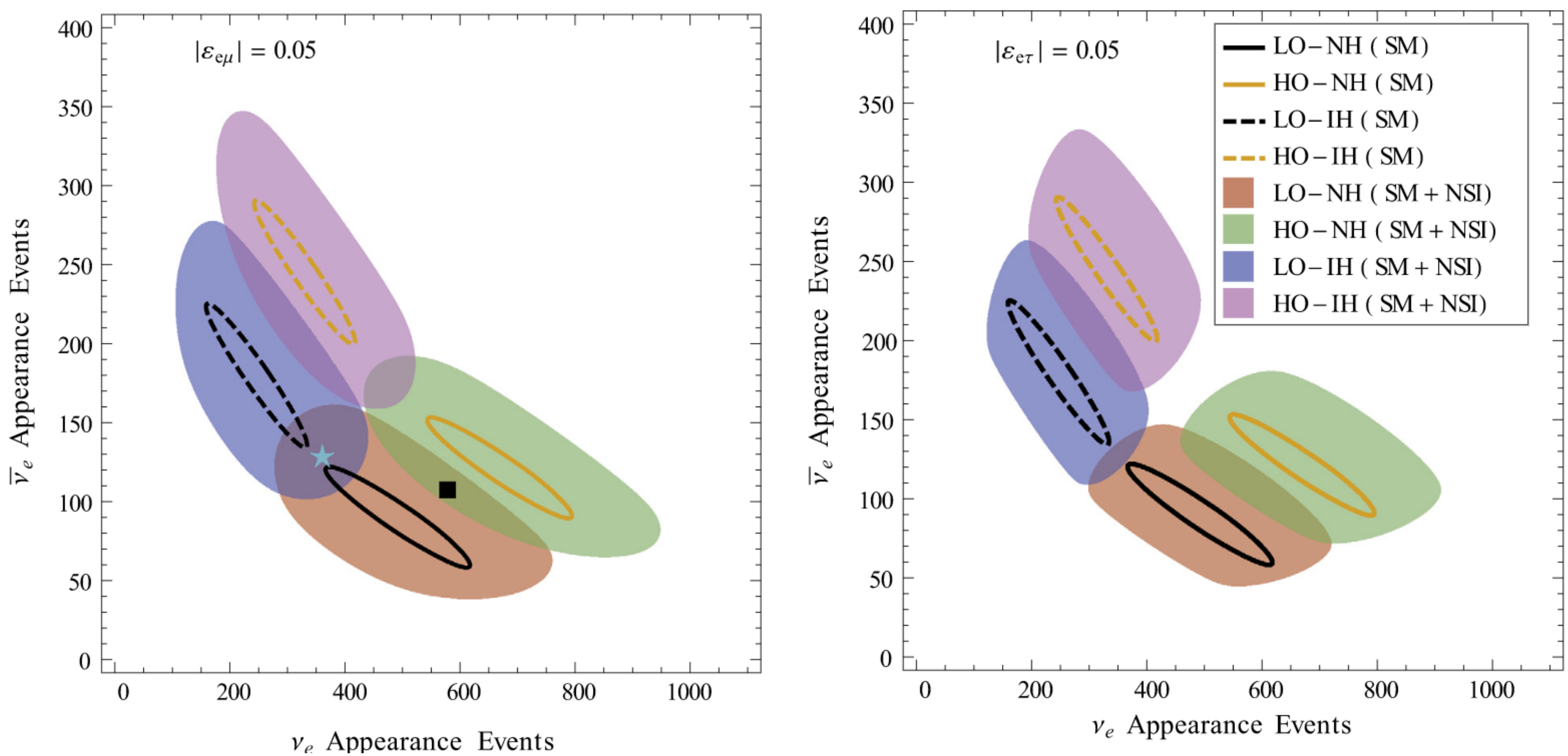
$\epsilon_{\alpha\beta}^{fV}$

NSI at future LBL experiments

Degeneracies in determination of θ_{23} octant in DUNE

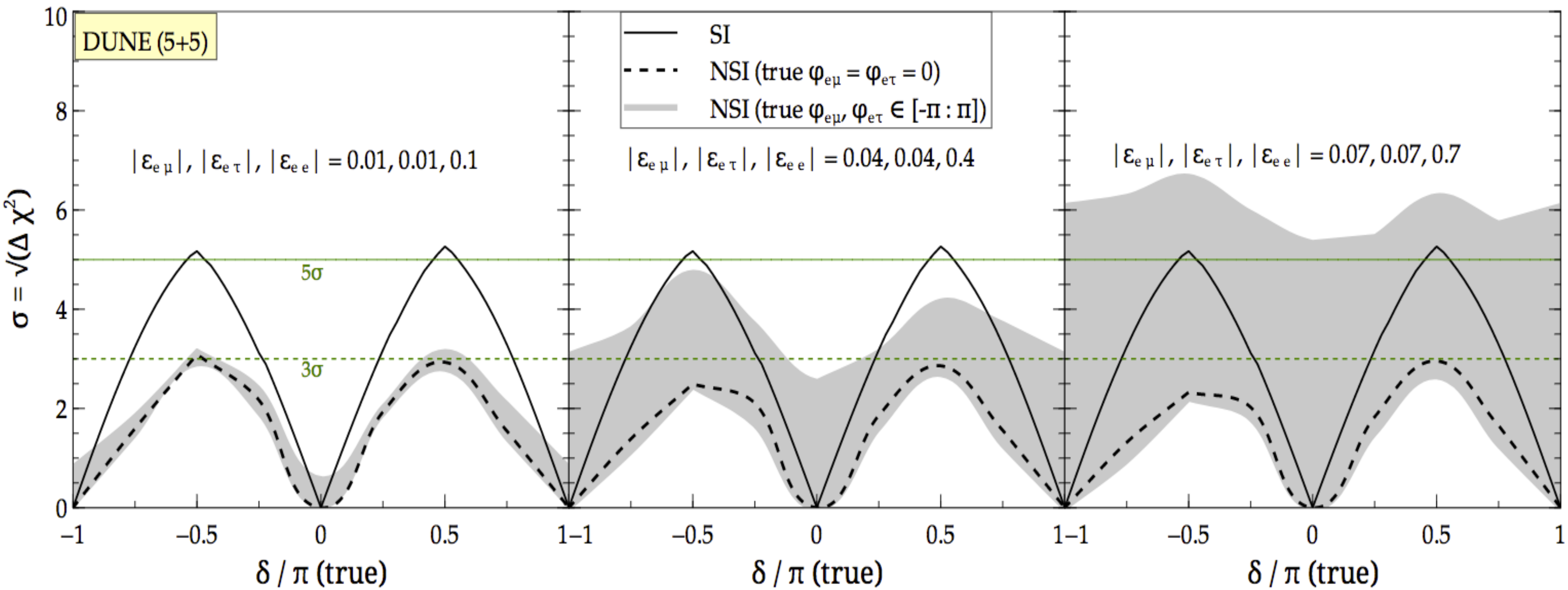


Agarwalla et al, PLB 2016

⇒ interference term in $\phi_{e\alpha}$ can mimic swap in the octant

NSI at future LBL experiments

NSI significantly spoil sensitivity to CP violation in DUNE



Masud and Mehta, PRD 2016

NSI at future LBL experiments

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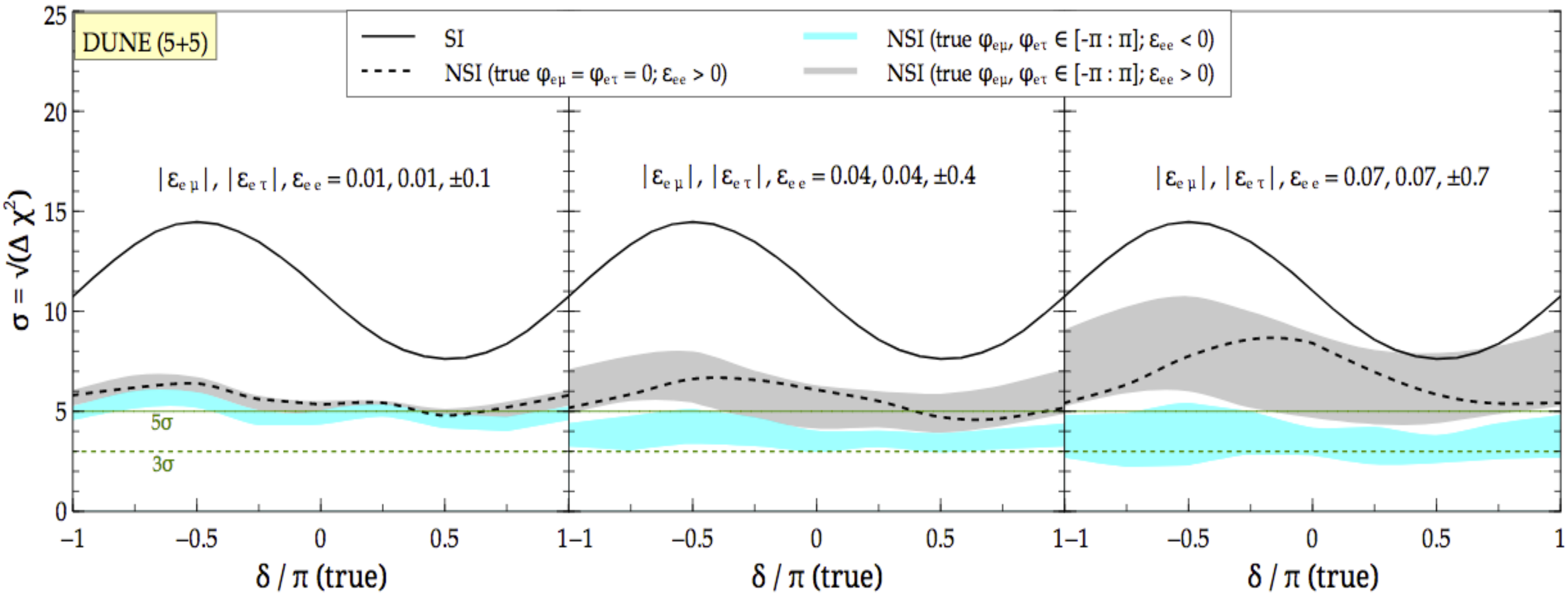


Masud and Mehta, PRD 2016

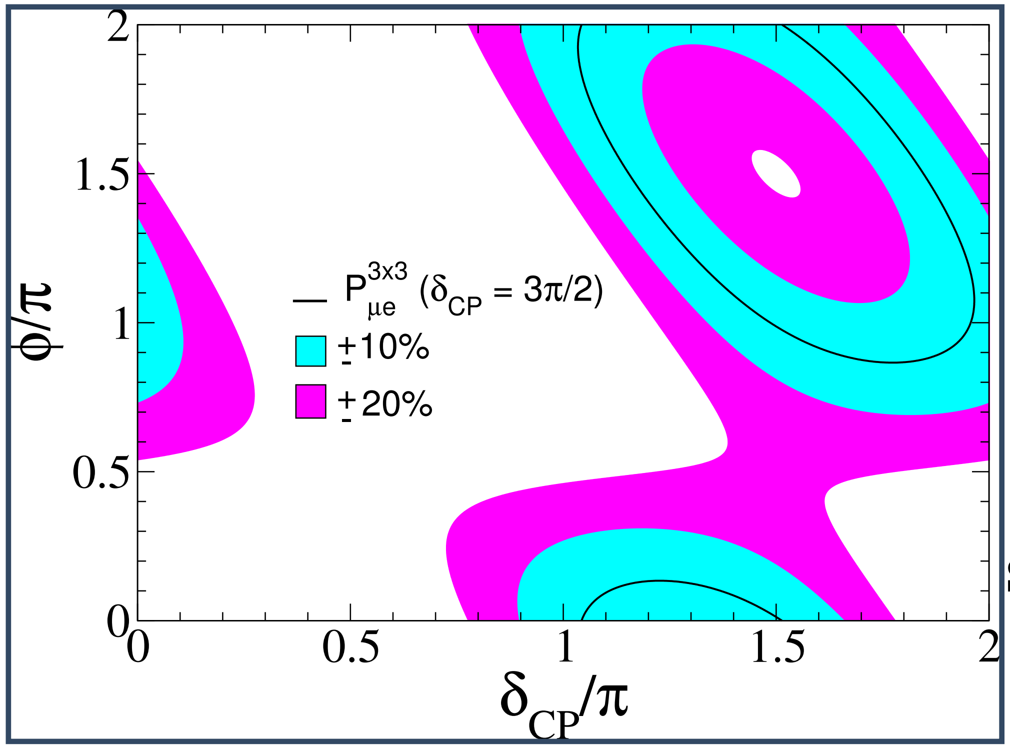
Non-unitary light ν mixing

- Most models of neutrino masses include **new extra heavy states**

Ex: type I seesaw, inverse seesaw $\begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix}$ $\begin{pmatrix} 0 & M_D & 0 \\ M_D^T & 0 & M \\ 0 & M^T & \mu \end{pmatrix}$

→ (3x3) light neutrino mixing matrix U is **non-unitary** in general

$$N = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U^{3x3}$$



Miranda, MT, Valle, PRL 117 (2016)

(δ, ϕ) degeneracies in $P_{\mu e}$

New phases will modify the standard oscillation picture in LBL

Non-unitary light ν mixing

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Ex: type I seesaw, inverse seesaw

$$\begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix} \qquad \begin{pmatrix} 0 & M_D & 0 \\ M_D^T & 0 & M \\ 0 & M^T & \mu \end{pmatrix}$$

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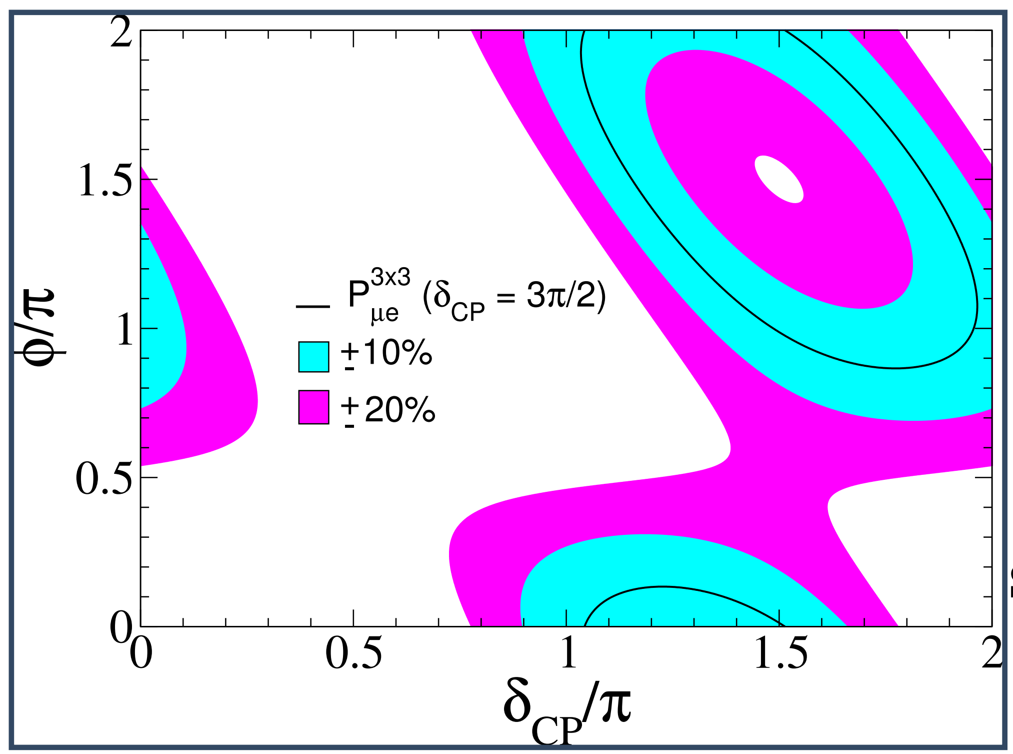
- General parameterization for non-unitary NxN mixing matrix

$$U^{n\times n} = \begin{pmatrix} N & W \\ V & T \end{pmatrix} \quad \text{with}$$

$$N = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U^{3x3}$$

→ α_{ii} real, α_{ij} complex: 9 new parameters



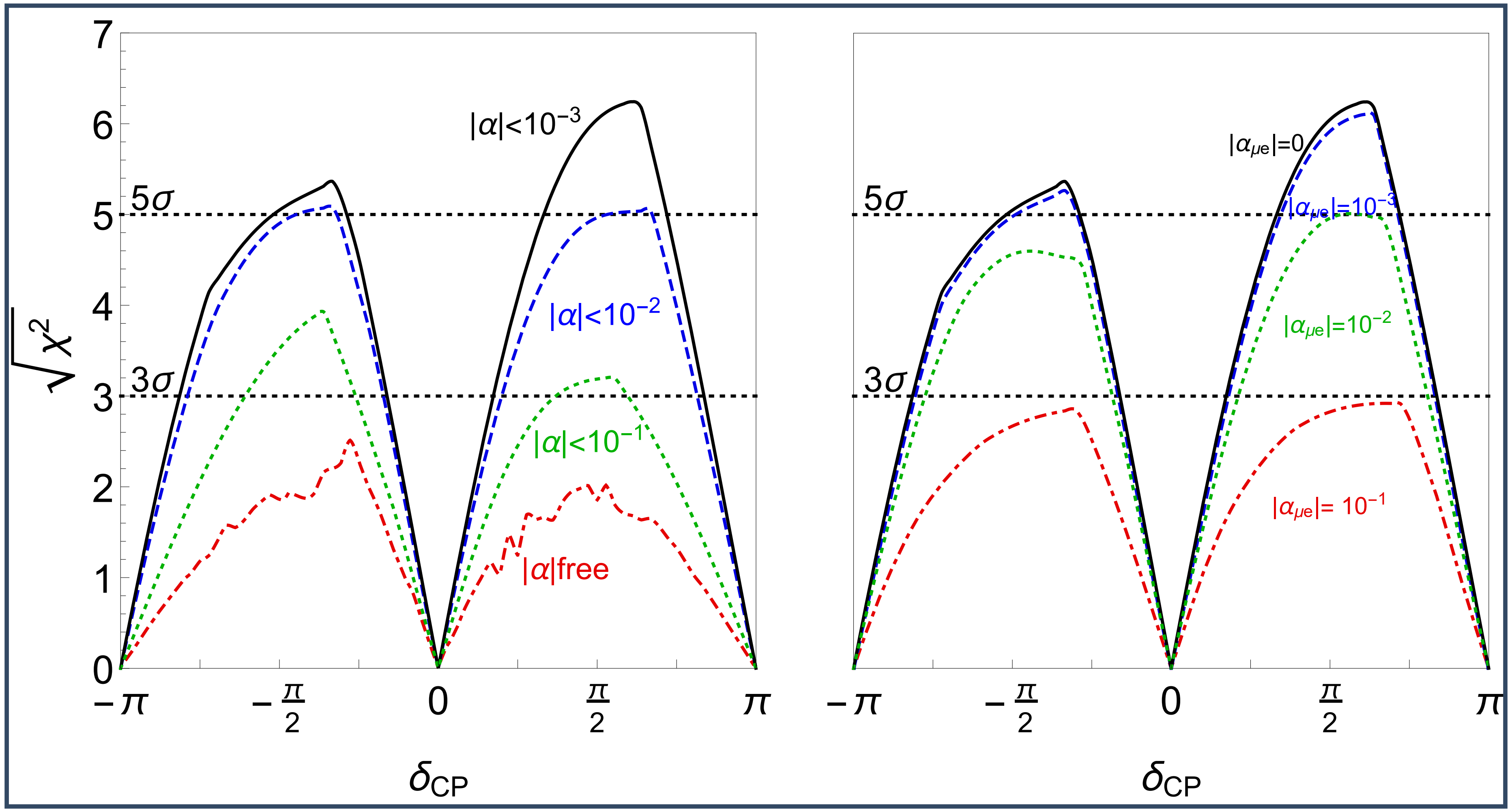
(δ, ϕ) degeneracies in $P_{\mu e}$

New phases will modify the standard oscillation picture in LBL

Escrihuela et al, PRD92 (2015)

Miranda, MT, Valle, PRL 117 (2016)

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

Non-unitary light ν mixing

- Most models of neutrino masses include **new extra heavy states**

  Ex: type I seesaw, inverse seesaw
  $$\begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix} \qquad \begin{pmatrix} 0 & M_D & 0 \\ M_D^T & 0 & M \\ 0 & M^T & \mu \end{pmatrix}$$

  → (3x3) light neutrino mixing matrix U is **non-unitary** in general

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  N(N-1)/2 mixing angles and (N-1)(N-2)/2 Dirac CP phases (4 param for N=3)

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  → besides the three standard θ_{ij} and δ_{CP}, 9 more parameters are needed

- General parameterization for non-unitary NxN mixing matrix

$$U^{n\times n} = \begin{pmatrix} N & W \\ V & T \end{pmatrix} \quad \text{with} \quad N = N^{NP} U^{3\times 3} = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U^{3\times 3}$$

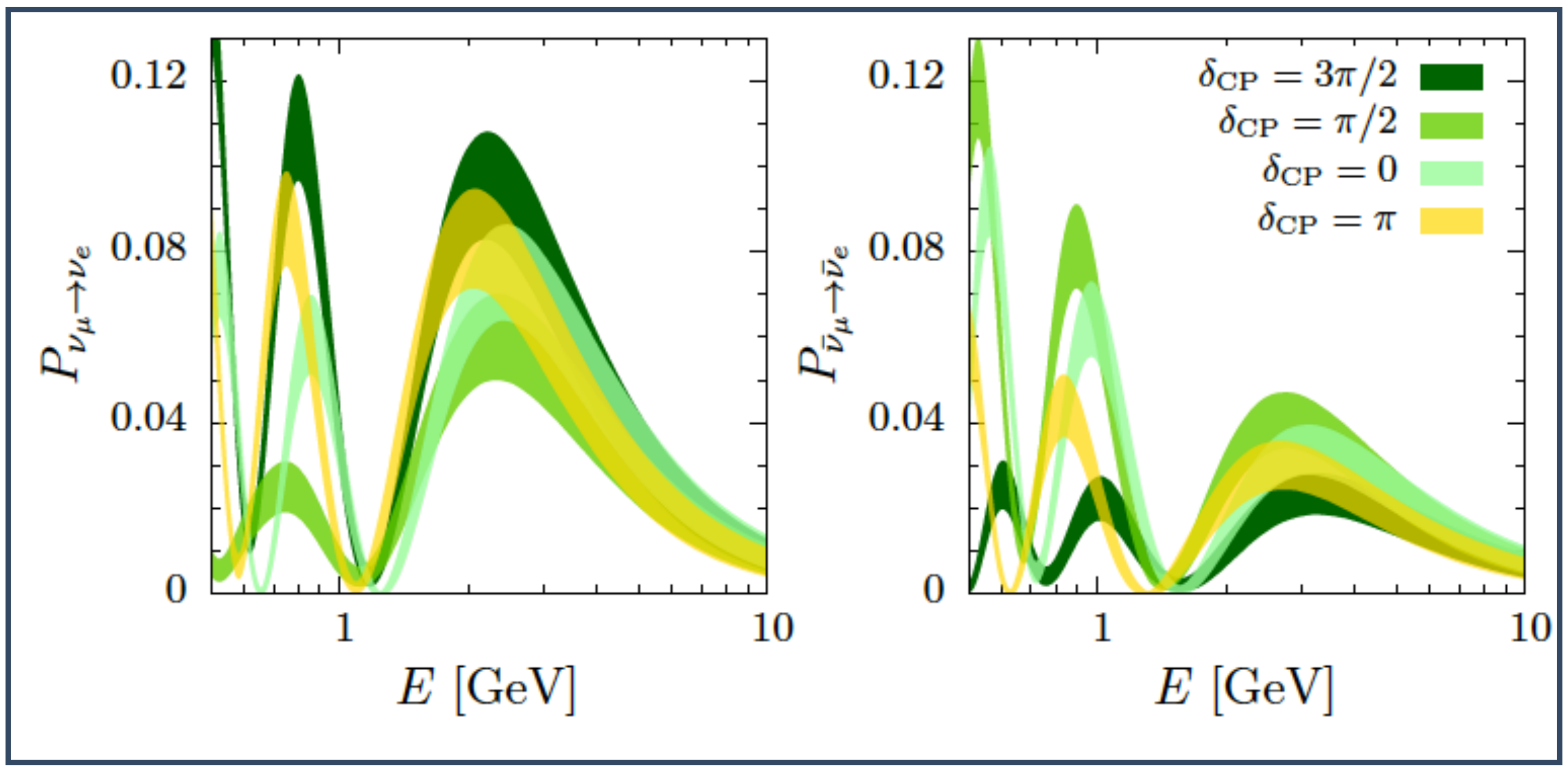
Escrihuela et al, PRD92 (2015)

See also Xing, PRD2012 for n=6

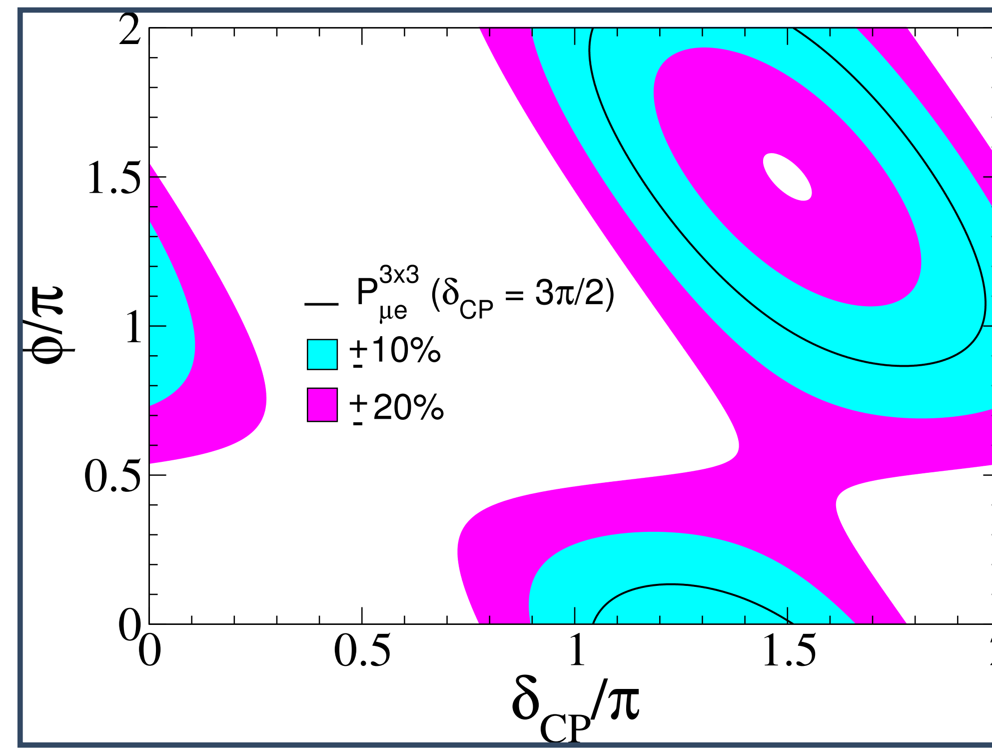
→ α_{ii} real, α_{ij} complex: 9 new parameters

NU ν oscillations in DUNE

The new phases will modify the standard oscillation picture in LBL experiments, such as DUNE



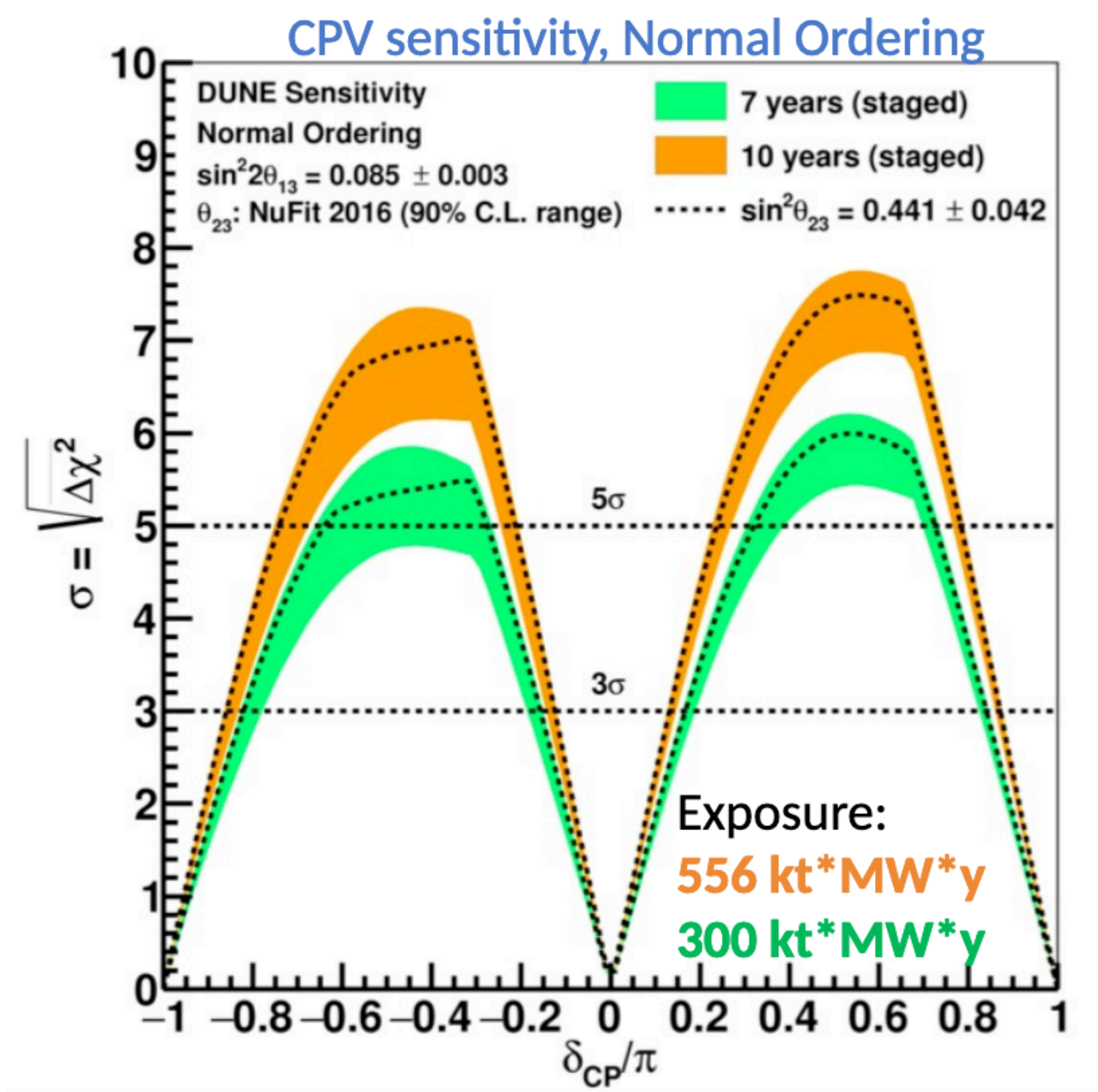
Escrihuela et al, NJP 2017



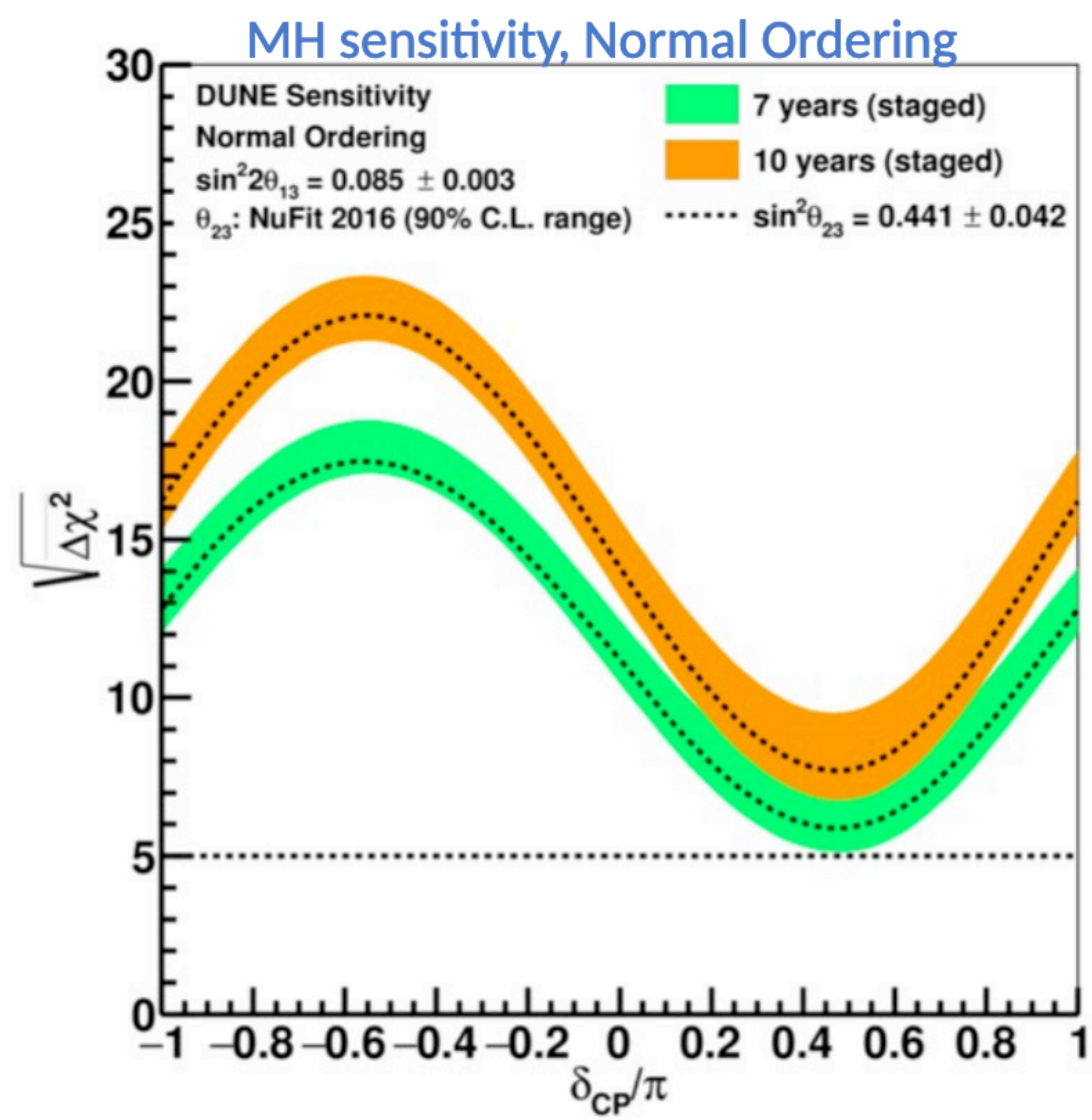
Miranda, MT, Valle, PRL 117 (2016)

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

Sensitivity to CP-violation and mass ordering in DUNE



DUNE Conceptual Design Report (CDR)
arXiv:1512.06148



Width of bands indicates variation in possible central values of θ_{23}

>5σ sensitivity for both orderings and the full range of δ_{CP}