

Why precision neutrino physics?

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What do we know

$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$

Solar neutrinos and KamLAND (solar Δm^2)

SNO neutral current

Reactor neutrinos (Daya Bay, RENO, Double Chooz)

Accelerator neutrinos (MINOS, NOvA, T2K, atmospheric Δm^2)

Atmospheric/accelerator neutrinos (SK)

We do not know the octant of θ_{23}

We do not know the mass ordering (Δm^2_{31} positive or negative?)

We have a mild hint for δ_{cp}

Almost no information on the tau row!

Unitarity and the tau row

Unitarity and the three flavour neutrino mixing matrix

Stephen Parke¹ and Mark Ross-Lonergan²

$$|U|_{3\sigma}^{\substack{\text{w/o Unitarity} \\ \text{(with Unitarity)}}} = \begin{pmatrix} 0.76 \rightarrow 0.85 & 0.50 \rightarrow 0.60 & 0.13 \rightarrow 0.16 \\ (0.79 \rightarrow 0.85) & (0.50 \rightarrow 0.59) & (0.14 \rightarrow 0.16) \\ 0.21 \rightarrow 0.54 & 0.42 \rightarrow 0.70 & 0.61 \rightarrow 0.79 \\ (0.22 \rightarrow 0.52) & (0.43 \rightarrow 0.70) & (0.62 \rightarrow 0.79) \\ 0.18 \rightarrow 0.58 & 0.38 \rightarrow 0.72 & 0.40 \rightarrow 0.78 \\ (0.24 \rightarrow 0.54) & (0.47 \rightarrow 0.72) & (0.60 \rightarrow 0.77) \end{pmatrix}$$

What do we know

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

Reactor SBL ($\bar{\nu}_e \rightarrow \bar{\nu}_e$)	$4 U_{e3} ^2 (U_{e1} ^2 + U_{e2} ^2)$
Reactor LBL ($\bar{\nu}_e \rightarrow \bar{\nu}_e$)	$4 U_{e1} ^2 U_{e2} ^2$
SNO (ϕ_{CC}/ϕ_{NC} Ratio)	$ U_{e2} ^2$

What do we know

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

SK/T2K/MINOS ($\nu_{\mu} \rightarrow \nu_{\mu}$)	$4 U_{\mu 3} ^2 (U_{\mu 1} ^2 + U_{\mu 2} ^2)$
T2K/MINOS ($\nu_{\mu} \rightarrow \nu_e$)	$-4 \operatorname{Re}\{U_{e3}^* U_{\mu 3} (U_{e1}^* U_{\mu 1} + U_{e2}^* U_{\mu 2})\}$

What do we know

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

SK/OPERA ($\nu_{\mu} \rightarrow \nu_{\tau}$)	$-4 \operatorname{Re}\{U_{\tau 3}^* U_{\mu 3} (U_{\tau 1}^* U_{\mu 1} + U_{\tau 2}^* U_{\mu 2})\}$
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Unitarity and the tau row

Unitarity and the three flavour neutrino mixing matrix

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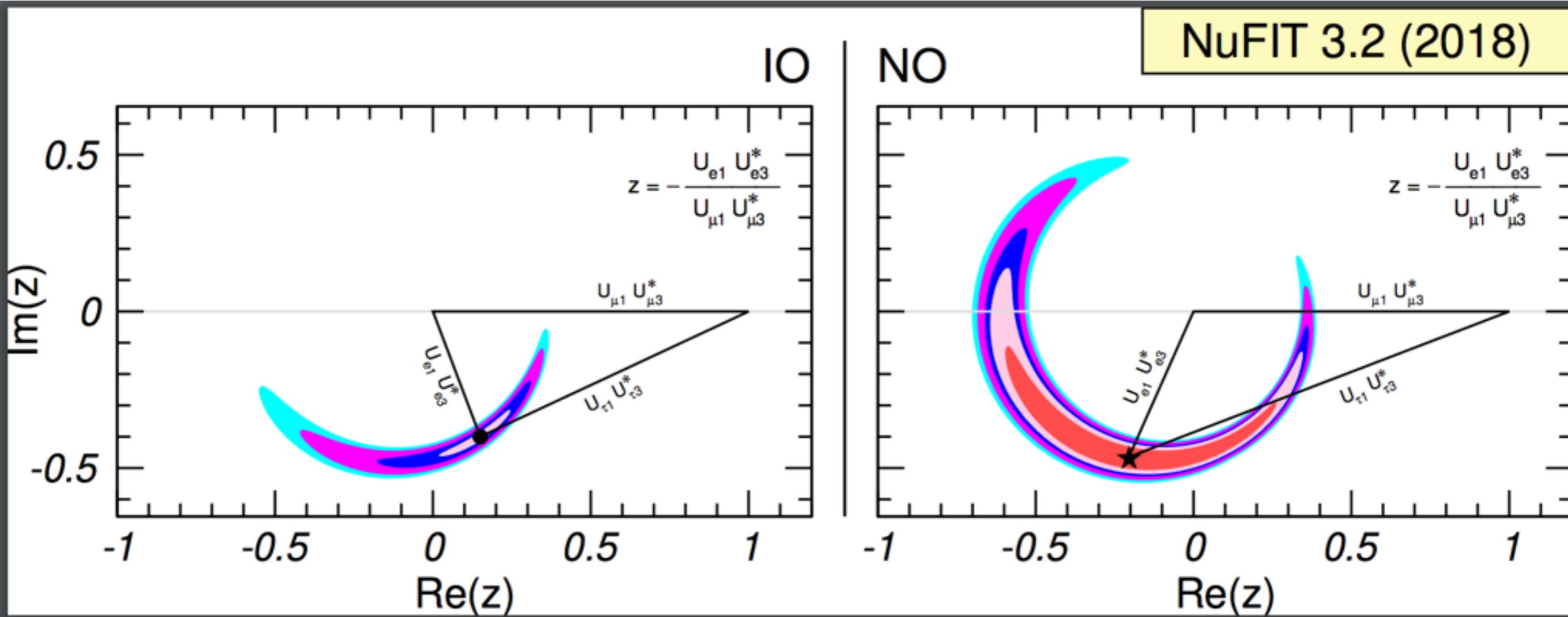
$$|U|_{3\sigma}^{\text{w/o Unitarity}} \text{ (with Unitarity)} =$$

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Unitarity and the tau row



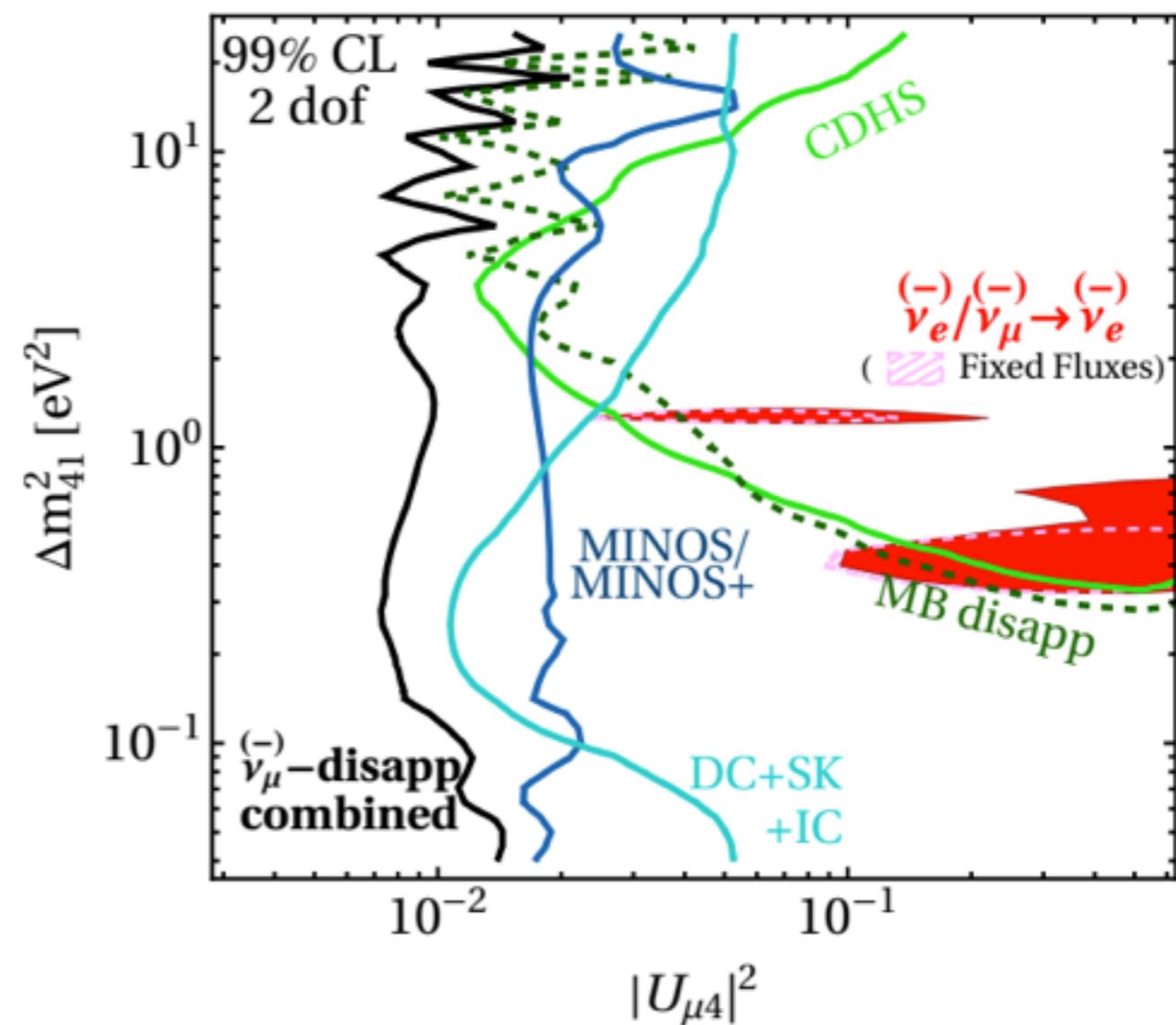
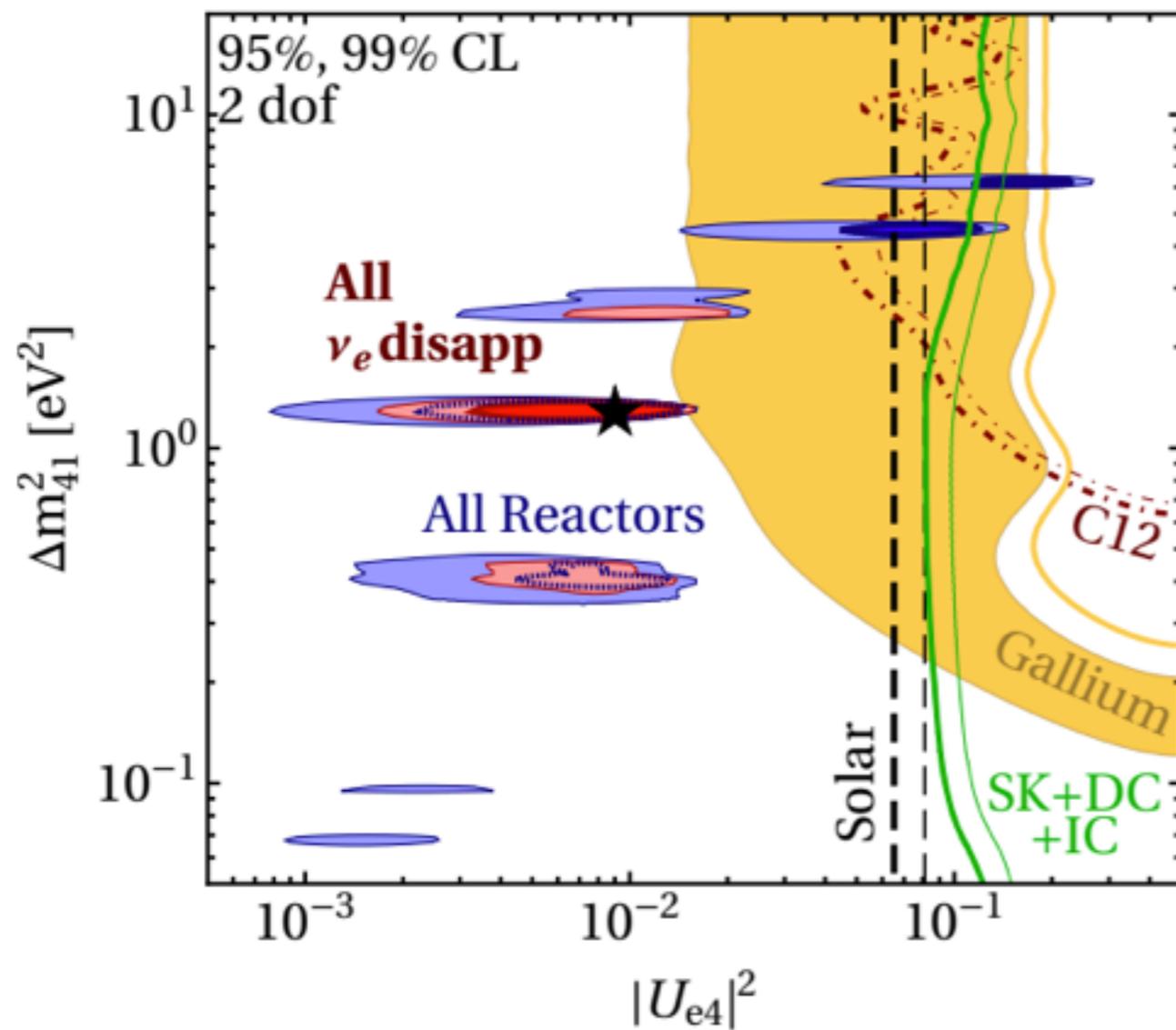
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Updated global analysis of neutrino oscillations in the presence of eV-scale sterile neutrinos

Mona Dentler,^{1, a} Álvaro Hernández-Cabezudo,^{2, b} Joachim Kopp,^{1, 3, c}

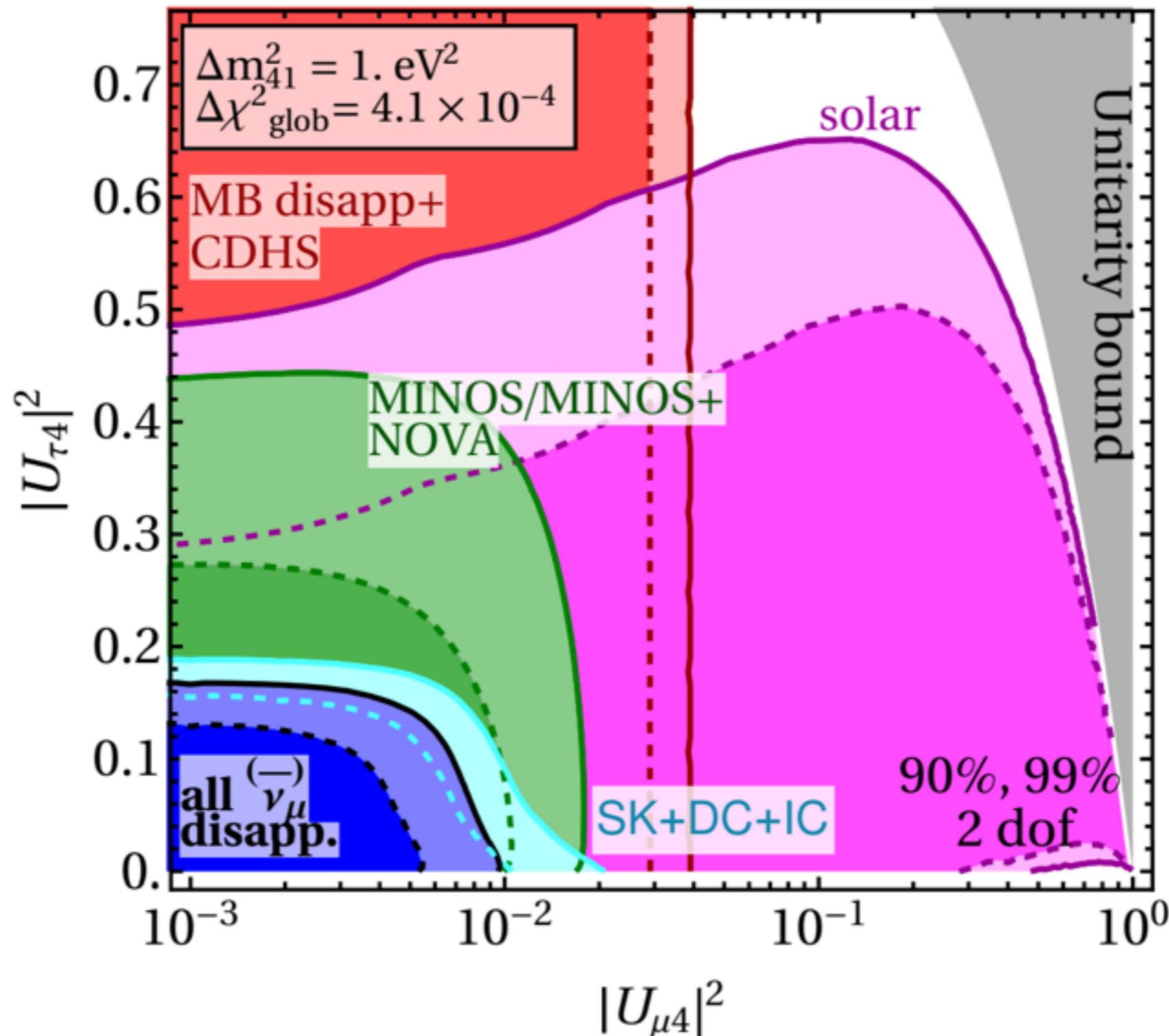
Pedro Machado,^{4, d} Michele Maltoni,^{5, e} Ivan Martinez-Soler,^{5, f} and Thomas Schwetz^{2, g}



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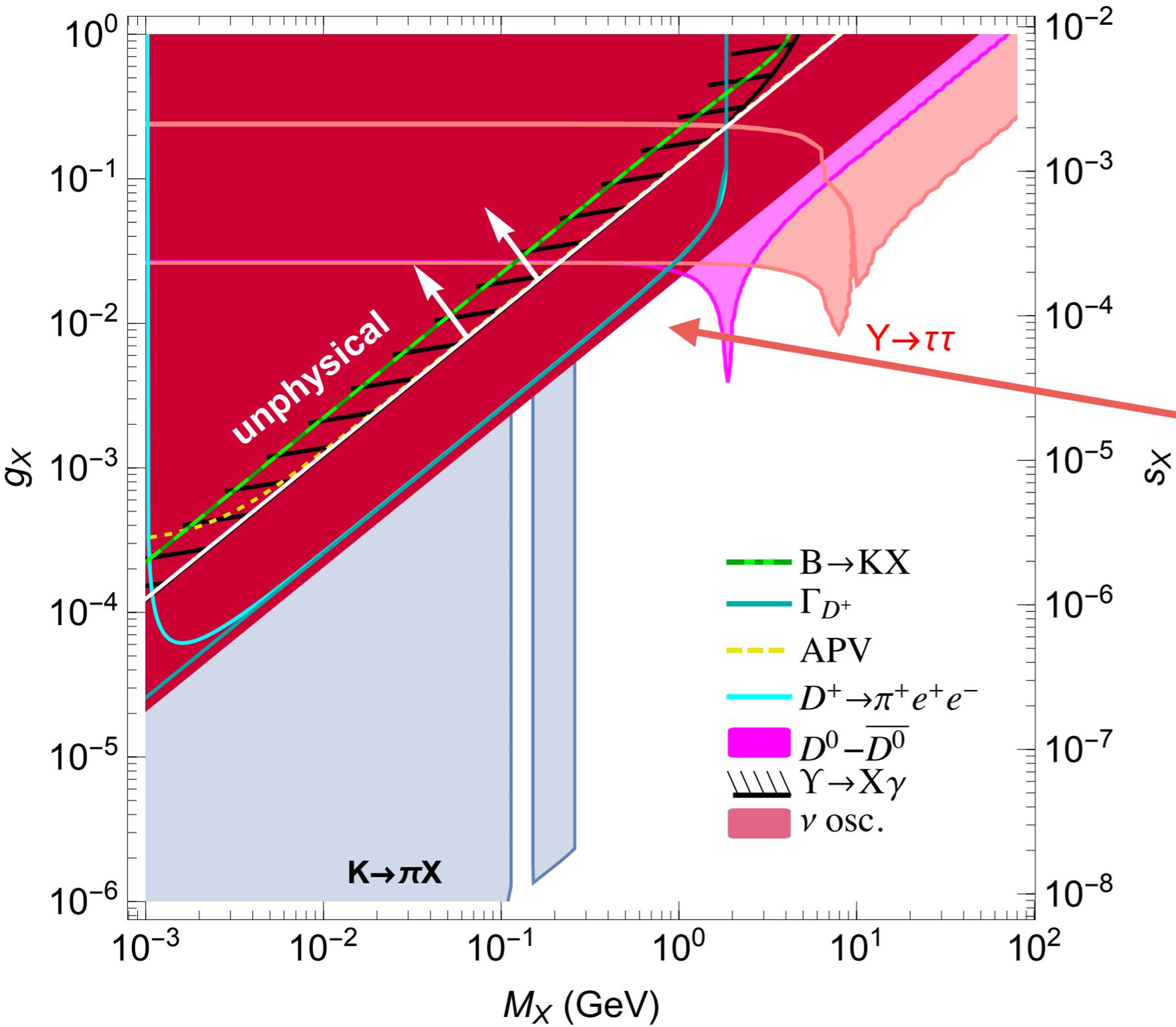


Third family, in general, is poorly known

Flavor Gauge Models Below the Fermi Scale

K.S. Babu^{a,1}, A. Friedland^{b,2}, P.A.N. Machado^{c,d,3}, and I. Mocioiu^{e,4}

$$\tan\beta = v_2/v_1 = 10$$



**Gauged
B₃ – L₃ model**

Neutrinos!

**Plenty of ν_τ at
far detectors...**

What is the precision we want to achieve ?

What is the precision we want to achieve ?

As a rule of thumb, the better the better

NOvA and T2K are the first experiments
to scratch the 3 neutrino paradigm

We barely measured the tau row

Flavor models are a fair goal but...

- How high in energy should the LHC go?
 - How precise do we want $(g-2)_\mu$?
- How well should we measure quark flavor observables?
 - and ...