A non-unitary solar constraint for long-baseline neutrino experiments

Andres Lopez Moreno

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A non-unitary solar constraint for long-baseline neutrino experiments

Andrés López Moreno*
King's College London. Strand, London WC2R 2LS
(Dated: January 24, 2024)

Long-baseline neutrino oscillation experiments require external constraints on $\sin^2\theta_{12}$ and Δm^2_{21} to make precision measurements of the leptonic mixing matrix. These constraints come from measurements of the Mikheyev-Smirnov-Wolfenstein (MSW) mixing in solar neutrinos. Here we develop an MSW large mixing angle approximation in the presence of heavy neutral leptons which adds a single new parameter (α_{11}) representing the magnitude of the mixing between the ν_e state and the heavy sector. We use data from the Borexino, SNO and KamLAND collaborations to find a solar constraint appropriate for heavy neutral lepton searches in long-baseline oscillation experiments. Solar data limits the magnitude of the non-unitary parameter to $(1-\alpha_{11}) < 0.046$ at the 99% credible interval and yields a strongly correlated constraint on the solar mass splitting and the magnitude of ν_e non-unitary mixing.

I. INTRODUCTION

The next generation of long-baseline (LBL) neutrino experiments (DUNE[1], HK[2]) will bring an era of unprecedented precision measurements to neutrino oscillation physics. This will enable further testing of the current 3-neutrino Pontecorvo-Maki-Nakagawa-Sakata (PMNS) paradigm [3] against non-standard neutrino interaction theories and sterile neutrino hypotheses.

LBL experiments compare the $\nu_\mu(\bar{\nu}_\mu)$ and $\nu_e(\bar{\nu}_e)$ fluxes of a neutrino beam at a near and far detector, and thus have, at most, 4 oscillation channels: $\nu_\mu(\bar{\nu}_\mu) \to \nu_\mu(\bar{\nu}_\mu)$, $\nu_e(\bar{\nu}_e) \to \nu_e(\bar{\nu}_e)$, $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$. Having few channels presents a difficulty when trying to get constraints on neutrino propagation models with a large number of parameters. Indeed, the PMNS oscillation framework has 6 free parameters (two mass square differences, three mixing angles and one complex phase) and LBL experiments typically fix or impose external constraints on Δm^2_{21} and θ_{12} to measure the remaining 4 parameters: $\theta_{13}, \theta_{23}, \Delta m^2_{32}$, and δ_{CP} [4][5].

Other than agnostic probes of non-unitarity via goodness of fit comparisons [6], the search for neutrino oscillations with heavy neutral leptons (HNLs) is a natural target for LBL physics due to the few extra free parameters. These HNLs are well-motivated by low-scale type-I seesaw models [7] that give a satisfying explanation to the origin and smallness of neutrino masses —allowing for deviations from unitarity by introducing mixing into new electroweak-scale leptons. We expect seesaw-scale HNLs to be so heavy that they decay (almost) immediately after being produced, thus not taking part in oscillations. This will manifest as a deficit in the un-normalised neutrino flux for all flavours and at all baselines due to a portion of the active states disappearing into the heavy sector and decaying during propagation [8], but near-detector normalisation will hide this deficit in the disappearance channels [9].

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The need for external solar constraints in long-baseline experiments becomes even greater when trying to set limits on non-unitary mixing, where oscillation models have additional degrees of freedom and the usual solar constraint must be updated under the non-unitary formalism. Currently, the lack of a non-unitary solar constraint is a hard wall for LBL analysers hoping to search for HNL mixing in oscillation data. This paper aims to produce one such constraint by finding a non-unitary expression for the Mikheyev-Smirnov-Wolfenstein (MSW) in the presence of HNLs.

In section II we discuss the relevance of the solar constraint on the PMNS parameters for LBL experiments. In section III we review the non-unitary neutrino mixing formalism and use it in deriving a non-unitary large mixing angle (LMA) MSW solution [10]. Finally, in section IV we use our previous result to extract a new non-unitary solar constraint from Borexino[11], SNO[12], and KamLAND[13] data to be used in LBL non-unitary fits.

II. THE SOLAR CONSTRAINT IN LBL EXPERIMENTS

A. The need for a solar constraint

LBL experiments can produce ν_μ and $\bar{\nu}_\mu$ dominated beams by choosing the charge of decaying hadrons with a magnetic horn. These beams contain non-negligible ν_e and $\bar{\nu}_e$ fluxes which contribute to the oscillation signals in the far detector. In the 3ν-PMNS model, the oscillations follow the familiar formula

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i>j}^{3} \mathbb{R}[U_{\alpha i}U^*_{\alpha j}U^*_{\beta i}U_{\beta j}]\sin^2\frac{\Delta\hat{m}^2_{ij}L}{4E} \pm 2\sum_{i>j}^{3} \mathbb{I}[U_{\alpha i}U^*_{\alpha j}U^*_{\beta i}U_{\beta j}]\sin\frac{\Delta\hat{m}^2_{ij}L}{2E} \quad (1)$$

where $(U)_{\alpha j}$ is a change of basis matrix between the flavour states and the propagation states, and $\hat{m}^2_{ij}$ are

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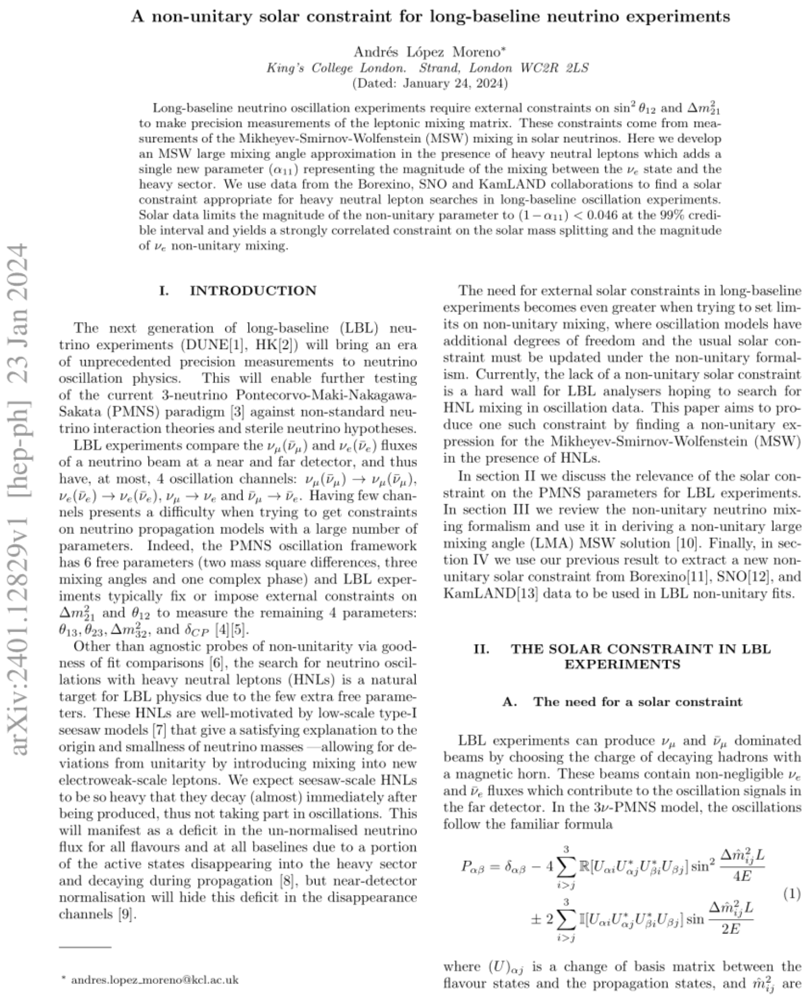
3 → **A non-unitary** ← 2 **solar constraint** **for** ← 1 **long-baseline neutrino experiments**



arXiv:2401.12829v1 [hep-ph] 23 Jan 2024

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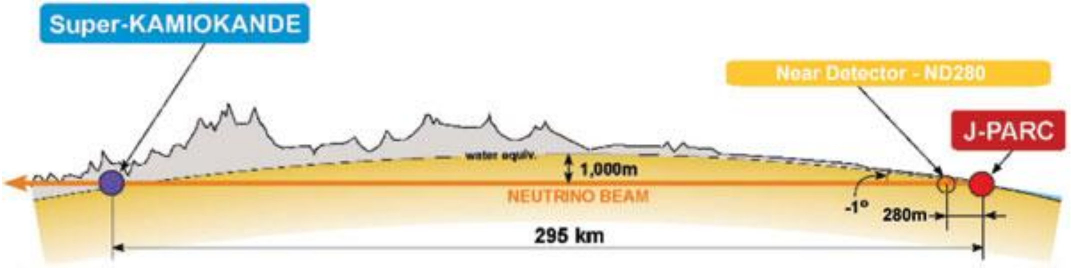
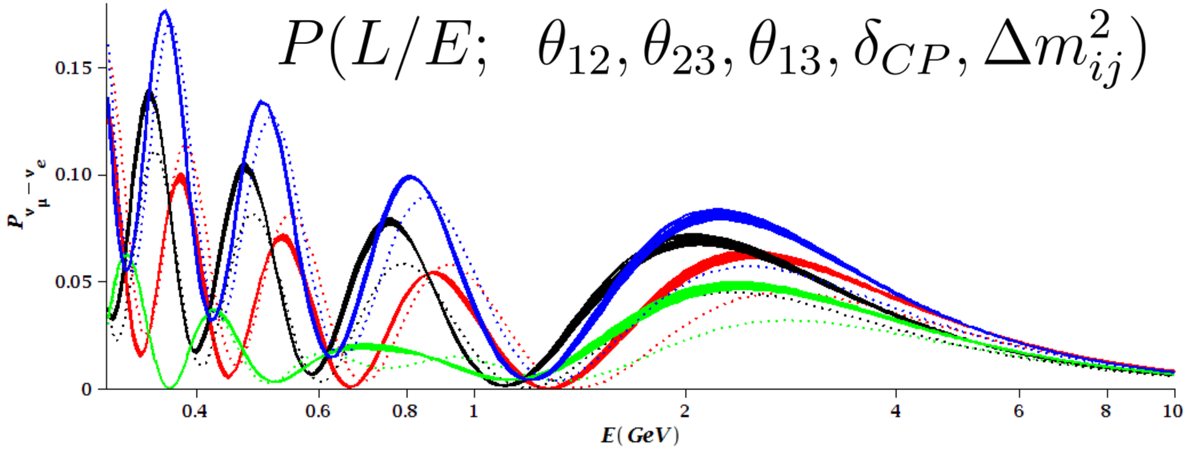
Long-baseline neutrino experiments





Neutrino oscillations can be written measured as the sum of three evolving phases

$$f_1(\phi_{12}) + f_2(\phi_{23}) + f_3(\phi_{13})$$

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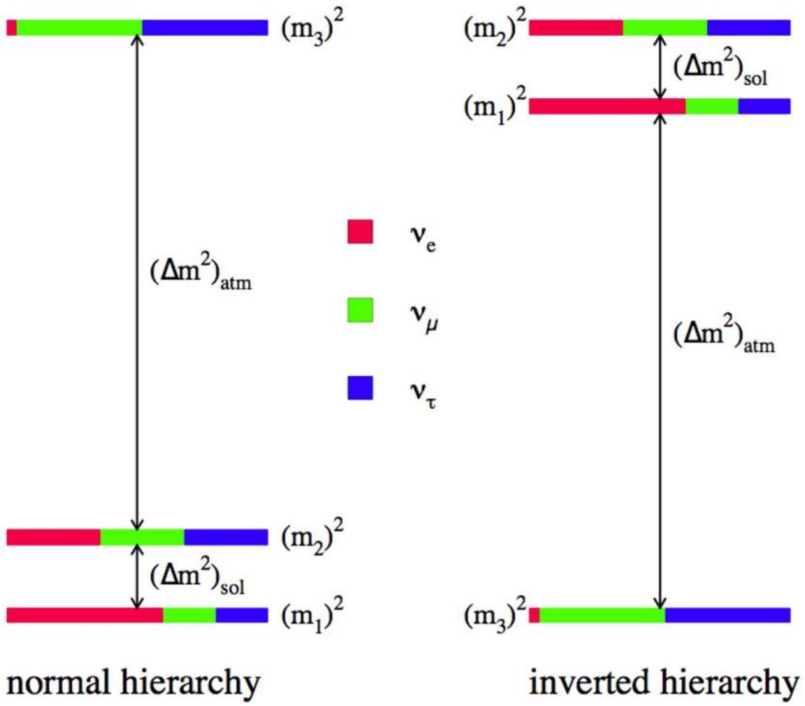
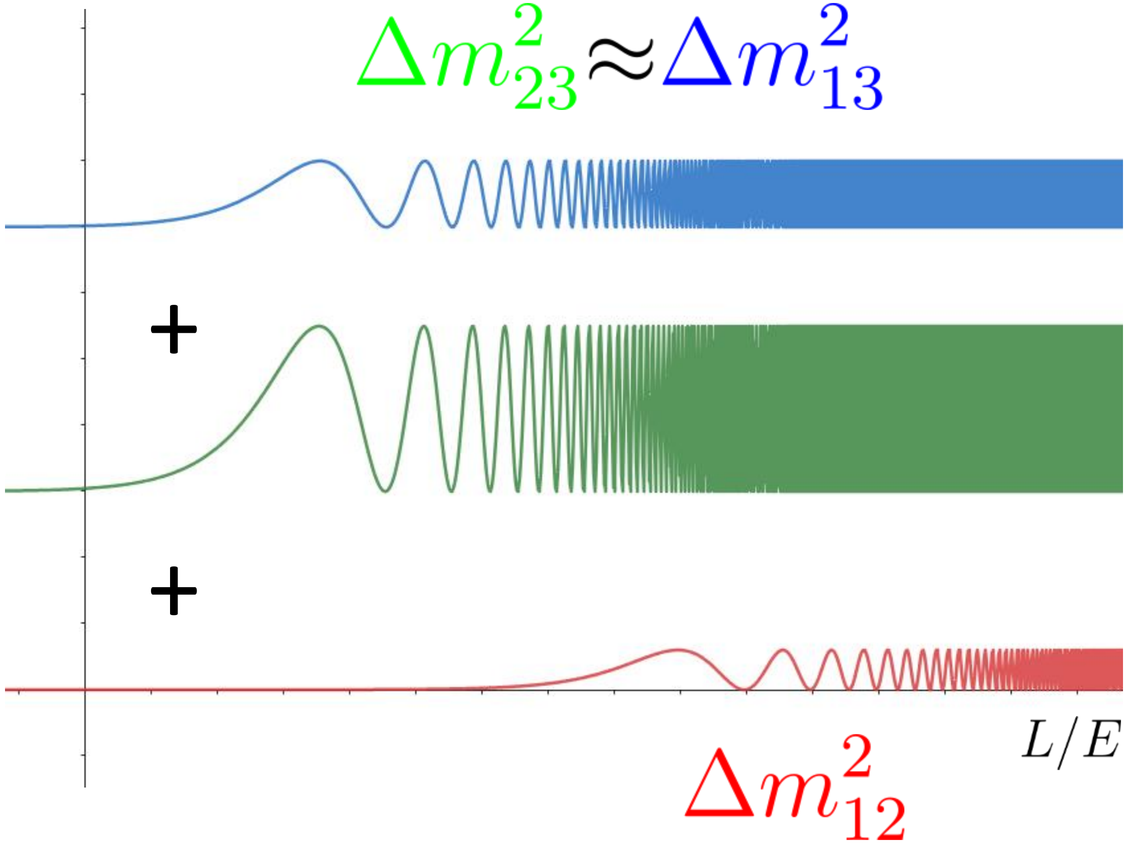
Long-baseline neutrino experiments

m_3



$m_1 \approx m_2$



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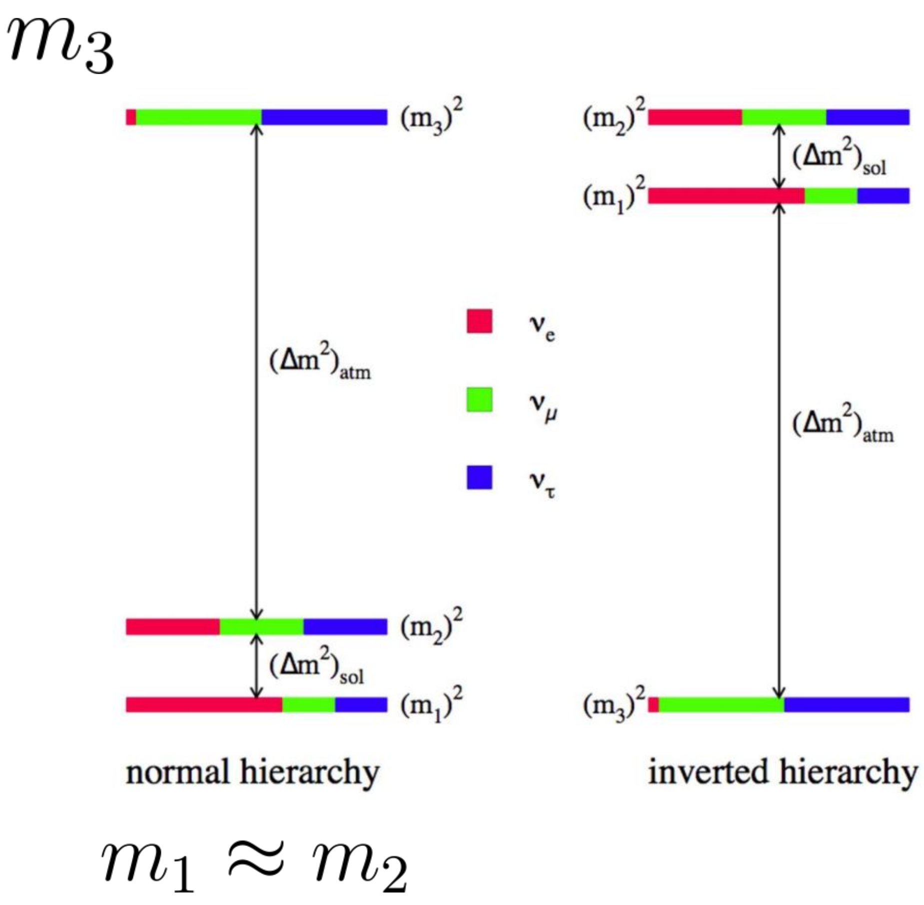
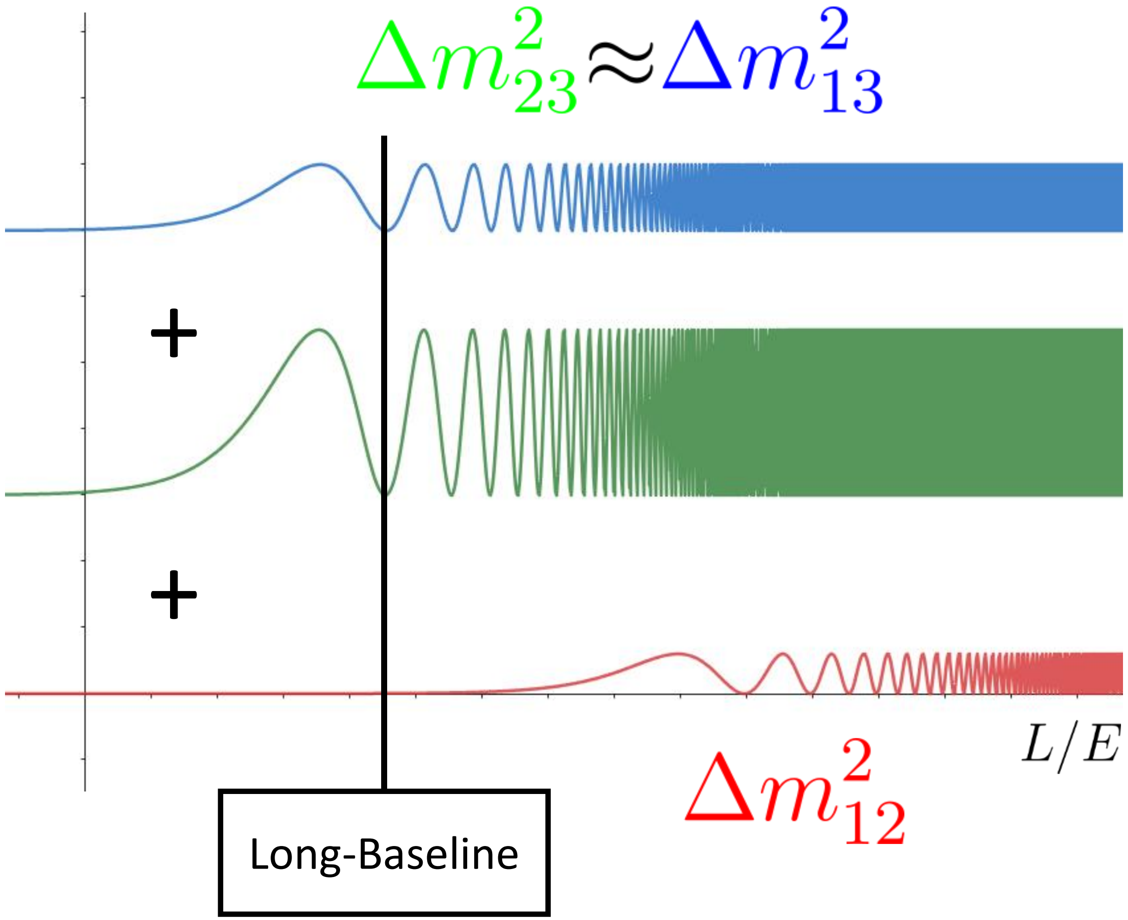
Long-baseline neutrino experiments





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Long-baseline neutrino experiments

$$P^{LBL}_{\nu_e\rightarrow\nu_e} \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{32} L}{4E}$$

$$P^{LBL}_{\nu_\mu\rightarrow\nu_\mu} \approx 1 - \sin^2 2\theta_{23} \sin^2 \frac{\Delta m^2_{32} L}{4E}$$

$$P^{LBL}_{\nu_\mu\rightarrow\nu_e} \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \frac{\Delta m^2_{32} L}{4E} \pm \frac{\Delta m^2_{21} L}{4E} 8 J_{CP} \sin^2 \frac{\Delta m^2_{32} L}{4E}$$

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Solar parameters are (at leading order) degenerate with dcp

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External constraint on $\Delta m^2_{21}, \theta_{12}$

Solar parameters are (at leading order) degenerate with dcp

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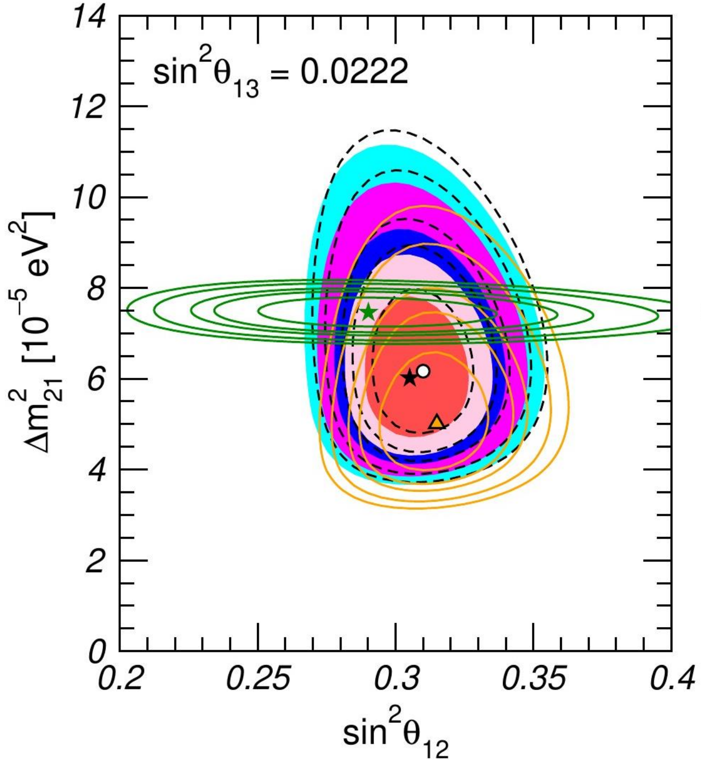
Long-baseline neutrino experiments

External constraint on $\Delta m^2_{21}, \theta_{12}$

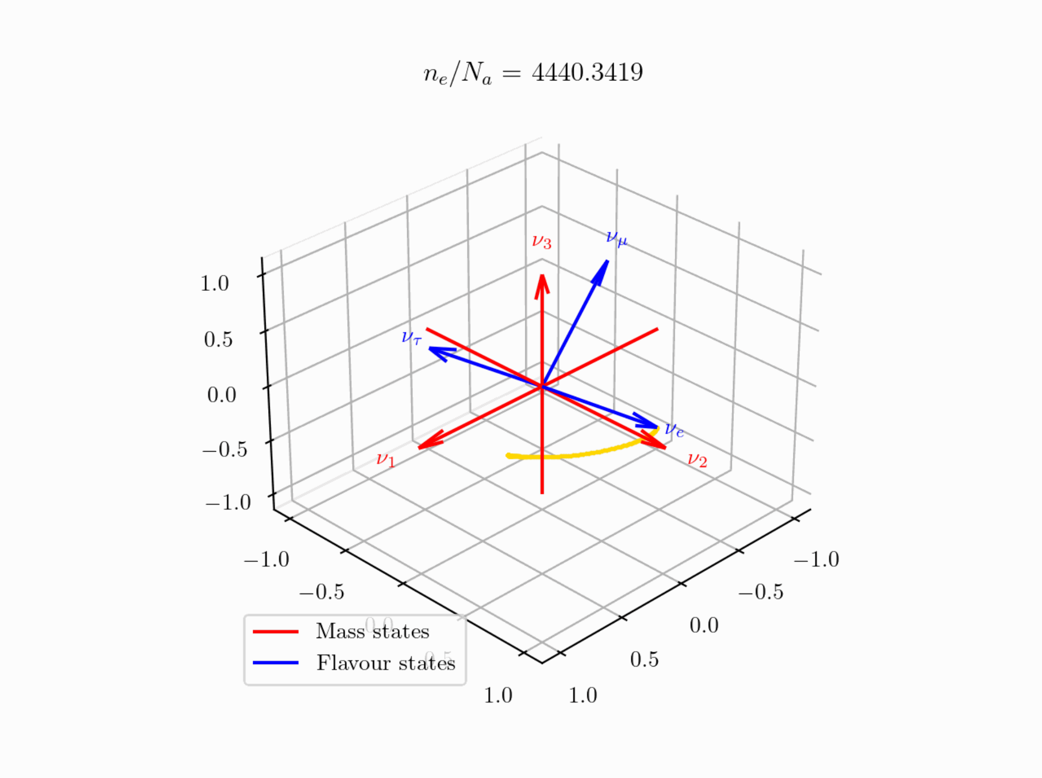
Esteban et al, 2020



- Solar experiments measuring the MSW effect (SNO, Borexino, SK)
- KamLAND measuring the shape and flux of the diffuse reactor neutrino background

The solar constraint

- Solar experiments measuring the MSW effect (SNO, Borexino, SK)



- Electron neutrino is produced
- Neutrino propagates as the ν_2 state
- On earth, $\nu_2 \rightarrow \nu_e, \nu_\mu, \nu_\tau$

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The solar constraint

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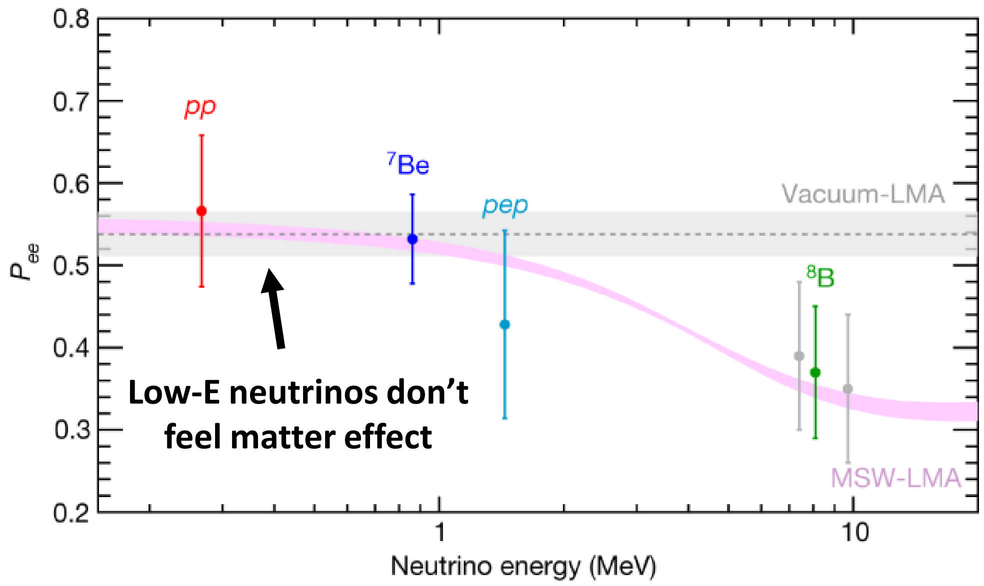

The Borexino Collaboration. Comprehensive measurement of *pp*-chain solar neutrinos. *Nature* **562**, 505–510 (2018)

← **MSW resonance**

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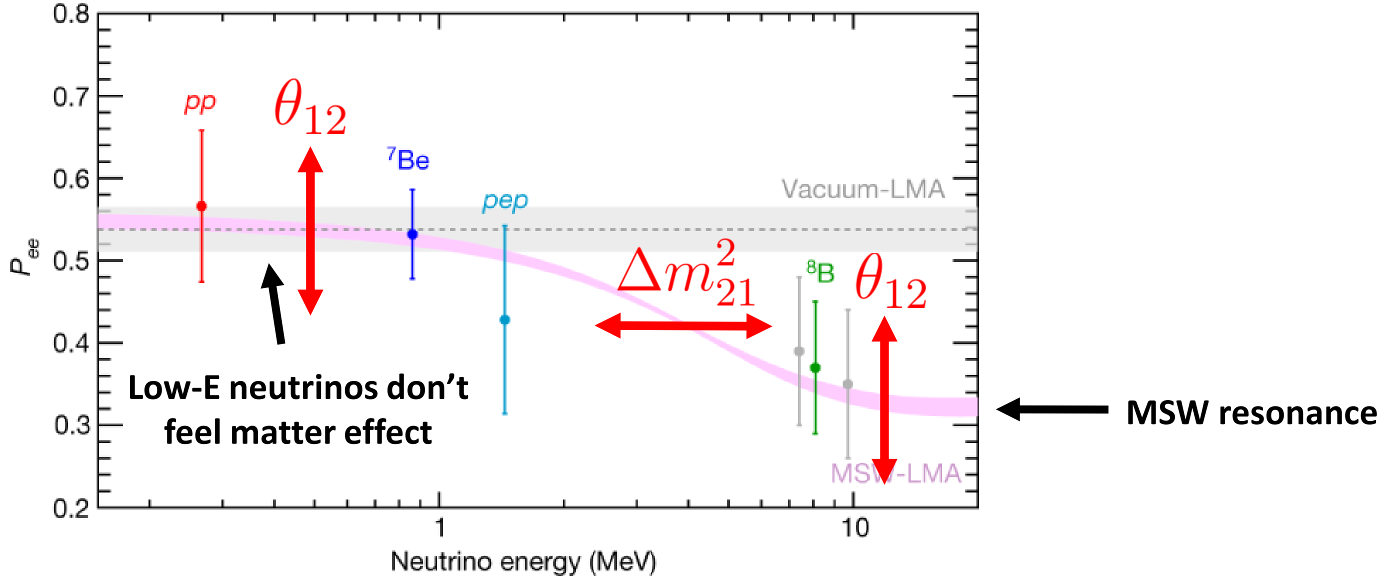

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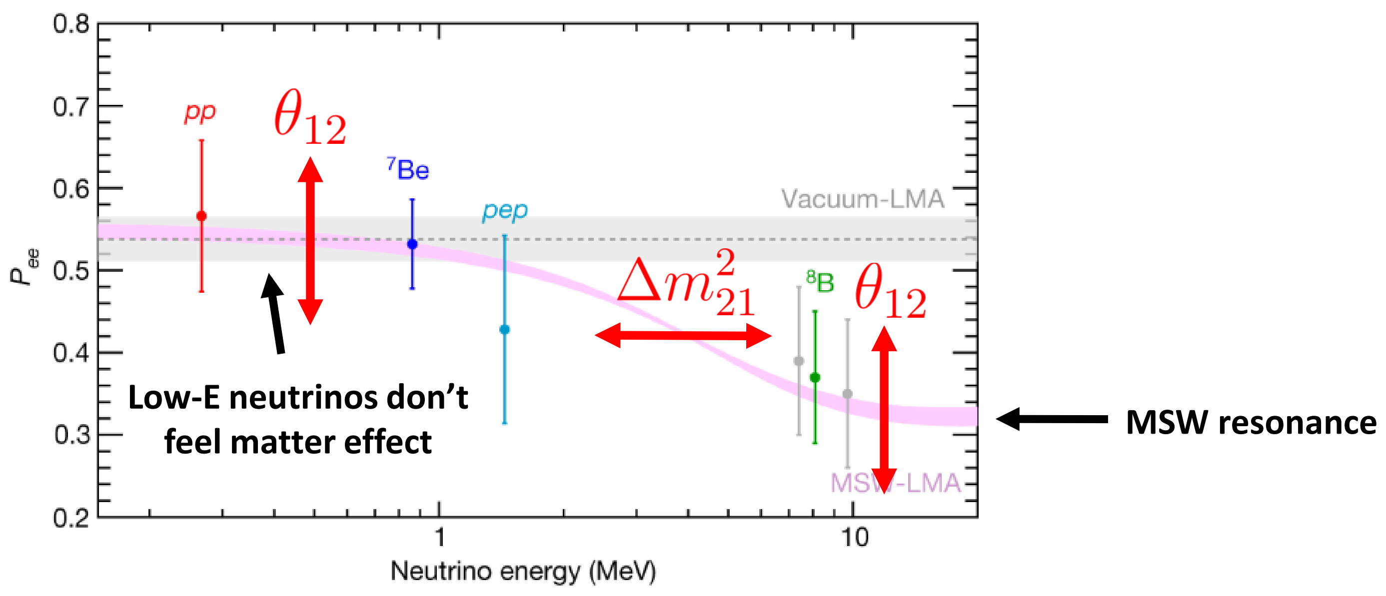

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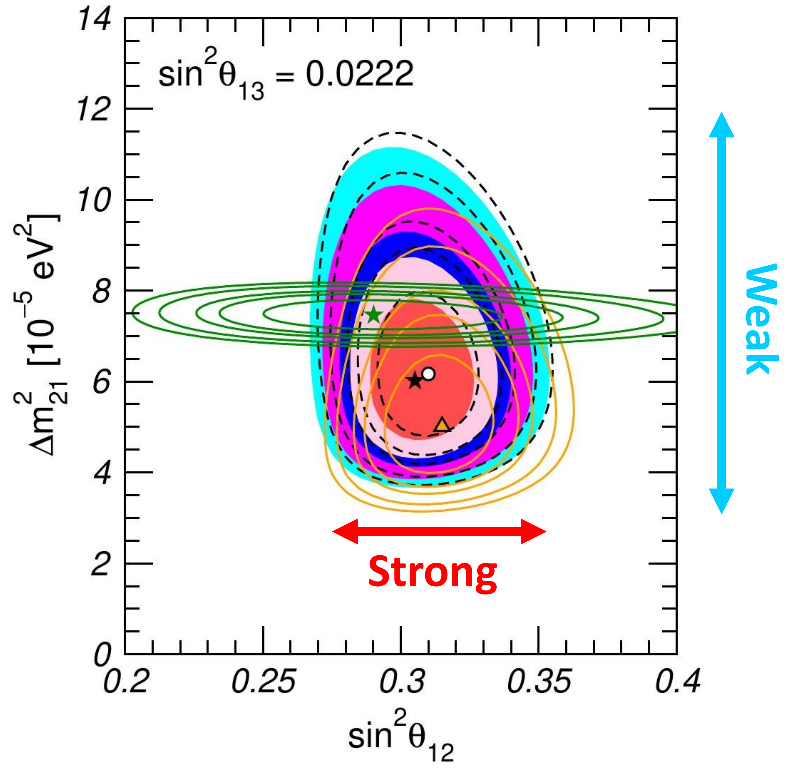

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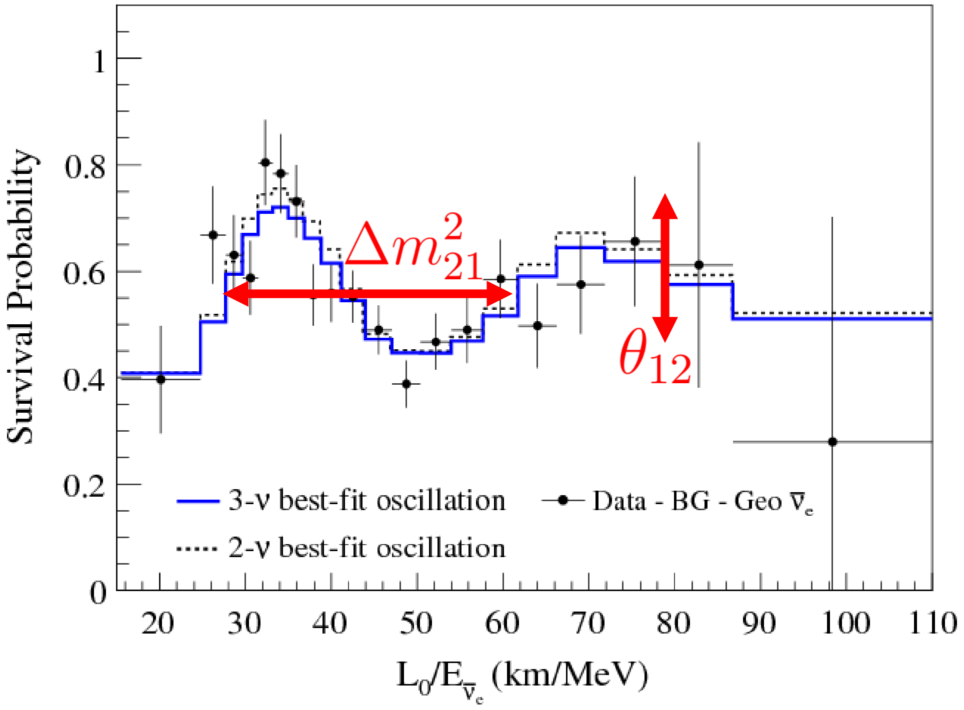
The solar constraint

- KamLAND measuring the shape and flux of the diffuse reactor neutrino background

Vogel et al, 2015



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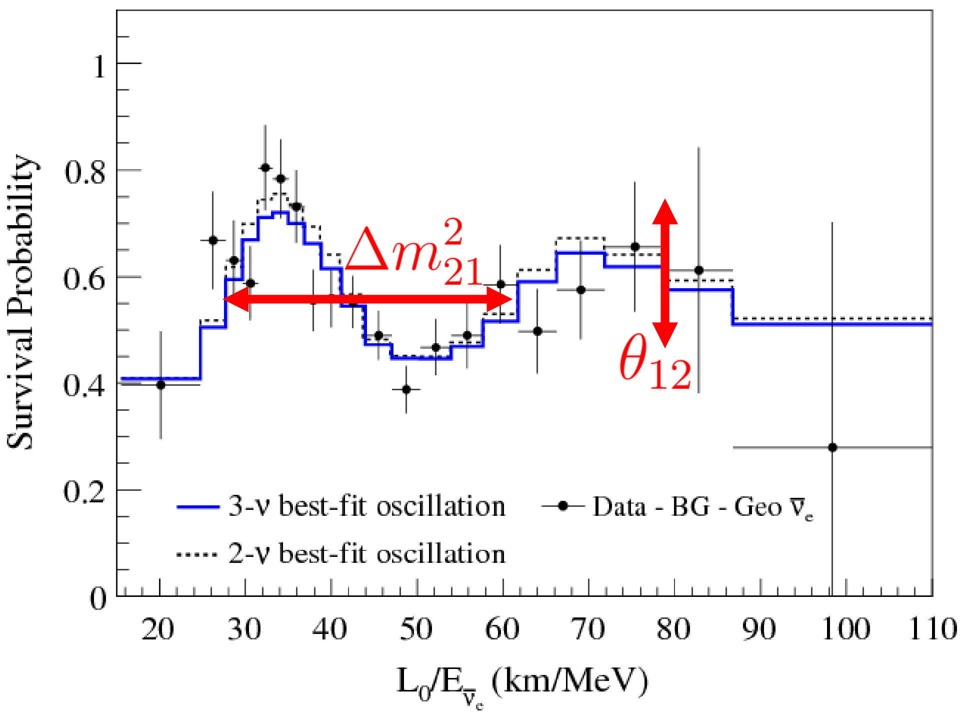

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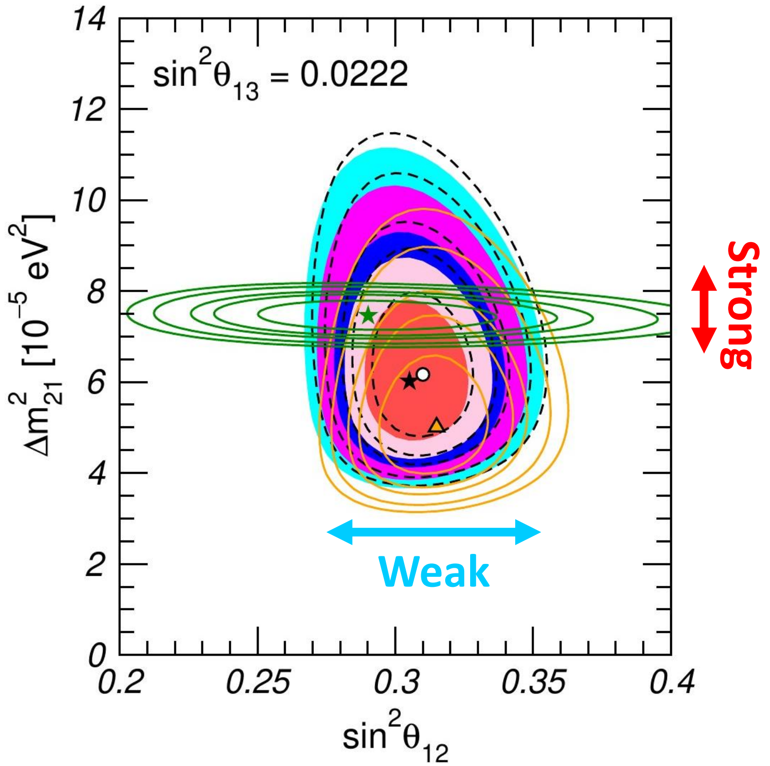

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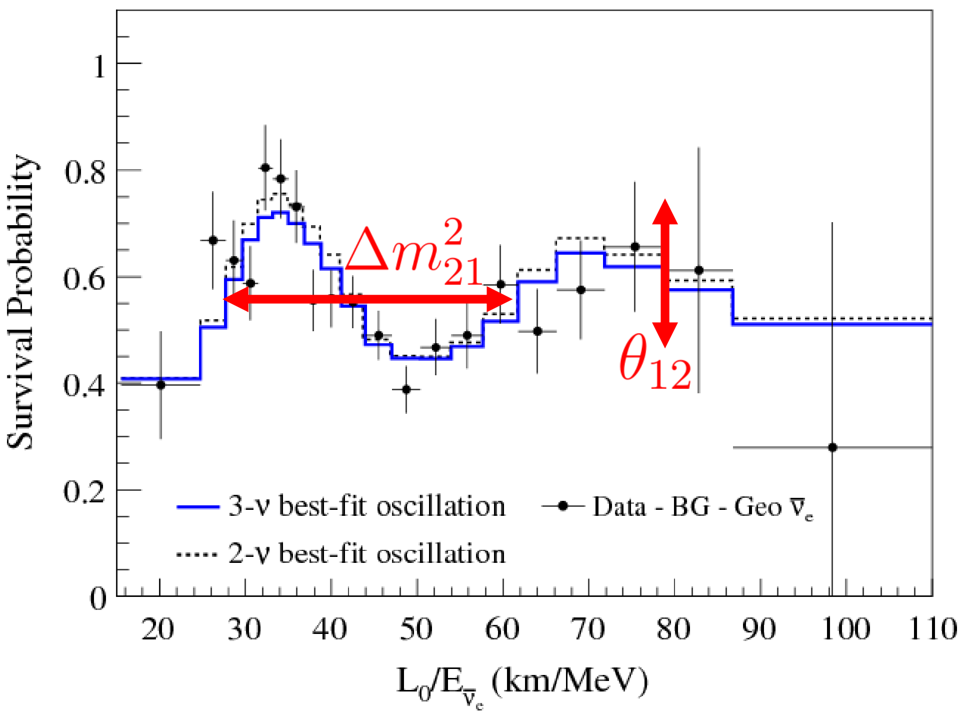

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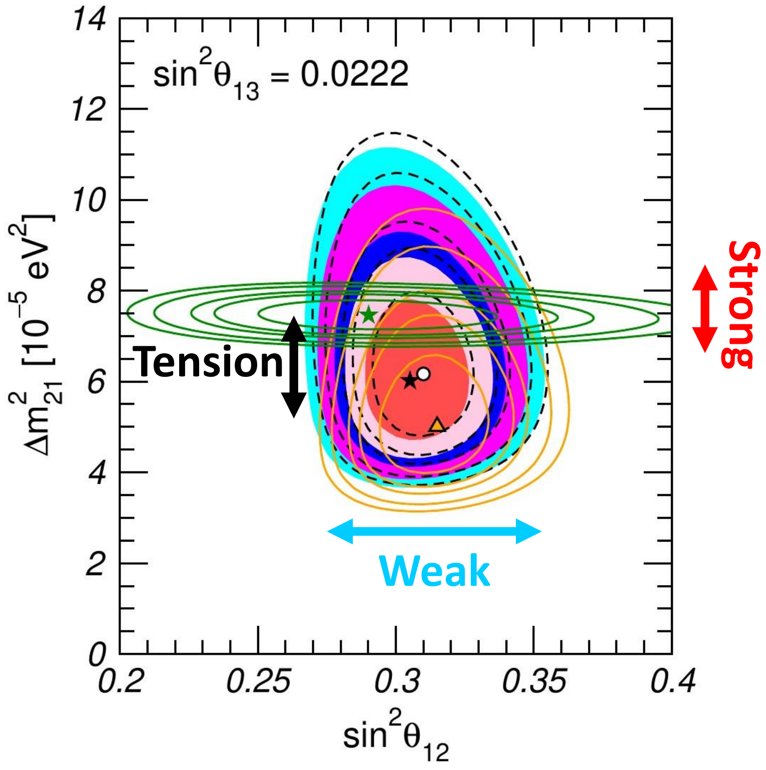

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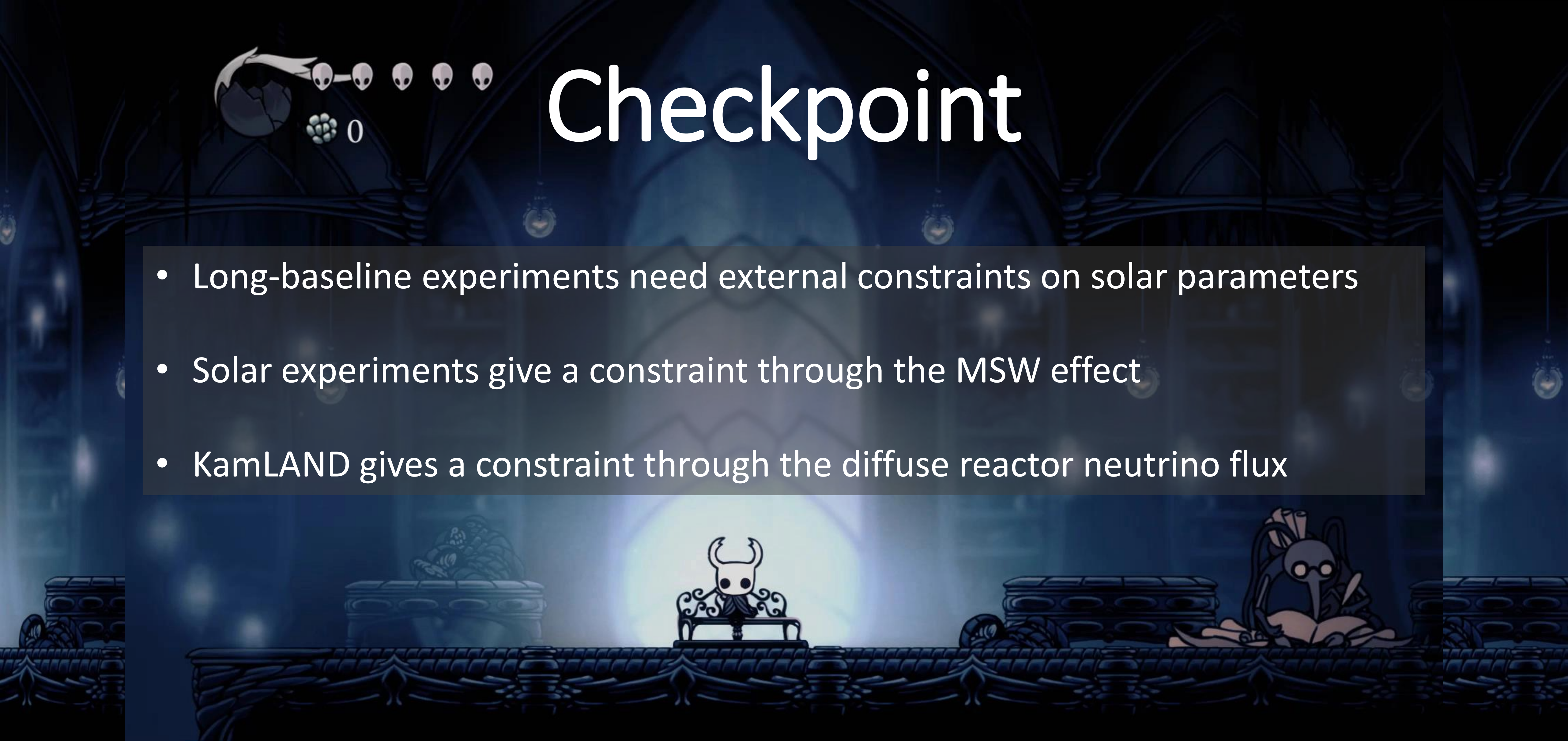

Checkpoint

- Long-baseline experiments need external constraints on solar parameters
- Solar experiments give a constraint through the MSW effect
- KamLAND gives a constraint through the diffuse reactor neutrino flux

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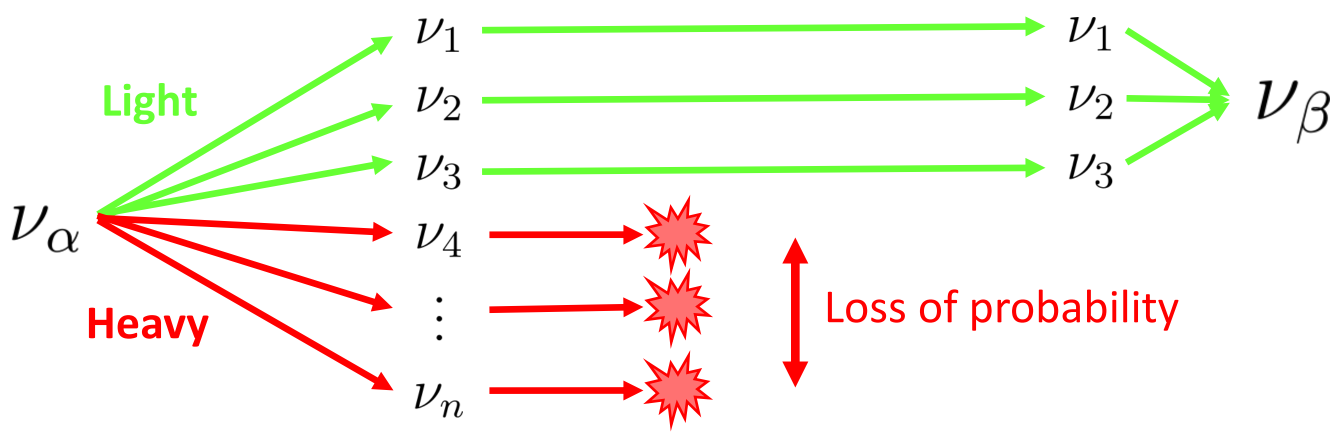
Non-unitarity

- We consider heavy neutral leptons (HNLs) from the seesaw mechanism
- M > GeV scale
- Too heavy to partake in oscillations



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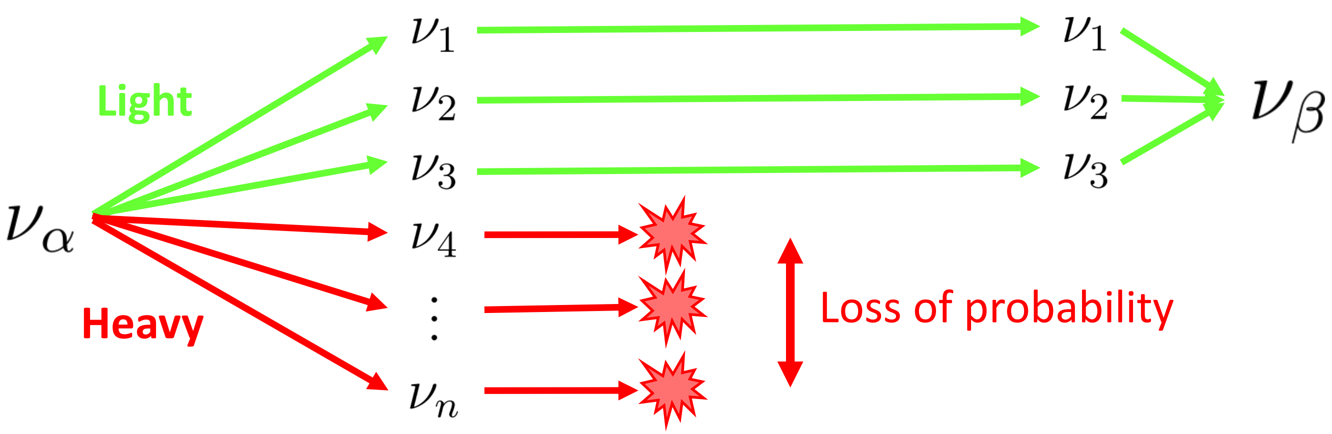
Non-unitarity

- Solid theoretical motivation
- Independent from the mass of the steriles
- Energy independent
- NC and CC signals



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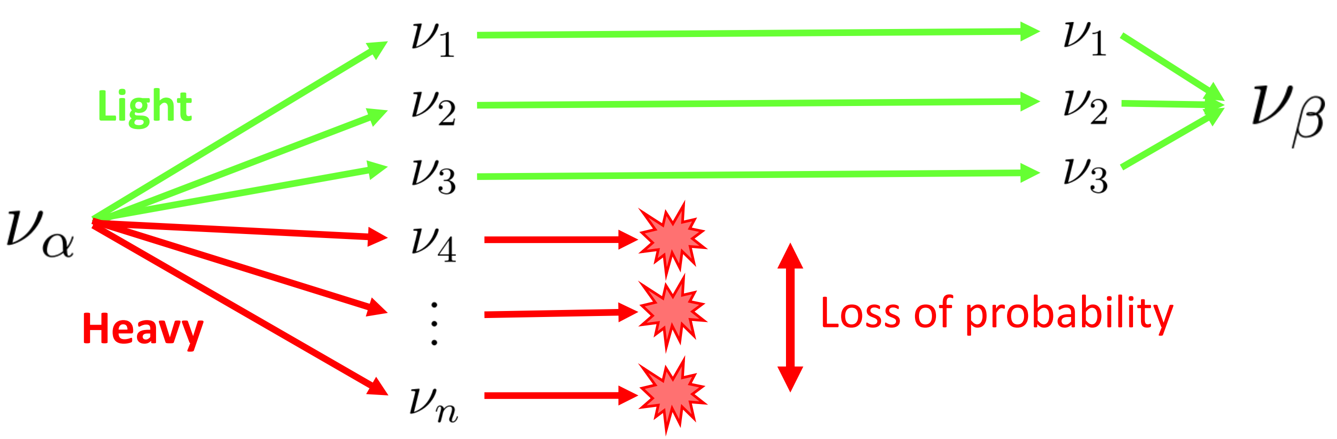
We want to test this in long-baseline experiments!!



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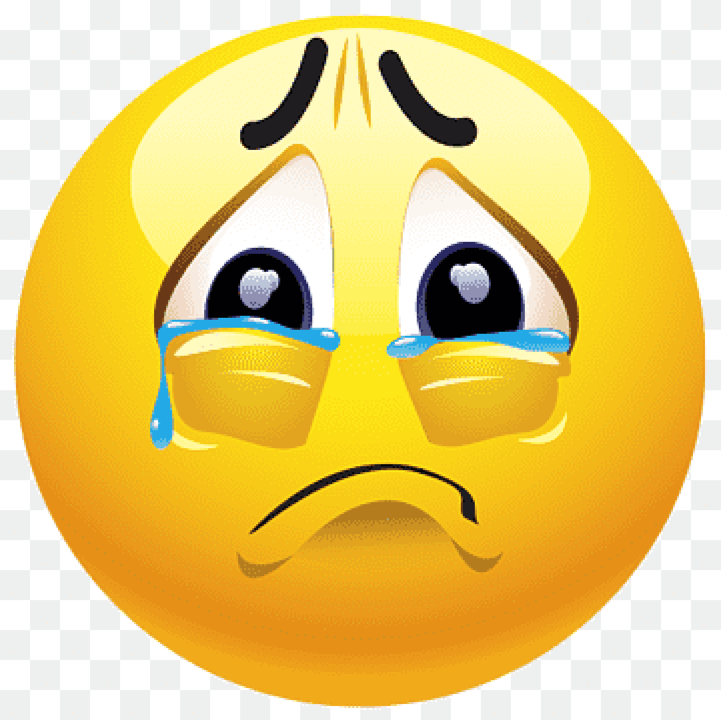

The external solar constraint assumes unitarity!!!

Non-unitarity

The external solar constraint assumes unitarity!!!

↓

We derive the MSW effect in the presence of HNLs

A non-unitary solar constraint for long-baseline neutrino experiments

$$\mathcal{H}_{prop} = NMN^\dagger \pm (NN^\dagger)\begin{pmatrix} v_{cc} - v_{nc} & 0 & 0 \\ 0 & -v_{nc} & 0 \\ 0 & 0 & -v_{nc} \end{pmatrix}(NN^\dagger)$$

$$\hat{\mathcal{H}}_{11} = 2\alpha_{11}^4 \Delta v_c \cos^2\theta_{13} - 2\alpha_{11}^2 v_{nc}(I_{13}^+)^2$$

$$\hat{\mathcal{H}}_{12} = 2\alpha_{11}^3 \alpha_{21} \Delta v \cos^2\theta_{13} - 2\alpha_{11} v_{nc}(I_{13}^-)(\alpha_{21}(I_{13}^-) + \alpha_{22}\alpha_{32})$$

$$\hat{\mathcal{H}}_{13} = 2\alpha_{11}^3 \alpha_{31} \Delta v (I_{13}^+) - \alpha_{11}\alpha_{33}^2\alpha_{31} v_{nc}(I_{13}^-)$$

$$\beta \approx \frac{\sqrt{2} G_f E}{\Delta m_{21}^2}\left([2\alpha_{11}^2 N_e + (1 - \alpha_{11}^2) N_n] \cos^2\theta_{13}\right)$$

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A non-unitary solar constraint for long-baseline neutrino experiments

In the sun!!

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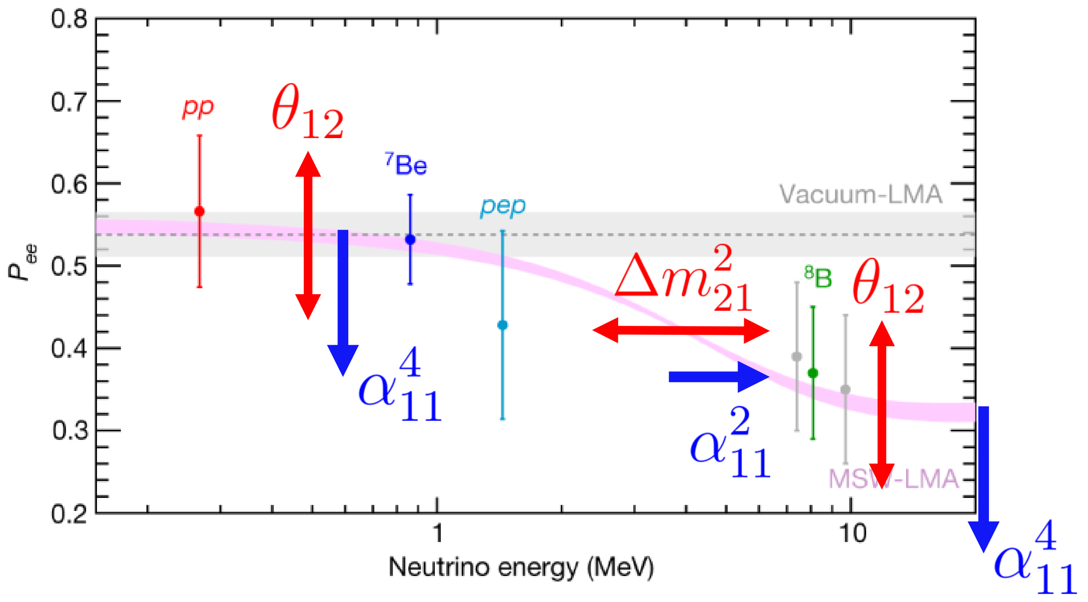
A non-unitary solar constraint for long-baseline neutrino experiments

New parameters (at leading order):

N_n : neutron density (known from solar models)

α_{11} : fraction of ν_e made up of light neutrinos



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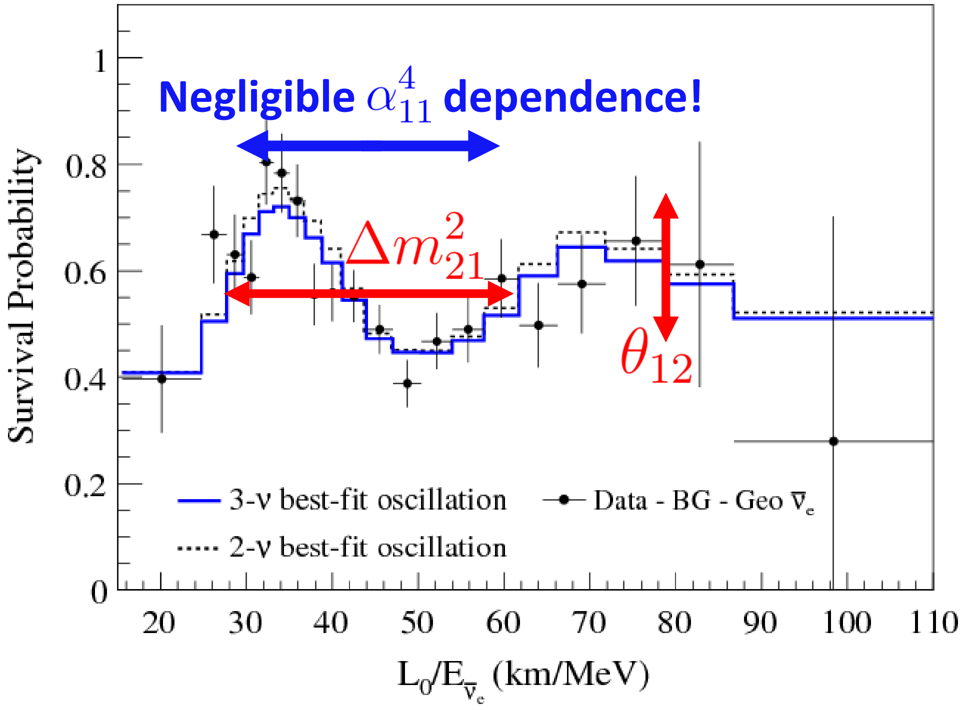
Vogel et al, 2015



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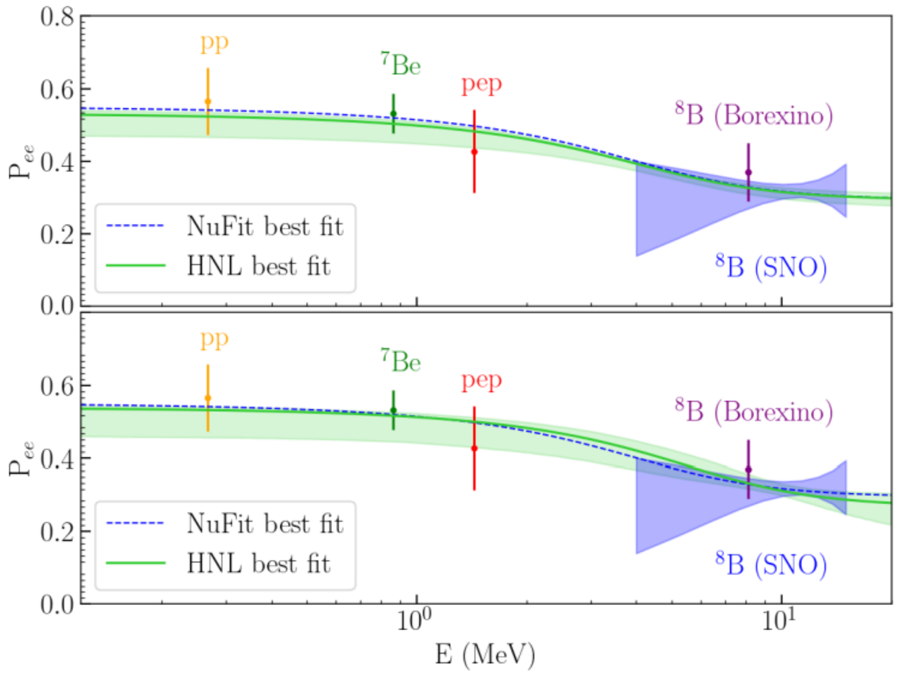
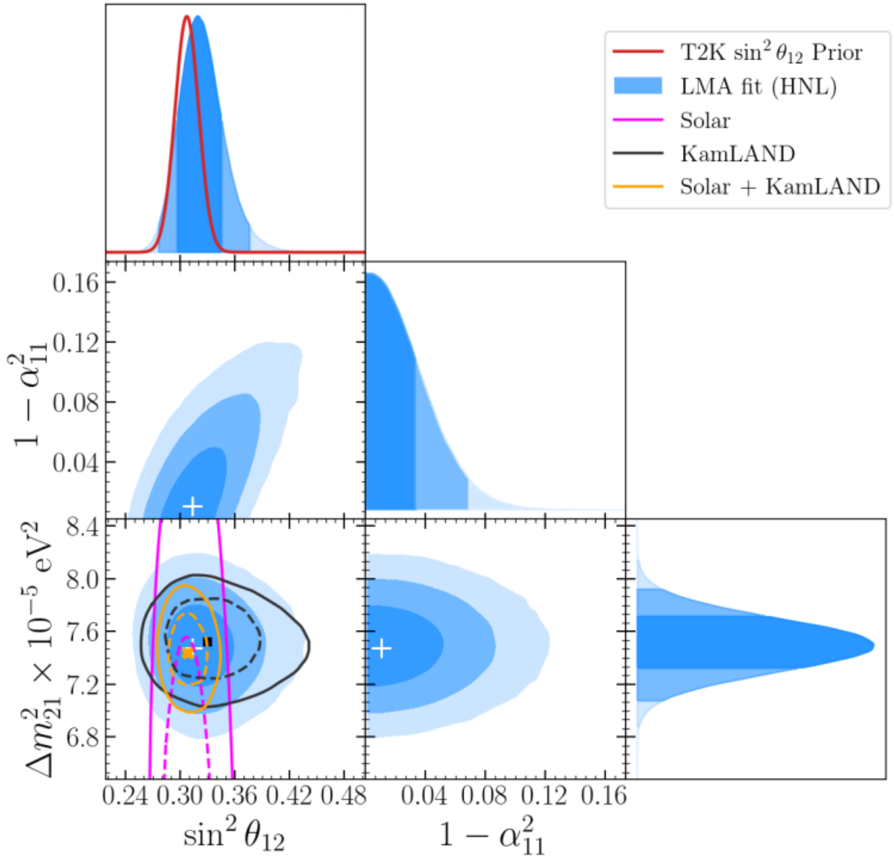
A non-unitary solar constraint for long-baseline neutrino experiments

- Non-unitary fit to solar data + KamLAND mass-splitting constraint!





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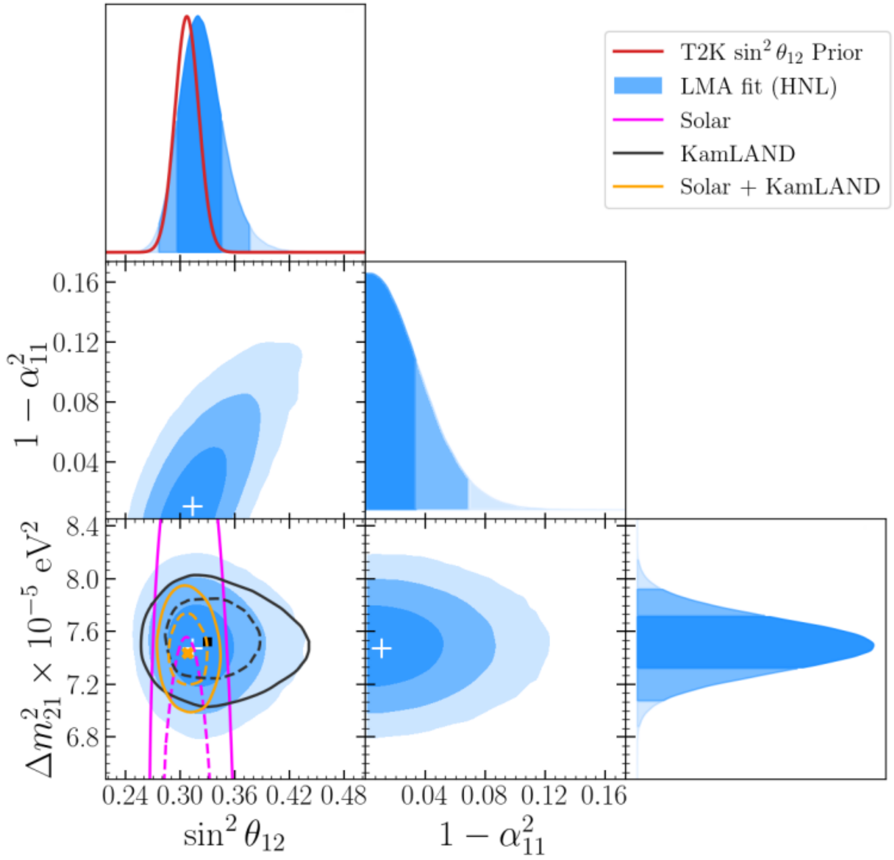
A non-unitary solar constraint for long-baseline neutrino experiments

- Results consistent with unitarity
- The non-unitary parameter is strongly correlated with the solar angle
- Constraint on the solar angle becomes weaker overall



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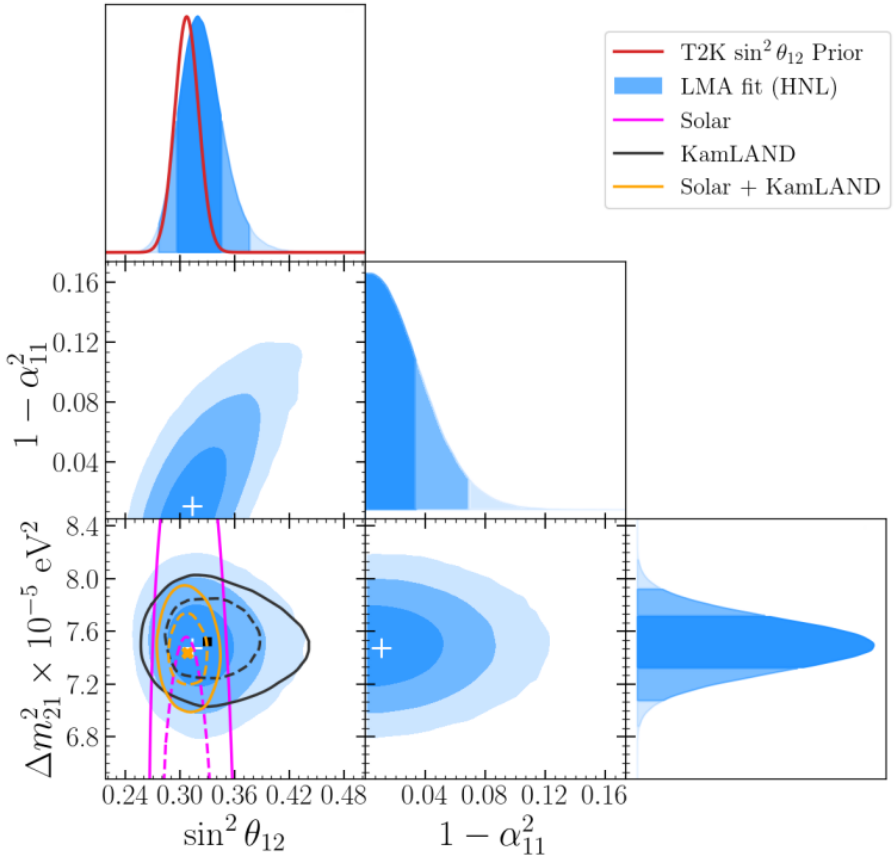
A non-unitary solar constraint for long-baseline neutrino experiments

- **Solar data constraint on unitarity is competitive!!**

Data set	90% C.L	99% C.L
NOMAD + NuTeV [8]	< 0.031	< 0.056
Global seesaw fit (+LFT) [35][32]	$< 2.6 \times 10^{-3}$	$< 3.78 \times 10^{-3}$
Global oscillation fit (SBL + LBL + reactor) [36]	< 0.02	< 0.05
This work	< 0.028	< 0.046



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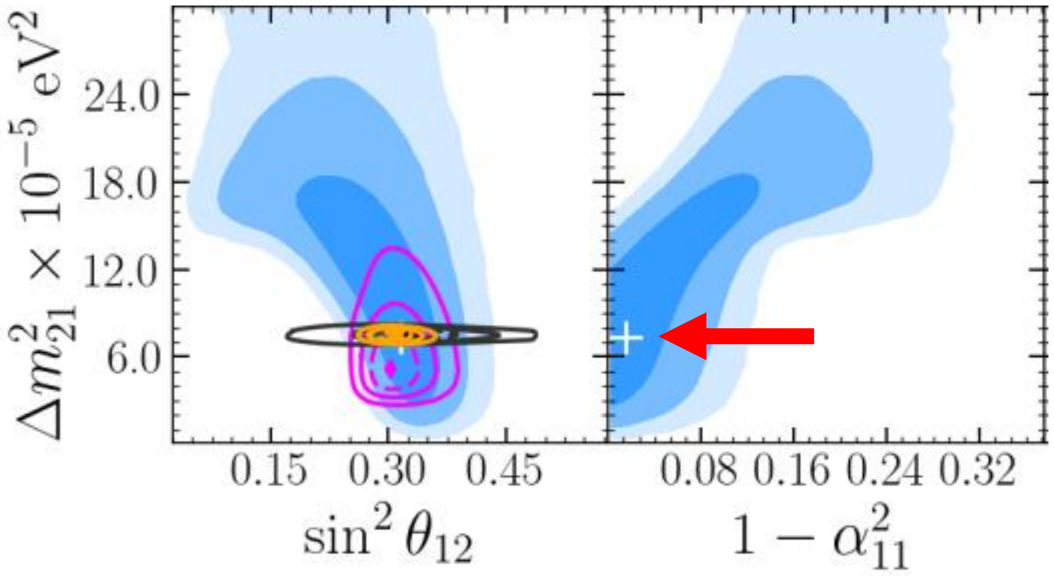
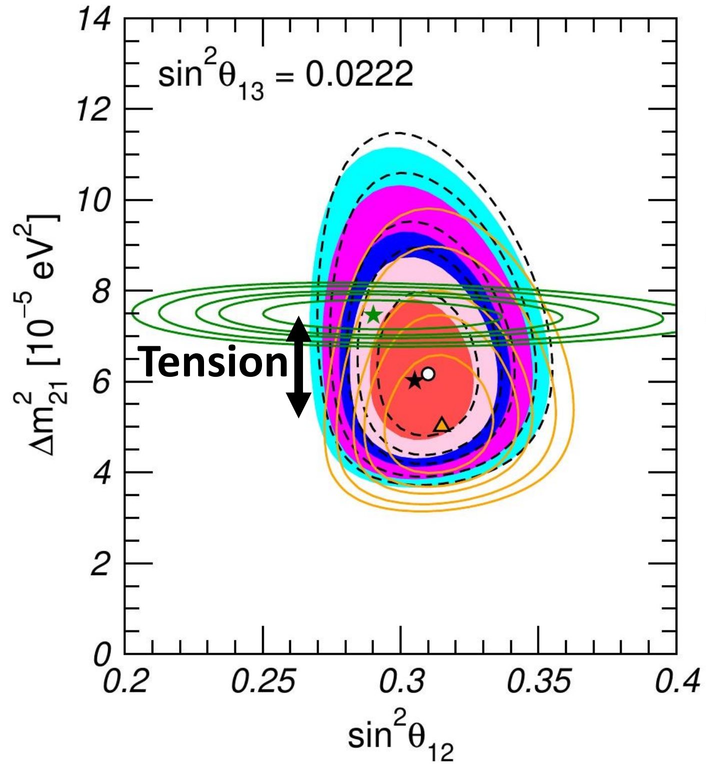
A non-unitary solar constraint for long-baseline neutrino experiments

- **KamLAND tension disappears!**



Esteban et al, 2020



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A non-unitary solar constraint for long-baseline neutrino experiments

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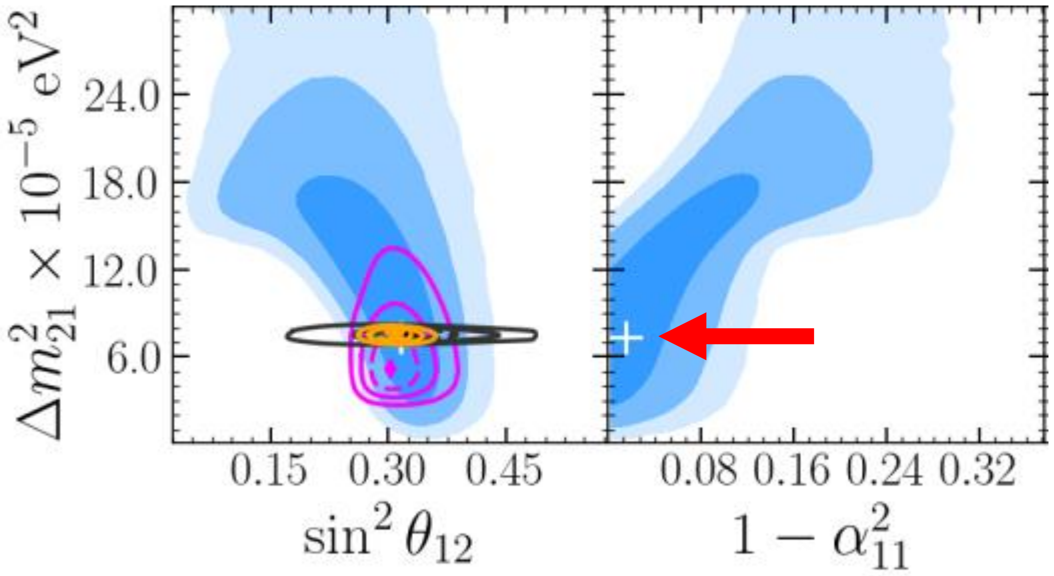
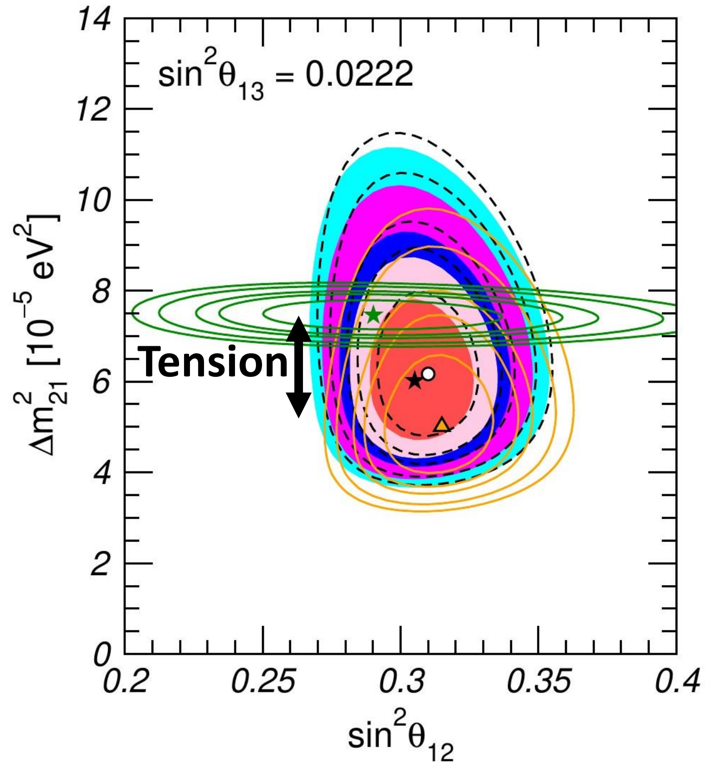


Esteban et al, 2020



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Some remarks

- I have no access to the binned distributions from solar experiments, which would give additional information on the shape of the inflexion point

- A weaker constraint in the solar angle leads to a loss of resolution for the CP phase in long-baseline experiments

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Some remarks

- I have no access to the binned distributions from solar experiments, which would give additional information on the shape of the inflexion point

→ The difficult part (deriving the non-unitary MSW effect) is already done! Anyone pick up this analysis and give it proper treatment

- A weaker constraint in the solar angle leads to a loss of resolution for the CP phase in long-baseline experiments

→ This is bound to happen in non-unitary frameworks. The larger loss of resolution will come from the non-unitary matter effect in the long-baseline experiment

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Recap

- We now have a non-unitary solar constraint which makes unitarity tests possible in long-baseline oscillation analysis
- The constraint was stronger than expected, to the point of setting a competitive limit on unitarity violation
- A small deviation from unitarity in the electron sector would relax the KamLAND tension
- There is room for repeating this analysis with better access to data

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Thank you

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