Measuring Non-Standard Neutrino Interactions (NSI) of Solar Neutrinos with Existing and Future Neutrino and Dark Matter Experiments

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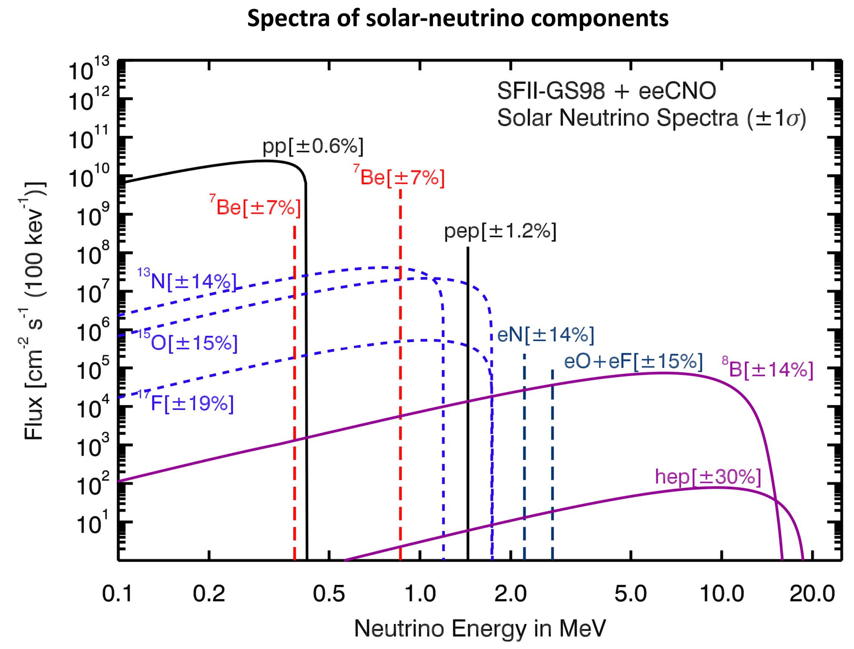
Introduction

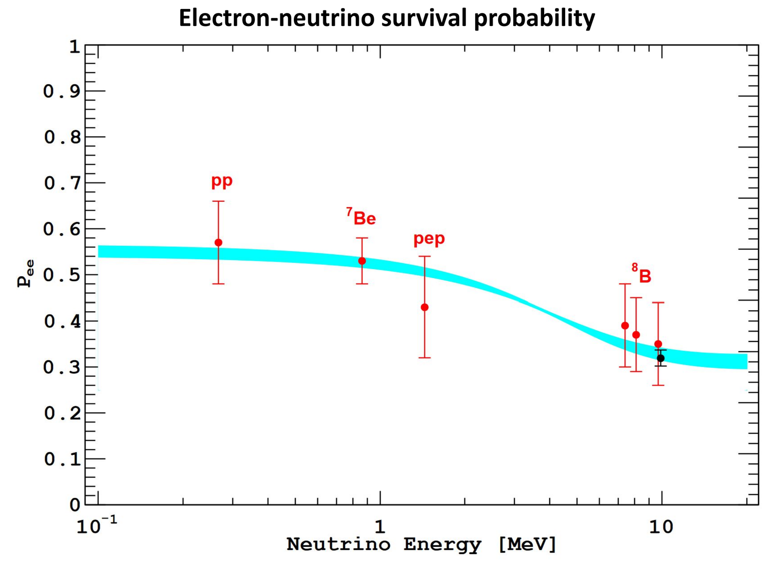
Our Sun is an intense source of neutrinos with <20 MeV energy (see energy spectra of its components on right). It provides a great natural source to study low-energy neutrino physics (for example, see representation of solar-neutrino oscillations below).

Spectra of solar-neutrino components



https://arxiv.org/pdf/1601.07179.pdf A. Serenelli (2016)
https://pdg.lbl.gov/2020/reviews/rpp2020-rev-neutrino-mixing.pdf
PDG 2020

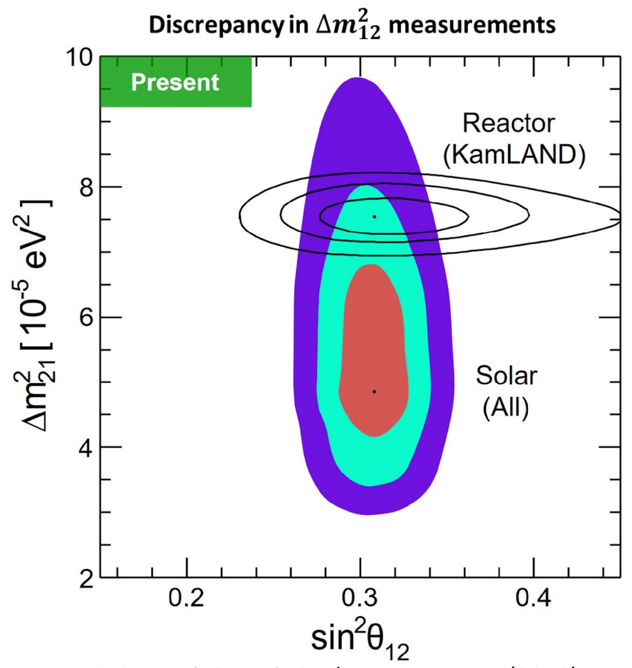
Electron-neutrino survival probability



http://pdg.lbl.gov/2020/reviews/rpp2020-rev-neutrino-mixing.pdf
PDG 2020

Indications of discrepancy between reactor and solar neutrino-oscillation measurements exist; so-called "solar neutrino anomaly" (see right)

Discrepancy in Δm^2_{12} measurements



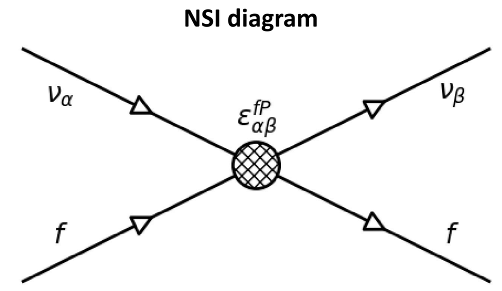
F. Capozzi, S.W. Li, G. Zhu, J.F. Beacom (2018)
arXiv:1808.08232

NSI in Solar Neutrinos

NSI 2-flavor solar-ν Hamiltonian (see diagram on right)

$$H_\nu^{NSI} = \sqrt{2}G_F(n_u + n_d)\begin{pmatrix} -\epsilon_D & \epsilon_N \\ \epsilon_N^* & \epsilon_D \end{pmatrix}$$

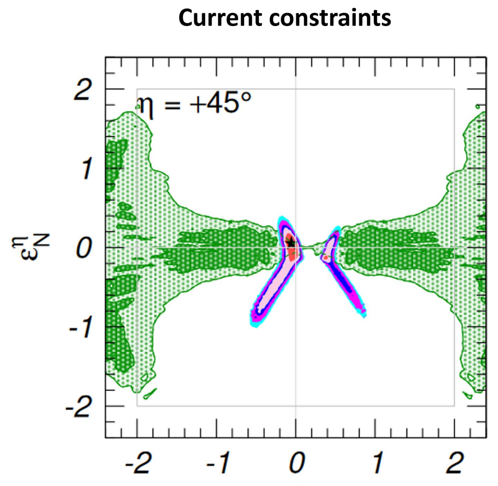
NSI diagram



NSI change ν_e survival probability, diagonal couplings can mimic different Δm^2 (see bottom-right plot)

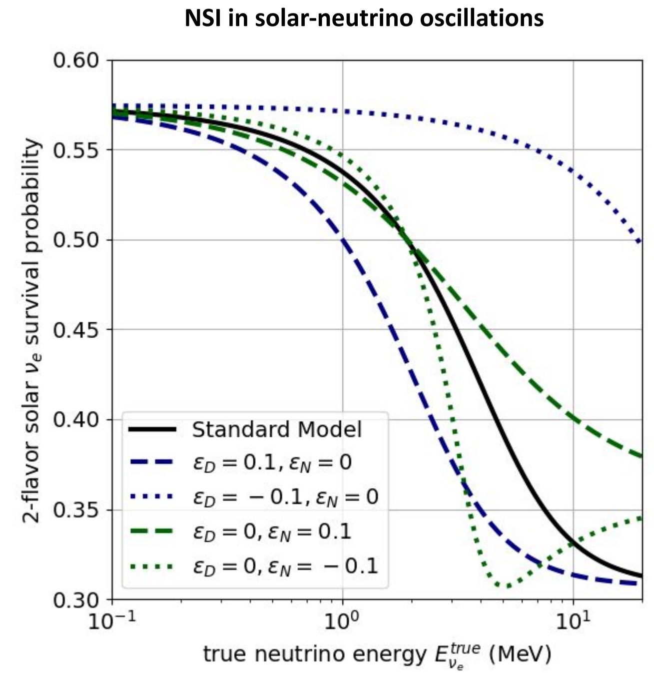
Experiments that are sensitive to oscillations in solar neutrinos can measure this effect (see constraints below)

Current constraints

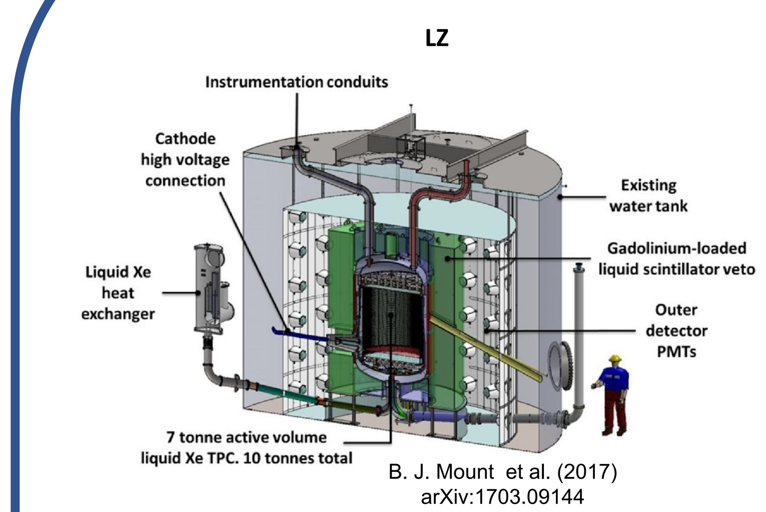


I. Esteban, M.C. Gonzalez-Garcia, M. Maltoni, I. Martinez-Soler, J. Salvado (2018)
arXiv:1805.04530

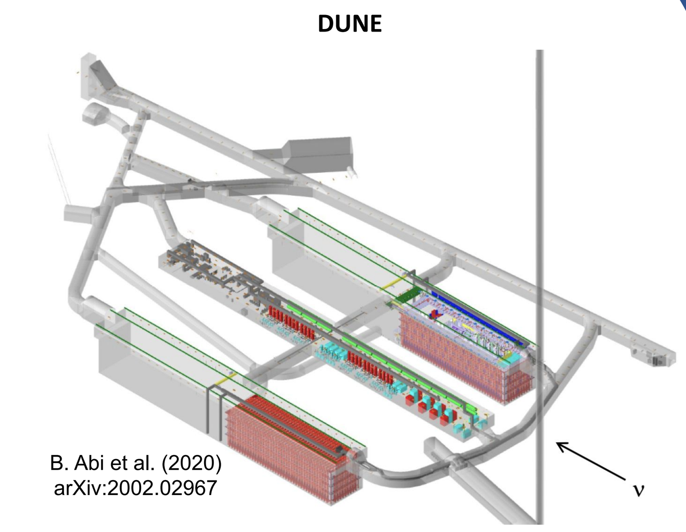
NSI in solar-neutrino oscillations



Detectors



B. J. Mount et al. (2017)
arXiv:1703.09144



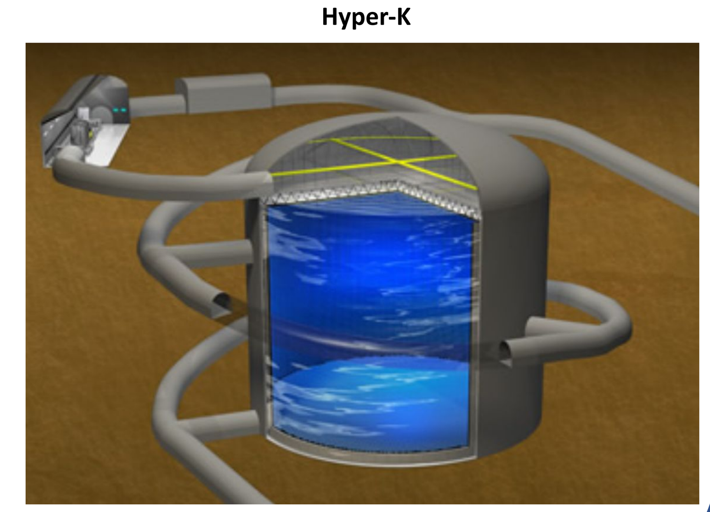
B. Abi et al. (2020)
arXiv:2002.02967

Top left – LUX-ZEPLIN (LZ): 7-t Xe double-phase time-projection chamber for direct dark-matter searches

Top right – Deep Underground Neutrino Experiment (DUNE): 40-kt liquid-Ar neutrino experiment with proposed 3-kt low-background module

Bottom right – Hyper-Kamiokande (Hyper-K): 217-kt water-Cherenkov neutrino experiment with possible additional module

Hyper-K



K. Abe et al. (2018)
arXiv:1805.04163

Event Rates

Elastic scattering of neutrinos on electrons (ES) does not have physical threshold, convenient for low-energy physics

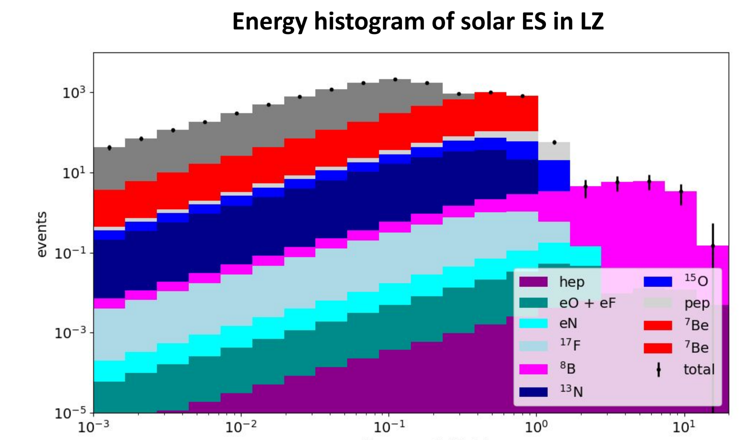
Assume ES on free electrons, SM solar-neutrino oscillations, no backgrounds, no systematics

For LZ (top right plot), assume 3 years of data taking and mass of 7 t

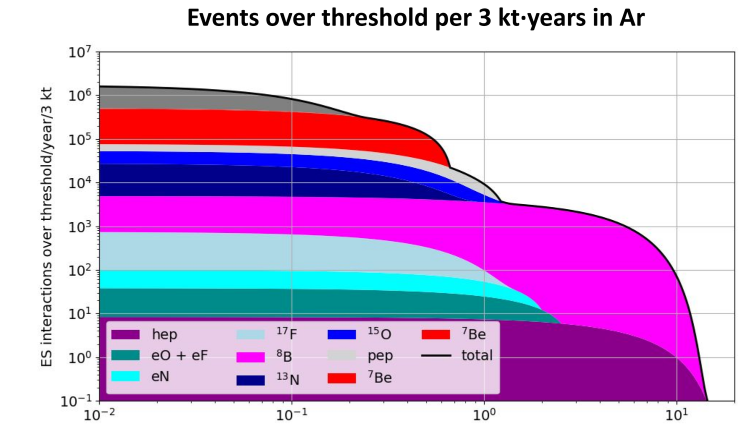
For DUNE low-background module (center right plot), assume exposure of 3 kt-years, 1-MeV threshold

For Hyper-K (bottom right plot), assume 217 kt of water and 3.5-MeV threshold

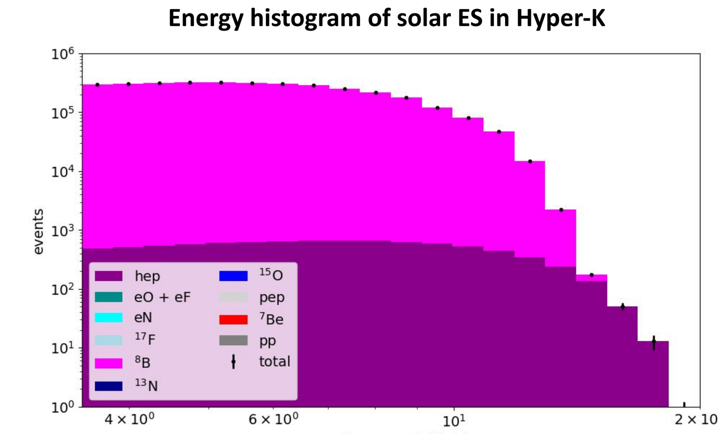
Energy histogram of solar ES in LZ



Events over threshold per 3 kt-years in Ar



Energy histogram of solar ES in Hyper-K



Statistical Analysis

Estimating sensitivity

Assume we observe SM prediction

What NSI we allow/exclude?

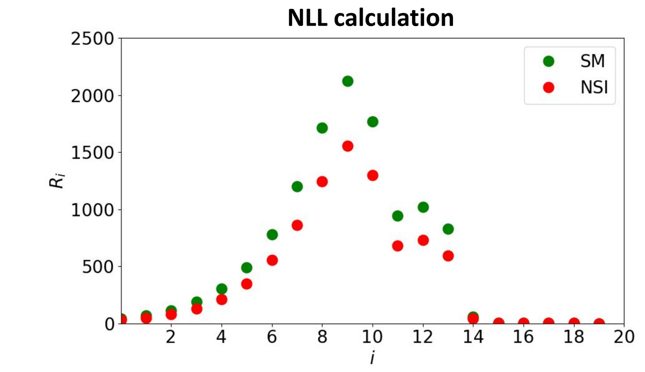
Use Poisson negative log likelihood

(see histograms on right for i, R_i^{SM}, R_i^{NSI})

$$NLL = -2\log\mathcal{L}$$

$$= 2\sum_{i=1}^{N}\left[R_i^{SM} - R_i^{NSI} + R_i^{SM}\log\frac{R_i^{NSI}}{R_i^{SM}}\right]$$

Example histograms for NLL calculation



Allowed NSI to 1σ, 90% CL, 2σ, 99% CL, 3σ

$NLL < 2.30, 4.61, 6.18, 9.21, 11.83$

Critical values from 2-df χ^2 distribution

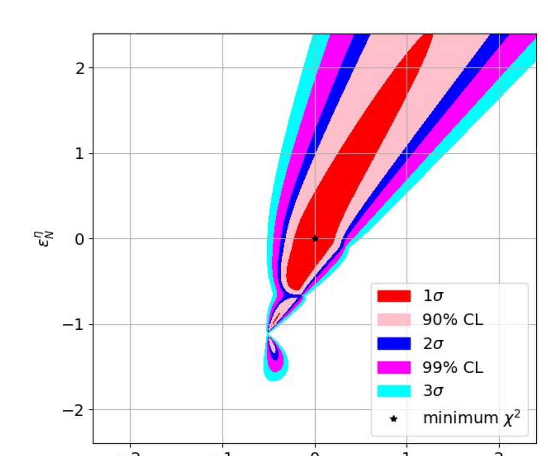
Expected Constraints/Sensitivity

Right – expected constraint for LZ

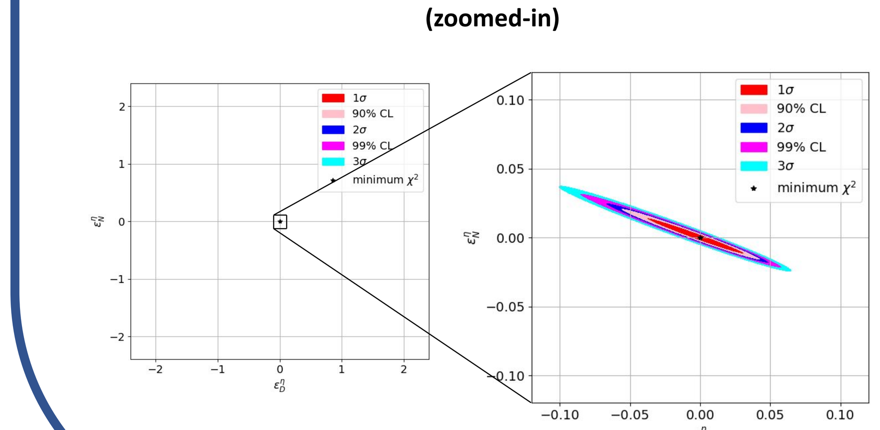
Bottom right – expected constraint for low-background DUNE module

Bottom left – expected constraint for Hyper-K. Has to be zoomed in compared to others to see shape because of high statistics

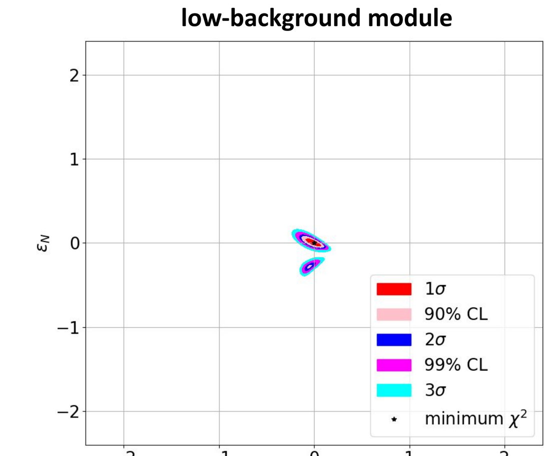
Estimated constraint for LZ



Estimated constraint for Hyper-K (zoomed-in)



Estimated constraint for DUNE low-background module



Conclusions

Expect to detect many solar neutrinos in current and future detectors.

Using them to estimate Non-Standard Neutrino Interactions (NSI) can result in significant improvement of constraints on NSI couplings or even give rise to new physics, potentially resolving the so-called "solar neutrino anomaly".