Non-standard interactions from the future solar sector

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OUTLINE

Neutrino oscillations. Where do we stand?

Neutrino non-standard interactions.
An introduction to the formalism.

Non-standard interactions with quarks. What to expect from the solar sector.

NEUTRINO OSCILLATIONS

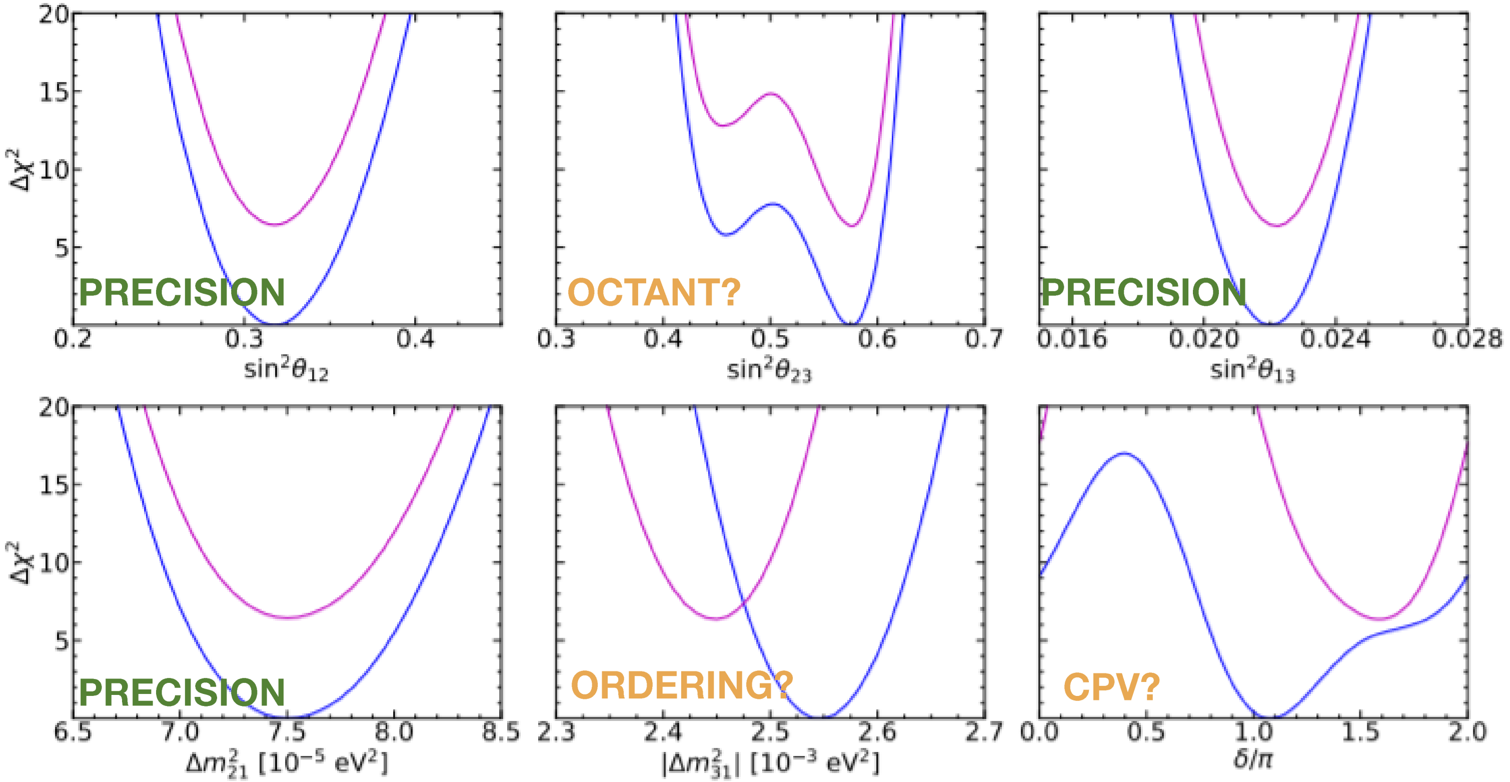
Parametrised with **3 angles**, **1 phase** and **2 mass splittings**.

Tested against different sources, baselines and energies for neutrinos and antineutrinos.

Neutrino oscillation experiments have reached the **precision era**.

de Salas *et al*. JHEP 02 (2021) 071 https://globalfit.astroparticles.es

See also: Esteban *et al.* JHEP 09 (2020) 178 & Capozzi *et al.* PRD 104 (2021) 8, 083031



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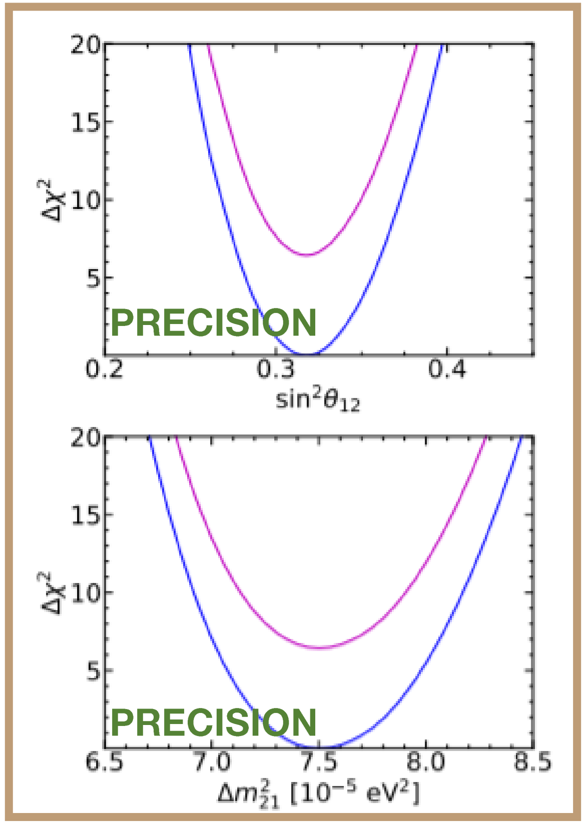

Current and future experiments can test **BSM scenarios!**

Non-standard interactions

An introduction to the formalism

Neutrino non-standard interactions (NSI)

They can be studied in the framework of Effective Field Theories and parametrised in terms of four-fermion operators.

In the case of neutral-current NSI (NC-NSI),

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

with

$X = \{L, R\}$ (chirality)

$\alpha, \beta = \{e, \mu, \tau\}$ (initial and final neutrino flavour)

$f = \{e, u, d\}$ (matter fields)

Neutrino non-standard interactions (NSI)

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Dimensionless coefficients $\varepsilon_{\alpha\beta}^{fX}$ quantify the strength of the interactions with respect to the SM.

They can be classified in two types:

$\varepsilon_{\alpha\alpha}^{fX}$ Non – universal NSI

$\varepsilon_{\alpha\beta}^{fX}$ $(\text{with } \alpha \neq \beta)$ Flavour – changing NSI

NSI* from the future solar sector

*NSI with d-quarks

A combination of JUNO and Hyper-Kamiokande will allow to simultaneously provide stringent bounds on NSI with quarks and a subpercet determination of the oscillation parameters of the solar sector.

NSI IN OSCILLATION EXPERIMENTS

In the presence of NSI, the evolution of neutrinos in matter is modified since NSI give rise to an effective potential.

$$H = H_{\text{vac}} + V_{\text{SM}} + V_{\text{NSI}} =$$

$$= U \frac{1}{2E} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U^\dagger + \sqrt{2} G_F \left[N_e \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + \sum_{f=e,u,d} N_f \begin{pmatrix} \varepsilon^{fV}_{ee} & \varepsilon^{fV}_{e\mu} & \varepsilon^{fV}_{e\tau} \\ \varepsilon^{fV*}_{e\mu} & \varepsilon^{fV}_{\mu\mu} & \varepsilon^{fV}_{\mu\tau} \\ \varepsilon^{fV*}_{e\tau} & \varepsilon^{fV*}_{\mu\tau} & \varepsilon^{fV}_{\tau\tau} \end{pmatrix} \right]$$

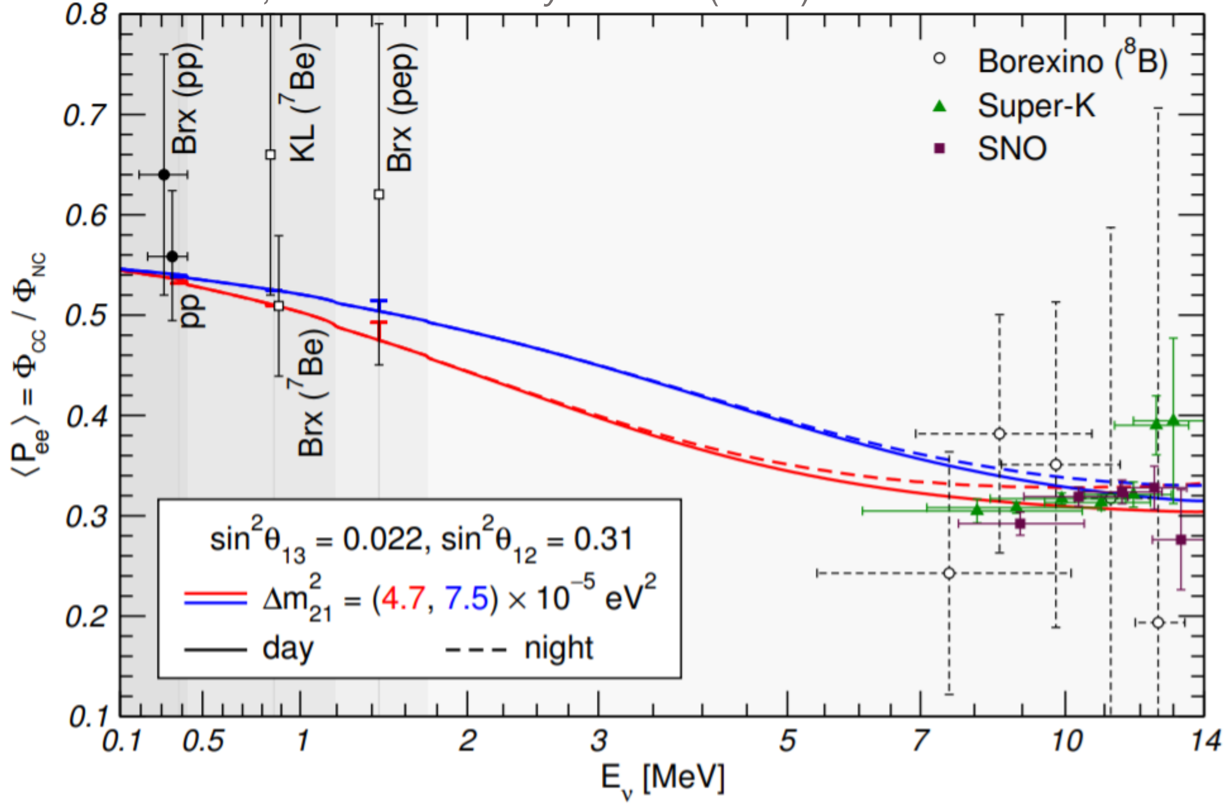
- The vector component of the interaction is the only one that alters propagation.
- The effect depends on the number density of electrons, up and down quarks in matter.

SOLAR NEUTRINOS

PRESENT AND FUTURE OF THE NEUTRINO SOLAR SECTOR

SOLAR NEUTRINOS

Maltoni, Smirnov. *Eur.Phys.J.A* 52 (2016)



At low energies, E < 1 MeV we have (almost) vacuum oscillations.

PRESENT AND FUTURE OF THE NEUTRINO SOLAR SECTOR

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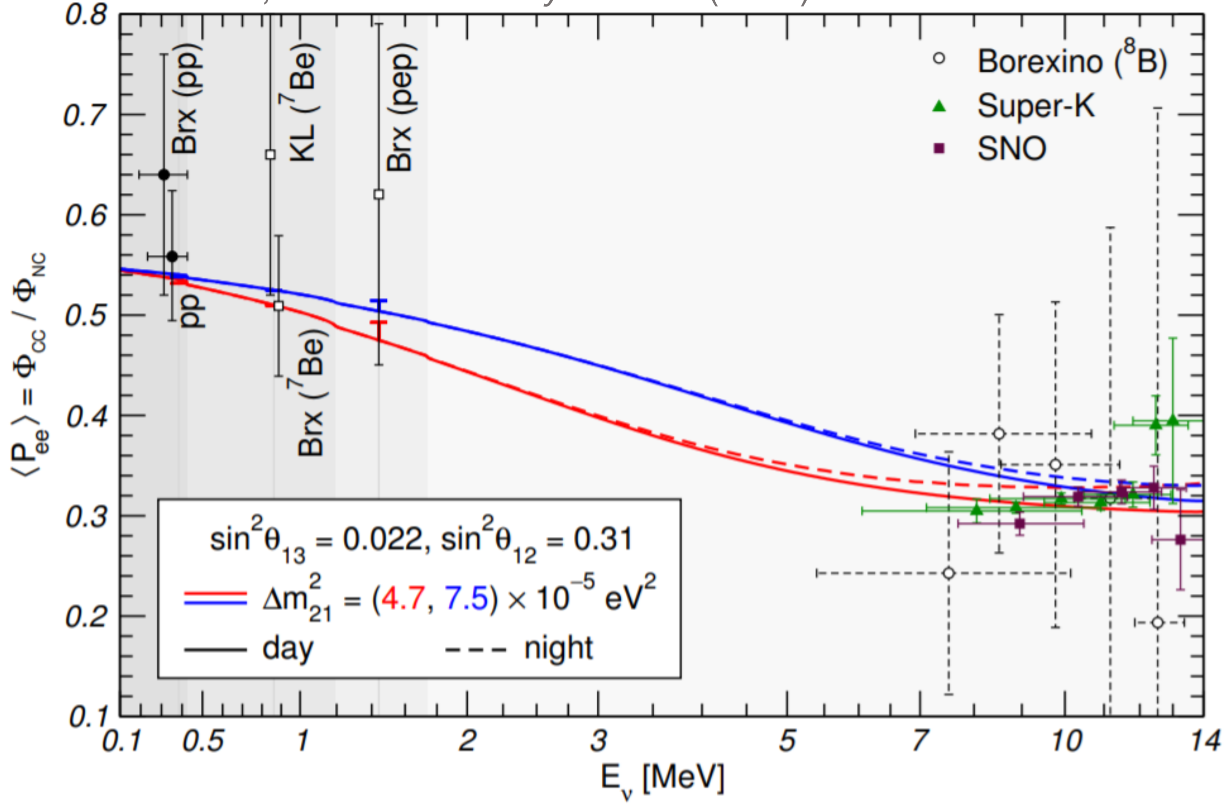

At higher energies, matter effects in the Sun are relevant.

PRESENT AND FUTURE OF THE NEUTRINO SOLAR SECTOR

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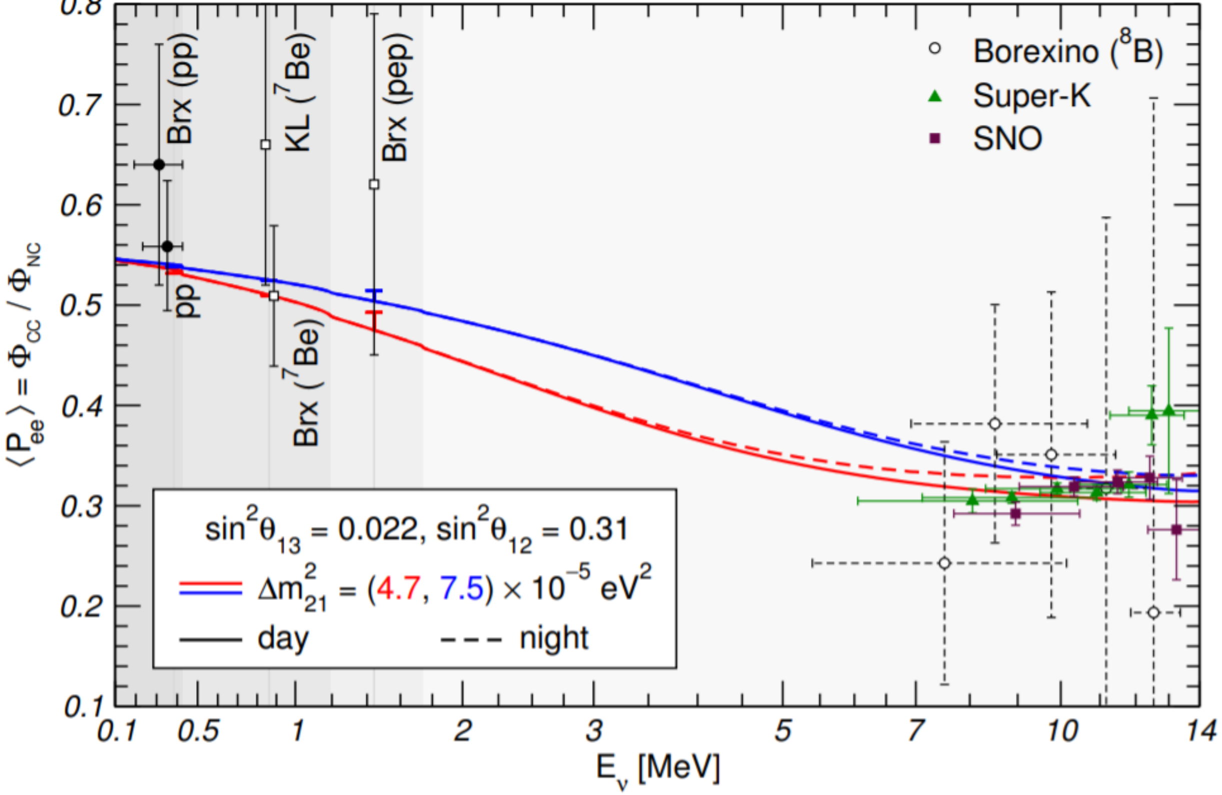
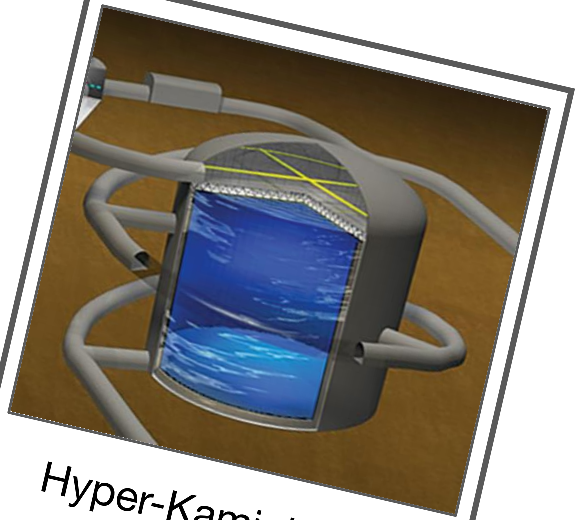


Day-night asymmetry as a consequence of matter effects on Earth.

PRESENT AND FUTURE OF THE NEUTRINO SOLAR SECTOR



Hyper-Kamiokande

HYPER-KAMIOKANDE

- Water Cherenkov detector
- Energy threshold of 3.5 MeV
- Fiducial volume ~ 8.3 times larger than Super-Kamiokande
- Sensitive to all neutrino flavours.

  Elastic neutrino-electron scattering:

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

Since we are only considering NC-NSI with quarks, this cross section is not modified.

PRESENT AND FUTURE OF THE NEUTRINO SOLAR SECTOR

SOLAR NEUTRINOS WITH NSI

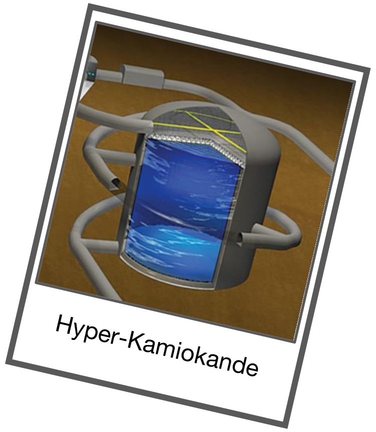
An effective 2-neutrino description is possible for solar neutrinos

$$P_{ee} = \cos^4\theta_{13} P_{ee}^{2\nu} + \sin^4\theta_{13},$$

Effective NSI parameters

$$H^{2\nu} = \frac{\Delta m_{21}^2}{4E}\begin{pmatrix} -\cos 2\theta_{12} & \sin 2\theta_{12} \\ \sin 2\theta_{12} & \cos 2\theta_{12} \end{pmatrix} + \sqrt{2} G_F \left[\cos^2\theta_{13} N_e \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} + \sum_{f=e,u,d} N_f \begin{pmatrix} 0 & \varepsilon_f \\ \varepsilon_f^* & \varepsilon_f' \end{pmatrix} \right]$$

PRESENT AND FUTURE OF THE NEUTRINO SOLAR SECTOR



HYPER-KAMIOKANDE

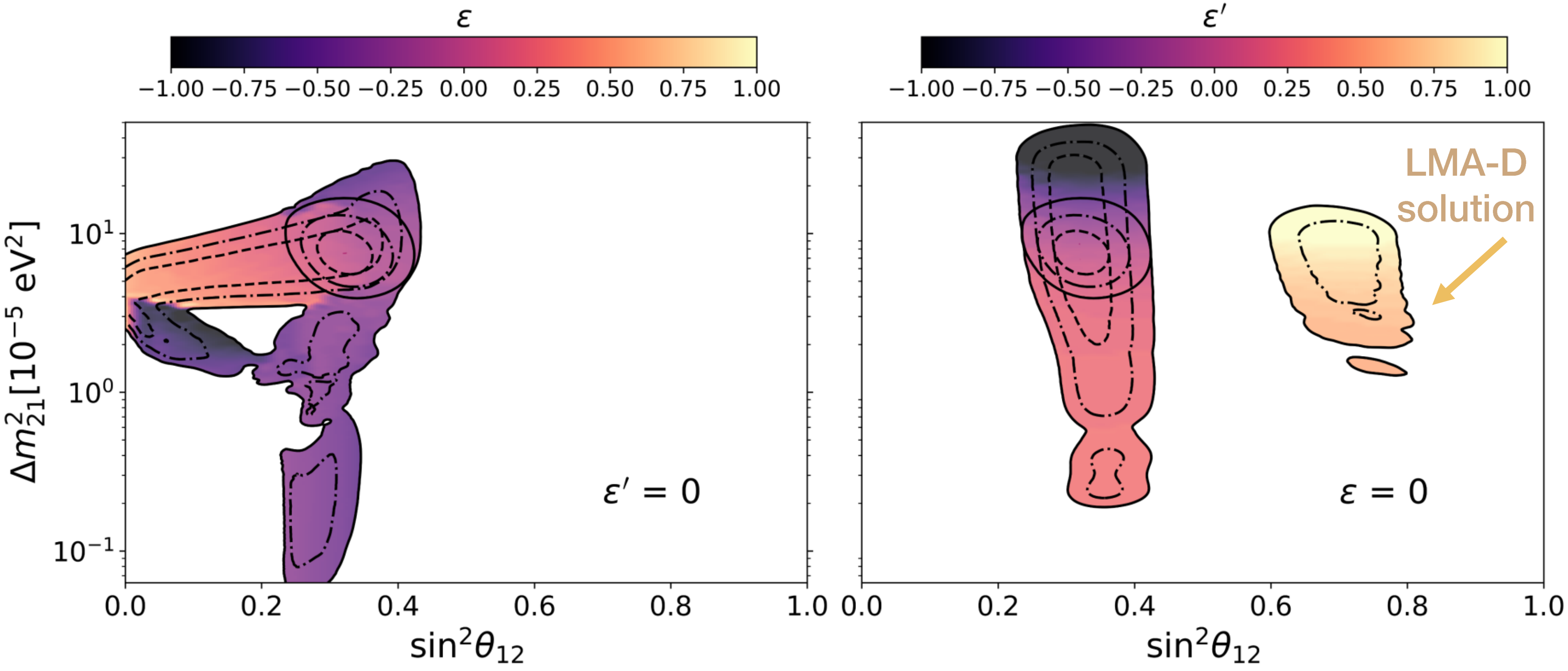


Figure shows 1σ, 2σ and 3σ C.L contours. Mock data assumes no NSI.

MEDIUM & LONG BASELINE REACTOR EXPERIMENTS

PRESENT AND FUTURE OF THE NEUTRINO SOLAR SECTOR

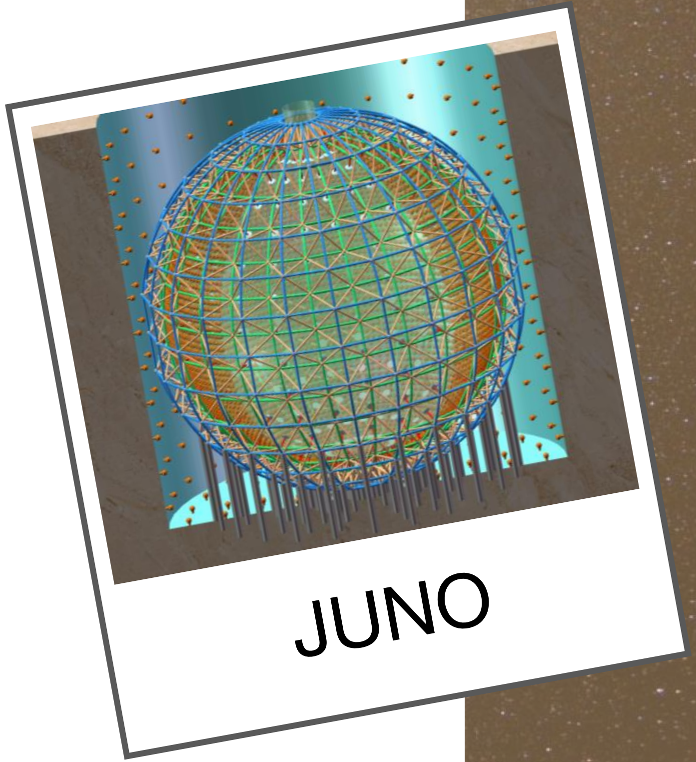
MEDIUM AND LONG BASELINE REACTOR EXPERIMENTS

JUNO:

- 20 kt Liquid Scintillator
- Average baseline of ~53 km.
- Inverse Beta Decay (IBD) for detection

$$\bar{\nu}_e + p \rightarrow e^- + n$$

NC-NSI do not modify this



- Large statistics and great energy resolution.

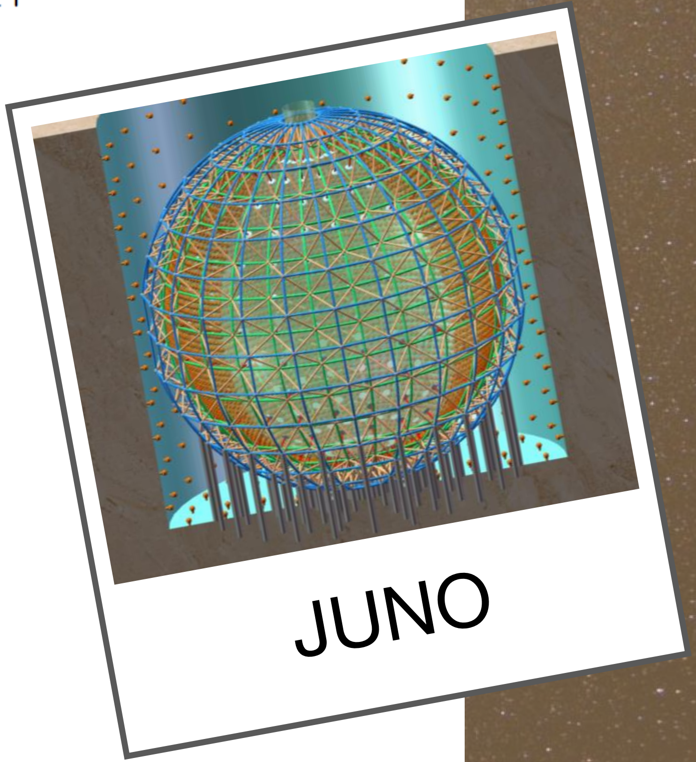
PRESENT AND FUTURE OF THE NEUTRINO SOLAR SECTOR

MEDIUM AND LONG BASELINE REACTOR EXPERIMENTS

JUNO aims to determine θ_{12}, Δm^2_{21}, θ_{13}, and $|\Delta m^2_{31}|$ and the mass hierarchy.

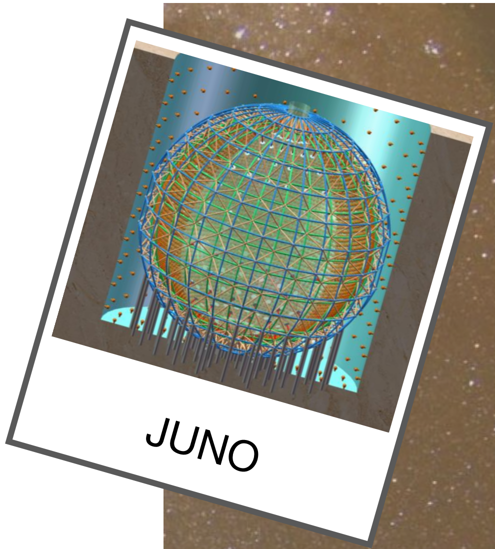
Matter effects (and NSI) have a small impact in JUNO…

… but they need to be accounted for when doing PRECISION physics.



PRESENT AND FUTURE OF THE NEUTRINO SOLAR SECTOR

MEDIUM AND LONG BASELINE REACTOR EXPERIMENTS



JUNO's sensitivity would not reach its precision goals if one includes the possibility of having non-zero NSI (with d-quarks).

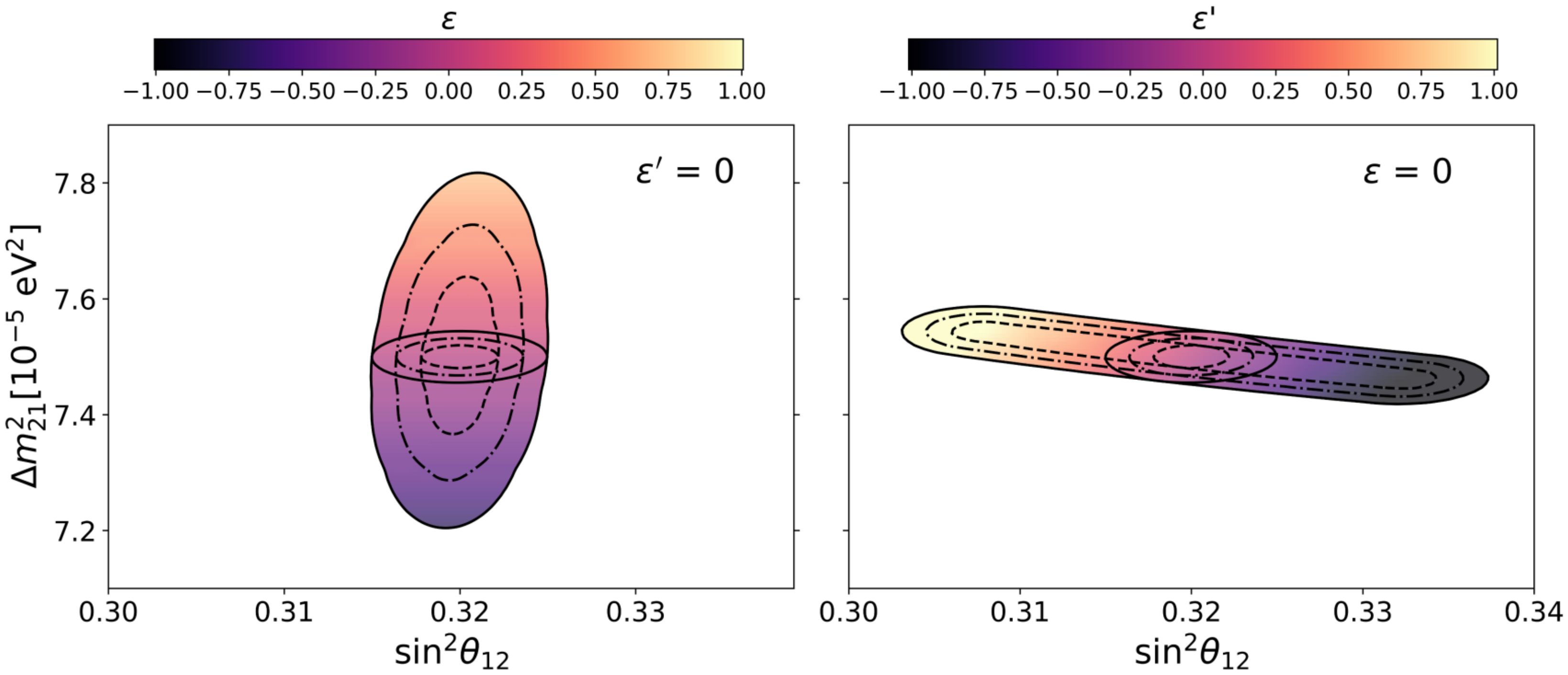


Figure shows 1σ, 2σ and 3σ C.L contours. Mock data assumes no NSI.

COMBINED ANALYSIS
JUNO AND HYPER-KAMIOKANDE

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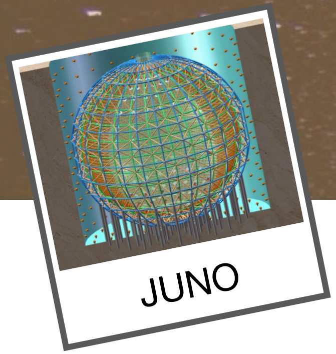
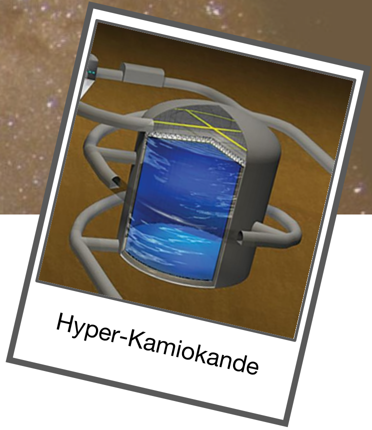




JUNO

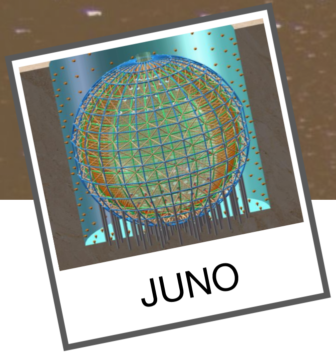
- can measure oscillations precisely.
- is not very sensitive to NSI.

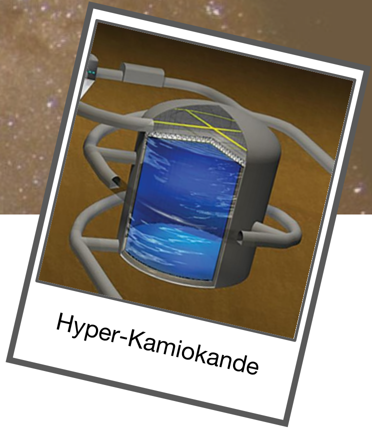
HYPER-KAMIOKANDE

- can not measure oscillations so precisely.
- is very sensitive to NSI (and other effects altering propagation in matter).

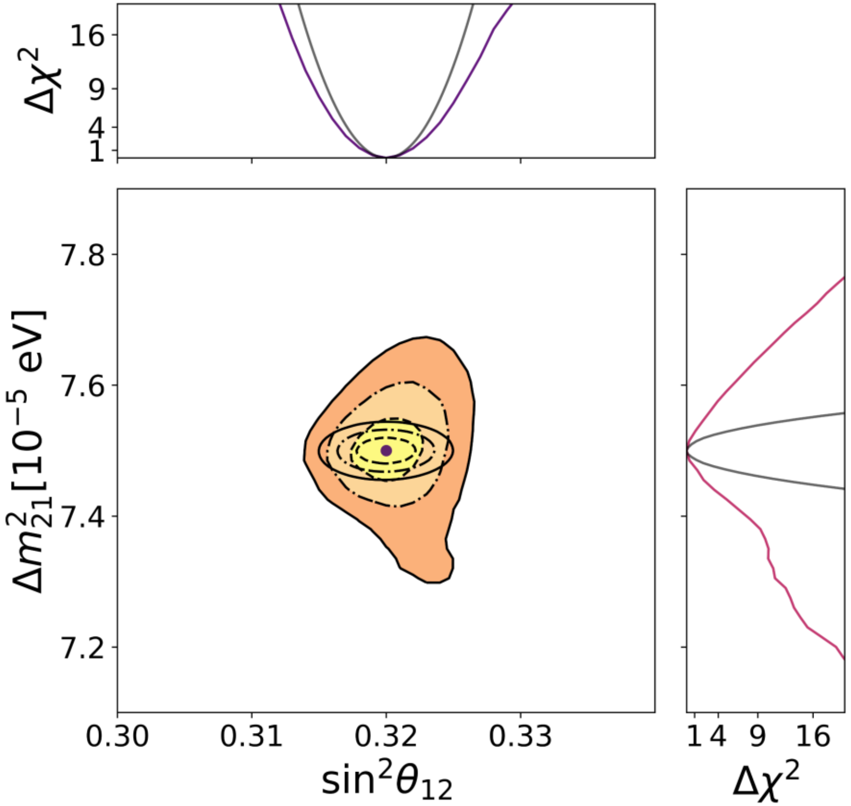
They can nicely complement each other.

COMBINED ANALYSIS JUNO AND HYPER-KAMIOKANDE

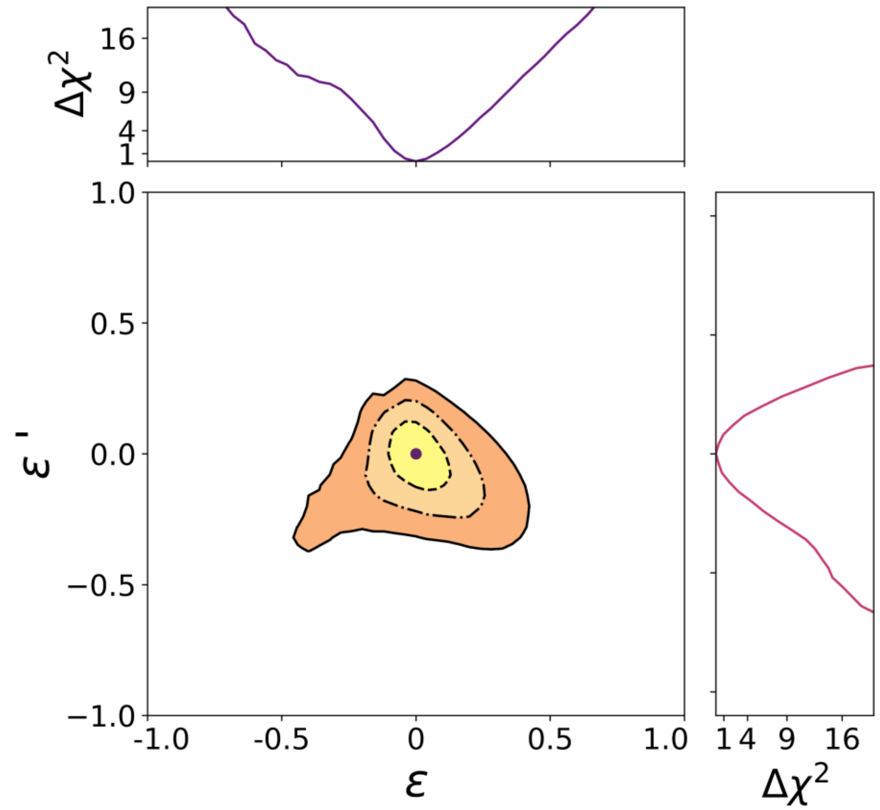




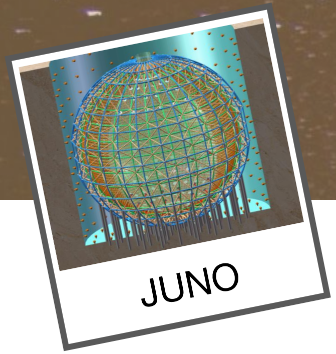
OSCILLATION PARAMETERS

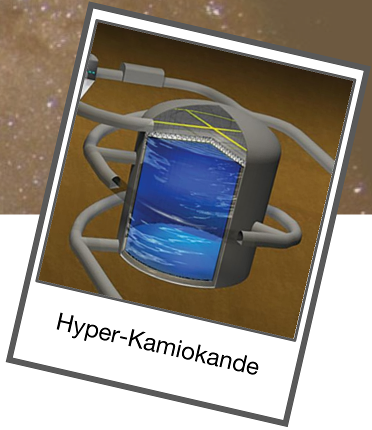


NSI PARAMETERS



COMBINED ANALYSIS JUNO AND HYPER-KAMIOKANDE





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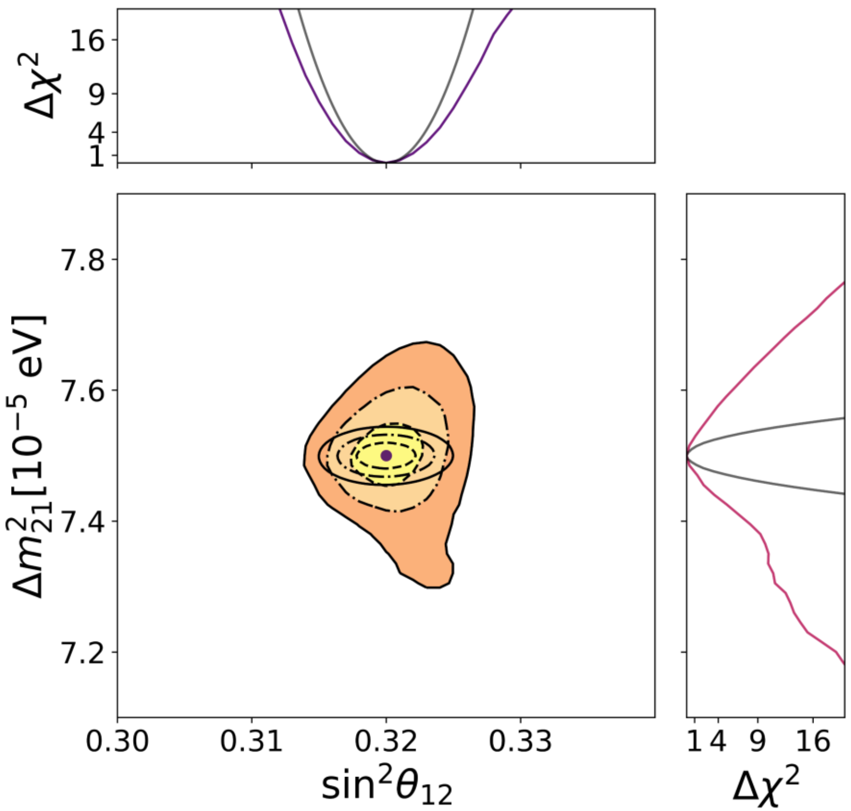


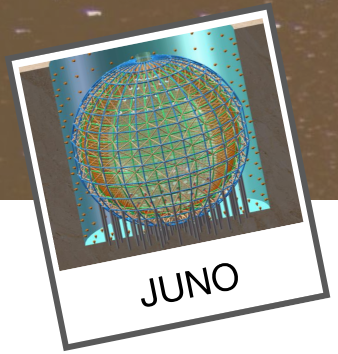
A combination of Hyper-Kamiokande and JUNO will ensure an accurate determination of the oscillation parameters.

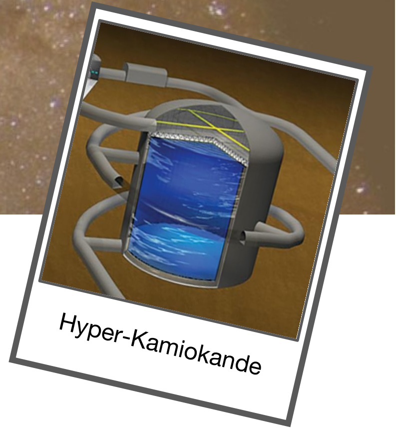
At 90%C.L,

$$0.318 < \sin^2\theta_{12} < 0.322$$

$$7.48 \times 10^{-5}\mathrm{eV}^2 < \Delta m^2_{21} < 7.52 \times 10^{-5}\mathrm{eV}^2$$

COMBINED ANALYSIS
JUNO AND HYPER-KAMIOKANDE





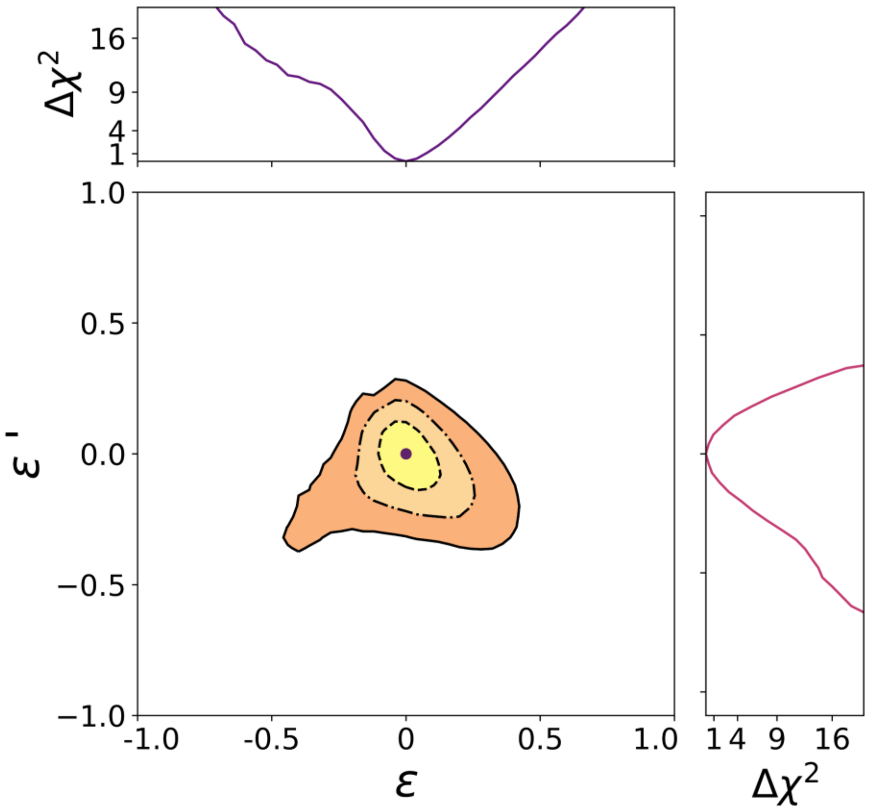
A combination of Hyper-Kamiokande and JUNO will set stringent bounds on NSI too.

At 90%C.L,

$$-0.153 < \varepsilon' < 0.135$$
$$-0.113 < \varepsilon < 0.144$$

*reconstructing with the same mass ordering that we use for generating mock data.

NSI PARAMETERS



NSI from the future solar sector

A combination of JUNO and Hyper-Kamiokande will allow to simultaneously provide stringent bounds on NSI with quarks and a subpercet determination of the oscillation parameters of the solar sector.

https://arxiv.org/abs/2111.03031

https://journals.aps.org/prd/pdf/10.1103/PhysRevD.105.035004