



NSI Studies with Solar Neutrinos

Gleb Sinev, Juergen Reichenbacher

South Dakota Mines

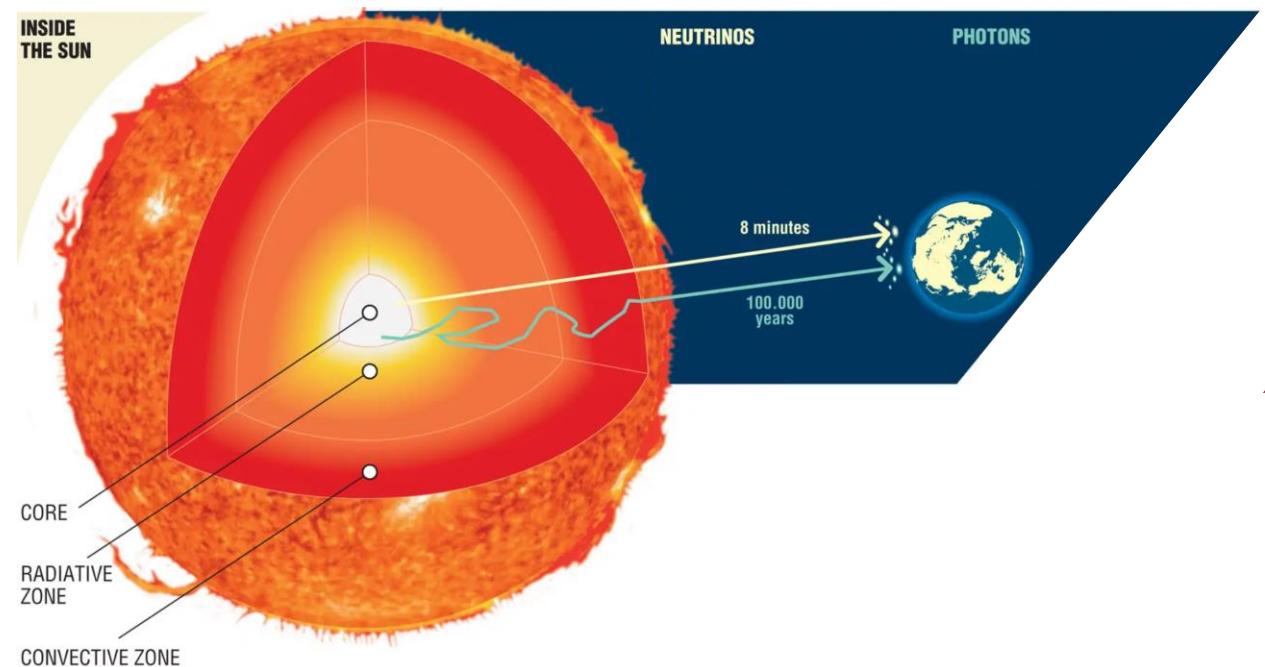
NPN2023

July 11, 2023



Outline

- Non-standard neutrino interactions (NSI)
 - Solar neutrinos, oscillations
- Rates and measurement
- Potential experimental constraints
- Conclusions



<https://www.businessinsider.com/neutrinos-forged-in-the-heart-of-the-sun-2014-8>

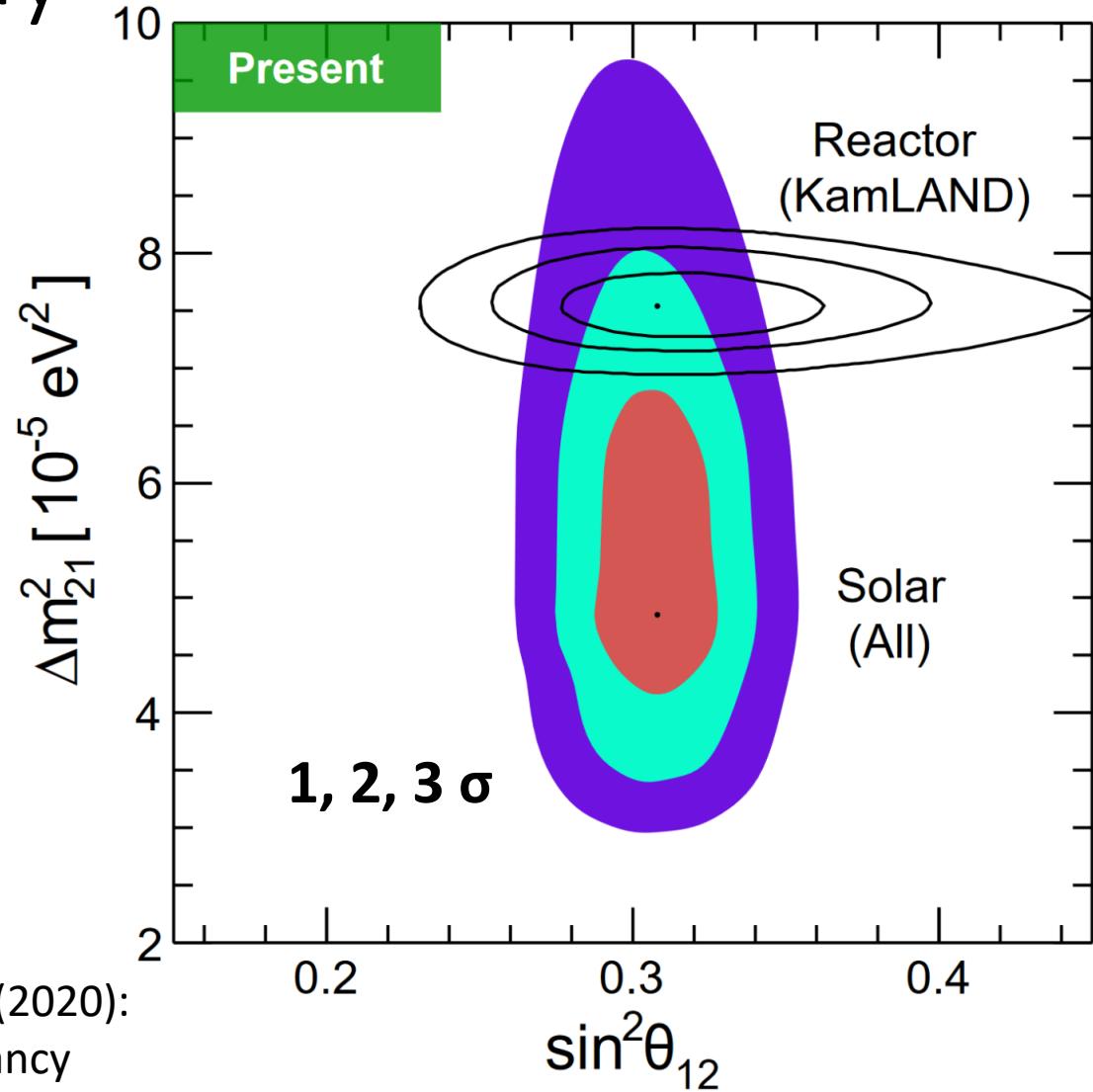
Solar neutrino anomaly

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

arXiv:1808.08232

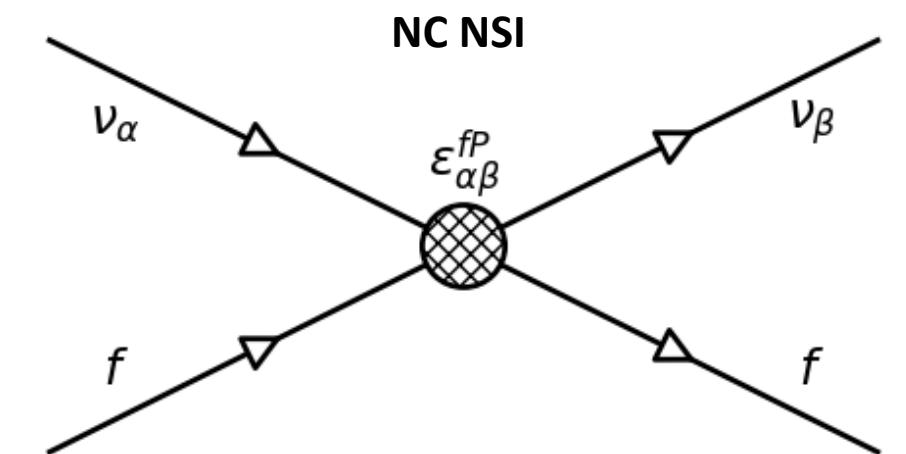
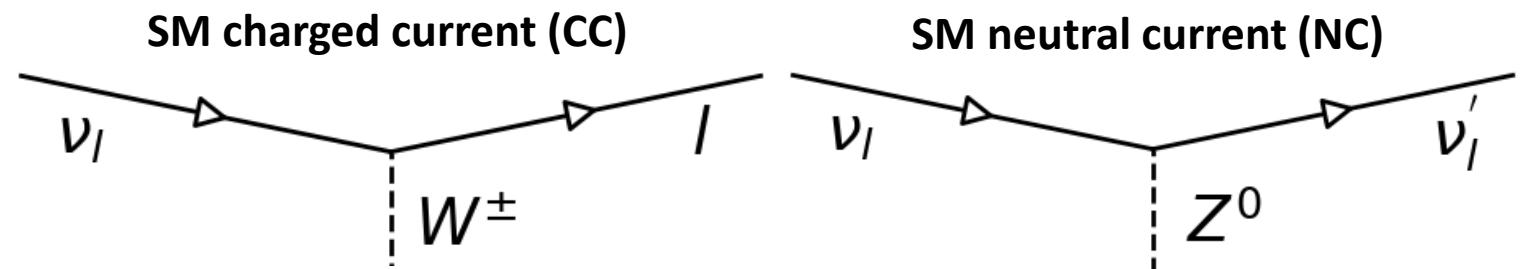
- $\sim 2\sigma$ discrepancy in solar Δm^2 measured by solar ν experiments and KamLAND (reactor ν experiment)
- Just statistics?
 - If not...

New Super-K results (2020):
now 1.4σ discrepancy



Non-standard neutrino interactions (NSI)

- One possible explanation
- Standard model (SM) neutrino interactions
 - Everything else: NSI
- Here focus on neutral-current models with heavy mediators ($m_Z^2 \gg Q^2$)
 - $\mathcal{L}_{\alpha\beta}^{fP} = -2\sqrt{2}G_F \varepsilon_{\alpha\beta}^{fP} [\bar{\nu}_\alpha \gamma^\mu (1 - \gamma^5) \nu_\beta] [\bar{f} \gamma_\mu P f]$
 - Can change ν flavor, not fermion (f)
 - Parameterized by ε 's

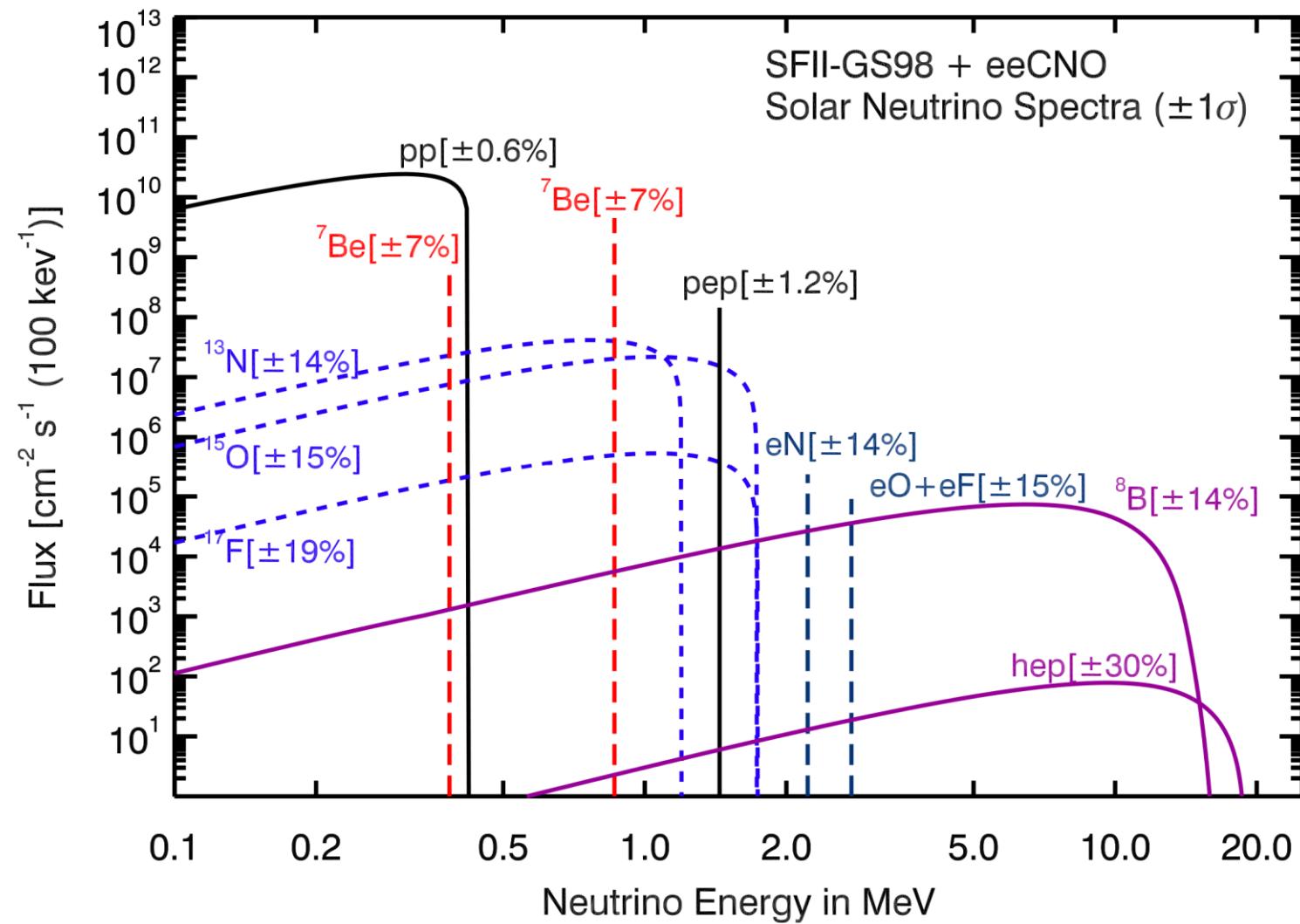


Solar neutrinos

- High flux of neutrinos < 20 MeV produced in Sun
 - Most < 1 MeV
- Produced as ν_e
 - ~0.5 change flavor

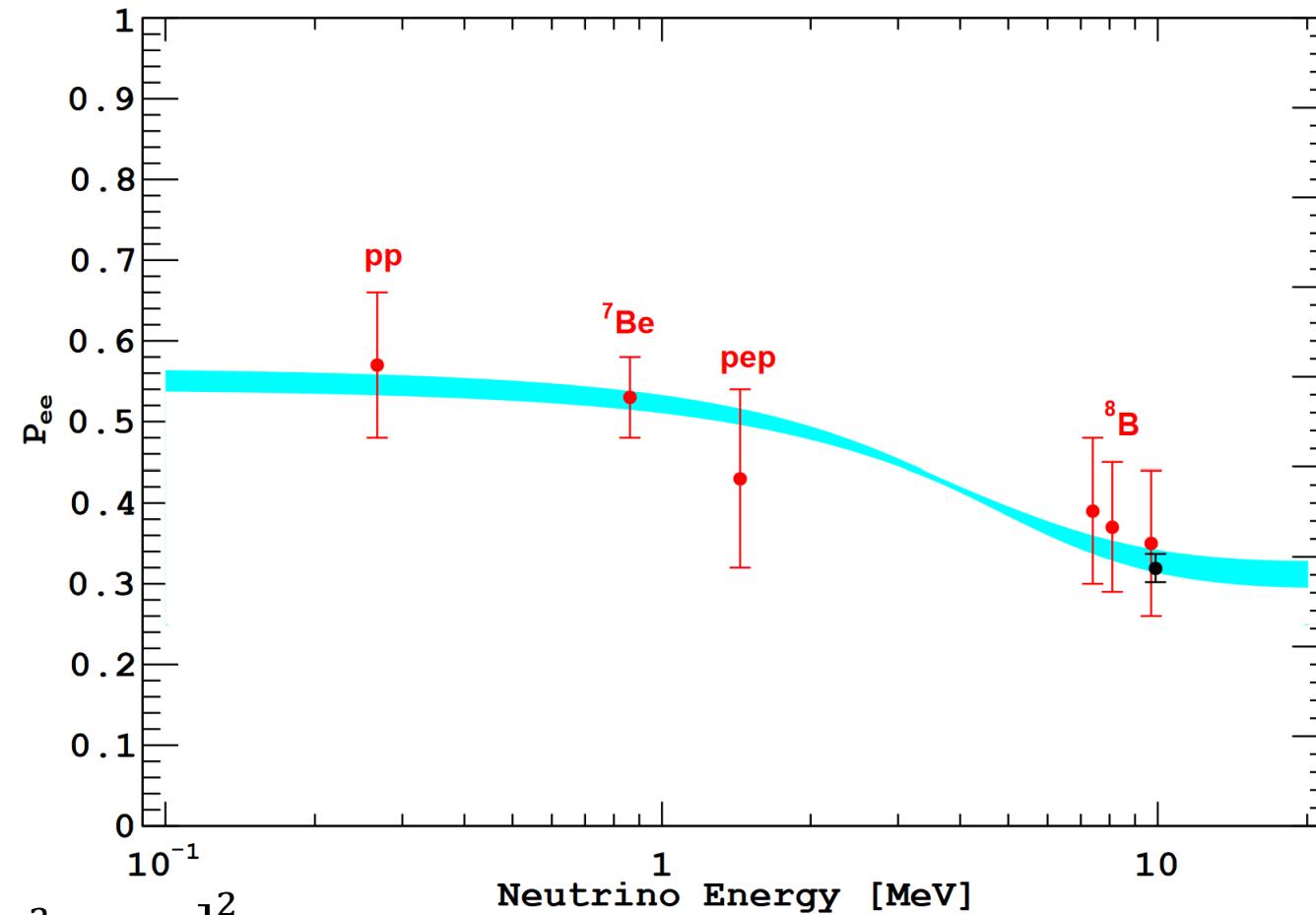
<https://arxiv.org/pdf/1601.07179.pdf> A. Serenelli (2016)
<https://pdg.lbl.gov/2020/reviews/rpp2020-rev-neutrino-mixing.pdf>

PDG 2020



Solar neutrino oscillations

- Vacuum oscillations + matter effect in Sun
- ν_e survival probability
 - $P_{ee}^{3\nu} = \cos^4 \theta_{13} P_{ee}^{2\nu} + \sin^4 \theta_{13}$
 - $P_{ee}^{2\nu} = \frac{1}{2} [1 + \cos 2\theta \cos 2\theta_m]$
 - $\cos 2\theta_m = \frac{\Delta m^2 \cos 2\theta - 2\sqrt{2} E G_F N_e}{[\Delta m^2]_{matter}}$
 - $[\Delta m^2]_{matter}^2 = [\Delta m^2 \cos 2\theta - 2\sqrt{2} E G_F N_e]^2 + [\Delta m^2 \sin 2\theta]^2$



NSI in Sun

- 2-flavor model

$$\bullet \quad H = \begin{pmatrix} \text{SM vacuum oscillations + matter effect} & \text{NSI} \\ \begin{pmatrix} -\frac{\Delta m^2}{4E} \cos 2\theta + \sqrt{2}G_F N_e & \frac{\Delta m^2}{4E} \sin 2\theta \\ \frac{\Delta m^2}{4E} \sin 2\theta & \frac{\Delta m^2}{4E} \cos 2\theta \end{pmatrix} & \sqrt{2}G_F(N_d + N_u) \begin{pmatrix} \varepsilon_D & \varepsilon_N \\ \varepsilon_N & -\varepsilon_D \end{pmatrix} \end{pmatrix}$$

- Measurement: $P(\nu_e \rightarrow \nu_e) = \frac{1}{2} [1 + \cos 2\theta \cos 2\theta_m]$
- $\cos 2\theta_m = \frac{\Delta m^2 \cos 2\theta - 2\sqrt{2}EG_F(N_e + 2\varepsilon_D(N_d + N_u))}{[\Delta m^2]_{matter}}$
- $[\Delta m^2]_{matter}^2 = [\Delta m^2 \cos 2\theta - 2\sqrt{2}EG_F(N_e + 2\varepsilon_D(N_d + N_u))]^2 + [\Delta m^2 \sin 2\theta + 4\sqrt{2}\varepsilon_N EG_F(N_d + N_u)]^2$

NSI in Sun

- 2-flavor model

$$\bullet \quad H = \begin{pmatrix} \text{SM vacuum oscillations + matter effect} & \text{NSI} \\ \begin{pmatrix} -\frac{\Delta m^2}{4E} \cos 2\theta + \sqrt{2}G_F N_e & \frac{\Delta m^2}{4E} \sin 2\theta \\ \frac{\Delta m^2}{4E} \sin 2\theta & \frac{\Delta m^2}{4E} \cos 2\theta \end{pmatrix} & \boxed{\sqrt{2}G_F(N_d + N_u) \begin{pmatrix} \varepsilon_D & \varepsilon_N \\ \varepsilon_N & -\varepsilon_D \end{pmatrix}} \end{pmatrix}$$

$$\bullet \quad \text{Measurement: } P(\nu_e \rightarrow \nu_e) = \frac{1}{2} [1 + \cos 2\theta \cos 2\theta_m]$$

$$\bullet \quad \cos 2\theta_m = \frac{\Delta m^2 \cos 2\theta - 2\sqrt{2}EG_F(N_e + 2\varepsilon_D(N_d + N_u))}{[\Delta m^2]_{\text{matter}}} \quad \text{NSI}_D$$

$$\bullet \quad [\Delta m^2]_{\text{matter}}^2 = [\Delta m^2 \cos 2\theta - 2\sqrt{2}EG_F(N_e + 2\varepsilon_D(N_d + N_u))]^2 + [\Delta m^2 \sin 2\theta + 4\sqrt{2}\varepsilon_N EG_F(N_d + N_u)]^2 \quad \text{NSI}_N$$

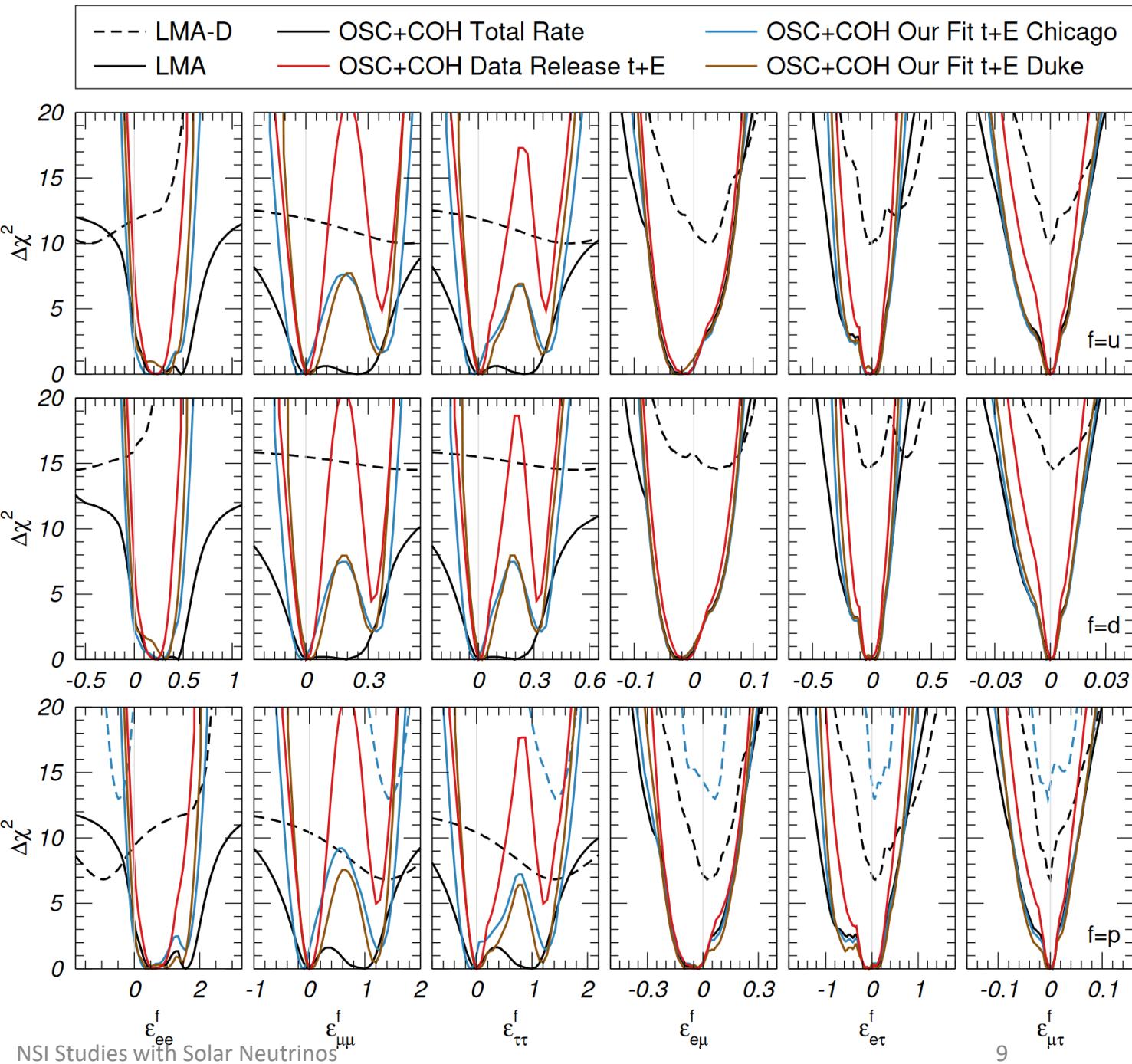
NSI constraints (early 2020)

- All but plotted NSI coupling marginalized

Excellent global fit and summary of NSI:

P. Coloma, I. Esteban,
M.C. Gonzalez-Garcia, M. Maltoni (2019)
arXiv:1911.09109

07/11/2023



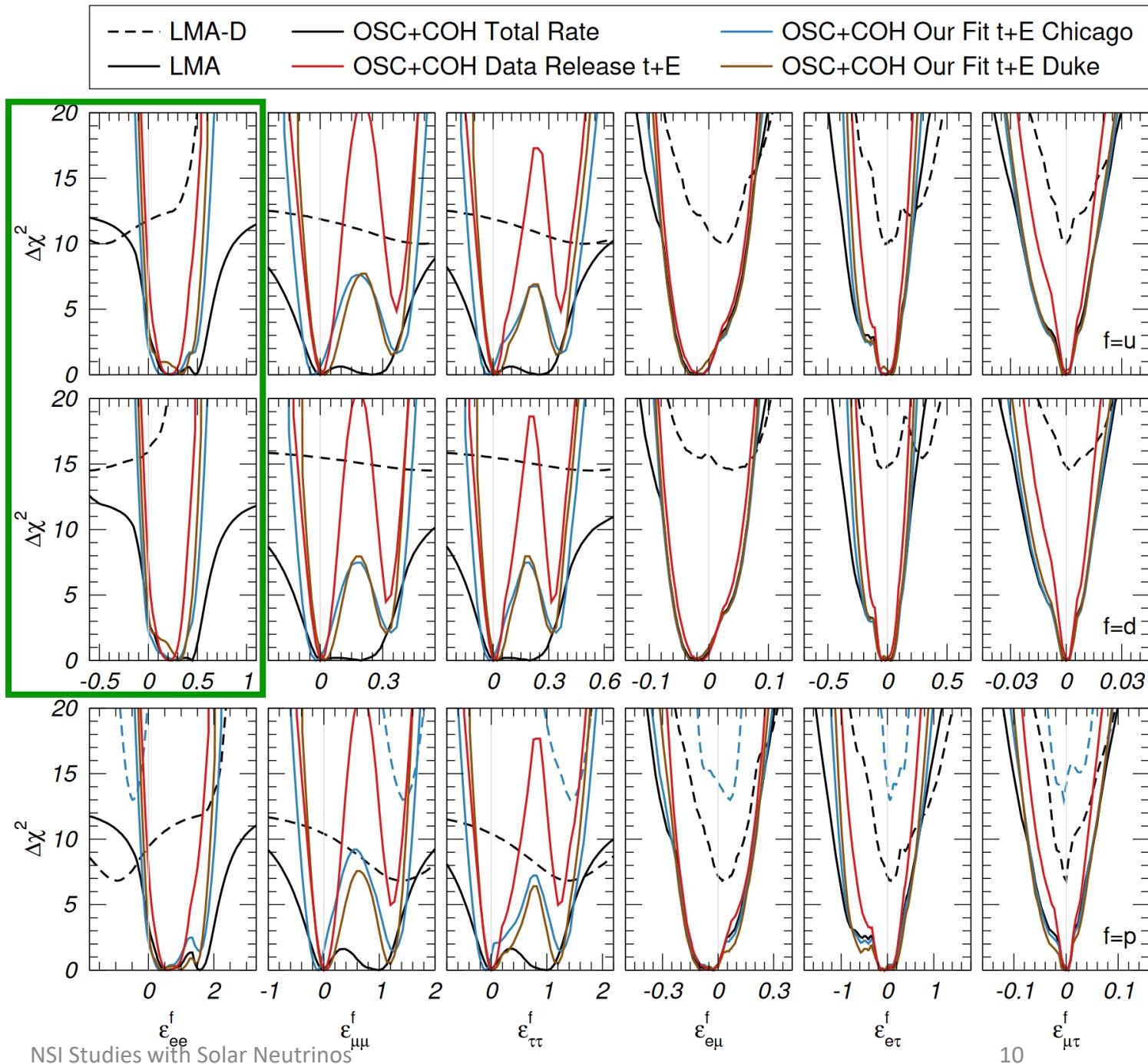
NSI constraints (early 2020)

- All but plotted NSI coupling marginalized
- Looking primarily at ε_{ee}^u and ε_{ee}^d
 - Most promising for non-zero NSI
 - What if we set $\varepsilon_{ee}^u = \varepsilon_{ee}^d$ and rest to 0?

Excellent global fit and summary of NSI:

P. Coloma, I. Esteban,
M.C. Gonzalez-Garcia, M. Maltoni (2019)
arXiv:1911.09109

07/11/2023



Simplified model

- 2-flavor model

$$\bullet H = \begin{pmatrix} \text{SM vacuum oscillations + matter effect} & \text{NSI} \\ \begin{pmatrix} -\frac{\Delta m^2}{4E} \cos 2\theta + \sqrt{2}G_F N_e & \frac{\Delta m^2}{4E} \sin 2\theta \\ \frac{\Delta m^2}{4E} \sin 2\theta & \frac{\Delta m^2}{4E} \cos 2\theta \end{pmatrix} & \boxed{\sqrt{2}G_F(N_d + N_u) \begin{pmatrix} \varepsilon_D & 0 \\ 0 & -\varepsilon_D \end{pmatrix}} \end{pmatrix}$$

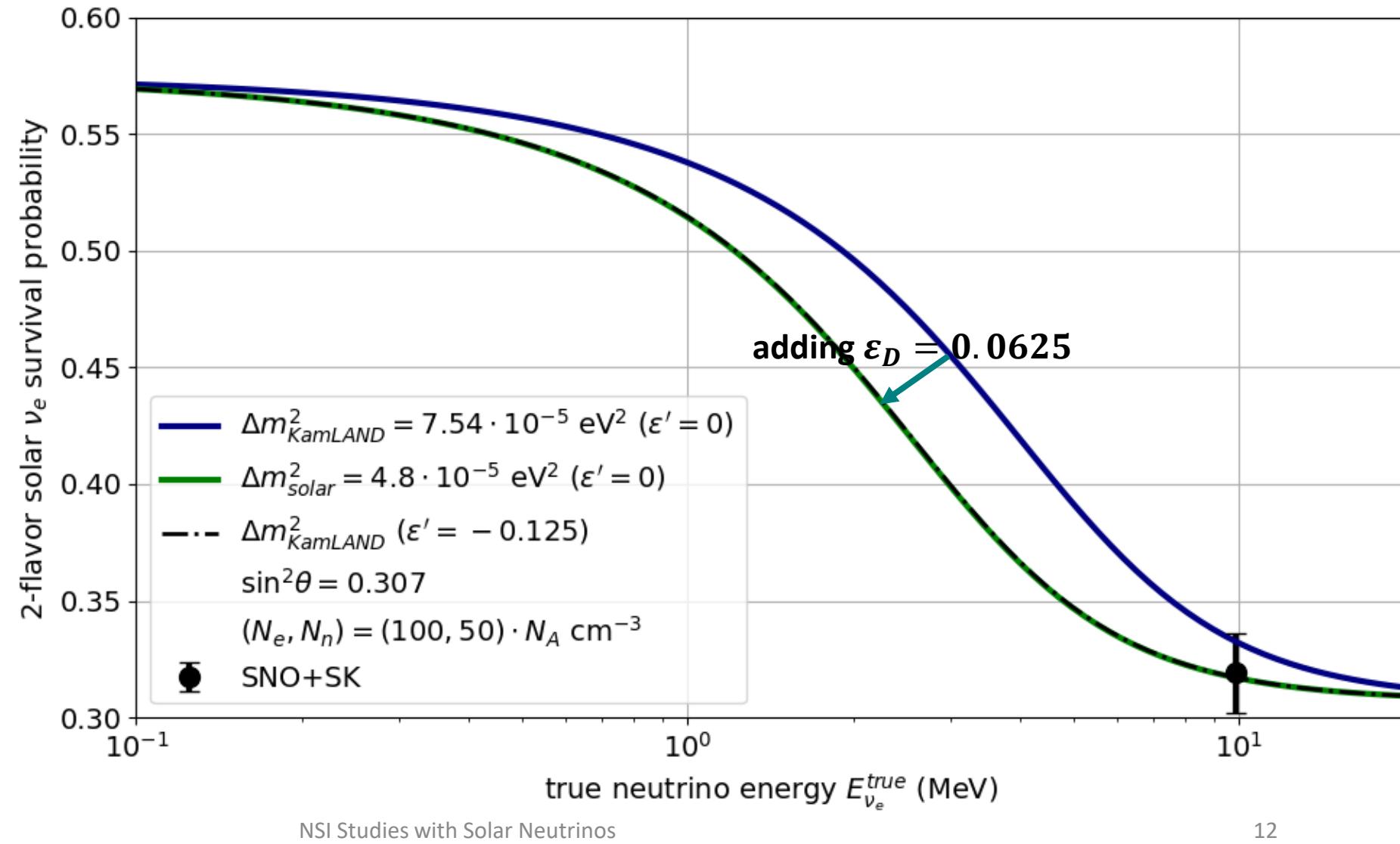
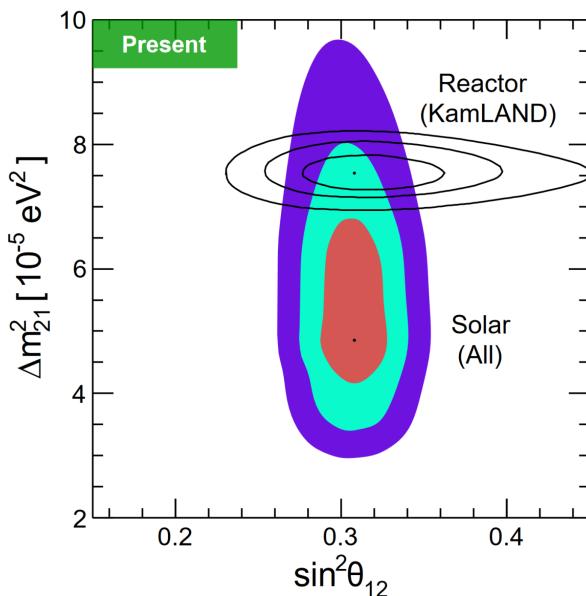
$$\bullet \text{Measurement: } P(\nu_e \rightarrow \nu_e) = \frac{1}{2} [1 + \cos 2\theta \cos 2\theta_m] \quad \varepsilon_D = \frac{\varepsilon_{ee}^u}{2} = \frac{\varepsilon_{ee}^d}{2}$$

$$\bullet \cos 2\theta_m = \frac{\Delta m^2 \cos 2\theta - 2\sqrt{2}EG_F(N_e + \boxed{2\varepsilon_D(N_d + N_u)})}{[\Delta m^2]_{\text{matter}}} \quad \text{NSI}_D \quad \text{NSI}_N = 0$$

$$\bullet [\Delta m^2]_{\text{matter}}^2 = [\Delta m^2 \cos 2\theta - 2\sqrt{2}EG_F(N_e + \boxed{2\varepsilon_D(N_d + N_u)})]^2 + [\Delta m^2 \sin 2\theta]^2$$

NSI-modified oscillations

- Correcting KamLAND result (**blue**) with $\varepsilon_D = 0.0625$ (dot-dashed) produces same survival probability as solar fit (**green**)
- Could possibly explain neutrino anomaly



Back to full model

- 2-flavor model

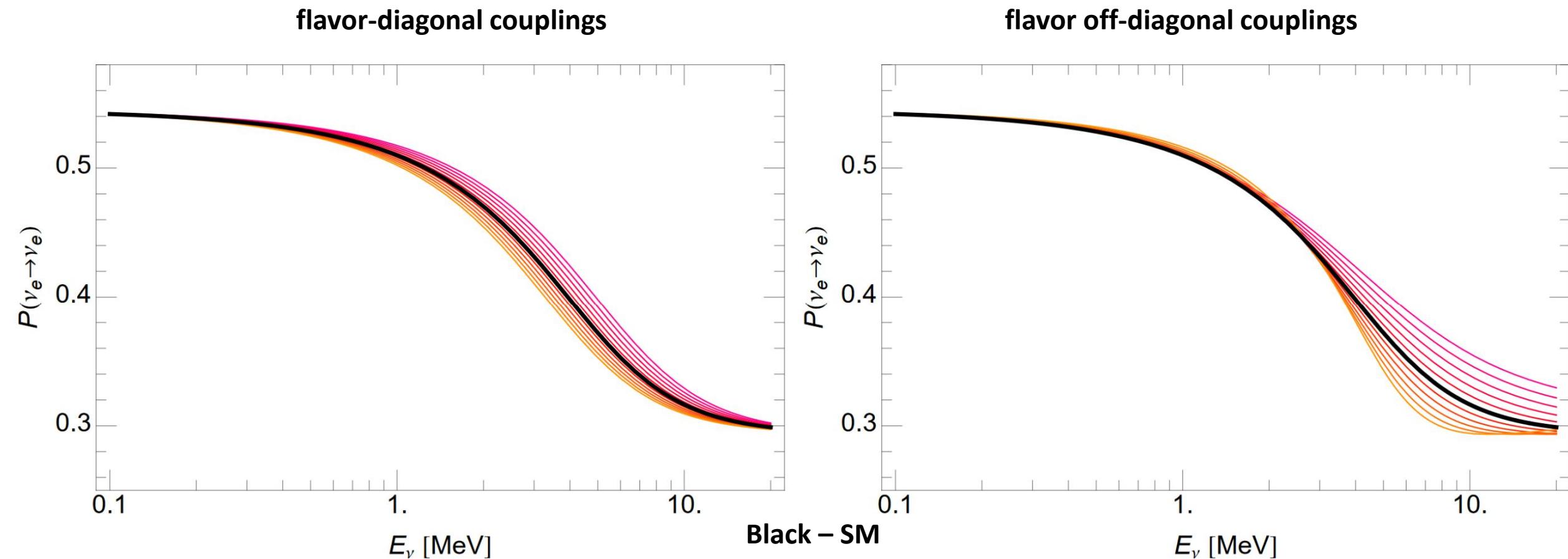
$$\bullet H = \begin{pmatrix} \text{SM vacuum oscillations + matter effect} & \text{NSI} \\ -\frac{\Delta m^2}{4E} \cos 2\theta + \sqrt{2}G_F N_e & \frac{\Delta m^2}{4E} \sin 2\theta \\ \frac{\Delta m^2}{4E} \sin 2\theta & \frac{\Delta m^2}{4E} \cos 2\theta \end{pmatrix} + \boxed{\sqrt{2}G_F(N_d + N_u) \begin{pmatrix} \varepsilon_D & \varepsilon_N \\ \varepsilon_N & -\varepsilon_D \end{pmatrix}}$$

$$\bullet \text{Measurement: } P(\nu_e \rightarrow \nu_e) = \frac{1}{2} [1 + \cos 2\theta \cos 2\theta_m]$$

$$\bullet \cos 2\theta_m = \frac{\Delta m^2 \cos 2\theta - 2\sqrt{2}EG_F(N_e + 2\varepsilon_D(N_d + N_u))}{[\Delta m^2]_{\text{matter}}} \quad \text{NSI}_D$$

$$\bullet [\Delta m^2]_{\text{matter}}^2 = [\Delta m^2 \cos 2\theta - 2\sqrt{2}EG_F(N_e + 2\varepsilon_D(N_d + N_u))]^2 + [\Delta m^2 \sin 2\theta + 4\sqrt{2}\varepsilon_N EG_F(N_d + N_u)]^2 \quad \text{NSI}_N$$

How do NSI affect survival probability?



Current constraints

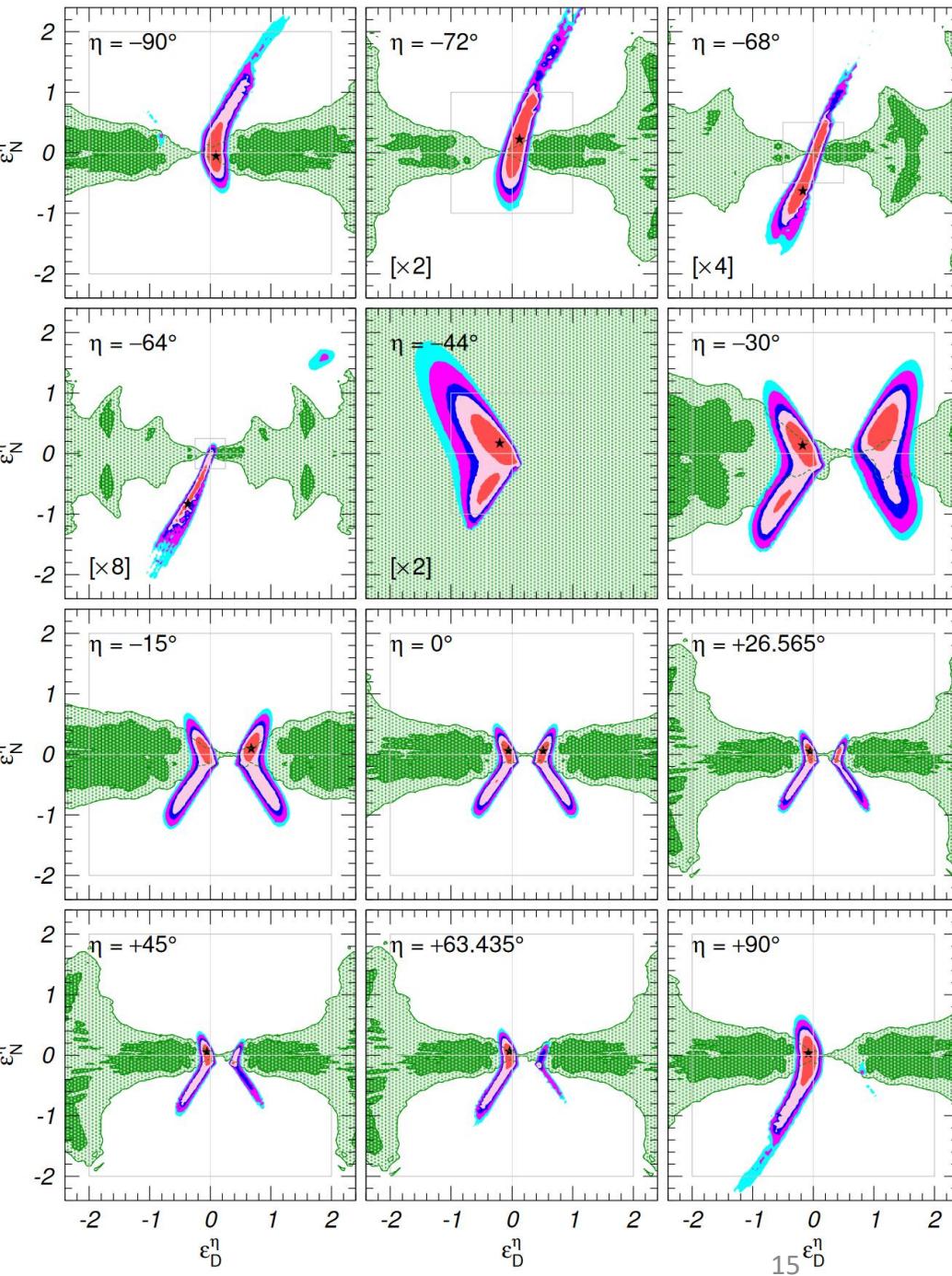
- Thorough study in paper
 - Global fit of neutrino experiments (2020)
- Marginalized over oscillation parameters
- Green contours – 90% and 3σ CL from atmospheric and LBL fit
- Other colors – 1σ , 90%, 2σ , 99%, 3σ CL from solar+KamLAND fit
- What can we compare our result to?

I. Esteban, M.C. Gonzalez-Garcia, M. Maltoni,

I. Martinez-Soler, J. Salvado (2018)

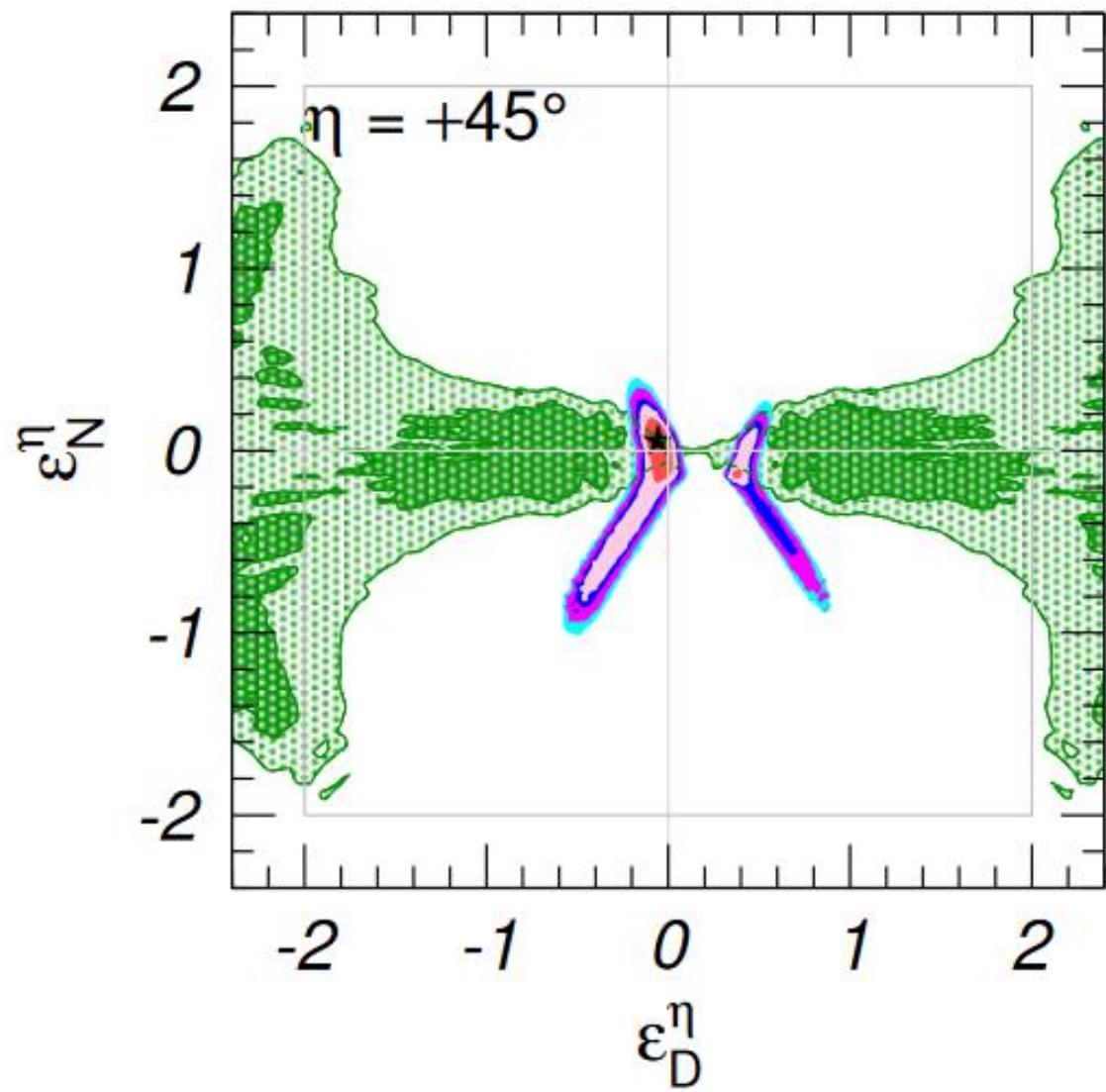
arXiv:1805.04530

07/11/2023



Current constraints

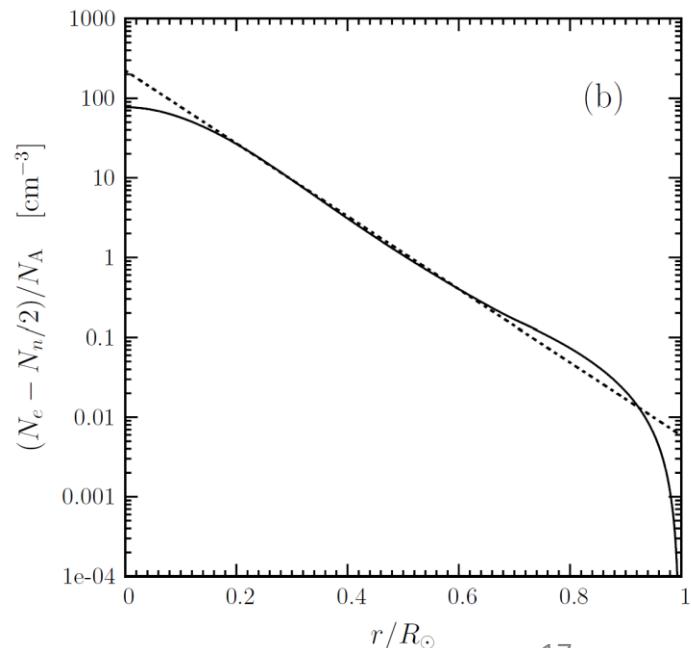
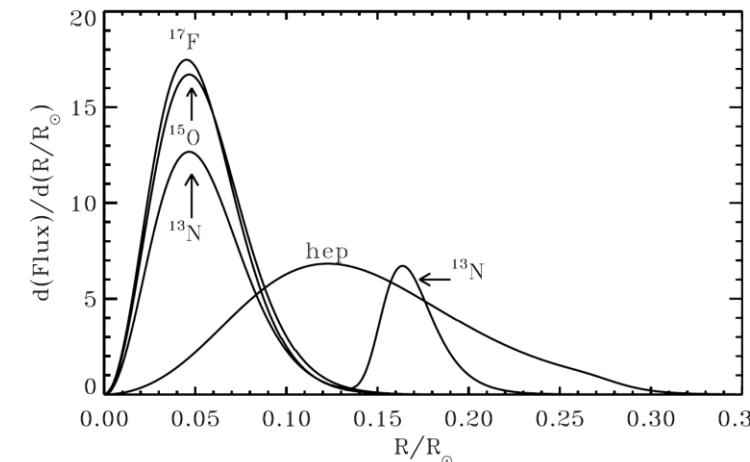
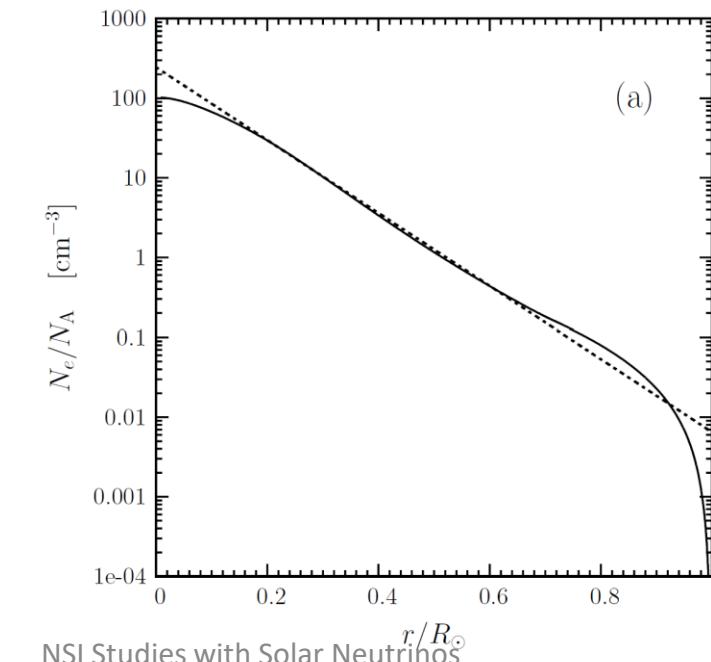
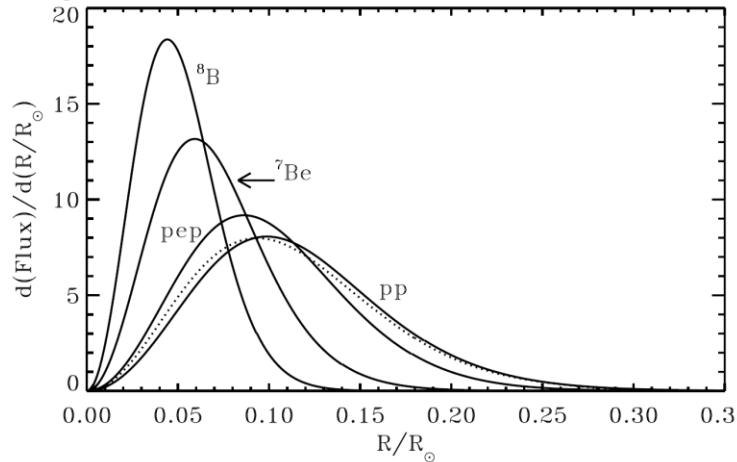
- Relevant limit corresponding to same NSI couplings for u and d quarks
 - Our assumptions



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

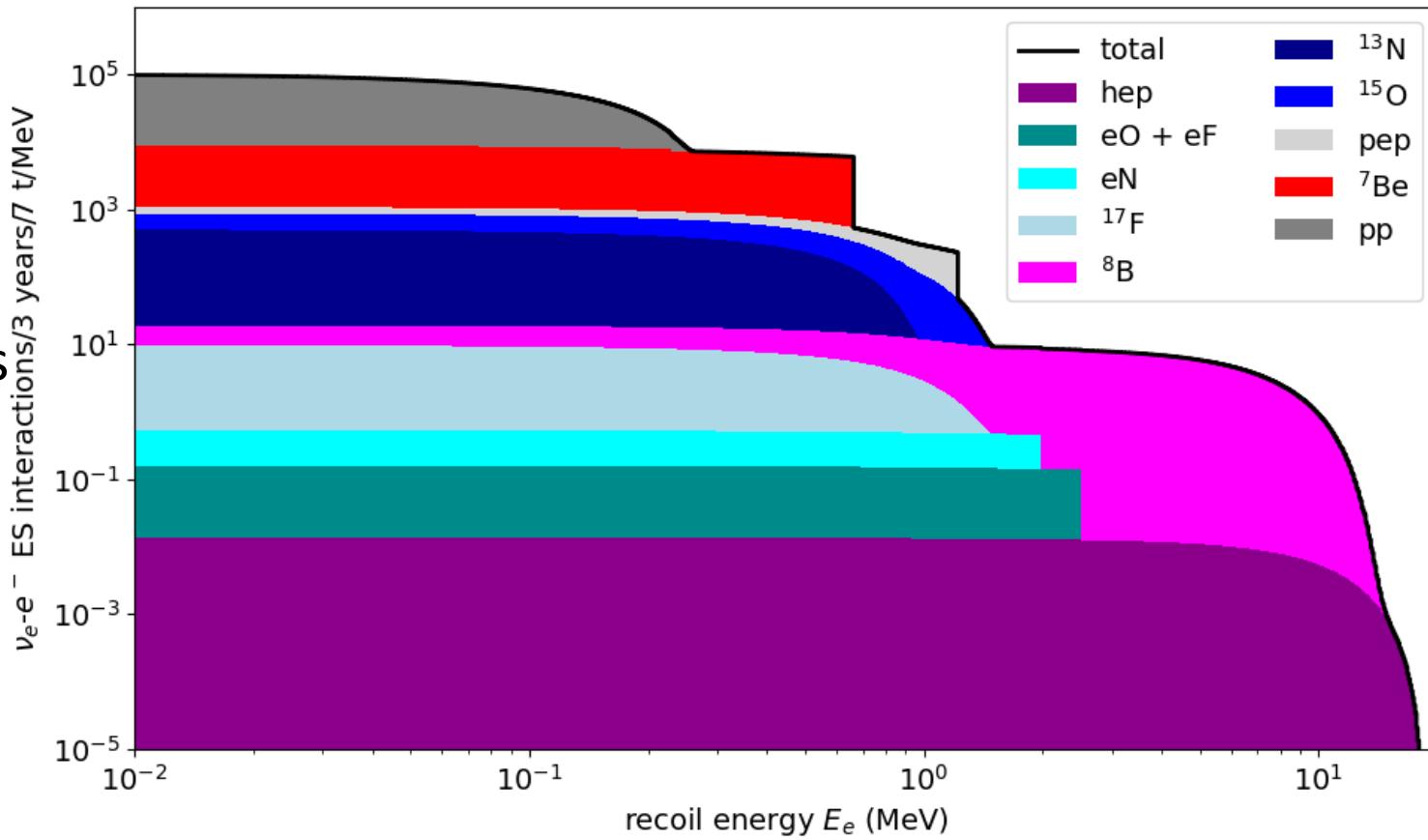
Model assumptions

- Production
 - Assume at 0.1 solar radius
- Density of protons
 - $100 N_A/\text{cm}^3$
- Density of neutrons
 - $50 N_A/\text{cm}^3$
- Vacuum oscillations
 - From PDG 2020



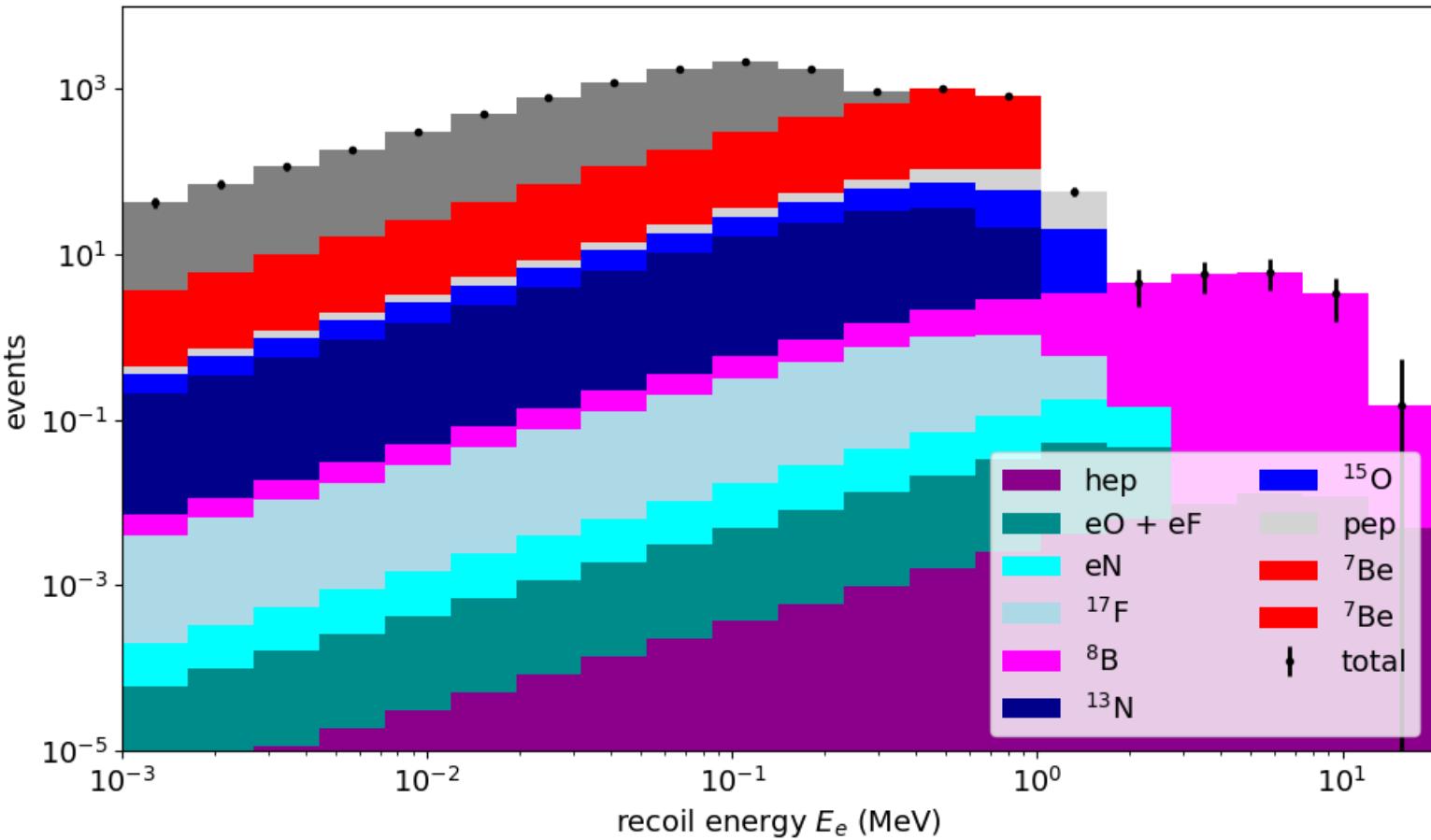
Elastic scattering (ES)

- Assume free electrons
 - Holds down to ~ 10 s keV
 - Shape is same for all targets
- Ignore oscillations for now
 - Convert fluxes to recoil distributions



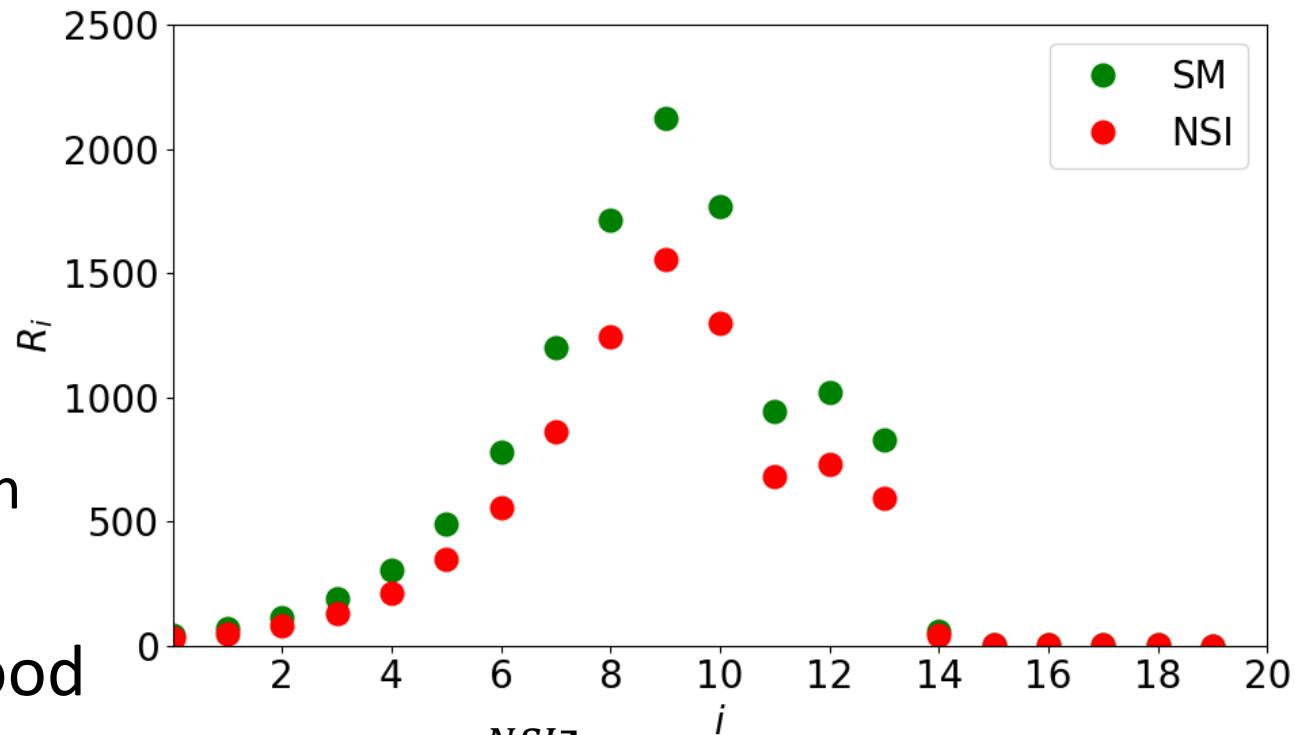
Rates

- Integrating previous plot for exposure and number of electrons



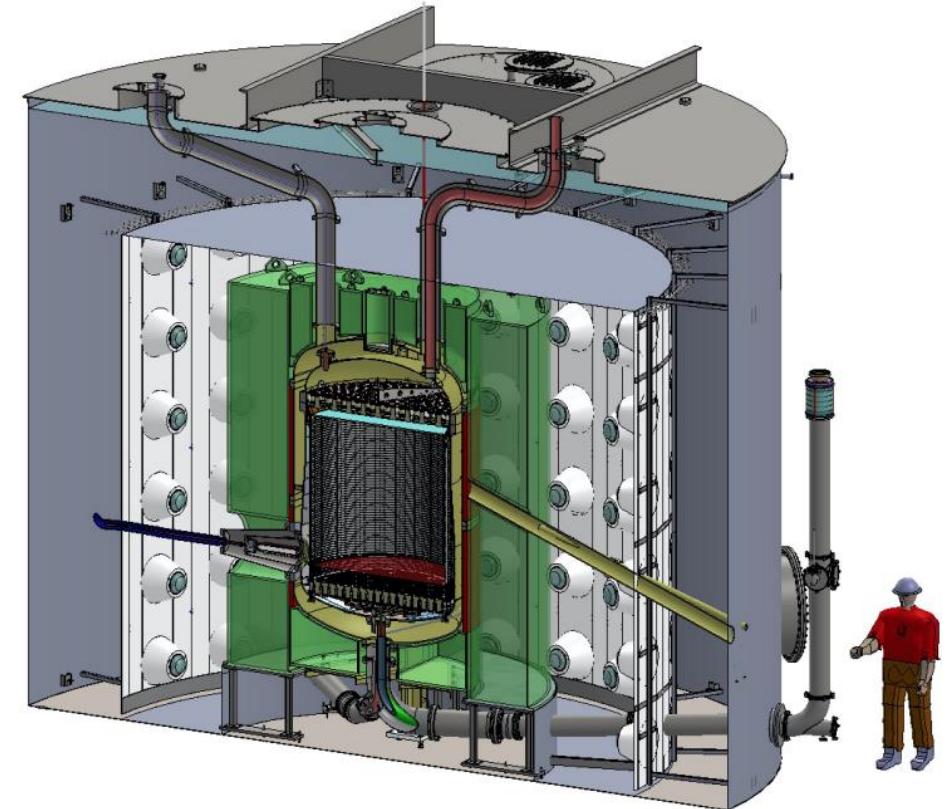
Statistical analysis

- Estimating sensitivity
 - Assume we observe SM prediction
 - What NSI we allow/exclude?
- Use Poisson negative log likelihood
 - $NLL = -2 \log \mathcal{L} = 2 \sum_{i=1}^N \left[R_i^{SM} - R_i^{NSI} + R_i^{SM} \log \frac{R_i^{NSI}}{R_i^{SM}} \right]$
 - 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



Current-generation Xe DM experiments

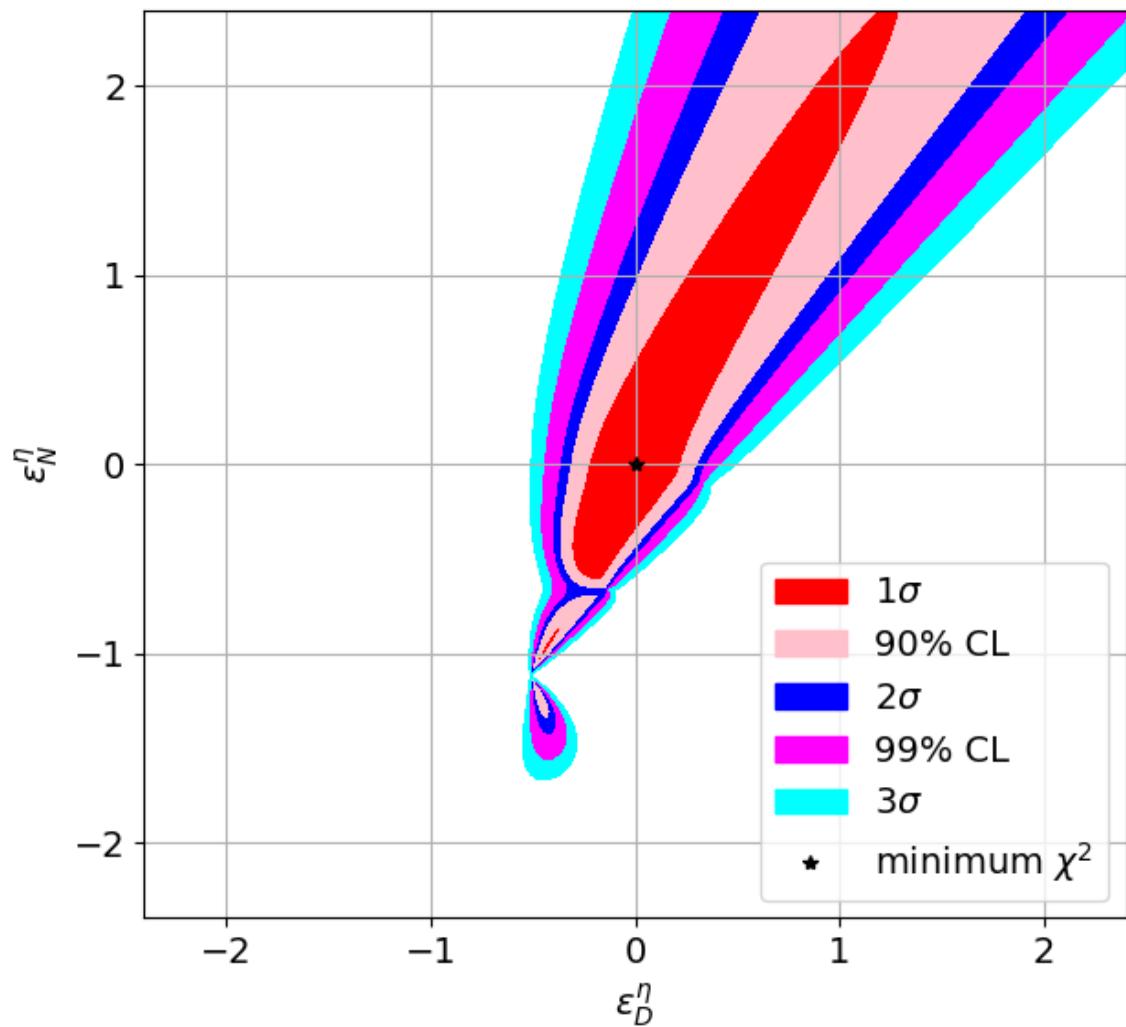
- LZ, XENONnT
- Assume
 - 7 t of Xe
 - 3 years of running
 - No backgrounds,
perfect energy resolution
- MeVs of deposited energy
is high energy



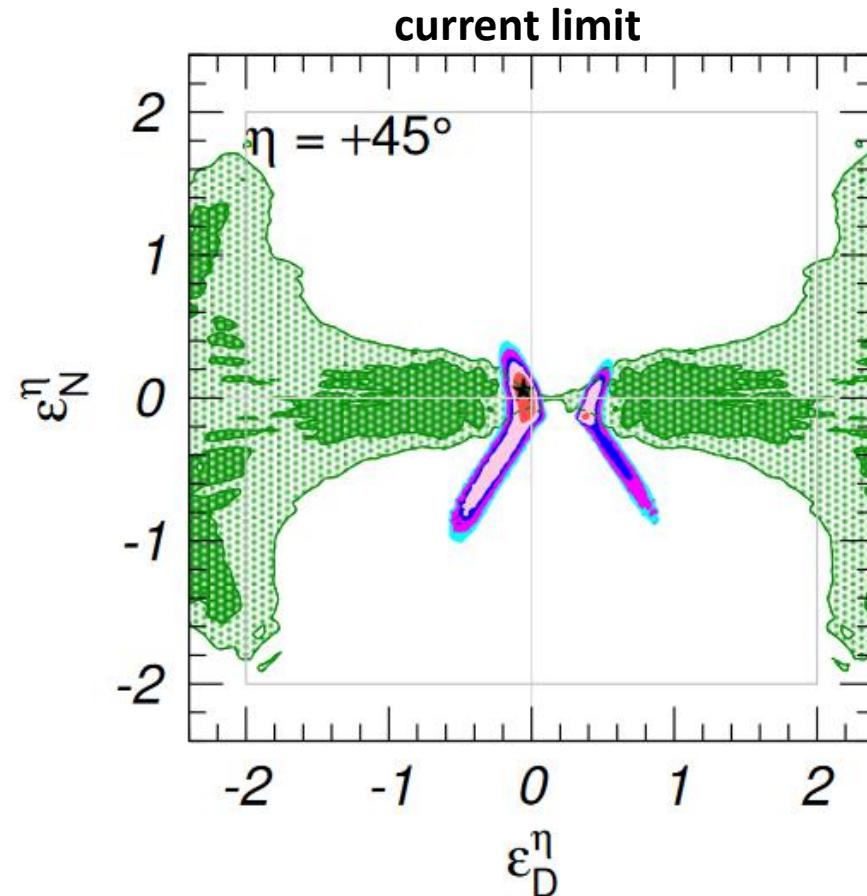
D.S. Akerib et al. (2018), arXiv:1802.06039

Potential Xe constraint

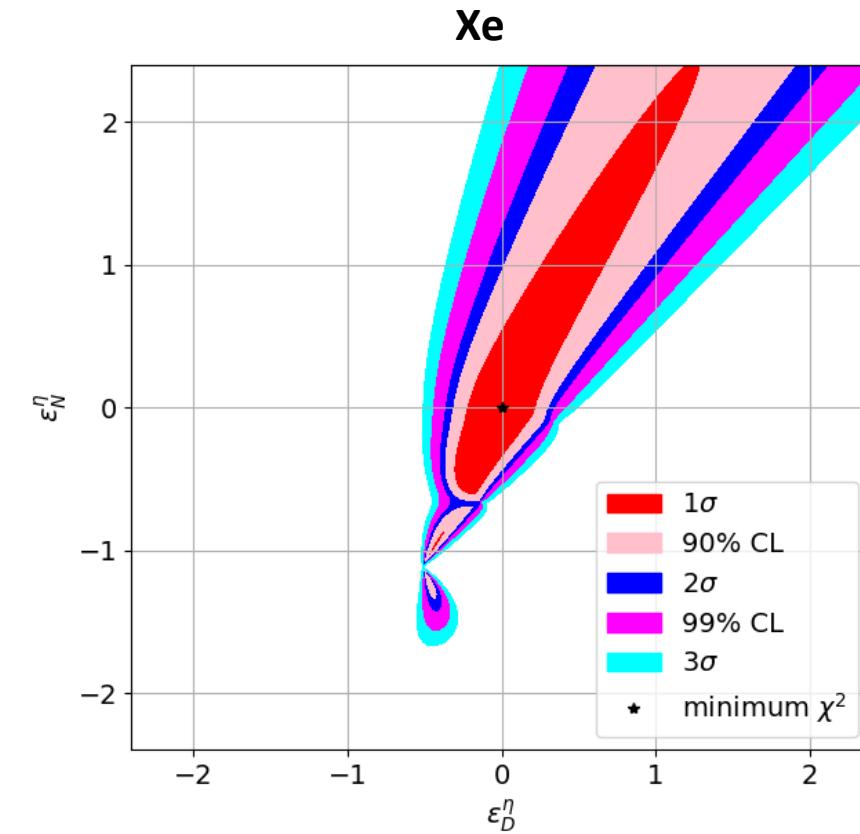
- May exclude significant part of parameter space
 - If we detect every neutrino, have perfect energy resolution, etc.
- What is currently allowed?



Comparison with current constraints



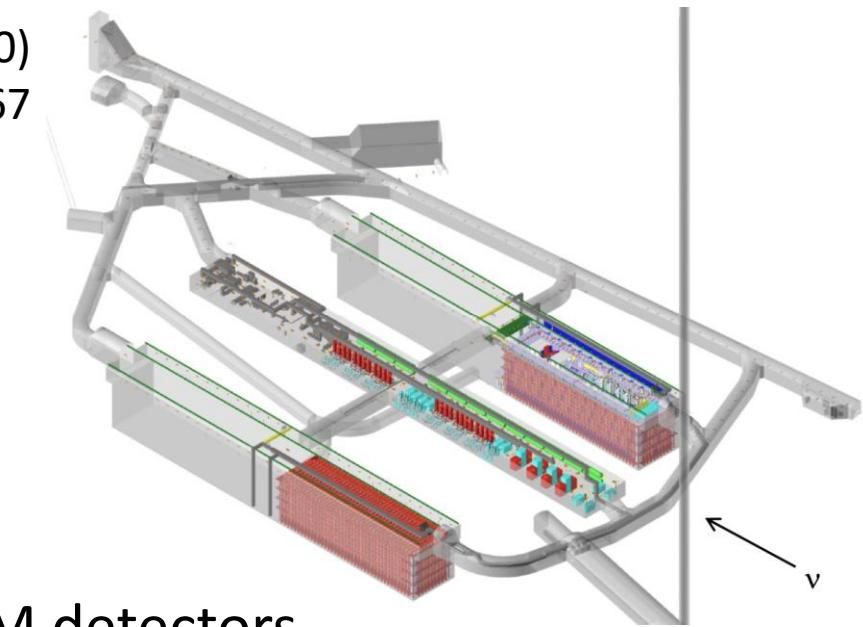
I. Esteban, M.C. Gonzalez-Garcia, M. Maltoni,
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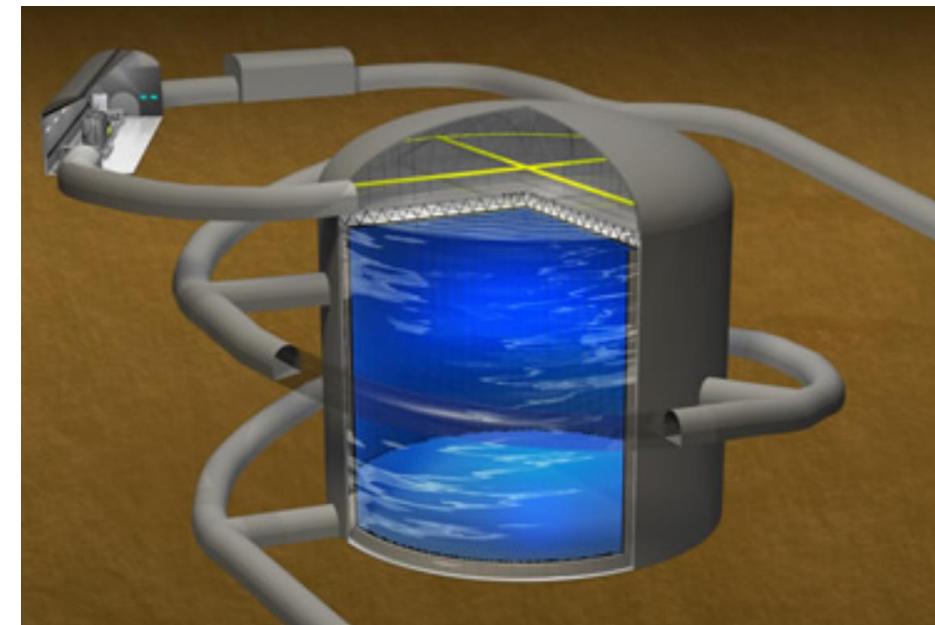
Global fit is better overall,
but combining data may improve fit

Future neutrino experiments

- Looked into possible constraint in 10s of years
 - Until then, solar neutrinos measured primarily by DM detectors
 - Maybe also SNO+
- Focus on Ar



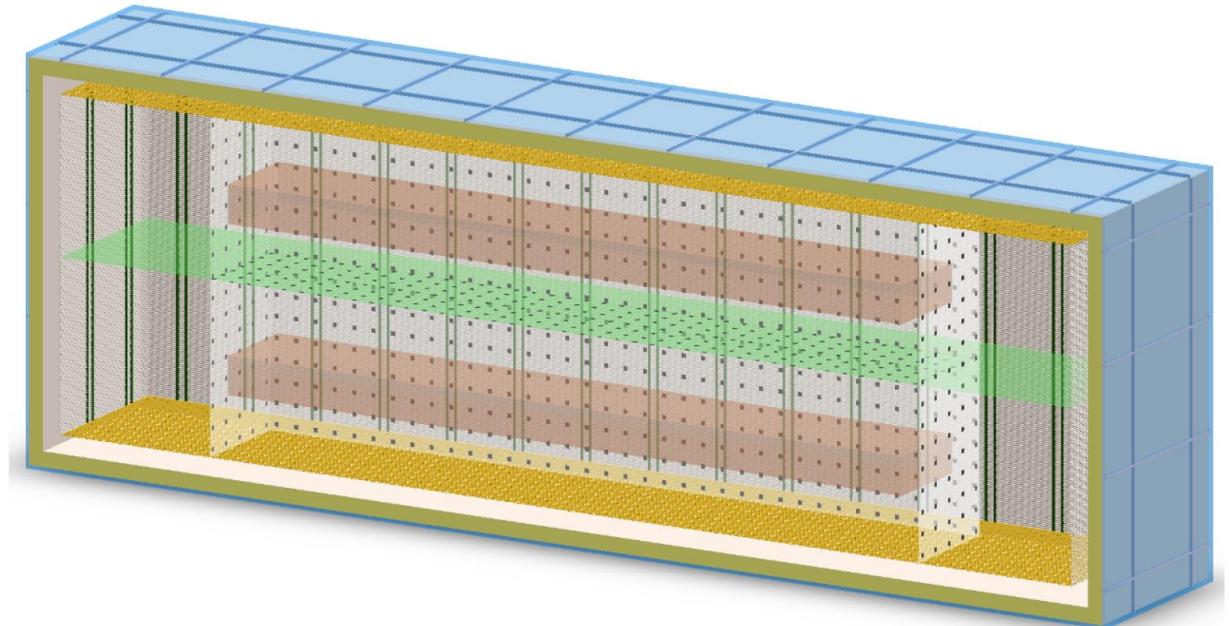
HUGE DETECTORS



Low-background kt-scale Ar detector

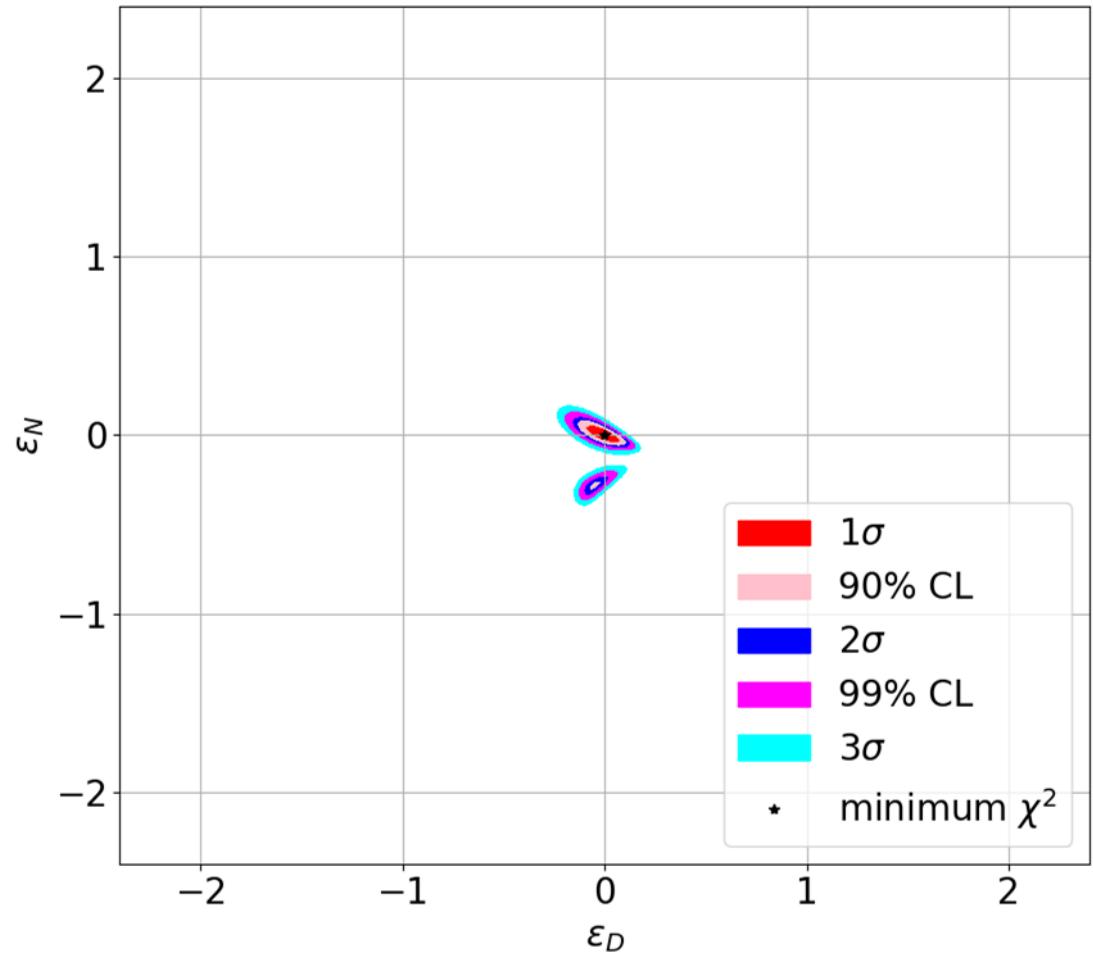
- Potential module for Deep Underground Neutrino Experiment
- Assume
 - 3 kt of Ar
 - 1 year of data
 - Early result
 - No backgrounds, perfect energy resolution
 - Energy threshold of 1 MeV

T. Bezerra et al. (2023)
arXiv:2301.11878



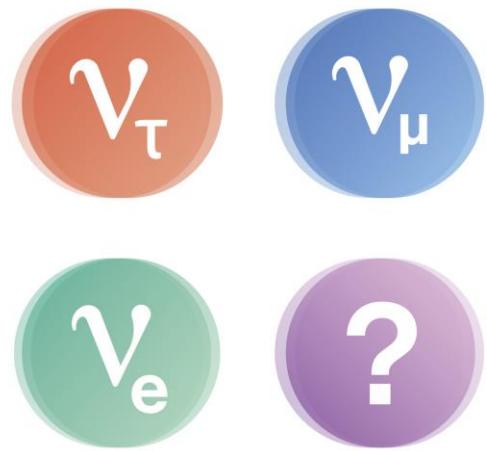
Potential future Ar constraint

- May exclude significant part of parameter space
 - If we detect every neutrino, have perfect energy resolution, etc.



Conclusions

- Expect many solar neutrinos to interact in current DM and future neutrino detectors
- Plan to use them to constrain NSI
 - May not significantly improve global fit at first, but will add independent measurement
 - Expect future neutrino experiments to constrain NSI much further
 - Could potentially explain solar neutrino anomaly



Backup slides

KamLAND result

- Fit survival probability
 - Measured L/E over expected L/E for vs from reactors around KamLAND

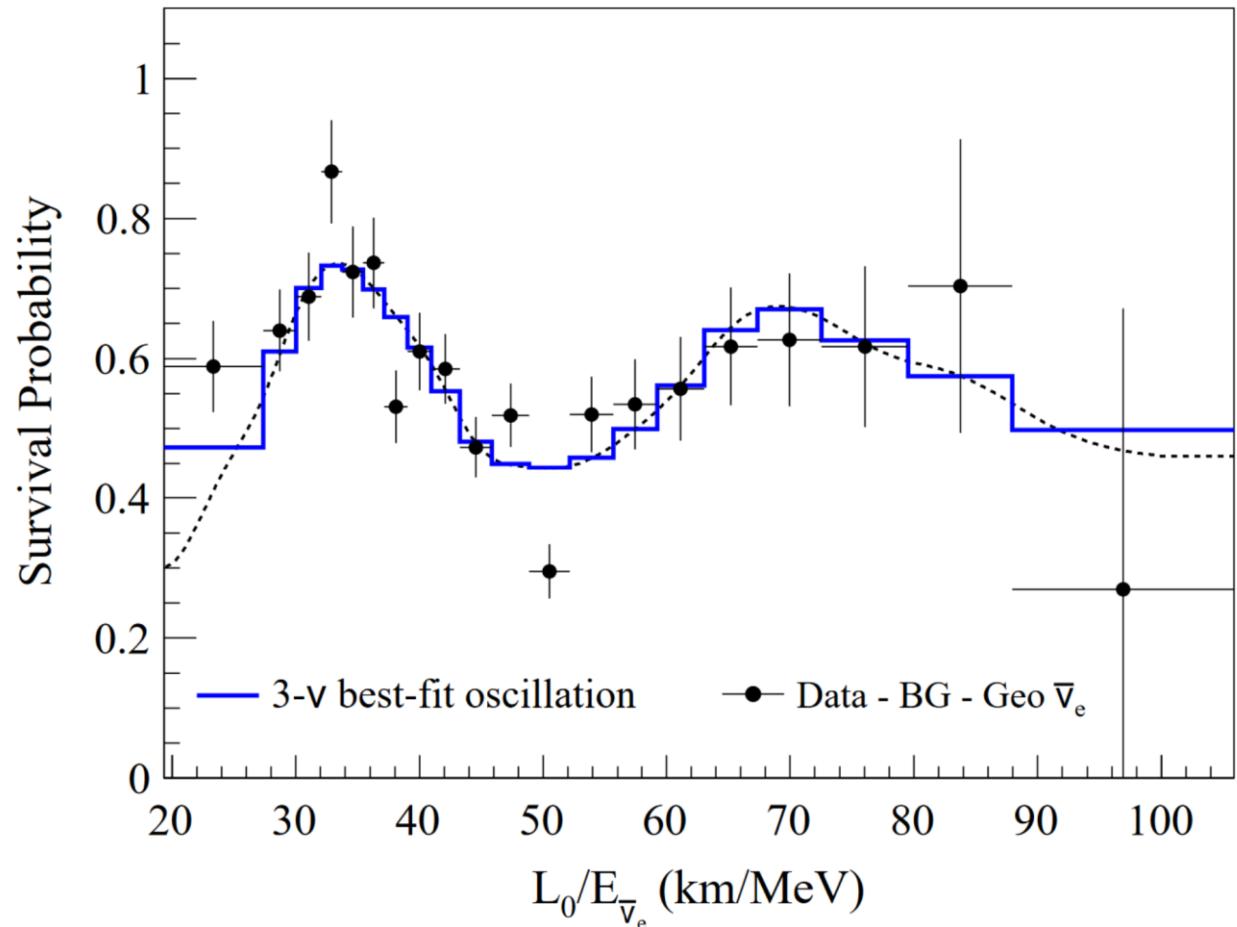
$$P_{ee}^{3\nu} = \cos^4 \theta_{13} \tilde{P}_{ee}^{2\nu} + \sin^4 \theta_{13}$$

$$\tilde{P}_{ee}^{2\nu} = 1 - \sin^2 2\theta_{12M} \sin^2 \left(\frac{\Delta m_{21M}^2 L}{4E_\nu} \right)$$

$$\sin^2 2\theta_{12M} = \frac{\sin^2 2\theta_{12}}{(\cos 2\theta_{12} - A/\Delta m_{21}^2)^2 + \sin^2 2\theta_{12}}$$

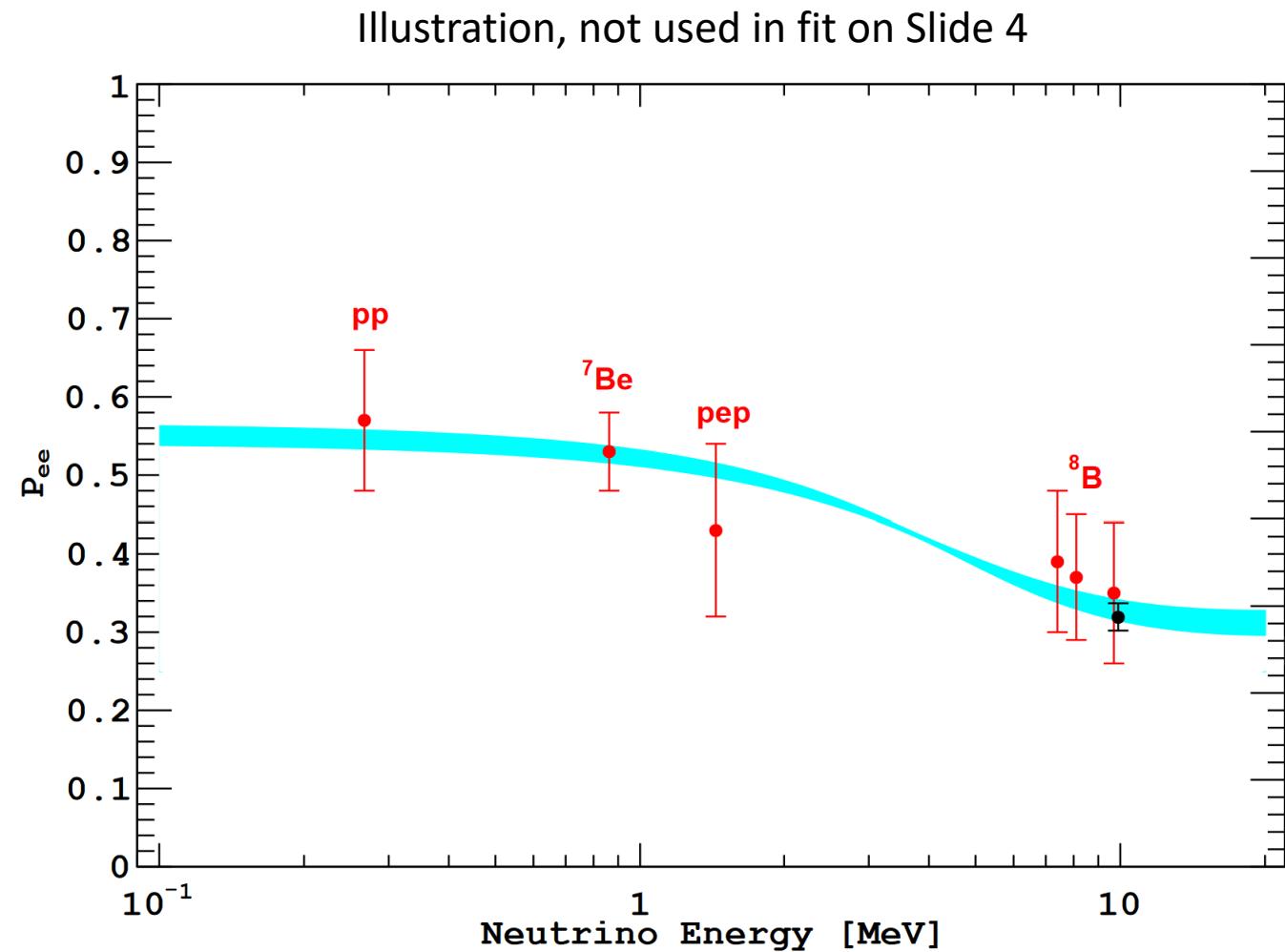
$$\Delta m_{21M}^2 = \Delta m_{21}^2 \sqrt{(\cos 2\theta_{12} - A/\Delta m_{21}^2)^2 + \sin^2 2\theta_{12}}$$

$$A = \pm 2\sqrt{2}G_F \tilde{N}_e E_\nu \quad \tilde{N}_e = N_e \cos^2 \theta_{13}$$



Solar results

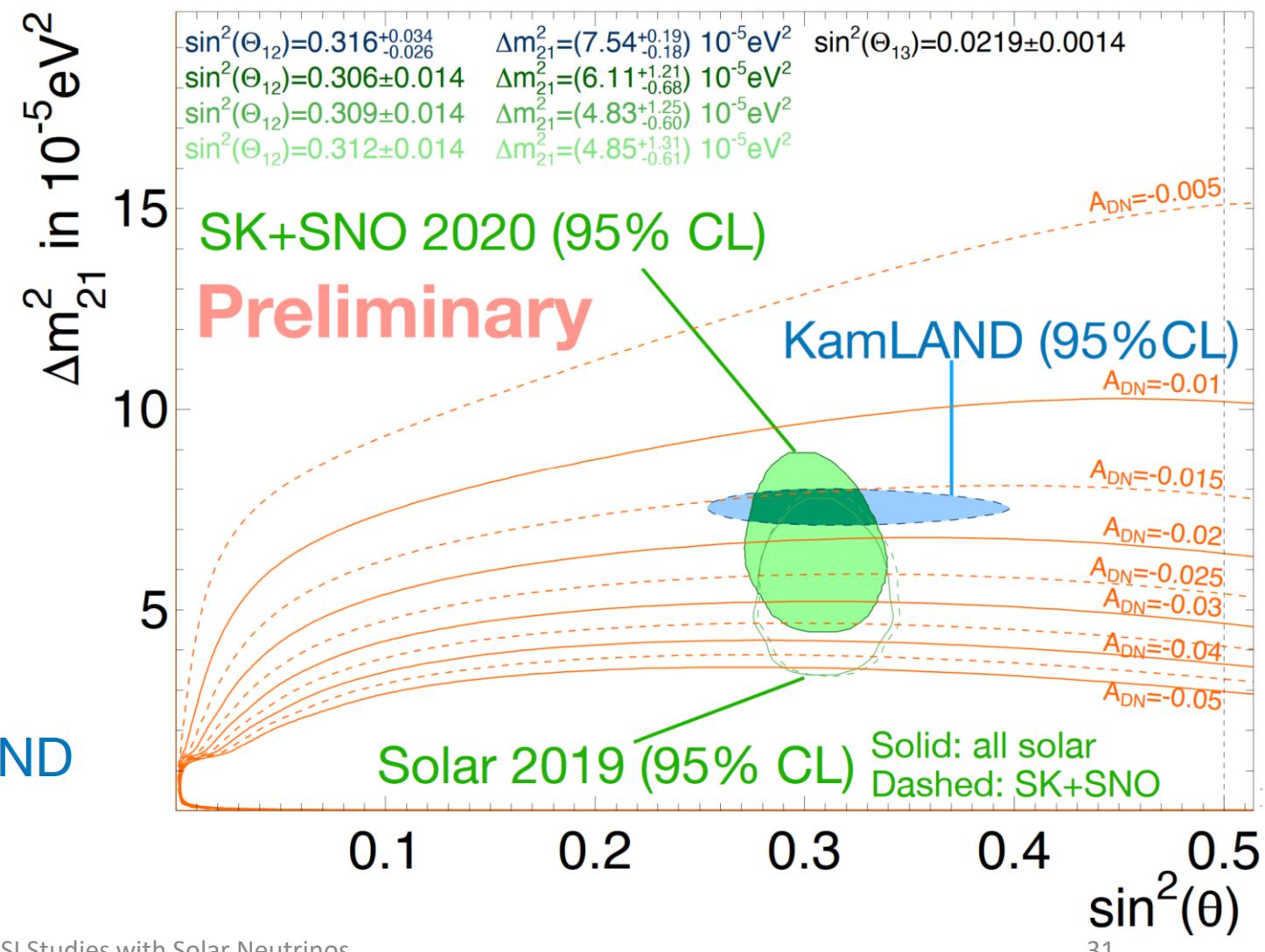
- Many solar-neutrino experiments
 - **Borexino, Super-K, SNO, ...**
- Fit survival probability
 - $P_{ee}^{3\nu} = \cos^4 \theta_{13} P_{ee}^{2\nu} + \sin^4 \theta_{13}$
 - $P_{ee}^{2\nu} = \frac{1}{2} [1 + \cos 2\theta \cos 2\theta_m]$
 - $\cos 2\theta_m = \frac{\Delta m^2 \cos 2\theta - 2\sqrt{2}EG_F N_e}{[\Delta m^2]_{matter}}$
 - $[\Delta m^2]_{matter}^2 = [\Delta m^2 \cos 2\theta - 2\sqrt{2}EG_F N_e]^2 + [\Delta m^2 \sin 2\theta]^2$



Solar neutrino anomaly in 2020

- Started looking into NSI to explain solar neutrino anomaly
- Its significance decreased 2019 → 2020
- Not game changer
 - still worthwhile NSI search with solar v's

SK+SNO fit disfavors the KamLAND best fit value at $\sim 1.4\sigma$ (was $\sim 2\sigma$)

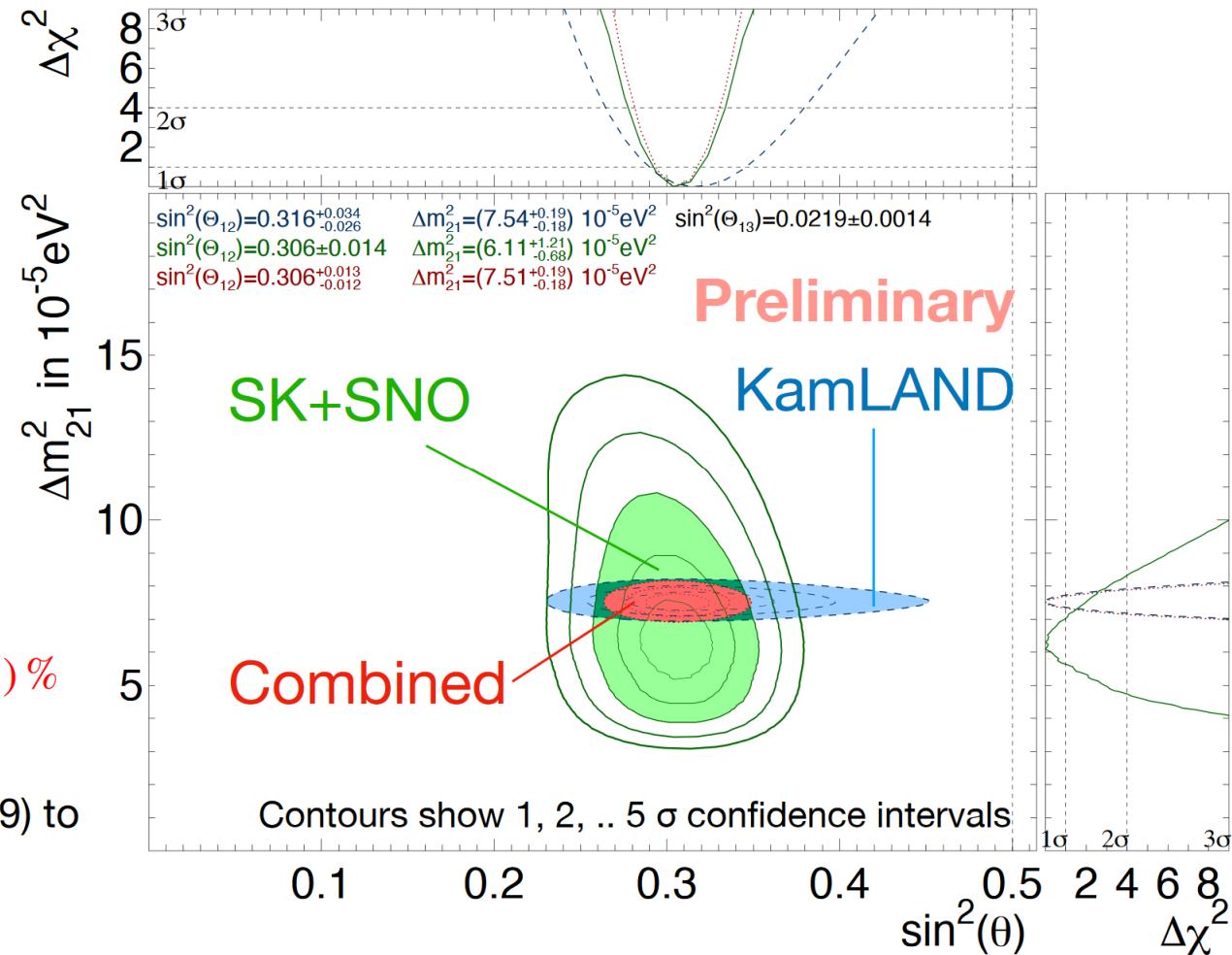


New Super-K solar oscillation results

	$\sin^2(\theta_{12})$	$\Delta m^2_{21} [10^{-5} \text{ eV}^2]$
KamLAND	$0.316^{+0.034}_{-0.026}$	$7.54^{+0.19}_{-0.18}$
SK+SNO	0.306 ± 0.014	$6.11^{+1.21}_{-0.68}$
Combined	$0.306^{+0.013}_{-0.012}$	$7.51^{+0.19}_{-0.18}$

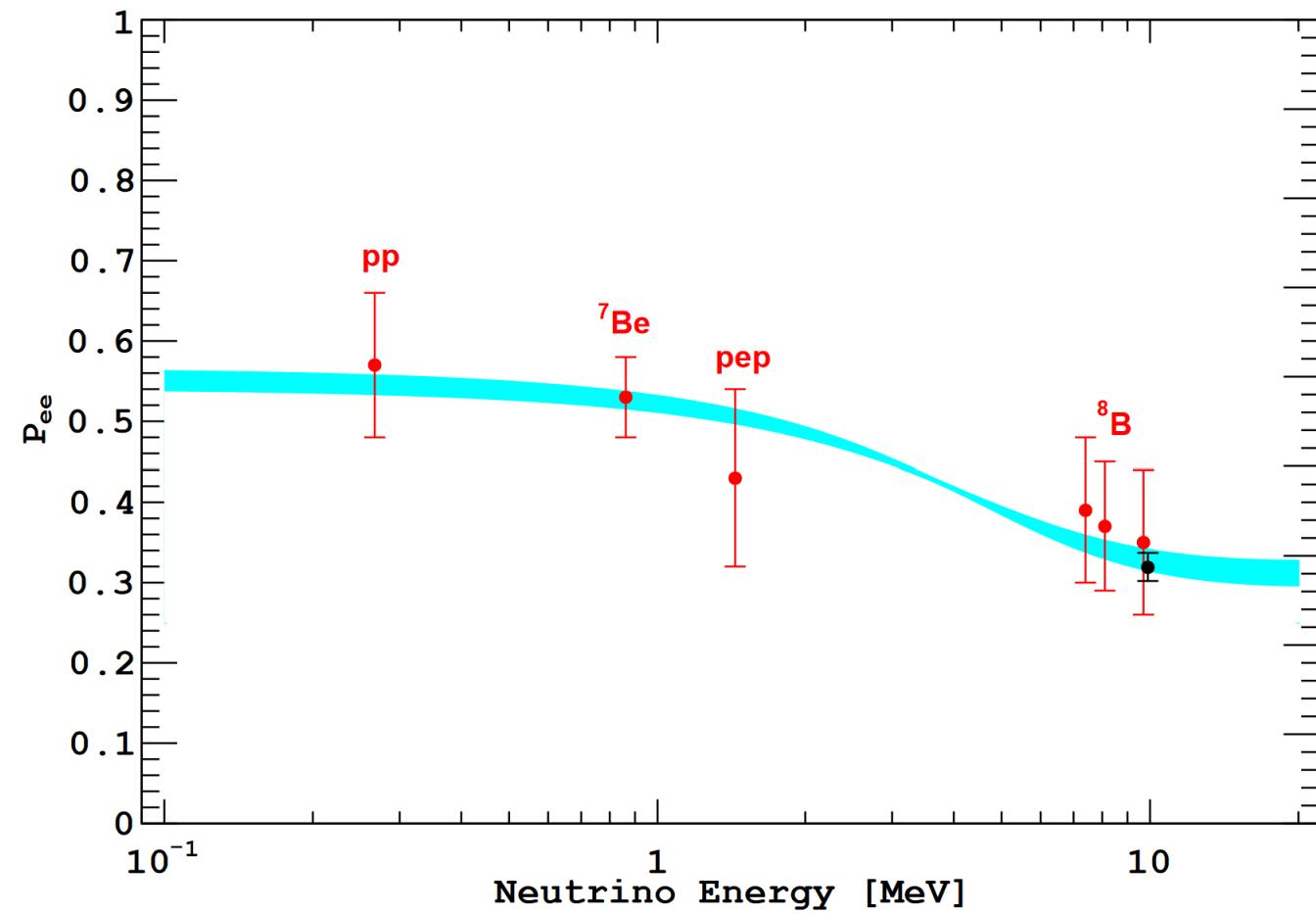
$$A_{DN}^{Fit} = (-3.6 \pm 1.6(\text{stat}) \pm 0.6(\text{syst})) \% \rightarrow A_{DN}^{Fit} = (-2.1 \pm 1.1) \%$$

Best fit value of solar Δm^2_{21} changed from $4.8 \times 10^{-5} \text{ eV}^2$ (2019) to $6.1 \times 10^{-5} \text{ eV}^2$



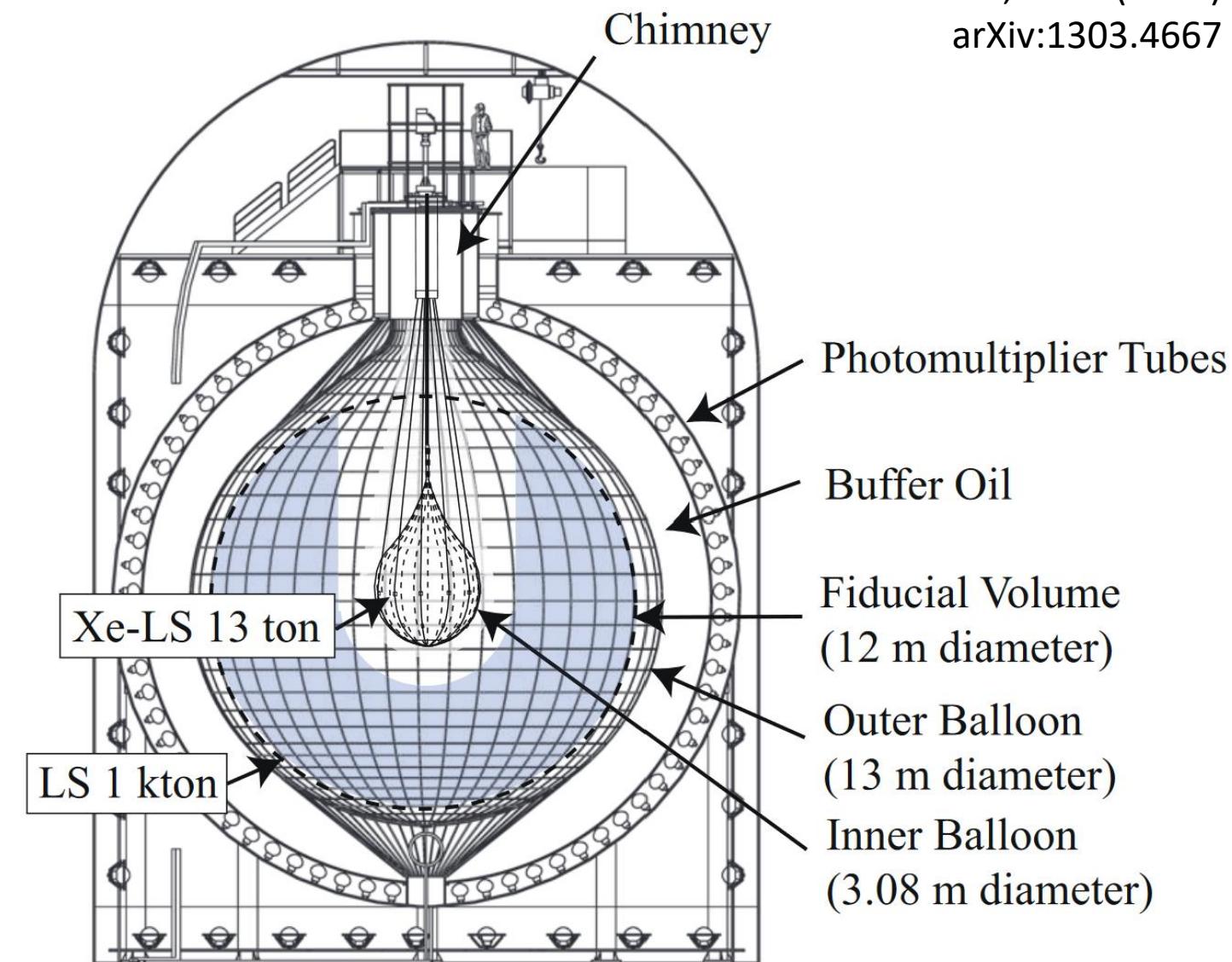
Matter oscillations

- Survival probability depends on energy
- Measurements agree with theory
- Best oscillation fit from SNO+SK (**black**)
- Need better statistics and more measurements in transition region



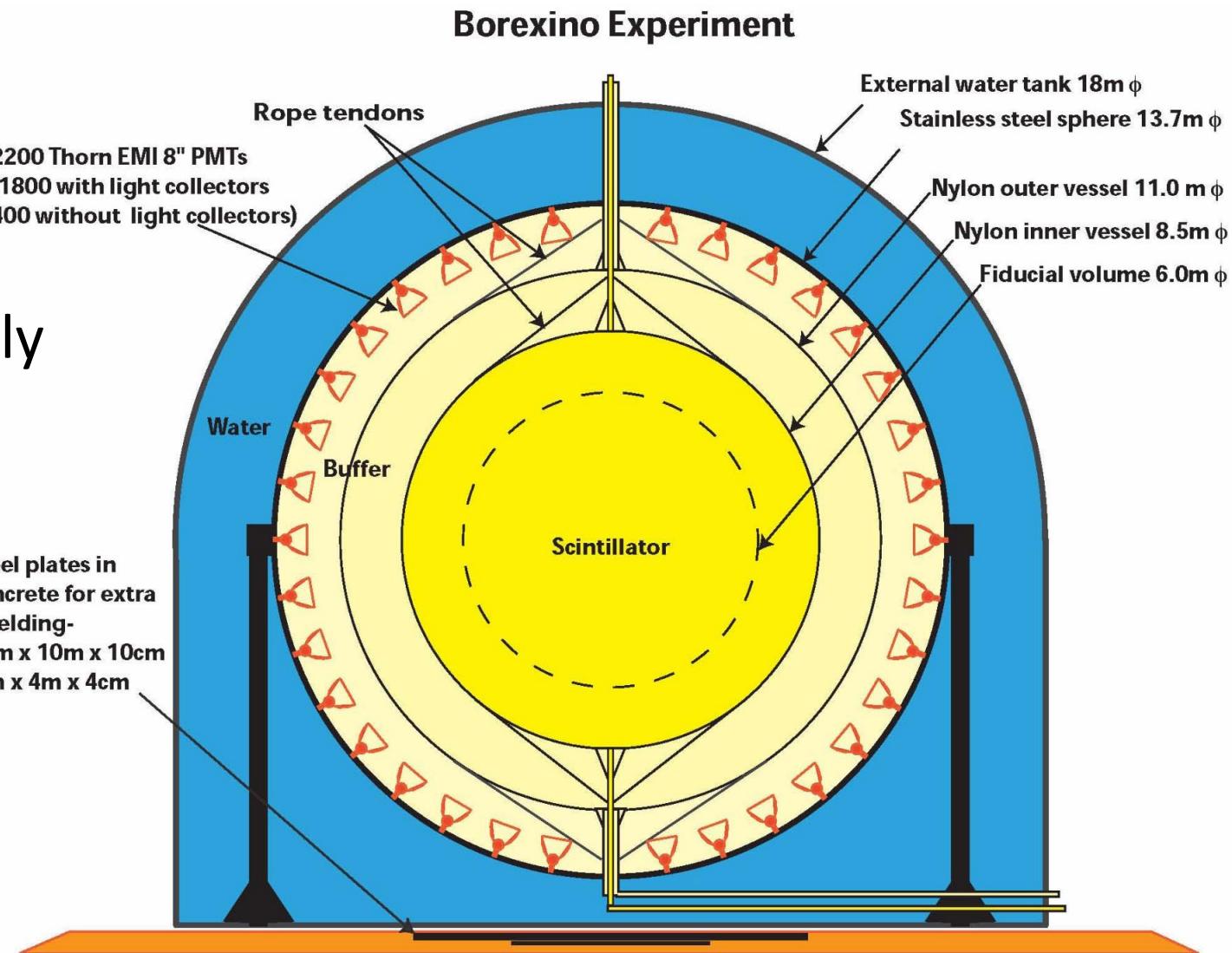
KamLAND

- 1 kton of liquid scintillator
- Located in Kamioka, Japan
 - Detects neutrinos from reactors in Japan

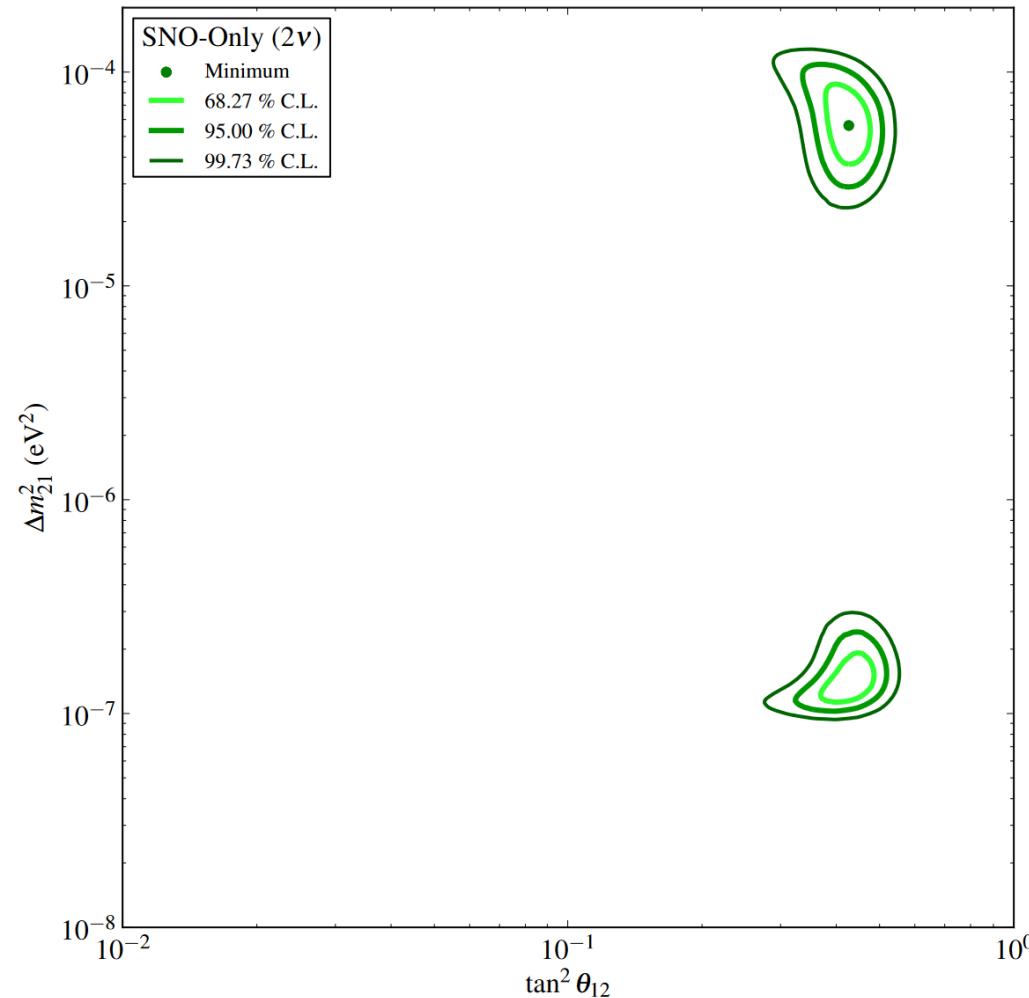


Borexino

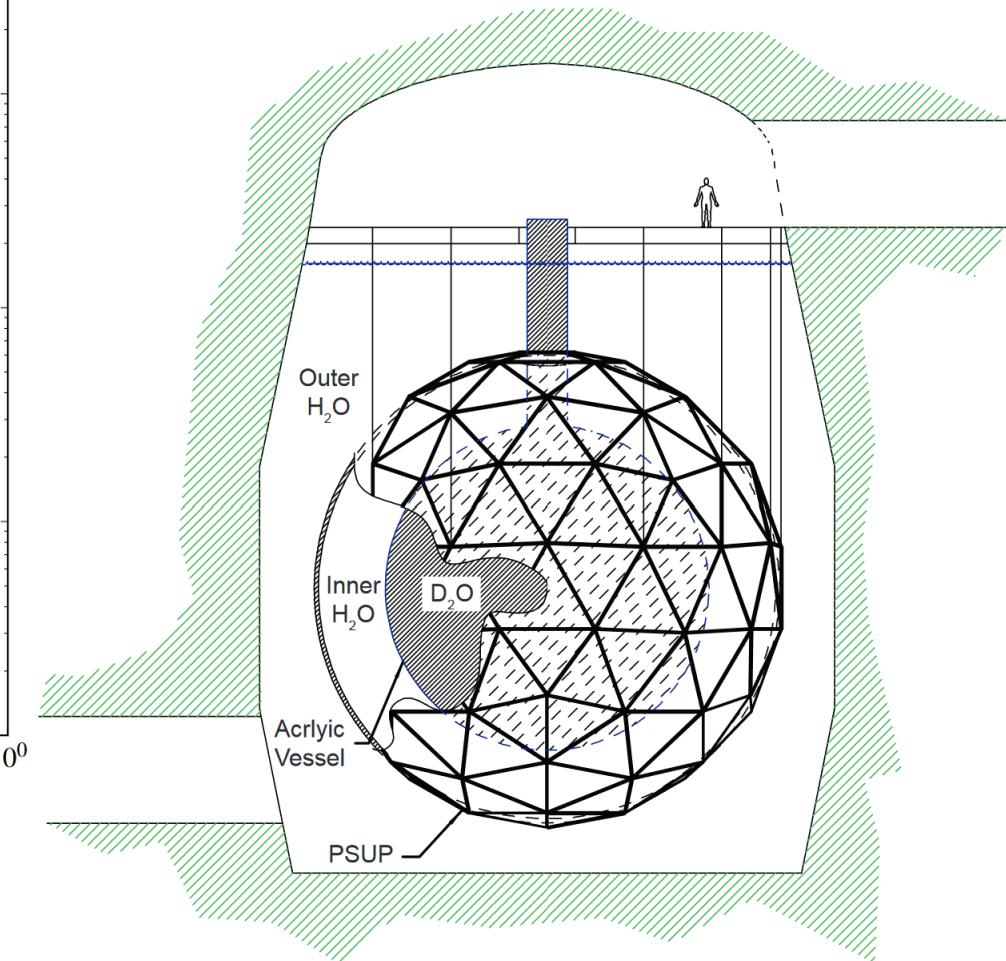
- 278 t of organic scintillator in Gran Sasso, Italy



SNO

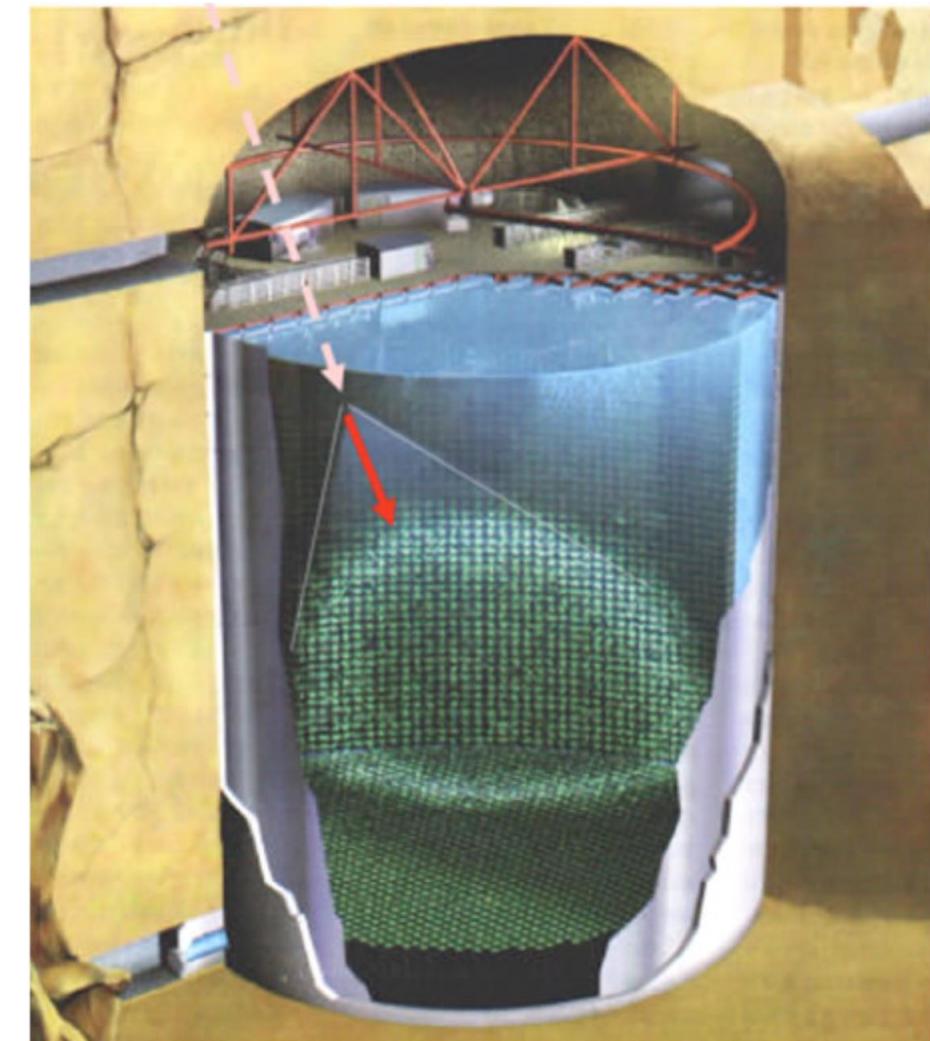
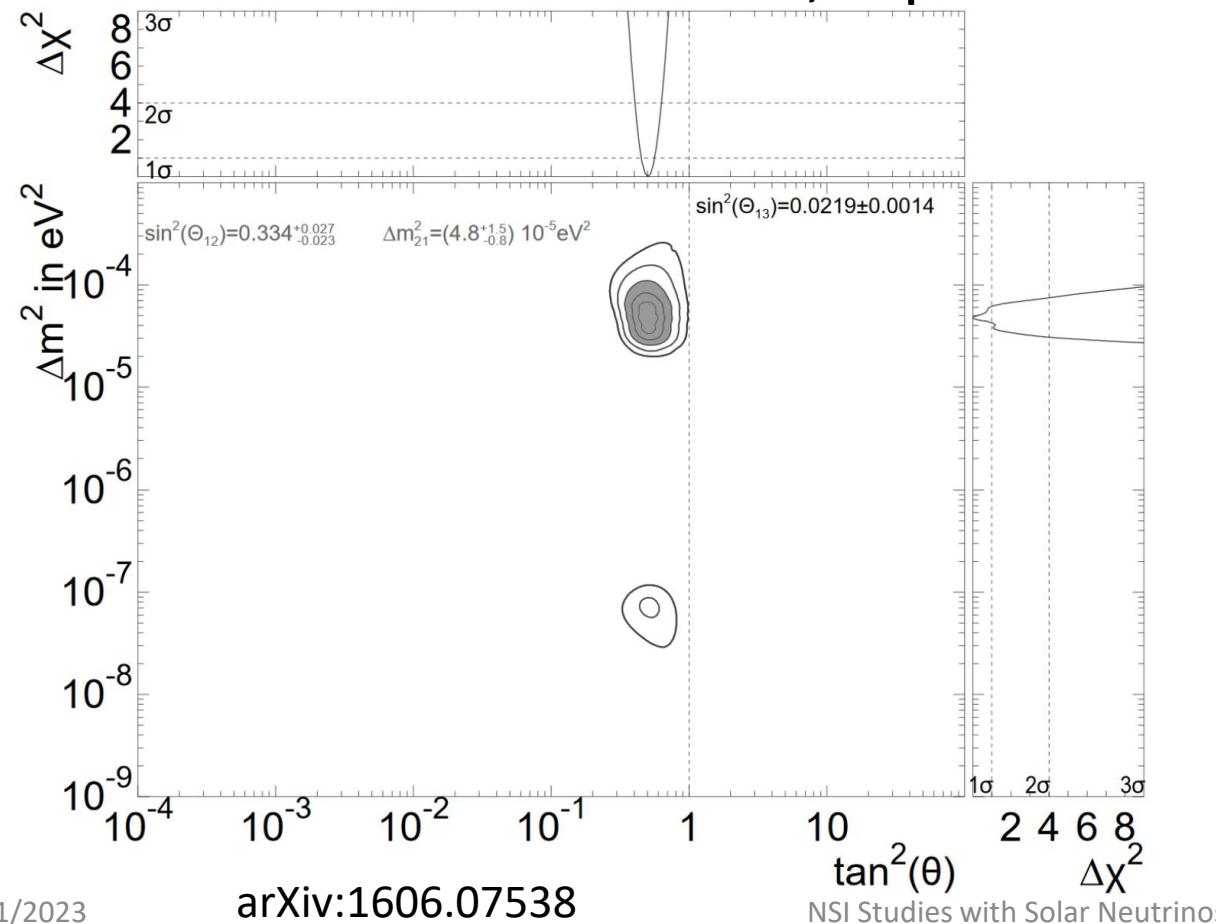


- 1 kt of heavy water in Sudbury, Canada
- Measured both ν_e and total ν fluxes

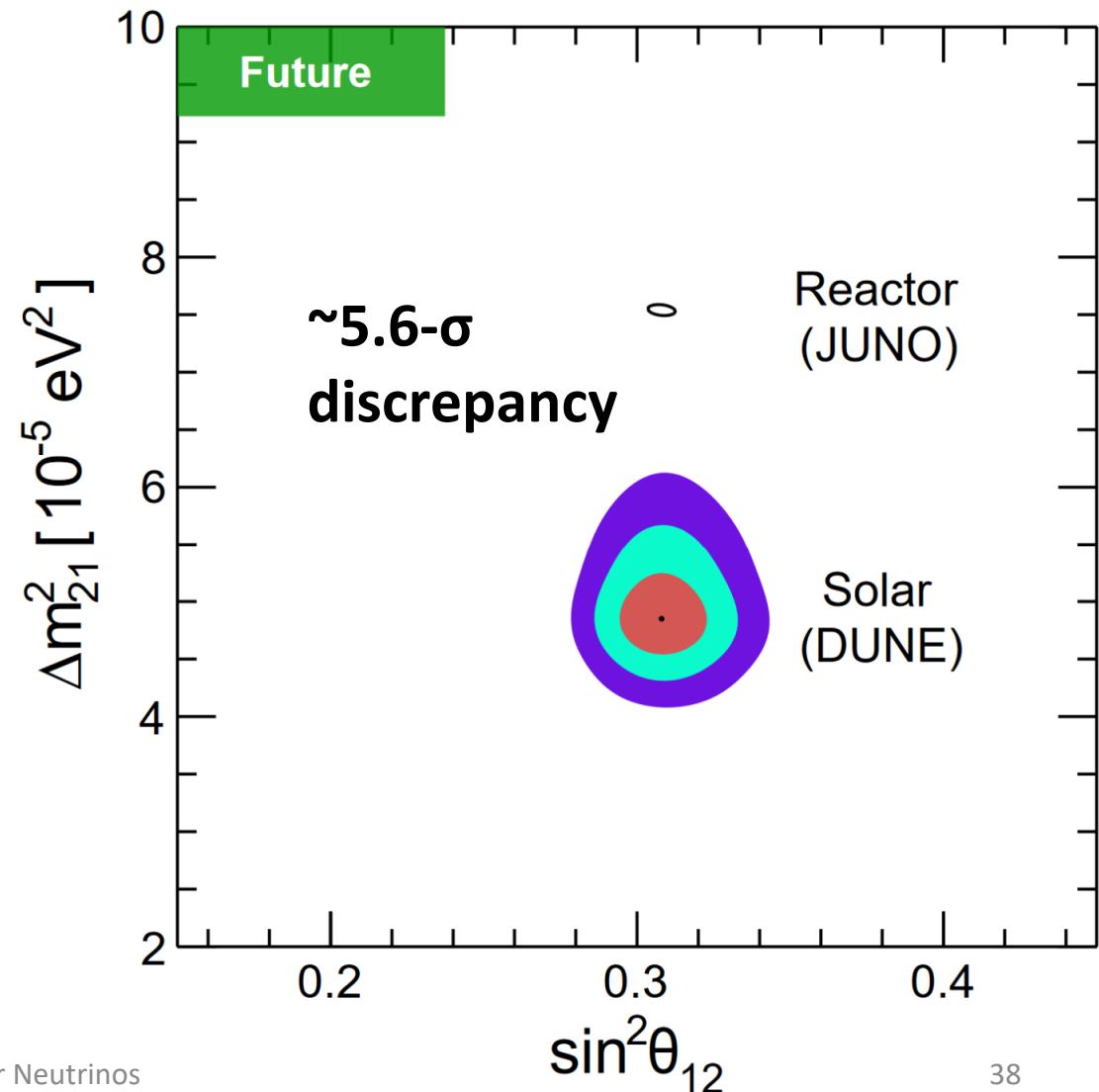
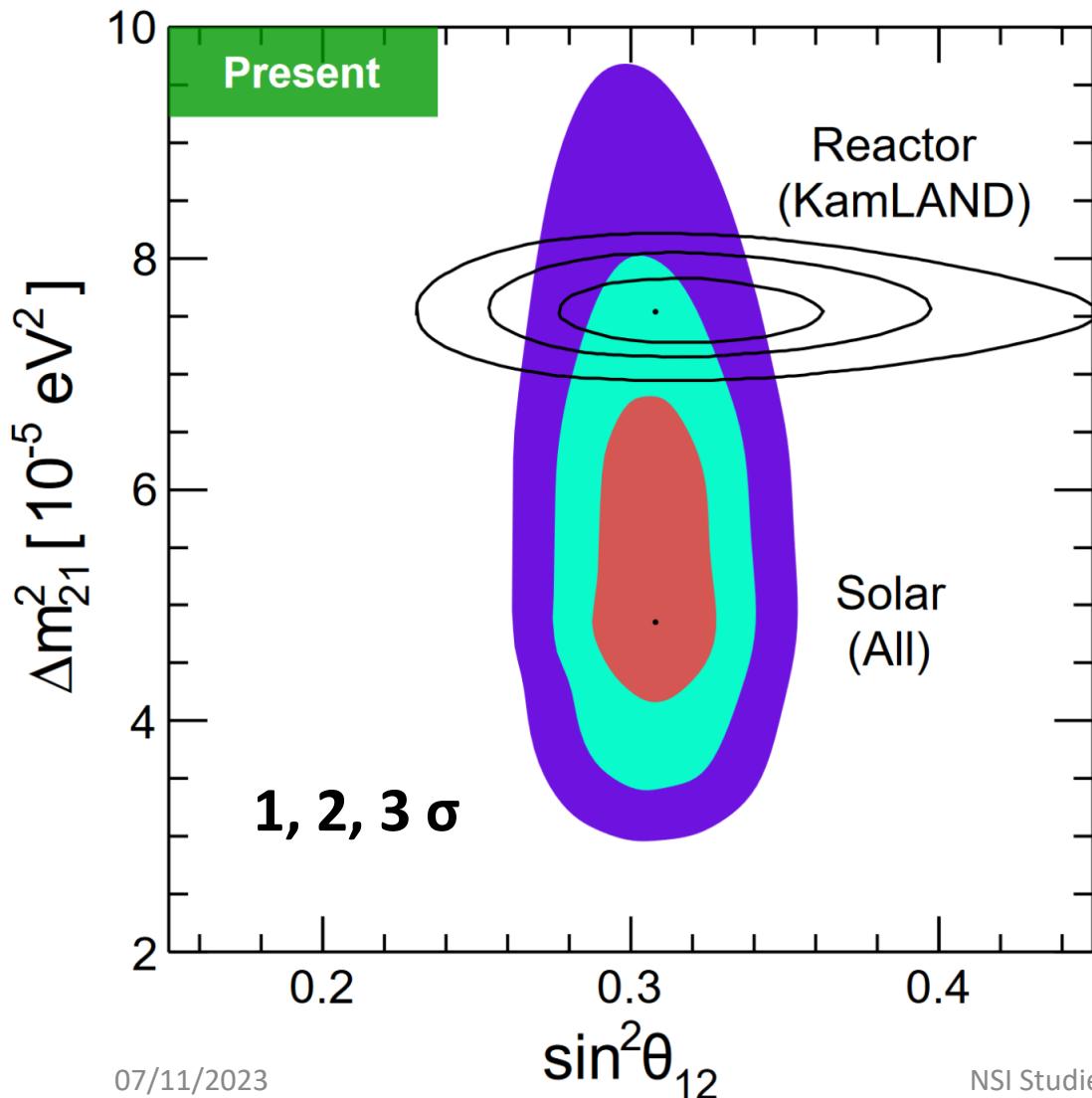


Super-Kamiokande

- 32.5 kt of water in Kamioka, Japan



Possible anomaly in ~ 10 years



Neutral-current NSI in Sun

- 2-flavor model

SM vacuum oscillations + matter effect	NSI	
$H = \begin{pmatrix} -\frac{\Delta m^2}{4E} \cos 2\theta + \sqrt{2}G_F N_e & \frac{\Delta m^2}{4E} \sin 2\theta \\ \frac{\Delta m^2}{4E} \sin 2\theta & \frac{\Delta m^2}{4E} \cos 2\theta \end{pmatrix} + \sqrt{2}G_F N_d \begin{pmatrix} 0 & \varepsilon \\ \varepsilon & \varepsilon' \end{pmatrix}$		$\varepsilon_{\alpha\beta}^{uP} = 0$ $\varepsilon_{\mu\beta}^{dP} = 0$
$P(\nu_e \rightarrow \nu_e) = \frac{1}{2} [1 + \cos 2\theta \cos 2\theta_m]$	$\varepsilon = -\sin \theta_{23} \varepsilon_{e\tau}^{dV}$ $\varepsilon' = \sin^2 \theta_{23} \varepsilon_{\tau\tau}^{dV} - \varepsilon_{ee}^{dV}$	
$\cos 2\theta_m = \frac{\Delta m^2 \cos 2\theta - 2\sqrt{2}EG_F(N_e - \varepsilon'N_d)}{[\Delta m^2]_{matter}}$		
$[\Delta m^2]_{matter}^2 = [\Delta m^2 \cos 2\theta - 2\sqrt{2}EG_F(N_e - \varepsilon'N_d)]^2 + [\Delta m^2 \sin 2\theta + 4\sqrt{2}\varepsilon EG_F N_d]^2$		

How well could DUNE do?

- SNO+SK detected ~80,000 v's
- Assume best-case 15,000 solar v's per 10 kt·year detected in DUNE
 - $E_\nu^{mean} = 8 \text{ MeV}$ ($E_{\nu vis}^{threshold} = 3 - 4 \text{ MeV}$)
 - Ignore systematics
- Assume SNO+SK uncertainties for 80,000 solar v's in DUNE
 - Scale as $\sqrt{\nu}$
 - Place at 8 MeV

How well could DUNE do?

- ~40 kt·years of DUNE could already validate SNO+SK

exposure	years	statistics (relative to SNO+SK)	uncertainty
10 kt·years	1 (1 module)	0.19	$2.3 \sigma_{\text{SNO+SK}}$
40 kt·years	1 (4 modules)	0.75	$1.2 \sigma_{\text{SNO+SK}}$
160 kt·years	4 (4 modules)	3	$0.58 \sigma_{\text{SNO+SK}}$
400 kt·years	10 (4 modules)	7.5	$0.37 \sigma_{\text{SNO+SK}}$
1,600 kt·years	40 (4 modules)	30	$0.18 \sigma_{\text{SNO+SK}}$

Statistical analysis for DUNE

- Estimating sensitivity
 - Assume we observe SM prediction
 - What NSI we allow/exclude?
- Use this negative log likelihood
 - $NLL = -2 \log \mathcal{L} = \sum_{i=1}^N \frac{(P_i^{SM} - P_i^{NSI})^2}{\sigma_i^2}$
 - 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

Differential ES cross section

- Taken from Fundamentals of Neutrino Physics and Astrophysics by C. Giunti and C.W. Kim

$$\frac{d\sigma}{dT_e}(E_\nu, T_e) = \frac{\sigma_0}{m_e} \left[g_1^2 + g_2^2 \left(1 - \frac{T_e}{E_\nu} \right)^2 - g_1 g_2 \frac{m_e T_e}{E_\nu^2} \right] \quad T_e^{\max}(E_\nu) = \frac{2 E_\nu^2}{m_e + 2 E_\nu}$$

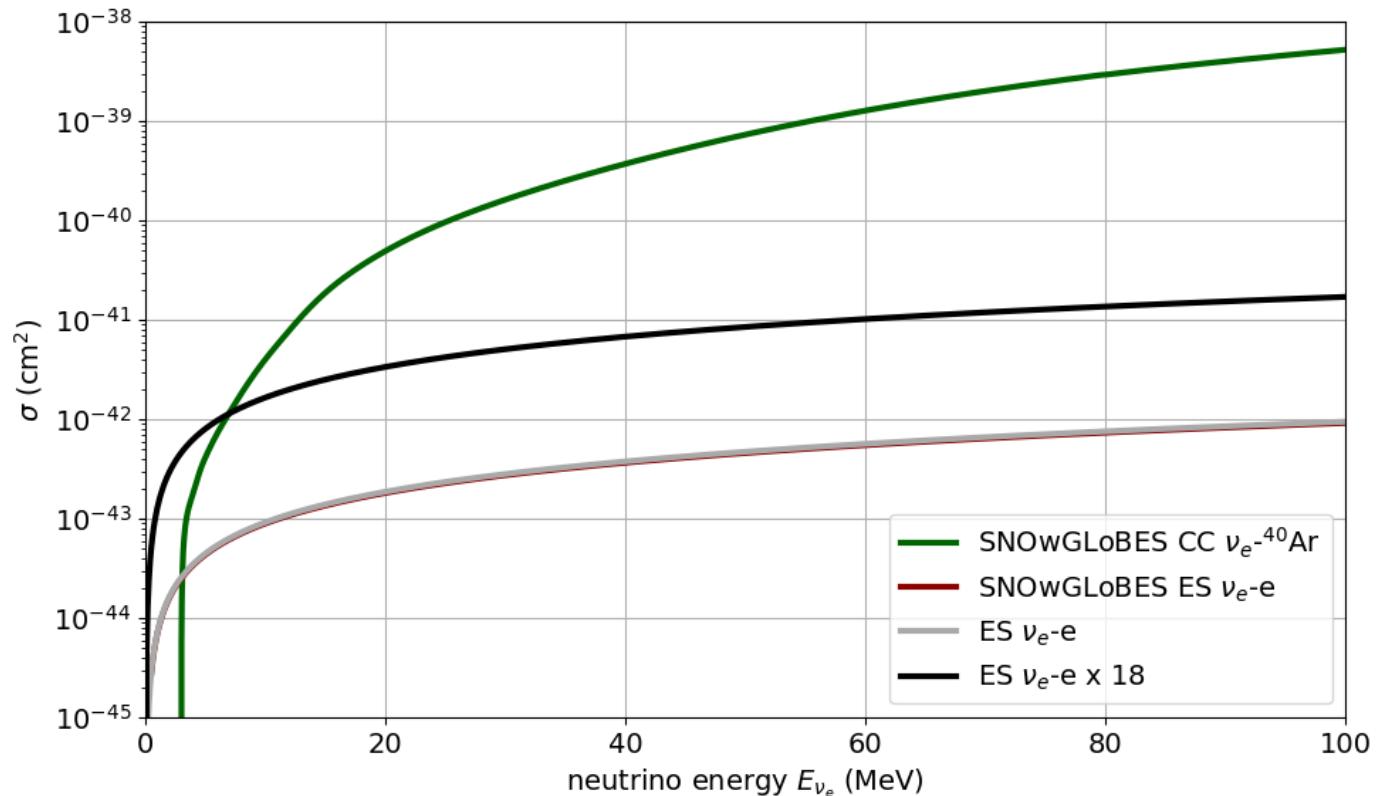
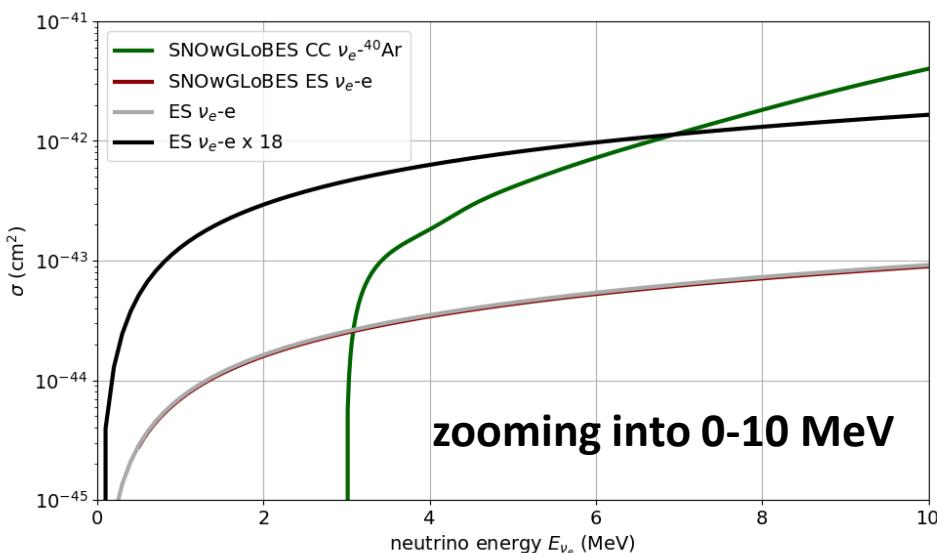
$$\sigma_0 = \frac{2 G_F^2 m_e^2}{\pi} \simeq 88.06 \times 10^{-46} \text{ cm}^2 \quad m_e = 0.511 \text{ MeV}$$

$$g_1^{(\nu_e)} = g_2^{(\bar{\nu}_e)} = 1 + \frac{g_V^l + g_A^l}{2} = 1 + g_L^l = \frac{1}{2} + \sin^2 \vartheta_W \simeq 0.73$$

$$g_2^{(\nu_e)} = g_1^{(\bar{\nu}_e)} = \frac{g_V^l - g_A^l}{2} = g_R^l = \sin^2 \vartheta_W \simeq 0.23$$

Elastic scattering of solar neutrinos in DUNE

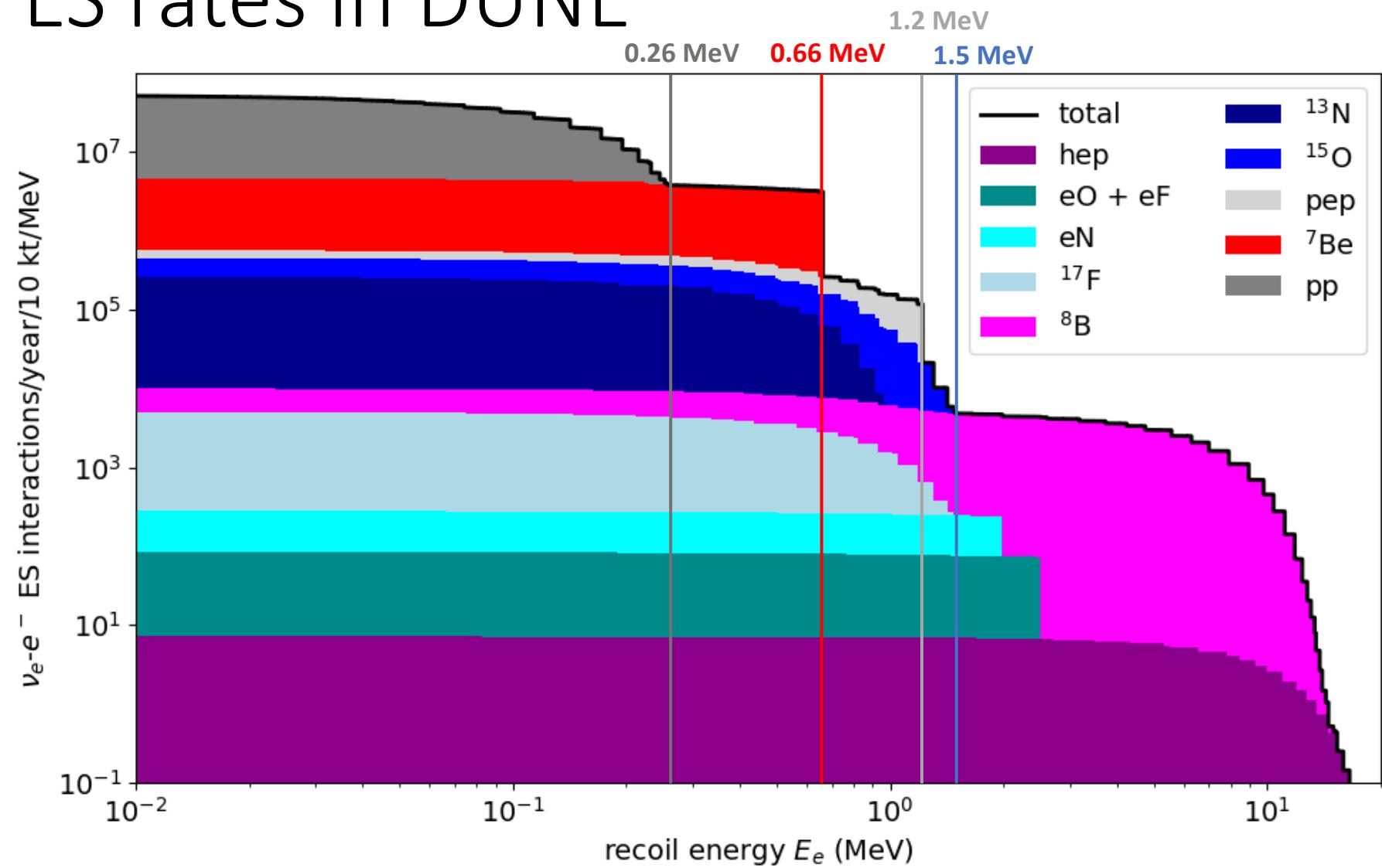
- Below $E_{\nu_e} = 7$ MeV will have more ES interactions in Ar
- Close to threshold, but...



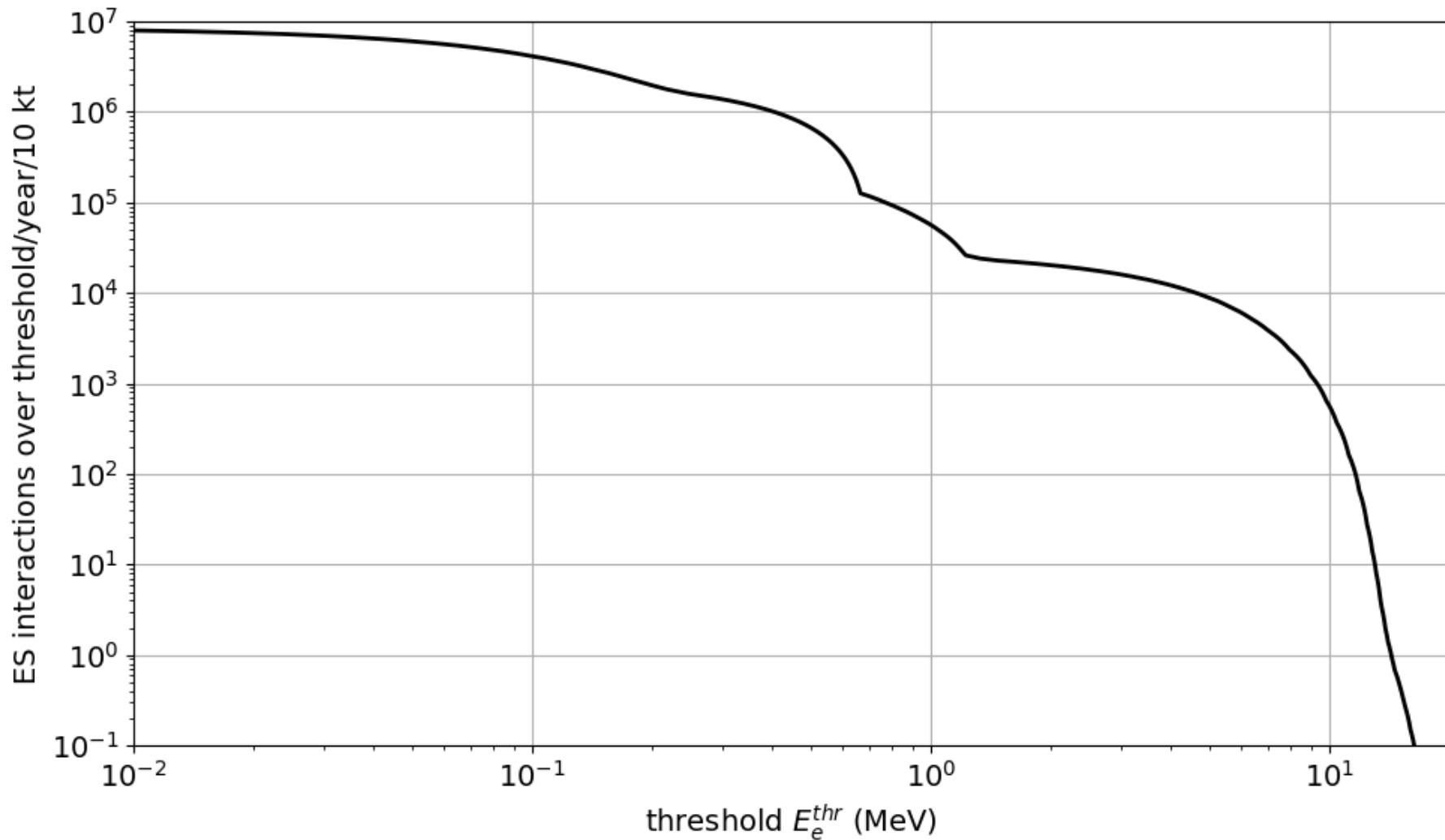
CC and 18·ES cross sections cross at ~ 7 MeV

Differential ES rates in DUNE

- For 10 kt·years
 - 10 years with 1-kt low-background module
- No oscillations



ES rate over threshold in DUNE



Parameter definitions

- Matter Hamiltonian $H_{\text{mat}}^{\text{eff}} = \sqrt{2}G_F N_e(x) \left[\begin{pmatrix} c_{13}^2 & 0 \\ 0 & 0 \end{pmatrix} + [\xi^p + Y_n(x)\xi^n] \begin{pmatrix} -\varepsilon_D^\eta & \varepsilon_N^\eta \\ \varepsilon_N^{\eta*} & \varepsilon_D^\eta \end{pmatrix} \right]$
- Diagonal and non-diagonal NSI

$$\begin{aligned} \varepsilon_D^\eta = & c_{13}s_{13} \operatorname{Re}(s_{23}\varepsilon_{e\mu}^\eta + c_{23}\varepsilon_{e\tau}^\eta) - (1 + s_{13}^2)c_{23}s_{23} \operatorname{Re}(\varepsilon_{\mu\tau}^\eta) \\ & - \frac{c_{13}^2}{2}(\varepsilon_{ee}^\eta - \varepsilon_{\mu\mu}^\eta) + \frac{s_{23}^2 - s_{13}^2c_{23}^2}{2}(\varepsilon_{\tau\tau}^\eta - \varepsilon_{\mu\mu}^\eta) \end{aligned}$$

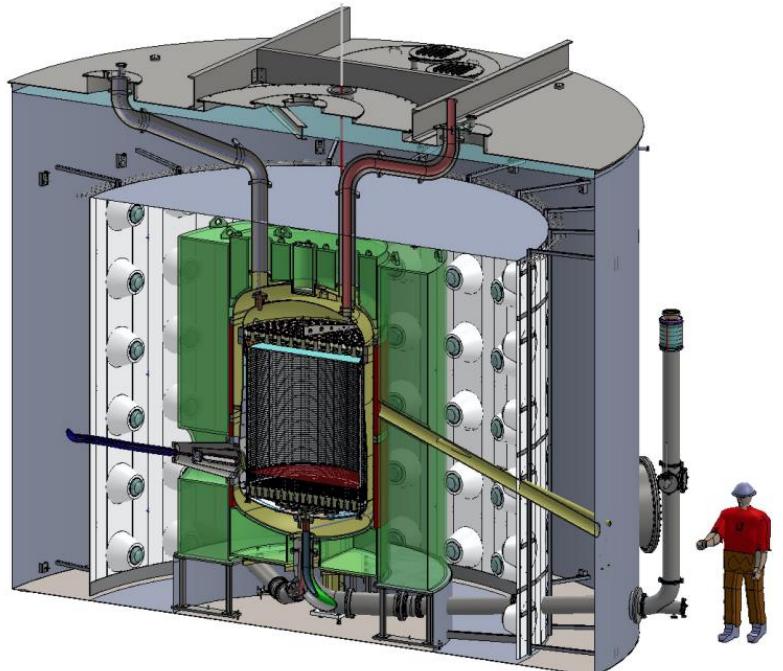
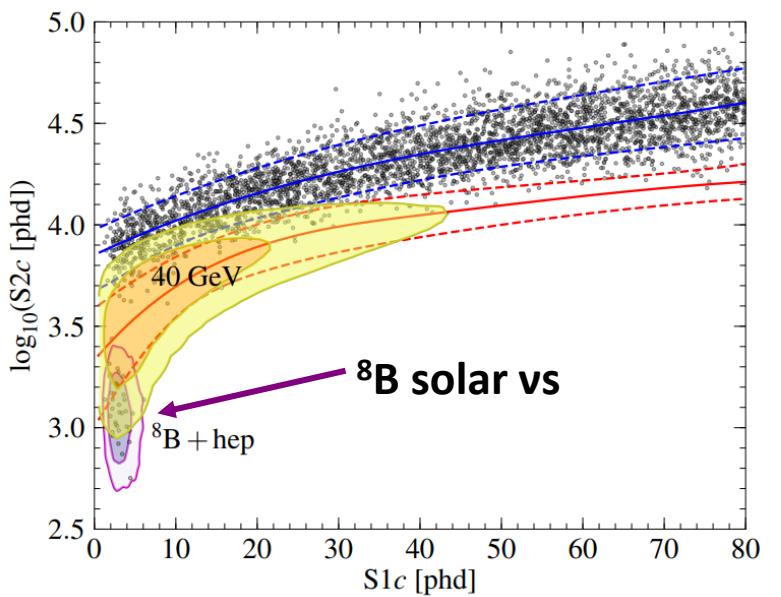
$$\varepsilon_N^\eta = c_{13}(c_{23}\varepsilon_{e\mu}^\eta - s_{23}\varepsilon_{e\tau}^\eta) + s_{13}[s_{23}^2\varepsilon_{\mu\tau}^\eta - c_{23}^2\varepsilon_{\mu\tau}^{\eta*} + c_{23}s_{23}(\varepsilon_{\tau\tau}^\eta - \varepsilon_{\mu\mu}^\eta)]$$

- Assumed usual NSI couplings can be factorized into neutrino and charged-fermion parts

$$\varepsilon_{\alpha\beta}^f \equiv \varepsilon_{\alpha\beta}^{f,L} + \varepsilon_{\alpha\beta}^{f,R} = \varepsilon_{\alpha\beta}^\eta \xi^f \quad \begin{aligned} \xi^p &= \sqrt{5} \cos \eta \\ \xi^n &= \sqrt{5} \sin \eta \end{aligned}$$

Neutrinos in LZ

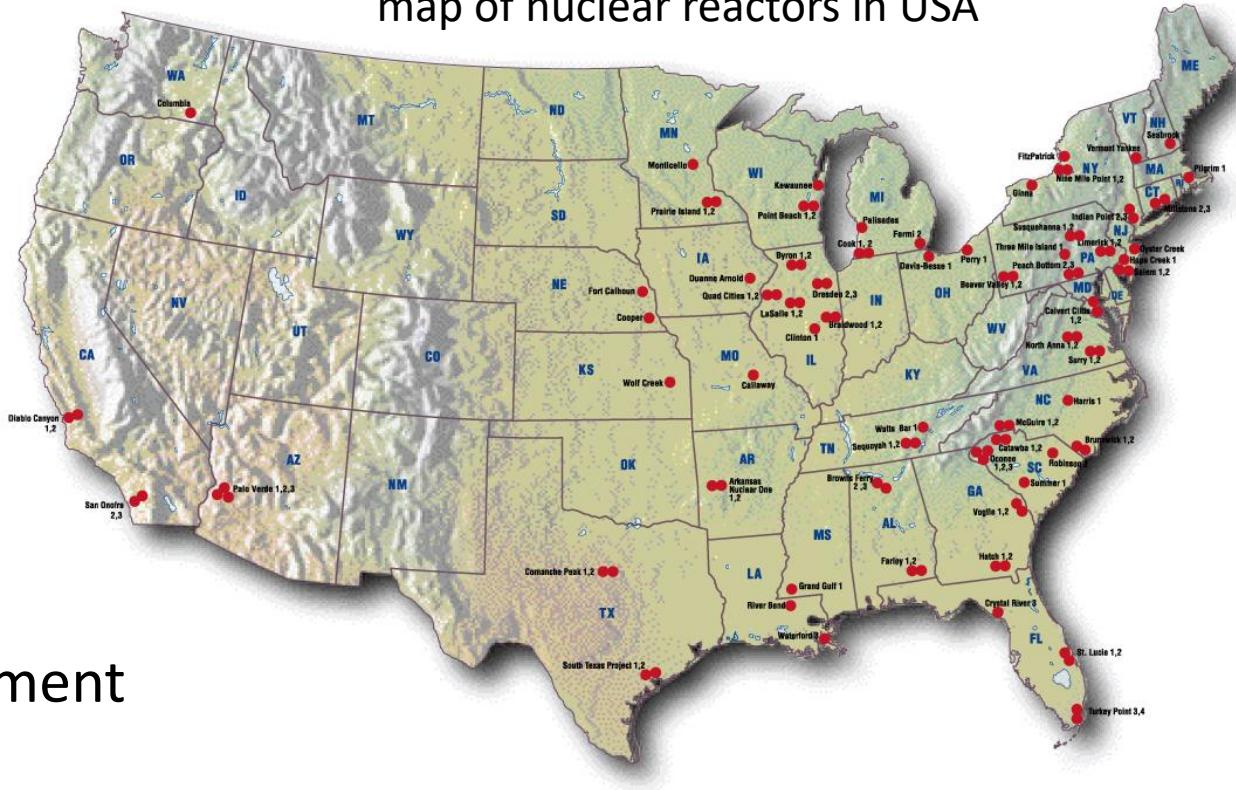
- ${}^8\text{B}$ neutrinos via CEvNS
 - CEvNS (nuclear) recoils – look exactly like WIMP recoils ($m_\chi \approx 6 \text{ GeV}$)
 - Expect few events
 - Have not been observed yet
 - important measurement
- Many other neutrinos will interact in LZ
 - What can we learn from them?



map of nuclear reactors in USA

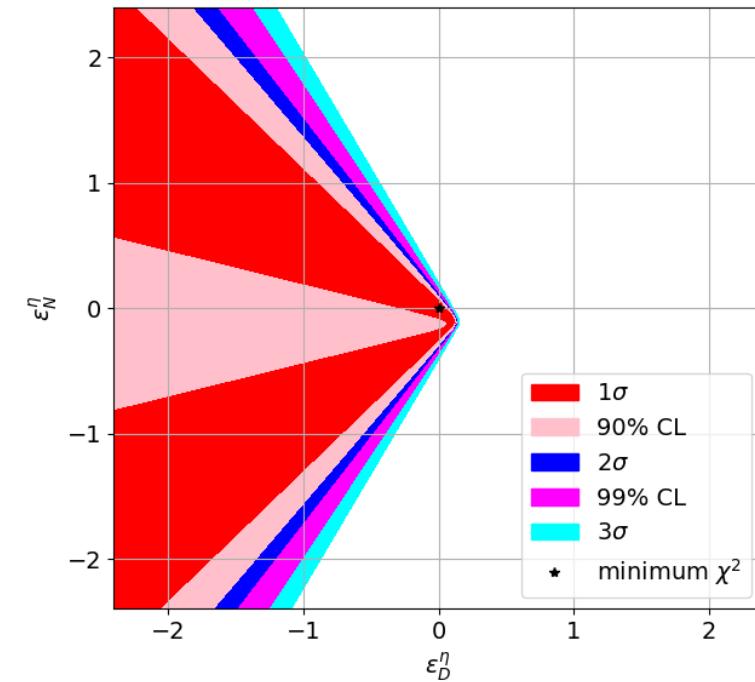
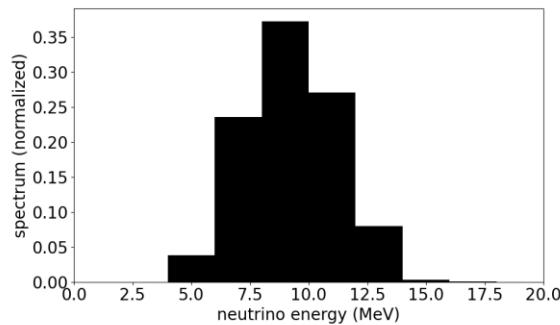
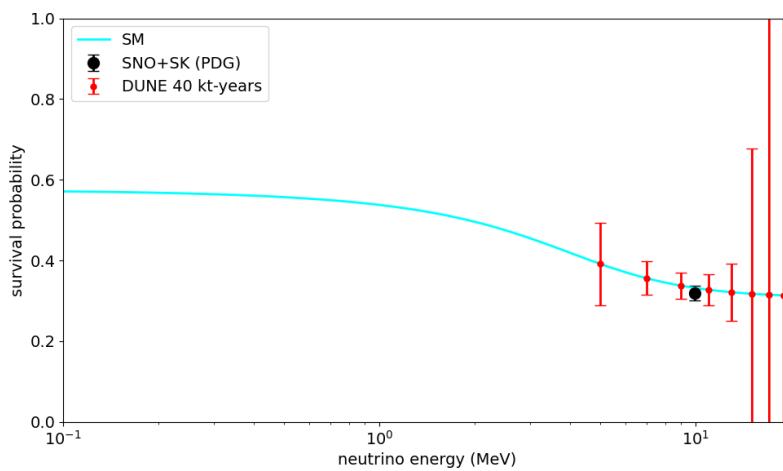
What can LZ do?

- Not seeing reactor neutrinos
 - Not many reactors around
 - Detector not big enough
 - Cannot improve KamLAND measurement
- Expect to see many solar neutrinos
 - More matter effect from high solar density
 - Interested to pursue this



Deep Underground Neutrino Experiment

- 40 kt of liquid argon
 - Staged
- First couple years assume 40 kt·years
- Solar neutrinos via CC
- Possible module with low-threshold (~ 100 keV) 1 kt of liquid argon
 - Solar neutrinos via ES



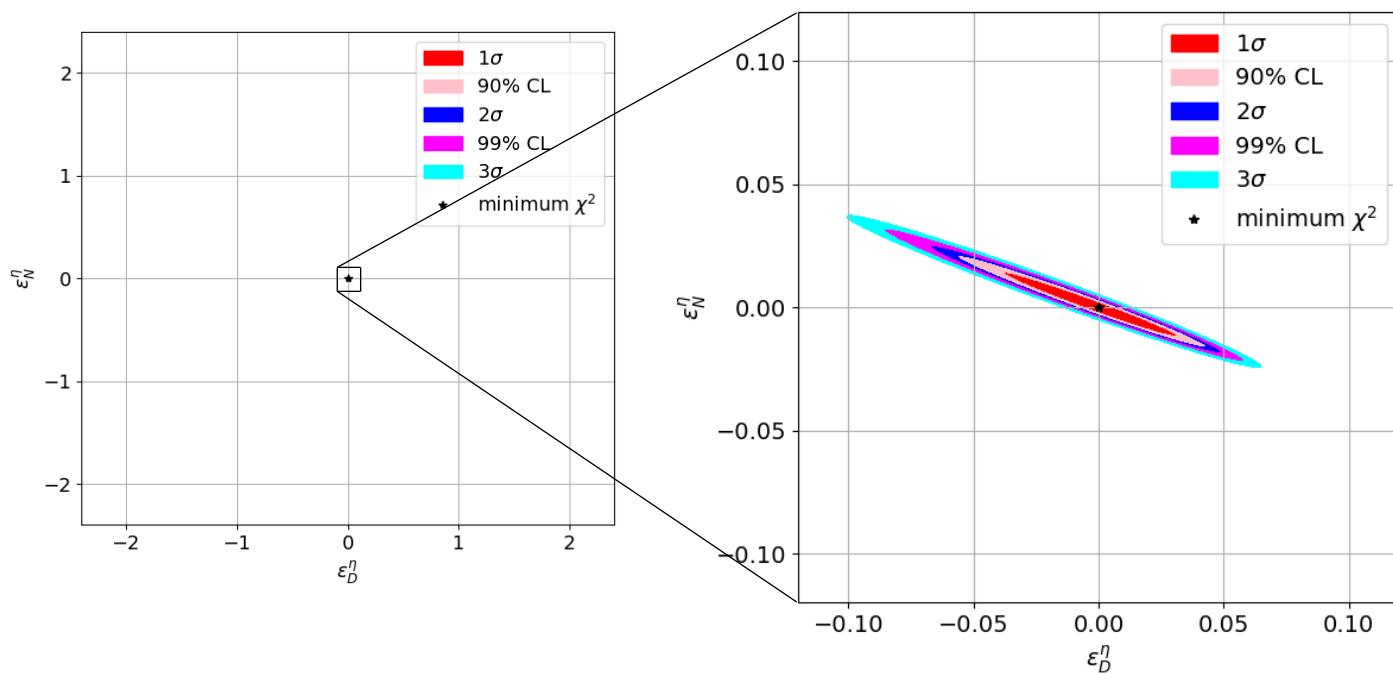
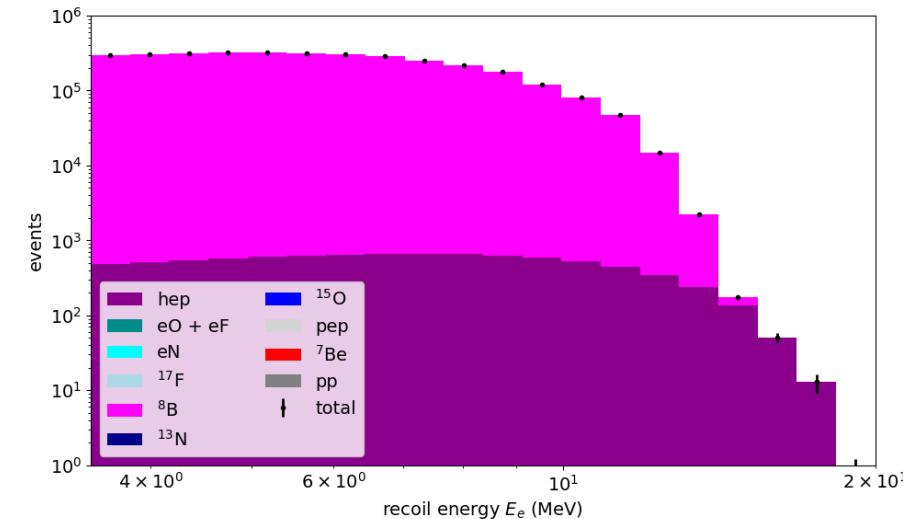
Not strong early constraint due to high threshold

E. Church, C. Jackson, R. Saldanha (2020)
arXiv:2005.04824

Hyper-Kamiokande

- 217 kt of water
 - 2nd module may be added
- Assume 4 years of statistics
- Solar neutrinos via ES
 - Recent Super-K analysis with 3.5-MeV threshold

Very strong constraint
due to high statistics
**(no systematics or
backgrounds here)**



Alex Friedland et al. NSI model

- Using all NSI couplings in 2-flavor Hamiltonian

$$H_{\text{mat}}^{\text{NSI}} = \frac{G_F n_e}{\sqrt{2}} \begin{pmatrix} 1 + \epsilon_{11} & \epsilon_{12}^* \\ \epsilon_{12} & -1 - \epsilon_{11} \end{pmatrix}$$

$$= \begin{pmatrix} A \cos 2\alpha & Ae^{-2i\phi} \sin 2\alpha \\ Ae^{2i\phi} \sin 2\alpha & -A \cos 2\alpha \end{pmatrix}$$

$$\epsilon_{\alpha\beta} \equiv \sum_{f=u,d,e} \epsilon_{\alpha\beta}^f n_f / n_e$$

