Non-Standard Interactions in Solar Neutrinos

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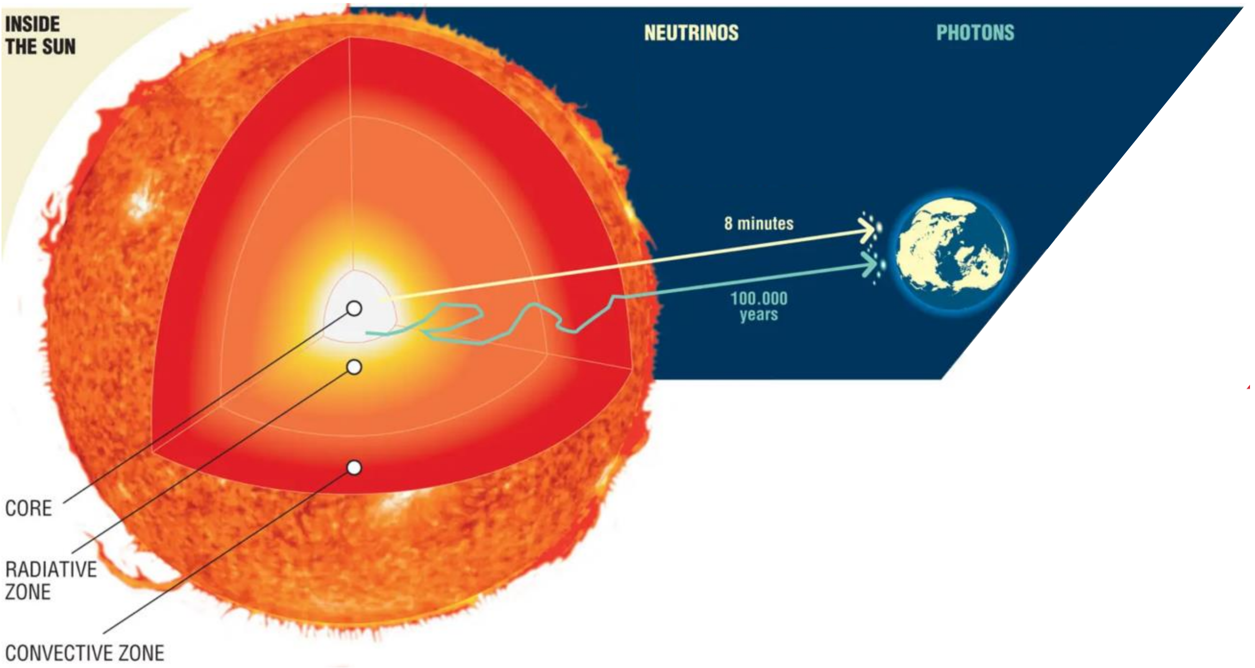
South Dakota Mines

July 7, 2023

Outline

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



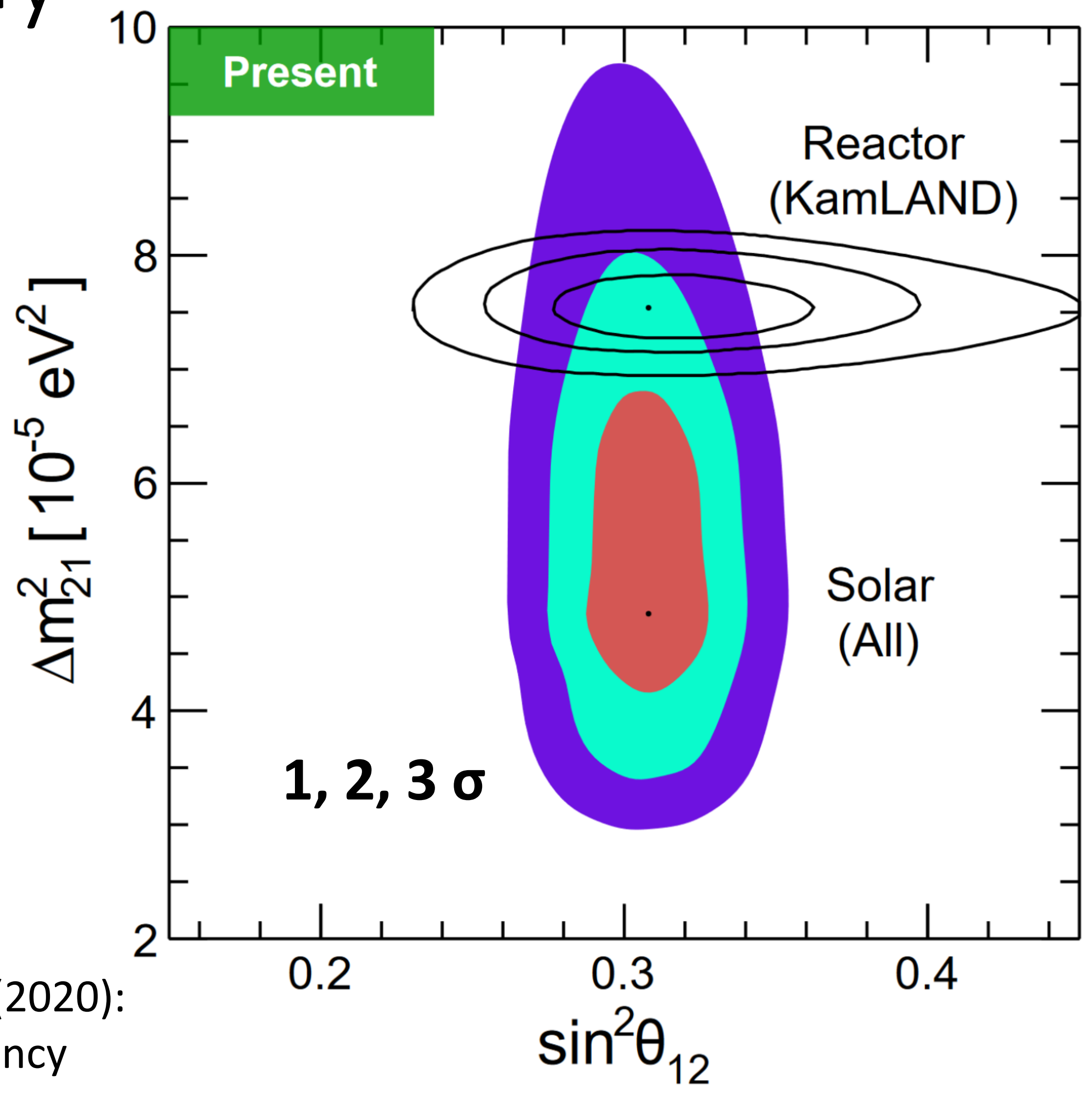
https://www.businessinsider.com/neutrinos-forged-in-the-heart-of-the-sun-2014-8

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

Solar neutrino anomaly

- ~2σ discrepancy in solar Δm^2 measured by solar ν experiments and KamLAND (reactor ν experiment)

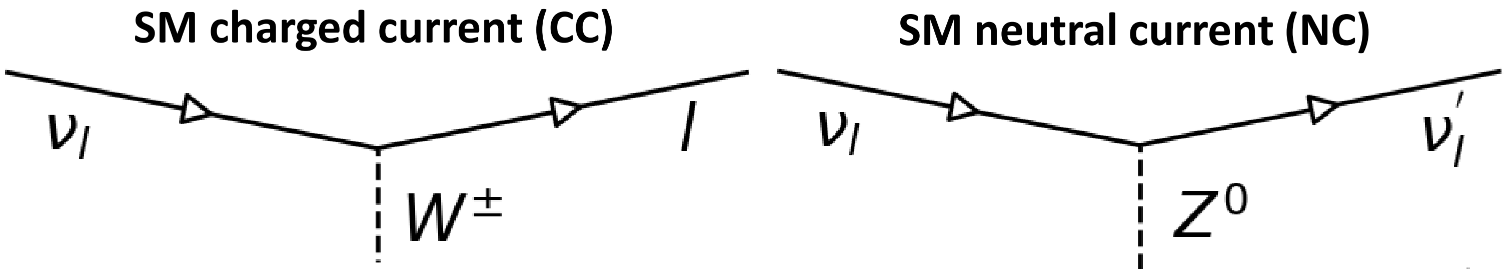
- Just statistics?
  - If not…



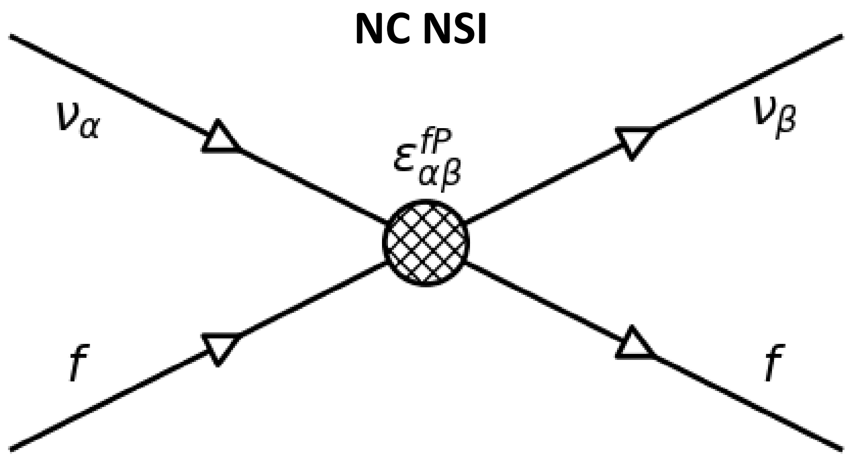
New Super-K results (2020): now 1.4σ discrepancy

Non-standard neutrino interactions (NSI)

- One possible explanation
- Standard model (SM) neutrino interactions
  - Everything else: NSI



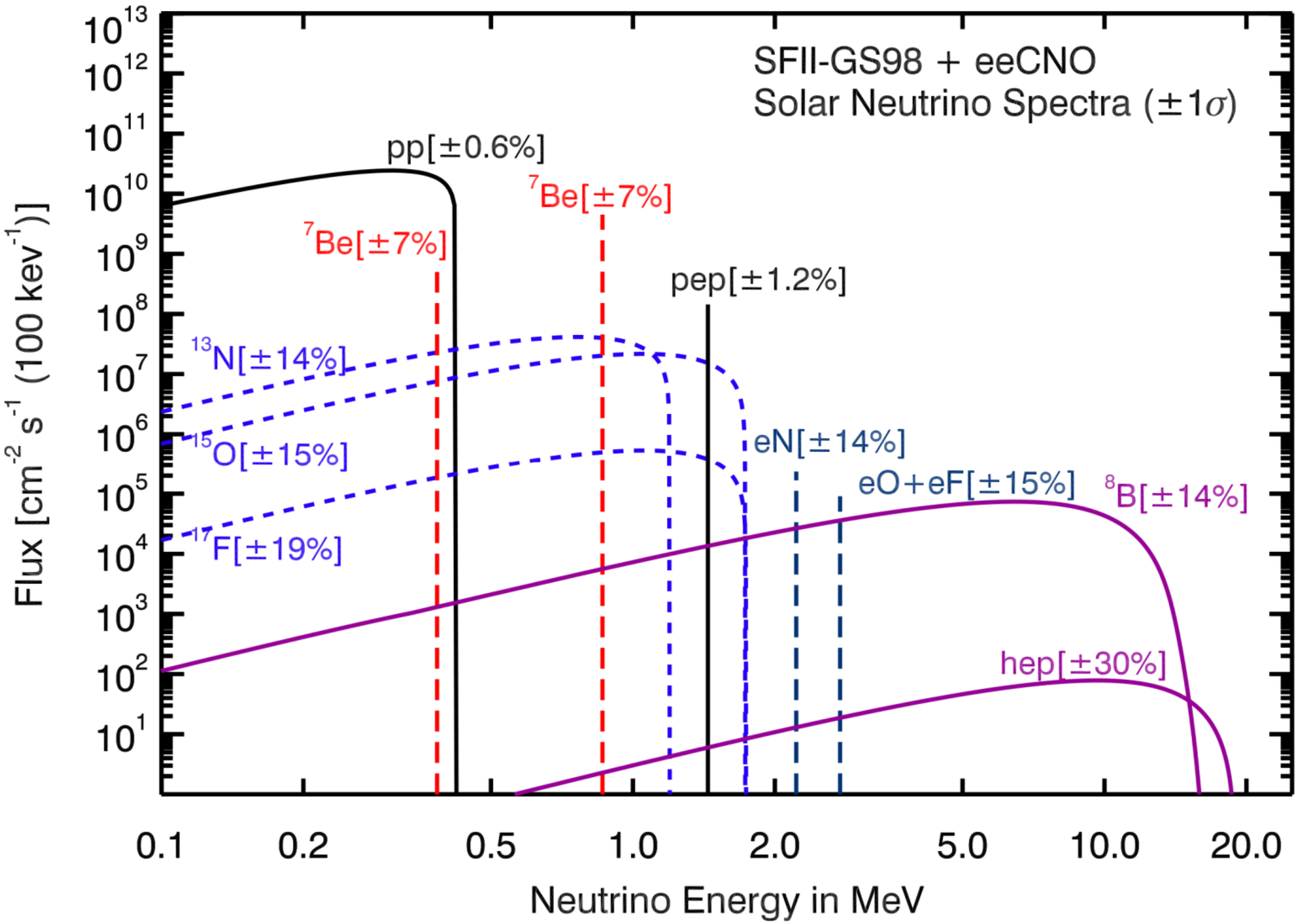
- Here focus on neutral-current models with heavy mediators ($m_{Z'}^2 \gg Q^2$)
  - $\mathcal{L}_{\alpha\beta}^{fP} = -2\sqrt{2}G_F\varepsilon_{\alpha\beta}^{fP}[\bar{\nu}_\alpha\gamma^\mu(1-\gamma^5)\nu_\beta][\bar{f}\gamma_\mu P f]$
  - Can change ν flavor, not fermion (*f*)
  - Parameterized by ε's



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

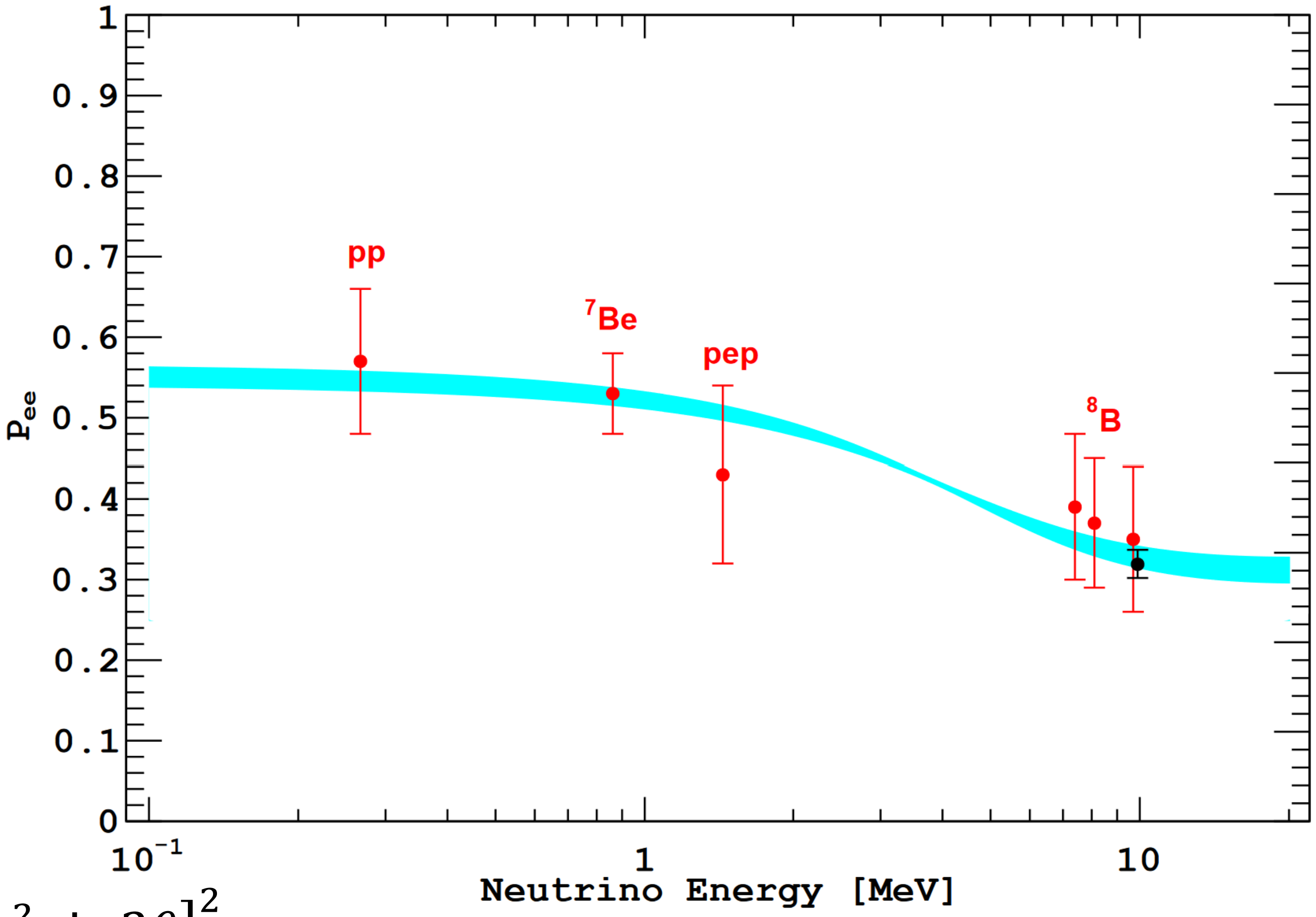
Solar neutrinos

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



Solar neutrino oscillations

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



O.G. Miranda, M.A. Tórtola, J.W.F. Valle (2006)
arXiv:hep-ph/0406280
(extended with up-quark NSI and different NSI parameterization)

NSI in Sun

- 2-flavor model

SM vacuum oscillations + matter effect **NSI**

  - $H = \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta + \sqrt{2}G_F N_e & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix} + \sqrt{2}G_F(N_d + N_u)\begin{pmatrix} \varepsilon_D & \varepsilon_N \\ \varepsilon_N & -\varepsilon_D \end{pmatrix}$

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

    - $\cos 2\theta_m = \frac{\Delta m^2 \cos 2\theta - 2\sqrt{2}EG_F\left(N_e + 2\varepsilon_D(N_d + N_u)\right)}{[\Delta m^2]_{matter}}$

      - $\left[\Delta \mathrm{m}^2\right]^2_{matter} = \left[\Delta m^2 \cos 2\theta - 2\sqrt{2}EG_F\left(N_e + 2\varepsilon_D(N_d + N_u)\right)\right]^2 + \left[\Delta \mathrm{m}^2 \sin 2\theta + 4\sqrt{2}\varepsilon_N E G_F(N_d + N_u)\right]^2$

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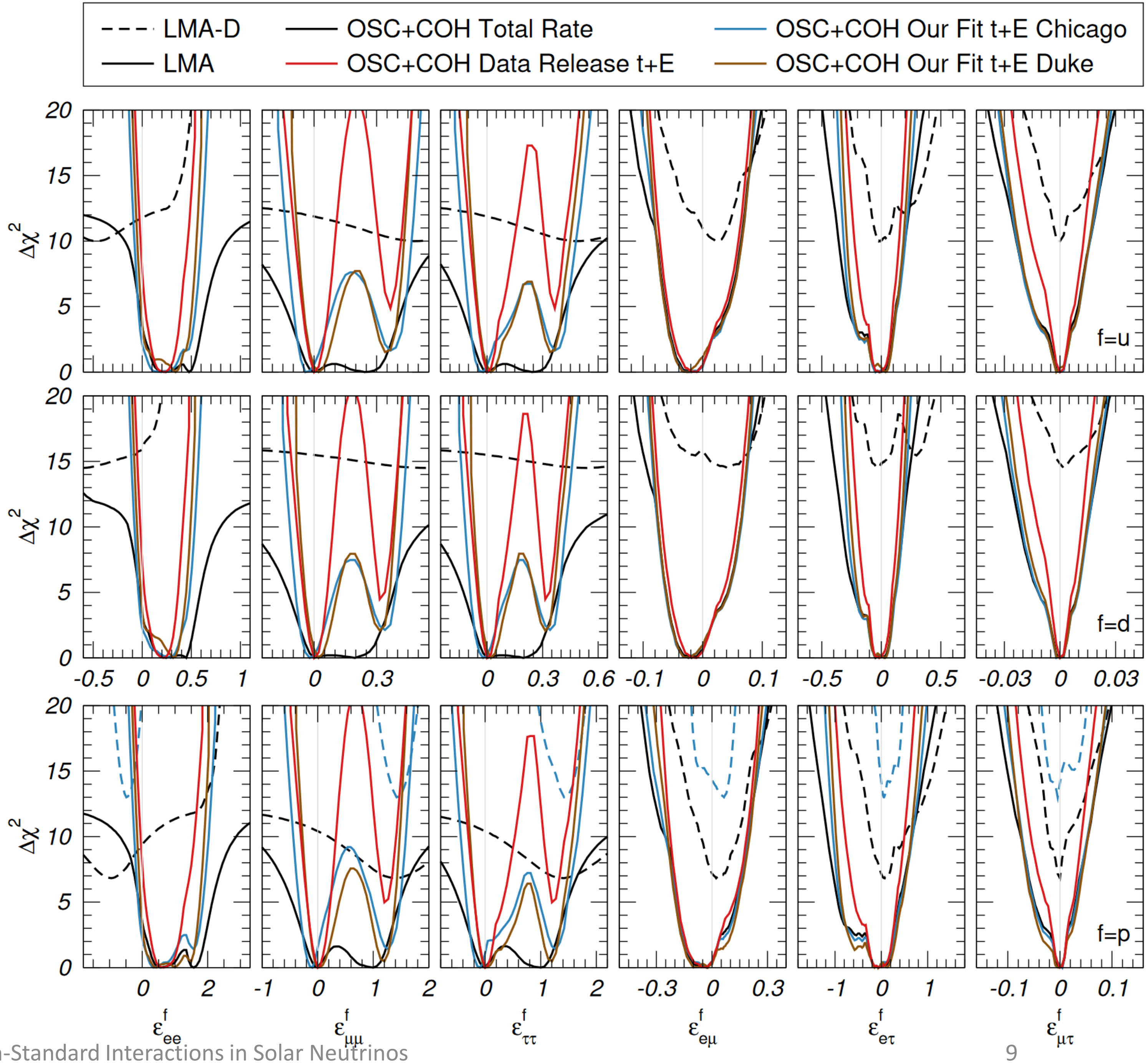
$\mathrm{NSI_D}$

$\mathrm{NSI_N}$

NSI constraints (early 2020)

- All but plotted NSI coupling marginalized

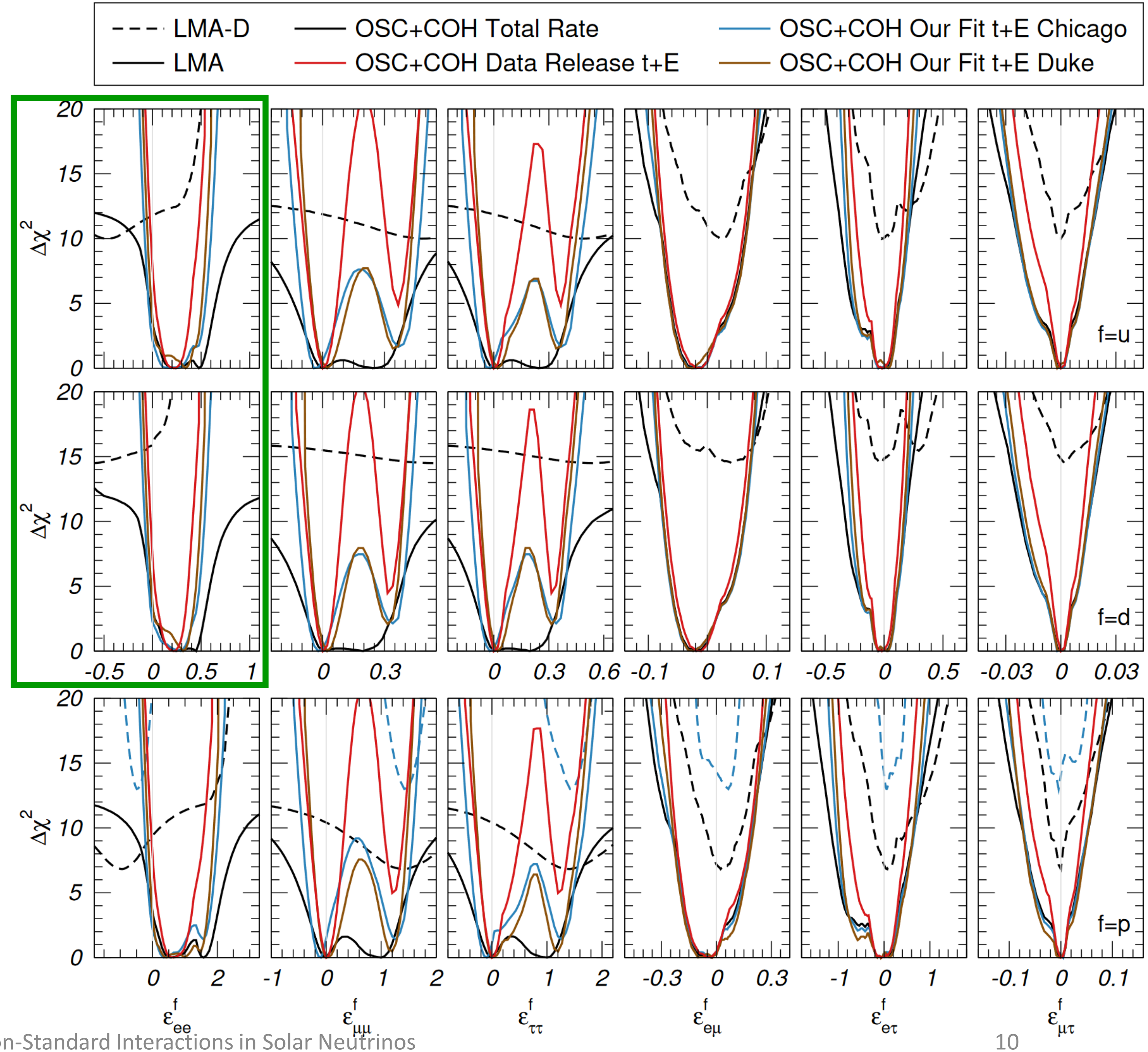


Excellent global fit and summary of NSI:

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

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?



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Simplified model

- 2-flavor model

SM vacuum oscillations + matter effect **NSI**

- $$H = \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta + \sqrt{2}G_F N_e & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix} + \sqrt{2}G_F(N_d + N_u)\begin{pmatrix} \varepsilon_D & 0 \\ 0 & -\varepsilon_D \end{pmatrix}$$

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

$$\boldsymbol{\varepsilon_D = \frac{\varepsilon_{ee}^u}{2} = \frac{\varepsilon_{ee}^d}{2}}$$

- $$\cos 2\theta_m = \frac{\Delta m^2 \cos 2\theta - 2\sqrt{2}EG_F(N_e + 2\varepsilon_D(N_d + N_u))}{[\Delta m^2]_{matter}}$$
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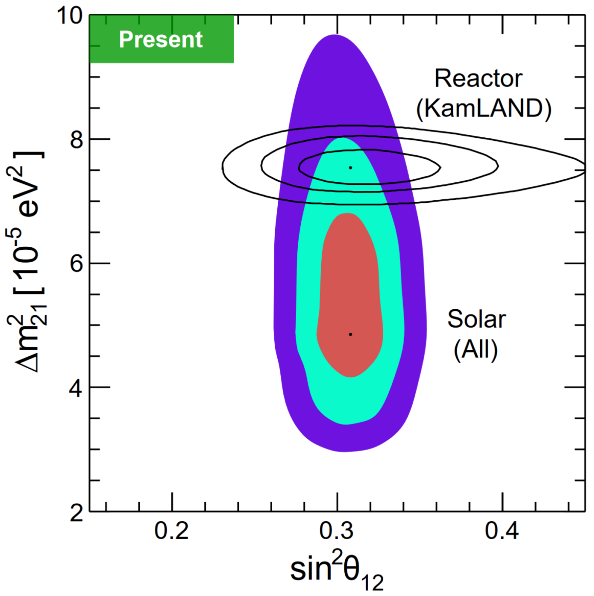
$\mathrm{NSI_D}$

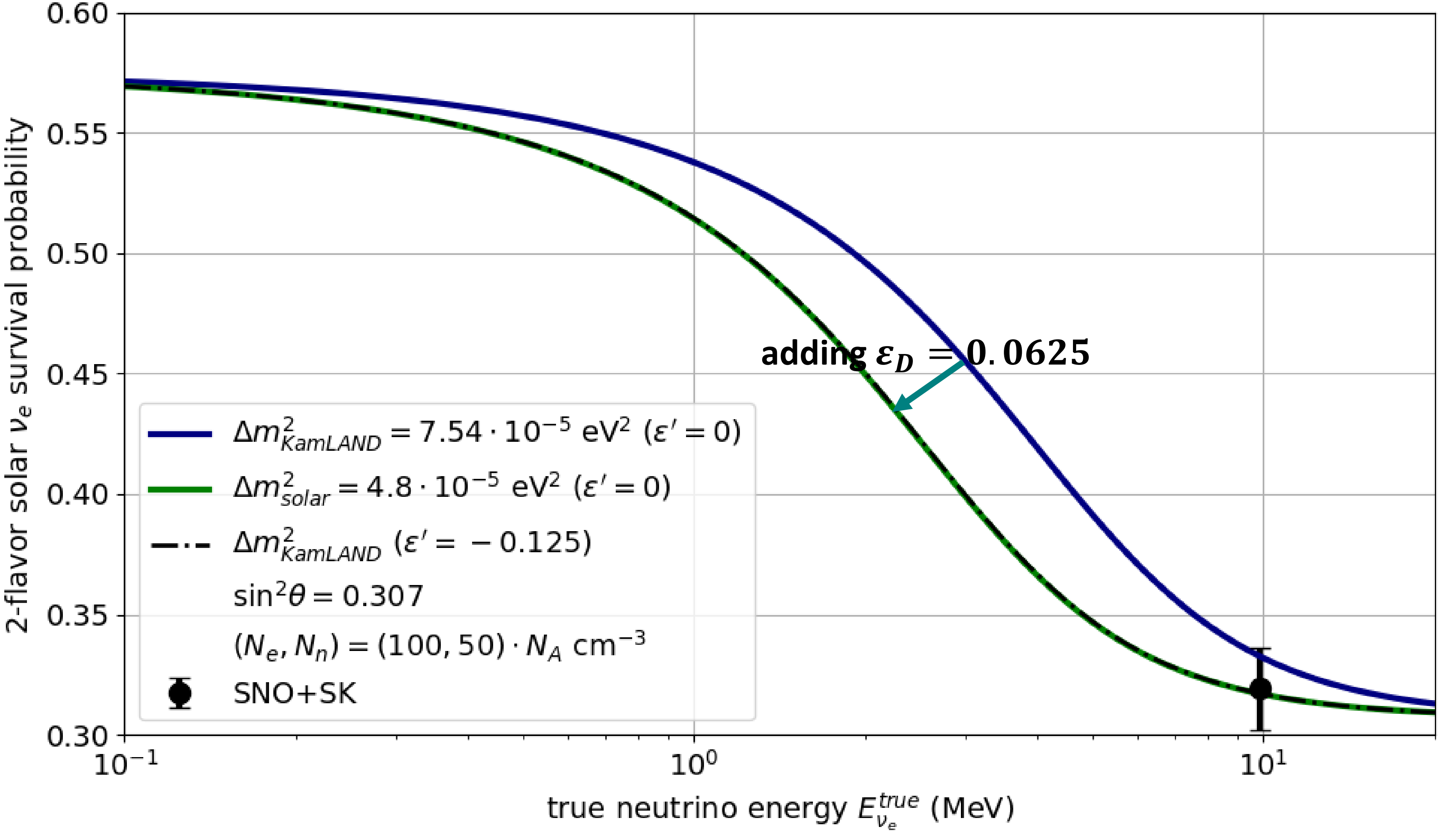
$\mathrm{NSI_N}$ = 0

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

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

O.G. Miranda, M.A. Tórtola, J.W.F. Valle (2006)
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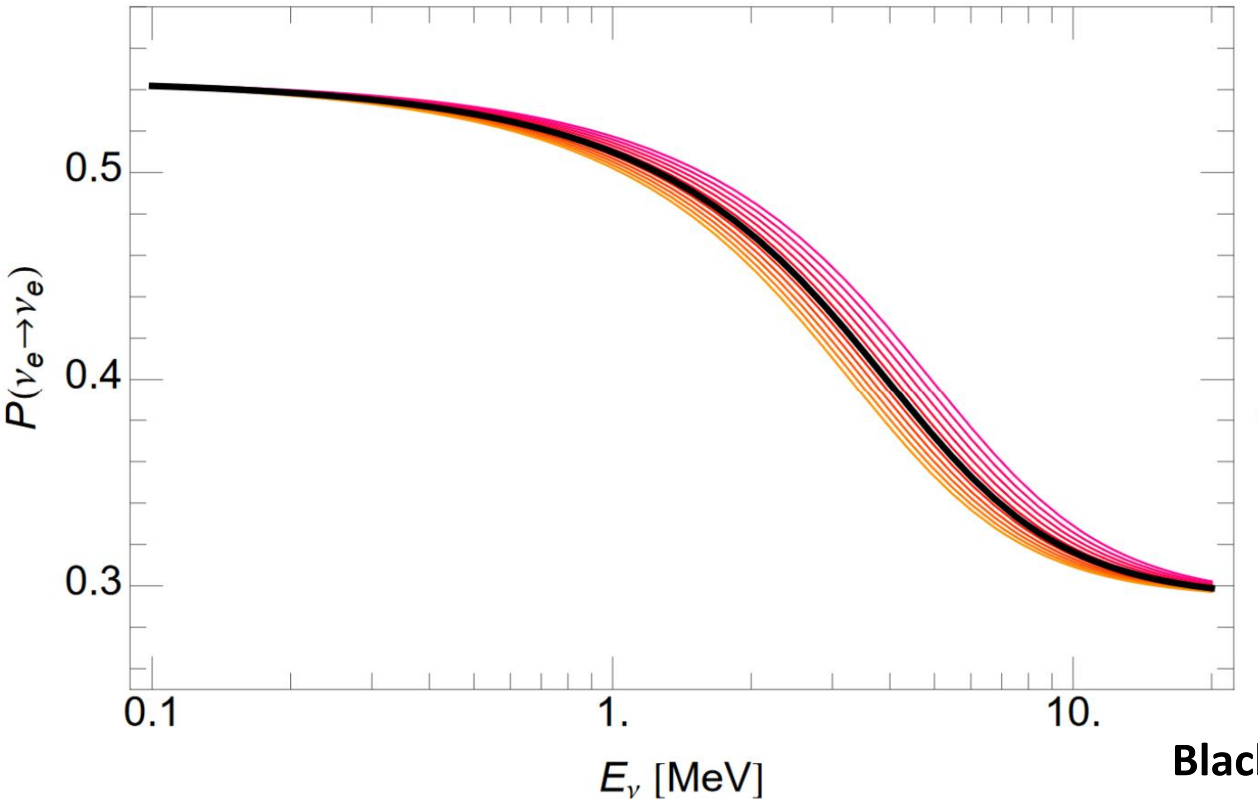
$\mathrm{NSI_D}$

$\mathrm{NSI_N}$

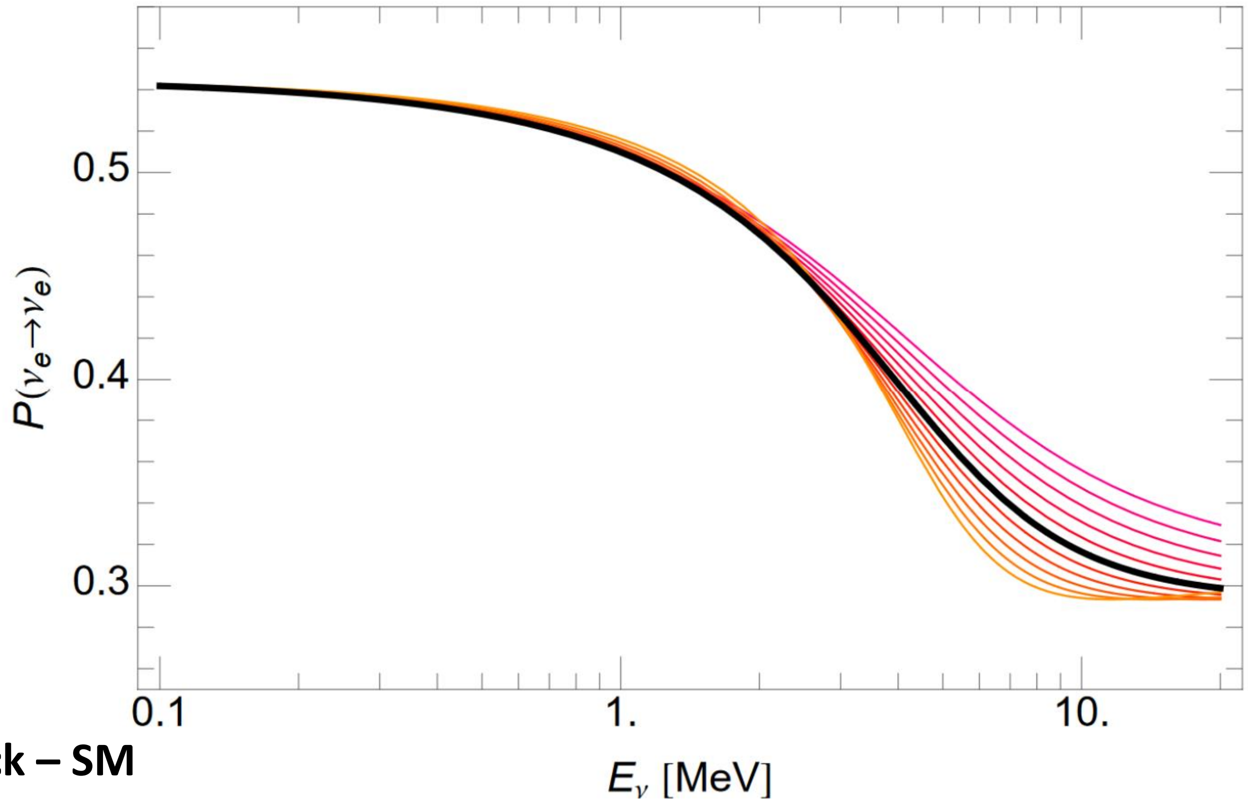
A. Friedland, M.L. Graesser, I.M. Shoemaker, L. Vecchi (2012)
arXiv:1111.5331

How do NSI affect survival probability?

flavor-diagonal couplings



flavor off-diagonal couplings

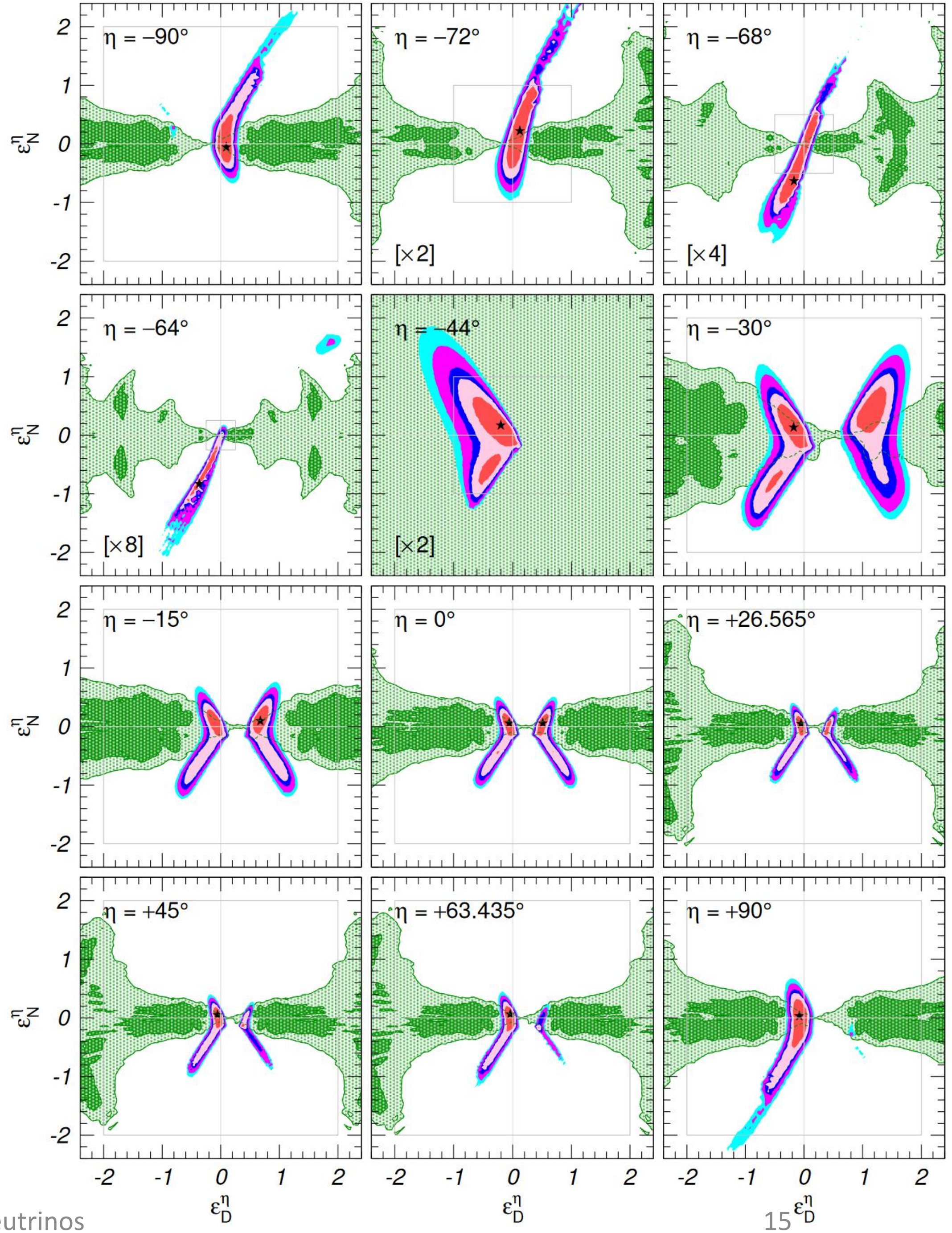


Black – SM

Current constraints

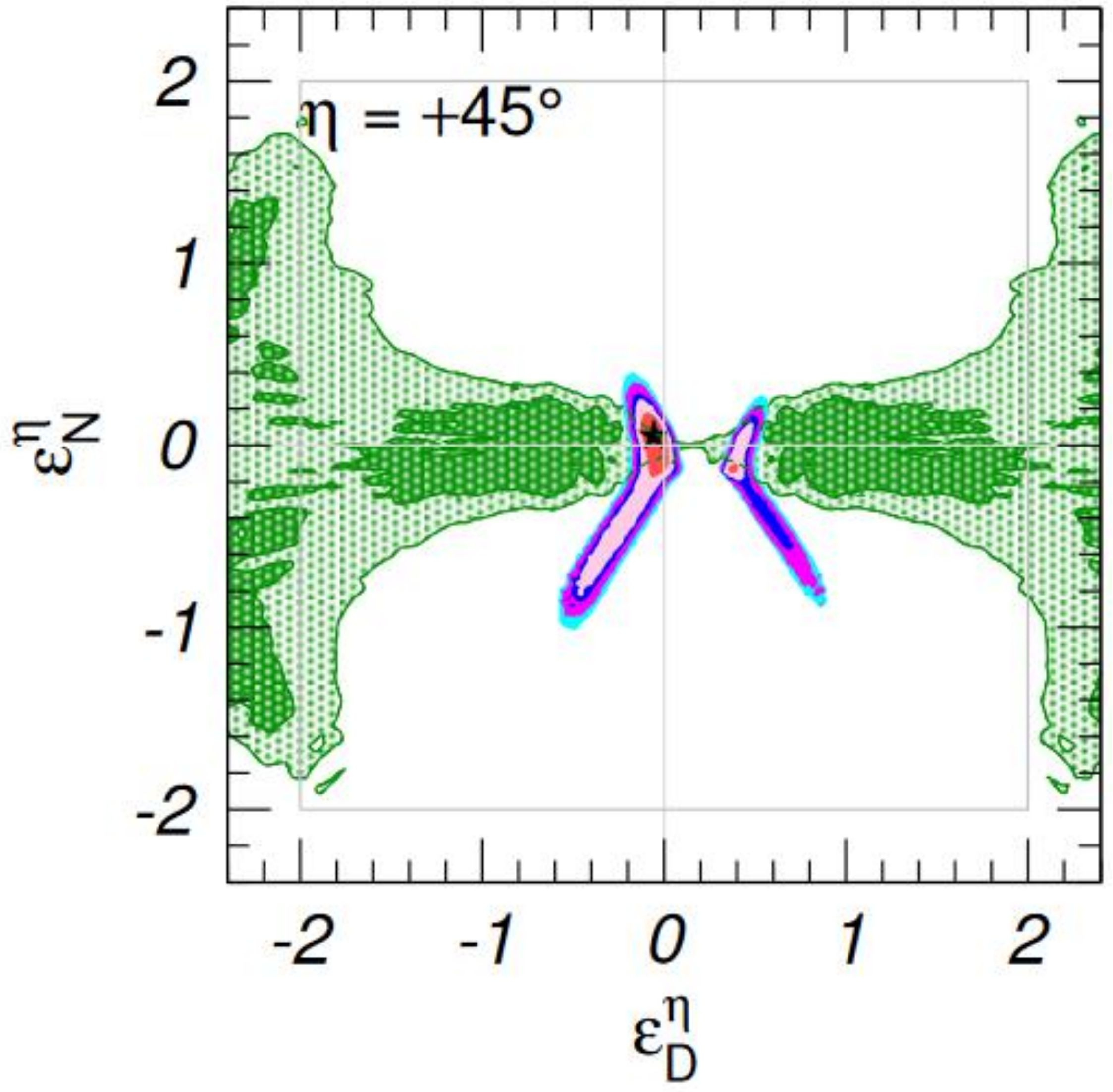
- Thorough study in paper
  - Global fit of neutrino experiments (2020)
- Marginalized over oscillation parameters
- Green contours – 90% and 3σ CL from atmospheric and LBL fit
- Other colors – 1σ, 90%, 2σ, 99%, 3σ CL from solar+KamLAND fit
- What can we compare our result to?

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



Current constraints

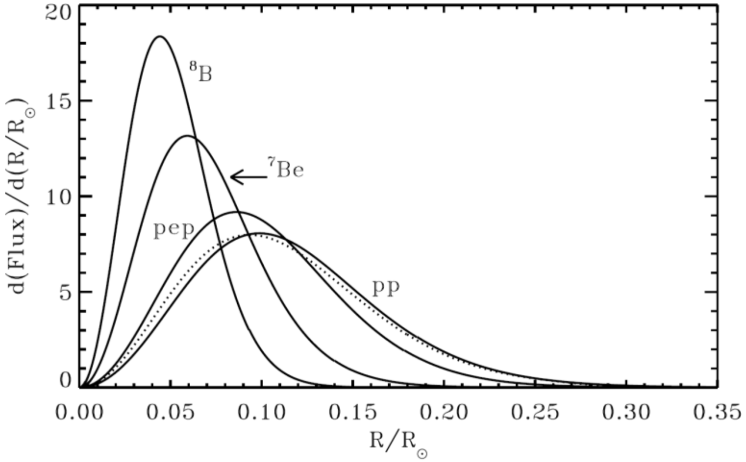
- Relevant limit corresponding to same NSI couplings for u and d quarks
  - Our assumptions

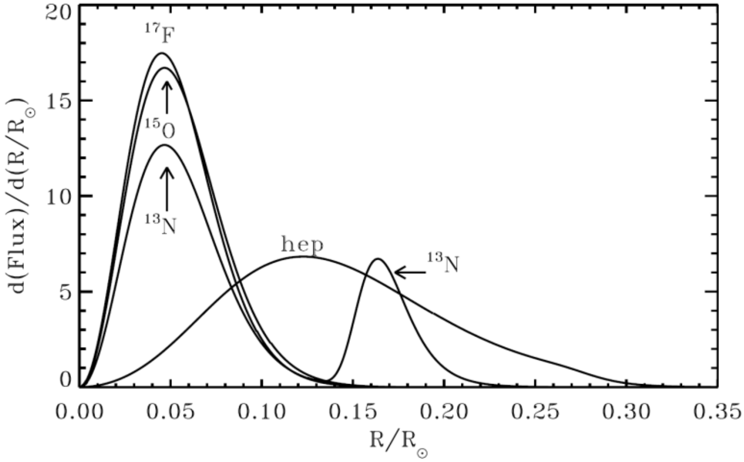


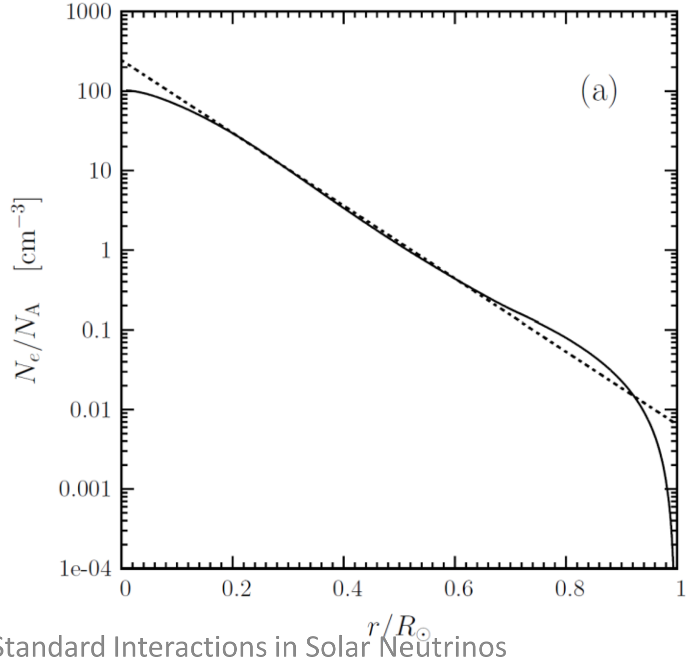
I. Esteban, M.C. Gonzalez-Garcia, M. Maltoni, I. Martinez-Soler, J. Salvado (2018) arXiv:1805.04530

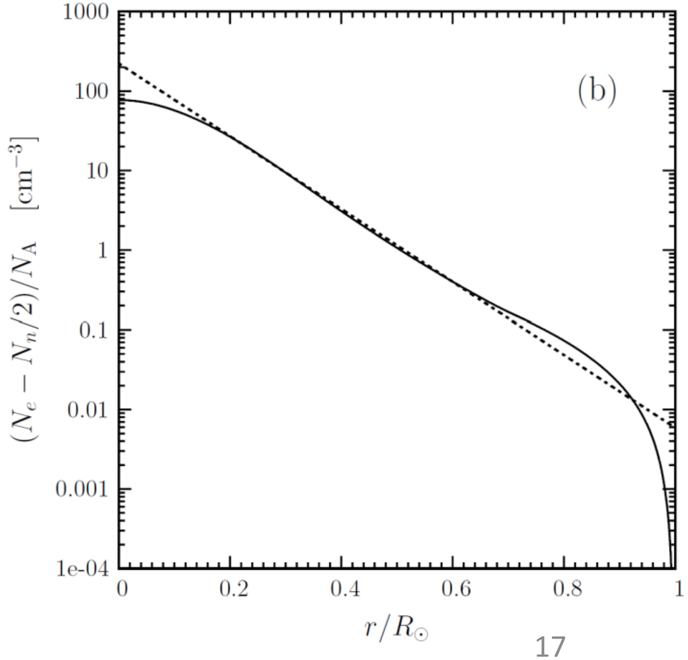
Model assumptions

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



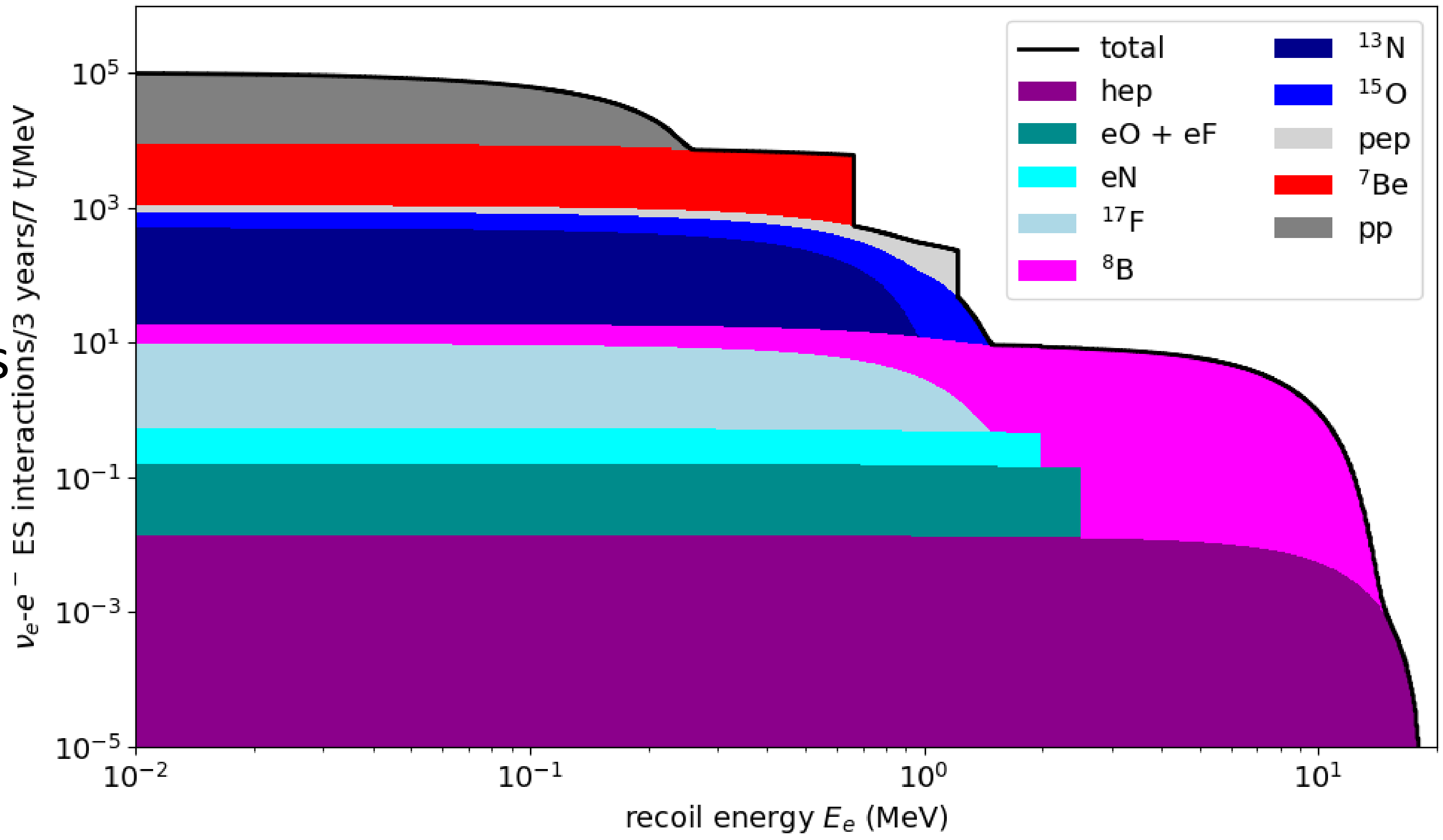






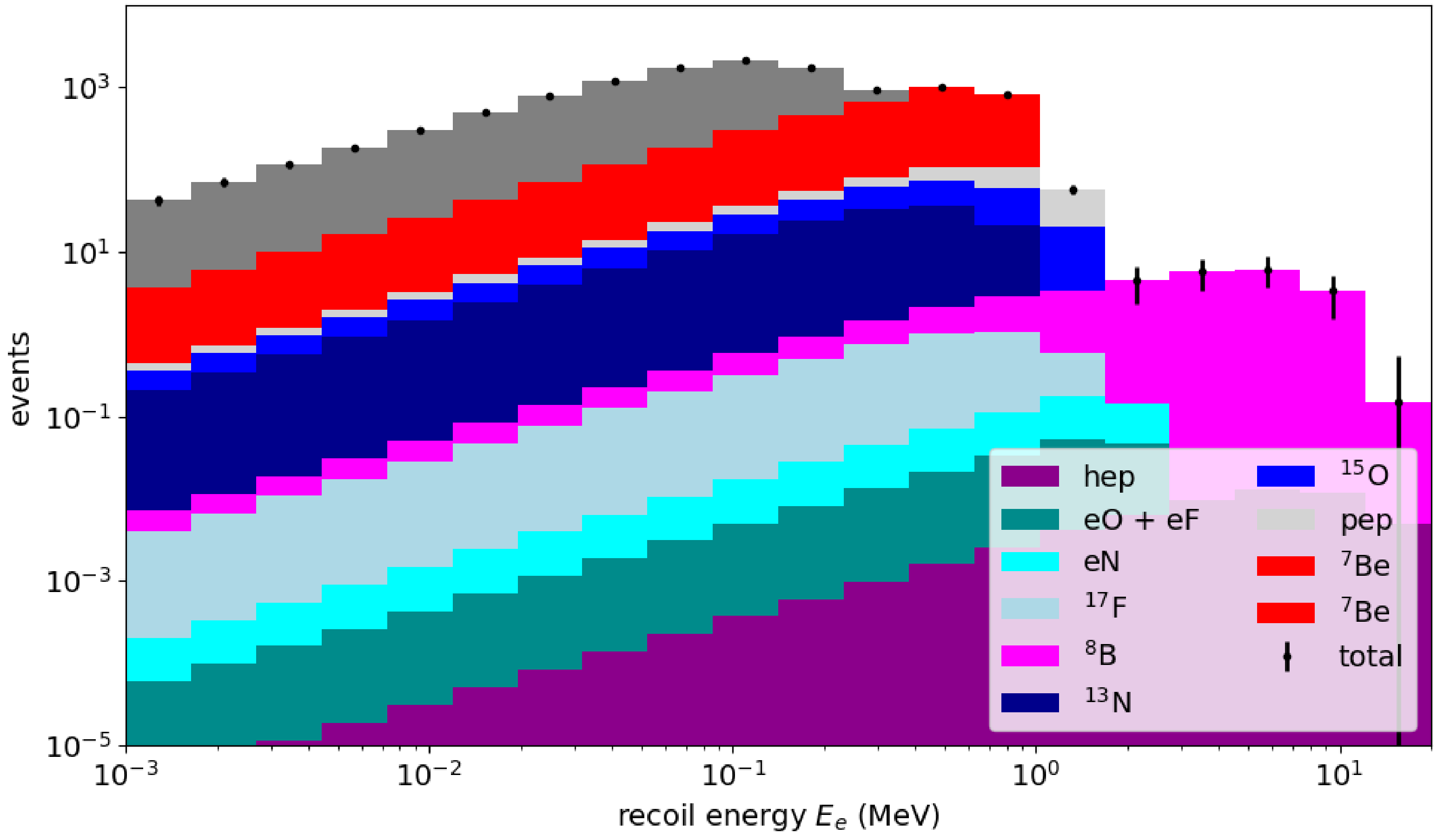
Elastic scattering (ES)

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

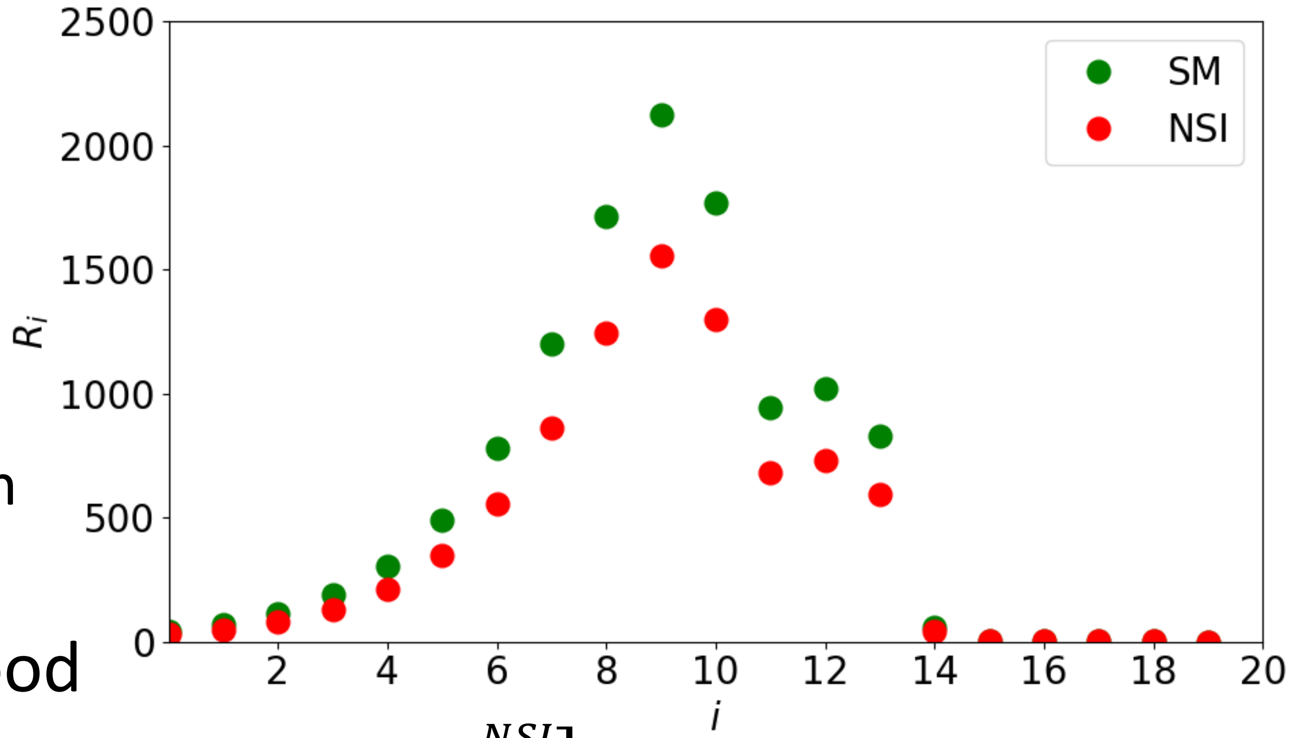


Rates

- Integrating previous plot for exposure
  and number of electrons



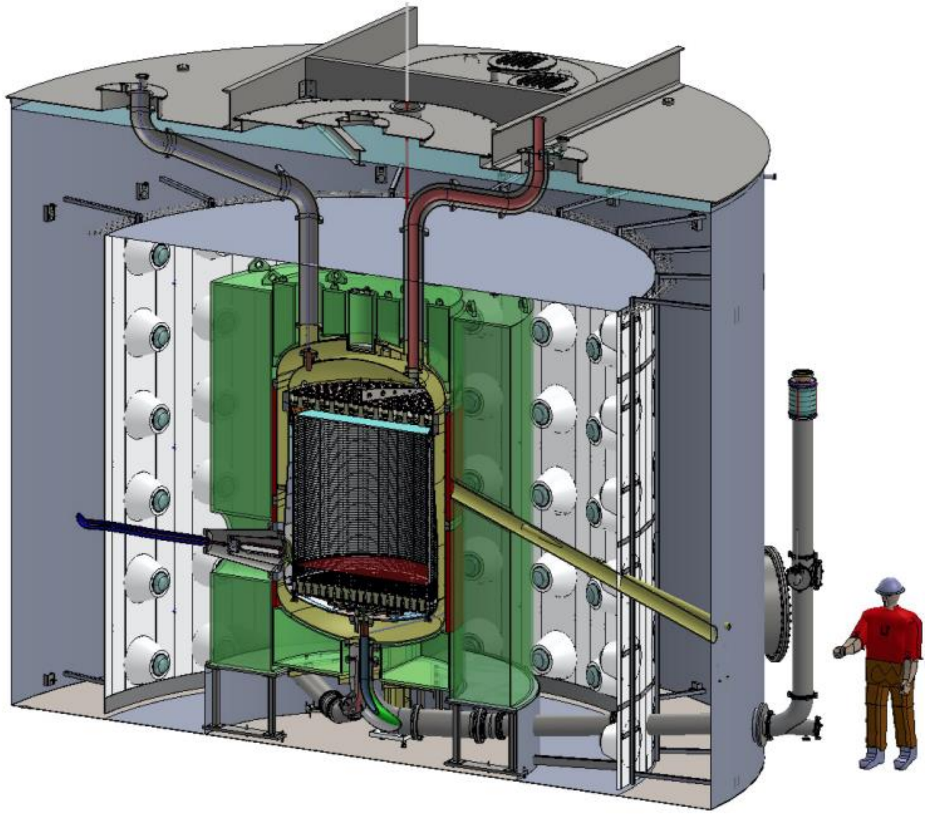
Statistical analysis



- 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

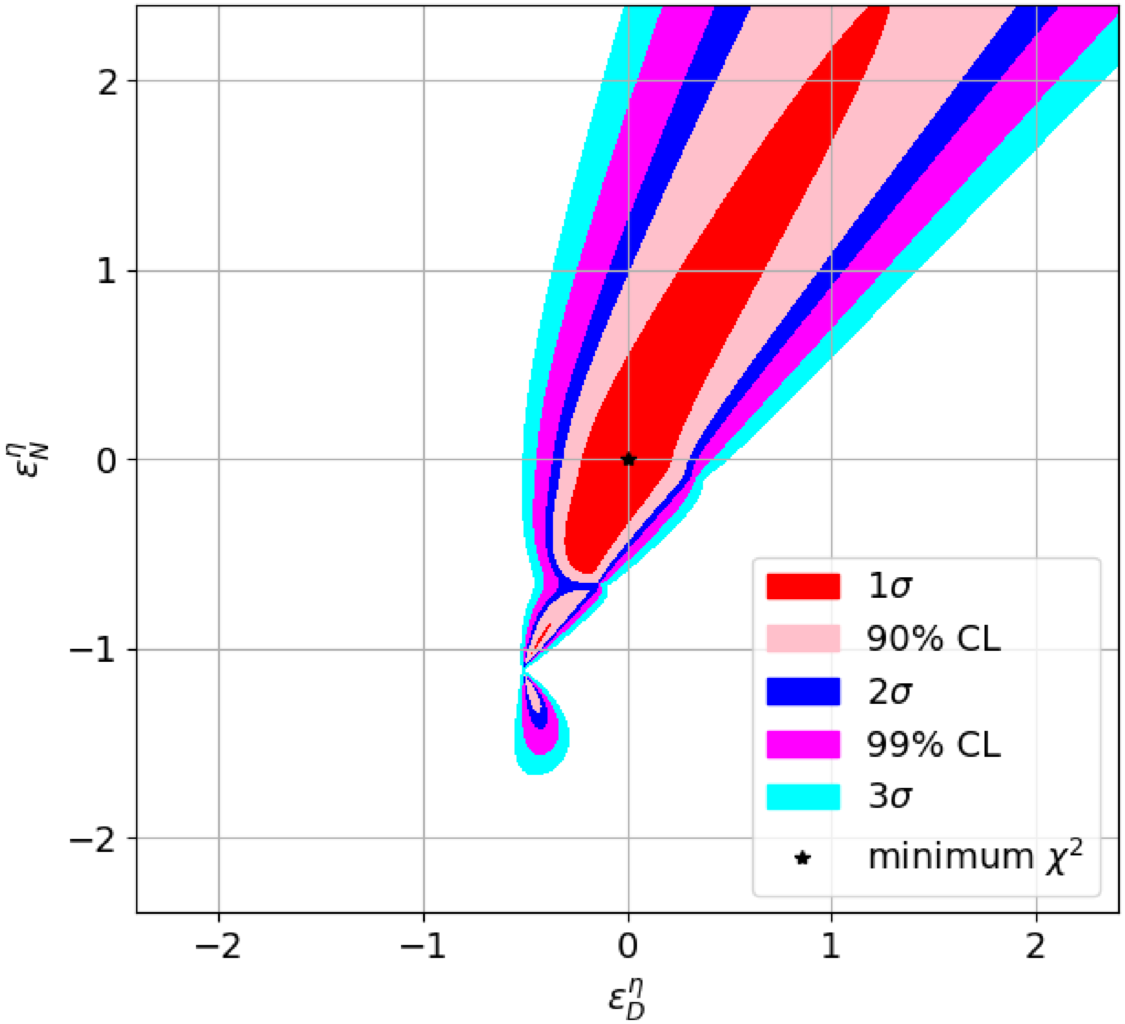
- LZ, XENONnT
- Assume
  - 7 t of Xe
  - 3 years of running
  - No backgrounds,
    perfect energy resolution
- MeVs of deposited energy
  is high energy



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

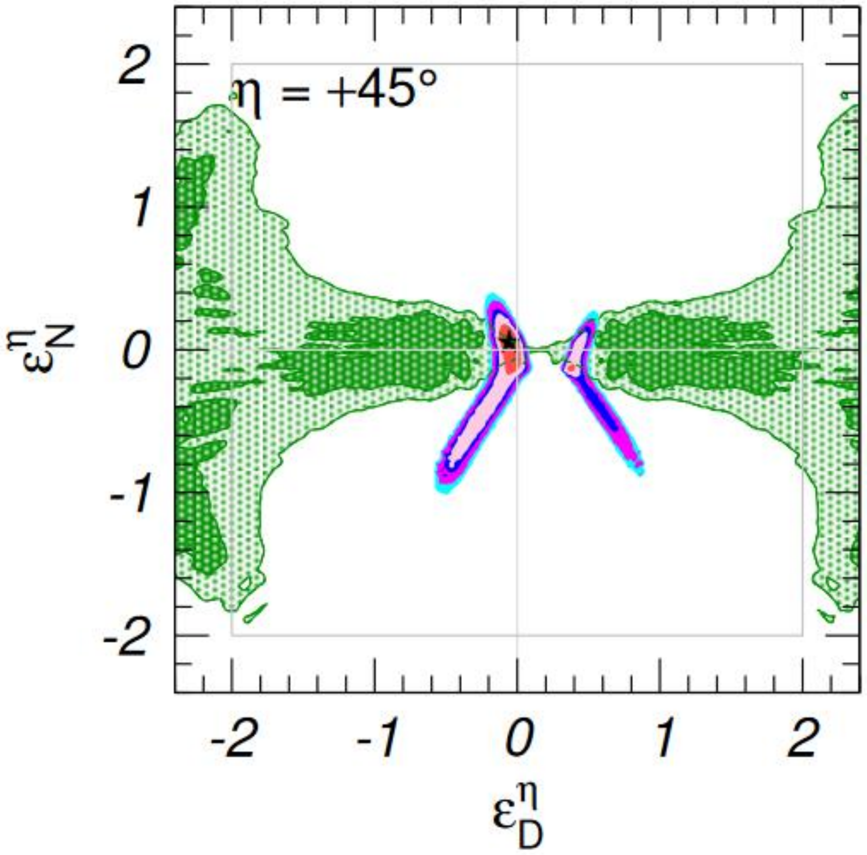
Potential Xe constraint

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



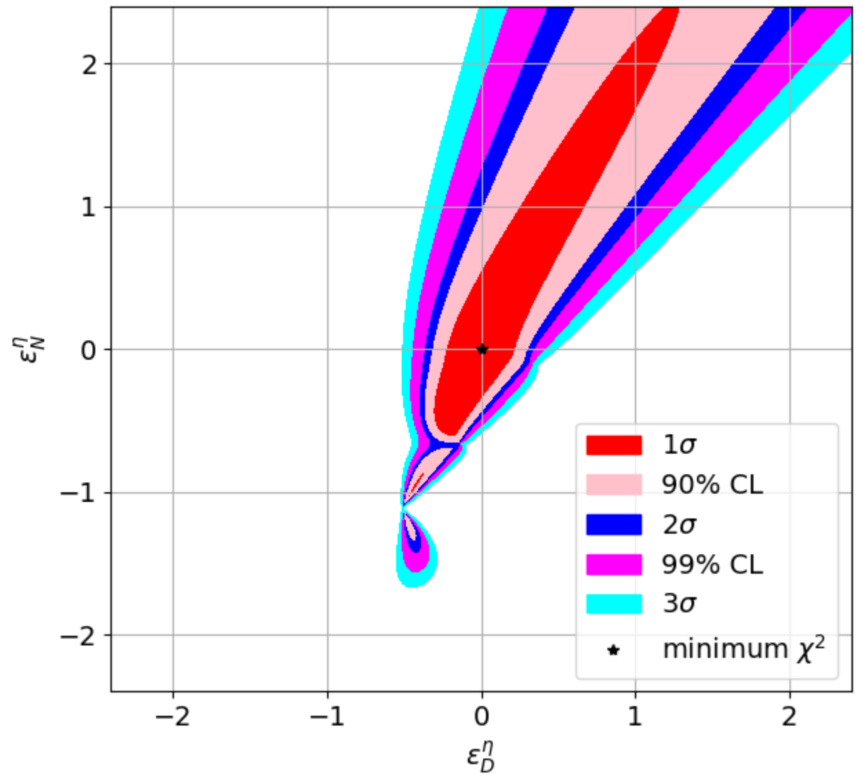
Comparison with current constraints

current limit



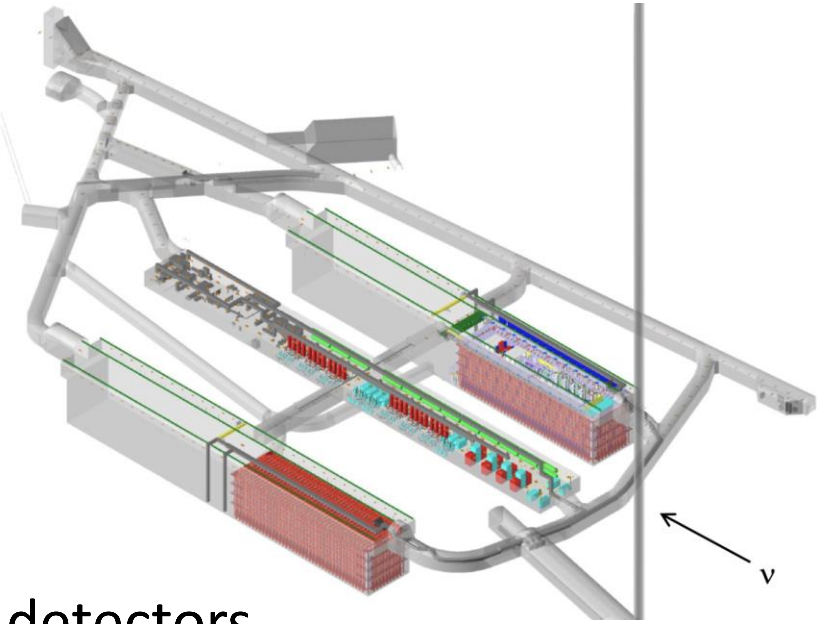
I. Esteban, M.C. Gonzalez-Garcia, M. Maltoni, I. Martinez-Soler, J. Salvado (2018) arXiv:1805.04530

Xe



Global fit is better overall,
but combining data may improve fit

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

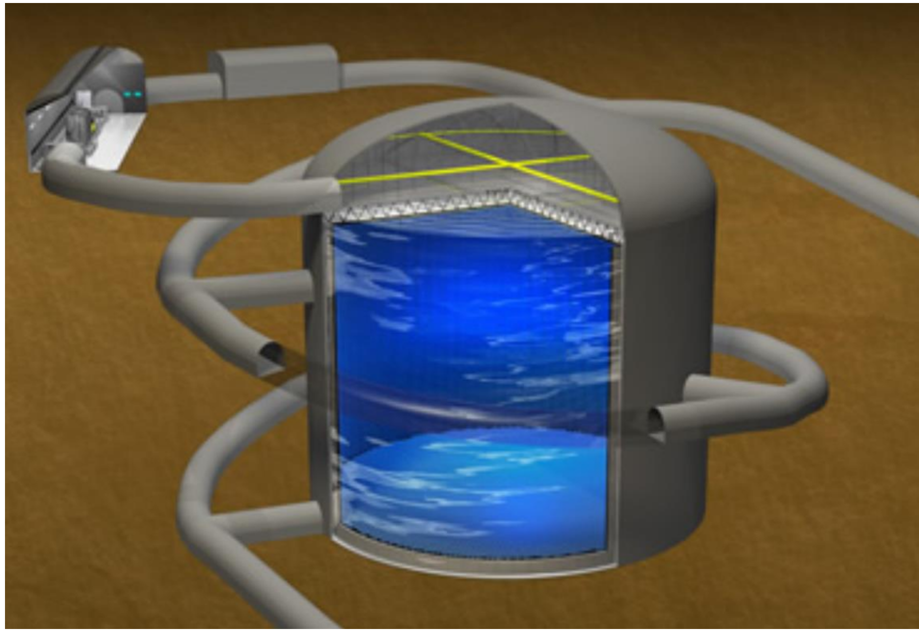


Future neutrino experiments

- 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

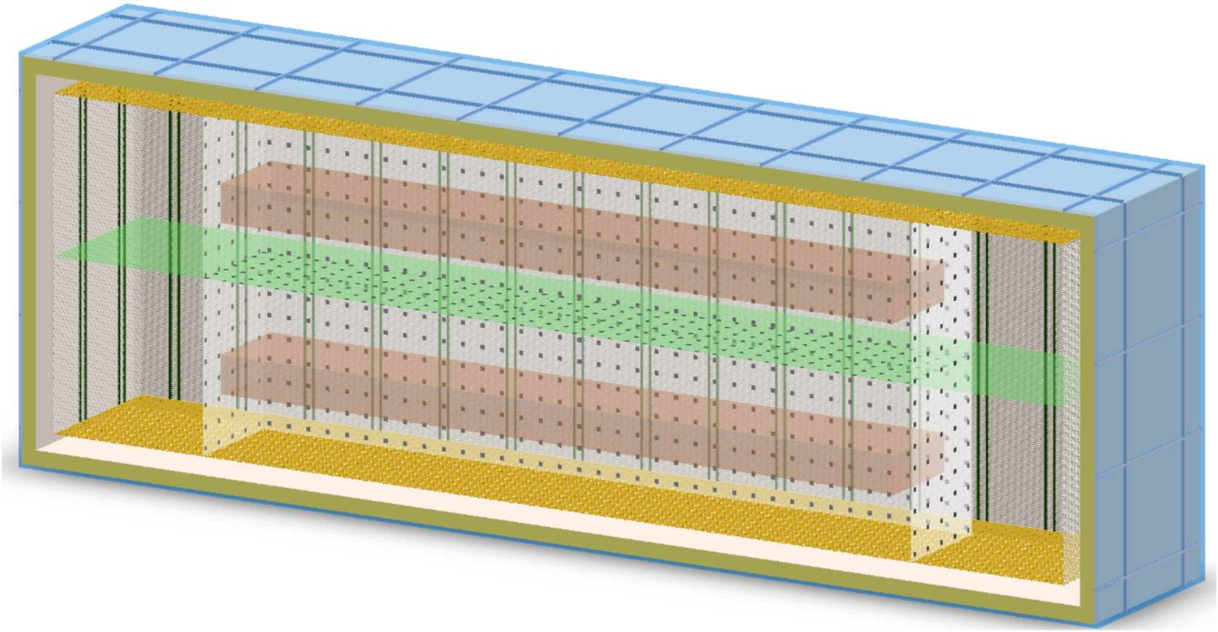


K. Abe et al. (2018)
arXiv:1805.04163

Low-background kt-scale Ar detector

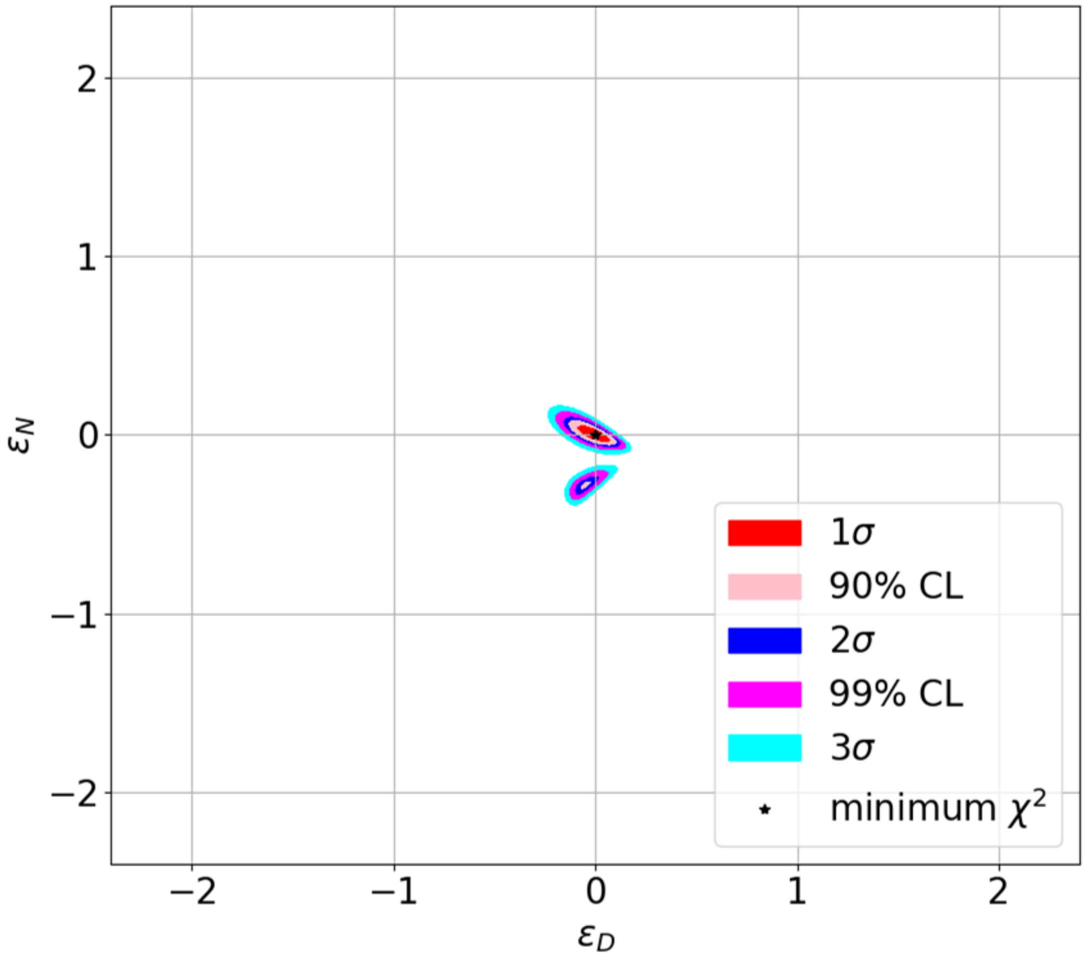
- Potential module for Deep Underground Neutrino Experiment
- Assume
  - 3 kt of Ar
  - 1 year of data
    - Early result
  - No backgrounds, perfect energy resolution
  - Energy threshold of 1 MeV

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



Potential future Ar constraint

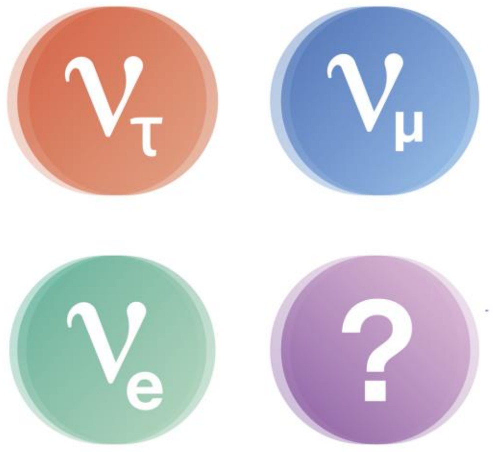
- May exclude significant part of parameter space
  - If we detect every neutrino, have perfect energy resolution, etc.



https://www.sanfordlab.org/article/why-dune-shedding-light-unification-natures-forces

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

A. Gando, et al. (2013)
arXiv:1303.4667

KamLAND result

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

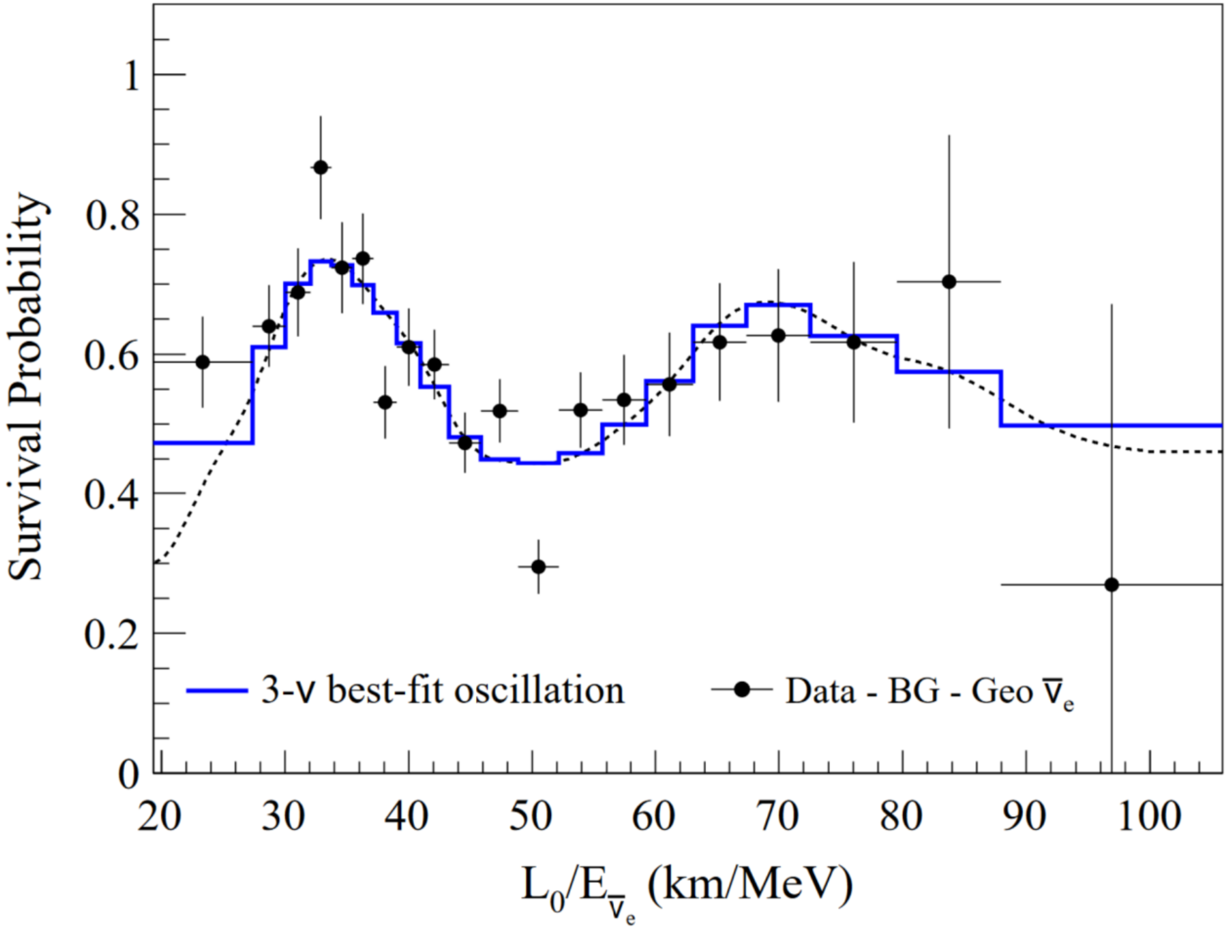
$$P_{ee}^{3\nu} = \cos^4\theta_{13}\widetilde{P}_{ee}^{2\nu} + \sin^4\theta_{13}$$

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

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

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

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



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

PDG 2020

Solar results

- Many solar-neutrino experiments
  - **Borexino**, **Super-K**, **SNO**, …
- Fit survival probability
  - $P_{ee}^{3\nu} = \cos^4\theta_{13}\, P_{ee}^{2\nu} + \sin^4\theta_{13}$
  - $P_{ee}^{2\nu} = \frac{1}{2}[1 + \cos 2\theta \cos 2\theta_m]$
  - $\cos 2\theta_m = \frac{\Delta m^2 \cos 2\theta - 2\sqrt{2} E G_F N_e}{[\Delta m^2]_{matter}}$
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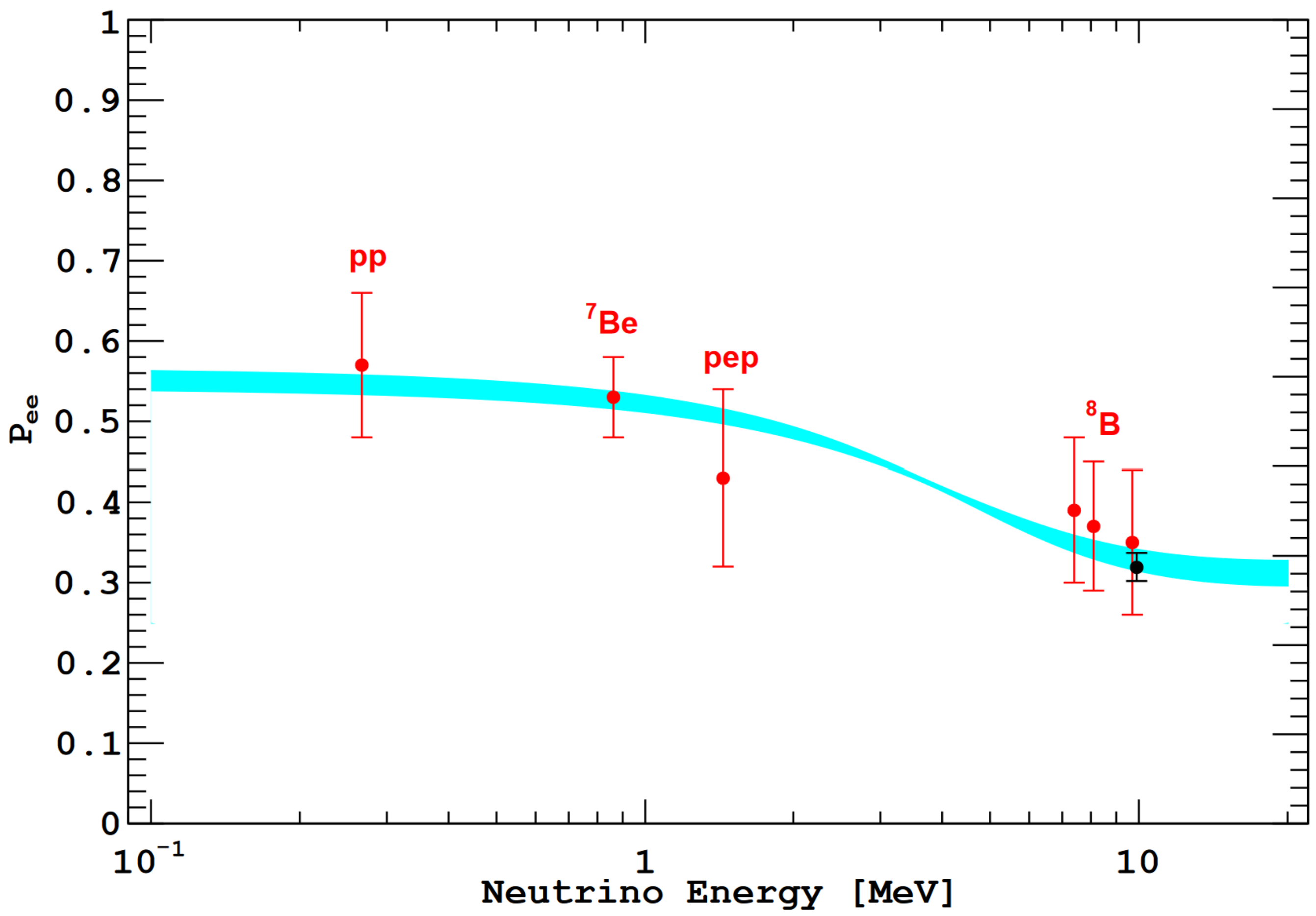
Illustration, not used in fit on Slide 4



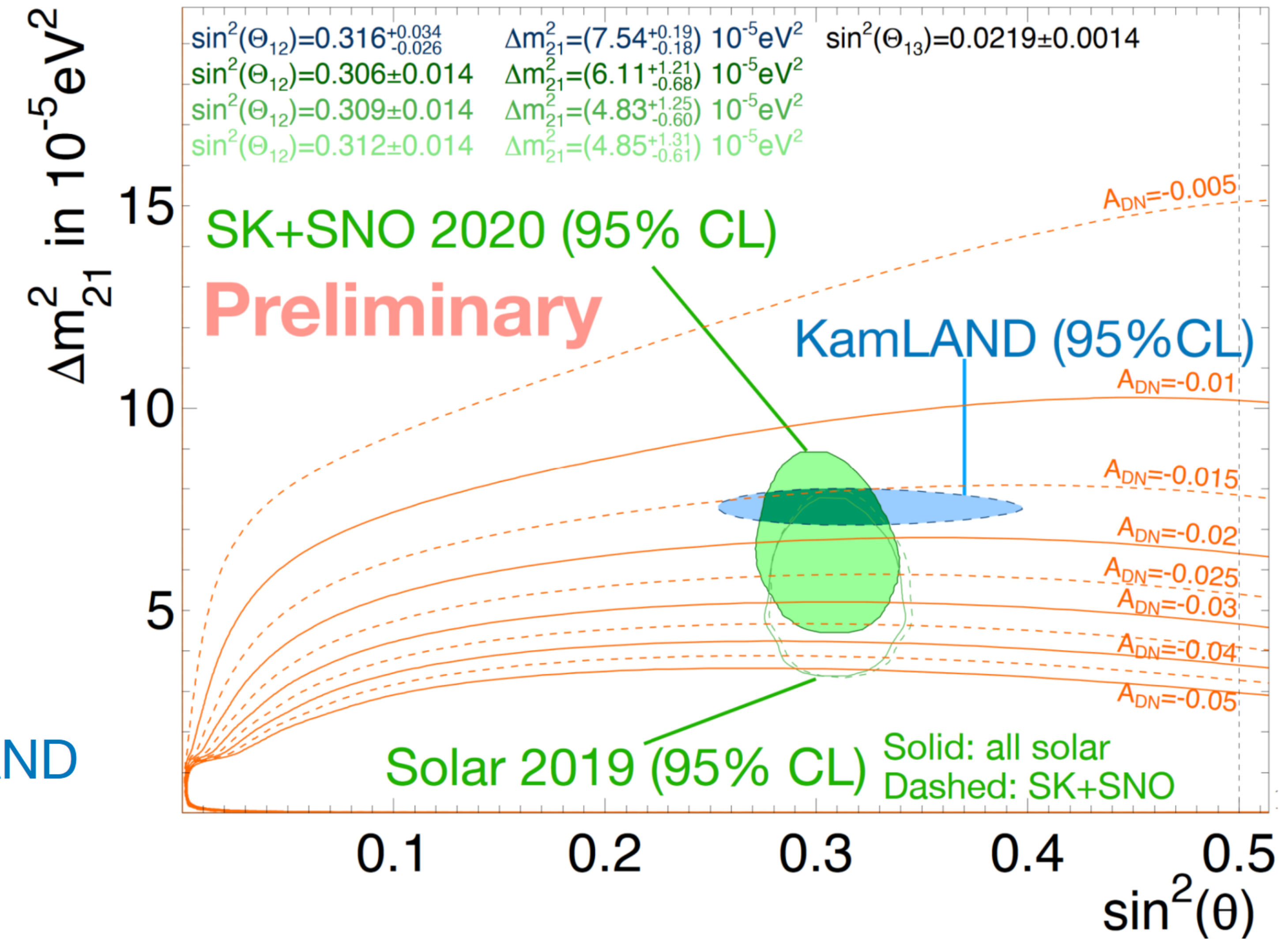
https://indico.fnal.gov/event/43209/contributions/187863/attachments/129474/159089/nakajima_Neutrino2020.pdf

Y. Nakajima, NEUTRINO2020

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 ν's

SK+SNO fit disfavors the KamLAND best fit value at ~1.4σ (was ~2σ)

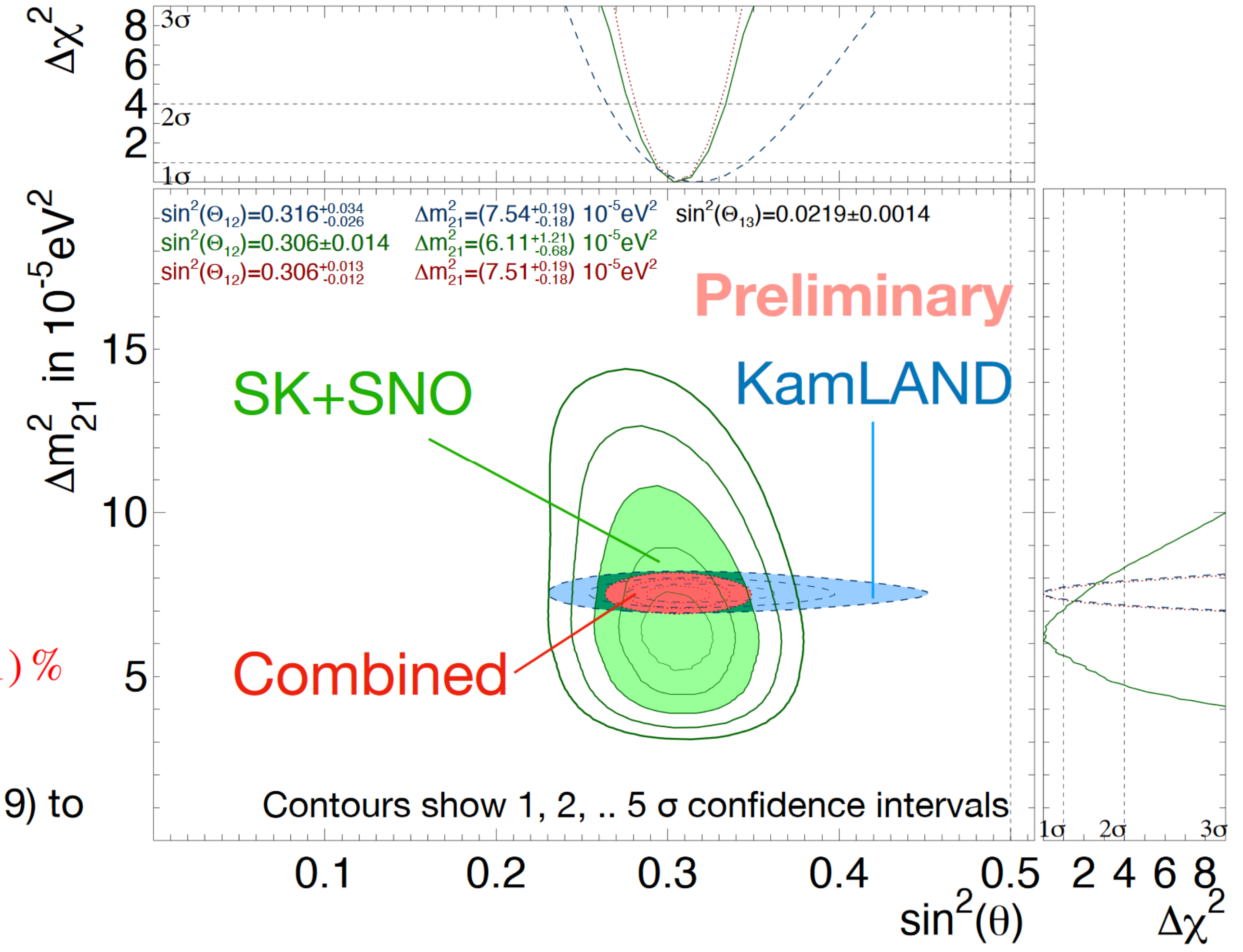


New Super-K solar oscillation results

	$\sin^2(\theta_{12})$	Δm^2_{21} [10^{-5} 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	$0.306^{+0.013}_{-0.012}$	$7.51^{+0.19}_{-0.18}$

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

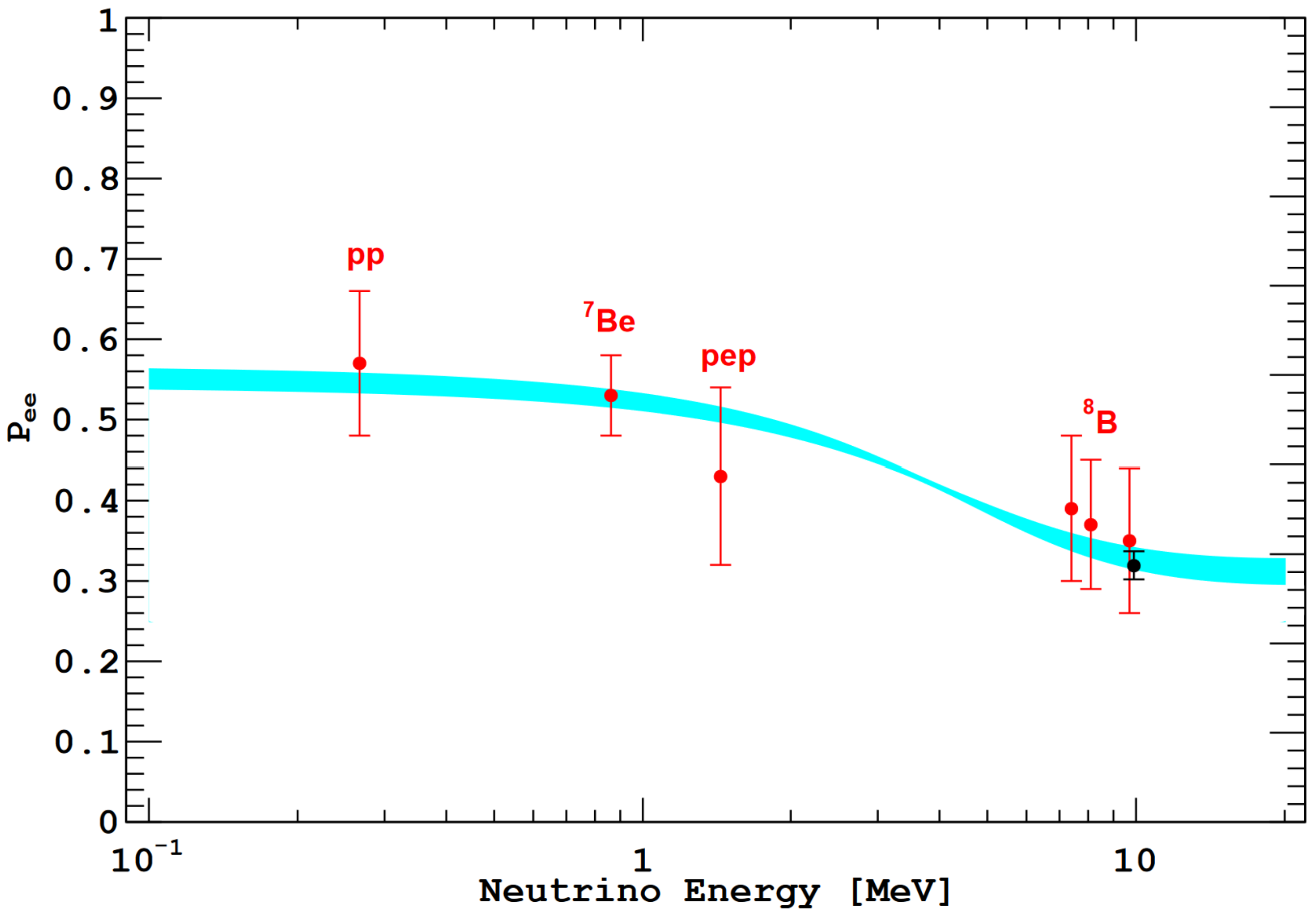
Best fit value of solar Δm^2_{21} changed from 4.8 x 10^{-5} eV^2 (2019) to 6.1 x 10^{-5} eV^2



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

Matter oscillations

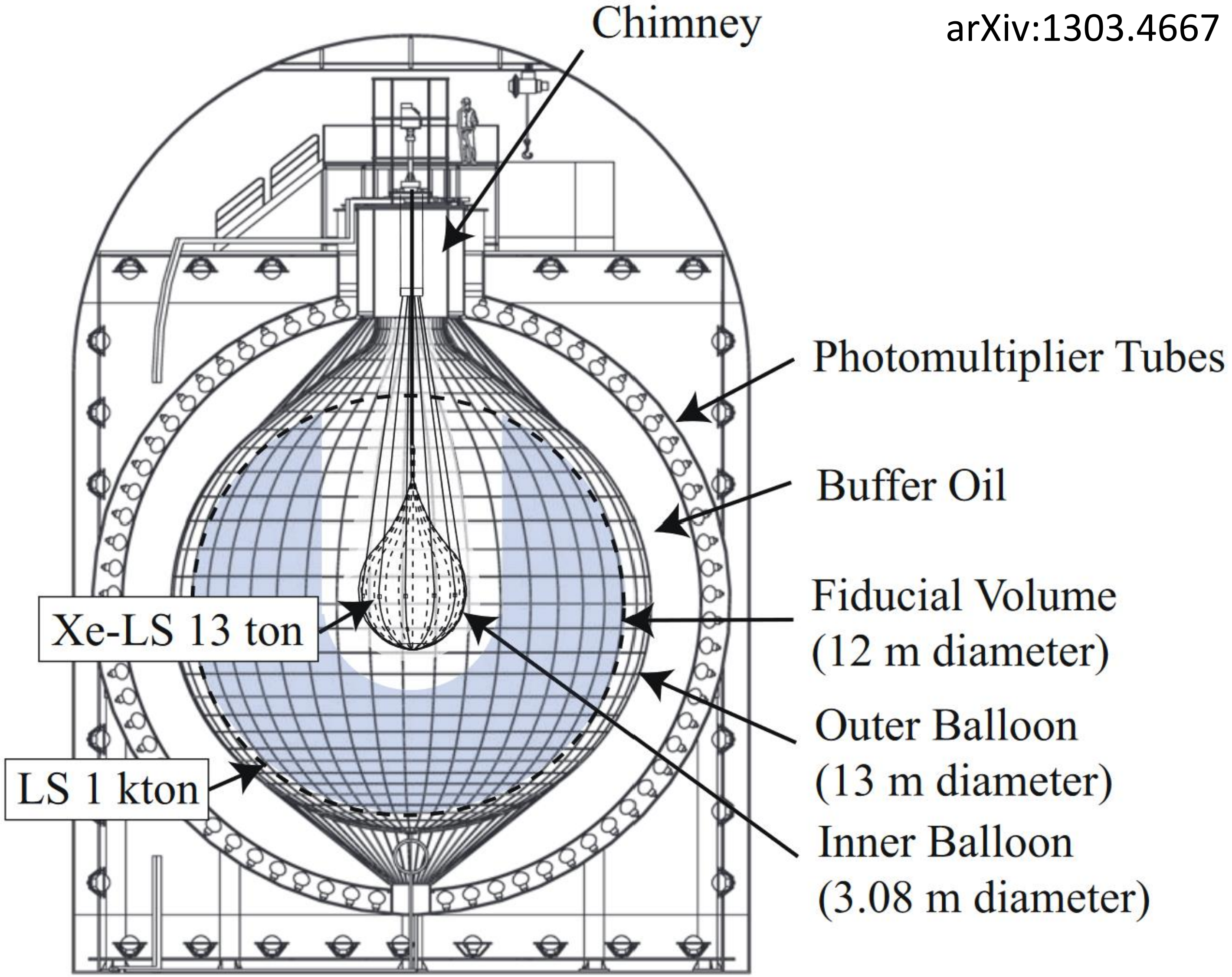
- Survival probability depends on energy
- Measurements agree with theory
- Best oscillation fit from SNO+SK (**black**)
- Need better statistics and more measurements in transition region



A. Gando, et al. (2013)
arXiv:1303.4667

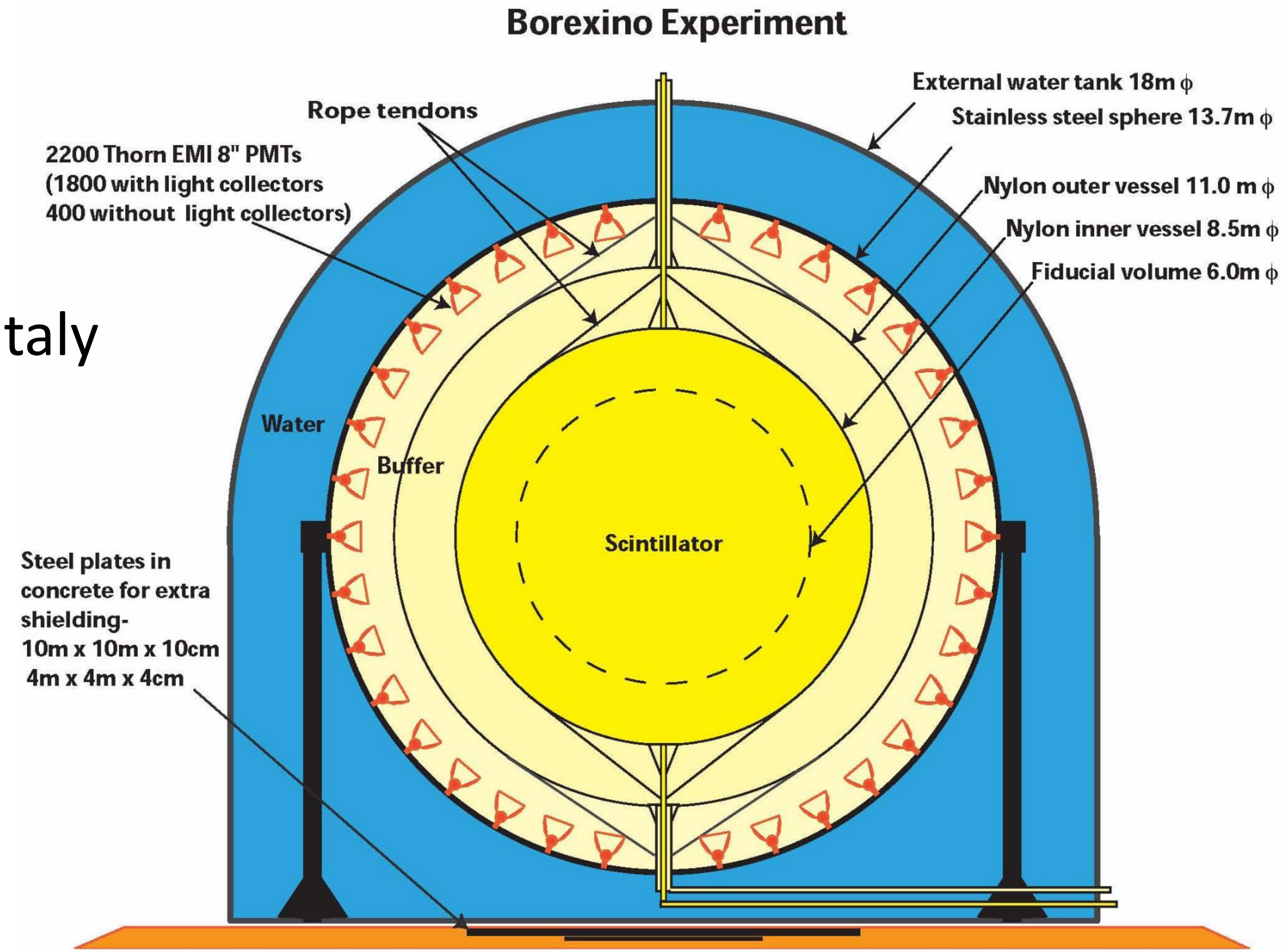
KamLAND

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

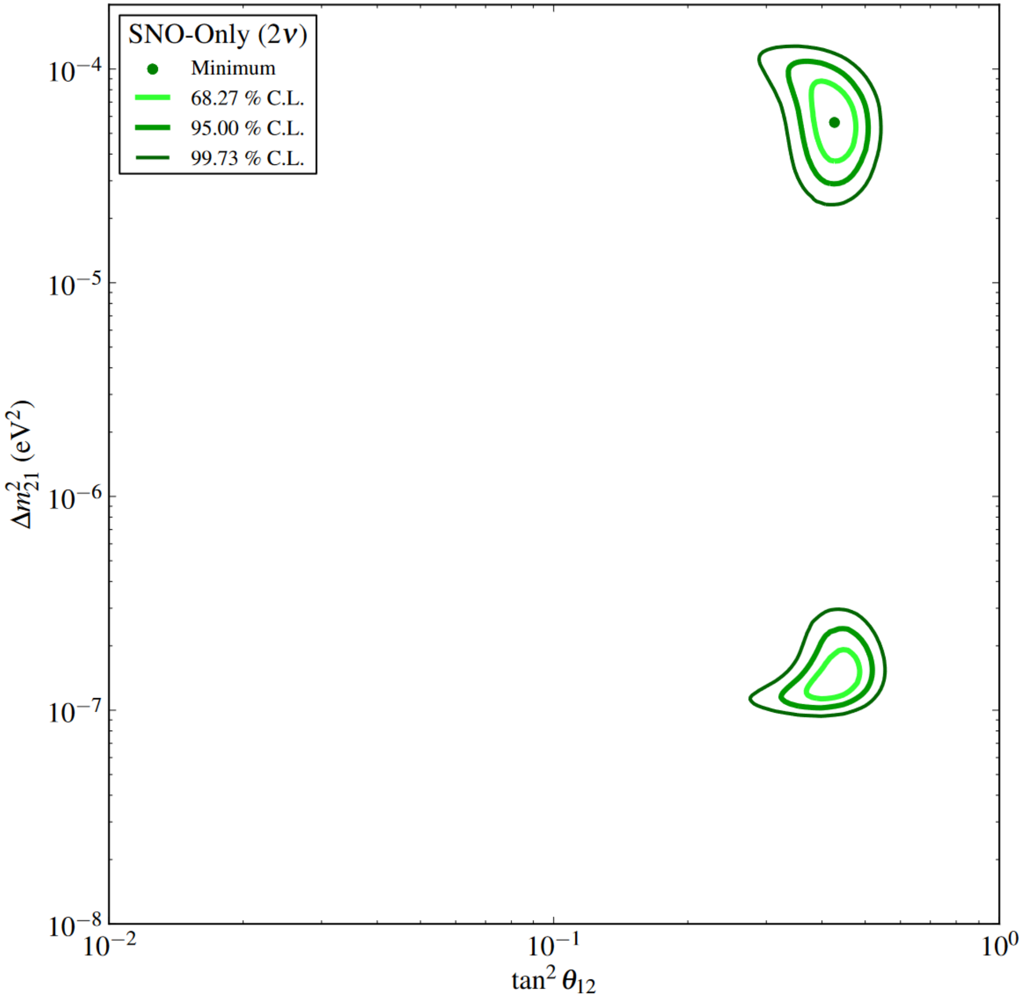


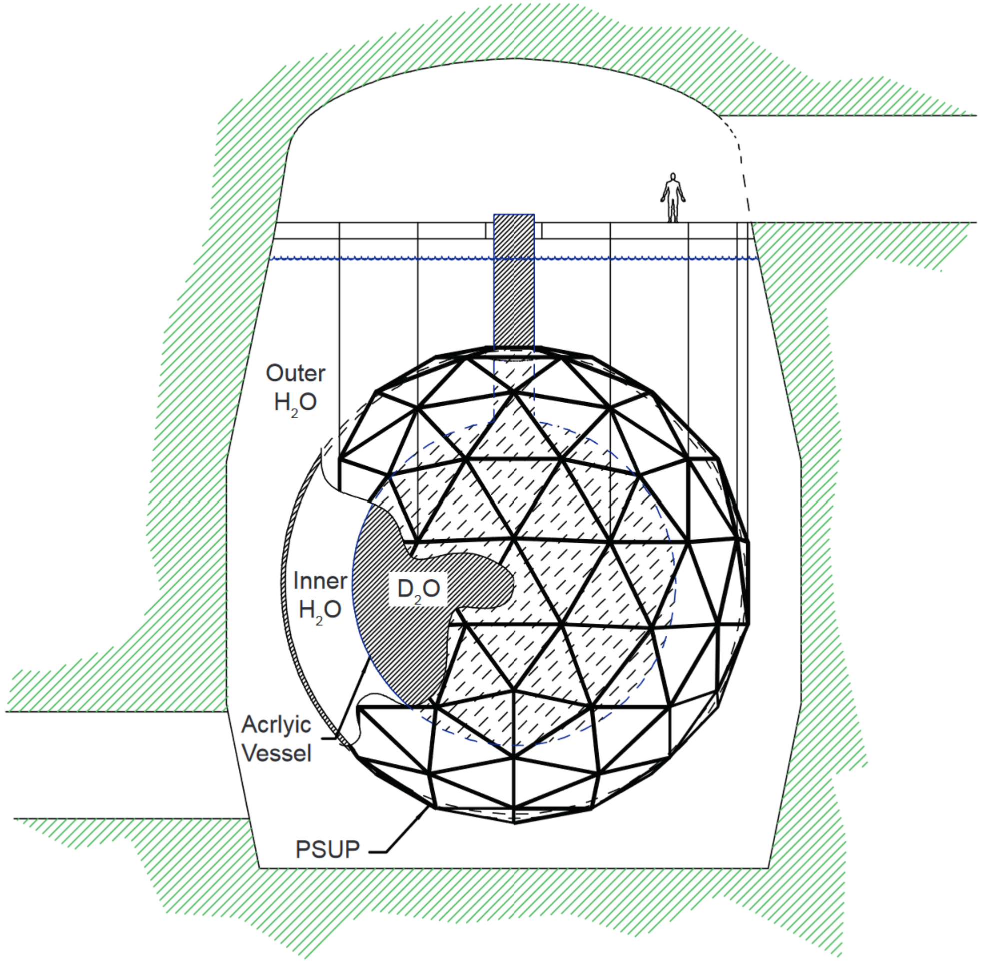
Borexino

- 278 t of organic scintillator in Gran Sasso, Italy



SNO



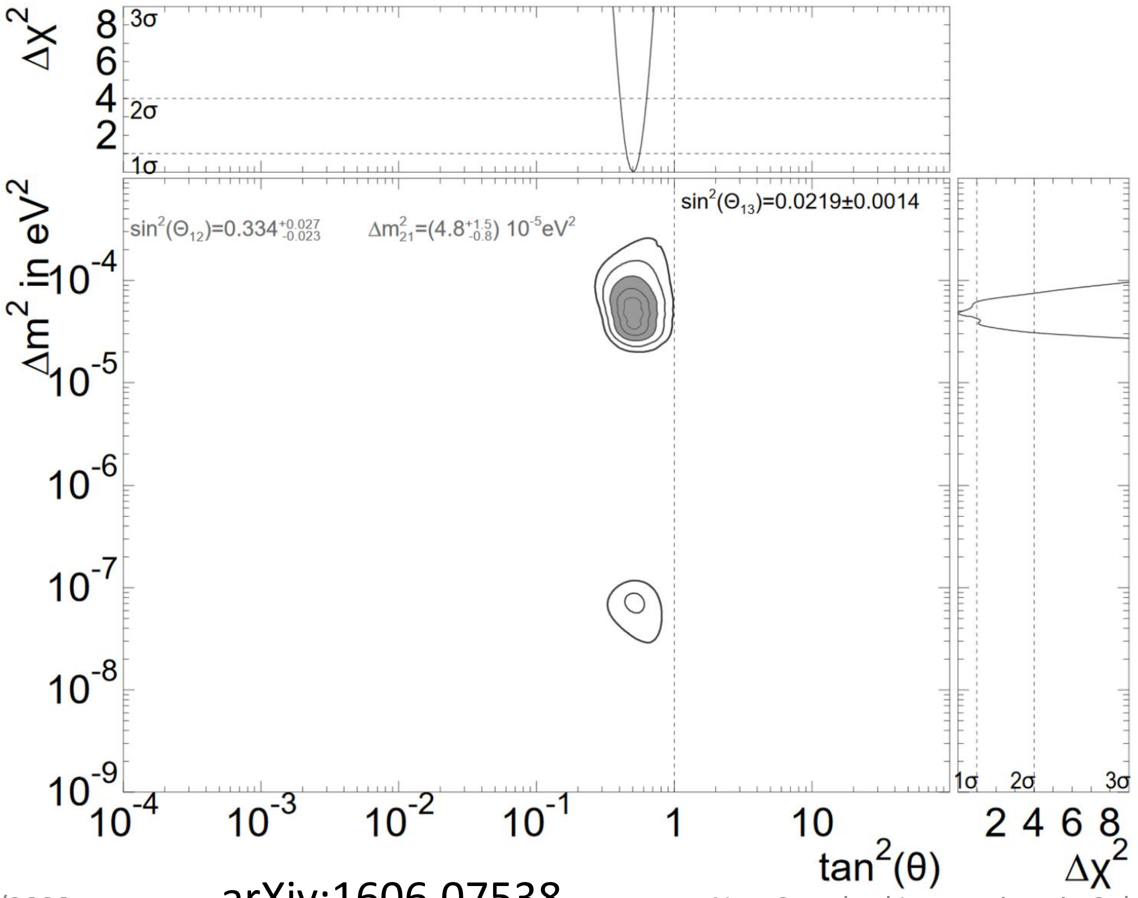


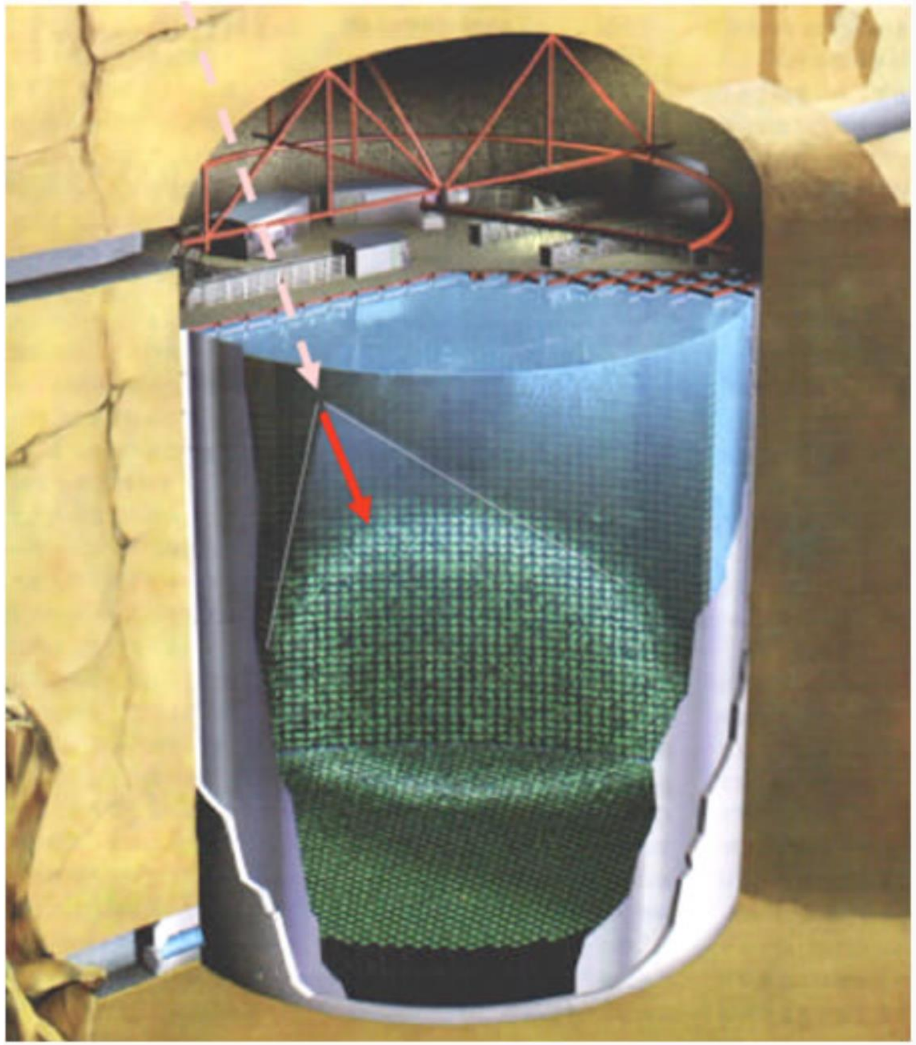
- 1 kt of heavy water in Sudbury, Canada
- Measured both ν_e and total ν fluxes

http://www-sk.icrr.u-tokyo.ac.jp/sk/detector/cherenkov-e.html

Super-Kamiokande

- 32.5 kt of water in Kamioka, Japan

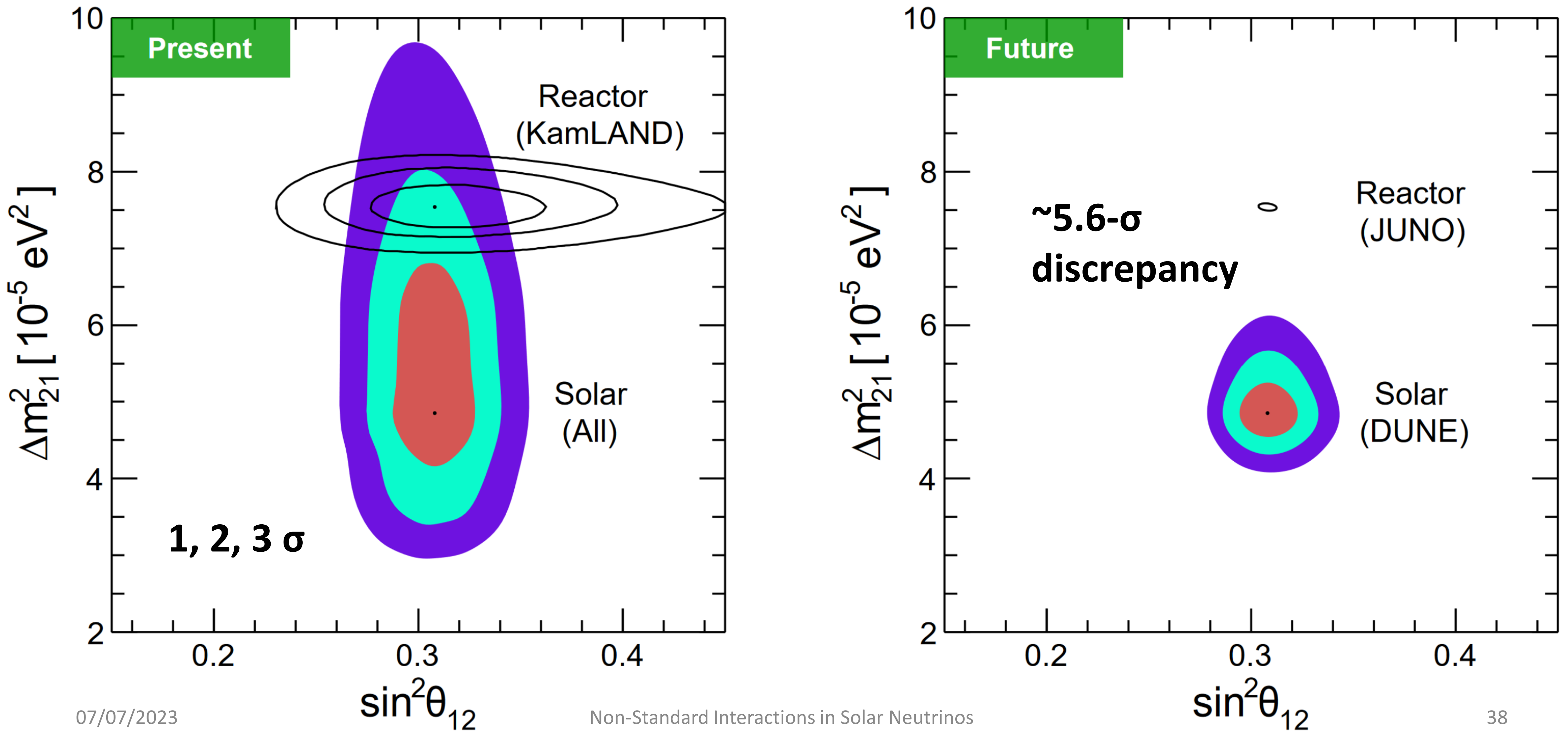




arXiv:1606.07538

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

Possible anomaly in ~10 years



O.G. Miranda, M.A. Tórtola, J.W.F. Valle (2006)
arXiv:hep-ph/0406280

Neutral-current NSI in Sun

- 2-flavor model

SM vacuum oscillations + matter effect **NSI**

- $H = \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta + \sqrt{2}G_F N_e & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix} + \sqrt{2}G_F N_d \begin{pmatrix} 0 & \varepsilon \\ \varepsilon & \varepsilon' \end{pmatrix}$

$\varepsilon^{uP}_{\alpha\beta} = 0$

$\varepsilon^{dP}_{\mu\beta} = 0$

$\varepsilon = -\sin\theta_{23}\,\varepsilon^{dV}_{e\tau}$

$\varepsilon' = \sin^2\theta_{23}\,\varepsilon^{dV}_{\tau\tau} - \varepsilon^{dV}_{ee}$

- Measurement: $P(\nu_e \to \nu_e) = \frac{1}{2}[1 + \cos 2\theta \cos 2\theta_m]$
  - $\cos 2\theta_m = \frac{\Delta m^2 \cos 2\theta - 2\sqrt{2}EG_F(N_e - \varepsilon' N_d)}{[\Delta m^2]_{matter}}$
    - $[\Delta \mathrm{m}^2]^2_{matter} = [\Delta m^2 \cos 2\theta - 2\sqrt{2}EG_F(N_e - \varepsilon' N_d)]^2 + [\Delta \mathrm{m}^2 \sin 2\theta + 4\sqrt{2}\varepsilon E G_F N_d]^2$

How well could DUNE do?

- SNO+SK detected ~80,000 ν's

- Assume best-case 15,000 solar ν's per 10 kt·year detected in DUNE
  - $E_{\nu}^{mean} = 8$ MeV ($E_{vis}^{threshold} = 3 - 4$ MeV)
  - Ignore systematics

- Assume SNO+SK uncertainties for 80,000 solar ν'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 σ_{SNO+SK}
40 kt·years	1 (4 modules)	0.75	1.2 σ_{SNO+SK}
160 kt·years	4 (4 modules)	3	0.58 σ_{SNO+SK}
400 kt·years	10 (4 modules)	7.5	0.37 σ_{SNO+SK}
1,600 kt·years	40 (4 modules)	30	0.18 σ_{SNO+SK}

Statistical analysis for DUNE

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

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

$$T_e^{\mathrm{max}}(E_\nu) = \frac{2\,E_\nu^2}{m_e + 2\,E_\nu}$$

$$\sigma_0 = \frac{2\,G_\mathrm{F}^2\, m_e^2}{\pi} \simeq 88.06 \times 10^{-46}\,\mathrm{cm}^2$$

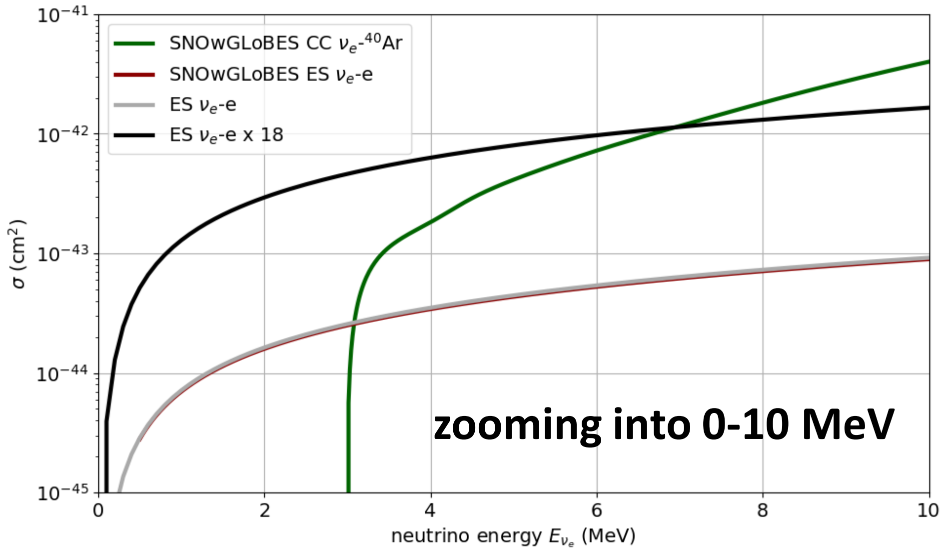
$m_e = 0.511$ MeV

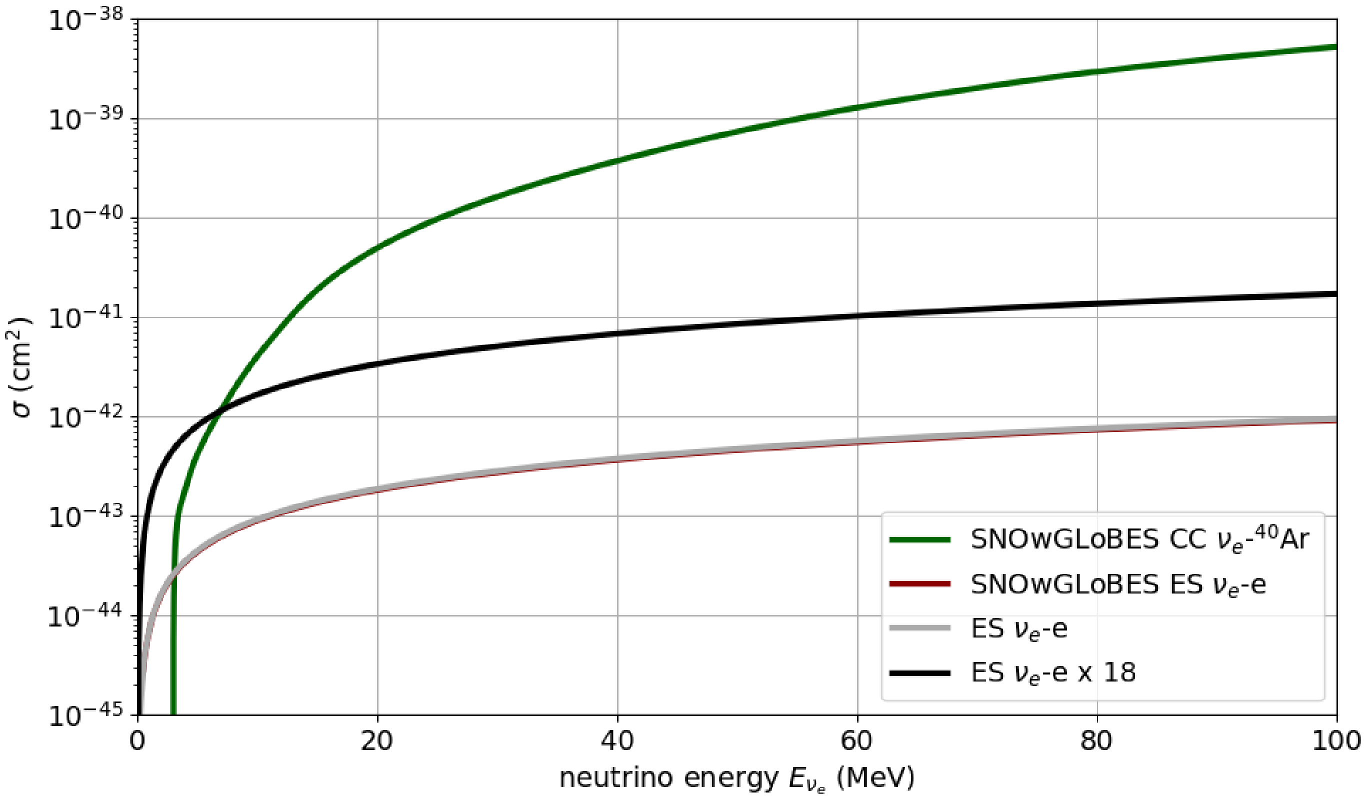
$$g_1^{(\nu_e)} = g_2^{(\bar{\nu}_e)} = 1 + \frac{g_V^l + g_A^l}{2} = 1 + g_L^l = \frac{1}{2} + \sin^2\vartheta_\mathrm{W} \simeq 0.73$$

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

Elastic scattering of solar neutrinos in DUNE

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

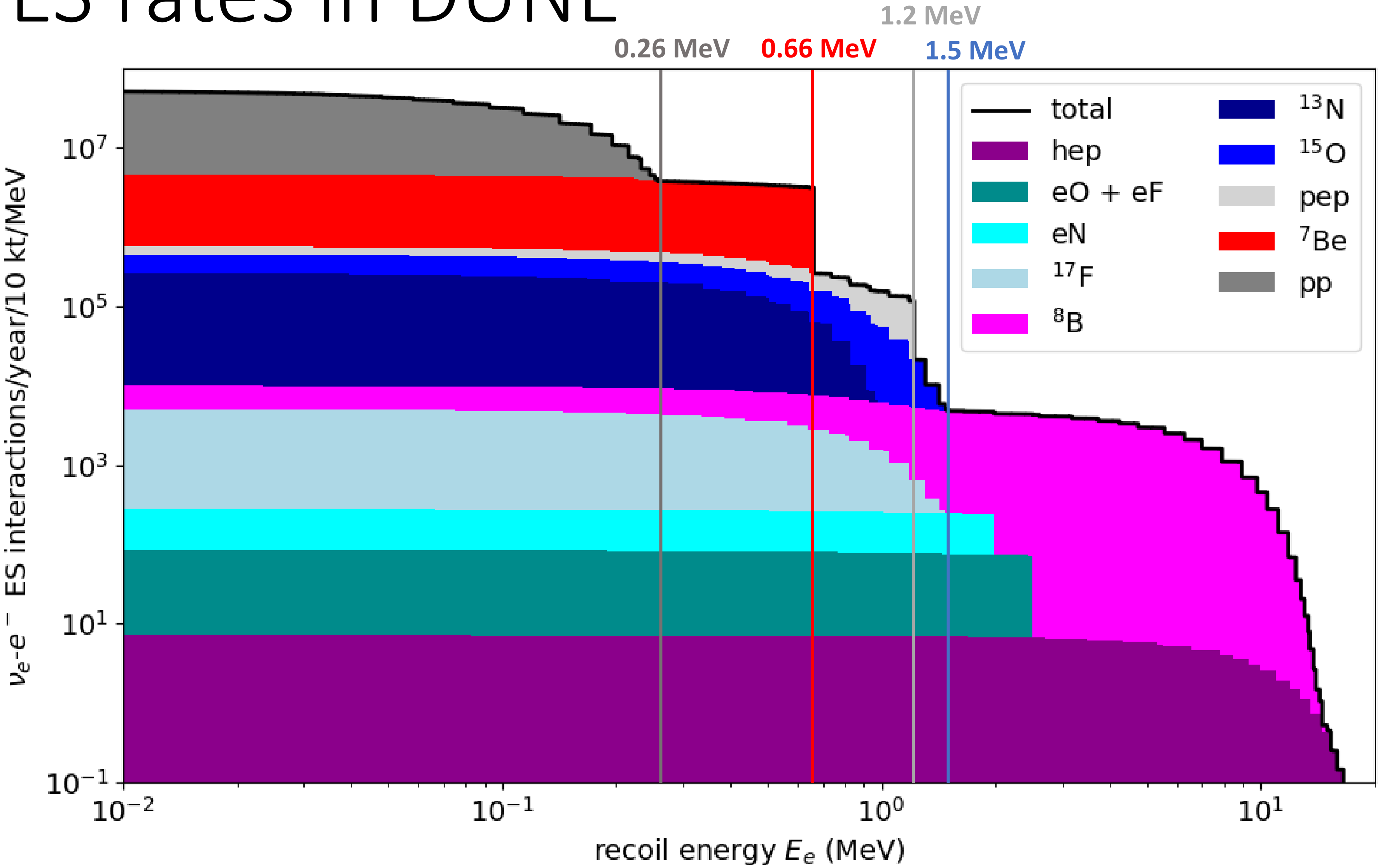




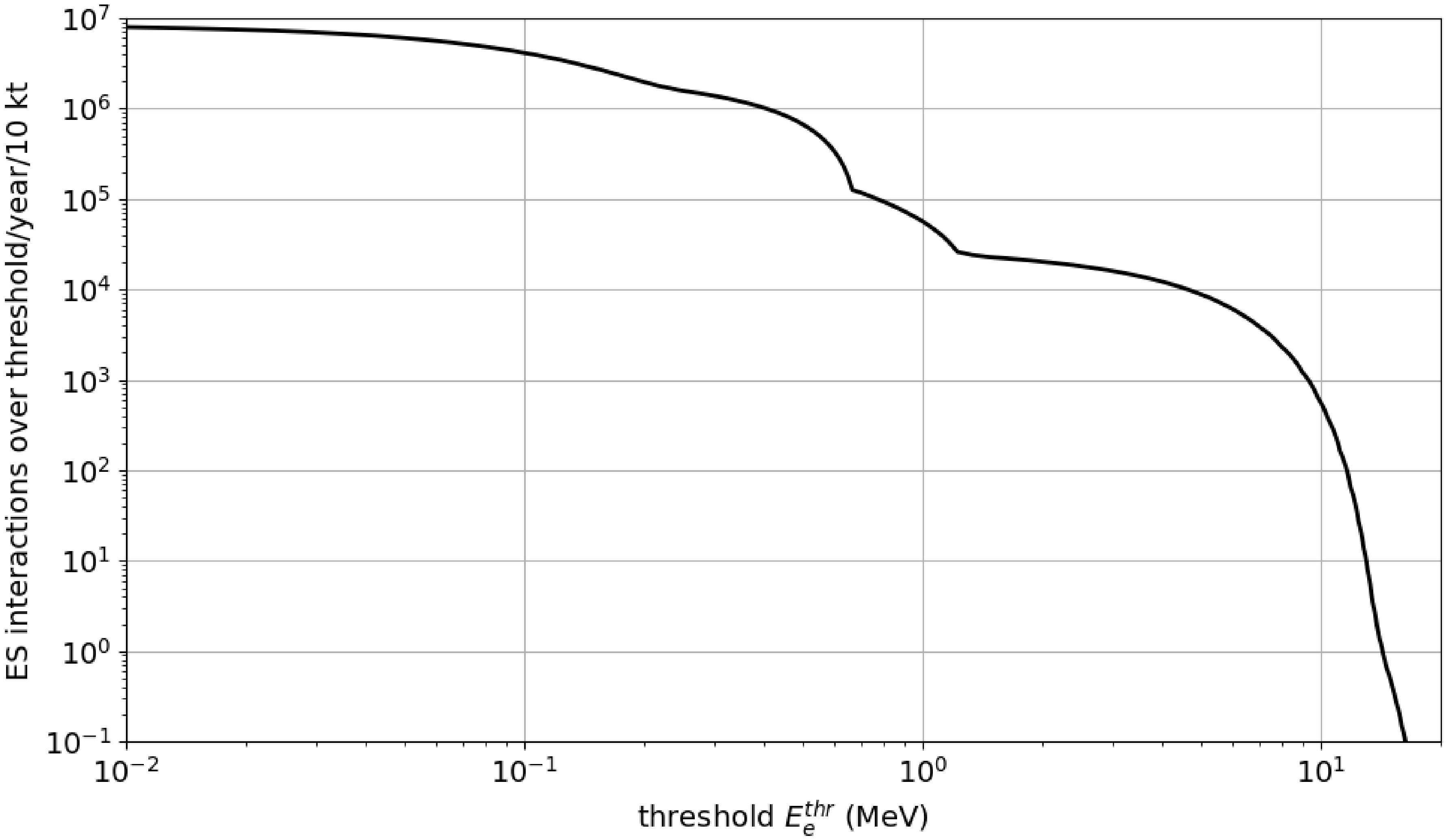
CC and 18·ES cross sections cross at ~7 MeV

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



threshold (E_e)	rate /10 kt-year	neutrinos
10 MeV	566	hep, ^8B
8 MeV	2,300	hep, ^8B
5 MeV	8,850	hep, ^8B
1 MeV	56,600	hep, ^8B, eO, eF, eN, ^{17}F, ^{15}O, pep
0.1 MeV	4,130,000	All

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

Parameter definitions

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

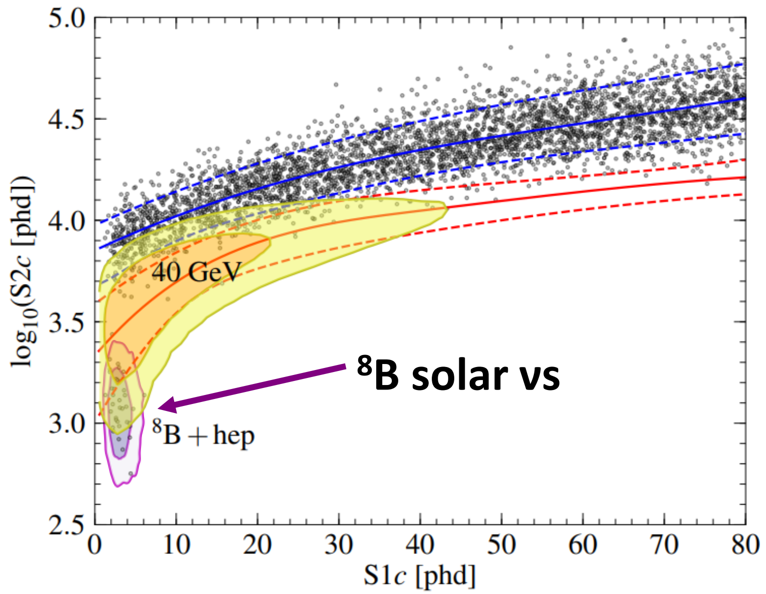
$$\begin{aligned} \varepsilon_D^\eta &= c_{13} s_{13} \ \text{Re}\big(s_{23}\, \varepsilon_{e\mu}^\eta + c_{23}\, \varepsilon_{e\tau}^\eta\big) - \big(1 + s_{13}^2\big)\, c_{23} s_{23} \ \text{Re}\big(\varepsilon_{\mu\tau}^\eta\big) \\ &\quad - \frac{c_{13}^2}{2}\big(\varepsilon_{ee}^\eta - \varepsilon_{\mu\mu}^\eta\big) + \frac{s_{23}^2 - s_{13}^2 c_{23}^2}{2}\big(\varepsilon_{\tau\tau}^\eta - \varepsilon_{\mu\mu}^\eta\big) \\ \varepsilon_N^\eta &= c_{13}\big(c_{23}\, \varepsilon_{e\mu}^\eta - s_{23}\, \varepsilon_{e\tau}^\eta\big) + s_{13}\left[s_{23}^2\, \varepsilon_{\mu\tau}^\eta - c_{23}^2\, \varepsilon_{\mu\tau}^{\eta *} + c_{23} s_{23}\big(\varepsilon_{\tau\tau}^\eta - \varepsilon_{\mu\mu}^\eta\big)\right] \end{aligned}$$

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

$$\varepsilon_{\alpha\beta}^f \equiv \varepsilon_{\alpha\beta}^{f,L} + \varepsilon_{\alpha\beta}^{f,R} = \varepsilon_{\alpha\beta}^\eta\, \xi^f \qquad \xi^p = \sqrt{5}\cos\eta$$

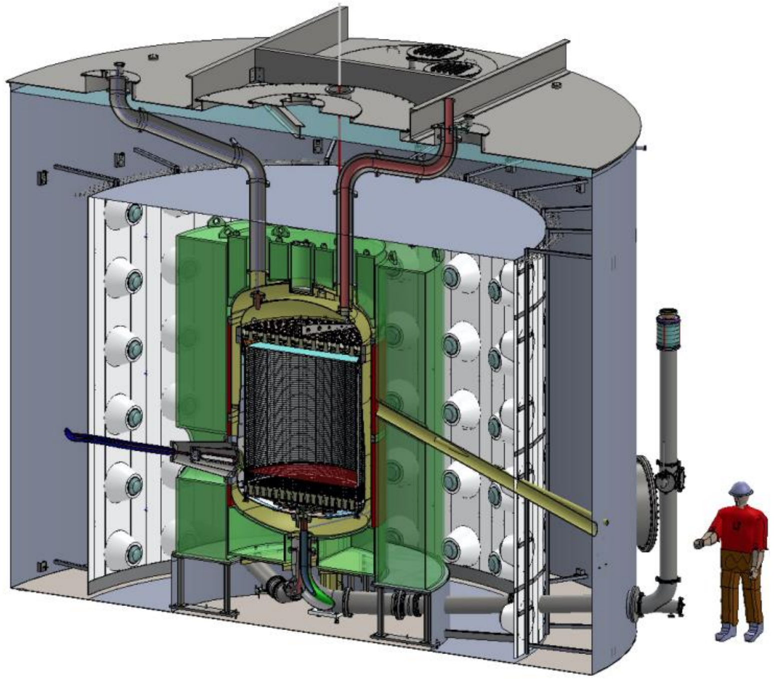
$$\xi^n = \sqrt{5}\sin\eta$$

Neutrinos in LZ



- ^{8}B neutrinos via CEvNS
  - CEvNS (nuclear) recoils – look exactly like WIMP recoils ($m_\chi \approx 6$ GeV)
  - Expect few events
  - Have not been observed yet
    - important measurement

- Many other neutrinos will interact in LZ
  - What can we learn from them?



D.S. Akerib et al. (2018), arXiv:1802.06039 http://www.world-nuclear.org/uploadedImages/org/info/Country_Profiles/Countries_T-Z/us_nuclear_map.jpg

map of nuclear reactors in USA

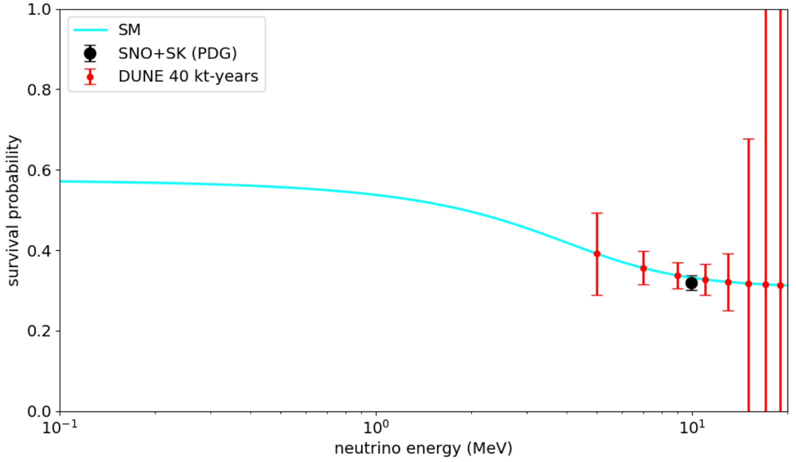
What can LZ do?

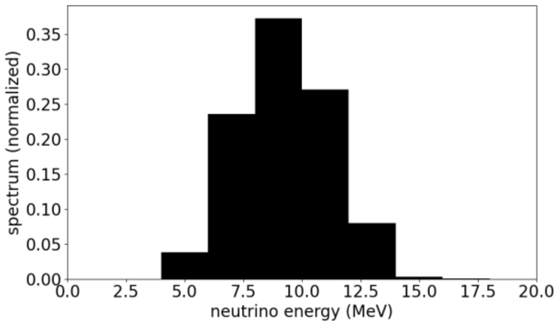
- Not seeing reactor neutrinos
  - Not many reactors around
  - Detector not big enough
  - Cannot improve KamLAND measurement

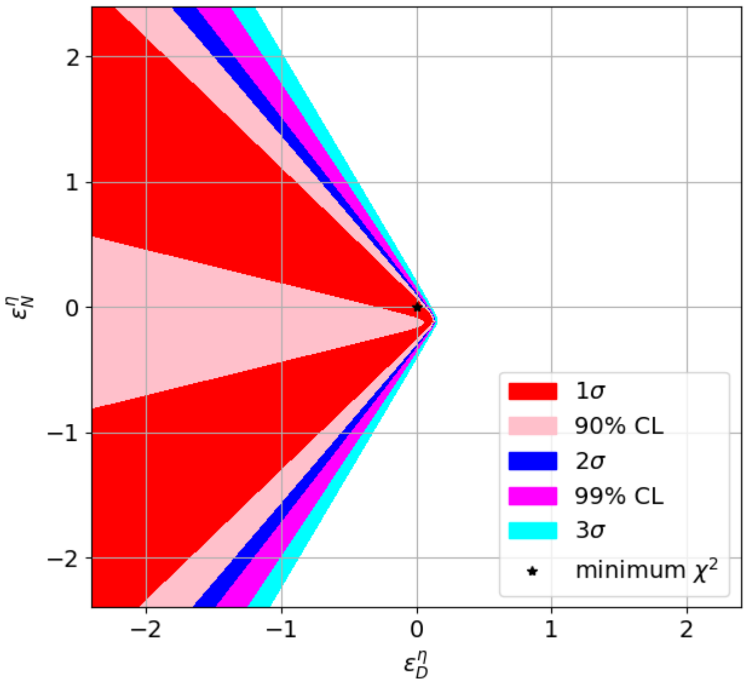
- Expect to see many solar neutrinos
  - More matter effect from high solar density
  - Interested to pursue this

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





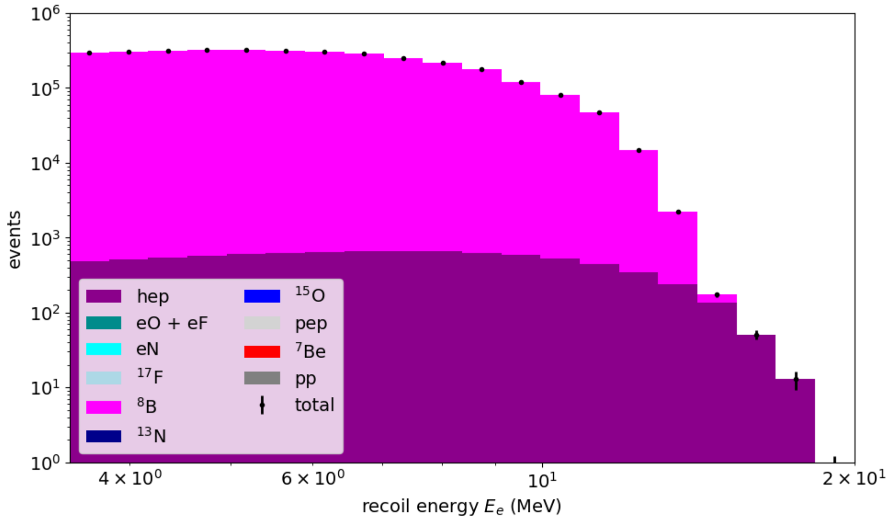


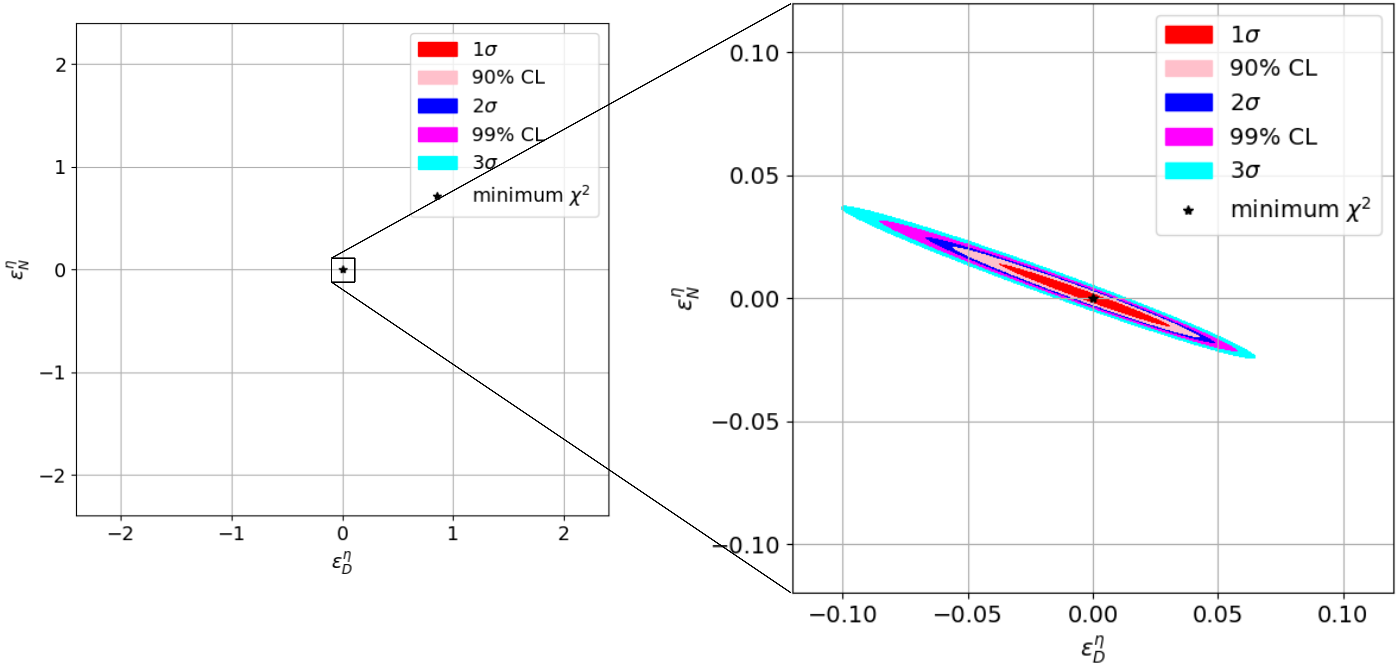
Not strong early constraint due to high threshold

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)