



A Direct Detection View of the Neutrino NSI Landscape

arXiv:2302.12846

Magnificent CE ν NS 2023

Dorian Amaral¹ David G. Cerdeño² Andrew Cheek³ Patrick Foldenauer²

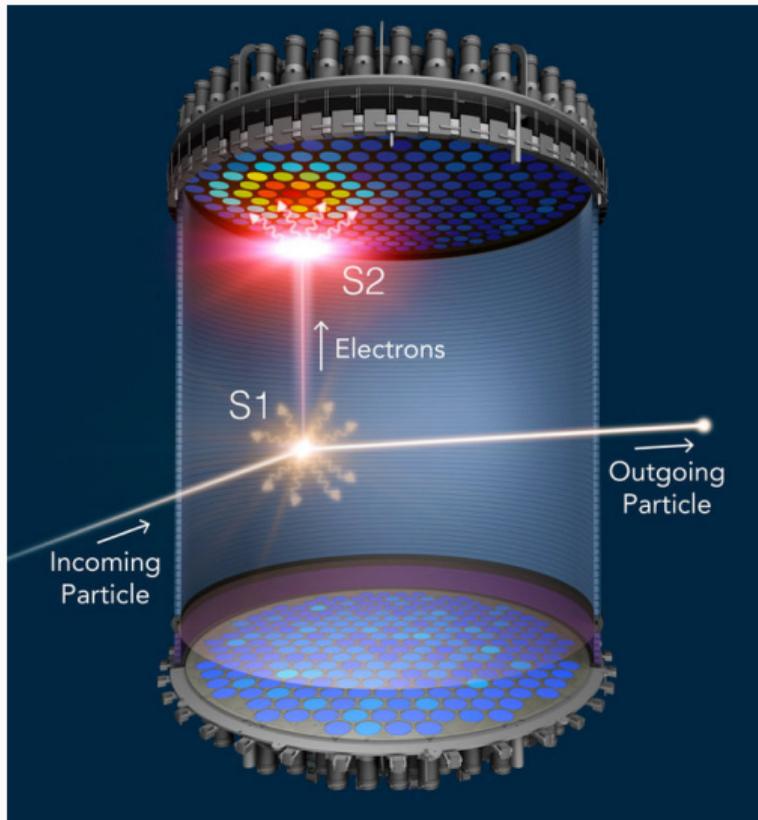
March 23rd, 2023

¹Rice University ²IFT, Madrid ³Astrocent, Warsaw

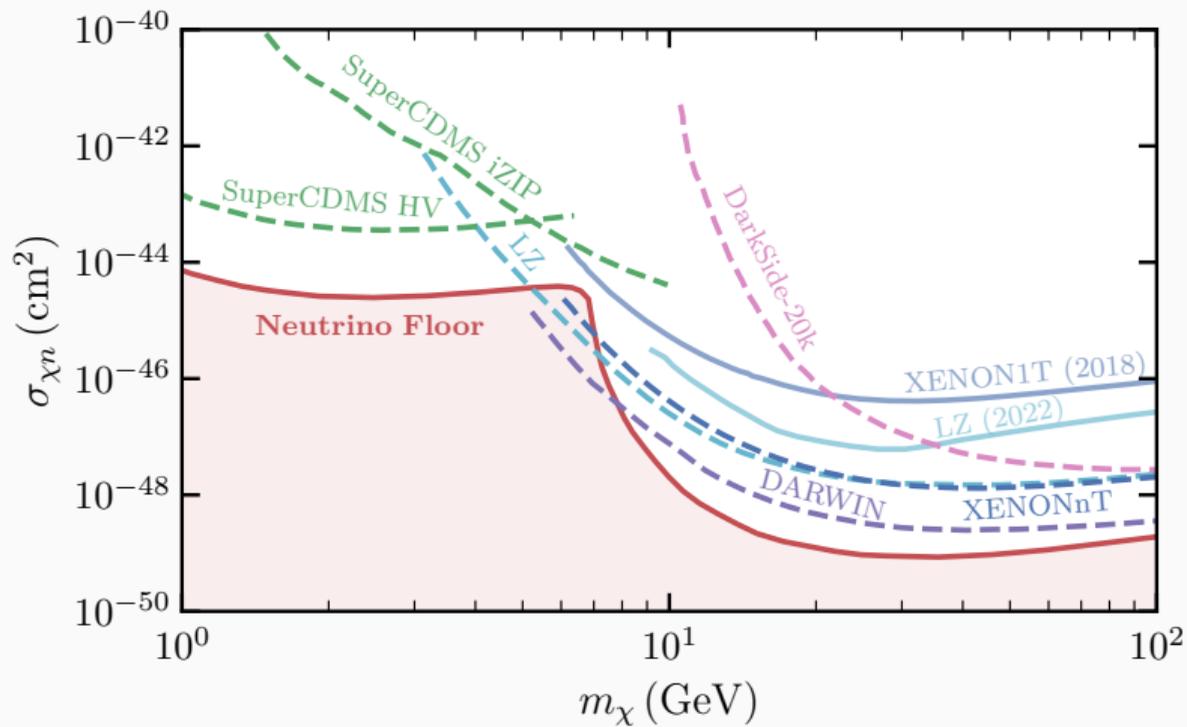
New Neutrino Physics is Already Here!

The Direct Detection Experiment Time Projection Chamber

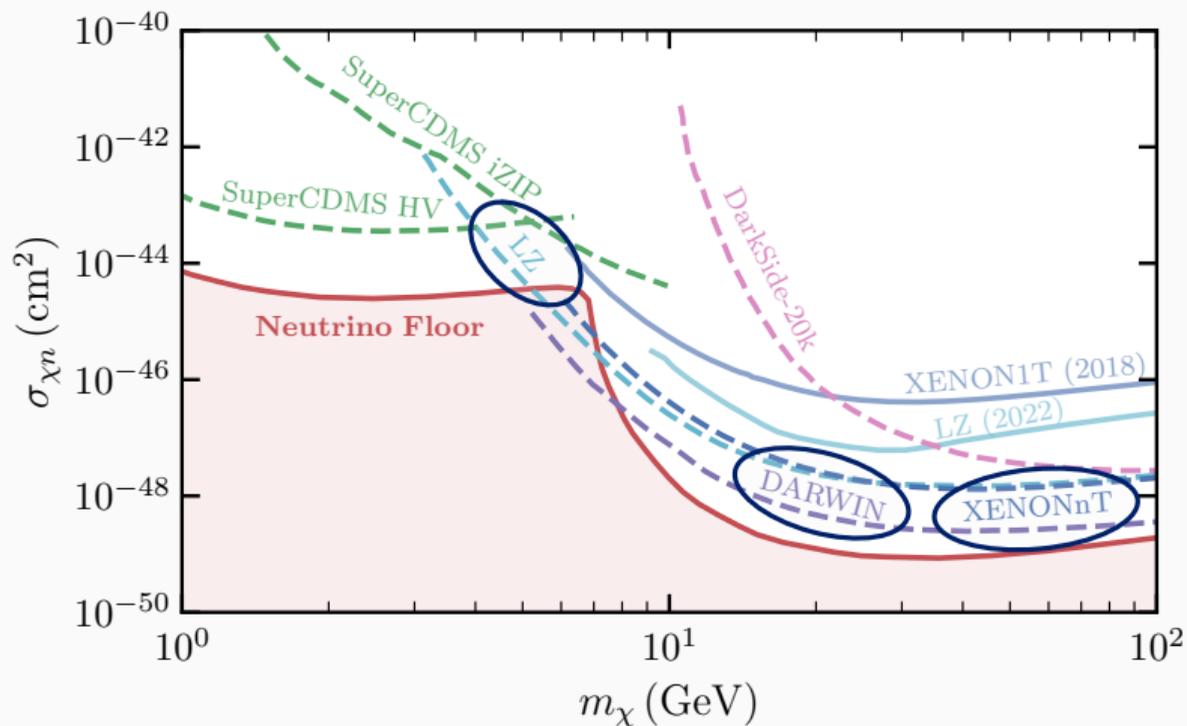
Vitaly A. Kudryavtsev ICNFP contrib.



Direct Detection Experiments: A New Era of Neutrino Experiments

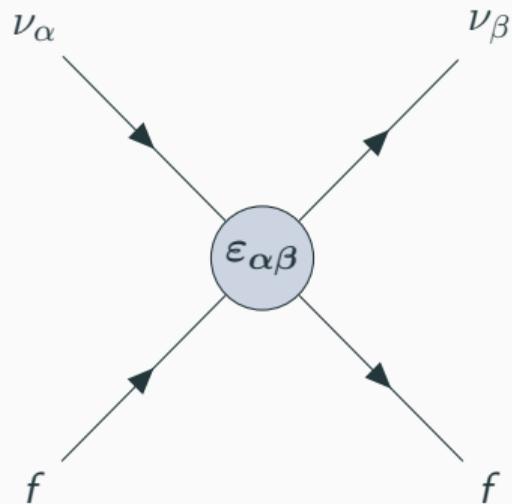


Direct Detection Experiments: A New Era of Neutrino Experiments



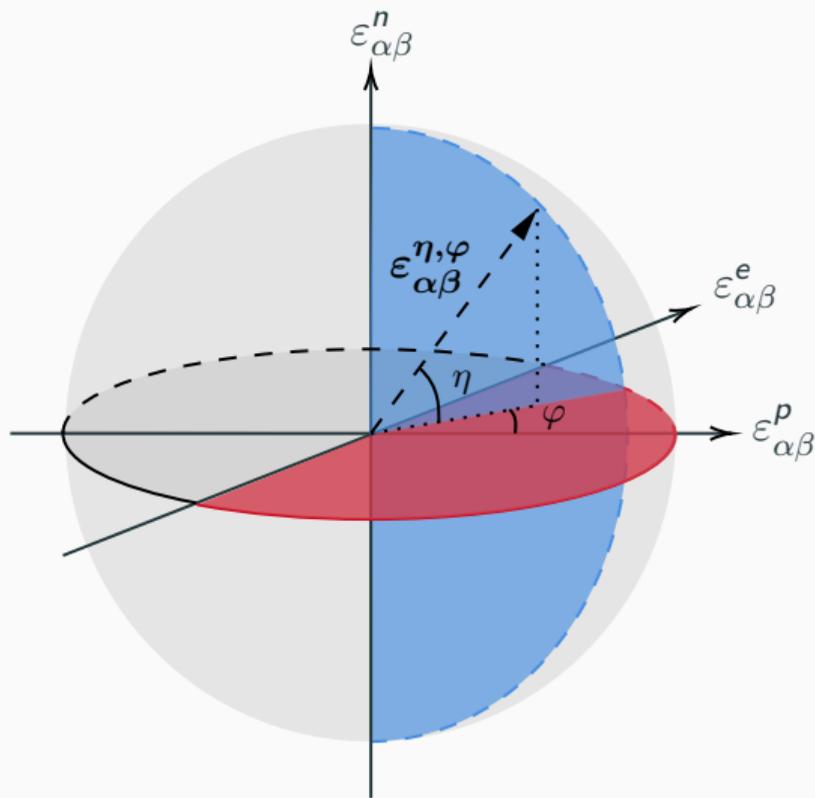
How can we turn the irreducible solar neutrino 'background' into an invaluable signal of new physics in the neutrino sector?

Neutrino Non-Standard Interactions (NSI)



- A general way to model new neutrino physics
- Effective framework: care about low-energy pheno (ignore UV completions)
- Strength of new physics **completely described** by Wilson coefficient $\epsilon_{\alpha\beta}$

A New Parametrisation: Introducing the Generalised Ball



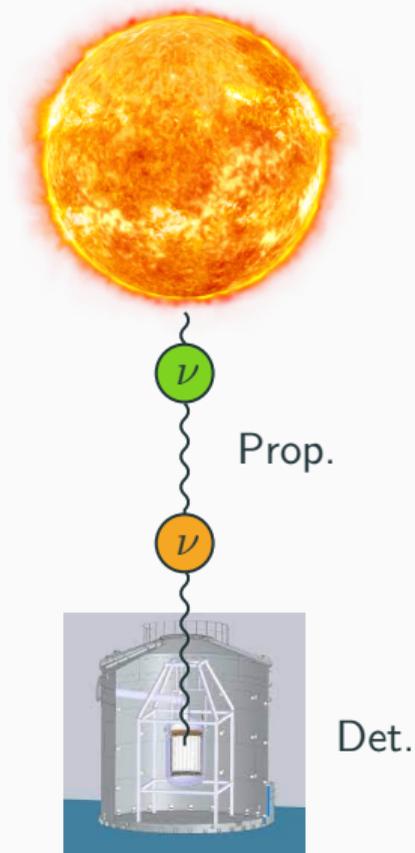
We have developed an extended NSI parametrisation

Usual assumptions:

- NSI only with electron
- NSI only in p - n plane

With our parametrisation, we can explore neutrino NSI phenomenology more generally!

NSI Phenomenology Breakdown



NSI Phenomenology

1. **Propagation effect:**
Non-standard component to matter Hamiltonian in Sun
2. **Detection effect:**
Non-standard $CE\nu NS$ and $E\nu ES$ cross section

Calculating the Neutrino Event Rate: The Right Way

Usually, the expected neutrino scattering rate is written as

$$\frac{dR}{dE_R} \propto \sum_{\alpha} \int_{E_{\nu}^{\min}} \overbrace{\frac{d\phi_{\nu_e}}{dE_{\nu}}}^{\nu_e \text{ production}} \underbrace{P(\nu_e \rightarrow \nu_{\alpha})}_{\text{Transition prob.}} \overbrace{\frac{d\sigma^{\alpha}}{dE_R}}^{\text{CS for flavour } \alpha} dE_{\nu}$$

This is **wrong** in general NSI case! [Pilar Coloma et al. 2204.03011](#)

NSI can lead to flavour-changing neutral currents: **not diagonal** in flavour basis!

Correct treatment requires a statistical approach:

$$\frac{dR}{dE_R} \propto \int_{E_{\nu}^{\min}} \frac{d\phi_{\nu_e}}{dE_{\nu}} \text{Tr} \left(\rho \frac{d\zeta}{dE_R} \right) dE_{\nu}$$

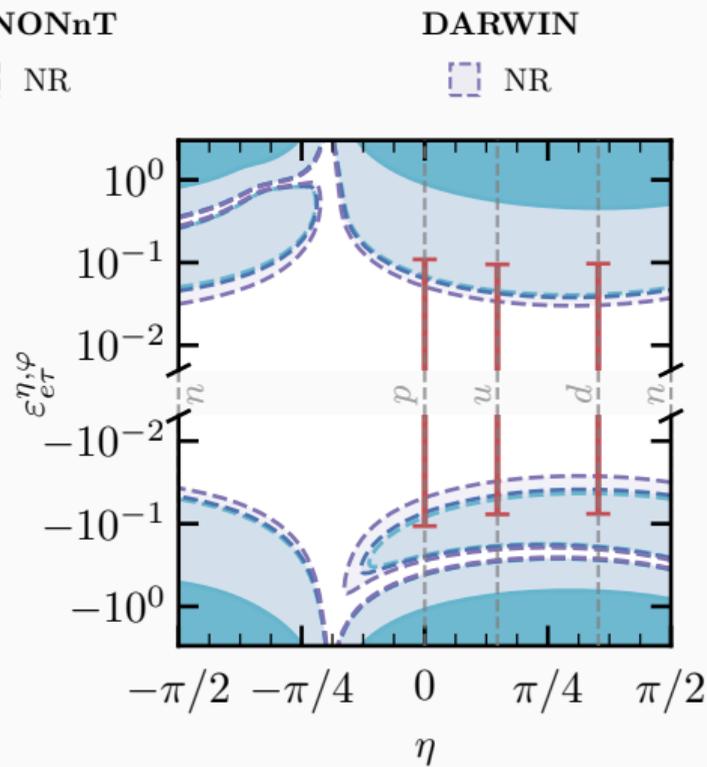
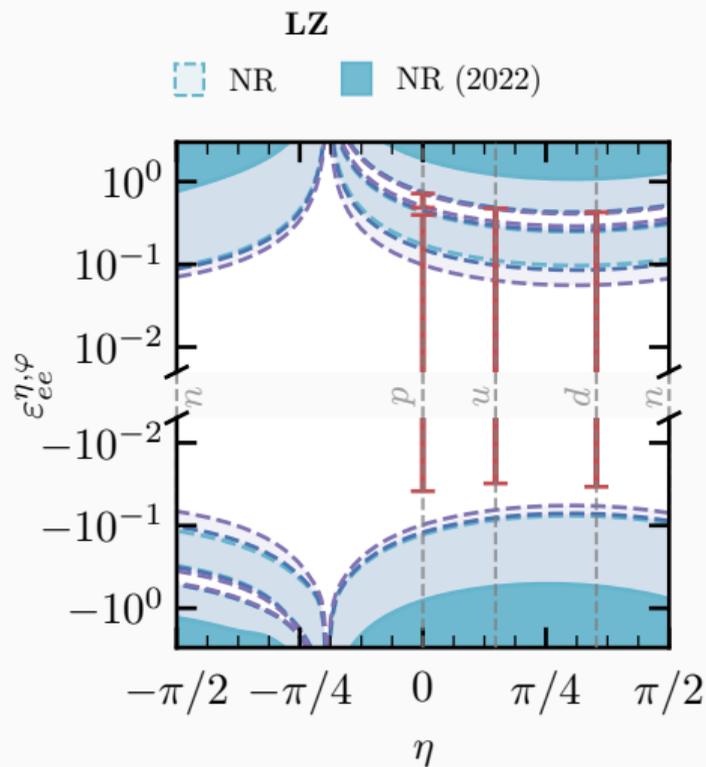
$\rho \equiv$ Neutrino density matrix

$d\zeta/dE_R \equiv$ Generalised scattering cross section

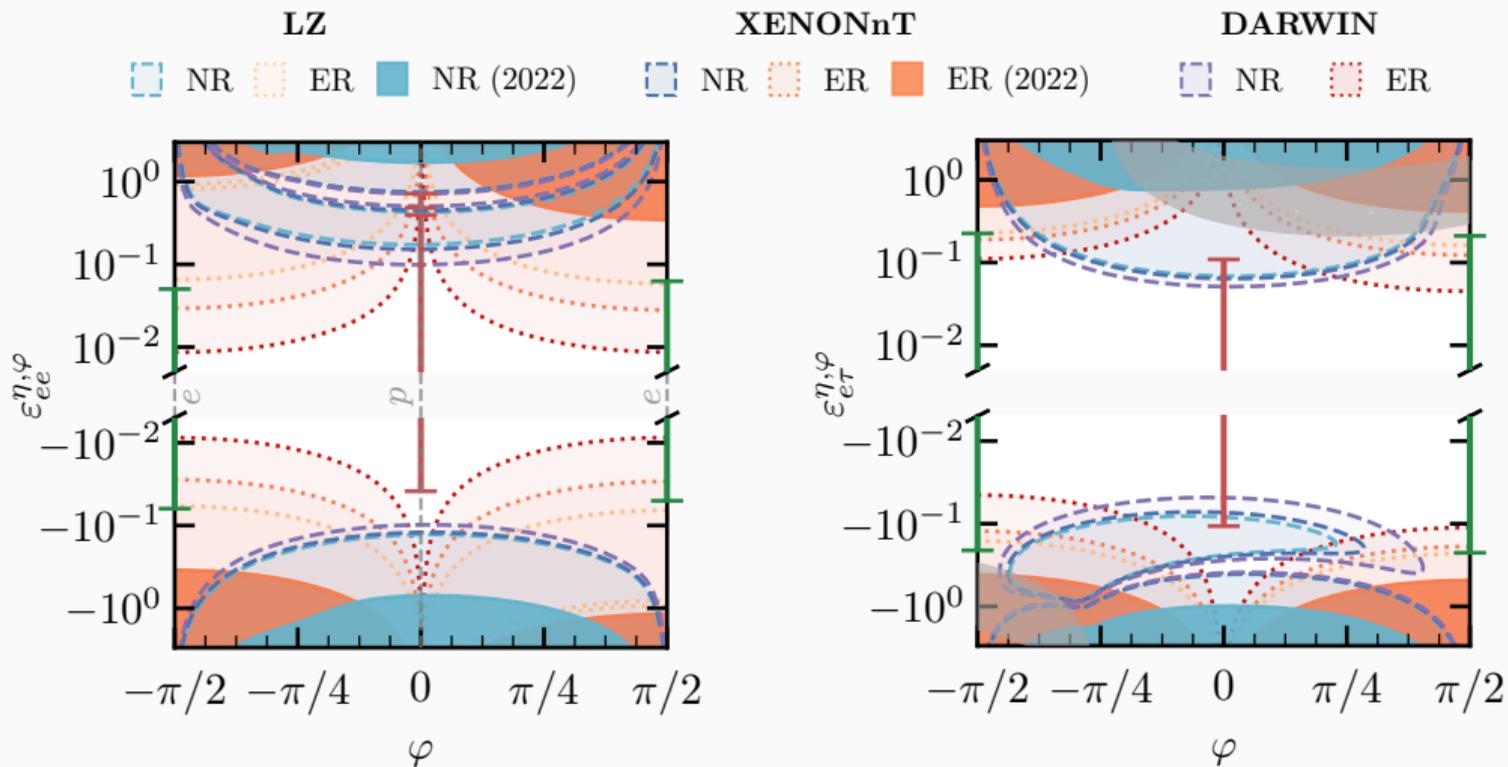
DD Experiments: We Are Ready for You

- Our framework allows us to treat NSI signal with both NRs and ERs
- Project bounds for XENONnT, LZ, and far-future DARWIN assuming that we observe the SM expectation
- Derive data-driven bounds from recent LZ NR and XENONnT ER results
J. Aalbers et al. [2207.03764](#), E. Aprile et al. [2207.11330](#)
- **Bounds derived assuming only one NSI parameter switched on at a time!**

Constraining Power from Nuclear Recoils ($\varphi = 0$)



Constraining Power from Electron and Nuclear Recoils ($\eta = 0$)



DA, D. Cerdeño, A. Cheek, P. Foldenauer
2302.12846

Additional Borexino limits (green bars) from
Pilar Coloma et al. [2204.03011](#)

- Neutrinos are taunting us with new physics
- Our novel parametrisation can capture NSI NR and ER phenomenology
- DD experiments will be **invaluable** in the NSI landscape!

DD experiments will become key players in the search for BSM neutrino physics, giving them a compelling research mission beyond their search for DM



To the Trace Formalism

$$\begin{aligned}
 |\mathcal{A}_{\alpha \rightarrow f}|^2 &= \left| \sum_{\beta} \mathcal{A}_{\alpha \rightarrow \beta} \right|^2 \\
 &= \left| \sum_{\beta} \langle \nu_{\beta} | \mathcal{S}_{\text{int}} \left(\sum_{\gamma} |\nu_{\gamma}\rangle \langle \nu_{\gamma}| \right) \mathcal{S}_{\text{prop}} | \nu_{\alpha} \rangle \right|^2 \\
 &= \sum_{\beta, \gamma, \delta, \lambda} \langle \nu_{\beta} | \mathcal{S}_{\text{int}} | \nu_{\gamma} \rangle \langle \nu_{\gamma} | \mathcal{S}_{\text{prop}} \left(\sum_{\rho} |\nu_{\rho}\rangle \langle \nu_{\rho}| \right) | \nu_{\alpha} \rangle \langle \nu_{\alpha} | \left(\sum_{\sigma} |\nu_{\sigma}\rangle \langle \nu_{\sigma}| \right) \mathcal{S}_{\text{prop}}^{\dagger} | \nu_{\delta} \rangle \langle \nu_{\delta} | \mathcal{S}_{\text{int}}^{\dagger} | \nu_{\lambda} \rangle \\
 &= \sum_{\gamma, \delta, \rho, \sigma} \underbrace{(\mathcal{S}_{\text{prop}})_{\gamma\rho} \pi_{\rho\sigma}^{(\alpha)} (\mathcal{S}_{\text{prop}})_{\delta\sigma}^*}_{\equiv \rho_{\gamma\delta}^{(\alpha)}} \underbrace{\sum_{\lambda, \beta} (\mathcal{S}_{\text{int}})_{\lambda\delta}^* (\mathcal{S}_{\text{int}})_{\beta\gamma}}_{\mathcal{M}^*(\nu_{\delta} \rightarrow f) \mathcal{M}(\nu_{\gamma} \rightarrow f)} .
 \end{aligned}$$

$$\chi^2(\varepsilon_{\alpha\beta}^{\eta,\varphi}, \varphi) = \min_a \left[\left(\frac{N_{\text{exp}} - (1+a) N_{\text{CE}\nu\text{NS}}(\varepsilon_{\alpha\beta}^{\eta,\varphi}, \varphi)}{\sqrt{N_{\text{exp}} + N_{\text{bkg}}}} \right)^2 + \left(\frac{a}{\sigma_a} \right)^2 \right]$$

$$\chi^2(\varepsilon_{\alpha\beta}^{\eta,\varphi}, \varphi) \equiv \min_{\vec{a}} \left[\sum_p \left(\frac{R_{\text{Borexino}}^p - (1 + a^p) R_{\text{Theo}}^p(\varepsilon_{\alpha\beta}^{\eta,\varphi}, \varphi)}{\sigma_{\text{stat}}^p} \right)^2 + \left(\frac{a^p}{\sigma_a^p} \right)^2 \right]$$

$$\mathcal{L}(\varepsilon_{\alpha\beta}^{\eta,\varphi}, \eta, \varphi, a, b) \equiv \prod_i^{N_{\text{bins}}} \text{Po} \left[N_{\text{obs}}^i \mid (1+a)N_{\nu}^i(\varepsilon_{\alpha\beta}^{\eta,\varphi}, \eta, \varphi) + (1+b)N_{\text{bkg}}^i \right] \\ \times \text{Gauss}(a \mid 0, \sigma_a) \text{Gauss}(b \mid 0, \sigma_b)$$

$$\eta = \tan^{-1} \left(-\frac{Z}{N} \cos \varphi \right)$$

$$\varepsilon_{\alpha\alpha}^{\eta,\varphi} = \frac{Q_{\nu N}}{\xi^p Z + \xi^n N}$$

$$\int_{E_{\nu}^{\min}} \frac{d\phi_{\nu e}}{dE_{\nu}} \left(1 - \frac{m_N E_R}{2E_{\nu}^2} \right) \left[(\xi^p Z + \xi^n N) (\rho_{\alpha\alpha} + \rho_{\beta\beta}) \varepsilon_{\alpha\beta}^{\eta,\varphi} - 2 Q_{\nu N} \rho_{\alpha\beta} \right] dE_{\nu} = 0.$$

$$\int_{E_\nu^{\min}} \frac{d\phi_{\nu_e}}{dE_\nu} \rho_{\alpha\alpha} \left\{ \left(1 - \frac{E_R}{E_\nu} \left(1 + \frac{m_e - E_R}{2E_\nu} \right) \right) [4s_W^2 + \xi^e \varepsilon_{\alpha\alpha}^{\eta,\varphi}] \xi^e \varepsilon_{\alpha\alpha}^{\eta,\varphi} + \left(1 - \frac{m_e E_R}{2E_\nu^2} \right) \left[4s_W^2 \frac{\rho_{ee} - \rho_{ee}^{\text{SM}}}{\rho_{\alpha\alpha}} + (2\delta_{\alpha e} - 1) \xi^e \varepsilon_{\alpha\alpha}^{\eta,\varphi} \right] \right\} dE_\nu = 0. \quad (1)$$

$$\int_{E_\nu^{\min}} \frac{d\phi_{\nu_e}}{dE_\nu} \left\{ \left(1 - \frac{E_R}{E_\nu} \left(1 + \frac{m_e - E_R}{2E_\nu} \right) \right) \left[\left(\xi^e \varepsilon_{\alpha\beta}^{\eta,\varphi} \right)^2 (\rho_{\alpha\alpha} + \rho_{\beta\beta}) + 8s_W^2 \xi^e \varepsilon_{\alpha\beta}^{\eta,\varphi} \rho_{\alpha\beta} \right] + \left(1 - \frac{m_e E_R}{2E_\nu^2} \right) \left[4s_W^2 (\rho_{ee} - \rho_{ee}^{\text{SM}}) - \delta_{\alpha\mu} \delta_{\beta\tau} 2\xi^e \varepsilon_{\alpha\beta}^{\eta,\varphi} \rho_{\alpha\beta} \right] \right\} dE_\nu = 0, \quad (2)$$

Calculating the Neutrino Event Rate: The Right Way

Electron neutrinos produced at Sun go through the following story arc:

1. Oscillate from $|\nu_e\rangle$ into a coherent superposition of flavour states via \hat{S}_{prop}
2. That state interacts with a target via \hat{S}_{int} and then flies off into some arbitrary final state $|f\rangle = \sum_{\beta} |\nu_{\beta}\rangle$.

$$\frac{dR}{dE_R} \propto |\mathcal{A}_{e \rightarrow f}|^2 = \left| \sum_{\beta} \langle \nu_{\beta} | \hat{S}_{\text{int}} \hat{S}_{\text{prop}} | \nu_e \rangle \right|^2 = \dots$$
$$\therefore \frac{dR}{dE_R} \propto \int_{E_{\nu}^{\text{min}}} \frac{d\phi_{\nu_e}}{dE_{\nu}} \text{Tr} \left(\rho \frac{d\zeta}{dE_R} \right) dE_{\nu}$$

$\rho \equiv$ Neutrino density matrix

$d\zeta/dE_R \equiv$ Generalised scattering cross section