



A Direct Detection View of the Neutrino NSI Landscape

arXiv:2302.12846

SUSY 2023

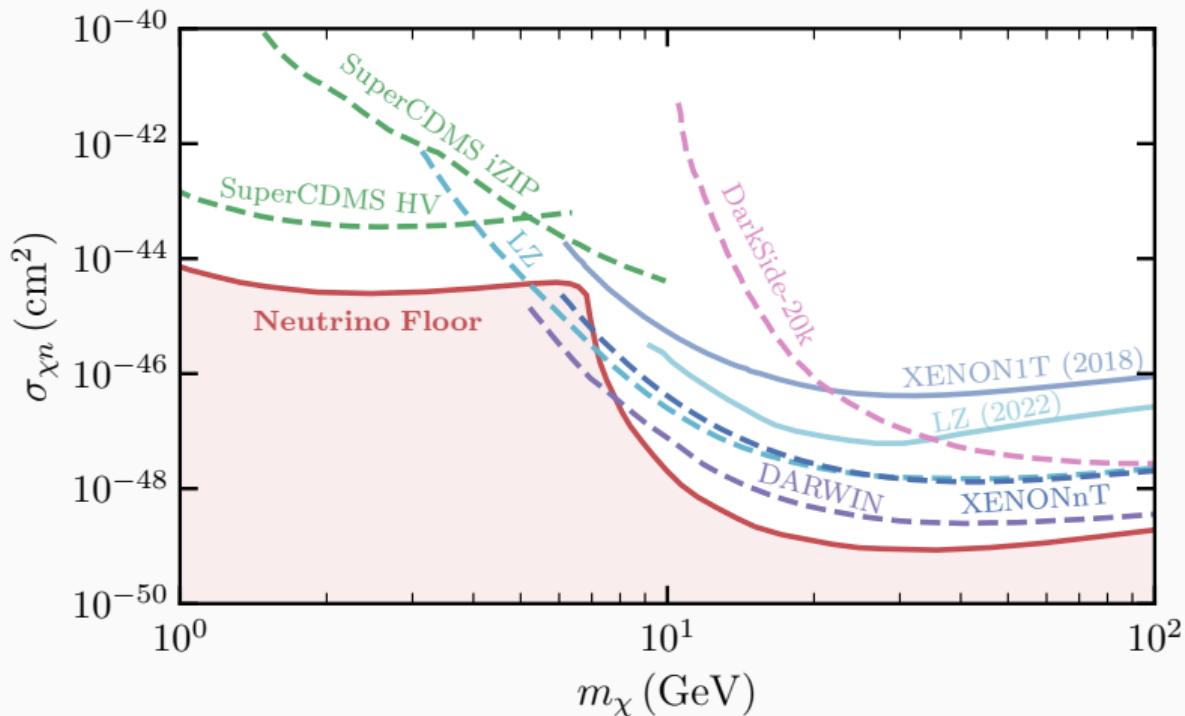
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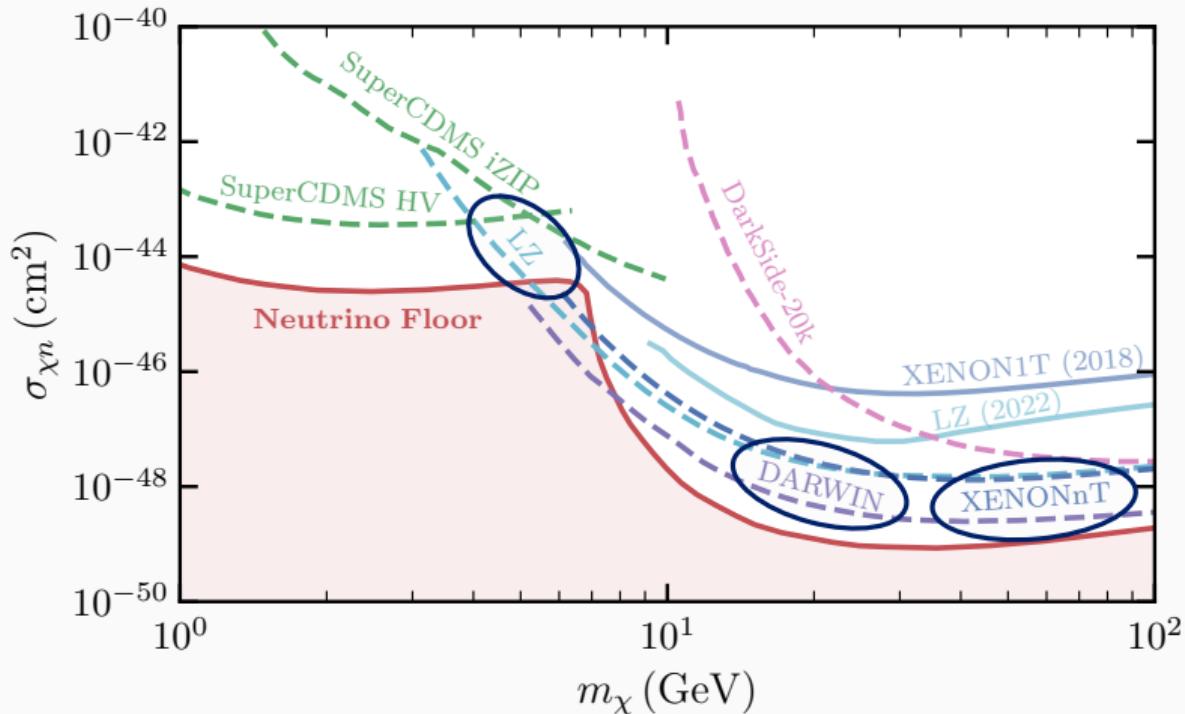
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**New Neutrino Physics is
Already Here!**

Direct Detection Experiments: A New Era of Neutrino Experiments

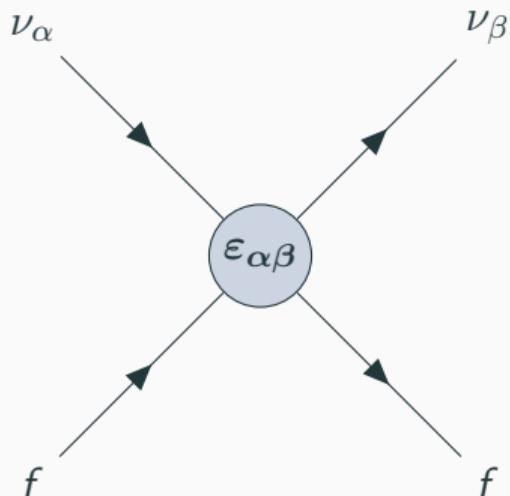


Direct Detection Experiments: A New Era of Neutrino Experiments



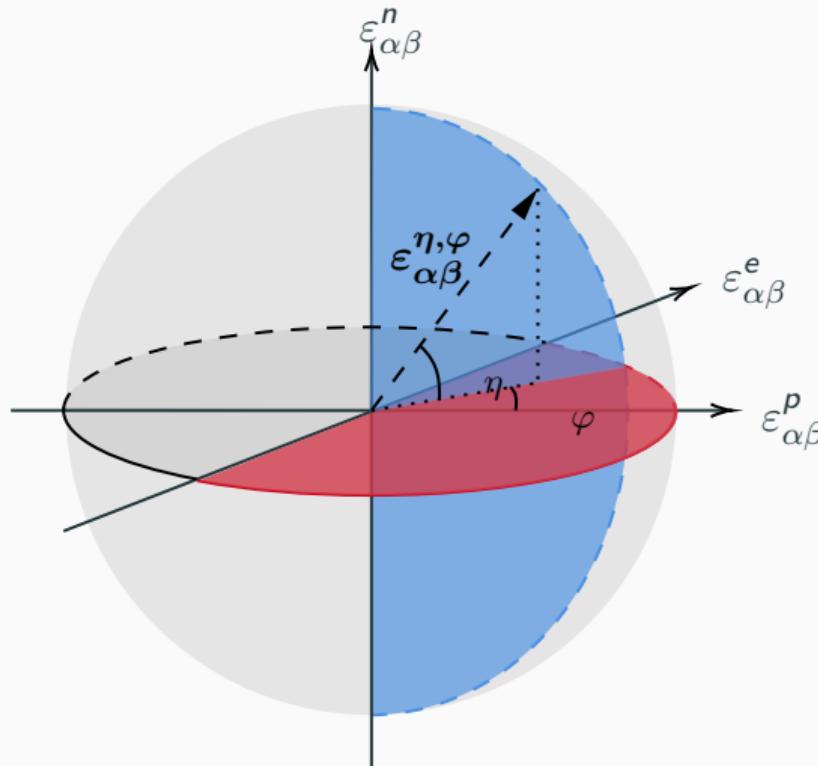
**How can we turn the irreducible solar neutrino ‘background’ into
an invaluable signal of new physics in the neutrino sector?**

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 $\varepsilon_{\alpha\beta}$

A New Parametrisation: Introducing the Generalised Ball



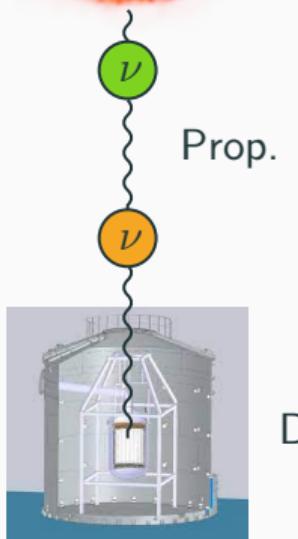
We have developed an extended NSI parametrisation

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 ν NS and E ν 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

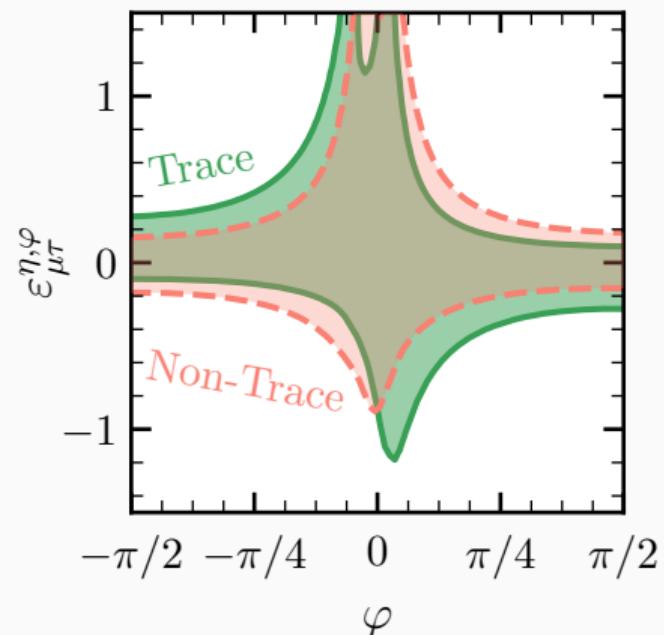
$d\zeta/dE_R \equiv$ Generalised scattering cross section

The Importance of the Trace Formalism

For all off-diagonal NSI ($\varepsilon_{\alpha\beta}^{\eta,\varphi}$, $\alpha \neq \beta$), trace formalism yields a term proportional to $\rho_{\alpha\beta}$ in rate calculation

If we do not take this into account, we miss this **interference** term completely!

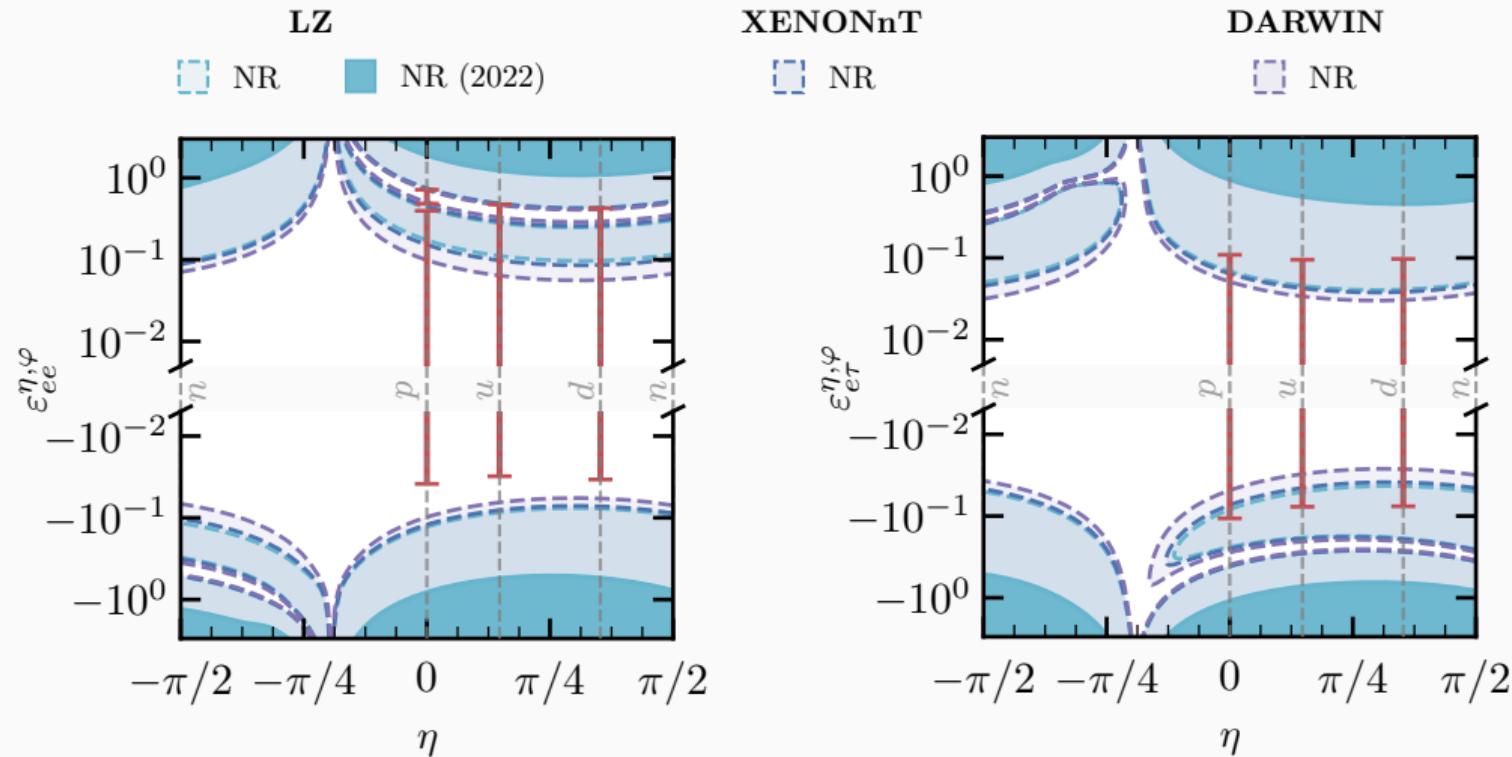
To capture all physical effects and produce accurate bounds, we must work with the trace formalism!



DD Experiments: We Are Ready for You

- Our framework allows us to treat NSI signal with both NRs and ERs
- We have developed a Python package that handles it all: **SNuDD**
- 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!**

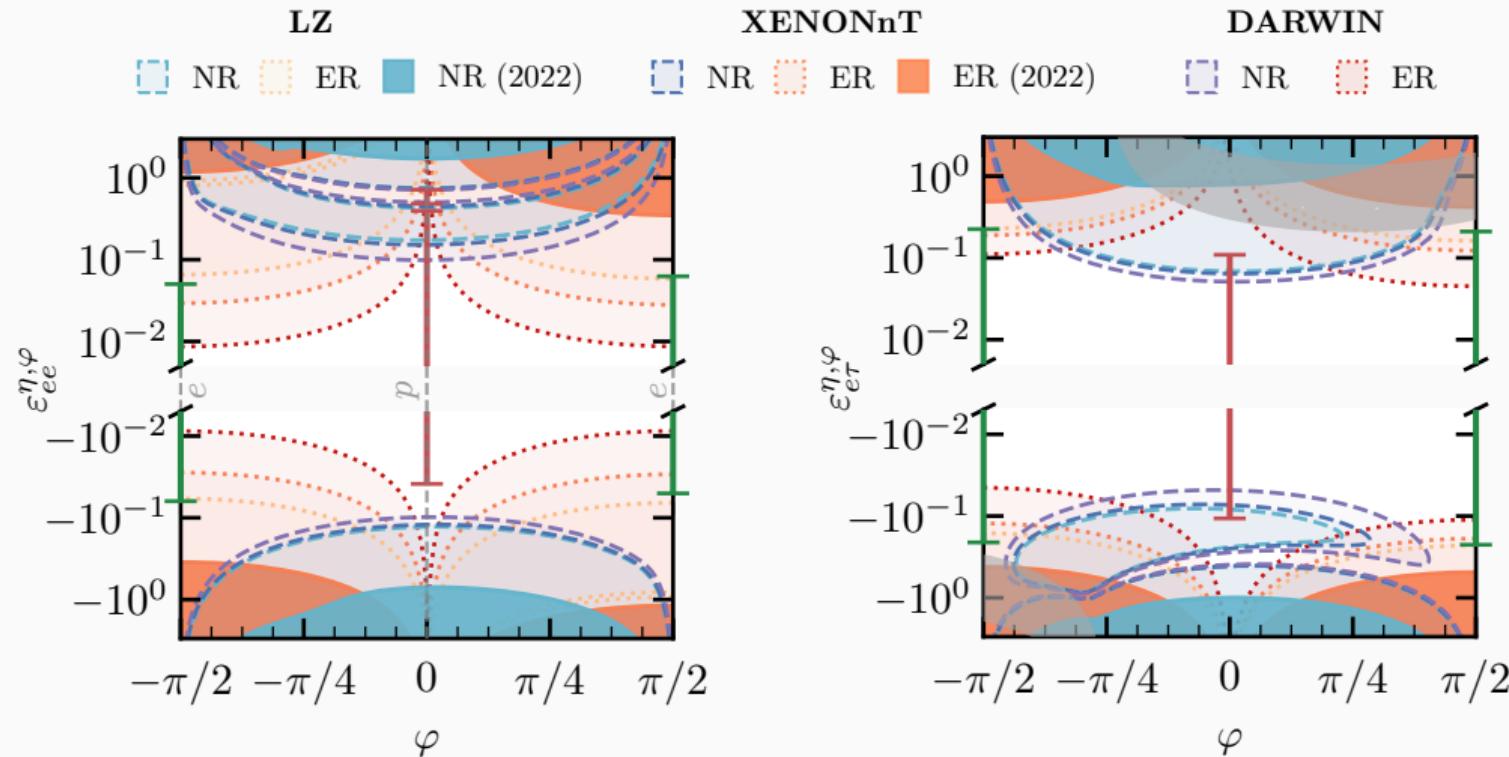
Constraining Power from Nuclear Recoils ($\varphi = 0$)



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

Global limits (red bars) from
Pilar Coloma et al. 1911.09109

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



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2302.12846

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

Summary

- 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

$$\begin{aligned} |\mathcal{A}_{\nu_\alpha \rightarrow \sum_i \nu_i}|^2 &= \sum_i \left| \sum_\beta U_{\beta i}^* \langle \nu_\beta | S_{\text{int}} \left(\sum_\gamma |\nu_\gamma\rangle \langle \nu_\gamma| \right) S_{\text{prop}} |\nu_\alpha\rangle \right|^2 \\ &= \sum_{\beta, \gamma, \delta, \lambda} \overbrace{\sum_i U_{\beta i}^* U_{\lambda i}}^{\delta_{\beta \lambda}} \langle \nu_\beta | S_{\text{int}} |\nu_\gamma\rangle \langle \nu_\gamma | S_{\text{prop}} \left(\sum_\rho |\nu_\rho\rangle \langle \nu_\rho| \right) |\nu_\alpha\rangle \langle \nu_\alpha| \left(\sum_\sigma |\nu_\sigma\rangle \langle \nu_\sigma| \right) \\ &\quad \times S_{\text{prop}}^\dagger |\nu_\delta\rangle \langle \nu_\delta| S_{\text{int}}^\dagger |\nu_\lambda\rangle \\ &= \sum_{\gamma, \delta, \rho, \sigma} \underbrace{(S_{\text{prop}})_{\gamma \rho} \pi_{\rho \sigma}^{(\alpha)} (S_{\text{prop}})_{\delta \sigma}^*}_{\equiv \rho_{\gamma \delta}^{(\alpha)}} \underbrace{\sum_\beta (S_{\text{int}})_{\beta \delta}^* (S_{\text{int}})_{\beta \gamma}}_{\mathcal{M}^*(\nu_\delta \rightarrow f) \mathcal{M}(\nu_\gamma \rightarrow f)}, \end{aligned}$$

χ^2 for CE ν NS

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

χ^2 for Borexino

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

Likelihood for DD

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

NR Blindspots

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

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

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

ER Blindspots

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

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

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 $|f\rangle = \sum_{\beta} |\nu_{\beta}\rangle$.

$$\frac{dR}{dE_R} \propto |\mathcal{A}_{e \rightarrow f}|^2 = \left| \sum_{\beta} \langle \nu_{\beta} | \hat{S}_{\text{int}} \hat{S}_{\text{prop}} | \nu_e \rangle \right|^2 = \dots$$

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

$\rho \equiv$ Neutrino density matrix

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