ENTERING THE ERA OF NEUTRINO DIRECT DETECTION

***JHEP* 07 (2023) 071** [**[arXiv: 2302.12846]**](https://arxiv.org/abs/2302.12846)

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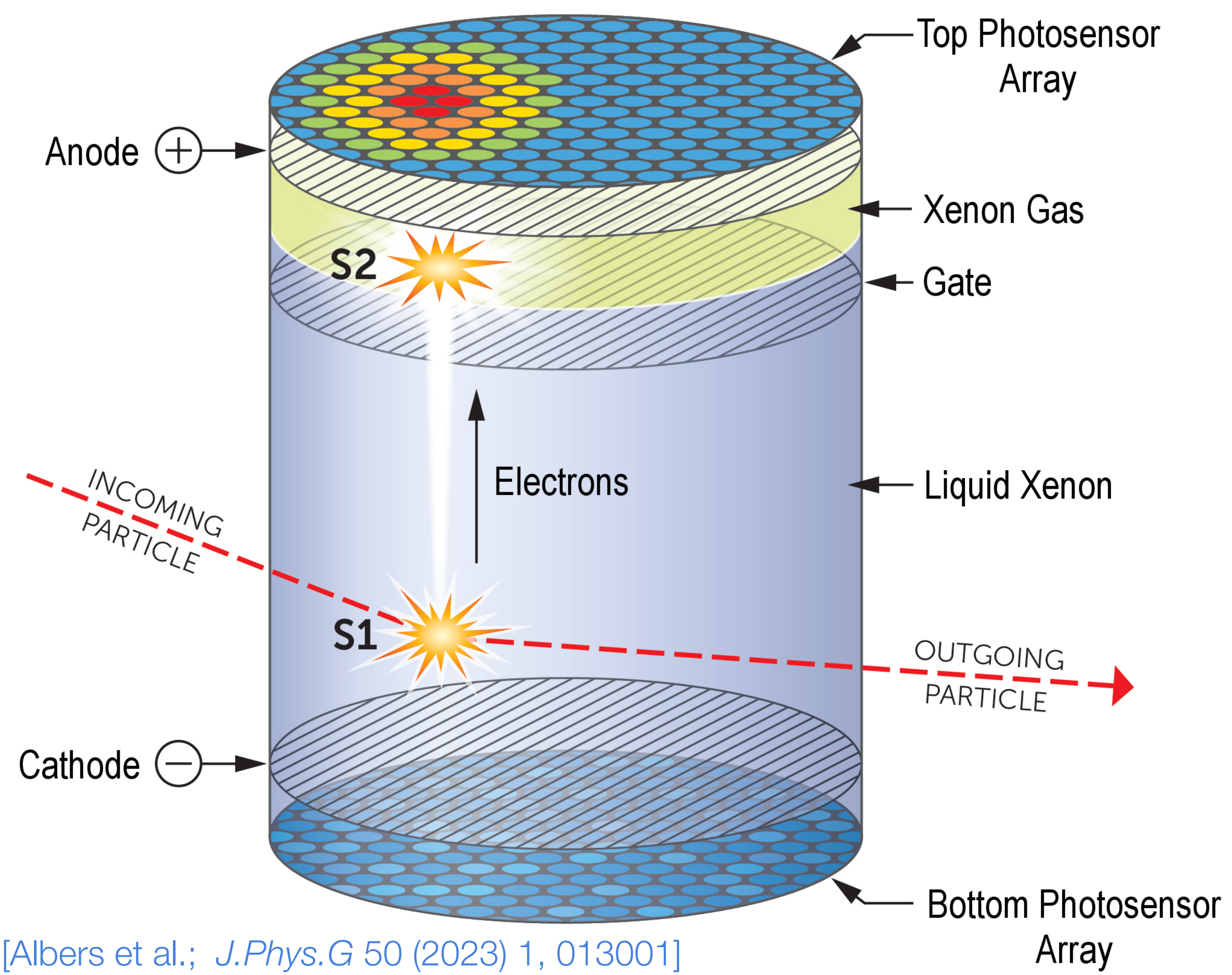
HOW TO LOOK BEYOND SM?

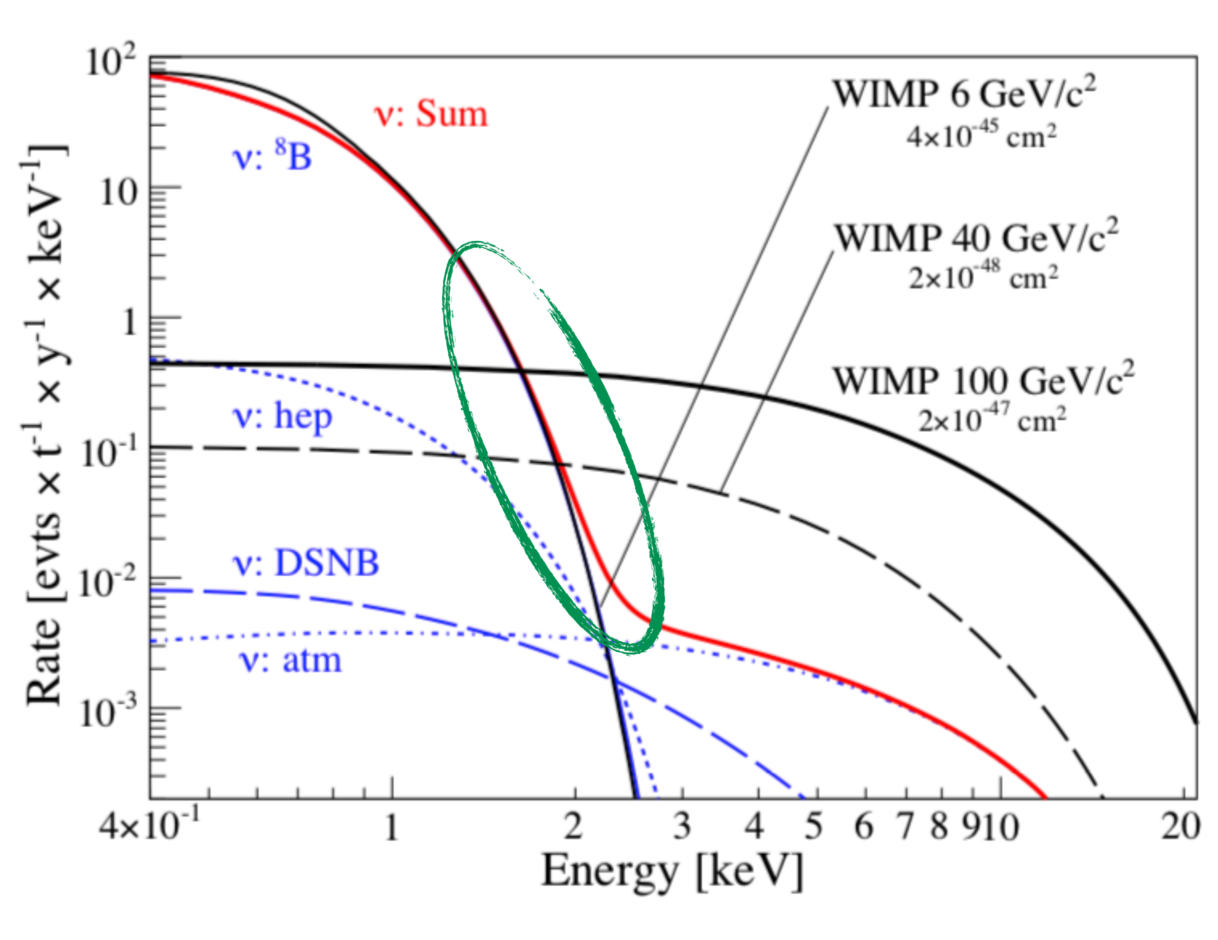
- State-of-the-art **DM experiments**: multi ton liquid noble gas detectors (Xe, Ar)
- **Signature**: Incident particles produce prompt scintillation light in scattering (S1); secondary signal from electroluminescence in gaseous layer (S2)

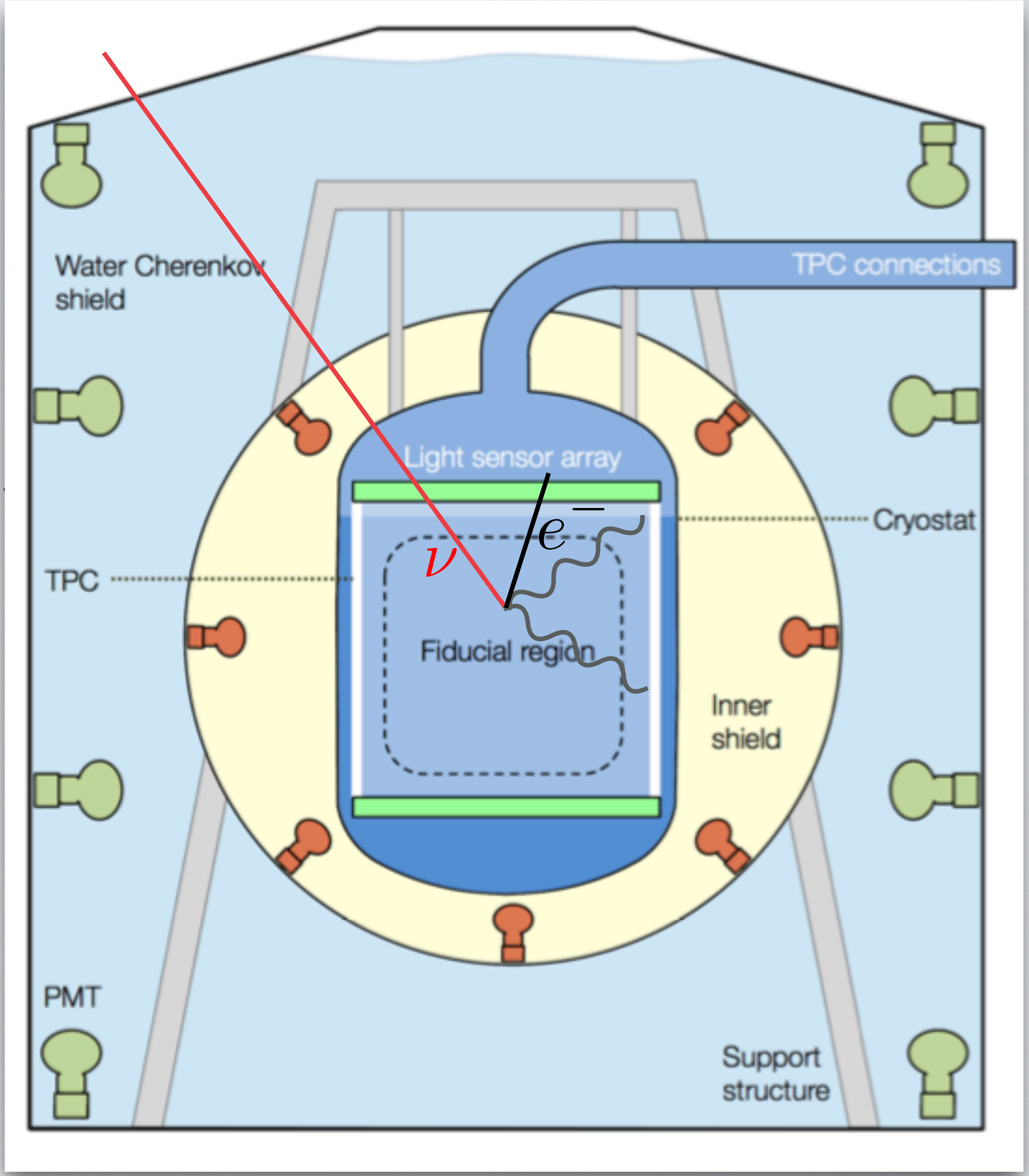


[Albers et al.; *J.Phys.G* 50 (2023) 1, 013001]

PROBLEM: NEUTRINO BACKGROUND

- Incident energetic neutrinos can fake the DM signal, as they leave a similar signature
- Most importantly, **irreducible solar neutrino background looks like WIMP signal!**
- **Energy thresholds of ~ O(few) keV**
  ⇒ typical solar neutrino scattering energies!
- (LUX has achieved 1.1 keV with NR/ER discrimina

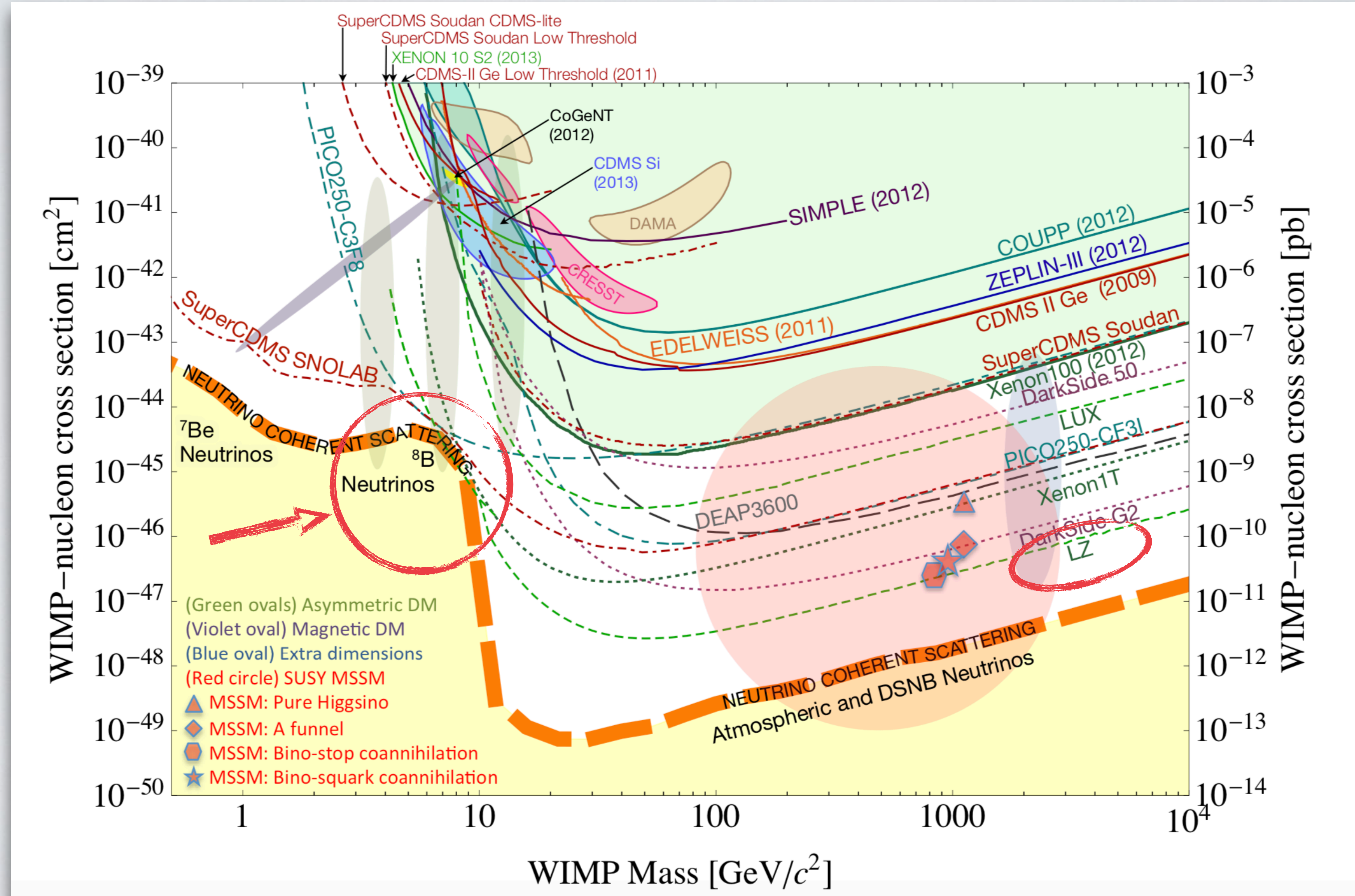




[DARWIN collaboration; JCAP 1611 (2016) no.11, 017]

NEUTRINO FLOOR

- Direct detection experiments will become sensitive to solar neutrino scattering (in particular coherent scattering)

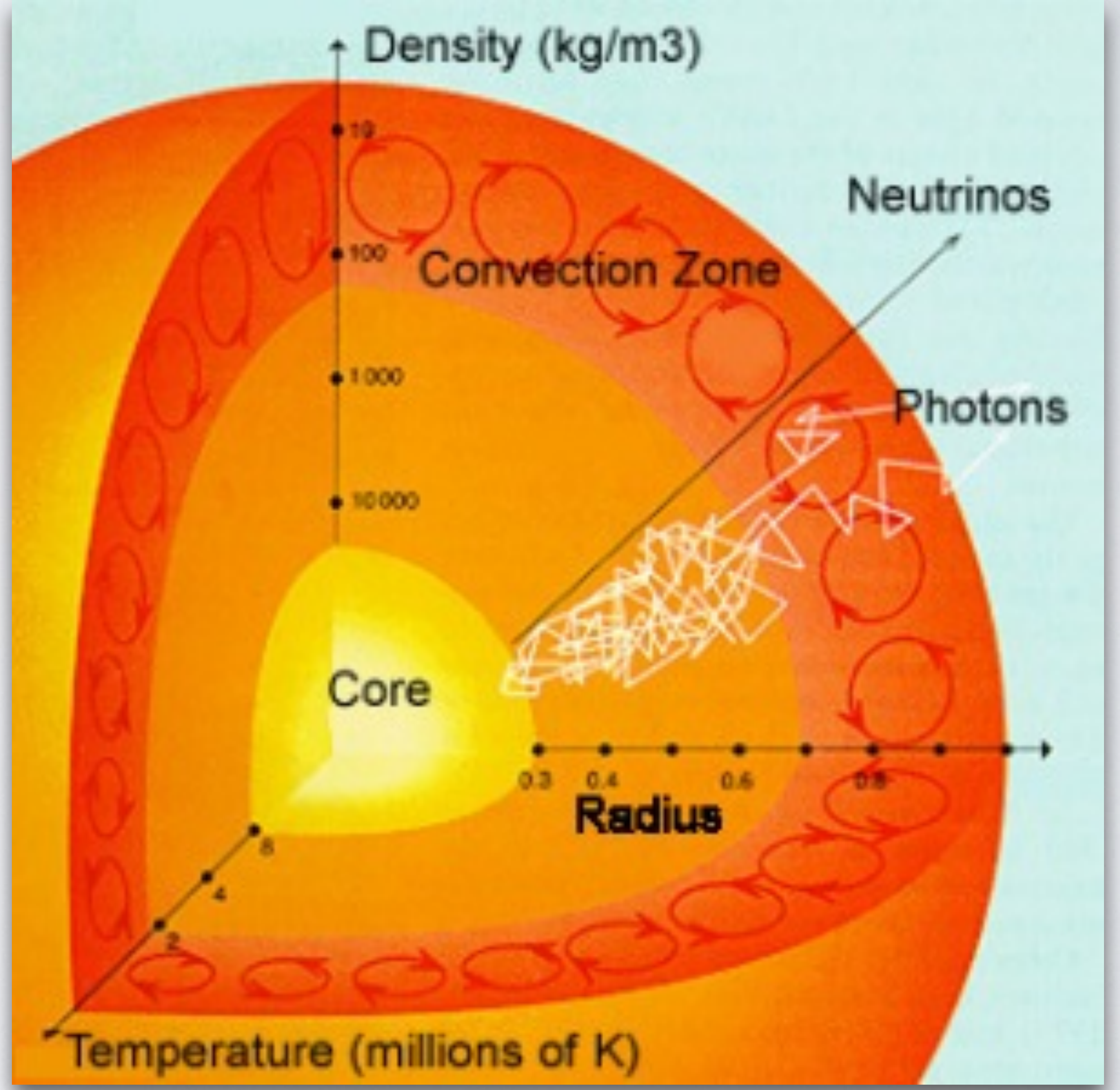


[Snowmass CF1 Summary; 1310.8327]

WHAT ARE SOLAR NEUTRINOS?

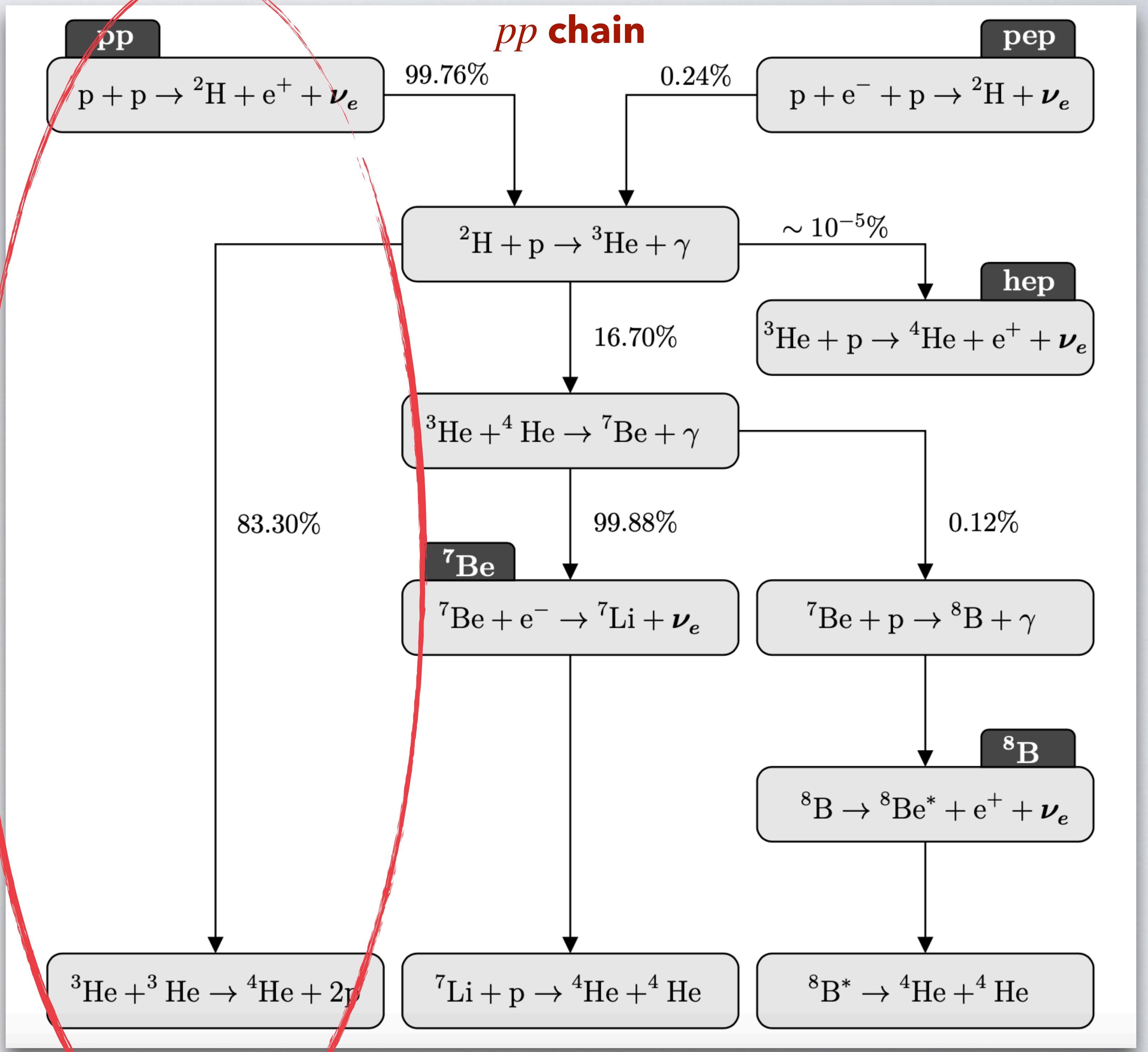
- Neutrinos are produced in fusion processes in solar interior
- Neutrinos leave sun almost instantaneously (2s); photons get scattered and reabsorbed
- Photons require 50 000 years to leave sun!

⇒ Neutrinos allow us to study interior of Sun!

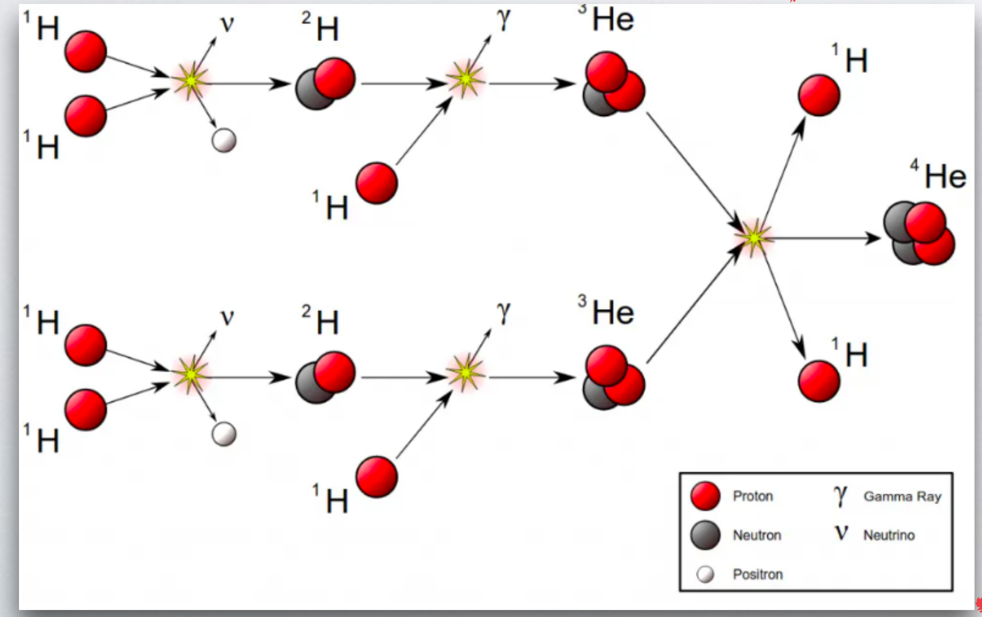


HOW ARE SOLAR ν PRODUCED?

- Sun powered by fusion
- Intermediate proton-rich nuclei decay either through β^+ or electron capture, **producing pure ν_e**
- Solar production cycles ultimately fuse *H* into *He*

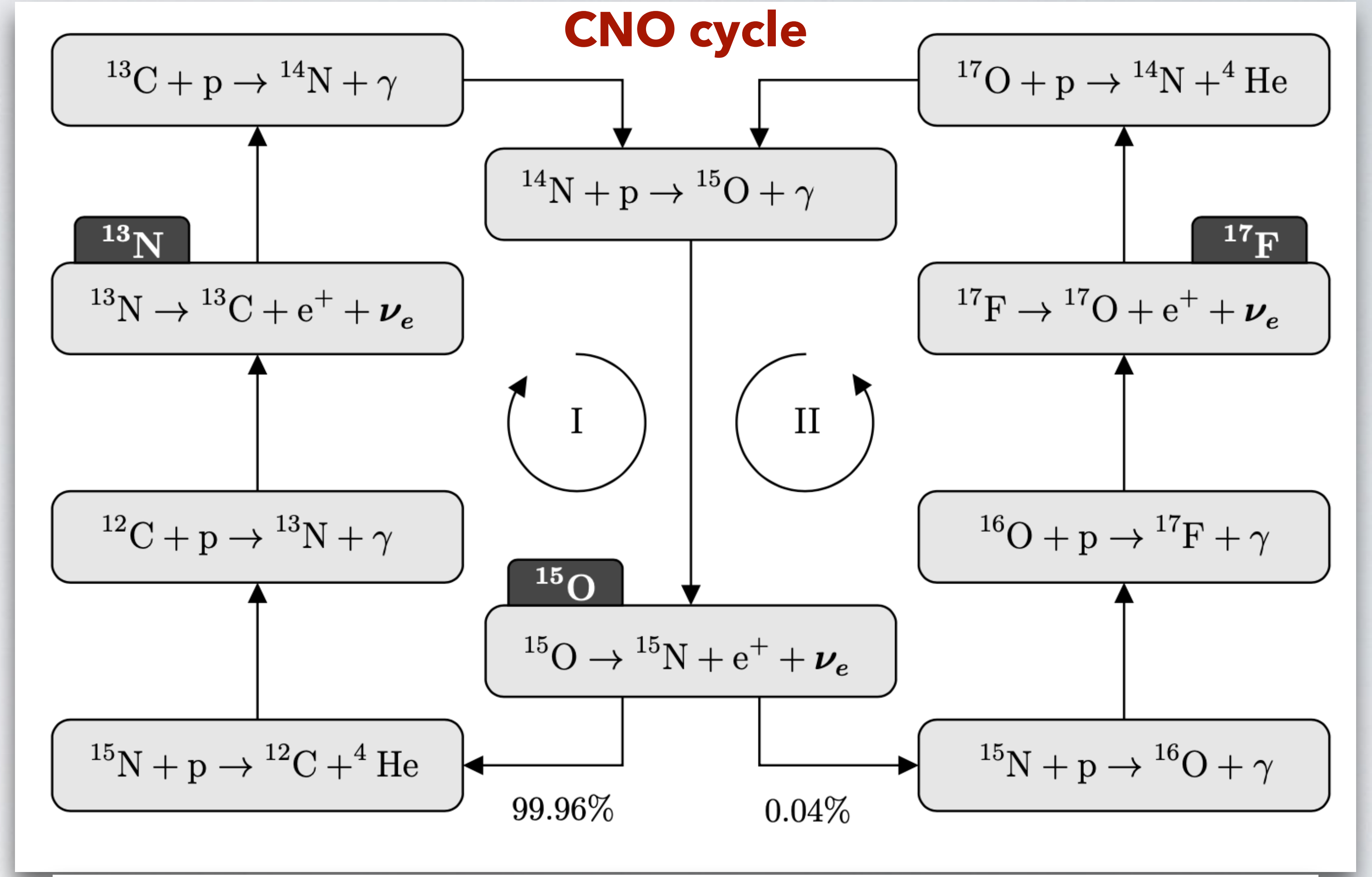


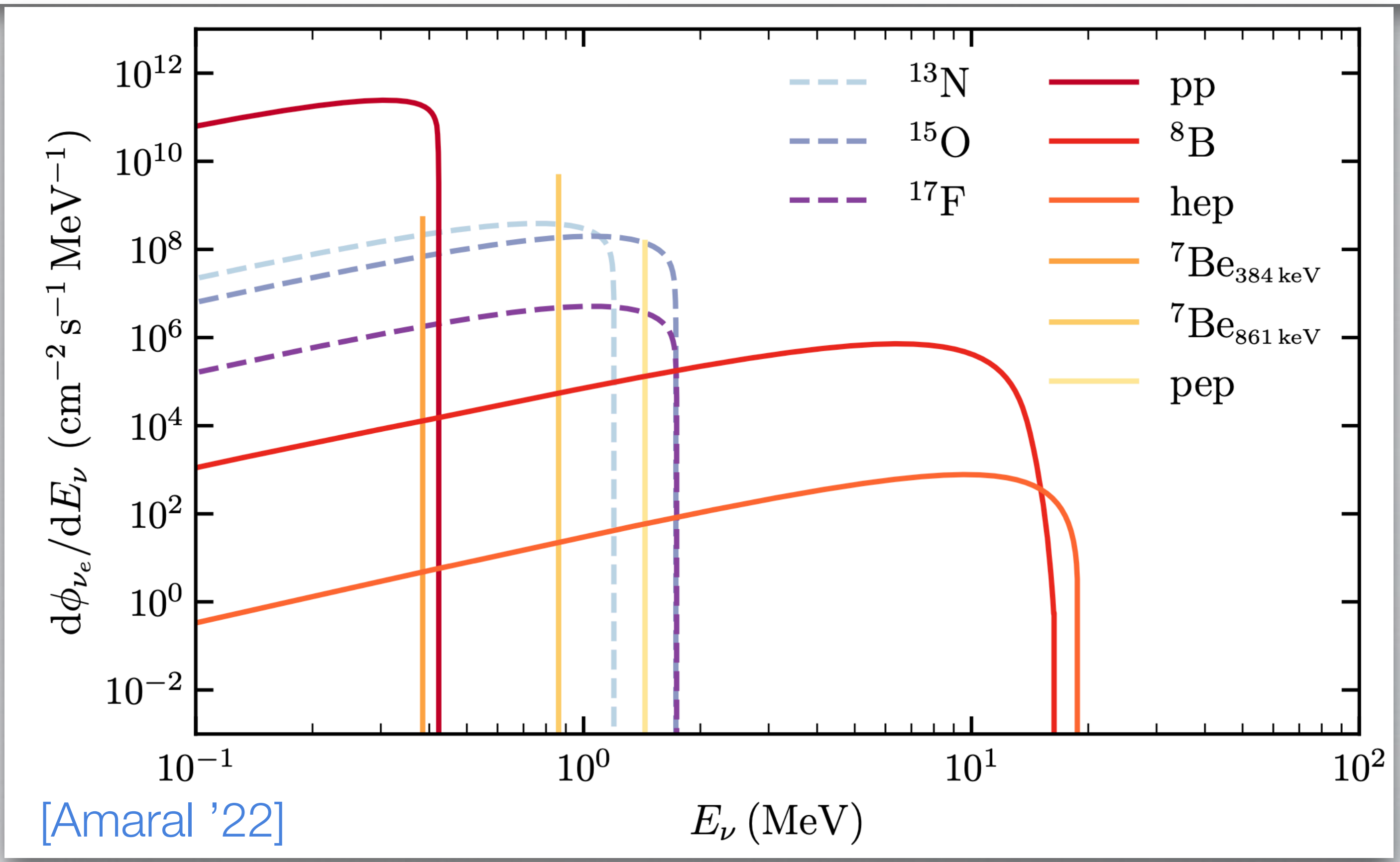
[Amaral '22]



HOW ARE SOLAR ν PRODUCED?

- Sun powered by fusion
- Intermediate proton-rich nuclei decay either through β^+ or electron capture, **producing pure ν_e**
- Solar production cycles ultimately fuse H into He
- Fusion cycles produce very rich solar neutrino spectrum with **MeV energies and high fluxes**
- **This is an excellent source for neutrino physics!**



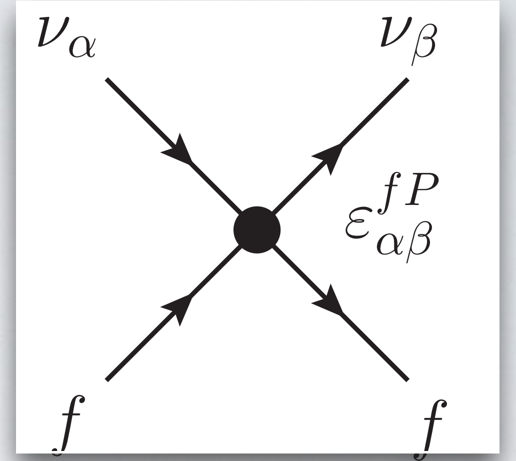


LABORATORY FOR NEW NEUTRINO PHYSICS

NON-STANDARD INTERACTIONS

- Neutral current low-energy effective theory called **non-standard interactions (NSI)**

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}\,G_F \sum_{f,P,\alpha,\beta} \varepsilon^{fP}_{\alpha\beta}\ [\bar{\nu}_\alpha \gamma_\rho P_L \nu_\beta]\ [\bar{f}\gamma^\rho P f]$$



- Ordinary matter is composed of $f = \{e, u, d\}$. Only these are relevant for matter effects and scattering. Propagation only sensitive to **vector component.**

$$\varepsilon^{f}_{\alpha\beta} = \varepsilon^{fL}_{\alpha\beta} + \varepsilon^{fR}_{\alpha\beta}$$

- Assuming neutrino flavour structure of NSI to be independent of charged fermion, NSI coupling can be factorised in neutrino and fermionic part

$$\varepsilon^{f}_{\alpha\beta} = \varepsilon^{\eta,\varphi}_{\alpha\beta}\,\xi^f \quad \Longrightarrow \quad \mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F \left[\sum_{\alpha\beta} \varepsilon^{\eta,\varphi}_{\alpha\beta}\ (\bar{\nu}_\alpha \gamma_\mu P_L \nu_\beta)\right] \left[\sum_f \xi^f\ \bar{f}\gamma^\mu f\right]$$

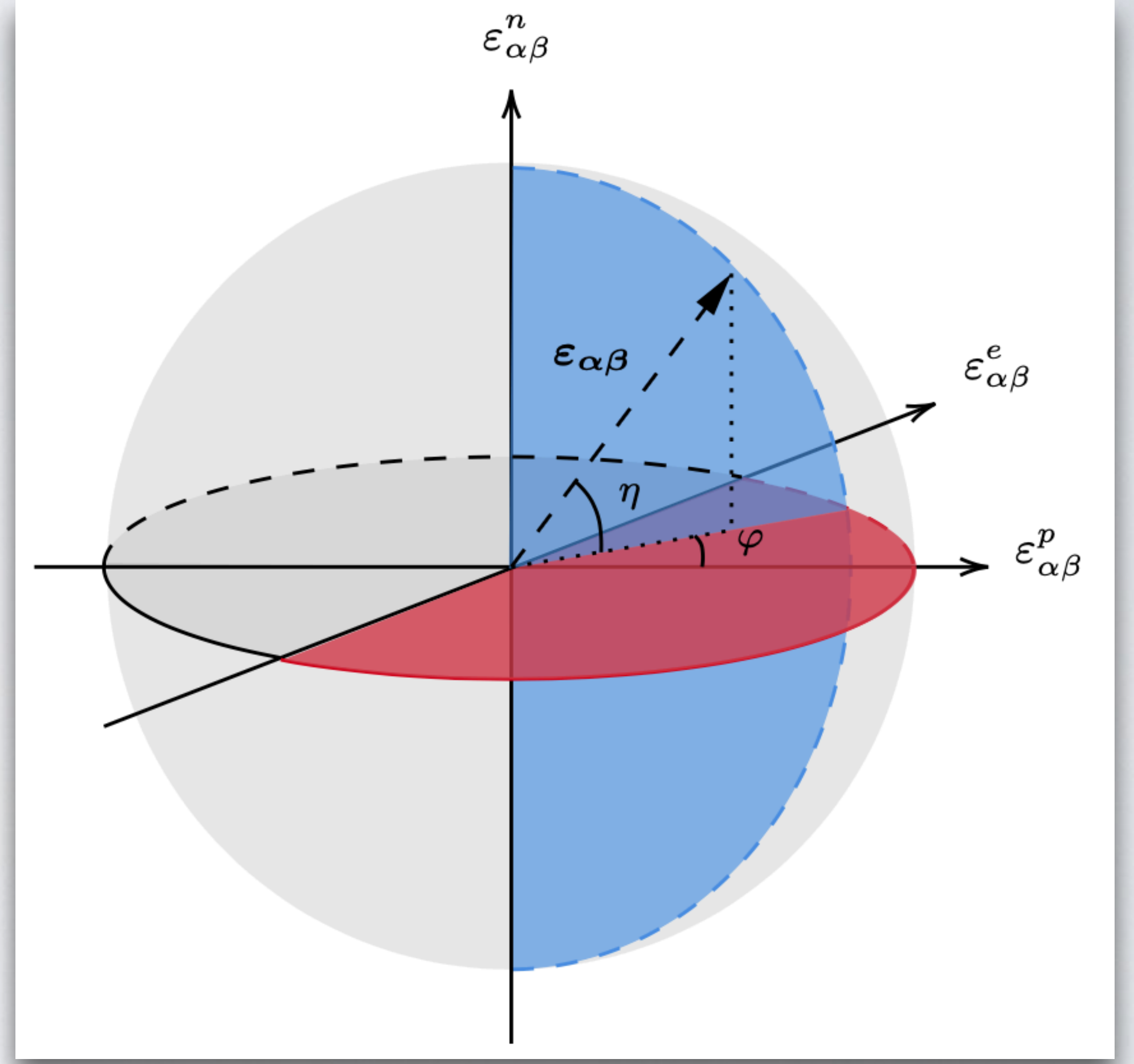
NON-STANDARD INTERACTIONS

- For direct detection **electron scattering** is crucial! We extend this parameterisation by **electron direction**

$$\varepsilon^{f}_{\alpha\beta} = \varepsilon^{\eta,\varphi}_{\alpha\beta}\,\xi^{f}$$

- Parametrising the direction in terms of $\{e, p, n\}$

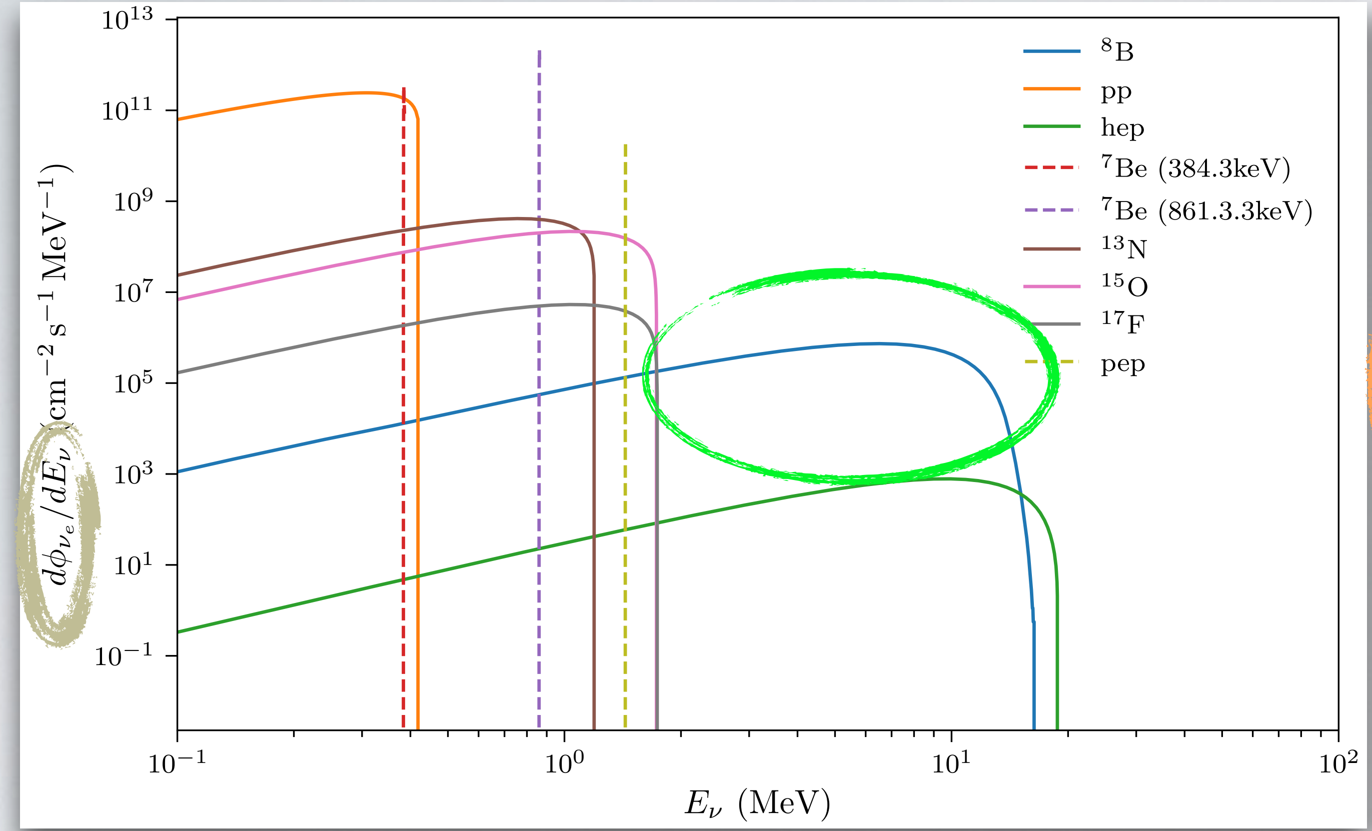
$$\xi^{e} = \sqrt{5}\,\cos\eta\,\sin\varphi\,,$$
$$\xi^{p} = \sqrt{5}\,\cos\eta\,\cos\varphi\,,$$
$$\xi^{n} = \sqrt{5}\,\sin\eta$$

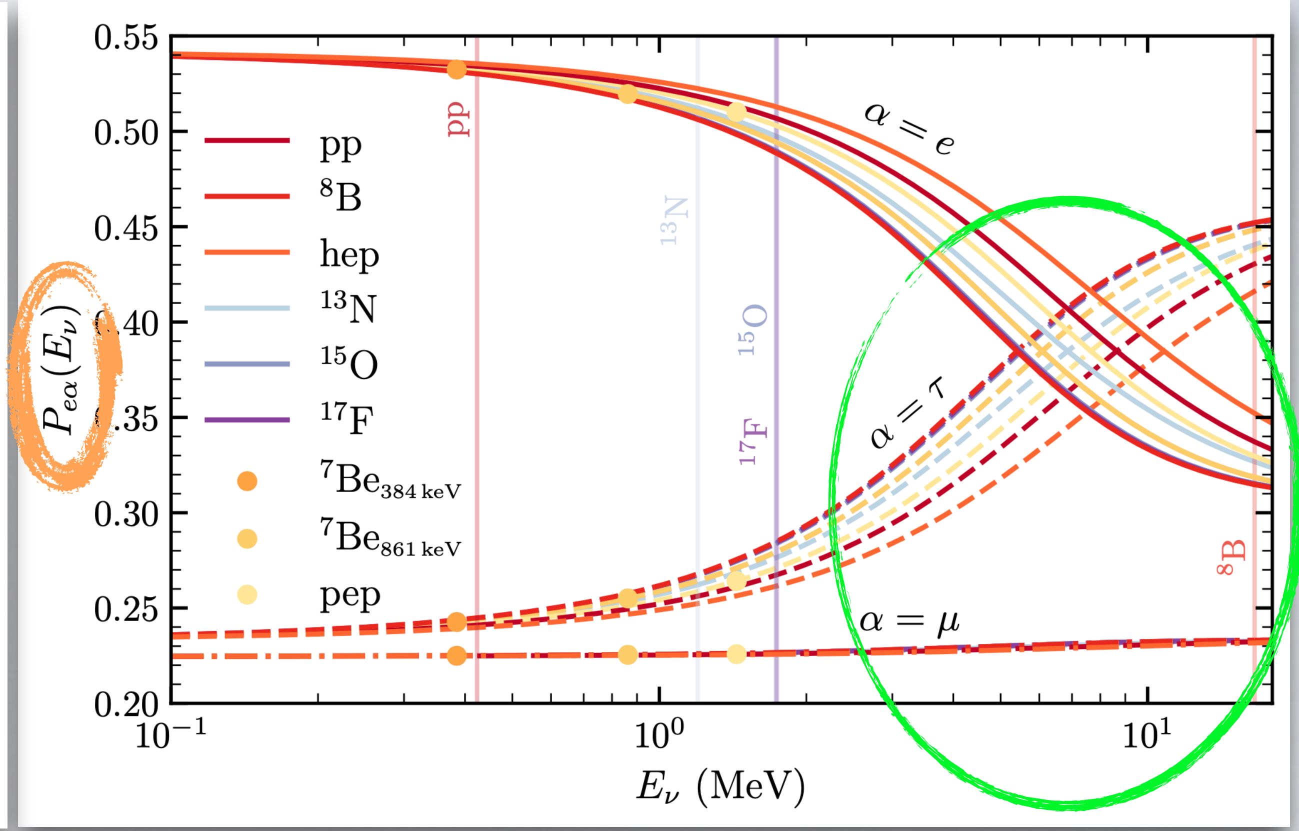


- The angles η, φ run in the interval $[-\pi/2, \pi/2]$ and the radial component $\varepsilon^{\eta,\varphi}_{\alpha\beta}$ can be **positive and negative!**

- η is the angle in the $\{\xi^{p}, \xi^{n}\}$ plane, φ in the $\{\xi^{p}, \xi^{e}\}$ plane

RATE — NAIVE APPROACH





[Vinyoles et al.; *Astrophys.J.* 835 (2017) 2, 202]

[Amaral, Cerdeno, PF, Reid; 2006.11225]

- Solar neutrinos produced in various processes, but **initially always in electron flavour.**
- **Matter oscillation** in solar medium dominates flavour composition reaching earth. **⇒ at ~10 MeV significant ν_τ (and ν_μ) admixture (^8B flux)!**
- Total rate in scattering experiment is written as

$$\frac{dR}{dE_R} = n_T \int_{E_\nu^{\min}} \frac{d\phi_\nu}{dE_\nu} \sum_{\nu_\alpha} P(\nu_e \to \nu_\alpha) \frac{d\sigma_{\nu_\alpha T}}{dE_R} \, dE_\nu$$

RATE — FIRST PRINCIPLES

- Neutrinos are produced in the core of the Sun as **pure** ν_e . Propagate through the solar matter to the surface of the Sun and **undergo matter oscillations**; free stream in vacuum to earth

- Scatter with detector into any neutrino final state. Have to **sum over asymptotic final states**

$$\left|\mathcal{A}_{\nu_\alpha \to \sum_i \nu_i}\right|^2 = \sum_i |\langle \nu_i | S | \nu_\alpha \rangle|^2 = \sum_i \left| \sum_\beta U^*_{\beta i} \langle \nu_\beta | S | \nu_\alpha \rangle \right|^2$$

Asymptotic outstate i

Propagation and scattering

Initial flavour α

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$$\left|\mathcal{A}_{\nu_\alpha \to \sum_i \nu_i}\right|^2 = \sum_i \left| \sum_\beta U^*_{\beta i} \langle \nu_\beta | S_{\text{int}} \left(\sum_\gamma |\nu_\gamma\rangle\langle\nu_\gamma| \right) S_{\text{prop}} |\nu_\alpha\rangle \right|^2$$

$$= \sum_{\beta,\gamma,\delta,\lambda} \overbrace{\sum_i U^*_{\beta i} U_{\lambda i}}^{\delta_{\beta\lambda}} \langle \nu_\beta | S_{\text{int}} | \nu_\gamma \rangle \langle \nu_\gamma | S_{\text{prop}} \left(\sum_\rho |\nu_\rho\rangle\langle\nu_\rho| \right) |\nu_\alpha\rangle\langle\nu_\alpha| \left(\sum_\sigma |\nu_\sigma\rangle\langle\nu_\sigma| \right) S^\dagger_{\text{prop}} |\nu_\delta\rangle$$

$$\times \langle \nu_\delta | S^\dagger_{\text{int}} | \nu_\lambda \rangle$$

$$= \sum_{\gamma,\delta,\rho,\sigma} \underbrace{(S_{\text{prop}})_{\gamma\rho}\, \pi^{(\alpha)}_{\rho\sigma}\, (S_{\text{prop}})^*_{\delta\sigma}}_{\equiv \rho^{(\alpha)}_{\gamma\delta}} \underbrace{\sum_\beta (S_{\text{int}})^*_{\beta\delta}\, (S_{\text{int}})_{\beta\gamma}}_{\mathcal{M}^*(\nu_\delta \to f)\, \mathcal{M}(\nu_\gamma \to f)}$$

generalised matrix element

Neutrino density matrix

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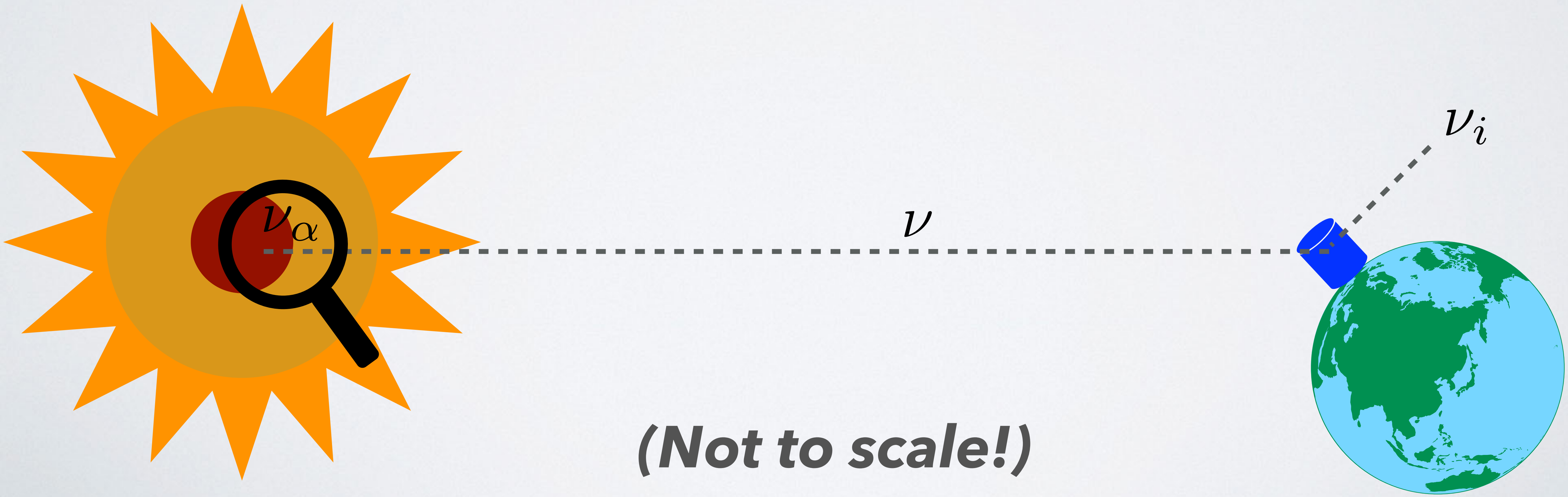
Neutrino density matrix

generalised matrix element

$$\Rightarrow \frac{dR}{dE_R} = n_T \int_{E_\nu^{\rm min}} \frac{d\phi_\nu}{dE_\nu} \, {\rm Tr}\left[\boldsymbol{\rho} \frac{d\zeta}{dE_R} \right] dE_\nu$$

- **Retains full phase correlation**
- **Captures all interferences**

SOLAR NEUTRINO FLUXES

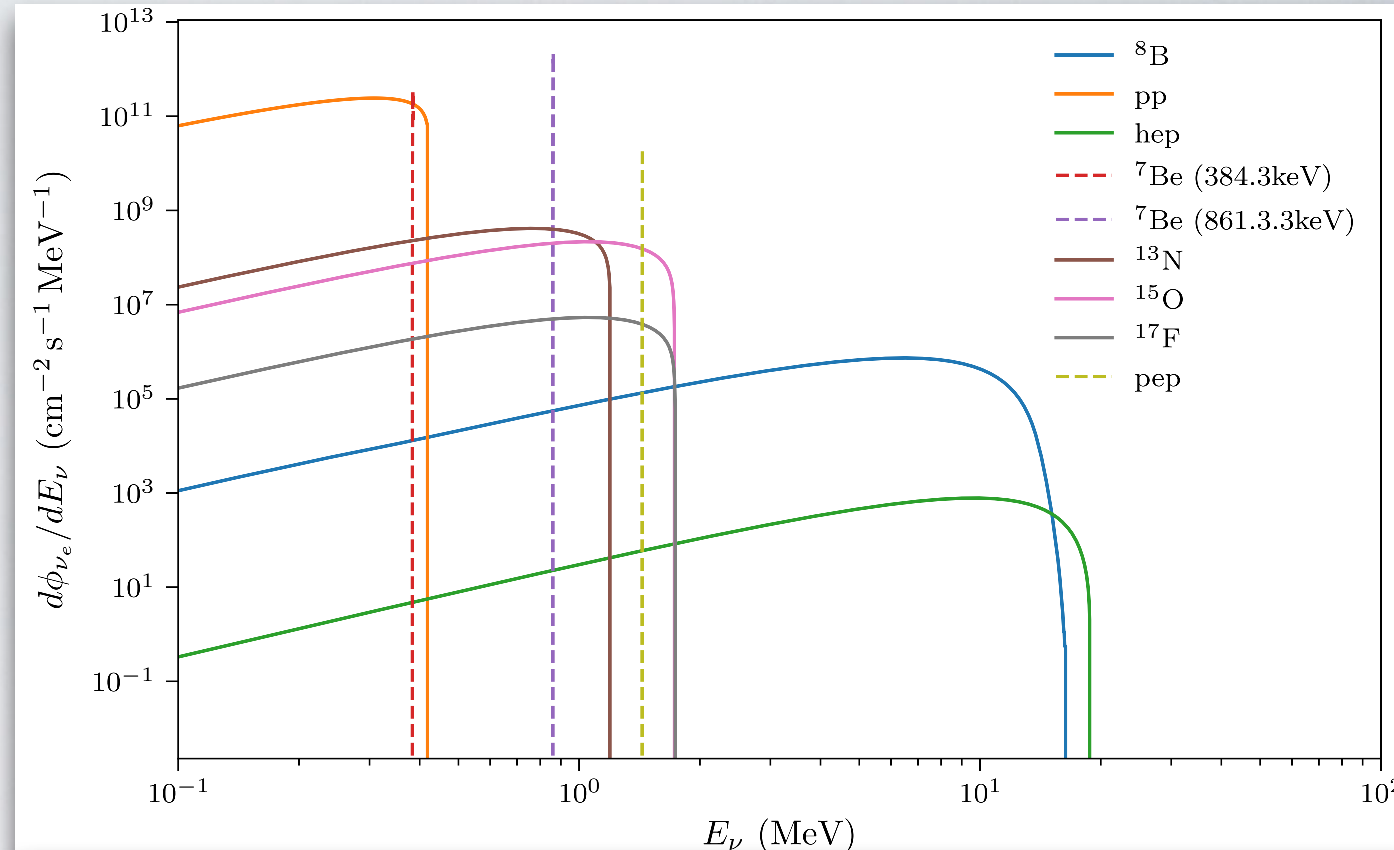


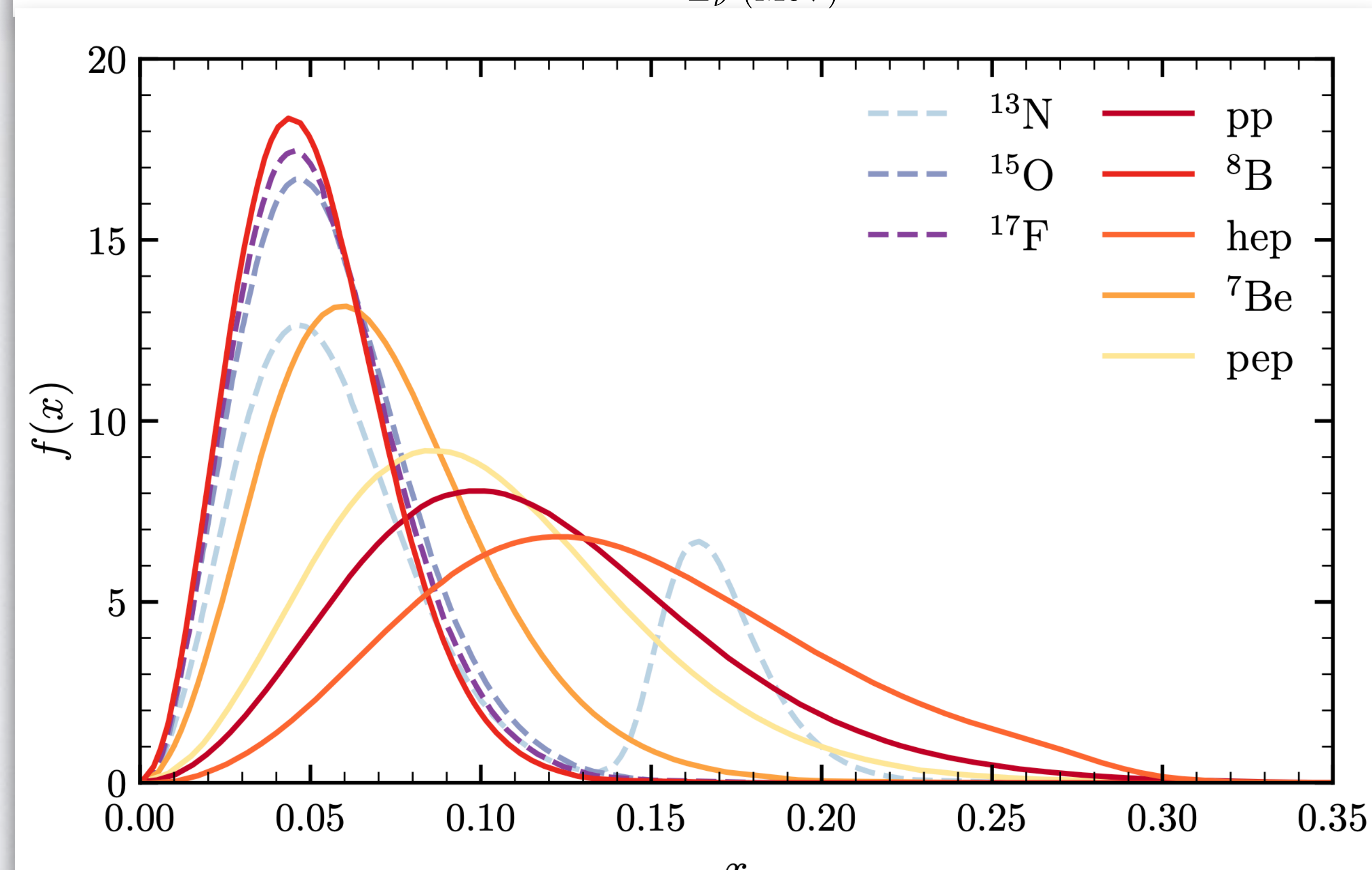
(Not to scale!)

SOLAR NEUTRINO SCATTERING

- There exist a number of **solar models** predicting the different neutrino flux components
- Neutrino production is driven by weak charged currents
- Also predicting the **production point of neutrinos** in the various processes

- The abundant solar neutrino flux makes this an excellent laboratory for **testing novel neutrino physics in all flavours!**





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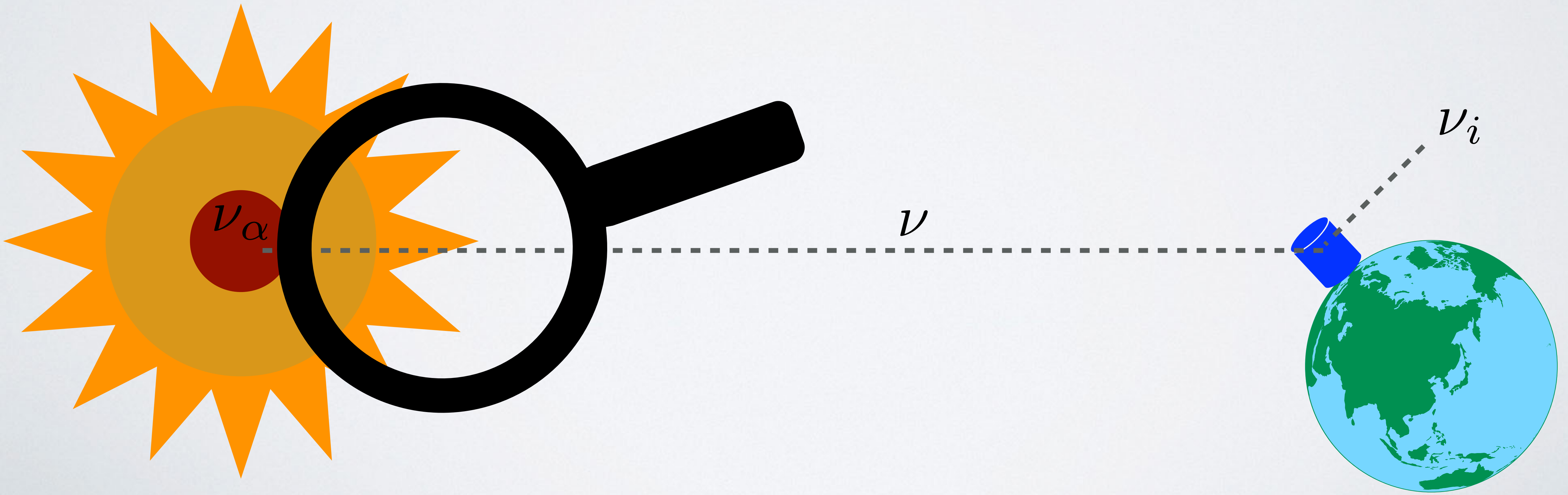
NEUTRINO PROPAGATION



SOLAR NEUTRINO PROPAGATION

- Need to **find the density matrix** $\boldsymbol{\rho^{(e)} = S\,\pi^{(e)} S^\dagger}$ of solar neutrinos reaching earth!

- To obtain propagation S-matrix need to solve **Schroedinger equation**

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \left[\frac{1}{2E_\nu}\,U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^\dagger + \begin{pmatrix}V_{cc} & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

where $\Delta m^2_{ij} = m_i^2 - m_j^2$ $\qquad V_{cc} = \sqrt{2}\,G_F\,N_e(x)$

- We define the PMNS matrix as

$$U = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\equiv R_{23}}\underbrace{\begin{pmatrix}c_{13} & 0 & s_{13}\\ 0 & 1 & 0\\ -s_{13} & 0 & c_{13}\end{pmatrix}}_{\equiv R_{13}}\underbrace{\begin{pmatrix}c_{12} & s_{12}\,e^{i\,\delta_{\rm CP}} & 0\\ -s_{12}\,e^{-i\,\delta_{\rm CP}} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\equiv U_{12}}$$

NEUTRINO PROPAGATION

- In **solar neutrino physics** it is convenient to **switch basis** to $\hat{\boldsymbol{\nu}} = O^\dagger \boldsymbol{\nu}$ with $O = R_{23} R_{13}$

- The evolution of $\hat{\boldsymbol{\nu}}$ is then governed by the Hamiltonian

$$\hat{H} = \frac{1}{2E_\nu} \begin{pmatrix} c_{13}^2 A_{cc} + s_{12}^2 \Delta m_{21}^2 & s_{12} c_{12} e^{i\delta} \Delta m_{21}^2 & s_{13} c_{13} A_{cc} \\ s_{12} c_{12} e^{-i\delta} \Delta m_{21}^2 & c_{12}^2 \Delta m_{21}^2 & 0 \\ s_{13} c_{13} A_{cc} & 0 & s_{13}^2 A_{cc} + \Delta m_{31}^2 \end{pmatrix}$$

- If $\Delta m_{31}^2 \gg \Delta m_{21}^2 \sim A_{cc}$ the third eigenvalue Δm_{31}^2 will dominate the matrix and the third neutrino state decouples from the lighter ones $\Rightarrow$ **reduces to two-state problem**

- Solar best fit values:

$$\Delta m_{31}^2 = \left(2.515^{+0.028}_{-0.028}\right) \times 10^{-3} \mathrm{eV}^2$$

$$\Delta m_{21}^2 = \left(7.42^{+0.21}_{-0.20}\right) \times 10^{-5} \mathrm{eV}^2$$

$$A_{cc} \sim 10^{-4} \mathrm{eV}^2 \ @\ E_\nu \sim 10\,\mathrm{MeV}$$

[Esteban et al., JHEP **09** (2020) 178 & NuFIT 5.1 [http://www.nu-fit.org]]

[Bahcall et al., Astrophys. J. Suppl. **165** (2006) 400]

FULL PROPAGATION

- After the orthogonal rotation $O = R_{23}\, R_{13}$, full three-flavour propagation becomes block-diagonal $\Rightarrow$ **effective two-state mixing**

$$i\,\partial_t \begin{pmatrix} \hat{\nu}_e \\ \hat{\nu}_\alpha \\ \hat{\nu}_\beta \end{pmatrix} = \underbrace{\begin{pmatrix} \mathrm{Evol}[H^{\mathrm{eff}}] & 0 \\ 0 & \exp[-i\,\frac{\Delta m^2_{31}}{2\,E_\nu}\,L] \end{pmatrix}}_{\equiv \tilde{S}} \begin{pmatrix} \hat{\nu}_e \\ \hat{\nu}_\alpha \\ \hat{\nu}_\beta \end{pmatrix}$$

- Assuming adiabaticity ($|\,\Delta E^m_{12}\,| \gg 2\,|\,\dot{\theta}^m_{12}\,|$) within the Sun (slowly varying matter profile), get expression for **full propagation S-matrix:**

$$S = O\,\tilde{S}\,O^\dagger = \underbrace{O\,U_{12}}_{U_{\mathrm{PMNS}}} \begin{pmatrix} \exp\left[-i\,\int_0^L D(x)dx\right] & 0 \\ 0 & \exp[-i\,\frac{\Delta m^2_{31}}{2\,E_\nu}\,L] \end{pmatrix} \underbrace{U^m_{12}(x_0)^\dagger O^\dagger}_{U^m_{\mathrm{PMNS}}(x_0)^\dagger}$$

with

$$D(x) = \begin{pmatrix} E^m_1 & -i\,\dot{\theta}^m_{12} \\ i\,\dot{\theta}^m_{12} & E^m_2 \end{pmatrix} \sim \mathrm{diag}(E^m_1, E^m_2)$$

TWO-STATE MIXING

- The two-state system can be described by effective Hamiltonian $H^{\text{eff}} \equiv H^{\text{eff}}_{\text{vac}} + H^{\text{eff}}_{\text{mat}}$

$$H^{\text{eff}}_{\text{vac}} \equiv \frac{\Delta m^2_{21}}{4E_\nu}\begin{pmatrix} -\cos 2\theta_{12} & \sin 2\theta_{12}\, e^{i\,\delta} \\ \sin 2\theta_{12}\, e^{-i\,\delta} & \cos 2\theta_{12} \end{pmatrix} \qquad H^{\text{eff}}_{\text{mat}} \equiv \sqrt{2} G_F N_e(x) \begin{pmatrix} c^2_{13} & 0 \\ 0 & 0 \end{pmatrix}$$

- **Diagonalise** this Hamiltonian via matter mixing matrix

$$U^m_{12} = \begin{pmatrix} \cos\theta^m_{12} & \sin\theta^m_{12} \\ -\sin\theta^m_{12} & \cos\theta^m_{12} \end{pmatrix}$$

defining $\Delta E_{21} \equiv \Delta m^2_{21}/(2E_\nu)$ we find the **matter eigenvalues and mixing angle:**

$$E^m_1 = \frac{1}{2}\left[V_{cc}\, c^2_{13} - \Delta E_{21}\sqrt{p^2+q^2}\right], \quad E^m_2 = \frac{1}{2}\left[V_{cc}\, c^2_{13} + \Delta E_{21}\sqrt{p^2+q^2}\right]$$

$$\sin 2\theta^m_{12} = \frac{p}{\sqrt{p^2+q^2}}, \qquad \cos 2\theta^m_{12} = \frac{q}{\sqrt{p^2+q^2}}$$

with

$$p = \sin 2\theta_{12} \qquad q = \cos 2\theta_{12} - c^2_{13}\frac{V_{cc}}{\Delta E_{21}}$$

MATTER EFFECTS WITH NSI

- The presence of NSI leads to the **presence of additional matter potentials**

$$H^{\rm eff}_{\rm mat} \equiv \sqrt{2} G_F N_e(x) \left[\begin{pmatrix} c_{13}^2 & 0 \\ 0 & 0 \end{pmatrix} + [(\xi^p + \xi^e) + Y_n(x)\xi^n] \begin{pmatrix} -\varepsilon_D^{\eta,\varphi} & \varepsilon_N^{\eta,\varphi} \\ \varepsilon_N^{\eta,\varphi} & \varepsilon_D^{\eta,\varphi} \end{pmatrix} \right]$$

with $Y_n(x) \equiv N_n(x)/N_e(x)$ and the *matter NSIs*

$$\begin{aligned} \varepsilon_D^{\eta,\varphi} \equiv\, & c_{13}\, s_{13} \left(s_{23}\, \varepsilon_{e\mu}^{\eta,\varphi} + c_{23}\, \varepsilon_{e\tau}^{\eta,\varphi} \right) - \left(1 + s_{13}^2\right) c_{23}\, s_{23}\, \varepsilon_{\mu\tau}^{\eta,\varphi} \\ & - \frac{c_{13}^2}{2} \left(\varepsilon_{ee}^{\eta,\varphi} - \varepsilon_{\mu\mu}^{\eta,\varphi} \right) + \frac{s_{23}^2 - s_{13}^2\, c_{23}^2}{2} \left(\varepsilon_{\tau\tau}^{\eta,\varphi} - \varepsilon_{\mu\mu}^{\eta,\varphi} \right) \end{aligned}$$

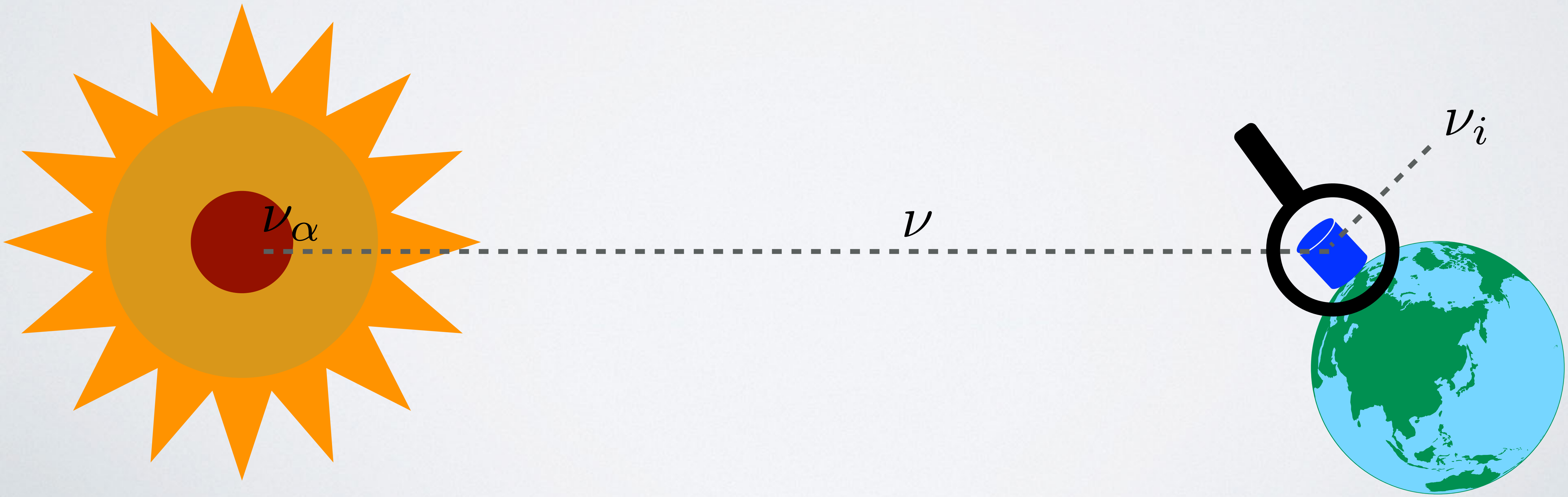
$$\varepsilon_N^{\eta,\varphi} \equiv c_{13} \left(c_{23}\, \varepsilon_{e\mu}^{\eta,\varphi} - s_{23}\, \varepsilon_{e\tau}^{\eta,\varphi} \right) + s_{13} \left[s_{23}^2\, \varepsilon_{\mu\tau}^{\eta,\varphi} - c_{23}^2\, \varepsilon_{\mu\tau}^{\eta,\varphi} + c_{23}\, s_{23} \left(\varepsilon_{\tau\tau}^{\eta,\varphi} - \varepsilon_{\mu\mu}^{\eta,\varphi} \right) \right]$$

- **This modifies the matter quantities**

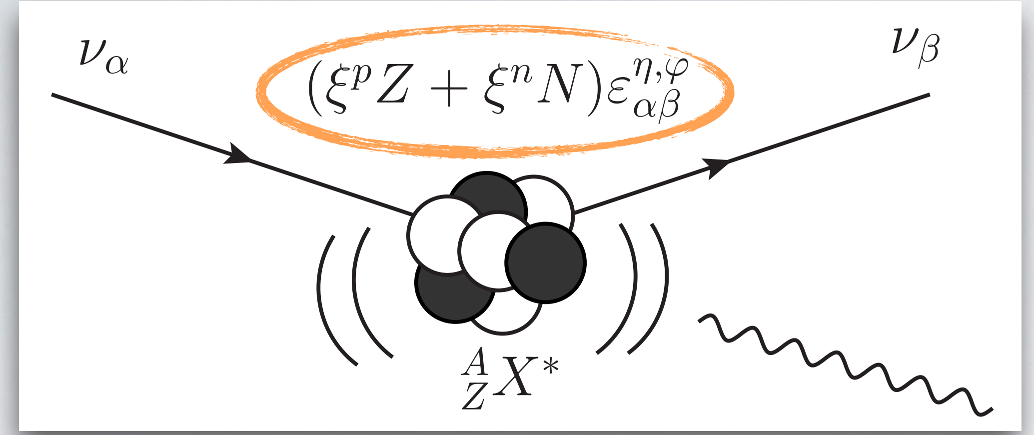
$$p = \sin 2\theta_{12} + 2\,\boldsymbol{\xi}\, \varepsilon_N^{\eta,\varphi} \frac{V_{cc}}{\Delta E_{21}}\,, \qquad q = \cos 2\theta_{12} + (2\,\boldsymbol{\xi}\, \varepsilon_D^{\eta,\varphi} - c_{13}^2) \frac{V_{cc}}{\Delta E_{21}}$$

where $\boldsymbol{\xi} \equiv \xi^e + \xi^p + Y_n(x)\xi^n$

NEUTRINO SCATTERING



SOLAR NEUTRINO SCATTERING

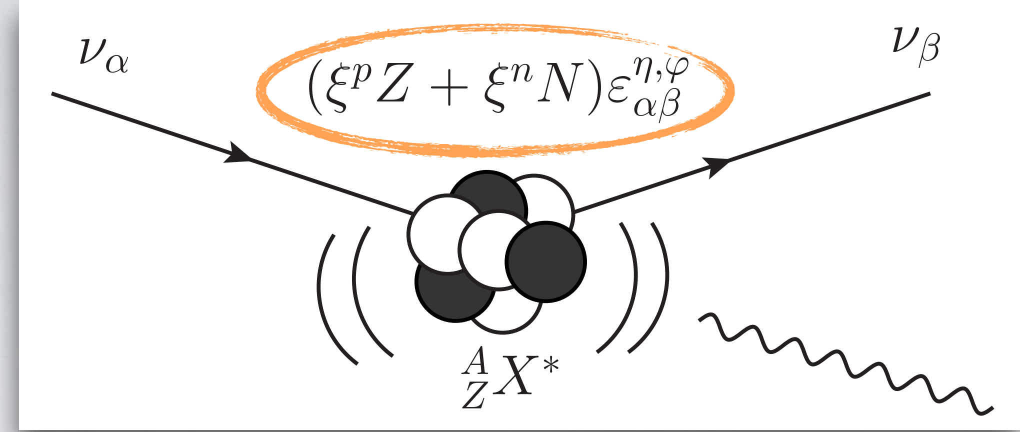


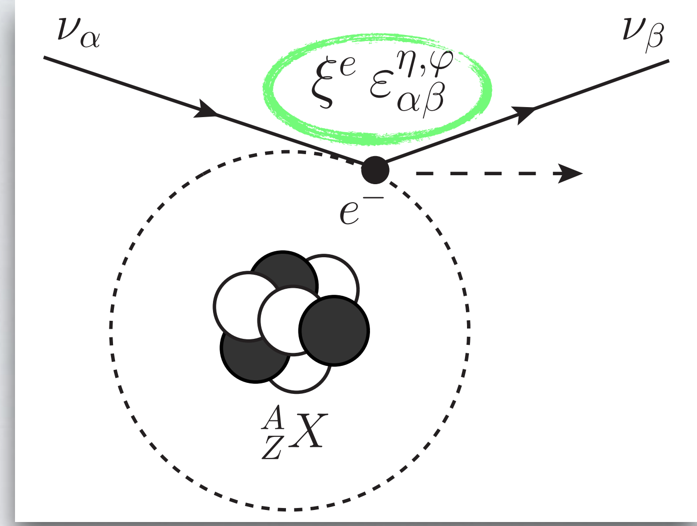
1. The **generalised coherent elastic neutrino nucleus scattering (CEνNS) cross section** is

$$\left(\frac{d\zeta_{\nu N}}{dE_R}\right)_{\alpha\beta} = \frac{G_F^2\, M_N}{\pi}\left(1 - \frac{M_N\, E_R}{2E_\nu^2}\right)\left[\frac{1}{4}\, Q_{\nu N}^2\, \delta_{\alpha\beta} - Q_{\nu N}\, G_{\alpha\beta}^{\rm NSI} + \sum_\gamma G_{\alpha\gamma}^{\rm NSI} G_{\gamma\beta}^{\rm NSI}\right] F^2(E_R)$$

with $Q_{\nu N} = N - (1 - 4\,\sin^2\theta_W)\, Z$ and $G_{\alpha\beta}^{\rm NSI} = (\xi^p\, Z + \xi^n\, N)\; \varepsilon_{\alpha\beta}^{\eta,\varphi}$

SOLAR NEUTRINO SCATTERING





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2. The **generalised elastic neutrino-electron scattering (EνES) cross section**:

$$\left(\frac{d\zeta_{\nu e}}{dE_R}\right)_{\alpha\beta} = \frac{2\, G_F^2\, m_e}{\pi} \sum_\gamma \left\{ G^L_{\alpha\gamma} G^L_{\gamma\beta} + G^R_{\alpha\gamma} G^R_{\gamma\beta}\left(1 - \frac{E_R}{E_\nu}\right)^2 - (G^L_{\alpha\gamma} G^R_{\gamma\beta} + G^R_{\alpha\gamma} G^L_{\gamma\beta})\, \frac{m_e\, E_R}{2E_\nu^2}\right\}$$

with $g^f_P = T^3_f - \sin^2\theta_w\, Q^{\rm EM}_f$ and (vector NSI only):

$$G^L_{\alpha\beta} = (\delta_{e\alpha} + g^e_L)\,\delta_{\alpha\beta} + \frac{1}{2}\,\varepsilon^{\eta,\varphi}_{\alpha\beta}\,\xi^e, \qquad G^R_{\alpha\beta} = g^e_R\,\delta_{\alpha\beta} + \frac{1}{2}\,\varepsilon^{\eta,\varphi}_{\alpha\beta}\,\xi^e$$

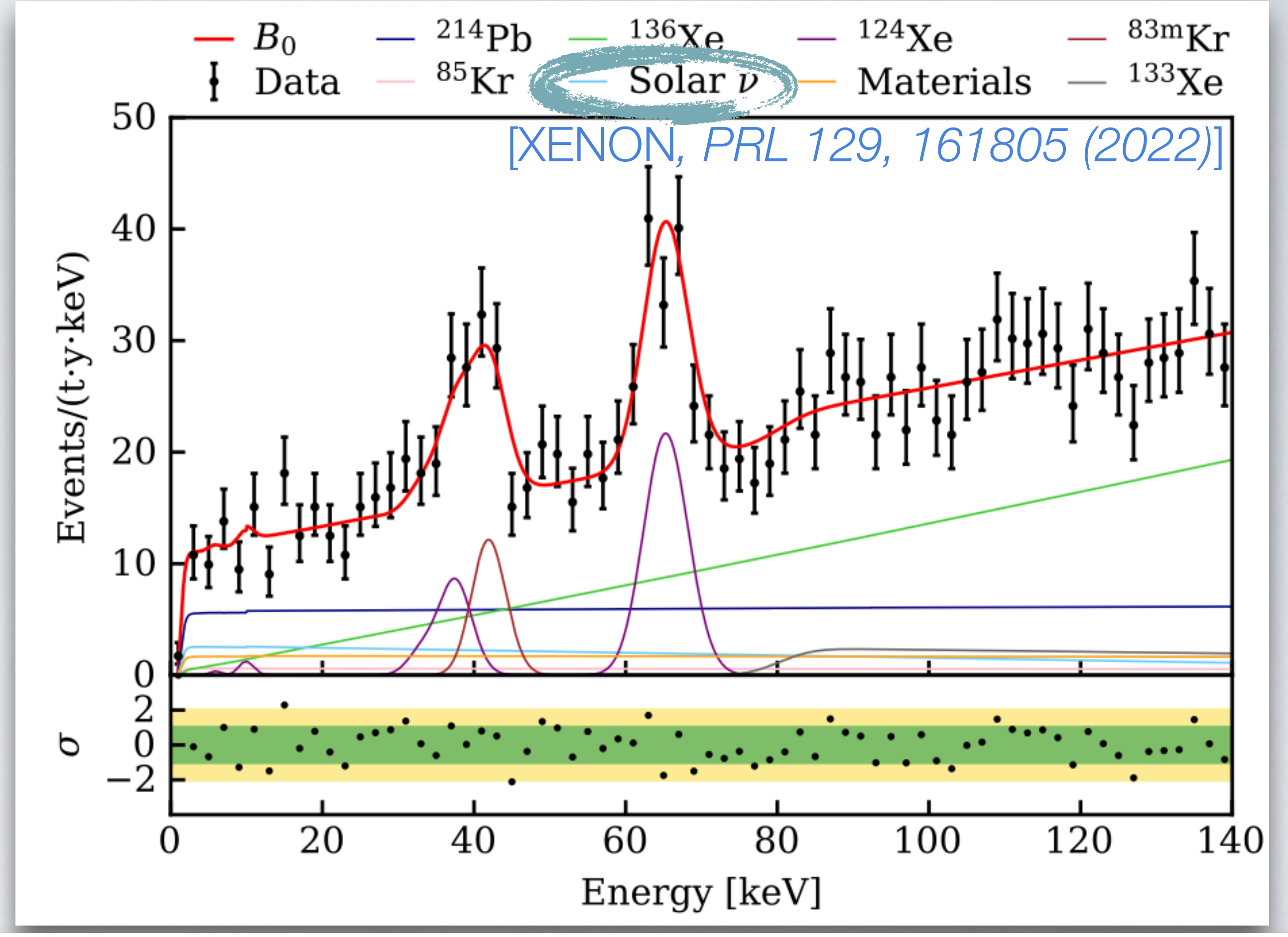
PUTTING THINGS TOGETHER:

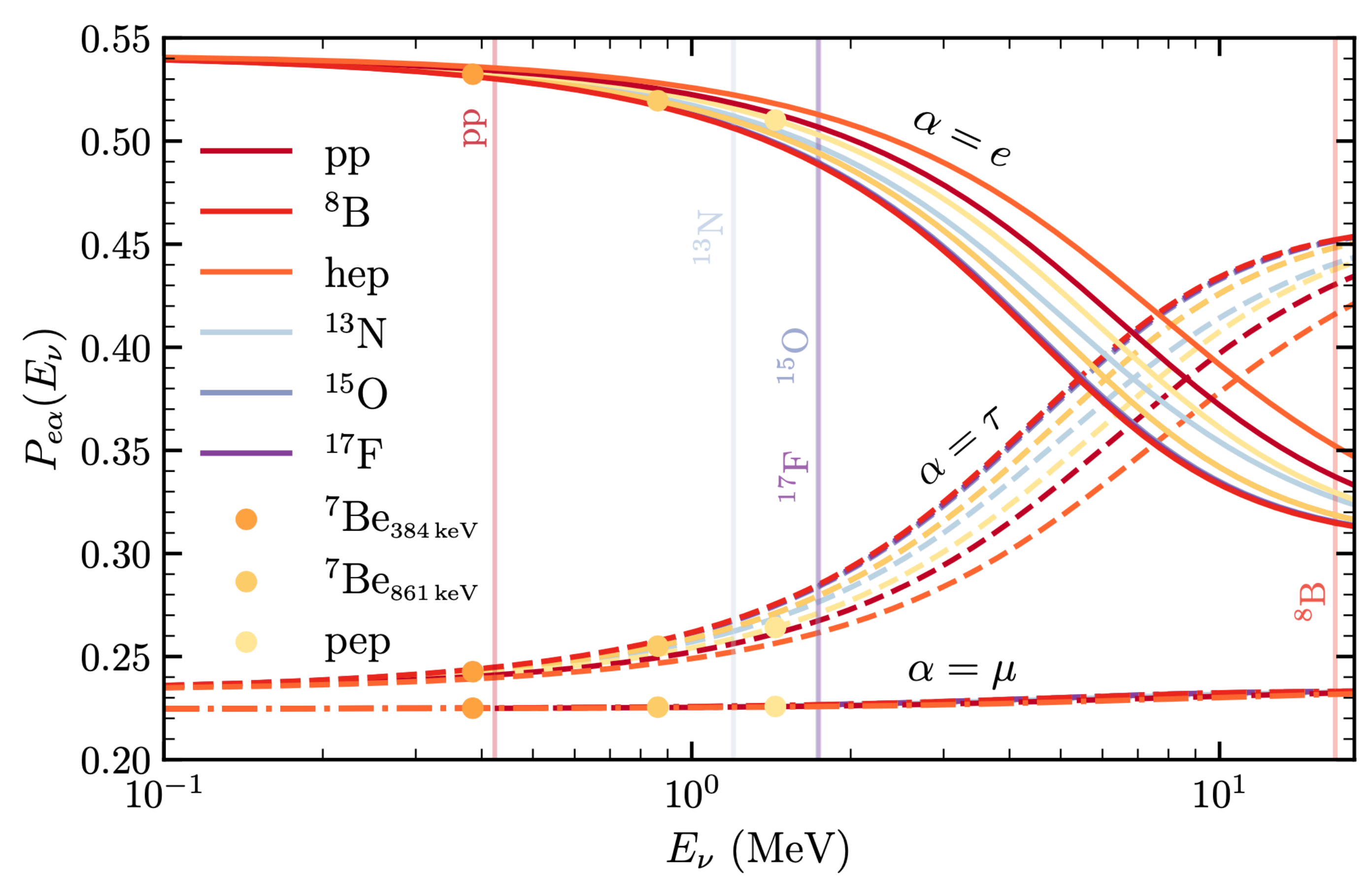
NEUTRINO DIRECT DETECTION

SOLAR NEUTRINOS @ DD

- Including DD experiments has many advantages for NSI searches
- Sensitive to **both nuclear and electron scattering**
- Solar neutrino flux has **large admixtures of ν_τ at high energies**
- XENONnT published **first observation of 300 EνES events** (8% of BG)
- With future improvements, solar ν will dominate ER background for DM searches

Experiment	ε (t·yr)	E_{th}^{NR} (keV$_{\mathrm{nr}}$)	E_{th}^{ER} (keV$_{\mathrm{ee}}$)
LZ	15.34	3	1.46
XENONnT	20	3	1.51
DARWIN	200	3	1.51

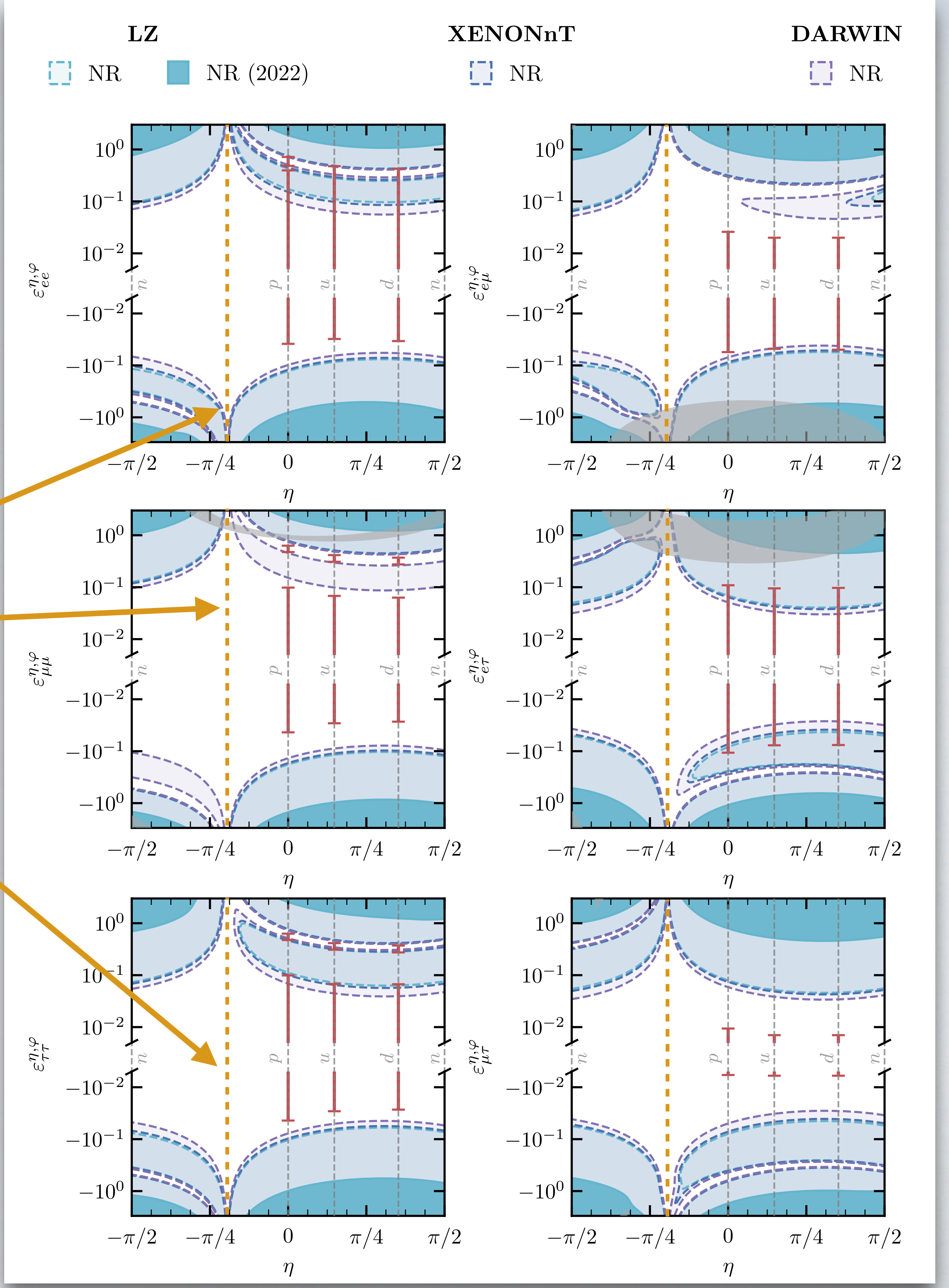




NUCLEAR SCATTERING

- Consider one NSI coupling at a time and compare sensitivity to global fit limits from [Coloma et al., *JHEP* **02** (2020) 023]
- **In the future DD can improve over existing constraints**
- **Target material dependent blind spot where neutron and proton NSI cancel**

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



[Amaral, Cheek, Cerdeño, PF; 2302.12846]

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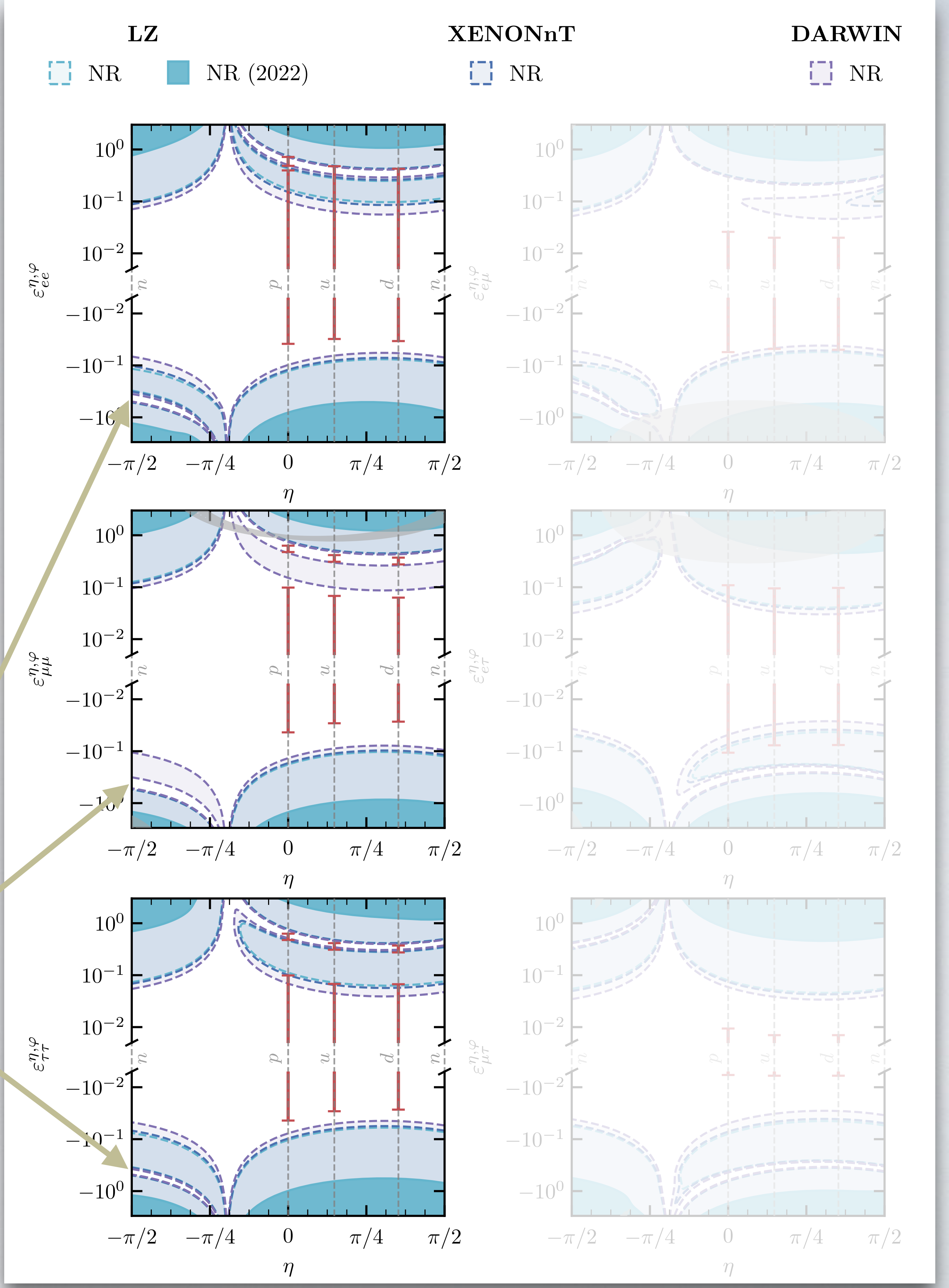
- Blind spot due to **SM-NSI interference** terms in CEνNS cross section

Diagonal: $$\varepsilon^{\eta,\varphi}_{\alpha\alpha} = \frac{Q_{\nu N}}{\xi^p Z + \xi^n N}$$



[Amaral, Cheek, Cerdeño, PF; 2302.12846]

NUCLEAR SCATTERING

- Consider one NSI coupling at a time and compare sensitivity to global fit limits from [Coloma et al., *JHEP* **02** (2020) 023]
- **In the future DD can improve one existing constraints**
- **Target material dependent blind spot** where cross section vanishes

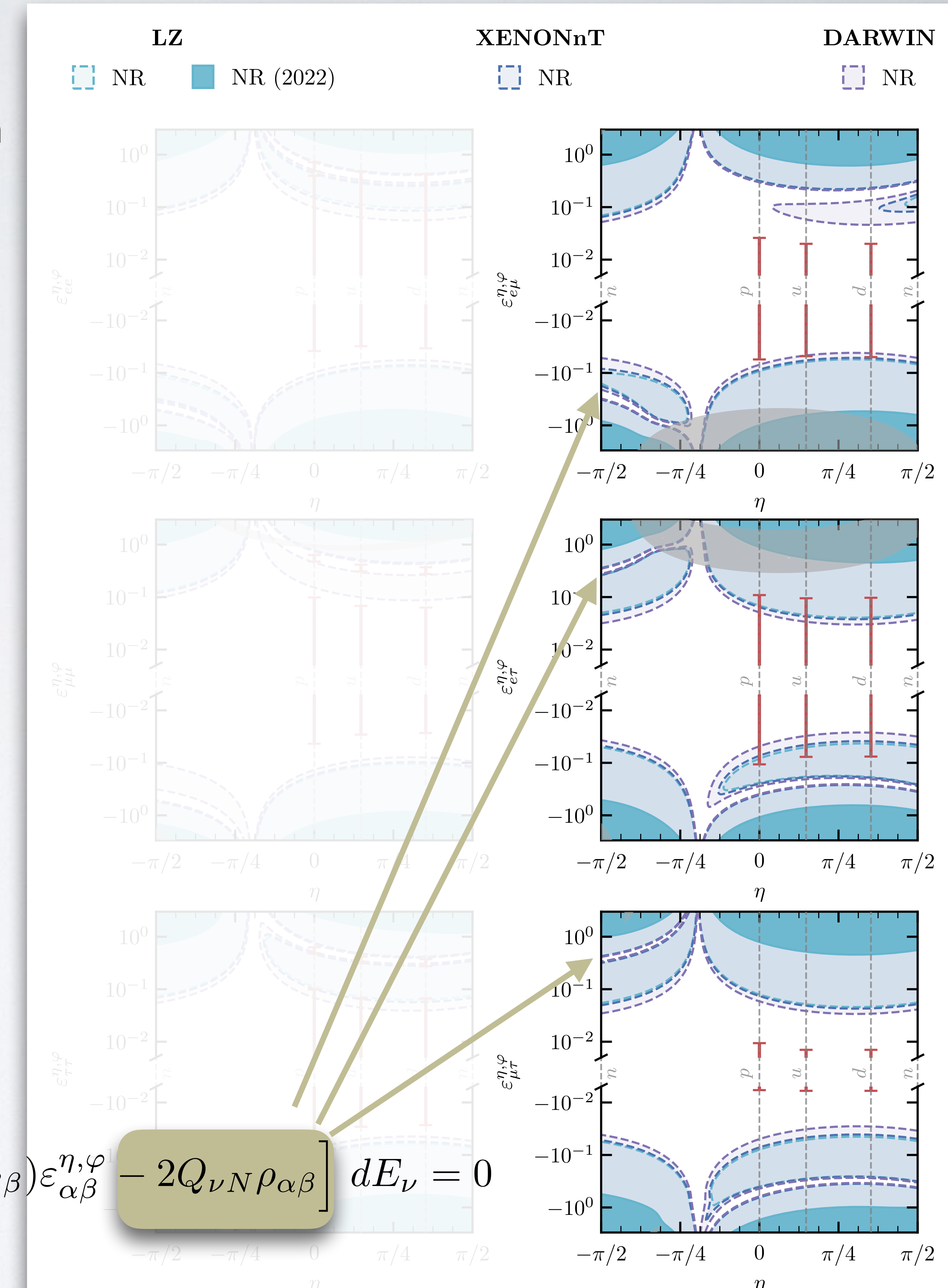
$$\eta = \tan^{-1}\left(-\frac{Z}{N}\cos\varphi\right)$$

- Blind spot due to **SM-NSI interference** terms in CEνNS cross section

Diagonal: $$\varepsilon^{\eta,\varphi}_{\alpha\alpha} = \frac{Q_{\nu N}}{\xi^p Z + \xi^n N}$$

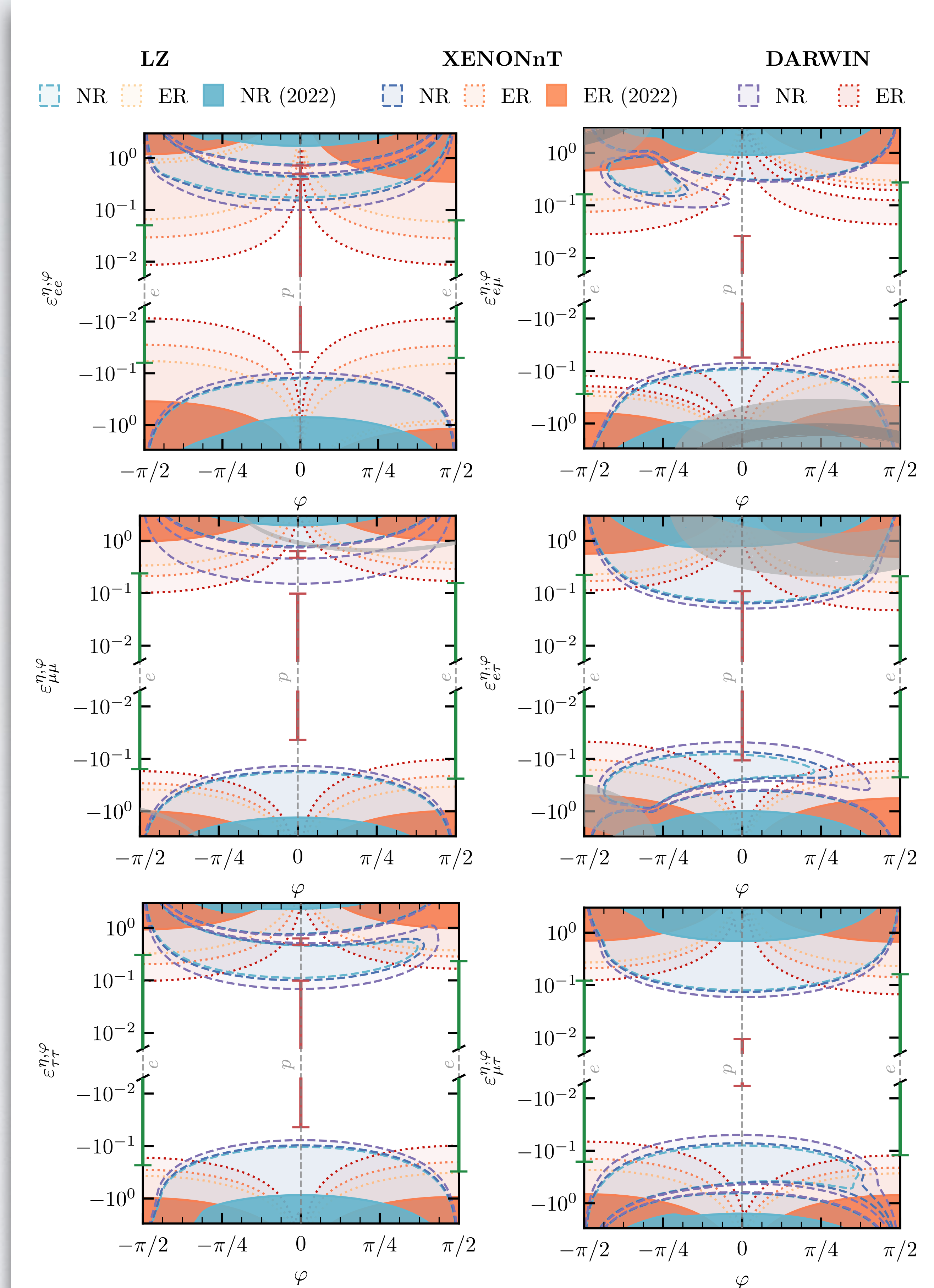
Off-diagonal:

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



ADDING ELECTRON SCATTERING

- We show the sensitivities in the $\{\xi^p, \xi^e\}$ plane
- The **current limits** on the NSI for pure electron couplings is illustrated by the **green bar at $\varphi = \pm\pi/2$**
- ER sensitivities drop off towards $\varphi = 0$ (pure proton), whereas NR sensitivities become maximal
- Direct detection experiments have **excellent sensitivity to ER**!
- Future **DARWIN** can potentially **improve by an order of magnitude** over current electron NSI bounds
- Direct detection experiments become an important player for neutrino physics!

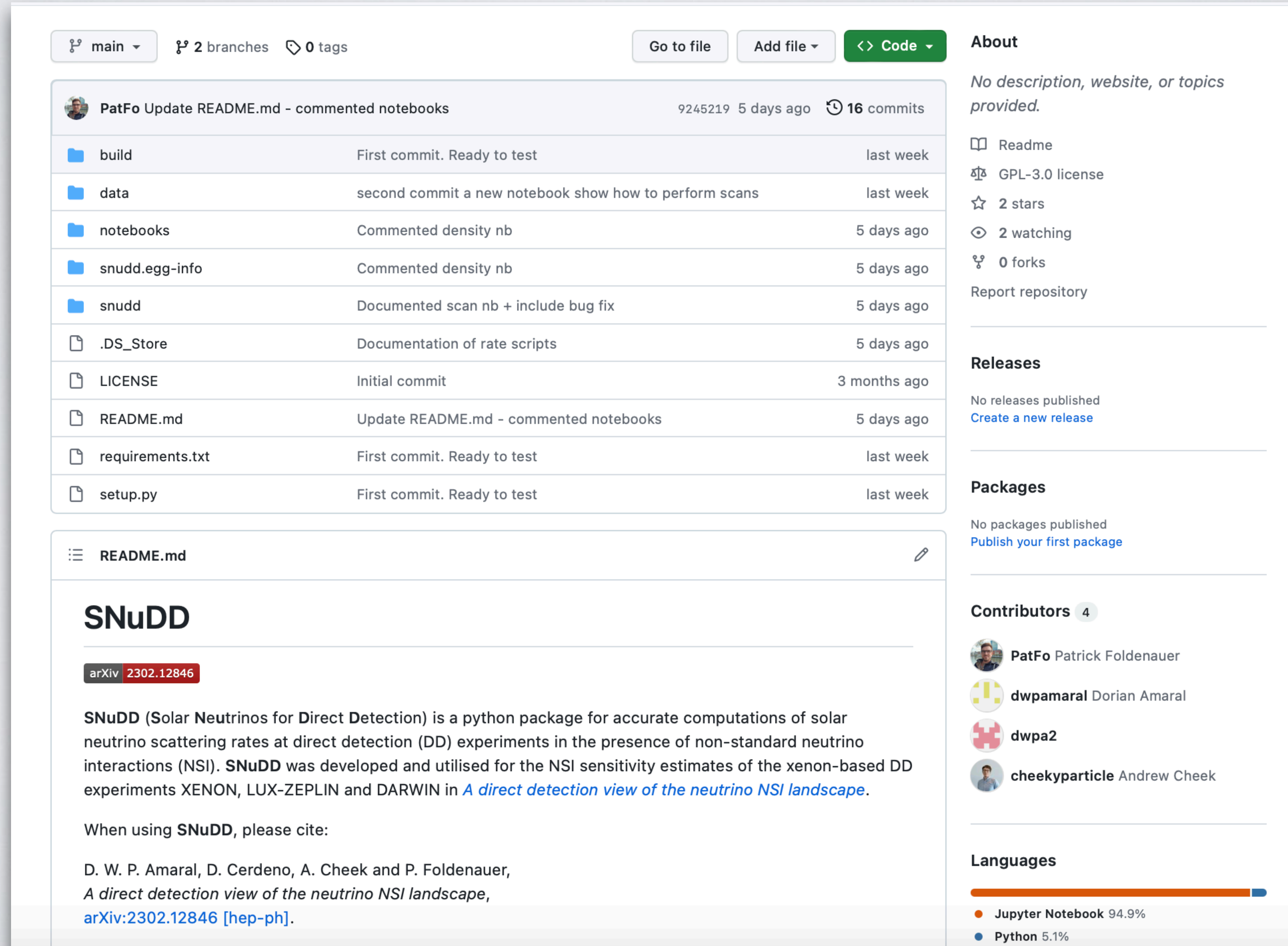


[Amaral, Cheek, Cerdeño, PF; 2302.12846]

SNuDD

"Solar Neutrinos for Direct Detection"

- Implemented the full chain of **propagation, scattering** plus **detector effects** for **NSI in solar** ν in open-source **Python package**: https://github.com/SNuDD/SNuDD.git



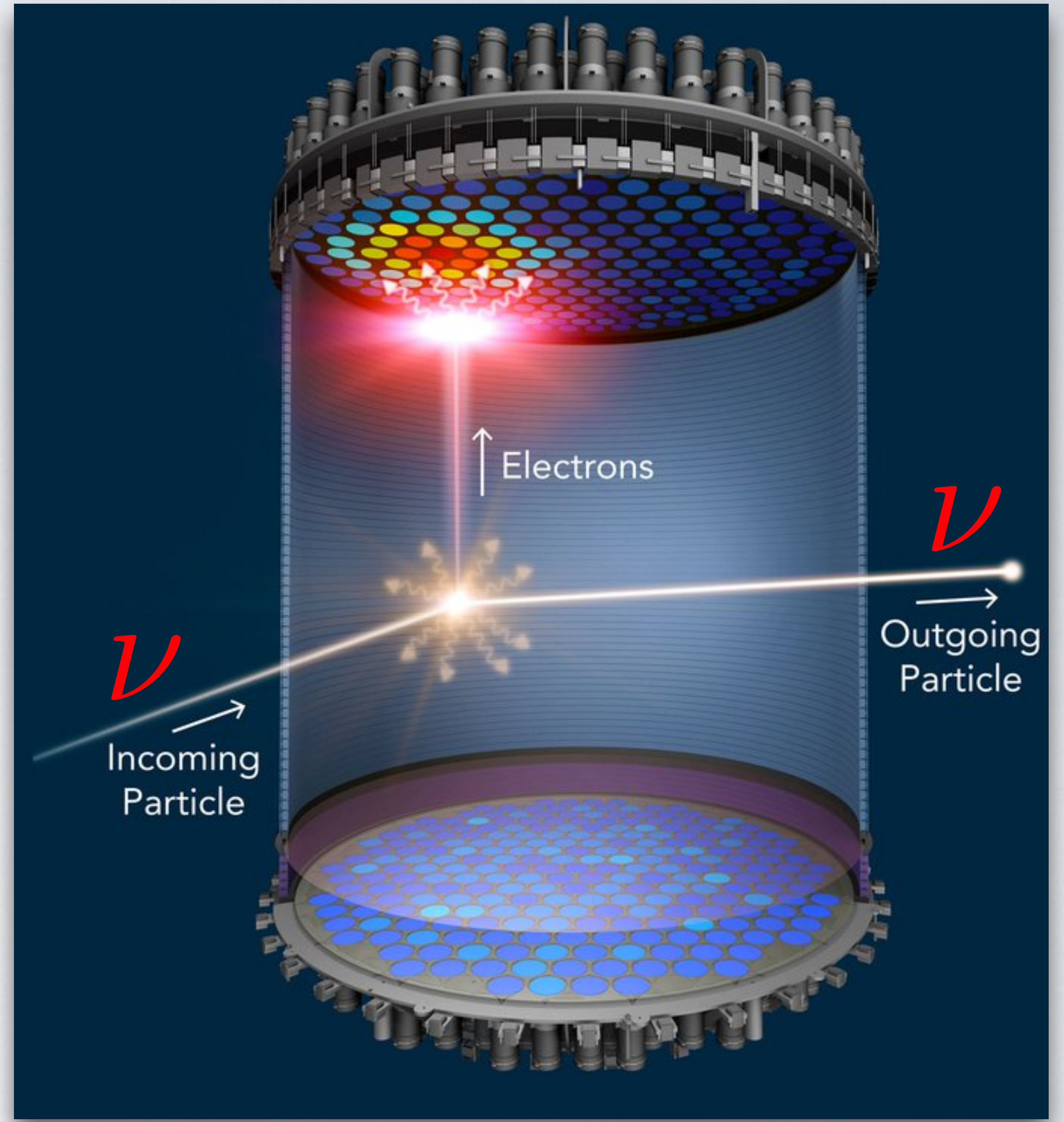
CONCLUSIONS

- In the next years **direct detection experiments** will see large numbers of solar neutrinos
  ⇒ We get **neutrino experiments for free**!

- Direct detection sensitive to **full NSI parameter space spanned by** $\{\varepsilon^e, \varepsilon^p, \varepsilon^n\}$, both in propagation and scattering

- **SNuDD** (https://github.com/SNuDD/SNuDD.git) is the **first tool on the market** to make consistent rate prediction of solar neutrinos at DD

- In particular, future **sensitivity to electronic recoils will provide complementary information** to spallation source and oscillation experiments!



- **Direct detection experiments will become an important player for neutrino physics!**

- **GOAL: Work towards global fit for NSIs including DD experiments!**

BACKUP

CENNS-10 RESULTS

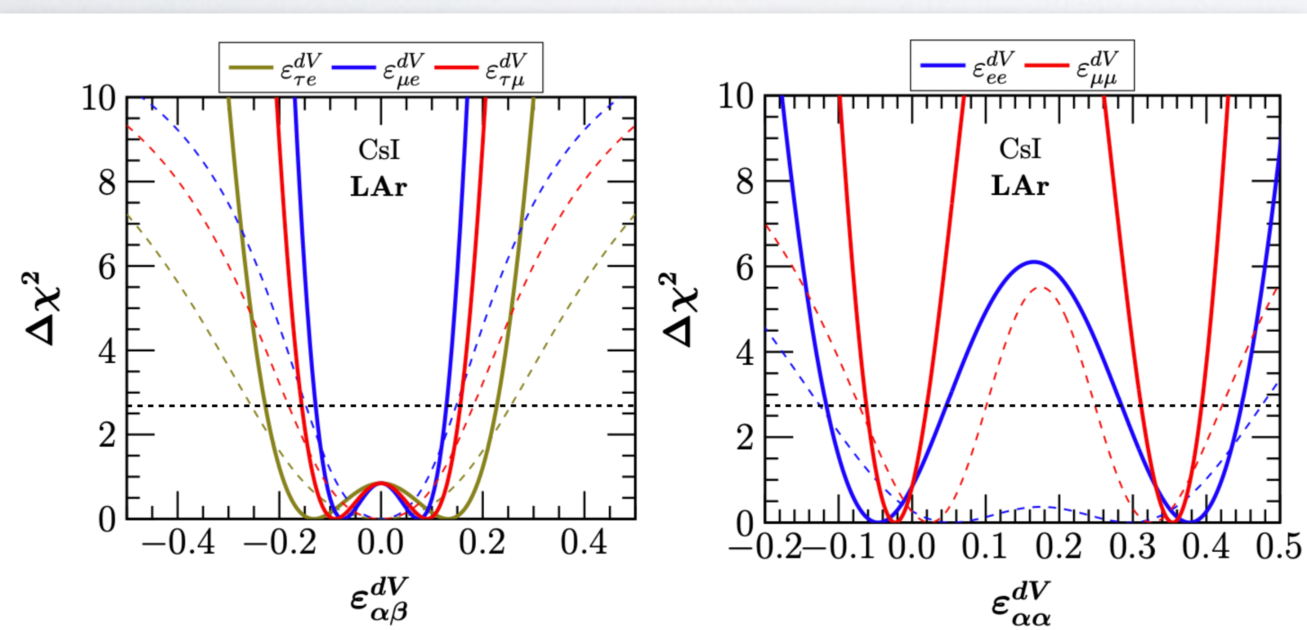
- We repeat the analysis done for **pure up-quark** NSIs ($\eta = \tan^{-1}(1/2)$, $\varphi = 0$)

- Two minima, since **CENNS-10 LAr has observed slight excess** w.r.t. SM

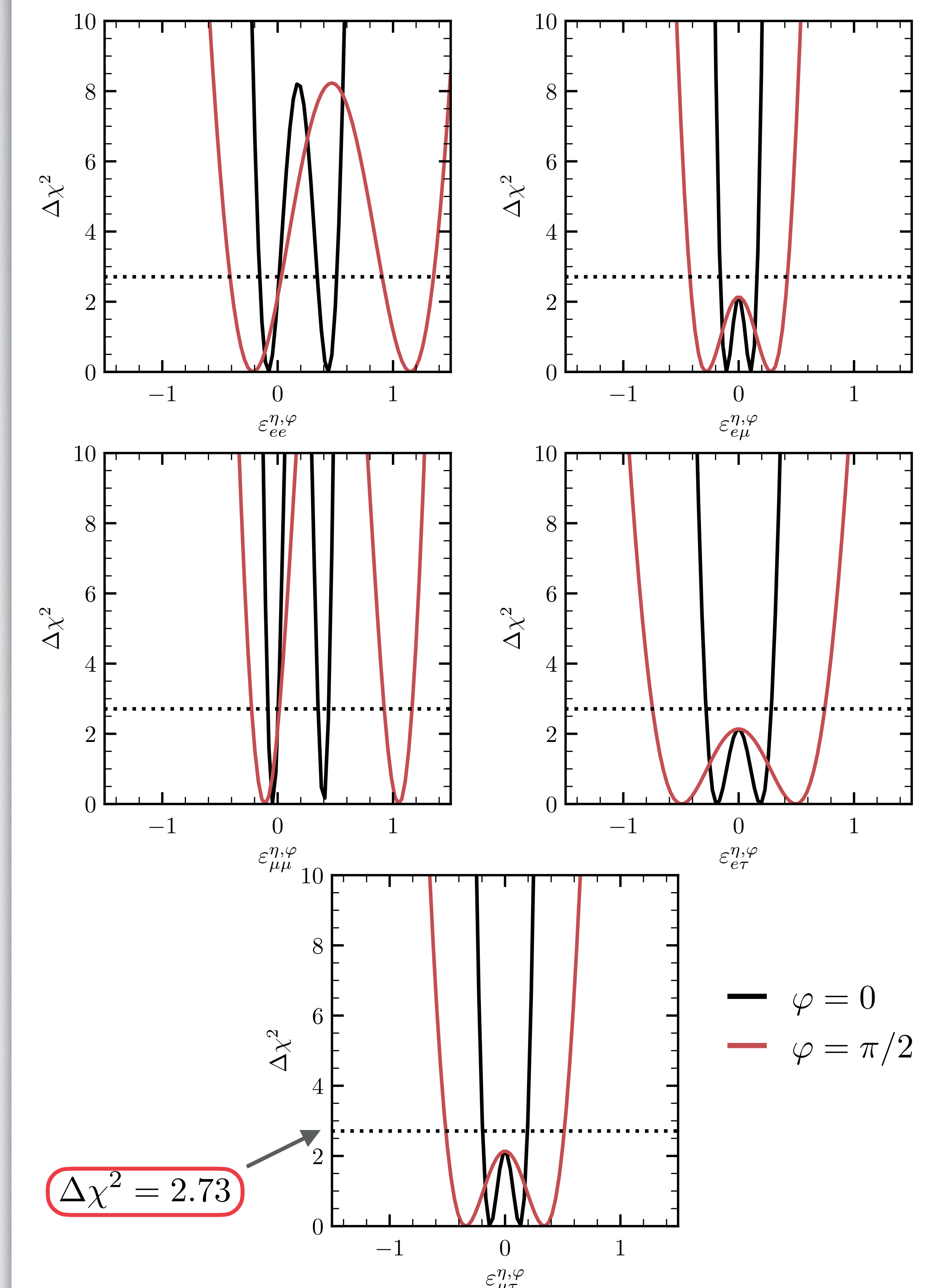
- Compare the results for **pure proton ($\varphi = 0$)** to **pure electron ($\varphi = \pi/2$)** in the charged fermion direction

- Constraints weaken in electron direction as the contribution to proton is minimal, also the location of the minima shift to higher $\varepsilon_{\alpha\beta}$

[Miranda et al., *JHEP* **05** (2020) 130]



[Amaral, Cheek, Cerdeño, PF; 2302.12846]



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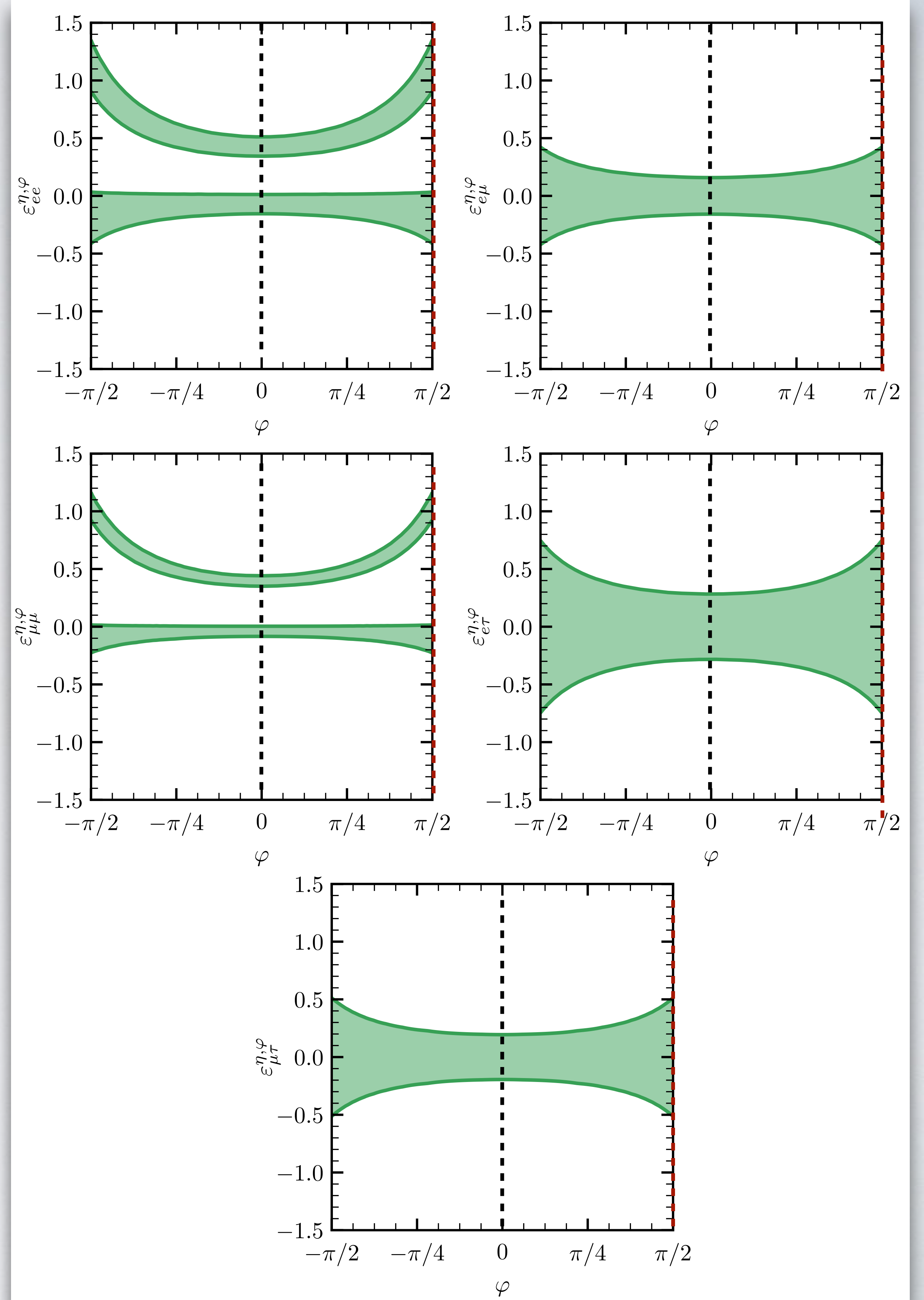
- Constraints weaken in electron direction as the contribution to proton is minimal, also the location of the minima shift to higher $\varepsilon_{\alpha\beta}$
- Since CEvNS is only sensitive to $\varepsilon^{p}_{\alpha\beta}$ in charged direction, the limits are expected to scale like $1/\cos\varphi$ due to parameterisation (for $\eta = 0$)

$$\xi^p = \sqrt{5}\,\cos\eta\,\cos\varphi$$

[Amaral, Cheek, Cerdeño, PF; 2302.12846]



BOREXINO

- Repeat simplistic Borexino-only analysis, only allowing for theoretical uncertainties:

$$\varepsilon_{ee}^{V} \in [-0.12, 0.08]$$

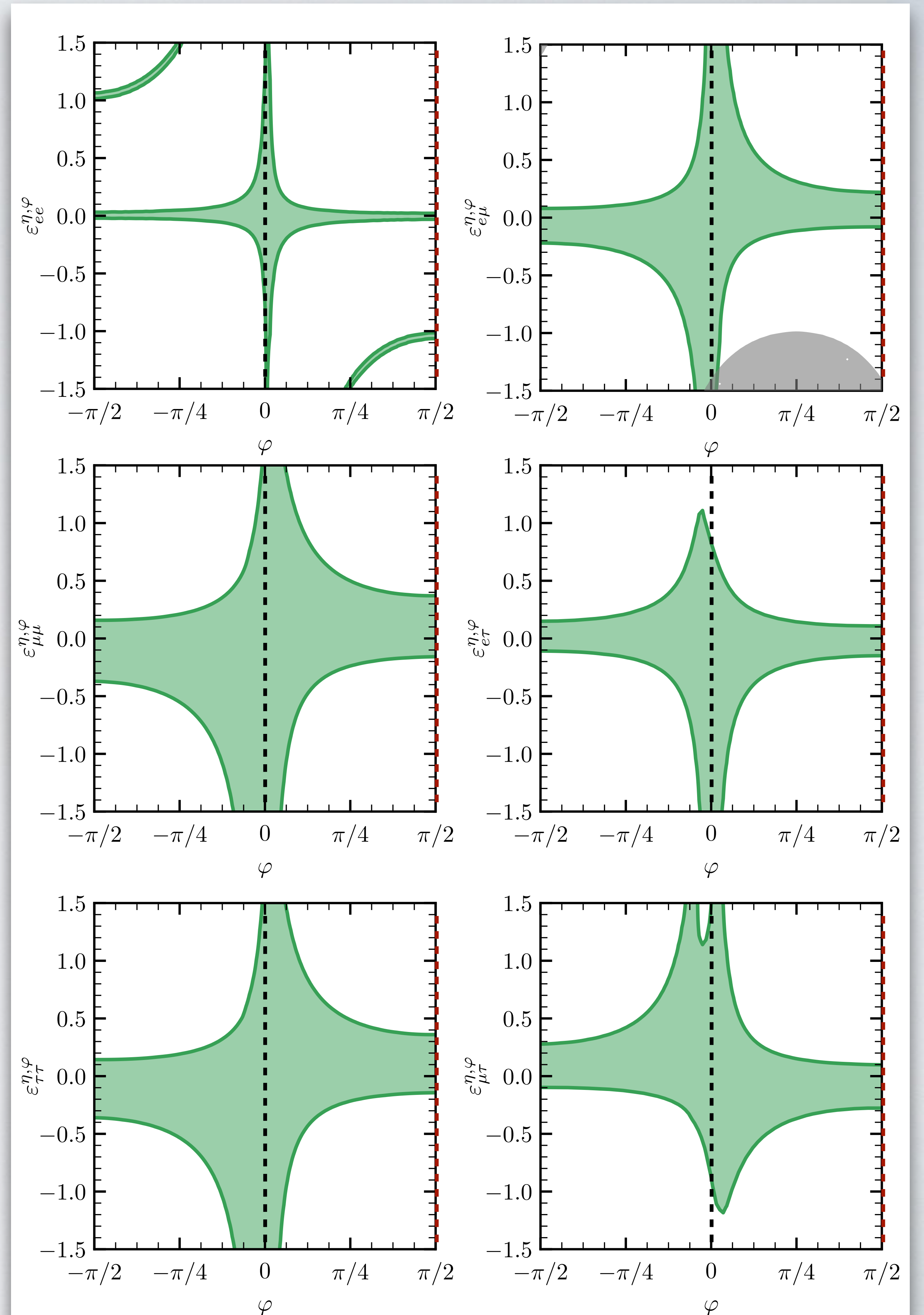
[Khan et al., *Phys. Rev. D 101, 055047 (2020)*]
[Coloma et al., *JHEP 07 (2022) 138*]

- At $\varphi = 0$ **(pure proton) NSI only impact the neutrino propagation**; cross section unaltered $\Rightarrow$ NSI least constrained

- At $\varphi = \pi/2$ **(pure electron) maximal effect** both in propagation and cross section
  $\Rightarrow$ most stringent bounds

- **Off-diagonal more tightly constrained** due to appearance of NSI elements twice in trace

$$\frac{dR}{dE_R} \propto \mathrm{Tr}\left[\boldsymbol{\rho}\, \frac{d\zeta}{dE_R}\right]$$



[Amaral, Cheek, Cerdeño, PF; 2302.12846]

BOREXINO

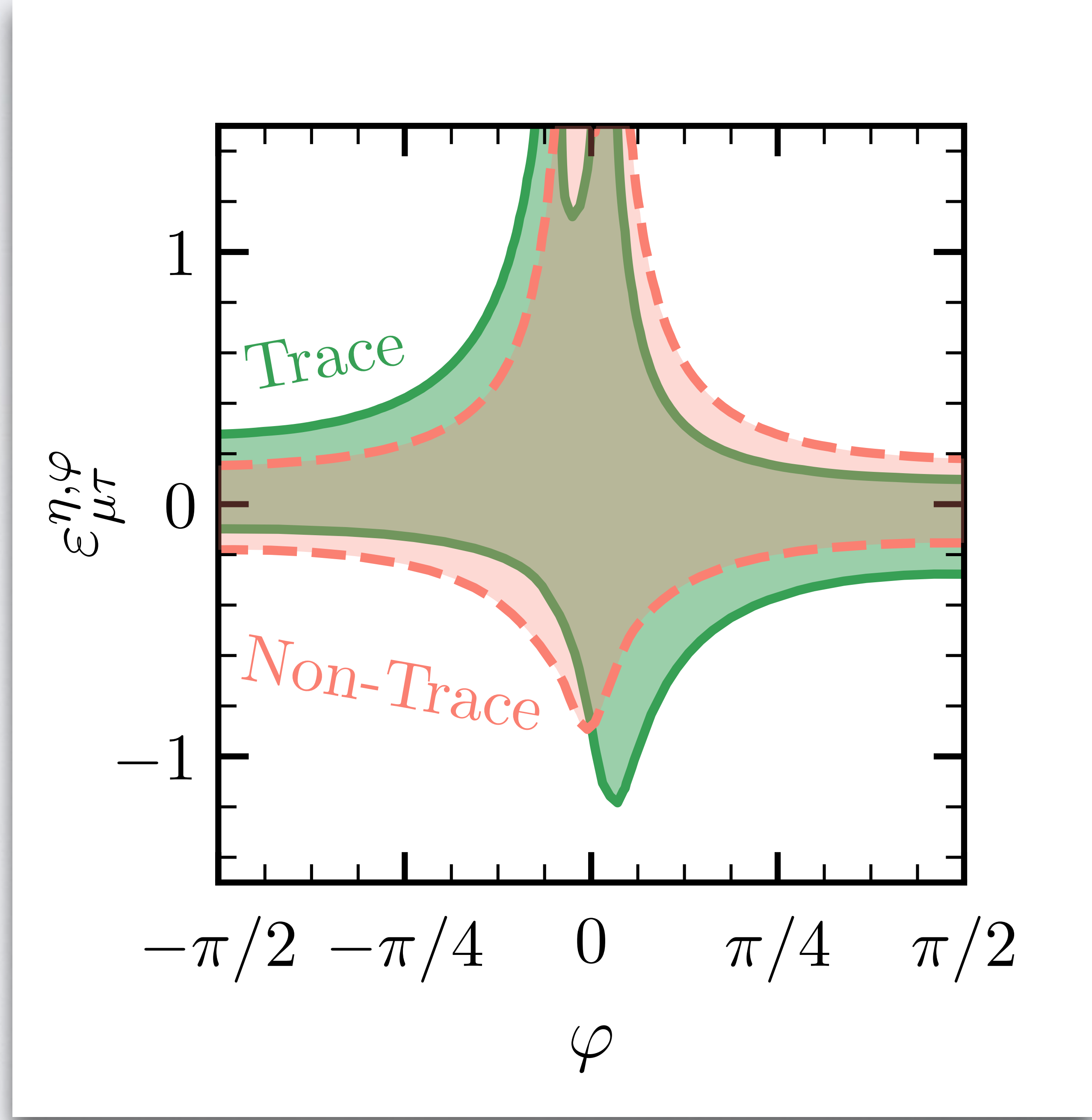
- For all off-diagonal NSI elements ($\varepsilon_{\alpha\beta}^{\eta,\varphi}, \alpha \neq \beta$), trace contains term proportional to $\rho_{\alpha\beta}$

$$\frac{dR}{dE_R} \propto A(E_R)\ \rho_{ee} + B(E_R)\ \varepsilon_{\alpha\beta}^{\eta,\varphi}\ \rho_{\alpha\beta} + C(E_R)\ \left(\xi^e\ \varepsilon_{\alpha\beta}^{\eta,\varphi}\right)^2 (\rho_{\alpha\alpha} + \rho_{\beta\beta})$$

Without trace, this interference term would be **entirely missed!**

- **Cross section** symmetric under $\{\varepsilon_{\alpha\beta}^{\eta,\varphi}, \varphi\} \to \{-\varepsilon_{\alpha\beta}^{\eta,\varphi}, -\varphi\}$

BUT:
oscillation effects break symmetry via presence of full density matrix!

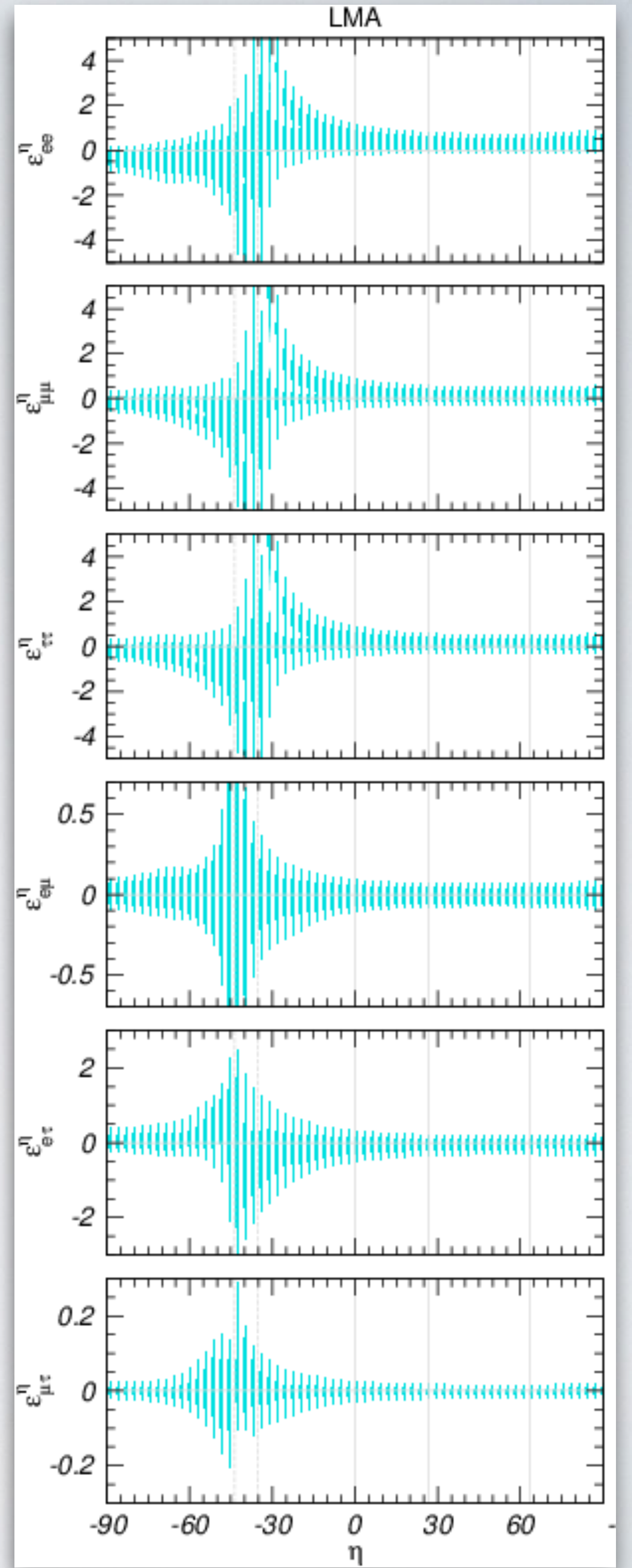


GLOBAL FITS - CURRENT

- **Most robust limits are determined from global fits** including **both oscillation and coherent type** experiments
- For complexity these have been only derived in $\{\xi^p, \xi^n\}$ plane characterised by angle η
- **CEνNS cross section has a blind direction** for $\eta = \tan^{-1}(-Z/N)$
- First COHERENT run with CsI target with average $Z/N \approx 1.407 \;\Rightarrow\;$ degradation @ $\eta \approx -35.4°$

[Coloma et al., *JHEP* **02** (2020) 023]

		Total Rate	Data Release t+E	Our Fit t+E Chicago	Our Fit t+E Duke
$\eta = \tan^{-1}(1/2)$	ε^u_{ee}	[−0.012, +0.621]	[+0.043, +0.384]	[−0.032, +0.533]	[−0.004, +0.496]
	$\varepsilon^u_{\mu\mu}$	[−0.115, +0.405]	[−0.050, +0.062]	[−0.094, +0.071] ⊕ [+0.302, +0.429]	[−0.045, +0.108] ⊕ [+0.290, +0.399]
	$\varepsilon^u_{\tau\tau}$	[−0.116, +0.406]	[−0.050, +0.065]	[−0.095, +0.125] ⊕ [+0.302, +0.428]	[−0.045, +0.141] ⊕ [+0.290, +0.399]
	$\varepsilon^u_{e\mu}$	[−0.059, +0.033]	[−0.055, +0.027]	[−0.060, +0.036]	[−0.060, +0.034]
	$\varepsilon^u_{e\tau}$	[−0.250, +0.110]	[−0.141, +0.090]	[−0.243, +0.118]	[−0.222, +0.113]
	$\varepsilon^u_{\mu\tau}$	[−0.012, +0.008]	[−0.006, +0.006]	[−0.013, +0.009]	[−0.012, +0.009]
$\eta = \tan^{-1}(2)$	ε^d_{ee}	[−0.015, +0.566]	[+0.036, +0.354]	[−0.030, +0.468]	[−0.006, +0.434]
	$\varepsilon^d_{\mu\mu}$	[−0.104, +0.363]	[−0.046, +0.057]	[−0.083, +0.077] ⊕ [+0.278, +0.384]	[−0.037, +0.099] ⊕ [+0.267, +0.356]
	$\varepsilon^d_{\tau\tau}$	[−0.104, +0.363]	[−0.046, +0.059]	[−0.083, +0.083] ⊕ [+0.279, +0.383]	[−0.038, +0.104] ⊕ [+0.268, +0.354]
	$\varepsilon^d_{e\mu}$	[−0.058, +0.032]	[−0.052, +0.024]	[−0.059, +0.034]	[−0.058, +0.034]
	$\varepsilon^d_{e\tau}$	[−0.198, +0.103]	[−0.106, +0.082]	[−0.196, +0.107]	[−0.181, +0.101]
	$\varepsilon^d_{\mu\tau}$	[−0.008, +0.008]	[−0.005, +0.005]	[−0.008, +0.008]	[−0.007, +0.008]
$\eta = 0$	ε^p_{ee}	[−0.035, +2.056]	[+0.142, +1.239]	[−0.095, +1.812]	[−0.024, +1.723]
	$\varepsilon^p_{\mu\mu}$	[−0.379, +1.402]	[−0.166, +0.204]	[−0.312, +0.138] ⊕ [+1.036, +1.456]	[−0.166, +0.337] ⊕ [+0.952, +1.374]
	$\varepsilon^p_{\tau\tau}$	[−0.379, +1.409]	[−0.168, +0.257]	[−0.313, +0.478] ⊕ [+1.038, +1.453]	[−0.167, +0.582] ⊕ [+0.950, +1.382]
	$\varepsilon^p_{e\mu}$	[−0.179, +0.112]	[−0.174, +0.086]	[−0.179, +0.120]	[−0.187, +0.131]
	$\varepsilon^p_{e\tau}$	[−0.877, +0.340]	[−0.503, +0.295]	[−0.841, +0.355]	[−0.817, +0.386]
	$\varepsilon^p_{\mu\tau}$	[−0.041, +0.025]	[−0.020, +0.019]	[−0.044, +0.026]	[−0.048, +0.030]



[Esteban et al., *JHEP* **08** (2018) 180]