Testing New Physics with Neutrinos at DM Experiments

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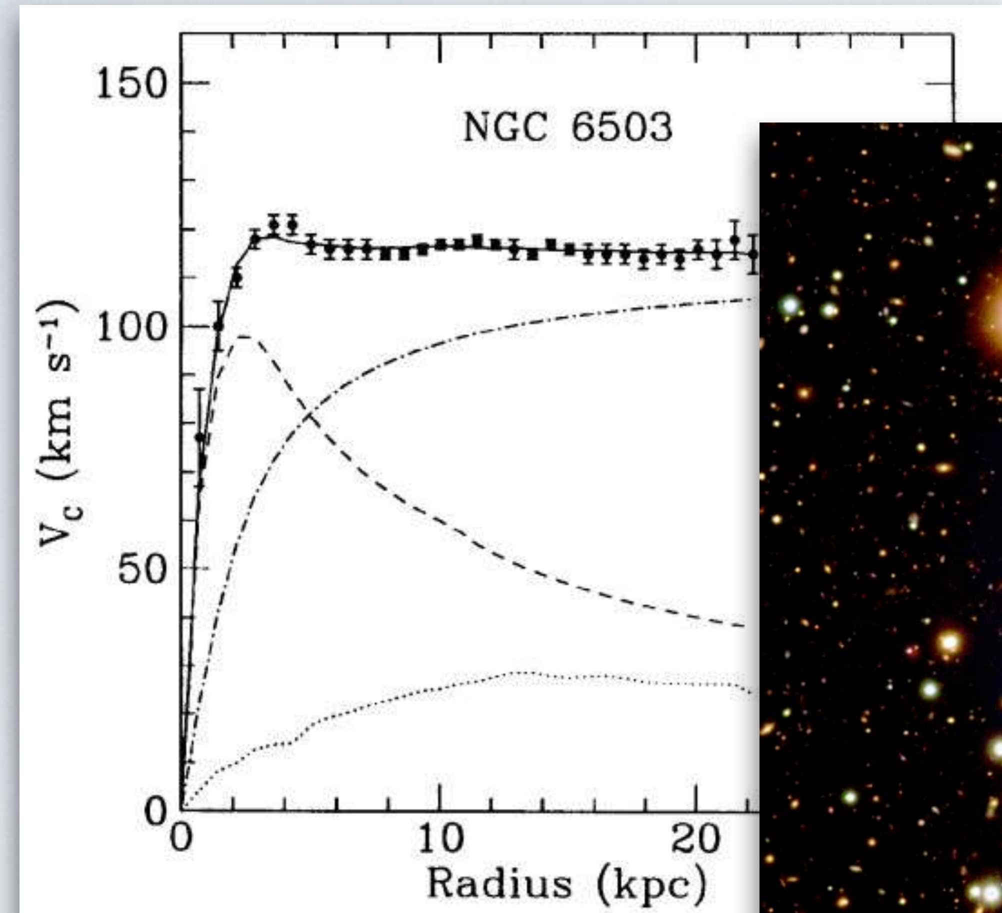
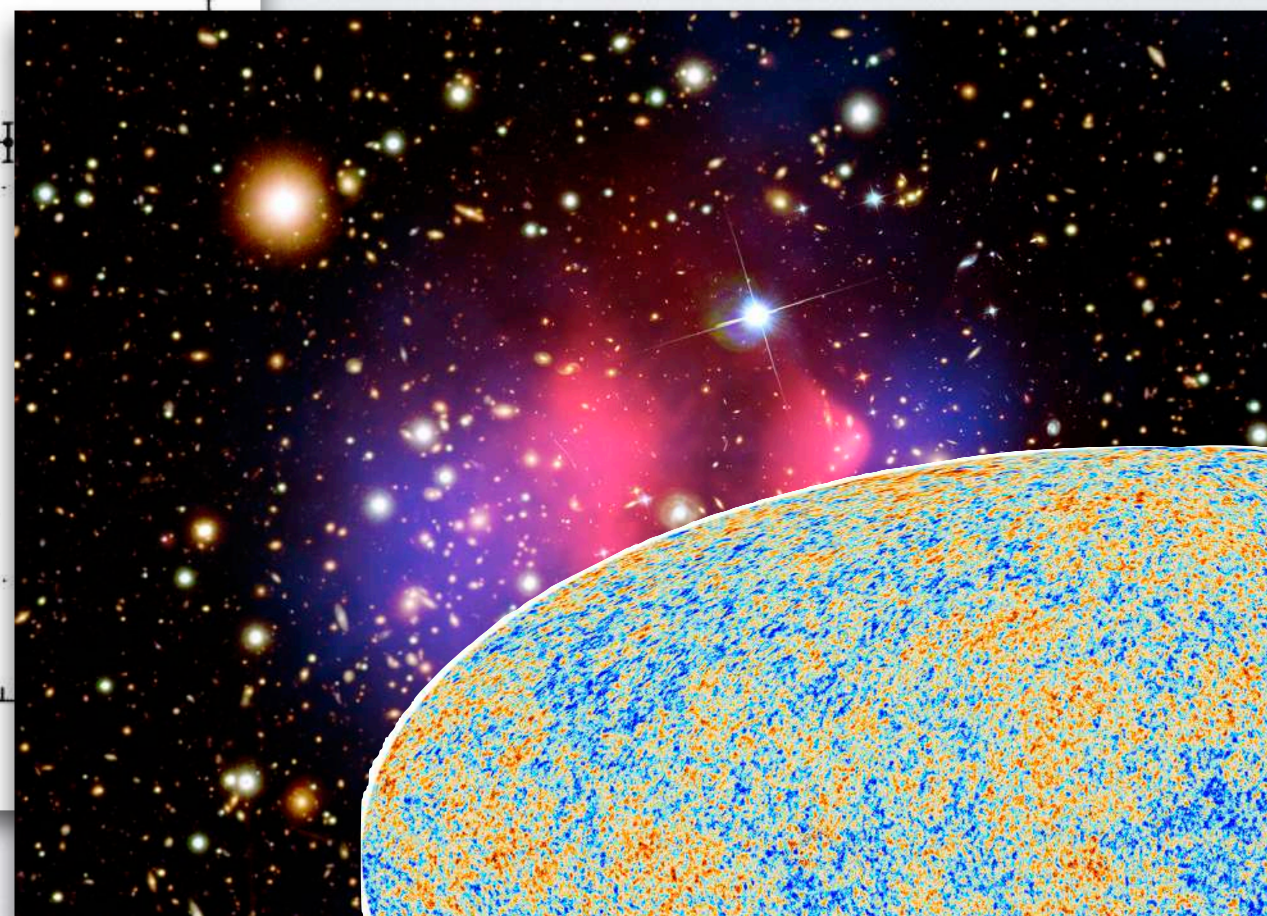
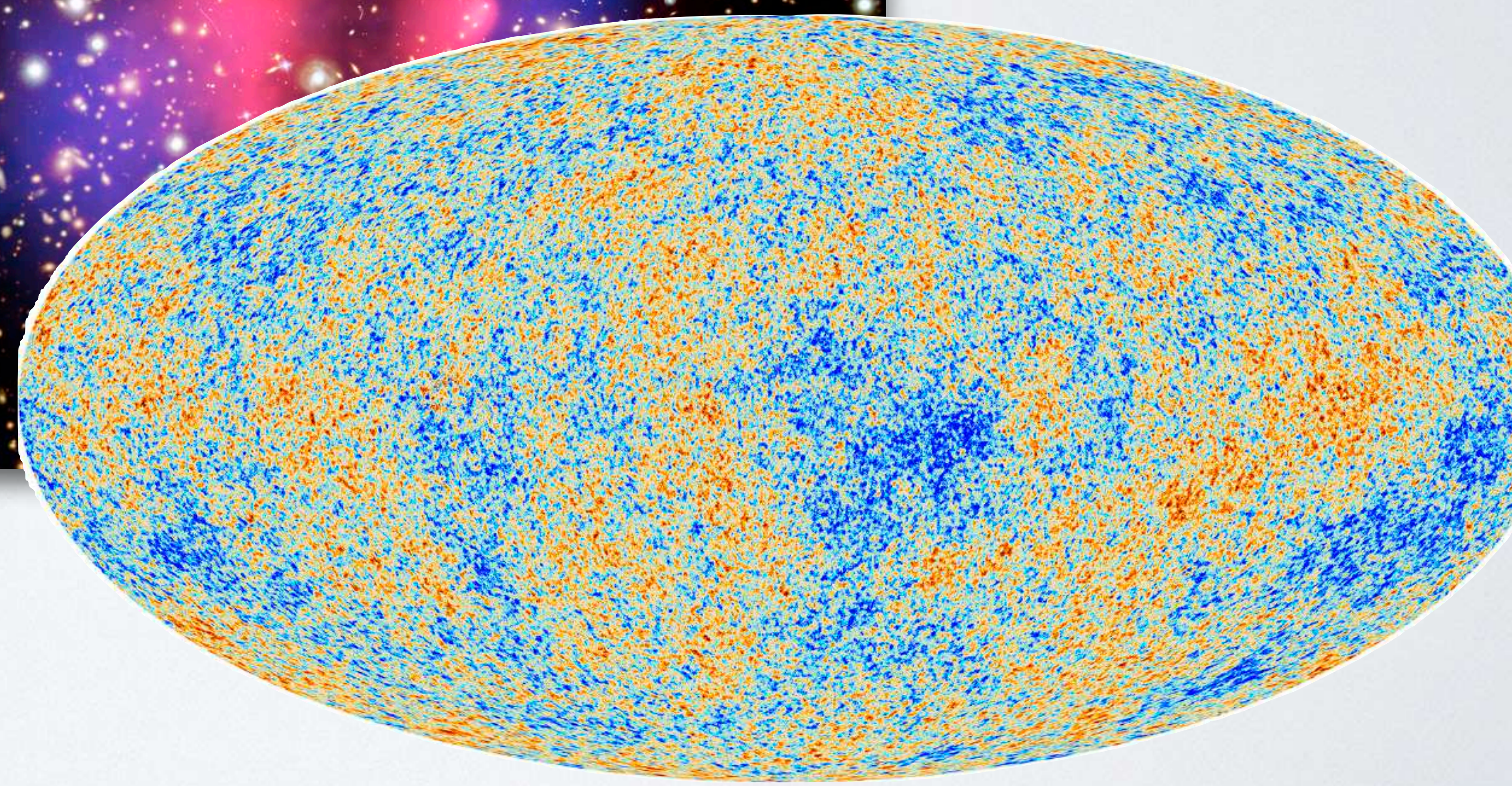
Gyeongju – Aug 21, 2026

THE QUEST FOR THE INVISIBLE

- Made various indirect (gravitational) observations of very abundant **dark matter**







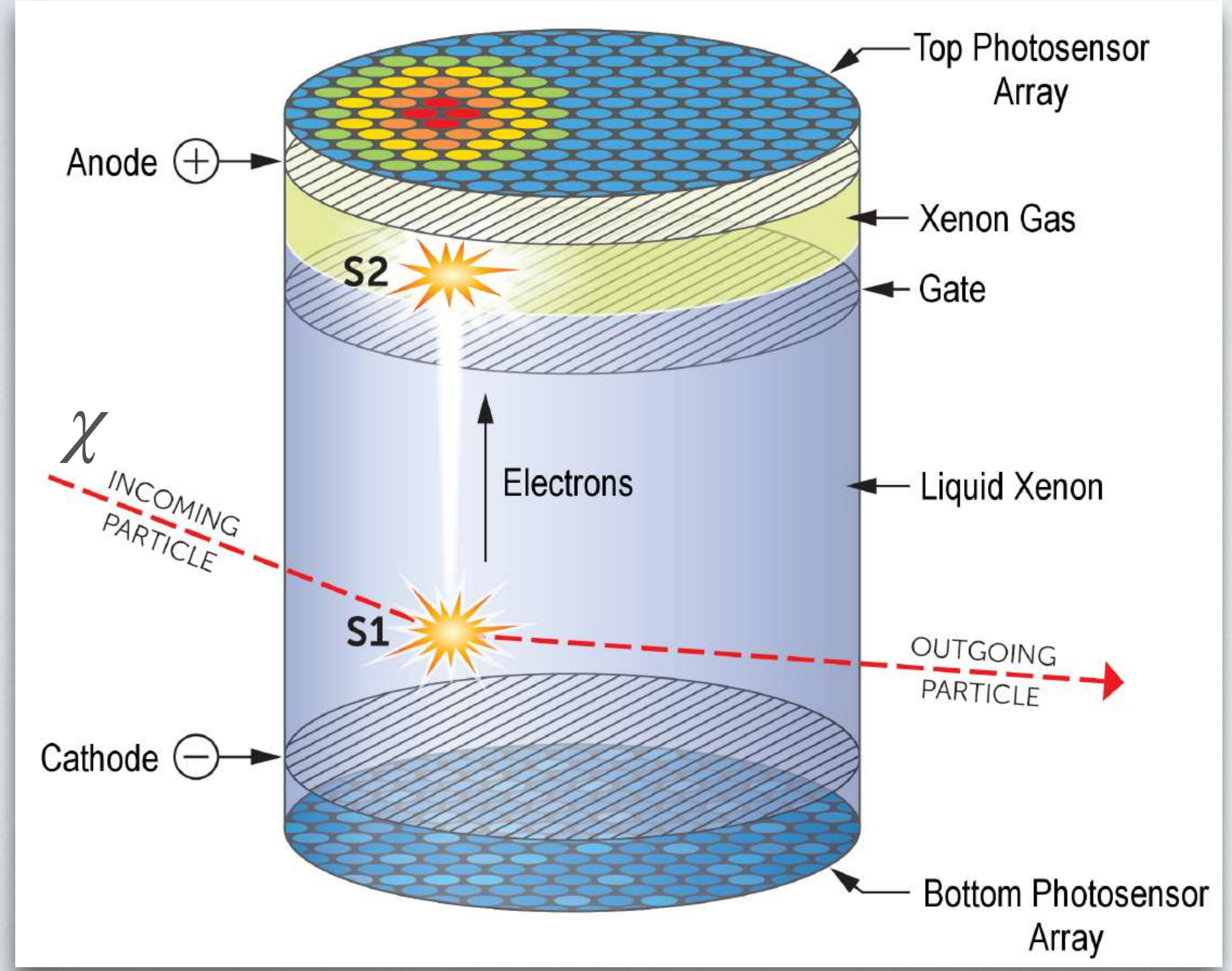
- *Plausible hypothesis*: DM is some **new type of particle**

PROTOTYPICAL DD EXPERIMENT

- State-of-the-art **DM experiments**: multi ton liquid noble gas detectors (Xe, Ar)

- **Expect events:**

$$N = \int_{E_T} \epsilon \frac{\boxed{\rho}}{m_\chi m_N} \int_{v_{\min}} \boxed{v f(\vec{v})} \boxed{\frac{d\sigma_{\chi N}}{dE_R}} \, d\vec{v} \, dE_R$$

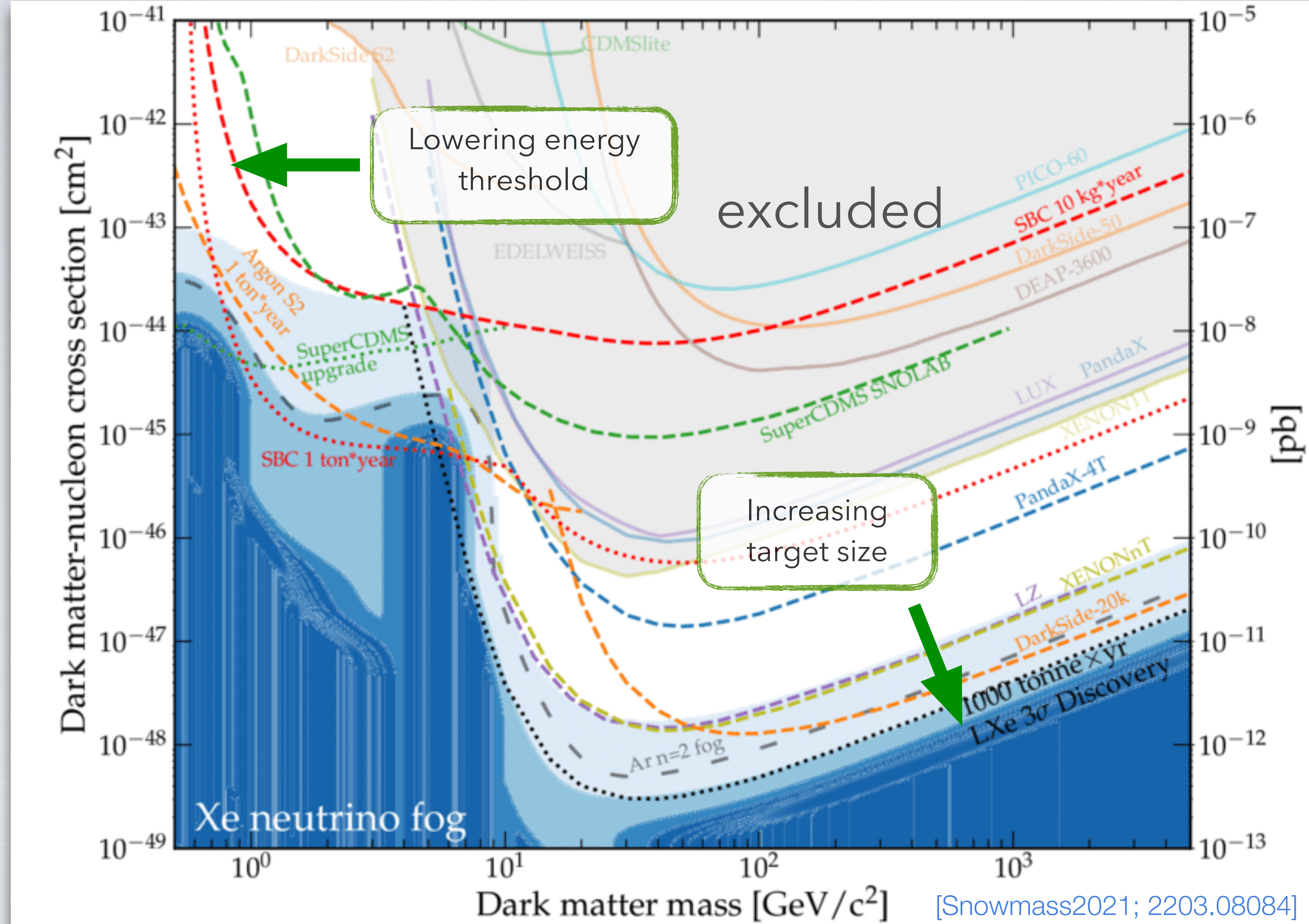


[Albers et al.; *J.Phys.G* 50 (2023) 1, 013001]

- Directly testing **DM-SM interactions:**
  - primary scintillation light (S1)
  - electroluminescence/ionisation (S2)

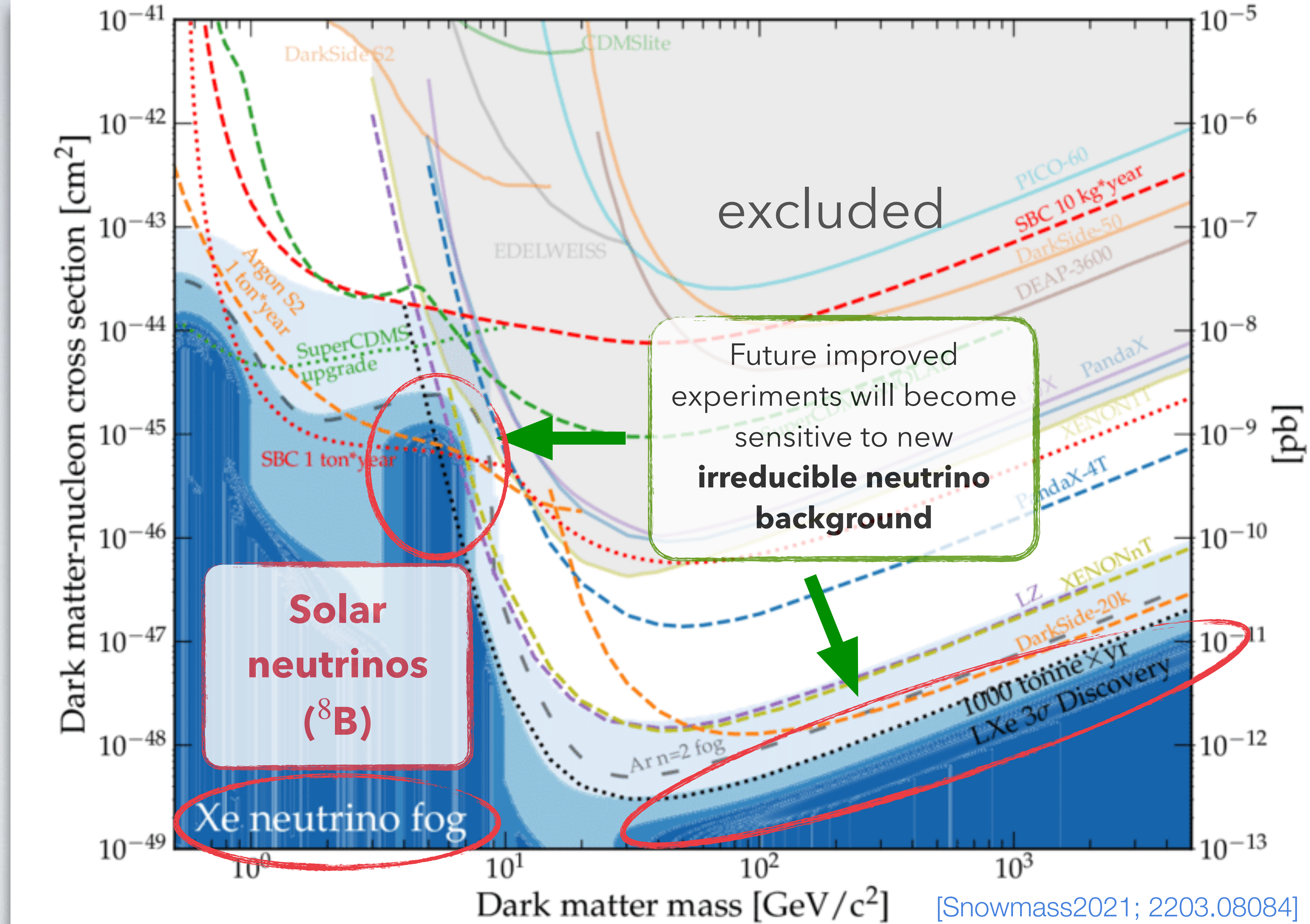
- **Scattering cross section:**
  - particle physics (DM model)
  - nuclear physics (form factors)
  - material science (structure of target)

DIRECT DETECTION LANDSCAPE



See talk by Hyunsu Lee!

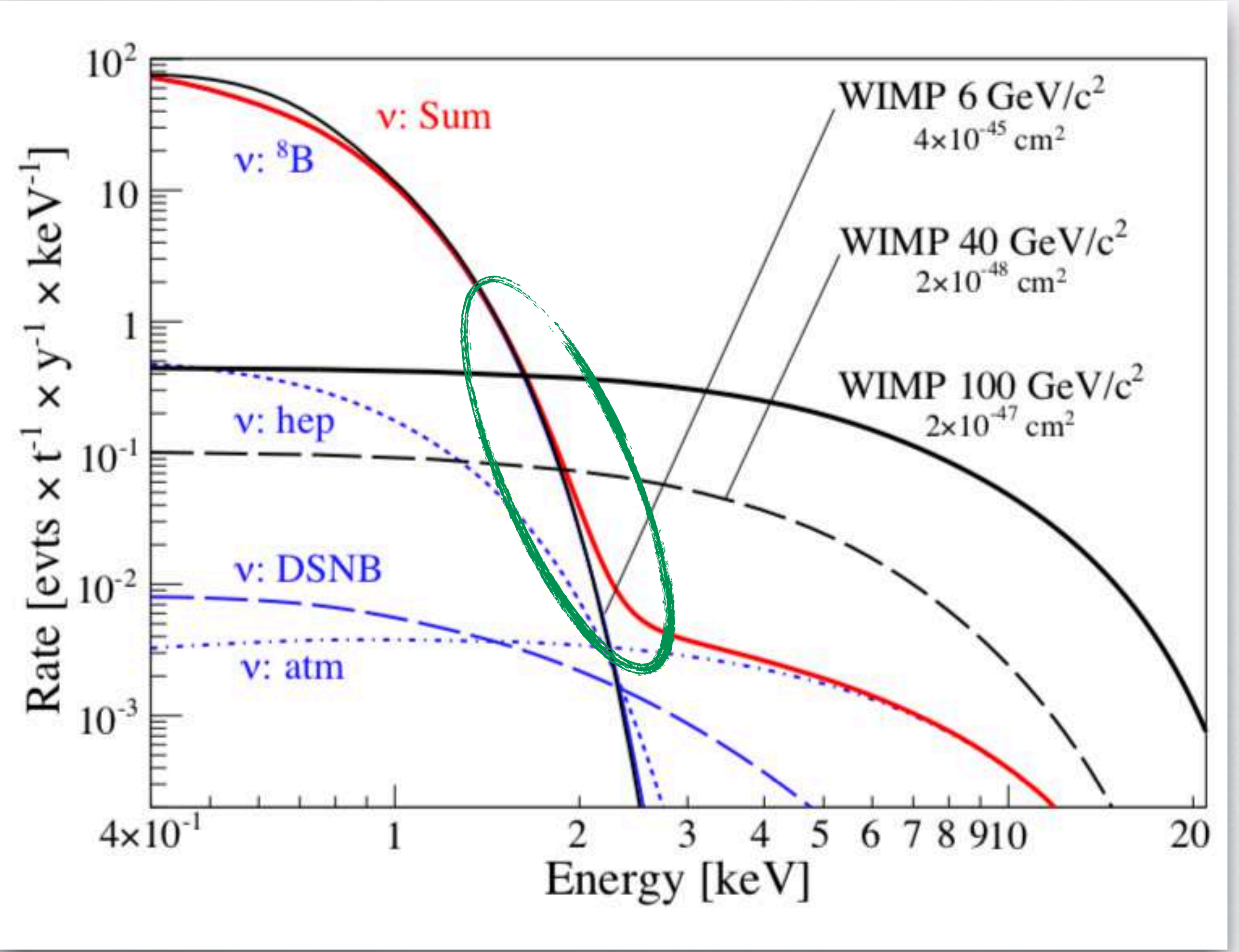
DIRECT DETECTION LANDSCAPE

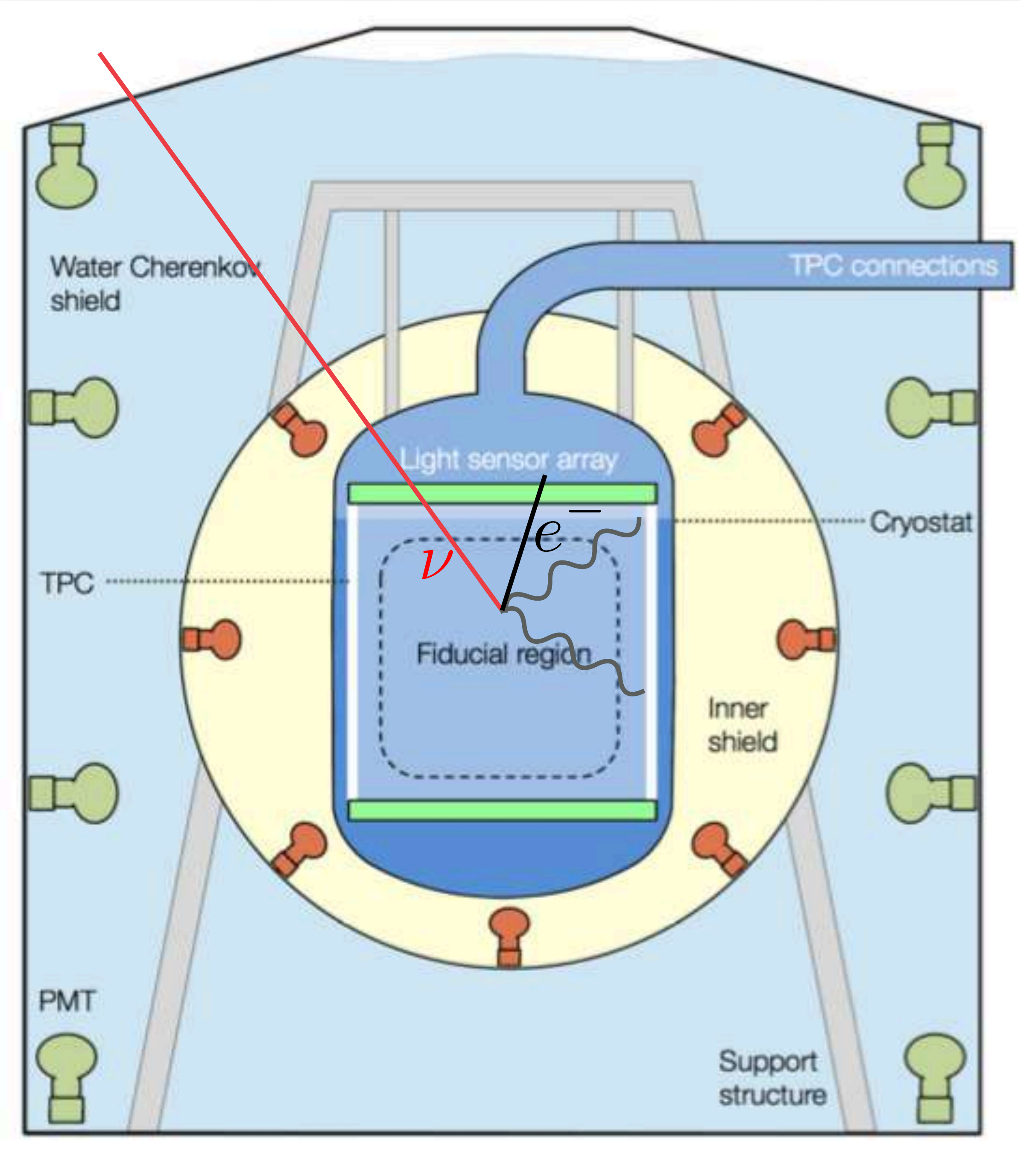


[Snowmass2021; 2203.08084]

NEUTRINO BACKGROUND

- Incident energetic neutrinos can fake the DM signal e.g. by undergoing **coherent elastic neutrino-nucleus scattering (CEvNS)**
- Most importantly, **irreducible CEvNS background looks like WIMP signal!**
- **Energy thresholds of ~ O(few) keV ⇒ typical solar neutrino scattering energies!**





[DARWIN; JCAP 1611 (2016) 11, 017]

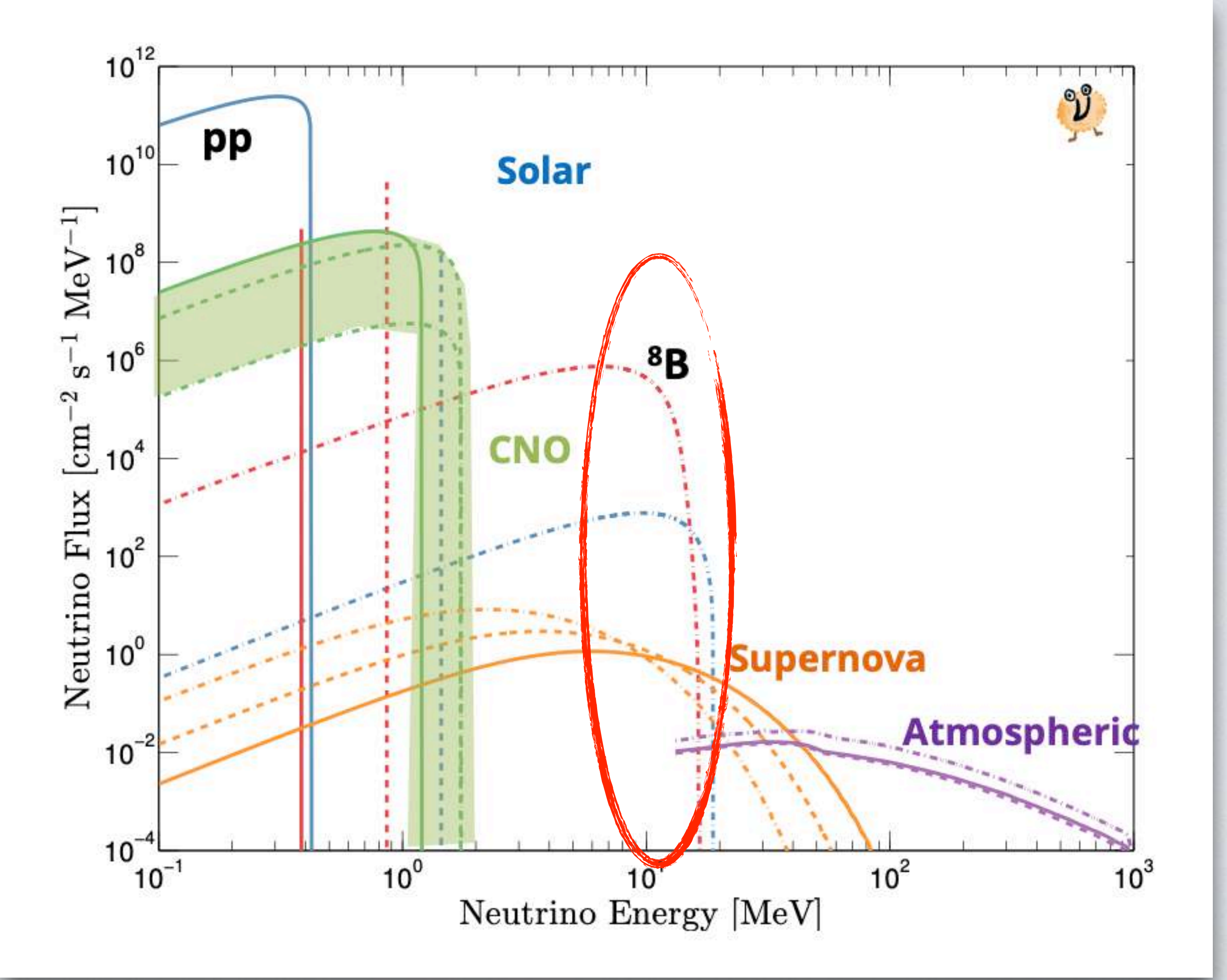
CEVNS WITH SOLAR NEUTRINOS

$$\frac{dR}{dE_R} = n_T \int_{E_\nu^{\min}} \boxed{\frac{d\phi_{\nu_\alpha}}{dE_\nu}} \frac{d\sigma_{\nu_\alpha} T}{dE_R} dE_\nu$$

- **Solar neutrinos**
  dominate at low energies
  ^8B leading flux at ~10 MeV
  → **start observing this now!**

- **Diffuse supernova neutrinos**
  leading background at ~20-50 MeV →undetected, future target

- **Atmospheric**
  dominate at high energies, but much smaller fluxes
  → XLZD, PandaX-xT?



Credit: D. Cerdeño

CEVNS WITH SOLAR NEUTRINOS

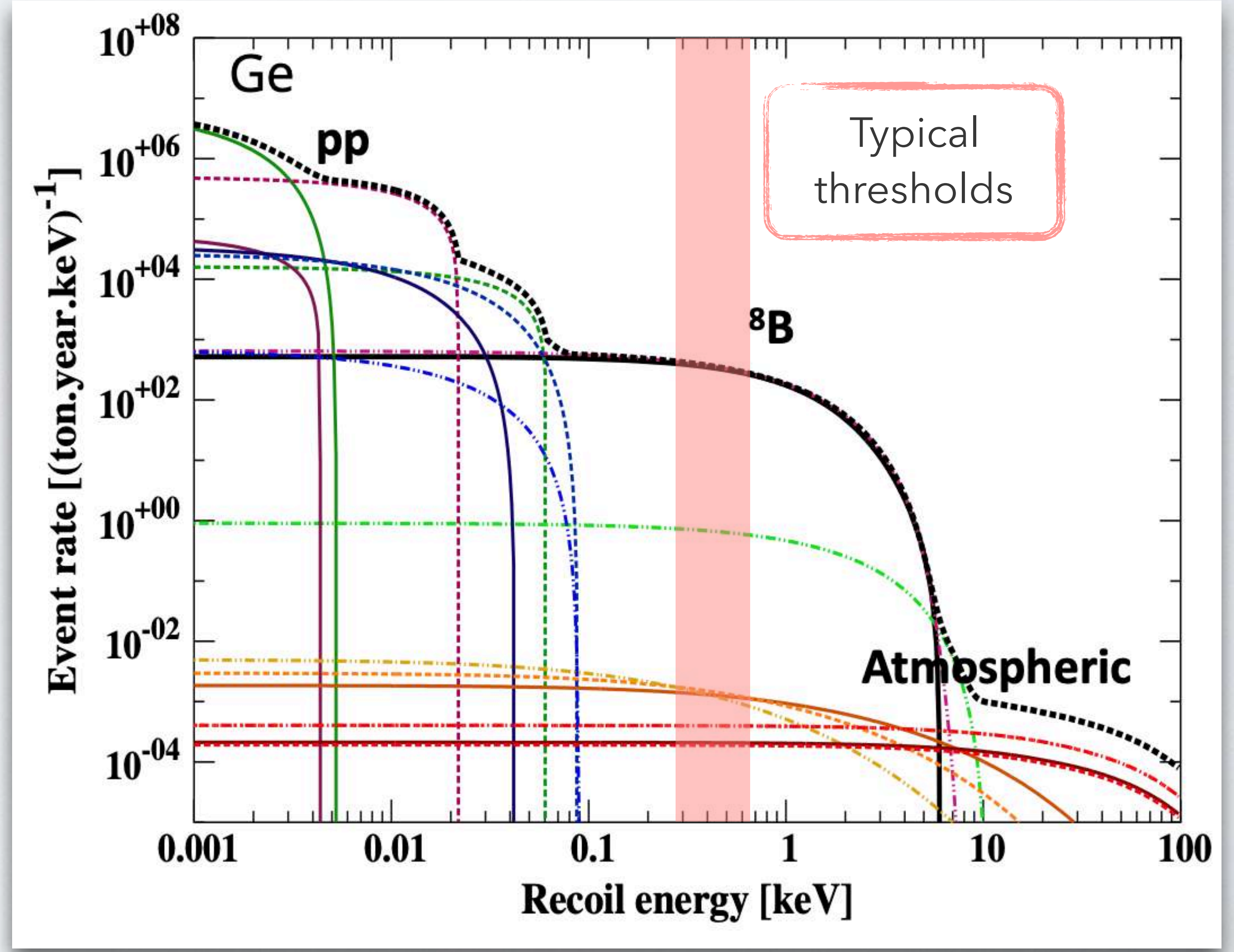
$$\frac{dR}{dE_R} = n_T \int_{E_\nu^{\min}} \boxed{\frac{d\phi_{\nu_\alpha}}{dE_\nu}} \frac{d\sigma_{\nu_\alpha} T}{dE_R} dE_\nu$$

- Current and upcoming DD experiments will be sensitive to mostly ^8B solar neutrino flux!
- First **hints** for observation:

  XENONnT @ 2.73σ
  [XENONnT, *PRL* 133 (2024) 19, 191002]

  PandaX-4T @ 2.64σ
  [PandaX, *PRL* 133 (2024) 19, 191001]

  LZ @ 4.5σ
  [LZ, *arXiv:2512.08065*]
- **Lowering threshold** is key to pick up more solar neutrino signal!



[Ruppin+, *Phys.Rev.D* 90 (2014) 8, 083510]

LABORATORY FOR (NEW) NEUTRINO PHYSICS

- Complementary measurement of solar neutrino fluxes
- Sensitive to ν_τ flavour
- Tests of new neutrino interactions
- Both sensitive to nuclear and electron scattering
- …

$\sin\theta_W$ AT LOW ENERGY

- SM "precision" physics: **CEvNS cross section** directly depends on the value of $\sin\theta_W$:

$$\left(\frac{d\sigma_{\nu N}}{dE_R}\right)_{\rm SM} = \frac{G_F^2 M_N}{4\pi}\left(1-\frac{M_N E_R}{2E_\nu^2}\right) Q_\nu^2 F^2(E_R)$$

$$Q_\nu = N - (1 - 4\sin^2\theta_W)\, Z$$

- $\sin\theta_W$ **not well measured at low energies!**

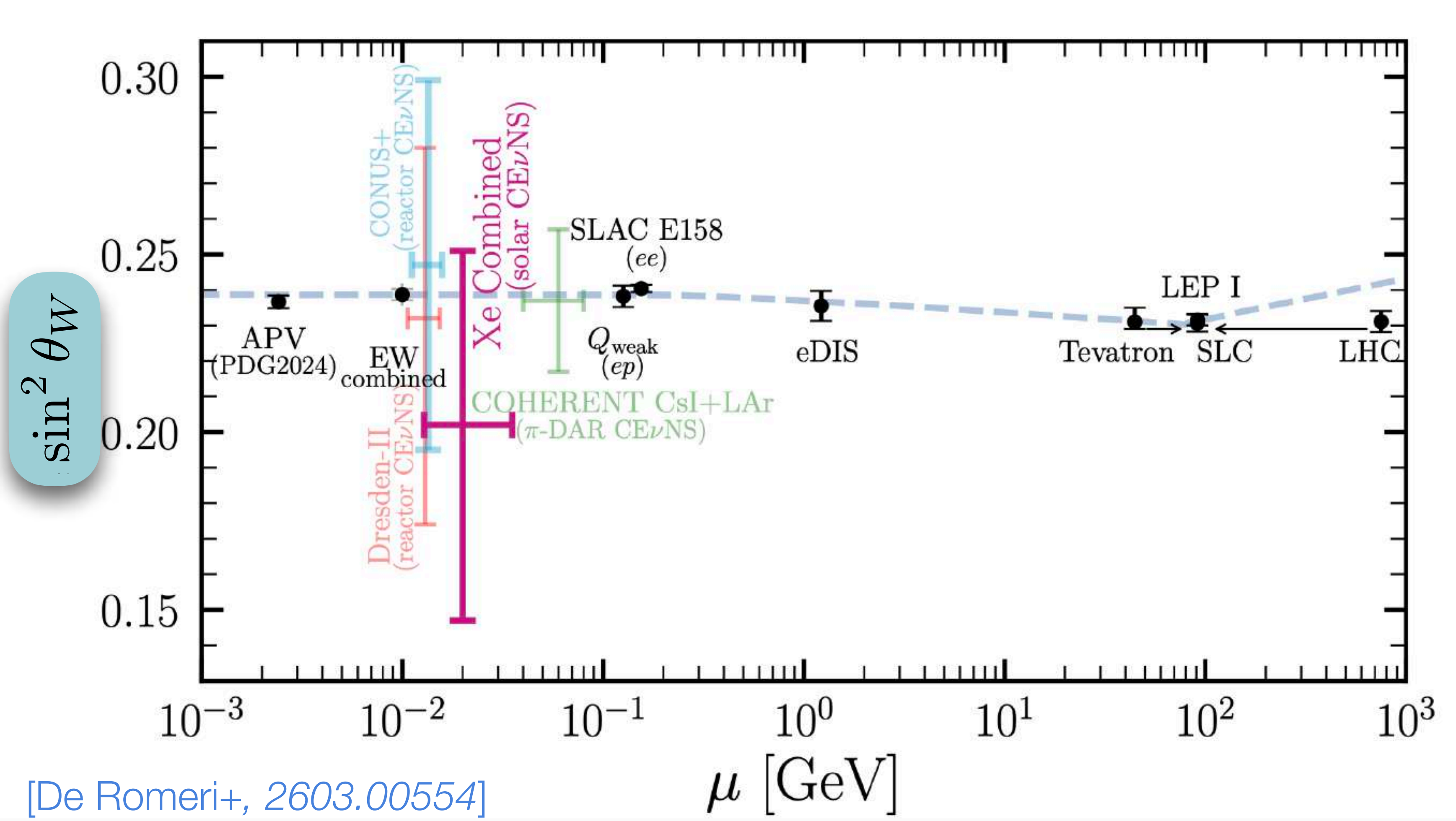
- can be extracted from neutrino scattering at DD experiments

[Maity, Boehm, *PRD* 112 5, 053001]

- Combined results from direct detection:

$$\begin{aligned}
\sin^2\theta_W &= 0.30^{+0.16}_{-0.21} \quad (\text{PandaX-4T}),\\
\sin^2\theta_W &= 0.25^{+0.09}_{-0.10} \quad (\text{XENONnT}),\\
\sin^2\theta_W &= 0.17^{+0.06}_{-0.06} \quad (\text{LZ}),\\
\sin^2\theta_W &= 0.20^{+0.05}_{-0.06} \quad (\text{combined}).
\end{aligned}$$

[De Romeri+, *JCAP* 05 (2025) 012]

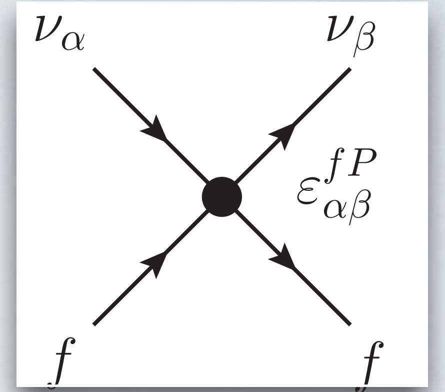


[De Romeri+, *2603.00554*]

NON-STANDARD INTERACTIONS

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

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

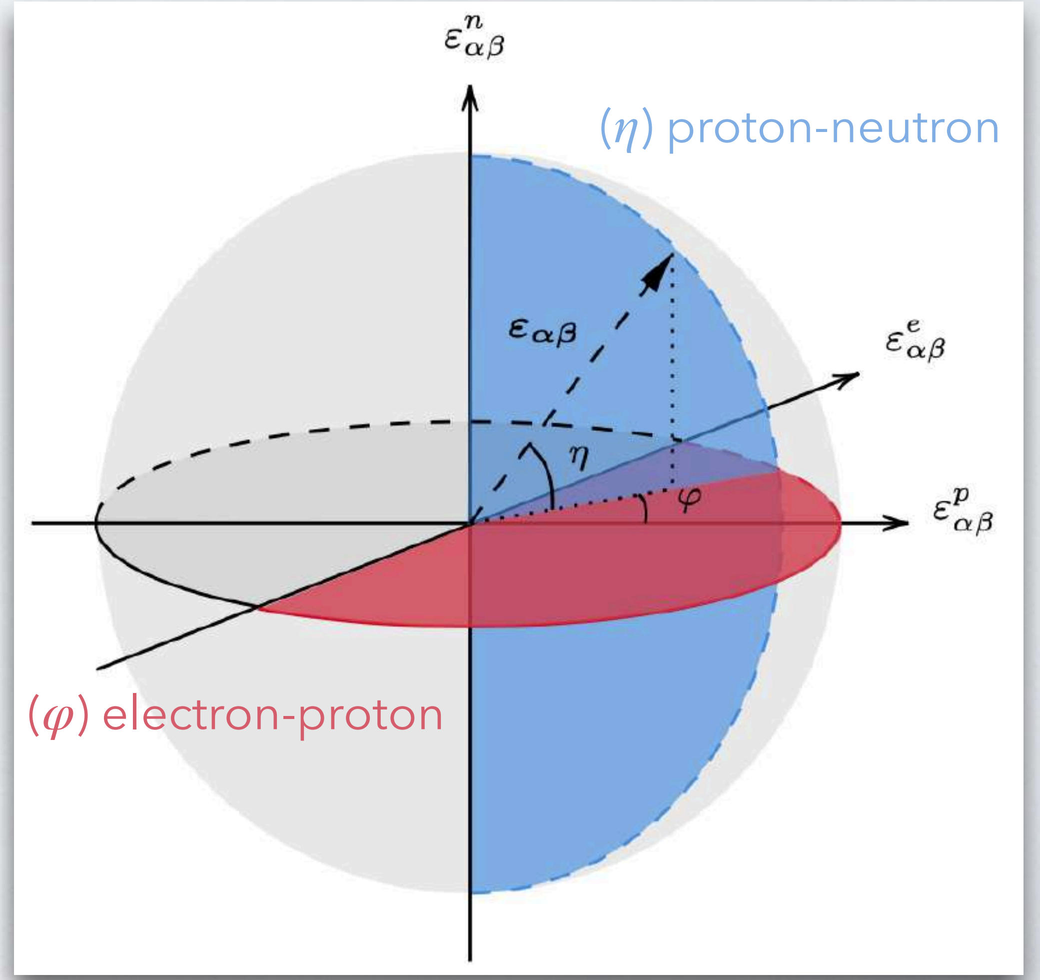


- Ordinary matter is composed of $f = \{e, u, d\}$. Only these are relevant for matter effects and scattering. Propagation only sensitive to **vector component.**

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

- **Three dimensional parameterisation** including neutron, proton and electron couplings

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



[Amaral, Cheek, Cerdeño, **PF**; 2302.12846]

[Coloma+; *JHEP* 08 (2023) 032]

RATE — FIRST PRINCIPLES

- Solar neutrinos propagate to the surface of the Sun and **undergo matter oscillations**; free stream in vacuum to Earth; undergo second phase of terrestrial matter oscillations

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

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

Asymptotic outstate i

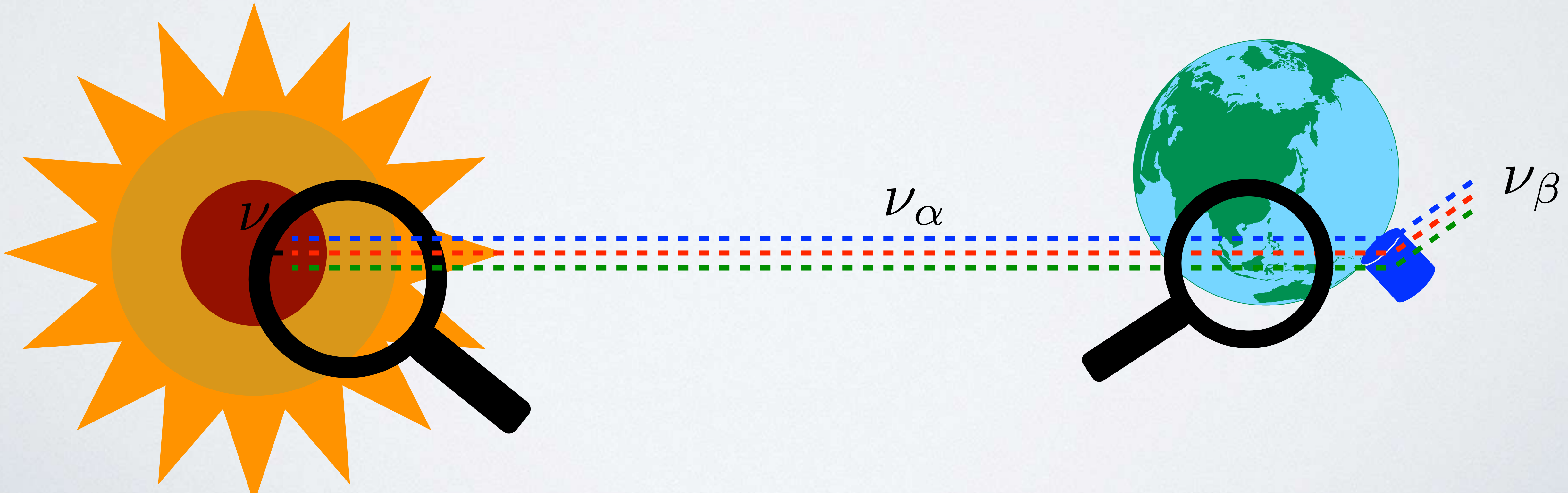
Propagation and scattering

Initial flavour α

- Consistent treatment captured by **density matrix** and **generalised cross section**

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

NSI NEUTRINO PROPAGATION



SOLAR PROPAGATION

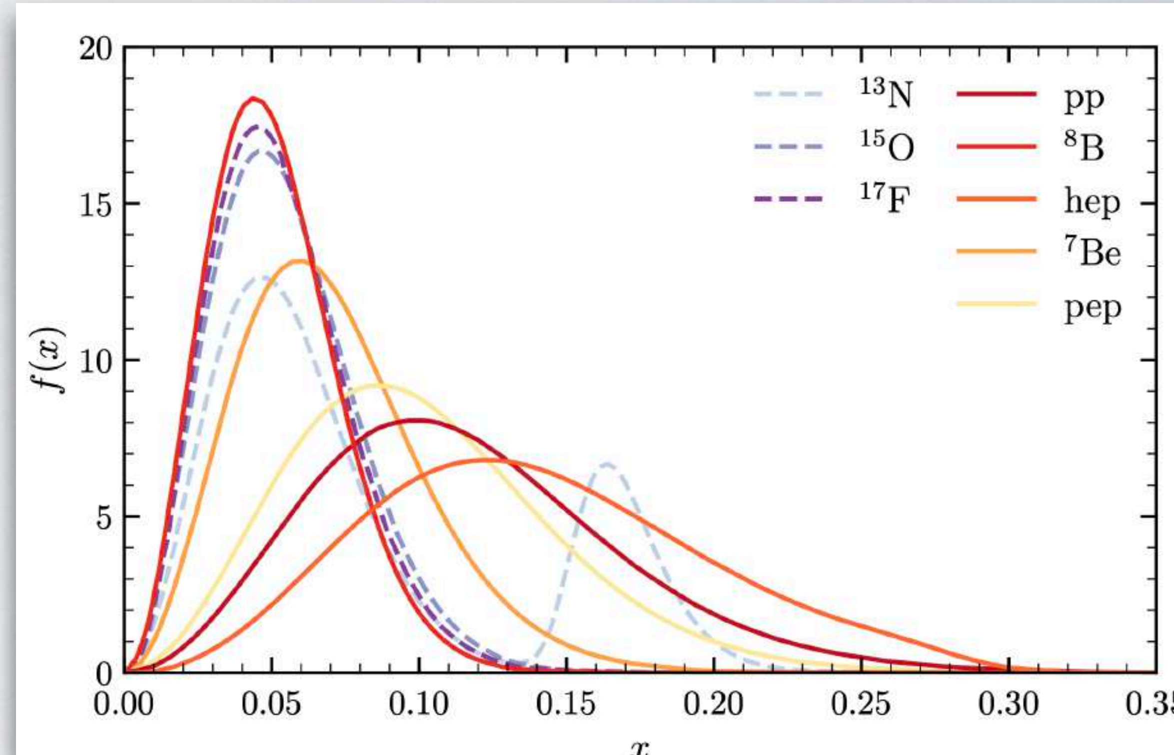
- Have to solve the time-depdendent Schroeding equation in matter with Hamiltonian.

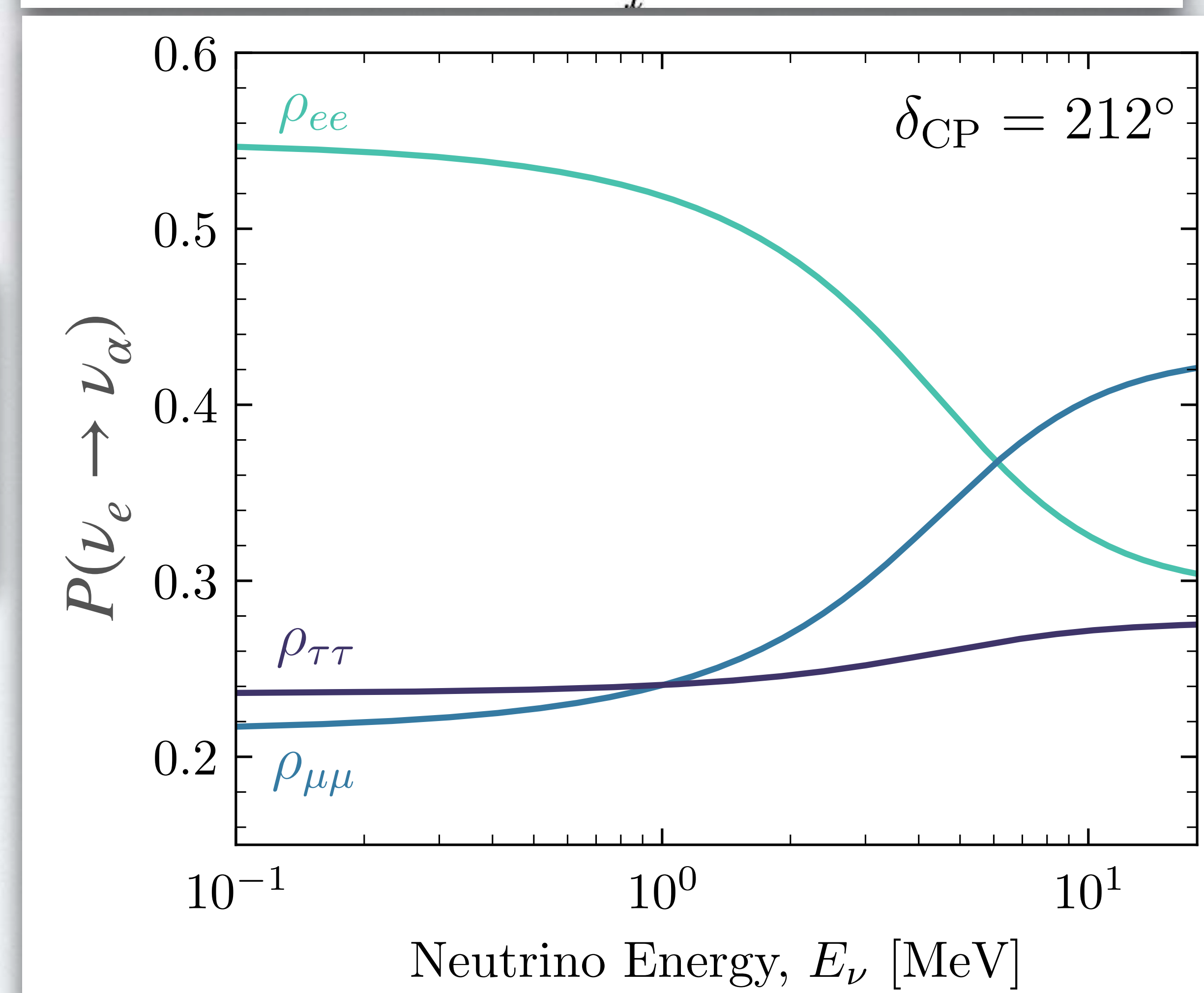
$$i\partial_x \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = H_m \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

- In the Sun, this can be reduced to a **two-flavour problem** and solved assuming **adiabatic evolution**, with the matter eigenvalues $D(x) = \mathrm{diag}(E_1^m(x), E_2^m(x))$

$$S = \begin{pmatrix} \exp\left[-i\int_0^L D(x)dx\right] & 0 \\ 0 & \exp\left[-i\Phi_{33}\right] \end{pmatrix} U^m(x_0)^\dagger$$

$$\rho^{(e)} = S\,\pi^{(e)}\,S^\dagger = \begin{pmatrix} |S_{11}|^2 & S_{11}\,S_{21}^* & S_{11}\,S_{31}^* \\ S_{11}^*\,S_{21} & |S_{21}|^2 & S_{21}\,S_{31}^* \\ S_{11}^*\,S_{31} & S_{21}^*\,S_{31} & |S_{31}|^2 \end{pmatrix}$$

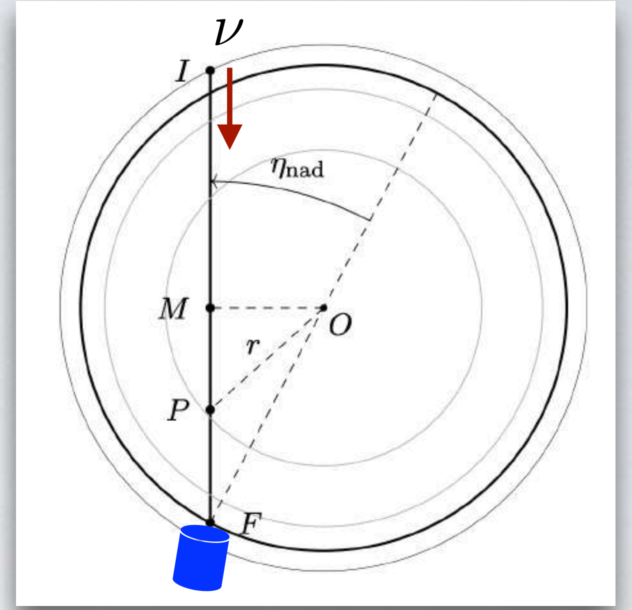




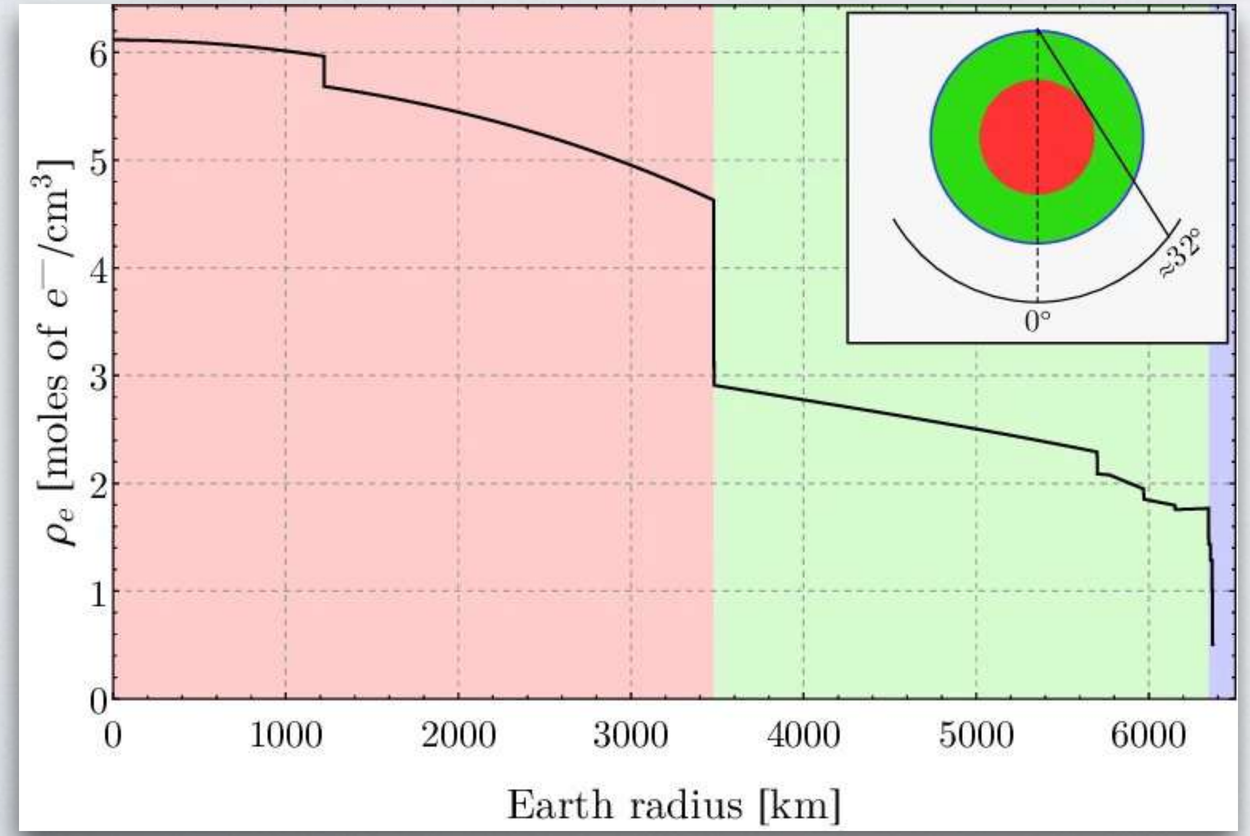
TERRESTRIAL PROPAGATION

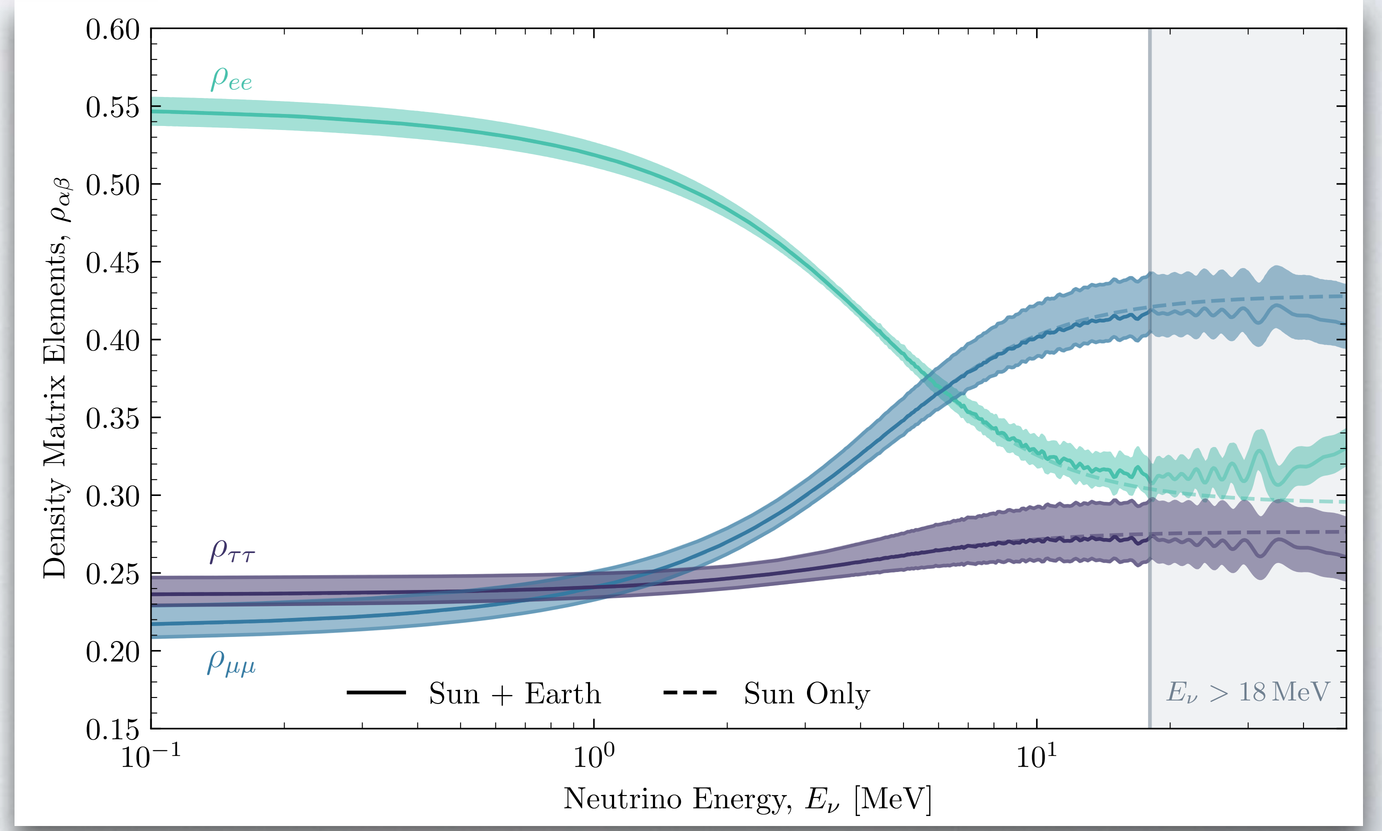
- For terrestrial propagation, have to **diagonalise the full Hamiltonian iteratively along the path** through the Earth

$$H_m = U_{\rm PMNS}\frac{1}{2E_\nu}\begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^\dagger_{\rm PMNS} + V(x)\begin{pmatrix} 1+\mathcal{E}_{ee}(x) & \mathcal{E}_{e\mu}(x) & \mathcal{E}_{e\tau}(x) \\ \mathcal{E}^*_{e\mu}(x) & \mathcal{E}_{\mu\mu}(x) & \mathcal{E}_{\mu\tau}(x) \\ \mathcal{E}^*_{e\tau}(x) & \mathcal{E}^*_{\mu\tau}(x) & \mathcal{E}_{\tau\tau}(x)\end{pmatrix}$$



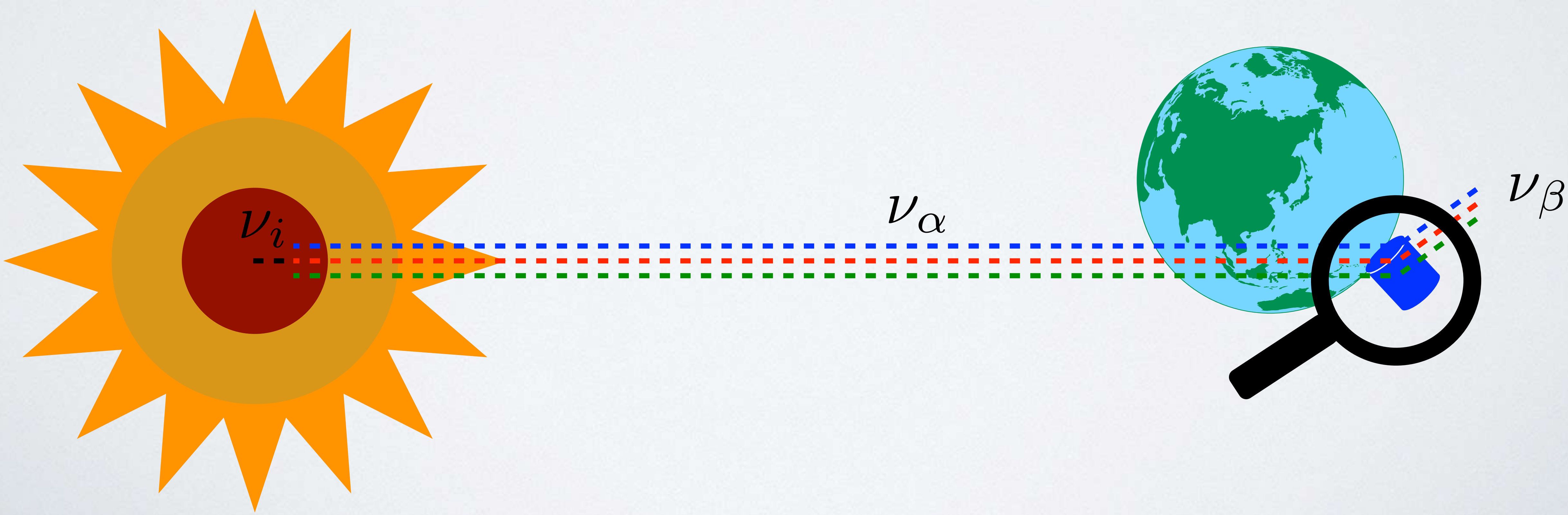
$$\boxed{S_k = U_k^m \begin{pmatrix} e^{-iE_1^m \Delta x_k} & 0 & 0 \\ 0 & e^{-iE_2^m \Delta x_k} & 0 \\ 0 & 0 & e^{-iE_3^m \Delta x_k}\end{pmatrix} U_k^{m\dagger}}$$





[Amaral, Cerdeno, Cheek, Costa, **PF**; 2607.22817]

NSI NEUTRINO DETECTION



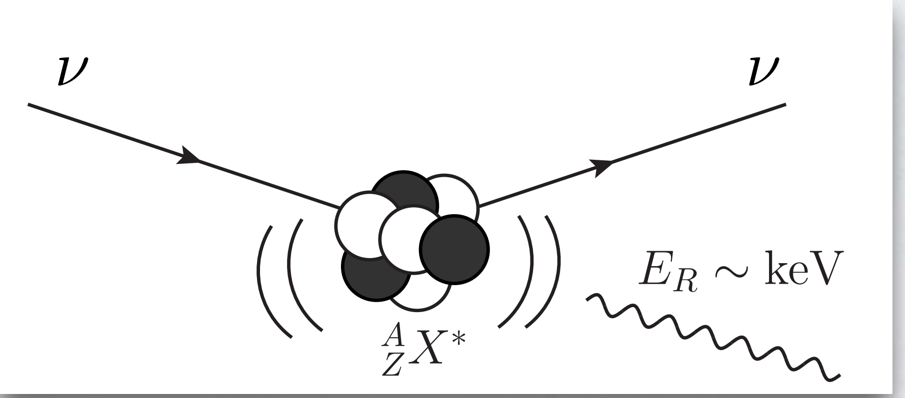
NSI @ DD EXPERIMENTS

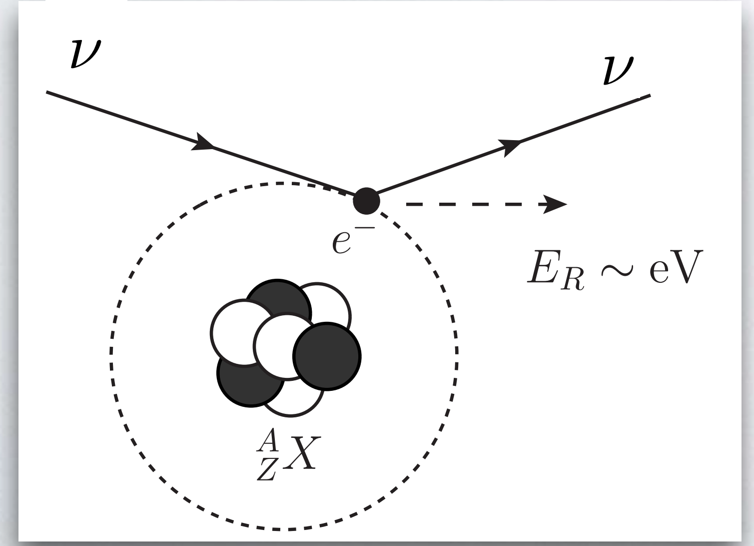
- Sensitive to both **nuclear** and **electron scattering!**
- **Exploit signal complementarity!**

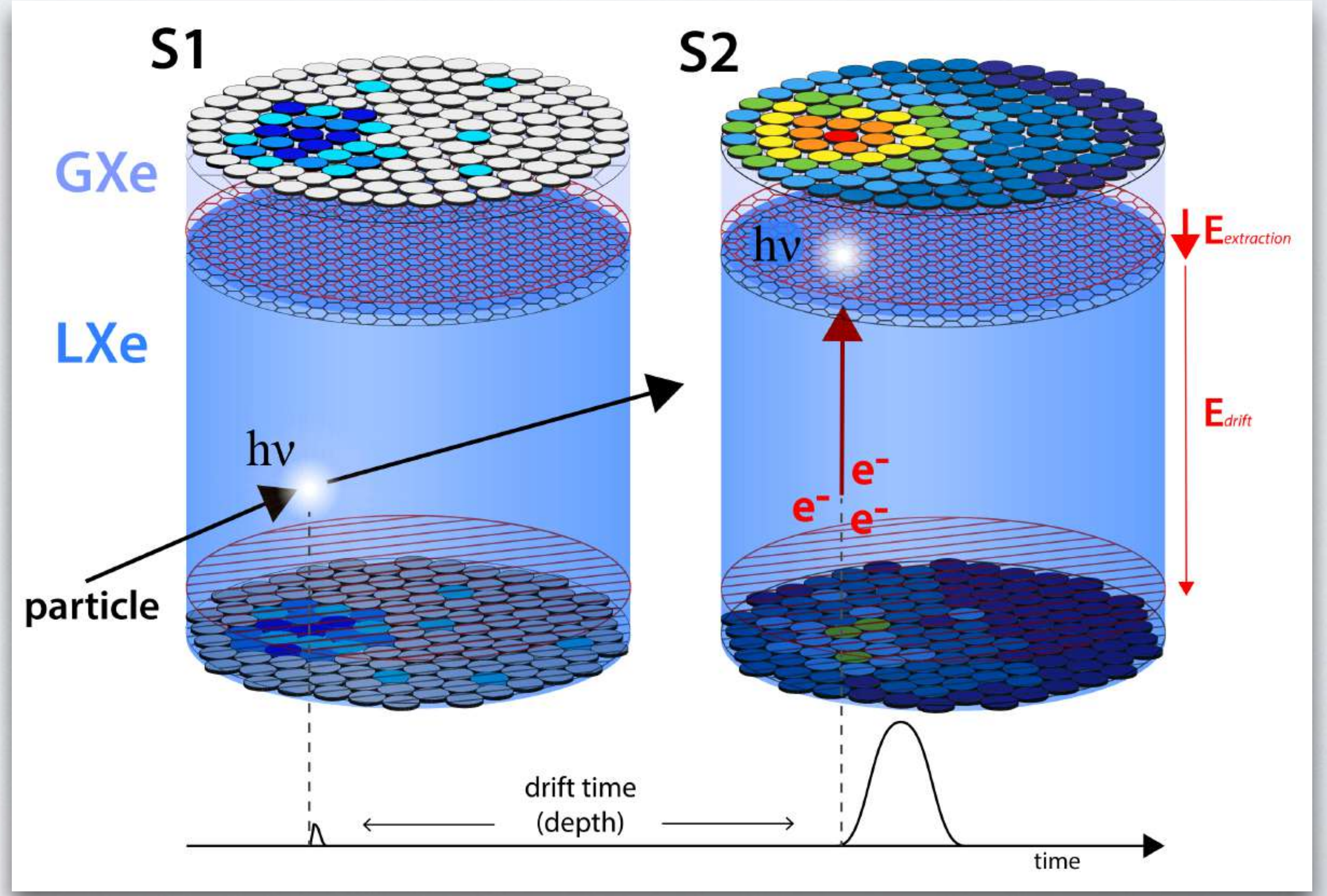
XENONnT

LZ

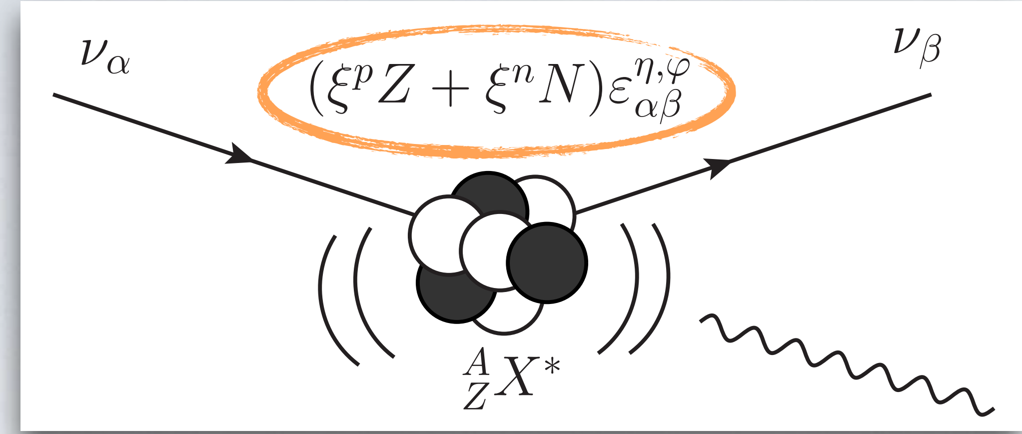
PandaX-4T

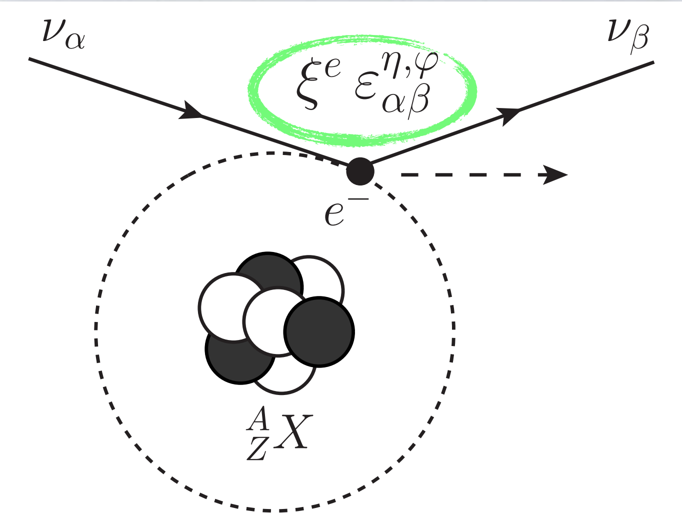






SOLAR NEUTRINO SCATTERING





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

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

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

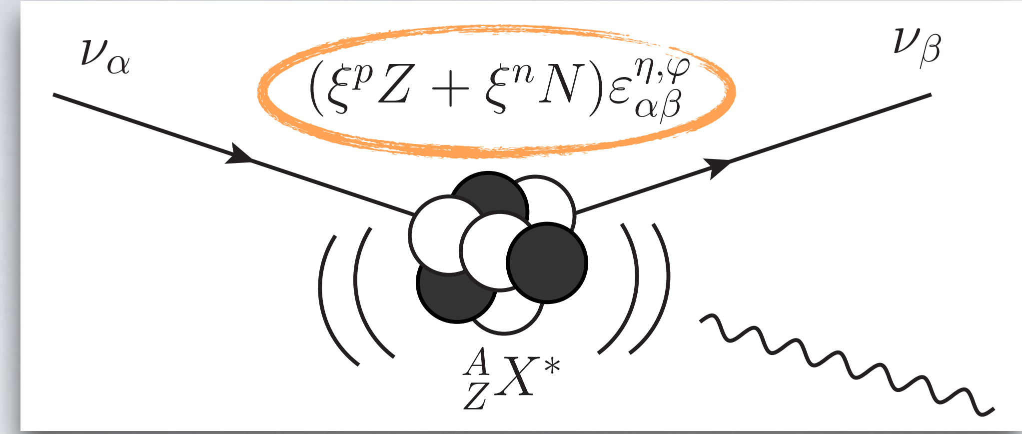
2. The **generalised elastic neutrino-electron scattering (EνES) cross section**:

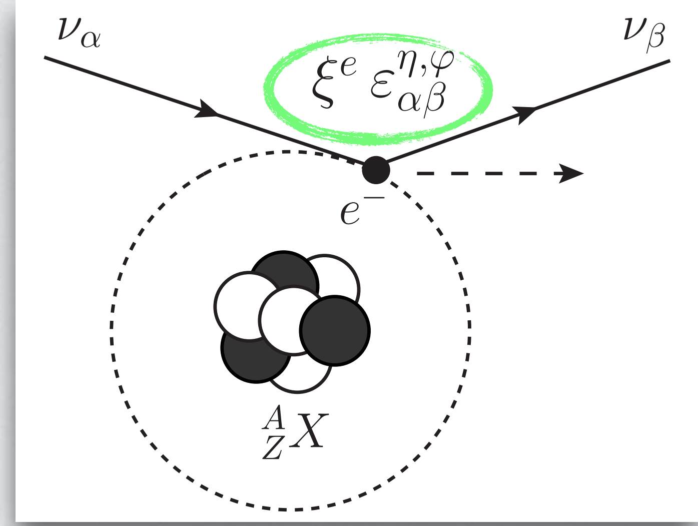
$$\left(\frac{d\zeta_{\nu e}}{dE_R}\right)_{\alpha\beta} = \frac{2\, G_F^2\, m_e}{\pi} \sum_\gamma \left\{ G^L_{\alpha\gamma} G^L_{\gamma\beta} + G^R_{\alpha\gamma} G^R_{\gamma\beta}\left(1 - \frac{E_R}{E_\nu}\right)^2 - \left(G^L_{\alpha\gamma} G^R_{\gamma\beta} + G^R_{\alpha\gamma} G^L_{\gamma\beta}\right)\frac{m_e\,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

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

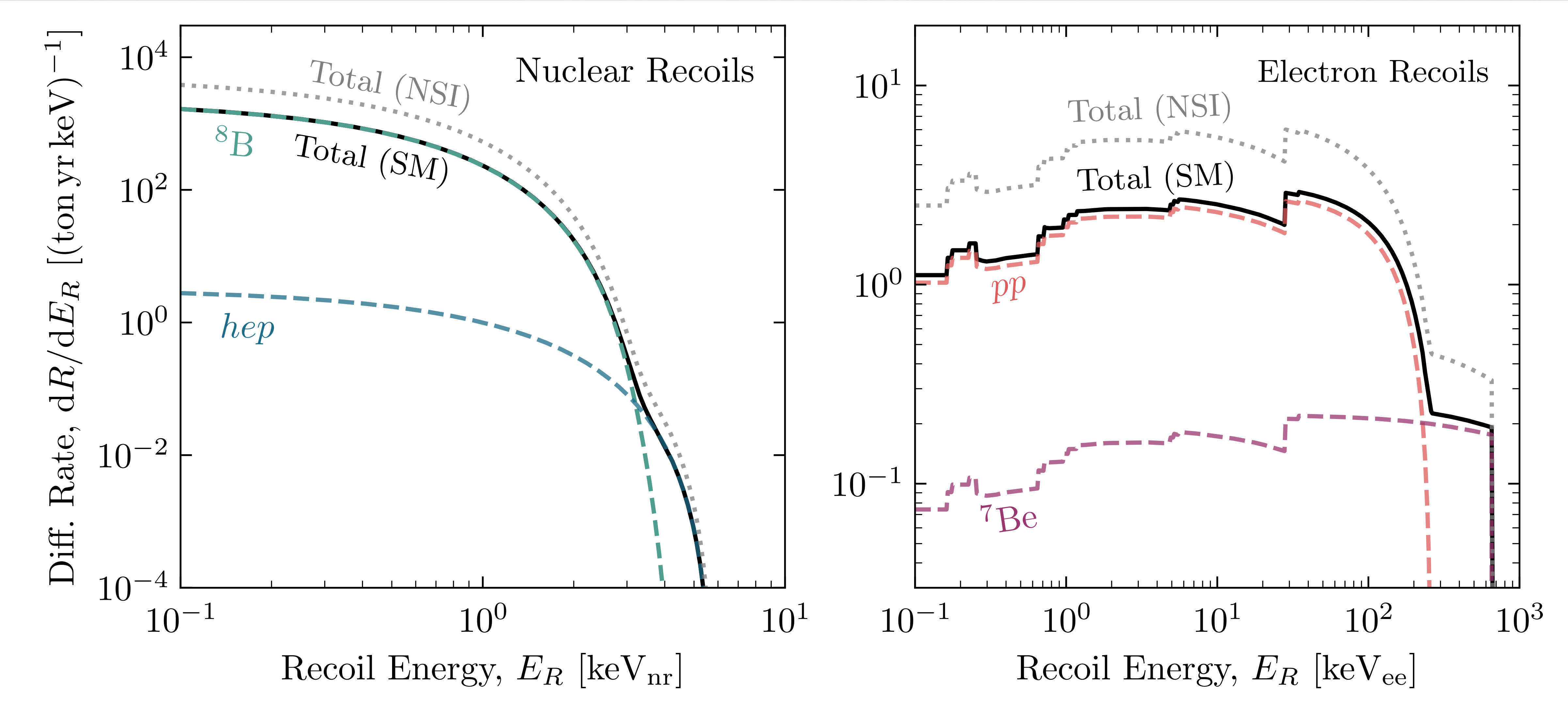
$$G^L_{\alpha\beta} = (\delta_{e\alpha} + g^e_L)\,\delta_{\alpha\beta} + \frac{1}{2}\,\varepsilon^{\eta,\varphi}_{\alpha\beta}\,\xi^e, \qquad G^R_{\alpha\beta} = g^e_R\,\delta_{\alpha\beta} + \frac{1}{2}\,\varepsilon^{\eta,\varphi}_{\alpha\beta}\,\xi^e$$

SOLAR NEUTRINO SCATTERING





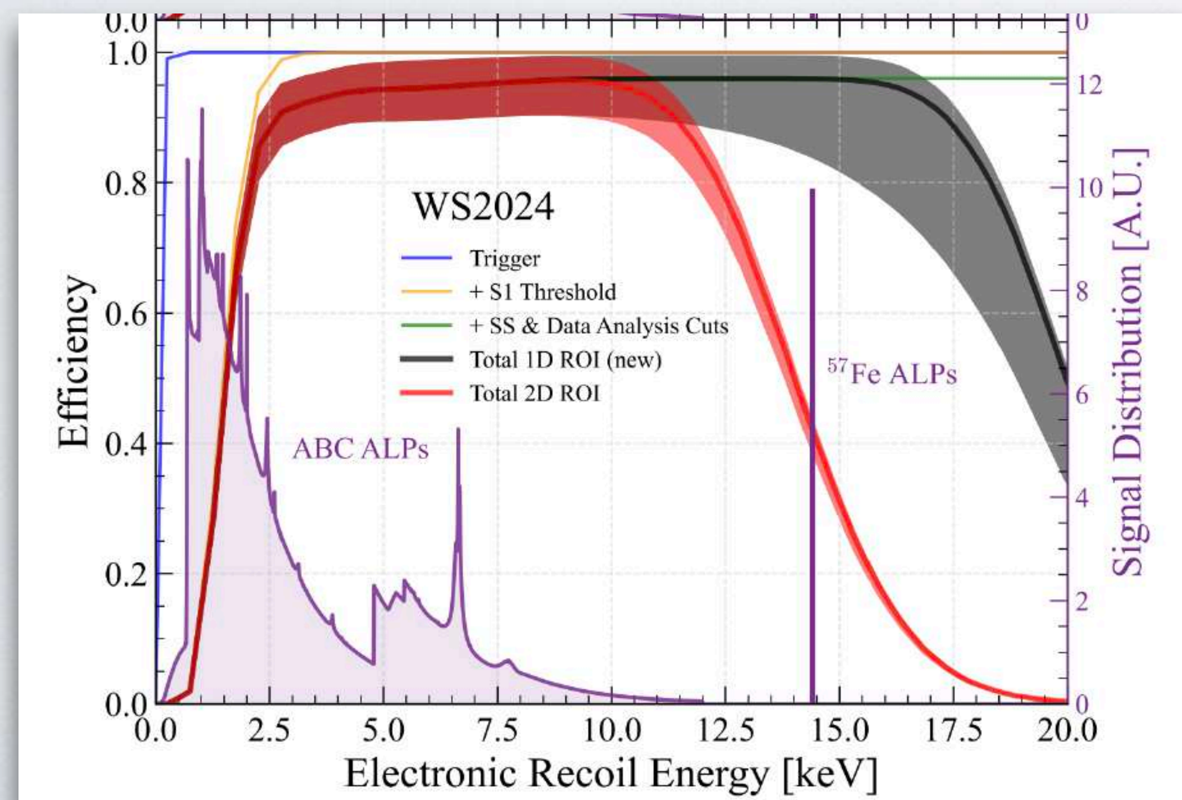
- Can compute solar neutrino **scattering rate including NSI in propagation and scattering:**



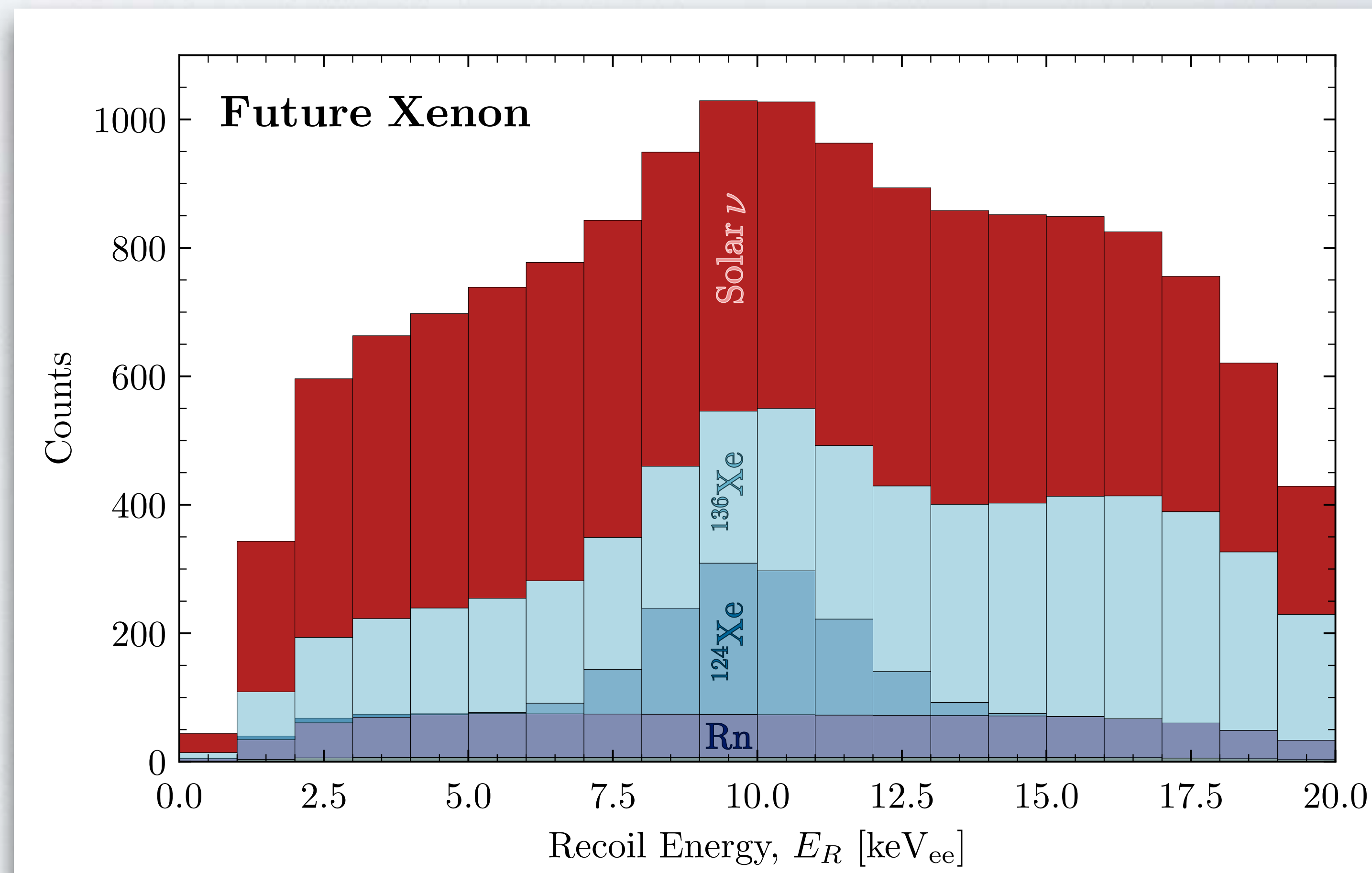
DETECTOR EFFECTS

- Realistic signal predictions have to include **detector effects** and **backgrounds**
- Model **energy thresholds**, **detector resolution and efficiencies** via convolution integral

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = \int_0^\infty \frac{\mathrm{d}R}{\mathrm{d}E'_R}\epsilon\left(E'_R\right)\frac{1}{\sigma\left(E'_R\right)\sqrt{2\pi}}e^{-\frac{\left(E_R-E'_R\right)^2}{2\sigma^2\left(E'_R\right)}}\,\mathrm{d}E'_R$$



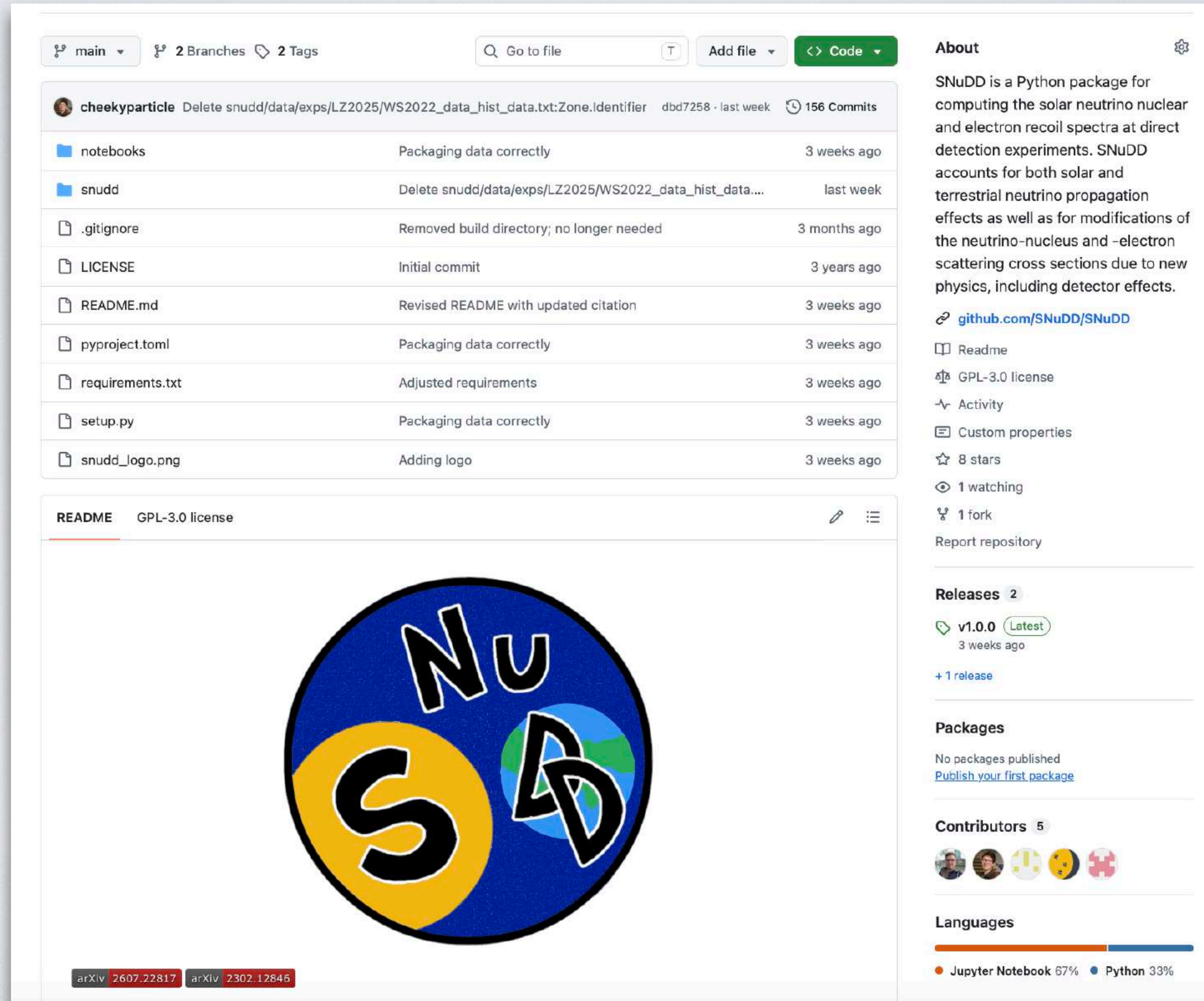
[LZ collaboration; 2511.17350]



[Amaral, Cerdeno, Cheek, Costa, **PF**; 2607.22817]

SNuDD

- 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



NSI @ DD – NUCLEAR SCATTERING

- Consider one NSI coupling at a time and compare sensitivity to global fit limits

  [Coloma et al., *JHEP* **02** (2020) 023]
  [Coloma et al., *JHEP* **08** *(2023) 032*]

- **Constraints from DD are becoming competitive with dedicated neutrino experiments!**

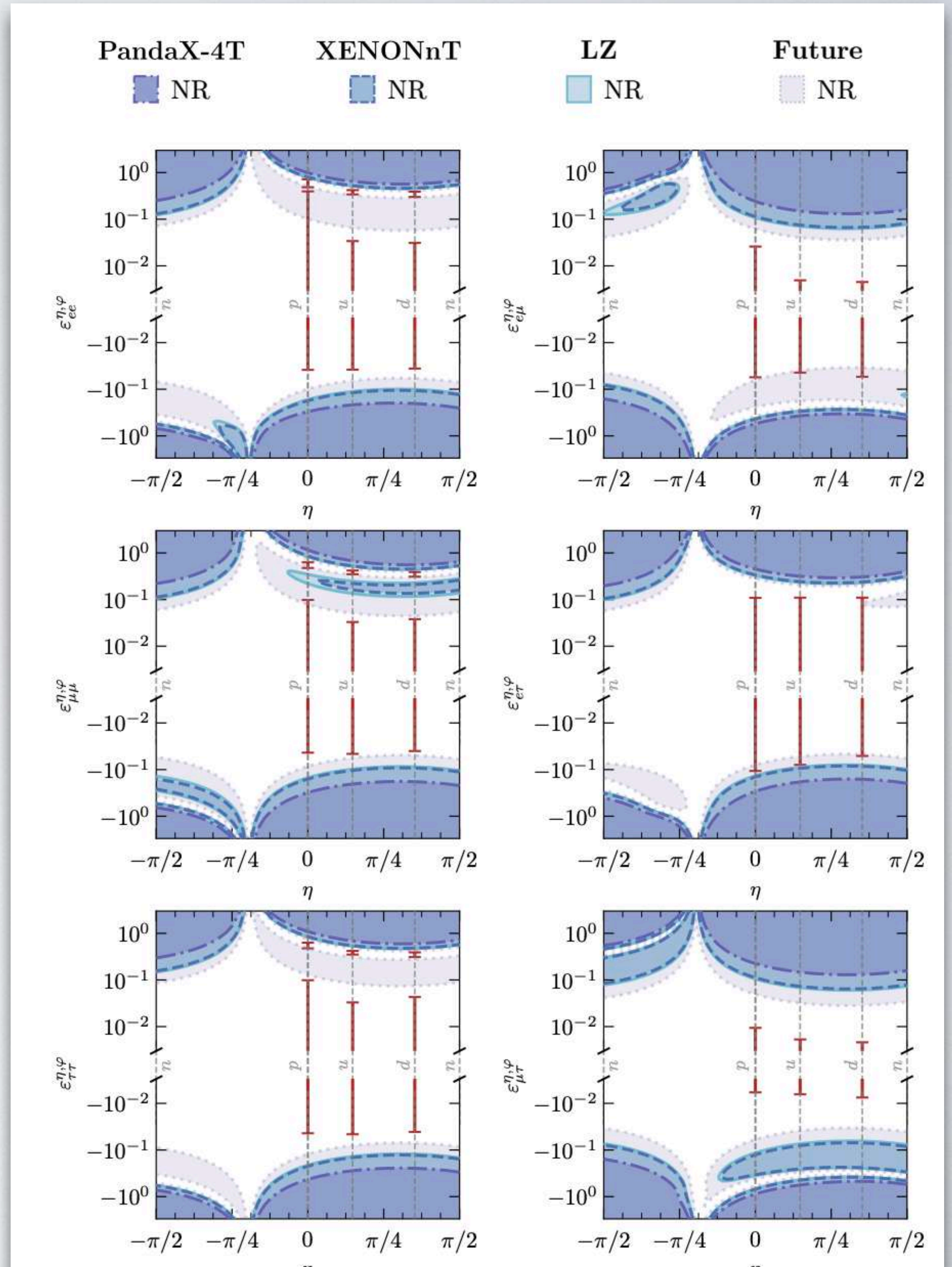
- Target **material-dependent blind spot** where neutron and proton NSI cancel

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

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

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

[Amaral, Cerdeno, Cheek, Costa, **PF**; 2607.22817]



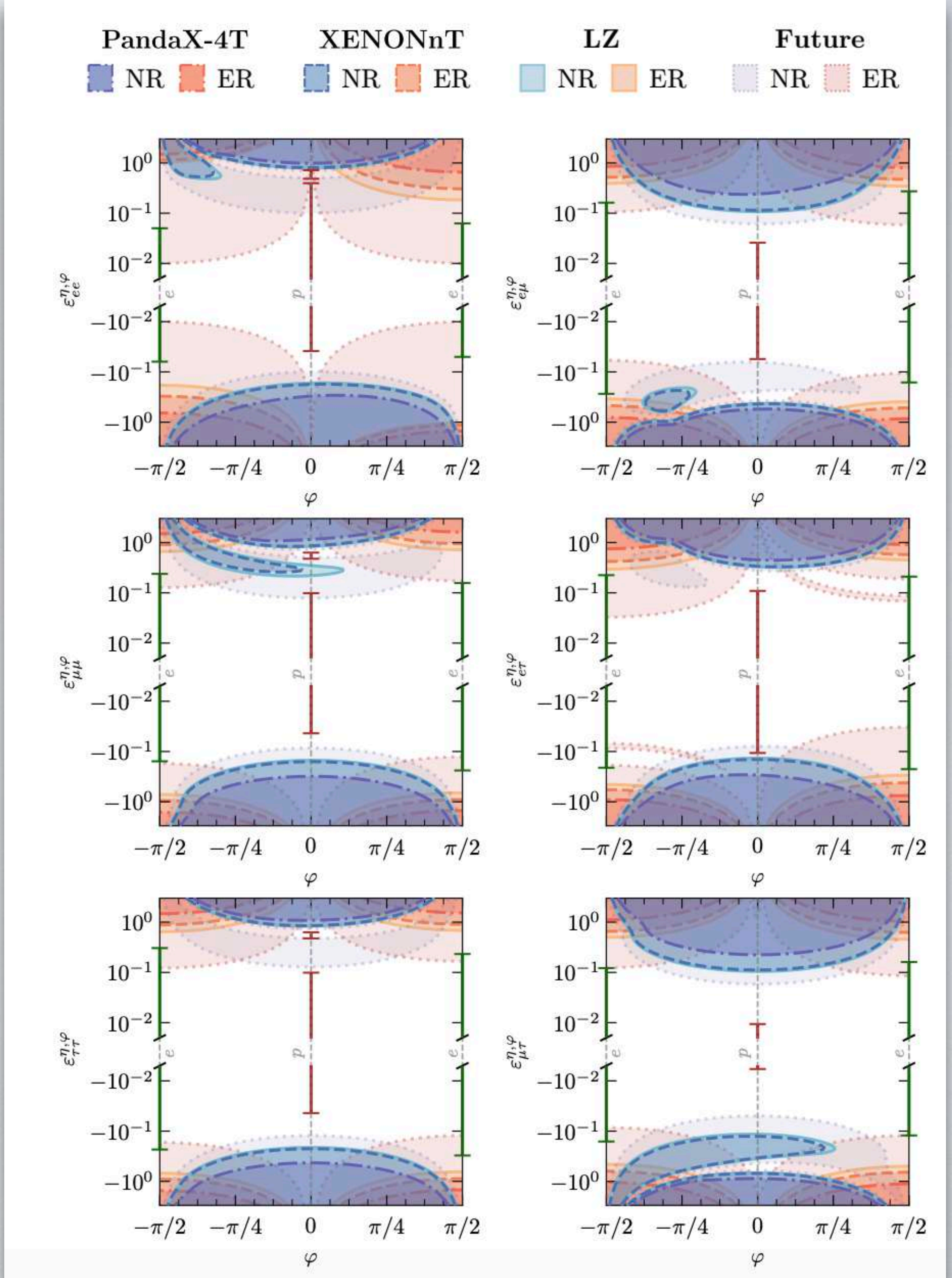
NSI @ DD – ELECTRON SCATTERING

- 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 $\varphi = \pm\pi/2$**

  [Coloma et al., *JHEP* **08** *(2023) 032*]
- ER sensitivities drop off towards $\varphi = 0$ (pure proton), whereas NR sensitivities become maximal
- Direct detection experiments have **excellent sensitivity to ER**!
- **Future Xe** can **improve by an order of magnitude** over current electron NSI bounds

DD experiments **have complementary sensitivity**
→ **include in future global fit**

[Amaral, Cerdeno, Cheek, Costa, **PF**; 2607.22817]

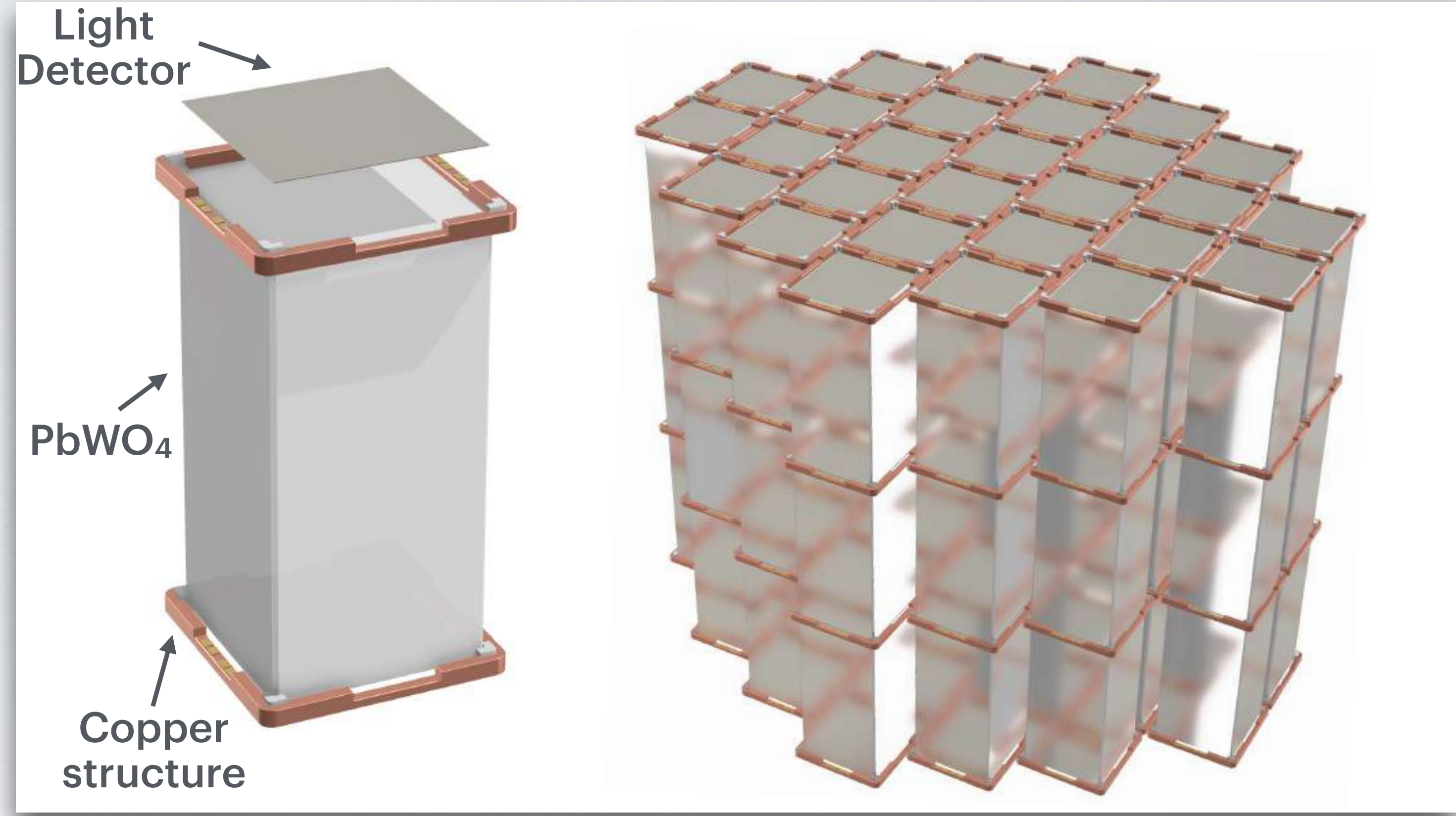


NEW DETECTORS: RES-NOVA

NEW TECHNOLOGIES: RES-NOVA

- Upcoming underground cryogenic scintillator neutrino observatory based in Gran Sasso
- Array of 8 tons of $PbWO_4$ scintillating crystals optimised for detecting CEvNS
- Powerfull background suppression:
  - simultaneous readout of **phonons and light**
  - **coincidence analysis** with different detector modules
- **Problem:** commercial lead has 10^4 Bq/ton of radioactive ^{210}Pb

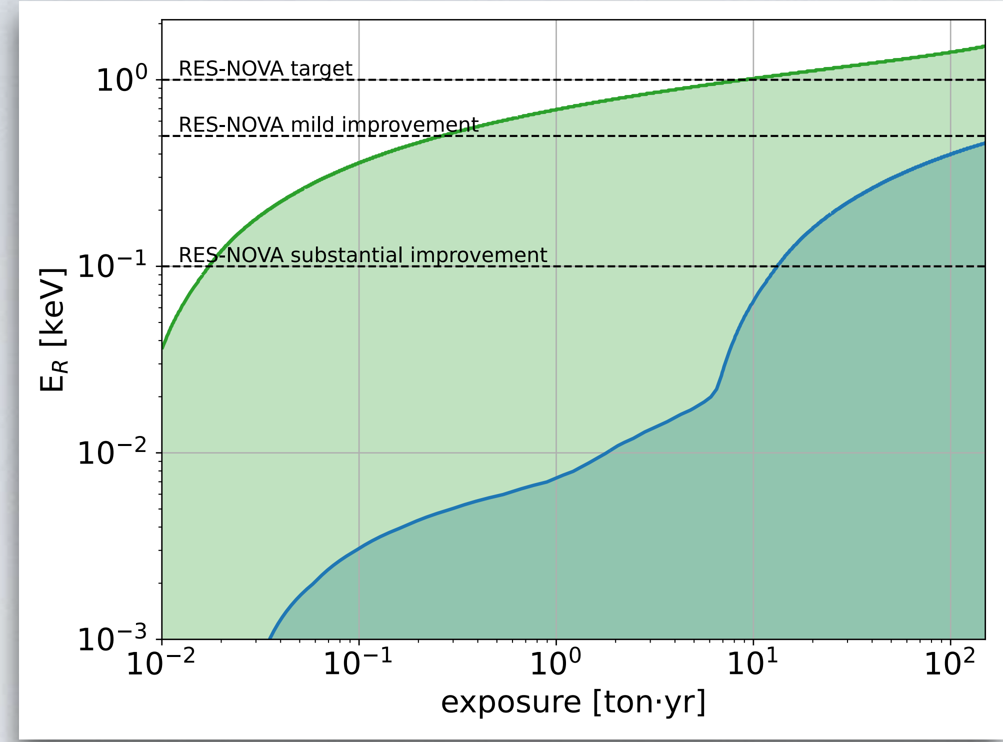
  → Use $PbWO_4$ grown with 2000 yr old archeological **lead from sunken Roman ships**
  (expected ^{210}Pb below 1 mBq/ton!)



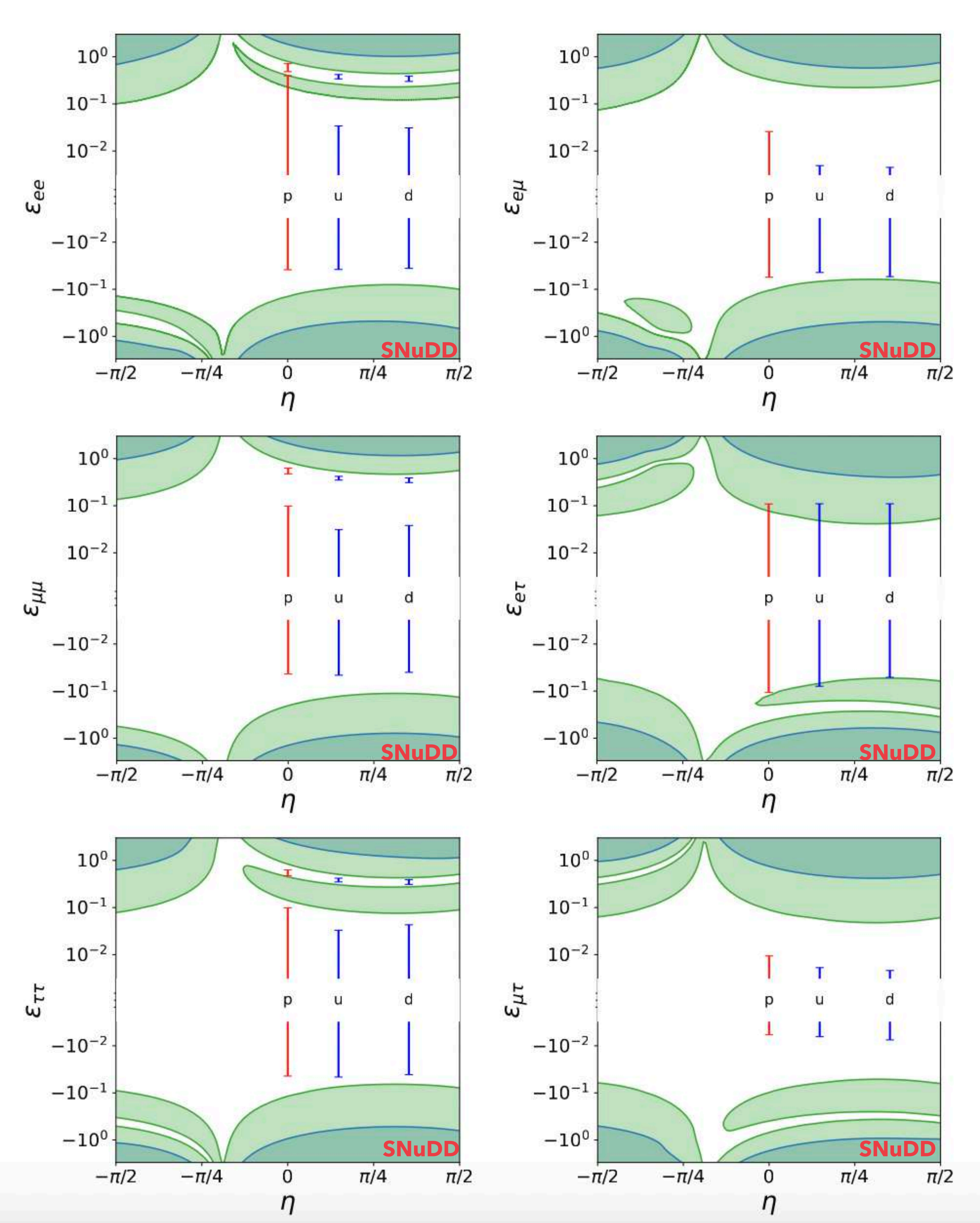
[RES-NOVA; *Phys.Rev.D* 111 (2025) 10, 103050]

Credit: N. Ferreiro Iachellini

NEW DETECTORS: RES-NOVA



- Projections for RES-NOVA demonstrator with **1-ton** fiducial volume and threshold of **0.5 keV** show **promising sensitivity to NSI**
- Sensitivity depends crucially on **background rejection**
- **Especially sensitive to $\varepsilon_{e\tau}$,** compared to global fits



[RES-NOVA, **PF**; *2602.23419*]

VECTOR MEDIATORS

ANOMALY-FREE PORTALS

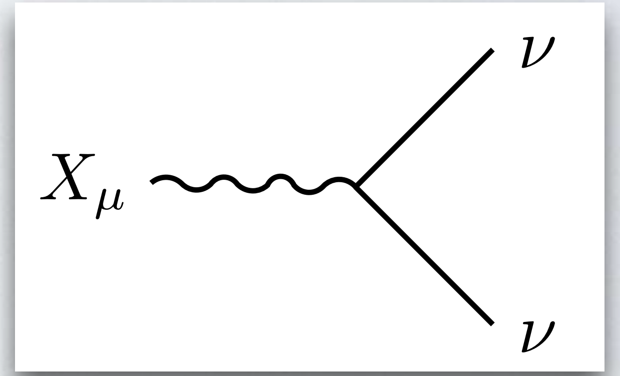
- Natural UV-completions of NSI by anomaly-free U(1)s

SM fields

$$J_X^\mu = \sum_\psi \bar{\psi}\, Q_\psi\, \gamma^\mu \psi \qquad \text{with } \psi = Q, L, u, d, \ell, \nu$$

- Infinite family of **anomaly-free U(1) with SM field content**. Simple examples are:

$B-L$	$L_\mu - L_e$	$L_e - L_\tau$	$L_\mu - L_\tau$
charging quarks & leptons	charging 1st & 2nd generation leptons	charging 1st & 3rd generation leptons	charging 2nd & 3rd generation leptons



- All of these have interactions with neutrinos

$$\varepsilon_{\alpha\alpha}^{f\,P}\,(E_R) = \frac{g_f\, g_\nu}{2\sqrt{2}G_F\,(2m_f E_R + M_X^2)}$$

⇒ Solar neutrino scattering will be enhanced in direct detection!

LIGHT MEDIATORS

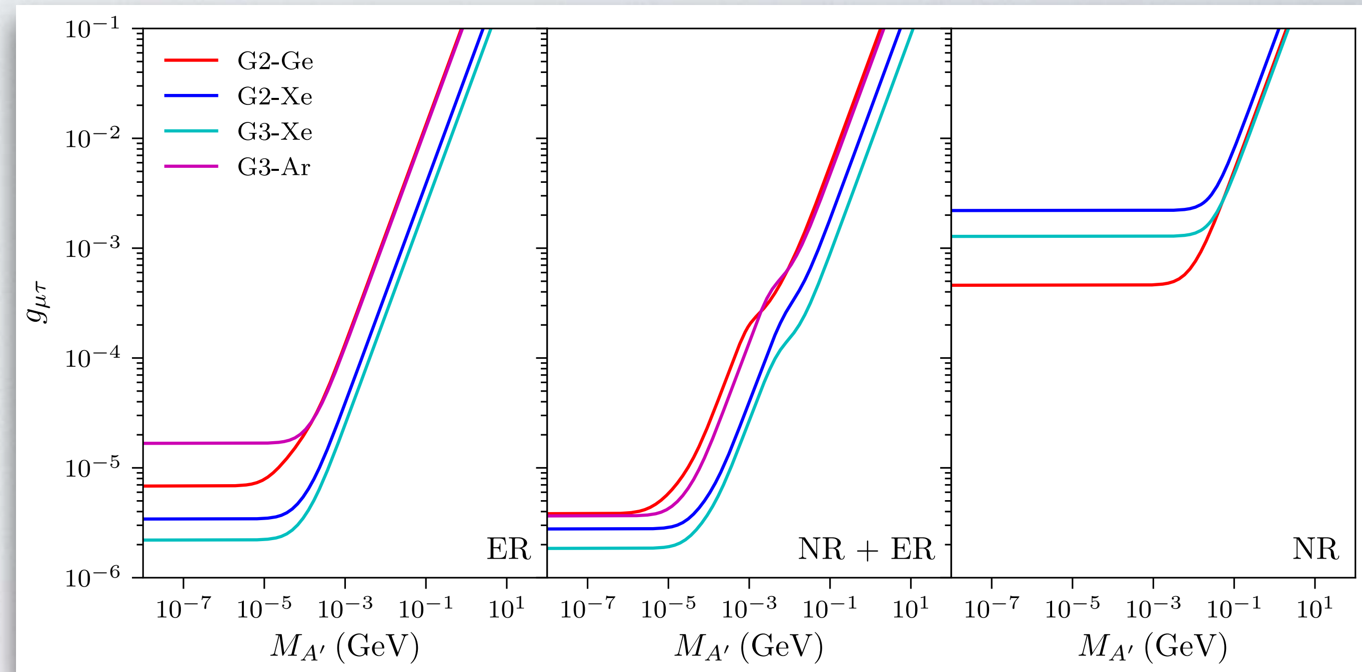
- DD experiments sensitive to neutrinos both in **electron and nuclear scattering!**

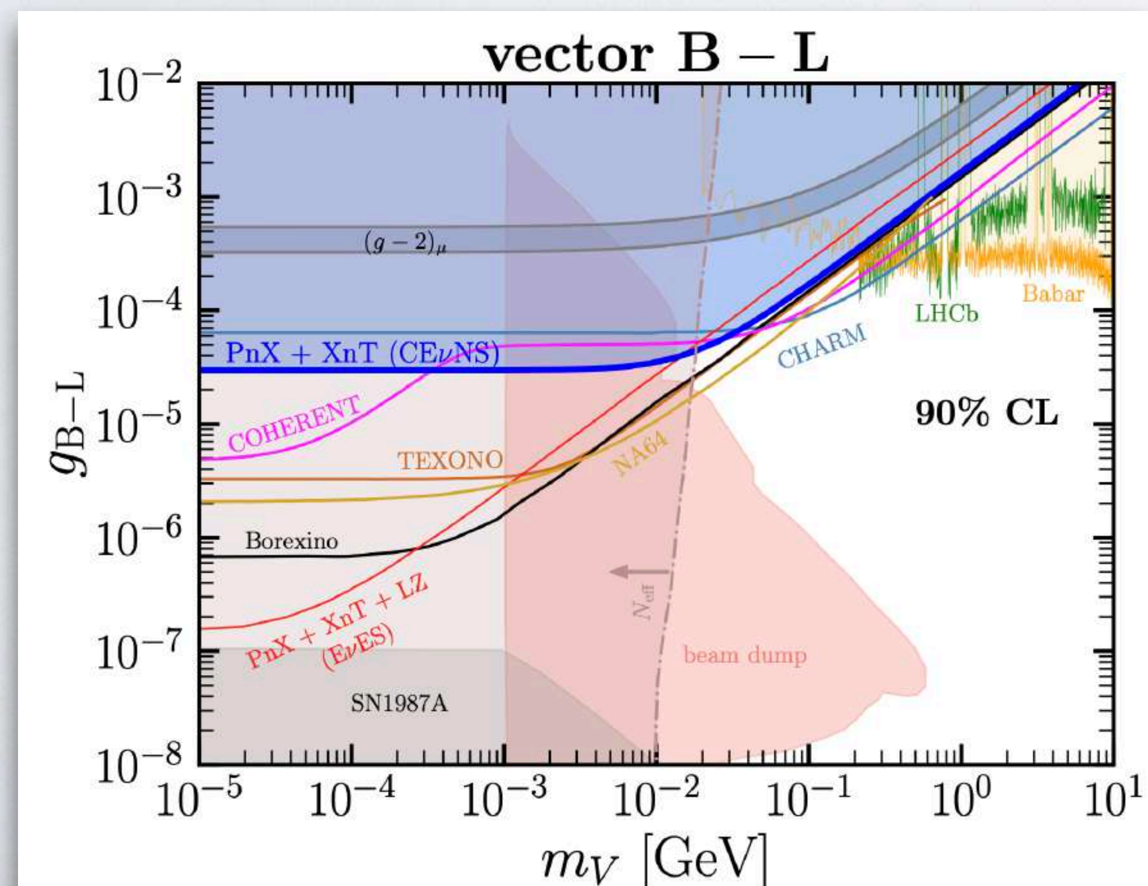
  [Amaral, Cerdeno, **PF**, Reid; 2006.11225]

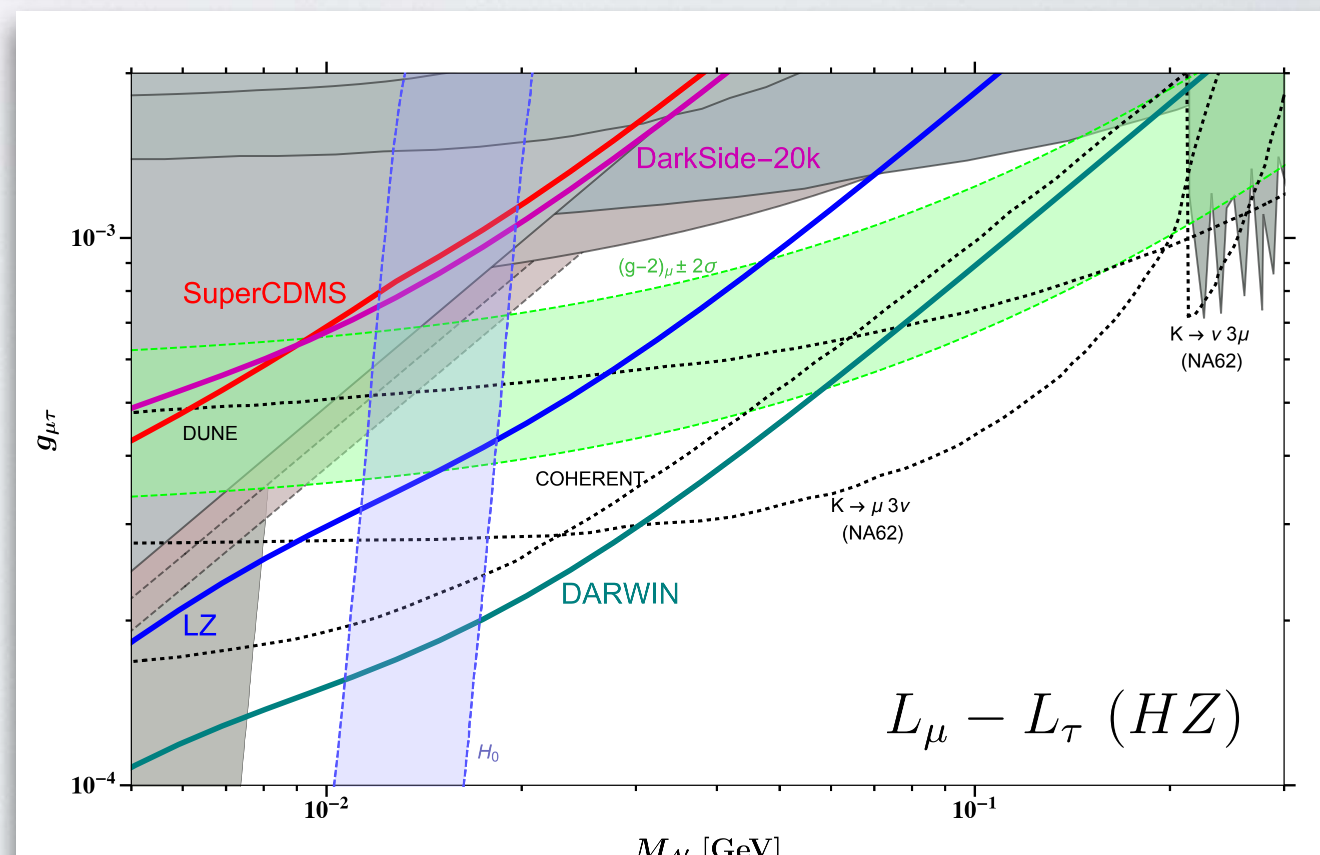
  [Amaral, Cerdeno, Cheek, **PF**; 2104.03297]

  [Blanco-Mas+, *JHEP* 08 (2025) 043]

  [De Romeri+, *JCAP* 05 (2025) 012]





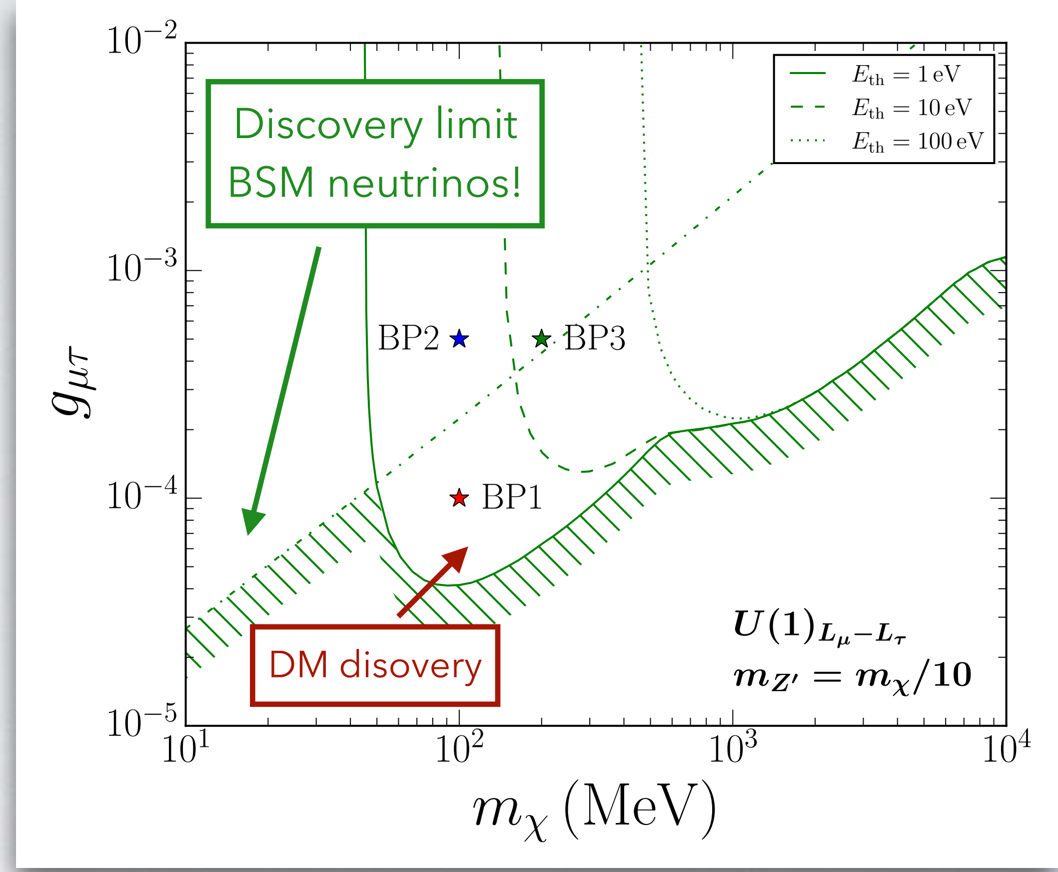


[De Romeri+, *JCAP* 05 (2025) 012]

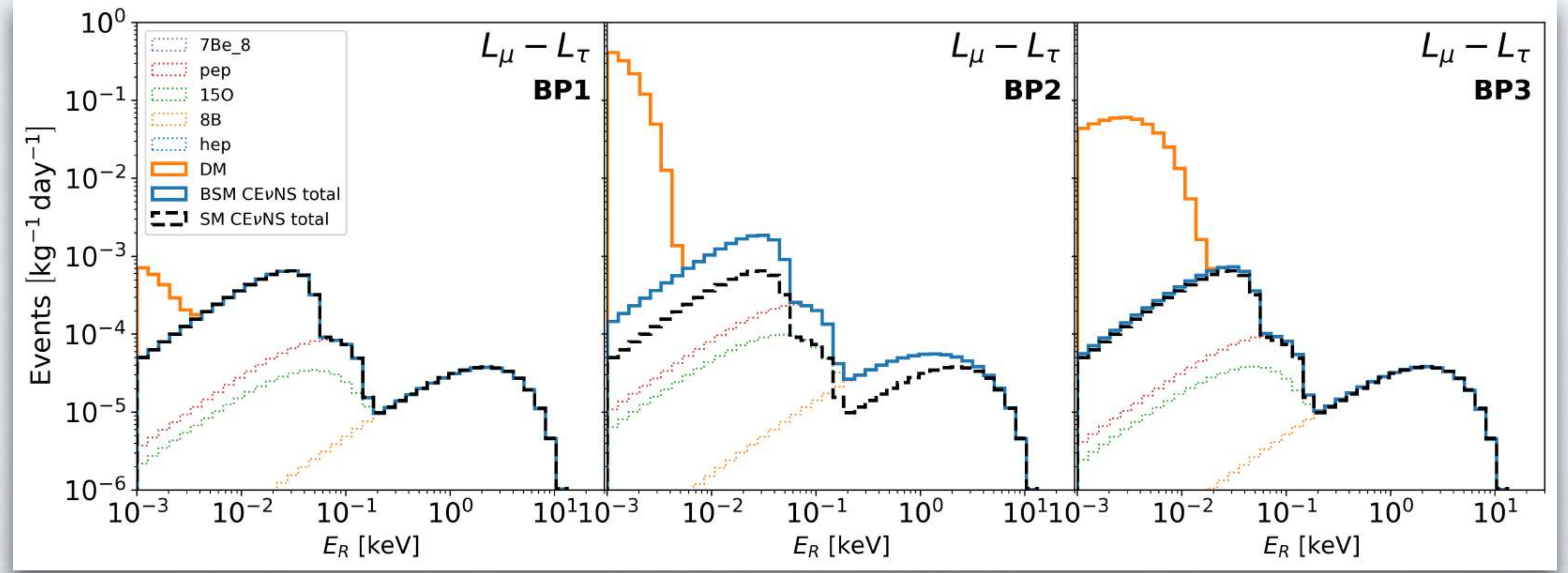
[Amaral, Cerdeno, **PF**, Reid; 2006.11225]

LIGHT MEDIATORS: ADDING DM

- Adding DM: $$\boxed{\mathcal{L}_{\mathrm{DM}} = -g_D\, \bar{\chi}\gamma_\mu\chi\, X^\mu}$$
- Leptophilic mediators lead to **observable DM and neutrino signals** ⇒ **modified neutrino fog!**
- DM discovery limit (neutrino floor) depends on **experimental threshold E_{th}**
- Potential signal discrimination via spectral info ⇒ need statistics (**exposure, background**)

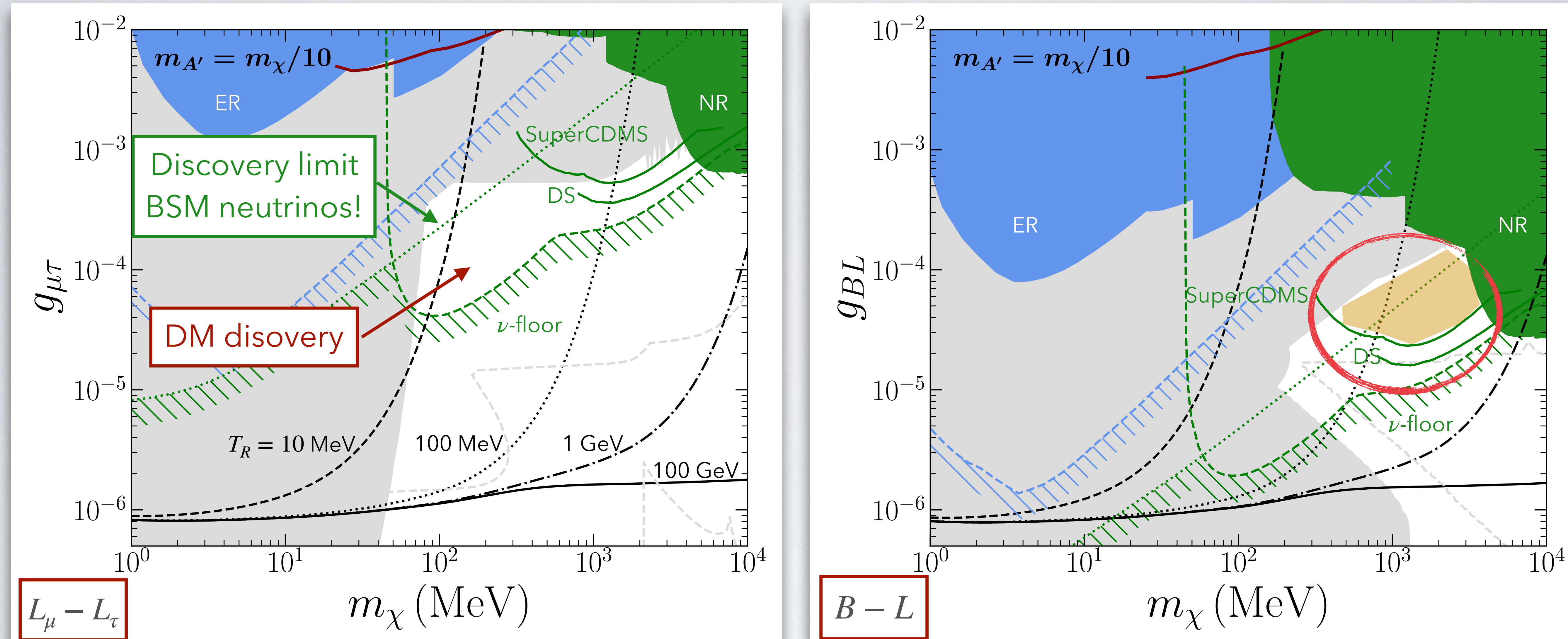


[Cerdeño, **PF**, López Noé, Zapata; 2603.16863]



LIGHT MEDIATORS: TESTING FREEZE-IN

- **Vector mediator** models ($B-L$, $L_i - L_j$) **can accommodate (low reheating) freeze-in!**



[Cerdeño, **PF**, López Noé, Zapata; 2603.16863]

- Direct detection can observe **DM and neutrino signal** $\Rightarrow$ **DISCRIMINATION!**

CONCLUSIONS

- In the next years, **direct detection experiments** will observe large numbers of **(solar) neutrinos**

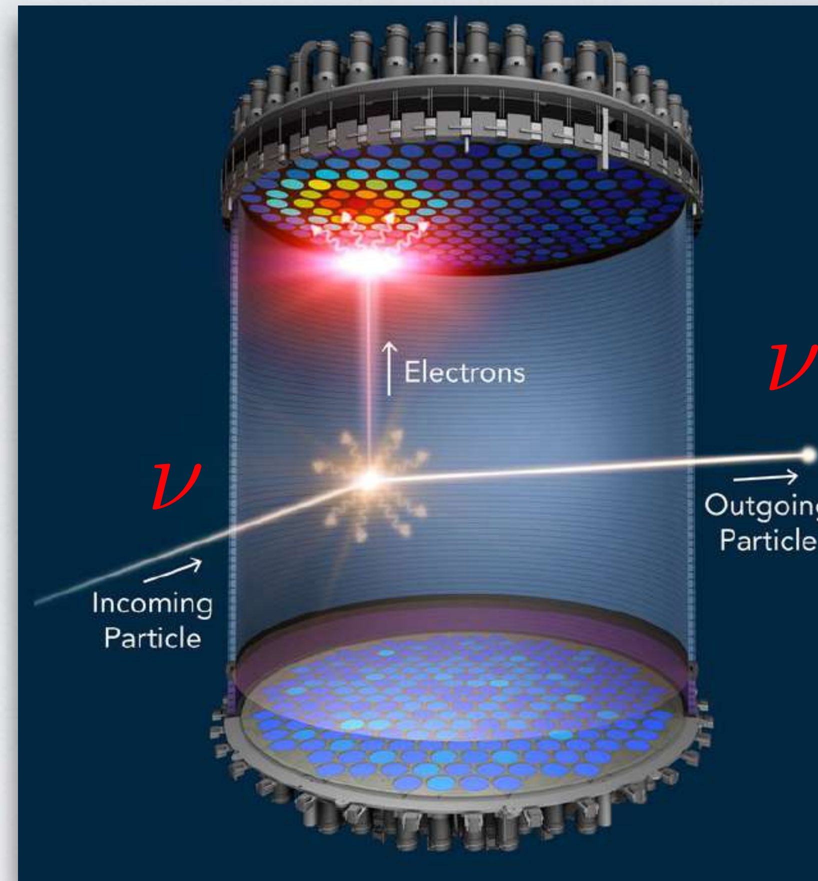
  $\Rightarrow$ Novel type of **neutrino experiments for free**!

- **Low energy thresholds** and **large exposures** gives them **great sensitivity to solar neutrinos**

- Sensitive to both **CEvNS** and **EvES** provides **complementary information** to reactor and spallation source neutrino experiments

- DD experiments already allow to **test neutrino properties within and beyond the SM:**
  - NSI
  - light mediators
  - sterile neutrinos
  - …

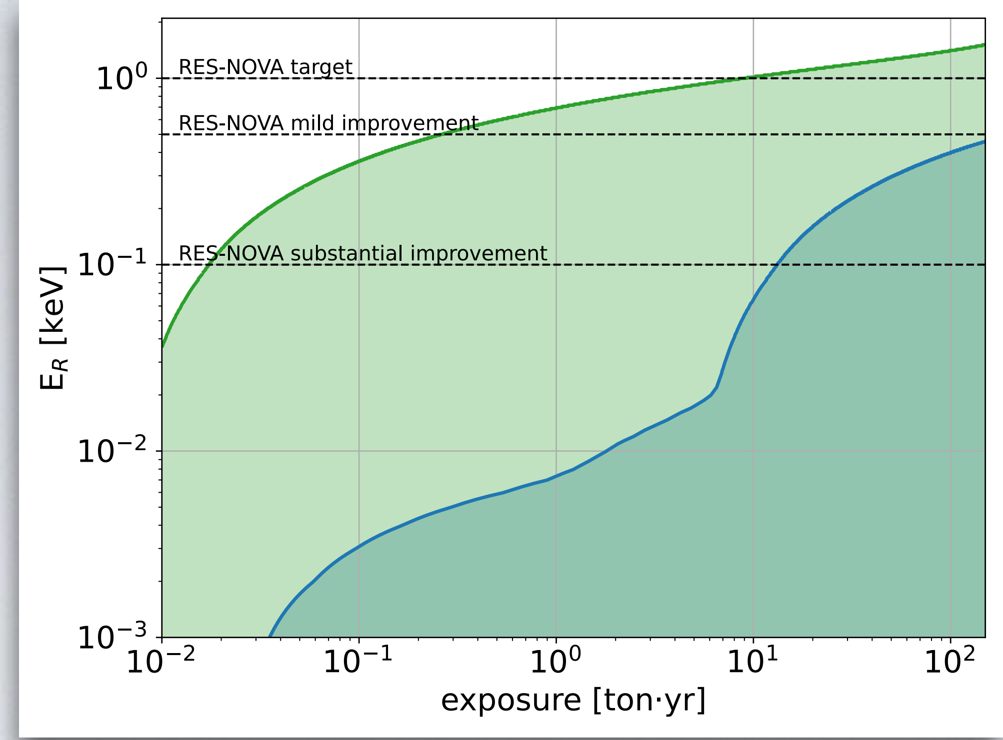
- Novel **cryogenic scintillators (RES-NOVA)** promising for detecting **solar** ^8B in **CEνNS**



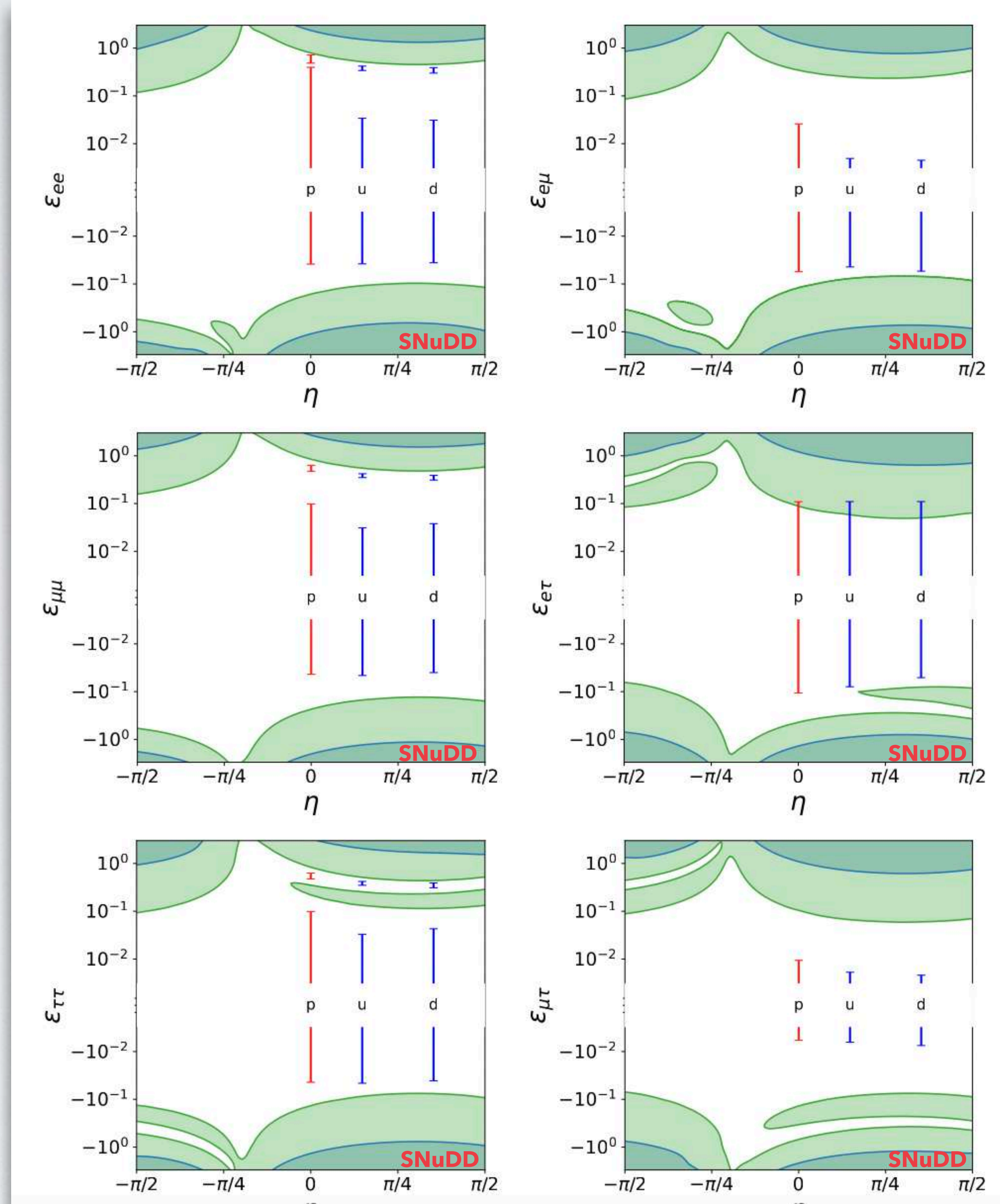
- **Direct detection experiments will become an important player for neutrinos!**

BACKUP

NEW DETECTORS: RES-NOVA



- Easily scalable to **multi-ton experiment**
- Optimise for volume:
  10-ton volume and threshold of 1 **keV**
- RES-NOVA also targeting future **core-collapse supernova neutrinos**; see e.g. [RES-NOVA; *JCAP* 10 (2021) 064]



[RES-NOVA, **PF**; *2602.23419*]

ADIABATIC PROPAGATION

- Two-state evolution in solar matter across finite distance Δx given by Hamiltonian:

$$D(x) + iU_{12}^{m\dagger}\dot{U}_{12}^{m} = \begin{pmatrix} E_1^m + \sin^2\theta_{12}^m\ \dot{\chi} & e^{i\chi}[i\dot{\theta}_{12}^m - \sin\theta_{12}^m\cos\theta_{12}^m\ \dot{\chi}] \\ -e^{-i\chi}[i\dot{\theta}_{12}^m + \sin\theta_{12}^m\cos\theta_{12}^m\ \dot{\chi}] & E_2^m - \sin^2\theta_{12}^m\ \dot{\chi} \end{pmatrix}$$

with matter phase $\tan\chi = -\dfrac{\Delta\sin 2\theta_{12}\sin\delta_{CP} + V(x)\mathrm{Im}(\varepsilon_N(x))}{\Delta\sin 2\theta_{12}\cos\delta_{CP} + V(x)\mathrm{Re}(\varepsilon_N(x))}$

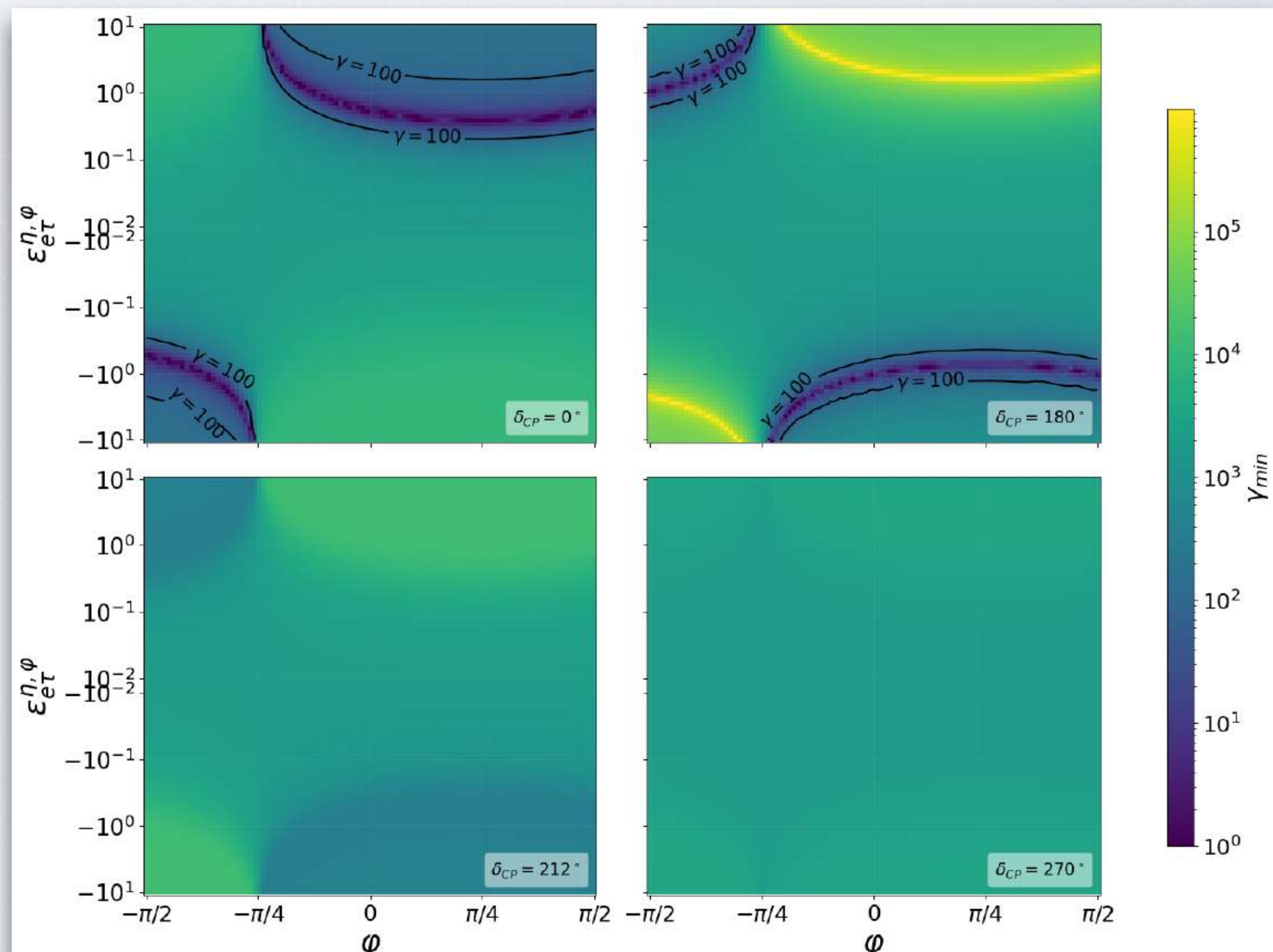
- Evolution **adiabatic if**

$$\boxed{\gamma_\pm = \frac{|\frac{1}{2}\Delta E_{21}^m - \sin^2\theta_{12}^m\ \dot{\chi}|}{|i\dot{\theta}_{12}^m \pm \sin\theta_{12}^m\cos\theta_{12}^m\ \dot{\chi}|} \gg 1}$$

- Adiabaticity **depends on the CP phase!**

- Complex NSI can modify the adiabaticty of neutrino evolution!

[Amaral, Cerdeno, Cheek, Costa, **PF**; 2607.22817]



1. NEUTRINO PROPAGATION

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

- In presence of a non-zero electron density neutrino oscillations are described by the **Schroedinger equation**

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

where

$$\Delta m^2_{ij} = m_i^2 - m_j^2 \qquad V_{cc} = \sqrt{2}\,G_F\,N_e(x) \qquad \boldsymbol{\nu} = \begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

- We define the PMNS matrix as

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

1. 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

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

- 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]

1. NEUTRINO PROPAGATION

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

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

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

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

defining $\Delta \equiv \Delta m^2_{21}/(4E_\nu)$ we find the **matter eigenvalues and mixing angle:**

$$\Delta E^m_{21} \equiv E^m_2 - E^m_1 = 2\Delta\sqrt{p^2+q^2}$$

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

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

with

$$p = \sin 2\theta_{12} \qquad q = \cos 2\theta_{12} - \frac{1}{2} c^2_{13} \frac{V(x)}{\Delta}$$

MATTER EFFECTS WITH NSI

- **Presence of additional NSI matter potentials modifies propagation**

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

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

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

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

- **Modifies matter mixing angle and energy eigenvalues through the quantities**

$$p = \frac{\sqrt{(\Delta \sin 2\theta_{12} \cos\delta_{CP} + V(x) \mathrm{Re}(\epsilon_N))^2 + (\Delta \sin 2\theta_{12} \sin\delta_{CP} + V(x) \mathrm{Im}(\epsilon_N))^2}}{\Delta}$$

$$q = \cos 2\theta_{12} + \frac{V(x) \varepsilon_D(x)}{\Delta} - \frac{1}{2} c_{13}^2 \frac{V(x)}{\Delta}$$

PROPAGATION S-MATRIX

- The full three-flavour propagation in matter is then given by the evolution equation

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

- Assuming **adiabaticity** $|\Delta E^m_{12}| \gg 2|\dot{\theta}^m_{12}|$ within the Sun (i.e. a slowly varying matter profile), we can describe the full propagation in matter from the point of neutrino creation to the surface of the sun by the 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

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