TESTING NEW PHYSICS WITH NEUTRINOS AT DM EXPERIMENTS

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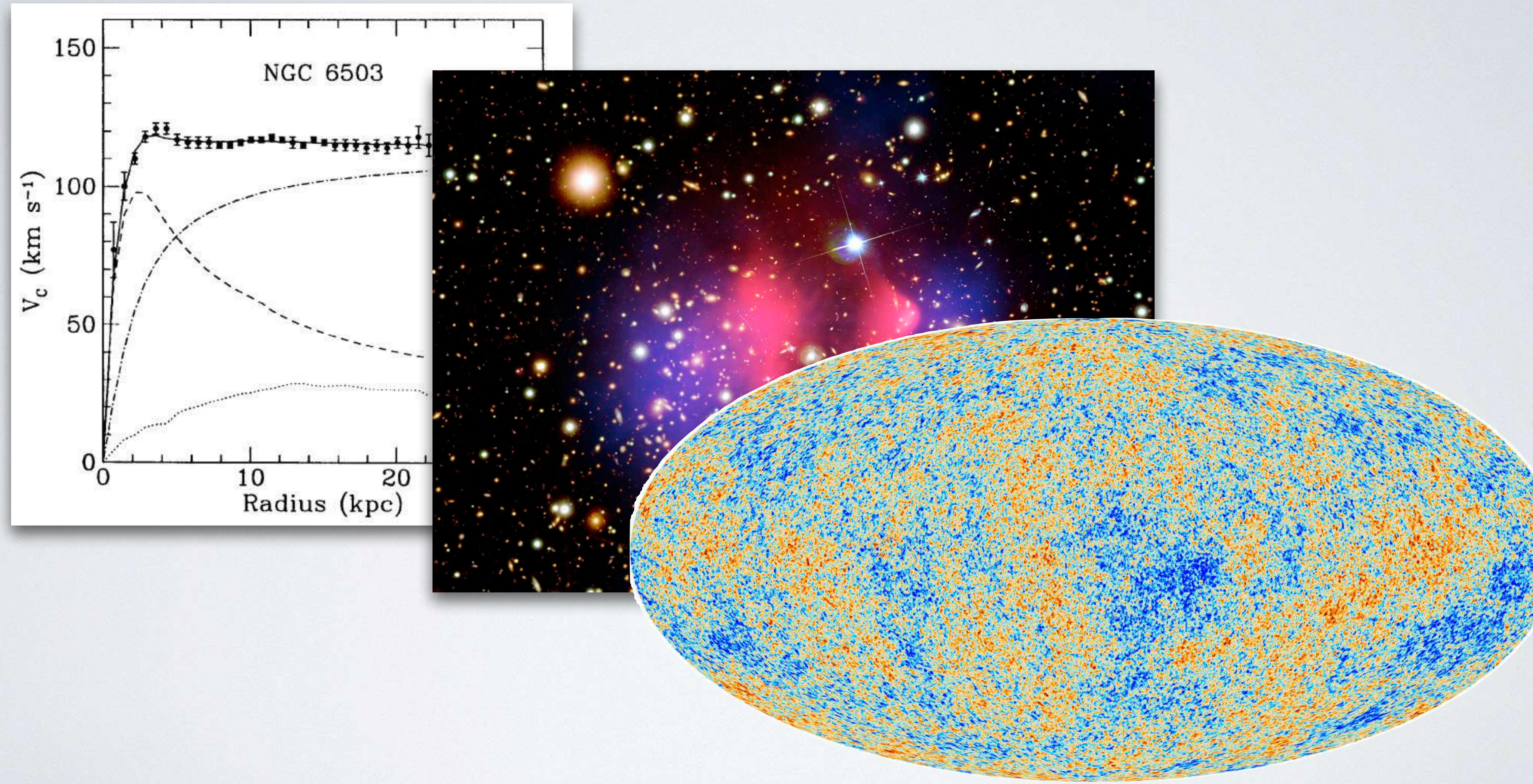
THE QUEST FOR THE INVISIBLE

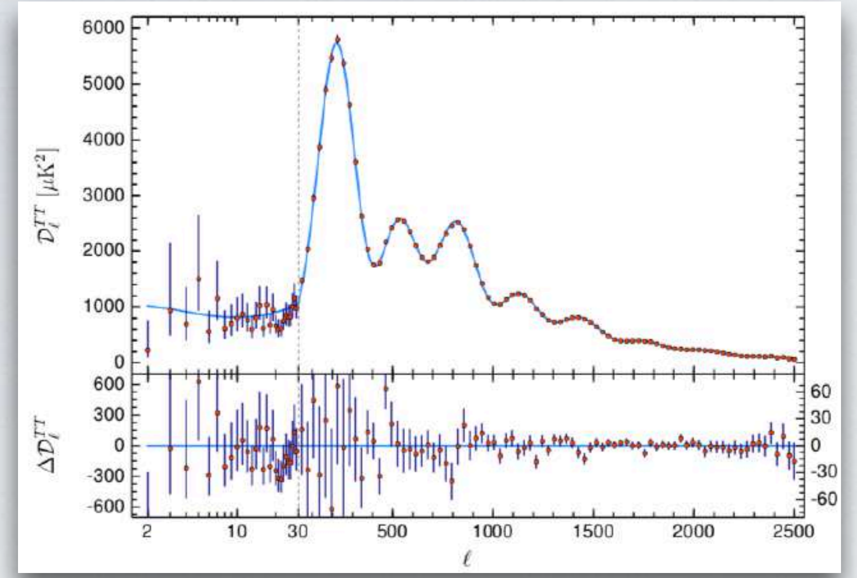
- Made various indirect (gravitational) observations of very abundant **dark matter**



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

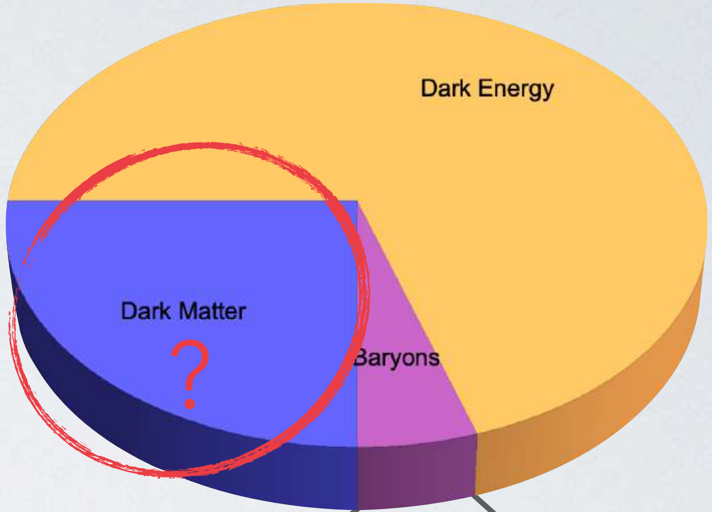
WHERE TO LOOK BEYOND SM?

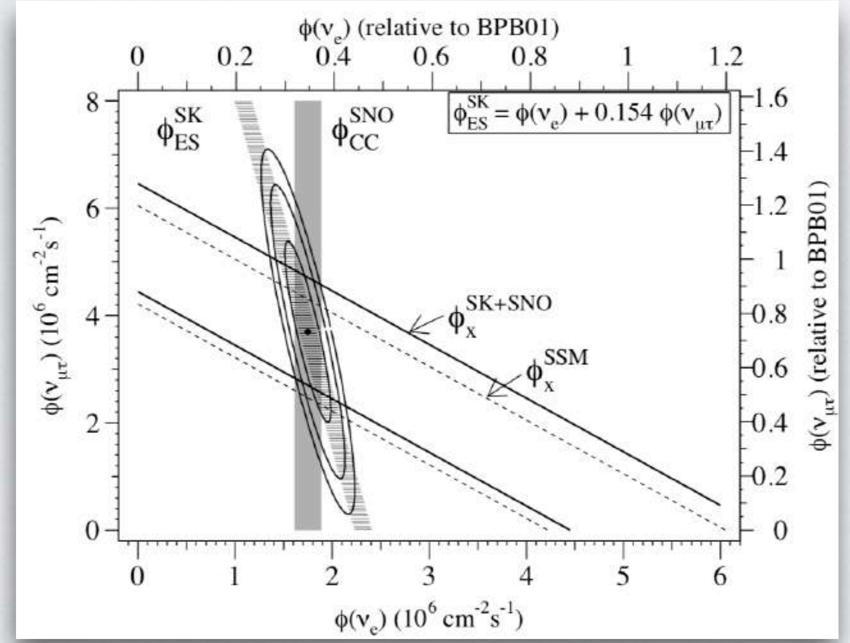
Two obvious targets:



[Planck Collaboration; 1807.06209]

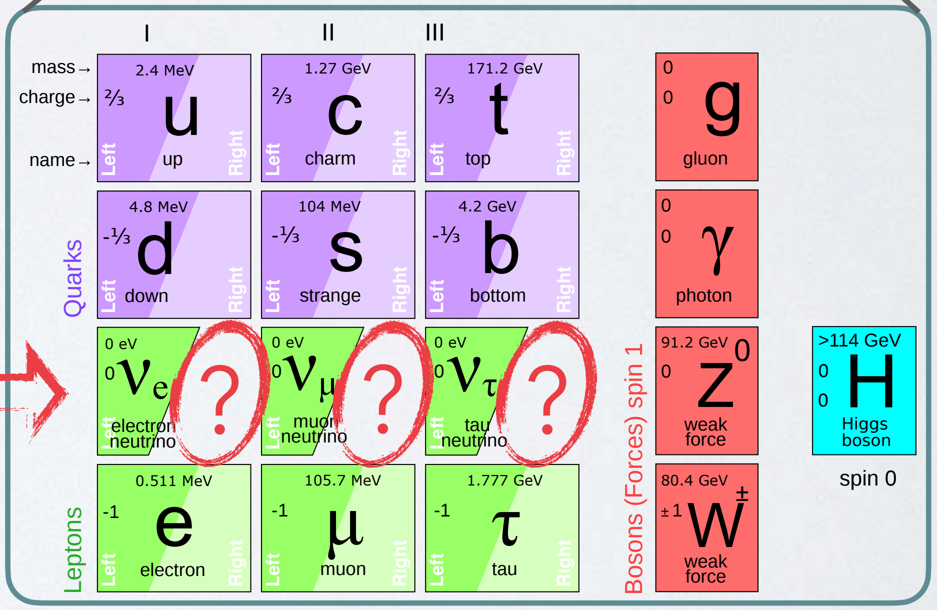
CMB informs us about energy budget





[SNO Collaboration PRL 87:071301]

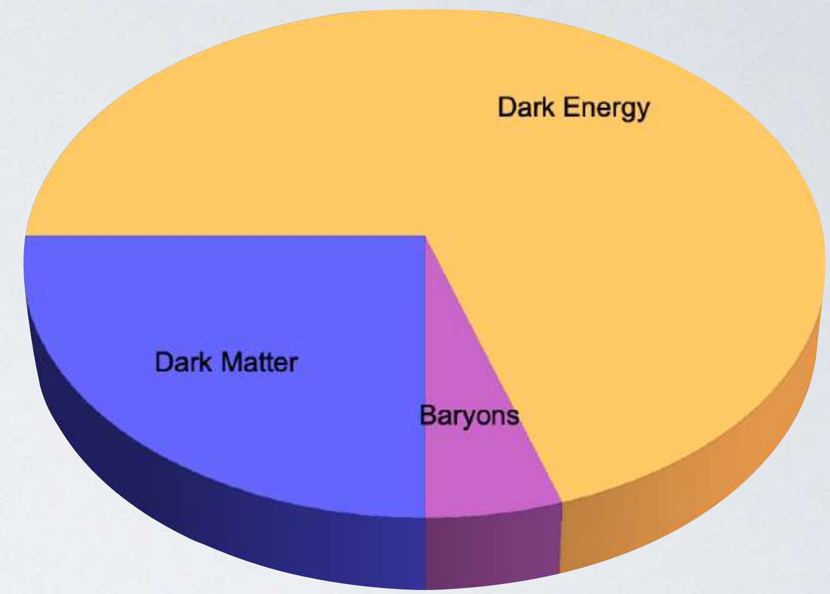
Oscillations require massive neutrinos

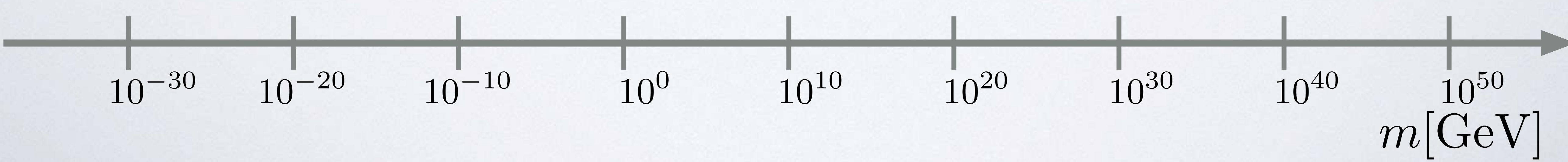


[Gninenko et al., 1301.5516]

WHAT IS DARK MATTER?

1. Stable, cold, (almost) collisionless, dissipationless substance
2. Interacts (only?) gravitationally
3. Makes up ~25 % of the energy density of the universe
4. Mass ?





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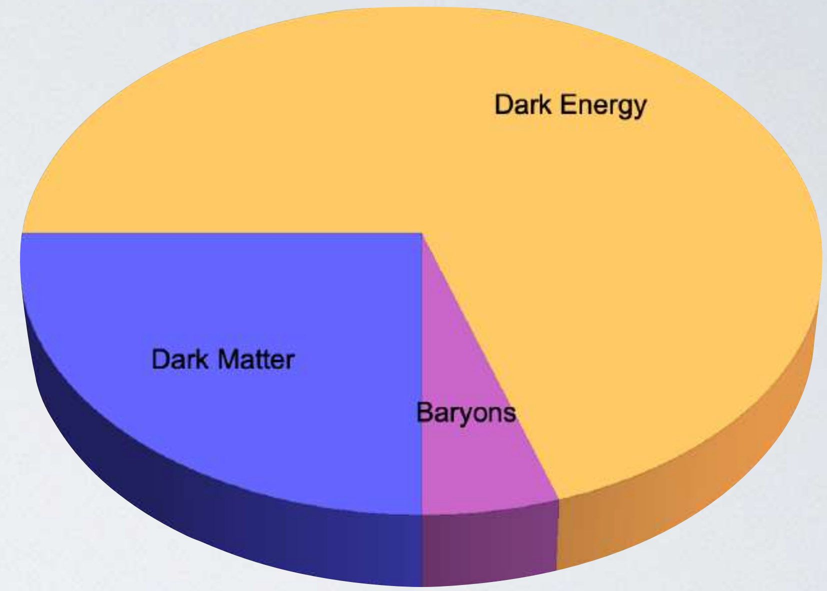


[Niikura et al., Nat. Astr. 3 (2019) 6]

Galaxy formation

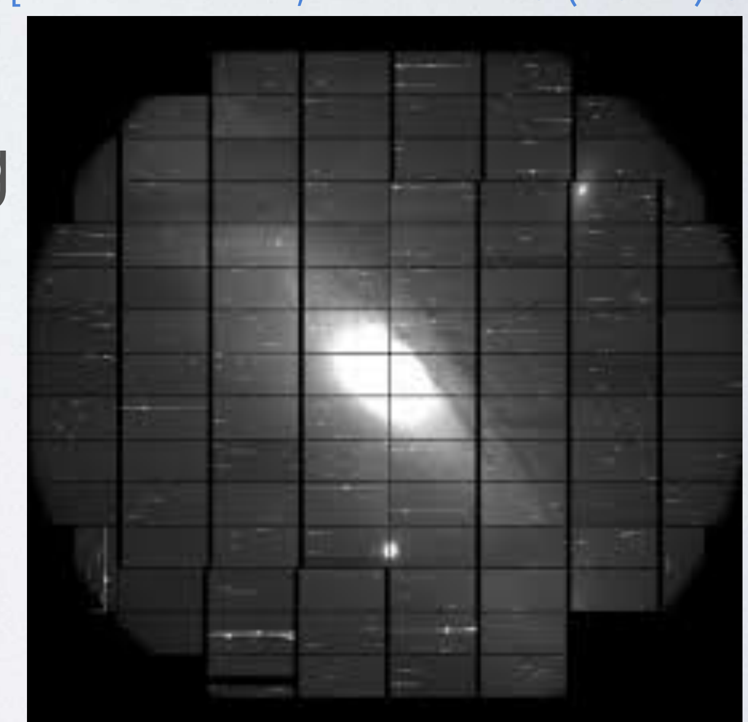
$$\lambda_{dB} = \frac{2\pi}{mv} \lesssim 100 \text{ kpc}$$

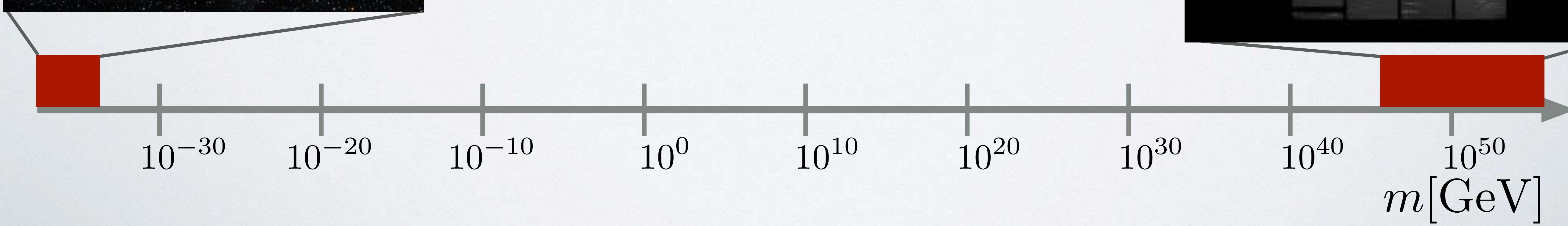
$$m \gtrsim 10^{-24}\,\text{eV}$$

[Hlozek et al., PRD **91** (2015)]

microlensing searches of PBHs

$$m \lesssim 10^{46}\,\text{GeV}$$

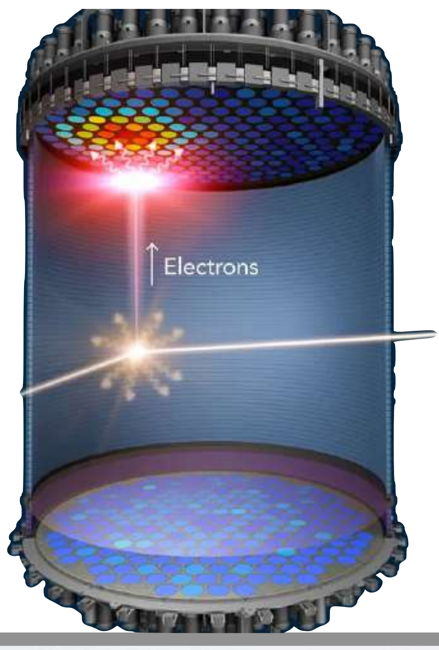




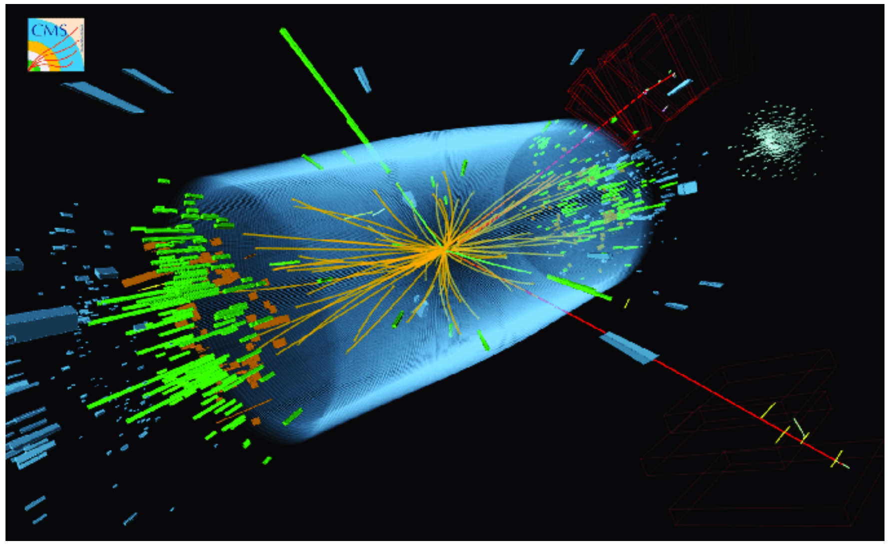
HOW TO SEARCH FOR DM?

- Complementary strategies testing different aspects of DM

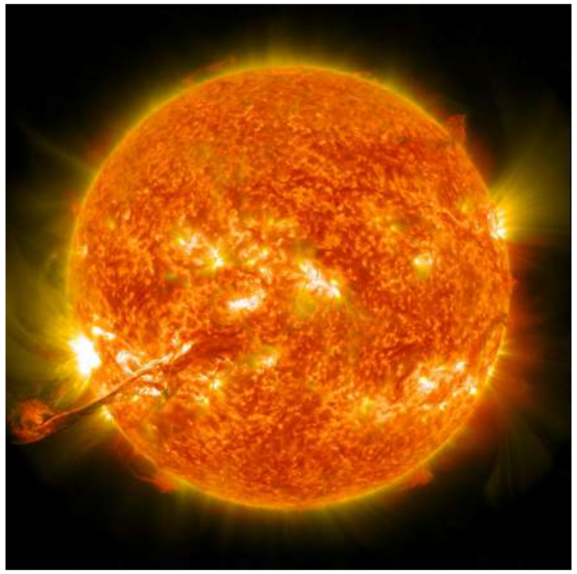
Direct Detection
(Dispersion)



Accelerators
(Production)



Astrophysics and Cosmo
(Production)



Indirect detection
(Annihilation and decay)

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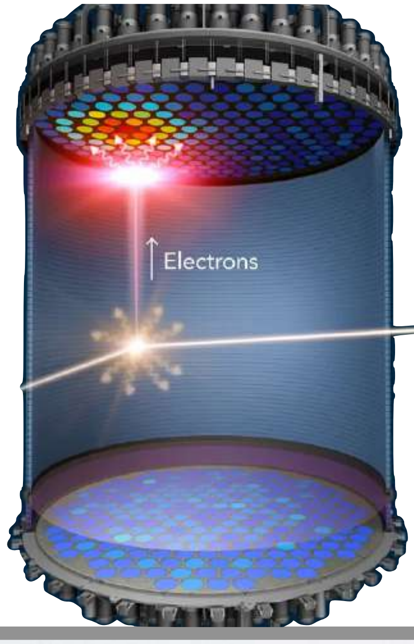
- Complementary strategies testing different aspects of DM

This talk

Direct Detection
(Dispersion)



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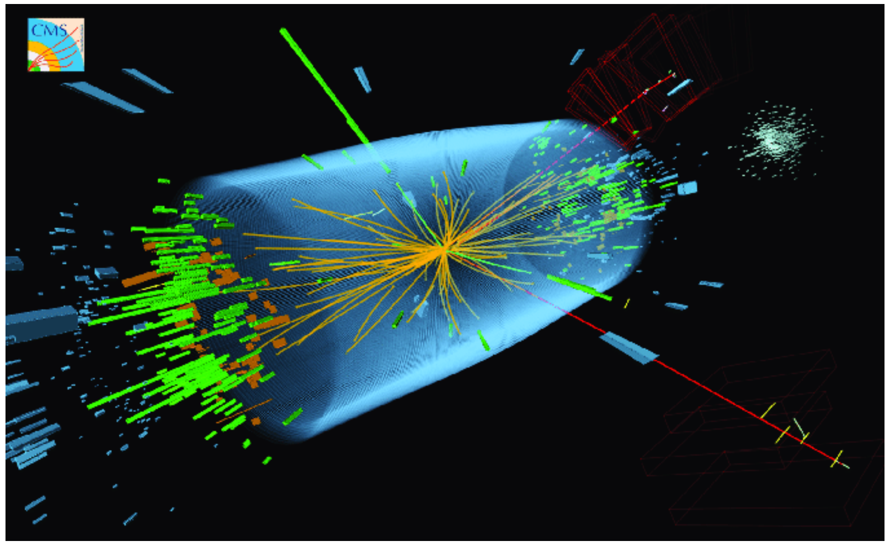

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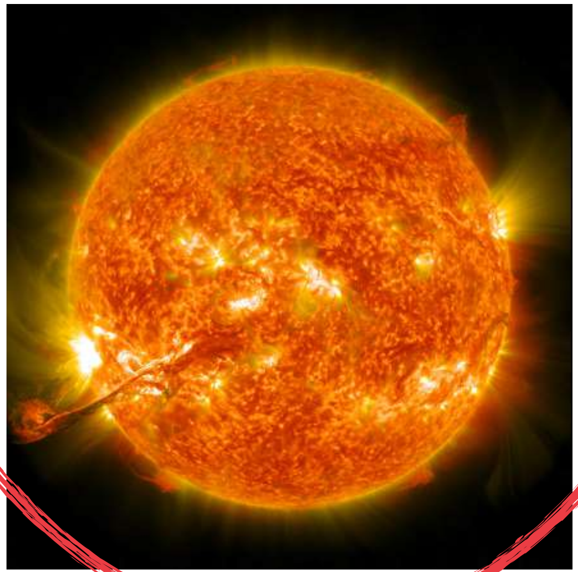

Indirect detection
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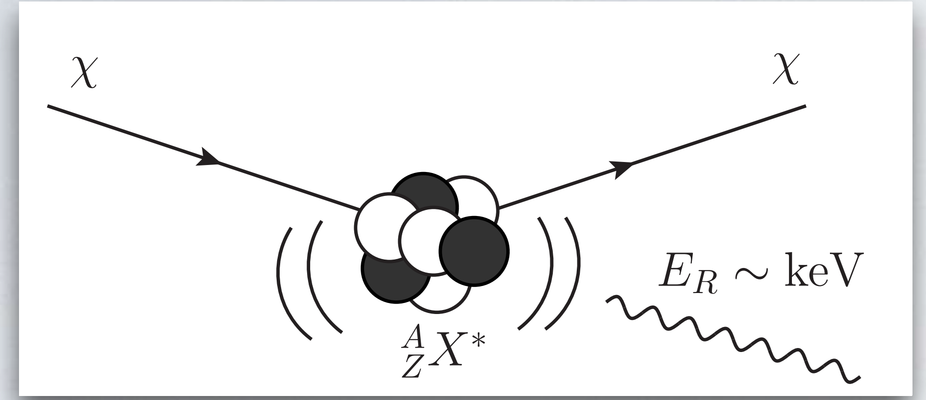
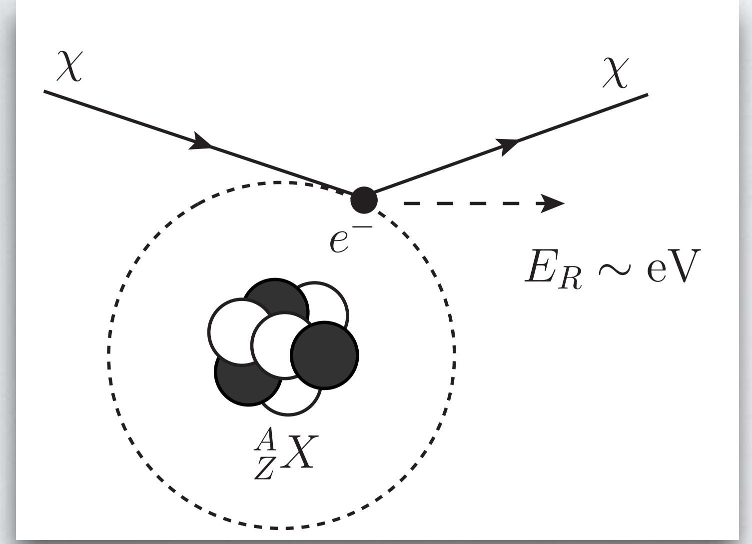
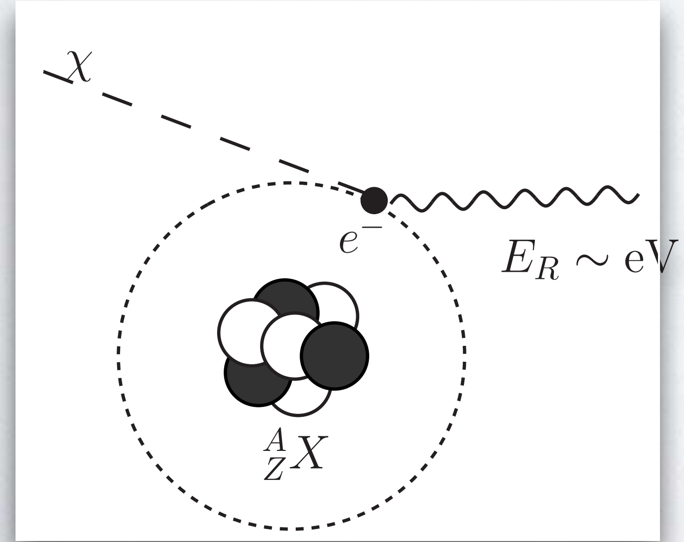
DM DIRECT DETECTION SIGNALS





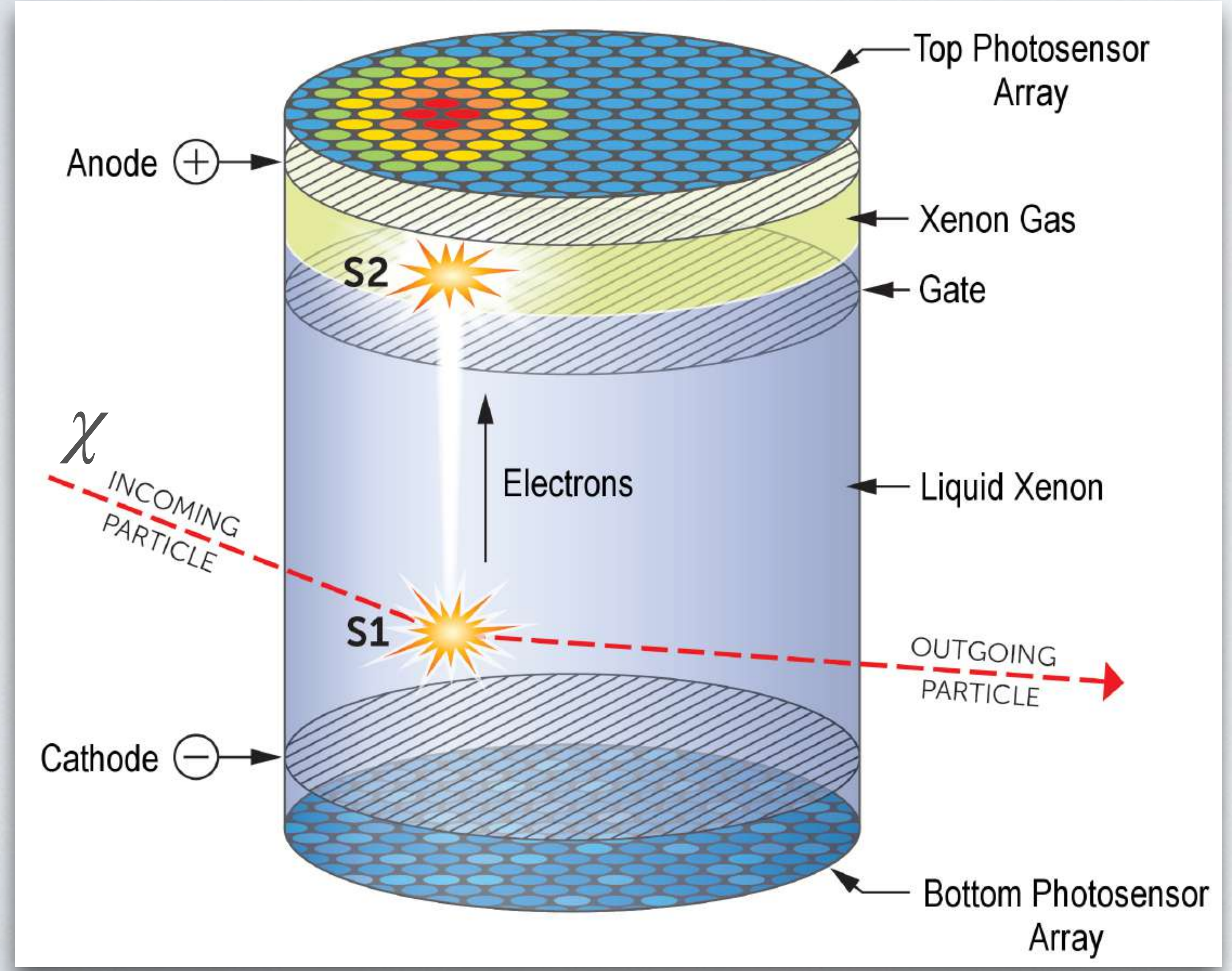


- **Elastic (or inelastic) DM nucleus scattering:**
  typically sensitive to m > 1 GeV WIMPs
- **Electron scattering:**
  sensitive to light WIMPs
- **Electron absorption:**
  (ultra) light bosonic non-WIMP DM

PROTOTYPICAL DD EXPERIMENT

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

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

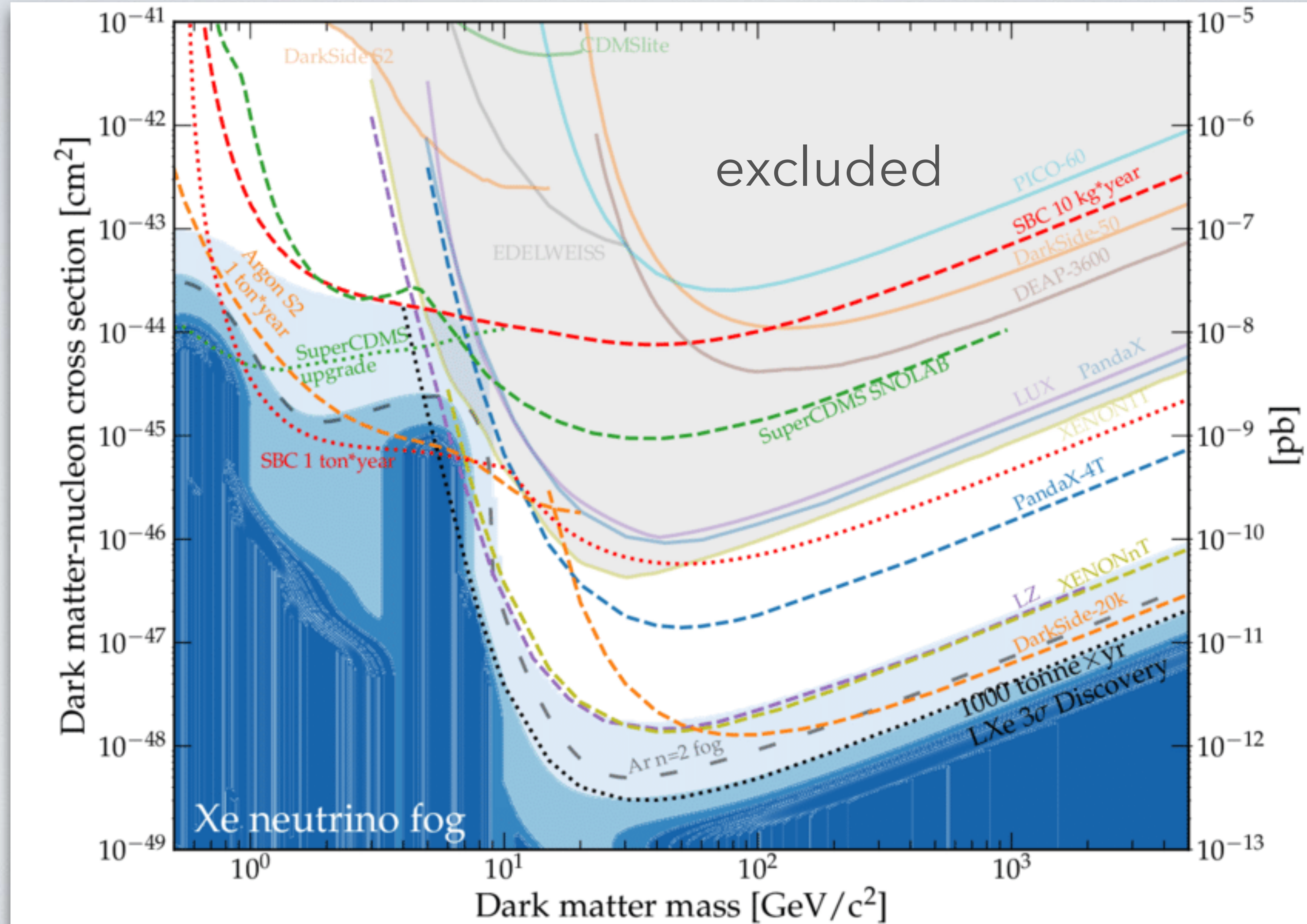


[Albers et al.; *J.Phys.G* 50 (2023) 1, 013001]

- 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



[Snowmass2021; 2203.08084]

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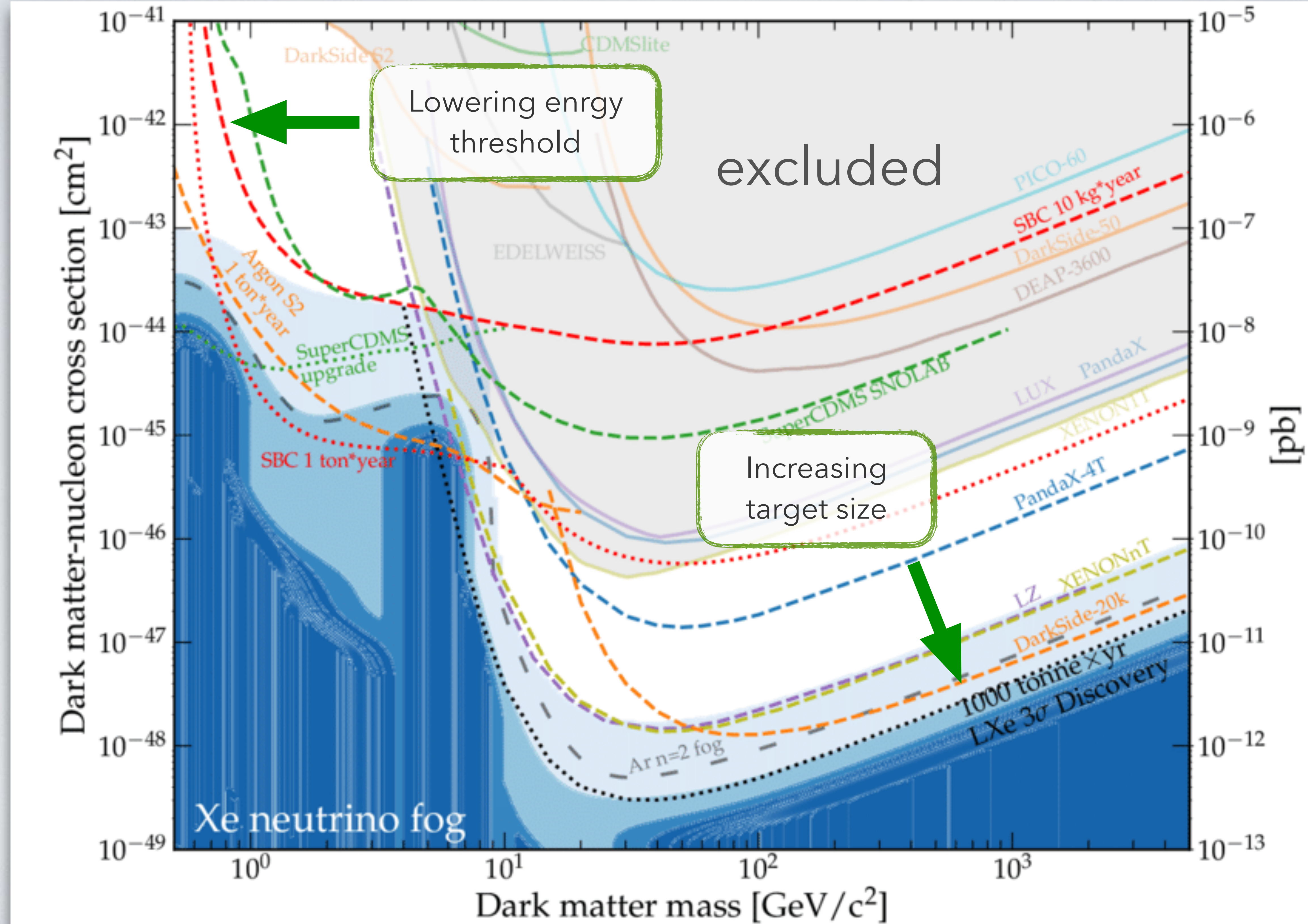

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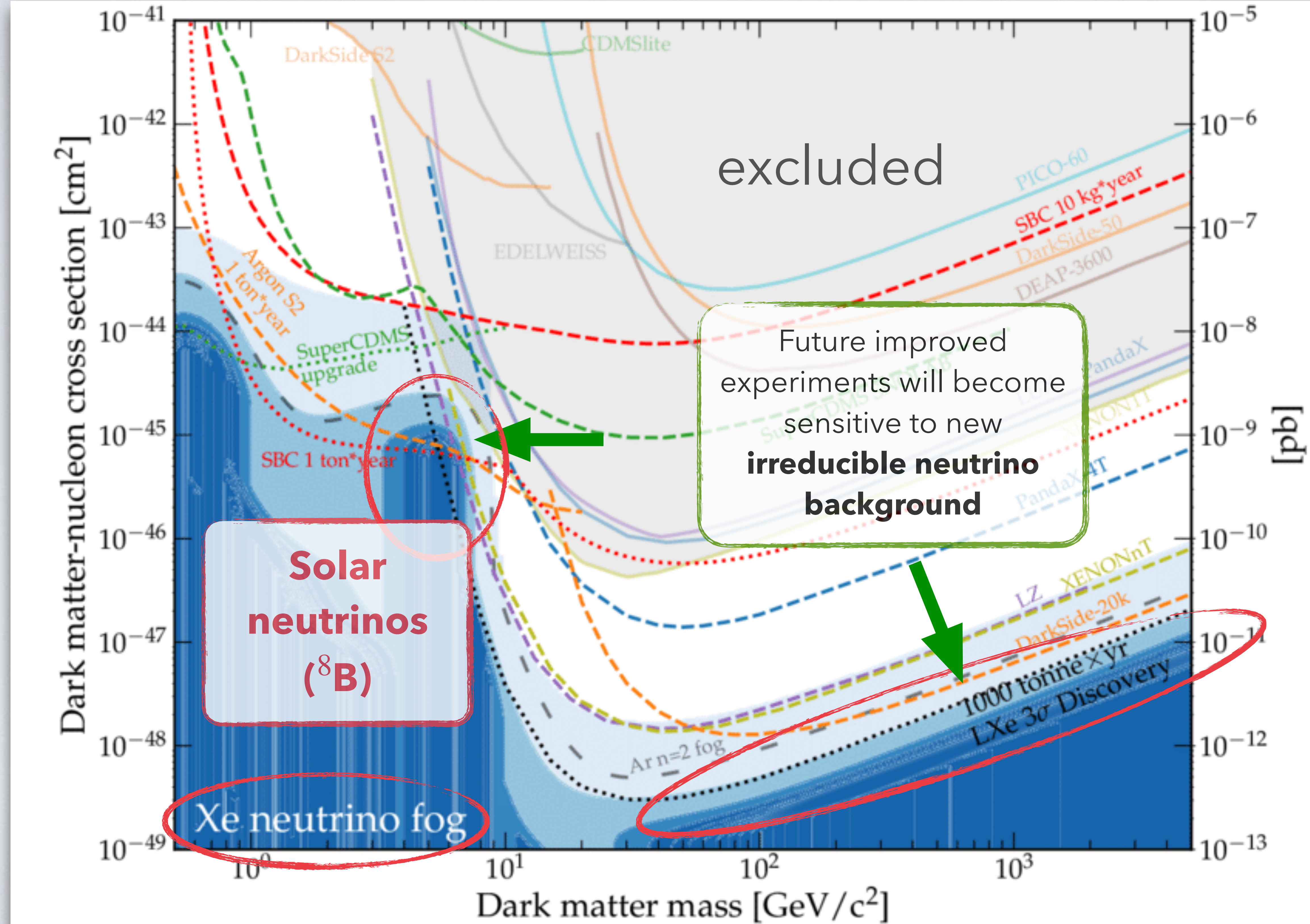
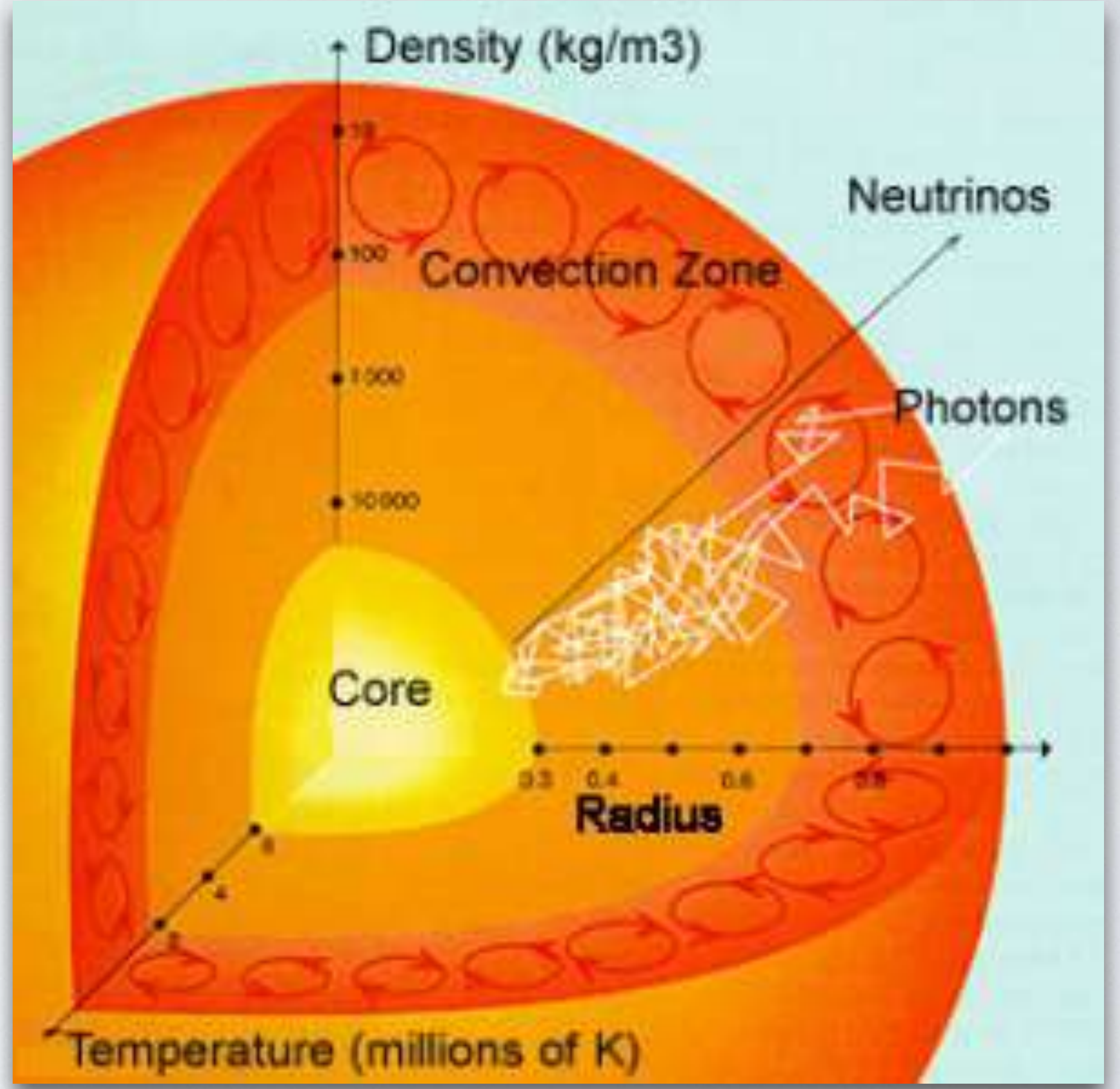


[Snowmass2021; 2203.08084]

WHAT ARE SOLAR NEUTRINOS?

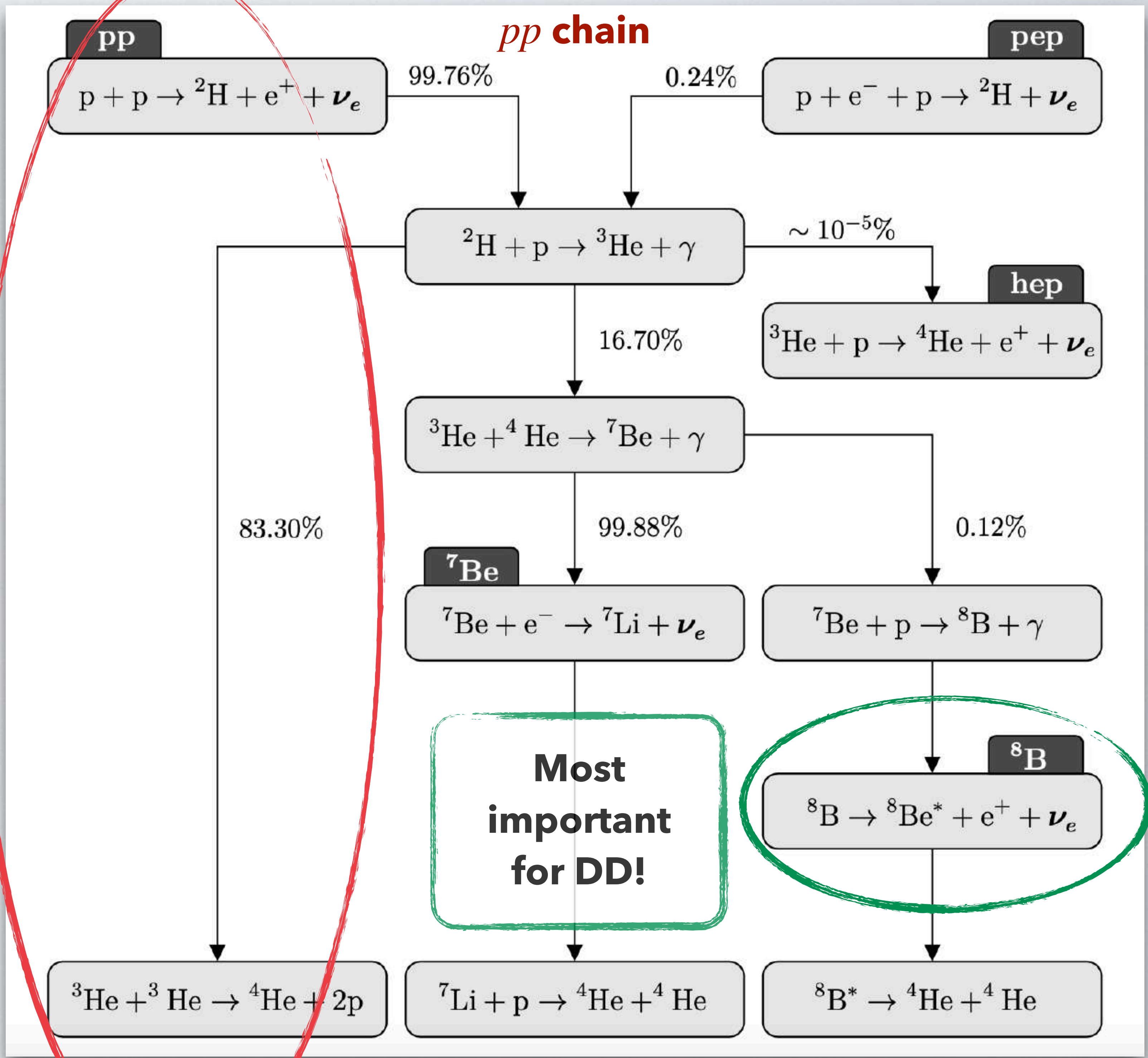
- Neutrinos are produced in fusion processes in **solar core**
- Neutrinos **leave** sun almost **instantaneously (2s)**; photons get scattered and reabsorbed
- Photons require 50 000 years to leave sun!

⇒ Neutrinos allow us to study interior of Sun!

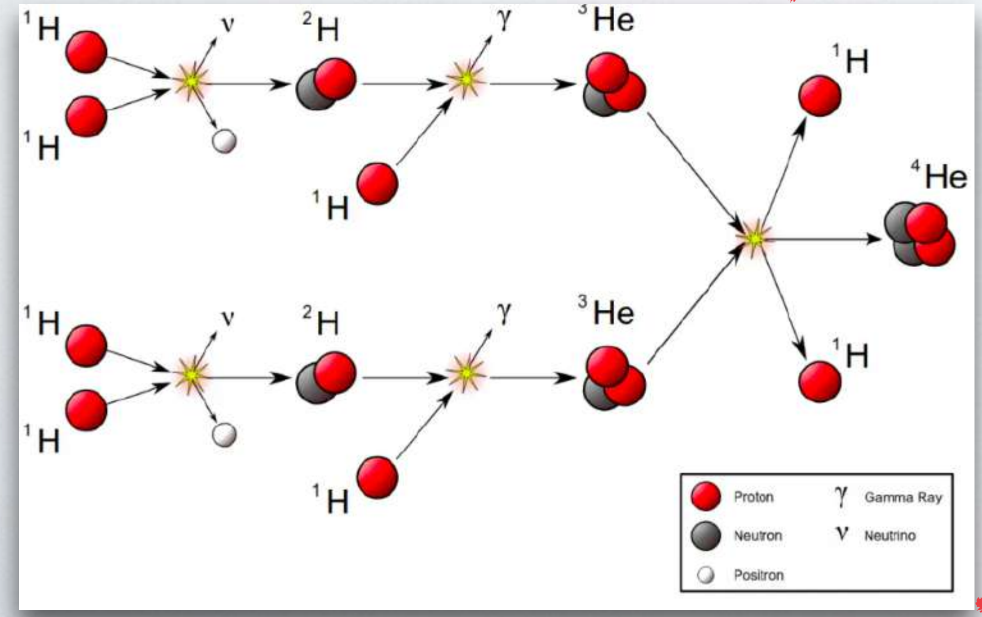


HOW ARE SOLAR ν PRODUCED?

- 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

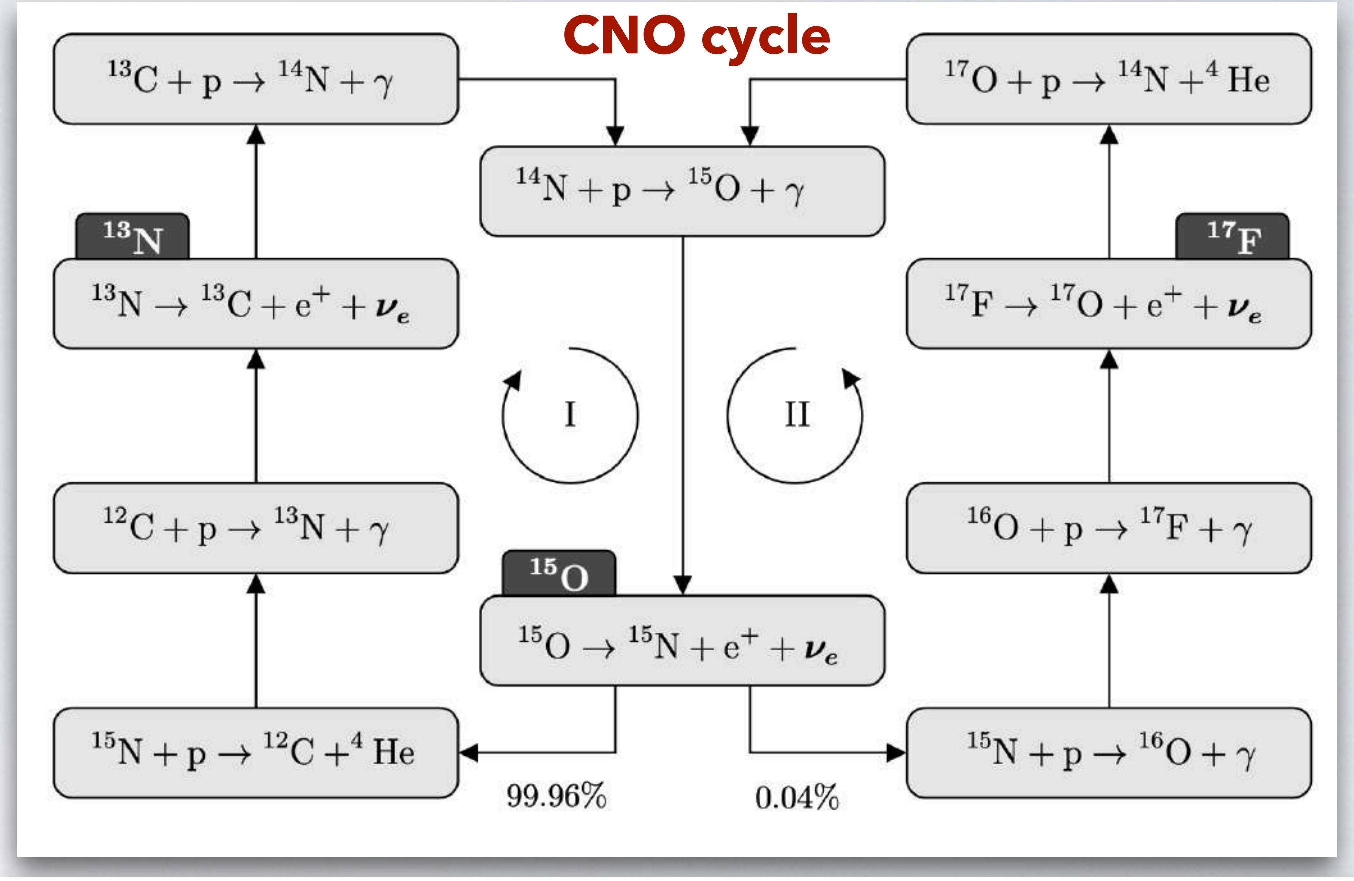


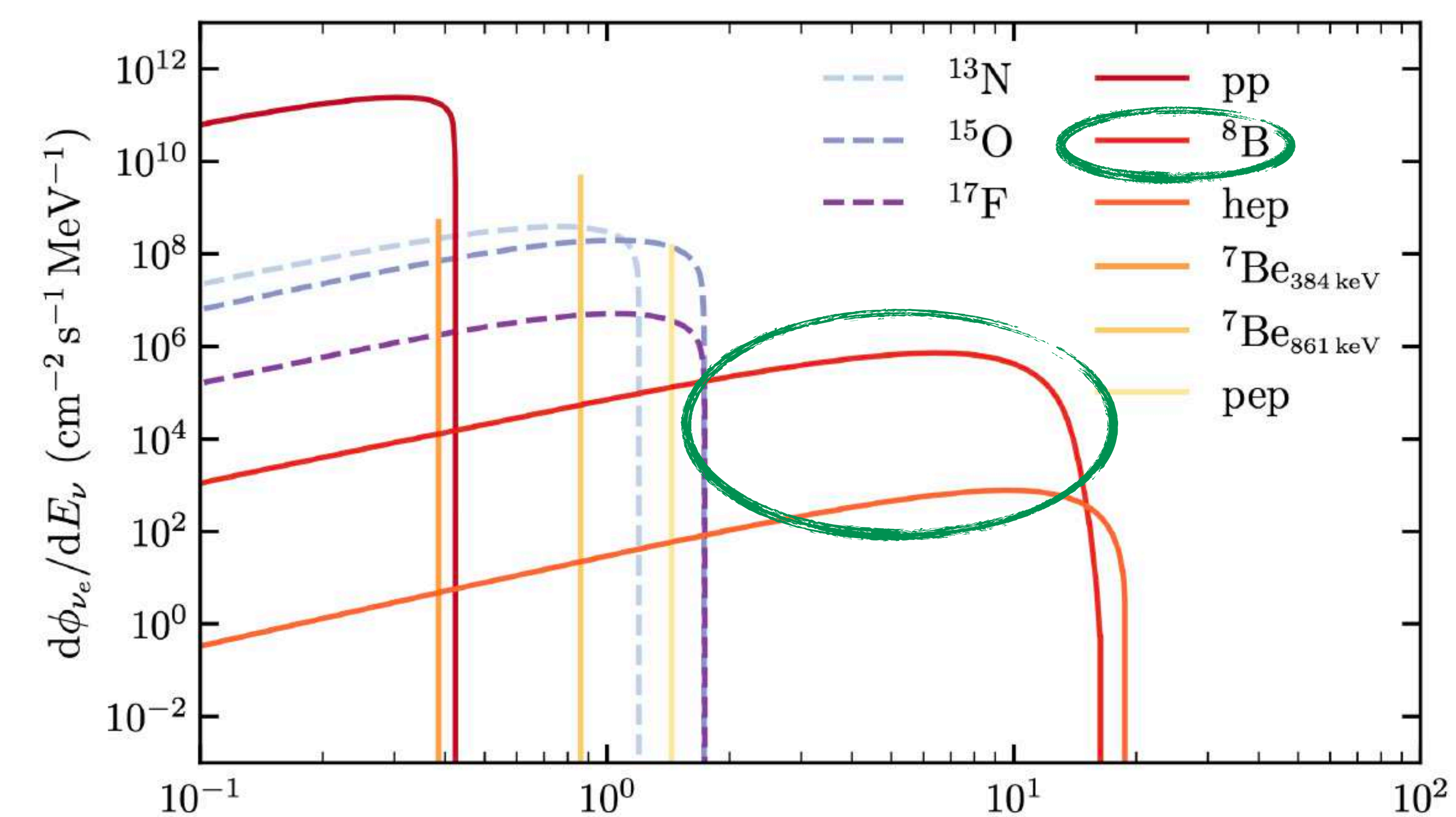
[Amaral '22]



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!**

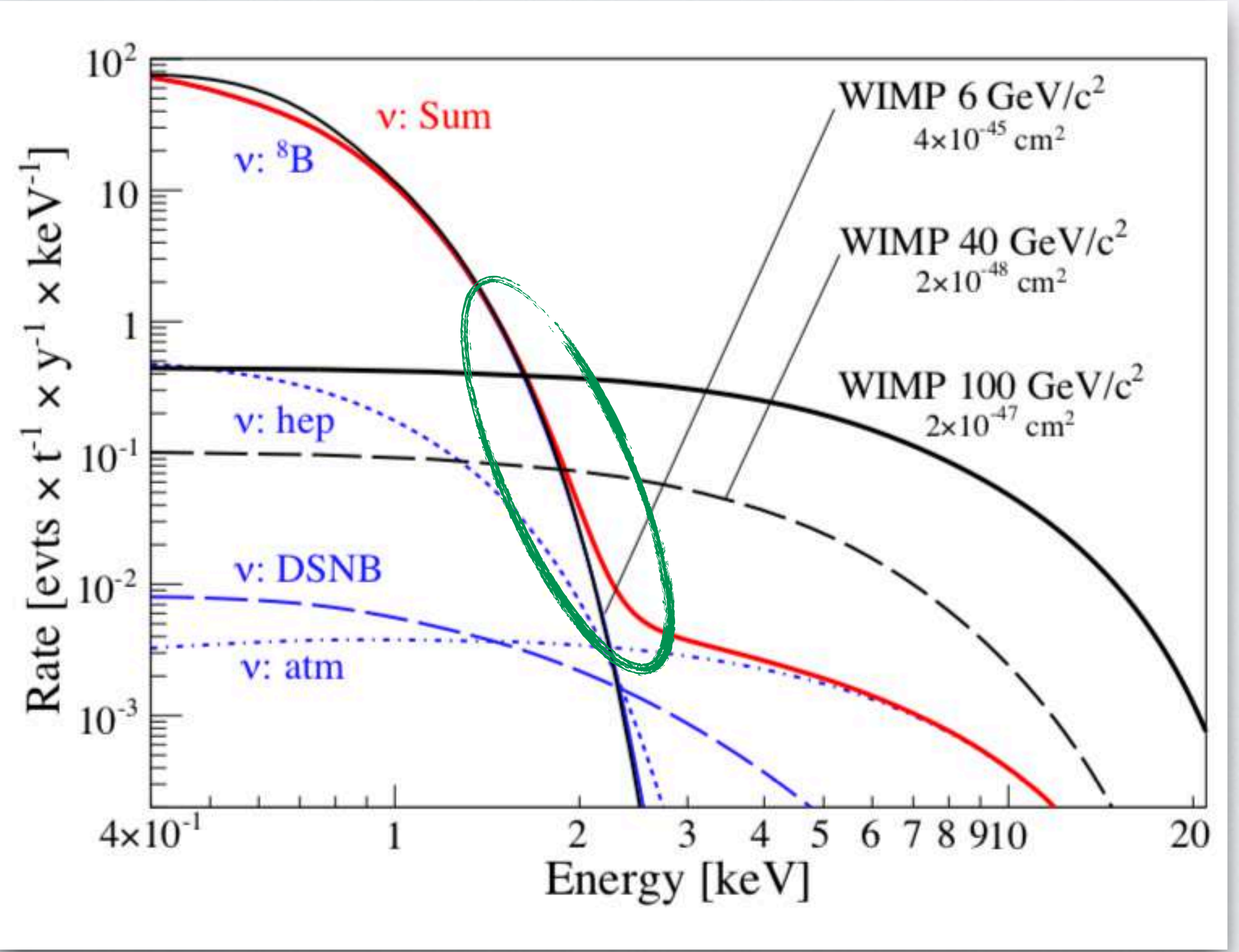


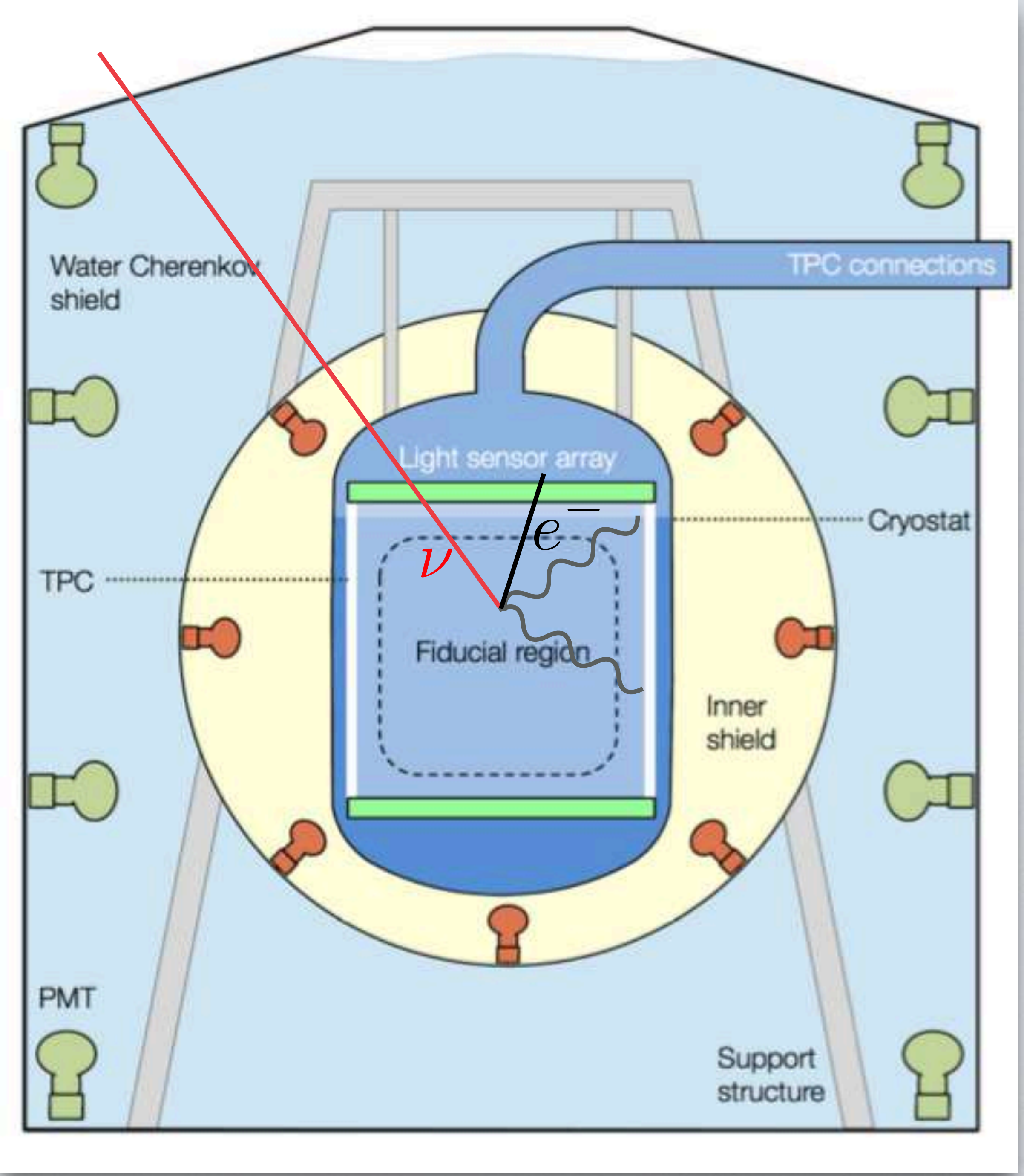


[Amaral '22]

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!**





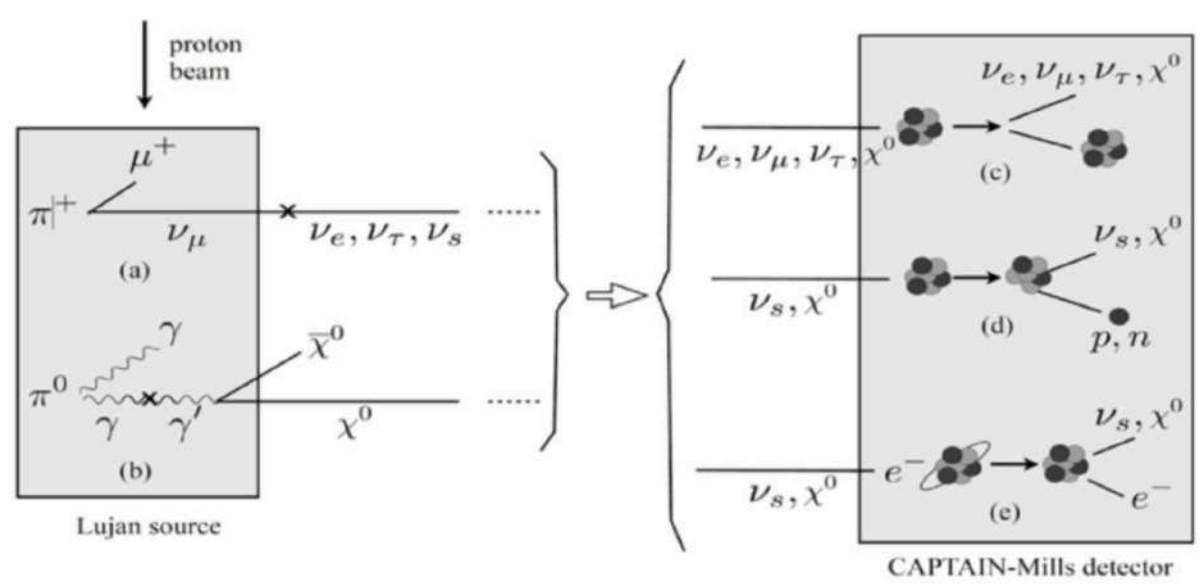
[DARWIN; JCAP 1611 (2016) 11, 017]

FIRST CEνNS OBSERVARTION

- At **spallation sources** stopped pions decay into muons and neutrinos

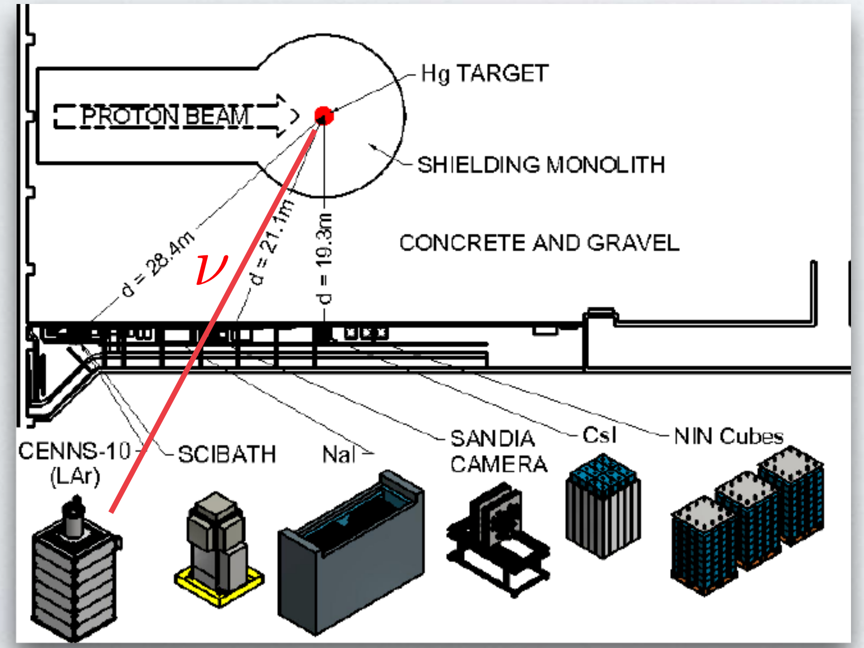
$$\pi^+ \to \nu_\mu \mu^+ \quad \hookrightarrow e^+ \bar{\nu}_\mu \nu_e$$

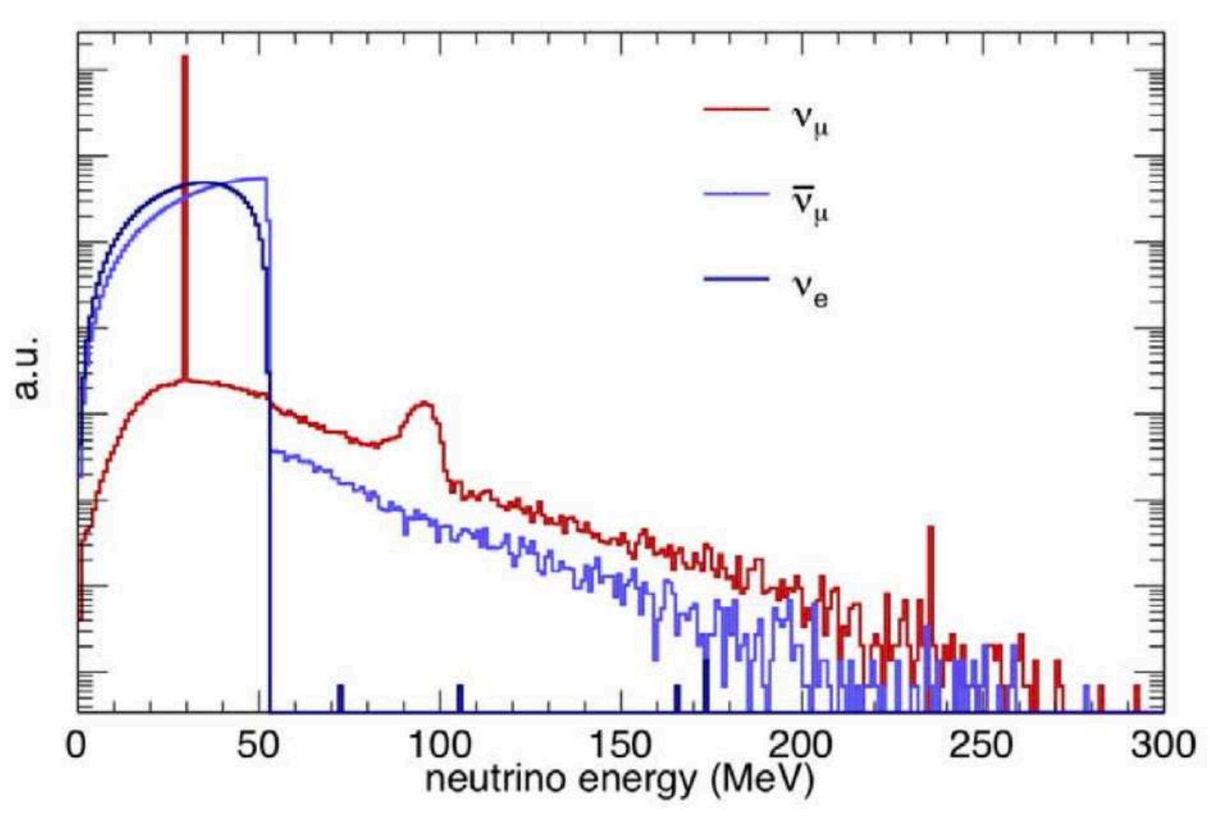
- MeV neutrinos have ~fm wavelength → scatter coherently off the nucleus



[COHERENT, *Science* 357 (2017) 6356, 1123]
[COHERENT, *PRL 126, 012002 (2021)*]
[COHERENT, *PRL. 129, 081801*]

- **First observation** of CEvNS at the **COHERENT** experiment with a CsI target (also LAr and Ge)





[COHERENT, *JINST* 13 (2018) 04, C04005]

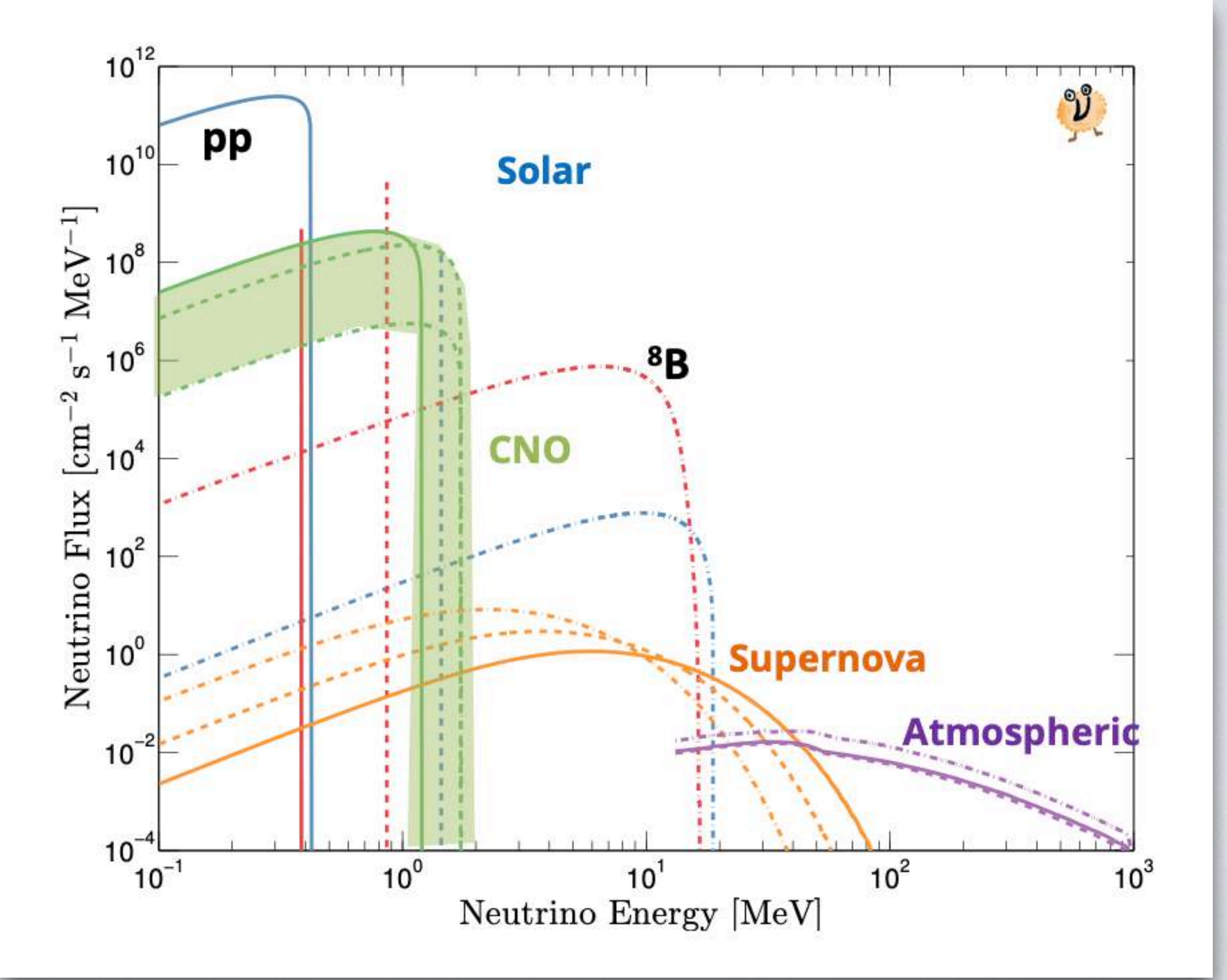
CEVNS WITH SOLAR NEUTRINOS

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

- **Solar neutrinos**
  dominate at low energies
  ^8B leading contribution at ~10 MeV

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

- **Atmospheric**
  dominate at high energies, but much smaller fluxes

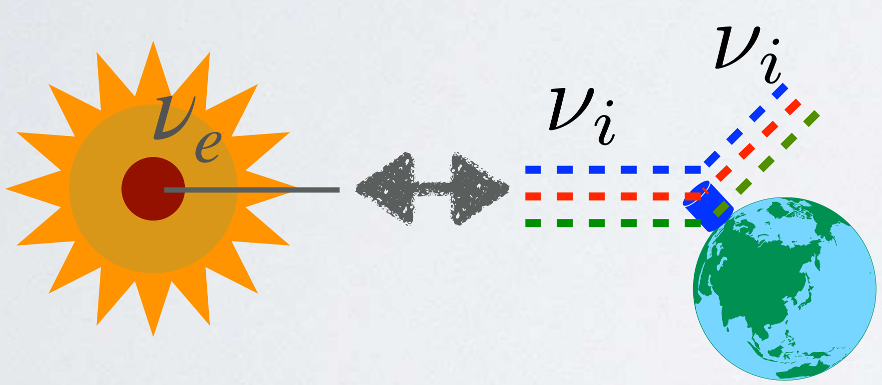


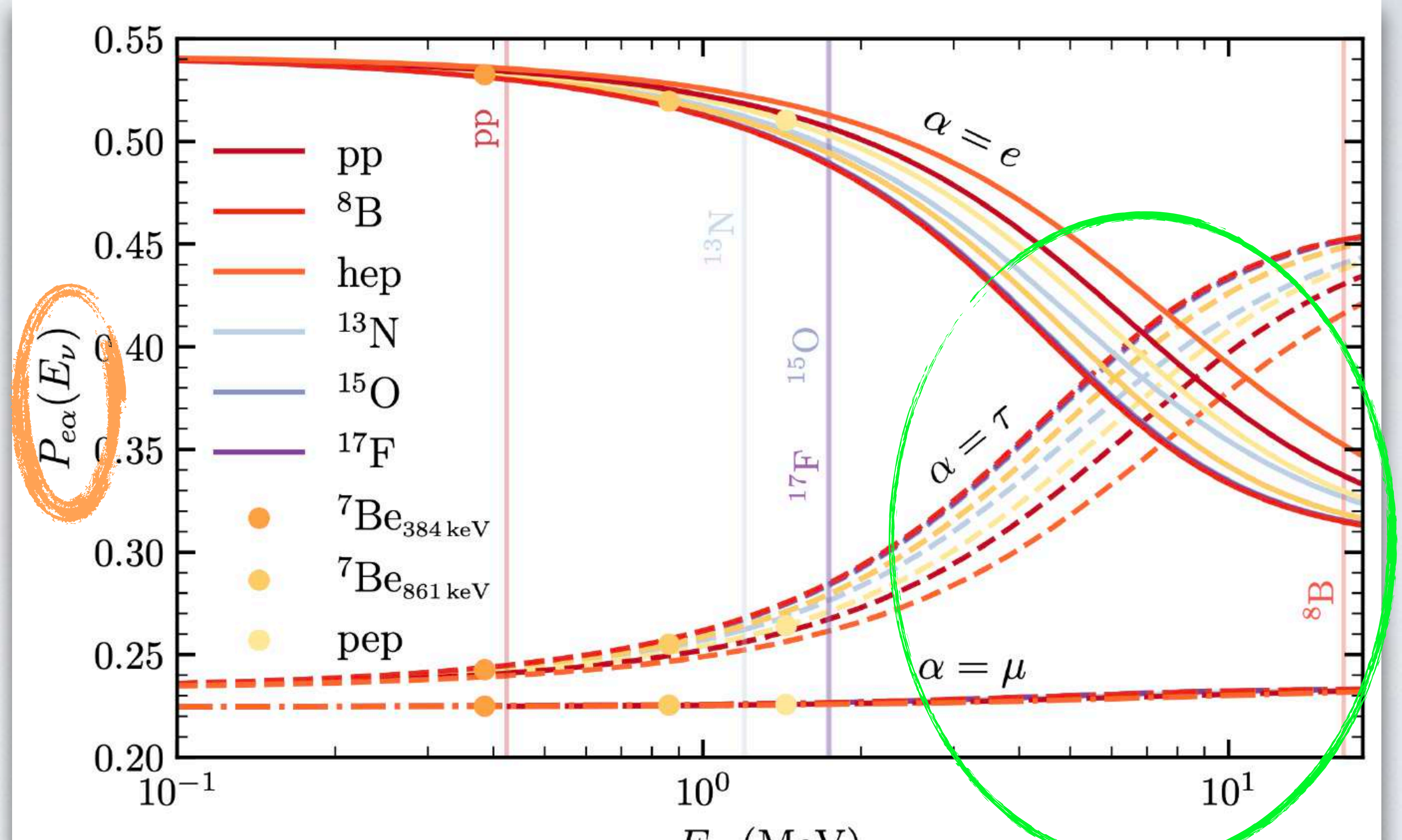
Credit: D. Cerdeño

CEVNS WITH SOLAR NEUTRINOS

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

- Solar neutrinos produced as pure **electron neutrinos**
- **Oscillate** into all flavours on propagation to Earth





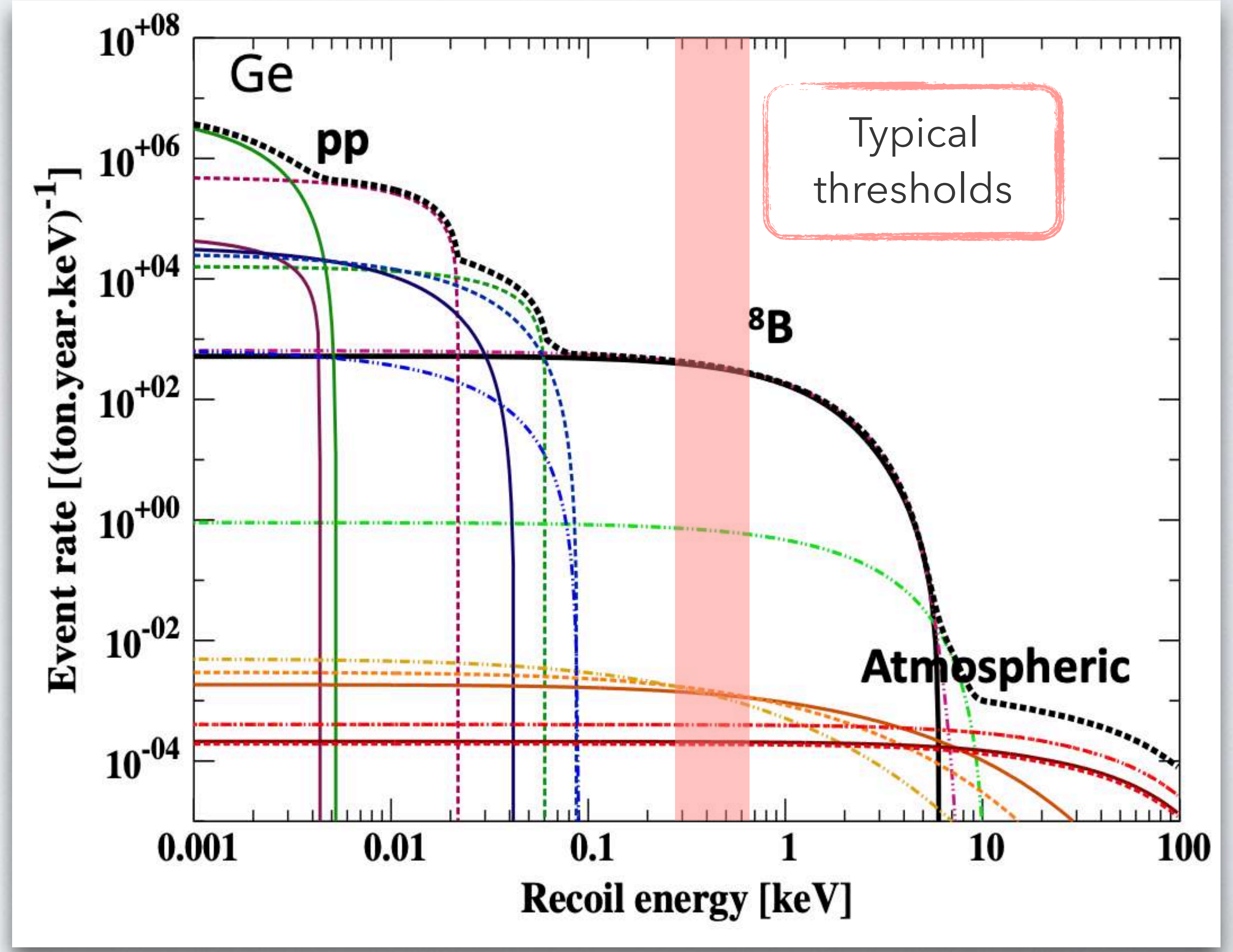
[Amaral, Cerdeno, PF, Reid; 2006.11225]

- **Matter oscillation** in solar medium dominates flavour composition reaching earth. ⇒ **at ~10 MeV significant ν_τ (and ν_μ) admixture (^8B flux)!**

CEVNS WITH SOLAR NEUTRINOS

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

- 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 $\sin\theta_W$:

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

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

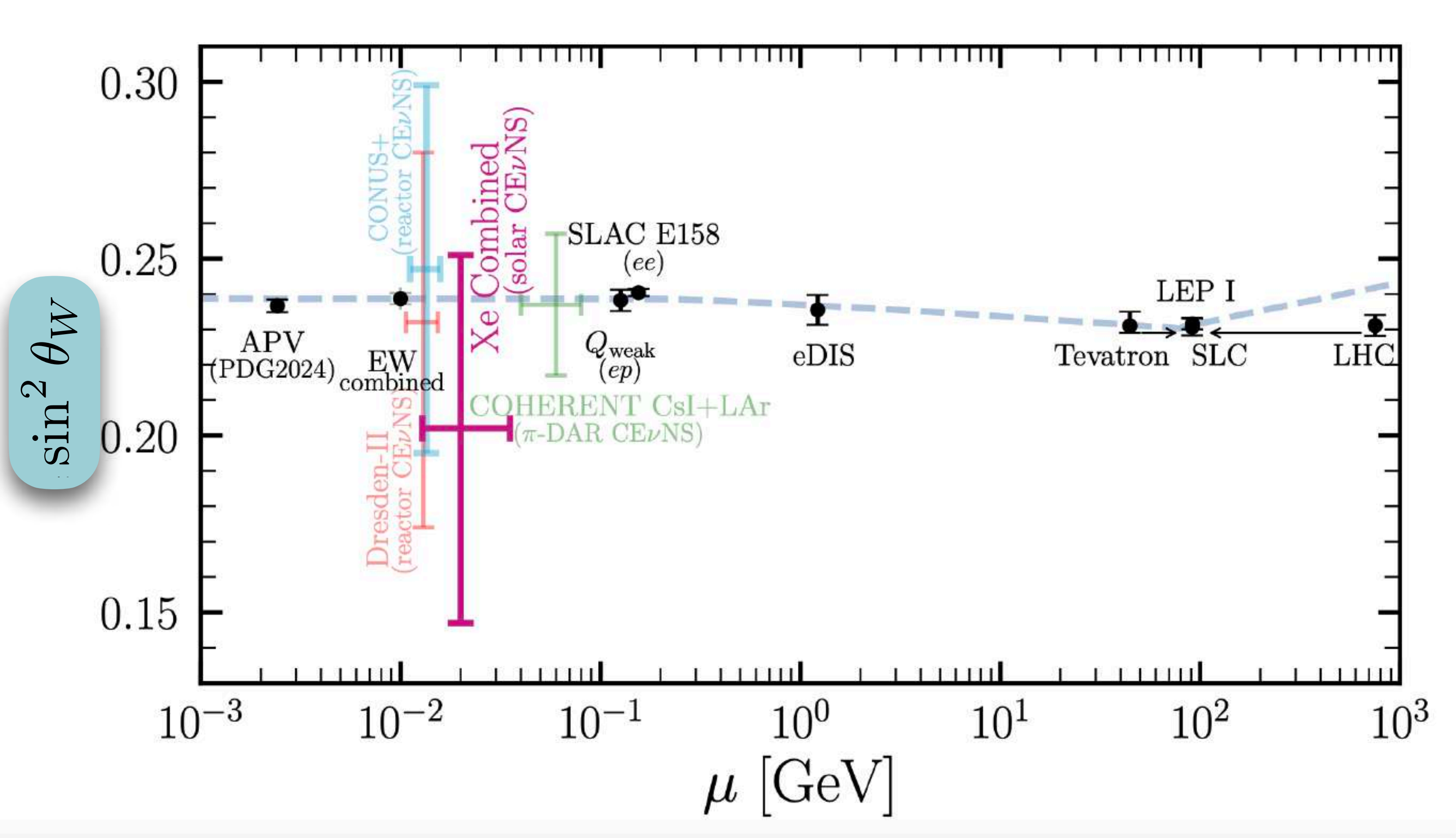
- $\sin\theta_W$ **not well measured at low energies!**

- can be extracted from neutrino scattering at DD experiments

[Maity, Boehm, *PRD* 112 (2025) 5, 053001]

- Combined results from direct detection:

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



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

[De Romeri+, *2603.00554*]

NEW INTERACTIONS: LIGHT MEDIATORS

- New light leptophilic mediators generically lead to modification of CEvNS and EvES
- Infinite family of anomaly-free $U(1)_X$ $B - L$ $L_\mu - L_e$ $L_e - L_\tau$ $L_\mu - L_\tau$

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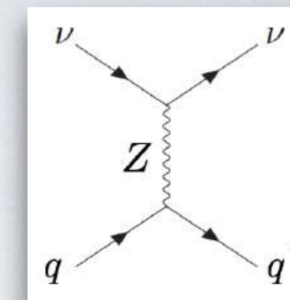
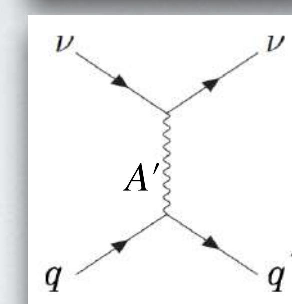
- Infinite family of anomaly-free $U(1)_X$ — $B-L$ — $L_\mu - L_e$ — $L_e - L_\tau$ — $L_\mu - L_\tau$

CEvNS: (for universal vector couplings)

$$\frac{d\sigma_{\nu_\alpha N}}{dE_R} = \frac{G_F^2 M_N}{\pi}\left(1-\frac{M_N E_R}{2E_\nu^2}\right) \times \left\{\underbrace{\frac{Q_{\nu N}^2}{4}}_{\text{SM}} + \underbrace{\frac{g_{xN}\, g_{x\nu}}{\sqrt{2}G_F\left(2M_N E_R + M_{A'}^2\right)} + \frac{g_{xN}^2\, g_{x\nu}^2}{2G_F^2\left(2M_N E_R + M_{A'}^2\right)^2}}_{\text{BSM}}\right\} F^2\left(E_R\right)$$

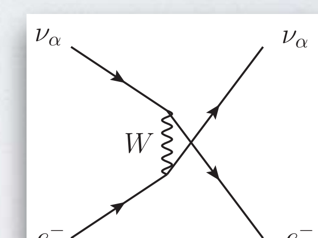


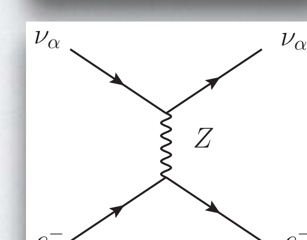


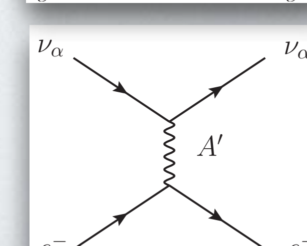
EvES:

$$\frac{d\sigma_{\nu_\alpha e}}{dE_R} = \frac{2G_F^2 m_e}{\pi}\left\{\underbrace{\left[{g_L^e}^2 + {g_R^e}^2\left(1-\frac{E_R}{E_\nu}\right)^2 - g_L^e g_R^e \frac{m_e E_R}{E_\nu^2}\right]}_{\text{SM}}\right.$$

$$\underbrace{+ \frac{g_{xe}\, g_{x\nu}}{\sqrt{2}G_F\left(2E_R m_e + M_{A'}^2\right)}\left[\left(g_L^e + g_R^e\right)\left(1-\frac{m_e E_R}{2E_\nu^2}\right) - g_R^e \frac{E_R}{E_\nu}\left(2-\frac{E_R}{E_\nu}\right)\right] + \frac{g_{xe}^2\, g_{x\nu}^2}{4G_F^2\left(2E_R m_e + M_{A'}^2\right)^2}\left[1-\frac{E_R}{E_\nu}\left(1-\frac{E_R - m_e}{2E_\nu}\right)\right]}_{\text{BSM}}\left.\vphantom{\frac{1}{1}}\right\}$$







NEW INTERACTIONS: LIGHT MEDIATORS

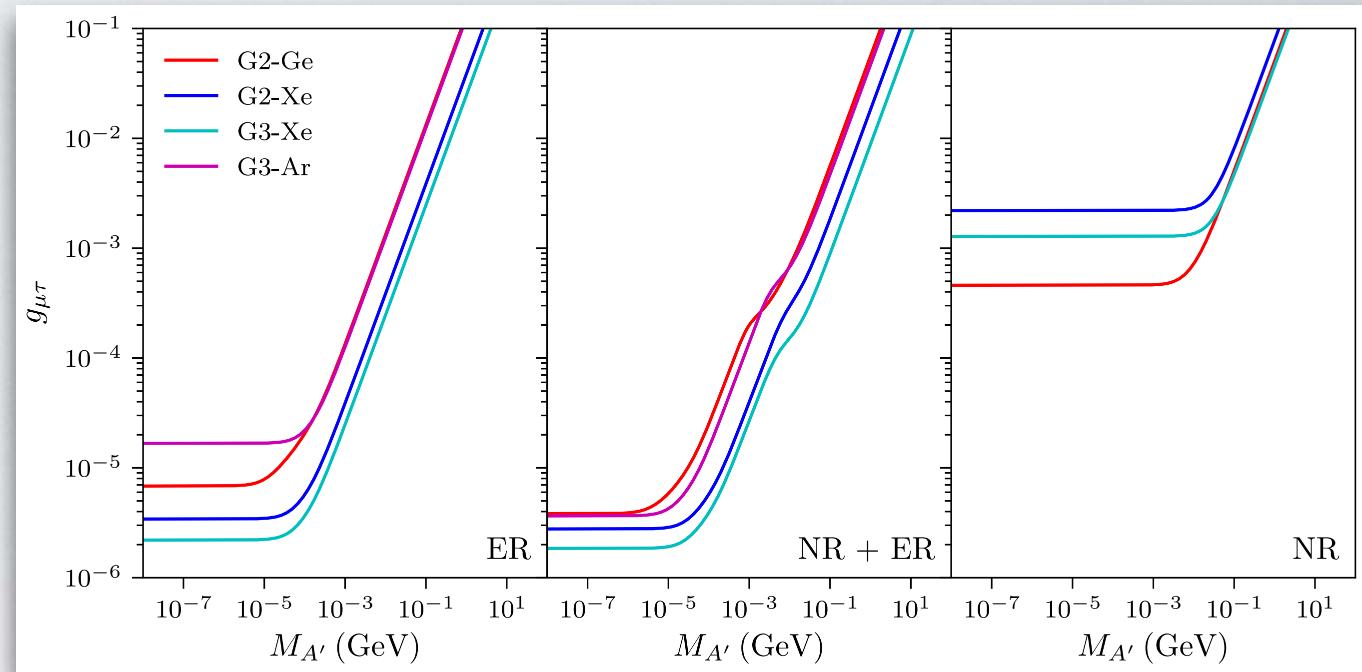
- DD experiments sensitive to neutrinos both in **electron and nuclear scattering!**

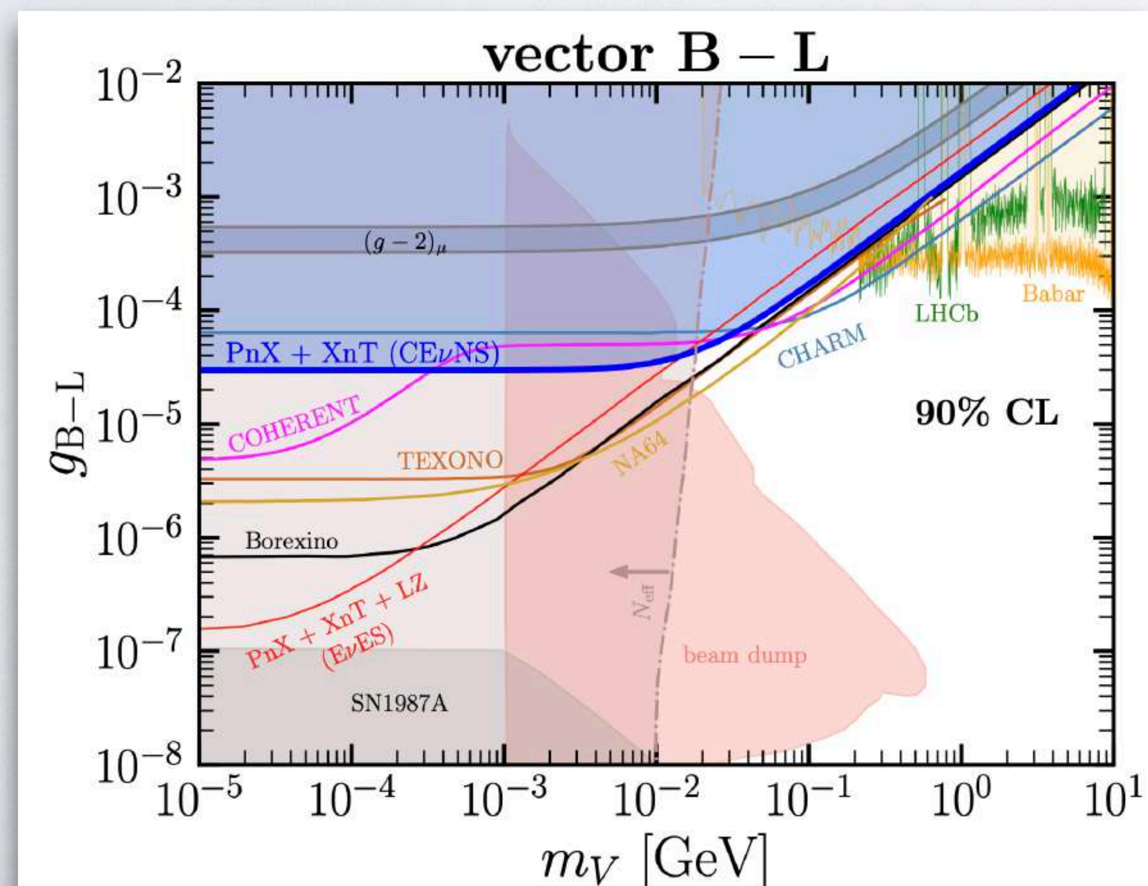
[Amaral, Cerdeno, **PF**, Reid; 2006.11225]

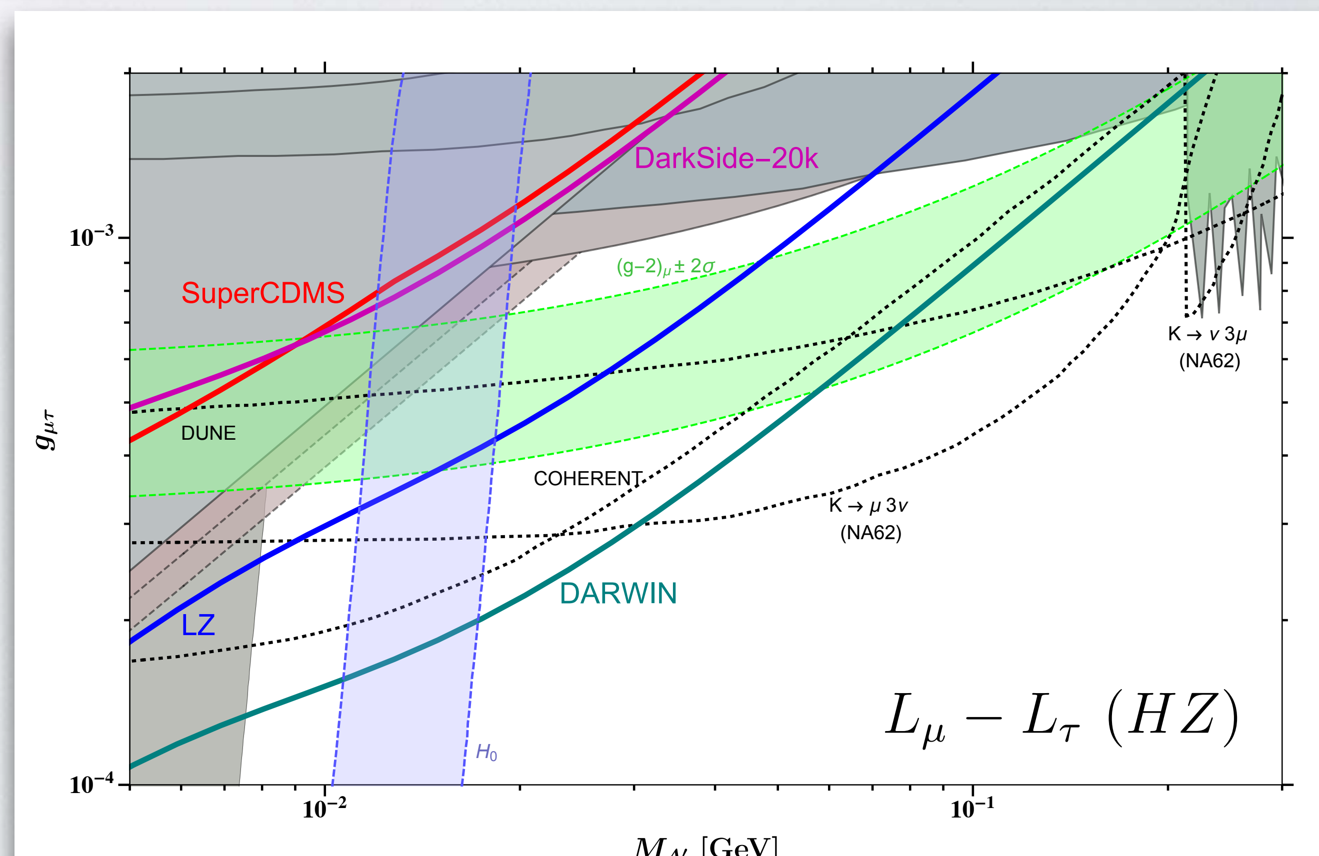
[Amaral, Cerdeno, Cheek, **PF**; 2104.03297]

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

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





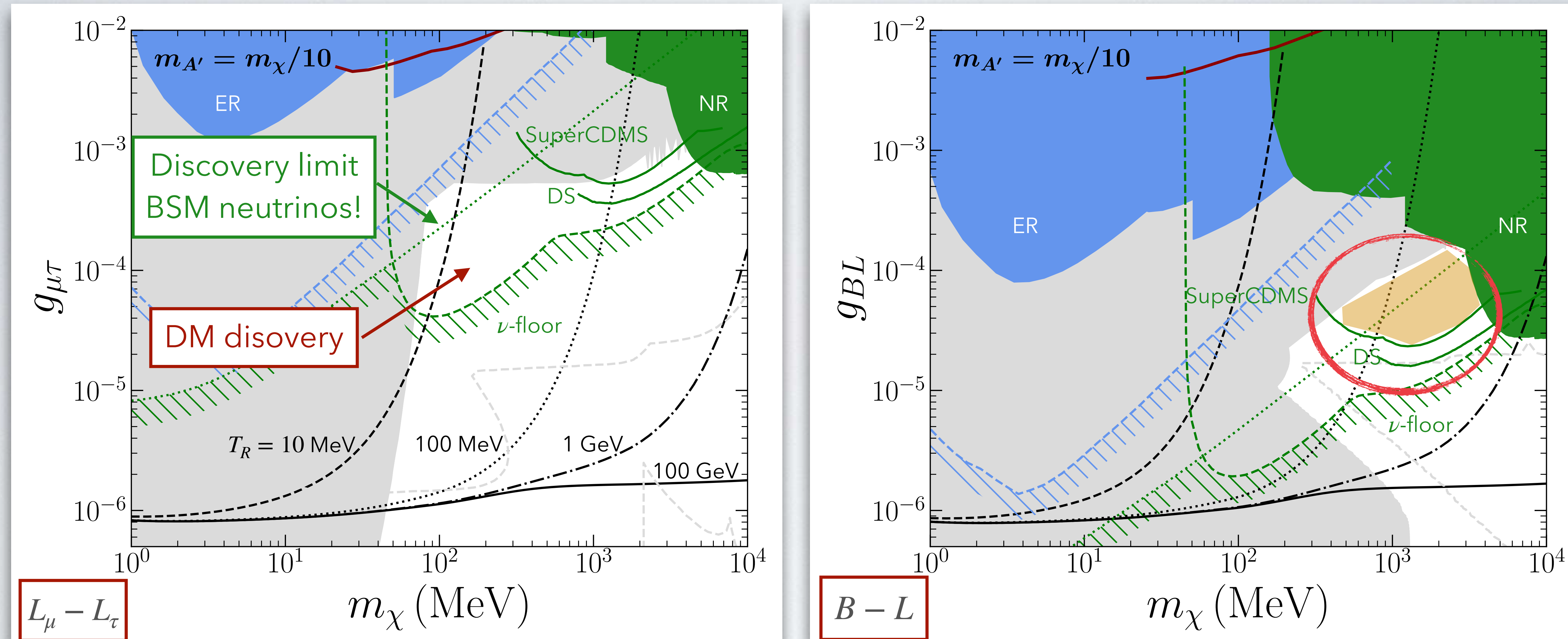


[De Romeri+, *JCAP* 05 (2025) 012]

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

LIGHT MEDIATORS: TESTING FREEZE-IN

- Adding DM: $$\mathcal{L}_{\rm DM} = -g_D\, \bar{\chi}\gamma_\mu \chi\, X^\mu$$



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

- **Vector mediator** models ($B-L$, $L_i - L_j$) **can accommodate (low reheating) freeze-in!**
- Direct detection sensitive to **DM and neutrino signal** $\Rightarrow$ **NEED DISCRIMINATION!**

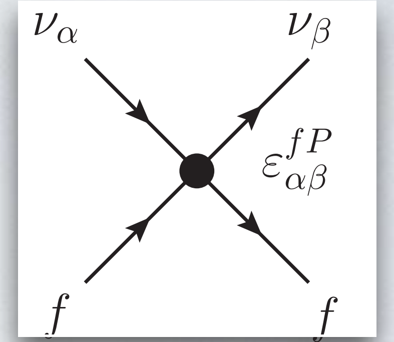
GOING MODEL-INDEPENDENT:

NON-STANDARD INTERACTIONS

NEW INTERACTIONS: NSI

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

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



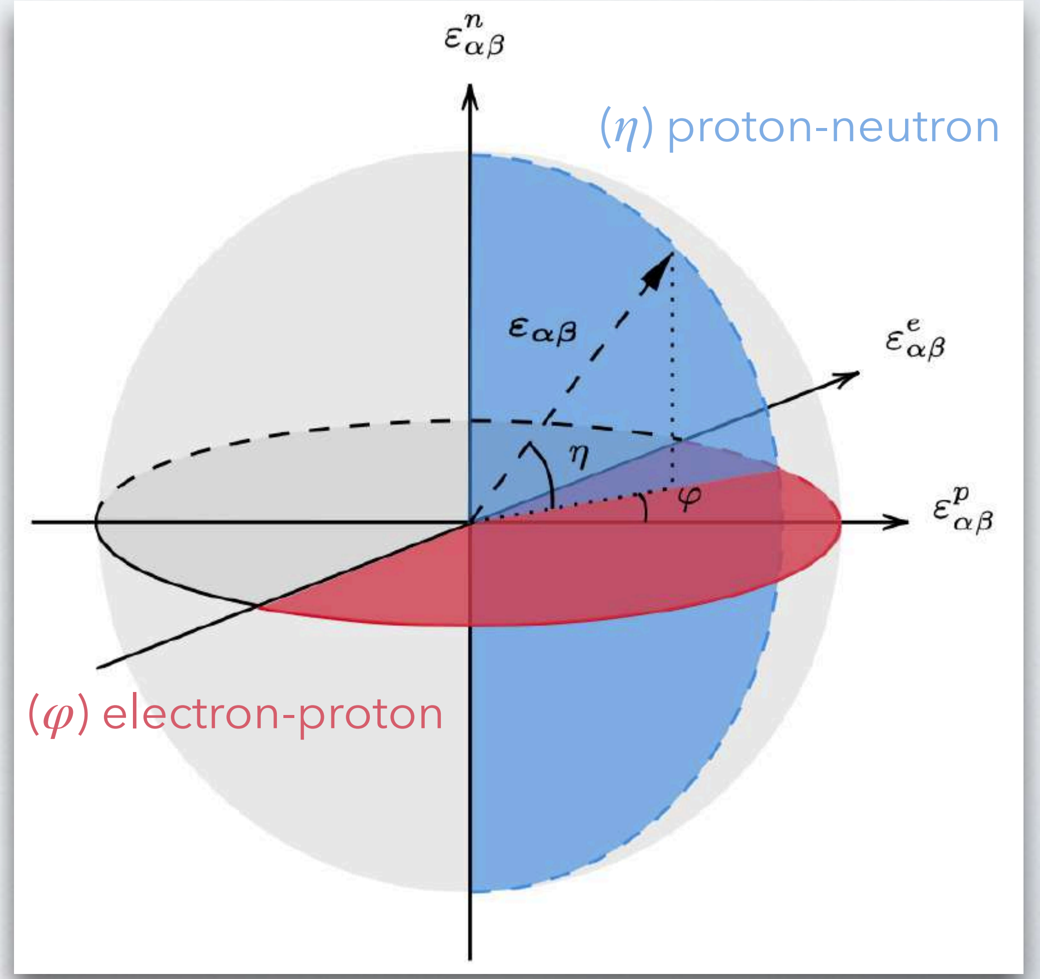
- Ordinary matter is composed of $f = \{e, u, d\}$. Only these are relevant for matter effects and scattering. Propagation only sensitive to **vector component.**

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

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

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

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



[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

- 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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Asymptotic outstate i

Propagation and scattering

Initial flavour α

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

Neutrino density matrix

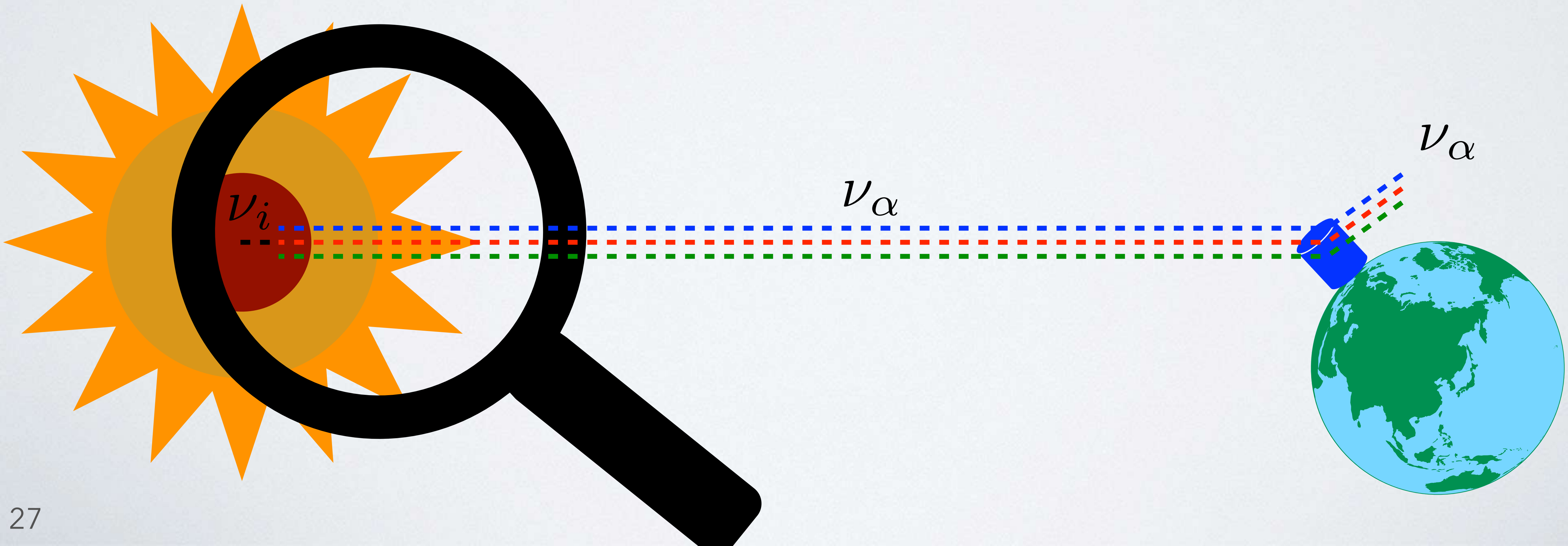
generalised matrix element

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

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

[Coloma+; *JHEP* 07 (2022) 138] [Amaral, Cheek, Cerdeño, **PF**; 2302.12846]

NSI NEUTRINO PROPAGATION



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

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

- We define the PMNS matrix as

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

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 ⇒ reduces to **two-state problem**

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- 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:**

$$\Delta E^m_{21} \equiv E^m_2 - E^m_1 = 2\Delta\sqrt{p^2+q^2} \qquad \sin 2\theta^m_{12} = \frac{p}{\sqrt{p^2+q^2}} \qquad \cos 2\theta^m_{12} = \frac{q}{\sqrt{p^2+q^2}}$$

with

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

MATTER EFFECTS WITH NSI

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

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

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

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

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

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

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

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

1. NEUTRINO PROPAGATION

- From the **NSI matter Hamiltonian** can compute the **full S-matrix**

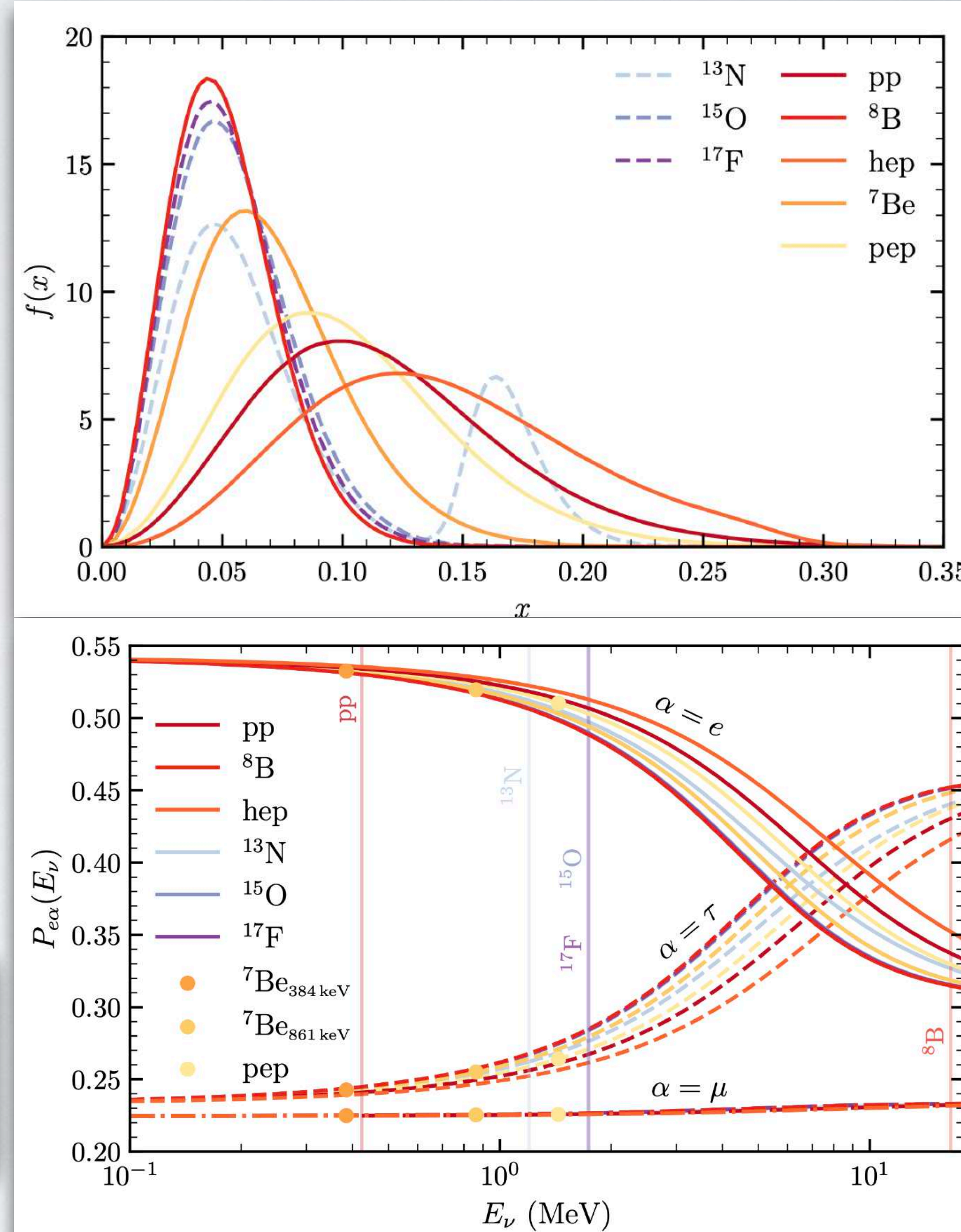
$$i\,\partial_t \begin{pmatrix} \hat{\nu}_e \\ \hat{\nu}_\alpha \\ \hat{\nu}_\beta \end{pmatrix} = \underbrace{\begin{pmatrix} \mathrm{Evol}[H^{\mathrm{eff}}] & 0 \\ 0 & \exp[-i\,\frac{\Delta m_{31}^2}{2\,E_\nu} L] \end{pmatrix}}_{\equiv \tilde{S}} \begin{pmatrix} \hat{\nu}_e \\ \hat{\nu}_\alpha \\ \hat{\nu}_\beta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

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

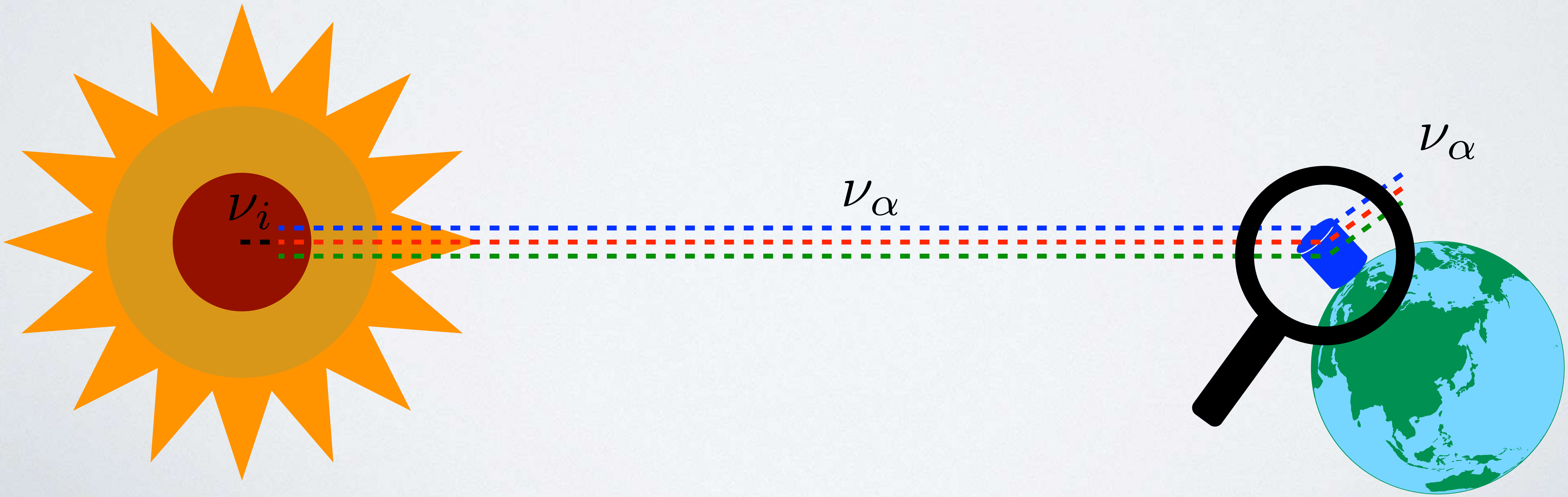
- Can extract the neutrino transition **probabilities from the density matrix**

$$P_{e\alpha} = \rho_{\alpha\alpha}^{(e)}$$

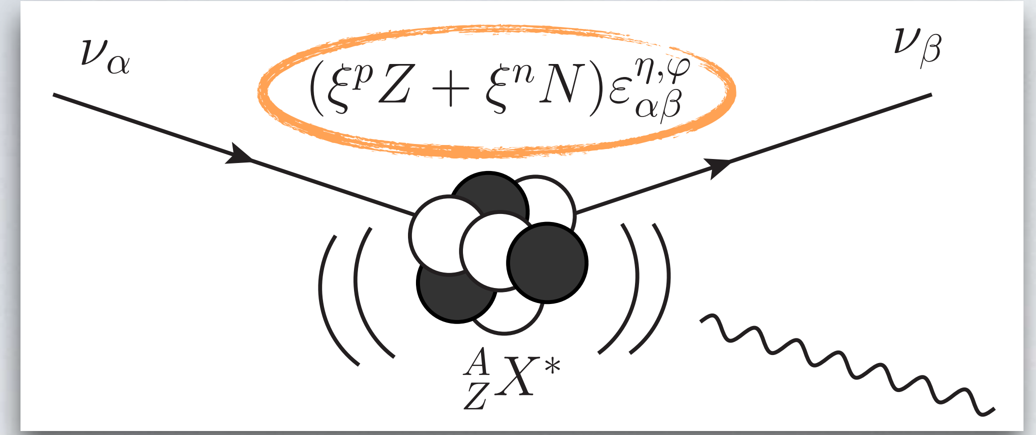
- The abundant solar neutrino flux makes this an excellent laboratory for **testing novel neutrino physics in all flavours!**



NSI NEUTRINO DETECTION



2. 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 $G^{\rm NSI}_{\alpha\beta} = (\xi^p Z + \xi^n N)\, \varepsilon^{\eta,\varphi}_{\alpha\beta}$

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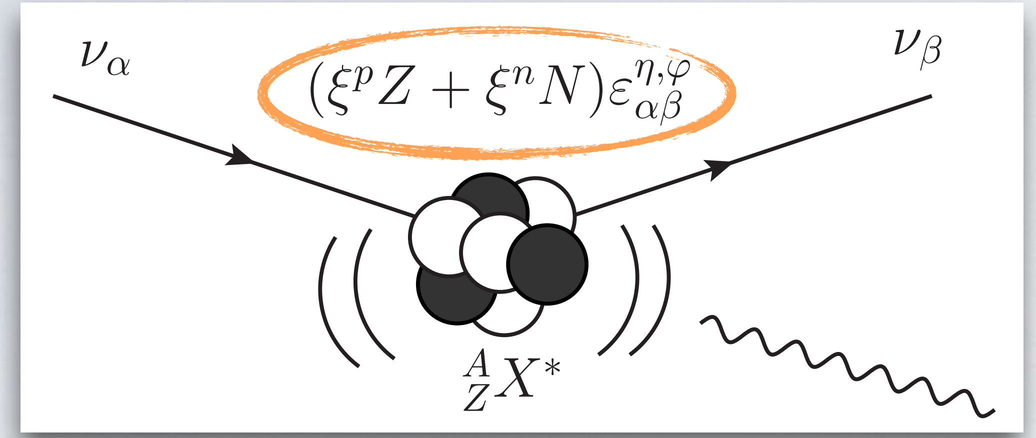

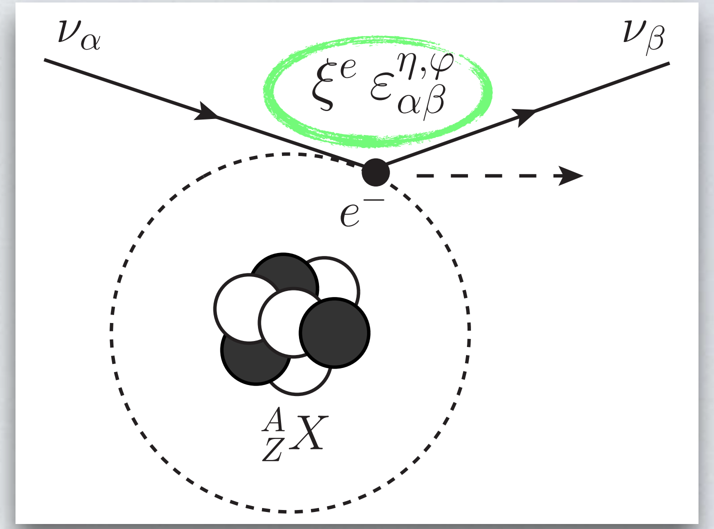

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2. The **generalised elastic neutrino-electron scattering (EνES) cross section**:

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

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

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

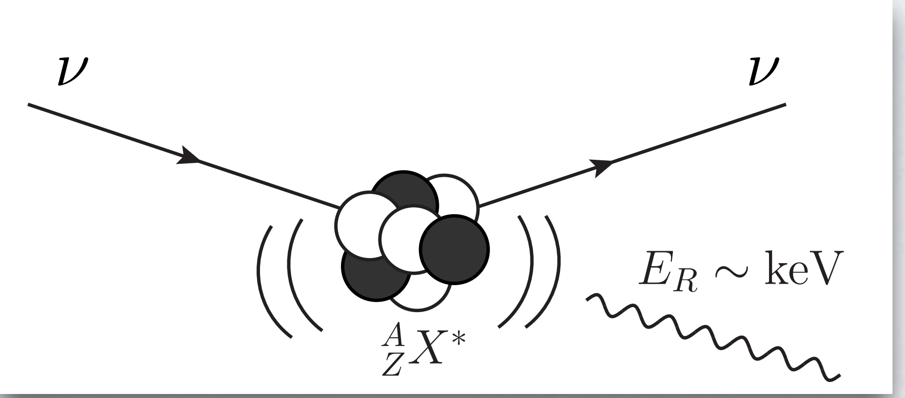
NSI @ DD EXPERIMENTS

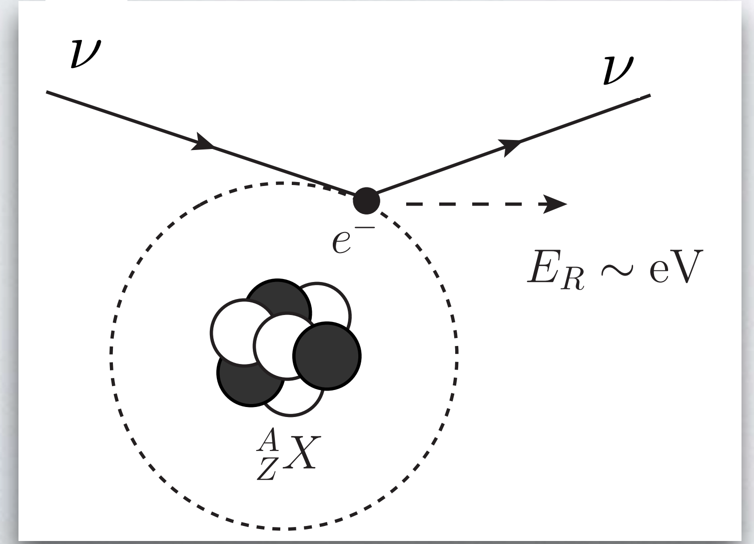
- Sensitive to both **nuclear** and **electron scattering!**
- **Exploit signal complementarity!**

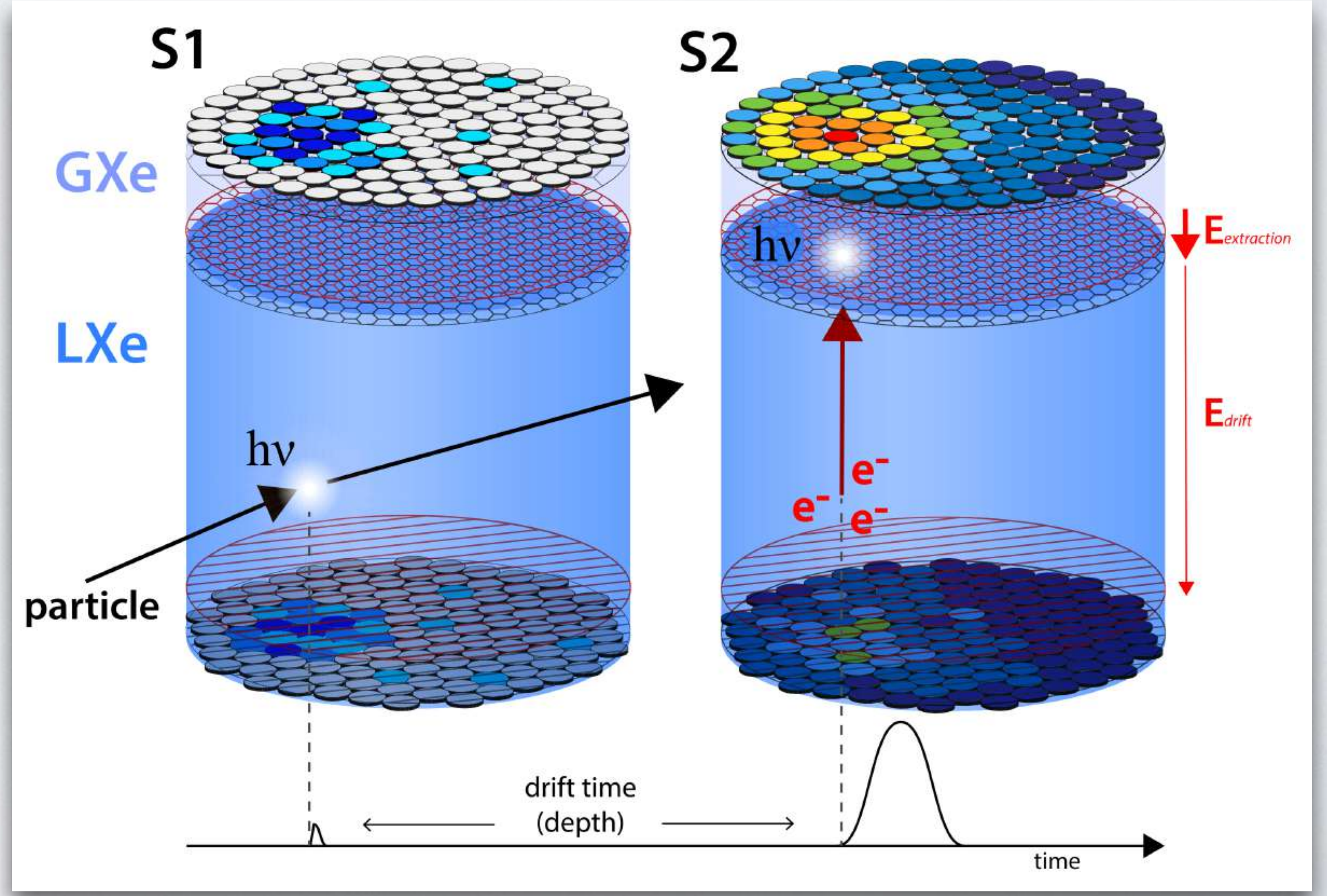
XENONnT

LZ

PandaX-4T



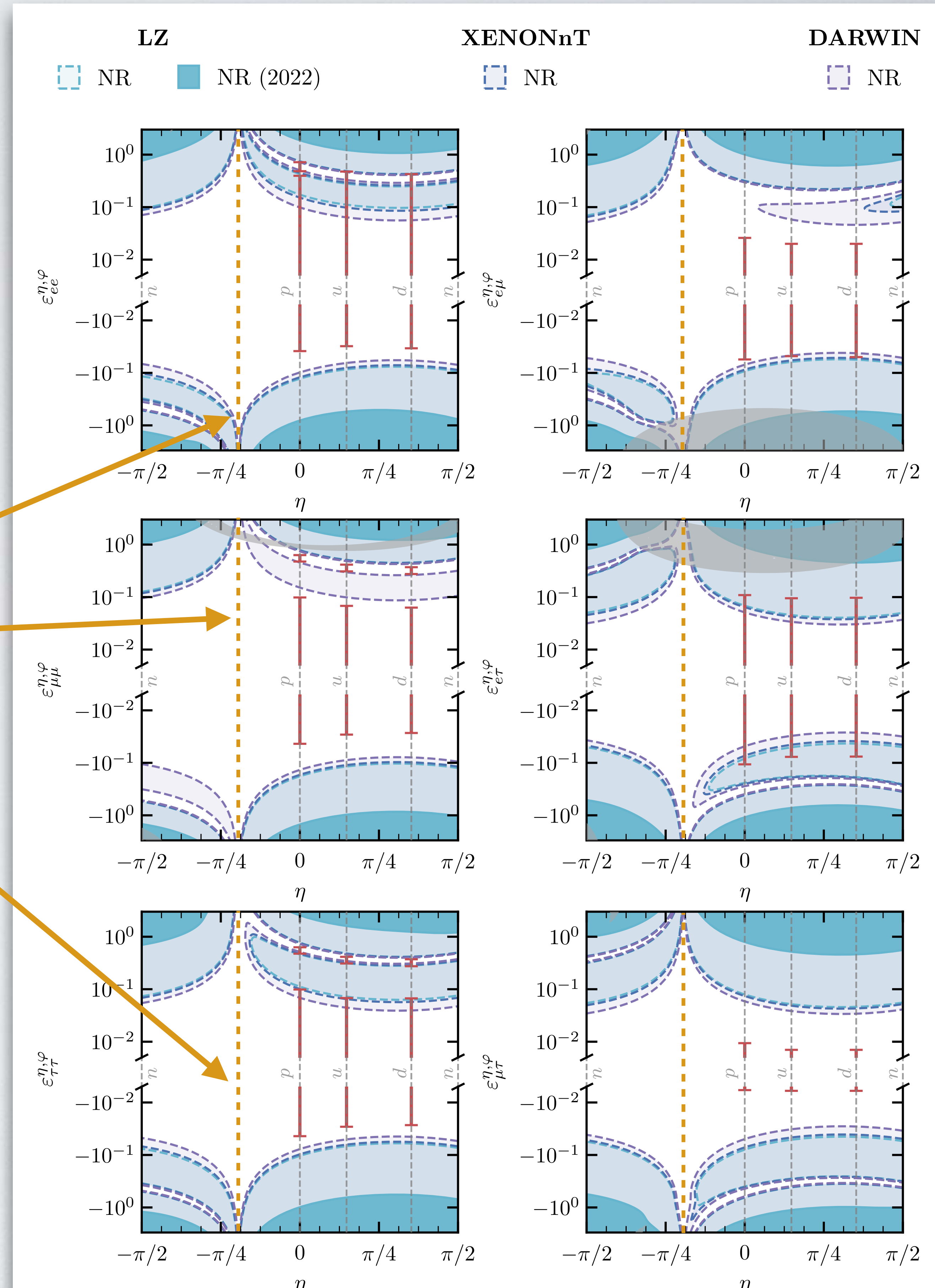




NSI @ DD – NUCLEAR SCATTERING

- Consider one NSI coupling at a time and compare sensitivity to global fit limits from [Coloma et al., *JHEP* **02** (2020) 023]
- **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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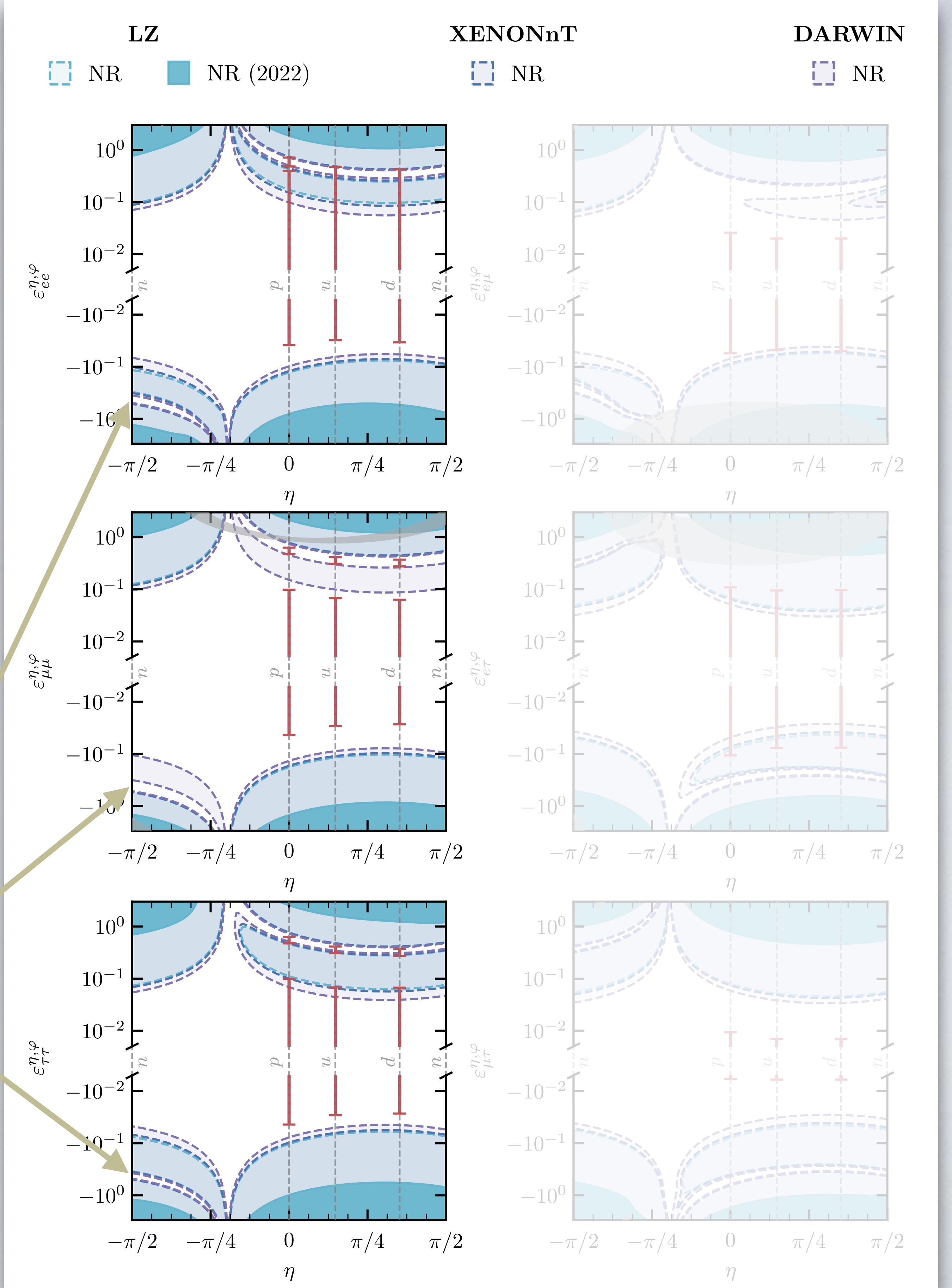
- Blind spot due to **SM-NSI interference** terms in CEνNS cross section

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



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

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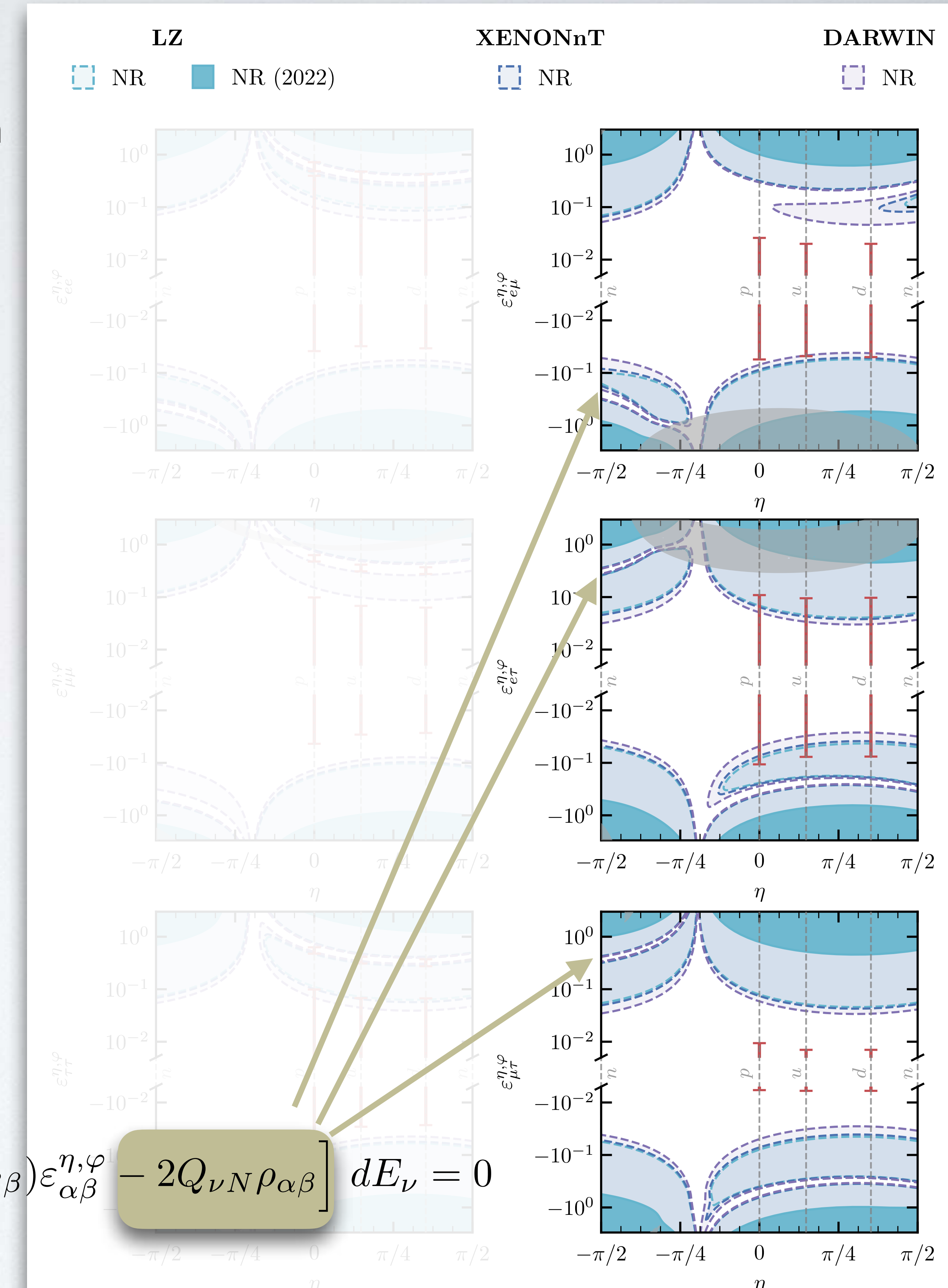
Off-diagonal:

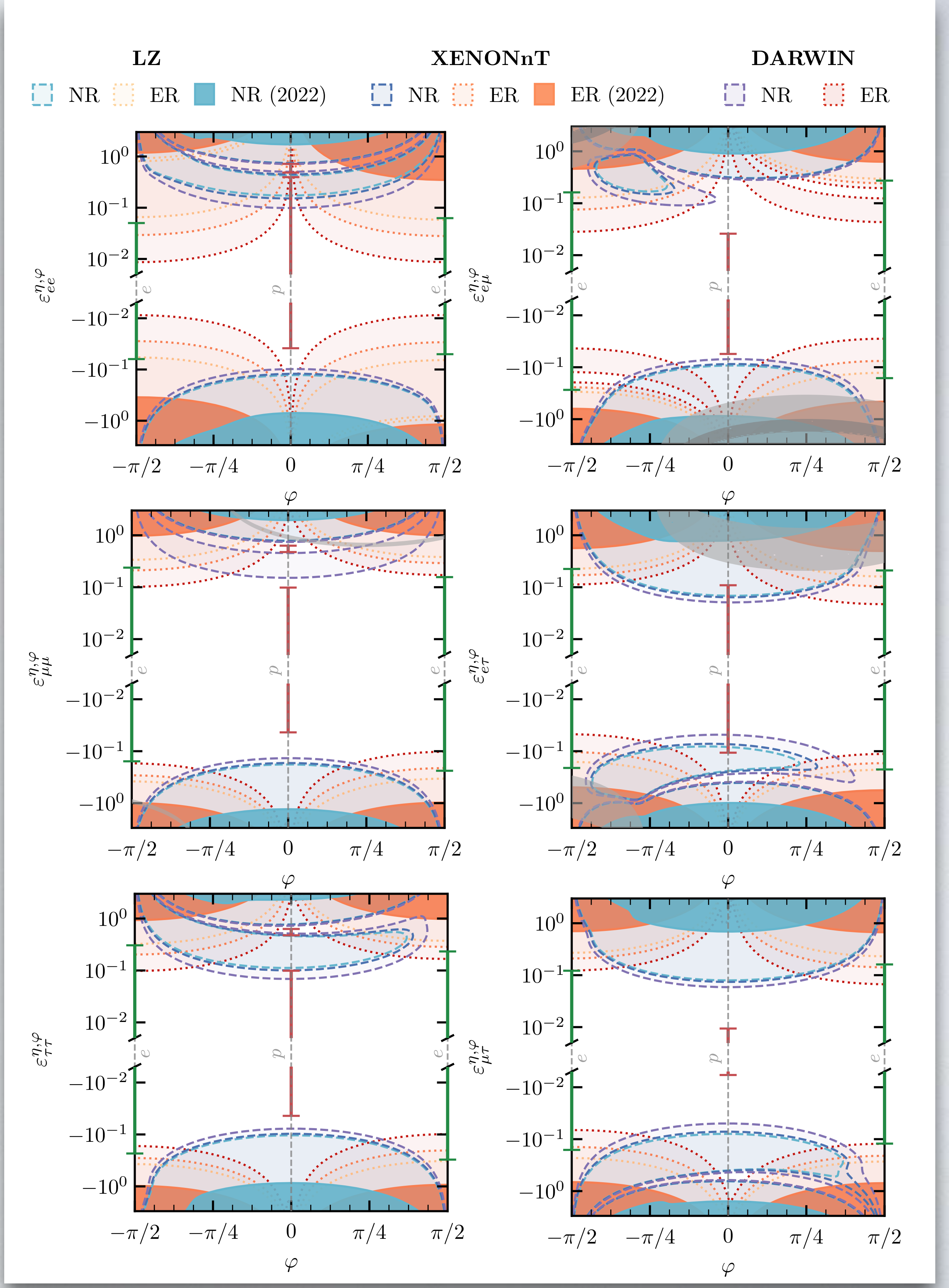
$$\int_{E_\nu^{\min}} \frac{d\phi_{\nu_e}}{dE_\nu}\left(1 - \frac{m_N E_R}{2E_\nu^2}\right)\left[(\xi^p Z + \xi^n N)(\rho_{\alpha\alpha} + \rho_{\beta\beta})\varepsilon^{\eta,\varphi}_{\alpha\beta} - 2Q_{\nu N}\rho_{\alpha\beta}\right] dE_\nu = 0$$



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** $\boldsymbol{\varphi = \pm\pi/2}$
- 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

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

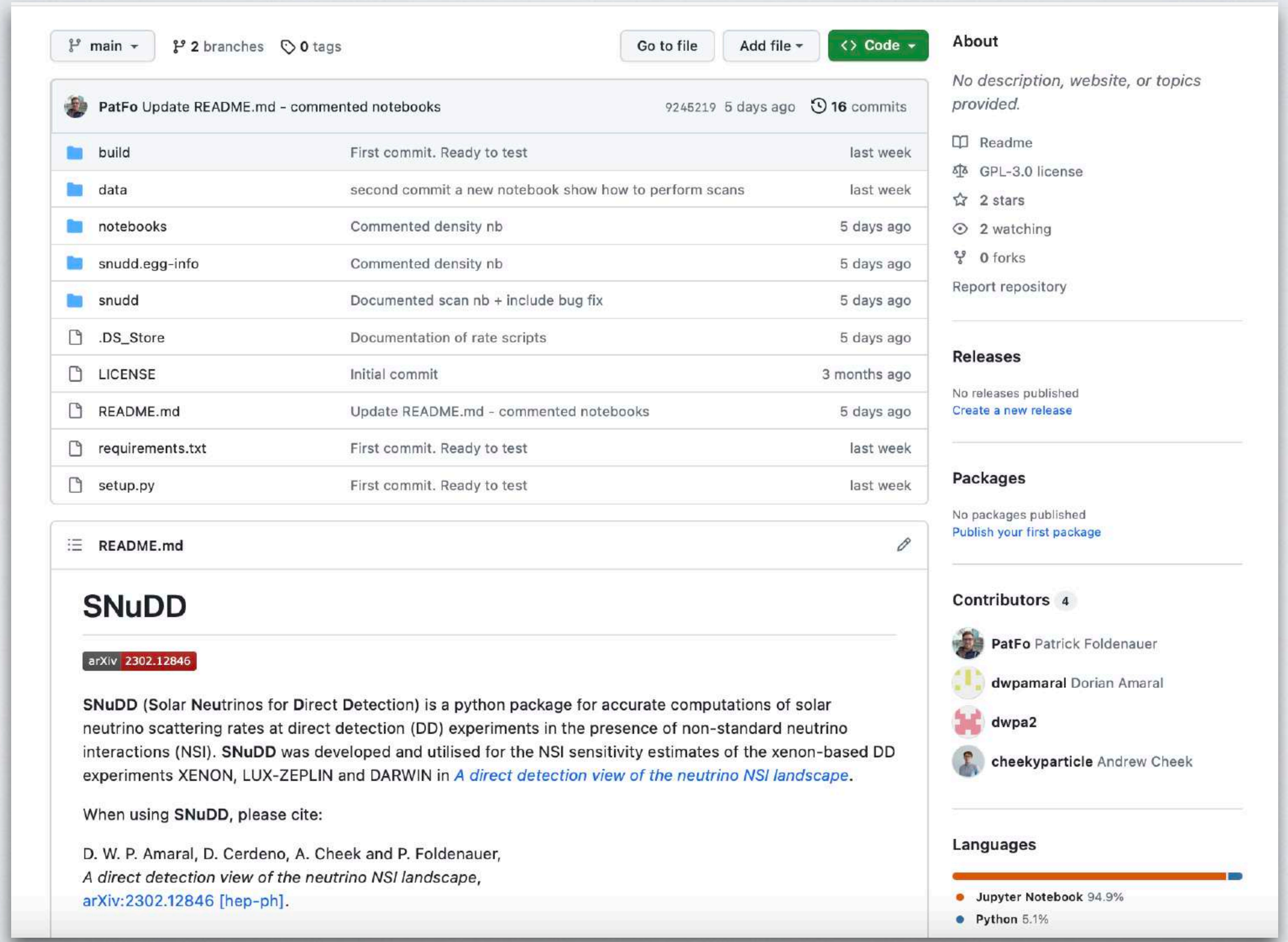


[Amaral, Cheek, Cerdeño, **PF**; 2302.12846]

SNuDD

"**S**olar **N**eutrinos for **D**irect **D**etection"

- 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

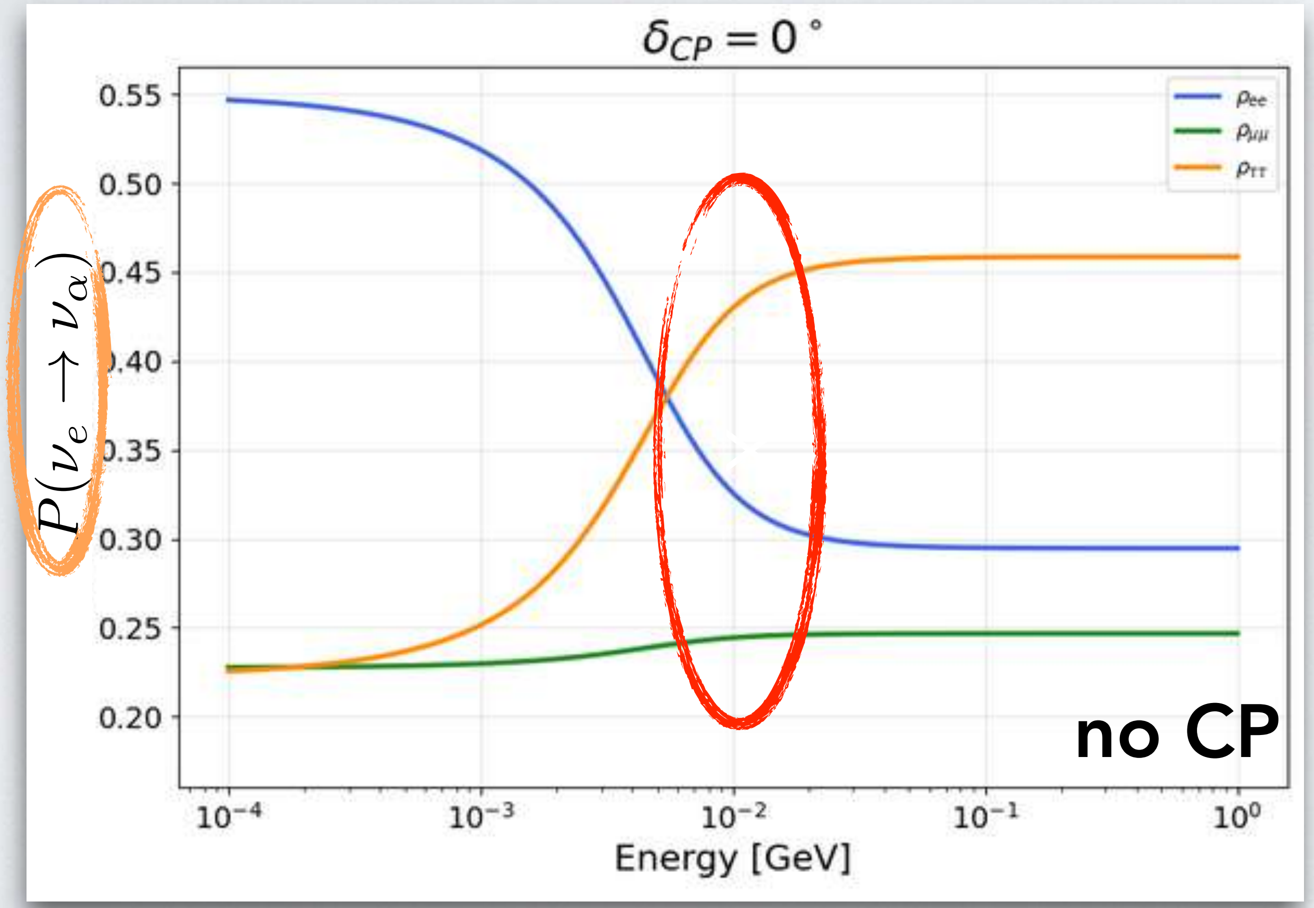


SNuDD: Next steps

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

$$\rho_{ee} = s_{13}^4 + c_{13}^4 \, P_{\rm ee}^{2\nu} \,,$$
$$\rho_{\mu\mu} = c_{13}^2 \left[c_{23}^2 \, (1 - P_{\rm ee}^{2\nu}) + s_{13}^2 \, s_{23}^2 \, (1 + P_{\rm ee}^{2\nu}) + \Delta_\delta\right],$$
$$\rho_{\tau\tau} = c_{13}^2 \left[s_{23}^2 \, (1 - P_{\rm ee}^{2\nu}) + s_{13}^2 \, c_{23}^2 \, (1 + P_{\rm ee}^{2\nu}) - \Delta_\delta\right],$$

- Neutrino density matrix has explicit **CP dependence!**



[Amaral, Cerdeno, Cheek, Costa, **PF**; *in progress*]

$\Rightarrow \nu_\mu, \nu_\tau$ **flavour admixture is CP-dependent!**

SNuDD: Next steps

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$$\begin{aligned}
\rho_{ee} &= s_{13}^4 + c_{13}^4\, P_{\rm ee}^{2\nu}\,, \\
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\rho_{\tau\tau} &= c_{13}^2 \left[s_{23}^2 \left(1 - P_{\rm ee}^{2\nu}\right) + s_{13}^2\, c_{23}^2 \left(1 + P_{\rm ee}^{2\nu}\right) - \Delta_\delta \right],
\end{aligned}$$

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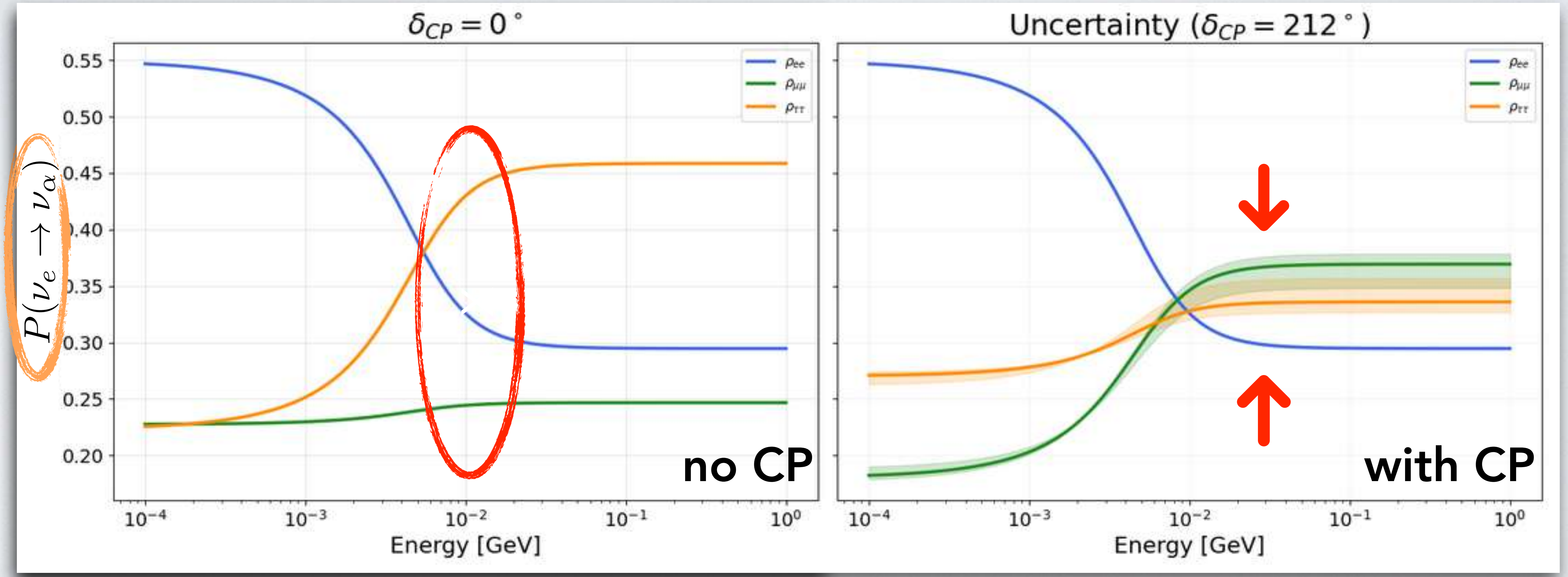
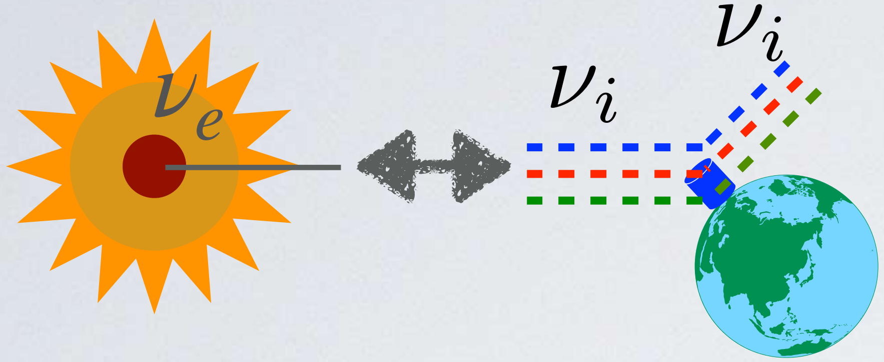
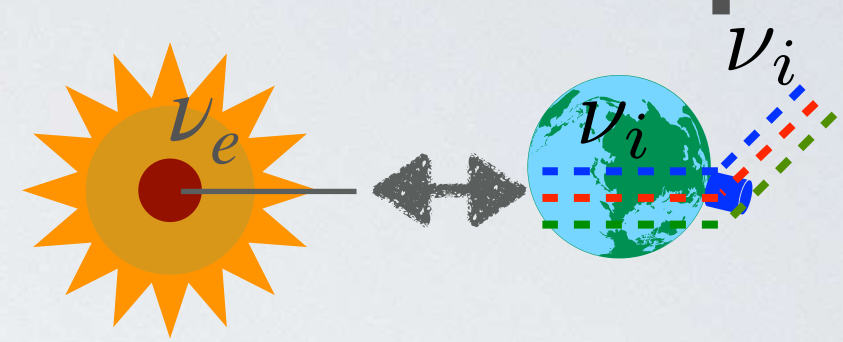


[Amaral, Cerdeno, Cheek, Costa, **PF**; *in progress*]

$\Rightarrow \nu_\mu, \nu_\tau$ **flavour admixture is CP-dependent!** $\Rightarrow$ **FCNC could test this!**

SNuDD: Next steps

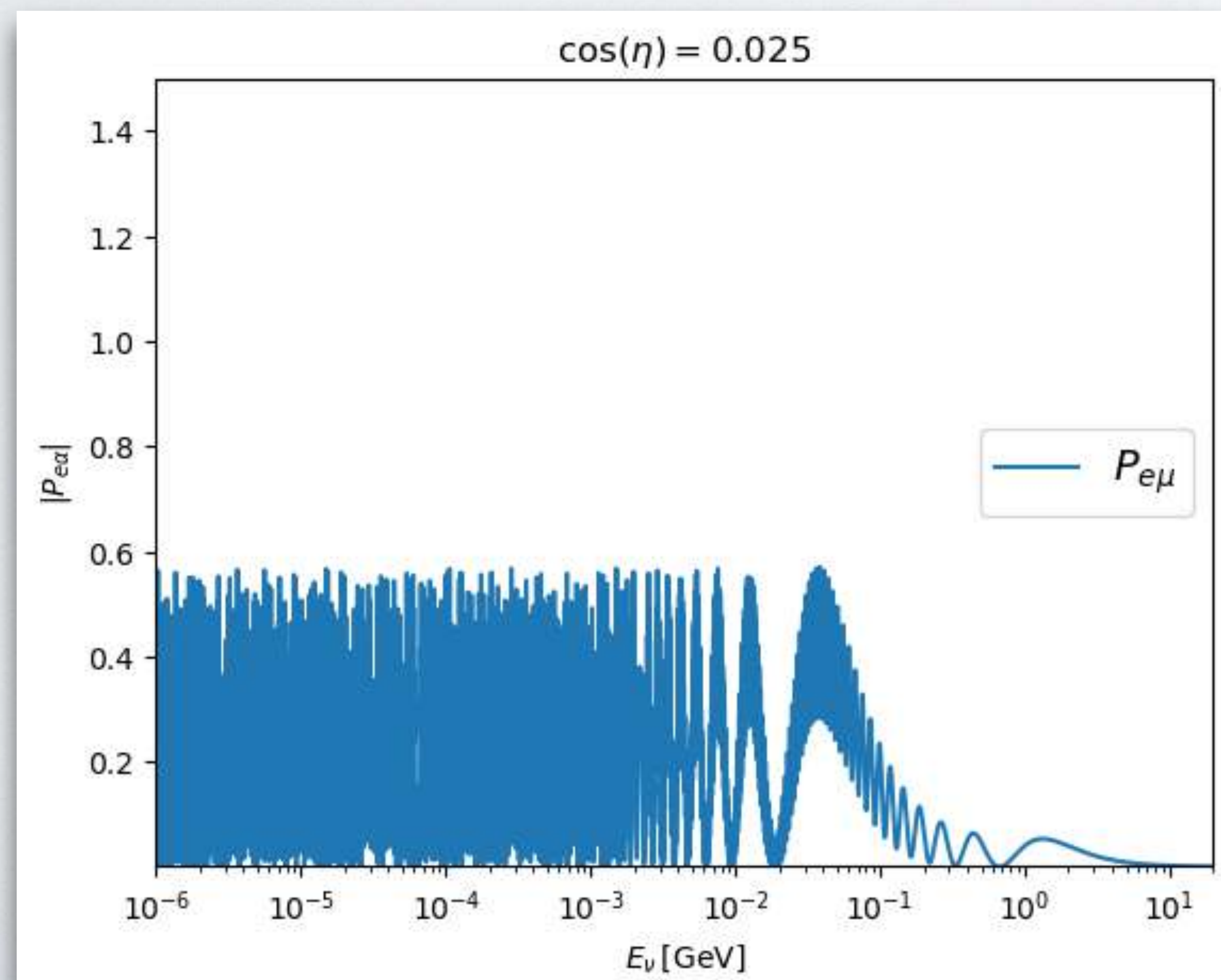


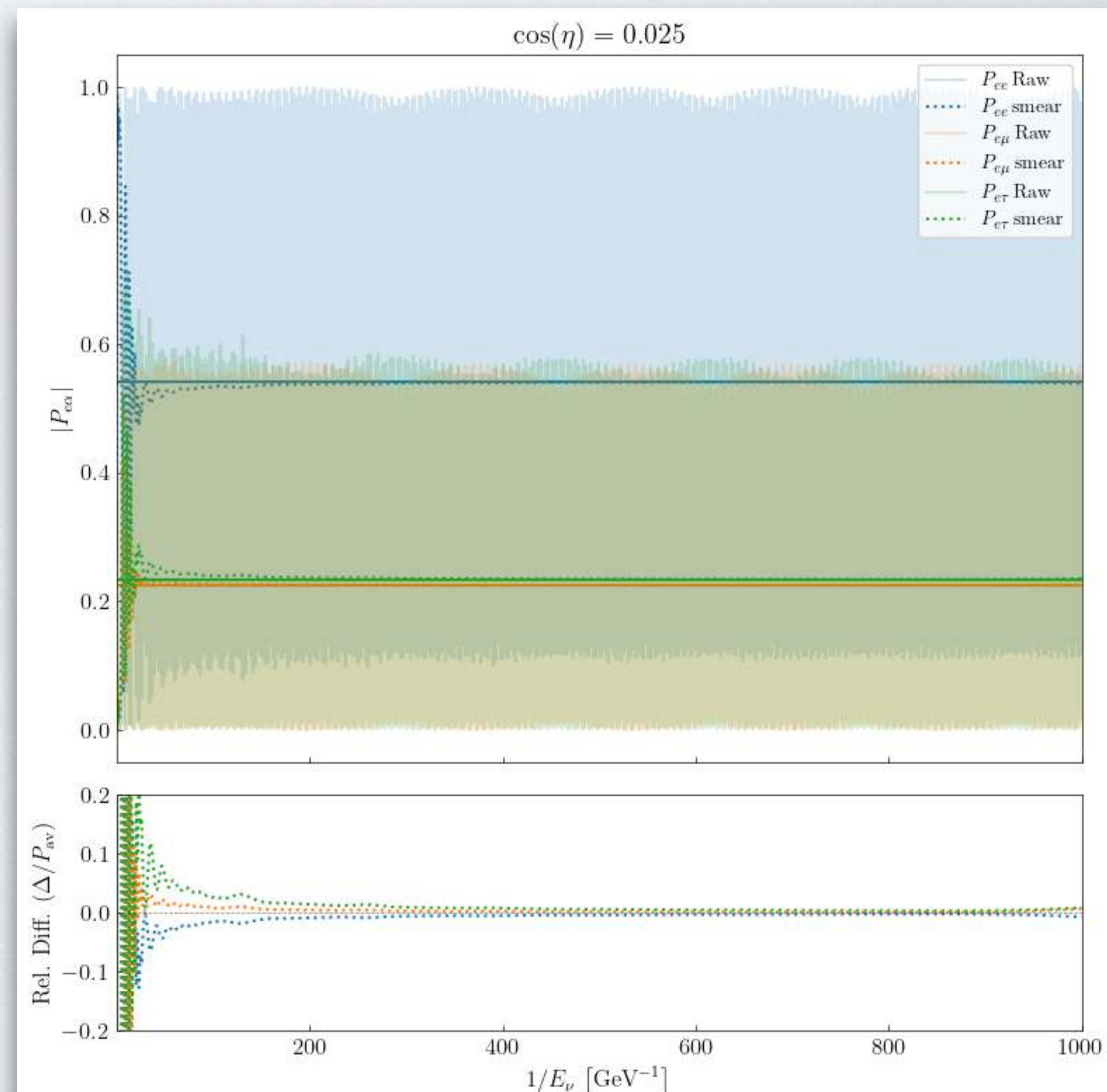


Earth Matter Effects

[Amaral, Cerdeno, Cheek, Costa, **PF**; *in progress*]

- There are additional **NSI matter effects in Earth**





NEW DETECTORS: RES-NOVA

NEW DETECTORS: RES-NOVA

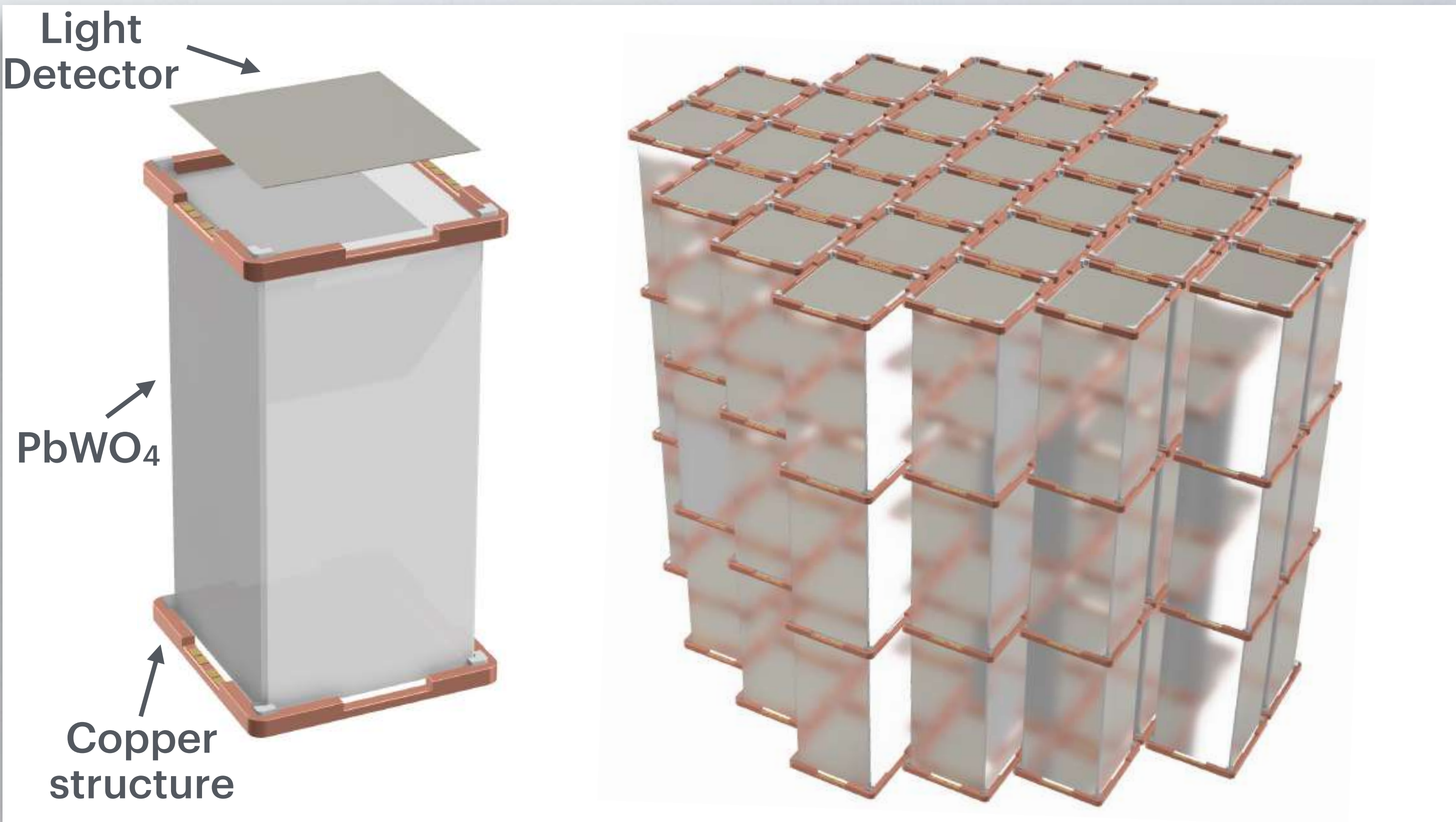
- Upcoming underground cryogenic scintillator neutrino observatory based in Gran Sasso

- 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

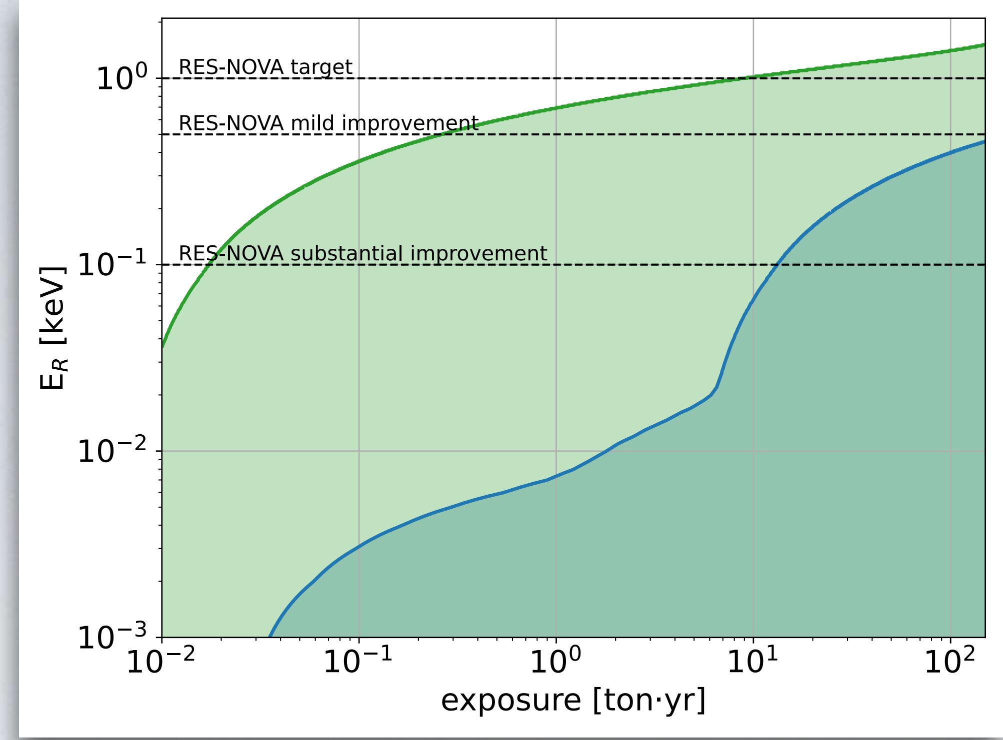
  → Use $PbWO_4$ grown with 2000 yr old archeological **lead from sunken Roman ships**
  (expected ^{210}Pb below 1 mBq/ton!)



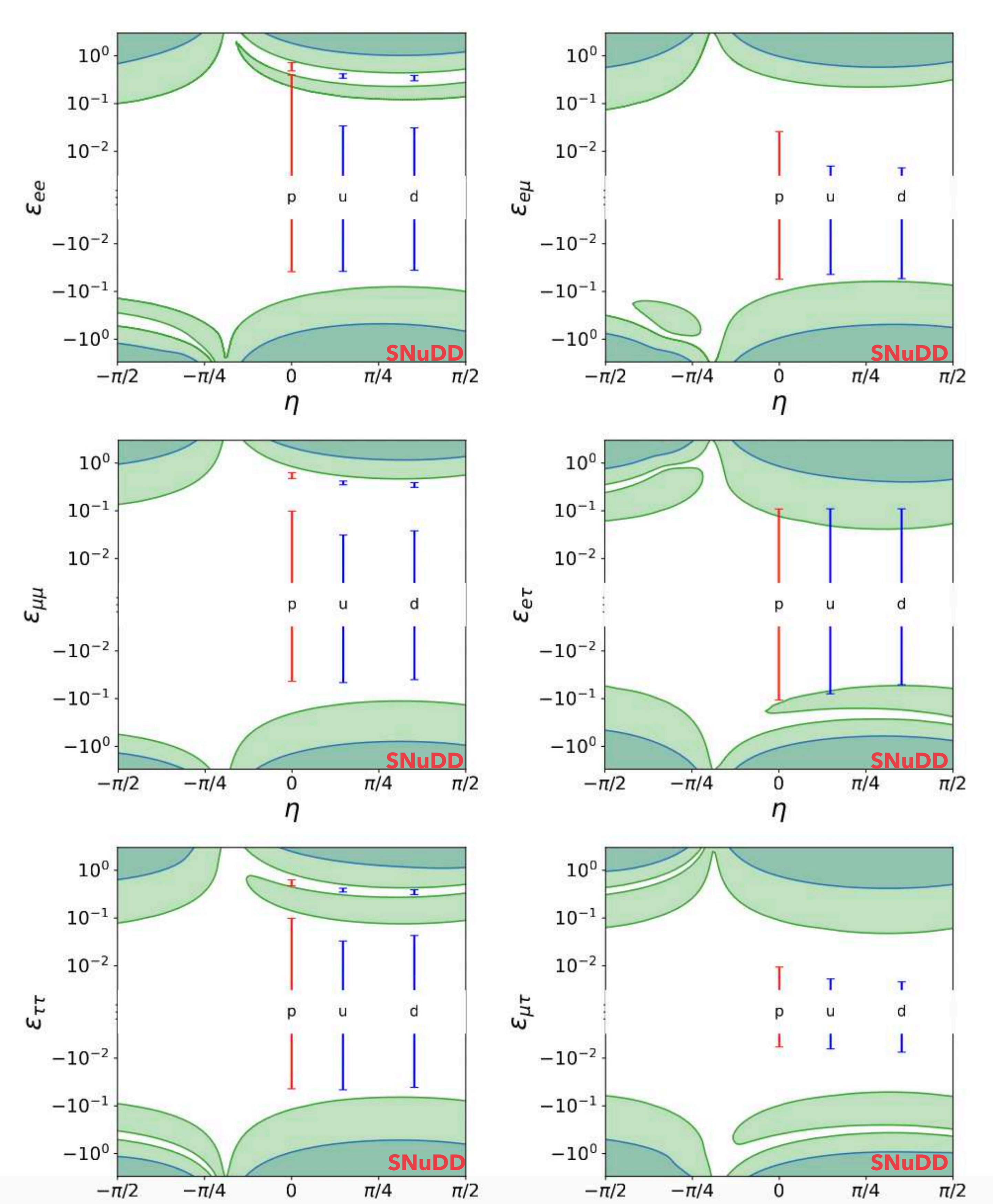
[RES-NOVA; *Phys.Rev.D* 111 (2025) 10, 103050]

Credit: N. Ferreiro Iachellini

NEW DETECTORS: RES-NOVA

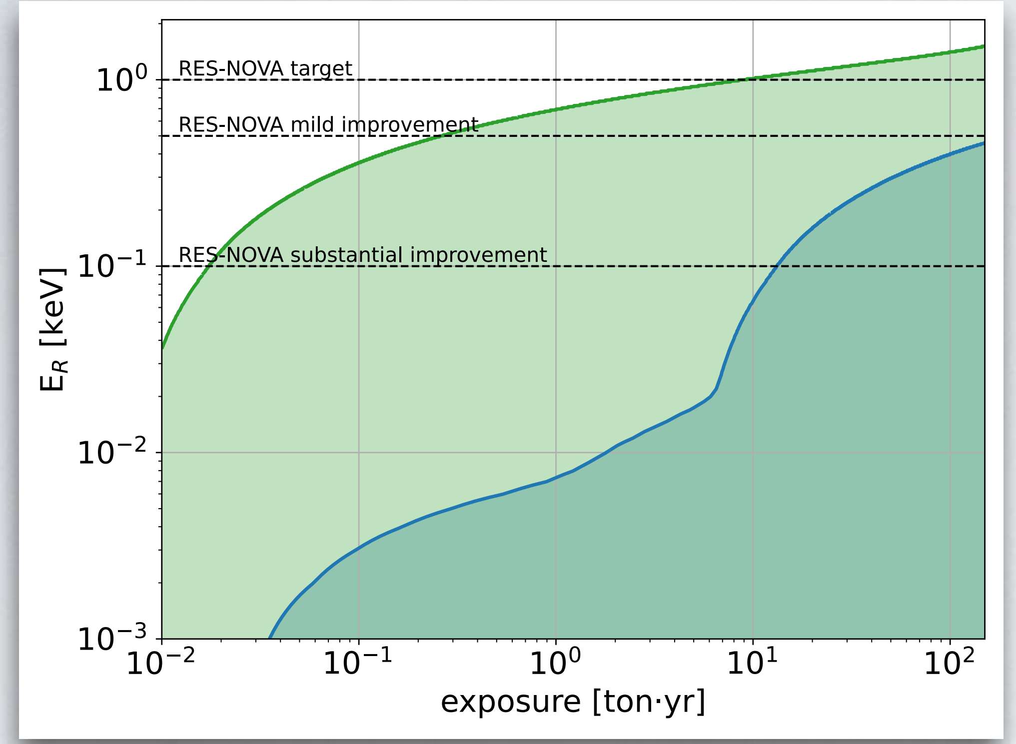


- Projections for RES-NOVA demonstrator with **1-ton** fiducial volume and threshold of **0.5 keV** show **promising sensitivity to NSI**
- Sensitivity depends crucially on **background rejection**
- **Especially sensitive to $\varepsilon_{e\tau}$,** compared to global fits [Coloma et al., *JHEP* **02** (2020) 023] [Coloma et al., *JHEP* **08** (2023) 032]



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

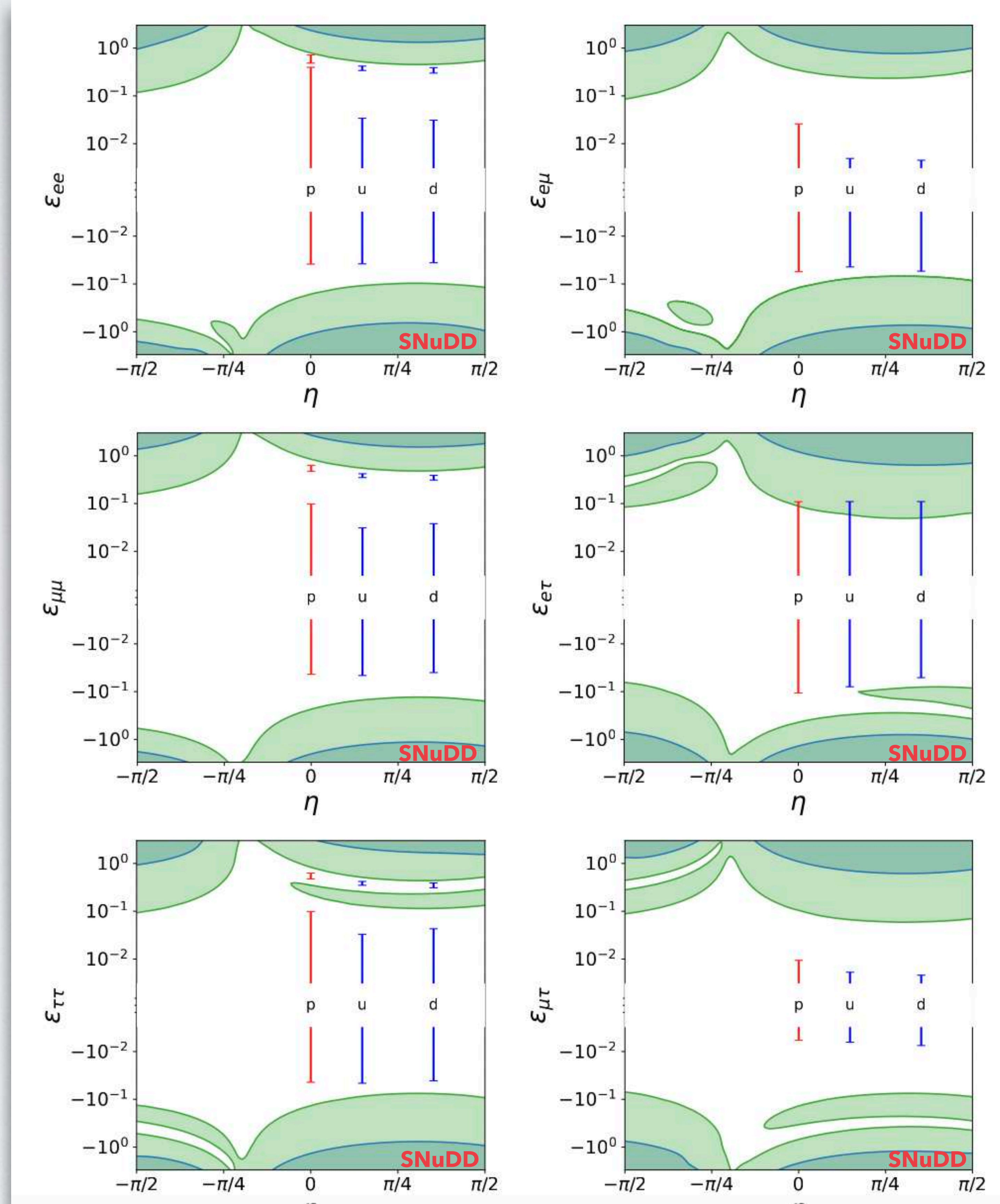
NEW DETECTORS: RES-NOVA



- 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*]

CONCLUSIONS

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

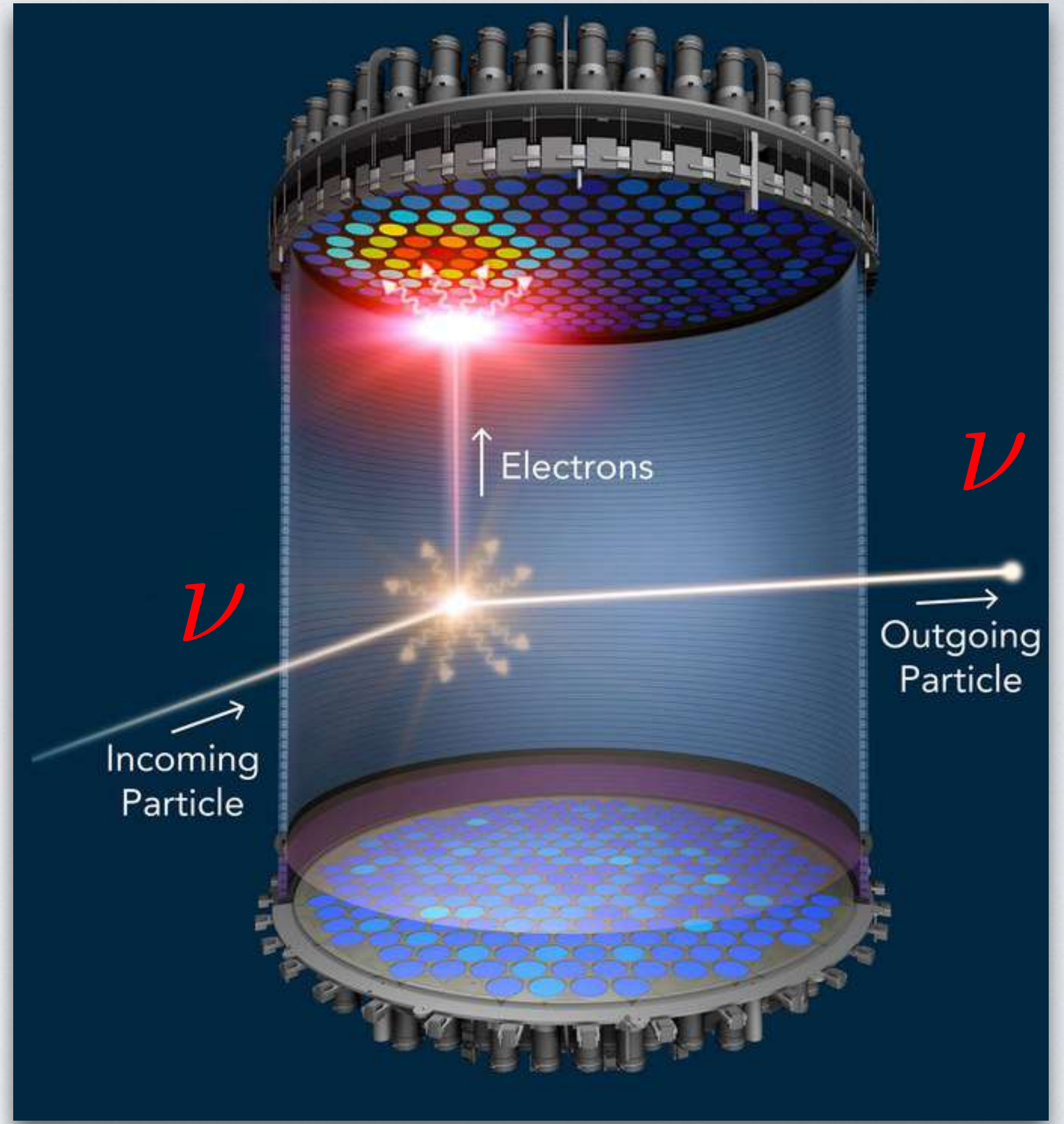
  ⇒ Novel type of **neutrino experiments for free**!

- **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:**
  - light mediators
  - NSI
  - sterile neutrinos
  - …

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



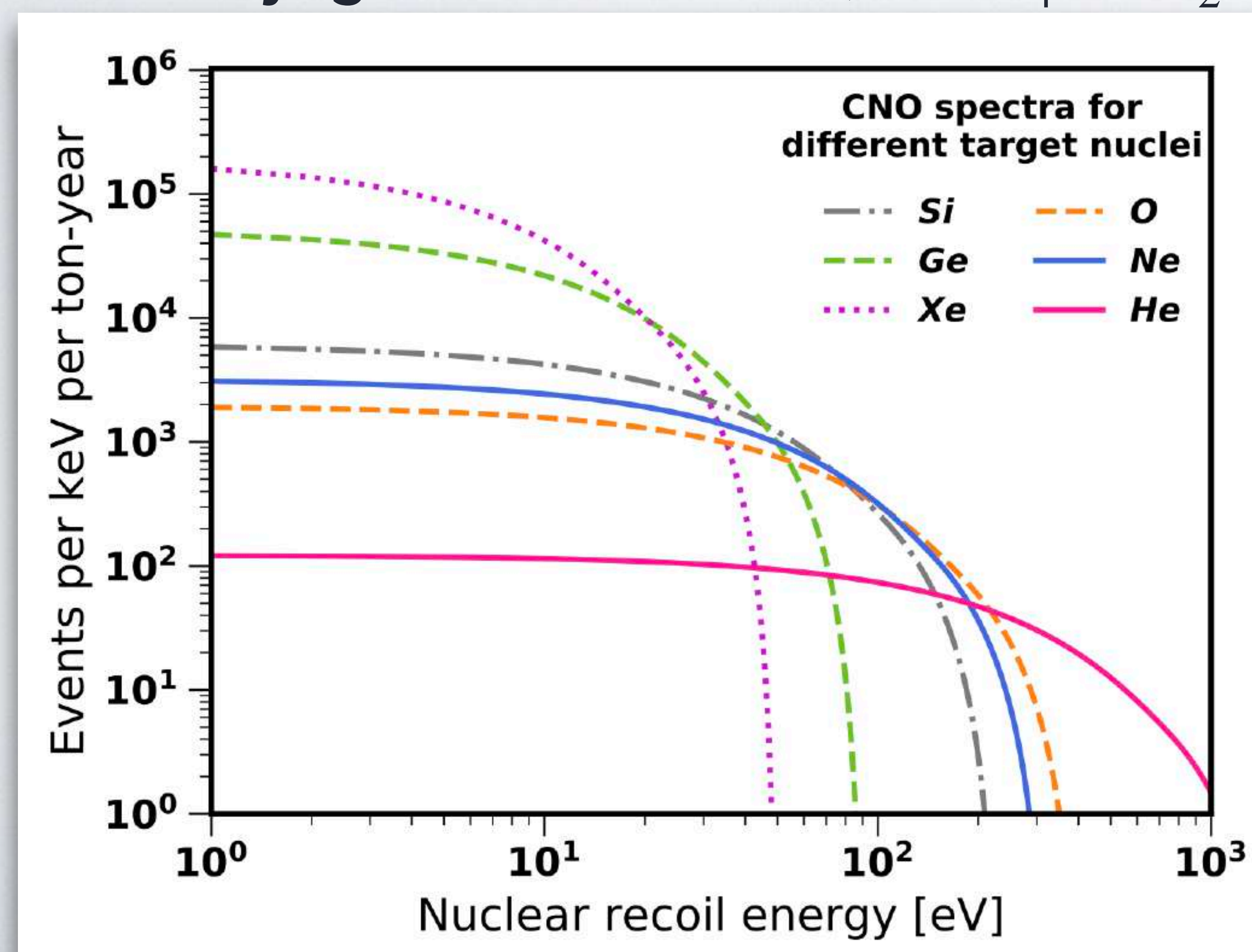
- **Direct detection experiments will become an important player for neutrinos!**

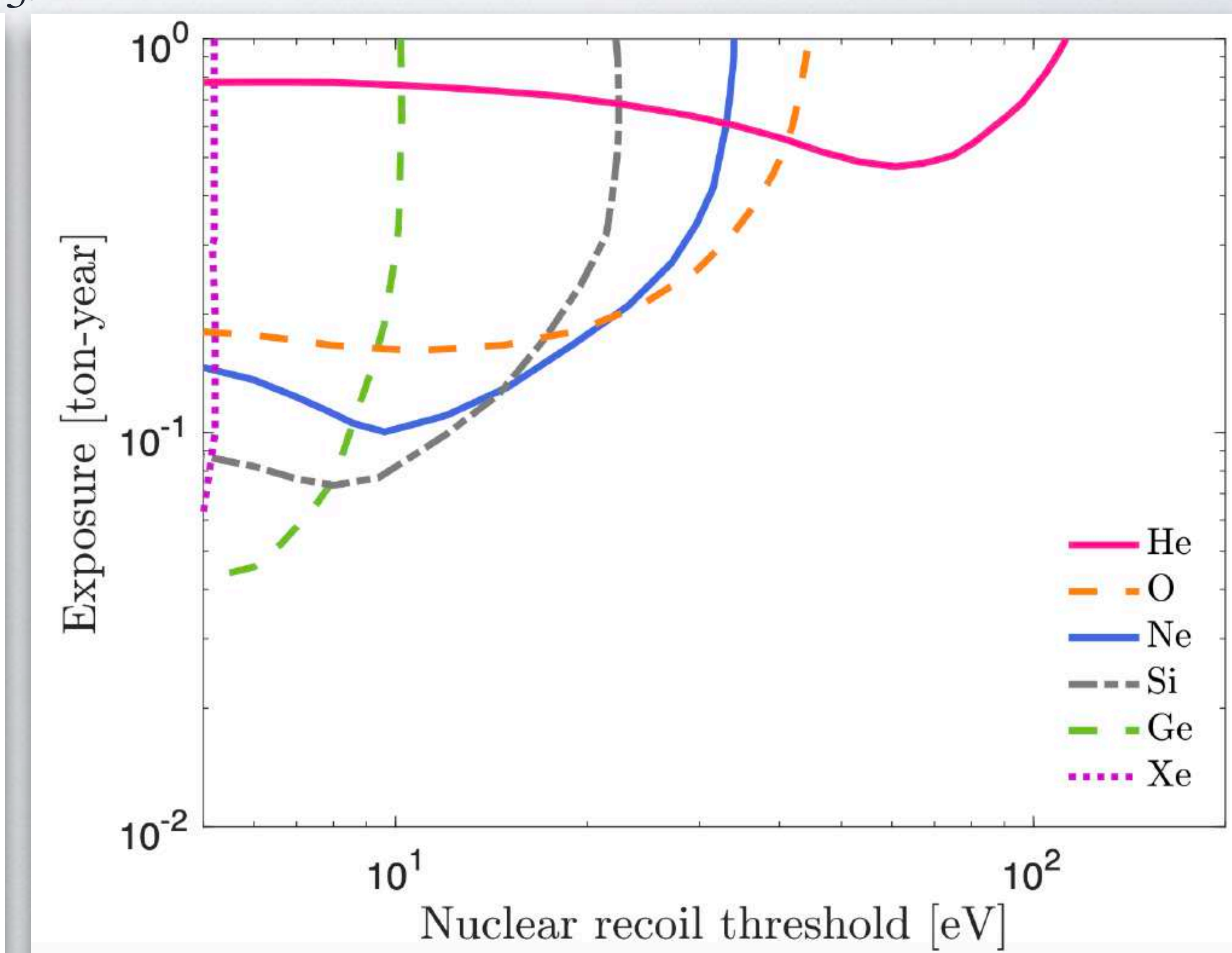
THANK YOU!

BACKUP

CNO DETECTION AT DD

- Future DD experiments could provide independent measurement of **CNO flux**
- **Extremely low energies required** (typically below 100 eV)
- Promising sensitivities at **solid state (Ge or Si) detectors;** have achievable low thresholds [Cerdeño+, *PRD* 90 (2014) 8, 083510]
- Alternative large (1 kton yr) **dual phase liquid argon** TPCs, [Franco+, JCAP08(2016)017] or **cryogenic scintillators (**$CaWO_4$ or Al_2O_3) [Bento+, *Eur.Phys.J.C* 84 (2024) 10, 1118]





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

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**

$$\left|\mathcal{A}_{\nu_\alpha \to \sum_i \nu_i}\right|^2$$

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

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

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

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

Neutrino density matrix

generalised matrix element

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

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

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

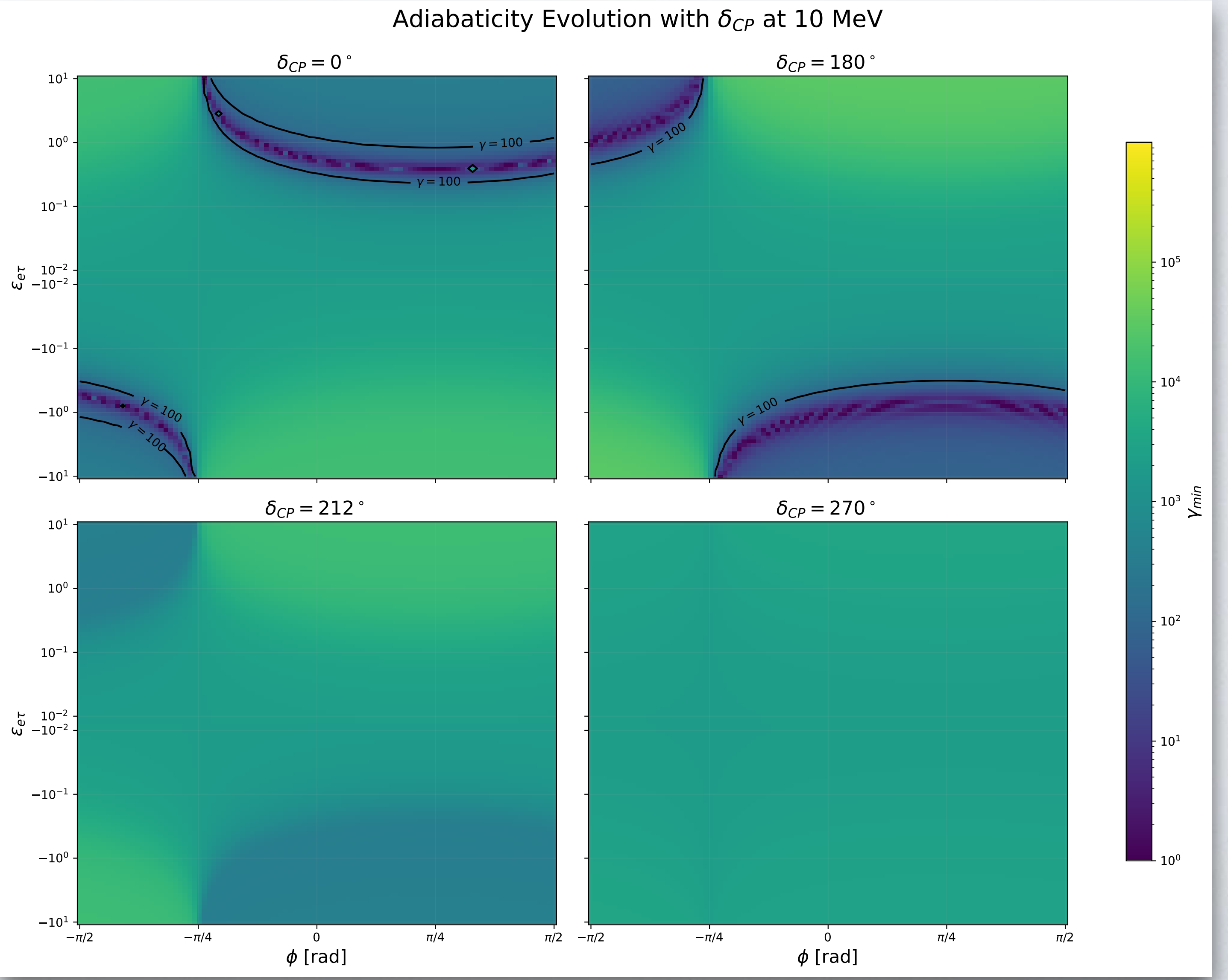
- Evolution **adiabatic if**

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

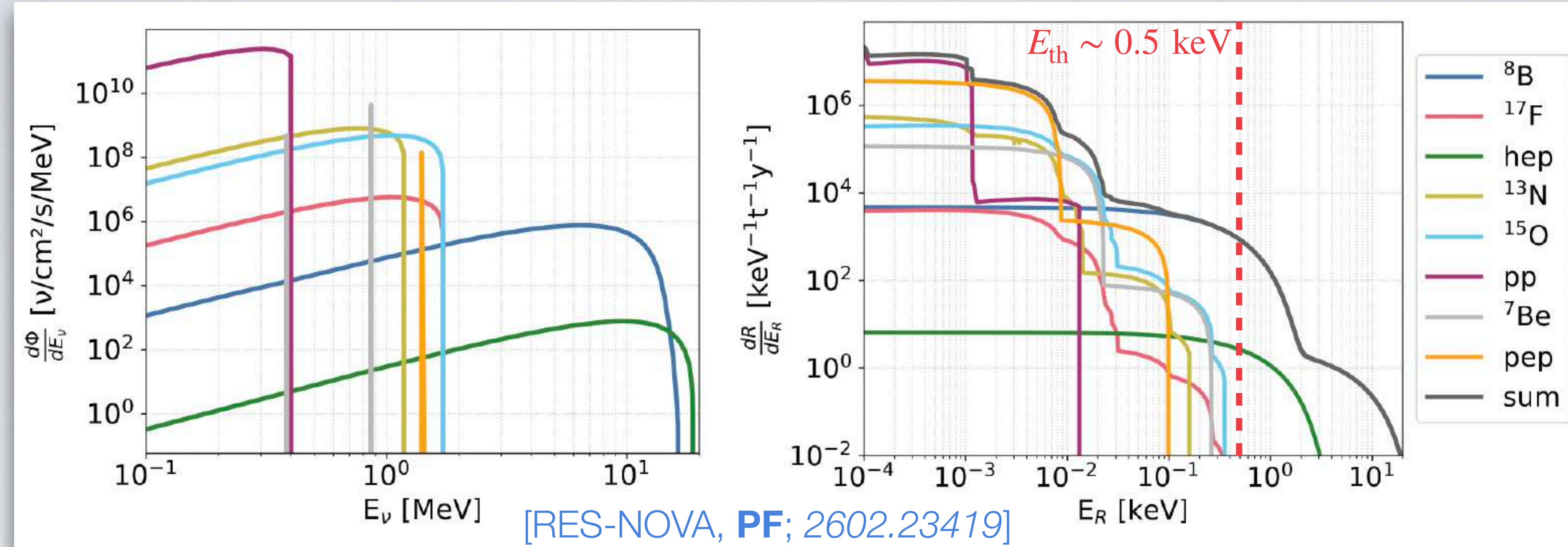
- Adiabaticity **depends on the CP phase!**

- Complex NSI can modify the adiabaticty of neutrino evolution!

[Amaral, Cerdeno, Cheek, Costa, **PF**; *in progress*]



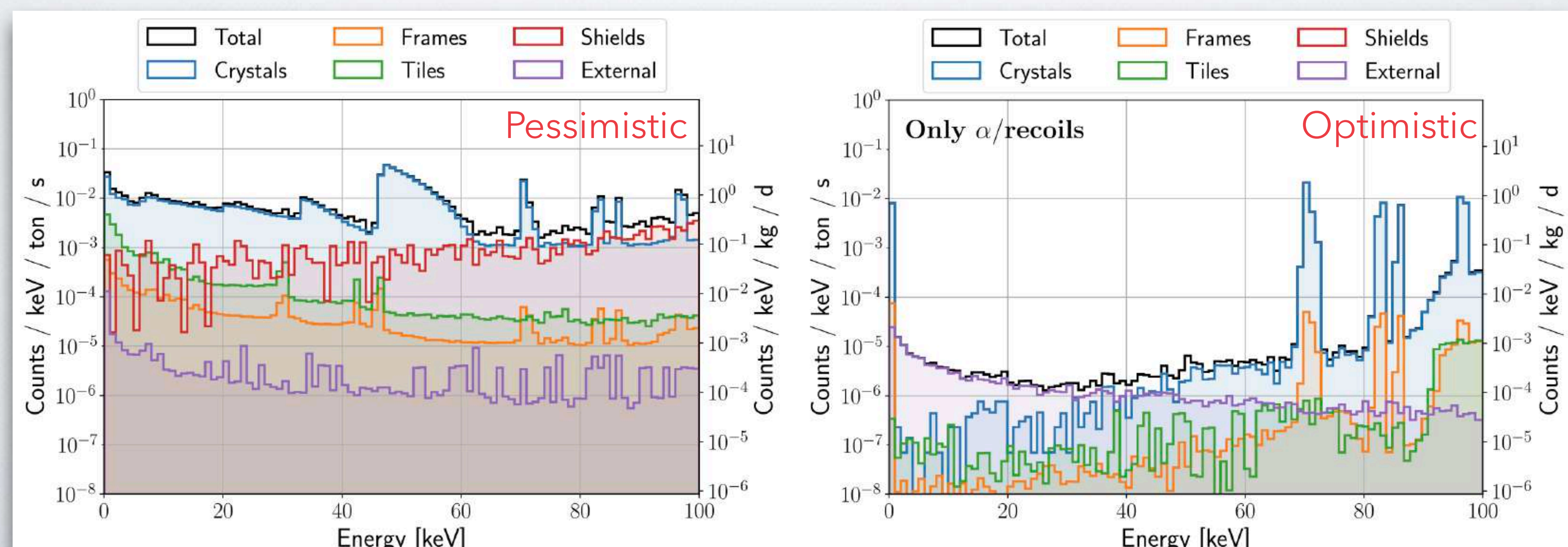
NEW DETECTORS: RES-NOVA



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

- RES-NOVA can achieve realistic thresholds of 0.5 keV $\rightarrow$ significant ^8B **signal!**

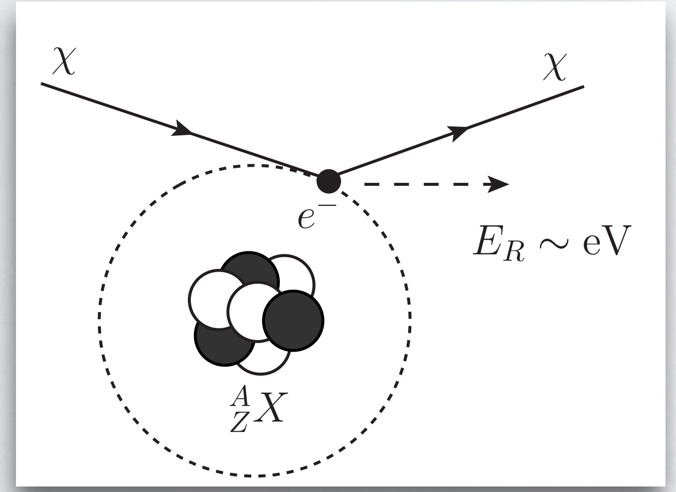
- **Background suppression** will be crucial for high sensitivity:
  Pessimistic: phonon-only readout w/o particle ID
  Optimistic: e−/γ rejection through combined phonon and scintillation light readout.



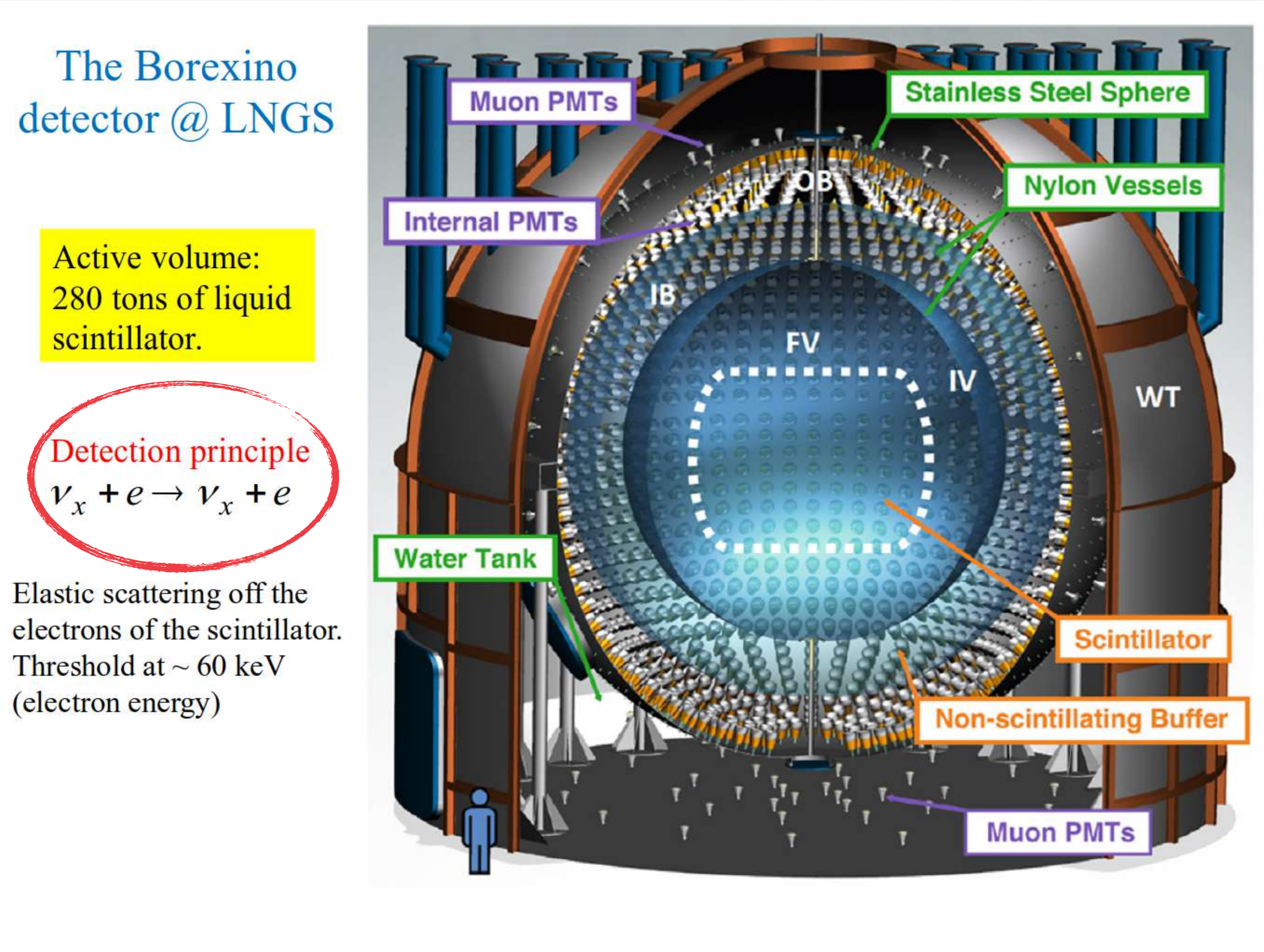
NSI @ NEUTRINO OBSERVATORIES

- **Borexino** is very **low threshold** and radio pure liquid scintillator detector @ Gran Sasso

- Main goals: **neutrino spectroscopy** and measuring the ^{7}**Be solar neutrino flux** via **electron recoils**



- produced some of the most accurate measurements of solar neutrino interactions



BOREXINO

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

$$\varepsilon^V_{ee} \in [-0.12, 0.08]$$

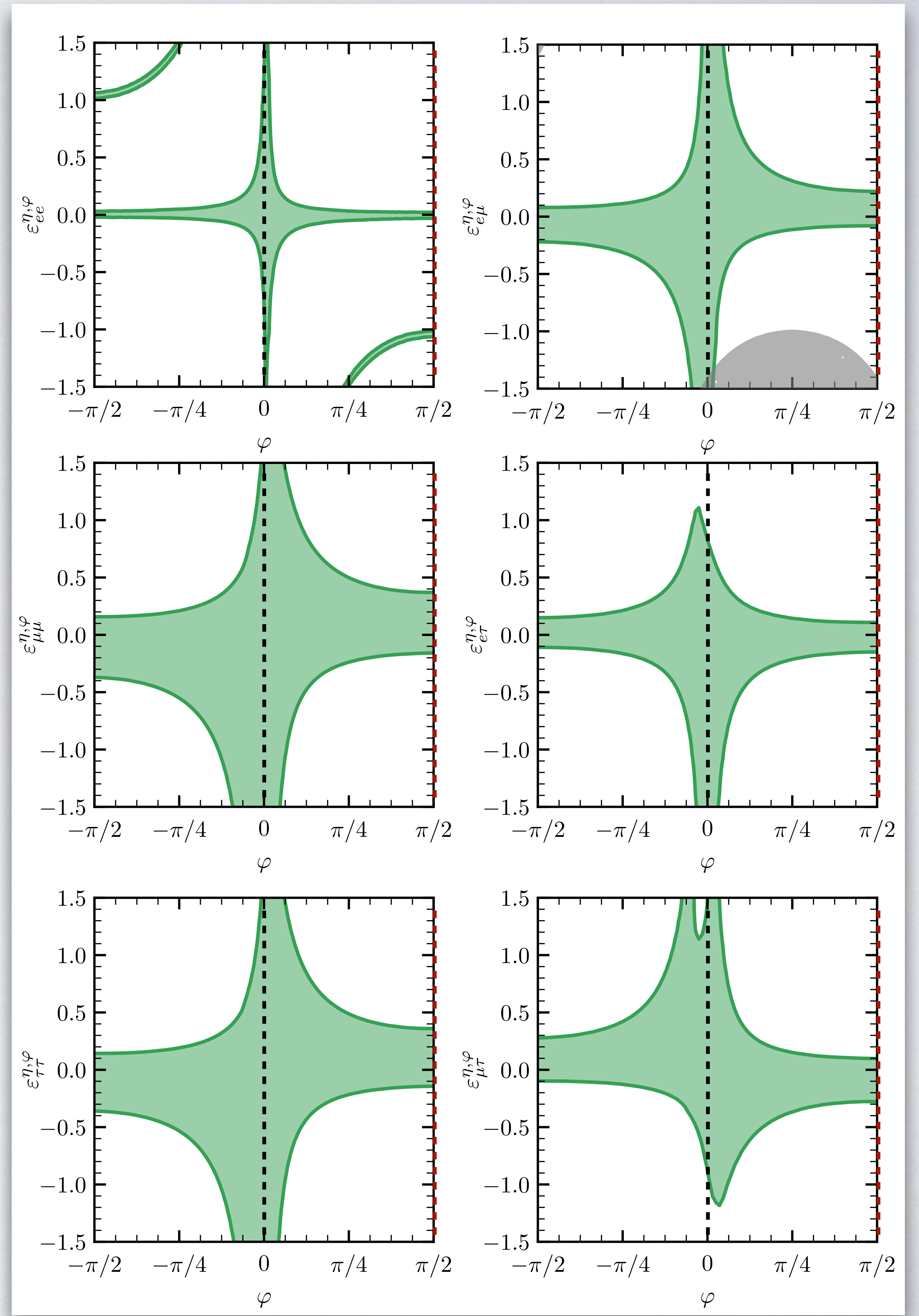
[Khan et al., *Phys. Rev. D 101, 055047 (2020)*]
[Coloma et al., *JHEP 07 (2022) 138*]

- 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

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



[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!