Data-Driven Neutrino Floor

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MultiDark 18, 18 October 2021, Huelva, Spain

Based on arXiv: 2109.03247 [hep-ph]

in collab. with D. Aristizabal, V. De Romeri & L.J. Flores

Ευρωπαϊκή Ένωση
European Social Fund

Operational Programme
Human Resources Development,
Education and Lifelong Learning

Co-financed by Greece and the European Union

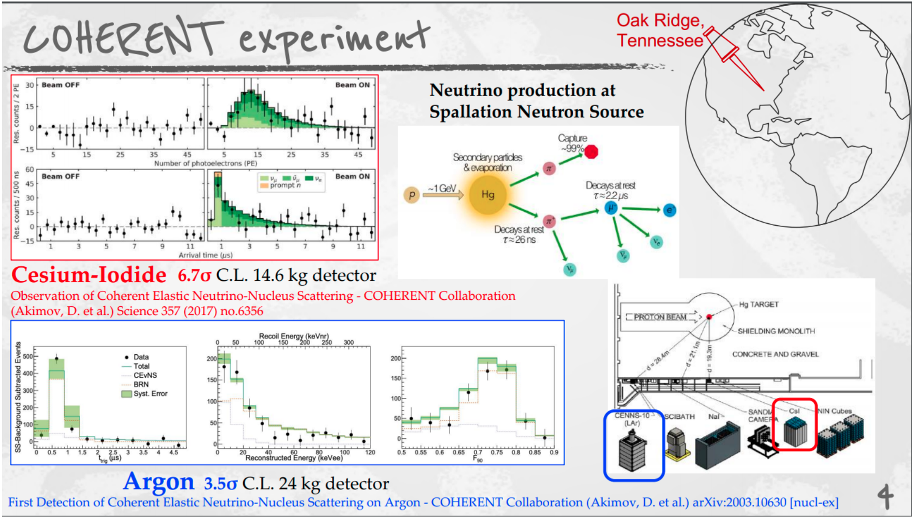
ΕΣΠΑ
2014-2020
ανάπτυξη - εργασία - αλληλεγγύη

Outline

1. Introduction and motivations
   - Coherent elastic neutrino nucleus scattering (CEνNS)
   - WIMP-nucleus scattering
2. Neutrino floor calculations
   - incorporating electroweak and nuclear uncertainties
   - including new physics scenarios
   - relying on data from the COHERENT experiment
3. Summary

Observation of CEνNS by the COHERENT experiment

CEνNS: Coherent elastic neutrino nucleus scattering



slide taken from N. Cargioli: Magnificent CEvNS 2020

Standard Model CEνNS cross section

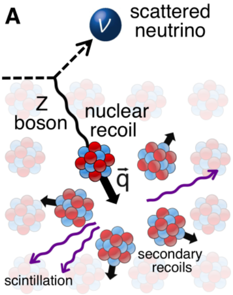
CEνNS cross section expressed through the nuclear recoil energy E_r

$$\left(\frac{d\sigma}{dE_r}\right)_{\mathrm{SM}} = \frac{G_F^2 m_N}{2\pi} \mathcal{Q}_W^2 \left(2 - \frac{m_N E_r}{E_\nu^2}\right) F^2(q^2)$$

[DKP, Kosmas: PRD 97 (2018)]

- E_ν: is the incident neutrino energy
- m_N: the nuclear mass of the detector material
- 3-momentum transfer $q^2 = 2 m_N E_r$
- $F(Q^2)$: is the nuclear form factor
- vector weak charge $\mathcal{Q}_W$

$$\mathcal{Q}_W = \left(\frac{1}{2} - 2\sin^2\theta_W\right) Z - \frac{1}{2} N$$

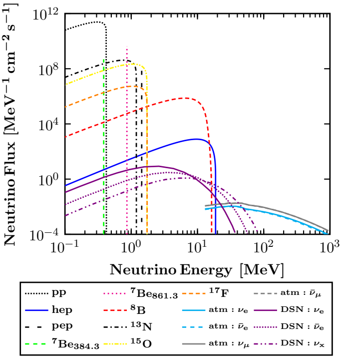


Neutrino backgrounds at direct dark matter detection experiments

Irreducible background

- **Solar neutrinos**
  [W. C. Haxton, R. G. Hamish Robertson, and A. M. Serenelli, Ann. Rev. Astron. Astrophys. **51** (2013), 21]
- **Atmospheric neutrinos**
  (FLUKA simulations)
  [G. Battistoni, A. Ferrari, T. Montaruli, and P. R. Sala, Astropart. Phys. **23** (2005) 526]
- **Diffuse Supernova Neutrinos (DSN)**
  [Horiuchi, Beacom, Dwek, PR **D79** (2009) 083013]

Type	$E_{\nu_{\max}}$ [MeV]	Flux $[\mathrm{cm}^{-2}\mathrm{s}^{-1}]$
pp	0.423	$(5.98 \pm 0.006) \times 10^{10}$
pep	1.440	$(1.44 \pm 0.012) \times 10^{8}$
hep	18.784	$(8.04 \pm 1.30) \times 10^{3}$
$^{7}\mathrm{Be}_{\mathrm{low}}$	0.3843	$(4.84 \pm 0.48) \times 10^{8}$
$^{7}\mathrm{Be}_{\mathrm{high}}$	0.8613	$(4.35 \pm 0.35) \times 10^{9}$
$^{8}\mathrm{B}$	16.360	$(5.58 \pm 0.14) \times 10^{6}$
$^{13}\mathrm{N}$	1.199	$(2.97 \pm 0.14) \times 10^{8}$
$^{15}\mathrm{O}$	1.732	$(2.23 \pm 0.15) \times 10^{8}$
$^{17}\mathrm{F}$	1.740	$(5.52 \pm 0.17) \times 10^{6}$



WIMP-nucleus scattering

weakly interacting massive particles (WIMPs)

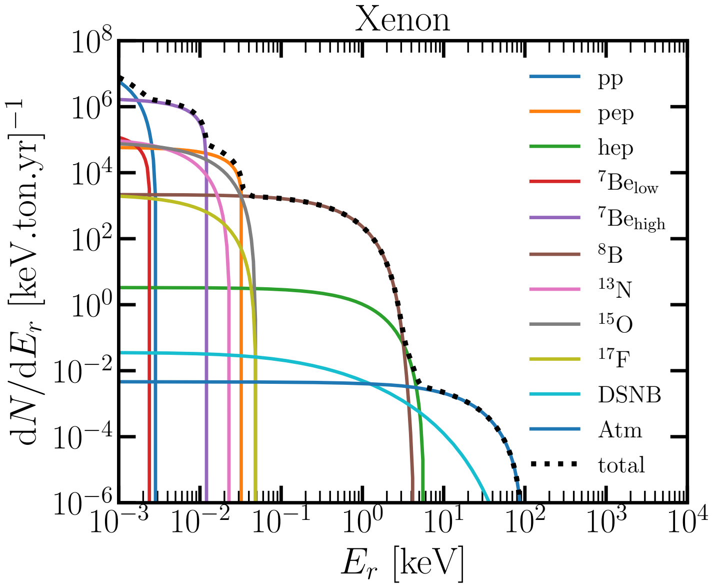
Differential event rate as a function of E_r

$$\frac{dR_W}{dE_r} = \varepsilon \frac{\rho_0 \sigma_{\mathrm{SI}}(q)}{2 m_\chi \mu^2} \int_{|\boldsymbol{v}| > v_{\mathrm{min}}} d^3 v \, \frac{f(\boldsymbol{v})}{v}$$

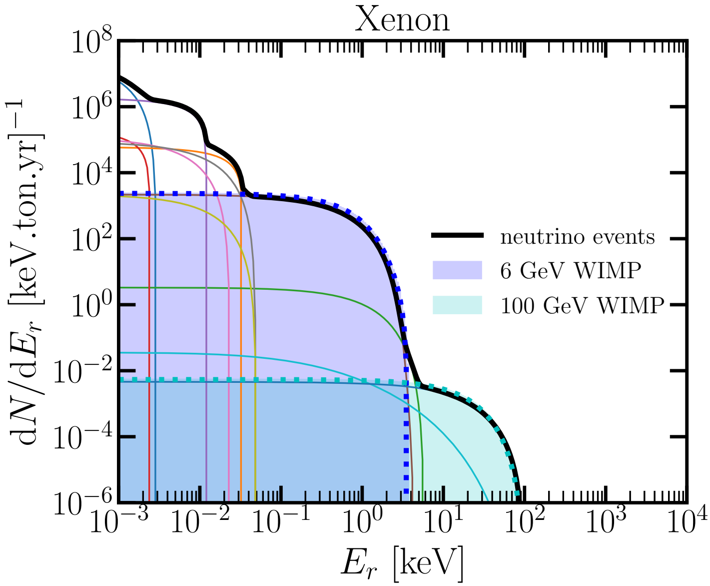
[Lewin and Smith: Astropart. Phys. 6 (1996)]

- $\rho_0 = 0.3\ \mathrm{GeV}/\mathrm{cm}^2$ local Halo DM density
- $\sigma_{\mathrm{SI}}(q) = \frac{\mu^2}{\mu_n^2} \left[Z F_p(q) + (A - Z) F_n(q) \right]^2 \sigma_{\chi - n}$
  Spin-independent WIMP-nucleus scattering
- m_χ: WIMP mass
- $\mu = m_\chi m_N / (m_\chi + m_N)$: WIMP-nucleus reduced mass
- $f(v) = \begin{cases} \frac{1}{N_{\mathrm{esc}}} \left(\frac{3}{2\pi\sigma_v^2} \right)^{3/2} e^{-3\boldsymbol{v}^2/2\sigma_v^2} & \text{for} \quad v < v_{\mathrm{esc}} \\ 0 & \text{for} \quad v > v_{\mathrm{esc}} \end{cases}$ (Maxwell distribution)

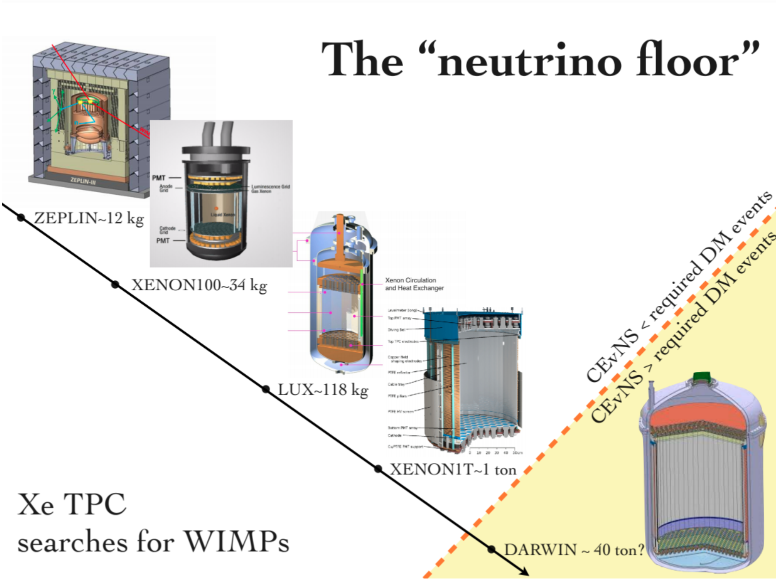
Neutrino events at dark matter direct detection exps



Neutrino vs. WIMP events



Neutrino floor



slide taken from: C. O'Hare Magnificent CEvNS 2020 Workshop

Statistical analysis

Likelihood

[Billard, Strigari, Figueroa-Feliciano PRD 89(2014)]

$$\mathcal{L}(m_\chi, \sigma_{\chi-n}, \Phi, \mathcal{P}) = \prod_{i=1}^{n_{\text{bins}}} P(N^i_{\text{Exp}}, N^i_{\text{Obs}}) \times \prod_{\alpha=1}^{n_\nu} G(\phi_\alpha, \mu_\alpha, \sigma_\alpha)$$

- Poisson distribution $P(k,\lambda) = \frac{\lambda^k e^{-\lambda}}{k!}$
- Gauss distribution $G(x,\mu,\sigma^2) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}$
- $N^i_{\text{Exp}} = N^i_\nu(\Phi_\alpha)$
- $N^i_{\text{Obs}} = \sum_\alpha N^i_\nu(\Phi_\alpha) + N^i_W$
- $\lambda(0) = \frac{\mathcal{L}_0}{\mathcal{L}_1}$ where $\mathcal{L}_0$ is the minimized function
- statistical significance: $\mathcal{Z} = \sqrt{-2 \ln \lambda(0)}$.
  e.g. $\mathcal{Z} = 3$ corresponds to 90% C.L.

Neutrino flux normalizations & uncertainties					
Type	Norm $[\text{cm}^{-2} \cdot \text{s}^{-1}]$	Unc.	Type	Norm $[\text{cm}^{-2} \cdot \text{s}^{-1}]$	Unc.
^{7}Be (0.38 MeV)	4.84×10^8	3%	^{7}Be (0.86 MeV)	4.35×10^9	3%
pep	1.44×10^8	1%	pp	5.98×10^{10}	0.6%
^{8}B	5.25×10^6	4%	hep	7.98×10^3	30%
^{13}N	2.78×10^8	15%	^{15}O	2.05×10^8	17%
^{17}F	5.29×10^6	20%	DSNB	86	50%
Atm	10.5	20%	—	—	—

Statistical analysis

Likelihood

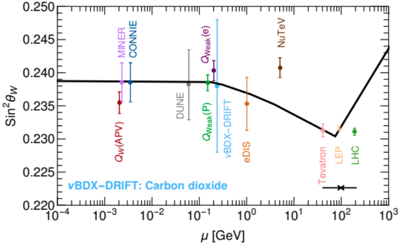
[Aristizabal, De Romeri, Flores, DKP: 2109.03247 [hep-ph]]

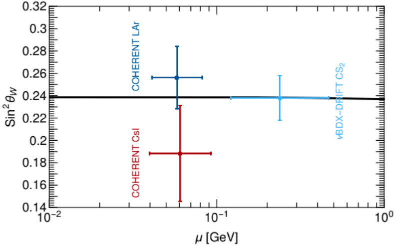
$$\mathcal{L}(m_\chi, \sigma_{\chi-n}, \Phi, \mathcal{P}) = \prod_{i=1}^{n_{\text{bins}}} P(N^i_{\text{Exp}}, N^i_{\text{Obs}}) \times \boxed{G(\mathcal{P}_i, \mu_{\mathcal{P}_i}, \sigma_{\mathcal{P}_i})} \times \prod_{\alpha=1}^{n_\nu} G(\phi_\alpha, \mu_\alpha, \sigma_\alpha)$$

- Poisson distribution $P(k,\lambda) = \frac{\lambda^k e^{-\lambda}}{k!}$
- Gauss distribution $G(x,\mu,\sigma^2) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}$
- $N^i_{\text{Exp}} = N^i_\nu(\Phi_\alpha, \mathcal{P}_i)$
- $N^i_{\text{Obs}} = \sum_\alpha N^i_\nu(\Phi_\alpha, \mathcal{P}_i) + N^i_W(\mathcal{P}_i)$
- $\lambda(0) = \frac{\mathcal{L}_0}{\mathcal{L}_1}$ where $\mathcal{L}_0$ is the minimized function
- statistical significance: $\mathcal{Z} = \sqrt{-2 \ln \lambda(0)}$.
  e.g. $\mathcal{Z} = 3$ corresponds to 90% C.L.

Parameter ($\mathcal{P}$)	Normalization (μ)	Uncertainty
R_n	4.78 fm	10%
$\sin^2\theta_W$	0.2387	10%

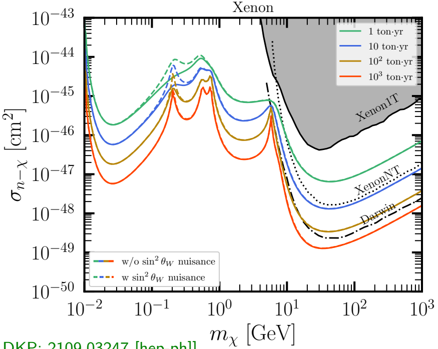
Neutrino floor: SM uncertainties (weak mixing angle)





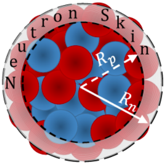
[Aristizabal et al. PRD 104 (2021)]

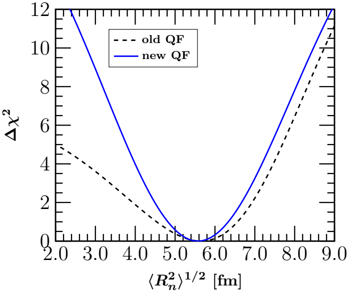
- $\mathcal{Q}_W = (\frac{1}{2} - 2\sin^2\theta_W)Z - \frac{1}{2}N$
- assume 10% uncertainty
- vary around the central value: $\sin^2\theta_W = 0.2387$



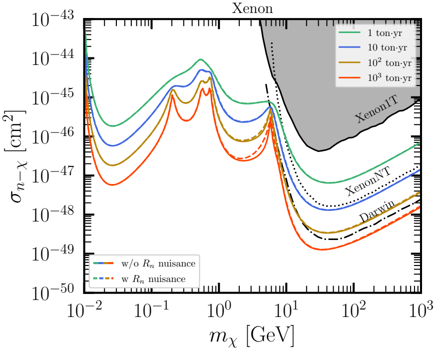
[Aristizabal, De Romeri, Flores, DKP: 2109.03247 [hep-ph]]

Neutrino floor: SM uncertainties (nuclear physics)





[DKP: PRD 102 (2020)]



Helm form factor

$$F(q^2) = 3\frac{j_1(qR_0)}{qR_0}\, e^{-\frac{1}{2}(qs)^2}$$

- use $R_p = 4.78$ fm (fixed)
- vary around $R_n = 4.78$ fm (central value)
- assume 10% uncertainty on R_n

- $R_0 = \sqrt{\frac{5}{3}\left(R_X^2 - 3s^2\right)}$
- $s = 0.9$ fm

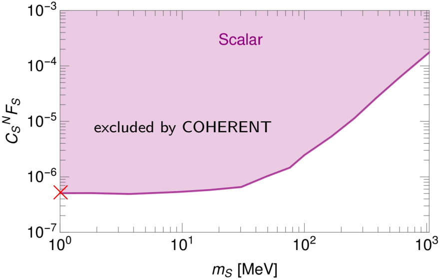
[Aristizabal, De Romeri, Flores, DKP: 2109.03247 [hep-ph]]

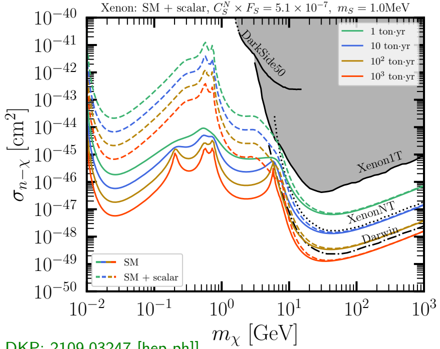
A new scalar boson mediating CEvNS ?

$$\frac{d\sigma_S}{dE_r} = \frac{G_F^2}{2\pi} m_N \mathcal{Q}_S^2 \frac{m_N E_r}{2E_\nu^2} F^2(q^2)$$ [Cerdeno et al. JHEP 05 (2016)]

scalar charge: $$\mathcal{Q}_S = \frac{C_S^N F_S}{G_F(2m_N E_r + m_S^2)}$$

[Aristizabal et al. JHEP 12 (2019)]





[Aristizabal, De Romeri, Flores, DKP: 2109.03247 [hep-ph]]

Neutrino floor: uncertainties beyond the SM (II)

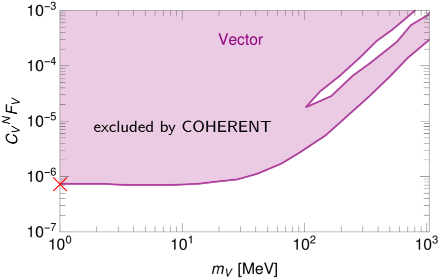
A new vector boson mediating CEvNS ?

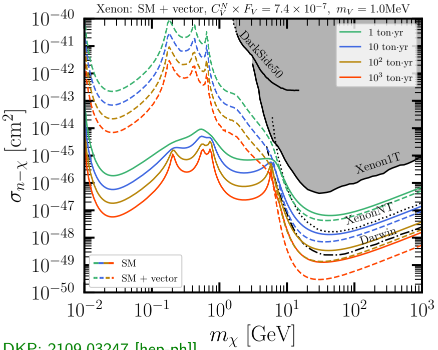
$$\frac{d\sigma}{dE_r} = \frac{m_N G_F}{2\pi} \mathcal{Q}_V^2 \left(2 - \frac{m_N E_r}{E_\nu^2}\right) F^2(q)$$

[Cerdeno et al. JHEP 05 (2016)]

vector charge: $$\mathcal{Q}_V = \mathcal{Q}_W + \frac{C_V^N F_V}{\sqrt{2} G_F (2 m_N E_r + m_V^2)}$$

[Aristizabal et al. JHEP 12 (2019)]





[Aristizabal, De Romeri, Flores, DKP: 2109.03247 [hep-ph]]

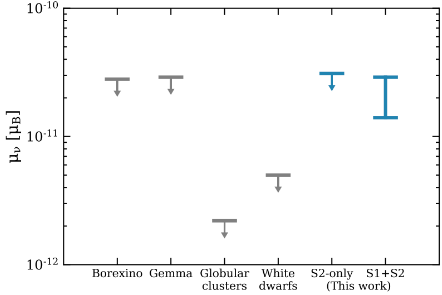
Electromagnetic neutrino properties

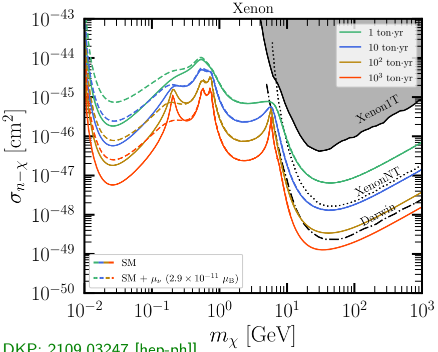
$$\frac{d\sigma_\gamma}{dE_r} = \pi\alpha_{\rm em}^2\, Z^2 \frac{\mu_{\rm eff}^2}{m_e^2}\left(\frac{1}{E_r} - \frac{1}{E_\nu}\right) F^2(q^2)$$

[Vogel, Engel et al. PRD 39 (1989)]

magnetic moment: μ_ν

[XENON collab. PRD 102 (2020)]

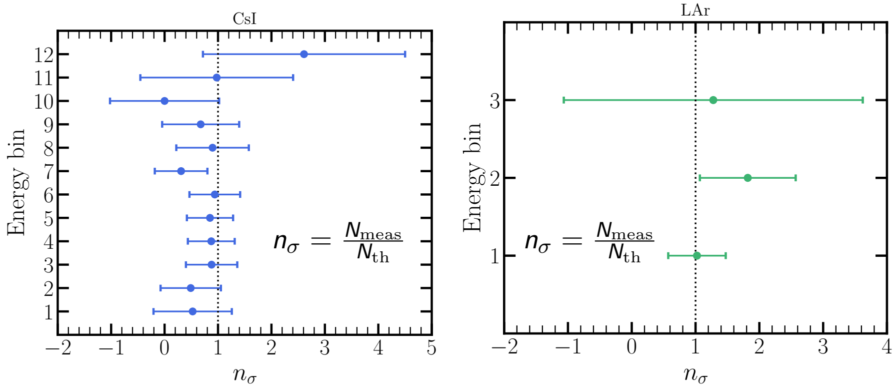




[Aristizabal, De Romeri, Flores, DKP: 2109.03247 [hep-ph]]

Neutrino floor: data-driven analysis

Utilize the measured CEνNS cross section with its uncertainty

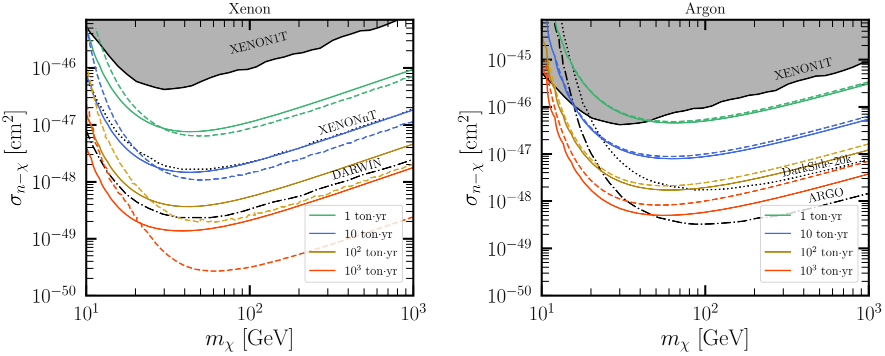


- **what?** extract the CEνNS cross section central values & standard deviations
- **how?** weigh the theoretical SM value of the CEνNS differential cross section with a multiplicative factor *i.e.* $\sigma^i_{\rm meas} = n^i_\sigma \sigma^i_{\rm th}$ and use a spectral χ^2 fit
- **why?** all possible uncertainties that the cross section can involve–independently of assumption–are encoded.

[Aristizabal, De Romeri, Flores, DKP: 2109.03247 [hep-ph]]

Neutrino floor: data-driven analysis

Utilize the measured CEνNS cross section with its uncertainty



- **analysis of CsI data:** WIMP discovery limits improve compared to the SM expectation (solid curves).
  The measured CEνNS cross section (central values) is smaller than the SM expectation, thus resulting in a background depletion.
- **analysis of LAr data:** Results behave differently.

[Aristizabal, De Romeri, Flores, DKP: 2109.03247 [hep-ph]]

Summary

WIMP searches at next generation direct dark matter detection experiments require a precise understanding of WIMP discovery limits

Revisited the neutrino floor exploiting actual data and considering subdominant uncertainties of the SM and new physics scenarios

On top of the usual uncertainties in the solar, atmospheric and DSN neutrino spectra, we considered the effects of:

- COHERENT data
- SM uncertainties: nuclear form factor and weak mixing angle
- New physics uncertainties (vector/scalar mediators and neutrino magnetic moment)

Thank you for your attention !

Extras

Extracting the cross sections from COHERENT data

For the case of CsI we adopt the χ^2 function

$$\chi_i^2 = \left[\frac{N_{\mathrm{exp}}^i - (1+\alpha) N_{\mathrm{meas}}^i(n_\sigma^i) - (1+\beta) B_{0\mathrm{n}}^i}{\sqrt{N_{\mathrm{exp}}^i + B_{0\mathrm{n}}^i + 2B_{\mathrm{ss}}^i}} \right]^2 + \left(\frac{\alpha}{\sigma_\alpha} \right)^2 + \left(\frac{\beta}{\sigma_\beta} \right)^2$$

For the case of LAr, we use

$$\chi_i^2 = \frac{\left(N_{\mathsf{exp}}^i - \alpha N_{\mathrm{meas}}^i(n_\sigma^i) - \beta B_{\mathrm{PBRN}}^i - \gamma B_{\mathrm{LBRN}}^i\right)^2}{\left(\sigma_{\mathrm{exp}}^i\right)^2 + \left[\sigma_{\mathrm{BRNES}}\left(B_{\mathrm{PBRN}}^i + B_{\mathrm{LBRN}}^i\right)\right]^2} + \left(\frac{\alpha - 1}{\sigma_\alpha}\right)^2 + \left(\frac{\beta - 1}{\sigma_\beta}\right)^2 + \left(\frac{\gamma - 1}{\sigma_\gamma}\right)^2.$$