# New physics directions from CEvNS

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# Outline

1. CEvNS implications to WIMP searches
    - The Neutrino floor
        - uncertainties in CEvNS cross section
        - data-driven analysis using COHERENT results
2. Axion-like particles (ALPs) @ CEvNS experiments
    - Photon flux
    - Production mechanisms and ALP flux
    - Sensitivities
3. Summary

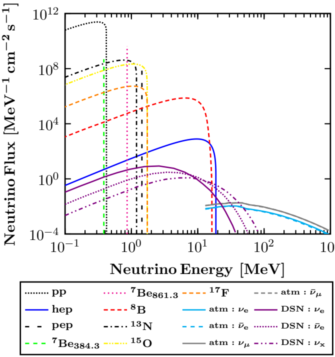
# CEvNS implications to WIMP searches

# Neutrino backgrounds at direct dark matter detection experiments

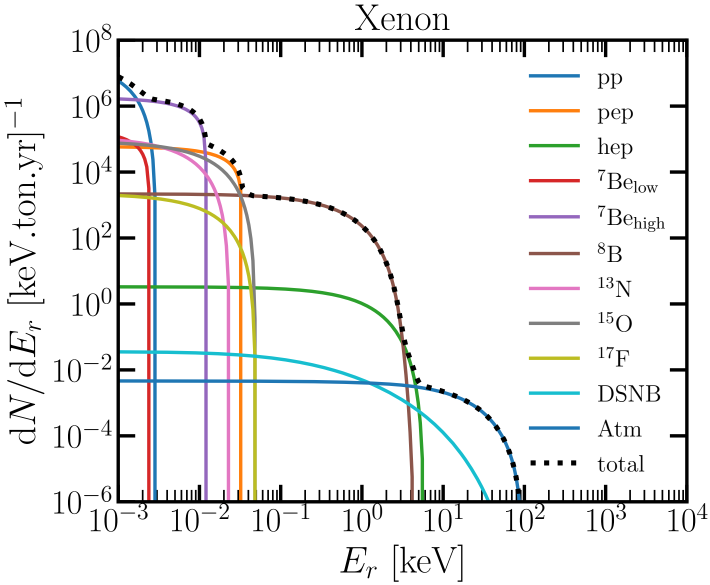
## Irreducible background

- **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]

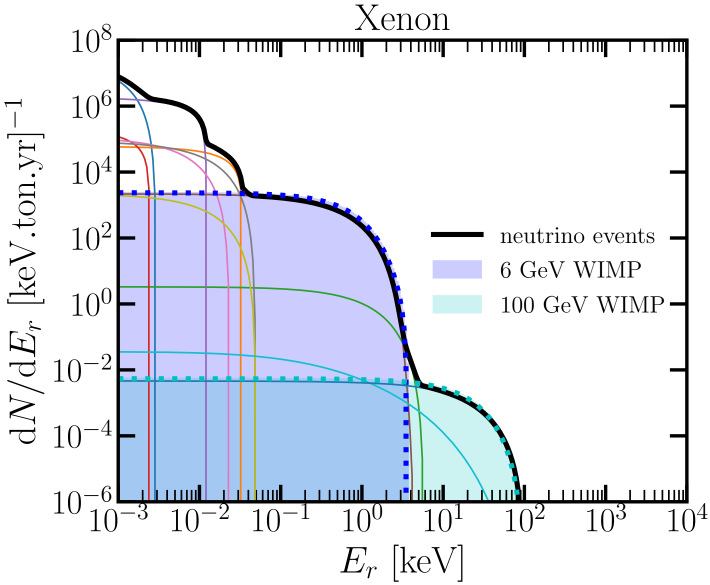
| Type | $E_{\nu_{\max}}$ [MeV] | Flux $[\mathrm{cm}^{-2}\mathrm{s}^{-1}]$ |
|---|---|---|
| *pp* | 0.423 | $(5.98 \pm 0.006) \times 10^{10}$ |
| *pep* | 1.440 | $(1.44 \pm 0.012) \times 10^{8}$ |
| *hep* | 18.784 | $(8.04 \pm 1.30) \times 10^{3}$ |
| $^7\mathrm{Be}_{\mathrm{low}}$ | 0.3843 | $(4.84 \pm 0.48) \times 10^{8}$ |
| $^7\mathrm{Be}_{\mathrm{high}}$ | 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 | $(5.52 \pm 0.17) \times 10^{6}$ |



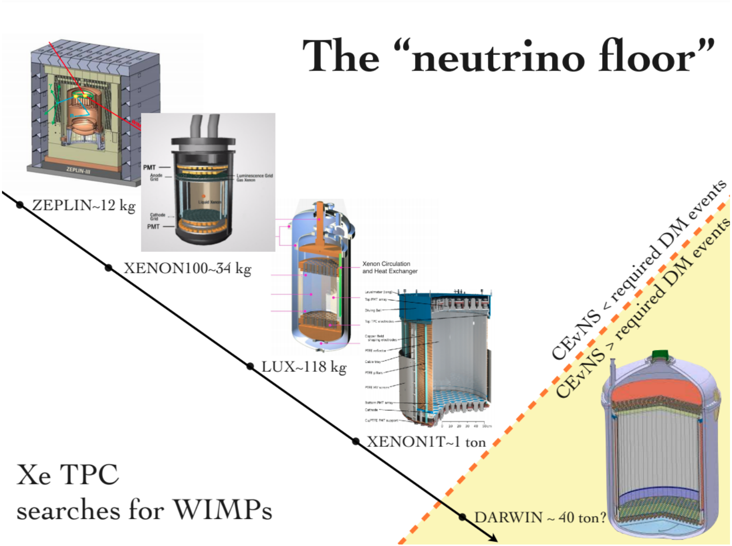
# CEvNS events @ dark matter direct detection exps



# CEvNS vs. WIMP events



# The neutrino floor



## The “neutrino floor”

ZEPLIN~12 kg

XENON100~34 kg

LUX~118 kg

XENON1T~1 ton

DARWIN ~ 40 ton?

CEvNS < required DM events

CEvNS > required DM events

Xe TPC
searches for WIMPs

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

# Statistical analysis

**Likelihood**

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

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

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- $\lambda(0) = \frac{\mathcal{L}_0}{\mathcal{L}_1}$ 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.

**Discovery limit:** smallest WIMP cross section for which a given experiment has a 90% probability of detecting a WIMP signal at $\geq 3\sigma$.

**Profile likelihood ratio:** test against the null hypothesis $H_0$ (CEvNS background only) vs. the alternative hypothesis $H_1$ (WIMP signal + CEvNS background).

# Statistical analysis

## introducing new nuisances

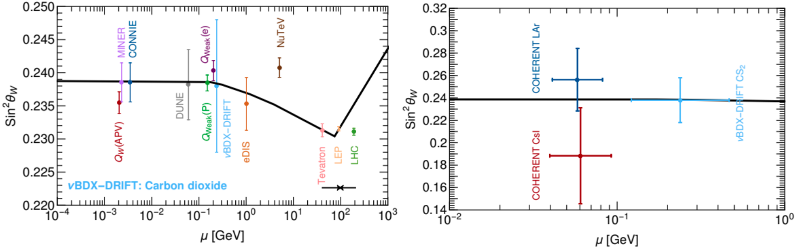
[Aristizabal, De Romeri, Flores, DKP: JCAP 01 (2022) 055]

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

- Poisson distribution $P(k, \lambda) = \frac{\lambda^k e^{-\lambda}}{k!}$
- Gauss distribution $G(x, \mu, \sigma^2) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}$
- $N^i_{\rm Exp} = N^i_\nu(\Phi_\alpha, \mathcal{P}_i)$
- $N^i_{\rm Obs} = \sum_\alpha N^i_\nu(\Phi_\alpha, \mathcal{P}_i) + N^i_W(\mathcal{P}_i)$
- $\lambda(0) = \frac{\mathcal{L}_0}{\mathcal{L}_1}$ 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.

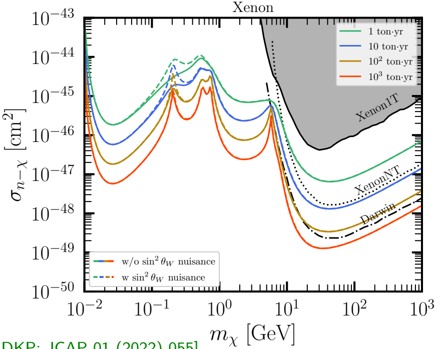
| Parameter ($\mathcal{P}$) | Normalization ($\mu$) | Uncertainty |
|---|---|---|
| $R_n$ | 4.78 fm | 10% |
| $\sin^2\theta_W$ | 0.2387 | 10% |

# Neutrino floor: SM uncertainties (weak mixing angle)



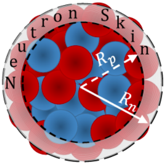
[Aristizabal et al. PRD 104 (2021)]

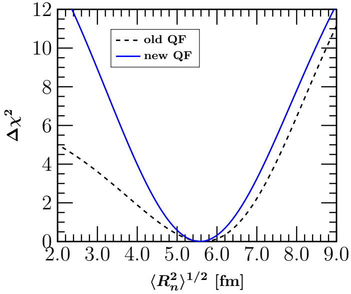
- $\mathcal{Q}_W = (\frac{1}{2} - 2\sin^2\theta_W)Z - \frac{1}{2}N$
- assume 10% uncertainty
- vary around the central value: $\sin^2\theta_W = 0.2387$



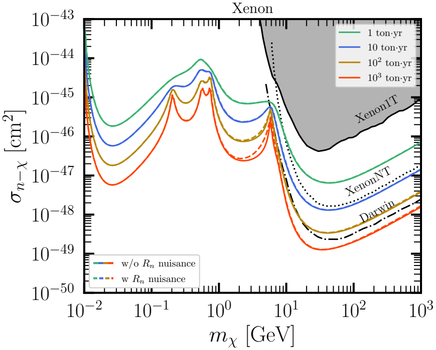
[Aristizabal, De Romeri, Flores, DKP: JCAP 01 (2022) 055]

# 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: JCAP 01 (2022) 055]

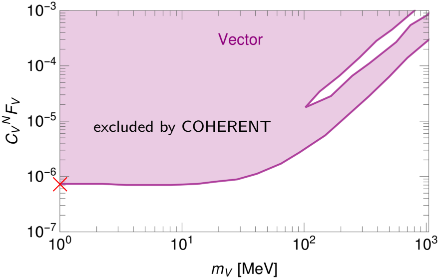
# Neutrino floor: uncertainties beyond the SM

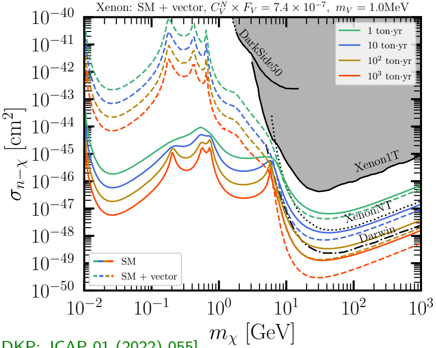
## A new vector boson mediating CEvNS ?

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

[Cerdeno et al. JHEP 05 (2016)]

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

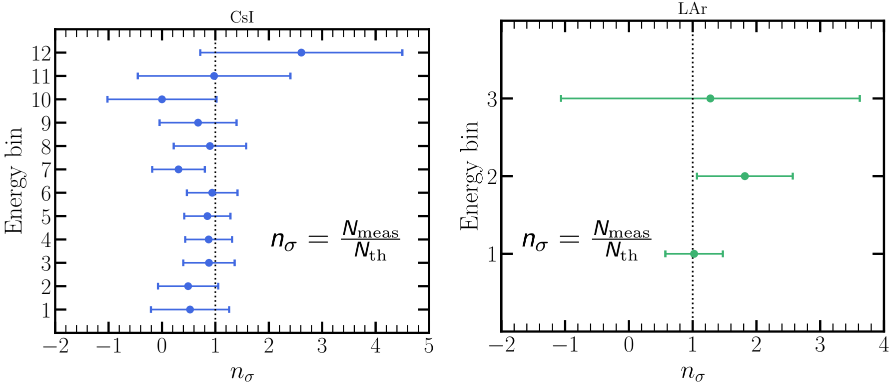

[Aristizabal et al. JHEP 12 (2019)]



[Aristizabal, De Romeri, Flores, DKP: JCAP 01 (2022) 055]

# Neutrino floor: data-driven analysis

**Utilize the measured CE$\nu$NS cross section with its uncertainty**

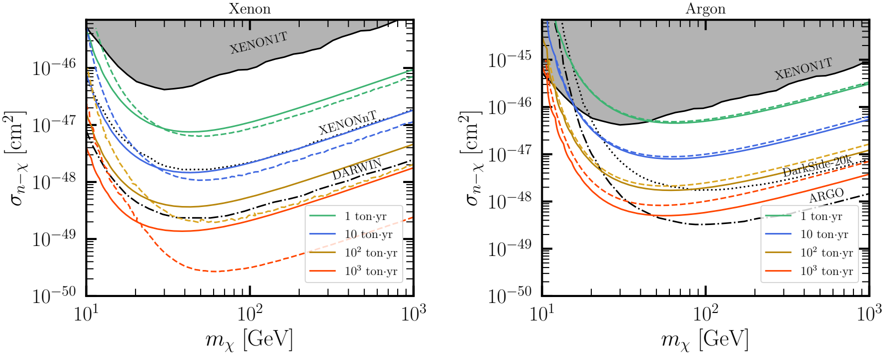


- **what?** extract the CE$\nu$NS cross section central values & standard deviations
- **how?** weigh the theoretical SM value of the CE$\nu$NS differential cross section with a multiplicative factor *i.e.* $\sigma^i_{\text{meas}} = n^i_\sigma \sigma^i_{\text{th}}$ and use a spectral $\chi^2$ fit
- **why?**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

[Aristizabal, De Romeri, Flores, DKP: JCAP 01 (2022) 055]

# Neutrino floor: data-driven analysis

**Utilize the measured CE$\nu$NS cross section with its uncertainty**



- **analysis of CsI data:** WIMP discovery limits improve compared to the SM expectation (solid curves).
  The measured CE$\nu$NS 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: JCAP 01 (2022) 055]

# ALPs @ CEvNS experiments

# ALP motivations

**Axions:** *Nambu-Goldstone bosons from the breaking of a color anomalous global chiral U(1) symmetry which is spontaneously broken in the vacuum.*

[Peccei & Quinn, PRL 38 (1977) 1440], [Weinberg, PRL 40 (1978) 223], [Wilczek, PRL 40 (1978) 279]

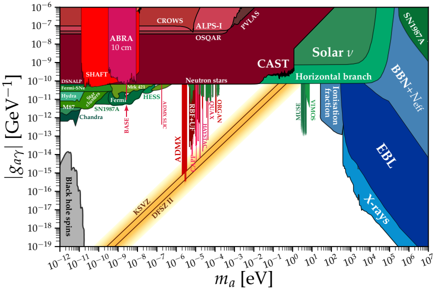
- solution to the strong CP problem
- dark matter candidate
- $m_a$ and $f_a$ are related → $m_a = 5.7\left(10^{12}\mathrm{GeV}/f_a\right)\mu\mathrm{eV}$

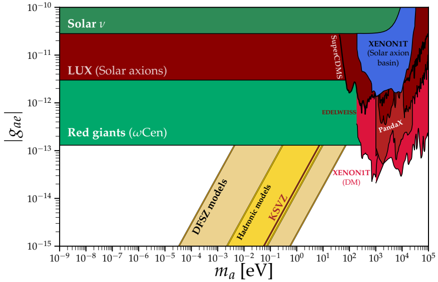
**Axion-like particles (ALPs):** *Pseudo Nambu-Goldstone bosons of spontaneously broken global symmetries.*

- Lepton symmetry: Majoron [Chikashige et. al, PLB 98 (1981) 2651981]
- Family symmetry: Familon [Wilczek, PRL 49 (1982) 1549]
- Flavor symmetry: Flavon
- $m_a$ and $f_a$ are not related → mass does not arise from QCD effects

# Current status of ALP-related experimental searches

- **helioscopes** (CAST) & **haloscopes** (Abracadabra, ADMX, CASPEr...)
- **interferometry** (ADBC, DANCE) & **polarization exps** (PVLAS)
- **beam dump** & **fixed target** experiments (FASER, LDMX, NA62, NA64..)
- **colliders** & **dark matter DD** experiments (XENON, LUX, CDMS..)
- **astrophysical observations** (Stellar energy-losses)





plots from: C. O'Hare (`https://github.com/cajohare/AxionLimits`)

10.5281/zenodo.3932430 and references therein

**Our goal:** Explore ALPs in view of reactor neutrino experiments via nuclear and electron recoil measurements [Dent et al. PRL. 124 (2020) 21, 211804]

# Nuclear reactors utilized as a high intensity photon flux

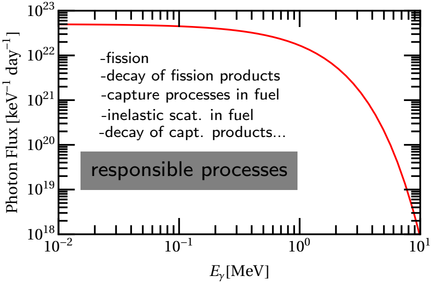
## Continuous $\gamma$-flux

$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{5.8\times 10^{17}}{\mathrm{MeV}\cdot\mathrm{sec}}\left(\frac{P}{\mathrm{MW}}\right) e^{-1.1\,E_\gamma/\mathrm{MeV}}$$

- P: reactor power in MW

[Bechteler et al., Technical Report, Inst. fuer Kernphysik (1984)]

Reactor Power P=1 GW

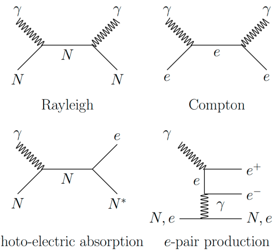


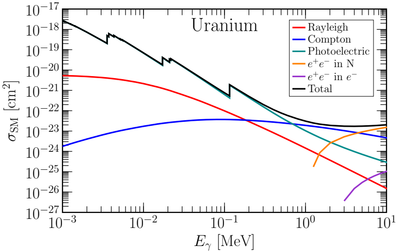
-fission
-decay of fission products
-capture processes in fuel
-inelastic scat. in fuel
-decay of capt. products...

responsible processes

## SM $\gamma$-fuel interactions

[https://physics.nist.gov/PhysRefData/Xcom/html/xcom1.html]



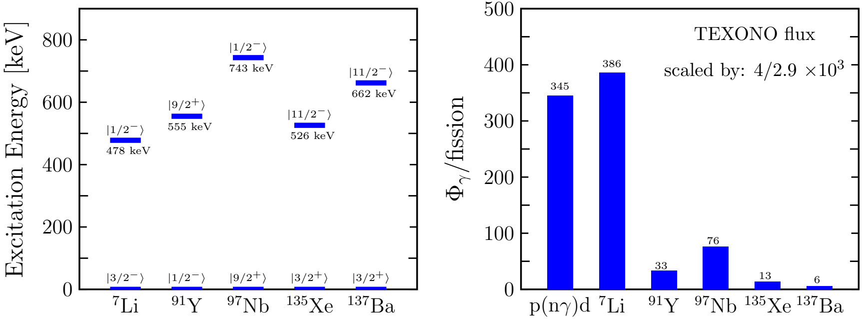


**a fraction of these photons can be converted into ALPs**

# Nuclear reactors utilized as a high intensity photon flux

## Monochromatic $\gamma$-flux from nuclear transitions

TEXONO Collab., Phys. Rev. D 75 (2007) 052004



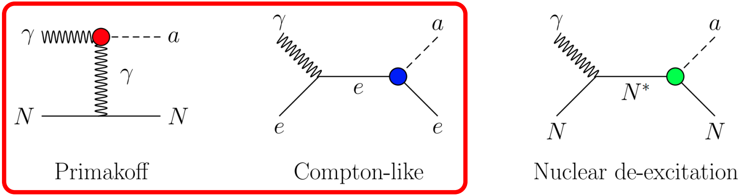
- (mainly) M1 transition from the excited state to the ground state of $^7$Li
- M4 transitions from the excited to the ground state of $^{91}$Y, $^{97}$Nb, $^{135}$Xe and $^{137}$Ba
- thermal neutron capture on proton in the cooling water, $\mathrm{p} + \mathrm{n} \to \mathrm{d} + \gamma$. The deuteron ground state has magnetic dipole and electric quadrupole moments, the emitted $\gamma$ is therefore mainly M1

**a fraction of these photons can be converted into ALPs**

# ALP production mechanisms

Phenomenological parametrization via up to dim-5 effective operators

$$\mathcal{L} = -\frac{1}{4} g_{a\gamma\gamma}\, aF_{\mu\nu}\widetilde{F}^{\mu\nu} - i g_{aee}\, a\, \bar{e}\gamma_5 e - ia\bar{n}\gamma_5 \left( g_{ann}^{(0)} + \tau_3 g_{ann}^{(1)} \right) n$$



## Continuous ALP flux

$$\frac{d\Phi_a^{\mathrm{P}}}{dE_a} = \mathcal{P}_{\mathrm{surv}} \int_{E_{\gamma'},\mathrm{min}}^{E_{\gamma'},\mathrm{max}} \frac{1}{\sigma_{\mathrm{Tot}}} \frac{d\sigma_{\mathrm{ALP}}^{\mathrm{prod}}}{dE_a}(E_{\gamma'}, E_a) \frac{d\Phi_{\gamma'}}{dE_{\gamma'}}\, dE_{\gamma'} \ , \quad \text{with} \quad \sigma_{\mathrm{Tot}} = \sigma_{\mathrm{SM}} + \sigma_{\mathrm{ALP}}^{\mathrm{prod}}$$

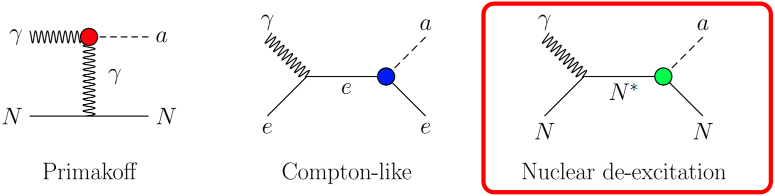
[Dent et al. PRL. 124 (2020) 21, 211804]

- Survival probability, assuring that the ALP flux reaches the detector: $\mathcal{P}_{\mathrm{surv}} = e^{-LE_a/|\vec{p}_a|\tau}$
- $L$: distance between the reactor and detector
- $\tau$: ALP lifetime in the fixed target frame

# ALP production mechanisms

Phenomenological parametrization via up to dim-5 effective operators

$$\mathcal{L} = -\frac{1}{4}\, g_{a\gamma\gamma}\, aF_{\mu\nu}\widetilde{F}^{\mu\nu} - i g_{aee}\, a\, \bar{e}\gamma_5 e - i a\bar{n}\gamma_5 \left(g_{ann}^{(0)} + \tau_3 g_{ann}^{(1)}\right) n$$

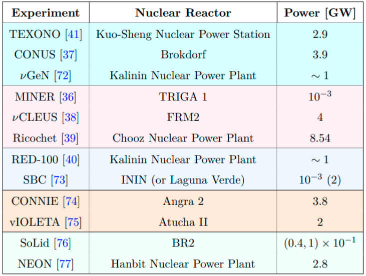


## Monochromatic ALP flux for the $i-$th transition

$$\left(\frac{\mathrm{d}\Phi_a^{\mathrm{MT}}}{\mathrm{d}E_a}\right)_i = \phi_a^i\, \delta(E_{\gamma'} - E_a) = R_f \Phi_\gamma^i \left(\frac{\Gamma_a}{\Gamma_\gamma}\right)_i \mathcal{P}_{\mathrm{surv}}\, \delta(E_{\gamma'} - E_a) \qquad (i = \mathrm{p(n,\gamma)d},\ \mathrm{M}J)\ ,$$

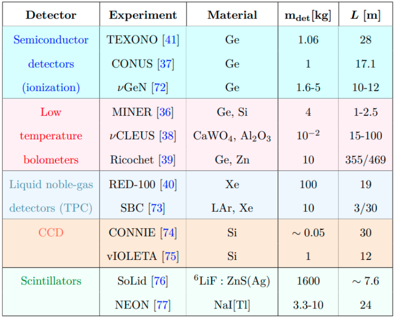
- fission rate: $R_f$
- photon flux per fission: $\Phi_\gamma^i$
- branching ratio of ALP to photon emission in the nuclear transitions: $\left(\frac{\Gamma_a}{\Gamma_\gamma}\right)_i$

# Typical ALP fluxes from a nuclear reactor



| Experiment | Nuclear Reactor | Power [GW] |
|---|---|---|
| TEXONO [41] | Kuo-Sheng Nuclear Power Station | 2.9 |
| CONUS [37] | Brokdorf | 3.9 |
| $\nu$GeN [72] | Kalinin Nuclear Power Plant | $\sim 1$ |
| MINER [36] | TRIGA 1 | $10^{-3}$ |
| $\nu$CLEUS [38] | FRM2 | 4 |
| Ricochet [39] | Chooz Nuclear Power Plant | 8.54 |
| RED-100 [40] | Kalinin Nuclear Power Plant | $\sim 1$ |
| SBC [73] | ININ (or Laguna Verde) | $10^{-3}$ (2) |
| CONNIE [74] | Angra 2 | 3.8 |
| vIOLETA [75] | Atucha II | 2 |
| SoLid [76] | BR2 | $(0.4, 1) \times 10^{-1}$ |
| NEON [77] | Hanbit Nuclear Power Plant | 2.8 |

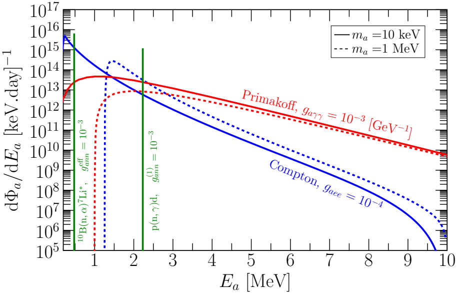
[Aristizabal, De Romeri, Flores, DKP, JHEP 03 (2021) 294]



| Detector | Experiment | Material | $m_{\rm det}$[kg] | $L$ [m] |
|---|---|---|---|---|
| Semiconductor detectors (ionization) | TEXONO [41] | Ge | 1.06 | 28 |
| | CONUS [37] | Ge | 1 | 17.1 |
| | $\nu$GeN [72] | Ge | 1.6-5 | 10-12 |
| Low temperature bolometers | MINER [36] | Ge, Si | 4 | 1-2.5 |
| | $\nu$CLEUS [38] | $CaWO_4$, $Al_2O_3$ | $10^{-2}$ | 15-100 |
| | Ricochet [39] | Ge, Zn | 10 | 355/469 |
| Liquid noble-gas detectors (TPC) | RED-100 [40] | Xe | 100 | 19 |
| | SBC [73] | LAr, Xe | 10 | 3/30 |
| CCD | CONNIE [74] | Si | $\sim 0.05$ | 30 |
| | vIOLETA [75] | Si | 1 | 12 |
| Scintillators | SoLid [76] | $^6$LiF : ZnS(Ag) | 1600 | $\sim 7.6$ |
| | NEON [77] | NaI[Tl] | 3.3-10 | 24 |

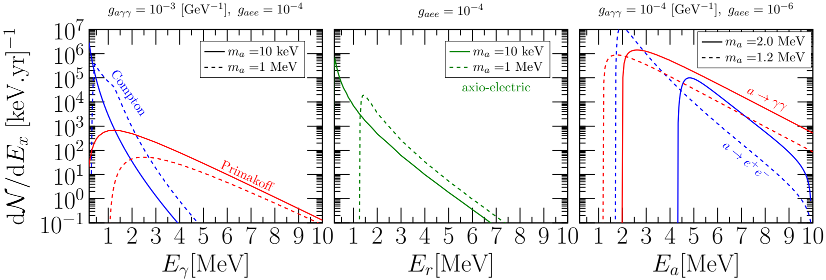
## Typical reactor

- $P = 4$ GW
- $L = 10$ m



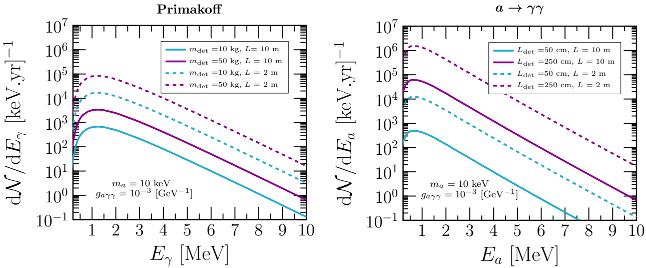
# Number of events

## varying the ALP mass



[Aristizabal, De Romeri, Flores, DKP, JHEP 03 (2021) 294]

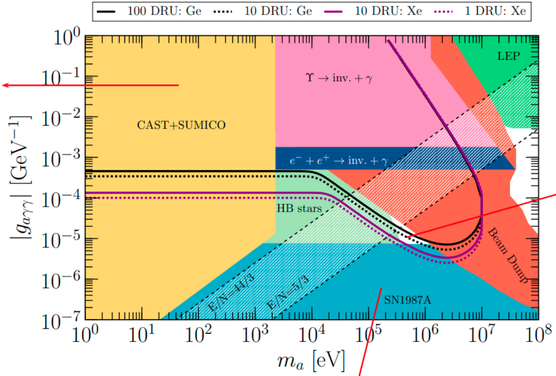
## varying the detector specifications



# Probing the $g_{a\gamma\gamma}$ coupling

## Assumed detector specifications: current vs. future

| P[GW] | PM | TM | $m_{\text{det}}$[kg] | $L$[m] | $L_{\text{det}}$[cm] | bkg [1/keV/day/kg] |
|---|---|---|---|---|---|---|
| 4 | $^{235}$U | Ge | 10 | 10 | 50 | 10–100 |
| 8 | $^{235}$U | Xe | $10^3$ | 10 | 140 | 1–10 |



Test of medium effects

Test ΛCDM hypotheses

Test of ALP effects in $\nu$ emission

[Aristizabal, De Romeri, Flores, DKP, JHEP 03 (2021) 294]

# Summary

## CEvNS implications to WIMP searches

- 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

## Reactor experiments can be used as ALP factories:

- extend the physics reach of reactor neutrino programmes
- probe ALPs with $m_a \leq 10$ MeV utilizing their intense photon flux
- complementary information on ALPs in the low-energy frontier

Thank you for your attention !

# The End
# Extras

# 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)]

- $\rho_0 = 0.3 \ \mathrm{GeV/cm^2}$ 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
- $m_\chi$: 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)

# ALP production cross sections

## $g_{a\gamma\gamma}$ coupling

- Primakoff scattering: $\gamma + N \to a + N$ [Aloni et al. PRL 123 (2019) 7, 071801]

$$\frac{\mathrm{d}\sigma^{\mathrm{prod}}_{\mathrm{Prim}}}{\mathrm{d}t} = 2\alpha Z^2 F^2(t)\, g^2_{a\gamma\gamma}\, \frac{M_N^4}{t^2(M_N^2 - s)^2(t - 4M_N^2)^2} \left\{ m_a^2 t(M_N^2 + s) - m_a^4 M_N^2 - t\left[(M_N^2 - s)^2 + st\right] \right\}$$

Primakoff scattering: $E_\gamma \simeq E_a$ photon energy is coherently converted into ALP energy

## $g_{aee}$ coupling

- Compton-like scattering: $\gamma + e^- \to a + e^-$ [Brodsky et al. PRL 56 (1986) 1763]

$$\frac{\mathrm{d}\sigma^{\mathrm{prod}}_{\mathrm{Compt}}}{\mathrm{d}E_a} = \frac{Z\pi g^2_{aee}\alpha x}{4\pi(s - m_e^2)(1 - x)E_{\gamma'}} \left[ x - \frac{2m_a^2 s}{(s - m_e^2)^2} + \frac{2m_a^2}{(s - m_e^2)^2}\left(\frac{m_e^2}{1 - x} + \frac{m_a^2}{x}\right)\right],$$

where $x = 1 - \frac{E_a}{E_{\gamma'}} + \frac{m_a^2}{2E_{\gamma'} m_e}$.

# ALP production from MJ transitions

## $g_{ann}$ coupling

- neutron capture isovector $M1$ transitions (pn→ d$\gamma$) depend only on kinematics

$$\left(\frac{\Gamma_a}{\Gamma_\gamma}\right)_{\text{pn}} = \frac{1}{2\pi\alpha}\left(\frac{|\vec{p}_a|}{|\vec{p}_\gamma|}\right)^3 \left(\frac{g_{ann}^{(1)}}{\mu_1}\right)^2 ,$$

[Barroso, Mukhopadhyay, PRC C24 (1981) 2382]

- M$J$ transitions are nuclear structure dependent

$$\left(\frac{\Gamma_a}{\Gamma_\gamma}\right)_{\text{M}J} = \frac{1}{\pi\alpha}\left(\frac{1}{1+\delta^2}\right)\left(\frac{J}{J+1}\right)\left(\frac{|\vec{p}_a|}{|\vec{p}_\gamma|}\right)^{2J+1}\left(\frac{g_{ann}^{(0)}\kappa + g_{ann}^{(1)}}{(\mu_0 - 1/2)\kappa + (\mu_1+\eta)}\right)^2 .$$

- Isovector magnetic moment: $\mu_1 = \mu_p - \mu_n = 4.71\ \mu_{\rm N}$
- Isosinglet magnetic moment: $\mu_0 = \mu_p + \mu_n = 0.88\ \mu_{\rm N}$
- $\delta,\ \eta,\ \kappa$ are nuclear structure dependent

  [TEXONO collab., PRD 75 (2007) 052004]

  [Avignone III et al., PRD 35 (1987) 2752]

# ALP detection cross sections

## $g_{a\gamma\gamma}$ coupling

- inverse Primakoff scattering: $a + N \to \gamma + N$
  same as the production cross section but a factor 2 larger due to spin

## $g_{aee}$ coupling

- inverse Compton-like scattering: $a + e^- \to \gamma + e^-$ [Avignone et al. PRD 37 (1988) 618-630]

$$\frac{d\sigma^{\text{det}}_{\text{Compt}}}{dE_\gamma} = \frac{Z g_{aee}^2 \alpha E_\gamma}{4 m_e^2 |\vec{p}_a|} \left| \frac{2(E_a + m_e - |\vec{p}_a| \cos\theta)^2}{|\vec{p}_a| y} \right| \times \left( 1 + \frac{4 m_e^2 E_\gamma^2}{y^2} - \frac{4 m_e E_\gamma}{y} - \frac{4 m_a^2 |\vec{p}_a|^2 m_e E_\gamma (1 - \cos^2\theta)}{y^3} \right), \qquad y = 2 m_e E_a + m_a^2$$

- axio-electric cross section: $a + e^- + Z \to e^- + Z$ [Derevianko et al. PRD 82 (2010) 065006]

$$\sigma^{\text{det}}_{\text{axioel}} = \frac{g_{aee}^2}{\beta} \frac{3 E_a^2}{16 \pi \alpha m_e^2} \left( 1 - \frac{\beta^{2/3}}{3} \right) \sigma_{\text{PE}}\,, \qquad \beta = |\vec{p}_a| / E_a$$

# ALP decays

## $g_{a\gamma\gamma}$ **coupling**

- ALP diphoton decay:

$$\Gamma_{a\to 2\gamma} \equiv \Gamma(a \to \gamma\gamma) = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}$$

## $g_{aee}$ **coupling**

- ALP decay to electron pair:

$$\Gamma_{a\to e^+e^-} = \frac{g_{aee}^2 m_a}{8\pi}\sqrt{1 - 4\frac{m_e^2}{m_a^2}}$$

# Number of ALP-induced events

**scattering processes**

$$\frac{d\mathcal{N}_X^{\text{scatt}}}{dE_a} = m_{\text{det}} \frac{N_T \Delta t}{4\pi L^2} \int \frac{d\Phi_a}{dE_a} \frac{d\sigma_X^{\text{det}}}{dE_\gamma}\, dE_\gamma \ , \quad \text{X} = \{\text{Prim., Compt.}\}$$

$$\frac{d\mathcal{N}_{\text{axioel}}}{dE_a} = m_{\text{det}} \frac{N_T \Delta t}{4\pi L^2} \frac{d\Phi_a}{dE_a}\, \sigma_{\text{axioel}}^{\text{det}}(E_\gamma, E_a)$$

**decay processes**

$$\frac{d\mathcal{N}_X^{\text{decay}}}{dE_a} = \frac{\mathcal{A} \Delta t}{4\pi L^2} \frac{d\Phi_a}{dE_a}\, \mathcal{P}_{\text{decay}}^{\text{X}}, \quad \text{X} = \{\text{Prim., Compt.}\}$$

- $P_{\text{decay}}$: probability that the decay occurs within the detector

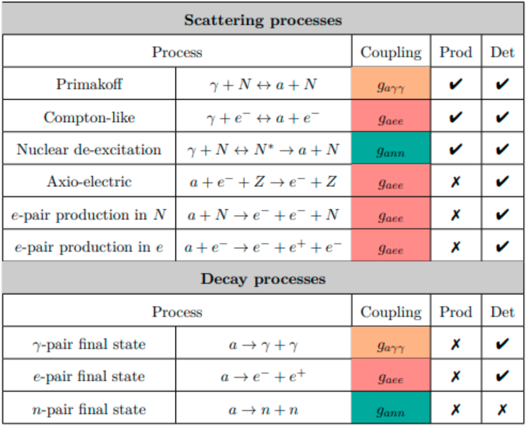
$$\mathcal{P}_{\text{decay}}^{\text{X}} = 1 - e^{-L_{\text{det}} E_a / |\vec{p}_a| \tau_{\text{X}}}$$

- $\mathcal{A} = L_{\text{det}}^2$ denotes the detector transverse area.

[Dent et al. PRL. 124 (2020) 21, 211804]

# Summary

## Summary ALP production and detection mechanisms considered



| **Scattering processes** | | | | |
|---|---|---|---|---|
| Process | | Coupling | Prod | Det |
| Primakoff | $\gamma + N \leftrightarrow a + N$ | $g_{a\gamma\gamma}$ | ✔ | ✔ |
| Compton-like | $\gamma + e^- \leftrightarrow a + e^-$ | $g_{aee}$ | ✔ | ✔ |
| Nuclear de-excitation | $\gamma + N \leftrightarrow N^* \to a + N$ | $g_{ann}$ | ✔ | ✔ |
| Axio-electric | $a + e^- + Z \to e^- + Z$ | $g_{aee}$ | ✗ | ✔ |
| $e$-pair production in $N$ | $a + N \to e^- + e^- + N$ | $g_{aee}$ | ✗ | ✔ |
| $e$-pair production in $e$ | $a + e^- \to e^- + e^+ + e^-$ | $g_{aee}$ | ✗ | ✔ |
| **Decay processes** | | | | |
| Process | | Coupling | Prod | Det |
| $\gamma$-pair final state | $a \to \gamma + \gamma$ | $g_{a\gamma\gamma}$ | ✗ | ✔ |
| $e$-pair final state | $a \to e^- + e^+$ | $g_{aee}$ | ✗ | ✔ |
| $n$-pair final state | $a \to n + n$ | $g_{ann}$ | ✗ | ✗ |

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