Probing axion-like particles with reactor neutrino experiments

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

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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]

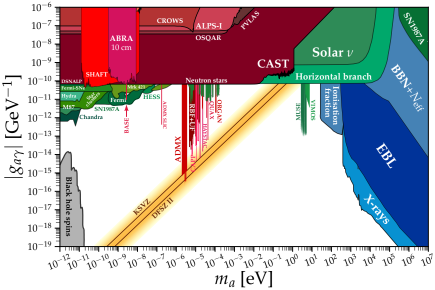
- solution to the strong CP problem
- dark matter candidate
- m_a and f_a are related → $m_a = 5.7 \left(10^{12} \mathrm{GeV}/f_a\right) \mu\mathrm{eV}$

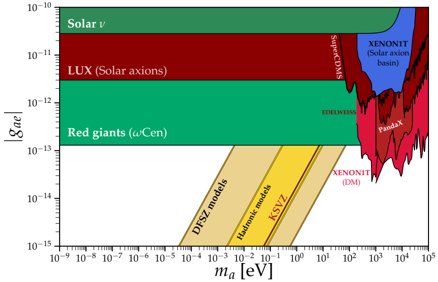
Axion-like particles (ALPs): *Pseudo Nambu-Goldstone bosons of spontaneously broken global symmetries.*

- 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]

ALP production @ nuclear reactors

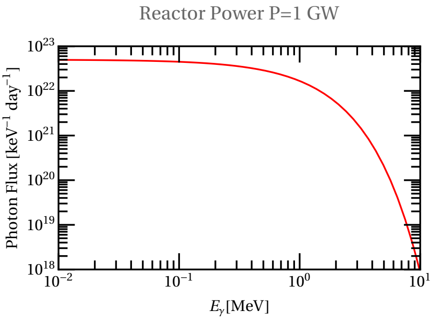
Nuclear reactors utilized as a high intensity photon flux

Photon flux

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

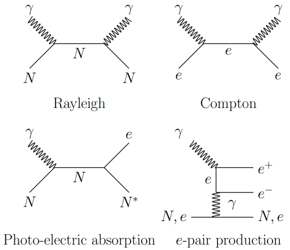
- P: reactor power in MW

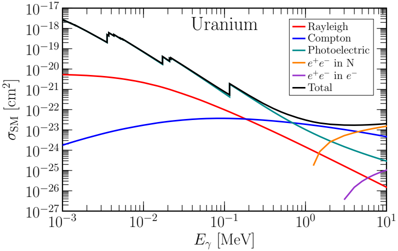
[Bechteler et al., Technical Report, Inst. fuer Kernphysik (1984)]



SM processes

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



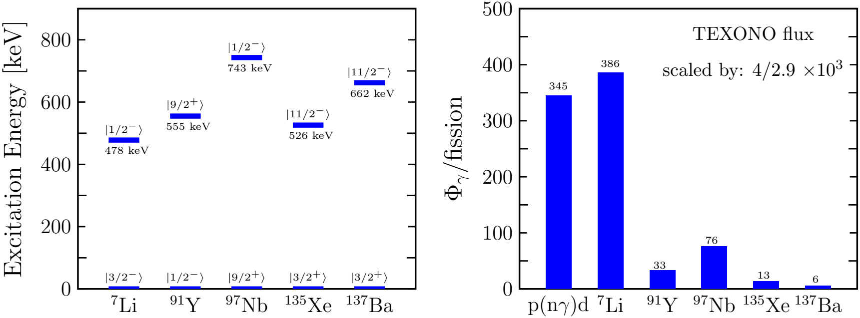


a fraction of these photons can be converted into ALPs

Nuclear reactors utilized as a high intensity photon flux

Photon flux from nuclear transitions

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



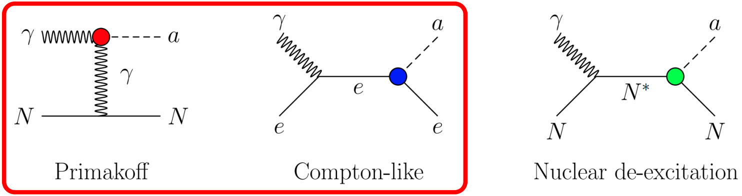
- (mainly) M1 transition from the excited state to the ground state of ^{7}Li
- M4 transitions from the excited to the ground state of ^{91}Y, ^{97}Nb, ^{135}Xe and ^{137}Ba
- thermal neutron capture on proton in the cooling water, $\mathrm{p} + \mathrm{n} \rightarrow \mathrm{d} + \gamma$. The deuteron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

a fraction of these photons can be converted into ALPs

ALP production mechanisms

Phenomenological parametrization via dim-5 effective operators

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



Continuous ALP flux

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

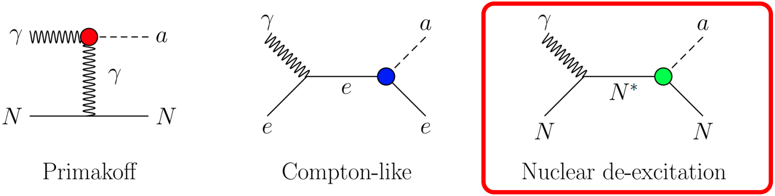
[Dent et al. PRL. 124 (2020) 21, 211804]

- 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
- τ: ALP lifetime in the fixed target frame

ALP production mechanisms

Phenomenological parametrization via 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

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

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

ALP production cross sections

$g_{a\gamma\gamma}$ coupling

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

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

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$\to$ dγ) depend only on kinematics

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

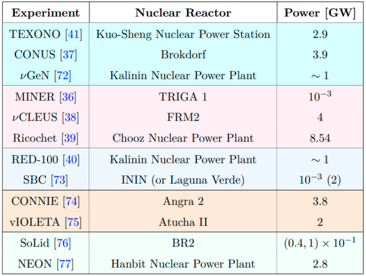
[Barroso, Mukhopadhyay, PRC C24 (1981) 2382]

- MJ transitions are nuclear structure dependent

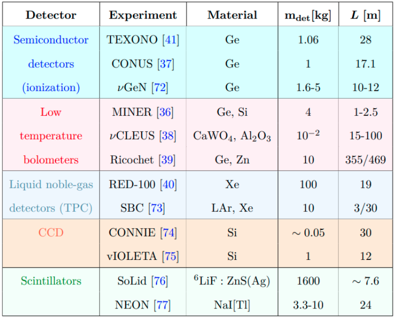
$$\left(\frac{\Gamma_a}{\Gamma_\gamma}\right)_{\mathrm{M}J} = \frac{1}{\pi\alpha}\left(\frac{1}{1+\delta^2}\right)\left(\frac{J}{J+1}\right)\left(\frac{|\vec{p}_a|}{|\vec{p}_\gamma|}\right)^{2J+1}\left(\frac{g_{ann}^{(0)}\kappa + g_{ann}^{(1)}}{(\mu_0 - 1/2)\kappa + (\mu_1 + \eta)}\right)^2 .$$

- Isovector magnetic moment: $\mu_1 = \mu_p - \mu_n = 4.71\ \mu_{\mathrm{N}}$
- Isosinglet magnetic moment: $\mu_0 = \mu_p + \mu_n = 0.88\ \mu_{\mathrm{N}}$
- $\delta,\ \eta,\ \kappa$ are nuclear structure dependent
  [TEXONO collab., PRD 75 (2007) 052004]
  [Avignone III et al., PRD 35 (1987) 2752]

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
νGeN [72]	Kalinin Nuclear Power Plant	~ 1
MINER [36]	TRIGA 1	10^{-3}
νCLEUS [38]	FRM2	4
Ricochet [39]	Chooz Nuclear Power Plant	8.54
RED-100 [40]	Kalinin Nuclear Power Plant	~ 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

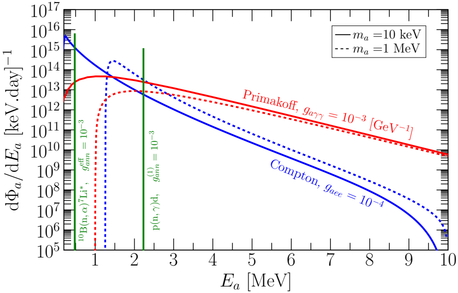


Detector	Experiment	Material	$m_{\rm det}$[kg]	L [m]
Semiconductor detectors (ionization)	TEXONO [41]	Ge	1.06	28
	CONUS [37]	Ge	1	17.1
	νGeN [72]	Ge	1.6-5	10-12
Low temperature bolometers	MINER [36]	Ge, Si	4	1-2.5
	νCLEUS [38]	$CaWO_4$, Al_2O_3	10^{-2}	15-100
	Ricochet [39]	Ge, Zn	10	355/469
Liquid noble-gas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

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

Typical reactor

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



ALP detection

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]

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

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

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

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 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

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

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

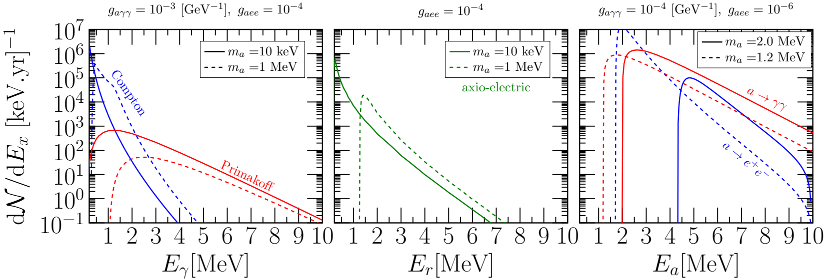
$$\mathcal{P}_{\text{decay}}^X = 1 - e^{-L_{\text{det}} E_a / |\vec{p}_a| \tau_X}$$

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

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

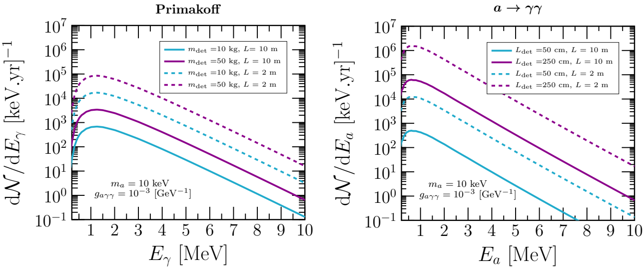
Number of events

varying the ALP mass



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

varying the detector specifications

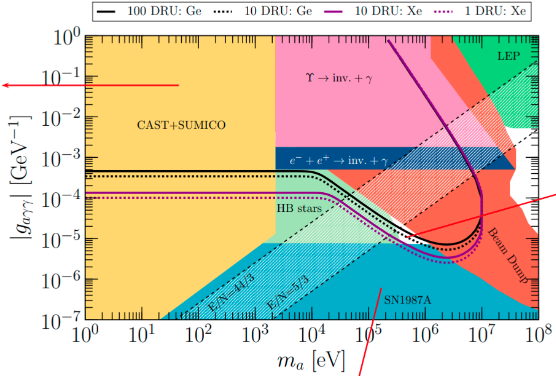


Sensitivities

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

Assumed detector specifications: current vs. future

P[GW]	PM	TM	m_{det}[kg]	L[m]	L_{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 ν emission

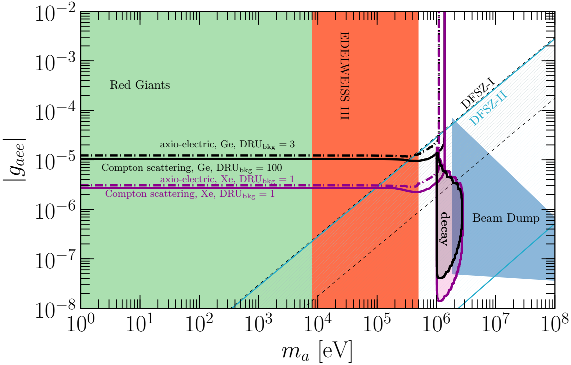
[Aristizabal, De Romeri, Flores, DKP, JHEP 03 (2021) 294]

Probing the g_{aee} coupling

Assumed detector specifications: current vs. future

P[GW]	PM	TM	$m_{\rm det}$[kg]	L[m]	$L_{\rm det}$[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

Testing: environmental effects in Red Giants, unexplored regions

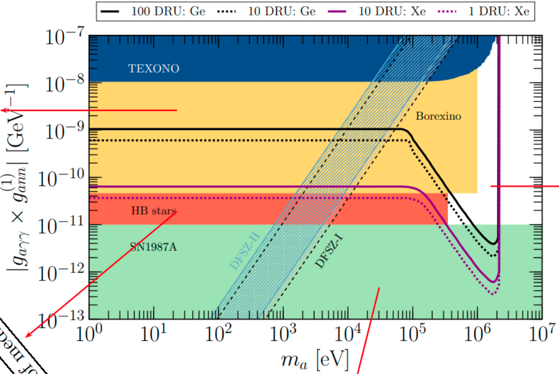


[Aristizabal, De Romeri, Flores, DKP, JHEP 03 (2021) 294]

Probing the $g_{a\gamma\gamma}$ and g_{ann} couplings

Assumed detector specifications: current vs. future

P[GW]	**PM**	**TM**	m_{det}**[kg]**	L**[m]**	L_{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

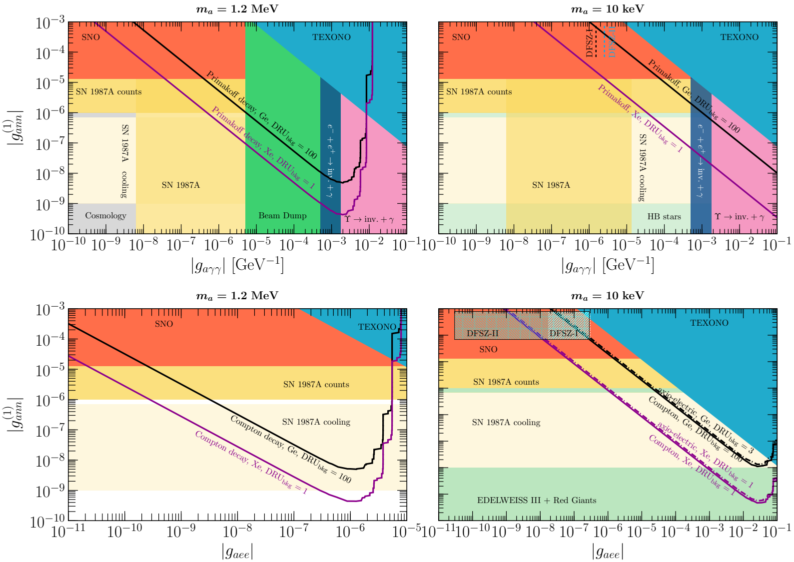
Test of medium effects

Region not yet tested

Test of ALP effects in ν emission

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

Combined analyses

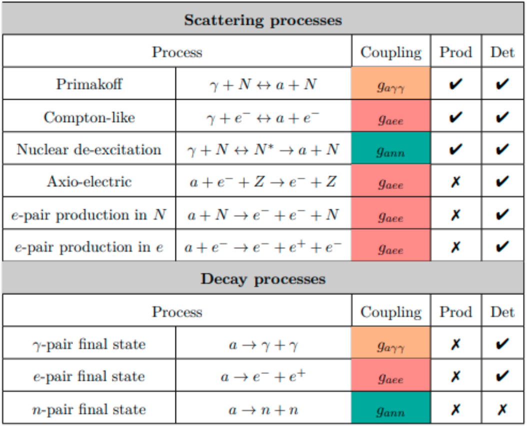


[Aristizabal, De Romeri, Flores, DKP, JHEP 03 (2021) 294]

complementary laboratory probes especially in the regions currently tested only by astrophysics

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
γ-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}	✗	✗

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 !