Search for axion-like particles at NA62

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Outline

- Strong CP problem of QCD
- Axions
- Axion-like particles (ALPs)
- Cosmological hints
- How to look for ALPs?
- NA62 experiment @CERN
- Search for ALPs @NA62

Strong CP problem

$$\mathcal{L}_{QCD} = \sum_{f=1}^{N_f} \bar{q}_f (i\gamma^\mu D_\mu - m_f) q_f - \frac{1}{2}\mathrm{Tr}_c[G_{\mu\nu}G^{\mu\nu}] - \left(\theta \frac{g^2}{16}\mathrm{Tr}_c[G_{\mu\nu}\tilde{G}^{\mu\nu}]\right),$$

$$\text{where } G^a_{\mu\nu}\tilde{G}^{a\mu\nu} = \epsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma} \sim E^a \cdot B^a$$

- The surface term has to be taken into account (instantons)
- But.. neutron electric dipole moment $|d_n| < 3 \cdot 10^{-26}\mathrm{e} \cdot \mathrm{cm} \to |\theta| < 10^{-9}$
- Why is it so small? Yes.. another fine-tuning problem

Axions

Peccei-Quinn: presenting new field a transforming under $U(1)_A$ as $a \to a + \alpha f_a$ solves dynamically strong CP problem:

$$\mathcal{L}_{total} = \mathcal{L}_{SM} + \bar{\theta}\frac{g^2}{32\pi^2} G^a_{\mu\nu}\tilde{G}^{a\mu\nu} - \frac{1}{2}\partial_\mu a \partial^\mu a + \mathcal{L}_{int}[\partial^\mu a/f_a; \Psi] + \xi\frac{a}{f_a}\frac{g^2}{32\pi^2} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

VEV drives to minimum of effective potential

$$\left\langle \frac{\partial V_{eff}}{\partial a} \right\rangle = -\frac{\xi}{f_a}\frac{g_s^2}{32\pi^2}\left\langle G^a_{\mu\nu}\tilde{G}^{a\mu\nu}\right\rangle \Big|_{\langle a\rangle = -\bar{\theta} f_a/\xi} = 0 \to a_{phys} \equiv a - \langle a \rangle$$

$$m_a^2 \equiv \left\langle \frac{\partial^2 V_{eff}}{\partial a^2} \right\rangle = -\frac{\xi}{f_a}\frac{g_s^2}{32\pi^2}\frac{\partial}{\partial a}\left\langle G^a_{\mu\nu}\tilde{G}^{a\mu\nu}\right\rangle \Big|_{\langle a\rangle = -\bar{\theta} f_a/\xi}$$

We get model-independent effective Lagrangian:

$$\mathcal{L}_{total} = \mathcal{L}_{SM} + \mathcal{L}_{int}[\partial^\mu a_{phys}/f_a; \Psi] - \frac{1}{2}\partial^\mu a_{phys}\partial_\mu a_{phys} - \frac{1}{2}m_a^2 a_{phys}^2 + \xi\frac{a_{phys}}{f_a}\frac{g^2}{32\pi^2} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}.$$

Axions

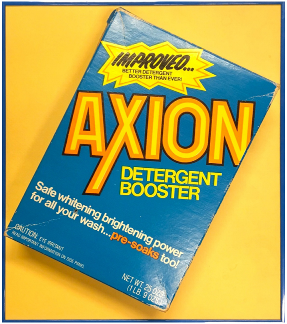
Weinberg-Wilczek (independently): particle interpretation and first model

Two Higgs doublets & Yukawa:

$$\phi_1 = \frac{v_1}{\sqrt{2}} e^{i\frac{a}{v_F}x} \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \quad \phi_2 = \frac{v_2}{\sqrt{2}} e^{i\frac{a}{v_F}\frac{1}{x}} \begin{pmatrix} 0 \\ 1 \end{pmatrix},$$

where $x = v_2/v_1$ and $v_F = \sqrt{v_1^2 + v_2^2}$

$$\mathcal{L}_{\text{Yukawa}} = \bar{q}_L \phi_1 u_R + \bar{q}_L \phi_2 d_R + \bar{L}_L \phi_1 l_R + \text{h.c.}$$



".. a supermarket display of brightly colored boxes of a laundry detergent named Axion had caught my eye. It occurred to me that *axion* sounded like the name of a particle and really ought to be one. So when I noticed a new particle that cleaned up a problem with an *axial* current, I saw my chance." (Frank Wilczek)

Axions

QCD in low-energy limit $\rightarrow$ we will replace quarks by their condensates $\langle \bar{q} q \rangle$
$\rightarrow \pi$ and η mesons and eff. Lagrangian

$$\mathcal{L}_{eff} = \frac{f_\pi^2}{4} \mathrm{Tr}[\partial_\mu U \partial^\mu U^\dagger], \; U = \exp\left(i \frac{\tau_i \pi_i + \eta}{f_\pi}, \right), \; \tau_i \pi_i \equiv \begin{pmatrix} \pi^0 & \sqrt{2}\pi^+ \\ \sqrt{2}\pi^- & \pi^0 \end{pmatrix}$$

flavour $U(1)_A$ and $U(1)_{PQ}$ broken by anomalous term - responsible for axion mass and a-π, a-η mixing:

$$\mathcal{L}_{anomaly} = -\frac{M_\eta^2}{2} \left[\eta + \frac{f_\pi}{v_F} \frac{1}{2} \left(\frac{N_f}{2} - 1 \right) \left(x + \frac{1}{x} \right) a \right]^2, \; m_a = \frac{N_f}{2} \left(x + \frac{1}{x} \right) \frac{f_\pi}{v_F} m_\pi \frac{\sqrt{m_u m_d}}{m_u + m_d}$$

$\rightarrow$ via EM anomaly coupling to two photons:

$$\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma} a_{phys} F_{\mu\nu} \tilde{F}^{\mu\nu} = \frac{e^2}{32\pi^2} N_f \left(x + \frac{1}{x} \right) \frac{m_u}{m_u + m_d} \frac{a_{phys}}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

- This construction where $f_a = v_F$ quickly ruled out ... but in different models can be a free parameter .. still $m_a \sim 1/f_a$ (constant is model-dependent)
- And remarkably for $f_a \gg v_F$ axions become serious DM candidate (for $m_a \sim$ eV would account for all DM!)

ALPs

What about accessing the whole $(g_{a\gamma\gamma}, m_a)$ parameter space?

- If one does not rely on solving strong CP
- SSB of $U(1)$ symmetries is very generic property of many theories BSM (breaking of lepton number, family number, ..)
- pNGB of the same properties like axions $\rightarrow$ axion-like particles (ALPs)

general interaction Lagrangian

$$\mathcal{L}_{ALP}^{int} = g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} + \bar{g}_{a\gamma\gamma} a F_{\mu\nu} F^{\mu\nu} + g_{af\bar{f}} a \sum_f i\bar{f}\gamma_5 f + \bar{g}_{af\bar{f}} a \sum_f \bar{f} f$$
$$+ g_{a\gamma f\bar{f}} a F_{\mu\nu} \sum_f i\bar{f}\sigma^{\mu\nu}\gamma_5 f + \dots$$

ALPs in cosmology - hints

Very important cosmological implications (most of which are model-dependent).. but a generic feature:

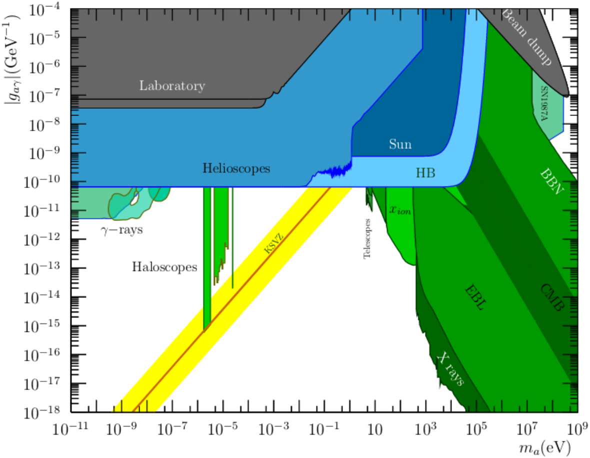
Dark matter would be an optical medium .. any observations?

- evolution of stars - white dwarfs
- DM halo interactions in proximity of black holes - fast radio bursts
- universe transparency

Too big systematic errors and also different possible mechanisms
- but give us hints where to look!

Search for ALPs

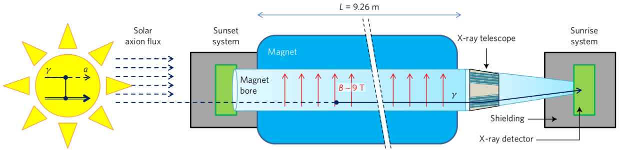
Current constraints in $(g_{a\gamma\gamma}, m_a)$ parameter space:



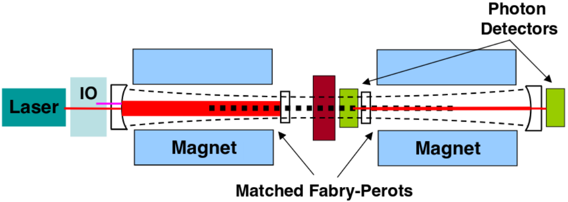
Search for ALPs

How to look for ALPs?

- Dark matter: haloscopes
- Solar ALPs: helioscopes



- Laboratory: Light-Shining-through-Wall



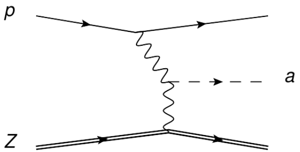
Search for ALPs

Heavy ALPs? $\rightarrow$ proton/electron beam dumped in target with high Z

How?

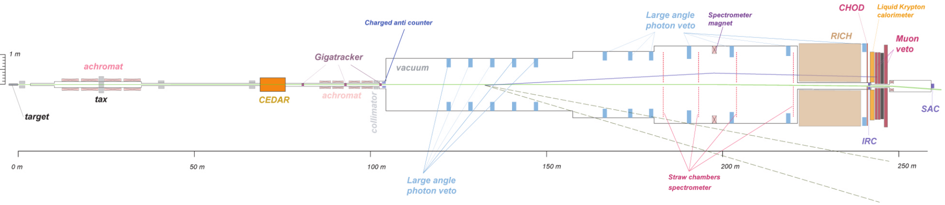
- Elastic scattering (beam proton on target nucleus)
- Inelastic scattering (beam proton constituents on target nucleus ones)
- Other non-perturbative processes (decays of hadrons)

Predominantly elastic scattering - Primakoff production:



NA62 experiment

- Fixed-target experiment @CERN - North Area (SPS - 400 GeV)
- Main goal - kaon physics (very rare decays): $K^+ \to \pi^+ \nu \bar{\nu}$
- BR (10^{-10}): theory 0.84 ± 0.10, experiment $1.73^{+1.15}_{-1.05}$



Search for ALPs at NA62

Special conditions for beam-dump mode:

- TAXes are closed
- target is removed $\rightarrow$ proton beam directly impinged onto copper target
- downstream part of detector used
- different trigger setup:
  - NewCHOD: Q1,Q2
  - LKr: $E > 2$ GeV $\wedge$ $N_{clus} \geq 2$

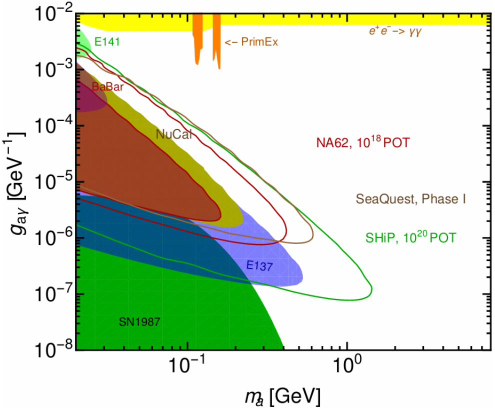
So far (period 2016-2018) several runs:

- $2.6 \cdot 10^{16}$ PoT for neutral events .. actually ..
- $2.9 \cdot 10^{16}$ PoT for charged events

Search for ALPs at NA62

Potential of NA62 in future runs: $\sim 10^{18}$ PoT

In fact: recent study show even higher sensitivity thanks to high energetic photons from secondary π^0 and η:



Conclusions

- Theoretical motivation: generic result of many BSM theories
- Cosmological motivation: can explain many cosmological phenomena (WD, DM, FRB, ..)
- Experimental motivation: technologically accessible hinted areas in parameter space
- Search for ALPs at NA62 (and many other current and near-future proposals $\sim$ yr)

Thank you for your attention!