Axion searches with the CASPEr experiment

Dark Matter search with nuclear magnetic resonance

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Axion Dark Matter

Dark Matter

- I do not need to convince you about the presence of Dark Matter in the Universe
- The dark matter puzzle remains fundamental: dark matter is matter - it leads to the formation of structure and galaxies in our universe
- We have a standard model of CDM, from 'precision cosmology (CMB, LSS): however measurement $\neq$ understanding

$\sim$ 85% of matter in the universe is of unknown nature

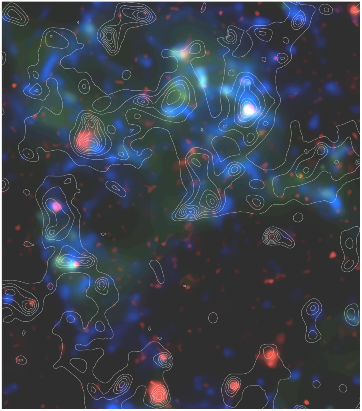
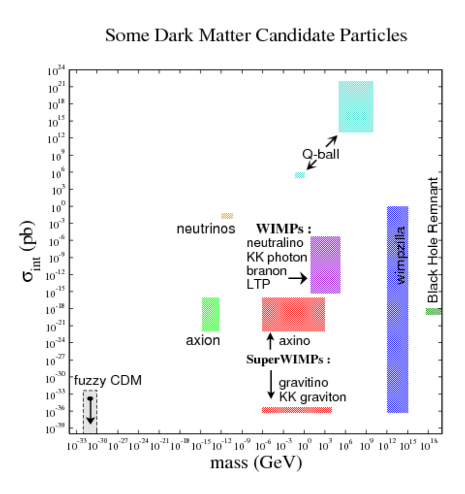


Figure 1: Large scale distribution of dark matter, probed through gravitational lensing

HST COSMOS survey; Nature 445 (2007), 268

Particle Dark Matter

- very many candidates
- masses and interaction strength span over a lot of orders of magnitudes
- but we prefer one specific class: Axions



Baer, Howard arXiv:0901.4732 [hep-ph]

Why axions are so interesting?

- Axion: pseudo scalar (NG) boson emerging from the spontaneous PQ symmetry breaking
- PQ symmetry: (chiral) introduced to solve the "strong-CP problem"
- "strong-CP problem": experimental evidences (i.e. neutron EDM) show that QCD respects CP-symmetry; not expected and requires fine tuning in SM

References

F. Wilczek, Phys. Rev. Lett. 40, 279 (1978)
R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. 38, 1440 (1977)
J. Preskill, M. B. Wise and F. Wilczek, Phys. Lett. B 120, 127 (1983)

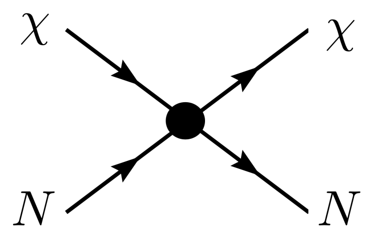
Axion cleans!

Moreover:

- if the symmetry breaking scale (f_a) is larger than $\sim 10^9$ GeV $\Rightarrow$ axion is a Cold Dark Matter (CDM) candidate
- Axion-like-particles (ALPs) are a broader class of light particles that arise from BSM theories with similar characteristics (not necessarily strong-CP problem solver)

Axion field

e.g. WIMPs (heavy particles) $\Rightarrow$ search for particle scattering on nuclei

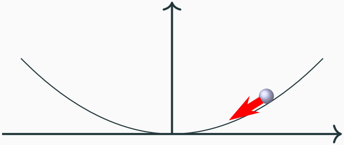


Axion is a light scalar field $\Rightarrow$

- large phase-space density
- described by as a classical field $a(t, x)$
- search for the coherent effects of the entire field, not single "hard" particle scattering

Axion cosmology

- Low mass ($m_a <$ eV) axions can be produced via non-thermal mechanisms (vacuum misalignment) in the early Universe
- Field has some initial value $\rightarrow$ oscillates coherently
- The oscillating field carries an energy density $\langle\rho_a\rangle \sim \rho_{DM}$



$a(t) = a_0 cos(m_a c^2 t/\hbar) \longrightarrow \omega_a = \frac{m_a c^2}{\hbar}$

$\langle\rho_a\rangle \sim \frac{c m_a^2 a^2}{2\hbar^3}$

On Earth:

the temporal coherence of $a(t)$ is limited by the relative motion through the fluctuations

size of fluctuation $\sim \lambda_{dB}$, corresponding to a coherence time $\tau_a \sim \frac{\lambda_{dB}}{\nu} = \frac{2\pi\hbar}{m_a \nu^2}$ $(\nu \sim 10^{-3} c)$

therefore axions moving at ν relative to a detector are measured with a frequency $\omega' \sim \omega_a \left(1 + \frac{\nu^2}{2c^2}\right) \rightarrow a(t) = a_0 cos(\omega' t)$, $\langle\rho_a\rangle = \rho_{DM}^{loc} \sim 0.4$ GeV/cm^3

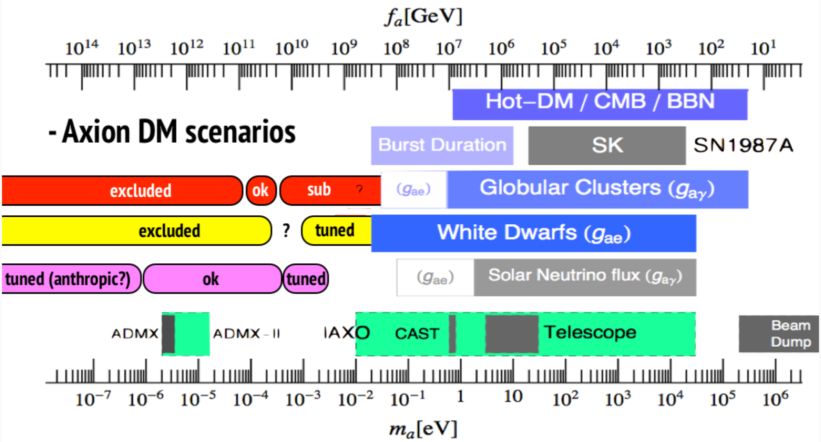
Axion searches

Axion couplings

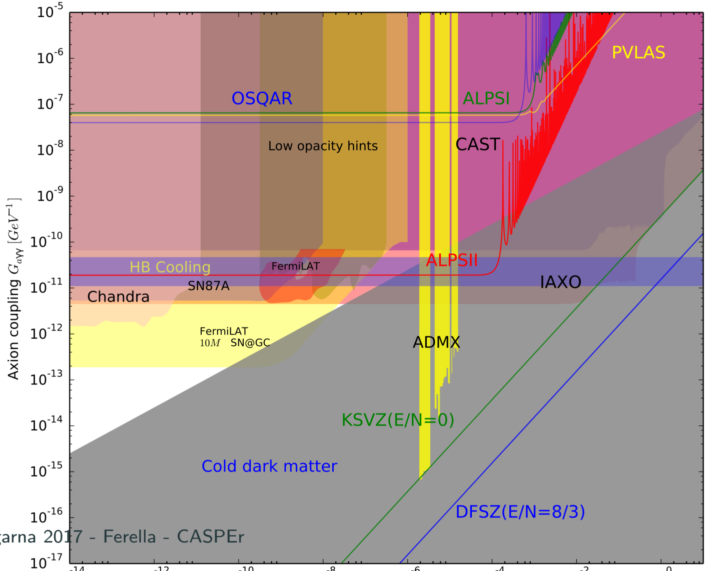
Search for non-gravitational interaction of $a(t)$ with SM fields/particles:

$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$	Coupling to electromagnetic field ADMX, DM Radio, LC Circuit
$\frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu}$	Coupling to gluon field $H_{EDM} = -\mathbf{d}_n \cdot \mathbf{E}$ **CASPEr-Electric**
$\frac{\partial a}{f_a} \bar{\Psi}_f \gamma^{\mu}\gamma_5 \Psi$	Coupling to fermions $H_{wind} = \hbar c g_{aNN} \nabla a \cdot \hat{\boldsymbol{\sigma}}_n$ **CASPEr-Wind, QUAX**

Where to search for axions?



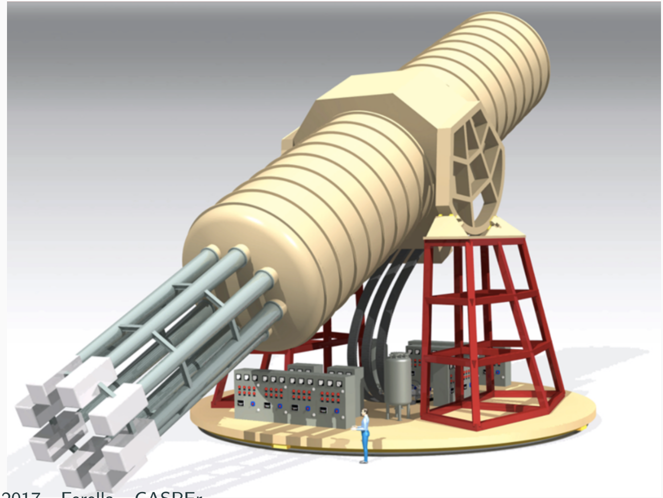
Maybe better from this perspective?



How to search for axions?

Helioscope

$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$ - Primakoff effect - $a \rightarrow \gamma$ conversion



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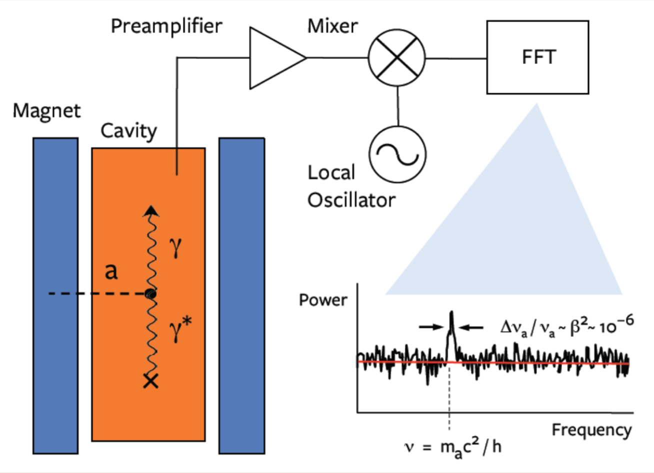
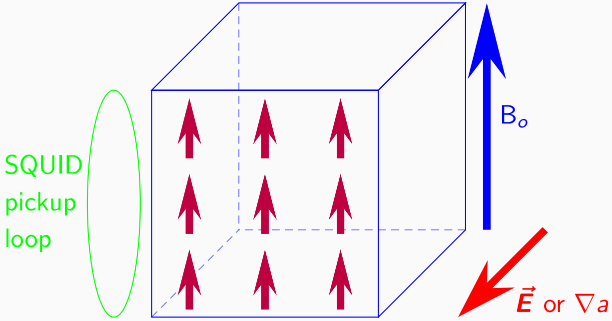


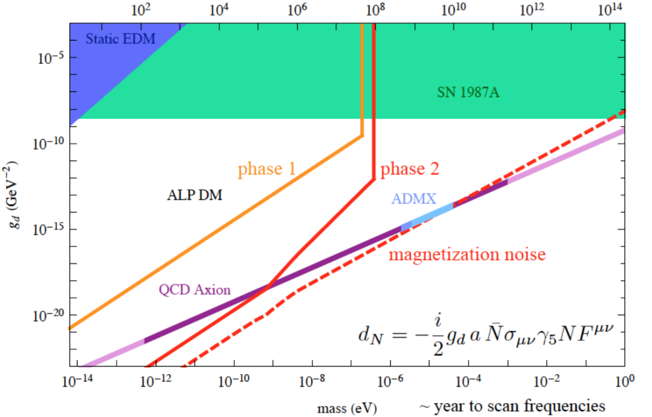
CASPEr

Use NMR technique



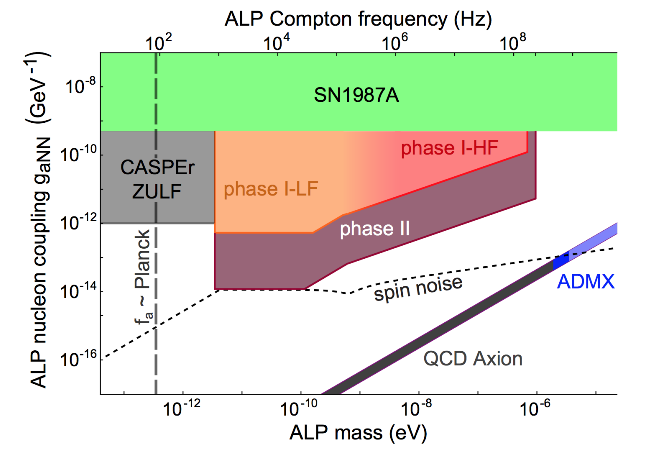
- Larmour frequency $\sim$ axion mass
- SQUID measures resulting transverse magnetization
- Example materials: liquid ^{129}Xe, ferroelectric $PbTiO_3$

CASPEr-E sensitivity



Verify signal with **spatial coherence** of axion field

CASPEr-wind sensitivity



CASPEr-wind quick estimates

$$M(t) \approx np\mu \left(g_{\mathrm{aNN}} \sqrt{2\rho_{DM}} v \right) \frac{\sin\left((2\mu B_{\mathrm{ext}} - m_a)\, t \right)}{2\mu B_{\mathrm{ext}} - m_a} \sin\left(2\mu B_{\mathrm{ext}} t \right)$$

Parameters

$$n = 10^{22} \frac{1}{\mathrm{cm}^3} \qquad \rho_{\mathrm{DM}} \approx 0.3 \frac{\mathrm{GeV}}{\mathrm{cm}^3}$$

$$v \sim 10^{-3} \qquad \tau_a \sim \frac{2\pi}{m_a v^2} \sim 1\ \mathrm{s} \left(\frac{\mathrm{MHz}}{m_a} \right)$$

Material Choice

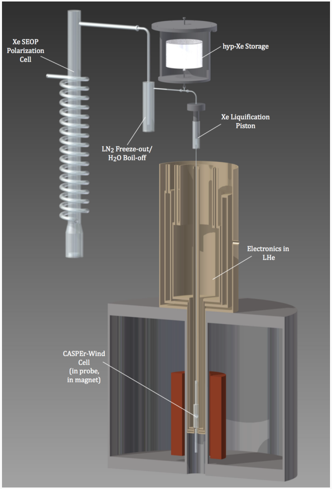
$$\mu_{\mathrm{Xe}} = 0.35 \mu_N$$

Technology

$$p \approx 1 \qquad \boxed{T_2 \gtrapprox \tau_a \sim 1\ \mathrm{s}} \quad m_a \lessapprox \mathrm{MHz}$$

$$\delta M \sim 10^3\ \mathrm{fT} \left(\frac{g_{\mathrm{aNN}}}{10^{-10}\,\mathrm{GeV}^{-1}} \right)$$

Our group involvement



All subsystems are being worked out (mostly ready)

out tasks:

Integration of all subsystems

Slow control and DAQ