Probe Dark Matter Axions with Broadband and Narrowband methods

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To solve the strong CP problem, P.&Q. introduces the $U(1)_{PQ}$ symmetry which is spontaneously broken and then relaxes to zero after the QCD phase transition.

The relaxation process created axion dark matter (P. Sikivie, F. Wilczek, et al.) have a very high phase space density which is different from the thermally created dark matter particles.

Cosmic axions can form BEC (P. Sikivie, Q. Yang) which makes the energy spectrum density even higher.

Axion like particles

- alps arises due to compactification of the antisymmetric tensor fields

$$B = \frac{1}{2\pi} \sum b^i(x)\omega_i(y) + \dots ,$$

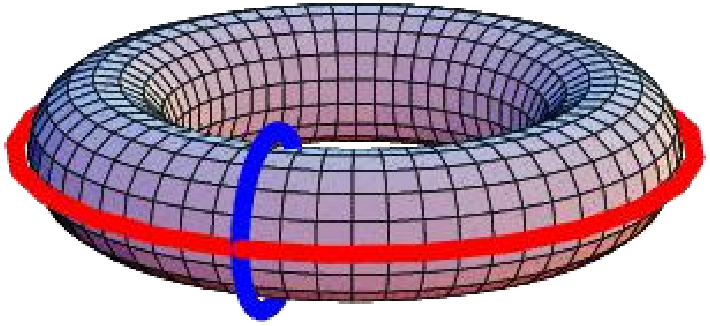
- the x are non-compact coordinate, y are compact coordinates.

The Axiverse

Svrcek and Witten, arXiv:hep-th/0605206

• String theory has extra dimensions which can be compactified.

• Axions are KK zero-modes of gauge fields compactified on closed cycles.



• Potentials from non-perturbative physics (D-branes, instantons etc.) give rise to axion masses.

So there are many different axion like particles (alps)

ALPs were also created by the misalignment mechanism and could form BEC

So if string theory is true, alps seems to be inevitable.

To detect: what is the mass of the particle?

Solution 1: BroadBand Detection

arxiv:2012.13946

The modified Maxwell equation is:

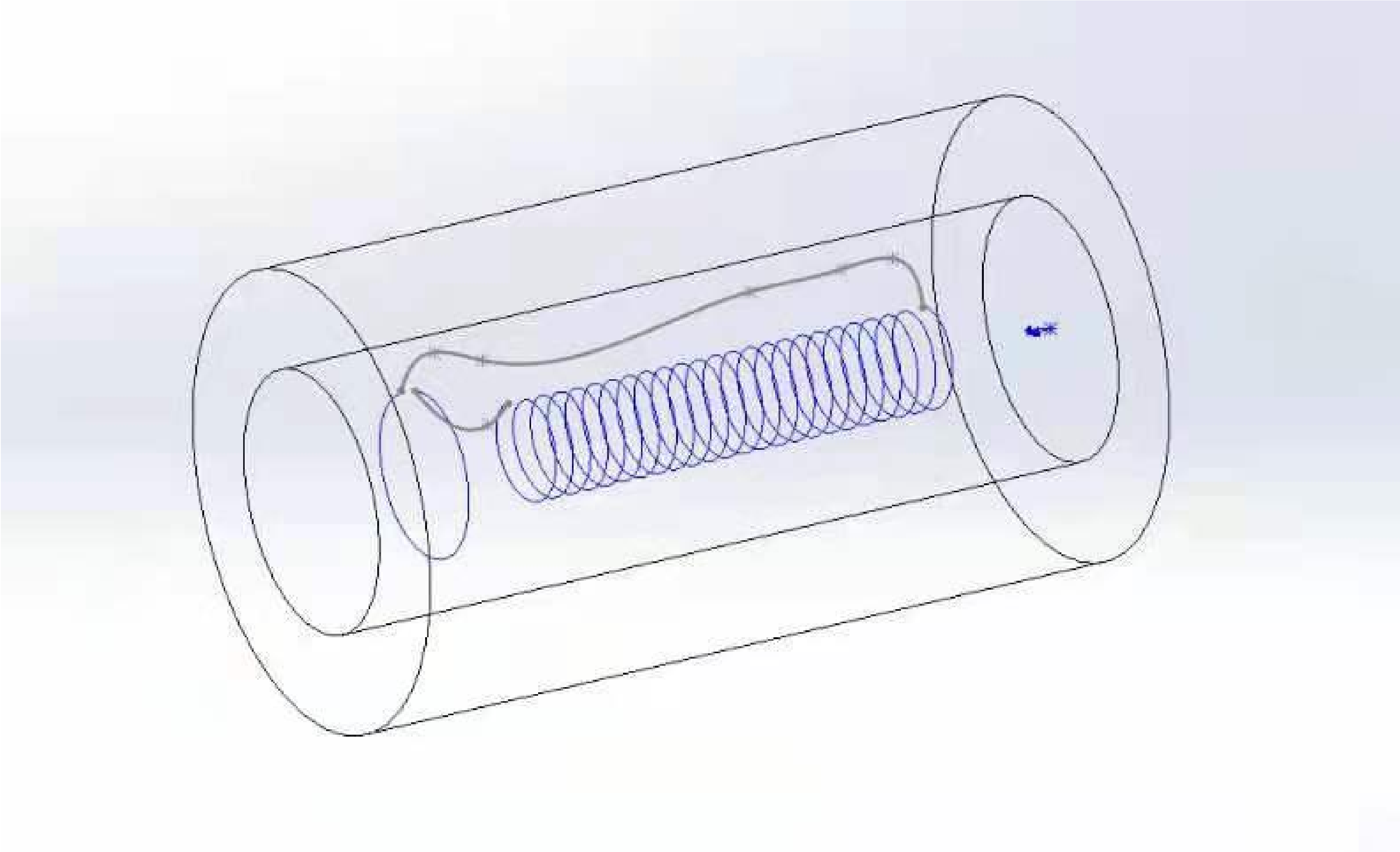
$$\vec{\nabla} \cdot \vec{E} = \rho_e + g_{a\gamma} \vec{B} \cdot \nabla a$$

$$\vec{\nabla} \times \vec{B} - \frac{\partial \vec{E}}{\partial t} = g_{a\gamma} \vec{E} \times \vec{\nabla} a - g_{a\gamma} \vec{B} \frac{\partial a}{\partial t} + \vec{j}_e$$

$$\vec{\nabla} \cdot \vec{B} = 0$$

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} ,$$

$$\vec{\nabla} \times \vec{B} = g_{a\gamma} \vec{E} \times \vec{\nabla} a$$



The front end can measure a wide range of alps without modifications

The signals can be read out one time and be analyzed later.

$$
\begin{aligned}
B_a &= \mu_0 R j_a = g_{a\gamma} \bar{E}_0 v \sqrt{2\rho_{CDM}} R\cos(\omega_a t) \\
&= 2.0 \times 10^{-7}\mathrm{T}(\frac{g_{a\gamma}}{\mathrm{GeV}^{-1}})(\frac{\bar{E}_0}{\mathrm{Gvolt/m}})(\frac{R}{1\mathrm{m}})
\end{aligned}
$$

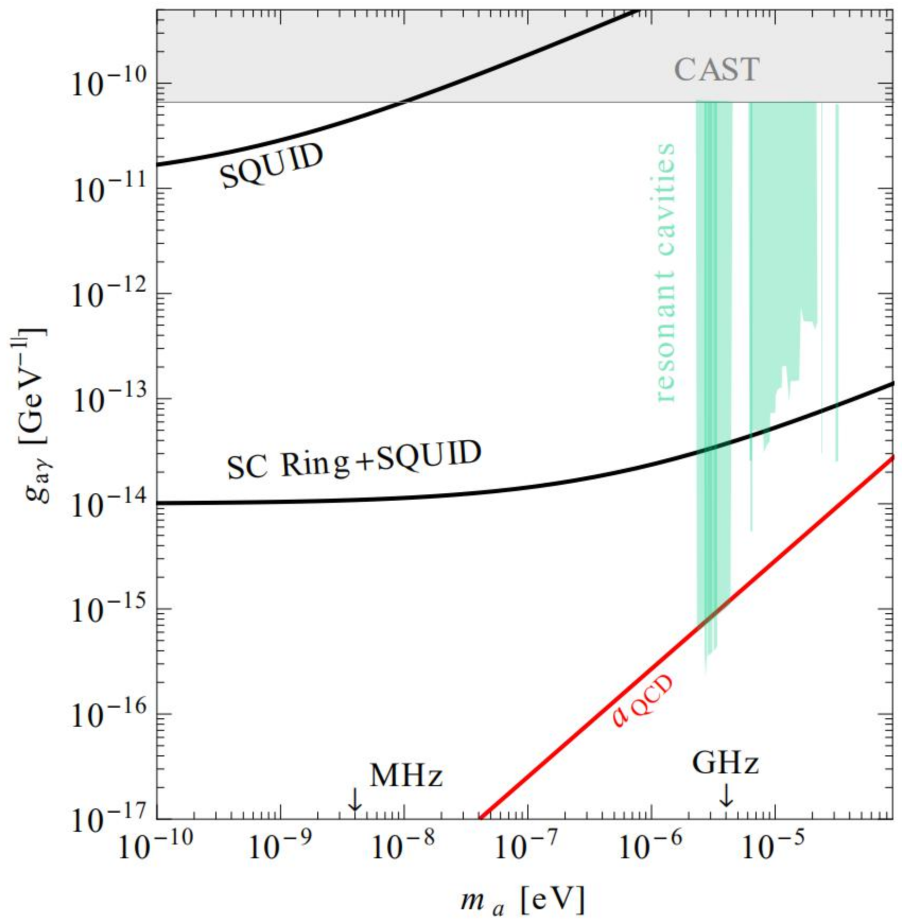
By adding a superconductor ring and coil system , the magnetic field can be magnified:

$$
B_1 \approx F_r N(\frac{r_2}{r_1}) B_a
$$

Where N is the winding number, r_1 and r_2 are the ring diameter and the coil diameter respectively, , F_r is a constant of order one.

The bandwidth of the axion signal is:

$$
\begin{aligned}
\delta f_a &= \frac{\delta E}{2\pi} = \frac{m_a v}{2\pi} \delta v \sim 0.5 * 10^{-10} m_a \\
&\sim 0.75\mathrm{Hz}(\frac{m_a}{10^{-5}\mathrm{eV}})
\end{aligned}
$$



Assuming the ring diameter is order of meters, mm of the coil diameter, N\sim 10^4, E\sim MV/m

Solution 2: theoretical constrains & scanning the possible mass ranges

Axion fluctuations are correlated to the CMB fluctuation.

$$\langle \delta S_a^2 \rangle = \frac{2\sigma_\theta^2(2\theta_0^2 + \sigma_\theta^2)}{(\theta_0^2 + \sigma_\theta^2)^2}$$

- The observed CMB isocurvature fluctuation is small

$$\left\langle \left(\frac{\delta T}{T}\right)^2_{\rm iso} \right\rangle \sim \langle \delta S_a^2 \rangle \lesssim \mathcal{O}(10^{-11}).$$

$$m_0 \approx 6 \times 10^{-5}\text{eV}(\frac{10^{11}\text{GeV}}{f_a})$$

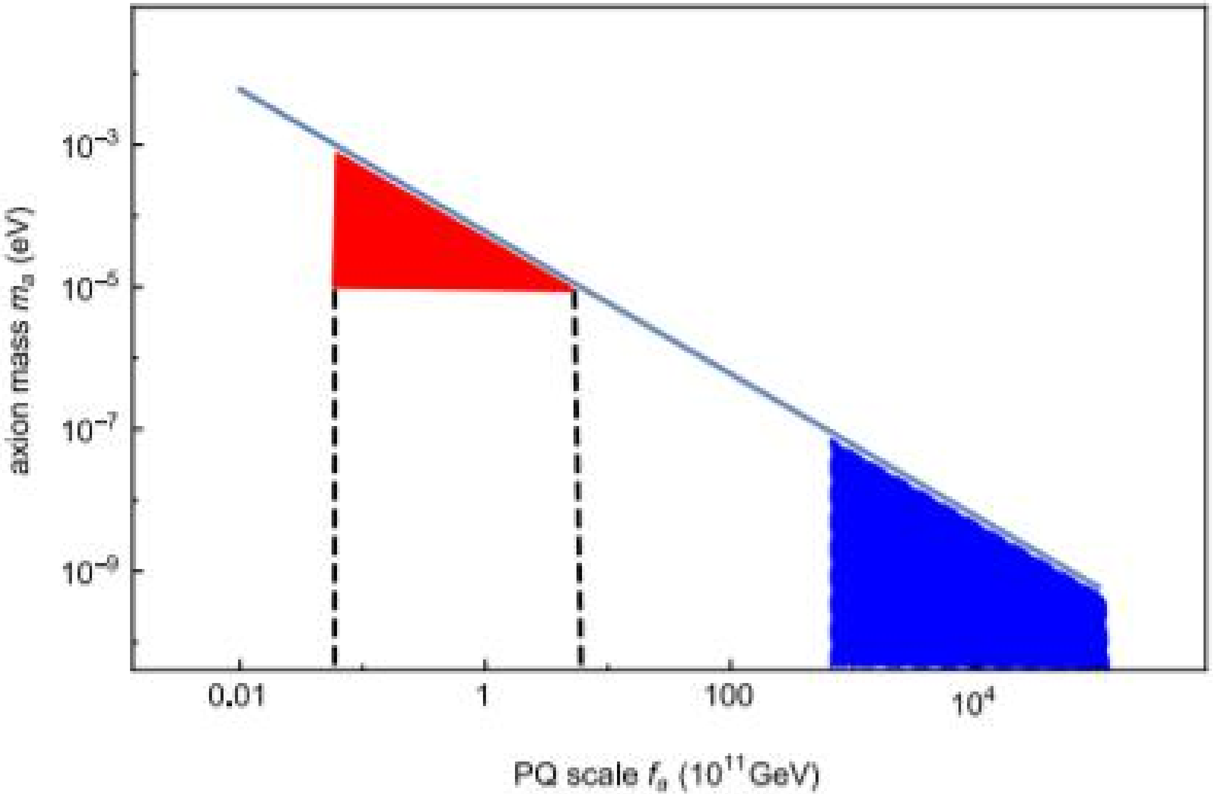


FIG. 1: The two possible windows of the dark matter axions. The upper-left one is often called the classical window and the lower-right one is the anthropic window assuming that $H_I < 10^{10}$GeV and the PQ symmetry was not restored after inflation.

Dark matter axion induced quantum transitions

$$a(x) \approx a_0 \cos(-m_a t - \frac{m_a}{2} v^2 t + m_a \vec{v} \cdot \vec{x} + \phi_0)$$

$$\bar{a}_0 \approx \sqrt{2\rho_{\rm CDM}}/m_a$$

The axion spectrum density I_a is high

$$I_a = \frac{\rho_{CDM}}{(1/2)m_a\delta v^2}$$

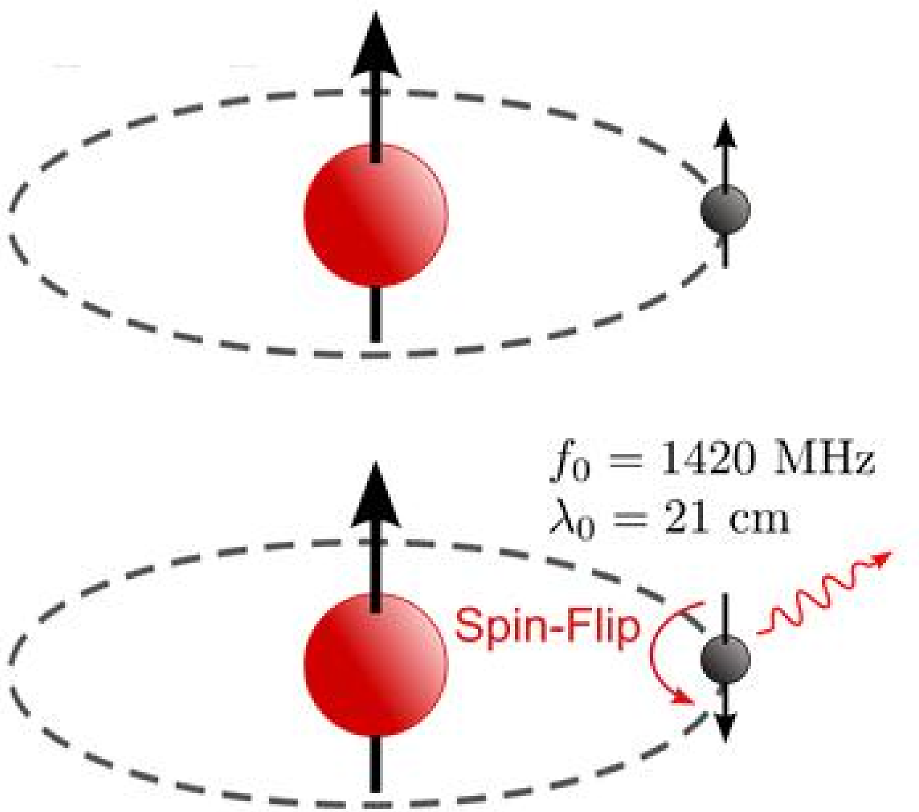
The interaction term in non-relativistic limit is:

$$H_{int} = \frac{1}{f_a}\sum g_f(\partial_t a\frac{\vec{p}_f \cdot \vec{\sigma}_f}{m_f} + \vec{\sigma}_f \cdot \vec{\nabla} a)$$

The transition rate is

$$R = \frac{\pi}{f_a^2}|\sum g_f < f|(\vec{v} \cdot \vec{\sigma}_f)|i > |^2 I_a$$

Hydrogen 1S state transitions



Hydrogen atoms are idea targets for the classical window

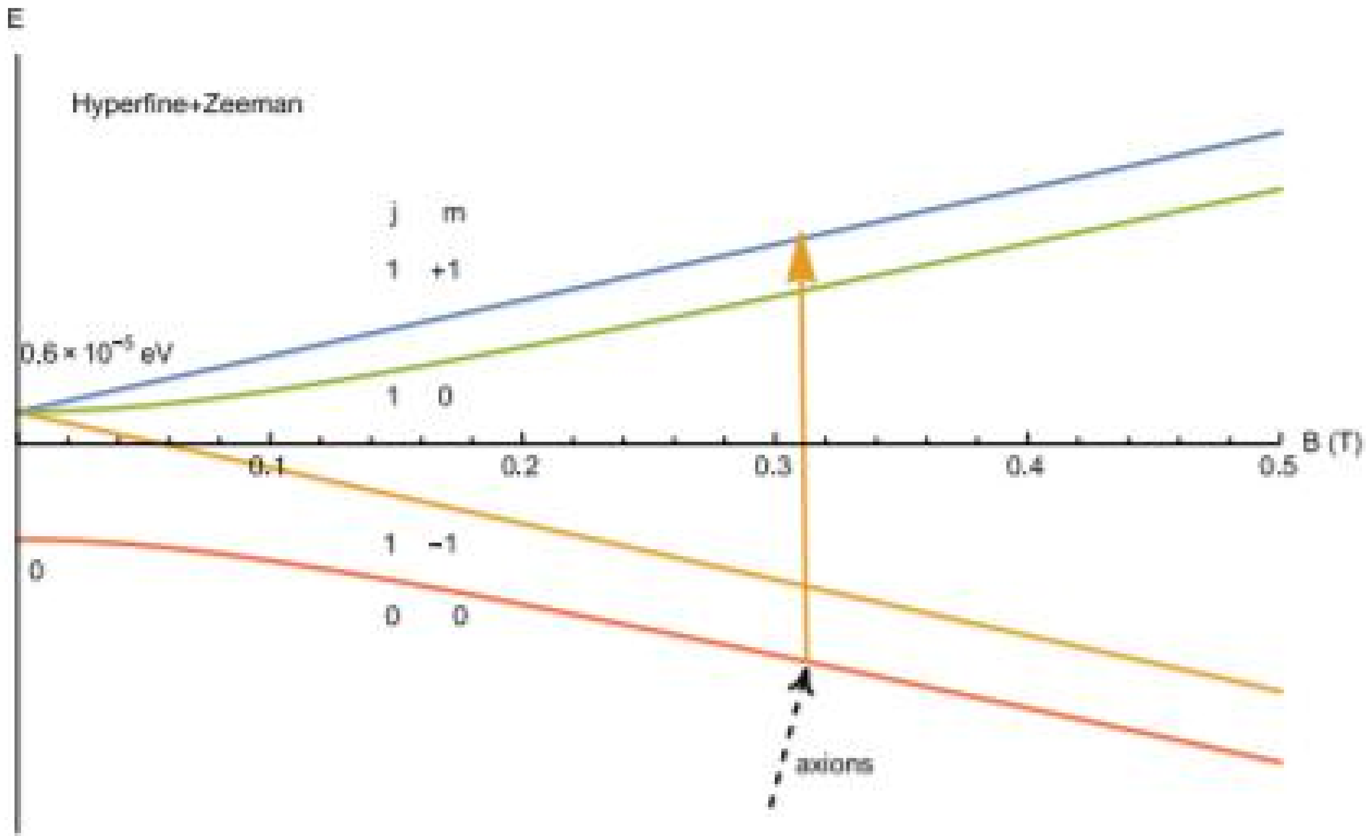


FIG. 2: The splitting of the hydrogen 1S state. For the classical window, $|0,0> \to |1,1>$ transition is suitable for the axion detection.

(arxiv:1912.11472)

Hydrogen atoms are also idea targets for the anthropic window

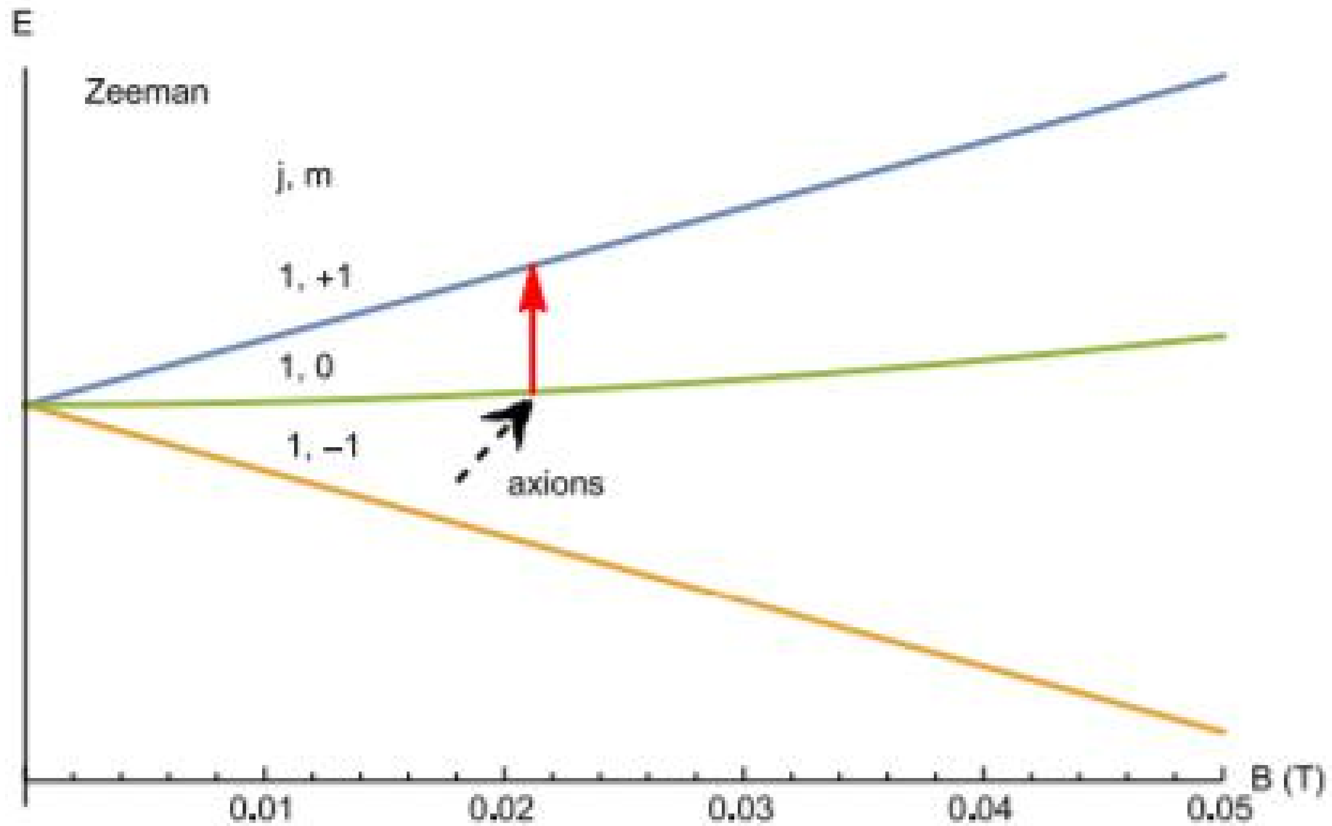


FIG. 3: The splitting of the hydrogen 1S triplet state. For the anthropic window $|1,0> \to |1,1>$ transition is suitable for the axion detection.

(arxiv:1912.11472)