QCD axion, atypical Hubble volume and possible experimental probes

Qiaoli Yang

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Y. Gao, T. Li, and Q. Yang, arxiv:1912.12963(2019)
Q. Yang, arxiv:1912.11472(2019)

Cold Dark Matter (CDM)

- CDM is widely believed to be an important part of the universe based on a large number of observations:

a. Dynamics of galaxy clusters.
b. Rotation curves of galaxies.
c. Abundance of light elements.
d. Gravitational lensing.
e. Anisotropies of the CMBR.

The QCD Axions

To solve the strong CP problem, one introduces the $U(1)_{PQ}$ symmetry which is spontaneously broken

$$L = -1/4g^2 Tr(G_{\mu\nu} G_{\mu\nu}) + \sum \bar{q}_(D_\mu \gamma_\mu + m_i) q_i$$
$$+ \theta/32\pi^2 TrG_{\mu\nu}\tilde{G}_{\mu\nu} + 1/2\partial_\mu a \partial^\mu a + a/(f_a 32\pi^2) TrG_{\mu\nu}\tilde{G}_{\mu\nu},$$

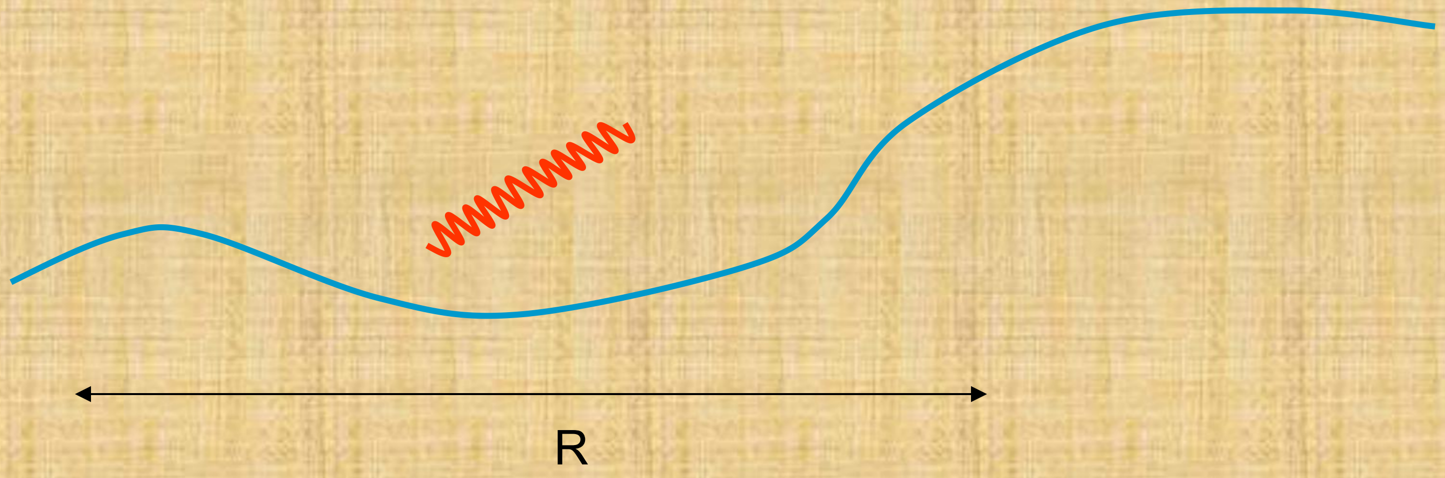
$\theta + a/f_a \to 0$ relaxes to zero during QCD phase transition.

The million dollar question:

If the QCD axions contribute to a major part of CDM,

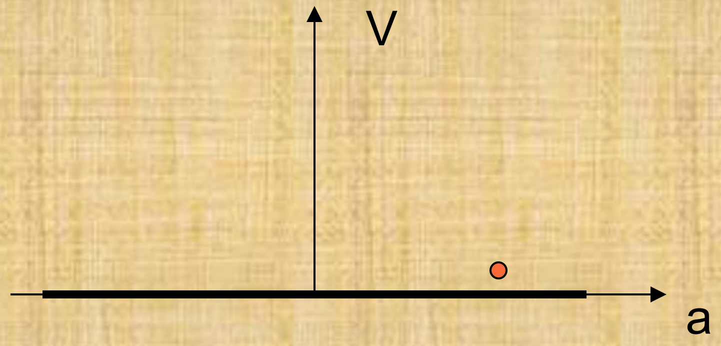
what is the mass?

There are two cosmic axion populations: hot and cold.

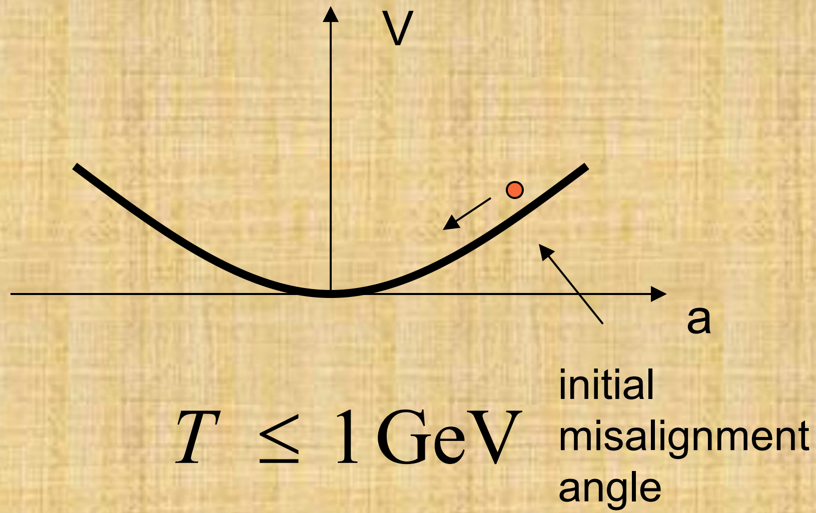


The hot part was created in the thermal bath, and the cold part is believed to be created by the realignment mechanism.

CDM Axions produced by vacuum realignment



$T \geq 1\,\mathrm{GeV}$



$T \leq 1\,\mathrm{GeV}$

$$\partial_t^2 a + 3H\partial_t a - \frac{1}{R^2}\nabla^2 a + \partial_a V(a) = 0$$

$$V(a) \approx f_a^2 m_a^2(T)\left[1 - \cos\left(\frac{a}{f_a}\right)\right]$$

Cold axion properties

- density $\rho_a \sim \frac{1}{2} m_a(T_0)^2 \langle a_0^2 \rangle$

- density fluctuation σ_θ^2

$$\langle a_0^2 \rangle = (\theta_0^2 + \sigma_\theta^2) f_a^2$$

The energy of axions are transferred from the QCD sector

- $$\delta\rho_{total} = m_a \delta n_a + m_i \delta n_i + 4\rho_{rad}\frac{\delta T}{T} = 0.$$

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

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

The axion field acquires a fluctuation during the inflation .

$$\sigma_\theta \sim \frac{H_I}{2\pi f_a}$$

For a moderate small $H_I \sim 10^{10}$ GeV (low scale inflation)

$$f_a \gtrsim 10^{14}\ \mathrm{GeV}$$

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

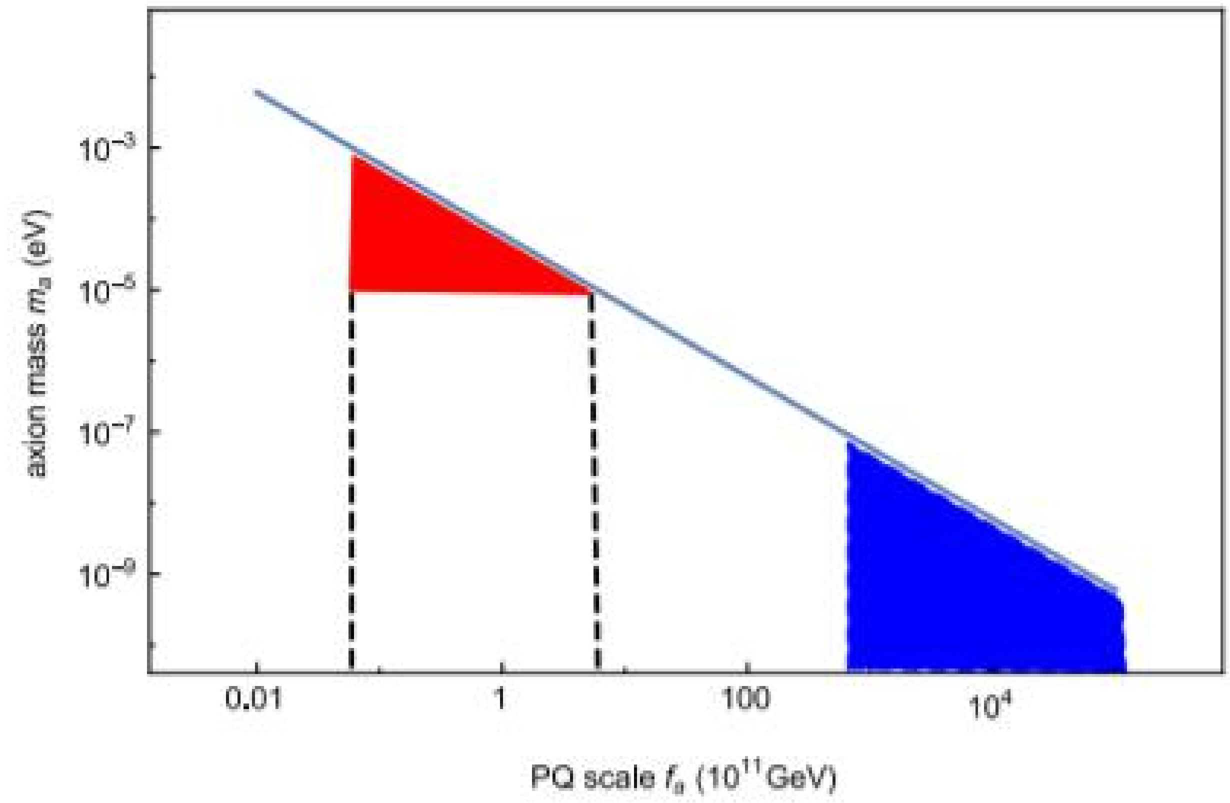


FIG. 1: The two possible windows of the dark matter axions. The upper-left one is often called the classical window and the lower-right one is the anthropic window assuming that $H_I < 10^{10}$GeV and the PQ symmetry was not restored after inflation.

arxiv:1912.11472(2019)

Inflation

The classical window may require the PQ symmetry breaking happened after Inflation or a very low scale inflation.

If the PQ symmetry breaking happened after inflation, we have domain wall, cosmic string etc....

we may need to consider both windows.

If we find dark matter QCD axion in the anthropic window.

We live in an atypical Hubble volume (dark matter detection may prove multiverse scenario).

Dark matter axion induced quantum transitions

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

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

The axion spectrum density I_a is high

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

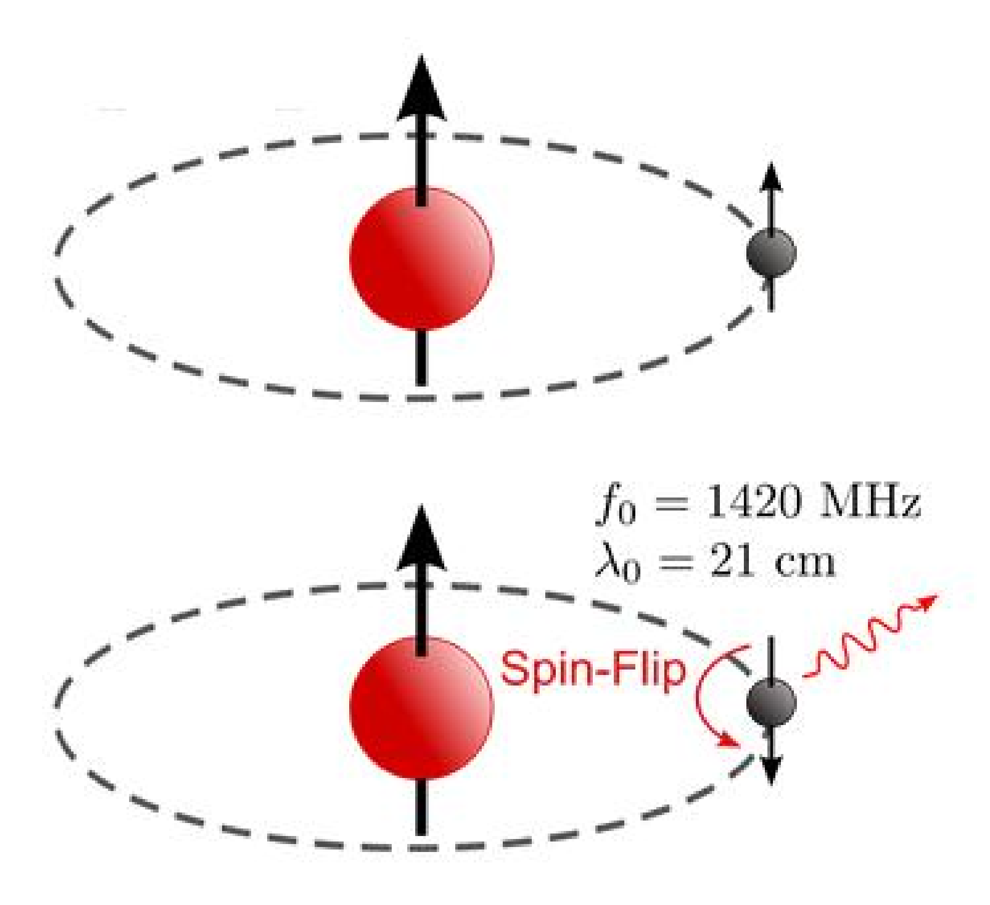
The interaction term in non-relativistic limit is:

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

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

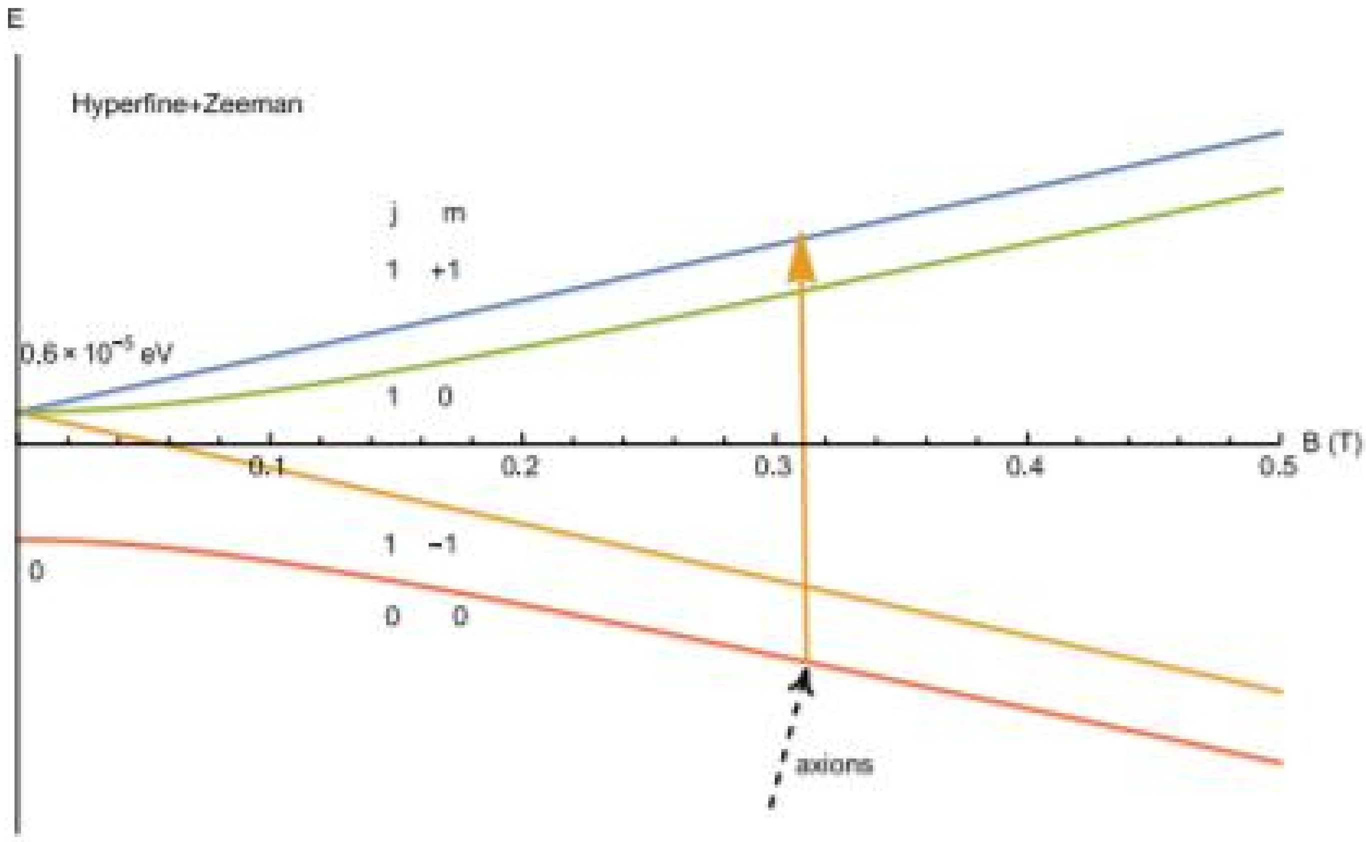


FIG. 2: The splitting of the hydrogen 1S state. For the classical window, $|0,0> \rightarrow |1,1>$ transition is suitable for the axion detection.

Hydrogen atoms are also idea targets for the anthropic window

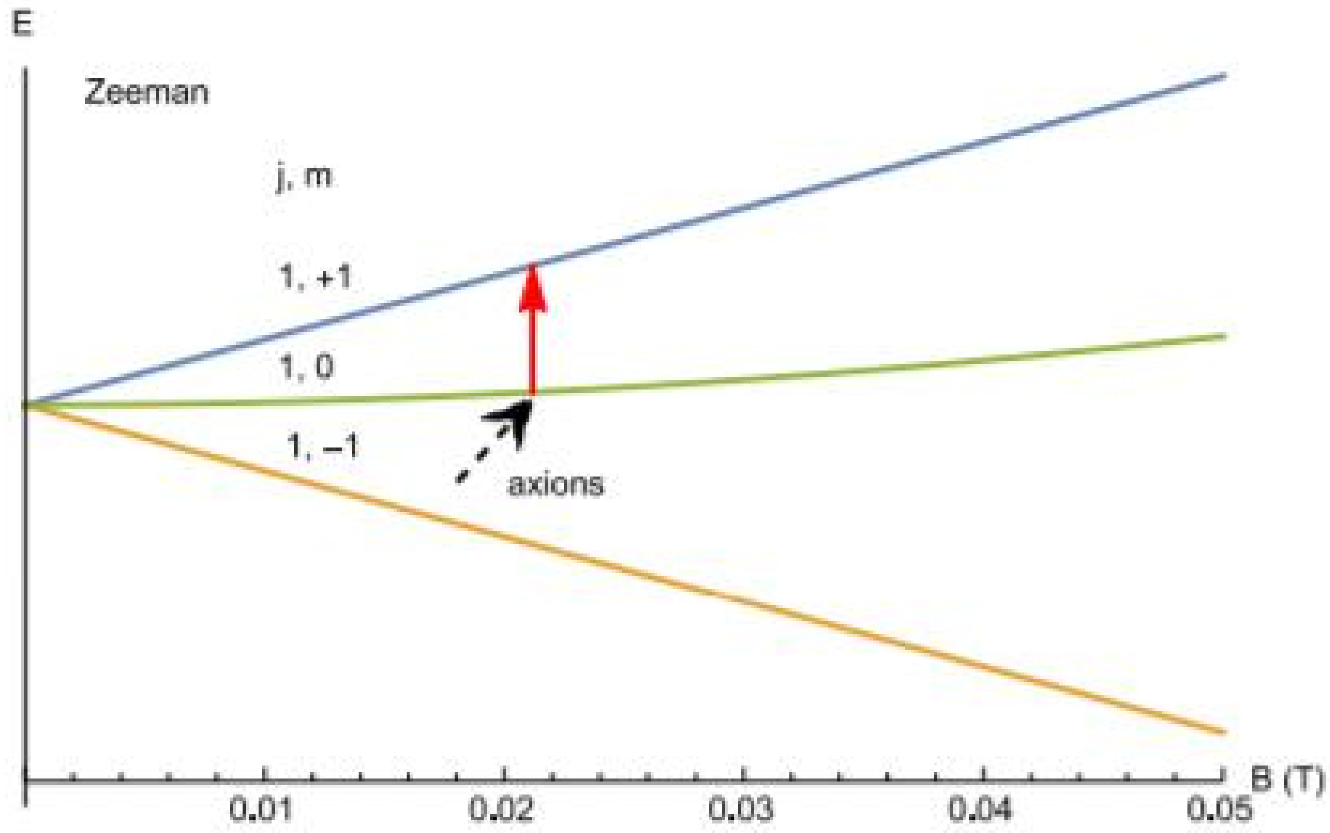


FIG. 3: The splitting of the hydrogen 1S triplet state. For the anthropic window $|1,0> \to |1,1>$ transition is suitable for the axion detection.

A particular set-up

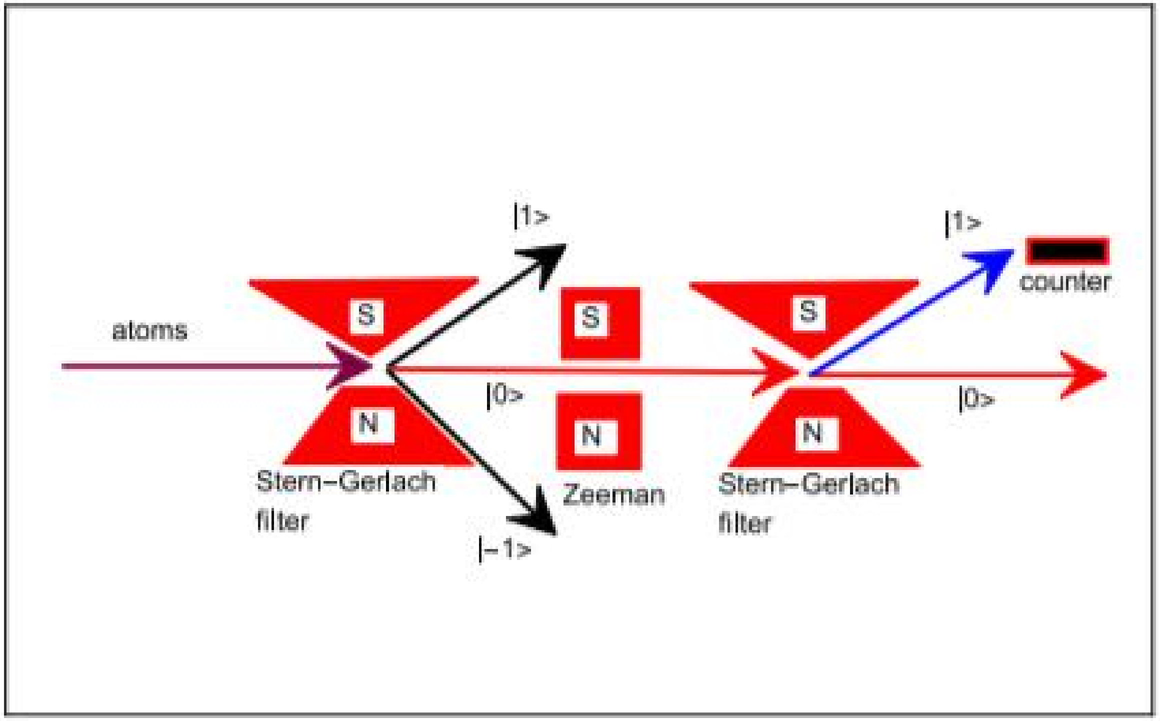


FIG. 4: A possible setup of the proposed scheme. The cold atoms enter the first Stem-Gerlach apparatus in which the $m_j \neq 0$ states are filtered and subsequently the $m_j = 0$ atoms go through a Zeeman effect region in which their atomic energy gaps are turned to match with the axion mass. A small portion of the atoms are resonantly excited to $m_j = 1$ state which will be deflected in the second Stern-Gerlach apparatus and received by a counter. The sensitivity depends on the number of atoms N presenting in the Zeeman effect region and the one year scanning bandwidth Δf.

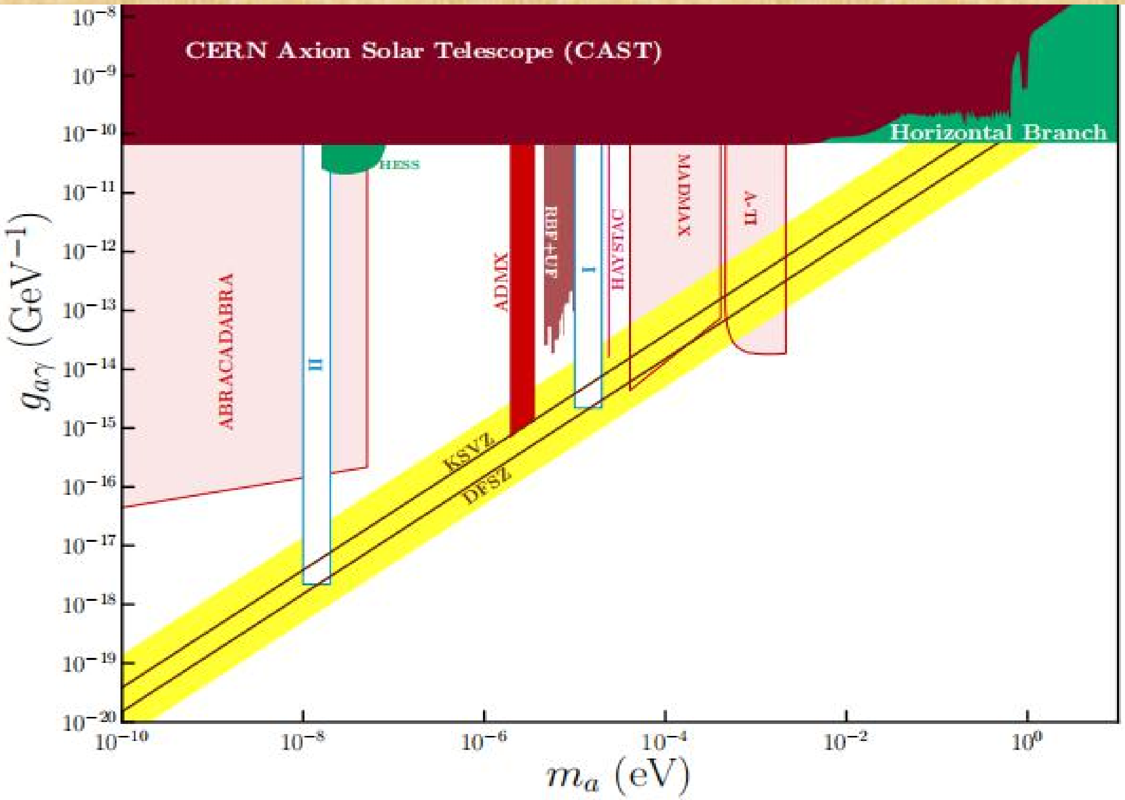


FIG. 5: Constraints on the axion-photon coupling $g_{a\gamma} \approx \alpha_{EM}/2\pi f_a$. The mass range that can be covered by the proposed method is determined by the available Zeeman field strength. To cover region I, $m_a \in [10^{-5}\text{eV}, 2 \times 10^{-5}\text{eV}]$, 0.15Tesla is required. Assuming one year data taking time with 10^{-2}mole of H, the effective sensitivity is $g_{a\gamma} \approx 2.2 \times 10^{-15}\text{GeV}^{-1}$. To cover region II, $m_a \in [10^{-8}\text{eV}, 2 \times 10^{-8}\text{eV}]$, 0.002T is required. Assuming one year data taking time with 10^{3}mole of H, the effective sensitivity is $g_{a\gamma} \approx 2.3 \times 10^{-18}\text{GeV}^{-1}$.