Axion Searches in light of string theory

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arxiv:2408.06652; 2410.12634

String Theory

- Still the most plausible theory of quantum gravity.
- Key Properties to phenomenology:

a. Extra Dimensions

Resulting KK modes of particles .

b. Landscape

Physical constants could be variable.

String Theory

- Key Properties to phenomenology:

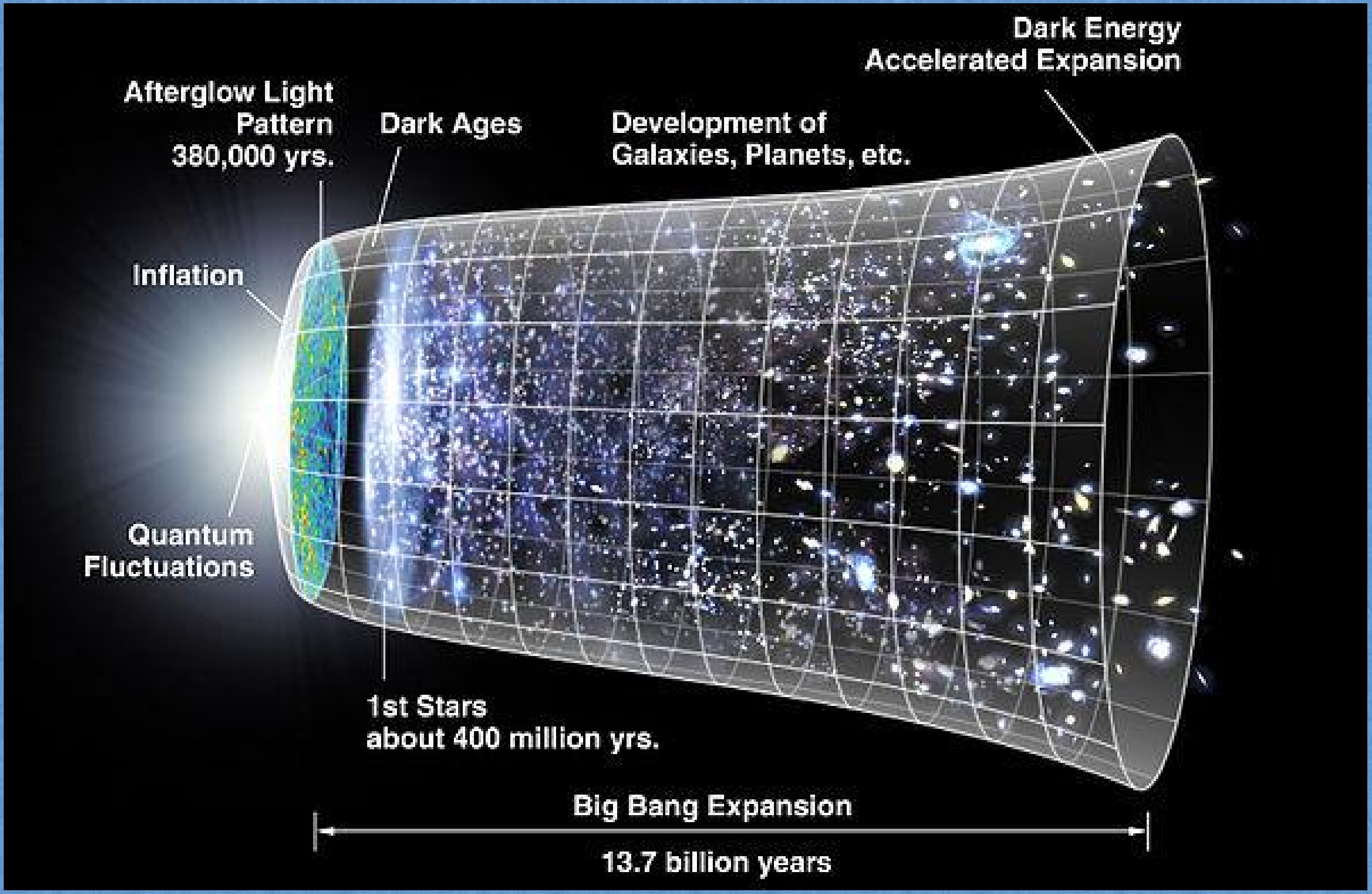
  a. Many axion-like particles

  Naively $\binom{6}{2} = 15$ actually many more: Axiverse .

  b. could solve the strong CP problem

  One of the alps potentiates is dominated by QCD instanton.

History of the Universe



picture by NASA

The General compactification

Low energy effective L

$$\mathcal{L} \supset \frac{f_a^2}{2}(\partial a)^2 - \Lambda^4 U(a),$$

$$\Lambda^4 = \mu^4 \mathrm{e}^{-S} \qquad f_a \sim \frac{M_{Pl}}{S} \sim 10^{16}\mathrm{GeV}$$

QCD Axion mass-symmetry breaking relations

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

General string theory: $f_a \sim 10^{16}\mathrm{GeV}$
Dark Dimension: $f_a \sim 10^{10}\mathrm{GeV}$

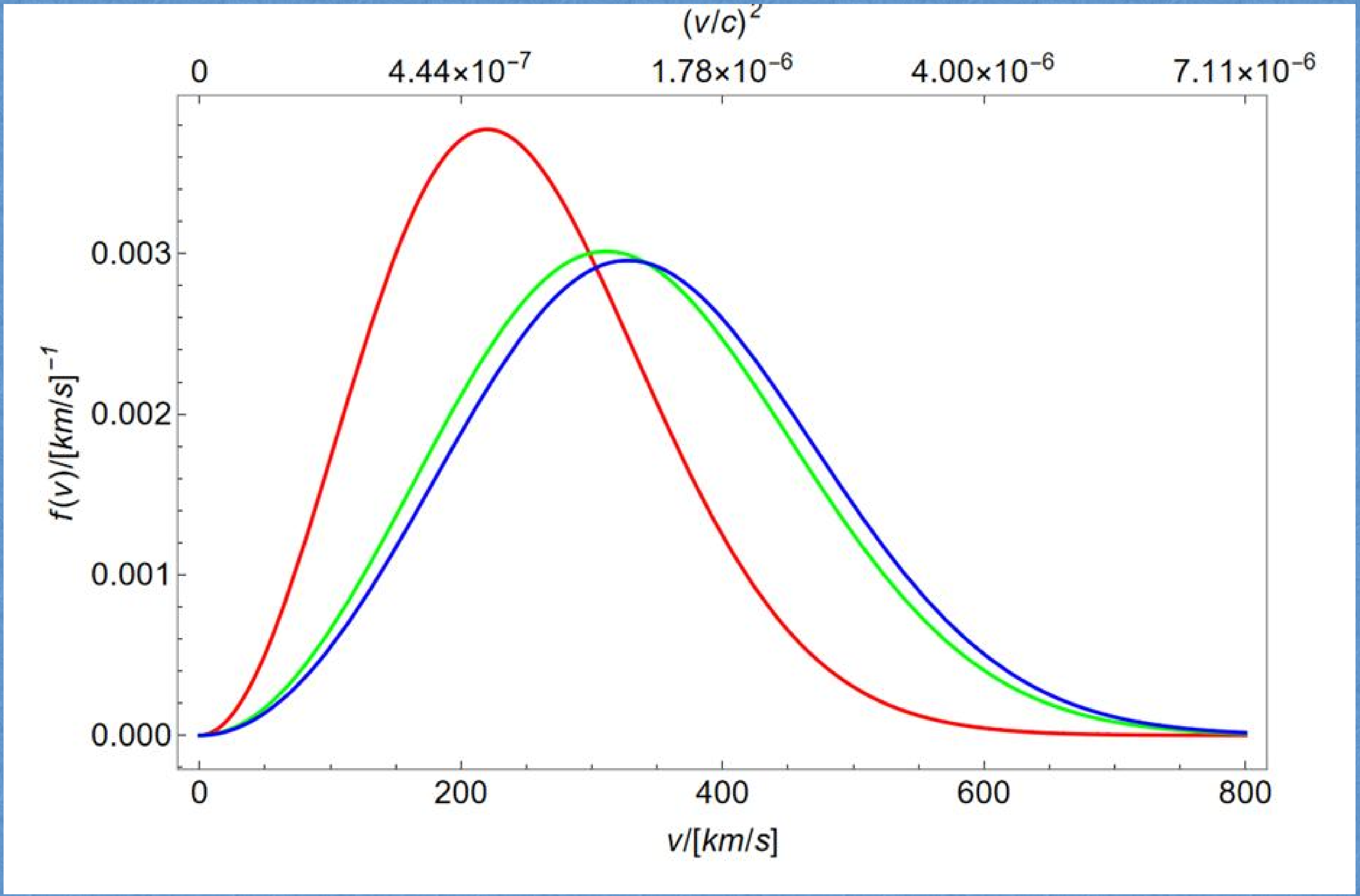
The Quantum picture of wave like dark matter

What we do know with certainties

density distribution

$$\rho_{DM} \approx 0.43 \mathrm{GeV}/\mathrm{cm}^3$$

The uncertainties: velocity distribution



$$f_1(v)dv = \frac{4v^2}{\sqrt{\pi}v_c^3}e^{-v^2/v_c^2}dv$$

The Quantum picture of wave like dark matter

wave function for a single particle:

$$D_i(v,t) = \frac{\sqrt{2\rho_{DM}/N}}{m} \cos\left[m\left(1+\frac{v_i^2}{2}\right)t+\phi_i\right]$$

wave function of the total system:

$$D(t) = \frac{\sqrt{\rho_{DM}}}{m} \sum_j \alpha_j \sqrt{f(v_j)\Delta v} \times \cos\left[m\left(1+\frac{v_j^2}{2}\right)t+\phi_j\right]$$

The Quantum transitions in the Cavity

$$
\begin{aligned}
H_I &= -\int d^3x \mathcal{L}_{a\gamma\gamma} = -g_{a\gamma\gamma} B_0 a(t) \int d^3x \vec{\mathbf{E}} \cdot \hat{z} \\
&= -\frac{i g_{a\gamma\gamma} B_0 \sqrt{\rho_{DM}}}{\sqrt{2} m_a} \cdot \sum_{j,k} \alpha_j \sqrt{f(v_j)\Delta v} \\
&\times \cos(\omega_j t + \phi_j) \sqrt{\omega_k} (a_k e^{-i\omega_k t} U_k - c.c.) \ .
\end{aligned}
$$

The Quantum transitions in the Cavity

$$P = \frac{\pi g_{a\gamma\gamma}^2 B_0^2 \rho_{DM} t V}{4m_a^2} \sum_{jk} C_k \delta(\omega_k - \omega_j) \omega_k \alpha_j^2 f(v_j) \Delta v$$

$$\approx \frac{\pi g_{a\gamma\gamma}^2 B_0^2 \rho_{DM} t V \langle \alpha^2 \rangle}{4m_a^2} \int dv f(v) \int d\omega_k C_k \frac{\omega_k}{d\omega_k} \delta(\omega_k - \omega_v)$$

$$\approx \frac{\pi g_{a\gamma\gamma}^2 B_0^2 t V}{2m_a^2} \rho_{DM} \int_0^{\Delta} dv_a f(v_a) C_{\omega_a} Q_c \ ,$$

The axion spectrum density I_a is high

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

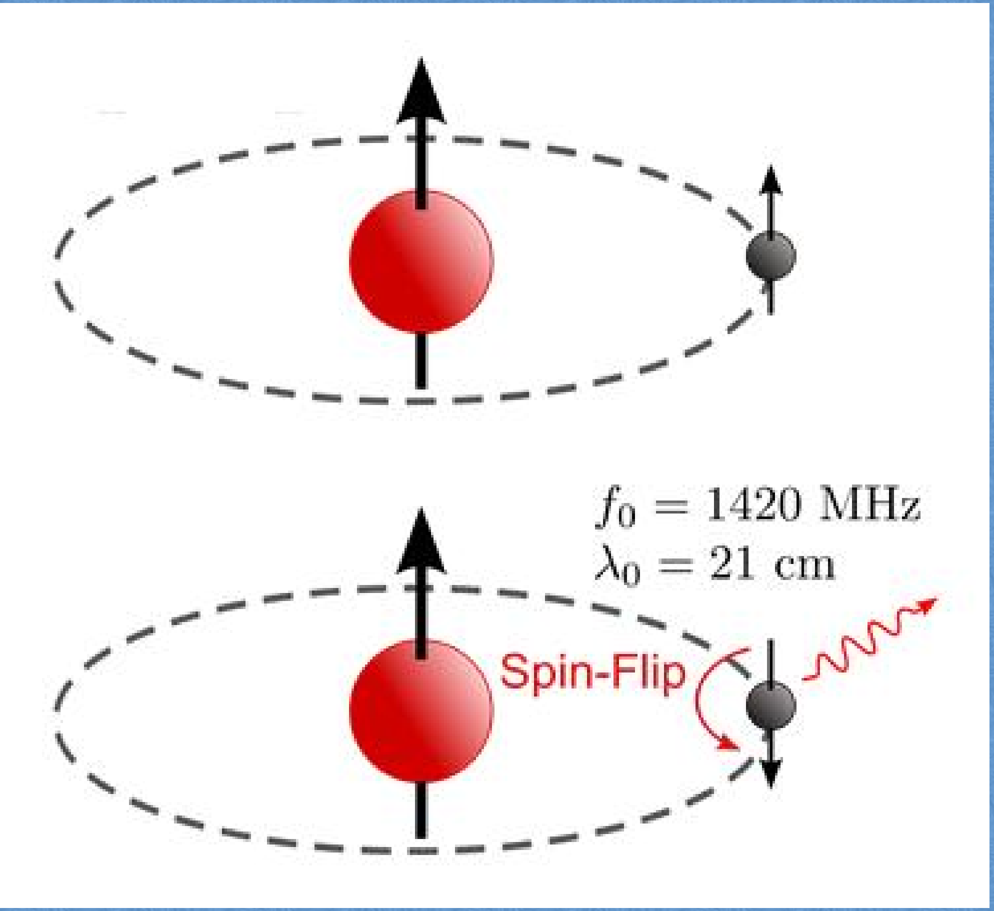
The interaction term in non-relativistic limit is:

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

The transition rate is

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

Hydrogen 1S state transitions



Hydrogen atoms are ideal targets for the quantum window

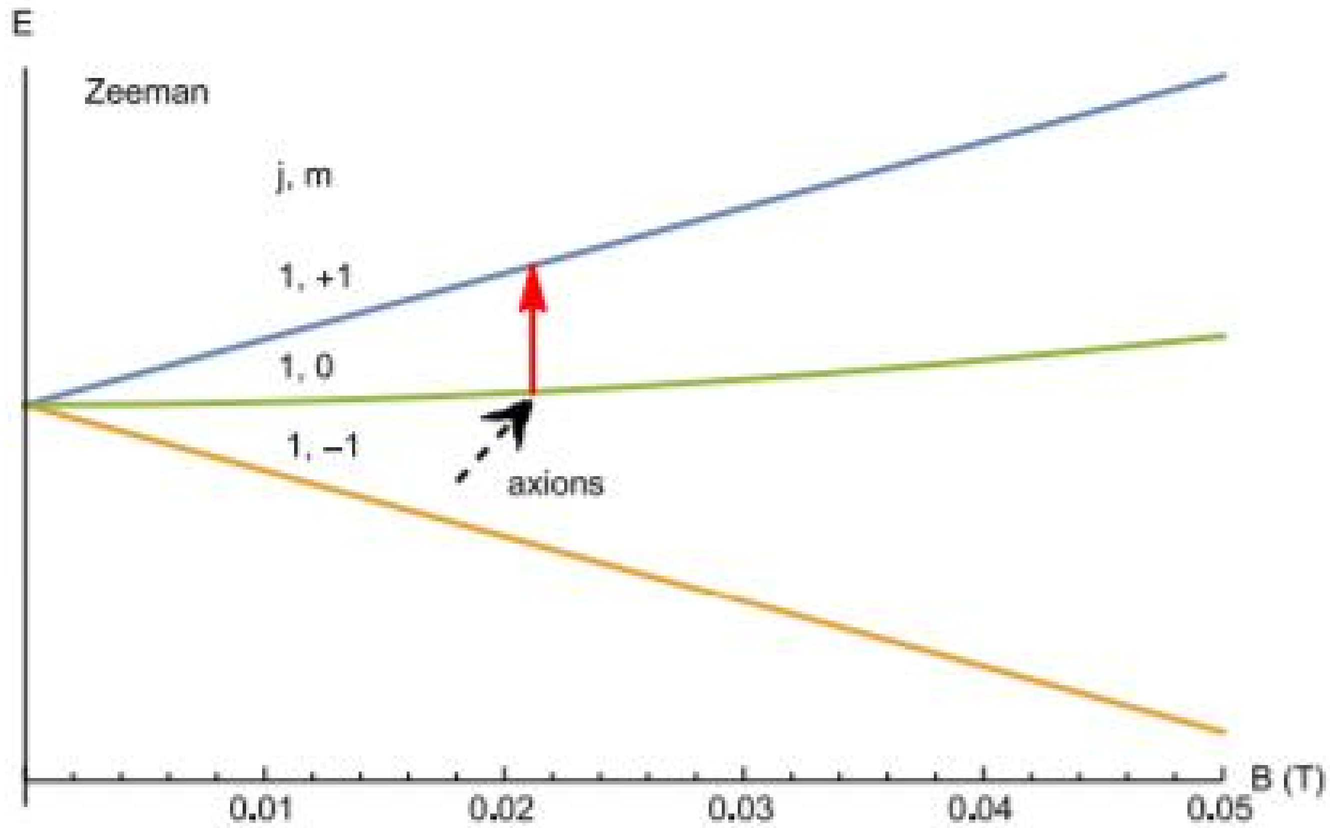


FIG. 3: The splitting of the hydrogen $1S$ triplet state. For the anthropic window $|1,0> \to |1,1>$ transition is suitable for the axion detection.

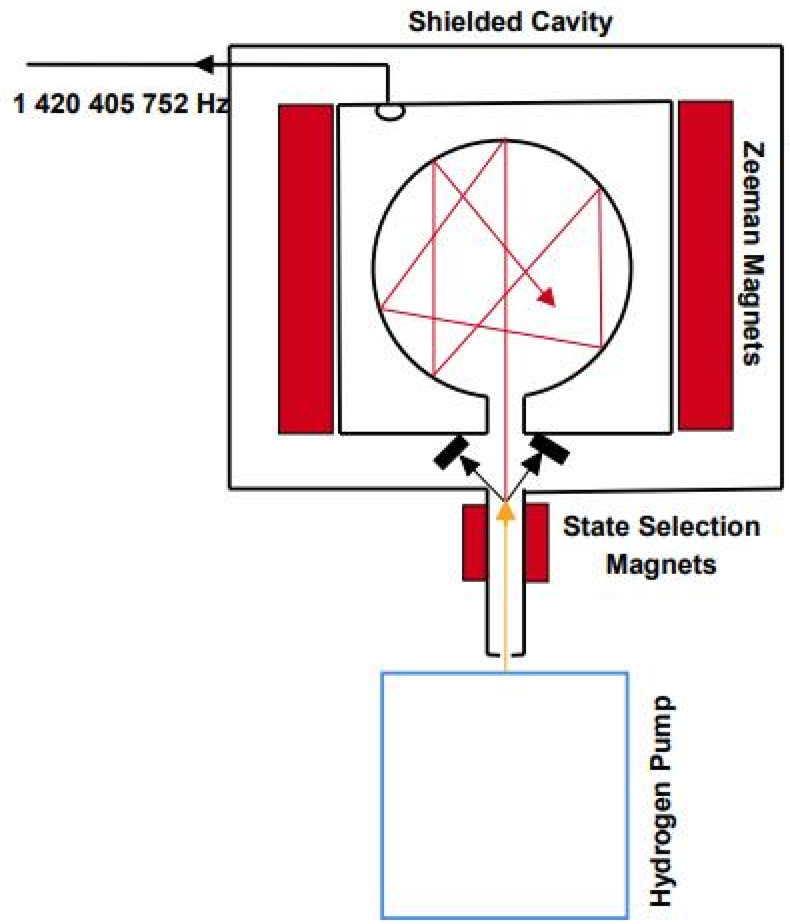
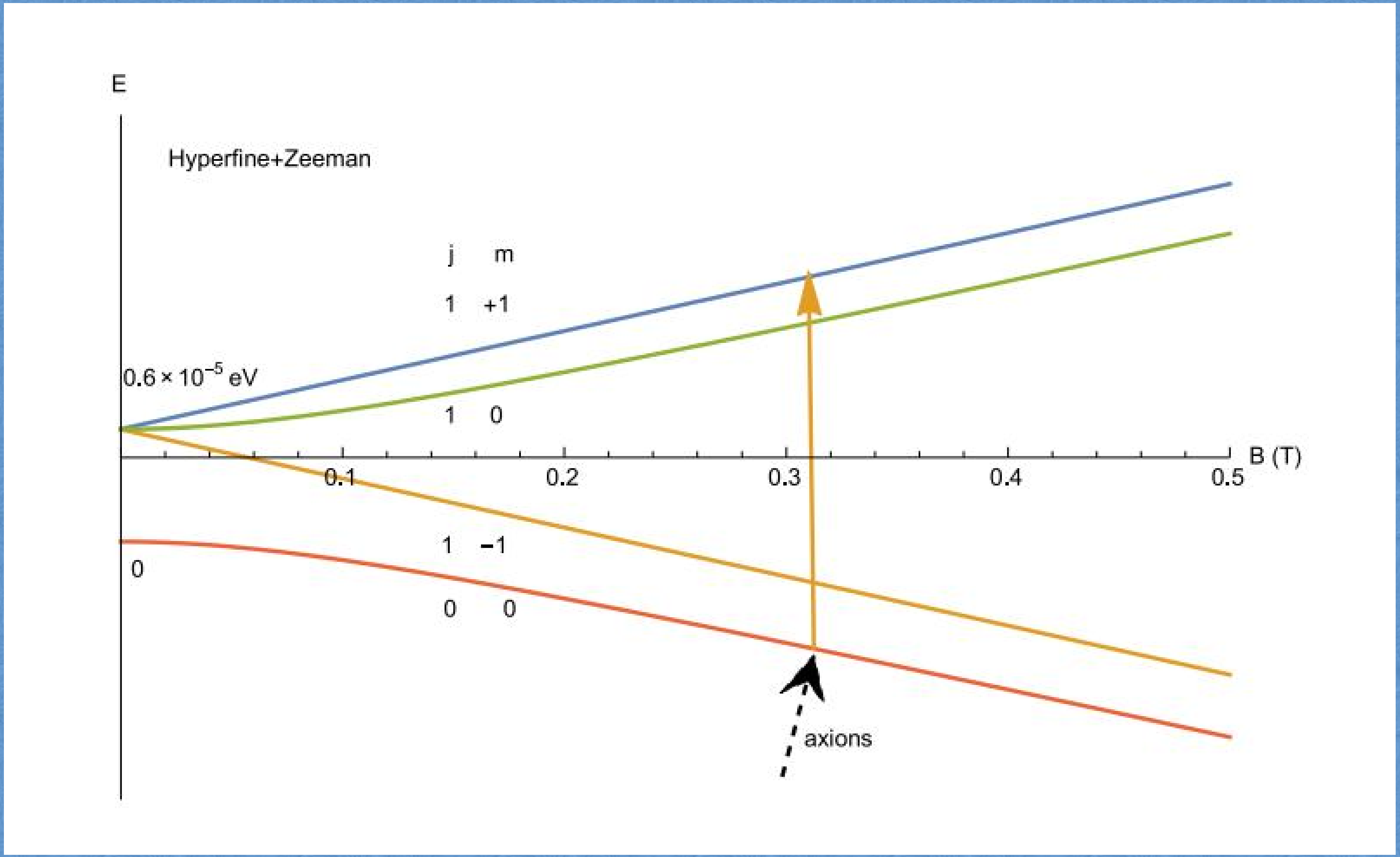
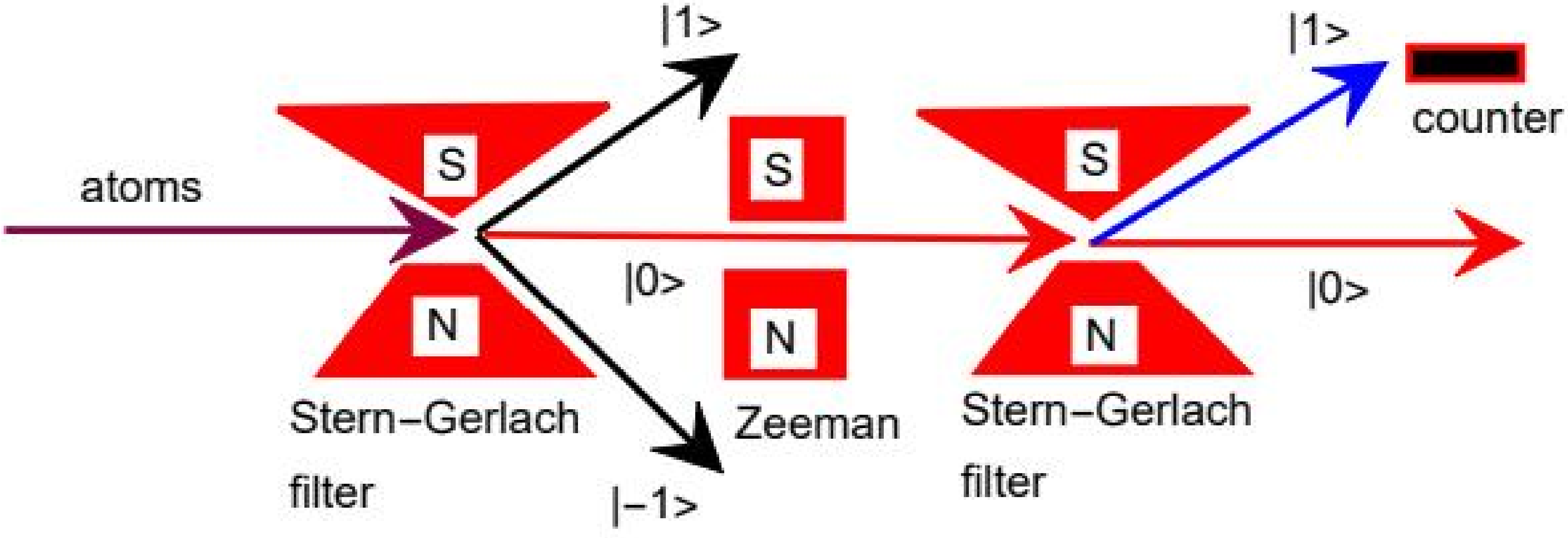


FIG. 5: An illustration of a typical hydrogen maser. With some modifications such as adding Zeeman magnets it may realize the scheme shown in Fig. 4.


E
Hyperfine+Zeeman
j m
1 +1
0.6×10^{-5} eV
1 0
B (T)
0.1
0.2
0.3
0.4
0.5
1 −1
0
0 0
axions


|1>
|1>
counter
atoms
S
S
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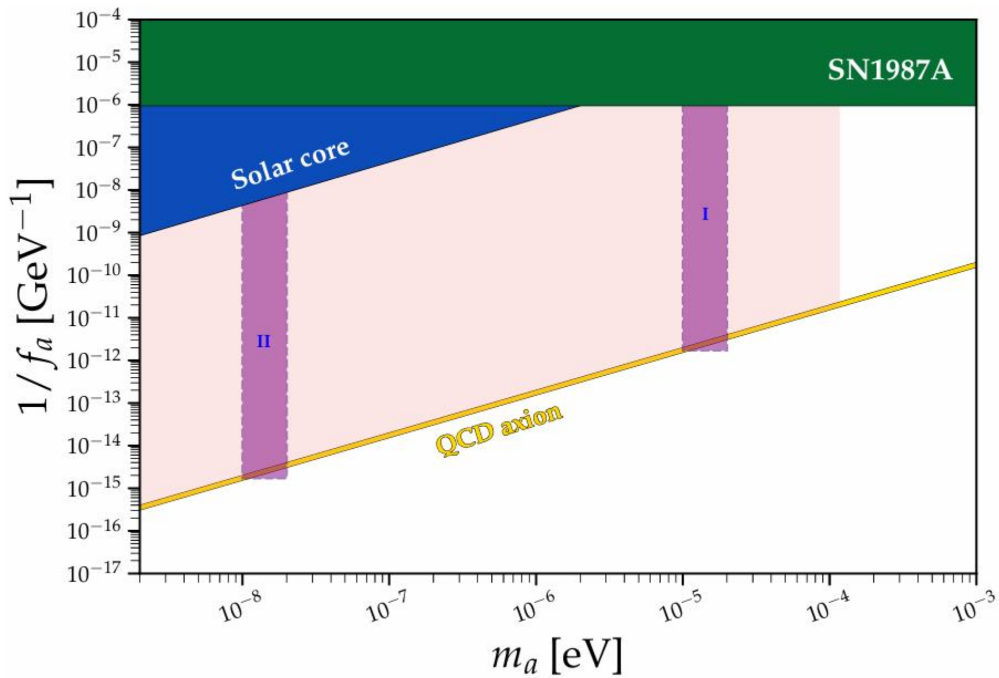


FIG. 3: The mass range that can be covered is determined by the available Zeeman field strength. To cover Region I ($m_a \in [10^{-5}$ eV, 2×10^{-5} eV$]$), a field strength of 0.15 Tesla is needed. Assuming 10% of this region is covered in a one-year data-taking period using 1 mole of H atoms, the sensitivity is $f_a = 5.8\times10^{11}$ GeV. For Region II ($m_a \in [10^{-8}$ eV, 2×10^{-8} eV$]$), a field strength of 0.002 Tesla is required. Assuming 10% of this region is covered using 10^3 moles of H over a one-year data-taking period, the sensitivity is $f_a = 5.8 \times 10^{14}$ GeV. The yellow band defines the QCD axion parameter space. The solid-colored regions, SN1987A and Solar Core, have been excluded by experiments and observations. The light coral region can be probed using this hydrogen splitting method if a 1 Tesla Zeeman field and an adequate amount of hydrogen atoms are deployed.

Dark Dimension

- Key Properties to phenomenology:

a. 1 Large Extra Dimension

a lot of KK modes of dark matter.

b. Standard Model particles are confined on 4D.

QCD axions can only account 1% dark matter.

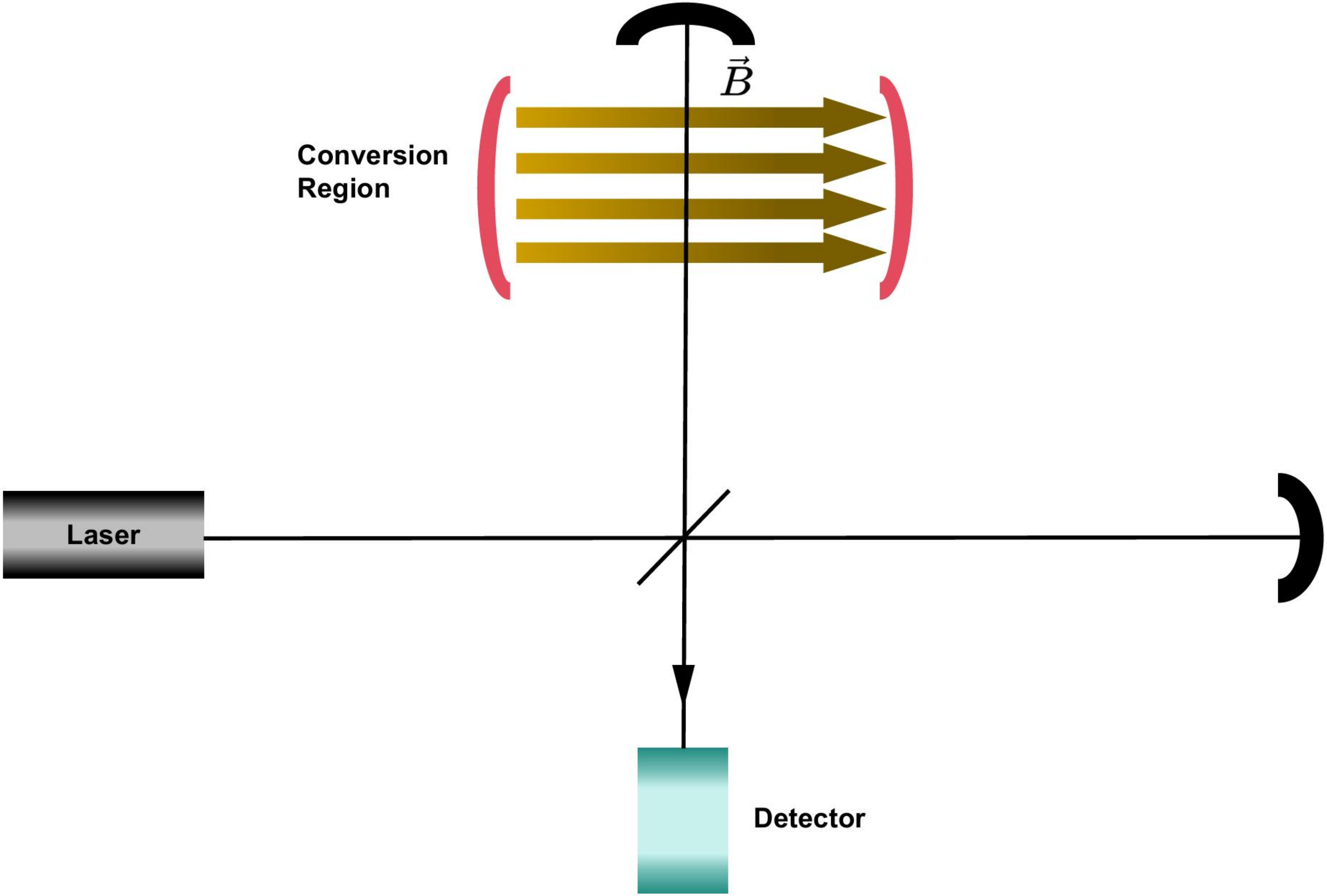
Dark Dimension

The one extra dimension is compactified with a radius on the order of microns. This dimension is "dark" because its effects are detectable only through gravitational, ultra high-energy phenomena.

Phenomenological Implications

Inflation: The dark dimension’s size inflates from a fundamental length

Gravitational Effects: Deviations from Newton’s inverse-square law at micron scales .


$\vec{B}$
Conversion
Region
Laser
Detector

Amplitude modulation (AM) should be used in interferometer that enhance measurement precision.

$$I(t) = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos(\phi(t))$$

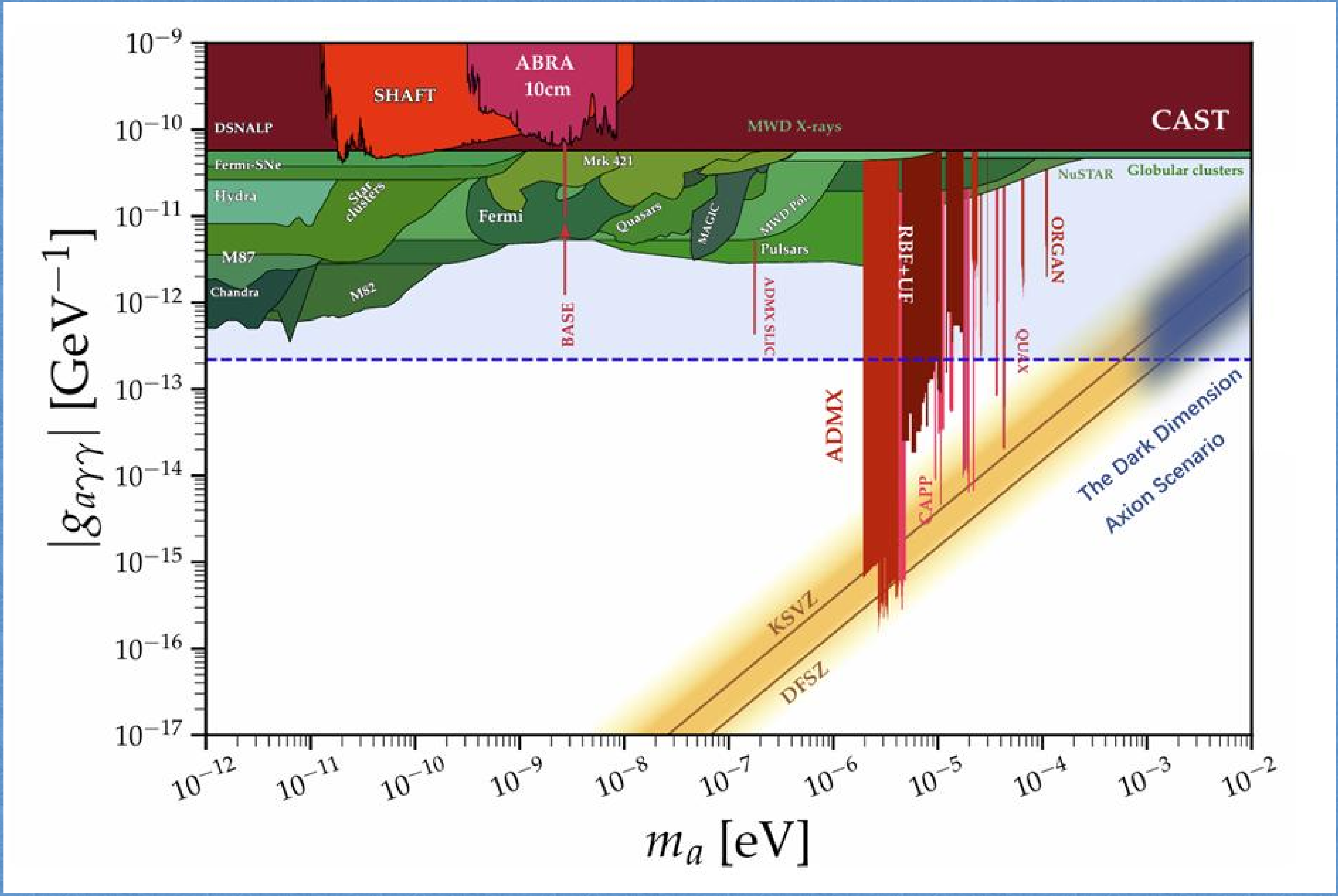
Squeezed light technology could give additional boost of sensitivity.

Axion in magnetic field

The conversion rate : $$\eta_{\gamma \to a} \approx \frac{1}{4}(g_{a\gamma\gamma} B L)^2$$

Amplitude modulation:

$$\vec{E}_{in} = \vec{E}_0 (1 + \beta \sin \omega_m t) e^{i\omega t}$$



Assuming n ~10^6, B ~ 40 T, L ~30 m with a 10 W (λ = 1μm) laser, and squeezed light achieving approximately O(10) dB shot noise reduction, after 10 days of operation.

Conclusion: Bridging Quantum Gravity, Dark Matter, and Precision Experiments

Extra Dimensions: Generate Kaluza-Klein (KK) particle modes.

Axiverse: Predicts a multitude of axion-like particles (ALPs).

QCD Axion: Solves the strong CP problem; potential dark matter (DM) candidate.

Dark Dimension Phenomenology

Large Extra Dimension: Compactified at ~micron scale ("dark" gravity/UV phenomena).

KK Dark Matter: Abundant modes; Standard Model confined to 4D.

Conclusion: Quantum Detection Strategies

Cavity Transitions

Hydrogen 1S states probe.

AM Interferometry: Amplitude modulation enhances precision (micron-scale sensitivity).

Squeezed Light: Reduces shot noise by ~10 dB for breakthrough sensitivity.

Implications

Unification: Links string theory, DM, and quantum experiments.

Future: AM + squeezed light enables next-gen axion searches.