New method of galactic axion detection

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Introduction: QCD-axion and its cosmology

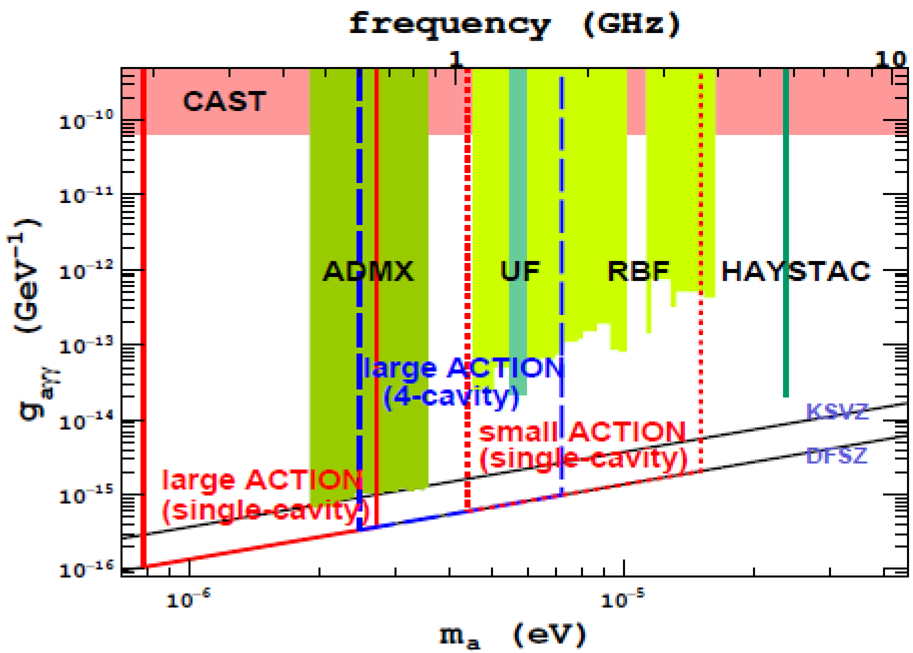
- PQ-symmetry solution to strong CP problem: the most compelling, leading to the axion

$$m_a = 10^2 \sim 10^{-3}\ \mathrm{meV} \qquad f_a = 10^8 \sim 10^{13}\mathrm{GeV}, \qquad g_{a\gamma\gamma} = c_{a\gamma\gamma}\frac{\alpha}{\pi f_a}$$

- Cold dark matter, perhaps the most attractive in view of absence of SUSY signals in LHC
- Galactic number density $n_a \sim 10^{13}\mathrm{cm}^{-3}$

  comparable to BB photons of T= 10^4 K

Ongoing and proposed experiments



Sikivie's original idea

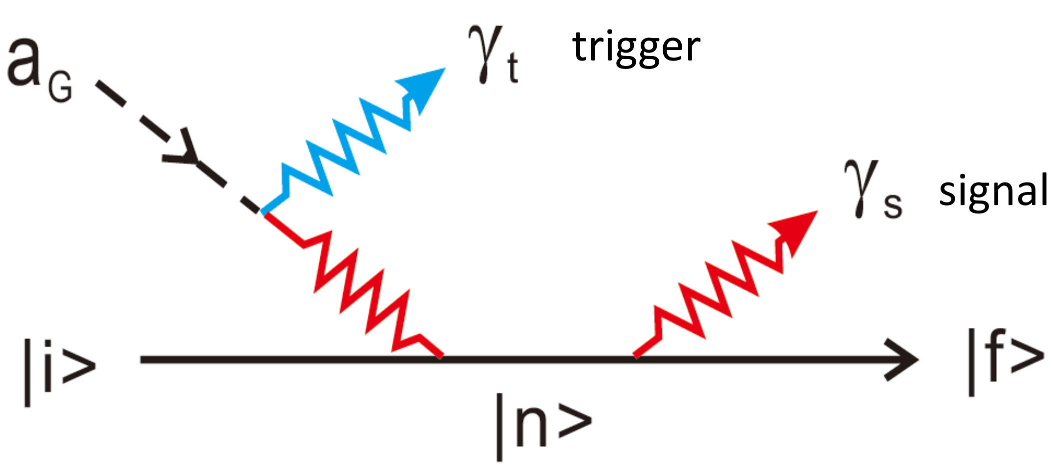
From CAST group paper

- Axion haloscope has the highest sensitivity, but time consuming experiment

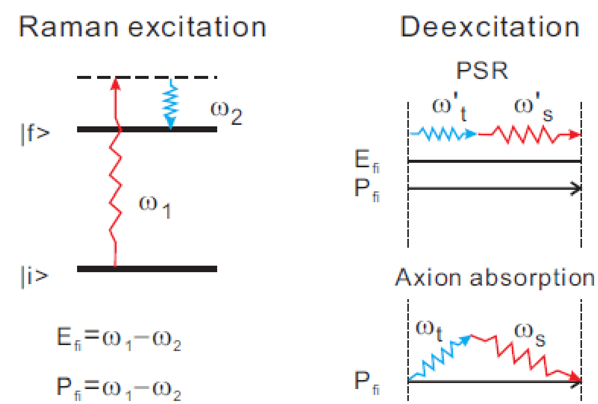
Microscopic process of detection using atoms and molecules

MY and N. Sasao, arXiv:1710.11262

TRACA (Triggered Radiative Absorption of Cosmic Axion)

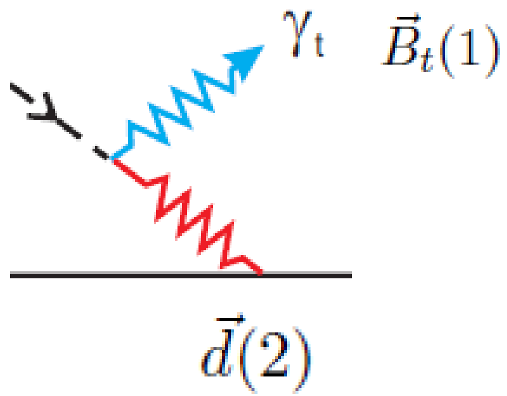


$$a_G + |i\rangle \to |f\rangle + \gamma_t + \gamma_s$$



$$\sqrt{\frac{\rho_a}{2}}\,\frac{c_{a\gamma\gamma}\,\alpha}{\pi m_a f_a}\left(\frac{\vec{d}_{nf}\cdot\vec{E}_s\vec{d}_{ni}\cdot\vec{B}_t}{\epsilon_{ni}}\frac{(k_t-q)_0^2}{(k_t-q)^2}+(s\leftrightarrow t)\right)\times 2\,,$$

Interesting feature of probability amplitude



propagator sandwiched
between external EM field and atomic dipole

$$\vec{B}_i(1) \cdot \langle 0 | T(\vec{E}(1)\vec{E}(2)) | 0 \rangle \cdot \vec{d}(2)\,, \; i = s, t$$

$$\Rightarrow i \frac{(k_i - q_a)_0^2}{(k_- q_a)^2} \vec{B}_i(1) \cdot \vec{d}(2) \sim -i \frac{\omega_i}{2m_a} \vec{B}_i(1) \cdot \vec{d}(2)$$

(1) apparently T-violating and P-violating
without directly detecting the axion

(2) large by $\frac{1}{m_a}$

3 enhancement factors

- Ambient axions, giving enhanced coupling

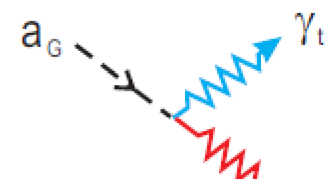
- Triggered photon number density

CO_2 laser of $\omega_t = 0.124\mathrm{eV}$ photon number density $10^{18}\,\mathrm{cm}^{-3}$

- Macro-coherence amplification

- Last two issues: verified by Okayama PSR experiments of p-H_2

Induced two-photon coupling by galactic axion



induced dimensionless "$g_{a\gamma\gamma}$" =

$$\sqrt{\frac{n_G}{2m_a}} g_{a\gamma\gamma} = c_{a\gamma\gamma} \sqrt{\frac{\rho_G}{2}} \frac{\alpha}{\pi m_a f_a} \sim 10^{-22} c_{a\gamma\gamma}$$

$\approx$ Fermi constant at 1eV scale

$$c_{a\gamma\gamma} = -0.97\,,\ \text{KSVZ}\,, \quad = 0.36\,,\ \text{DFSZ}$$

Rate amplification by macroscopic coherence: an oversimplifed view

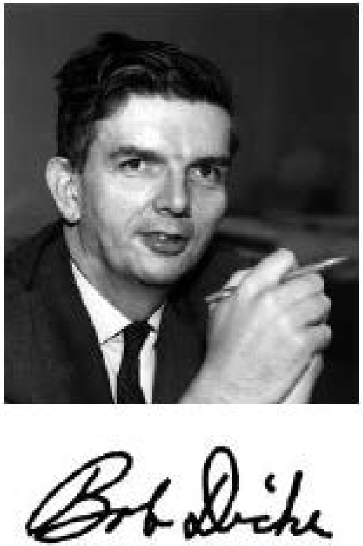
- Super-radiance coherent volume (Dicke)
  - In case of SR, coherent volume is proportional to $\lambda^2 L$.
  - Phase decoherence time (T_2) must be longer than T_{SR}

$$\mathrm{Rate} \propto \left| \sum_j^N e^{i\vec{k}\cdot\vec{r}_j} M_{atm} \right|^2 \propto N^2 \quad \left(\mathrm{for}\ |r_j - r_l| \leq \lambda\right)$$

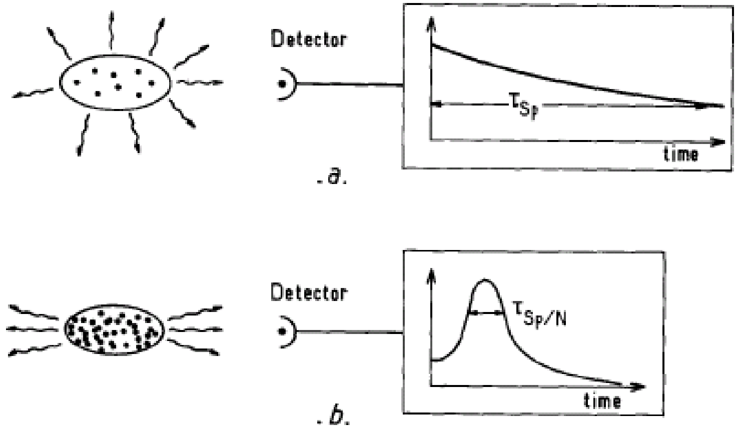
- For a process with plural outgoing particles (PSR, RENP etc)
  - Phase matching condition (momentum conservation) is satisfied.
  - Coherent volume is not limited by λ., can be macroscopic.

$$\mathrm{Rate} \propto \left| \sum_j^N e^{i(\vec{k}_1+\vec{k}_2+\vec{k}_3)\cdot\vec{r}_j} M_{atm} \right|^2 \propto N^2 \quad \left(\mathrm{for}\ \vec{k}_1+\vec{k}_2+\vec{k}_3 = 0\right)$$

Superradiance: 2 level and E1 photon case



1916 — 1997



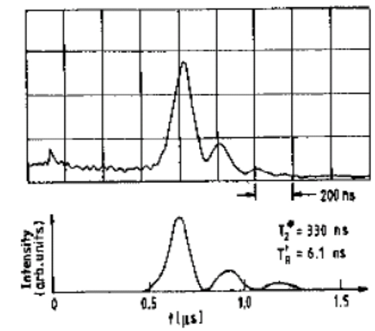
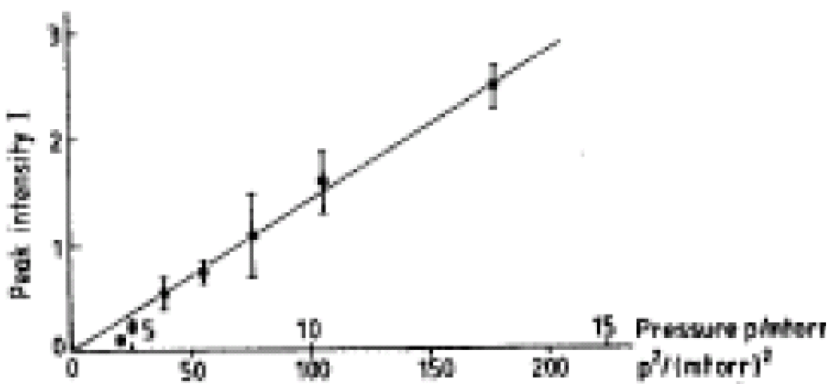
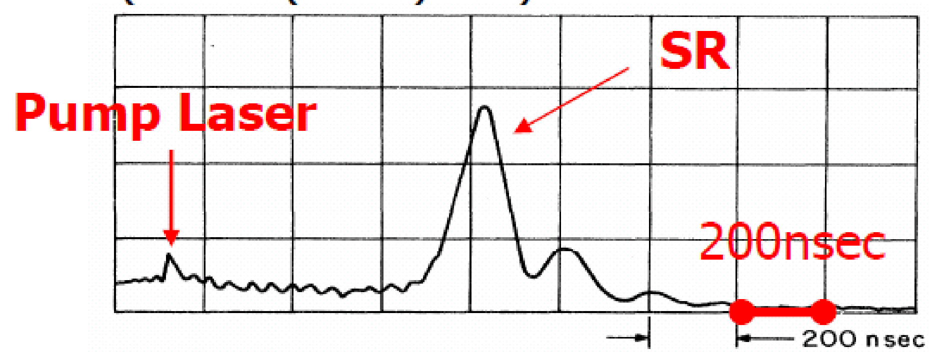


Figure 2.2. Oscilloscope trace of the super-radiance pulse observed by Skribanowitz *et al* [SHMF73] in HF gas at 84 μm ($J = 3 \to 2$), pumped by the $R_1(2)$ laser line, and the theoretical fit. The parameters are: pump intensity $I = 1$ kW cm^{-2}, $p = 1.3$ mTorr, $L = 100$ cm. The small peak on the oscilloscope trace at $t = 0$ is the 3 μm pump pulse, highly attenuated.



Rate enhanced by N

(PRL30(1973)309)

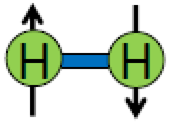


Delayed enhanced signal accompanied by ringing

PSR experiments at Okayama

Courtesy of H. Hara

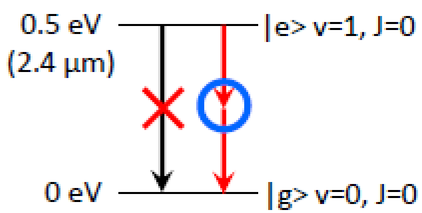
para-H_2



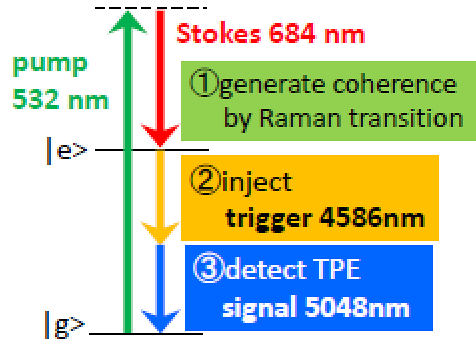
I = 0
J = 0, 2, 4, · ·

vibrational transition
of homonuclear molecule

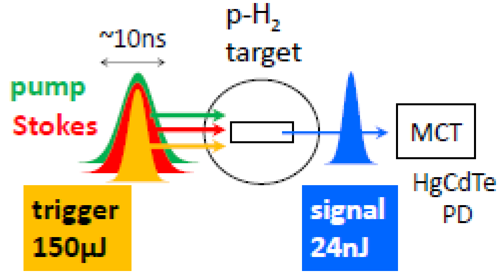
One-photon (E1) forbidden.
Two-photon (E1 × E1) allowed.



spontaneous TPE rate
7×10^{-12} Hz

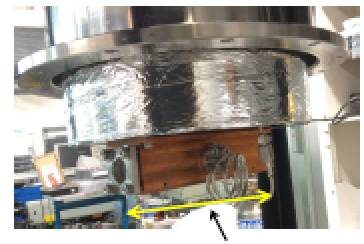


・high intensity ~ mJ
○ pulse , × CW
・narrow linewidth
near FT limit (~100MHz)



requirement for amplification

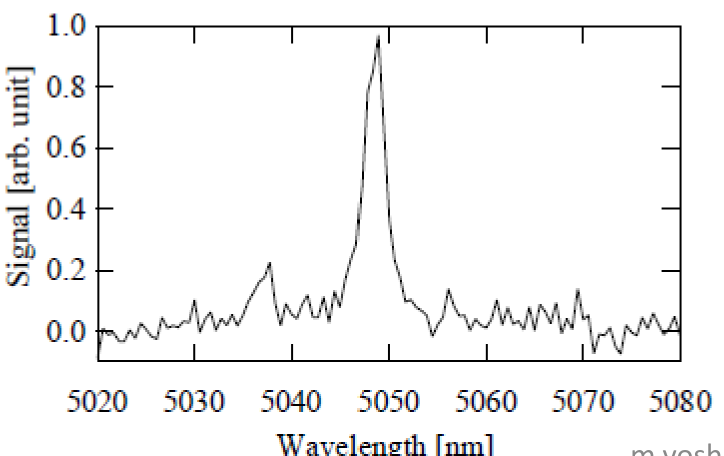
$$\vec{k}_{\rm pump} - \vec{k}_{\rm Stokes} = \vec{k}_{\rm trig} + \vec{k}_{\rm sig}$$

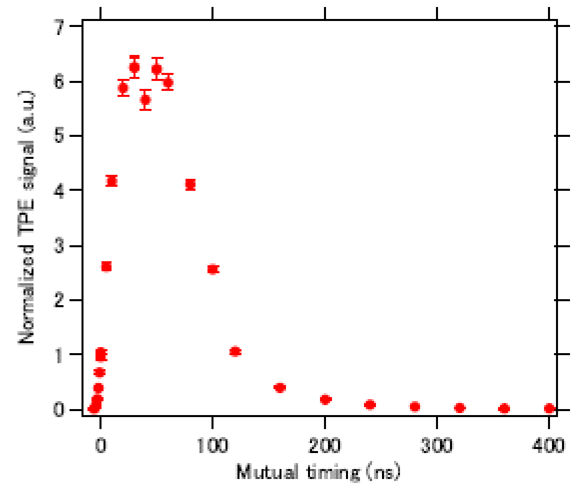


T = 78 K 150 mm

density 5.8×10^{19} cm^{-3}

decoherence time 2.4 ns





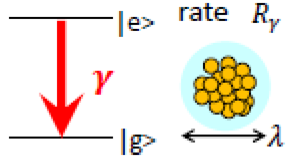
HH

Rate Amplification using Coherence

RENP rate is very low. Γ_{RENP} ~ 10^{-34} Hz ($1/10^{26}$ year)

Such small rate can be amplified by coherence.

superradiance R. H. Dicke, PR 93, 99 (1954)



rate $R_\gamma = \left|\sum_a^N \exp(i\vec{k}\cdot\vec{r}_a)\, M_a\right|^2 \approx N^2|M_a|^2$

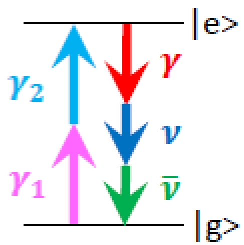
=0 ∝N² (amplified)

Enhancement occurs in a limited volume. $r_a \ll \lambda$

How about multi-particle emission process?

$R_\gamma = \left|\sum_a^N \exp[i\{(\vec{k}_1+\vec{k}_2)-(\vec{k}_\gamma+\vec{k}_\nu+\vec{k}_{\bar\nu})\}\cdot\vec{r}_a]\, M_a\right|^2 \approx N^2|M_a|^2$

=0 ∝N² (amplified)



Enhancement occurs when momentum conservation law of absorbed and emitted particles is satisfied.

$\vec{k}_1+\vec{k}_2=\vec{k}_\gamma+\vec{k}_\nu+\vec{k}_{\bar\nu}$

$r_a > \lambda$

Enhancement

$$\frac{\text{measured photon number}}{\text{spontaneous emission}} = \frac{6\times10^{11}}{2\times10^{-7}} = 10^{18}$$

Coherent amplification is demonstrated for multi-particle emission process.

Our target choice for axion detection

- p-H_2, since our group at Okayama has experiences with this molecule, such as coherence determination, PSR measurements both for gas and solid.

Y. Miyamoto *et al.*, "Externally triggered coherent two-photon emission from hydrogen molecules", Prog. Theor. Exp. Phys. vol. **2015**, 081C01 (2015); Y. Miyamoto *et al.*, "Vibrational Two-Photon Emission from Coherently Excited Solid Parahydrogen", J. Phys. Chem. A, vol. **121**, 3943 (2017); Y. Miyamoto *et al.*, "Observation of coherent two-photon emission from the first vibrationally-excited state of hydrogen molecules", Prog. Theor. Exp. Phys., vol. **2014**, 113C01 (2014).

$$\frac{d\Gamma_{\rm off}}{d\Omega_s} = \frac{\rho_G}{64\pi^4}(\frac{c_{a\gamma\gamma}\alpha}{m_a f_a})^2 \frac{\mu_{if}^2 \epsilon_{if}^2}{m_a^2}\omega_s^3 E_t^2 \rho_{if}^2 N_T^2 \sin^2\theta_{\rm pol}\, \mathcal{A}$$

$\mu_{if} = \text{polarizability} \sim 2\sum_n \frac{d_{ni}d_{nf}}{\epsilon_{ni}} \sim 1.43 \times 10^{-24}\,{\rm cm}^3$ For p-H_2

$\rho_{if} = \text{coherence}$

$\theta_{\rm pol} = \text{relative angle between trigger and signal linear polarizations}$

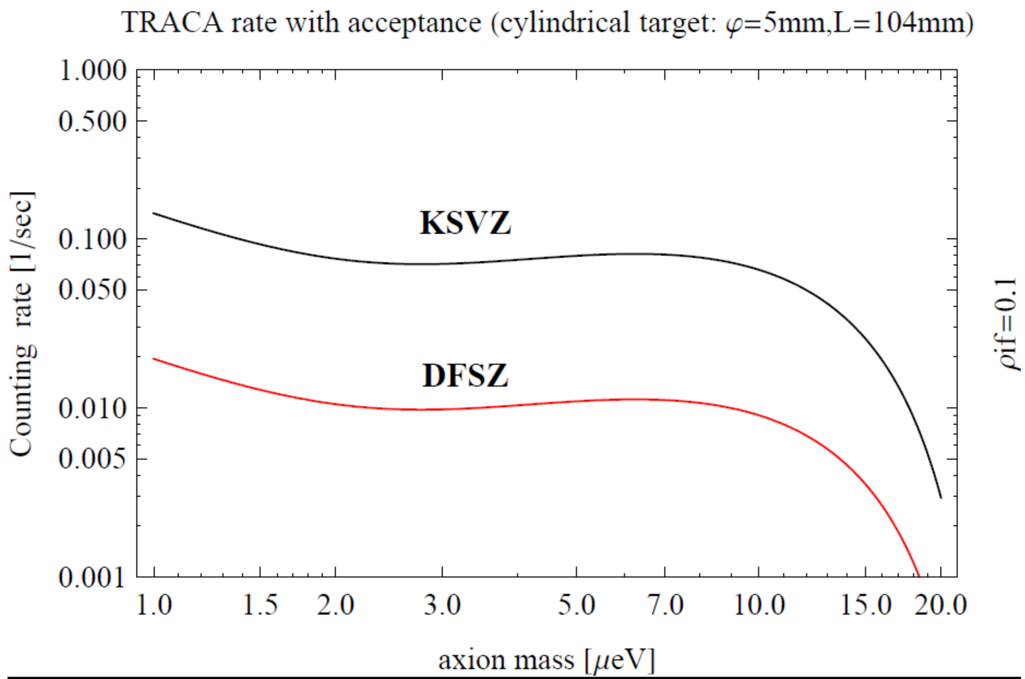
$$\mathcal{A} = \frac{1}{(\pi R^2 L)^2}\left(\frac{2\sin(K_{\parallel}L)}{K_{\parallel}}\right)^2 \left(\frac{2\pi R}{K_{\perp}}J_1(K_{\perp}R)\right)^2$$

$$\vec{K} = \vec{k}_s + \vec{k}_t - \vec{p}_{if} - \vec{q}_a$$

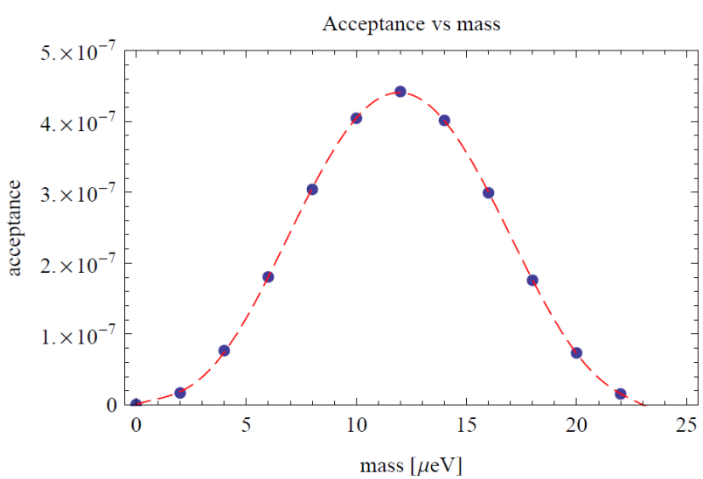
$$\frac{d\Gamma_{\rm off}}{d\Omega_s} \sim 2.9 \times 10^5\,{\rm sec}^{-1}(\frac{10\mu\,{\rm eV}}{m_a})^2 x_t(1-x_t)^3 \sin^2\theta_{\rm pol}\,\mathcal{A}X\,,\ \mathcal{A} = O(10^{-7})$$

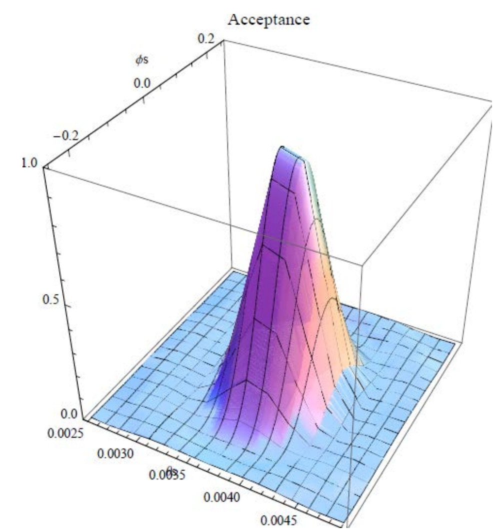
$$X = c_{a\gamma\gamma}^2(\frac{n_T}{2.6\times 10^{22}\,{\rm cm}^{-3}})^2(\frac{n_t}{10^{18}\,{\rm cm}^{-3}})(\frac{\rho_{if}}{0.1})^2(\frac{V}{{\rm cm}^3})^2\,, \quad x_t = \frac{\omega_t}{\epsilon_{if}}\,.$$

Detection rates: work with N.Sasao



Revised from arXiv paper





Finite target size effect

Formula $| \int_V d^3x e^{i\vec{K}\cdot\vec{x}} |^2 = V(2\pi)^3 \delta(\vec{K})$ is a useful guide, but cannot be used for rate calculation

$$\int d^3q | \int_V d^3x \rho_{if} n_T e^{i(\vec{q}-\vec{K})\cdot\vec{x}} |^2 F_a(\vec{q}) \equiv (\rho_{if} n_T)^2 V^2 \mathcal{A}$$

$\vec{K} = \vec{k}_t + \vec{k}_s - \vec{p}_{if}$ and $\vec{p}_{if}$ the phase imprinted

$$\mathcal{A} = \frac{1}{(\pi R^2 L)^2} \left(\frac{2\sin(K_{\parallel} L)}{K_{\parallel}} \right)^2 \left(\frac{2\pi R}{K_{\perp}} J_1(K_{\perp} R) \right)^2$$

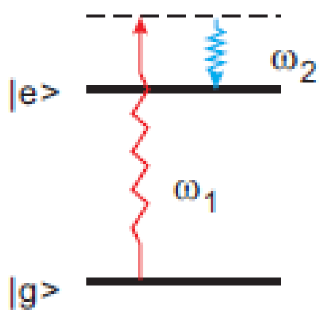
Cylinder of radius R, length L

$$K_{\parallel} = \epsilon_{if} - \omega_t \cos\theta_t - \omega_s \cos\theta_s \,, \qquad K_{\perp} =$$

$$\left((\omega_t \sin\theta_t - \omega_s \sin\theta_s)^2 + 4\omega_t \omega_s \sin\theta_t \sin\theta_s \sin^2 \frac{\varphi_s}{2} \right)^{1/2}$$

Excitation and trigger configuration

Raman excitation

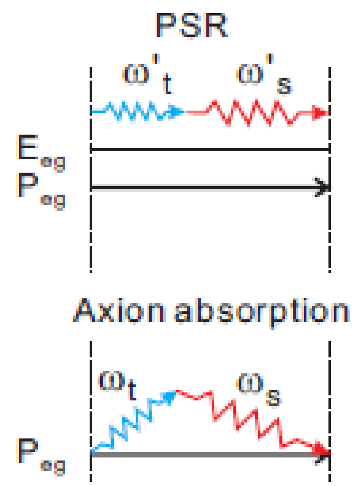


$E_{eg}=\omega_1-\omega_2$

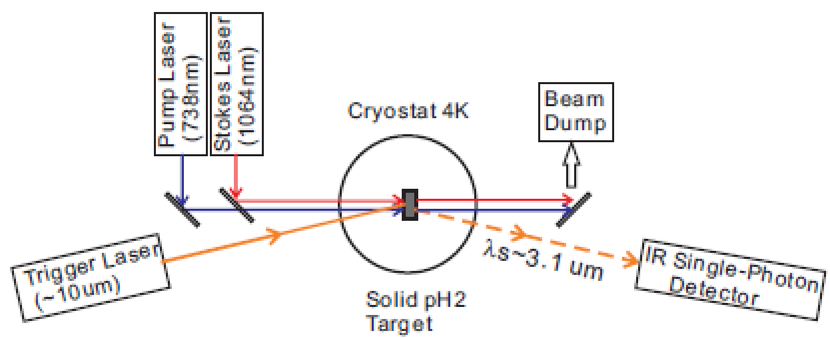
$P_{eg}=\omega_1-\omega_2$

From the same direction

Deexcitation



Energy and momentum conservation uses as a guide



Other possibilities: works in progress

- Targets of smaller level spacing: Fine-structure levels, HFS, molecular vibration (I_2 etc)

- Use of microwave or rf to get larger angular separation from PSR background

$$\theta_i \tan\frac{\theta_j}{2} = \frac{m_a}{\epsilon_{if}}\,, \qquad (ij) = (st)$$

- T-odd, P-odd asymmetries for background rejection

Summary

- Proposed atomic/molecular experiments for galactic axion search
- Detailed calculation for para-H_2 . Detectable rate without backgrounds
- Tunable for 10 umeV axion mass
- A wide parameter range search possible
- Many interesting alternatives to be studied