TRACA- a new way to track axion

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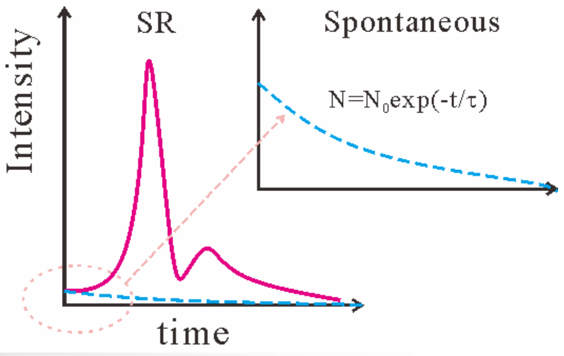
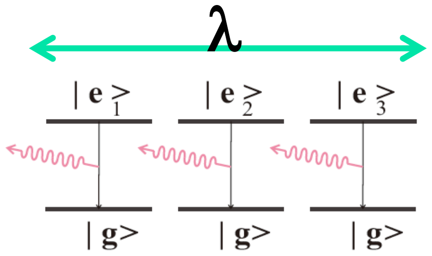
(work with M. Yoshimura)

Contents



Amplification by coherence among atoms



- Super-Radiance a la Dicke
  - De-excitation via single photon emission

$$R \propto \left| \sum_{m=0}^{N_T} \mathrm{Exp}\left(i\vec{k}_\gamma\ \vec{x}_m \right) M(\vec{x}_m) \right|^2 \propto N_T^2 \qquad \left[\because M(\vec{x}_m) = M(0),\ \ |\,\text{target size}\,| < \lambda \right]$$

- Macroscopic coherent amplification
  - De-excitation via multi-particle emission: $|e\rangle \to |g\rangle + \gamma\nu\nu$

$$R \propto \left| \sum_{m=0}^{N_T} \mathrm{Exp}\left(i(\vec{k}_\nu + \vec{k}_{\bar{\nu}} + \vec{k}_\gamma)\ \vec{x}_m \right) M(\vec{x}_m) \right|^2 \propto N_T^2 \quad \left[\because M(\vec{x}_m) = M(0),\ \vec{k}_\nu + \vec{k}_{\bar{\nu}} + \vec{k}_\gamma = 0 \right]$$

Effects of Spatial Phase Memory

- General conditions of amplification;

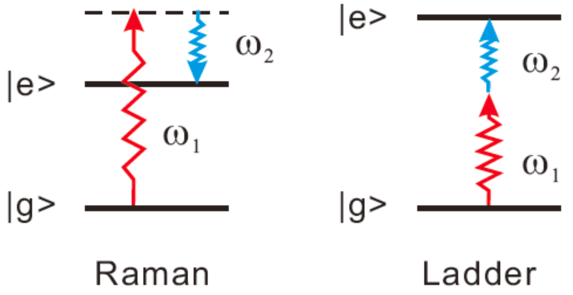
$$R \propto \left|\sum_{m=0}^{N_T} \mathrm{Exp}\left(i(\vec{k}_\gamma + \vec{k}_{\nu 1} + \vec{k}_{\nu 2})\ \vec{x}_m\right) M(\vec{x}_m)\right|^2 \propto N_T^2$$

$$\text{if}\quad M(\vec{x}_m) = M(0)\mathrm{Exp}\left(-i\vec{P}_{eg}\cdot\vec{x}_m\right) \rightarrow \vec{k}_\gamma + \vec{k}_{\nu 1} + \vec{k}_{\nu 2} = \vec{P}_{eg}$$

- Spatial phase Peg can be controlled;
  - Raman excitation:

$$P_{eg} = k_1 - k_2$$

Laser field: $E_0 e^{-i(\omega t - \vec{k}\cdot\vec{x})}$



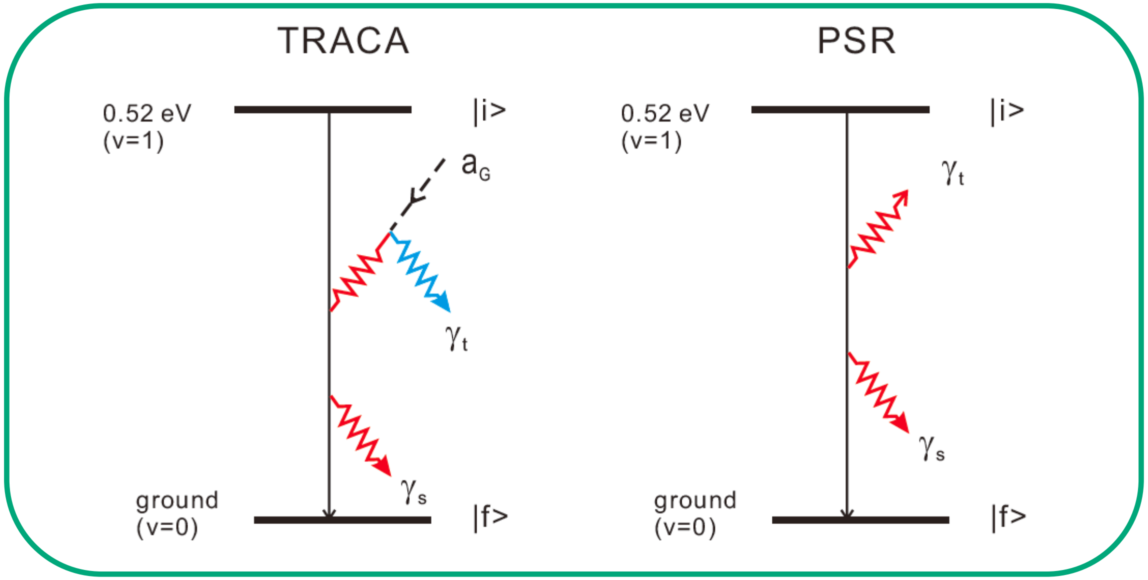
  - Ladder excitation: $P_{eg} = k_1 + k_2$ (co-propagating)

$$P_{eg} = k_1 - k_2 \quad \text{(counter-propagating)}$$

“Dynamics of two-photon paired superradiance”,
M. Yoshimura, N. S, and M. Tanaka, PHYSICAL REVIEW A 86, 013812 (2012)

Experimental proof of macroscopic coherent amplification

- PSR (paired super-radiance)
  - QED process where axion is replaced with a photon.
  - A pair of strong light pulses (SR) will be emitted.

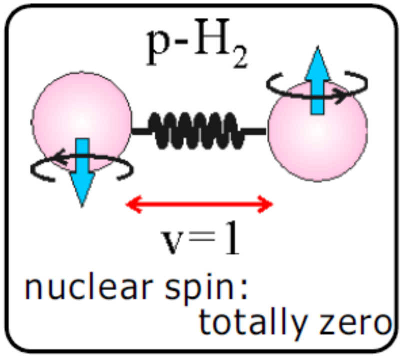


“Externally triggered coherent two-photon emission from hydrogen molecules”, Yuki Miyamoto et. al. Prog. Theor. Exp. Phys. **2015**, 081C01 (2015)

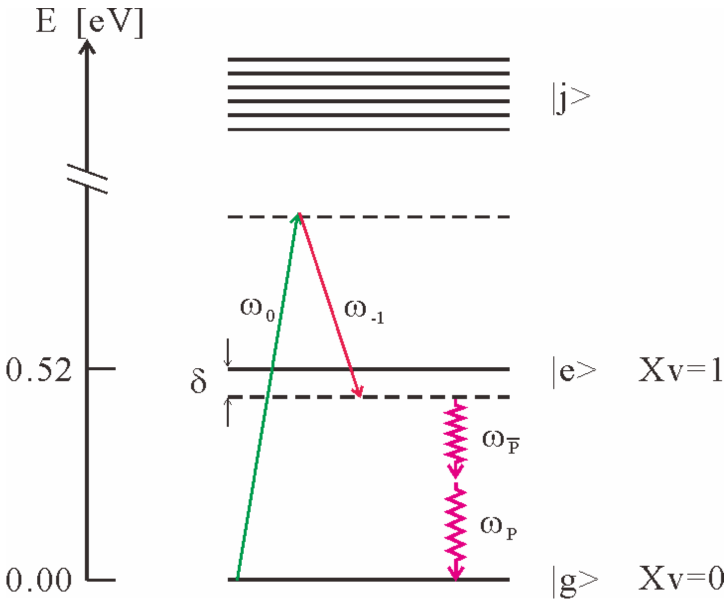
PSR experiments

- Para-hydrogen molecule (Spin=0)
  - Vibrational level (v=1) to ground level (v=0).
  - E1 forbidden.
  - Small 2-photon emission rate:

$$\Gamma \approx 1/2\times10^{12}\ \text{sec}$$

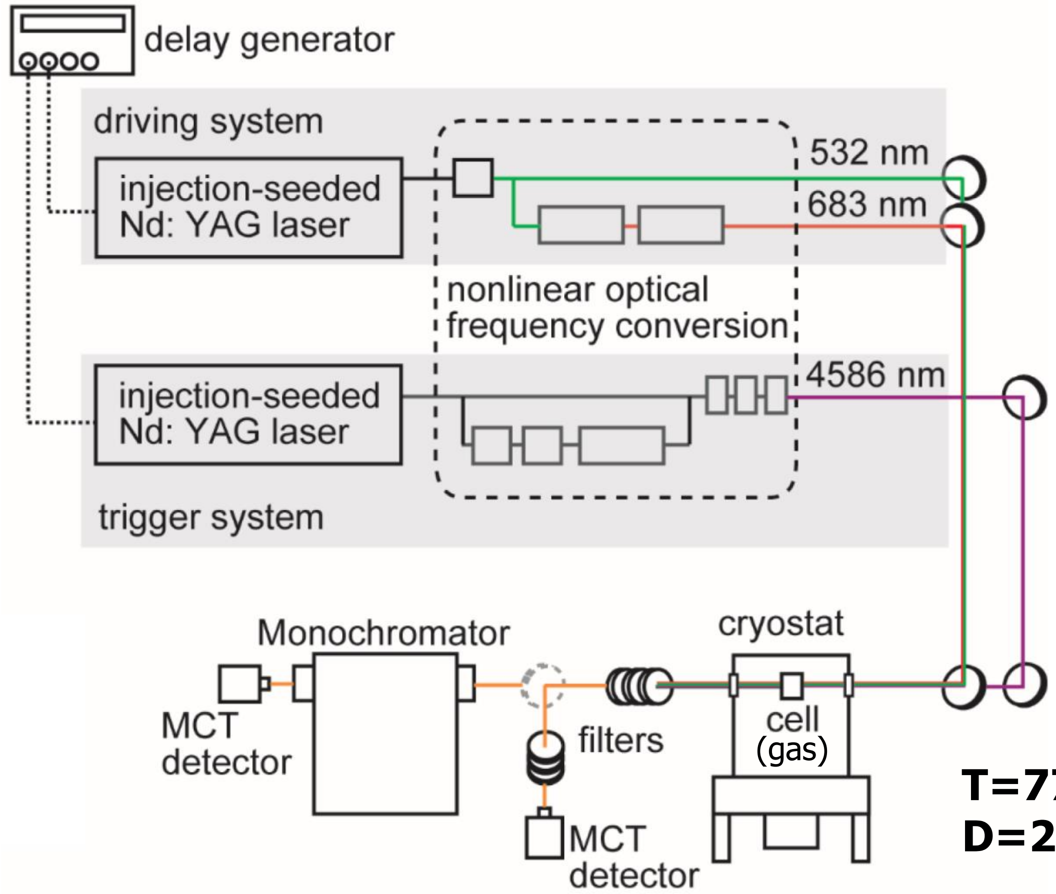


- Excitation scheme
  - Raman (co-propagating)
  - Ladder (counter-propagating)

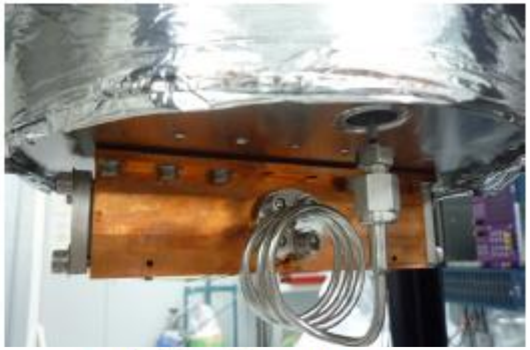


Experimental setup

Driving laser: 5 mJ/pulse, ~10nsec fwhm
Tigger laser: 150 uJ/pulse, ~2nsec fwhm



H$_2$ gas cell (15 cm long)

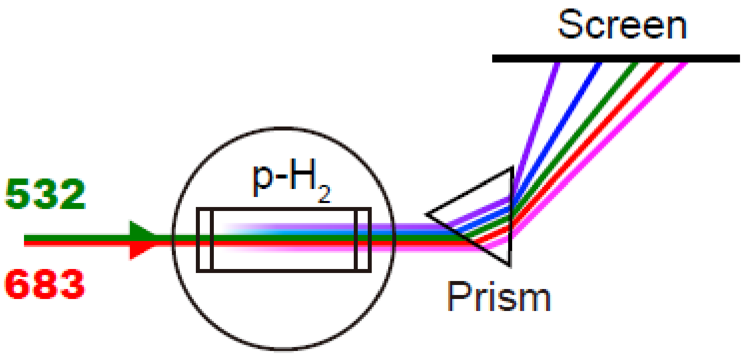


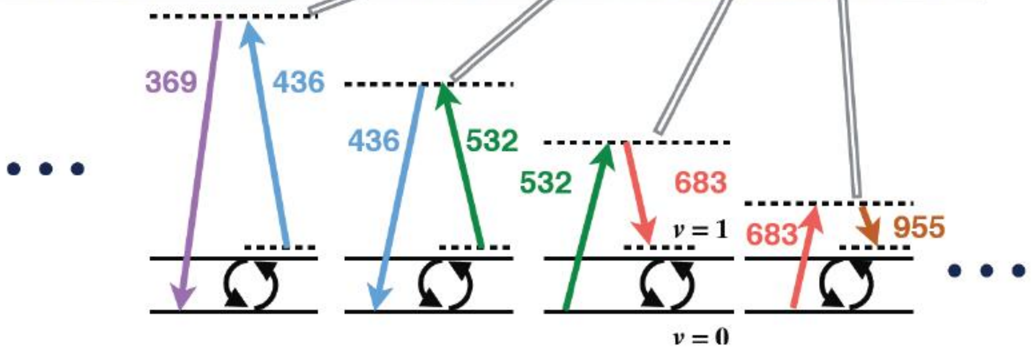
L-N$_2$ Cryostat

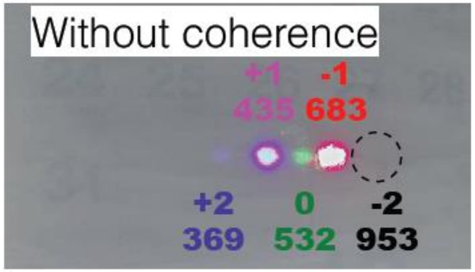
T=77K, P=60kPa
D=2cm, L=15cm

Observation of Raman sidebands

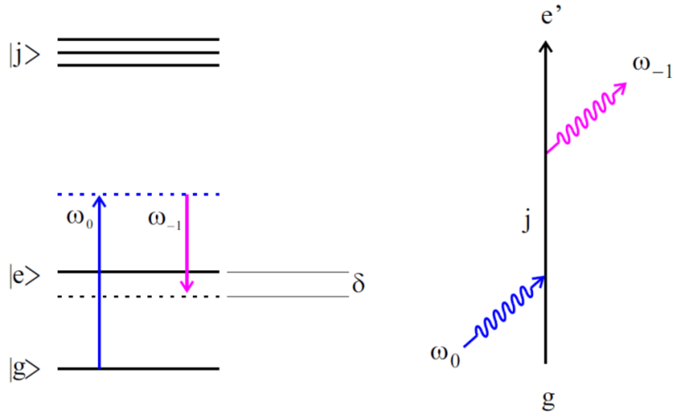
- 13 sidebands observed (λ=192 - 4662nm)
- Evidence for large coherence







Features of adiabatic Raman process



- Why we use Raman process?
  - Creation of coherence among two levels |e> and |g>
  - Generation of higher side-bands

$$\omega_q = \omega_0 + q\Delta\omega, \qquad \Delta\omega = \omega_0 - \omega_{-1},$$

Eigenstates:

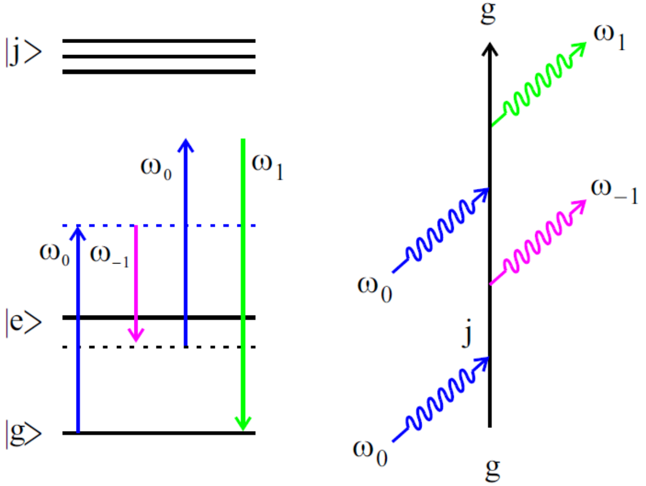
$$|\,+\,\rangle = \cos\theta|\,g\,\rangle + \sin\theta e^{-i\varphi}|\,e\,\rangle$$

$$|\,-\,\rangle = \cos\theta e^{-i\varphi}|\,e\,\rangle - \sin\theta|\,g\,\rangle$$

$$\tan 2\theta = \frac{|\Omega_{eg}|}{\Omega_{gg} - (\Omega_{ee} - \delta)}, \qquad \Omega_{eg} = |\Omega_{eg}|e^{i\varphi}$$

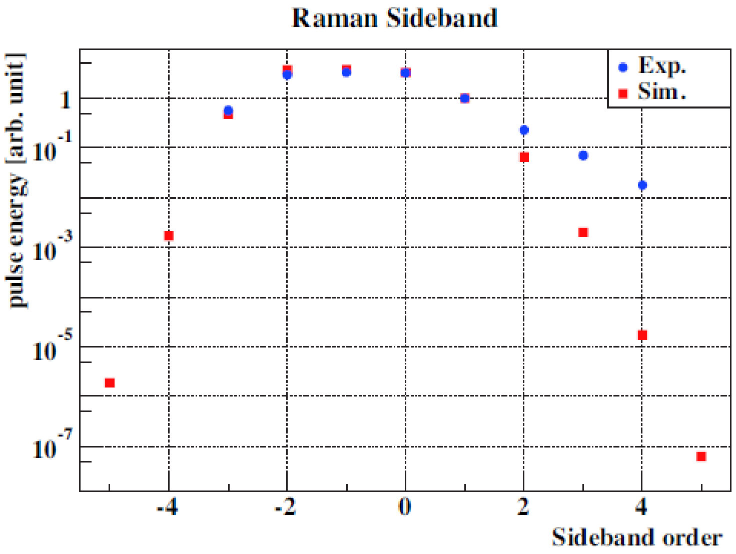
Density matrix ρ=|ψ><ψ|

$$\rho_{ge} = \cos\theta \sin\theta\, e^{i\varphi} = \frac{1}{2}\sin 2\theta\, e^{i\varphi}$$



Degree of coherence

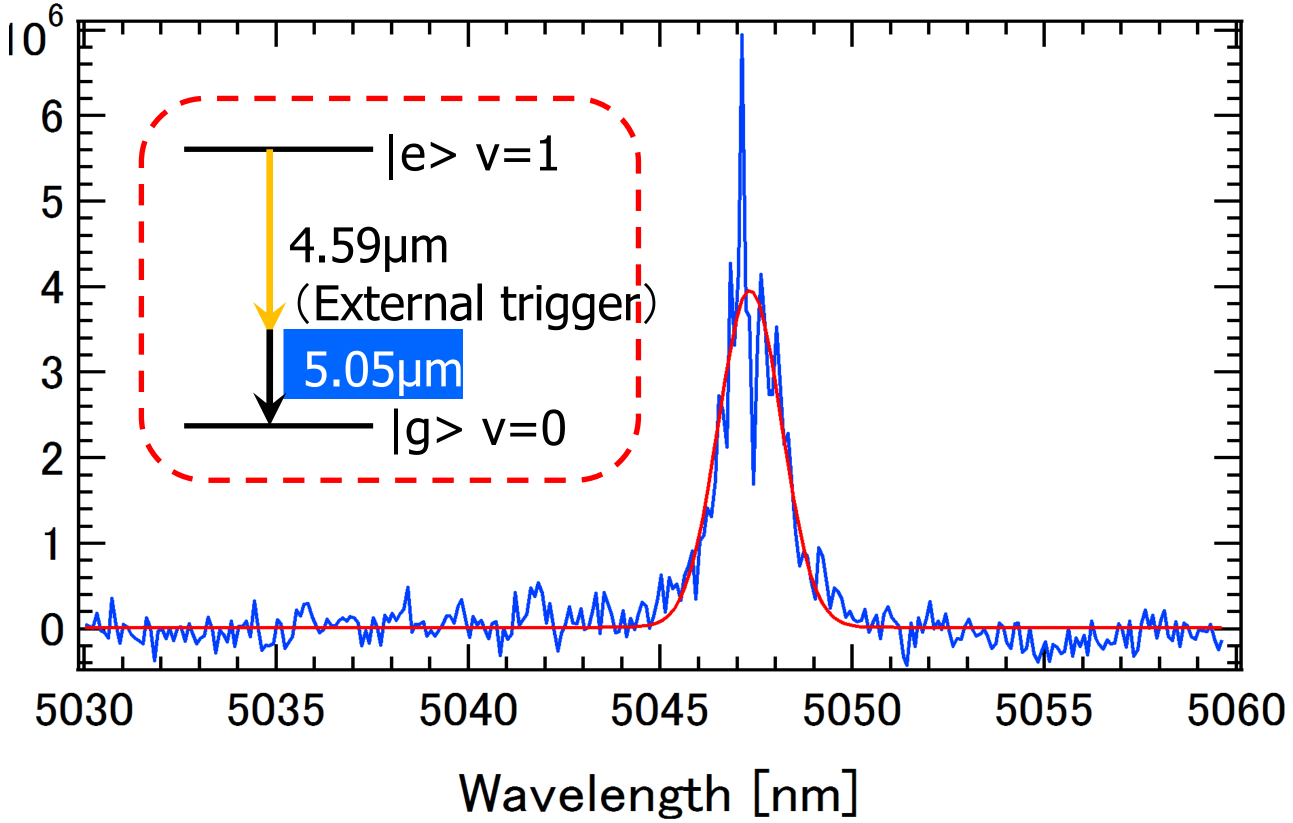
- Maxwell-Bloch eq.

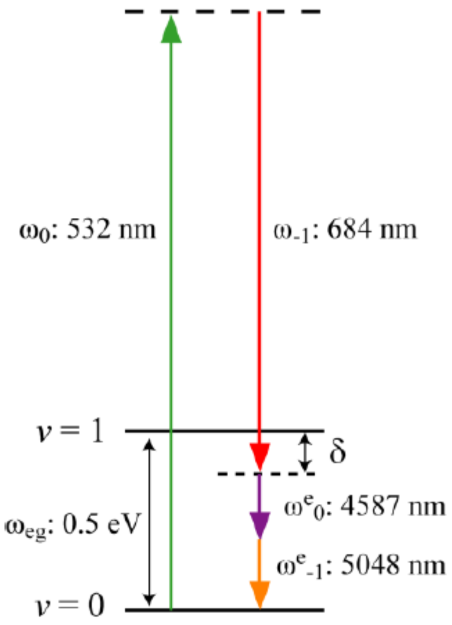


$$
\begin{aligned}
\frac{\partial \rho_{gg}}{\partial \tau} &= i\Big(\Omega_{ge}\rho_{eg} - \Omega_{eg}\rho_{ge}\Big) + \gamma_1 \rho_{gg}, \\
\frac{\partial \rho_{ee}}{\partial \tau} &= i\Big(\Omega_{eg}\rho_{ge} - \Omega_{ge}\rho_{eg}\Big) - \gamma_1 \rho_{ee}, \\
\frac{\partial \rho_{ge}}{\partial \tau} &= i\Big(\Omega_{gg} - \Omega_{ee} + \delta\Big)\rho_{ge} + i\Omega_{ge}\Big(\rho_{ee} - \rho_{gg}\Big) - \gamma_2 \rho_{ge}, \\
\frac{\partial E_q}{\partial \xi} &= \frac{i\omega_q n}{2c}\Big\{\Big(\rho_{gg}\alpha_{gg}^{(q)} + \rho_{ee}\alpha_{ee}^{(q)}\Big)E_q + \rho_{eg}\alpha_{eg}^{(q-1)}E_{q-1} + \rho_{ge}\alpha_{ge}^{(q)}E_{q+1}\Big\}, \\
\frac{\partial E_p}{\partial \xi} &= \frac{i\omega_p n}{2c}\Big\{\Big(\rho_{gg}\alpha_{gg}^{(p)} + \rho_{ee}\alpha_{ee}^{(p)}\Big)E_p + \rho_{eg}\alpha_{ge}^{(p\overline{p})}E_{\overline{p}}^{*}\Big\}.
\end{aligned}
$$

- Coherence estimated by simulation: $\rho_{ge} \simeq 0.032$

Observation of two-photon process





Comparison with spontaneous emission

- # of observed photons=6 x 10^11/pulse
- # of expected photons due to spontaneous emission

$$\frac{dA}{dz} = \frac{\omega_{eg}^{7}}{(2\pi)^3 c^6} \left|\alpha_{ge}^{(p\overline{p})}\right|^2 z^3(1-z)^3 \sim 3.2\times 10^{-11}\ 1/\mathrm{s} \quad (z=\frac{1}{2}) \qquad z=\omega/\omega_{eg}$$

$$\text{Expected photons}=\mathrm{R}_0 \cdot \pi w_0^2 L n_0 \cdot A \cdot \frac{\Delta E}{E}\Delta t \approx 10^{-7}\ /\ \mathrm{pulse}$$

- Huge amplification factor of >10^(18).
- Experimental confirmation of macroscopic coherent amplification mechanism.

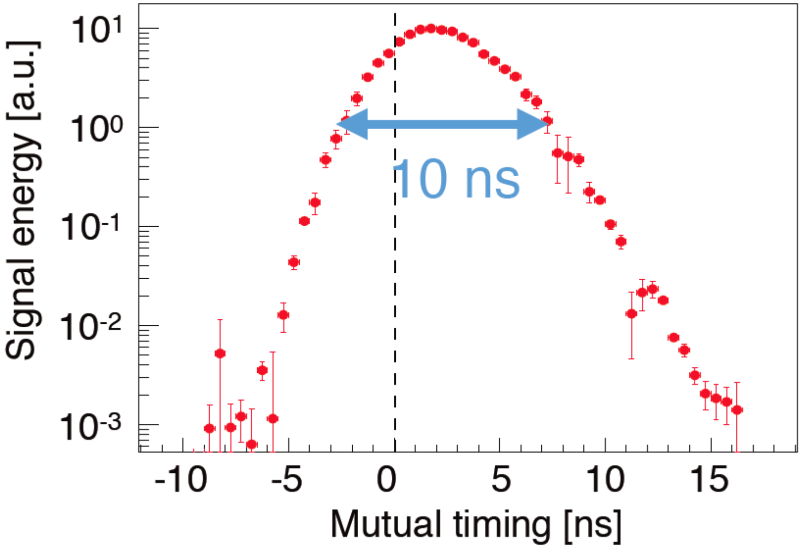
Y. Miyamoto, et al., "Vibrational Two-Photon Emission from Coherently Excited Solid Parahydrogen", J. Phys. Chem. A, vol. 121, 3943 (2017)

Solid instead of gas target

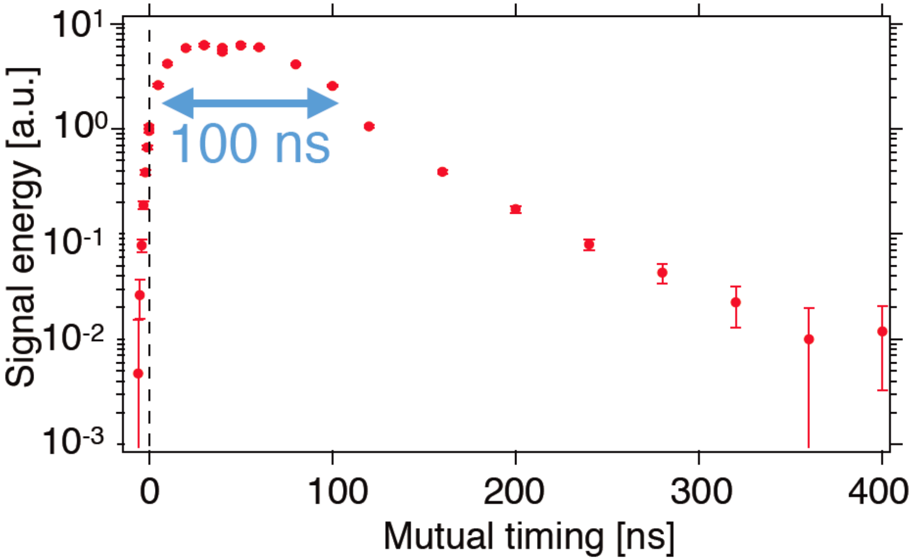
	Gas pH2 (78K,60kPa)	Solid pH2 (4K)
Density	~$5.6\times10^{19}/cm^3$	~$2.6\times10^{22}/cm^3$
De-coherence time	~1 nsec	~10 nsec

Y. Miyamoto et al., PTEP 2015 081C01 (2015)

gas



solid



Summary for PSR experiments

- PSR experiment
  - Two-photon decay process from pH2 v=1 -> v=0.
  - Confirmed the principle of macro-coherent amplification.

- Conditions of macro-coherence.
  - Energy-momentum conservation.

$$E_{eg} = \hbar(\omega_a + \omega_b + \omega_c)$$

$$\vec{P}_{eg} = \hbar(\vec{k}_a + \vec{k}_b + \vec{k}_c) \qquad \vec{P}_{eg} \text{ : controlled by excitation scheme}$$

  - Long de-coherence time for atoms/molecules.

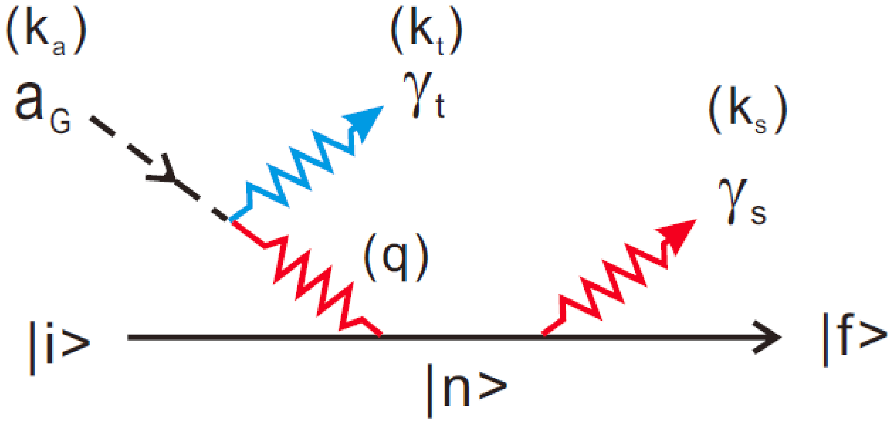
Contents

- Introduction
  - Macro-coherence and its experimental proof
- TRACA
  - Experimental principle
  - Experimental setup
  - Counting rate
- Summary

TRACA experiment

- Basic process of interest:

$$|i\rangle + m_a \rightarrow |f\rangle + \gamma_t + \gamma_s$$



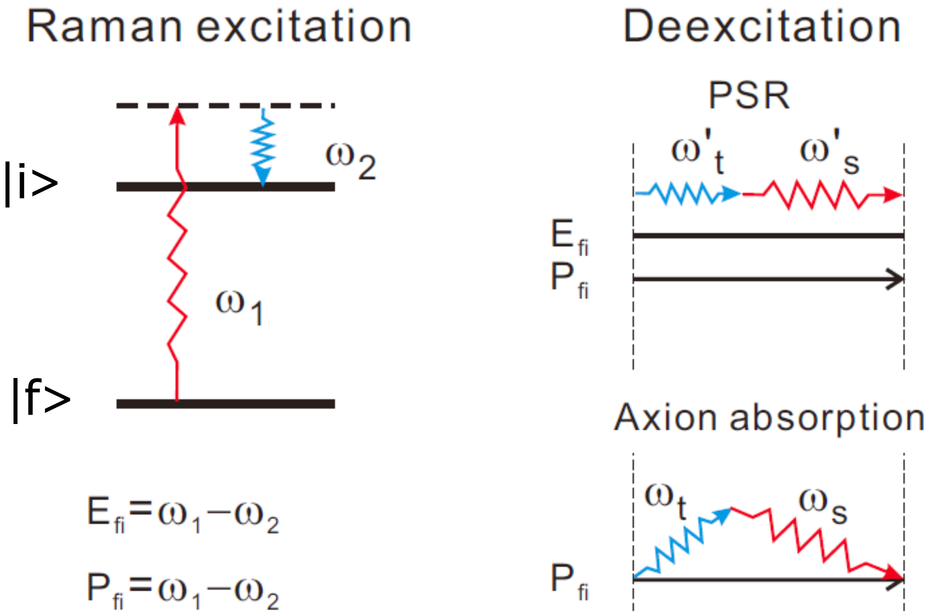
- Prepare excited states |i>, which are macro-coherent with the ground state |f>.
- Inject trigger laser to stimulate axion decay into two photons: $a \rightarrow \gamma_t + "\gamma"$
- One of the photons hits the atom to induce de-exicitation.

TRACA (Triggered Radiative Absorption of Cosmic Axion)
(TRACk Axion)

How to exploit macro-coherence ?
PSR vs TRACA

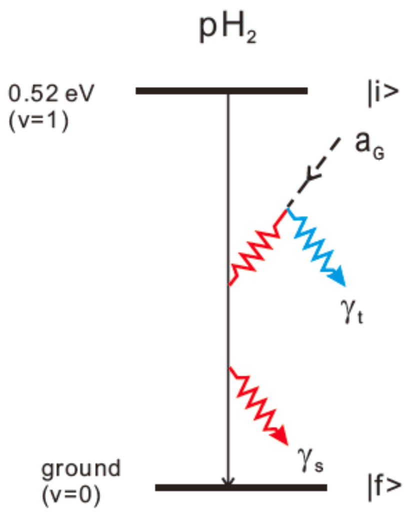
$$E_{if} + m_a = \omega_s + \omega_t$$

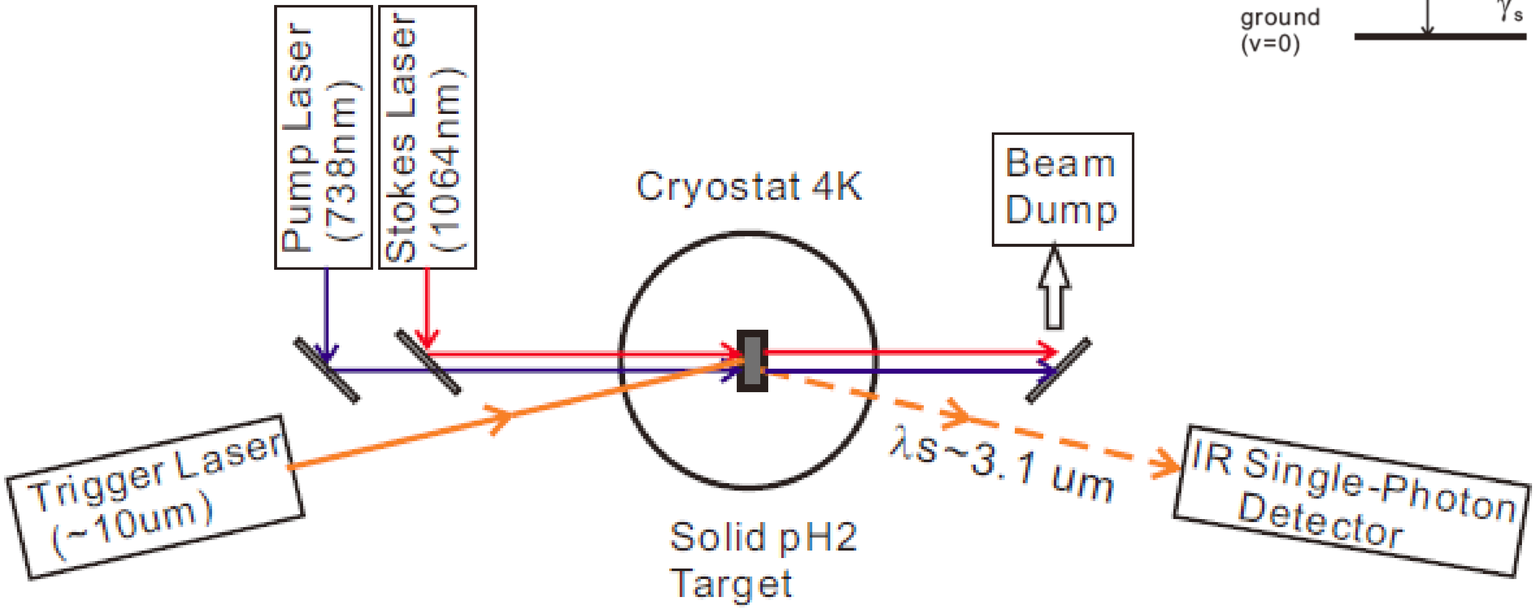
$$\vec{P}_{if} = \vec{k}_s + \vec{k}_t$$



- Principle of experiments
  - Prepare coherently-excited states |i> by Raman excitation scheme.
  - Inject trigger laser (γ_t) with angle w.r.t. pump lasers.
  - Detect signal photon (γ_s).

Experimental Layout




Pump Laser
(738nm)

Stokes Laser
(1064nm)

Cryostat 4K

Beam
Dump

Trigger Laser
(~10um)

λs~3.1 um

IR Single-Photon
Detector

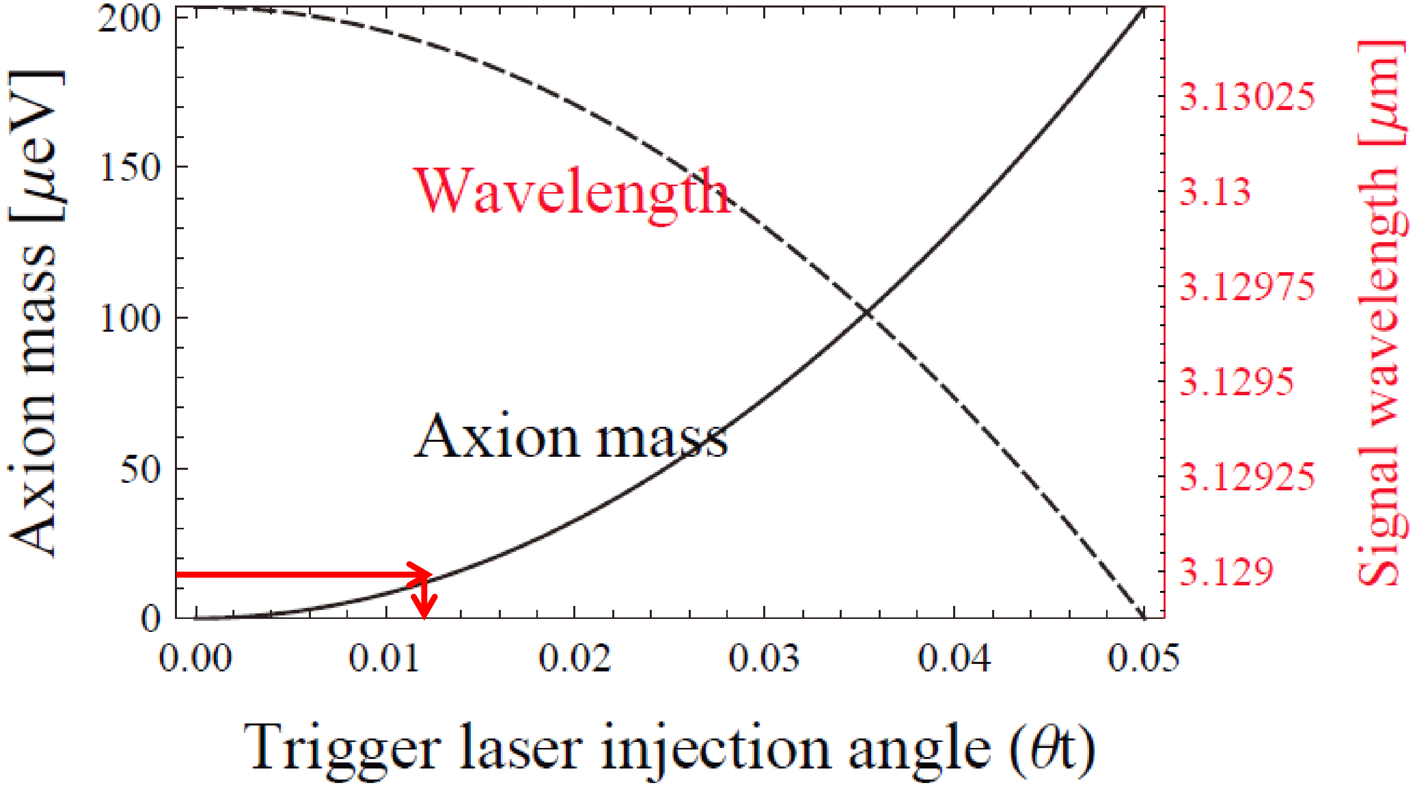
Solid pH2
Target

Kinematics of TRACA

$$E_{if} + m_a = \omega_s + \omega_t$$

$$\vec{P}_{if} = \vec{k}_s + \vec{k}_t$$

Axion absorption kinematics

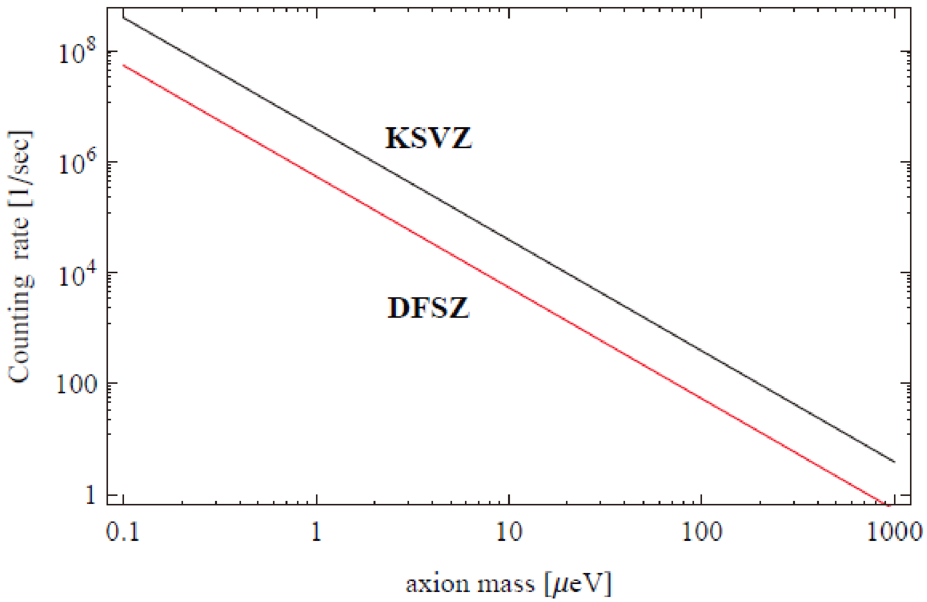


Counting rate

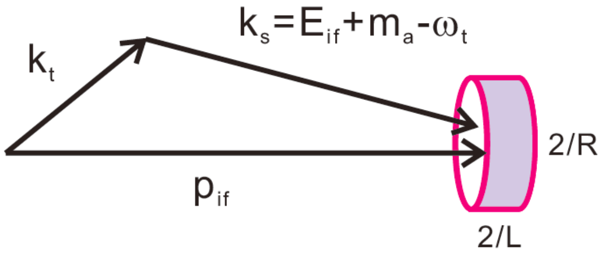
$$\frac{d\Gamma}{d\Omega_s} = \frac{|\rho_{if}|^2}{2^4(2\pi)^2}\ G_a^2\ N_T^2 n_{tr}\ \rho_G\ \alpha_{pol}^2 \frac{\omega_s^3 \omega_t E_{if}^2}{m_a^4}\ \mathcal{A}(\Delta\vec{k}, \vec{L})$$

$$m_a = 10\ [\mu\mathrm{eV}], \qquad \rho_G = 0.4\ [\mathrm{GeV}\cdot\mathrm{cm}^{-3}],$$
$$\omega_s \simeq 0.4\ [\mathrm{eV}], \qquad \omega_t \simeq 0.12\ [\mathrm{eV}],$$
$$n_{tr} = 10^{18}\ [\mathrm{cm}^{-3}], \qquad N_T = 2.6\times 10^{22},$$
$$|\rho_{if}|^2 = 10^{-2} \qquad \int \mathcal{A}\, d\Omega_s = 1.$$

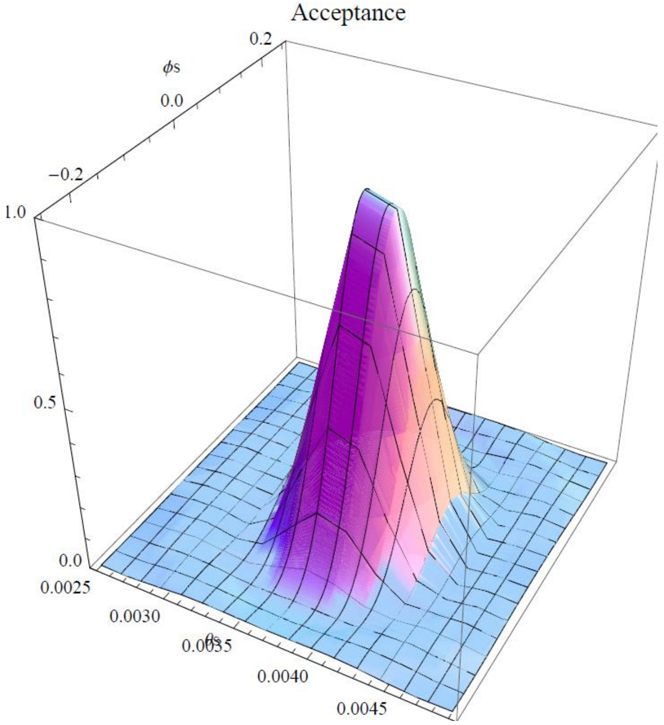
TRACA rate

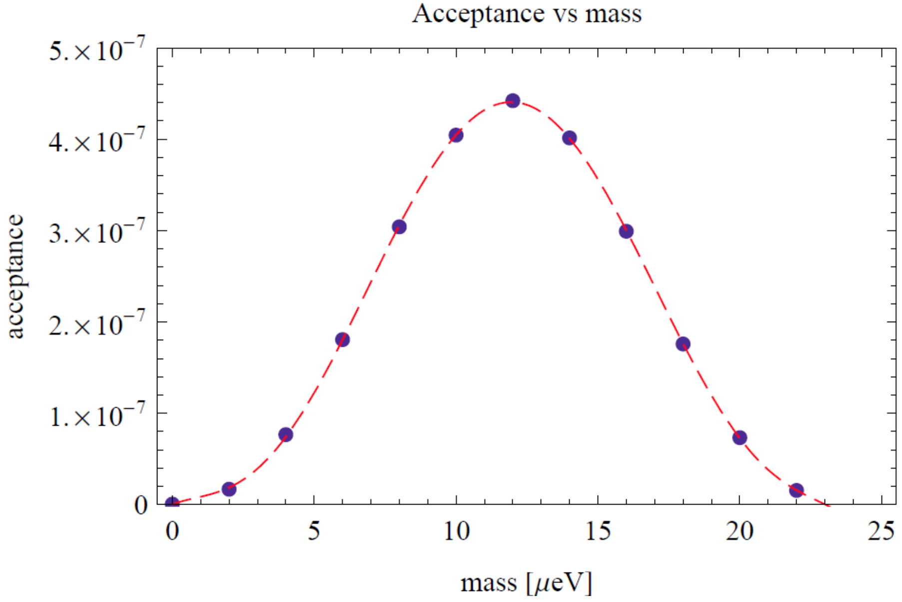


Finite target size effects (acceptance)

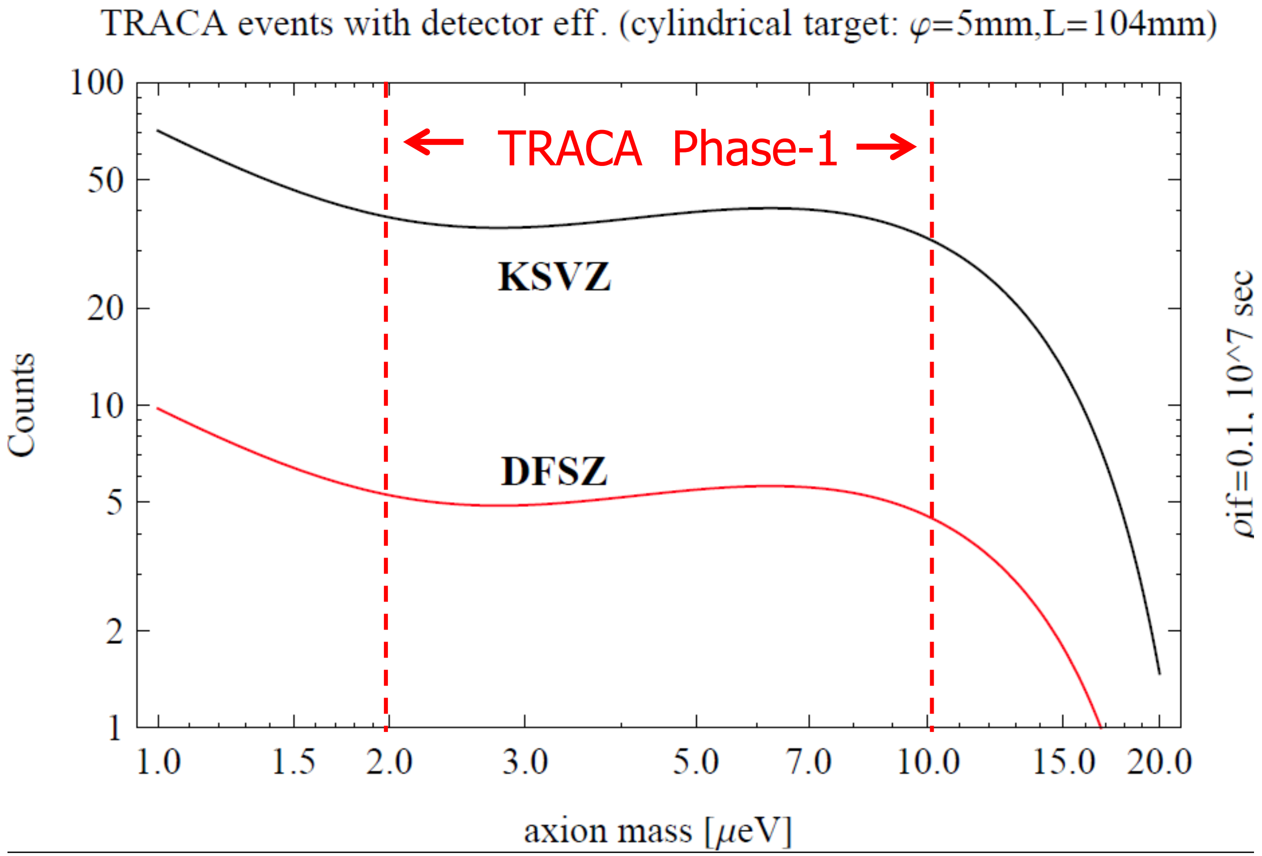


$$\mathcal{A}=\left(\frac{2}{\Delta k_z L}\sin\left(\frac{\Delta k_z L}{2}\right)\right)^2\left(\frac{2}{|\Delta\vec{k}_\perp|R}J_1(|\Delta\vec{k}_\perp|R)\right)^2$$





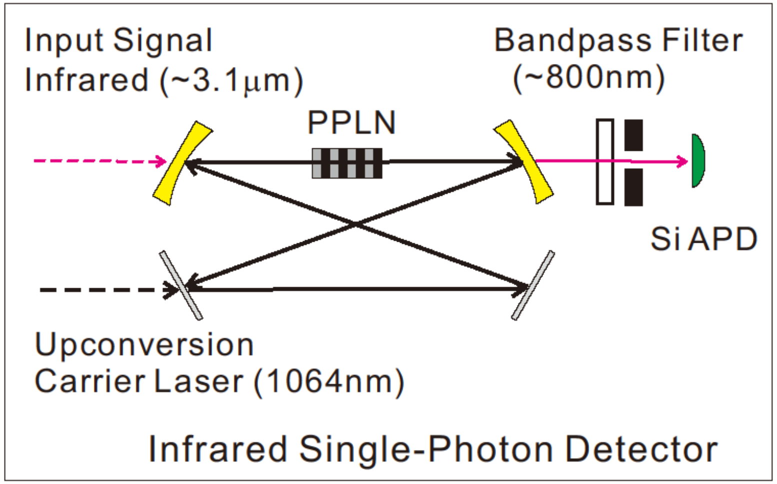
TRACA events with efficiency/acceptance



Experimental challenges

- Laser system
  - High power pump lasers
    - 1064nm+738nm (for Raman excitation)
    - ~400 mJ/pulse at 10kHz
  - High power trigger laser
    - CO_2 laser; new to us
    - ~1 J/pulse at 10kHz
- Solid pH_2 target
  - 10cm-long target

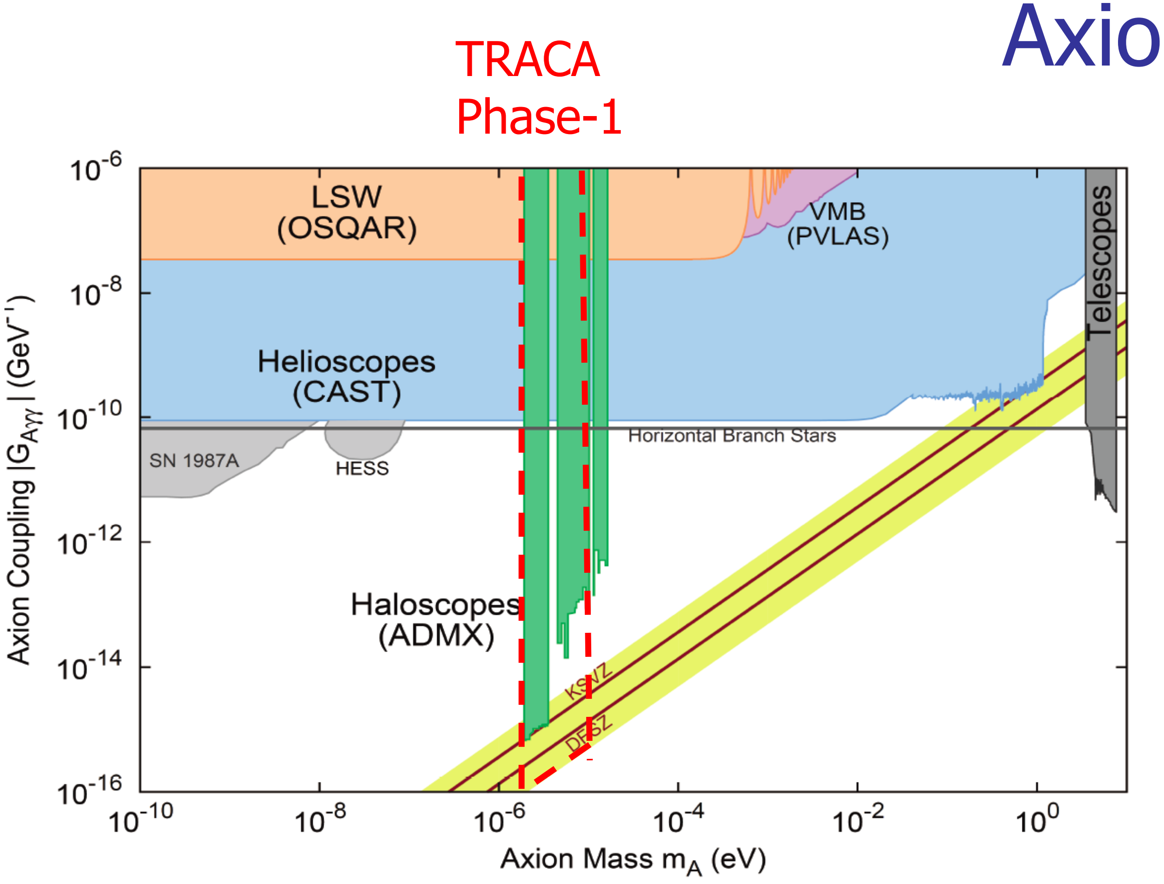
Infrared single-photon detector



Infrared Single-Photon Detector

- Detect infrared photon
  - Single photon
- Up-conversion method
  - Non-liner crystal
    - PPLN (Periodically Poled Lithium Niobate)
  - Carrier laser injection
  - Detect frequency-summed photon with APD (Avalanche Photo-Diode)
  - Conversion efficiency: $\varepsilon_{cnv} \approx 0.94$ at 2μm

Axion search



- Helioscope (M. Giannotti)
- Suzaku/XIS (R. Yamamoto)
- Light-shining-through a wall (A.Spector)

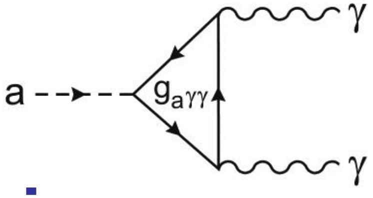
- NMR (D. Budker)
- XMASS (K. Abe)
- Clock (P. MOrzynski)
- Radio burst (A. Iwazaki)
- Haloscope (Y. Semertzidis)

Summary for TRACA experiment

- TRACA experiment
    - A new way to track axions
    - Exploits macro-coherence of atoms/molecules
    - Different systematics from others

- Challenges for TRACA experiment.
    - High-power pump laser system.
    - Long solid pH2 target
    - Low-noise and high-efficiency single-photon IR detector
    - Control of PSR backgrounds (under examination)

Theoretical background of axion



"invisible axion"

$$\tau_a \approx 10^{50}\ [\mathrm{sec}] \left(\frac{10\ [\mu\mathrm{eV}]}{m_a} \right)^5$$

- Why we need it?
  - To solve "Strong-CP" problem
    - QCD (Quantum Chromo-Dynamics) describes strong interaction
    - Contains a CP-violating term in its Lagrangian:
      - Contradicts with experiments, e.g. neutron EDM measurements
    - Axion solves the "Strong CP problem" in an elegant way.
- Properties
  - Interacts with electro-magnetic fields extremely weakly

$$L = G_{a\gamma\gamma}\ a\vec{E} \bullet \vec{B} \qquad G_{a\gamma\gamma} = c_{a\gamma\gamma} \frac{\alpha}{\pi f_a}$$

  - Mass and coupling strength has definite relation

$$m_a \cong 6\ [\mu\mathrm{eV}] \frac{10^{12}\ [\mathrm{GeV}]}{f_a}$$