Dark-matter Axion Search using Quantum Coherence Amplification Mechanism

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Recent papers

Eur. Phys. J. C (2018) 78:949

THE EUROPEAN

It is crucial to devise a clever method of PSR background rejection for a realistic experimental proposal.

|n>

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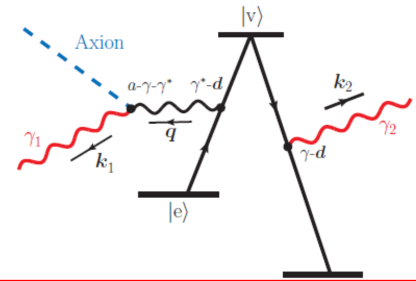

has to either invent a more powerful method of background reduction (as for p-H_2 a nearly background-free environment is required), or search for other atomic or molecular candidates with even larger signal rates.

Outline

- What is axion?: Physics motivation

Skip entirely!!!

- Amplification by coherence: Proof-of-principle experiment by PSR process
- Cosmic Axion search with atoms/molecules:
- Conclusion

Outline

- What is axion?: Physics motivation
- Amplification by coherence: Proof-of-principle experiment by PSR process
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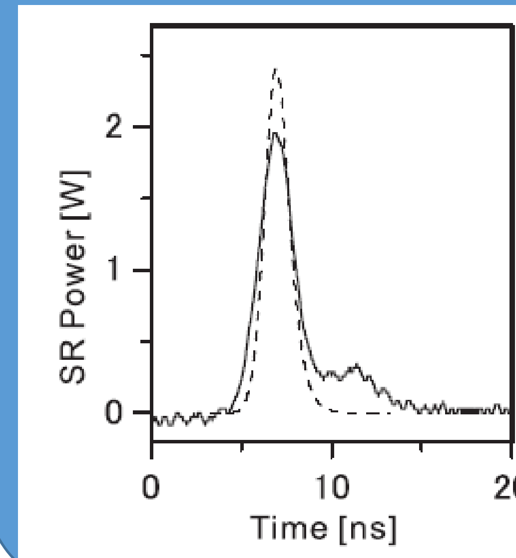
Amplification by coherence among atoms

Ba SR exp't @ Okayama



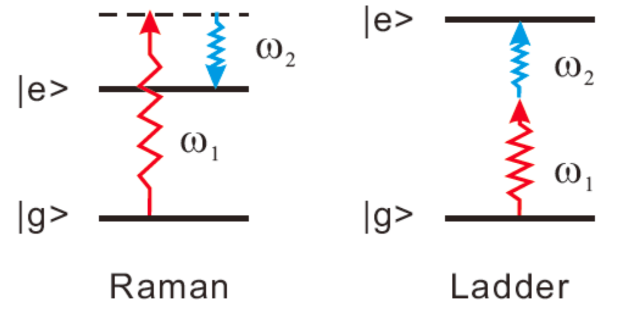
- Super-Radiance a la Dicke
  - De-excitation via single photon emission

$$R \propto \left| \sum_{m=1}^{N_T} \mathrm{Exp}\left(i\vec{k}_\gamma\ \vec{x}_m \right) M(\vec{x}_m) \right|^2 \propto N_T^2 \qquad \left[\because M(\vec{x}_m) = M(0),\ \ |\,\text{target size}\,| < \lambda \right]$$

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

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

Effects of Initial Spatial Phase



- General conditions of amplification;

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

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

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

$$E_{eg} = \omega_1 - \omega_2 \quad \& \quad P_{eg} = k_1 - k_2$$

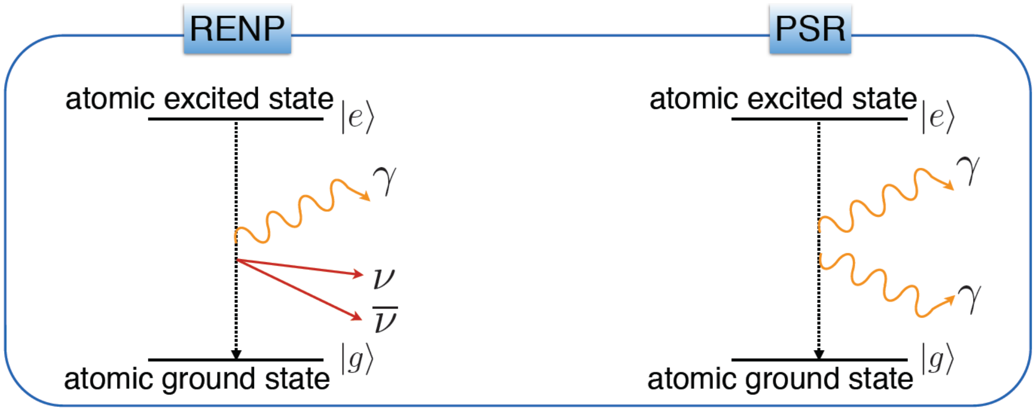
  - Ladder excitation:

$$E_{eg} = \omega_1 + \omega_2 \ \& \ P_{eg} = k_1 + k_2 \quad \text{(co-propagating)}$$

$$E_{eg} = \omega_1 + \omega_2 \ \& \ P_{eg} = k_1 - k_2 \quad \text{(counter-propagating)}$$

Experimental proof of macroscopic coherent amplification

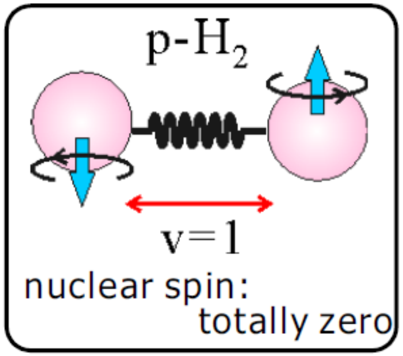
- PSR (paired super-radiance)
  - QED process where ν-pair is replaced with a photon.
  - A pair of strong light pulses (SR) will be emitted.



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

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

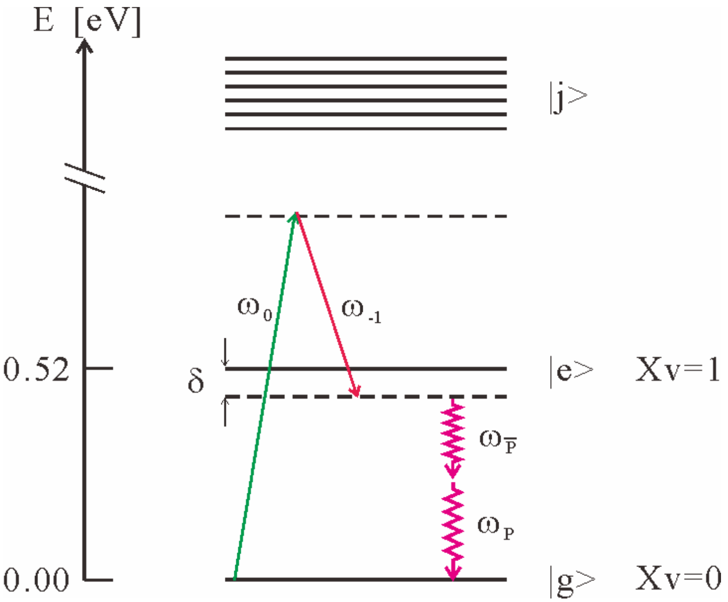
PSR experiments



- 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)

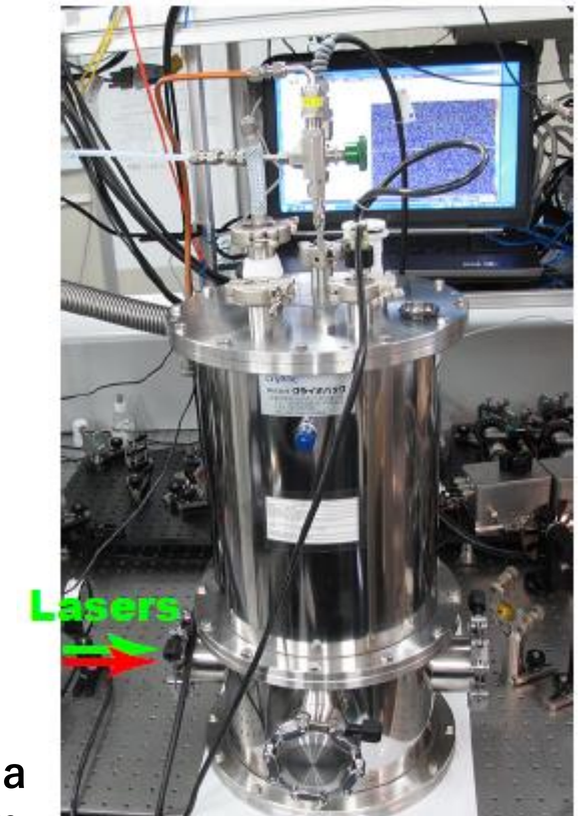


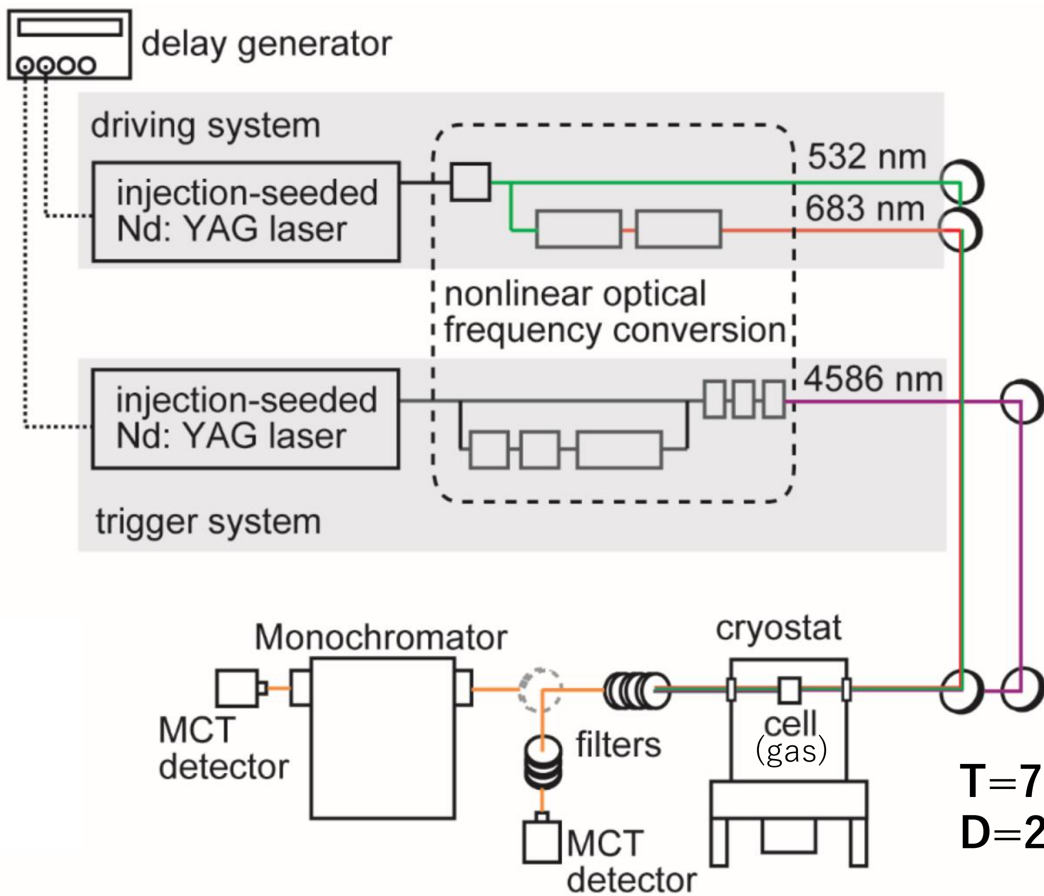
Driving laser: 5 mJ/pulse, ~10nsec fwhm
Tigger laser: 150 uJ/pulse, ~2nsec fwhm

Experimental setup

▶ H_2 gas cell (15 cm long)

▶ L-N_2 Cryostat

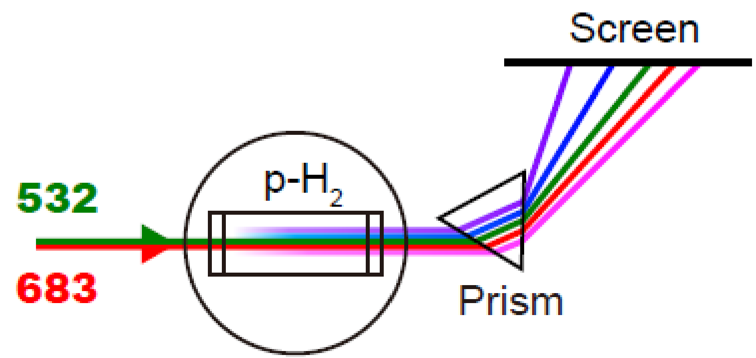


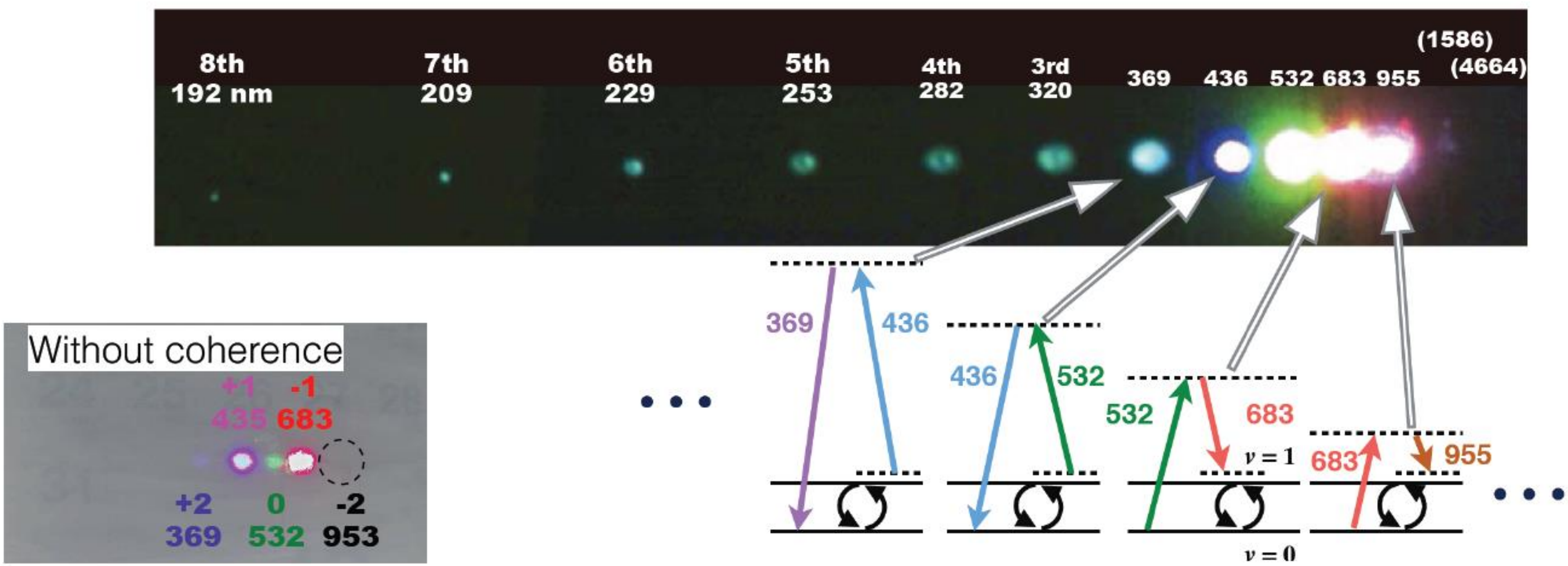


T=77K, P=60kPa
D=2cm, L=15cm

Observation of Raman sidebands

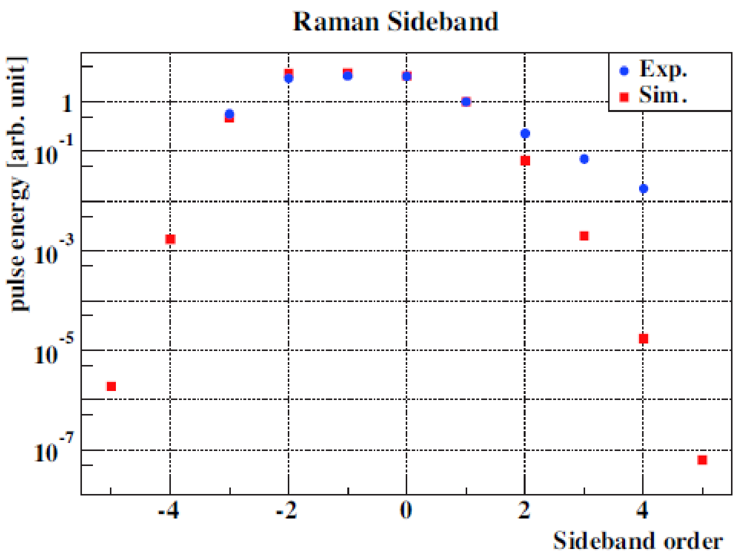
- 13 sidebands observed（λ =192 - 4662nm）
- Evidence for large coherence





Degree of coherence

- Maxwell-Bloch eq.



$$\frac{\partial \rho_{gg}}{\partial \tau} = i\Big(\Omega_{ge}\rho_{eg} - \Omega_{eg}\rho_{ge}\Big) + \gamma_1 \rho_{gg},$$

$$\frac{\partial \rho_{ee}}{\partial \tau} = i\Big(\Omega_{eg}\rho_{ge} - \Omega_{ge}\rho_{eg}\Big) - \gamma_1 \rho_{ee},$$

$$\frac{\partial \rho_{ge}}{\partial \tau} = i\Big(\Omega_{gg} - \Omega_{ee} + \delta\Big)\rho_{ge} + i\Omega_{ge}\Big(\rho_{ee} - \rho_{gg}\Big) - \gamma_2 \rho_{ge},$$

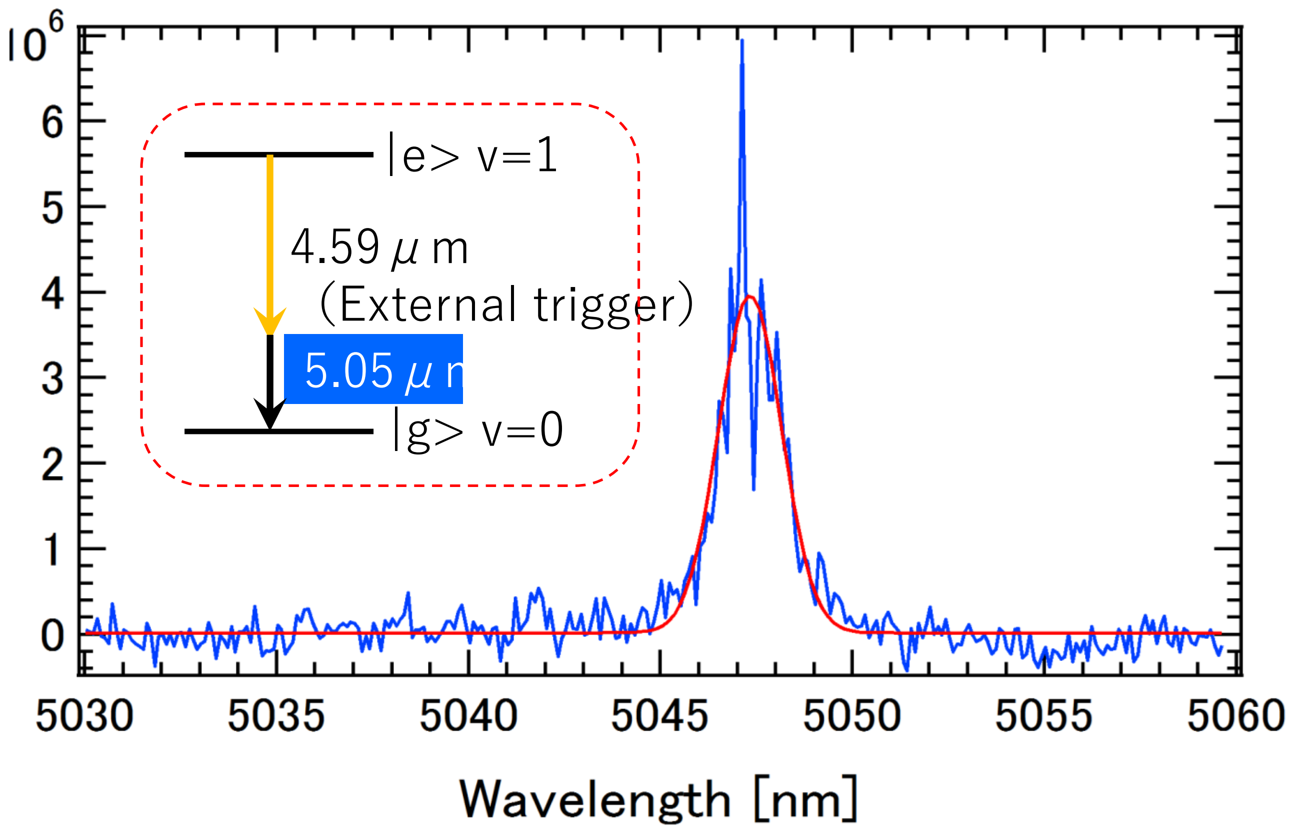
$$\frac{\partial E_q}{\partial \xi} = \frac{i\omega_q n}{2c}\Big\{\Big(\rho_{gg}\alpha_{gg}^{(q)} + \rho_{ee}\alpha_{ee}^{(q)}\Big)E_q + \rho_{eg}\alpha_{eg}^{(q-1)}E_{q-1} + \rho_{ge}\alpha_{ge}^{(q)}E_{q+1}\Big\},$$

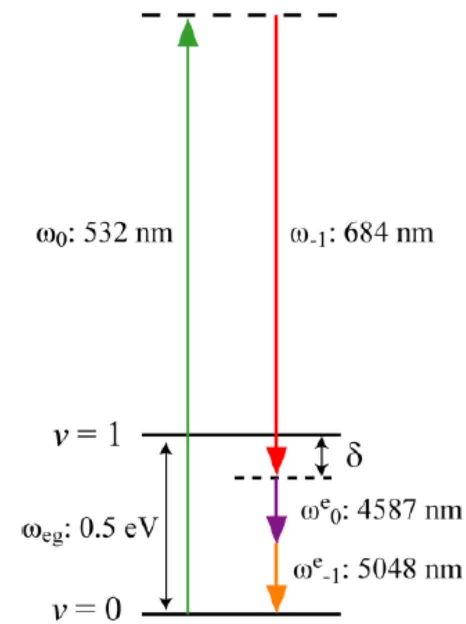
$$\frac{\partial E_p}{\partial \xi} = \frac{i\omega_p n}{2c}\Big\{\Big(\rho_{gg}\alpha_{gg}^{(p)} + \rho_{ee}\alpha_{ee}^{(p)}\Big)E_p + \rho_{eg}\alpha_{ge}^{(p\overline{p})}E_{\overline{p}}^{*}\Big\}.$$

- Coherence estimated by simulation:

$$\rho_{ge} \simeq 0.032$$

Observation of two-photon process



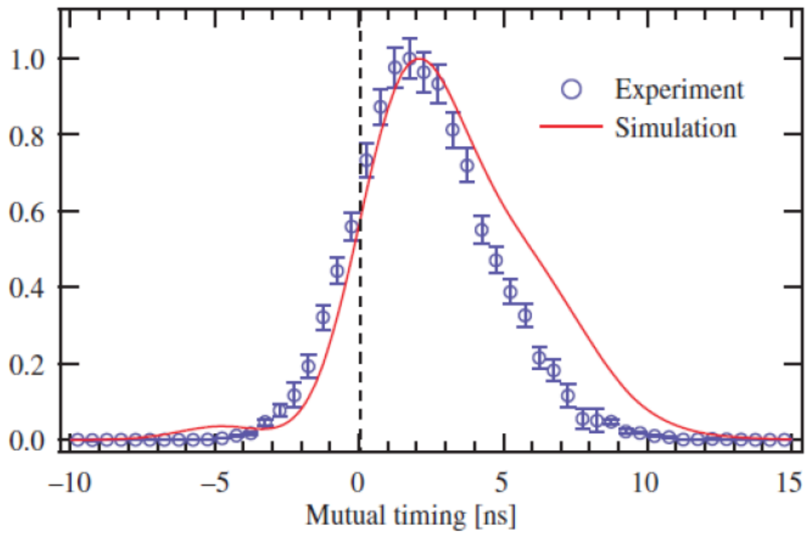


Amplification factor of >10^(18) is confirmed.

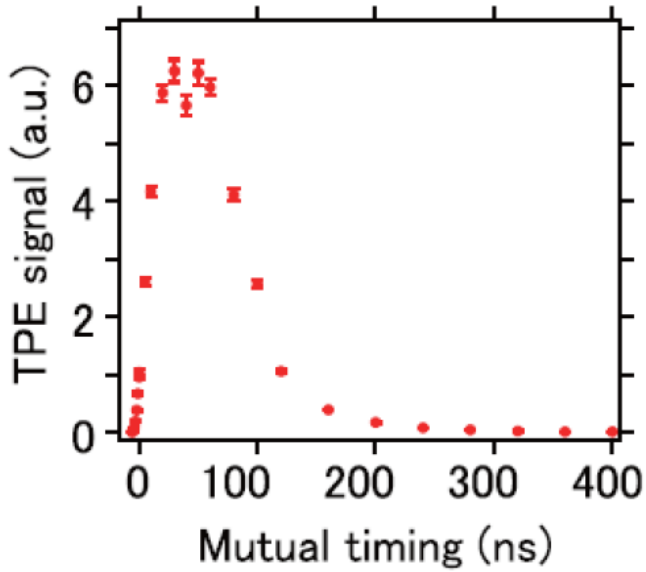
Recent developments on PSR (1)

- Solid vs gas pH2

trigger laser injected after pump laser



gas target

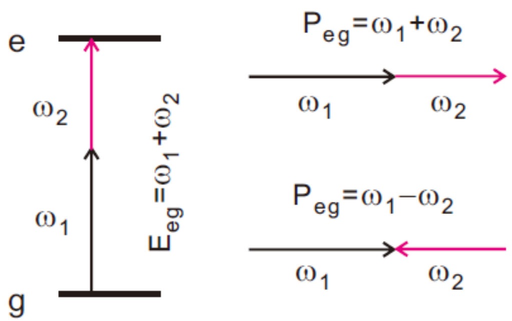


solid target

Solid pH2 has x10 longer coherence time

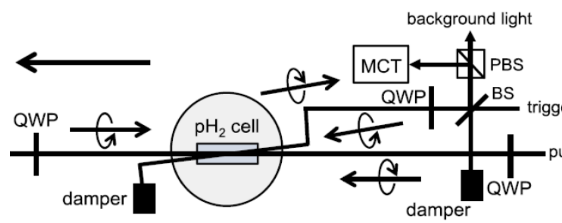
Recent developments on PSR (2)

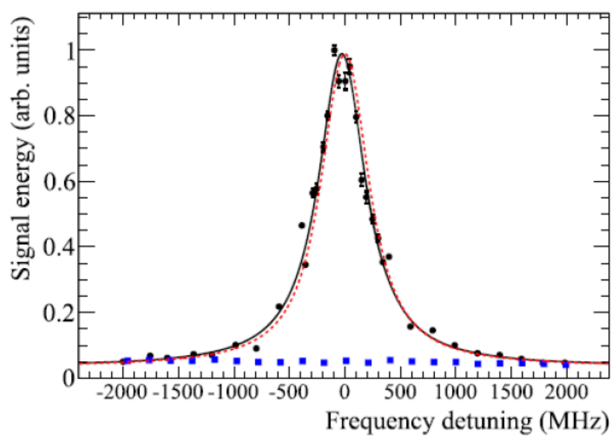
- Initial spatial phase imprinted to atomic system.



Invariant mass (E_{eg},P_{eg}) can be controlled.

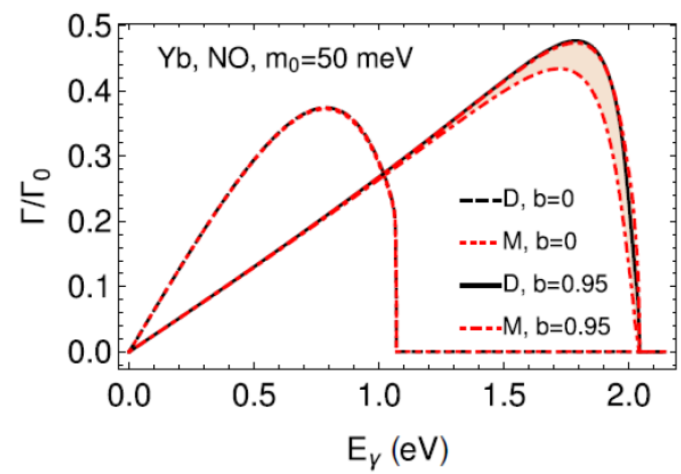
Experimental proof:





J.Phys.B: At Mol Opt. Phys 52 (2019) 045401

Initial spatial phase gives higher neutrino sensitivity:



Phys. Rev. D 96, 113005 (2017)

Outline

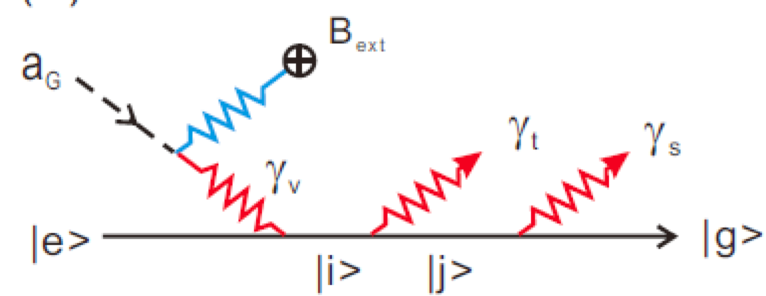
- What is axion?: Physics motivation
- Amplification by coherence: Proof-of-principle experiment by PSR process
- Cosmic Axion search with atoms/molecules:
- Conclusion

Basic process of interests

- Basic process of interest:

$$|e\rangle + m_a \rightarrow |g\rangle + \gamma_t + \gamma_s$$

(a)



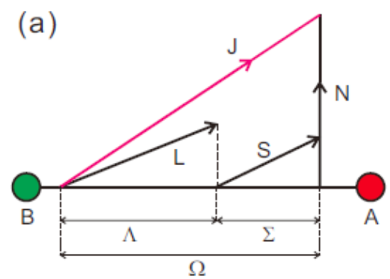
Principle of experiments

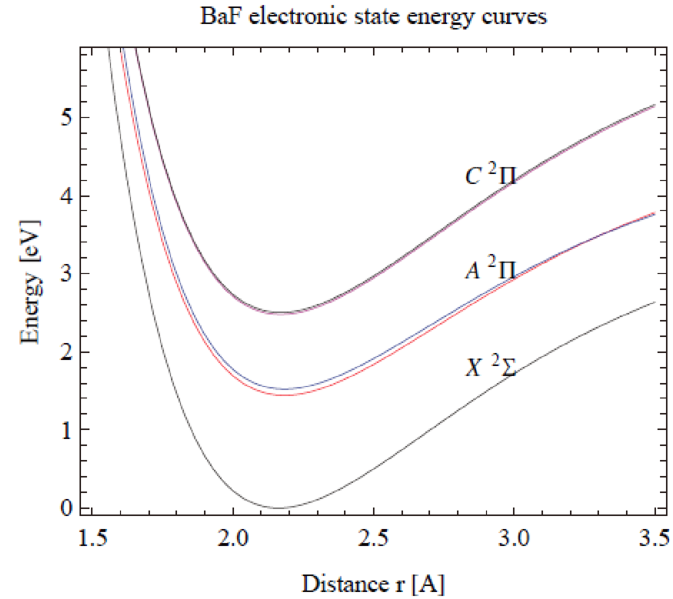
- Prepare coherently-excited states |e> by pump laser(s).
- Axion decays into 2γ in an external magnetic fields B_{ext}.
- Virtual photon is absorbed by |e>.
- Inject trigger laser (γ_t) with angle w.r.t. pump laser(s).
- Detect signal photon (γ_s).

$$a_G \rightarrow \gamma_v + "\gamma"$$

We use BaF as a target

- Electronic structure:
  - $^2\Sigma$:$L_z=0, S_z=1/2$
  - $^2\Pi$:$L_z=1, S_z=1/2$



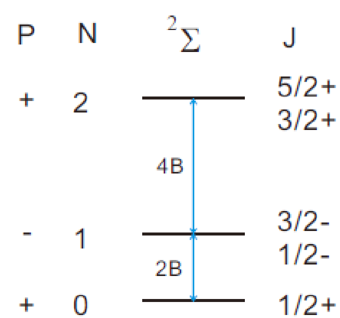


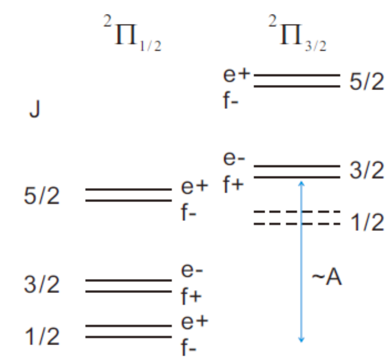
- Zeeman properties:
  - $^2\Pi_{1/2}$: no magnetic dipole moment
  - $^2\Sigma$ & $^2\Pi_{3/2}$: magnetic dipole moment ~ μ_B

$$\mu_B(g_s\vec{S} + g_l\vec{L})$$

$$\mu_B \simeq 57.88\ \mu\text{eV/T}$$

- Rotational structure:
  - A~ spin-orbit interaction energy
  - B~ rotational energy (B<A)





Zeeman splitting of BaF states

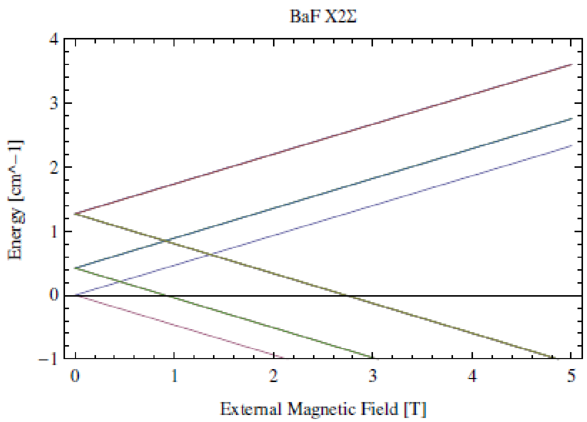


図 4: Zeeman energy of $X^2\Sigma$ state ($N = 0, 1, 2$).

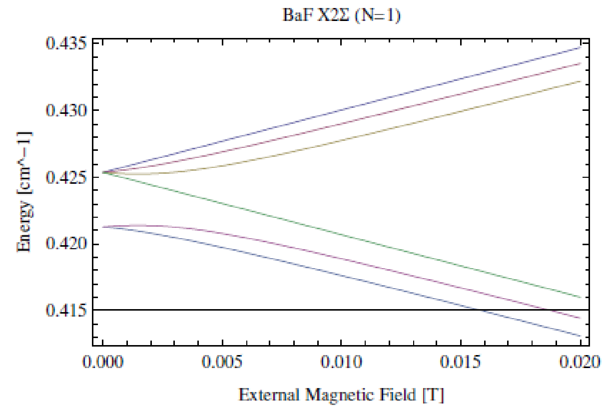


図 5: Zeeman energy of $X^2\Sigma$ state. Expanded for $N = 1$.

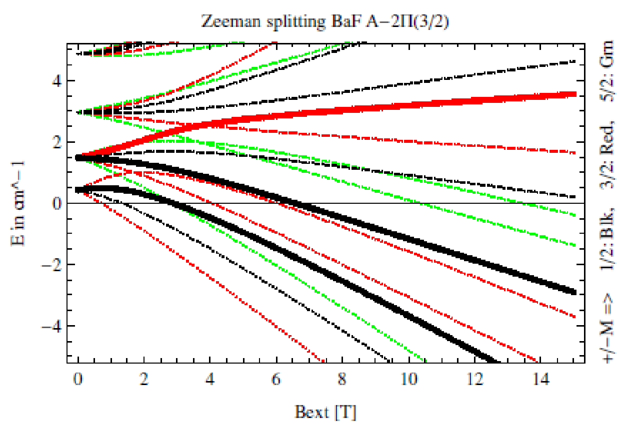


図 8: Zeeman energy of $A^2\Pi_{3/2}$ state of BaF.Possible Axion transition levels are indicated by bigger solid circles.

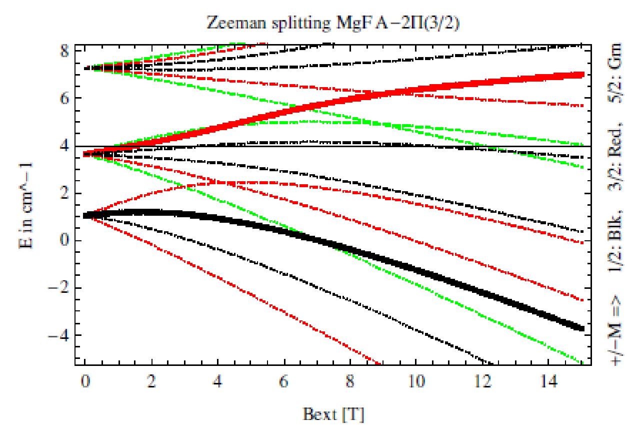
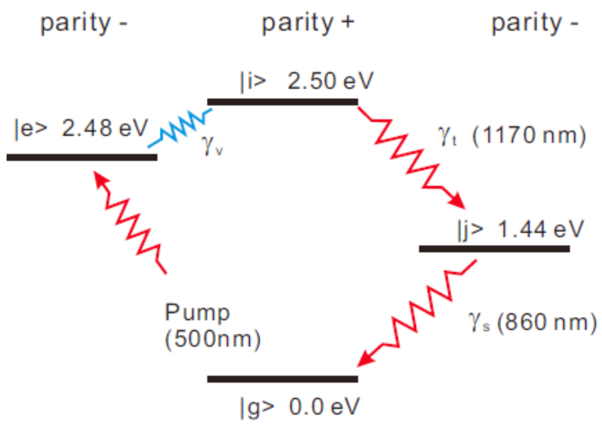


図 9: The same figure with 図 8 for MgF.

Actual states to be used

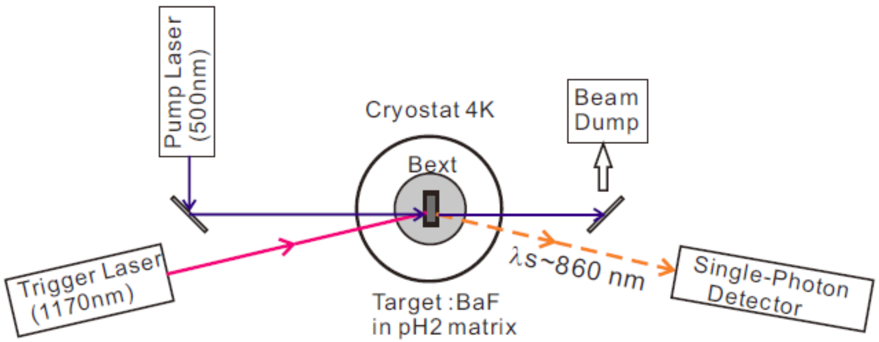


- The mass of axion in search:
  - E(|i>)-E(|e>) under B_{ext}
  - m_a~25 meV (in this example)

Forget for a moment: $\Omega_{ax} \approx \left(\frac{6\ [\mu\text{eV}]}{m_a} \right)^{7/6}$

	States	T_e		Lifetime	Rotational quantum #
	Unit	cm^{-1}	(eV)	ns	and Parity
$\vert g\rangle$	$X^2\Sigma$	0.	(0.0)	-	$J=\frac{1}{2},\ M_J=-\frac{1}{2}$,(+)
$\vert j\rangle$	$A^2\Pi_{1/2}$	11646.9	(1.44403)	56.0	$J=\frac{3}{2},\ M_J=-\frac{1}{2}$,(-)
$\vert e\rangle$	$C^2\Pi_{1/2}$	19998.2	(2.47946)	23.8	$J=\frac{3}{2},\ M_J=+\frac{1}{2}$,(-)
$\vert i\rangle$	$C^2\Pi_{3/2}$	20197.0	(2.50411)	23.5	$J=\frac{5}{2},\ M_J=+\frac{1}{2}$,(+)

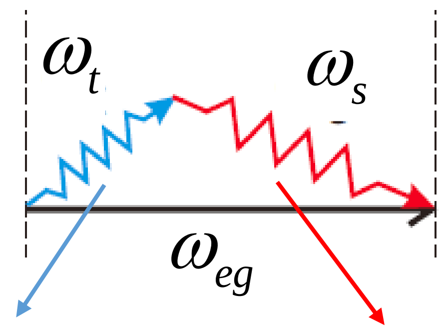
Experimental Layout



- 3 major components:
  - Laser system
  - BaF target in pH_2 matrix
  - IR detector
- Trigger laser
  - injected with angle w.r.t pump to satisfy macro-coherent amplification conditions.

$$(\omega_{eg} + m_a = \omega_t + \omega_s)$$

$$(\vec{k}_{eg} = \vec{k}_t + \vec{k}_s)$$



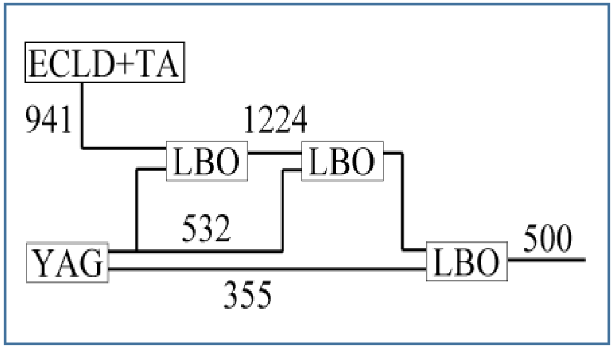
Laser and BaF target

表 2: BaF laser specifications

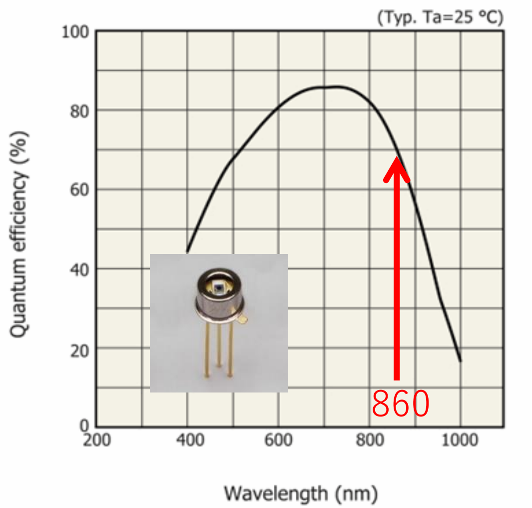
Name	Pump	Trigger
wavelength	500 nm	1170 nm
intensity	1 mJ/pulse	10 mJ/pulse
linewidth	100 MHz	100 MHz
pulse width	10 ns/10 Hz	10 ns/10 Hz

表 3: BaF target in pH_2 matrix. Note: length and diameter represent those passed by lasers.

Item	value	Item	value
Temp.	4 K	Doping	100 ppm
Length	5 mm	Diameter	1 mm
Volume	0.005 cm^3	# of BaF	1.3×10^{16}



IR detector : APD with bandpass filter or spectrometer



Signal counts

$$\frac{d\Gamma_{ax}}{d\Omega_s} = \frac{\rho_{eg}^2 N_T^2 (4\pi\alpha)^2}{2(4\pi)^2} \rho_G a_B^6 \left(\frac{G_a^2 \omega_s^3}{m_a^2}\right) \frac{|eE_t(0)|^2 B_{ext}^2}{|\omega_{ei} + \omega_t - i\Gamma_{ei}|^2 \, |\omega_{ij} + m_a - i\Gamma_{ij}|^2} \mathcal{A}(\Omega_s)$$

ρ_{eg} : coherence

N_T : number of target molecules

ρ_G : dark matter density

a_B : Bohr radius

E_t : tigger laser field

$\omega_p \ (p = e, g, i, j, s, t)$: energy of p

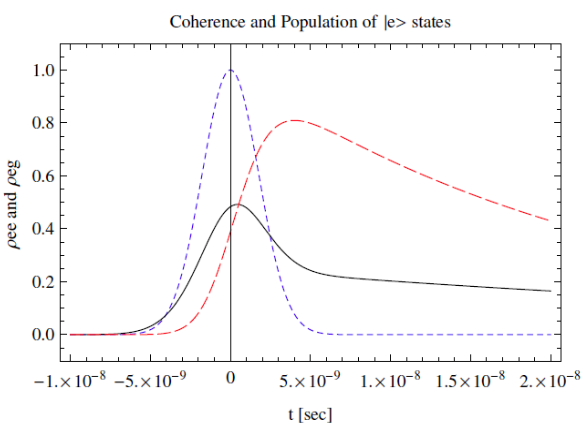
$\omega_{pq} \equiv \omega_p - \omega_q$

Γ_{pq} : resonace + laser width

$A(\Omega_s)$: geometrical acceptance

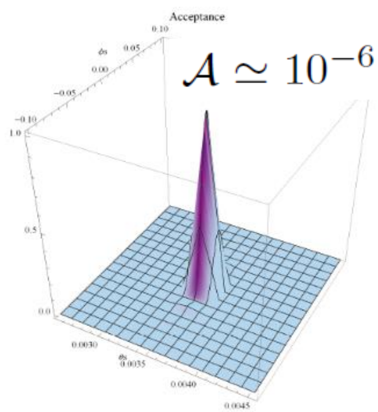
B_{ext}=1 T

ρ_{eg} : coherence

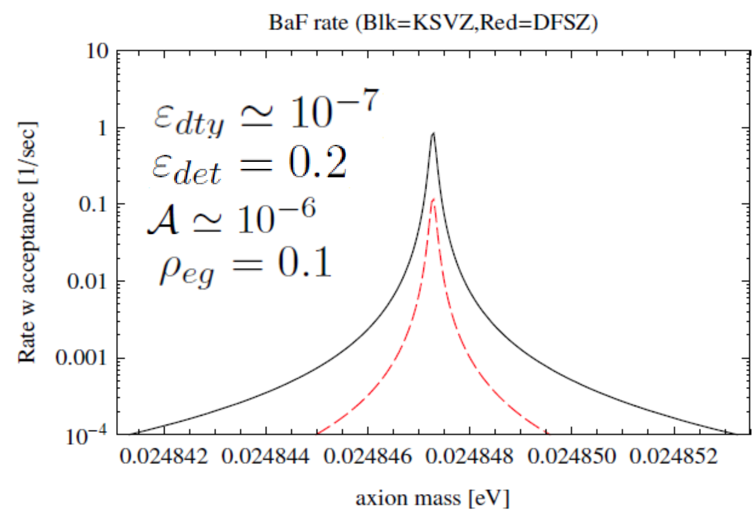


Blk: coherence
Blu: input laser
Red: population

$A(\Omega_s)$: geometrical acceptance



Signal count [1/s]



$\Delta m_a \sim \pm 0.001$ meV

Rate enhancement factors

- Large axion number density

$$\rho_G = 0.4 \text{ GeV/cm}^3 \rightarrow 10^{13} / \text{cm}^3 \ (m_a = 40\mu\text{eV})$$

- Macro-coherent amplification.

$N_T = 10^{16}$

- Strong magnetic field

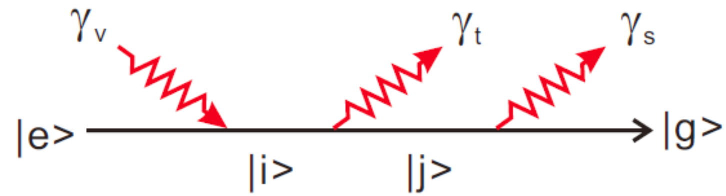
Bext =1 T

- Near resonance condition at axion absorption vertex
  - Energy denominator:

$$\frac{1}{E_{ei} - m_a - i\Gamma_i} \rightarrow \frac{1}{\Gamma_i}$$

The biggest background: black-body

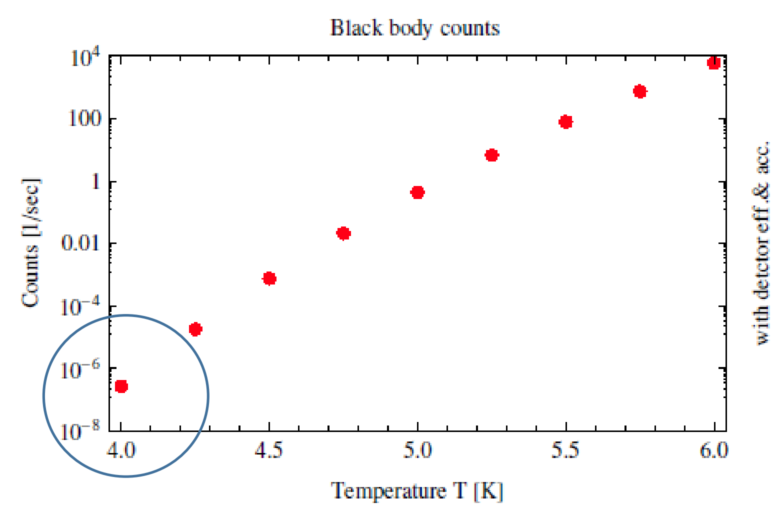
- Atoms absorb black-body photons.



$$S/N \equiv \frac{d\Gamma_{ax}}{d\Omega_s} \Big/ \frac{d\Gamma_{bg}}{d\Omega_s} = \frac{2\rho_G}{u_{bb}\Delta\omega_{bg}} \frac{G_a^2 B_{ext}^2}{m_a^2} \frac{\mathcal{A}}{\mathcal{A}_{bg}} \simeq \frac{0.5\times 10^{-23}\ \mathrm{eV/cm^3}}{u_{bb}\Delta\omega_{bg}} \frac{\mathcal{A}}{\mathcal{A}_{bg}}$$

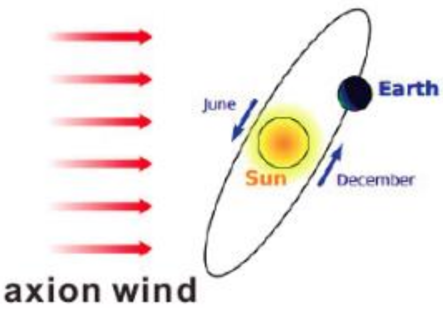
- The second biggest background:
  - Dark count of APD is negligible.
  - 100 Hz x ε_{dty}=10^{-3} Hz

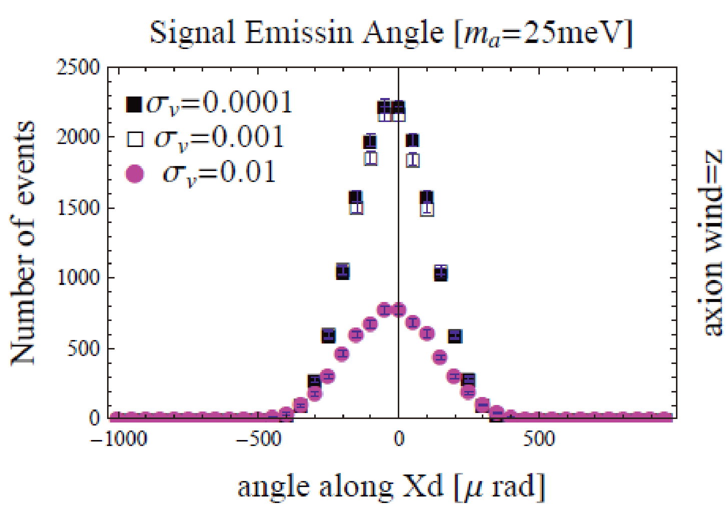
The sensitivity of the experiment can be calibrated by observing black-body spectrum.

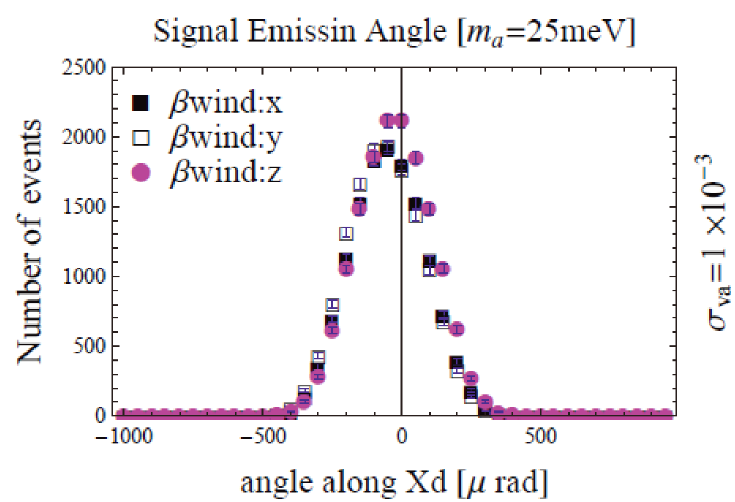


Velocity dispersion and wind direction

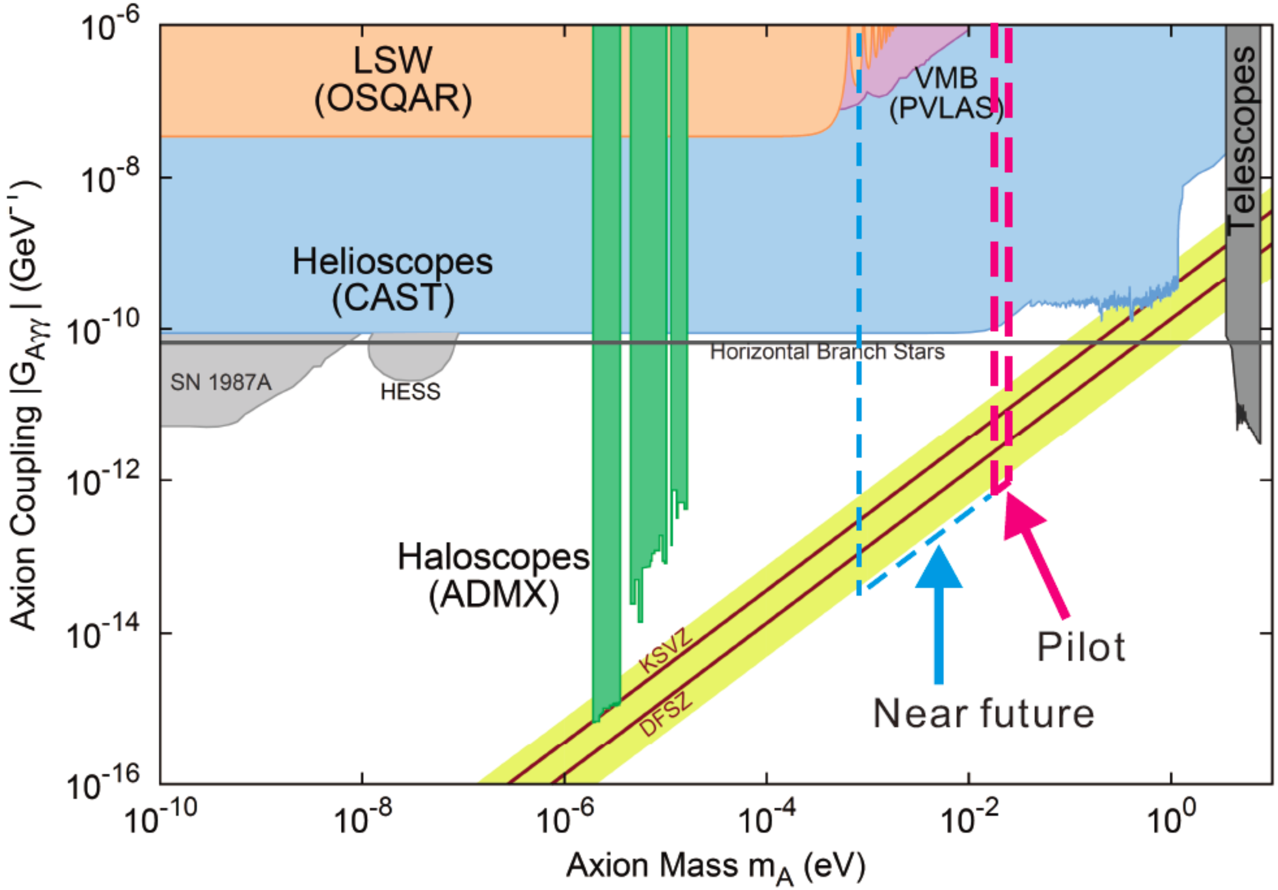
- Velocity dispersion σ_v:
  - Axions have been virialized during a large-scale formation.







Search sensitivity by this experiment



Summary for axion search

- New method of cosmic axion search.
  - Amplification by macroscopic coherence is KEY.
  - Use Zeeman-tunable molecular states
  - Large counting rate is expected for wide search region
  - Experimental sensitivity can be proved by b.b. "calibration" photons

- Road map
  - Pilot experiment with BaF $^2\Pi_{1/2}$ as |e>
  - Go to the smaller m_a (~1 meV) with $^2\Pi_{3/2}$ as |e>
    - Need a cryostat of lower temperature (250 mK) and stronger magnet (>10T)
  - Better target (crystal?) is needed to go below 1 meV.

Thank you for your attention!

- SPAN collaboration

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