Dark matter search with coherent atoms

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Outline

- ❑ **Introduction**
- ❑ **Macro-coherent amplification**
- ❑ **Cesium E2 transition measurement**
- ❑ **Future Prospect and summary**

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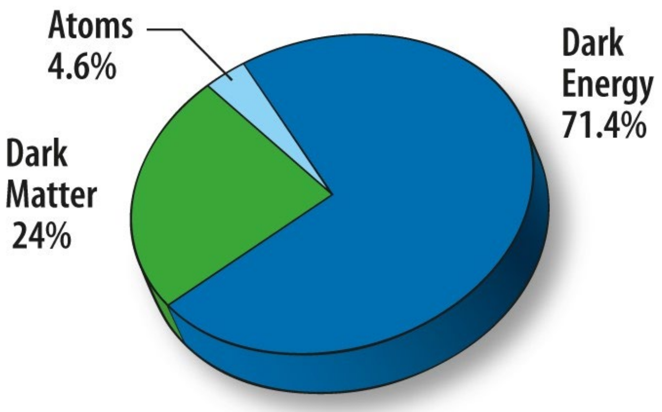
Introduction

- Nature of Dark Matter (DM) is still a big mystery.

- Dark matter candidates

  WIMPs, sterile neutrino…

  However, null results are found.



- Axion

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{4}g_{a\gamma\gamma} a F_{\mu\nu}\widetilde{F}^{\mu\nu} \qquad g_{a\gamma\gamma} = g\frac{\alpha}{\pi f_a}$$

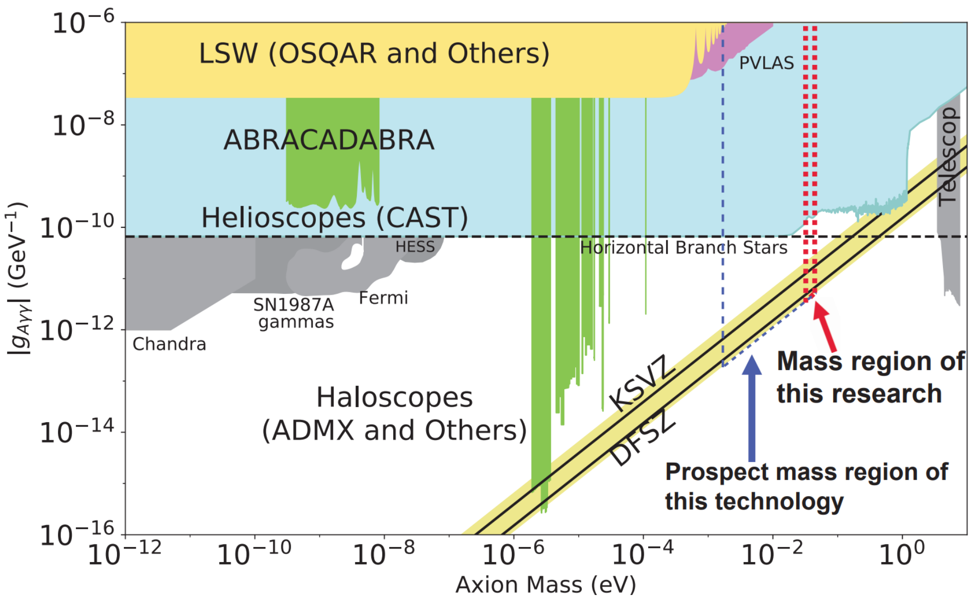
- Dark photon

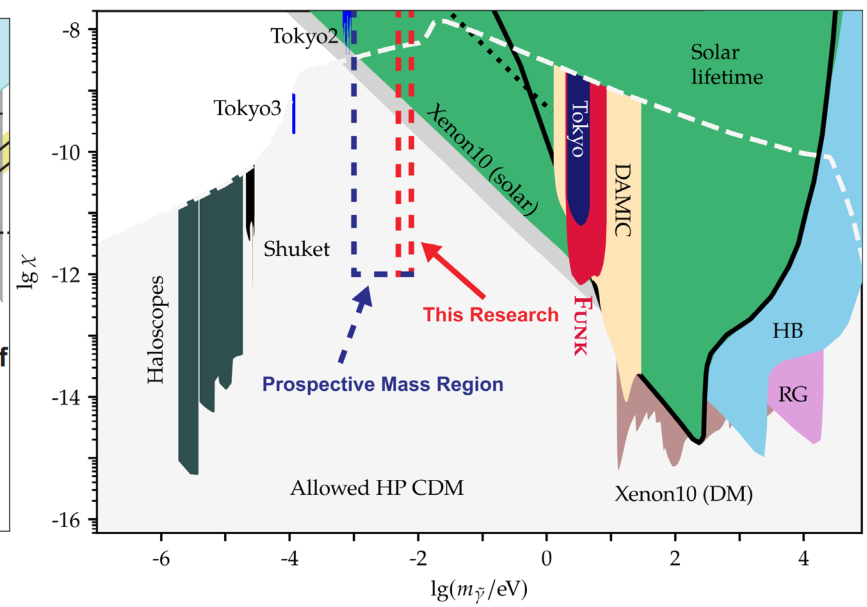
$$\mathcal{L}_{\mathcal{DP}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\chi}{2}F_{\mu\nu}X^{\mu\nu} + \frac{m_X^2}{2}X_{\mu\nu}X^{\mu\nu} + j_\mu A^\mu$$

Axion/Dark photon direct detection with atomic transition

Introduction

- Searching for DM with mass ~meV





- Amplification mechanism is required

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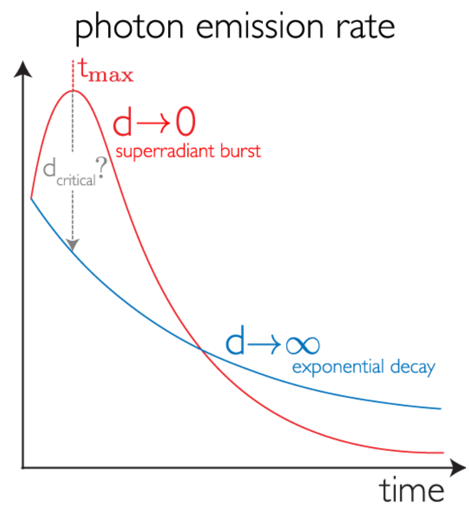
Macro-coherent amplification

- Super-Radiance [R. H. Dicke Phys. Rev. 93, 99–110 (1954)]

  De-excitation via single-photon emission. $|i\rangle \rightarrow |f\rangle + \gamma$



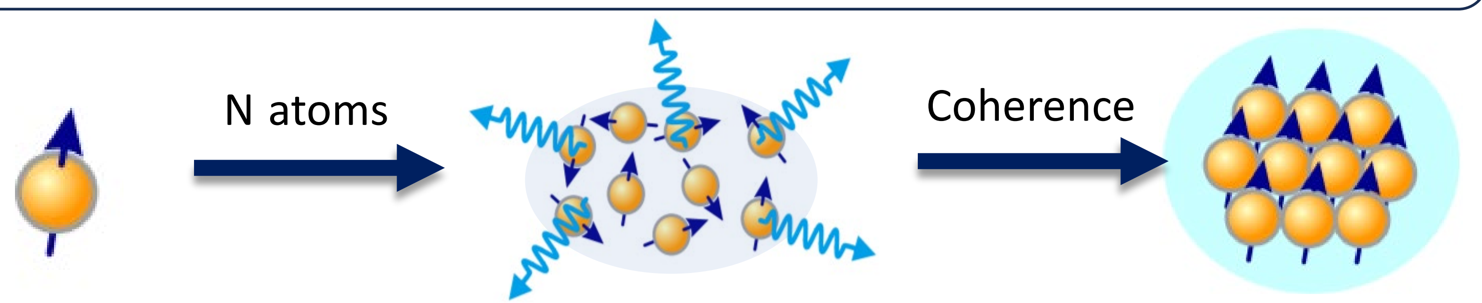
$$R \propto \left| \sum_{m=1}^{N_T} \mathrm{Exp}\left(i\vec{k}_\gamma \vec{x}_m\right) M(\vec{x}_m) \right|^2 \propto N_T^2 \quad [\because M(\vec{x}_m) = M(0), |\text{ target size }| \ll \lambda]$$

$$\mathrm{Exp}[0] = 1$$

- Macro-coherent amplification

  Multi-photon involved transition. $|g\rangle + \gamma_1 \rightarrow |i\rangle \rightarrow |f\rangle + \gamma_2 \ldots$

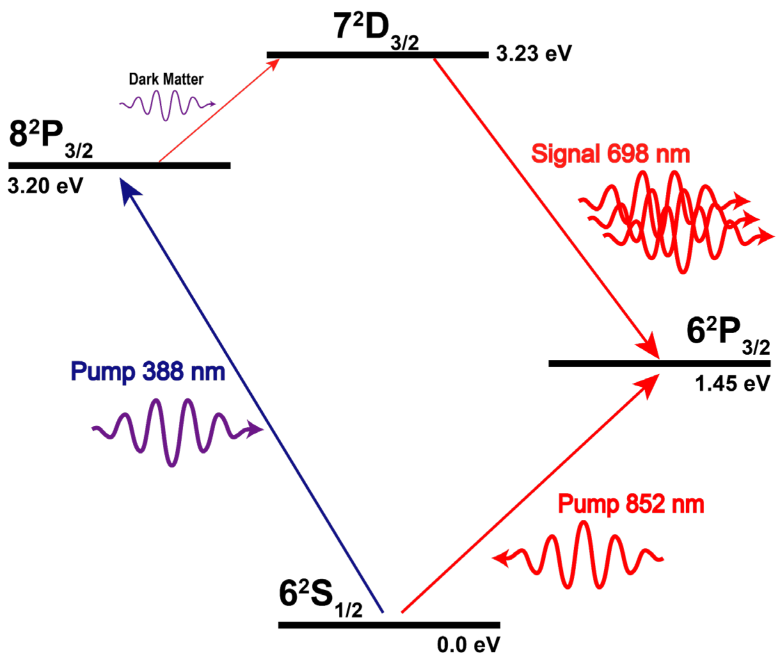
$$R \propto \left| \sum_{m=1}^{N_T} \mathrm{Exp}\left(i\Delta\vec{k} x_m\right) M(\vec{x}_m) \right|^2 \propto N_T^2 \quad \left[\because M(\vec{x}_m) = M(0), \Delta\vec{k} = -\vec{k}_{\gamma 1} + \vec{k}_{\gamma 2} + \ldots = 0\right]$$



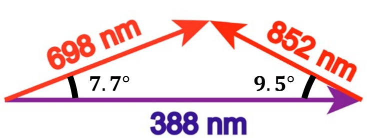
[Miyamoto et al. Prog. Theor. Exp. Phys.081C01 (2015)]

Dark matter detection scheme

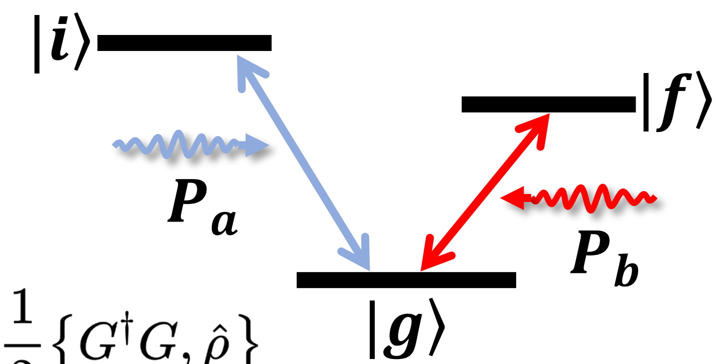
- DM absorption by cesium atom [Sasao et al. Eur. Phys. J. C (2018) 78:949]



- To satisfy $\Delta\vec{k} = 0$



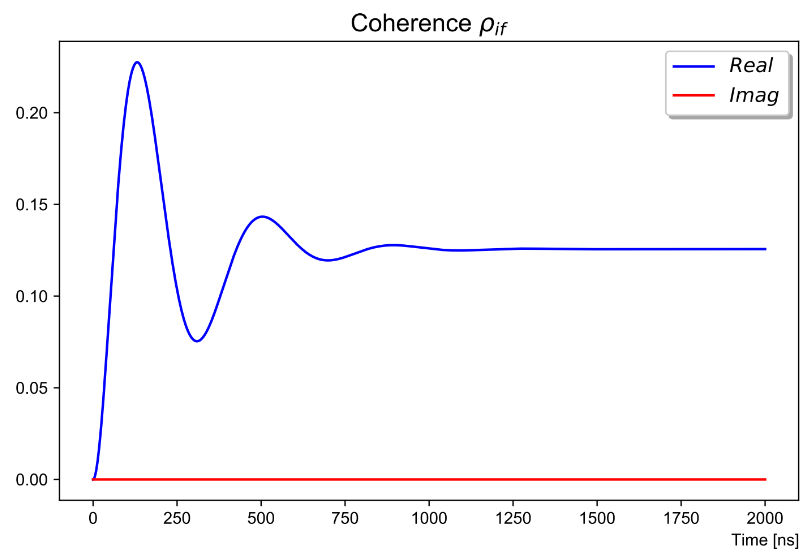
Coherence generation

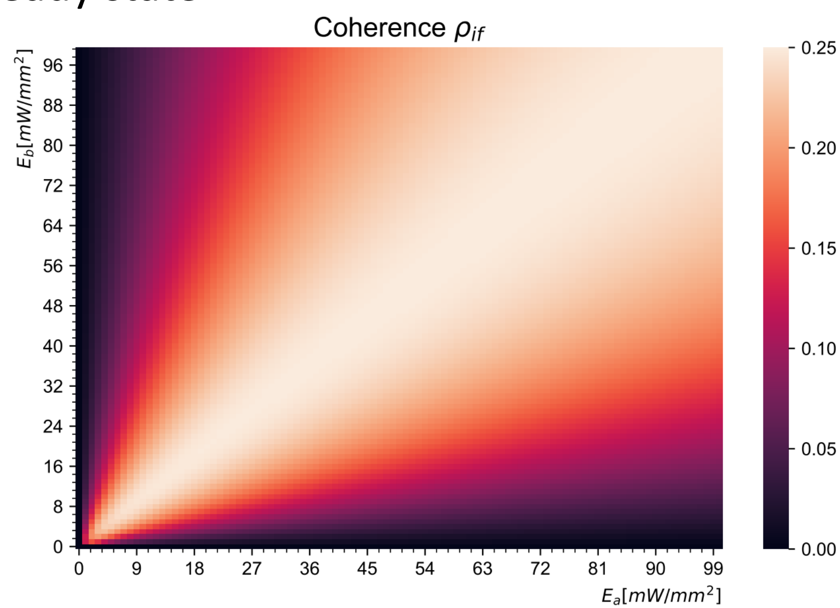


- The Von Neumann equation

$$\frac{d\hat{\rho}}{dt} = -\frac{i}{\hbar}[\hat{H}, \hat{\rho}] + G\hat{\rho}G^{\dagger} - \frac{1}{2}\{G^{\dagger}G, \hat{\rho}\}$$

- Inject two pump cw lasers: system reach steady state

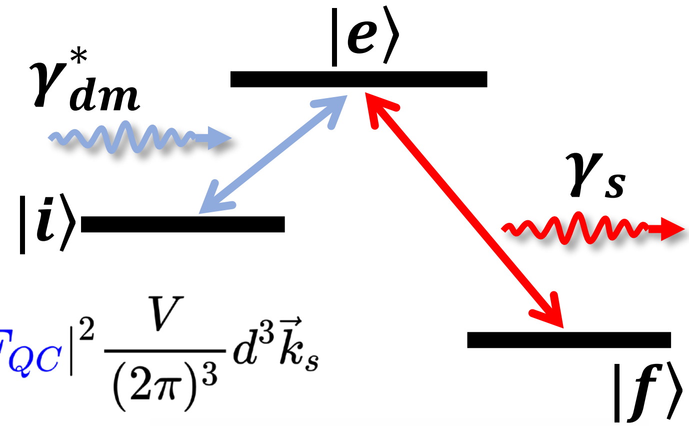




- Laser power requirements

$$P_a = \frac{10^{10} \times 3.198\text{eV}}{274\text{ ns}} \sim 20\text{ mW} \quad P_b = \frac{10^{10} \times 1.5\text{eV}}{35\text{ ns}} \sim 70\text{ mW}$$

DM signal rate

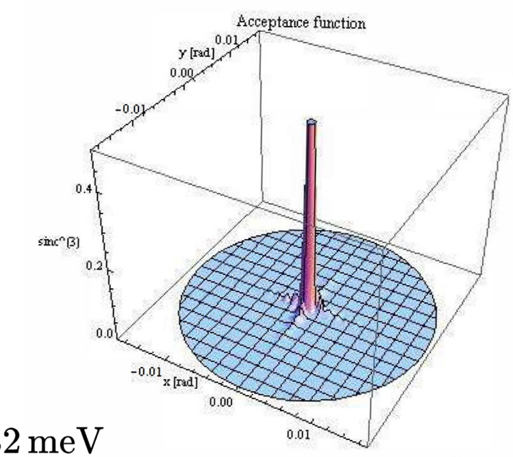


- Fermi's Golden Rule for N atoms system

$$d\Gamma = \frac{2\pi}{\hbar}\delta(\hbar(\omega_{fi}+\omega_s-\omega_d))|M_0 F_{QC}|^2 \frac{V}{(2\pi)^3} d^3\vec{k}_s$$

- For finite target ($1\ \mathrm{mm}^3$), F_{QC} is described by shape function

$$F_{QC} = N_T|\rho_{fi}|\sqrt{A(\Delta\vec{k})}$$



- And assuming the following parameters

$$N_T|\rho_{fi}| = 10^{10}, \quad \int A d\Omega = 10^{-7}, \quad T = 4\,\mathrm{K},$$
$$\rho_{DM} = 0.3\,\mathrm{GeV/cm^3}, \quad \vec{B}_{ext} = 1\,\mathrm{T}, \quad m_{dm} = 32\,\mathrm{meV}$$

- For dark photon, $\chi = 10^{-12}$

$$E_d = 3.3\times10^{-9}\mathrm{V/m} \quad \Gamma_{\mathrm{Dark}} \simeq 12.6\mathrm{Hz}$$

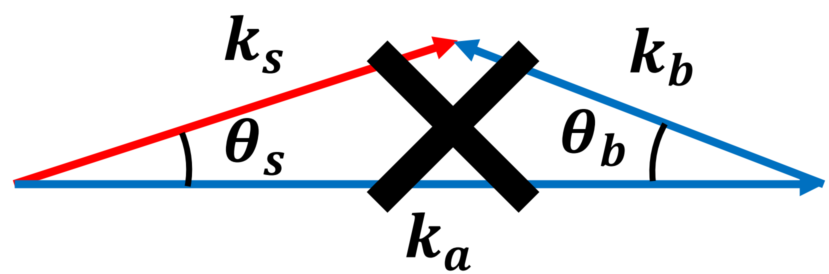
- For Axion, $g_{a\gamma\gamma} = 10^{-12}\mathrm{GeV}^{-1}$, need to increase N_T by 10^4

$$E_d \simeq 10^{-13}\mathrm{V/m} \quad \Gamma_{\mathrm{Axion}} \simeq 10\mathrm{Hz}$$

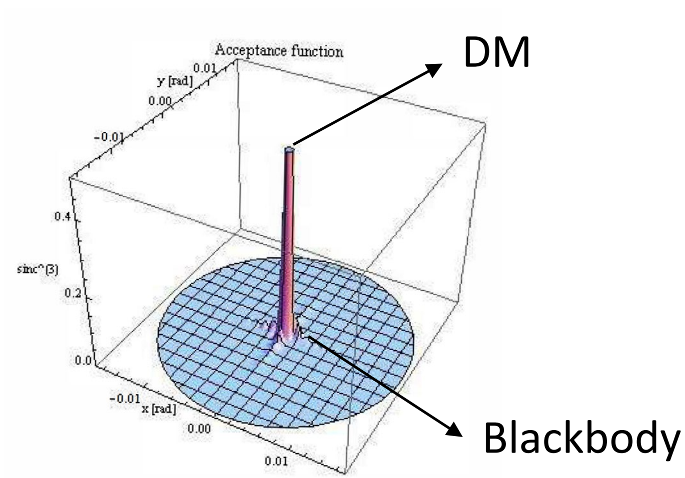
Blackbody background

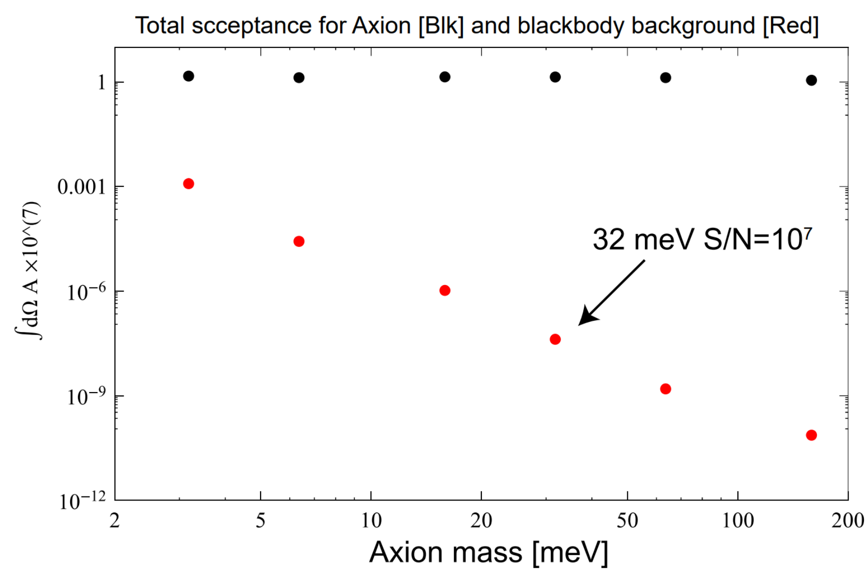
- Blackbody radiation field strength (T = 10 K, $m_a \approx 32$ meV)

$$E_{bb} \simeq 1.4 \times 10^{-9}\ \mathrm{V/m}$$



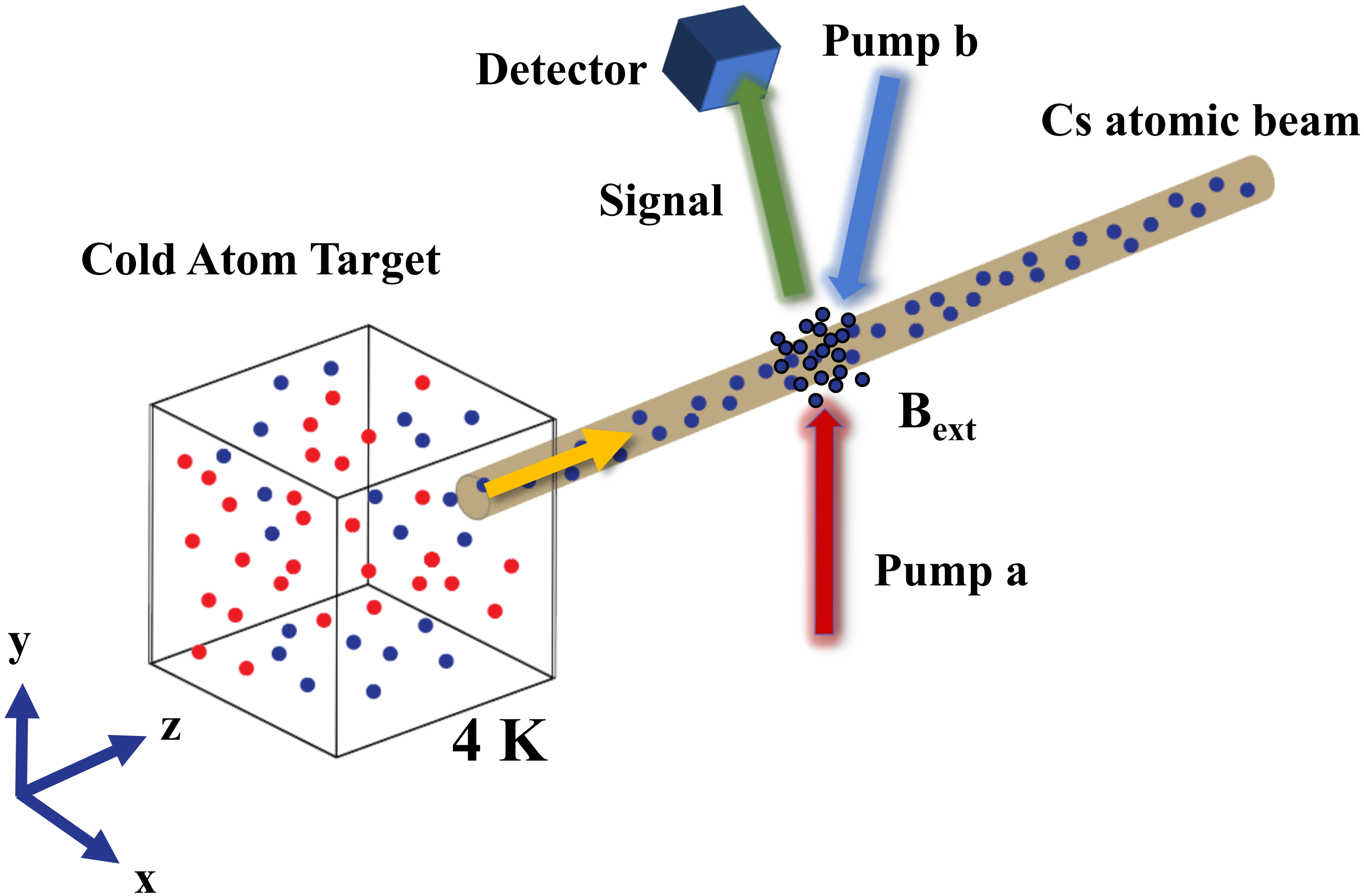
- Blackbody radiation Δk is larger, F_{QC} is small





- Cool down to $T < 20\ K$

Experiment setup



- Signal rate: ~ 10 Hz
- Temperature: ~ 4 K
- Detector dark count: < 1 Hz
- Mass scan range: $31.8^{+0.0}_{-0.3}$meV
- Initial coherence:$|\rho_{fi}| > 0.2$
- Laser line width: < 100 kHz

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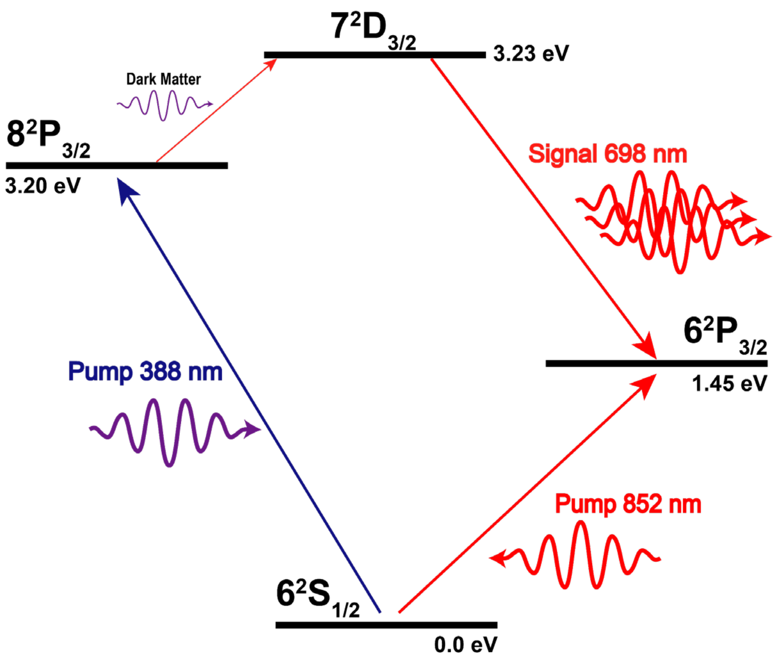
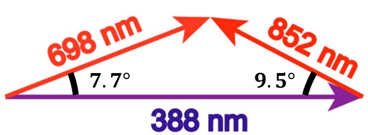
Coherence evaluation

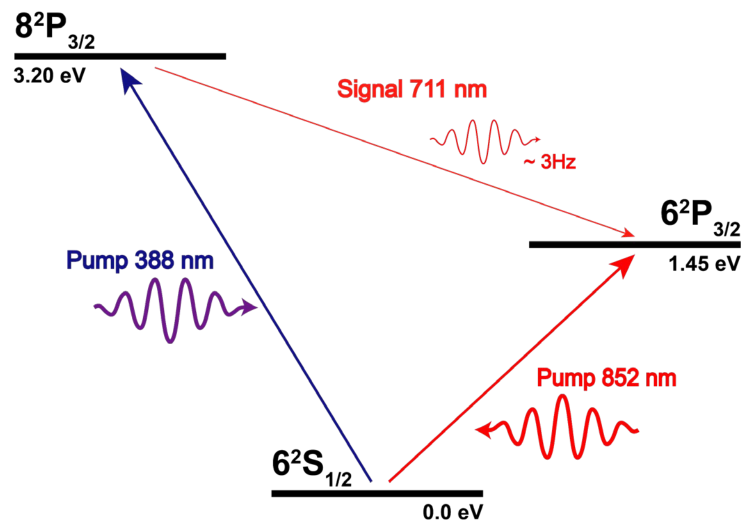
- Using cesium E2 transition

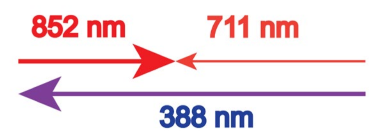


- To satisfy $\Delta\vec{k} = 0$



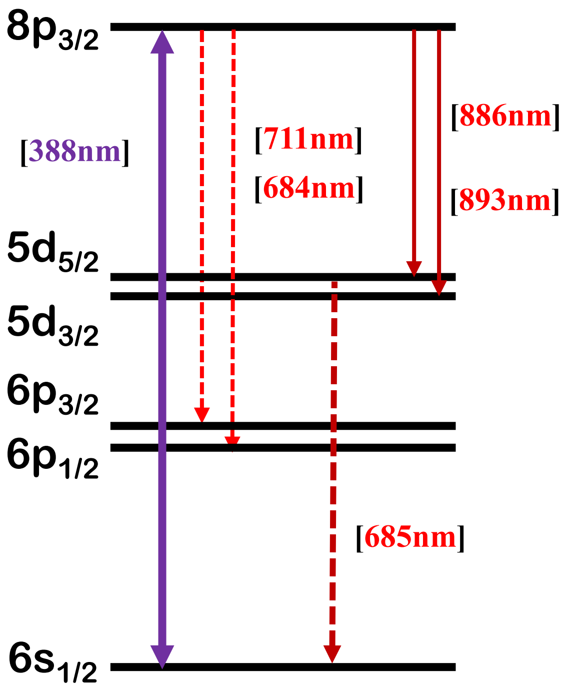
DM detection

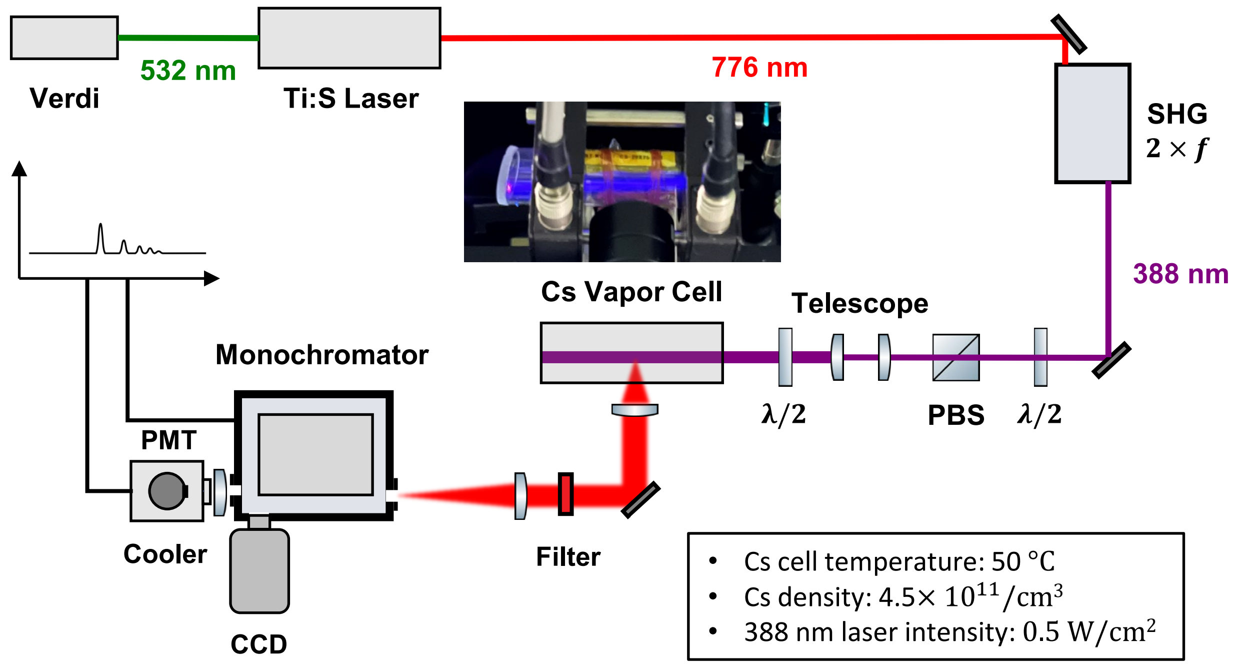




Evaluate the coherence

Spectroscopy Setup





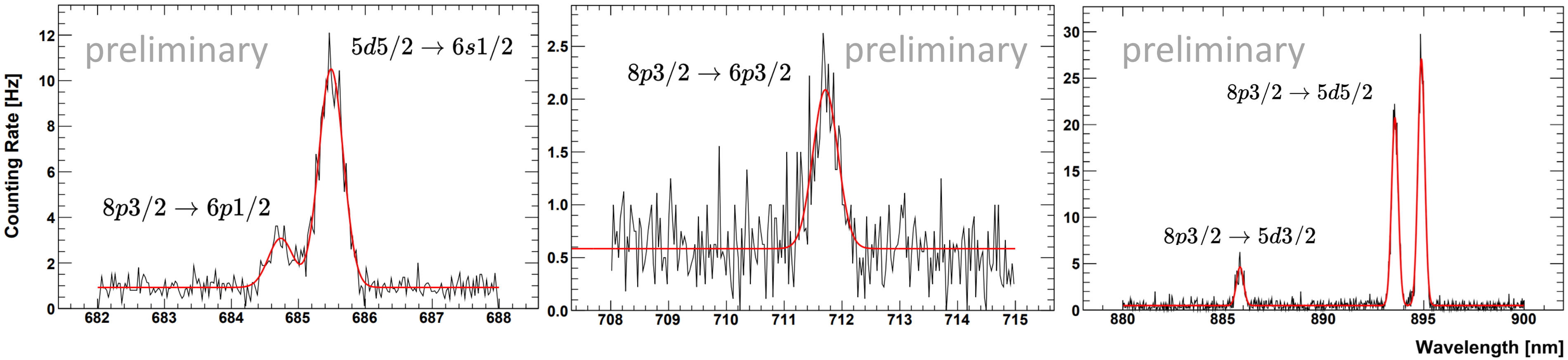
- Cs cell temperature: 50 °C
- Cs density: $4.5\times 10^{11}/\mathrm{cm}^3$
- 388 nm laser intensity: $0.5\ \mathrm{W/cm}^2$

❑ Compare the emission rate from same excited state

❑ Photomultiplier Tube (PMT Hamamatsu R13456P) is cooled down to -30 °C to reduce the dark count rate ($\sim$1 HZ)

Experiment result

- ❑ Spectrums by scanning the monochromator

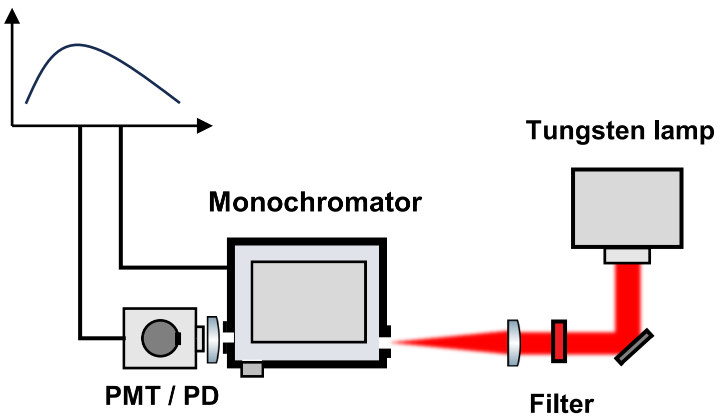


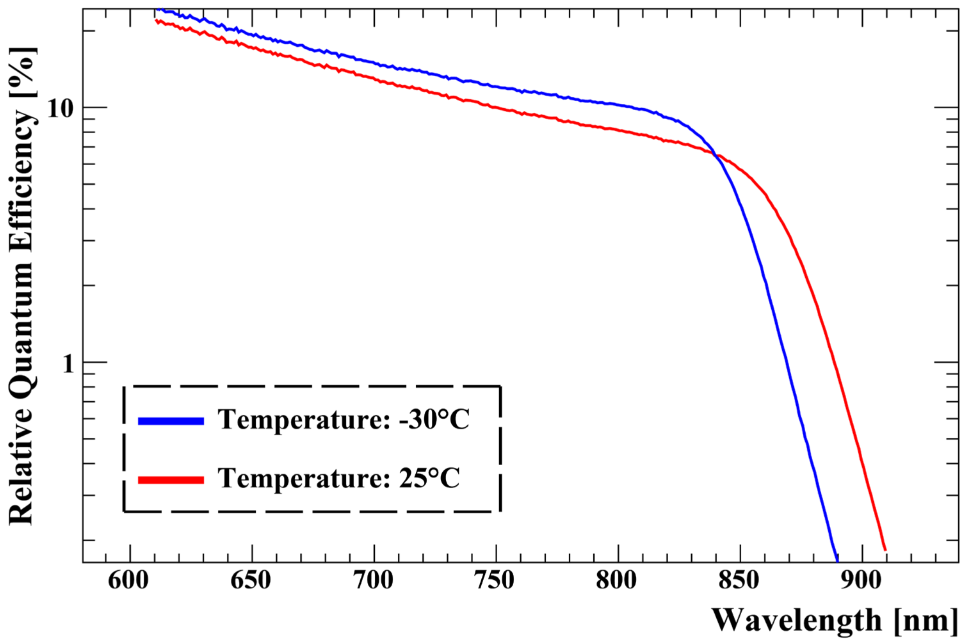
- ❑ Forbidden transitions are successfully observed

- ❑ Responsivity of the instruments is needed

PMT calibration

❑ Calibration experiment setup





❑ **Relative quantum efficiency of PMT is calibrated**

❑ A coefficient of the forbidden transition is estimated (2.3 Hz for 711 nm)

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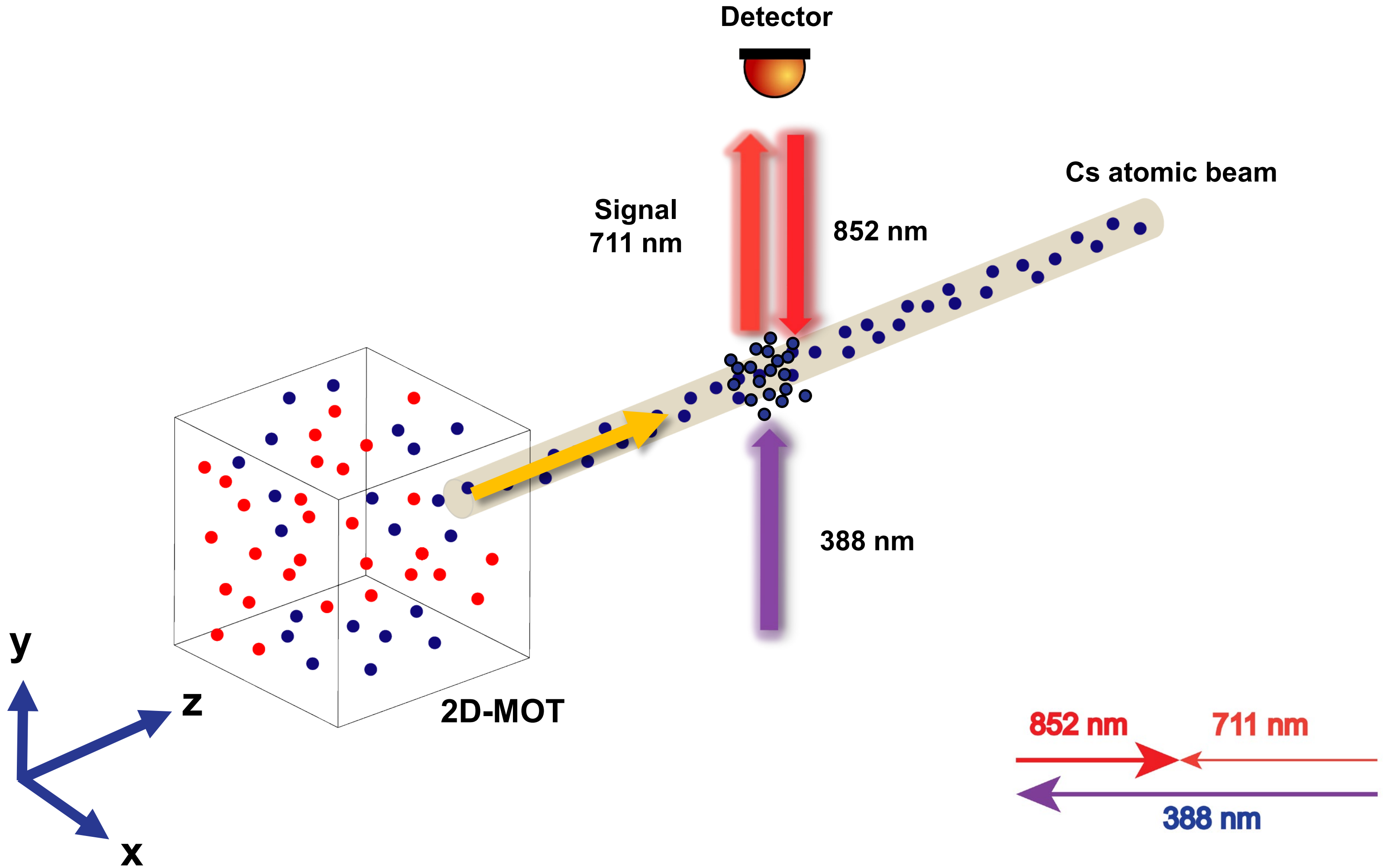
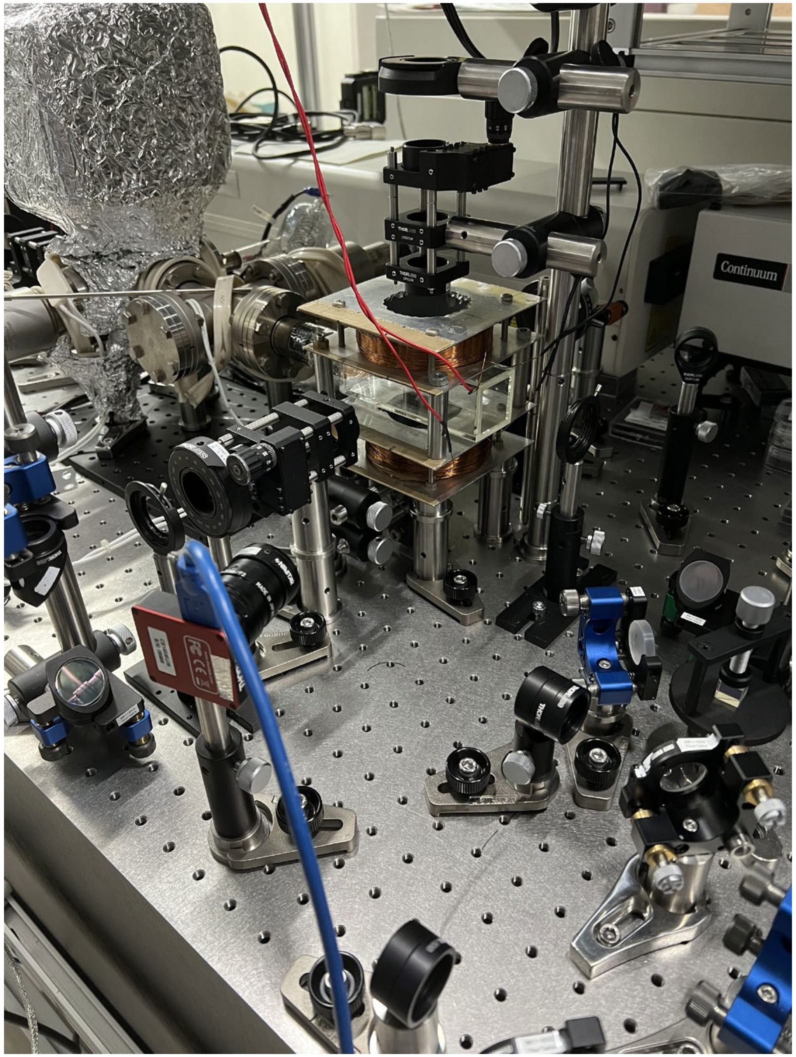
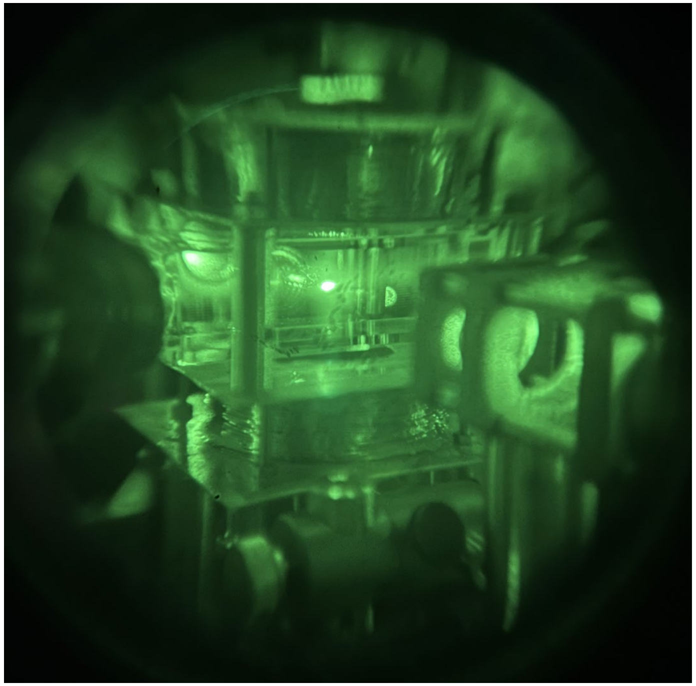
Future Prospect

- Coherence measurement experiment using 2D Magneto-optical trap(MOT)



3D-MOT of Cesium





Summary

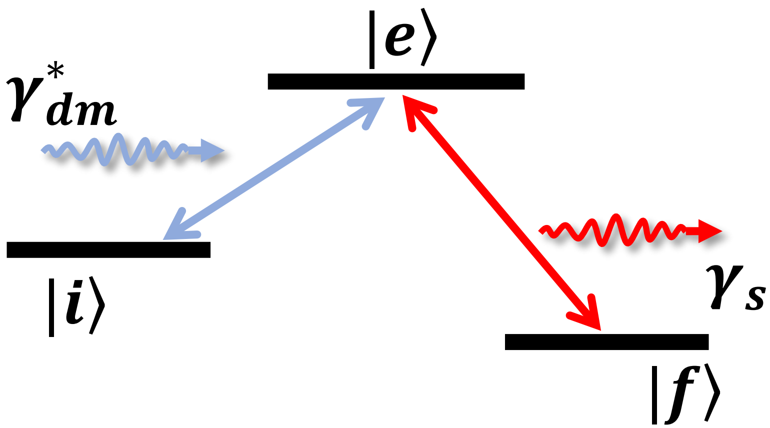
- New method of dark matter search.
  - Amplification by macroscopic coherence is KEY
- Coherence measurement experiment with Cs E2 transition
  - ✓ Determine E2 transition rate
  - Coherence measurement experiment
- Dark matter search in meV region

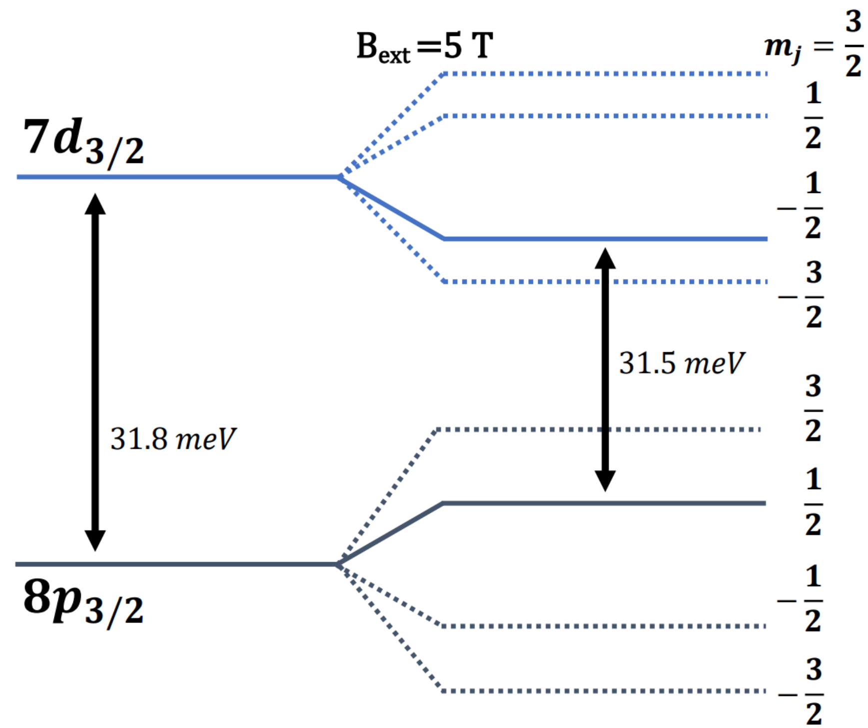
Thank you for your attention!

Mass scan

- Interaction Hamiltonian

$$\hat{H}_I = A\vec{L}\cdot\vec{S} + \mu_B(2\vec{S}_z + \vec{L}_z)\cdot\vec{B}_{ext}$$





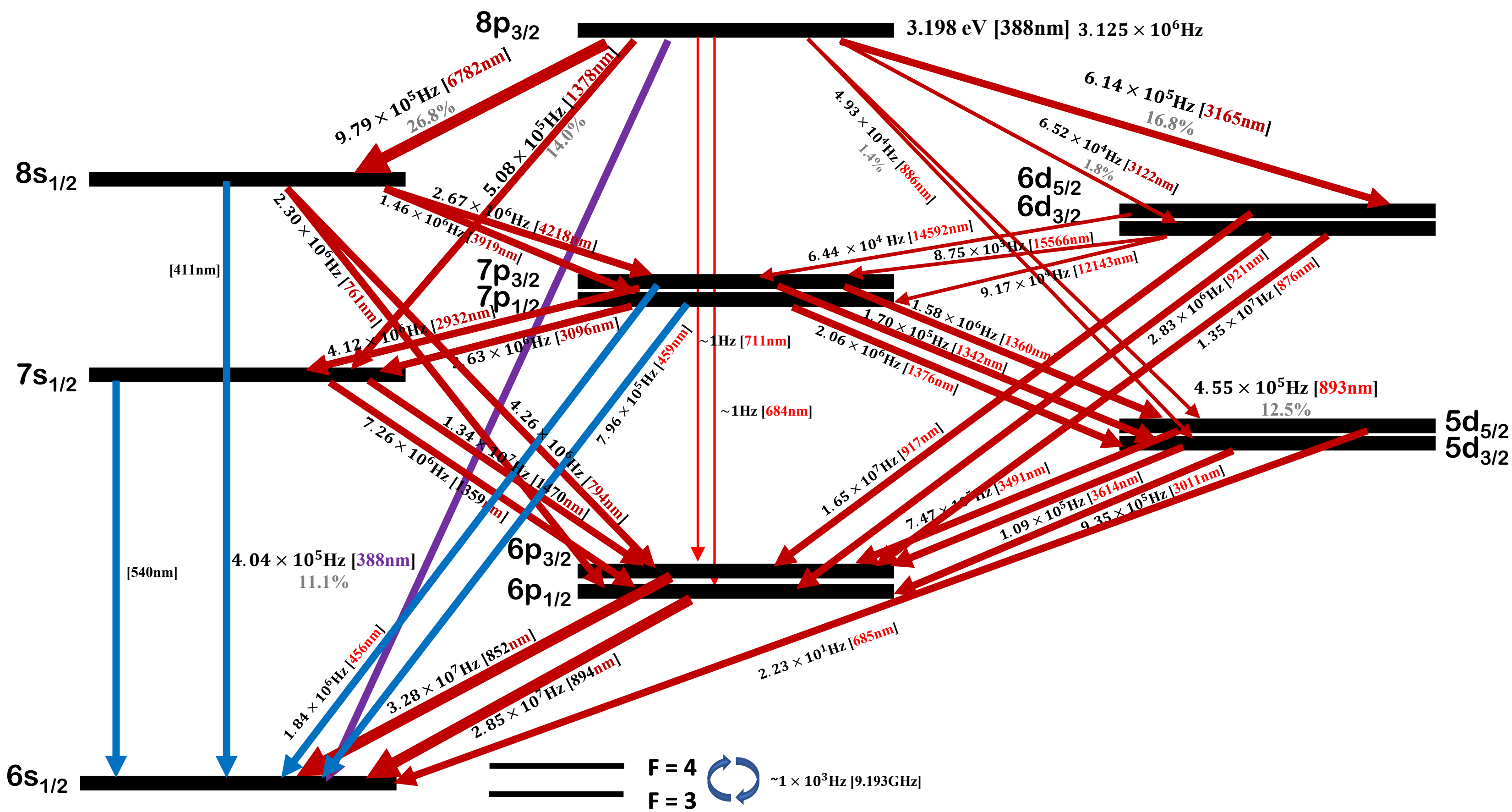
- Energy shift caused by Zeeman effect

$$\Delta E_{m_j} = g_L \mu_B B_{ext} m_j$$

- $8p_{\{\frac{3}{2},\frac{1}{2}\}} \rightarrow 7d_{\{\frac{3}{2},-\frac{1}{2}\}}$ under 5 T B_{ext}

$$\Delta m = -0.3meV$$

Cs Energy level



3D-MOT of Cesium