Quantum entanglement of ions for light dark matter detection

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Based on JHEP02(2024)124 [arXiv:2311.11632]
with Asuka Ito, Ryuichiro Kitano & Wakutaka Nakano

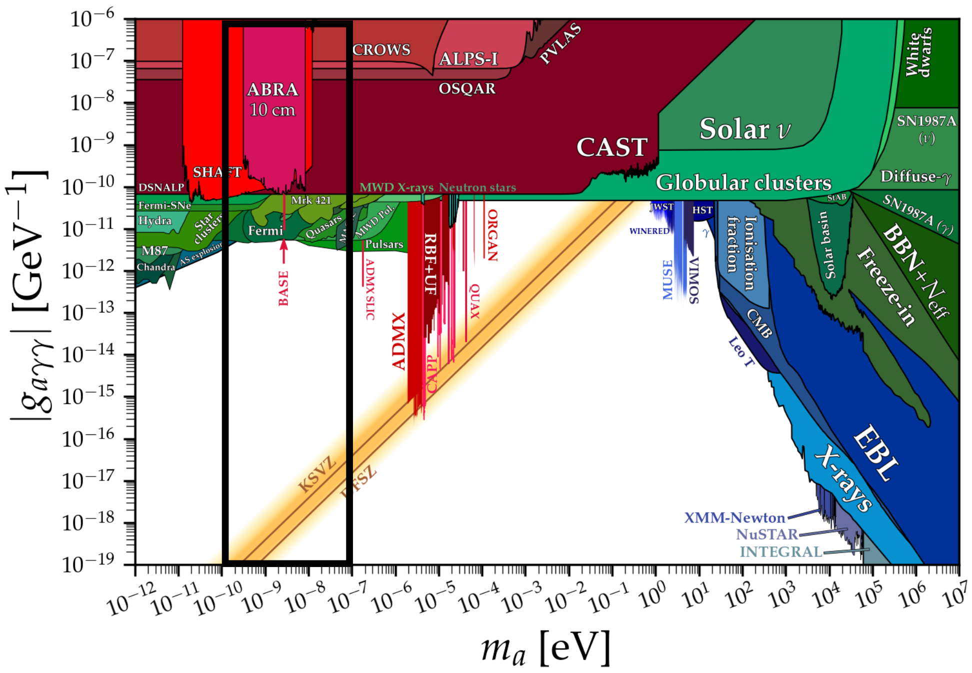
Summary

We considered using a quantum computer of the ion trap type to detect DM

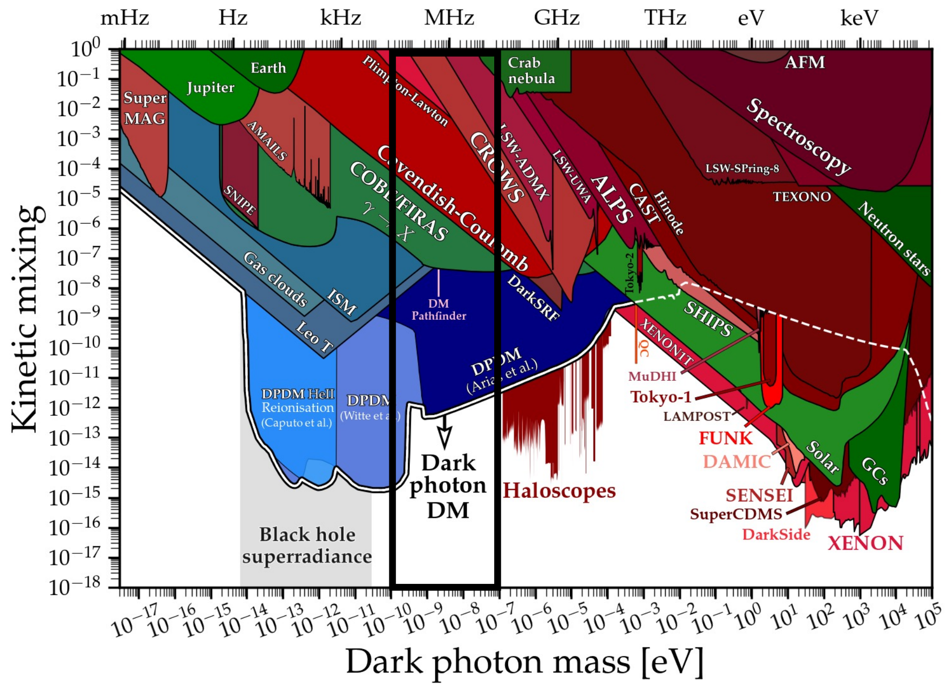
and found that the use of entanglement maximally enhances the signal rate

by (# qubit)^2

Targets



Axion (under a magnetic field B)



Dark photon

[AxionLimits]

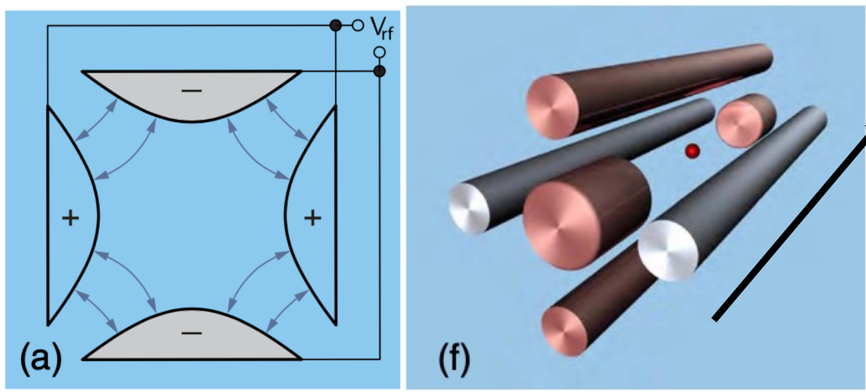
Linear Paul traps

- Ions are trapped in a vacuum chamber with static and radio-frequency voltage

- Each ion behaves as a quantum harmonic oscillator

- One of the platforms of quantum computers

- Gates are implemented by laser

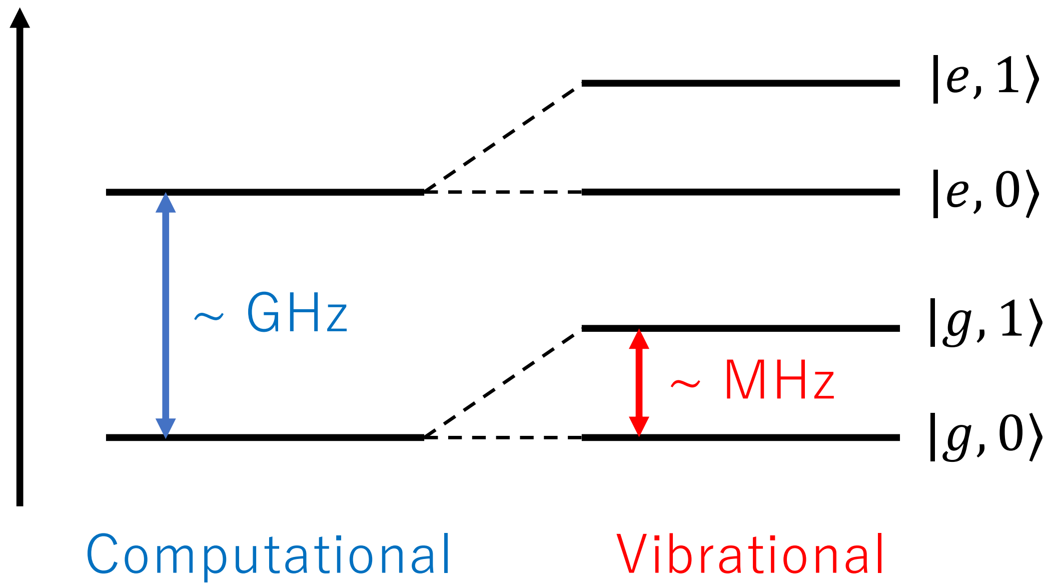


[Rev. Mod. Phys. **87**, 1419 (2015)]

States of an ion

- The ion with single valence electron is usually chosen
  - Ca^+, Ba^+, Yb^+, etc.

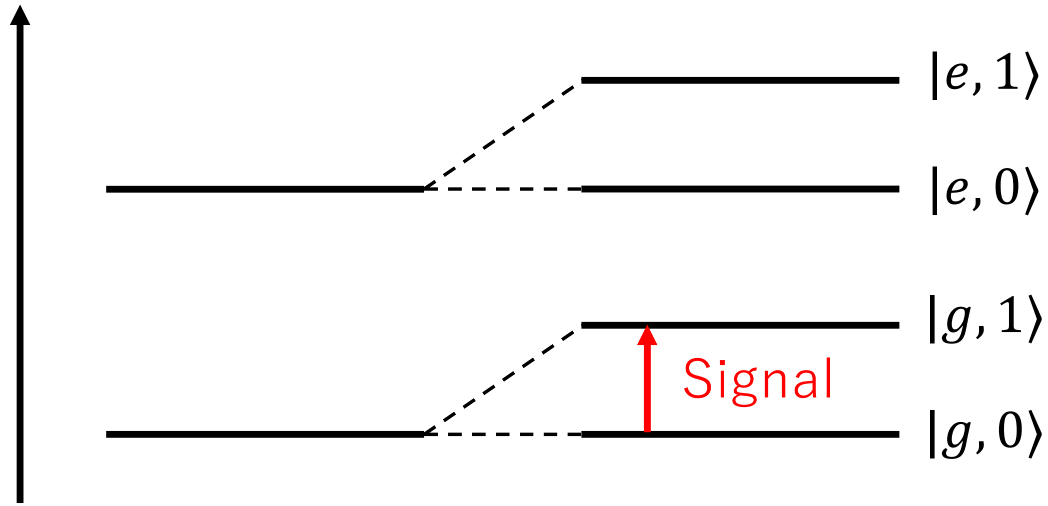
- Two “qubits”



Coupling with ions

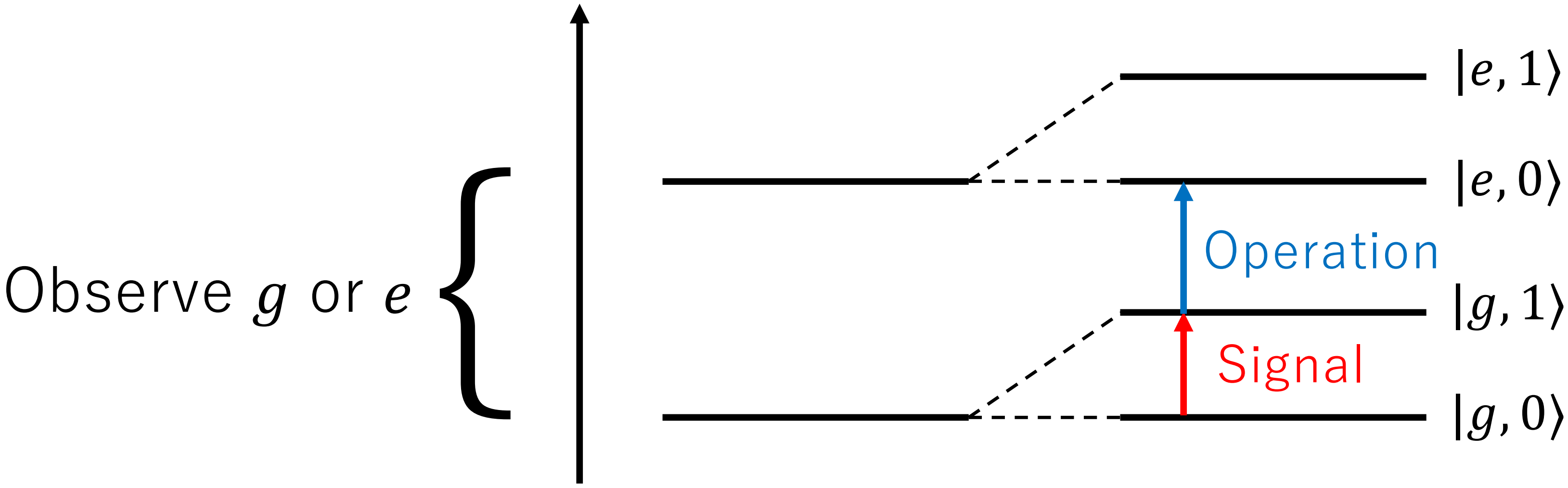
- Ions couple with an electric field induced by $X(= a \text{ or DP})$

$$E_{X,z} = \epsilon_X \sqrt{2\rho_{\rm DM}} \sin\left(m_X t - \phi_X\right) , \quad m_X \sim 0.1 - 100 \text{ neV} \sim \text{MHz}$$



Detection scheme for $N = 1$

- Start from $|g, 0\rangle$ and wait the interaction with DM
- Observe the computational qubit: g or e



Sensitivity

- Thermal photons from electrodes can be noise
- The total probability of e

$$P_1(T) = \dot{n}T + |\alpha_X|^2 T^2$$

- The signal $\propto T^2$, while the noise $\propto T$
- $\frac{\#\mathrm{Signal}}{\sqrt{\#\mathrm{Noise}}} = 1.645$ (95% C.L.)

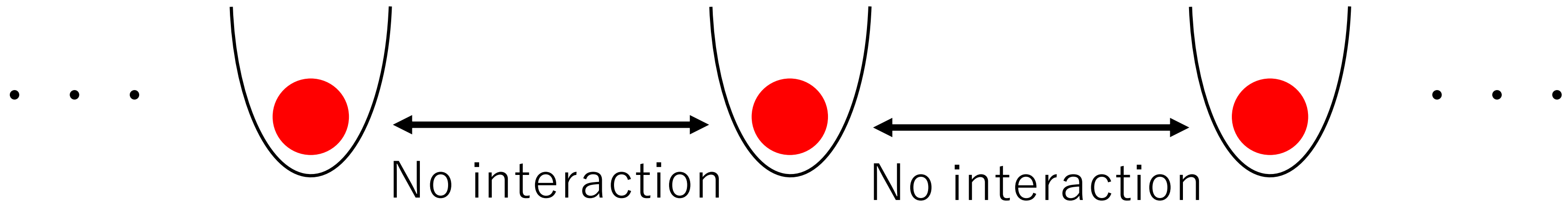
$$E_z = 3.6\ \mathrm{nV/m} \times \left(\frac{\dot{n}}{0.1\ \mathrm{s}^{-1}}\right)^{1/4} \left(\frac{T_{\mathrm{total}}}{1\ \mathrm{day}}\right)^{-1/4} \left(\frac{T}{0.4\ \mathrm{s}}\right)^{-1/2} \left(\frac{m_{\mathrm{ION}}}{37\ \mathrm{GeV}}\right)^{1/2} \left(\frac{\omega_z}{10\ \mathrm{neV}}\right)^{1/2}$$

$$\sim \quad g_{a\gamma} = 4.4 \times 10^{-11}\ \mathrm{GeV}^{-1}, \qquad \epsilon = 6.4 \times 10^{-12}$$

Maximally entangled state

- For example,

$$|\mathrm{GHZ}\rangle = \frac{1}{\sqrt{2}}(|0,0,\dots,0\rangle + |1,1,\dots,1\rangle)$$



- We observe either all 0 or all 1
- Quantum operations can prepare this state!

Detection scheme for $N > 1$

$$|g, g, g, \ldots, g, 0\rangle$$

Operations & moving ions

$$\frac{1}{\sqrt{2}}\left[\left(\frac{|g,0\rangle + |g,1\rangle}{\sqrt{2}}\right)^{\otimes N} + \left(\frac{|g,0\rangle - |g,1\rangle}{\sqrt{2}}\right)^{\otimes N}\right]$$

Interaction with DM

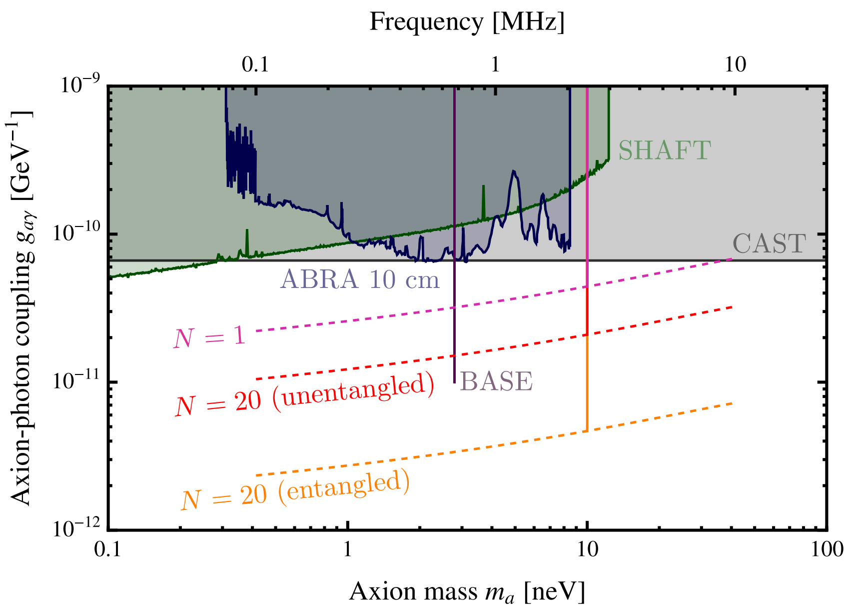
The inverse operations

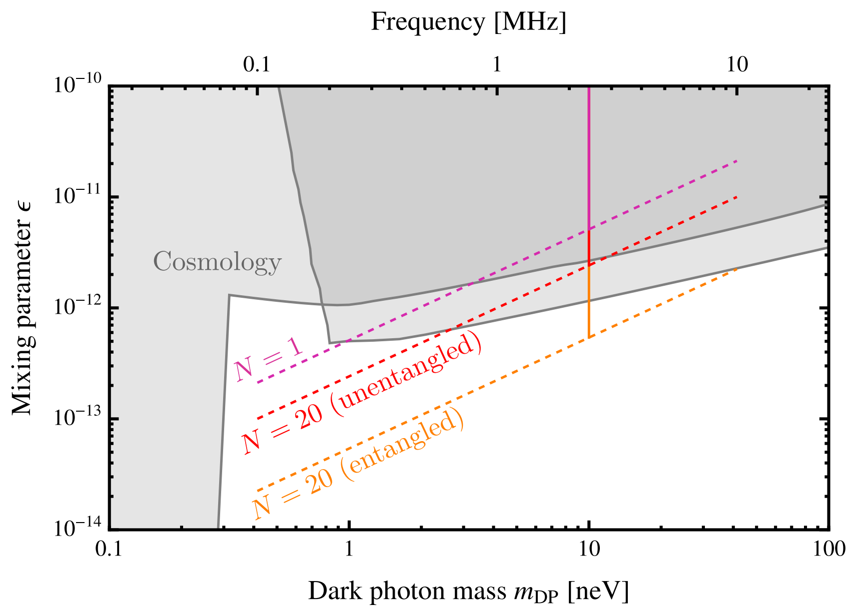
$$|g, g, g, \ldots, g, 0\rangle + \underline{iN\beta_{\mathrm{i}}}\, |e, g, g, \ldots, g, 0\rangle + \cdots$$

The probability of $|e, g, \ldots, g\rangle$ is enhanced by N^2

Sensitivity

- If the heating noise excites ions incoherently, $\frac{\#\mathrm{Signal}}{\sqrt{\#\mathrm{Noise}}} \propto N^{3/2}$, while $\frac{\#\mathrm{Signal}}{\sqrt{\#\mathrm{Noise}}} \propto N^{1/2}$ with unentangled ions





Conclusion

- The Paul trap system, which is one of platforms of quantum computers, is useful to detect a weak electric field from DM

- Quantum entanglement enables to enhance the signal: N^2 times larger than the single ion case

- This system can reach State of the Art of $g_{a\gamma}$ and ϵ with the DM masses of $\mathcal{O}$(neV)