Entanglement of cooled ions for dark wave search experiment

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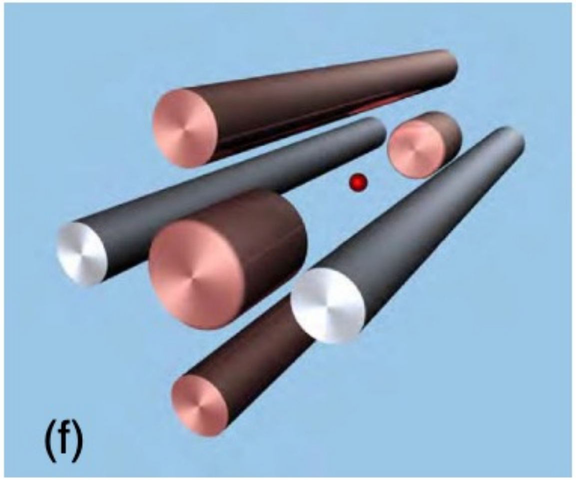
Based on **JHEP 02 (2024) 124** (+ work in progress),

with A. Ito, R. Kitano and W. Nakano

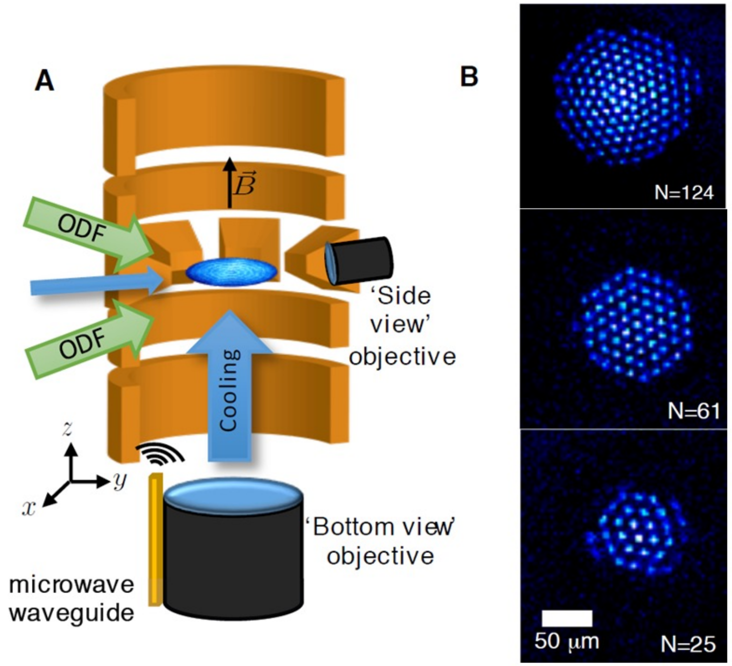
イオントラップ

Paul trap



[Bruzewicz+, 2015]

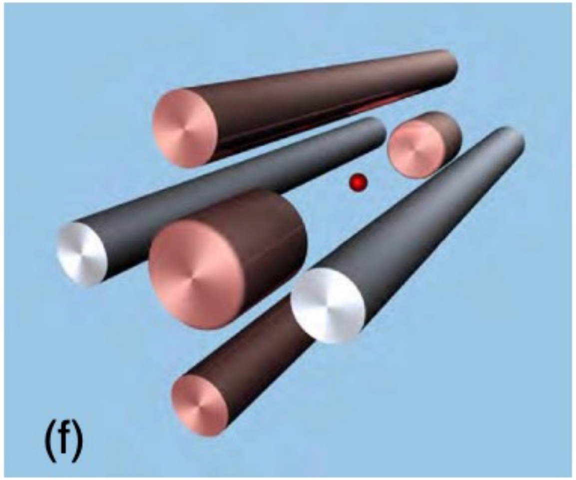
Penning trap



[NIST webpage]

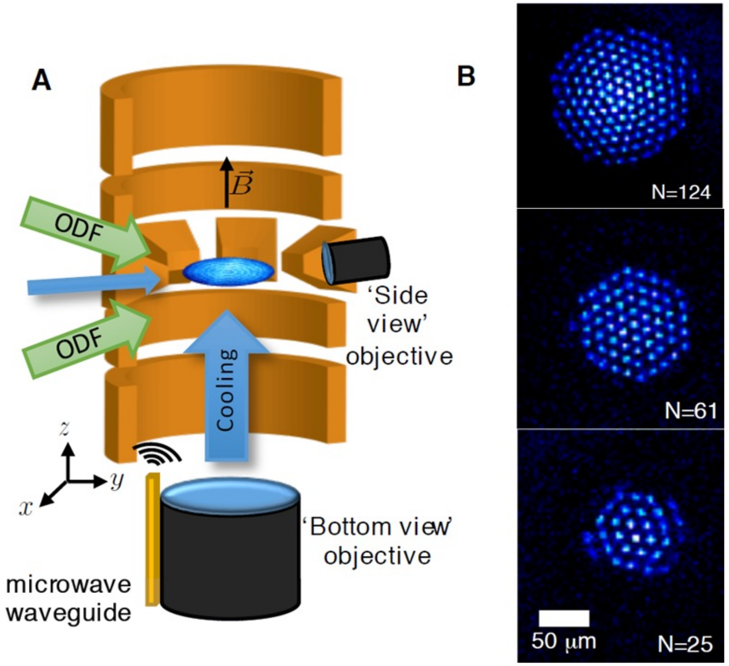
イオントラップ

Paul trap



[Bruzewicz+, 2015]

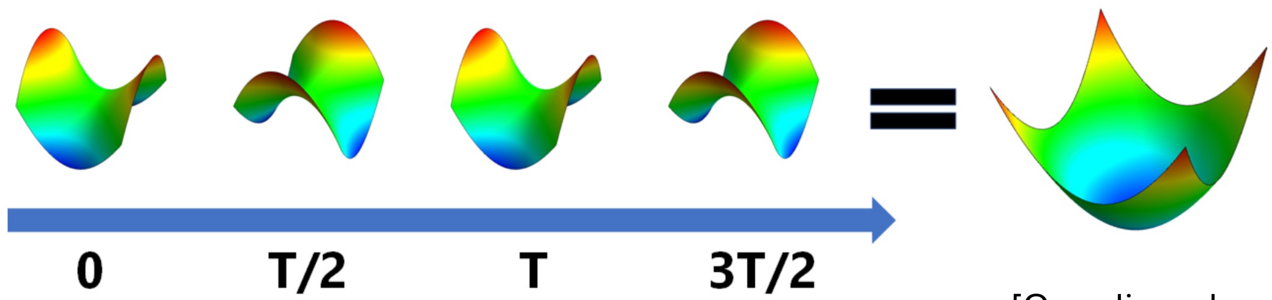
Penning trap



[NIST webpage]

Linear Paul trap

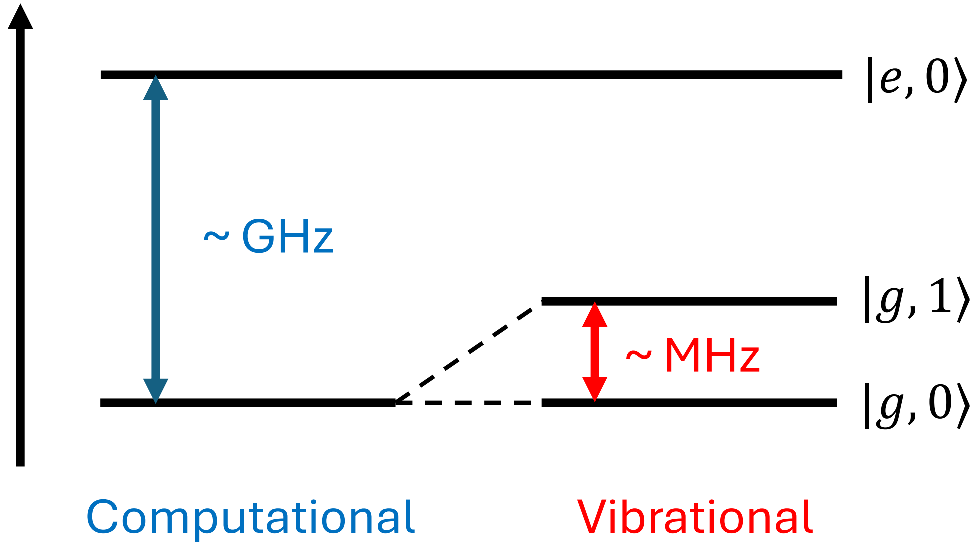
- Ions are trapped in a vacuum chamber with static and radio-frequency voltage
- The voltages make electric potential, so that ions are at the saddle point on xy-plane



[Qmedia webpage]

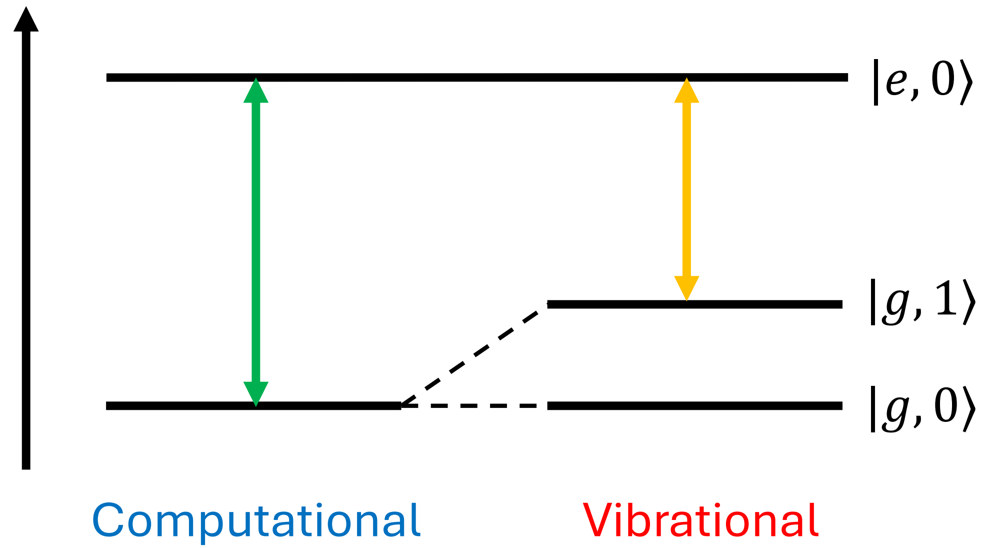
States

$$H_0 = \frac{\omega_0}{2}\sigma_z + \omega_z a^\dagger a$$



- Spins: $|g\rangle$ and $|e\rangle$
- Oscillation: $|n = 0, 1, \dots\rangle$
- 振動は z 方向だけ考慮する
- イオンが複数の場合は集団振動を利用

Gates



- Hadamard gate

$$|g\rangle \to \frac{|g\rangle + |e\rangle}{\sqrt{2}}, \qquad |e\rangle \to \frac{|g\rangle - |e\rangle}{\sqrt{2}}$$

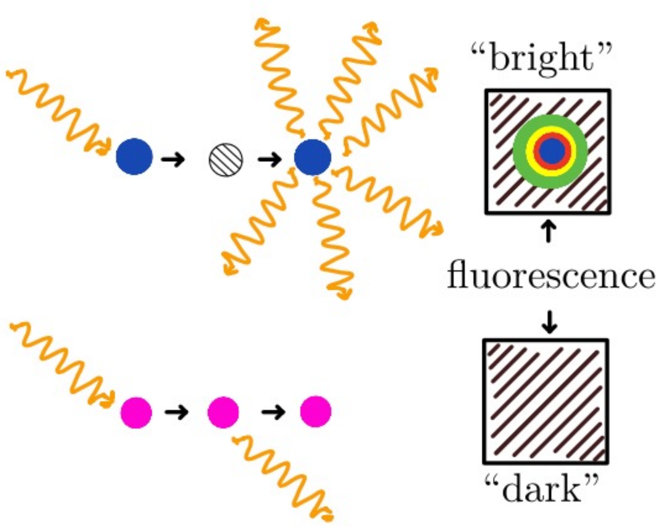
- Controlled-NOT (CNOT) gate

$$|g,g\rangle \to |g,g\rangle, \qquad |g,e\rangle \to |g,e\rangle,$$

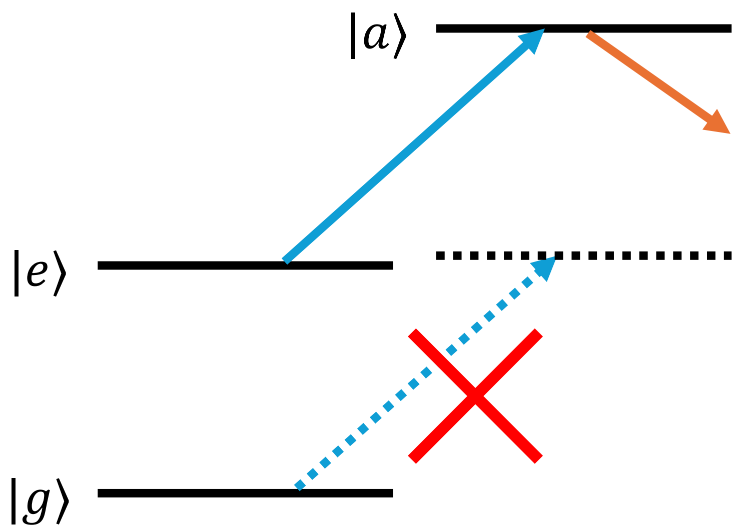
$$|e,g\rangle \to |e,e\rangle, \qquad |e,e\rangle \to |e,g\rangle$$

Readout

- 不安定な状態 $|a\rangle$ を準備
- レーザーで $|e\rangle \to |a\rangle$
- 状態 $|a\rangle$ のイオンから光が出る

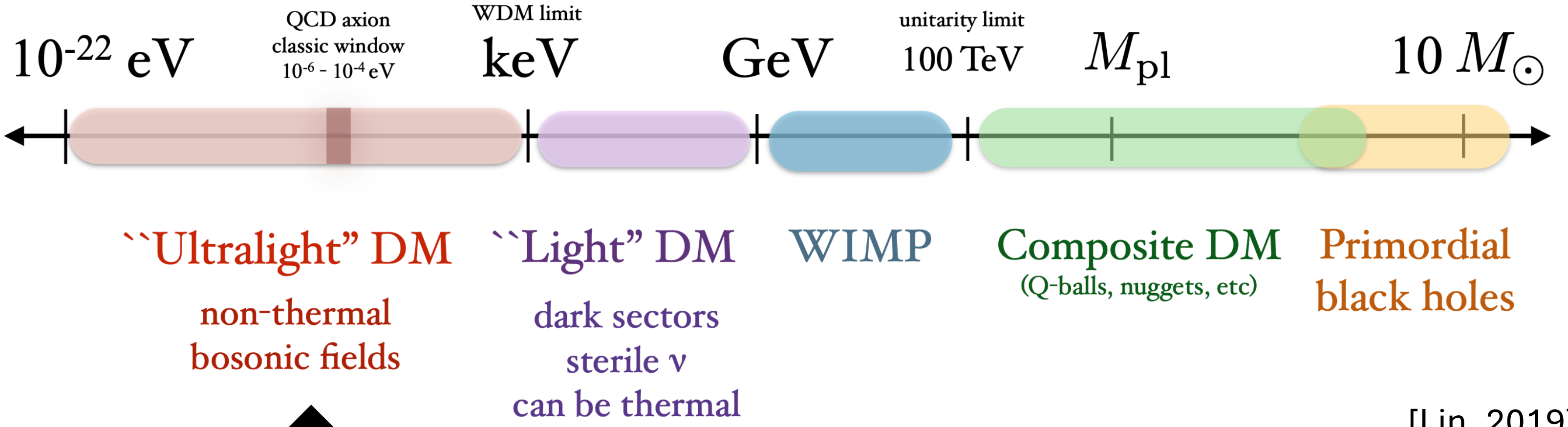


[Bernardini+, 2023]



Mass scale of dark matter

(not to scale)



[Lin, 2019]

見たいのはココ（~ neV）！

波状暗黒物質

- 暗黒物質が軽い（$m_{\mathrm{DM}} \lesssim 10$ eV）場合、 de Broglie 波長内の occupation number が 1 より大きくなる

- 暗黒物質を古典的な波として扱える

$$\varphi = \frac{\sqrt{2\rho_{\mathrm{DM}}}}{m_{\mathrm{DM}}} \cos(m_{\mathrm{DM}} \vec{v}_{\mathrm{DM}} \cdot \vec{x} - m_{\mathrm{DM}} t + \phi_{\mathrm{DM}})$$

- ただし coherent time $T_{\mathrm{DM}} = 2\pi / m_{\mathrm{DM}} v_{\mathrm{DM}}^2$ の中だけ

Axion

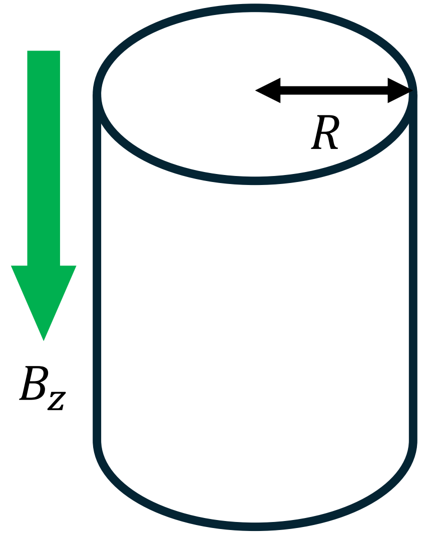
- Axion = QCD axion + axion-like particles
- 光子と結合:

$$-\frac{1}{4}g_{a\gamma}aF^{\mu\nu}\tilde{F}_{\mu\nu}$$

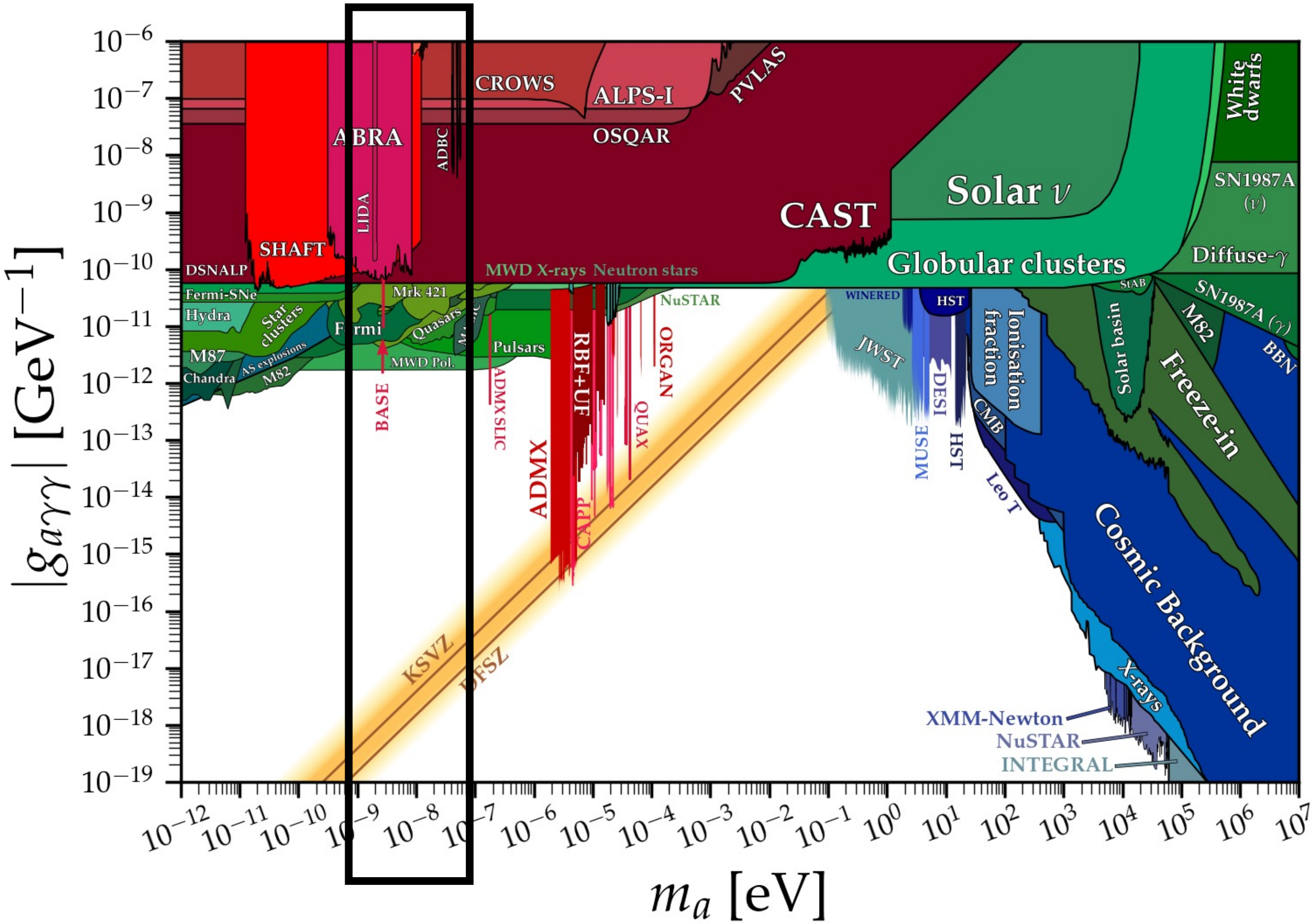
- 磁場を置いておくと電場ができる

$$E_{a,z} = \epsilon_a\sqrt{2\rho_{\mathrm{DM}}}\sin\left(m_a t - \phi_a\right),$$

$$\epsilon_a = \frac{B_z}{2}\frac{g_{a\gamma}}{m_a}(m_a R)^2\left[\left(\log\frac{m_a R}{2} + \gamma - \frac{1}{2}\right)^2 + \left(\frac{\pi}{2}\right)^2\right]^{1/2},$$



Axion



[Axion Limits]

Dark photon

- 新たな U(1) ゲージ場: 光子と混ざる

$$\frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}$$

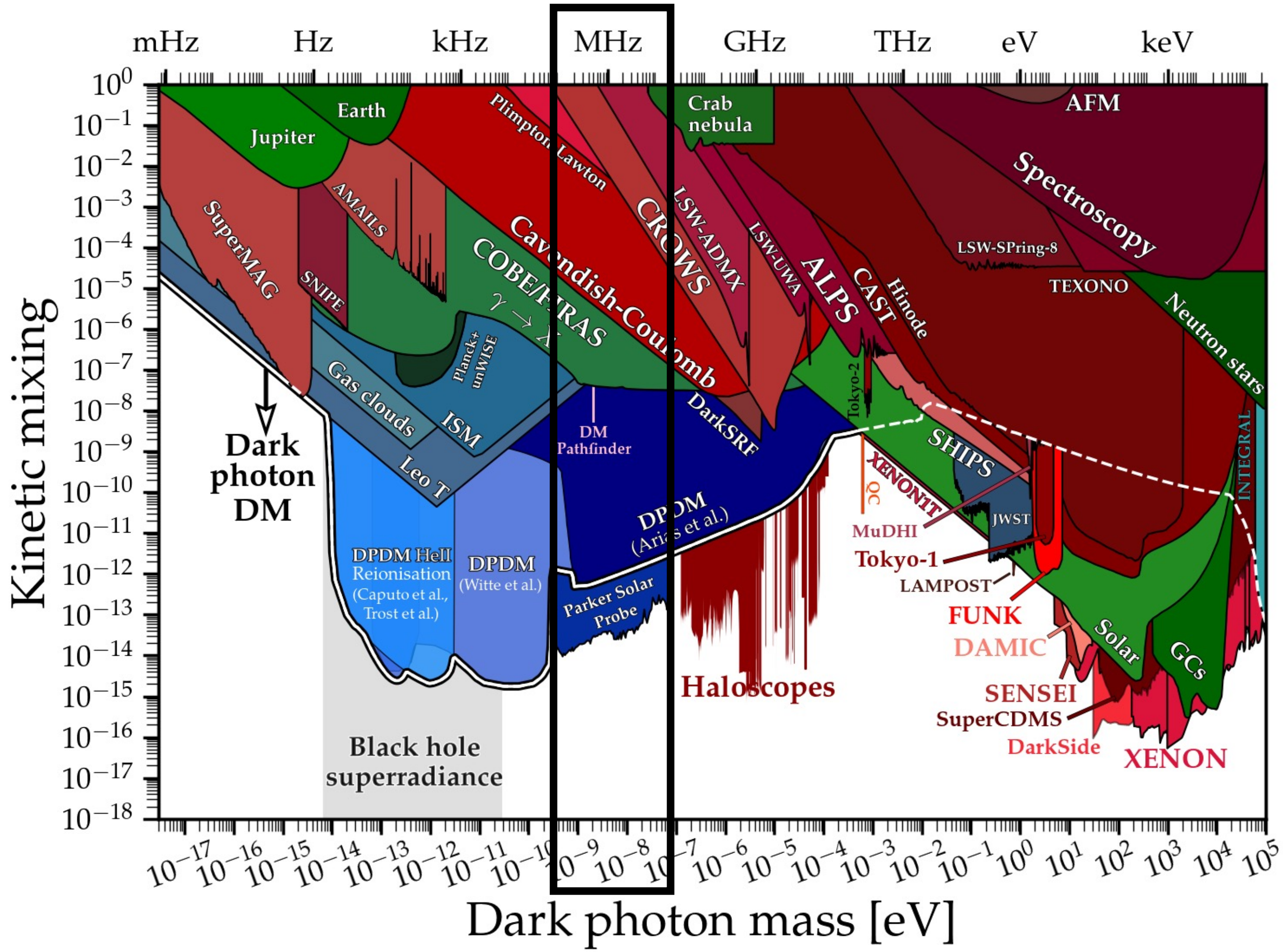
- 電場（磁場はいらない）

$$E_{\mathrm{DP},z} = \epsilon_{\mathrm{DP}} \sqrt{2\rho_{\mathrm{DM}}} \sin\left(m_{\mathrm{DP}} t - \phi_{\mathrm{DP}}\right)$$

$$\epsilon_{\mathrm{DP}} = \epsilon \cos\theta$$

- 仮定: polarization θ はランダム、no boundary condition

Dark photon



[Axion Limits]

Signal

- Hamiltonian

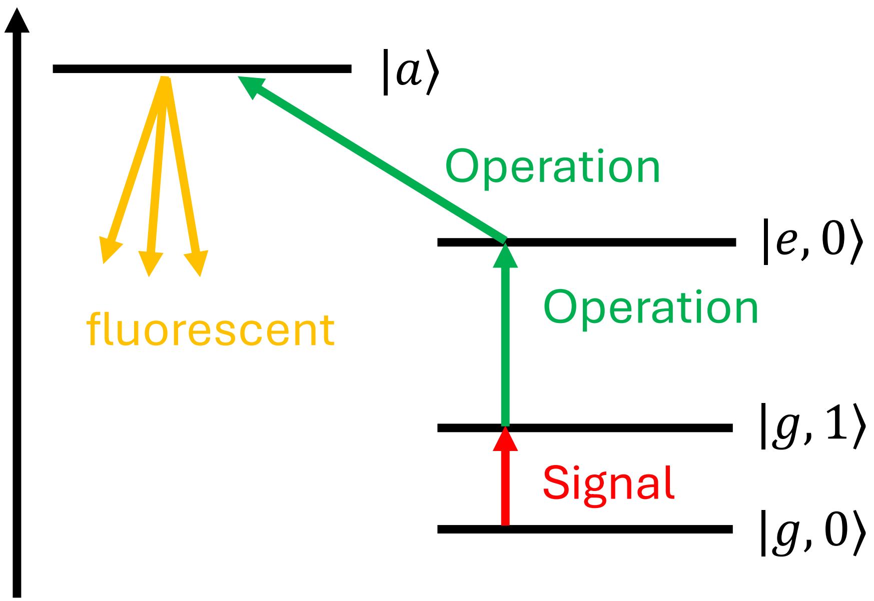
$$H_X = \frac{eE_{X,z}}{\sqrt{2m_{\mathrm{ION}}\omega_z}}(a^\dagger e^{i\omega_z t} + a e^{-i\omega_z t}) = e\epsilon_X \sin(m_X t - \phi_X)\sqrt{\frac{\rho_{\mathrm{DM}}}{m_{\mathrm{ION}}\omega_z}}(a^\dagger e^{i\omega_z t} + a e^{-i\omega_z t})$$

- 共鳴 @ $\omega_z = m_X$

- 時間発展

$$D(\beta) = \exp\left(\beta a^\dagger - \beta^* a\right),$$

$$\beta = \alpha_X T, \quad \alpha_X = \frac{e\epsilon_X e^{i\phi_X}}{2}\sqrt{\frac{\rho_{\mathrm{DM}}}{m_{\mathrm{ION}} m_X}}.$$



Noise

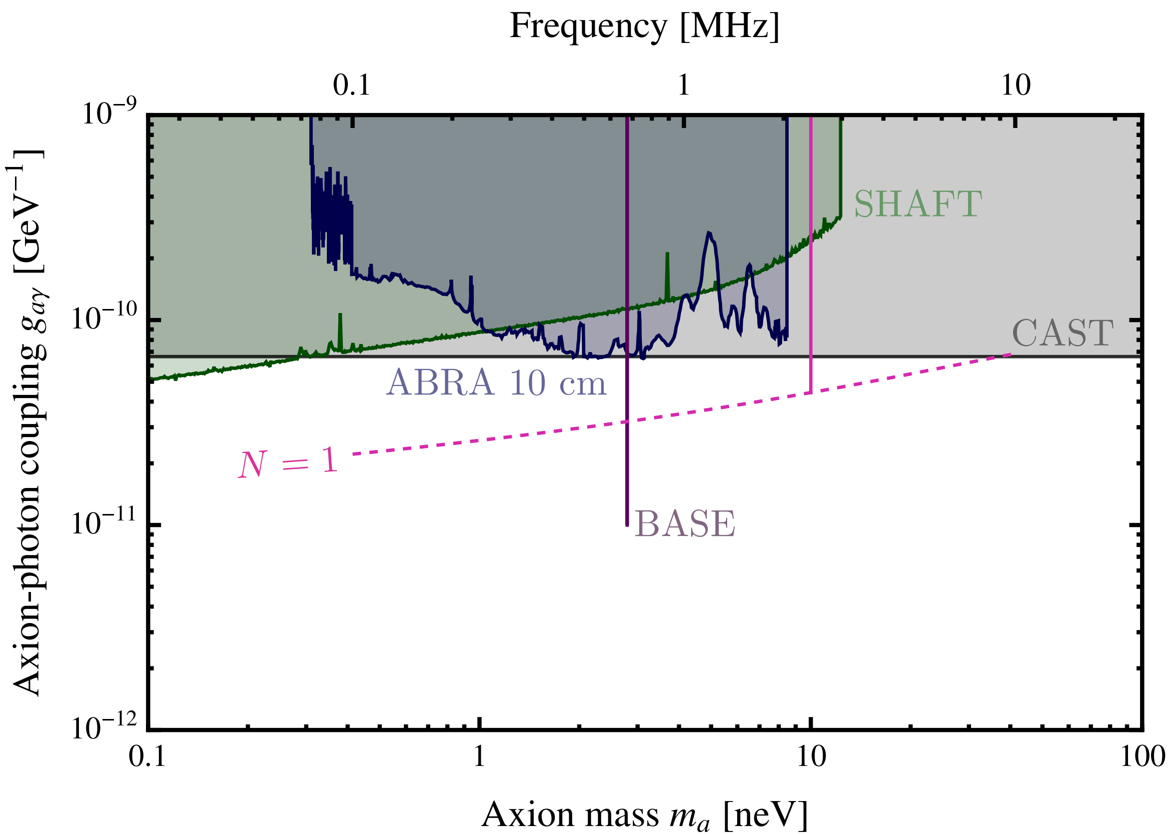
- 電極からの熱輻射が支配的
- Probability of $|e, 0\rangle = \dot{n}T + (|\alpha_X|T)^2$

$$T < T_{\mathrm{DM}} = 2\pi/m_{\mathrm{DM}}v_{\mathrm{DM}}^2$$

- Criteria: $\#\mathrm{Signal}/\sqrt{\#\mathrm{Noise}}$ = 1.645 (95% C.L.)

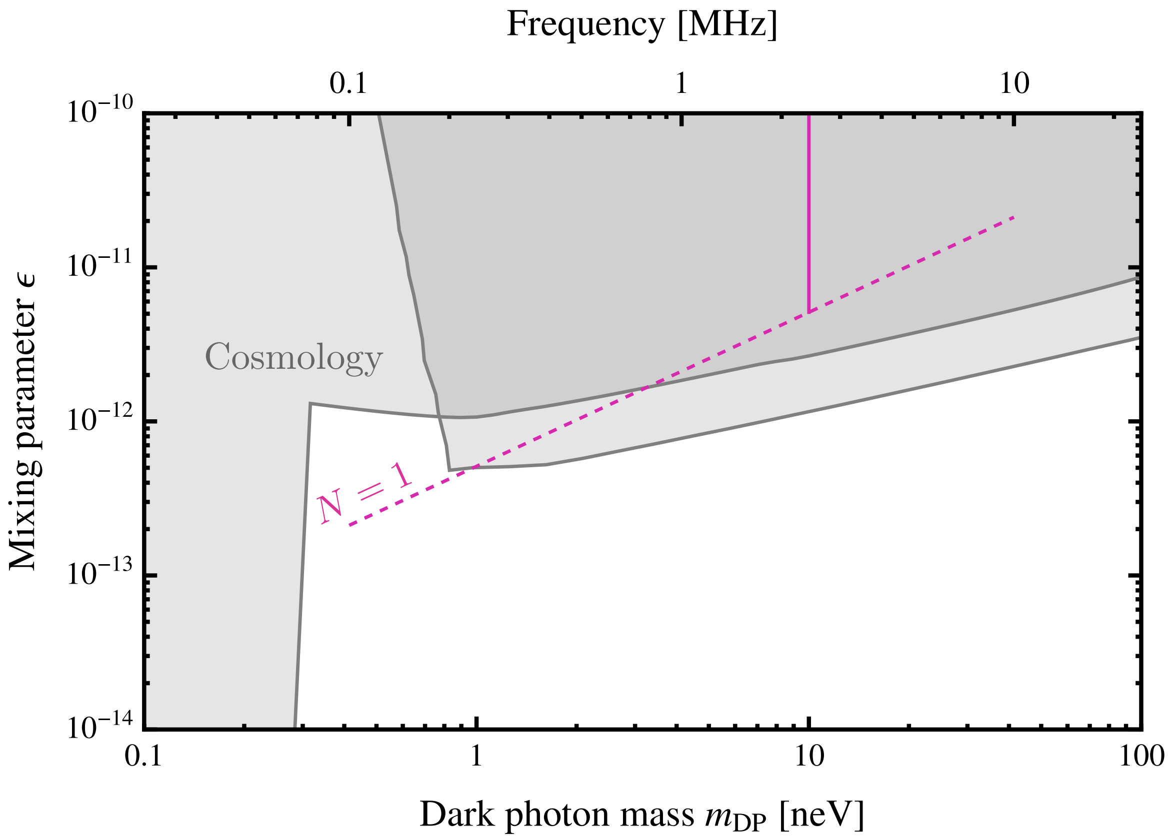
Axion dark matter

$$g_{a\gamma} = 4.4\times10^{-11}\ \mathrm{GeV}^{-1}\times\left(\frac{\dot{n}}{0.1\ \mathrm{s}^{-1}}\right)^{1/4}\left(\frac{T_{\mathrm{total}}}{1\ \mathrm{day}}\right)^{-1/4}\left(\frac{T}{0.4\ \mathrm{s}}\right)^{-1/2}\left(\frac{R}{3\ \mathrm{m}}\right)^{-2}$$
$$\times\left(\frac{B_z}{100\ \mathrm{mT}}\right)^{-1}\left(\frac{m_{\mathrm{ION}}}{37\ \mathrm{GeV}}\right)^{1/2}\left(\frac{m_a}{10\ \mathrm{neV}}\right)^{-1/2}\left(\frac{\rho_{\mathrm{DM}}}{0.45\ \mathrm{GeV\ cm}^{-3}}\right)^{-1/2}$$



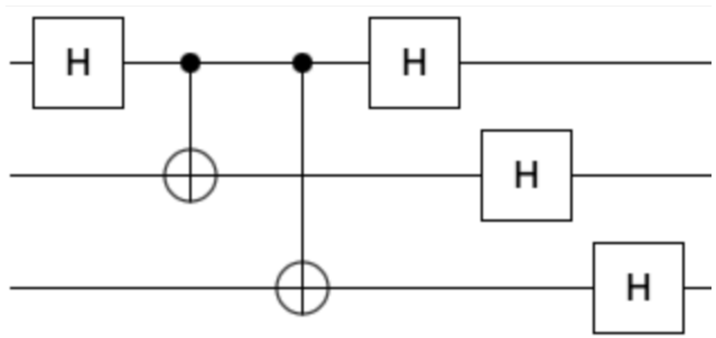
Dark photon dark matter

$$\epsilon = 6.4 \times 10^{-12} \times \left(\frac{\dot{\bar{n}}}{0.1\ \mathrm{s}^{-1}}\right)^{1/4} \left(\frac{T_{\mathrm{total}}}{1\ \mathrm{day}}\right)^{-1/4} \left(\frac{T}{0.4\ \mathrm{s}}\right)^{-1/2}$$
$$\times \left(\frac{m_{\mathrm{ION}}}{37\ \mathrm{GeV}}\right)^{1/2} \left(\frac{m_{\mathrm{DP}}}{10\ \mathrm{neV}}\right)^{1/2} \left(\frac{\rho_{\mathrm{DM}}}{0.45\ \mathrm{GeV\ cm}^{-3}}\right)^{-1/2}$$



Entanglement

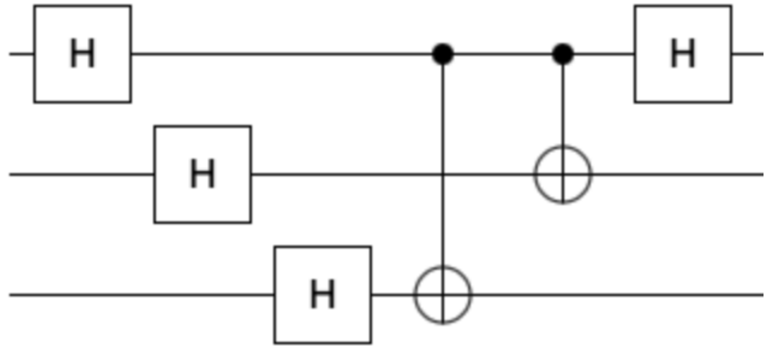
- 初期状態: $|g, g, \dots, g, 0\rangle$
- 1つのトラップの中で右の操作



- イオンを別々のトラップに移動

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

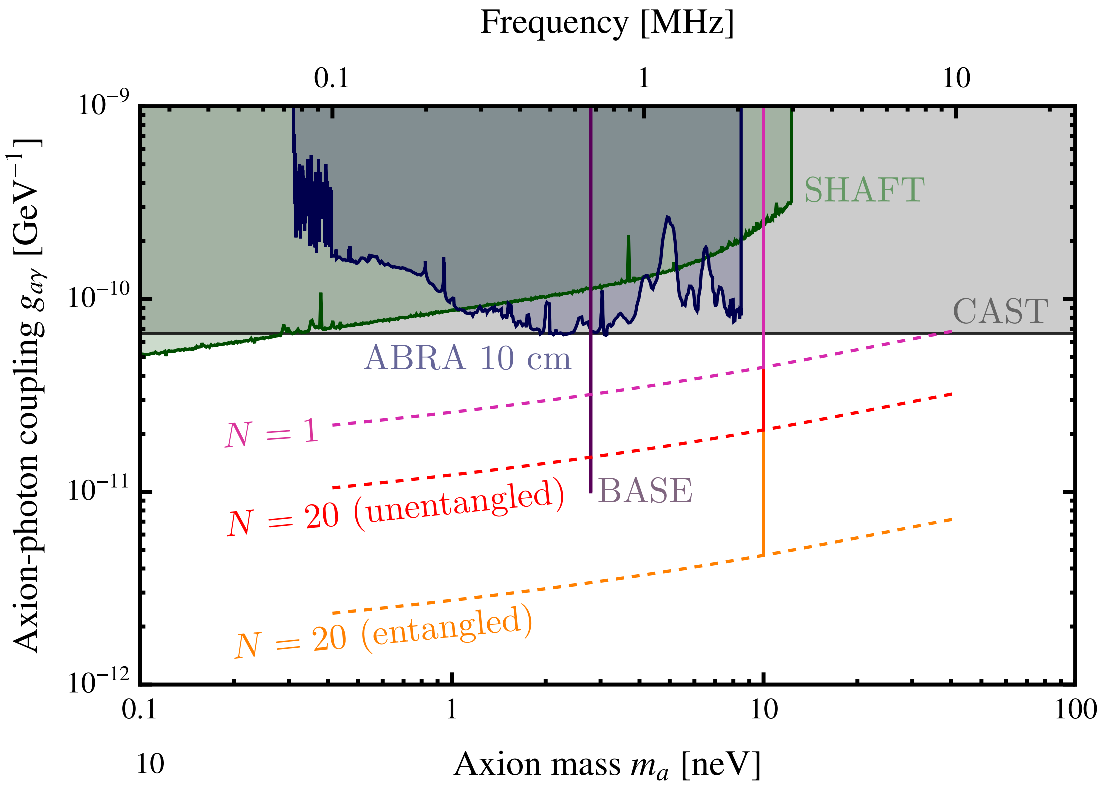
Entanglement



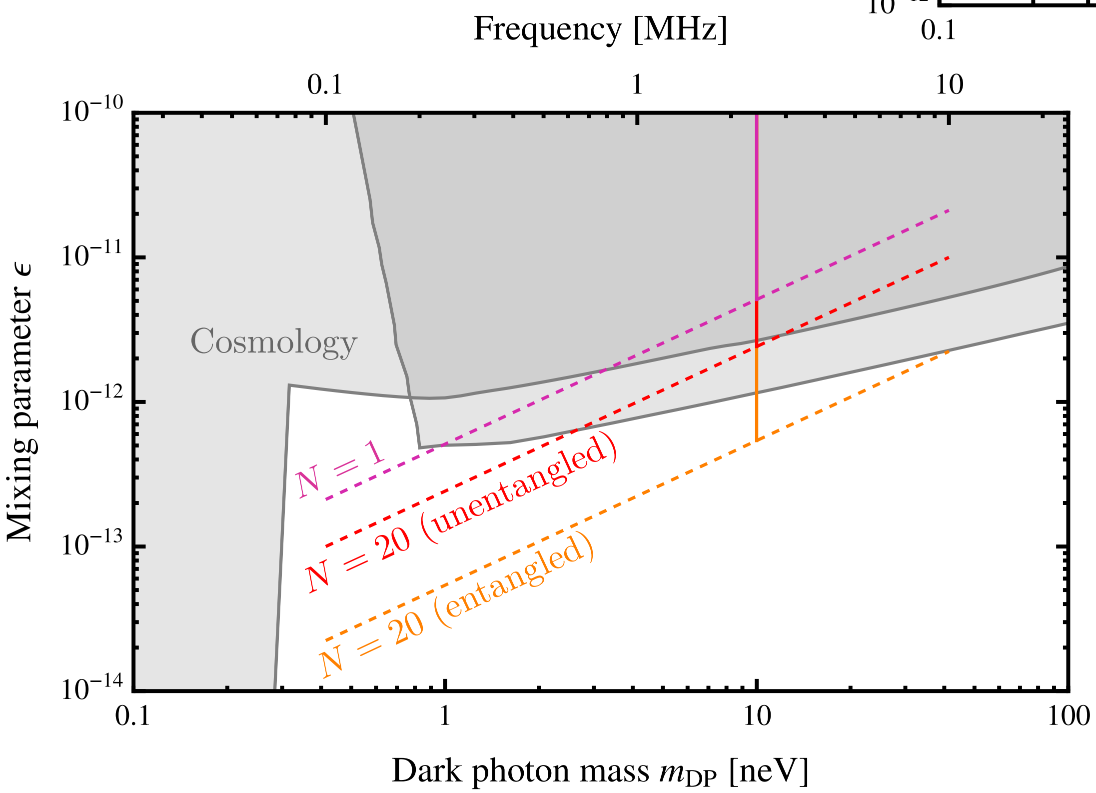
- 時間 $T < T_{\mathrm{DM}}$ だけ待つ
- イオンを別々のトラップに移動
- 1つのトラップの中で右の操作

$$(|g\rangle + iN\beta_{\mathrm{i}}|e\rangle)|g\rangle^{\otimes N-1}|0\rangle$$

- 状態 $|e, g, g, \ldots, g, 0\rangle$ の確率 $\propto N^2$
- $\#\mathrm{Signal}/\sqrt{\#\mathrm{Noise}} \propto N^{3/2}$



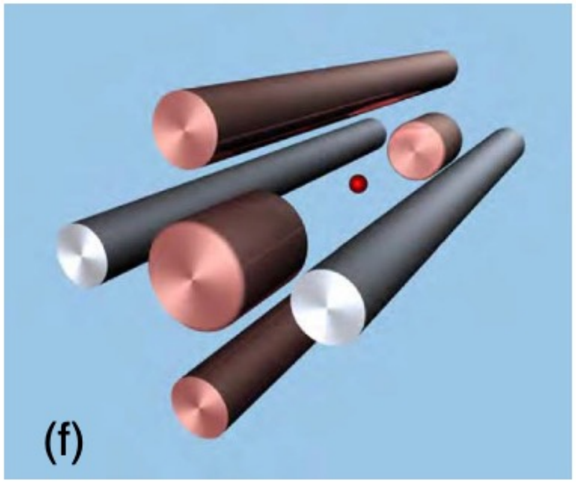
Frequency [MHz]
0.1
1
10
10^{-9}
10^{-10}
10^{-11}
10^{-12}
Axion-photon coupling $g_{a\gamma}$ [GeV^{-1}]
SHAFT
CAST
ABRA 10 cm
$N = 1$
$N = 20$ (unentangled)
BASE
$N = 20$ (entangled)
0.1
1
10
100
Axion mass m_a [neV]



Frequency [MHz]
0.1
1
10
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
Mixing parameter ϵ
Cosmology
$N = 1$
$N = 20$ (unentangled)
$N = 20$ (entangled)
0.1
1
10
100
Dark photon mass $m_{\rm DP}$ [neV]

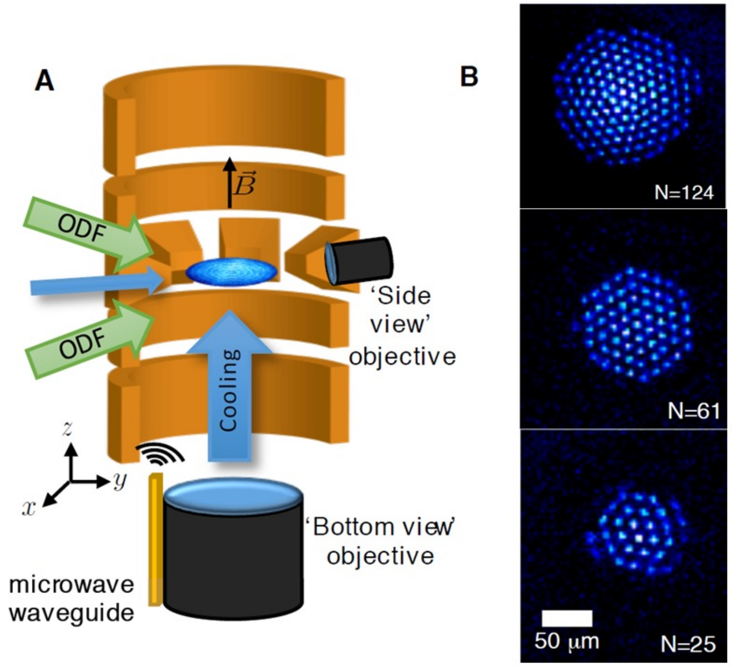
イオントラップ

Paul trap



[Bruzewicz+, 2015]

Penning trap

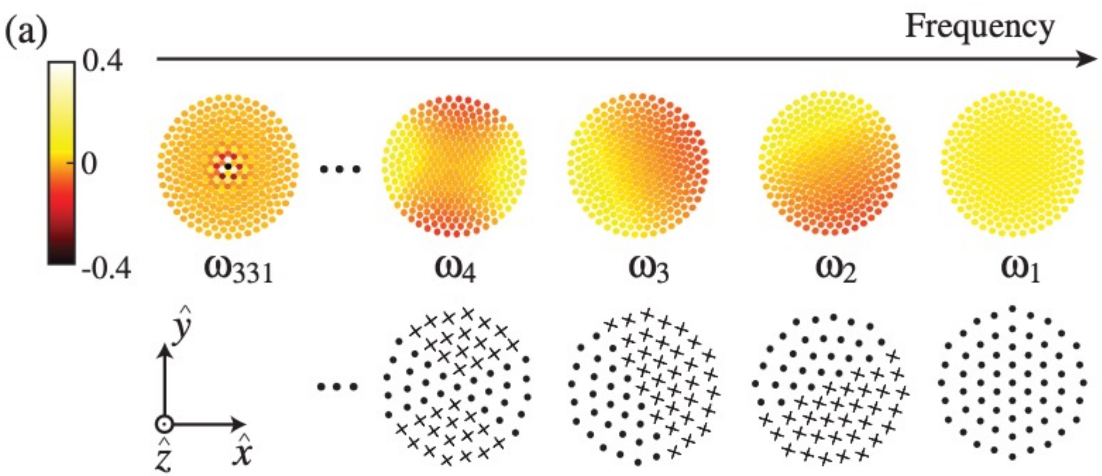


[NIST webpage]

Penning trap

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

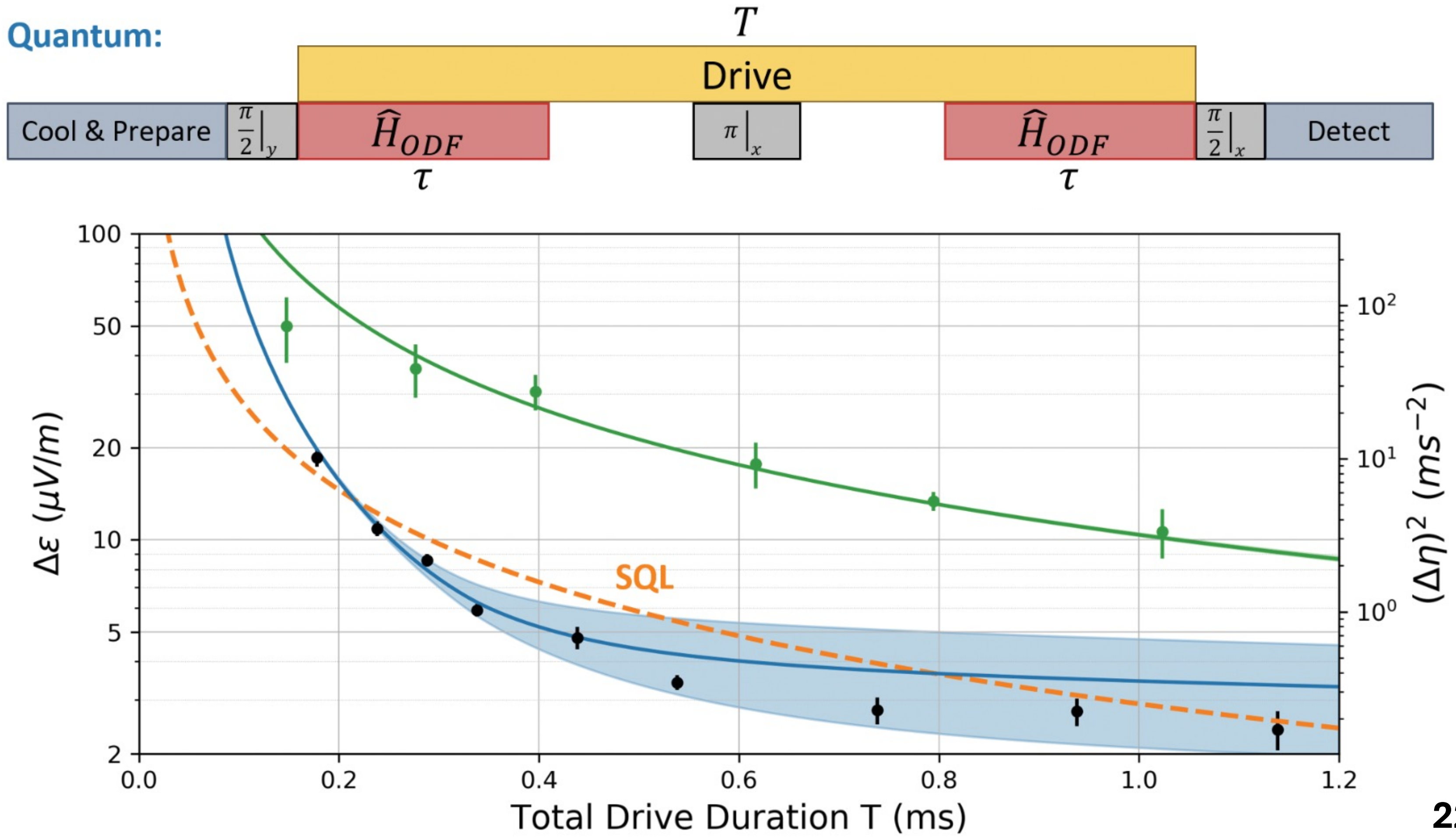
- 2次元三角格子にイオンが並んだ系に注目

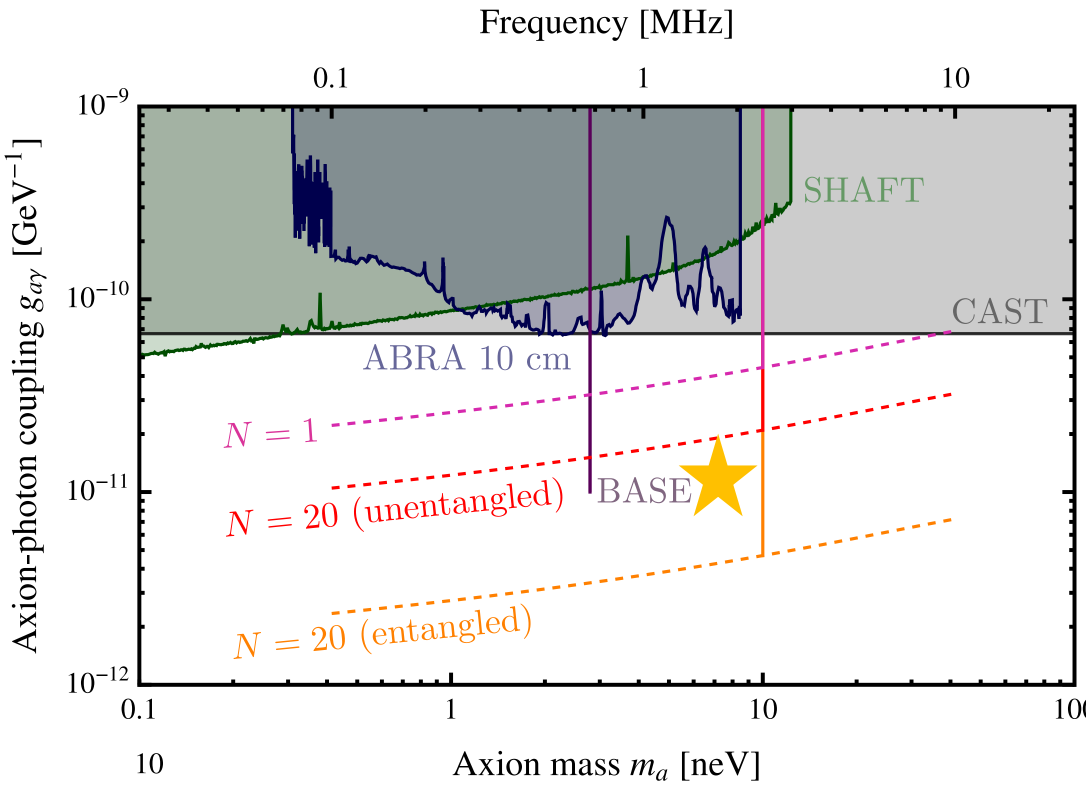


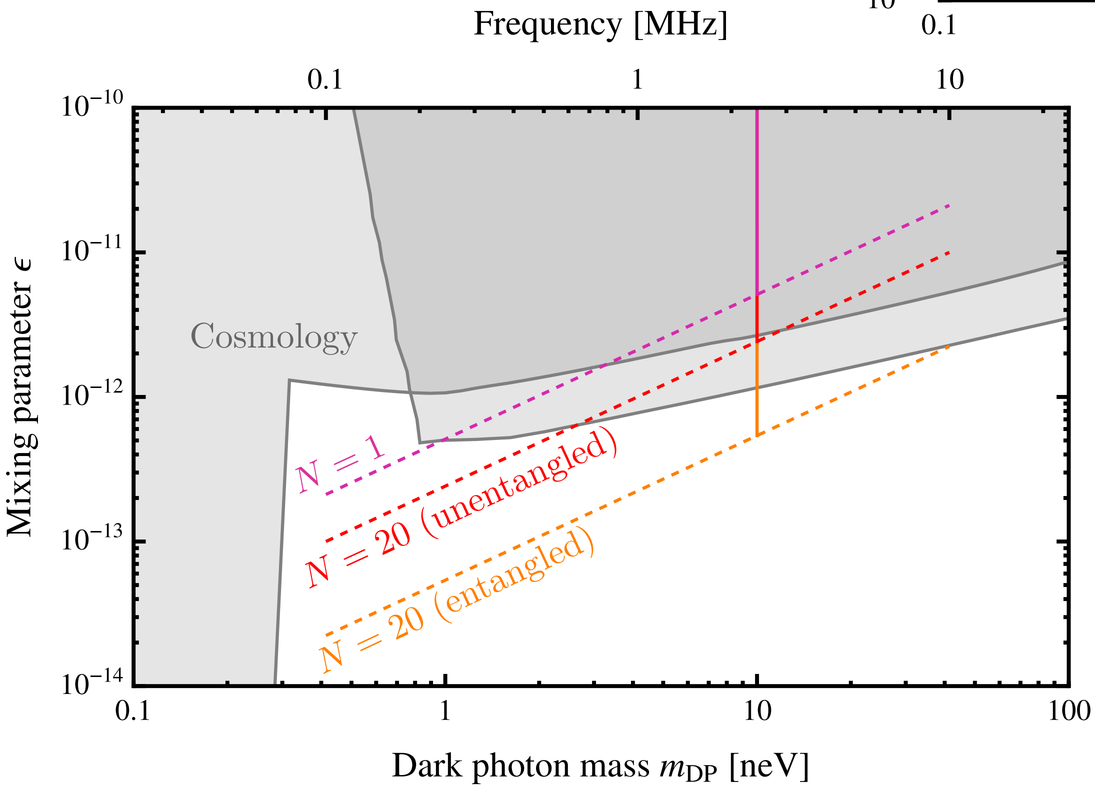
[Sawyer+, 2012]

重心モード: ω_1

[Gilmore et al., *Science* **373**, 673-678 (2021)]







$N \sim 150$

$B = 4.5$ T

$R = 6.5$ cm

別のモード: $\omega_{2,3}$


- 重力波とイオンの相互作用

$$H_{\text{int}} \propto \sum x_j\, z_j$$

- イオンの波動関数が大きいと相互作用も大きくなる

$$h_0 \sim 4 \times 10^{-13} \times \left(\frac{N}{150}\right)^{-1} \left(\frac{a_0}{15\ \mu\mathrm{m}}\right)^{-1} \left(\frac{m_{\mathrm{ion}}}{8.38\ \mathrm{GeV}}\right)^{-\frac{1}{2}} \left(\frac{\omega/2\pi}{1.75\ \mathrm{MHz}}\right)^{-\frac{3}{2}}$$

Very preliminary

まとめ

- イオントラップは、質量 ~ neV の（光子と結合する）暗黒物質や重力波の検出に使える

- エンタングルメントで信号強度 $\propto N^2$