מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

Prospects of nuclear-coupled dark-matter detection via correlation spectroscopy of I_2^+ and Ca^+

E.M., Gilad Perez and Ziv Meir – arXiv:2404.00616 [phys.atom-ph]

Eric Madge

SUSY – June 14, 2024

Atomic Spectroscopy

- measurements with (very) high precision

  e.g. $^{40}\mathrm{Ca}^{+}$ $(4s\,^2S_{1/2} - 3d\,^2D_{5/2})$: [BIPM (2020)]

  $$f\left(^{40}\mathrm{Ca}^{+}\right) = 411\,042\,129\,776\,400.4(7)\ \mathrm{Hz} \qquad \left(\delta f/f = 1.8\times10^{-15}\right)$$

- optical clock frequency comparison at 18 digits [BACON, Nature 591 (2021)]

  $$f_{\mathrm{Yb}}/f_{\mathrm{Sr}} = 1.207\,507\,039\,343\,337\,848\,2(82)$$

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$\Longrightarrow$ Can be used to probe ultra-light dark matter!

Ultra-Light Dark Matter

- behaves like classical field

$$\langle N \rangle \sim n\lambda_{\rm dB}^3 \sim \frac{\rho}{m}\,(mv)^{-3} \gg 1 \qquad \Longrightarrow \qquad m_{\rm DM} \lesssim 1\,\text{eV}$$

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- oscillates coherently $\left(\tau_{\rm coh} \sim \frac{2\pi}{mv^2} \sim 10^6\,\text{oscillations}\right)$

$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi^2 = 0 \qquad \Longrightarrow \qquad \phi(t) \sim a^{-\frac{3}{2}}\cos(mt+\delta)$$

Nuclear-Coupled Dark Matter

- scalar ϕ: $\mathcal{L} \supset -\frac{\beta_s}{2\, g_s} \underbrace{\sqrt{4\pi G_N}}_{\kappa} \, d_g \, \phi \, G^a_{\mu\nu} G^{a\,\mu\nu}$

$$\Longrightarrow \qquad \Lambda_{\rm QCD} = \Lambda^{(0)}_{\rm QCD} \left(1 + \kappa \, d_g \, \phi\right)$$

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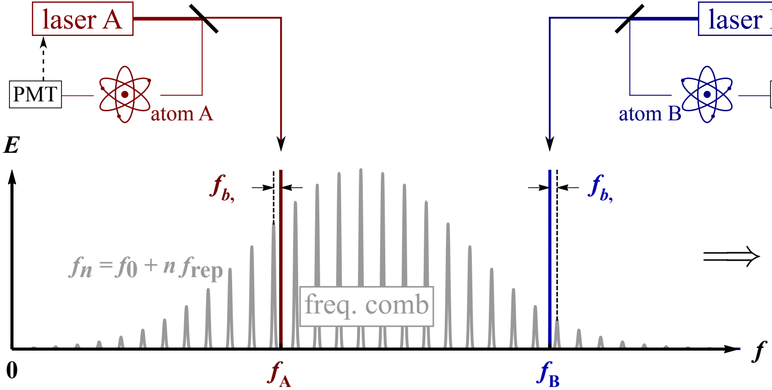
$\Longrightarrow$ oscillating nucleon mass:

$$\frac{\Delta m_N}{m_N} \propto d_g\,\phi \propto \cos(m_\phi t) \qquad \text{or} \qquad \frac{\Delta m_N}{m_N} \propto \frac{a^2}{f_a^2} \propto \cos(2\,m_a t)$$

Clock Comparison Experiments

e.g. I_2^+: $f_{\text{vib}} \propto m_N^{-\frac{1}{2}}$

e.g. Ca^+: $f_{\text{el}} \propto m_N^0$



$$\Longrightarrow \quad \frac{\Delta f_{I_2^+} / f_{I_2^+}}{\Delta f_{Ca^+} / f_{Ca^+}} \propto \frac{1}{2} \frac{\Delta m_N}{m_N}$$

[credit: Arvanitaki, Huang, Van Tilburg, PRD 91 (2015)]

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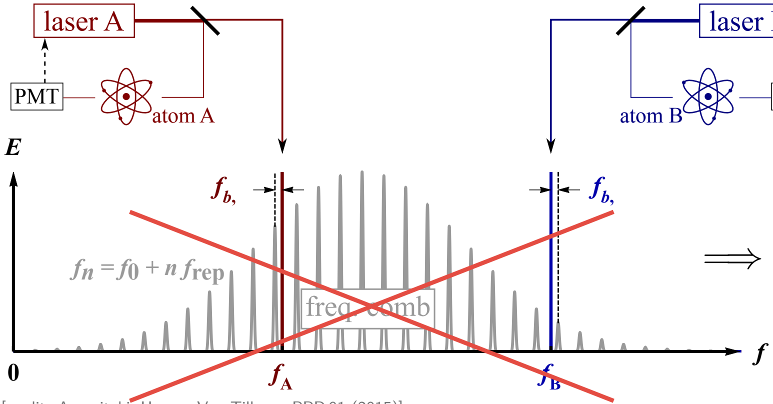

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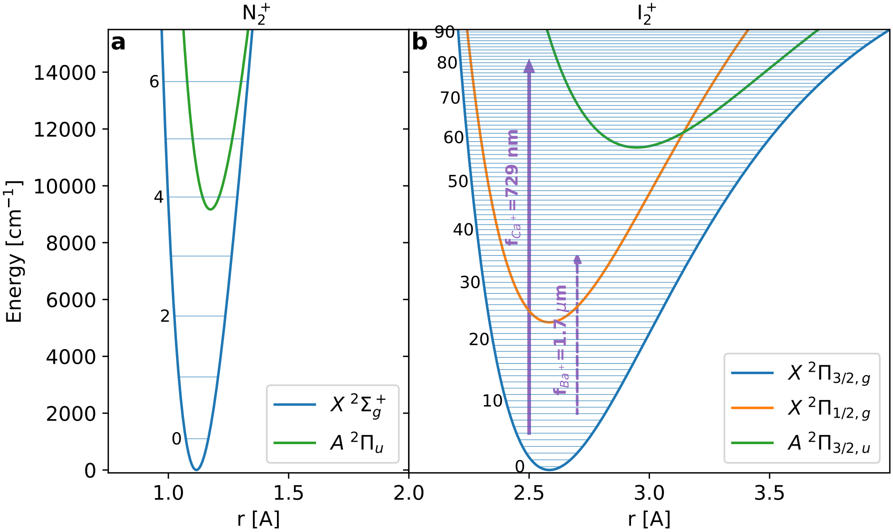
correlation spectroscopy: directly manipulate $A \otimes B$ bipartite system

Why I_2^+? $\Longrightarrow$ correlation spectroscopy



dense rovibrational spectrum $\Longrightarrow$ choose $f_{I_2^+} \sim f_{Ca^+} \approx 411\,\text{THz}$

Correlation Spectroscopy

- Ramsey interrogation : [Ramsey, PR 76 (1949), PR 78 (1950)]

$\frac{\pi}{2}$ pulse $+$ free evolution $+$ $\frac{\pi}{2}$ pulse $+$ measurement

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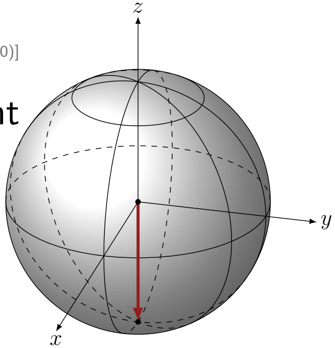

$|g\rangle$

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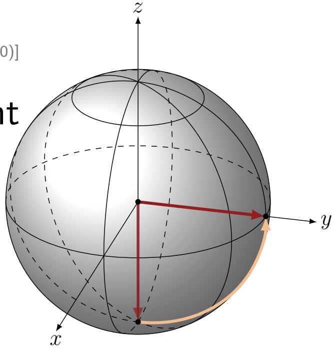

$$|g\rangle + \qquad |e\rangle$$

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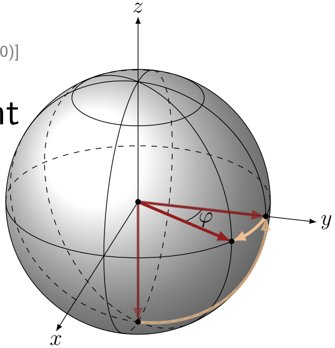

$$\varphi_i = 2\pi(f_i - f_L)\,T_R + \varphi_N + \tilde{\varphi}_i$$

$$|g\rangle + \quad e^{i\varphi_1} \; |e\rangle$$

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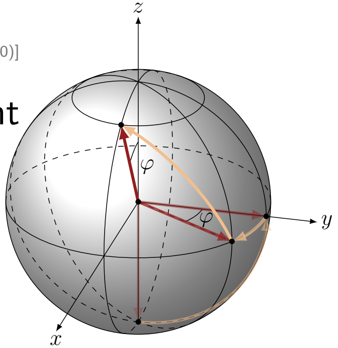

$$\left(1 + e^{i\varphi_1}\right)|g\rangle + \left(1 - e^{i\varphi_1}\right)|e\rangle$$

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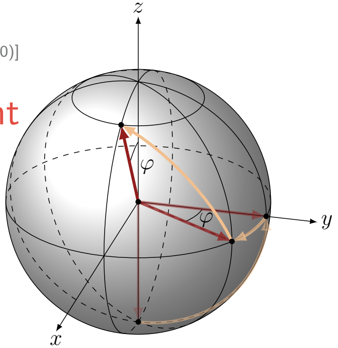

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$$\langle\sigma_z \quad\quad \rangle \propto \cos \quad \varphi_1$$

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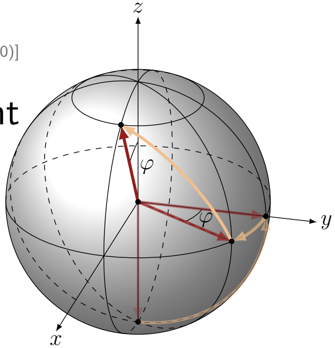

- Correlation spectroscopy: [Chwalla et al., APB 89 (2007)]

operate on product state of the two clocks

$$\left[\left(1+e^{i\varphi_1}\right)|g\rangle + \left(1-e^{i\varphi_1}\right)|e\rangle\right] \otimes \left[\left(1+e^{i\varphi_2}\right)|g\rangle + \left(1-e^{i\varphi_2}\right)|e\rangle\right]$$

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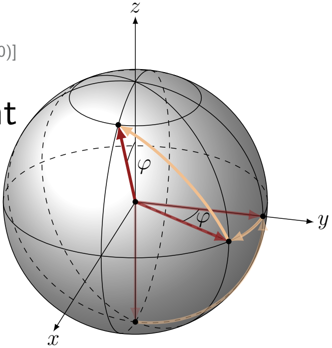

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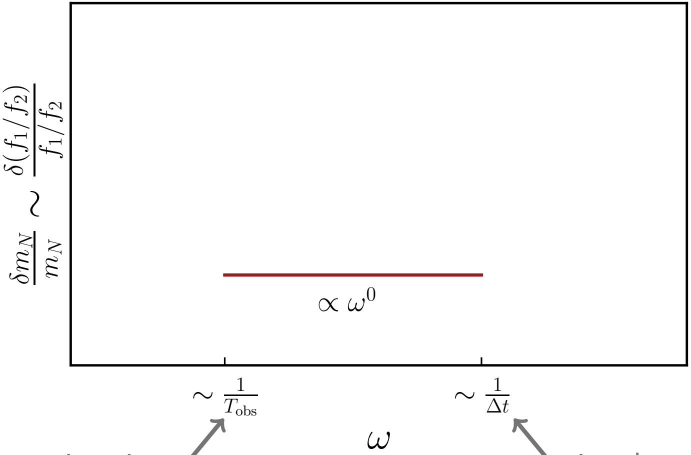
Sensitivity

[Arvanitaki, Huang, Van Tilburg, PRD 91 (2015)]
[Derevianko, PRA 97 (2018)]

$$f_1 \propto m_N^{K_1} \qquad f_2 \propto m_N^{K_2} \quad \Longrightarrow \quad \frac{\delta(f_1/f_2)}{f_1/f_2} \propto (K_1 - K_2)\,\frac{\delta m_N}{m_N}$$



total observation time

time between measurements

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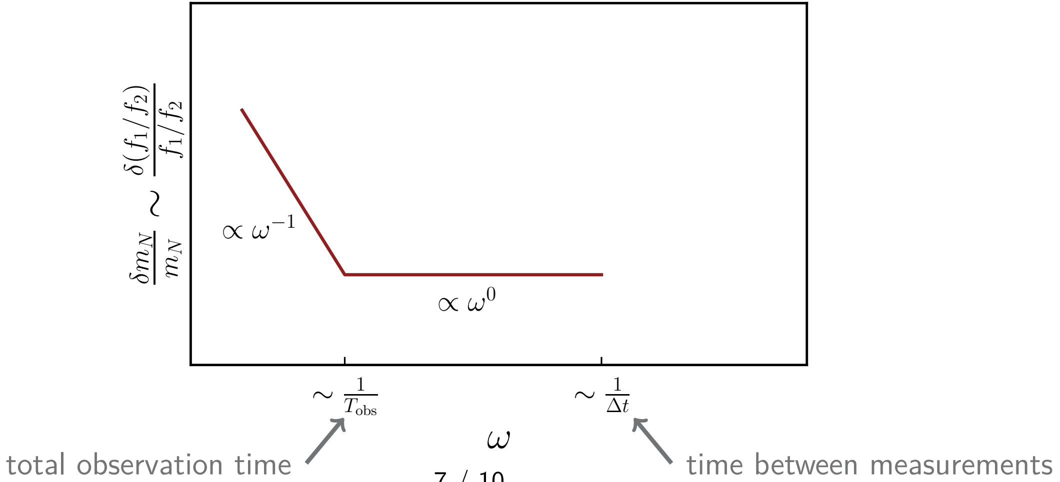

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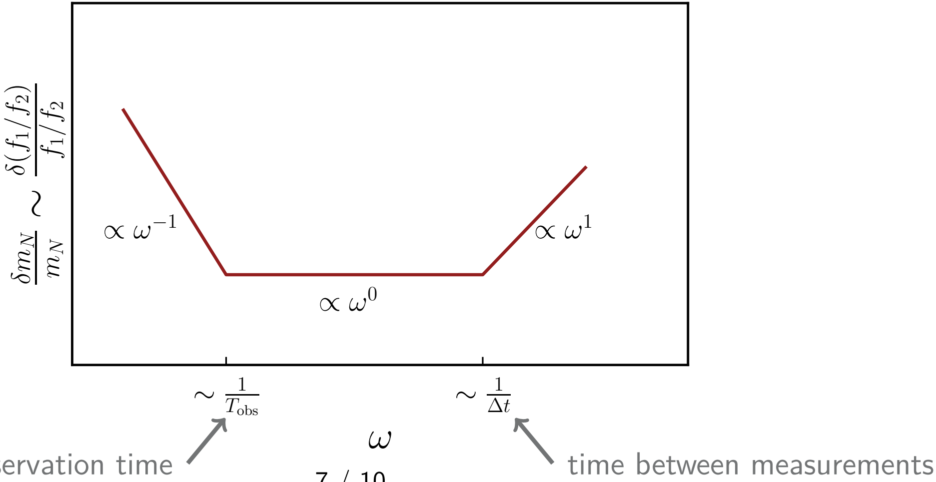

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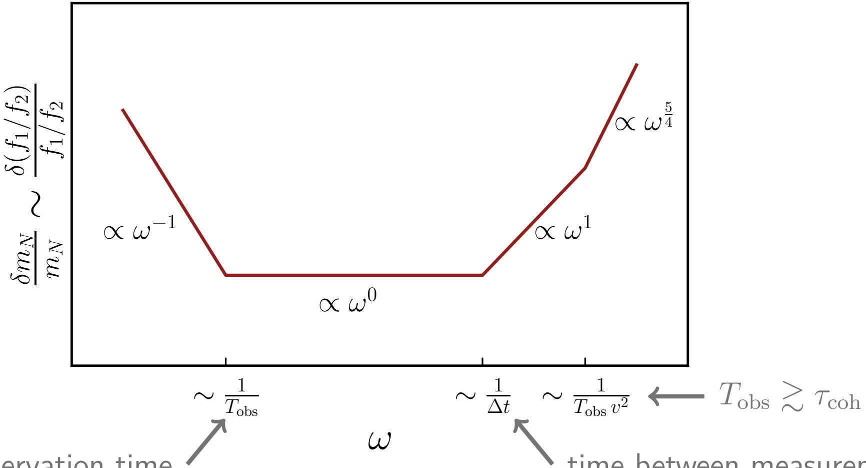
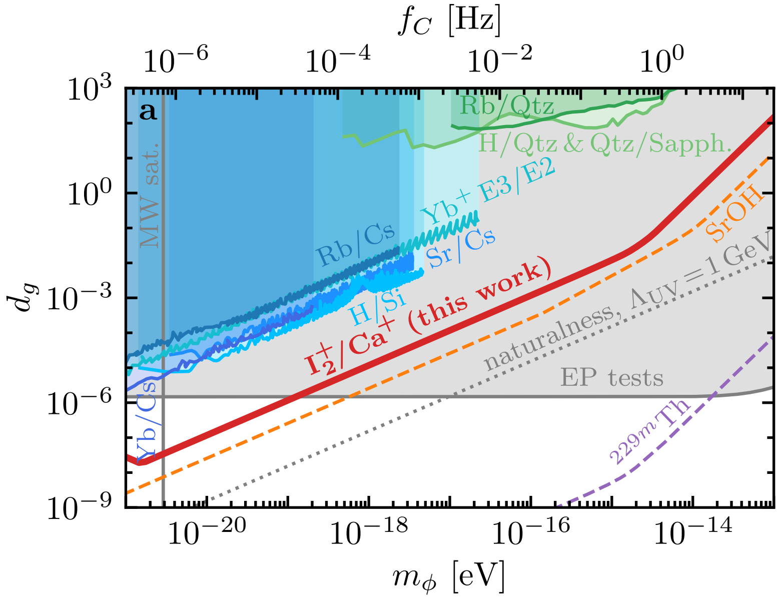
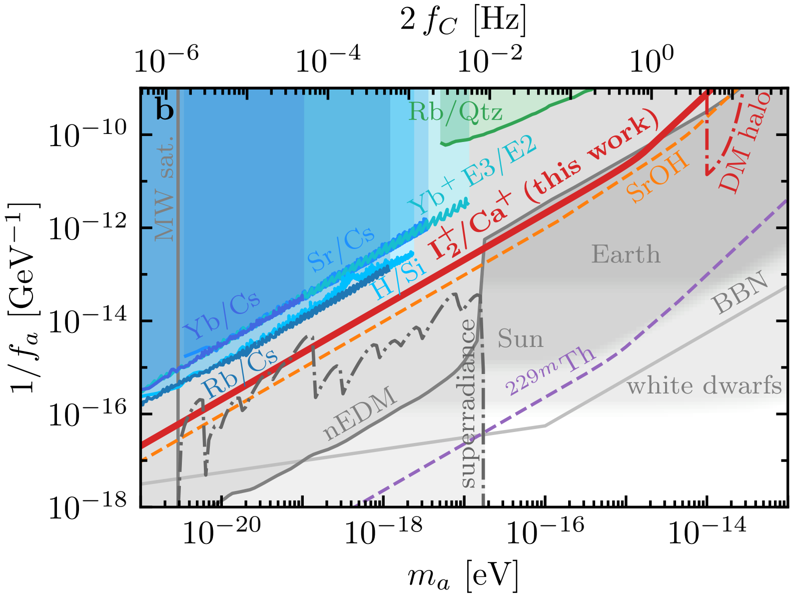


Scalar Dark Matter



Axion Dark Matter



Conclusion

- I_2^+/Ca^+ molecular-ion vs. atomic-ion clock comparison
- comparison via correlation spectroscopy
- for scalar ULDM:
  - ca. 2 to 3 orders of magnitude improvement compared to current clock bounds
  - strongest bounds for $m_\phi \lesssim 10^{-19}\,\mathrm{eV}$
- for axion ULDM:
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  - better than nEDM for $2 \times 10^{-17}\,\mathrm{eV} \lesssim m_a \lesssim 2 \times 10^{-15}\,\mathrm{eV}$

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Thank you for your attention!