Phenomenology of Quadratically Coupled ULDM

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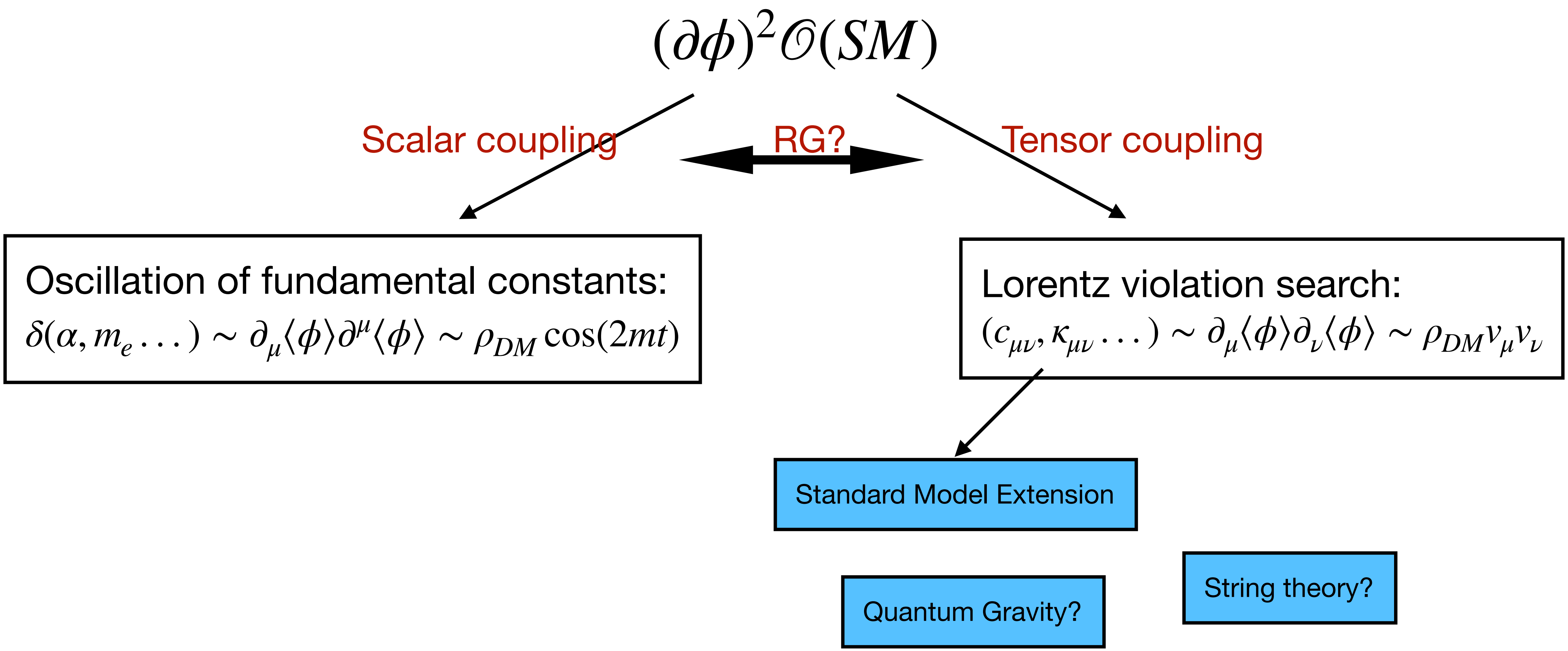
Based on work with:

Ben Pacjak, Gilad Perez, Aviv Shalit, Somasundaram Sankaranarayanan

$(\partial\phi)^2\mathcal{O}(SM)$: *why ?*

- Shift symmetry to protect the scalar mass
  Ultralight Dark Matter: $m_\phi <$ **eV**

- Quadratic coupling : Z_2 symmetry



Outline

- Theoretical aspects of the EFT
- Bounds from experiments
- Conclusion

The Effective Field Theory of Quadratically Coupled ULDM (QED sector):

$$\mathscr{L}_{\text{EFT}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\gamma_\mu D^\mu\psi + \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2 + \sum_{i=1} c_i O_i$$

CP even operators:

$$O_1 = \partial_\mu\phi\partial^\mu\phi\, i\bar{\psi}\gamma^\nu \overleftrightarrow{D}_\nu\psi \leftrightarrow \overline{O}_1 = m_e\partial_\mu\phi\partial^\mu\phi\,\bar{\psi}\psi$$

$$O_2 = \partial_\mu\phi\partial_\nu\phi\, i\bar{\psi}\gamma^\nu \overleftrightarrow{D}^\mu\psi$$

$$O_3 = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi F_{\nu\rho}F^{\nu\rho}$$

$$O_4 = \frac{1}{2}\partial_\mu\phi\partial_\nu\phi F^\mu{}_\rho F^{\nu\rho}$$

scalar coupling

tensor coupling

Renormalization Group Evolution

$$\frac{\mathrm{d}}{\mathrm{d}\log\mu}\begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \end{bmatrix} = \frac{e^2}{(4\pi)^2}\begin{bmatrix} 0 & \frac{-4}{3} & 12 & \frac{7}{3} \\ 0 & \frac{16}{3} & 0 & \frac{8}{3} \\ 0 & \frac{-4}{3} & \frac{8}{3} & 0 \\ 0 & \frac{16}{3} & 0 & \frac{8}{3} \end{bmatrix}\begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \end{bmatrix}$$

$$O_1 = \partial_\mu\phi\partial^\mu\phi\, i\bar{\psi}\gamma^\nu \overleftrightarrow{D}_\nu\psi$$

$$O_2 = \partial_\mu\phi\partial_\nu\phi\, i\bar{\psi}\gamma^\nu \overleftrightarrow{D}^\mu\psi$$

$$O_3 = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi F_{\nu\rho}F^{\nu\rho}$$

$$O_4 = \frac{1}{2}\partial_\mu\phi\partial_\nu\phi F^\mu{}_\rho F^{\nu\rho}$$

$$\frac{\mathrm{d}}{\mathrm{d}\log\mu}\begin{bmatrix} c'_1 \\ c'_3 \\ c'_2 \\ c'_4 \end{bmatrix} = \frac{e^2}{(4\pi)^2}\begin{bmatrix} 0 & 12 & 0 & 0 \\ 0 & \frac{8}{3} & 0 & 0 \\ 0 & 0 & \frac{16}{3} & \frac{8}{3} \\ 0 & 0 & \frac{16}{3} & \frac{8}{3} \end{bmatrix}\begin{bmatrix} c'_1 \\ c'_3 \\ c'_2 \\ c'_4 \end{bmatrix}$$

$J = 0$:

$$O'_1 \equiv O_1 = \left(\partial_\mu\phi\partial^\mu\phi\right) i\bar{\psi}\gamma^\nu \overleftrightarrow{D}_\nu\psi$$

$$O'_3 \equiv O_3 = \left(\partial_\mu\phi\partial^\mu\phi\right) \frac{1}{2}F_{\nu\rho}F^{\nu\rho}$$

$J = 2$:

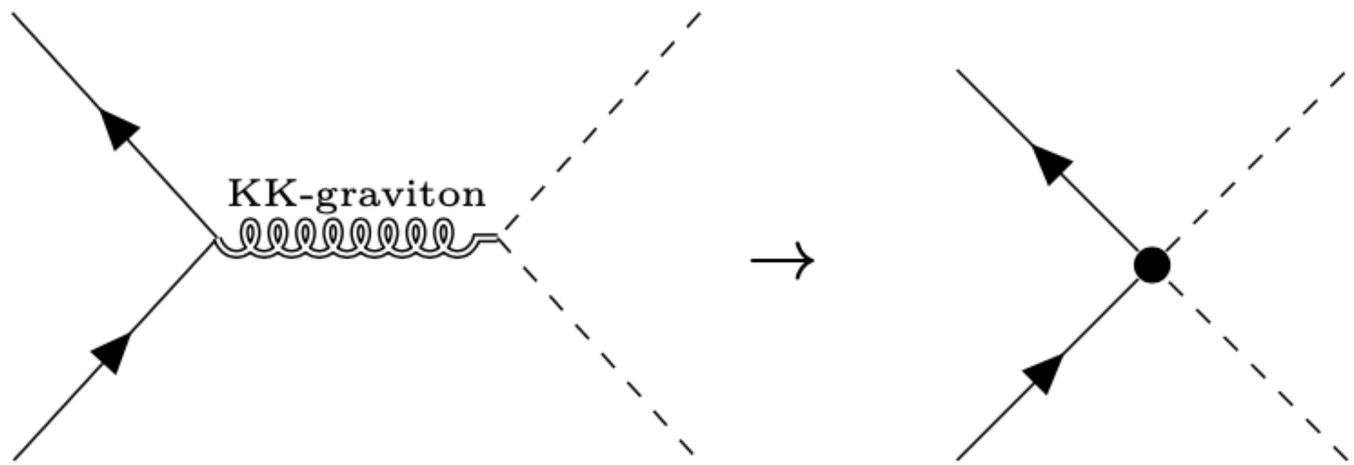
$$O'_2 \equiv O_2 - \frac{1}{4}O_1 = \left(\partial_\mu\phi\partial_\nu\phi - \frac{1}{4}\eta_{\mu\nu}\partial_\rho\phi\partial^\rho\phi\right) i\bar{\psi}\gamma^\nu \overleftrightarrow{D}^\mu\psi$$

$$O'_4 \equiv O_4 - \frac{1}{4}O_3 = \left(\partial_\mu\phi\partial_\nu\phi - \frac{1}{4}\eta_{\mu\nu}\partial_\rho\phi\partial^\rho\phi\right) \frac{1}{2}F^\mu{}_\rho F^{\nu\rho}$$

Angular momentum conservation!

(MJ, Shu, Xiao, Zheng ’20)

Example of UV origin



KK Graviton:

$$S=\int d^4x\frac{1}{2}h_{\mu\nu}\mathcal{O}^{\mu\nu\rho\sigma}h_{\rho\sigma}-\frac{1}{\Lambda_{KK}}h_{\mu\nu}T^{\mu\nu}\,,$$

$$\mathcal{O}^{\mu\nu}_{\rho\sigma}=-\left[\eta^{(\mu}_{(\rho}\eta^{\nu)}_{\sigma)}-\eta^{\mu\nu}\eta_{\rho\sigma}\right]\left(\Box+m^2_{KK}\right)+2\partial^{(\mu}\partial_{(\rho}\eta^{\nu)}_{\sigma)}-\partial^{\mu}\partial^{\nu}\eta_{\rho\sigma}-\partial_{\rho}\partial_{\sigma}\eta^{\mu\nu}\,.$$

RS: $m_{KK}\sim\Lambda_{KK}\sim$ TeV

Integrating our KK graviton at tree level

UV action:

$$S = \int d^4x \frac{1}{2} h_{\mu\nu} \mathcal{O}^{\mu\nu\rho\sigma} h_{\rho\sigma} - \frac{1}{\Lambda_{KK}} h_{\mu\nu} T^{\mu\nu},$$

Equation of Motion:

$$\mathcal{O}^{\mu\nu\rho\sigma} h_{\rho\sigma} = \frac{1}{\Lambda_{KK}} T^{\mu\nu}.$$

Solution:

$$h^c_{\rho\sigma} = \mathcal{O}^{-1}_{\rho\sigma\alpha\beta} \frac{1}{\Lambda_{KK}} T^{\alpha\beta},$$

$$\mathcal{O}^{-1}_{\mu\nu\rho\sigma} = -\frac{1}{m^2_{KK}} \left(\frac{1}{2}\eta^{\mu\rho}\eta^{\nu\sigma} + \frac{1}{2}\eta^{\mu\sigma}\eta^{\nu\rho} - \frac{1}{3}\eta^{\mu\nu}\eta^{\rho\sigma}\right) + O\left(\frac{1}{m^4_{KK}}\right)$$

$$T^{\psi}_{\mu\nu} = \frac{i}{4}\bar{\psi}\left(\gamma_\mu D_\nu + \gamma_\nu D_\mu\right)\psi - \frac{i}{4}\left(D_\mu\bar{\psi}\gamma_\nu + D_\nu\bar{\psi}\gamma_\nu\right)\psi$$
$$-\eta_{\mu\nu}\left(\bar{\psi}\gamma^\rho D_\rho\psi - m_\psi\bar{\psi}\psi\right) + \frac{i}{2}\eta_{\mu\nu}\partial^\rho\left(\bar{\psi}\gamma_\rho\psi\right);$$
$$T^{\gamma}_{\mu\nu} = \frac{1}{4}\eta_{\mu\nu}F^{\lambda\rho}F_{\lambda\rho} - F_{\mu\lambda}F_\nu^{\ \lambda};$$
$$T^{\phi}_{\mu\nu} = \partial^\mu\phi\partial^\nu\phi - \frac{1}{2}\eta^{\mu\nu}\left(\partial_\rho\phi\partial^\rho\phi - m^2_\phi\phi^2\right).$$

Put back to the action $h \to h_c$:

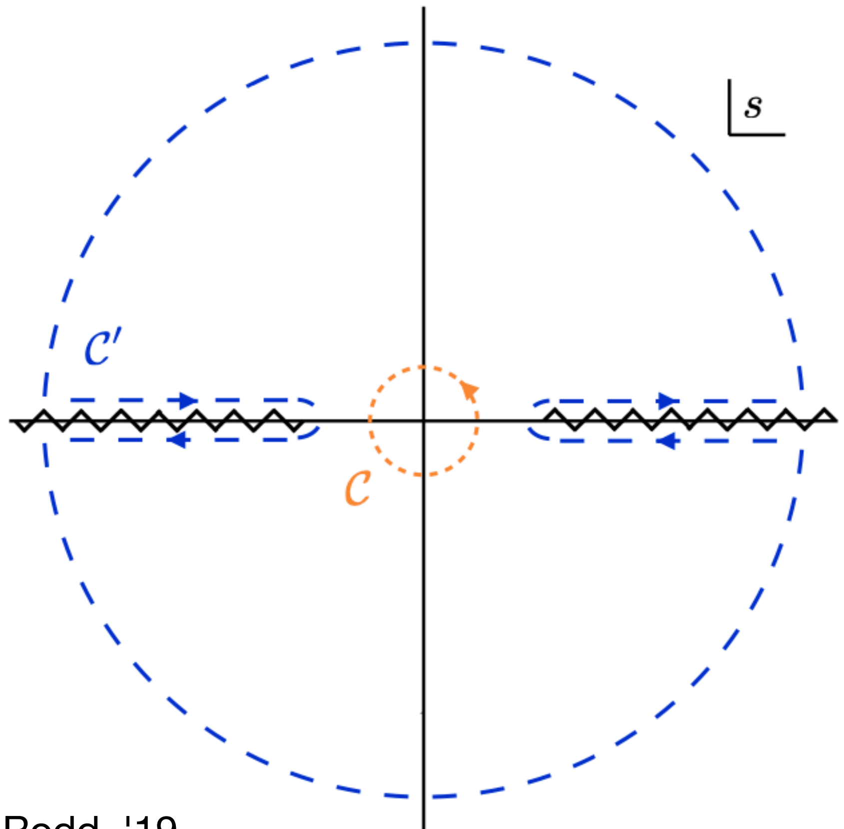
$$\mathscr{L}^{\text{EFT}} = -\frac{1}{2\Lambda_{KK}} h^c_{\mu\nu} T^{\mu\nu}$$
$$= -\frac{1}{2\Lambda^2_{KK}} T^{\mu\nu} \mathcal{O}^{-1}_{\mu\nu\rho\sigma} T^{\rho\sigma}$$

$$\mathscr{L}_{\text{EFT}} \supset \frac{1}{2\Lambda^2_{KK} m^2_{KK}} [(\partial^\mu\phi\partial^\nu\phi - \frac{1}{6}\eta^{\mu\nu}(\partial_\rho\phi\partial^\rho\phi + m^2_\phi\phi^2)) i\bar{\psi}\gamma^\nu \overleftrightarrow{D}_\mu\psi - (\partial^\mu\phi\partial^\nu\phi - \frac{1}{4}\eta^{\mu\nu}\partial_\rho\phi\partial^\rho\phi) F_{\mu\lambda}F^{\nu\lambda}].$$

$$c_1 = -\frac{1}{12\Lambda^2_{KK} m^2_{KK}}, \quad c_2 = \frac{1}{2\Lambda^2_{KK} m^2_{KK}}, \quad c_3 = \frac{1}{4\Lambda^2_{KK} m^2_{KK}}, \quad c_4 = -\frac{1}{2\Lambda^2_{KK} m^2_{KK}}.$$

Positivity bounds: the signs are not arbitrary !

Analyticity & Unitarity of the S-Matrix



Remmen, Rodd, '19

$$\frac{\mathrm{d}^2\mathscr{A}(\mathrm{s})}{\mathrm{ds}^2} = \oint \frac{ds}{2\pi i}\frac{\mathscr{A}(s)}{s^3} = \frac{2}{\pi}\int_{s_d}^{\infty}\frac{\sigma}{s^2}ds > 0$$

$$\mathscr{A}(\phi+\psi\to\phi+\psi)\supset 2c_2s^2$$
$$c_2 > 0$$

$$\mathscr{A}(\phi+\gamma\to\phi+\gamma)\supset -\frac{c_4}{2}s^2$$
$$c_4 < 0$$

Bounds from Experiments

Assuming ϕ as DM:

$$\phi(t,\vec{x}) = \phi_0 \cos(m_\phi(t - \vec{v}\cdot\vec{x}))$$

$$\phi_0 = \sqrt{2\rho_{\rm DM}}/m_\phi$$

Oscillation of fundamental constants:

$$c_1 O_1 \longrightarrow 2c_1\rho_{\rm DM}(1-\cos(2m_\phi t))m_e\bar{\psi}\psi$$

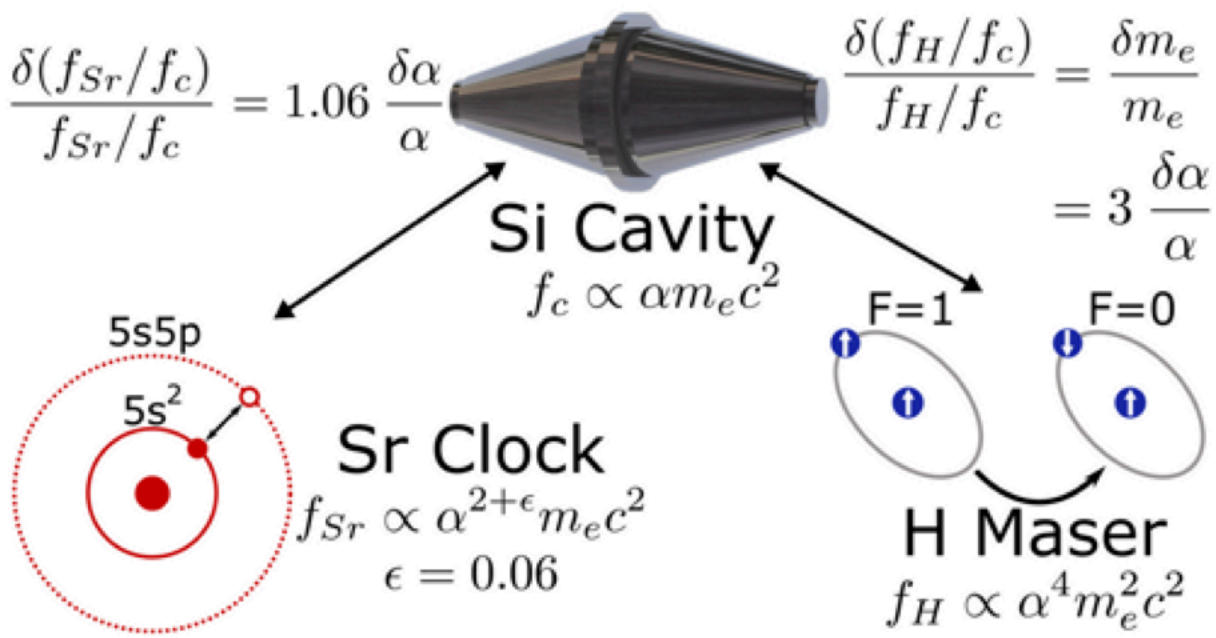
$$c_3 O_3 \longrightarrow \frac{c_3}{2}\rho_{\rm DM}(1-\cos(2m_\phi t))F_{\mu\nu}F^{\mu\nu}$$

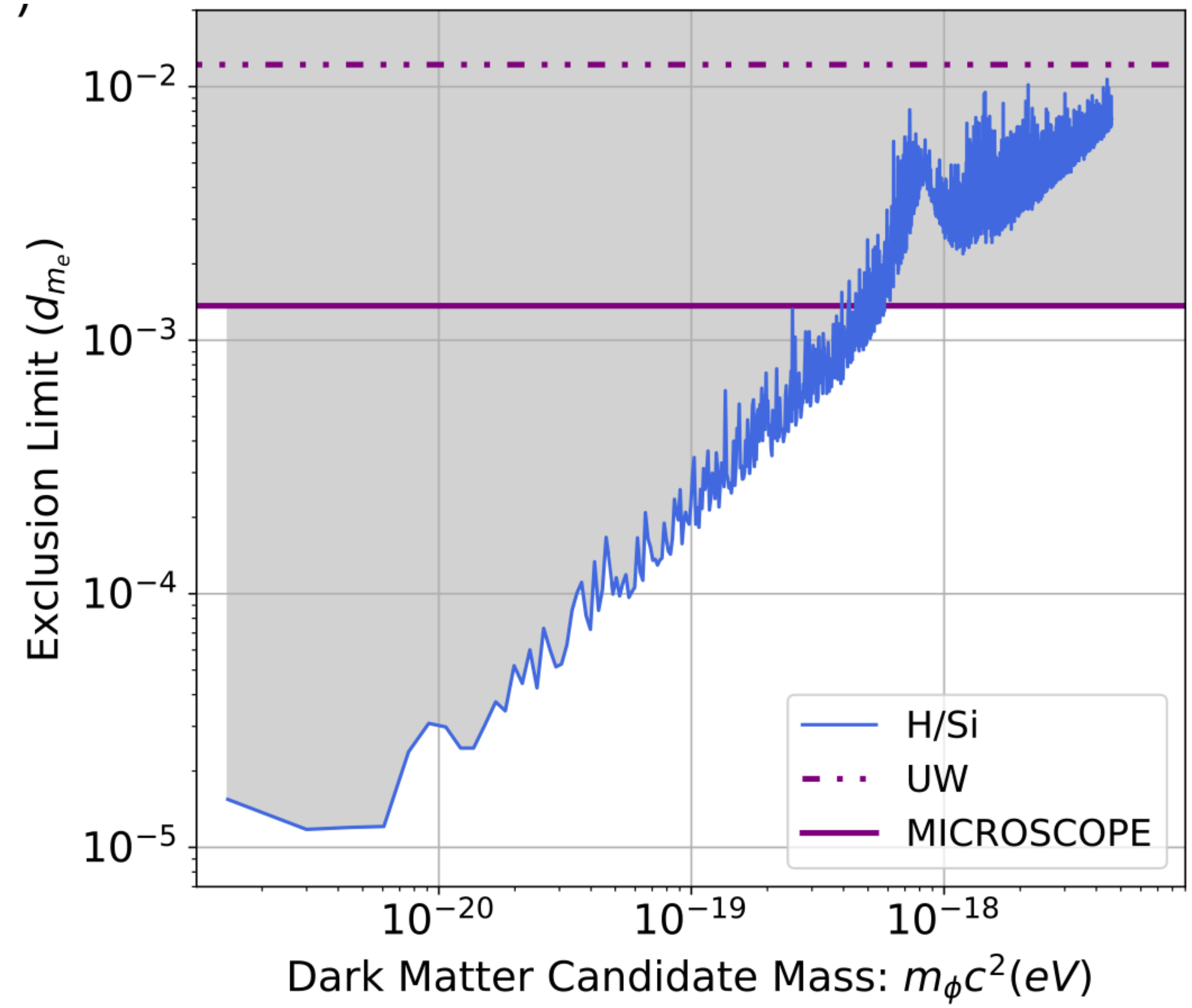
$$\frac{\Delta m_e}{m_e} = 2c_1\rho_{\rm DM}(1-\cos(2m_\phi t))$$

$$\frac{\Delta\alpha}{\alpha} = 2c_3\rho_{\rm DM}(1-\cos(2m_\phi t)),$$

Precision Metrology Meets Cosmology: Improved Constraints on Ultralight Dark Matter from Atom-Cavity Frequency Comparisons

Colin J. Kennedy,[1] Eric Oelker,[1] John M. Robinson,[1] Tobias Bothwell,[1] Dhruv Kedar,[1] William R. Milner,[1] G. Edward Marti,[1,2] Andrei Derevianko,[3] and Jun Ye[1]





$$\mathscr{L} \supset -d_{m_e}\frac{m_e}{M_{Pl}}\phi\bar{\psi}\psi$$

$$c_1 \sim \sqrt{\frac{2\pi G}{\rho_{\rm DM}}}d_{m_e} \lesssim 3\times 10^{-11}\text{ev}^{-4}$$
$$\Lambda \sim c_1^{-1/4} \gtrsim 0.4\text{ keV}$$

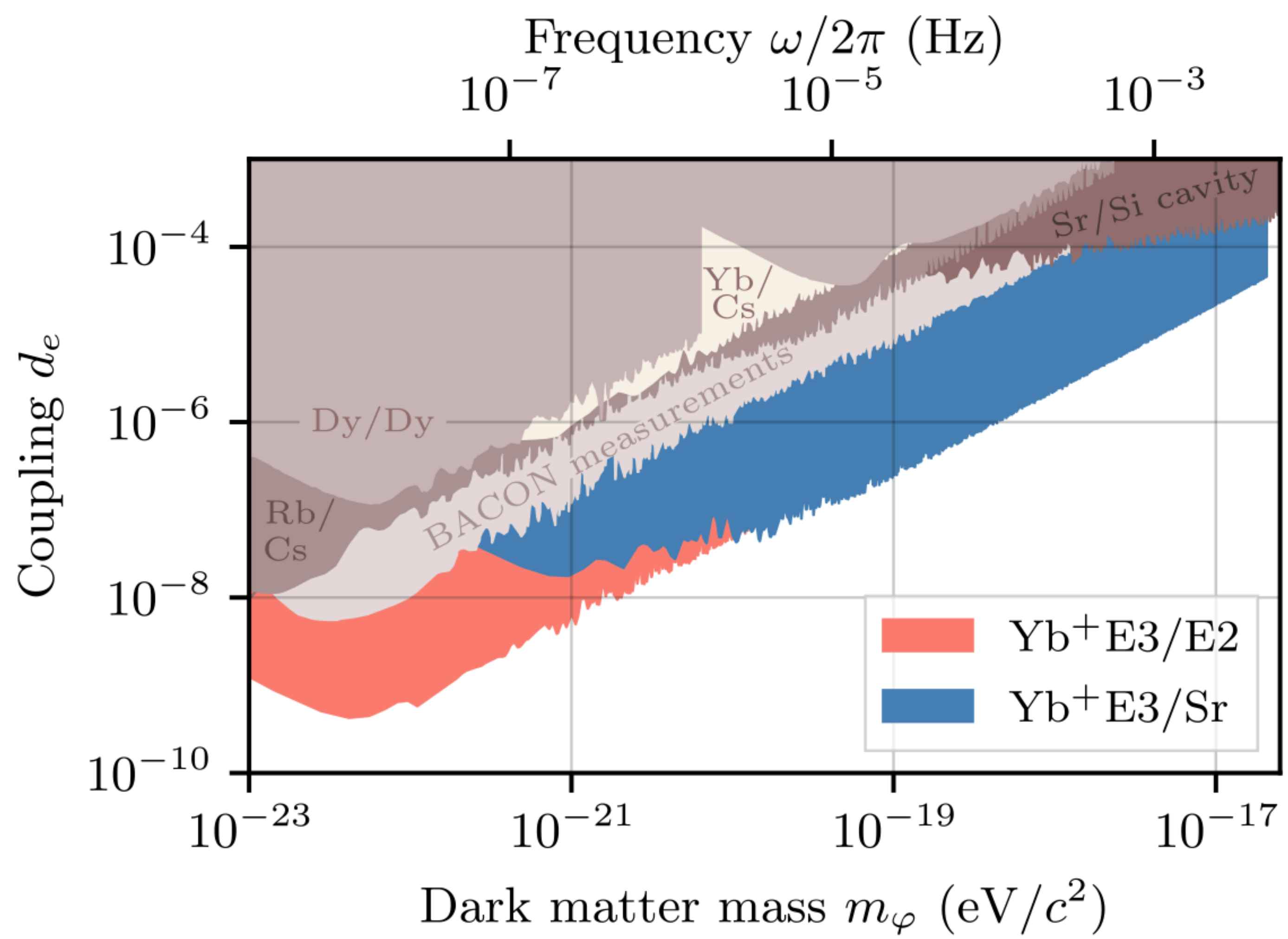
Improved limits on the coupling of ultralight bosonic dark matter to photons from optical atomic clock comparisons

M. Filzinger, S. Dörscher, R. Lange, J. Klose, M. Steinel, E. Benkler, E. Peik, C. Lisdat, and N. Huntemann*

$^{171}\mathrm{Yb}^+$:
E2: $^2S_{1/2}(F=0) \rightarrow {}^2D_{3/2}(F=2)$
E3: $^2S_{1/2}(F=0) \rightarrow {}^2F_{7/2}(F=3)$

$^{87}S_r$:
$^1S_0 \rightarrow {}^3P_0$

$$\mathcal{L} \supset \frac{d_e}{4}\frac{\phi}{M_{Pl}}F_{\mu\nu}F^{\mu\nu}$$

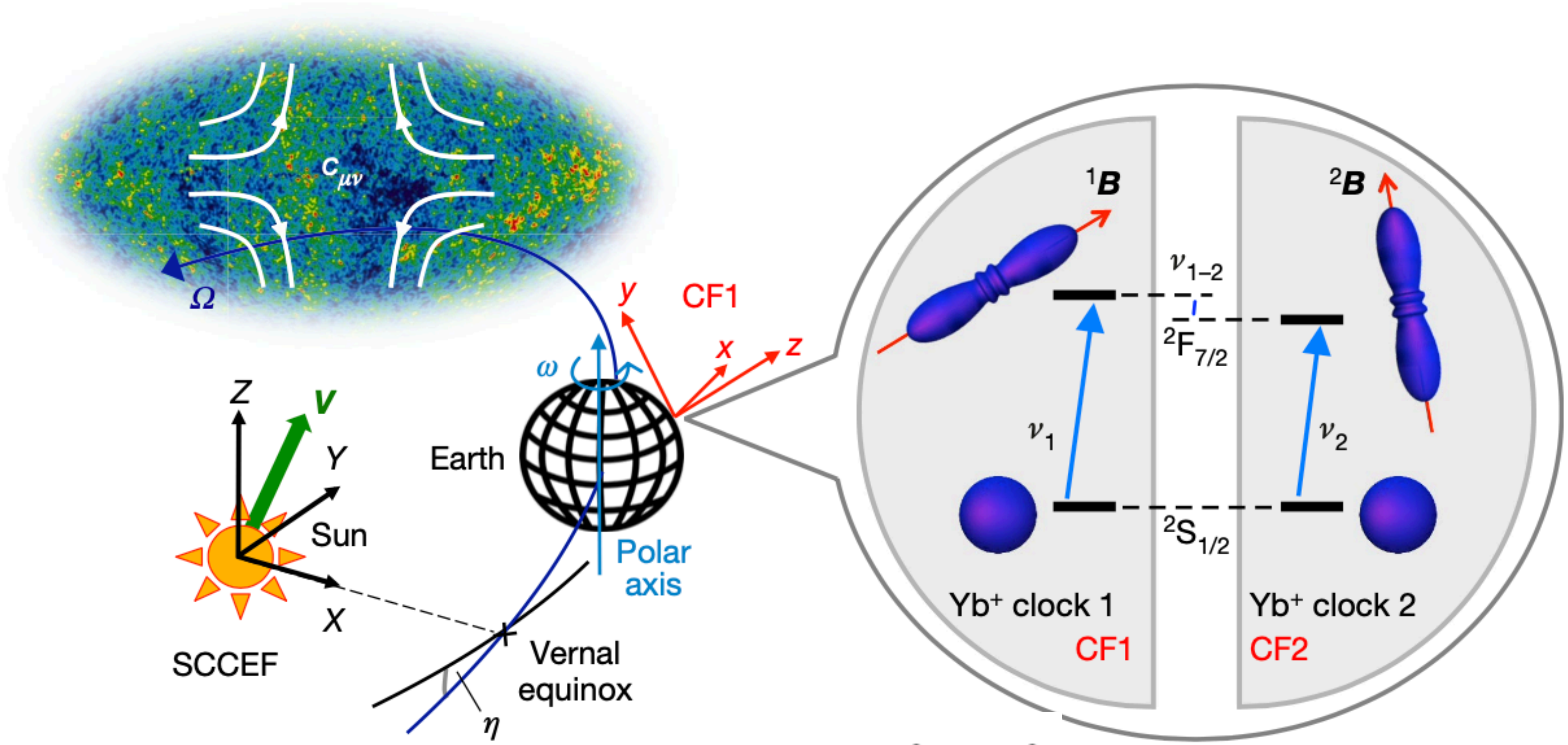


$$c_3 \sim \sqrt{\frac{2\pi G}{\rho_{\mathrm{DM}}}}d_e \lesssim 4\times 10^{-14}\mathrm{ev}^{-4}$$
$$\Lambda \sim c_3^{-1/4} \gtrsim 2\ \mathrm{keV}$$

Lorentz violation search

Optical clock comparison for Lorentz symmetry testing

Christian Sanner[1,5]*, Nils Huntemann[1], Richard Lange[1], Christian Tamm[1], Ekkehard Peik[1], Marianna S. Safronova[2,3] & Sergey G. Porsev[2,4]



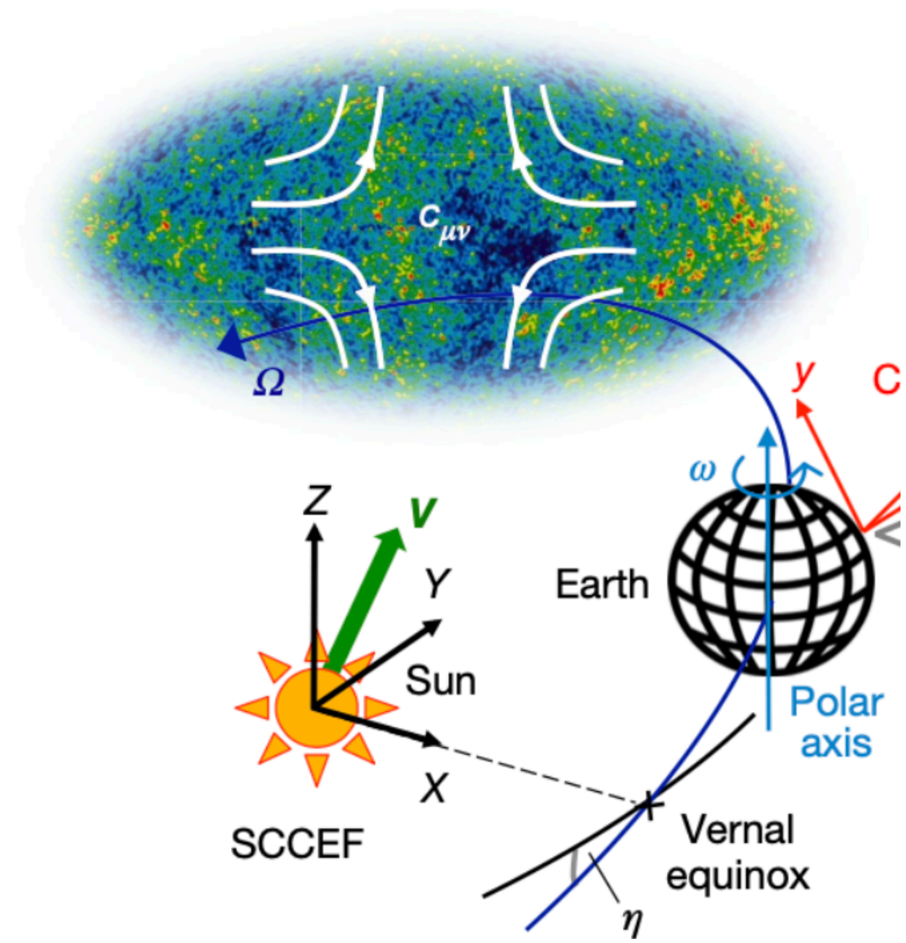
$$\delta H = -C_0^{(2)} \frac{\mathbf{p}^2 - 3p_z^2}{6m}$$

Standard Model Extension

Standard Model Extension in the QED sector :

$$\mathscr{L}_{\rm SME} \supset \frac{1}{2} i(\eta_{\mu\nu} + c_{\mu\nu})\bar{\psi}\gamma^{\mu}\overleftrightarrow{D}^{\nu}\psi - m_e\bar{\psi}\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}\left(k_F\right)_{\kappa\lambda\mu\nu} F^{\kappa\lambda}F^{\mu\nu} .$$

$c_{\mu\nu}, (k_F)_{\kappa\lambda\mu\nu}$:
Defined in the Sun-centred celestial equatorial frame (SCCEF) ;
$c^{\mu}_{\ \mu} = 0, \left(k_F\right)^{\mu\nu}_{\ \ \ \mu\nu} = 0$



$$c_{\mu\nu} = 2c_2'\rho_{\rm DM}(v_\mu v_\nu - \eta_{\mu\nu}/4)$$
$$k_{\mu\nu} \equiv \left(k_F\right)_{\alpha}^{\ \mu\alpha\nu} = -c_4'\rho_{\rm DM}(v_\mu v_\nu - \eta_{\mu\nu}/4)$$

$v_\mu = (\sqrt{1+v_{\rm DM}^2}, \vec{v}_{\rm DM})$

$$c'^{\mu\nu} \equiv c^{\mu\nu} + \frac{1}{2}k^{\mu\nu}$$

$$\delta H = -C_0^{(2)} \frac{\mathbf{p}^2 - 3p_z^2}{6m}$$

$$C_0^{(2)} \sim c'^{\rm CF}_{\mu\nu}(t) = \Lambda^{\mu}_{\rho}(t)\Lambda^{\nu}_{\sigma}(t)c'_{\rho\sigma}$$

$$c'^{xy} \lesssim 10^{-20} \rightarrow c_2' - c_4'/4 \lesssim 10^{-11}{\rm eV}^{-4}$$
$$\Lambda \gtrsim 0.5 \text{ keV}$$

Conclusion :

- ULDM with quadratically coupling to SM is theoretically interesting.
- The current bound is low $\Lambda \lesssim$ keV.

Thanks you ~