National Aeronautics and
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Searching for dark matter with atomic clocks in space

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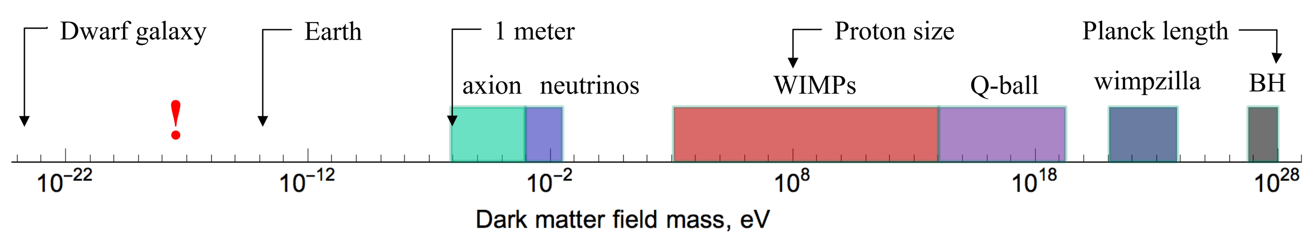
Introduction

- No direct detection of the dark matter to date, while having an overwhelming amount of indirect observations. Importance: 27% of energy content of the Universe, 85% of the mass content.
- Vast range of unexplored masses (about 80%) of the total span 10^{-24} eV - 10^{28} eV. WIMPs are typically tested above GeV and axions above μeV scale.
- Light bosons predicted by nearly every new theory beyond the Standard Model.
- Specifically for the clock stability studies: able to show high-frequency signals and make easier to identify different types of noise.



Theory

We consider an ultralight scalar field with the interaction Lagrangian:

$$\mathcal{L}_{int}^{(n)} = \phi^n \left[\frac{1}{4e^2\Lambda_{\gamma,n}^n} F_{\mu\nu}F^{\mu\nu} - \frac{\beta_{YM}}{2g_{YM}\Lambda_{g,n}^n} G_{\mu\nu}G^{\mu\nu} - \sum_{f=e,u,d} \left(\frac{1}{\Lambda_{f,n}^n} + \frac{\gamma_{m_f}}{\Lambda_{g,n}^n} \right) m_f \bar{\psi}_f \psi_f \right]$$

Presence of dark matter can induce a change in the fundamental constants:

$$\frac{\delta\alpha}{\alpha} = \left(\frac{\phi}{\Lambda_{\gamma,n}}\right)^n, \qquad \frac{\delta m_f}{m_f} = \left(\frac{\phi}{\Lambda_{f,n}}\right)^n, \qquad \frac{\delta\Lambda_{QCD}}{\Lambda_{QCD}} = \left(\frac{\phi}{\Lambda_{g,n}}\right)^n,$$

Clock response is due to the change in the atomic transition frequency:

$$\nu = \mathrm{const}\cdot R_\infty \cdot \alpha^{K_\alpha} \left(\frac{m_q}{\Lambda_{QCD}}\right)^{K_{q\Lambda}} \left(\frac{m_e}{\Lambda_{QCD}}\right)^{K_{e\Lambda}}$$

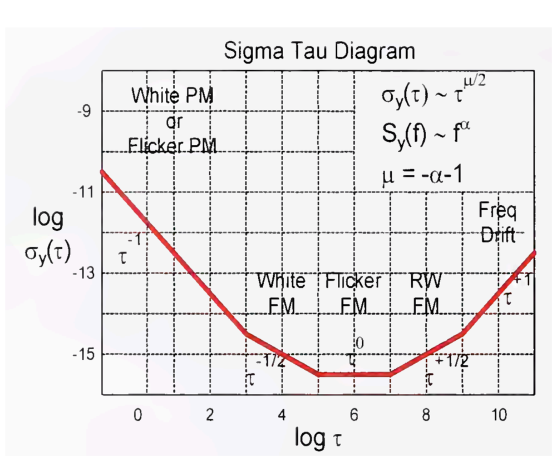
Average fractional frequency deviation:

$$\bar{y}(t) = \frac{1}{\tau}\int_{t-\tau}^{t} y(t')\,dt'$$

Allan variance (continuous version):

$$\sigma_y^2(\tau) = \frac{1}{2}\lim_{T\to\infty}\frac{1}{T}\int_0^T [\bar{y}(t+\tau) - \bar{y}(t)]^2\,dt$$

Regime of our interest: $\sigma_y(\tau) = \sigma_0/\sqrt{\tau}$



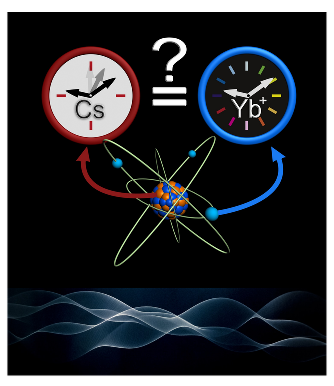
W.J. Riley's Handbook

Species	^{133}Cs	^{199}Hg$^+$	^{199}Hg	^{27}Al$^+$	^{87}Sr	^{162}Dy	^{164}Dy	^{229}Th
States	hyperfine	$5d^96s^2\,^2D_{\frac{5}{2}}$	$6s6p\,^3P_0$	$3s3p\,^3P_0$	$5s5p\,^3P_0$	$4f^95d^26s$	$4f^{10}5d6s$	nuclear
	hyperfine	$5d^{10}6s\,^2S_{\frac{1}{2}}$	$6s^2\,^1S_0$	$3s^2\,^1S_0$	$5s^2\,^1S_0$	$4f^{10}5d6s$	$4f^95d^26s$	nuclear
K_α	2.83	-3.19	0.81	0.008	0.06	8.5×10^6	-2.6×10^6	10^4(?)
$\sigma_0(10^{-16}\mathrm{Hz}^{-1/2})$	10^3	28	1.8	28	3.1	4×10^7	1×10^8	10(?)

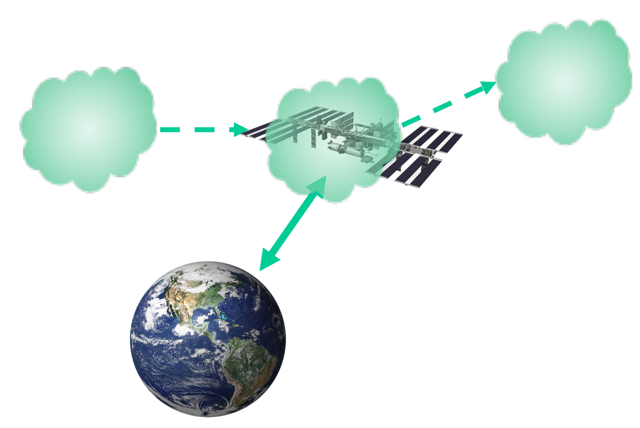
Method

Compare two clocks of different type or spatially separated. Investigate the two dark matter configurations: dark matter waves or clumps (e.g., topological defects: monopoles and strings).

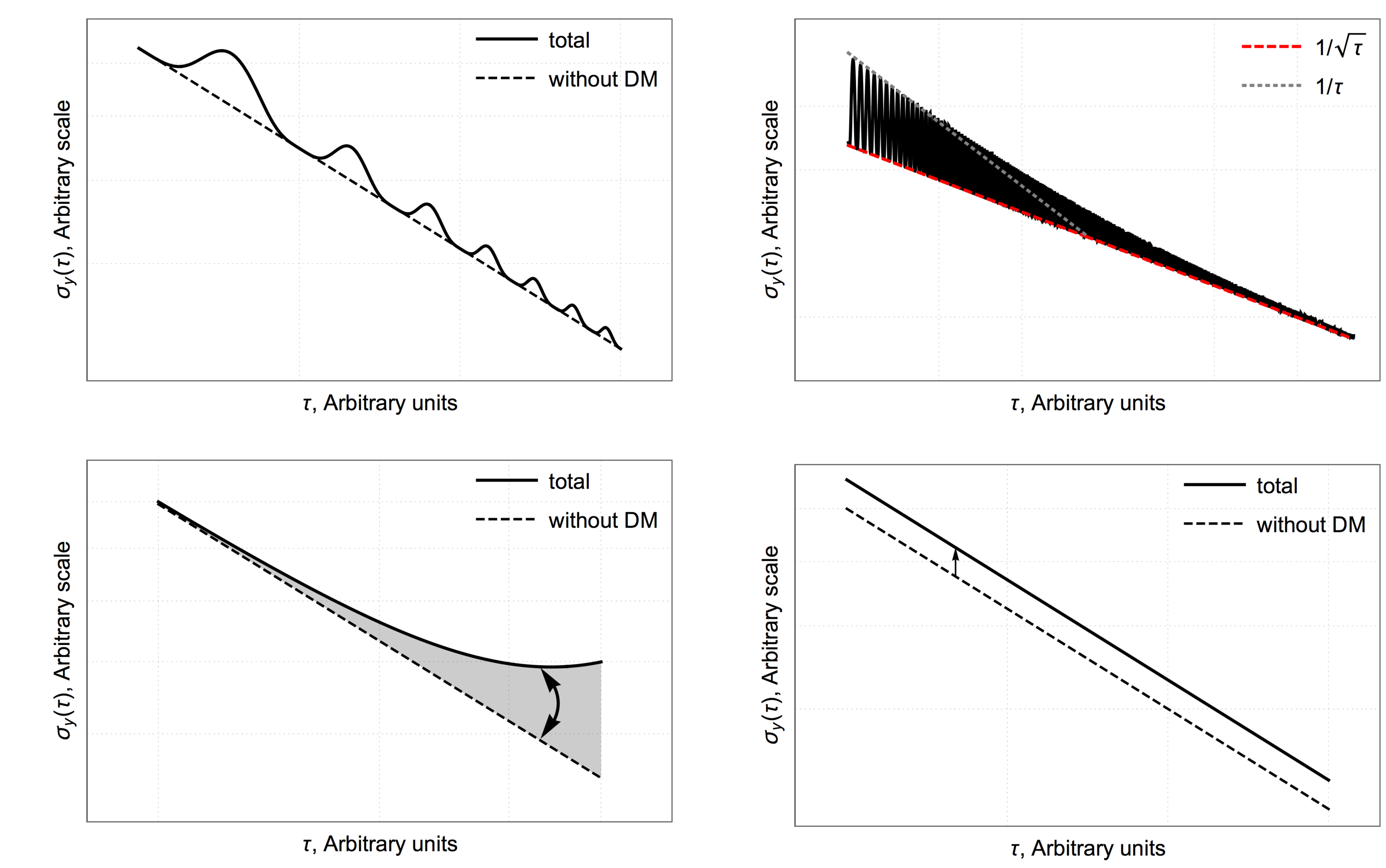
1. Waves with frequency $f = m_\phi/(2\pi)$



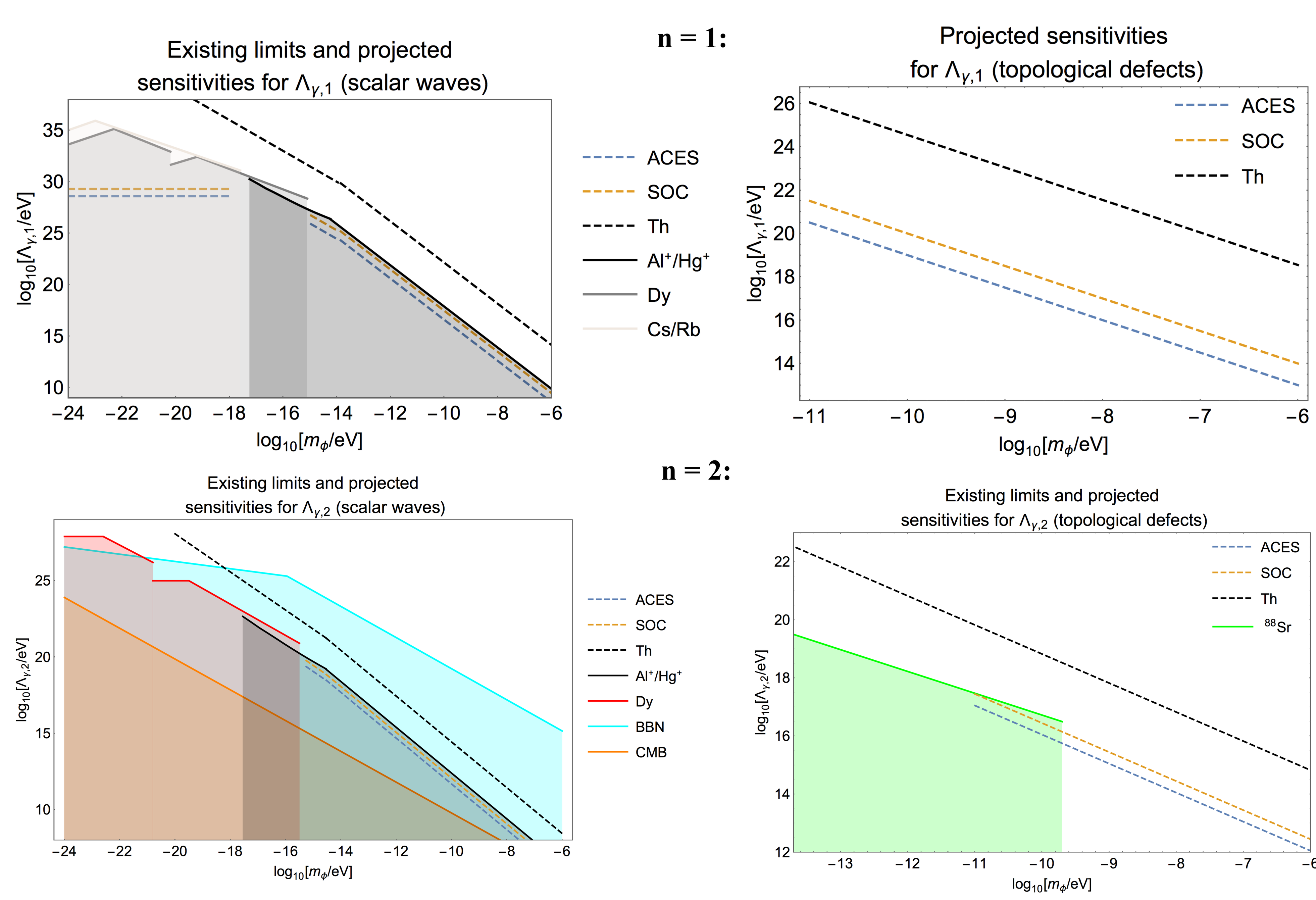
2. Clumps of dark matter of size $d \sim \hbar/(m_\phi c)$



Anomalies in the clock stability diagrams



Results



Conclusions

- Comparison of ultra-stable atomic clocks provides an opportunity for direct tests of light dark matter. Such comparison can be done in the nearest future, involving JPL.
- Clock stability analysis can be used as a tool and opens access to a new region of parameter space for the DM masses and couplings.
- We demonstrate the feasibility of our method by using existing data for Hg$^+$/Al$^+$ comparison to put new limits on the DM coupling in the DM wave background.
- As the next step, networks of atomic sensors can be used for the search of the stochastic backgrounds of new fields, including the dark matter.

For more information, see the preprint: arXiv:1705.05833

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