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Atomic clocks, space-time variation of the fundamental constants and dark matter

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Fundamental constants—such as the fine-structure constant α , the strong-interaction scale, and particle masses—may vary in an expanding Universe. A spatial variation could help explain apparent fine tuning: we inhabit a region where the values permit life. Hints from quasar absorption spectra suggest a gradient in α , but decisive confirmation requires laboratory tests. Atomic clocks provide such tests and, through their exquisite stability, enable sensitive searches for new physics.

Interactions between dark matter and ordinary matter can induce temporal variation of constants. For low-mass bosonic dark matter produced after the Big Bang, the field behaves classically, yielding first-order effects in the coupling—an enormous advantage over traditional second-order responses. Using clock comparisons, existing bounds on scalar dark-matter couplings to photons, electrons, quarks, and the Higgs can be tightened dramatically; our analyses improved previous limits by up to 15 orders of magnitude.

We assess several promising clock candidates - metastable transitions in Cu II, Yb III, Hf II, Hf IV, and W VI - where s-d transitions deliver enhanced sensitivity to α variation (enhancement coefficients up to $K \sim 8$) while offering accessible cooling E1 lines. Using relativistic many-body theory, we compute energies, Landé g factors, E1/E2/M1 amplitudes, lifetimes, quadrupole moments, scalar polarizabilities, second-order Zeeman shifts and black body-radiation shifts (BBR). Forming suitable linear combinations of clock transitions suppresses BBR.

Finally, highly charged-ion clocks offer reduced systematics due to their compact size, with α -variation and dark-matter responses enhanced by 1–2 orders of magnitude. Together, these strategies link precision metrology to cosmology, enabling high accuracy searches for space–time variation of the constants and for dark matter.

Authors: FLAMBAUM, Victor (University of New South Wales); DZUBA, Vladimir (University of New South Wales)

Presenter: DZUBA, Vladimir (University of New South Wales)

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