QUANTERA

ERA-NET Cofund in Quantum Technologies

Mid-term Strategic Conference

Granada, 13th - 14th November 2019

Cavity-Enhanced Quantum Optical Clocks
(Q-Clocks)

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Systèmes de Référence Temps-Espace

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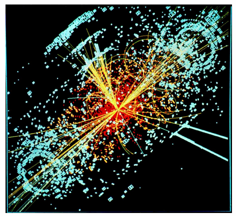
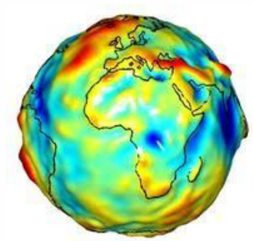
ICFO

Cavity-Enhanced Quantum Optical Clocks

Atomic clocks is a key technology in a broad range of application



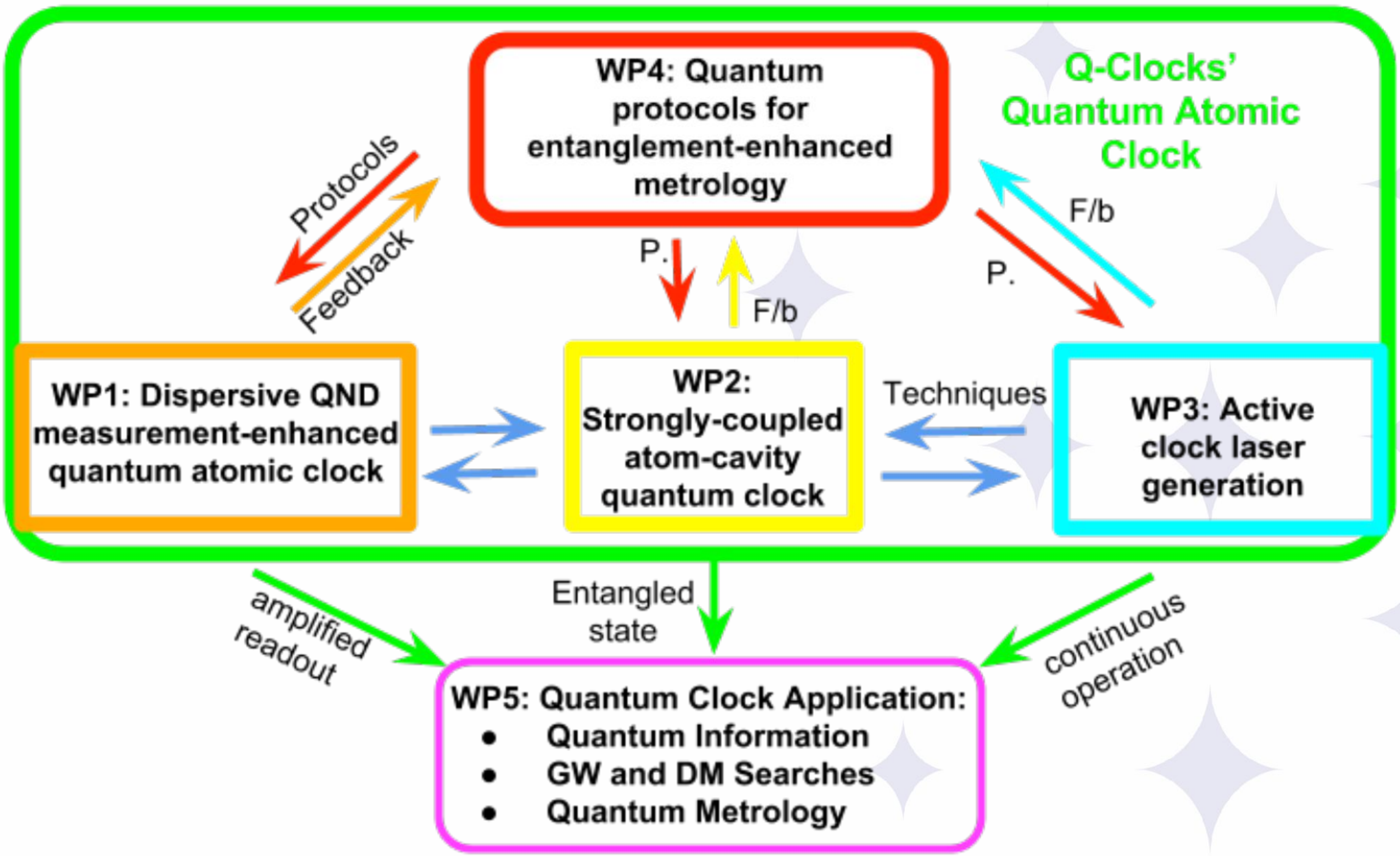



Test different innovative quantum techniques in state-of-the-art optical lattice clocks, demonstrating enhanced sensitivity while preserving long coherence times and the highest accuracy.

Expected impact

- Tighter tests on fundamental physics (DM detection, …)
- New possibilities for applied physics (precision geodesy , …)
- Joint large scale laser interferometers in gravitational wave detection

Q-Clocks Work Plan



WP1 - Project Progress

SYRTE proposed to demonstrate quantum correlations between successive weak measurements of Sr atoms in an optical lattice clock by means of cavity assisted dispersive detection (T1.1).

Two strategies:

1) **Handling the mechanical cavity vibrations to keep the cavity on resonance**
   - Design and implementation of new mechanical cavity support:
   - Mechanical resonances in agreement with the FEM simulations

2) **Increasing the frequency of the heterodyne detection of the atoms.**
   - Implementing fast modulation, detection and demodulation of the phase of the probing laser.
   - Studying possible dual modulation scheme with lower modulation frequency

Significal results:

New vacuum system for better metrological control:

- better control of Black Body Radiation

Wrong implementation of the sealing of vacuum windows prevent the cold-atom loading to the apparatus.

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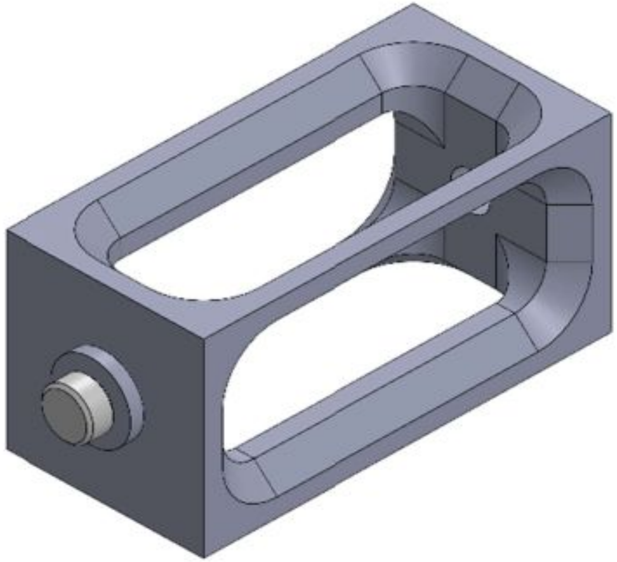
WP2 - Project Progress

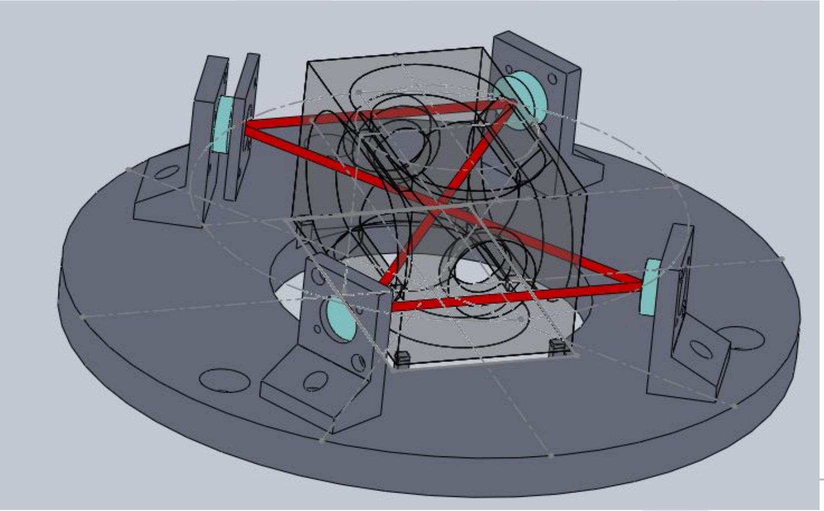
Completed optical design for clock transition cavity (T2.1)

- (L=66 mm,R=75 mm --> w_0=90µm)
- Cavity Finesse 70'000 - 100'000
- Monolithic, zerodur spacer
- silicate bonding used for cavity mirror mounting
- Dual PZT for position tunability



Design of ring enhancement cavity:

- Optimized system for cavity misalignment
- Custom design for mirror holders and vacuum actuators



The cavity system will be integrated in a new titanium vacuum chamber which will soon be shipped.

Simulation to find best SNR in cavity-aided clock transition detection with KU and CNR-INO

INRIM activities are about 9 months behind schedule because MIUR delayed the contract approval.

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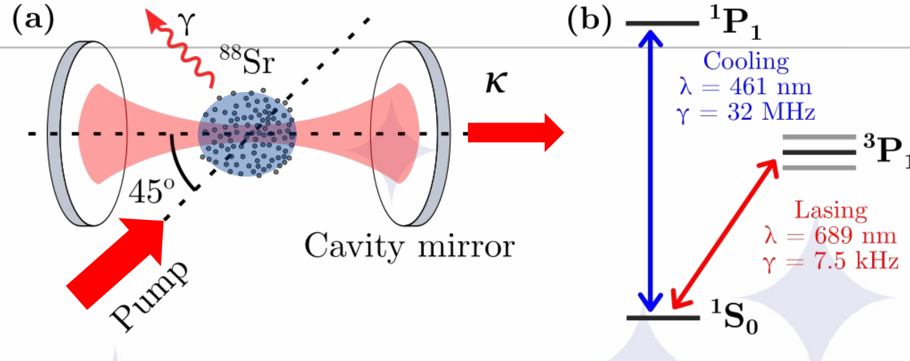
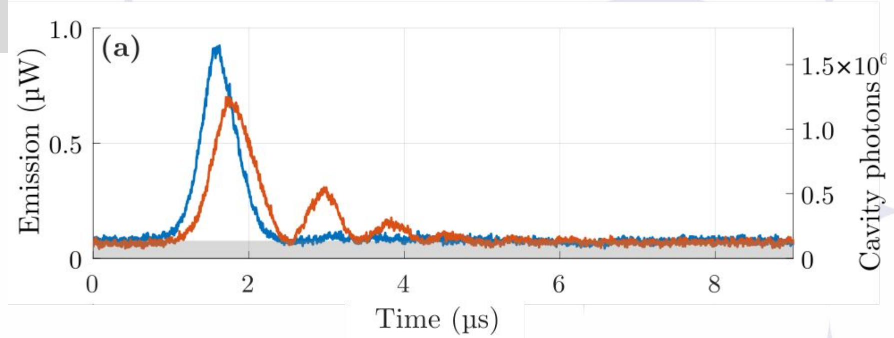
WP3 - Project Progress



Significant results (T 3.1-3.2):

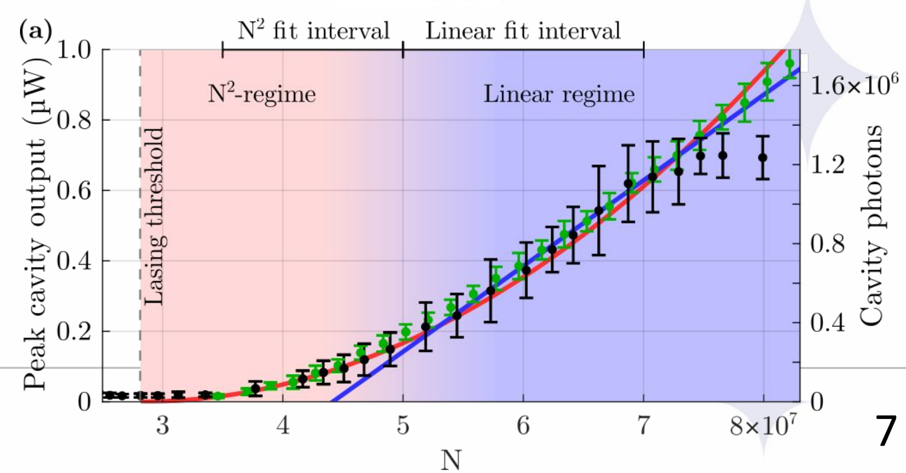
Experimental demonstration of pulsed superradiant lasing in Sr MOT placed in a optical cavity (F=1260):

- Experimental characterization of lasign dynamics: time evolution, lasing threshold lasing delay and atomic number dependency [*arXiv:1903.12593*]



Development of a theoretical framework to simulate cavity-assisted experiments (T2.4)

- model based on a Tavis-Cummings Hamiltonian
- inclusion of atomic sample temperature, 3D overlapping with cavity profile and 3D spatial of laser excitation
- Excellent agreement with experimental investigation



Progress toward passive cavity-enhanced clock laser stabilization:

- Demonstrated laser locking to the dispersive non-linear feature

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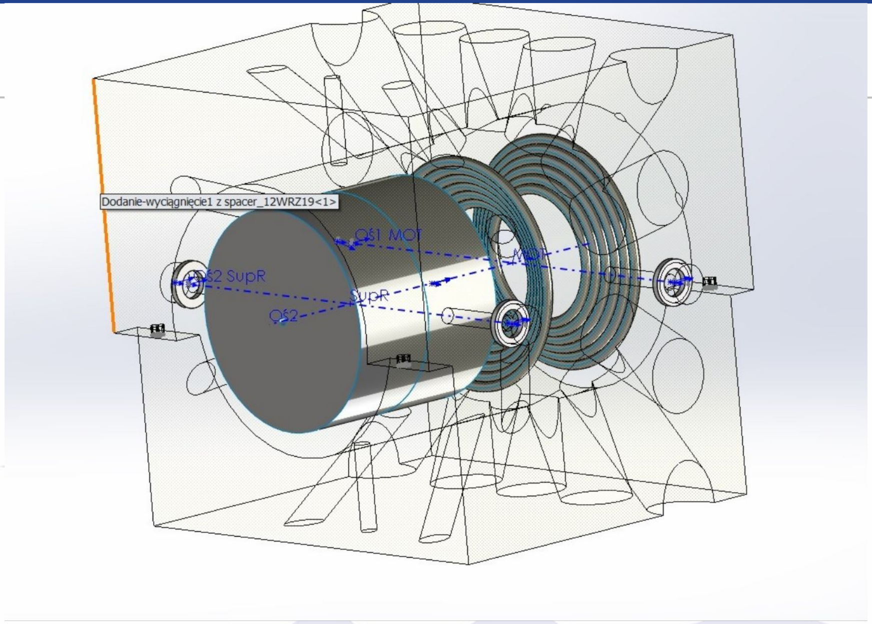
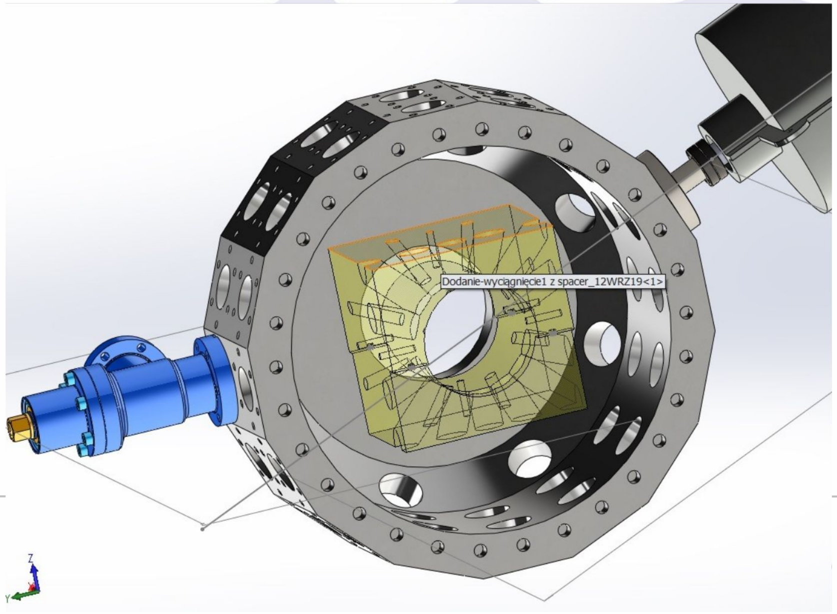
WP3 - Project Progress

Simulation (T3.1) and Design of cavity-assisted superradiance for ^{88}Sr and ^{87}Sr cold atomic sample:

- Superradiant cavity superimposed to blue-magic wavelength optical lattice of w=70 µm
- Optical atom replenishing system provided by moving red-magic wavelength trap of w=500 µm overlapped to the blue optical lattice
- Homogeneous magnetic field in the superradiance region ensured by two-layer magnetic shield.
- blue photon protection (strong cooling line of Sr) in the superradiance region exploiting the magnetic shield





Simulation for KU Sr-apparatus: different scale laws of superradiant pulse vs Number of atoms are explained (T3.2)

WP4 - Project Progress

Theoretical investigations:

- Interaction of a quantized light field of a cavity with two-level atoms in order to developing methods for the conditional creation of non-classical states of light through conditional measurements of the state of the considered atoms
- Proposed the clock stability improvement by means of interrogation of two atomic ensemble system sharing the same loca oscillator with $\pi/2$ phase difference
- Investigation of QND protocol to improve long-term stability of optical clocks
- Squeezing generation via nonlinear Hamiltonians

Significant results:

- Introduction of non linear squeezing parameter for non Gaussian state detection [***PRL 122, 090503 (2019)***]
- Study the optimal generation of entangled state by unitary quadratic Hamiltonian [***PRA 99, 022329 (2019)***]
- Proposed method to measure the entanglement robustness[***arXiv:1908.03117***]

WP4 - Project Progress

Significant results (T4.3, T4.4):

Prototype protocol of OLC exploiting a versatile ^{87}Rb system:

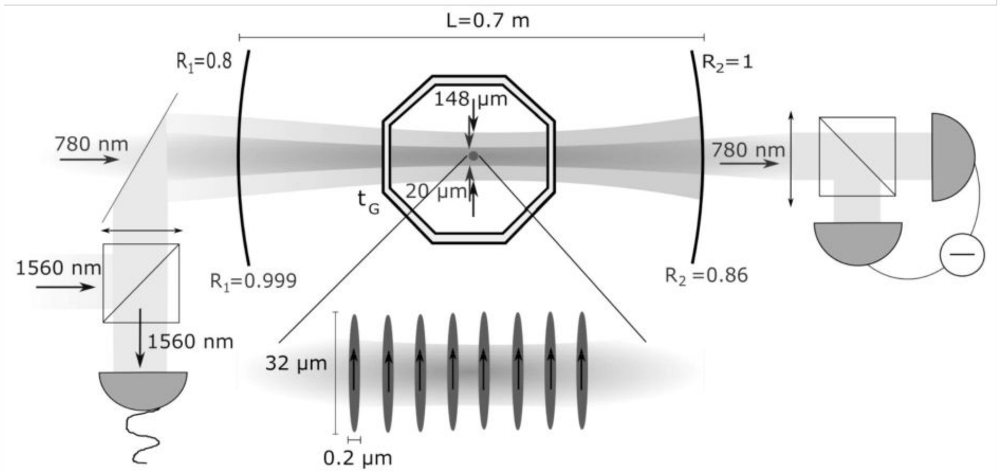
- Coherent two photons MW/RF excitation for coherent rotation |F=1,m_F=-1> —> |F=2,m_F=1>
- Design, simulation and construction of a resonant cavity for enhanced probing
- Non destructive probing performed by off-resonant beam at 780 nm (D2 line)
- Uniform coupling achieved by commensurate optical lattice at 1560 nm

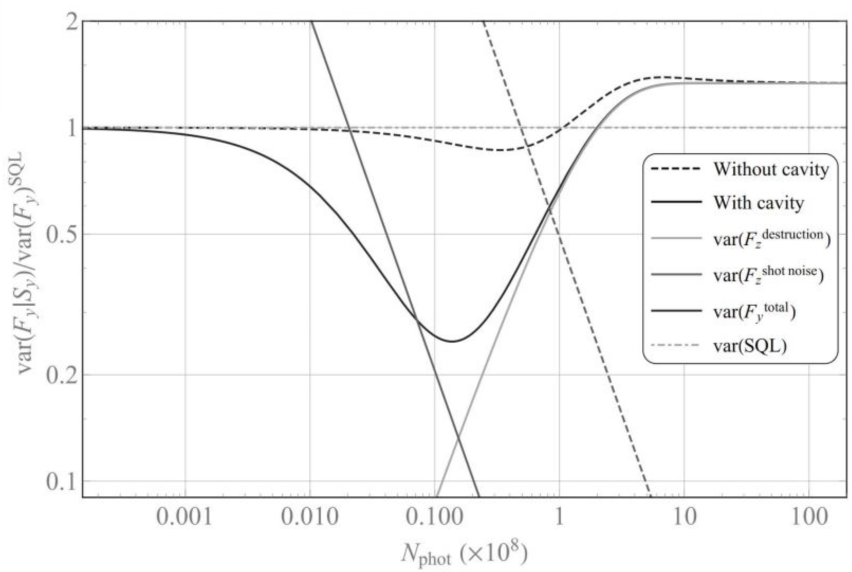
Expected performances:

- up to 6 dB of squeezing by QND with N = 70’000 atom

New advanced scientific methodology

- trapped atom comagnetometer for precision measurement of scattering lengths and collisional shifts in neutral atoms [*PRA 100, 032704 (2019)*]





Significant results (T5.1):

Demonstration Earth-scale networks of optical atomic clocks (EU, Japan, USA)

Comparison of different atoms - cavity fine constant susceptibilities without real-time frequency transfer

Applications: search of oscillation and transient variation in fine-constant originated from the presence of DM as topological defect or massive scalar fields.

Improvement of the previous constraints on transient variations in the fine-structure constant by two orders of magnitude

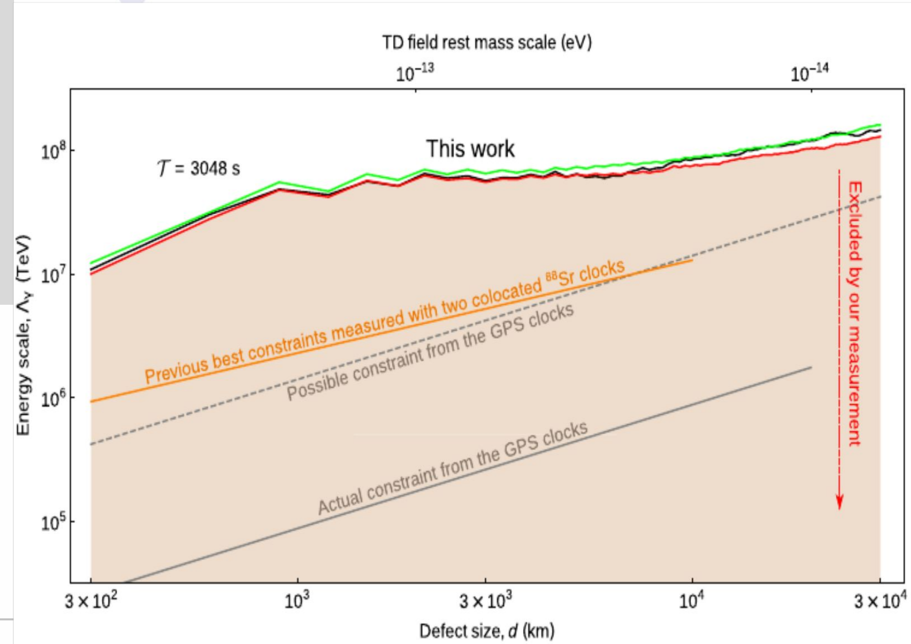
Measurement of Sr Photoionization cross section for 378.8nm and 403nm zero magic wavelength (T5.2)

SCIENCE ADVANCES | RESEARCH ARTICLE

APPLIED PHYSICS

New bounds on dark matter coupling from a global network of optical atomic clocks

P. Wcisło[1,2], P. Ablewski[1], K. Beloy[3], S. Bilicki[1,4], M. Bober[1], R. Brown[3], R. Fasano[3,5], R. Ciuryło[1], H. Hachisu[6], T. Ido[6], J. Lodewyck[4], A. Ludlow[3,5], W. McGrew[3,5], P. Morzyński[1,6], D. Nicolodi[3], M. Schioppo[3,7], M. Sekido[6], R. Le Targat[4], P. Wolf[4], X. Zhang[3], B. Zjawin[1], M. Zawada[1]*



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