Cold Atom Quantum Systems for High-Energy and Nuclear Physics Research

Principal Investigator(s): Sebastian Will (Senior Scientist and PI)
Raman Kumar (Postdoc and Co-PI)

Proposal term from: 10/2026 to: 09/2029

Annual funding: FY27 $600K FY28 $450K FY29 $450K

THE RESEARCH TEAM (SINCE NOV 2024)

Research Experience

- Ultra-cold Atoms and Molecules, Quantum Optics, Nanofabrication, Advanced Electromagnetics, Quantum Cryogenics, Solid-state Physics

Research Interests

- Quantum systems for computing, sensing and fundamental research

PI: Sebastian Will

Appointments: 1. **Columbia U. (80%), Prof. Physics**
2. **BNL (20%), Senior Scientist**

Postdoc: Raman Kumar, BNL (100%)

Previously: CUNY (Postdoc), UIUC (PhD)

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Article | Published: 03 June 2024

Observation of Bose–Einstein condensation of dipolar molecules

Niccolò Bigagli, Weijun Yuan, Siwei Zhang, Boris Bulatovic, Tijs Karman, Ian Stevenson & Sebastian Will

Nature **631**, 289–293 (2024) | Cite this article

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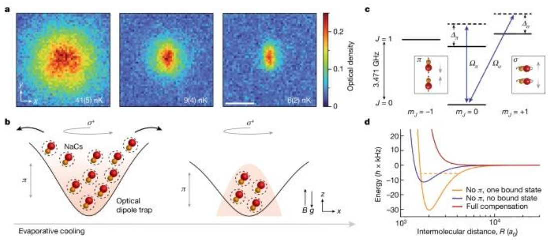
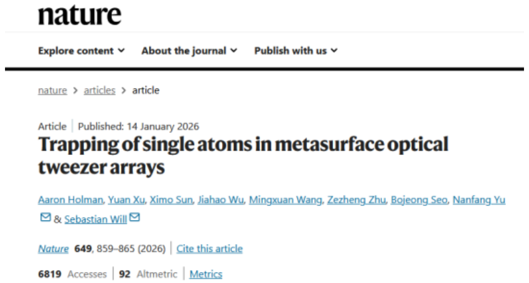
Fig. 1: BEC of dipolar NaCs molecules enabled by microwave shielding.





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Aaron Holman, Yuan Xu, Ximo Sun, Jiahao Wu, Mingxuan Wang, Zezheng Zhu, Bojeong Seo, Nanfang Yu & Sebastian Will

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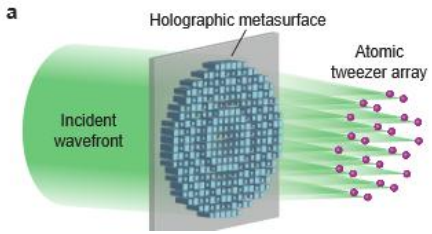

Will Lab @Columbia University

Brookhaven National Laboratory

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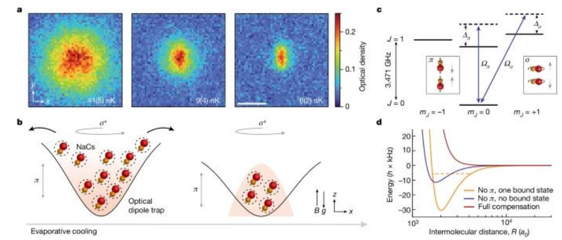

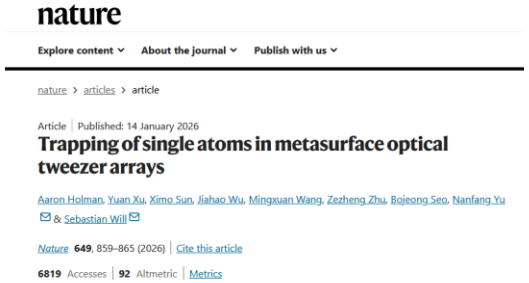

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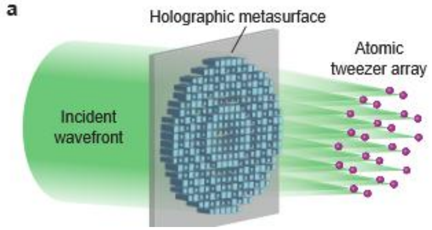

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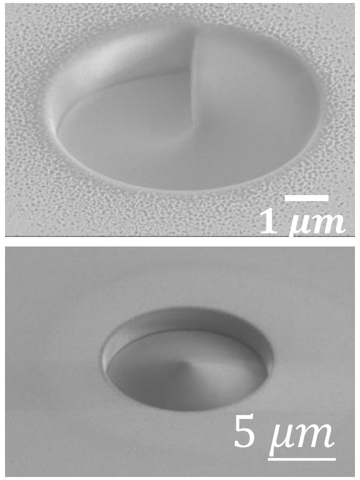
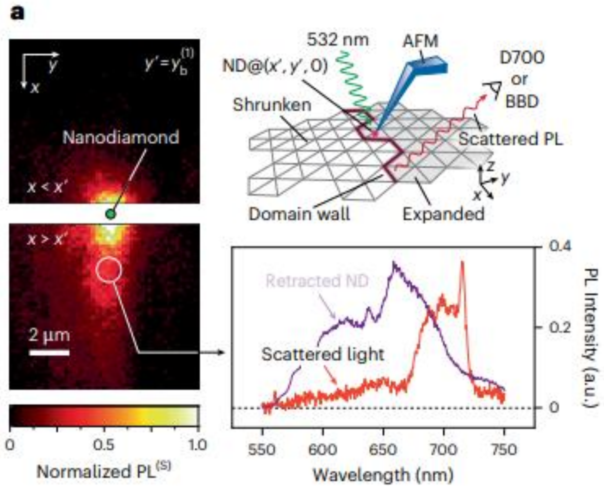
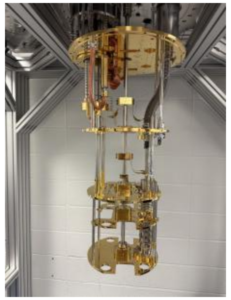
Nanofabrication



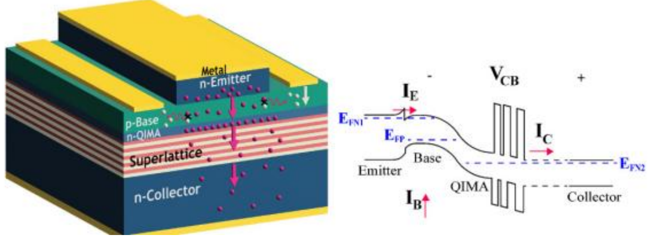
Instrumentation + Quantum Optics



Cryogenics



Semiconductor Physics



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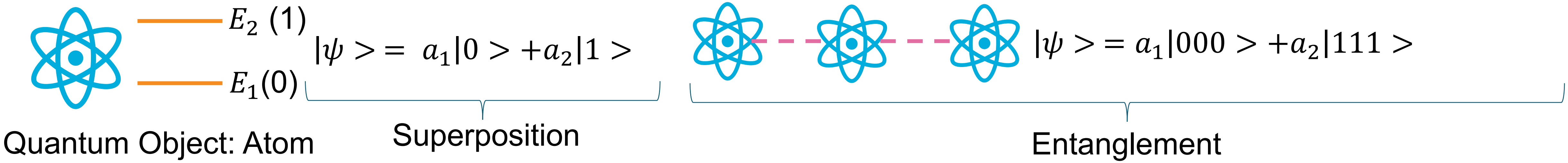
WHAT IS A QUANTUM SYSTEM?

- A quantum system is composed of quantum objects whose internal states and interactions can be manipulated in a controllable manner



$|\psi > = a_1|0 > +a_2|1 >$

Superposition

$|\psi > = a_1|000 > +a_2|111 >$

Entanglement

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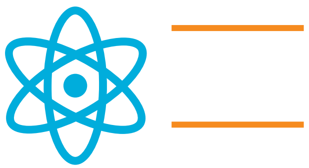
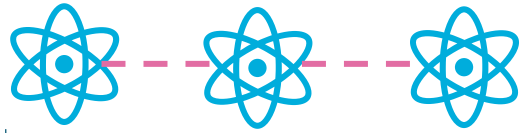


Quantum Object: Atom

$$\underbrace{|\psi >= \ a_1|0 > +a_2|1 >}_{\text{Superposition}}$$



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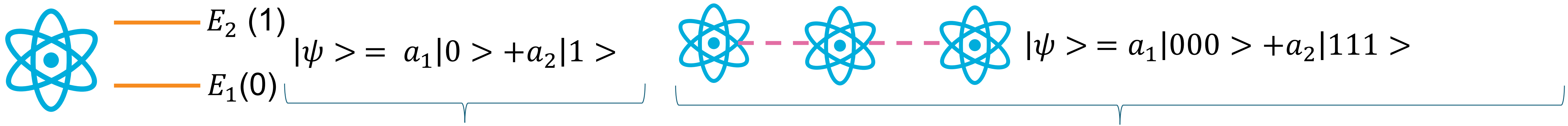

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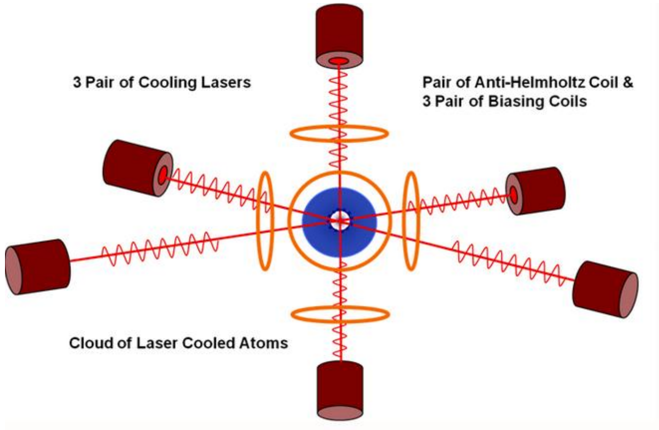

Laser Cooling ($\sim\mu K$)

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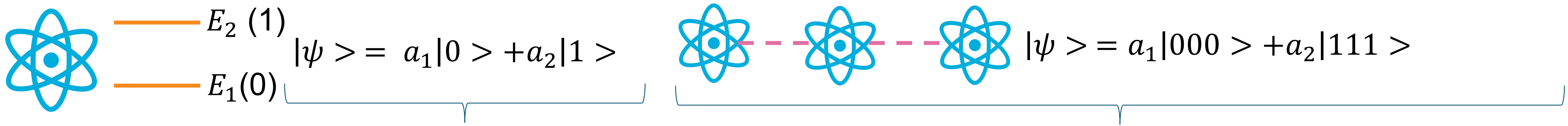

E_2 (1)

E_1(0)

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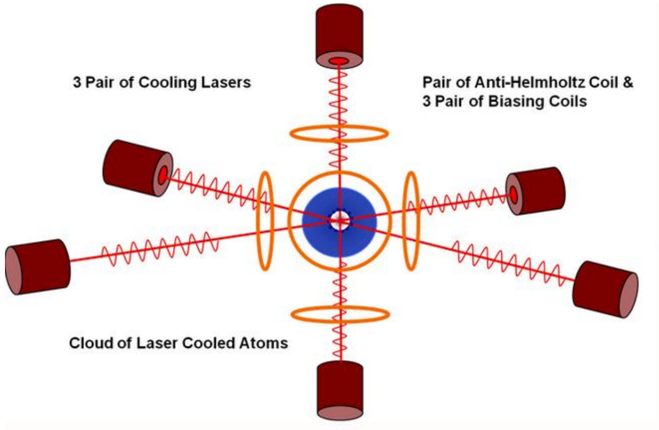

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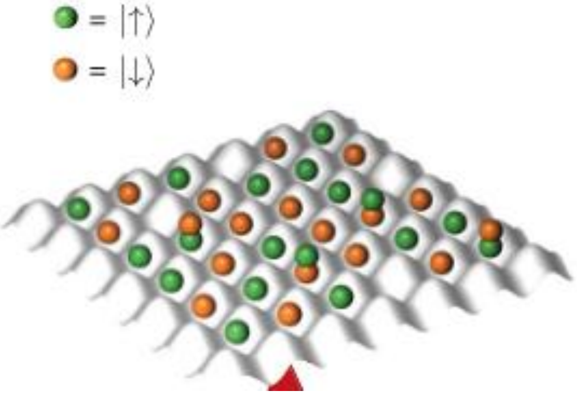

Controlled 2D Arrangement

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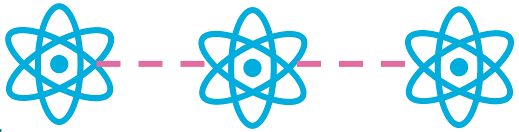

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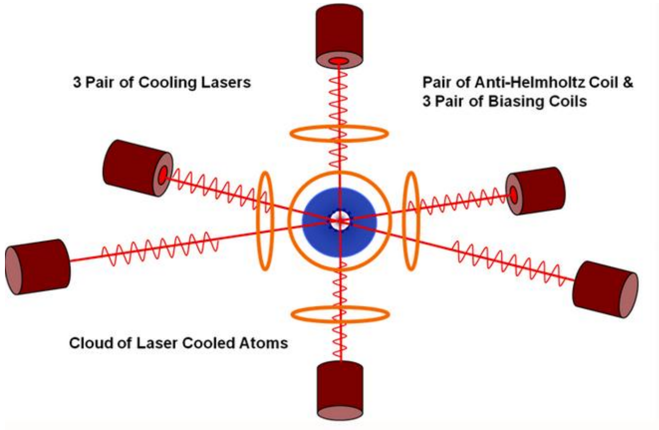

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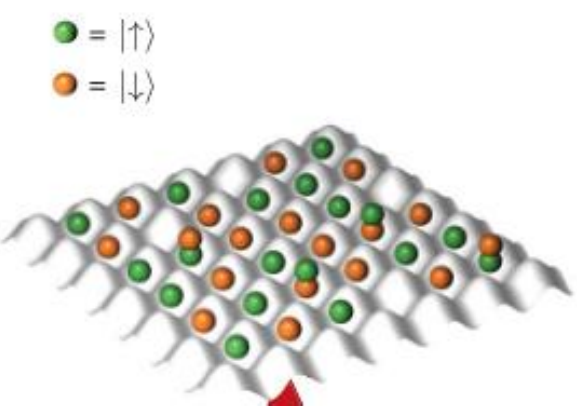

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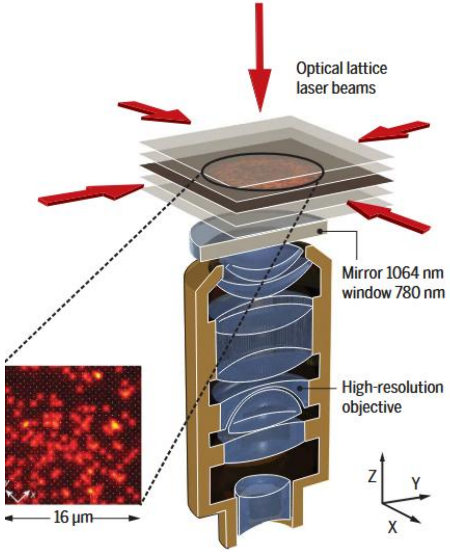
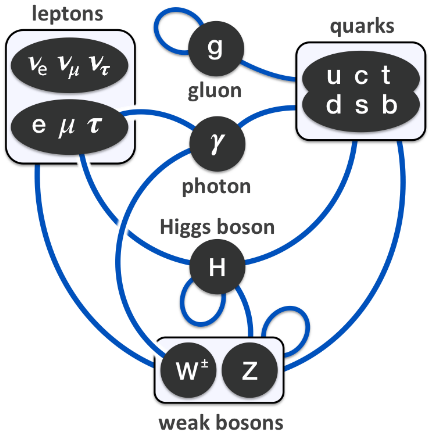


Readout

QUANTUM SIMLUATION OF LATTICE GAUGE THEORIES

Standard Model



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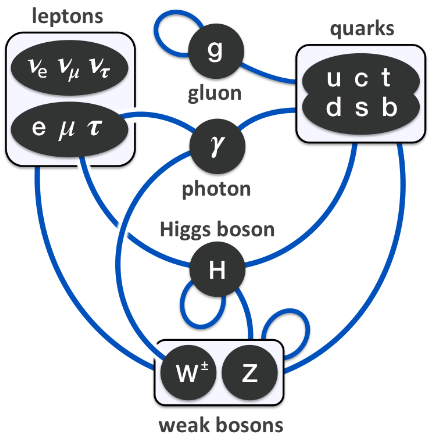
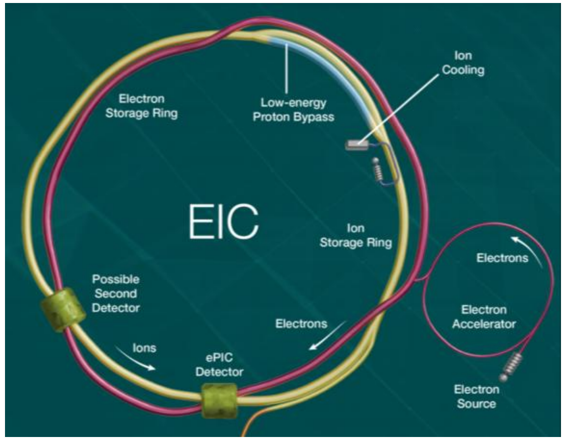


Experiment



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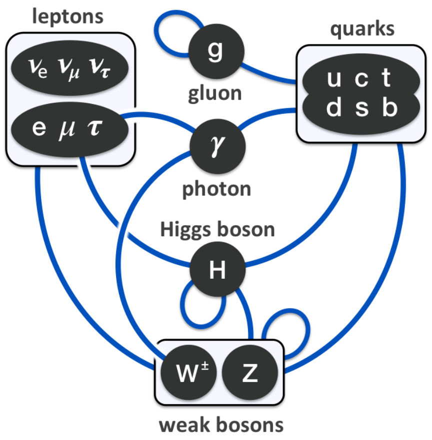

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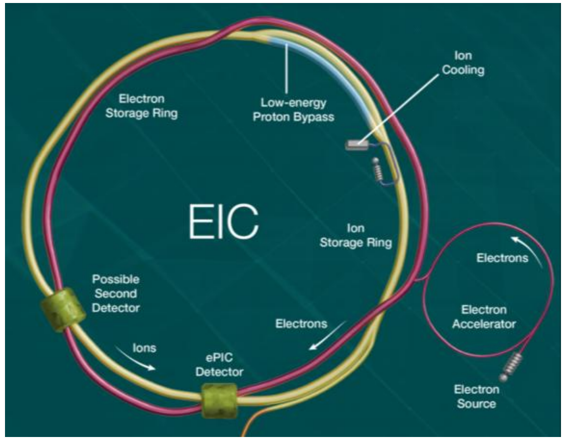

Computational Approaches

- Theoretical approaches to study properties of nuclei and neutron stars
- Hard to treat analytically
  - Supercomputer and Quantum Computing
- Require non-perturbative analysis
- Sign problem in simulating Fermionic systems

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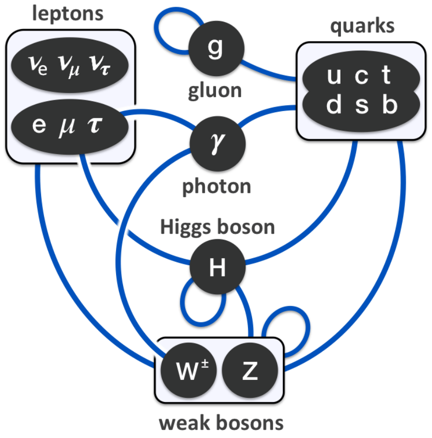

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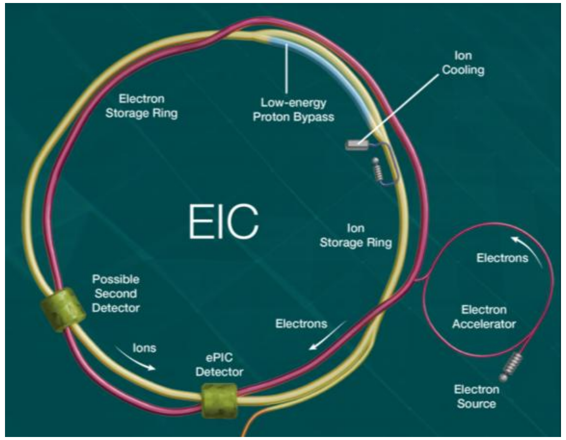

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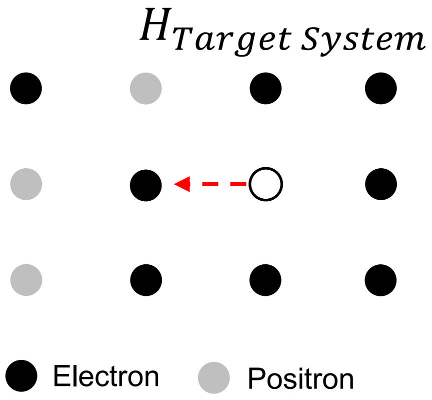
Another Approach: Quantum Simulation Using Cold Atoms

Basic Idea ➡ Engineer a synthetic system to emulate physics of a target model to provide qualitative/quantitative insights

A simple example: Simulate dynamics of charged particles



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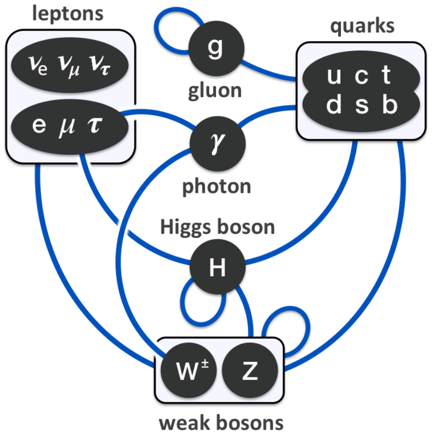

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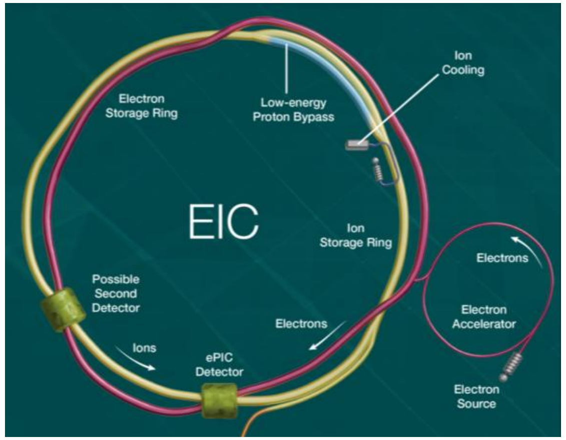

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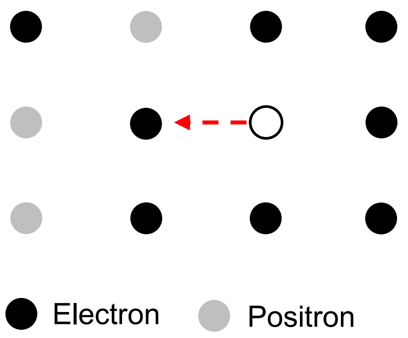
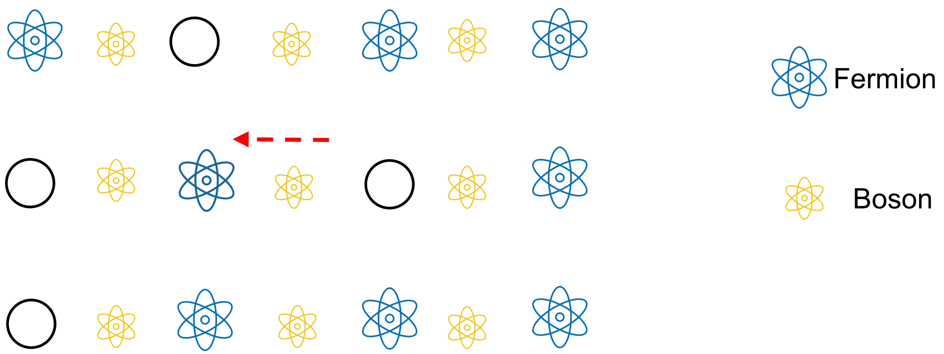
$H_{Target\ System}$



One-to-one Mapping

H_{Sim}



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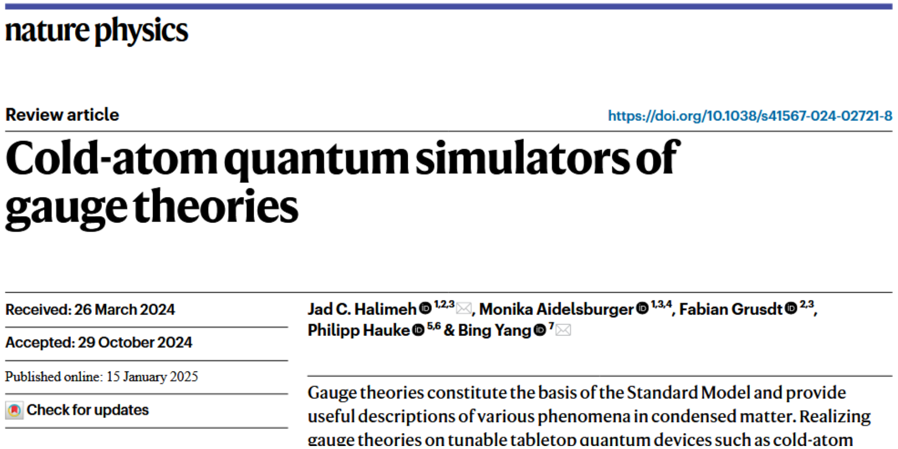

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Review article

https://doi.org/10.1038/s41567-024-02721-8

Cold-atom quantum simulators of gauge theories

Received: 26 March 2024

Accepted: 29 October 2024

Published online: 15 January 2025

Check for updates

Jad C. Halimeh[1,2,3], **Monika Aidelsburger**[1,3,4], **Fabian Grusdt**[2,3], **Philipp Hauke**[5,6] & **Bing Yang**[7]

Gauge theories constitute the basis of the Standard Model and provide useful descriptions of various phenomena in condensed matter. Realizing gauge theories on tunable tabletop quantum devices such as cold-atom

PHYSICAL REVIEW LETTERS **135,** 101902 (2025)

Editors' Suggestion | Featured in Physics

String-Breaking Mechanism in a Lattice Schwinger Model Simulator

Ying Liu,[1,2,*] Wei-Yong Zhang,[1,2,*] Zi-Hang Zhu,[1,2] Ming-Gen He,[1,2] Zhen-Sheng Yuan,[1,2,3] and Jian-Wei Pan[1,2,3]

[1]*Hefei National Research Center for Physical Sciences at the Microscale and School of Physical Sciences, University of Science and Technology of China, Hefei 230026, China*

[2]*CAS Center for Excellence in Quantum Information and Quantum Physics, University of Science and Technology of China, Hefei 230026, China*

[3]*Hefei National Laboratory, University of Science and Technology of China, Hefei 230088, China*

(Received 20 November 2024; revised 14 May 2025; accepted 26 June 2025; published 3 September 2025)

Recent Literature: Proof-of-concept simulations of 1+1D QED

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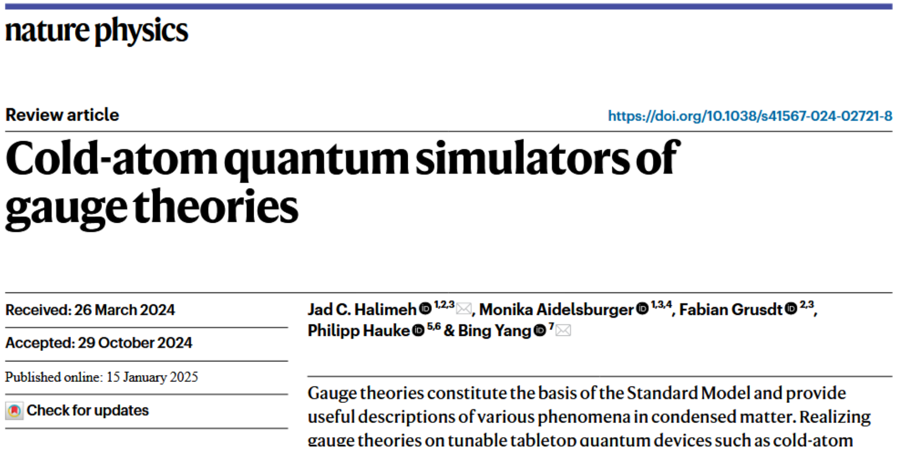

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[1]*Hefei National Research Center for Physical Sciences at the Microscale and School of Physical Sciences, University of Science and Technology of China, Hefei 230026, China*
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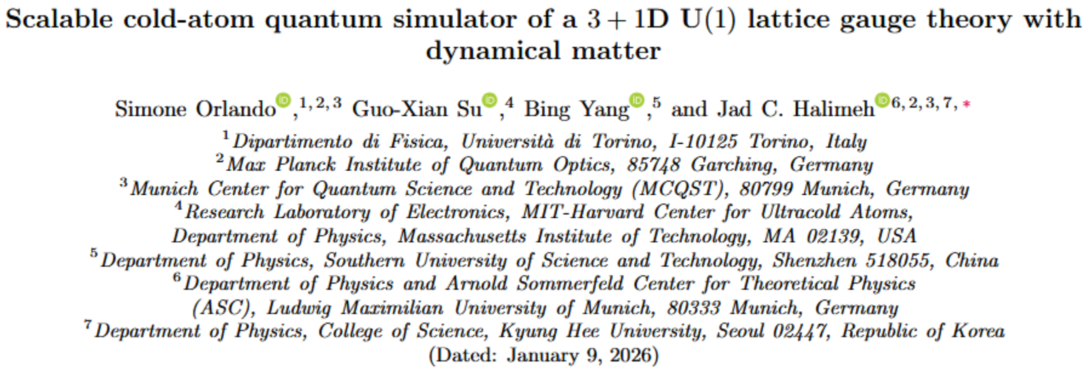
Recent Literature: Proof-of-concept simulations of 1+1D QED

Challenge ➡ Scaling to 2+1D and 3+1D model to simulate QED, Electroweak and QCD problems



Scalable cold-atom quantum simulator of a 3 + 1D U(1) lattice gauge theory with dynamical matter

Simone Orlando,[1,2,3] Guo-Xian Su,[4] Bing Yang,[5] and Jad C. Halimeh[6,2,3,7,*]
[1]*Dipartimento di Fisica, Università di Torino, I-10125 Torino, Italy*
[2]*Max Planck Institute of Quantum Optics, 85748 Garching, Germany*
[3]*Munich Center for Quantum Science and Technology (MCQST), 80799 Munich, Germany*
[4]*Research Laboratory of Electronics, MIT-Harvard Center for Ultracold Atoms, Department of Physics, Massachusetts Institute of Technology, MA 02139, USA*
[5]*Department of Physics, Southern University of Science and Technology, Shenzhen 518055, China*
[6]*Department of Physics and Arnold Sommerfeld Center for Theoretical Physics (ASC), Ludwig Maximilian University of Munich, 80333 Munich, Germany*
[7]*Department of Physics, College of Science, Kyung Hee University, Seoul 02447, Republic of Korea*

(Dated: January 9, 2026)

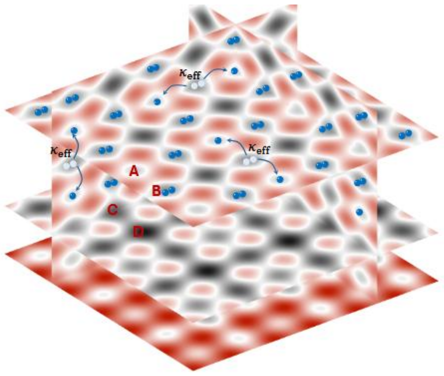
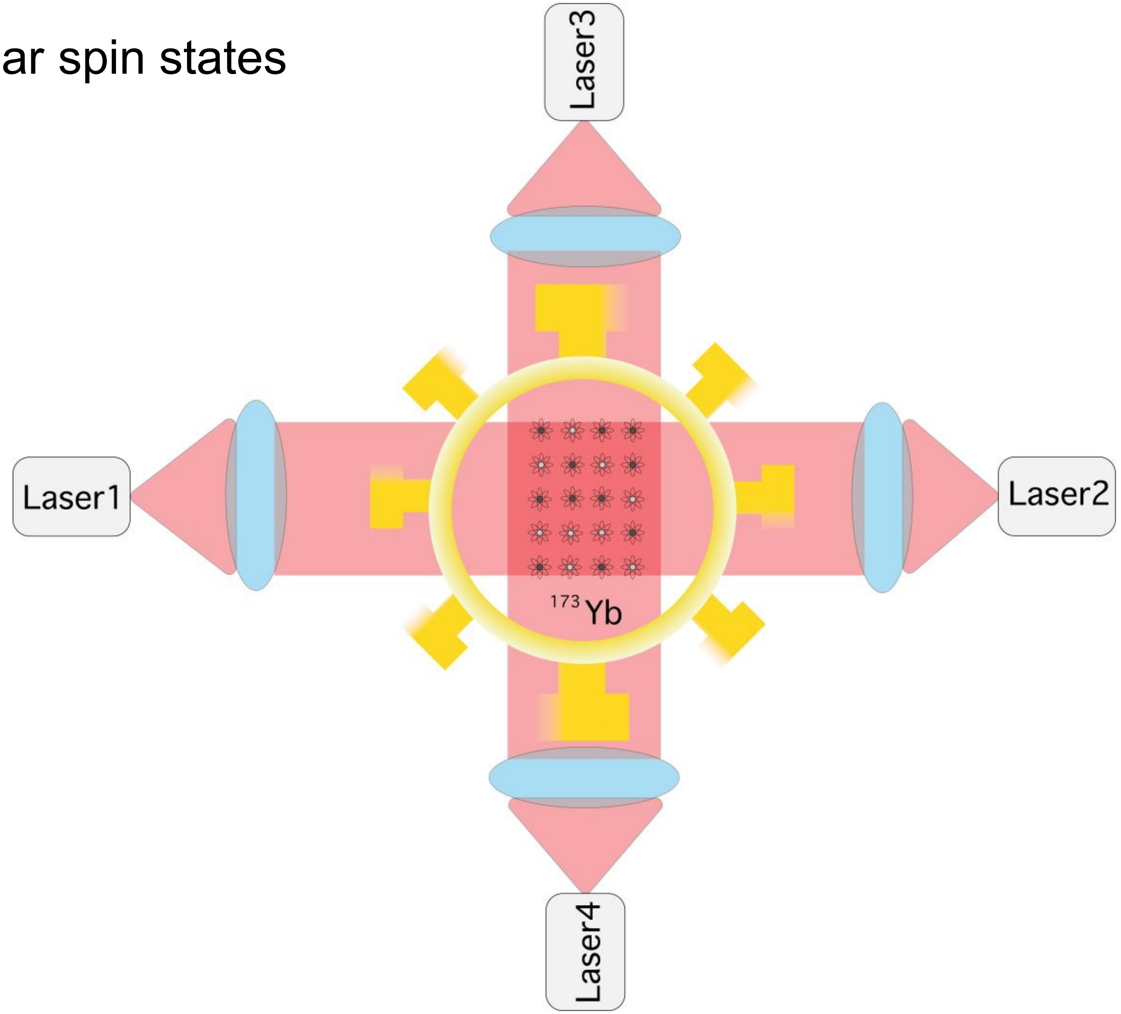


FIG. 2. Illustration of a 3d optical superlattice structure with gauge-invariant hopping along each axis. Atoms are prepared in each layer.

Collaborations: Dr. Raju Venugopalan

THE PROPOSED PLATFORM

- The BNL Advantage: Attack the QCD problem with extensive in-house Nuclear Physics expertise
- Use ^{173}Yb atoms with a nuclear spin $I = 5/2$ ➡ Total 6 nuclear spin states



A subset of system we want to build

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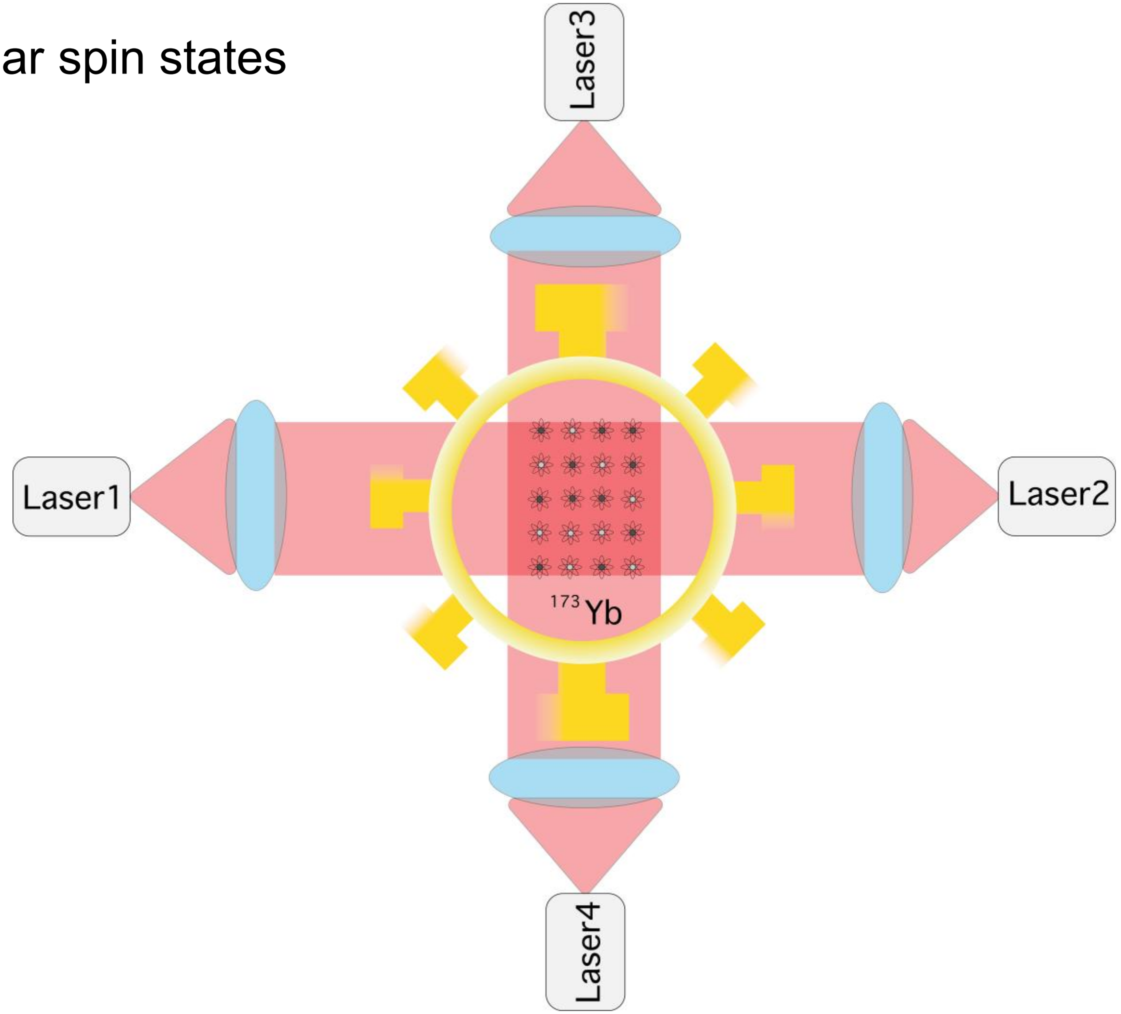
- States $|m_F = -\frac{5}{2}, -\frac{3}{2}, -\frac{1}{2} >$ → Encode Color Charge
- States $|m_F = \frac{1}{2}, \frac{3}{2}, \frac{5}{2} >$ → Gauge links or Gluon Field

1+1D Problems → Proof-of-concept
String formation and breaking

2+1D Problems → Phase Transitions
Transverse Gauge Field Dynamics

3+1D Problems → Full QCD



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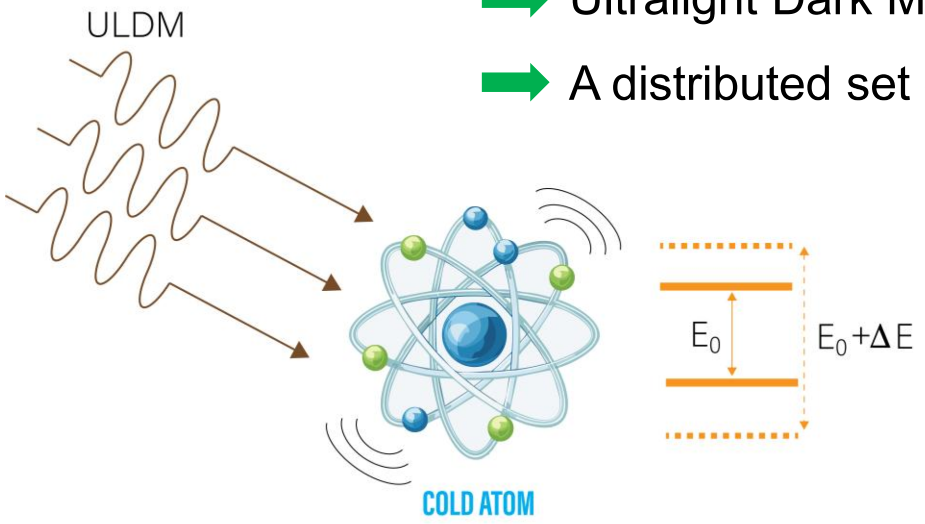
- Ultralight Dark Matter (ULDM): 10^{-12} to 10^{-22} eV
- A distributed set of entangled atomic sensors can improve sensitivity and bandwidth



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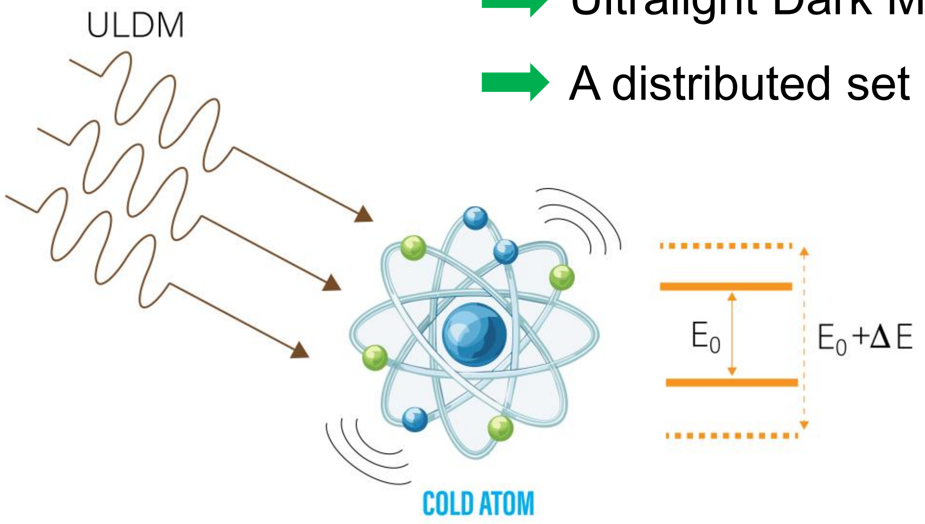
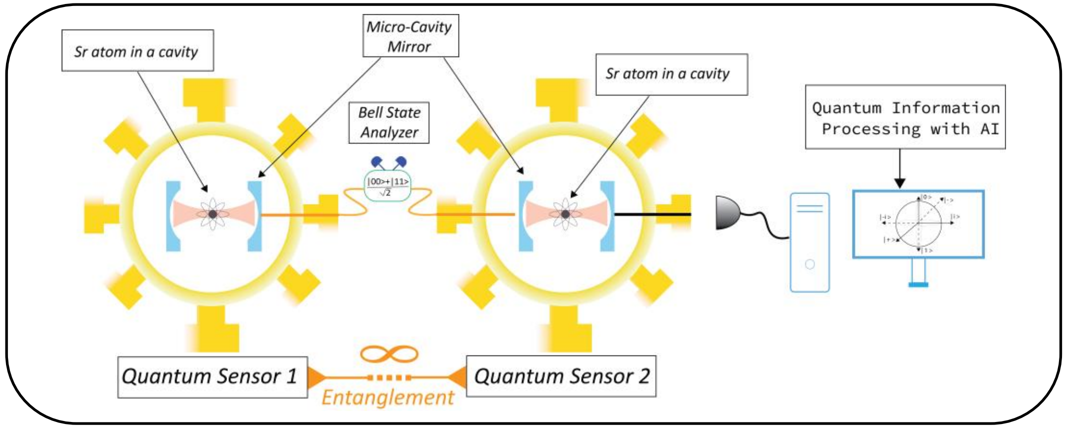
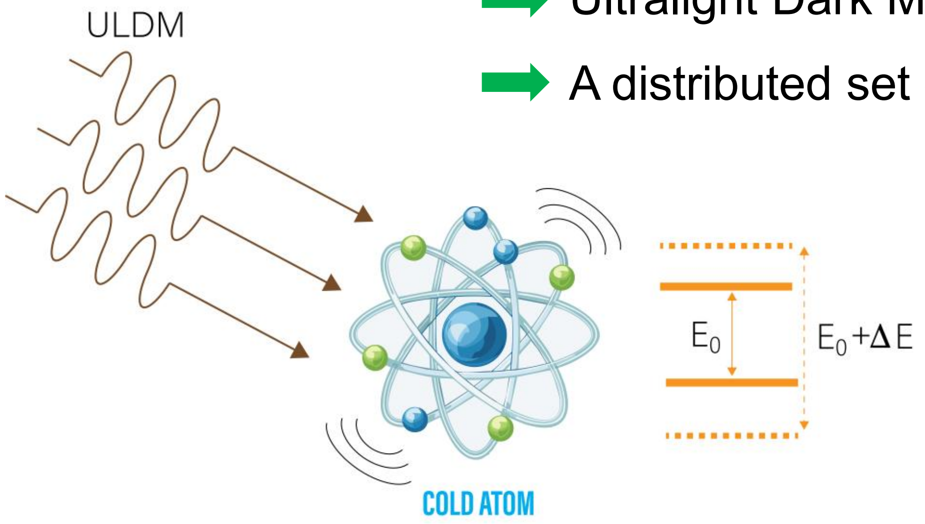
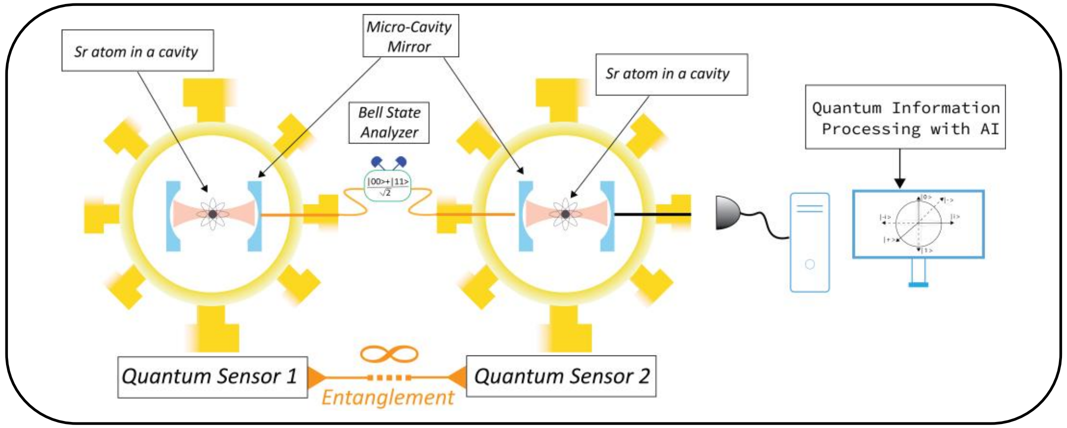


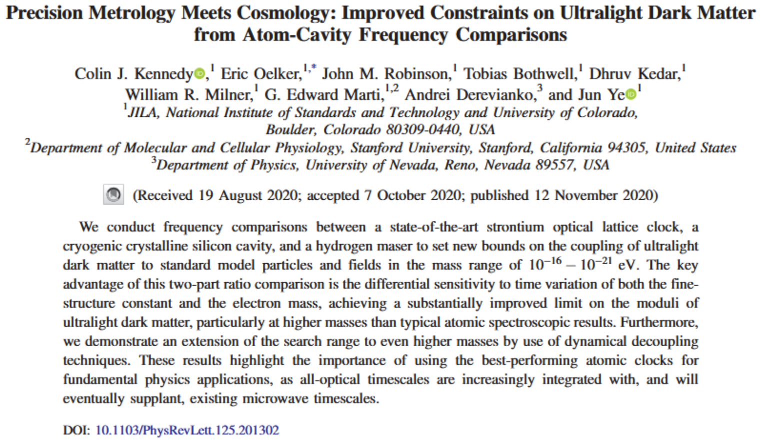


ULTRA LIGHT DARK MATTER SENSING

- Ultralight Dark Matter (ULDM): 10^{-12} to 10^{-22} eV
- A distributed set of entangled atomic sensors can improve sensitivity and bandwidth







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

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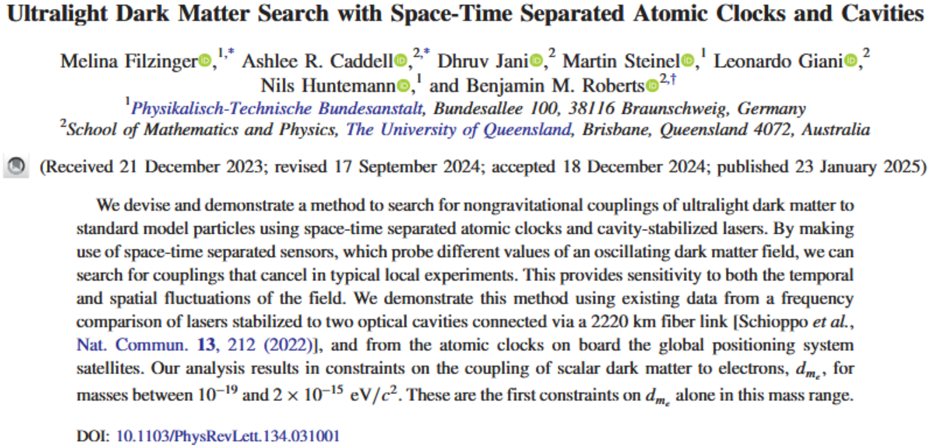
(Received 19 August 2020; accepted 7 October 2020; published 12 November 2020)

We conduct frequency comparisons between a state-of-the-art strontium optical lattice clock, a cryogenic crystalline silicon cavity, and a hydrogen maser to set new bounds on the coupling of ultralight dark matter to standard model particles and fields in the mass range of $10^{-16} - 10^{-21}$ eV. The key advantage of this two-part ratio comparison is the differential sensitivity to time variation of both the fine-structure constant and the electron mass, achieving a substantially improved limit on the moduli of ultralight dark matter, particularly at higher masses than typical atomic spectroscopic results. Furthermore, we demonstrate an extension of the search range to even higher masses by use of dynamical decoupling techniques. These results highlight the importance of using the best-performing atomic clocks for fundamental physics applications, as all-optical timescales are increasingly integrated with, and will eventually supplant, existing microwave timescales.

DOI: 10.1103/PhysRevLett.125.201302



Ultralight Dark Matter Search with Space-Time Separated Atomic Clocks and Cavities

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Nils Huntemann,[1] and Benjamin M. Roberts[2,†]
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(Received 21 December 2023; revised 17 September 2024; accepted 18 December 2024; published 23 January 2025)

We devise and demonstrate a method to search for nongravitational couplings of ultralight dark matter to standard model particles using space-time separated atomic clocks and cavity-stabilized lasers. By making use of space-time separated sensors, which probe different values of an oscillating dark matter field, we can search for couplings that cancel in typical local experiments. This provides sensitivity to both the temporal and spatial fluctuations of the field. We demonstrate this method using existing data from a frequency comparison of lasers stabilized to two optical cavities connected via a 2220 km fiber link [Schioppo *et al.*, Nat. Commun. **13**, 212 (2022)], and from the atomic clocks on board the global positioning system satellites. Our analysis results in constraints on the coupling of scalar dark matter to electrons, d_{m_e}, for masses between 10^{-19} and 2×10^{-15} eV$/c^2$. These are the first constraints on d_{m_e} alone in this mass range.

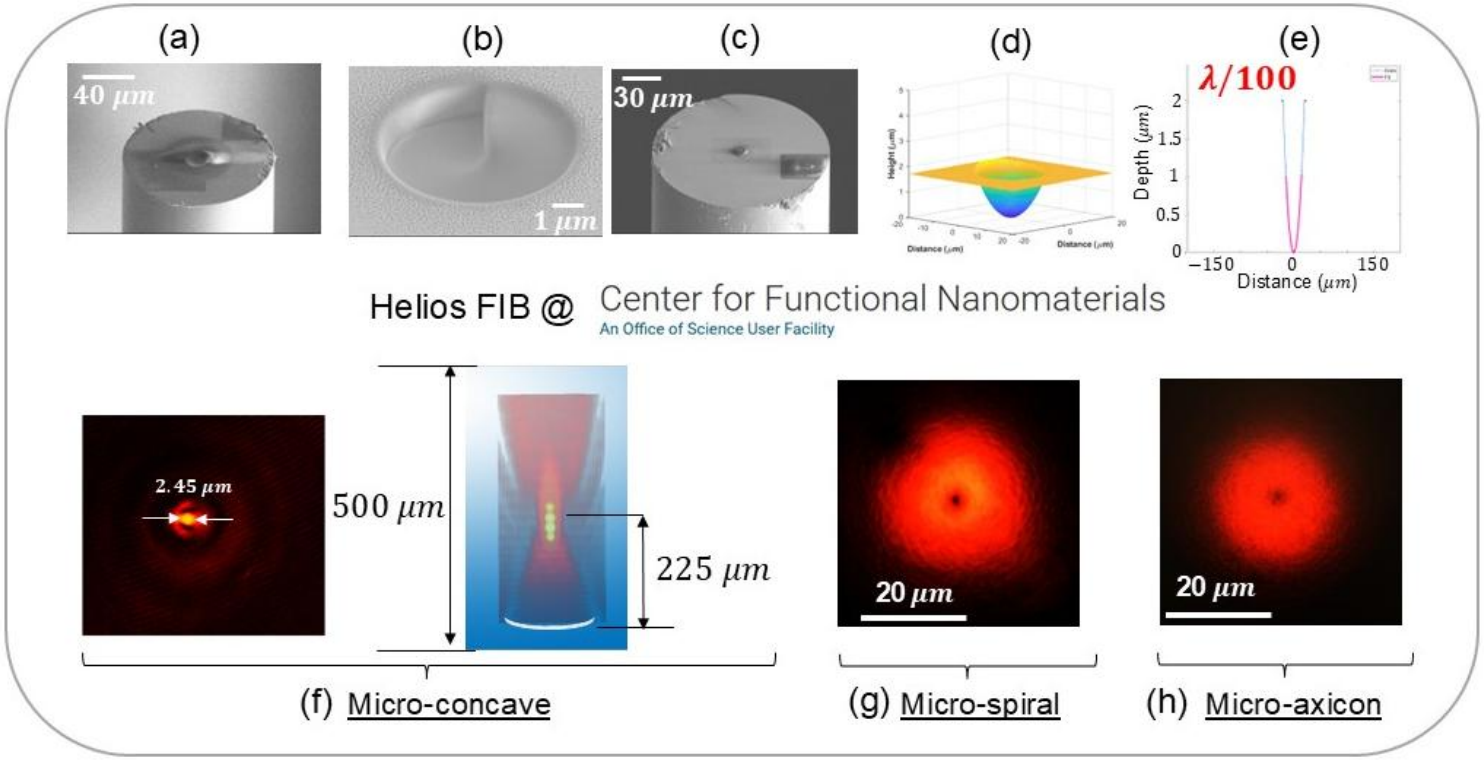
DOI: 10.1103/PhysRevLett.134.031001

Recent Literature

Collaborations: Dr. Lam Hui, Dr. Hooman Davoudiasl

OUR LAB SPACE AND RESULTS SO FAR

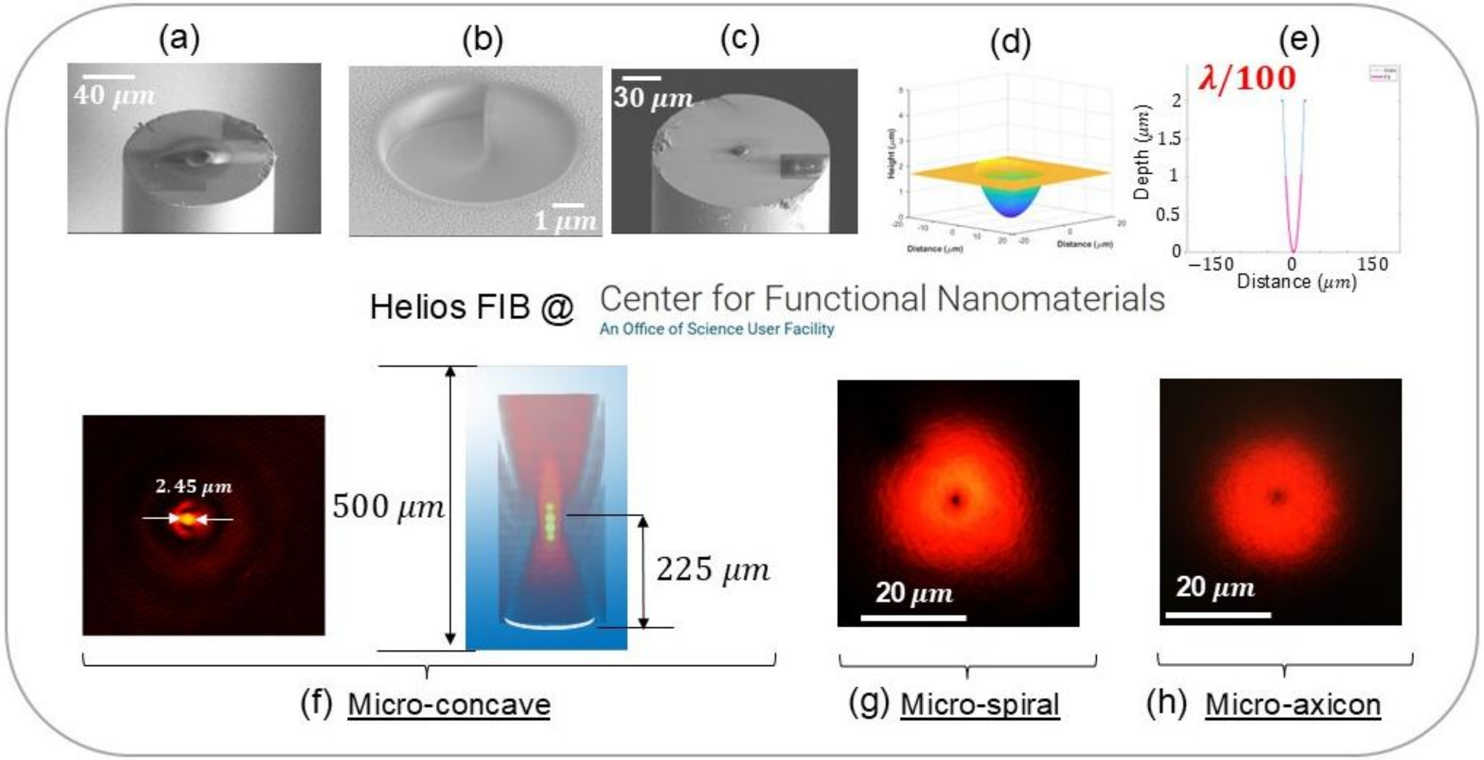
A141, Bldg. 535



Preliminary Results (Earlier LDRD grant)

OUR LAB SPACE AND RESULTS SO FAR

A141, Bldg. 535



Preliminary Results (Earlier LDRD grant)

WHY BNL?
- ➡ Aligns well with ‘Understanding the Basic Building Blocks of the Universe’
- ➡ Extensive Facilities: IO, CFN, Physics, and CAD
- ➡ Extensive expertise in nuclear and high-energy physics

FUNDING TABLE

	Item	**Cost (Including Burden and Overhead)**	
FY27	Labor (PI+Postdoc)	$250K	$600K
	UHV System and Accessories	$50K	
	Cooling Lasers (399 nm and 556 nm)	$250K	
	Misc Materials and Supplies	$50K	
FY28	Labor (PI+Postdoc)	$250K	$450K
	Low Noise Camera	$80K	
	Wavemeter	$70K	
	Misc Optics and Electronics	$50K	
FY29	Labor (PI+Postdoc)	$250K	$450K
	Trapping and Cavity Lasers	$100K	
	Misc Optics and Electronics	$100K	

Other Ideas → Spin polarization measurements of relativistic electron bunch