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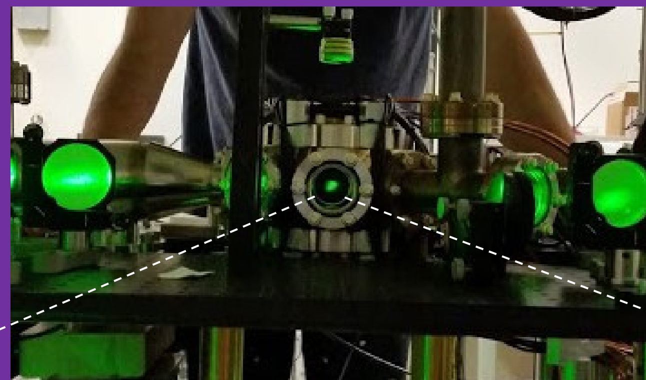
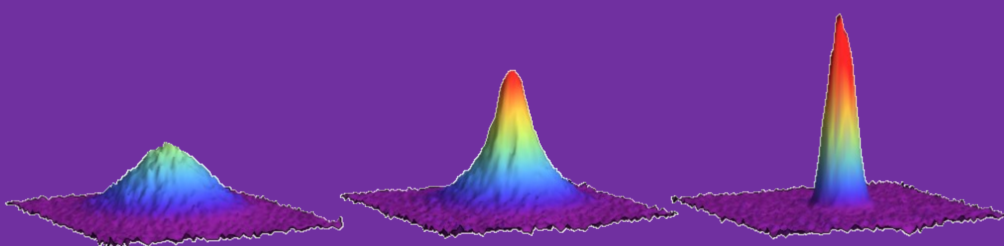
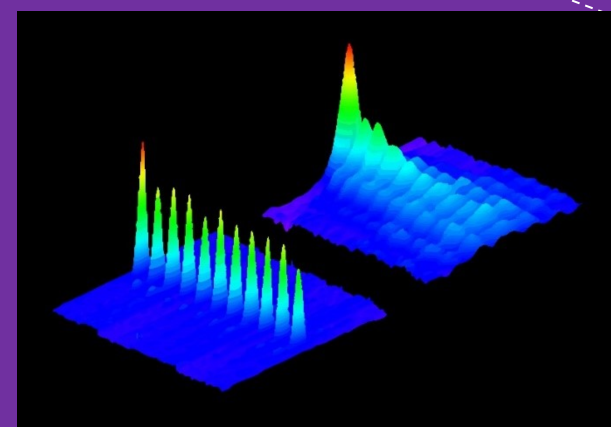
NanoKelvin Quantum Matters: Coherence, Correlations, Chaos.



some cold atoms

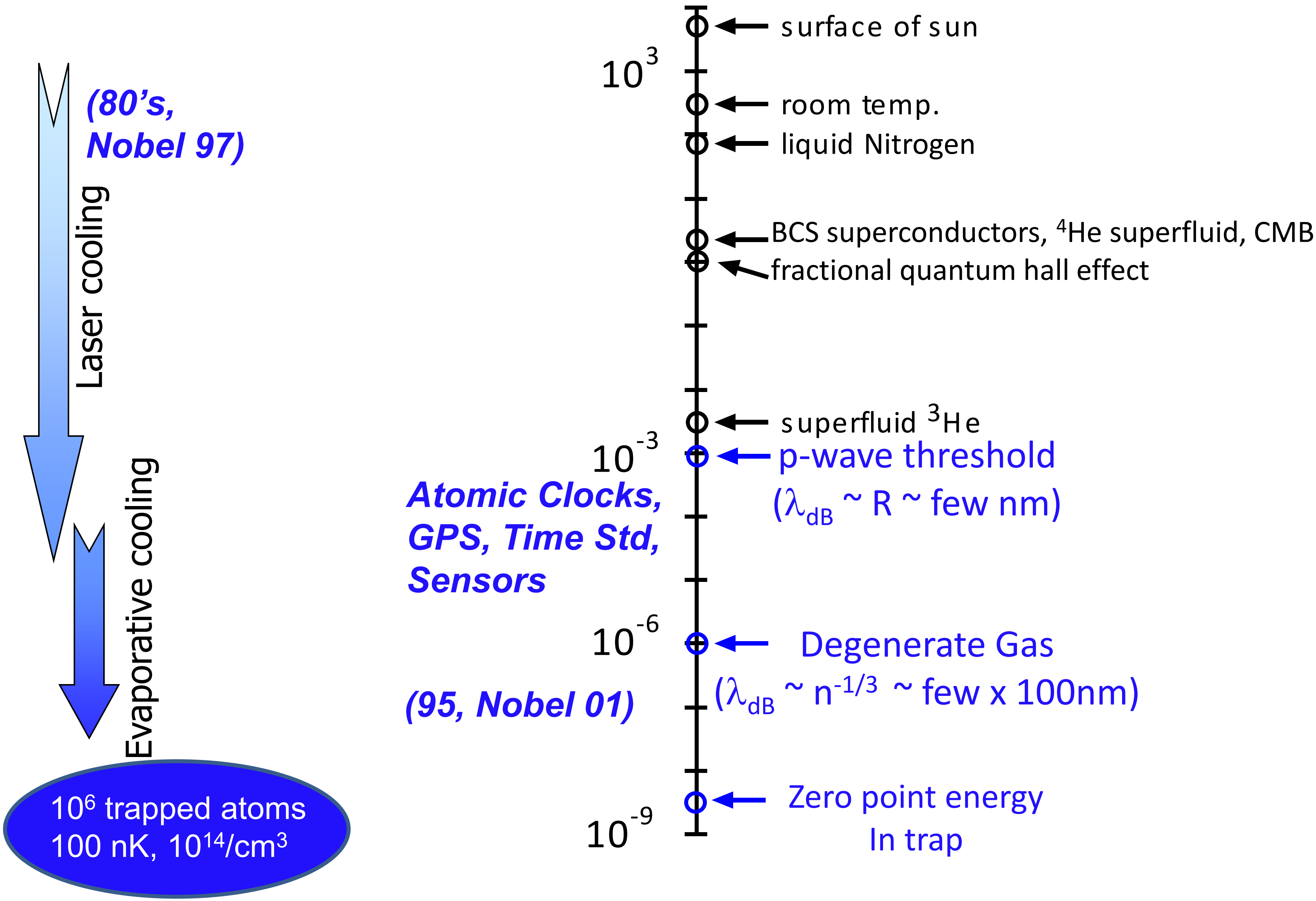




Subhadeep Gupta

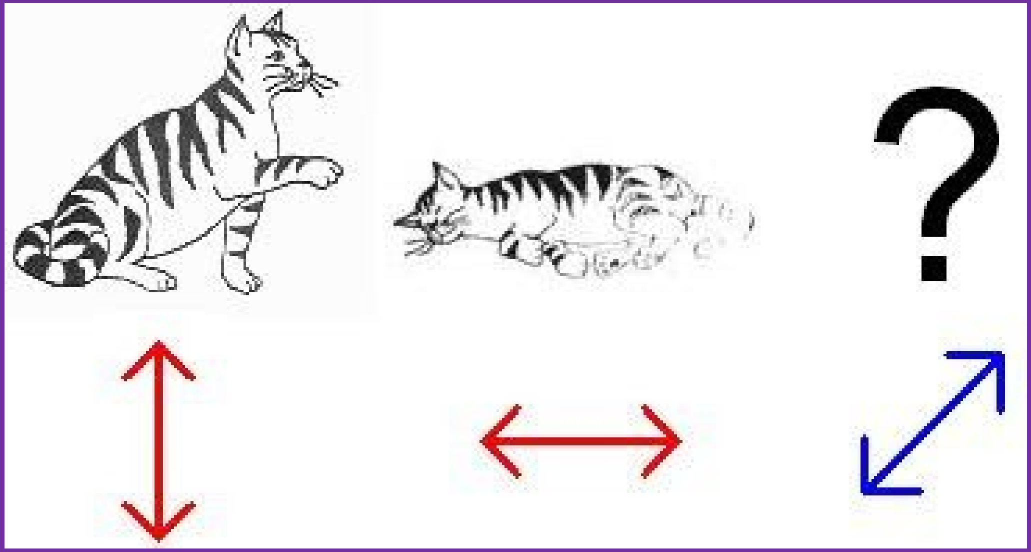
UW NSF Phys REU, 29th July 2024

Relevant Ultracold Temperatures on the Log Kelvin Scale



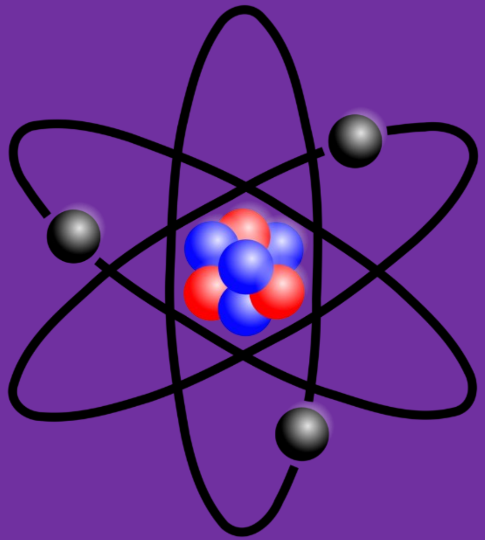
Quantum: Philosophical Questions
Precise Calculations

A century's worth of Technical Advances



Quantum: Tools (expt. and theor. harnessing) for Quantum metrology, sensing, simulation, computing.

Atom: Motivation and Test-bed for quantum mechanical ideas.



A century's worth of Technical Advances

Basic Research
(Curiosity/Measurement)
Driven Pursuits

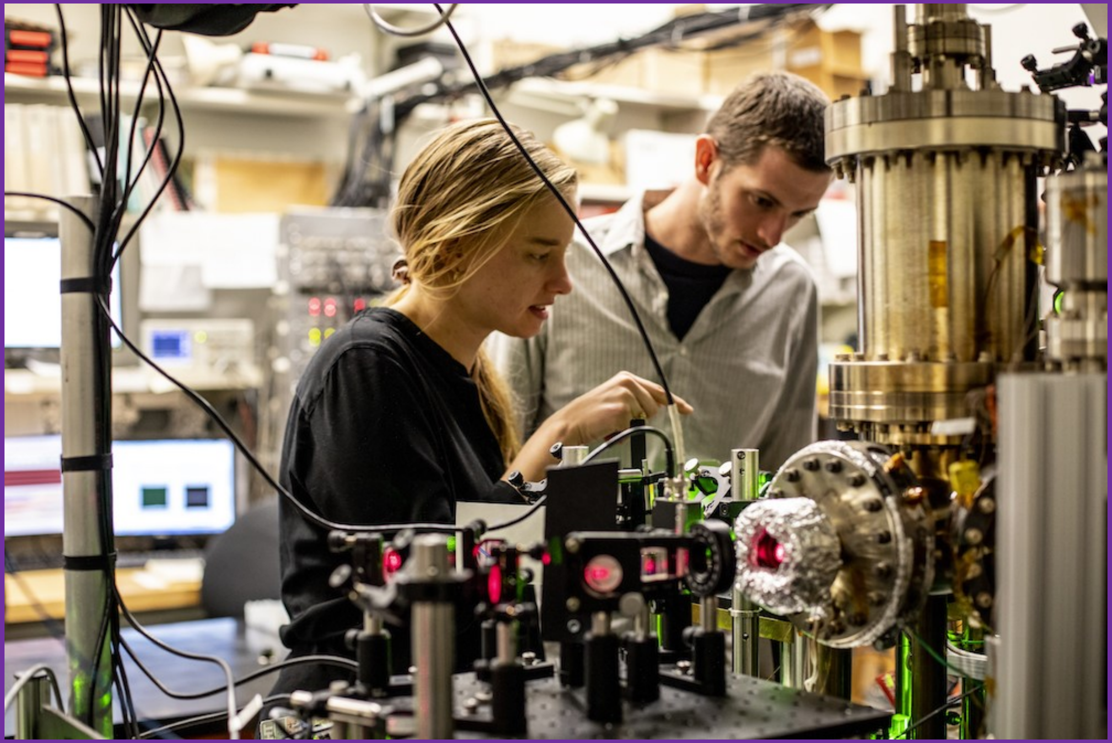
Technological Advances
(eg. Laser, Atomic Clock)

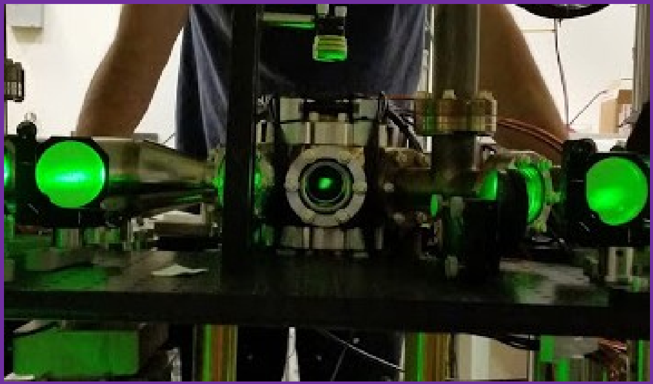
Atom(s): Pristine Quantum System(s) precisely manipulable with EM fields.

Interfacing with condensed matter, nuclear physics, particle physics.

Helping advance quantum technologies and the second quantum revolution.

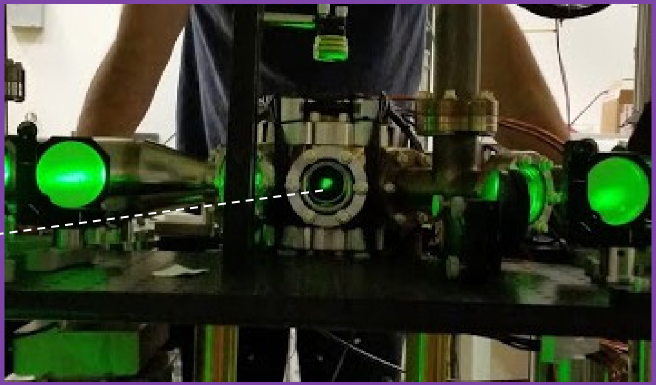
Taming and Controlling Atoms





- Experimental table-top physics. Work in few-member teams.
- Lasers, Electronics, Ultra-high vacuum.
- Direct Manipulation and Observation of Clean Quantum Systems
- Fundamental physics. Future quantum technologies.

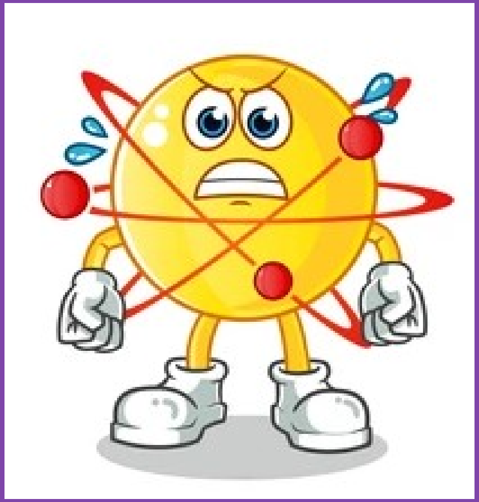
Taming/Training Atoms:



10^8 trapped
Yb atoms
at 50 μK

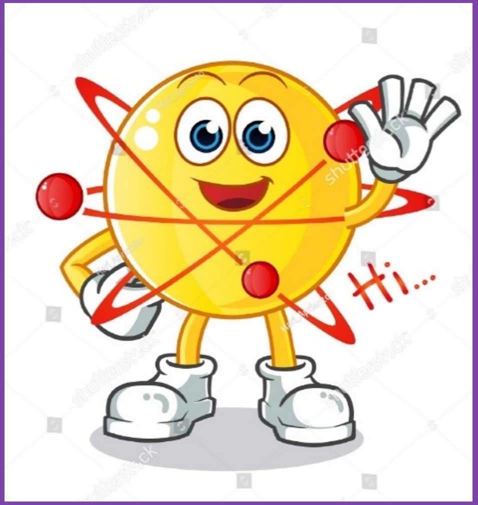
First remove the freedoms
Then re-introduce in a
controlled way

Random motion ⇔ Temperature



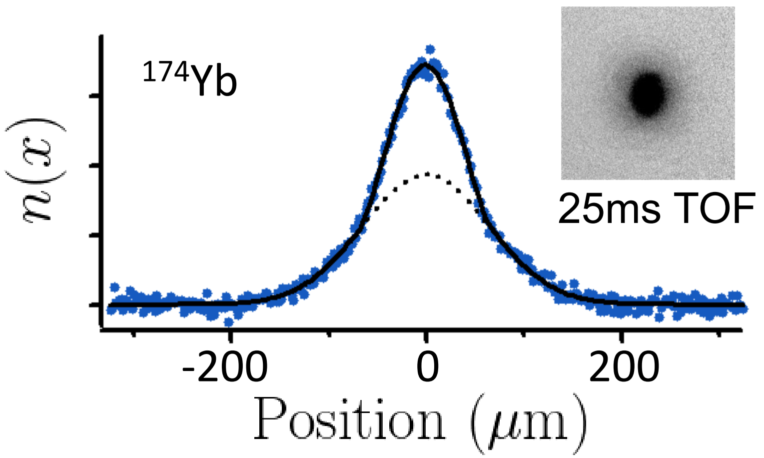
50yrs: bound electron(s) motion

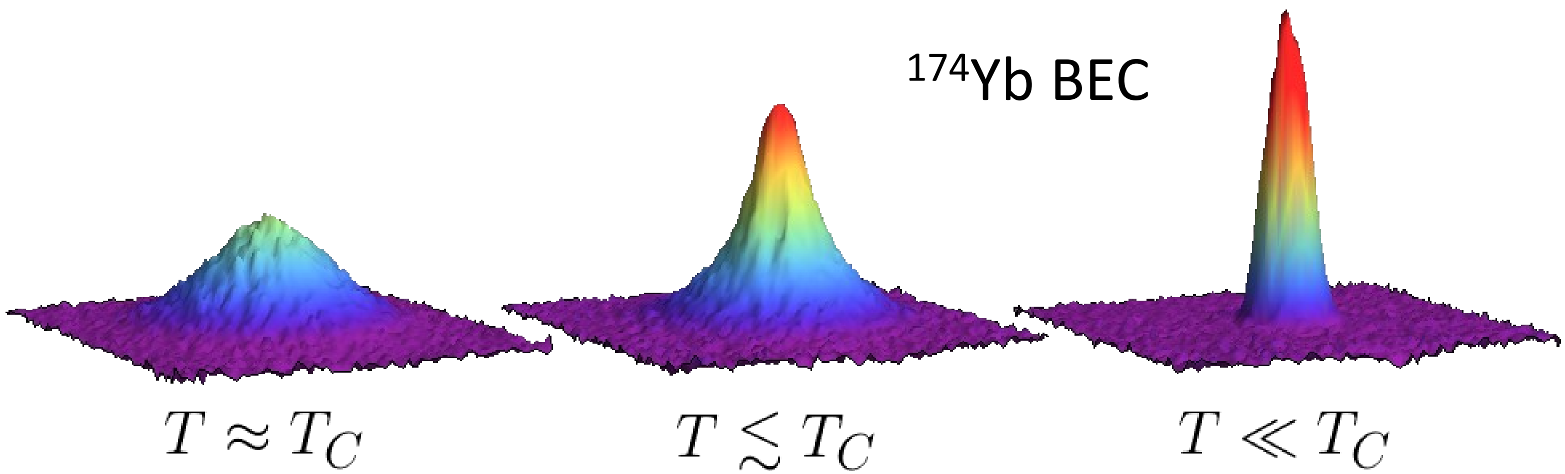
50yrs: atom c.o.m. motion



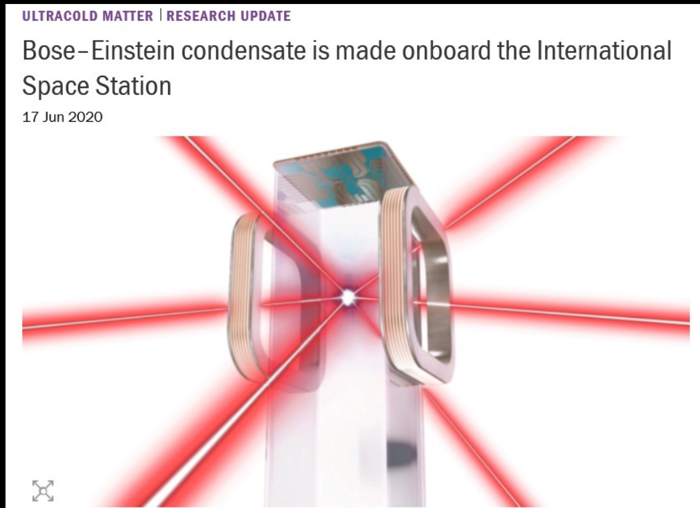
Boson degeneracy: Bose-Einstein condensate

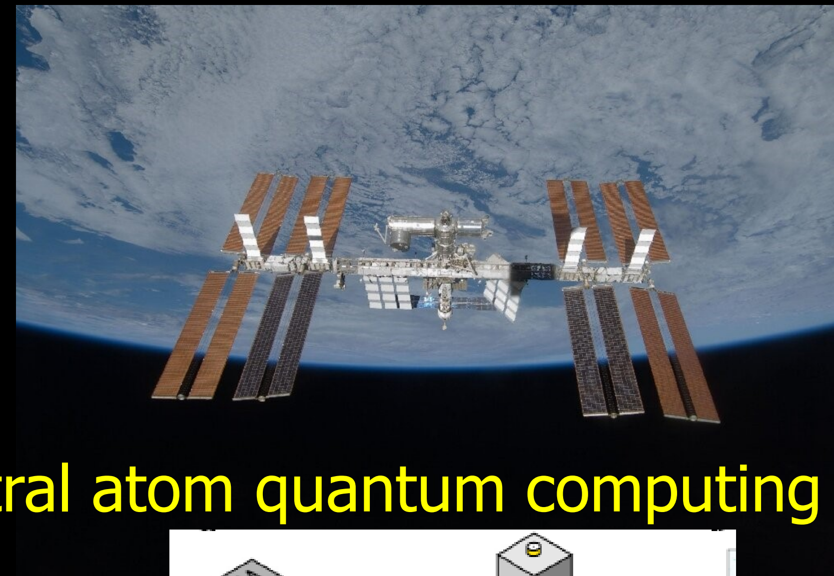
$$n(\vec{r}) = n_{\mathrm{BEC}}(\vec{r}) + n_{\mathrm{th}}(\vec{r})$$



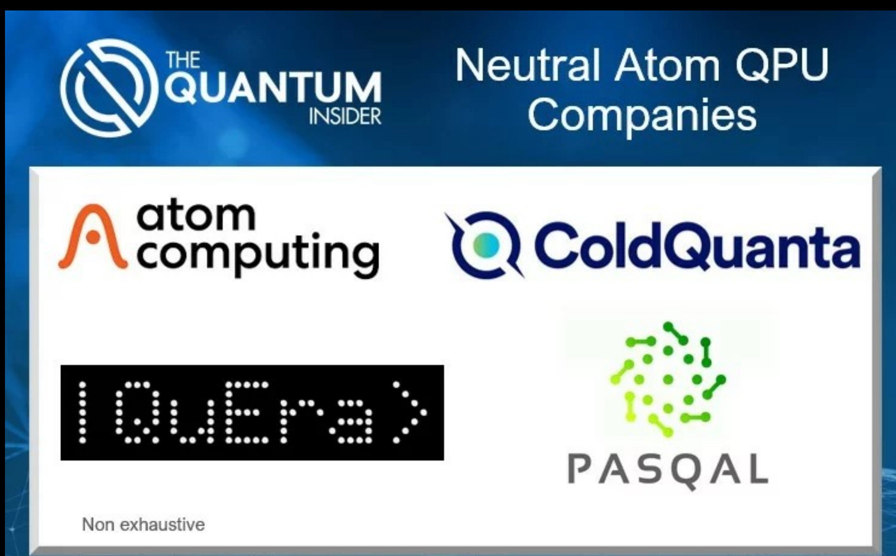


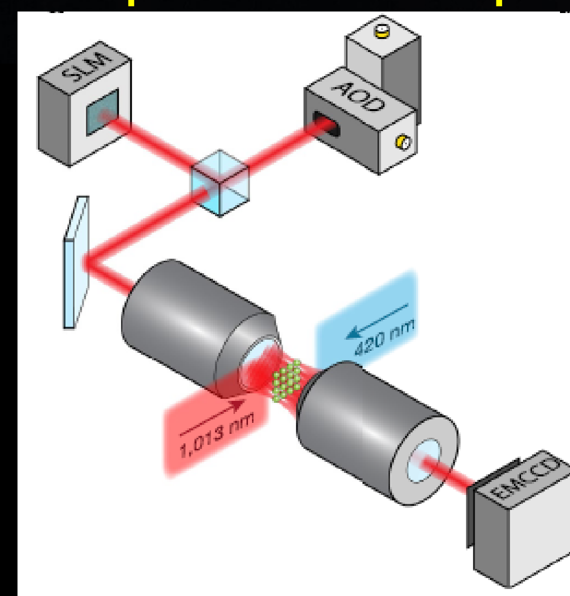
2020's – BECs in space, for fundamental physics (NASA)





2020's – companies pursuing neutral atom quantum computing

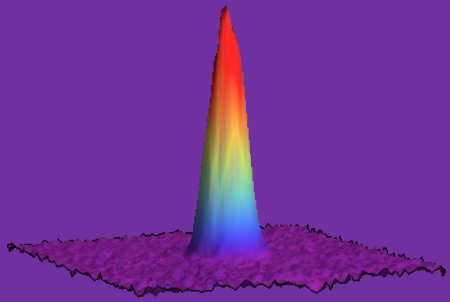




Sparked by basic research in small teams in various research labs around the world

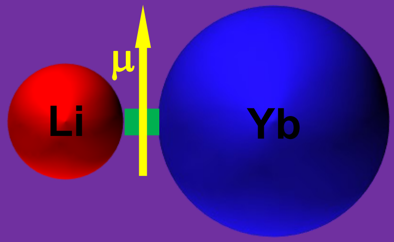
Ultracold Atoms and Quantum Gases @UW

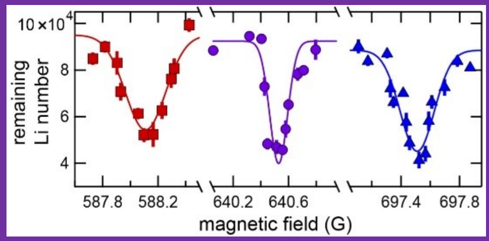
Superfluids



Atomic superfluids of bosons and fermions
Mixed superfluids, collective properties, dynamics

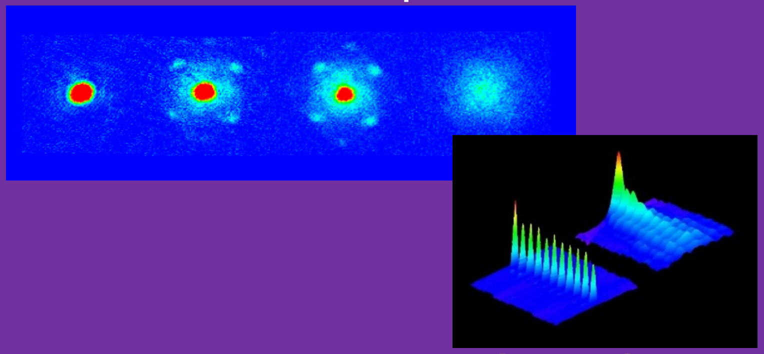
Few-body quantum science





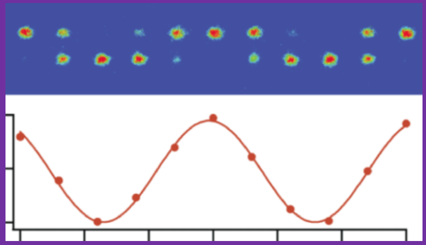
Ultracold few-body physics, chemistry.
Towards New **qubits** with strong long-range interactions

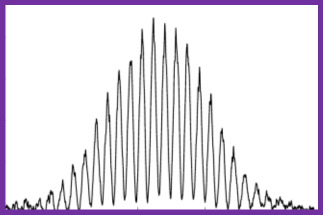
Ultracold Atoms in Optical Lattices



Tunable systems for **quantum simulations** that are challenging to calculate.
Quantum dynamics in lattices, transport
Out-of-equilibrium phenomena
Quantum Information Systems

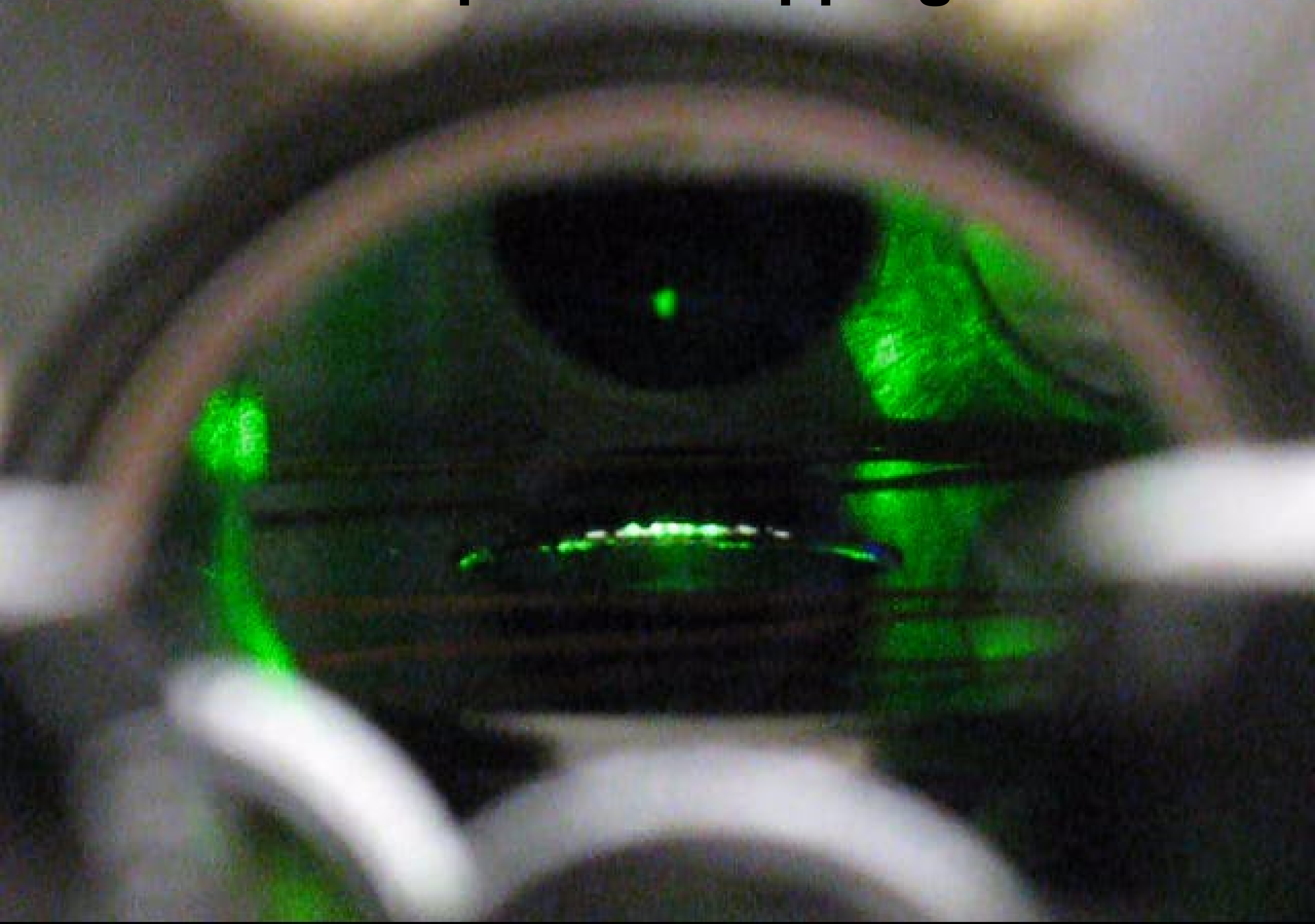
Atom Optics and Interferometry



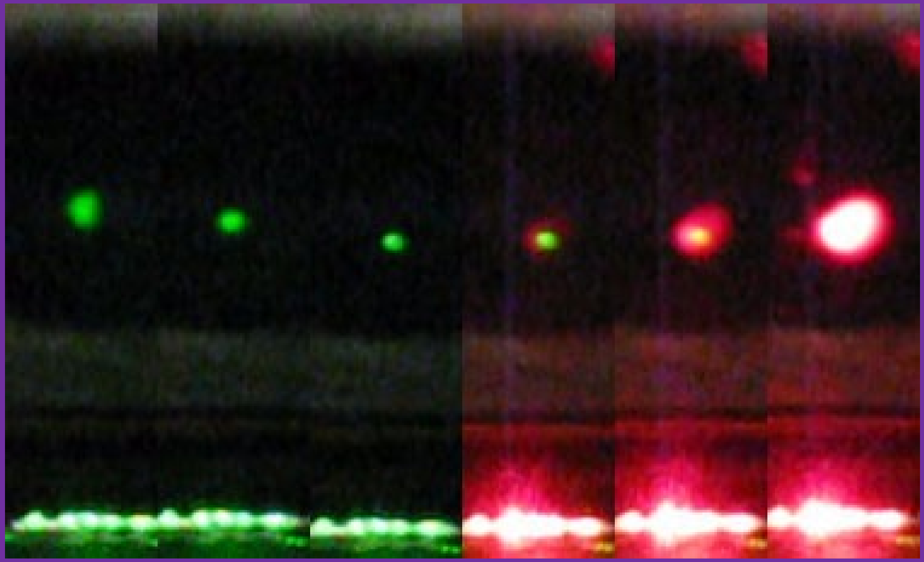


Pulsed optical lattices as diffraction gratings
Atom interferometric sensors for fundamental physics and **quantum sensing**.
Trapped Atom Interferometry
Towards squeezed/entangled states for sensing.

2-Species Trapping



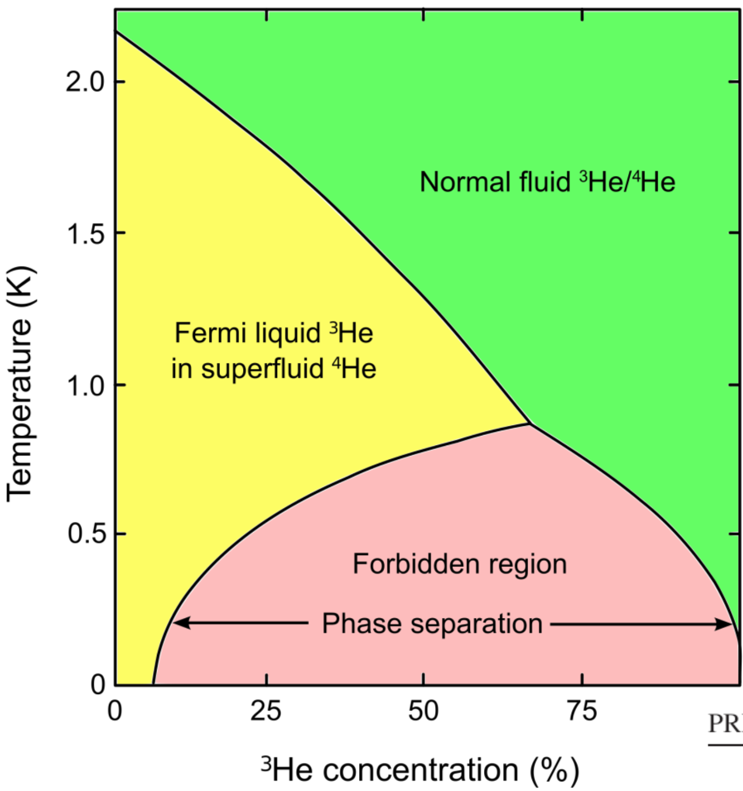
2-Species Trapping



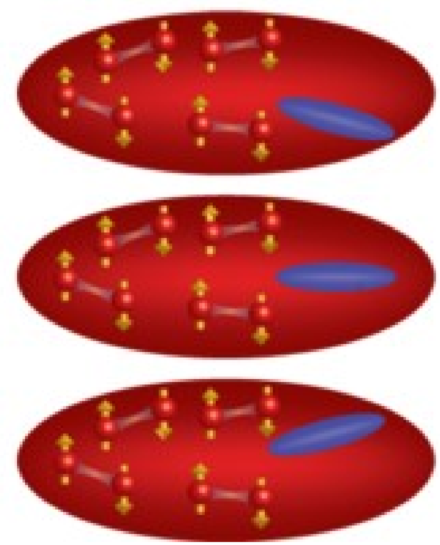
Time

Bose-Fermi Double Superfluid

^4He-^3He mixtures.
Strong B-F repulsion.
B-F superfluid not yet realized



Recently B-F superfluids in atomic systems in ^7Li-^6Li, ^{174}Yb-^6Li, ^{41}K-^6Li
NEW QUANTUM SYSTEM!

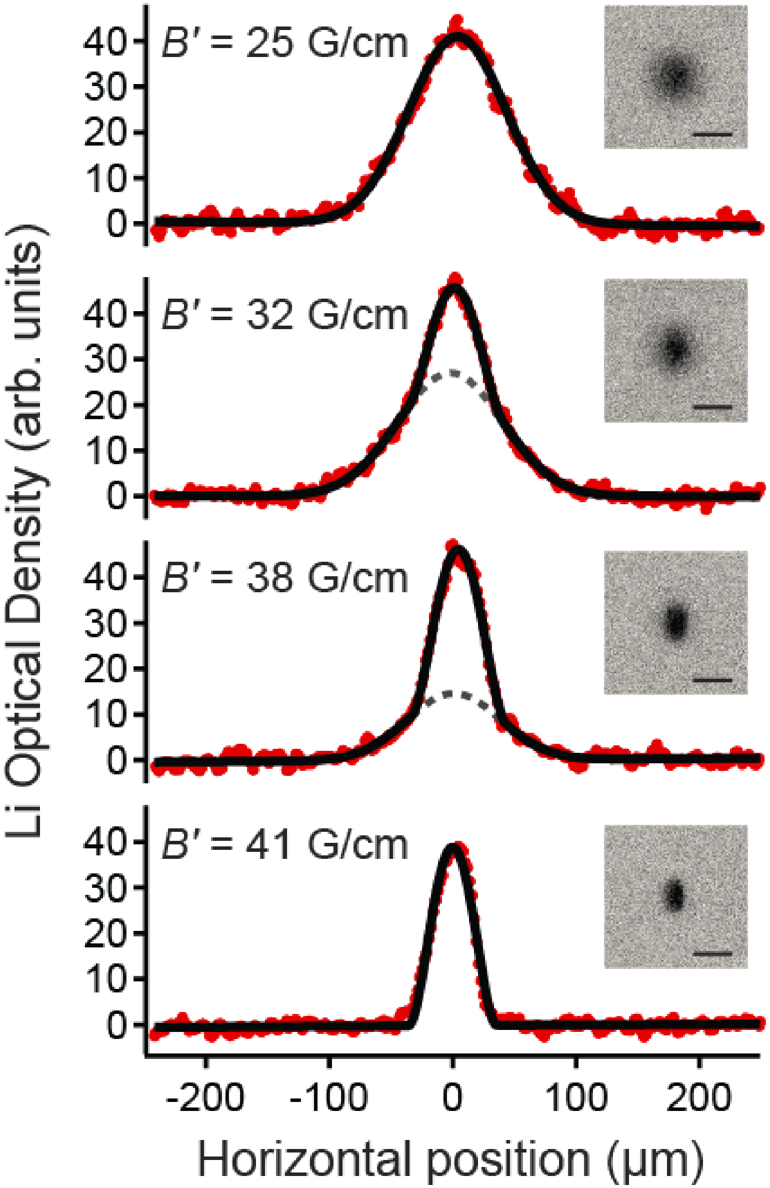


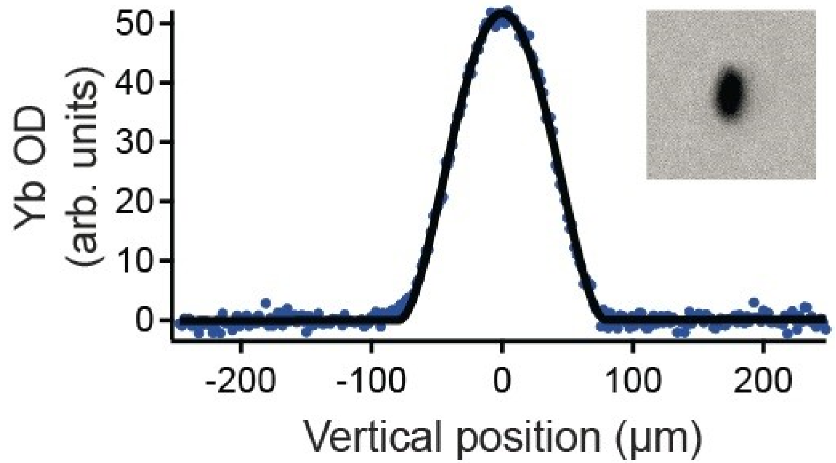
PRL **118,** 055301 (2017) PHYSICAL REVIEW LETTERS we
3 FEB

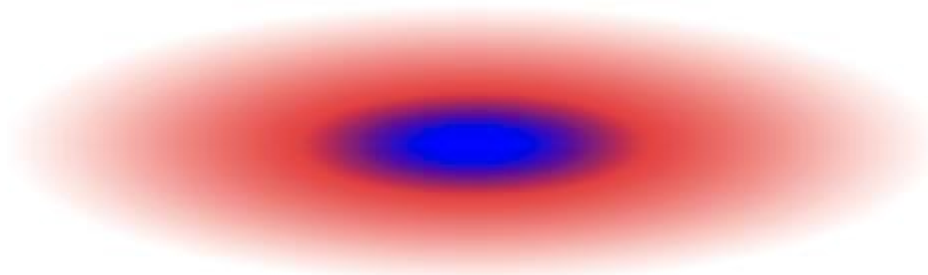
Two-Element Mixture of Bose and Fermi Superfluids

Richard Roy, Alaina Green, Ryan Bowler, and Subhadeep Gupta
Department of Physics, University of Washington, Seattle, Washington 98195, USA
(Received 11 July 2016; revised manuscript received 4 November 2016; published 2 February 2017)

^{174}Yb-^{6}Li Bose-Fermi Dual-Superfluid



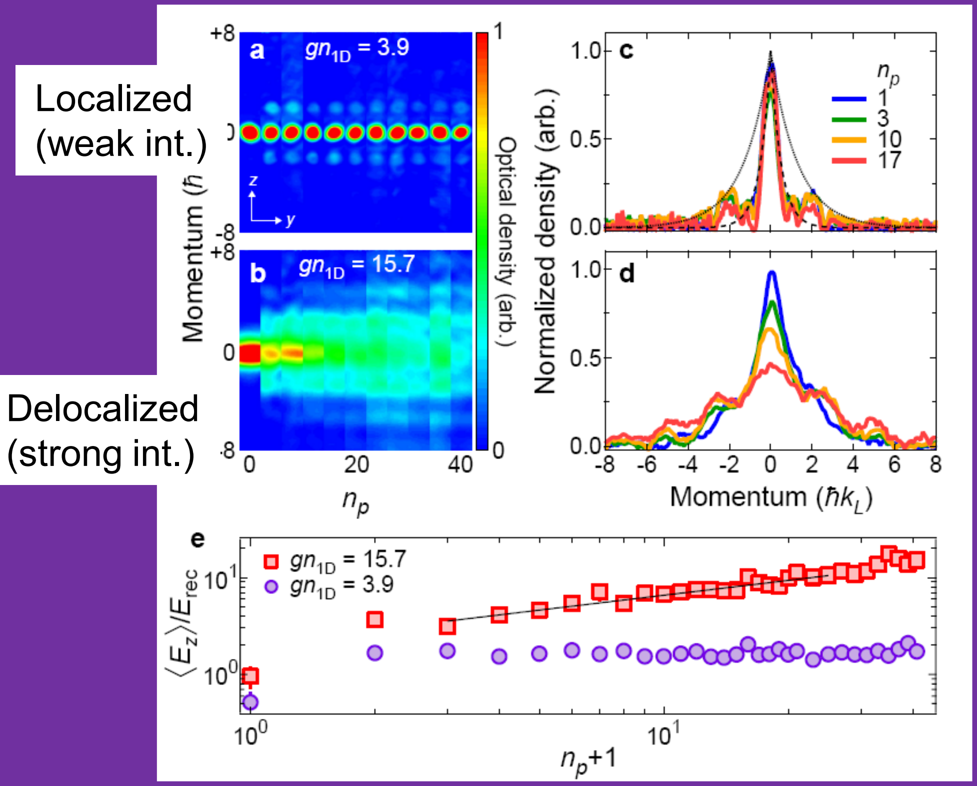




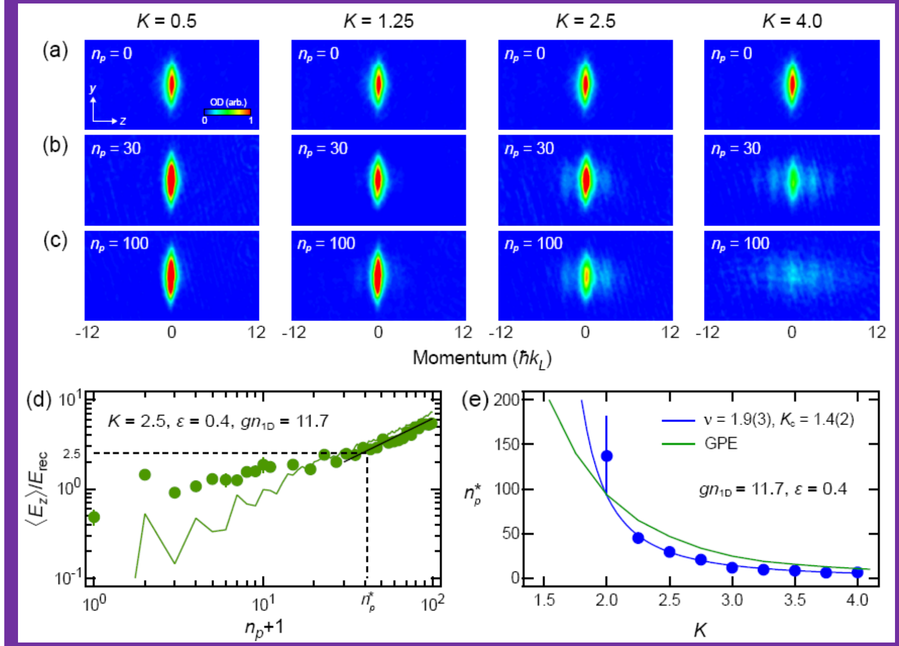
R.J. Roy et al. Phys Rev Lett **118**, 055301 (2017)

Quantum Evolution in presence of interactions
(Many-body effects on Quantum Transport)

Studied by Initialization, Manipulation (Hamiltonian-engineering) and Detection of ultracold (1μK) and trapped atoms using lasers



Time →

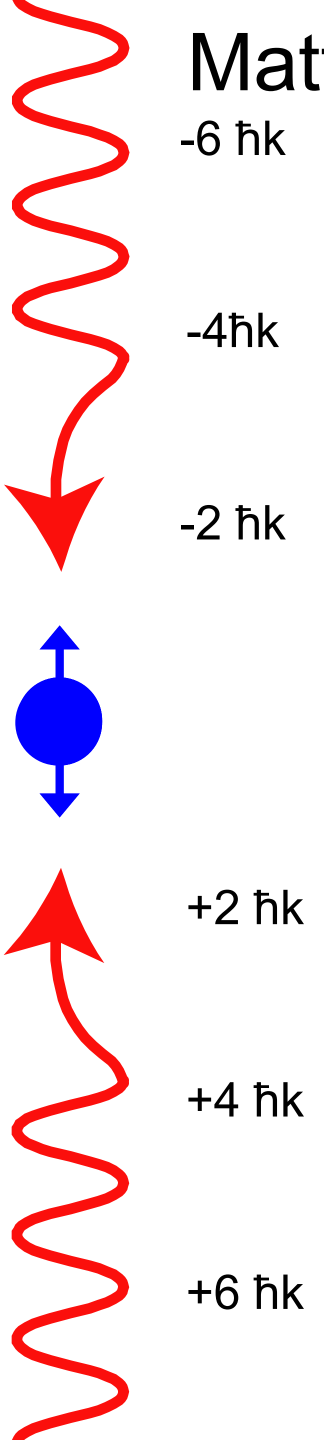


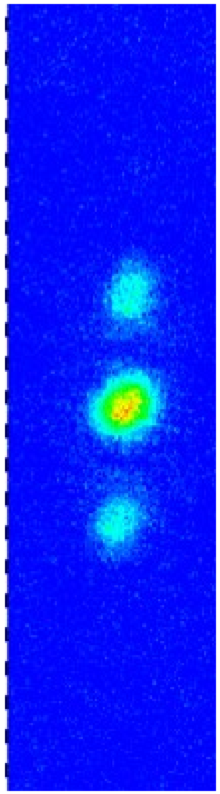
Interaction effects on Anderson Metal-Insulator transition

Jun Hui See Toh et al. Nature Physics 18, 1297 (2022)

Jun Hui See Toh et al. Phys. Rev. Lett (2024), *in press*

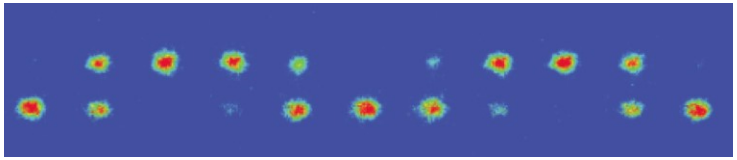
Matter Wave Diffraction off an Optical Crystal





Narrow Momentum width
<< 2 photon momentum

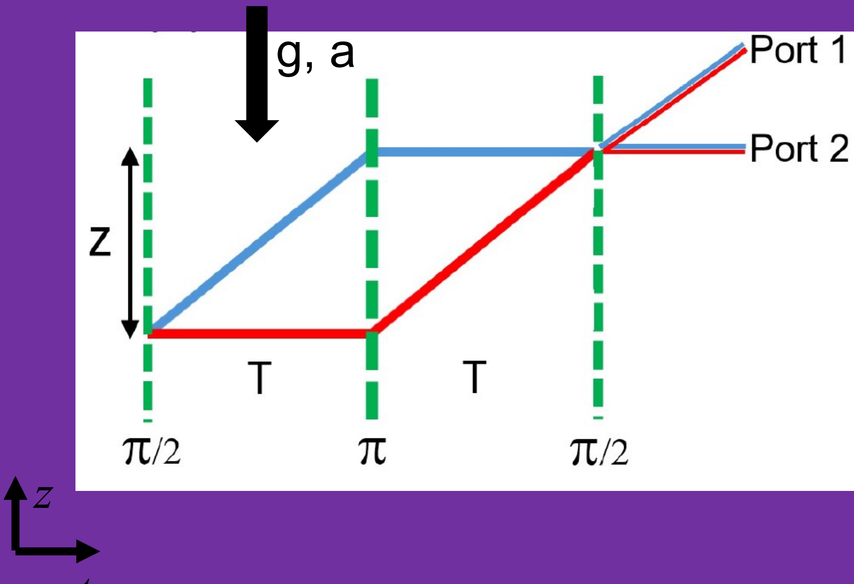
Diffraction from longer standing wave pulse with frequency difference

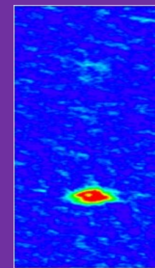


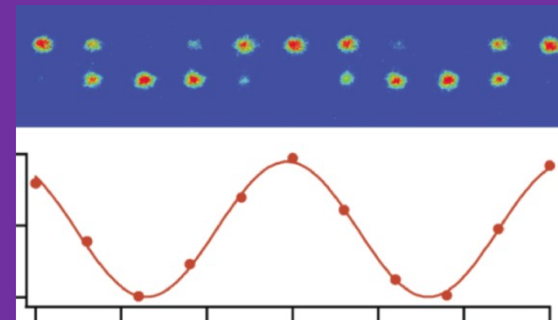
Increasing intensity of pulse →

Pulsed Standing Wave
Optical Dipole Potentials

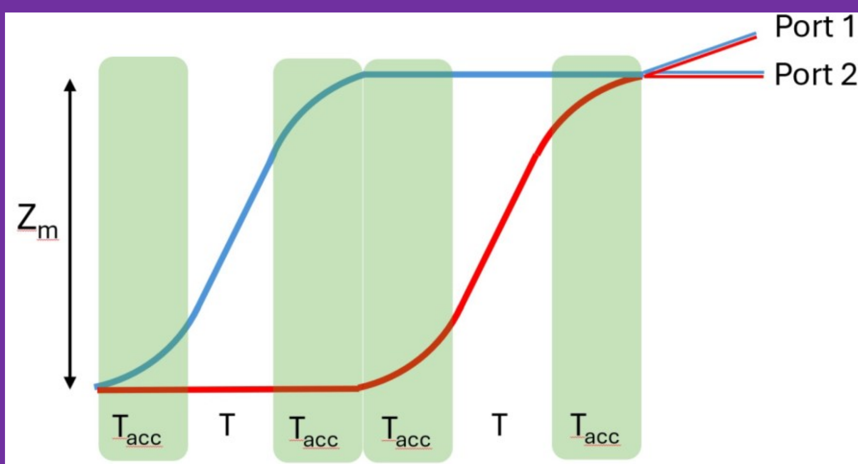
Atom Interferometric Quantum Sensors







Force sensing:
accelerometry
gravity (g, G)



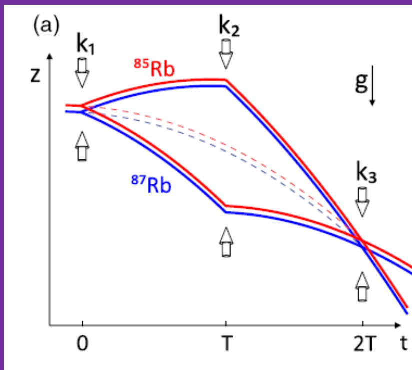
Coherently increase area (T, p)
→ increase sensitivity

eg.
$\Phi_1 - \Phi_2 \sim mgX^*T \sim gk^*T^2$

$\sim$ space-time area

Fundamental Tests:
Equivalence Principle
QED test

Large Area ATOM INTERFEROMETRY



PHYSICAL REVIEW LETTERS **125,** 191101 (2020)

Atom-Interferometric Test of the Equivalence Principle at the 10^{-12} Level

Peter Asenbaum,* Chris Overstreet,* Minjeong Kim, Joseph Curti, and Mark A. Kasevich†
Department of Physics, Stanford University, Stanford, California 94305, USA

Test of QED by light pulse Atom Interferometry: Determination of the Fine-structure constant at 81 parts per trillion,
L. Morel, et al Nature **588**, 61, Dec 2020

PHYSICAL REVIEW LETTERS **121,** 133201 (2018)

Three-Path Atom Interferometry with Large Momentum Separation

Benjamin Plotkin-Swing,* Daniel Gochnauer, Katherine E. McAlpine, Eric S. Cooper, Alan O. Jamison,† and Subhadeep Gupta
Department of Physics, University of Washington, Seattle, Washington 98195, USA

PHYSICAL REVIEW A **101**, 023614 (2020)

Editors' Suggestion

Excited-band Bloch oscillations for precision atom interferometry

Katherine E. McAlpine, Daniel Gochnauer, and Subhadeep Gupta
Department of Physics, University of Washington, Seattle, Washington 98195, USA

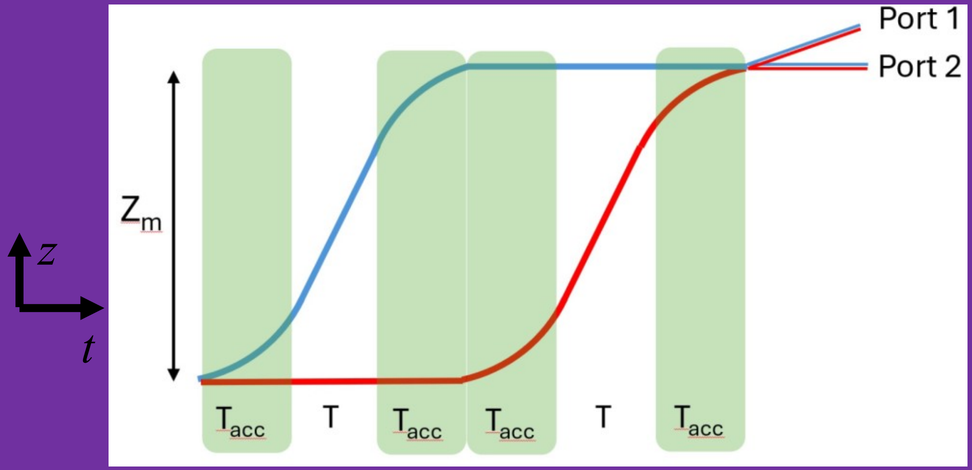
PHYSICAL REVIEW RESEARCH **6**, L022012 (2024)

Letter

Bloch oscillation phases investigated by multipath Stückelberg atom interferometry

Tahiyat Rahman,[1] Anna Wirth-Singh,[1] Andrew Ivanov,[2] Daniel Gochnauer,[1] Emmett Hough,[1] and Subhadeep Gupta[1]
[1]*Department of Physics, University of Washington, Seattle, Washington 98195, USA*
[2]*Department of Physics, California Institute of Technology, Pasadena, California 91125, USA*

Large Momentum Transfer for Atom Interferometric Quantum Sensing:
A Challenge in Quantum Coherent Control



Splitting Pulses | Acceleration Pulses | Mirror Pulses | Readout Pulses

Optical Lattices

Sensing Precision scales as
$\delta\Phi / \Phi \sim \delta\Phi$ / (space-time area)

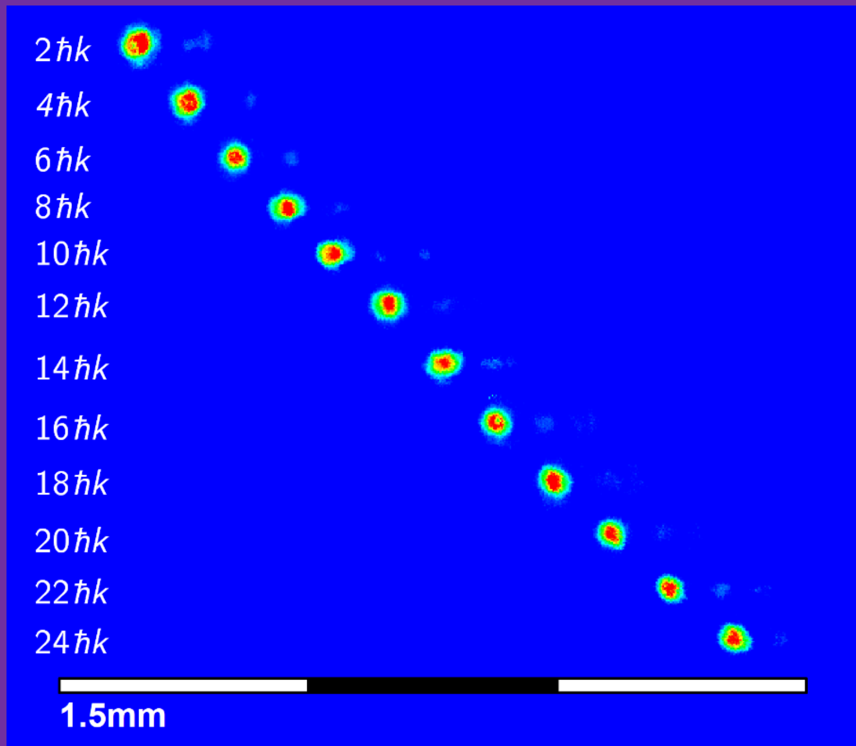
Can increase T with fountain, drop tower, rockets, in space

eg.
$\Phi_1 - \Phi_2 \sim mgX^*T \sim g(n)k^*T^2$

$\sim$ space-time area

Large momentum transfer atom optics can be very useful!

High Efficiency Momentum Transfer by Bloch Oscillations

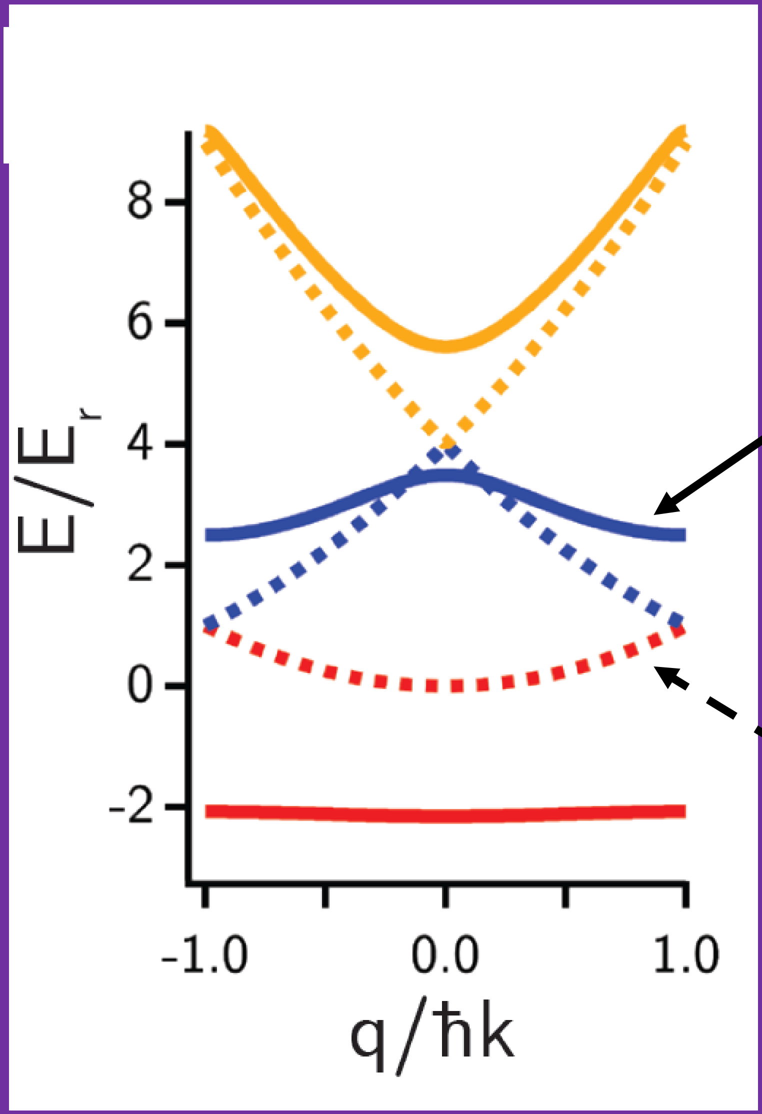


Bloch Oscillations: A condensed matter physics concept. Electrons in lattice + E field

Here Bloch oscillations by sweeping frequency difference between laser beams

Another method: Single photon “clock” transitions. Talk to Shaan Dias

Quantum Transport Approach to Atom Optics



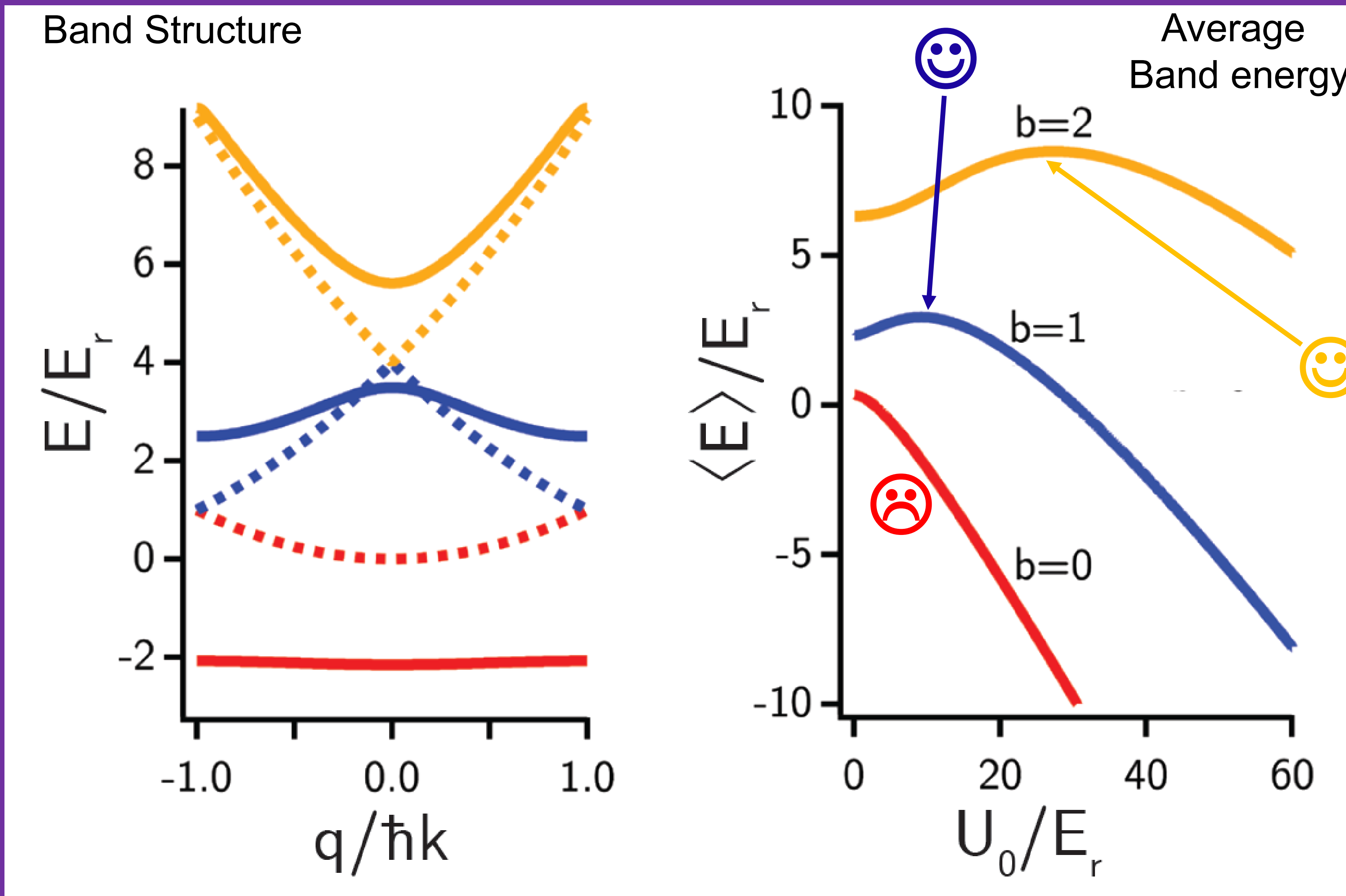
Using ideas from condensed-matter to develop a tool in precision atomic physics

Band energies in sinusoidal lattice with depth = 10 E_r
(E_r = recoil energy)

Free particle dispersion

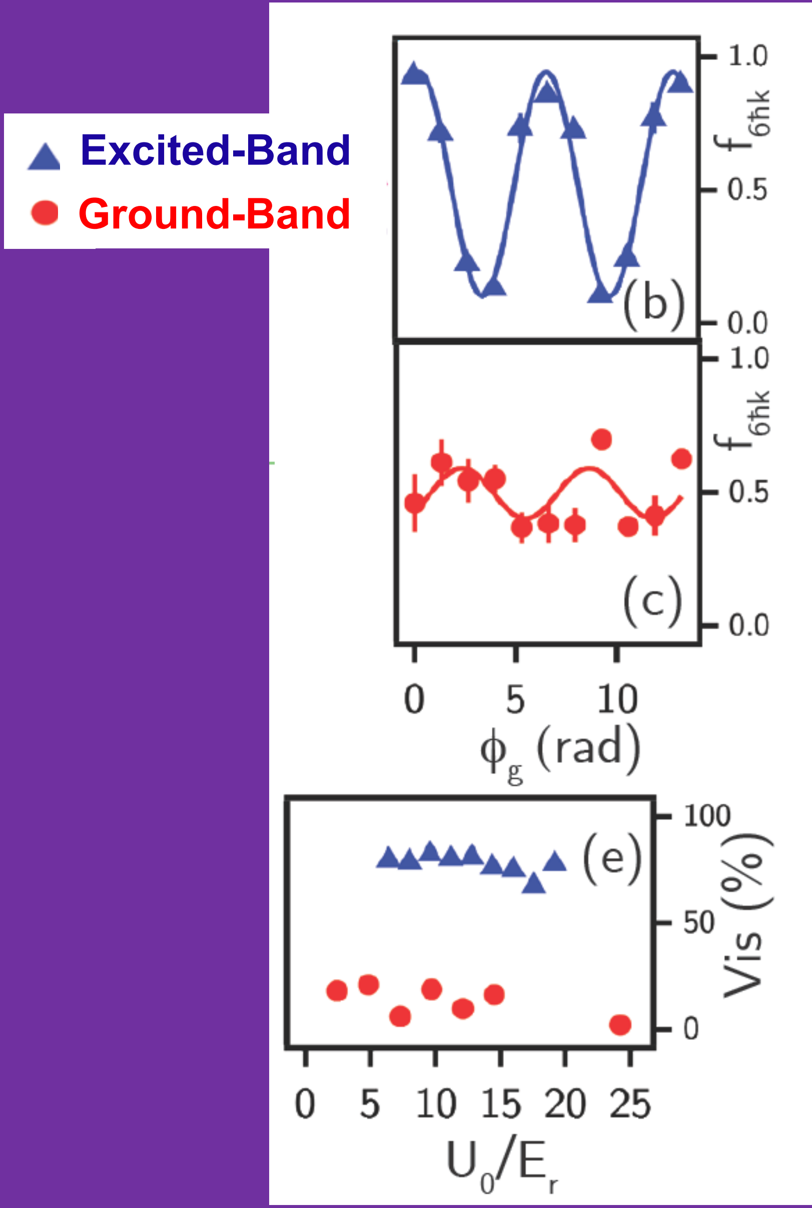
Band Structure in 1D sinusoidal periodic potential (Optical Lattice)

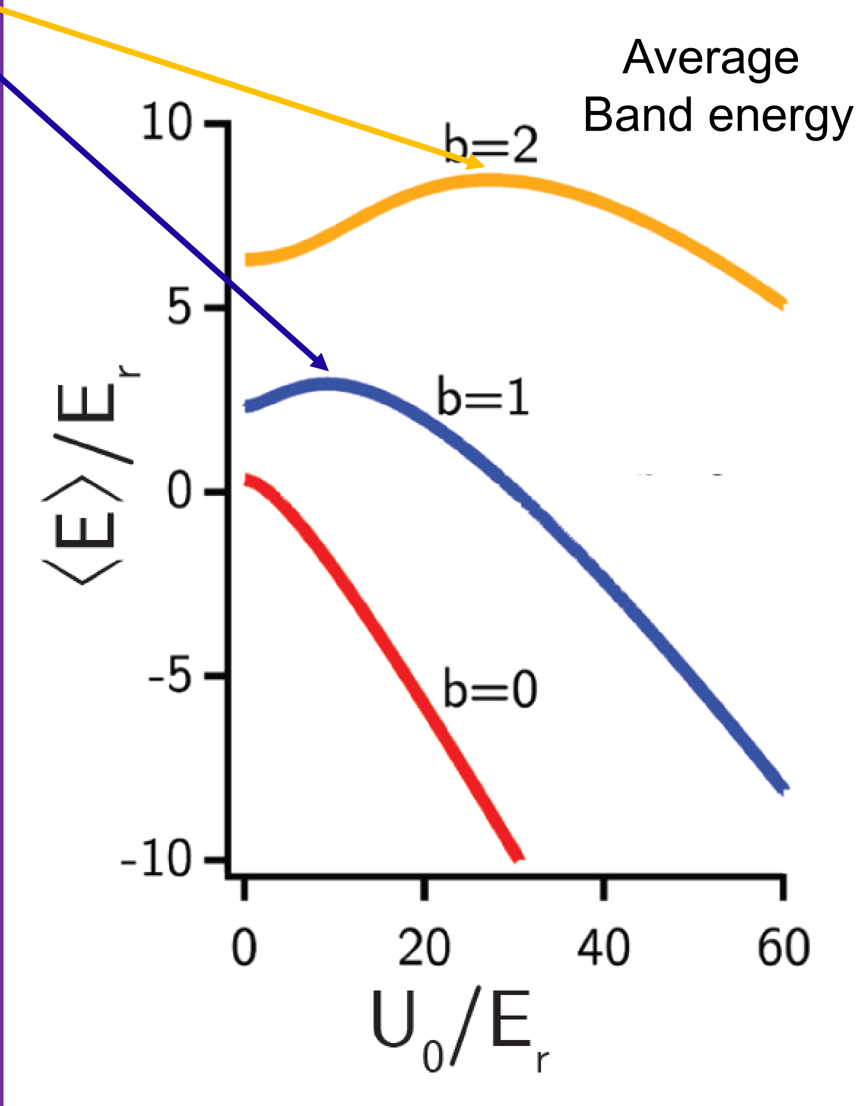
Quantum Transport Approach to Atom Optics



Phase and phase noise during transport process by Bloch oscillations as intensity (U_0) inevitably fluctuates

"Magic Depth" Interferometry

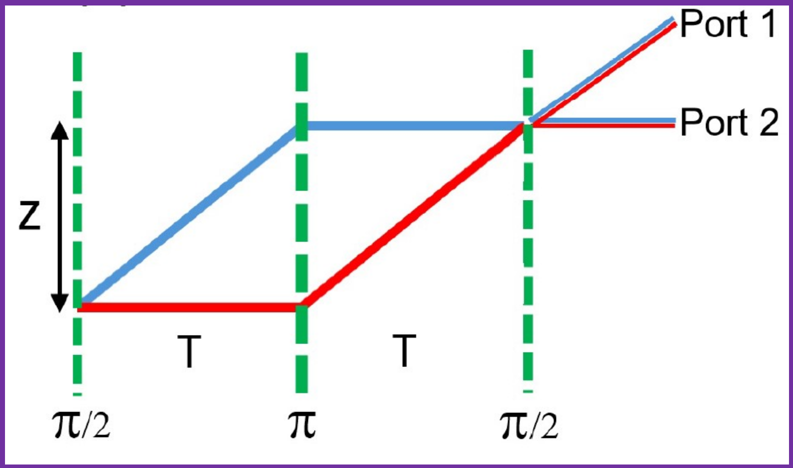




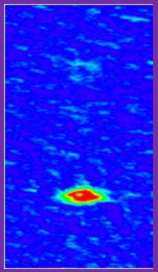
Next: Magic Trapped Atom Interferometry -
Gravimetry in a magic depth trapped geometry

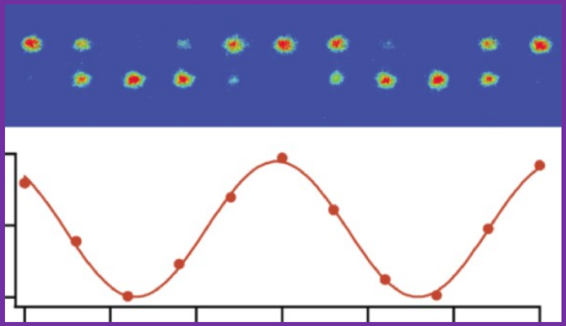
B. Plotkin-Swing et al. Phys Rev Lett **121**, 133201(2018)
Dan Gochnauer et al. Phys Rev A **100**, 043611 (2019)
Katie McAlpine et al. Phys Rev A **101**, 023614 (2020)
Dan Gochnauer et al. Atoms **9**(3), 58 (2021),
Tahiyat Rahman et al. Phys Rev Res **6**, L022012 (2024)

Trapped vs Free-fall Accelerometry



Free-fall geometry

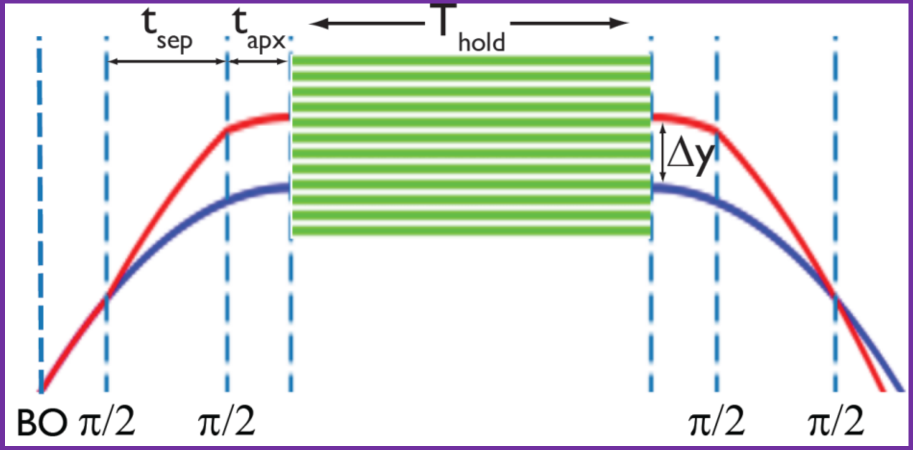




Sensitive to gravity and accelerations for fundamental science and navigation.

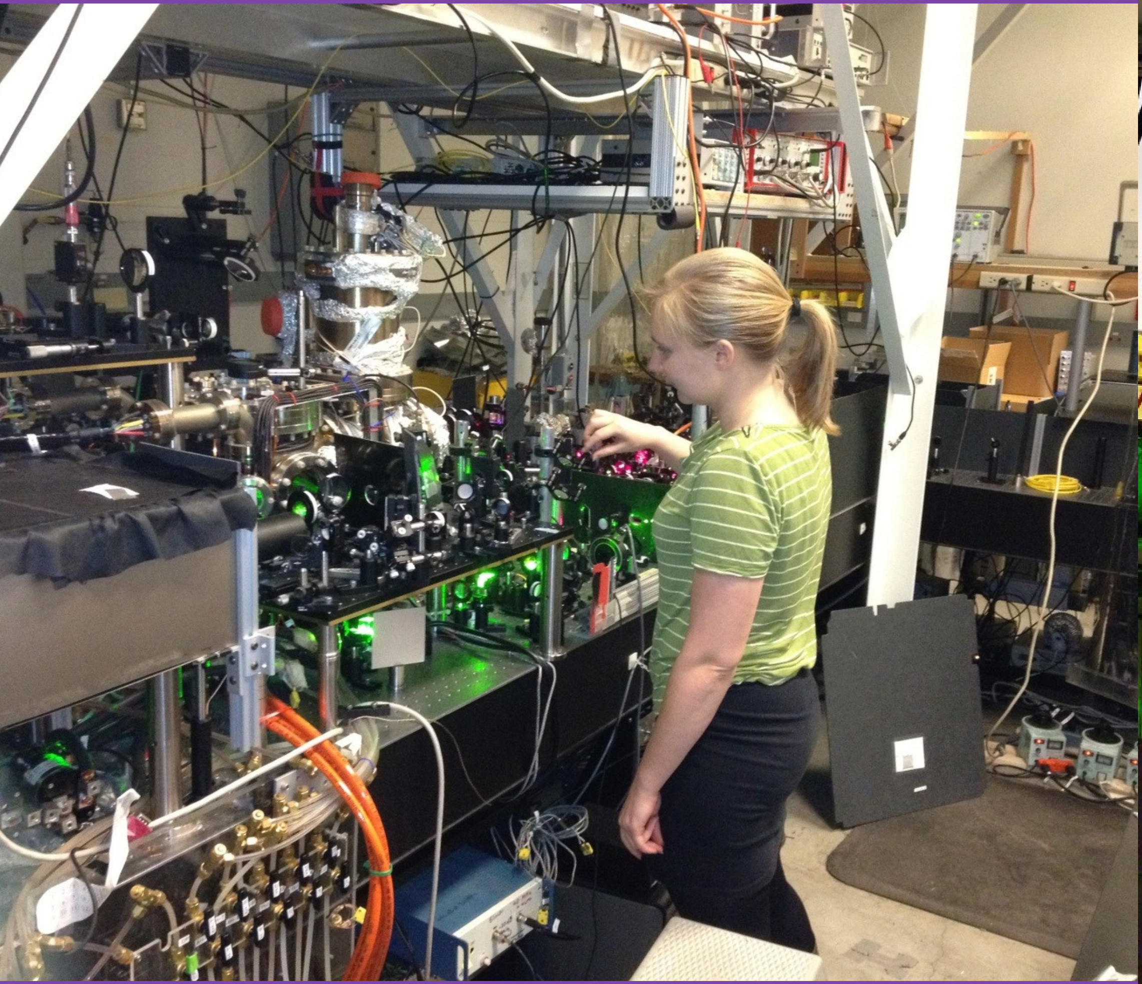
Coherent large momentum transfer techniques for area increase can exceed current commercial accelerometer Performance.

New systematic effects in compact geometry. But very long coherence times and compact instrument sizes possible.

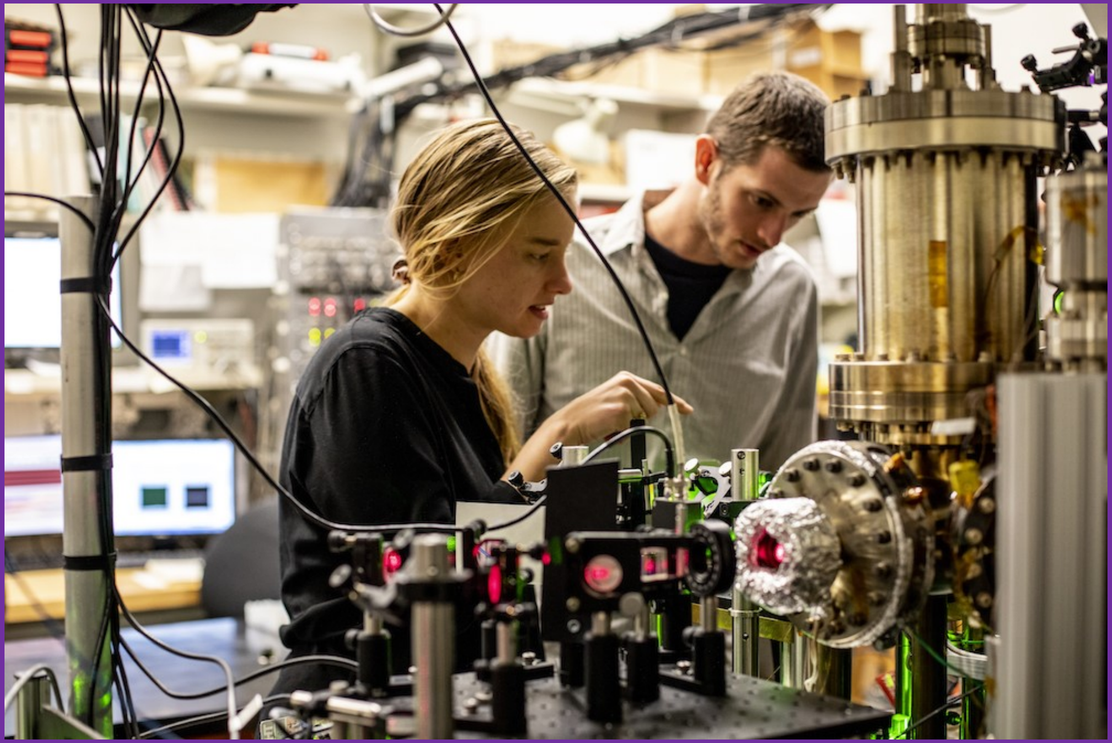


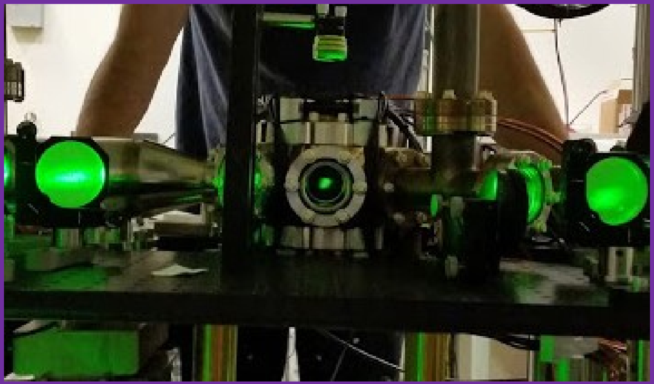
Trapped/Compact geometry: Initial signals freshly obtained

UW Ultracold Atoms Labs



Taming and Having Fun with Atoms





- Experimental table-top physics. Work in few-member teams.
- Lasers, Electronics, Ultra-high vacuum.
- Direct Manipulation and Observation of Clean Quantum Systems
- Fundamental physics. Future quantum technologies.

UW Ultracold Atoms and Quantum Gases Group

Members:

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Nicolas Williams
Emmett Hough
Carson Sander
Harini Ravi
Lynnx
Richard Kim
Shaan Dias
DG

Theory collaborators:

S. Kotochigova (Temple) E. Tiesinga (NIST)
Chuanwei Zhang (UT Dallas) Michael Forbes (WSU)