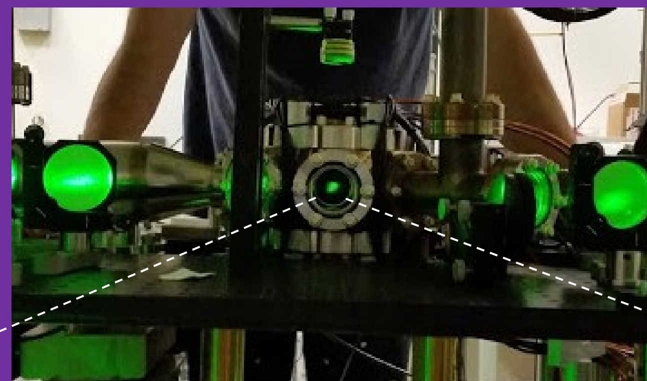
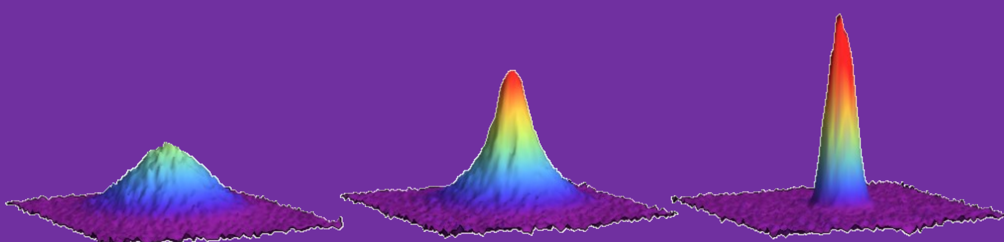
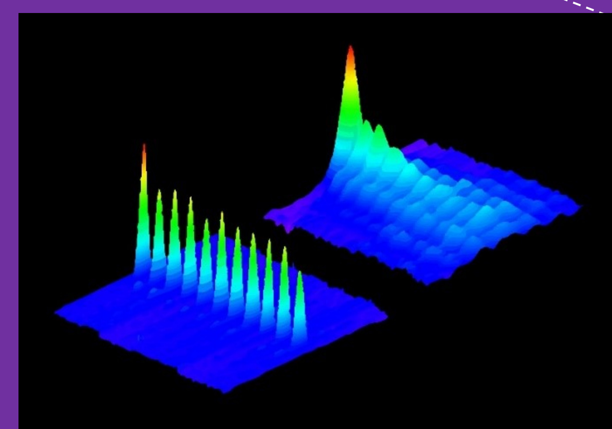
NanoKelvin Quantum Matters: Coherence, Correlations, Chaos.





$T \approx T_C$ $T \lesssim T_C$ $T \ll T_C$

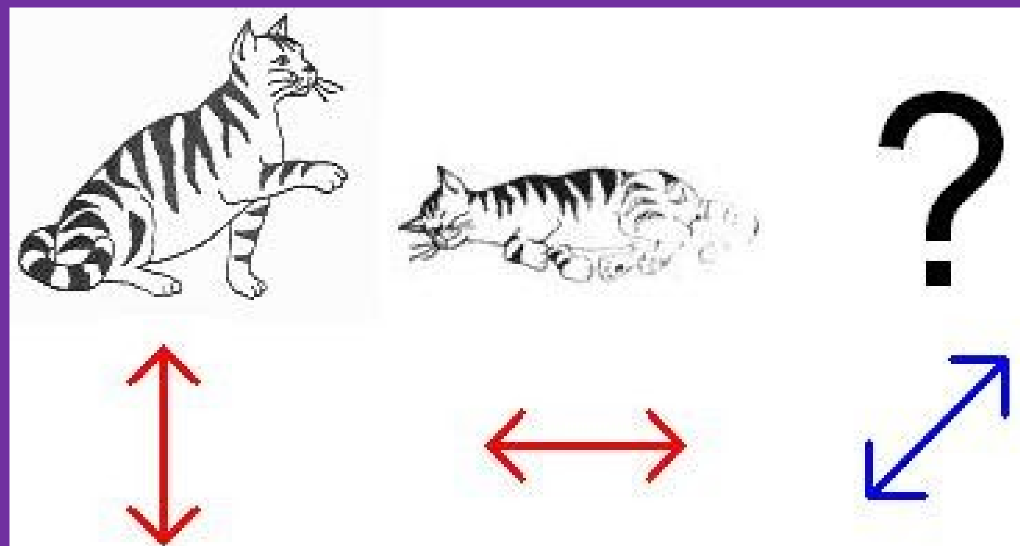


Subhadeep Gupta

UW NSF Phys REU, 31st July 2023

Quantum: Philosophical Questions
Precise Calculations

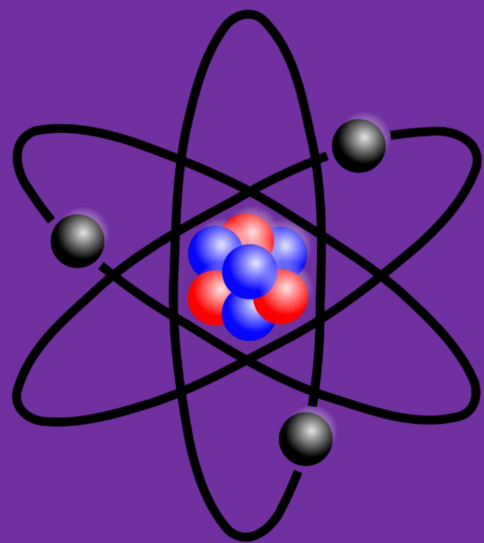
A century's worth of
Technical Advances



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

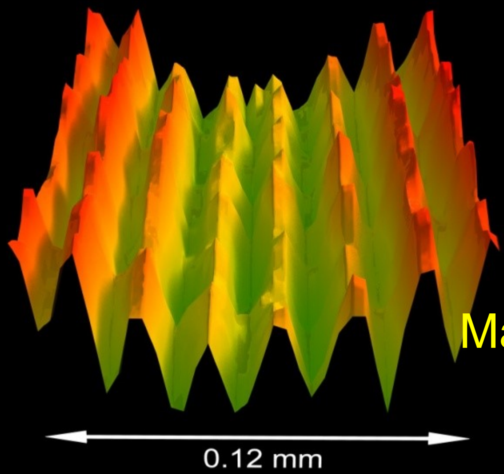


Basic Research
(Curiosity/Measurement)
Driven Pursuits

Technological Advances
(eg. Laser, Atomic Clock)

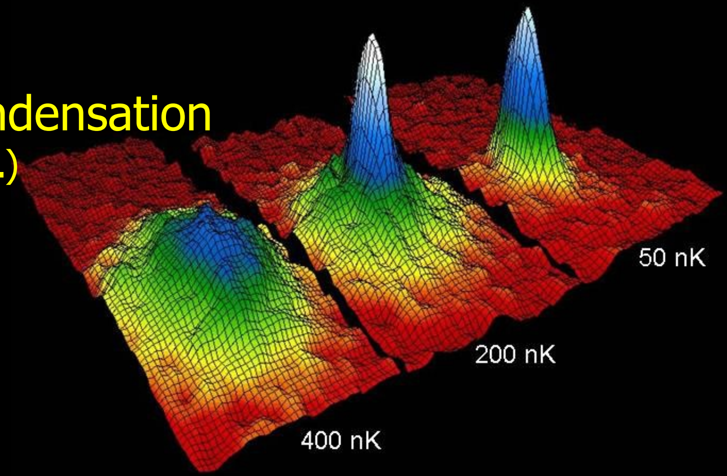
Atom(s): Pristine Quantum System(s) precisely manipulable with EM fields.
Interfacing with condensed matter, nuclear physics, particle physics.
Helping advance quantum technologies and the second quantum revolution.

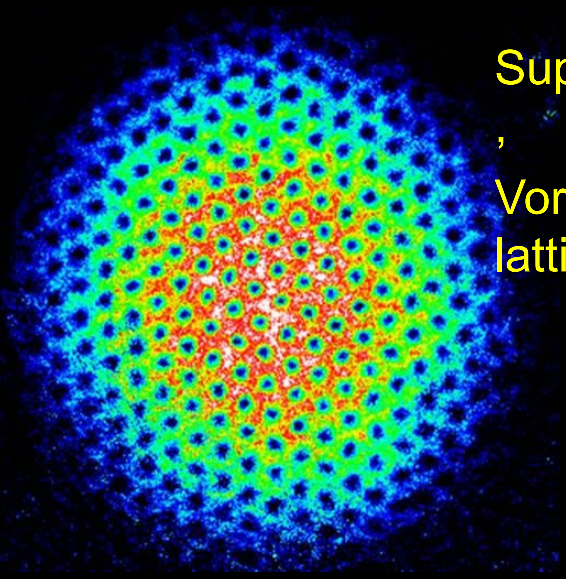
Some ultracold atomic physics landmarks (95-01)



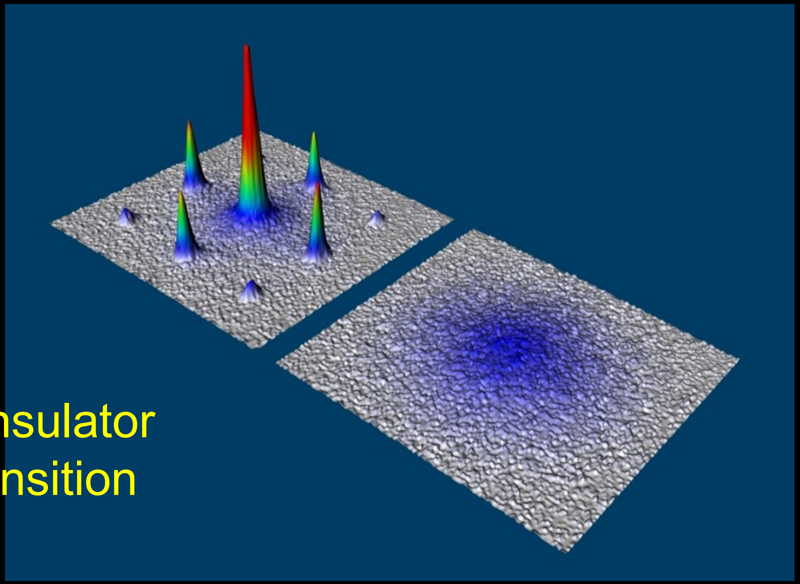
Macroscopic coherence

Bose-Einstein condensation
(JILA, MIT, Rice….)





Superfluidity
,
Vortex
lattice

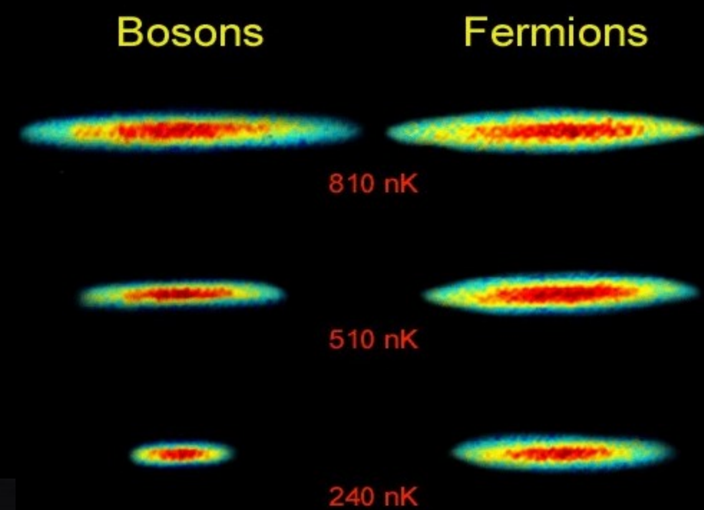


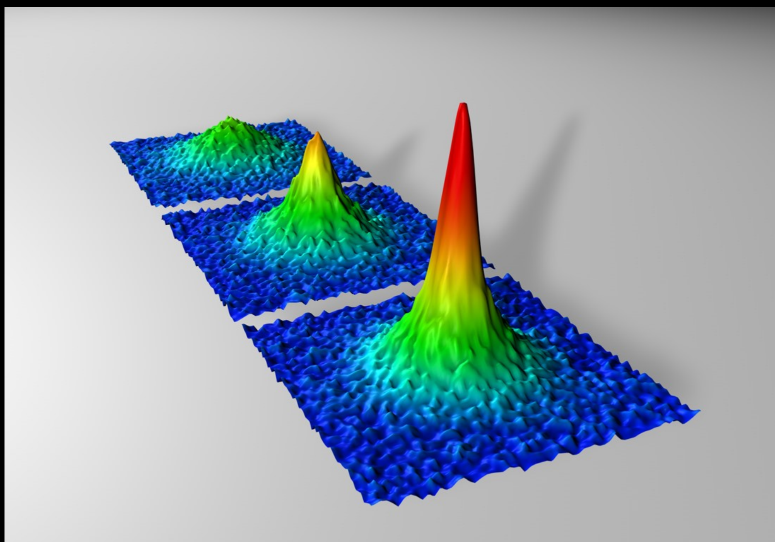
Superfluid to Mott-insulator
quantum phase transition

(Cornell, Wieman, Ketterle, Hulet, Hansch, others)

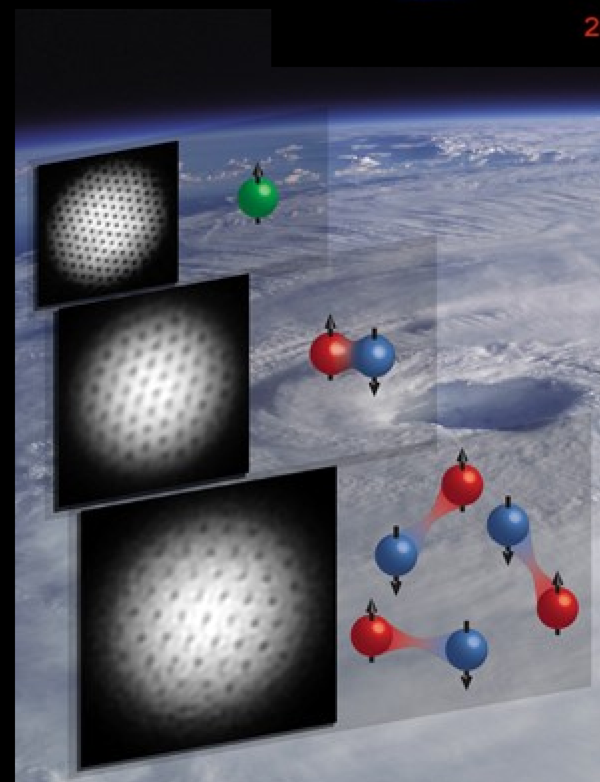
Some ultracold atomic physics landmarks (99-05)

Degenerate Fermi gas





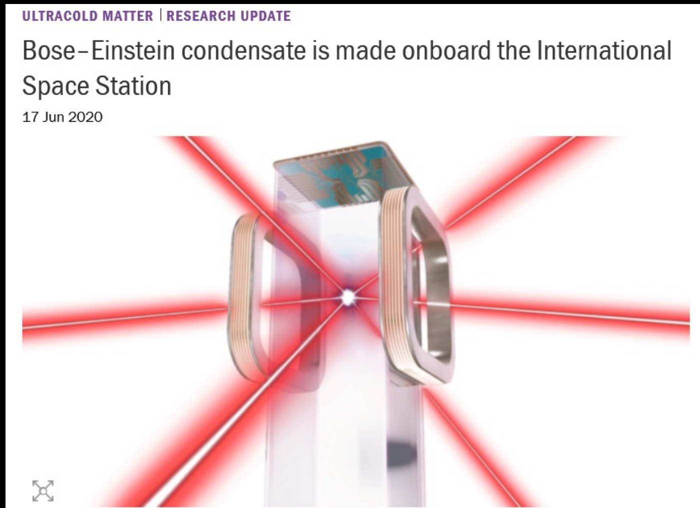
Molecular Bose-Einstein condensate

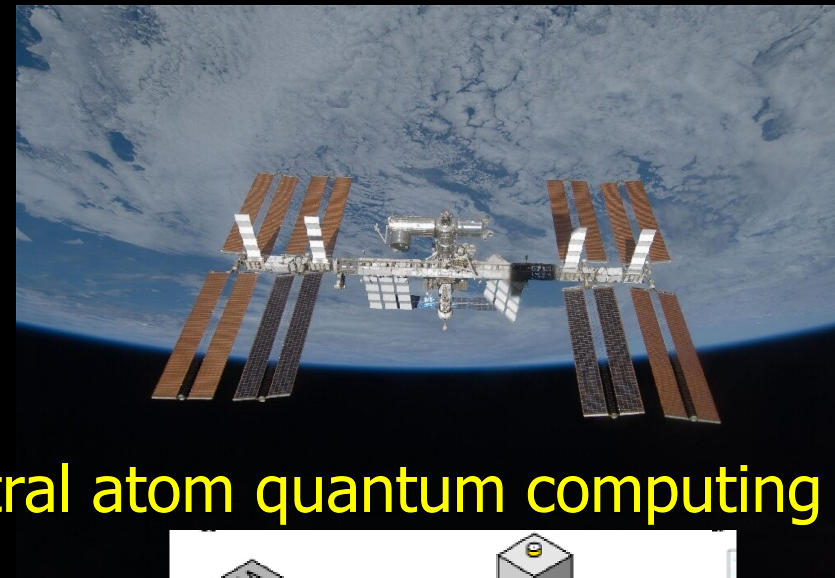


Superfluidity of Fermi pairs

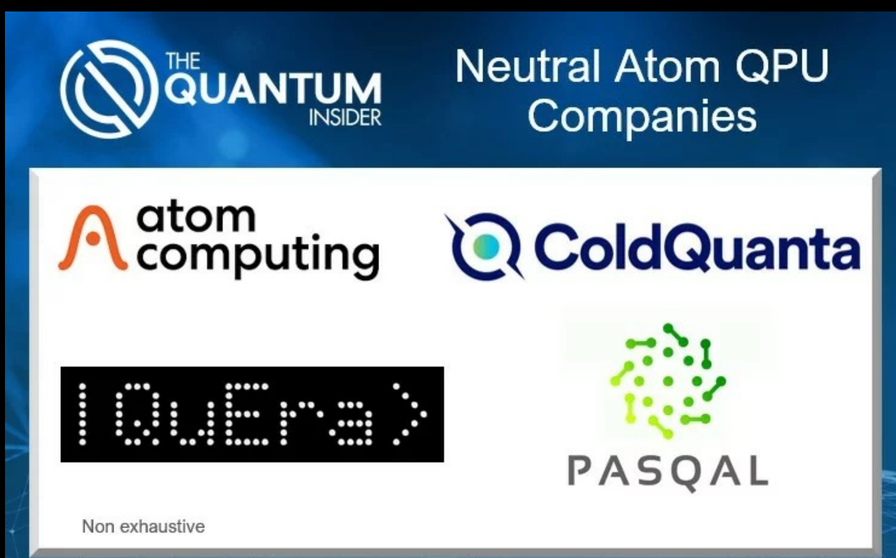
(Jin, Hulet, Thomas, Ketterle, Grimm, others)

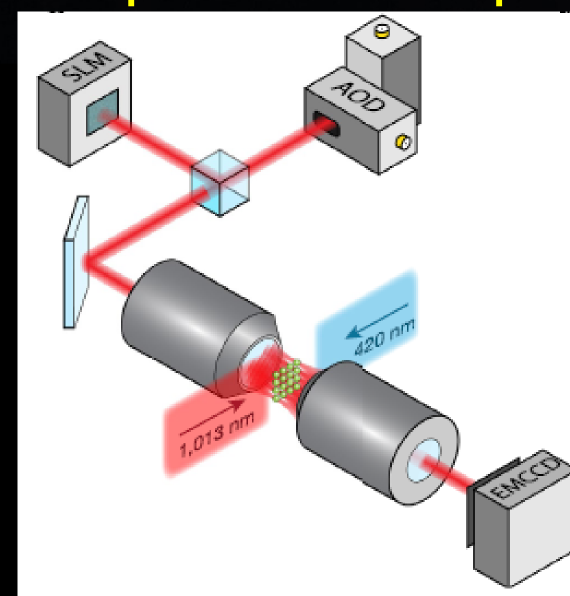
2020's – BECs in space, for fundamental physics (NASA)





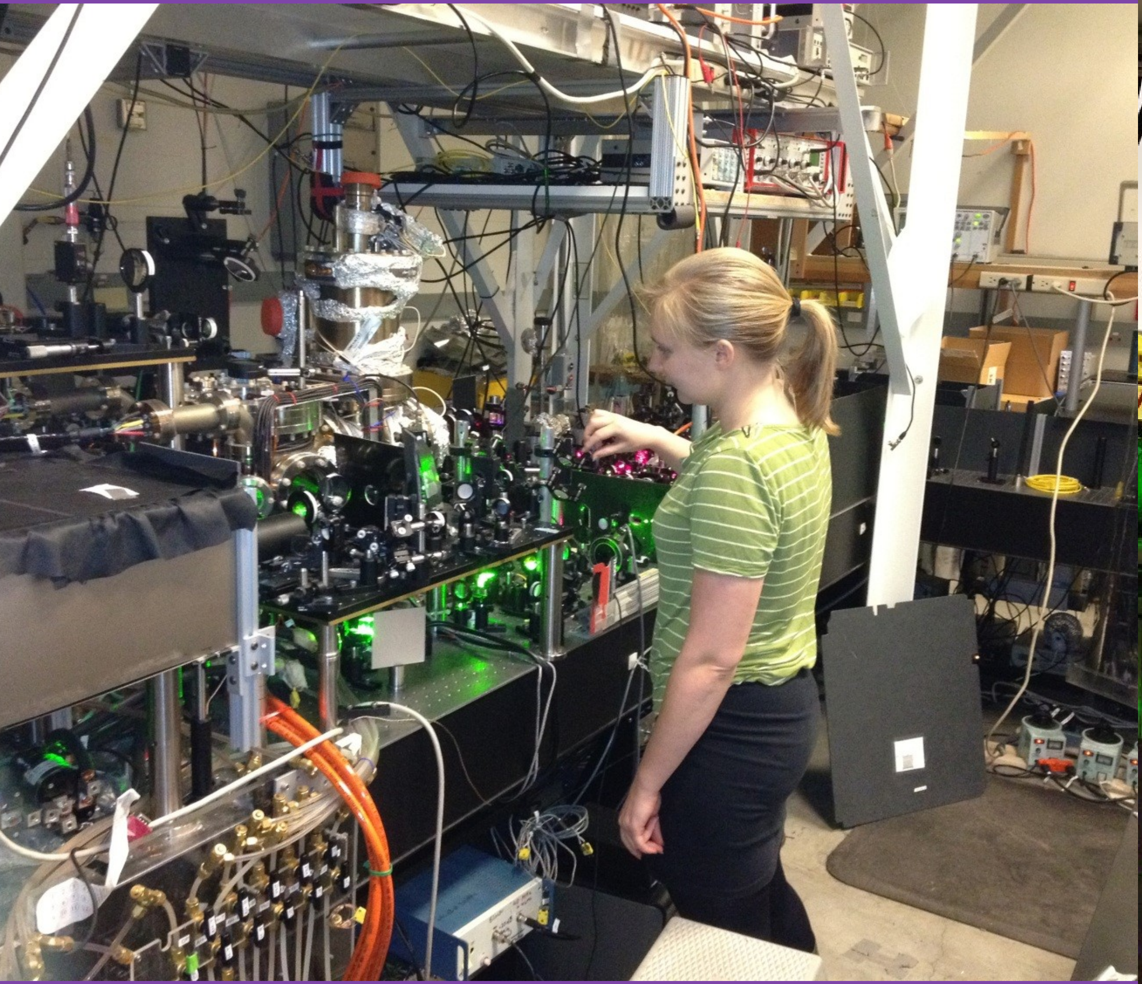
2020's – companies pursuing neutral atom quantum computing





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

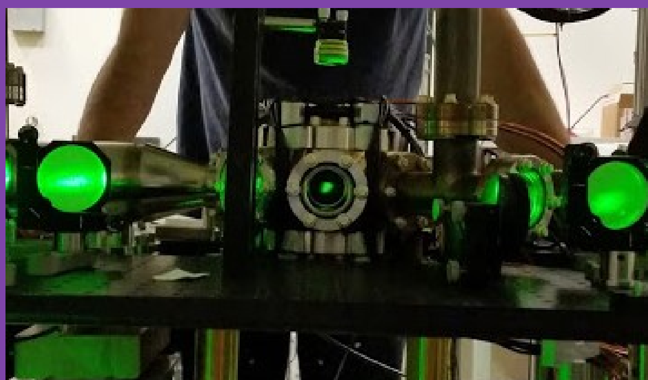
UW Ultracold Atoms Labs



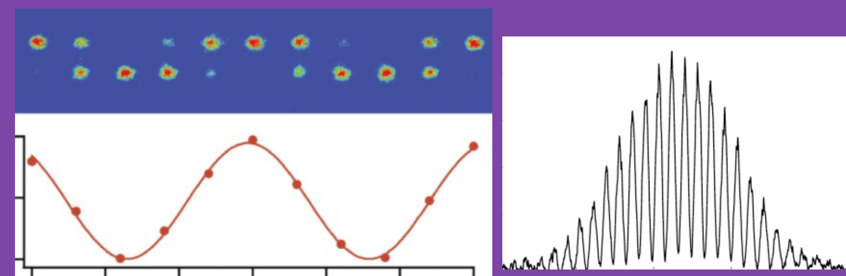
Today:

Taming Atoms:

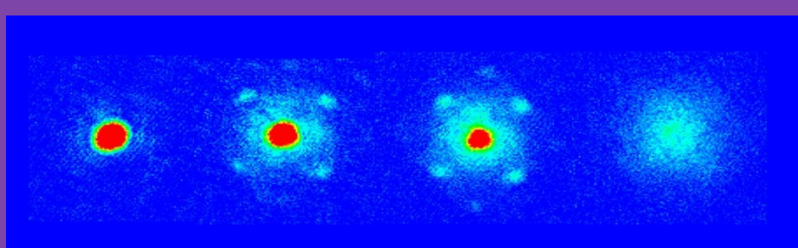
Making quantum gases

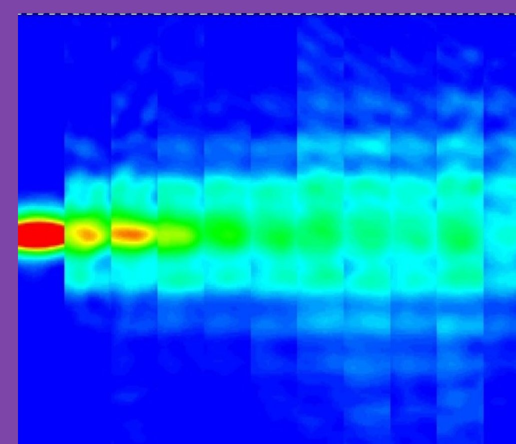


Coherence: Atom Optics and Interferometry



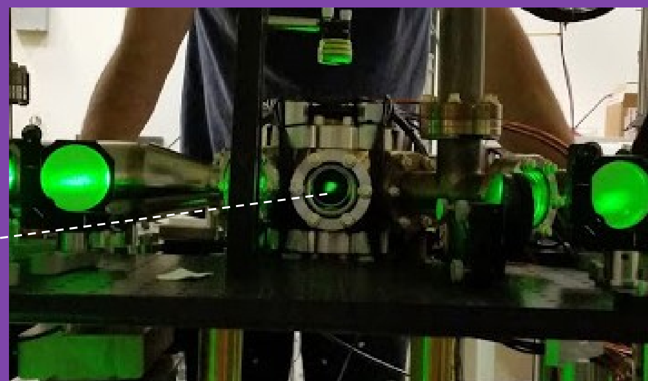
Correlations: Interactions, creating few- and many-body states





Chaos: Many-body Dynamical Delocalization

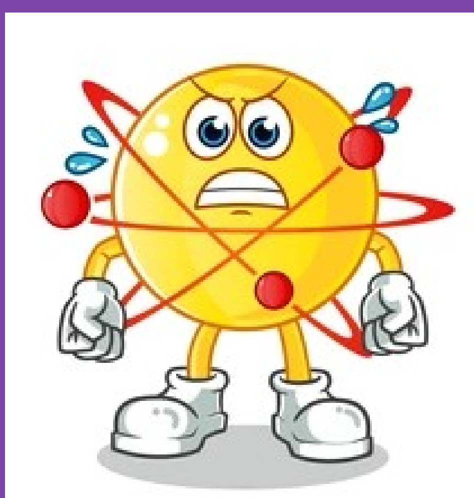
Taming/Training Atoms:



10^8 trapped
Yb atoms
at 50 μK

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

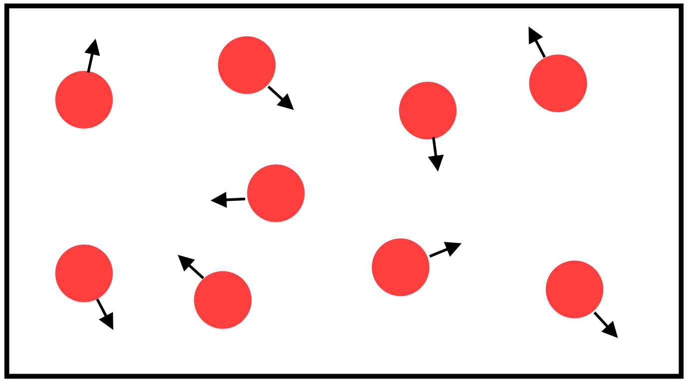
Random motion ⇔ Temperature



50yrs: bound electron(s) motion

50yrs: atom c.o.m. motion

Quantum Degeneracy in a gas of atoms



1 atom per quantum state

Cooling to the fundamental limits of quantum mechanics

N atoms

V volume

T temperature

position-momentum uncertainty principle

$(\Delta x)^3 \sim V$ $\qquad$ $(\Delta p)^3 \sim (m\, k_B\, T)^{3/2}$

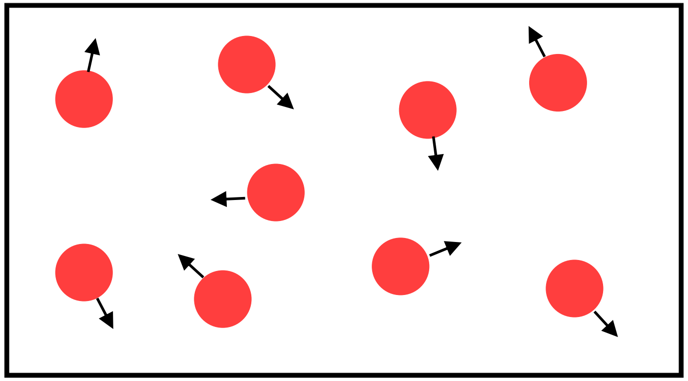
$$\text{Number of atoms} = \frac{(\text{available position space})\,(\text{available momentum space})}{\hbar^3}$$

Quantum Phase Space Density

$$\frac{n\,\hbar^3}{(m\,k_B\,T)^{3/2}} \sim 1 \qquad (n=N/V)$$

So all we have to do for a quantum degenerate gas is keep cooling it, right?

Quantum Degeneracy in a gas of atoms



1 atom per quantum state

Cooling to the fundamental limits of quantum mechanics

N atoms
V volume
T temperature

position-momentum uncertainty principle

$(\Delta x)^3 \sim V$ $\quad$ $(\Delta p)^3 \sim (m\, k_B\, T)^{3/2}$

$$\text{Number of atoms} = \frac{\text{(available position space) (available momentum space)}}{\hbar^3}$$

Quantum Phase Space Density

$$\frac{n\,\hbar^3}{(m\, k_B\, T)^{3/2}} \sim 1 \qquad (n=N/V)$$

$$n\lambda_{\mathrm{dB}}^3 \sim 1$$

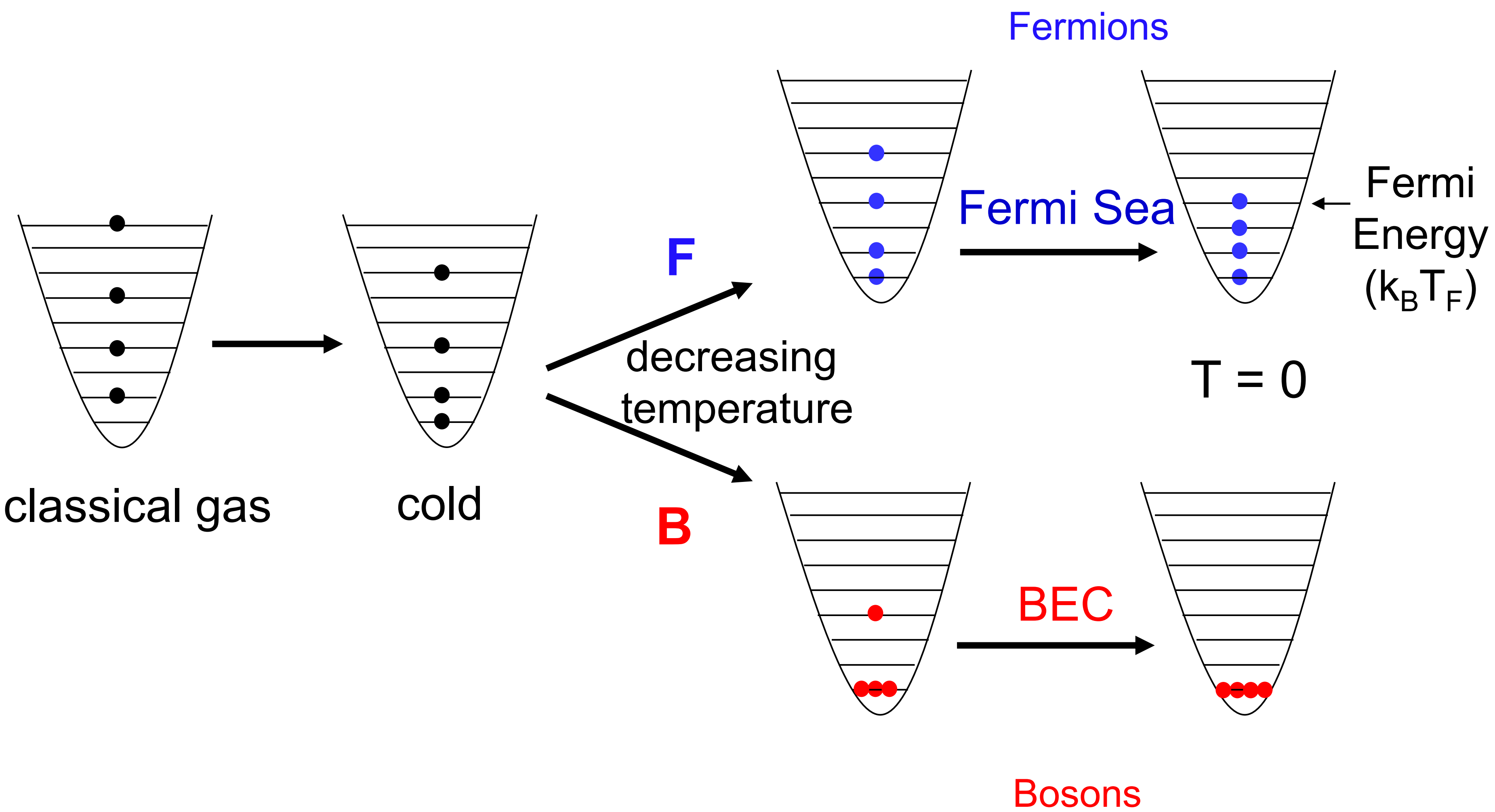
Air $n \sim 10^{19}/\mathrm{cm}^3$, $T_c \sim 1\mathrm{mK}$
Stuff $n \sim 10^{22}/\mathrm{cm}^3$, $T_c \sim 0.1\mathrm{K}$
Everything (except He) is solid

Dilute metastable gases $n \sim 10^{14}/\mathrm{cm}^3$

$T_c \sim 1\mu\mathrm{K}$!! Ultracold !!

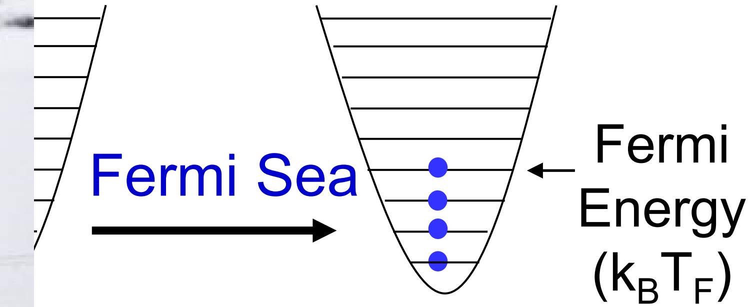
and ~ non-interacting

Different Behaviors in the Cold



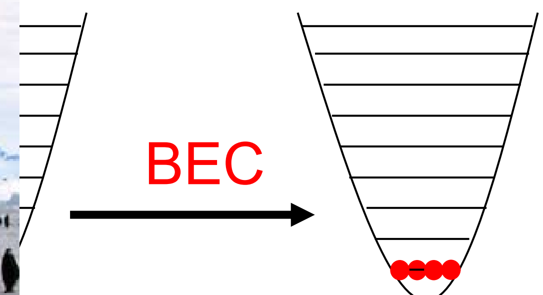
Different Behaviors in the Cold

Fermions



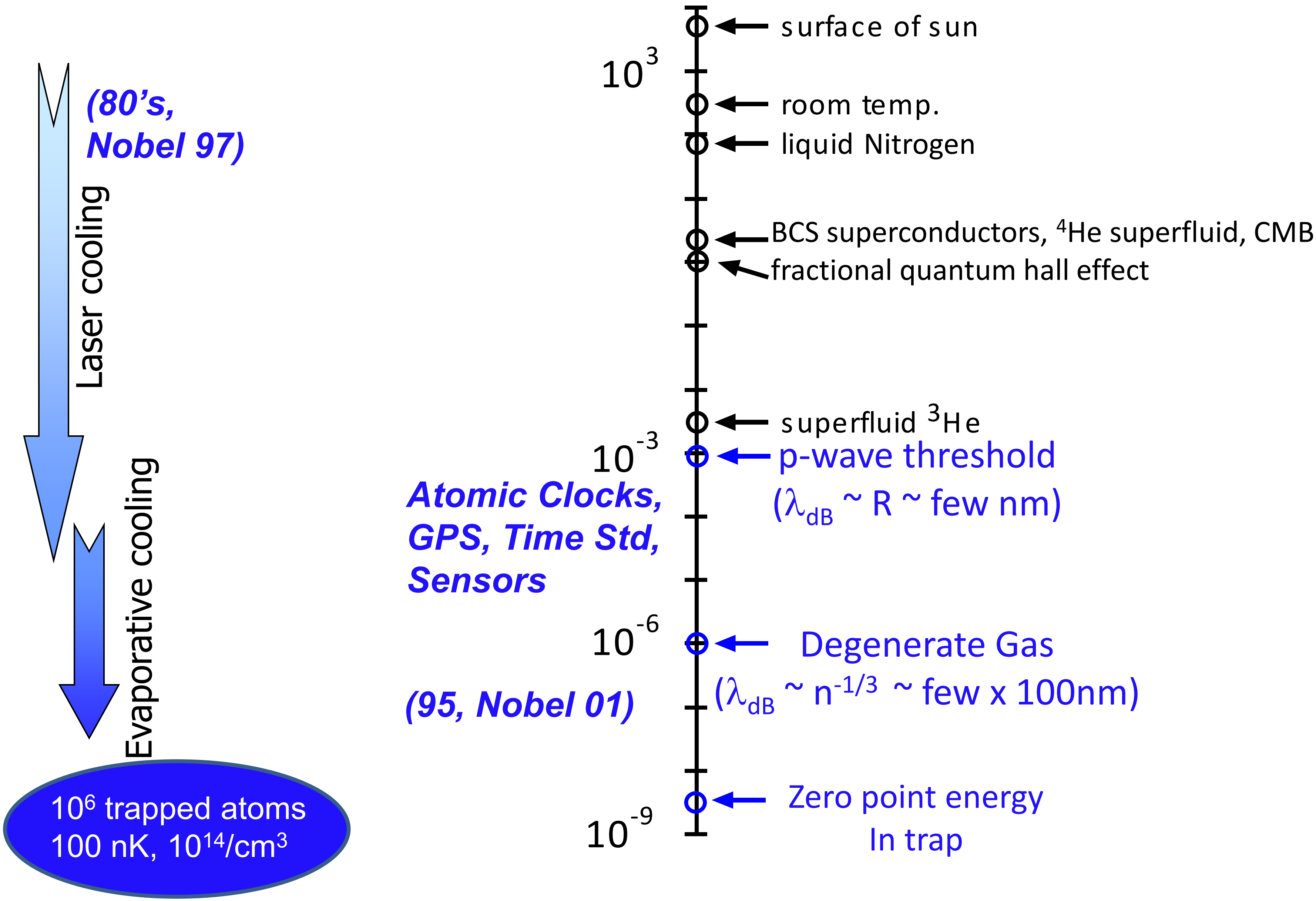
T = 0

class

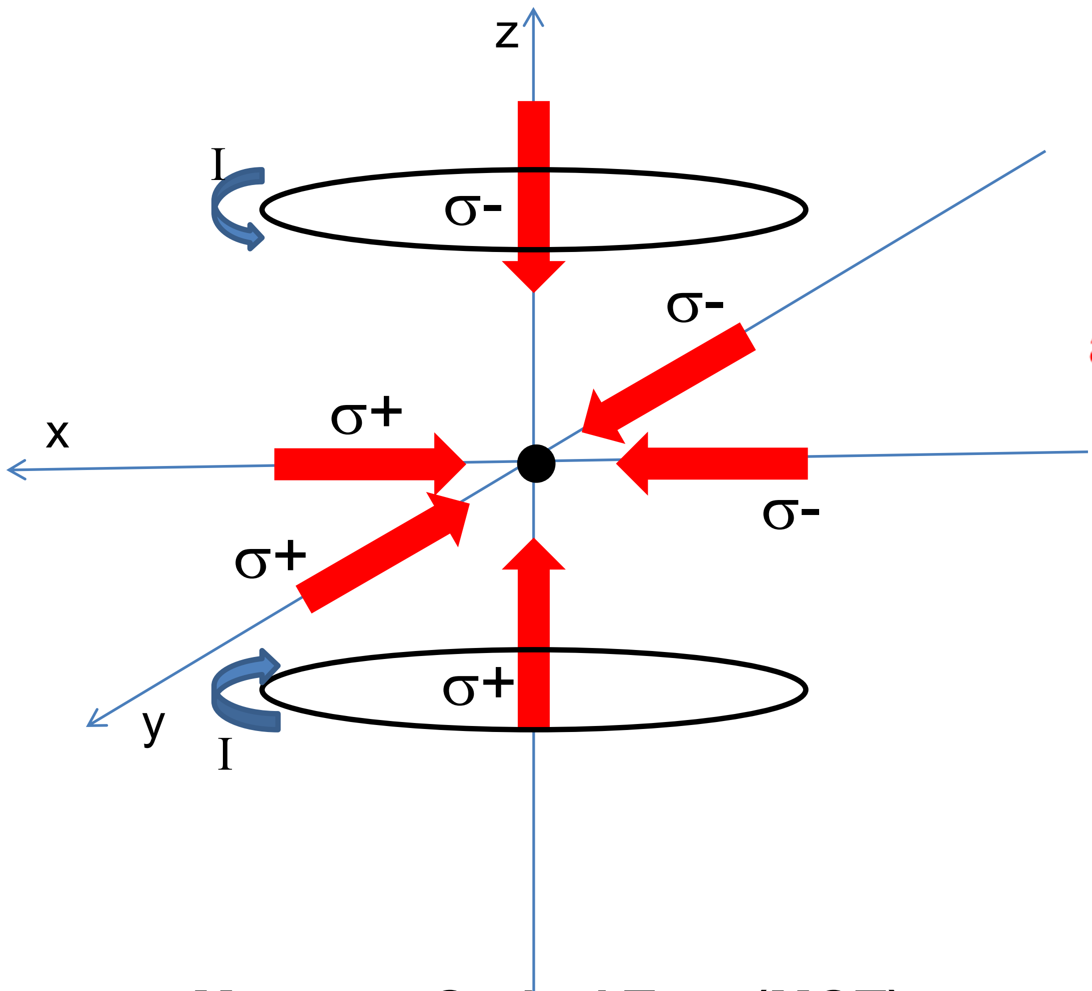


Bosons

Relevant Ultracold Temperatures on the Log Kelvin Scale

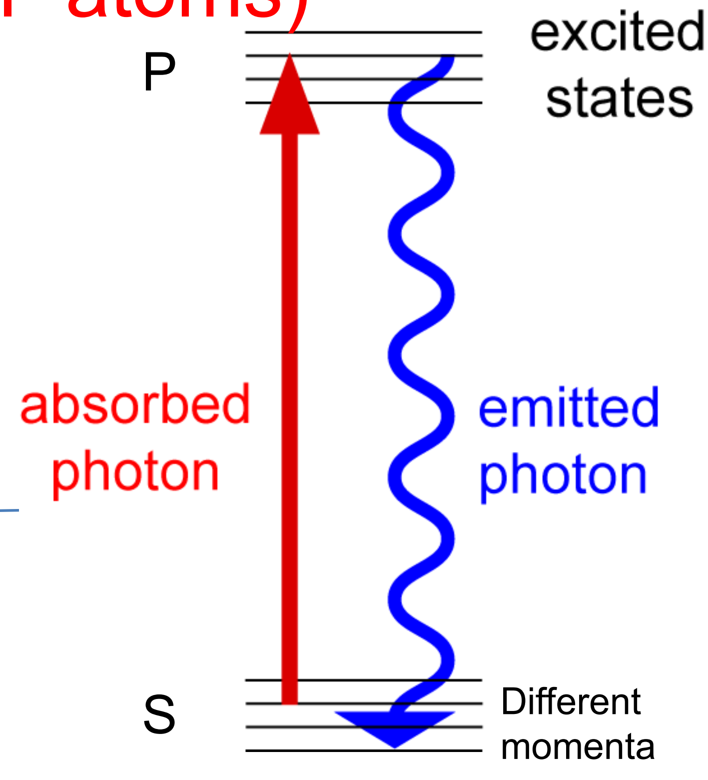


Laser Cooling (of "2-level" atoms)



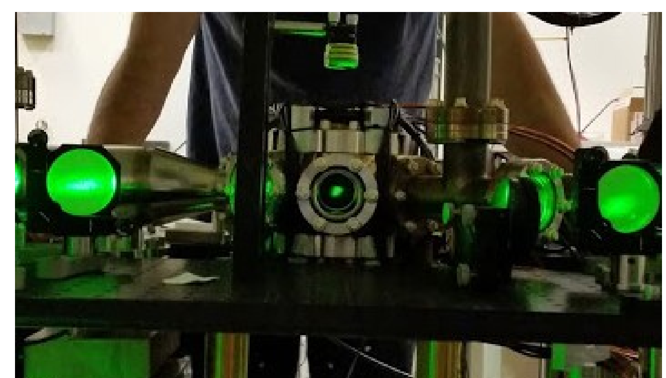
Magneto-Optical Trap (MOT)
"Workhorse" of laser cooling

Atom Source ~ 600 K; UHV environment



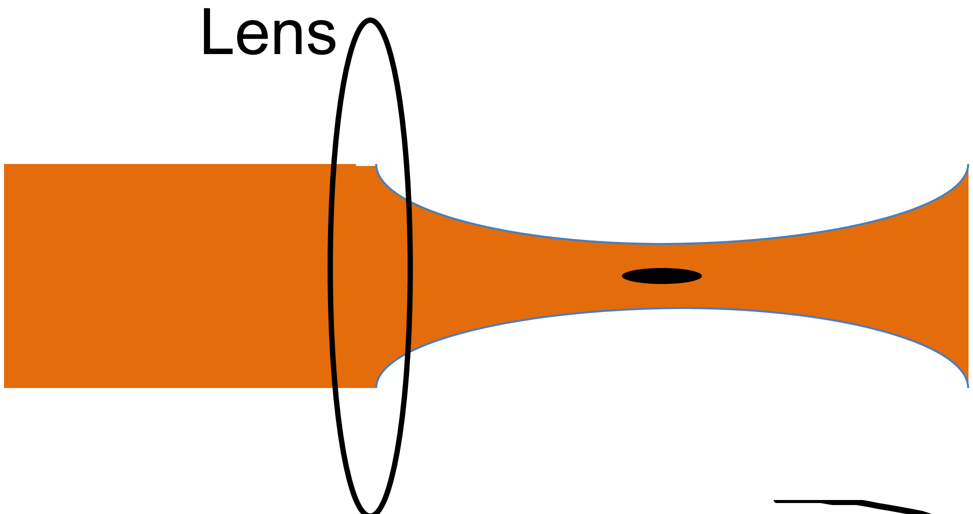
$$\hbar\omega_{abs} < \hbar\omega_{em}$$

=> COOLING !



Evaporative Cooling in a Conservative Trap

The “other” atom-light interaction

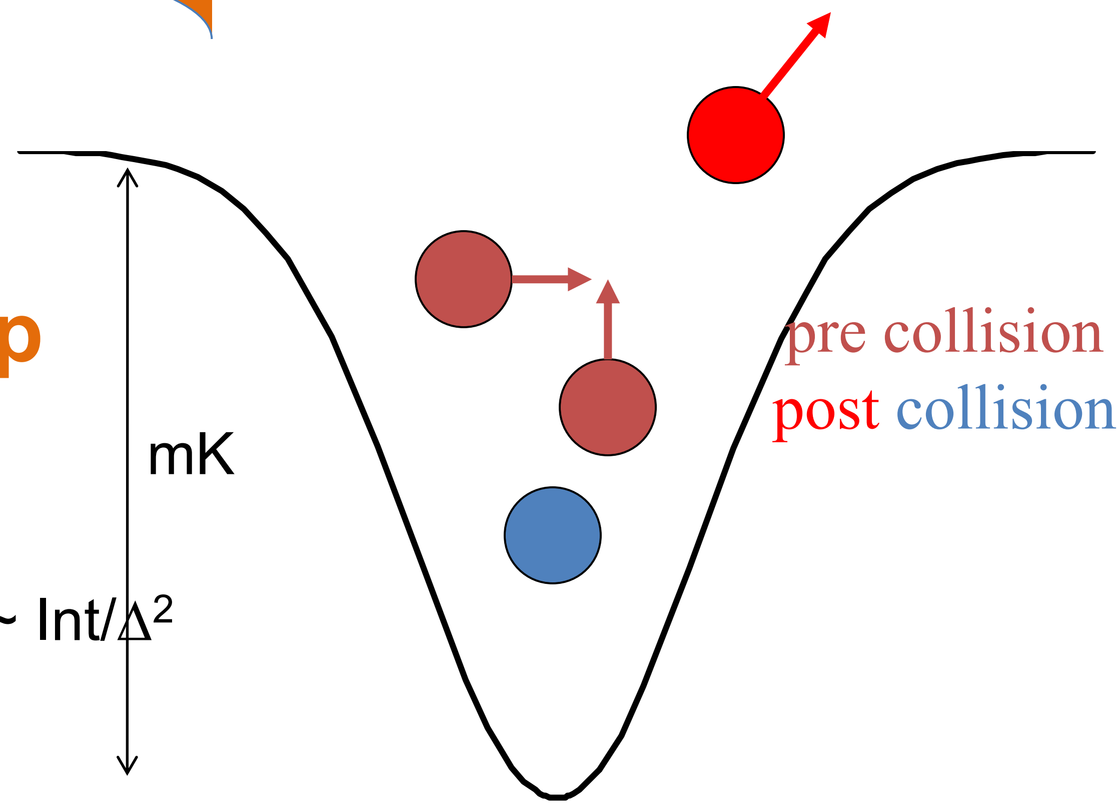


Optical Dipole Trap

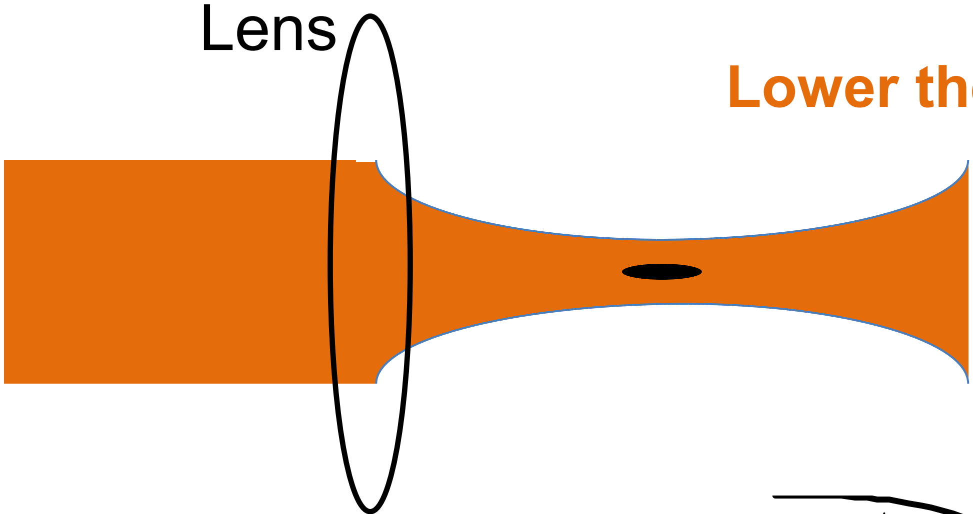
$\omega_L << \omega_{res}$

Depth ~ Int/Δ; Heating Rate ~ Int/Δ^2

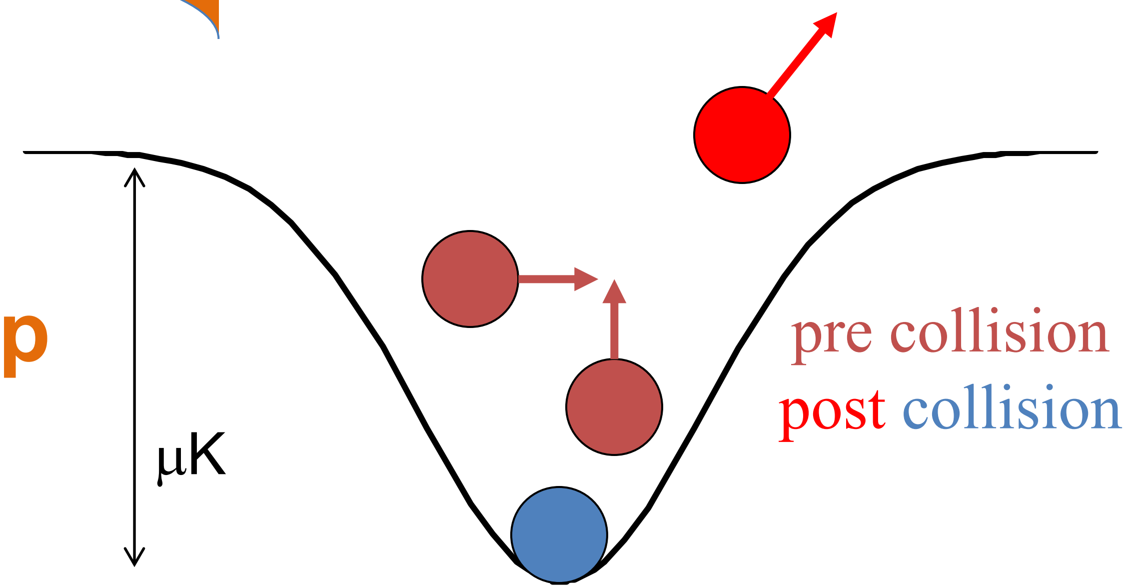
$\Delta = \omega_L - \omega_{res}$



Evaporative Cooling in a Conservative Trap



Lower the Power



Optical Dipole Trap

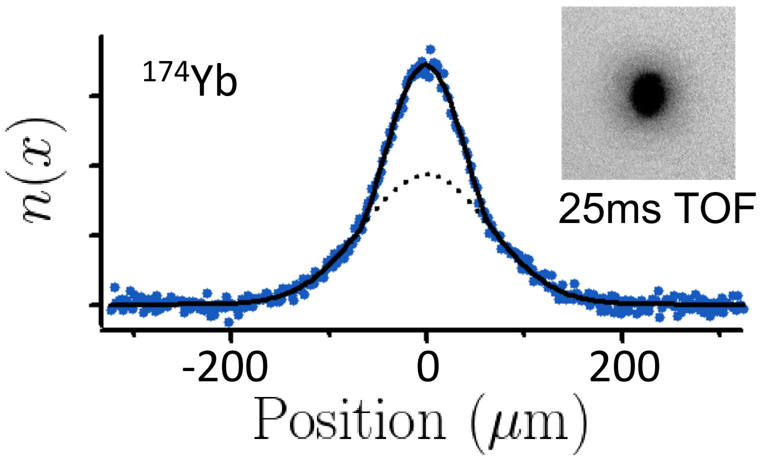
$\omega_L << \omega_{res}$

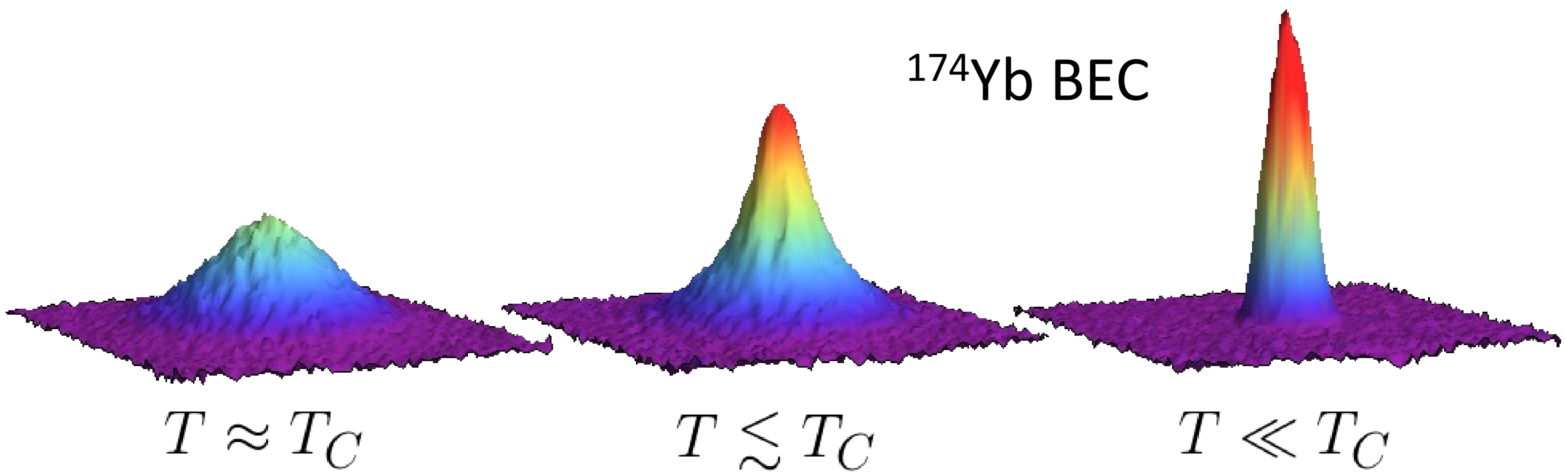
Depth ~ Int/Δ; Heating Rate ~ Int/Δ^2

$\Delta = \omega_L - \omega_{res}$

Boson degeneracy: Bose-Einstein condensate

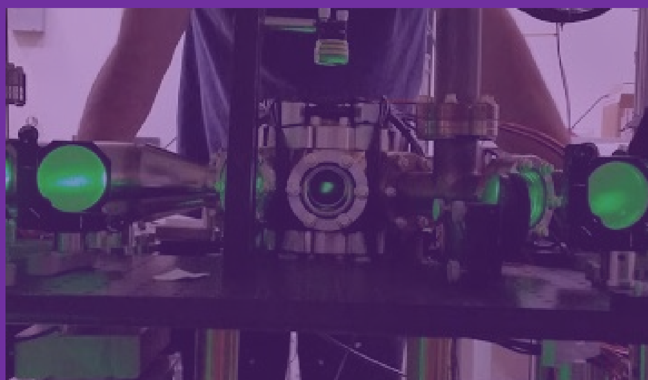
$$n(\vec{r}) = n_{\mathrm{BEC}}(\vec{r}) + n_{\mathrm{th}}(\vec{r})$$



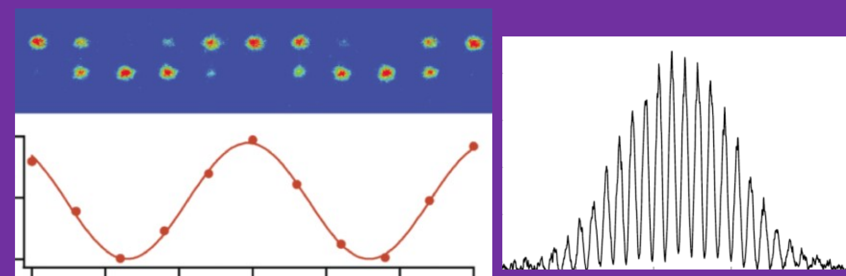


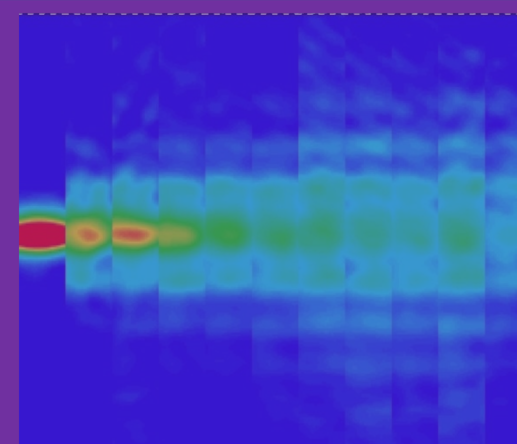
Today:

Taming Atoms:
Making quantum gases

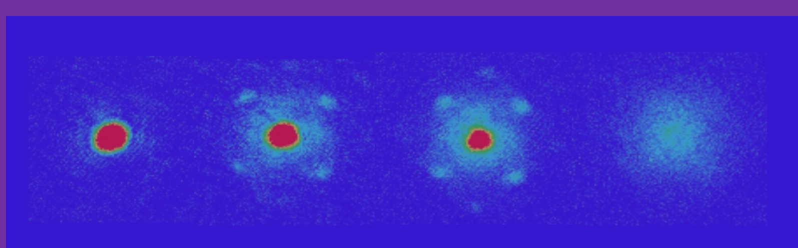


Coherence: Atom Optics and Interferometry



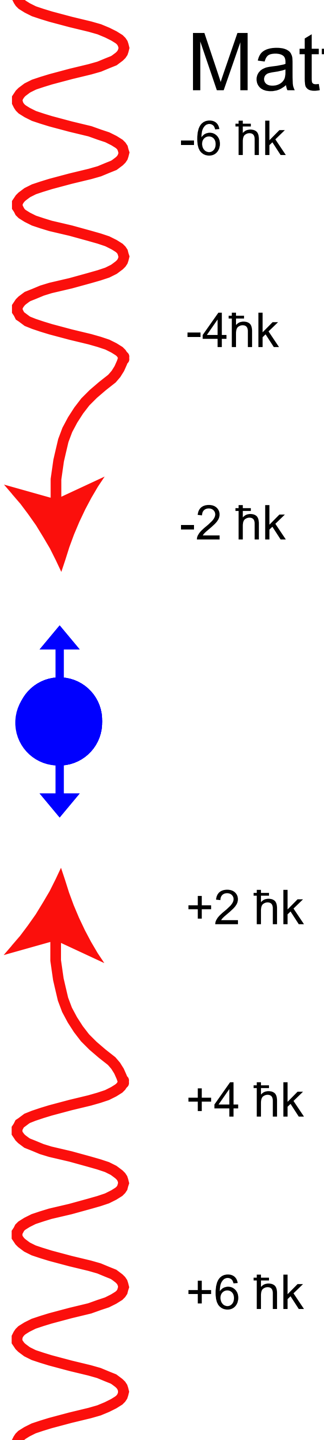


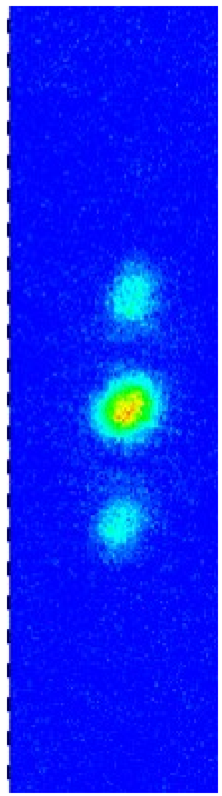
Correlations: Interactions, creating few- and many-body states



Chaos: Many-body Dynamical Delocalization

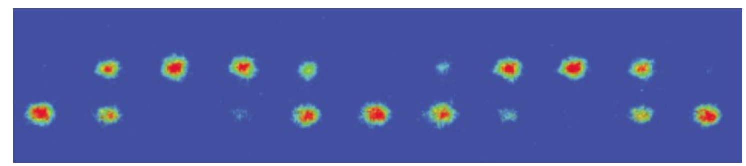
Matter Wave Diffraction off an Optical Crystal





Narrow Momentum width
<< 2 photon momentum

Diffraction from longer standing wave pulse with frequency difference

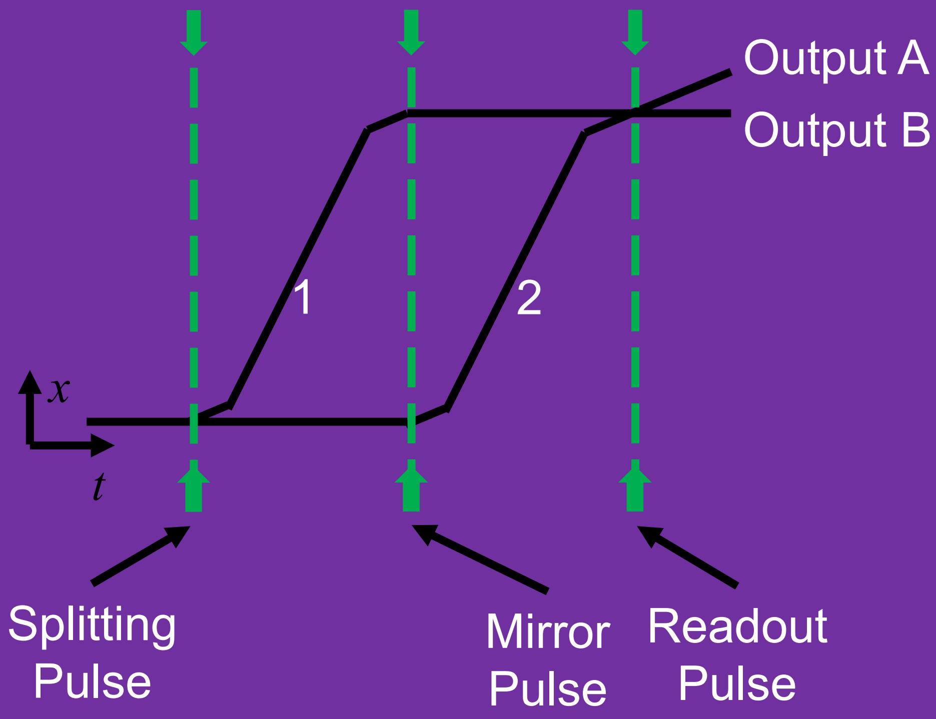


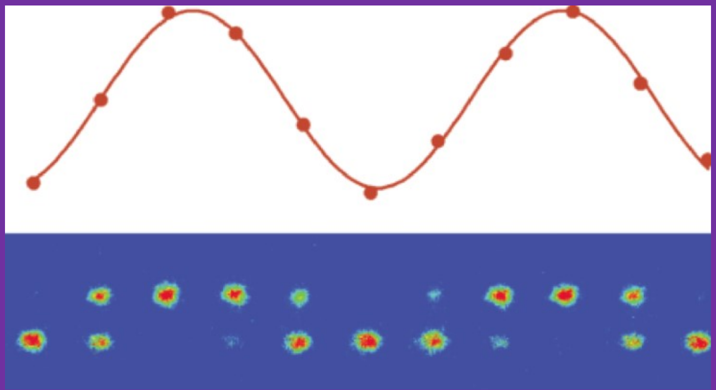
Increasing intensity of pulse →

Pulsed Standing Wave
Optical Dipole Potentials

Atom Optics and Interferometry

Output ports A and B record differential phase between paths 1 and 2.





Vary readout pulse phase

Force sensing:

- acceleration
- gravity (g, G)
- gradiometry
- grav. waves

eg.

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

$\sim$ space-time area

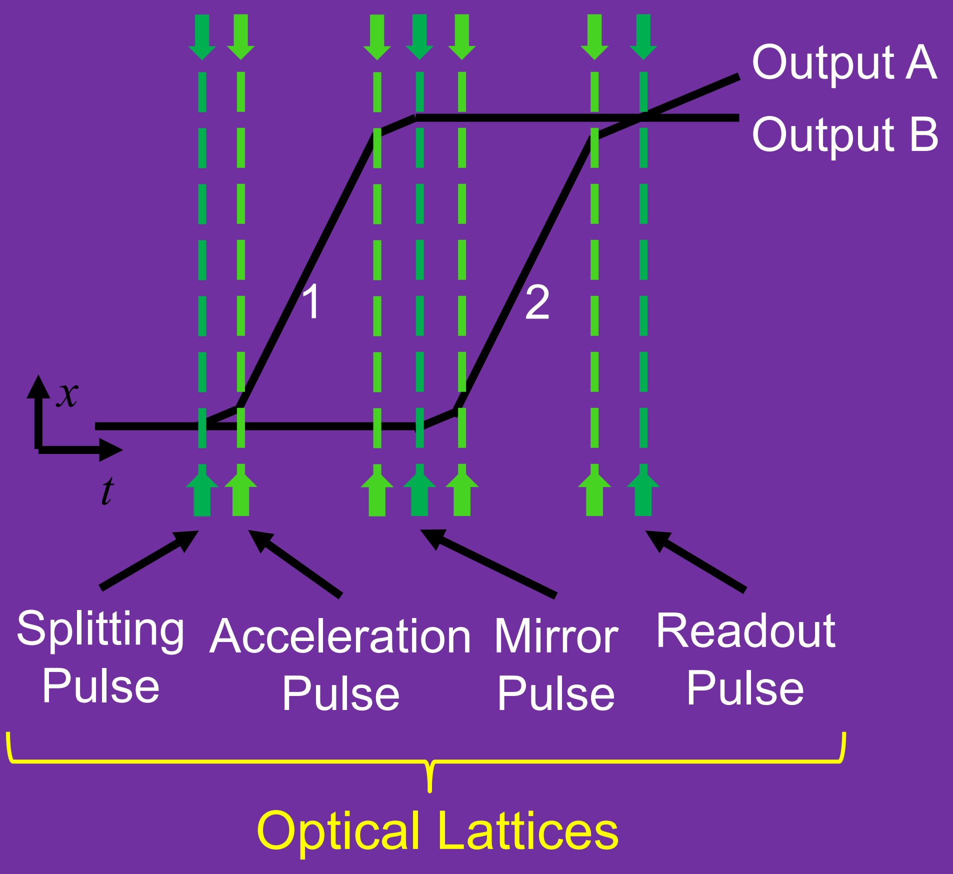
Atomic Properties:

- Polarizabilities
- Atom-surface interactions

Fundamental Tests:

- Decoherence/QM
- Equivalence Principle
- QED test

Large Momentum Transfer for precision AI



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

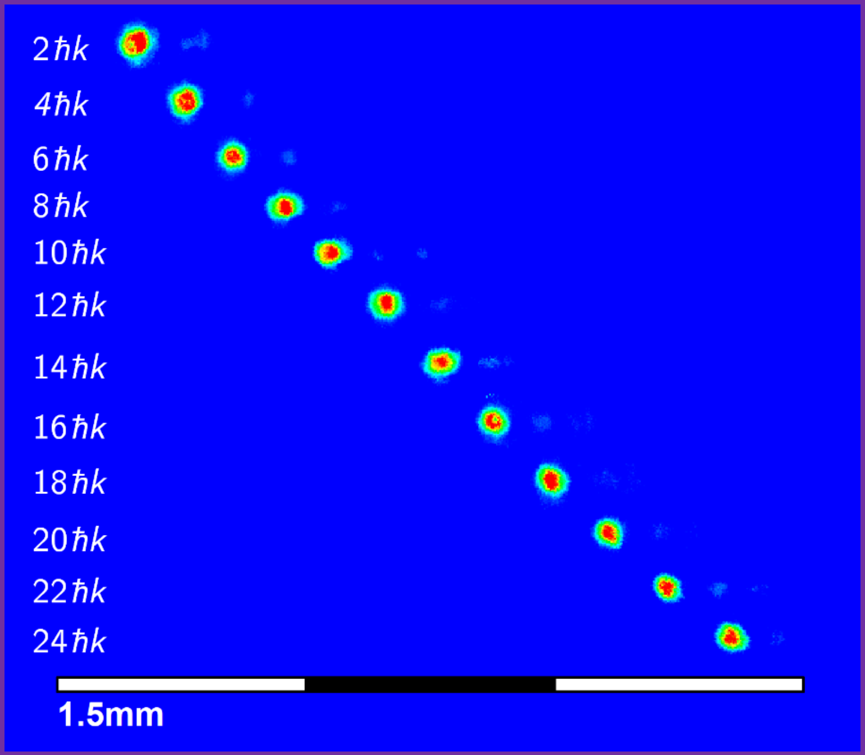
Can increase T with fountain, drop tower, rockets, in space

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

~ space-time area

Large momentum transfer atom optics can be very useful!

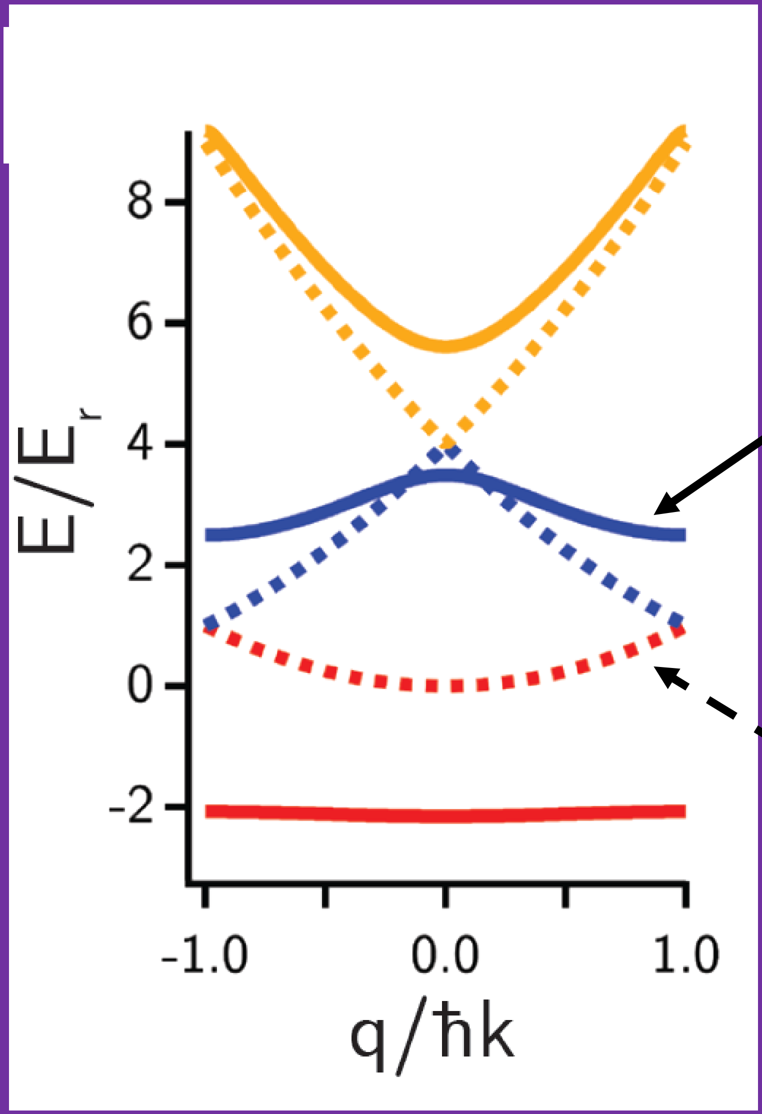
High Efficiency Momentum Transfer by Bloch Oscillations



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

Here Bloch oscillations by sweeping frequency difference between laser beams

Quantum Transport Approach to Atom Optics



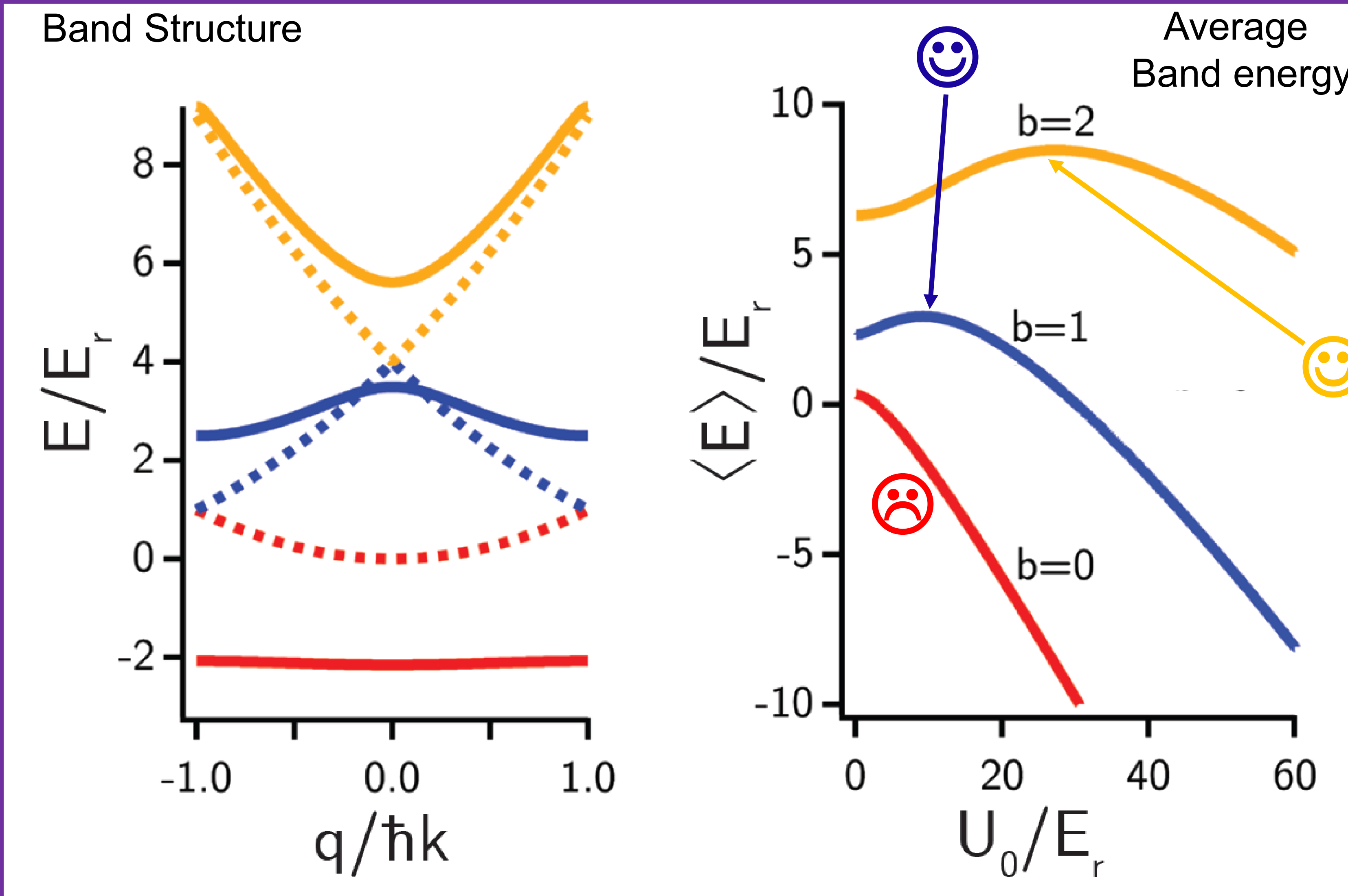
Using ideas from condensed-matter to develop a tool in precision atomic physics

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

Free particle dispersion

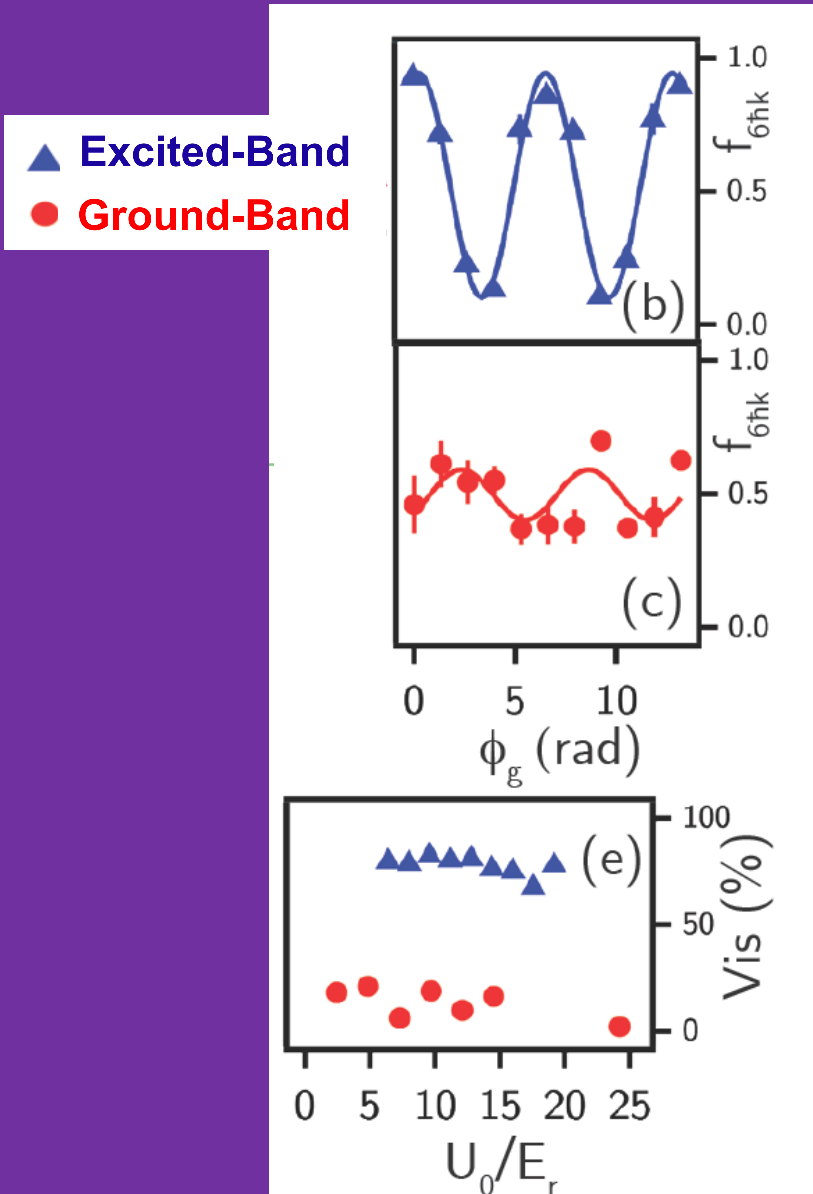
Band Structure in 1D sinusoidal periodic potential (Optical Lattice)

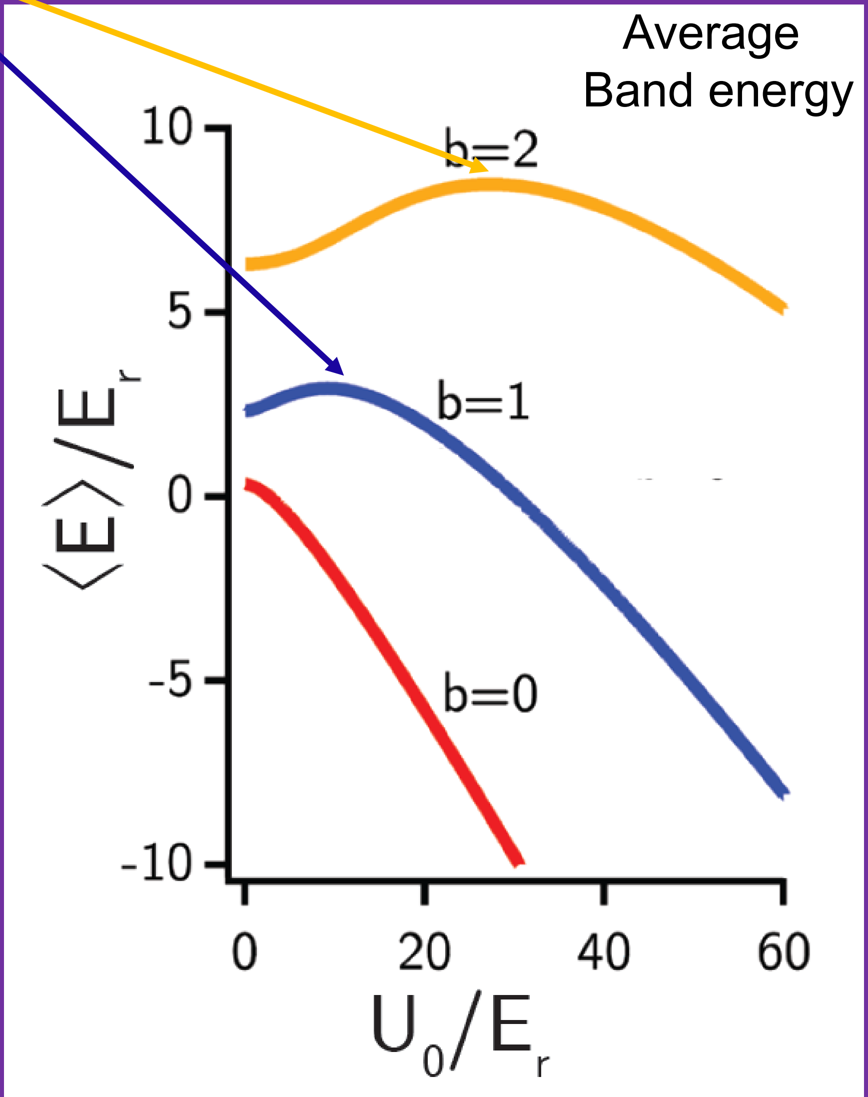
Quantum Transport Approach to Atom Optics



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

"Magic Depth" Interferometry





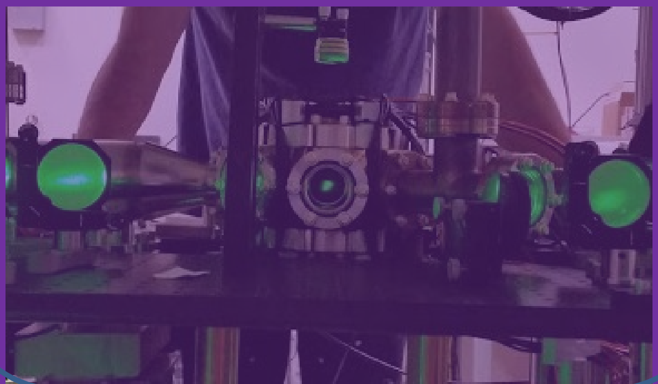
Next: Magic Trapped Atom Interferometry -
Gravimetry in a magic depth trapped geometry

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)

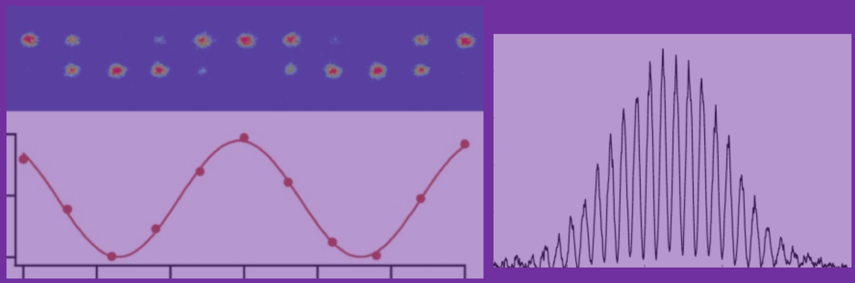
Today:

Taming Atoms:

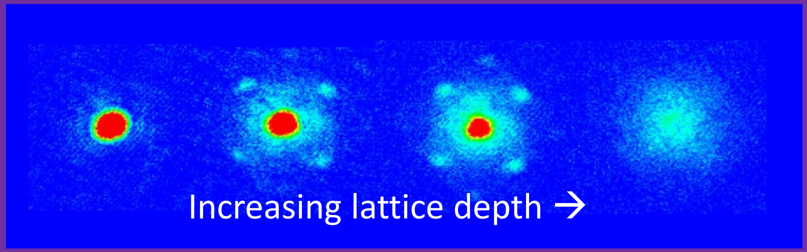
Making quantum gases



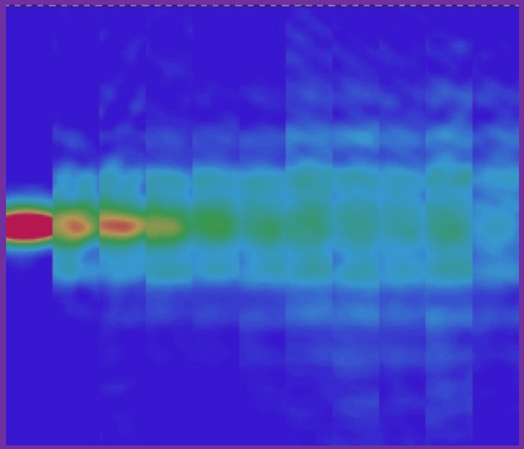
Coherence: Atom Optics and Interferometry



Correlations: Interactions, creating few- and many-body states

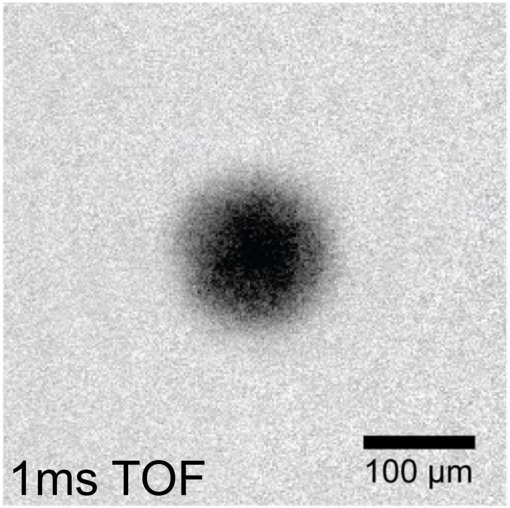


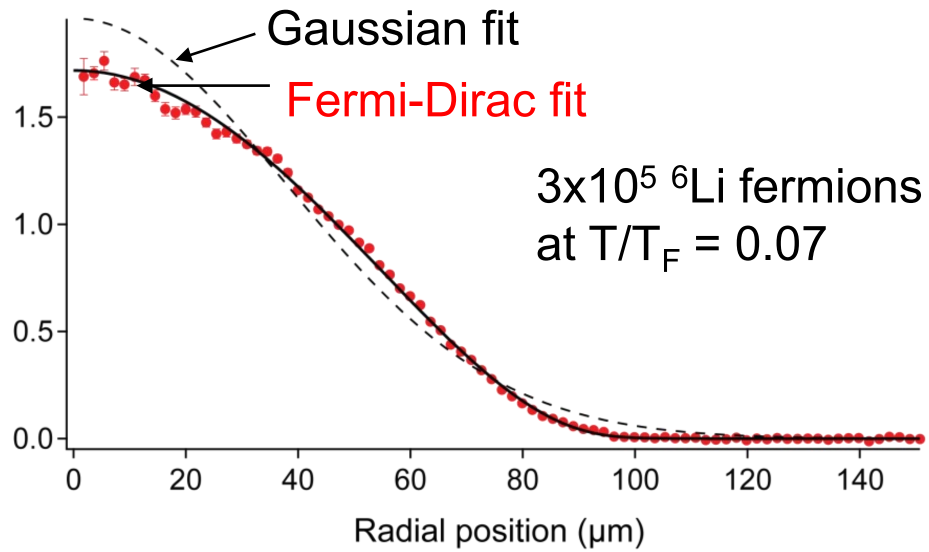
Mott Insulator Transition



Chaos: Many-body Dynamical Delocalization

Role of Quantum Statistics: Fermion Degeneracy

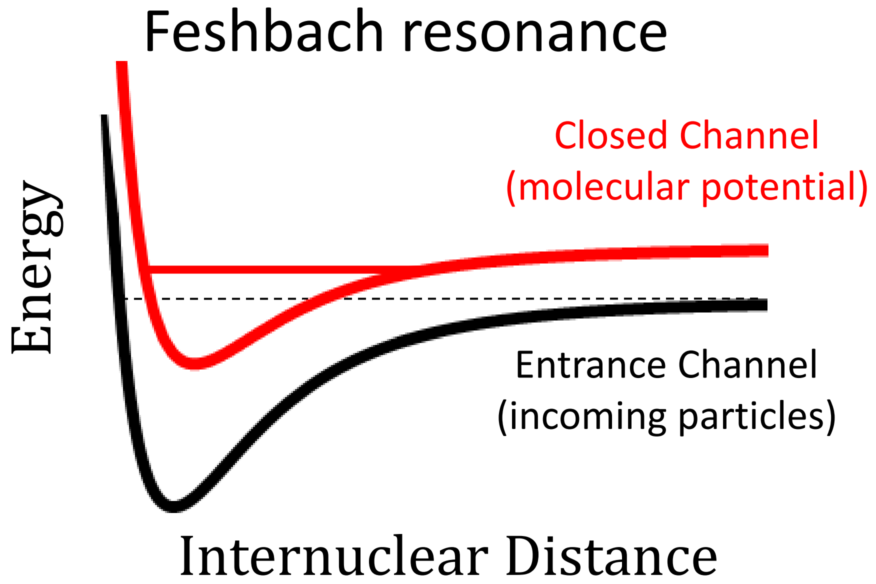




Fermi pressure due to Pauli Exclusion principle

Quantum Degeneracy: $n\lambda_{dB}^3 \sim 1$ => $T_F \sim 1\mu K$

Controlling interactions



Resonance between two free atoms and a molecule

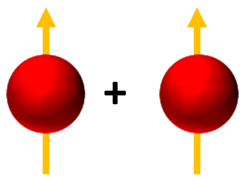
Control with external magnetic field

- Example

$^6\mathrm{Li} + {}^6\mathrm{Li}$

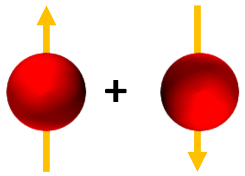
<u>Entrance channel</u>

Triplet:

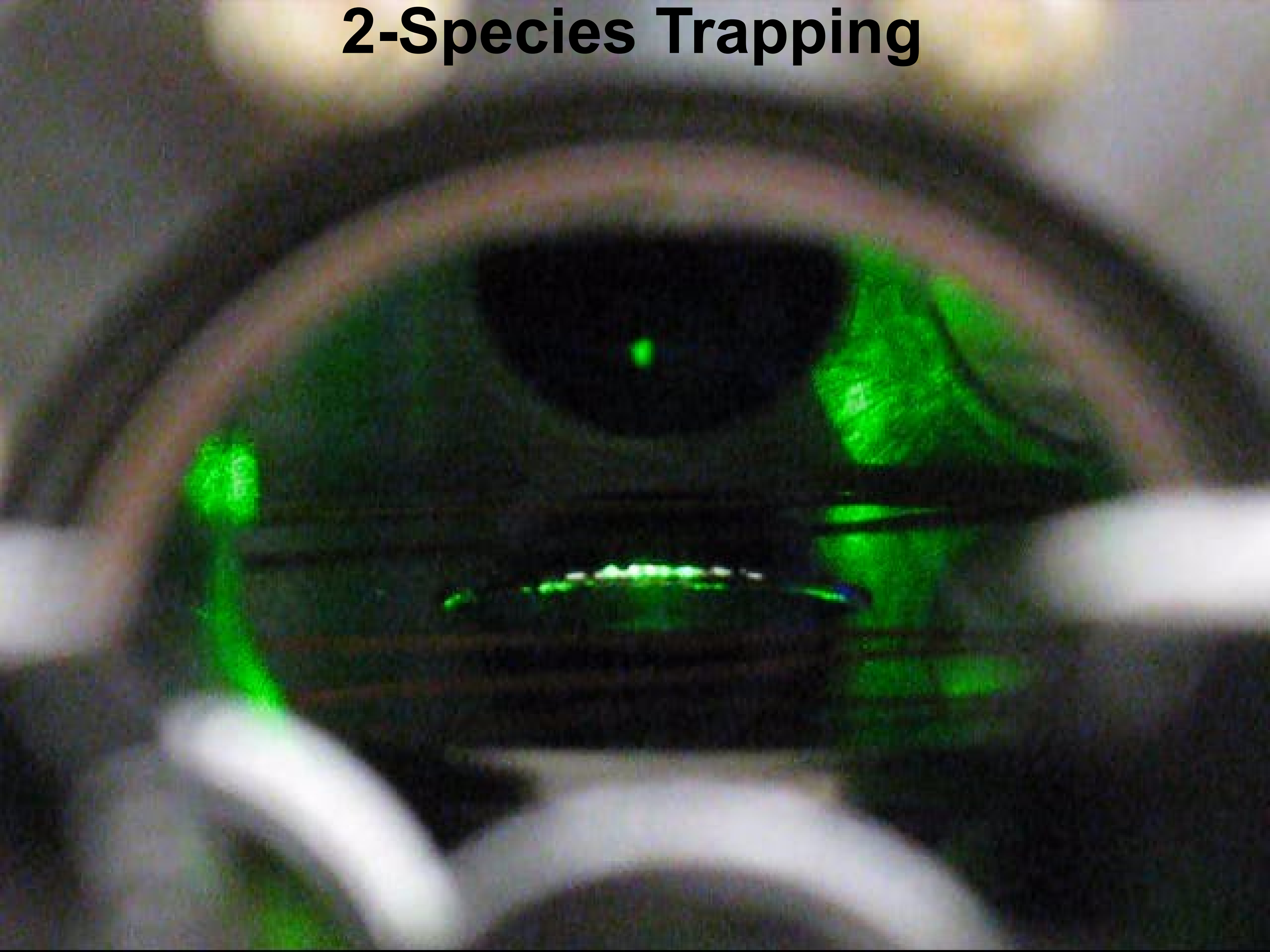


<u>Closed channel</u>

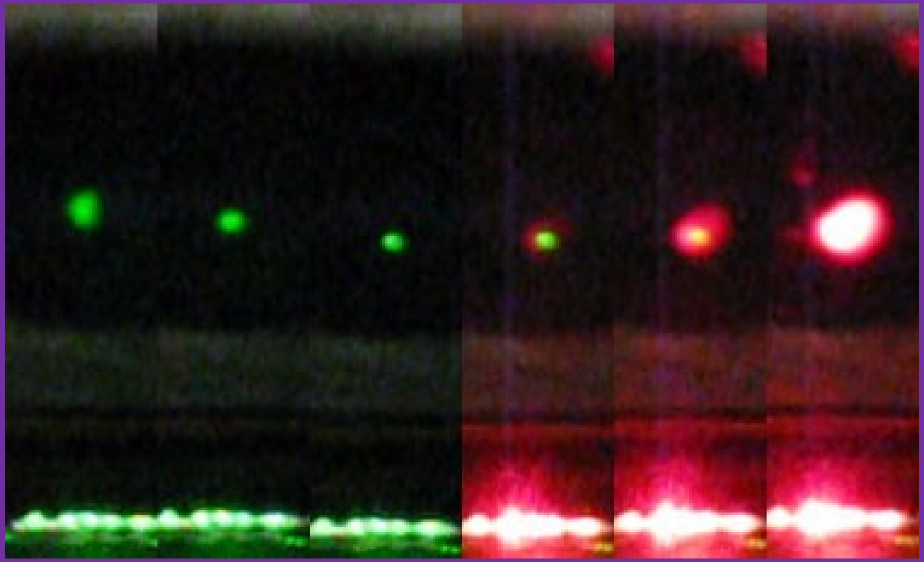
Singlet:



2-Species Trapping



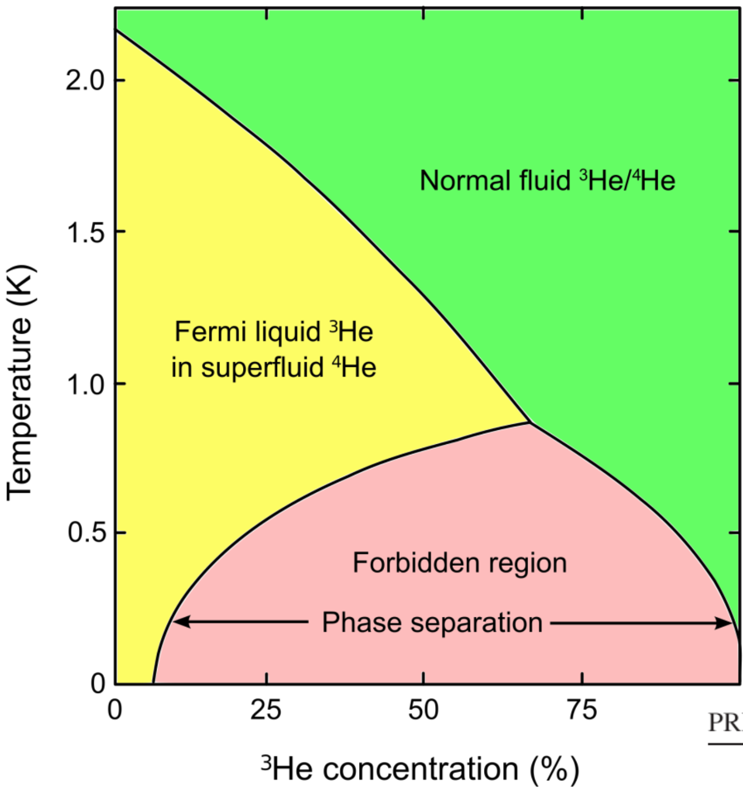
2-Species Trapping



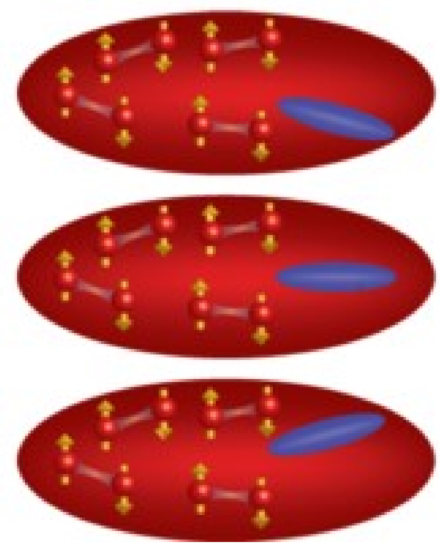
Time

Bose-Fermi Double Superfluid

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



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

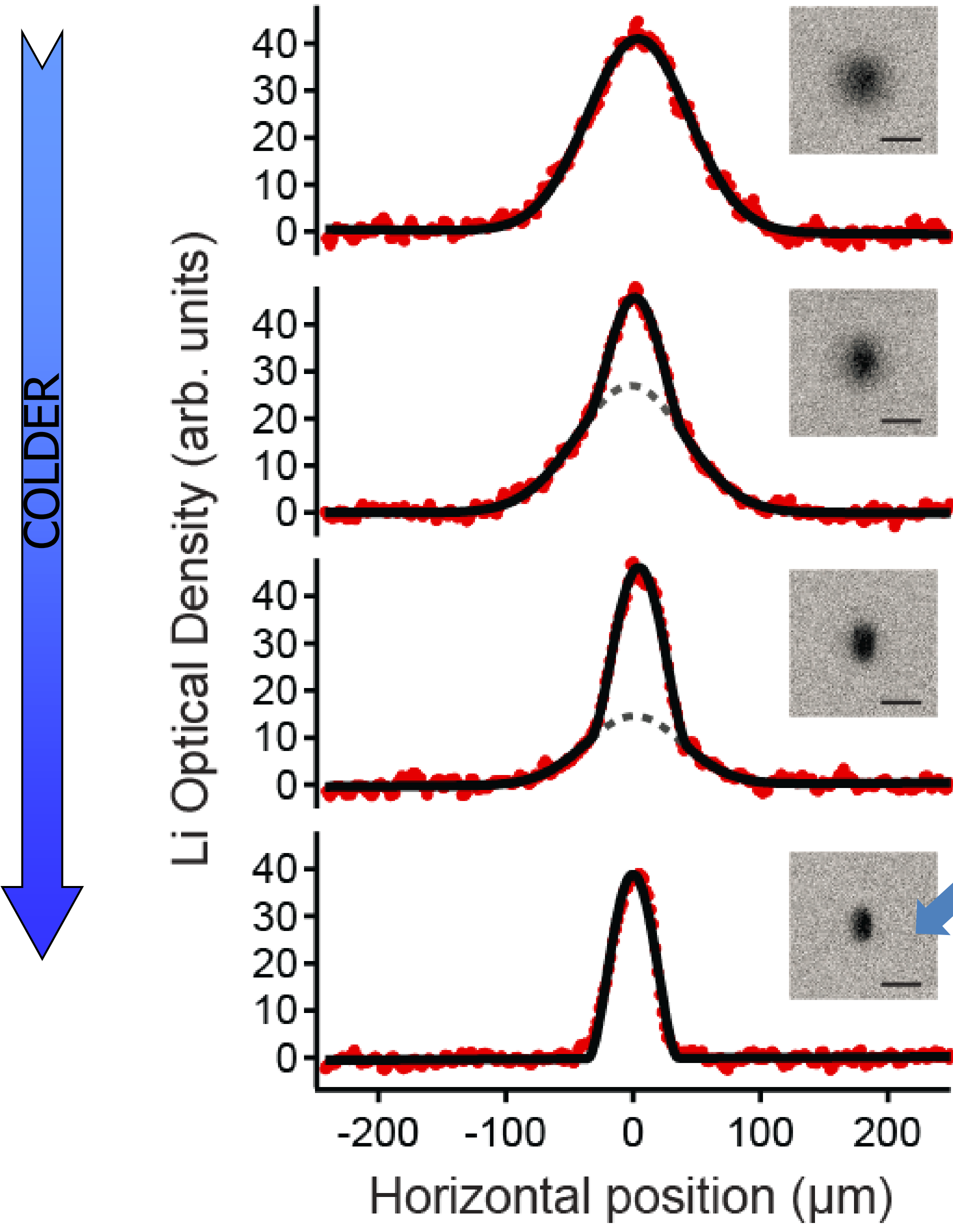


PRL **118,** 055301 (2017) PHYSICAL REVIEW LETTERS

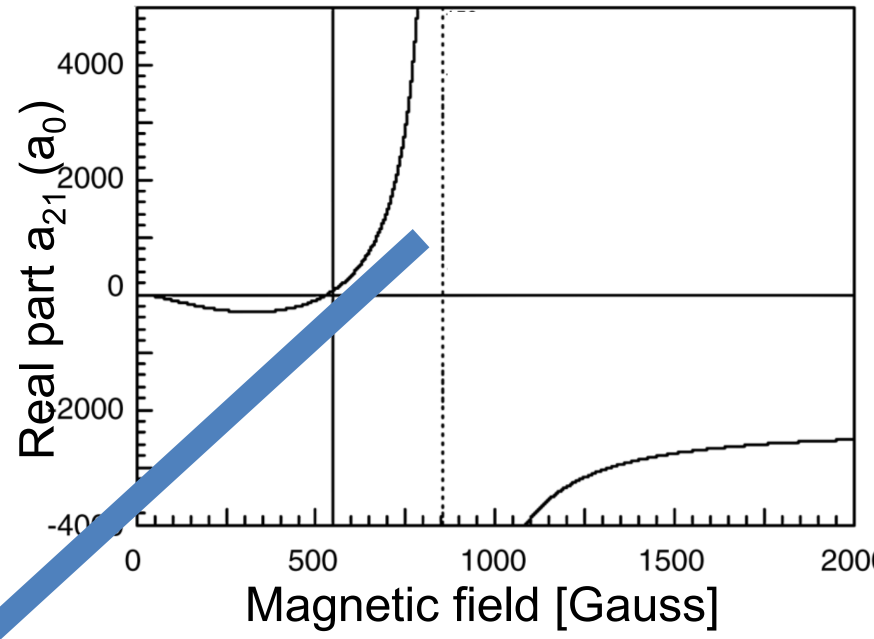
Two-Element Mixture of Bose and Fermi Superfluids

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)

Li_2 Fermionic Superfluidity

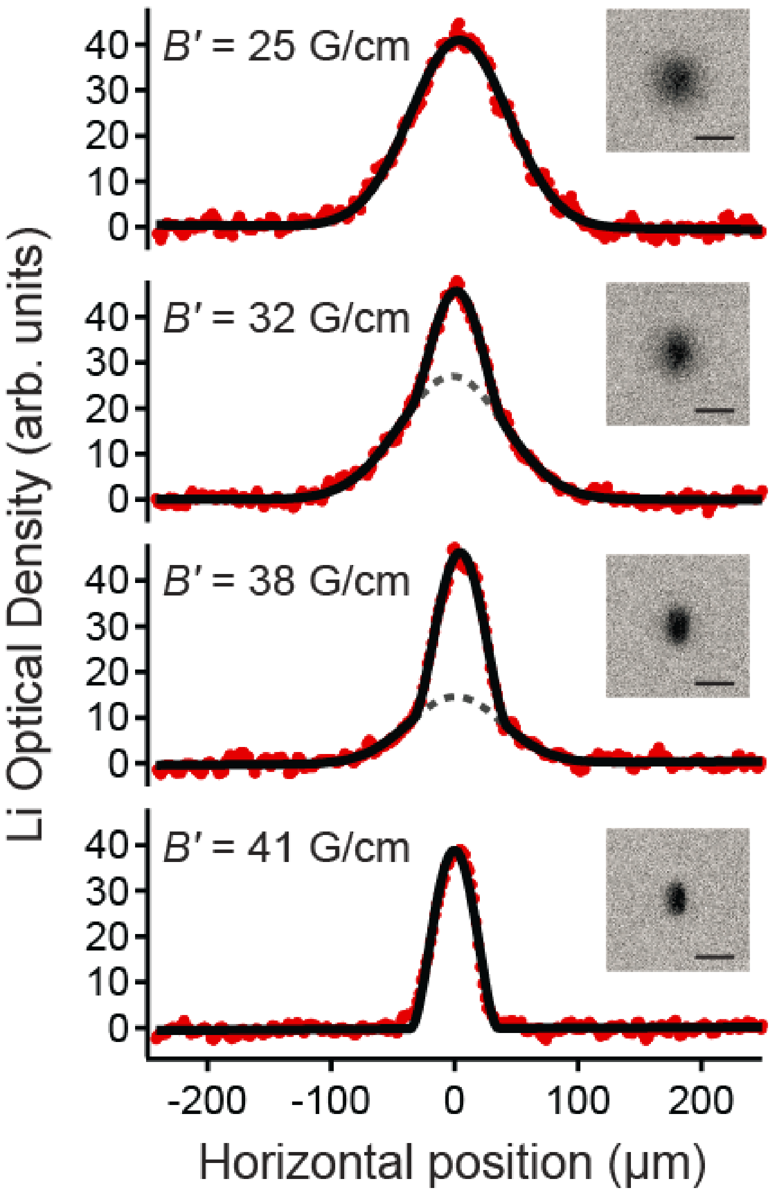


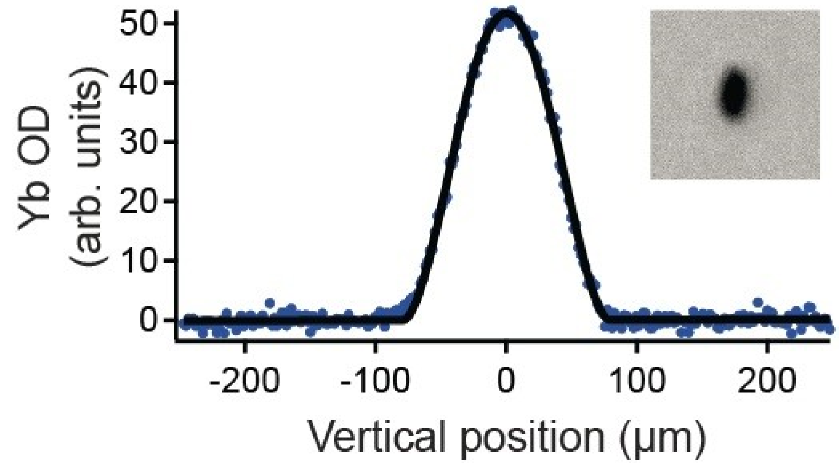
Magnetic Feshbach Resonance (MFR)

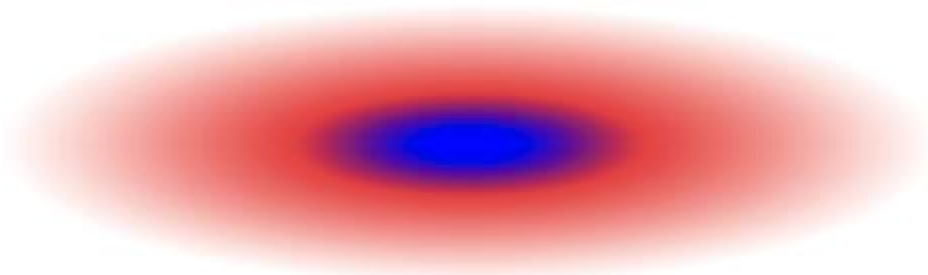


Formation of molecular BEC
(Fermionic SF $T_c \sim 0.18T_F$)

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







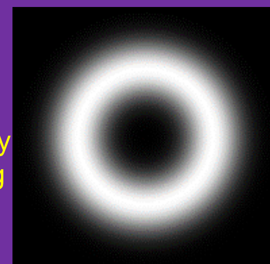
R.J. Roy et al. Phys Rev Lett **118**, 055301 (2017)

Proposed detection of Entrainment in a mixture of superfluids

(with Forbes group, WSU)

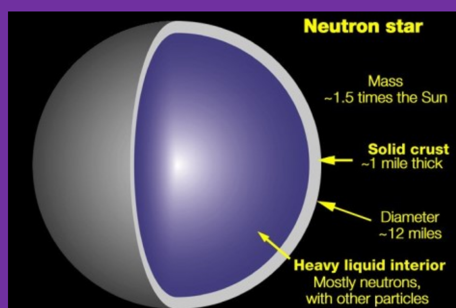
Dissipation-free drag of one SF by another: Current-Current coupling

Andreev-Bashkin effect predicted for ^{4}He-^{3}He superfluid mixture.



$$\boldsymbol{v}_b = \frac{\hbar \boldsymbol{\nabla} \phi_b}{m_b}$$

Ring trap to suppress density-density coupling (mean field) effects, X100 stronger in e.g. dipole oscillation

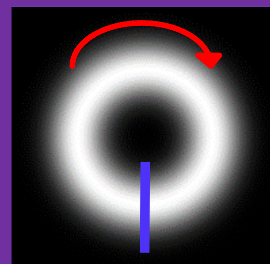


Entrainment between proton and neutron fluids in neutron stars play a role in "glitching" in pulsars

BEC in a ring trap: K.C. Wright et al. Phys Rev Lett **110**, 025302 (2013)

Proposed detection of Entrainment in a mixture of superfluids

(with Forbes group, WSU)

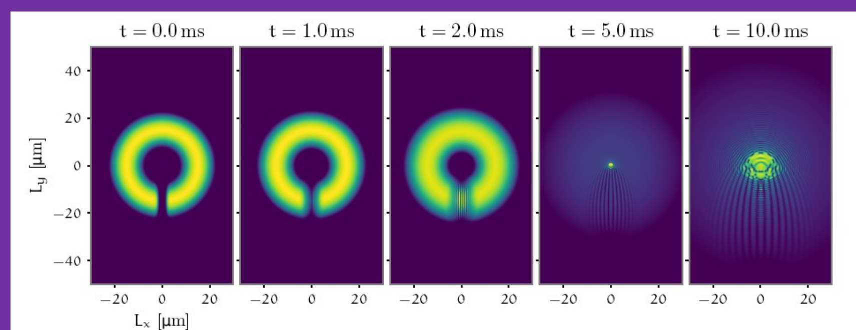


Block flow in one species, induce circulation in other

$$\boldsymbol{v}_b = \frac{\hbar\nabla\phi_b}{m_b} - \frac{\rho_{\mathrm{dr}}}{m_b n_b}\left(\frac{\hbar\nabla\phi_b}{m_b} - \frac{\hbar\nabla\phi_D}{m_D}\right),$$
$$\boldsymbol{v}_D = \frac{\hbar\nabla\phi_D}{m_D} - \frac{\rho_{\mathrm{dr}}}{m_D n_D}\left(\frac{\hbar\nabla\phi_D}{m_D} - \frac{\hbar\nabla\phi_b}{m_b}\right).$$

Finite $\nabla\phi_b$ leads to shift of up to 2/3 fringe in interference pattern (~ 5um in 60ms TOF)

Interference in time-of-flight



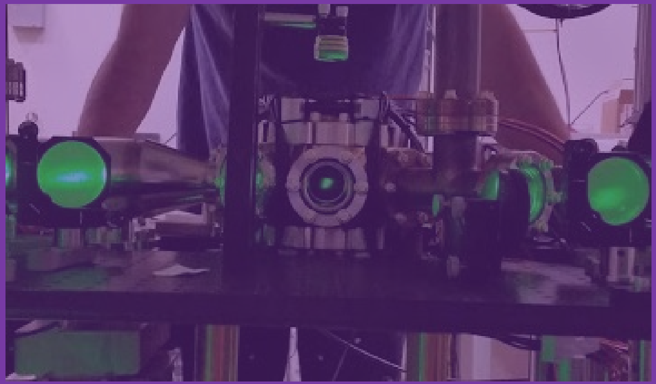
Numerical Simulation by Khalid Hossain, WSU

Hossain, Gupta, Forbes, Phys Rev A, 105, 063315 (2022).

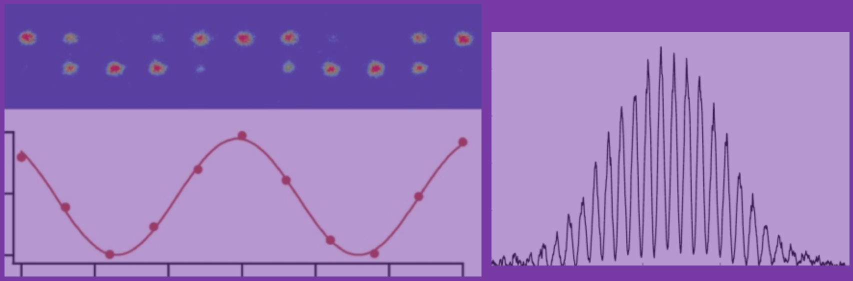
Today:

Taming Atoms:

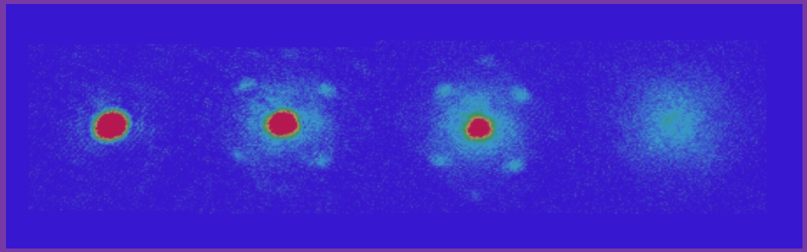
Making quantum gases

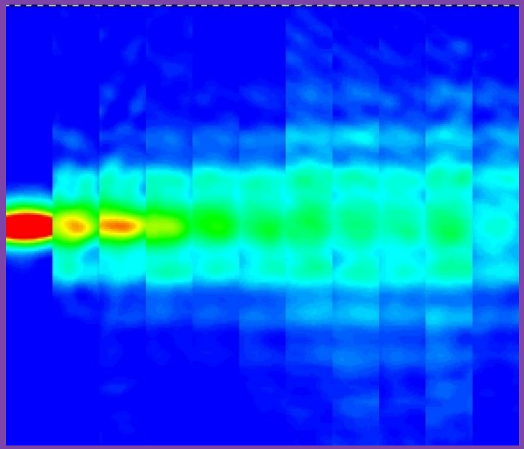


Coherence: Atom Optics and Interferometry



Correlations: Interactions, creating few- and many-body states





Chaos: Many-body Dynamical Delocalization

Some Simple Classical Systems Exhibit Chaos

Double Pendulum

Demo: https://www.youtube.com/watch?v=U39RMUzCjiU

δ-Kicked Rotor/Rotator

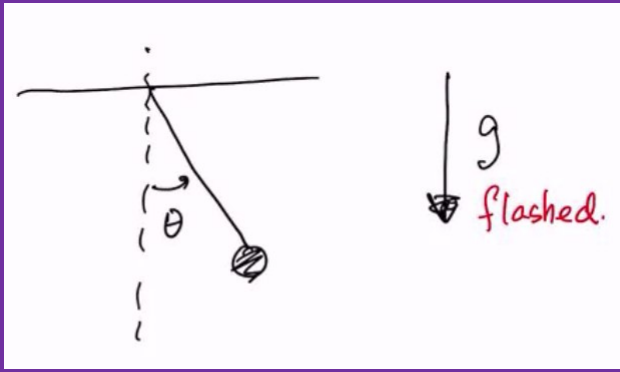
https://en.wikipedia.org/wiki/Kicked_rotator

What about the quantum version of classically chaotic systems?

Quantum Simulation of **Many-Body** Kicked Rotor/Rotator

Classical Kicked Rotor: textbook example of chaos in classical mechanics

B. Chirikov Phys. Rep. 52, 263 (1979)



$H(p,x,t) = p^2/2 + K \cos(\theta)\sum_n \delta(t-n)$

Total Energy = Kinetic + Potential (Potential is flashed)

The classical kicked rotor/rotator exhibits chaos above a critical kick strength K.

Energy grows **linearly** with *n* in the chaotic regime.

Many references, including Wikipedia: https://en.wikipedia.org/wiki/Kicked_rotator

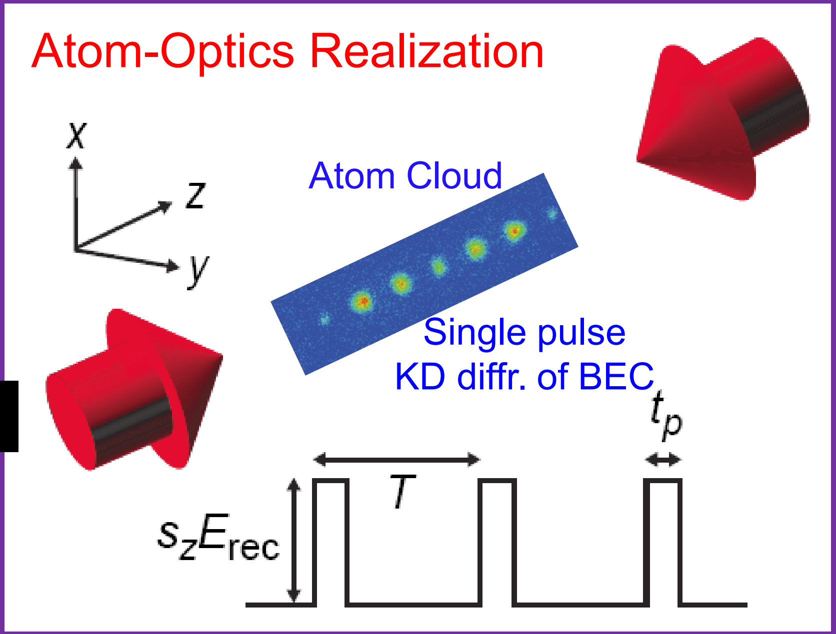
Quantum Kicked Rotor

Quantum Kicked Rotor (QKR) Hamiltonian

$$H = -\frac{\hbar^2}{2m}\frac{\partial^2}{\partial z^2} + K\cos(2kz)\sum_{n\in\mathbb{Z}}\delta(t-nT)$$

QKR: Atom Optics realization by Mark Raizen group
F. Moore et. al. PRL 75, 4598(1995)

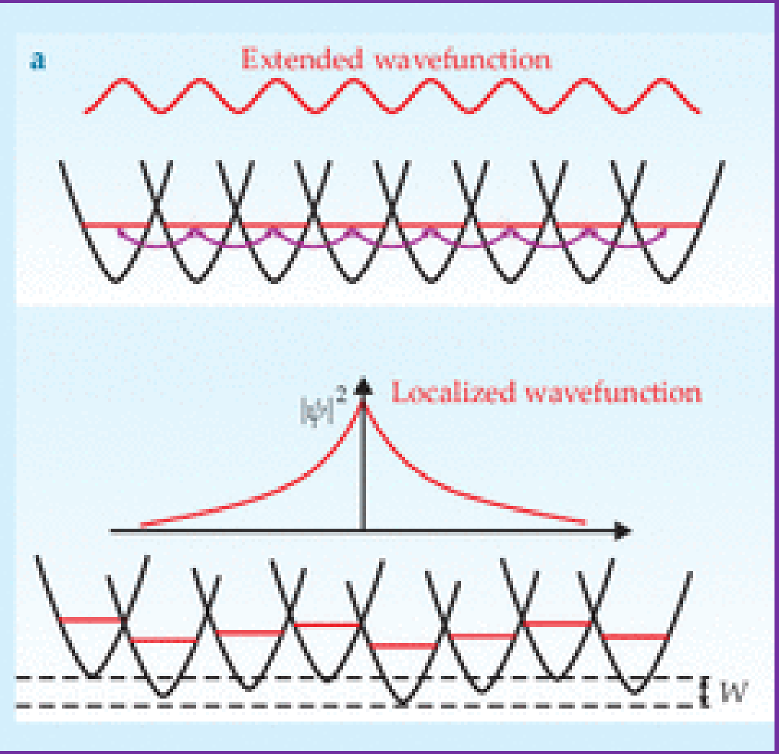
The energy growth of the classical case is arrested by quantum-mechanical interference.



$k=2\pi/\lambda$

Single-particle physics of dynamical localization and quantum resonances (kick period and Talbot time ($2m\lambda^2/h$) are (in) commensurate) studied by many groups since 1995….

Anderson Localization (1958):
Interference driven insulator due to lattice disorder



Recent questions:
How do interactions change this interplay between interference and disorder?
Under what conditions do you get many-body localization?

Fig. from Physics Today, August 2009

QKR equivalent to Anderson Quantum Transport in p-space

synthetic dimension

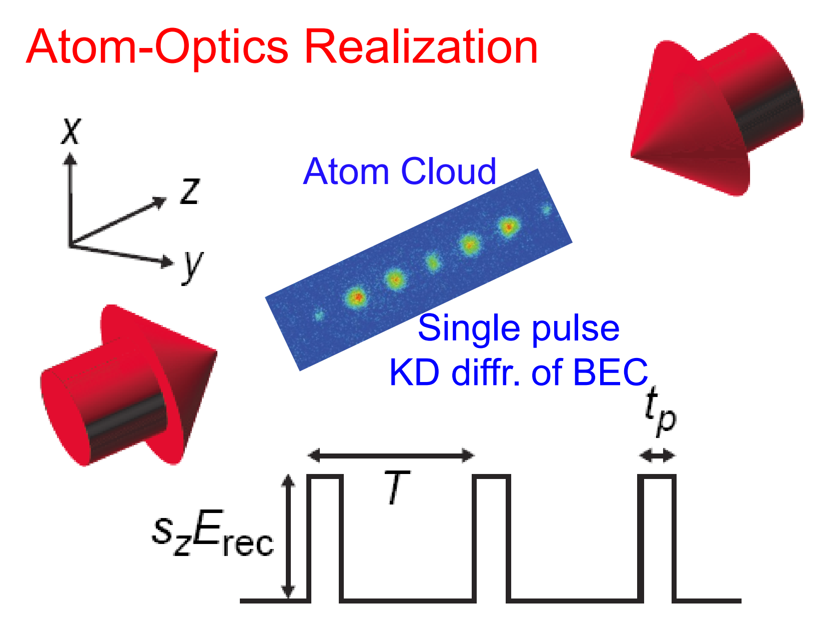
Quantum Kicked Rotor (QKR) Hamiltonian

$$H = -\frac{\hbar^2}{2m}\frac{\partial^2}{\partial z^2} + K\cos(2kz)\sum_{n\in\mathbb{Z}}\delta(t-nT)$$

Pseudo-random phase acquired at each lattice point in momentum.

K controls tunneling - Kapitza-Dirac diffraction (phase grating) to momenta ($2h/\lambda$) multiples apart

Dynamical Localization in *p*-lattice in the QKR is equivalent to Anderson localization in *z*.
S. Fishman et al. PRL 49, 509 (1982)
Disorder is “built-in”



Quantum Kicked Rotor + Interactions?

Kinetic + Potential

Quantum Kicked Rotor (QKR) Hamiltonian

$$H = -\frac{\hbar^2}{2m}\frac{\partial^2}{\partial z^2} + K\cos(2kz)\sum_{n\in\mathbb{Z}}\delta(t-nT) \quad \text{+ interactions}$$

simplest:
mean field interaction ~ a_s X density
but, contact in *x* => long-range in *p*

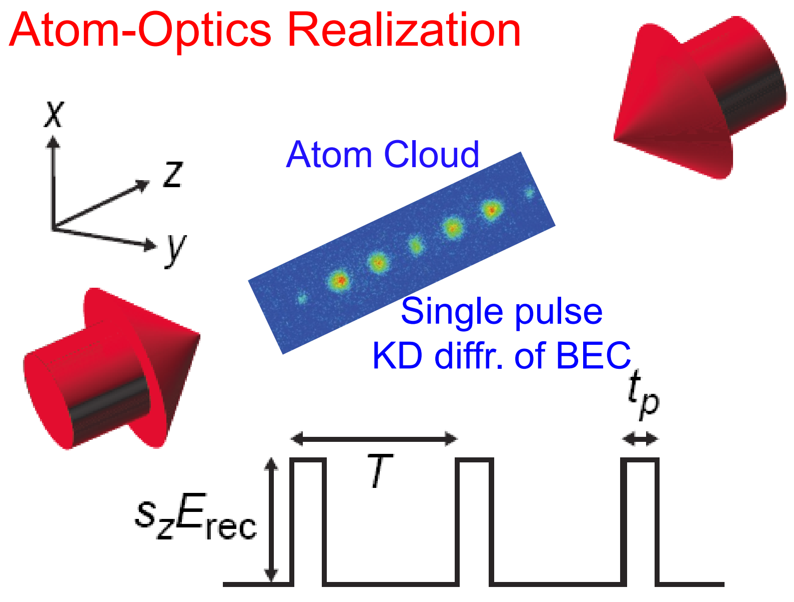
Interacting (or many-body) QKR:
Large body of theoretical work.
eg C. Zhang et al PRL **92**, 054101 (2004)
S. Lellouch et al PRA **101**, 043624 (2020).
V. Galitski & collabs. PRL **124**, 155302 (2020)
& several others (Sheplyanksy, Flach,..)
But no prior experimental signatures despite efforts since mid-90s.

Existing Contradictions in the theory:
Mean-field (gn_{1D}) numerics predict delocalization with sub-diffusive evolution: $\langle E_z \rangle = A^* t^{\alpha}$ ($0<\alpha<1$)

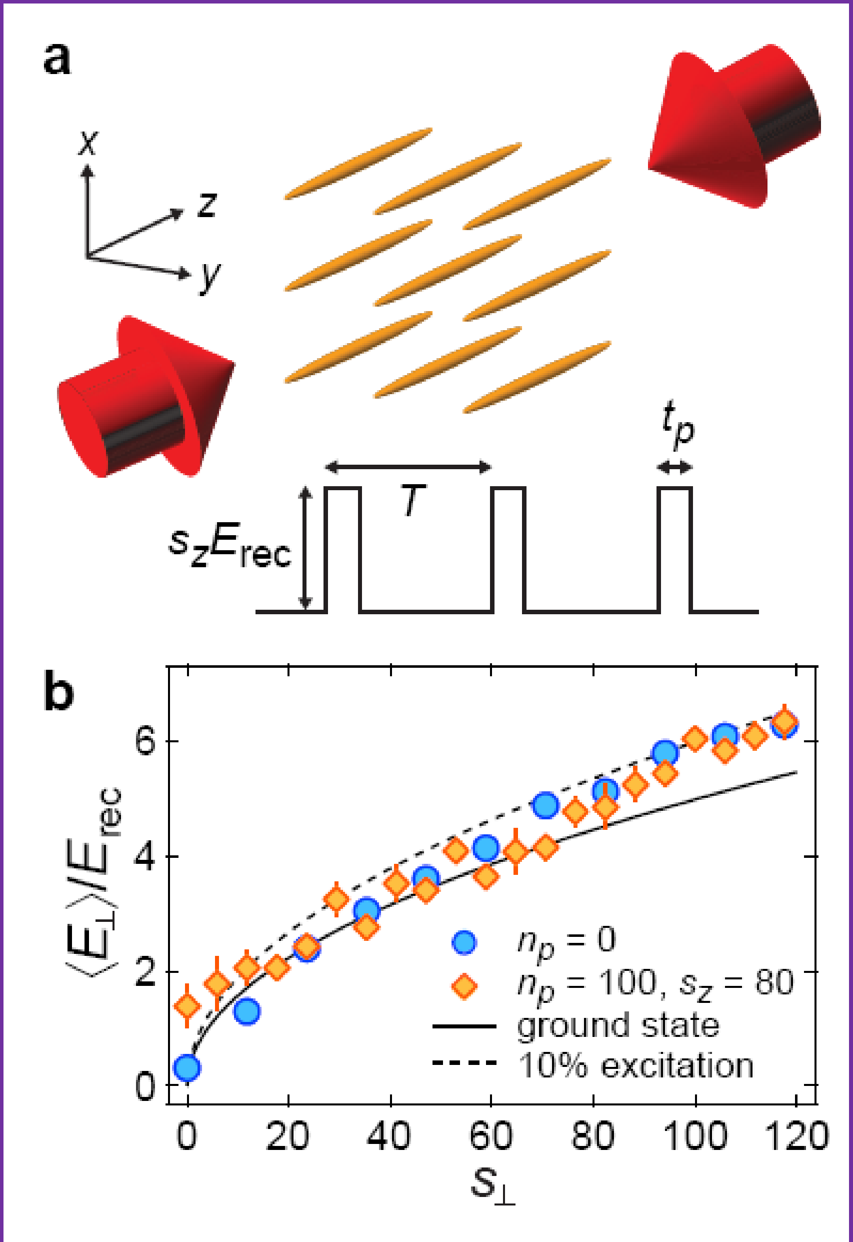
Beyond MF, low energy Luttinger liquid theory in 1D predicts $\alpha=0$ ie, localization

Connection to position-space many-body localization (MBL).

Atom-Optics Realization



QKR in tight 1D tubes

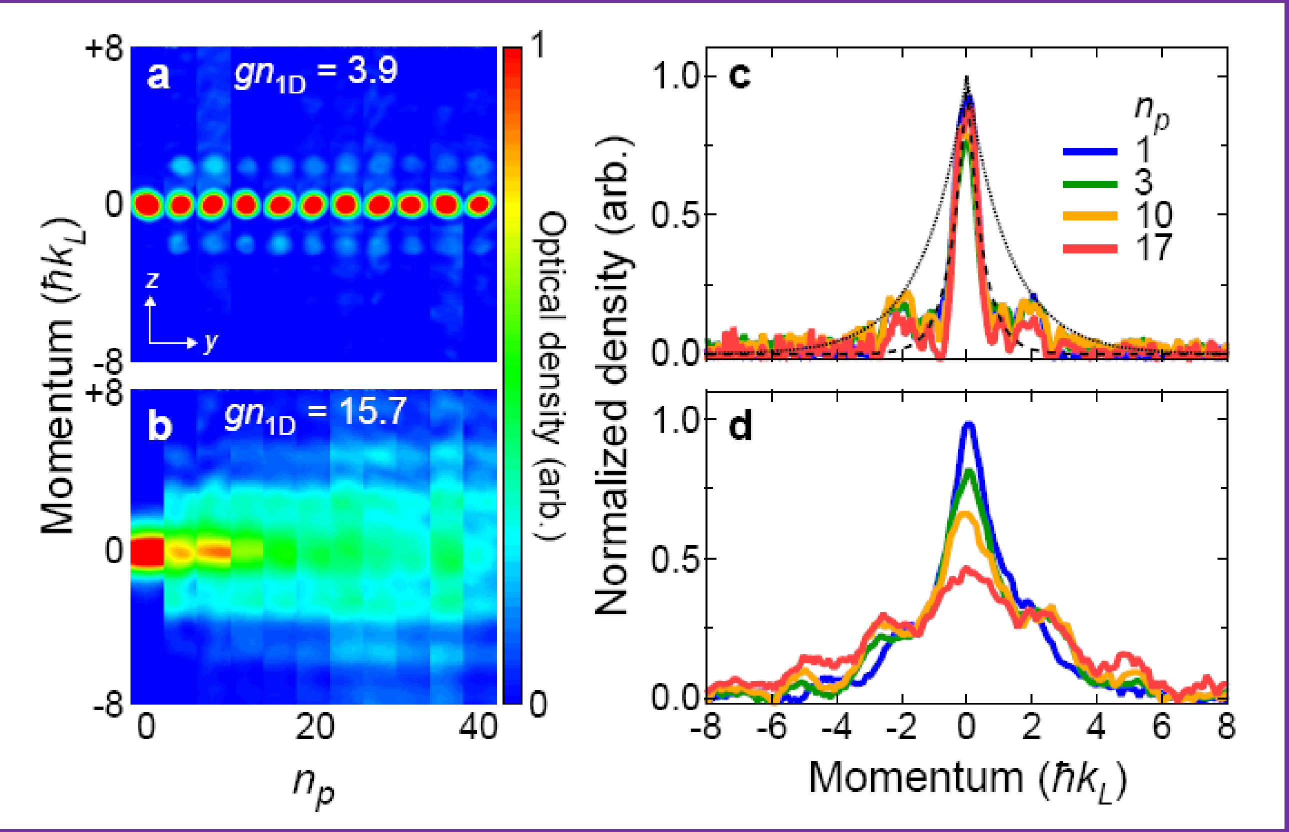


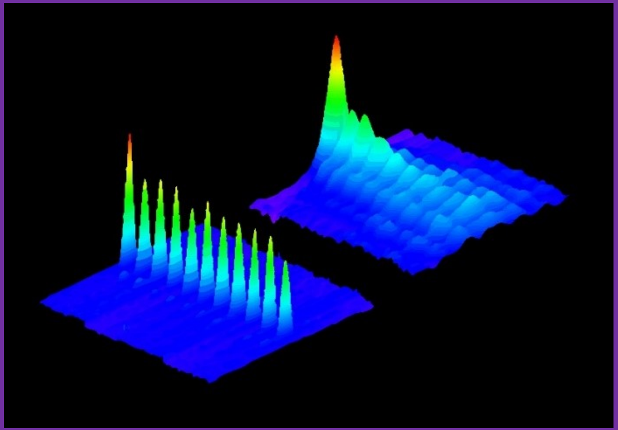
Size scales.
a_s = 5.6nm,
Osc length = 53nm,
Lattice spacing = 536nm.
Tunneling negligible for s > 15.

Dynamics restricted to 1D.
Emphasizes the “forward” part of the interaction.

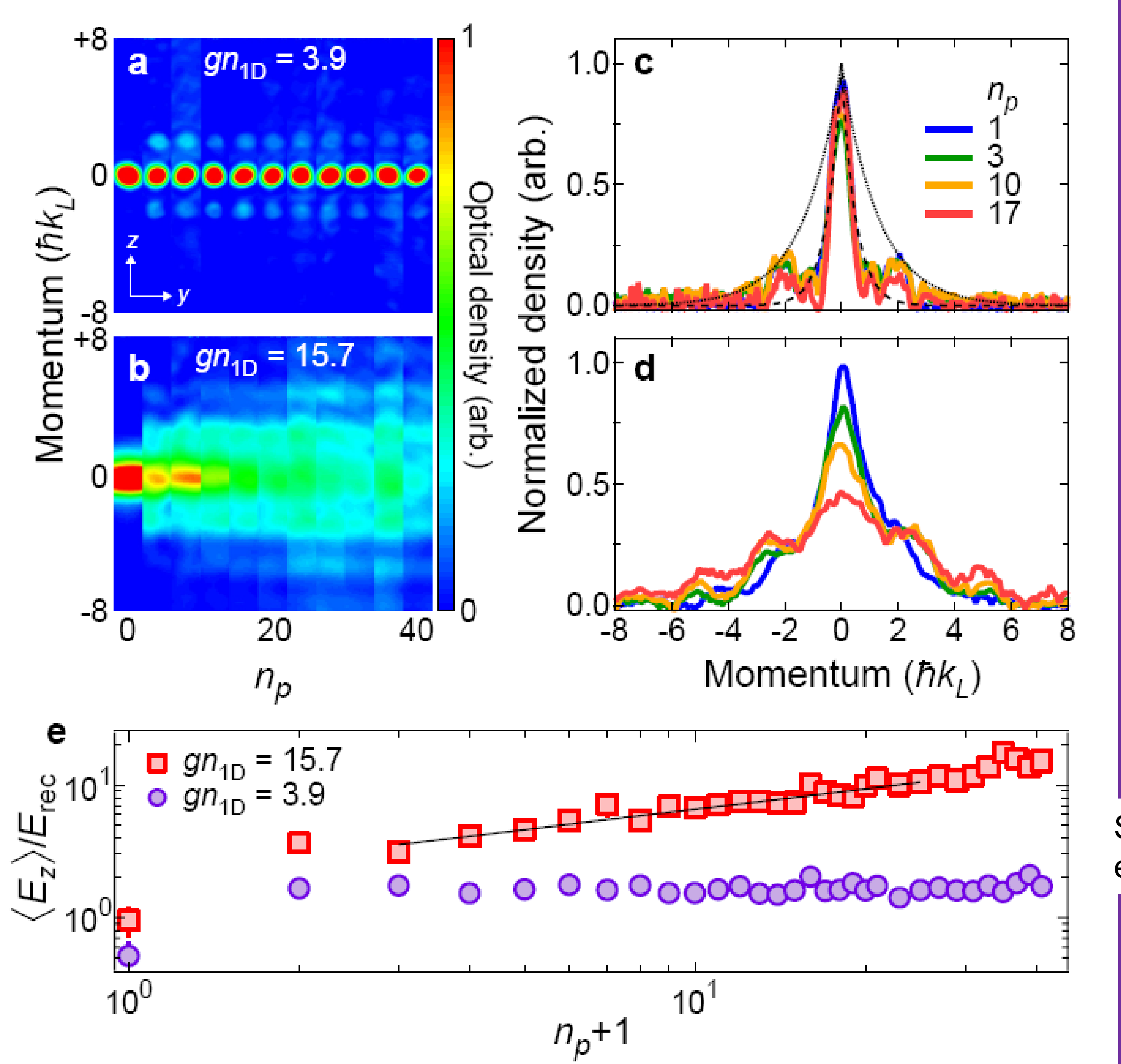
n_p = pulse number

Transition from Localization to Anomalous Diffusion





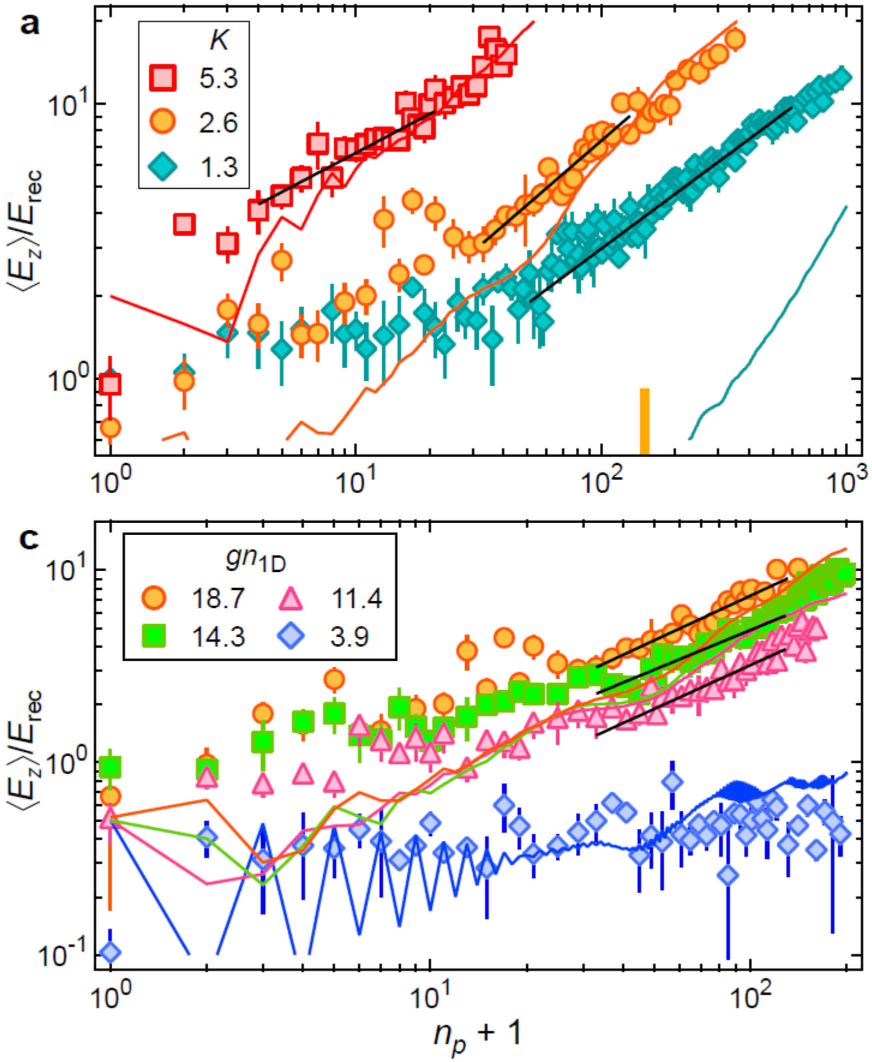
Transition from Localization to Anomalous Diffusion



Sub-diffusive with exponent ~ 0.5 (<1)

Jun Hui See Toh et al. Nat. Phys. **18**, 1297 (2022)

Delocalization vs Kick and Interaction Strengths

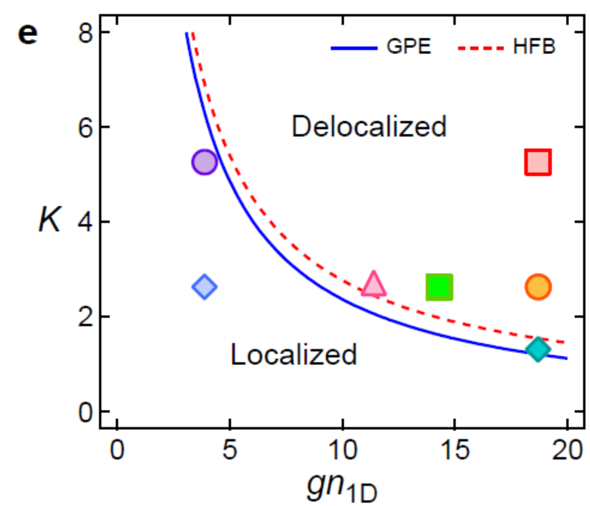


Earlier onset with K and gn

Exponent range (0.4-0.8)

Mean field theory breaks down for long onset times

Phase Diagram

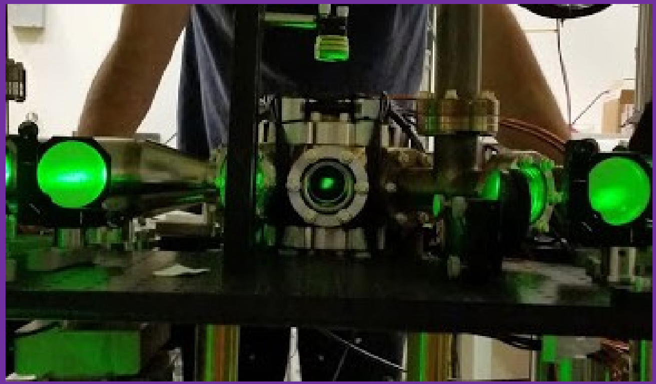


Jun Hui See Toh et al. Nat. Phys. **18**, 1297 (2022)

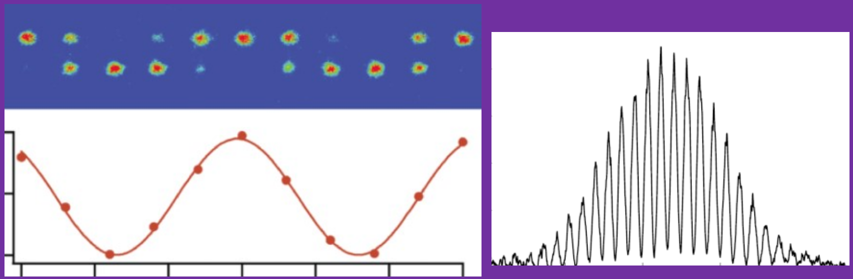
Today:

Taming Atoms:

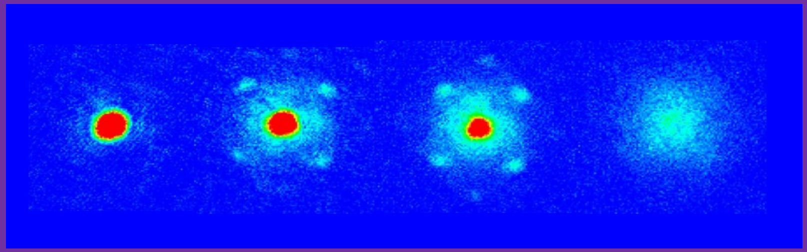
Making quantum gases

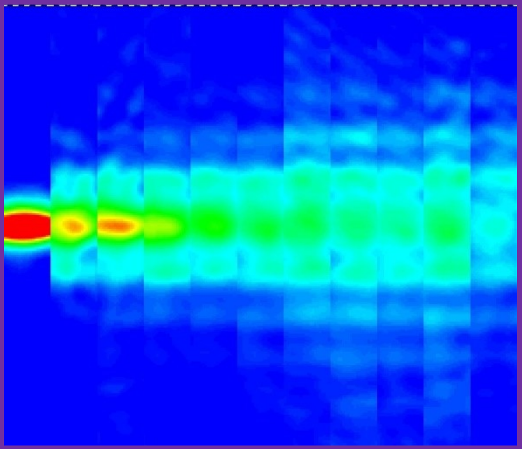


Coherence: Atom Optics and Interferometry



Correlations: Interactions, creating few- and many-body states





Chaos: Many-body Dynamical Delocalization

UW Ultracold Atoms and Quantum Gases Group

Members:

Xinxin Tang
Tahiyat Rahman
Carson Patterson
Nicolas Williams
Emmett Hough
Lynnx
Siddharth Mukherjee
Aidan Kemper
DG

Theory collaborators:

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