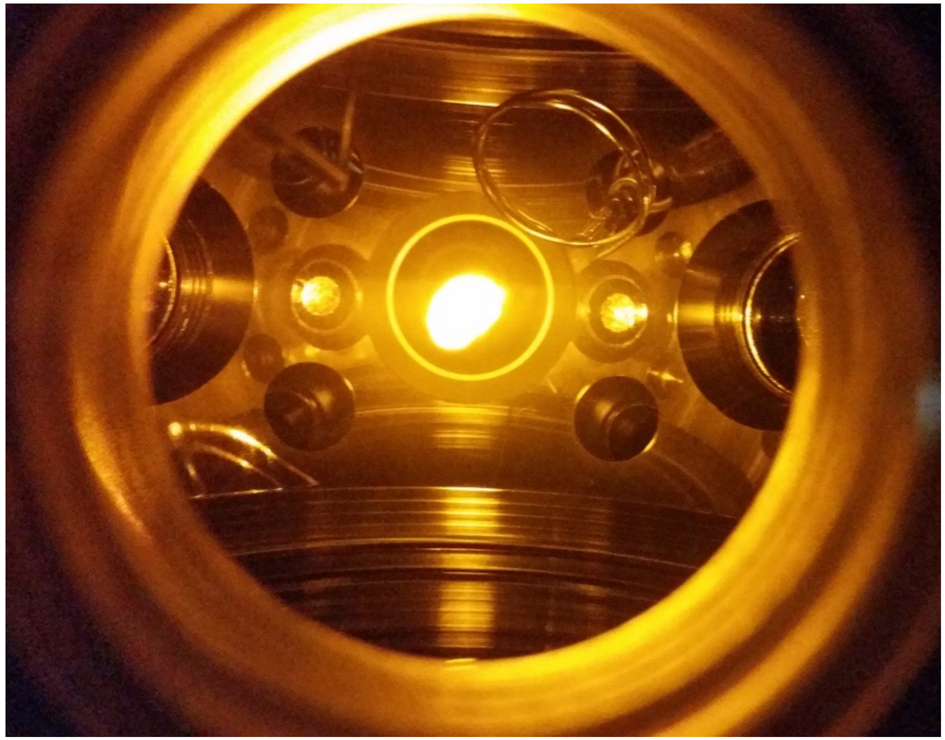
AMO Physics at OU



Arne Schwettmann

The University of Oklahoma
Homer L. Dodge Department of Physics and Astronomy

- New state-of-the art research building
- 18,000 sq. ft of research space, 12 labs
- NIST-A standards on vibration, temperature, and humidity control

CQRT

Center for Quantum Research and Technology

CENTER FOR QUANTUM RESEARCH AND TECHNOLOGY

The UNIVERSITY *of* OKLAHOMA

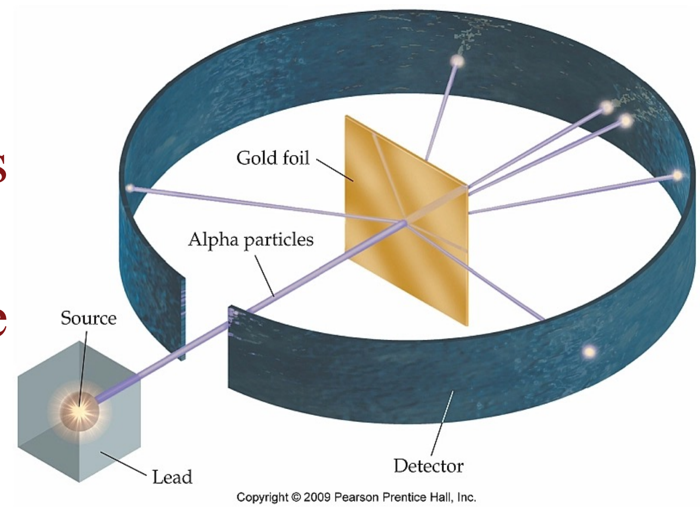
- World-class research complex for CM and AMO physics research
- New CQRT building seen adjacent to original physics building
- Always looking for graduate students, please apply.
- www.ou.edu/cqrt

Outline

- What is AMO?
- Why is AMO interesting?
  - Current developments
  - Quantum Technologies
- AMO Research at OU
  - Arne Schwettmann
  - Grant Biedermann
  - Eric Abraham
  - Emine Altuntas
  - D. Blume
  - Robert Lewis-Swan
  - Bihui Zhu

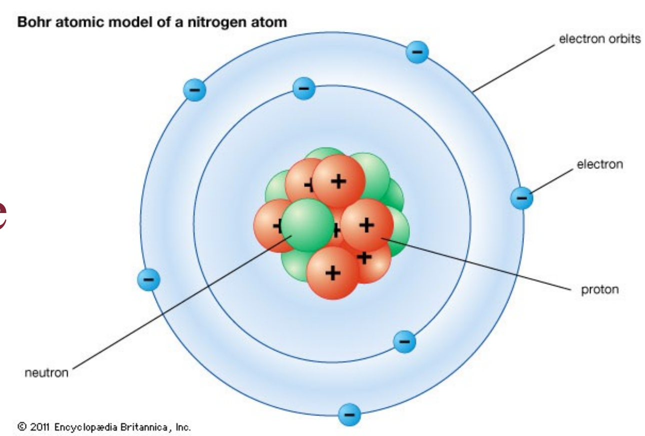
Atoms

- Ernest Rutherford, in 1911, discovered the structure of the atom by scattering alpha particles in gold foil
  - He won the 1908 Nobel prize



E. Rutherford

- Niels Bohr, in 1913, invents a quantized model of the atom
  - He won the 1922 Nobel prize

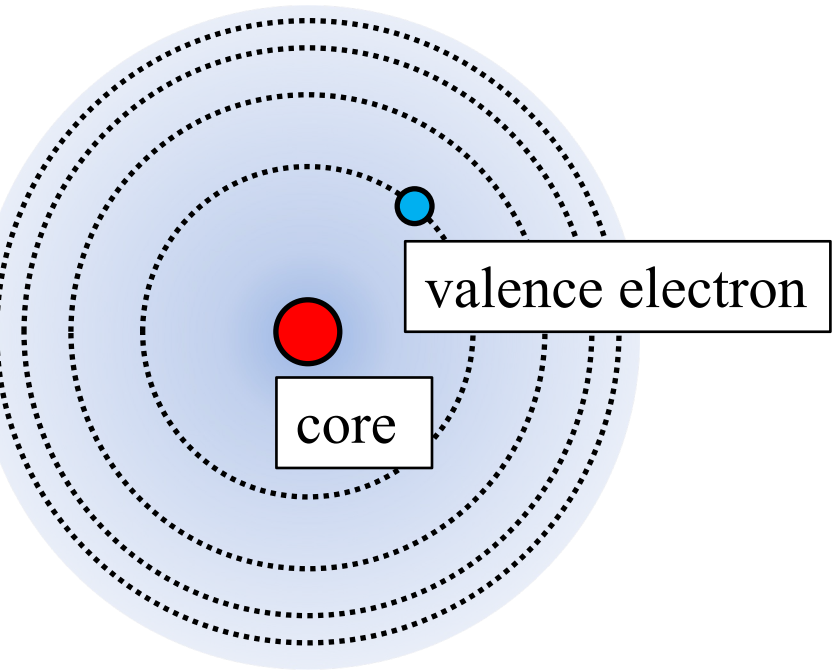


Niels Bohr

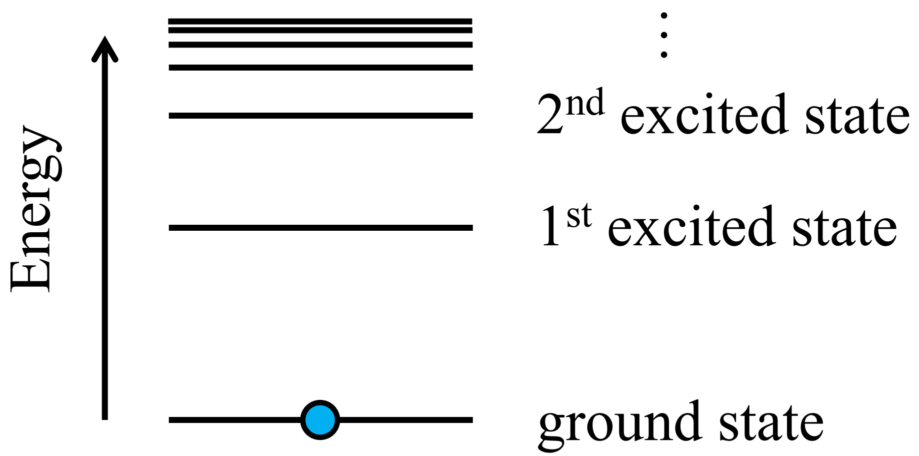
Atoms (cont'd)

- The valence electron in the atom has only discrete energies, called levels

Atom



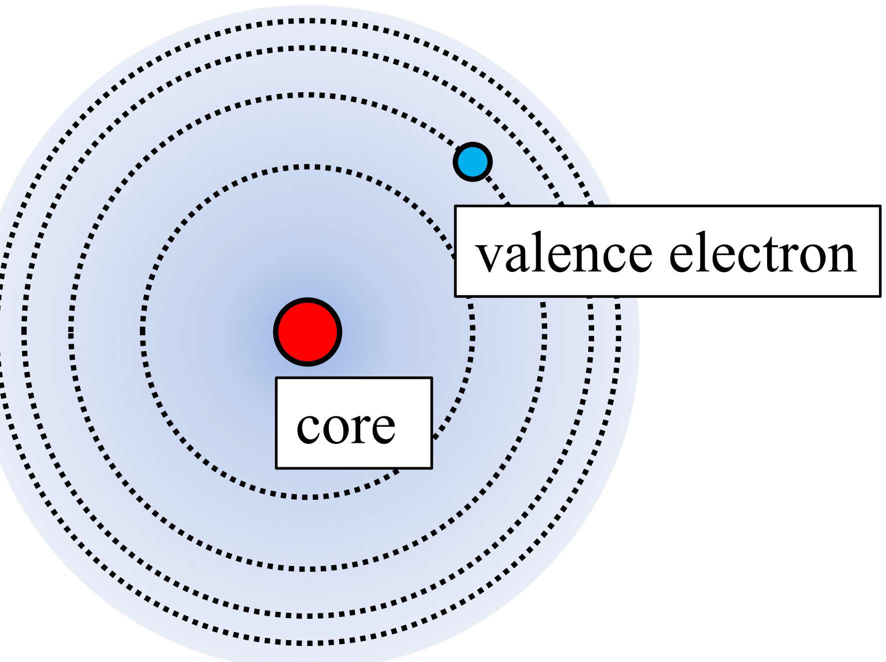
Energy Level Diagram



OU - AMO

Atoms (cont'd)

Atom



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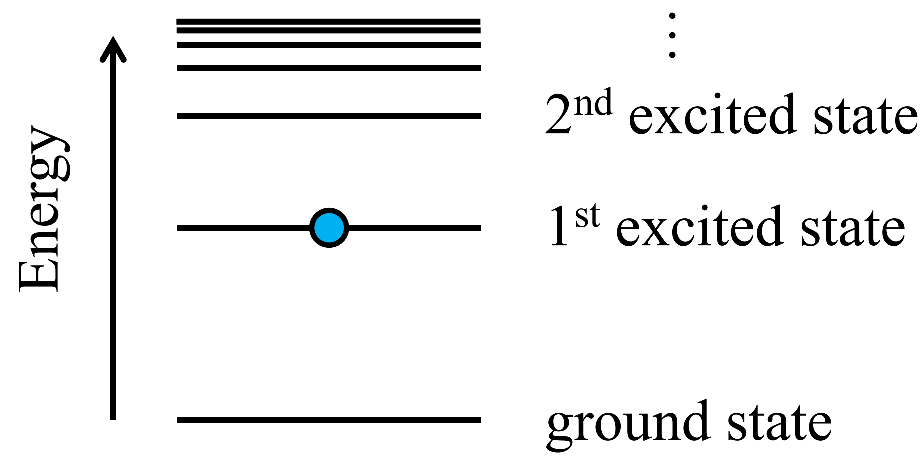

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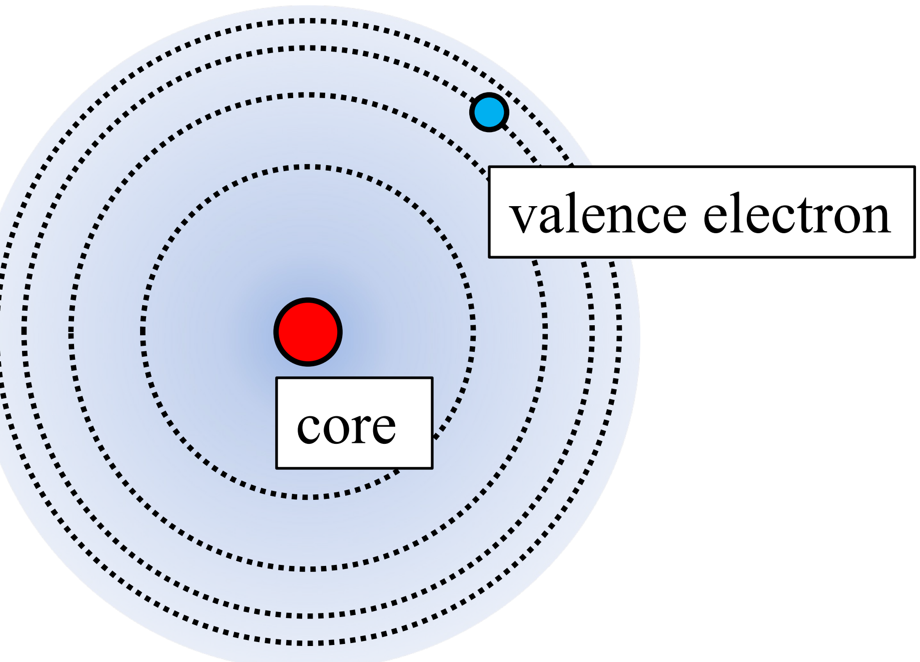

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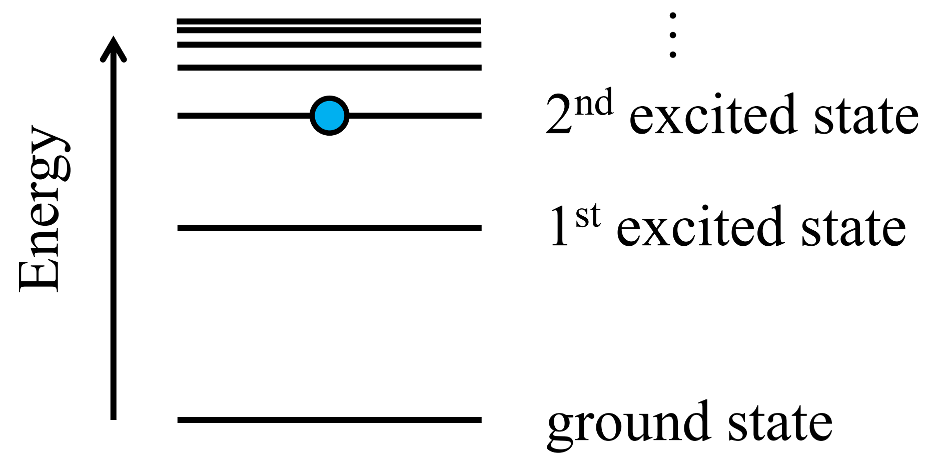

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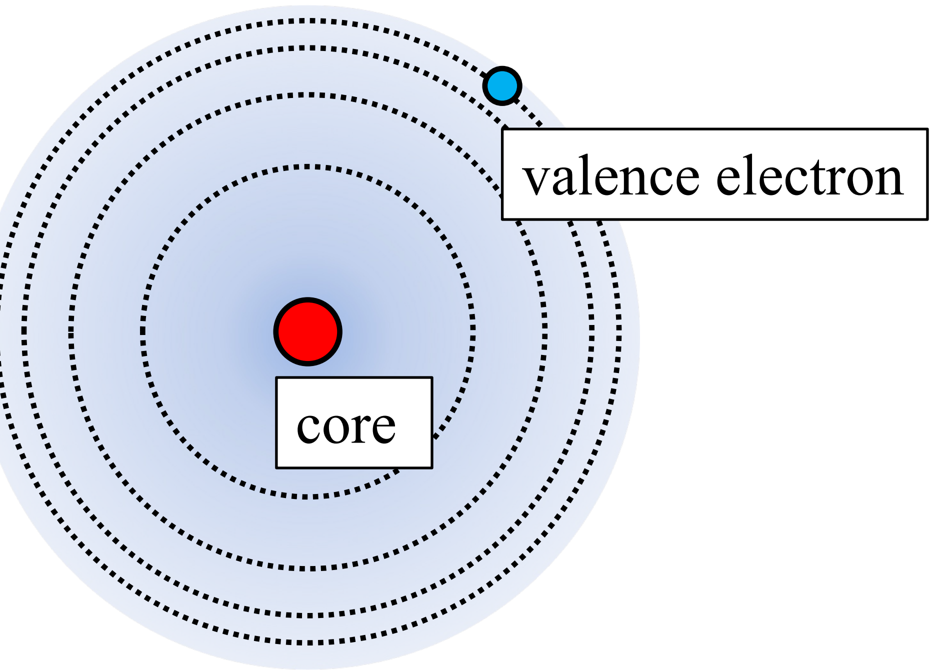

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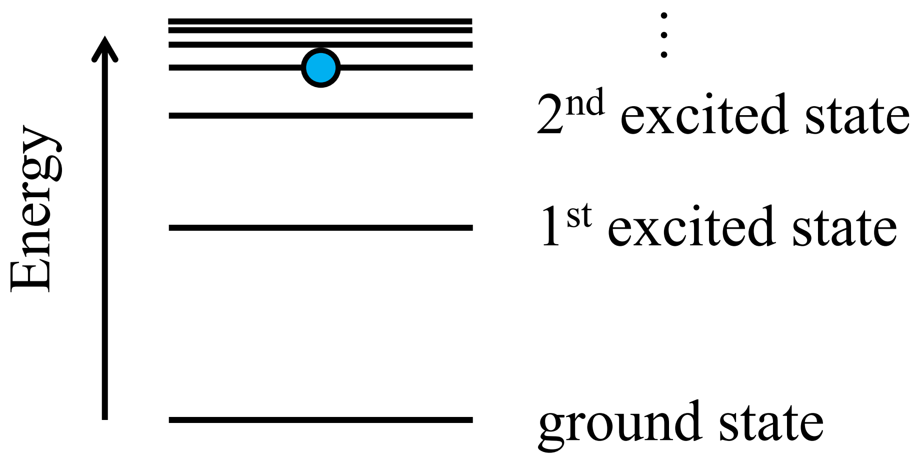

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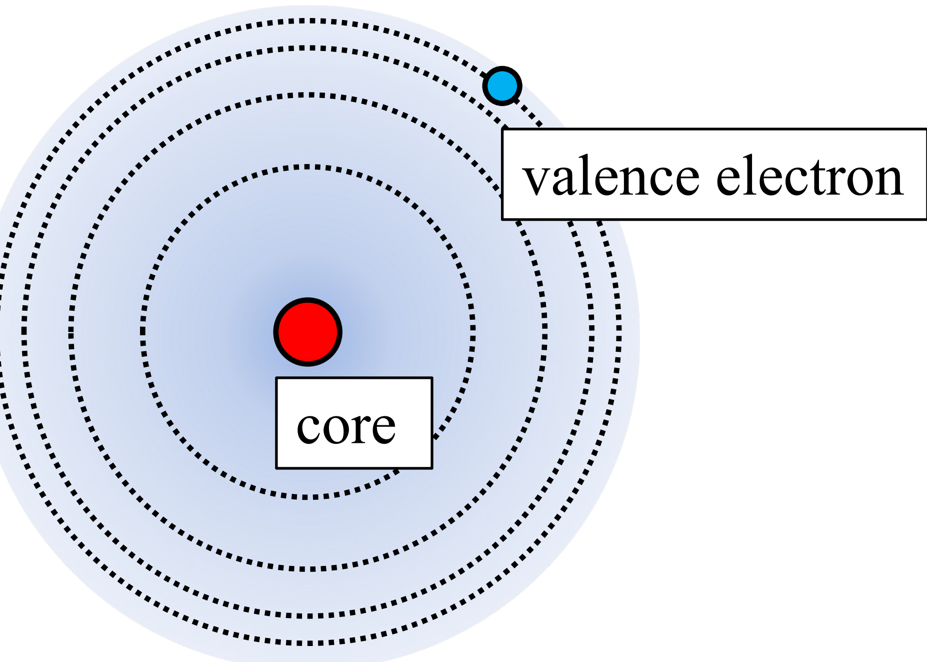

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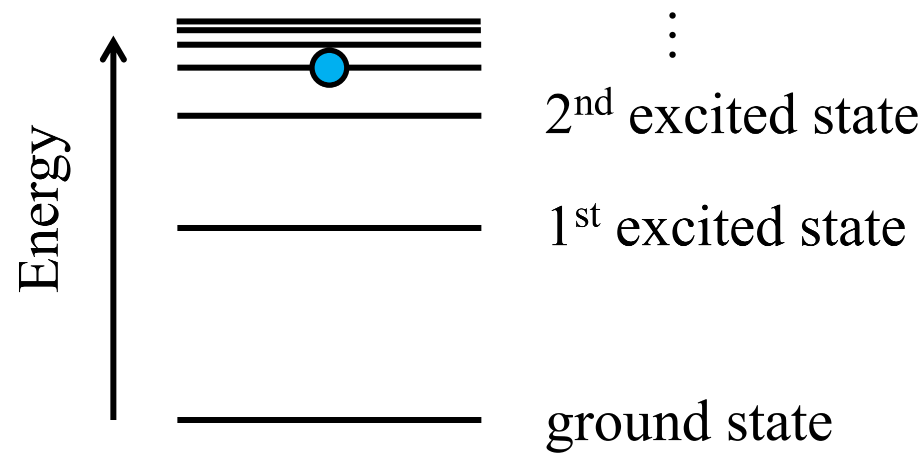


The higher the energy level,
the further the electron is away from
the core, *on average*

- AMO

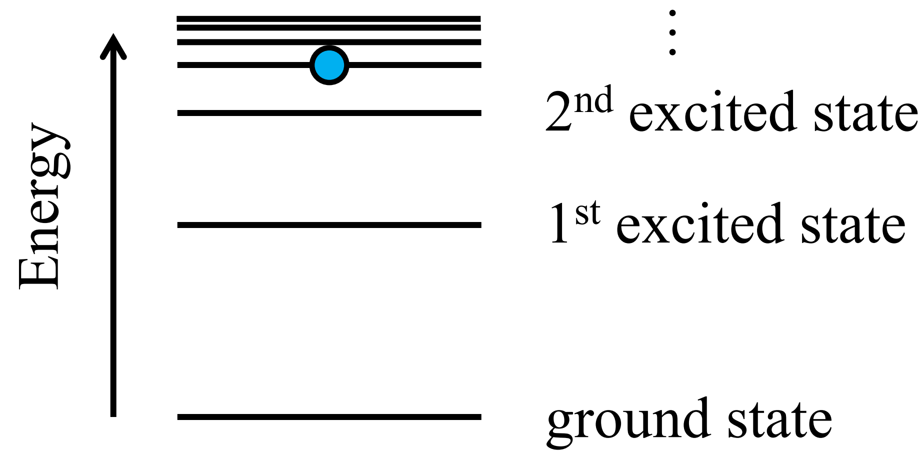
Atoms (cont'd)

- The electron in the atom has only discrete energies, called levels

Atom

From "Atom in a Box"

Energy Level Diagram



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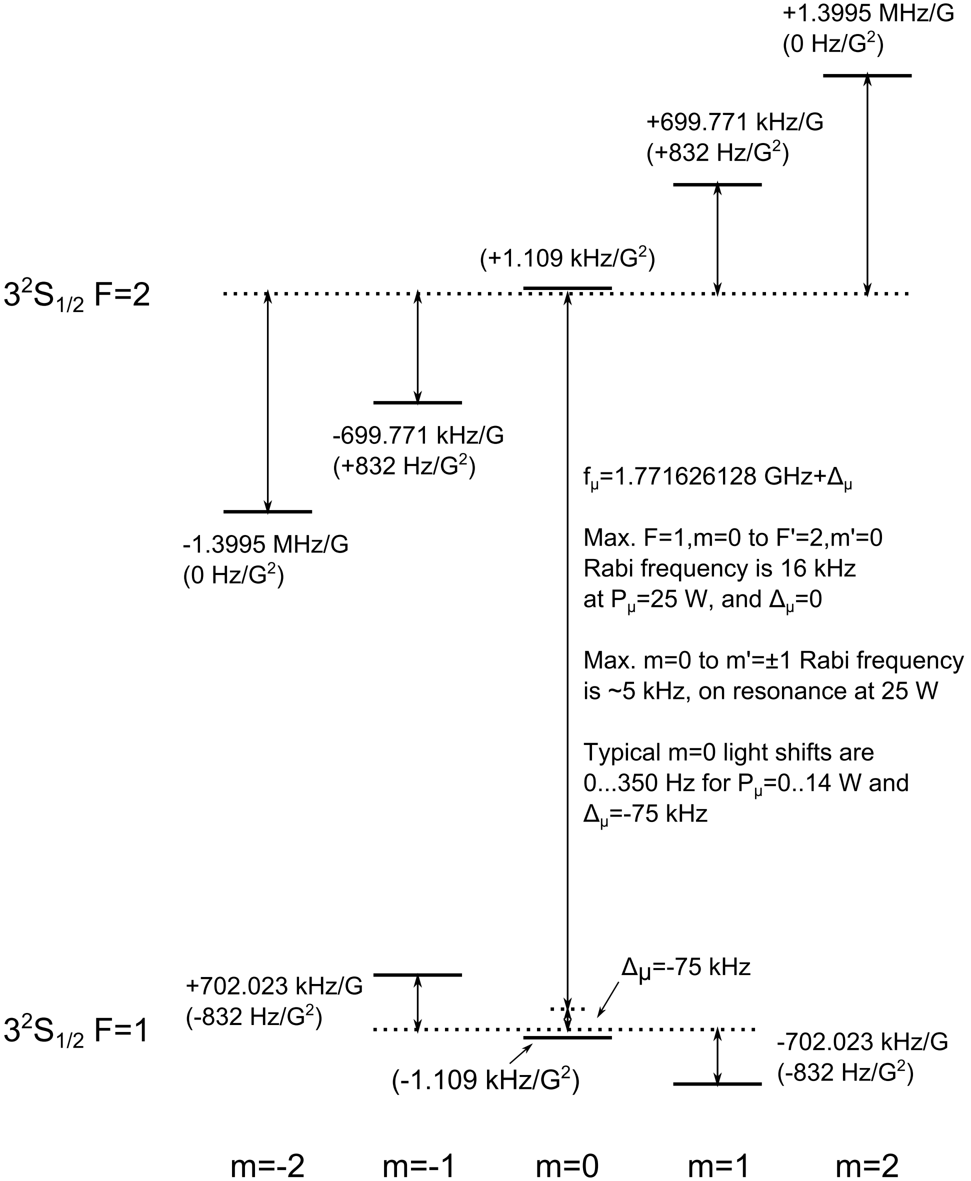
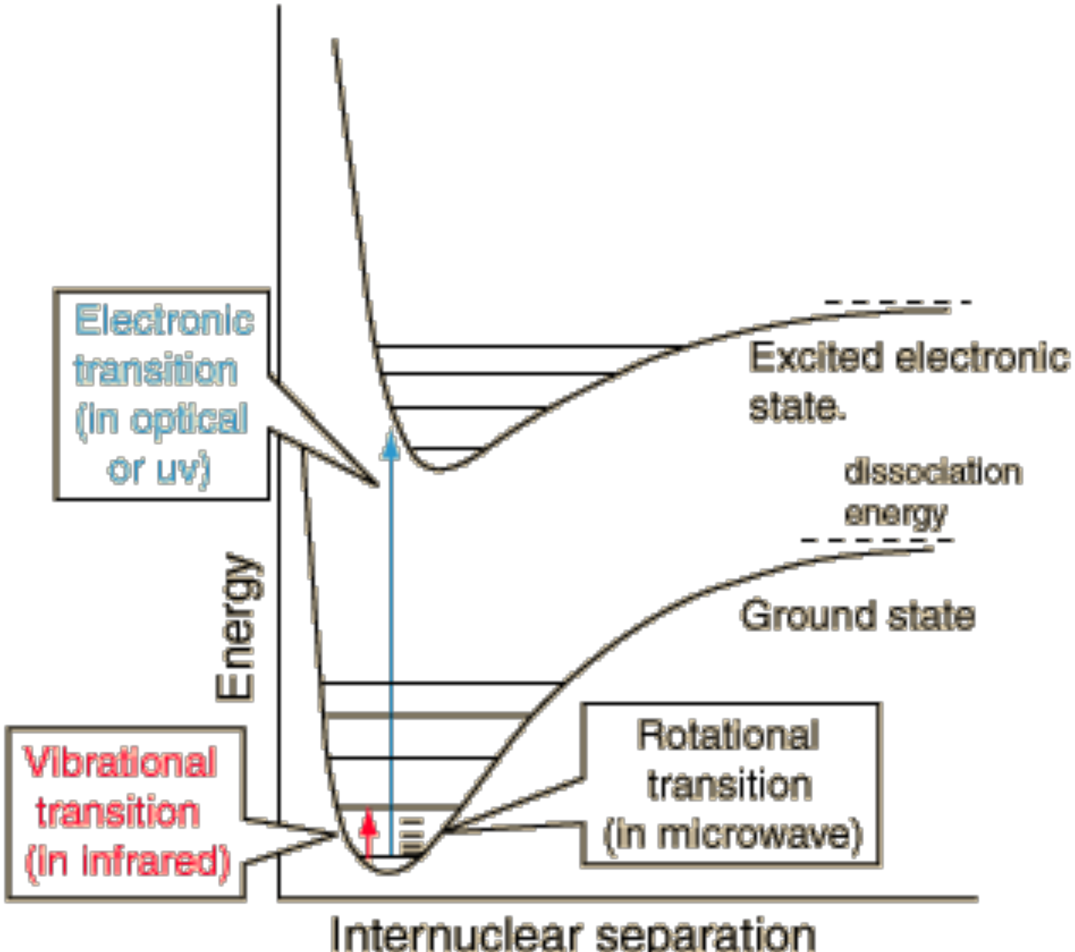
- AMO

Hyperfine Structure

- "There are no two-level atoms and sodium is not one of them" (W. Phillips, Nobel Prize 1997)



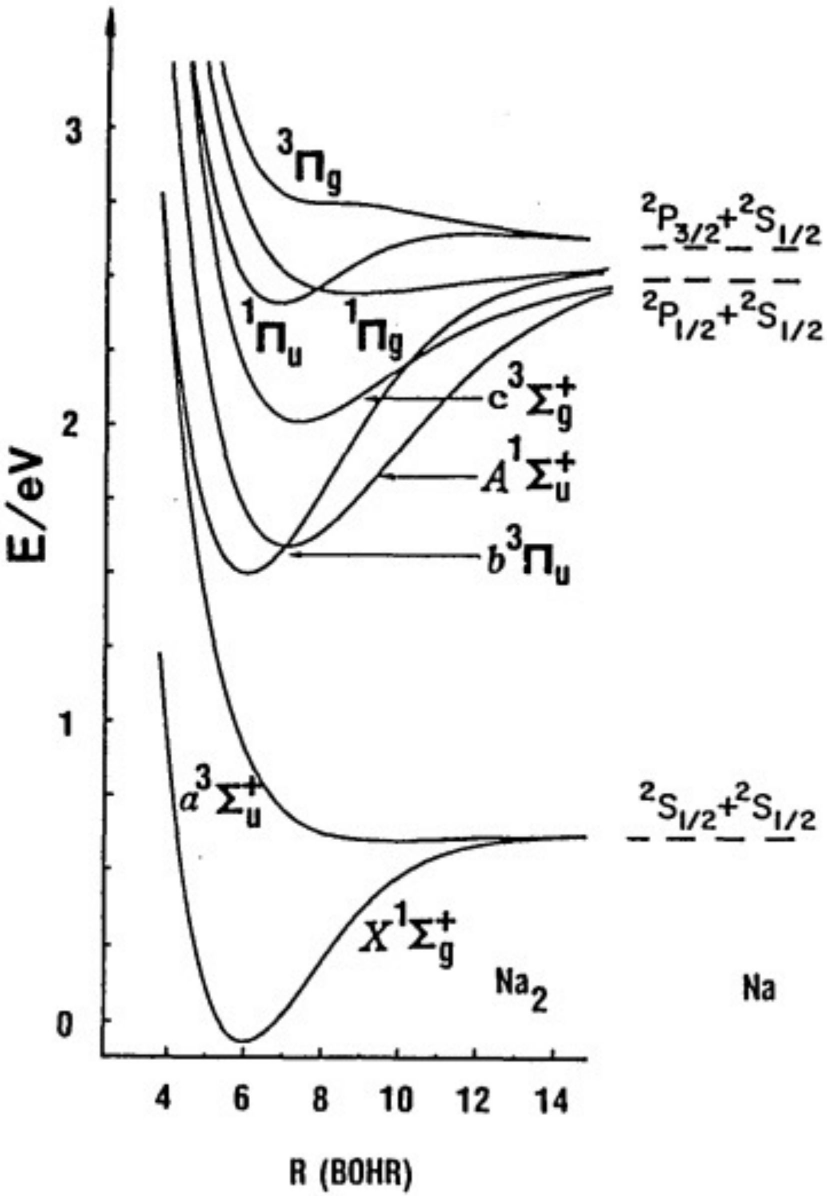
Molecules



- Molecules are more complicated
- "A diatomic molecule is a molecule with one atom too many"
(A. Shawlow, Nobel Prize in 1981)

- They rotate and vibrate
- Molecular spectroscopy
- Important for Astronomy

Molecules



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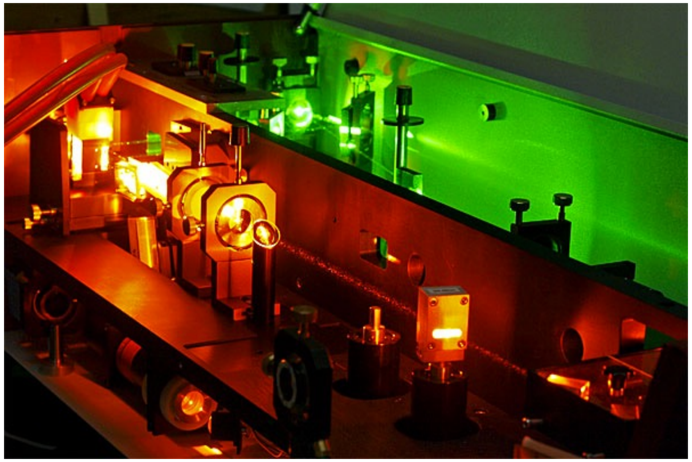
First Revolution in AMO

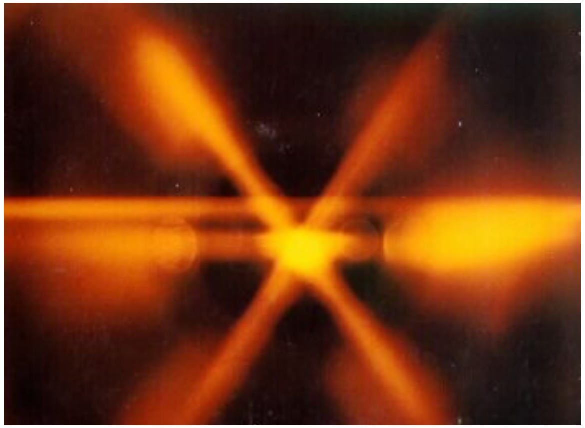
- **1960's: invention of the laser**
  - Allows us to probe atoms with unprecedented precision



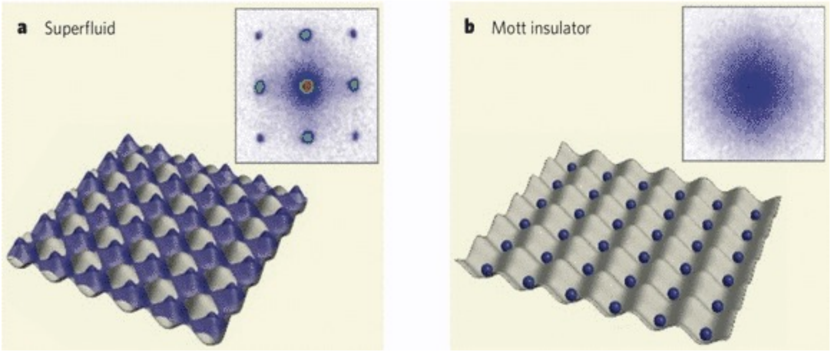
  - Until today, laser improvements push the field forward
    - Ultrastable solid state lasers at new wavelengths
    - White light laser, frequency combs, bridge the gap between microwave and optical frequencies
    - ...

Second revolution in AMO

- **1990's: laser cooling and trapping**
  - Allows us to cool and trap a gas of atoms at *nanokelvin temperatures*
  - Opened up the field of ultracold atomic gases
  - Optical lattices, atomic fountain clocks
  - Ultracold Fermi gases
  - Quantum Simulation
  - Bose-Einstein condensation



First optical molasses at NIST, 1988

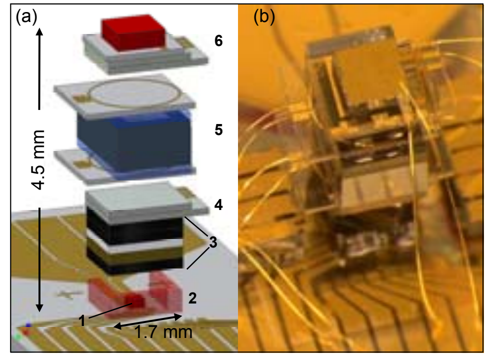


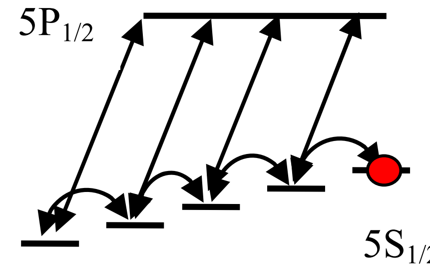
From Greiner and S. Fölling, Nature **453**, 736 (2008)

- AMO

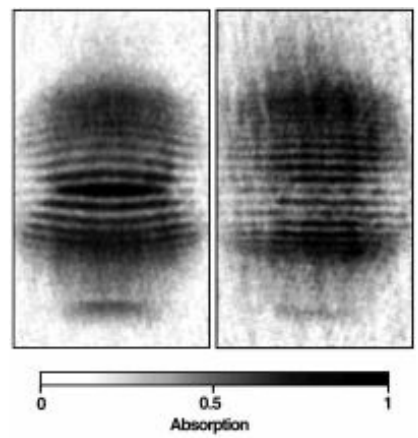
Why is AMO interesting?

- Atomic clocks (GPS)
  ~1 second in 5 billion years
- Atomic gases as quantum-enhanced sensors
    - No calibration – atoms are always the same
- Cold atoms for matter-wave interferometry
    - Cold atomic matter waves interfere with long interrogation times
    - Rotation and gravitational sensing, inertial navigation

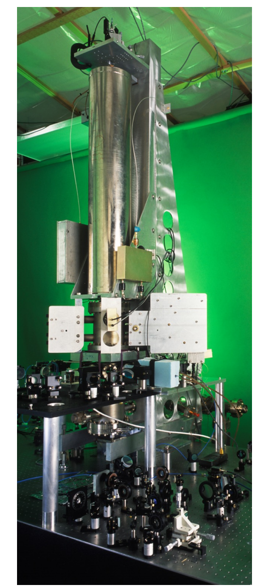




NIST: Chip scale atomic magnetometer



MIT: Interferometry of atomic matter waves

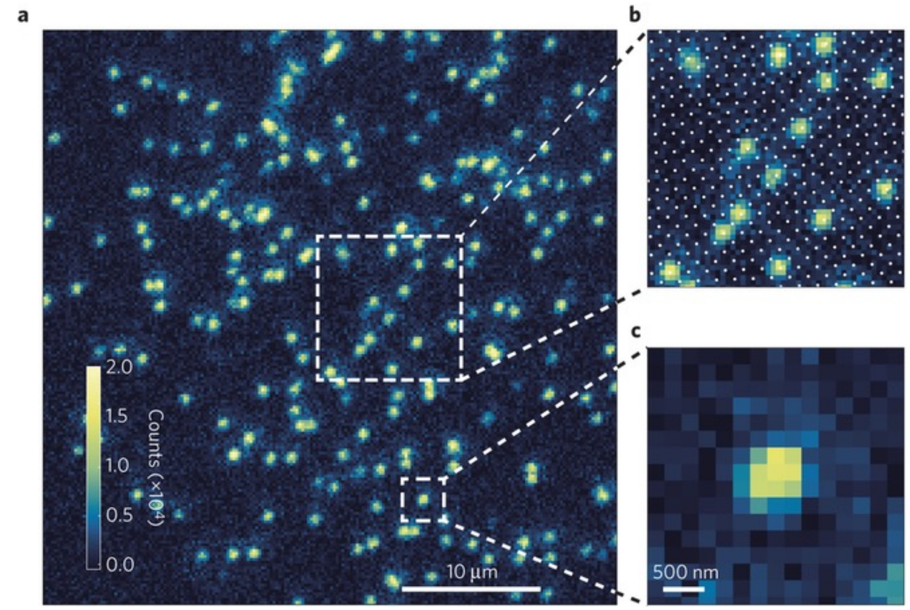


NIST: F1 Atomic fountain clock

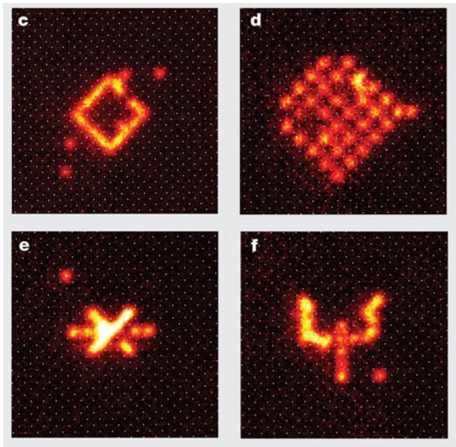
Why is AMO interesting?

- AMO

- Quantum emulation and simulation
  - Artificial perfect crystals
  - Solid-state type systems with absolute control and no defect
  - Learn about room temperature superconductivity and more!
  - Connection to solid-state physics
- Neutral atoms or charged ions
  - Qubits for quantum computing
  - Single site addressing has been demonstrated recently



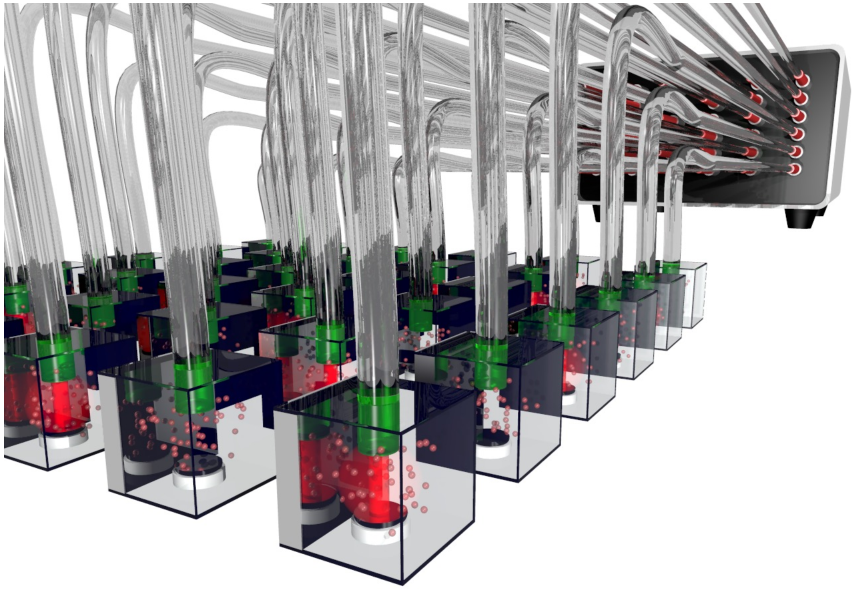
From Haller, Nature Physics **11**, 738–742 (2015) (Strathclyde group)



From C. Weitenberg, Nature **471**, 319–324 (2011) (Munich group)

Why is AMO interesting?

- Currently, there's a **paradigm shift**
  - Harness quantum mechanics and control of atoms to create new devices (quantum-enhanced sensors)
  - Use atoms to create single-photon sources and better photon detectors
- Sometimes called the **second quantum revolution**, after an article by J. Dowling and G. Milburn
- J. Dowling and G. Milburn, *Phil. Trans. R. Soc. Lond.* A **361**, 1655-1674 (2003).
- arXiv:quant-ph/0206091



The Quantum Internet?

Why AMO Research?

- Our experiments are tabletop style and done in small groups
- You can learn important hands-on lab skills
  - Lasers and optics
  - Vacuum Systems
  - Electronics
  - Programming
  - and of course physics
- There are lots of jobs
  - The optics and laser industries are huge (Telecom fibers etc)
  - Many companies are also doing R&D with atomic systems now

CORNING
Discovering Beyond Imagination

Microsemi

Honeywell

NORTHROP GRUMMAN

ColdQuanta

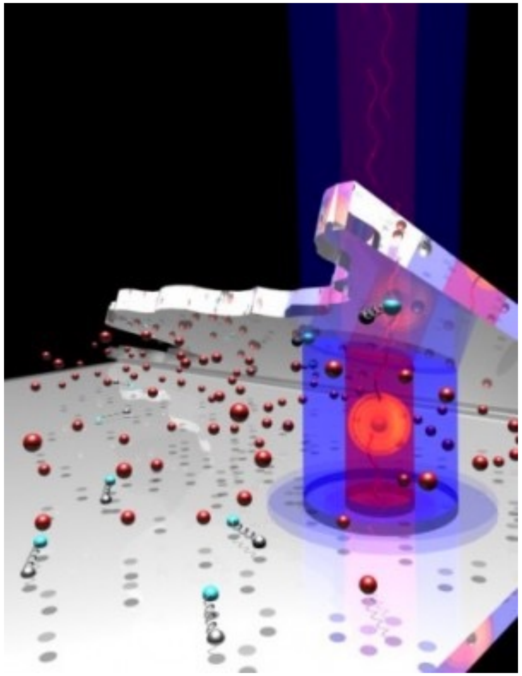
GEOMETRICS
Innovation • Experience • Results

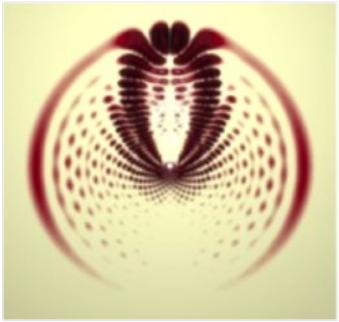
NATIONAL PHOTONICS INITIATIVE

- AMO

AMO Physics at OU

- Schwettmann Group
    - Ultracold atomic gases
    - Spinor Bose-Einstein condensates
- Marino Group
    - Quantum optics
    - Squeezed light
- Biedermann Group
    - Atom interferometry
    - Rydberg atoms
- Abraham Group
    - Ultracold atoms in Laguerre Gaussian beams
- Blume Group
    - Theory of few-body and many body systems
- Lewis-Swan Group
    - Theory of non-equilibrium many-body physics in ultracold gases





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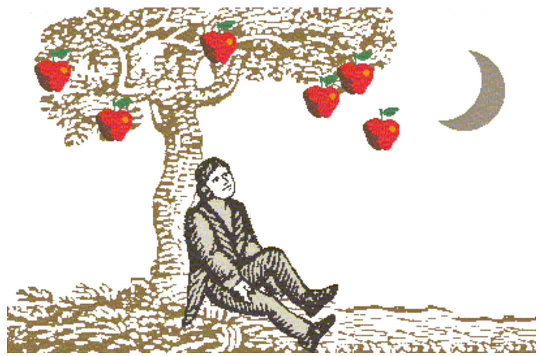
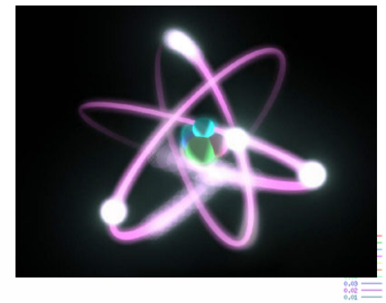
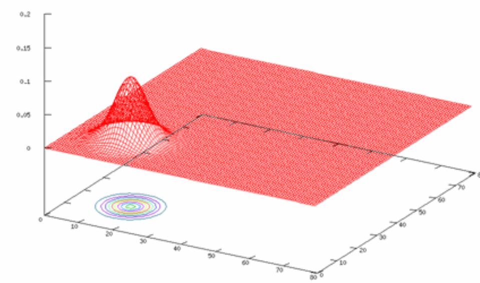
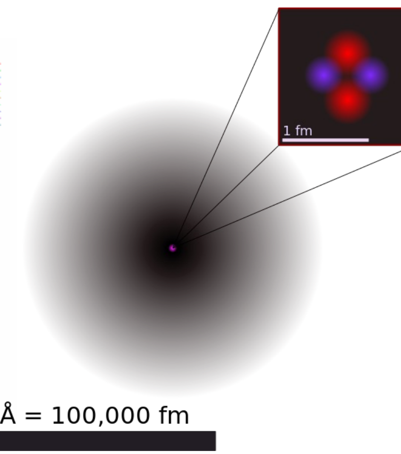
Two Realms of Physics

Classical Realm



Quantum Realm

Normal sizes

Extremely small sizes

- A Bose-Einstein condensate is a quantum gas, a cloud of atoms that behaves like a single **macroscopic quantum object**

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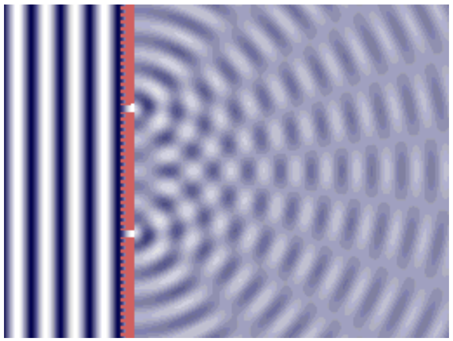
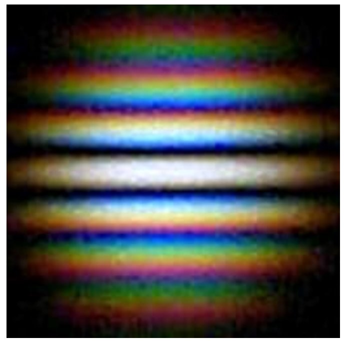
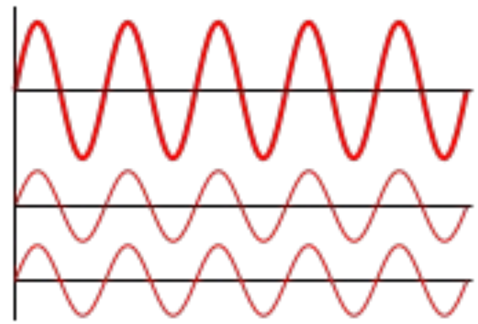
Investigations of Light

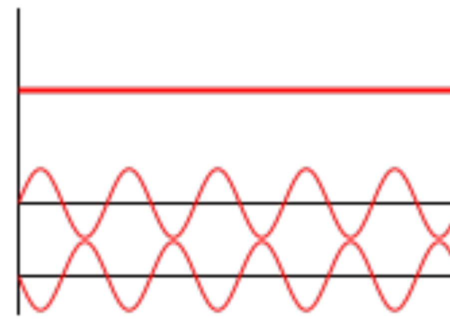


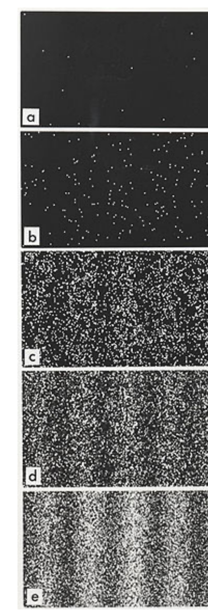


Constructive interference



Destructive interference





- Behaves like a **wave**: can add up but also cancel out (interference) (Huygen's wave theory, 1690)

- Behaves like a **particle**: single clicks on the detector (Newton's corpuscular theory, 1690)

- Is it a **particle or a wave**?

- Thinking about light spawned the **quantum revolution** in physics!

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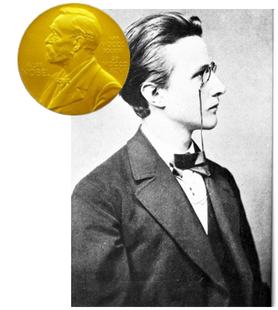
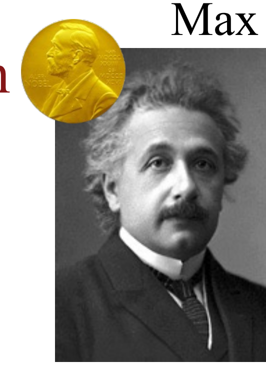
Light

- In 1900, Max Planck discovered the existence of quanta of energy (black-body radiation)
  - He won the 1918 Nobel prize
- Albert Einstein, in 1905, developed this idea into the modern concept of the photon (photoelectric effect)
  - He won the 1921 Nobel prize
- Luis deBroglie, in 1924, suggested that all particles should have wavelike qualities (matter waves)
  - He won the 1929 Nobel prize
- Quantum mechanics was developed by E. Schrödinger, W. Heisenberg, N. Bohr, M. Born, E. Fermi, P. Dirac, etc.



Max Planck



Albert Einstein

Luis DeBroglie

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DeBroglie's Matter Waves

- Luis deBroglie's idea in 1924:
  (He won the 1929 Nobel prize)

  If light has this dual nature, then so should everything! All particles should also be waves!

- Thermal deBroglie wavelength for atoms in a gas

$$\lambda_{dB} = \sqrt{\frac{h^2}{2\pi\, m\, k\, T}}$$

- The colder, the longer the wavelength

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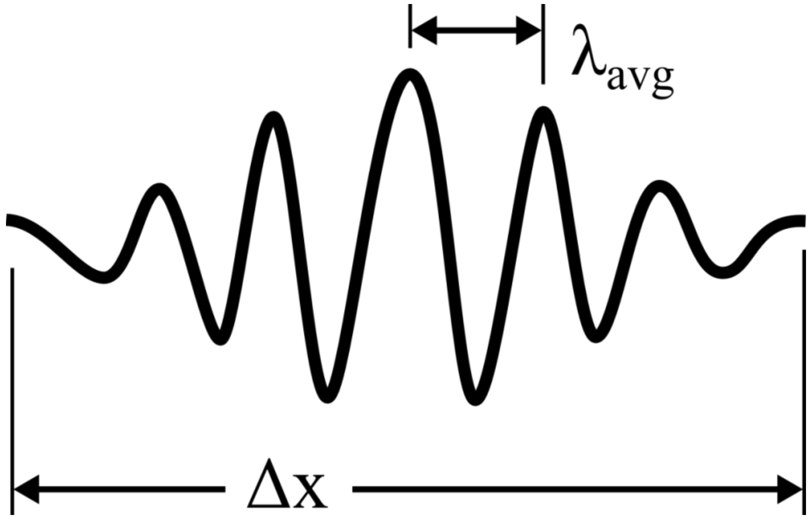
Wavepacket



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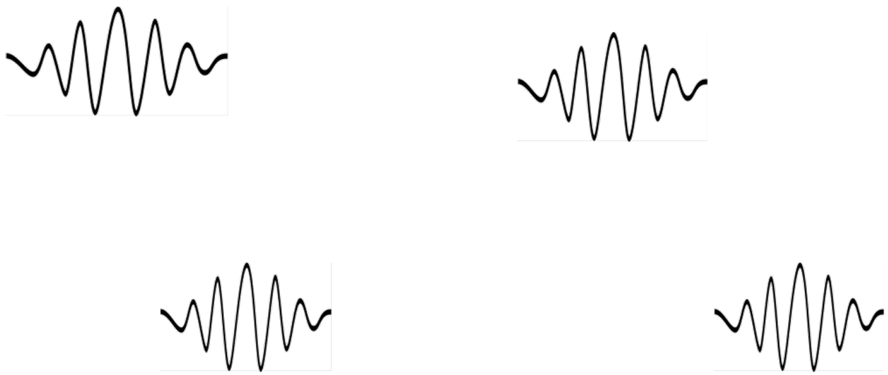
Wavepacket

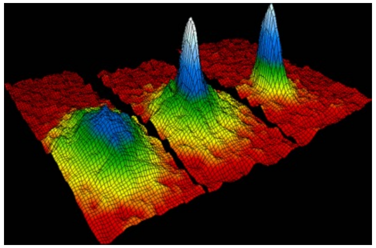
Bose and Einstein

- What happens if I take a gas of atoms and cool it down until all the wavepackets overlap?



- A "giant coherent matter wave" can form!
- Predicted by Bose and Einstein in 1925, **Bose-Einstein condensate (BEC)**

Einstein and Bose



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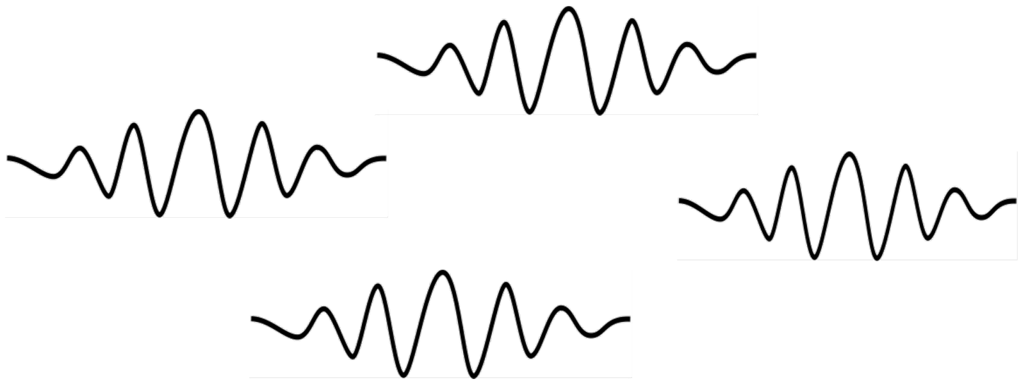

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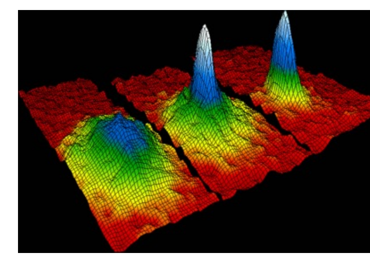

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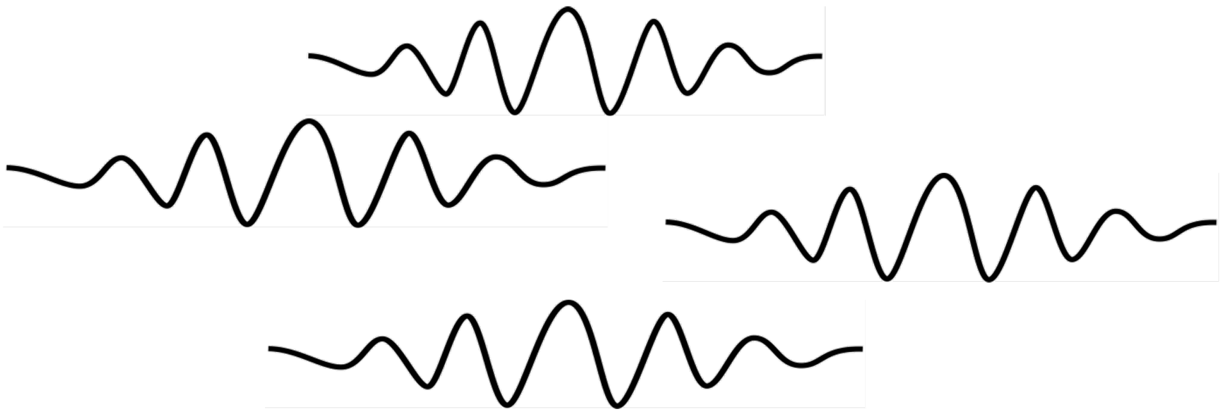

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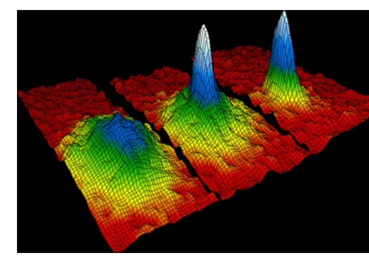

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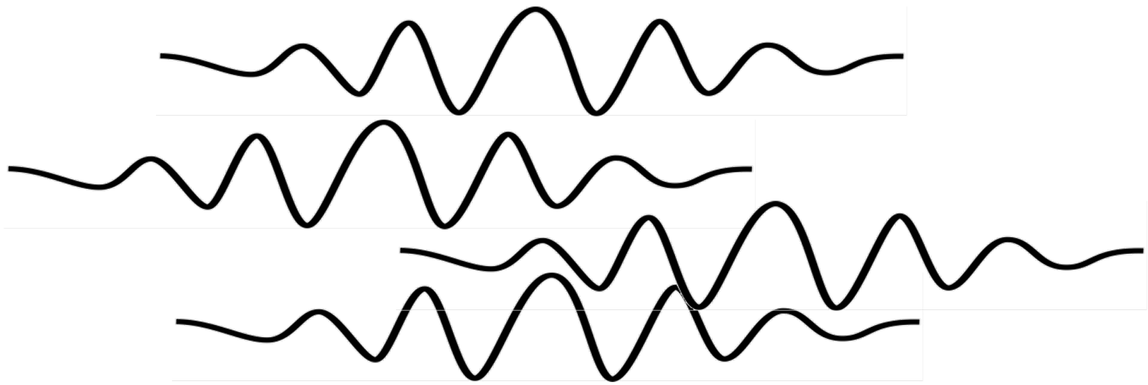

Einstein and Bose

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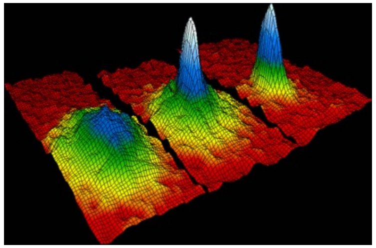

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Bose and Einstein

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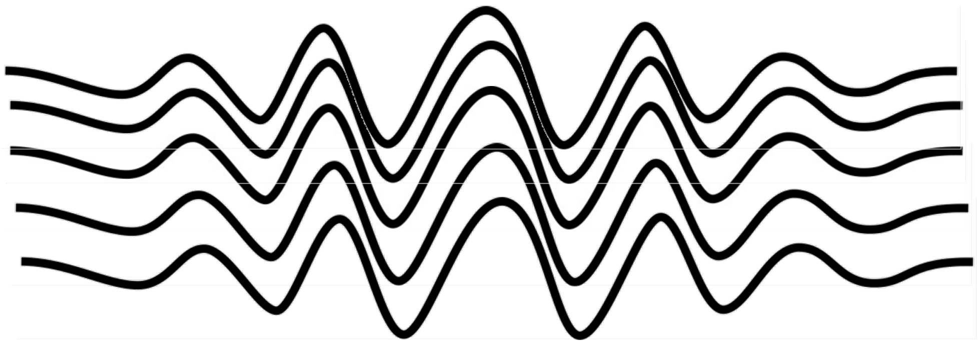

Einstein and Bose

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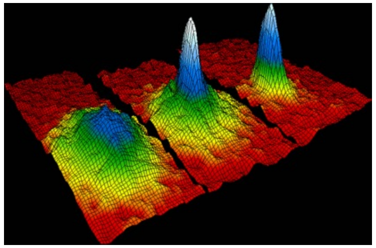

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- AMO

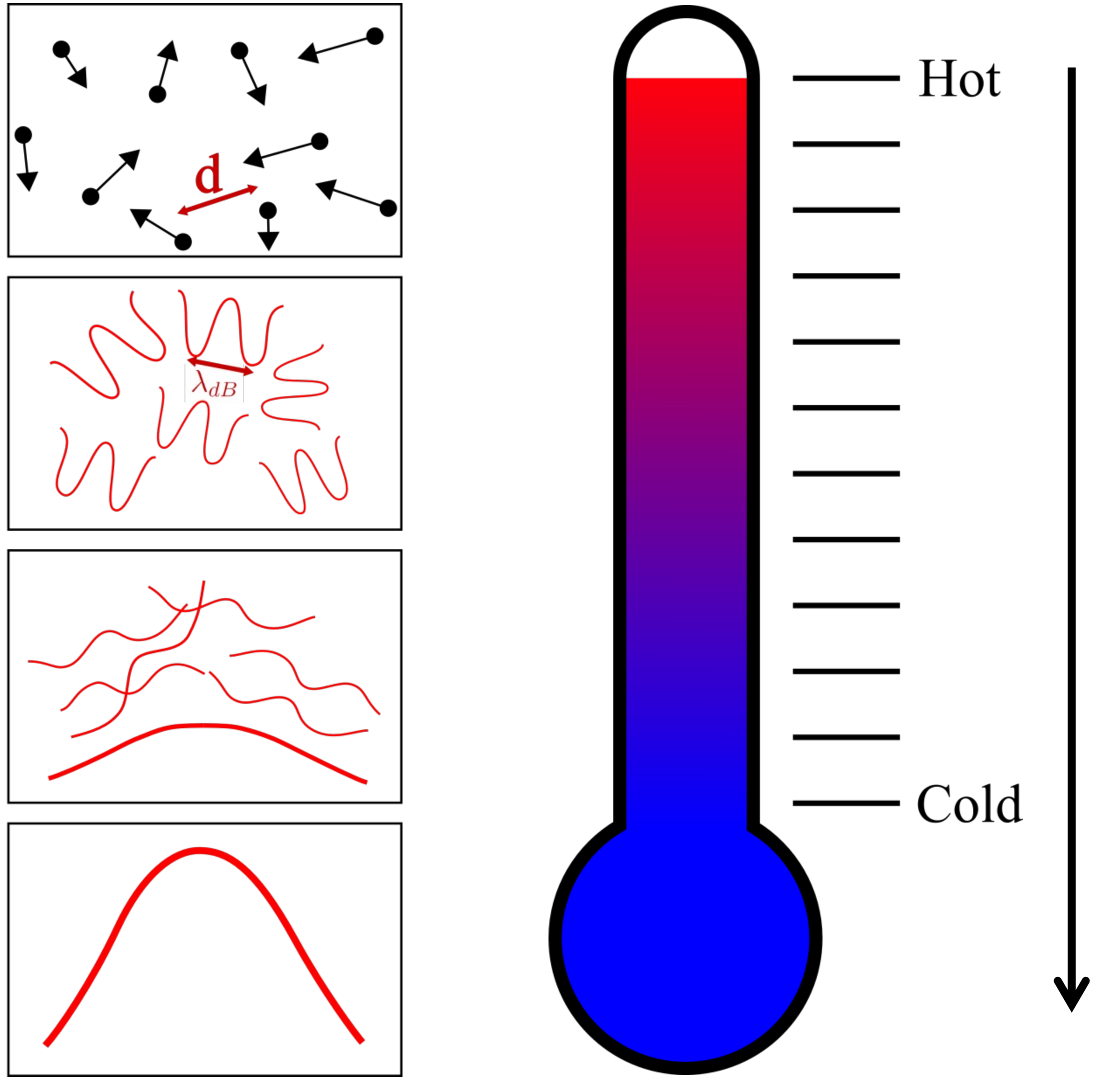
Cooling Towards BEC

High temperature
"Billiard balls"
density $n \sim d^{-3}$

Low temperature
"Wavepackets"
$\lambda_{dB} = h/p$

Bose-Einstein
Condensation
"Matter wave overlap"
(constructive interference)
$\lambda_{dB} \approx d$

Zero temperature
Pure condensate
"Giant matter wave"



- Ultracold: ~100 nK above absolute zero (−273.15 °C, −459.67 °F)

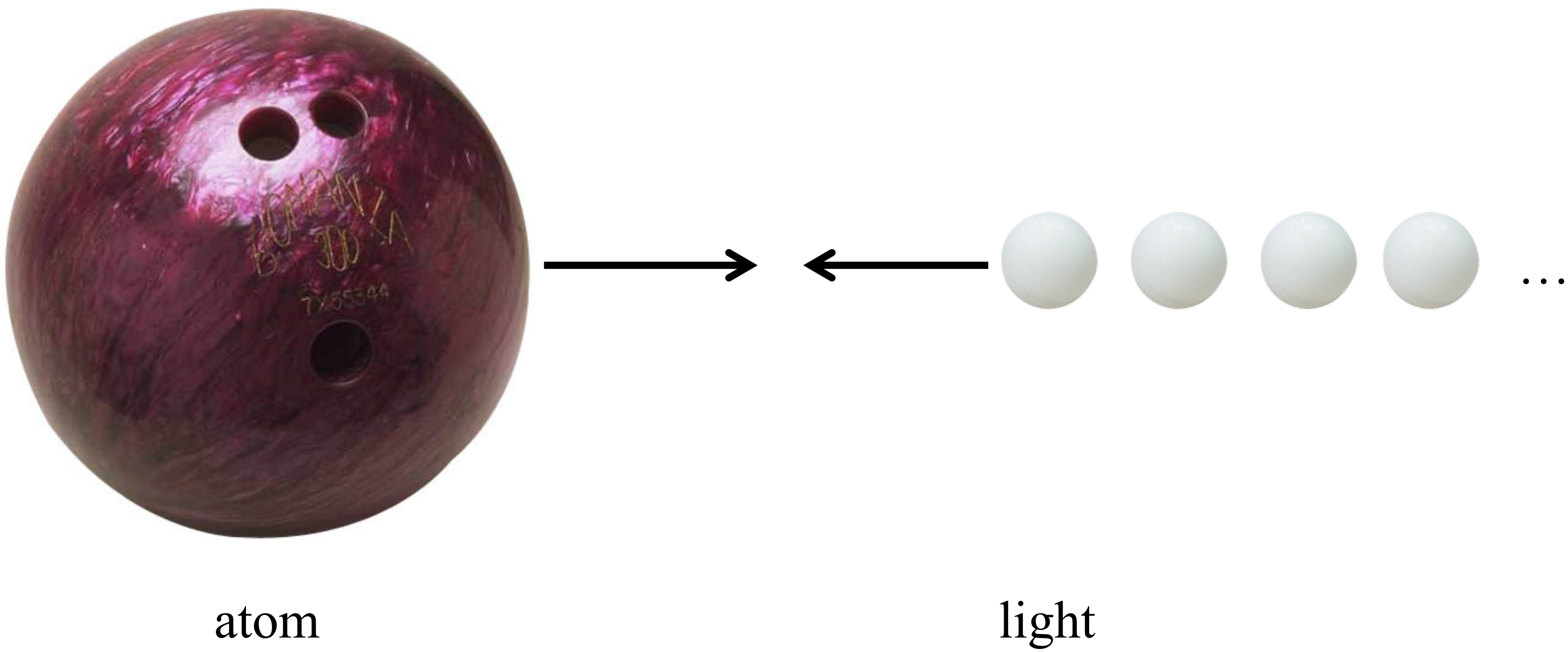
Laser Cooling and Trapping

- Cooling atoms means slowing them down
- Slow down atoms by shining light on them
- Slowing atoms down with laser light is like throwing ping-pong balls at a bowling ball

atom light

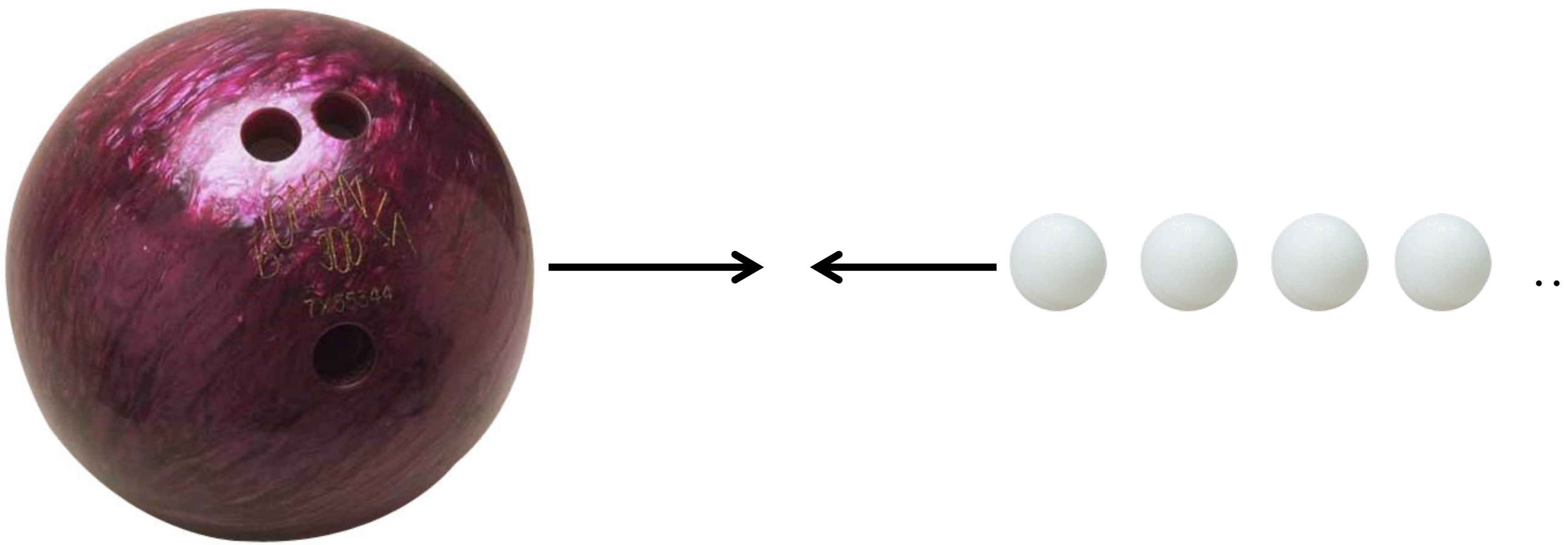
Laser Cooling and Trapping

- Cooling atoms means slowing them down
- Slow down atoms by shining light on them
- Slowing atoms down with laser light is like throwing ping-pong balls at a bowling ball – it works if I throw a hundred!



Laser Cooling and Trapping

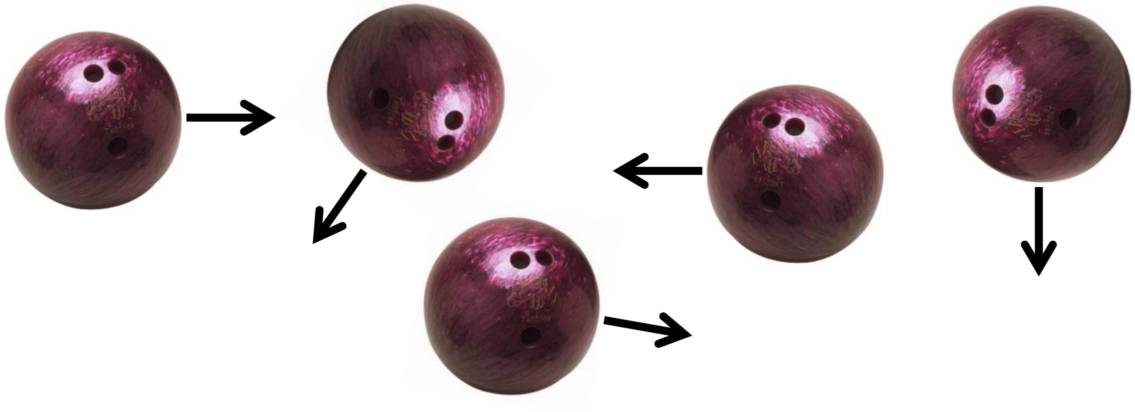
- Assumptions: Bowling ball mass: 14 lbs
  Bowling ball velocity: 2.2 mph
  Ping pong ball mass: 2.7 gram
  Ping pong ball velocity: 30 mph
  … perfectly elastic collisions etc. etc.



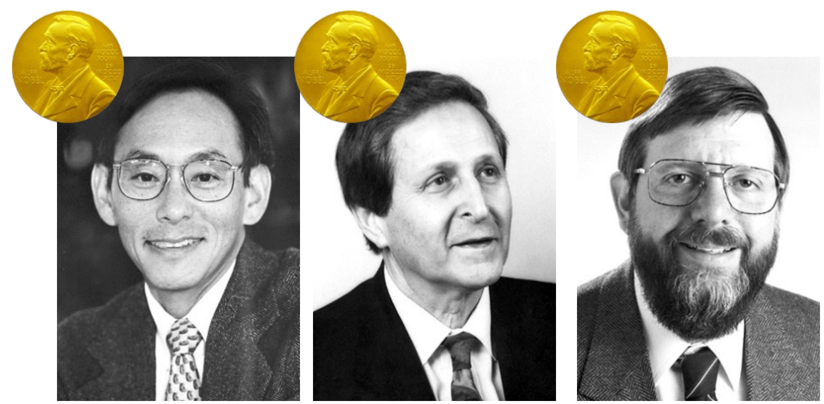
atom light

Doppler Cooling

- But atoms move around in all directions

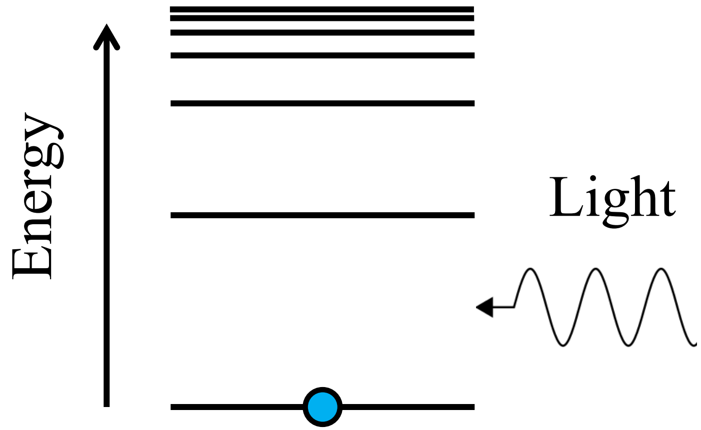


- How to slow them all down?
- Doppler cooling (W. Phillips, S. Chu and C. Cohen-Tannoudji)
  - Nobel prize in 1997
- Relies on absorption and spontaneous emission of light



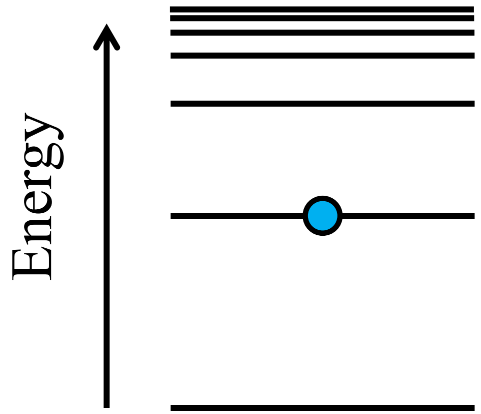
S. Chu   C. Cohen-Tannoudji   W. Phillips

Absorption and Emission



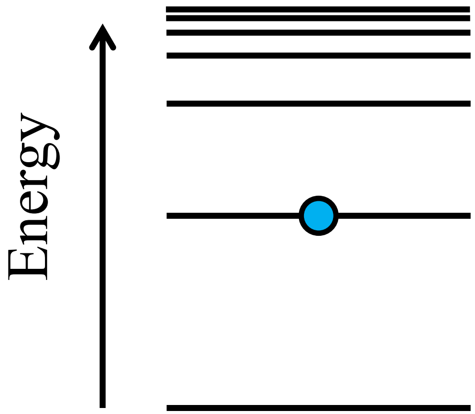
If I shine light of just the right color, the atom can absorb a photon

Absorption and Emission



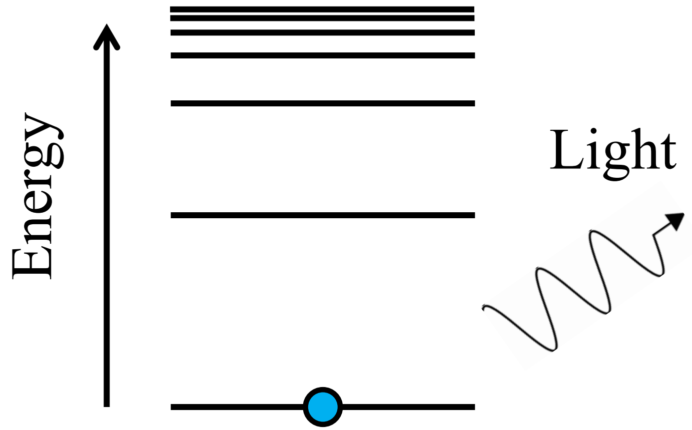
The electron is now in an excited state

Absorption and Emission



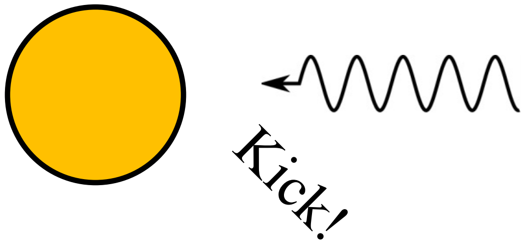
~16 nanoseconds pass…

Absorption and Emission



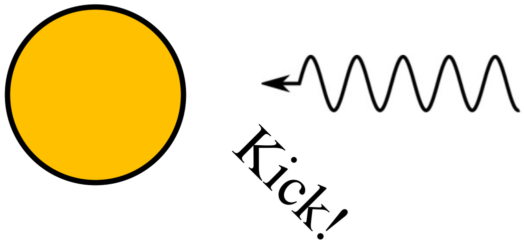
The electron decays back to the ground state and emits a photon in *a random direction* (spontaneous emission)

Exerting a Force on Atoms

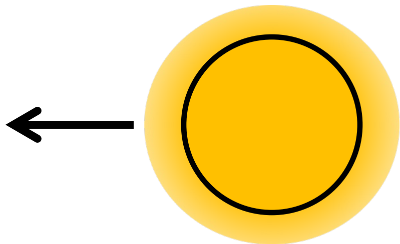


Absorption
Kick to the left

Exerting a Force on Atoms

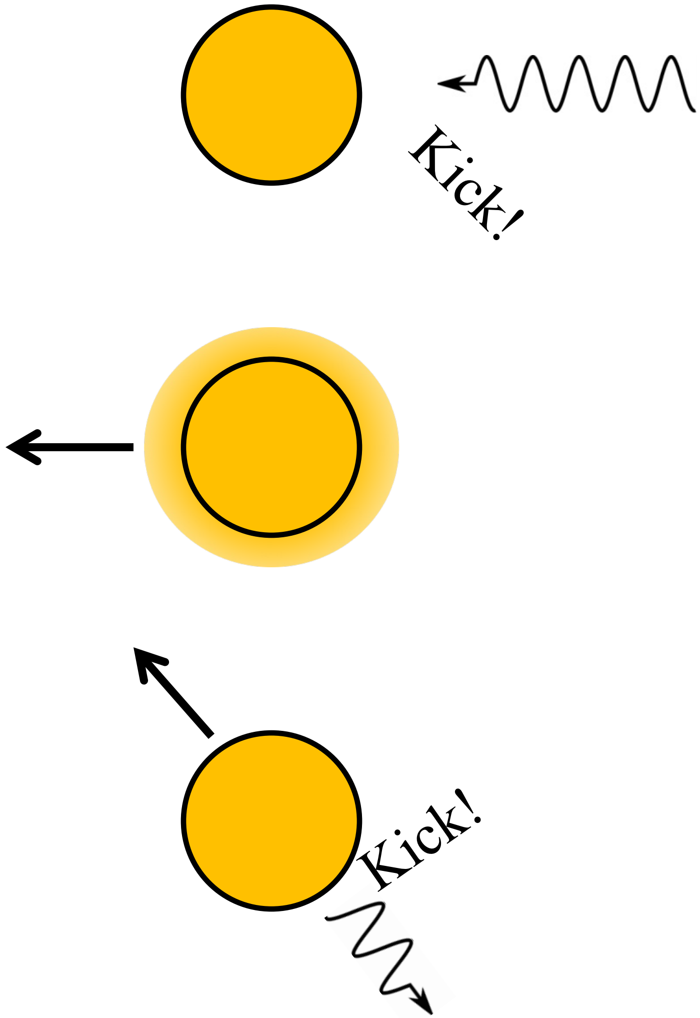


Absorption
Kick to the left



Excited State

Exerting a Force on Atoms

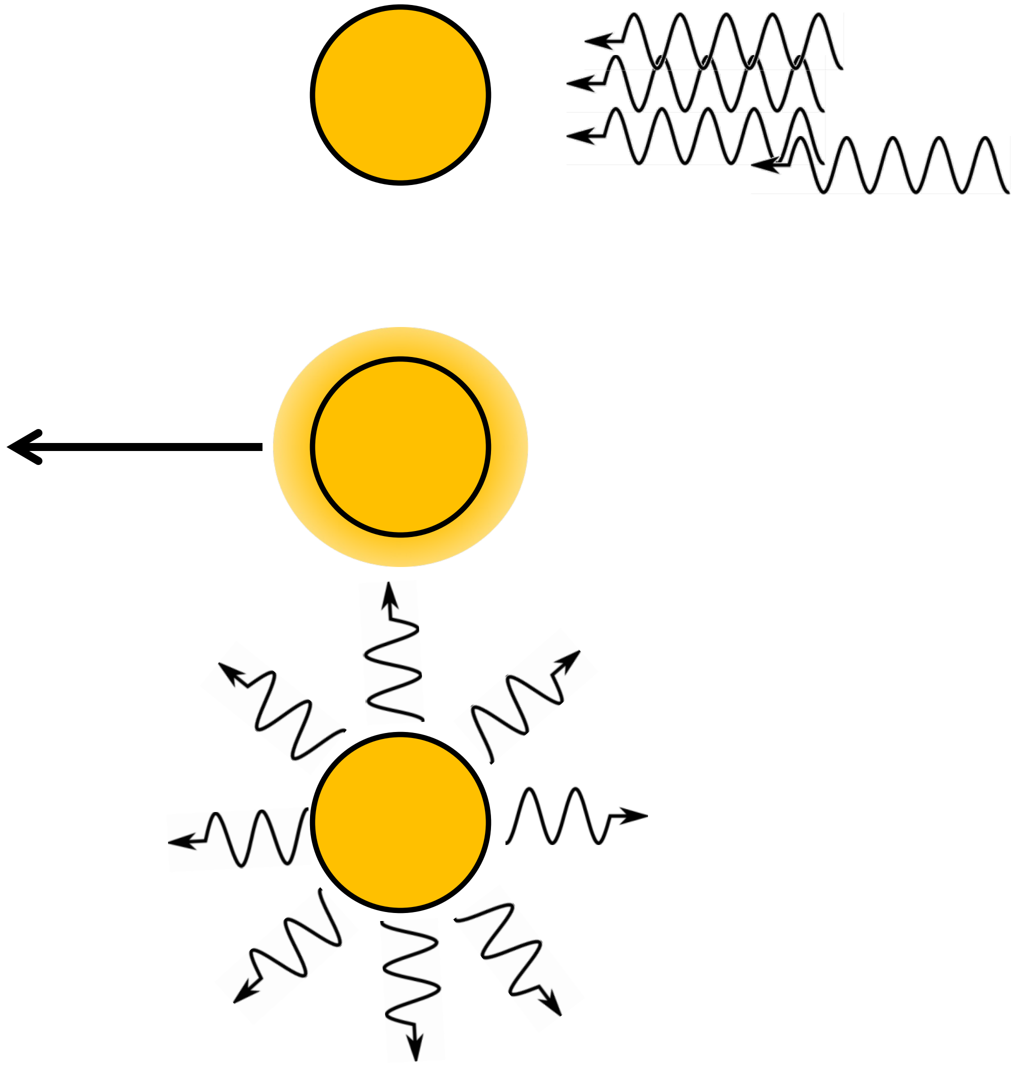


Absorption
Kick to the left

Excited State

Spontaneous Emission
Kick in random direction

Exerting a Force on Atoms



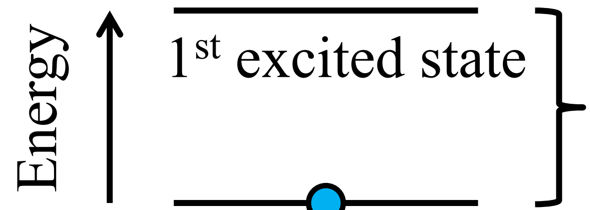
Kicks to the left all add up

Kicks in random directions average out

Color Matters!

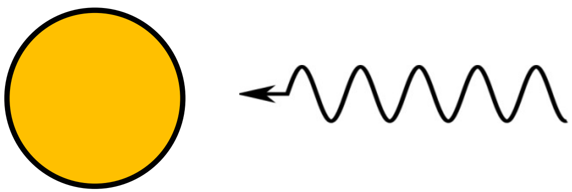
- AMO

- The color of light absorbed is determined by the energy spacing of levels



Energy gap determines colors!

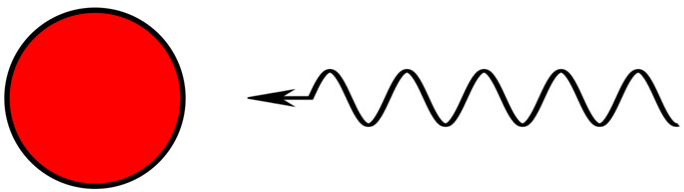
Sodium



Orange (589 nm)

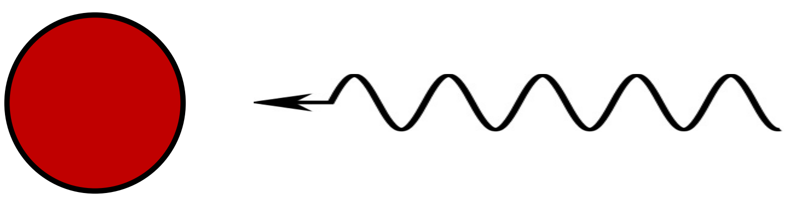
Sodium street lamp

Lithium

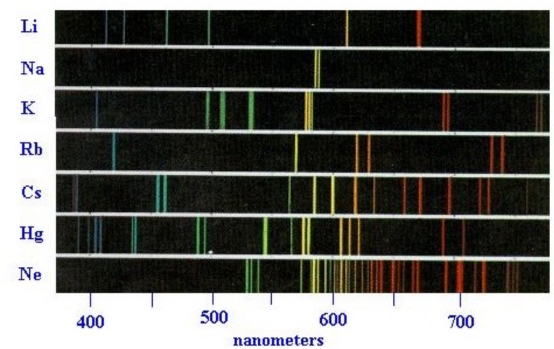


Red (671 nm)

Rubidium



Near Infrared (780 nm)



Line spectra

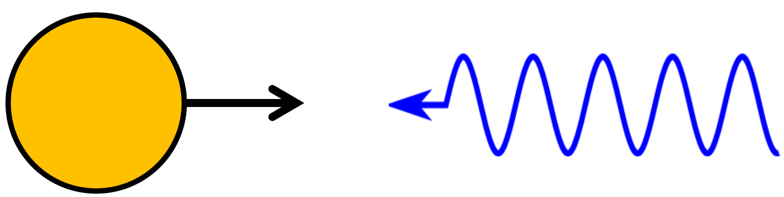
Doppler Shift

- Use the Doppler shift

High pitch

Low pitch

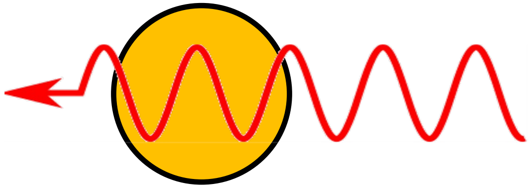
- An atom moving towards the light “sees” it **blue-shifted (high frequency)**



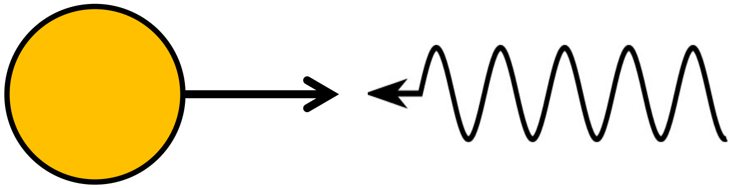
- An atom moving away from the light “sees” it **red-shifted (low frequency)**

Doppler Cooling

- **Trick:** Red-detune the light to begin with
- Atom at rest: Wrong color, nothing happens



- Atom moving towards the light: Right color, kick slows it down!

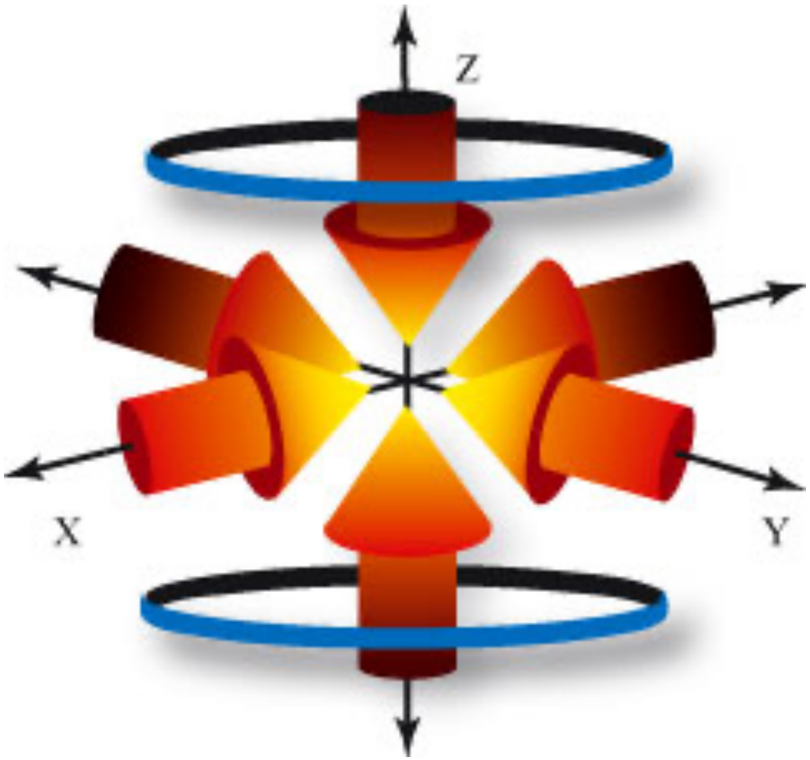


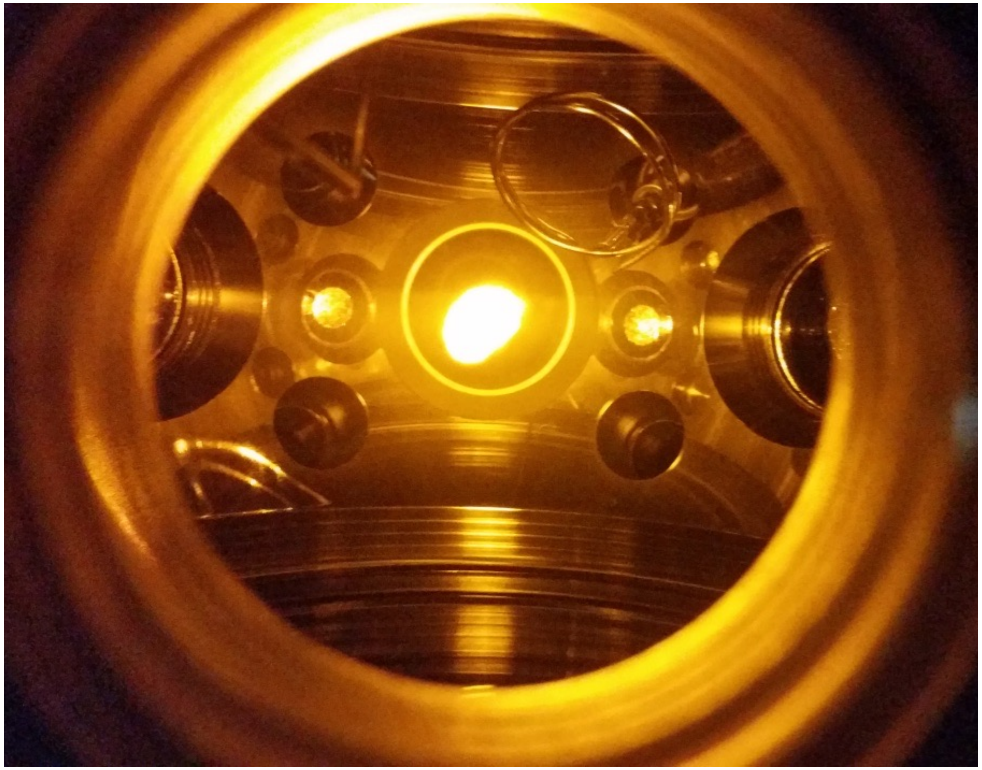
- Atom moving away from the light: Even further red, nothing happens

Ultracold Gases

- Magneto-Optical Trap (MOT): Combination of Doppler cooling and magnetic field to simultaneously cool and trap atoms in the center.

- "Workhorse of atomic physics"



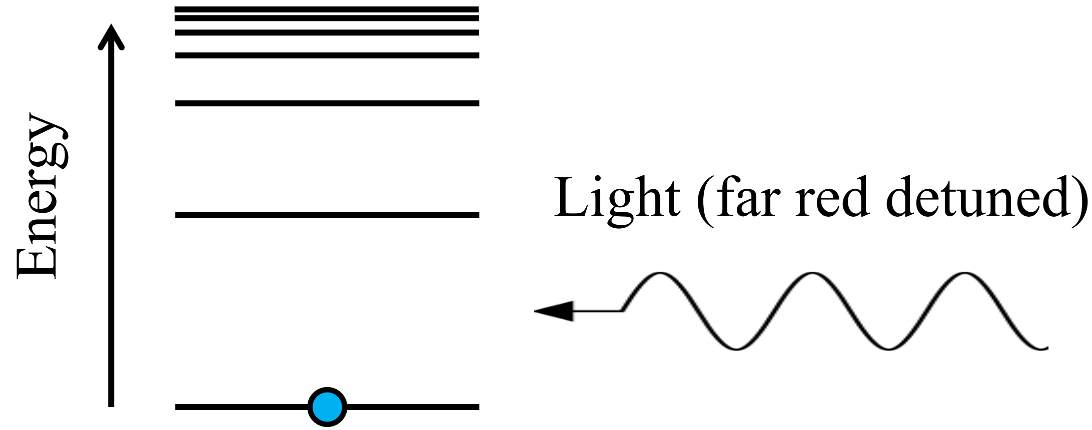


Sodium MOT at OU, radius ~ 5 mm
N ~ 600 million, T ~ 60 uK

- Emission causes heating ~ 2 uK

- AMO

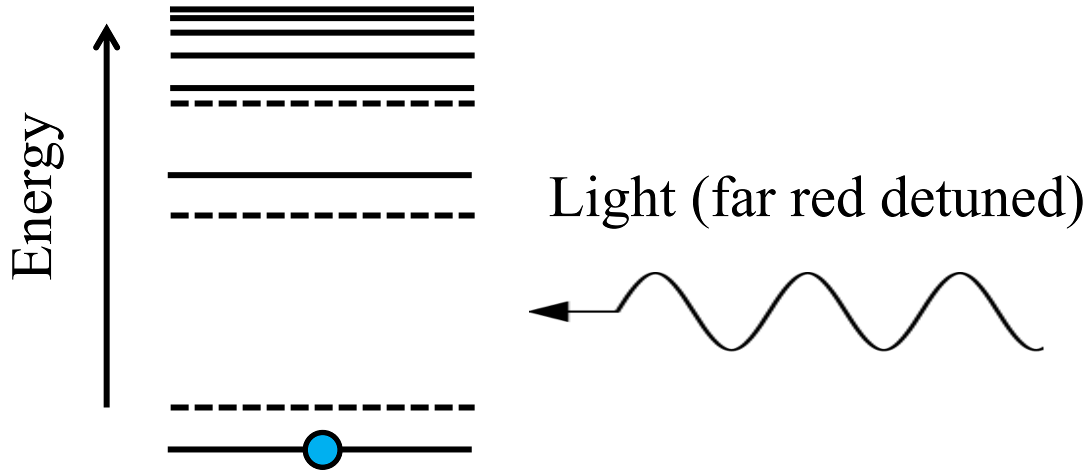
Light Shift



If I shine very intense light of the wrong color on the atom

- AMO

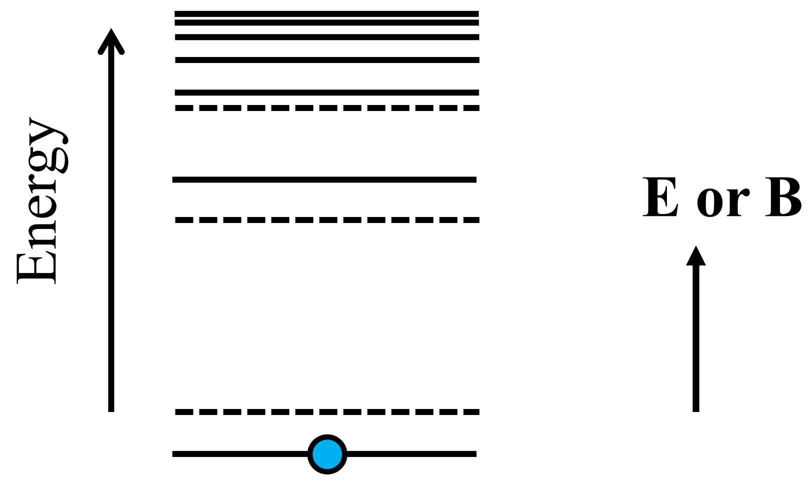
Light Shift



The energy levels *shift*

(light shift)

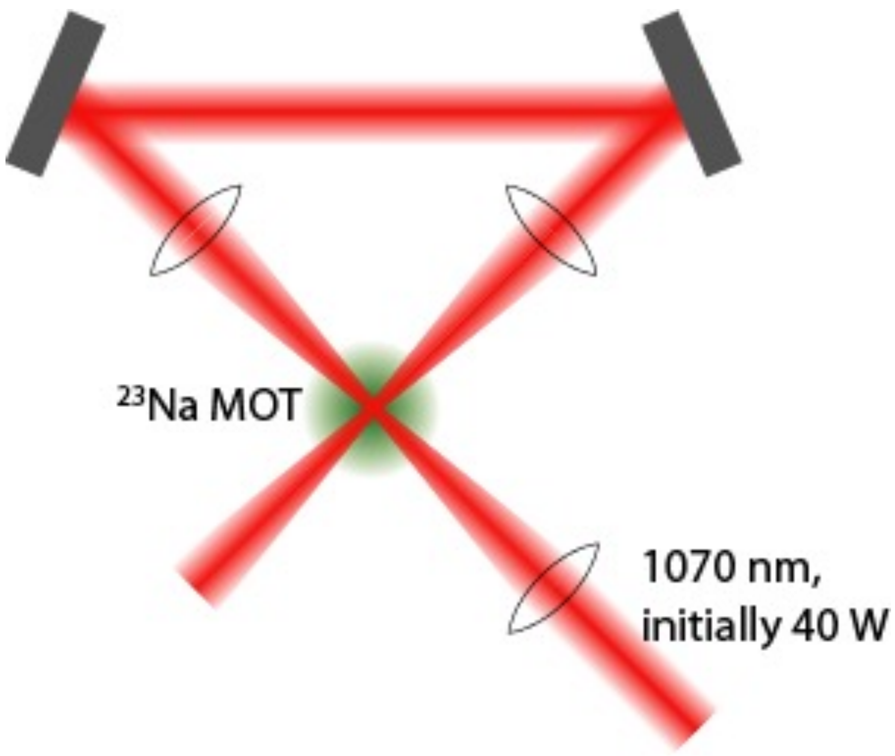
Light Shift

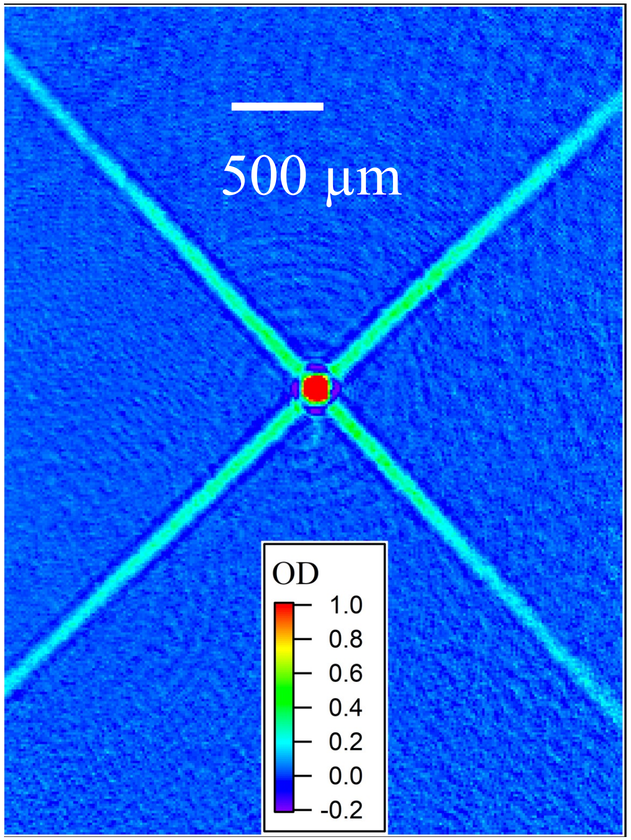


The same happens when applying a magnetic field (Zeeman shift) or electric field (Stark shift)

Optical Dipole Trap

- Transfer from MOT into far-off resonant crossed optical dipole trap (FORT)
- Electric of the laser light creates a force towards the focus.
- No absorption – no heating



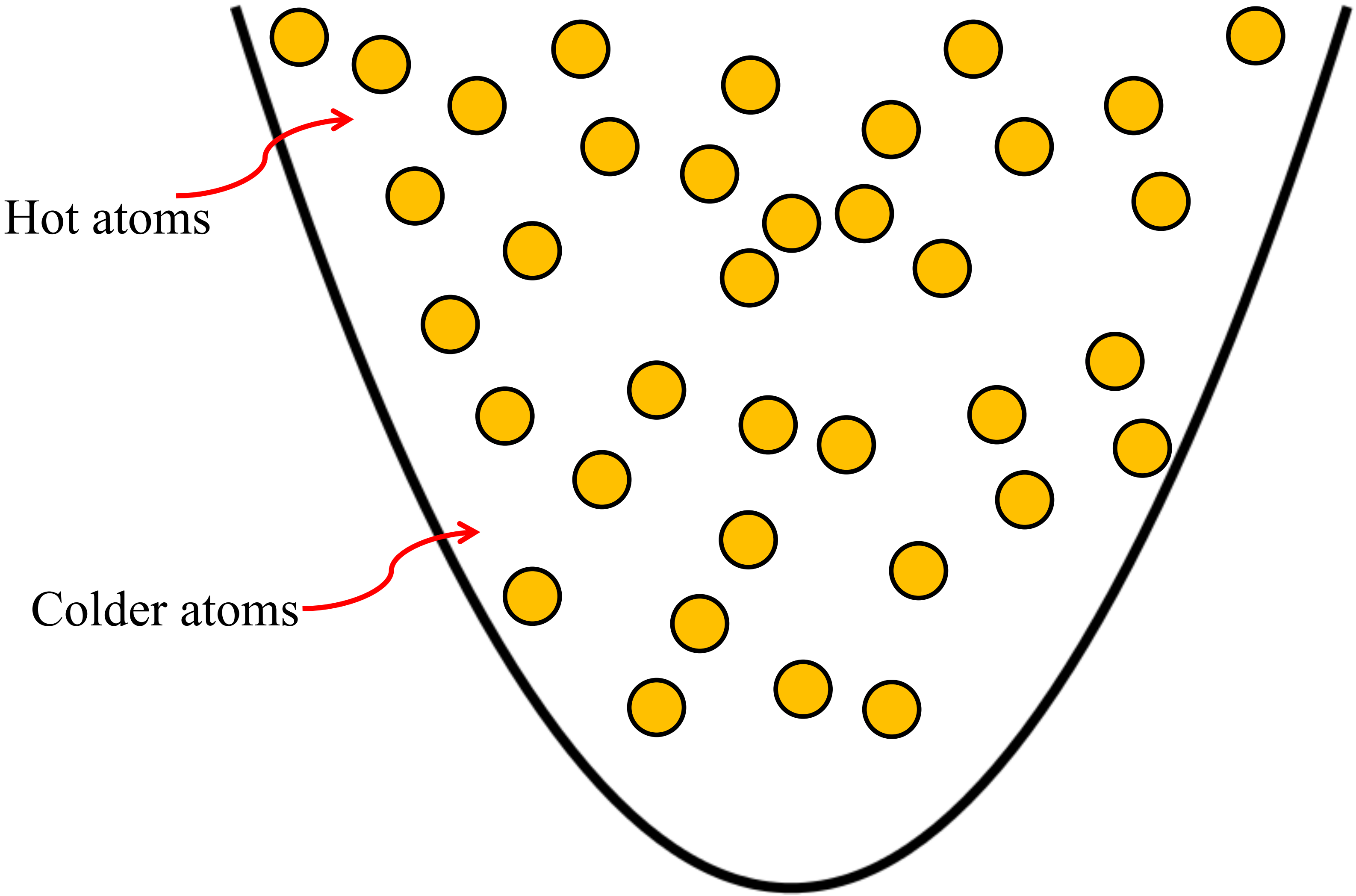


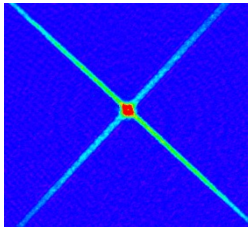
TOF-Image of atoms in our dipole trap, focal waist ~ 20 μm

Evaporative Cooling

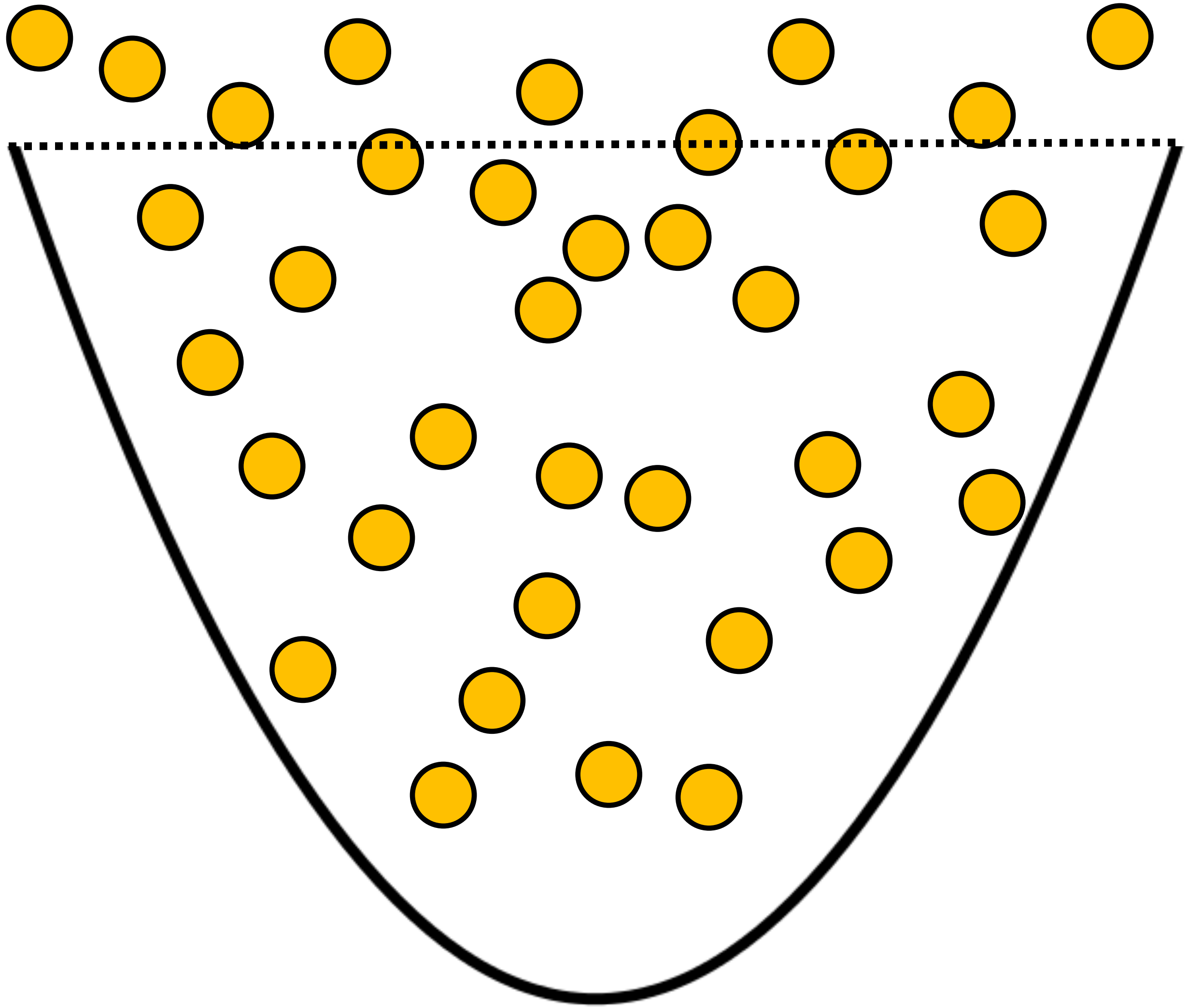
- Like blowing on a coffee cup
- Selectively remove only the hottest atoms
- Let the remaining atoms rethermalize
- Repeat

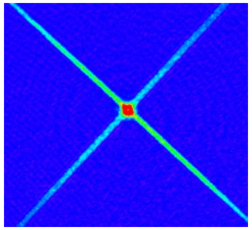
Forced Evaporation





Forced Evaporation





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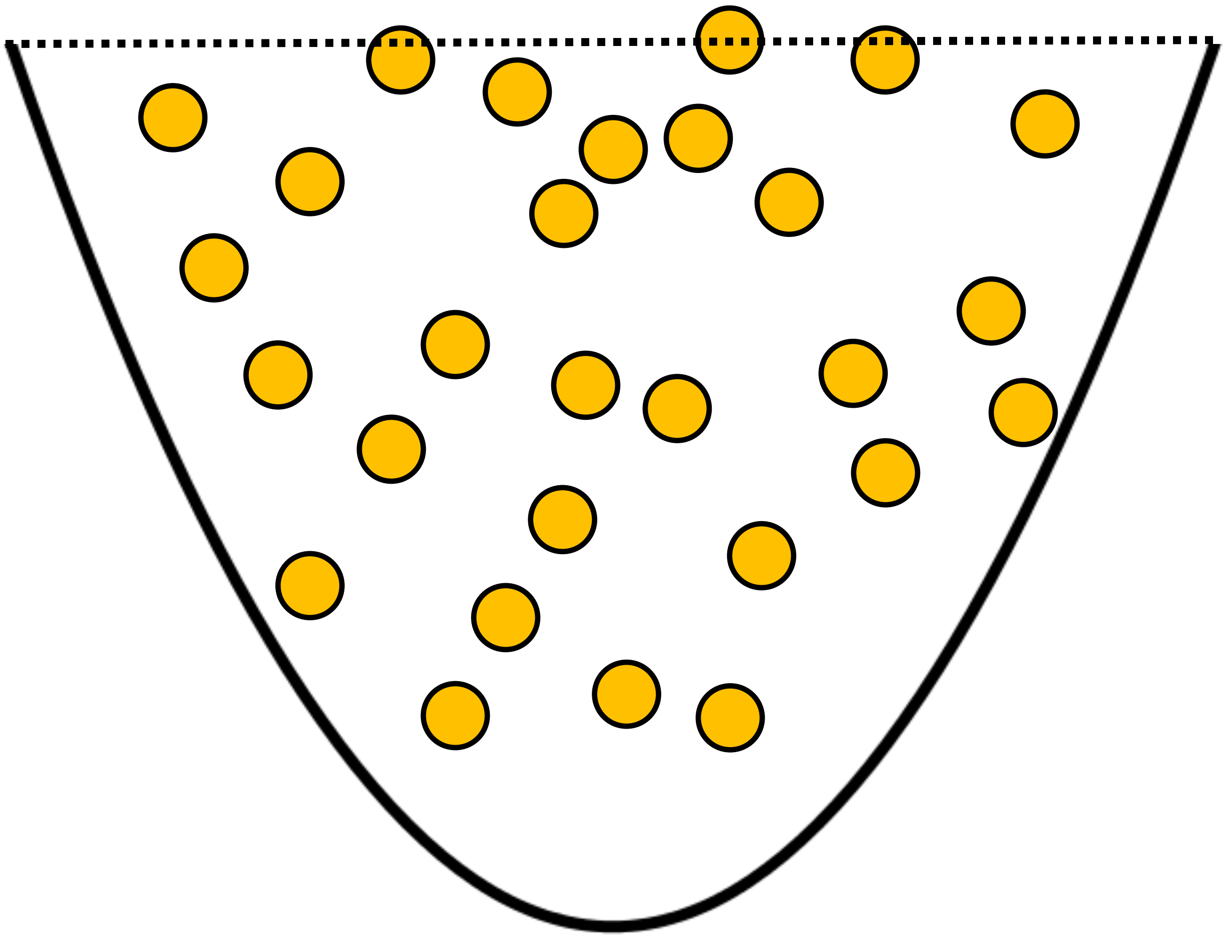

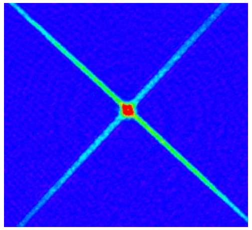

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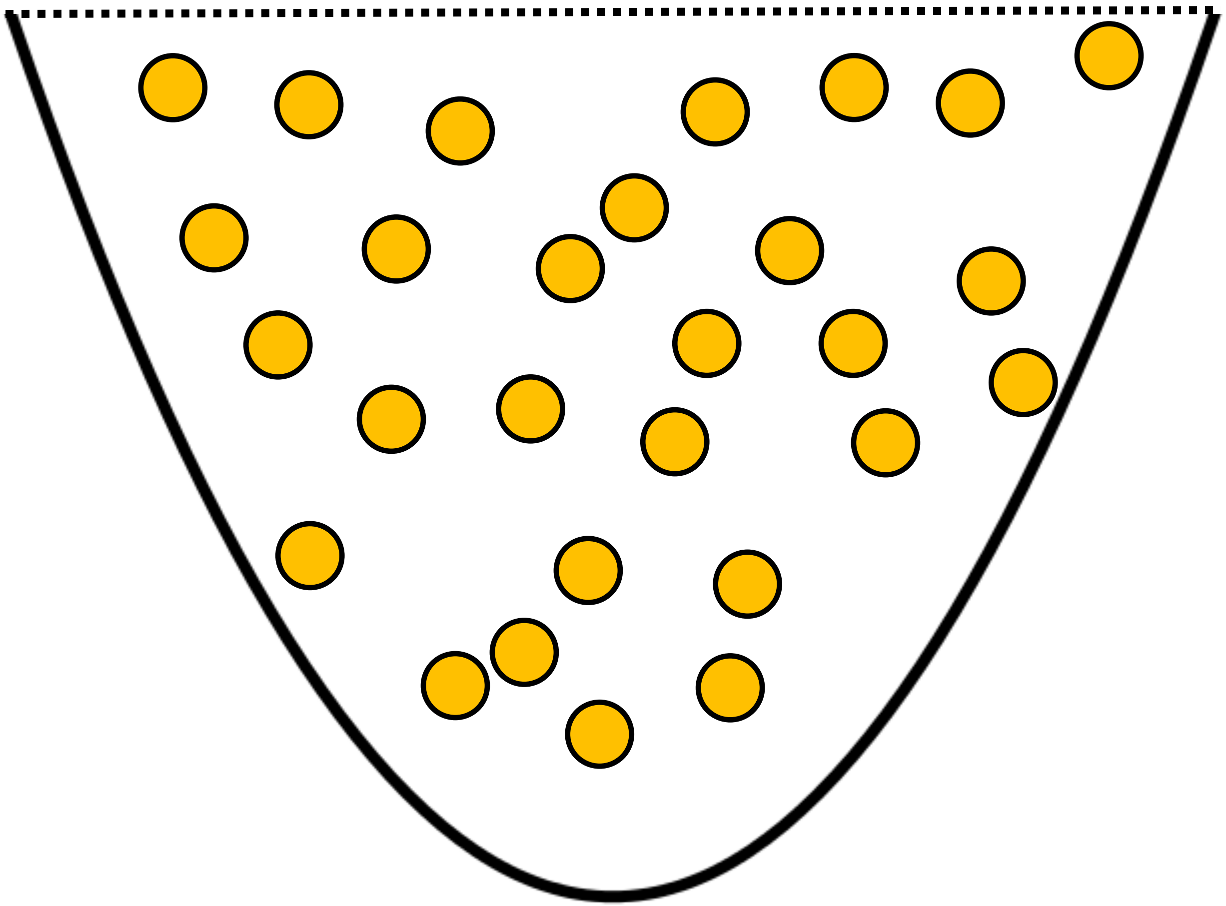

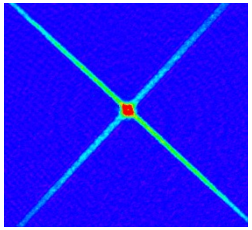

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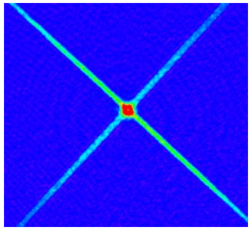

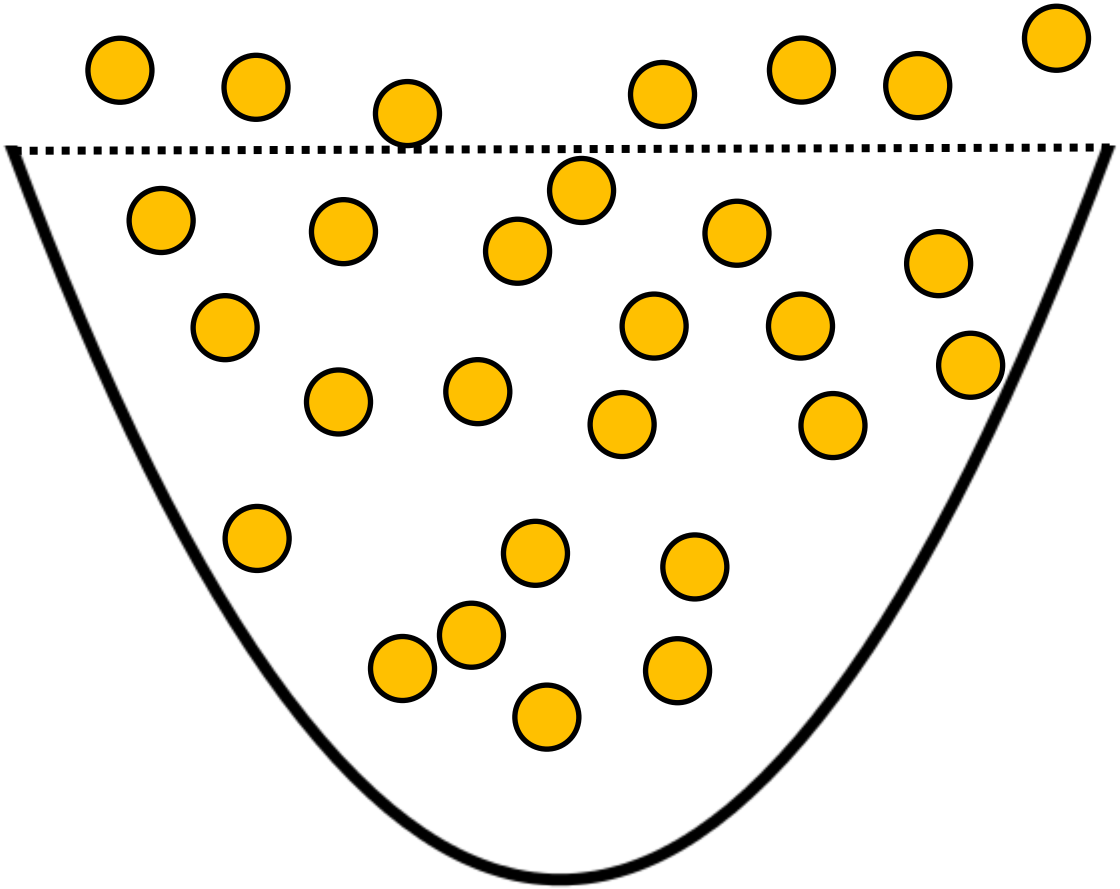

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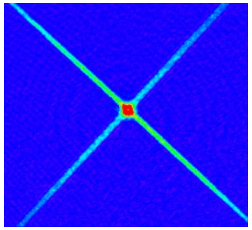

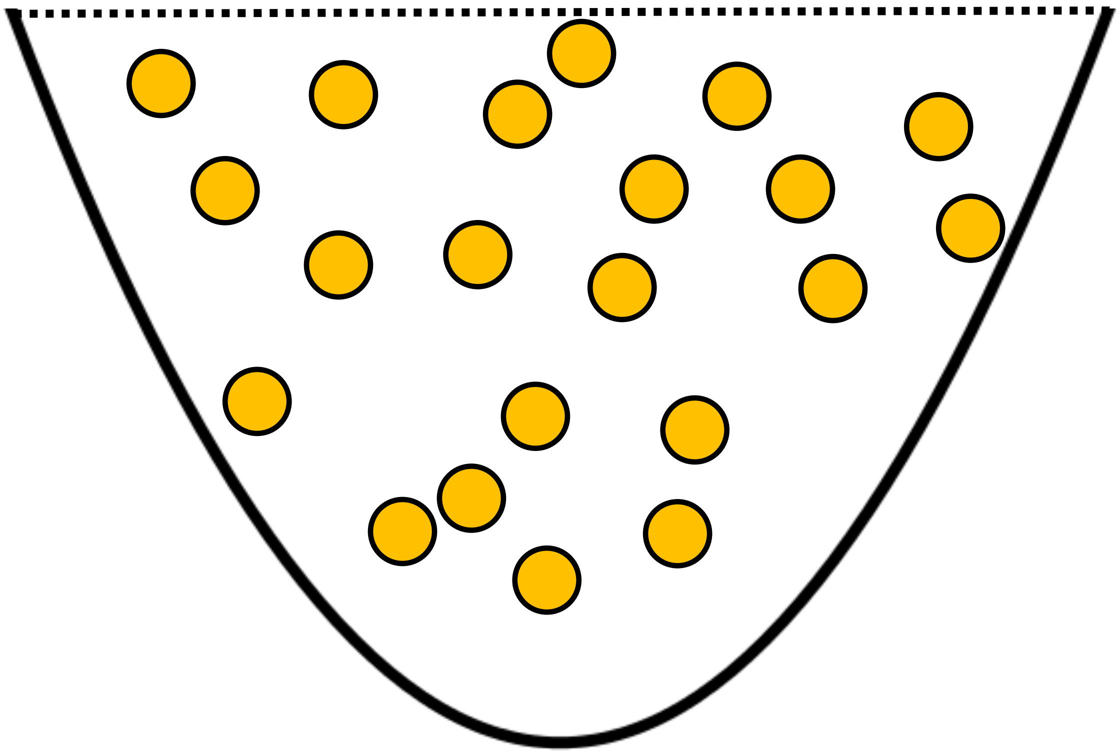

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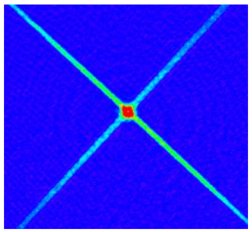

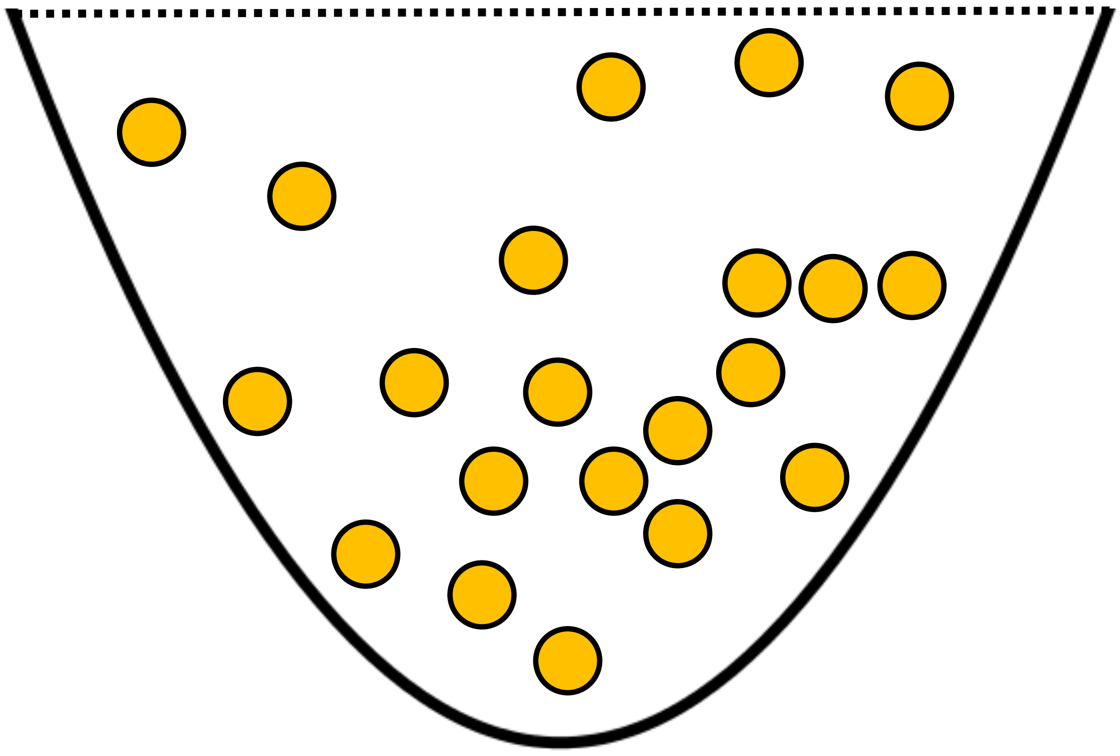

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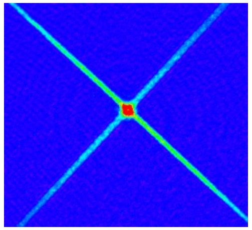

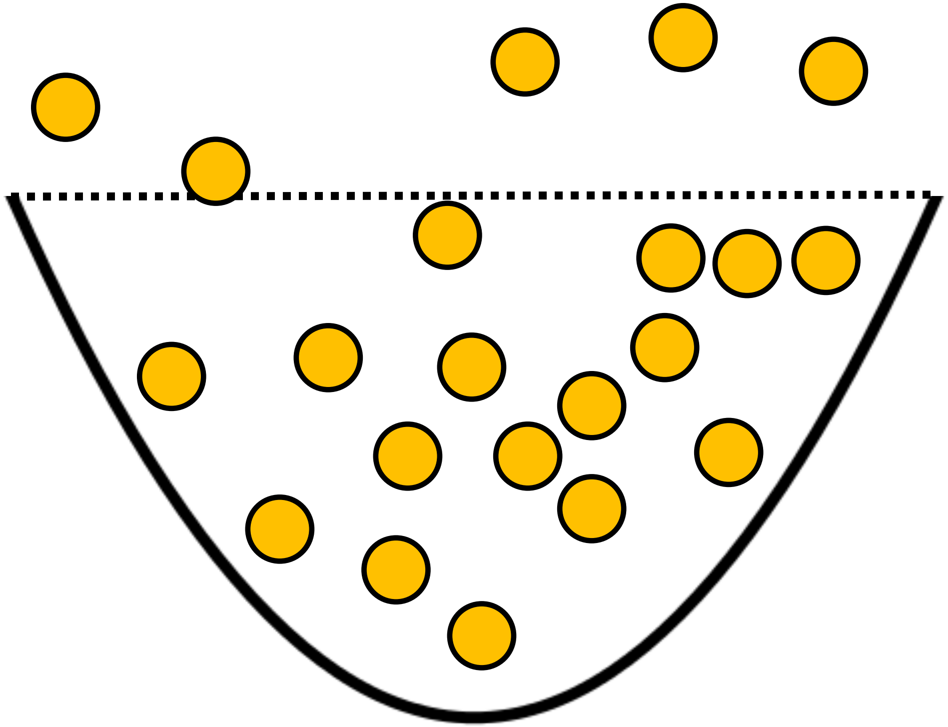

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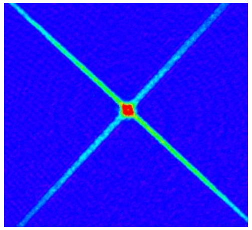

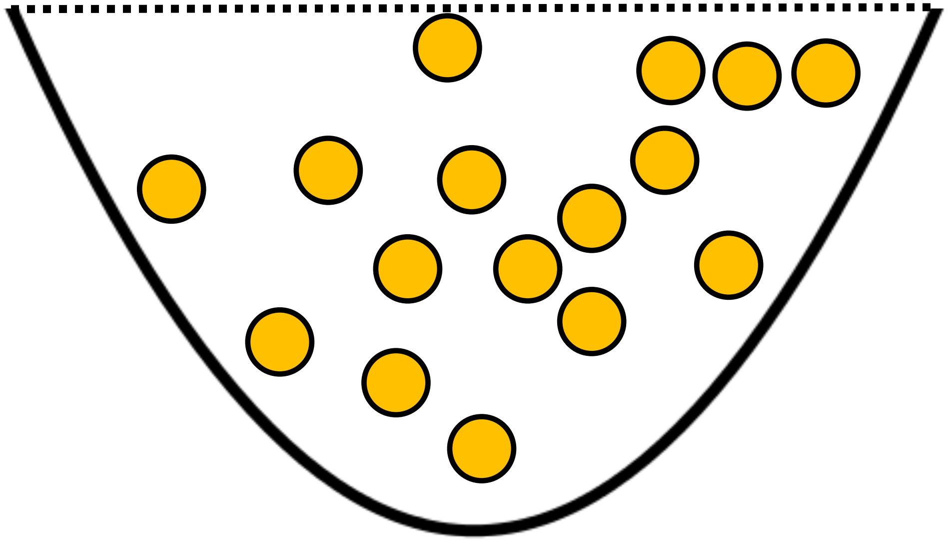

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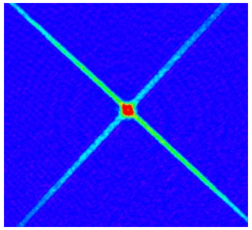
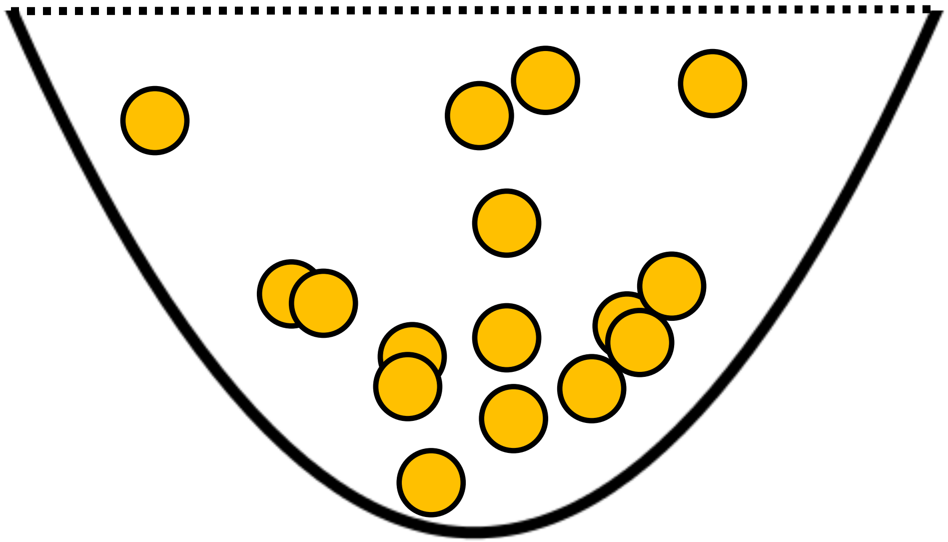
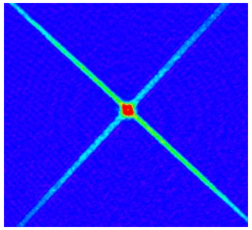
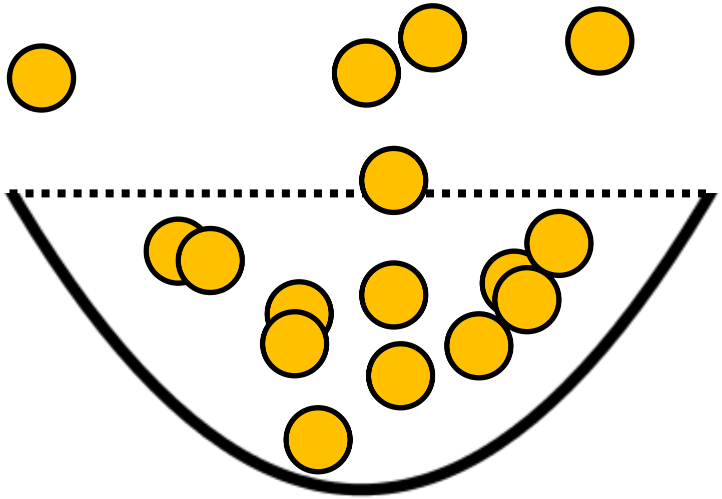




Forced Evaporation





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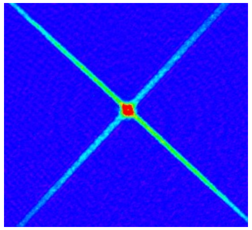

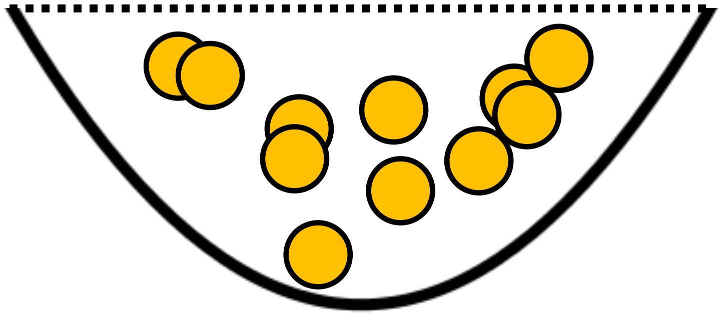

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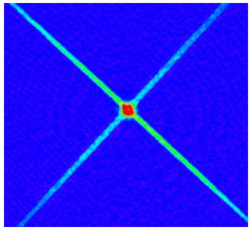

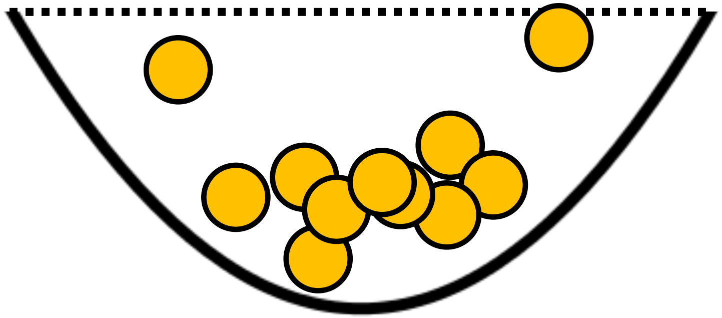

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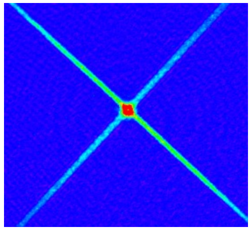

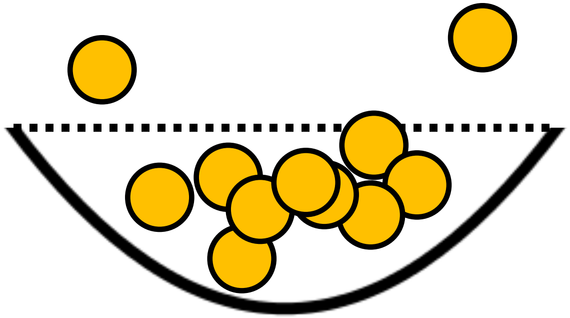

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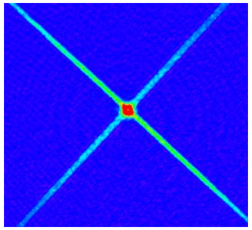

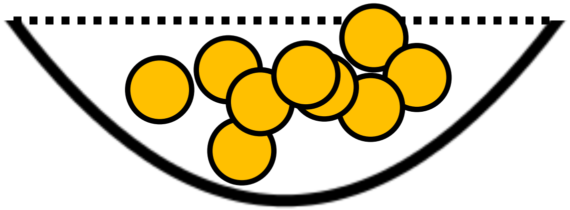

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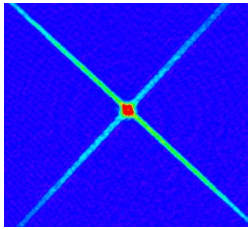
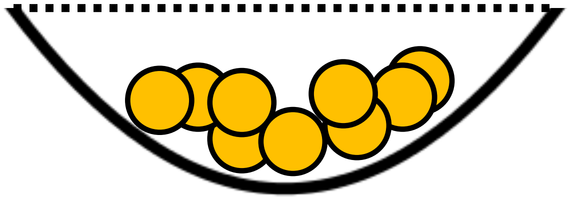
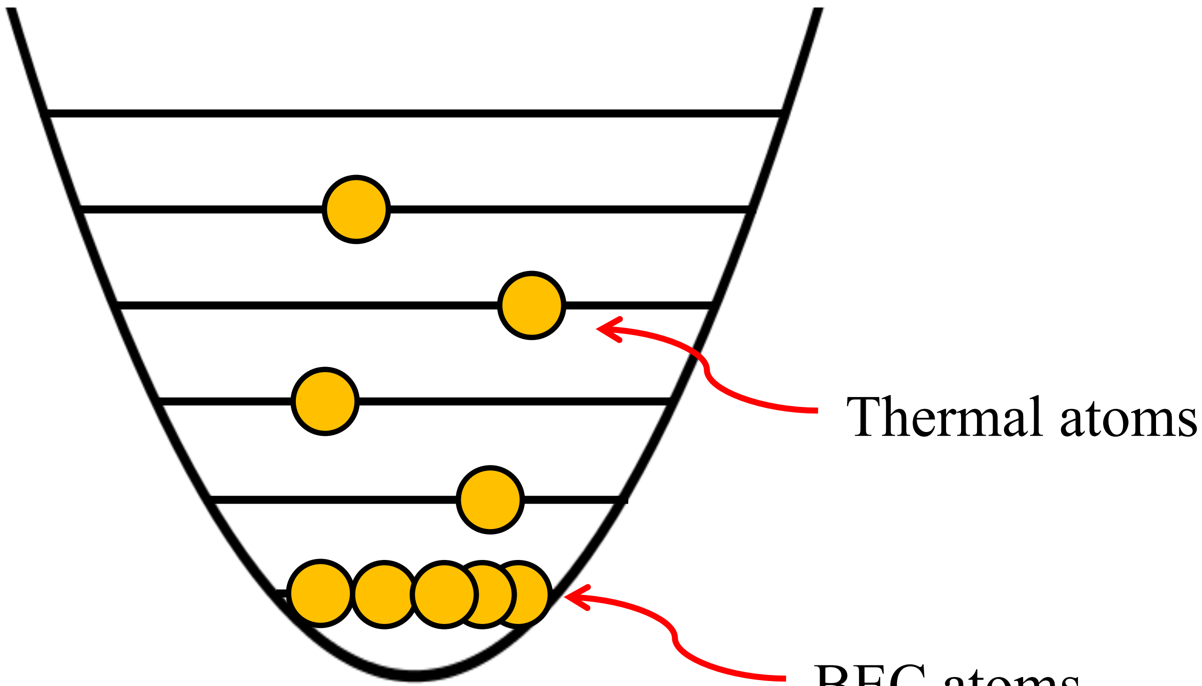




Bose-Einstein Condensation

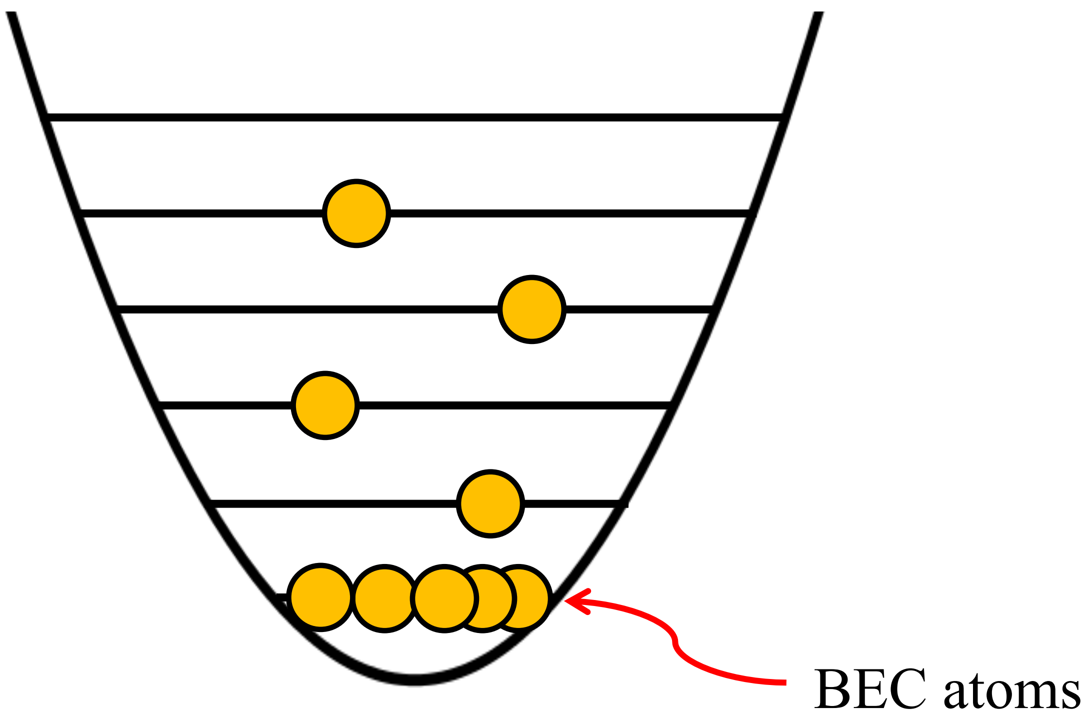
- Energies in the trap are also quantized
- BEC atoms are in the lowest energy level of the trapping potential



Absorption Imaging

- How to detect?

- Time-of-Flight absorption imaging



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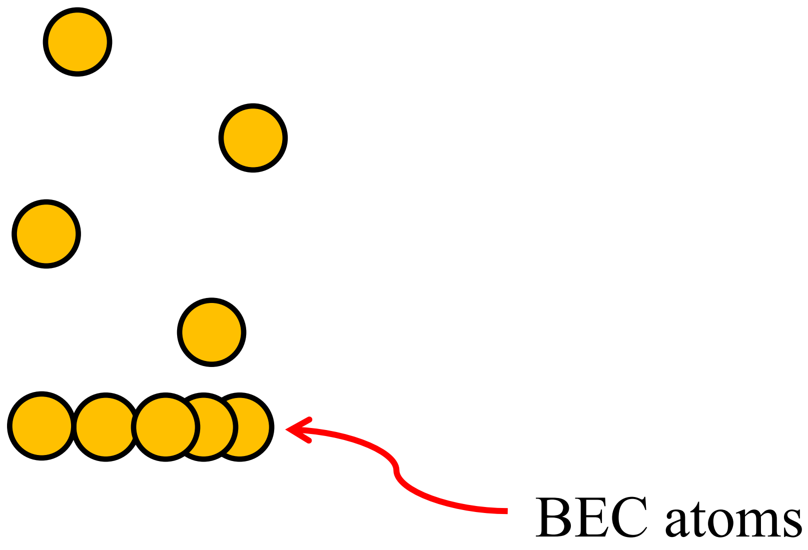

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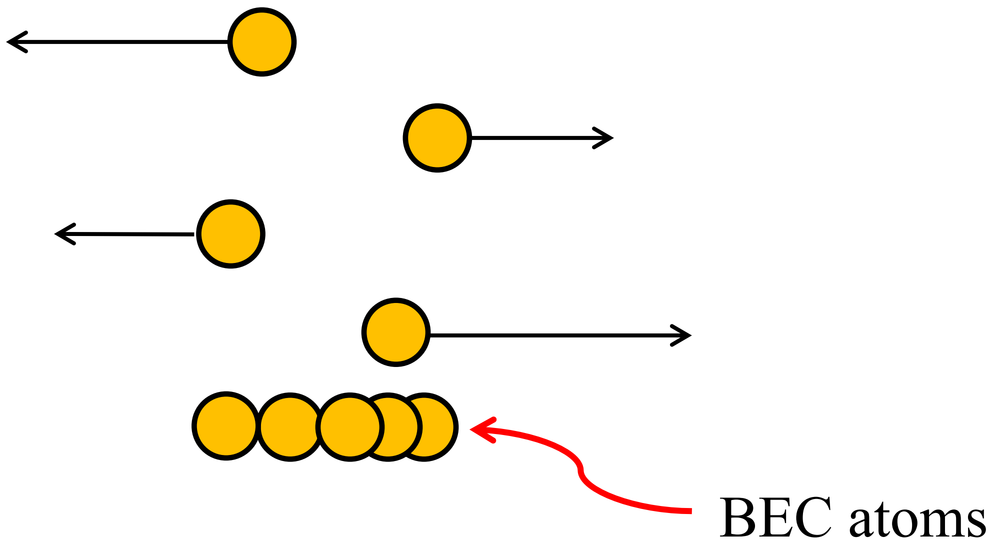

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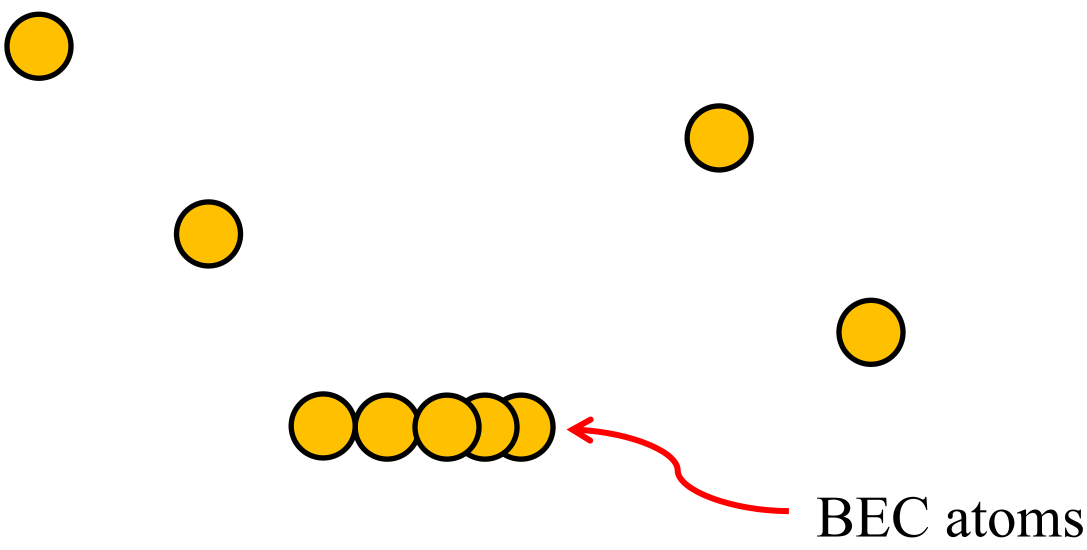

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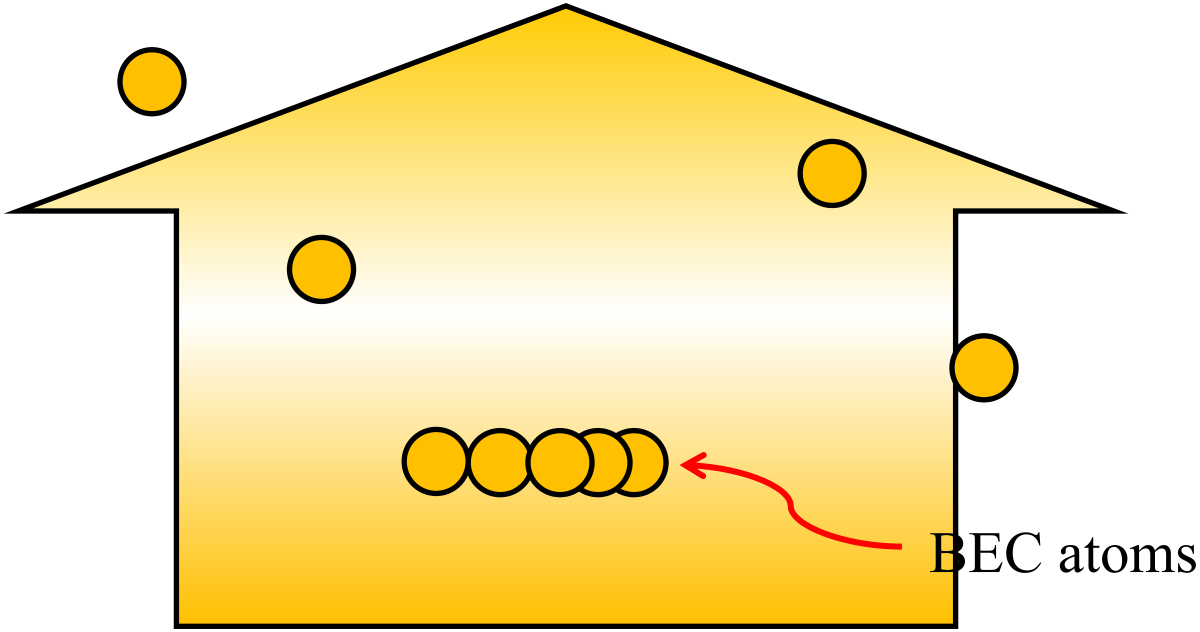

Absorption Imaging

- How to detect?
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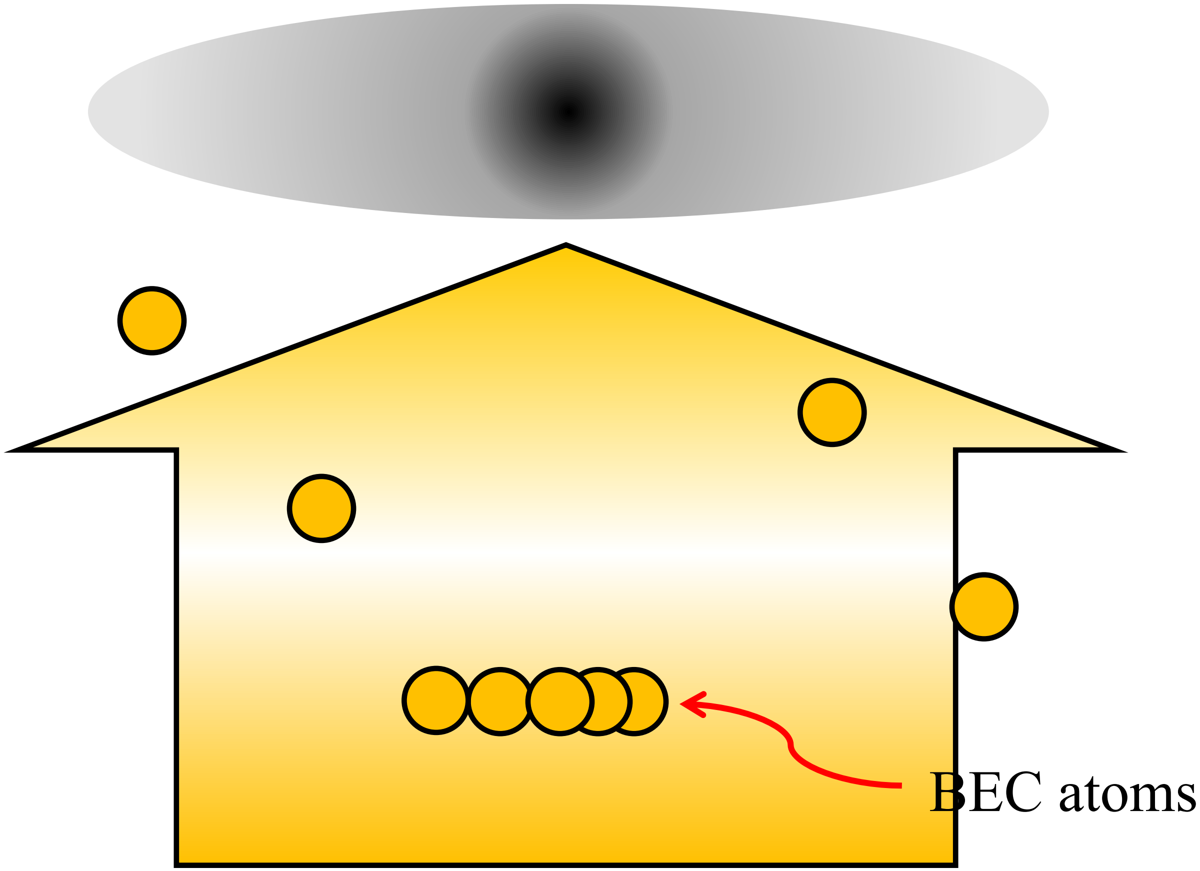
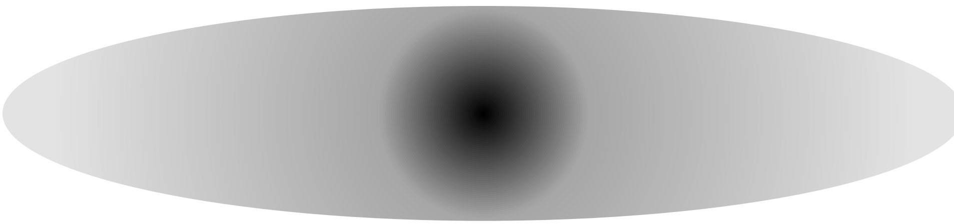
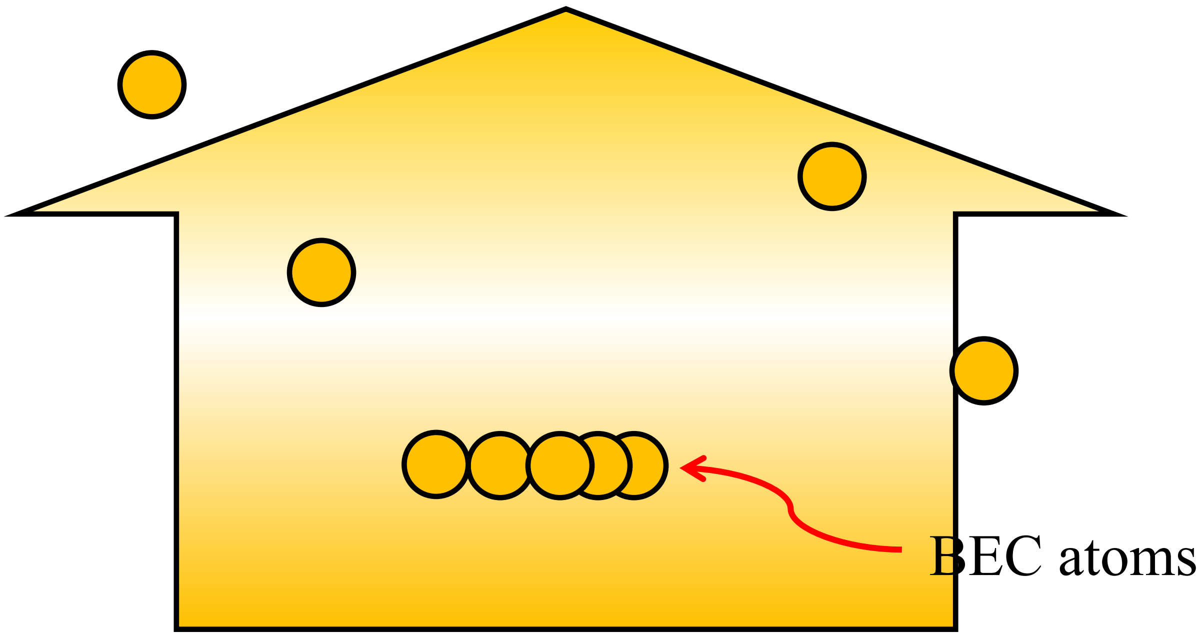


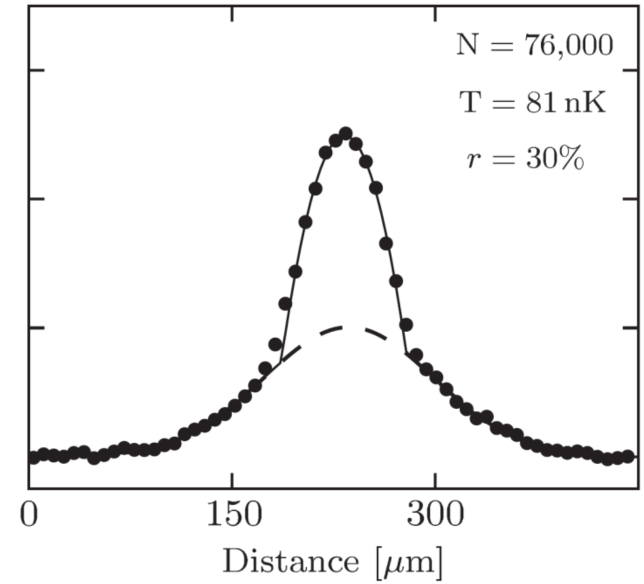
Absorption Imaging

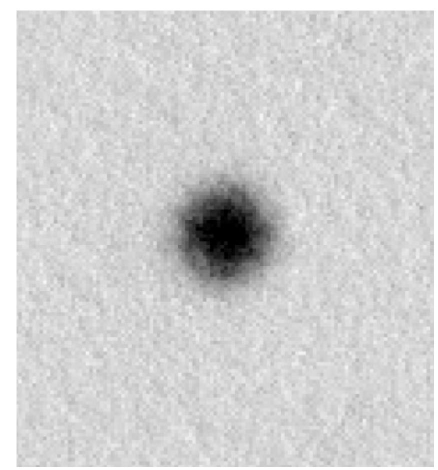
- How to detect?

- Time-of-Flight absorption imaging







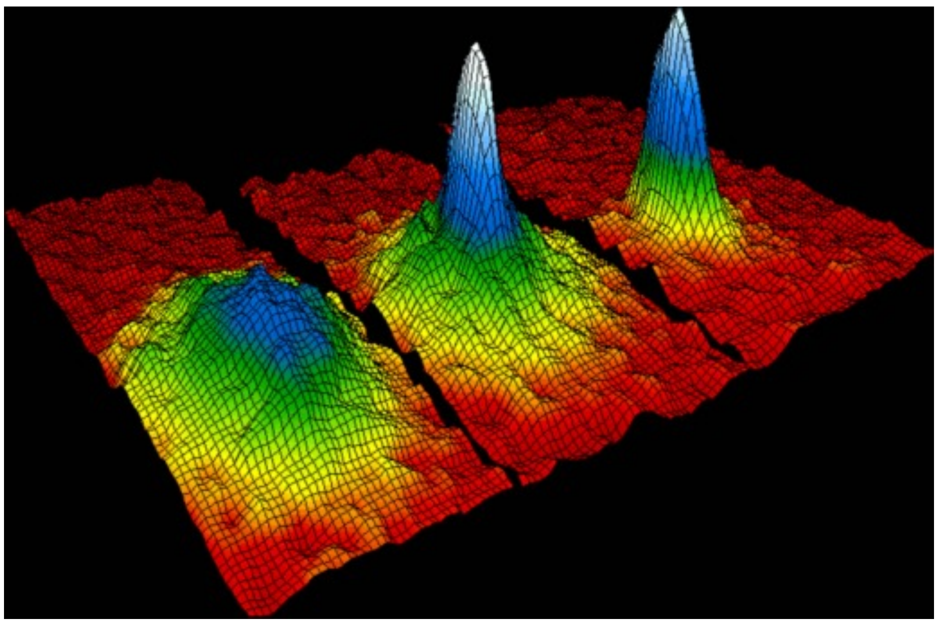


- AMO

BEC: Giant Matter Wave

- The first Bose-Einstein condensates were observed 1995 by Eric Cornell, Carl Wiemann, and Wolfgang Ketterle
  - They won the 2001 Nobel Prize

E. Cornell W. Ketterle C. Wiemann

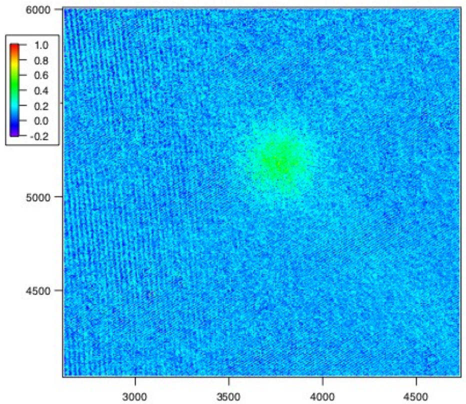


BEC observed at MIT
(left to right: thermal cloud, mixture, and pure BEC)

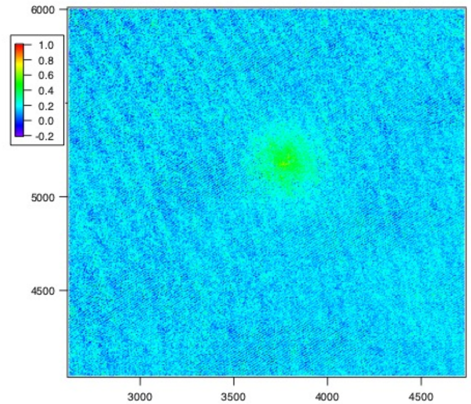
- AMO

Our BEC at OU

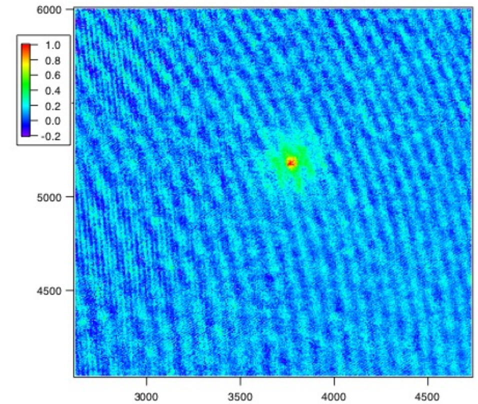
Time-of-flight absorption images of all-optical sodium Bose-Einstein condensate via evaporative cooling, ramping down dipole trap laser power from P = 40 W to P_f



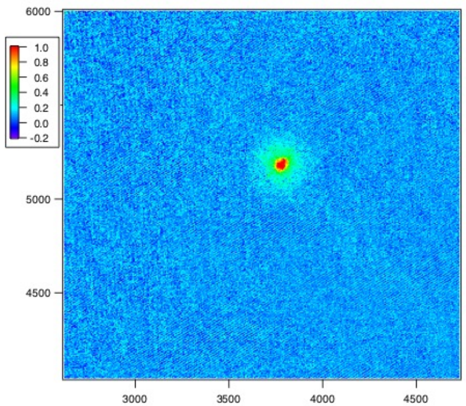
P_f = 281 mW



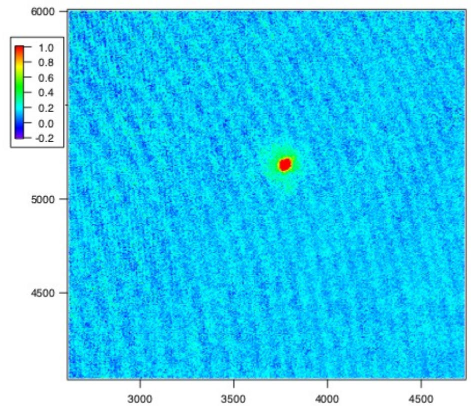
P_f = 234 mW



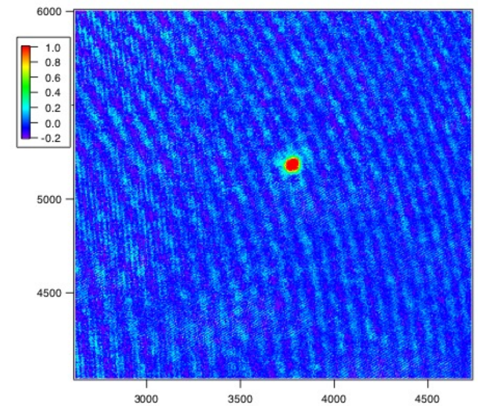
P_f = 198 mW, BEC appears!



P_f = 179 mW



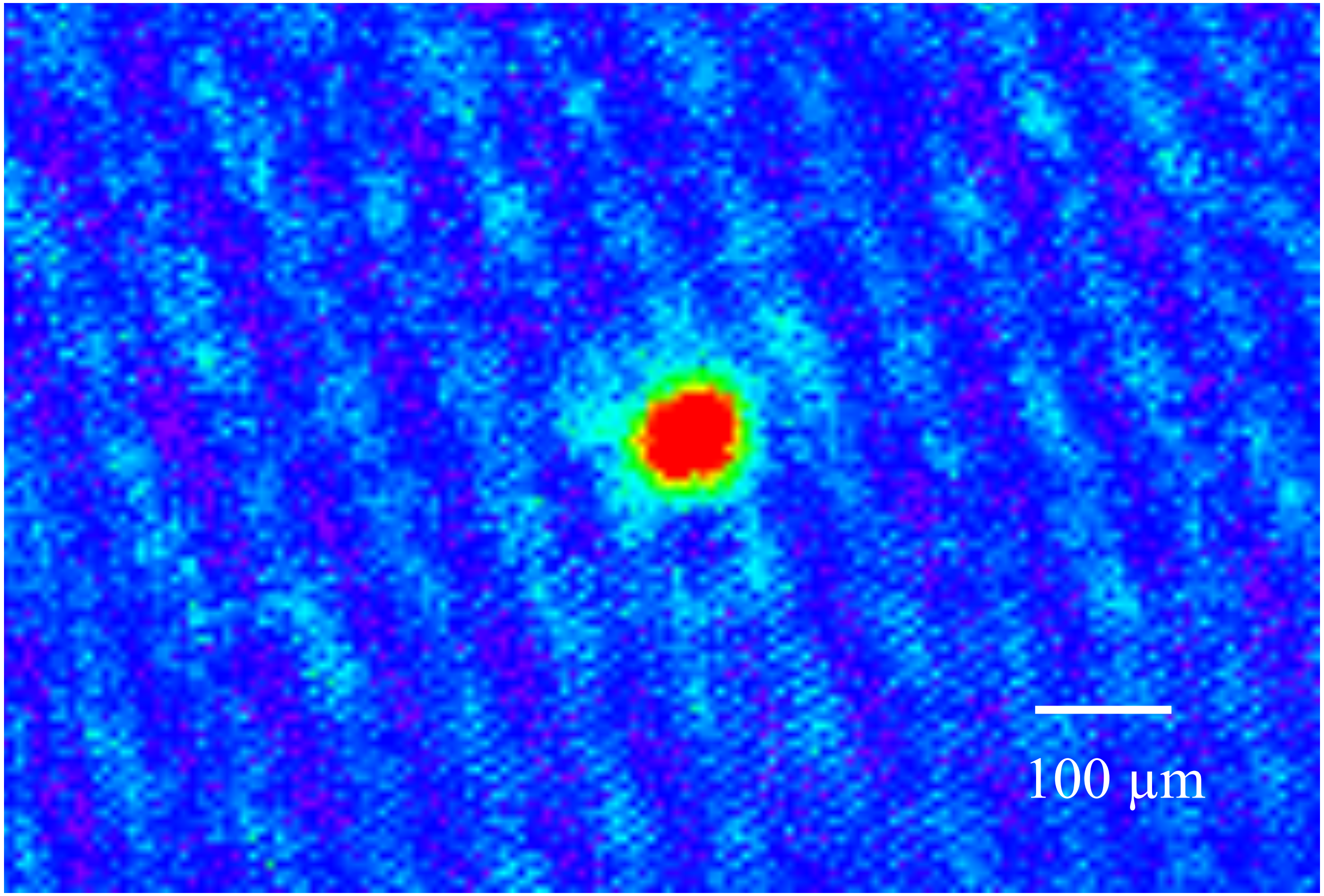
P_f= 143 mW



P_f = 125 mW, almost pure BEC!

- AMO

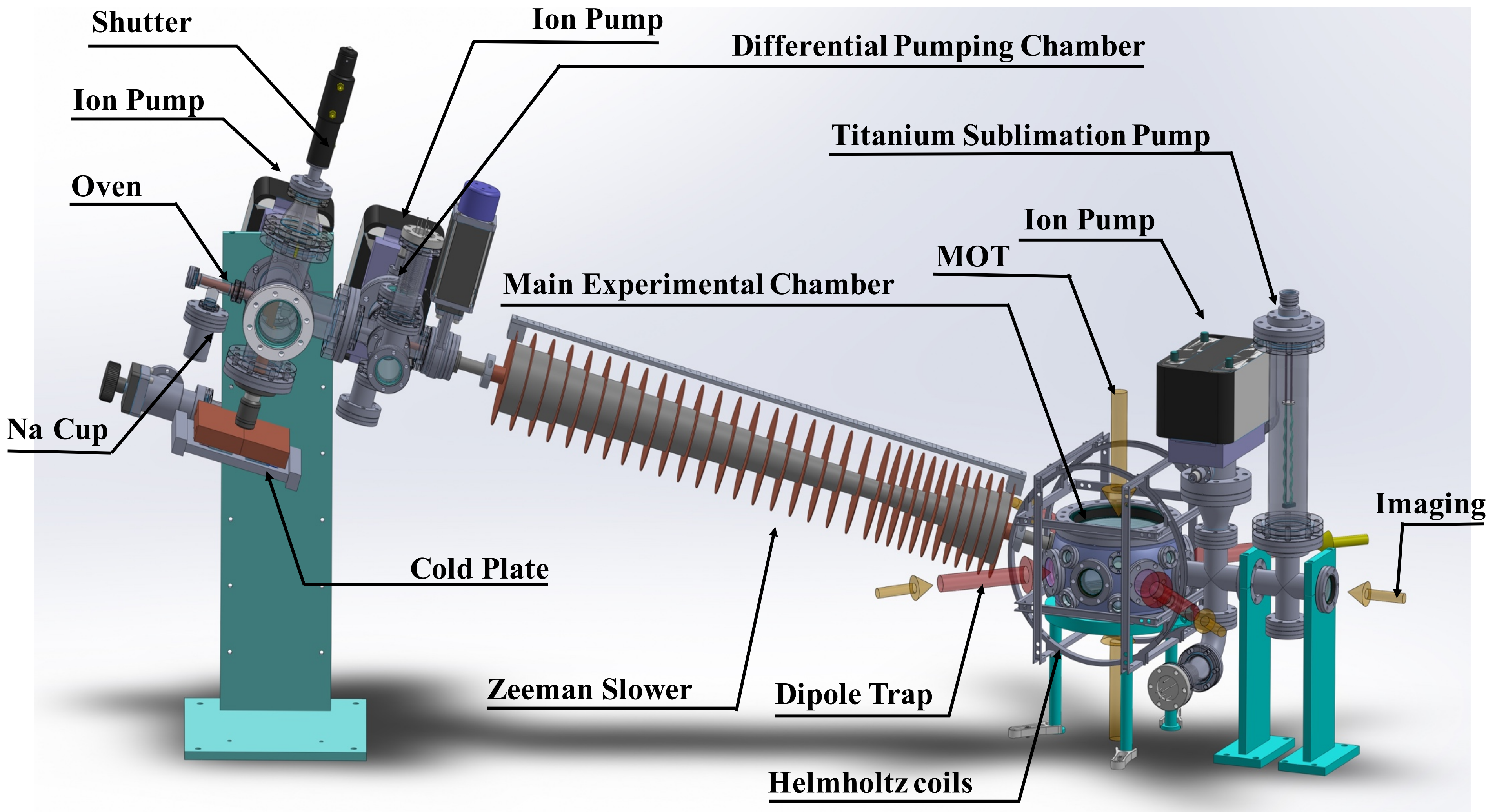
BEC: Giant Matter Wave



~20,000 atoms in our pure BEC after 10 ms expansion (false color absorption image)

- AMO

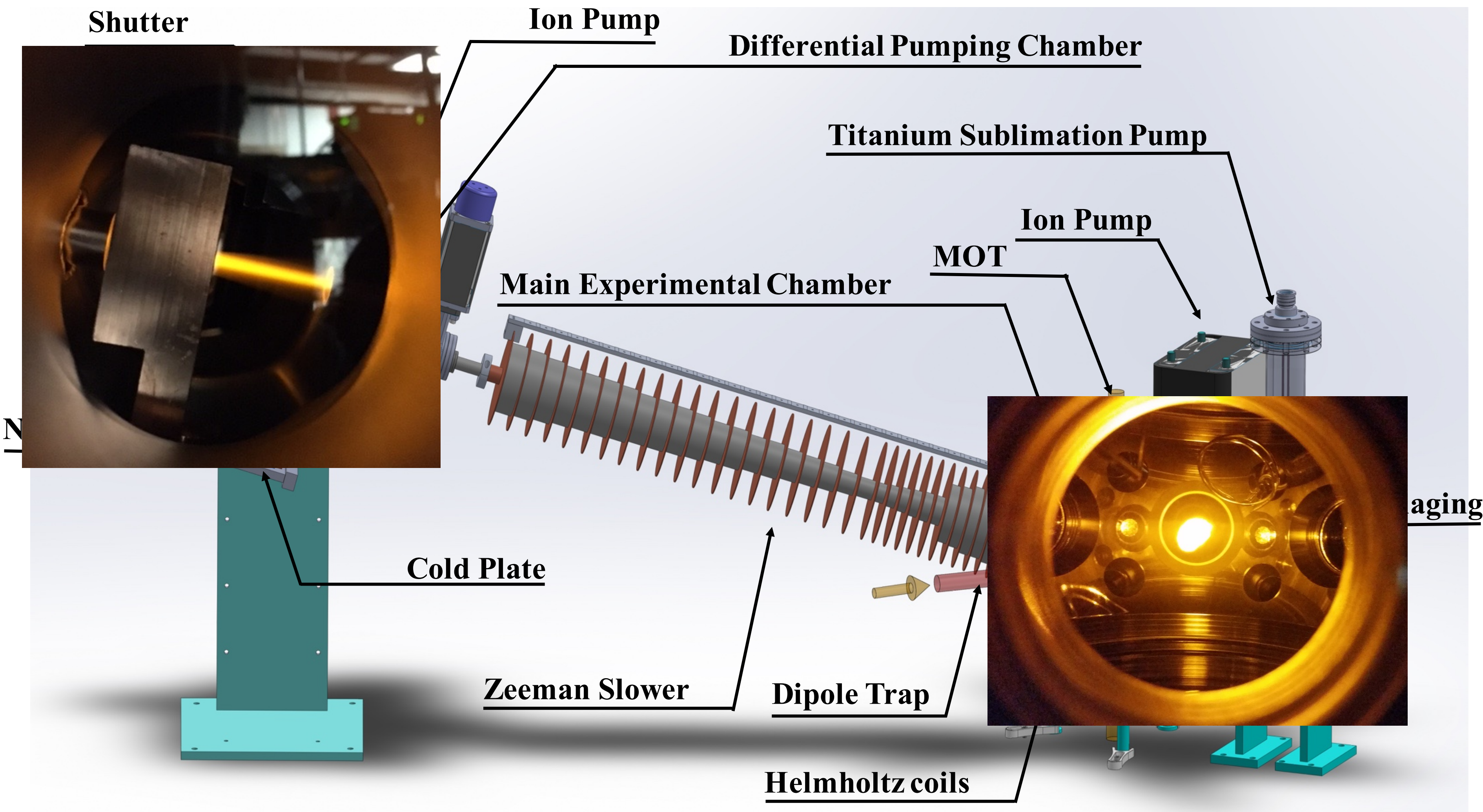
Spinor BEC Setup



- Hot atomic gas is created in an oven, slowed in the Zeeman slower tube, and then trapped and cooled in the main chamber

- AMO

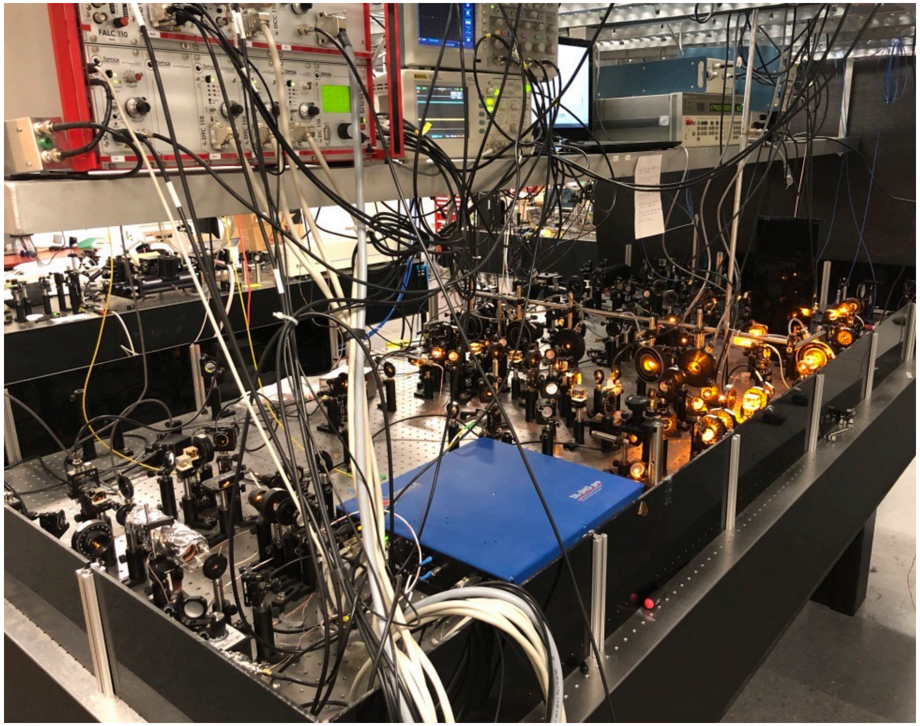
Spinor BEC Setup

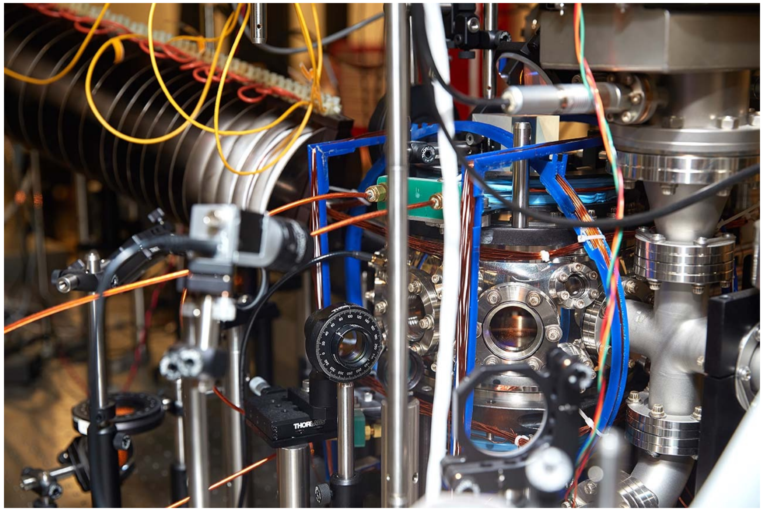
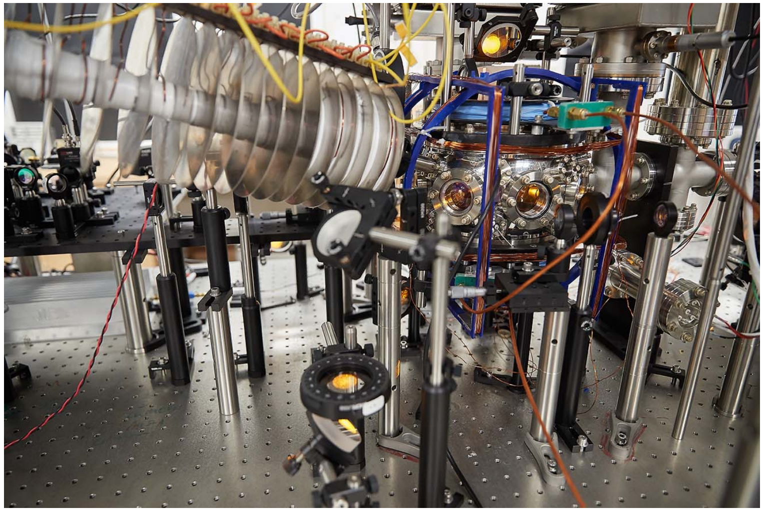


- Hot atomic gas is created in an oven, slowed in the Zeeman slower tube, and then trapped and cooled in the main chamber

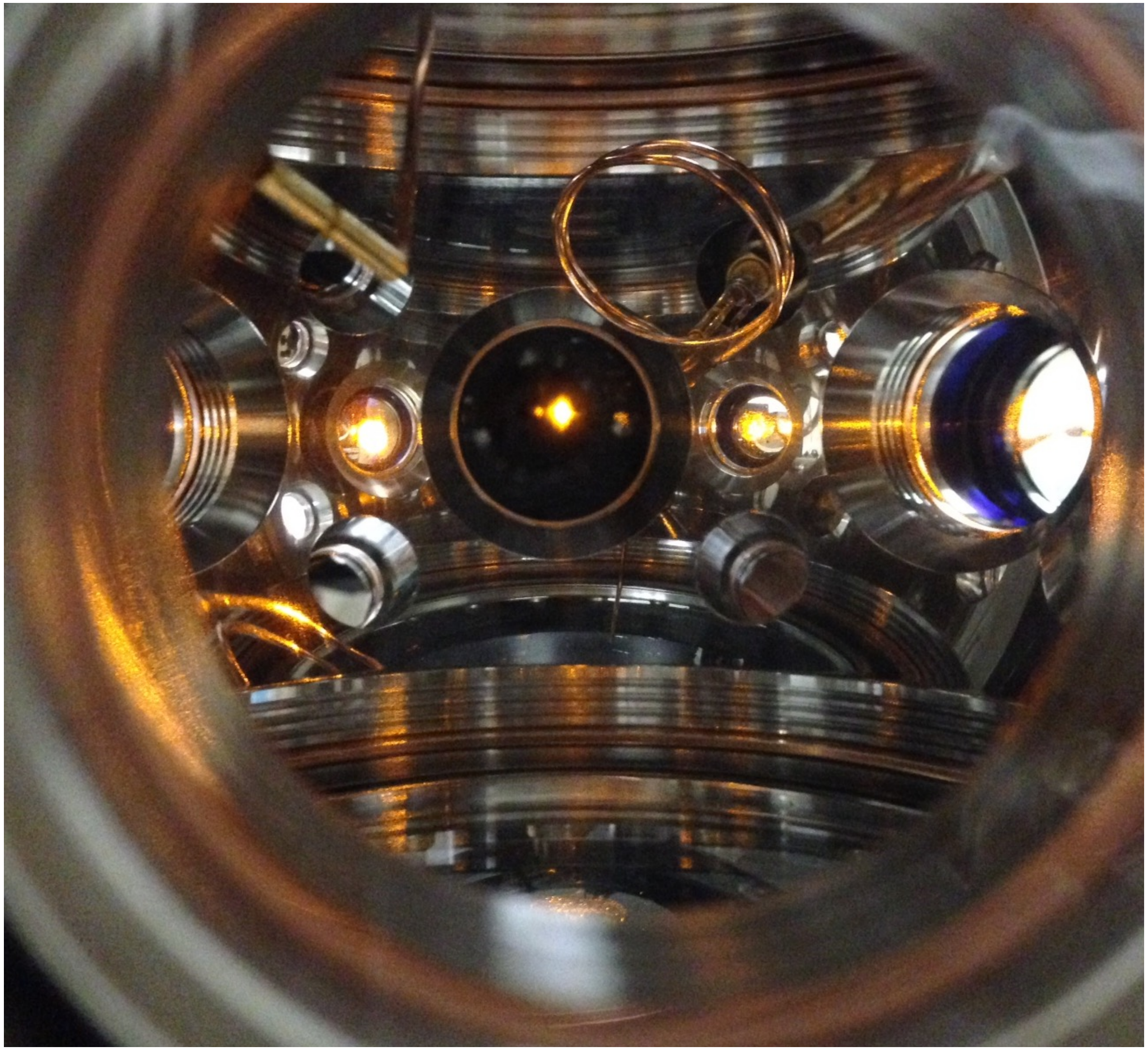
- AMO

Lab Pictures



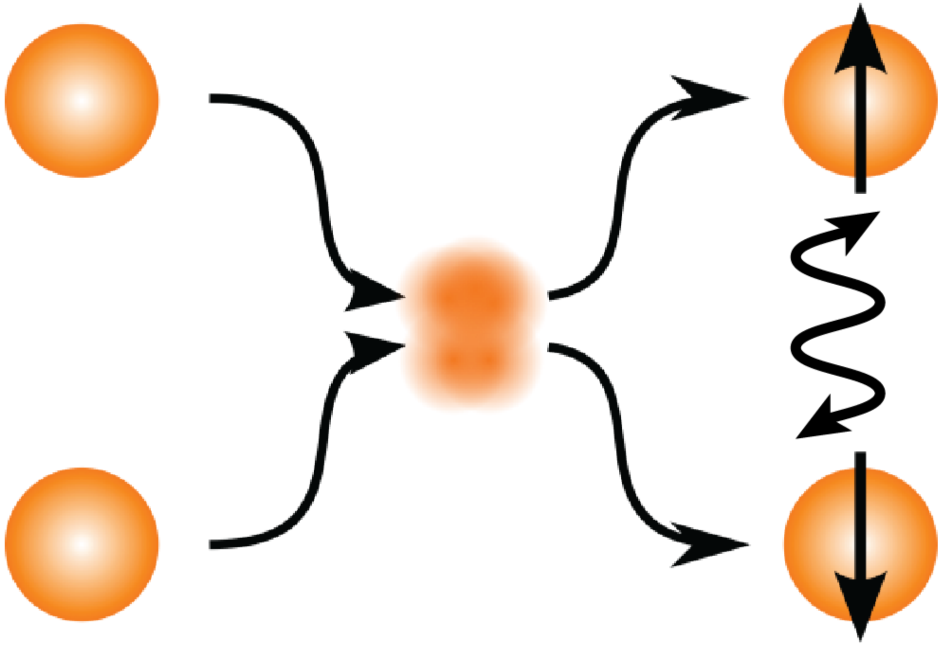



Lab Pictures



- AMO

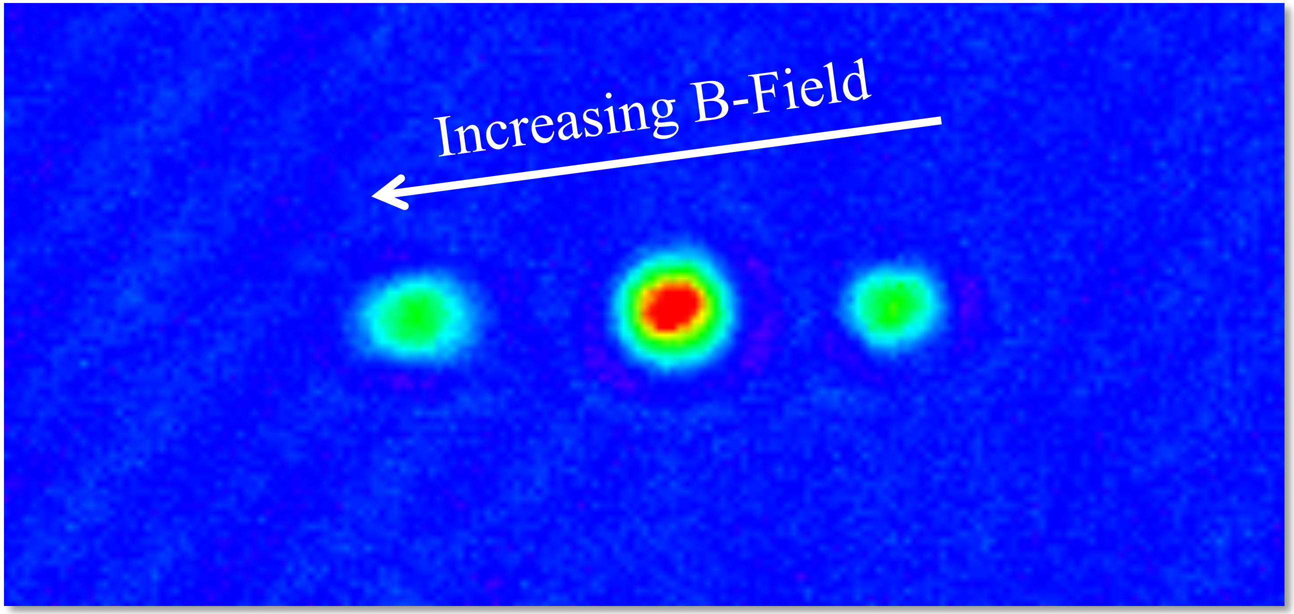
Spin Changing Collisions



- Spin-Exchange collisions always create pairs
- Source of entanglement
- Entanglement is a resource to reduce noise

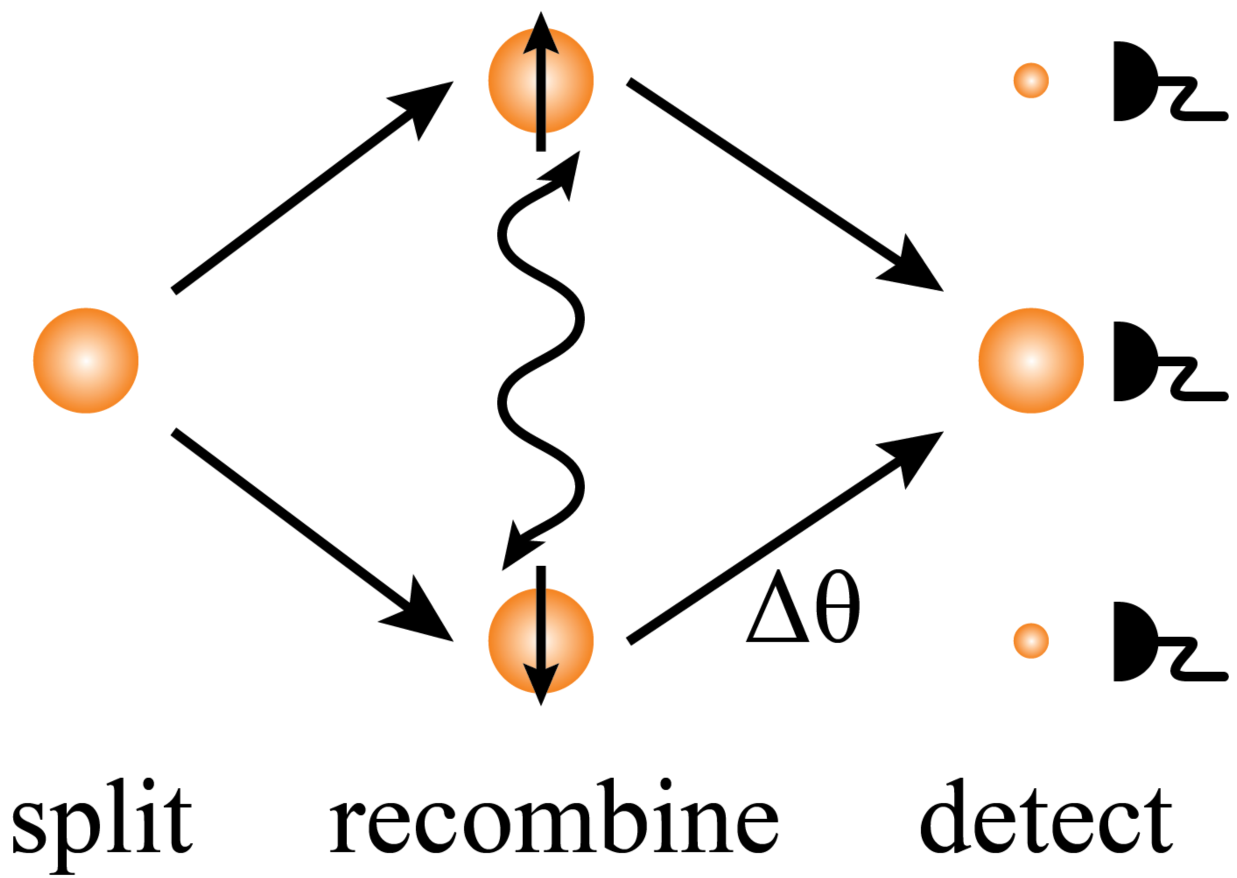
Stern-Gerlach Imaging

- We can image each spin state
- Apply magnetic field gradient during time-of-flight expansion
- Measure populations



Interferometry

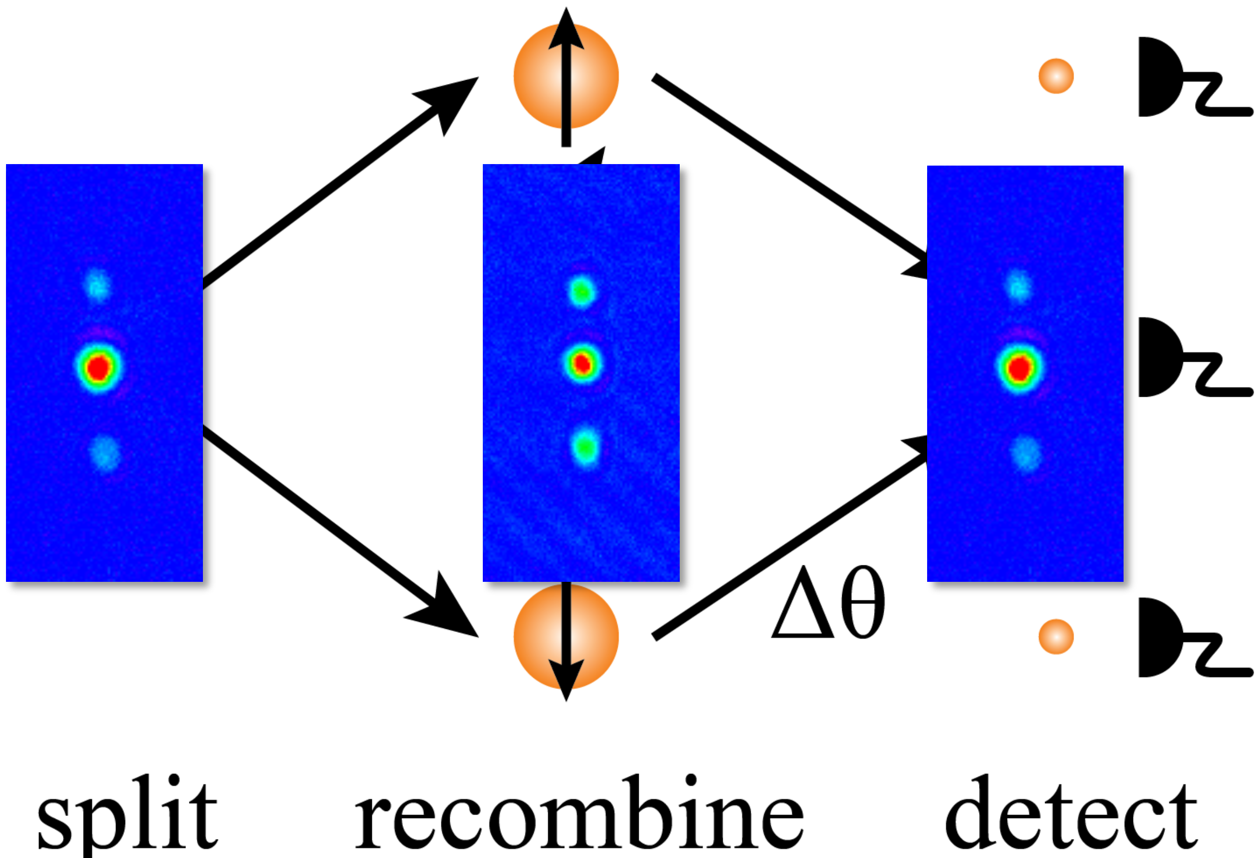
- Goal: "Split and Recombine" in spin space to measure interference!



- Collisions create spin-squeezing and reduce noise in interferometer

Interferometry

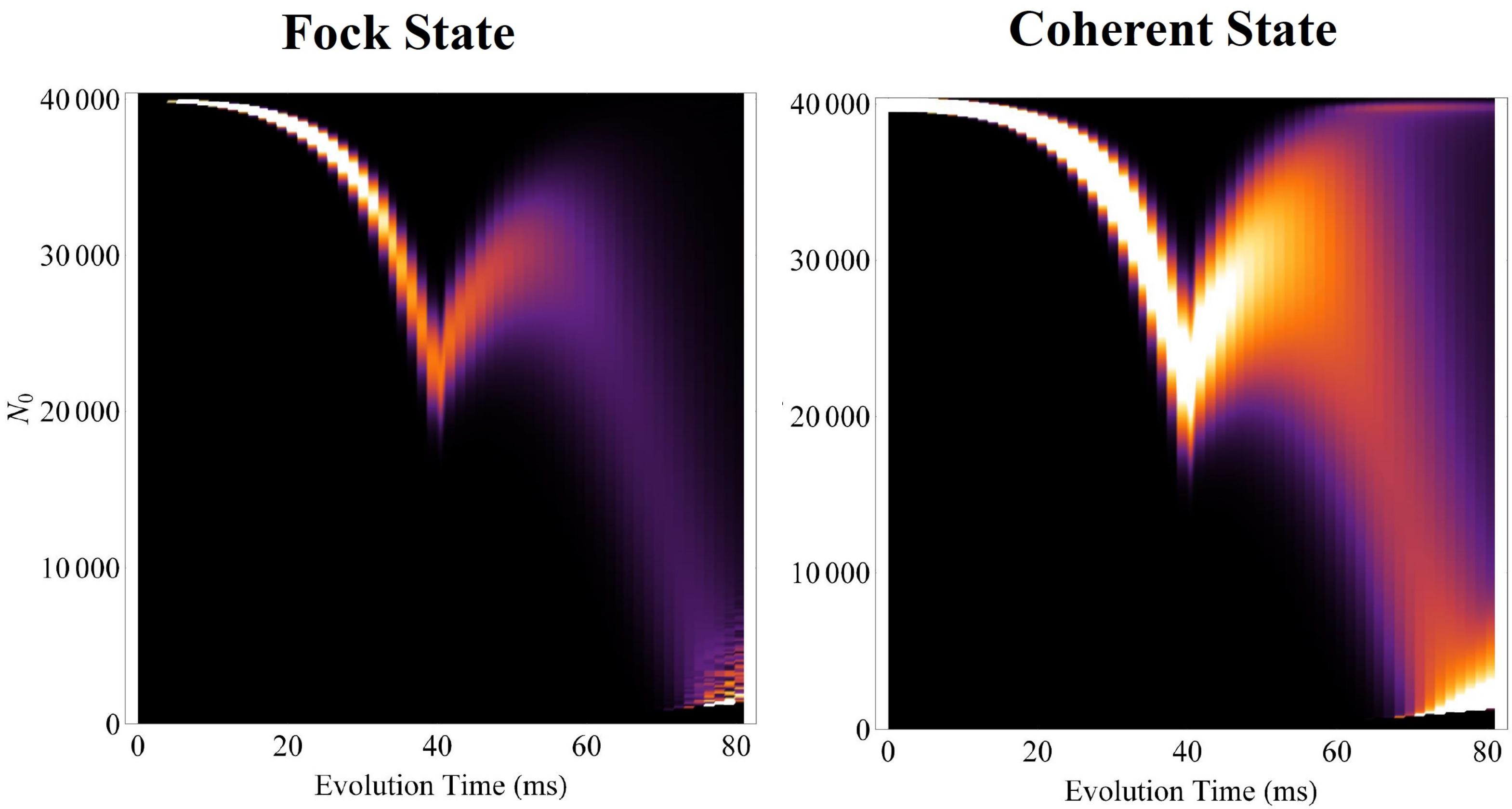
- Goal: "Split and Recombine" in spin space to measure interference!



- Collisions create spin-squeezing and reduce noise in interferometer

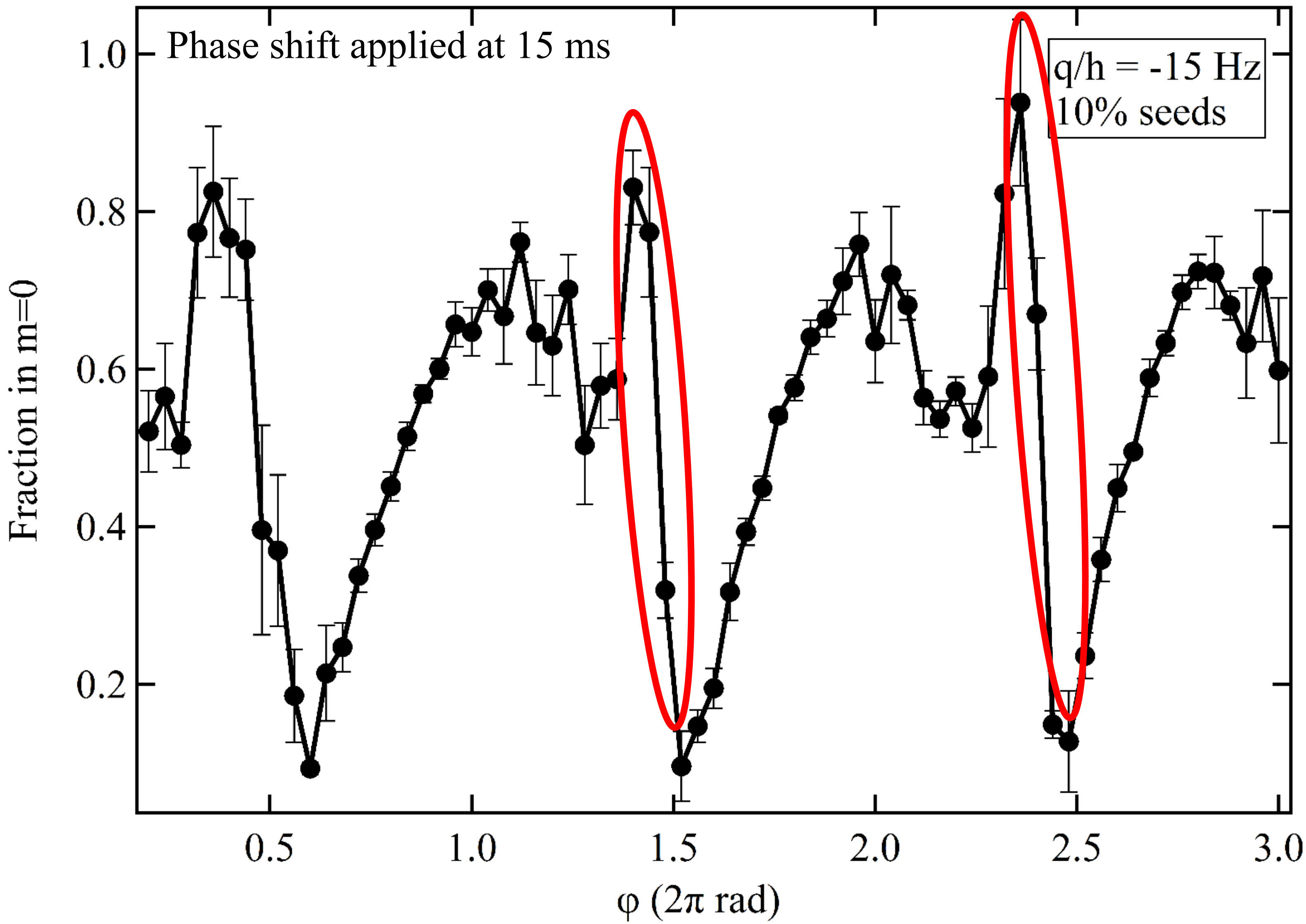
Calculations

- Full quantum calculation for N~40,000 on OU supercomputer
- Simulated interferometry sequence for different initial states



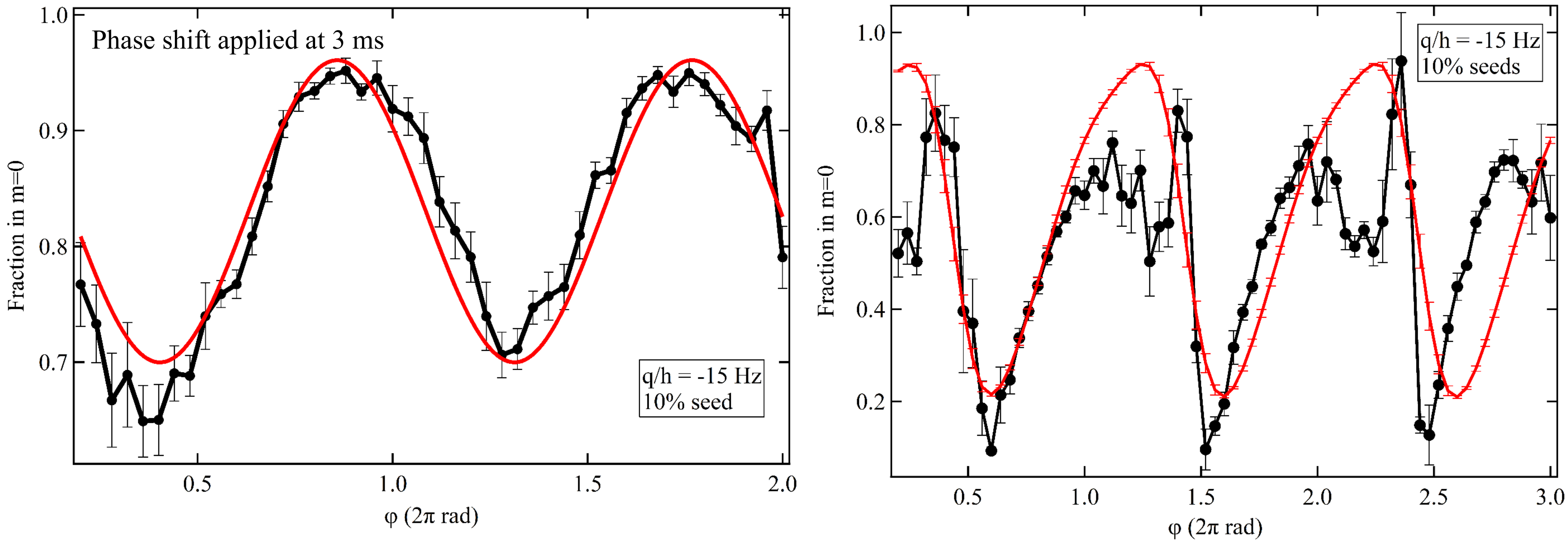
- Q. Zhang and A. Schwettmann, "Quantum interferometry with microwave-dressed F=1 spinor Bose-Einstein condensates: Role of initial states and long-time evolution," Phys. Rev. A **100**, 063637 (2019).

Interference Fringes



- A Sharp slope indicates enhanced phase sensitivity

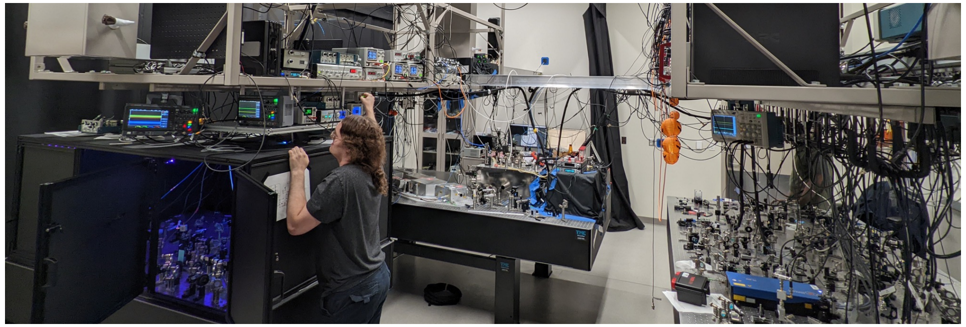
Fringes: Short vs. Long Time

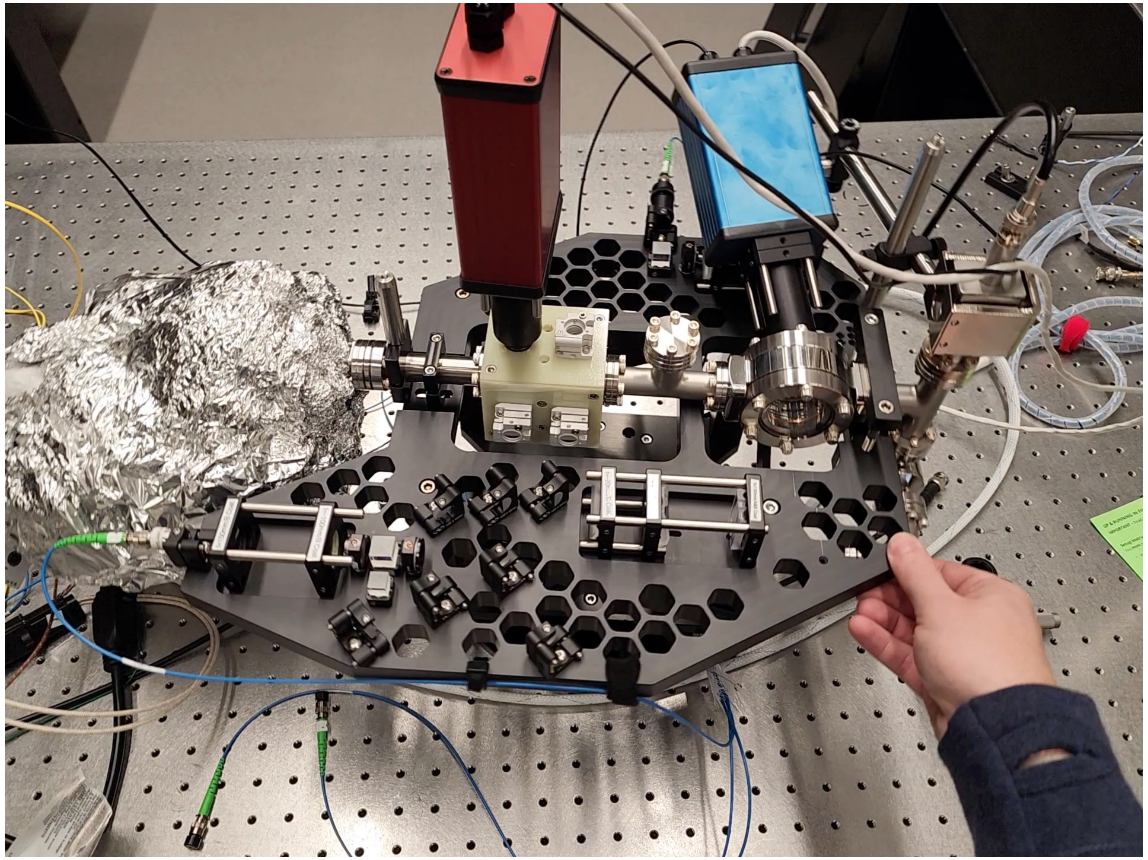


- For short evolution time the fringes are sinusoidal, for long evolution time they are non-sinusoidal
- Some qualitative agreement with full quantum calculation, but also some discrepancies
- S. Zhong, H. G. Ooi, S. Prajapati, Q. Zhang, and A. Schwettmann, "Seeded spin-mixing interferometry with long-time evolution in microwave-dressed sodium spinor Bose-Einstein condensates," J. Phys. B: At. Mol. Opt. Phys. **56**, 085502 (2023).

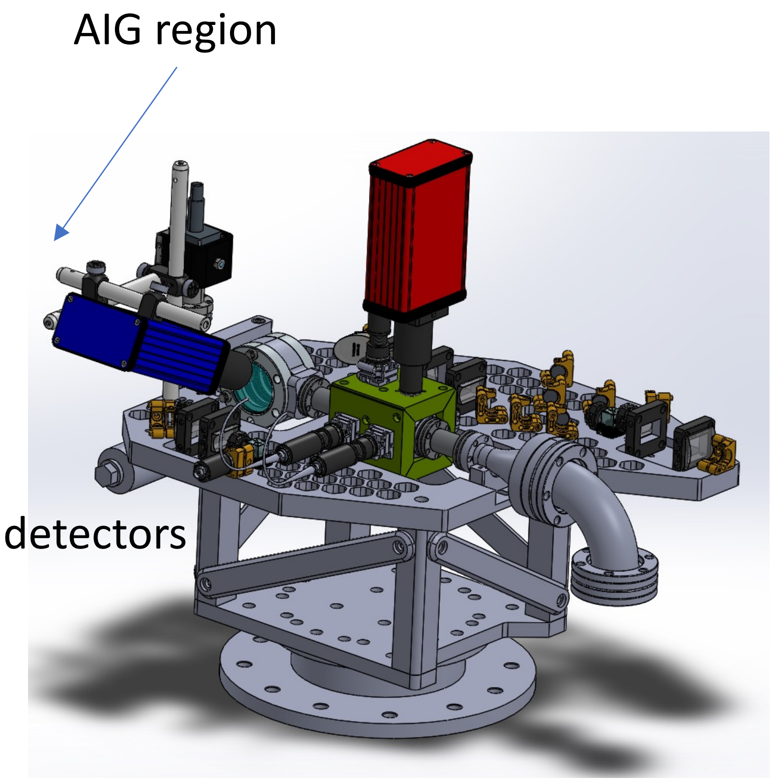
Strontium Matterwave Gyroscope Experiment

- Grant Biedermann group (slide 1/2)
- Rotational sensing with ultracold atoms





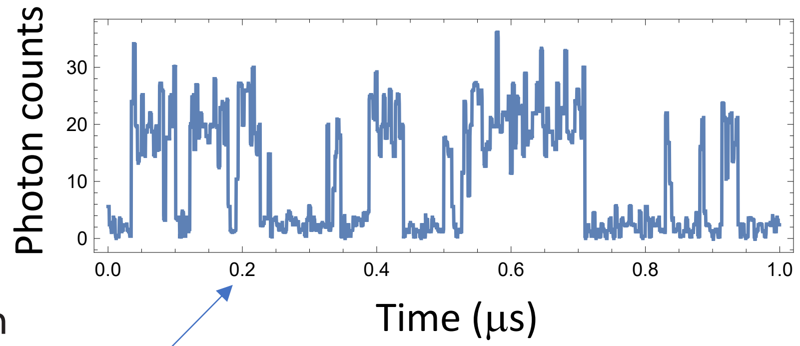
rotation testing

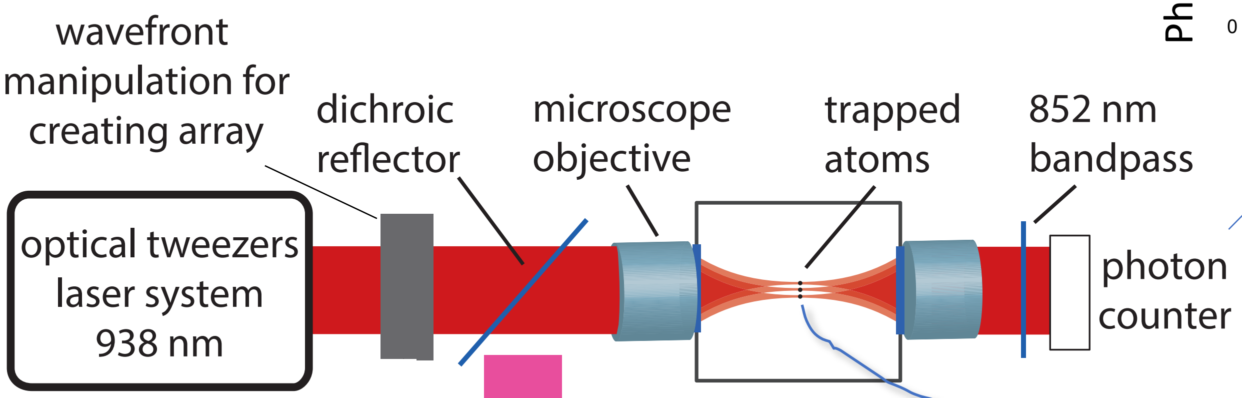


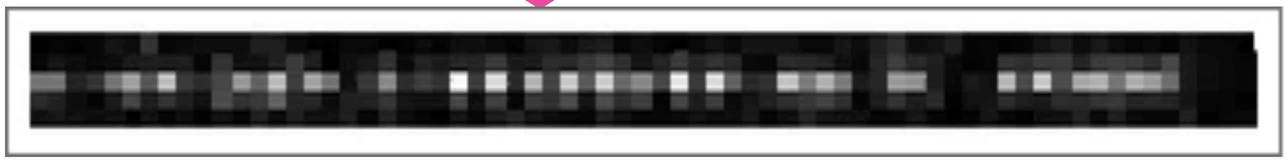
CAD model of setup

Quantum Control of Single Atoms

- Grant Biedermann group (slide 2/2)
- Atoms in tweezer arrays for quantum information

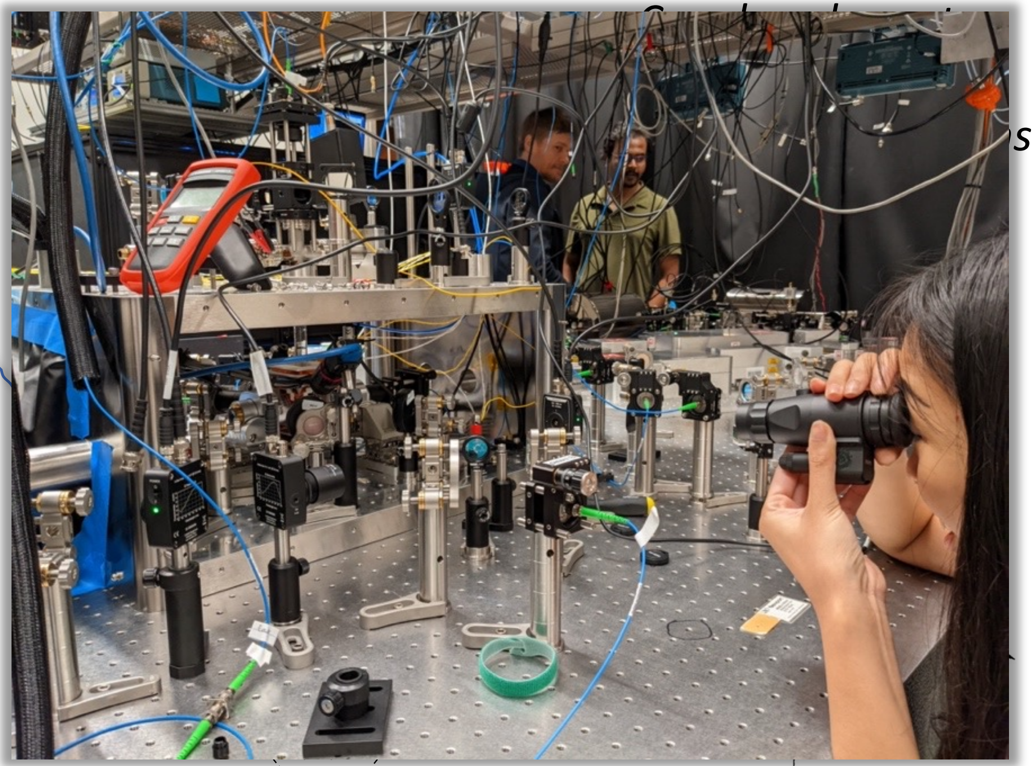






EMCCD picture of 32 tweezers loading single atoms

Hoang-Van Do aligning the experiment



^{133}Cs

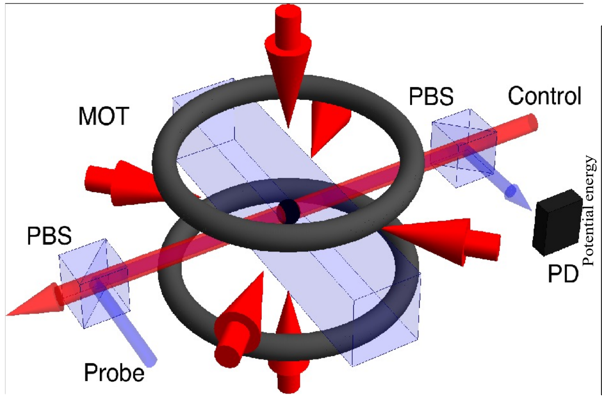
$|0\rangle$

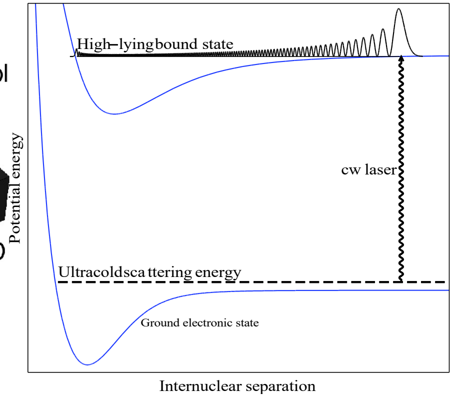
TESTBED FOR:
- QIS & Many-body dynamics
- Quantum gate protocols
- Testing quantum mechanics and gravity

Ultracold Atomic Physics and Quantum Optics

- Eric Abraham group
- Ultracold atoms
- Spectroscopy
- Quantum optics with Laguerre-Gaussian beams
- Ion Microscopy

1. Ultracold atoms: Photoassociative spectroscopy. Creating bound diatomic molecules from colliding ultracold atoms.

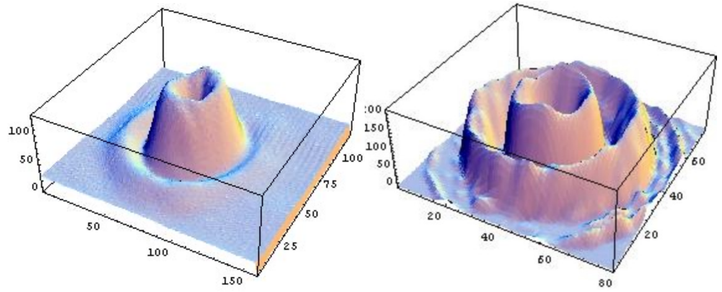




Core Capabilities

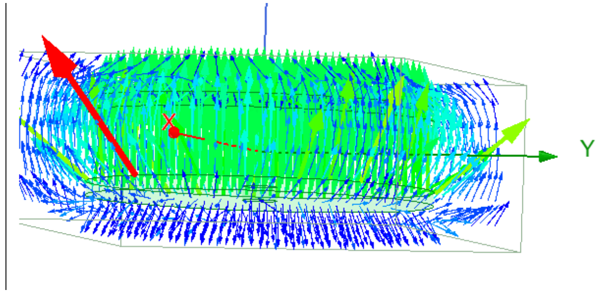
Laser cooling and trapping.
Magnetic and electric field trapping
Dipole traps of ultracold gases.
Ultracold collision physics.
Precision measurements, atomic lifetimes.
Electromagnetically induced transparency (EIT).
Cold molecules.
Hanle effect and precision spectroscopy.

2. Quantum Optics: use ultracold gas as a medium for quantum optics experiments using laser beams with orbital angular momentum (OAM).



Intensity profiles of OAM laser beams

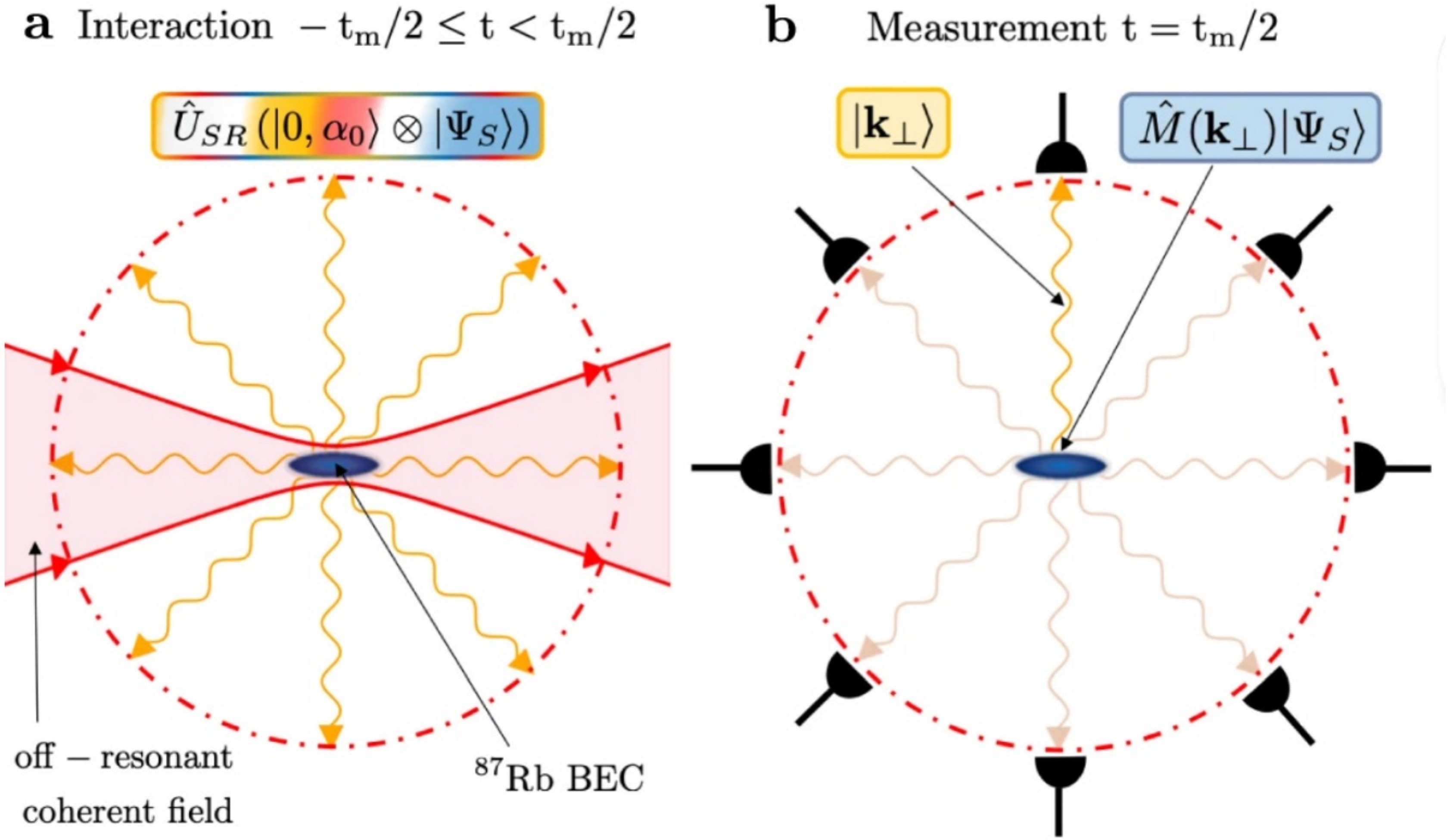
3: Ion Microscopy: Using ultracold atoms to create monochromatic ion beams for precision spectroscopy.



Precision Electric Field Simulations.

Open Quantum Systems and Precision Measurements

- Emine Altuntas group
- Bose-Einstein condensates for quantum simulation
- Feedback control to simulate interaction with thermal bath
- Precision measurements of atomic parity violation via nuclear-spin-dependent parity violation in Dysprosium

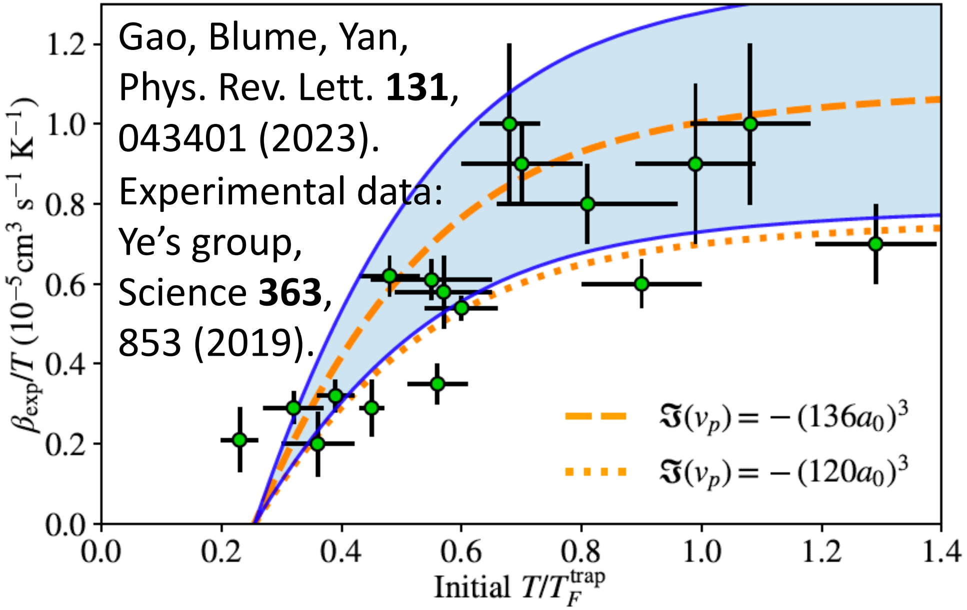


From E. Altuntas et al., Commun. Phys **6**, 66 (2023)

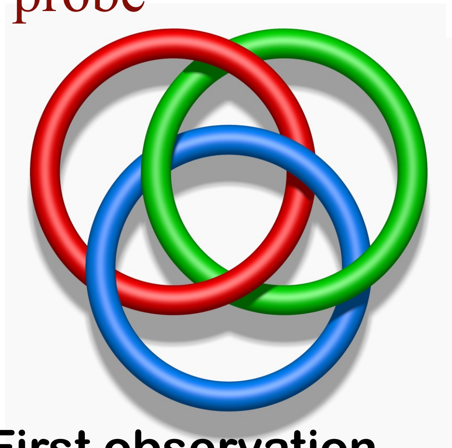
Quantum Correlation of Few- and Many-Body Systems

CQRT

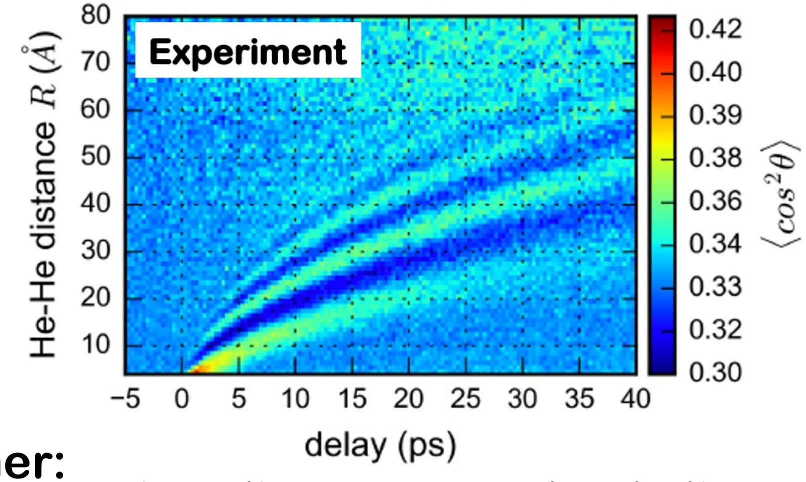
- D. Blume group (theory)
- Few- and many-body theory
- Theory of spinor and scalar BEC
- Losses in reactive molecular p-wave Fermi gas
- Dynamics of few-body systems: pump probe spectroscopy
- Efimov trimer

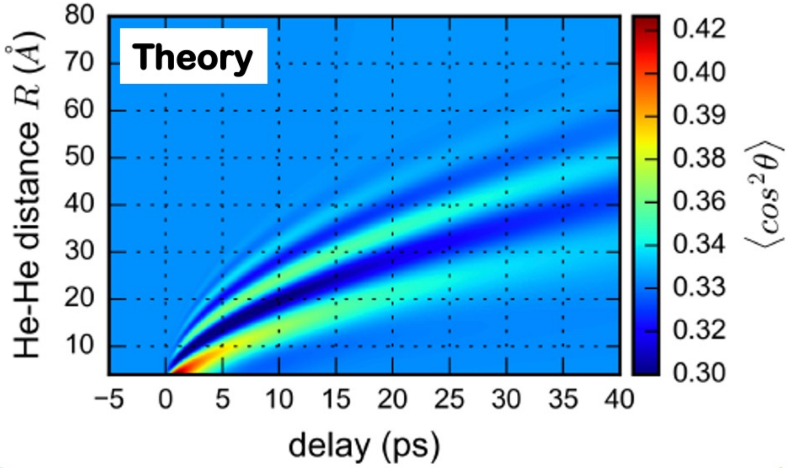


Parameter-free theory. Two-body input: Im(v_p). Losses from trap determined by p-wave contact, evaluated using Fermi liquid theory and virial expansion.



First observation of helium Efimov trimer: Kunitski,…, Blume, Doerner: Science 348, 551 (2015).

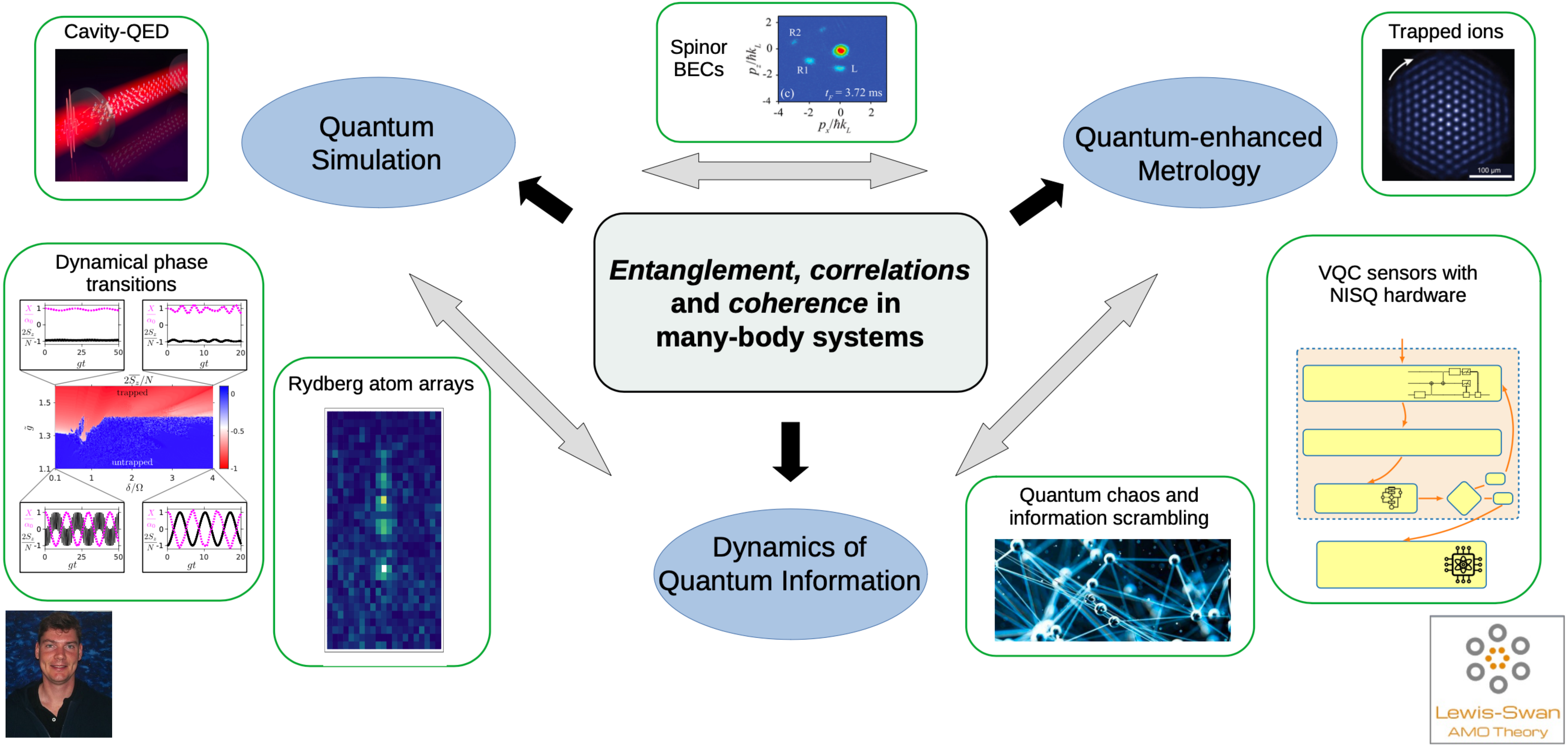




First distance-resolved alignment measurement that displays coupling of rotational and vibrational degrees of freedom. Kunitski, Guan,…,Blume, Doerner, Nature Physics 17, 174 (2021).

Entanglement, correlations and coherence in many-body systems

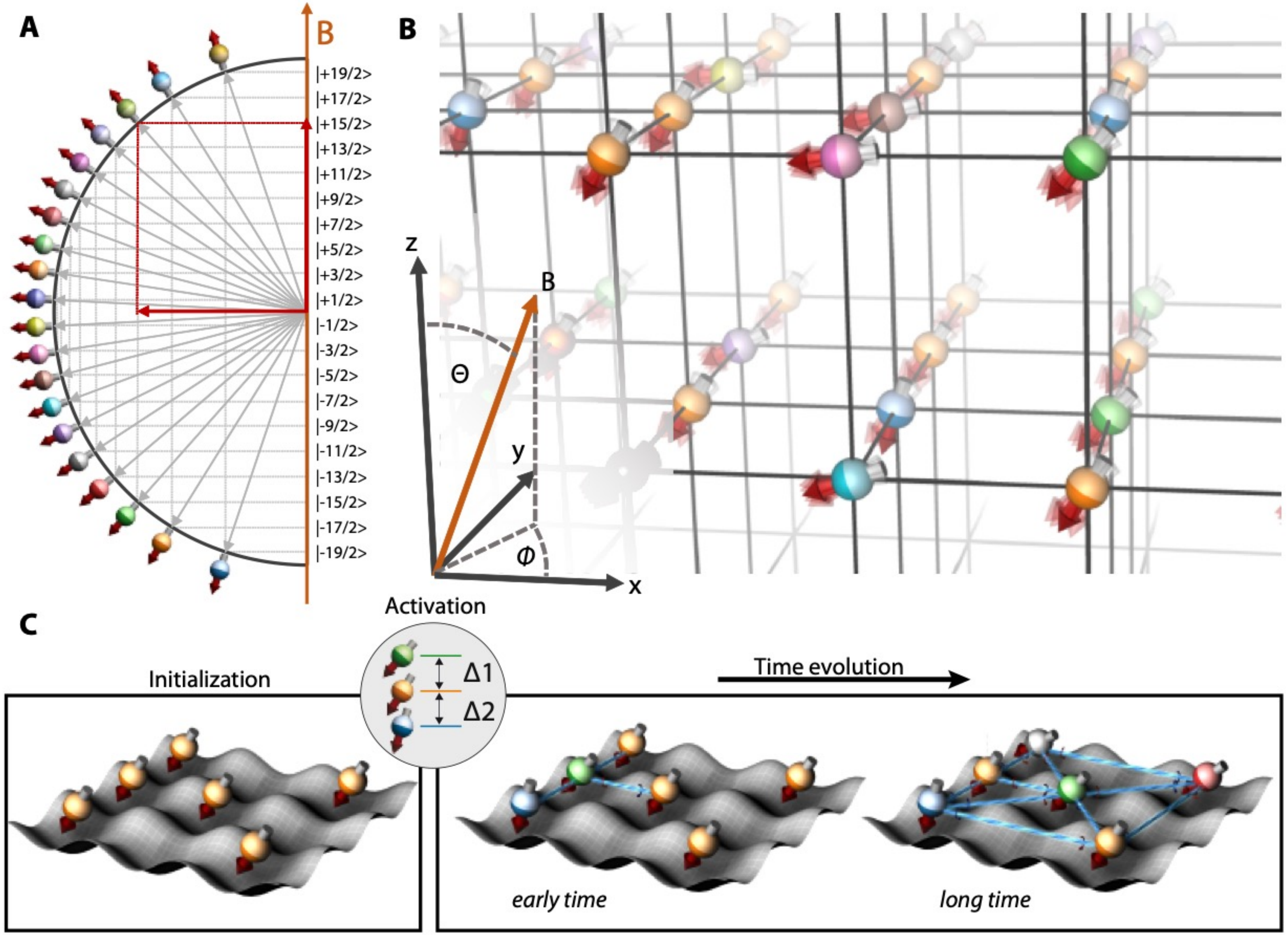
- Robert Lewis-Swan group (theory)



Nonequilibrium Phenomena in Strongly Interacting Quantum Systems

- Bihui Zhu group (theory)
- Exchange interactions with fermionic erbium
- Quantum computing
- XXZ Heisenberg model

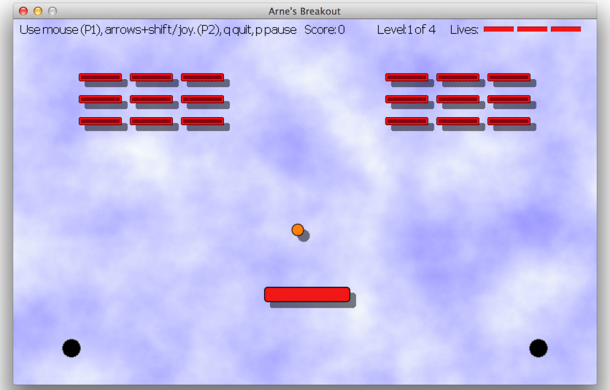
$$\hat{H} = \frac{1}{2}\sum_{i,j\neq i} V_{i,j}\left(\hat{F}_i^z\hat{F}_j^z - \frac{1}{4}(\hat{F}_i^+\hat{F}_j^- + \hat{F}_i^-\hat{F}_j^+)\right) + \sum_i \delta_i(\hat{F}_i^z)^2$$

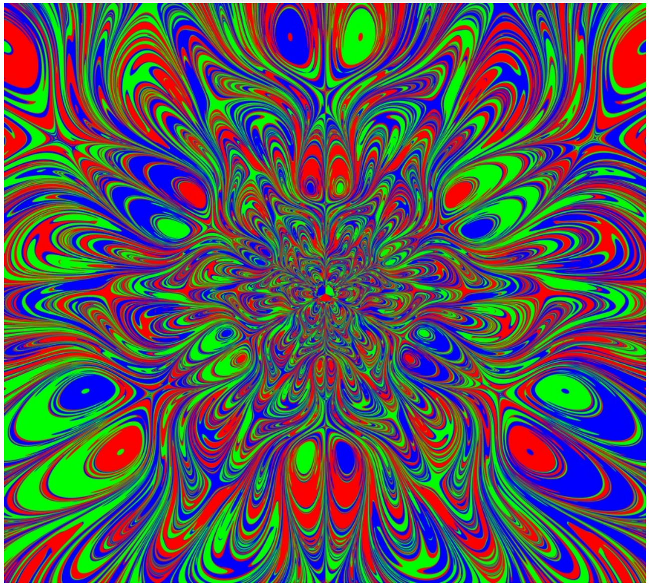


From B. Zhu et al., Phys. Rev. Research **2**, 023050 (2020)

What to do with AMO physics skills?

- The problem-solving skills you learn working in AMO enable you to do a host of things and work in many jobs, not only in academia
- Your imagination is the limit
- Work at companies such as MicroChip (miniature atomic clocks), Honeywell (quantum sensors), Google, IBM, Quantinuum (quantum computing), ColdQuanta (BEC in space), …
- Physics skills are widely applicable
  - Video game based on collisions
  - Art based on numerical integration of chaotic pendulum dynamics





Conclusions

- Atomic and molecular physics research is relevant today
- Impactful research can be done in small groups with tabletop experiments
- Students in AMO physics acquire a broad range of skills that are widely applicable
- The field is growing due to a paradigm shift from fundamental research to quantum engineering of novel AMO-based devices
- But the number of groups is still small compared to other fields such as solid state physics
- More and more, AMO physicists make contributions to other fields because of applications in quantum simulation and quantum computing

BEC in Space

From https://coldatomlab.jpl.nasa.gov

- AMO

BEC in Space

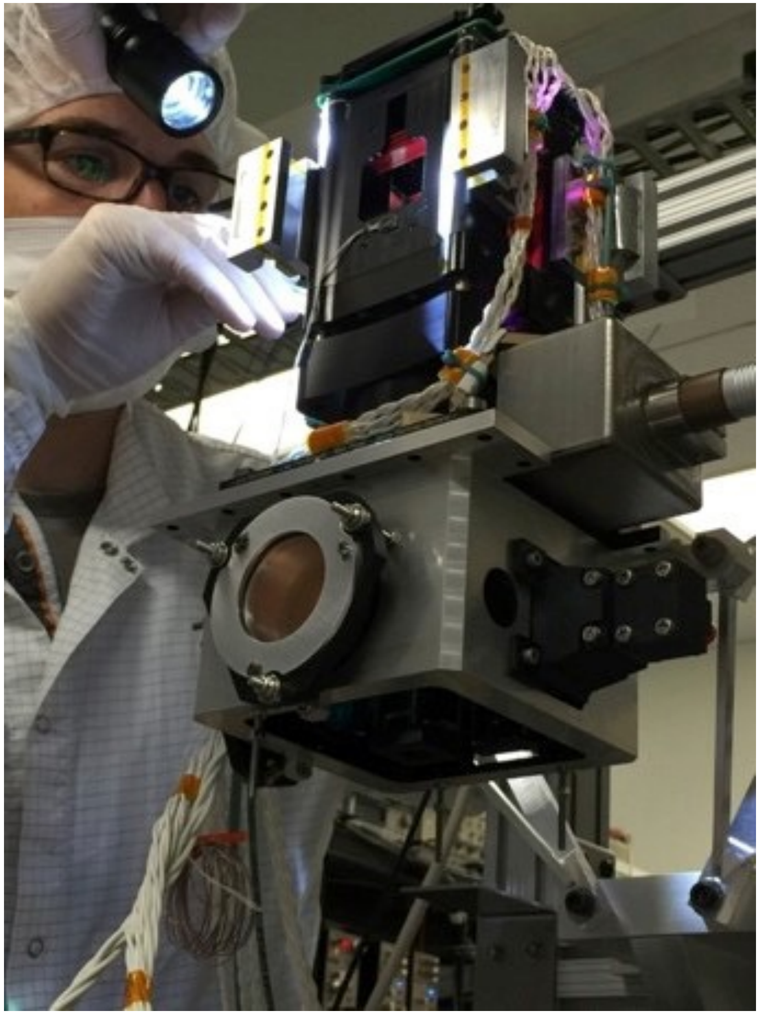
From https://coldatomlab.jpl.nasa.gov

BEC in Space

From https://coldatomlab.jpl.nasa.gov

- AMO

BEC in Space



From https://coldatomlab.jpl.nasa.gov

Chip-Scale-Atomic Clock

CSAC Key Features

- < 120mW power consumption
- < $17 cm^3$ volume
- 35g weight
- ±5.0E-11 accuracy at shipment
- <$1E^{-11}$ @1000s Short Term Stability (Allan Deviation)
- <$9E^{-10}$ /mo Aging Rate (Typical)
- -10ºC to +70ºC Operating Temperature
- 10MHz square wave and 1PPS, both in a CMOS 0V to 3.3V format.
- 1PPS input for synchronization
- RS-232 interface for monitoring and control
- Chip Scale Atomic Clock Video
- Space version available (090-02984-007)

- The Kasevich research group at Harvard has built a 10 m high atomic fountain interferometer for use with ultracold Rubidium atoms