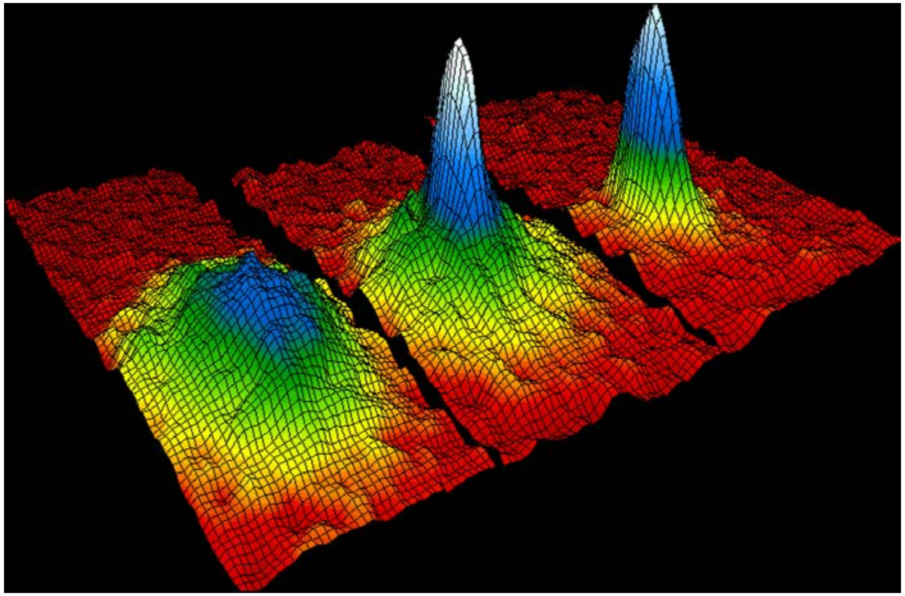
PHYS598 AQG
Introduction to the course



First quantum gas in dilute atomic vapors
^{87}Rb BEC : Wieman / Cornell group (1995)

- *Logistics*
- *A bit about the course material*

Logistics for the course

Website: https://courses.physics.illinois.edu/phys598AQG/fa2017/

The course site has info regarding:

- General info (personnel, text, office hours,…)
- Assessment (HWs = 60%, project = 35%, seminars = 5%)
- Course schedule
- Homework assignments
- Final paper
- Various and sundry

The course subject

Atomic Physics and Atomic Quantum Gases

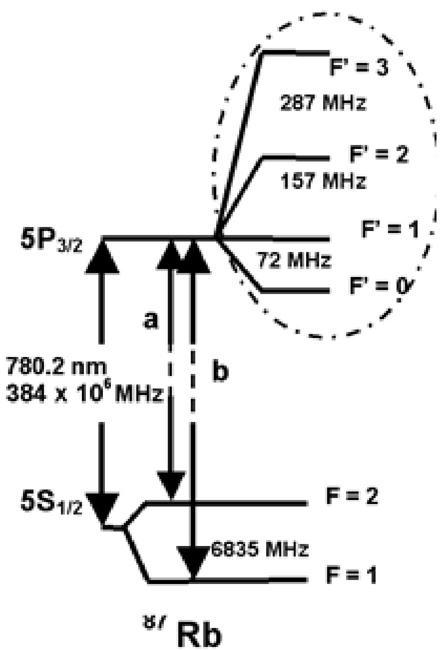
The course subject

Atomic Physics and Atomic Quantum Gases

We'll study everything that's made up of atoms ✖ NO

→ Most of this fall's under the category of "condensed matter"

We'll focus on the simple case of atoms isolated from an environment



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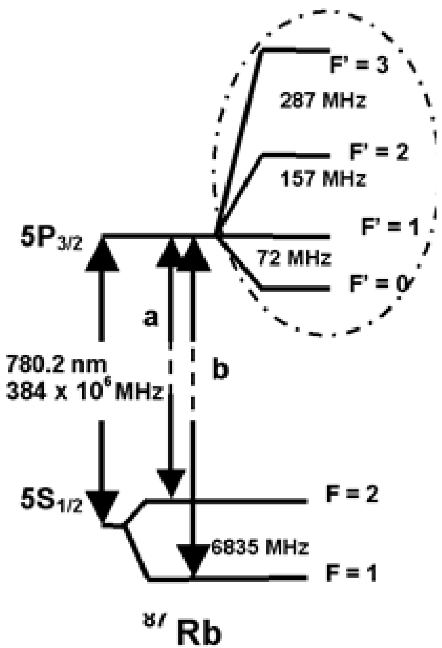

What determines their energy level structure?
(First 3 weeks of the course)

How can we exert control over their various degrees of freedom?
(~ Weeks 4-9)

These ideas can also be applied to "artificial" atoms: quantum dots, NV centers, superconducting circuits (fluxonium, quatronium, transmons)

The course subject

<u>Atomic Physics</u> and <u>Atomic Quantum Gases</u>

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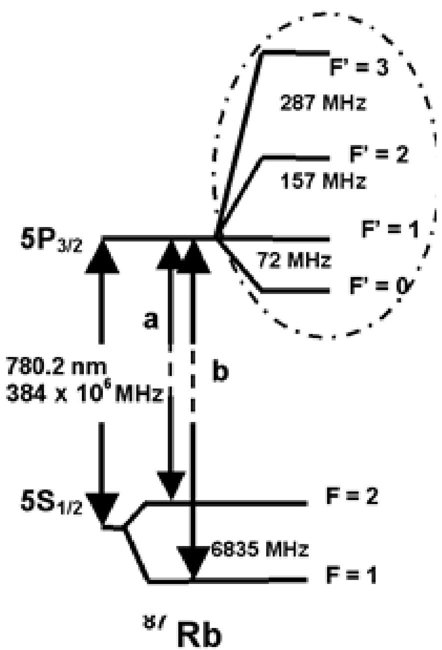


What determines their energy level structure?
(First 3 weeks of the course)

How can we exert control over their various degrees of freedom?
(~ Weeks 4-9)

What kind of novel phenomena can we study in many-atom systems?

Topics to be covered

<u>Atomic structure</u>: hydrogen, helium, alkali atoms; fine structure, hyperfine structure, Lamb shift, Zeeman effect

<u>Two-level systems</u>: Rabi problem, density matrices & open quantum systems, optical Bloch equations, adiabatic processes

<u>Light/atom interactions</u>: dipole selection rules, semiclassical treatment, quantum treatment, laser-cooling, magneto-optical traps, sub-Doppler cooling, ac Stark effect, optical traps, cavity QED

<u>Ultracold atoms</u>: magnetic trapping, evaporative cooling, ultracold collisions, Feshbach resonances, BECs & Fermi gases

<u>Quantum simulation</u>: optical lattices, cold-atom Hubbard models, special properties of some alkaline earth atoms and rare earth atoms, ultracold molecules, ions, and Rydberg atoms

AMO Physics more broadly

(Atomic, Molecular, & Optical Physics)

Many, many active research fronts

-**quantum gases:** of atoms, molecules, of various quasi-particles, etc.
-**quantum simulation:** many-body physics, connections to condensed matter
-**trapped ions:** precise measurements, quantum optics, quantum computing, quantum simulation
-**cold molecules**: precision measurements, cold chemistry, quantum computing, quantum simulation
-**Rydberg atoms**: quantum computing, sensing of fields, novel quantum states
-**expansion of the "toolbox“:** new atomic species for cooling, new capabilities
-**quantum optics:** cavity QED, nonlinear optics
-**quantum communications:** quantum repeaters, quantum memories, entangled state generation, etc.
-**optical sciences:** photonics, phononics, quantum dots, laser physics, high-harmonic generation, NV centers, etc.
-**precision measurement of fundamental constants:** PNC, EDM, dark energy searches
-**sensing:** clocks, gyroscopes, interferometers, ATTA
-**atom optics:** quantum-limited measurements, atomtronics, etc.
-and more (ion-atom collisions, atom-molecule collisions, ultracold plasmas)

Atomic **M**olecular & **O**ptical physics

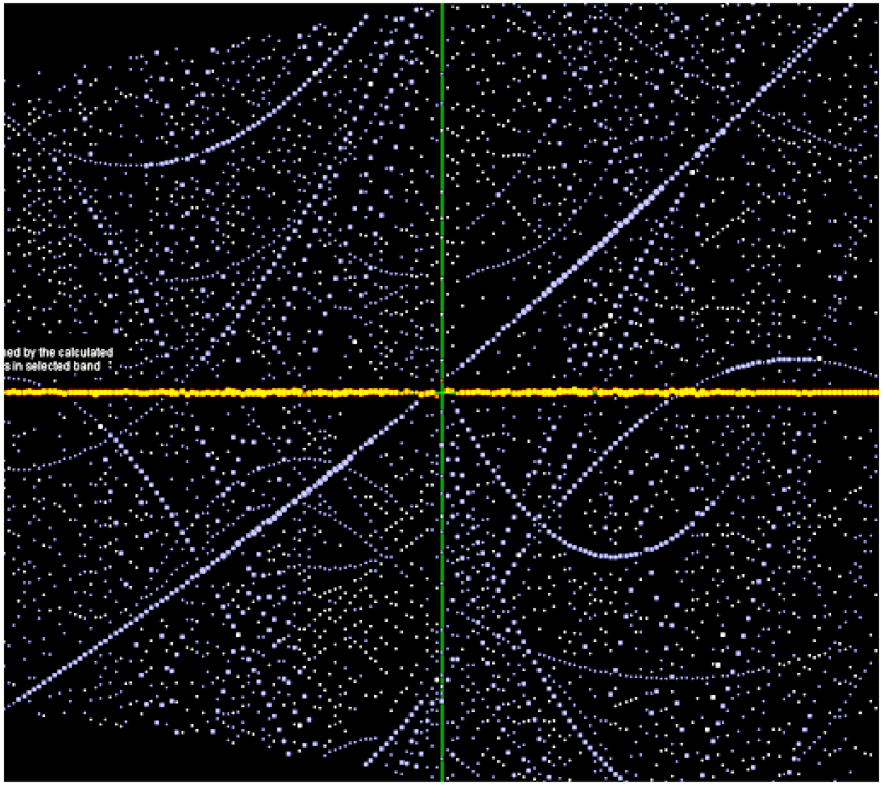
2 central themes:

<u>spectroscopy</u>

measuring physical quantities
with extreme precision and accuracy

<u>Some local history</u>

Loomis-Wood diagram
of molecular spectra



Atomic **M**olecular & **O**ptical physics

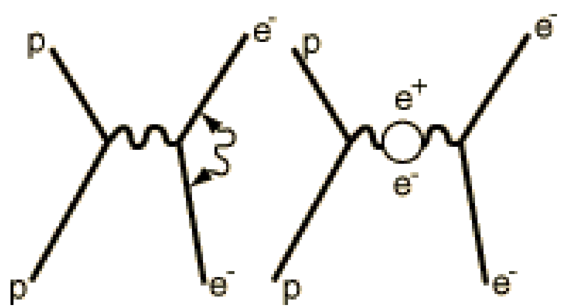
2 central themes:

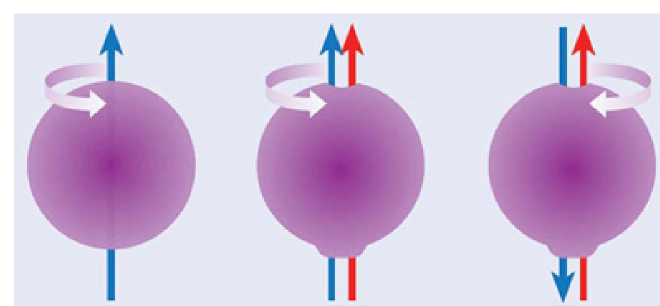
<u>spectroscopy</u>

measuring physical quantities with extreme precision and accuracy

Precise measurements tell us a lot about nature

- Development of quantum theory
- Development of QED (Lamb shift measurement)
- Search for physics beyond the Standard Model



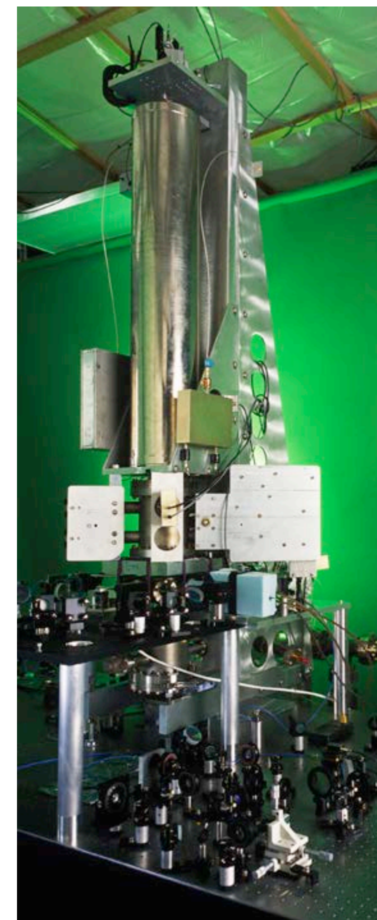


Atomic Molecular & Optical physics

2 central themes:

<u>spectroscopy</u>

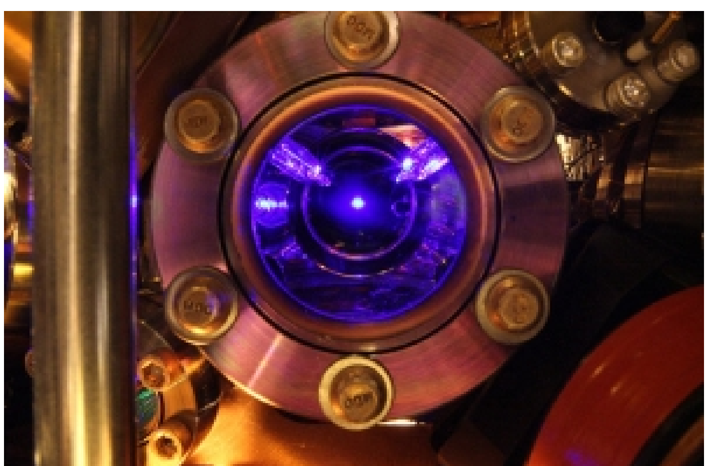
measuring physical quantities
with extreme precision and accuracy



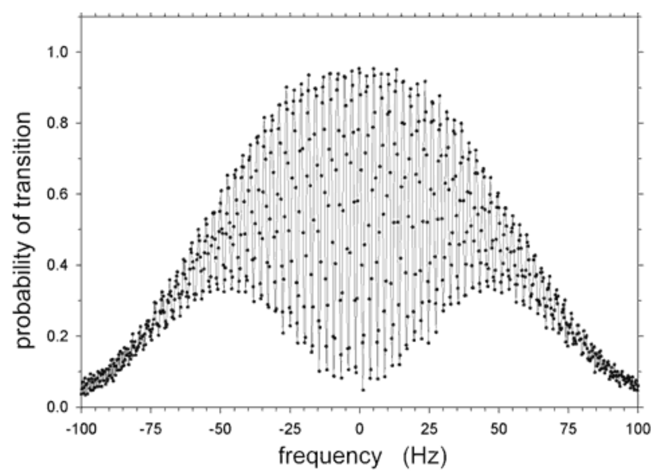
Precise measurements also tell us a lot about our environment

- SI definition of the second – application: GPS

Sr lattice clock JILA, Boulder



cesium clock at NIST Boulder



Atomic
Molecular &
Optical physics

2 central themes:

spectroscopy

measuring physical quantities
with extreme precision and accuracy

Precise measurements also tell us a lot about our environment

- SI definition of the second – application: GPS
- Global geodesy
- Precision magnetometry
- Search for non-Newtonian physics

Atomic **M**olecular & **O**ptical physics

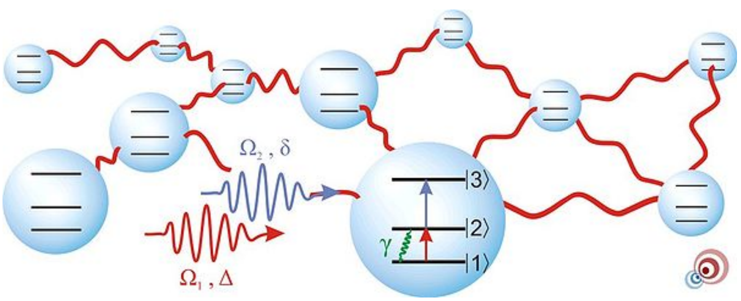
2 central themes:

<u>coherent control</u>

AMO systems are the most well-controlled, well-isolated quantum systems we have to study

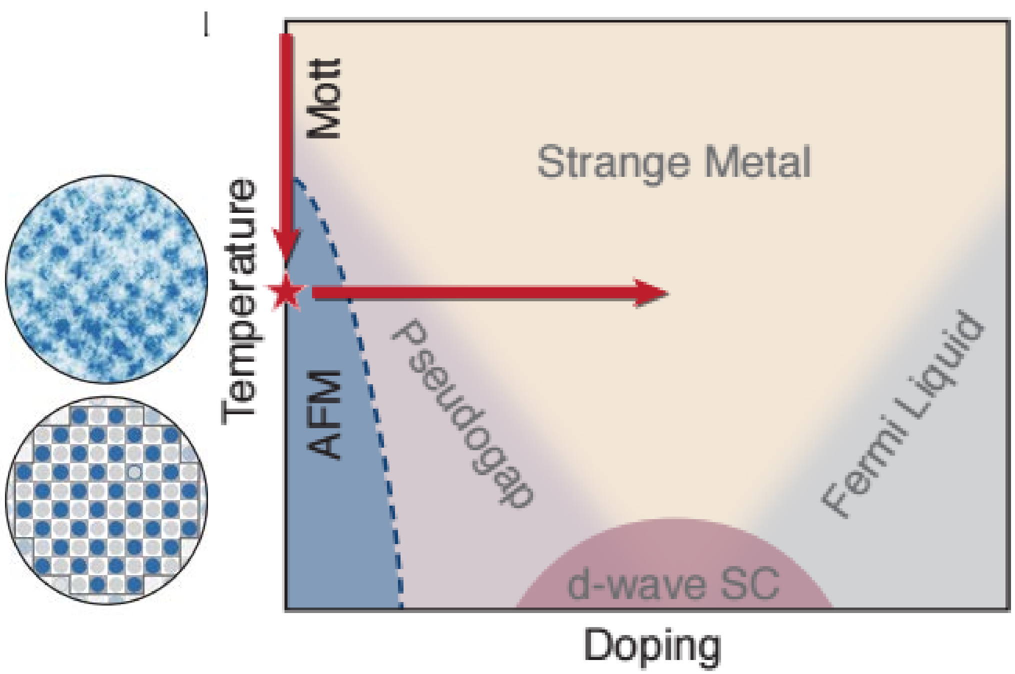
→ Great place to study emergent physics

strongly correlated quantum matter and non-equilibrium dynamics



Weidemüller group, Heidelberg

Greiner group, Harvard



AMO Physics

- Rich variety of possible "building blocks"

  - neutral atoms

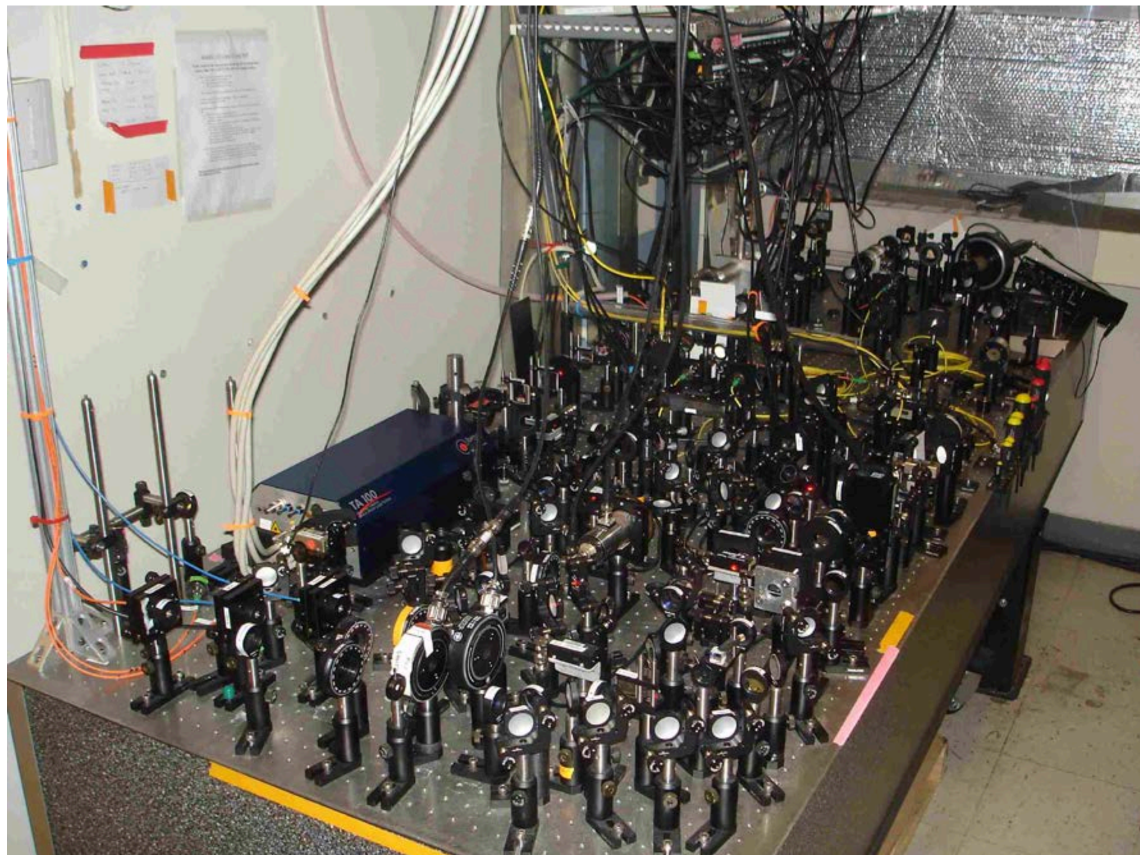
    bosons/fermions, various properties

  - ions (remove one electron)
  - Rydberg atoms (nearly ionize)
  - molecules (combine 2 or more atoms)
  - artificial atoms (NVs, quantum dots, SC qubits,...)
  - cavity QED, "quantum objects" (cantilevers, membranes,...)

Can study these systems separately, or combine the pieces in various ways

Research activity in the U.S.

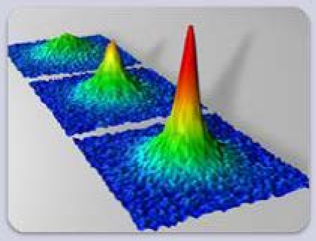
The scale of experiments is often small (a few students and a few optical tables), so there are research groups at most R1 institutions.



Li expt. optics table, Ketterle group, MIT

Research activity in the U.S.

There are a few “hot spots” in the US (the ones shown are active PFCs)



JILA

CUA

JQI

JILA & **JQI** both associated with NIST (formerly NBS)

There are also many, many groups worldwide in Europe, China, Japan, Korea, Australia, Canada, Singapore,…

https://ucan.physics.utoronto.ca/Groups

Where to start?

- Many atoms have been laser-cooled and trapped
  - let’s start with hydrogen