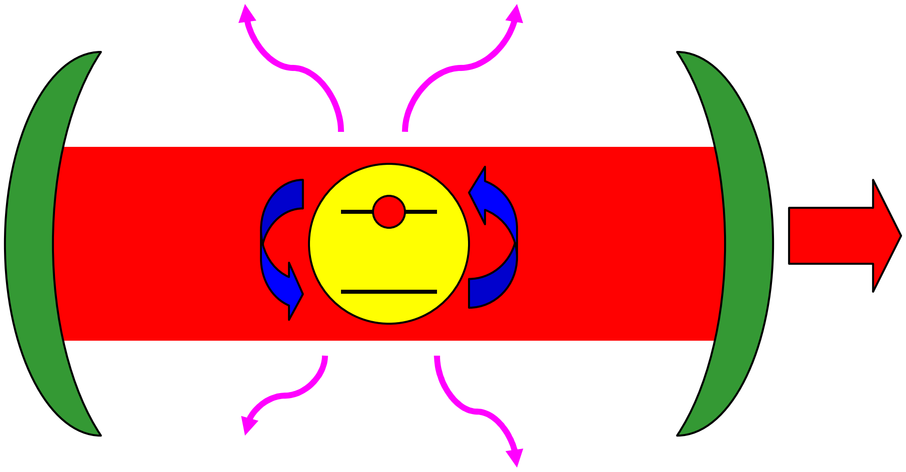
Quantum information processing with atoms and photons

A brief excursion into cavity quantum electrodynamics

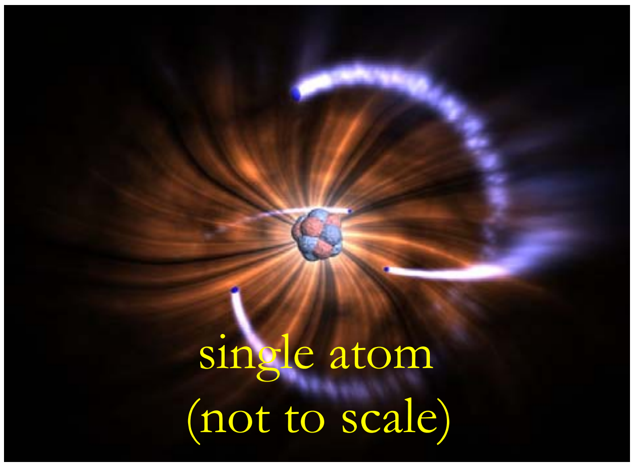


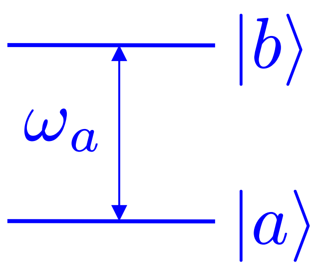
Kevin Moore

April 14th, 2005

Atoms and photons as qubits

Atoms





Quantum information is encoded in internal state of atom

(i.e. energy level of electron)

Photons

Quantum information can be encoded in photon polarization...

$$|\psi\rangle = \alpha|\leftrightarrow\rangle + \beta|\updownarrow\rangle$$

or, quantum information can be encoded in photon number!

$$|\psi\rangle = \alpha|0 photons\rangle + \beta|1 photon\rangle$$

Atoms and photons as qubits

Atoms

Atoms are great place to *store* quantum information

– long-lived states

– easy to interact with (lasers, microwaves)

– *hard* to manipulate

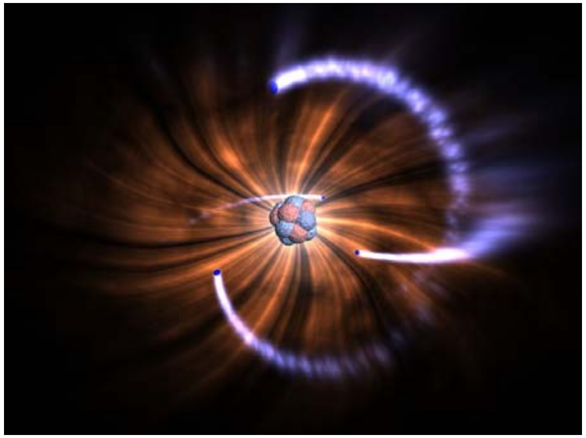
Photons

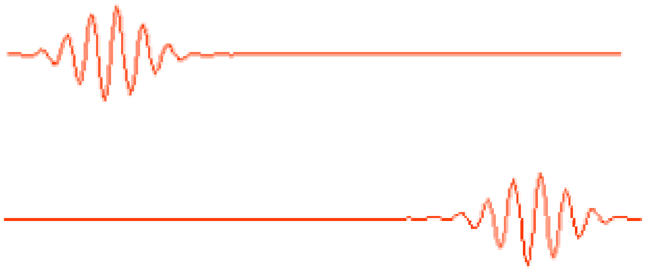
Photons are great for *transmitting* quantum information

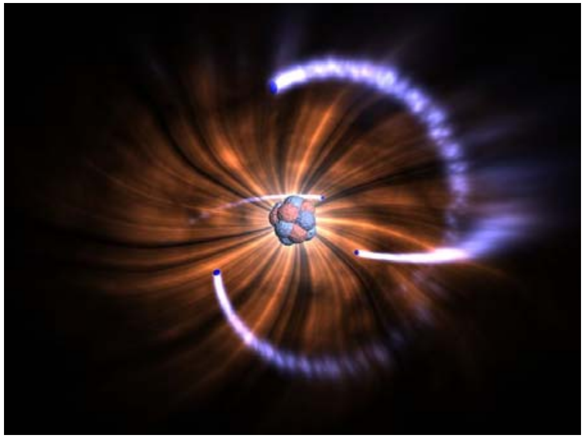
– travel fast (duh!)

– easy to manipulate (gates = waveplates, measurement = polarizers and photo counters)

– hard to store cause they're always moving... or are they?







What are our atomic control knobs?

$$\hat{H} = \sum_i \left(\frac{\hat{\mathbf{p}}_i^2}{2m_e} + \frac{Ze^2}{|\hat{\mathbf{r}}_i|} \right) + \sum_{i,j\neq i} \frac{e^2}{|\hat{\mathbf{r}}_i - \hat{\mathbf{r}}_j|} + V_{ext} + \frac{\hat{\mathbf{P}}_a^2}{2m_a}$$

What are our atomic control knobs?

specifies bare energy states for atom (or ion), taken as given

center of mass kinetic energy

$$\hat{H} = \sum_i \left(\frac{\hat{\mathbf{p}}_i^2}{2m_e} + \frac{Ze^2}{|\hat{\mathbf{r}}_i|} \right) + \sum_{i,j\neq i} \frac{e^2}{|\hat{\mathbf{r}}_i - \hat{\mathbf{r}}_j|} + V_{ext} + \frac{\hat{\mathbf{P}}_a^2}{2m_a}$$

External fields (electric, magnetic, and gravity)

<u>Examples of external fields one might use</u>

Magnetic fields (*Zeeman effect*): $V_{ext} = -\hat{\mu} \cdot \vec{B}$

Electric fields (*Stark effect*): $V_{ext} = -\hat{d} \cdot \vec{E}$

Oscillating E/M fields (*esp. AC Stark shift*): V_{ext} same, but resonance induces dipole moment...
use lasers or microwave fields

Gravity: $V_{ext} = m_a g h$

What are our atomic control knobs?

specifies bare energy states for atom (or ion), taken as given

center of mass kinetic energy

$$\hat{H} = \sum_i \left(\frac{\hat{\mathbf{p}}_i^2}{2m_e} + \frac{Ze^2}{|\hat{\mathbf{r}}_i|} \right) + \sum_{i,j\neq i} \frac{e^2}{|\hat{\mathbf{r}}_i - \hat{\mathbf{r}}_j|} + V_{ext} + \frac{\hat{\mathbf{P}}_a^2}{2m_a}$$

External fields (electric, magnetic, and gravity)

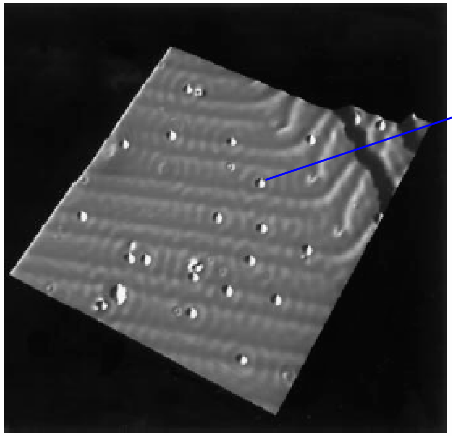
<u>What can we do about the center of mass motion?</u>

We need the atom to be localized somewhere, as we want to use it for, say, quantum computation.

How can we accomplish this?

Controlling the motion of atoms

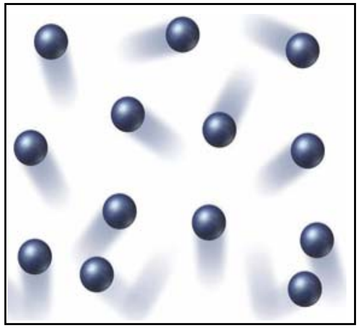
Atoms on surfaces don't move... could we use them?



Co atoms on gold surface

Answer: Maybe, but the energy levels get more complicated as the atom is strongly interacting with the surface
(ask Mike Crommie just how complicated things get!)

What we would really like is an atom in free space:
(energy levels are unperturbed)

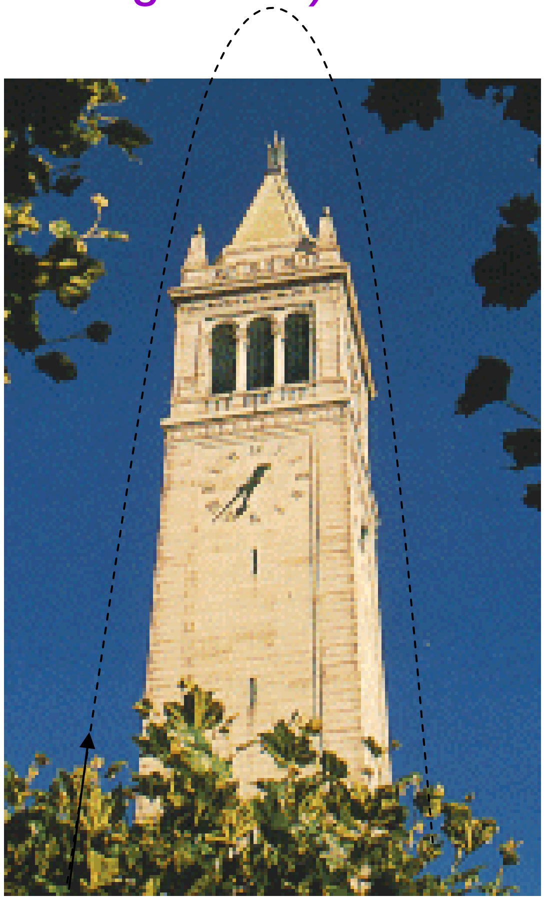


What determines the motion of a free atom? *Temperature!*

$$\frac{\hat{\mathbf{P}}_a^2}{2m_a} \approx kT$$

Just how fast do atoms move?

(in other words, how cold are we talking here?)



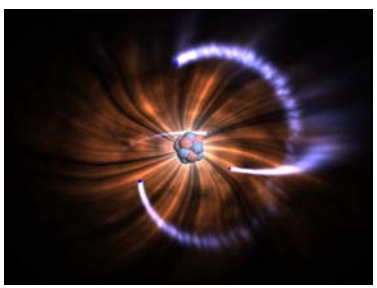
Surface temperature (300 K) N_2 gas has an average speed of 421 m/s, which would put it into the stratosphere (nearly outer space).

Liquid helium is pretty cold (4 K), but a 4 K nitrogen molecule would still easily clear the Campanile at 49 m/s!

Cooling atoms

In order for atoms not to zip away so fast that we can't do any quantum information processing, we must find a way to reduce their temperature (i.e. average speed).

Enter laser cooling!



$$p_a = mv$$

$$p_\gamma = \frac{h}{\lambda}$$

Cooling atoms

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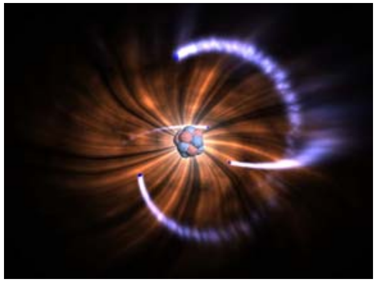
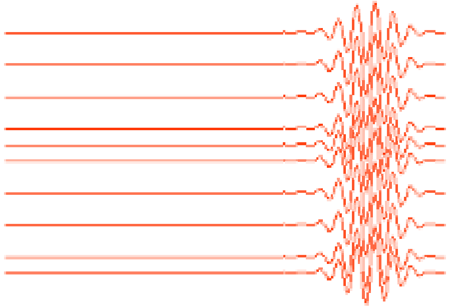
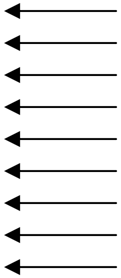
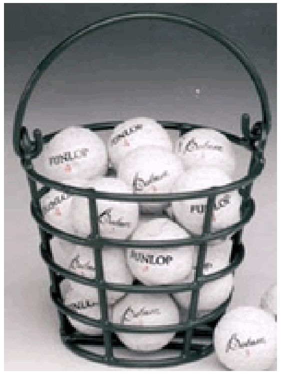




$\approx$





$$p_a = mv \qquad p_{tot} = N_\gamma \frac{h}{\lambda}$$

With laser cooling you can get atoms as cold as 0.000002 K!!

$$v_{avg} = \sqrt{\frac{2kT}{m}} \approx 2cm/sec$$

⟵ *that's more like it!*

Trapping atoms

So we have a way to cool atoms down, but how do we keep them in one place?

We need to (cleverly) apply external fields to accomplish this task.

Example: How might you trap a *chargeless* spin-½ particle with a magnetic field?

$$\hat{H} = -\hat{\mu} \cdot \vec{B}$$

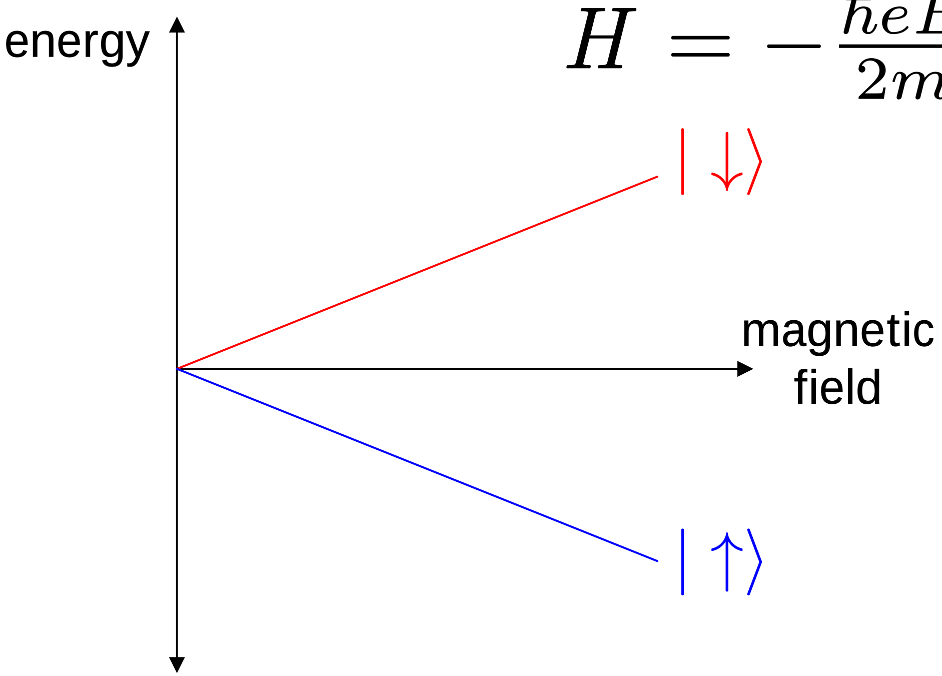
Trapping atoms

So we have a way to cool atoms down, but how do we keep them in one place?

We need to (cleverly) apply external fields to accomplish this task.

Example: How might you trap a *chargeless* spin-½ particle with a magnetic field?

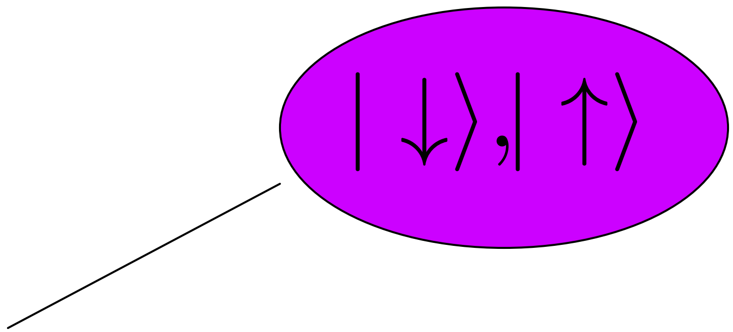
$$\hat{H} = -\frac{\hbar e B}{2m} | \uparrow\rangle\langle\uparrow | + \frac{\hbar e B}{2m} | \downarrow\rangle\langle\downarrow |$$



particles anti-aligned with field have lower energies in high magnetic fields

particles aligned with field have lower energies in high magnetic fields

Trapping atoms

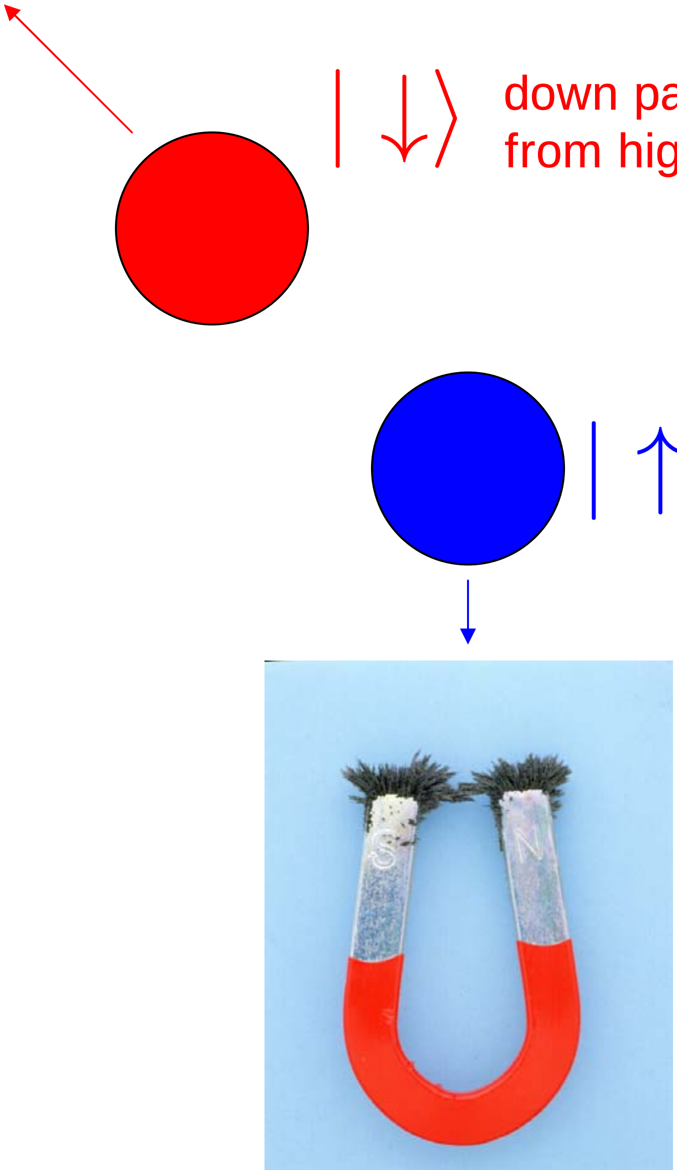


Suppose I have a ball of spin-½ particles with a mixture of both up and down spin states

Trapping atoms

$|\downarrow\rangle, |\uparrow\rangle$

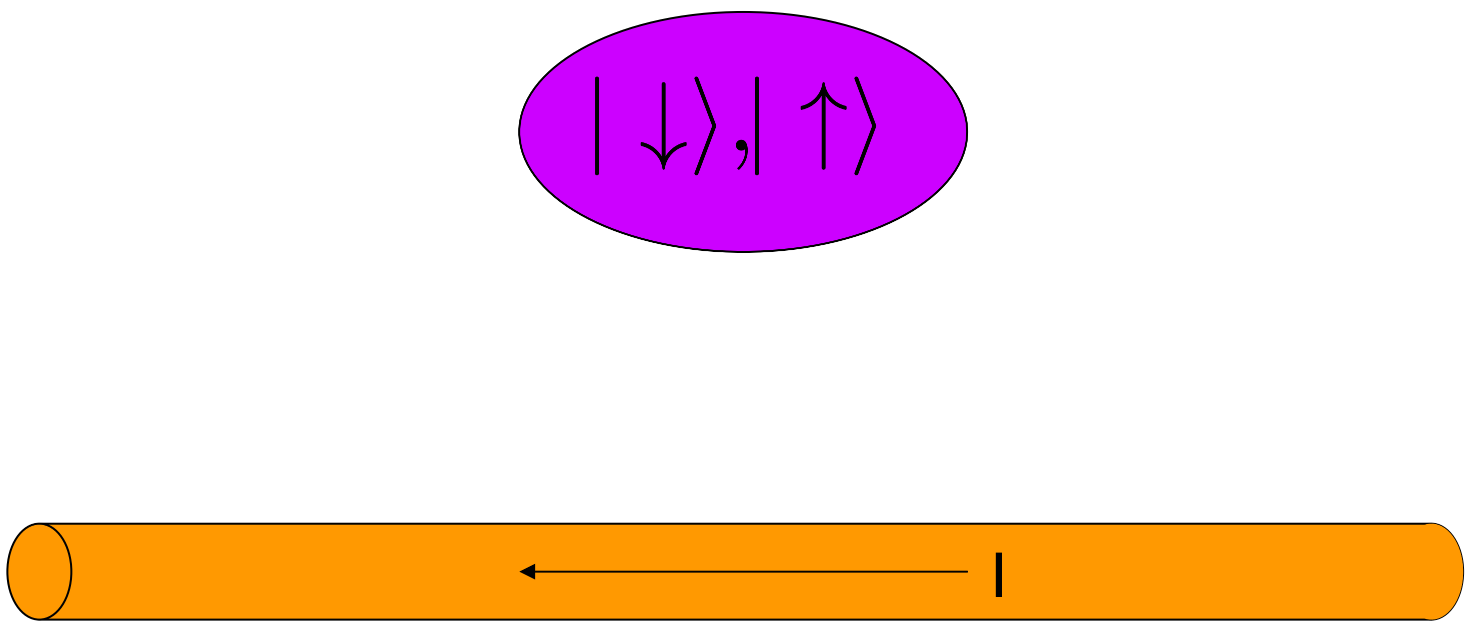
Trapping atoms



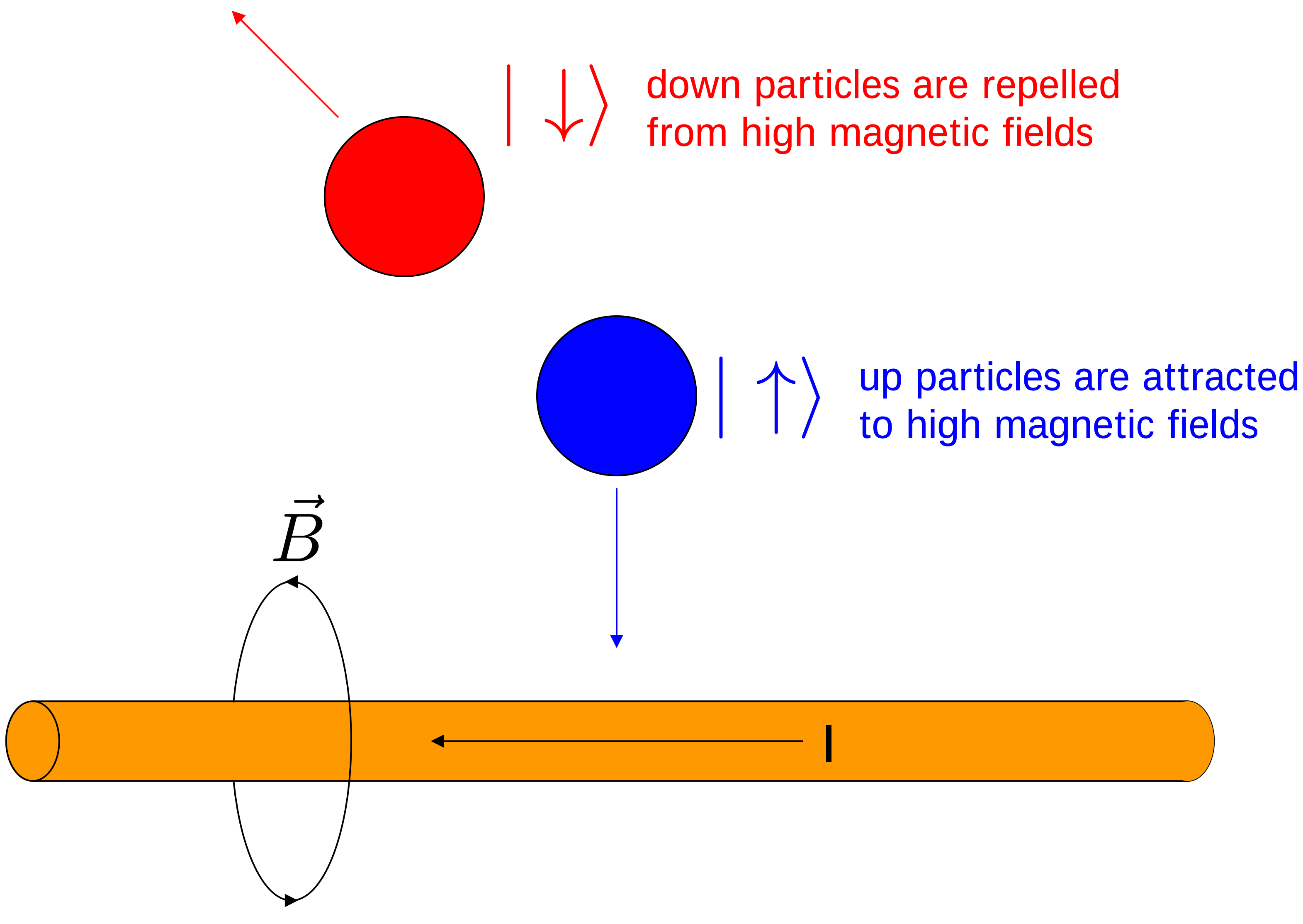
$|\downarrow\rangle$ down particles are repelled from high magnetic fields

$|\uparrow\rangle$ up particles are attracted to high magnetic fields

Trapping atoms



Trapping atoms



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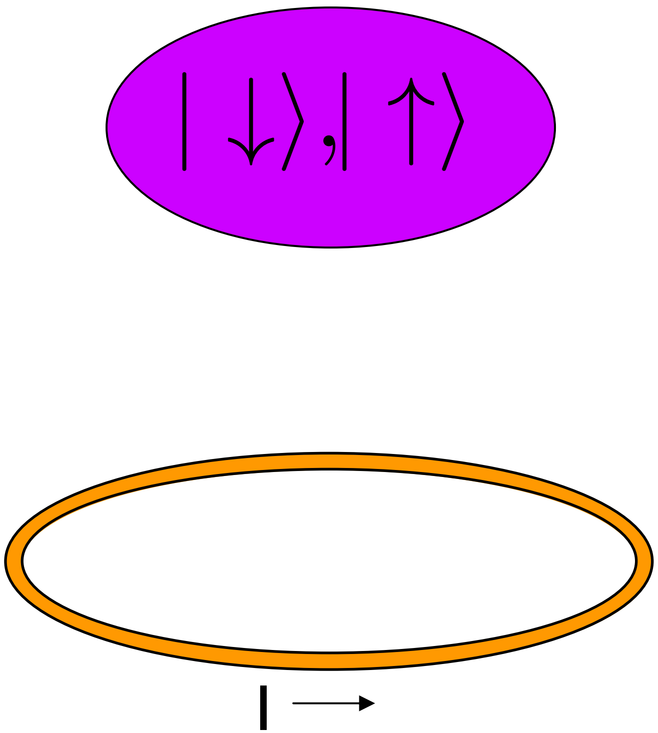

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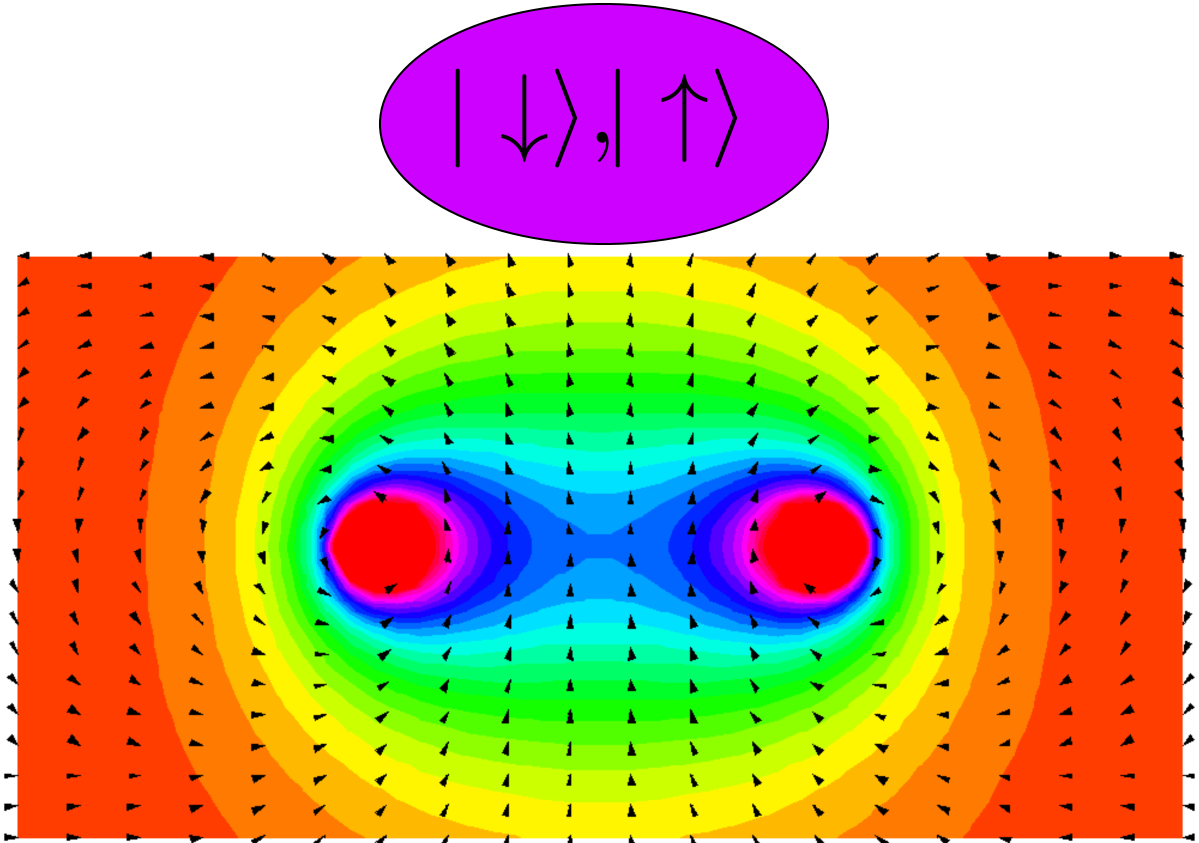
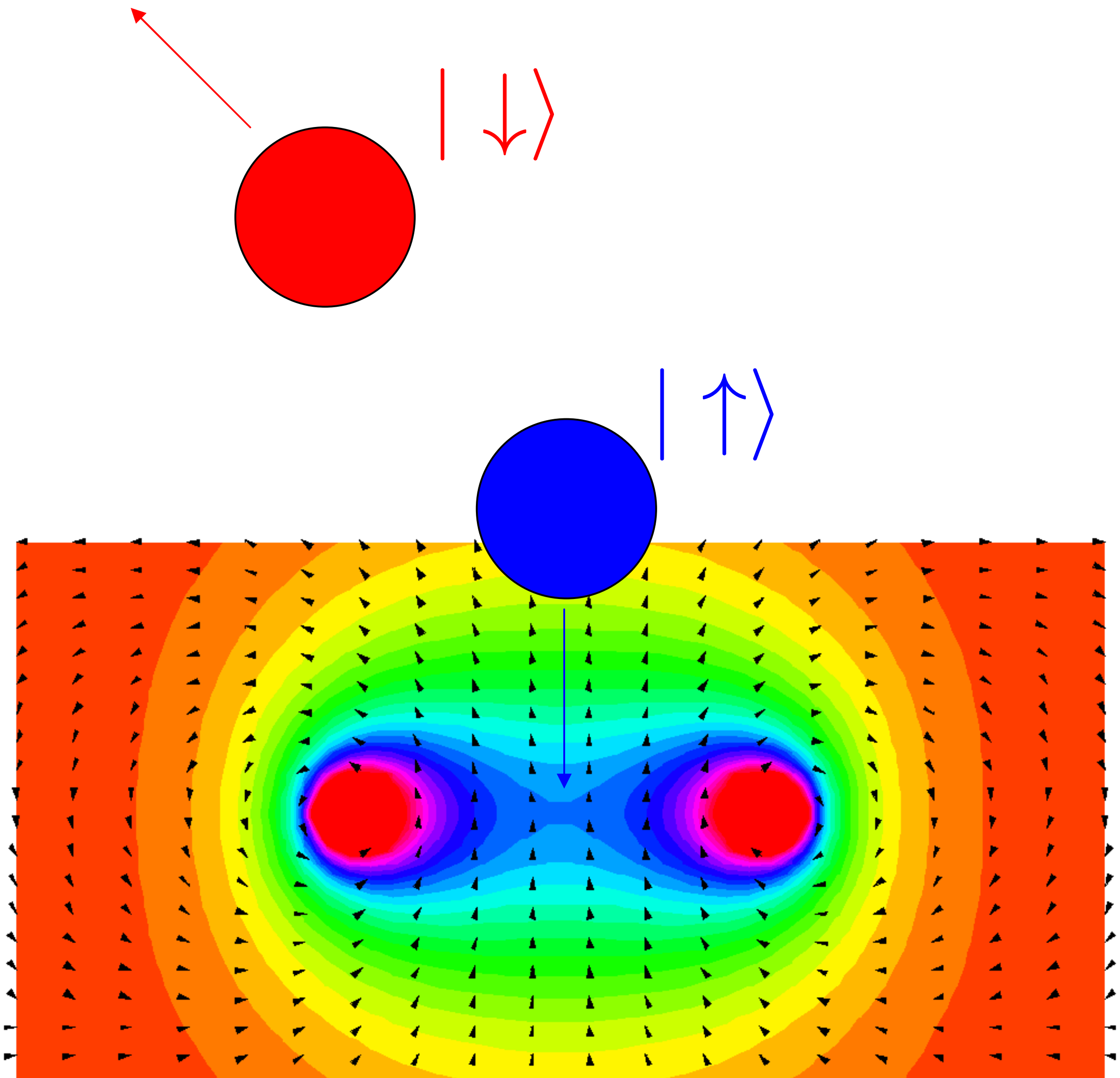
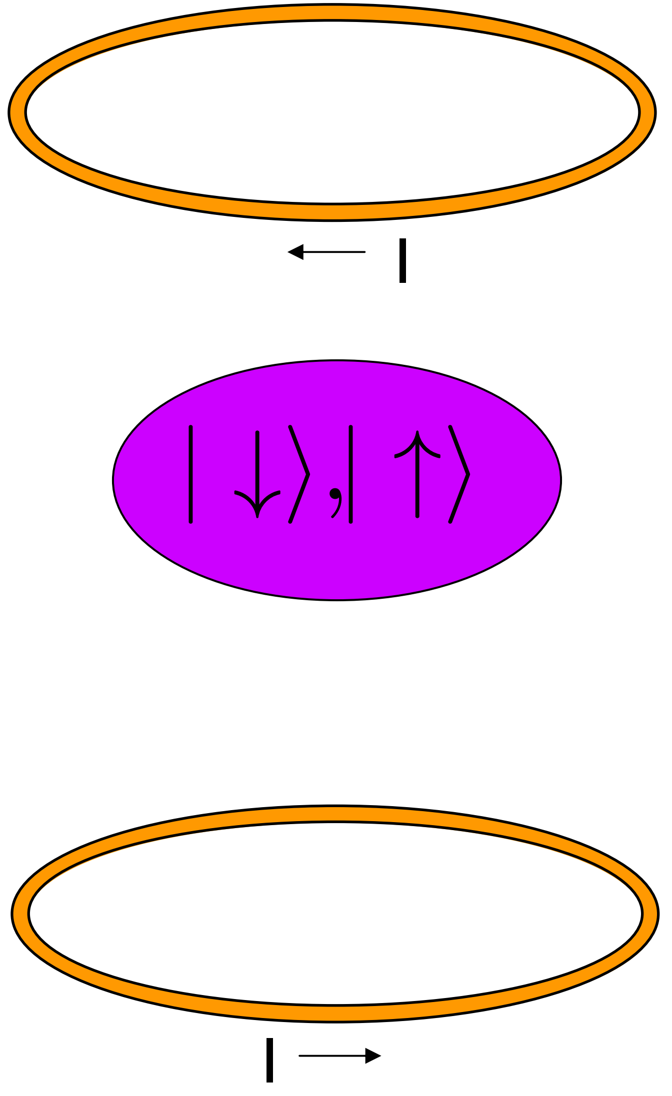


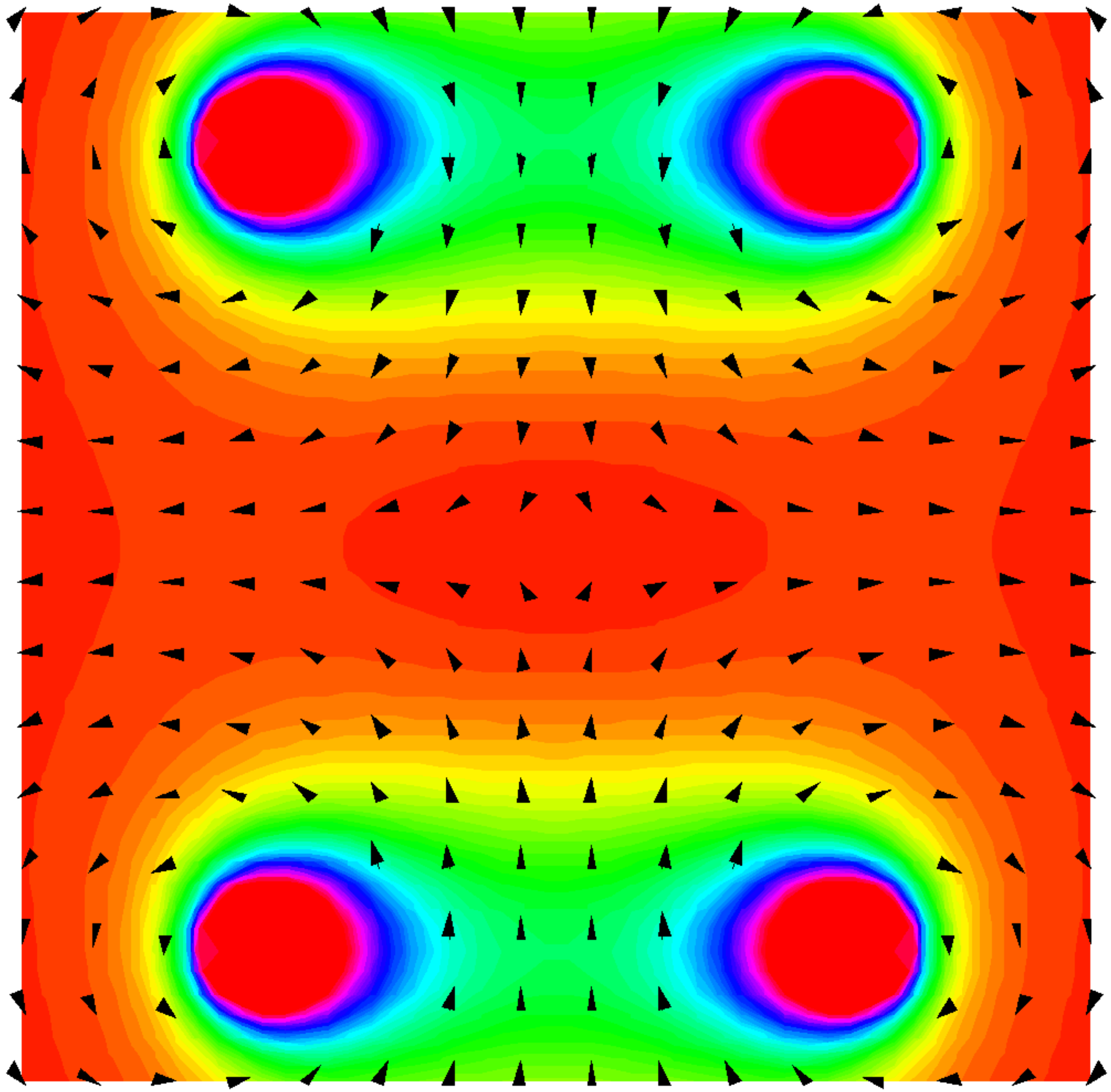
Trapping atoms



Trapping atoms



Trapping atoms



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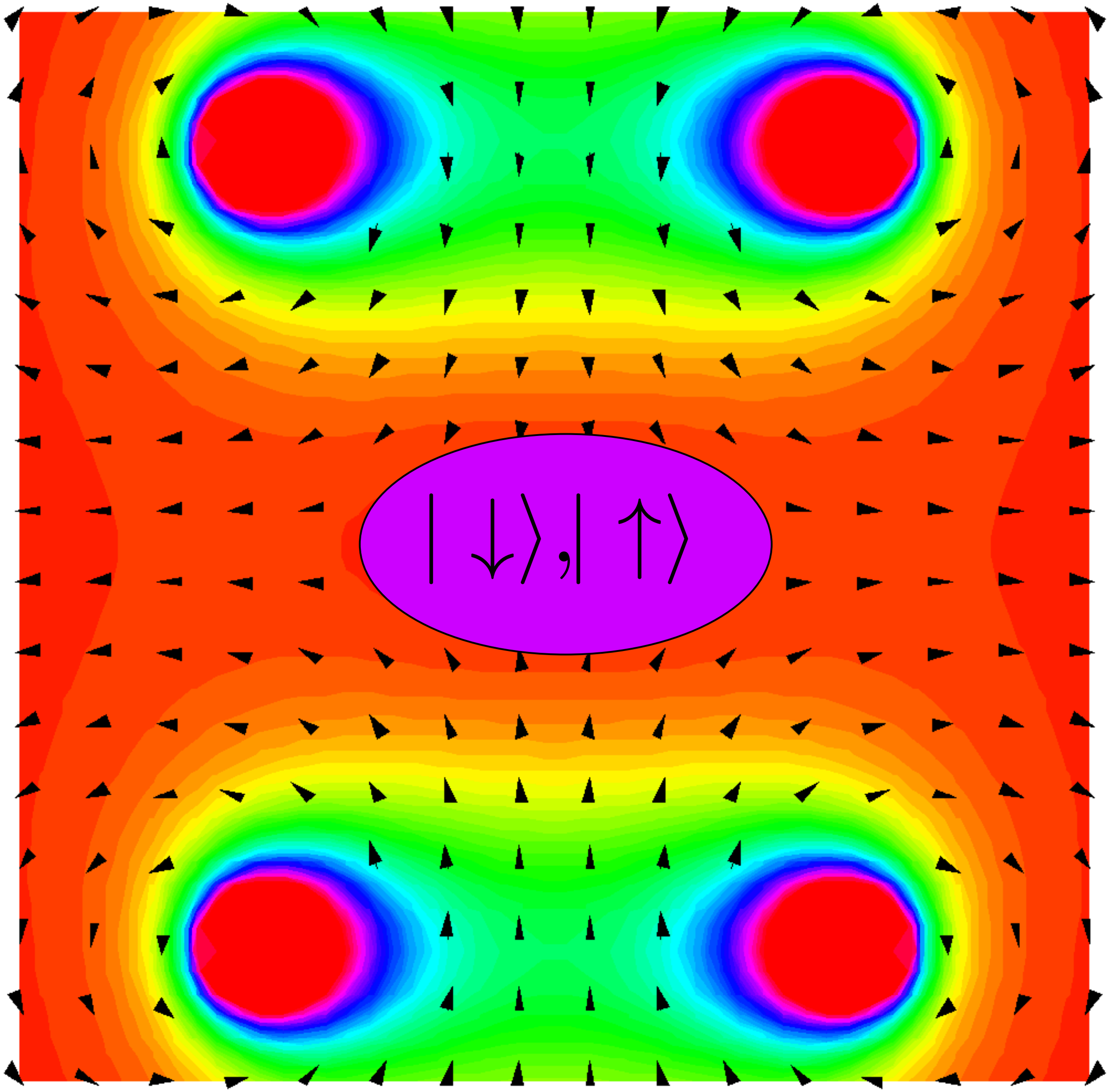

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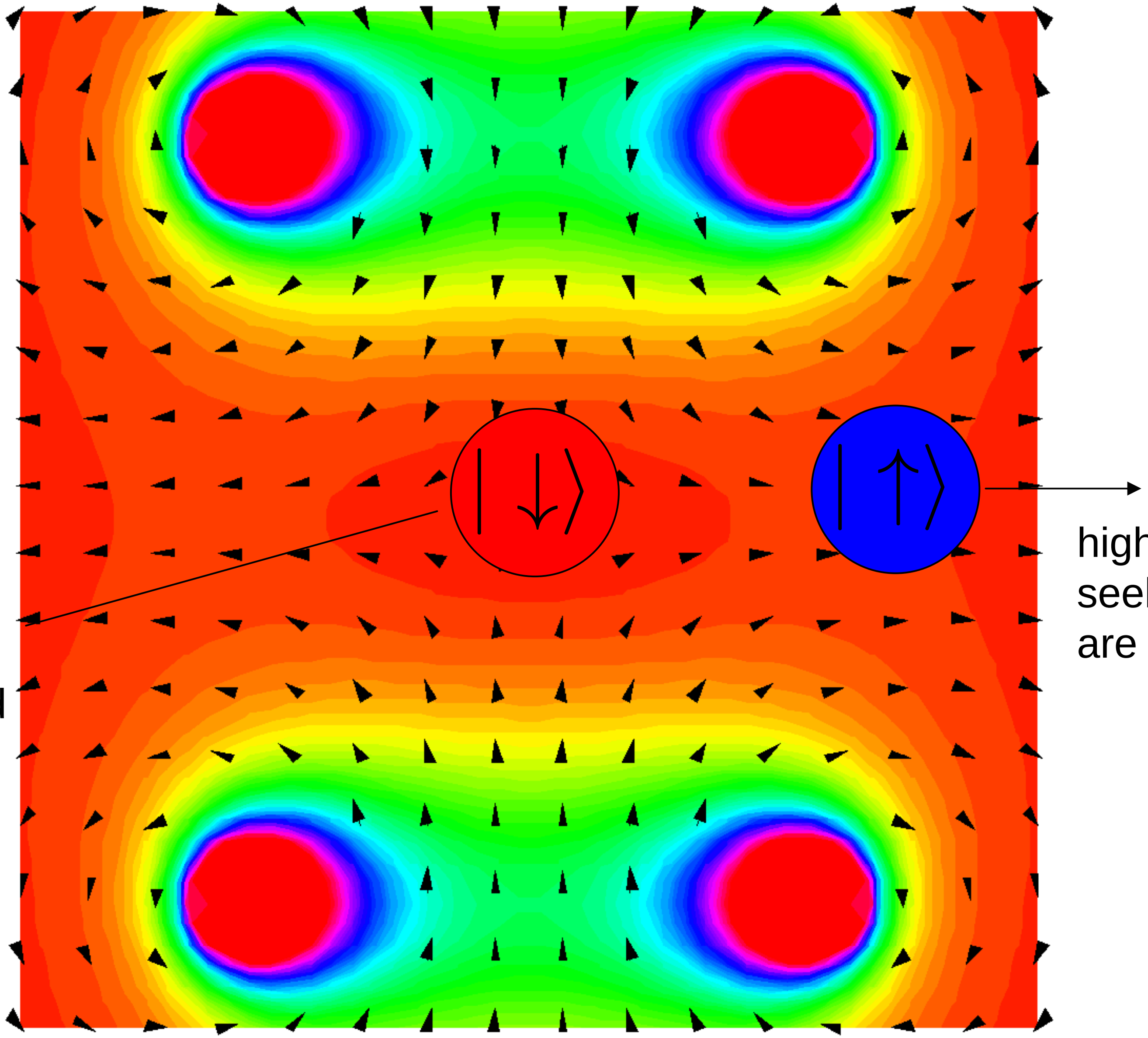
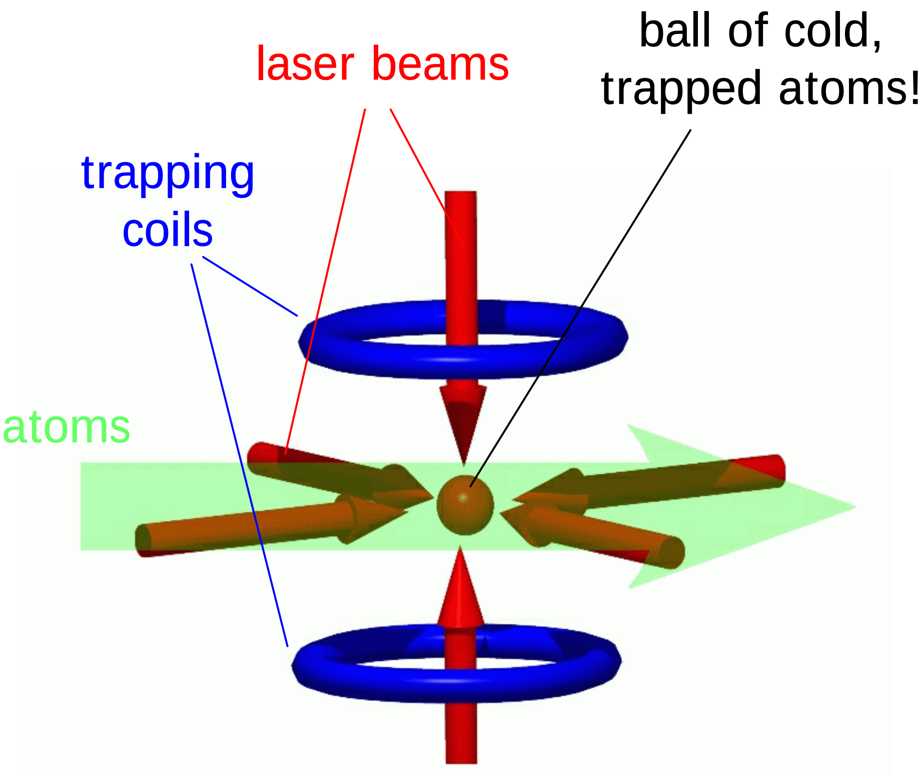
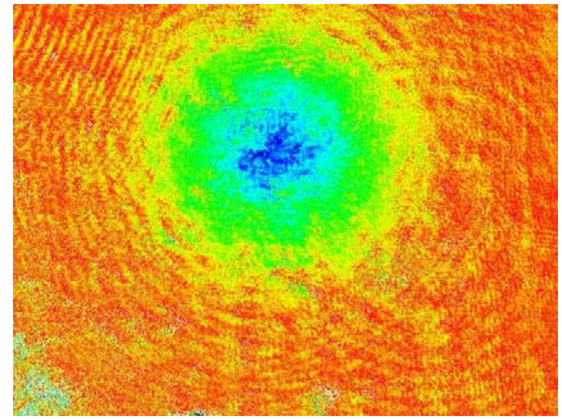


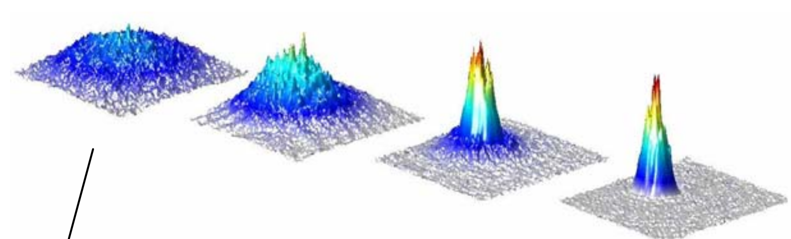
field minimum in the center traps weak field seekers!

high field seekers are expelled

Cooling and trapping together





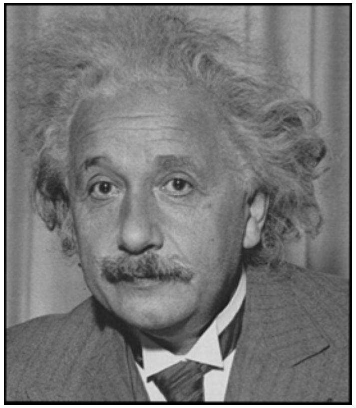


Laser cooling and trapping
Nobel Prize 1997

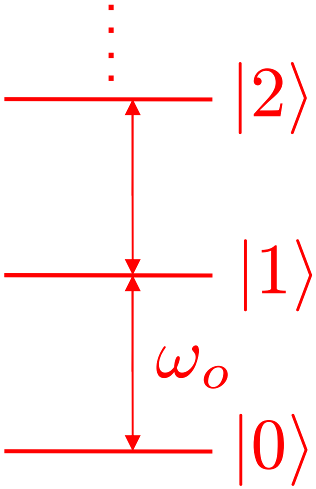
Bose-Einstein condensation
Nobel Prize 2001

Coldest stuff in the universe... N_2 at these temperatures would only travel 3 millionths of a meter!

Photons



Thanks to this guy, we found out 100 years ago that light comes in little packets of energy known as photons:



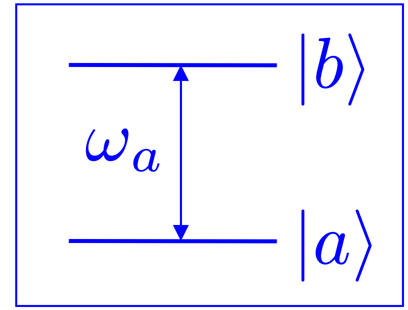
The energy of a photon is, from Einstein's relation, determined by its *frequency*. For a given frequency, the energy of the system is given by the total number of photons of that frequency times the energy per photon (hν).

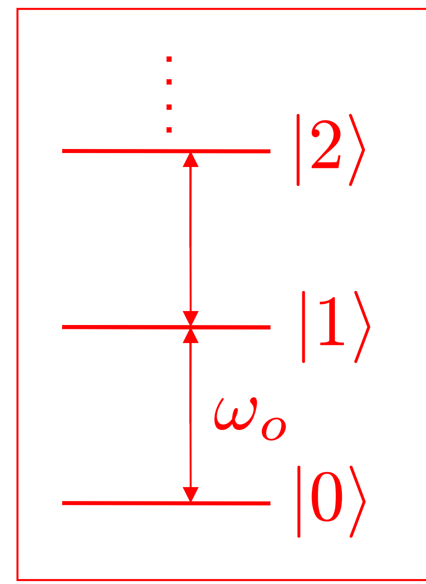
Quantum states of the photon field are given by eigenstates of a *number operator* which counts the number of photons in a mode.

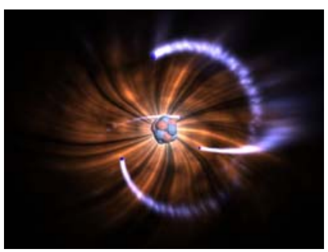
$$U_{classical} = \frac{1}{8\pi}\int d^3\vec{r}\left(\vec{E}^2 + \frac{1}{c^2}\vec{B}^2\right) \longrightarrow \hat{H} = \hat{N}\hbar\omega_o$$

Atoms and photons together

- Ingredients:
  - two-level atoms
  - discrete light quanta





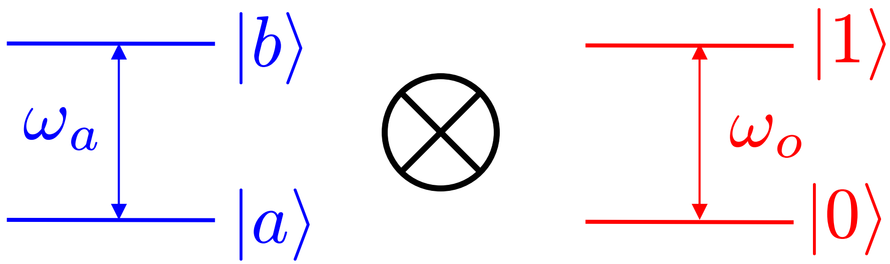


+

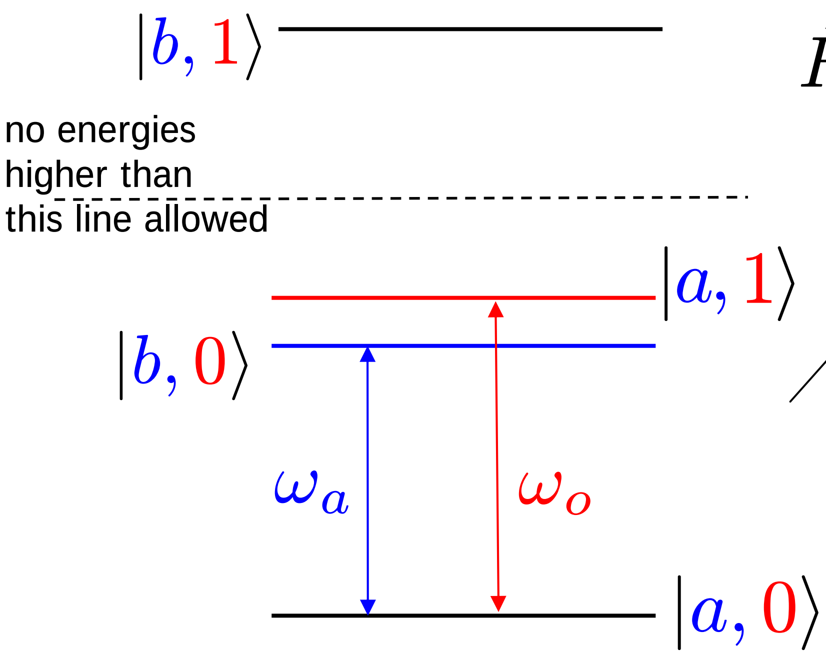
What does the Hamiltonian look like?

$$\hat{H} = \hbar\omega_a |b\rangle\langle b| + \hbar\omega_o |1\rangle\langle 1| + 2\hbar\omega_o |2\rangle\langle 2| + \ldots$$

A single atom and single photon



4-level state space: $\{|a,0\rangle, |a,1\rangle, |b,0\rangle, \cancel{|b,1\rangle}\}$



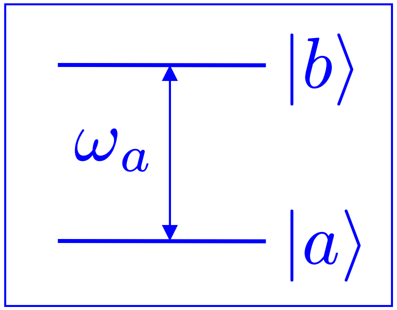
$$\hat{H} = \hbar\omega_a |b,0\rangle\langle b,0| + \hbar\omega_o |a,1\rangle\langle a,1|$$

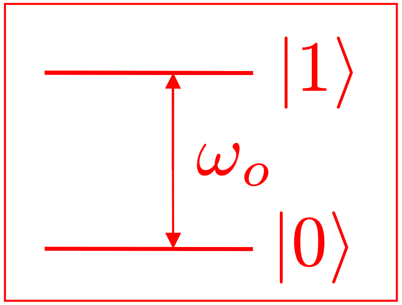
$$\begin{pmatrix} \hbar\omega_o & 0 & 0 \\ 0 & \hbar\omega_a & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

No off diagonal elements... boring!

Atoms and photons *interacting*

- Ingredients:
  - two-level atoms
  - discrete light quanta

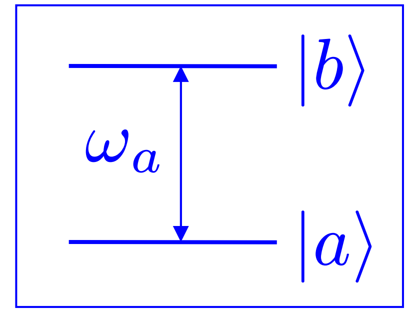


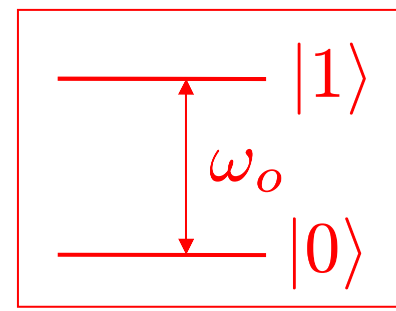


$$\hat{H} = \hbar\omega_a |b,0\rangle\langle b,0| + \hbar\omega_o |a,1\rangle\langle a,1|$$

Atoms and photons *interacting*

- Ingredients:
  - two-level atoms
  - discrete light quanta
  - interactions





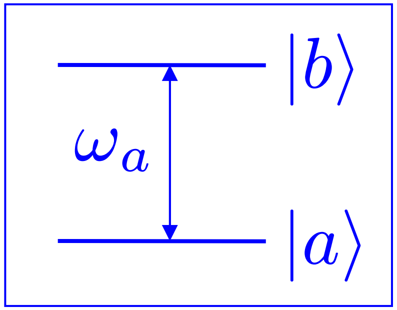
$$\hat{H} = \hbar\omega_a |b,0\rangle\langle b,0| + \hbar\omega_o |a,1\rangle\langle a,1| - \hat{\mathbf{d}} \cdot \vec{E}$$

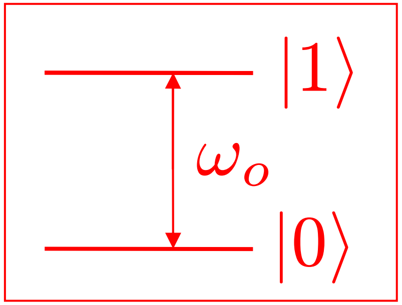
(it's like $\hat{H} = -\hat{\mu} \cdot \vec{B}$!)

Claim: interaction term should yield *off diagonal elements* !

Atoms and photons *interacting*

- Ingredients:
  - two-level atoms
  - discrete light quanta
  - interactions





$$\hat{H} = \hbar\omega_a |b,0\rangle\langle b,0| + \hbar\omega_o |a,1\rangle\langle a,1| + \hbar g_o \left(|b,0\rangle\langle a,1| + |a,1\rangle\langle b,0| \right)$$

destroys a photon, raises atom to excited state

brings an atom to the ground state, creates a photon

Atoms and photons *interacting*

$$\hat{H} = \hbar\omega_a |b,0\rangle\langle b,0| + \hbar\omega_o |a,1\rangle\langle a,1| + \hbar g_o \left(|b,0\rangle\langle a,1| + |a,1\rangle\langle b,0|\right)$$

$$\downarrow$$

$$\begin{pmatrix} \hbar\omega_o & \hbar g_o & 0 \\ \hbar g_o & \hbar\omega_a & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\downarrow$$

who cares about the ground state?

$$\begin{pmatrix} \hbar\omega_o & \hbar g_o \\ \hbar g_o & \hbar\omega_a \end{pmatrix}$$

Now that's a nice (and familiar) Hamiltonian!

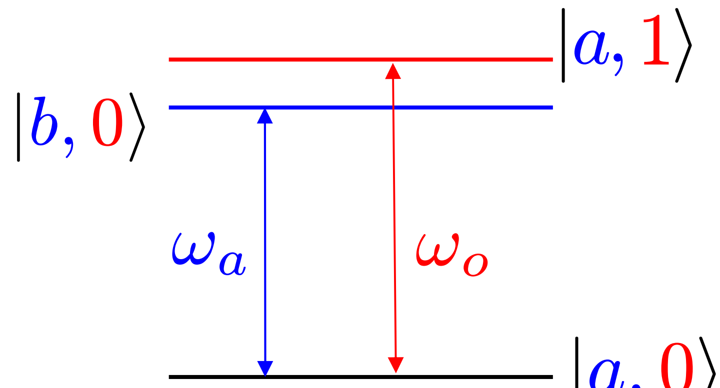
Atoms and photons not *interacting*

$$\hat{H} = \hbar\omega_a |b,0\rangle\langle b,0| + \hbar\omega_o |a,1\rangle\langle a,1|$$

$$\begin{pmatrix} \hbar\omega_o & 0 \\ 0 & \hbar\omega_a \end{pmatrix}$$

this is the photon frequency, which is usually under our control (a tunable laser or whatever)

this is the a property of the atom, not under our control (although we can choose which atom!)



Soooooo....

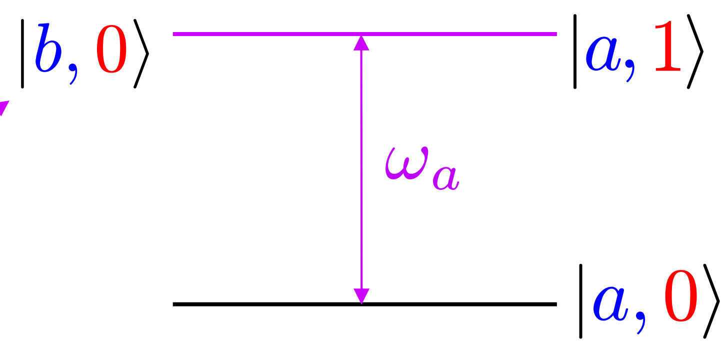
Atoms and photons not *interacting*

$$\hat{H} = \hbar\omega_a |b,0\rangle\langle b,0| + \hbar\omega_a |a,1\rangle\langle a,1|$$

$$\begin{pmatrix} \hbar\omega_a & 0 \\ 0 & \hbar\omega_a \end{pmatrix}$$

Tune the light to resonance!

$$set\ \omega_o = \omega_a!$$

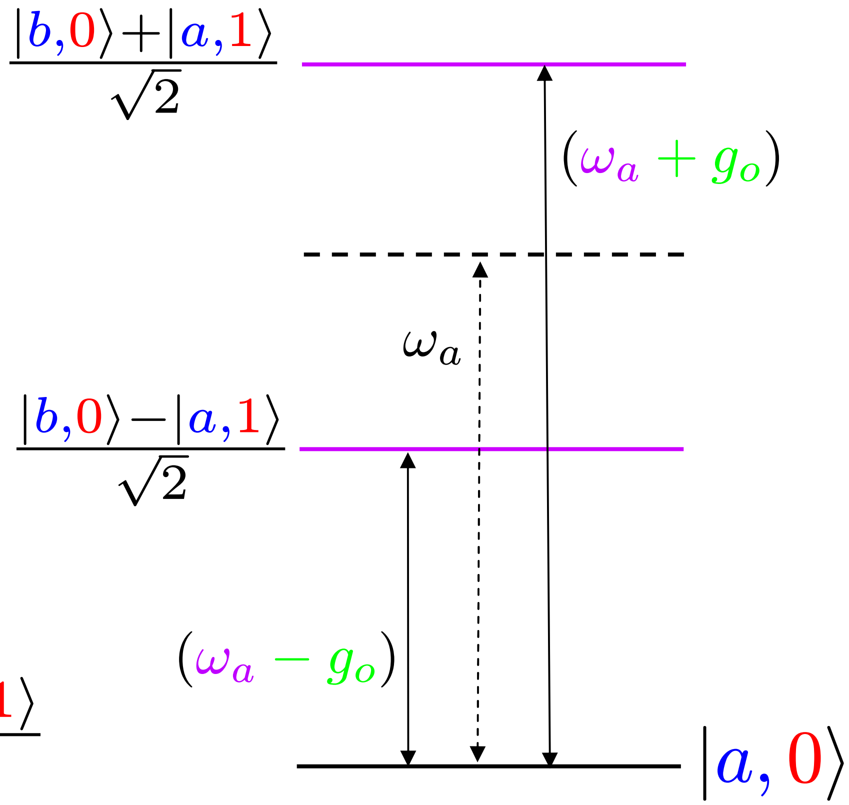


these two states have the same energy

Atoms and photons *interacting*

$$\hat{H} = \hbar\omega_a |b,0\rangle\langle b,0| + \hbar\omega_a |a,1\rangle\langle a,1| + \hbar g_o \left(|b,0\rangle\langle a,1| + |a,1\rangle\langle b,0|\right)$$

$$\begin{pmatrix} \hbar\omega_a & \hbar g_o \\ \hbar g_o & \hbar\omega_a \end{pmatrix}$$



What are the energy eigenstates of *H*?

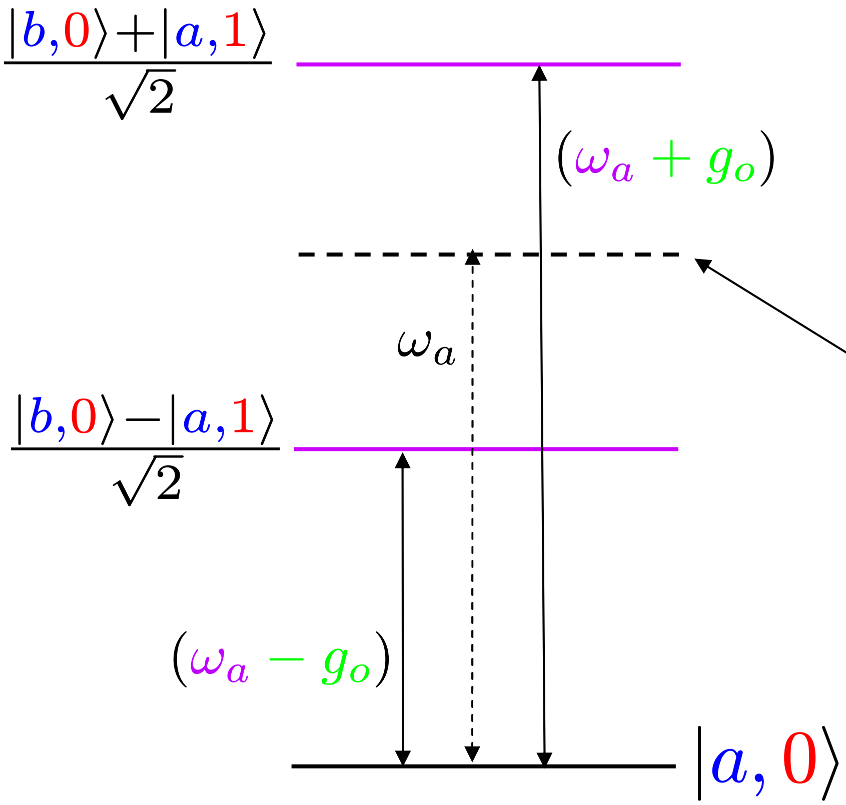
$$|E_+ = \hbar\left(\omega_a + g_o\right)\rangle = \frac{|b,0\rangle+|a,1\rangle}{\sqrt{2}}$$

$$|E_+ = \hbar\left(\omega_a - g_o\right)\rangle = \frac{|b,0\rangle-|a,1\rangle}{\sqrt{2}}$$

Atoms and photons *interacting*

$$\hat{H} = \hbar\omega_a |b,0\rangle\langle b,0| + \hbar\omega_a |a,1\rangle\langle a,1| + \hbar g_o \left(|b,0\rangle\langle a,1| + |a,1\rangle\langle b,0|\right)$$

Energy eigenstates are superpositions of having a photon and not having a photon!



There's no state where the atom's energy level used to be!

How I learned to stop worrying and make *d ·E* large

Single atom/photon Hamiltonian → (low excitation regime)

$$\begin{pmatrix} \hbar\omega_a & \hbar g_o \\ \hbar g_o & \hbar\omega_a \end{pmatrix}$$

We want g_o as big as possible… but how big is g_o?

Take my word for it…

$$g_o = -\hat{\mathbf{d}} \cdot \vec{E} = -d\sqrt{\frac{\hbar\omega_o}{2\epsilon_o V}} \sim d\sqrt{\frac{\omega_o}{V}}$$

d **is the electric dipole moment of the atomic transition… your choice of which atom, which levels**

V is the mode volume of the photon (i.e. how much space does the photon occupy)

Okay, seriously, what is this guy talking about?

- Can get interesting quantum states if we can get a single atom to feel the effect of a single photon →

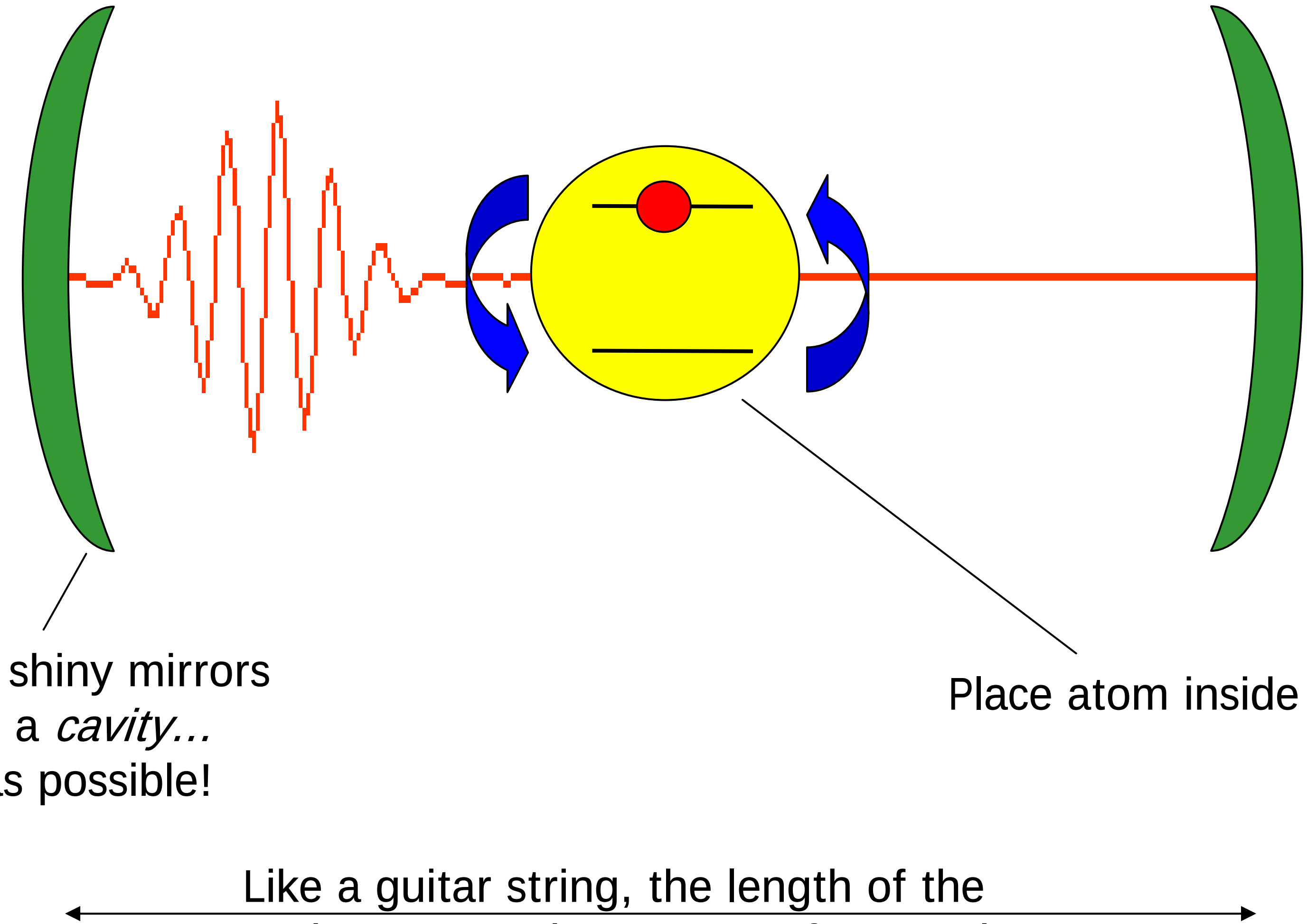
$$\begin{pmatrix} \hbar\omega_o & \hbar g_o \\ \hbar g_o & \hbar\omega_a \end{pmatrix}$$

- Those eigenstates have both a atom character (storage) and photon character (potential for transmission) →

$$\frac{|b,0\rangle \pm |a,1\rangle}{\sqrt{2}}$$

- At least two things must occur for this to make any sense
  1. photons must have large electric field → $\frac{|\vec{E}|}{photon} \propto d\sqrt{\frac{\omega_o}{V}}$
  2. photon must hang around the atom for longer than $1/g_o$ → **??????**

Enter cavity quantum electrodynamics!

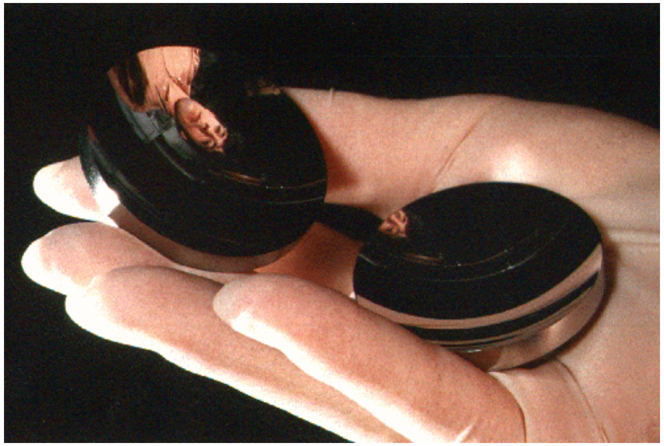


Get really shiny mirrors
and make a *cavity…*
as small as possible!

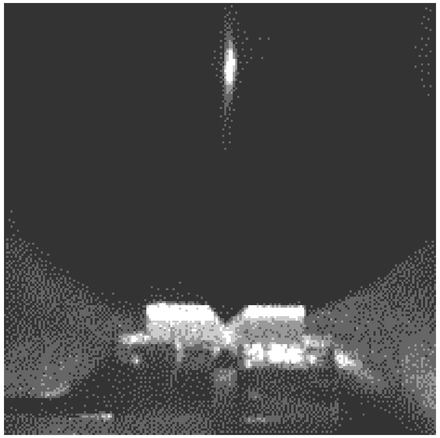
Place atom inside cavity

Like a guitar string, the length of the
cavity "tunes" the resonant frequencies…
set the length to have a resonance at ω_o

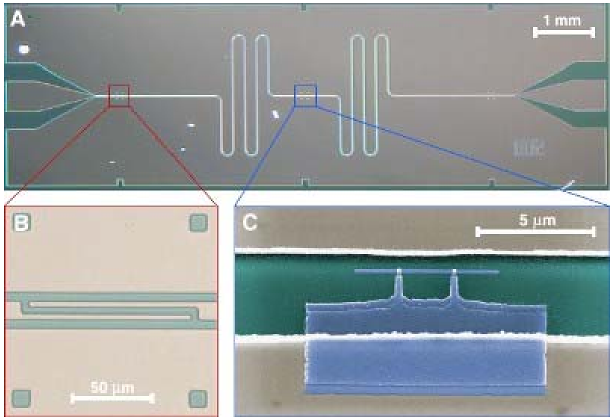
Some notable cavity QED experiments



Serge Haroche at ENS (France)



Jeff Kimble at Caltech



Robert Schoelkopf and Steve Girvin at Yale

Let’s bring it all together!

- Advances in laser cooling and *ultracold* atomic physics allow us to cool, trap, and control the position and velocity of atoms

- Shiny mirrors and small volumes (cavity QED) allows us to get a single photon (quantum information transmitter) to interact strongly with a single atom (quantum information storage)

- The ability to transfer quantum information between quantum systems is unique to cavity QED… this is the big payoff!

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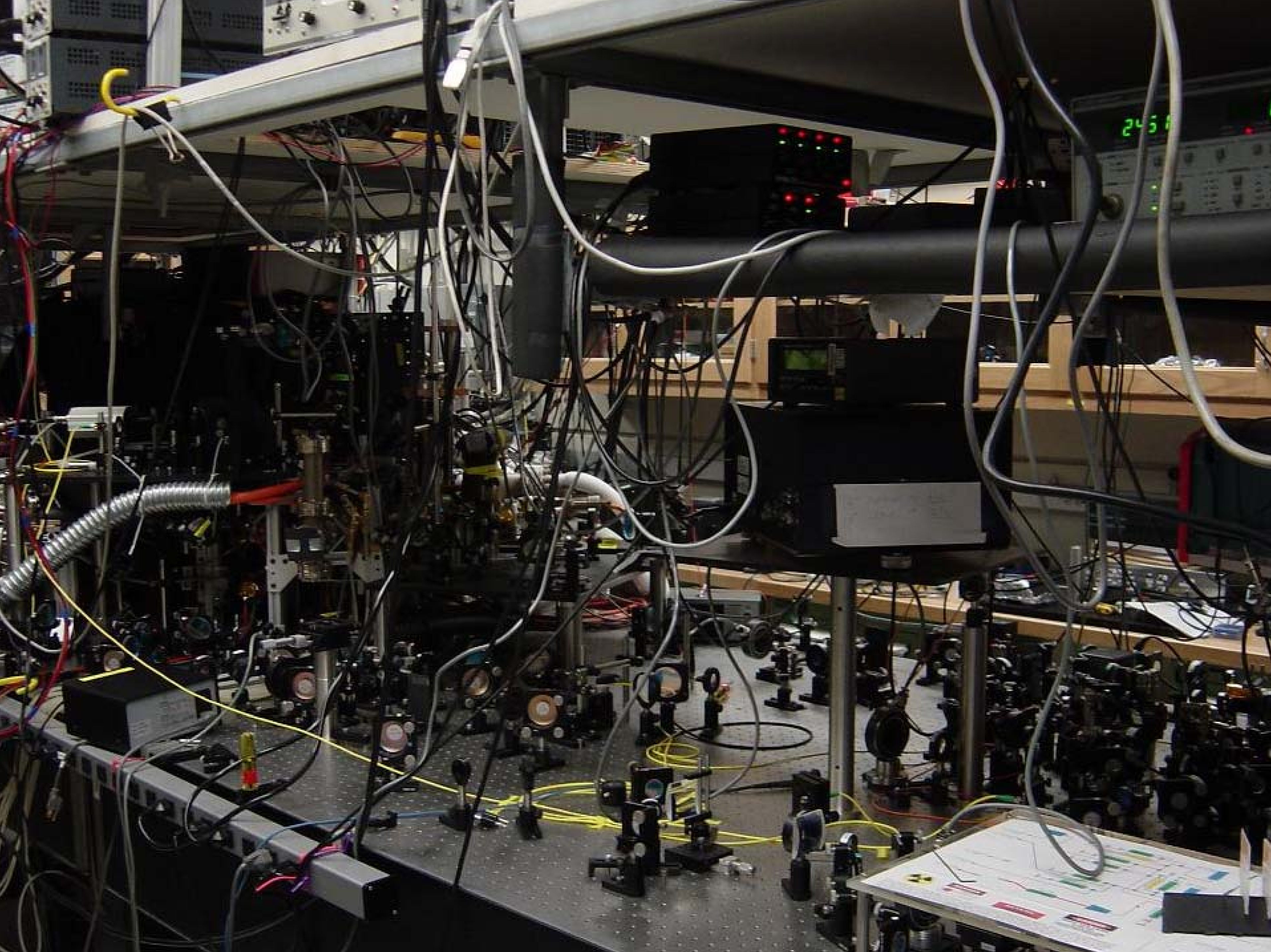
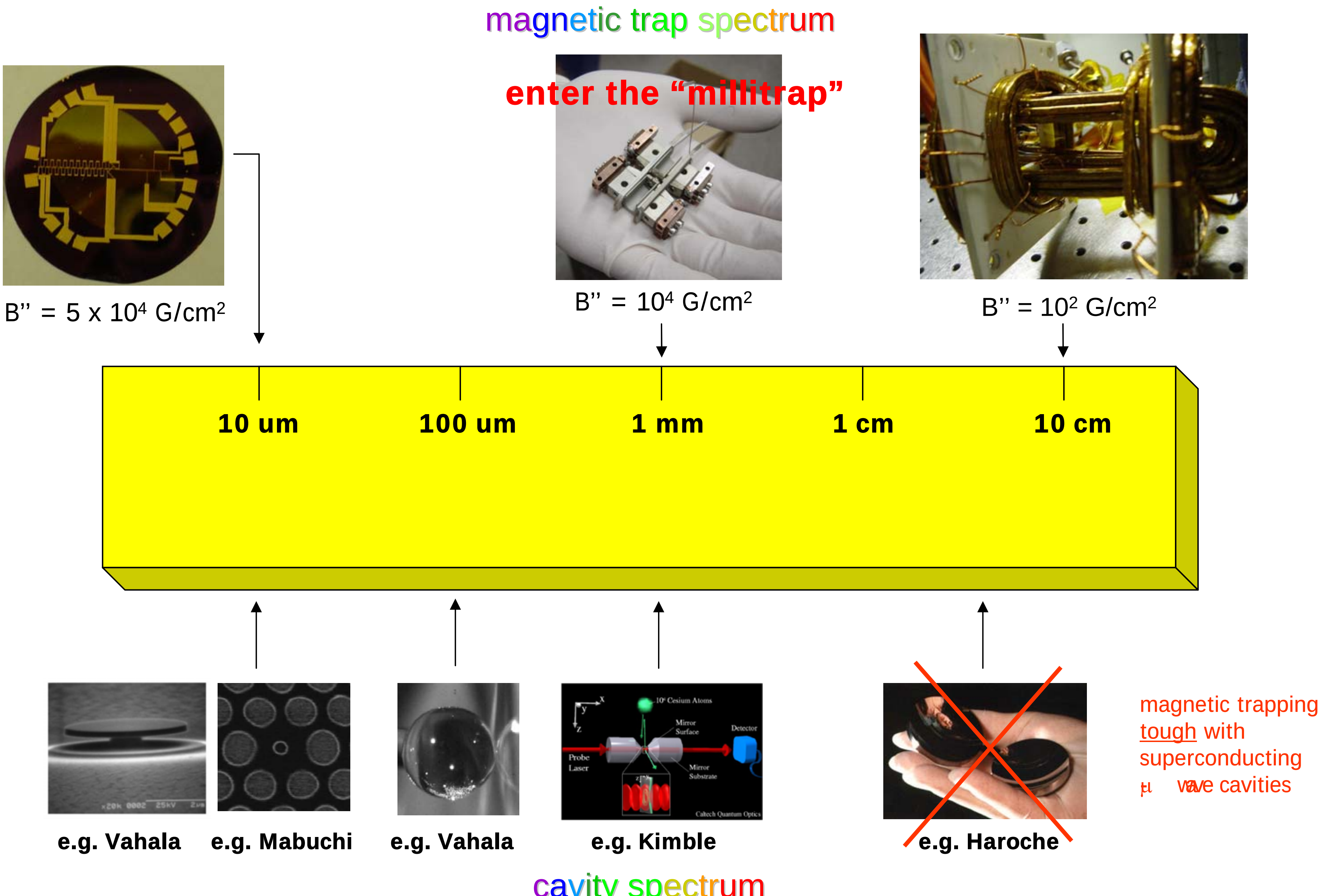
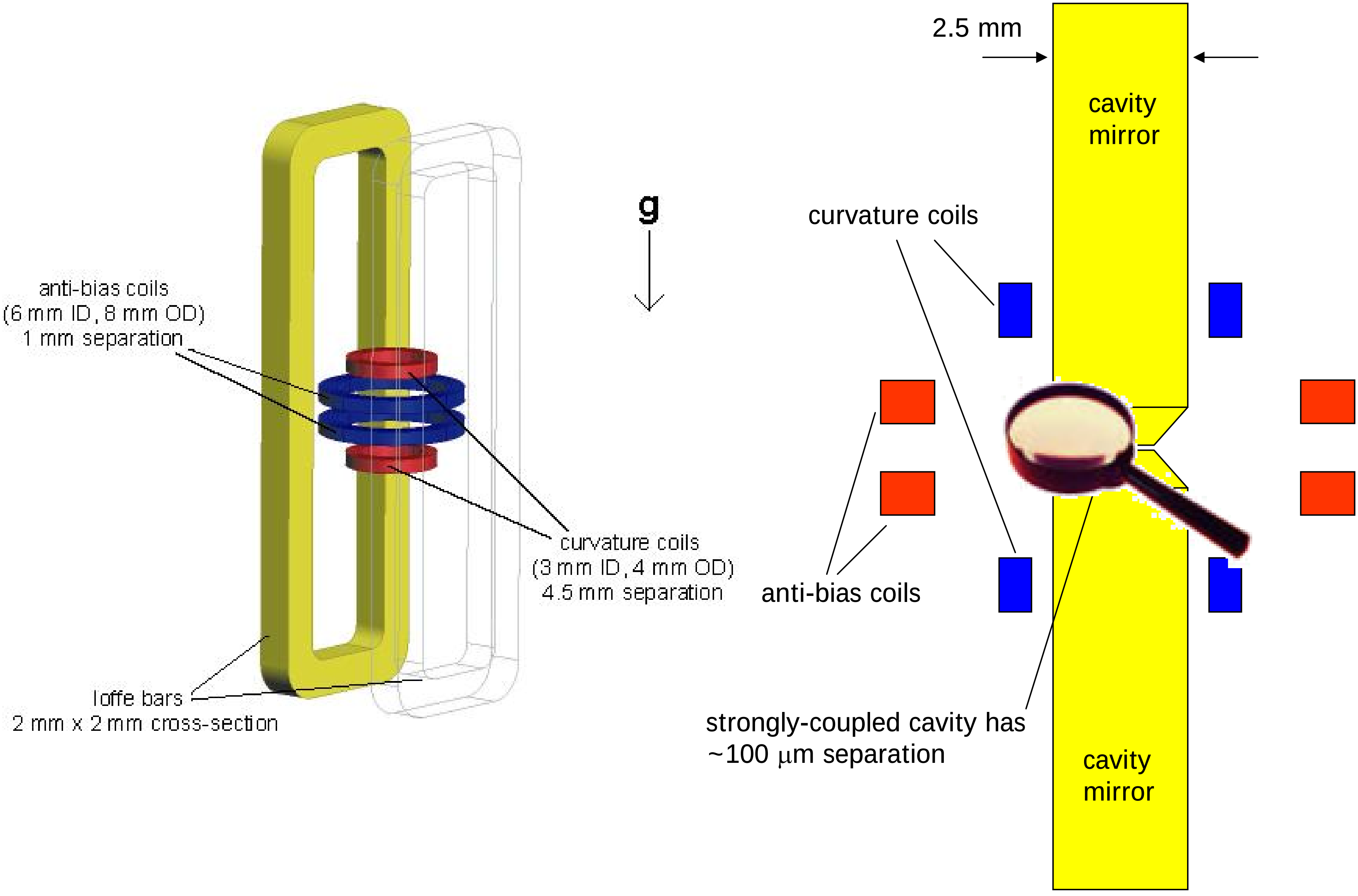
- Great! So how to do we do it?

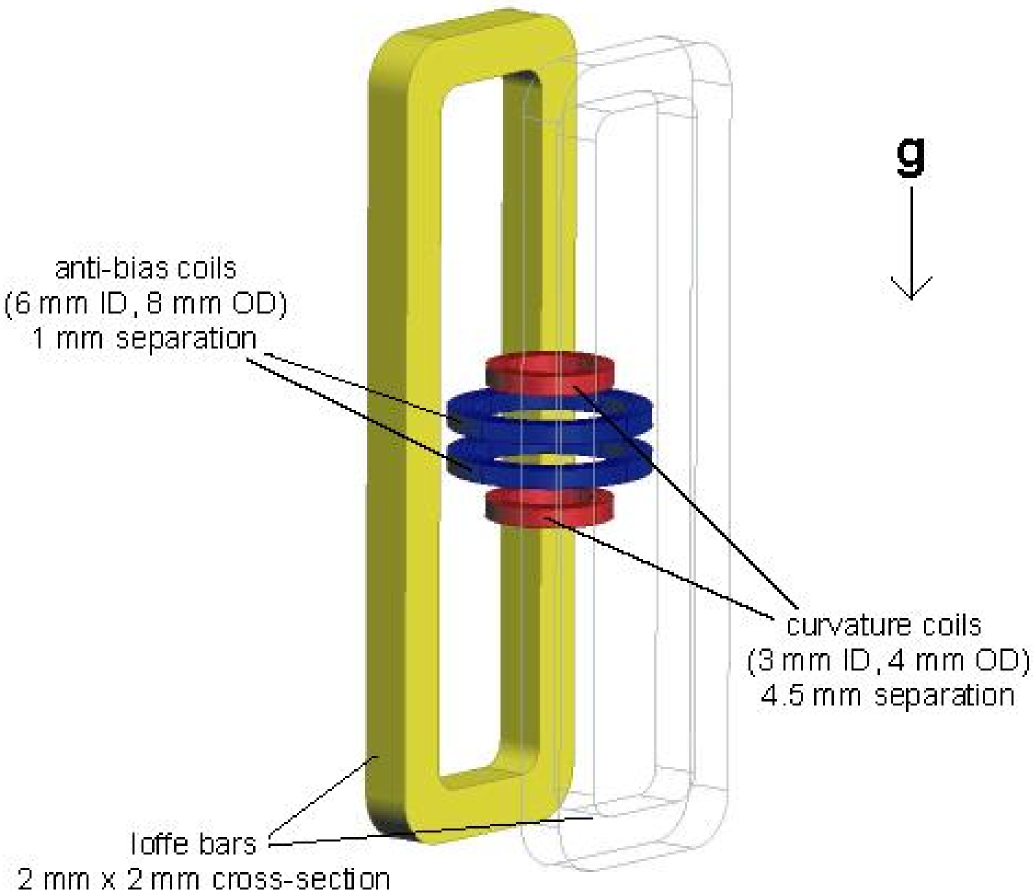


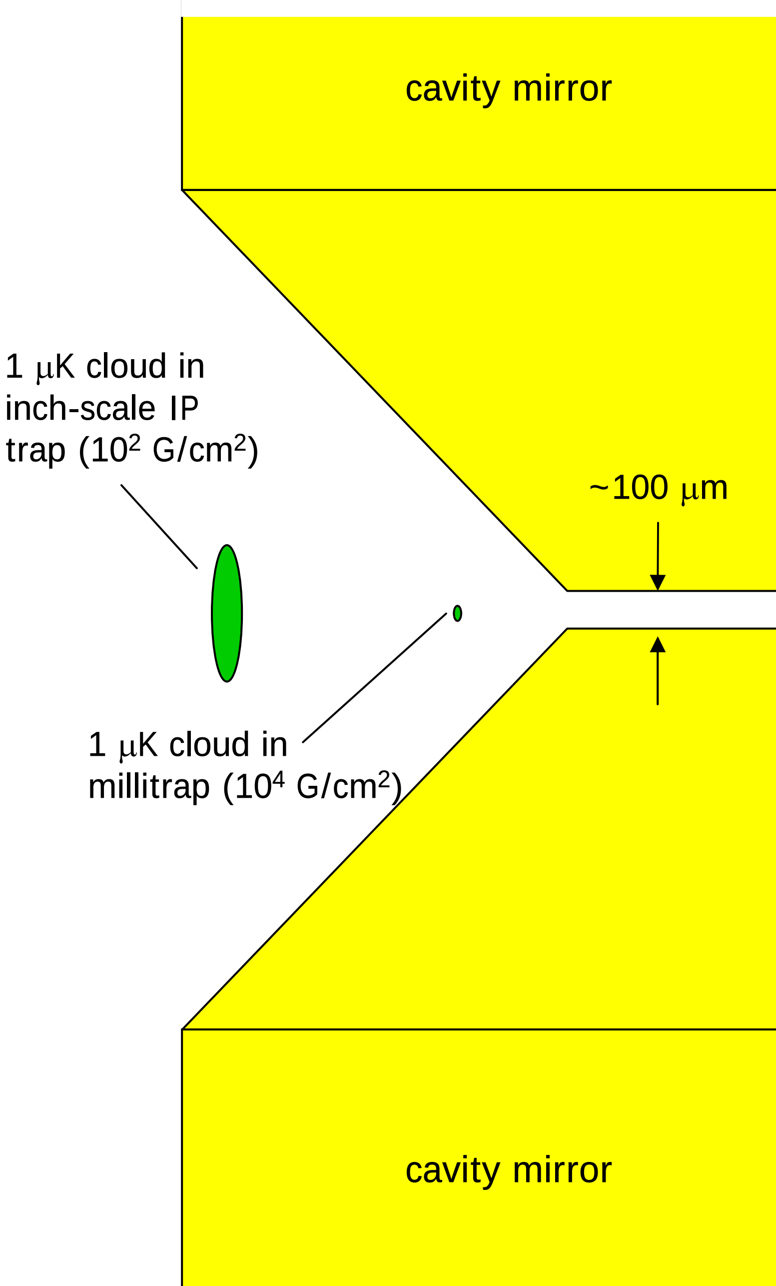

magnetic trap spectrum
enter the “millitrap”
B’’ = 5 x 10^4 G/cm^2
B’’ = 10^4 G/cm^2
B’’ = 10^2 G/cm^2
10 um
100 um
1 mm
1 cm
10 cm
e.g. Vahala
e.g. Mabuchi
e.g. Vahala
e.g. Kimble
e.g. Haroche
magnetic trapping tough with superconducting μwave cavities
cavity spectrum

Millimeter cavities and millimeter traps



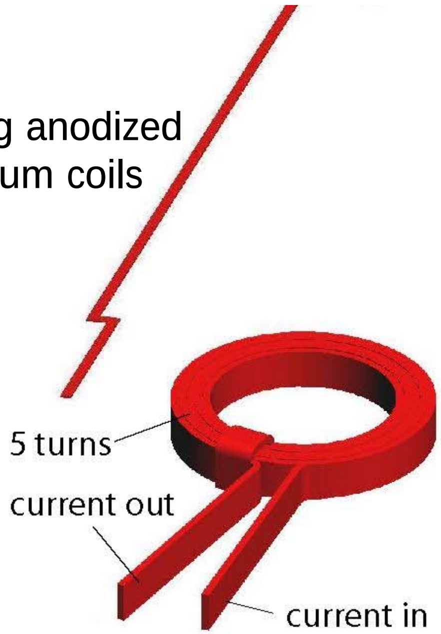
Millimeter cavities and millimeter traps



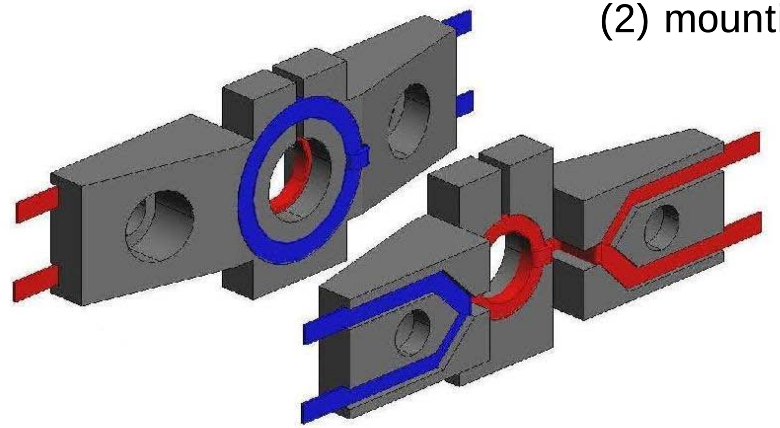


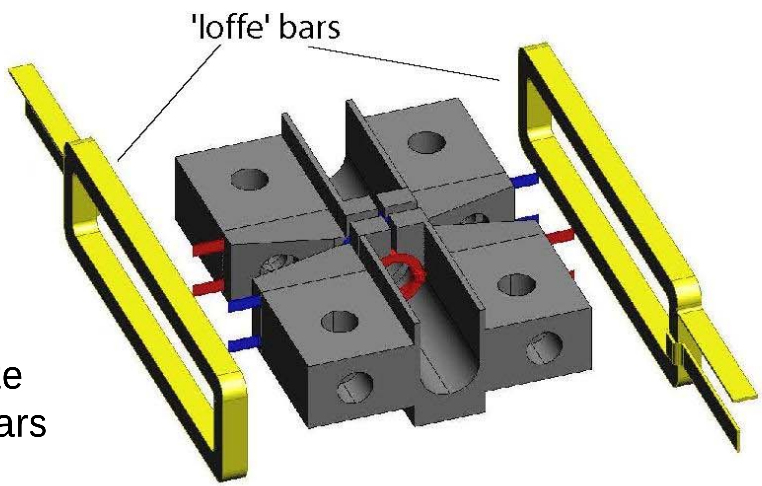
Millitrap assembly

(1) winding anodized aluminum coils

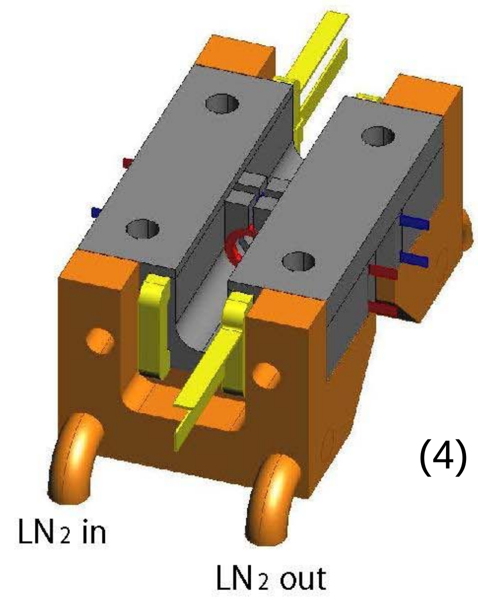


(2) mounting coils



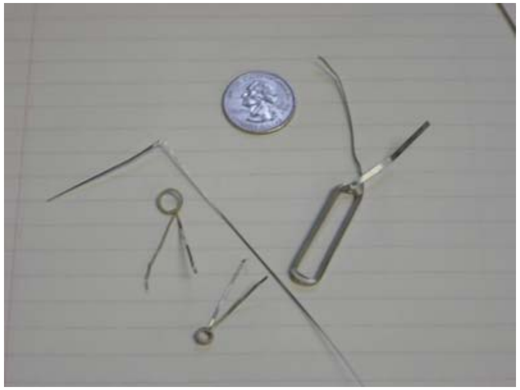


(3) integrate Ioffe bars



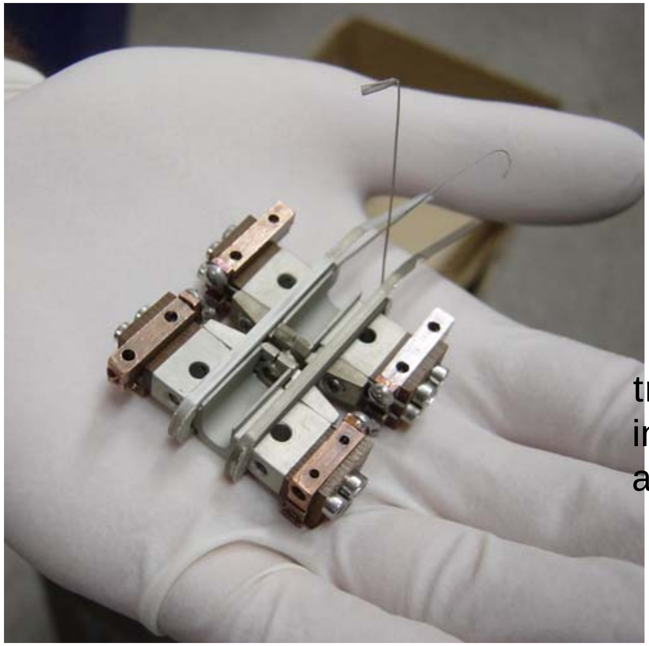
(4) mounting trap in UHV chamber

Millitrap assembly (continued)

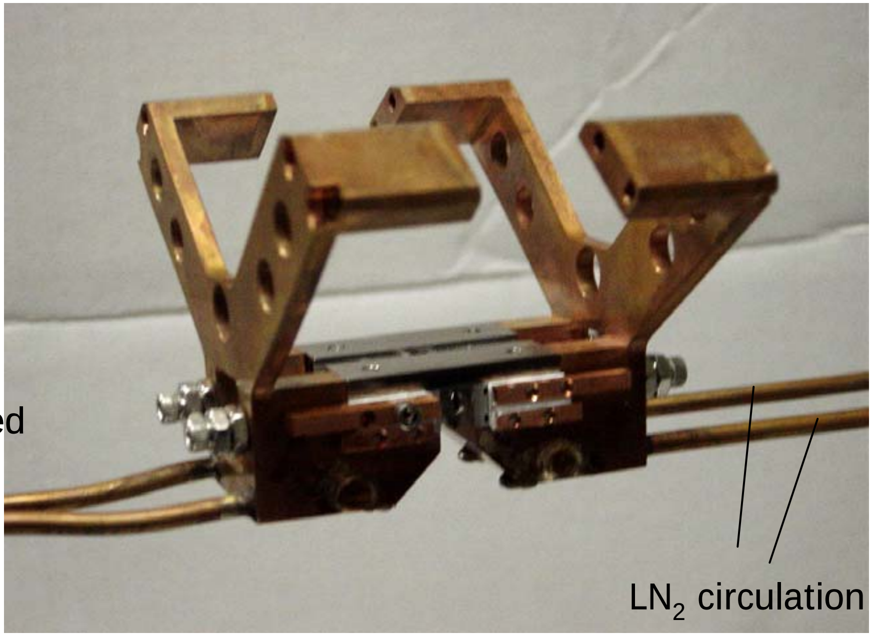


hand-winding aluminum foil
leads to lots of dead coils

after 100 bad coils, six
good coils make a trap!

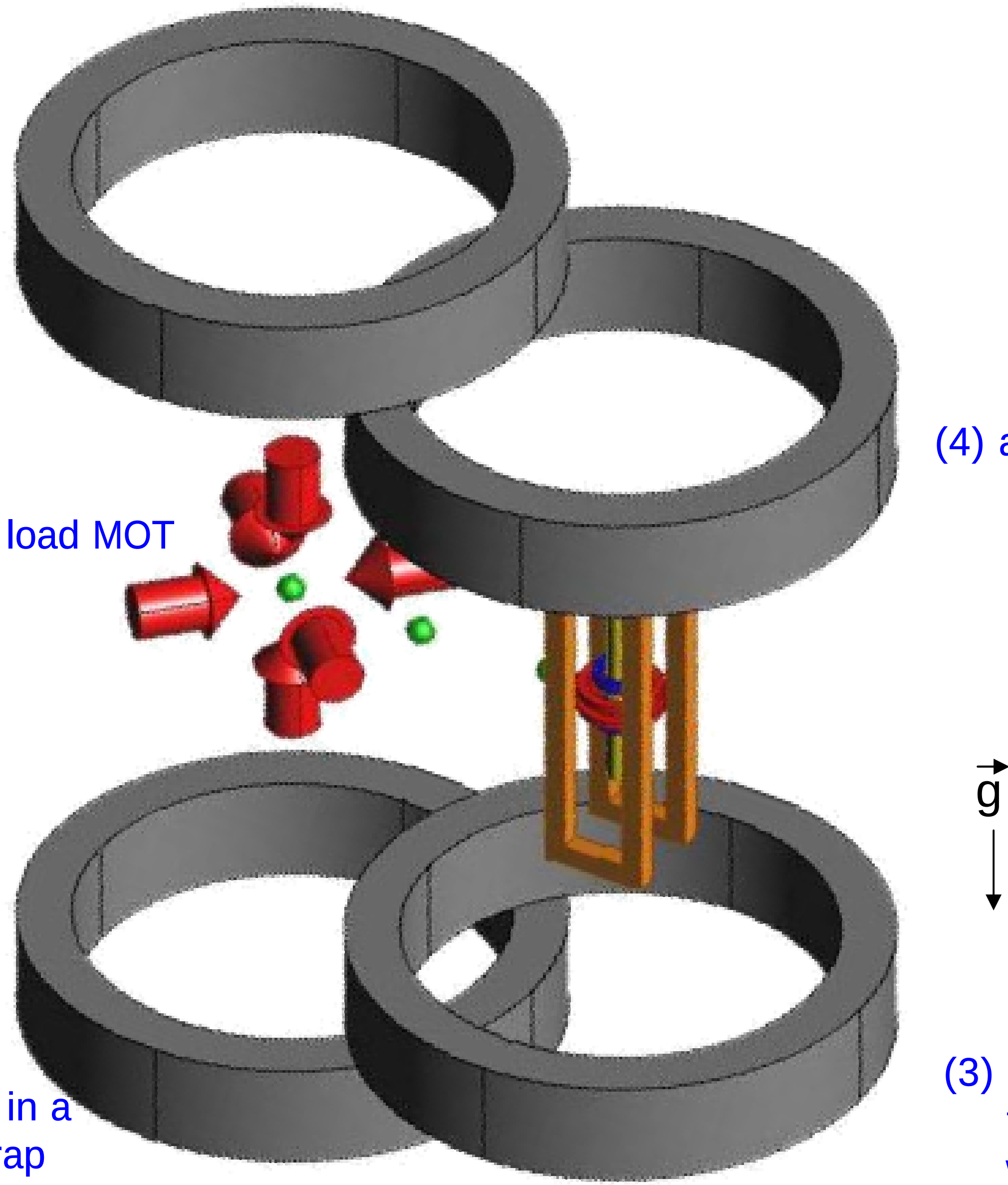


trap is mounted
in LN_2 cooled
assembly

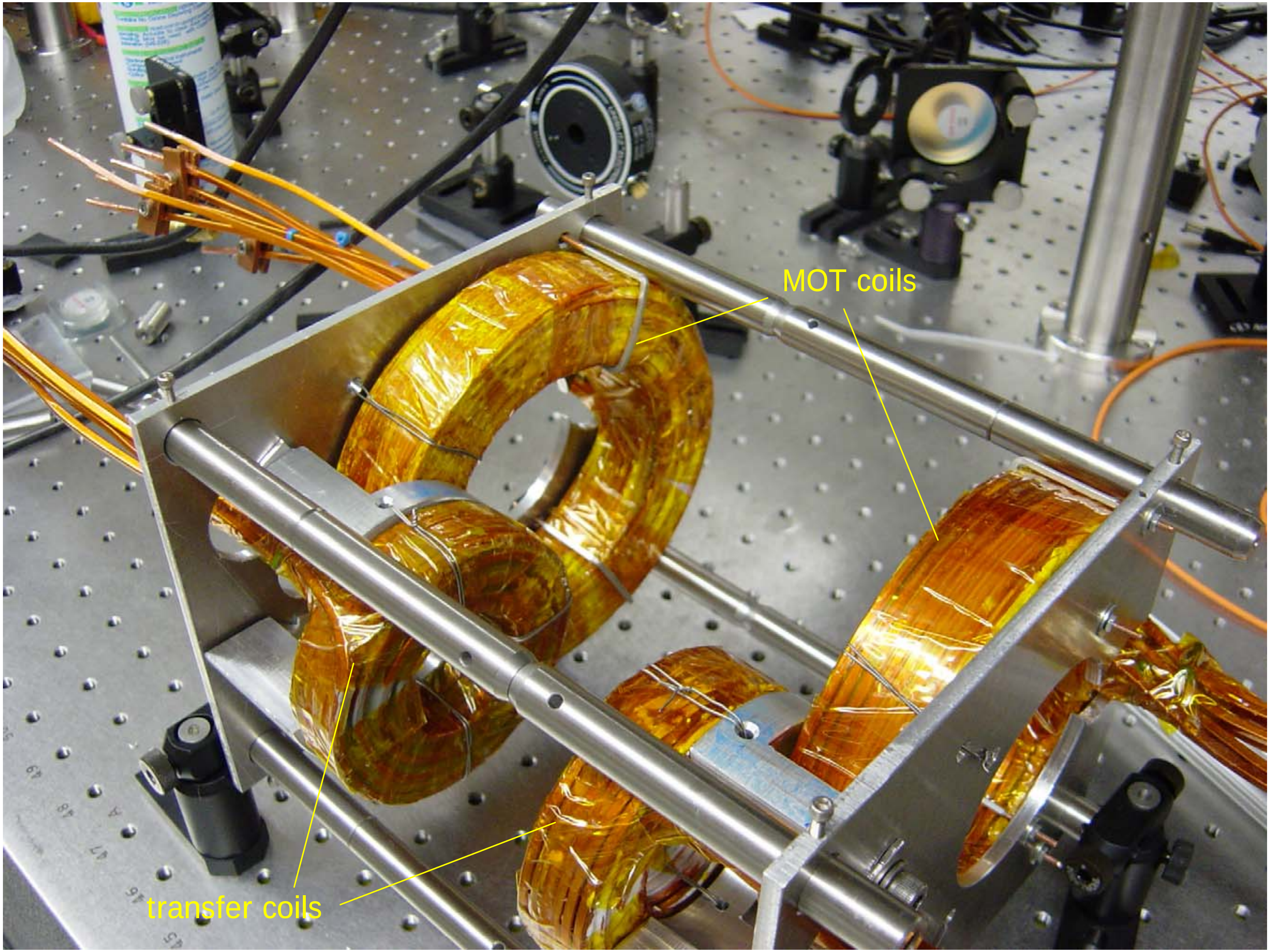


LN_2 circulation

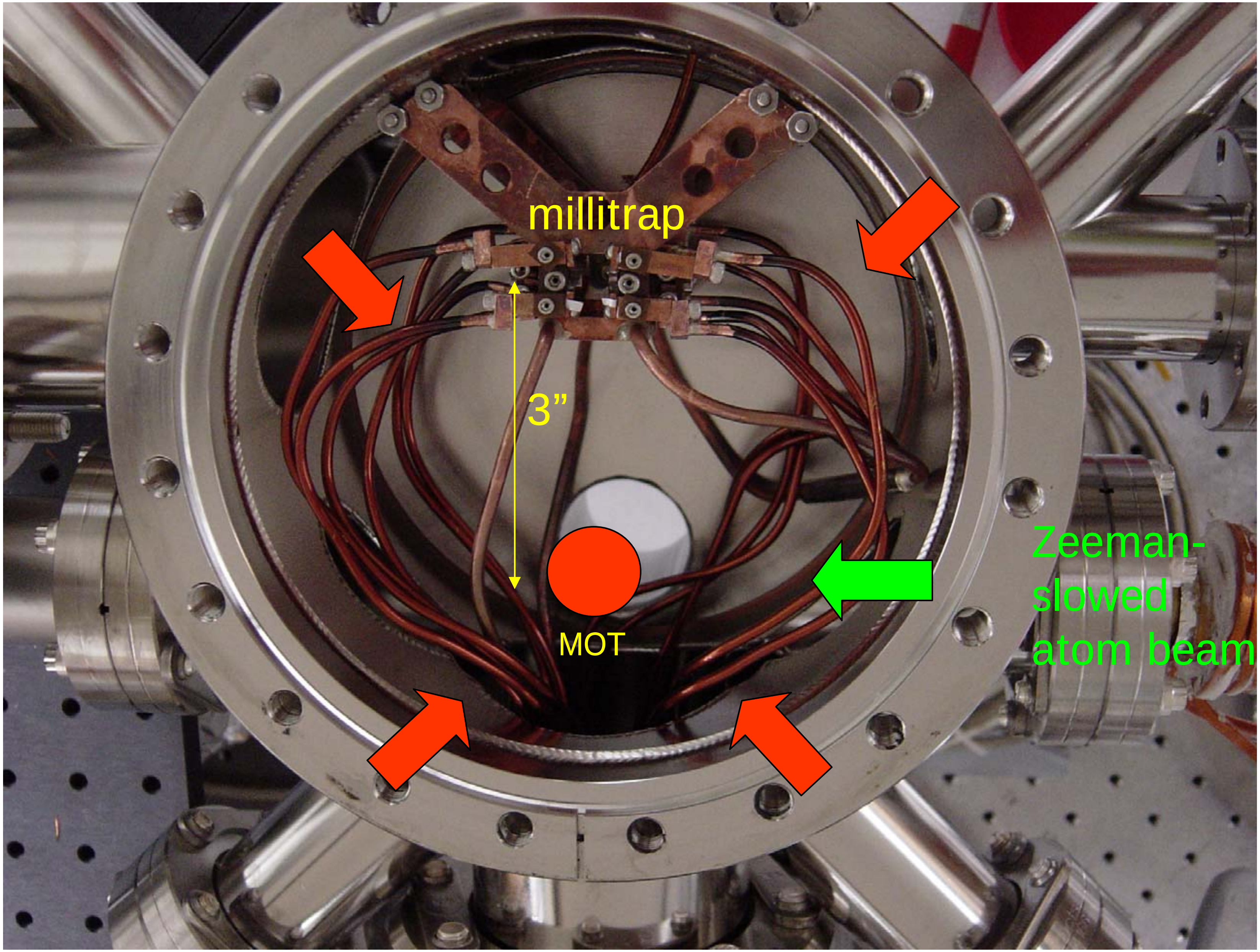
Ultracold atom production



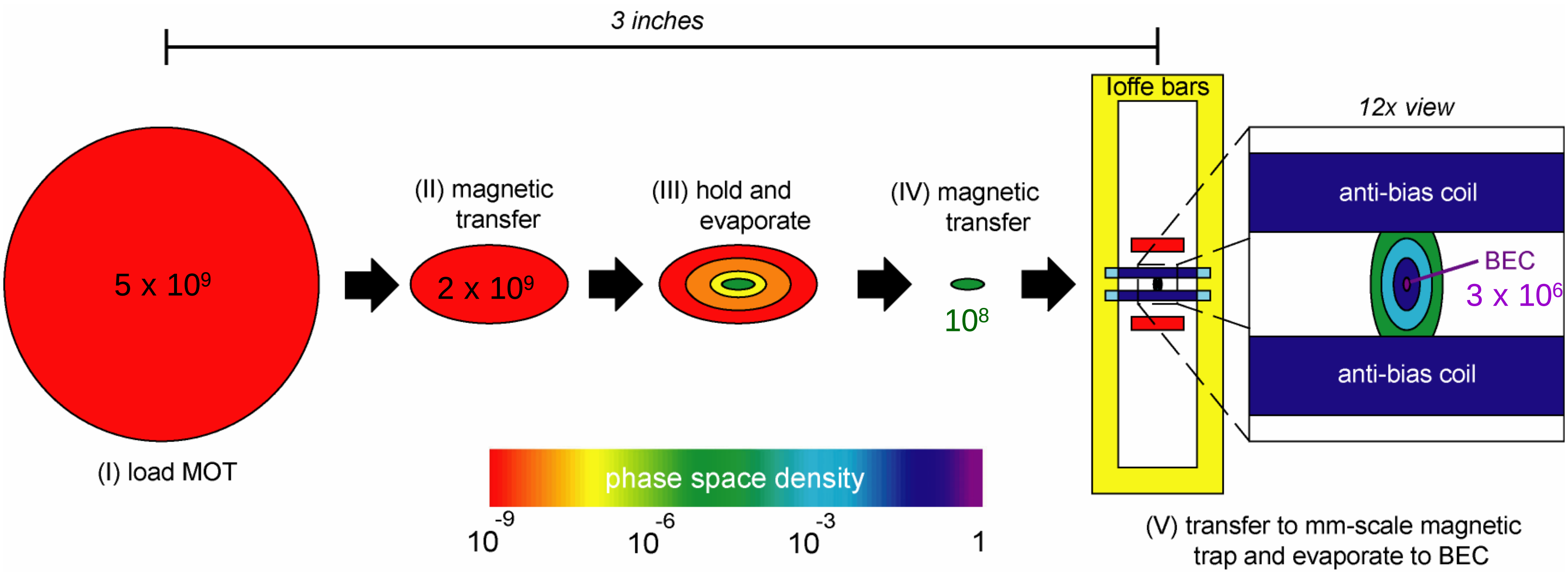
Ultracold atom production

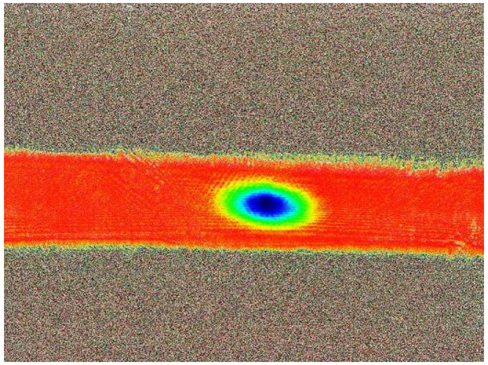


Ultracold atom production

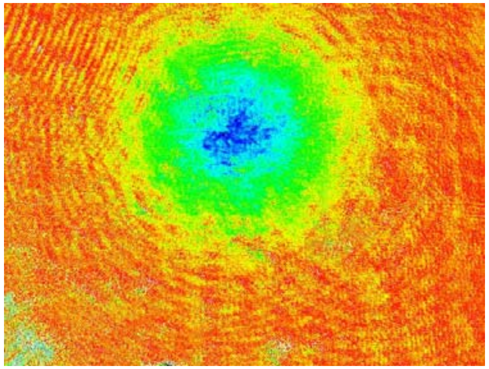


Ultracold atom production (continued)



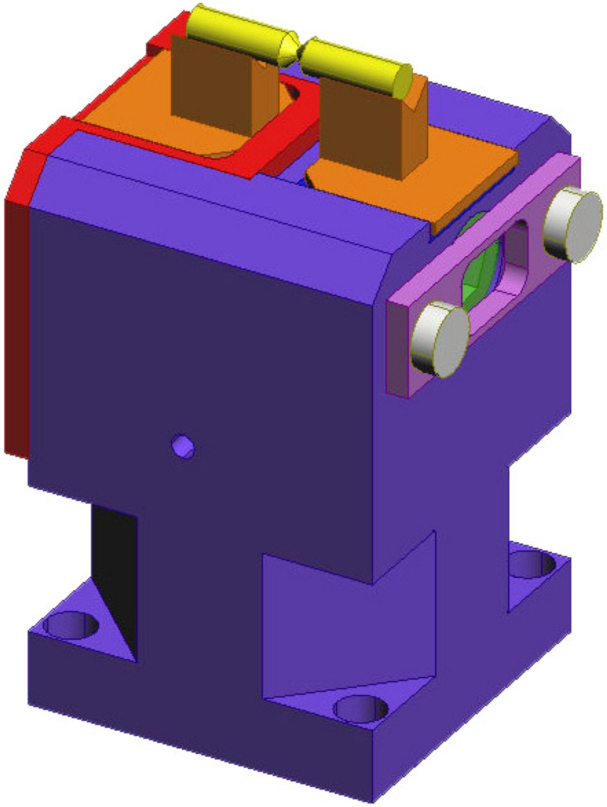


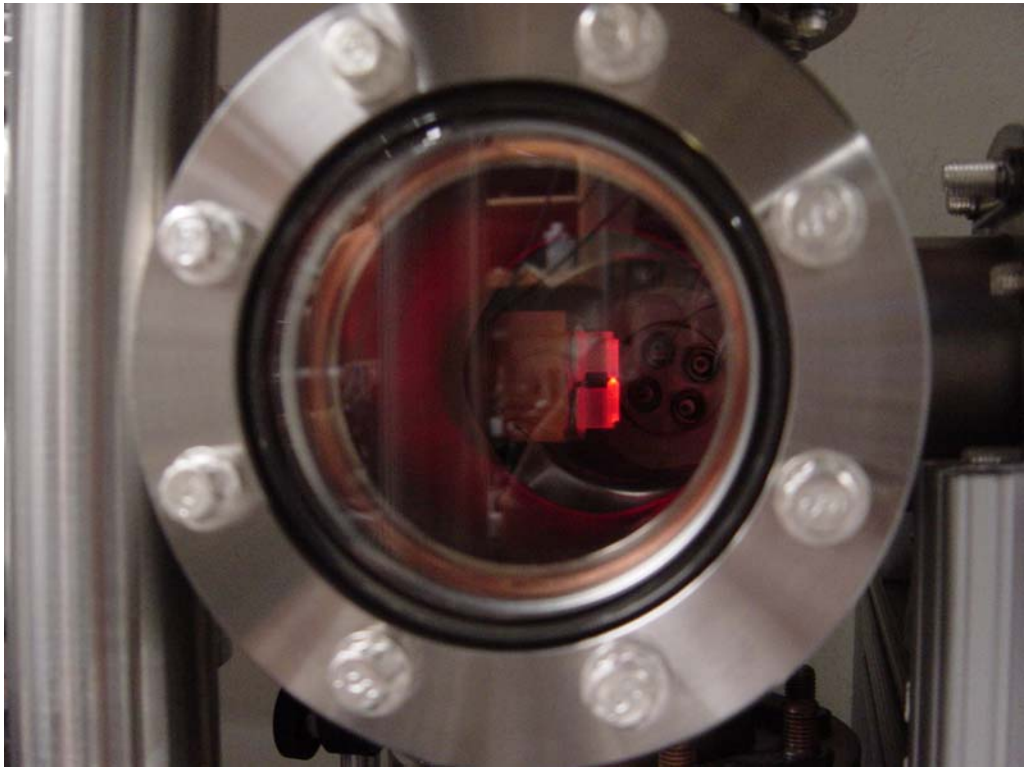
October 28th, 2004 – first magnetically-trapped atoms



Dec. 2nd, 2004 - Pure BECs of 3 million atoms produced

The cavity





http://physics.berkeley.edu/research/ultracold

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