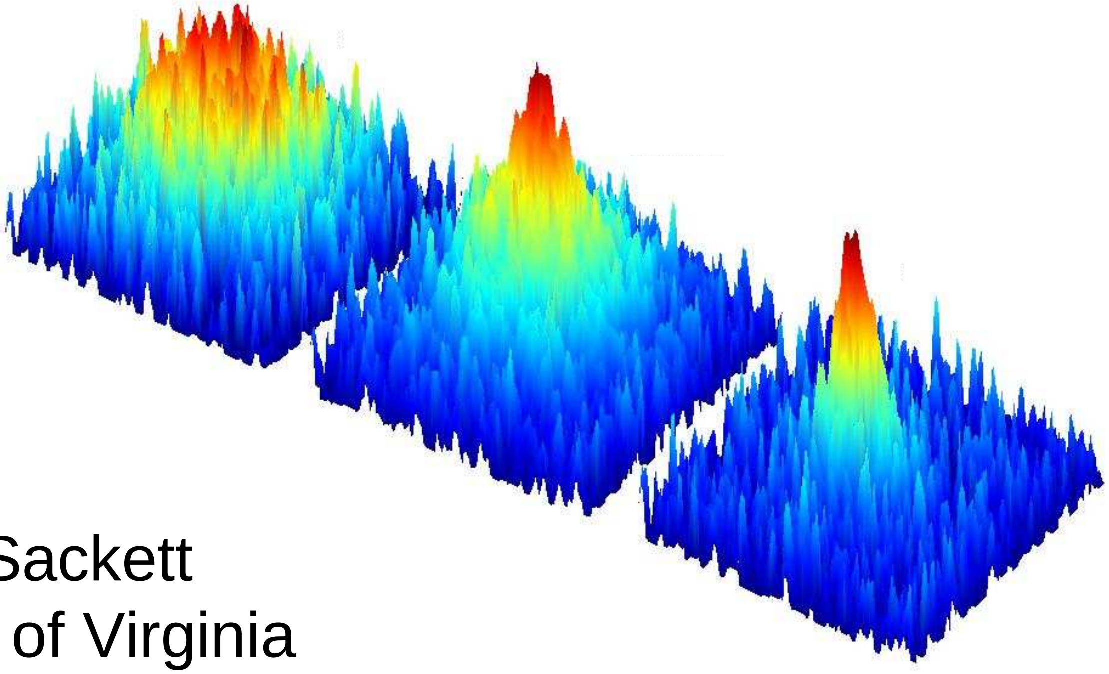
# Atom Interferometry
# using Bose-Einstein Condensates



Cass Sackett
University of Virginia

16 October 2006

- Atom interferometry
    - Why is it interesting?

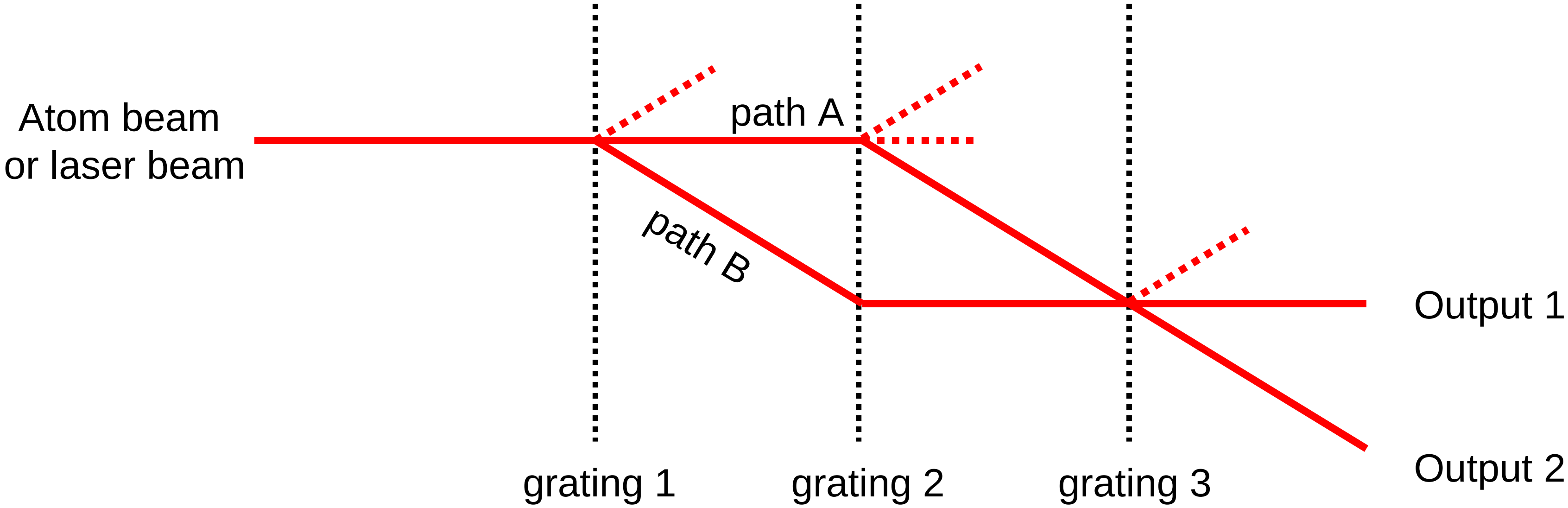
- Condensate interferometry

- Making BEC

- Interferometry results and prospects

# What is atom interferometry?

Just like optical interferometry:



Gratings can split and recombine waves
- whether from Maxwell or Schrodinger equations

Two waves contribute to flux in output 1:

$$P_1 \sim \left|\psi_A + \psi_B\right|^2$$

$\psi_A$ = amplitude to take path A
$\psi_B$ = amplitude to take path B

So $P_1 \sim \left|\psi_A\right|^2 + \left|\psi_B\right|^2 + 2\left|\psi_A \psi_B\right| \cos\phi$

$\phi$ = phase difference between $\psi_A$ and $\psi_B$

Output intensity depends on phase difference
Allows phase difference to be measured

$\Rightarrow$ It’s an interferometer!

# Differences between atoms and light:

## Light:

- High flux ($10^{16}$ photons/s)
- Easy to manipulate
  - beams in air
  - mirrors, beamsplitters

## Atoms (thermal beam):

- Low flux ($10^{9}$ photons/s)
- Hard to manipulate
  - atoms in vacuum
  - optical or mech. gratings
  - small deflection angles

# Differences between atoms and light:

## Light:

- High flux ($10^{16}$ photons/s)
- Easy to manipulate
  - beams in air
  - mirrors, beamsplitters
- Weak interactions with environment

$$\phi = \frac{2\pi n}{\lambda} \Delta d$$

- path length difference $d$
- index of refraction $n$

## Atoms (thermal beam):

- Low flux ($10^{9}$ photons/s)
- Hard to manipulate
  - atoms in vacuum
  - optical or mech. gratings
  - small deflection angles
- Strong interactions with environment

$$\phi = \frac{t}{\hbar} \Delta E$$

- energy difference $\Delta E$
- interaction time $t$

# Applications

Can measure anything that changes energy of an atom:
- All kinds of EM fields (external or collisions)
- Gravity

Also inertial effects:
- Acceleration and rotation

Light also sensitive to inertial effects
but atoms more sensitive by $mc^2/\hbar\omega \sim 10^{10}$

# Applications

Can measure anything that changes energy of an atom:
- All kinds of EM fields (external or collisions)
- Gravity

Also inertial effects:
- Acceleration and rotation

Light also sensitive to inertial effects
but atoms more sensitive by $mc^2/\hbar\omega \sim 10^{10}$

Potential uses:

- Fine-structure constant
- Atomic properties
- Surface characterization
- Quantum light detection
- Magnetometry
- Inertial navigation
- Geophysics
- Oil exploration

Many already realized with thermal atom interferometers

# Condensates vs Hot Atoms

Hot atoms ~ light from a light bulb

Condensate atoms ~ light from a laser

| Hot atoms: | Condensate atoms: |
|---|---|
| • “White light” geometry | • Flexible geometry |
| • Low contrast | • High contrast |
| • Small deflection angles | • Arbitrary deflection angles |
| • Long device length | • Short device length |
| • Low flux ($10^9$/s) | • *Really* low flux ($10^5$/s) |

Flux could be a problem!

Compensate for low flux with long measurement time:

Measure $\phi = \frac{t}{\hbar}\Delta E$

Energy shift $\Delta E$
Measurement time $t$

Best-case noise: $\Delta\phi = \frac{1}{\sqrt{N}}$

Total atom number $N$

So $\Delta E = \frac{\hbar}{t\sqrt{N}}$

If $N_{\mathrm{BEC}} \sim 10^{-4} N_{\mathrm{thermal}}$, use $t_{\mathrm{BEC}} \sim 10^{2}\, t_{\mathrm{thermal}}$

$t_{\mathrm{thermal}}$ typically 1-10 ms, so want $t_{\mathrm{BEC}} \sim$ 0.1 - 1 s

# Making an interferometer

Need long time to make a good interferometer

Not so easy though…

First problem: need to make condensate

BEC happens when $\Lambda \approx \ell$

deBroglie wavelength ≈ interparticle spacing

In air: $\Lambda = 10^{-11}$ m, $\ell = 10^{-9}$ m

$\Lambda \sim T^{-1/2}$, so could cool air to 30 mK

- but gases freeze first

Need to use dilute gas to avoid making solid or liquid

$\Rightarrow$ Get much colder

# Making BEC

Use 87Rb atoms

Aim for $T$ ~ 100 nK, $n$ ~ $10^{13}$ $\text{cm}^{-3}$ (about $10^{-6}$ $n_{\text{air}}$)

Achieve with 3 steps:

1. Laser cooling
2. Magnetic trapping
3. Evaporative cooling

Discuss briefly

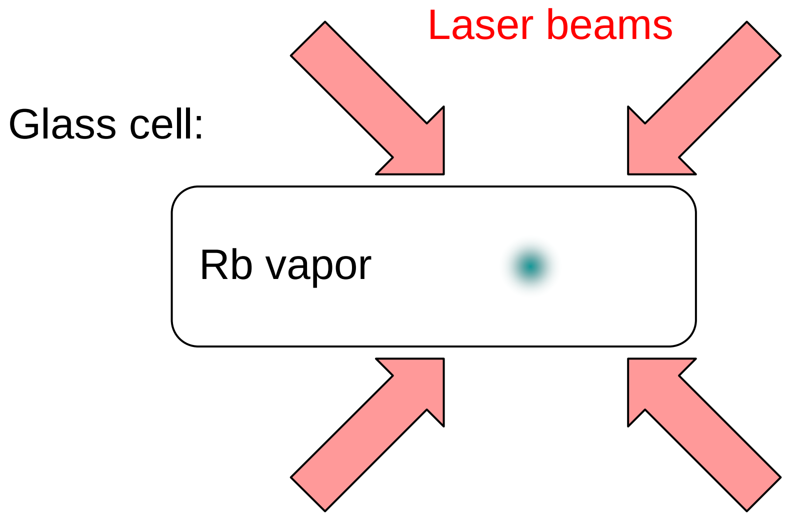
# Laser Cooling

Start with gas of rubidium atoms

Shine lasers from all directions
tuned below atomic resonance

Doppler shift:
- moving atoms scatter light from beam opposing motion

Atoms slow down = cool



Get sample of cold atoms:

$N \approx 4\times10^{9}$ atoms $T \approx 250\ \mu\text{K}$ $n \approx 3\times10^{11}\ \text{cm}^{-3}$

$n\Lambda^{3} \approx 5\times10^{-7}$ → Limited by opacity of cloud

# Magnetic Trap

Can’t get much colder or denser in laser trap

Hold instead with magnetic field $B$
How?

Rb atoms have one unpaired electron

Get energy shift in field due to magnetic moment
⇒ Zeeman effect: $U = 2\mu_{\mathrm{B}} B m_S$

$\mu_B$ = Bohr magneton = 58 μeV/T = 67 μK/G
$m_S$ = spin quantum number = ±½

For $m_S = +\frac{1}{2}$ state, have $U = \mu_B B$

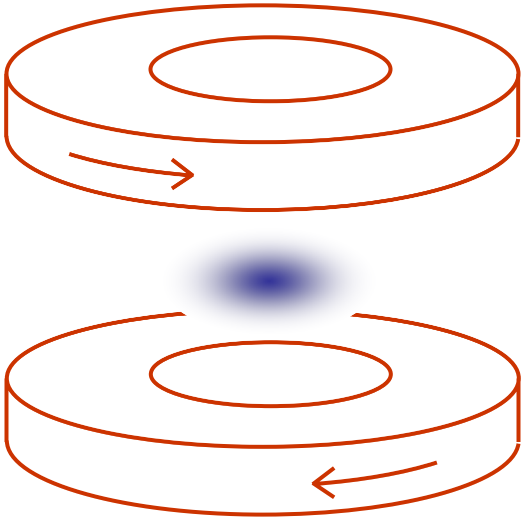
energy high when $B$ high
⇒ atom attracted to region of low $B$

So atoms trapped near minimum in $B$

Easy way to achieve: two opposed coils

Get $B = 0$ in center

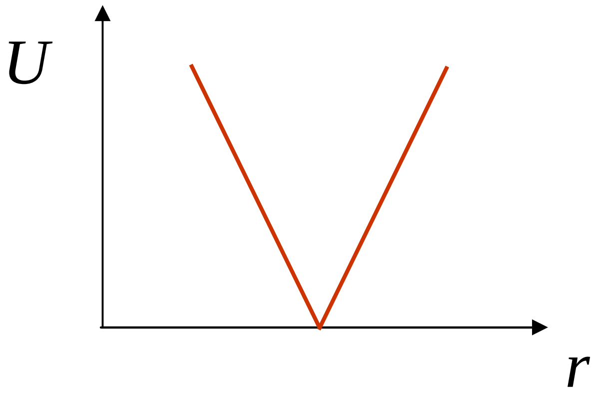
Can’t get lower than that!



Switch off lasers, turn on magnets

Good isolation from environment:

- Lifetime about 100 s
- Negligible heating



Gives linear potential

(We actually make it harmonic)

# Evaporative Cooling

How to get colder?
Take away hot atoms

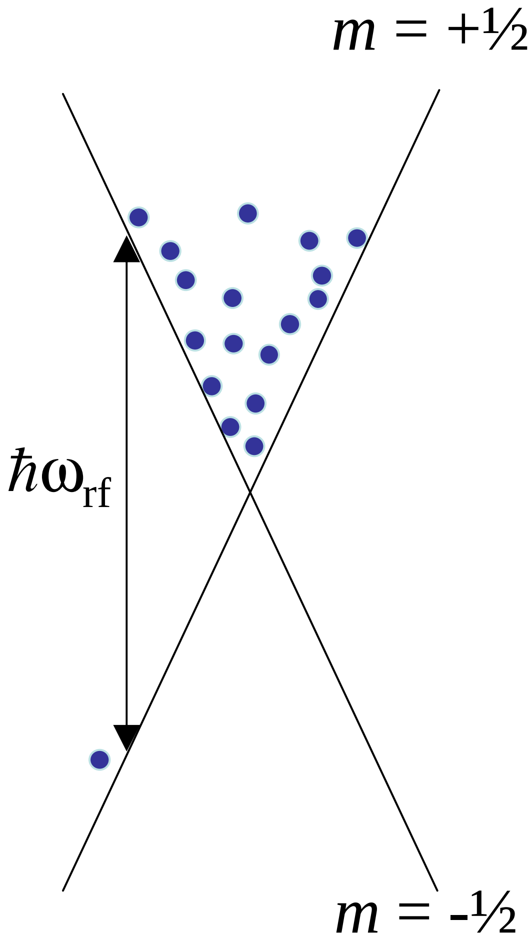
Drive transition $m = +½ \rightarrow -½$ using rf field

Only resonant if $\hbar\omega_{\mathrm{rf}} = 2\mu_{\mathrm{B}}B$

Tune $\omega_{\mathrm{rf}}$ above trap bottom:
only energetic atoms ejected

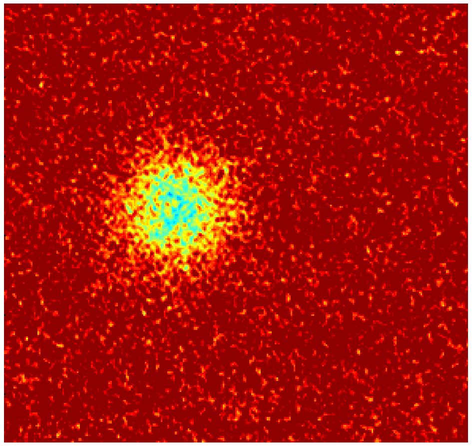
Take away more than average energy
- remaining atoms colder

Continue to BEC
$\rightarrow N \approx 2\times10^4$ atoms
$T \approx 200$ nK

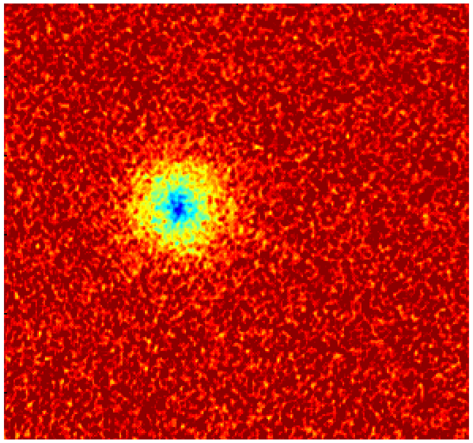


# Condensate Production

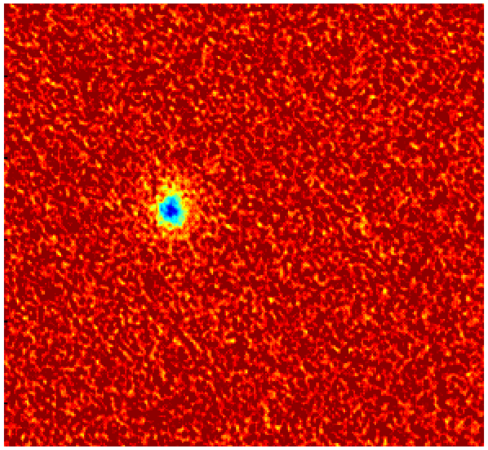
Just before condensation:
evaporate to 2.95MHz



Initiate condensate formation:
evaporate to 2.90MHz



Mostly condensate:
evaporate to 2.77MHz



Absorption images:
Shine laser on atoms, observe shadow

# Interferometry

So we get a condensate… yay!

Want to make an interferometer:

  Split wave function apart and later recombine

Hard to do in trap:

  - packets can’t move very far apart

But if we turn off trap, atoms fall in gravity

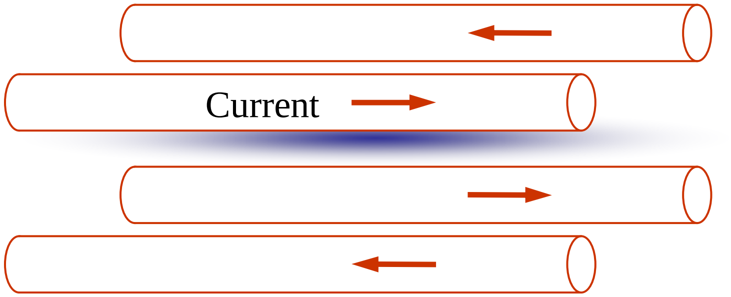
  - hard to deal with

Our solution: put atoms in magnetic waveguide

# Atom Guide

Two dimensional trap
- like optical fiber for atoms

Send atoms wherever we want

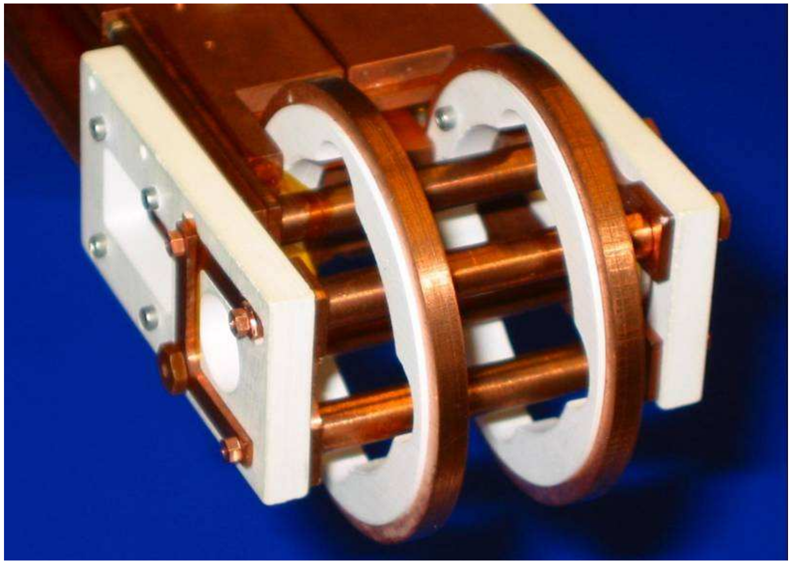


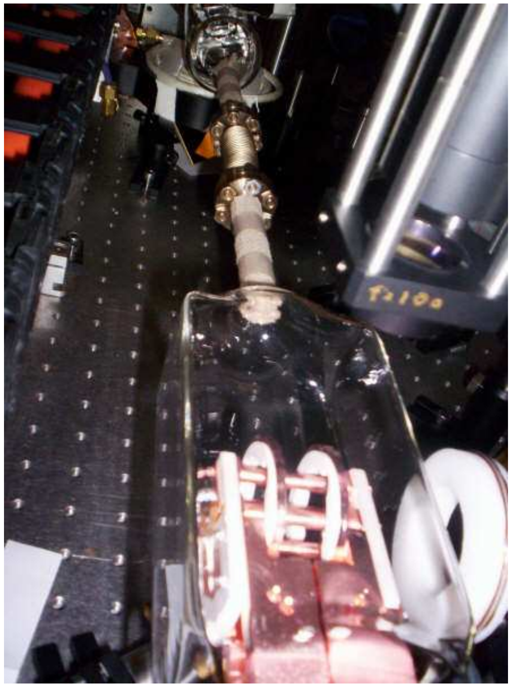
Basic design:
four wire, linear quadrupole

*Line* with $B = 0$ at center of rods
Confines atoms to axis

Again gives linear potential…
use tricks to make harmonic

# Waveguide Construction





Copper rods provide fields
Rod spacing ~ 1 cm

(all inside vacuum chamber at $P \sim 10^{-11}$ torr)

# Loading Guide

- BEC formed in center of guide

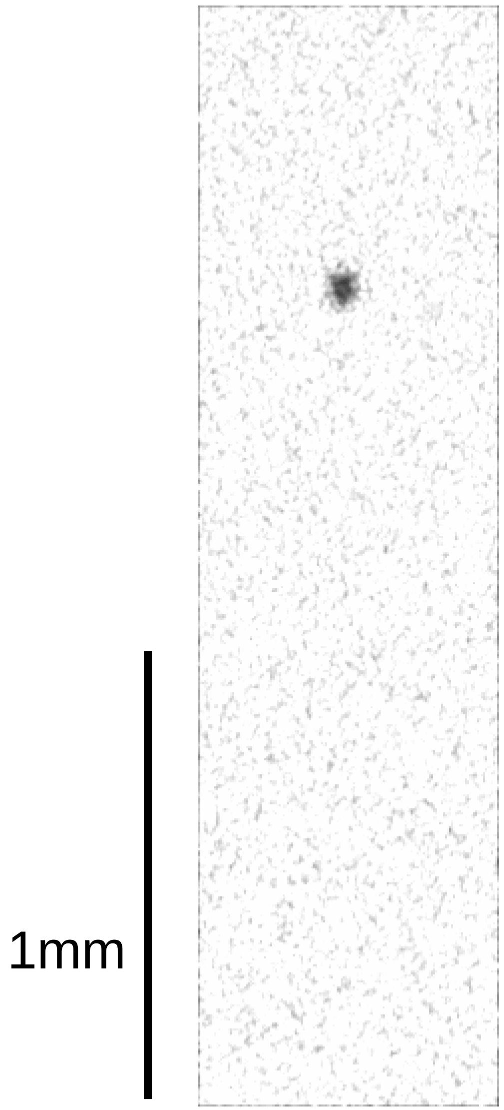
- Gradually decrease 3D trap,
  Increase linear quadrupole

Get adiabatic transfer to guide
no losses observed

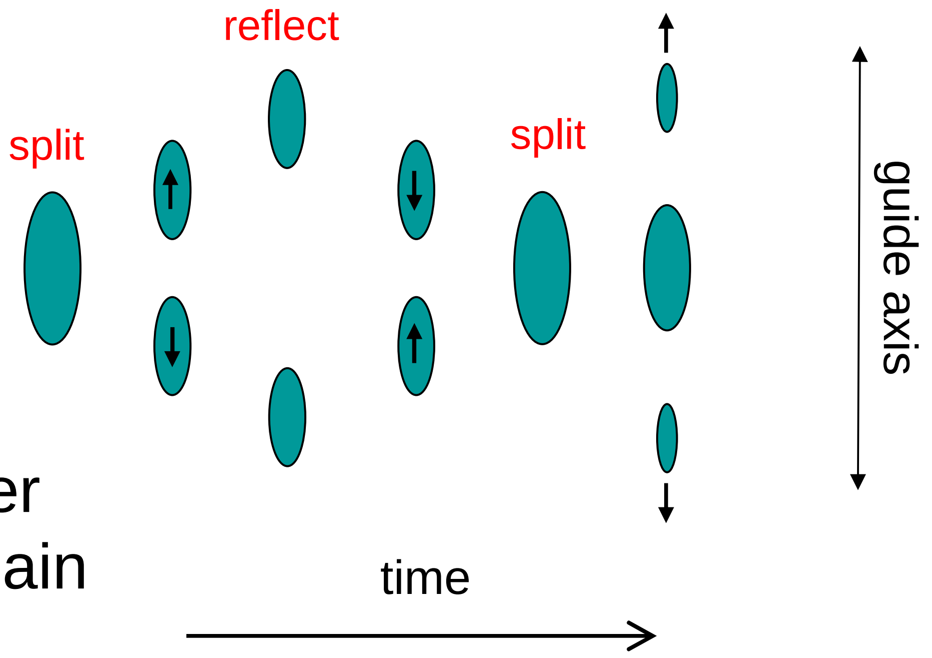
Linear trap is very weak

Residual confinement from leads:
$\omega/2\pi \sim 1$ Hz

Adiabatic expansion:
Cool to below 1 nK



# Interferometry



Basic scheme:

- Split into two packets
- Packets fly apart
- Turn around via reflection
- Packets come back together
- Apply splitting operation again

Quantum operations are reversible:

- If $\psi$ unchanged, atoms brought back to rest

But if packets have phase shift, $\psi$ is *not* the same

- Atoms keep moving

Probability to come to rest ~ $\cos^2\phi$

Mathematically: split operator $U_S$

$$U_S\left|0\right\rangle = \frac{1}{\sqrt{2}}\left(\left|+v_0\right\rangle + \left|-v_0\right\rangle\right) \equiv \left|+\right\rangle$$

Where $\left|0\right\rangle$ = atoms at rest

$\left|\pm v_0\right\rangle$ = atoms moving at ±$v_0$

$v_0$ = velocity imparted by splitting

Then $U_S\left|+\right\rangle = \left|0\right\rangle$

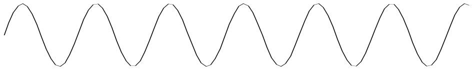
and $$U_S\frac{1}{\sqrt{2}}\left(\left|+v_0\right\rangle + e^{i\phi}\left|-v_0\right\rangle\right)$$

$$= \cos\phi\left|0\right\rangle + \frac{\sin\phi}{\sqrt{2}}\left(\left|+v_0\right\rangle - \left|-v_0\right\rangle\right)$$

So get $\phi$ by measuring number of atoms at rest $N_0$

# Splitting

Implement with standing wave laser beam

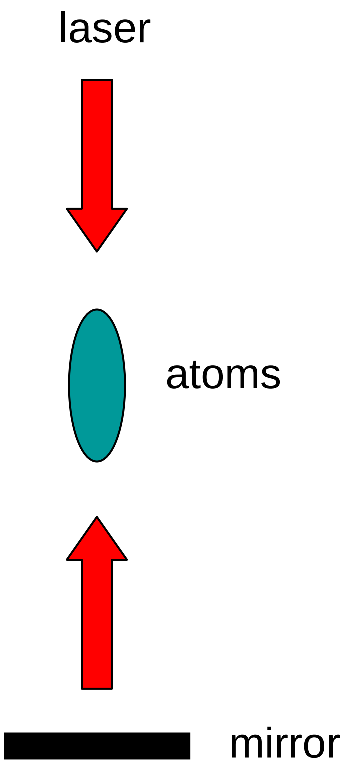
Intensity: 

Laser tuned far from resonance
- no absorption

But do get energy shift ~ intensity

$$V_{\text{laser}} = \beta \cos^2(kz)$$

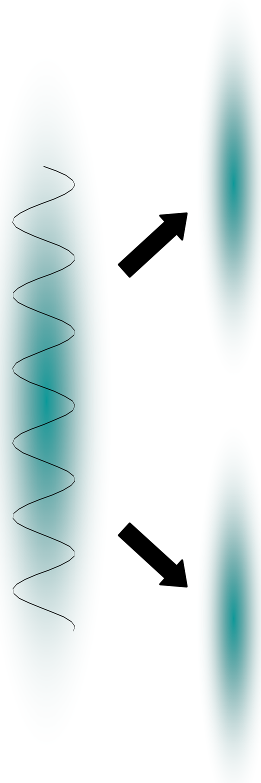
(atoms are dielectrics: field induces dipole moment $p \propto E$, get energy $pE \propto E^2$)



# Two pictures:

1) Atom wave diffracts from light potential
just like light diffracts from grating

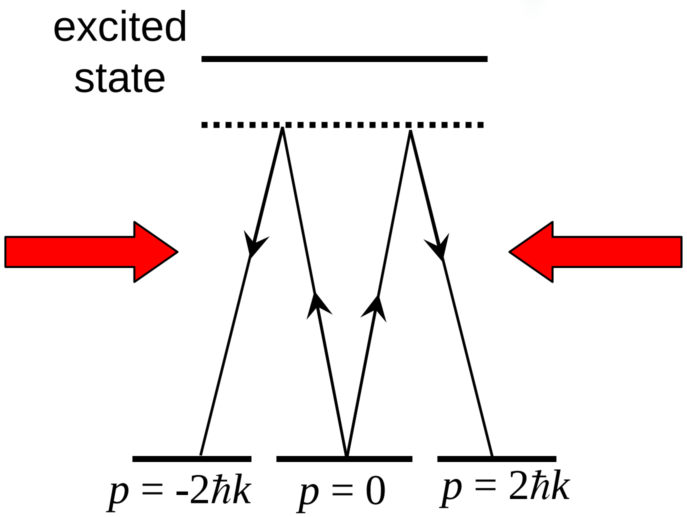
±1 diffraction orders
move at $v_0 = 2\hbar k/M$ = 1.2 cm/s



2) Atoms absorb photon from
one beam, emit into other

Net momentum transfer $2\hbar k$

Reverse process gives $-2\hbar k$

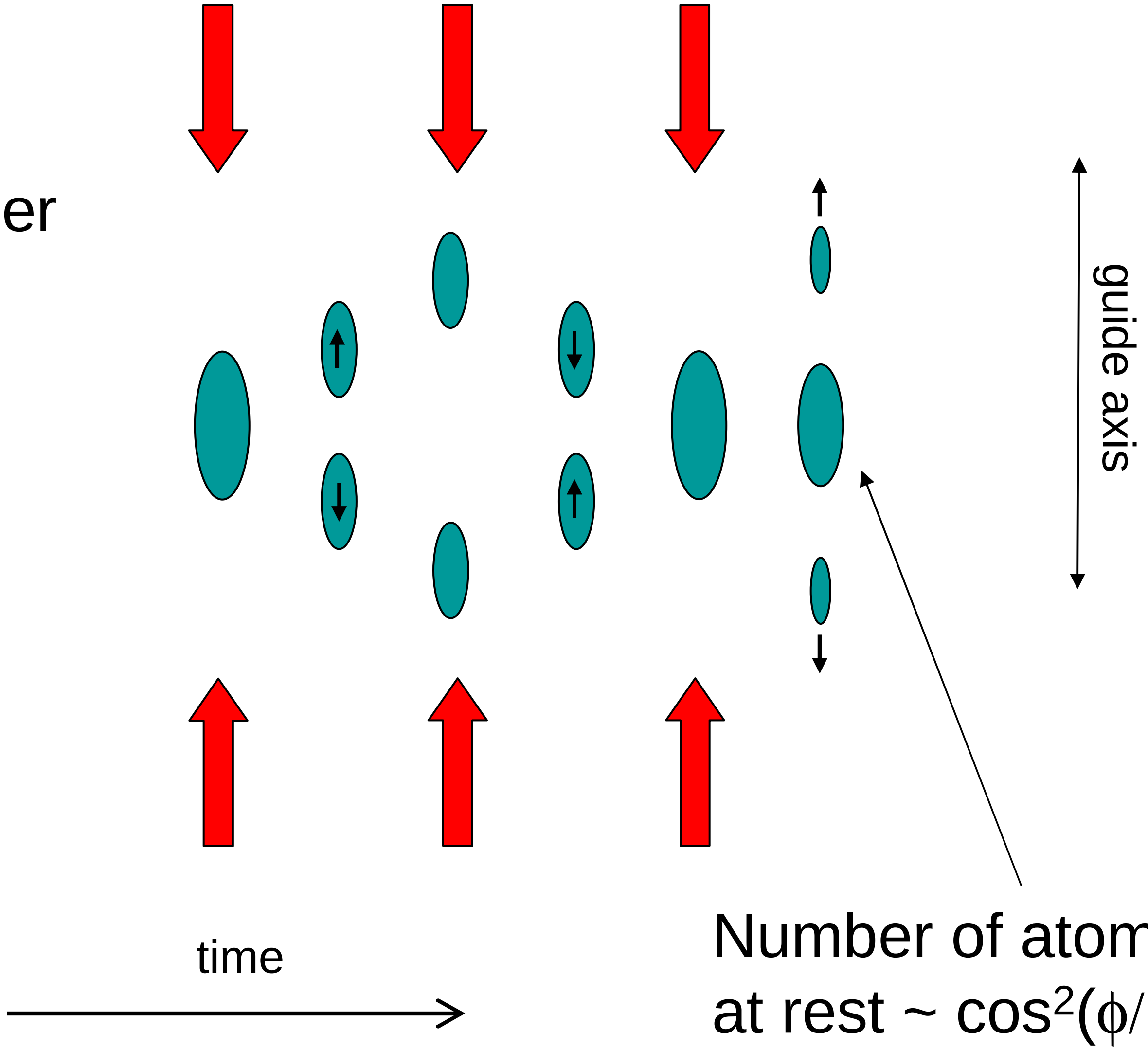


# Interferometry Experiment:

Standing wave laser
- splits
- reverses
- recombines

wave packets

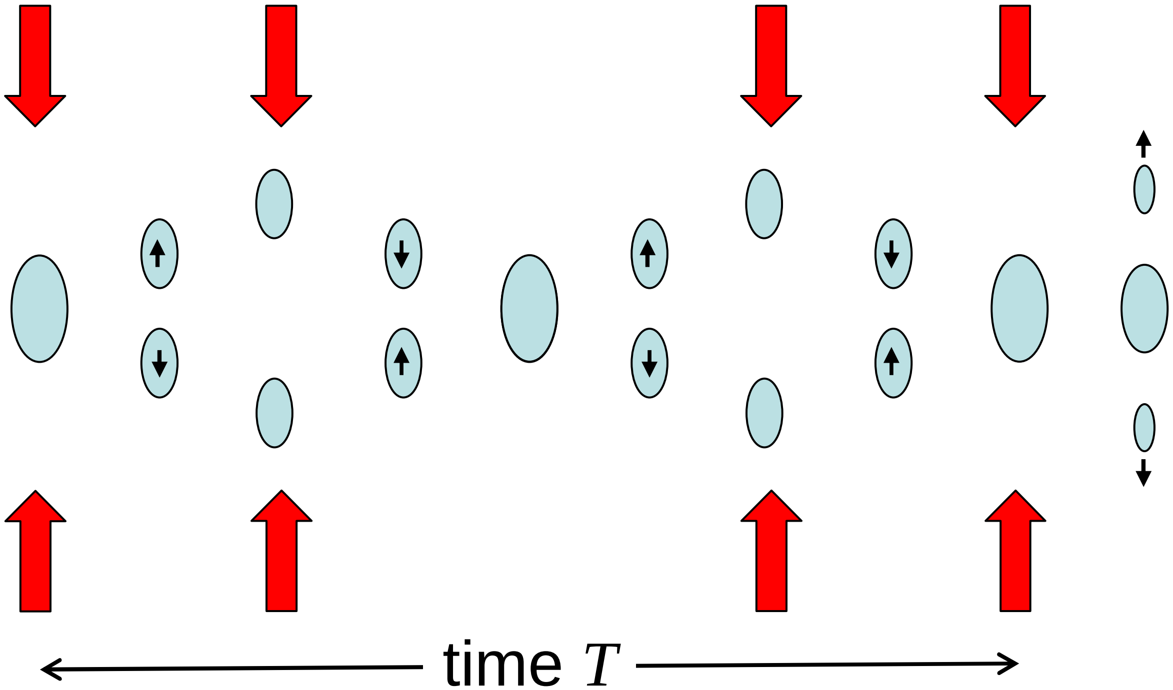
Measure number
that end up at rest



Number of atoms
at rest ~ $\cos^2(\phi/2)$

# Four Pulse Interferometer:

Works better if atoms make full oscillation:

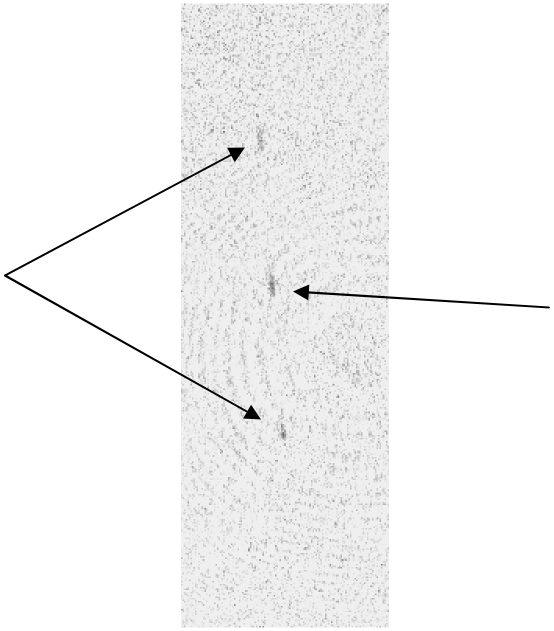


Gradients across trap cancel out

# Measurement

Measure $N_0/N$ = fraction of atoms ending at rest

Let moving atoms propagate, then take picture:

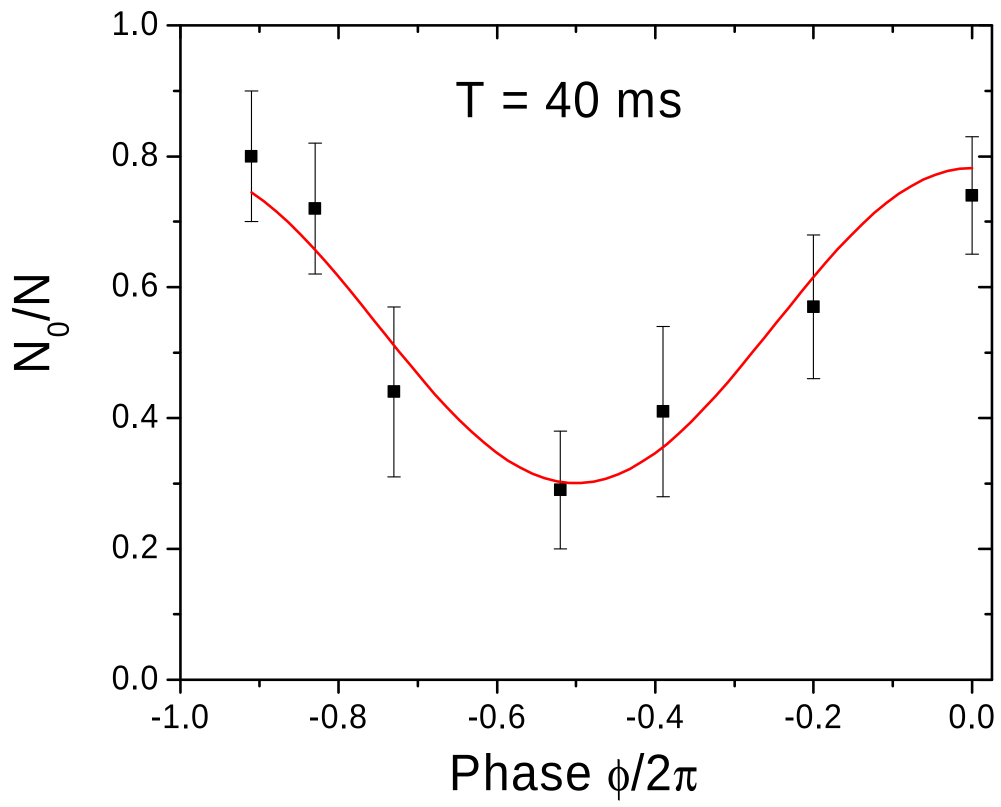


Atoms moving

Atoms at rest, $N_0$

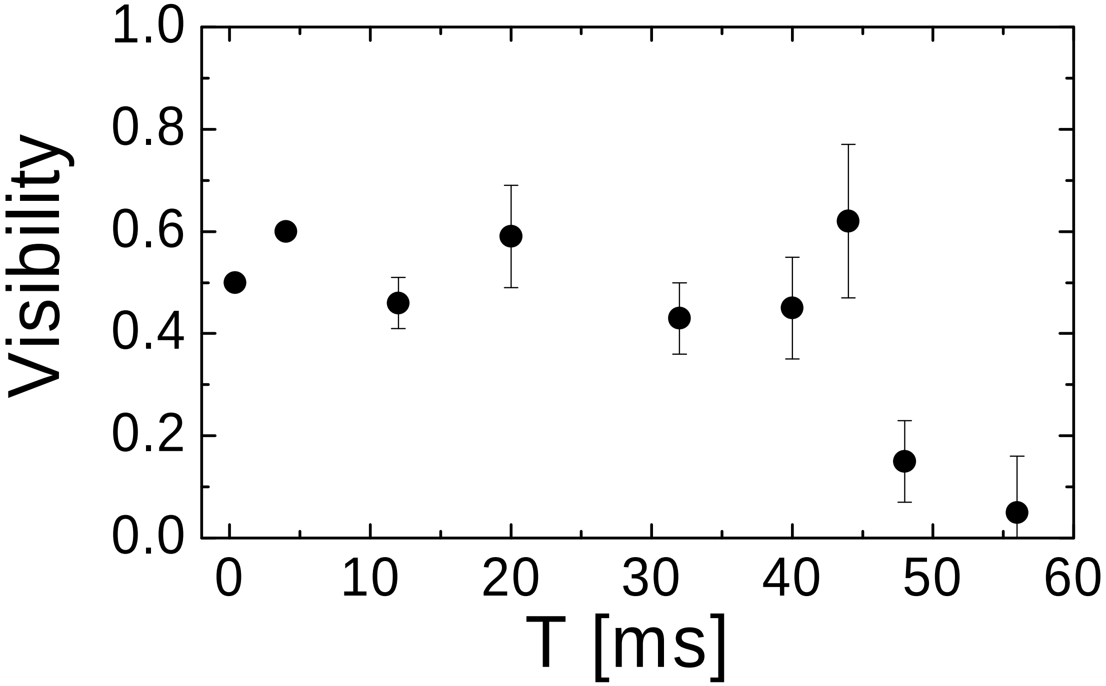
# Results

Clear interference for $T$ up to 44 ms



Adjust $\phi$ by shifting phase of standing wave pattern

# Visibility vs. Interference Time



Actually get good contrast all the time:

$N_0/N$ varies between 0 and 1

But it fluctuates from run to run

# How does this compare?

Similar experiment demonstrated at Univ. Colorado:

Wang et al., *Phys. Rev. Lett*. **94**, 090405 (2005)

Coherence time limited to 10 ms

Other BEC methods encounter similar limits:

| | |
|---|---|
| Gupta et al., *Phys. Rev. Lett* **89**, 140401 (2002) | ~ 6 ms |
| Shin et al., *Phys. Rev. Lett*. **92**, 050405 (2004) | ~ 5 ms |
| Saba et al. *Science* **307**, 1945 (2005) | ~ 1 ms |

Measurement sensitivity typically scales as $T^2$:

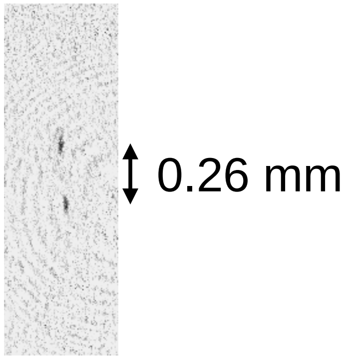
- factor of 20 improvement

(Non-BEC interferometers have $T$ up to 400 ms)

# Arm Separation

Atoms separate for time $T/4$ = 11 ms

Picture of split packets:



Atoms clearly separated

Never seen before in atom interferometry:
  Best previous separation ~ 10 μm
  (small compared to width of packets)

Large separation useful for putting different arms in different environments

Also, neat to make macroscopic quantum states

# Difficulties

Interference limited by many effects:

- Environmental B fields
- Trap field fluctuations
- Mechanical vibrations
- Stability of laser
- Transverse motional excitations
- Atomic interactions

JILA experiment: interactions were main problem

Olshanii and Dunjko, cond-mat/0505358

# Interactions

Atom in BEC repel each other

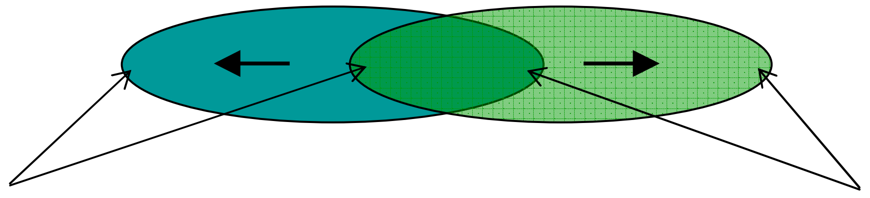
JILA experiment:

$N \approx$ 5000 atoms

$\omega_\perp \approx 2\pi\times100$ Hz

$\omega_z \approx 2\pi\times5$ Hz

Interaction energy ≈ 160 Hz/atom (~3 rad in 3 ms sep. time)



Extra phase for green

Extra phase for blue

Position dependent phase degrades contrast

Our solution: use lower density

$N \approx 5000$ atoms

$\omega_{\perp} \approx 2\pi \times 4$ Hz

$\omega_z \approx 2\pi \times 1$ Hz

Interaction energy ≈ 10 Hz/atom

reduces separation phase to ~ 0.2 rad

We developed special techniques for weak confinement

- seems to work

# Trap vibration

Think our problem is vibration of trap structure

Atoms see axial harmonic potential, $\omega/2\pi$ = 1 Hz
    (due to fields from current leads)

While atoms moving, trap moves too
    phase shift from field doesn’t cancel perfectly

Fix with better vibration isolation and measurement
    Or fix trap potential to be flatter

Aim to improve to $T$ = 1 s

# Prospects

With 1 s interaction time

$10^5$ atoms/s

$\Delta\phi = N^{-1/2}$ (not easy)

Could measure (in 1 s):

- gravity $\Delta g/g \sim 10^{-10}$
  compare $10^{-7}$
- rotation $\Delta\Omega \sim 10^{-8}$ rad/s
  compare $10^{-9}$ rad/s

Our next step:

measure electric polarizability ~ precision $10^{-3}$ or better

Compare $10^{-2}$

# Conclusions

Condensate interferometry has good prospects for precision measurements

Demonstrated 40 ms coherence time:
- longest ever for BEC

and large arm separation
- biggest for any atom interferometer

Hope to stabilize vibrations and get even better

# Group members

Funding: NSF, ONR

# TOP Trap

As atoms move, **B** changes directions

  Atomic spins follow adiabatically

  $\Rightarrow$ stay in $m = +\frac{1}{2}$ state

But one problem:

  Atoms passing through $B = 0$ have nothing to follow

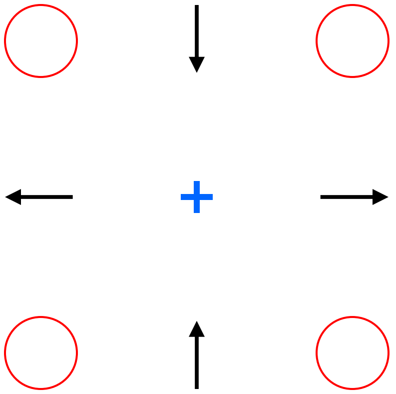
  Can change state: "Majorana transition"

If $m \rightarrow -\frac{1}{2}$, atom expelled from trap!

# TOP trap

We solve by applying rotating bias field

Static bias shifts zero off axis:



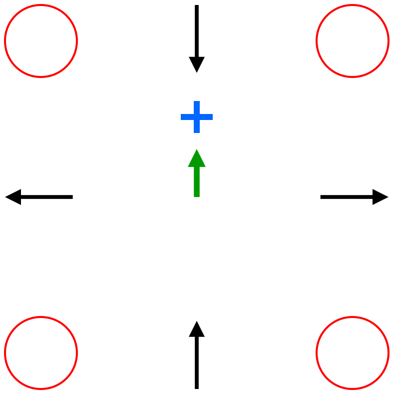
quadrupole field

zero

# TOP trap

We solve by applying rotating bias field

Static bias shifts zero off axis:



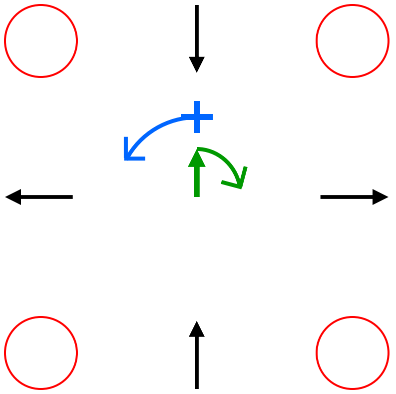
quadrupole field
zero
bias field

Doesn’t really help

# TOP trap

Make bias field rotate quickly:

Too fast for atoms to follow



quadrupole field

zero

bias field

Atoms see time-average potential:

minimum at center

Makes good trap: atoms held in guide