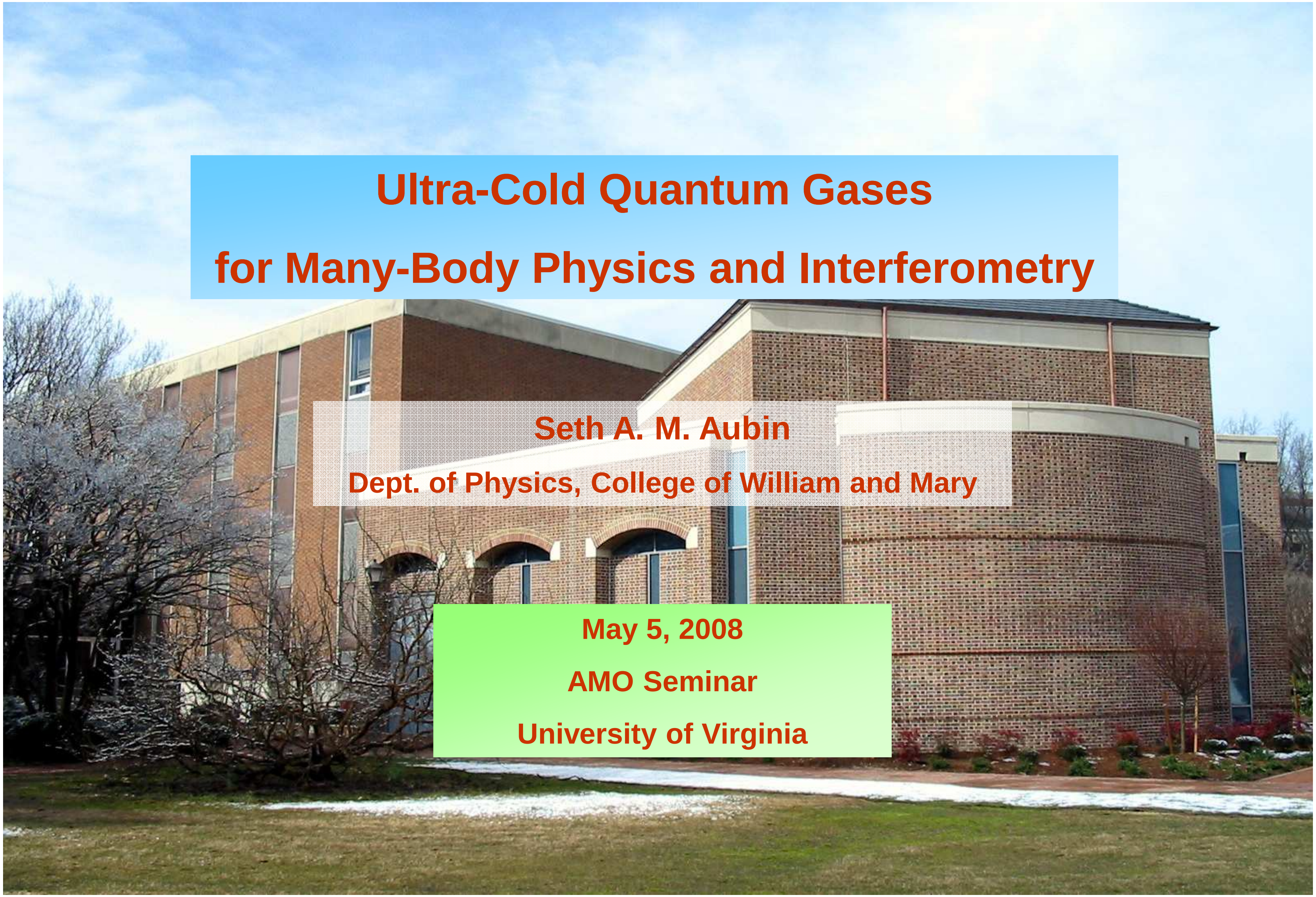


Ultra-Cold Quantum Gases

for Many-Body Physics and Interferometry

Seth A. M. Aubin

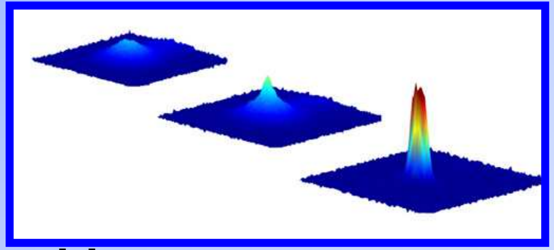
Dept. of Physics, College of William and Mary

May 5, 2008

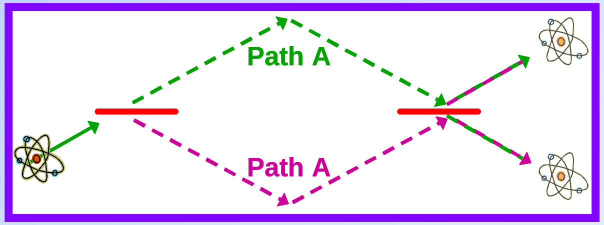
AMO Seminar

University of Virginia

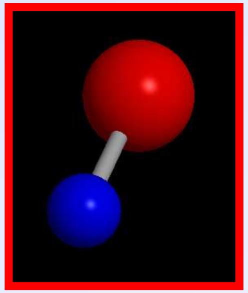
Outline



- Ultra-cold Matter Apparatus
  - → **Apparatus v1.0: The Thywissen U. of T. machine.**
  - → **Apparatus v2.0: The W&M machine.**

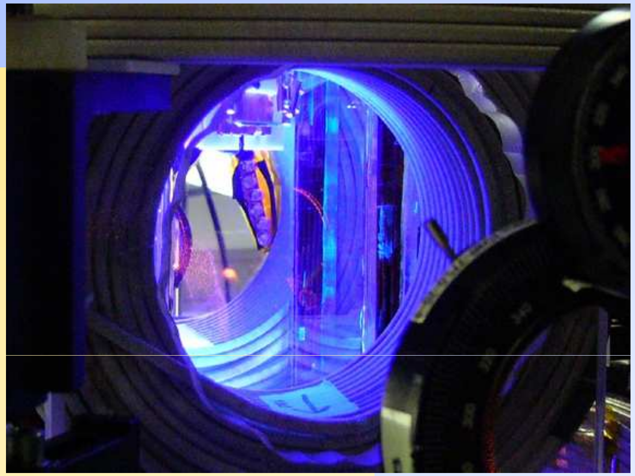


- Future physics plans
  - → **Near term: Fermion interferometry.**
  - → **Longer term: Ultra-cold molecules.**
    - ♦ **Superfluid polar molecules**

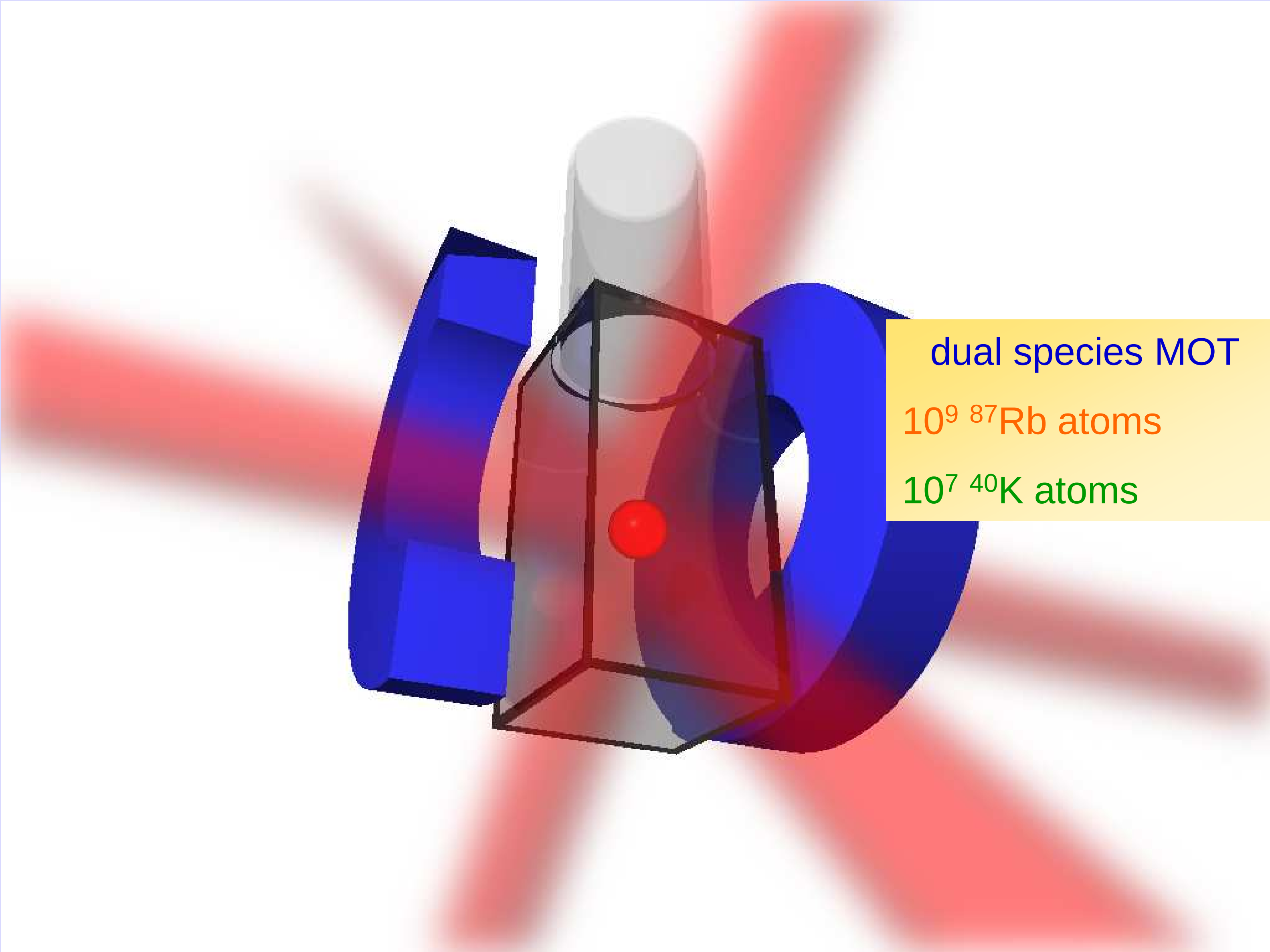


Thywissen Lab BEC-DFG machine

@ U. of Toronto



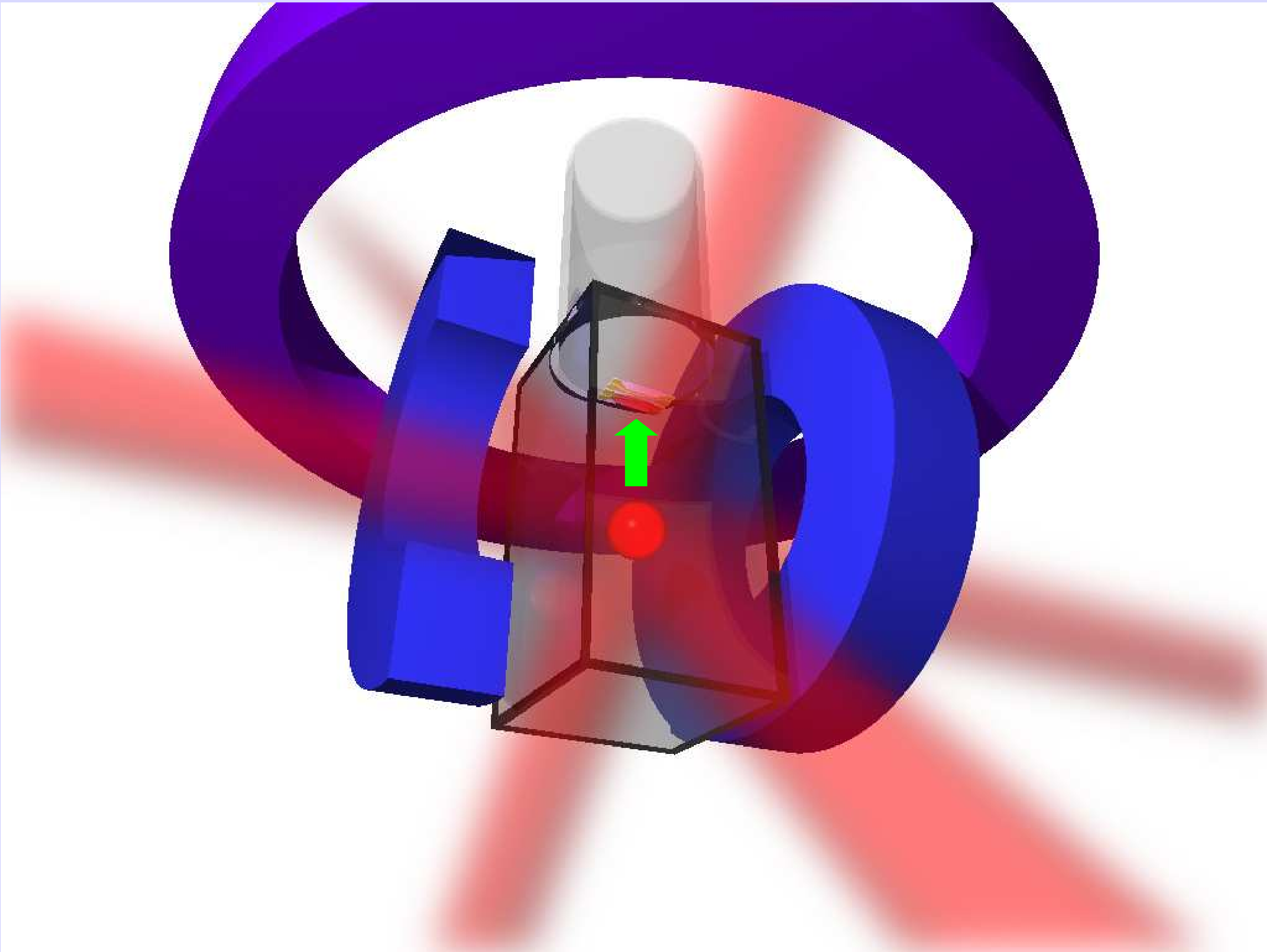
- Produces a BEC of ^{87}Rb and DFG of ^{40}K.
- Atom chip technology.
- Cycle time: 5-10 s for BEC, 20-40 s for DFG.
- $N_{BEC} = 10^4$-10^5, $N_{DFG} = 4 \times 10^4$.
- Simple design:
  - Conventional dual species MOT
  - Single vacuum chamber
  - Atom chip micro-magnetic trap
  - RF evaporation for ^{87}Rb.
  - Sympathetic cooling of ^{40}K with ^{87}Rb.

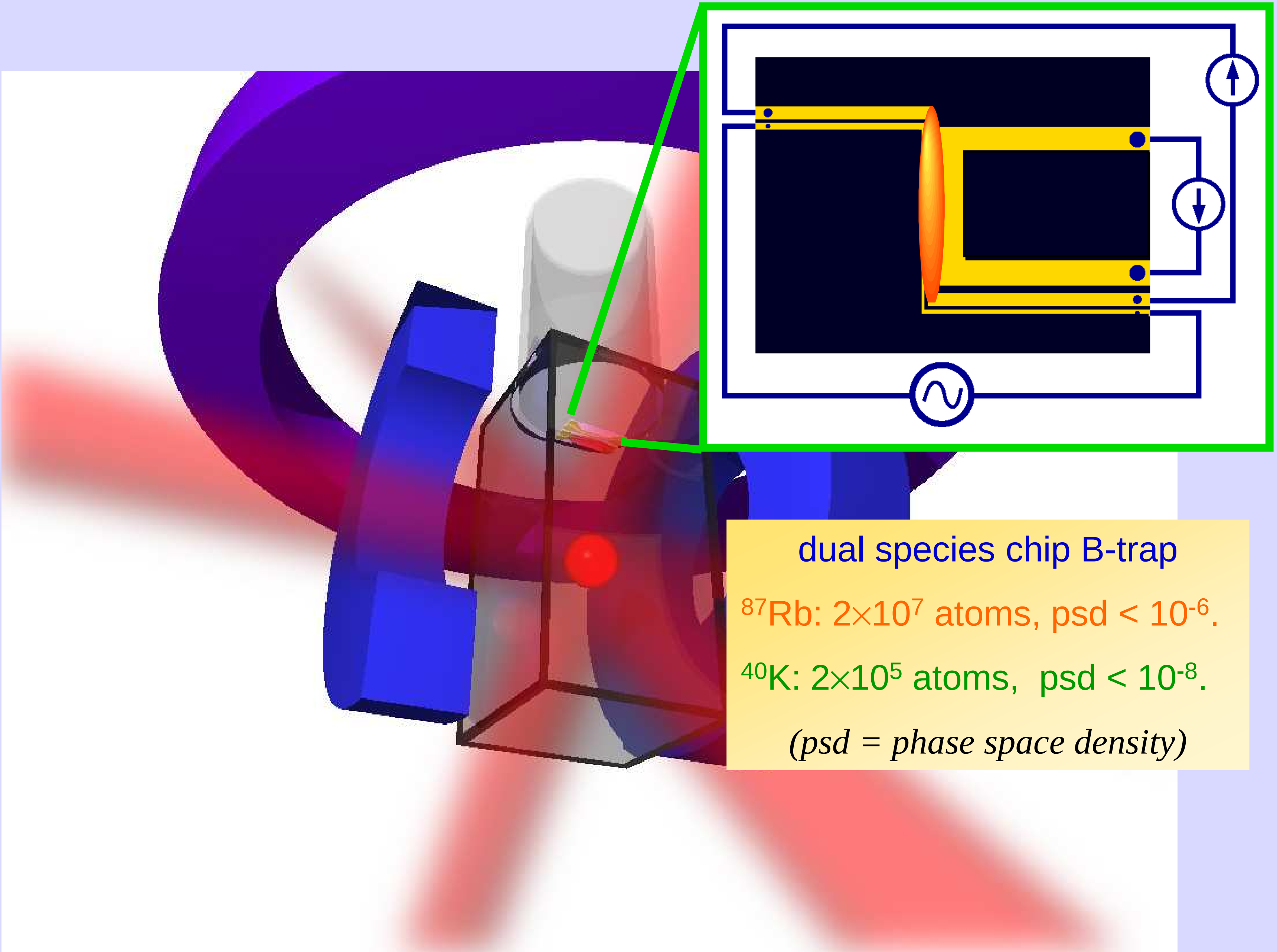


dual species MOT

10^9 ^{87}Rb atoms

10^7 ^{40}K atoms





dual species chip B-trap

^{87}Rb: 2×10^{7} atoms, psd $< 10^{-6}$.

^{40}K: 2×10^{5} atoms, psd $< 10^{-8}$.

(psd = phase space density)

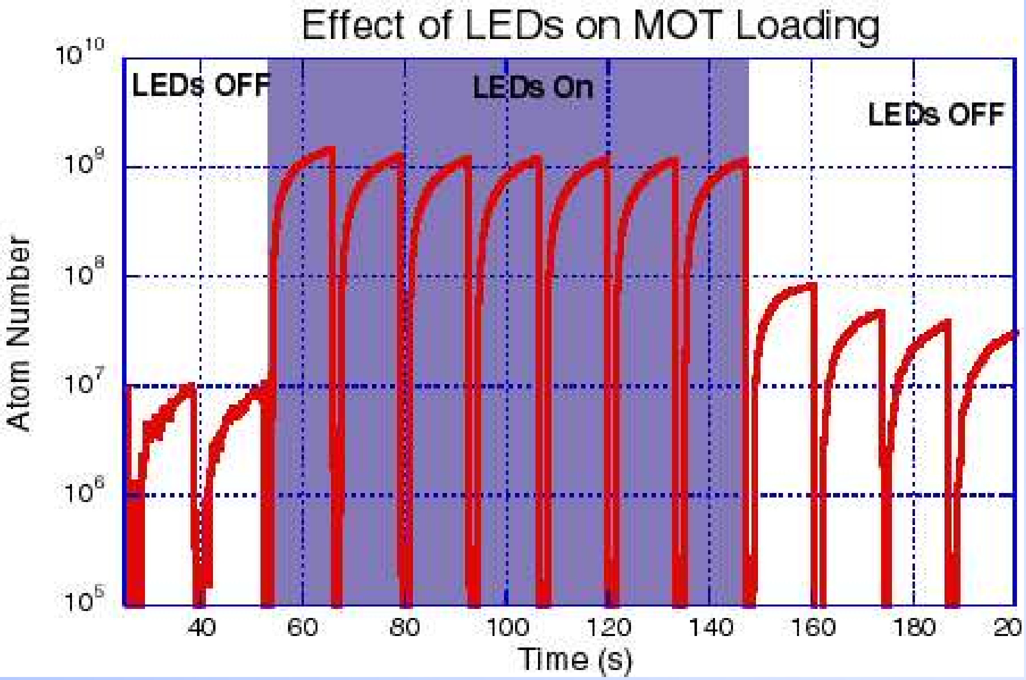
Light-Induced Atom Desorption (LIAD)

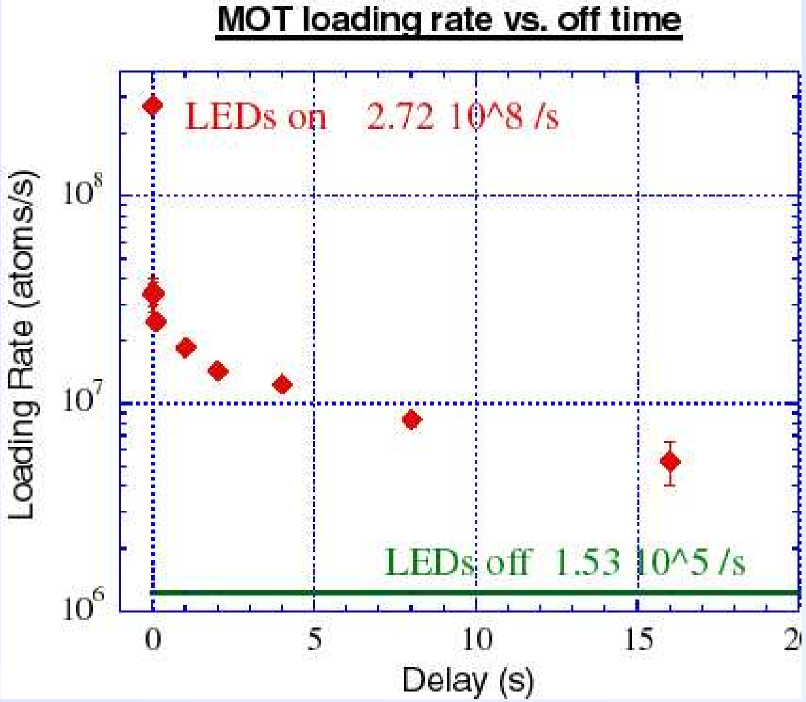
Conflicting pressure requirements:

- Large Alkali partial pressure → large MOT.
- UHV vacuum → long magnetic trap lifetime.

Solution: Use LIAD to control pressure <u>dynamically</u> !

→ 405nm LEDs (power=600 mW) in a pyrex cell.

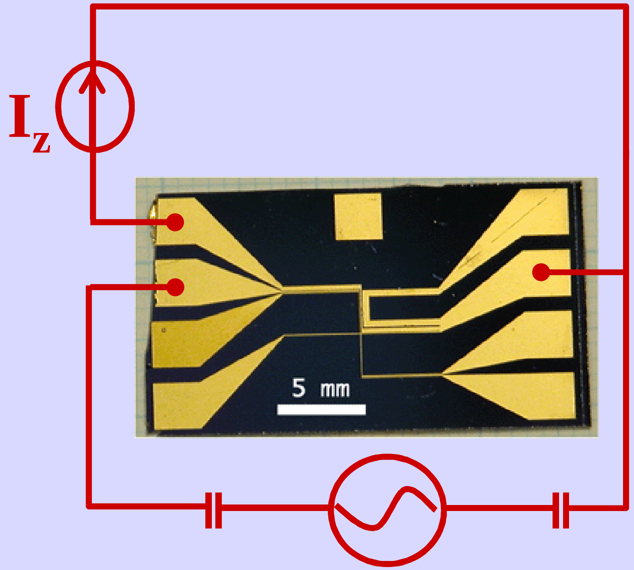


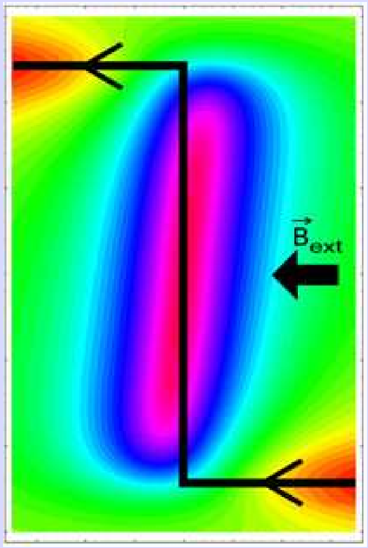


Micro-magnetic Traps

Advantages of "atom" chips:

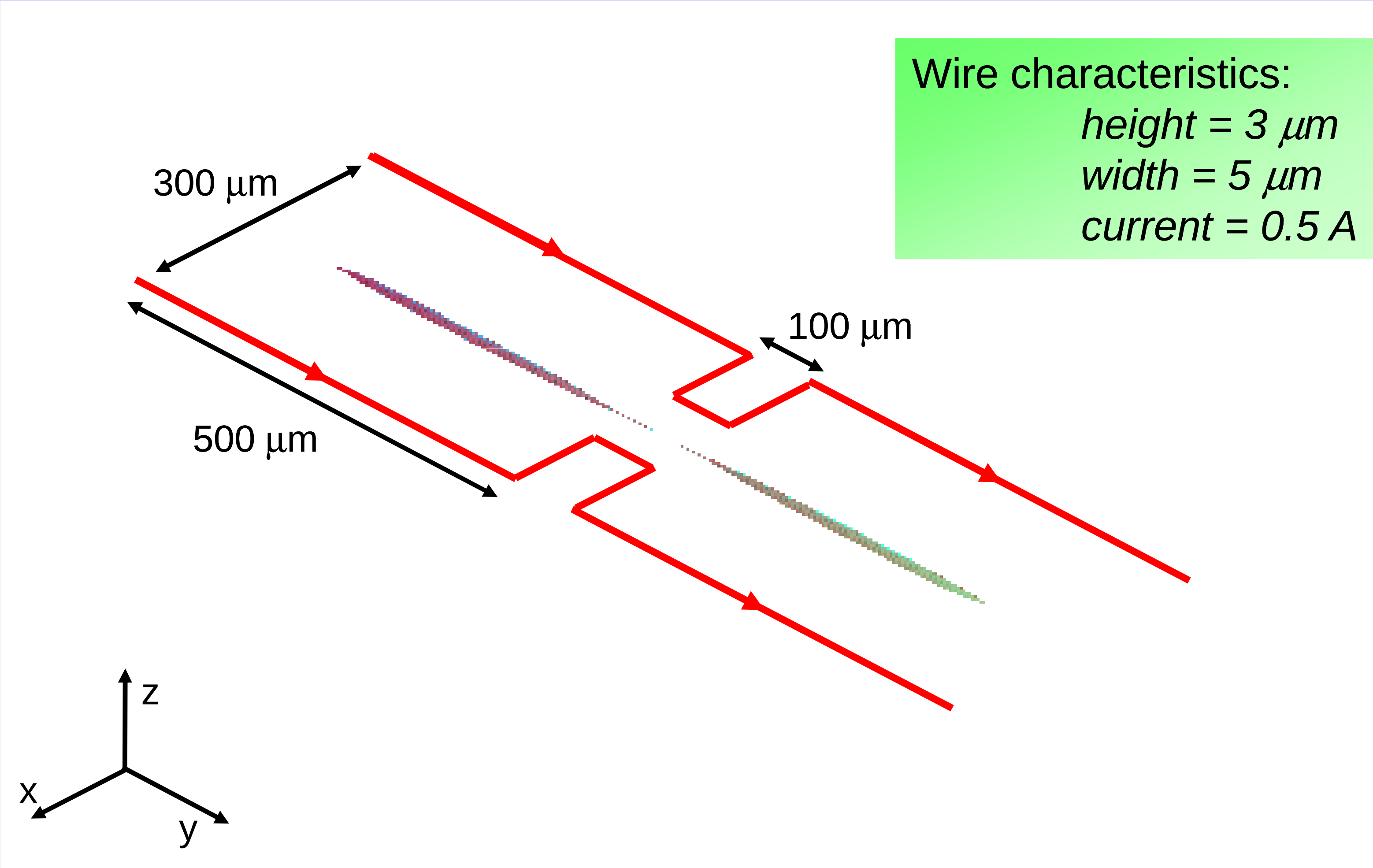
- Very **tight confinement**.
- **Fast evaporation** time.
- photo-lithographic production.
- Integration of complex trapping potentials.
- Integration of RF, microwave and optical elements.
- Reduced vacuum requirement.





A More Complicated Trapping Geometry

2 reservoirs coupled by a quasi-1D "quantum wire"



A More Complicated Trapping Geometry

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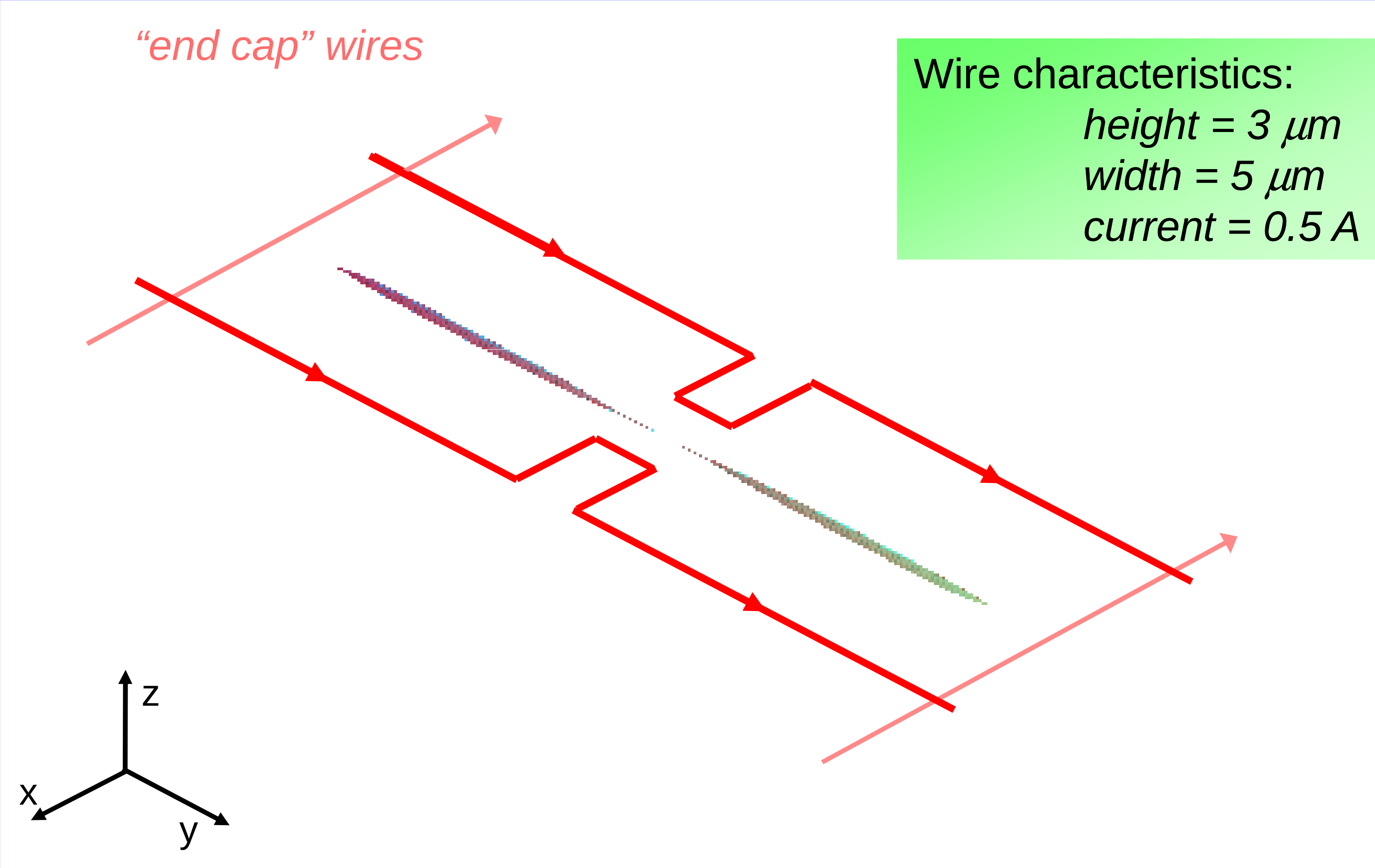
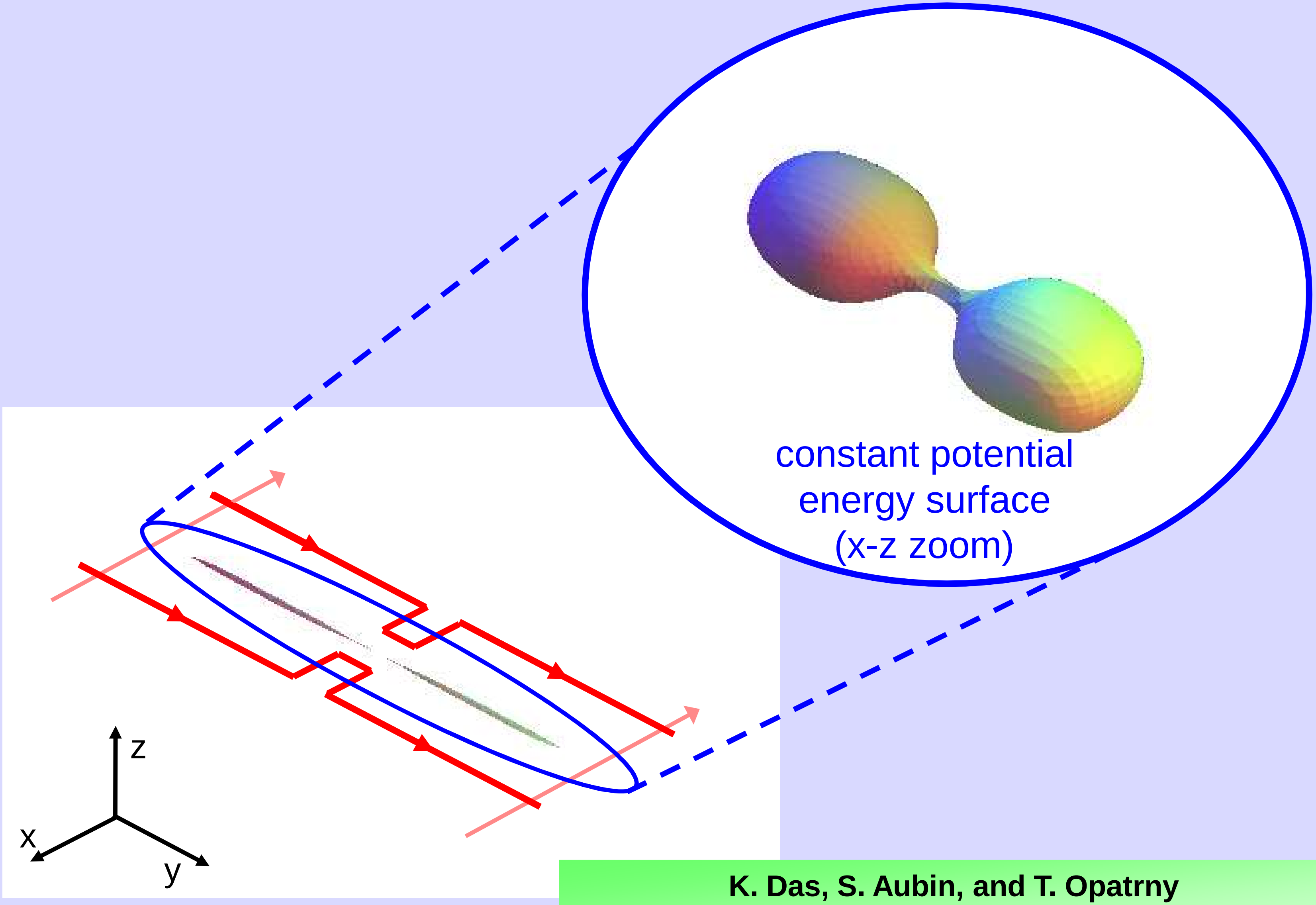


A More Complicated Trapping Geometry



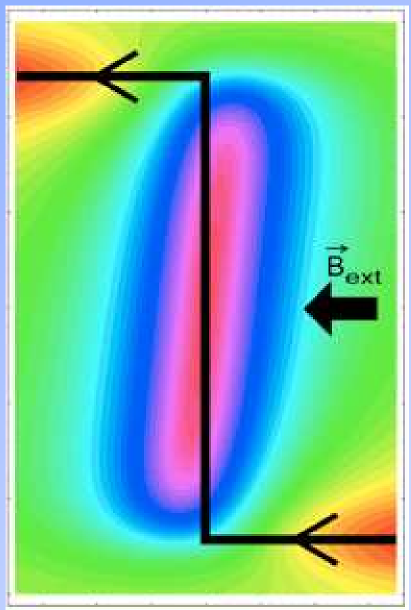
K. Das, S. Aubin, and T. Opatrny
Quantum pumping with ultracold atoms (in writing)

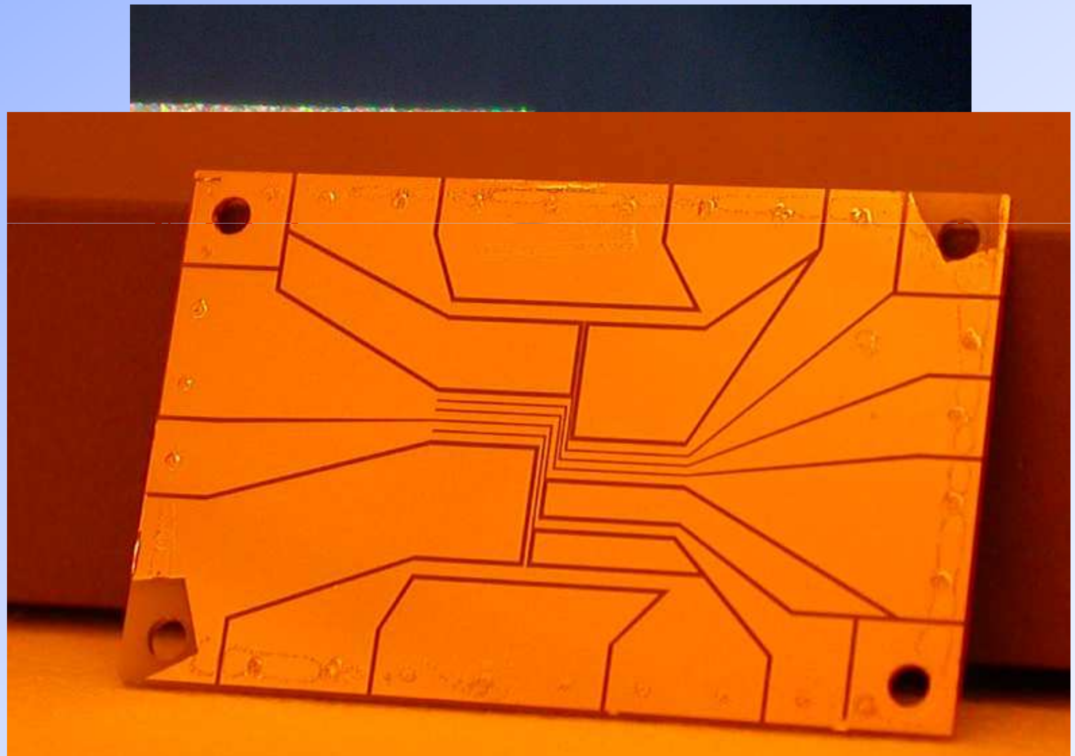
Micro-Magnetic Trap Difficulties

Technology:

- Electroplated gold wires on a silicon substrate.
- Manufactured by J. Estève (Aspect/Orsay).

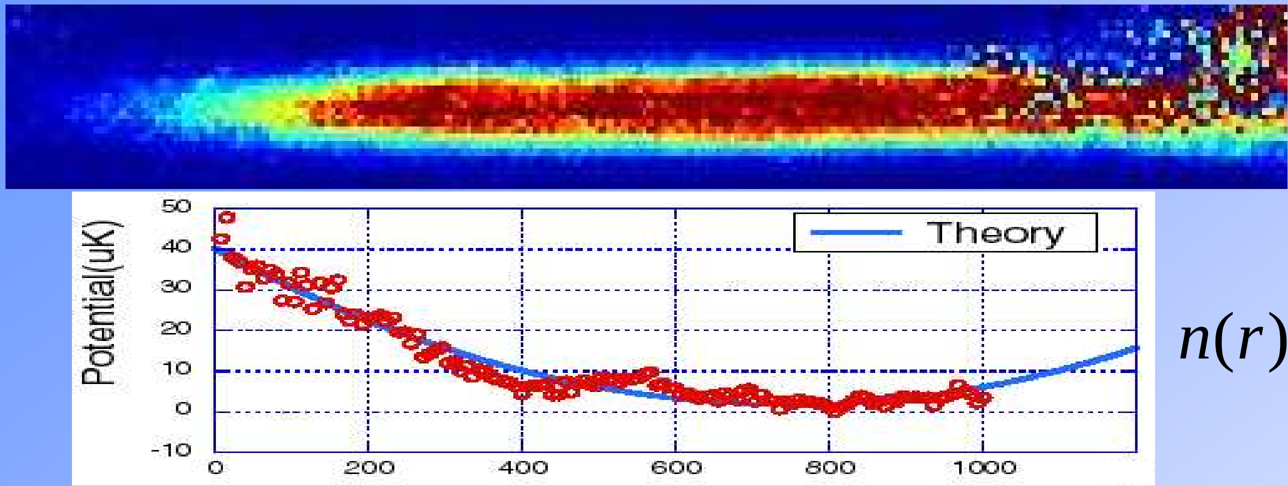
Trap Potential: Z-wire trap





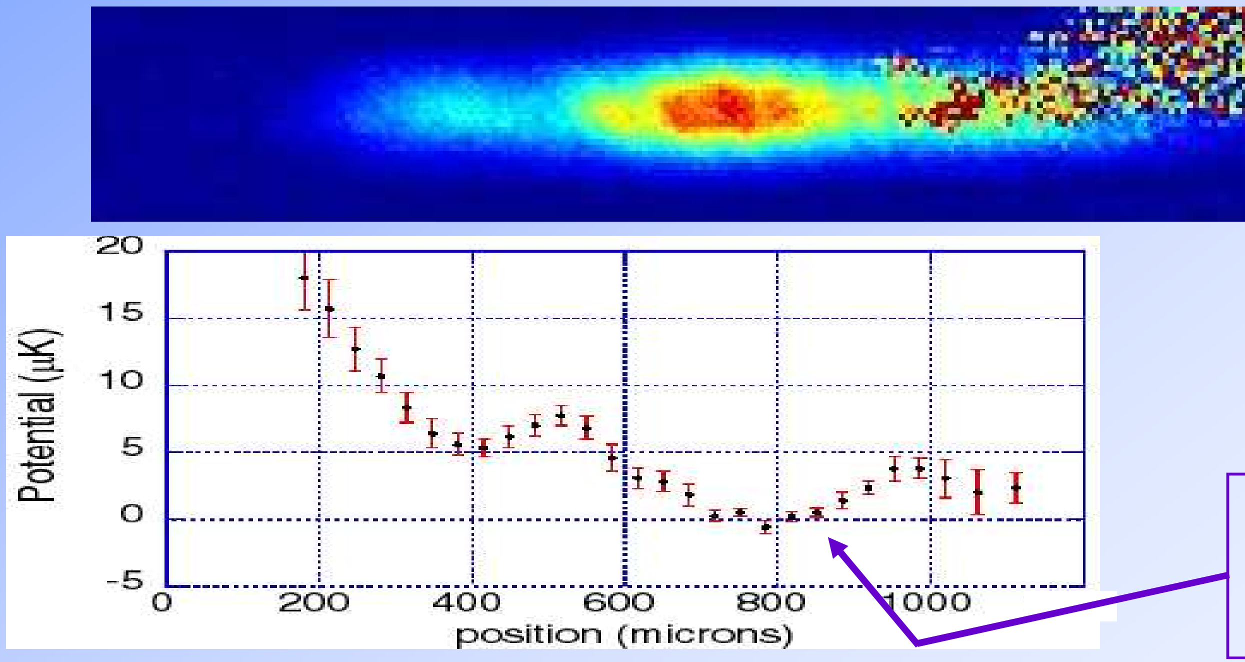
Evaporated *Ag* and *Au* (B. Cieslak and S. Myrskog)

Magnetic Dimple Trap: Extra Compression



T=19 μK

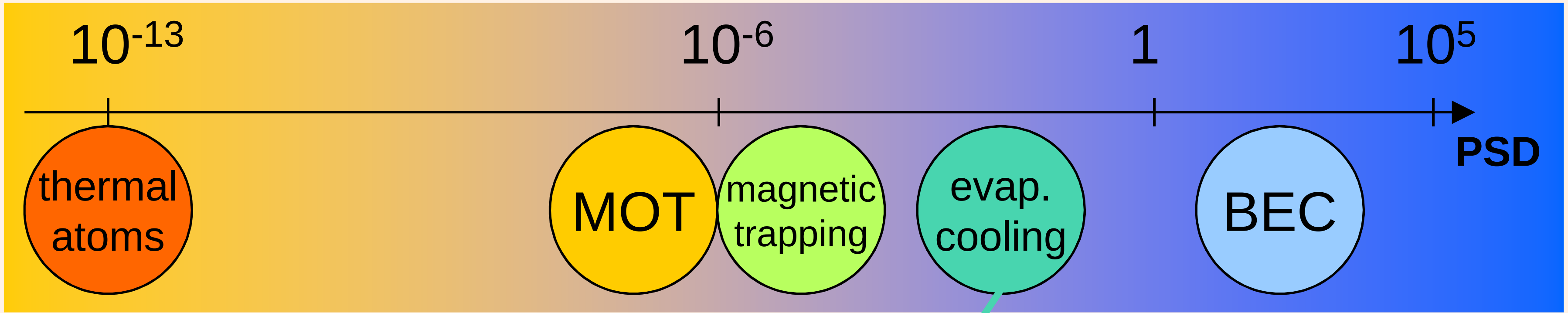
$$n(r) \approx \frac{1}{\Lambda^3} \exp\left(-U(r)/kT\right)$$

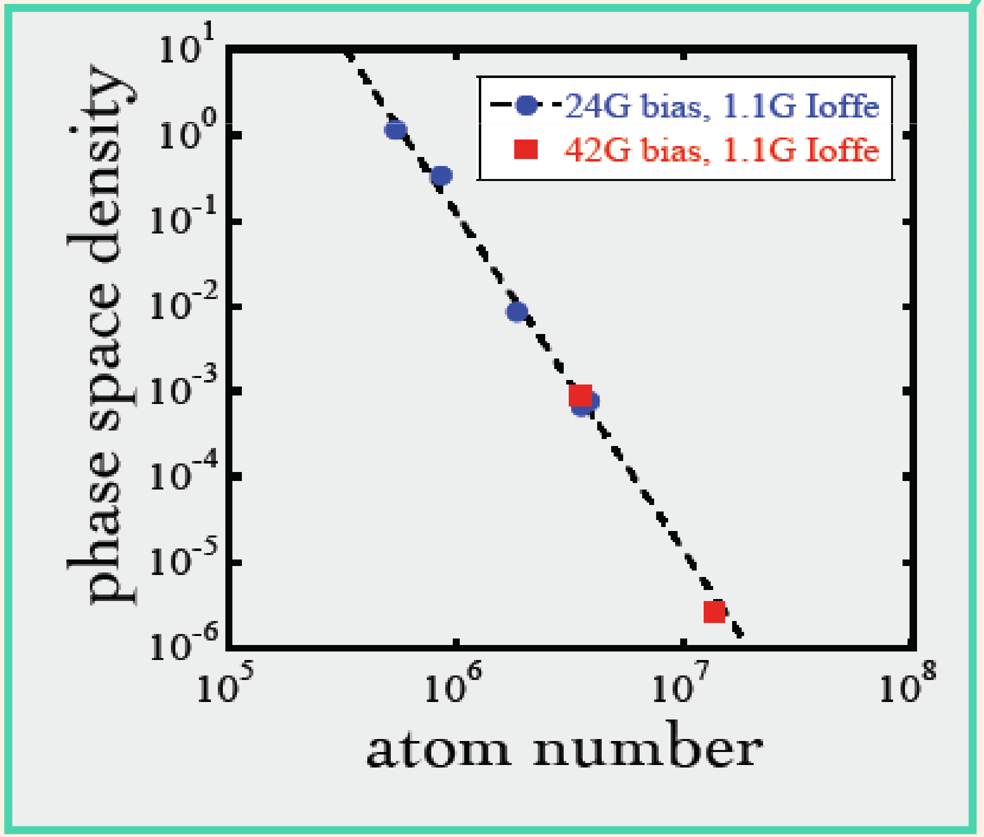


T=7 μK

f_{axial} boosted by two (to 26 Hz)

Bose-Einstein Condensation of ^{87}Rb





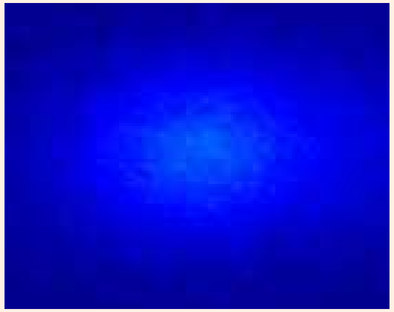
Evaporation Efficiency

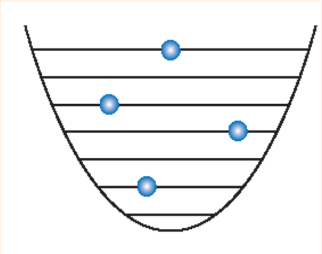
$$\frac{d\ \ln(\mathrm{PSD})}{d\ \ln(\mathrm{N})} = 3.95 \pm 0.1$$

^{87}Rb BEC

RF@1.740 MHz:

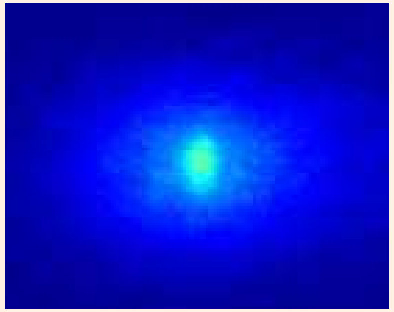
N = 7.3×10^5, $T > T_c$

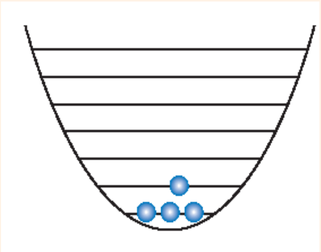




RF@1.725 MHz:

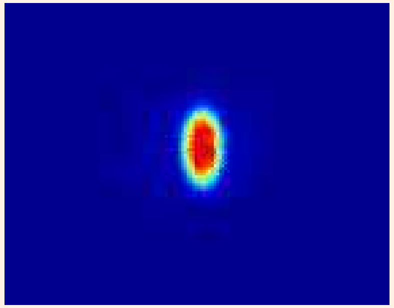
N = 6.4×10^5, $T \sim T_c$

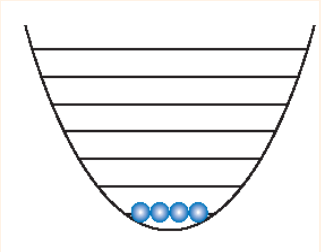




RF@1.660 MHz:

N=1.4×10^5, $T < T_c$

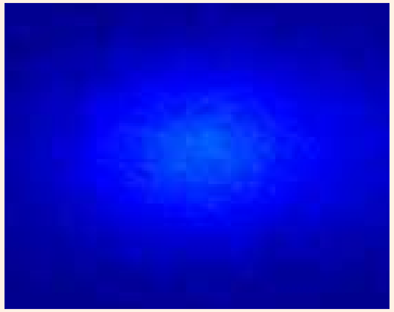


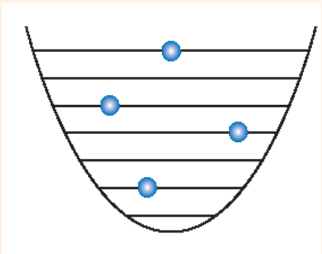


^{87}Rb BEC

RF@1.740 MHz:

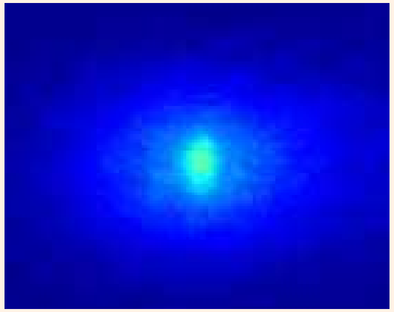
N = 7.3x10^{5}, T>T_c

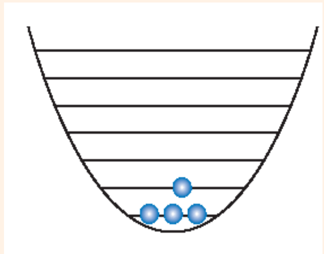




RF@1.725 MHz:

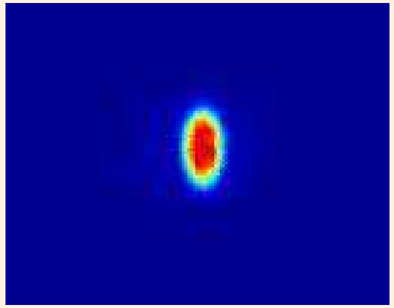
N = 6.4x10^{5}, T~T_c

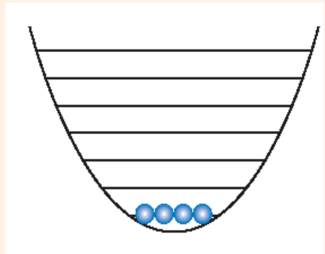




RF@1.660 MHz:

N=1.4x10^{5}, T<T_c

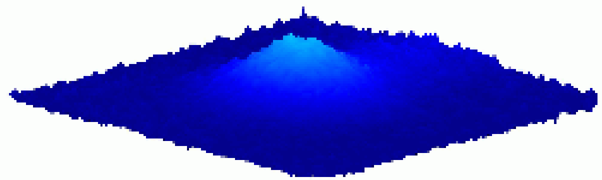




Surprise! Reach T_c with only a 30x loss in number.

(trap loaded with 2x10^{7} atoms)

→ Experimental cycle = 5 - 15 seconds



Fermions: Sympathetic Cooling

Problem:

Cold identical fermions **do not interact** due to Pauli Exclusion Principle.

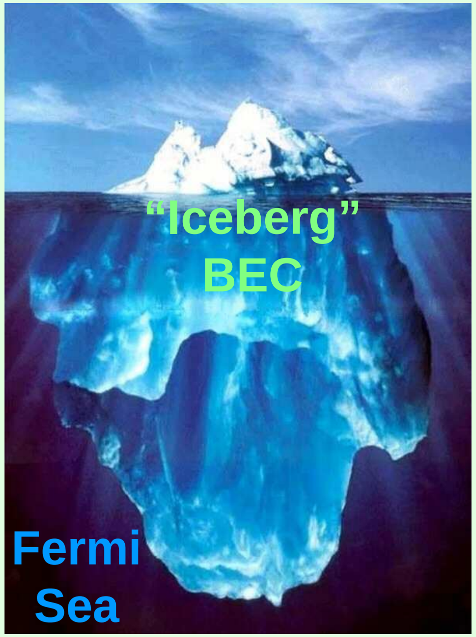
→ **No rethermalization.**

→ **No evaporative cooling.**

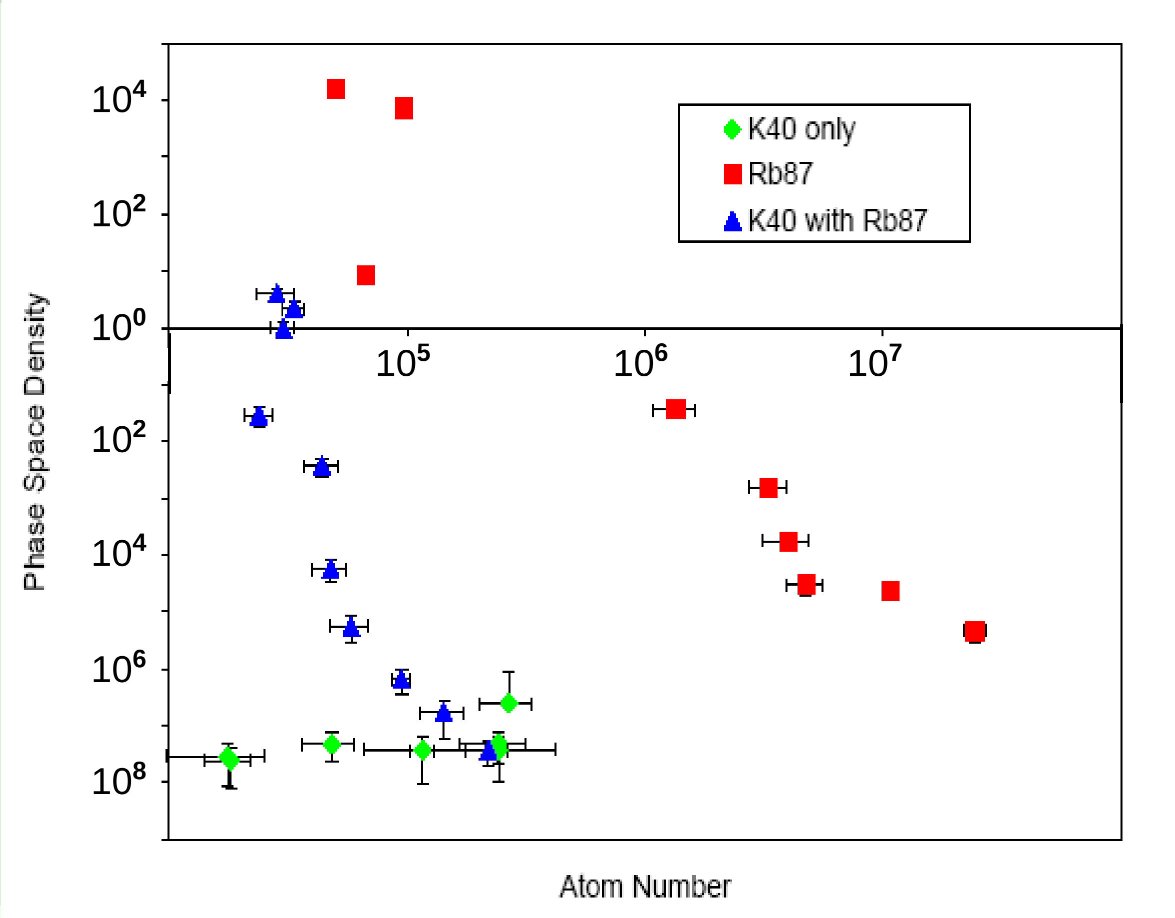
Solution: add non-identical particles

→ **Pauli exclusion principle does not apply.**

We cool our fermionic ^{40}**K** atoms sympathetically with an ^{87}**Rb BEC**.



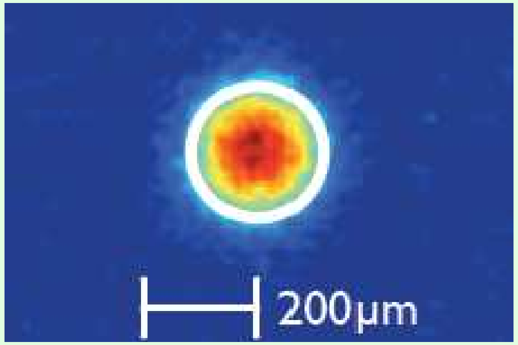
Sympathetic Cooling



Cooling Efficiency

$$\frac{\Delta \ln(\mathrm{PSD})}{\Delta \ln(\mathrm{N})} \approx 8$$

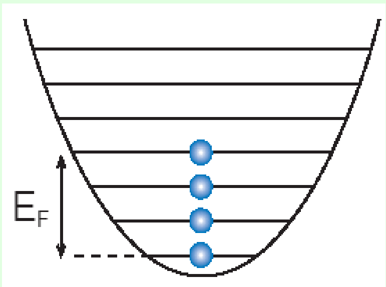
Below T_F



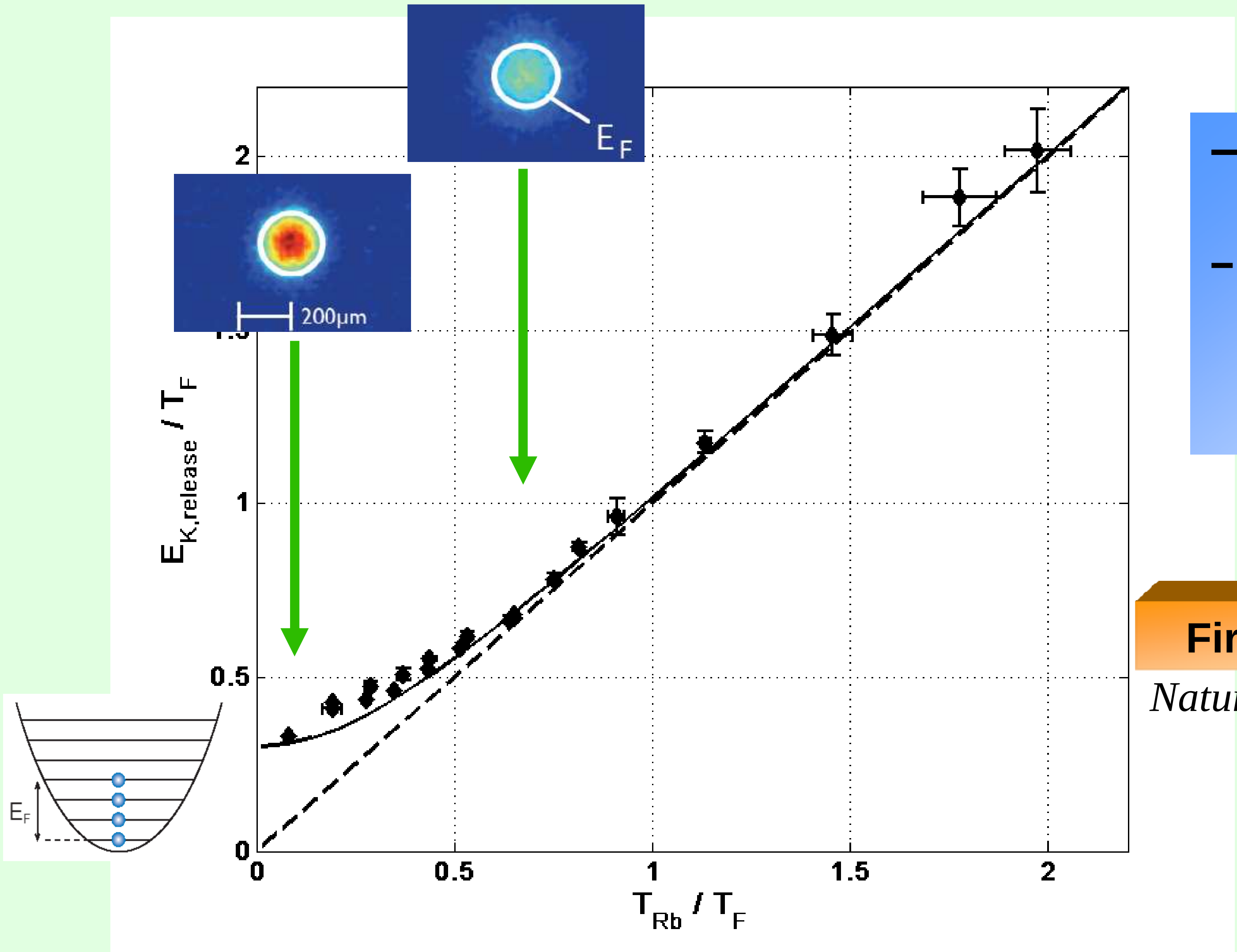
0.9 T_F **0.35 T_F**

- For Boltzmann statistics and a harmonic trap, $\frac{1}{2}mv^2 = \frac{1}{2}kT \;\rightarrow v \propto \sqrt{T}$

- For ultra-cold fermions, even at T=0, $\frac{1}{2}mv^2 = E_F \;\rightarrow v_F = 2\sqrt{\frac{E_F}{m}}$



Pauli Pressure



Fermi

Boltzmann

Gaussian Fit

First time on a chip !

Nature Physics **2**, 384 (2006).

Surprises with Rb-K

cold collisions

Naïve Scattering Theory

Collision Rates

Rb-Rb

$$\gamma_{RbRb} = n_{Rb}\sigma_{RbRb}\langle v_{RbRb}\rangle$$

$$8\pi a_{RbRb}^2$$

$$a_{RbRb} = 5.238\ \mathrm{nm}$$

Rb-K

$$\gamma_{RbK} = n_{Rb}\sigma_{RbK}\langle v_{RbK}\rangle$$

$$4\pi a_{RbK}^2$$

$$a_{RbK} = -10.8\ \mathrm{nm}$$

$$\frac{\gamma_{RbK}}{\gamma_{RbRb}} \approx 2.7$$

Sympathetic cooling should work really well !!!

Sympathetic cooling 1st try:

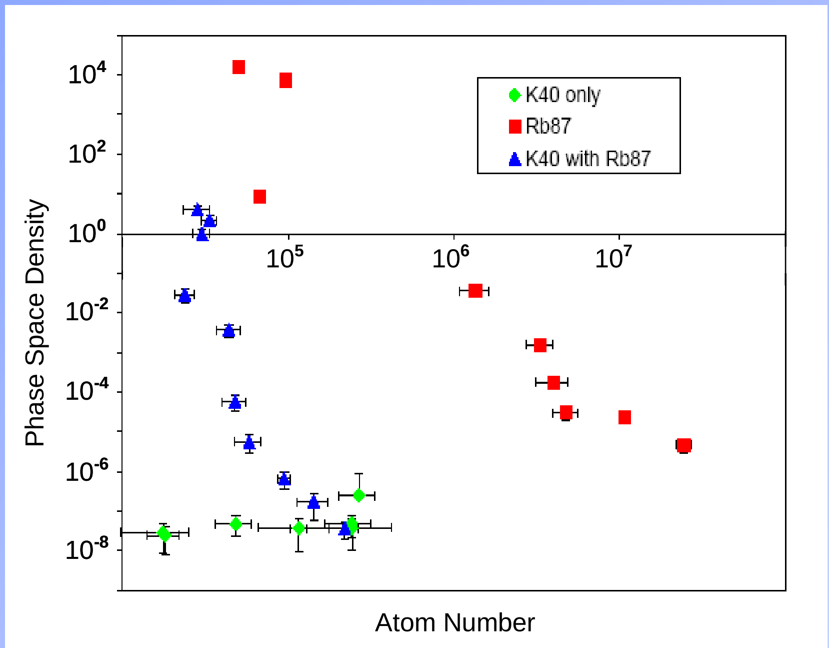
- "Should just work !" -- Anonymous
- Add ^{40}K to ^{87}Rb BEC → No sympathetic cooling observed !

Solution: Work Harder !!!

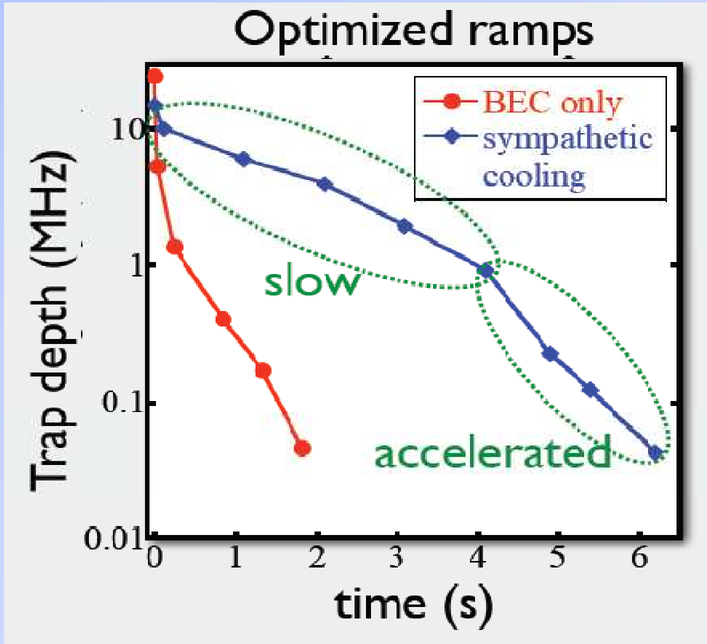
- **Slow down evaporative ramp 2s → 6s !!!**
- **Decrease amount of ^{87}Rb loaded !**
- Added Tapered Amplifier to boost 767 nm 40K MOT power.
- Direct absorption imaging of ^{40}K.
- Optical pumping of ^{40}K.
- More LIAD lights.
- Alternate MOTs: 25s ^{40}K + 3s ^{87}Rb.
- Dichroic waveplates for MOT power balance.
- Decompress micro B-Trap.
- Increase B-Trap Ioffe B-field.
- Clean up micro B-trap turn-off.

Experiment:

Sympathetic cooling only works for slow evaporation



Evaporation **3** times slower than for BEC



Cross-Section Measurement

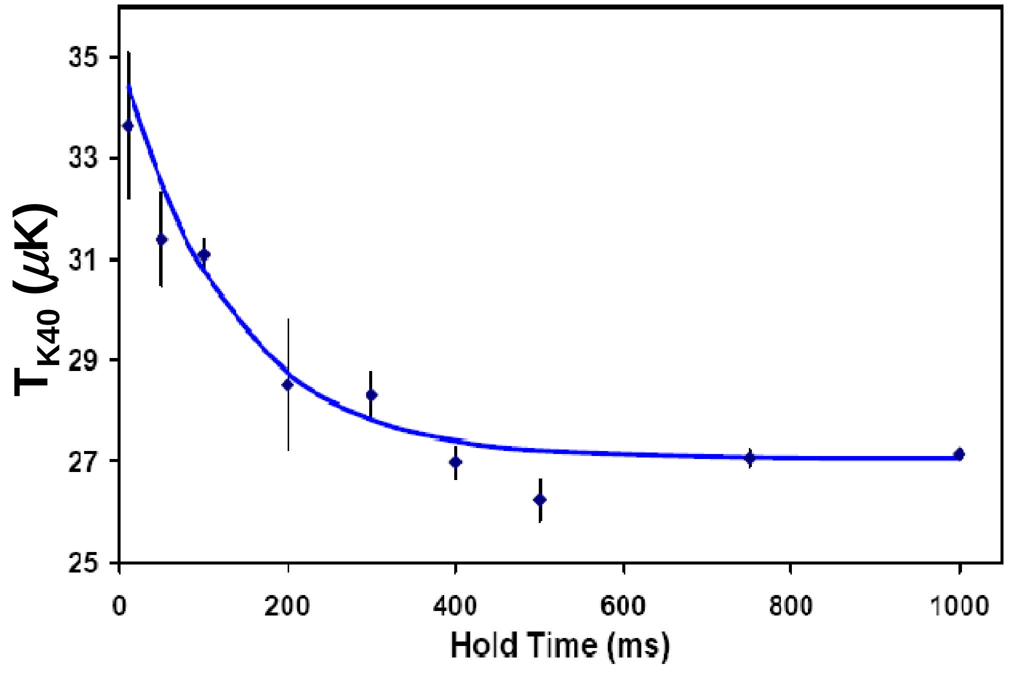
Procedure:

- Choose temperature T
- Step RF (cooling 87Rb)
- Measure relaxation of 40K temperature
- Use sympathetic cooling model to extract cross-section

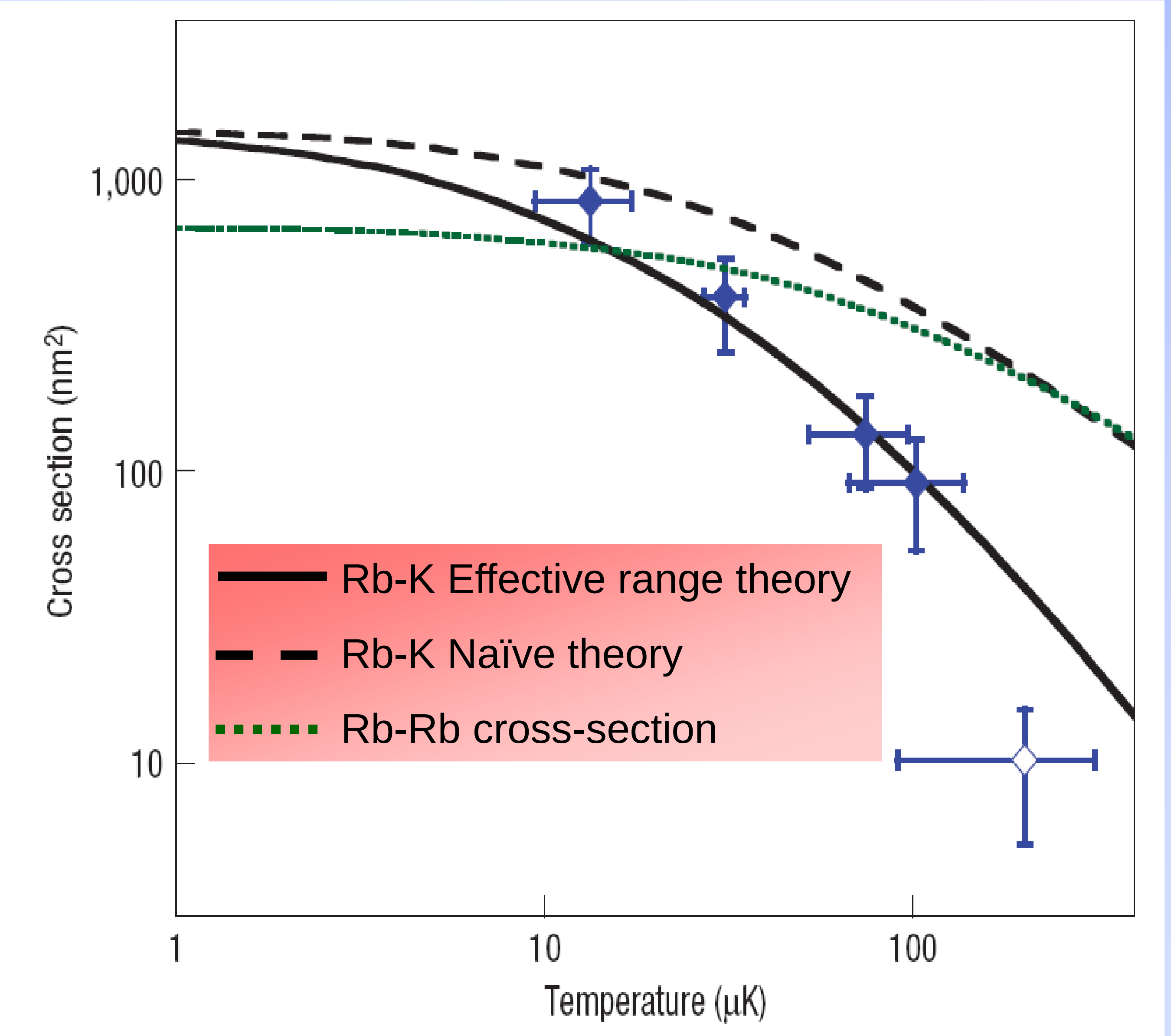
Repeat for various T's

[Model:] Mosk *et al*, Appl. Phys. B. **73**, 791 (2001).

Thermalization of ^{40}K with ^{87}Rb



What's happening?



Summary of Toronto Apparatus

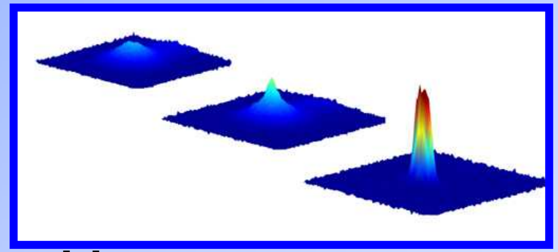
PROs:

- Fast cycle time: 5-10 s for BEC, 20-40 s for DFG.
- $N_{BEC} = 10^4$-10^5, $N_{DFG} = 4x10^4$.
- Simple design:
  - Conventional dual species MOT
  - Single vacuum chamber
  - Atom chip micro-magnetic trap
  - RF evaporation for ^{87}Rb.
  - Sympathetic cooling of ^{40}K with ^{87}Rb.

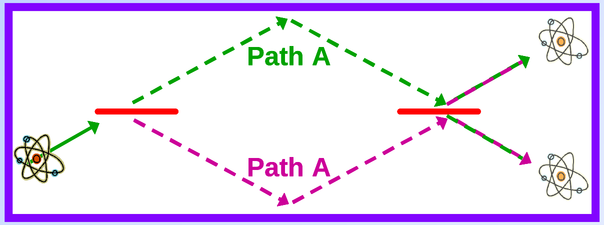
CONs:

- Chip B-trap lifetime is ~ 5 - 7 s (vacuum limited).
- Depends on LIAD.
- Good optical access, but more preferred.

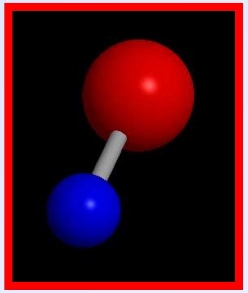
Outline



- Ultra-cold Matter Apparatus
  - → Apparatus v1.0: The Thywissen U. of T. machine.
  - → Apparatus v2.0: The W&M machine.



- Future physics plans
  - → Near term: Fermion interferometry.
  - → Longer term: Ultra-cold molecules.
    - Superfluid polar molecules

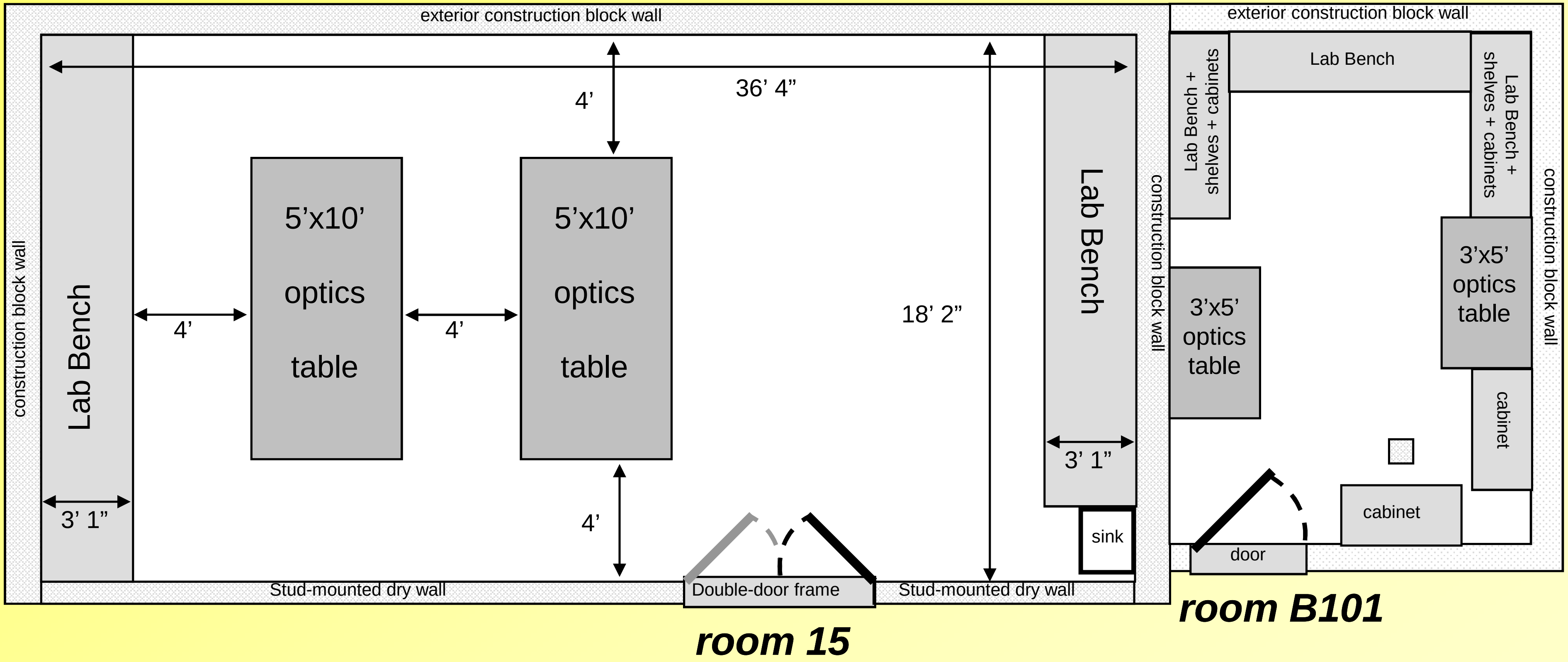


Ultra-cold AMO lab @ W & M

May 2007
(mid-renovation)

November 2007
(renovation finished)

Ultra-cold AMO lab @ W & M



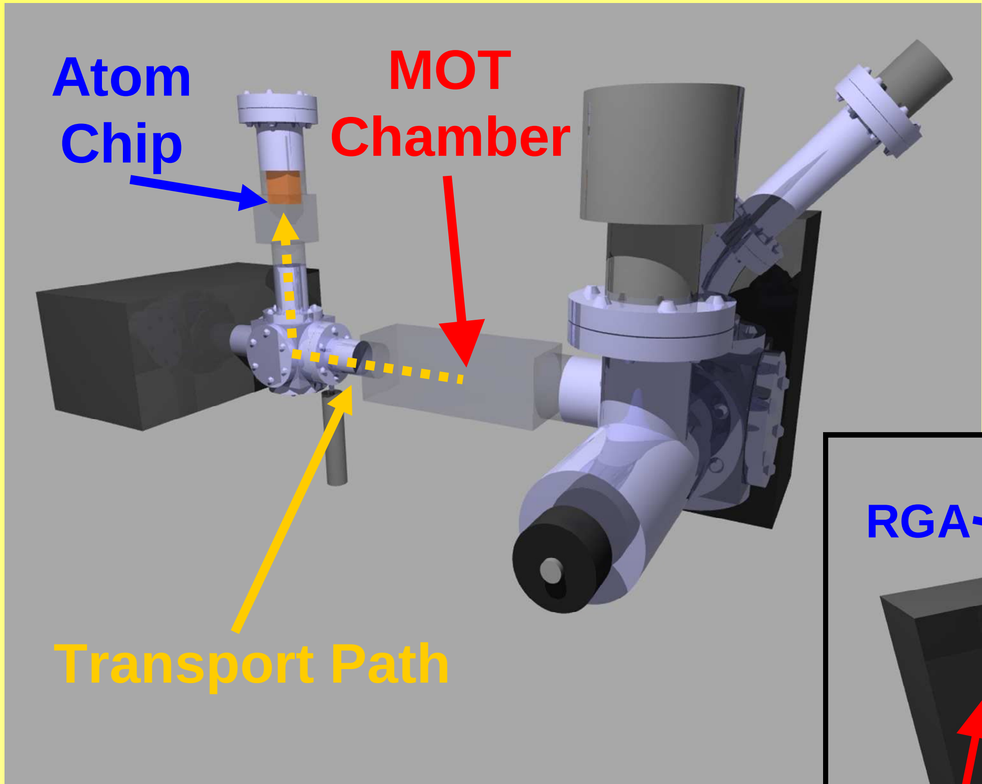
W&M BEC-DFG machine

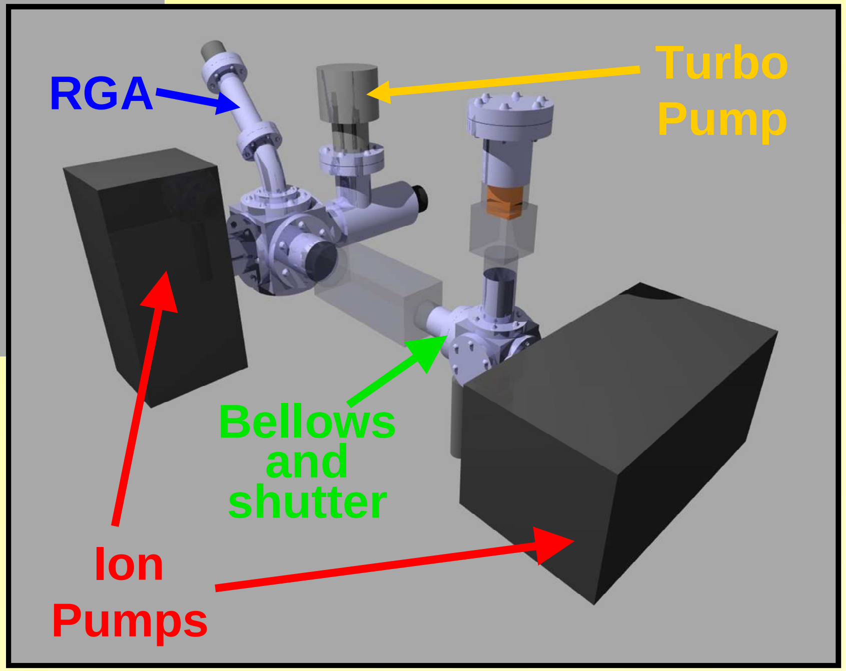
… under construction

Highlights:

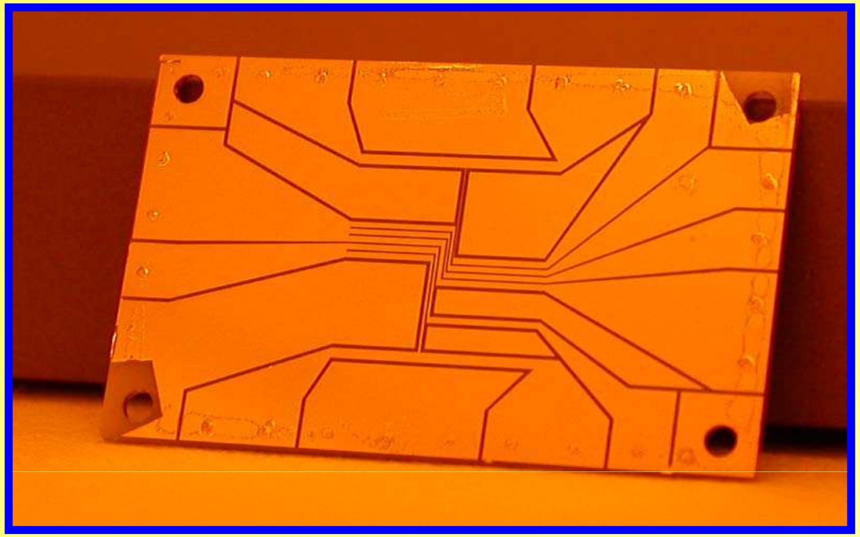
- 2 vacuum chambers for improved vacuum lifetime.
- Dual species MOT (^{87}Rb and ^{40}K).
- Magnetic transport *à la M. Greiner* (estimated time penalty: 3-4 s).
- Chip magnetic trap for fast, efficient cooling.
- Improved optical access for MOT and atom chip.
- Improved B-field management at atom chip.

Apparatus Design

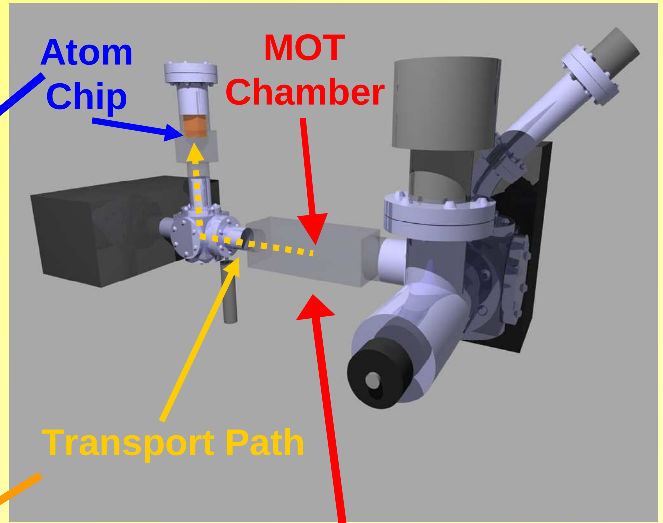


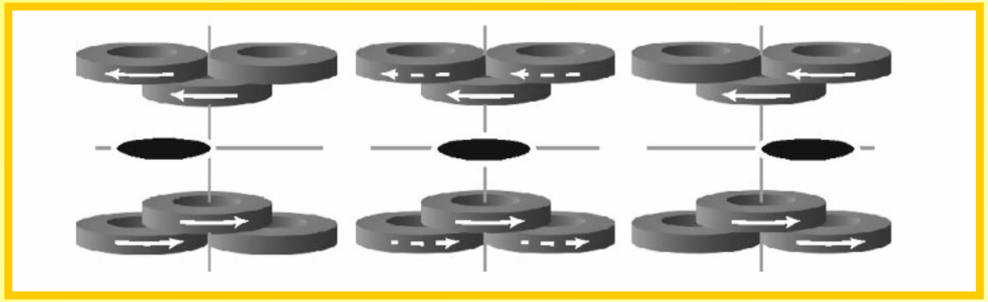


Apparatus … continued

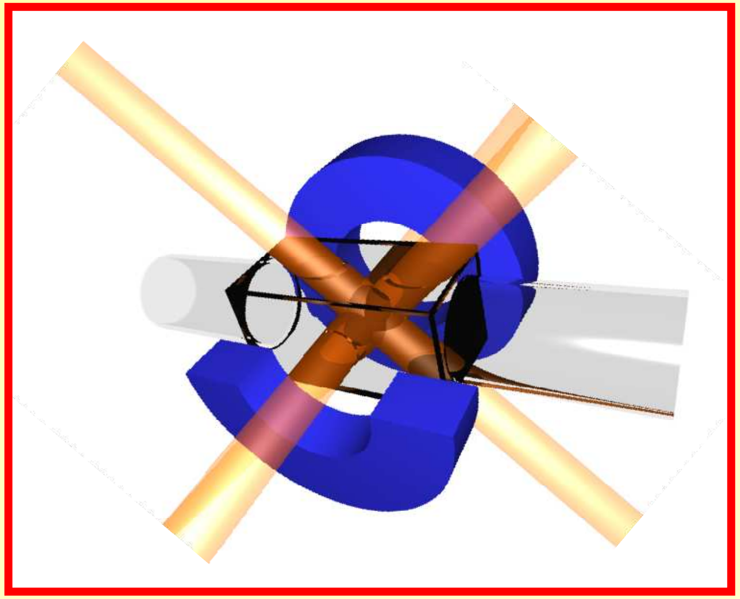


[B. Cieszlak and S. Myrskog, U. of Toronto]

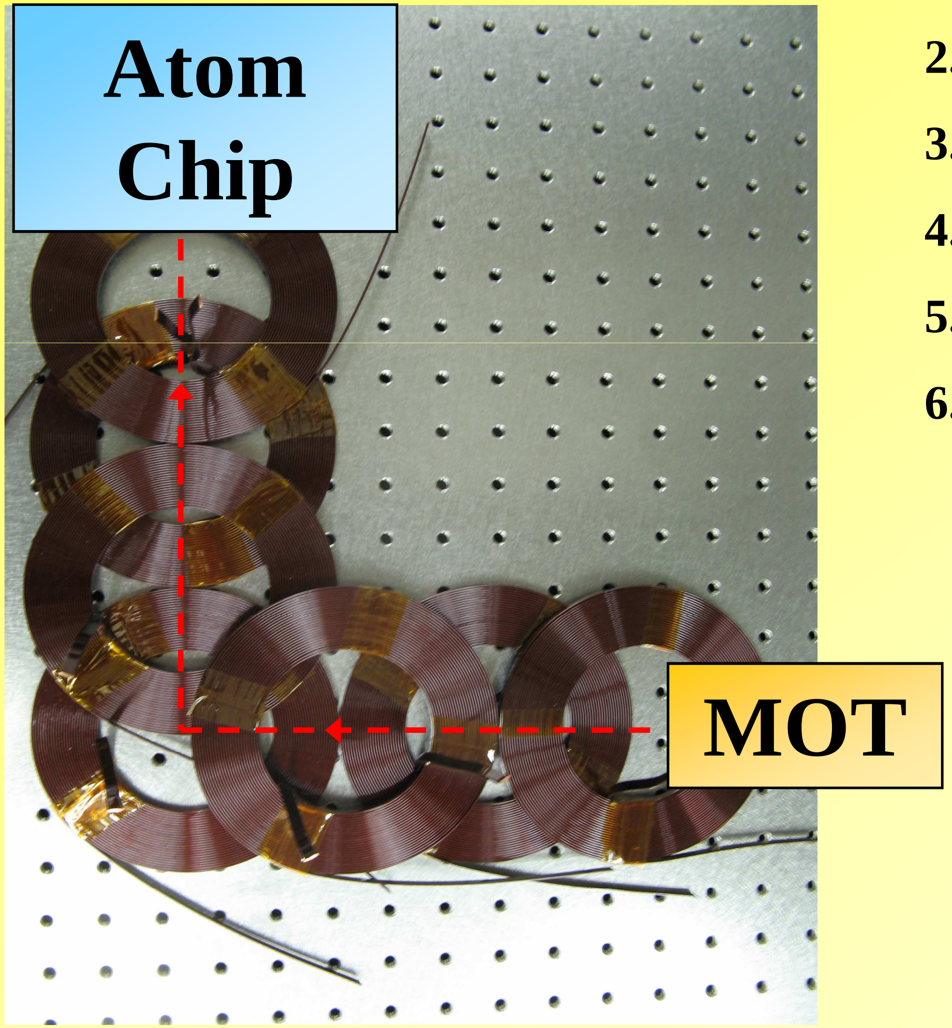




[M. Greiner et al. , Phys. Rev. A 63, 031401 (2001)]



Magnetic Transport Design

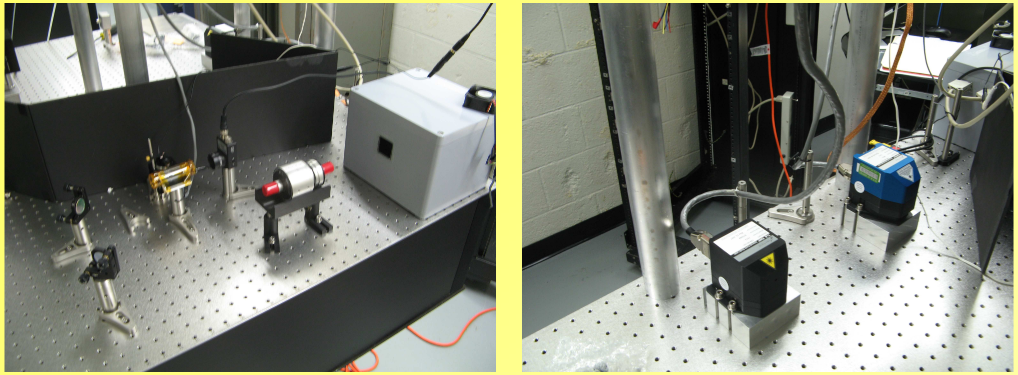


Design Requirements:

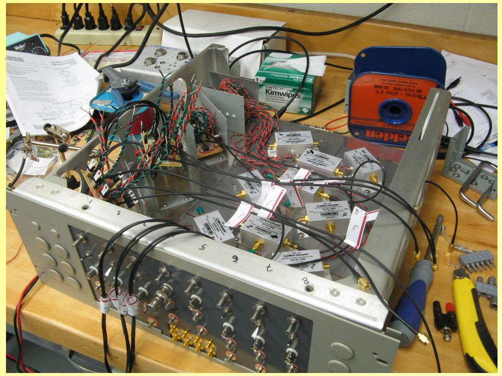
1. **Move atoms fast, but with low heating**
2. **Transport atoms reliably**
3. **Good optical access**
4. **Eddy current minimization**
5. **$\nabla B \geq 120$ Gauss/cm**
6. **Shape of trap remains constant**

Outer Diameter = 13.5 cm
Inner Diameter = 7.5 cm
Coil Separation = 7 cm
Current = 120 A
Voltage = 6.3 V
Power Supply = HP 6571A-J03
Support structure = Cool Polymers D5108 (10 W/m.K)

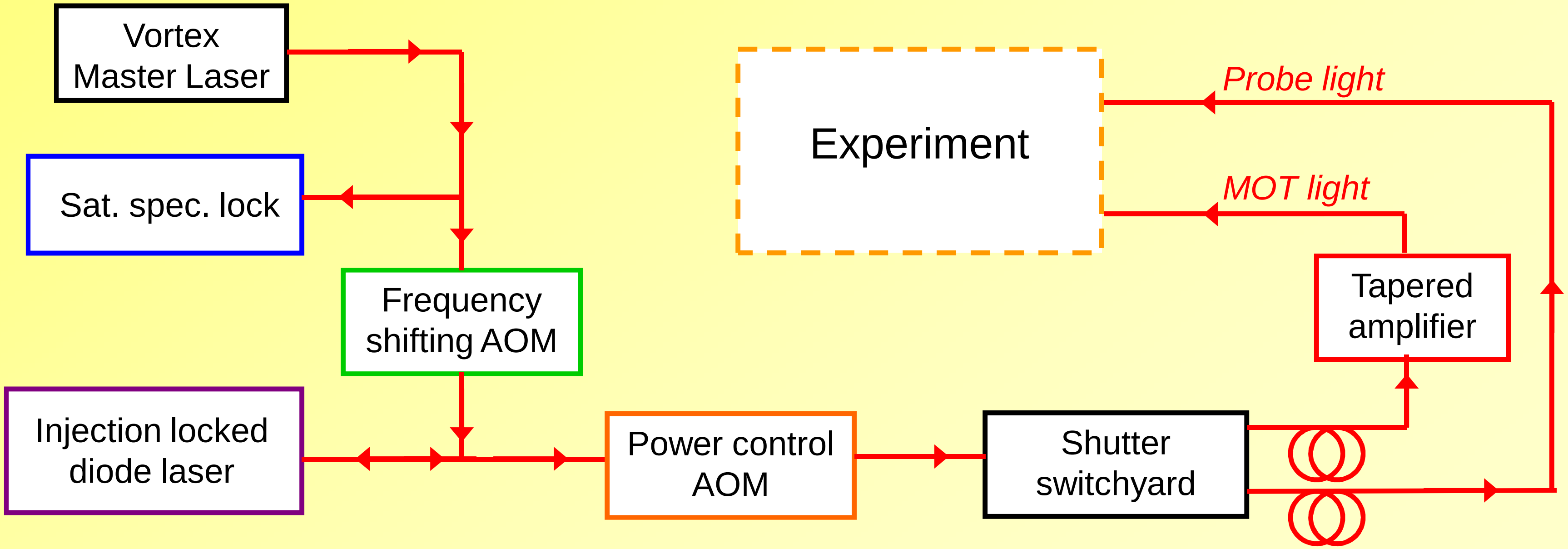
Laser System Design



MOT lasers

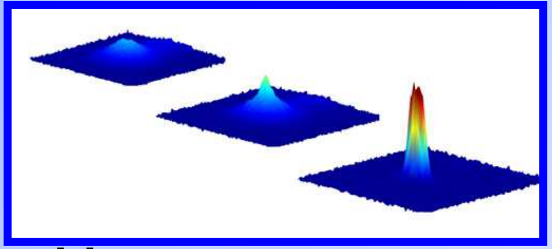


RF electronics
for acousto-optics



Outline

- Ultra-cold Matter Apparatus

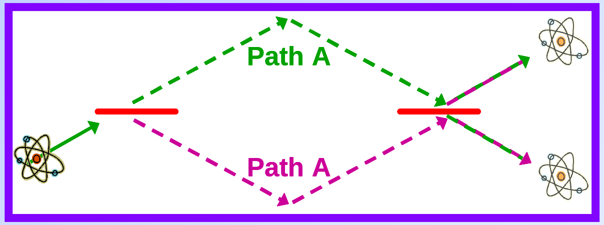


  → **Apparatus v1.0: The Thywissen U. of T. machine.**

  → **Apparatus v2.0: The W&M machine.**

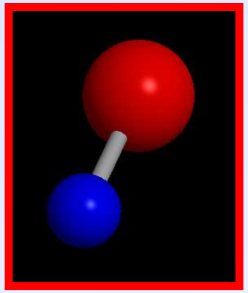
- Future physics plans

  → **Near term: Fermion interferometry.**



  → **Longer term: Ultra-cold molecules.**

  - **Superfluid polar molecules**



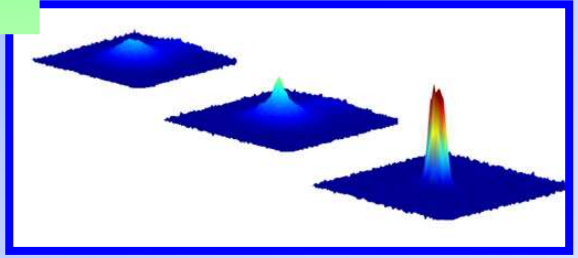
Boson vs. Fermion Interferometry

Bose-Einstein condensates

Photons (bosons) → ^{87}Rb (bosons)

✓ Laser has all photons in same "spatial mode"/state.

✓ BEC has all atoms in the same trap ground state.



Difficulty

Identical bosonic atoms interact through collisions.

→ Good for evaporative cooling.

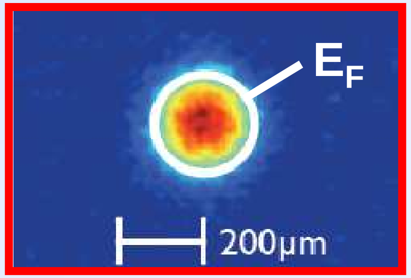
→ **Bad for phase stability: interaction potential energy depends on density --** $\Delta\phi_{AB}$ is unstable.

Degenerate fermions

- **Ultra-cold identical fermions don't interact.**

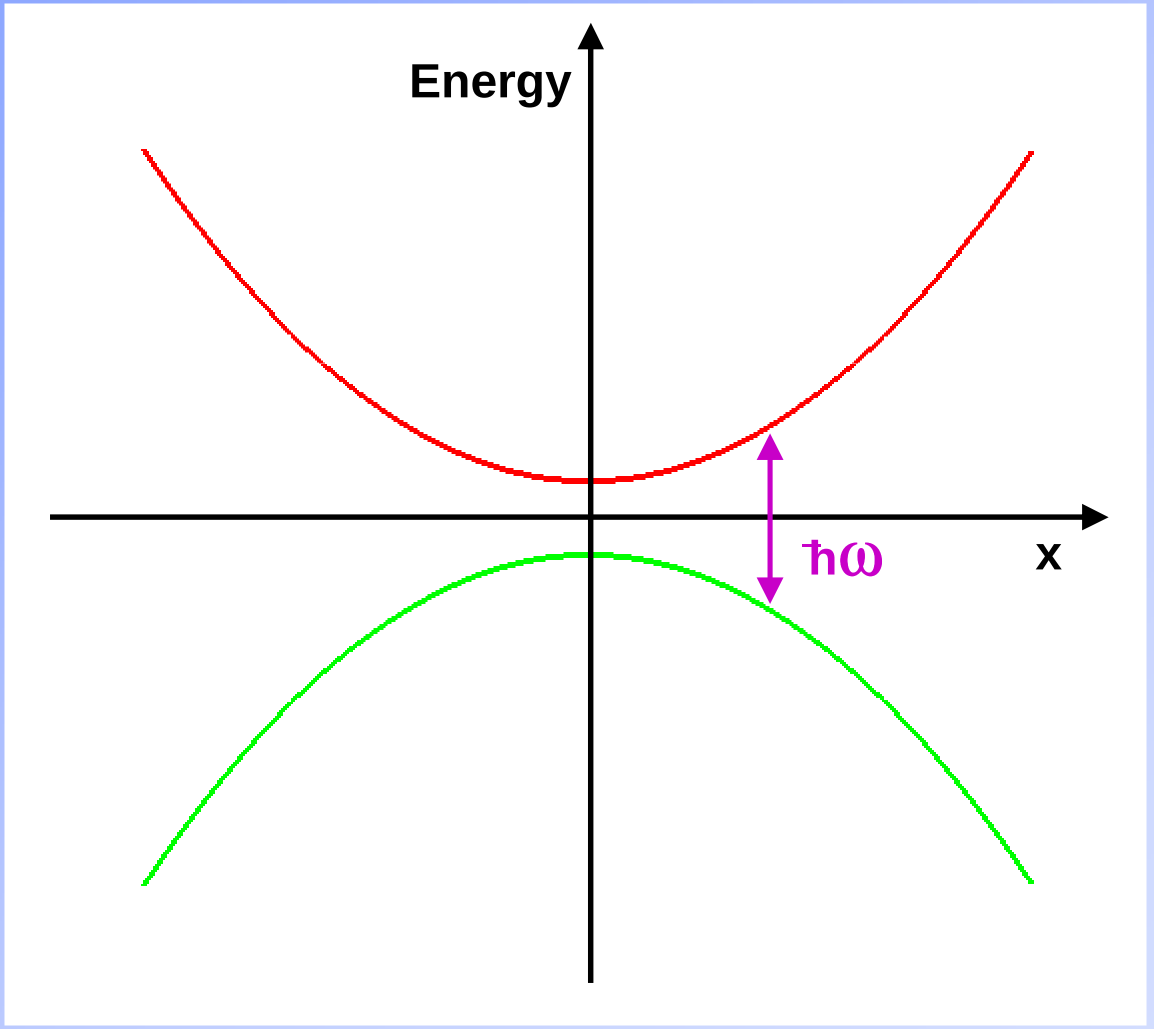
  → $\Delta\phi_{AB}$ is independent of density !!!

- Small/minor reduction in energy resolution since **$\Delta E \sim E_F$.**
- Equivalent to white light interferometry.



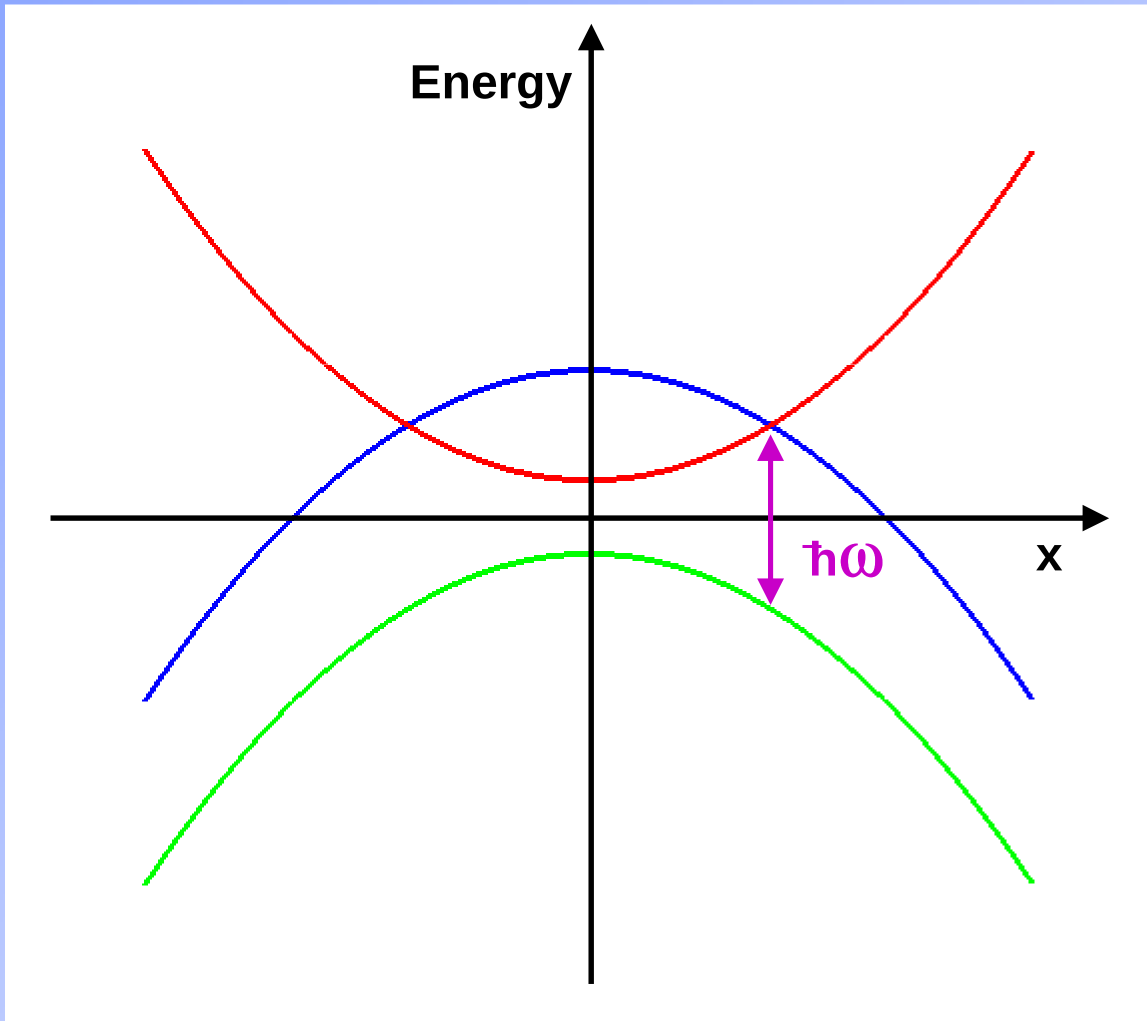
RF beamsplitter

How do you beamsplit ultra-cold atoms ?



RF beamsplitter

How do you beamsplit ultra-cold atoms ?



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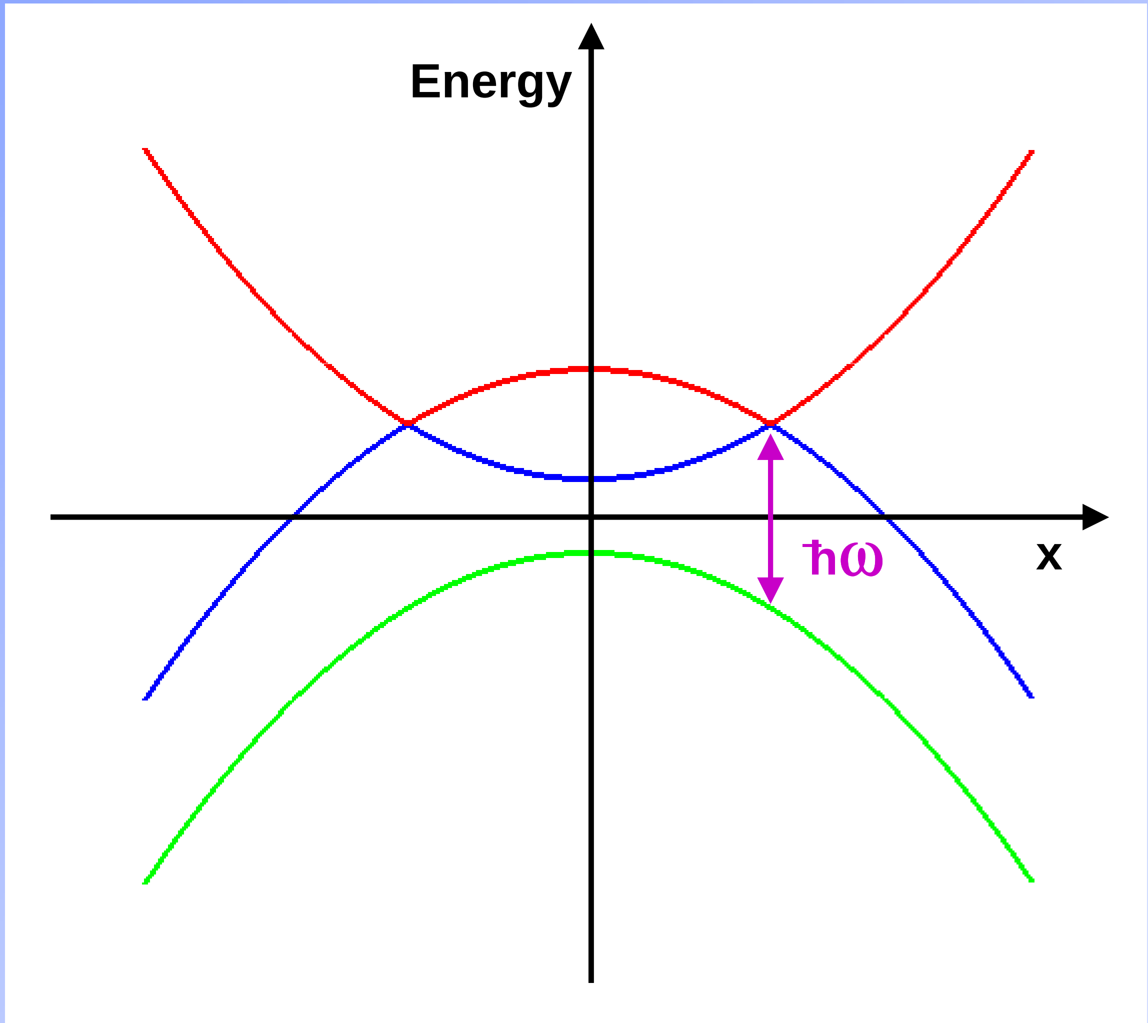
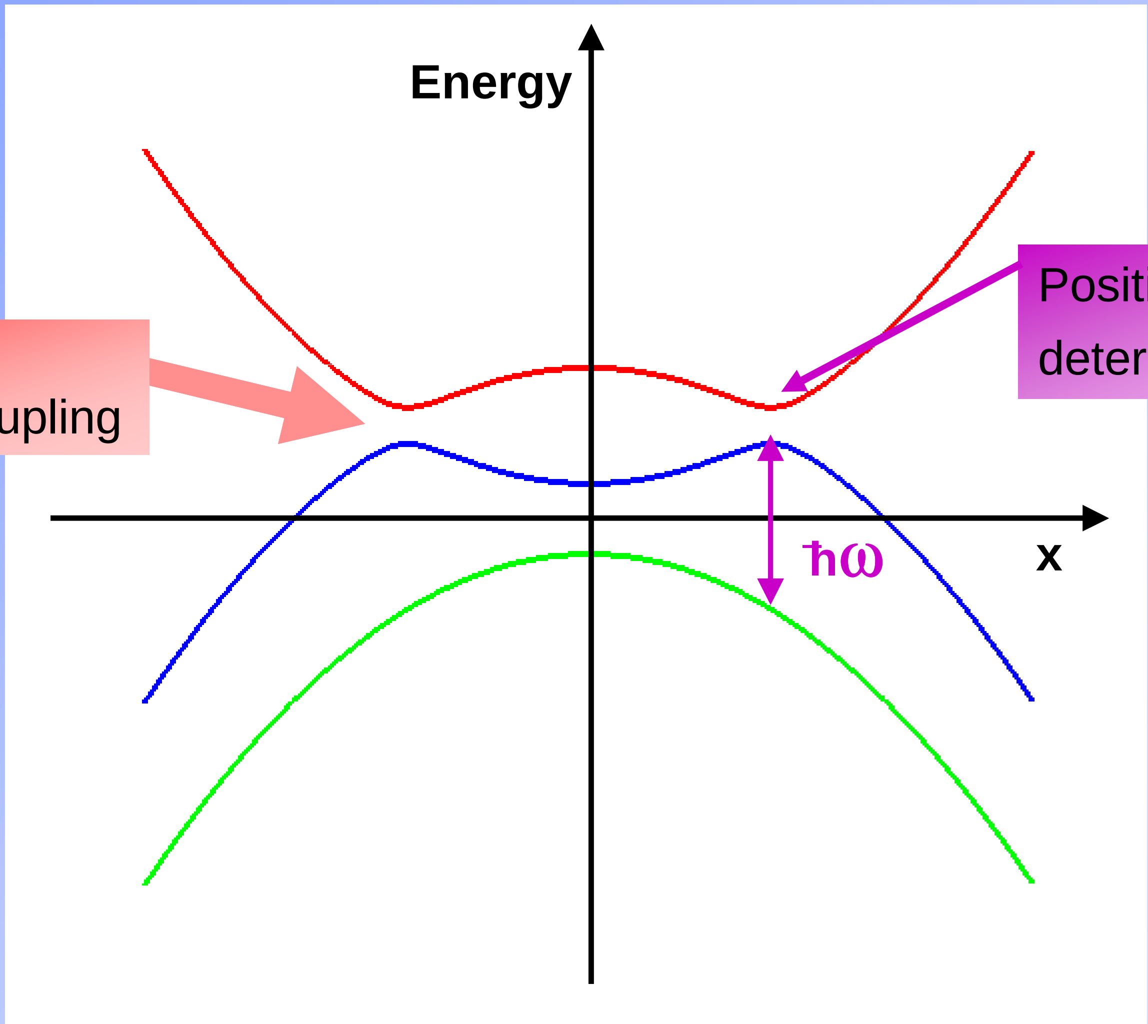


RF beamsplitter

How do you beamsplit ultra-cold atoms ?



hΩ$_{rabi}$ =
Atom-RF coupling

Position of well is determined by ω

Implementation

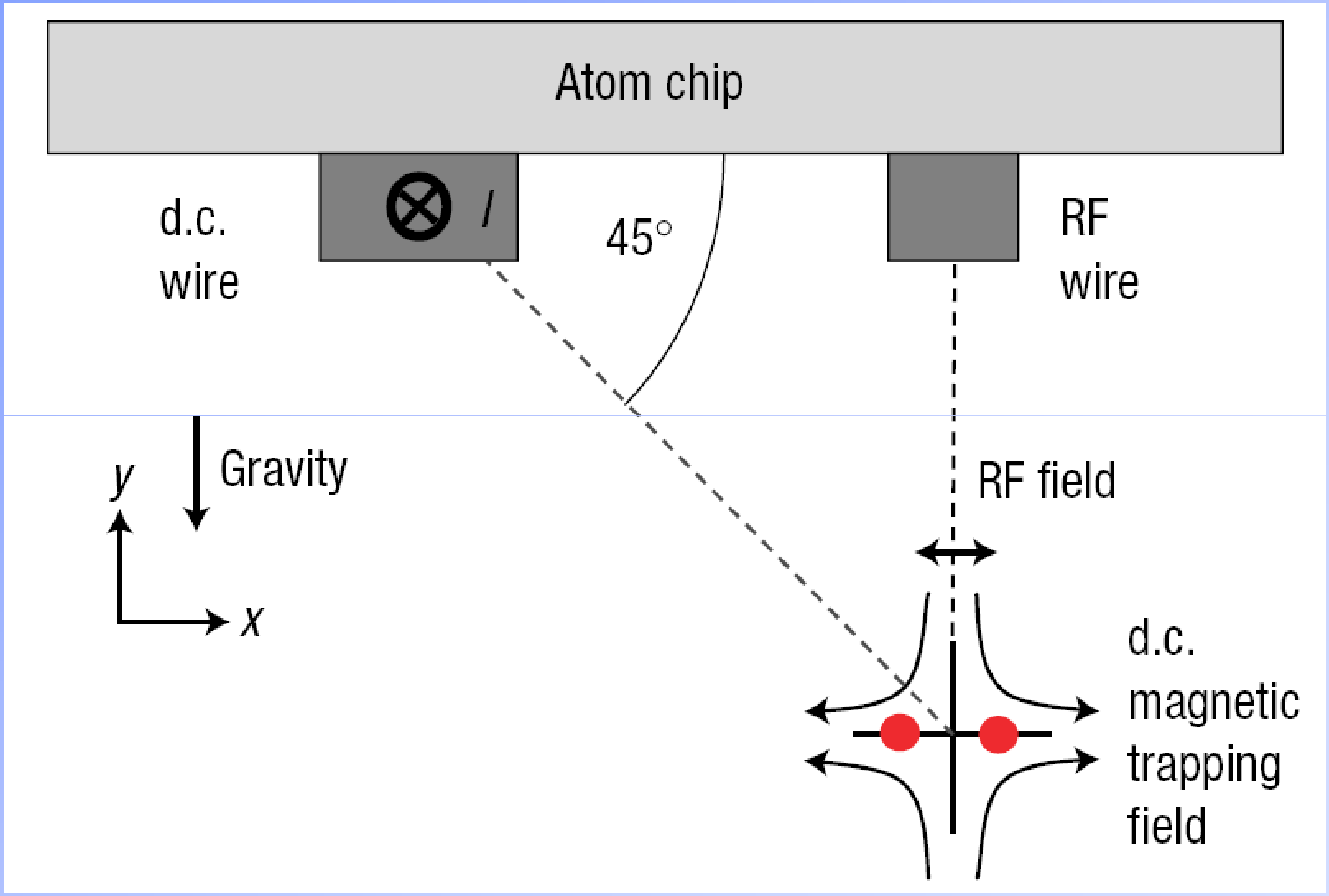
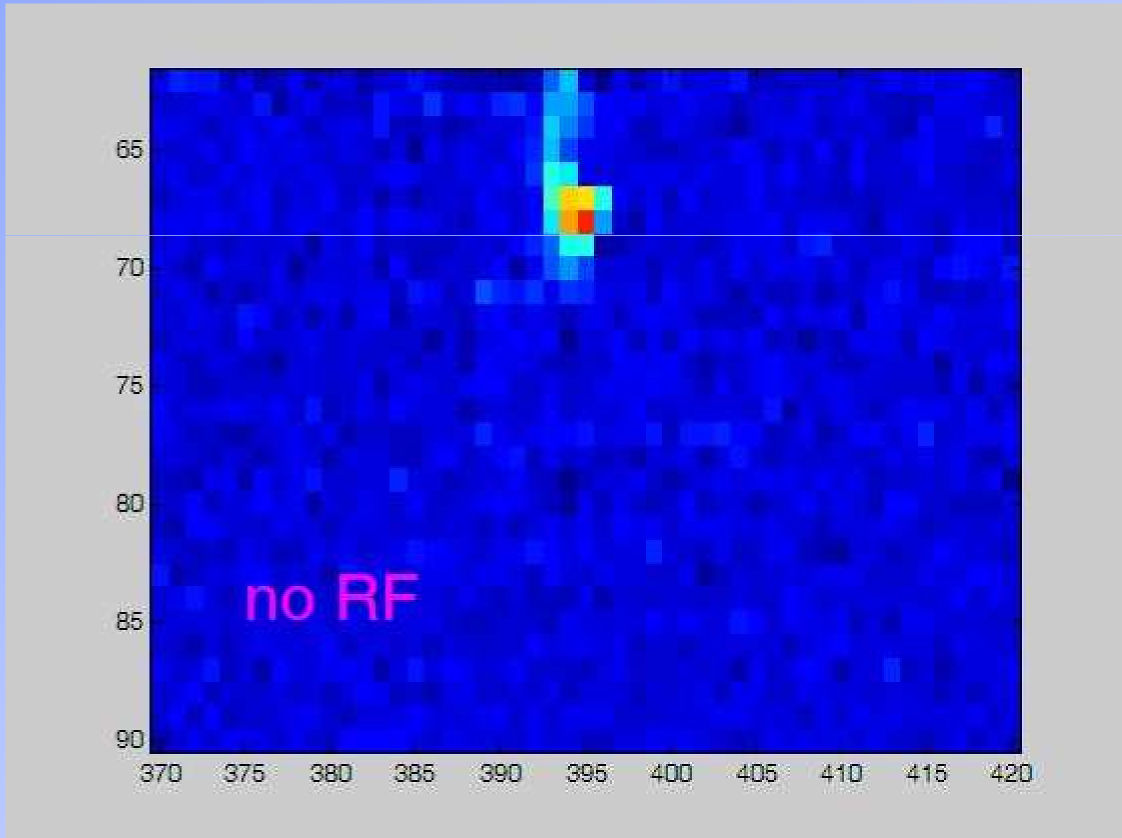


figure from Schumm et al., *Nature Physics* **1**, 57 (2005).

RF splitting of ultra-cold ^{87}Rb

Scan the RF magnetic field from 1.6 MHz to a final value

B_{RF} ~ 1 Gauss



RF splitting of ultra-cold ^{87}Rb

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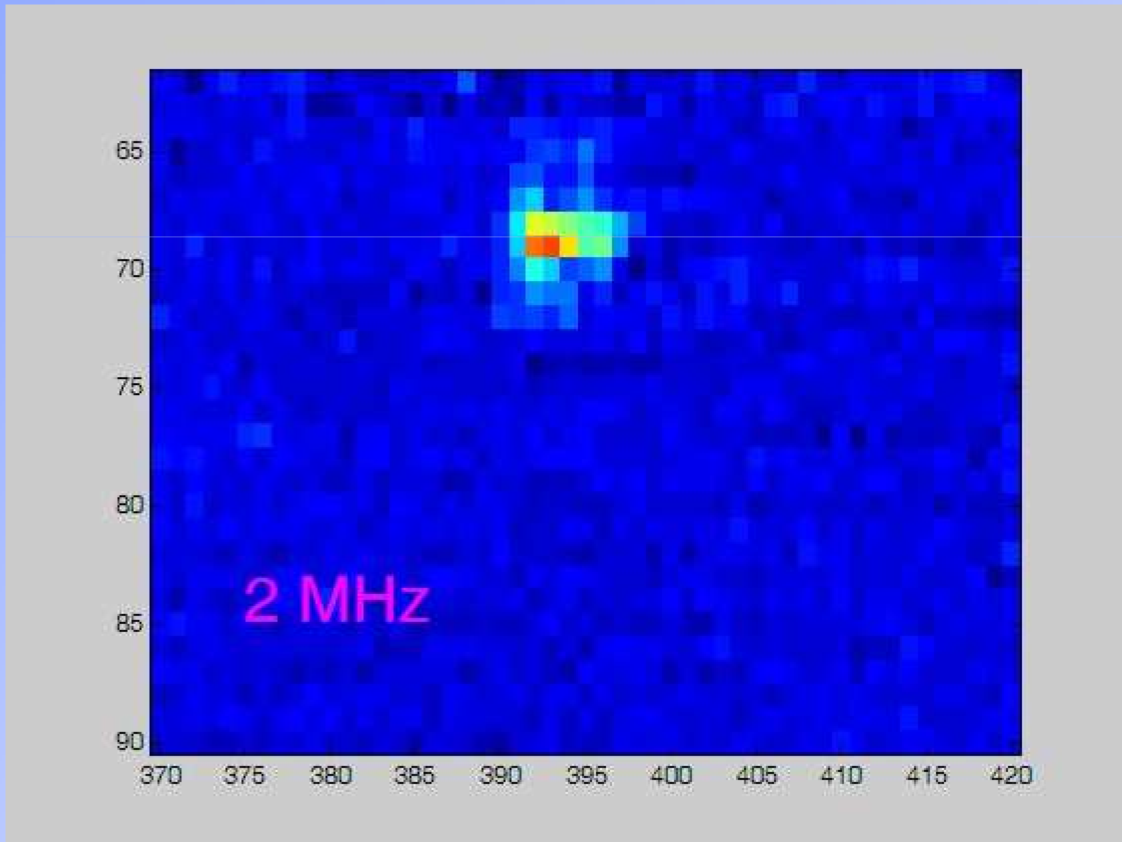

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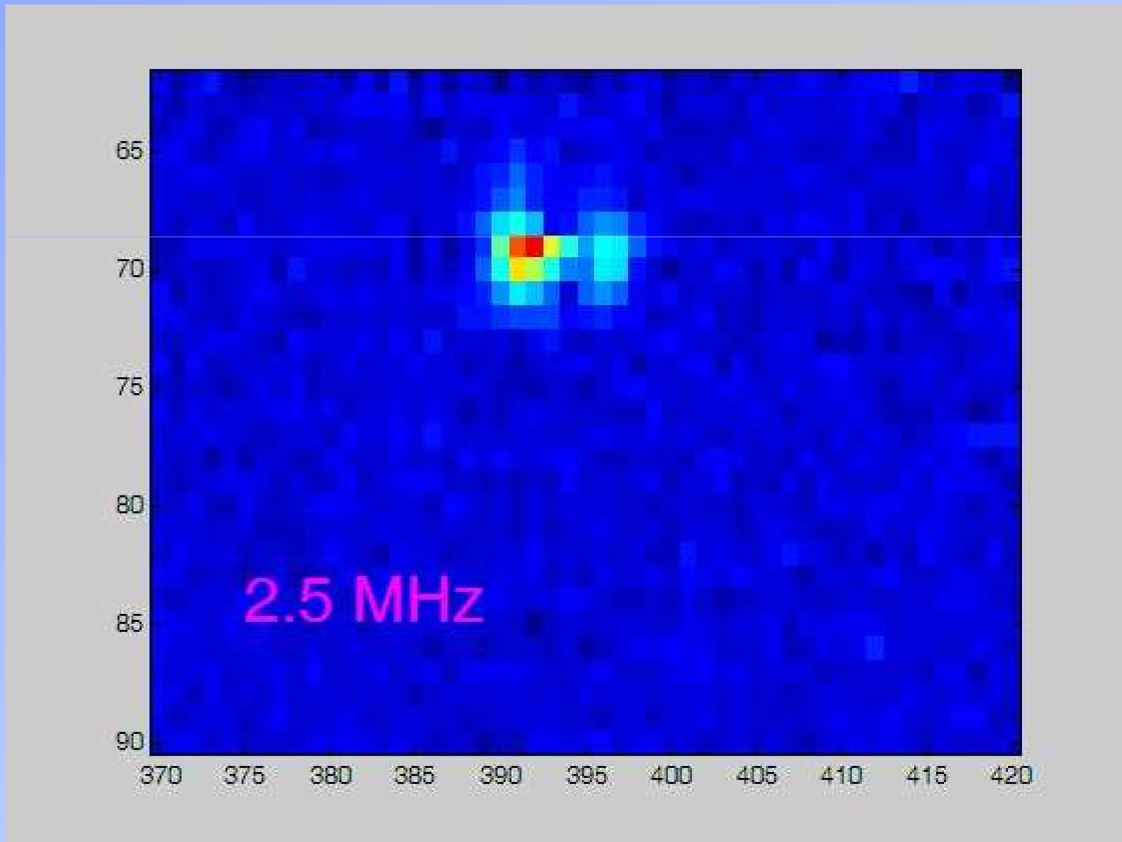

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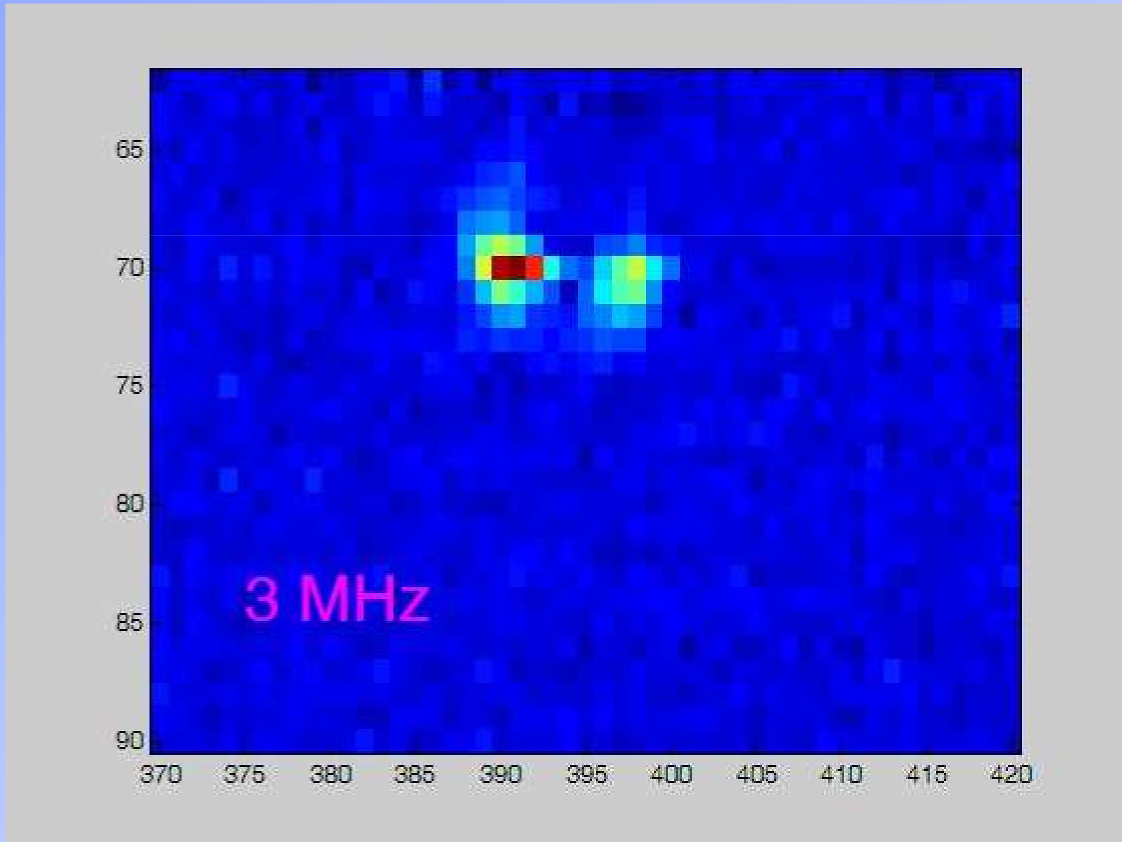

RF splitting of ultra-cold ^{87}Rb

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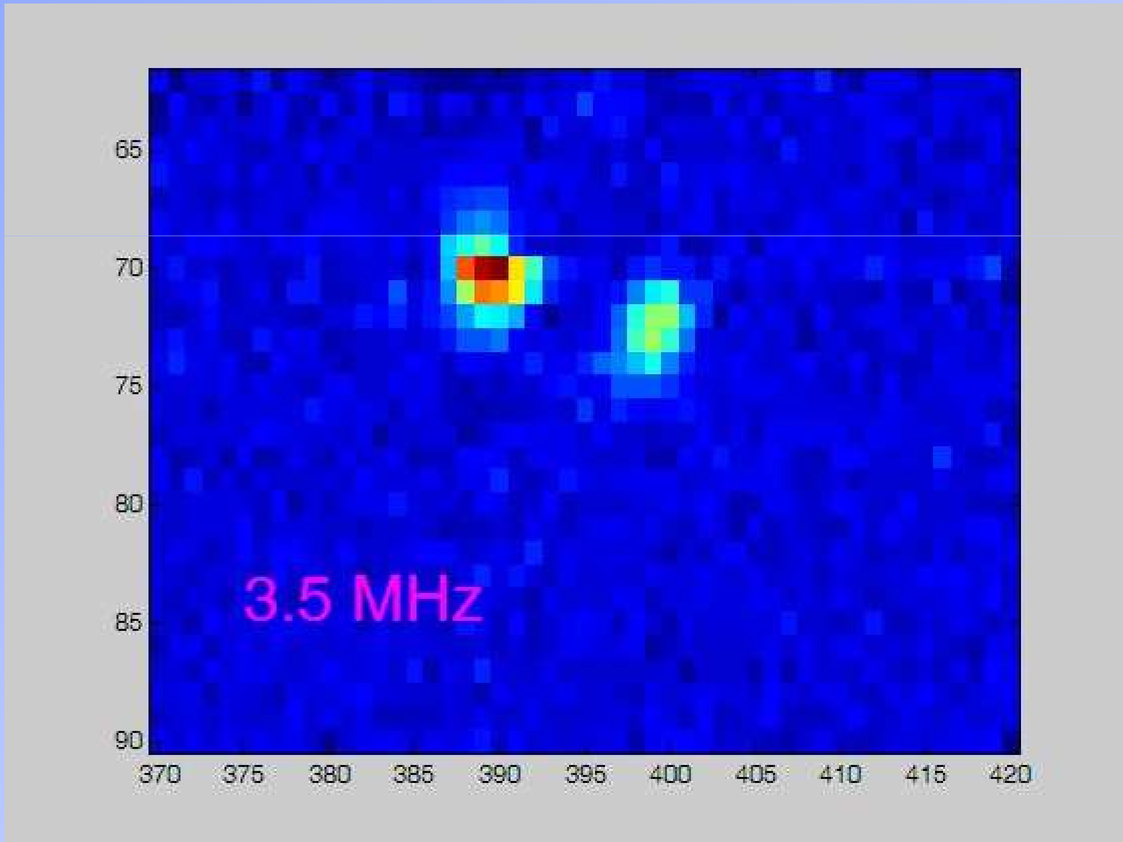

RF splitting of ultra-cold ^{87}Rb

Scan the RF magnetic field from 1.6 MHz to a final value

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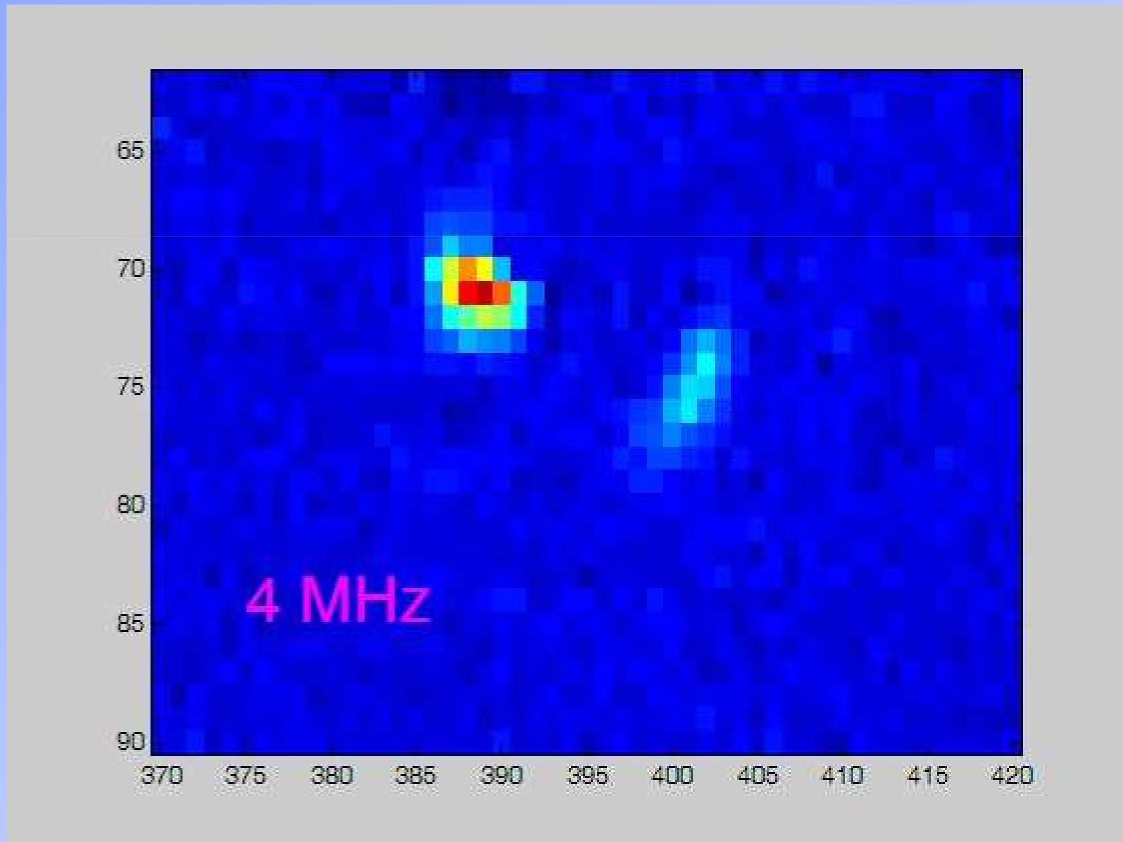

RF splitting of ultra-cold ^{87}Rb

Scan the RF magnetic field from 1.6 MHz to a final value

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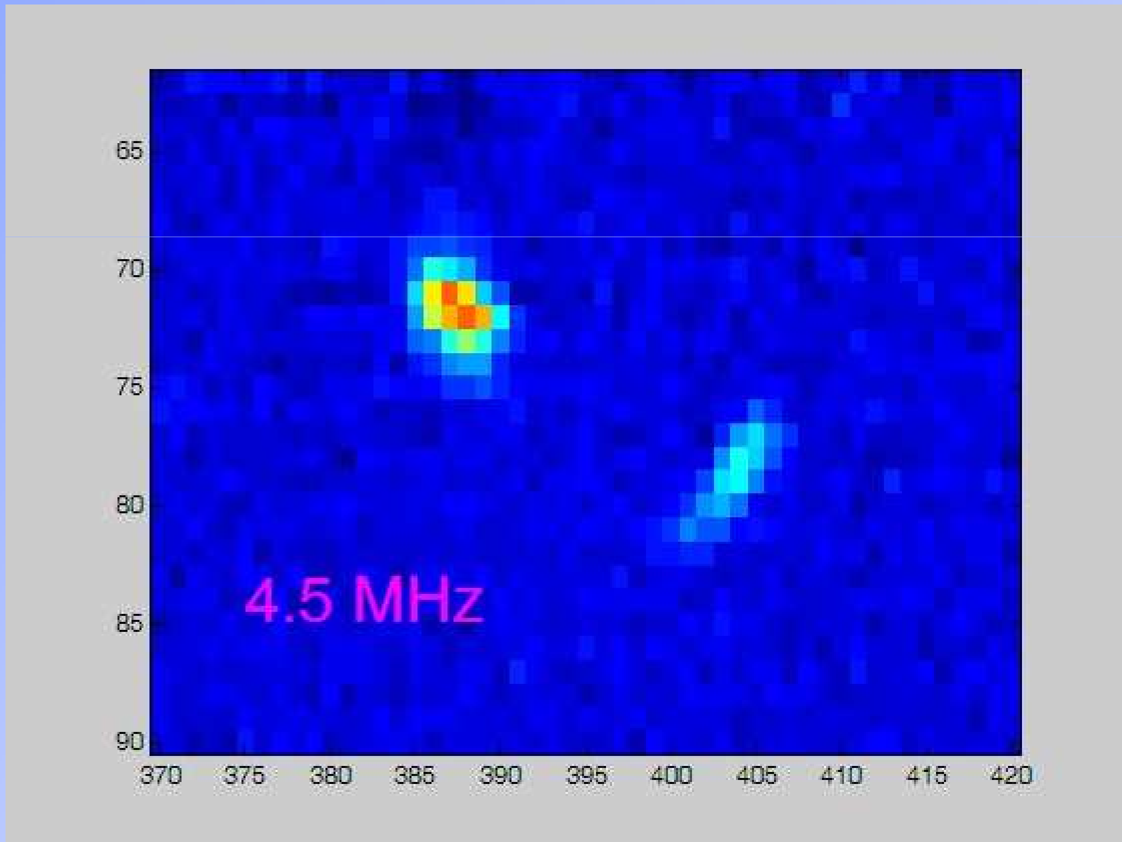

RF splitting of ultra-cold ^{87}Rb

Scan the RF magnetic field from 1.6 MHz to a final value

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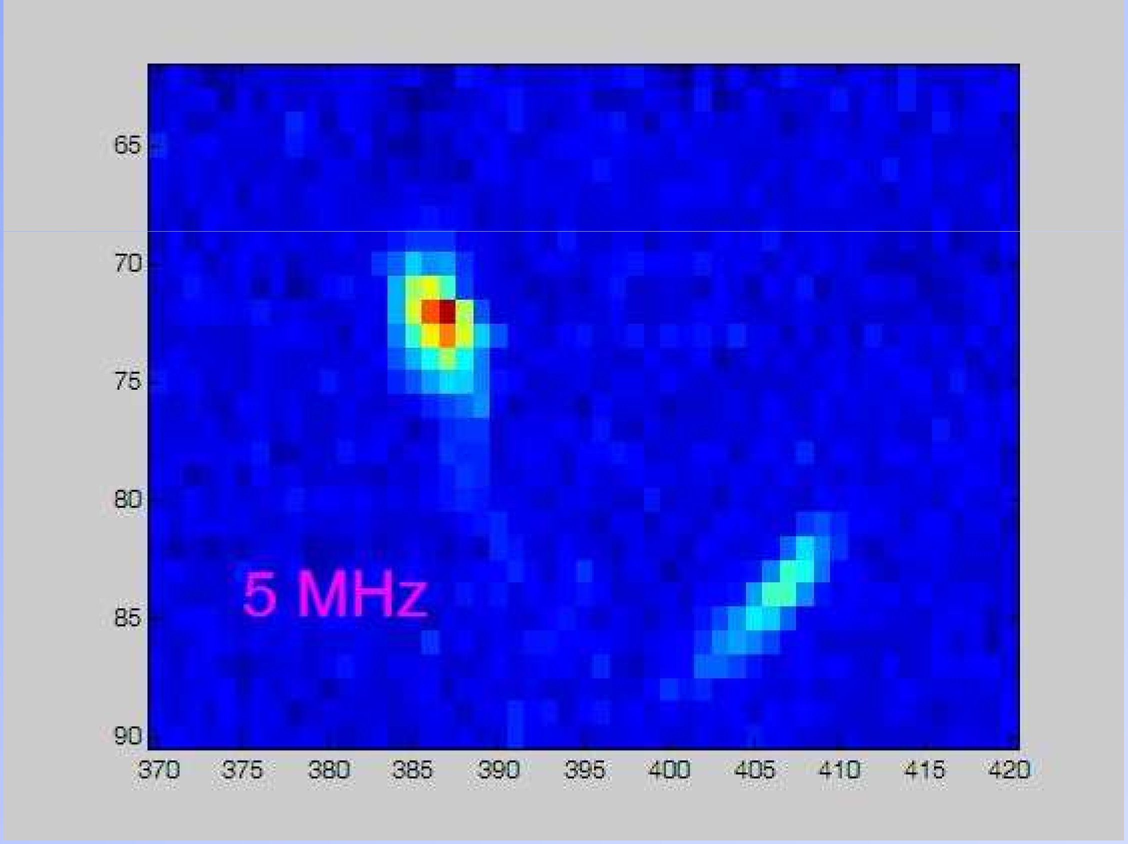
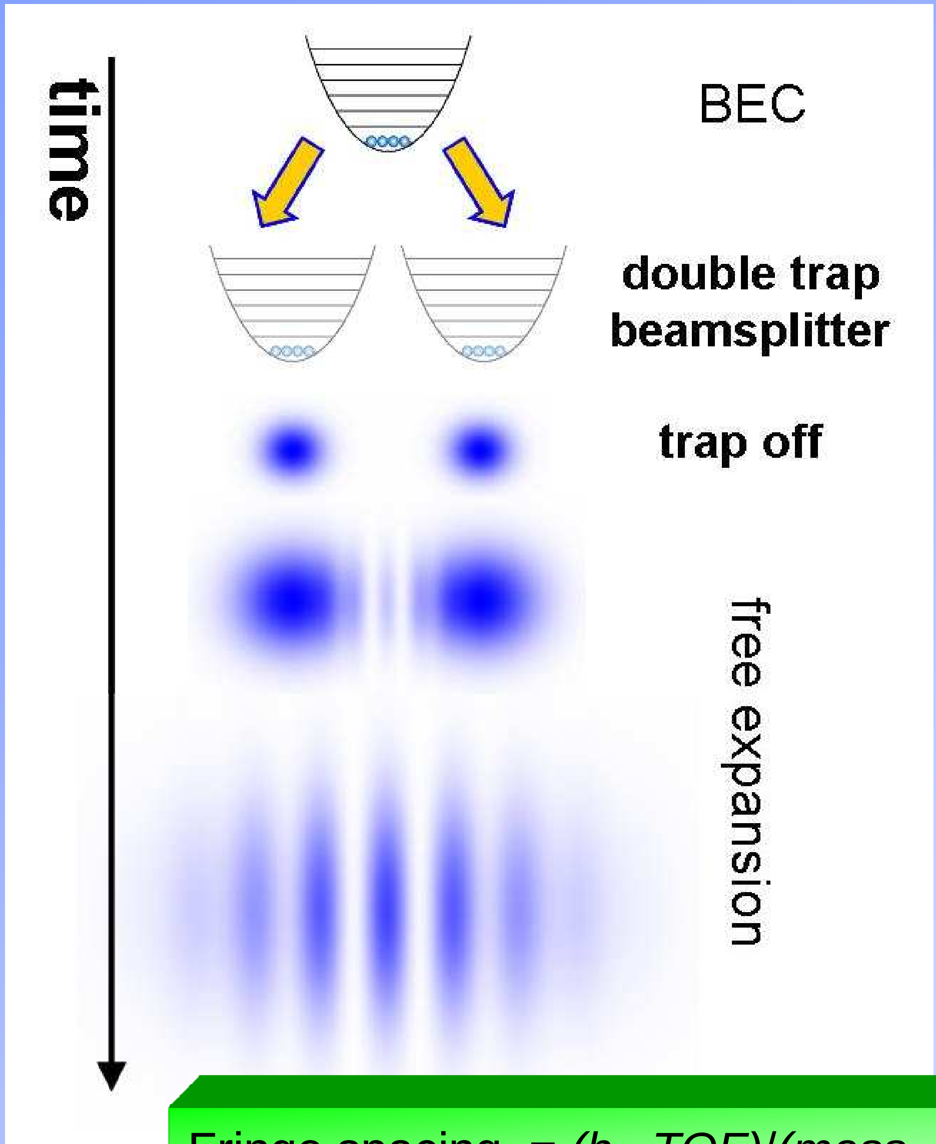
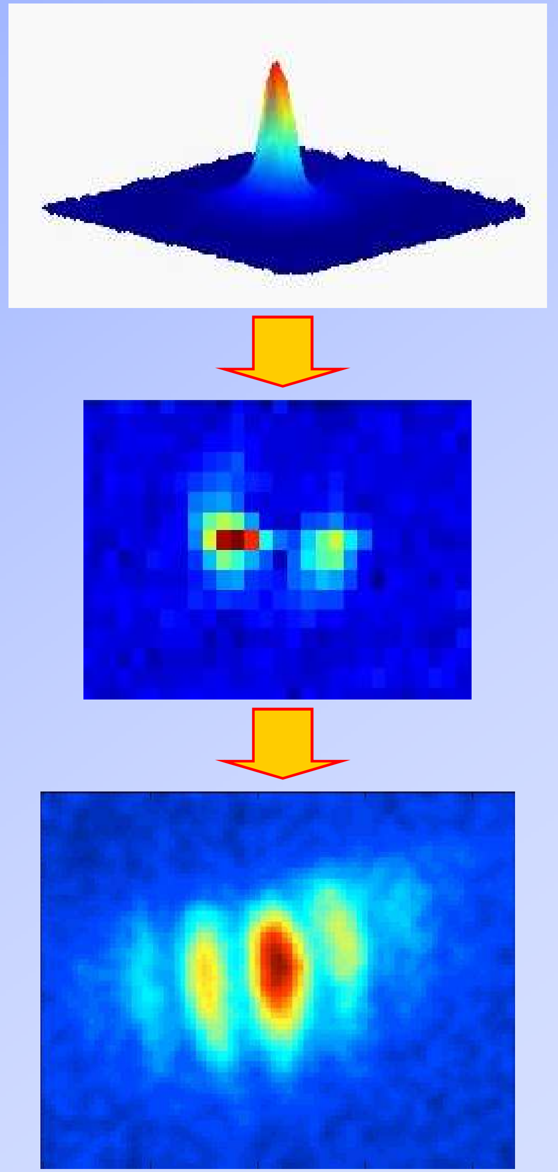


Interferometry Experiment

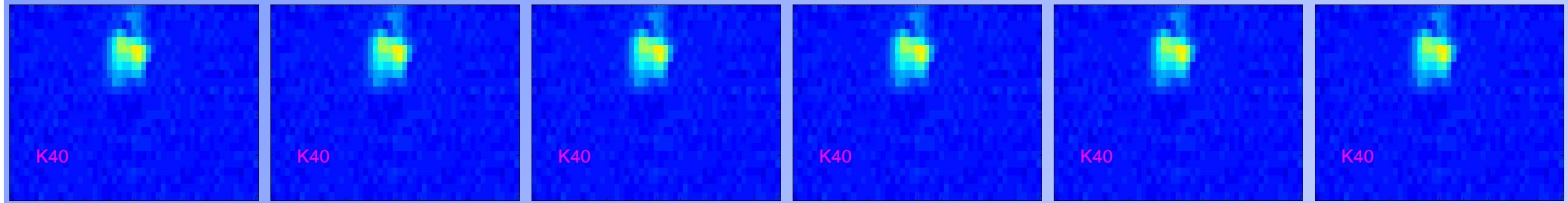




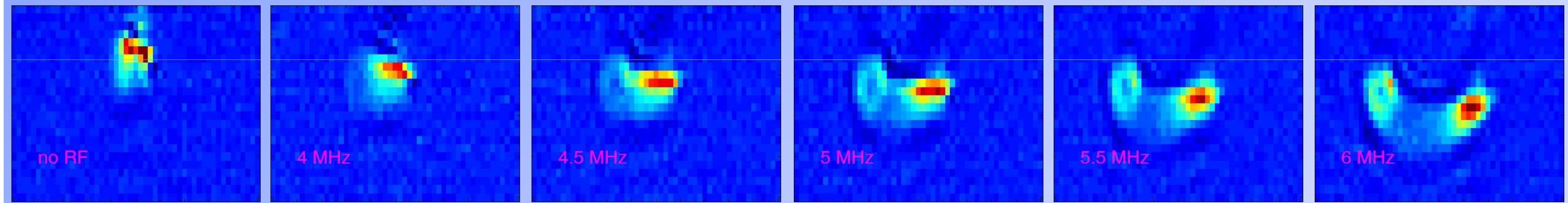
Fringe spacing = *(h · TOF)/(mass · splitting)*

Species-dependent Potentials

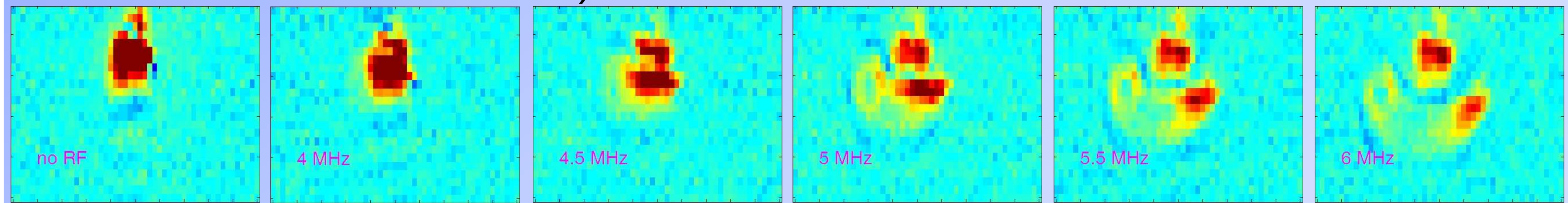
K40 probe (Rb87 present but unseen):



Rb87 probe (K40 present but unseen):



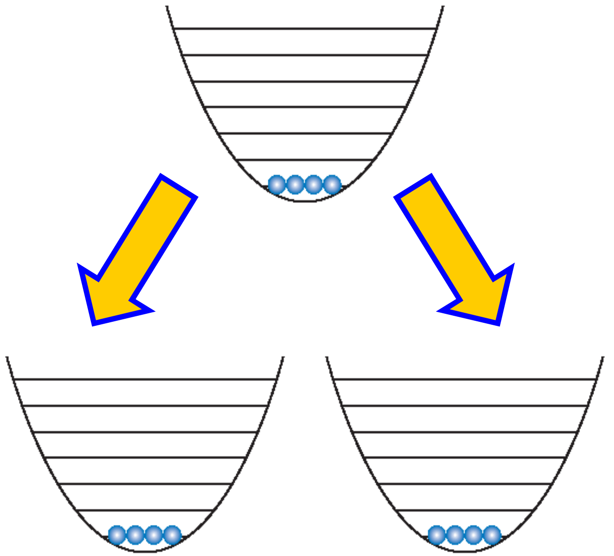
K40 +Rb87 probes (both species visible but apparent O.D. about 50% smaller than actual):



Atomic Physics **20**, 241-249 (2006).

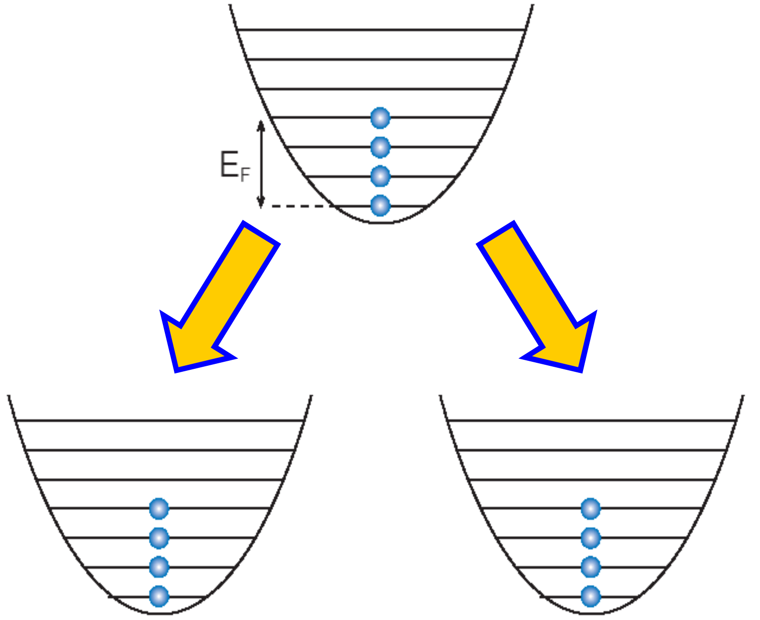
The problem with fermions (I)

BEC beamsplitting



$$|\psi\rangle = \left(|atom\rangle_{left} + e^{i\varphi}|atom\rangle_{right}\right)^N$$

DFG beamsplitting



$$|\psi\rangle = \left(|0\rangle_{left} + e^{i\varphi_0}|0\rangle_{right}\right)\left(|1\rangle_{left} + e^{i\varphi_1}|1\rangle_{right}\right)\ldots$$
$$\ldots\left(|N-1\rangle_{left} + e^{i\varphi_{N-1}}|N-1\rangle_{right}\right)$$

$\varphi_0 = \varphi_1 = \ldots = \varphi_{N-1} \rightarrow$ interference fringes!

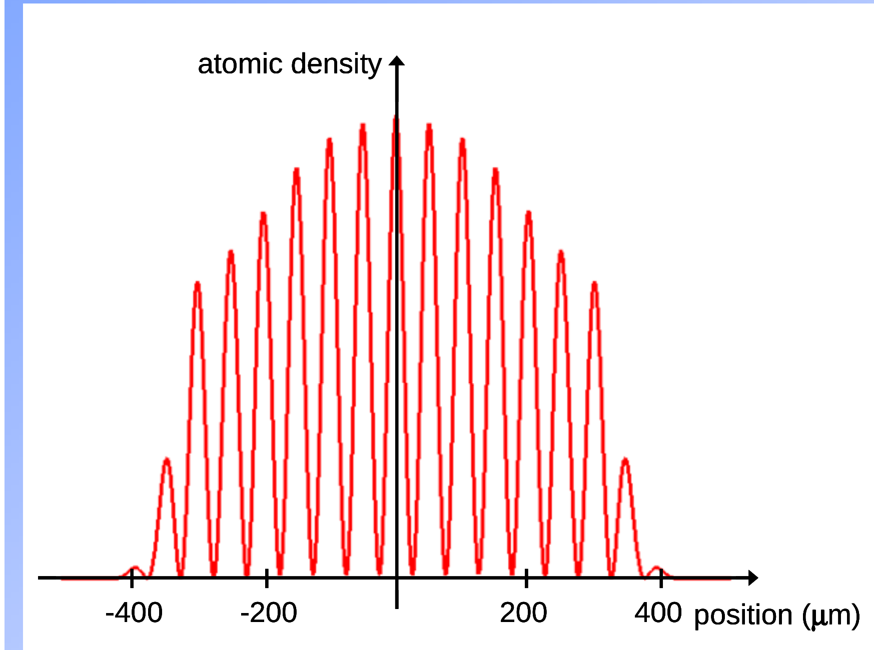
$\varphi_0 \neq \varphi_1 \neq \ldots \neq \varphi_{N-1} \rightarrow$ *interference washed out!*

The problem with fermions (II)

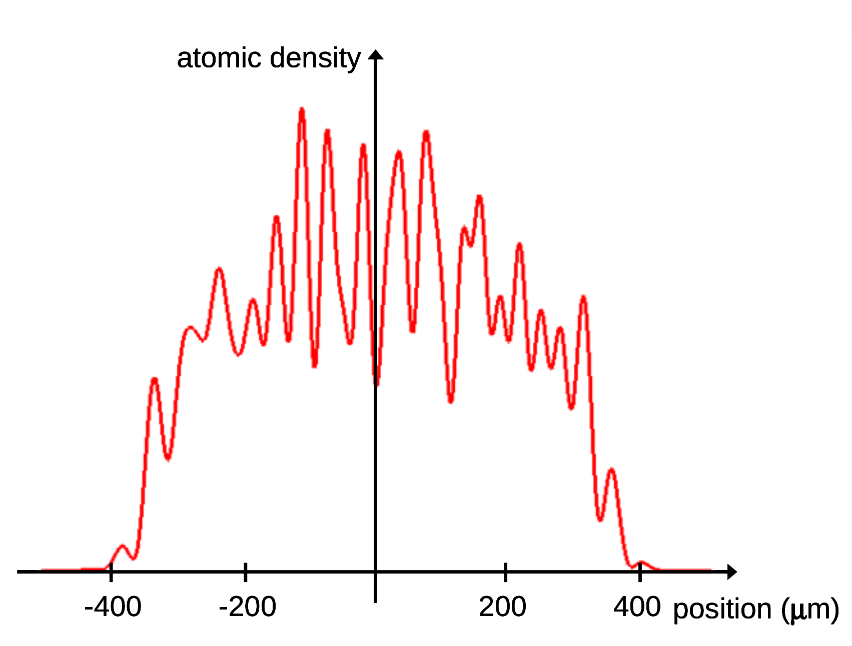
$$|\psi\rangle = \left(|0\rangle_{left} + e^{i\varphi_0}|0\rangle_{right}\right)\left(|1\rangle_{left} + e^{i\varphi_1}|1\rangle_{right}\right)\ldots\left(|N-1\rangle_{left} + e^{i\varphi_{N-1}}|N-1\rangle_{right}\right)$$

Beamsplitting process must not depend on external state of atoms.

$\varphi_0 = \varphi_1 = \ldots = \varphi_9 \rightarrow$ **interference fringes!**



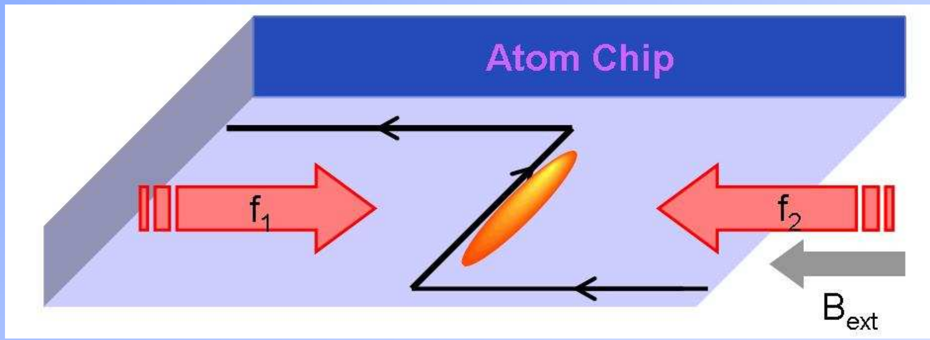
$\varphi_0 \neq \varphi_1 \neq \ldots \neq \varphi_9 \rightarrow$ ***interference washed out!***



Fermion Beamsplitters (I)

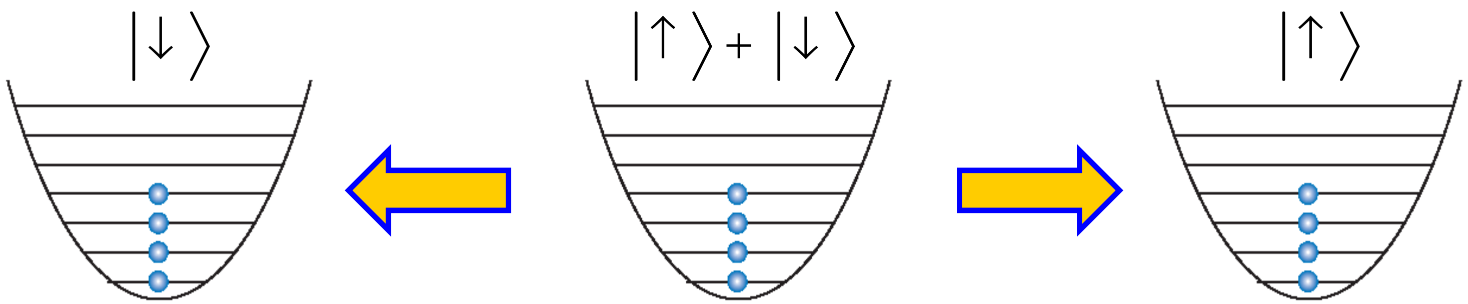
Free space beamsplitter:

→ Bragg pulse beamsplitter



Trapped fermion beamsplitters:

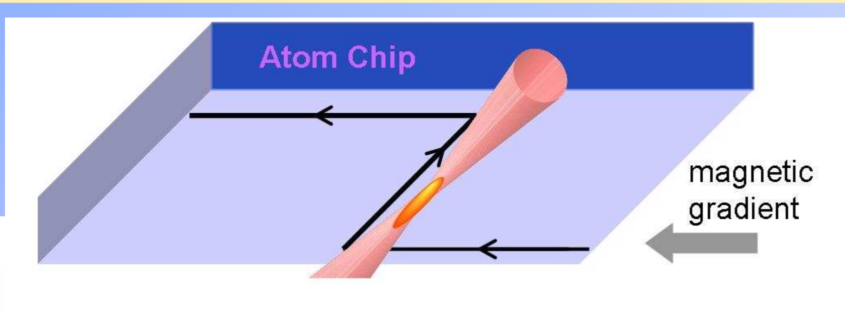
Idea: spin-dependent potential

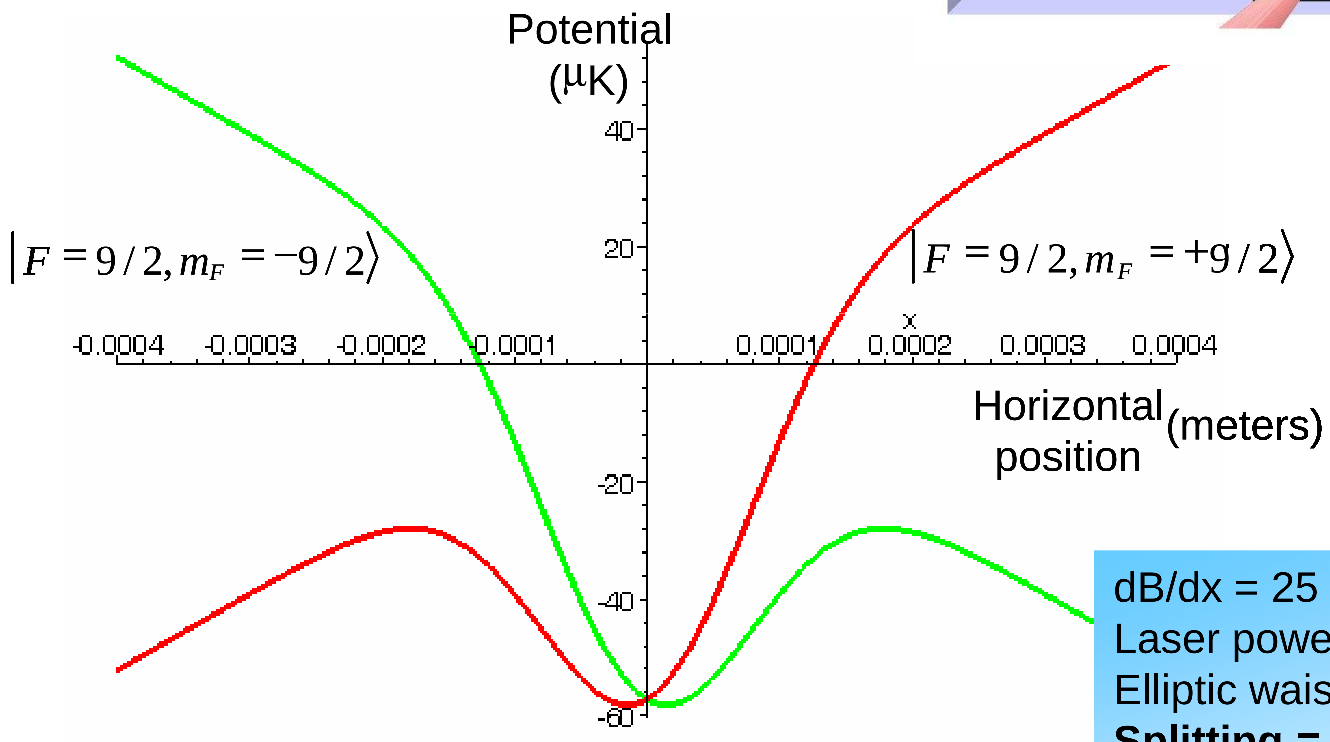


Opposite spins experience same potential, but shifted in opposite directions

Fermion Beamsplitters (II)

Magneto-optical beamsplitter





dB/dx = 25 Gauss/cm
Laser power = 2.5 W @ 1064 nm
Elliptic waist = 20 μm × 160 μm
Splitting = 30 μm

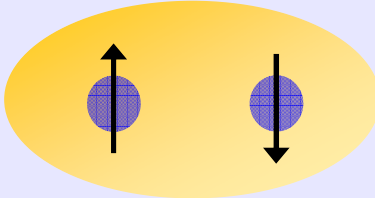
Other possibilites: adiabatic microwave potentials, spin-dependent lattices.

Long Term Future:

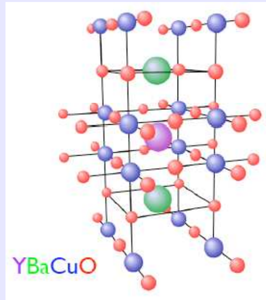
Novel Many-Body Physics

with Polar Molecules

Odd-wave Cooper Pairing



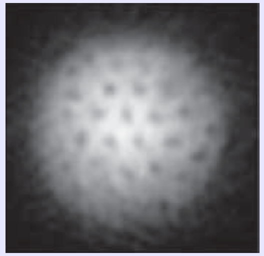
BCS superconductors/superfluids
The Cooper pair consists of S-wave pairing of spin ↑ and spin ↓ particles (S=0, L=0).



[Figure from K. Madison, UBC]

High-T_c superconductors
The pairing mechanism is D-wave in nature.

Superfluid ^{3}He
Cooper pair has P-wave orbital angular momentum.



Superfluid ultra-cold degenerate Fermi Gas
The pairing mechanism is S-wave in nature.

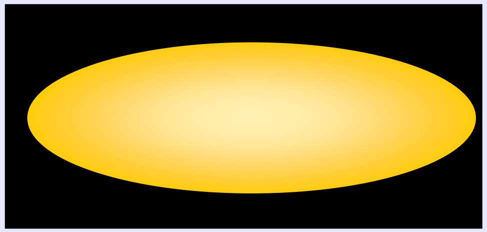
M. Zwierlein et al.,
Nature 435, 1047 (2005)

Ultra-cold Polar Molecular Gases

Predictions: → Superfluidity with odd-wave Cooper pairing.

[M. A. Baranov et al., PRA 66, 013606 (2002)]

→ Ferro-electric (super?)fluid.



[M. Iskin et al., PRL 99, 110402 (2007)]

Fermionic Superfluid KRb

Electric dipole moment of the ground state of KRb is $d = 0.3\,\mathrm{ea}_0$

[Kotochigova et al. PRA 68, 022501 (2003)]

Following the treatment of M. A. Baranov et al., PRA 66, 013606 (2002)

$$a_d = -\frac{2md^2}{\pi^2\hbar^2} = -2250\ \mathring{\mathrm{A}}$$

$$\frac{T_c}{T_F} = 1.44\exp\left(-\frac{\pi\hbar}{2p_F|a_d|}\right)$$

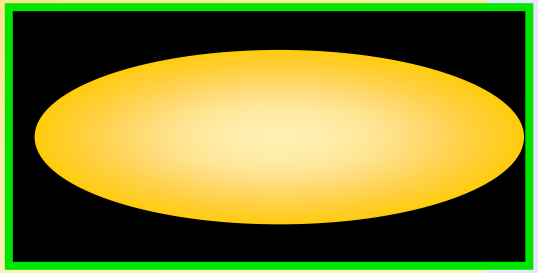
T_c = critical temperature for superfluidity

For 10^4 fermionic $^{40}K^{87}Rb$ molecules in a trap with f_r = 500 Hz and f_z = 30 Hz, we get

$n = 3 \times 10^{13}$ molecules/cm^3

$T_F = 0.6\ \mu K$

$T_c/T_F = 0.8 \rightarrow T_c = 0.5\ \mu K$



How do you get Ultra-Cold KRb?

Feshbach Resonance

→ weakly bound KRb in $a^3\Sigma^+$ potential

+

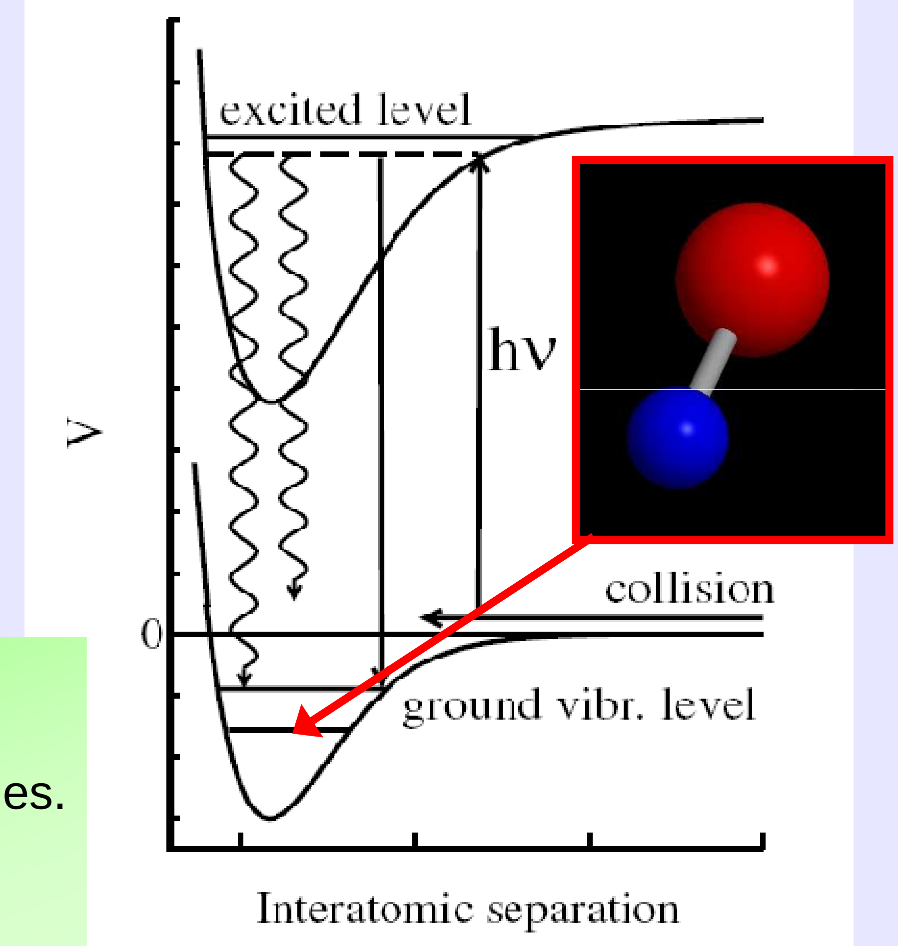
Photo-association

→ stimulated transition to the ground state. (STIRAP)

Advantages of ultra-cold atoms:

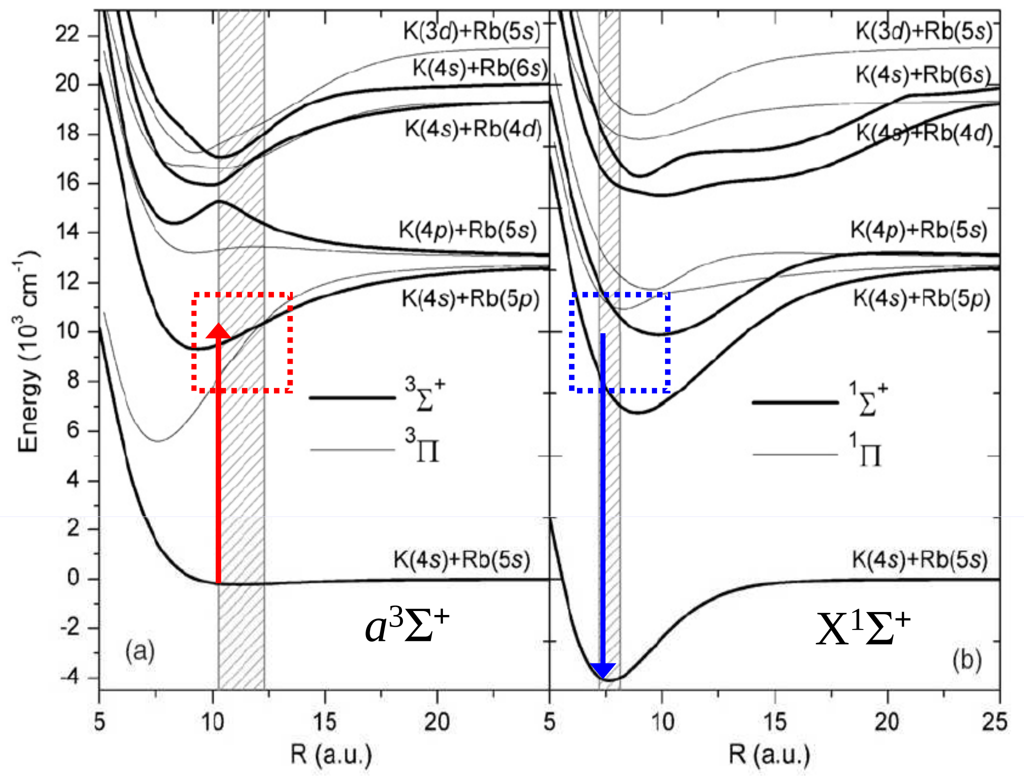
1. Small cloud size
   → focused laser & high Rabi frequencies.

2. Feshbach molecule is already made
   → just need to reduce binding energy.



S. Kotochigova et al., Eur. Phys. J. D 31, 189–194 (2004).

STIRAP to KRb ground states



[figure adapted from R. Beuc et al., *J. Phys. B* **39**, S1191 (2006).]

STIRAP paths

excited $a^3\Sigma^+$ → ground state $X^1\Sigma^+$

***Intermediate level:* $2^1\Sigma^+ + 1^3\Pi^+$**

1190 nm & 795 nm

W. C. Stwalley, *EPJD* **31**, 221 (2004).

1321 nm & 866 nm

M. Tschernek *et al.*, *PRA* **75**, 055401 (2007).

1575 nm & 950 nm

S. Kotochigova *et al.*, *EPJD* **31**, 189 (2004).

***Intermediate level:* $2^3\Sigma^+ + 1^1\Pi^+$**

870 nm & 640 nm

Sage et al., *PRL* **94**, 203001 (2005).

STIRAP path

excited $a^3\Sigma^+$ → ground state $a^3\Sigma^+$

***Intermediate level:* $2^3\Pi^+$**

746 nm & 732 nm

R. Beuc et al., *J. Phys. B* **39**, S1191 (2006).

How do you lock the STIRAP lasers?

… Or how do you make a ruler for optical frequencies?

- **Fabry-Perot cavities**

  → Established technology

  → Slow, piezo non-linearities make frequency determination more difficult.

  E. Gomez, S. Aubin, L. A. Orozco, G. D. Sprouse, E. Iskrenova-Tchoukova, and M. S. Safronova, "Nuclear Magnetic Moment of 210Fr: A combined Theoretical and Experimental Approach", *Phys. Rev. Lett.* **100**, 172502 (2008).

- **Frequency combs**

  → Fast and linear.

  → Femtosecond comb is ideal solution, but expensive.

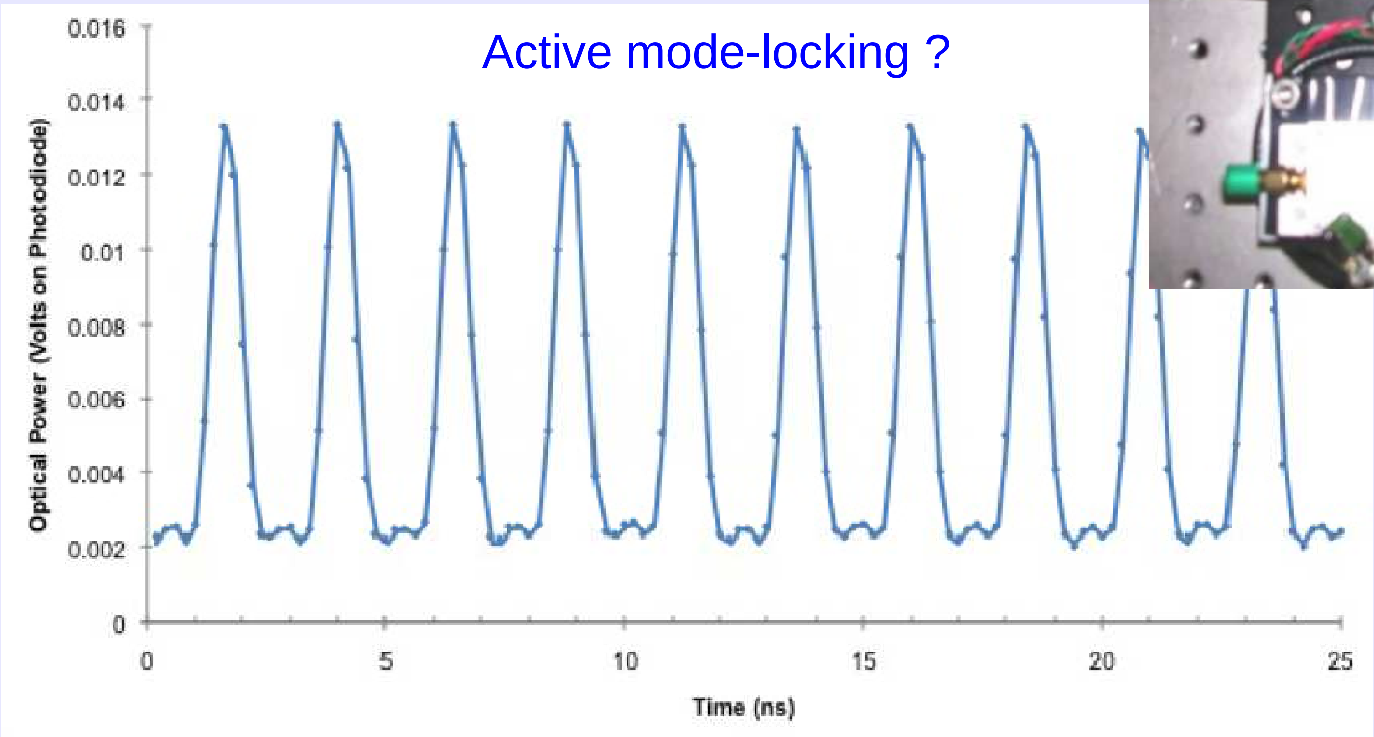
  → Hybrid mode-locked diode laser are cheaper, but not as broad.

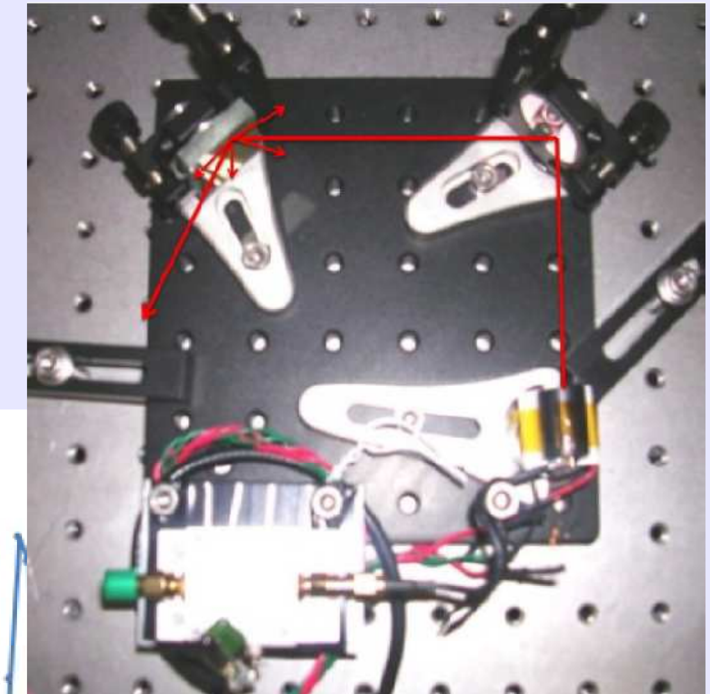
Recent News

External cavity diode laser frequency comb:

► Actively modulate current at external cavity FSR.

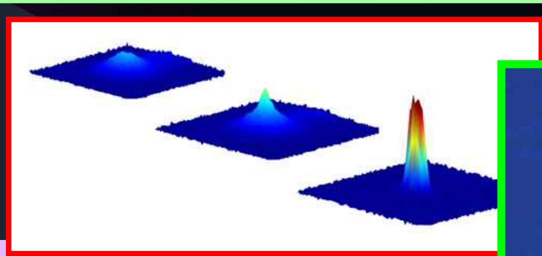
► Look for pulses.

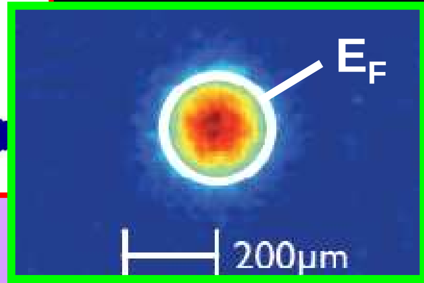




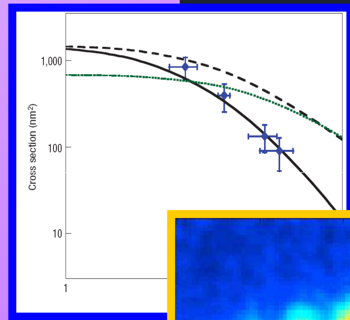
Next steps: look at bandwidth of comb and pulse width

Summary

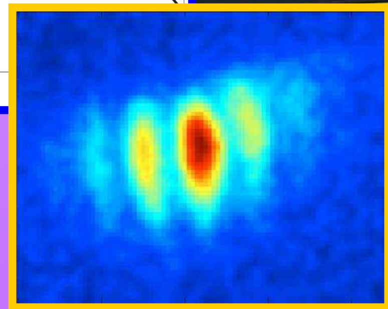




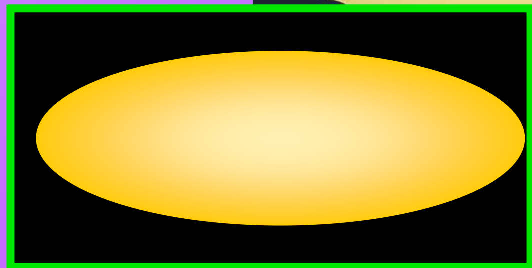
- Degenerate **Bose-Fermi mixture** on a chip.



- **^{40}K-^{87}Rb cross-section** measurement.
- W&M quantum degeneracy apparatus.



- **BEC Interferometry**.



- Future: **Fermion Interferometry**
- Future: Ultra-cold **polar molecules**.

Thywissen Group

Colors:

Staff/Faculty
Postdoc
Grad Student
Undergraduate

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B. Cieslak

M. H. T. Extavour

L. J. LeBlanc

D. McKay

S. Myrskog

A. Stummer

T. Schumm

J. H. Thywissen

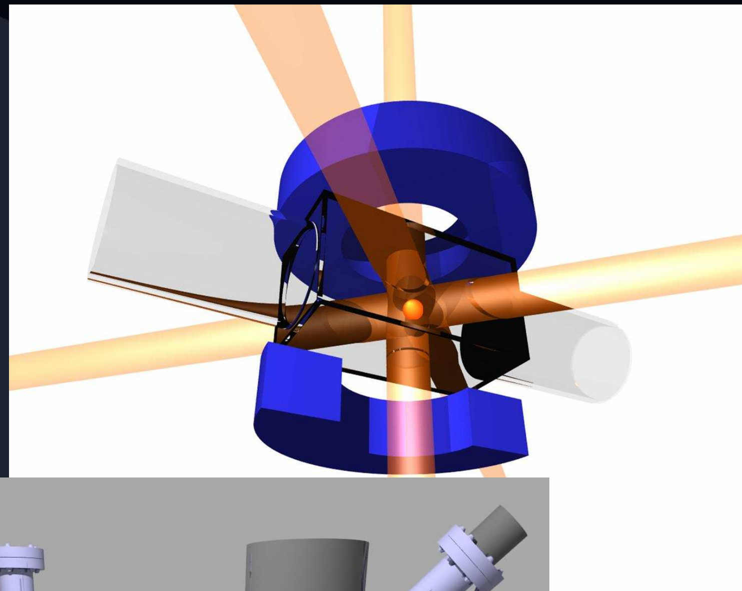
The College of WILLIAM & MARY

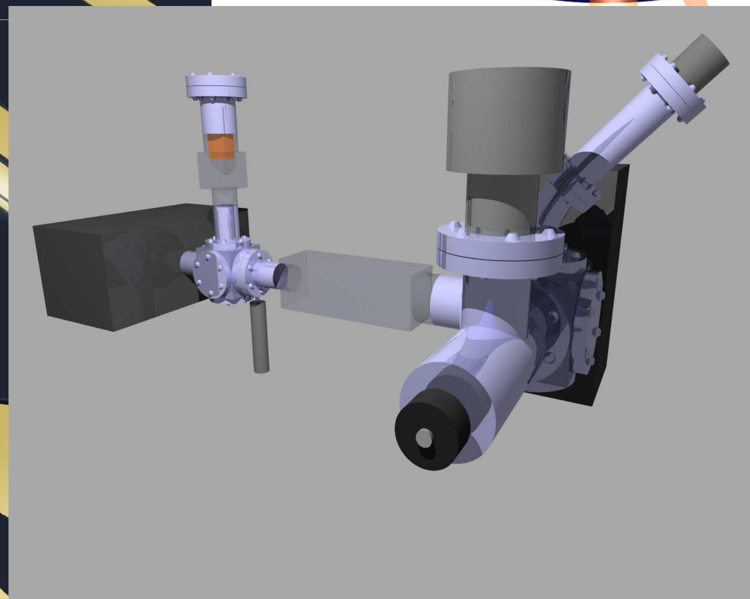
Ultra-cold atoms group

Aiyana Garcia
(magnetic transport)

Brian DeSalvo
(diode laser comb)

Seth Aubin
saaubi@wm.edu





Work supported by Jeffress Memorial Trust and ARO DURIP equipment grant.

The Problem with Fermions

Identical ultra-cold fermions **do not interact**

At very low temperatures, $\vec{l} = \vec{r} \times \vec{p} \;\longrightarrow 0$

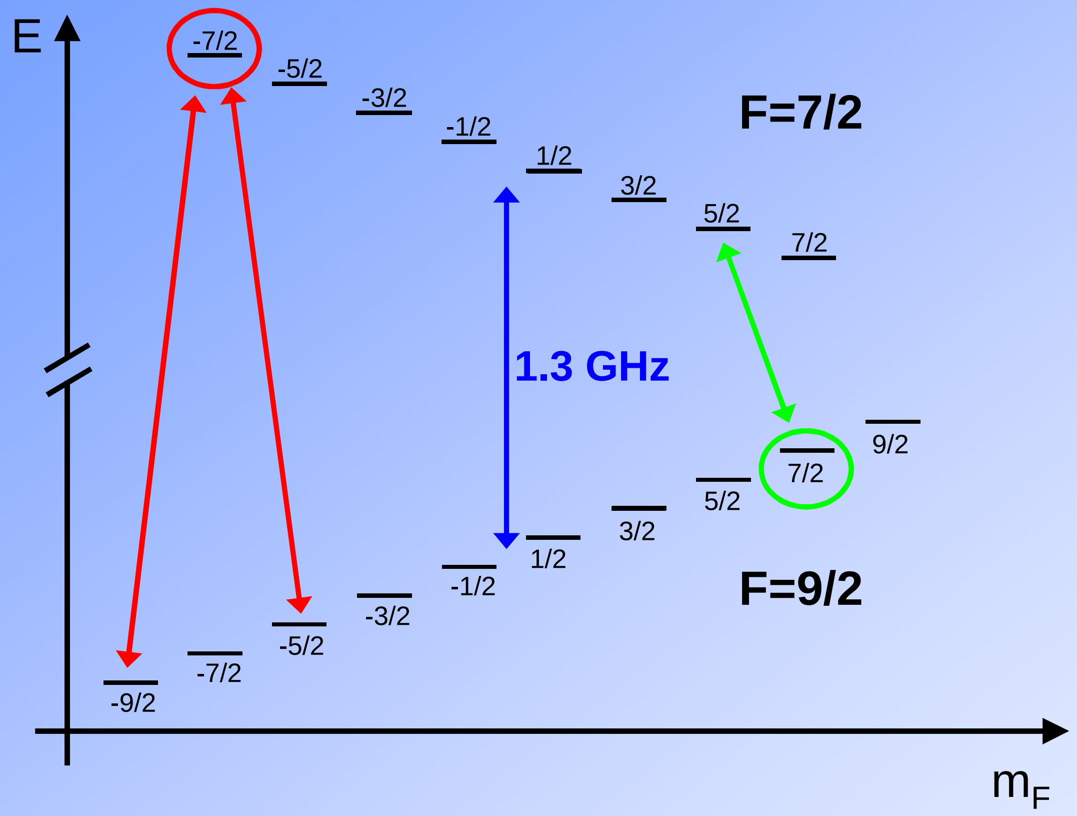
If $l \rightarrow 0$, then two atoms must scatter as an s-wave:

$$\Psi_{s-wave}(\vec{r} = \vec{r}_1 - \vec{r}_2) = e^{+ikz} \pm e^{-ikz} + 2a_s \frac{e^{ik|\vec{r}|}}{|\vec{r}|}$$

$\psi_{\text{s-wave}}$ **is symmetric** under exchange of particles: $\vec{r} \longrightarrow -\vec{r}$

$\mathbf{a_s}$ = 0 for fermions

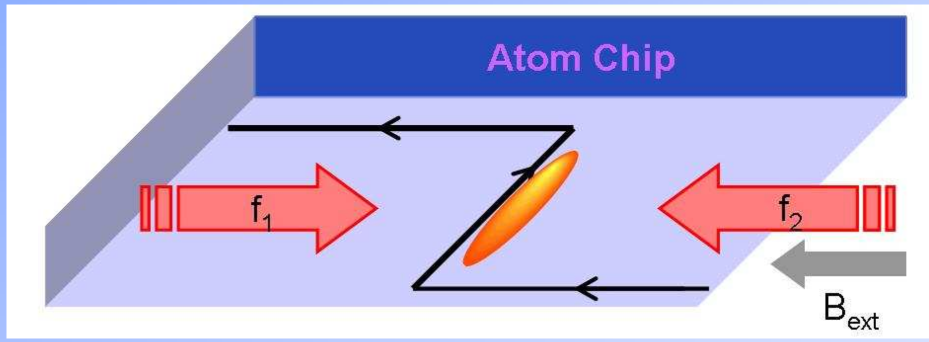
Fermion Beamsplitters



Fermion Beamsplitters (I)

Free space beamsplitter:

→ Bragg pulse beamsplitter



Trapped fermion beamsplitters:

- Spin-dependent adiabatic microwave potential