WILLIAM & MARY

Ultracold Atom Technology for Fundamental Physics

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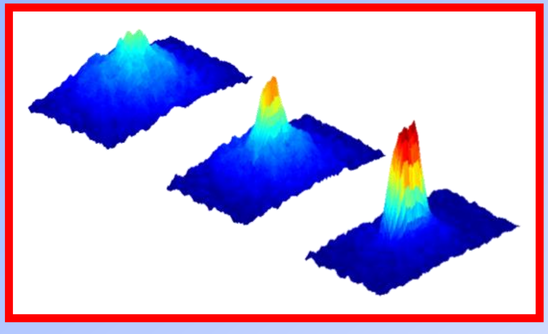
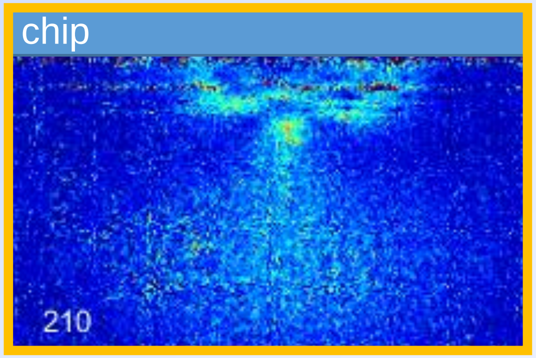
Undergrad Seminar, W&M Physics

Outline



- Intro to Ultra-cold Matter
  - → **What is it ?**
  - → **How do you make it ?**
  - → **Bose-Einstein Condensates**

- Physics with ultra-cold matter
  - → **Microwave traps for atom interferometry**



How cold is Ultra-Cold?

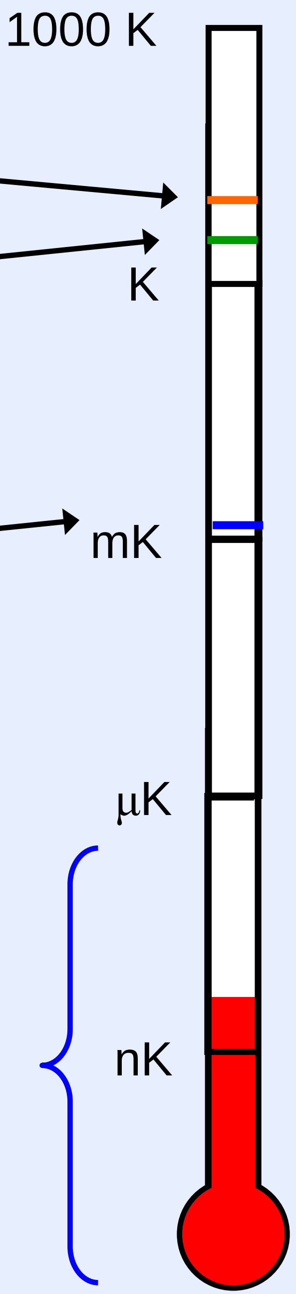
room temperature, 293 K

[priceofoil.org, 2008]

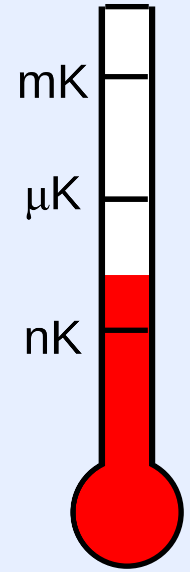
Antarctica, ~ 200 K

Dilution refrigerator, ~ 2 mK

Ultra-cold quantum temperatures

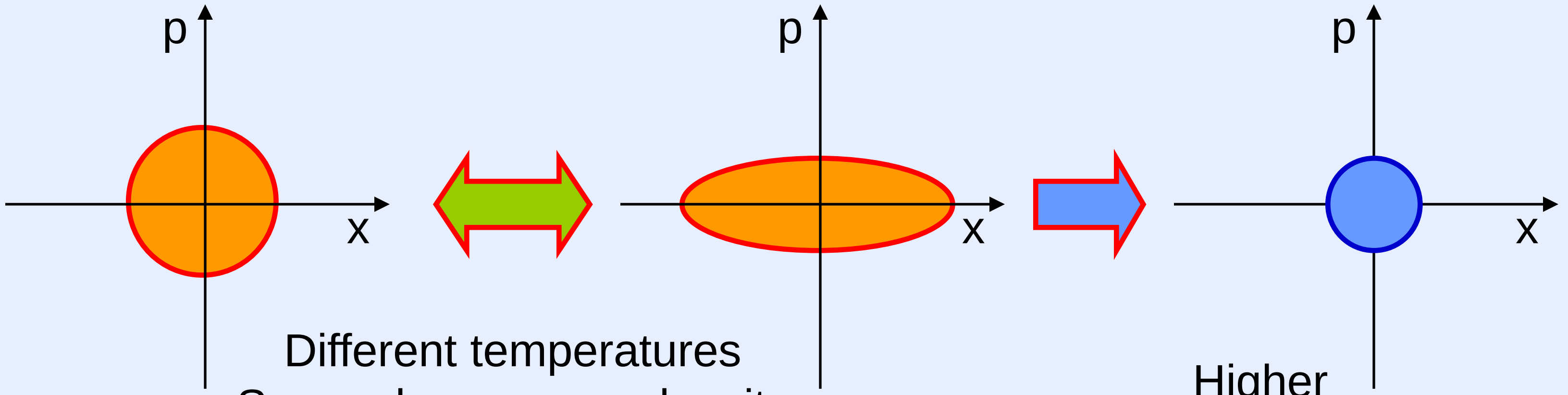


What's Ultra-Cold Matter ?



- **Very Cold**
  - → Typically nanoKelvin – microKelvin
  - → Atoms/particles have velocity ~ mm/s – cm/s

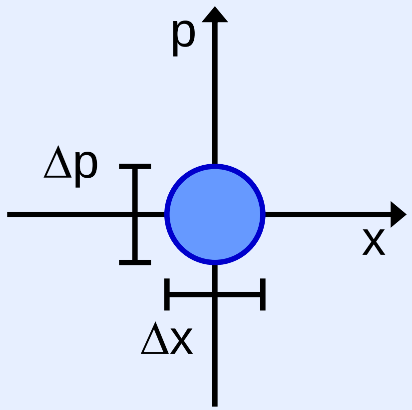
- **Very Dense … in Phase Space**



Different temperatures
Same phase space density

Higher
phase space density

Ultra-cold Quantum Mechanics



Quantum mechanics requires

$$\Delta x \cdot \Delta p \geq \hbar/2$$

→ fundamental unit of phase space volume

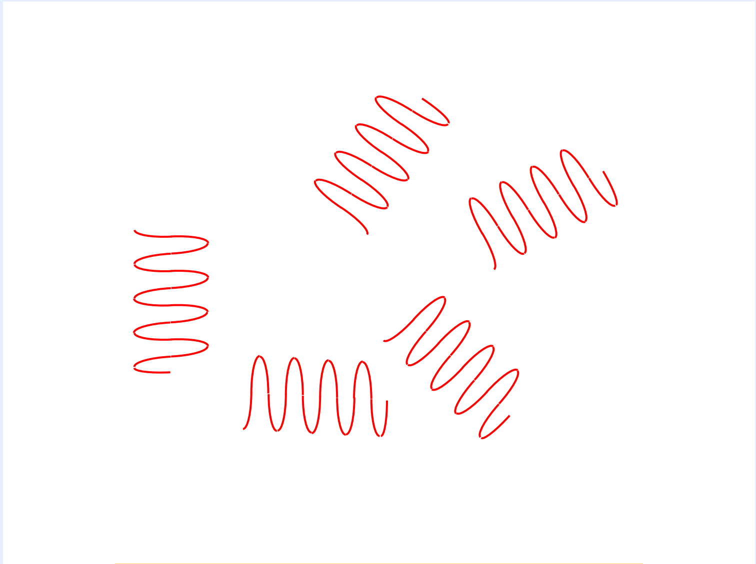
$$\Delta x \cdot \Delta p = \hbar/2$$

→ Quantum physics is important when $\mathrm{PSD} \sim 1$

Equivalent:

deBroglie wavelength ~ inter-particle separation

$$n\lambda_{deBroglie} \sim 1$$



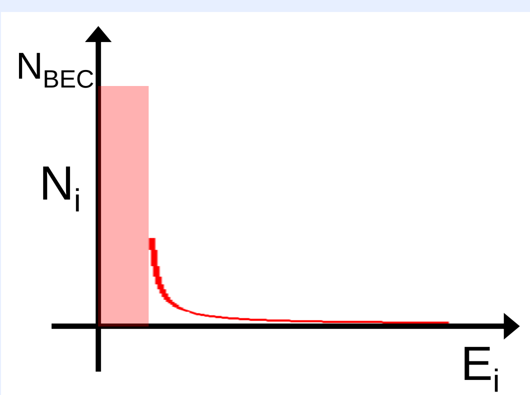
Boltzmann régime

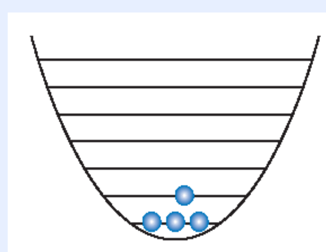
Quantum Statistics

Bosons

- **symmetric** multi-particle wavefunction.
- **Integer spin**: photons, ^{87}**Rb**.
- probability of occupying a state |i> with energy E_i.

$$P(E_i) \propto \frac{1}{e^{(E_i-\mu)/kT} - 1}$$

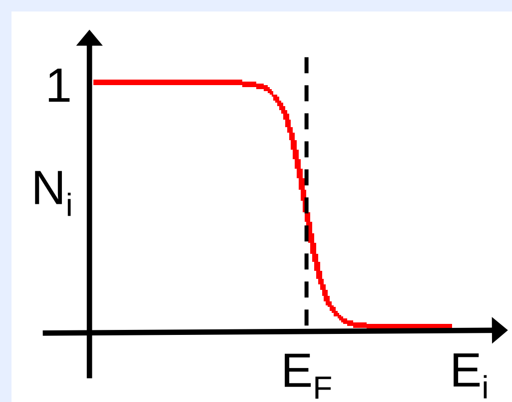


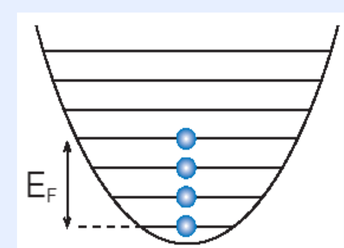


Fermions

- **anti-symmetric** multi-particle wavefunction.
- **½-integer spin**: electrons, protons, neutrons, ^{40}**K**.
- probability of occupying a state |i> with energy E_i.

$$P(E_i) \propto \frac{1}{e^{(E_i-\mu)/kT} + 1}$$

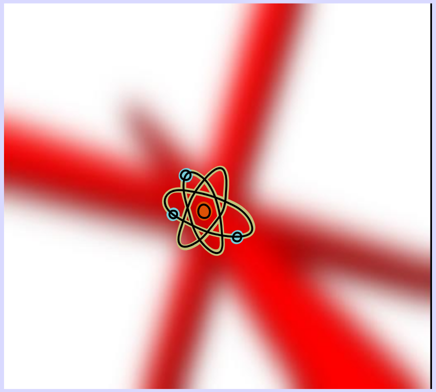




How do you make ULTRA-COLD matter?

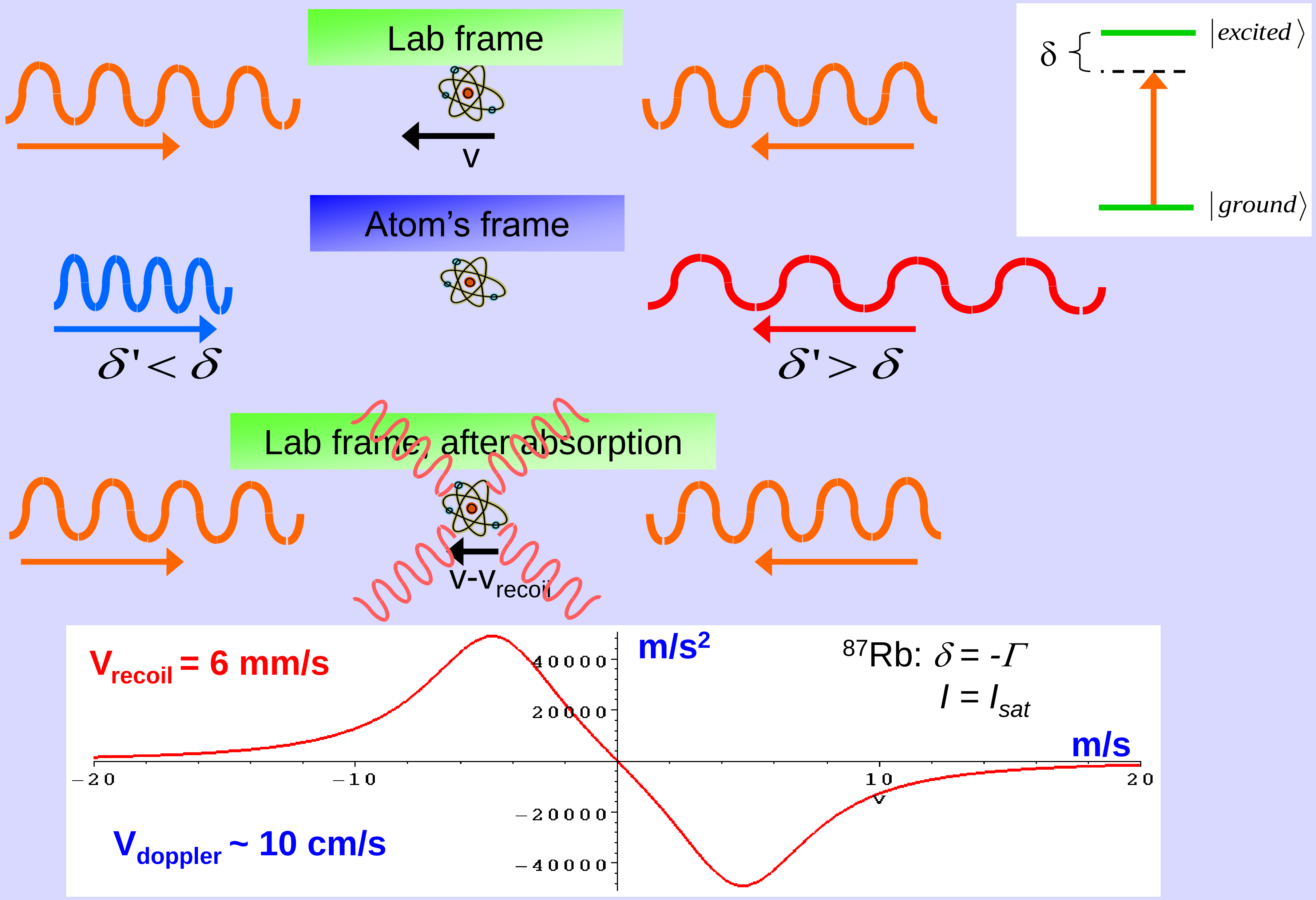
Two step process:

1. Laser cooling
   - Doppler cooling
   - Magneto-Optical Trap (MOT)



2. Evaporative cooling
   - Magnetic traps
   - RF Evaporation

Doppler Cooling



Magneto-Optical Trap (MOT)

Problem:

Doppler cooling reduces momentum spread of atoms only.

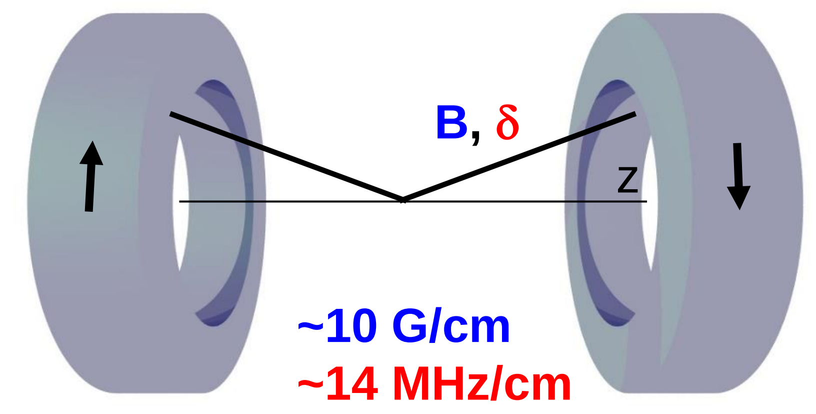
→ Similar to a damping or friction force.

→ Does not reduce spatial spread.

→ Does not confine the atoms.

Solution:

Spatially tune the laser-atom detuning with the Zeeman shift from a spatially varying **magnetic field**.



Magneto-Optical Trap (MOT)

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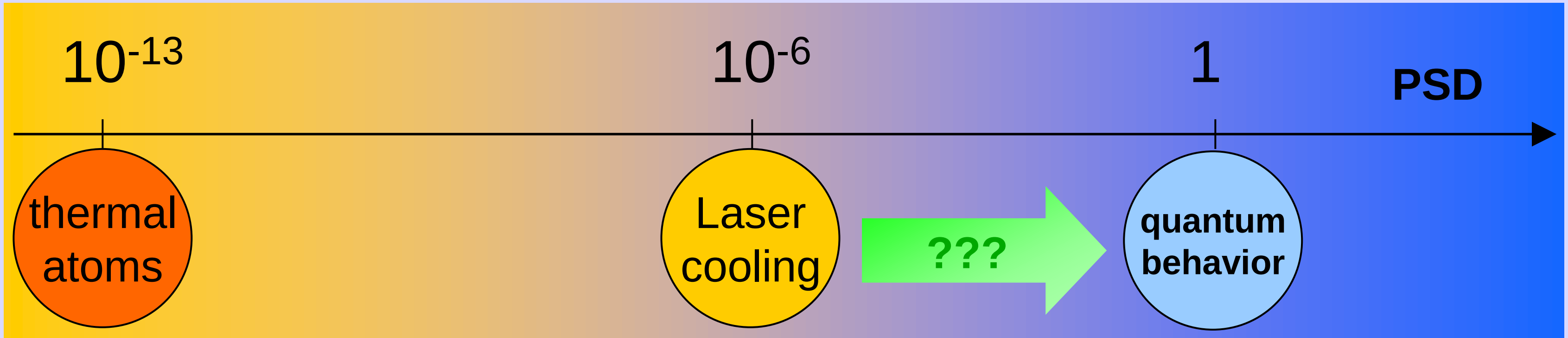
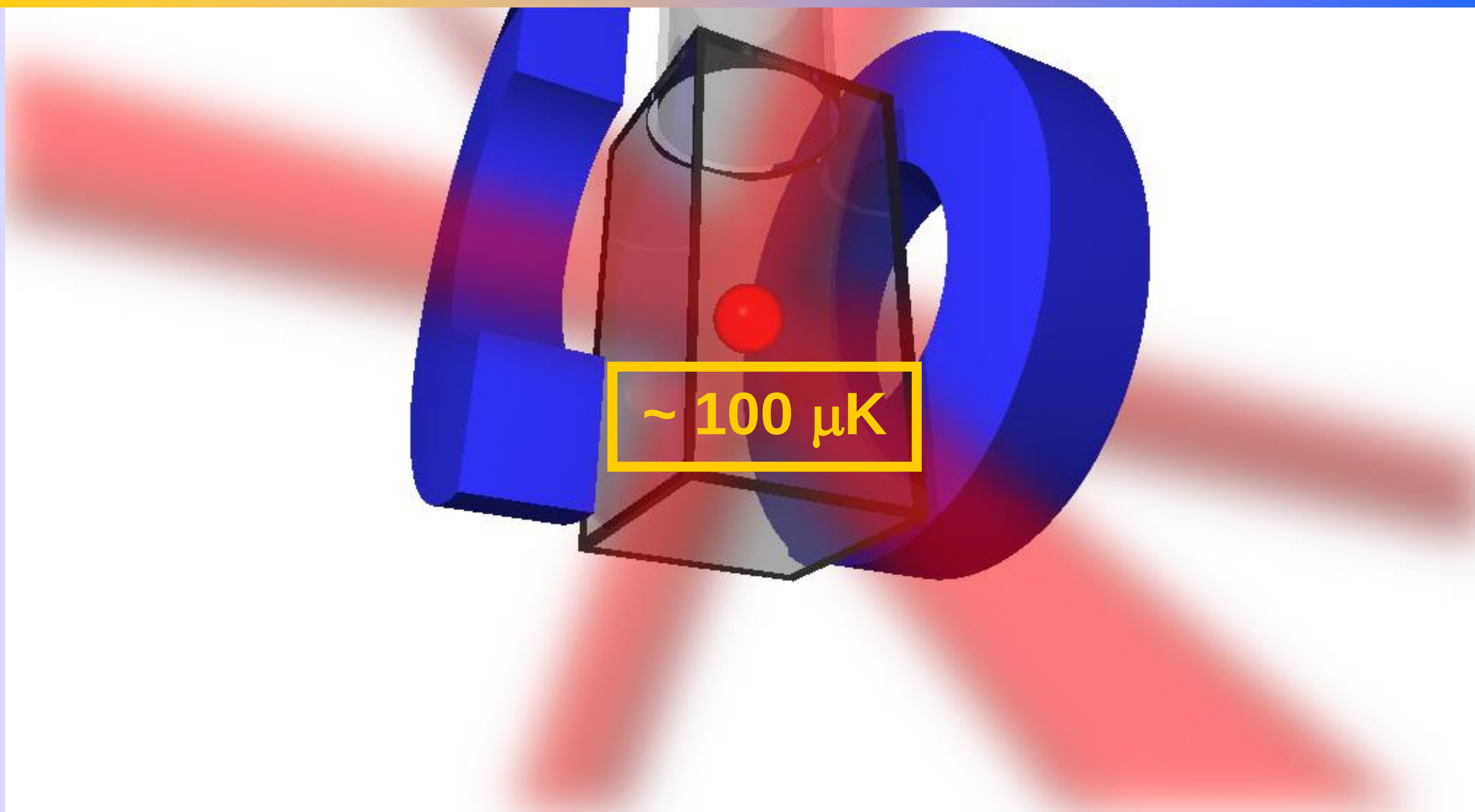
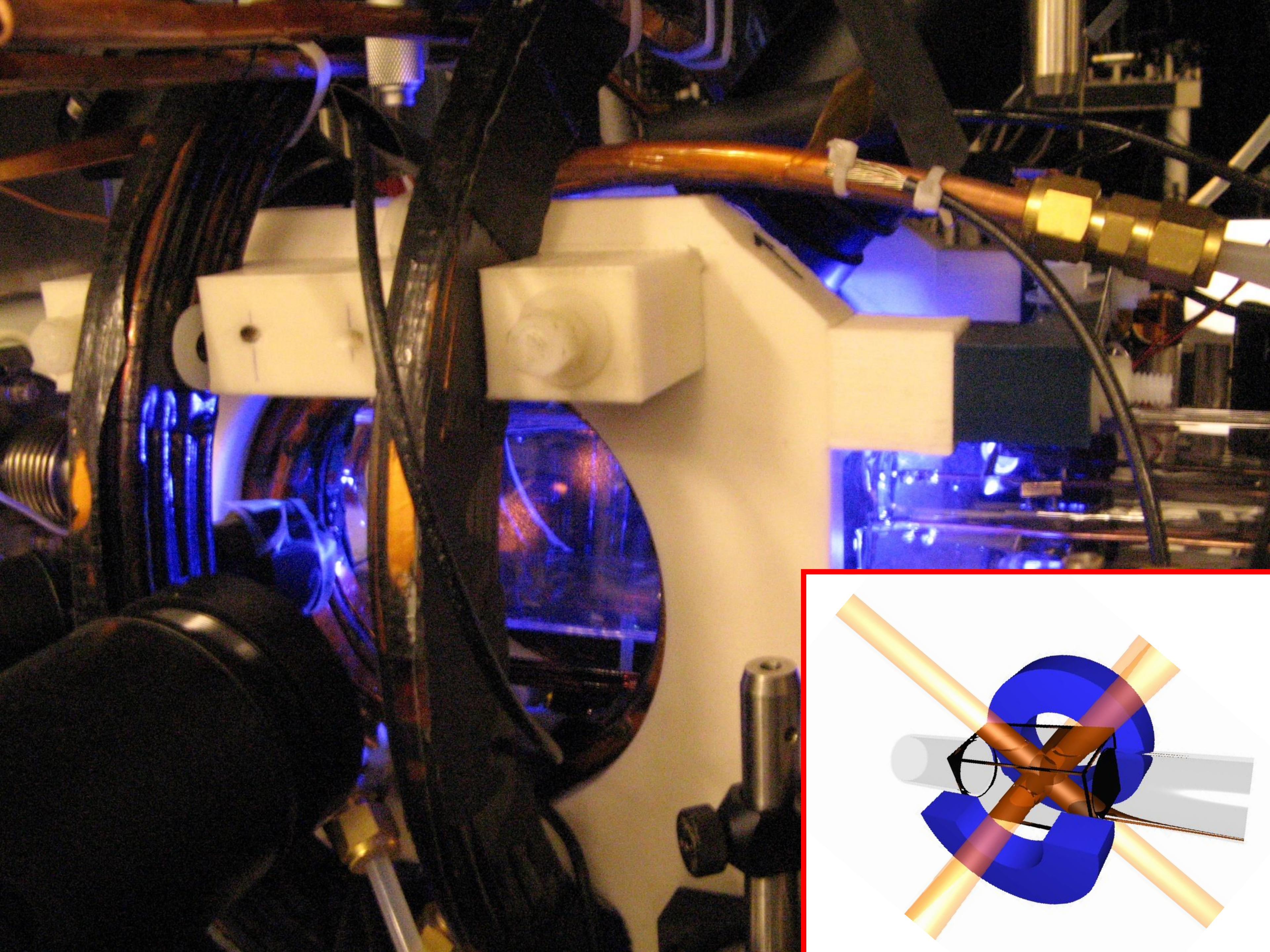
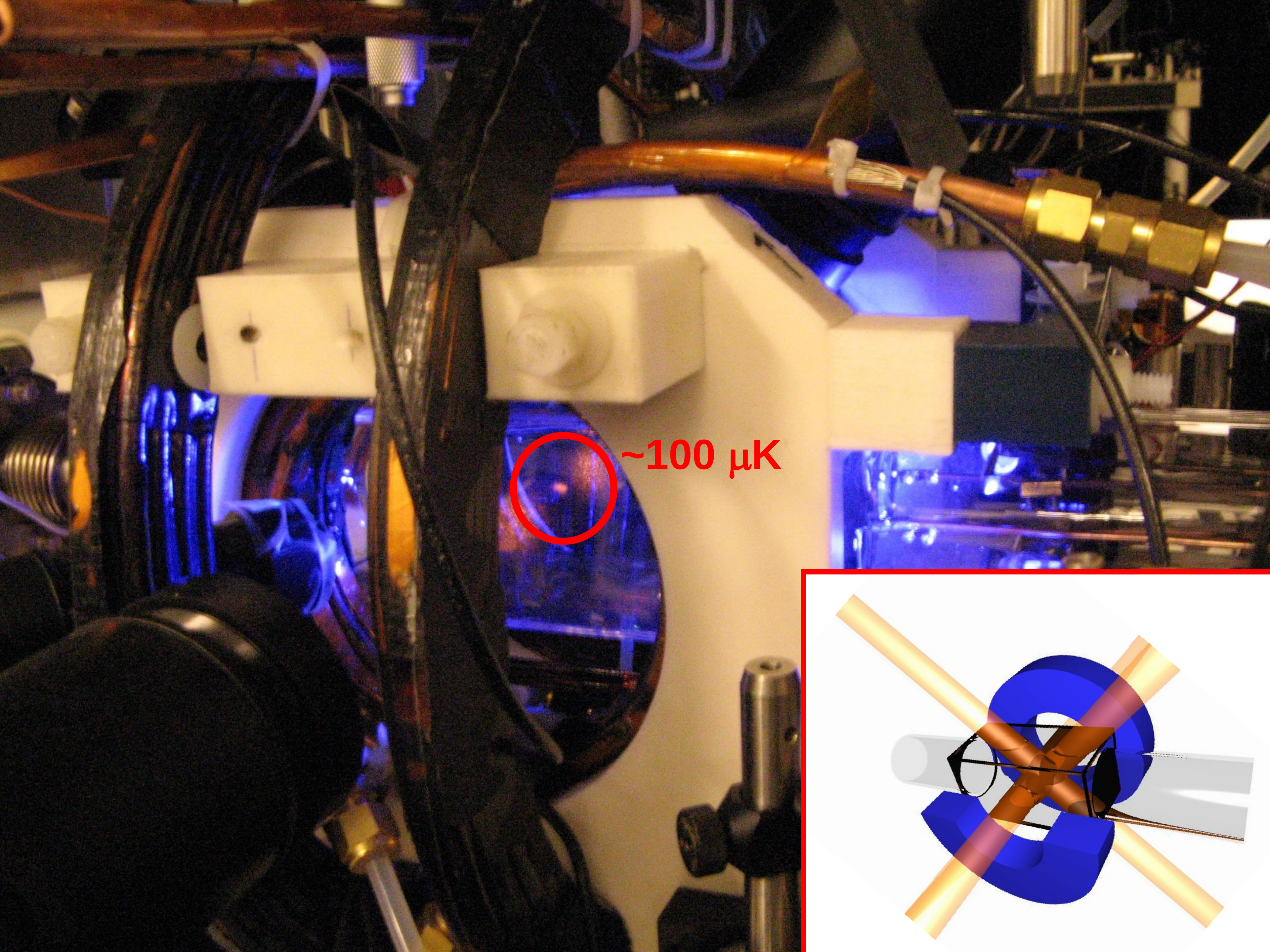
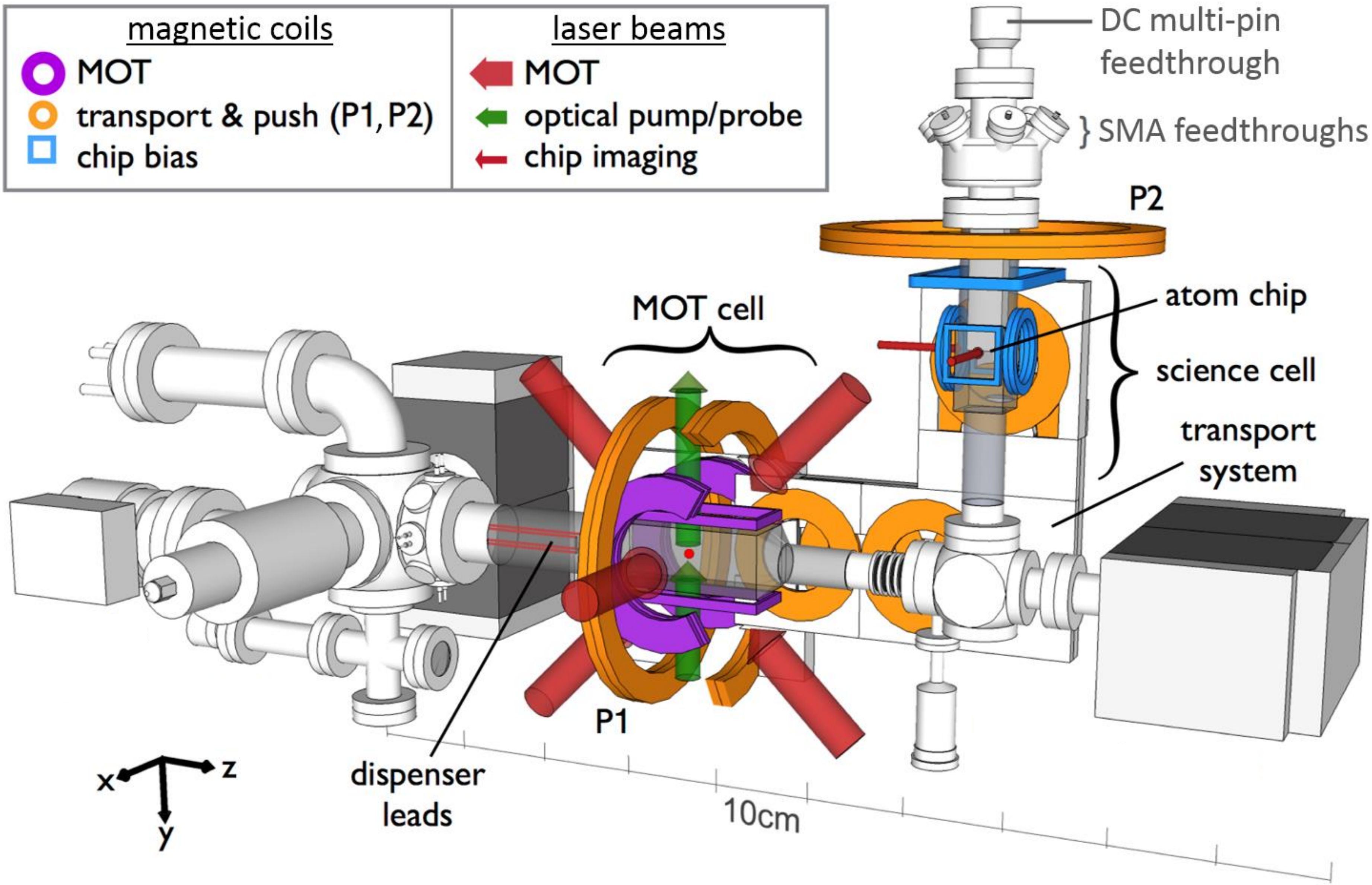







~100 μK

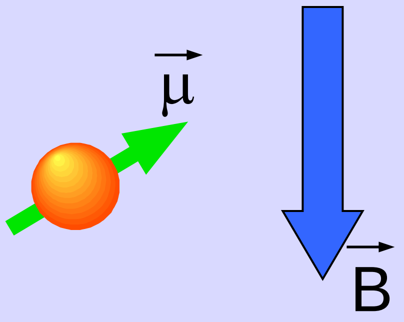
BEC Apparatus



Magnetic Traps

Interaction between external magnetic field and atomic magnetic moment:

$$U = -\vec{\mu} \cdot \vec{B}$$



For an atom in the hyperfine state $|F, m_F\rangle$

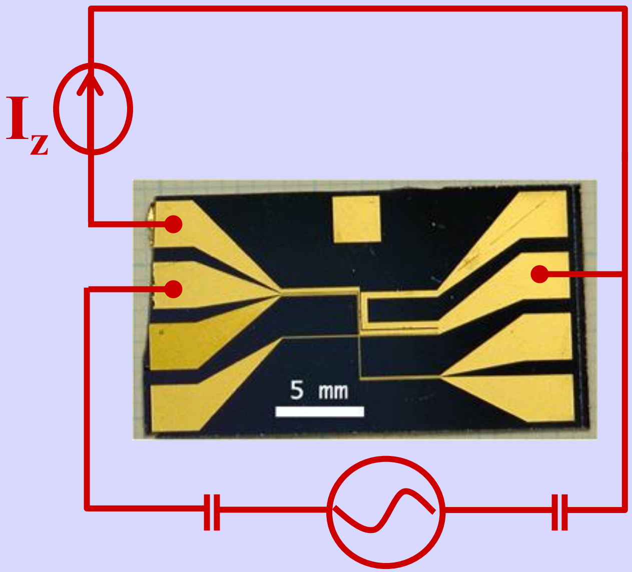
$$\cos\theta = m_F / F \quad \Rightarrow \quad U = g_F m_F \mu_B |\vec{B}|$$

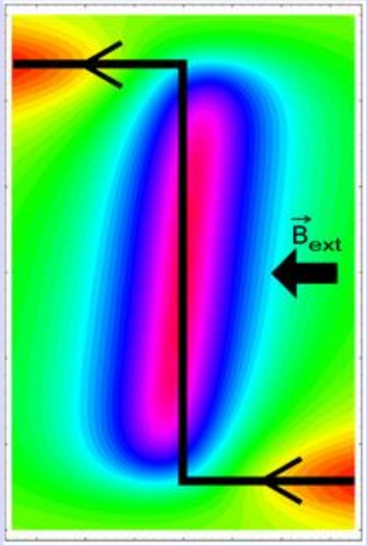
Energy = minimum ⟷ |B| = minimum

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.
- Single vacuum chamber apparatus.





Evaporative Cooling

Remove most energetic (hottest) atoms

Wait for atoms to rethermalize among themselves

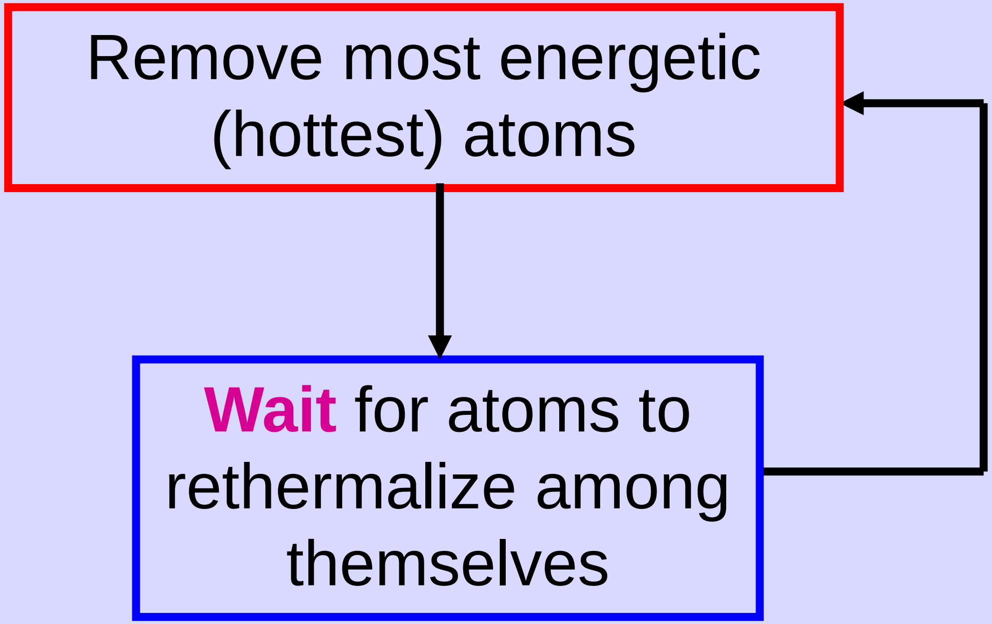
Wait time is given by the elastic collision rate $k_{elastic} = n\,\sigma\,v$

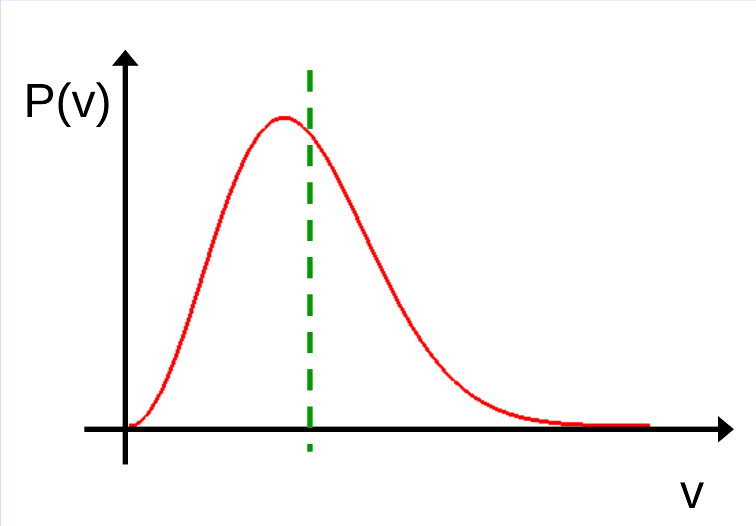
Macro-trap: low initial density, evaporation time ~ 10-30 *s*.

Micro-trap: high initial density, **evaporation time ~ 1-2 *s*.**

Sweep RF "knife" from 20 MHz to 3 MHz.

Evaporative Cooling





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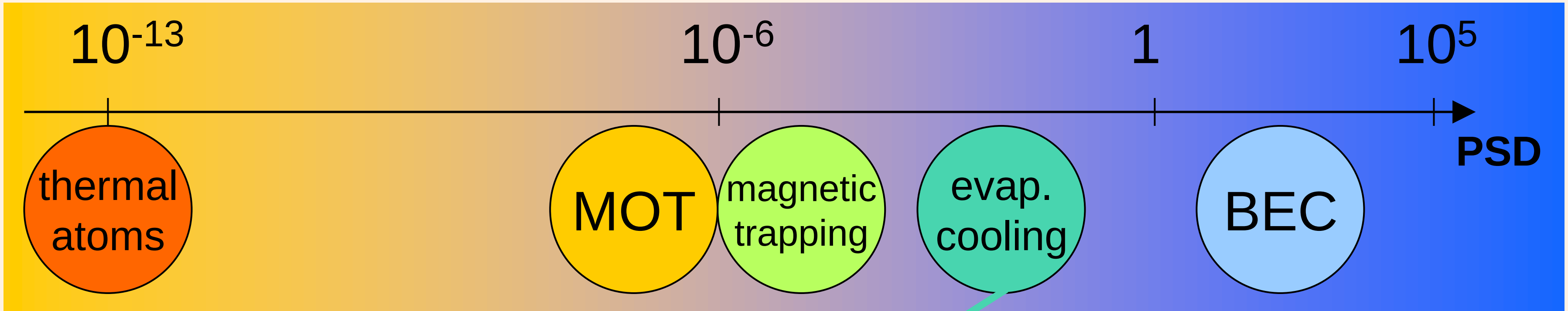
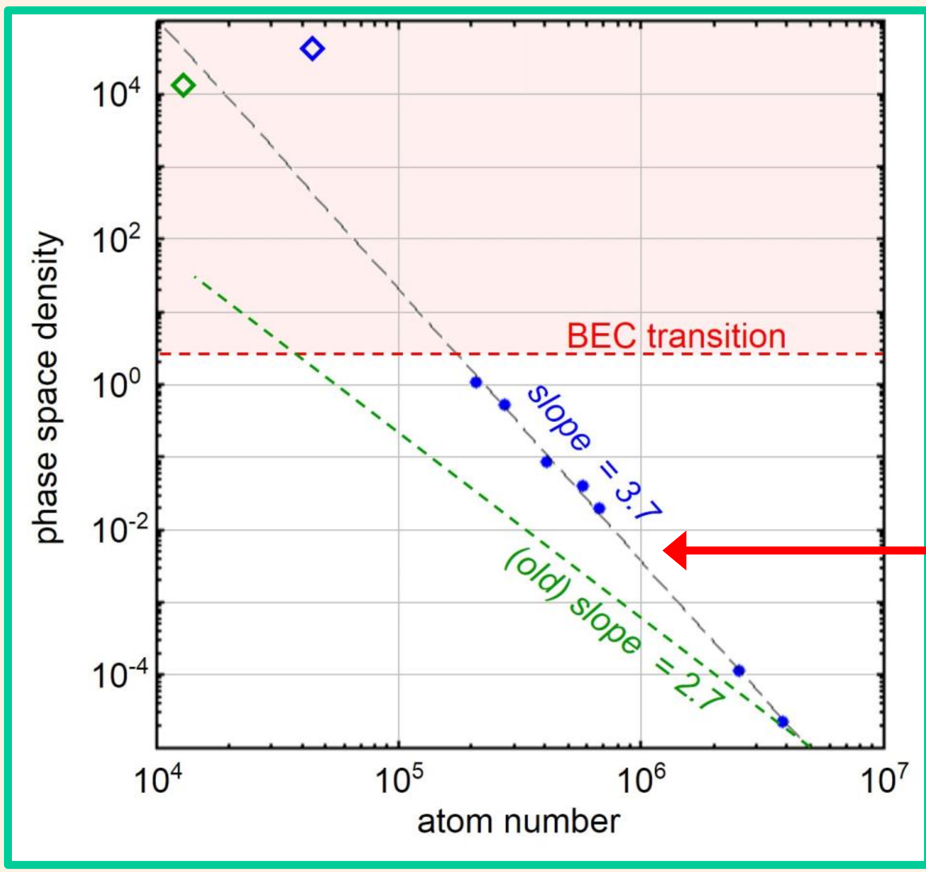
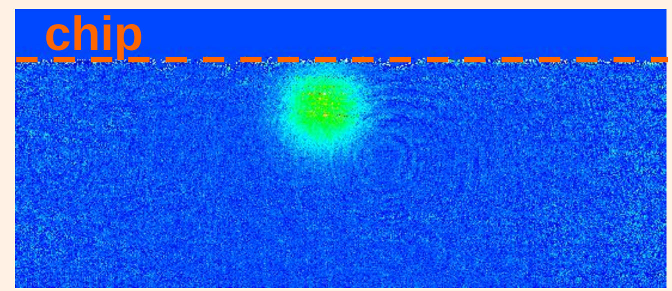
Bose-Einstein Condensation of ^{87}Rb



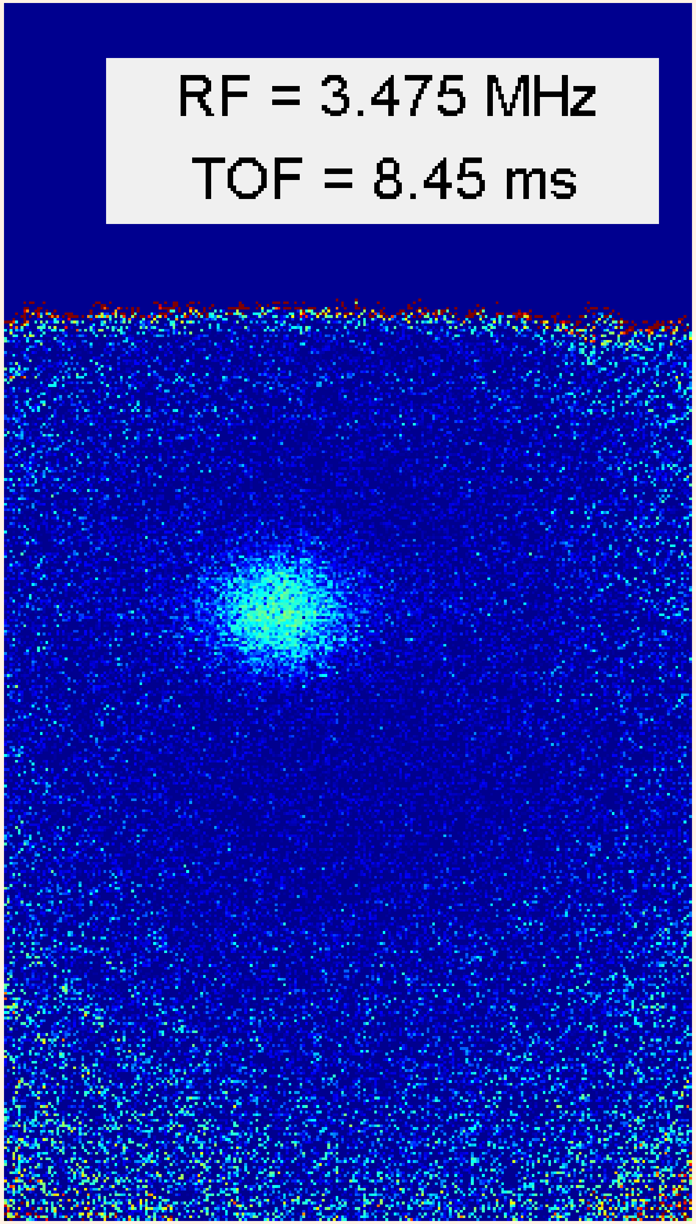




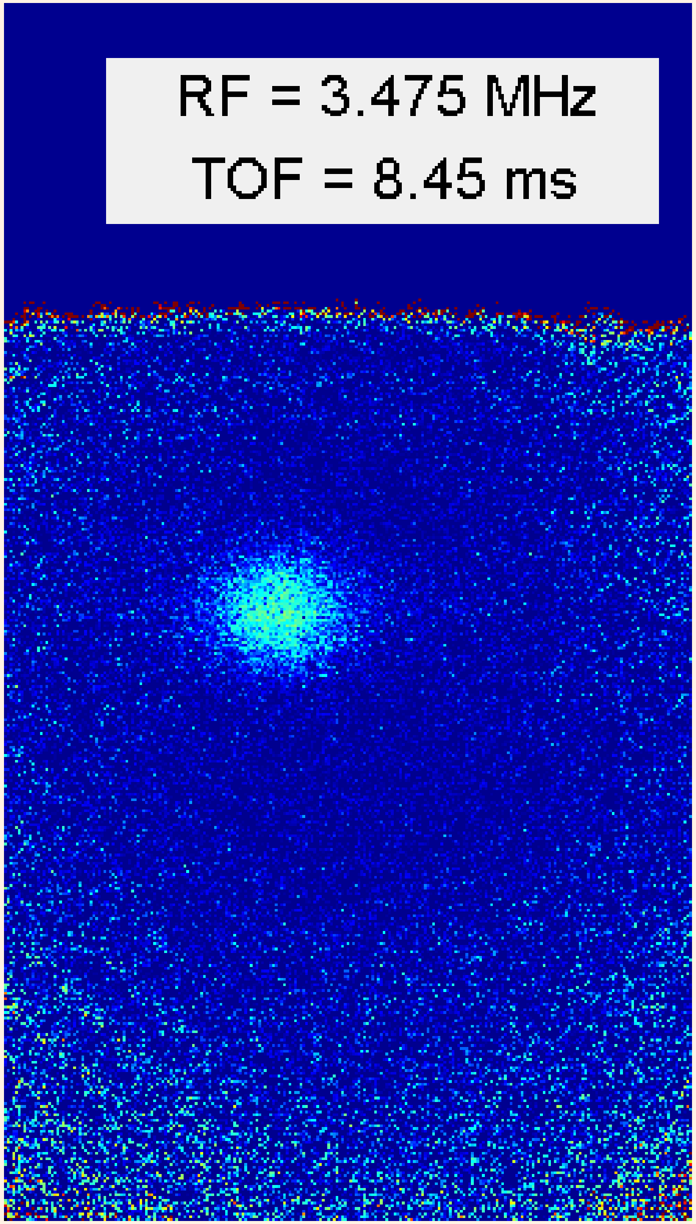
Evaporation Efficiency

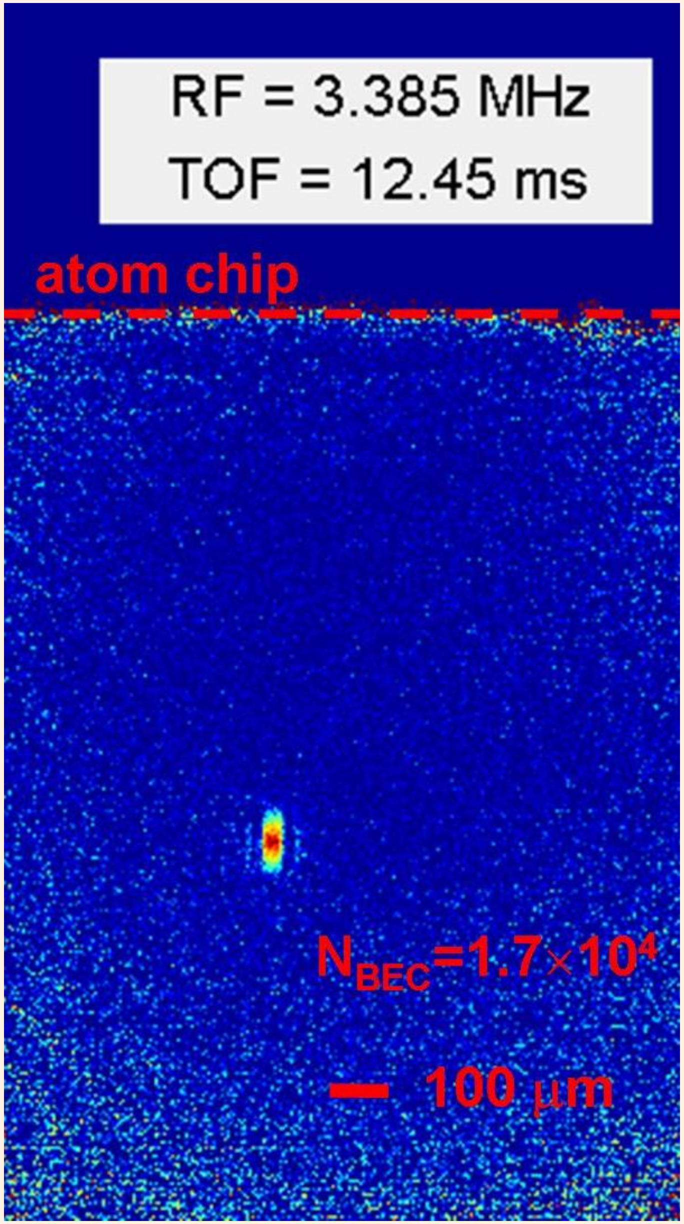
$$\frac{d\ \ln(\mathrm{PSD})}{d\ \ln(\mathrm{N})} \approx 3.7$$

^{87}Rb BEC

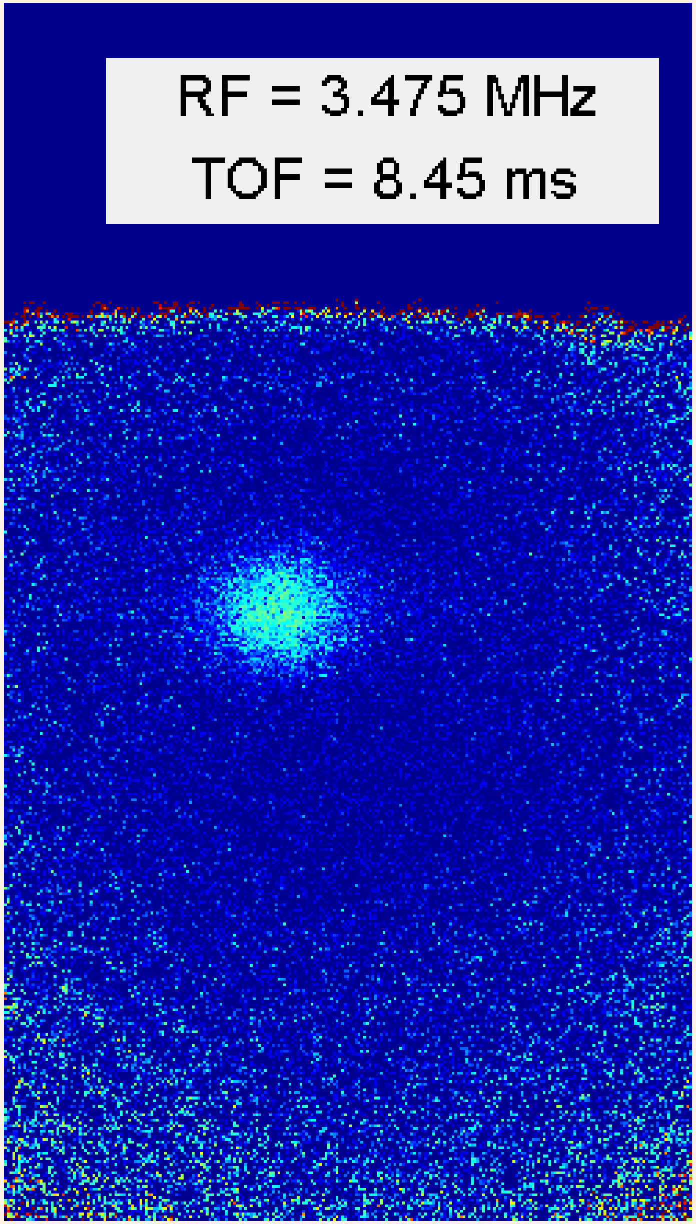


^{87}Rb BEC


RF = 3.475 MHz
TOF = 8.45 ms


RF = 3.385 MHz
TOF = 12.45 ms
atom chip
NBEC=1.7×10⁴
100 μm

^{87}Rb BEC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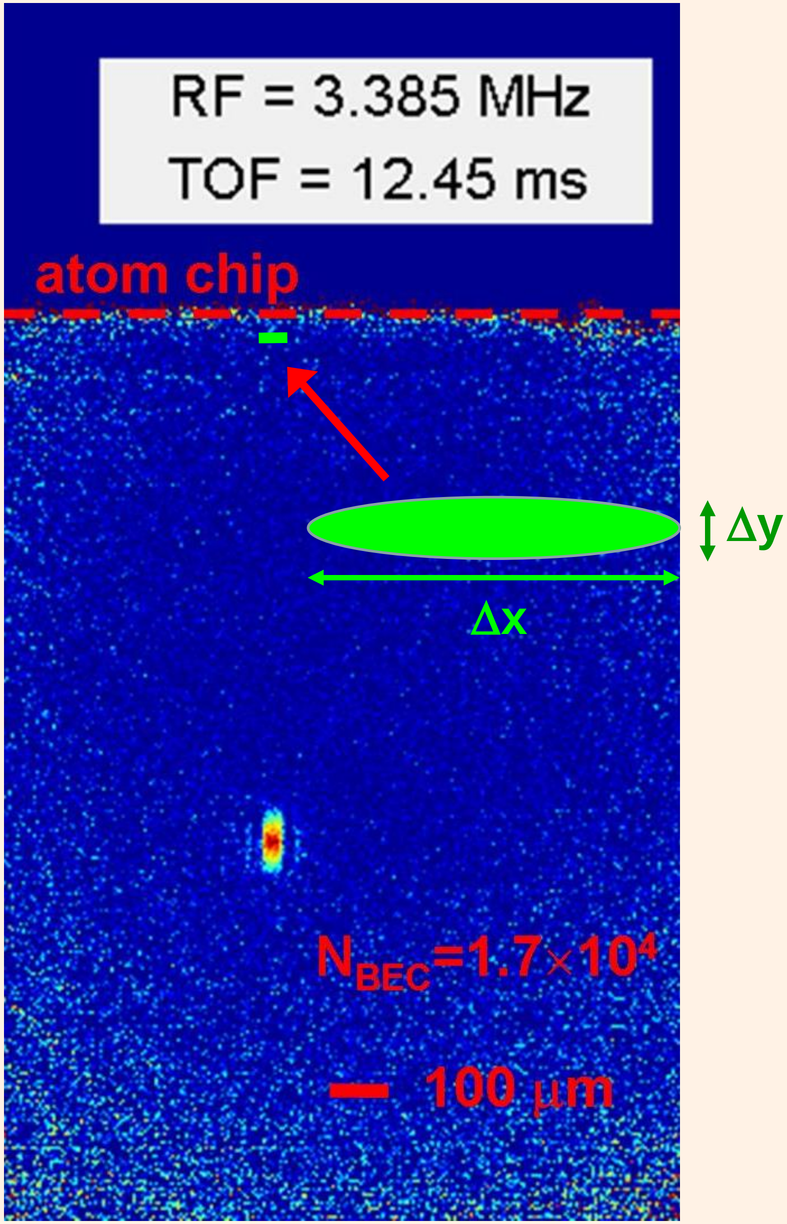
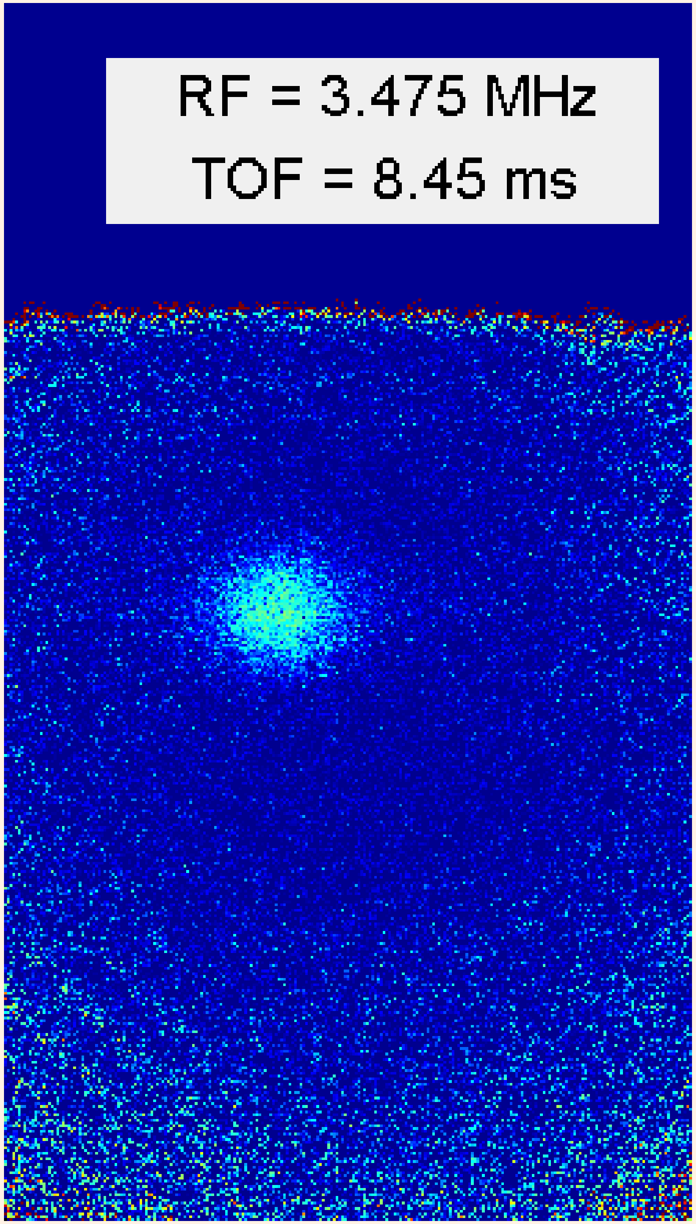

RF = 3.385 MHz
TOF = 12.45 ms
atom chip
Δy
Δx
N_BEC=1.7×10^4
100 μm

^{87}Rb BEC



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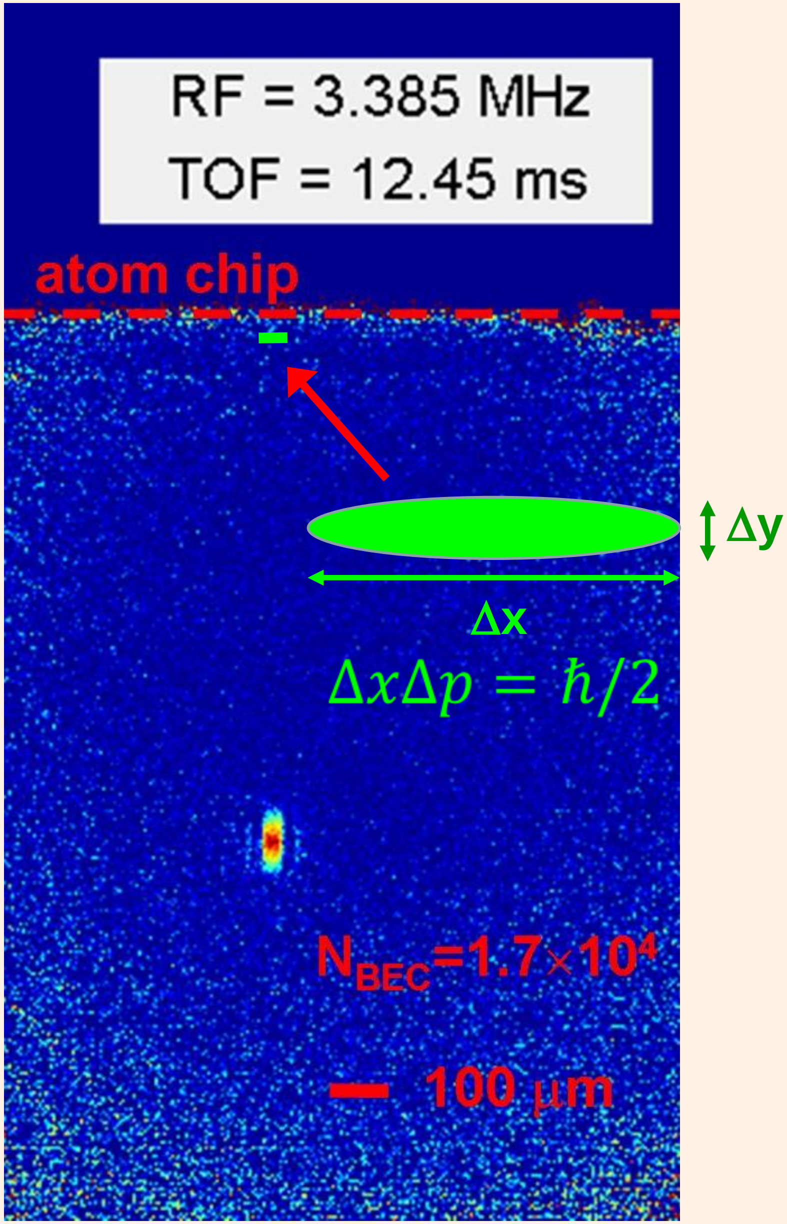
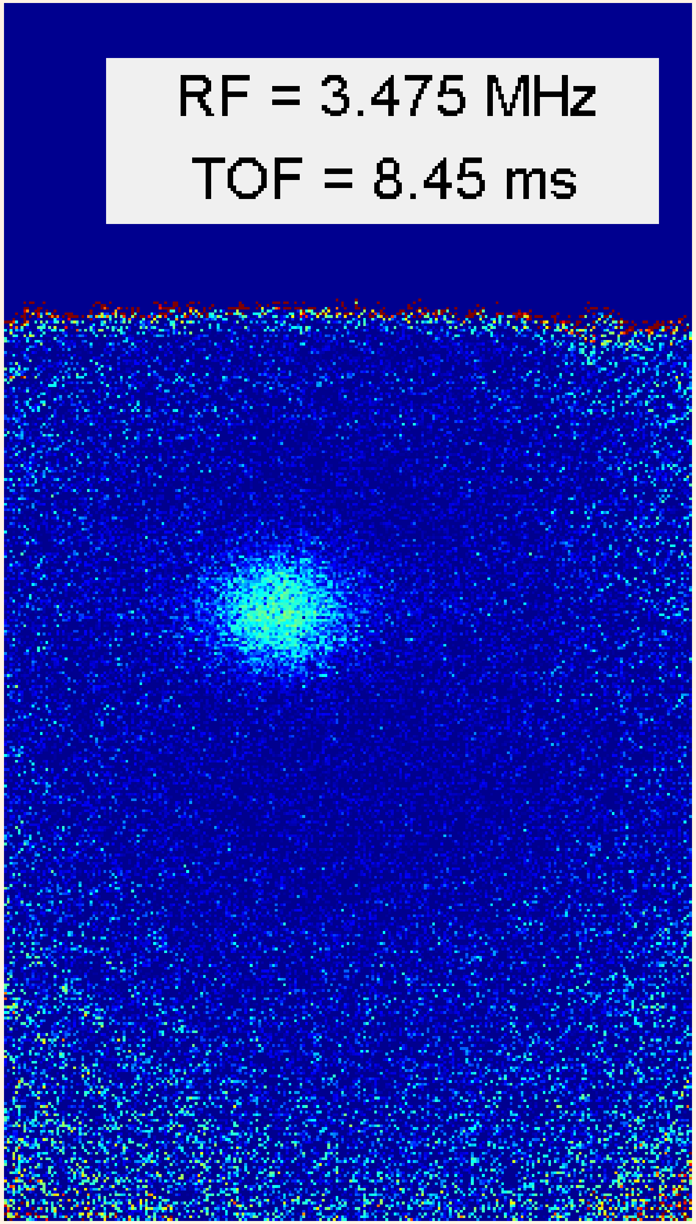


RF = 3.385 MHz
TOF = 12.45 ms
atom chip
Δy
Δx
$\Delta x \Delta p = \hbar/2$
$N_{BEC}=1.7\times10^4$
100 μm

^{87}Rb BEC



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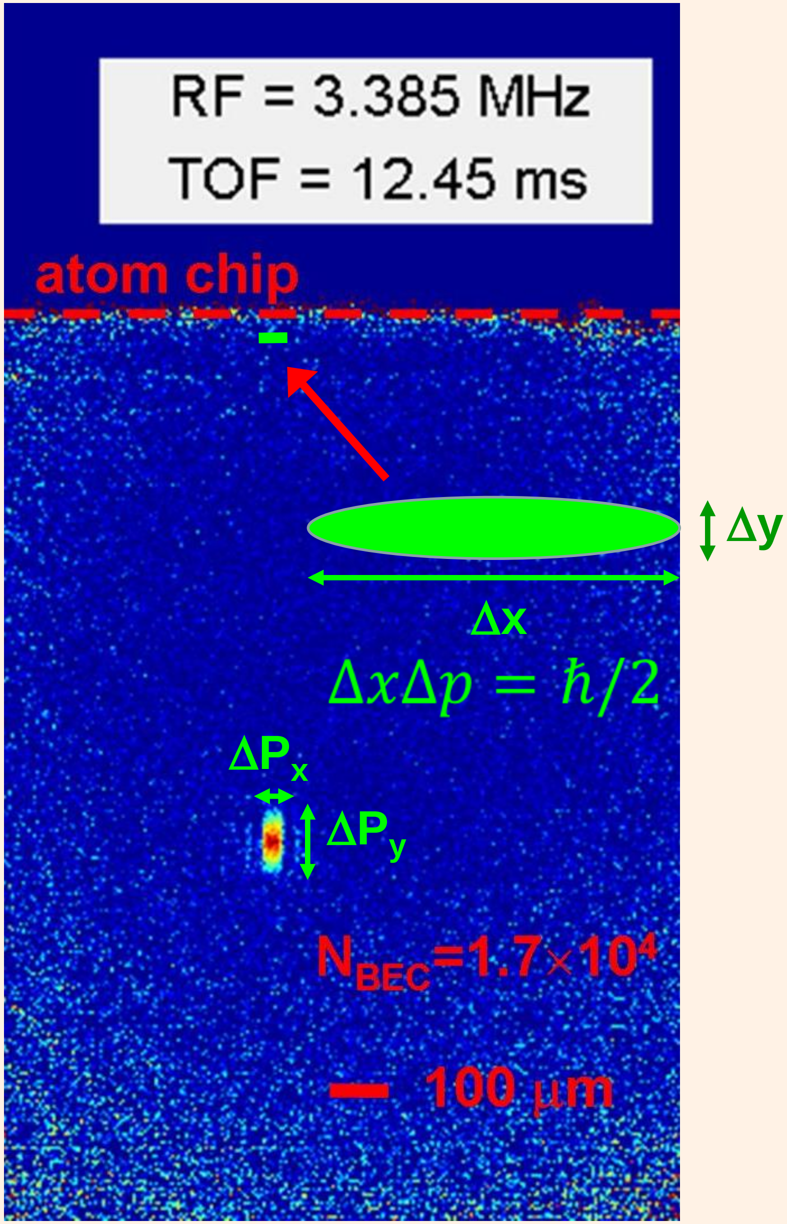


RF = 3.385 MHz
TOF = 12.45 ms
atom chip
Δy
Δx
$\Delta x \Delta p = \hbar/2$
ΔP_x
ΔP_y
$N_{BEC}=1.7\times10^4$
100 μm

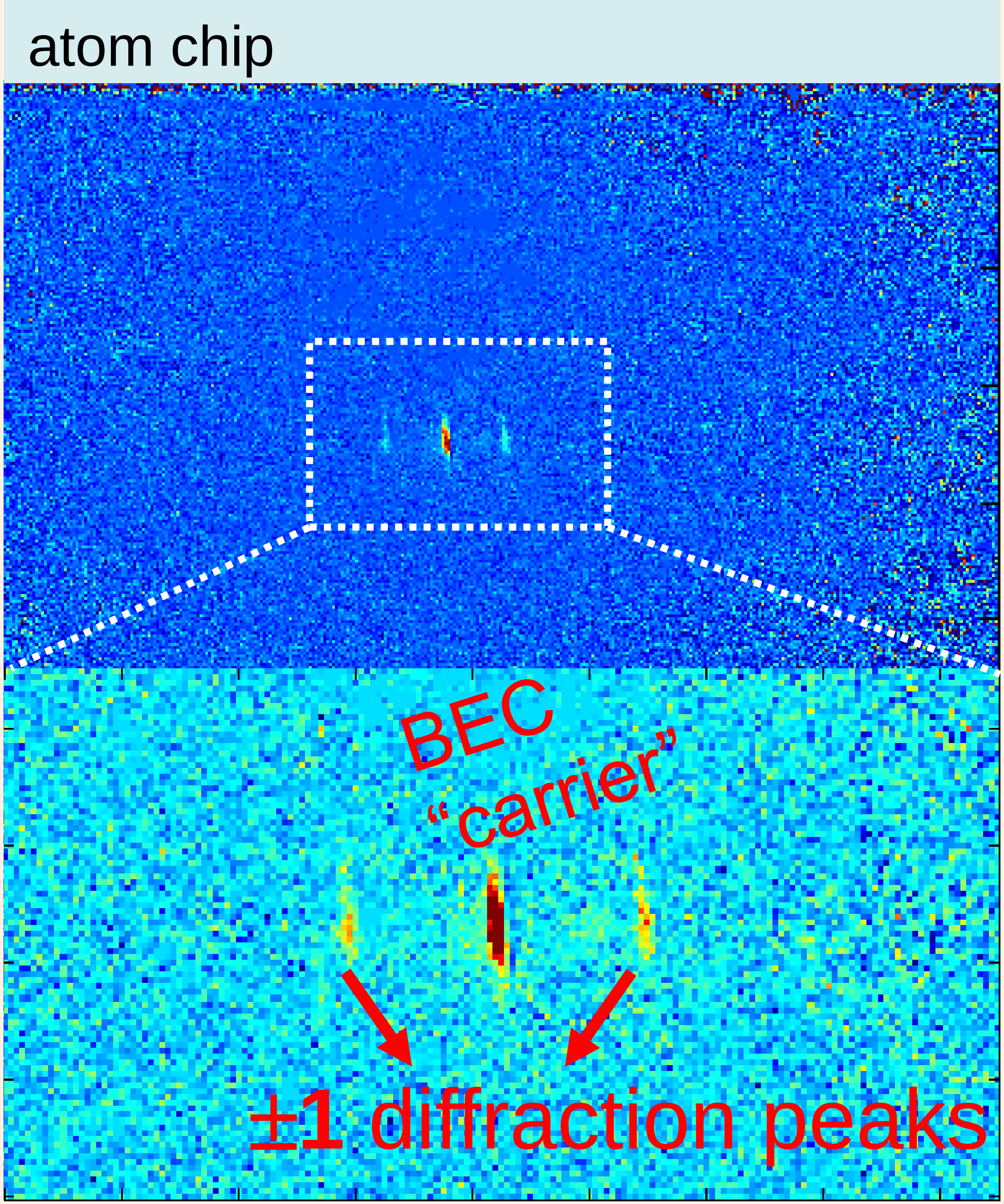
It's Quantum !

Bragg diffraction of a BEC by an accidental optical lattice grating (not visible).

BEC is a debugging tool.

→ quantum mechanics comes looking for you !!!

→ "Canary" for experimental imperfections.



What's Special about Ultra-cold Atoms ?

Extreme Control:

- **Perfect knowledge** (T=0).
- Precision external and internal control with **magnetic, electric, and electromagnetic fields**.

Interactions:

- **Tunable interactions** between atoms with a **magnetic Feshbach resonance**.
- Slow dynamics for imaging.

Narrow internal energy levels:

- Energy resolution of internal levels at the **1 part per 10^9 – 10^{17}** level.
- 100+ years of spectroscopy.
- **Frequency** measurements at **10^3-10^{14} Hz**.
- *Ab initio* calculable internal structure.

So What ?

What can you do with ultra-cold atoms ?

Larger ultra-cold quantum systems:

- Condensed matter physics: many-body systems
- Ultra-cold chemistry

Probe fundamental forces inside the atom:

- Electron-dipole moment measurements
- Parity violation in atoms and molecules
- Test the Standard Model, nuclear physics

Applied Physics:

- Atomic clocks
- Matter-wave interferometry
- Quantum sensors
- Quantum Information

Microwave Traps

Outline

- Intro to Ultra-cold Matter
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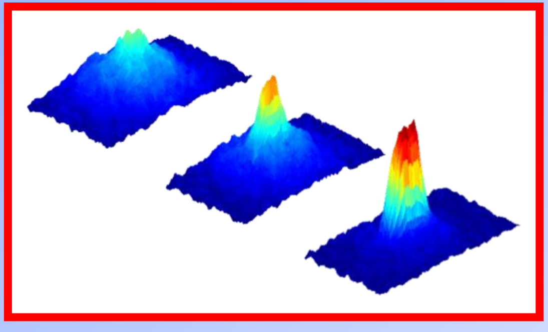
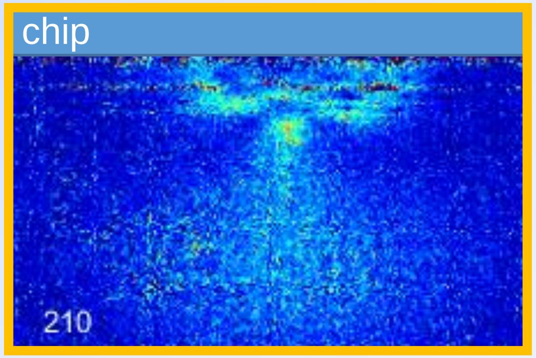
  - → **How do you make it ?**
  - → **Bose-Einstein Condensates**



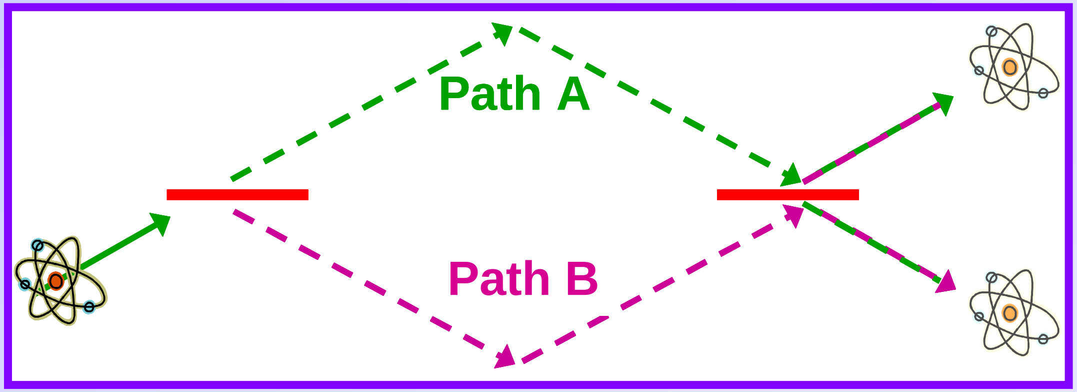
- Physics with ultra-cold matter
  - → **Microwave traps for atom interferometry**



Atom Interferometry

Atom Interferometry

- Most sensitive interferometers and force sensors.
  - → free-flight laser pulse interferometers: $\frac{\Delta g}{g} = 10^{-11}$ in 1 s (10 m tower). (Stanford U.)
  - → Single particle physics.
- Sensitive to *magnetic*, *electric*, and *gravitational* forces.
- Excellent for **inertial navigation**.
- Drawbacks: Large apparatus, large sensing region.



Trapped Atom Interferometry

<u>**Trapped** Atom Interferometry</u>

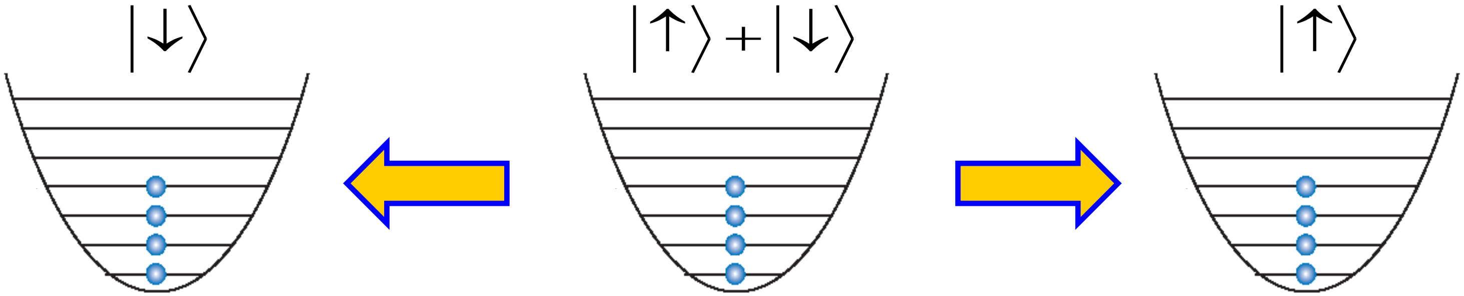
- Long integration times
  - → increased phase sensitivity, linear in time.
- Localized atomic packets … potentially compact.
  - → fixed position, well controlled volume.
  - → microscopy: Casimir-Polder force & sub-mm gravity measurements.
- Bose-Einstein condensates have excellent coherence.
- Drawback: sensitive to atom-atom interactions.

<u>**Fermion** advantage</u>

Ultracold fermions have strongly suppressed interactions.

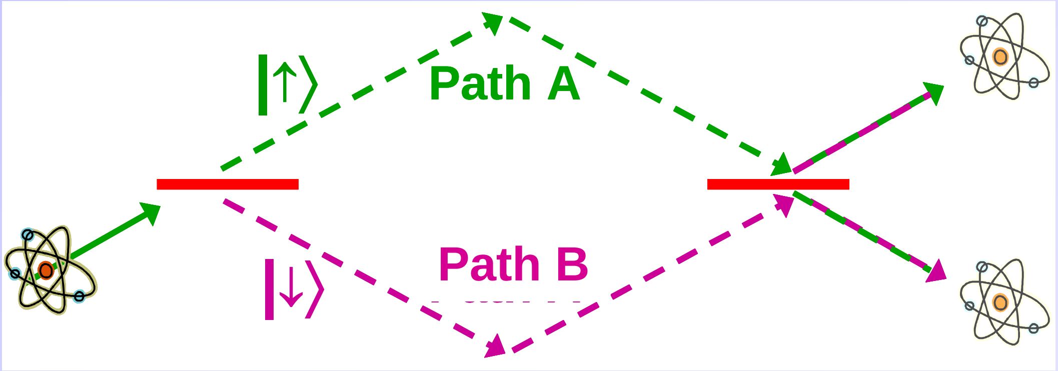
→ Ultracold fermions are used in optical clocks.

Spin-dependent Interferometer



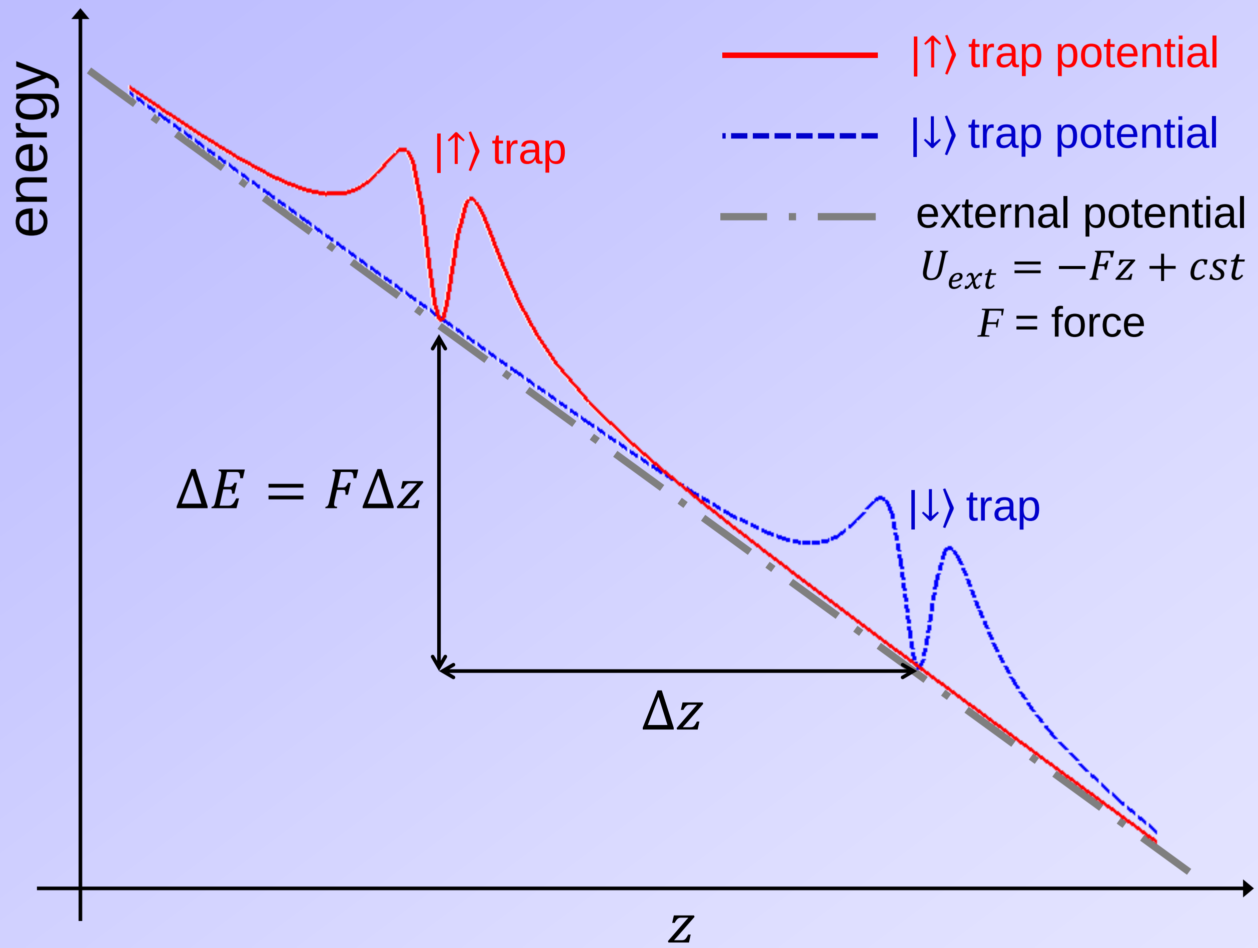
Opposite spins experience same potential, but shifted in opposite directions

→ Each level/state acquires the same splitting phase.



- Equivalent to a ***polarization Mach-Zender*** interferometer.
- Essentially, an ***atomic clock*** with spatially separated clock states.

Spin-dependent Interferometry



interferometer phase-signal: $\Delta\varphi = \Delta T(\delta E_{\uparrow\downarrow} + \Delta E)/\hbar$

interferometer noise: $\delta\varphi \sim 1/\sqrt{N_{atoms}}$

ΔT = integration time

$\delta E_{\uparrow\downarrow}$ = hyperfine splitting

Spin-dependent

AC Zeeman Traps

- AC Zeeman Theory
- Microwave force experiment
- RF trap experiment

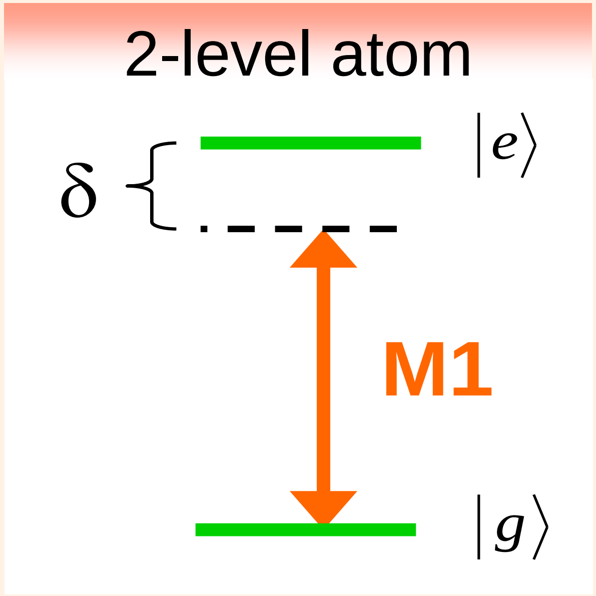
Benefits of

AC Zeeman Potentials

- **Easy** physics !!! *… easy-ish engineering.*
- **Spin-specific** potentials … for <u>any spin</u> !!!
- <u>No spontaneous emission</u>.
- Physics works at **all magnetic fields**.
  - → Feshbach resonances.
- Atom chip <u>potential roughness is reduced</u>.
  - → Orders of magnitude suppression.

AC Zeeman Theory

Simple Theory



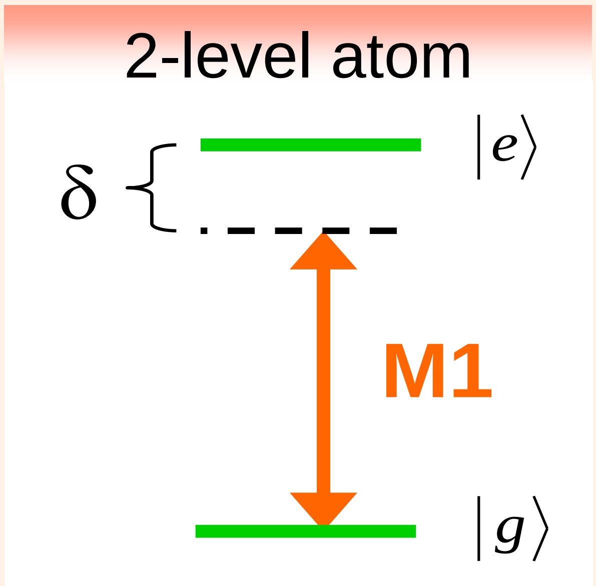
M1 transition amplitude (Rabi frequency):

$$\Omega = \frac{\langle g | H_{Zeeman} | e \rangle}{\hbar} = \frac{\langle g | -\vec{\mu} \cdot \vec{B}_{AC} | e \rangle}{\hbar}$$

with magnetic moment: $\vec{\mu} = (2\mu_B/\hbar)\vec{S}$

AC Zeeman Theory

Simple Theory



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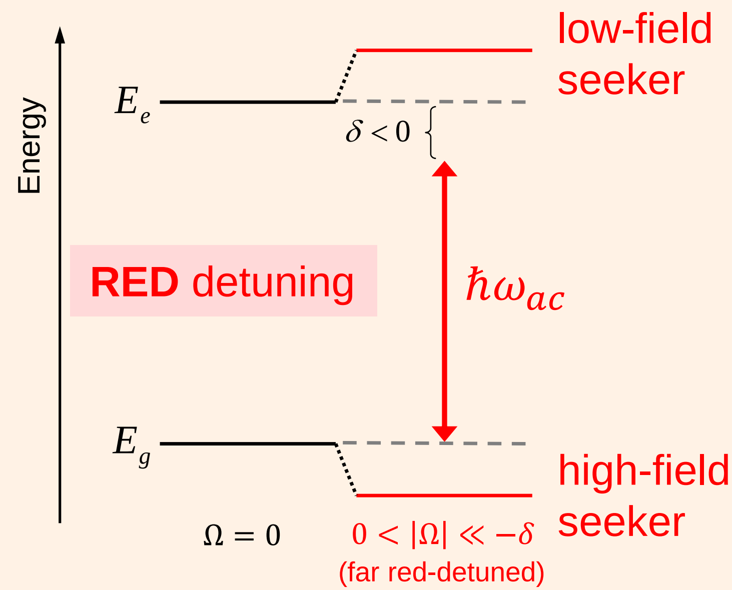

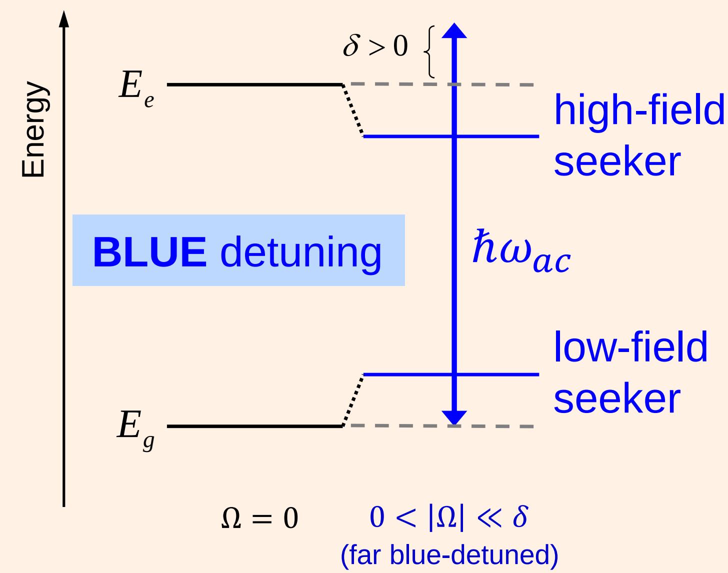

AC Zeeman: Dressed Atom Theory

dressed atom basis: $\{|g, N\rangle, |e, N-1\rangle\}$

atom in |g⟩, N RF-photons

atom in |e⟩, N-1 RF-photons

AC Zeeman Hamiltonian: $H = \hbar\omega_{ge}\begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} + \hbar\omega_{rf}\begin{bmatrix} N & 0 \\ 0 & N{-}1 \end{bmatrix}$

H_{atom} $H_{RF\text{-}field}$

AC Zeeman: Dressed Atom Theory

dressed atom basis: $\{|g, N\rangle, |e, N-1\rangle\}$

atom in |g⟩, N RF-photons

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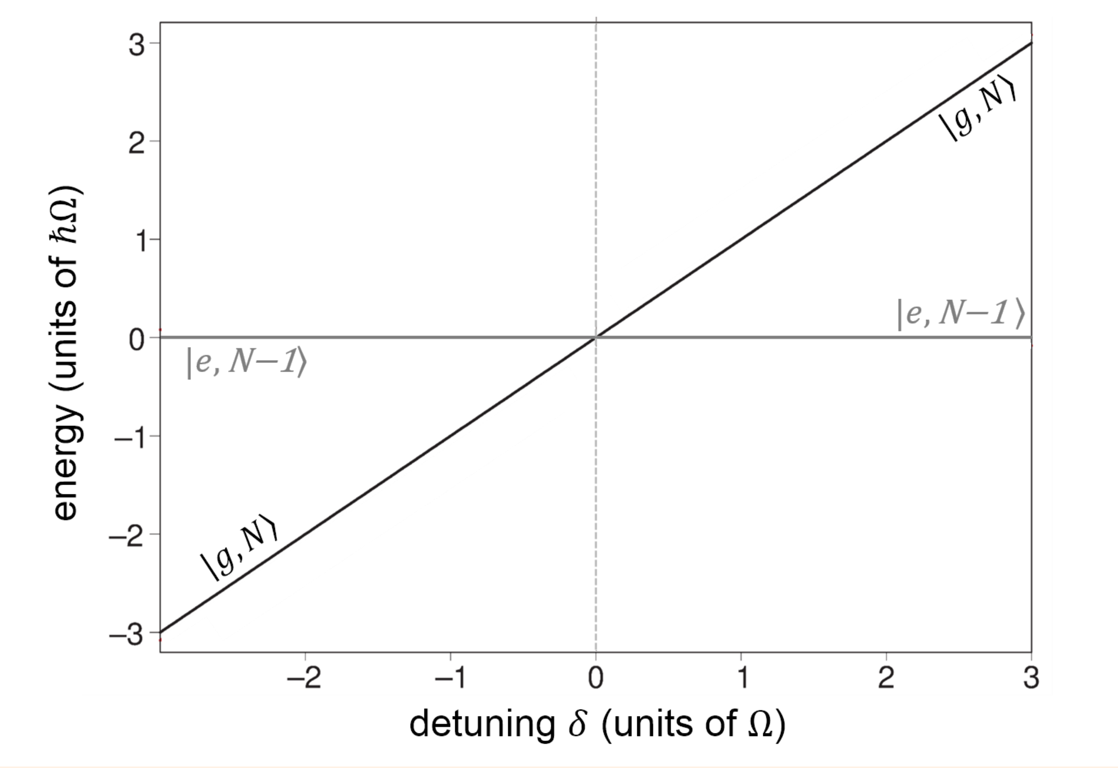


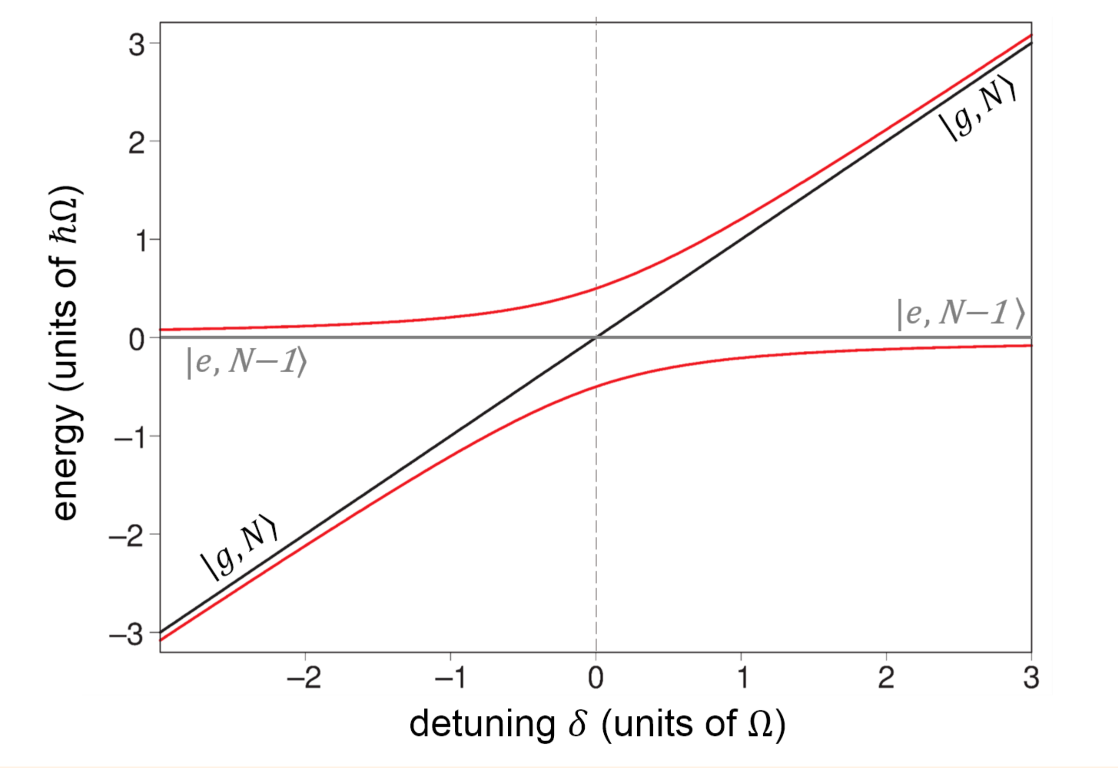
AC Zeeman: Dressed Atom Theory

dressed atom basis: $\{|g, N\rangle, |e, N-1\rangle\}$

atom in |g⟩, N RF-photons — atom in |e⟩, N-1 RF-photons

AC Zeeman Hamiltonian: $H = \hbar\omega_{ge}\begin{bmatrix}0 & 0\\ 0 & 1\end{bmatrix} + \hbar\omega_{rf}\begin{bmatrix}N & 0\\ 0 & N-1\end{bmatrix} + \frac{\hbar}{2}\begin{bmatrix}0 & \Omega\\ \Omega^* & 0\end{bmatrix}$

H_{atom} — $H_{RF\text{-}field}$ — $H_{interaction}$



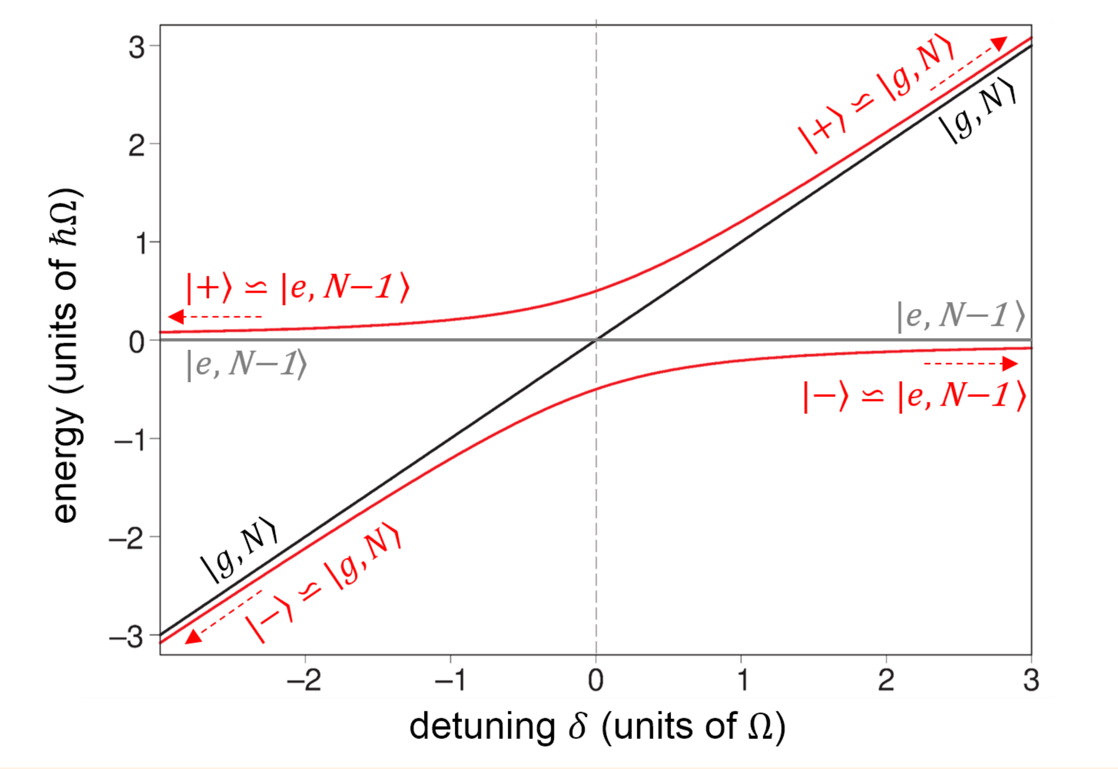
AC Zeeman: Dressed Atom Theory

dressed atom basis: $\{|g, N\rangle, |e, N-1\rangle\}$

atom in |g⟩, N RF-photons — atom in |e⟩, N-1 RF-photons

AC Zeeman Hamiltonian: $H = \hbar\omega_{ge}\begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} + \hbar\omega_{rf}\begin{bmatrix} N & 0 \\ 0 & N{-}1 \end{bmatrix} + \frac{\hbar}{2}\begin{bmatrix} 0 & \Omega \\ \Omega^* & 0 \end{bmatrix}$

H_{atom} $H_{RF\text{-}field}$ $H_{interaction}$



AC Zeeman: Dressed Atom Theory

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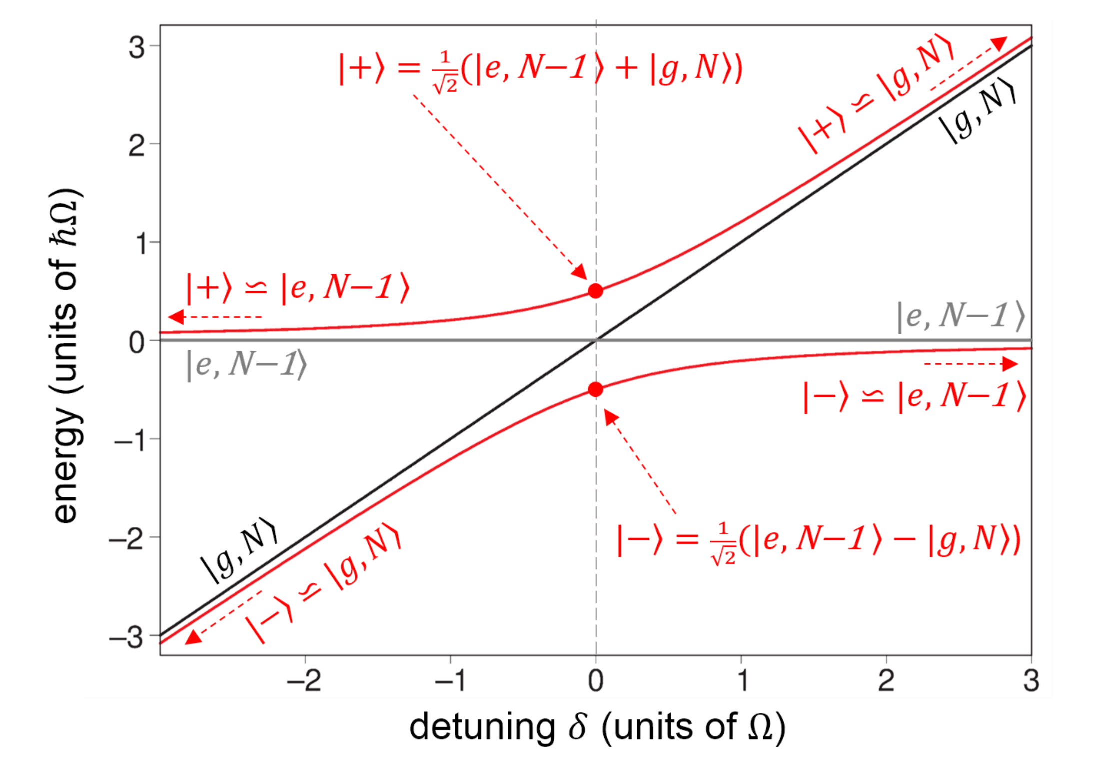
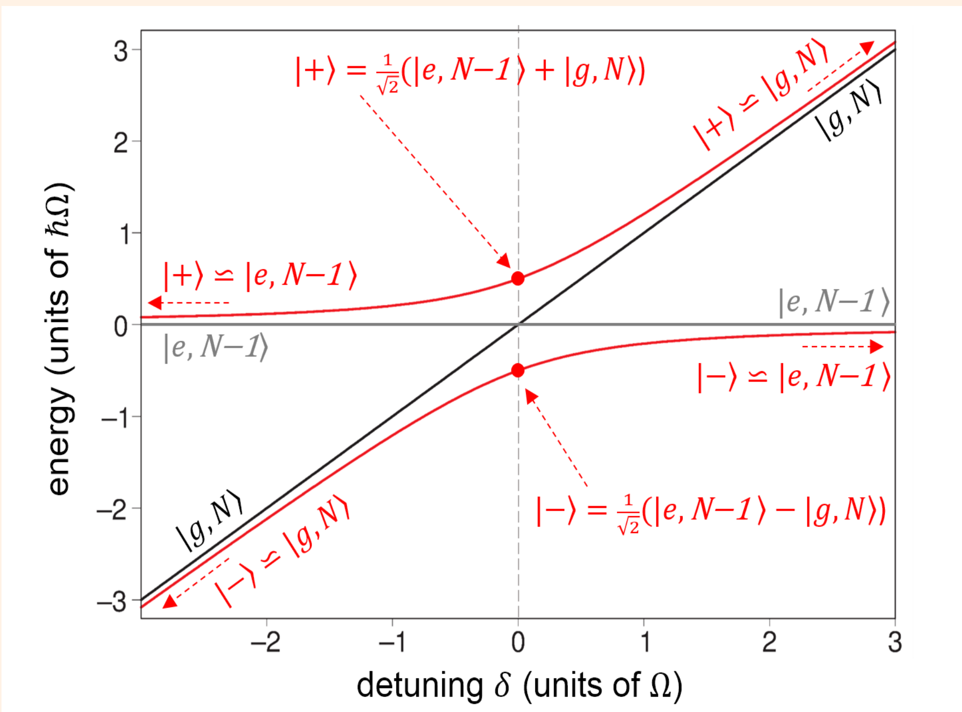
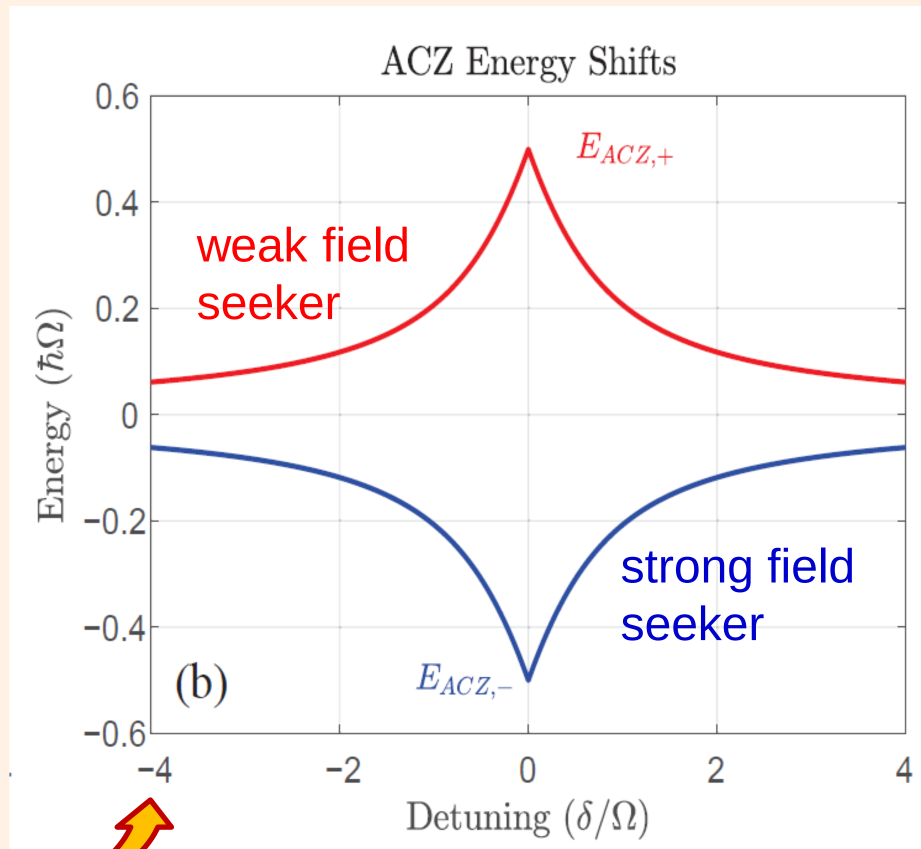
H_{atom} $H_{RF\text{-}field}$ $H_{interaction}$



AC Zeeman: Dressed Atom Theory





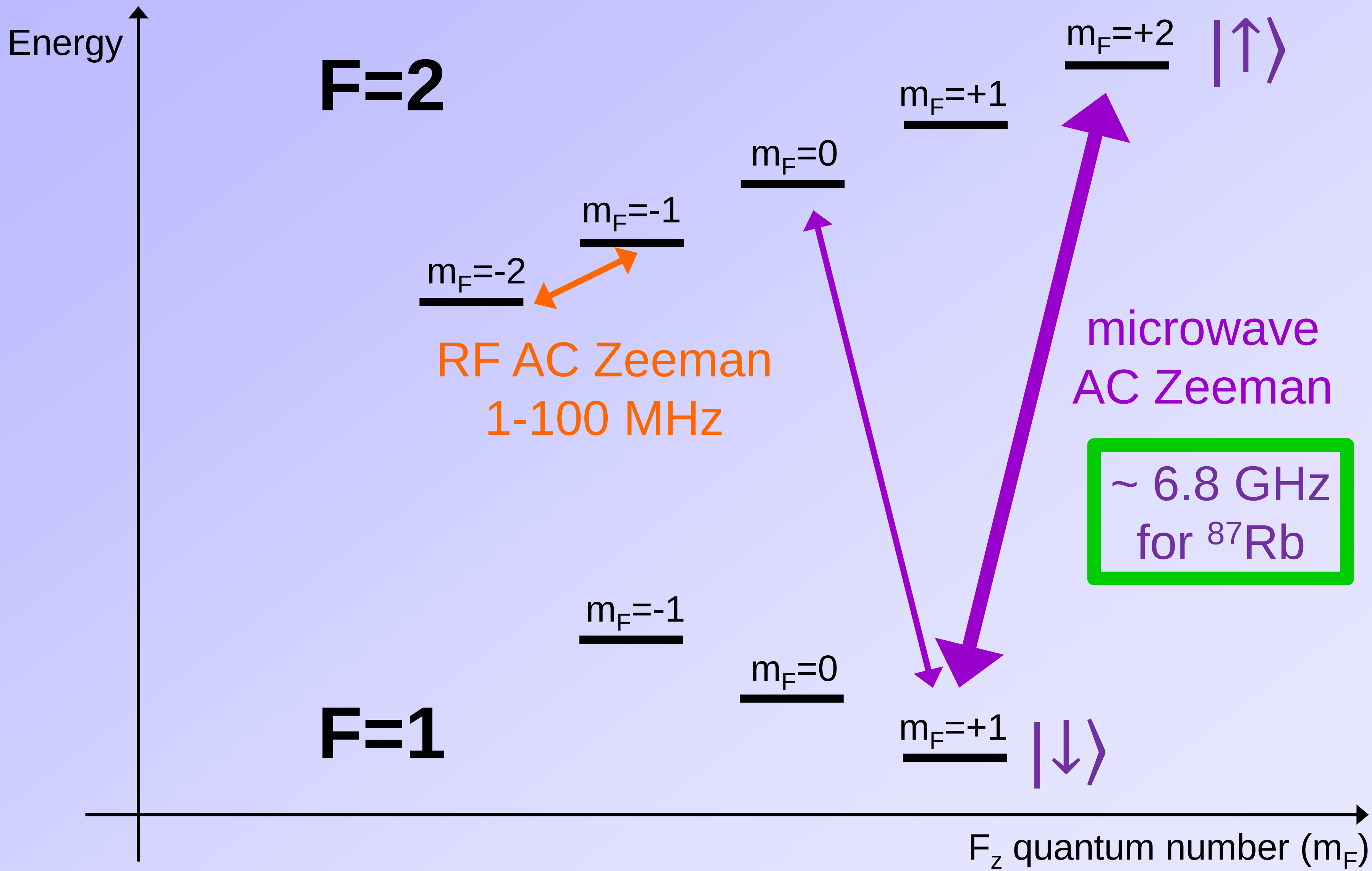
subtract the bare energy

Miyahira, Rotunno, Du, Aubin, *MDPI Atoms* **9**, 54 (2021)

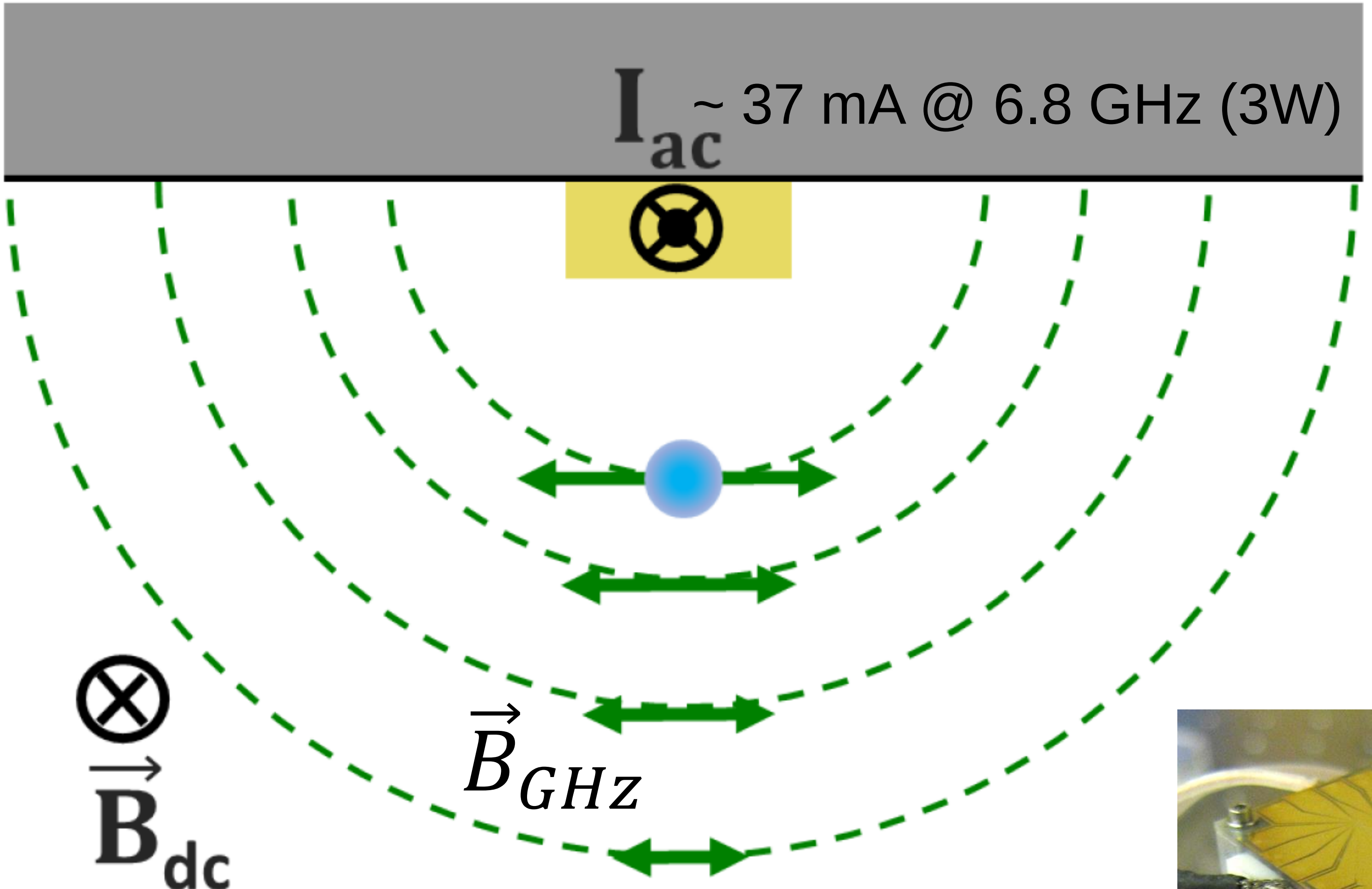
AC Zeeman Transitions

[^{87}Rb, ^{39}K, ^{41}K]

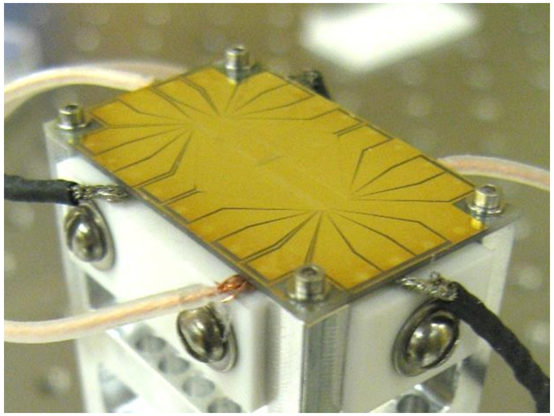
[@ Low Magnetic Field]



EXPERIMENT: Atom Chip Set-up

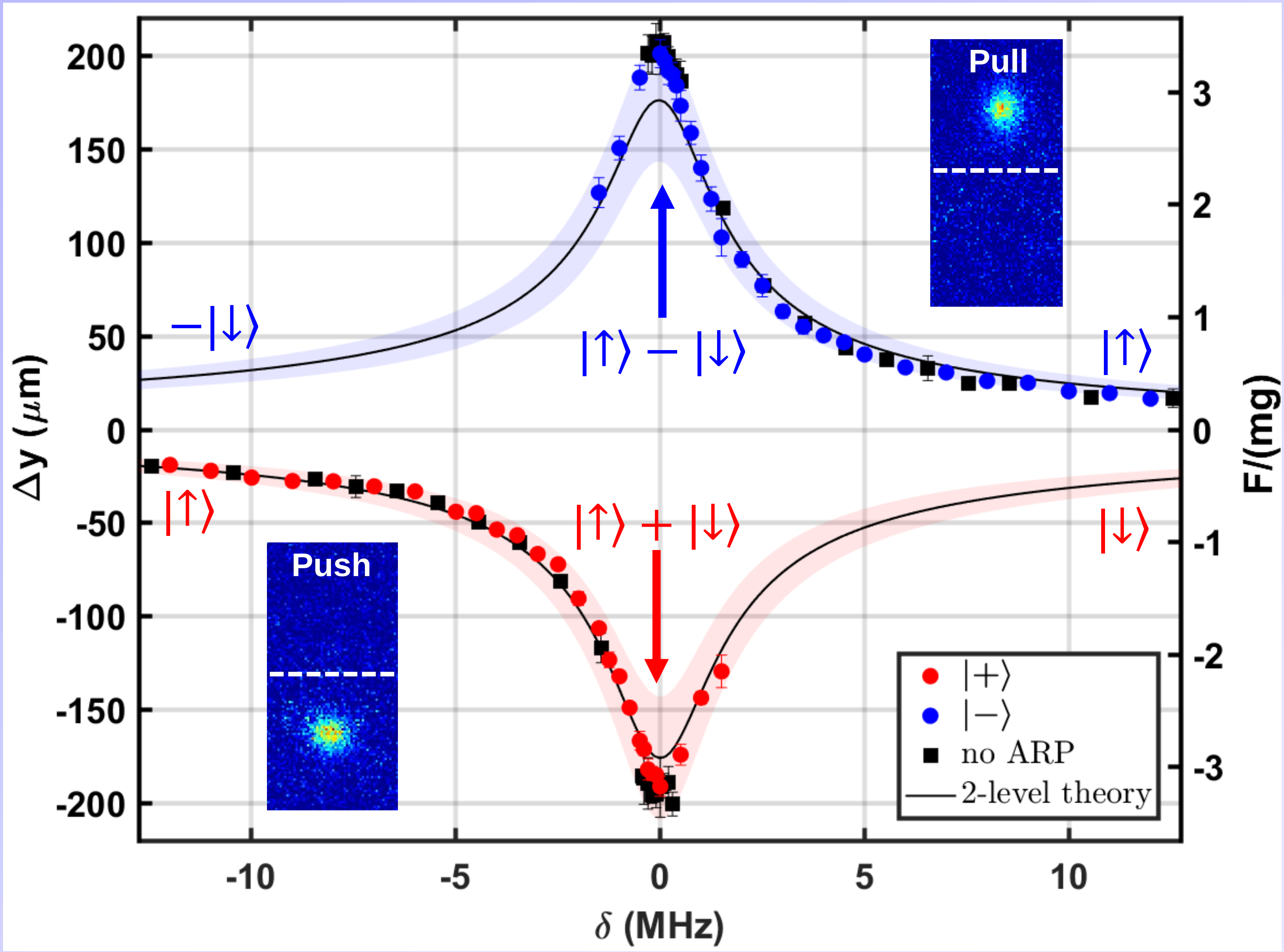


no impedance matching



Fancher, Pyle, Rotunno, Aubin, *Phys. Rev. A* **97**, 043430 (2018)

AC Zeeman Force



Fancher, Pyle, Rotunno, Aubin, *Phys. Rev. A* **97**, 043430 (2018)

Spin-Specific Force

spin mixture released

GHz ON

0.5 ms on-resonance

horizontal Stern-Gerlach separation

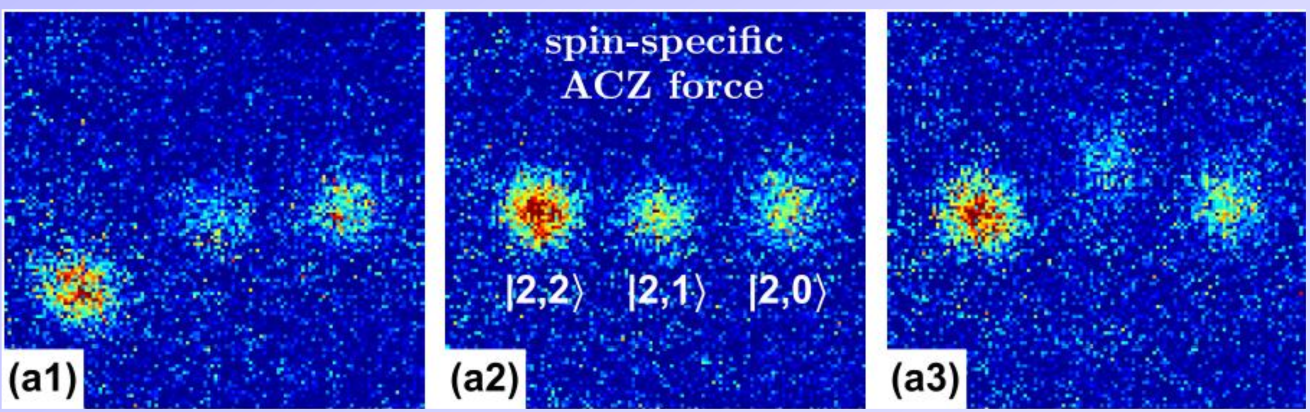
12.25 ms

imaging probe

|2,2⟩ push

GHz OFF

|2,1⟩ pull

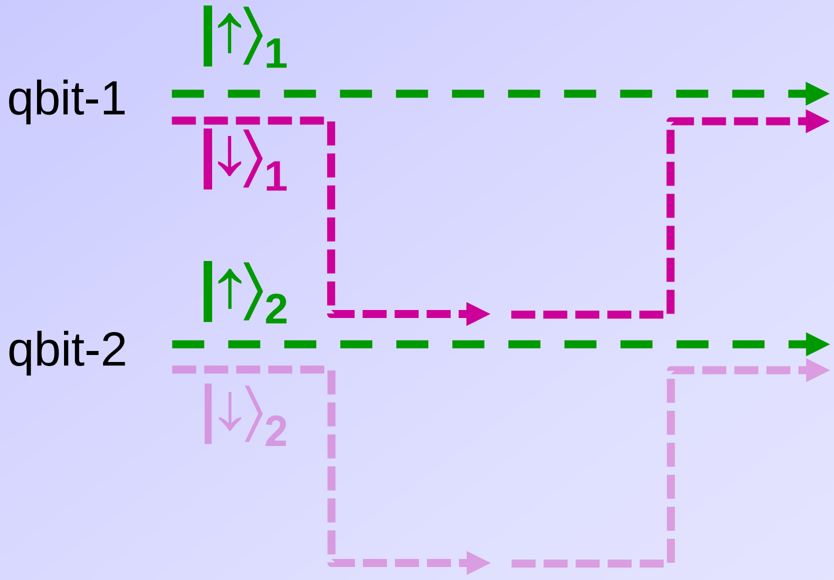


Fancher, Pyle, Rotunno, Aubin, *Phys. Rev. A* **97**, 043430 (2018)

Application

Quantum Gate

- Spin states can serve as qbit states.
- A spin-dependent force selectively controls one or more qbits based on their quantum states.

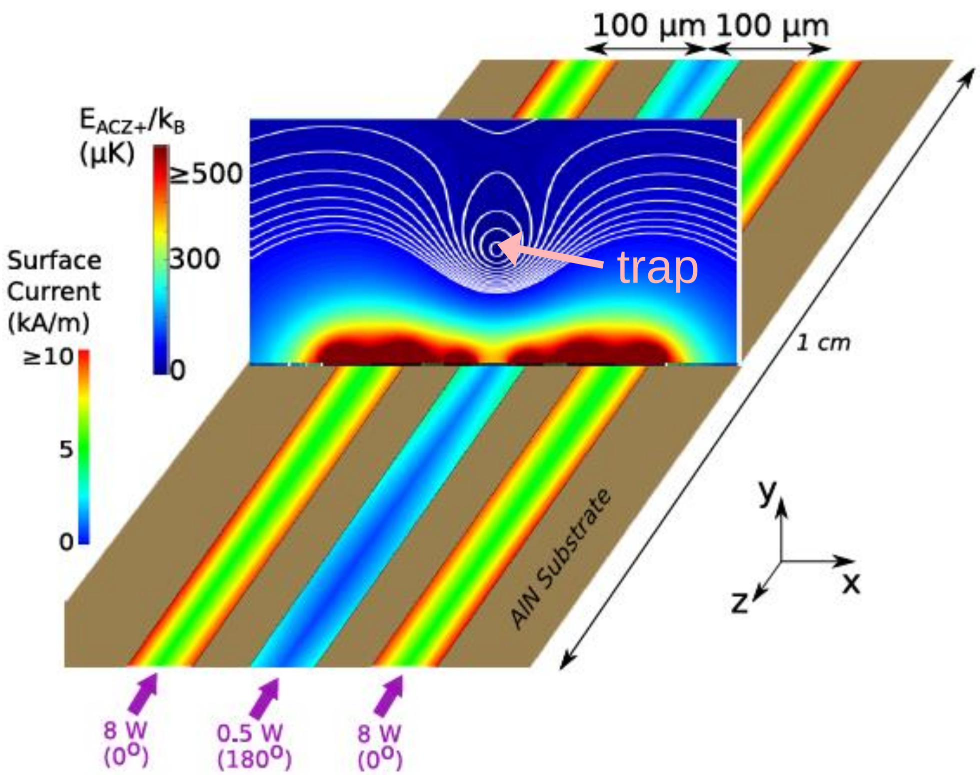


Microwave Trap Design

Microwave near-fields have the **same form as static fields**.

→ NO wavelength dependence.

→ Large gradients at moderate power (<10 W) and currents (< 1 A).

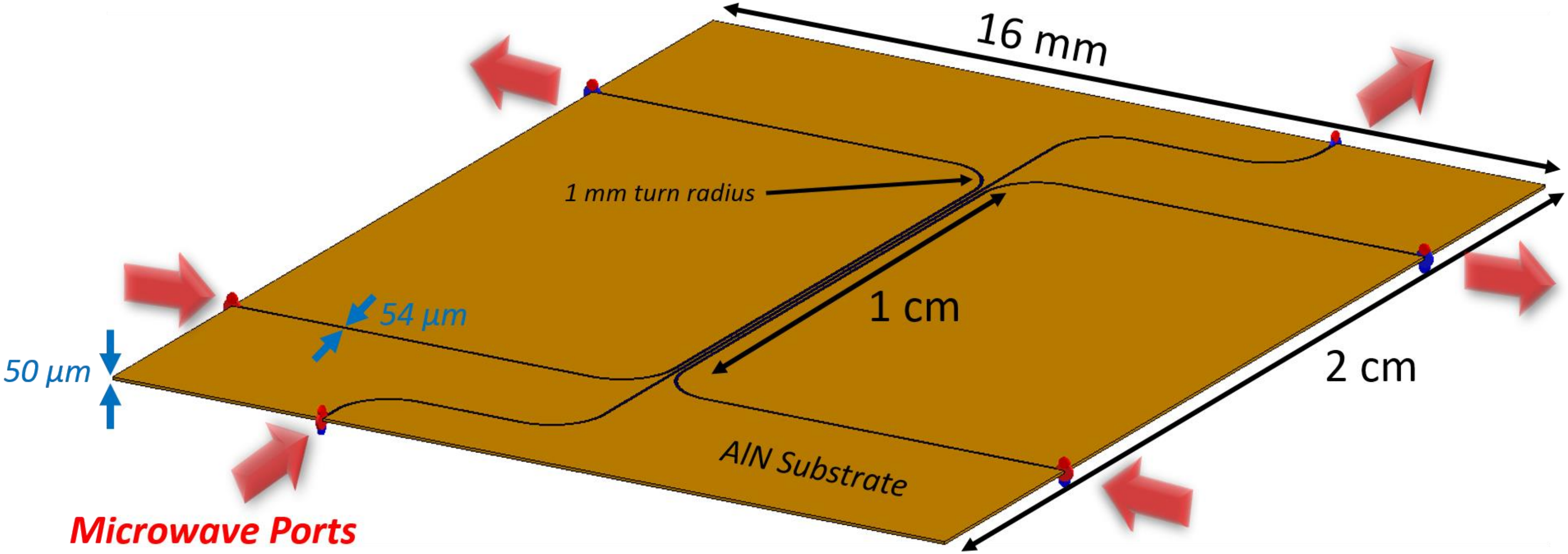


Microwaves at 6.8 GHz

- detuning $\delta = 2\pi \times 1$ MHz
- trap depth = 15 μK
- trap height = 93 μm

Miyahira, Rotunno, Du, Aubin,
MDPI Atoms **9**, 54 (2021)

Microwave Atom Chip Design

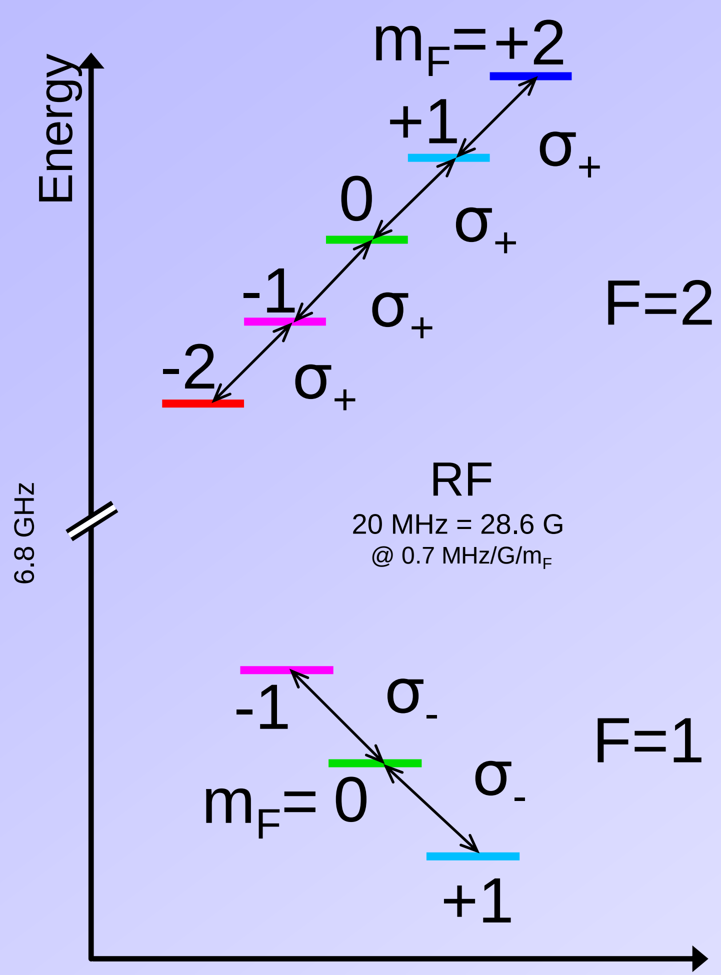


✓ Microstrip-based design

✓ 50 Ω microstrips

RF AC Zeeman Physics

intra-hyperfine transitions



$$\hbar\Omega_{eg} = \langle e| - \mu \cdot B_{RF} |g\rangle$$

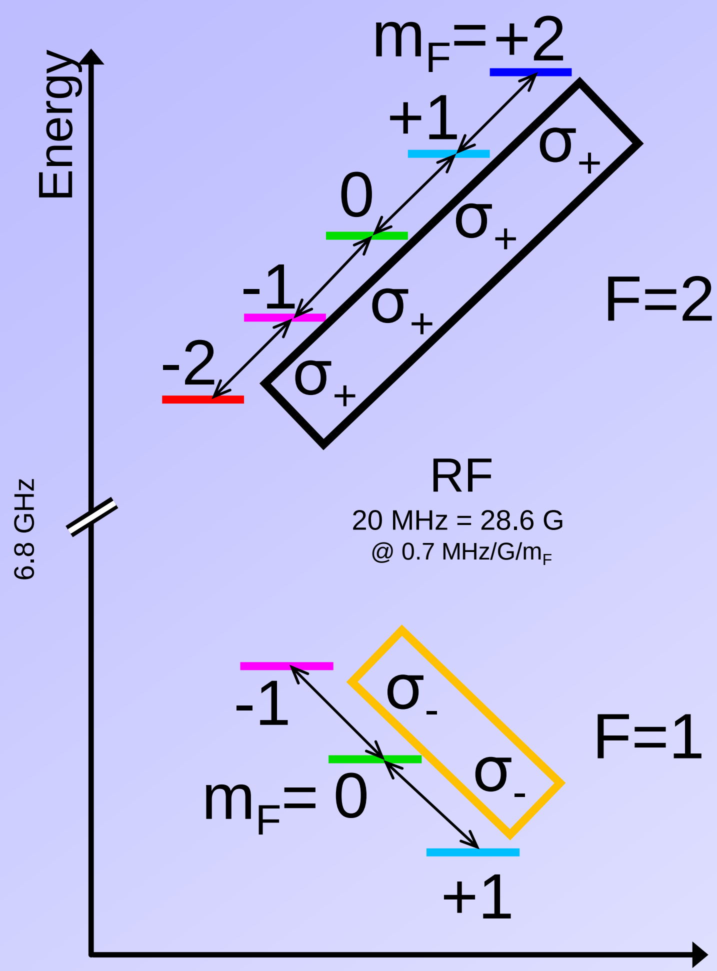
$$= \frac{\mu_B g_S}{\hbar} \langle e| \frac{S_+ B_-}{2} + \frac{S_- B_+}{2} + S_\pi B_z |g\rangle$$

with $B_\pm = B_x \pm iB_y$

(circularly polarized RF field)

RF AC Zeeman Physics

intra-hyperfine transitions



$$\hbar\Omega_{eg} = \langle e| -\mu \cdot B_{RF} |g\rangle$$
$$= \frac{\mu_B g_S}{\hbar} \langle e| \boxed{\frac{S_+ B_-}{2}} + \boxed{\frac{S_- B_+}{2}} + S_\pi B_z |g\rangle$$

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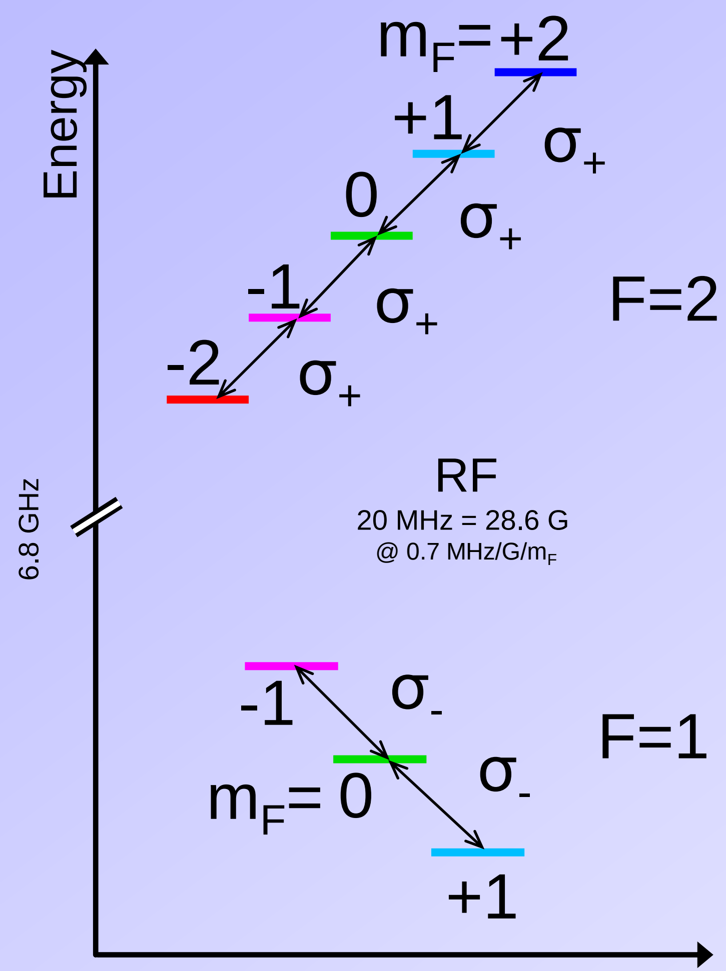
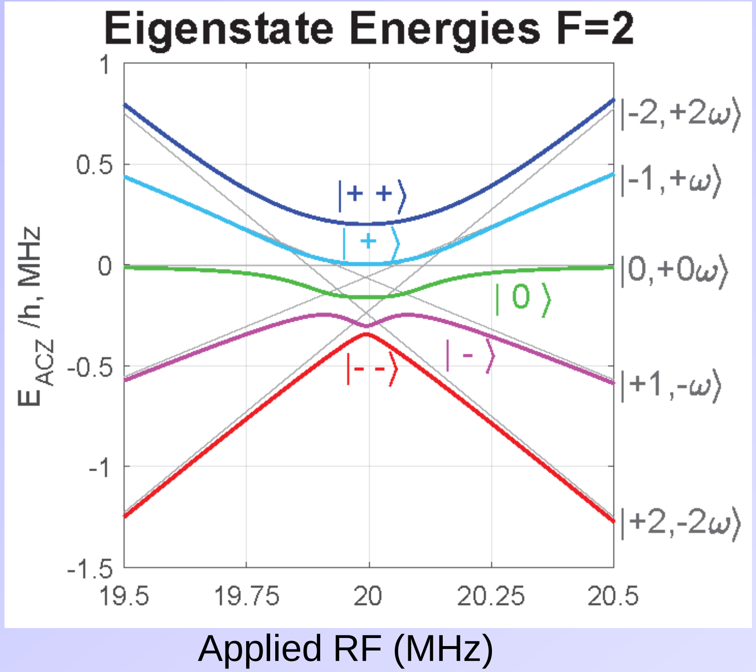
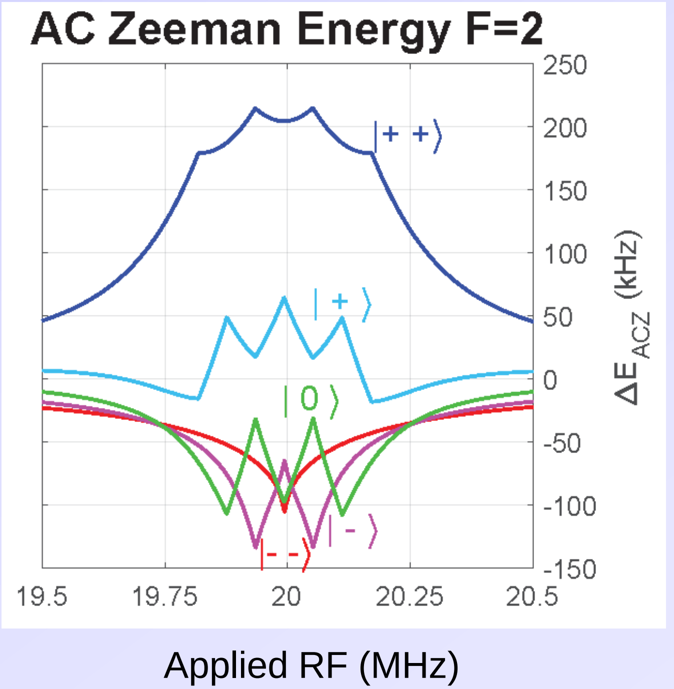
intra-hyperfine transitions







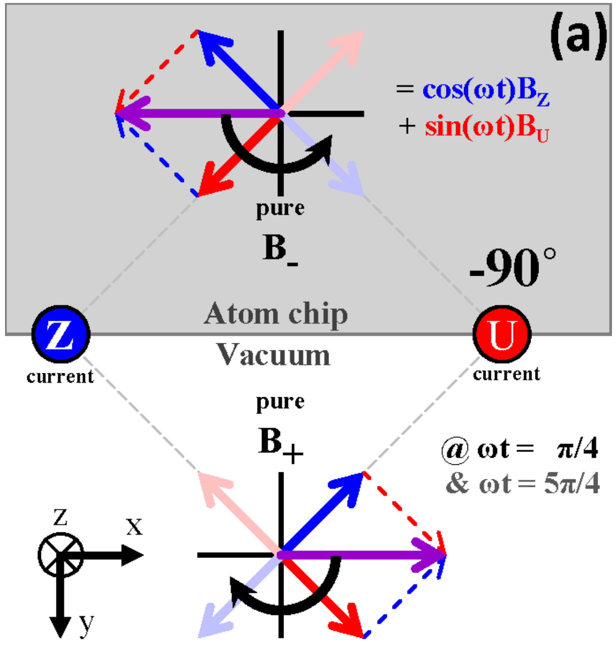
How to make a σ^+/B_ trap

$$\hbar\Omega_{eg} = \frac{\mu_B g_S}{2\hbar} \langle e | S_+ B_- | g \rangle$$

- Phase control in two wires
- Pure B+ polarization

  → Zero in B- polarization

- Adjust phase to move



How to make a σ^+/B_- trap

$$\hbar\Omega_{eg} = \frac{\mu_B g_S}{2\hbar} \langle e| S_+ B_- |g\rangle$$

- Phase control in two wires
- Pure B+ polarization

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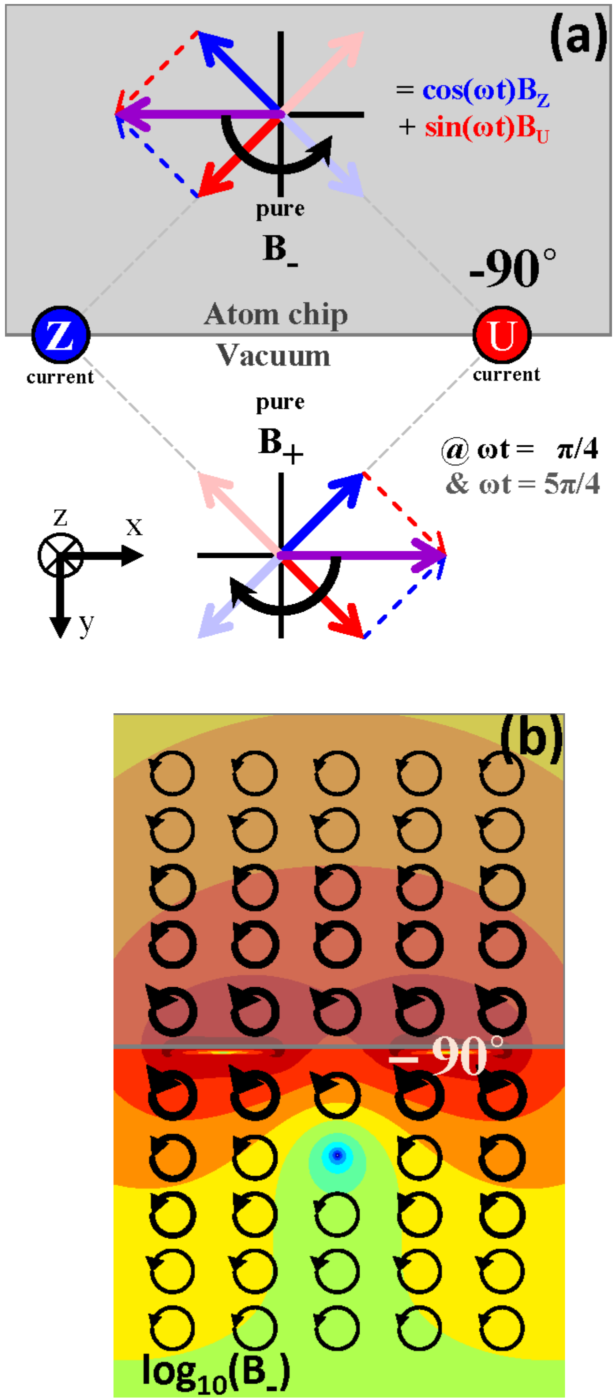
- Adjust phase to move



How to make a $\sigma^+/B\_$ trap

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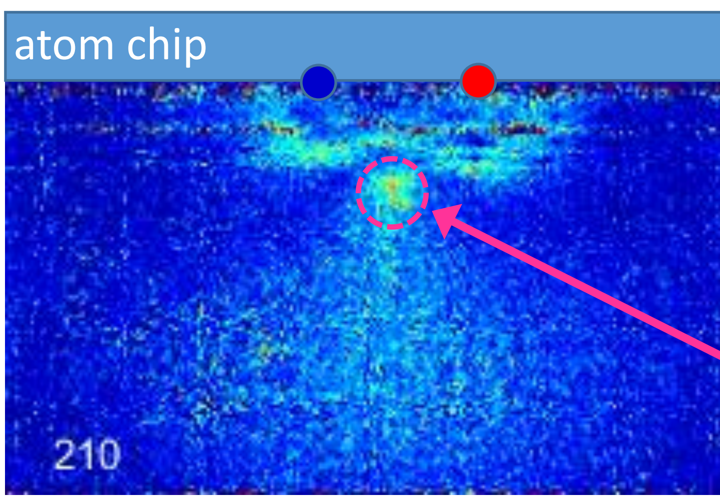
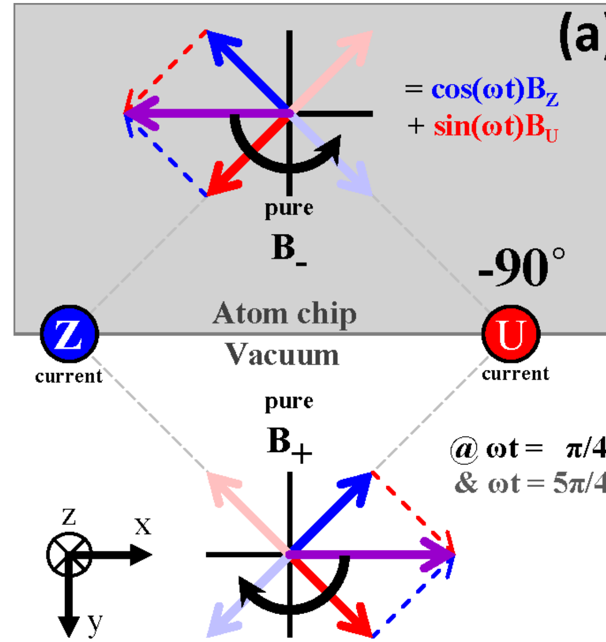
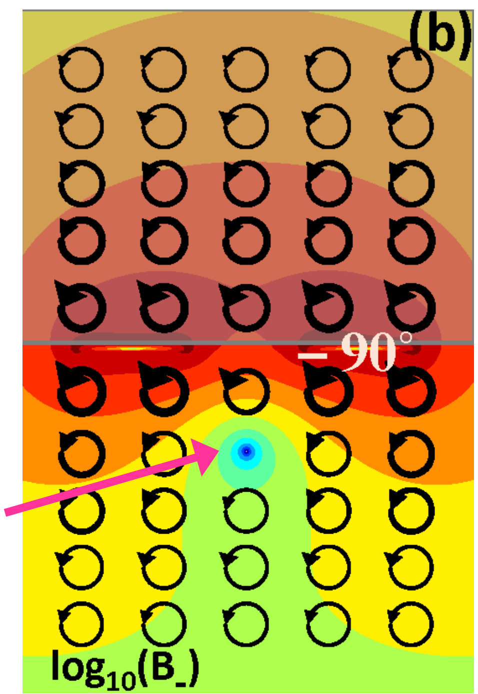


low power RF test: B- “contour plot.”

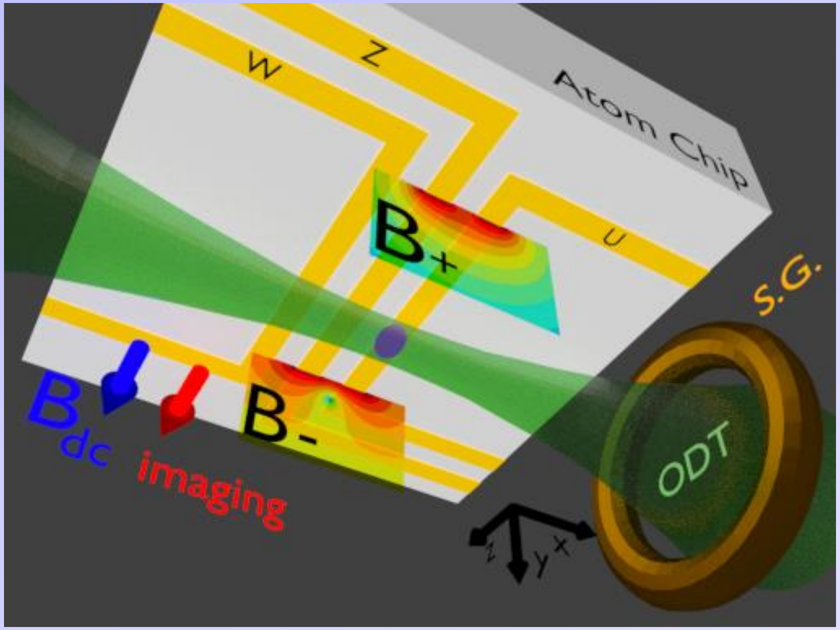
B- minimum





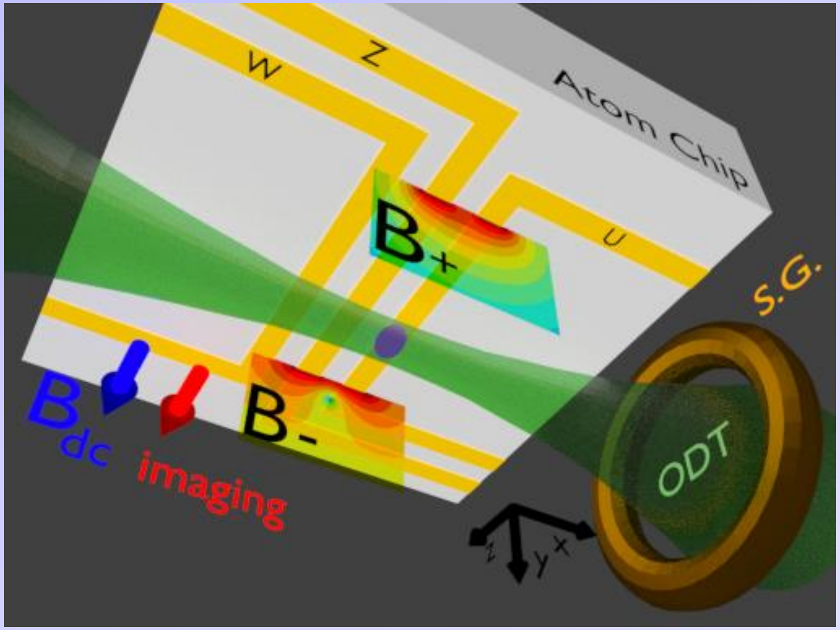
Trapping Results

- Transverse-xy trap: RF AC Zeeman.
  - → RF power: 200-400 mW at 20 MHz
- Axial-z trap: Laser endcapping.

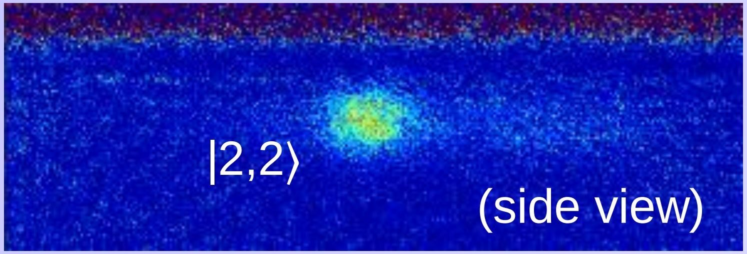


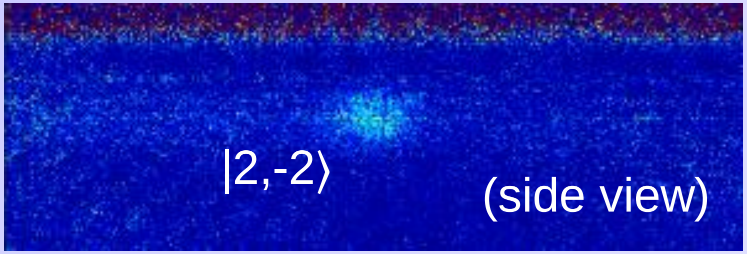
Trapping Results

- Transverse-xy trap: RF AC Zeeman.
  → RF power: 200-400 mW at 20 MHz
- Axial-z trap: Laser endcapping.
- First trap for F=2, m_F=-2 (lifetime ~ 0.5 s)



AC Zeeman trap

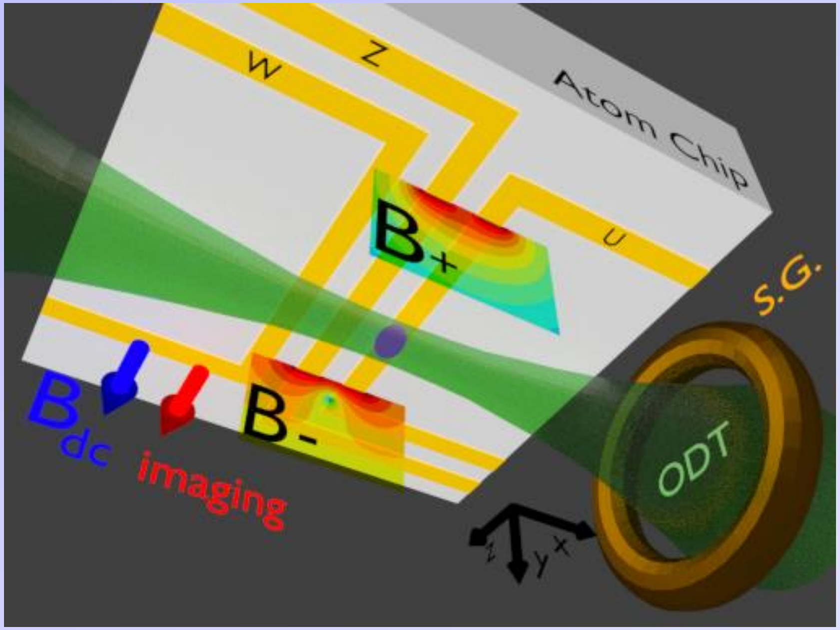




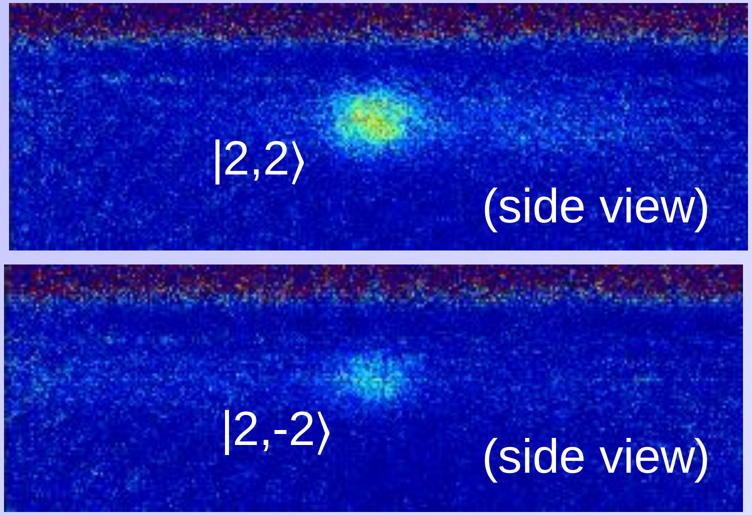
Rotunno, Miyahira, Du, Aubin, *in preparation* (2022)

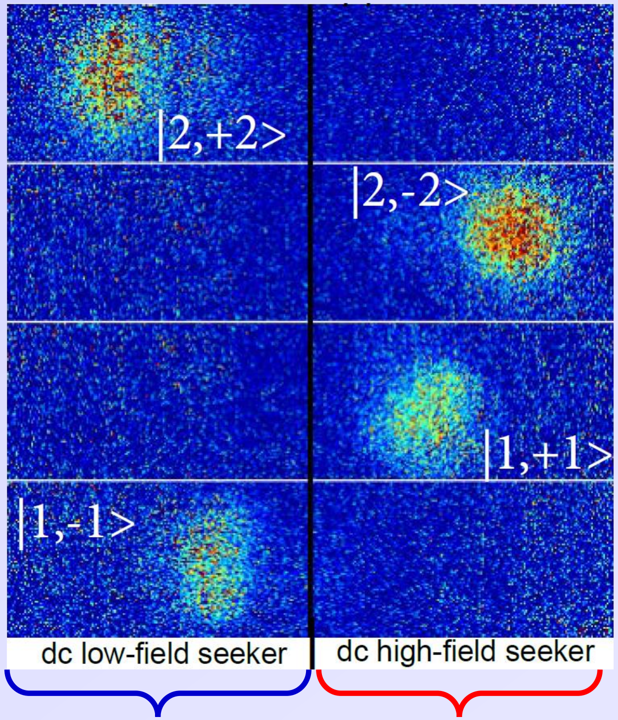
Trapping Results

- Transverse-xy trap: RF AC Zeeman.
  - → RF power: 200-400 mW at 20 MHz
- Axial-z trap: Laser endcapping.
- First trap for F=2, m_F=-2 (lifetime ~ 0.5 s)
- First trap for F=1, m_F=+1



AC Zeeman trap



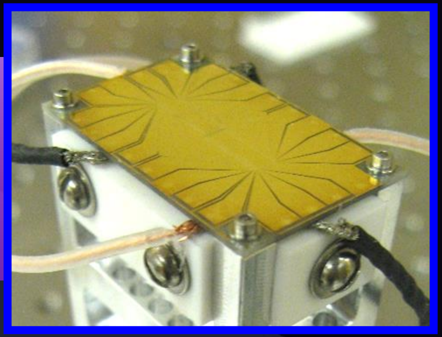


DCZ trappable DCZ untrappable

Rotunno, Miyahira, Du, Aubin, *in preparation* (2022)

Summary

- **Ultracold** atom technology.
- **Spin-dependent traps** & interferometry.



What's next? → *Is ACZ* ***trap roughness*** *suppressed?*

→ *Build* ***microwave atom chip.***

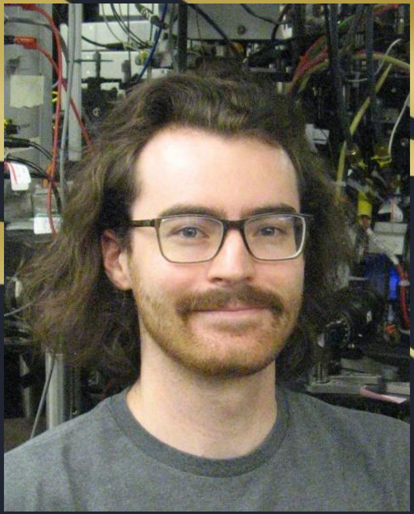
with Virginia Commonwealth U. (V. Avrutin)

→ *Test* ***microwave trap & lattice.***

→ *Trapped atom* ***interferometry****.*

WILLIAM & MARY

Ultra-cold atoms group



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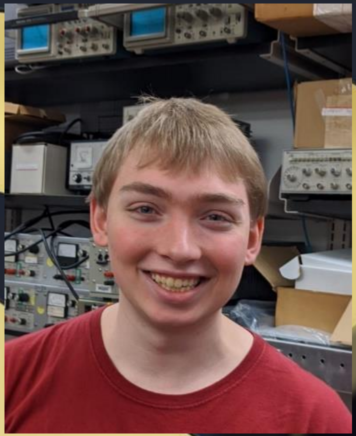
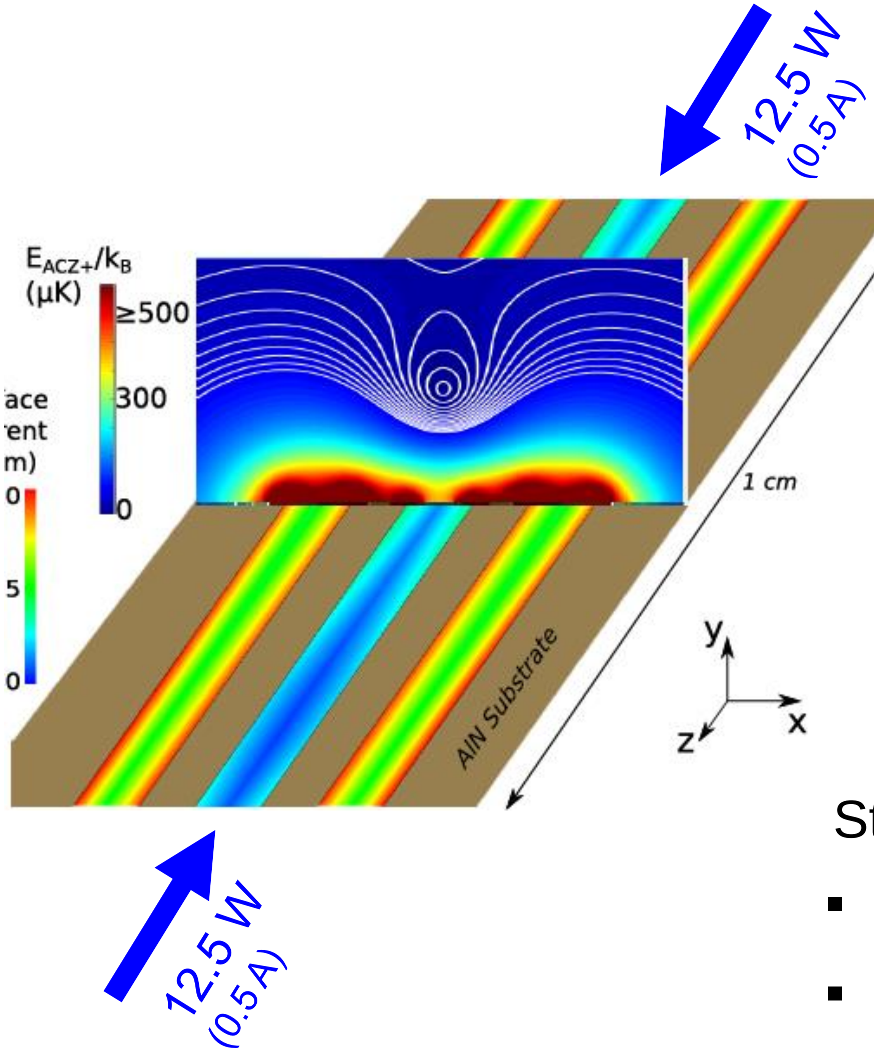


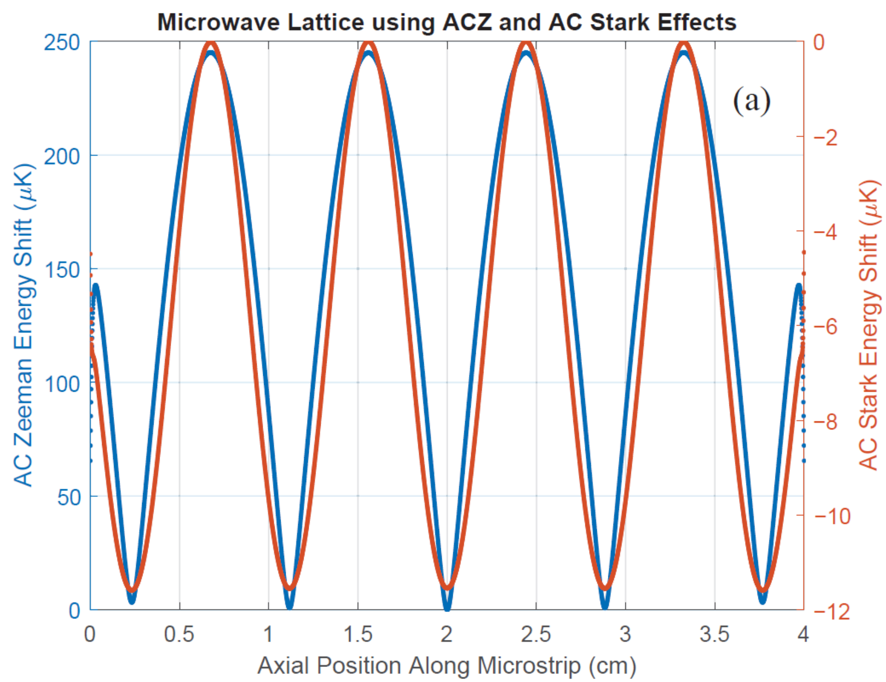
S. Rosene

Backup Slides

Microwave Lattice

axial confinement & positioning





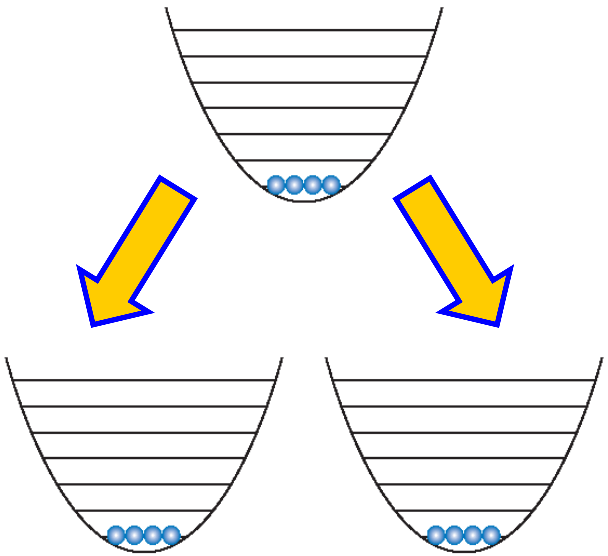
Standing wave at 6.8 GHz

- detuning $\delta = 2\pi \times 1$ MHz
- Axial confinement $\omega_z = 2\pi \times 30$ Hz

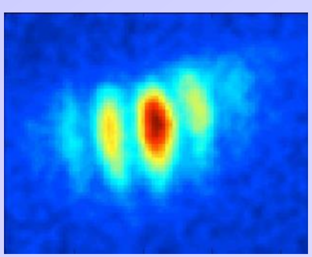
Miyahira, Rotunno, Du, Aubin, *MDPI Atoms* **9**, 54 (2021)

The problem with fermions

BEC beamsplitting

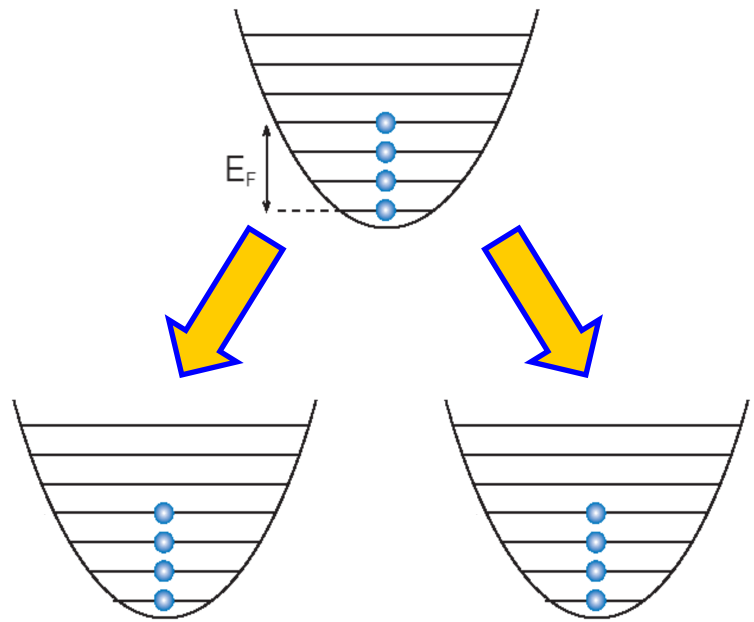


$$|\psi\rangle = \left(|atom\rangle_{left} + e^{i\varphi}|atom\rangle_{right}\right)^N$$



[Thywissen group, U. of Toronto]

DFG beamsplitting



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

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

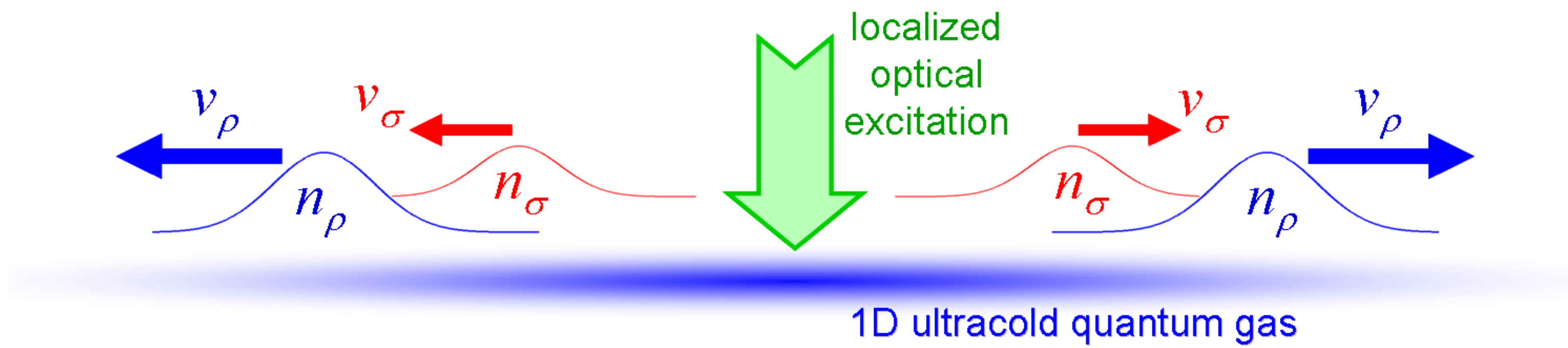
$\varphi_0 \neq \varphi_1 \neq \ldots \neq \varphi_{N-1}$ → *interference washed out!*

Sensitivity Estimates (optimistic)

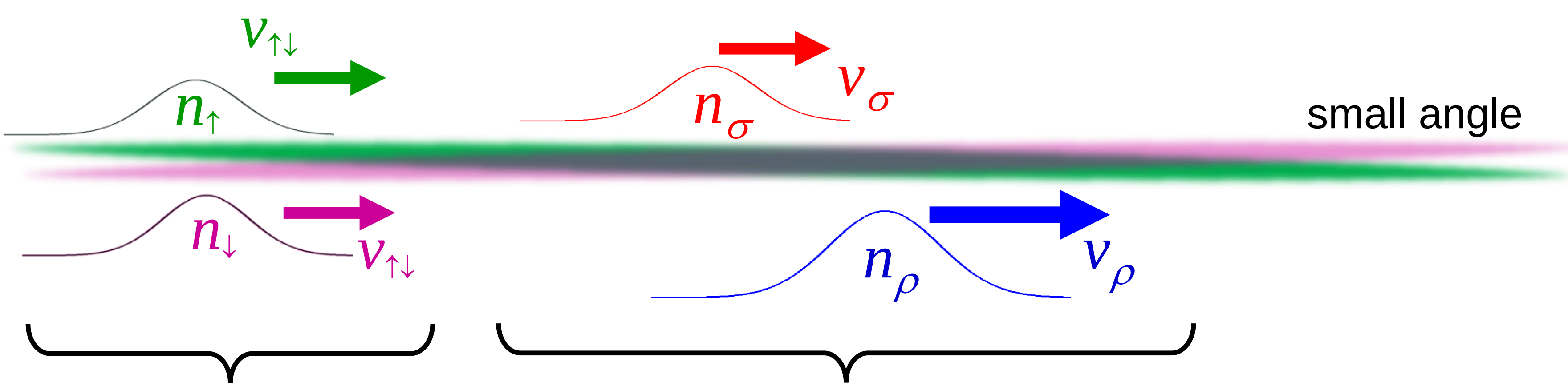
- Quantum **projection noise** limited (no spin-squeezing).
- Atom: ^{87}Rb.

	gravimetry	**sub-mm gravity**	**Casimir-Polder**
Description	Measurement of local gravity g.	Measurement of gravity at 50 µm from a 2 mm iridium sphere.	Force measurement at 20 µm from fused silica surface (300 K).
atom number: N	10^5	10^5	10^5
arm separation: Δl	1 mm	100 µm	20 µm
phase int. time: Δt	1 s	10 s	1 s
acc. phase: ϕ (rads)	1.4×10^7	7.2×10^{-3}	0.029
Sensitivity (per exp. cycle)	**2×10^{-10} g**	**S/N ~ 2**	**S/N ~ 9**

Spin- “charge” separation (1D gas)



<u>Spin-specific traps</u> allow independent control of $n_\uparrow$ *and* $n_\downarrow$ excitations:



single-particle physics

<u>spin-“charge” separation physics</u>

spin or “charge” excitation depends on arrival phase of $n_\uparrow$ *and* $n_\downarrow$ *excitations*

AC vs. DC Potential Roughness

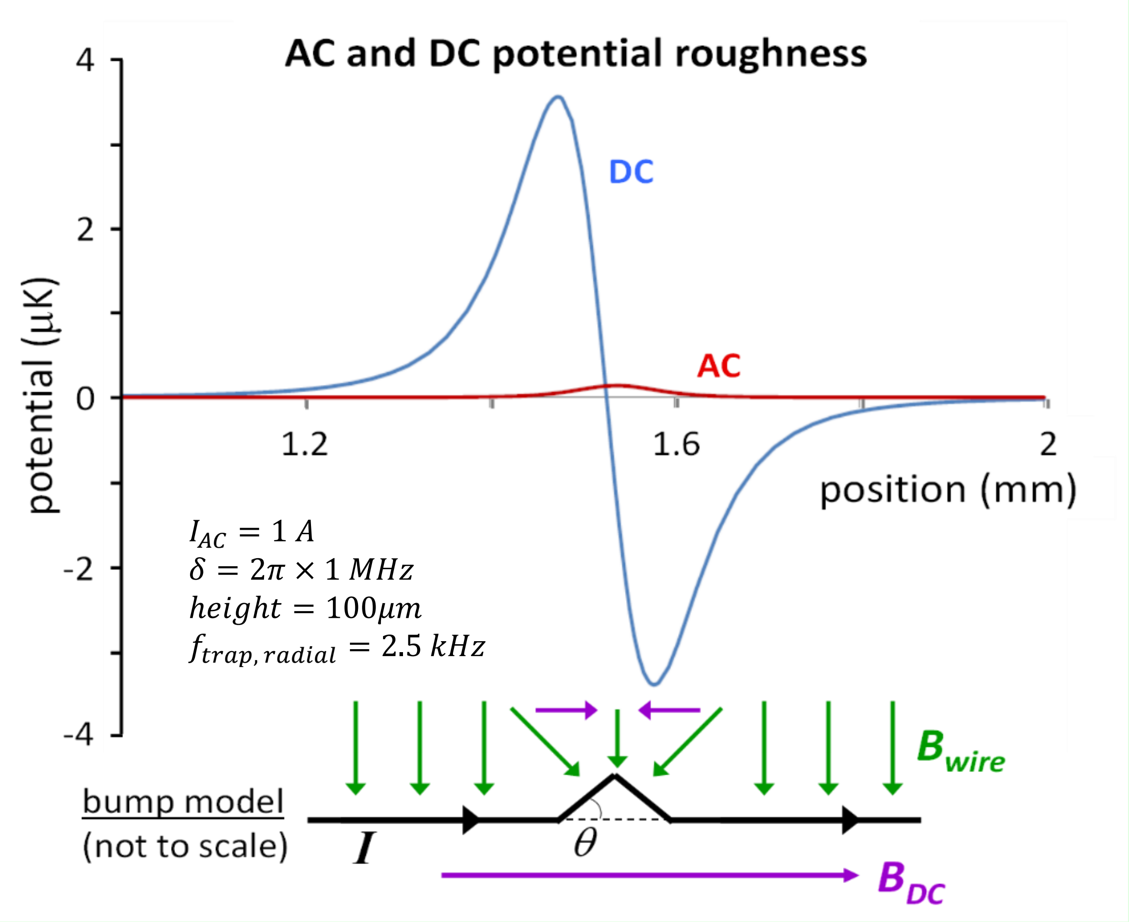
<u>Bump</u>

2.5 μm deviation over 50 μm length.

<u>Traps</u>

DC and RF traps have identical trapping frequency: 2.5 kHz

DC and RF traps are both 100 μm above their central wire.



Order of magnitude suppression of roughness !!!