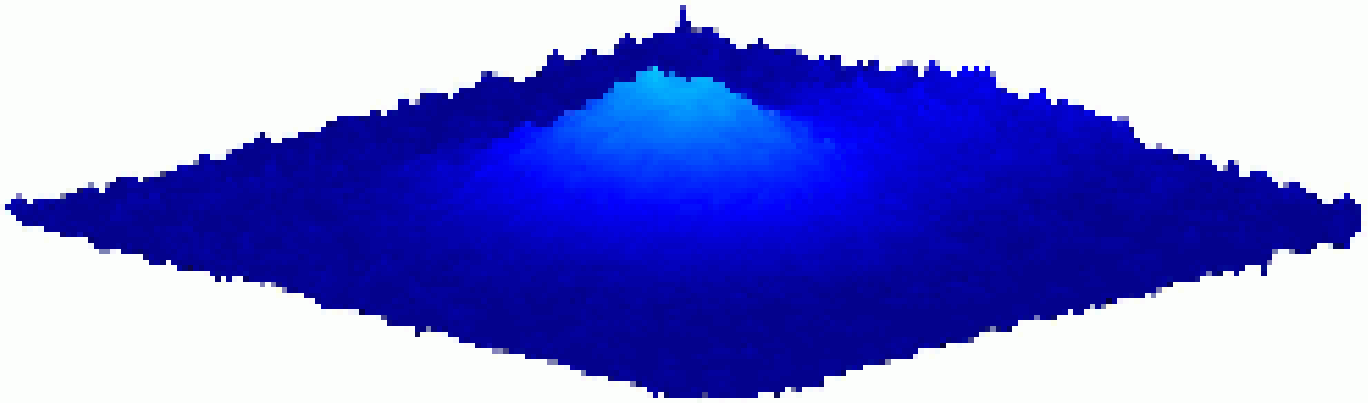
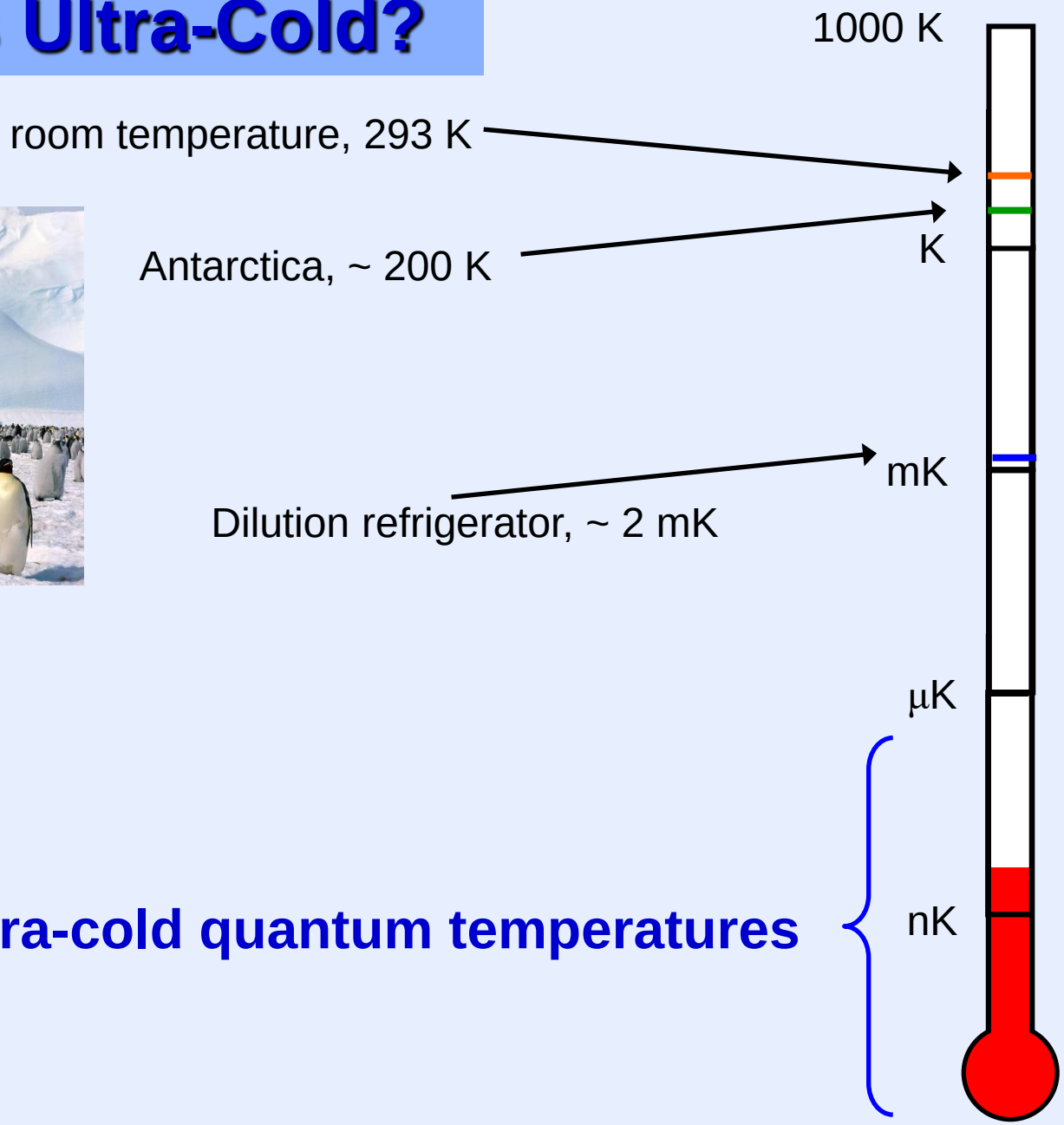
Bose-Einstein Condensation

Ultracold Quantum Gases



How cold is Ultra-Cold?

[priceofoil.org, 2008]



How cold is Ultra-Cold?

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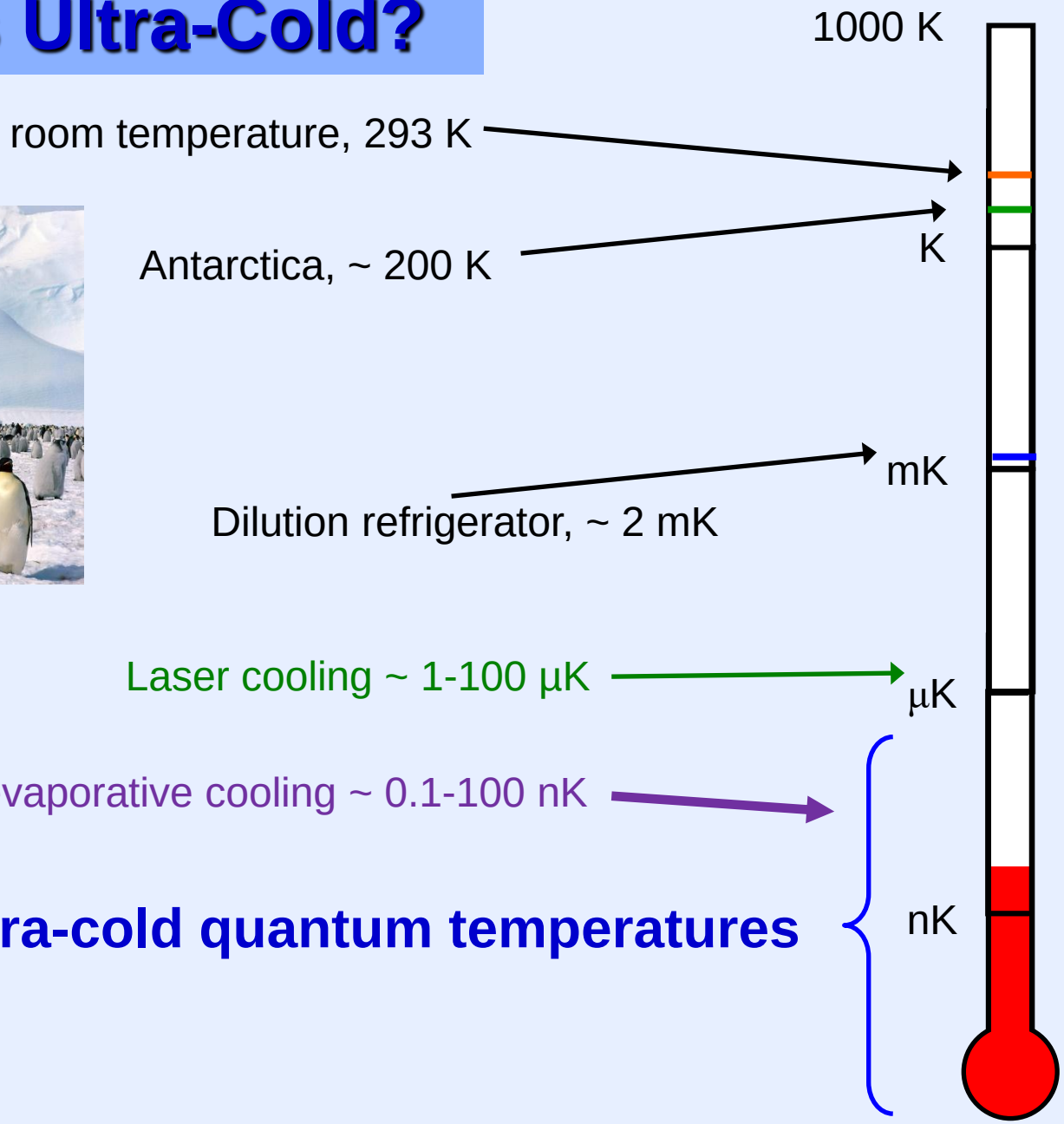
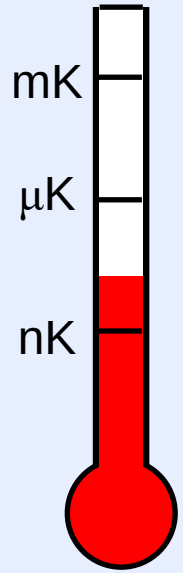


What's Ultra-Cold Matter ?

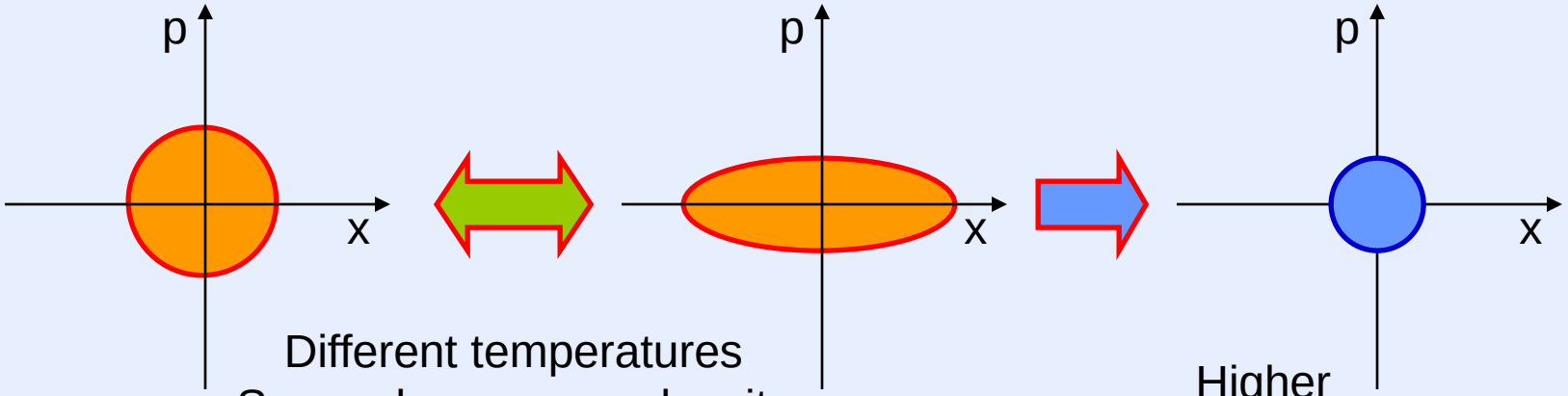


➢ Very Cold

→ Typically nanoKelvin – microKelvin

→ Atoms/particles have velocity ~ mm/s – cm/s

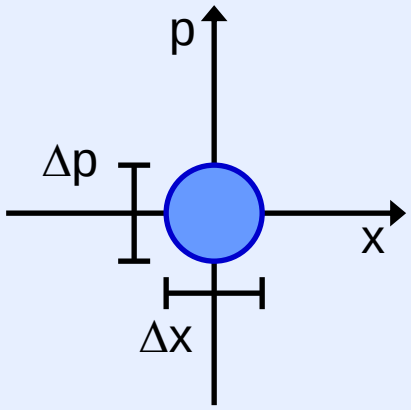
➢ Very Dense … in Phase Space



Different temperatures
Same phase space density

Higher
phase space density

Ultracold Quantum Mechanics



Quantum mechanics requires

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

→ fundamental unit of phase space volume

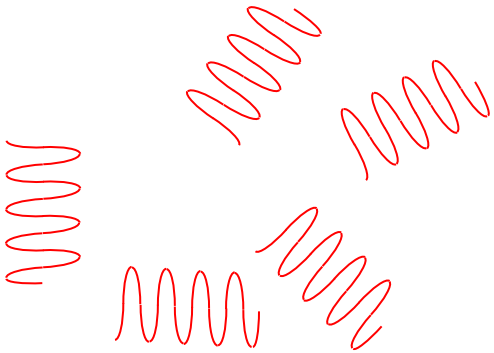
$$\Delta x \cdot \Delta p = \hbar/2$$

→ Quantum physics is important when $PSD \sim 1$

Equivalent:

deBroglie wavelength ~ inter-particle separation

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



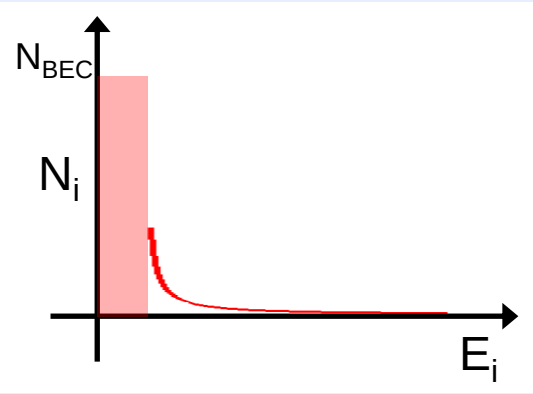
Boltzmann régime

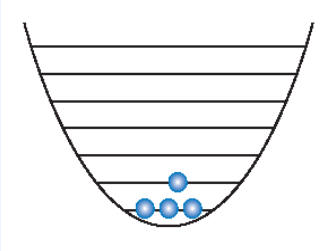
Quantum Statistics

Bosons

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

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

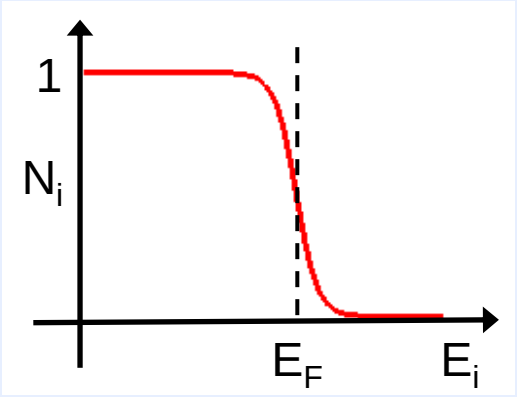


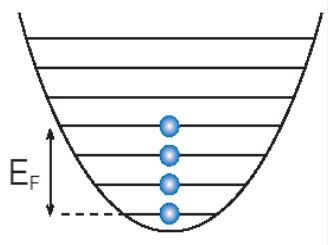


Fermions

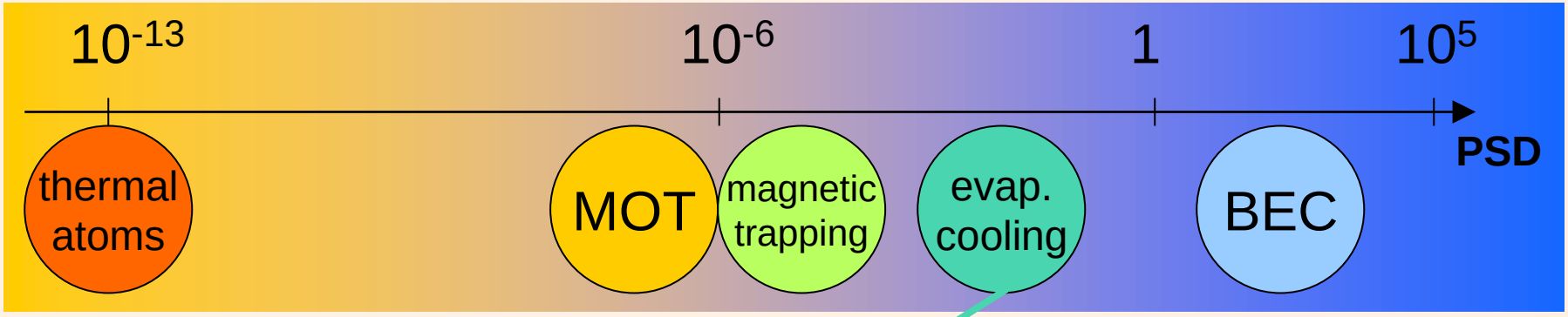
- **anti-symmetric** multi-particle wavefunction.
- **½-integer spin**: electrons, protons, neutrons, ^{40}**K**.
- probability of occupying a state |i> with energy E_i.

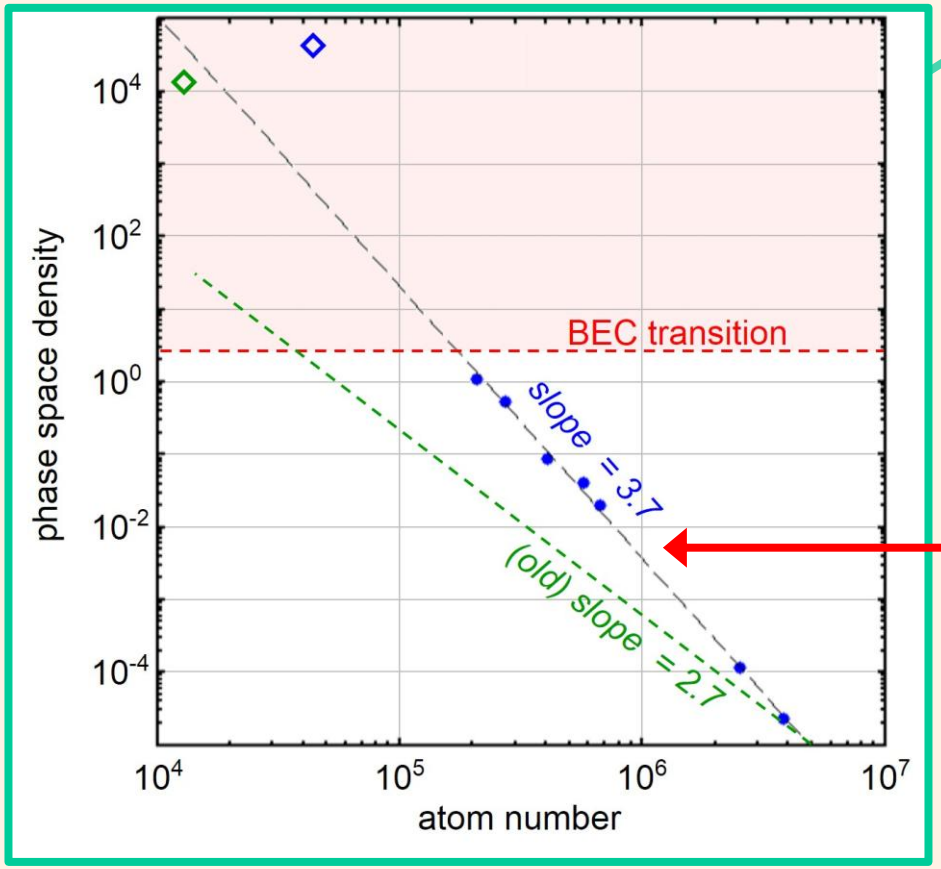
$$P(E_i) \propto \frac{1}{e^{(E_i-\mu)/kT} + 1}$$

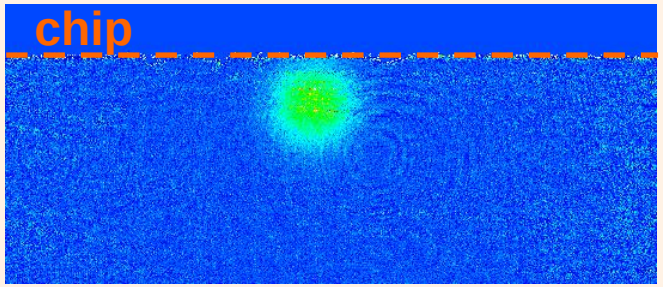




Bose-Einstein Condensation of ^{87}Rb



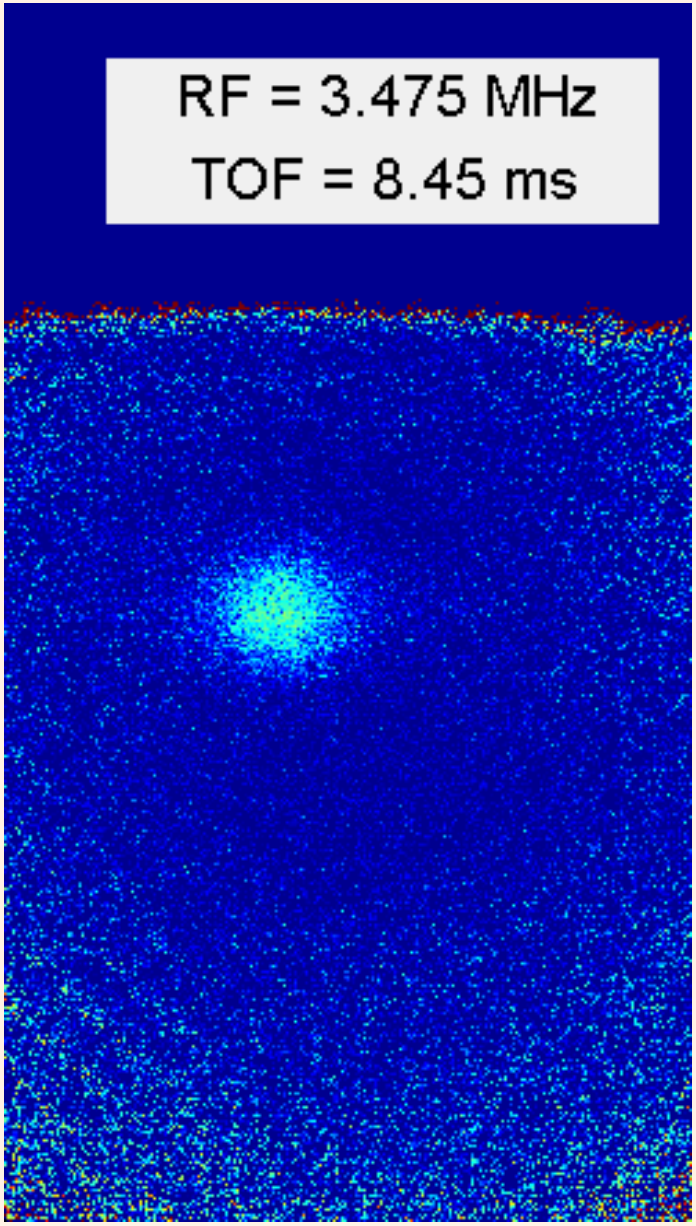




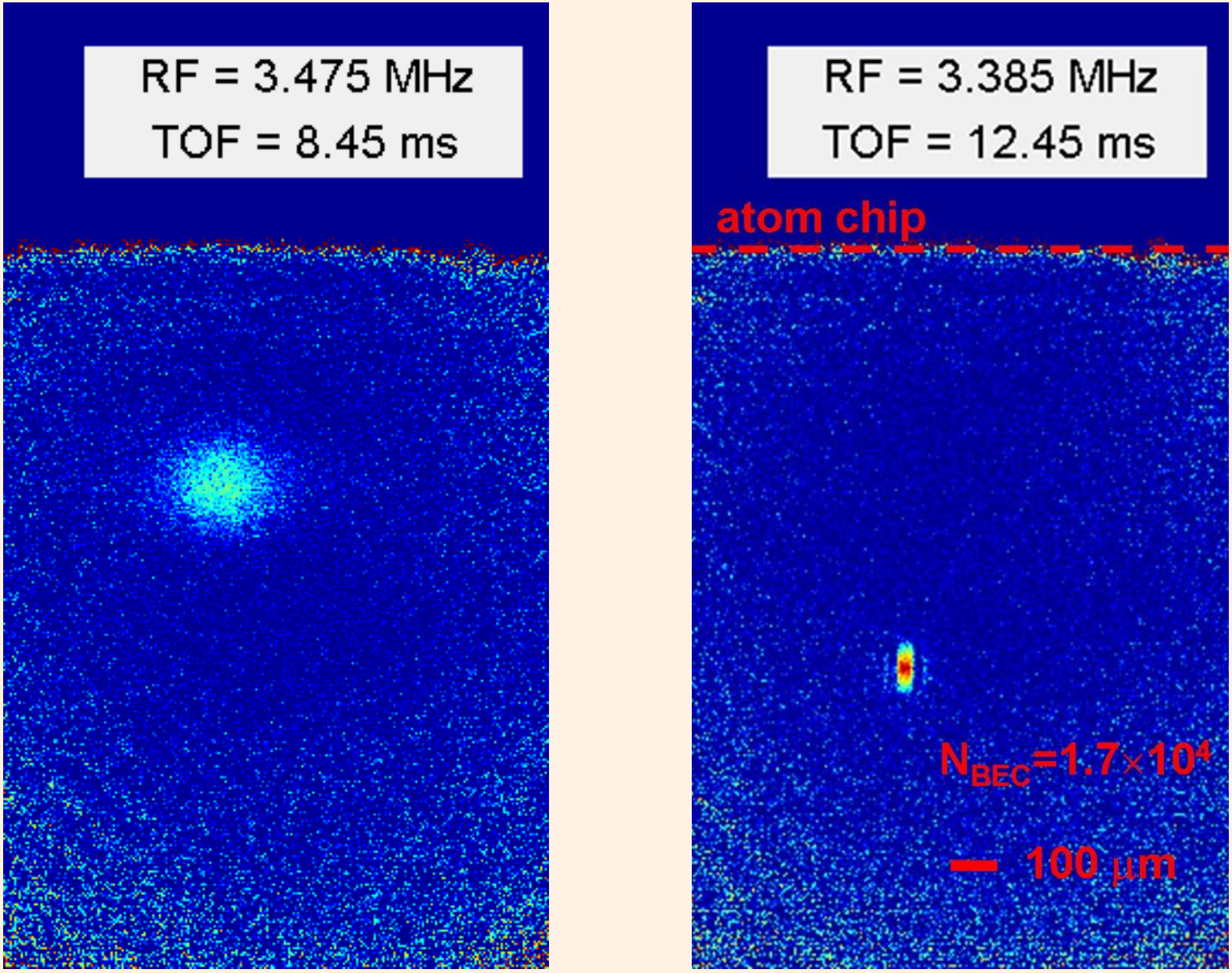
Evaporation Efficiency

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

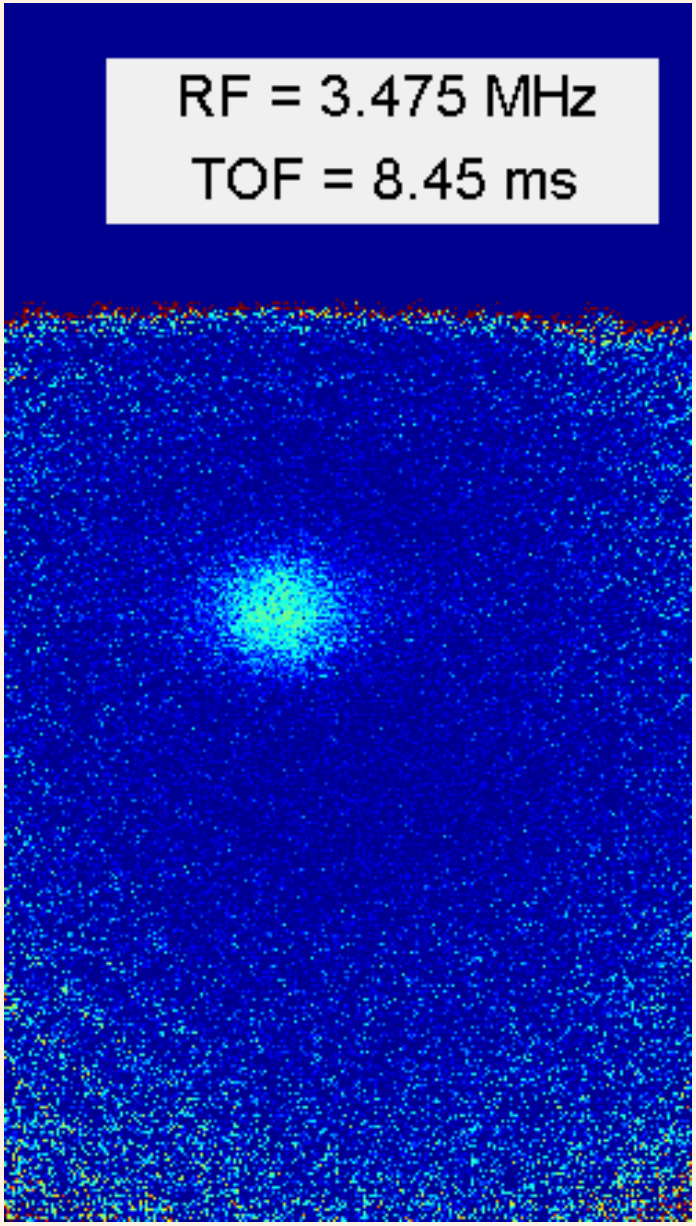
^{87}Rb BEC



^{87}Rb BEC


RF = 3.475 MHz
TOF = 8.45 ms
RF = 3.385 MHz
TOF = 12.45 ms
atom chip
$N_{BEC}=1.7\times10^4$
100 μm

^{87}Rb BEC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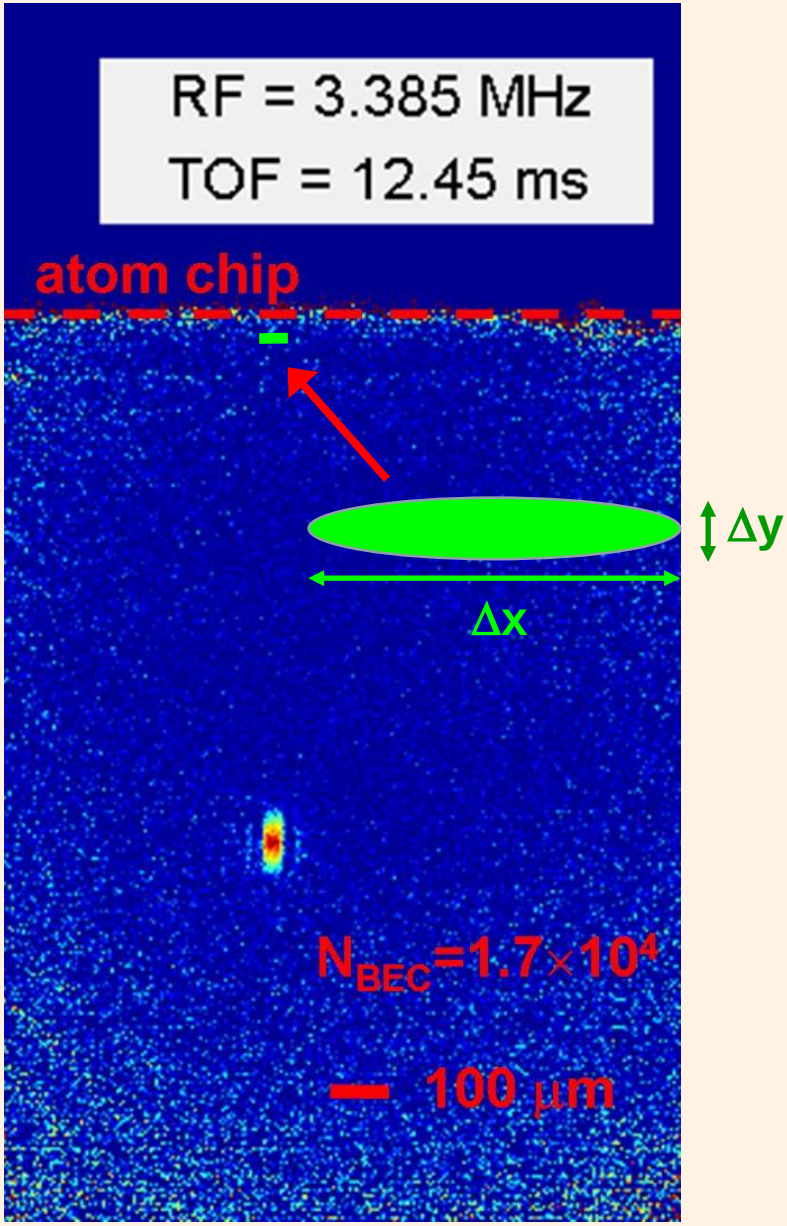
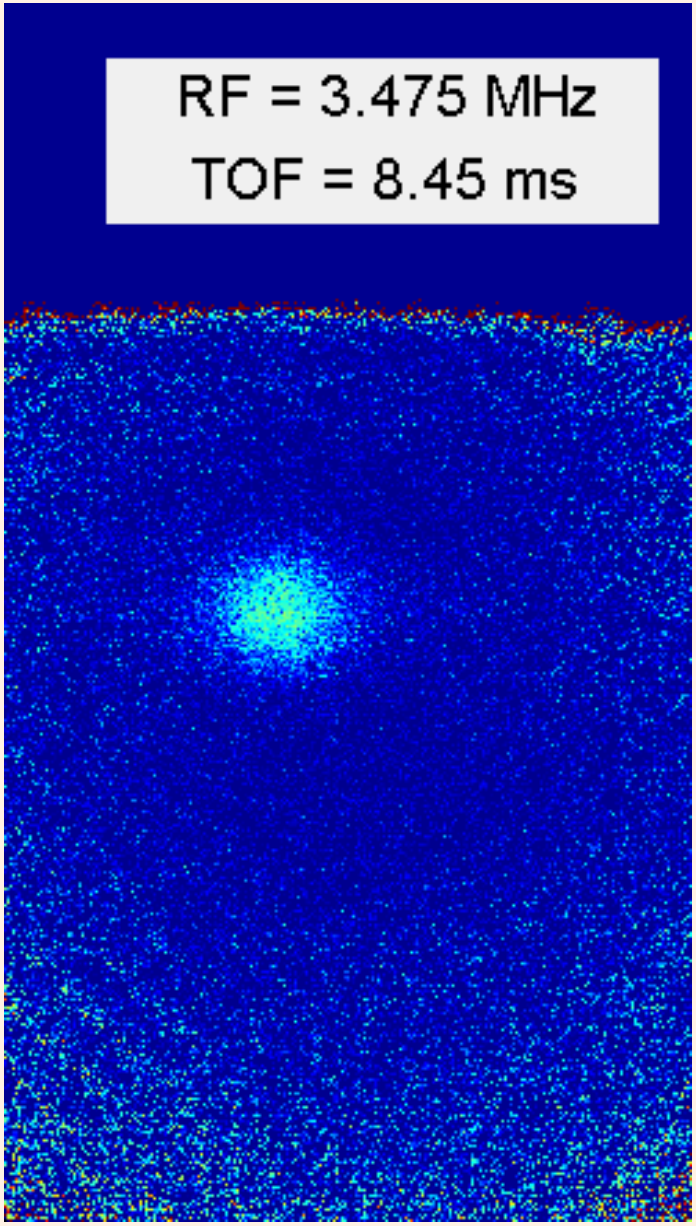

RF = 3.385 MHz
TOF = 12.45 ms
atom chip
Δy
Δx
N_BEC=1.7×10^4
100 μm

^{87}Rb BEC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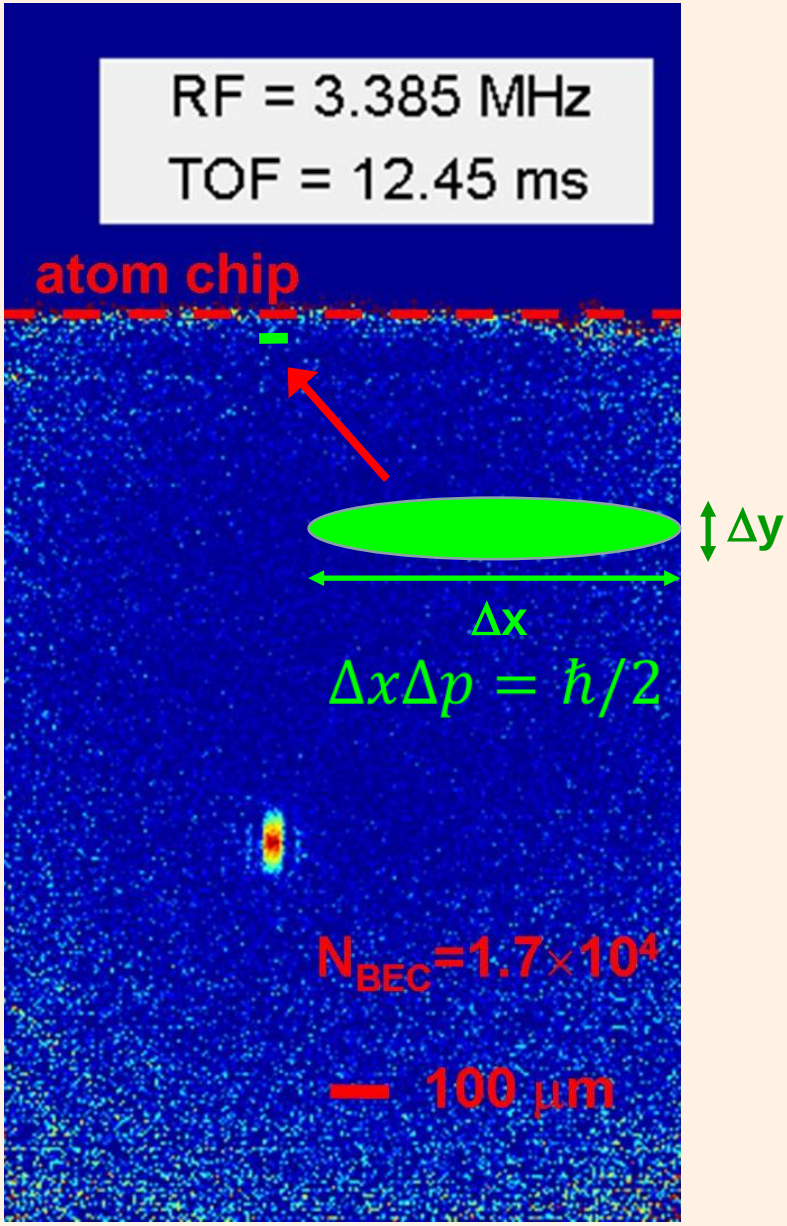
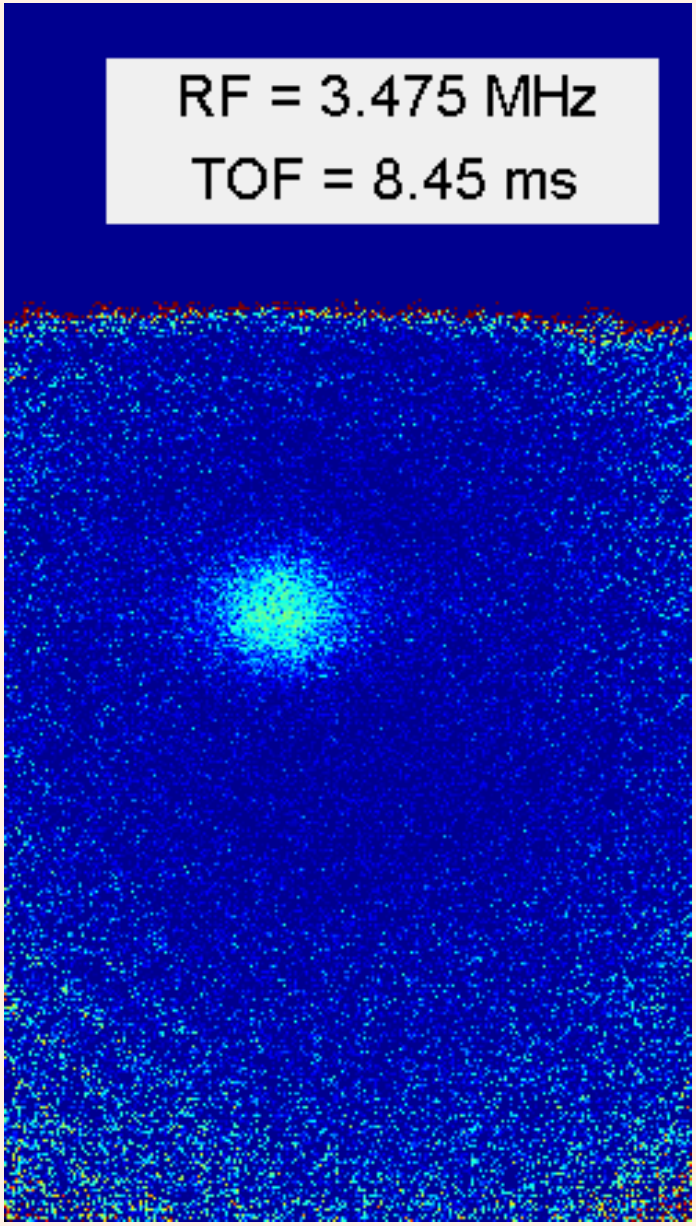
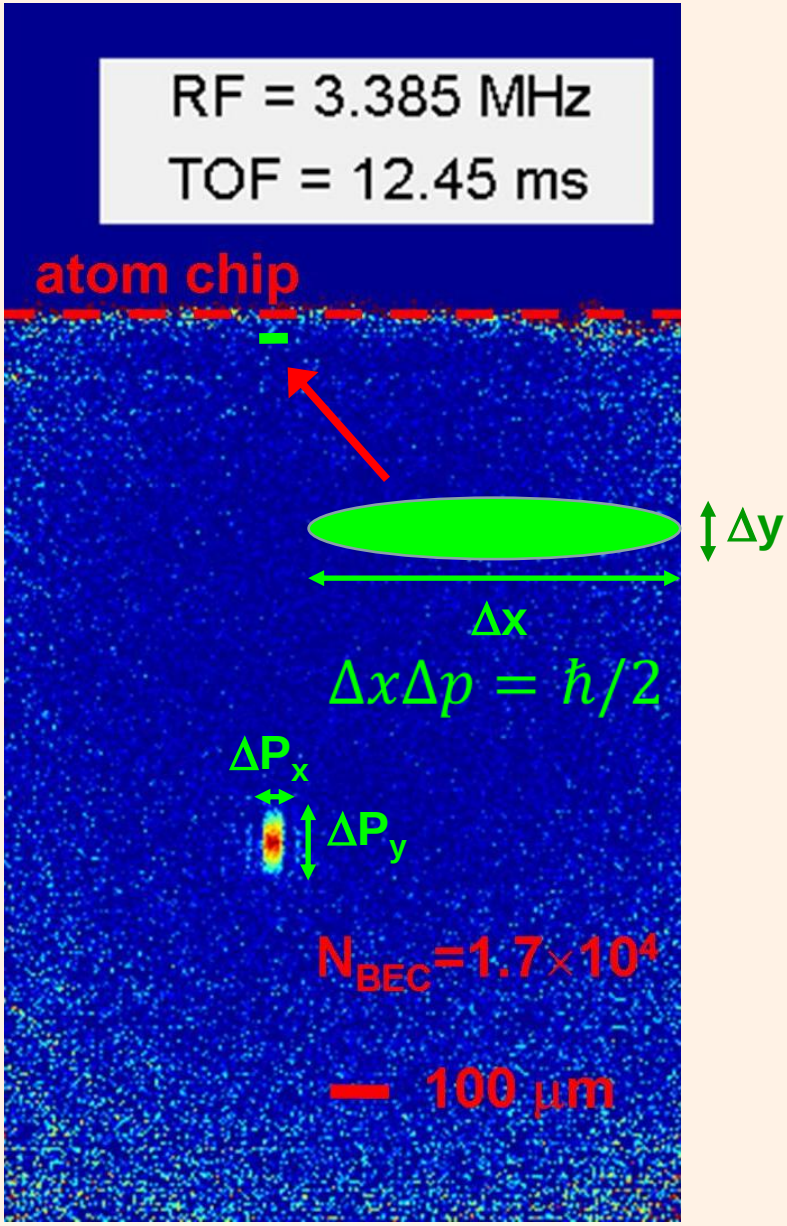
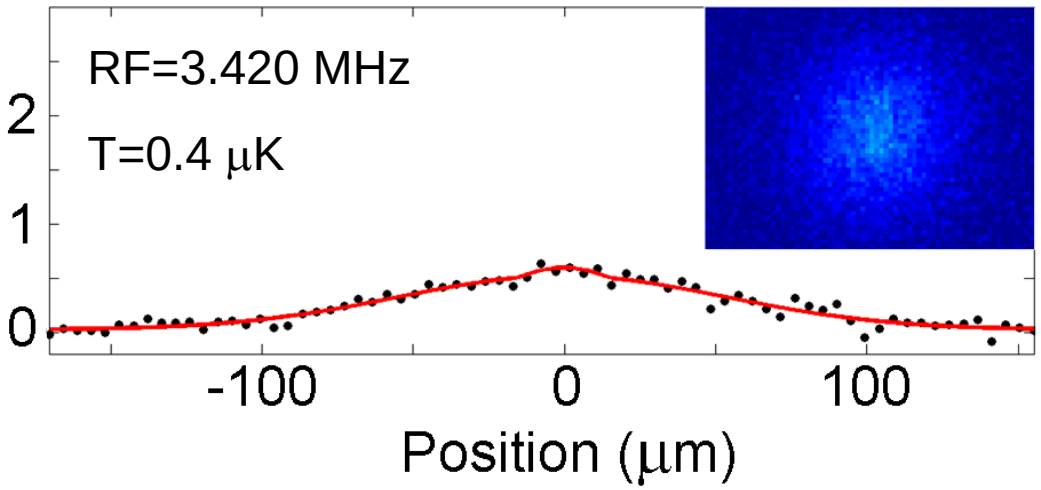

RF = 3.385 MHz
TOF = 12.45 ms
atom chip
Δy
Δx
$\Delta x \Delta p = \hbar/2$
$N_{BEC}=1.7\times10^4$
100 μm

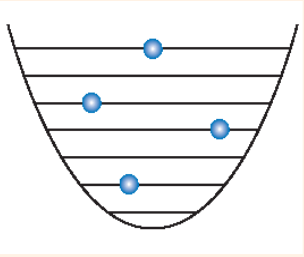
^{87}Rb BEC


RF = 3.475 MHz
TOF = 8.45 ms


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

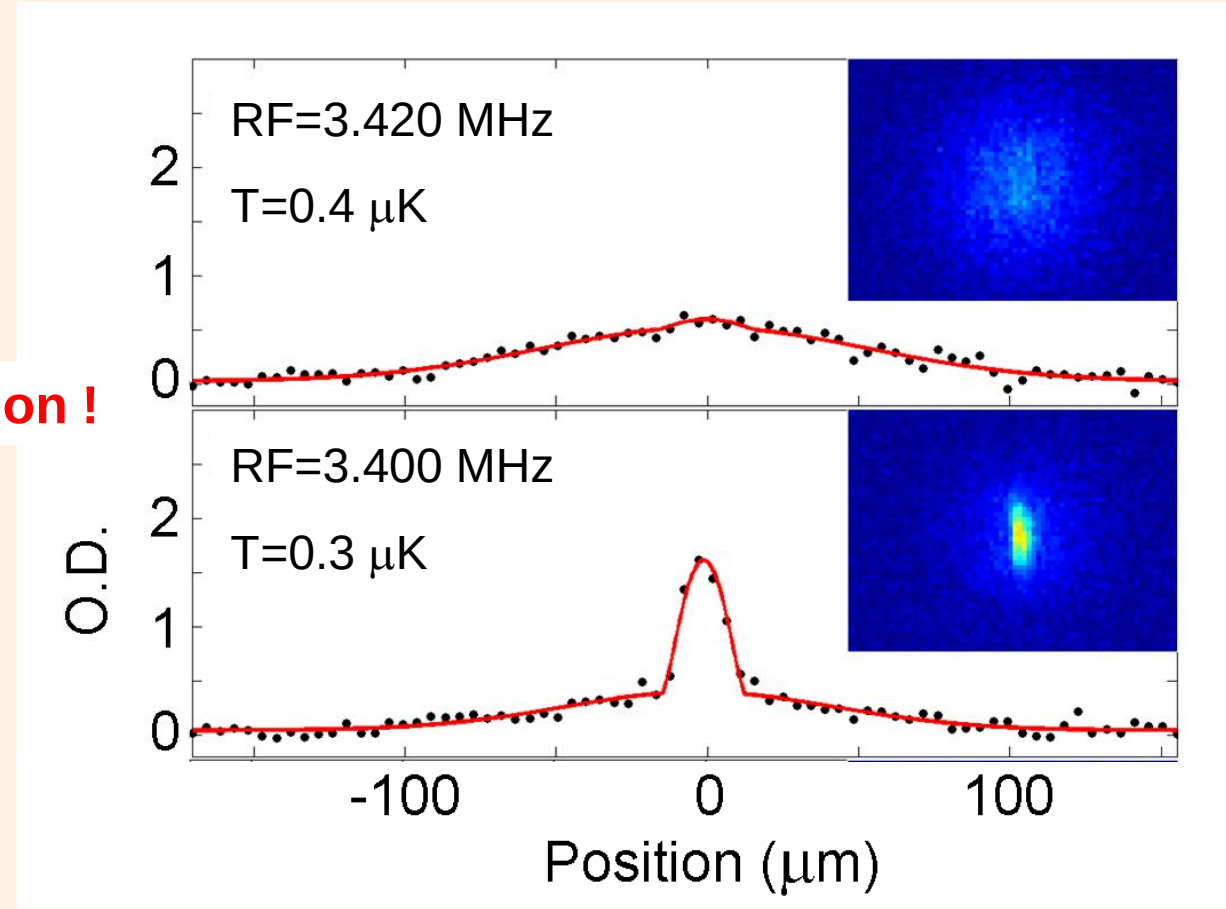
^{87}Rb BEC

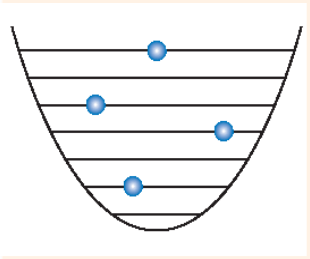


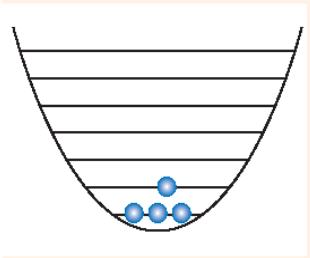


^{87}Rb BEC

BEC transition !



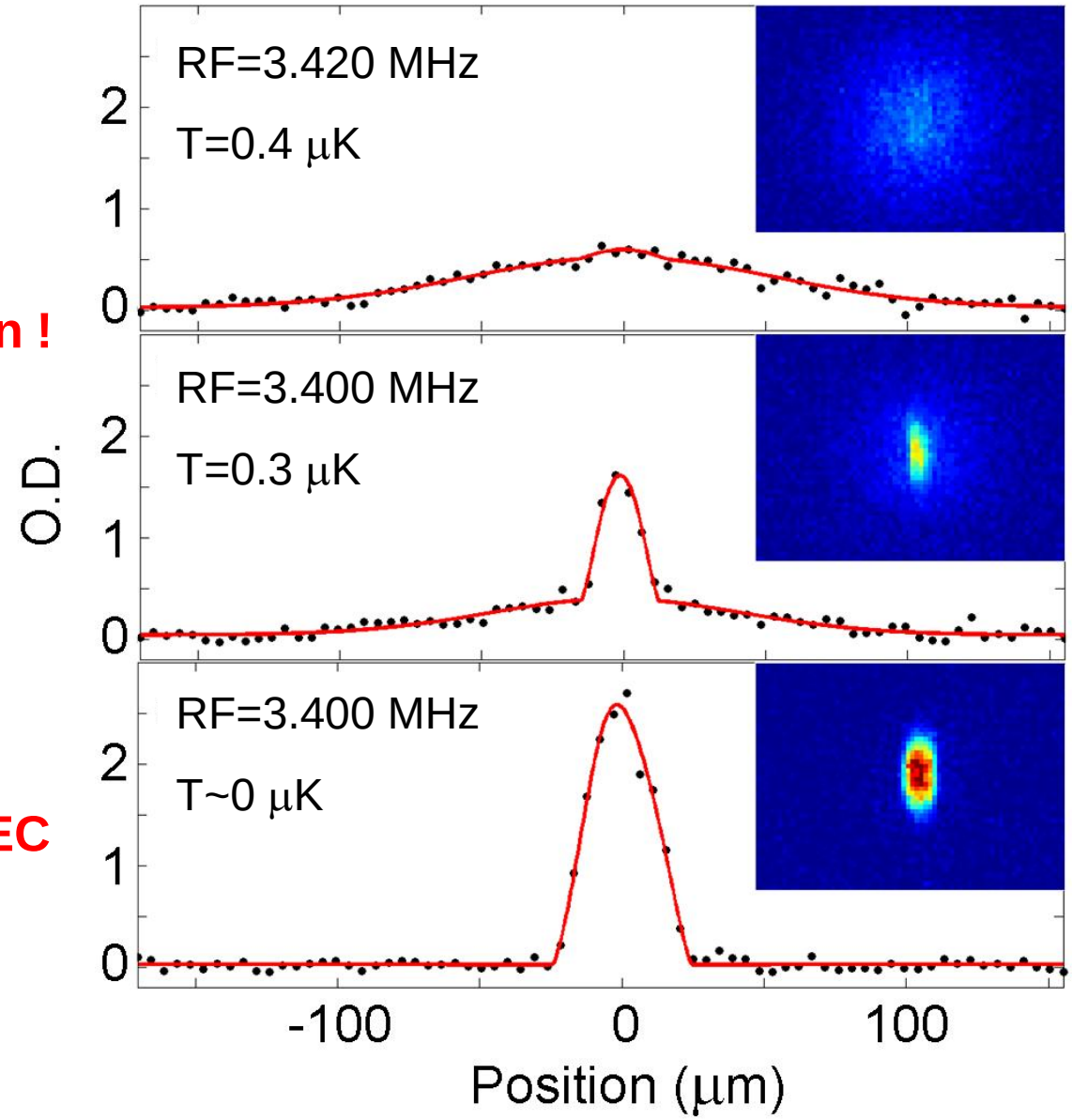


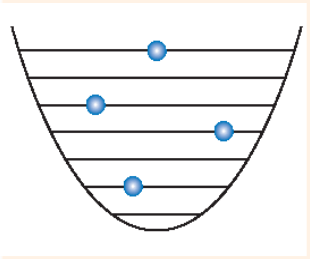


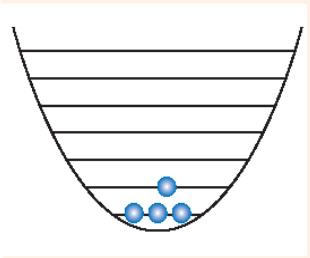
^{87}Rb BEC

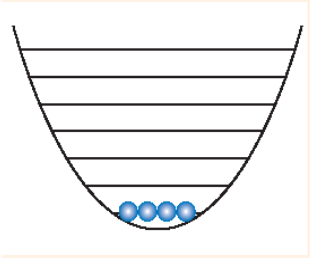
BEC transition !

quasi-pure BEC

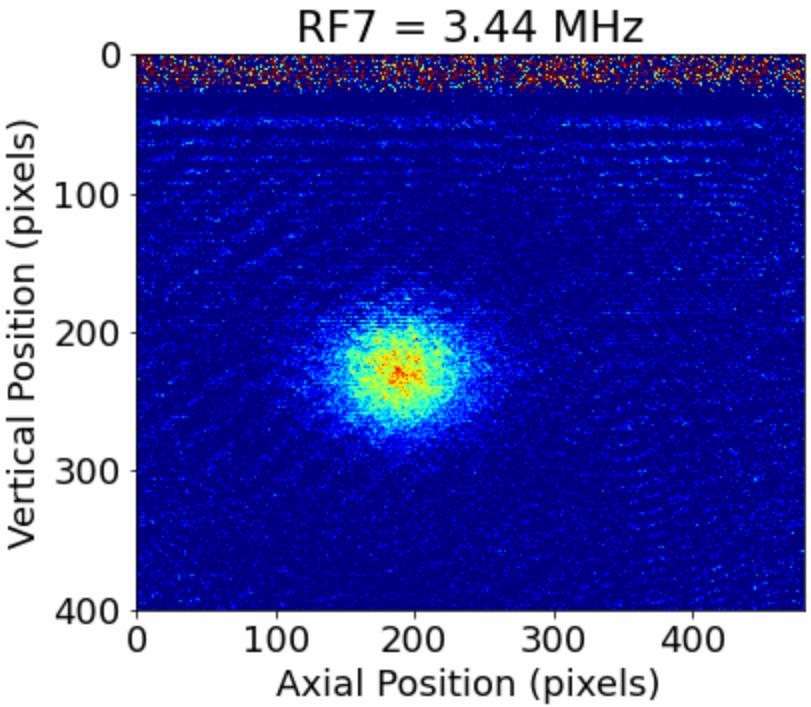


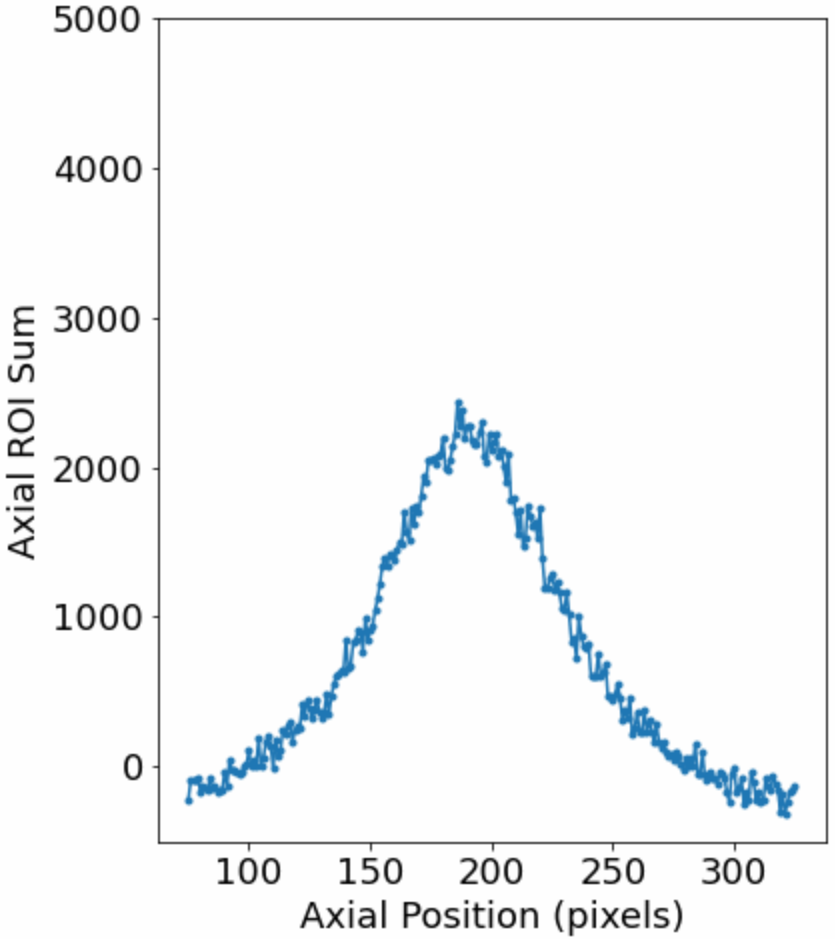






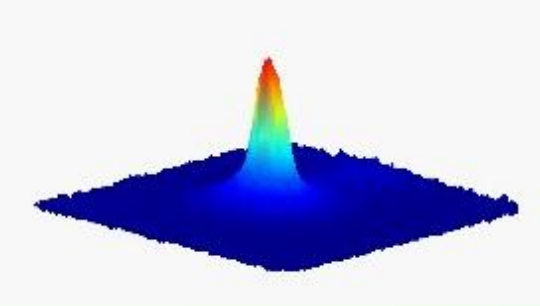
^{87}Rb BEC

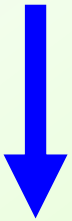

RF7 = 3.44 MHz
Vertical Position (pixels)
Axial Position (pixels)
0
100
200
300
400


Axial ROI Sum
Axial Position (pixels)
5000
4000
3000
2000
1000
0
100
150
200
250
300

BEC Diffraction

Quantum mechanics will find you

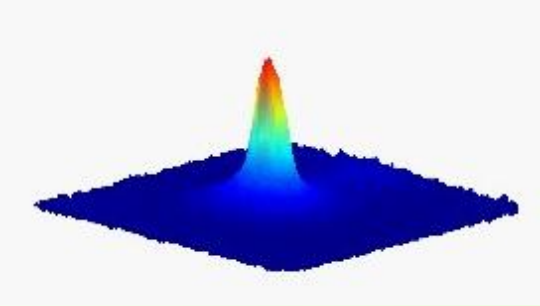




laser barrier

BEC Diffraction

Quantum mechanics will find you

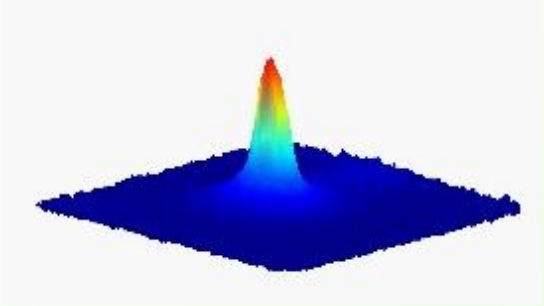


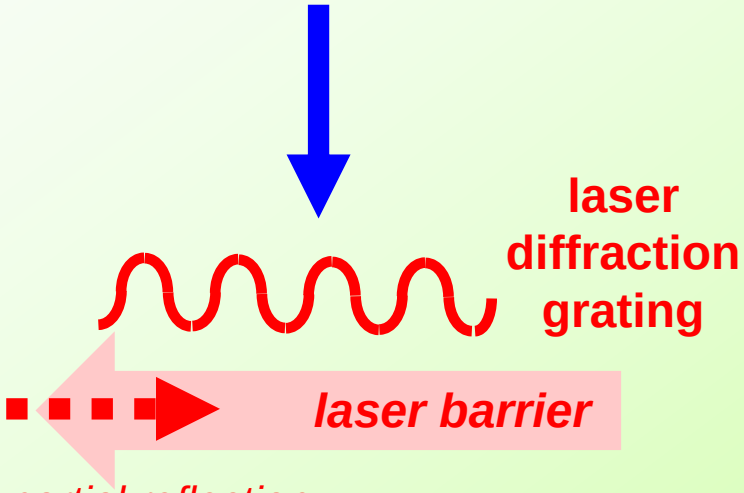
laser barrier

partial reflection of laser

BEC Diffraction

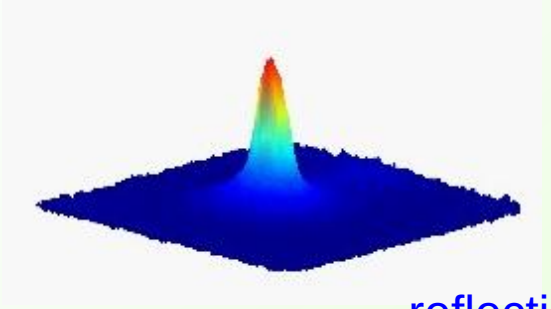
Quantum mechanics will find you





BEC Diffraction

Quantum mechanics will find you



reflection with
±1 **diffraction**
orders

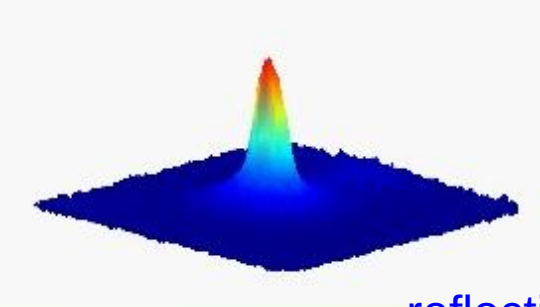
laser
diffraction
grating

laser barrier

partial reflection
of laser

BEC Diffraction

Quantum mechanics will find you

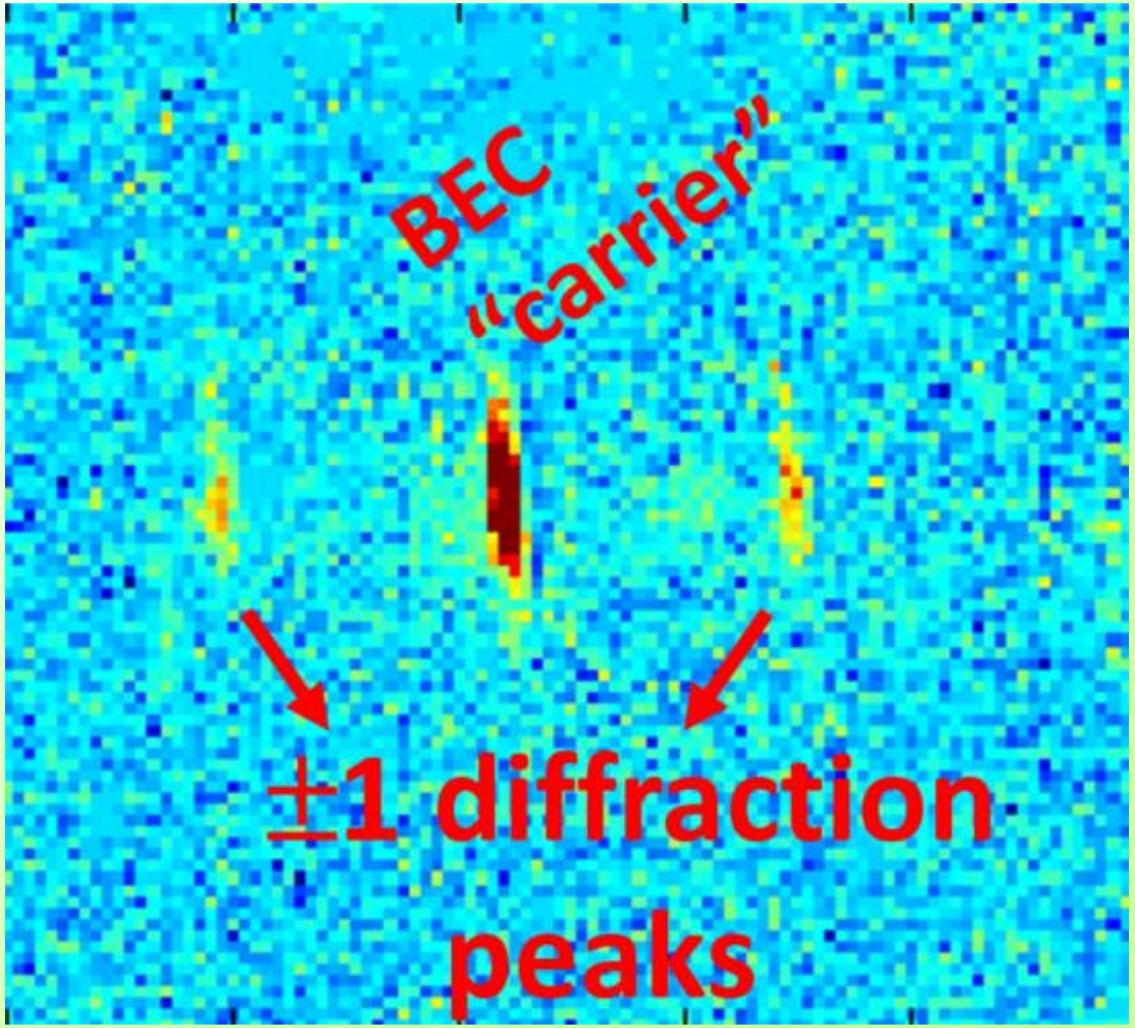


reflection with ±1 **diffraction** orders

laser diffraction grating

laser barrier

partial reflection of laser



A. J. Pyle, PhD thesis (2019)

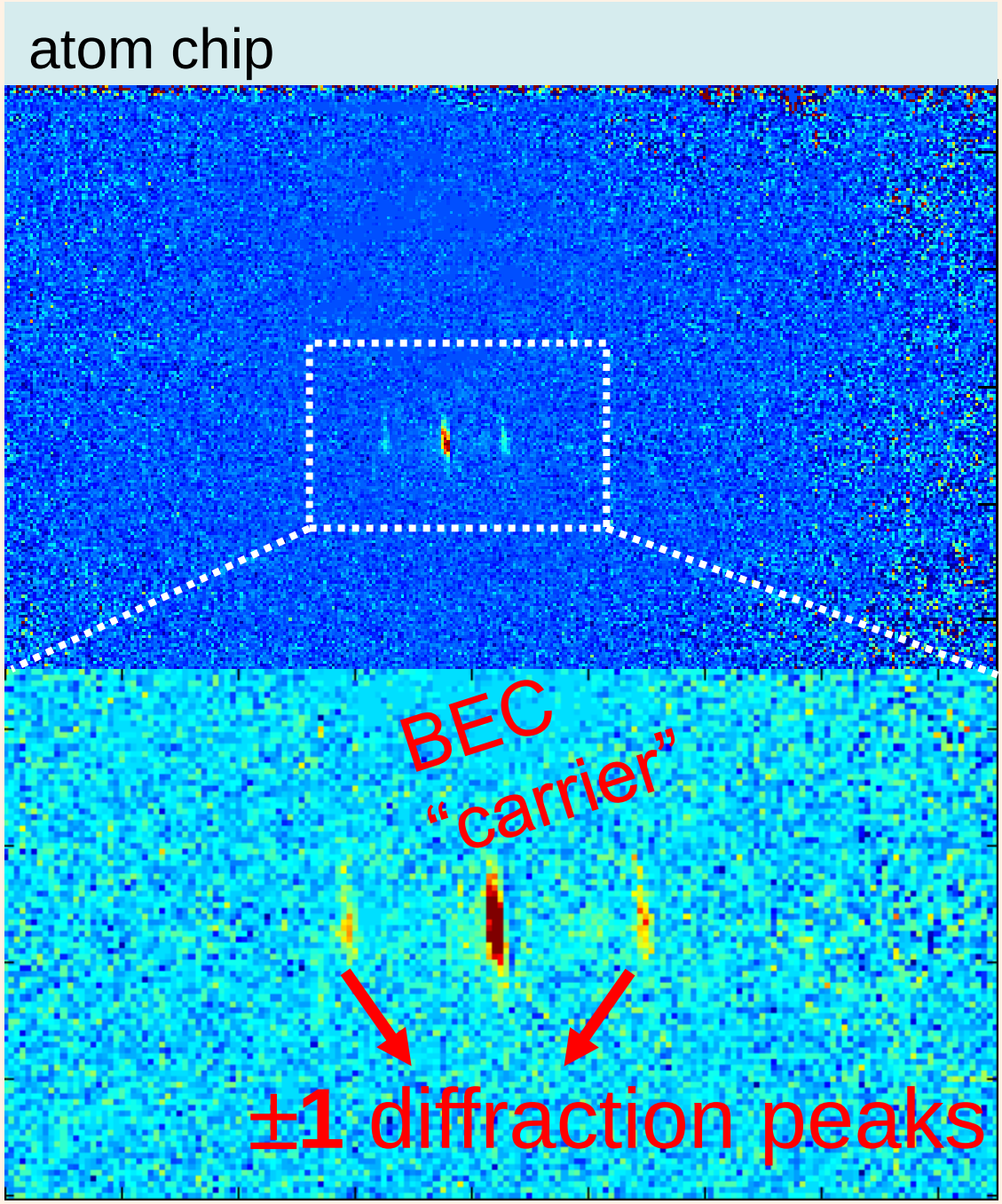
It's Quantum !

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.



Laser light vs. BEC

Is a BEC like a laser, but with atoms instead of photons?

Laser light vs. BEC

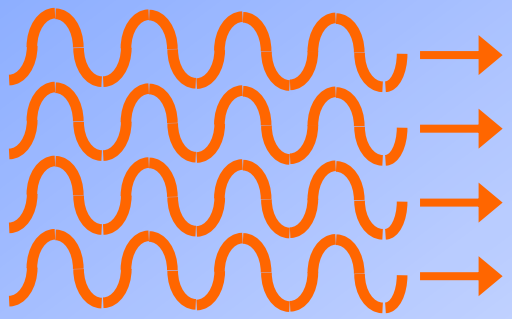
Is a BEC like a laser, but with atoms instead of photons?

LASER

- Laser light consists of waves.

  → All the light waves are the same.

  → All the light waves are in sync.



- Laser light interferes.

  → Lasers have 1^{st} and 2^{nd} order coherence.

- Photons do not interact.

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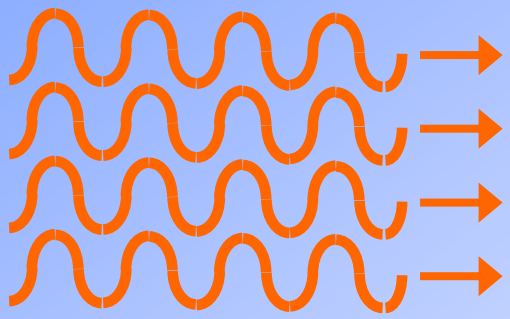

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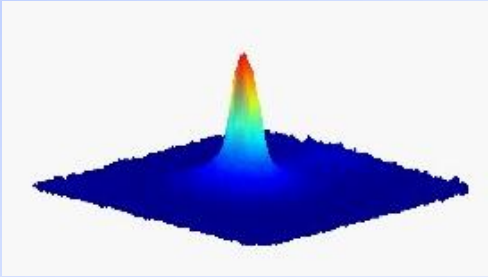
BEC

- Atoms behaves like waves

(i.e. obey the Schrodinger equation)

→ In a BEC, all the atoms have the same wavefunction.



- BEC can interfere.

  → BECs have 1st and 2nd order coherence.

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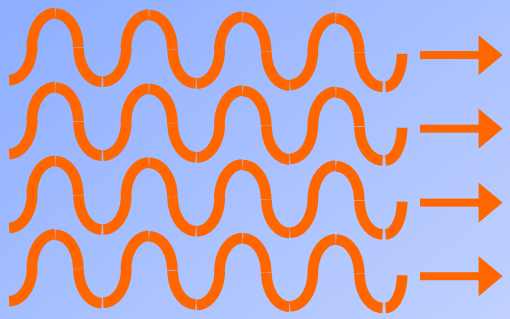

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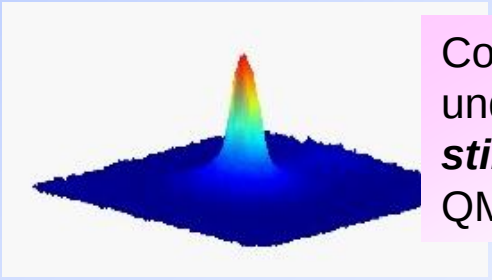


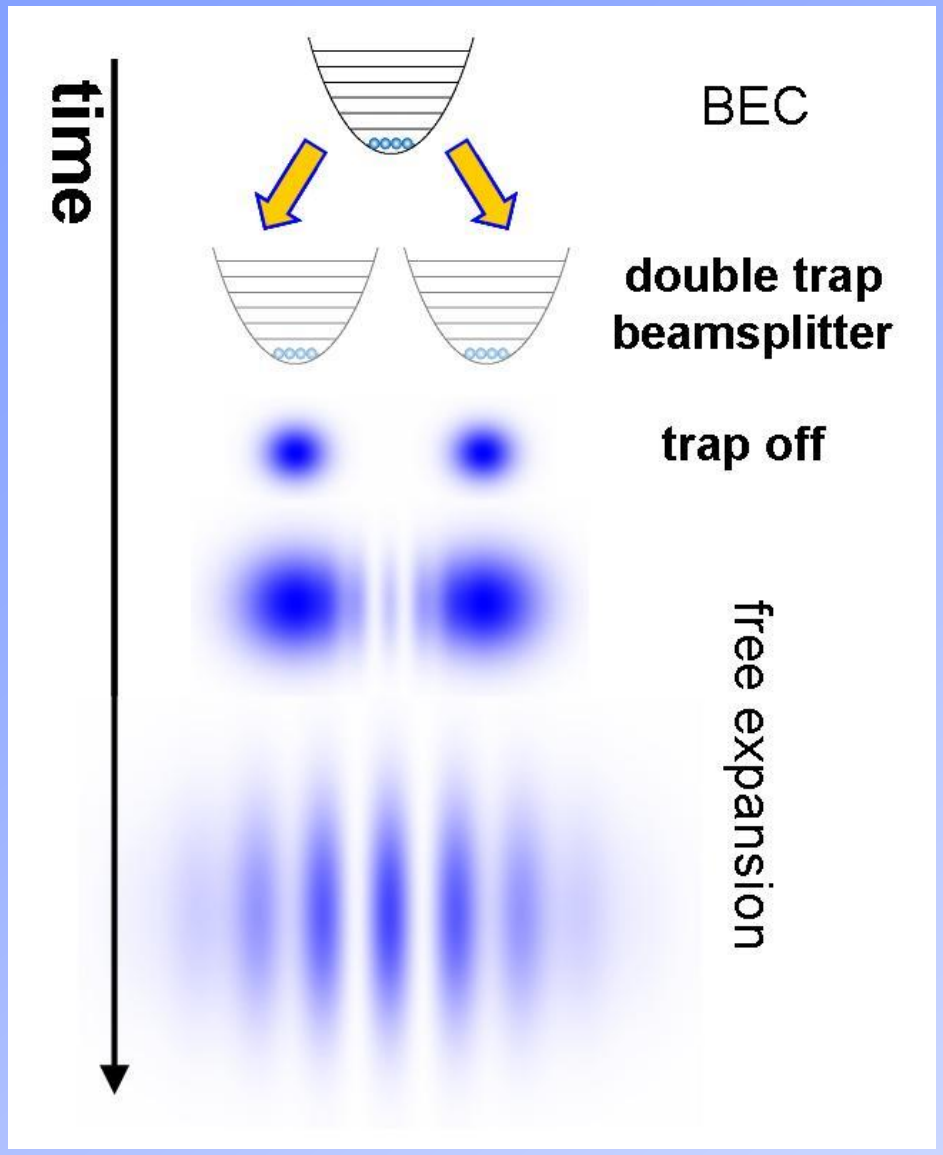
Colliding particles undergo ***bosonic stimulation*** to the QM ground state.

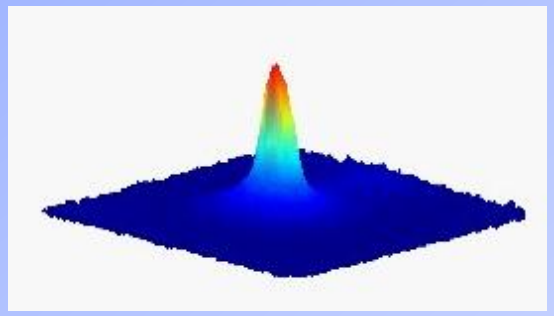
- BEC can interfere.

→ BECs have 1st and 2nd order coherence.

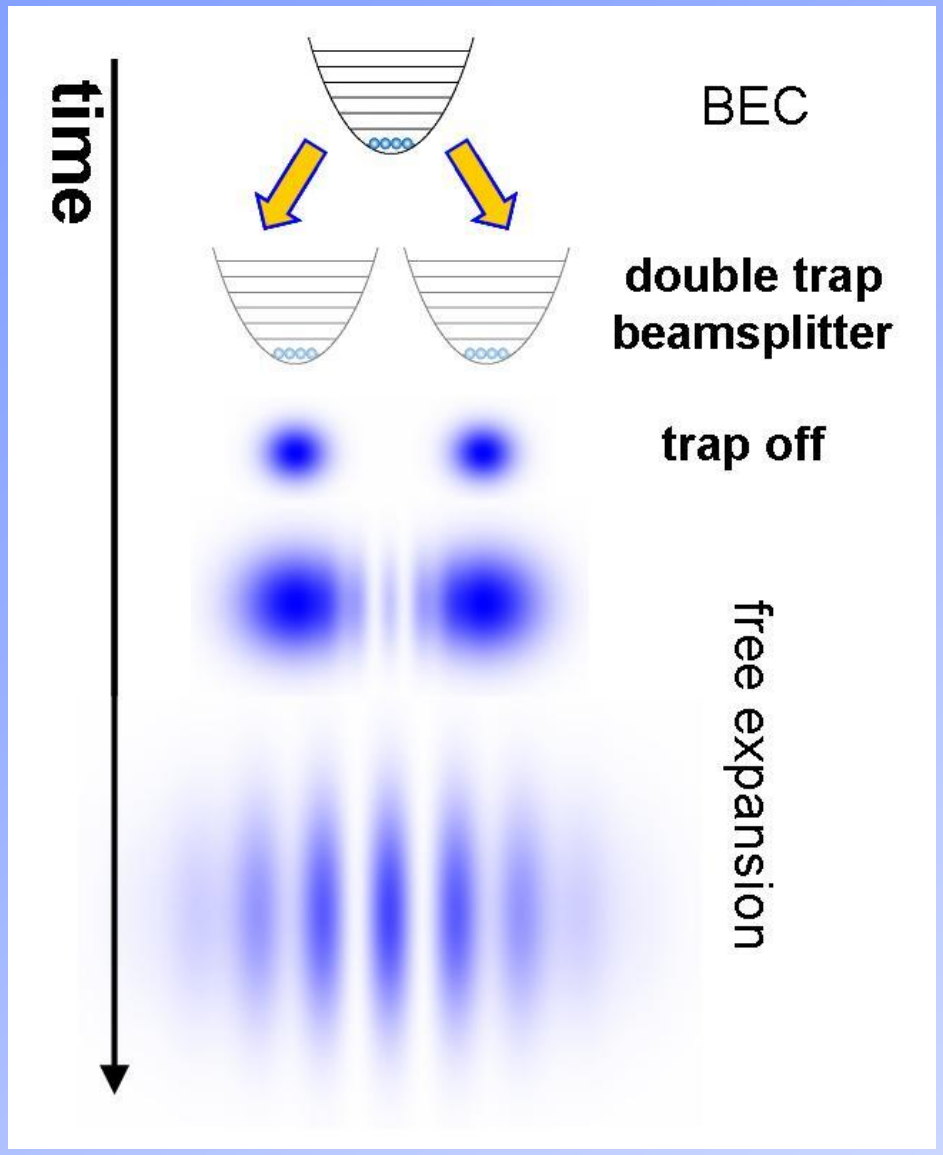
- Atoms do interact !!!

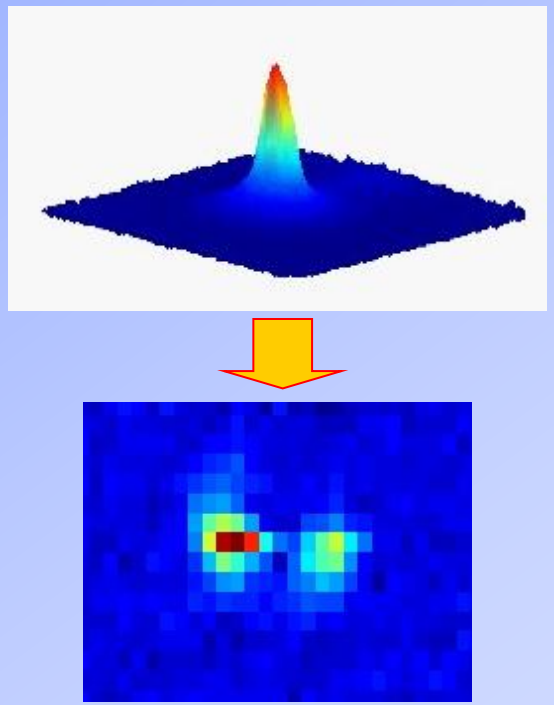
BEC: Atom Interferometry



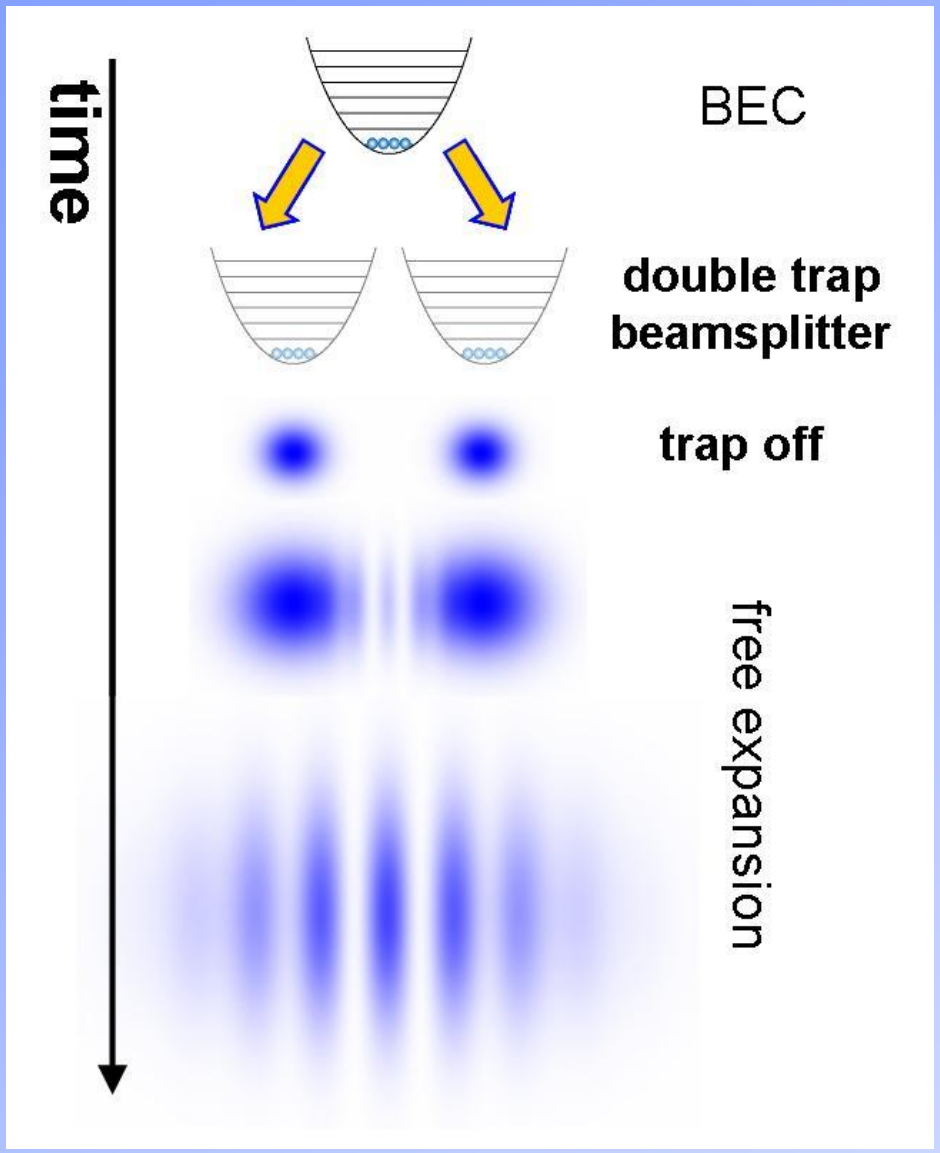


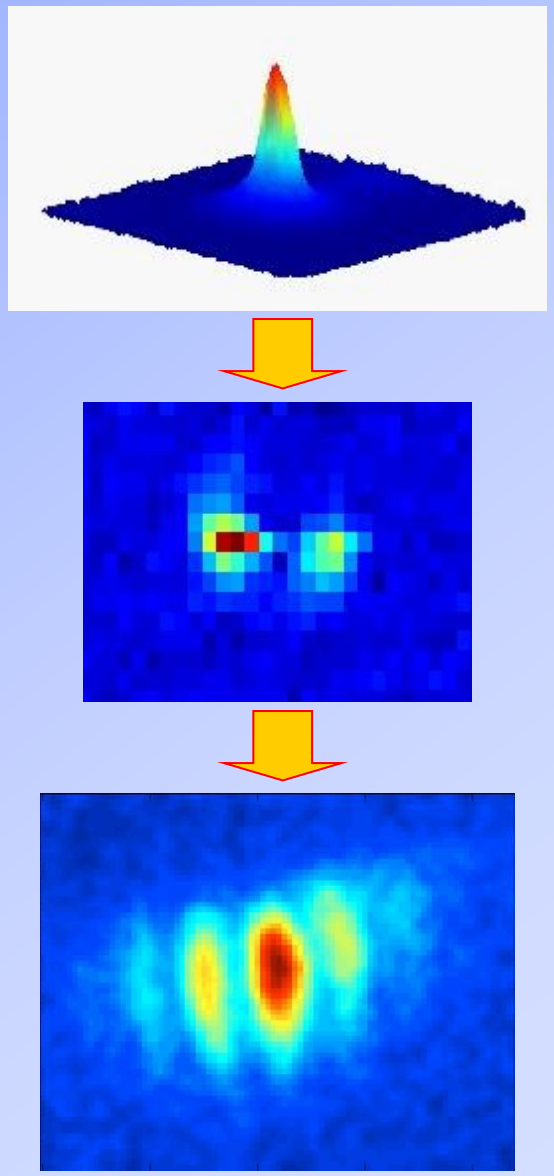
BEC: Atom Interferometry





BEC: Atom Interferometry





[data from Thywissen group, U. of Toronto]