DeBroglie Wave Atom Optics with Coherent (Laser-Like) Atoms

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$upport: NIST, ONR, NASA, ARDA

What are laser-like atom waves?

All matter is wave-like: $l_{\mathbf{dB}} = h/p$

Hot atoms have short l_{dB} ; 1000K Na (~10^3 m/s)

→ $l \approx 2 \times 10^{\mathbf{-11}}$ m

Cold atoms have long l ; 1 cm/s (< 1 mK) → $l = 2 \times 10^{\mathbf{-6}}$ m

But, just as ordinary (thermal) light is a jumble of different wavelengths and directions, a cold, thermal gas is a jumble of atom waves.

Laser light, or Bose-Einstein condensed atoms, are different: orderly, organized waves.

BEC provides <u>coherent</u> matter waves - different from "ordinary" atoms as laser light from ordinary light.

ordinary light

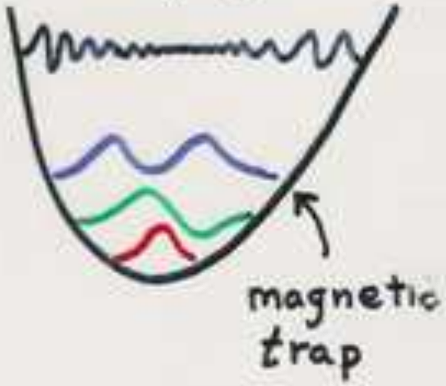
laser light:

many photons in the same mode

BEC provides coherent matter waves - different from "ordinary" atoms as laser light from ordinary light.

ordinary light

ordinary gas

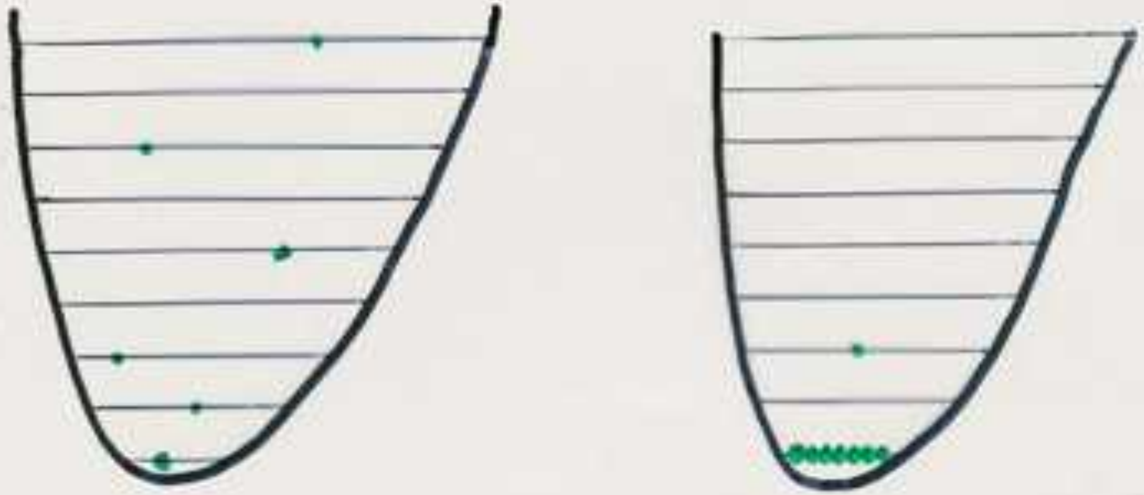


laser light:

many photons in the same mode

BEC: many atoms in the same quantum state

BEC represents many atoms in a single quantum state of motion.



This is like a laser field — many photons in a single mode of the E-M field.

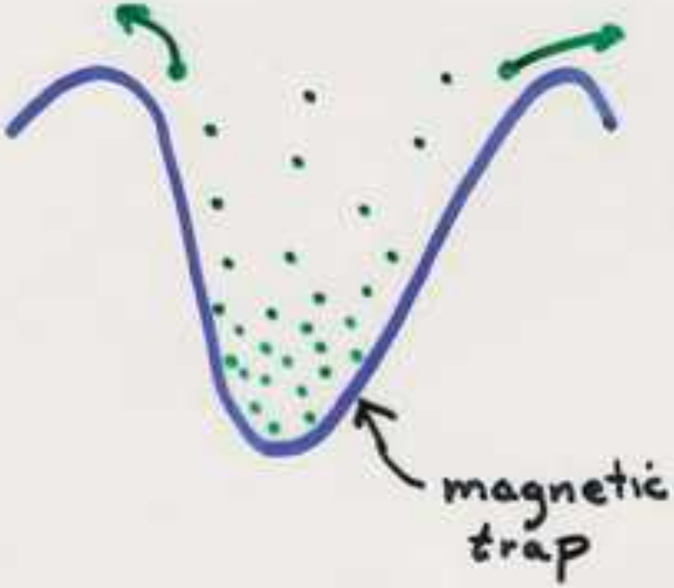
The intensity and coherence of a BEC are laser-like.

Making a BEC?

- Start with, e.g., Na atoms, at T ≈ 1000 K
  (or Rb-87 atoms at T ≈ 500 K, or other things)
- Laser cool the Na to ~50 mK
- Trap the atoms in a magnetic bottle
- Evaporatively cool
- Bose condense at T ≈ 1 mK; n ≈ 10^{13} atoms/cm^3
  (approximate parameters for Na in out lab)
- Continue to evaporate and adiabatically expand

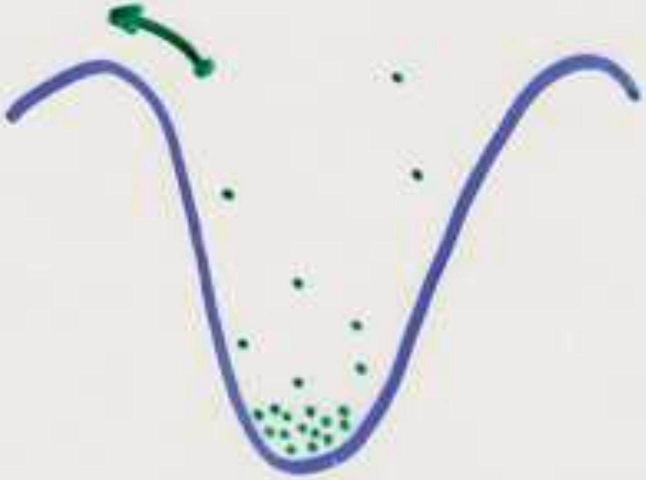
nearly pure condensate ~100 mm diameter, ~10^6 atoms

Evaporative Cooling

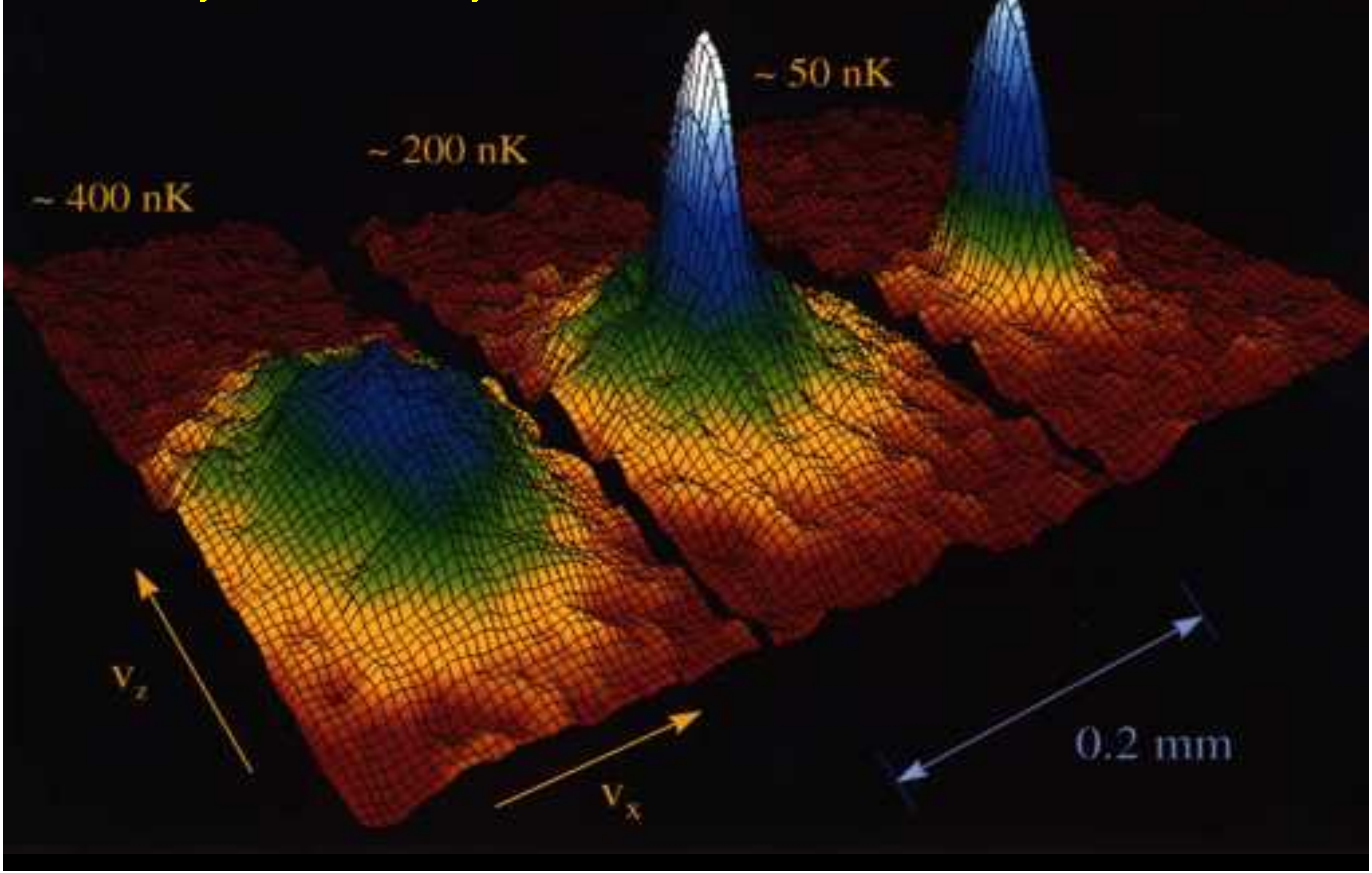


Evaporation lets the most energetic atoms escape.

The remaining ones re-equilibrate, are left colder.



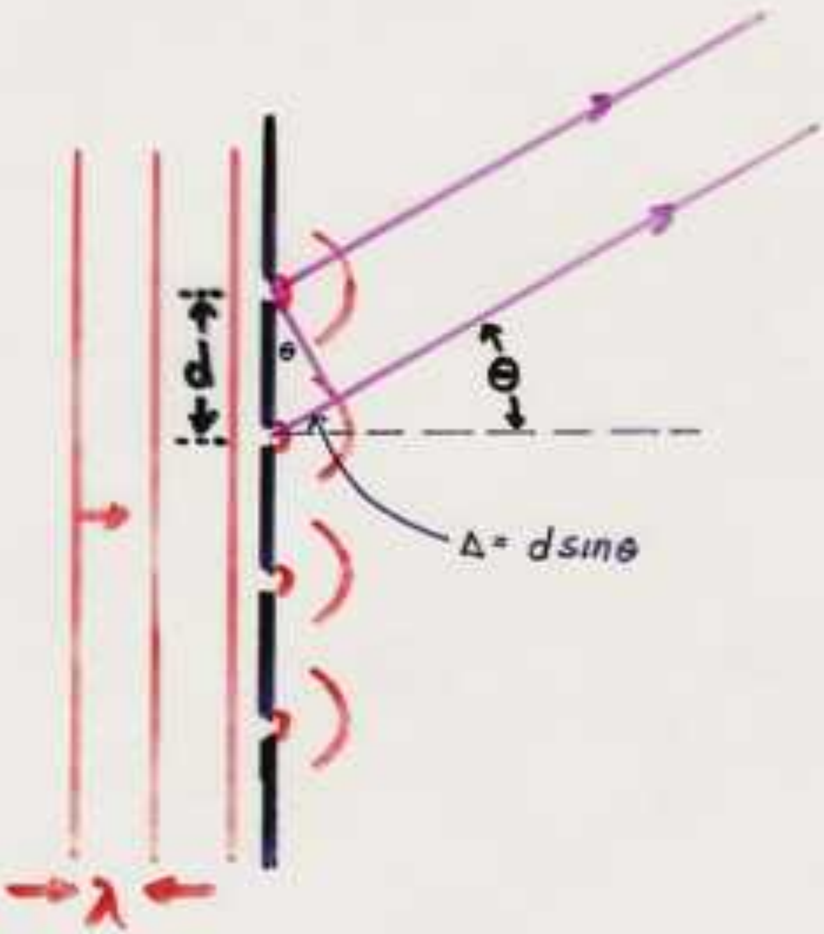
2D Velocity distribution by TOF



Coherent Atom Optics

Using coherent atoms, let’s do the sorts of things we do with coherent light--like diffraction, interference, non-linear optics, ….

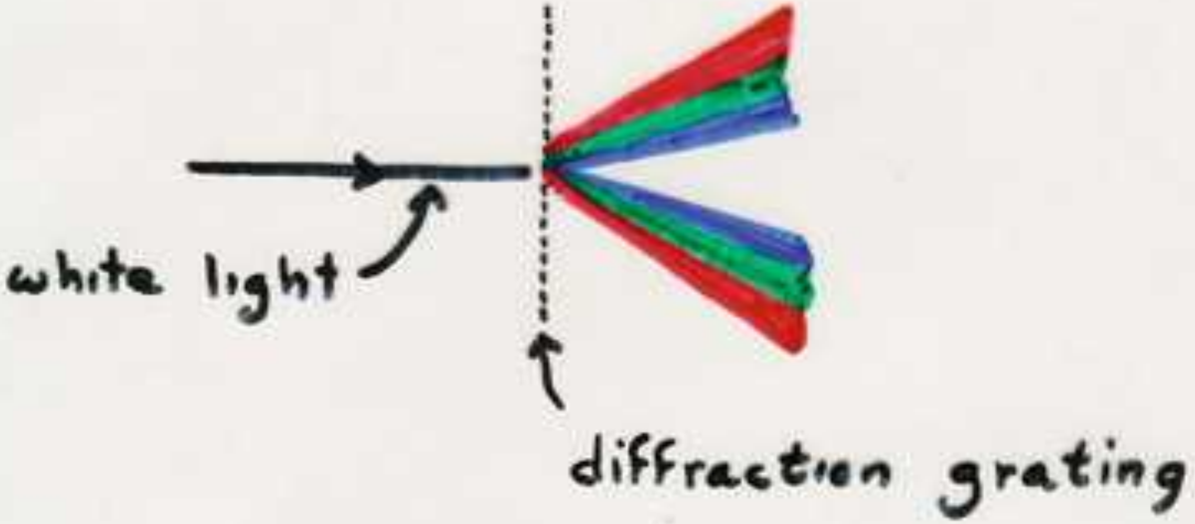
Diffraction Grating

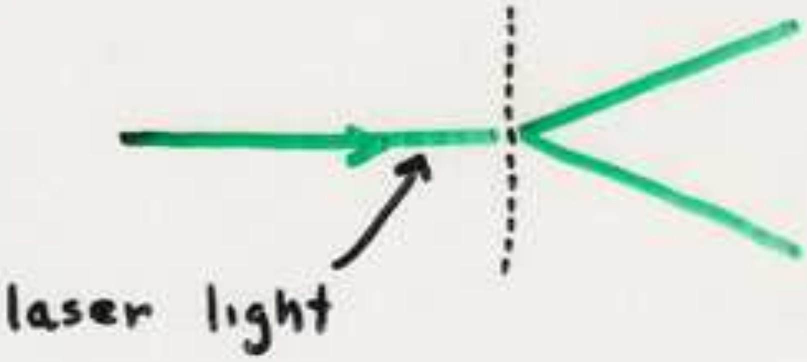


For constructive interference at θ.

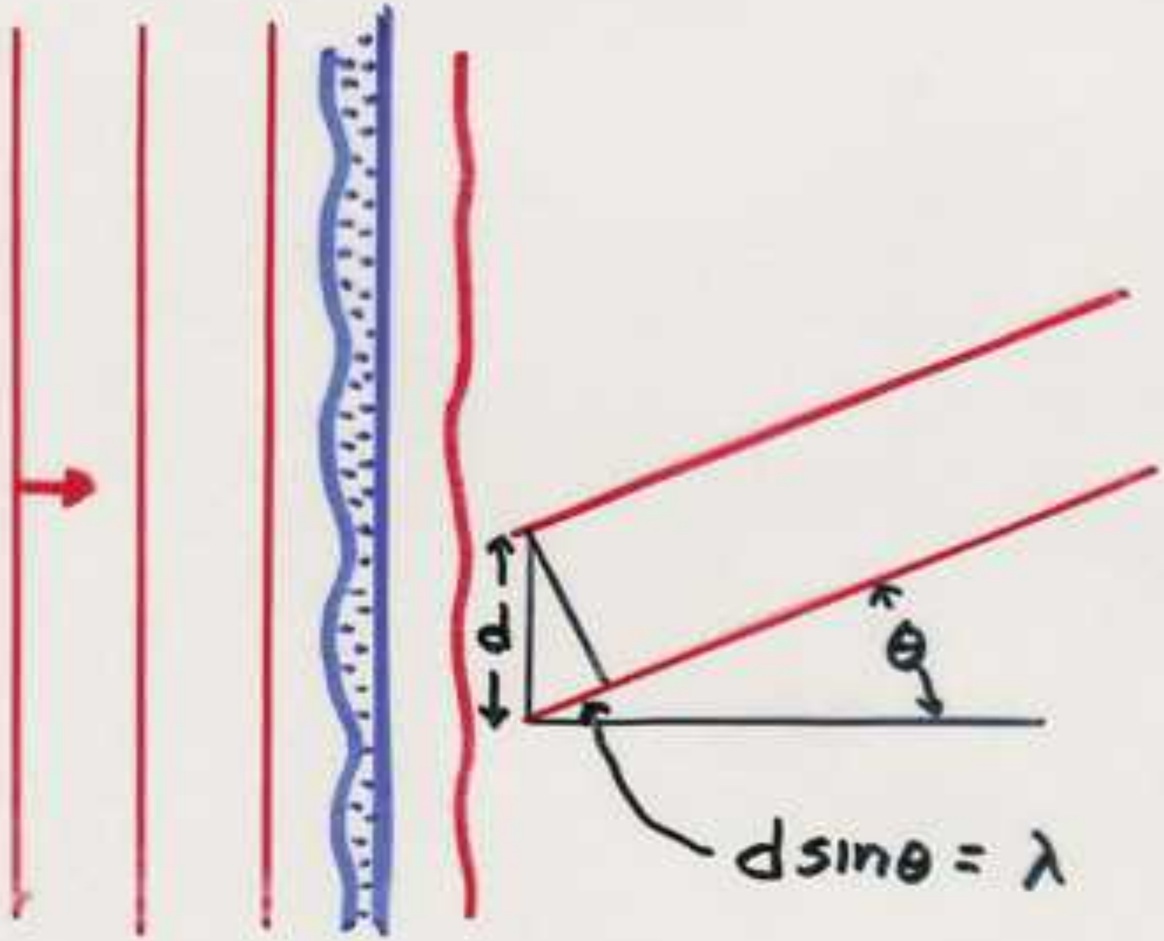
$$\Delta = n\lambda = d\sin\theta$$

optical diffraction

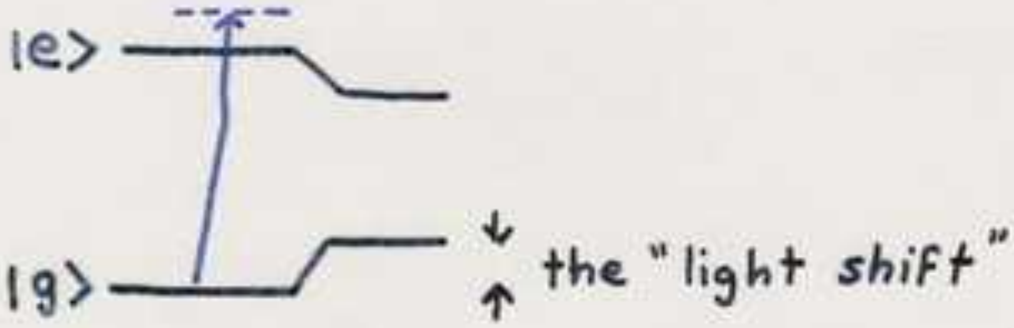




A phase grating diffracts light just like an amplitude grating – a periodic array of slits (at least in the far-field).

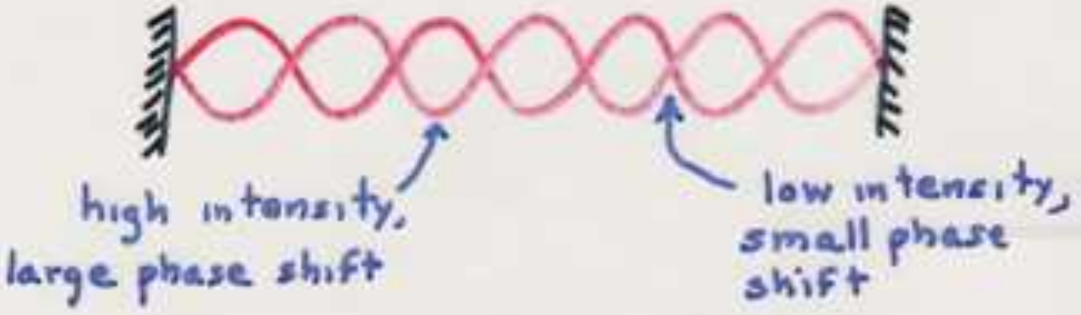


Light tuned far from an atomic resonance shifts the energy of the atoms :



An energy shift applied for a time interval produces a phase shift in the atomic wave function.

A standing wave of light acts like a phase grating for atom waves :



diffraction of an atomic beam by a standing wave of light

(MIT – Pritchard – 1980's)

like diffraction of light by a <u>thin</u> phase grating.

Also, interpreted as redistribution of photon momentum by absorption / stimulated emission

P. Moskowitz, P. Gould, S. Atlas, & D. Pritchard (1983)

(Incoherent atomic beam)

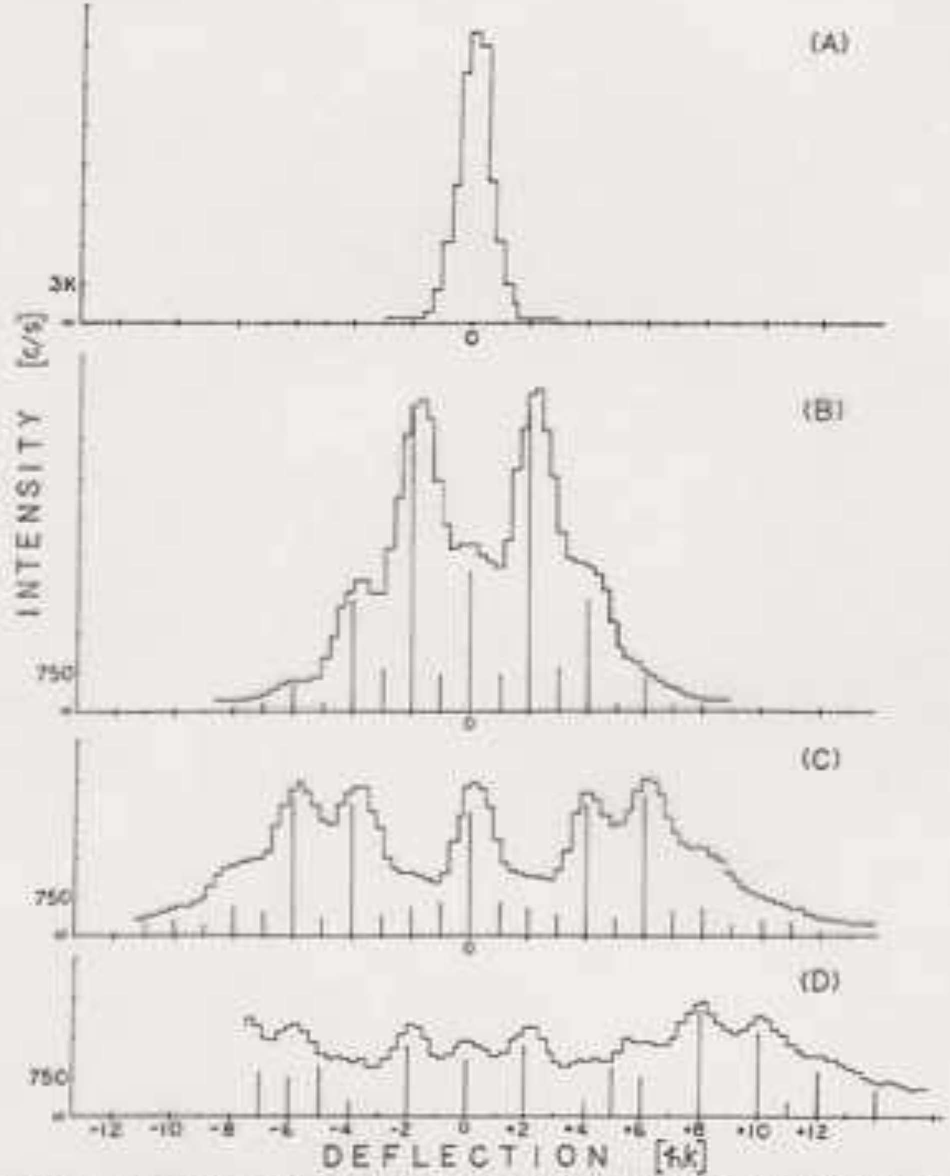


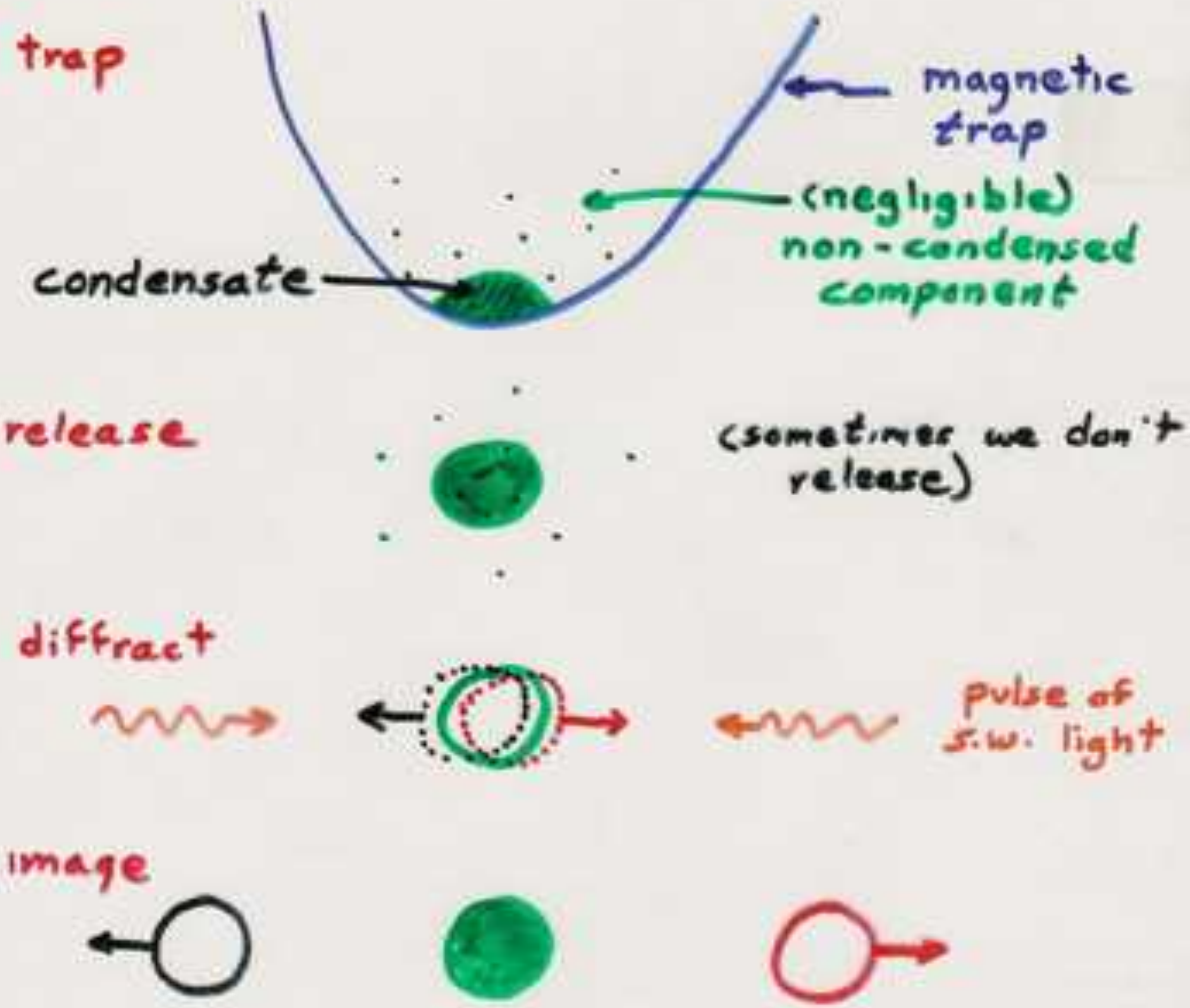
FIG. 2. Atomic beam profiles for the following laser powers: (a) 0, (b) 5, (c) 10, and (d) 20 mW. Vertical bars under data depict momentum transfer imparted by the field, i.e., a computer deconvolution accounting for the atomic beam profile, velocity distribution, and spontaneous emission recoil after the interaction. The height of each bar at position n is proportional to the probability that an atom gains $n\hbar k$ momentum.

For atoms at rest (BEC)

passage through a <u>thin</u> grating is analogous to receiving a <u>short</u> standing wave pulse:

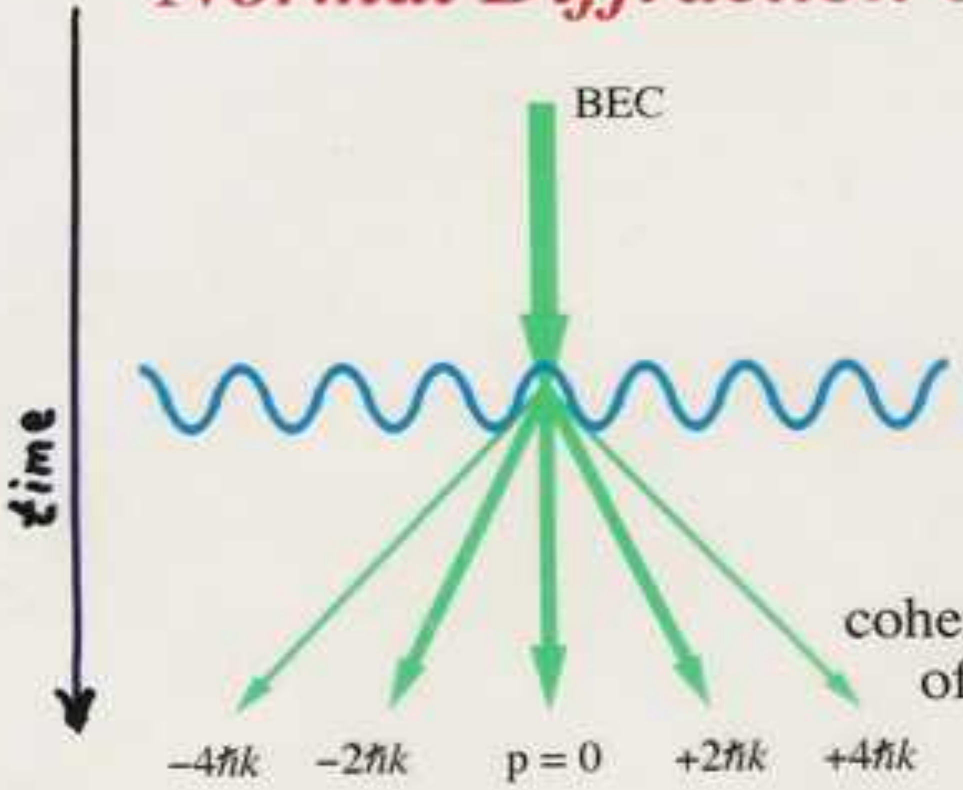
<u>and</u>

General Experimental Procedure



absorption imaging after free-flight converts momentum distribution into a spatial distribution. Line-of-sight is vertical.

Normal Diffraction of BEC



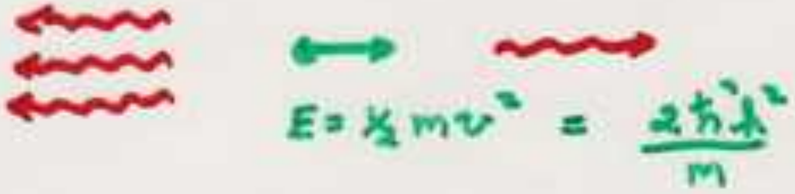
pulsed optical standing wave

coherent diffraction of condensate

short pulse

long pulse

But – diffraction appears not to conserve energy:



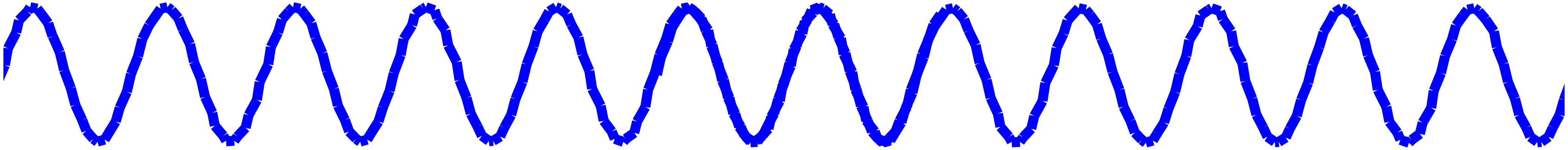
Initial energy = $N \cdot \hbar\omega$

Final energy = $N \cdot \hbar\omega + \frac{2\hbar^2 k^2}{m}$

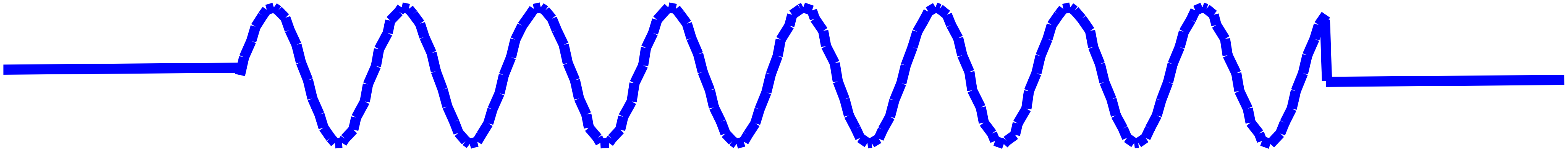
How is this possible?

The light is <u>pulsed</u>!

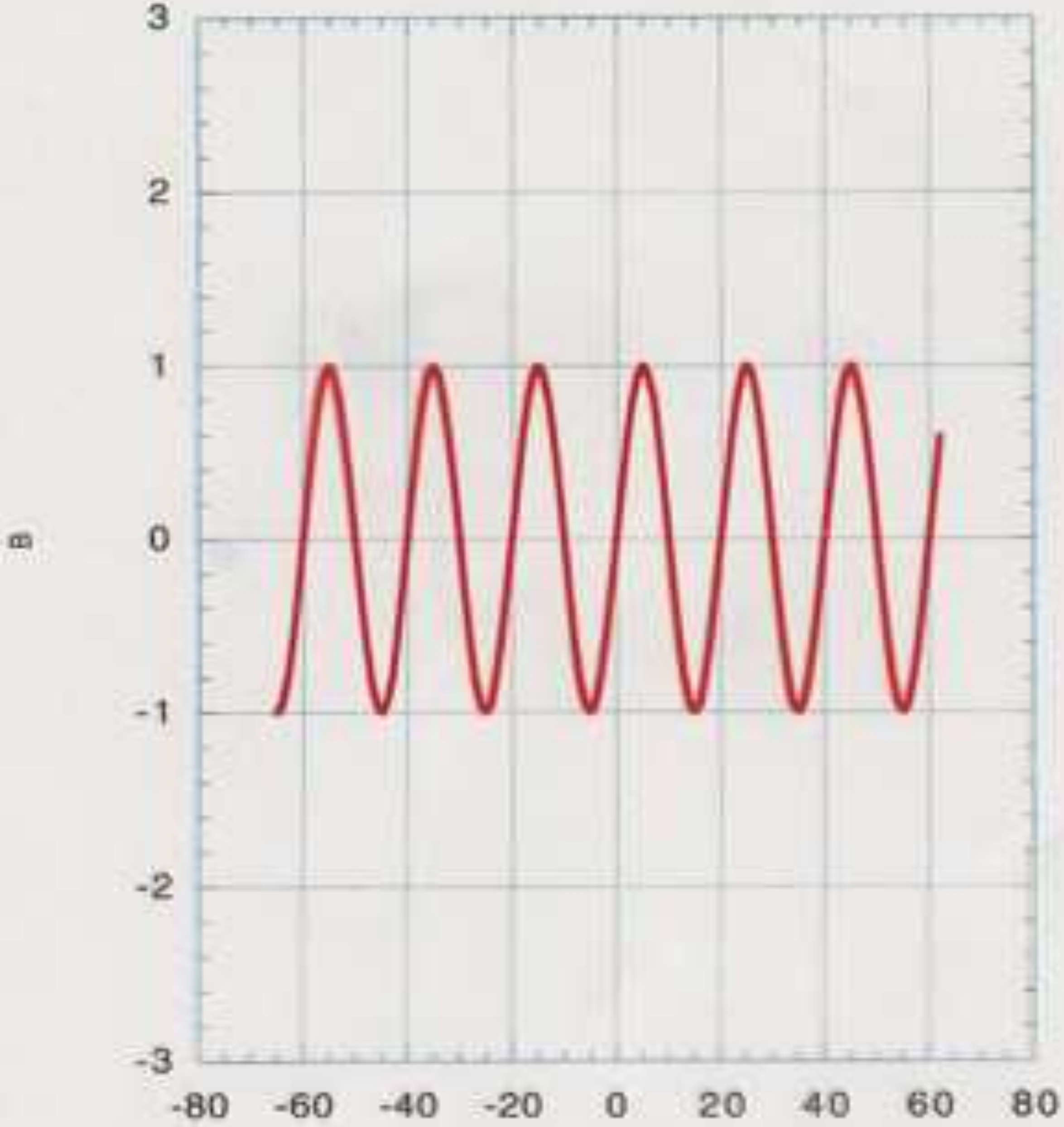
Fourier composition of a pulse

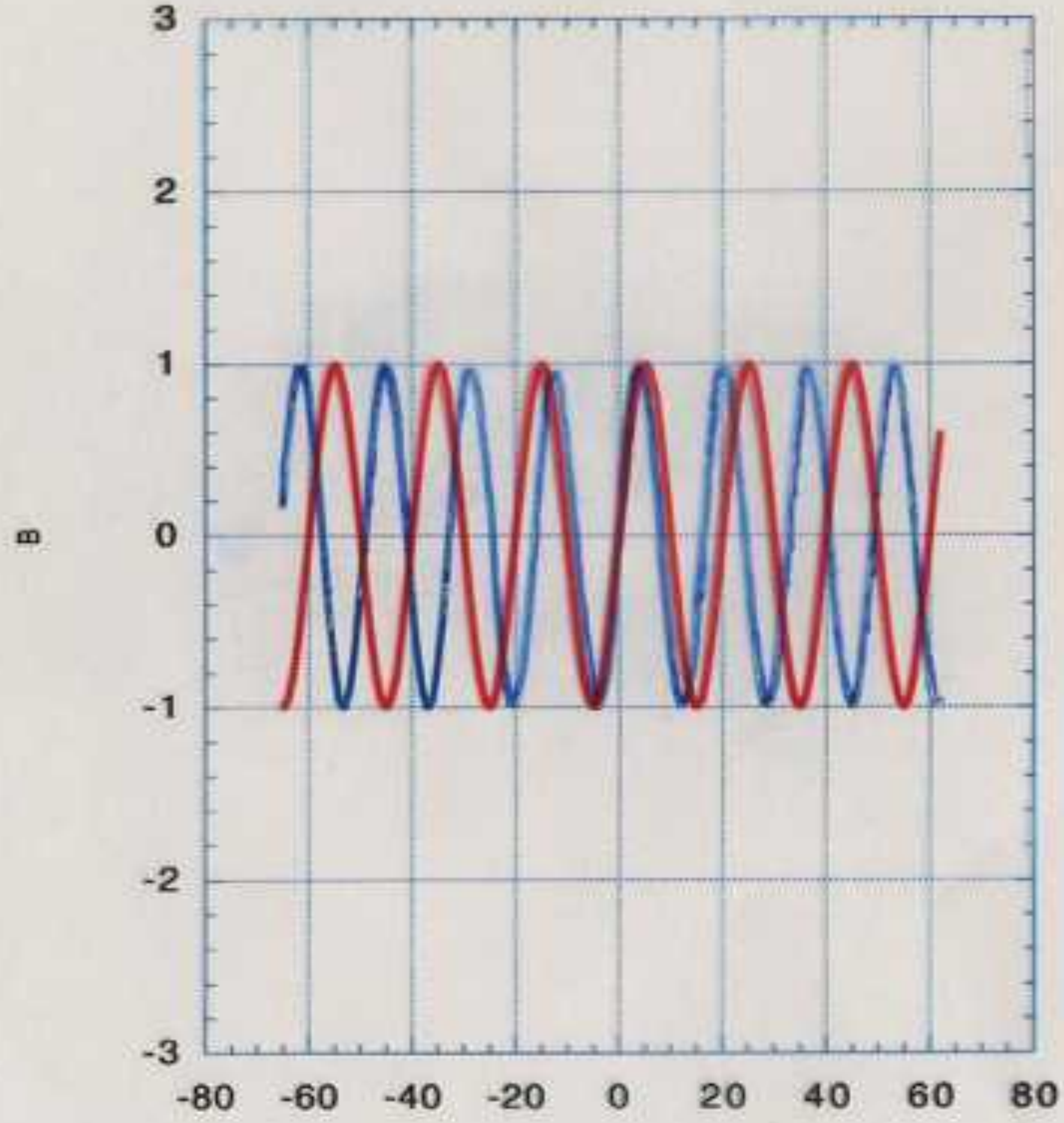


Single frequency

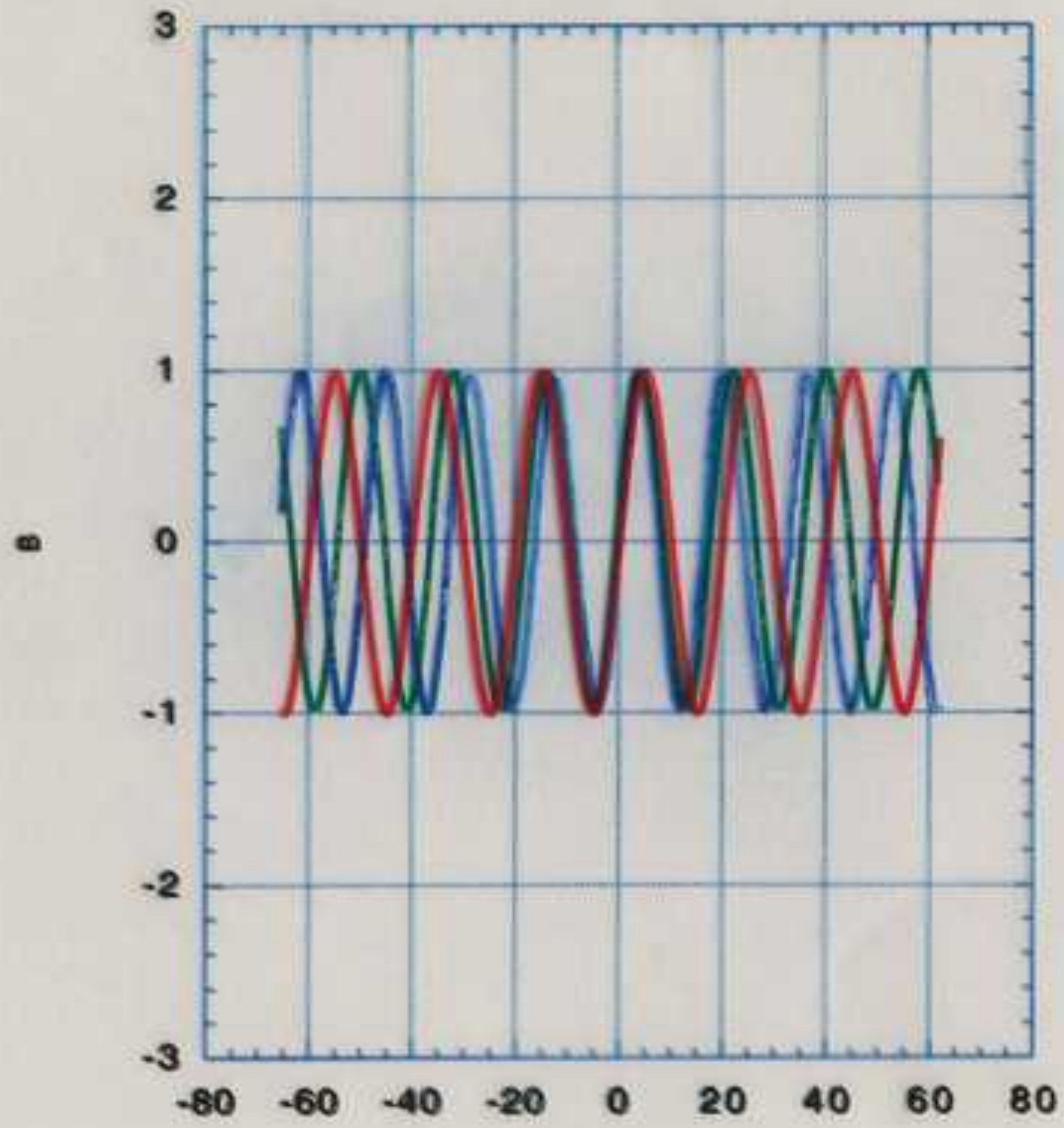


Combination of frequencies


3
2
1
0
-1
-2
-3
a
-80
-60
-40
-20
0
20
40
60
80



3
2
1
0
-1
-2
-3
B
-80
-60
-40
-20
0
20
40
60
80


B
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-20
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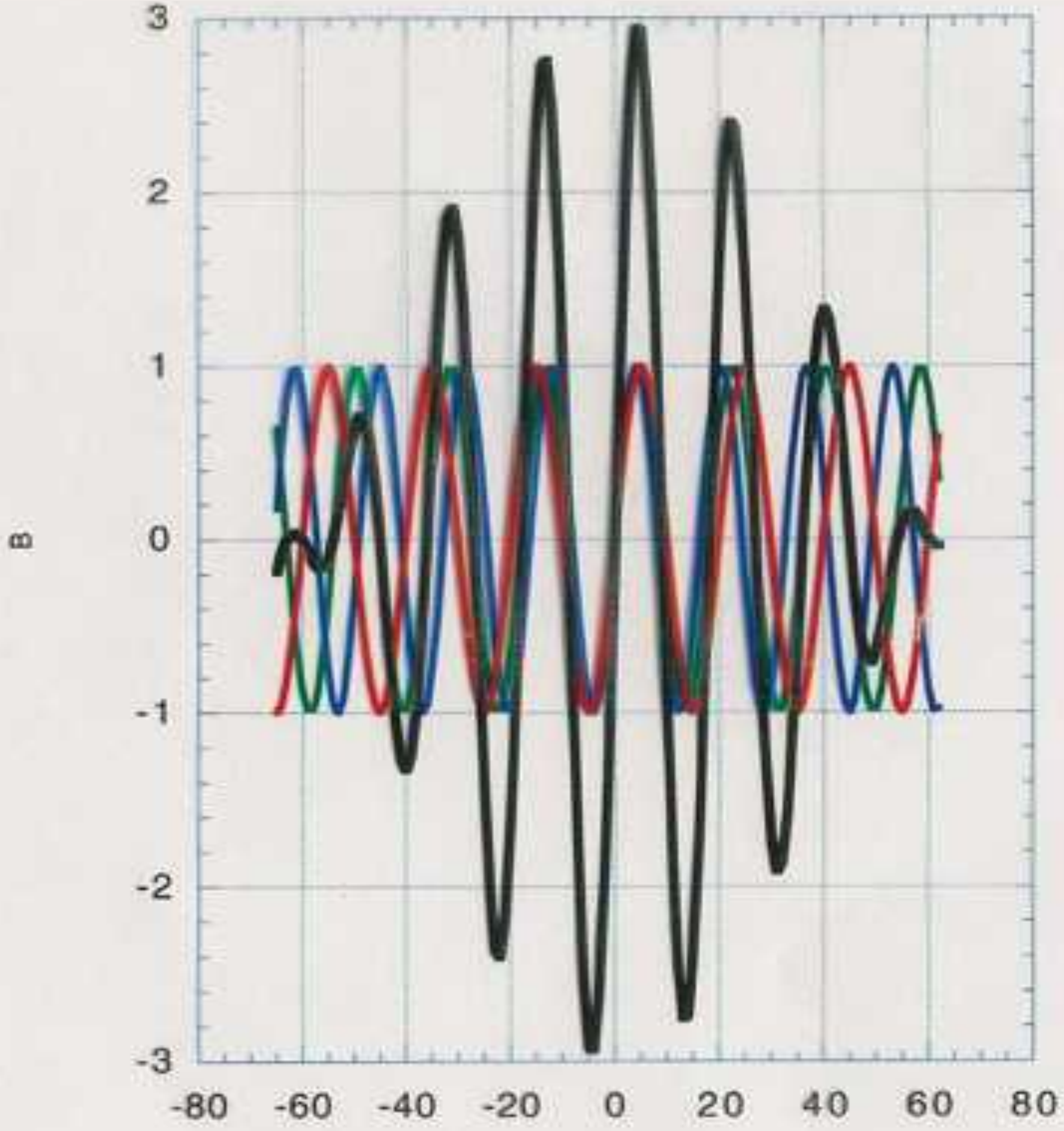
B
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-1
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-3
-80
-60
-40
-20
0
20
40
60
80

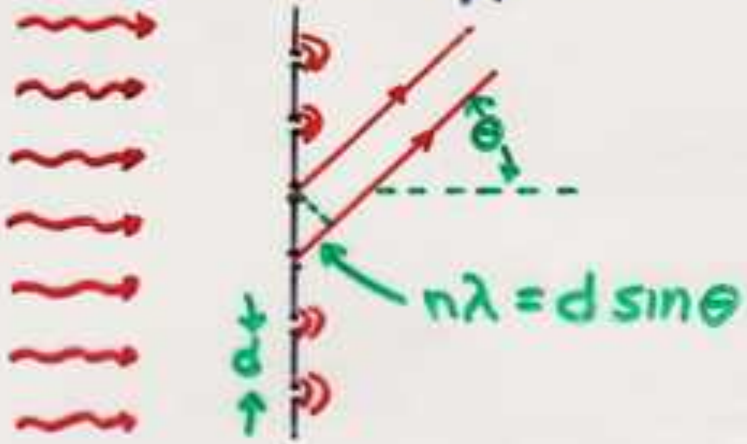
A <u>short</u> pulsed standing wave diffracts atoms because of the Fourier spread of frequencies

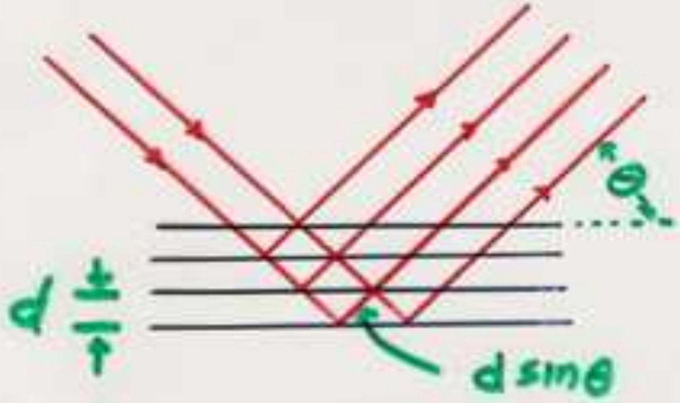
Short: $\tau_{\mathrm{pulse}} << \dfrac{\hbar}{E_{\mathrm{rec}}}$ $\qquad E_{\mathrm{rec}} \equiv \dfrac{\hbar^2 k^2}{2M}$

If the pulse is <u>long</u> $(\tau_{\mathrm{pulse}} >> \hbar/\mathrm{E}_{\mathrm{rec}})$

there is too little Fourier spread to allow energy conservation, so there is no diffraction – unless the Bragg condition is fulfilled.

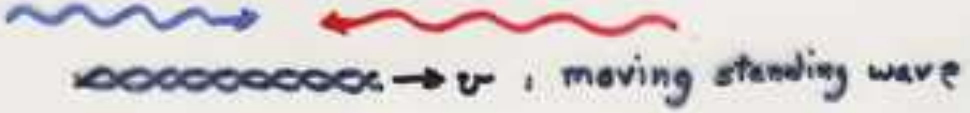
“Normal” diffraction vs. Bragg diffraction



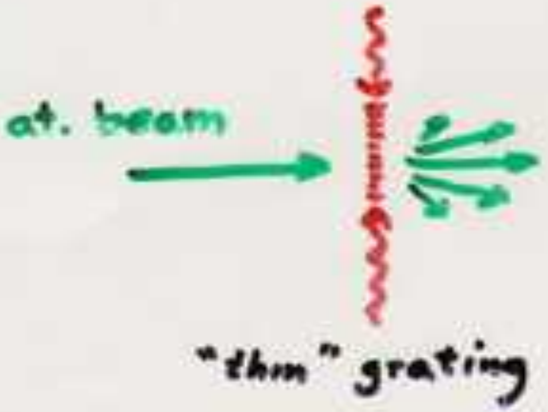


$$n\lambda = 2d\sin\theta$$

Bragg requires specular reflection, a condition on incident angle.



Diffraction and Bragg reflection of an atomic beam from a static grating (a standing light wave) - MIT, 1980s



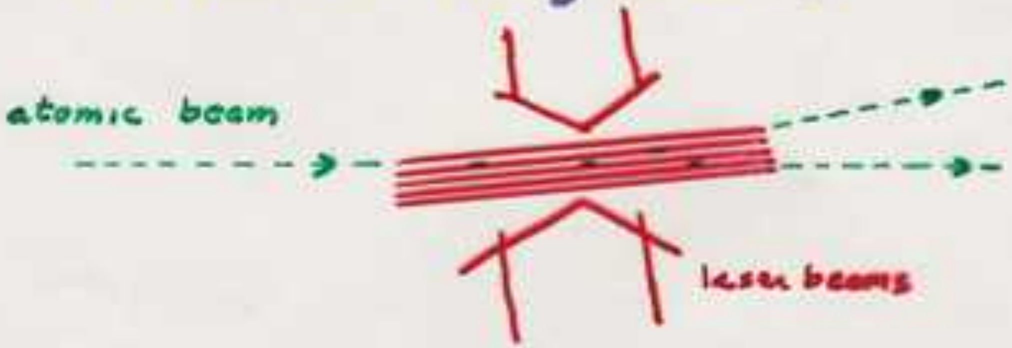
Diffracts into multiple orders, both directions

Specular reflection from planes.

Single order

Satisfies condition on angle of incidence

A standing-wave light field makes a periodic set of planes from which to reflect de Broglie waves

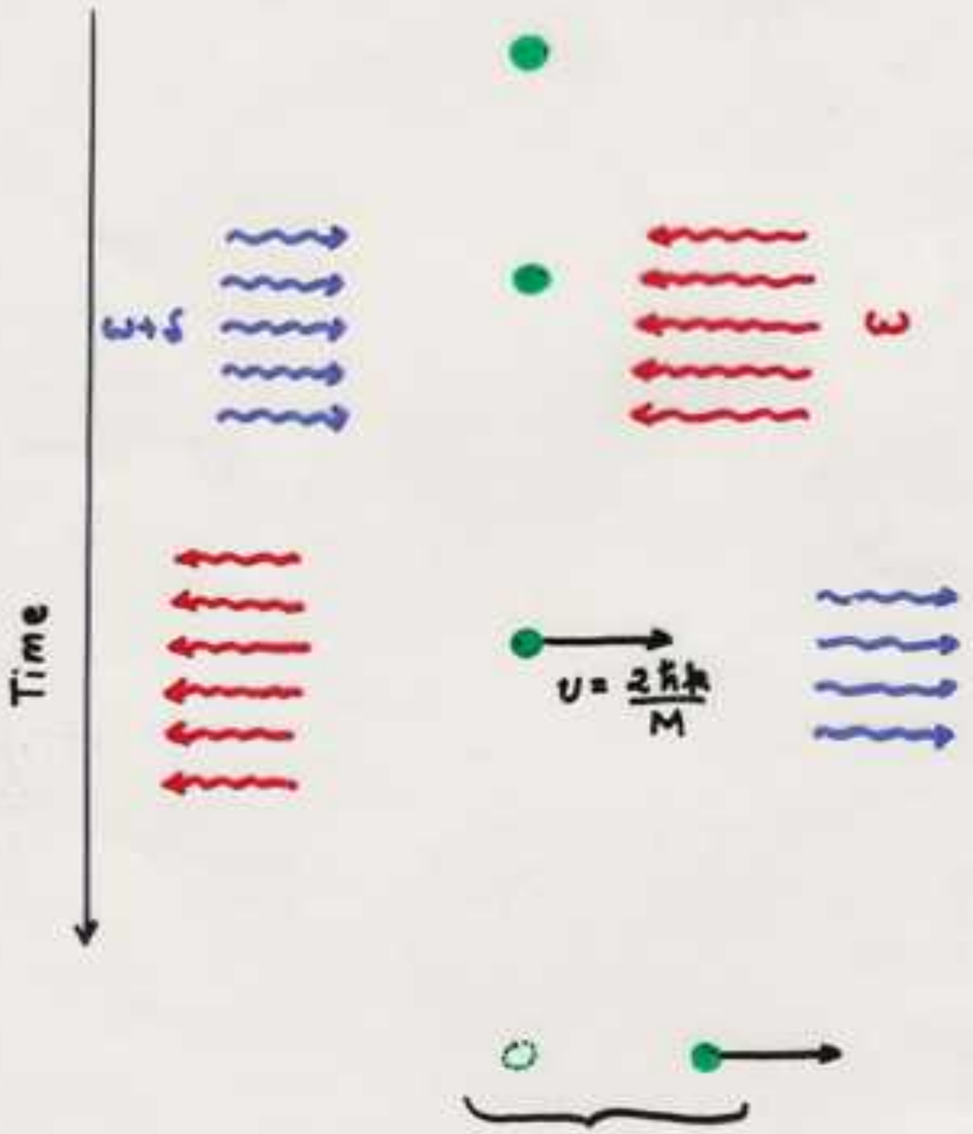


Martin, Oldaker, Miklich + Pritchard (MIT - 1988)
for incoherent atoms.

for a BEC at rest:

move a pulsed standing wave past the atoms (Kozuma, Deng, Hagley, Wen, Lutwak, Helmerson, Rolston + Phillips - NIST Gaithersburg 1999)

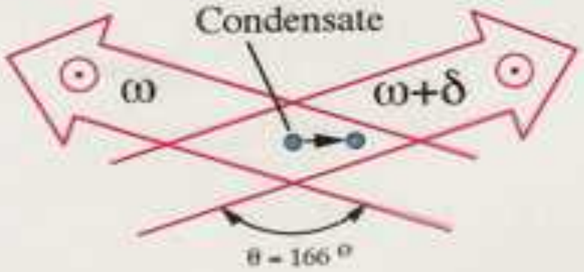
Bragg "reflection" of a BEC



We make an image of the atoms after they have separated.

Bragg Diffraction of BEC

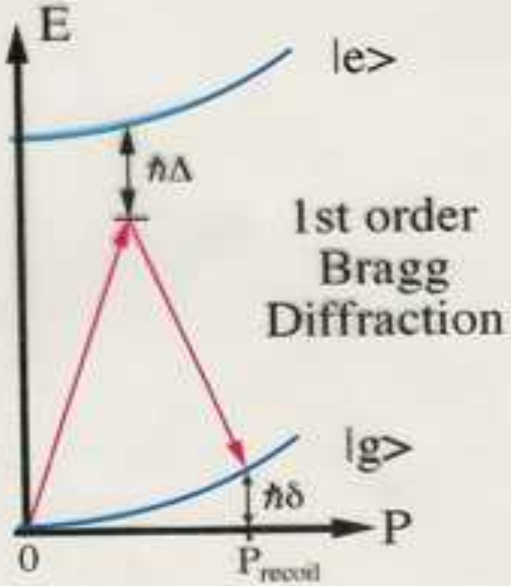
($\Delta m_F = 0$)

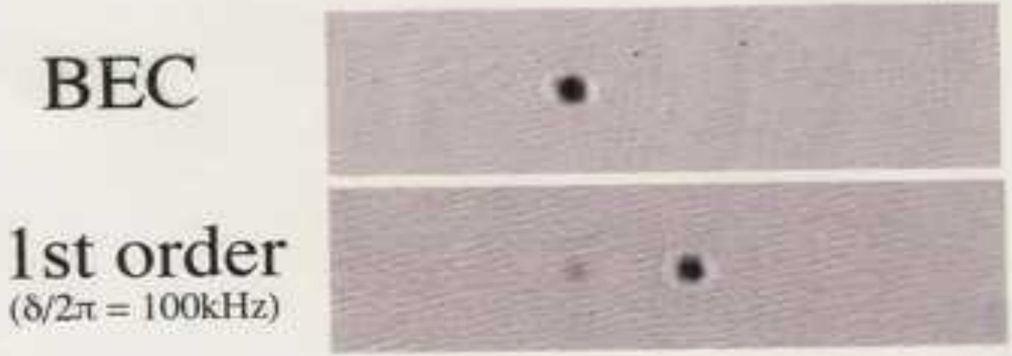


$P_{recoil} = 2\hbar k \sin(\theta/2) \approx 2\hbar k$

$\hbar\delta = P^2/2M$

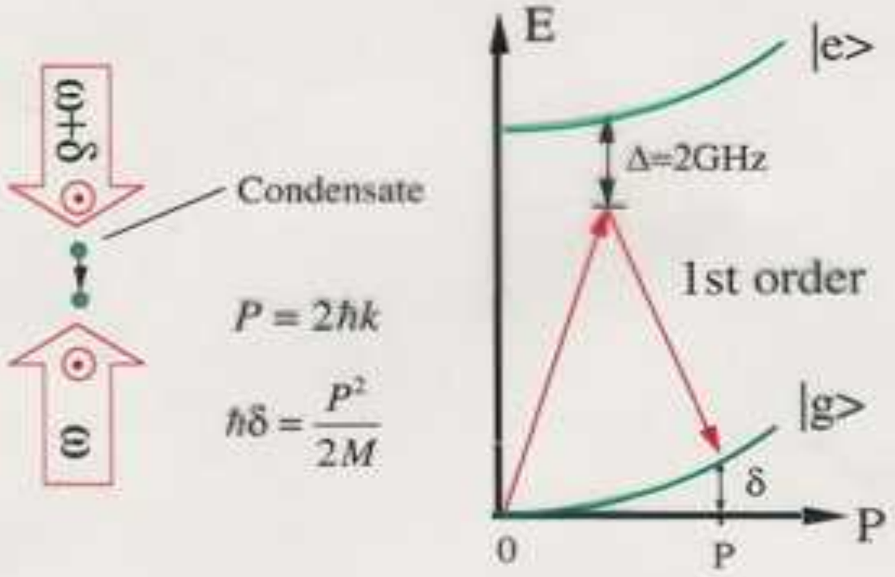
$\hbar\Delta \sim 1.8$ GHz





M. Kozuma, L. Deng, E. Hagley, J. Wen, R. Lutwak,
K. Helmerson, S. Rolston, WDP (1999)

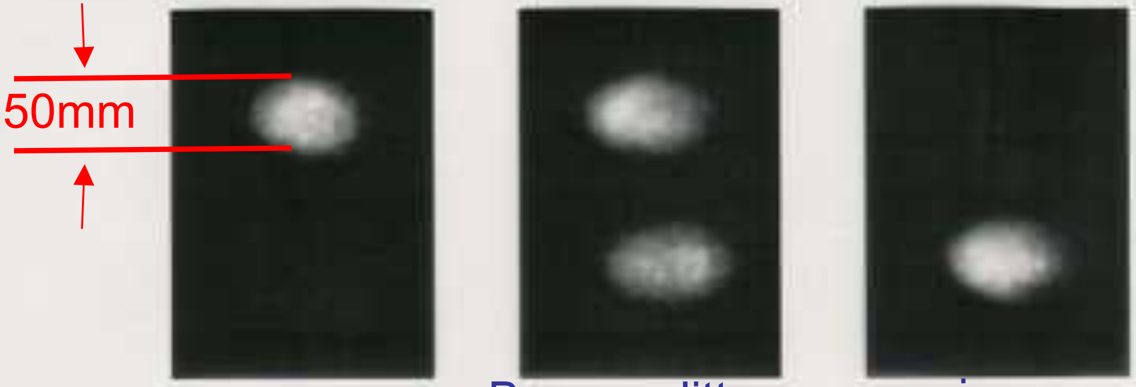
Bragg diffraction of a BEC



$$P = 2\hbar k$$

$$\hbar\delta = \frac{P^2}{2M}$$

No pulse   "π/2" pulse   "π" pulse

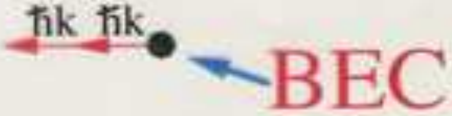


Beam-splitter   mirror

The Mechanical Effects of Light

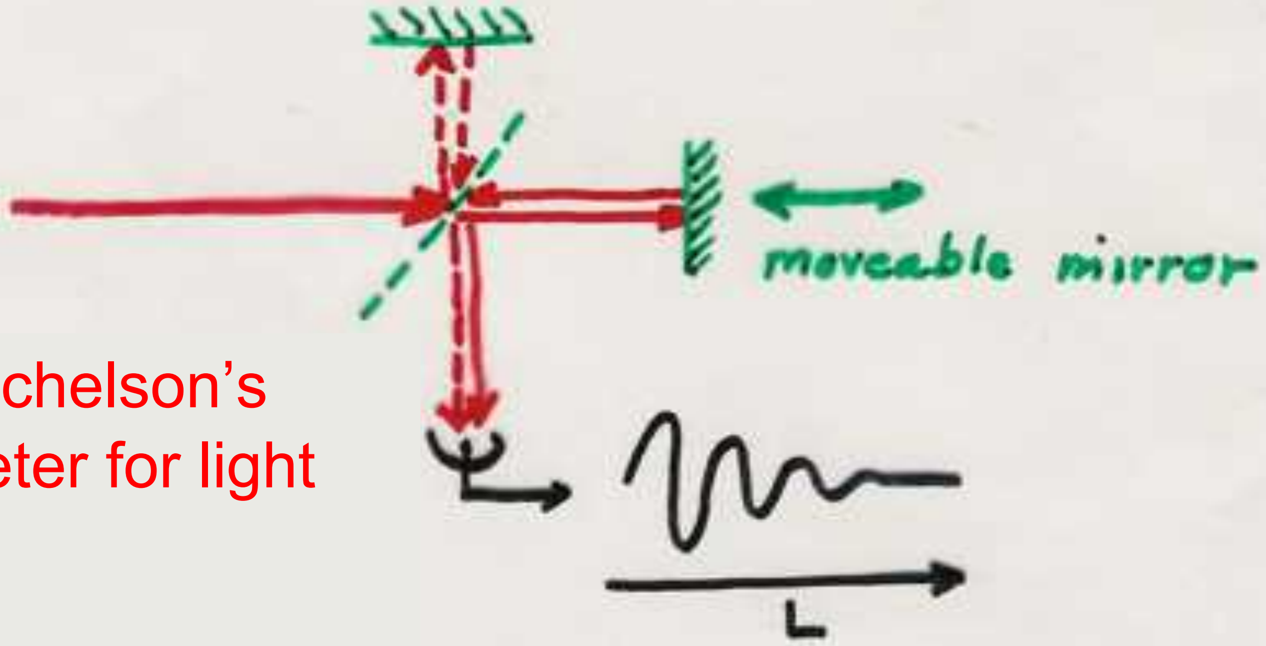
Cold cloud
of atoms

Dipole force
absorption
followed by
stimulated emission



Scattering force
absorption
followed by
spontaneous emission

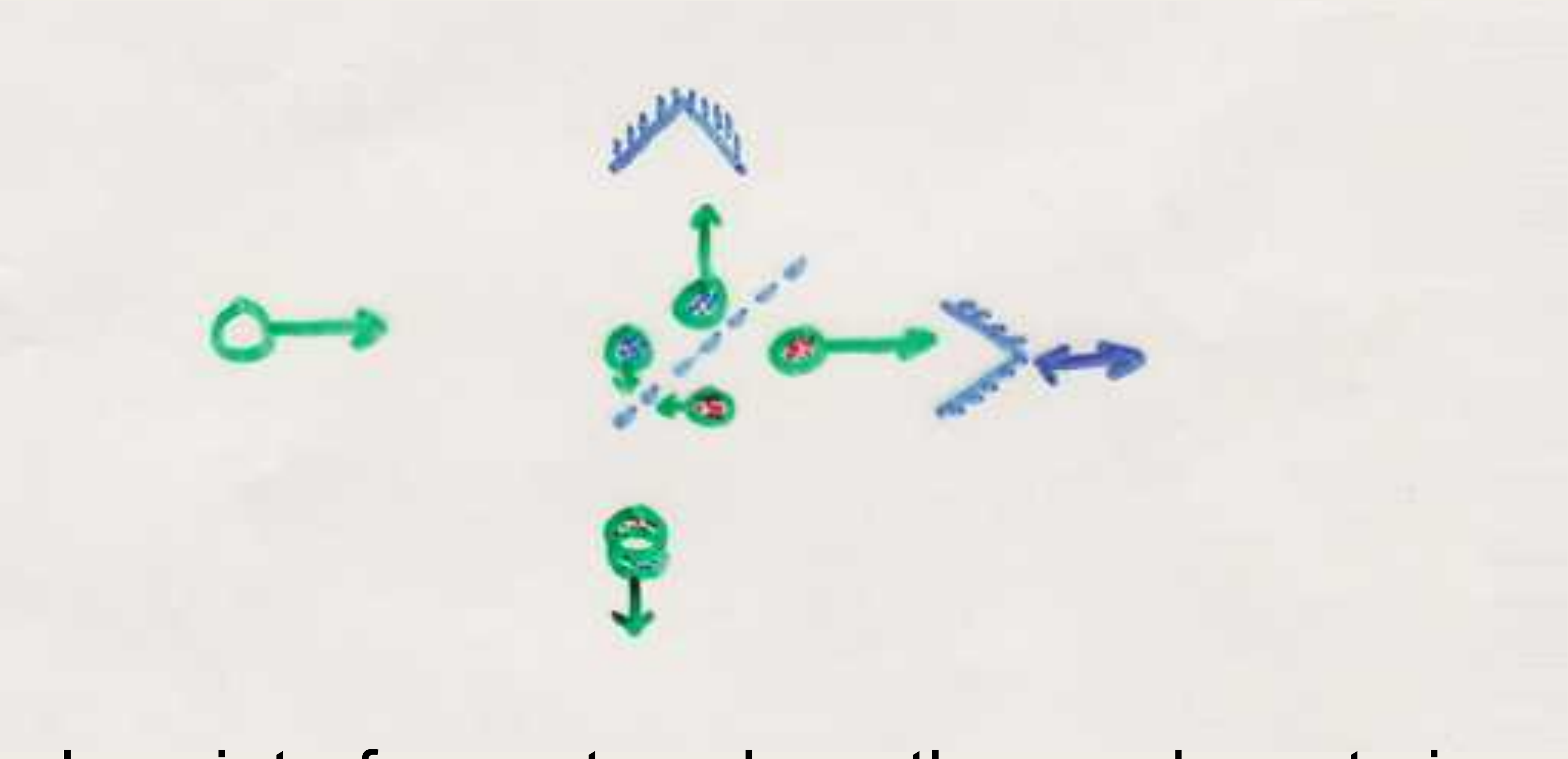
Techniques like Bragg reflection are coherent (if we avoid spontaneous emission) and may be used in studying the intrinsic coherence of a condensate.



Recall Michelson's interferometer for light

Path-length difference, L, over which interference happens gives the Coherence length of the light.

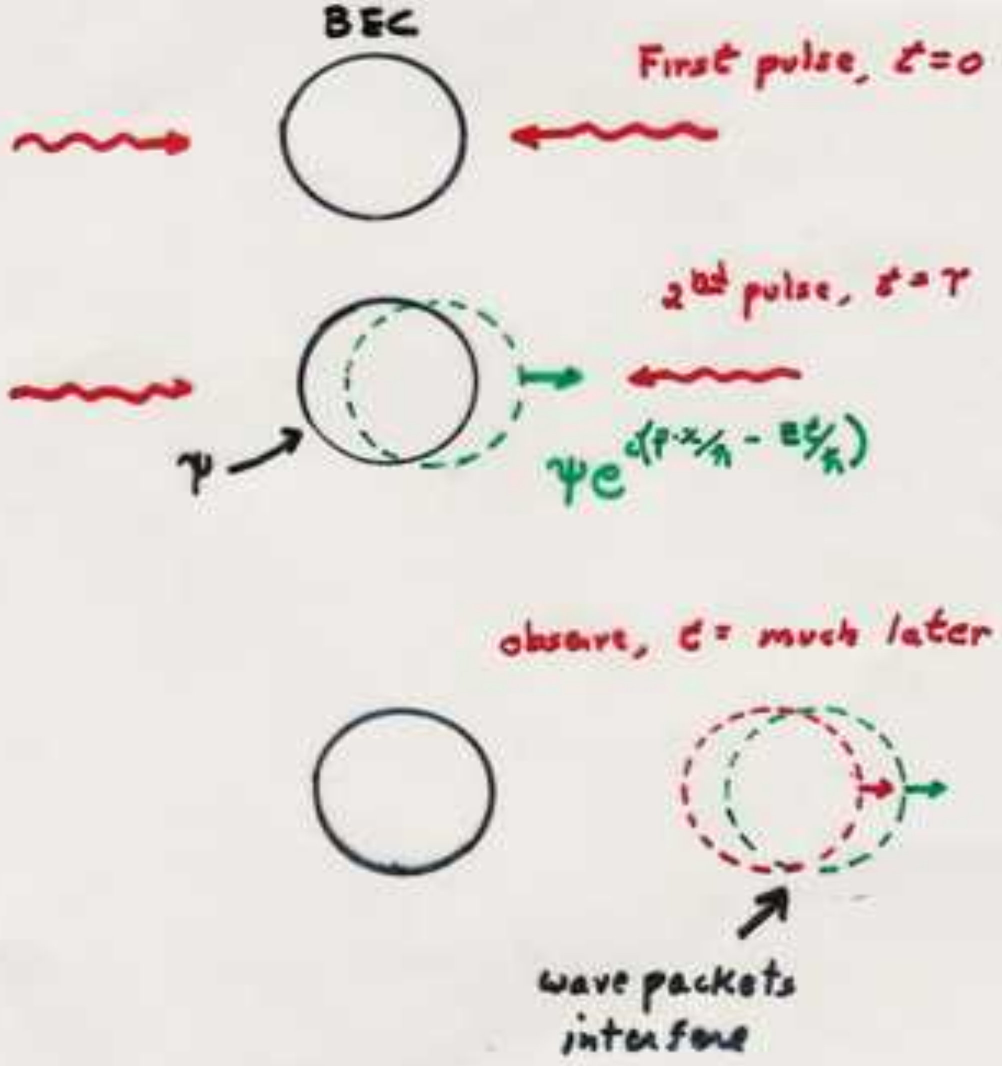
The NIST BEC coherence experiment is equivalent to:



a Michelson interferometer where the condensate is split and recombined after a variable delay. We look at fringes and fringe visibility as the path-length difference changes.

Measuring the coherence of the BEC

Hagley, Deng, Kozuma, Trippenbach, Band, Edwards, Doery
Julienne, Helmerson, Rolston, Phillips (NIST 1999)



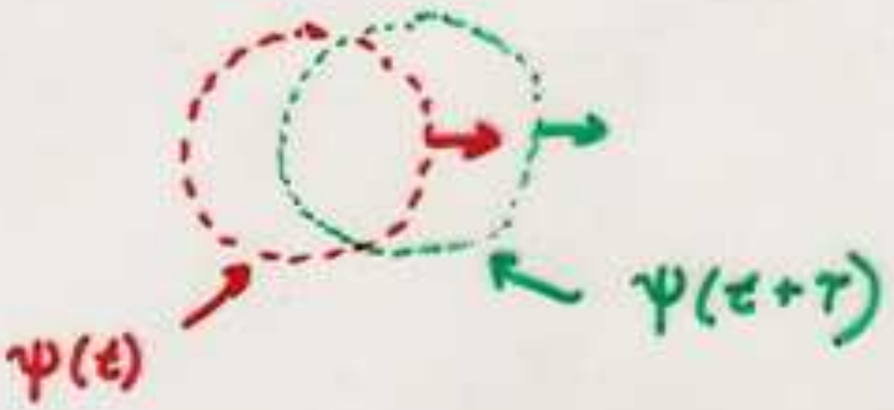
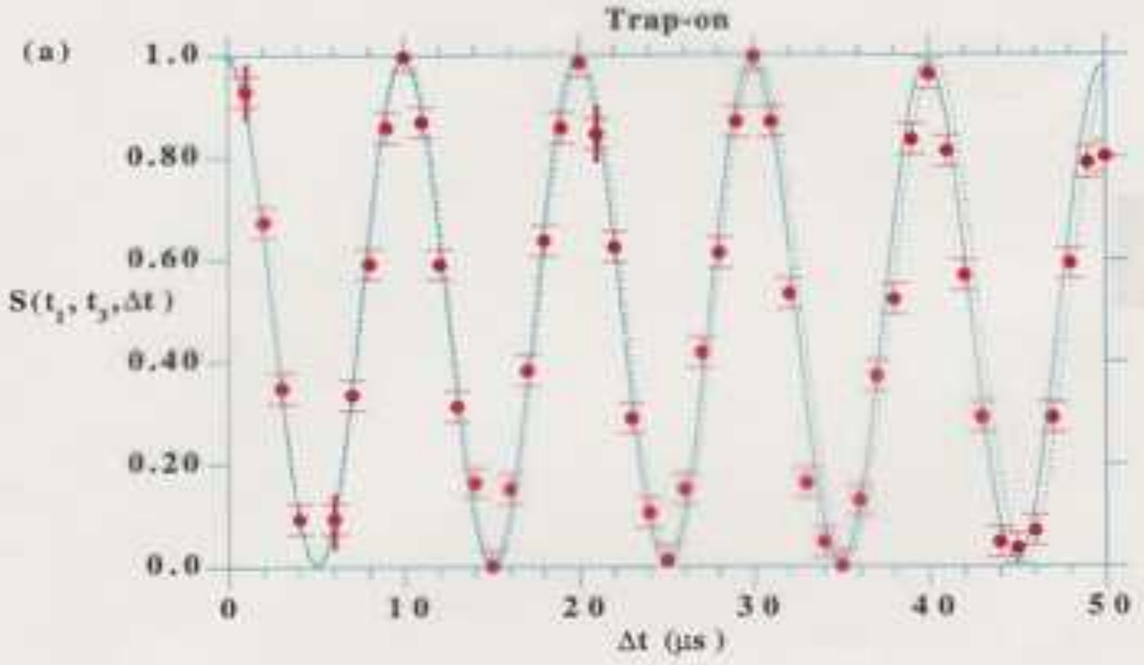
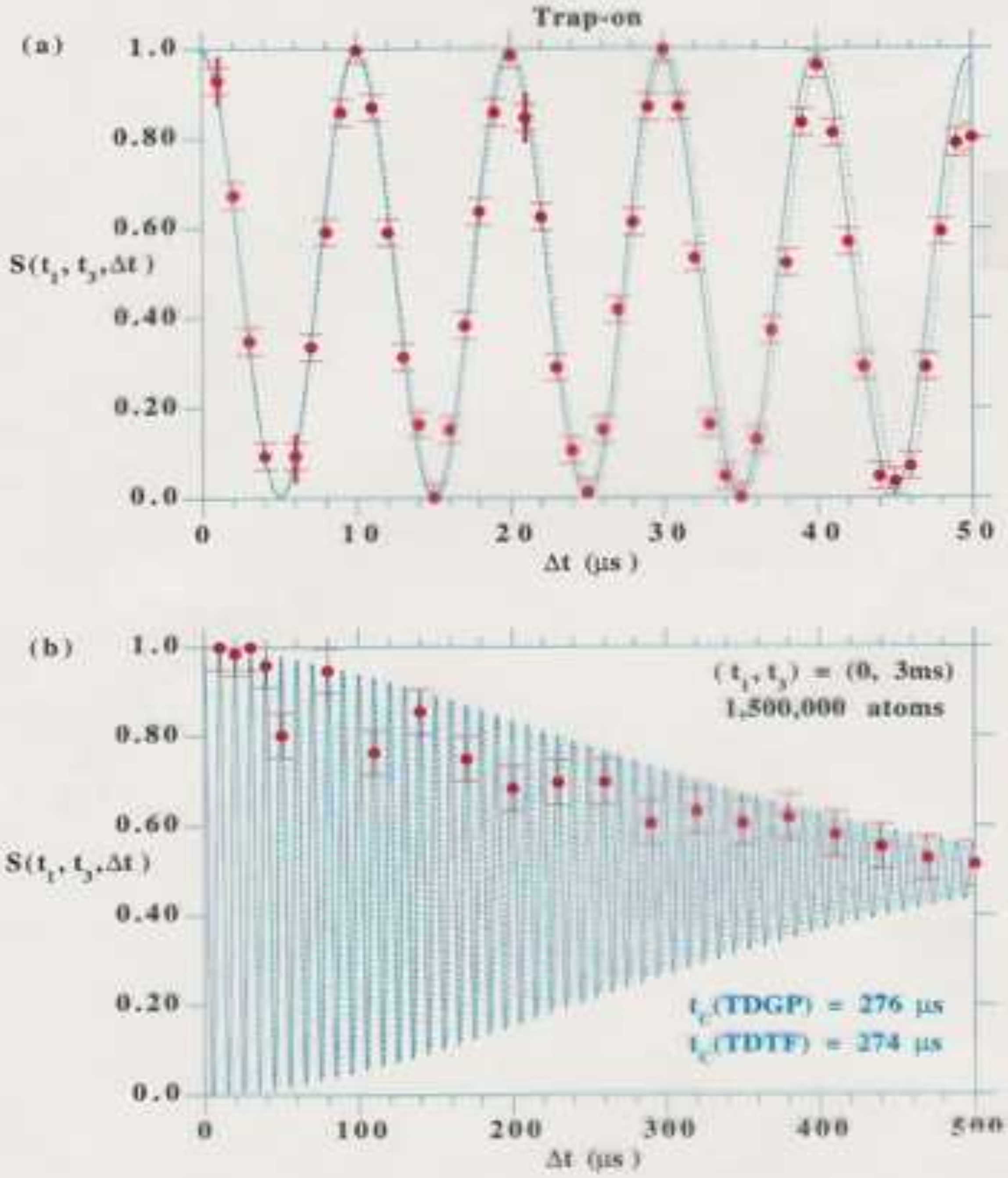


Image density $\sim |\psi(t) + \psi(t+\tau)|^2$

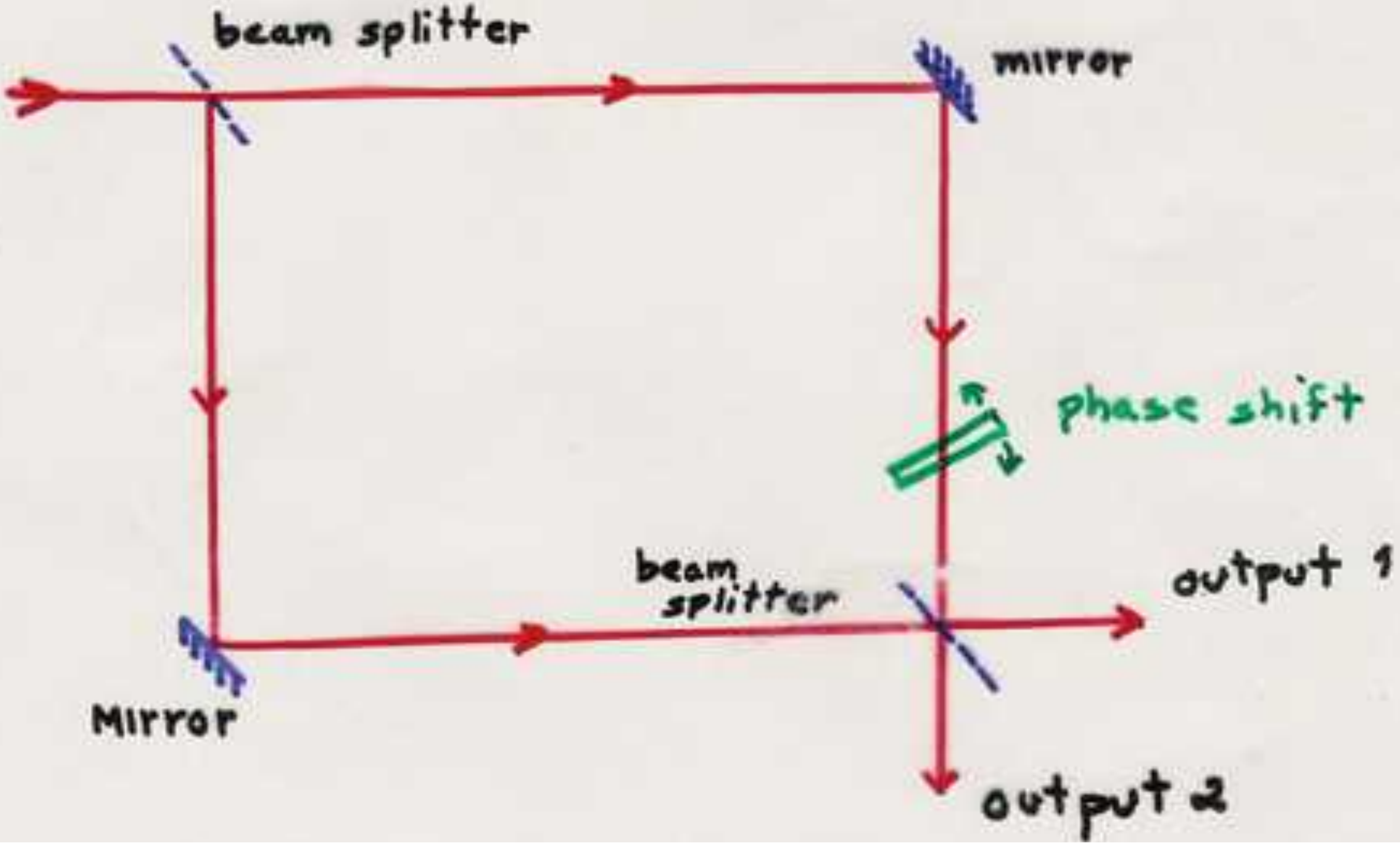
$$\sim |\psi(t)|^2 + |\psi(t+\tau)|^2 + \underbrace{\psi^*(t)\,\psi(t+\tau)}_{\sim \text{correlation function } g_1(\tau)} + \text{c.c.}$$


(a)
Trap-on
1.0
0.80
0.60
0.40
0.20
0.0
S(t1, t3, Δt)
0
10
20
30
40
50
Δt (μs)


Trap-on
(a)
1.0
0.80
0.60
0.40
0.20
0.0
$S(t_1, t_3, \Delta t)$
0
10
20
30
40
50
Δt (µs)
(b)
$(t_1, t_3) = (0, 3\text{ms})$
1,500,000 atoms
t_c(TDGP) = 276 µs
t_c(TDTF) = 274 µs
1.0
0.80
0.60
0.40
0.20
0.0
$S(t_1, t_3, \Delta t)$
0
100
200
300
400
500
Δt (µs)

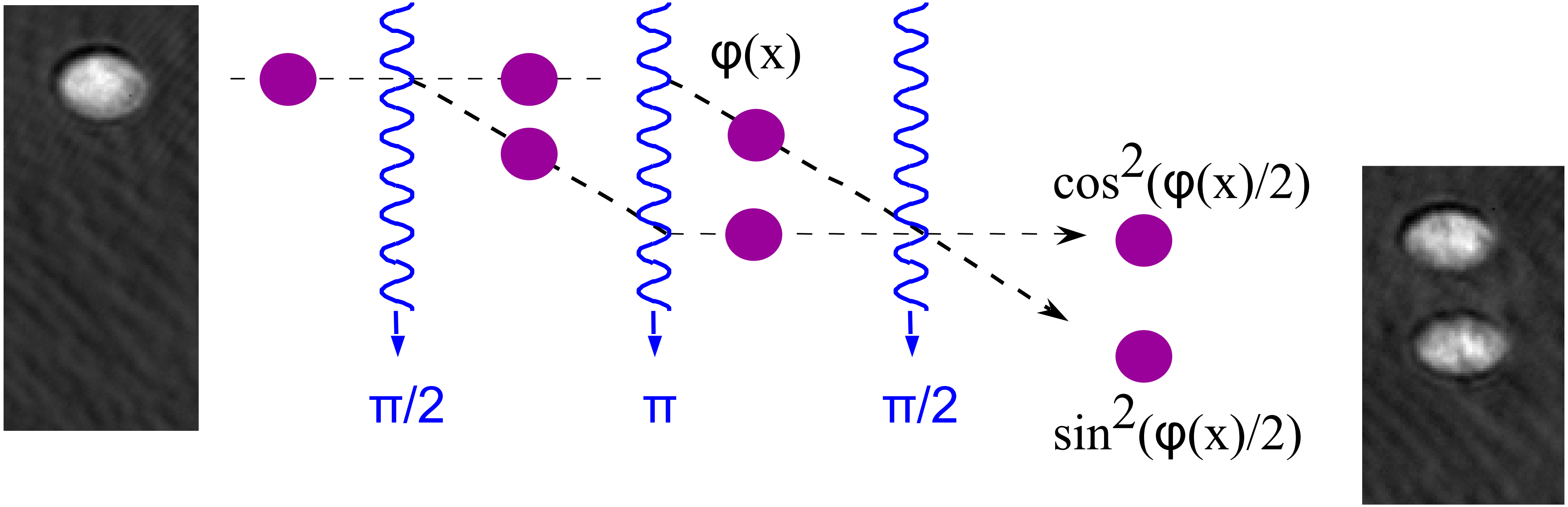
A reminder:

Optical Mach-Zehnder Interferometer



Atom Interferometer

Use Bragg diffraction as 50/50 beamsplitter (π/2 pulse) and mirror (π pulse) between 0 and $2\hbar k$ momentum states



Atom Interferometer

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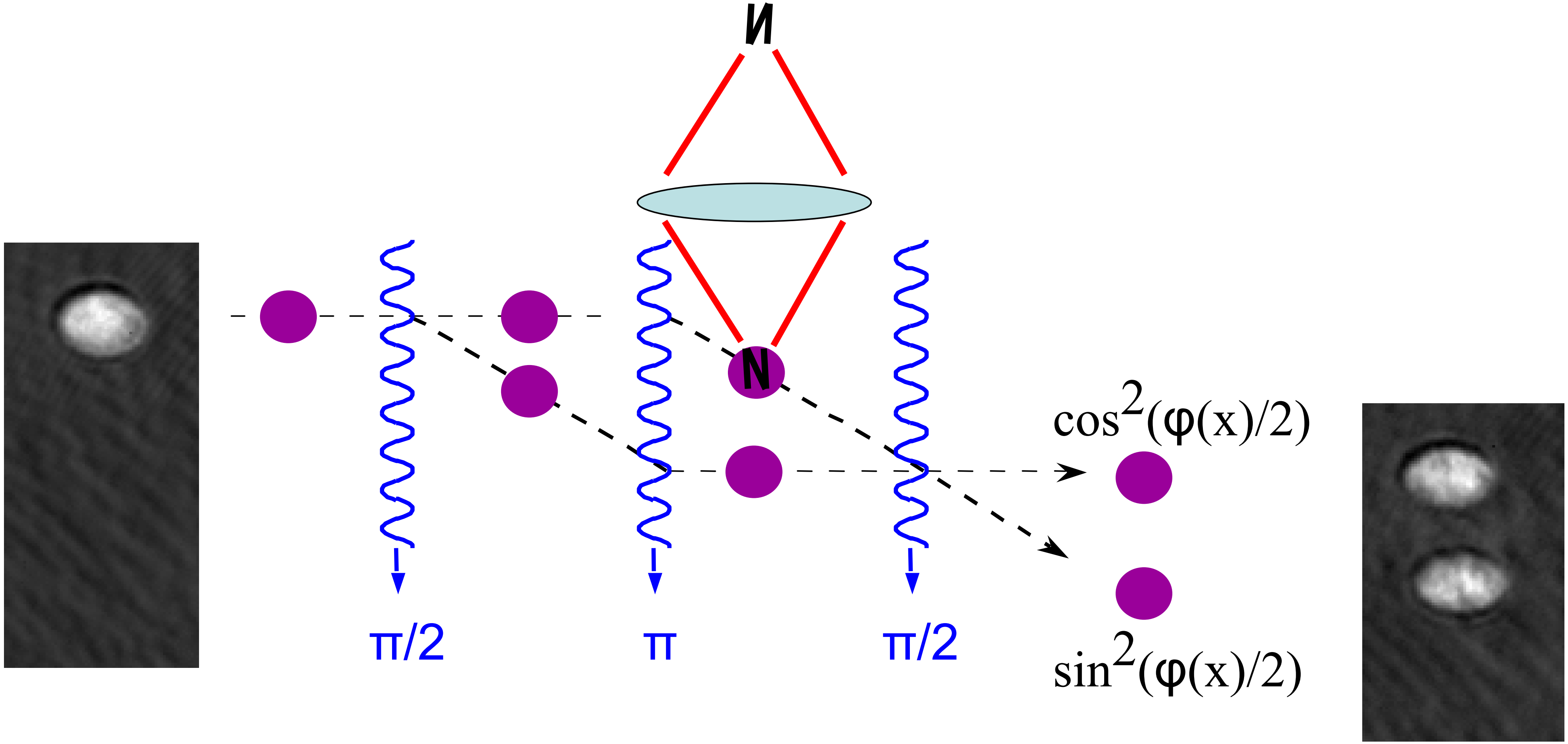
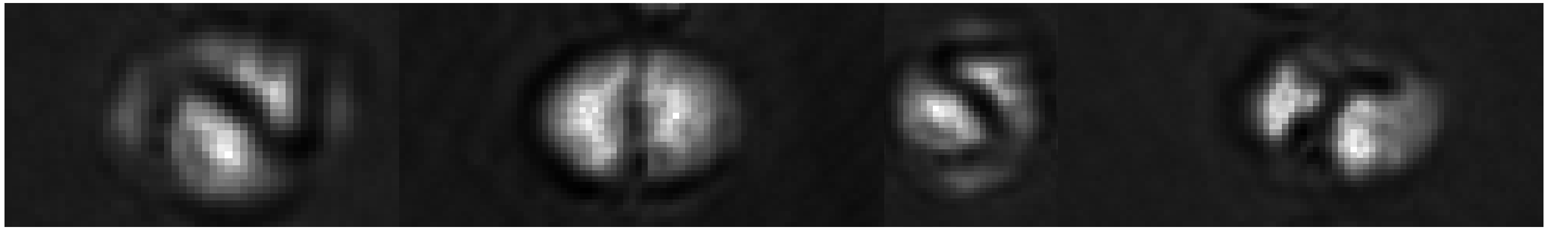
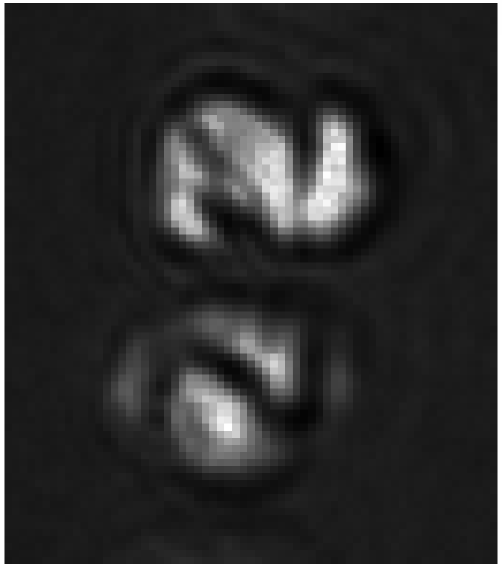


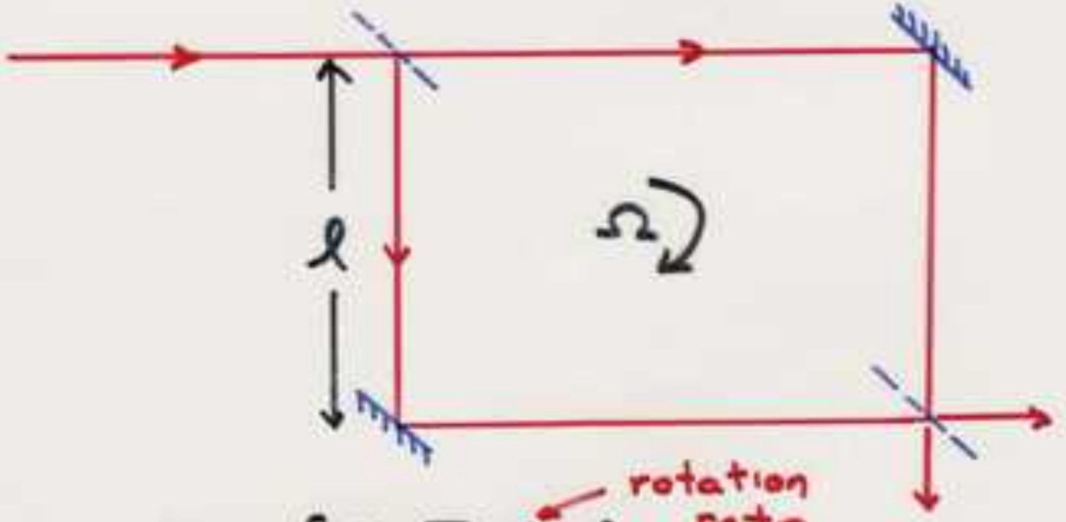
Arbitrary Phase Patterns





An application of atom interference:

Sagnac Interferometer



rotation rate

$\delta \simeq T \cdot \Omega \, \ell$

path difference for rotation

time in interferometer

$T \sim \ell / v$

$\delta \sim \frac{\Omega \ell^2}{v} \sim \frac{\Omega A}{v}$

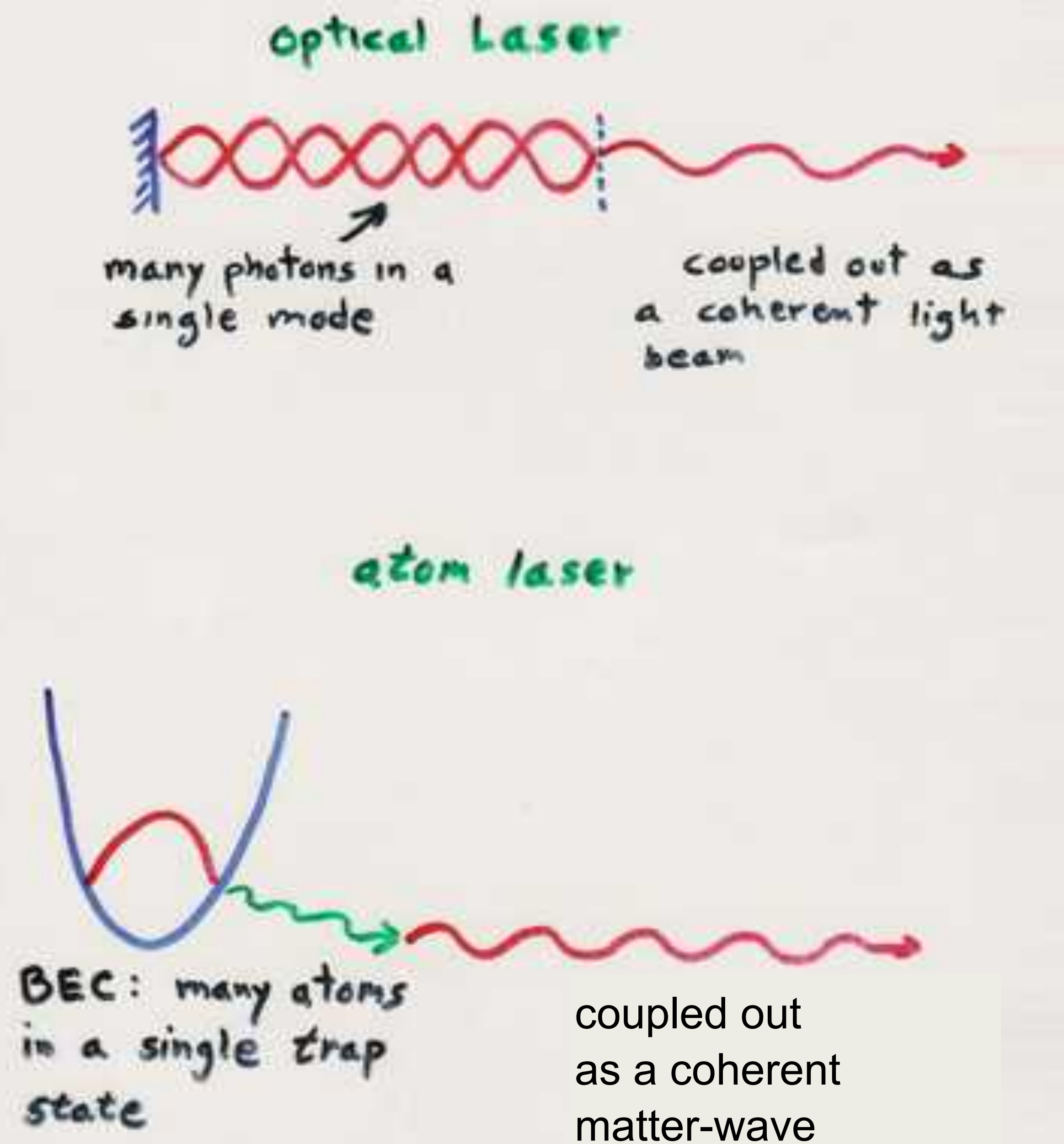
sensitivity $= \delta/\lambda = \frac{\Omega A}{v\lambda}$

$(v\lambda)_{part} = \frac{h}{m}$

$(v\lambda)_{light} = c^2/\nu$

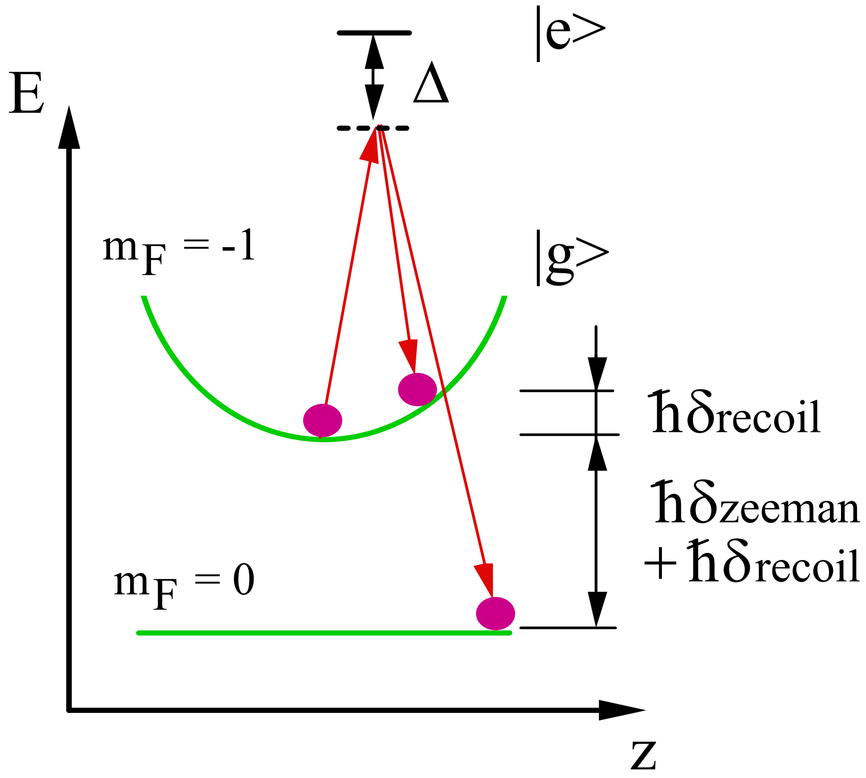
$$\frac{(\delta/\lambda)_{part}}{(\delta/\lambda)_{light}} = \frac{mc^2}{h\nu} = \frac{E_{rest}}{E_{photon}} \approx 10^{11}$$

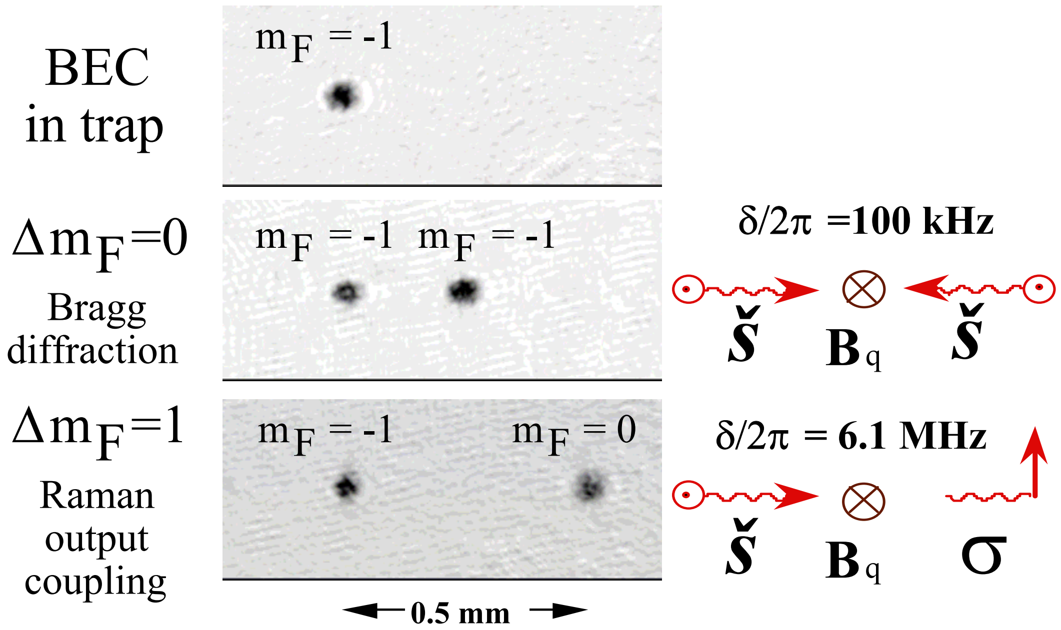
The laser/atom laser analogy



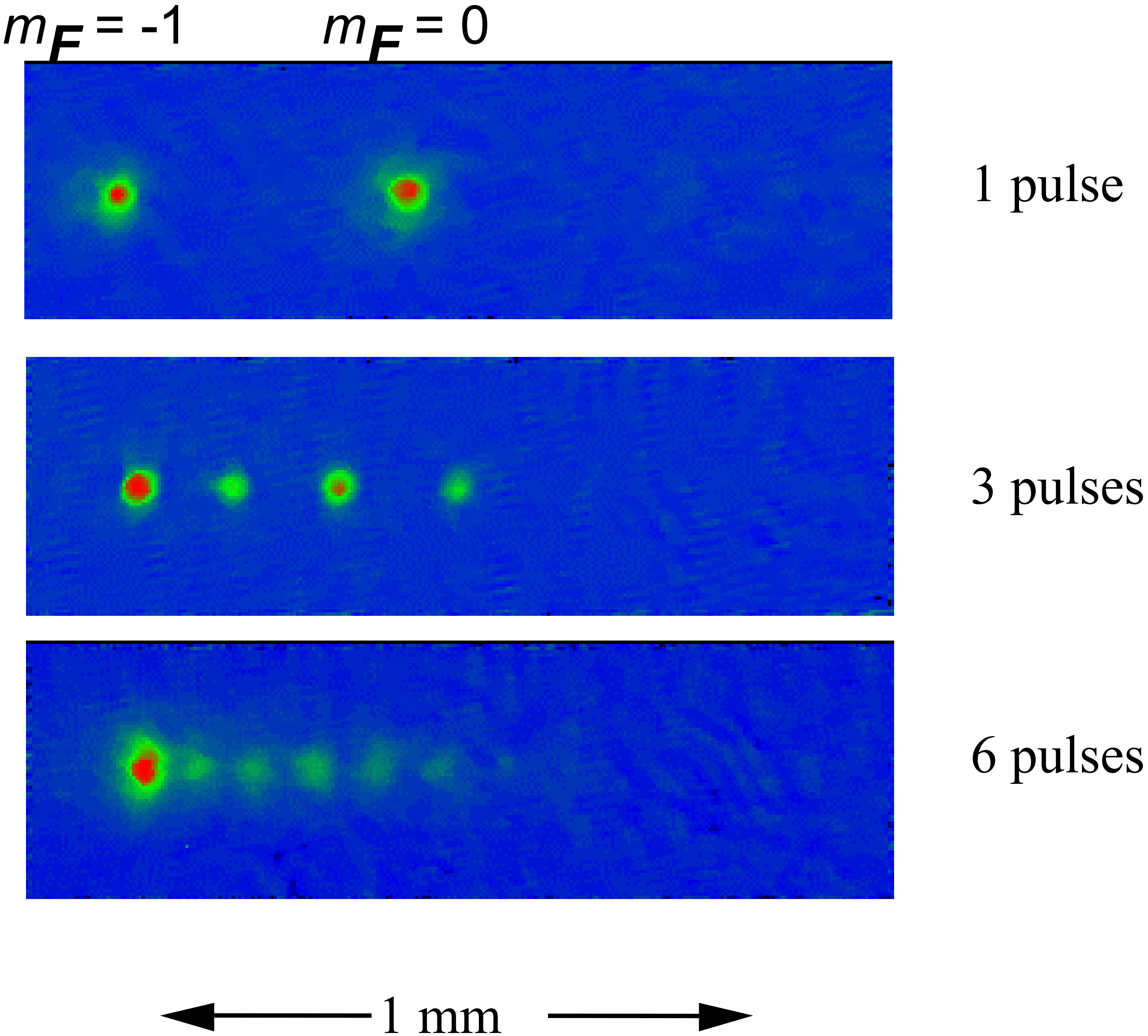
coupled out
as a coherent
matter-wave
beam

Raman Output Coupler



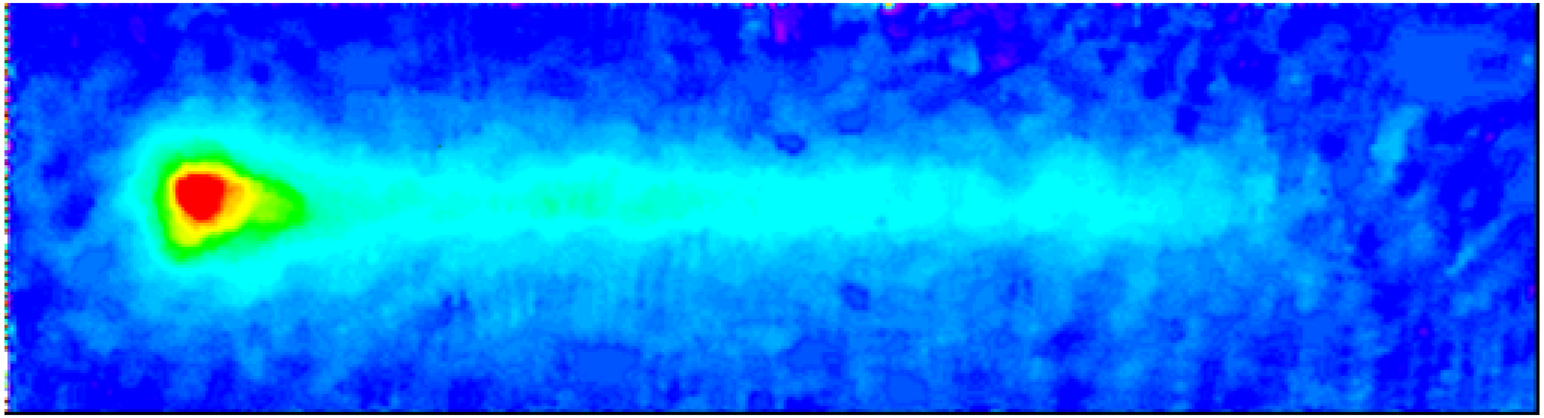


Repeated Raman output coupling

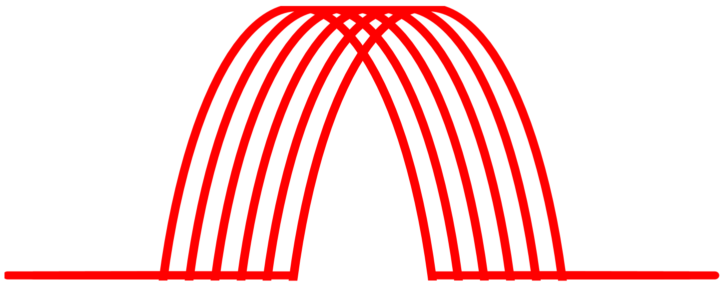


Quasi -Continuous Atom Laser

E. Hagley *et al*., Science 283, 1706 (1999).



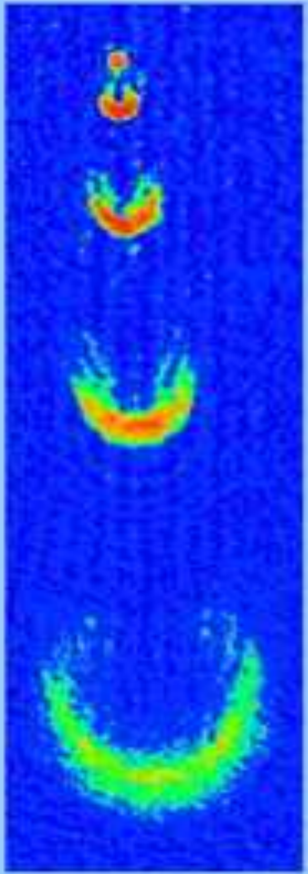
140 pulses (1 μs duration) at 20 kHz (7 ms total)



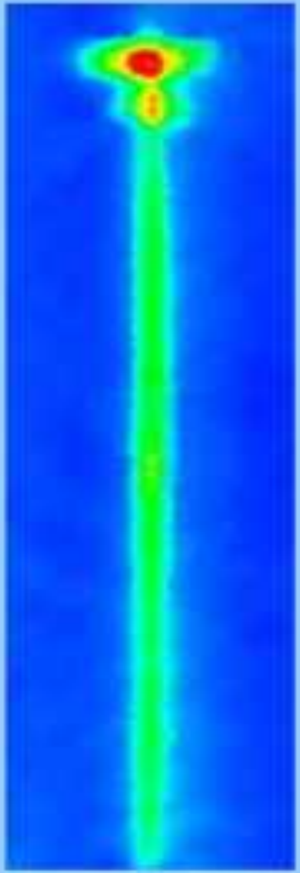
Pulse length ~ 34 μm

Pulse separation = 2.9 μm

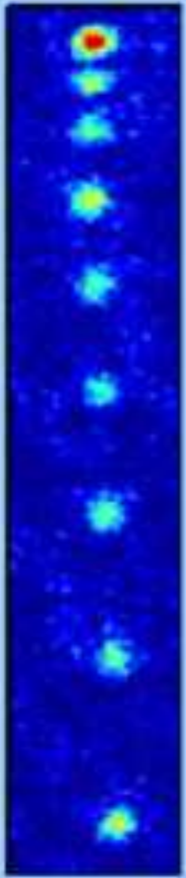
Atom Lasers



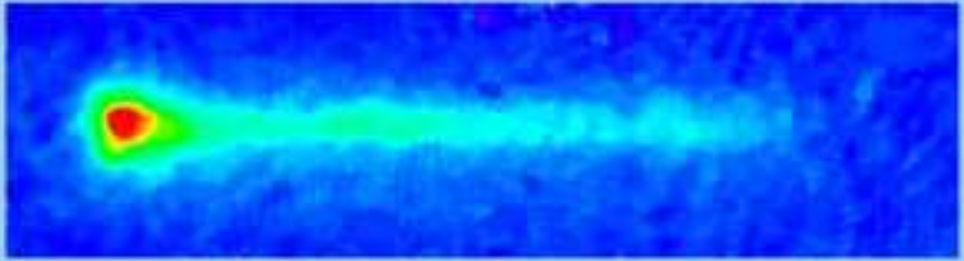
MIT



Munich



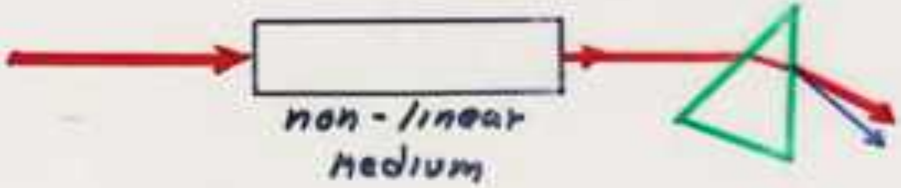
Yale



NIST-Gaithersburg

One of the first new phenomena to come from the high intensity and high coherence of optical lasers was

non-linear optics



2nd harmonic generation : P. Francken ca. 1961
(This is similar to rectified 60Hz yielding 120 Hz, 180 Hz, etc.)

non-linearity (index depends on intensity or conductance depends on voltage) causes the harmonic generation.

Can we do this with atom waves?

Optical 4WM:

energy conservation:

$$\omega_4 = \omega_1 + \omega_2 - \omega_3$$

momentum conservation:

$$\vec{k}_4 = \vec{k}_1 + \vec{k}_2 - \vec{k}_3$$

(caution: notation for 1, 2, 3, 4 may not be consistent.

The 3 input waves create an oscillating polarization

$$P(x,t) \sim \underset{\uparrow}{\chi_3} \cdot E_1(x,t)\, E_2(x,t)\, E_3^*(x,t)$$

3rd order susceptibility

this oscillating polarization radiates the 4th wave.

In the G-P equation there is a term in

$$\frac{\partial}{\partial t} \psi(x,t) \sim g(\psi^* \psi)\, \psi(x,t)$$ which has

the same structure and gives rise to generation of a new momentum component when ψ has the proper 3 components.

4-Matter-Wave-Mixing at NIST

Theory: M. Trippenbach, Y. Band, P. Julienne
Expt.: L. Deng, E. Hagley, J. Wen, K. Helmerson, S. Rolston, WDP
(earlier ideas by Meystre)

One way to understand 4WM:

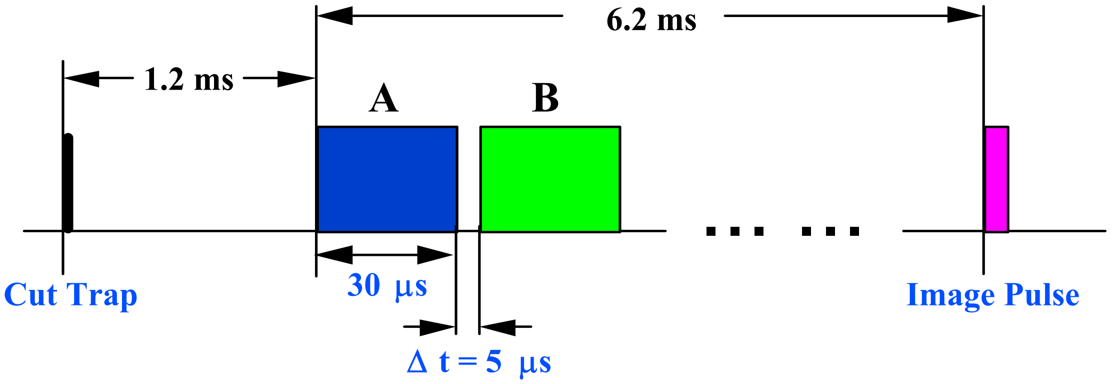
- Two deBroglie waves interfere to create a standing matter wave-equivalent to a refractive-index grating.

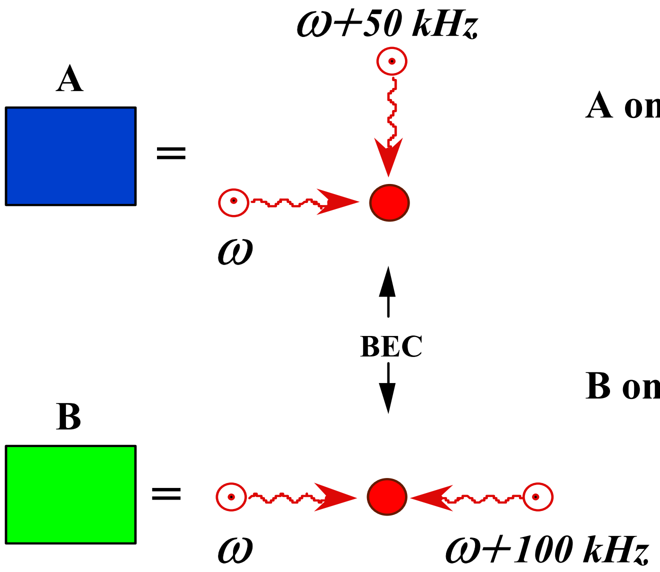
- A 3rd deBroglie wave Bragg-reflects from this grating, and the reflected wave is the

fourth deBroglie wave – a new matter wave arising from the non-linearity (mean-field effect)

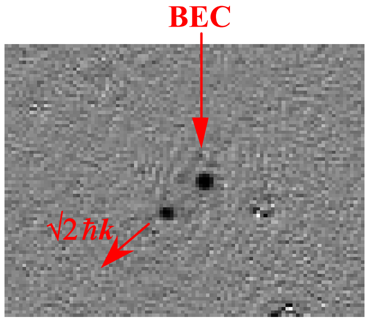
phase matching = satisfaction of Bragg condition

Four Wave Mixing Experiment

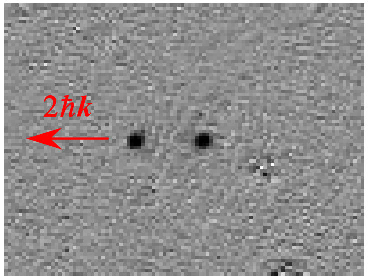




A only -->

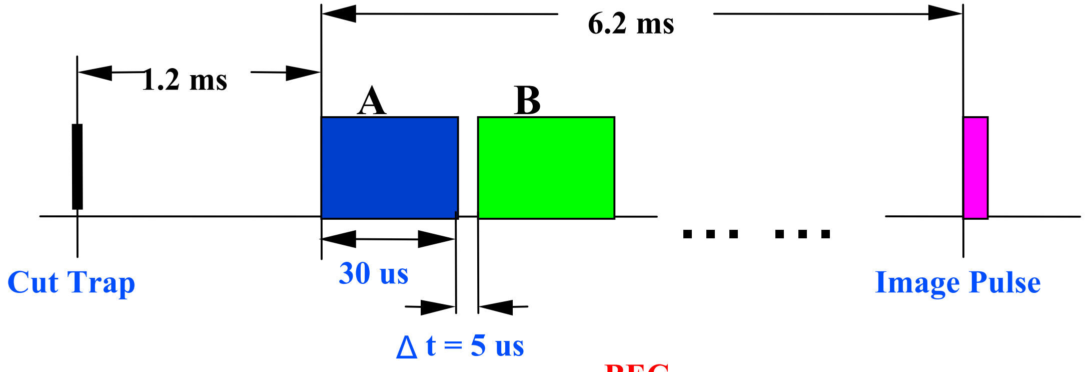


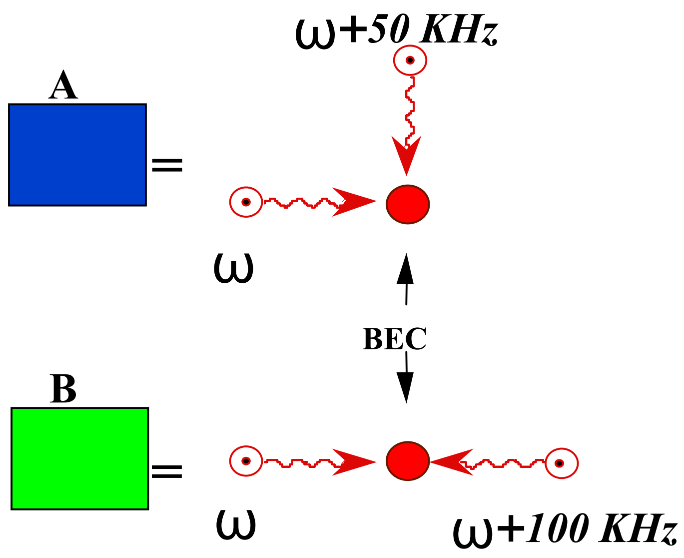
B only -->



A then B ----> **?**

Four Wave Mixing Experiment

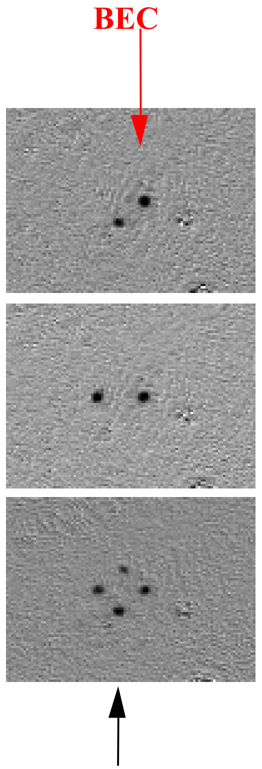




A no B ------>

B no A ------>

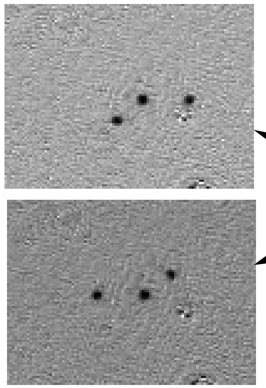
A then B ---->



Bragg Condition Satisfied
34% Reflected

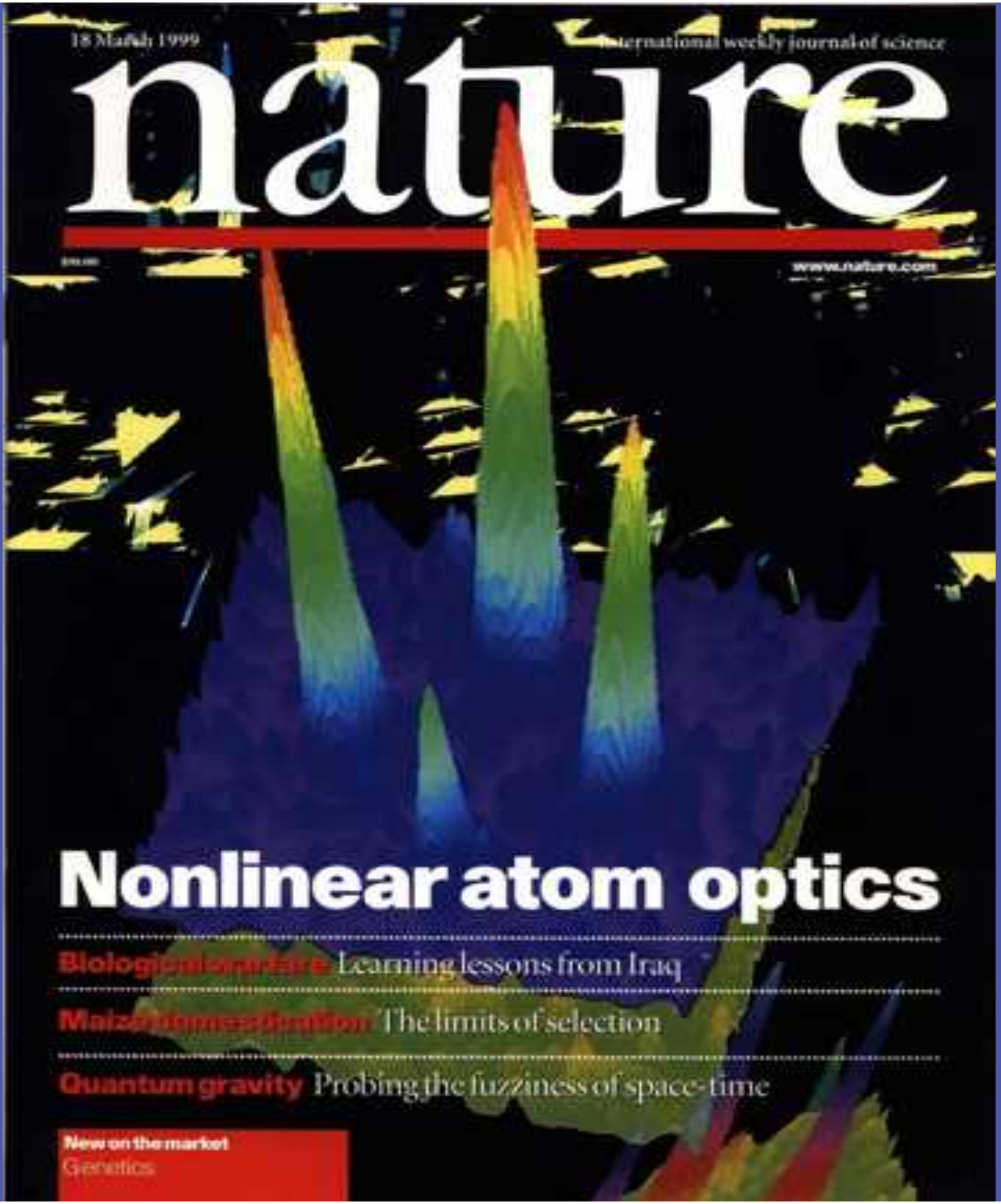
A then B (ω-100 KHz)--->

A(ω-50 KHz) then B ---->



Bragg Condition NOT Satisfied, Nothing Reflected

In all images there were 2 million atoms in original BEC with ${}_{max}$ = 84 Hz



18 March 1999

International weekly journal of science

nature

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Nonlinear atom optics

Biological warfare Learning lessons from Iraq

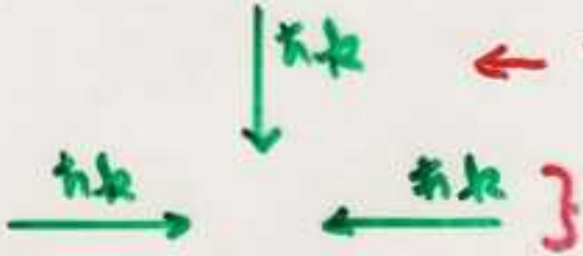
Maize domestication The limits of selection

Quantum gravity Probing the fuzziness of space-time

New on the market
Genetics

4-Wave Mixing

reference frame for degenerate 4WM



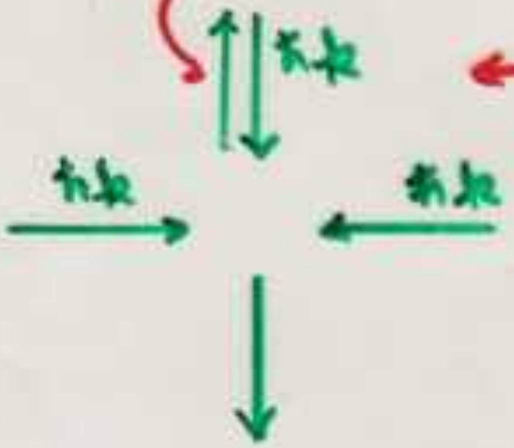
this is amplified

these two form a gain medium

4-Wave Mixing

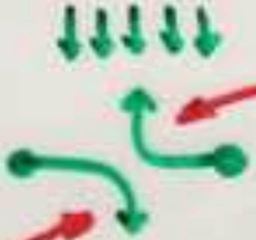
reference frame for degenerate 4WM

new, 4th wave needed to conserve E, $\vec{p}$



this is amplified

these two form a gain medium



Energy, momentum conservation

stimulated scattering in the presence of incident wave

“Quantum” atom optics

The fourth wave and the amplified wave are correlated--for every atom in the fourth wave, there is an amplified atom. This is similar to the quantum correlation between twin photons in parametric downconversion. These atoms are entangled. Can this entanglement be useful? This remains to be seen.

Other things in atom optics

- Evanescent-wave and magnetic mirrors
- Optical and magnetic waveguides
- Higher order Bragg mirrors and beamsplitters
- Talbot effect
- More output couplers for atom lasers
- Material diffraction gratings
- ….more

THE END

(of Phillips lecture # 1)