COLLECTIVE LASER COOLING
DUE TO
SPATIAL SELF-ORGANIZATION
OF CLASSICAL ATOMS:

FROM RAYLEIGH TO BRAGG SCATTERING

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IS IT POSSIBLE TO GENERALIZE LASER COOLING TO ARBITRARY LIGHT SCATTERERS (CLASSICAL ATOMS) ?

TO N-ATOM SAMPLES ?

TO OTHER OBJECTS ?

MOTIVATION

LASER COOLING REQUIRES ATOMS WITH SIMPLE QM LEVEL STRUCTURE.

$\Rightarrow$ FEW ATOMS, NO MOLECULES

ARE THERE LASER COOLING METHODS THAT ARE (LARGELY) INDEPENDENT OF ATOMIC LEVEL STRUCTURE?

COOLING OF CLASSICAL ATOMS

HOW TO BREAK SYMMETRY BETWEEN COOLING AND HEATING?

MOTIVATION

ALL KNOWN LASER COOLING METHODS ARE BASED ON SINGLE-ATOM FORCES, DETIORATE AS ATOM NUMBER N IS INCREASED.

ARE THERE COLLECTIVE FORCES?

(FORCE PER ATOM $\propto N$
FORCE ON SAMPLE $\propto N^2$)

OUTLINE

I. INTRODUCTION: LASER COOLING AND EMISSION SIDEBAND ASYMMETRY

II. CAVITY FORCES FOR CLASSICAL ATOMS

- SELF-ORGANIZATION AND SPONTANEOUS SYMMETRY BREAKING
- COLLECTIVE FRICTION FORCE FOR CENTER-OF-MASS MOTION

III. TOWARDS MOLECULES ?

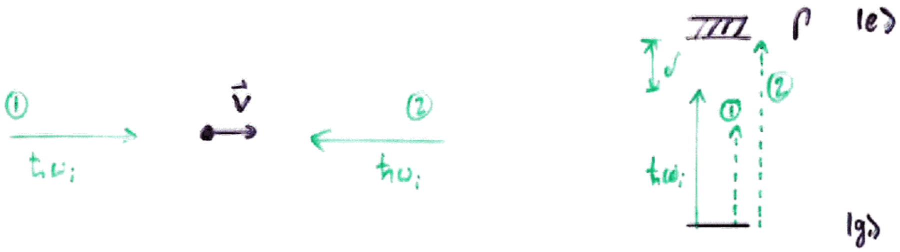
INTRODUCTION

LASER COOLING HAS ENABLED

- BOSE-EINSTEIN CONDENSATION
- MANY PRECISION EXPERIMENTS

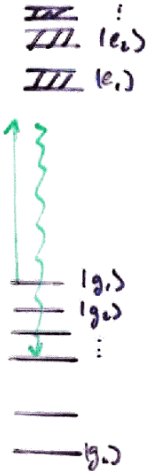
CAN BE APPLIED ONLY TO FEW ATOMIC AND NO MOLECULAR SPECIES.

Conventional Doppler cooling for two-level atoms



Detuning $|\delta| \sim$ Doppler effect kv

… is not possible for atoms with multilevel internal structure

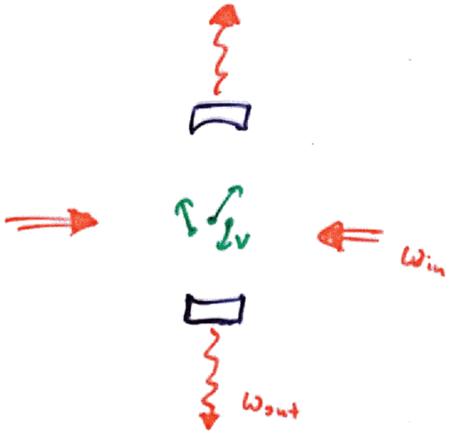


condition on detuning $|\delta| \sim$ kv relative to atomic transitions cannot be maintained

(optical pumping to different internal level)

ROLE OF OPTICAL RESONATOR

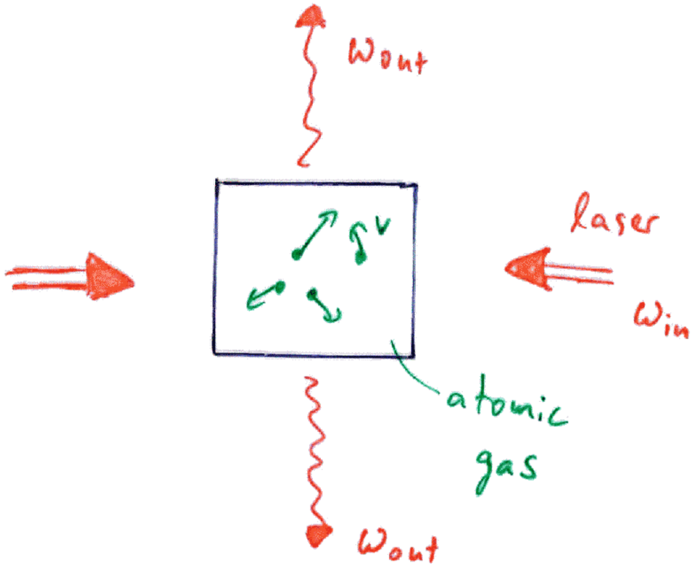
BLACK BOX: OPTICAL RESONATOR



SYMMETRY BETWEEN COOLING AND HEATING BROKEN VIA LIGHT-RESONATOR DETUNING:

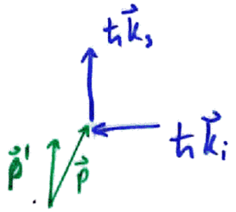
$$\langle \omega_{out} \rangle > \omega_{in}$$

FREQUENCY ANALYSIS



If $\langle \omega_{out} \rangle > \omega_{in}$ → COOLING

EMISSION FREQUENCY AND ATOMIC MOTION



$$\vec{p}' = \vec{p} + \hbar \vec{k}_i - \hbar \vec{k}_s$$ momentum conservation

$$W' = \frac{\vec{p}'^2}{2m} = W + \hbar(\vec{k}_i - \vec{k}_s)\cdot\vec{v} + \frac{\hbar^2}{2m}(\vec{k}_i - \vec{k}_s)^2$$

Two-photon Doppler effect

Recoil heating

$$\Delta' = \omega_s - \omega_i = -(\vec{k}_i - \vec{k}_s)\cdot\vec{v} - \frac{\hbar}{2m}(\vec{k}_i - \vec{k}_s)^2$$ energy conservation

$W' - W$: ATOMIC ENERGY CHANGE IN SCATTERING

$\Delta' = \omega_s - \omega_i$: PHOTON FREQUENCY SHIFT IN SCATTERING

COOLING AND BLUE EMISSION SIDEBAND

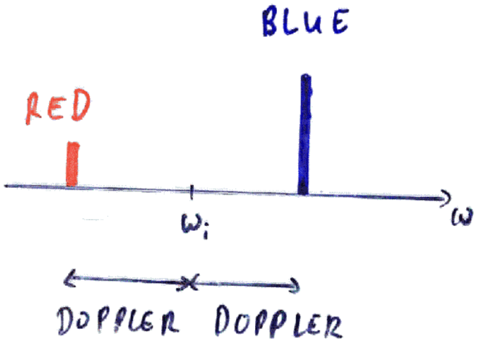
$$\underset{\substack{\uparrow\\ \text{ATOMIC ENERGY}\\ \text{CHANGE}}}{W'-W} = \underset{\substack{\uparrow\\ \text{DOPPLER}}}{\hbar(\vec{k}_i-\vec{k}_s)\cdot\vec{v}} + \underset{\substack{\uparrow\\ \text{RECOIL}}}{\frac{\hbar^2}{2m}(\vec{k}_i-\vec{k}_s)^2}$$

$$\downarrow$$

$$W'-W = -\hbar\Delta' \swarrow \text{EMITTED PHOTON FREQUENCY SHIFT}$$

$$W' < W \quad \Leftrightarrow \quad \Delta' > 0$$

COOLING $\Leftrightarrow$ BLUE PHOTON EMISSION



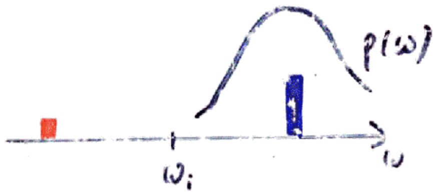
EMISSION SPECTRUM AND VACUUM MODES

WE NEED $\langle\omega_{EM}\rangle > \omega_{IN}$,

i.e. ASYMMETRIC EMISSION SPECTRUM

ALTERNATIVE TO CONVENTIONAL COOLING:

EMISSION RATE $\Gamma(\omega)$ $\propto$ ELECTROMAGNETIC MODE DENSITY $\rho(\omega)$



IF $\rho(\omega>\omega_{in}) > \rho(\omega<\omega_{in}) \Rightarrow \langle\omega_{out}\rangle > \omega_{in}$

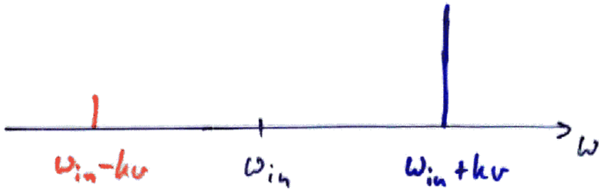
$\Rightarrow$ COOLING INDEPENDENT OF TARGET LEVEL STRUCTURE

(ATOMS, MOLECULES, ELECTRONS, GLASS SPHERES, ...)

EMISSION COOLING AND COLLECTIVE FORCES

$P_{tot} \propto N$: SINGLE ATOM

$P_{tot} \propto N^2$: COLLECTIVE FORCE



dominant blue sideband ↔ cooling

Collective forces possible when emission is collective ($P_{tot} \propto N^2$):

- laser emission ↔ inversion between internal states
- recoil-induced resonances (Bragg scattering) ↔ inversion between momentum states

ATOM-CAVITY COUPLING

characterized by

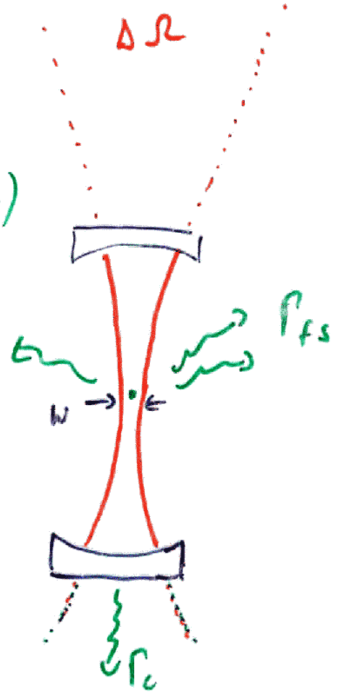
cavity to free space scattering ratio

$$\eta = \frac{\Gamma_c}{\Gamma_{fs}} = \frac{\text{scattering rate into cavity}}{\text{scattering rate into free space}}$$

For single atoms:

$\eta_s \propto$ (solid angle) x (finesse)

$\eta_s \propto$ (mode area)$^{-1}$ x (mirror loss)$^{-1}$



cavity to free space scattering ratio

$\eta = \frac{g^2}{\kappa \Gamma}$ is cooperativity parameter in cavity QED

g single-photon Rabi frequency

κ cavity linewidth

Γ atomic linewidth

$\eta \gtrless 1$ strong / weak coupling

For our setup: $\eta_s = 5 \cdot 10^{-2}$

WEAK SINGLE-ATOM COUPLING

CLASSICAL RESONATOR COUPLED TO CLASSICAL ATOMS

EXPERIMENTS PERFORMED AT

LIGHT-ATOM DETUNING $-(2..6)$ GHz >> ATOMIC HYPERFINE STRUCTURE $\lesssim 500$ MHz

⇒ CLASSICAL ATOMS

(CLASSICAL COHERENT SCATTERING)

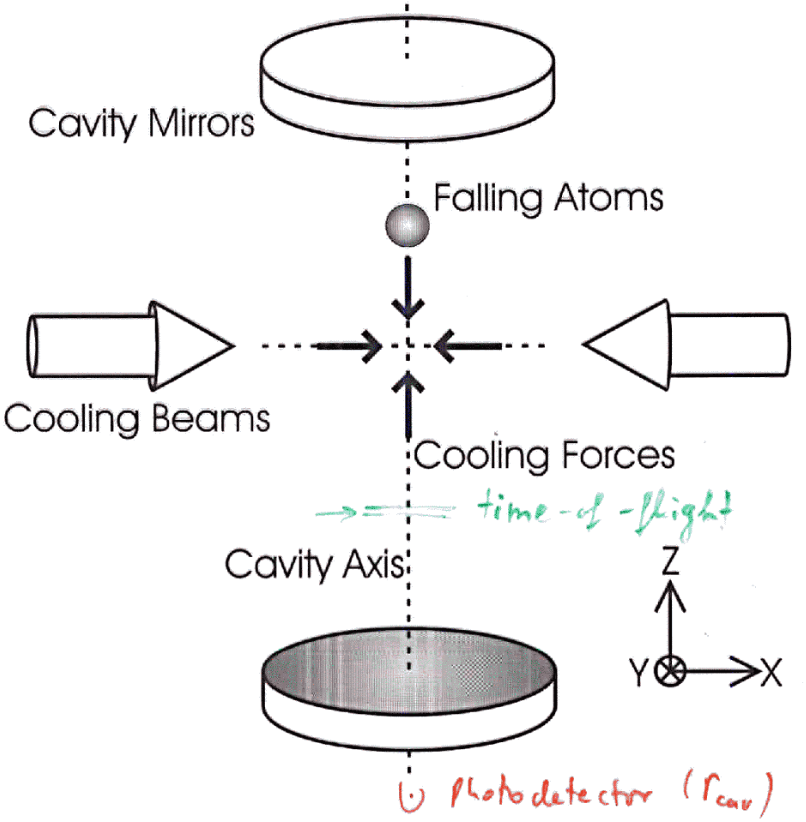
ATOMIC STRUCTURE IRRELEVANT

WEAK ATOM-RESONATOR COUPLING

$\eta_s = \frac{\Gamma_{cavity}}{\Gamma_{fs}} = 5 \cdot 10^{-2} \ll 1$ FOR SINGLE ATOM

⇒ CLASSICAL RESONATOR

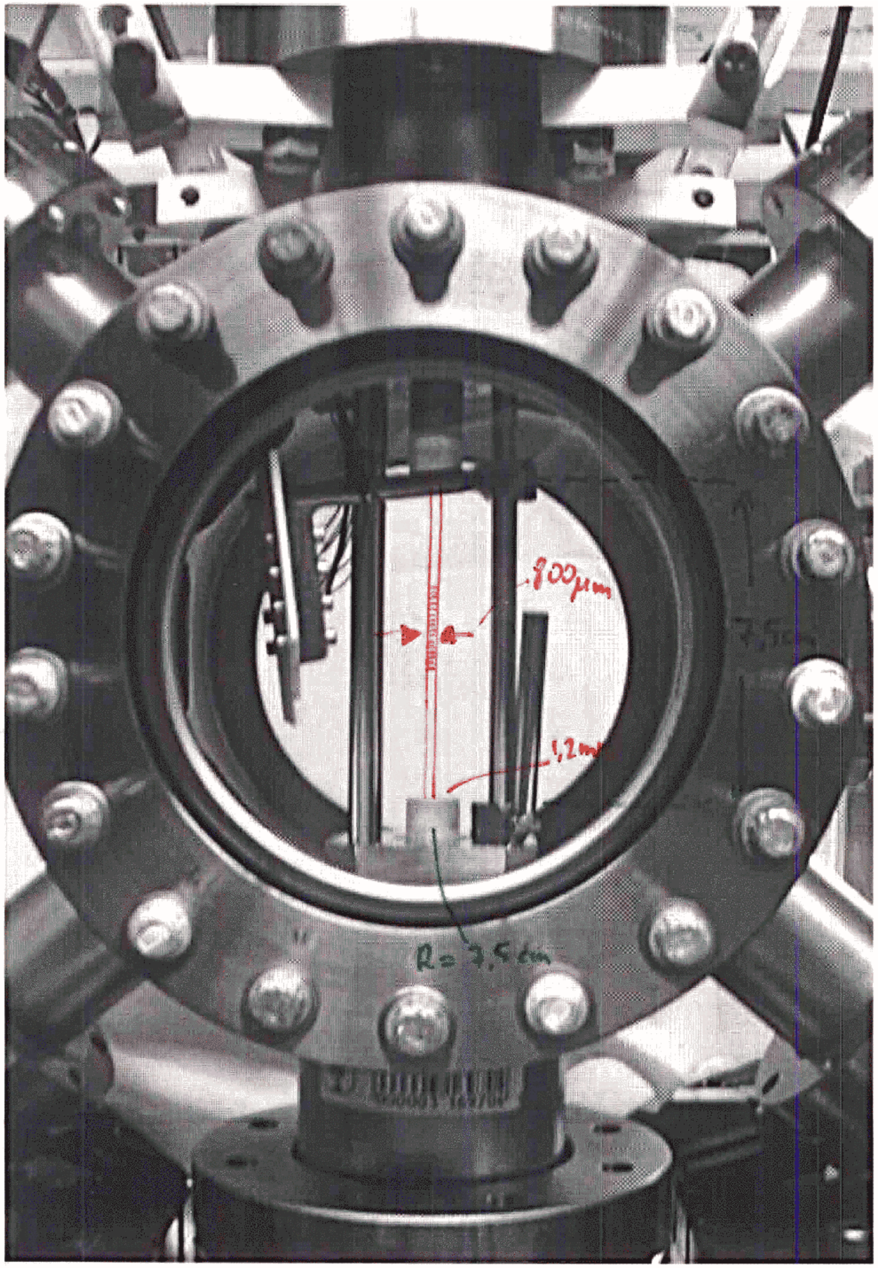
EXPERIMENTAL SETUP

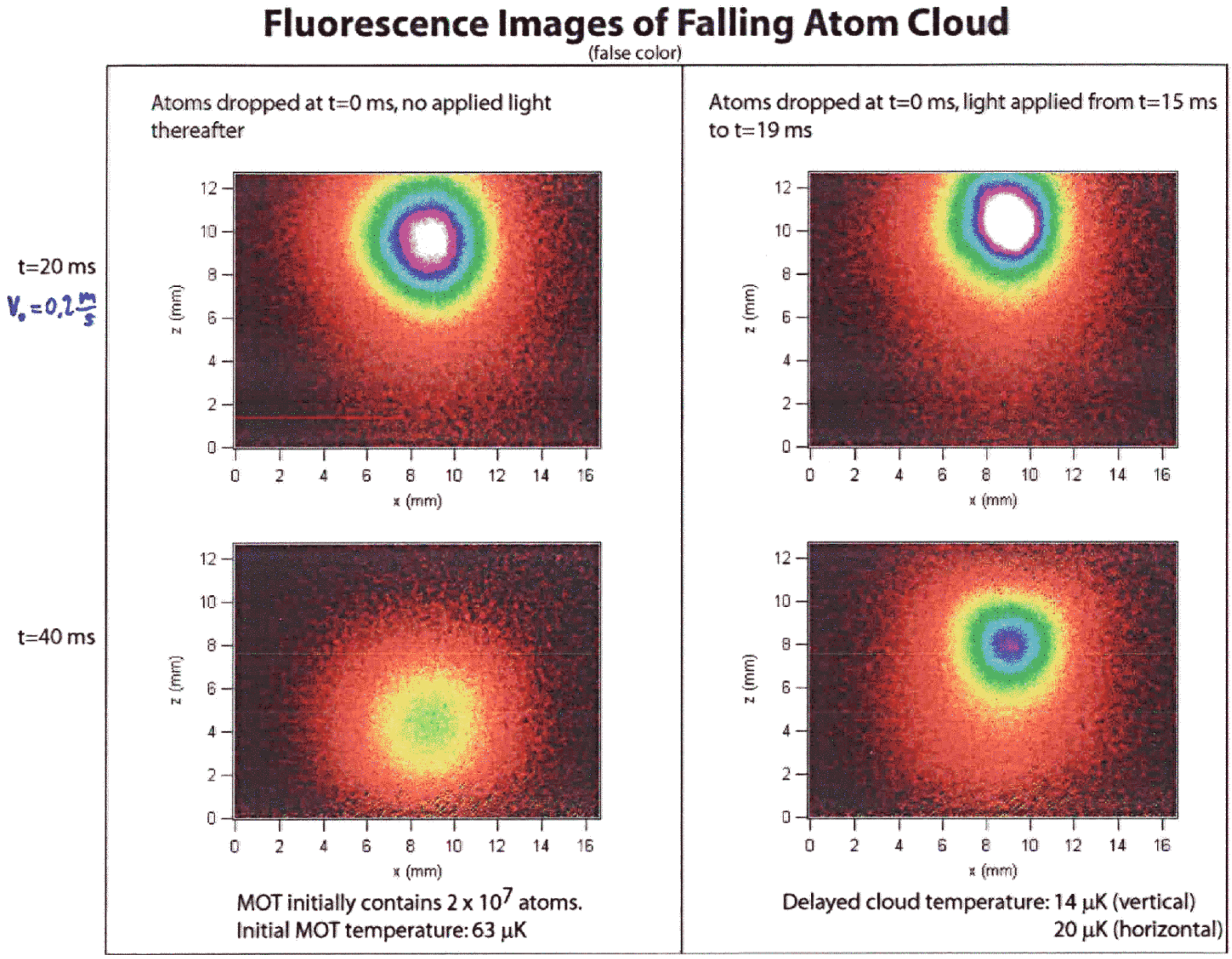


measure temperature and deceleration

near-confocal resonator:

cooling volume 2,5 mm × 0,8 mm × 7,5 cm





Fluorescence Images of Falling Atom Cloud

(false color)

MOT initially contains 2 x 10^7 atoms.
Initial MOT temperature: 63 μK

Delayed cloud temperature: 14 μK (vertical)
20 μK (horizontal)

QUALITATIVE EVIDENCE FOR CAVITY COOLING

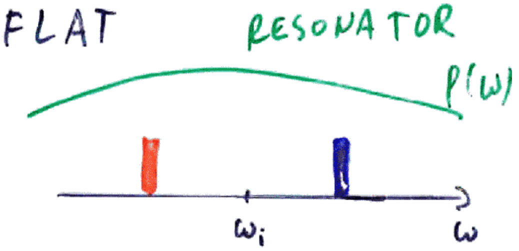
- COOLING ONLY IF RESONATOR TUNED CLOSE TO INCIDENT LIGHT FREQUENCY
- TUNING OF INCIDENT LIGHT RELATIVE TO ATOMIC TRANSITIONS UNCRITICAL
- FORCE ACTING PERPENDICULAR TO INCIDENT LIGHT (I.E. ALONG CAVITY)
- FORCE IS DISSIPATIVE (CLOUD STOPPED INDEPENDENT OF INITIAL VELOCITY)

OBSERVATIONS

- STRONG RESONATOR-INDUCED LIGHT FORCES

BUT

- FORCE SIGNIFICANTLY TOO LARGE (FACTOR 20.. 100)
- FORCE EXISTS WHERE RESONATOR SPECTRUM IS FLAT



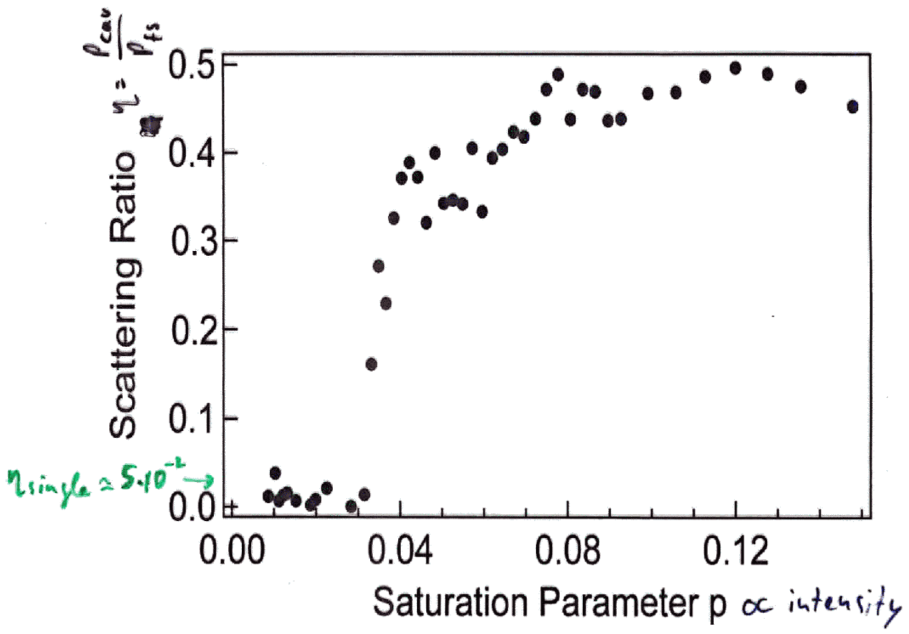
- TOO MUCH LIGHT EMITTED INTO RESONATOR (UP TO FACTOR 20.000)

EXPLANATION?

MAYBE LARGE FORCES OBSERVED EVEN FOR FLAT RESONATOR SPECTRUM ARE CONSEQUENCE OF VERY LARGE LASER-LIKE EMISSION INTO RESONATOR.

ORIGIN OF OPTICAL GAIN?

Threshold behavior of collective emission



Threshold occurs at constant scattering rate as light-atom detuning is varied

ANOMALOUS RESONATOR EMISSION

EXPECTED : $\eta_s = \frac{P_c}{P_{fs}} = 5\cdot10^{-2}$

OBSERVED : $\eta = \frac{P_c}{P_{fs}} = 300..1000$

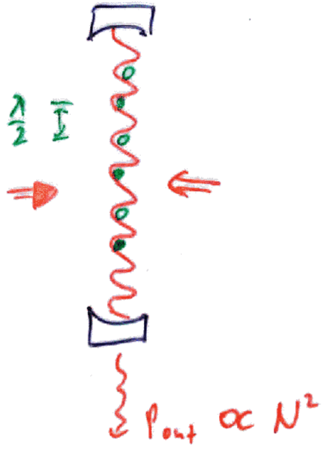
(1000 PHOTONS EMITTED INTO RESONATOR PER PHOTON EMISSION INTO FREE SPACE, RESONATOR SOLID ANGLE $\simeq 10^{-4}$)

EXPLANATION:

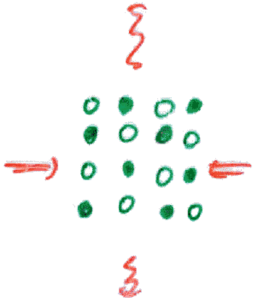
P. Domokos and H. Ritsch, PRL 89, 253003 (2002).

Origin of optical gain: Bragg diffraction

Atoms self-organize into density grating that Bragg scatters light into cavity (Domokos & Ritsch)

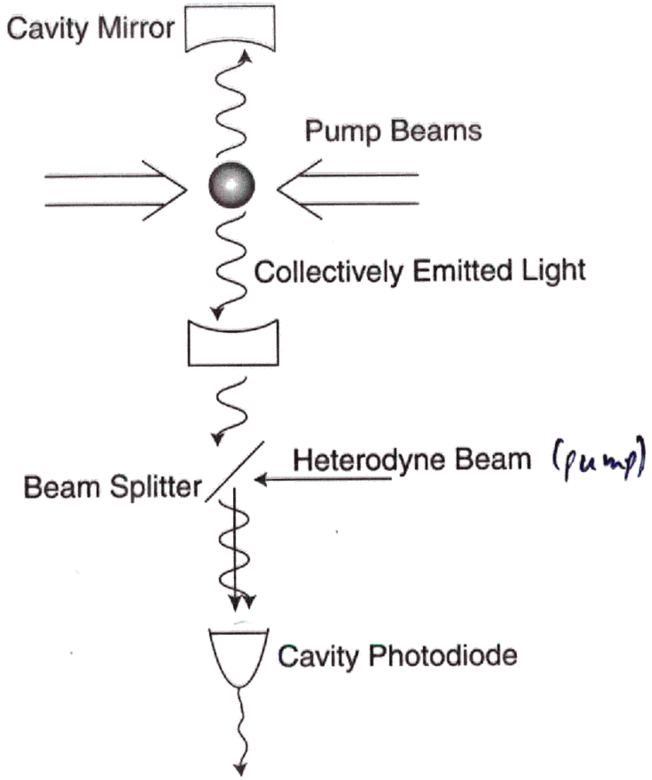


Constructive interference
only for
only even or
only odd occupation



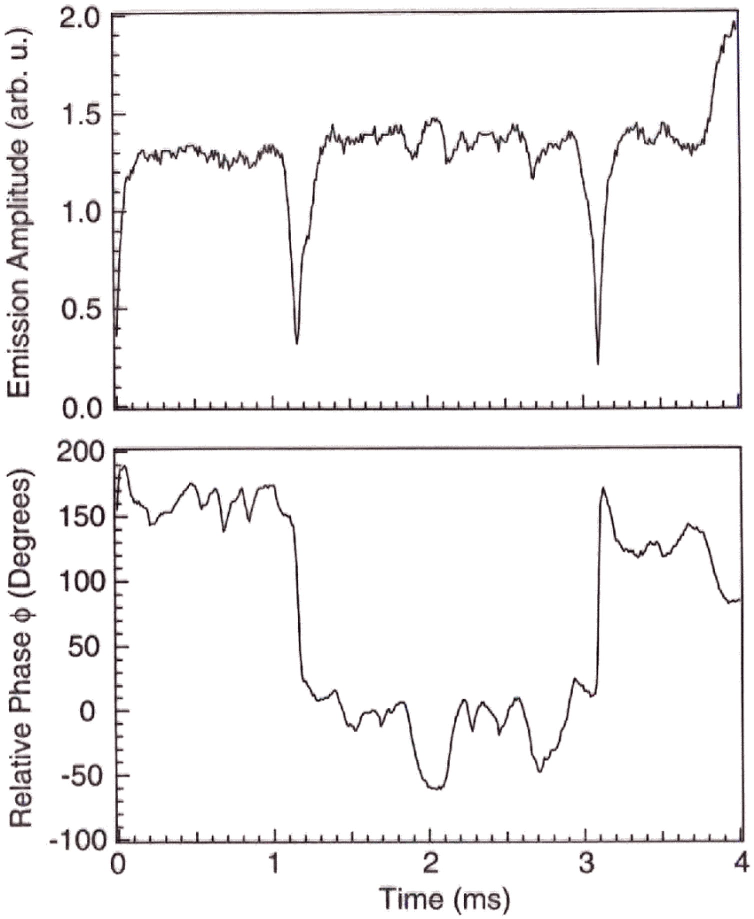
In 2D

OBSERVATION OF ATOMIC SELF-ORGANIZATION



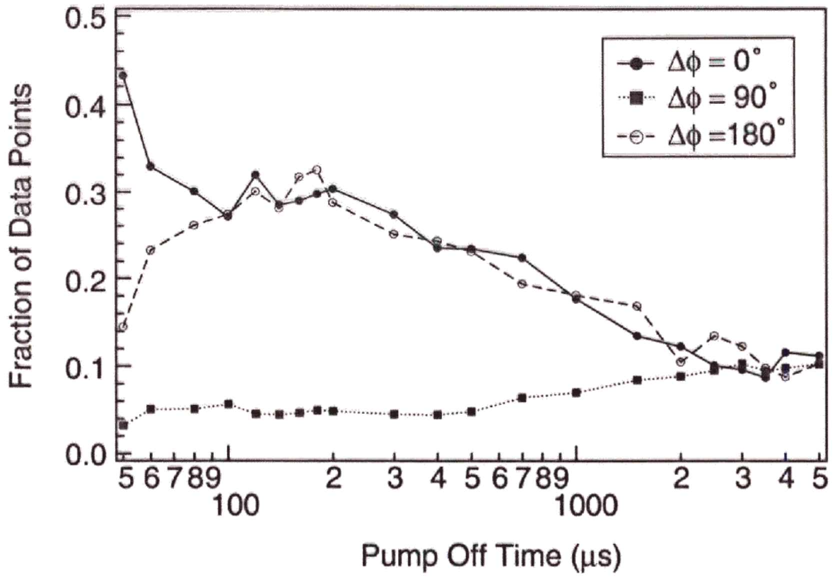
MEASURE PHASE OF INTRACAVITY LIGHT RELATIVE TO PUMP FIELD

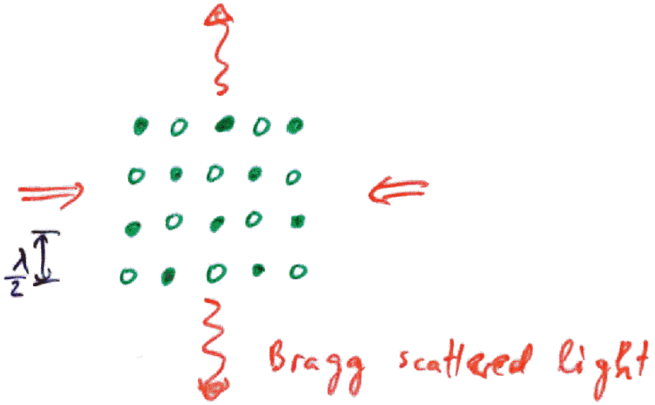
"SPONTANEOUS SYMMETRY BREAKING" IN ATOMIC SELF-ORGANIZATION



A. T. Black, H. W. Chan, and V. Vuletic,
PRL 91, 203001 (2003).

ATOMIC SELF-ORGANIZATION: DIFFUSION BETWEEN EVEN AND ODD LATTICES





COHERENT SCATTERING BY A SAMPLE

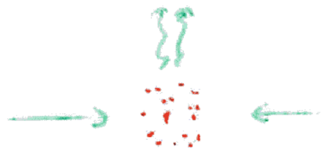
$|E_1|^2 = I_1$

SINGLE ATOM:

RAYLEIGH SCATTERING

(= BRAGG SCATTERING)

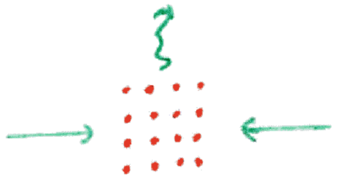
$|\sqrt{N}E_1|^2 = N|E_1|^2 = N I_1$



ATOMIC GAS:

RAYLEIGH SCATTERING

$|NE_1|^2 = N^2|E_1|^2 = N^2 I_1$

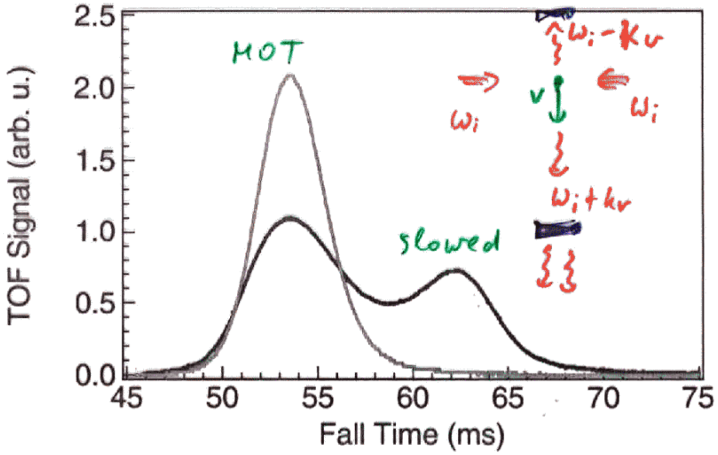


ATOMIC DENSITY

GRATING:

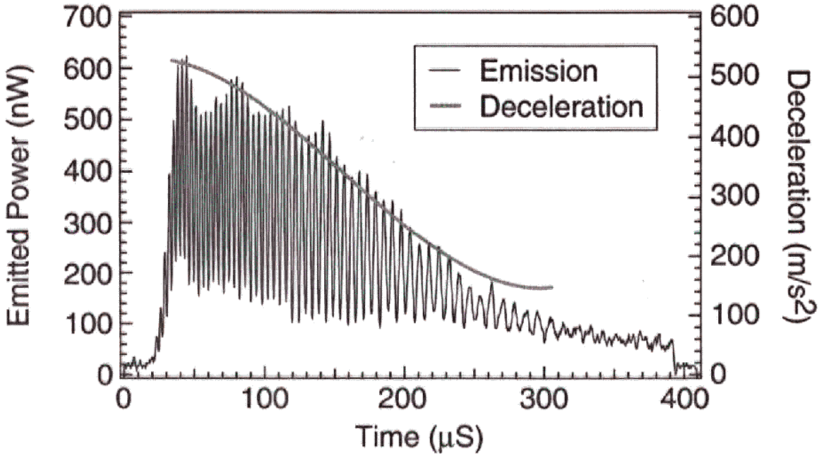
BRAGG SCATTERING

Cooling of center-of mass motion



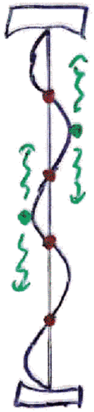
light-atom detuning

$\delta = -1.7$ GHz



For falling cloud, output light is amplitude modulated at $2\omega_D = 2kv$

SPATIAL VARIATION OF ATOM-CAVITY COUPLING



CAVITY EMISSION

- MAXIMUM AT ANTINODE
- ZERO AT NODE

MOVING ATOM $\Leftrightarrow$ AM OF CAVITY EMISSION AT $2kv$

ATOM AS REFRACTIVE INDEX

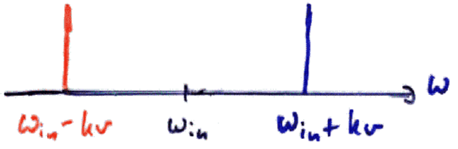
- MAXIMUM EFFECT AT ANTINODE
- NO EFFECT AT NODE

MOVING ATOM $\Leftrightarrow$ FM OF CAVITY (LIGHT) AT $2kv$

WHY COOLING OF CM MOTION?

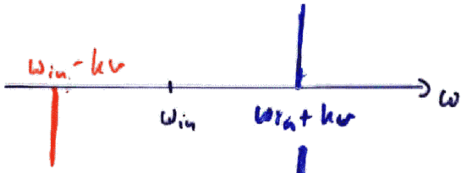
Cloud (scatterer) falling past $\frac{\lambda}{2}$ cavity lattice

$\Rightarrow$ AM at $2kv$



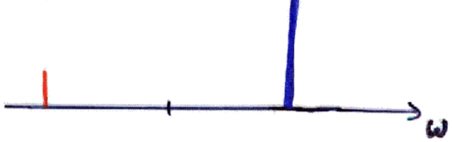
Cloud (refractive index) falling past $\frac{\lambda}{2}$ cavity lattice

$\Rightarrow$ FM at $2kv$



AM + FM

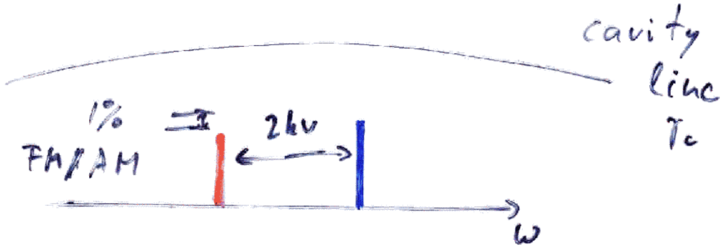
= single sideband modulation



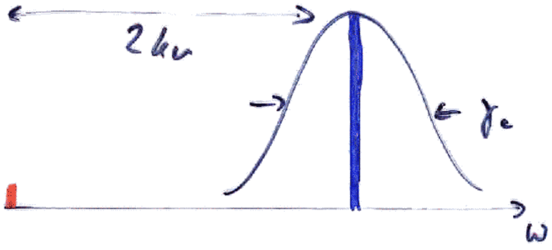
$\Rightarrow$ cooling for <u>any</u> red light-atom detuning

TOWARDS COOLING MOLECULES?

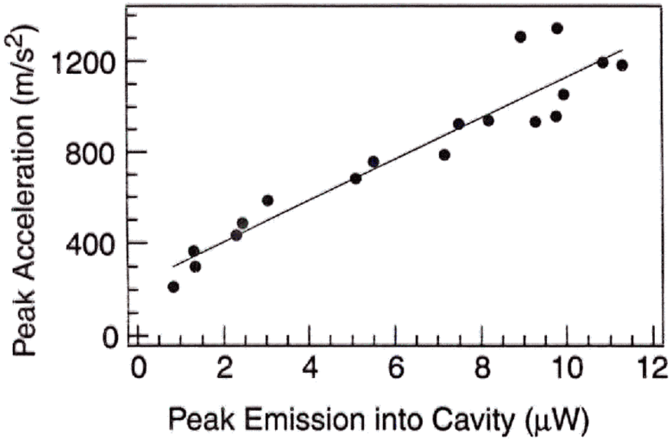
- observed large forces at only 1% sideband asymmetry



- expect much larger forces for resolved sidebands

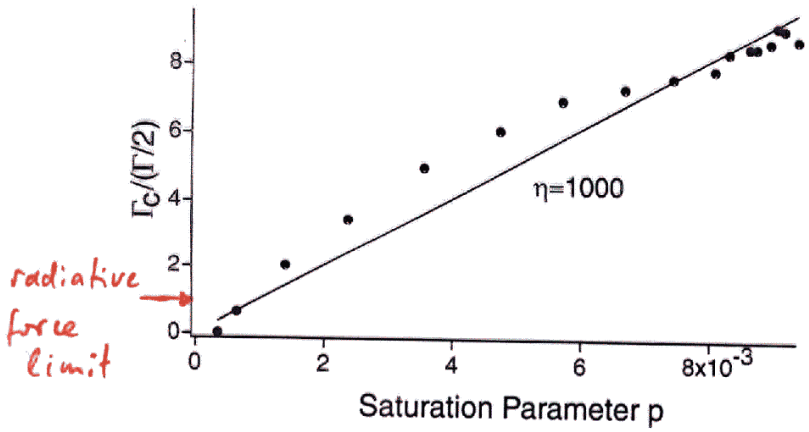


FORCE AND CAVITY EMISSION



LARGEST DECELERATIONS OBSERVED ~ 6000 m/s^2

SATURATION BEHAVIOR OF COLLECTIVE CAVITY EMISSION



Emission rate per atom Γ_c does not saturate at $\Gamma/2$

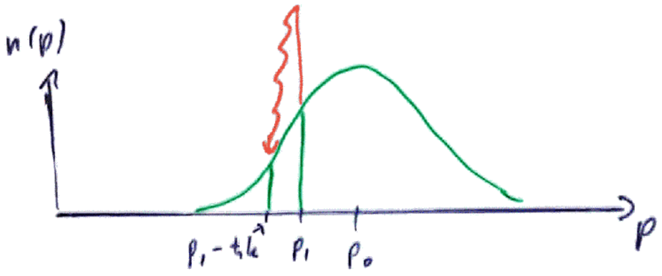
$\Rightarrow$ collective force can exceed maximum "radiative force" $F_{rad} = \hbar k \frac{\Gamma}{2}$

observed $F_{coll} > F_{Doppler}$ for given v

THRESHOLD CONDITION

COLLECTIVE FORCE LARGE ABOVE THRESHOLD, BUT WHAT IS THRESHOLD CONDITION?

Assumption: process initiated by recoil-induced gain



gain $\propto n(p) - n(p-\hbar k)$

gain = cavity loss $\Rightarrow$

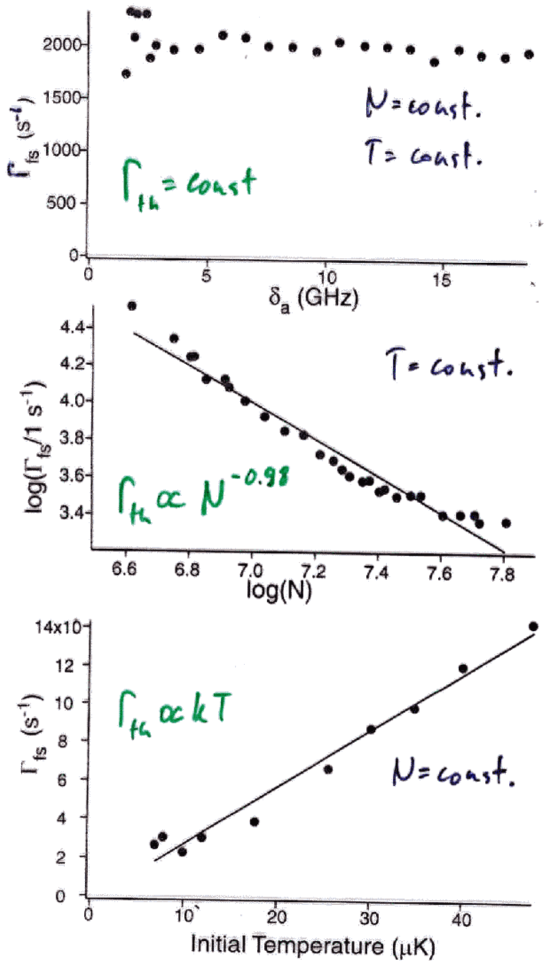
$$\Gamma_{fs,th} = \frac{1}{\sqrt{32\pi e}} \frac{kT}{\hbar} \frac{\ln N}{N \eta_s}$$

threshold condition

$\uparrow$ free-space scattering rate at threshold

$\uparrow$ single-atom cavity-to-free space ratio

SCALING LAWS FOR COLLECTIVE THRESHOLD



expected free-space scattering rate at threshold

$$\Gamma_{th} = C \frac{kT}{\hbar} \frac{\ln N}{N \eta_s}$$

η_s : single-atom cooperativity parameter

TOWARDS MOLECULES?

COLLECTIVE DECELERATION VERY LARGE ($6000 \frac{m}{s^2}$ AT 1% EMISSION SIDEBAND ASYMMETRY) AND CAN BE INCREASED FURTHER.

DIFFICULTY LIES IN REACHING THRESHOLD.

$$\Gamma_{sc,th} = \frac{kT}{\hbar} \frac{1}{N\eta}$$

THRESHOLD SINGLE-ATOM SCATTERING RATE

ATOM NUMBER

CAVITY RATIO

FOR $\eta = 0.1$, $N = 2 \cdot 10^7$

$$\Gamma_{sc} = 10^4 s^{-1} \cdot \left(\frac{T}{1K}\right)$$

SUMMARY

- AT SUFFICIENTLY LARGE INTENSITY AN ATOMIC ENSEMBLE SELF-ORGANIZES INTO A DENSITY GRATING

  RAYLEIGH SCATTERING ⇒ BRAGG SCATTERING

- FOR $Re(n) > 0$ $(n>1)$ BRAGG SCATTERING RESULTS IN STRONG FRICTION FORCE ACTING ON SAMPLE'S CM MOTION

- STOPPING A MOLECULAR BEAM?