SynQS

1st day: How to go ultracold

Trento Summer school

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Overview

Why go for ultracold ?

see also the talk by Bill Philipps called
‚Einstein, time and the coolest stuff in the Universe‘

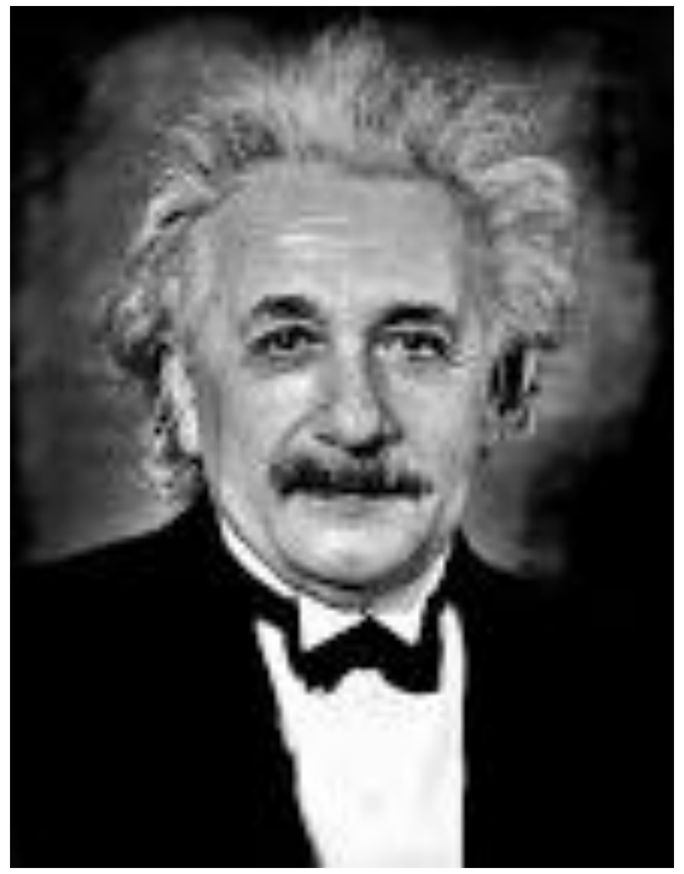
The first step: Getting ultracold by laser cooling

The second step: Get degeneracy by collisions

Good reads

- **Lecture notes on AMO physics** by *Mikhail Lukin*
- **Making, probing understanding Bose-Einstein condensates** by *W. Ketterle*
- **Laser cooling and trapping** by *Metcalf and van der Straten*
- **Theory of Bose-Einstein condensation in trapped gases** by *Dalfovo et al.*
- **Bose-Einstein condensation in dilute gases** by *Pethick and Smith*

What is time ?



Einsteins' special relativity:

Time is what a clock measures.

Experimentalists dilemma: What is a clock ?

Something that ‚ticks', i.e. provides a regular series of events

Traditional clocks

1 tick = 1 day

1 tick = few seconds

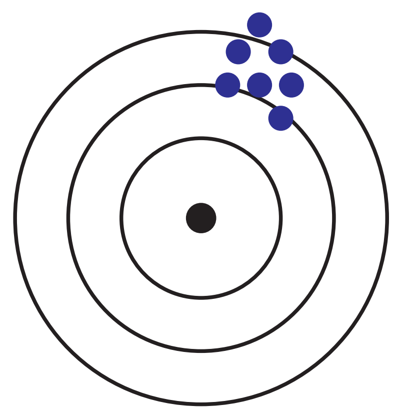
1 tick = 0.1 ms

<u>Problems:</u>

- Not very stable
- Very slow ticking
- Reproducility

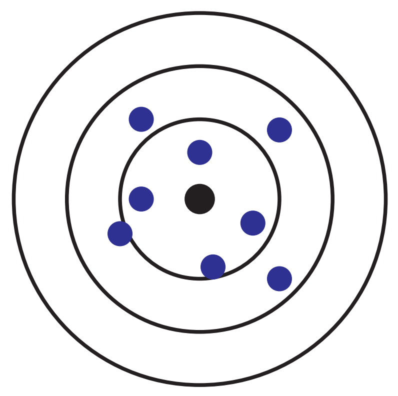
What is a good clock ?

Stable



repeat with the same clock lots of
measurements and get similar results

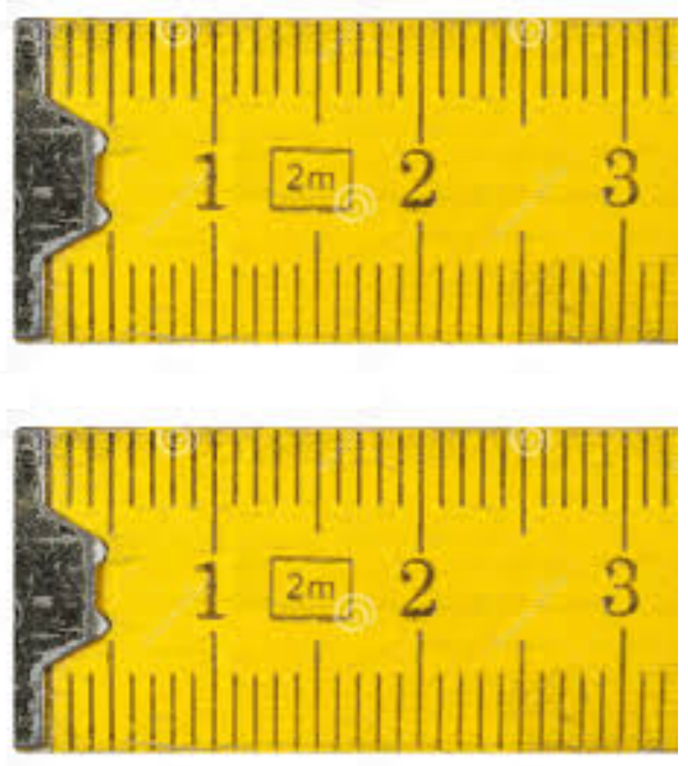
Precise

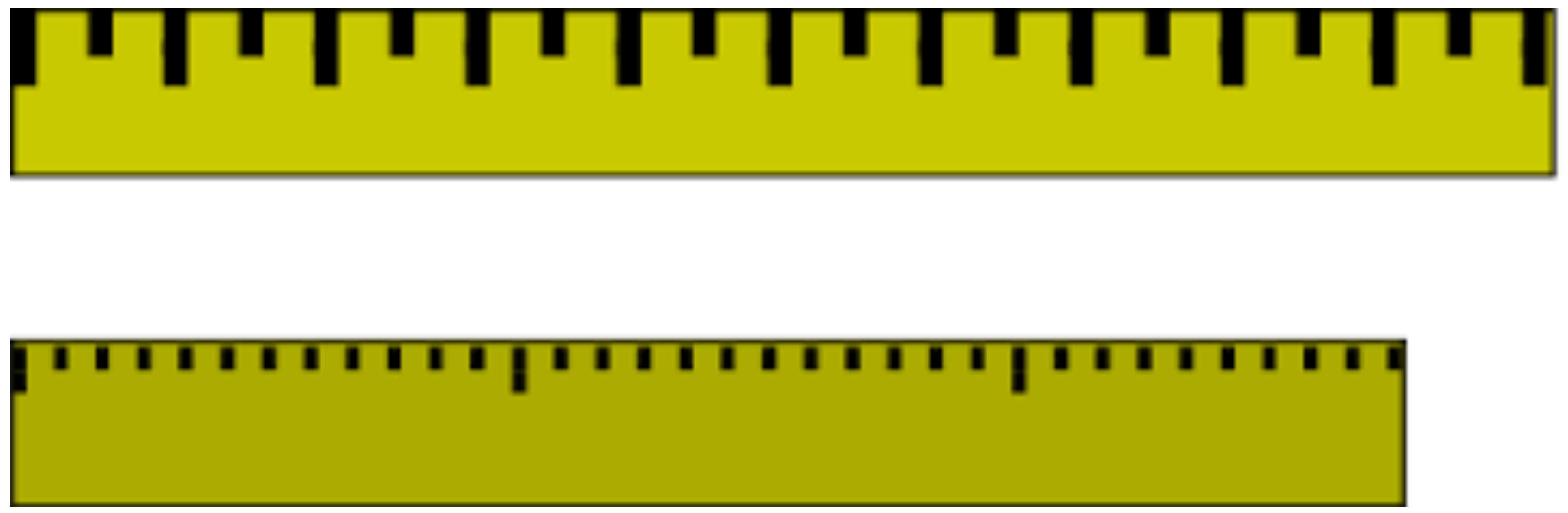


build several clocks
and obtain same results

most of the time much, much
harder to estimate

Characterization of clocks





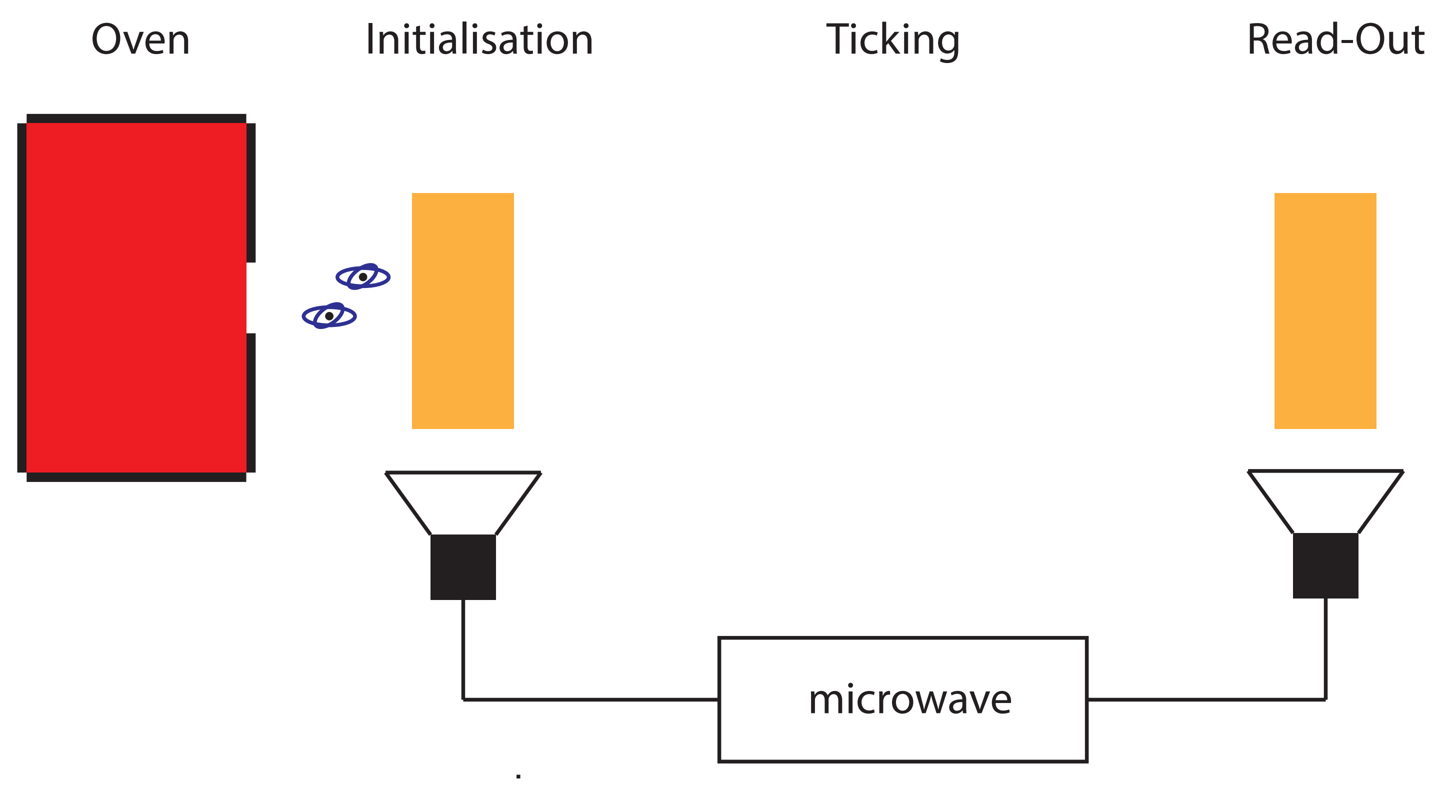
let them tick for a long time

compare the result

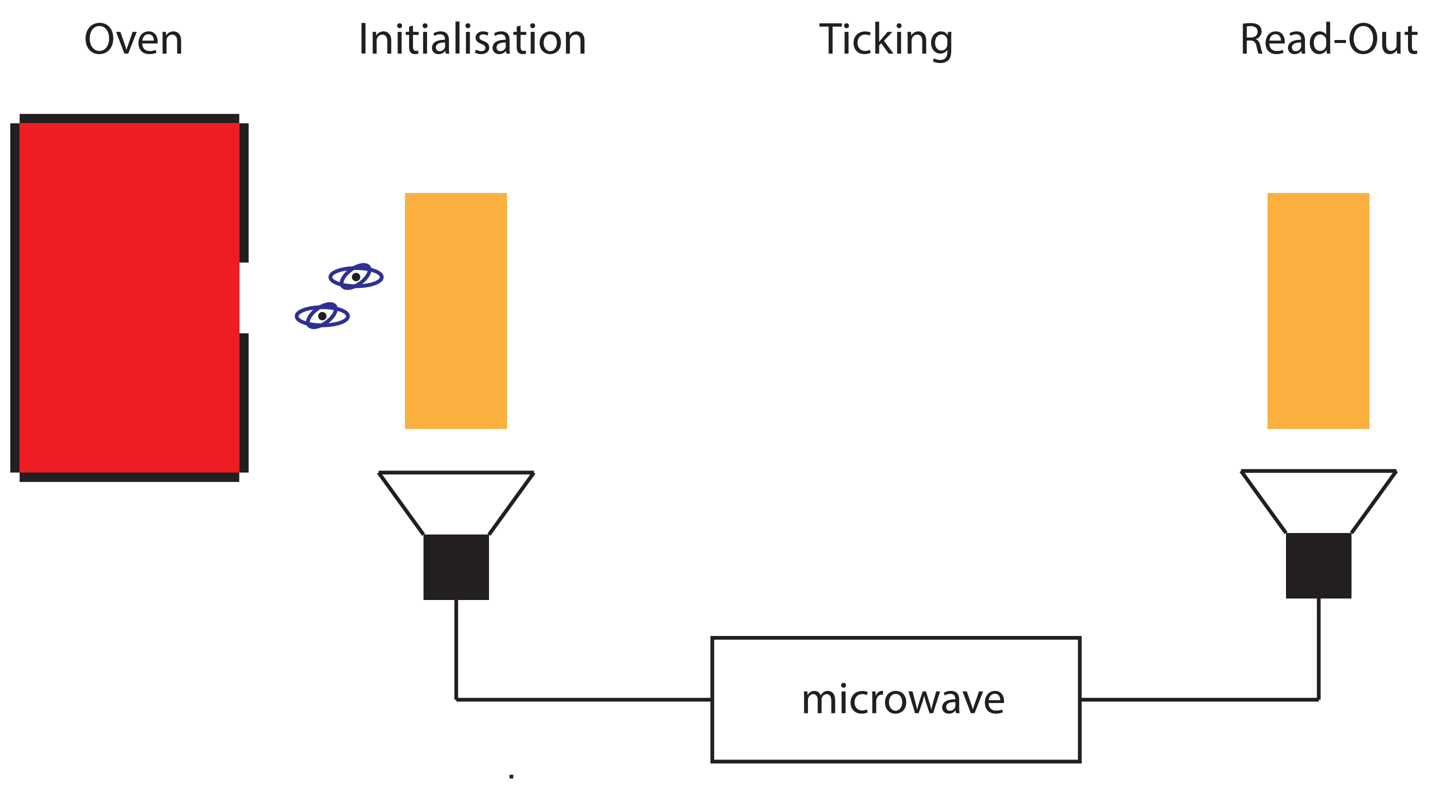
What about precision?

We need a good standard and atoms give this

Atomic clocks



Atom-light interaction



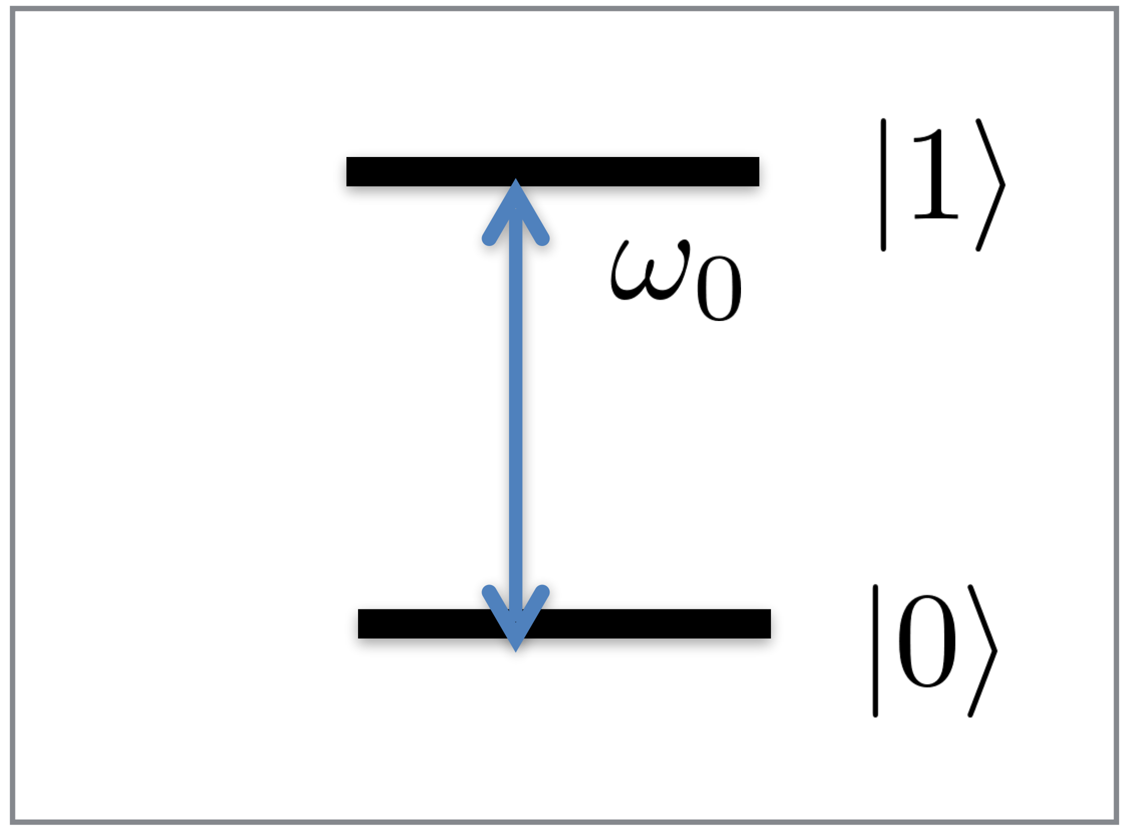
The Atom

(see notes)

The electric field

$$\mathcal{H} = E_0 \left|0\right\rangle \left\langle 0\right| + E_1 \left|1\right\rangle \left\langle 1\right|$$

$$\mathbf{E} = E(\mathrm{e}^{\mathrm{i}\omega t + \mathrm{i}\varphi} + \mathrm{e}^{-\mathrm{i}\omega t - \mathrm{i}\varphi})$$



Interaction via

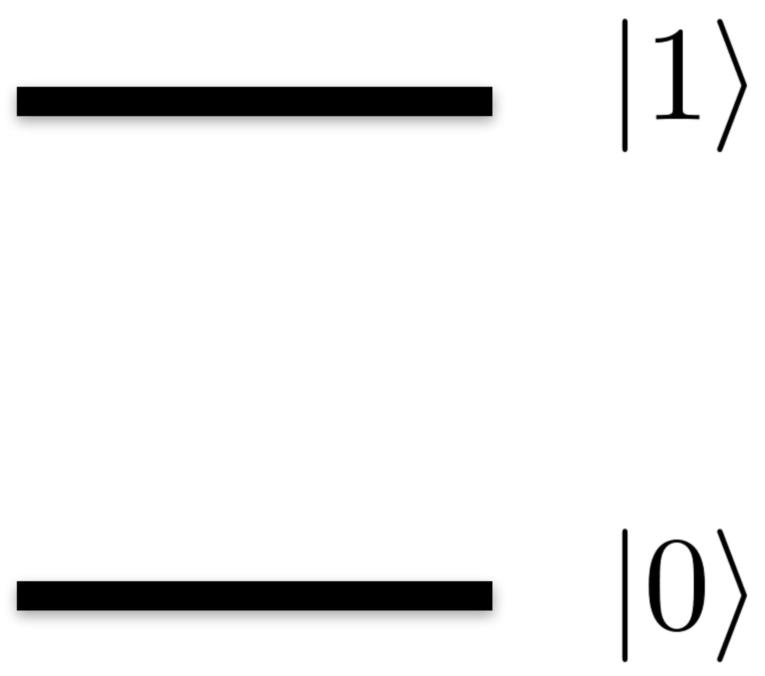
$$\mathcal{H} = -\mathbf{d}\cdot\mathbf{E}$$

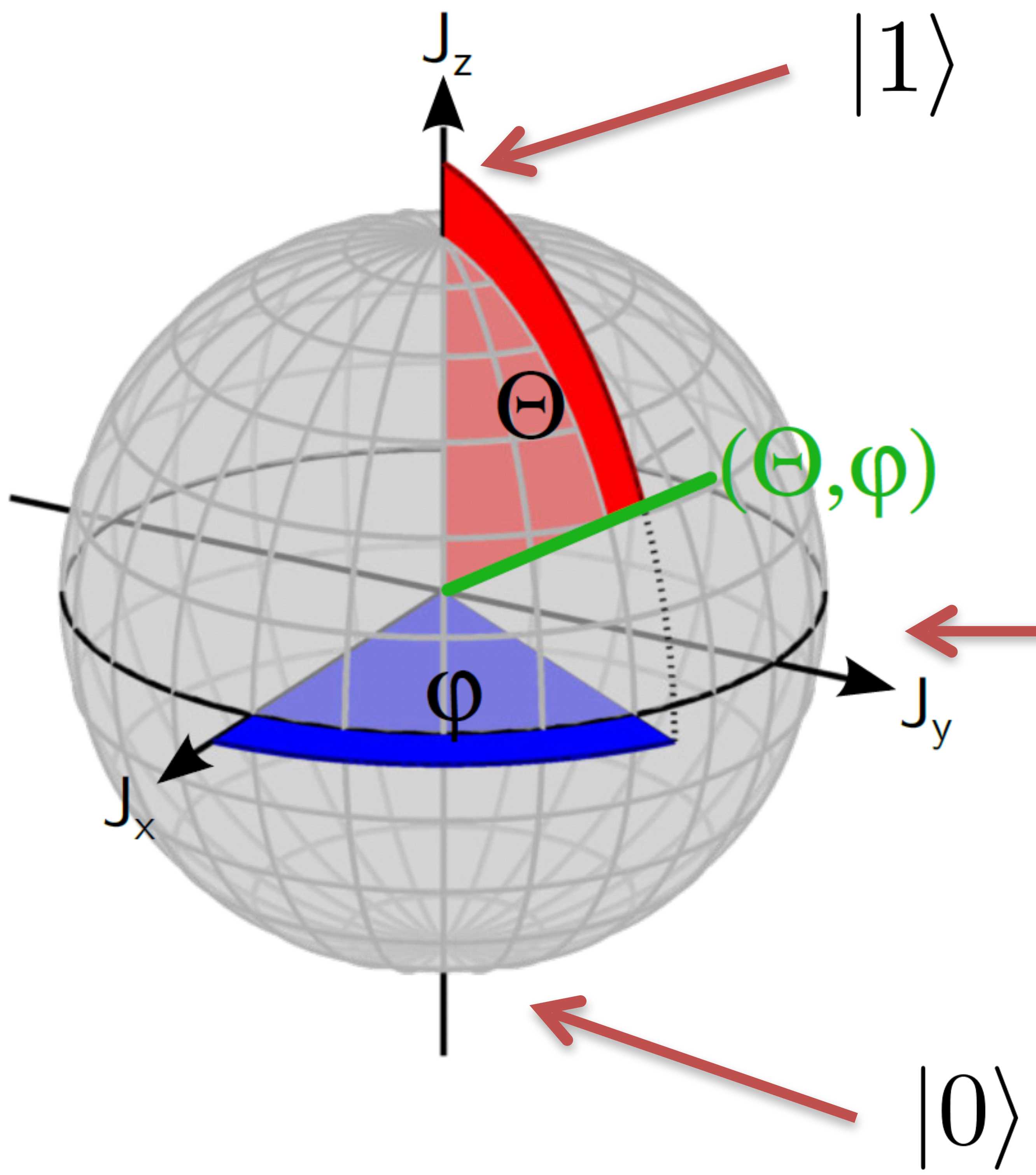
$$\mathbf{d} = d\left(|0\rangle\langle 1| + |1\rangle\langle 0|\right)$$

Two-level system: Bloch-sphere representation

Any two-level system can be mapped onto a spin 1/2 system

$$|\Psi(\Theta,\phi)\rangle = \sin\frac{\Theta}{2}\,|0\rangle + \cos\frac{\Theta}{2}\mathrm{e}^{\mathrm{i}\varphi}\,|1\rangle$$





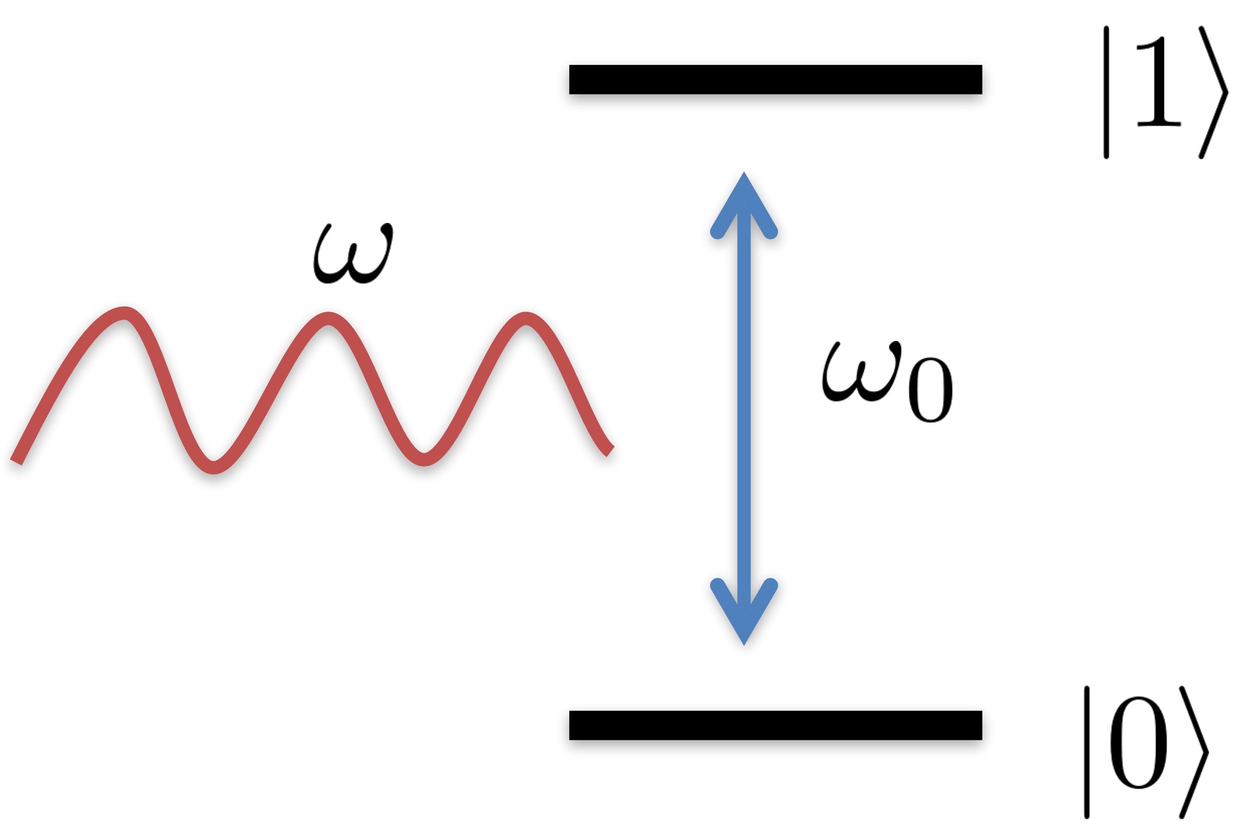
$$\sim |0\rangle + \mathrm{e}^{\mathrm{i}\phi}\,|1\rangle$$

equal superposition

Summary: Rotations on Bloch sphere

Detuning = **Rotation** about z-axis

$$\mathcal{H} \sim \hbar\Delta\sigma_z$$



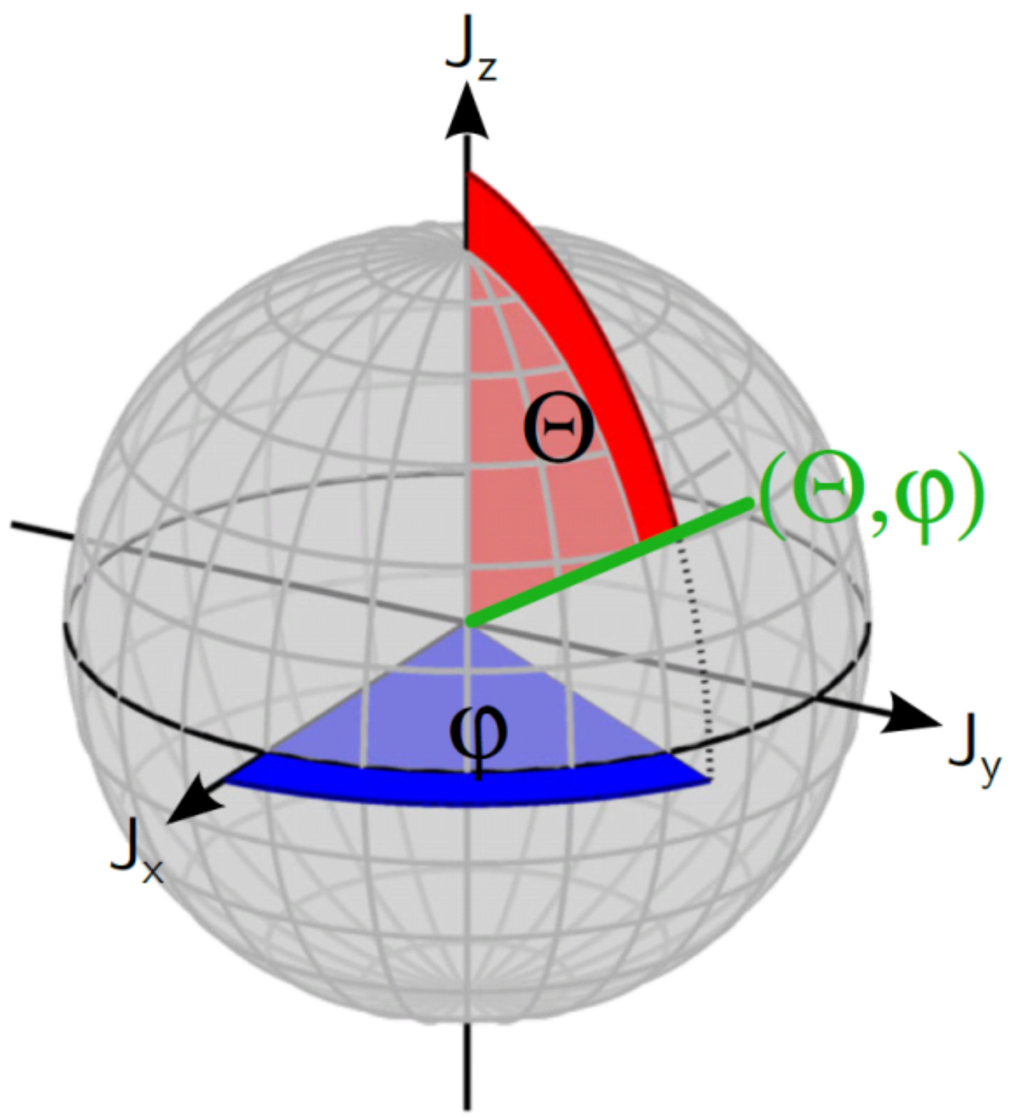
Phase of coupling = **Rotation** about x- or y-axis

$$\mathcal{H} \sim \hbar\Omega\sigma_x$$

Rotation about x-axis

$$\mathcal{H} \sim \hbar\Omega\sigma_y$$

Rotation about y-axis



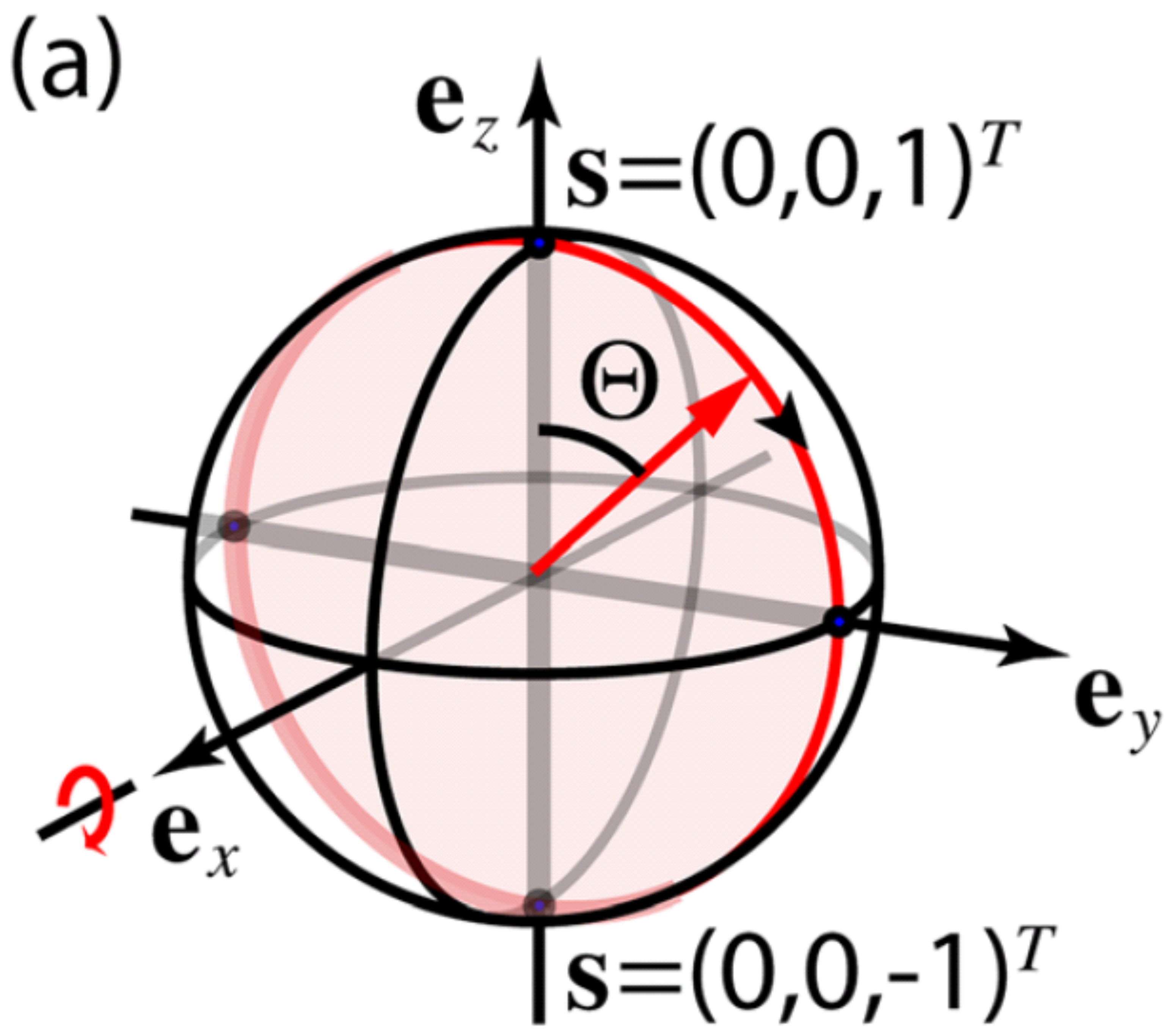
Example: Rabi oscillations

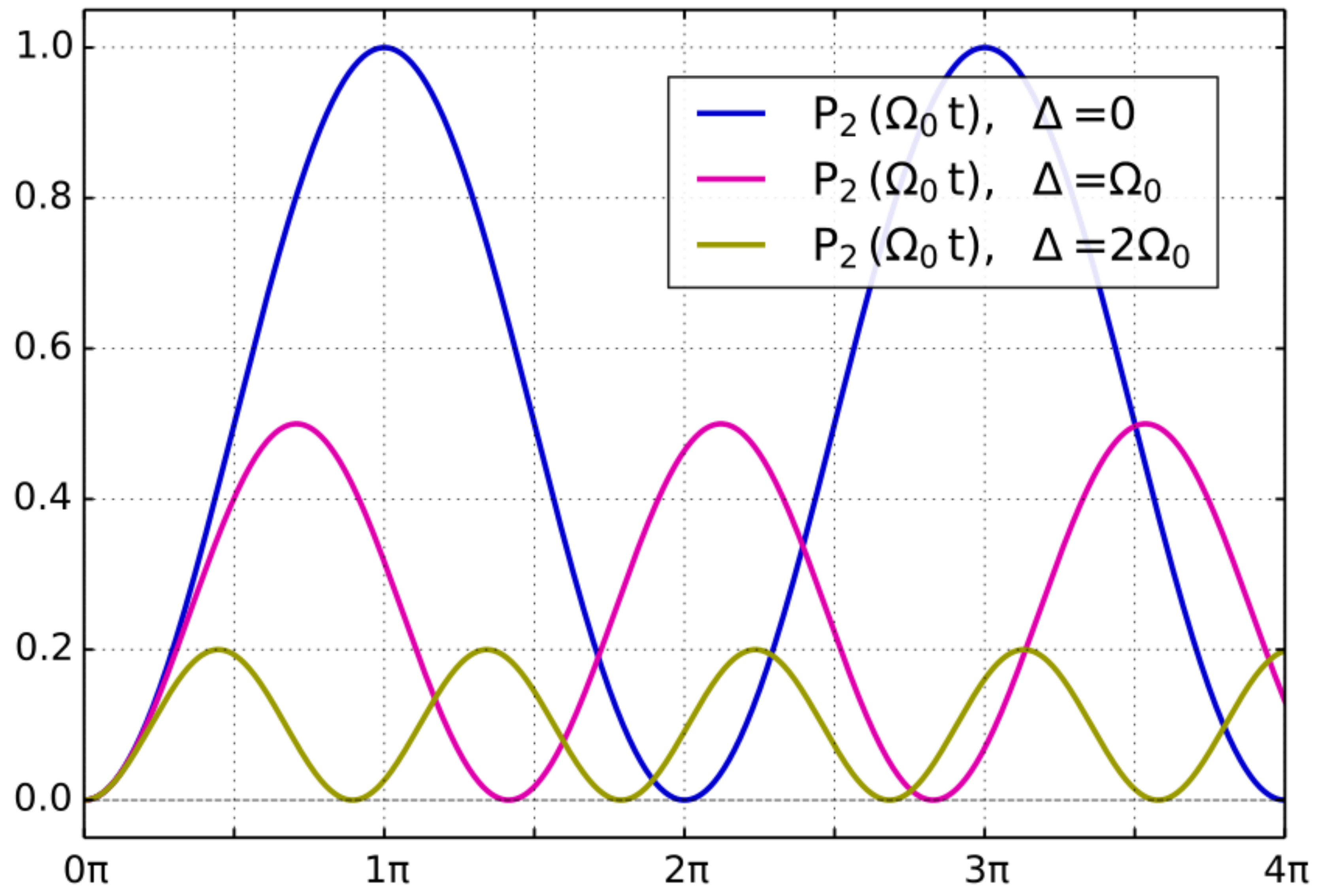
$\mathcal{H} = \hbar\Omega S_x$

(see notes)

time evolution: $\mathrm{e}^{\mathrm{i}\Omega\sigma_x t}$

Rotation about **x-axis** angle $\Theta = \Omega t$





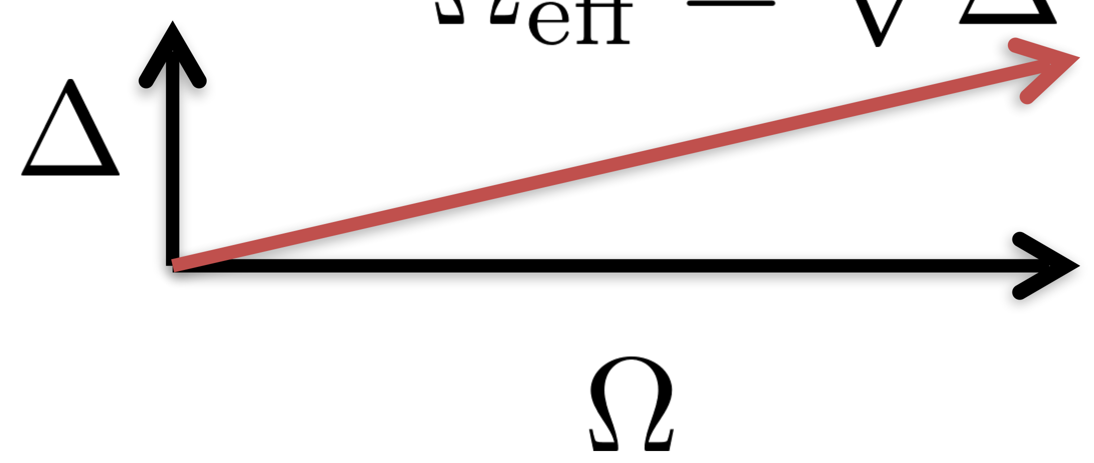
Example: Offresonant Rabi oscillations

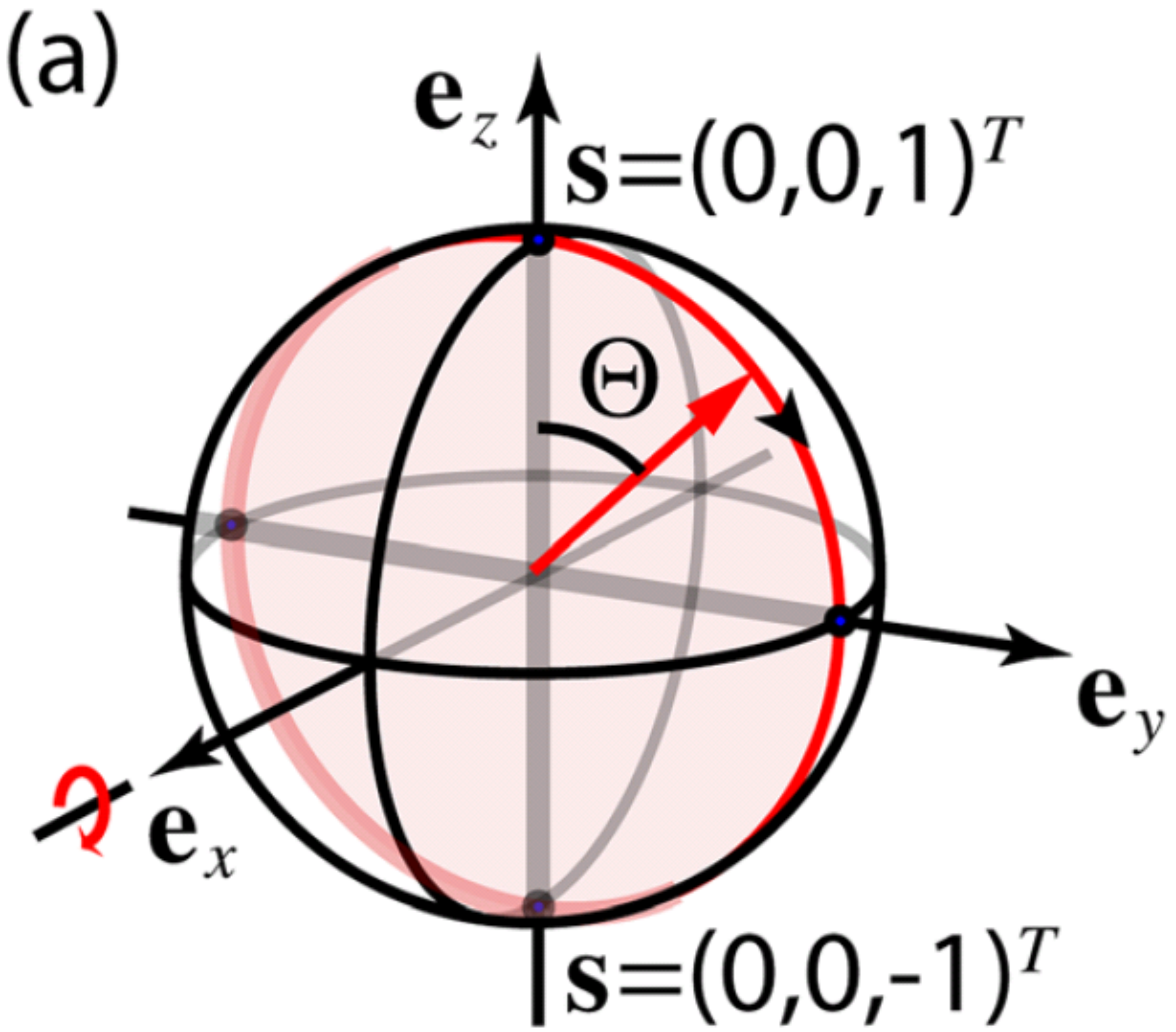
$$\mathcal{H} = \hbar\Omega S_x + \hbar\Delta S_z$$

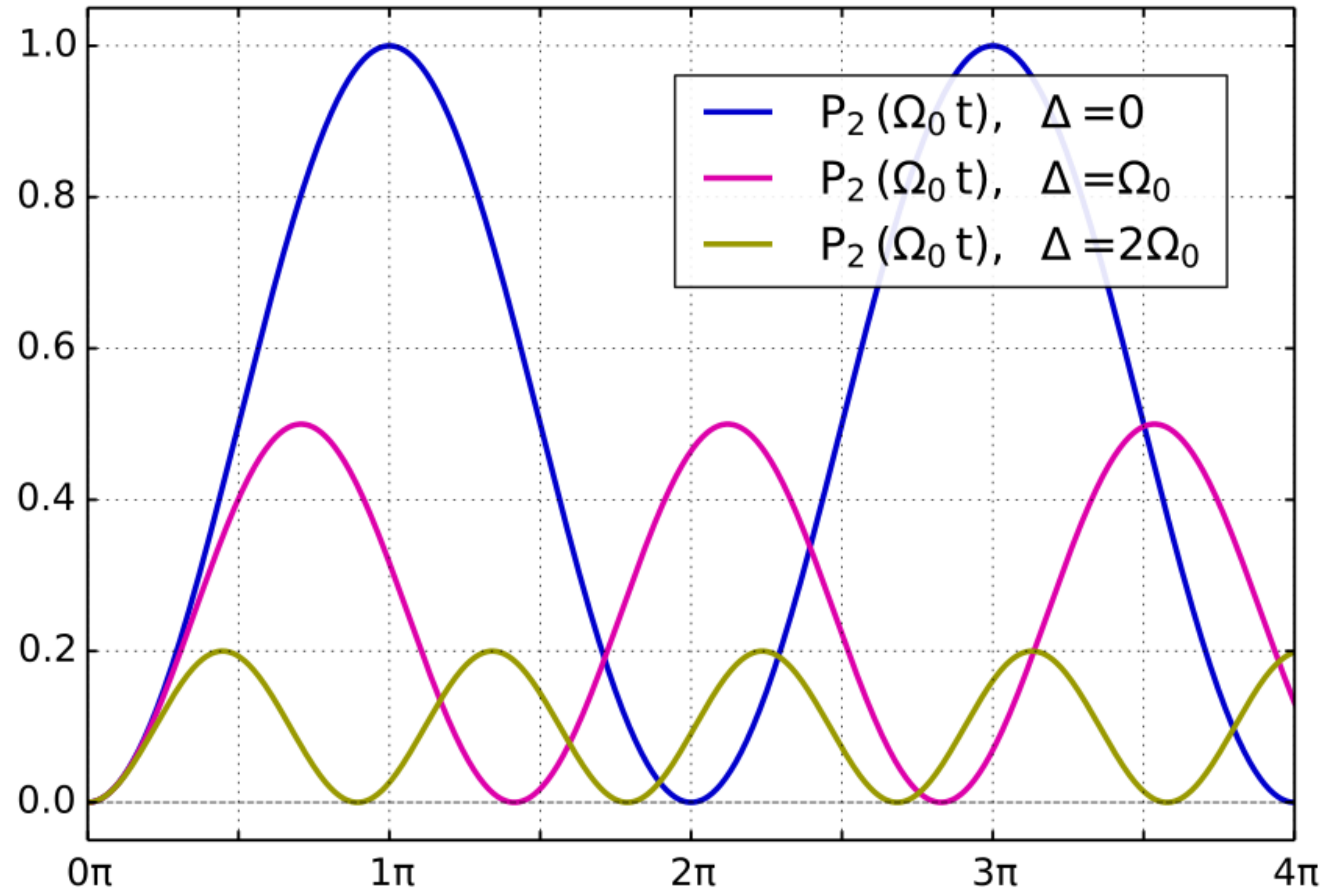
detuning

tilted rotation axis $J = \begin{pmatrix} \Omega \\ 0 \\ \Delta \end{pmatrix}$

$$\Omega_{\text{eff}} = \sqrt{\Delta^2 + \Omega^2}$$



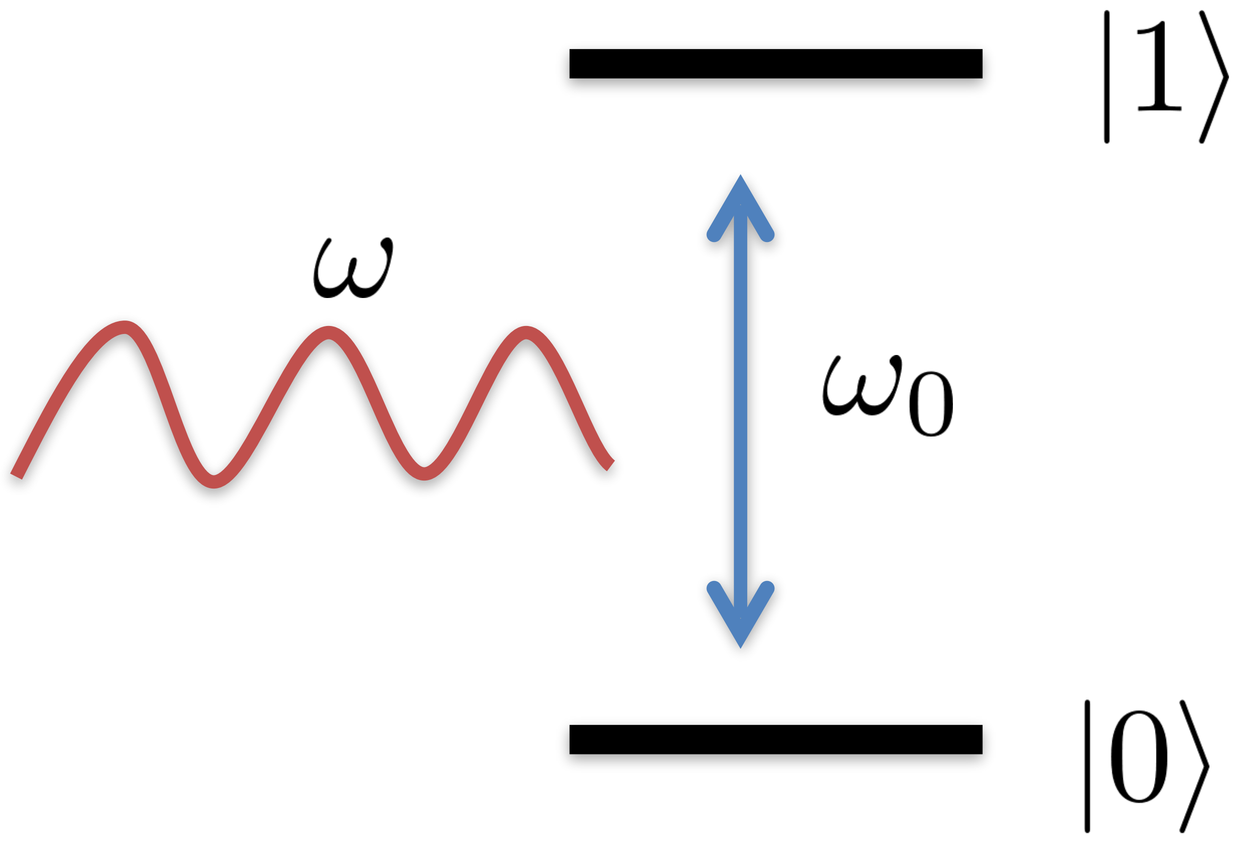




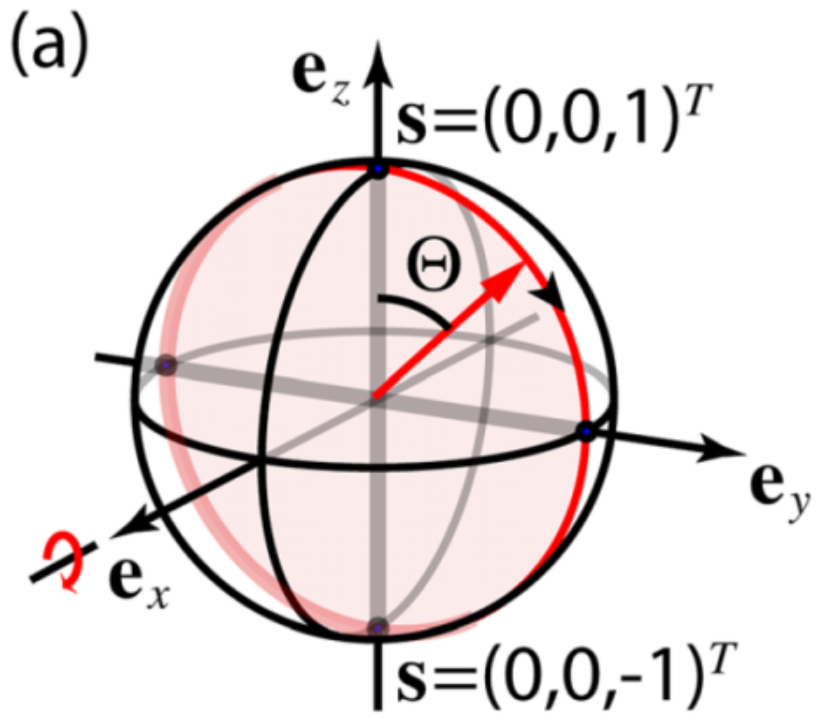
How to measure a detuning?

Want to measure detuning of radiation and atomic resonance

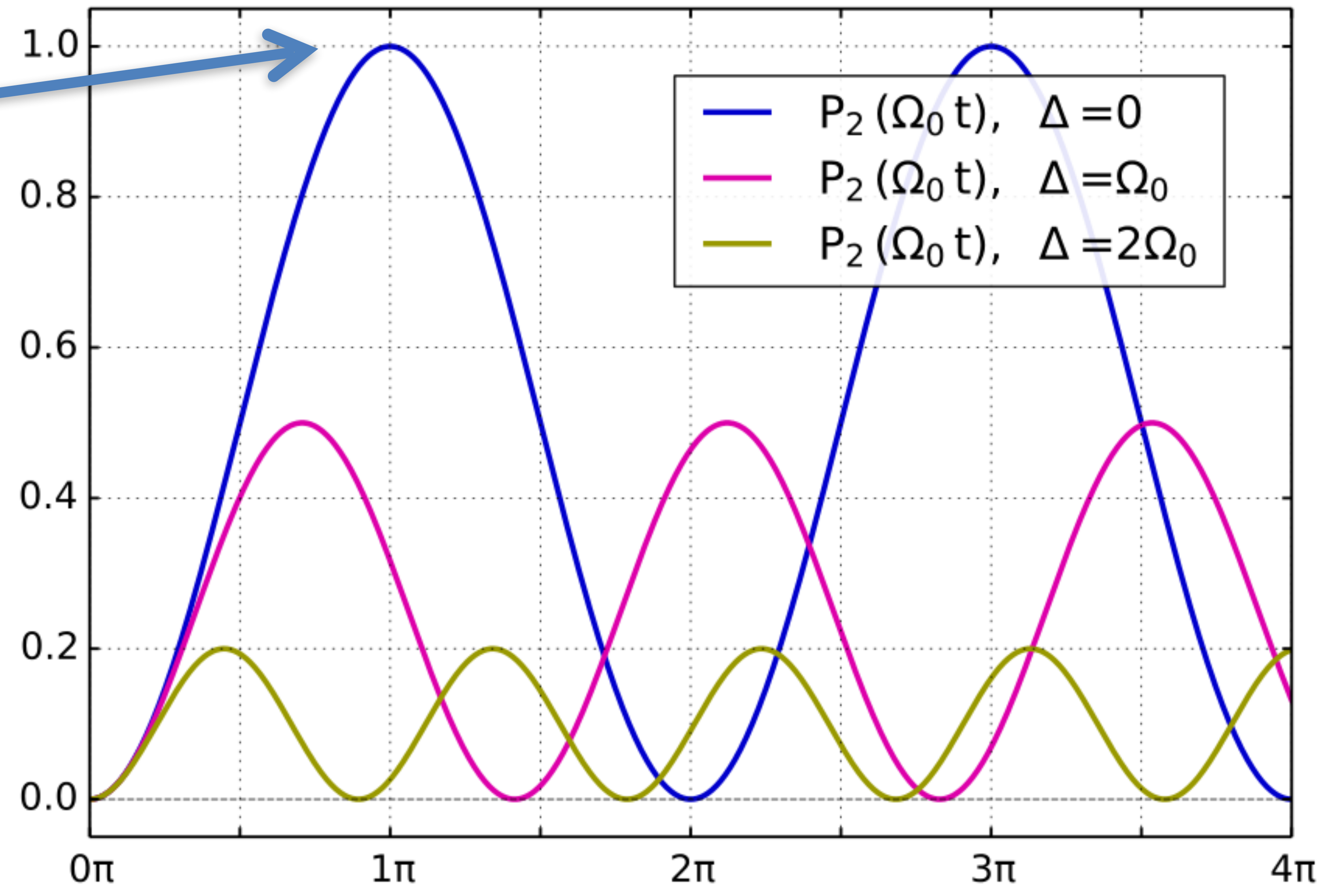
$$\mathcal{H} = \hbar\Delta S_z + \hbar\Omega S_x$$



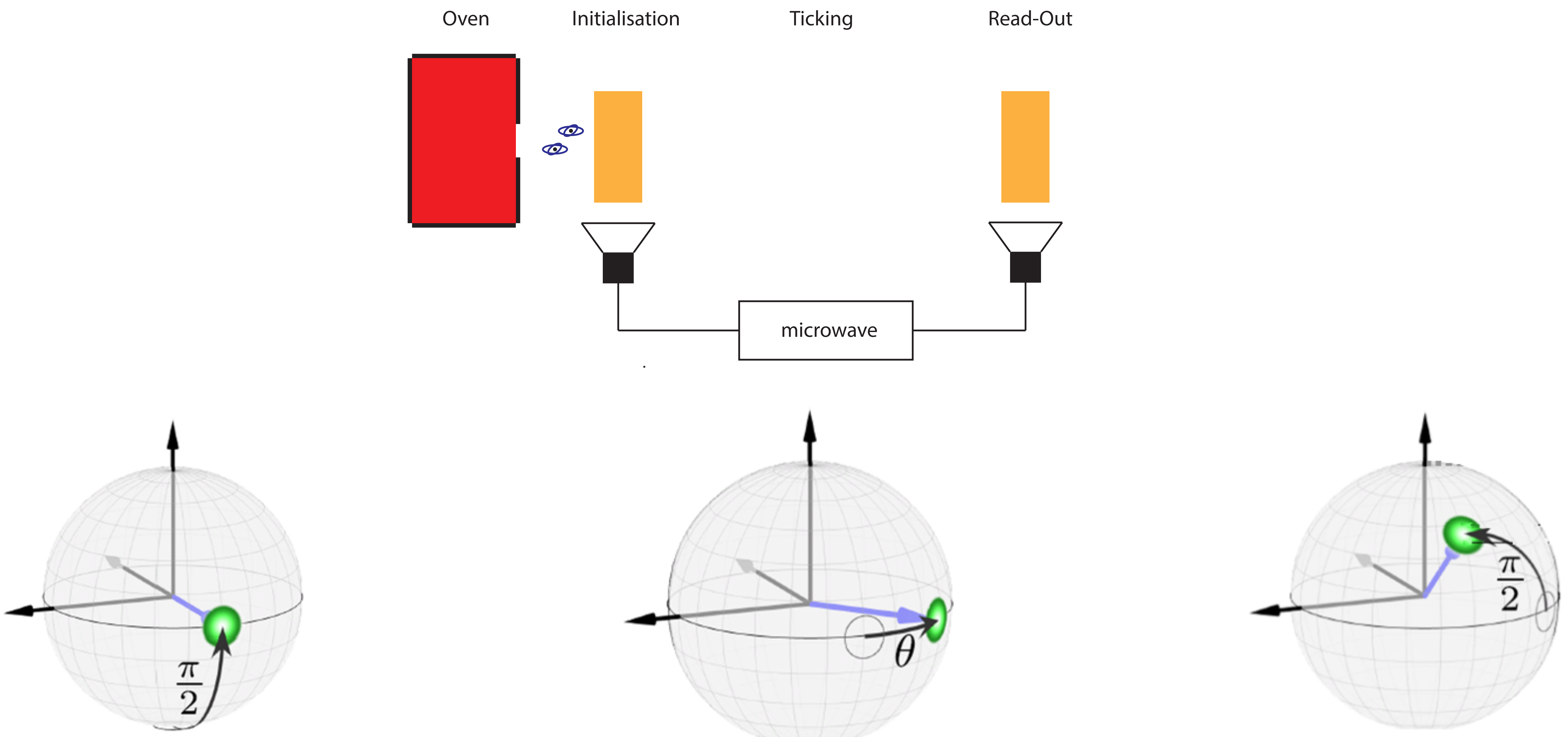
$$\frac{\Omega^2}{\Omega_{\text{eff}}^2}\sin^2\Omega_{\text{eff}}t$$



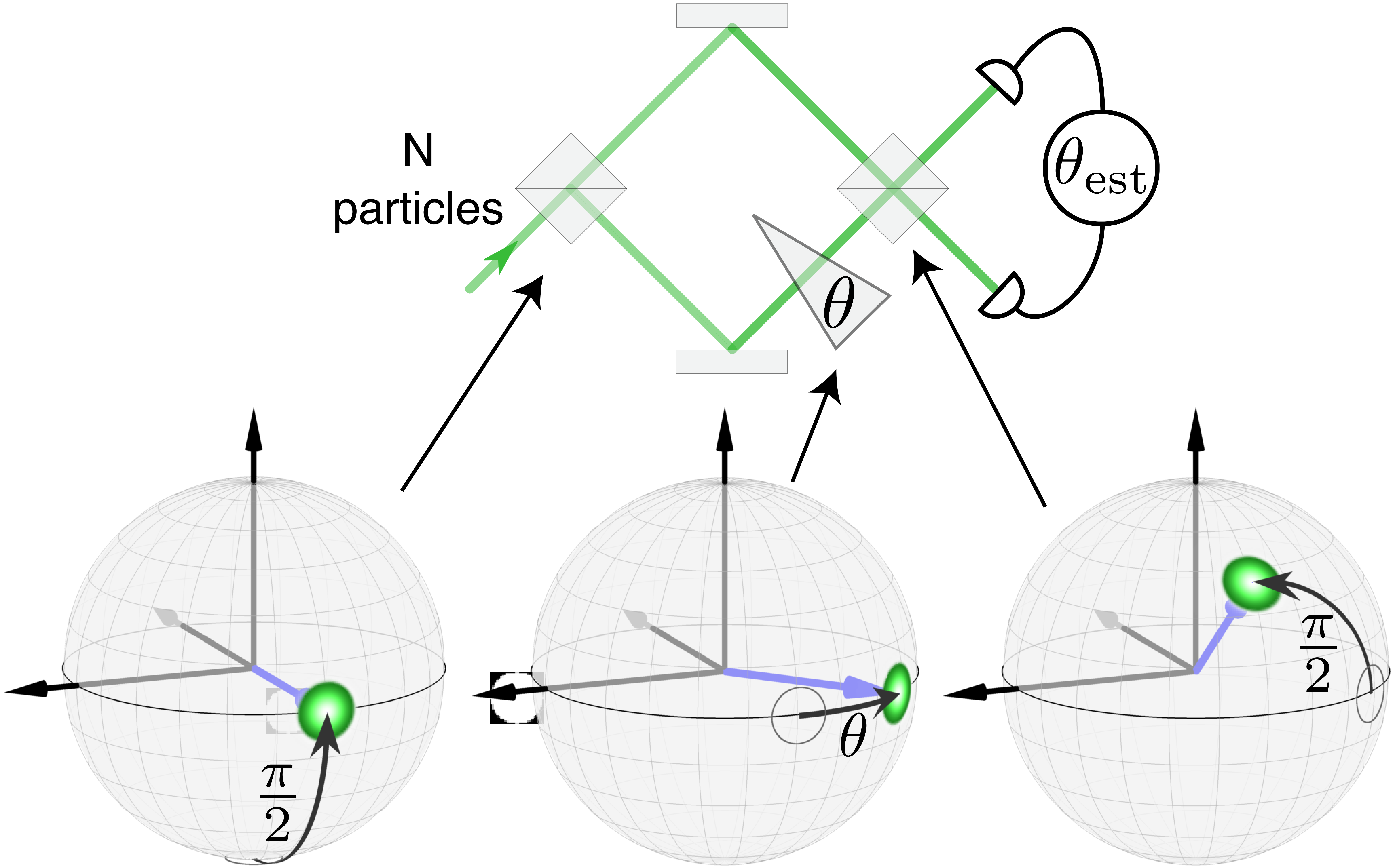
$$\frac{\Omega^2}{(\Omega+\Delta)^2}\sin^2\Omega_{\text{eff}}t$$



Back to our atomic clocks

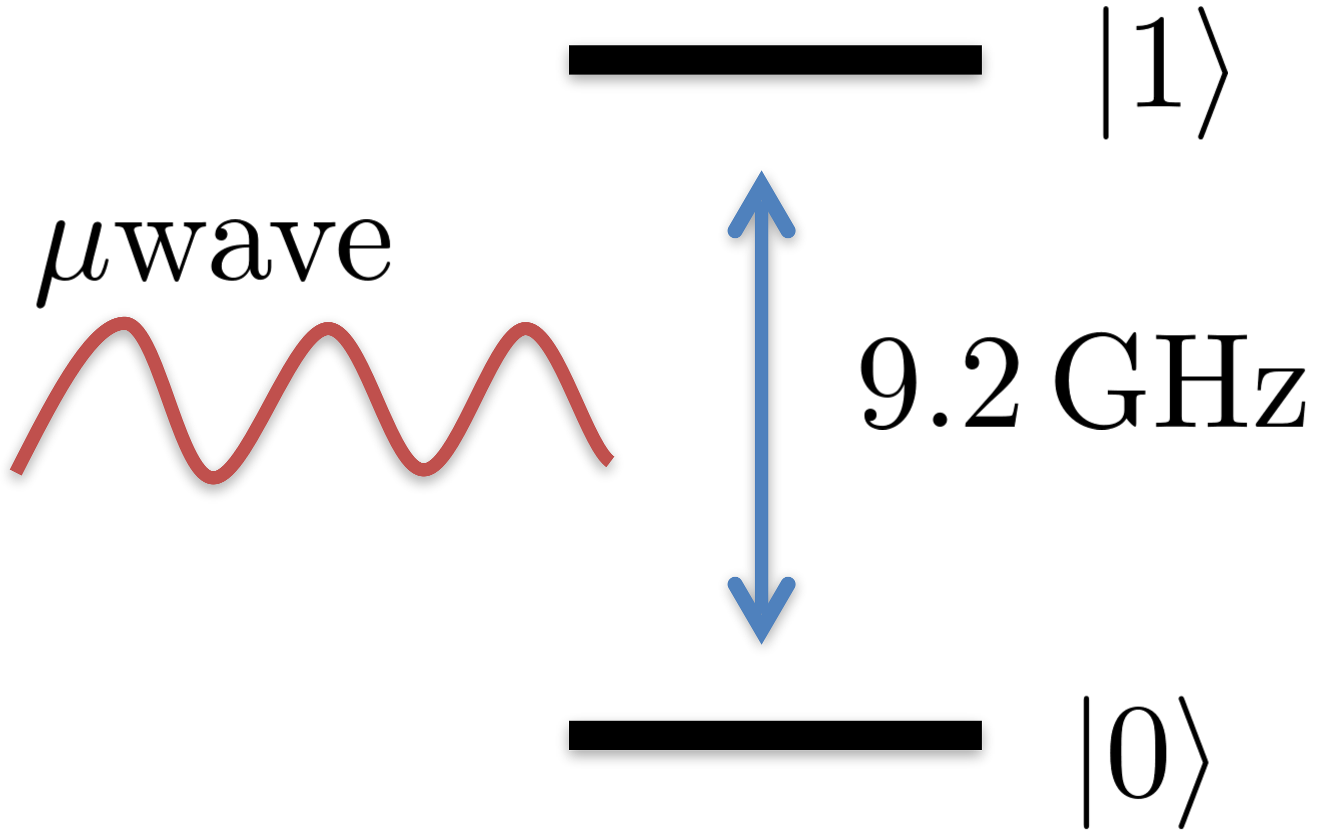


Ramsey sequence



Application: Time standard with Cesium fountain clock

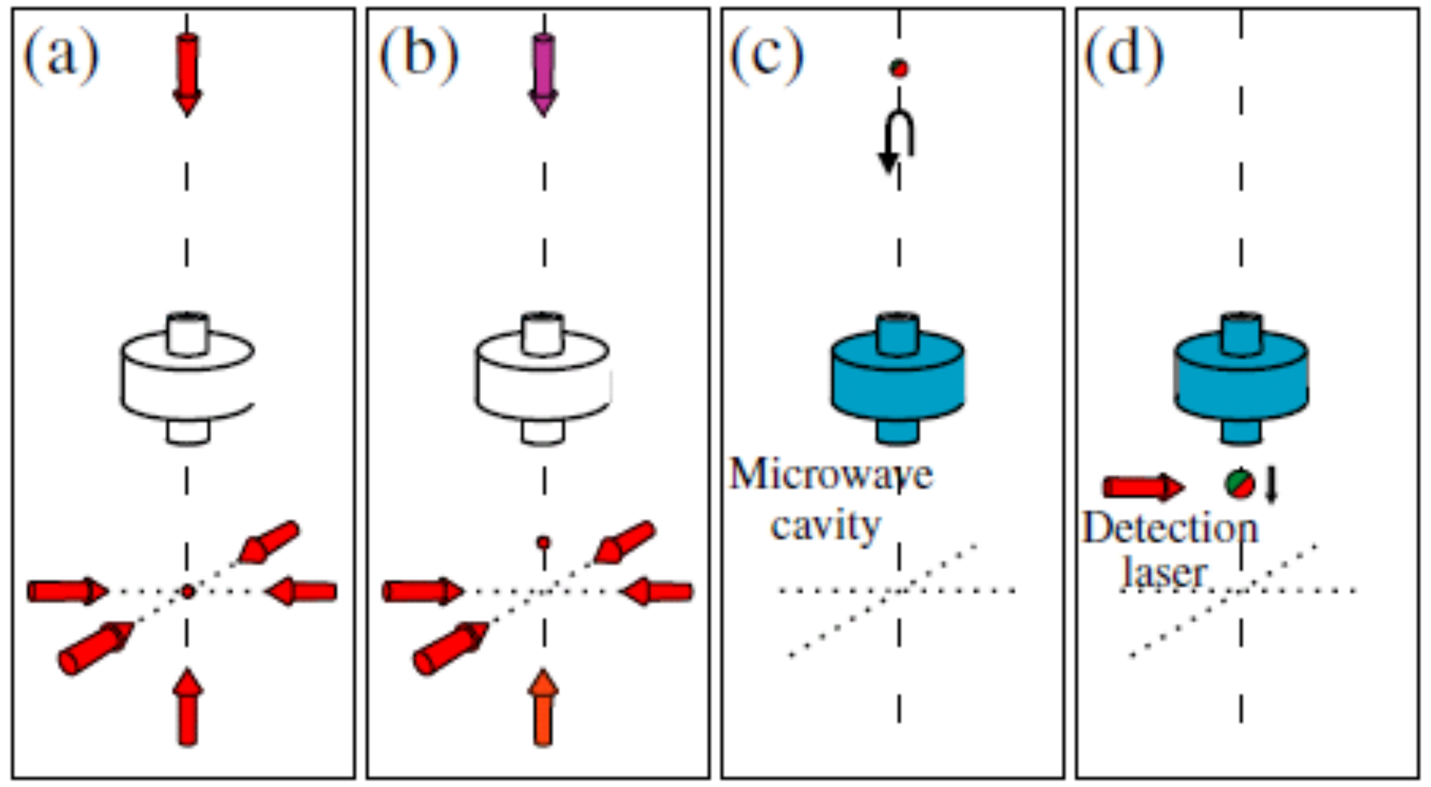
^{133}Cs: Hyperfine splitting 9.2 GHz

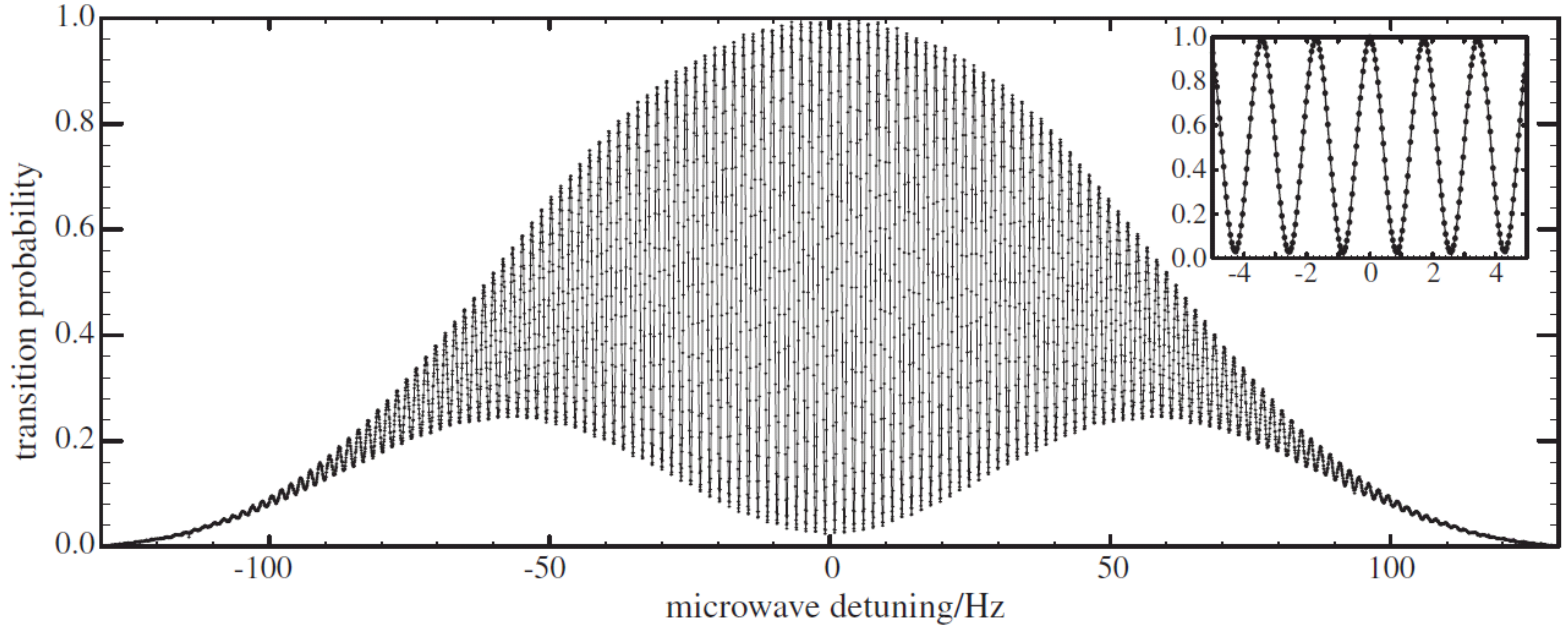


$$\text{envelope } \times \cos \Delta E t/\hbar$$

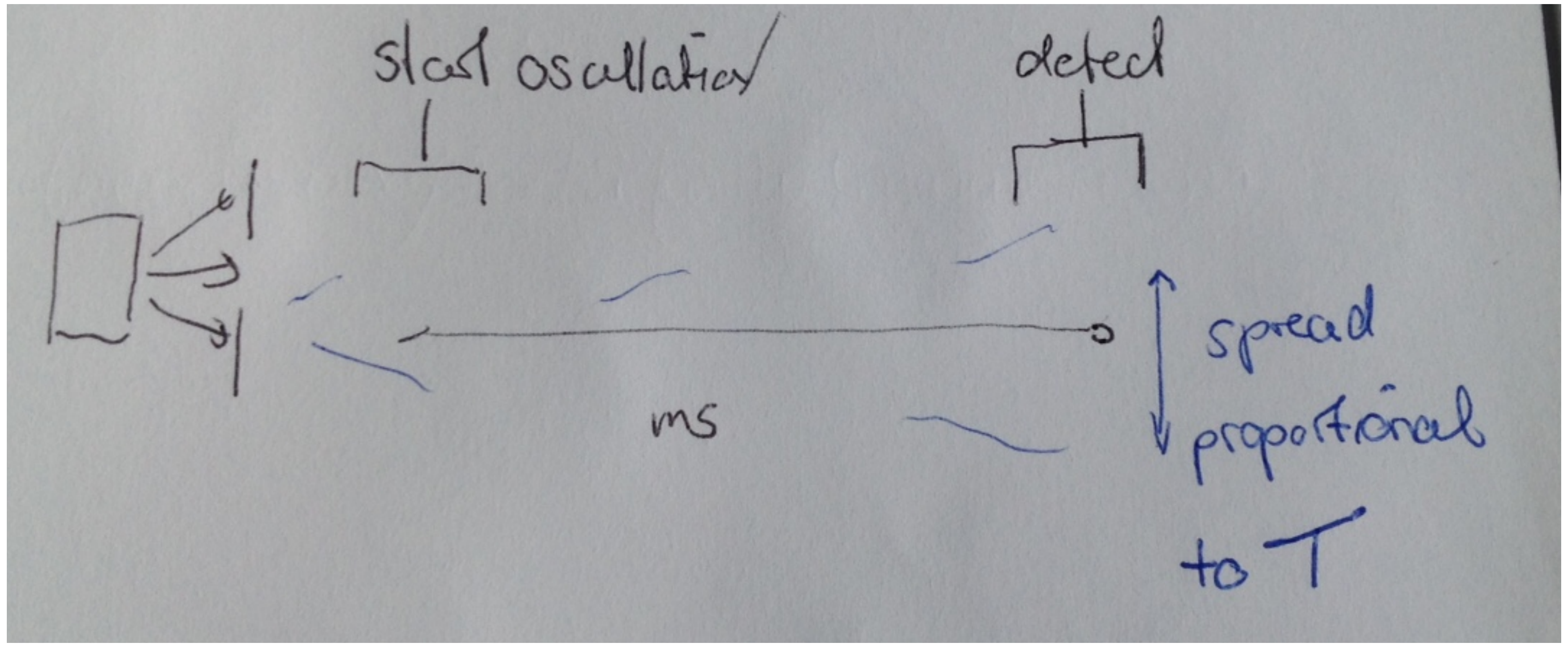
$$\Delta\omega \times \Delta t \geq 1$$

$$\rightarrow \text{precision: } \frac{\Delta\omega}{\omega} \times \frac{1}{\sqrt{N}} \approx 10^{-13}$$





Ramsey limitations

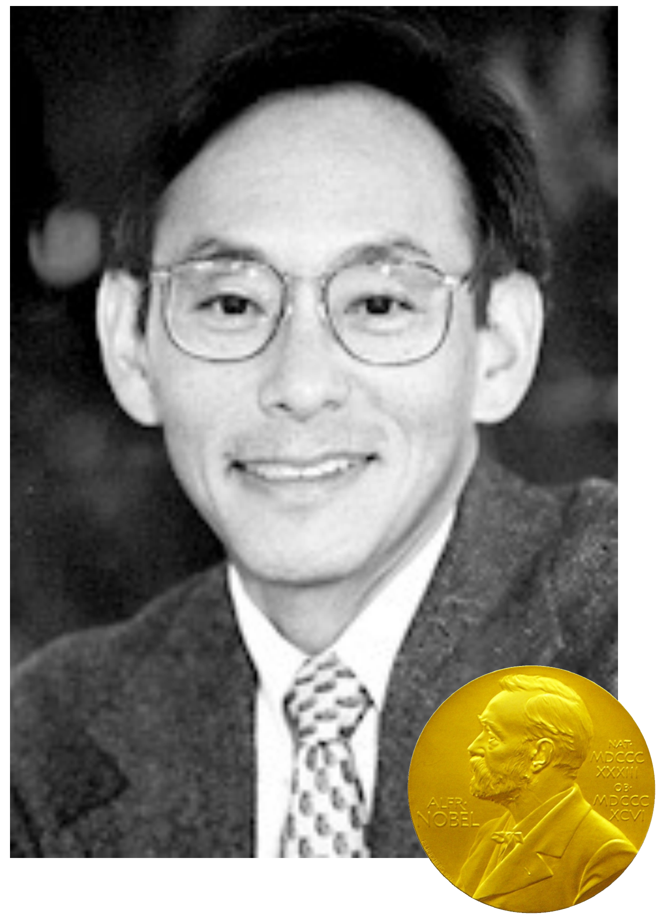


Detection better if atoms are slower

Overview

Why go for ultracold ?

The first step: Getting ultracold by laser cooling



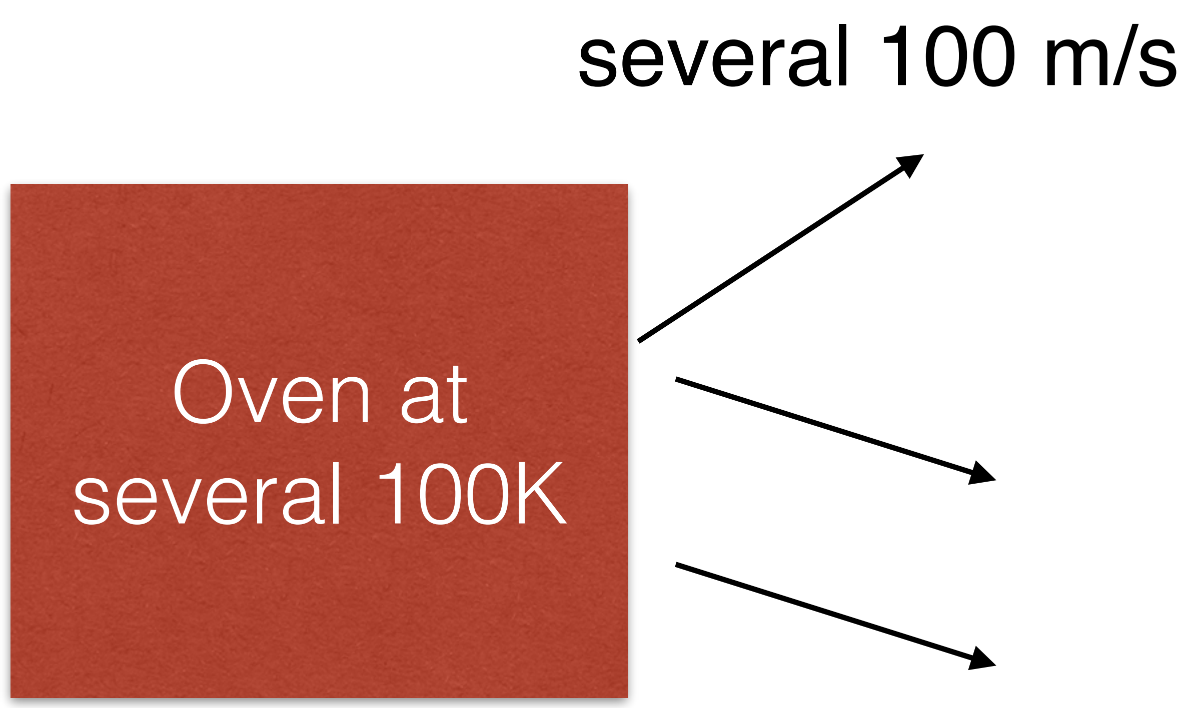
Steven Chu

William Phillips

Claude Cohen-Tannoudji

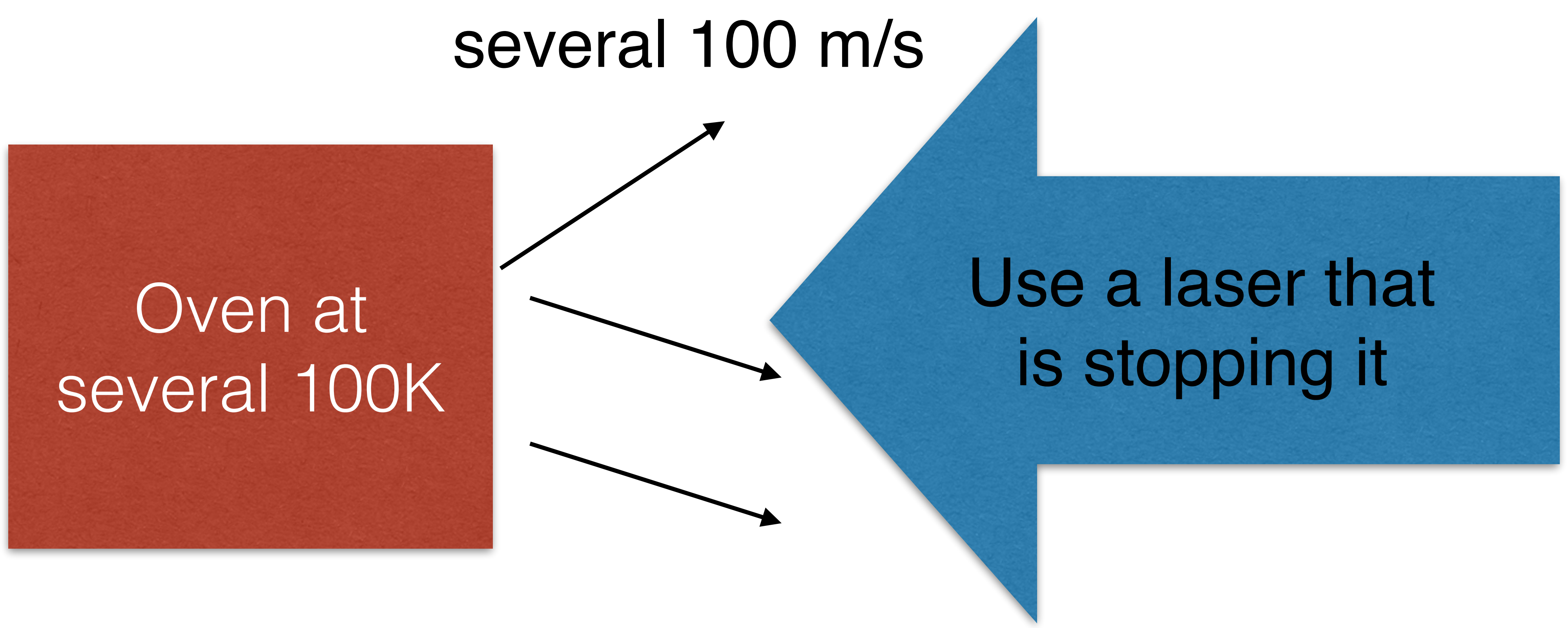
The idea of laser cooling

How to stop the atoms?



The idea of laser cooling

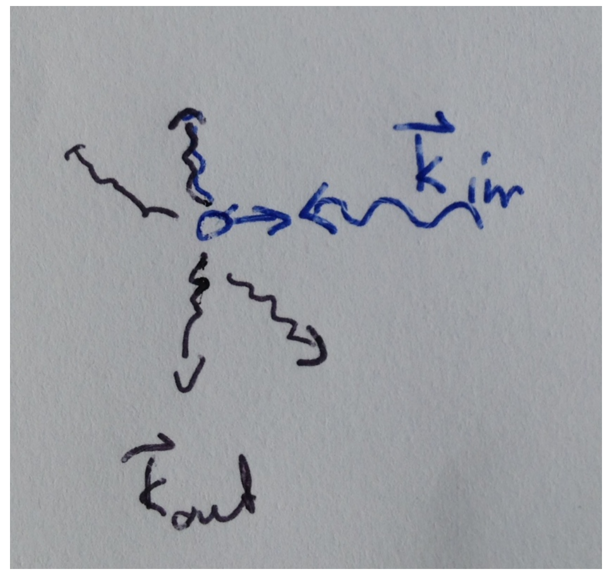
How to stop the atoms?



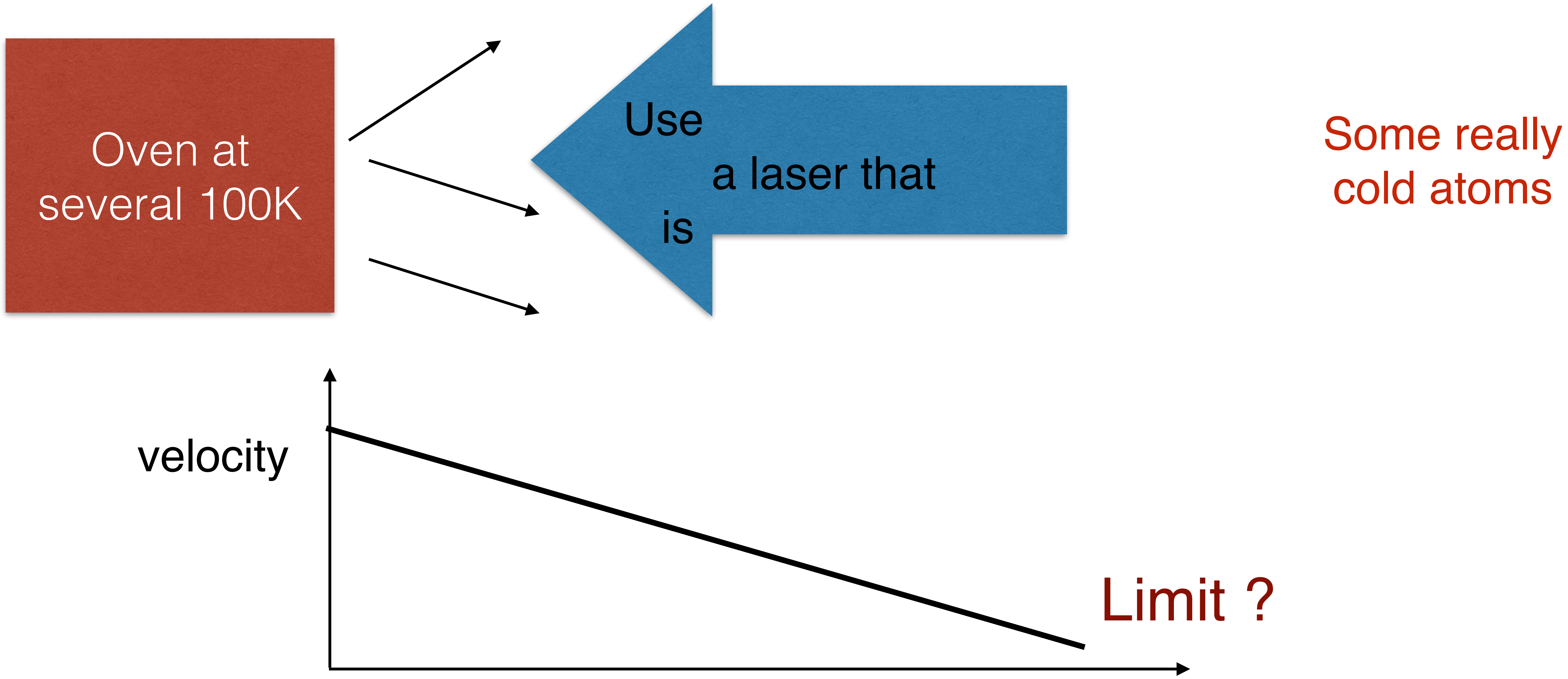
Some really
cold atoms

Idea of Laser cooling by Wineland, Dehmelt, Hänsch and Schawlow (1975)

Microscopic idea of radiation pressure



The idea of laser cooling



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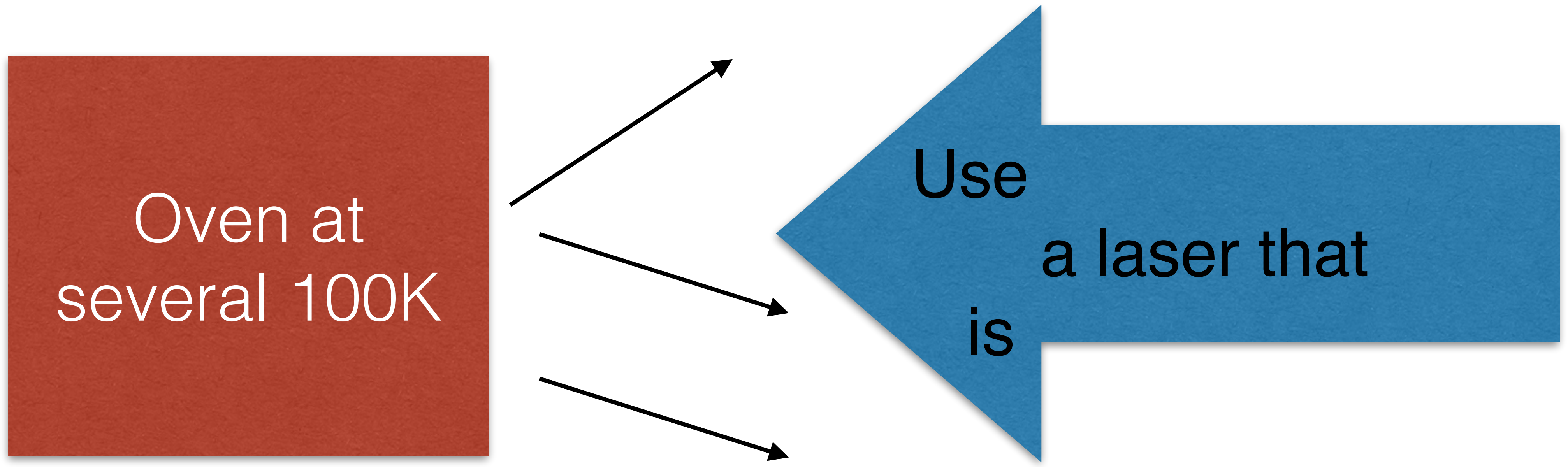
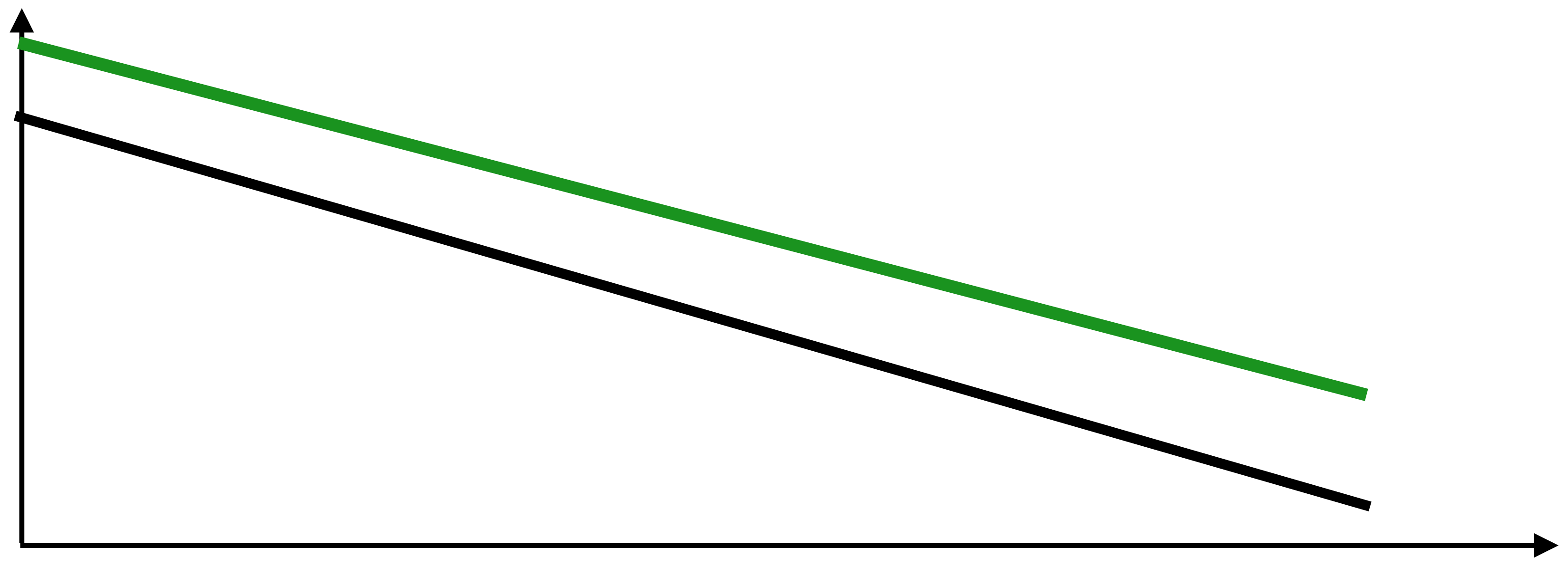


Some really cold atoms

velocity

Resonance frequency

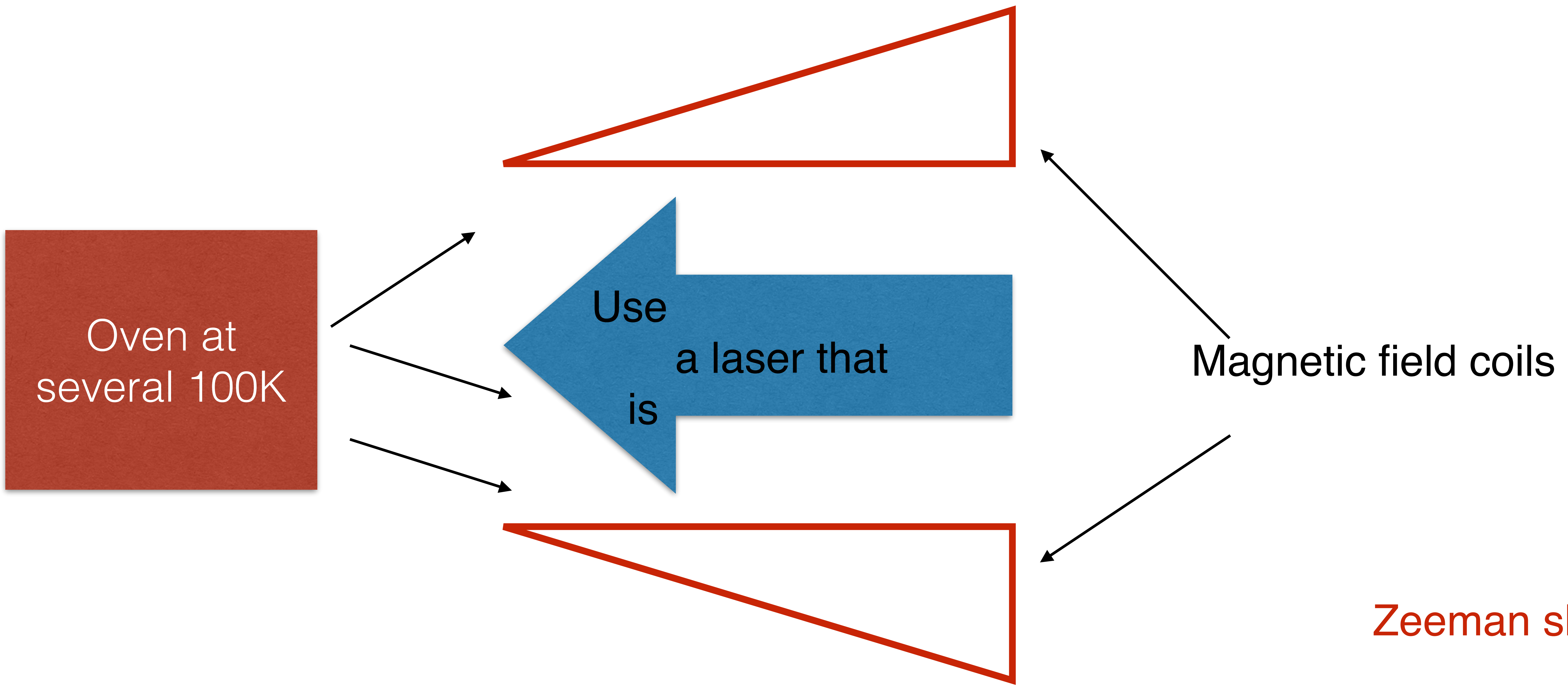


$$f = f_0 + \underbrace{\boxed{k \cdot v}}_{\text{Doppler shift}}$$

Ideas: frequency changes (chirping)

Zeeman cooling

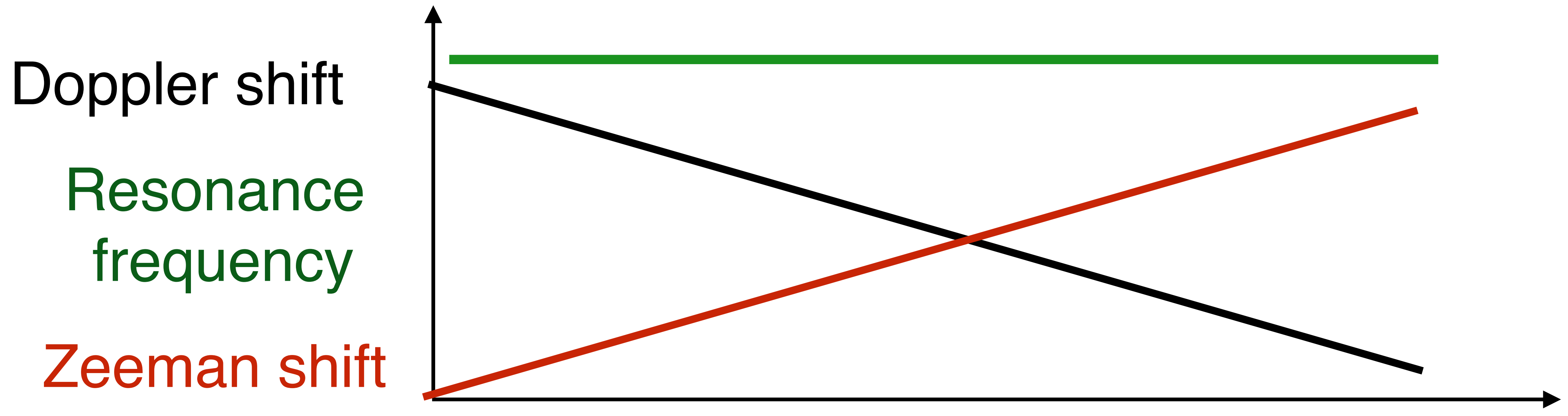
The Zeeman slower



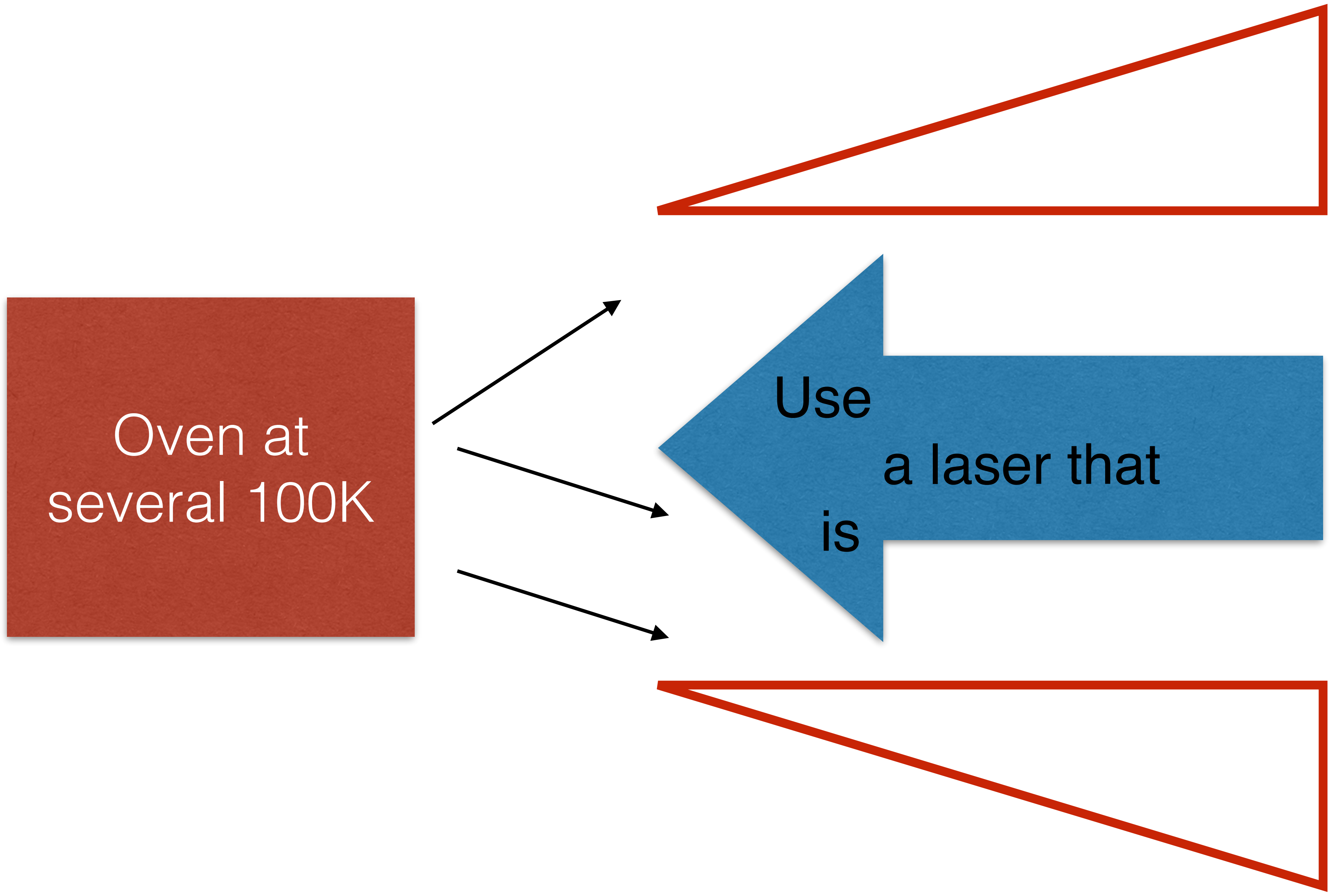
Zeeman shift

$$f = f_0 + \boxed{k \cdot v} + \boxed{\mu \cdot B}$$

Doppler shift



The Zeeman slower



a few m/s

VOLUME 48, NUMBER 9 PHYSICAL REVIEW LETTERS 1 MARCH 1982

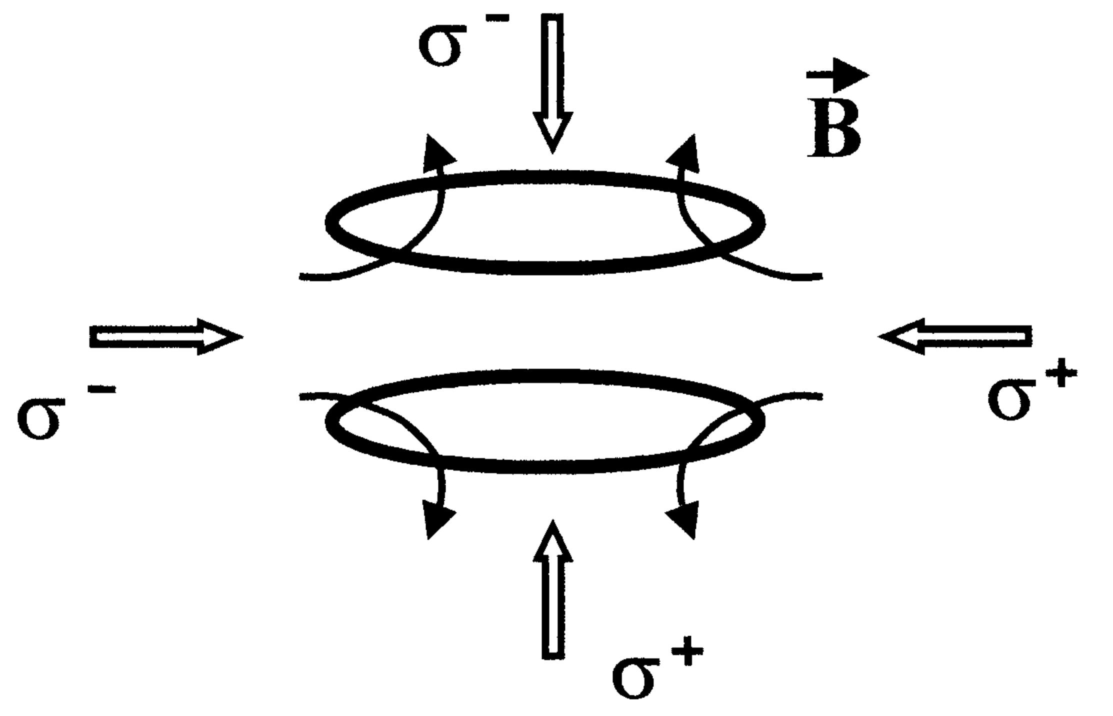
Laser Deceleration of an Atomic Beam

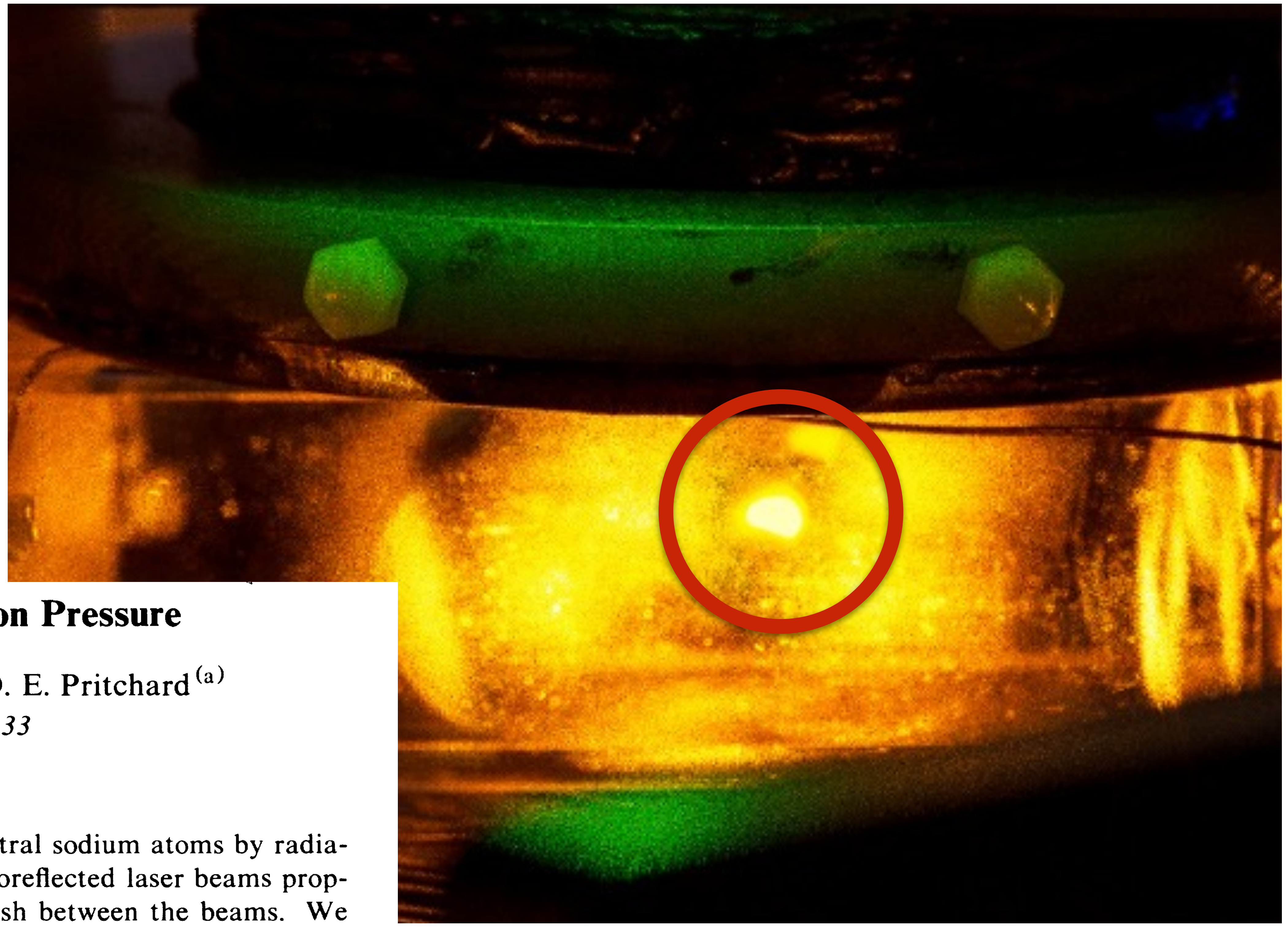
William D. Phillips and Harold Metcalf[(a)]
Electrical Measurements and Standards Division Center for Absolute Physical Quantities, National Bureau of Standards, Washington, D. C. 20234
(Received 23 December 1981)

Deceleration and velocity bunching of Na atoms in an atomic beam have been observed. The deceleration, caused by absorption of counterpropagating resonant laser light, amounts to 40% of the initial thermal velocity, corresponding to about 15 000 absorptions. Atoms were kept in resonance with the laser by using a spatially varying magnetic field to provide a changing Zeeman shift to compensate for the changing Doppler shift as the atoms decelerated.

The MOT

static magnetic fields + radiation pressure



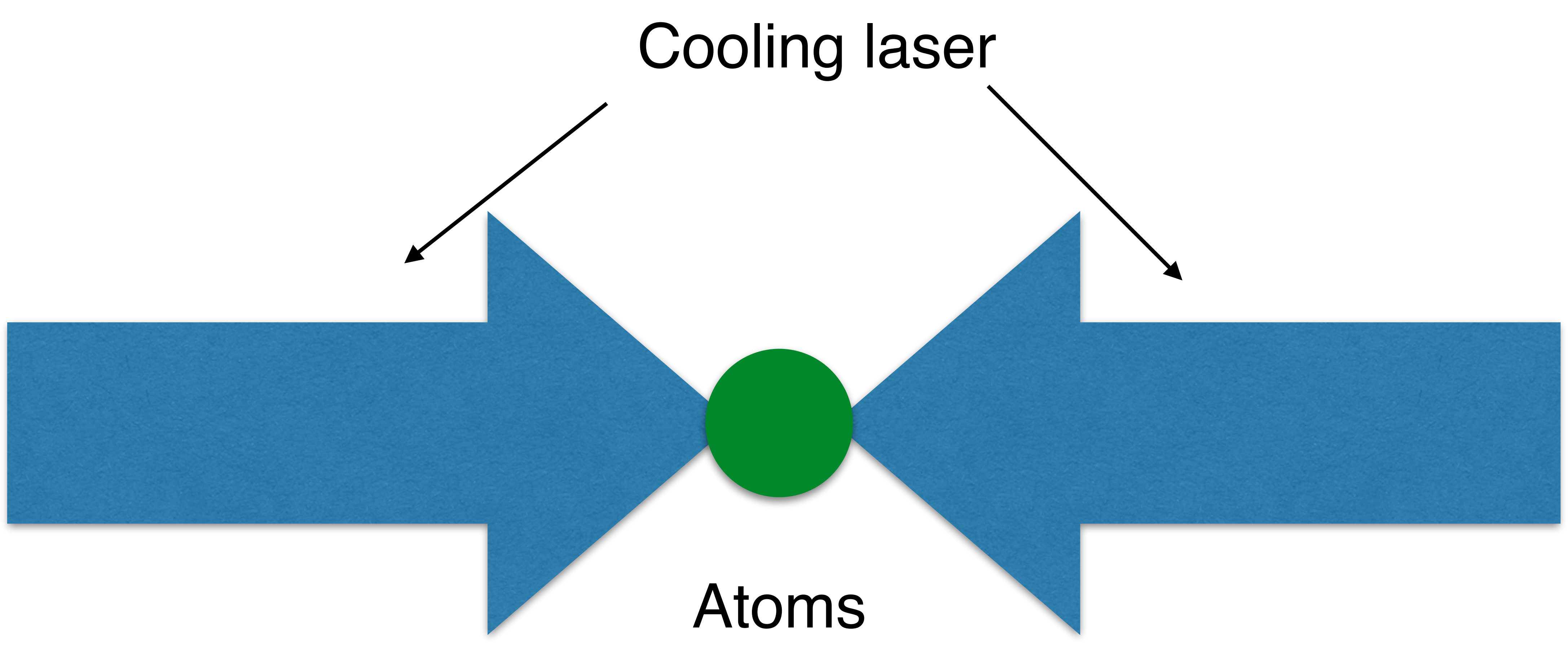


Trapping of Neutral Sodium Atoms with Radiation Pressure

E. L. Raab,[a] M. Prentiss, Alex Cable, Steven Chu,[b] and D. E. Pritchard[a]
AT&T Bell Laboratories, Holmdel, New Jersey 07733
(Received 16 July 1987)

We report the confinement and cooling of an optically dense cloud of neutral sodium atoms by radiation pressure. The trapping and damping forces were provided by three retroreflected laser beams propagating along orthogonal axes, with a weak magnetic field used to distinguish between the beams. We have trapped as many as 10^7 atoms for 2 min at densities exceeding 10^{11} atoms cm^{-3}. The trap was $\simeq 0.4$ K deep and the atoms, once trapped, were cooled to less than a millikelvin and compacted into a region less than 0.5 mm in diameter.

Doppler Cooling/Optical Molasses



atoms undergo diffusive motion and feel ‚friction' from collisions with laser

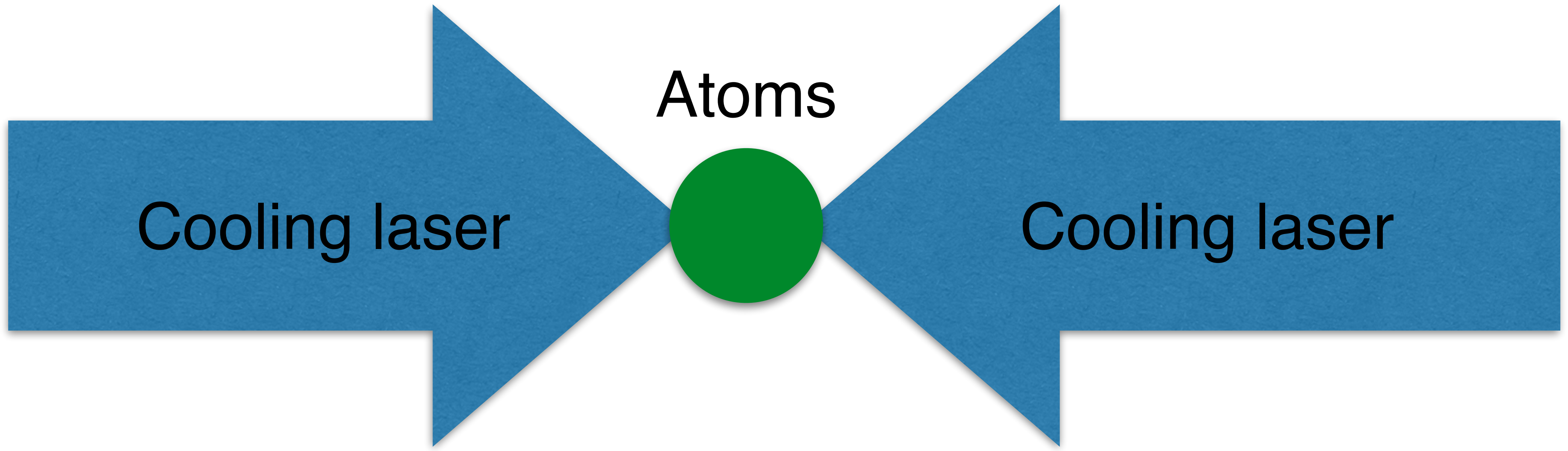
VOLUME 55, NUMBER 1 PHYSICAL REVIEW LETTERS 1 JULY 1985

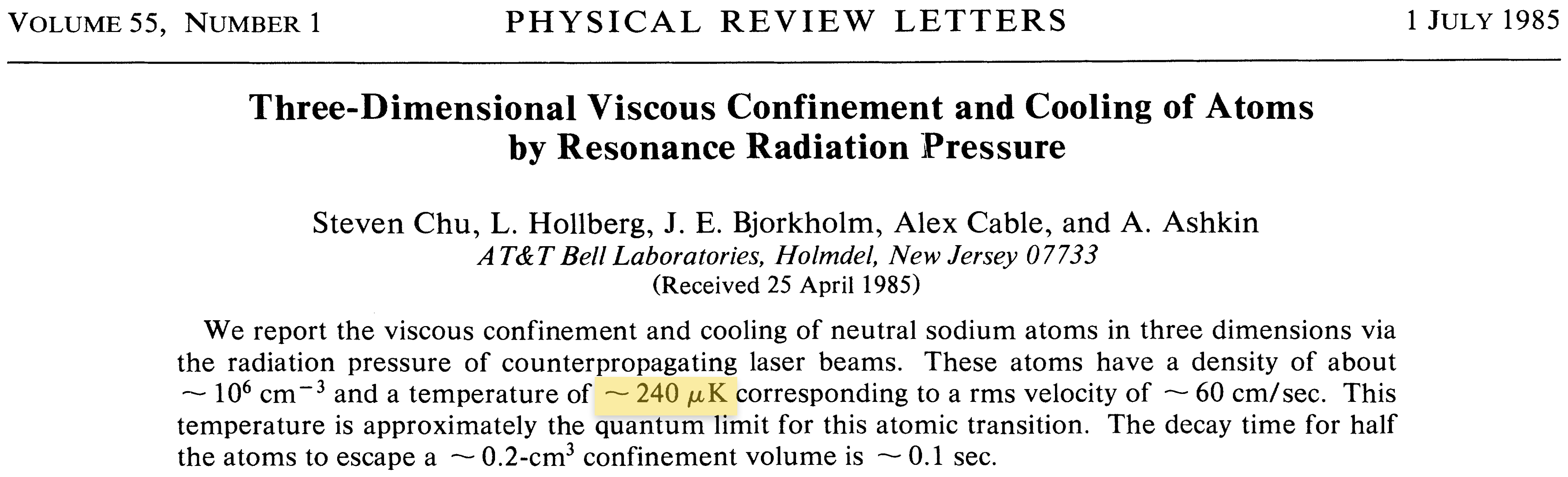
Three-Dimensional Viscous Confinement and Cooling of Atoms by Resonance Radiation Pressure

Steven Chu, L. Hollberg, J. E. Bjorkholm, Alex Cable, and A. Ashkin
AT&T Bell Laboratories, Holmdel, New Jersey 07733
(Received 25 April 1985)

We report the viscous confinement and cooling of neutral sodium atoms in three dimensions via the radiation pressure of counterpropagating laser beams. These atoms have a density of about $\sim 10^6$ cm^{-3} and a temperature of ~ 240 μK corresponding to a rms velocity of ~ 60 cm/sec. This temperature is approximately the quantum limit for this atomic transition. The decay time for half the atoms to escape a ~ 0.2-cm^3 confinement volume is ~ 0.1 sec.

Doppler Cooling/Optical Molasses

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Doppler limit (lowest ‚possible‘ temperature) $T_D \approx 240 \mu K$

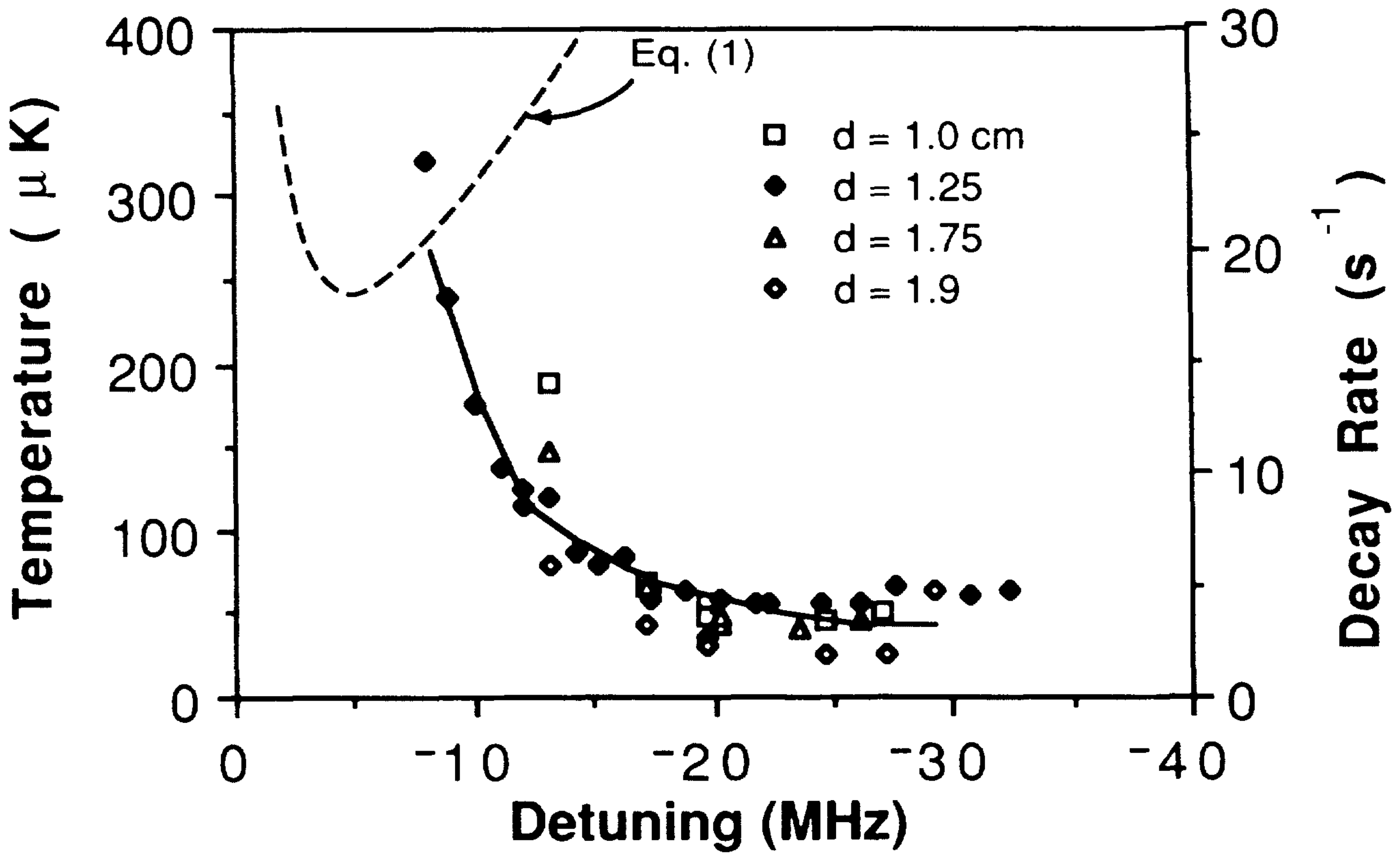
observed: $T \approx 240^{+200}_{-60} \mu K$

The miracle of subdoppler cooling

Comment by Steve Chu:

sure the velocity distribution. Our first measurements showed a temperature of 185 μK, slightly lower than the minimum temperature allowed by the theory of Doppler cooling. We then made the cardinal mistake of experimental physics: instead of listening to Nature, we were overly influenced by theoretical expectations. By including a fudge factor to account for the way atoms filled the molasses region, we were able to bring our measurement into accord with our expectations.

The result by the Phillips group:



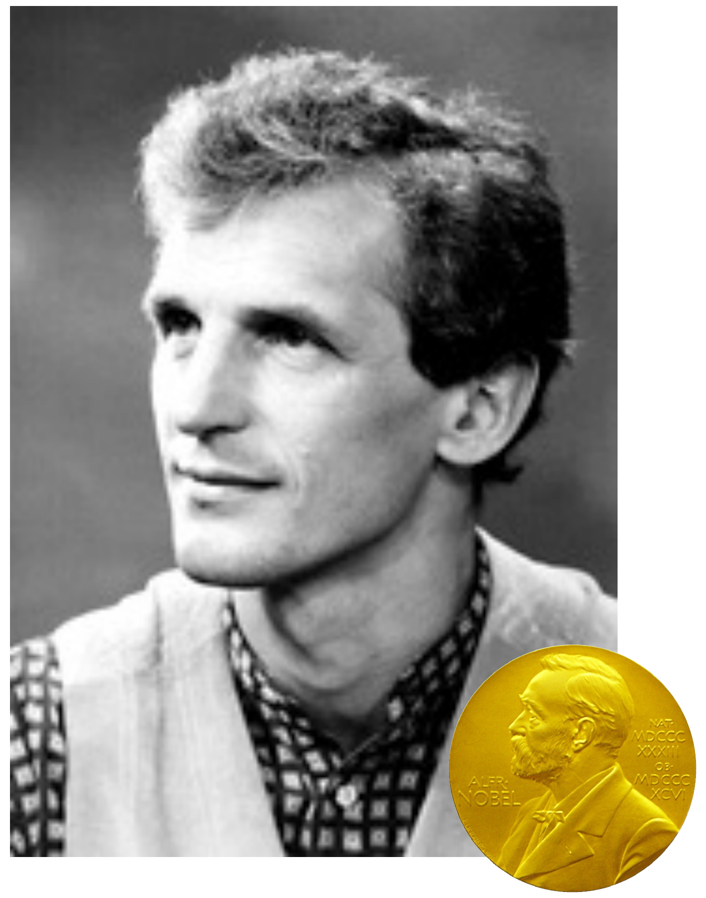
Lett *et al.* PRL **61** 169 (1988)

Overview

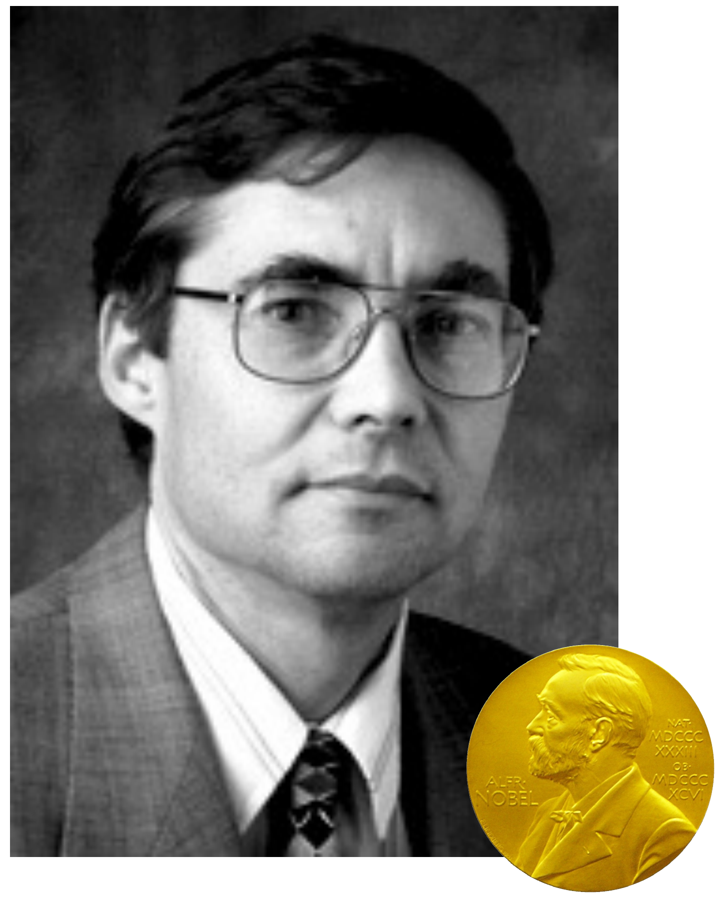
Why go for ultracold ?

The second step: Get degeneracy by collisions

Eric Cornell



Wolfgang Ketterle



Carl Wieman

Some good reads

REVIEWS OF MODERN PHYSICS, VOLUME 74, OCTOBER 2002

Nobel lecture: When atoms behave as waves: Bose-Einstein condensation and the atom laser*

Wolfgang Ketterle†

Making, probing and understanding Bose-Einstein condensates

W. Ketterle, D.S. Durfee, and D.M. Stamper-Kurn

Department of Physics and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139

Observation of Bose-Einstein Condensation in a Dilute Atomic Vapor

M. H. Anderson, J. R. Ensher, M. R. Matthews, C. E. Wieman,* E. A. Cornell

Bose-Einstein Condensation in a Gas of Sodium Atoms

K. B. Davis, M.-O. Mewes, M. R. Andrews, N. J. van Druten, D. S. Durfee, D. M. Kurn, and W. Ketterle

Department of Physics and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

(Received 17 October 1995)

What happens when you cool a gas?

Average velocity of thermal atoms:

$$\langle |v| \rangle = \sqrt{\frac{3k_B T}{m}}$$

atoms = wave packets

$$\lambda_{dB} = \frac{h}{mv} = \sqrt{\frac{h^2}{3mk_B T}}$$

Thermal de Broglie wavelength

High Temperature T:

thermal velocity v

density d^{-3}

"Billiard balls"

Low Temperature T:

De Broglie wavelength

$\lambda_{dB}=h/mv \propto T^{-1/2}$

"Wave packets"

$T=T_{crit}$: Bose-Einstein Condensation

$\lambda_{dB} \approx d$

"Matter wave overlap"

T=0: Pure Bose condensate

"Giant matter wave"

Who would like collisions ?

- at 1mK normally always solids liquids etc.

- here we do not have them as there are only weak interactions

- but how do you have a **thermal phase transition without** interactions (**thermalization**)**?**

Can one get degeneracy without ‚solidification' ?

Common wisdom:

Yes, do really good laser cooling and **avoid collisions**

Eric Cornell:

Laser cooling will never work well enough, we will **need collisions**

How to get colder?

Evaporative Cooling

Hess, PRB **34** 3476 (1985)

Good vs bad collisions

<u>Good</u>

elastic collisions to
change momentum

<u>Bad</u>

three body collisions
(simplest form of ‚solid‘)

How do you know that it will work ?

Good vs bad collisions

<u>Good</u>

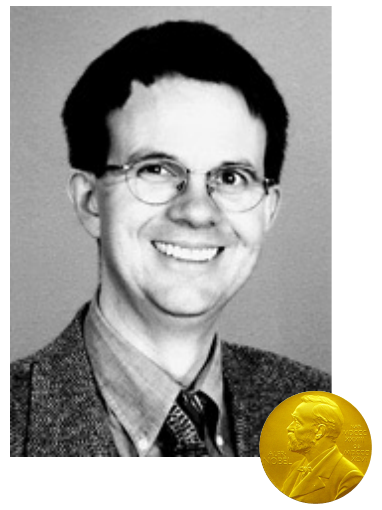
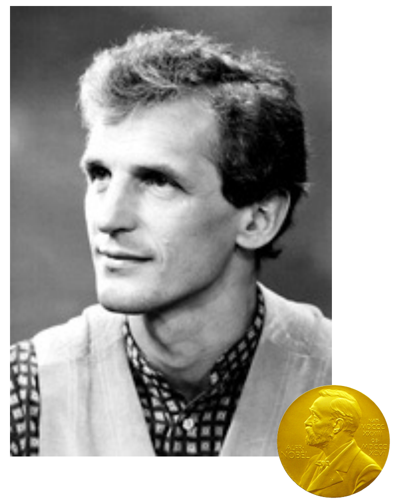
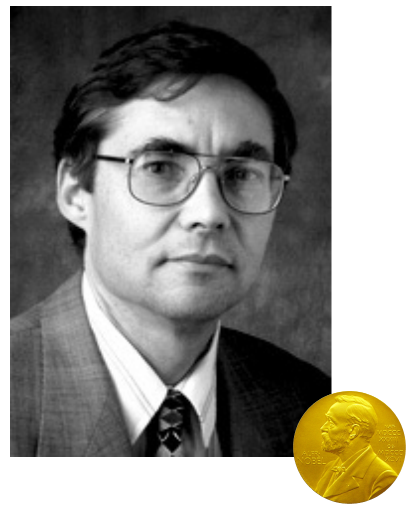
elastic collisions to
change momentum

<u>Bad</u>

three body collisions
(simplest form of ‚solid‘)

How do you know that it will work ?

What worked initially ? Rubidium, Sodium

Today:

Rubidium, Sodium, Cesium, Potassium,

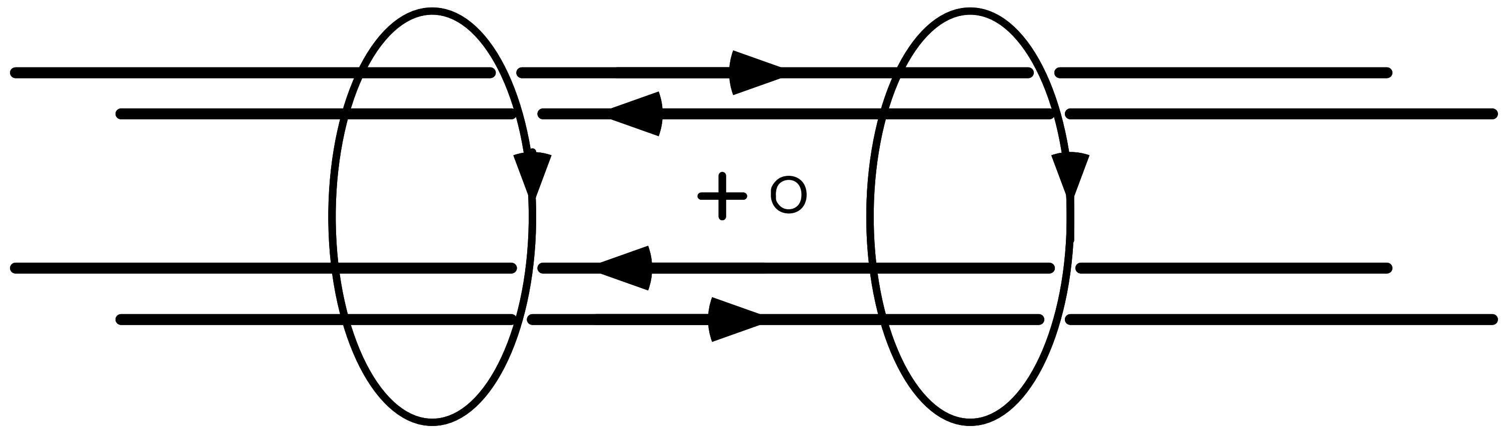
Lithium, Hydrogen, Helium, Chromium,

Dysprosium, Erbium, Ytterbium, Strontium, …

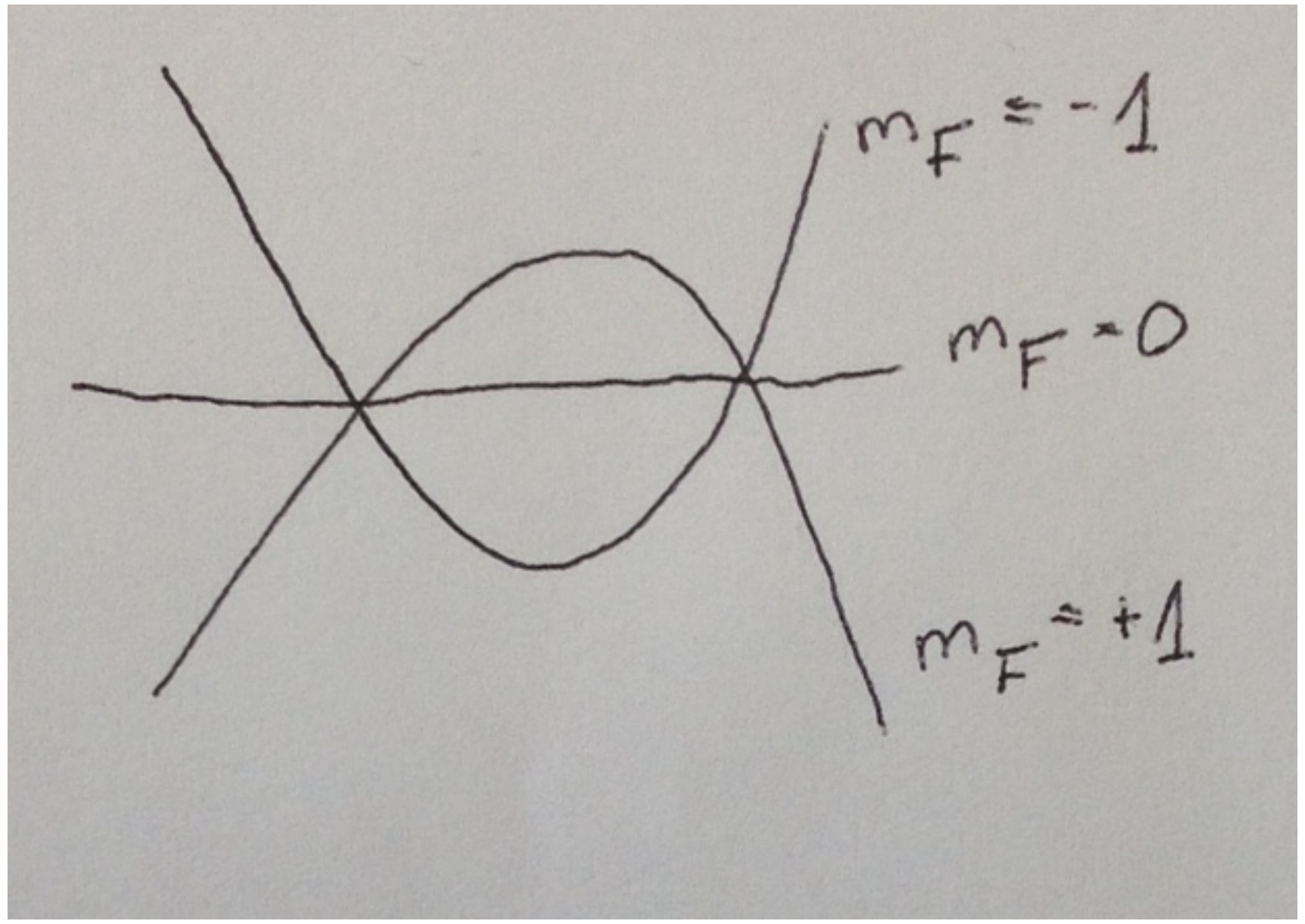
Polaritons, Light

Magnetic traps

Ioffe-Pritchard:

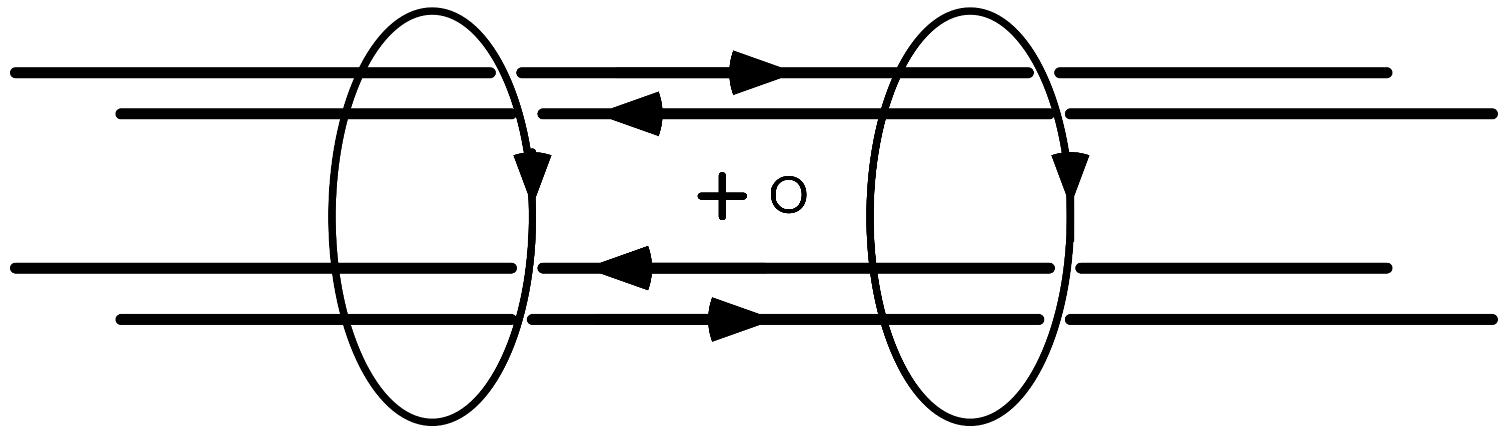


Resulting field:

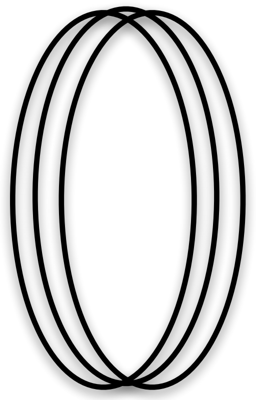


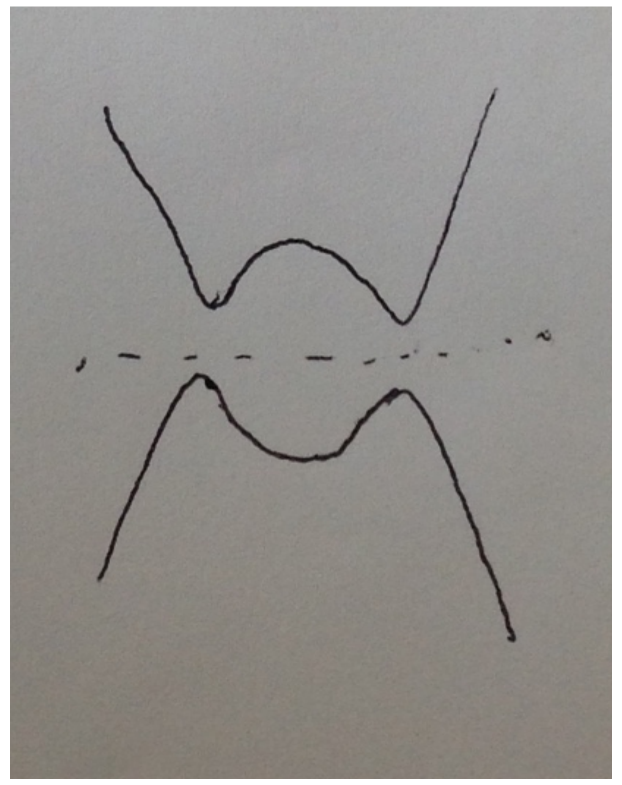
Magnetic traps

Ioffe-Pritchard:



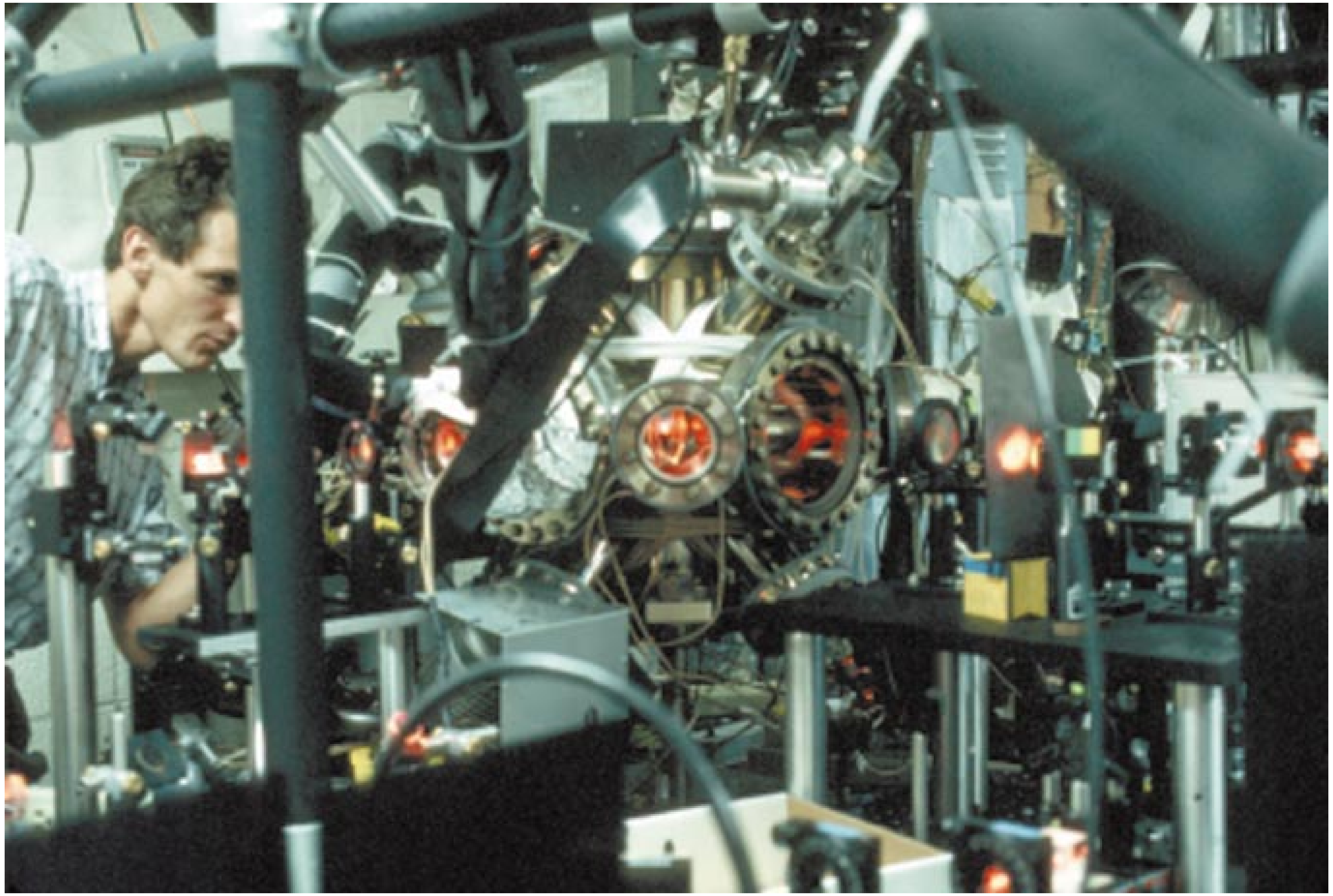
Resulting field + rf-field:





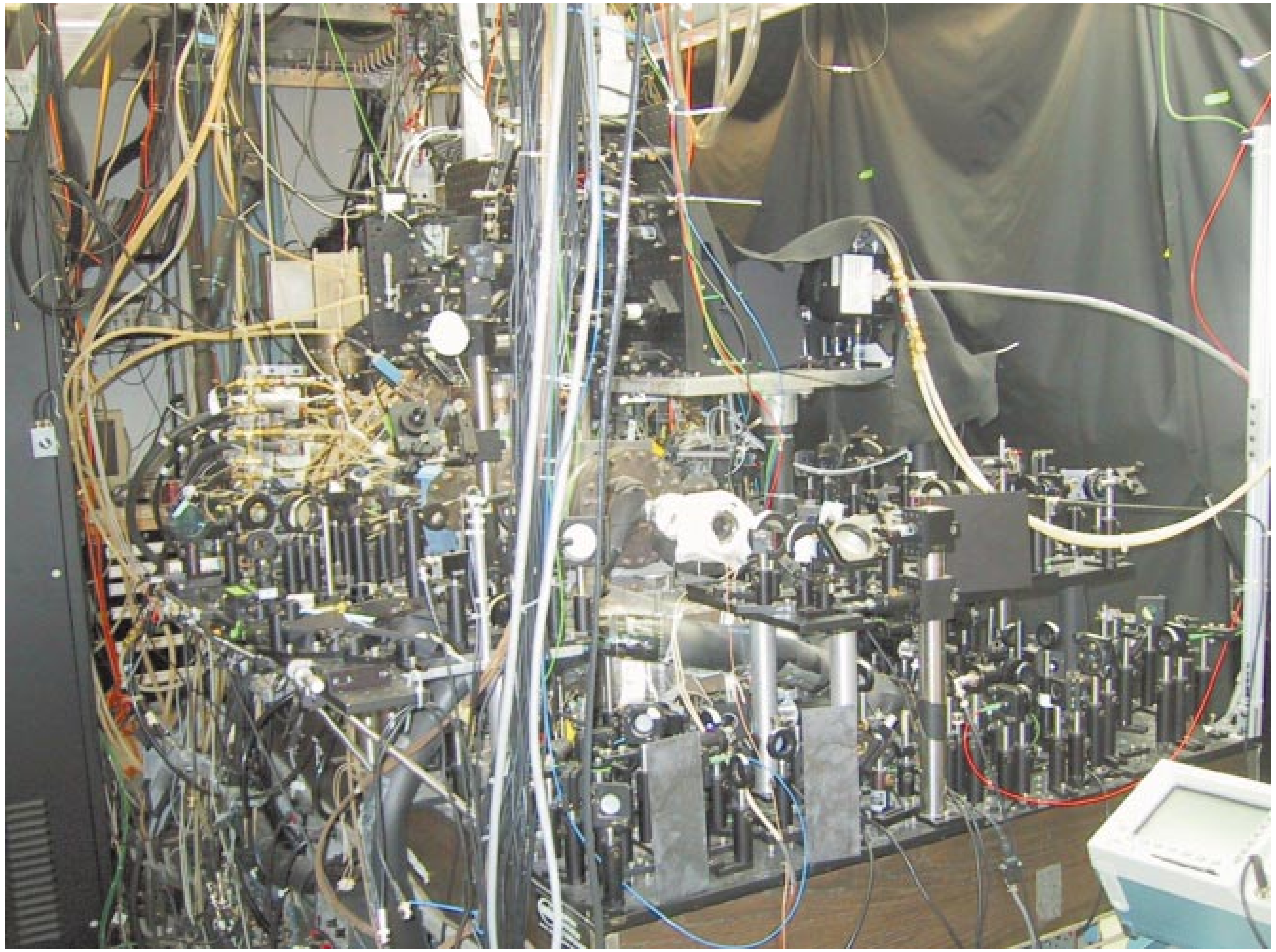
How do you see a BEC ?

before BEC



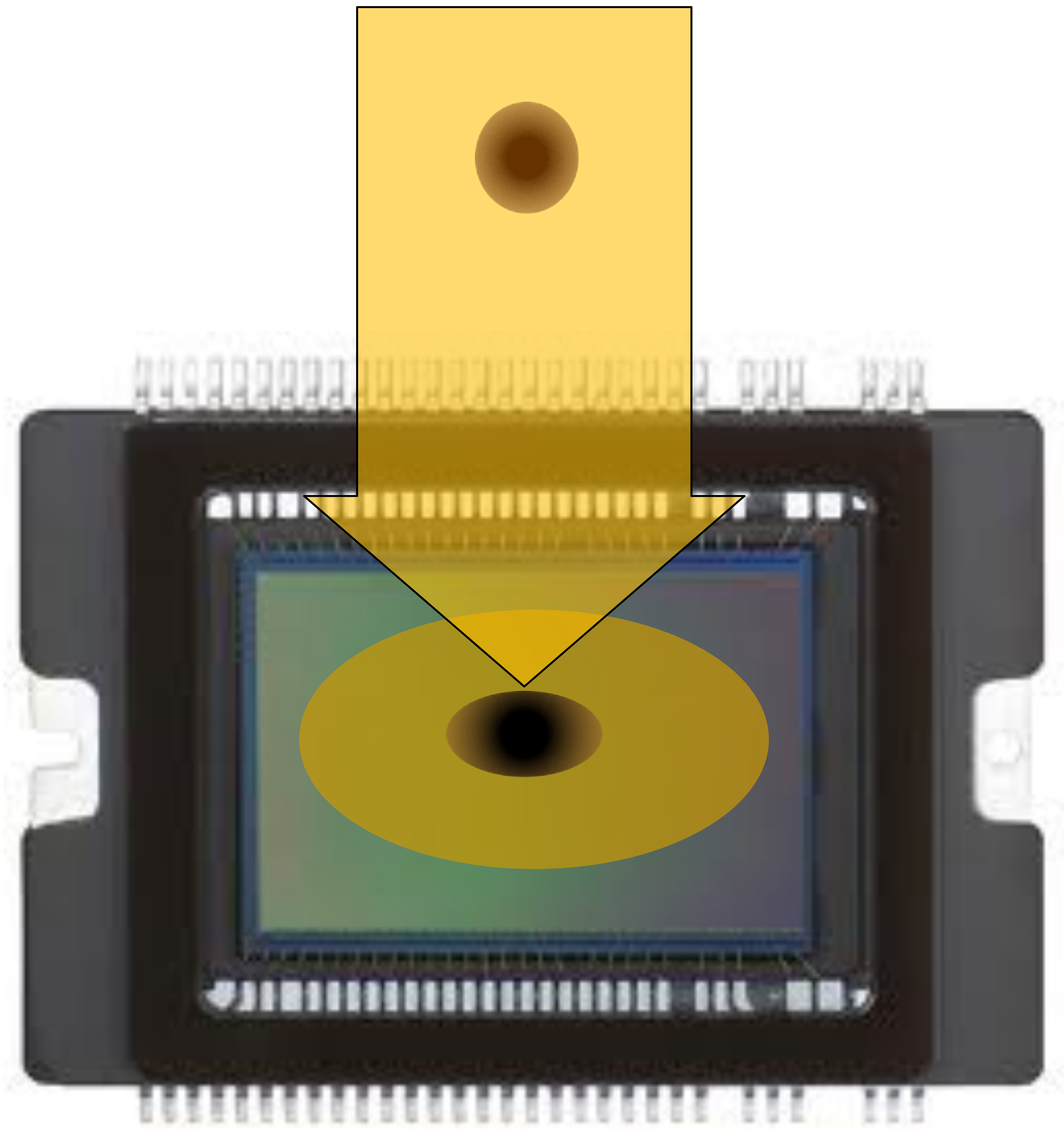
How do you see a BEC ?

with BEC



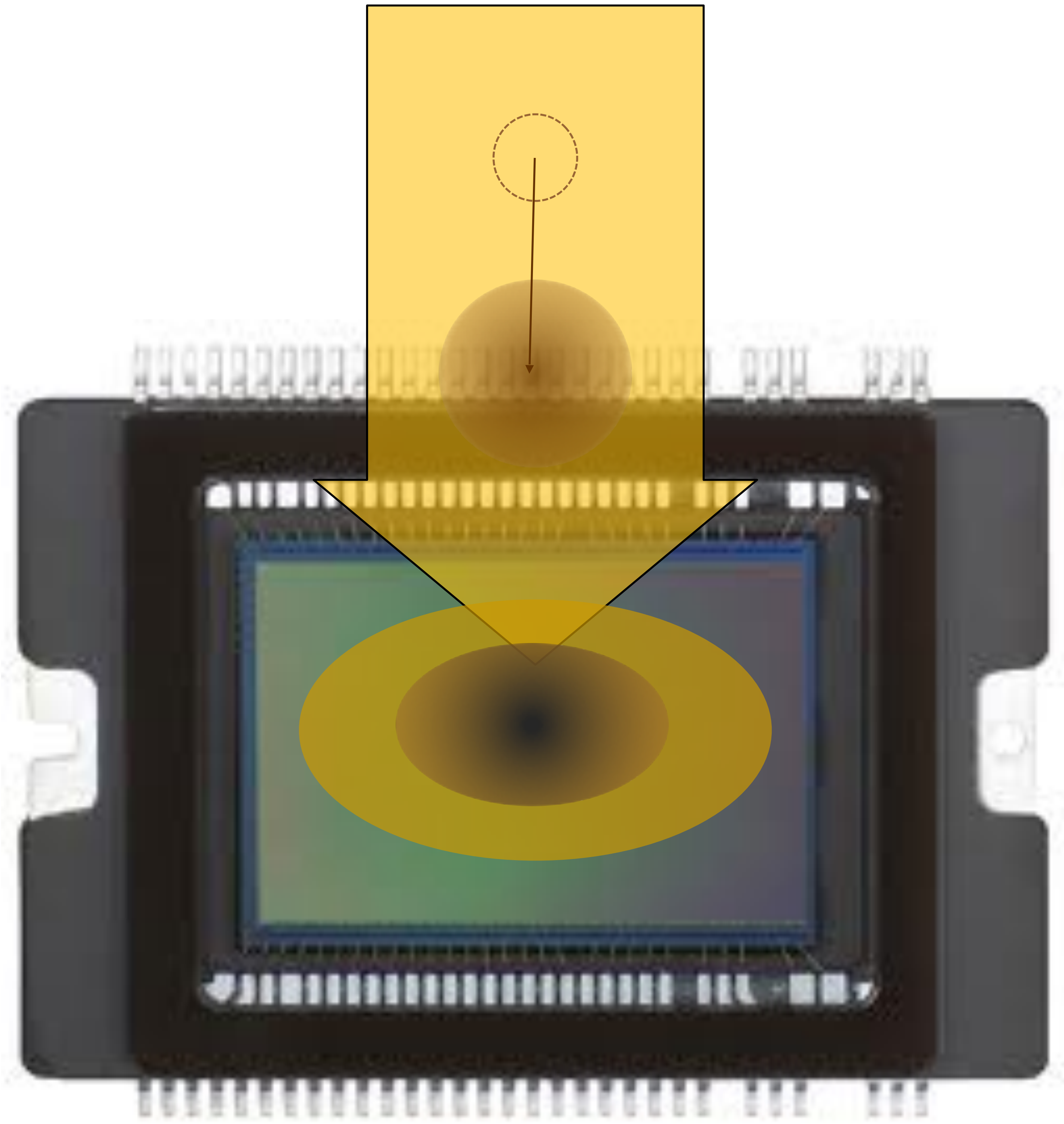
Absorption Imaging

In-situ



Spatial Information

Time-of-Flight (TOF)



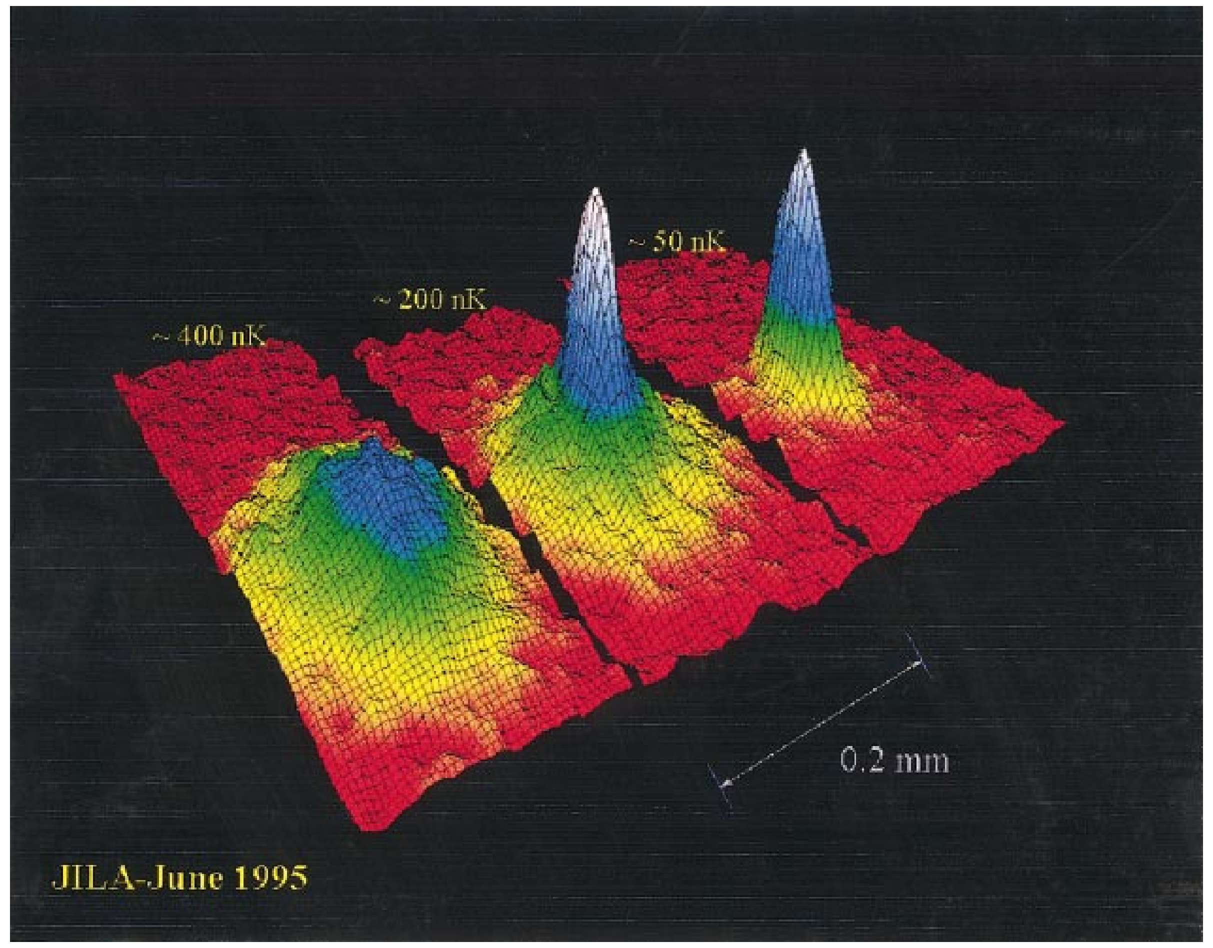
Momentum Information

How do you see a BEC ?

Initial trap (Real space):

Time of flight
cut the trap and
let it expand freely

Momentum distribution:

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question
QUESTION