Laser-cooling and trapping (some history)

Theory

(neutral atoms) Hansch & Schawlow, 1975

COOLING OF GASES BY LASER RADIATION[1*]

T.W. HÄNSCH[2†] and A.L. SCHAWLOW

Department of Physics, Stanford University, Stanford, California 94305, USA

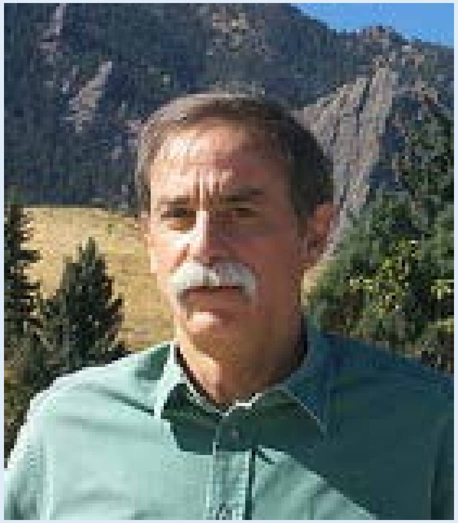
Received 20 October 1974

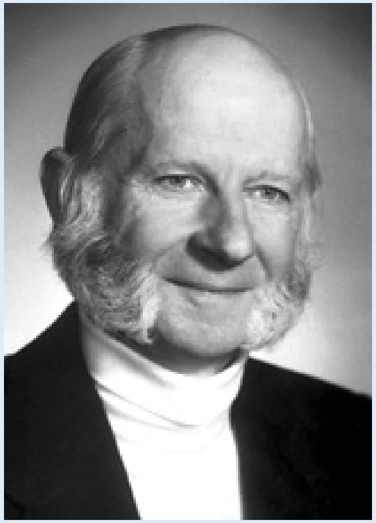
It is shown that a low-density gas can be cooled by illuminating it with intense, quasi-monochromatic light confined to the lower-frequency half of a resonance line's Doppler width. Translational kinetic energy can be transferred from the gas to the scattered light, until the atomic velocity is reduced by the ratio of the Doppler width to the natural line width.

Laser-cooling and trapping (some history)

<u>Theory</u>

(neutral atoms) Hansch & Schawlow, 1975
(trapped ions) Wineland & Dehmelt, 1975
(neutral atoms) Ashkin, 1978





Laser-cooling and trapping (some history)

Theory
(neutral atoms) Hansch & Schawlow, 1975
(trapped ions) Wineland & Dehmelt, 1975
(neutral atoms) Ashkin, 1978

Experiments
(ions) Wineland, Drullinger, Walls, 1978
(ions) Neuhauser, Hohenstatt, Toschek & Dehmelt, 1978

Atom slowing experiments in 1980s, and then:
3D molasses of neutral atoms: Chu, Hollberg, Bjorkholm, Cable & Ashkin, 1985

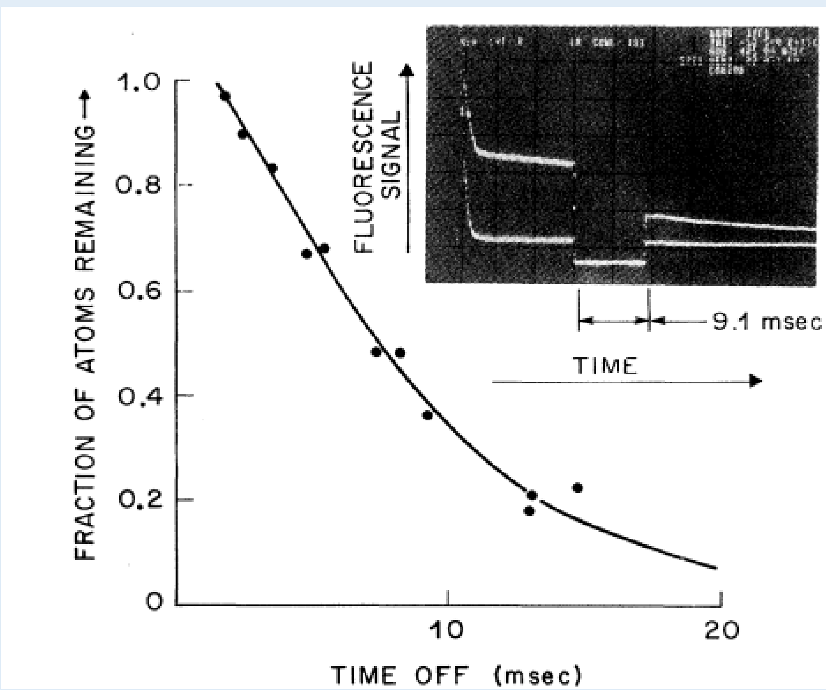
First 3D molasses, with neutral sodium

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.



Based on "release and recapture," measured temperatures ~$T_{Doppler}$

~240 μK

Another 3D molasses of neutral sodium and a surprise!

(1988) Lett, Watts, Westbrook, Phillips, Gould & Metcalf

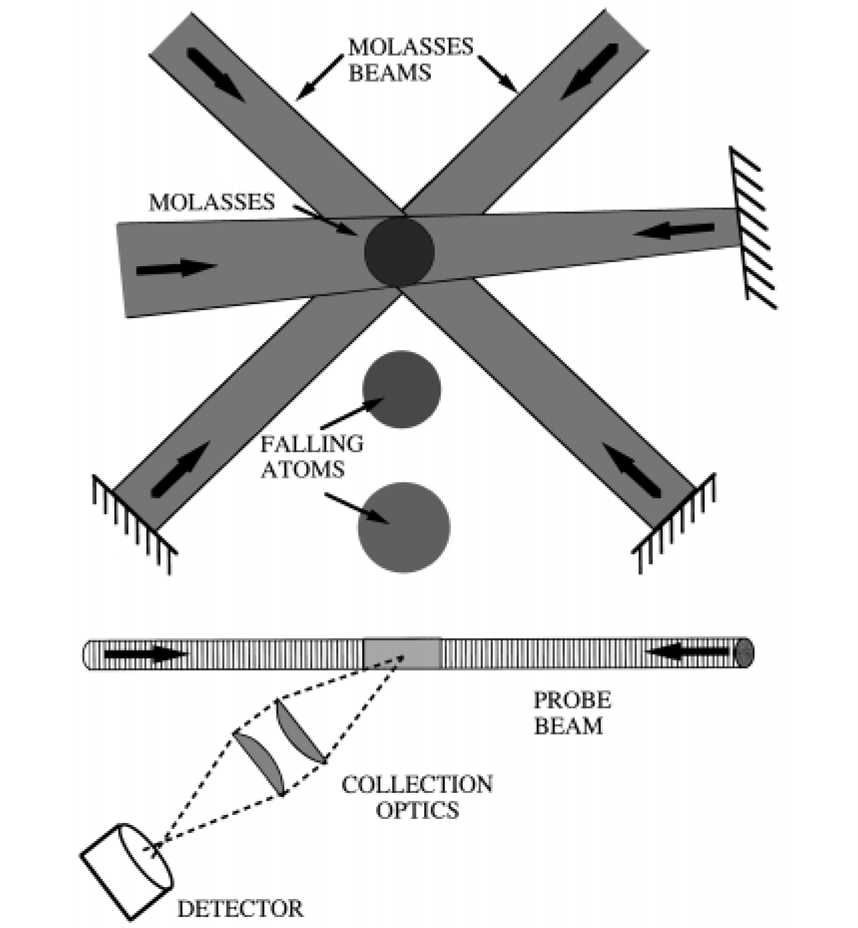
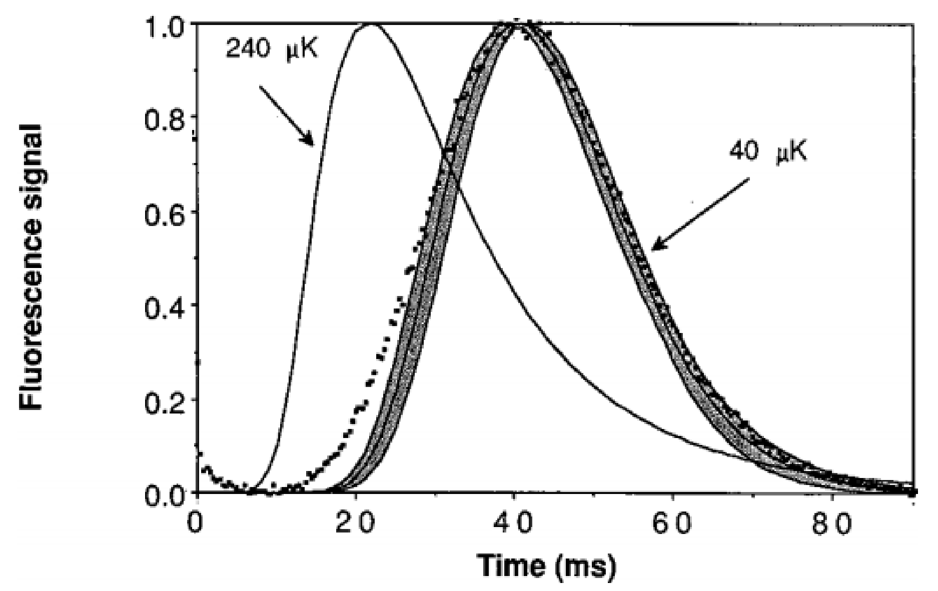


FIG. 15. Time-of-flight method for measuring laser cooling temperatures.



Atoms a lot colder than expected!

Another 3D molasses of neutral sodium and a surprise!

(1988) Lett, Watts, Westbrook, Phillips, Gould & Metcalf

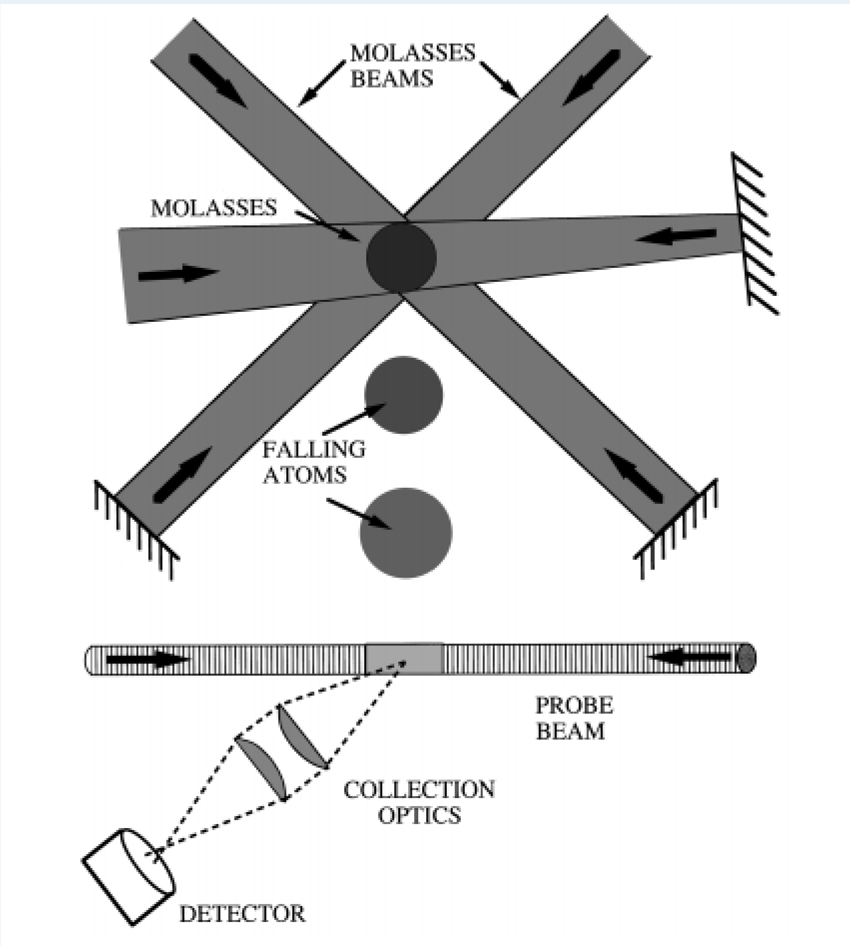
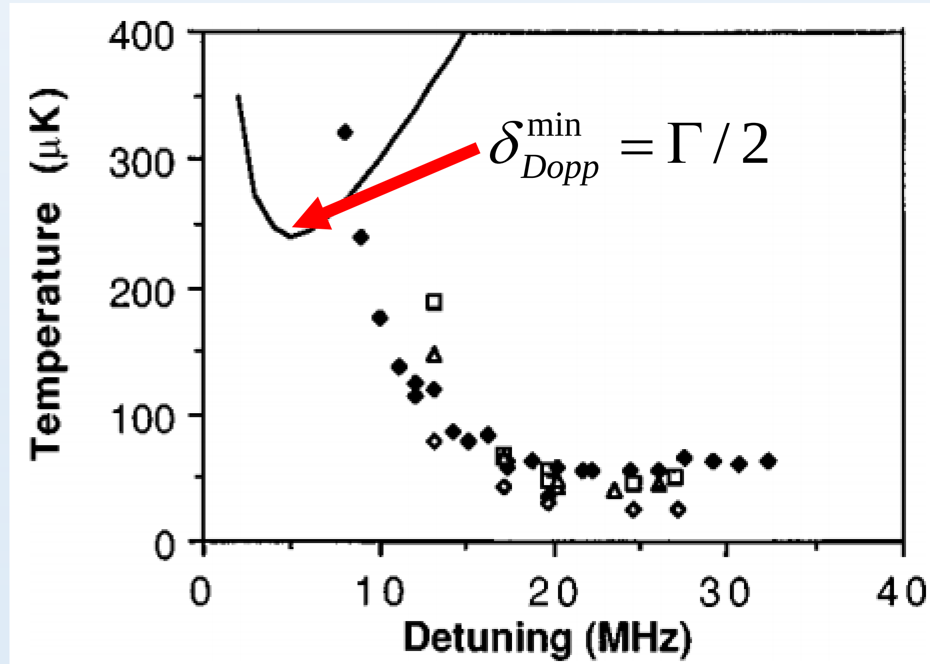


FIG. 15. Time-of-flight method for measuring laser cooling temperatures.



Strange dependence on detuning!

reason: real atoms have more than 2 levels!

polarization gradient cooling
(Cohen-Tannoudji, Dalibard, others)

Another 3D molasses of neutral sodium and a surprise!

(1988) Lett, Watts, Westbrook, Phillips, Gould & Metcalf

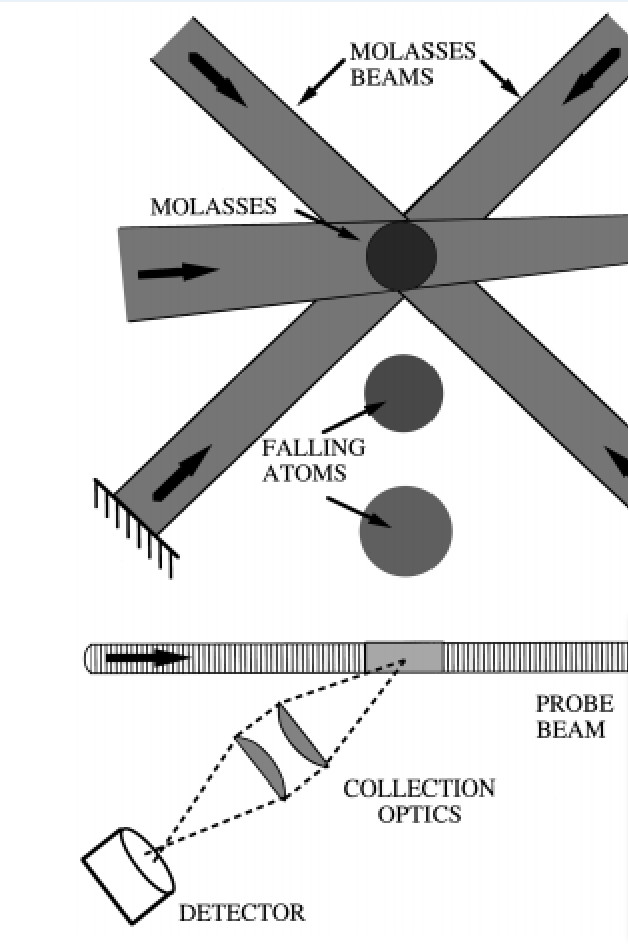
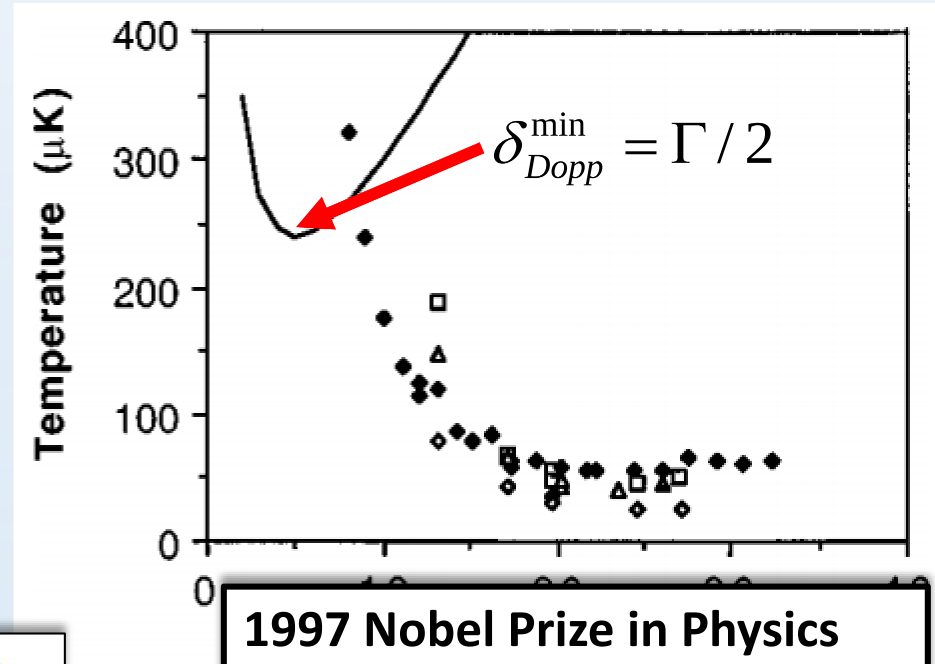


FIG. 15. Time-of-flight method for measuring laser cooling temperatures.



St

reason

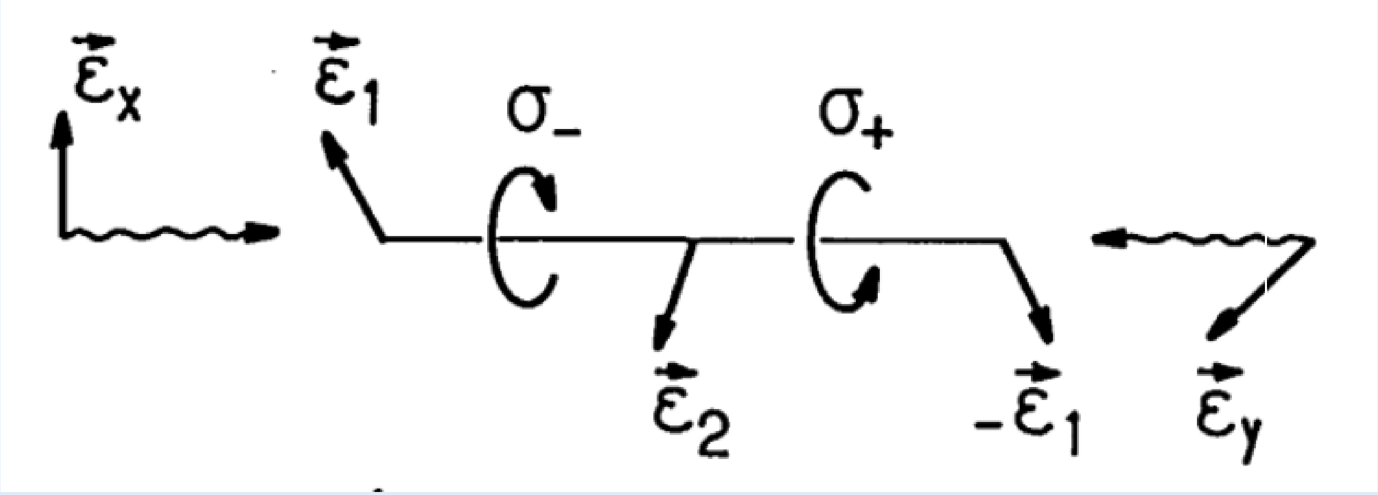
polariz

(Cohen-Tannoudji, Dalibard, others)

1997 Nobel Prize in Physics
Chu, Phillips, Cohen-Tannoudji
"for development of methods to cool and trap atoms with laser light"

Polarization gradient cooling

(aka, Sisyphus cooling)

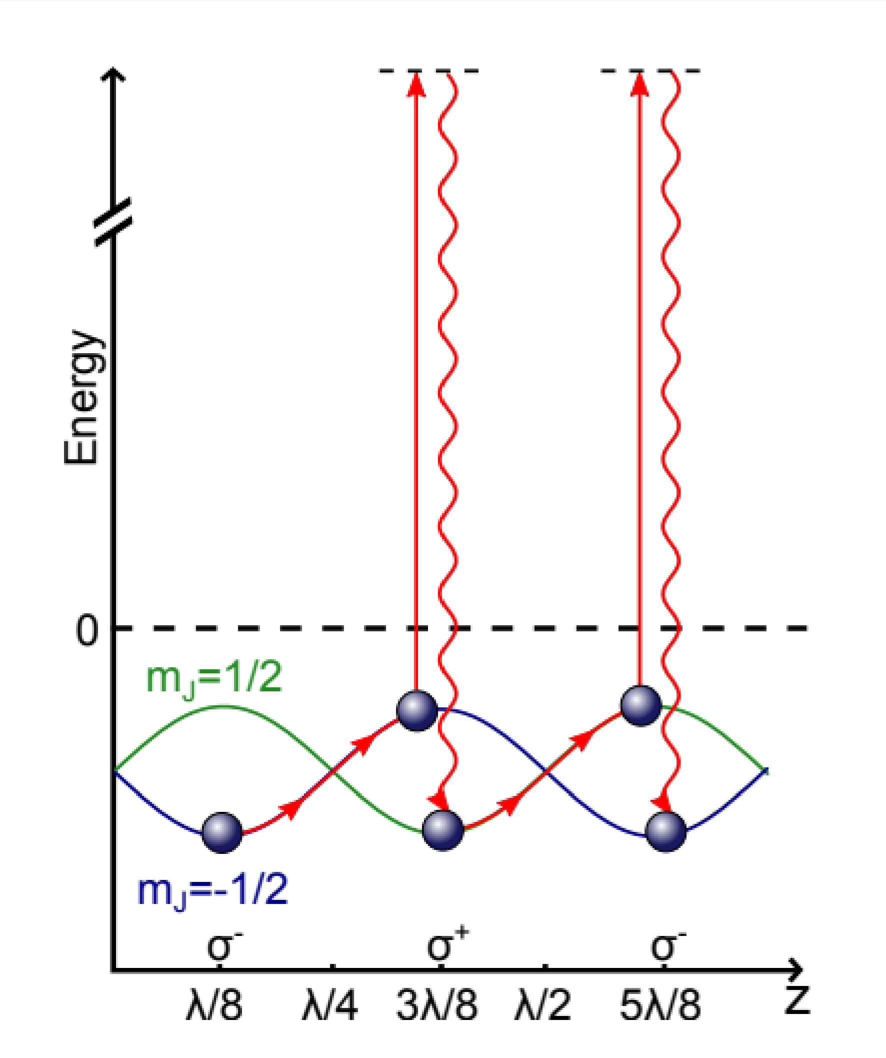


C. Tanoudji, J. Dalibard (1989)

lin ⊥ lin

Polarization gradient cooling

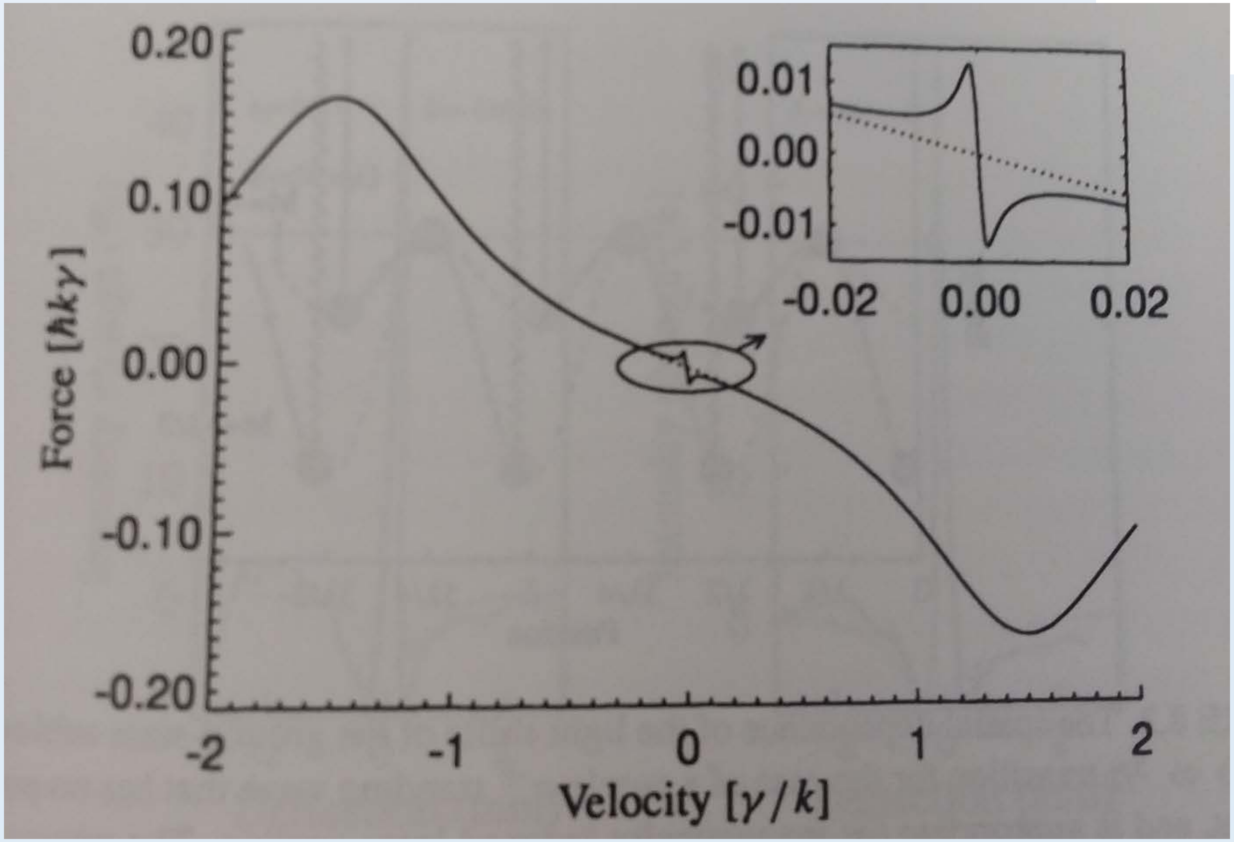
(aka, Sisyphus cooling)



Florian Meinert

Polarization gradient cooling

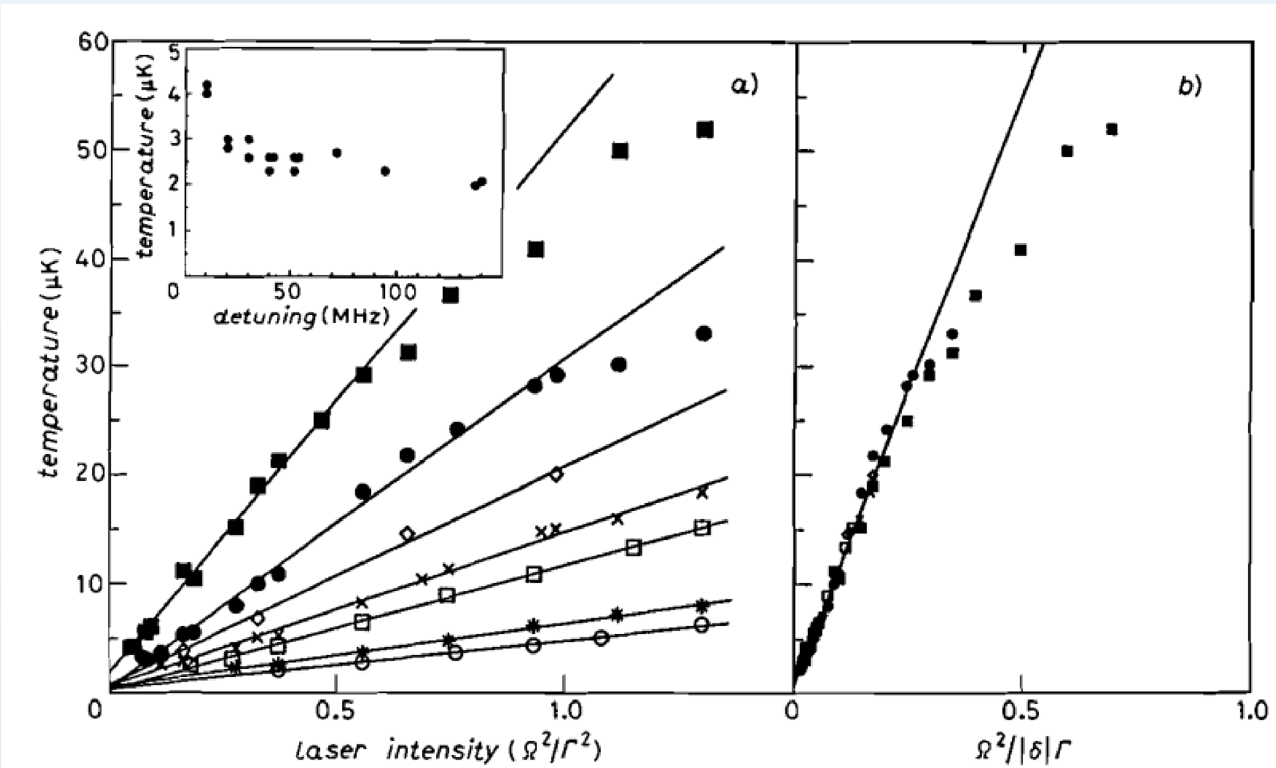
(aka, Sisyphus cooling)



Metcalf & van der Straten

Polarization gradient cooling

Get very cold, but need large detuning (with respect to natural linewidth)

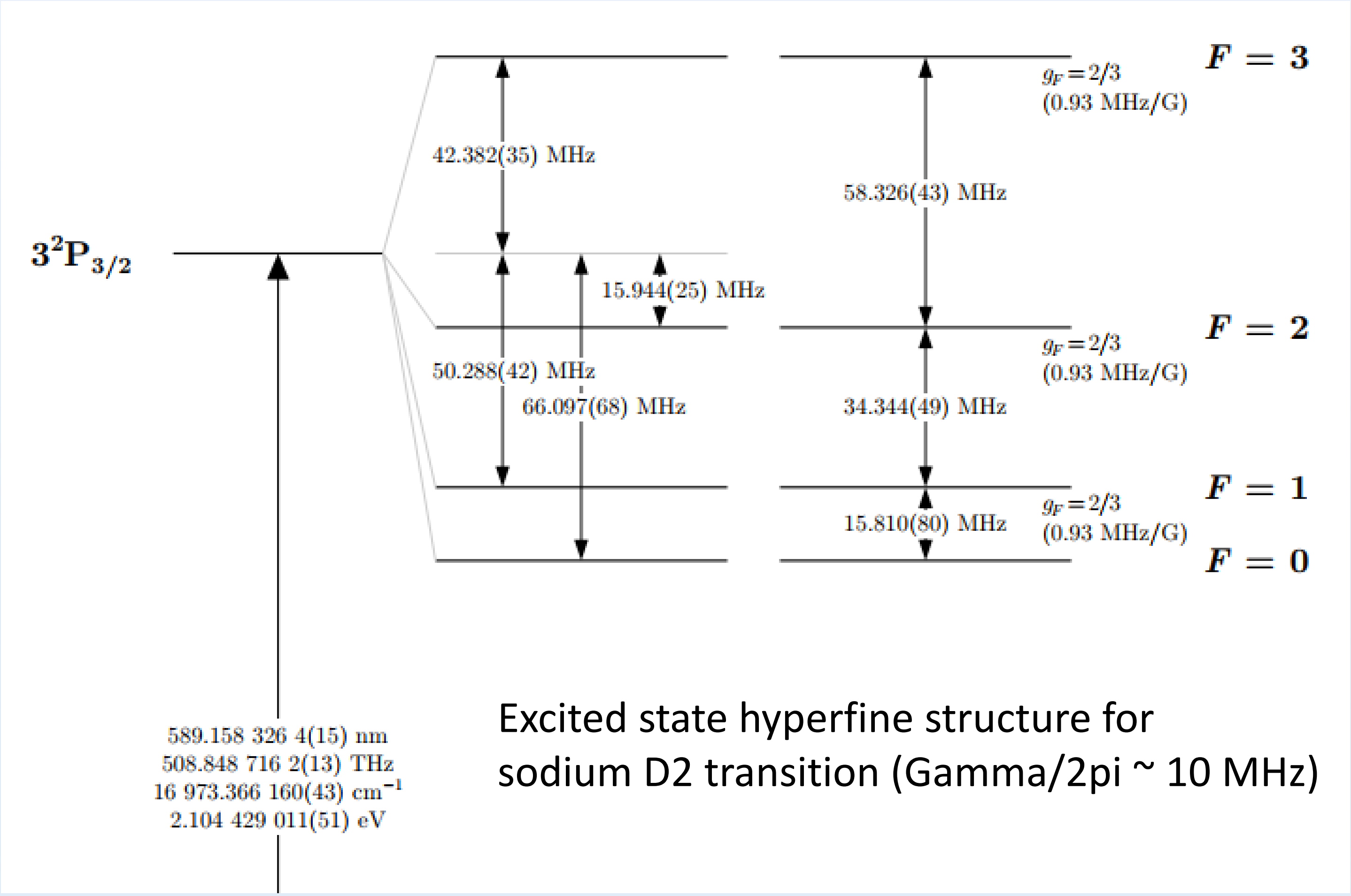


Laser Cooling of Cesium Atoms below 3 μK.

C. Salomon (*), J. Dalibard (*), W. D. Phillips (*)(§)
A. Clairon (**) and S. Guellati (***)

Polarization gradient cooling

Get very cold, but need large detuning (with respect to natural linewidth)
this is hard to come by for the lighter alkalis (small excited state hyperfine splittings)



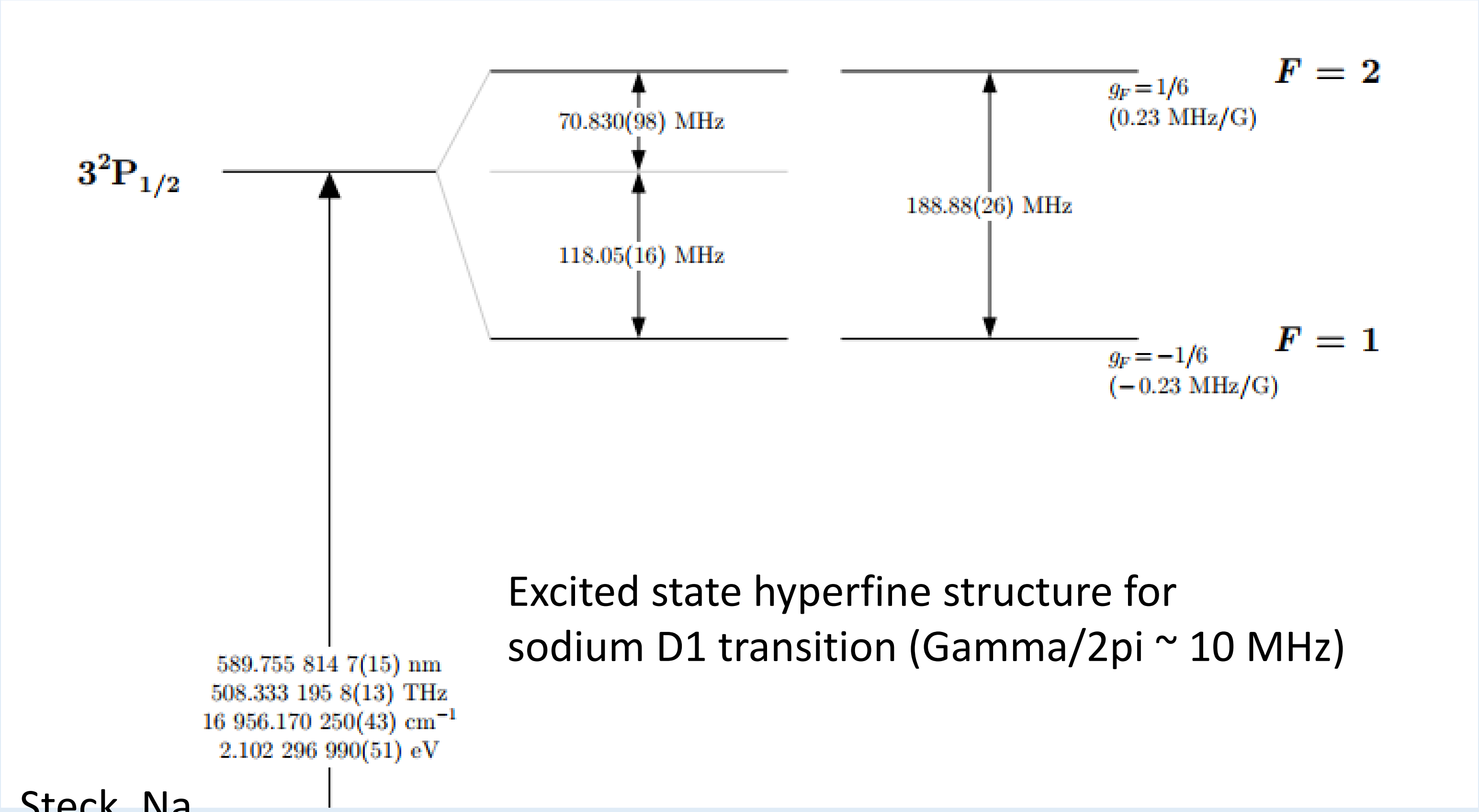
Excited state hyperfine structure for sodium D2 transition (Gamma/2pi ~ 10 MHz)

Steck, Na

"Gray molasses"

Get very cold, but need large detuning (with respect to natural linewidth)
this is hard to come by for the lighter alkalis (small excited state hyperfine splittings)

One solution – use D1 line instead, larger splitting of excited hyperfine levels
(there's more to it than this, but it relies on this fact)



Excited state hyperfine structure for sodium D1 transition (Gamma/2pi ~ 10 MHz)

Steck, Na

Another view of Sisyphus cooling

VOLUME 69, NUMBER 1 PHYSICAL REVIEW LETTERS 6 JULY 1992

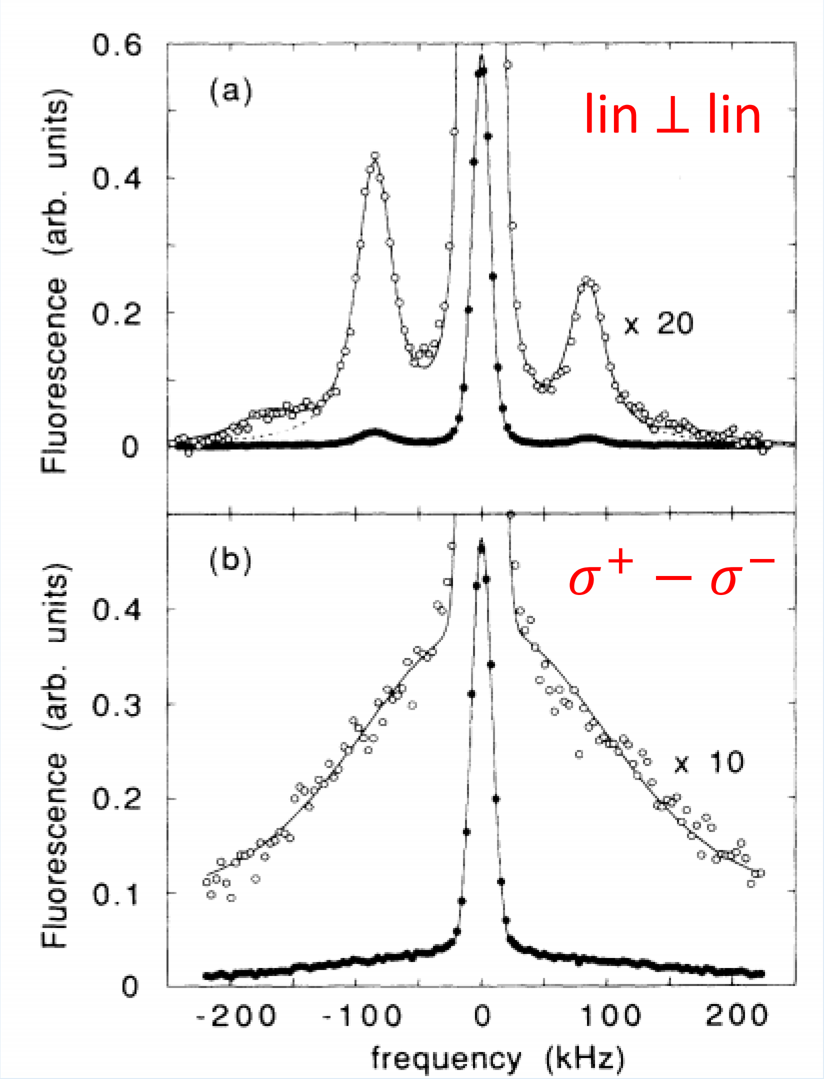
Observation of Quantized Motion of Rb Atoms in an Optical Field

P. S. Jessen,[a] C. Gerz, P. D. Lett, W. D. Phillips, S. L. Rolston, R. J. C. Spreeuw, and C. I. Westbrook
National Institute of Standards and Technology, U.S. Department of Commerce, Technology Administration, PHYS A167, Gaithersburg, Maryland 20899
(Received 6 May 1992)

We observe transitions of laser-cooled Rb between vibrational levels in subwavelength-sized optical potential wells, using high-resolution spectroscopy of resonance fluorescence. We measure the spacing of the levels and the population distribution, and find the atoms to be localized to $\frac{1}{15}$ of the optical wavelength. We find up to 60% of the population of trapped atoms in the vibrational ground state. The dependence of the spectrum on the parameters of the optical field provides detailed information about the dynamics of laser-cooled atoms.

^{87}Rb atoms in optical molasses,
heterodyne measurement of the scattered photons

Another view of Sisyphus cooling



- Discrete frequency "sidebands"
- Asymmetry in their weights

Another view of Sisyphus cooling

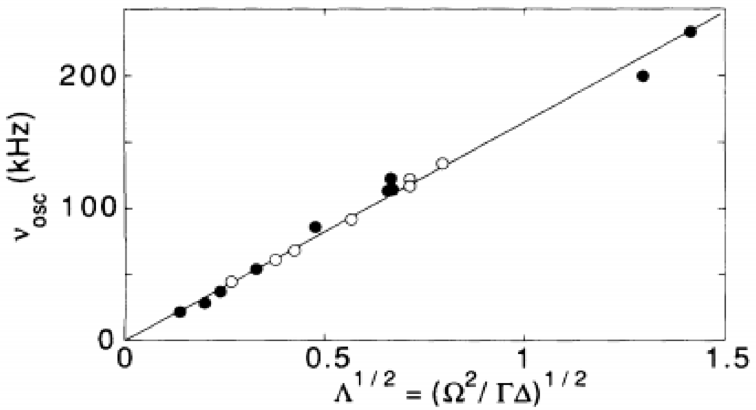


FIG. 2. Measured splitting between sidebands and central peak, as a function of $\Lambda^{1/2}$. Solid circles represent data for $\Delta = -4\Gamma$; open circles, data for $\Delta = -8\Gamma$. The line is a fit of $\nu_{osc} = \alpha\Lambda^{1/2}$.

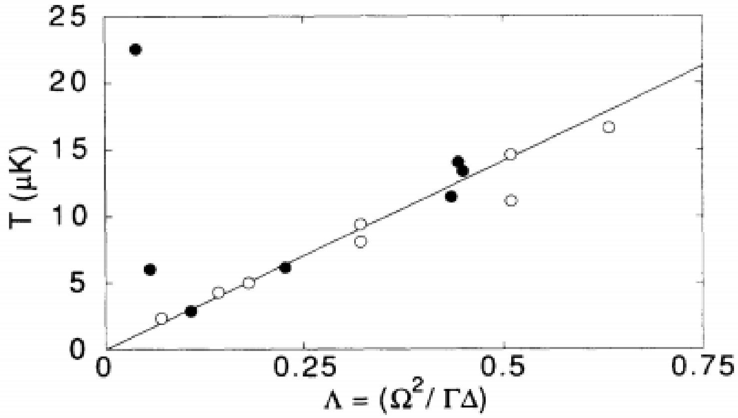


FIG. 3. Measured temperature as a function of Λ. Solid circles represent data for $\Delta = -4\Gamma$; open circles, data for $\Delta = -8\Gamma$. The line is a fit of $T = \alpha\Lambda$ to all the data, omitting the two points with the smallest Λ. The sharp rise in temperature for small Λ is due to a breakdown of laser cooling (see Ref. [12]).

harmonic frequency vs. “lattice” depth

zero-point energy vs. “lattice” depth

Another view of Sisyphus cooling

With up to 60% of the population in the vibrational ground state, a trapped atom begins to approximate a minimum uncertainty wave packet. This suggests interesting experiments with driven atomic motion: production of superpositions of vibrational states corresponding to a coherent, oscillating atomic wave packet, or even a squeezed atomic state. It may also be possible to employ sideband-cooling schemes using stimulated and spontaneous Raman transitions between vibrational levels.

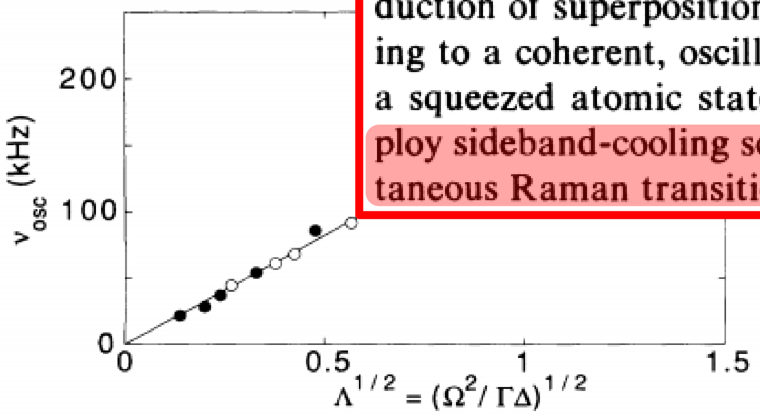


FIG. 2. Measured splitting between sidebands and central peak, as a function of $\Lambda^{1/2}$. Solid circles represent data for $\Delta = -4\Gamma$; open circles, data for $\Delta = -8\Gamma$. The line is a fit of $\nu_{osc} = \alpha\Lambda^{1/2}$.

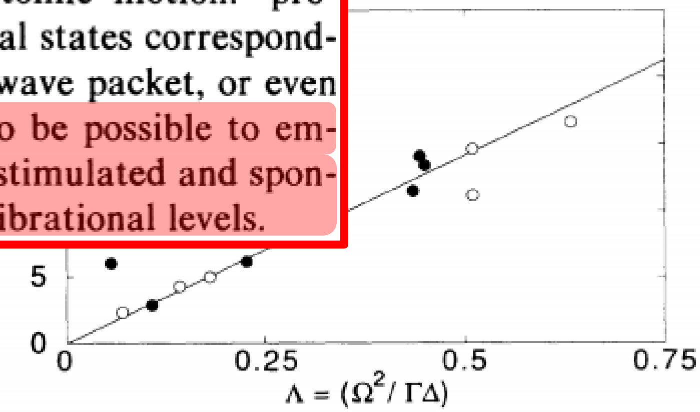
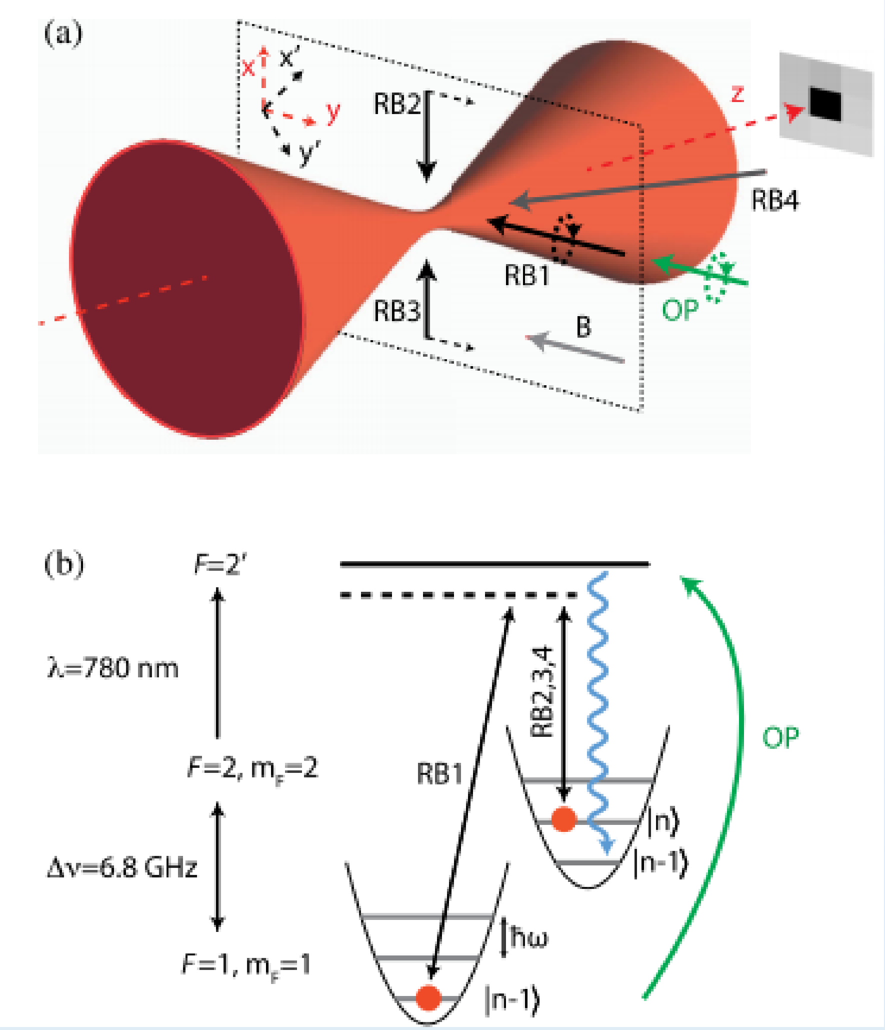


FIG. 3. Measured temperature as a function of Λ. Solid circles represent data for $\Delta = -4\Gamma$; open circles, data for $\Delta = -8\Gamma$. The line is a fit of $T = \alpha\Lambda$ to all the data, omitting the two points with the smallest Λ. The sharp rise in temperature for small Λ is due to a breakdown of laser cooling (see Ref. [12]).

harmonic frequency vs. “lattice” depth

zero-point energy vs. “lattice” depth

Raman sideband cooling – recent result on cooling of individually trapped atoms



Key ingredients

- stimulated Raman transition to reduce motional quanta (remove a phonon)
- optical pumping to "refresh" the cycle

Regal group, 2012

Raman sideband cooling with trapped ions

VOLUME 75, NUMBER 22 PHYSICAL REVIEW LETTERS 27 NOVEMBER 1995

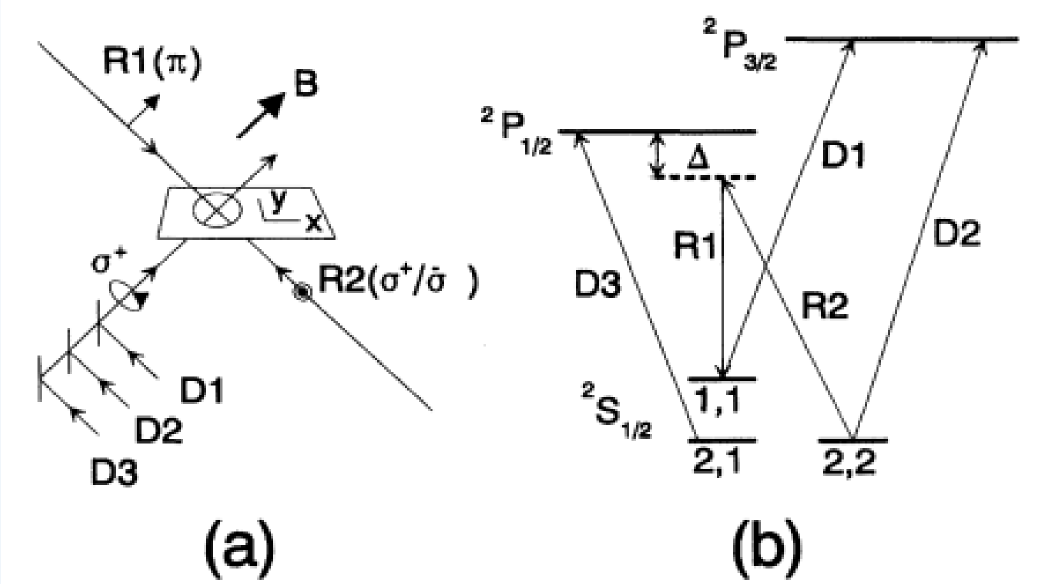
Resolved-Sideband Raman Cooling of a Bound Atom to the 3D Zero-Point Energy

C. Monroe, D. M. Meekhof, B. E. King, S. R. Jefferts, W. M. Itano, and D. J. Wineland
Time and Frequency Division, National Institute of Standards and Technology, Boulder, Colorado 80303

P. Gould
Department of Physics, University of Connecticut, Storrs, Connecticut 06269
(Received 19 December 1994)

We report laser cooling of a single $^{9}Be^{+}$ ion held in a rf (Paul) ion trap to where it occupies the quantum-mechanical ground state of motion. With the use of resolved-sideband stimulated Raman cooling, the zero point of motion is achieved 98% of the time in 1D and 92% of the time in 3D. Cooling to the zero-point energy appears to be a crucial prerequisite for future experiments such as the realization of simple quantum logic gates applicable to quantum computation.

Raman sideband cooling with trapped ions



Key ingredients

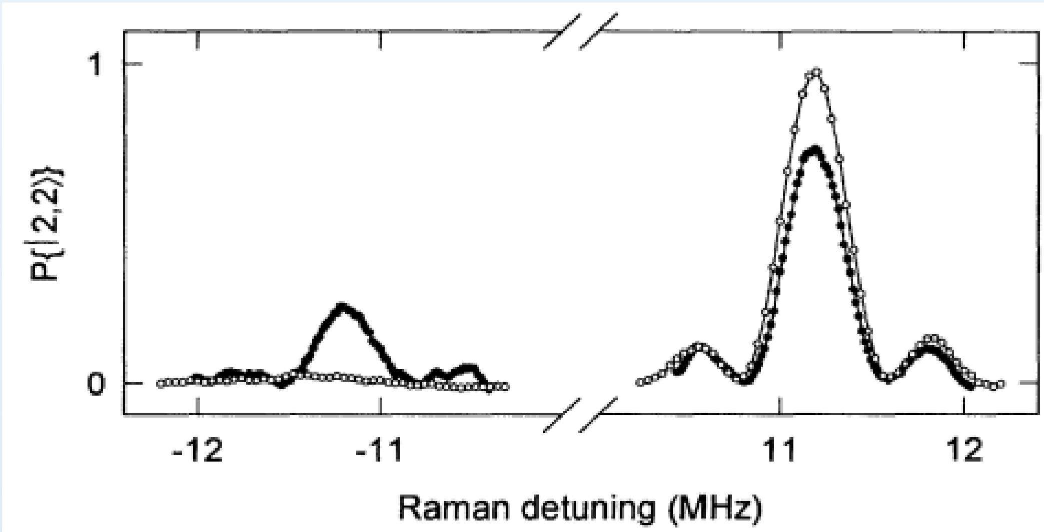
- stimulated Raman transition to reduce motional quanta (remove a phonon)
- optical pumping to "refresh" the cycle

TABLE I. Timing sequence for Doppler precooling, resolved-sideband stimulated Raman cooling and Raman detection of $\langle n_v \rangle$. As the sequence is repeated through steps 1–7, δ_{pr} is slowly swept across absorption features. Raman cooling steps (3 and 4) are repeated as desired within the sequence.

Step	Duration (μs)	Beams $D1$, $D3$	$D2$	$R1$, $R2$	Raman tuning	Function
1	≃50	On	On	Off	⋯	Doppler precool
2	≃7	On	Off	Off	⋯	Prepare in $\|2,2\rangle$ state
3	1–3	Off	Off	On	$\omega_0 - \omega_v$	Stimulated Raman transition $\|2,2\rangle\|n_v\rangle \rightarrow \|1,1\rangle\|n_v - 1\rangle$
4	≃7	On	Off	Off	⋯	Spontaneous Raman recycle $\|1,1\rangle\|n_v - 1\rangle \rightarrow \|2,2\rangle\|n_v - 1\rangle$
5	1–3	Off	Off	On	$\omega_0 + \delta_{pr}$	Probe $\langle n_v \rangle$ with stimulated Raman transitions $\|2,2\rangle\|n_v\rangle \rightarrow \|1,1\rangle\|n_v'\rangle$
6	≃1	Off	Off	On	ω_0	Exchange π pulse: $\|2,2\rangle\|n_v\rangle \leftrightarrow \|1,1\rangle\|n_v\rangle$
7	≃200	Off	On	Off	⋯	Detect transition in step 5: cycle on $\|2,2\rangle \rightarrow \|3,3\rangle$; collect fluorescence

Raman sideband cooling with trapped ions

anti-Stokes Stokes



$\langle n_x \rangle \simeq 0.47(5).$

$\langle n_x \rangle \simeq 0.014(10)$

Dark = before Raman sideband cooling
Light = after

Raman sideband cooling with cold atoms

Degenerate Raman Sideband Cooling of Trapped Cesium Atoms at Very High Atomic Densities

Vladan Vuletić, Cheng Chin, Andrew J. Kerman, and Steven Chu
Department of Physics, Stanford University, Stanford, California 94305-4060
(Received 25 August 1998)

We trap 10^7 cesium atoms in a far red detuned 1D optical lattice. With degenerate Raman sideband cooling we achieve a vibrational ground state population of 80% for the steep trapping direction. Collisional coupling enables us to cool the spin-polarized gas in 3D without loss of atoms to a peak phase space density of 1/180 at a mean temperature of 2.8 μK and a density of 1.4×10^{13} cm^{-3}. [S0031-9007(98)08002-8]

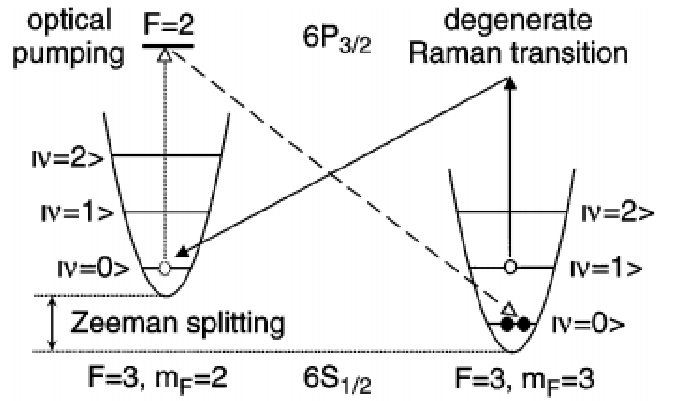


FIG. 1. Degenerate Raman sideband cooling in a Lamb-Dicke trap using the two lowest-energy magnetic levels. One cooling cycle consists of a vibration-changing Raman transition followed by optical pumping back to the $m_F = 3$ sublevel. The atoms accumulate in the vibrational ground state of the $m_F = 3$ level (black dots) which is dark to both the optical pumping light and the Raman transitions.

Raman sideband cooling to BEC

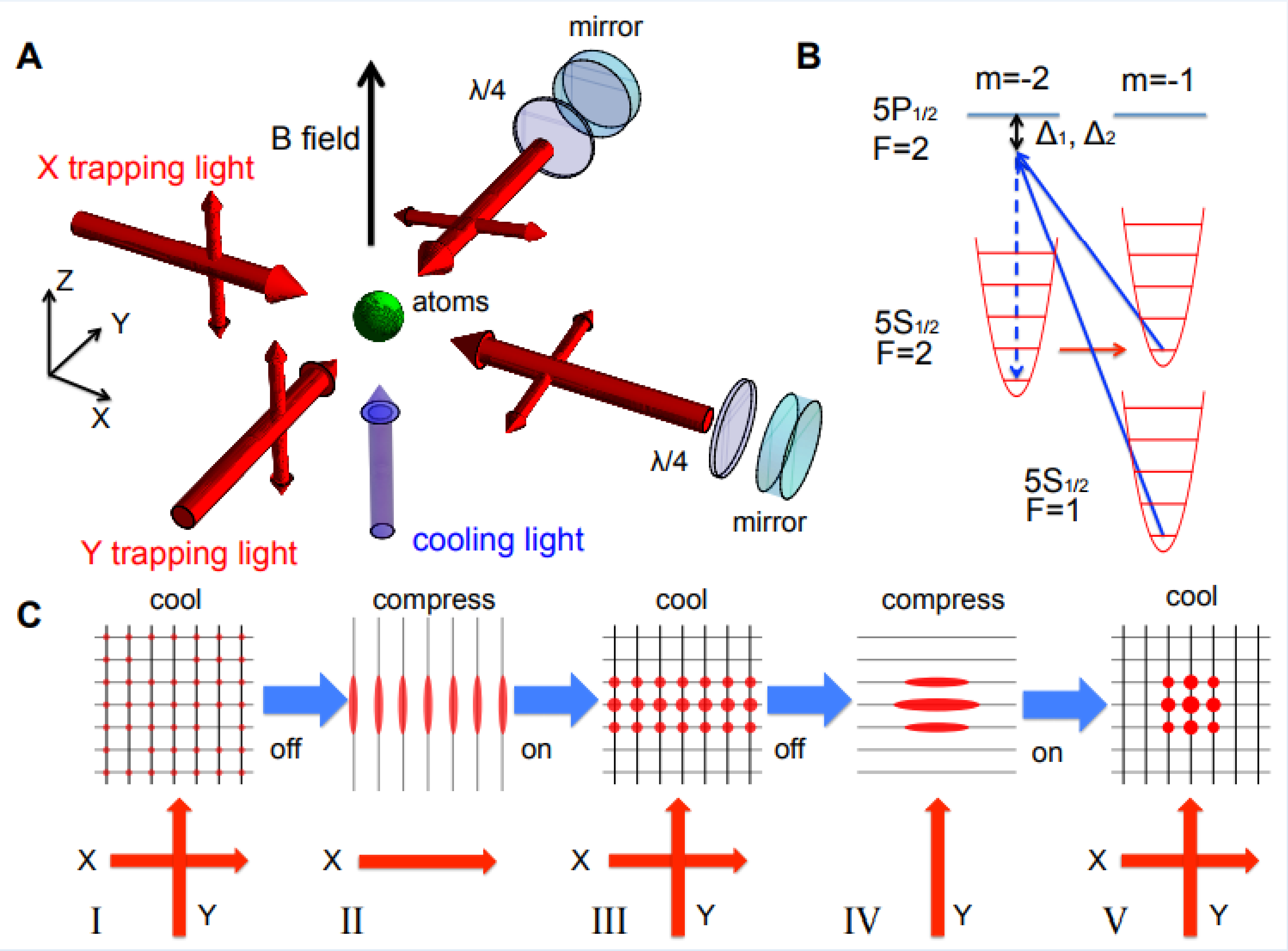
Creation of a Bose-condensed gas of rubidium 87 by laser cooling

Jiazhong Hu,* Alban Urvoy,* Zachary Vendeiro, Valentin Crépel, Wenlan Chen, and Vladan Vuletić
Department of Physics and Research Laboratory of Electronics,
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

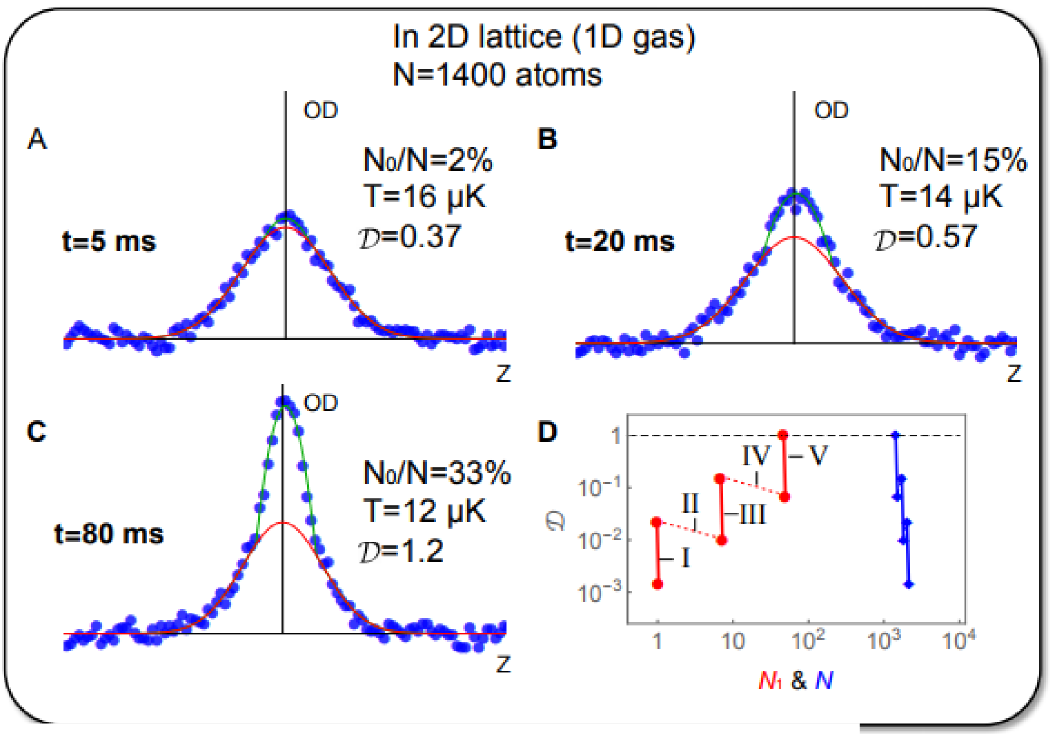
We demonstrate direct laser cooling of a gas of rubidium 87 atoms to quantum degeneracy. The method does not involve evaporative cooling, is fast, and induces little atom loss. The atoms are trapped in a two-dimensional optical lattice that enables cycles of cloud compression to increase the density, followed by degenerate Raman sideband cooling to decrease the temperature. Light-induced loss at high atomic density is substantially reduced by using far red detuned optical pumping light. Starting with 2000 atoms, we prepare 1400 atoms in 300 ms at quantum degeneracy, as confirmed by the appearance of a bimodal velocity distribution as the system crosses over from a classical gas to a Bose-condensed, interacting one-dimensional gas with a macroscopic population of the quantum ground state. The method should be broadly applicable to many bosonic and fermionic species, and to systems where evaporative cooling is not possible.

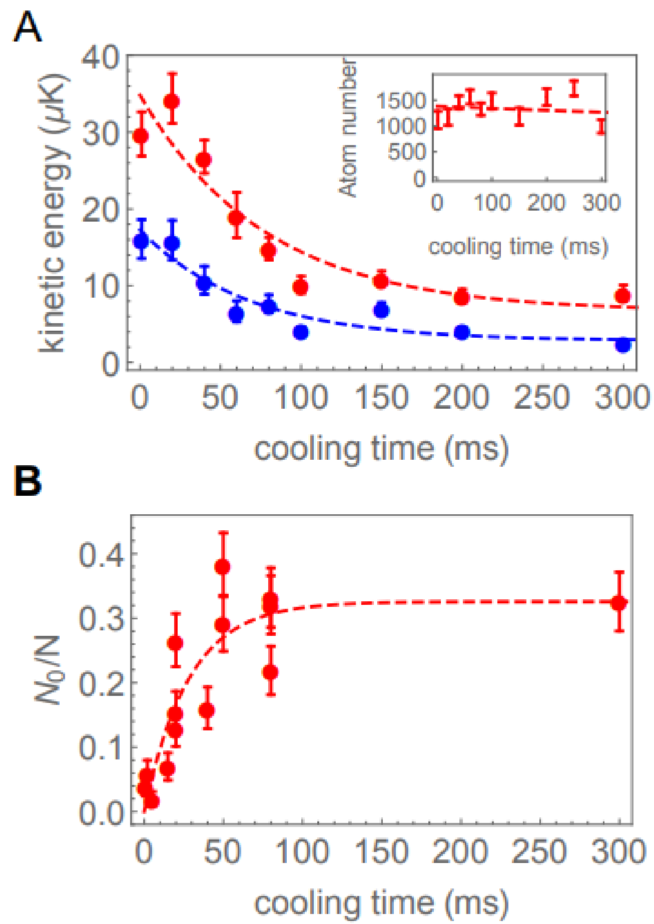
Vuletić colloquium on Nov. 1, on “attractive photons”

Raman sideband cooling to BEC



Raman sideband cooling to BEC





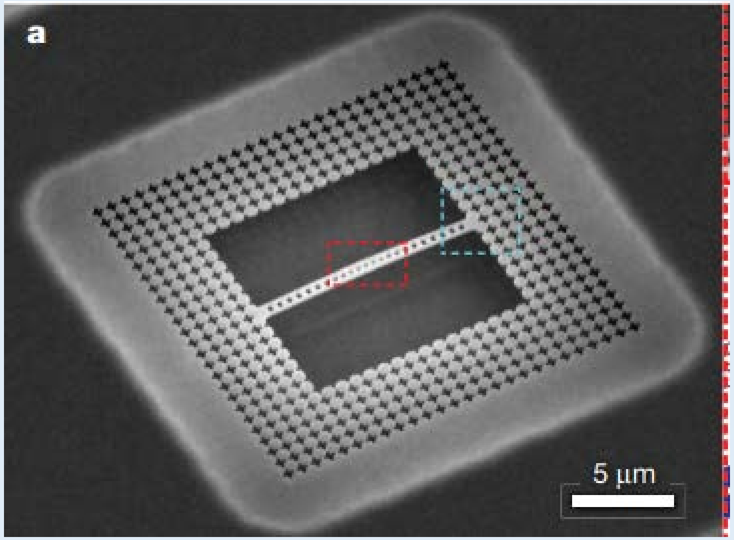
Related work – radiation forces of large mechanical objects (not atoms / ions)

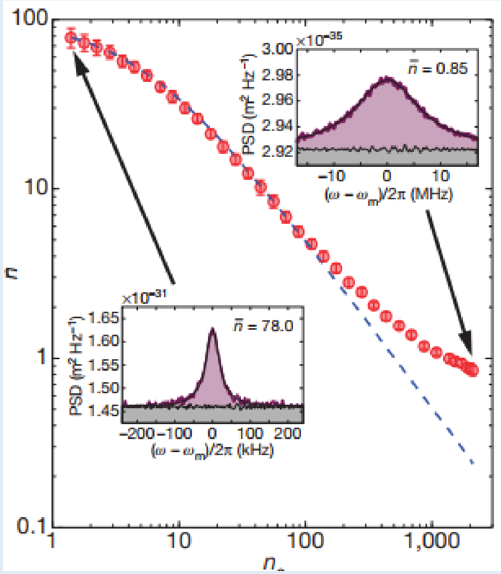
LETTER

doi:10.1038/nature10461

Laser cooling of a nanomechanical oscillator into its quantum ground state

Jasper Chan[1], T. P. Mayer Alegre[1]†, Amir H. Safavi-Naeini[1], Jeff T. Hill[1], Alex Krause[1], Simon Gröblacher[1,2], Markus Aspelmeyer[2] & Oskar Painter[1]





Related work – radiation forces of large mechanical objects (not atoms / ions)

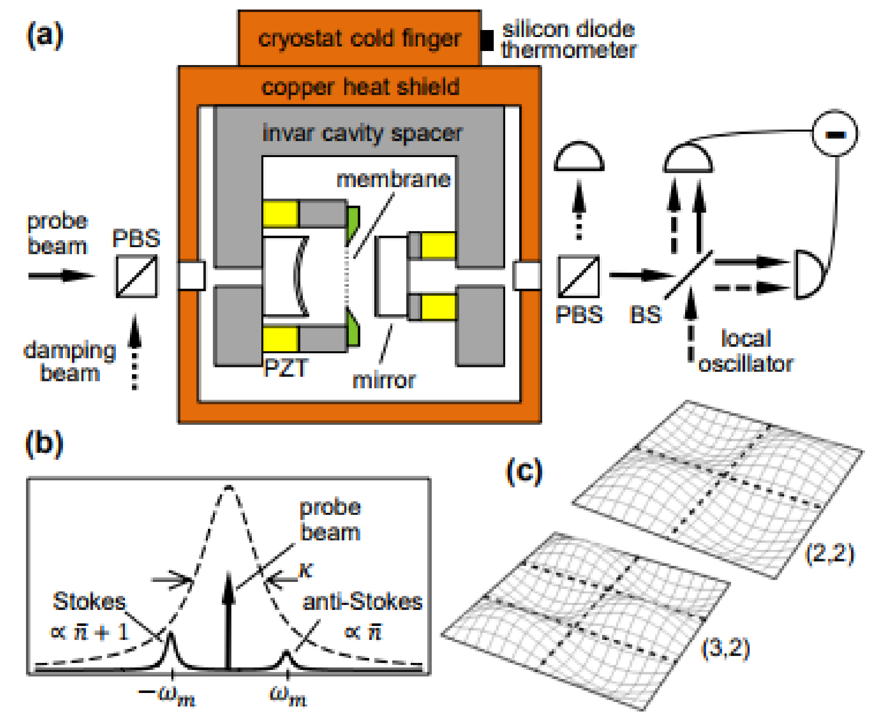
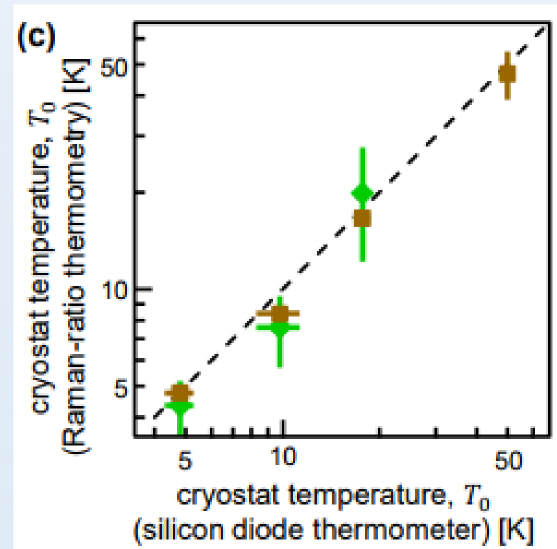


FIG. 1. Optomechanical Raman-ratio thermometry. (a) Two

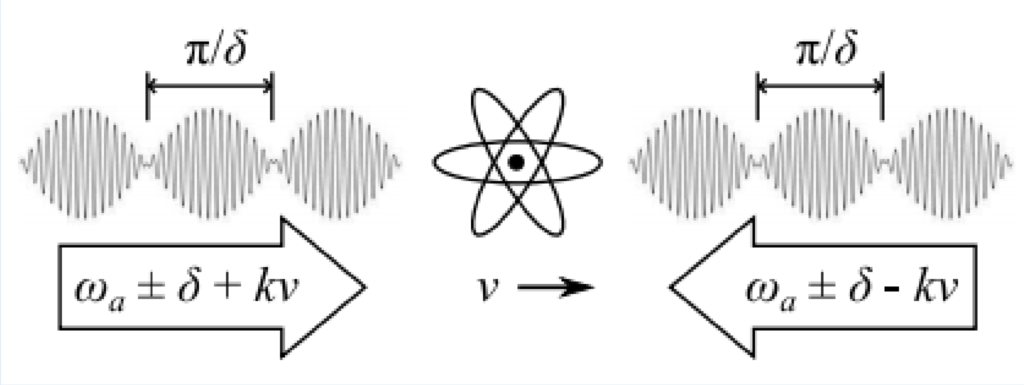


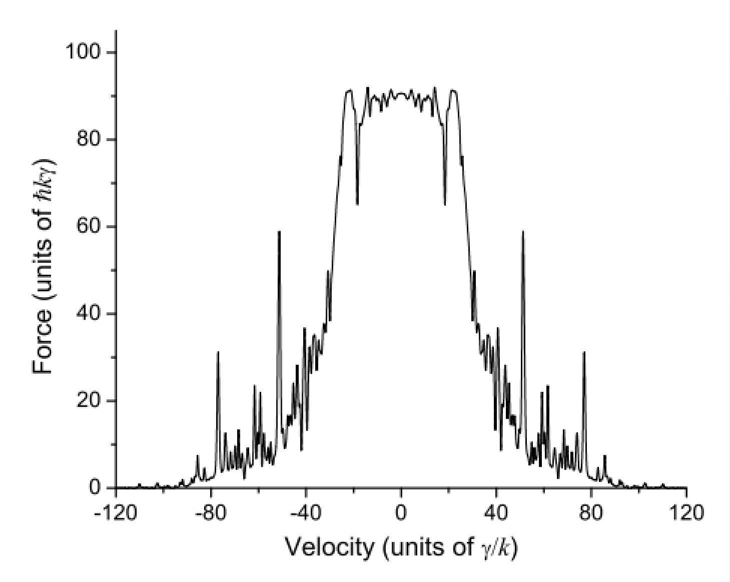
Purdy / Regal

Detection of temperature by Stokes/anti-Stokes asymmetry

Bichromatic forces [another "stimulated" process]

Two-color beating gives dominant stimulated absorption/emission
(Grimm, Metcalf, Eyler, DeMille, others)





π-pulse condition, with time
much less than excited state lifetime

-> much faster rate of excitation, larger force

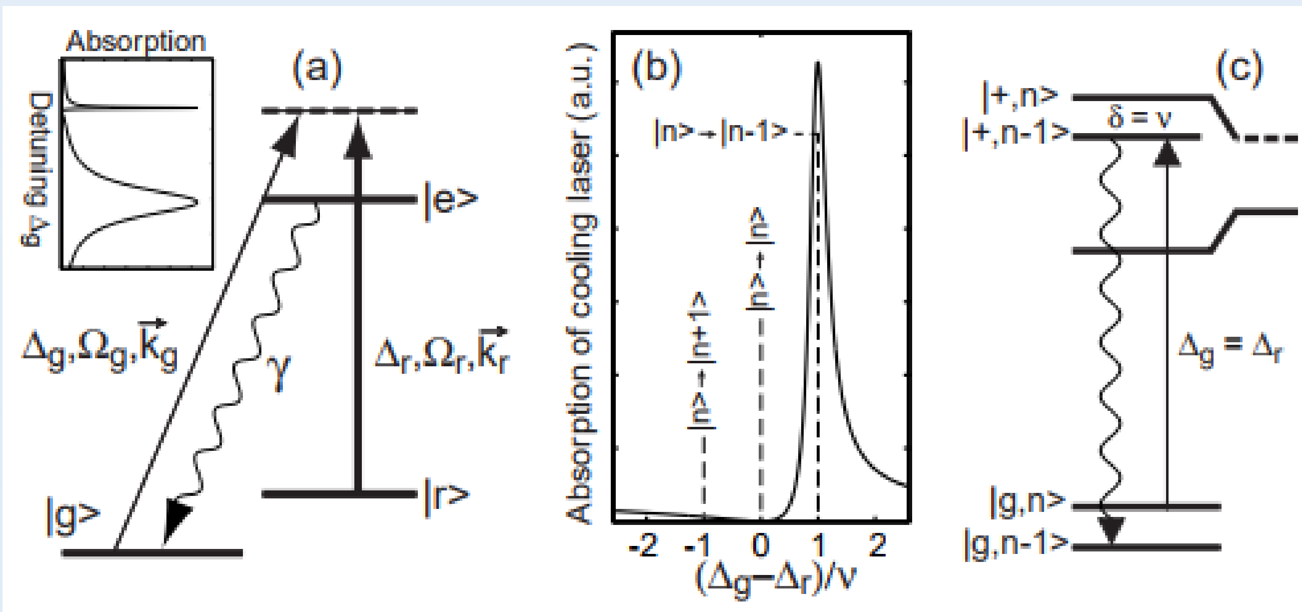
Figures from (Chieda, Eyler 2012)

Electromagnetically-induced transparency (EIT) cooling

VOLUME 85, NUMBER 21 PHYSICAL REVIEW LETTERS 20 NOVEMBER 2000

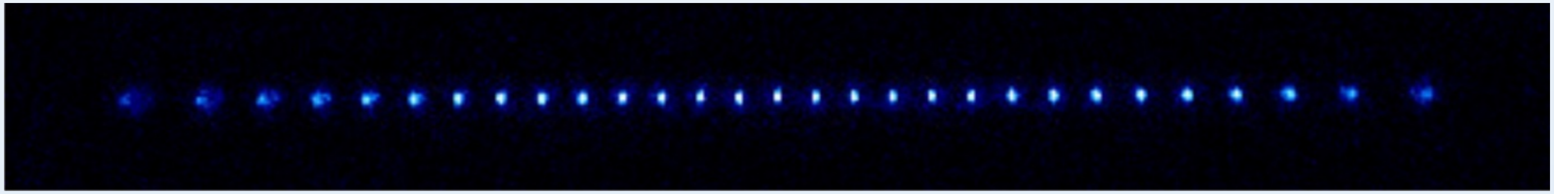
Ground State Laser Cooling Using Electromagnetically Induced Transparency

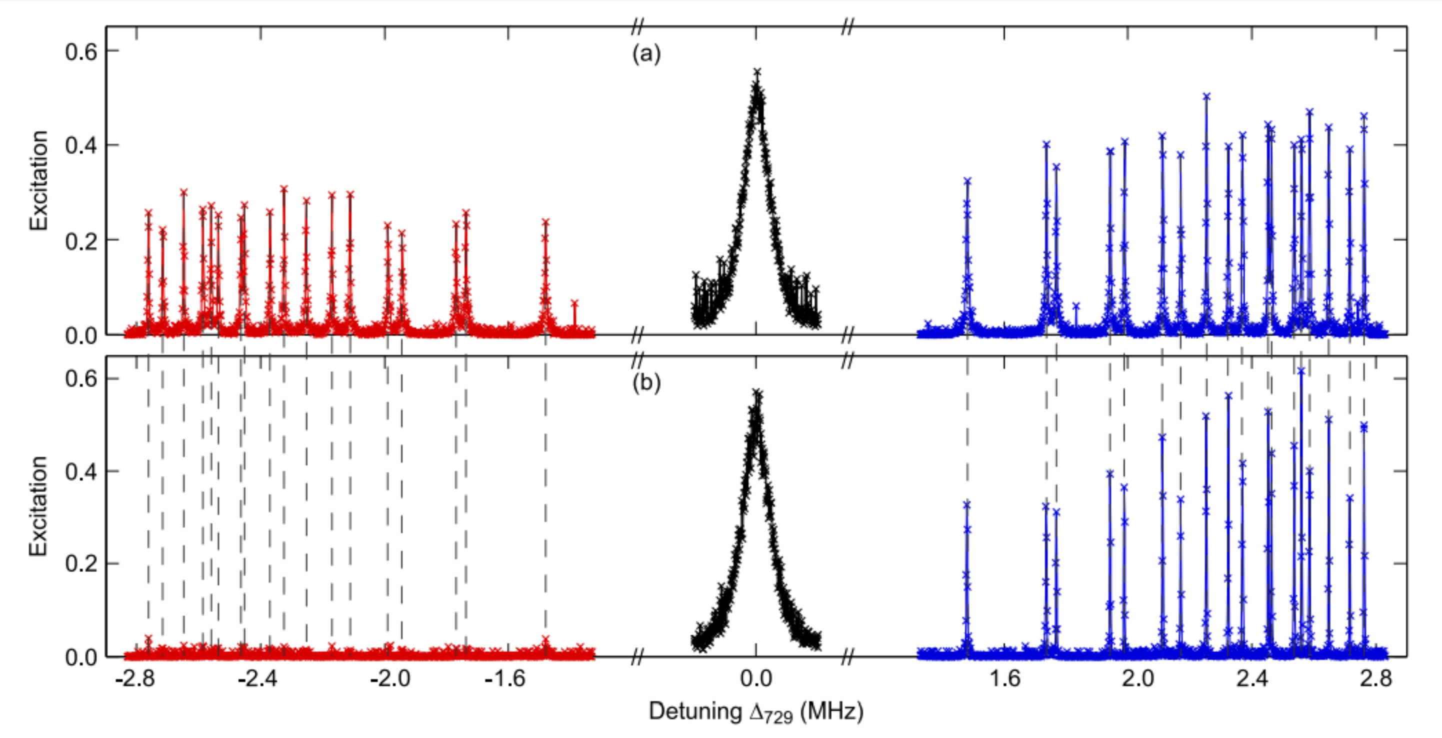
Giovanna Morigi,[1] Jürgen Eschner,[2] and Christoph H. Keitel[3]
[1]*Max-Planck Institut für Quantenoptik, D-85748 Garching, Germany*
[2]*Institut für Experimentalphysik, University of Innsbruck, A-6020 Innsbruck, Austria*
[3]*Theoretische Quantendynamik, Fakultät für Physik, University of Freiburg, D-79104 Freiburg, Germany*
(Received 5 May 2000)



An effect of "dark states" in multi- (beyond 2) level systems

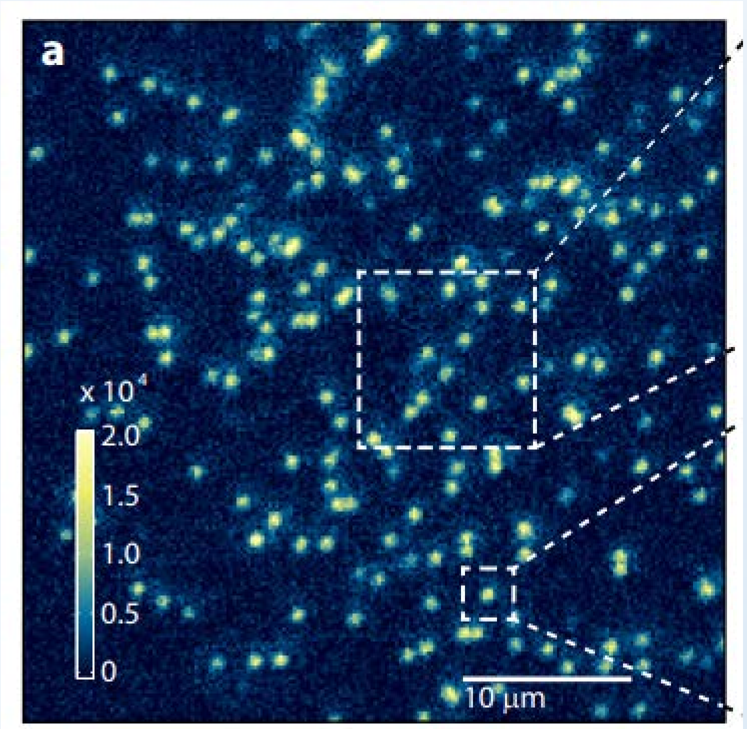
EIT cooling of a chain of ions

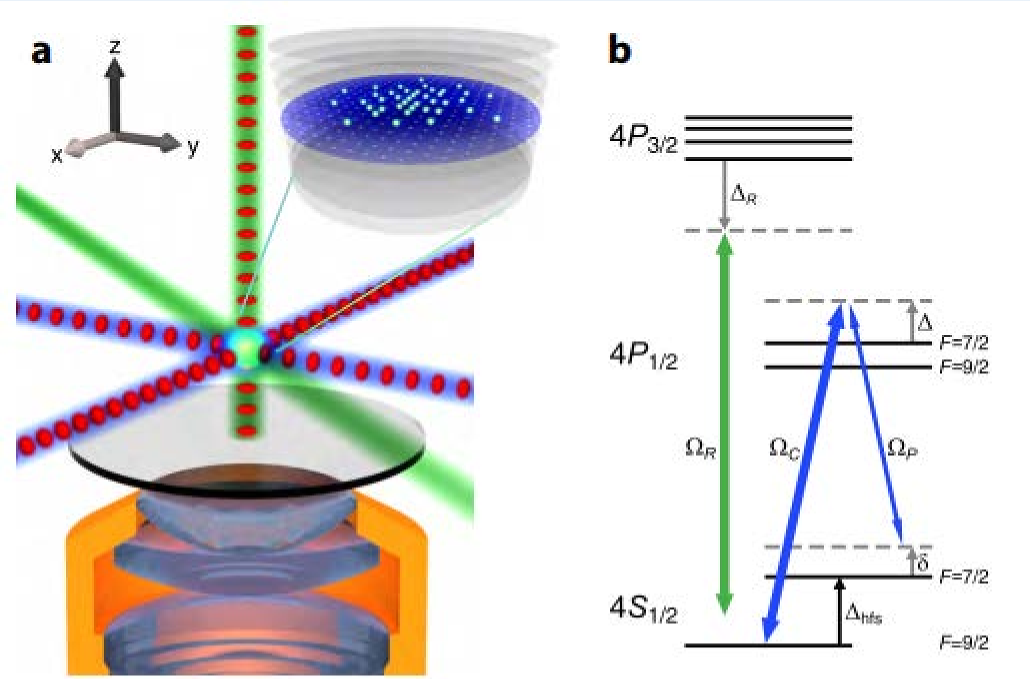




Roos, Blatt

EIT cooling of atoms in a QGM





Kuhr group, Strathclyde