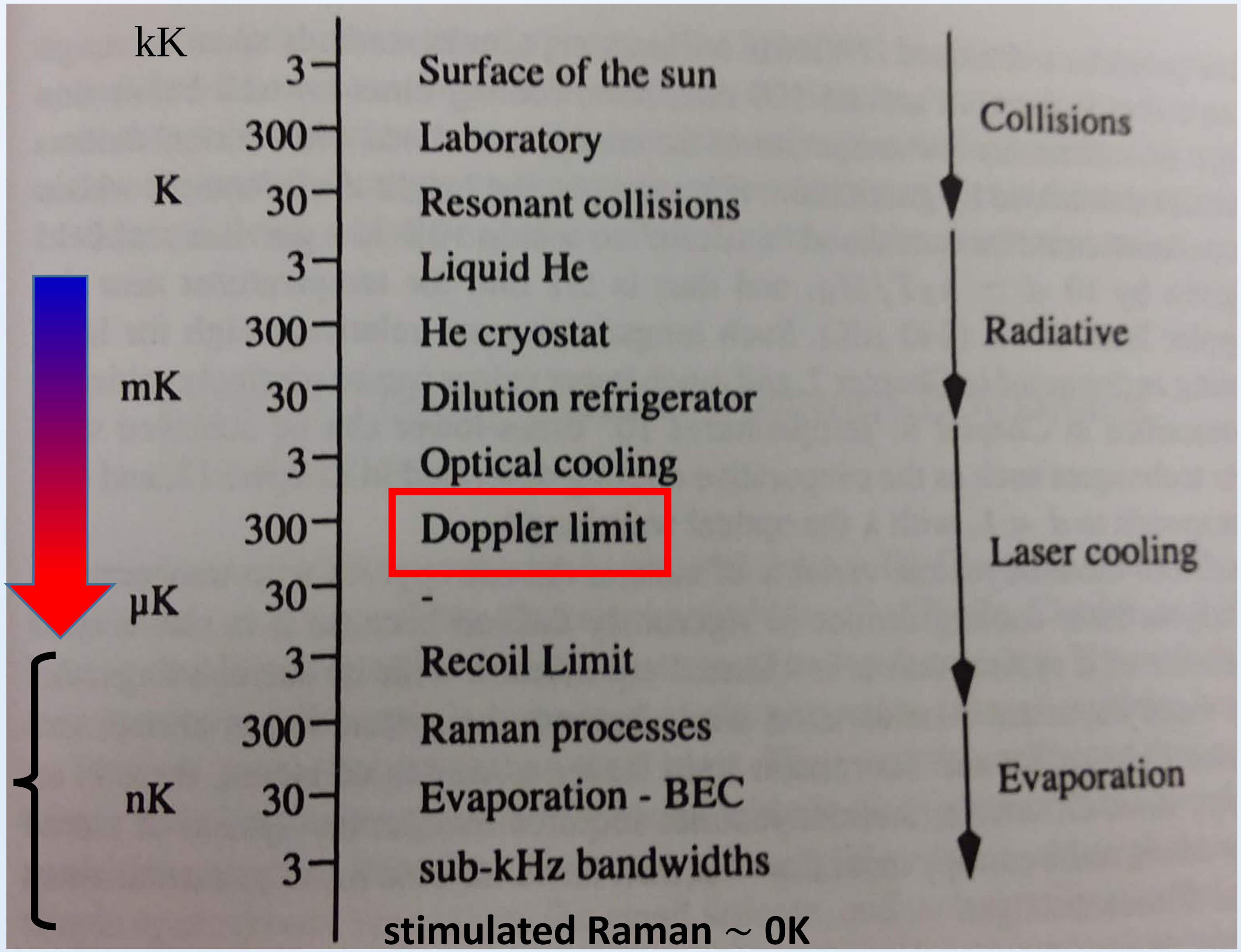
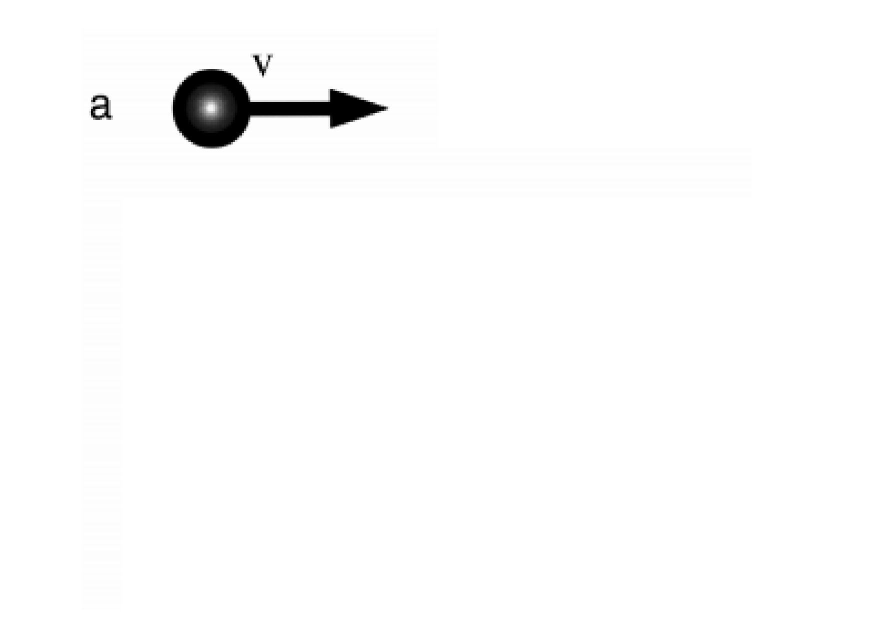
Laser-cooling and scattering forces

quantum
gas expts.



Metcalf & van der Straten, Laser Cooling and Trapping

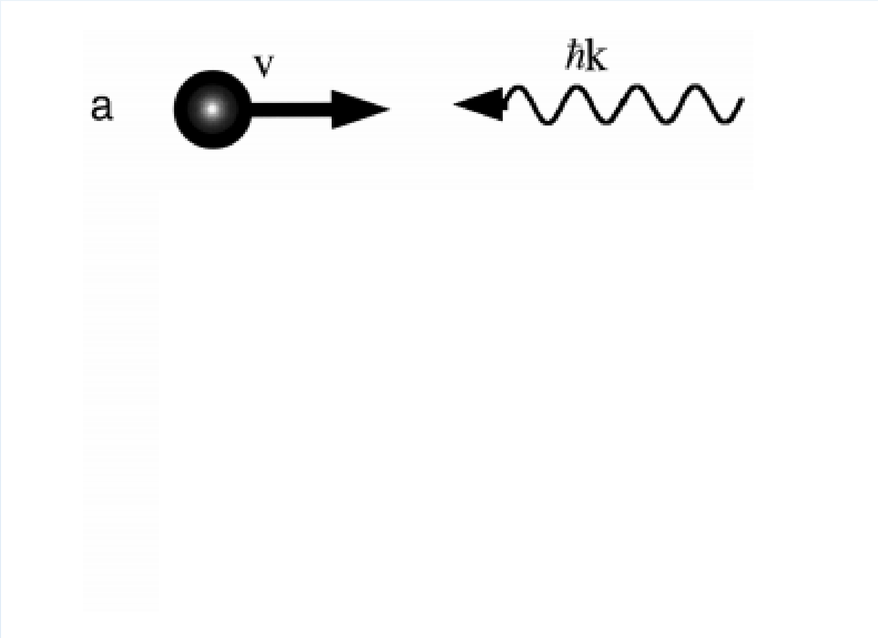
Laser-cooling and scattering forces



William D. Phillips: Laser cooling and trapping of neutral atoms

At room temperature,
typical speeds on the order of few $\times$ 100 m/s

Laser-cooling and scattering forces



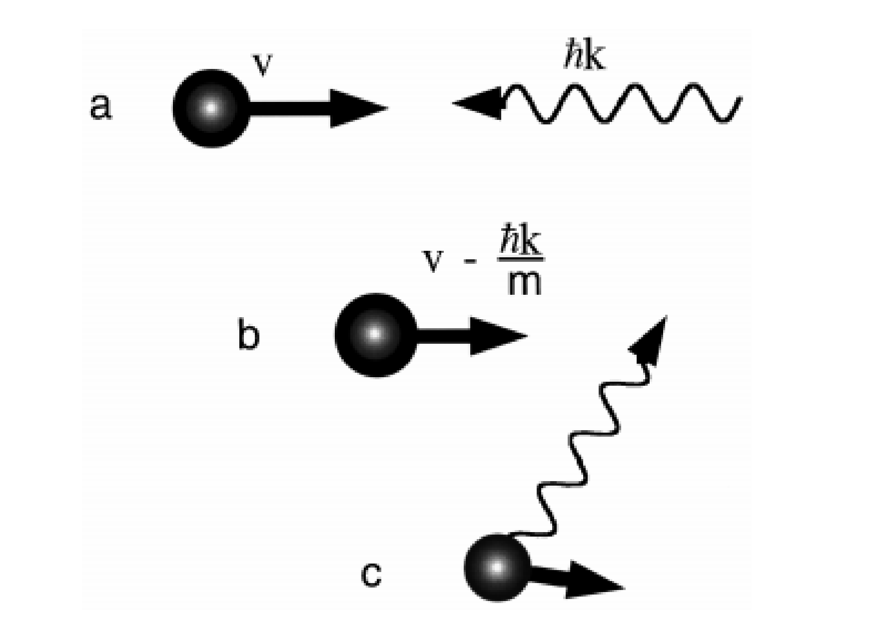
need to excite / de-excite few × 10,000 times!

William D. Phillips: Laser cooling and trapping of neutral atoms

At room temperature,
typical speeds on the order of few × 100 m/s

For sodium (23 amu), $\lambda \sim 600$ nm , $\frac{\hbar k}{m} \sim 3\ cm/s$

Laser-cooling and scattering forces



need to excite / de-excite few × 10,000 times!

William D. Phillips: Laser cooling and trapping of neutral atoms

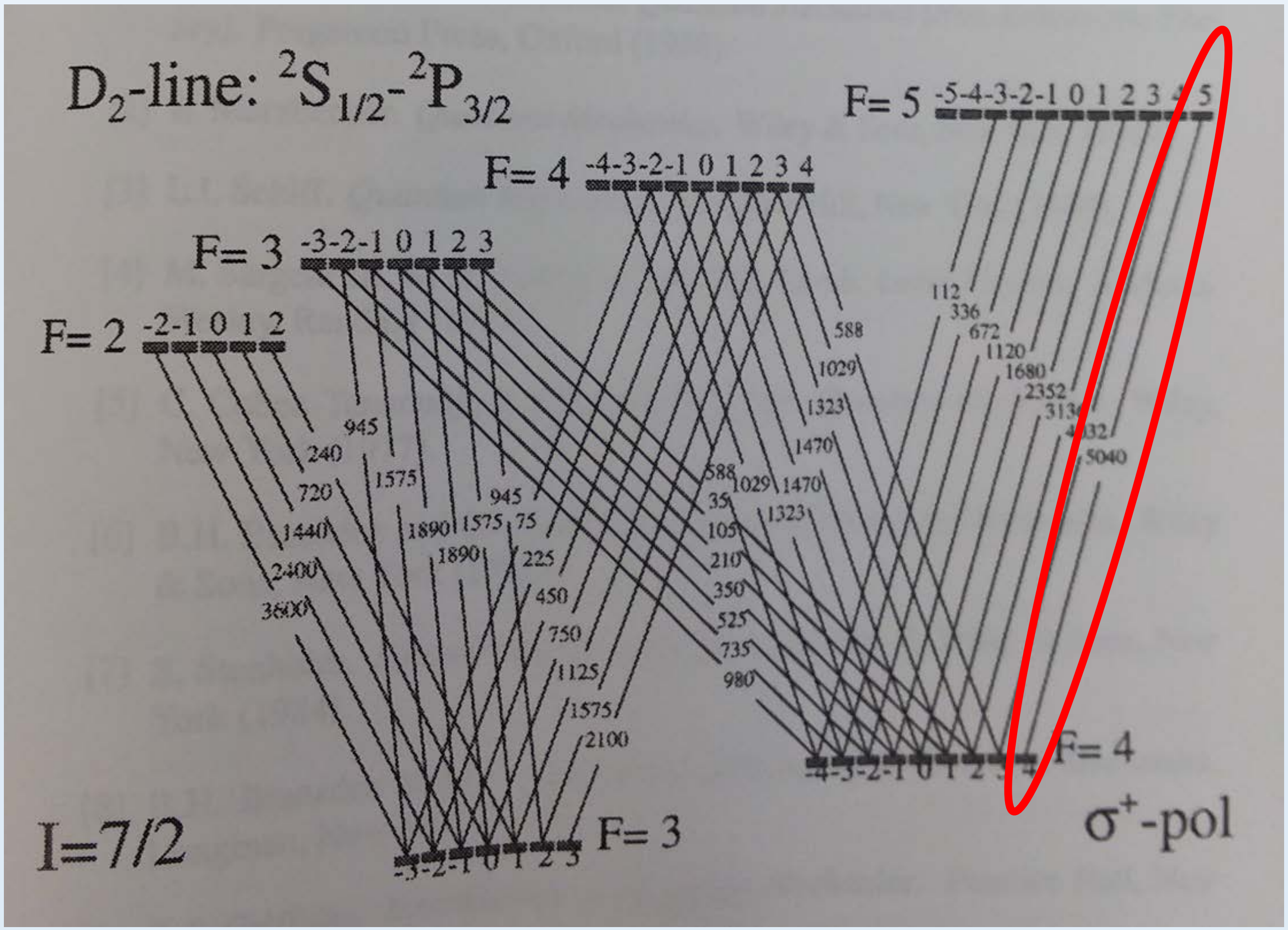
At room temperature,
typical speeds on the order of few × 100 m/s

For sodium (23 amu), $\lambda \sim 600$ nm , $\frac{\hbar k}{m} \sim 3\ cm/s$

Making a “2-level” atom

Dipole Matrix Elements – charts, tables, etc.

Cycling transition – cycles back and forth many times between two states



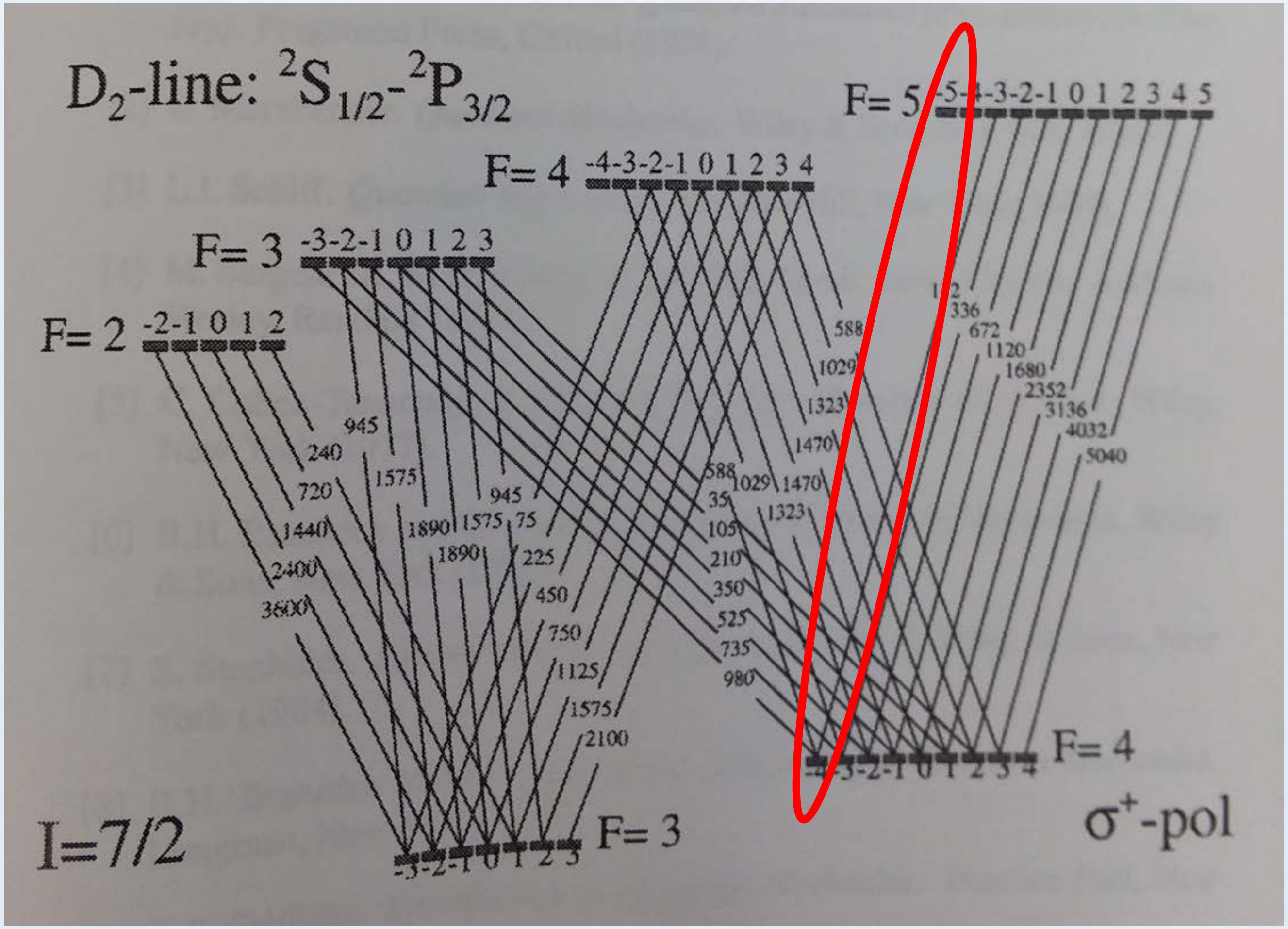
For σ_+

Effective “2-level atom”

Metcalf & van der Straten, Laser Cooling and Trapping

Making a "2-level" atom

Cycling transition – cycles back and forth many times between two states



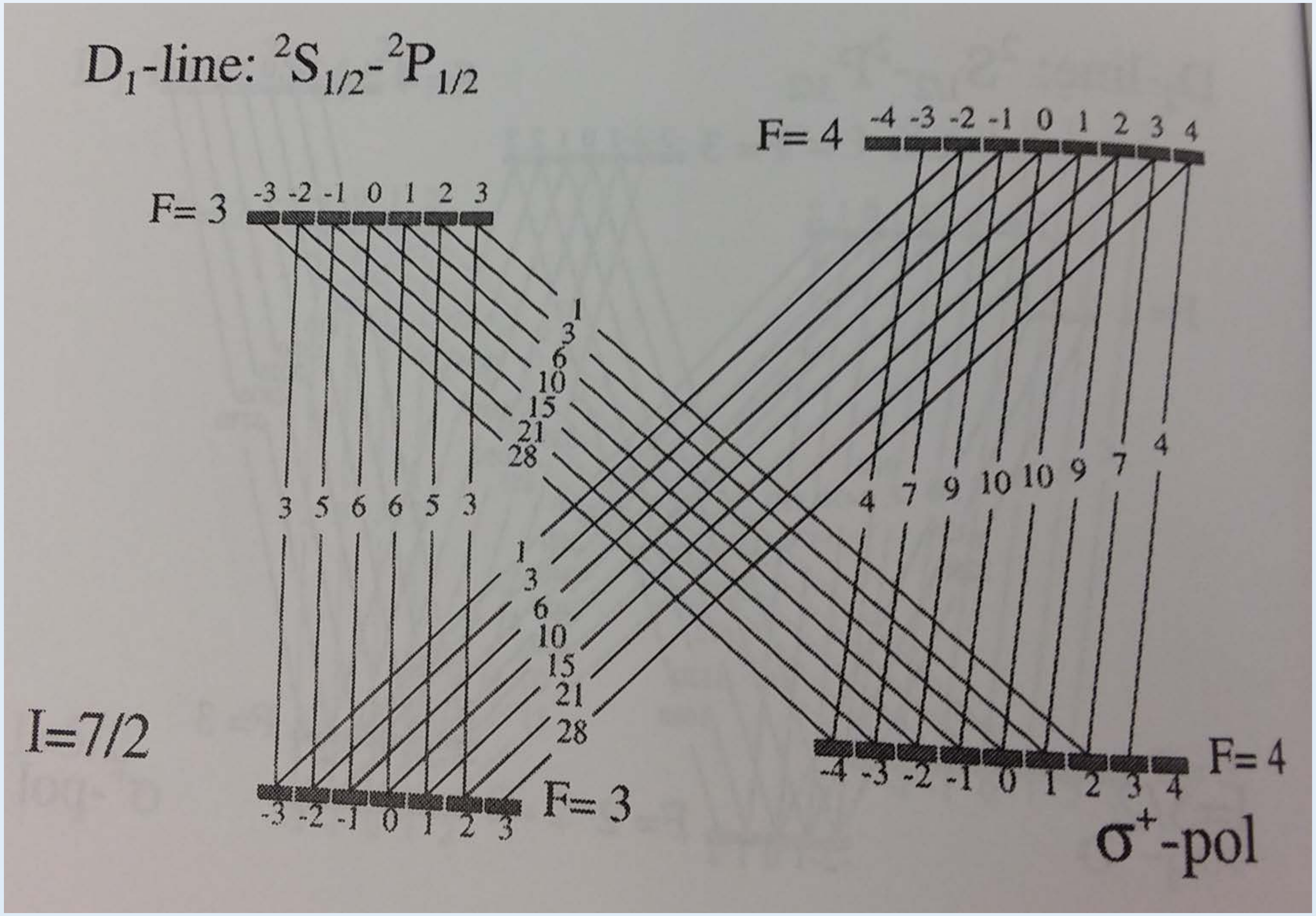
For σ_{-}

Effective "2-level atom"

Metcalf & van der Straten, Laser Cooling and Trapping

Making a "2-level" atom

Cycling transition – cycles back and forth many times between two states

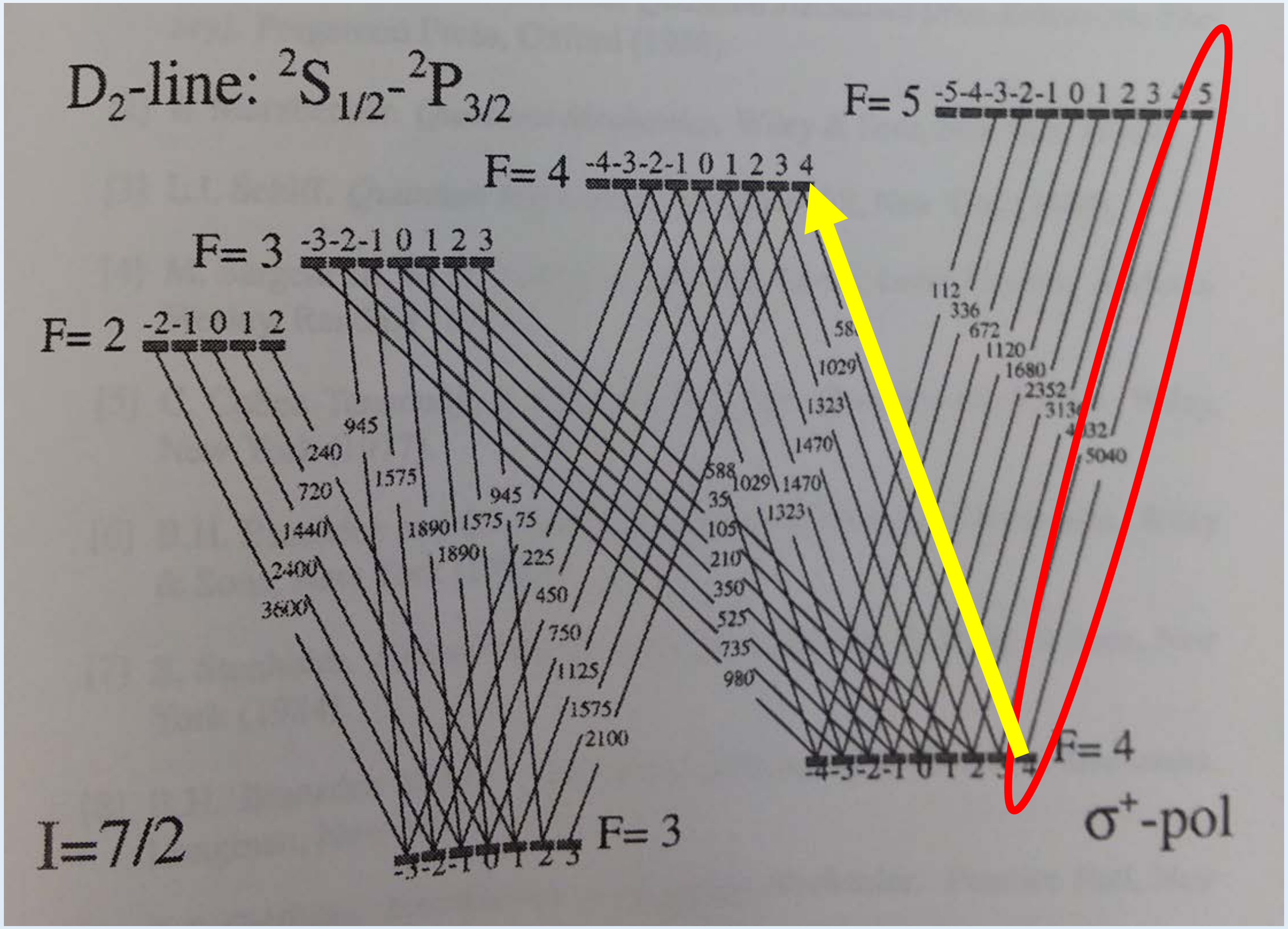


Can you make a cycling transition on the D1 line?

Metcalf & van der Straten, Laser Cooling and Trapping

Making a "2-level" atom

Cycling transition – cycles back and forth … until it doesn't



For σ_+

Effective "2-level atom"

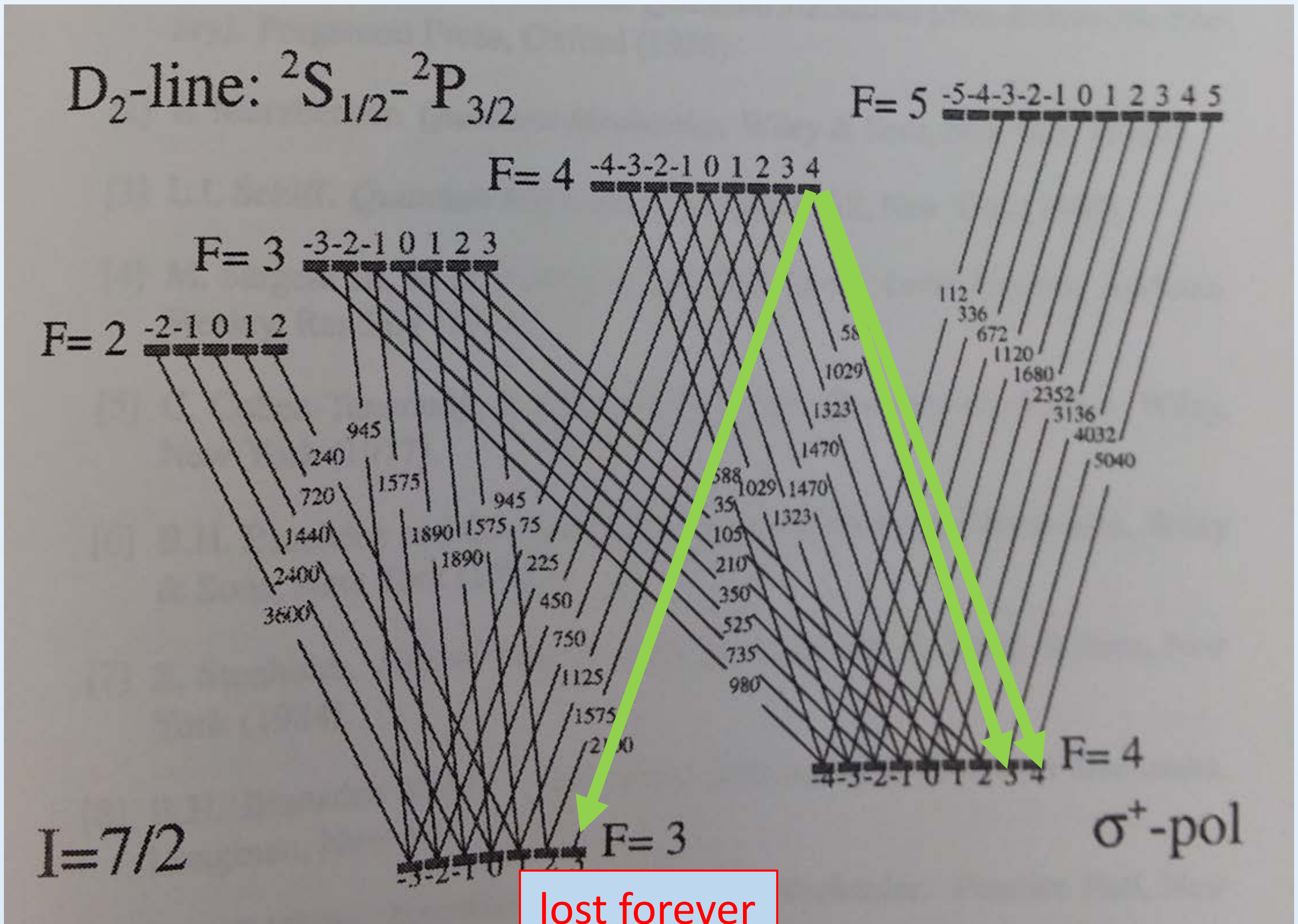
polarization not perfect…

sometimes drive wrong transition

Metcalf & van der Straten, Laser Cooling and Trapping

Making a "2-level" atom

Cycling transition – cycles back and forth … until it doesn't



lost forever

For σ_+

Effective "2-level atom"

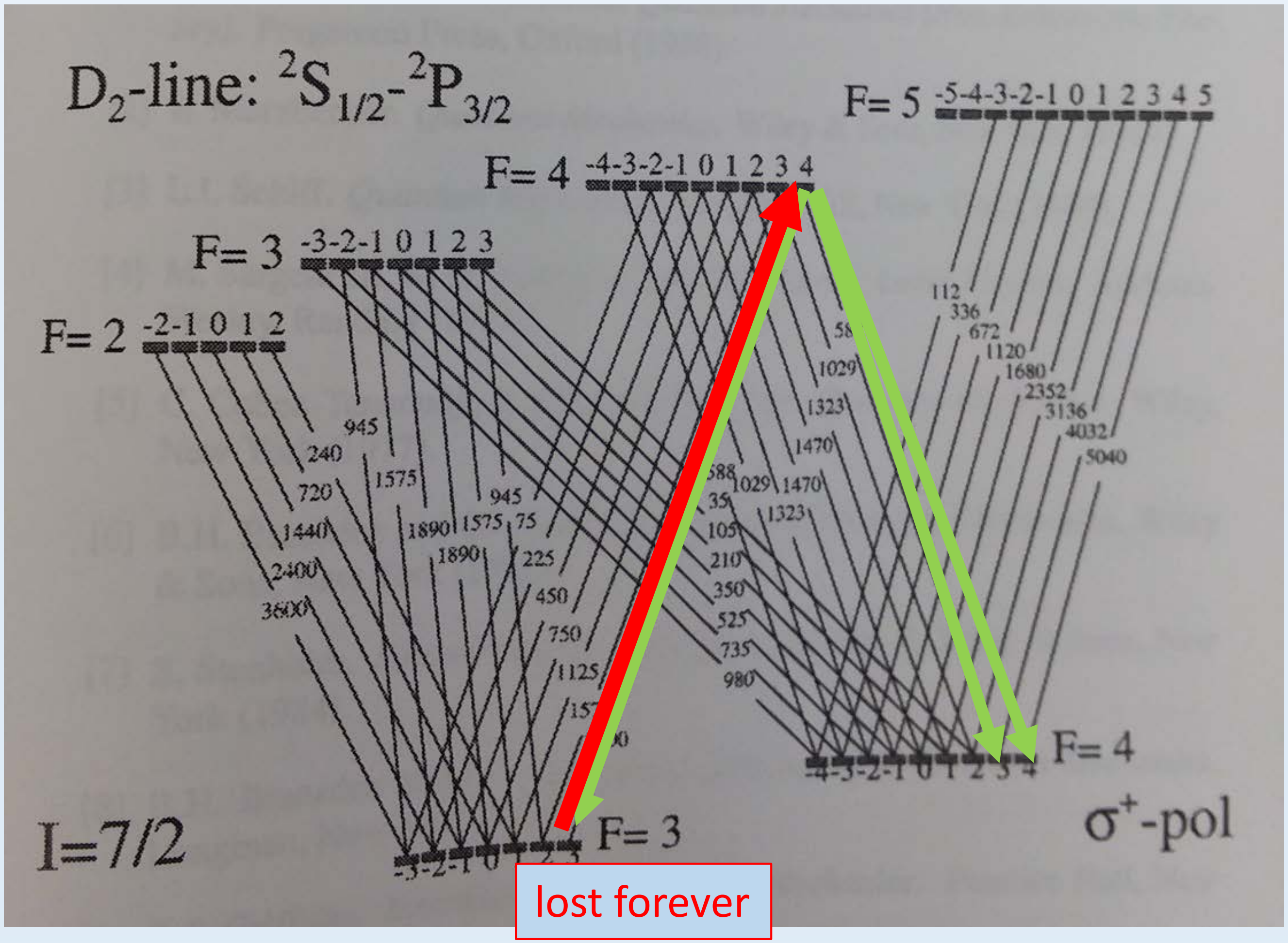
polarization not perfect…

sometimes drive wrong transition

Metcalf & van der Straten, Laser Cooling and Trapping

Making a "2-level" atom

Cycling transition – cycles back and forth … until it doesn't



Metcalf & van der Straten, Laser Cooling and Trapping

For σ_+

Effective "2-level atom"

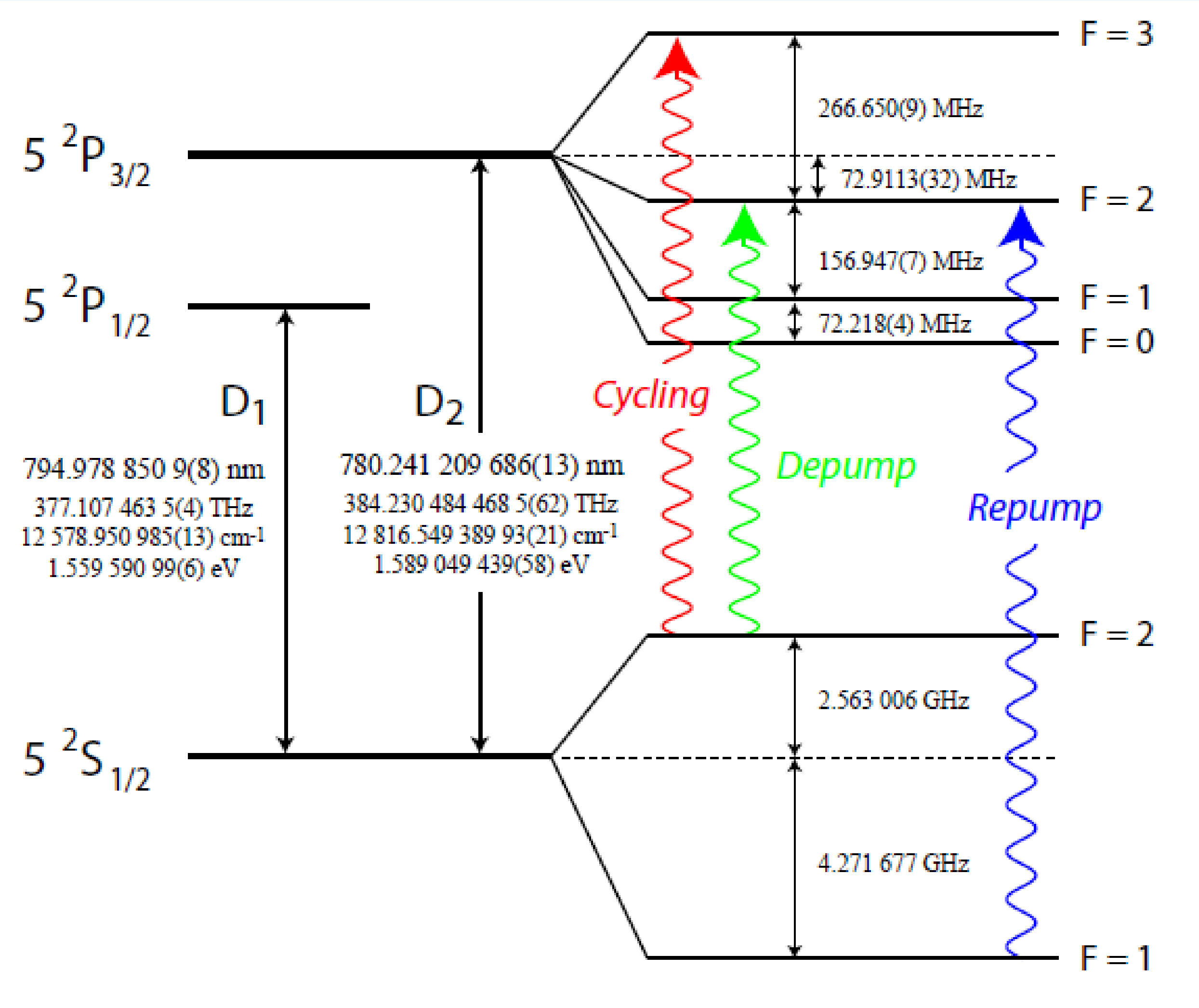
polarization not perfect…

sometimes drive wrong transition

add a **"repump"** to plug the hole

Making a “2-level” atom

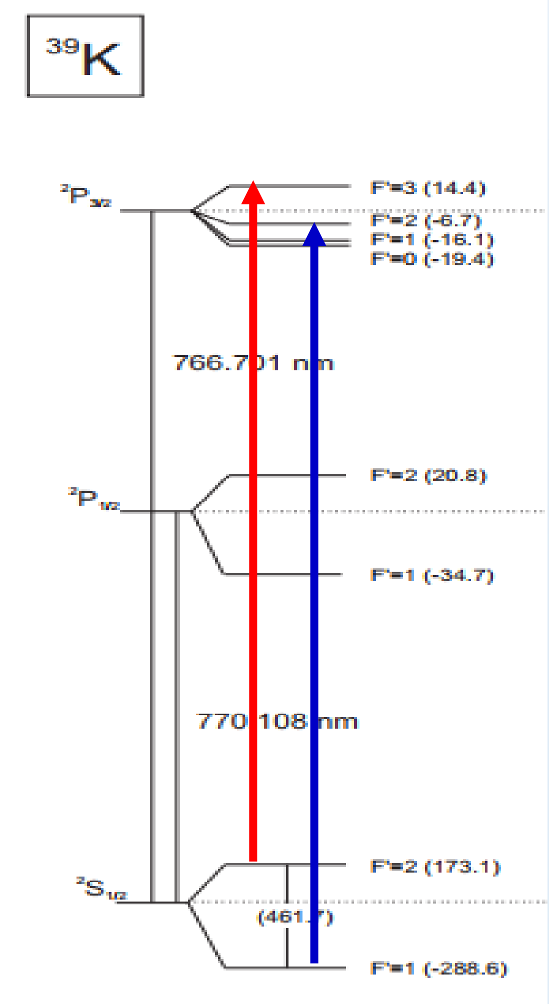
For some atoms, cycling transition well-resolved ($\Delta \gg \Gamma$)



not much repump light needed

Making a "2-level" atom

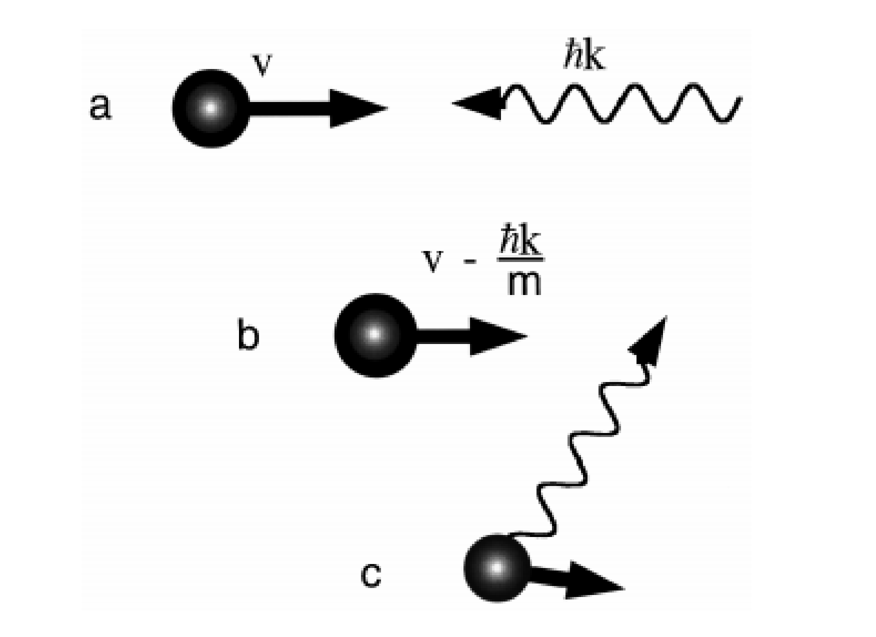
For others, excited-state hyperfine structure no well-resolved $(\Delta \sim \Gamma)$



Lots of repump light is needed

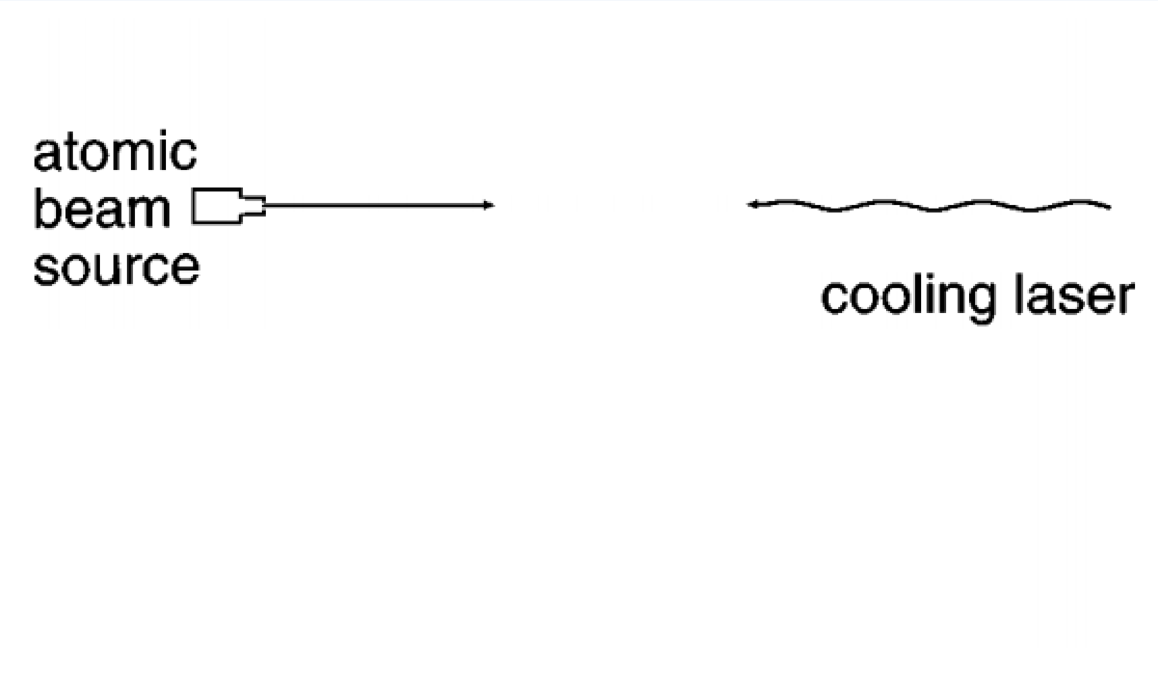
slightly harder, but still relatively straightforward (only one loss pathway to plug)

Laser-cooling and scattering forces

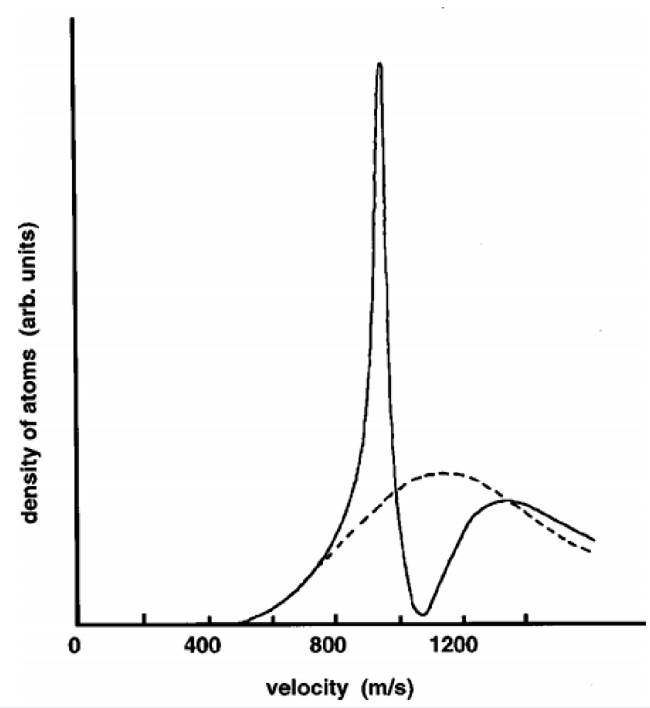


William D. Phillips: Laser cooling and trapping of neutral atoms

Slowing down atomic beams



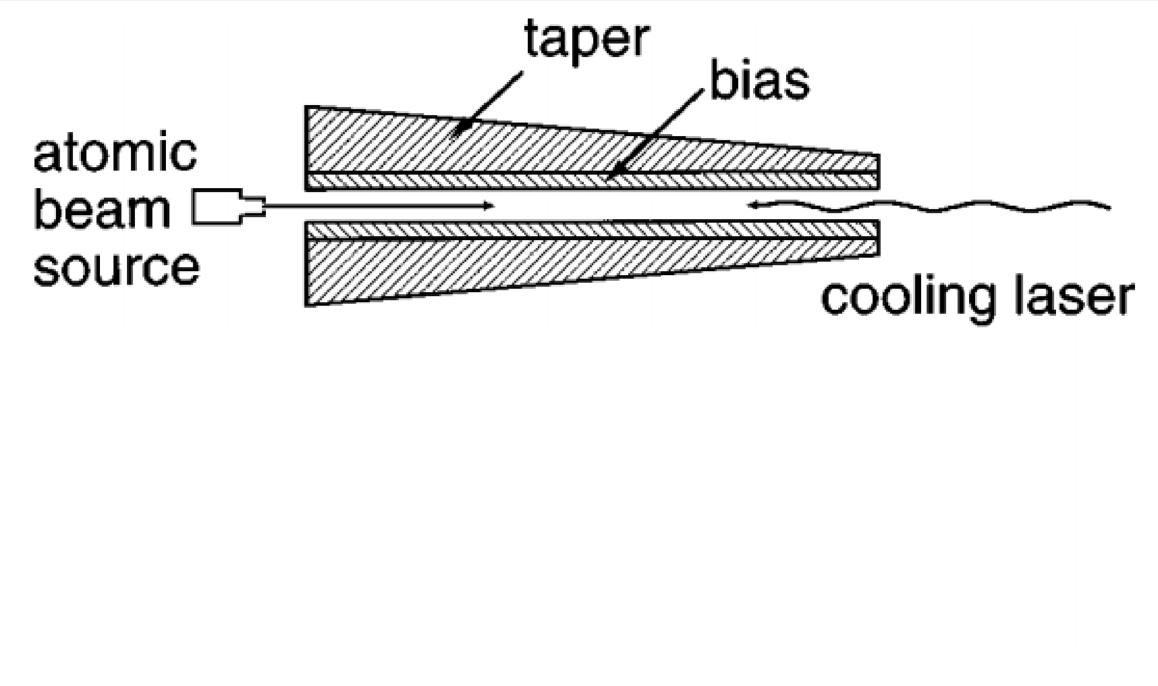
Effect of slowing:
simple case



Doppler shift! $\delta = \omega - \omega_{eg} + kv$

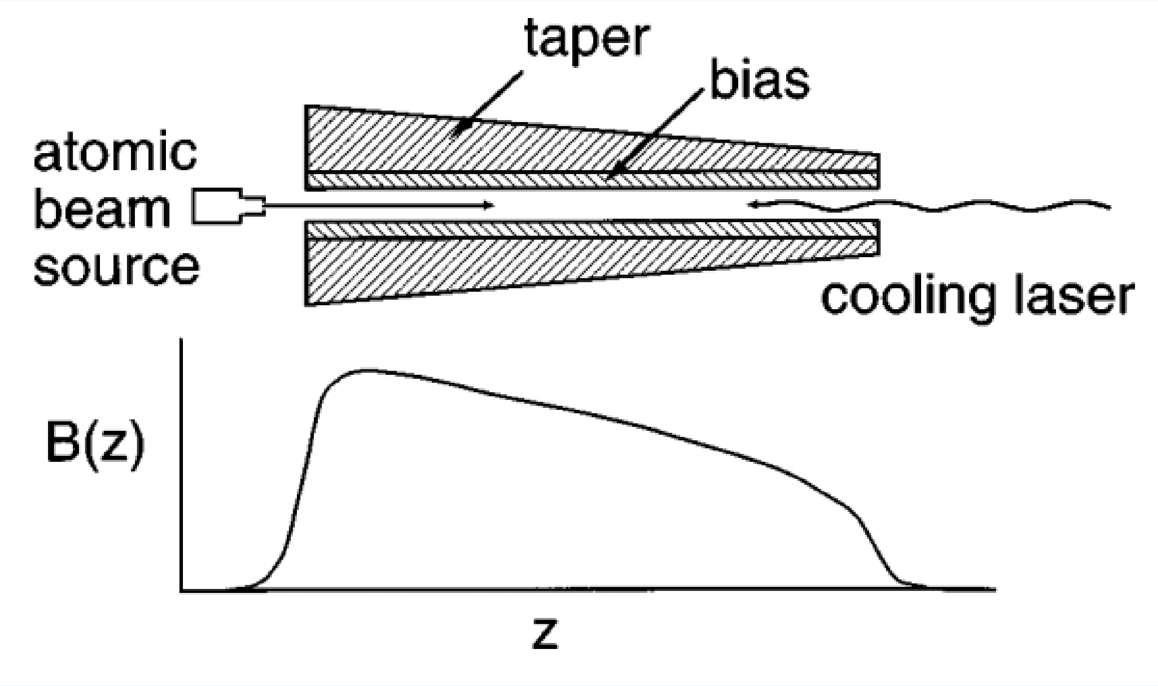
Can't address all atoms (if spread in velocity) and quickly go off-resonant

Zeeman slowers



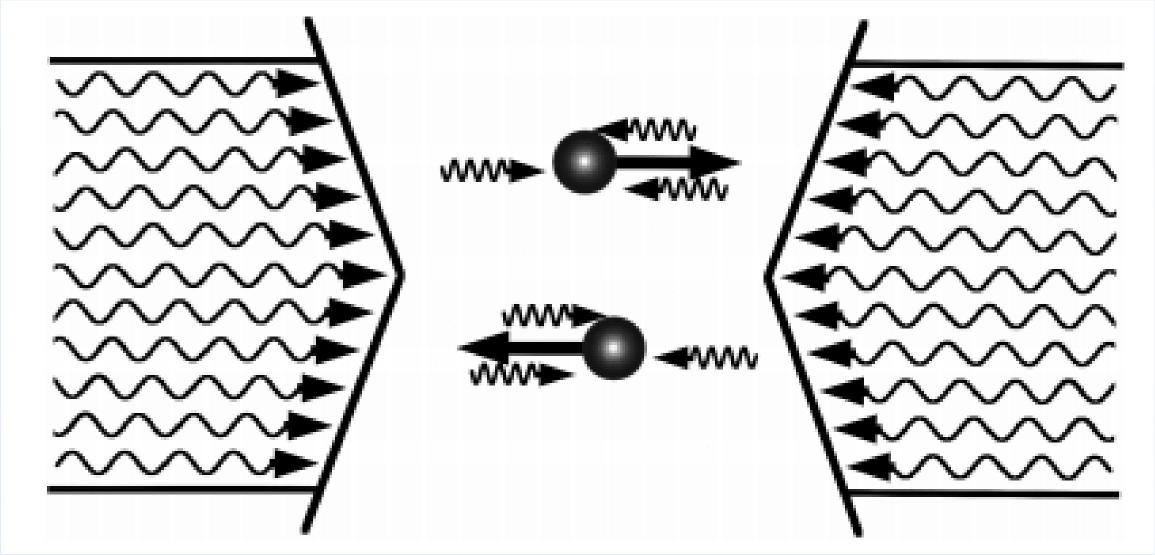
Compensate Doppler shift with shift of resonance
(or alternatively shift of light frequency)

Zeeman slowers

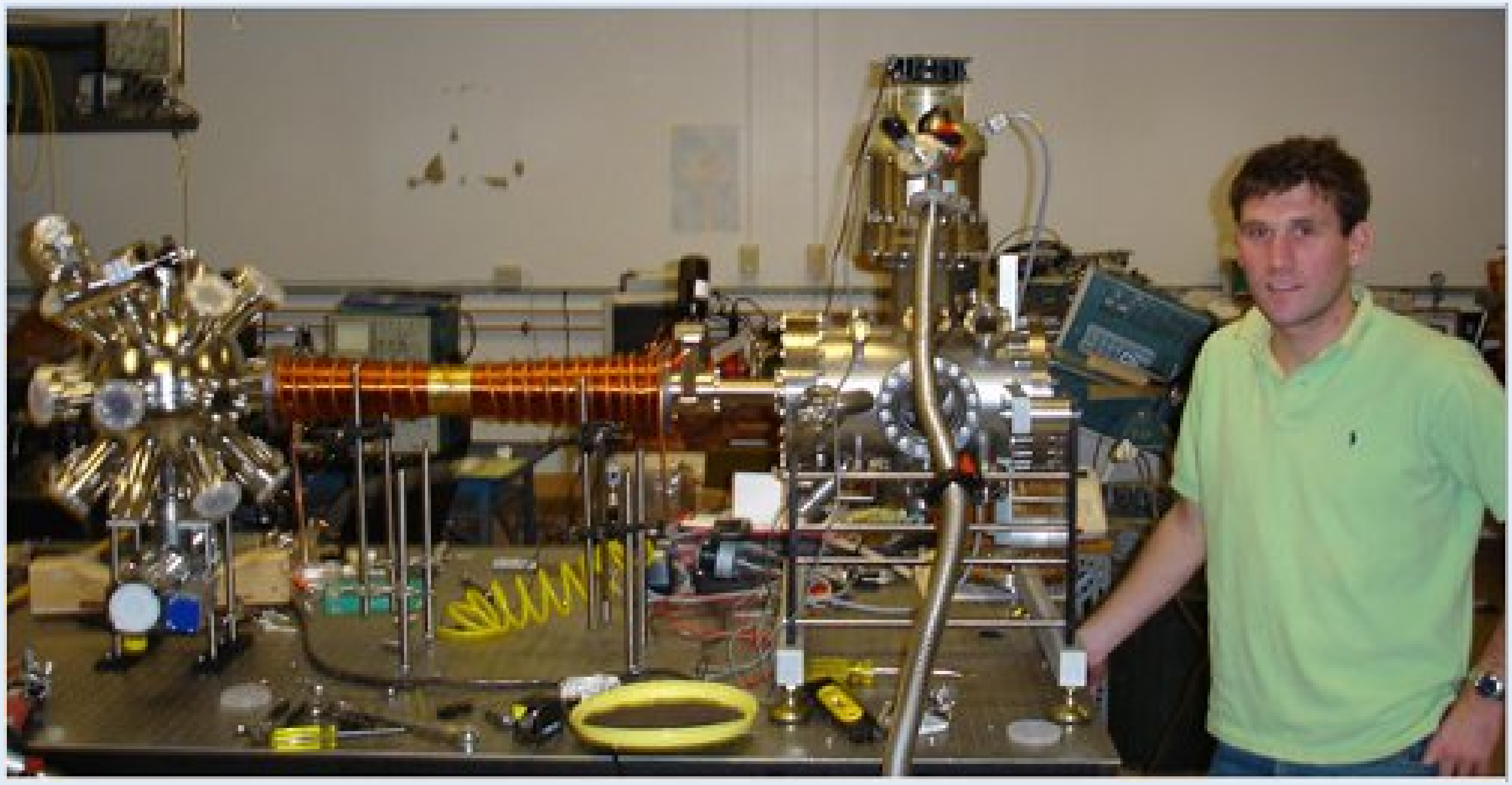


Compensate Doppler shift with shift of resonance
(or alternatively shift of light frequency)

1D Doppler cooling – optical molasses

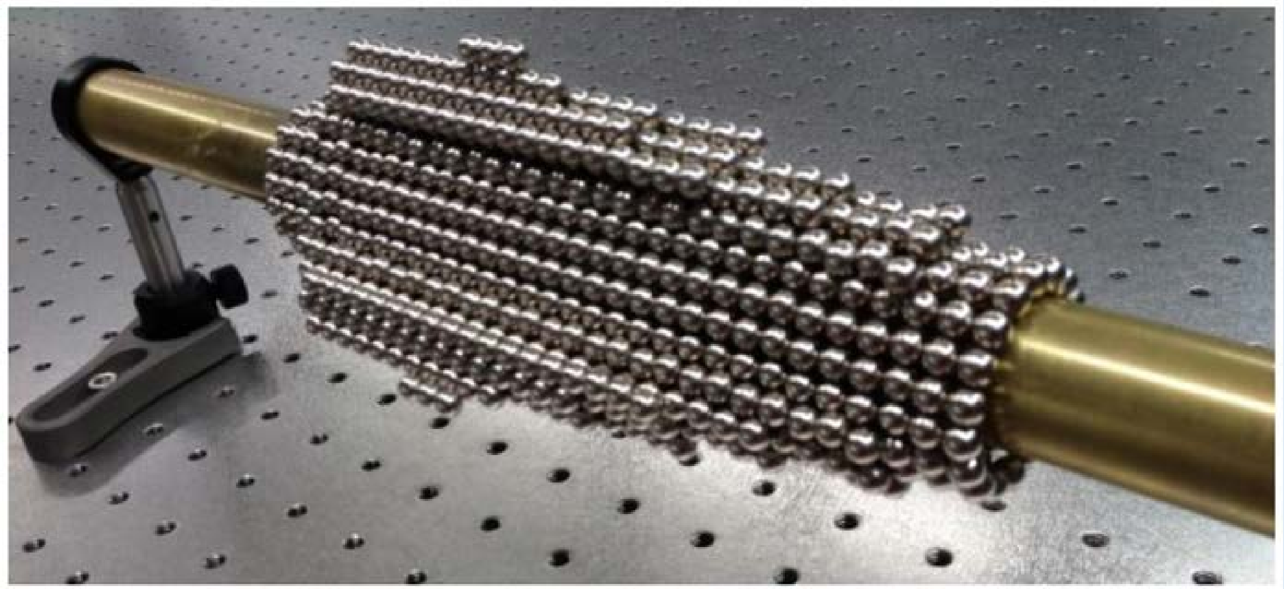


Electromagnet Zeeman slowers



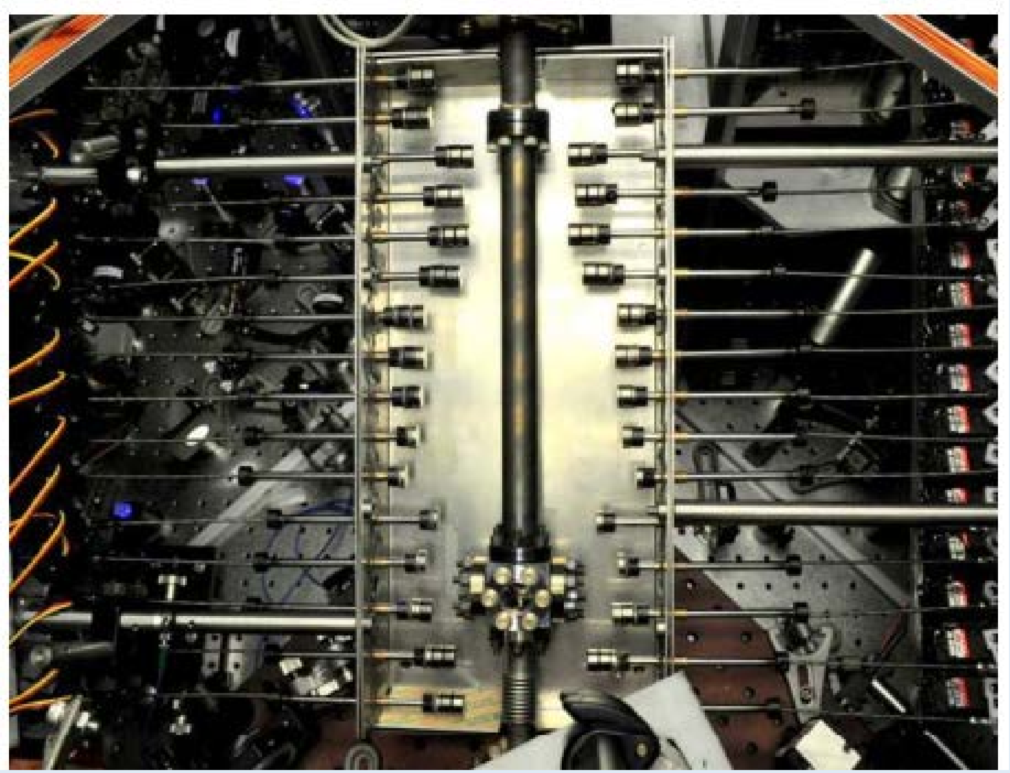
Orzel lab, Union

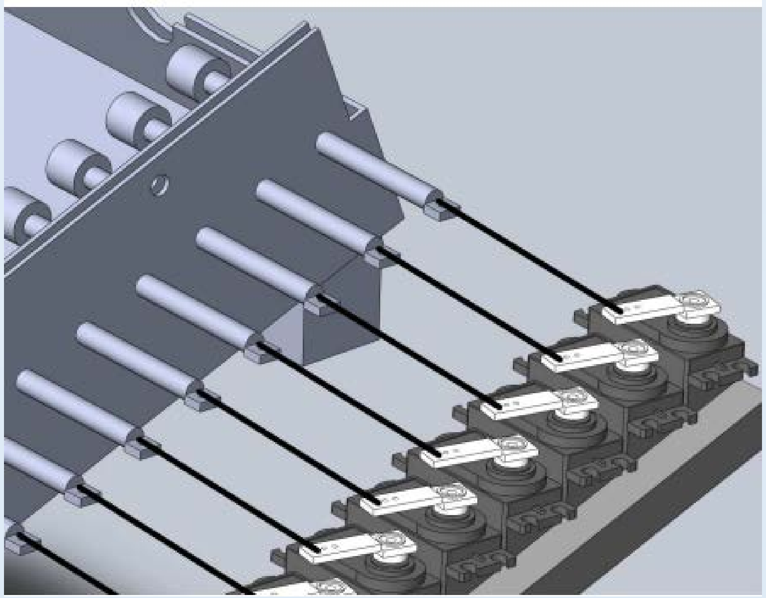
Permanent magnet Zeeman slowers



Weld group, UCSB

Reconfigurable Zeeman slowers



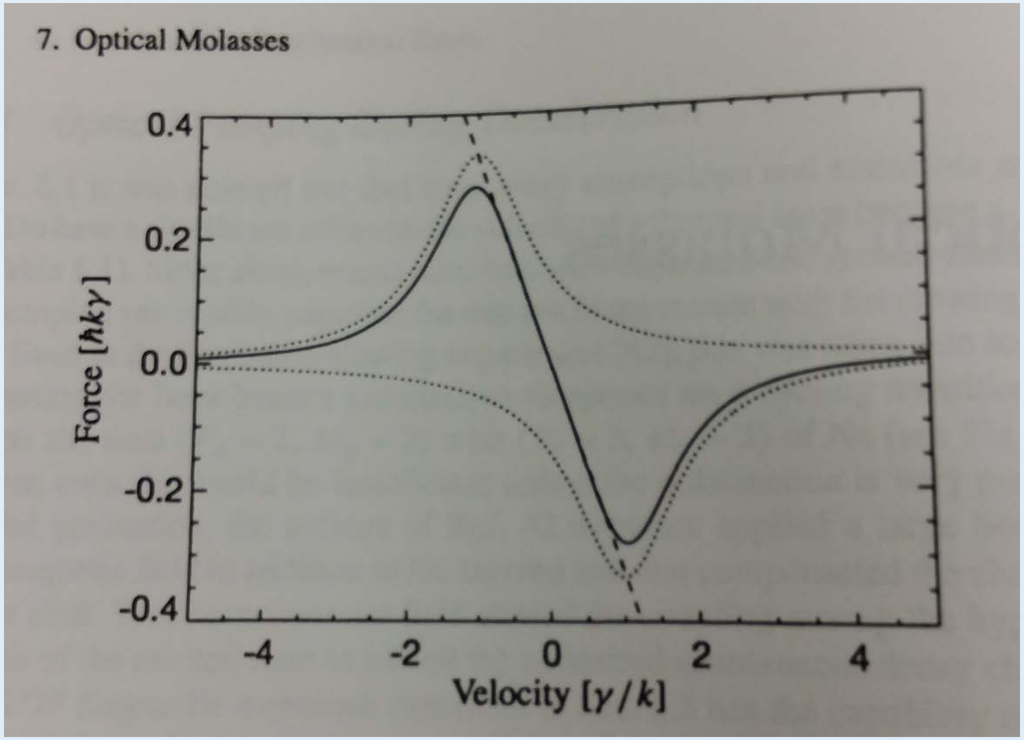


Zelevinsky group, Columbia

The Doppler limit – how low can you go?

$$k_B T_{Dopp} \approx \frac{\hbar\Gamma}{2}$$

Just look for a
“narrow-line” (small Γ)
transition



But need to start with
$|v| \lesssim \Gamma/k$

One approach – use multiple cooling transitions

with successively smaller linewidths Γ

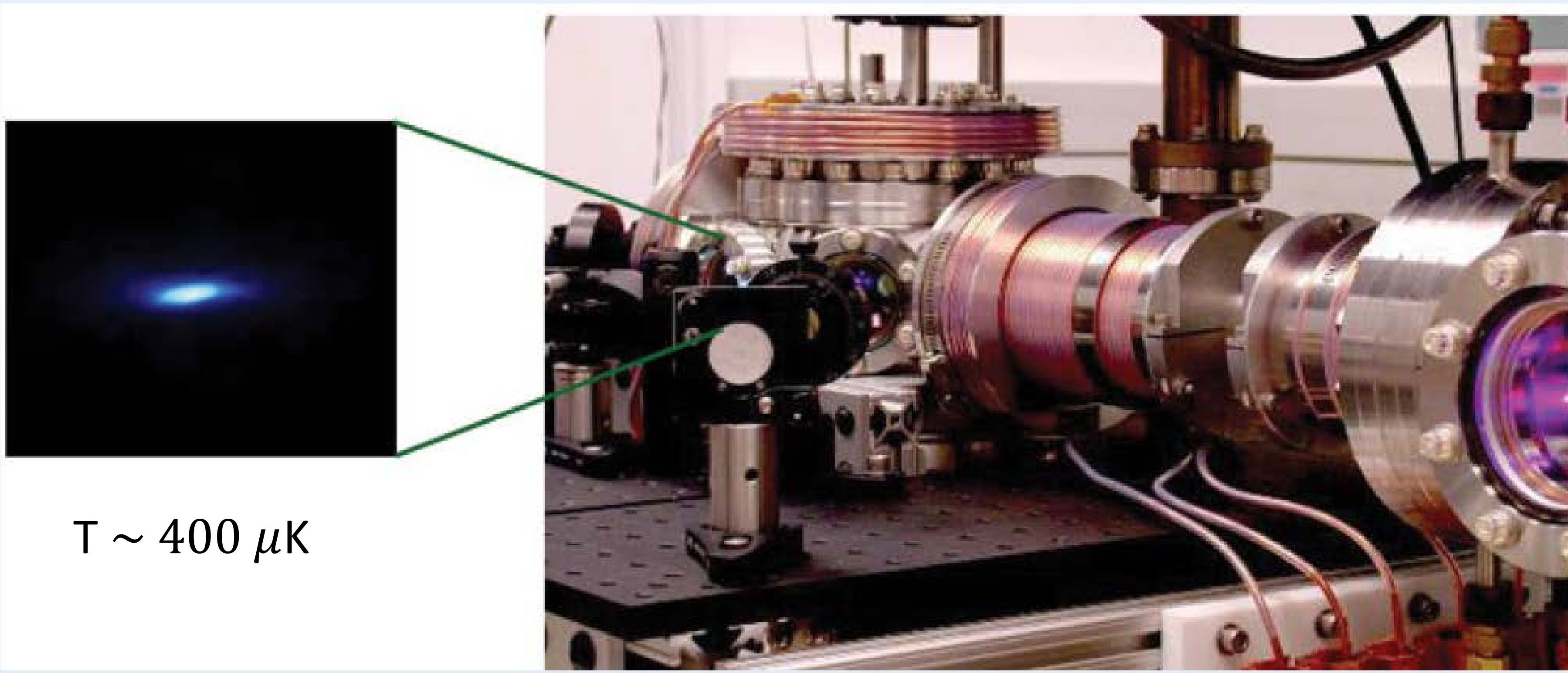
laser cooling parameter		transition 401 nm	583 nm
transition rate	Γ (s^{-1})	1.87×10^8	1.17×10^6
lifetime	τ (ns)	5.35	857
natural linewidth	$\Delta\nu$ (MHz)	29.7 →	0.19
saturation intensity	I_S (mW/cm^2)	60.3	0.13
Doppler temperature	T_D (μK)	714 →	4.6
Doppler velocity	v_D (mm/s)	267	21
recoil temperature	T_r (nK)	717	339
recoil velocity	v_r (mm/s)	6.0	4.1
	Refs.	[Har10] Appendix A	[Har10] [Law10]

A. Frisch, Ph.D. thesis

two of the stronger transitions in erbium

One approach – use multiple cooling transitions

with successively smaller linewidths Γ

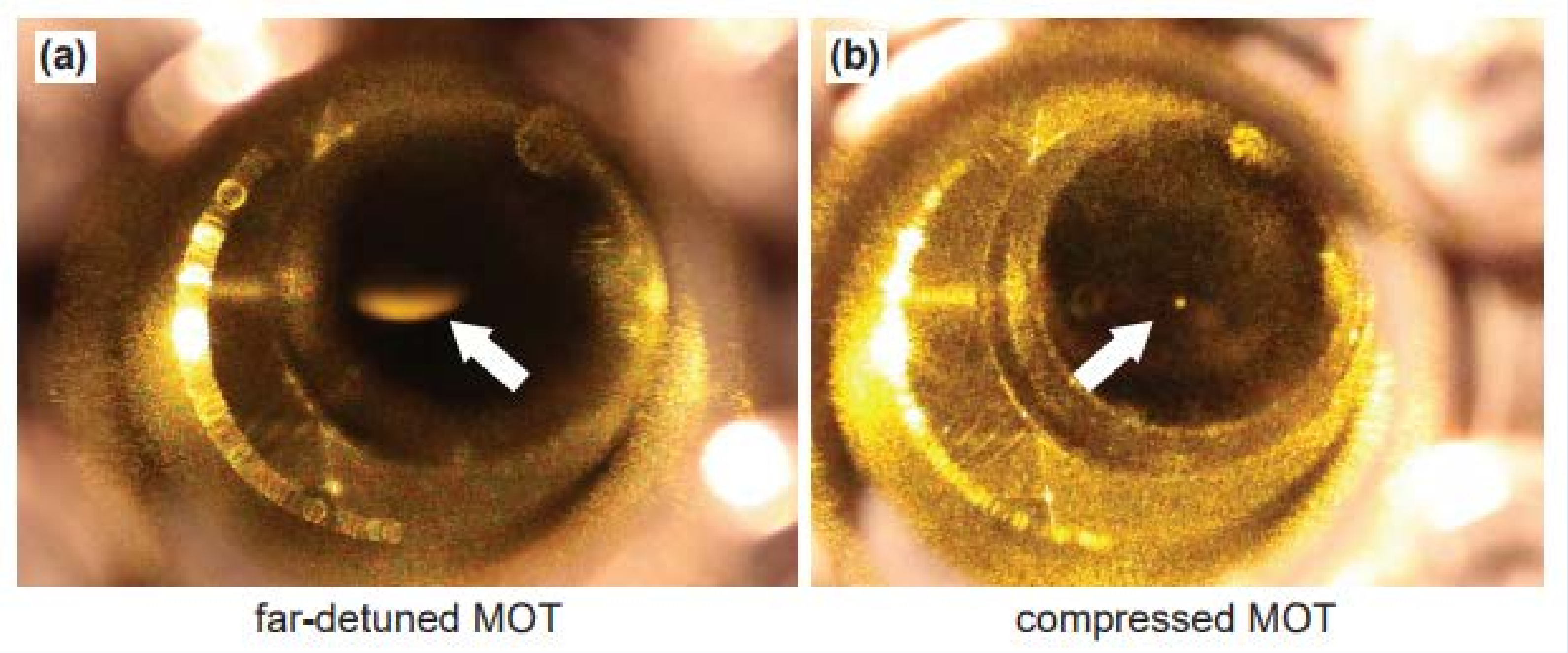


Erbium MOT on 401 nm transition (McClelland group, NIST Gaith.)

One approach – use multiple cooling transitions

with successively smaller linewidths Γ

$T \sim 10\ \mu K$



Erbium MOT on 583 nm transition (Ferlaino group, Innsbruck)

One approach – use multiple cooling transitions

with successively smaller linewidths Γ

VOLUME 82, NUMBER 6 PHYSICAL REVIEW LETTERS 8 FEBRUARY 1999

Magneto-Optical Trapping and Cooling of Strontium Atoms down to the Photon Recoil Temperature

Hidetoshi Katori, Tetsuya Ido, Yoshitomo Isoya, and Makoto Kuwata-Gonokami
Cooperative Excitation Project, ERATO, Japan Science and Technology Corporation (JST), KSP D-842, 3-2-1 Sakado, Takatsu-ku Kawasaki, 213-0012, Japan
(Received 4 September 1998)

We report narrow-line laser cooling and trapping of strontium atoms down to the photon recoil temperature. ^{88}Sr atoms precooled by the broad $^1S_0$-$^1P_1$ transition at 461 nm were further cooled in a magneto-optical trap using the spin-forbidden transition $^1S_0$-$^3P_1$ at 689 nm. We have thus obtained an atomic sample with a density over 10^{12} cm^{-3} and a minimum temperature of 400 nK, corresponding to a maximum phase space density of 10^{-2} which is 3 orders of magnitude larger than the value that has been obtained by magneto-optical traps to date. This scheme provides us an opportunity and system to study quantum statistical properties of degenerate fermions as well as bosons. [S0031-9007(98)08352-5]

PACS numbers: 32.80.Pj

First observations by Katori, et al. in Sr

One approach – use multiple cooling transitions

with successively smaller linewidths Γ

VOLUME 82, NUMBER 6 PHYSICAL REV

Magneto-Optical Trapping and Cooling o
Recoil Tem

Hidetoshi Katori, Tetsuya Ido, Yoshitomo
Cooperative Excitation Project, ERATO, Japan Science and T
Takatsu-ku Kawasaki
(Received 4 Sep

We report narrow-line laser cooling and trapping temperature. ^{88}Sr atoms precooled by the broad $^1S_0$- magneto-optical trap using the spin-forbidden transiti atomic sample with a density over 10^{12} cm^{-3} and a m maximum phase space density of 10^{-2} which is 3 orde obtained by magneto-optical traps to date. This schem quantum statistical properties of degenerate fermions

PACS numbers: 32.80.Pj

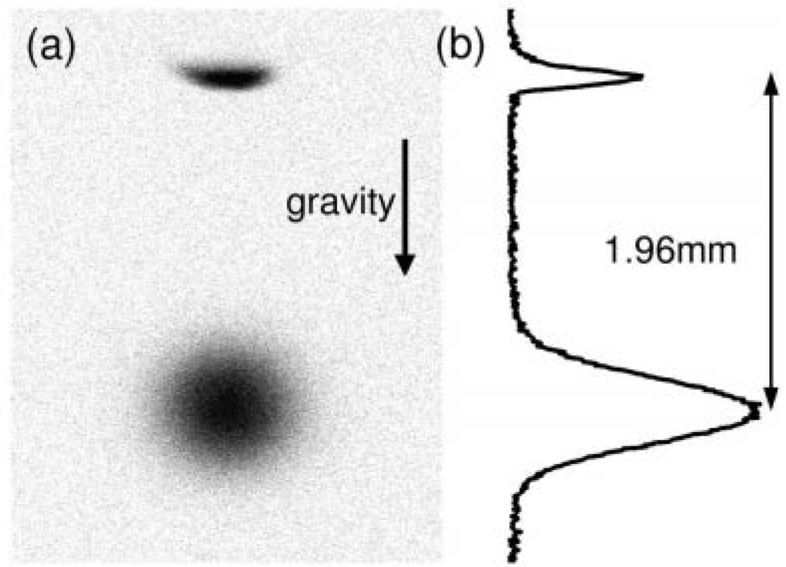


FIG. 2. (a) CCD image of a red-MOT (upper disk) and an expanded atomic cloud in 20 ms free flight (a sphere below the MOT). The gravity directs toward the bottom. (b) A cross section of the image (a) along the vertical axis. The expanded atom cloud was well fit by the Gaussian profile with $T = 830$ nK.

First observations by Katori, et al. in Sr

Laser-cooling to BEC

Narrow-line MOT of Sr

PRL **110**, 263003 (2013) PHYSICAL REVIEW LETTERS week ending 28 JUNE 2013

Laser Cooling to Quantum Degeneracy

Simon Stellmer,[1] Benjamin Pasquiou,[1] Rudolf Grimm,[1,2] and Florian Schreck[1]

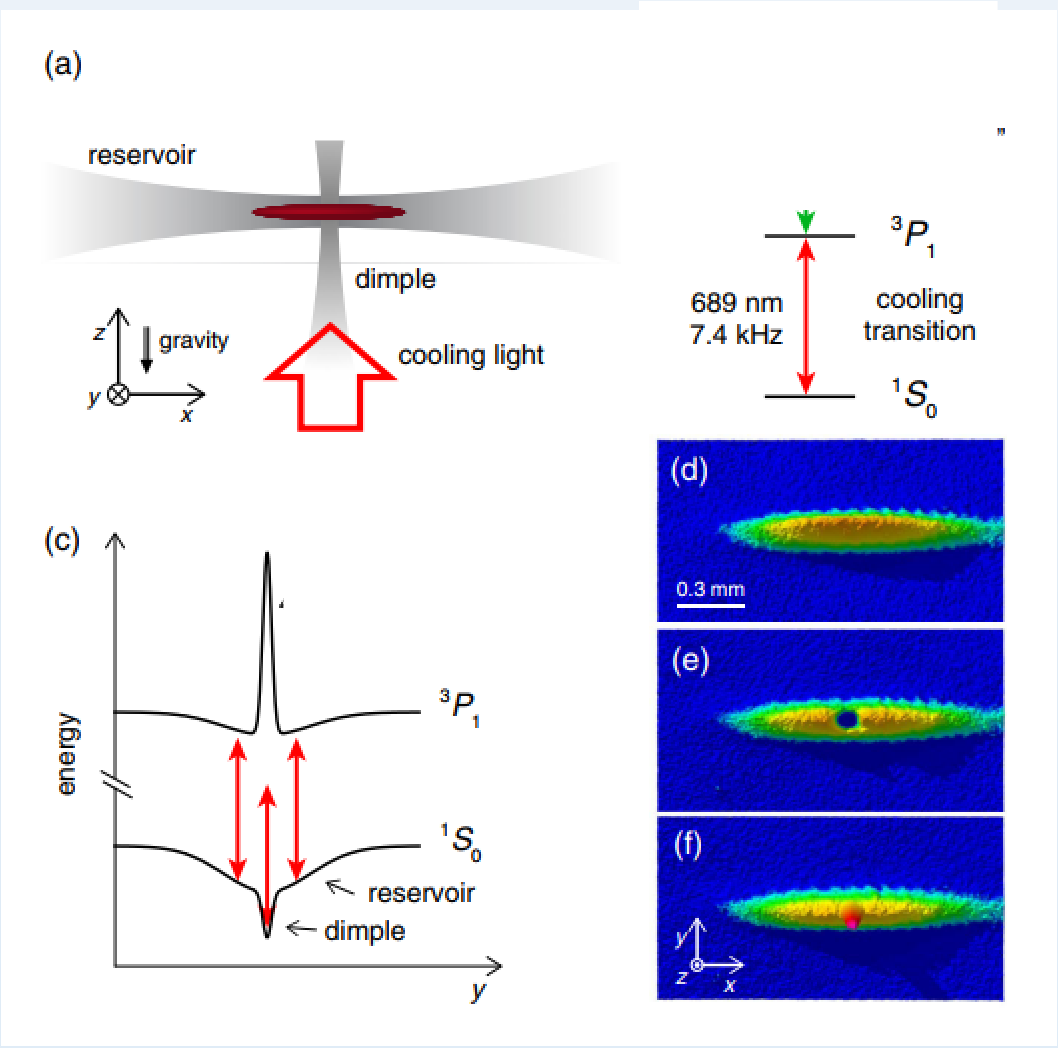
[1]*Institut für Quantenoptik und Quanteninformation (IQOQI), Österreichische Akademie der Wissenschaften, 6020 Innsbruck, Austria*
[2]*Institut für Experimentalphysik und Zentrum für Quantenphysik, Universität Innsbruck, 6020 Innsbruck, Austria*
(Received 20 January 2013; published 25 June 2013)

We report on Bose-Einstein condensation in a gas of strontium atoms, using laser cooling as the only cooling mechanism. The condensate is formed within a sample that is continuously Doppler cooled to below 1 μK on a narrow-linewidth transition. The critical phase-space density for condensation is reached in a central region of the sample, in which atoms are rendered transparent for laser cooling photons. The density in this region is enhanced by an additional dipole trap potential. Thermal equilibrium between the gas in this central region and the surrounding laser cooled part of the cloud is established by elastic collisions. Condensates of up to 10^5 atoms can be repeatedly formed on a time scale of 100 ms, with prospects for the generation of a continuous atom laser.

Laser-cooling to BEC

Narrow-line MOT of Sr

+ "dimple" to increase density

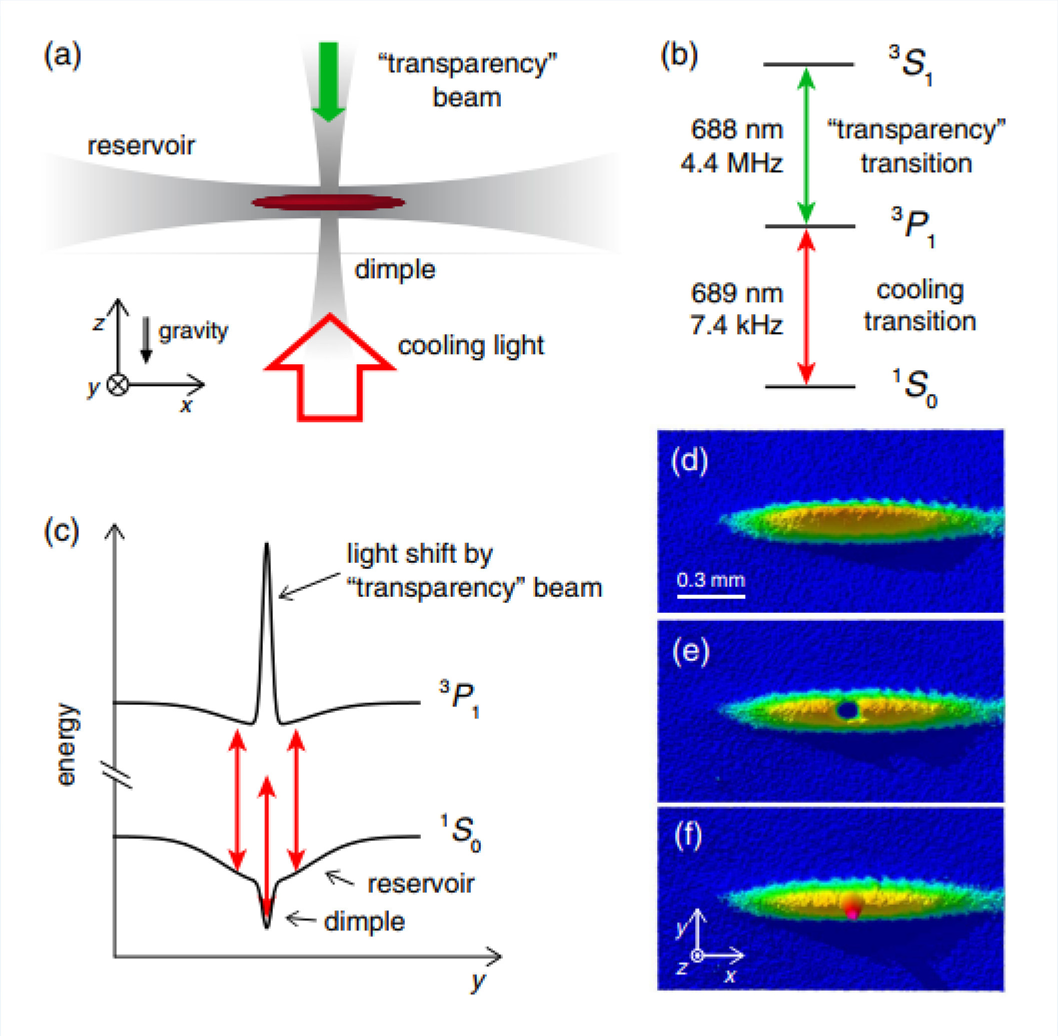


Laser-cooling to BEC

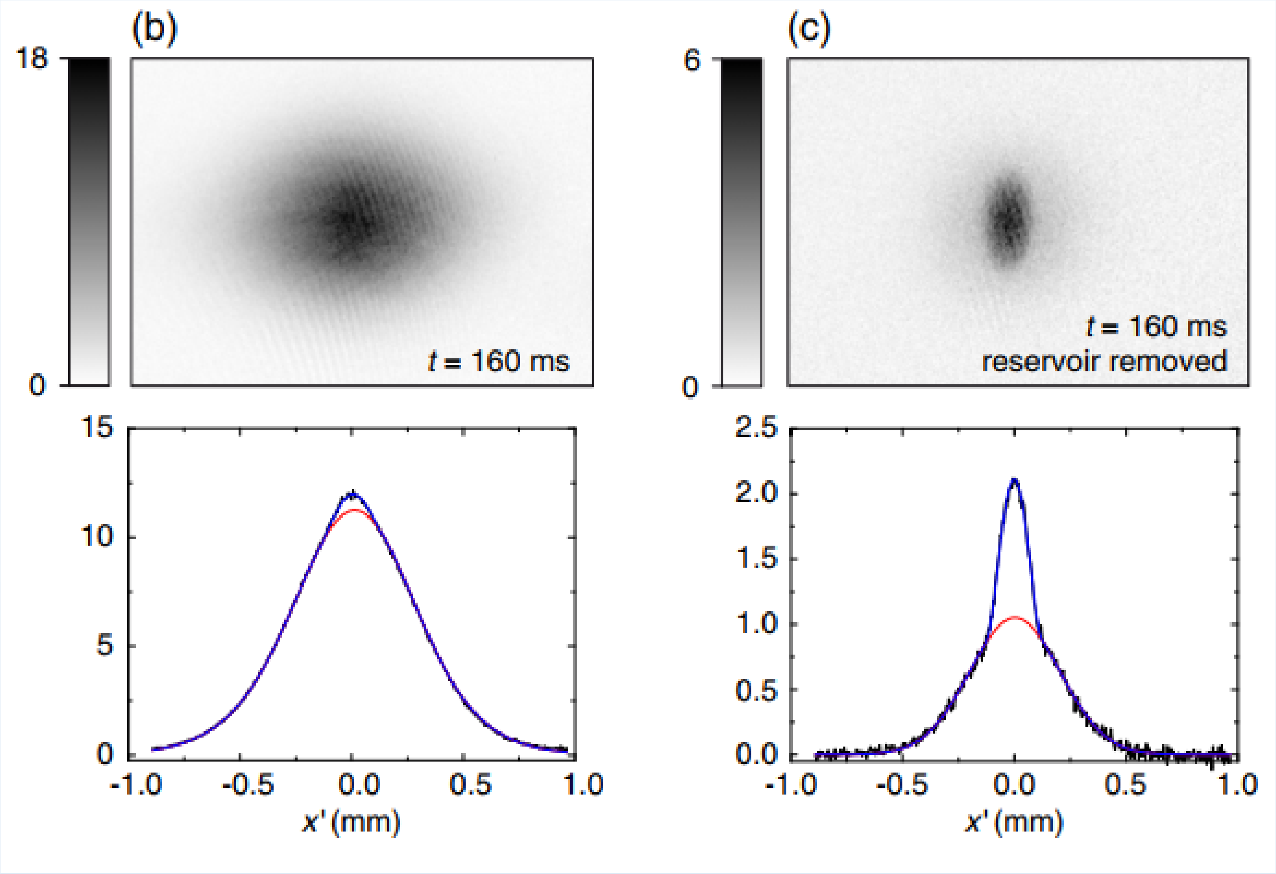
Narrow-line MOT of Sr

+ “dimple” to increase density

+ “invisibility cloak” to avoid scattering in dense region



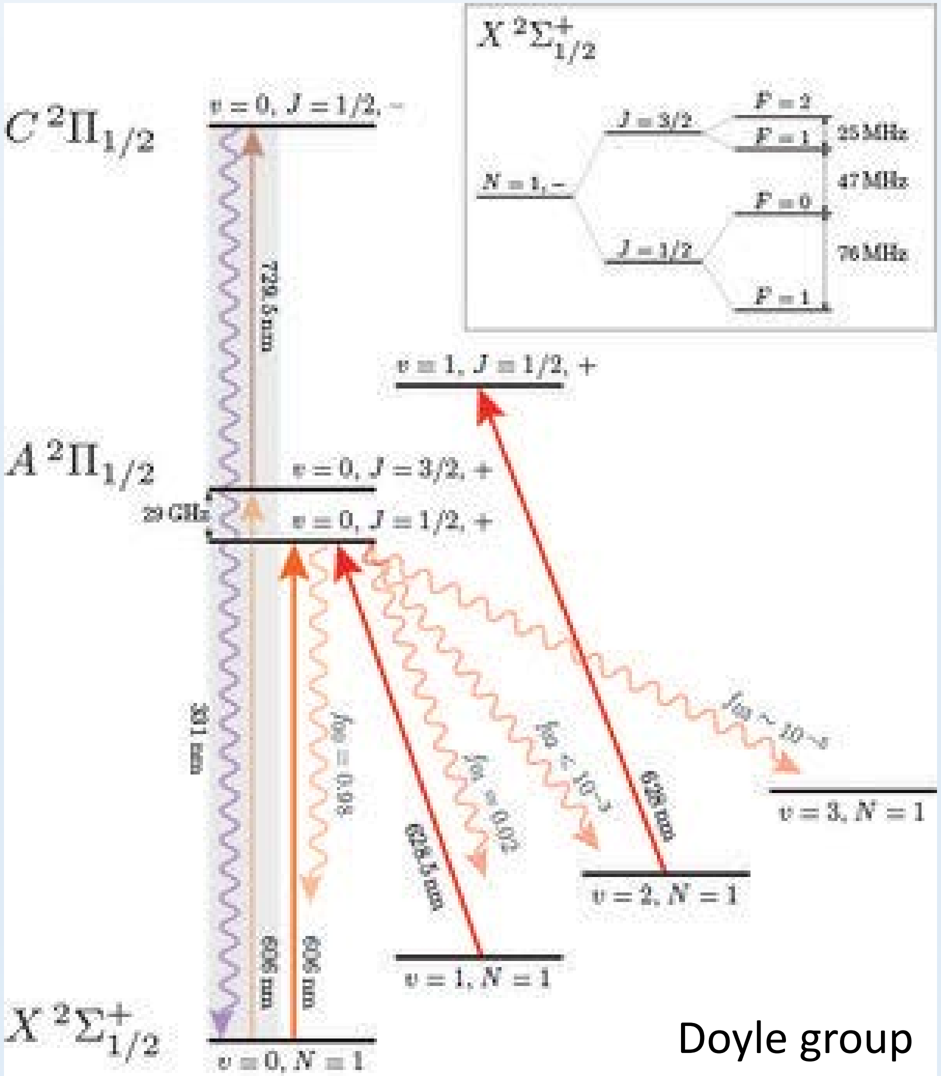
Laser-cooling to BEC



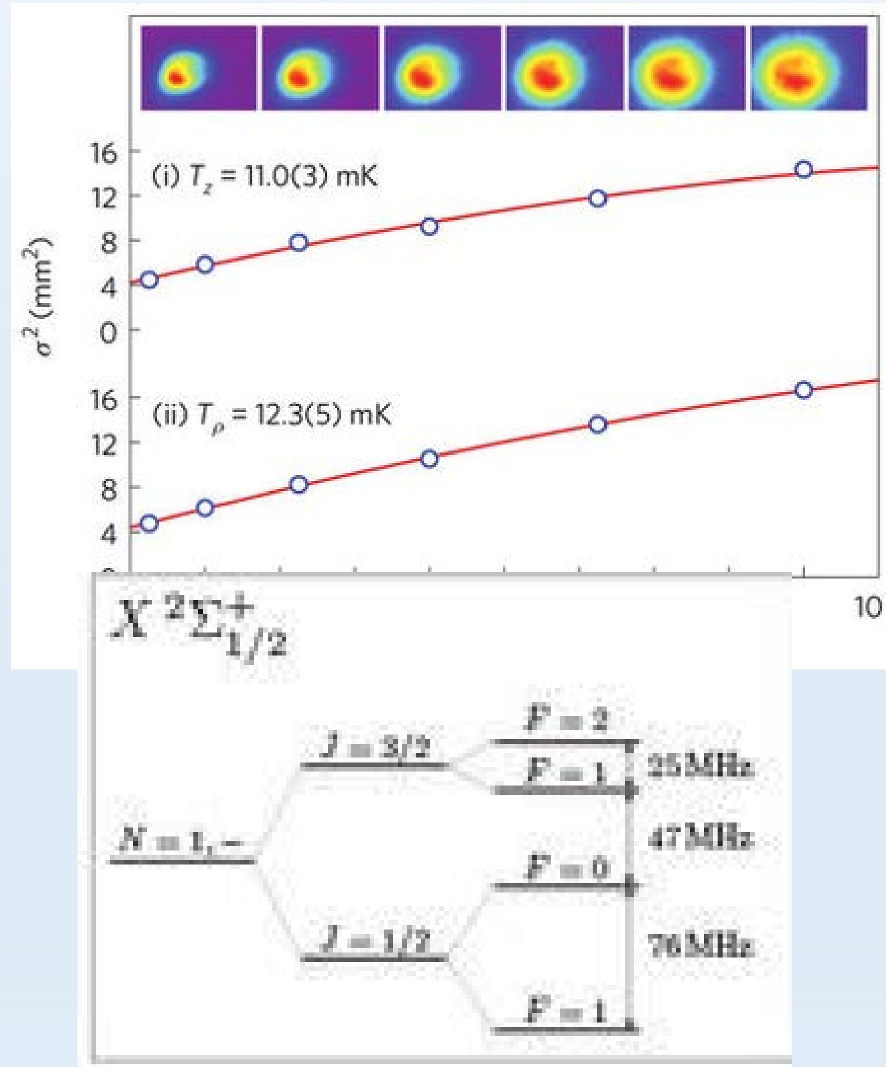
maybe an "atom laser" in the not-too-distant future!

Laser-cooling of molecules

Tarbutt / Hinds group

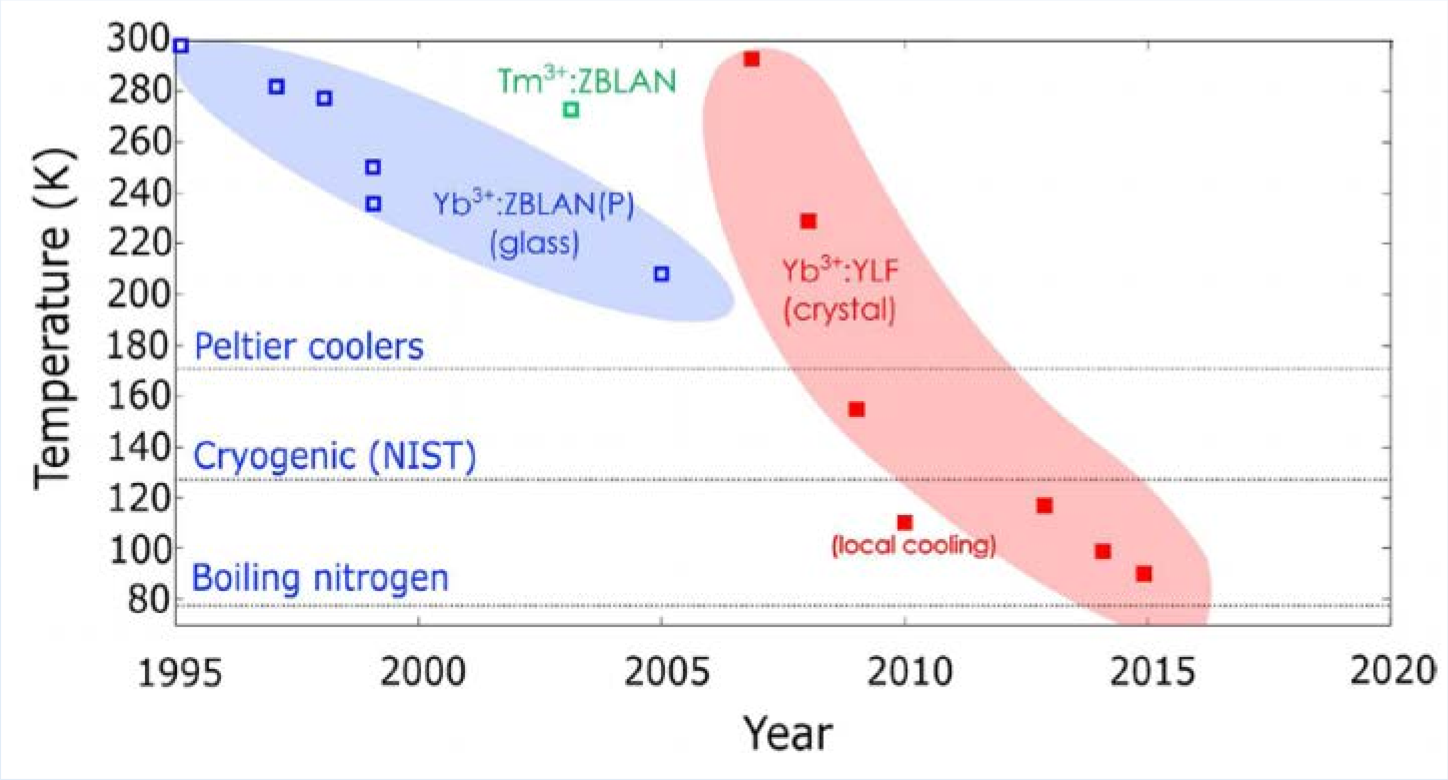


Doyle group



Laser-cooling of solids

Rep. Prog. Phys. **79** (2016) 096401



Laser-cooling of solids

Rep. Prog. Phys. **79** (2016) 096401