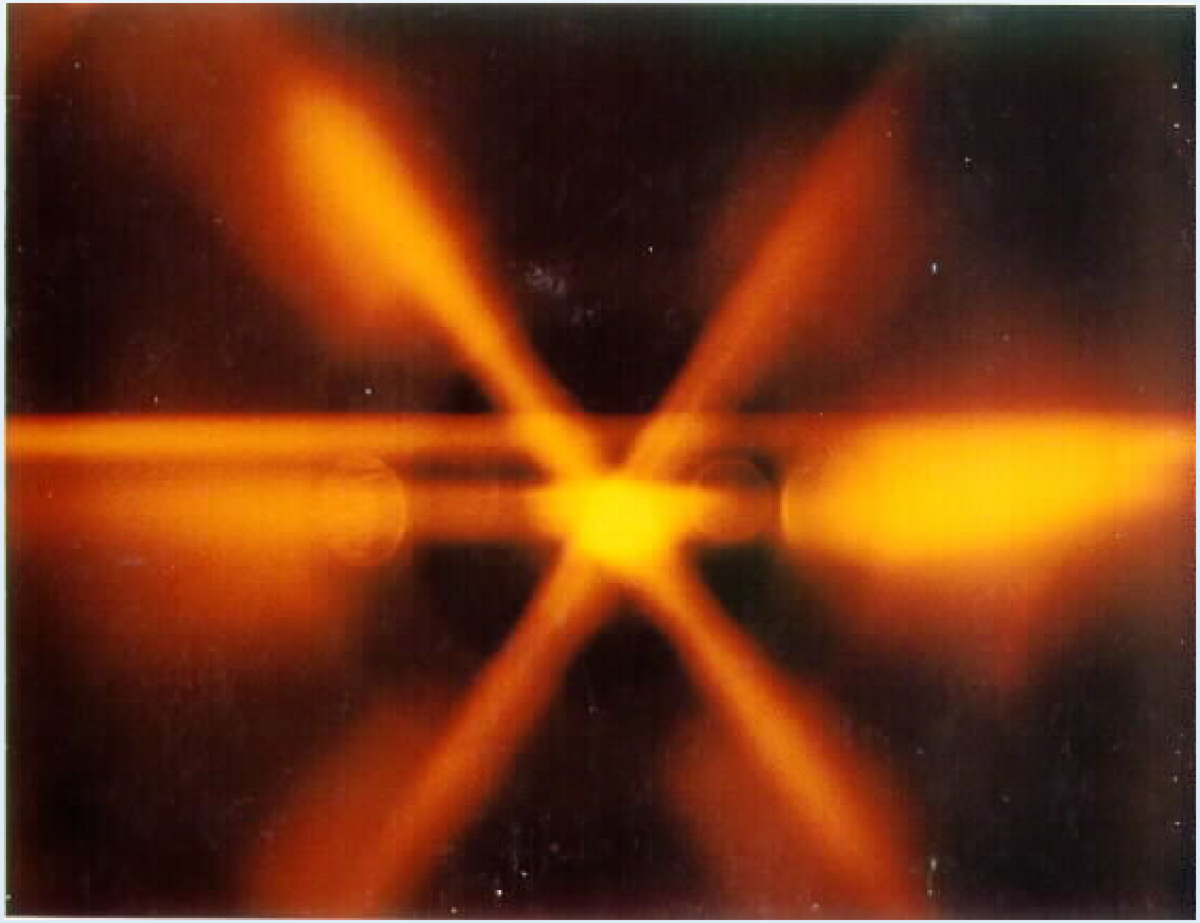
Optical molasses

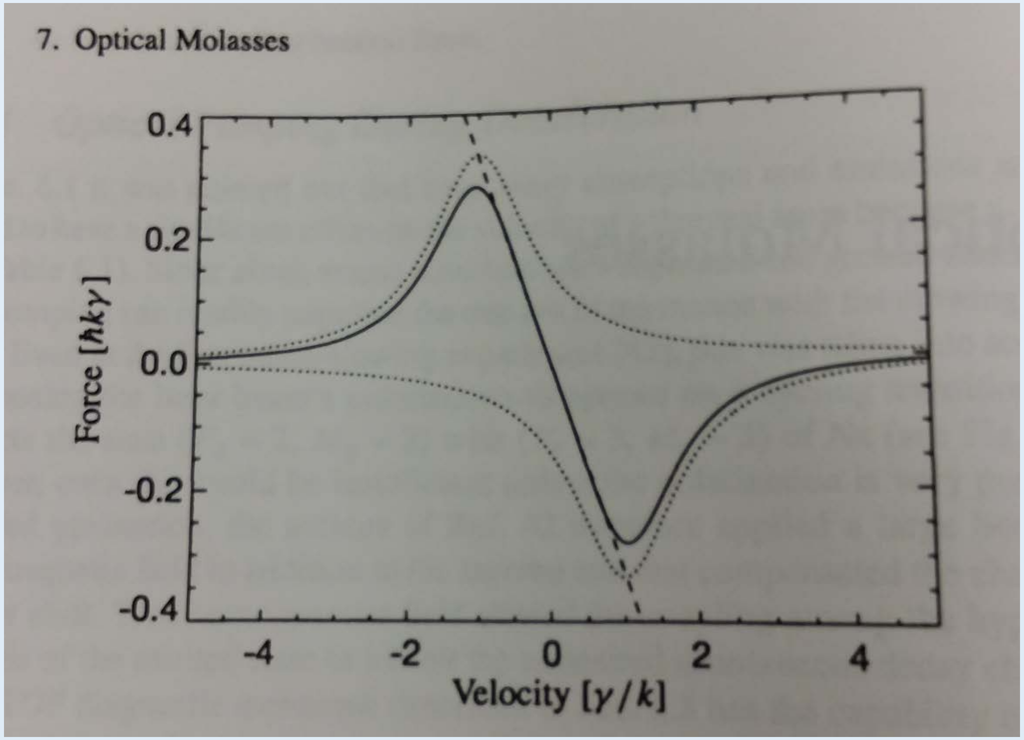


Early images of 3D sodium optical molasses [Phillips / Metcalf]

The Doppler limit – how cold can you get?

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

To get cold, just look for a "narrow-line" (small Γ) transition

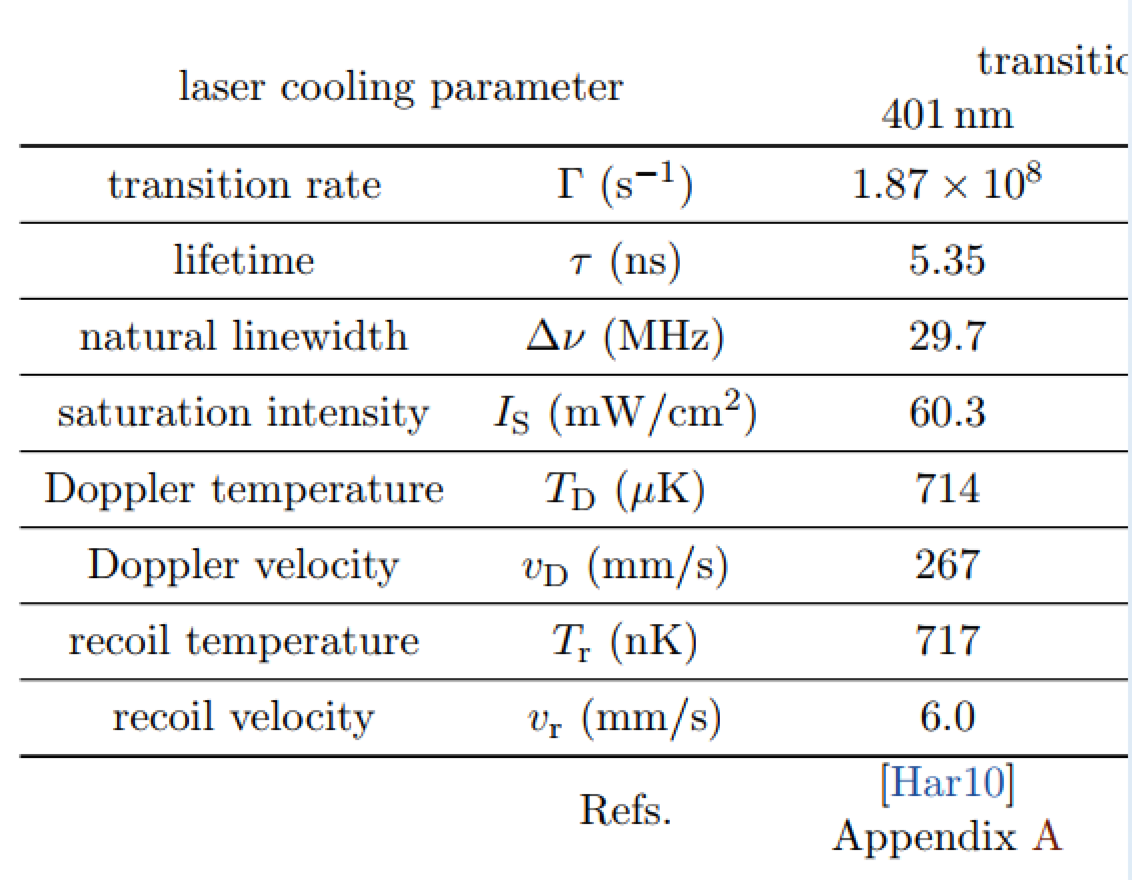


Metcalf/van der Straten

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

One approach – use multiple cooling transitions

with successively smaller linewidths Γ

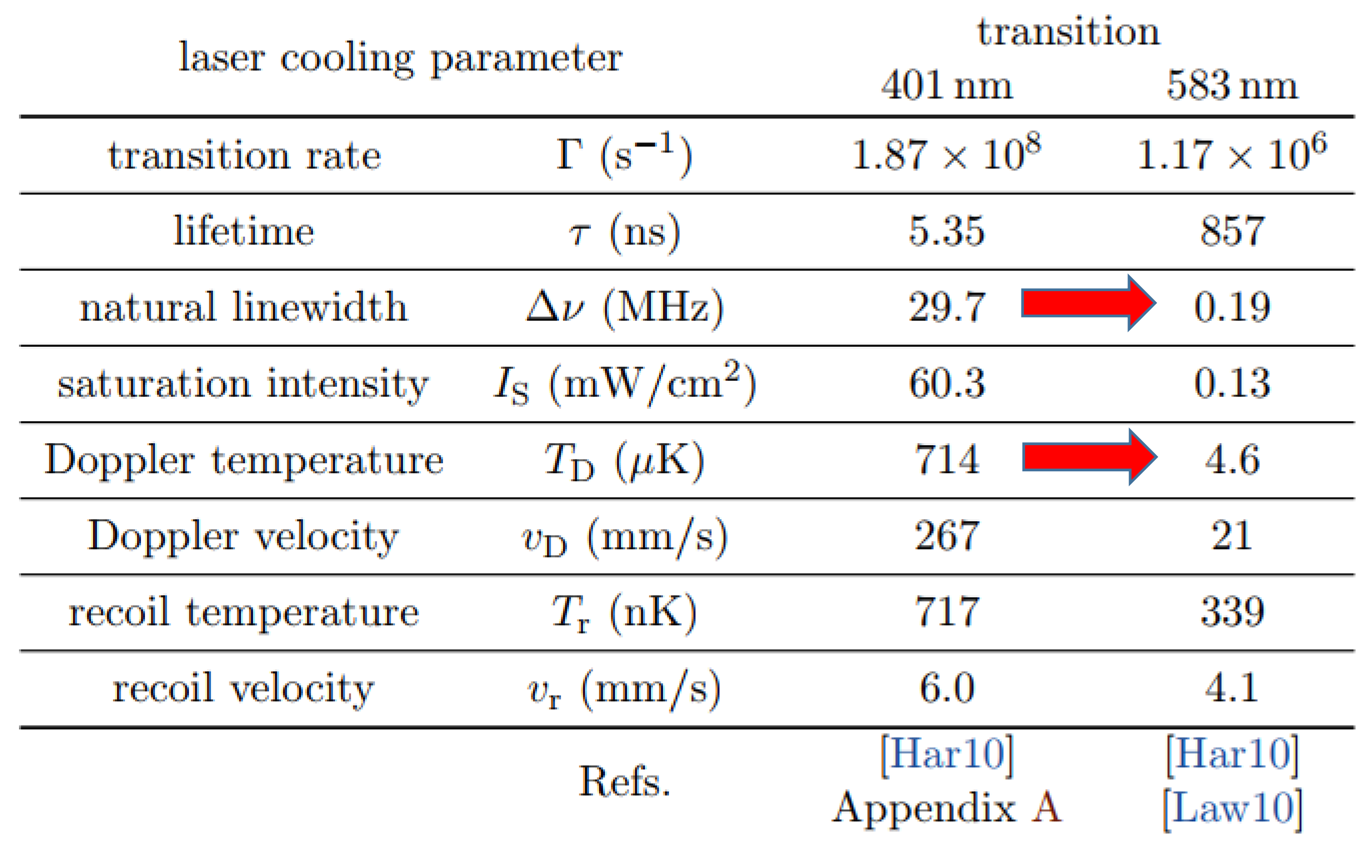


laser cooling parameter		transitio 401 nm
transition rate	Γ (s^{-1})	1.87×10^8
lifetime	τ (ns)	5.35
natural linewidth	$\Delta\nu$ (MHz)	29.7
saturation intensity	I_S (mW/cm^2)	60.3
Doppler temperature	T_D (μK)	714
Doppler velocity	v_D (mm/s)	267
recoil temperature	T_r (nK)	717
recoil velocity	v_r (mm/s)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

A. Frisch, Ph.D. thesis

One approach – use multiple cooling transitions

with successively smaller linewidths Γ



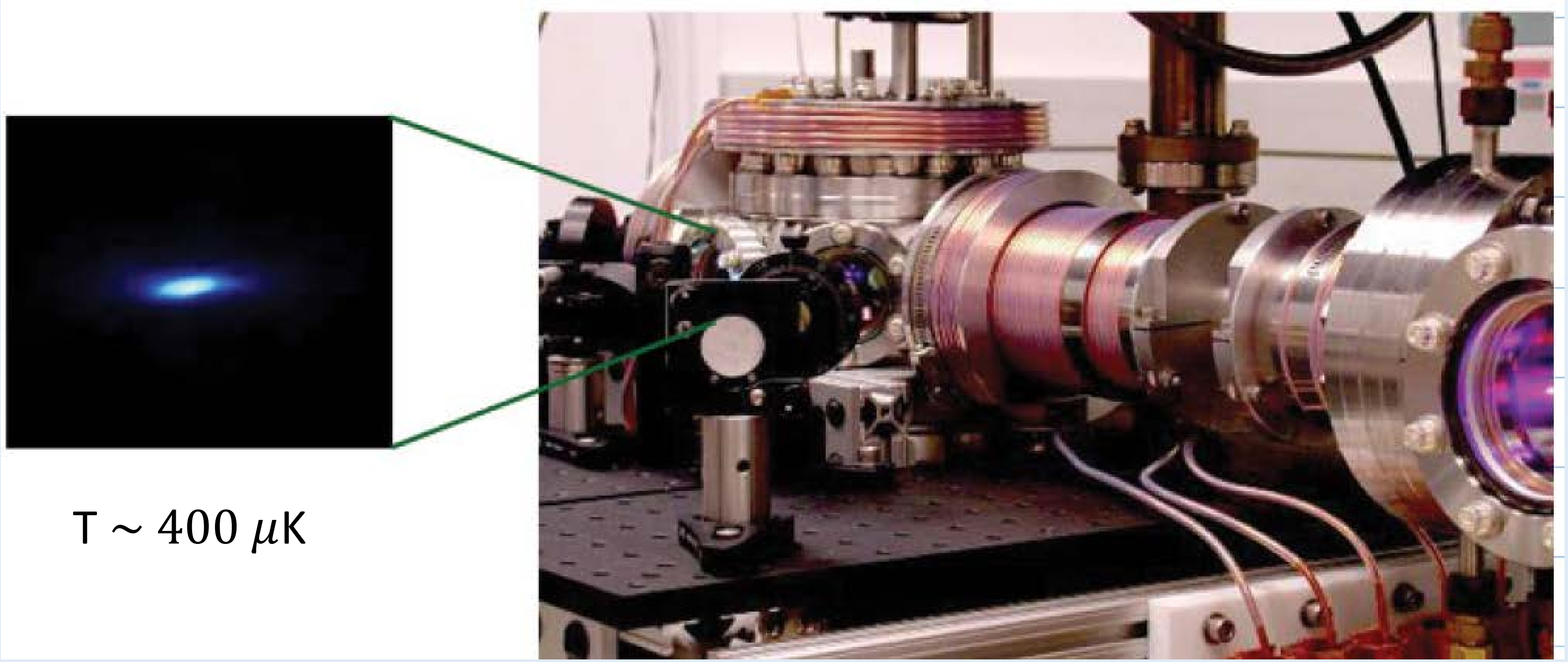
laser cooling parameter		transition 401 nm	 583 nm
transition rate	Γ (s^{-1})	1.87×10^8	1.17×10^6
lifetime	τ (ns)	5.35	857
natural linewidth	$\Delta\nu$ (MHz)	29.7 →	0.19
saturation intensity	I_S (mW/cm^2)	60.3	0.13
Doppler temperature	T_D (μK)	714 →	4.6
Doppler velocity	v_D (mm/s)	267	21
recoil temperature	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



$T \sim 400\ \mu\mathrm{K}$

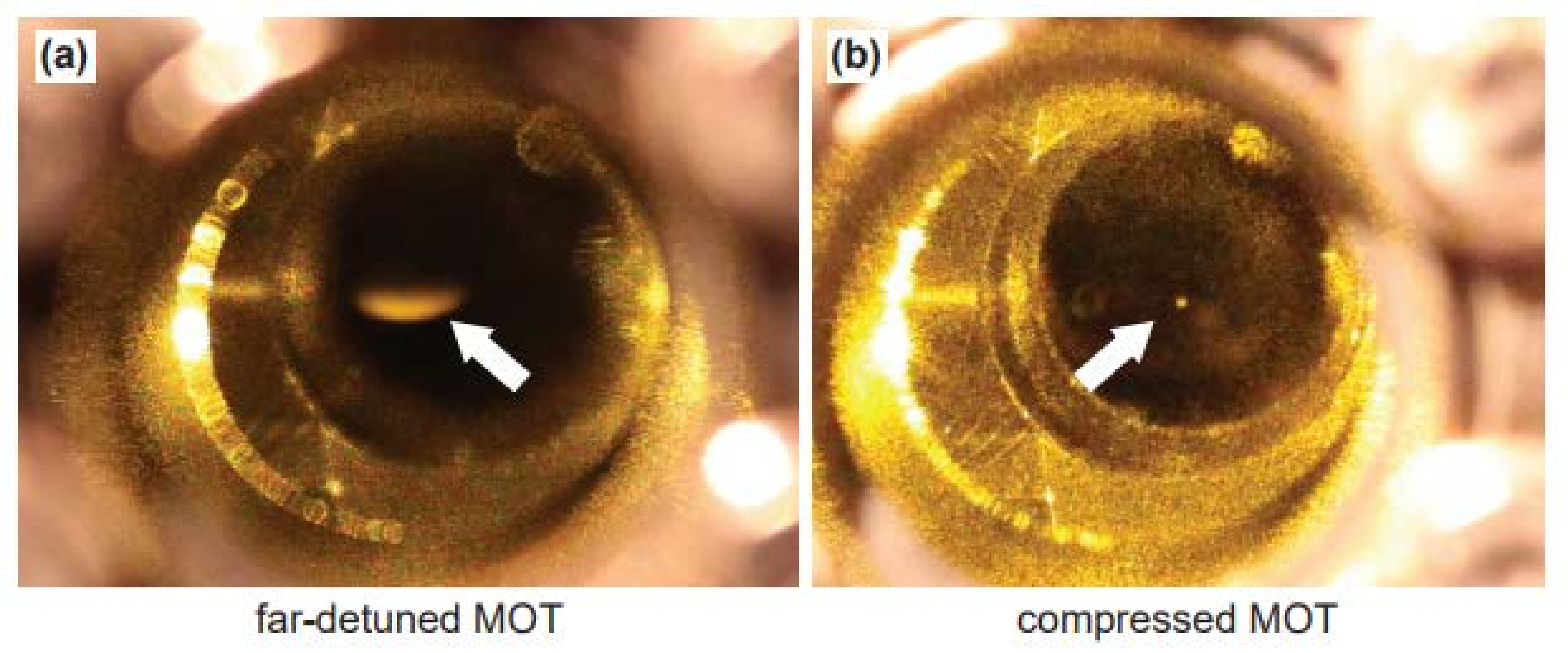
Erbium MOT on 401 nm transition (McClelland group, NIST Gaith.)

magneto-optical trap (MOT)

One approach – use multiple cooling transitions

with successively smaller linewidths Γ

$\mathrm{T} \sim 10\ \mu\mathrm{K}$



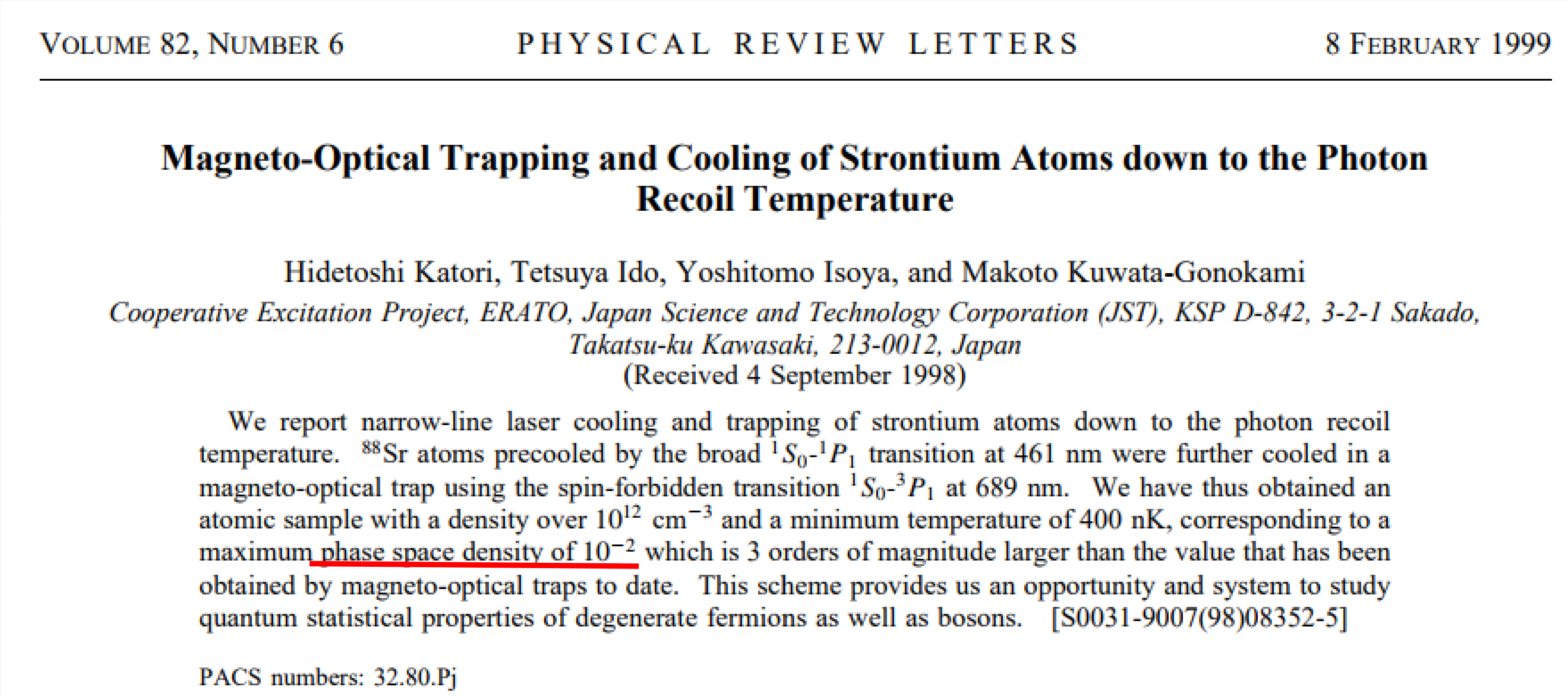
far-detuned MOT

compressed MOT

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)

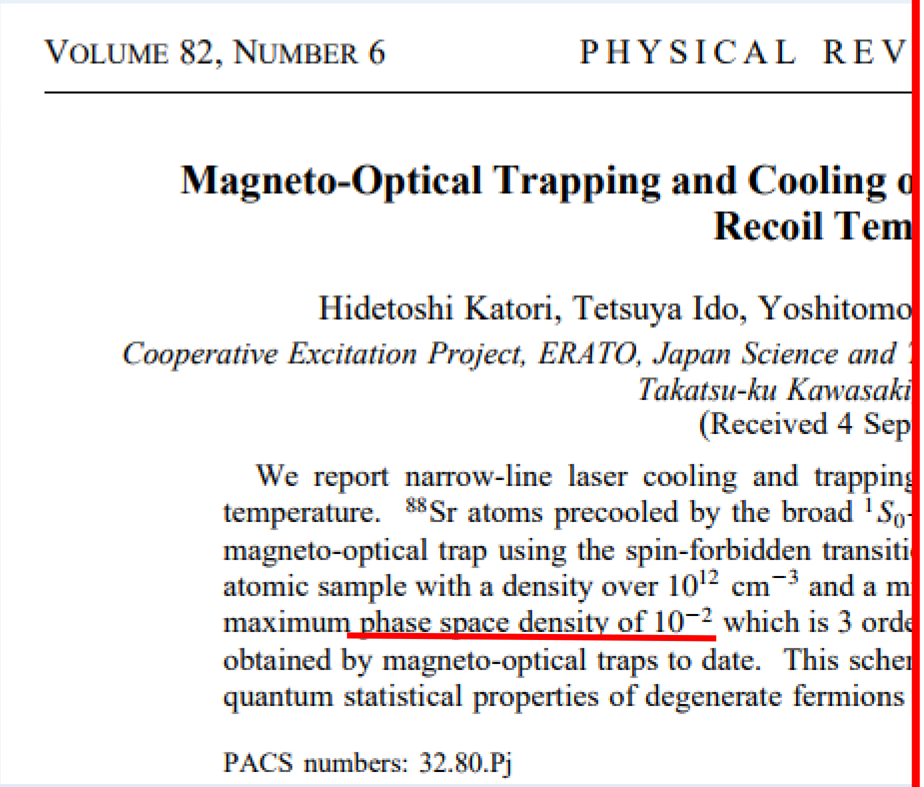
We report narrow-line laser cooling and trapping of strontium atoms down to the photon recoil temperature. ^{88}Sr atoms precooled by the broad $^1S_0$-$^1P_1$ transition at 461 nm were further cooled in a magneto-optical trap using the spin-forbidden transition $^1S_0$-$^3P_1$ at 689 nm. We have thus 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
Takatsu-ku Kawasaki
(Received 4 Sep

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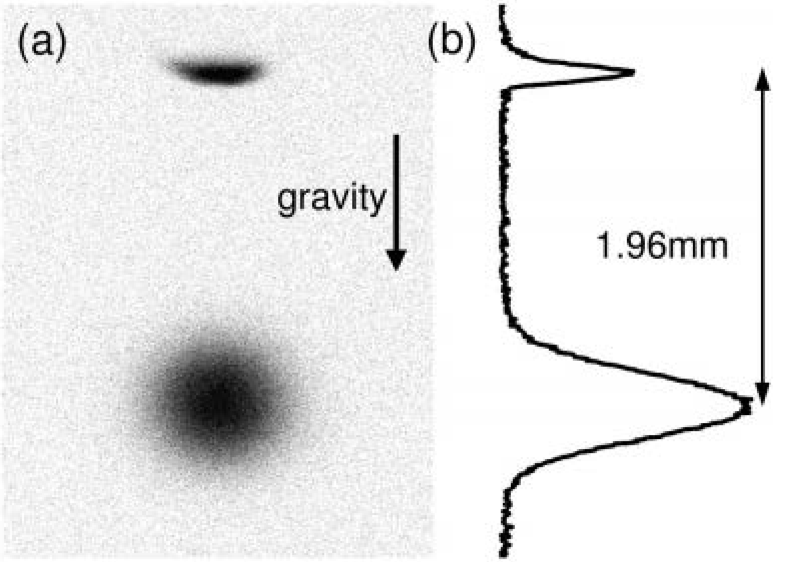
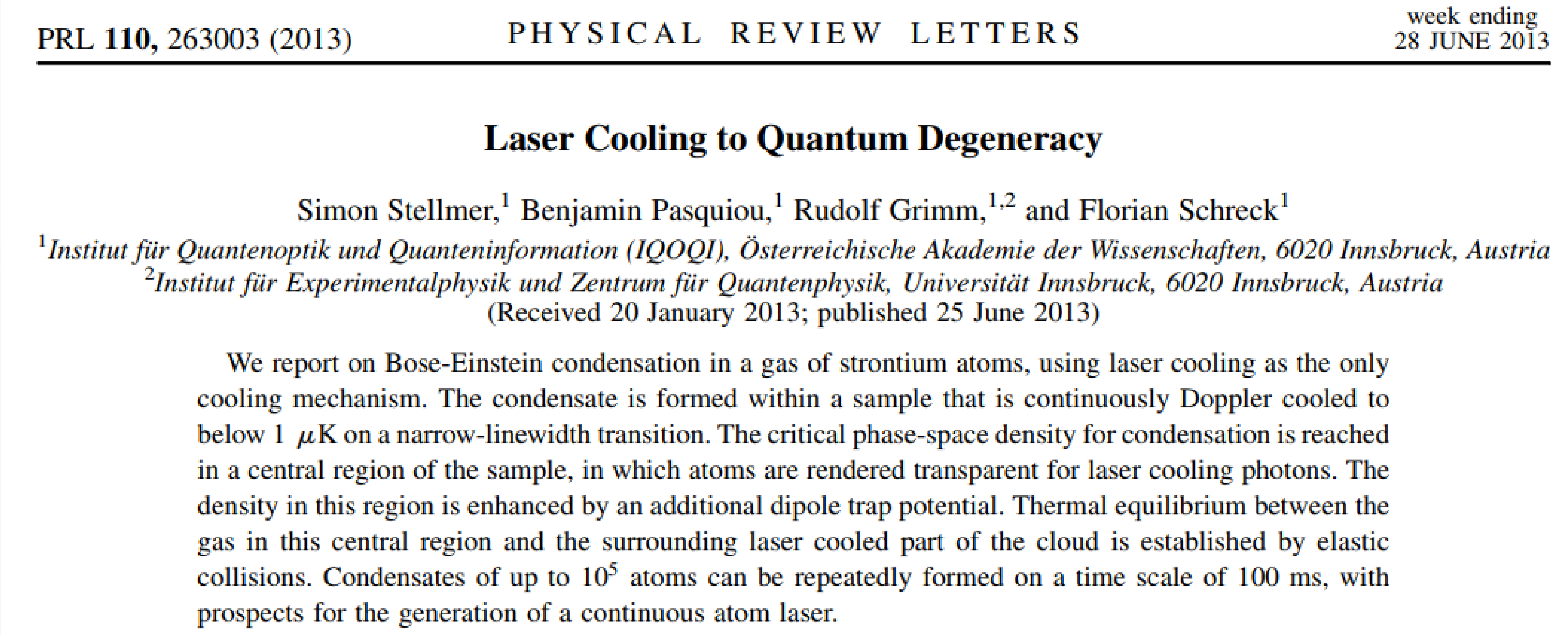


FIG. 2. (a) CCD image of a red-MOT (upper disk) and an expanded atomic cloud in 20 ms free flight (a sphere below the MOT). The gravity directs toward the bottom. (b) A cross section of the image (a) along the vertical axis. The expanded atom cloud was well fit by the Gaussian profile with $T = 830$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

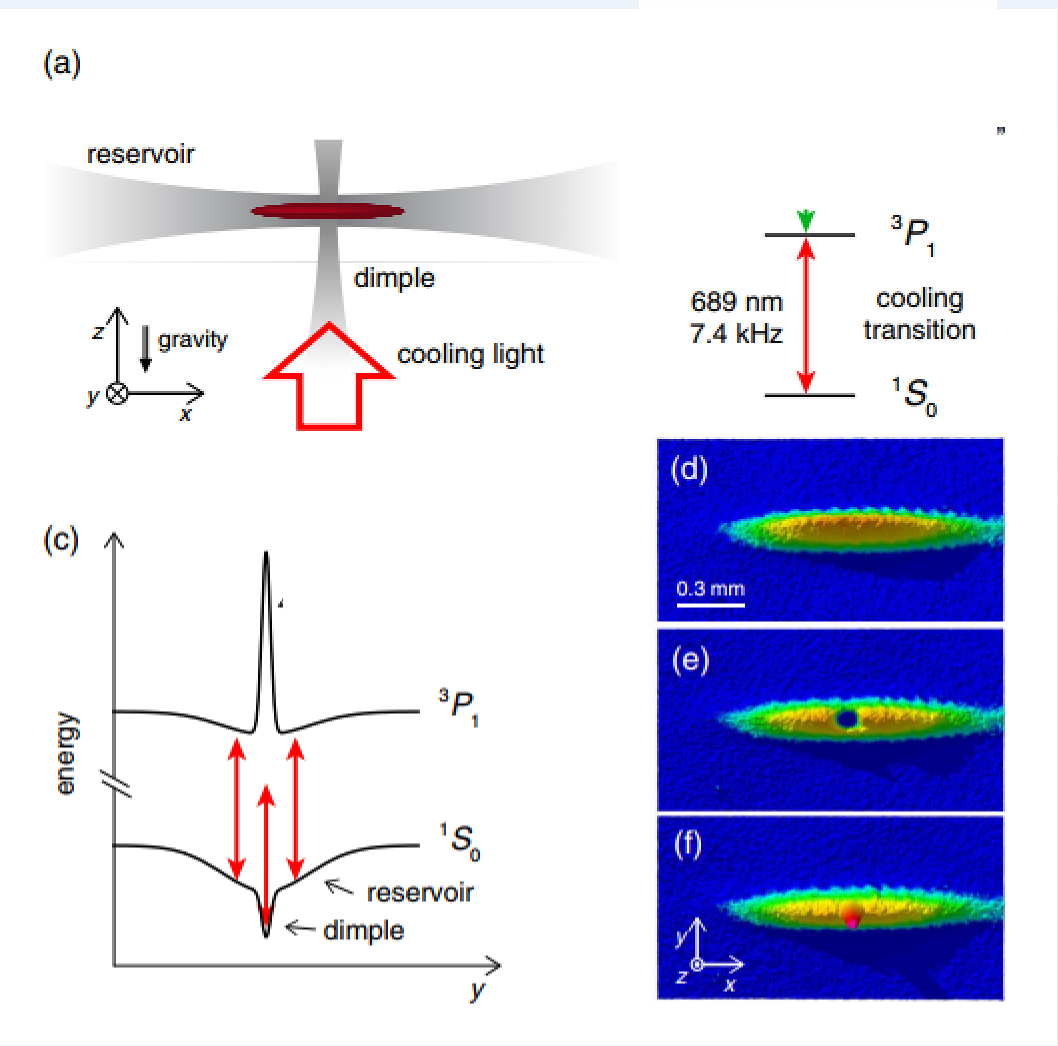
Simon Stellmer,[1] Benjamin Pasquiou,[1] Rudolf Grimm,[1,2] and Florian Schreck[1]
[1]*Institut für Quantenoptik und Quanteninformation (IQOQI), Österreichische Akademie der Wissenschaften, 6020 Innsbruck, Austria*
[2]*Institut für Experimentalphysik und Zentrum für Quantenphysik, Universität Innsbruck, 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

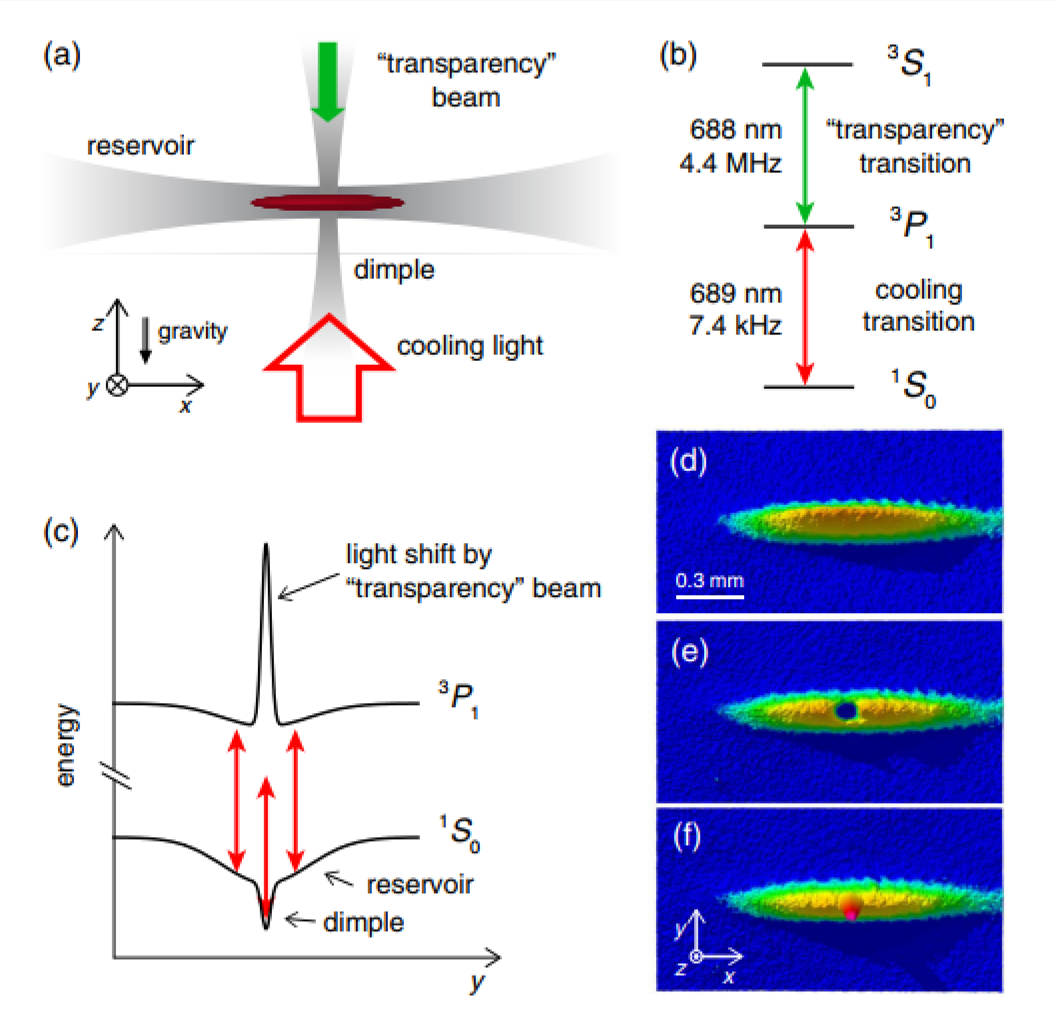


Laser-cooling to BEC

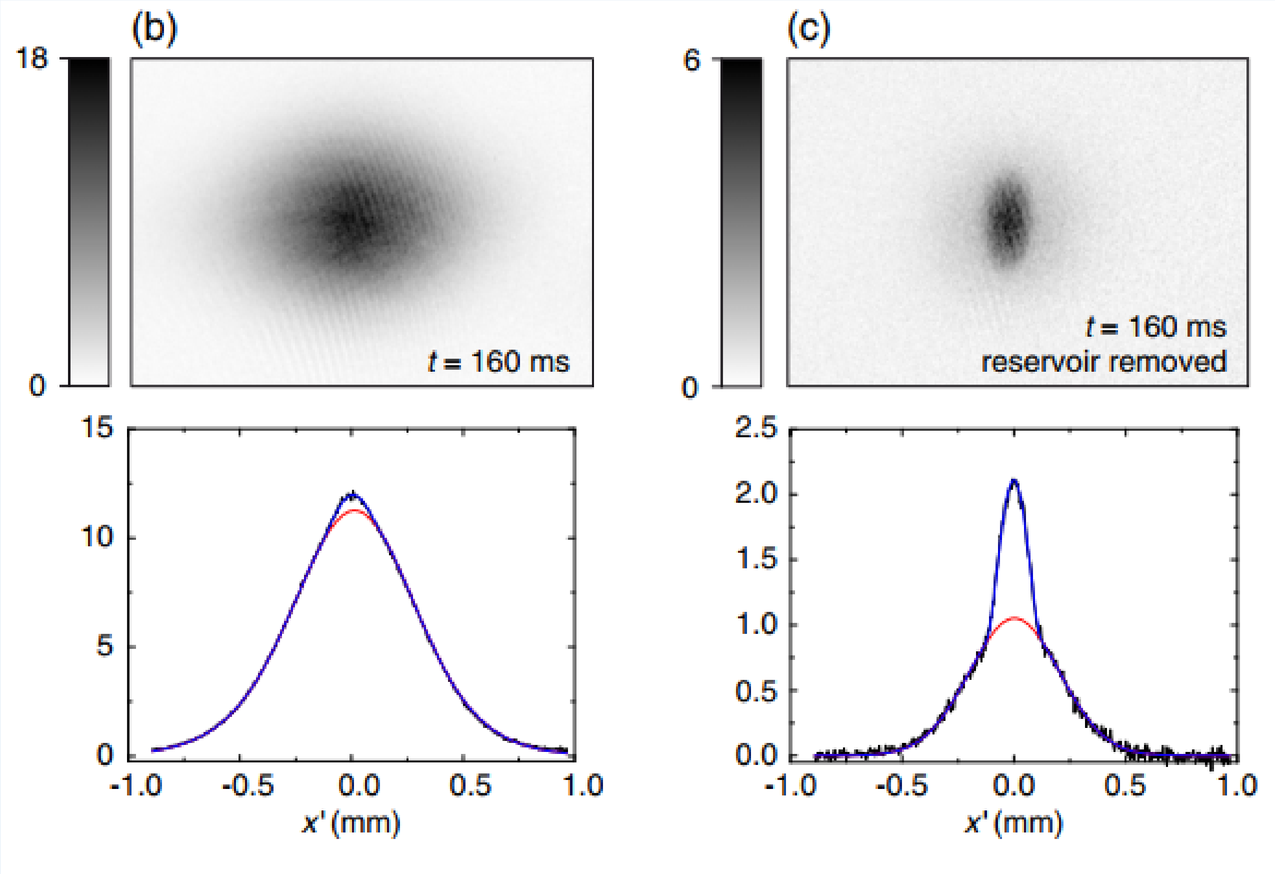
Narrow-line MOT of Sr

+ "dimple" to increase density

+ "invisibility cloak" to avoid scattering in dense region

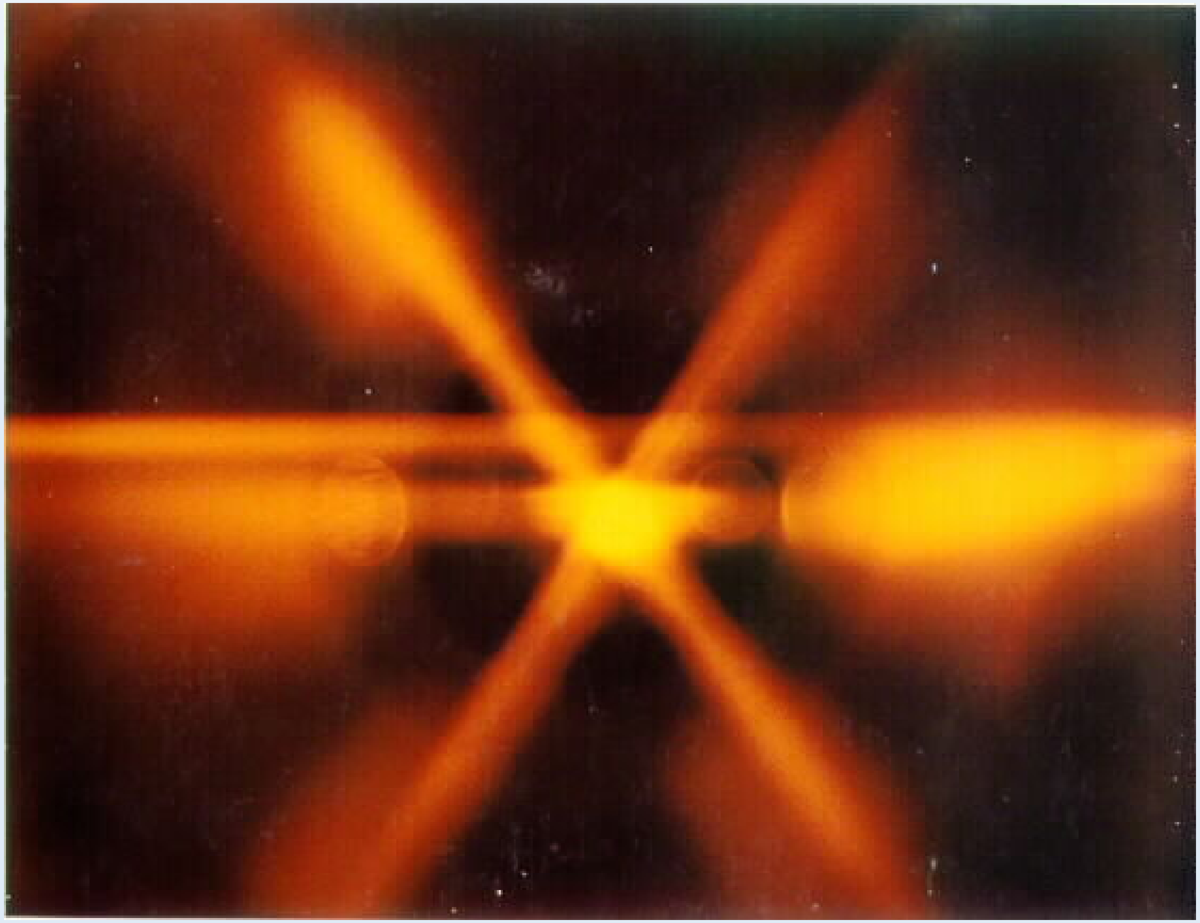


Laser-cooling to BEC



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

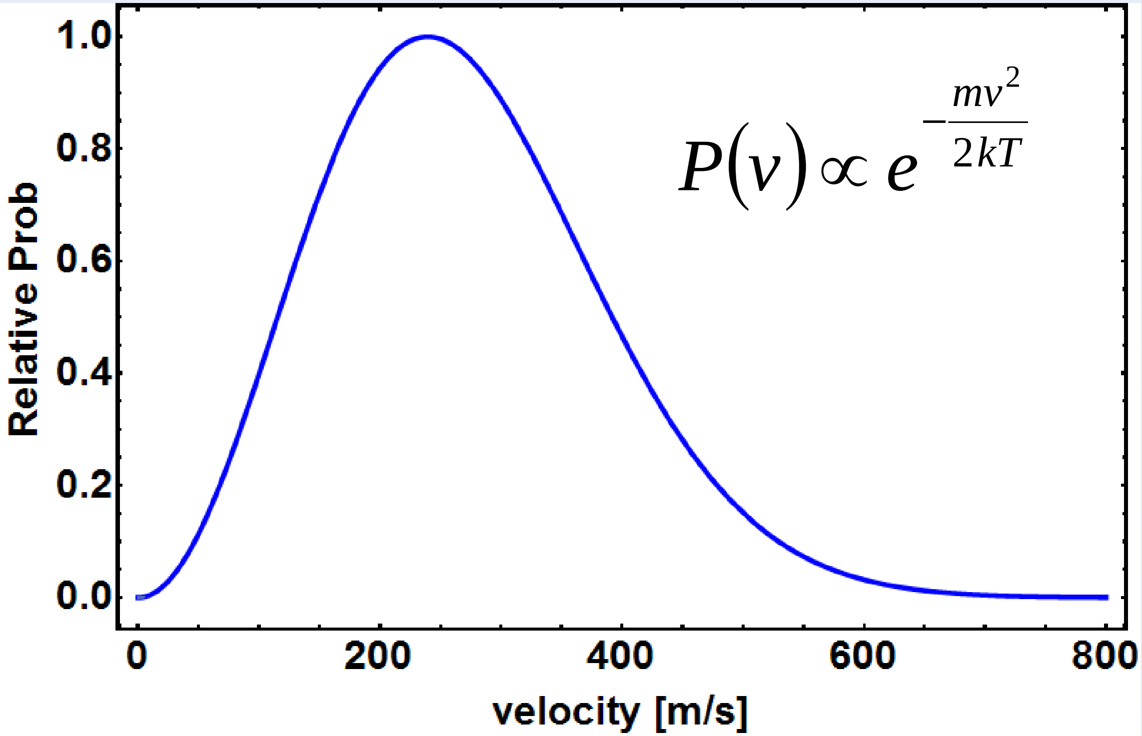
Optical molasses - revisited



Early images of 3D sodium optical molasses [Phillips / Metcalf]

Loading from thermal vapor - limitations

Capture range of molasses limited to
$|v| < v_c \approx \Gamma/k \sim$ few m/s for alkalis



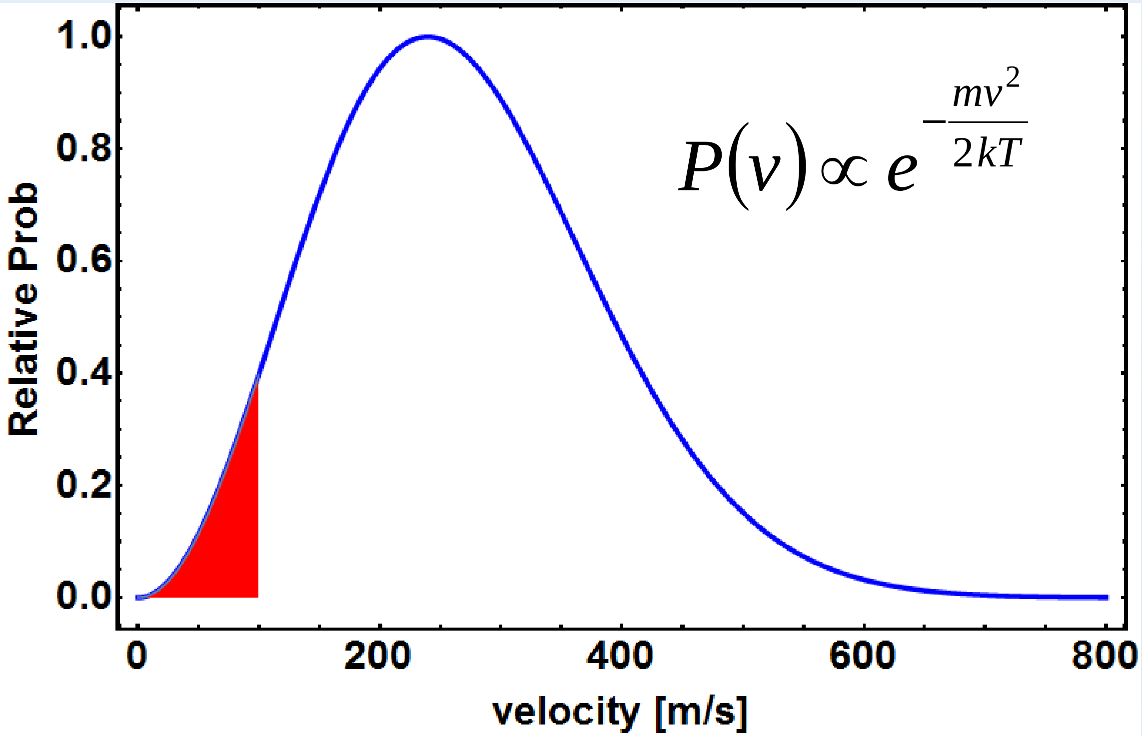
For ^{87}Rb
~ 5 m/s

~ 0.0005% captured

Loading from thermal vapor - limitations

Capture range of molasses limited to

$|v| < v_c \approx \Gamma/k$ ~ few m/s for alkalis



If $v_c \sim 100$ m/s

~ 5% captured

(× 10^4 gain!)

One way to increase v_c

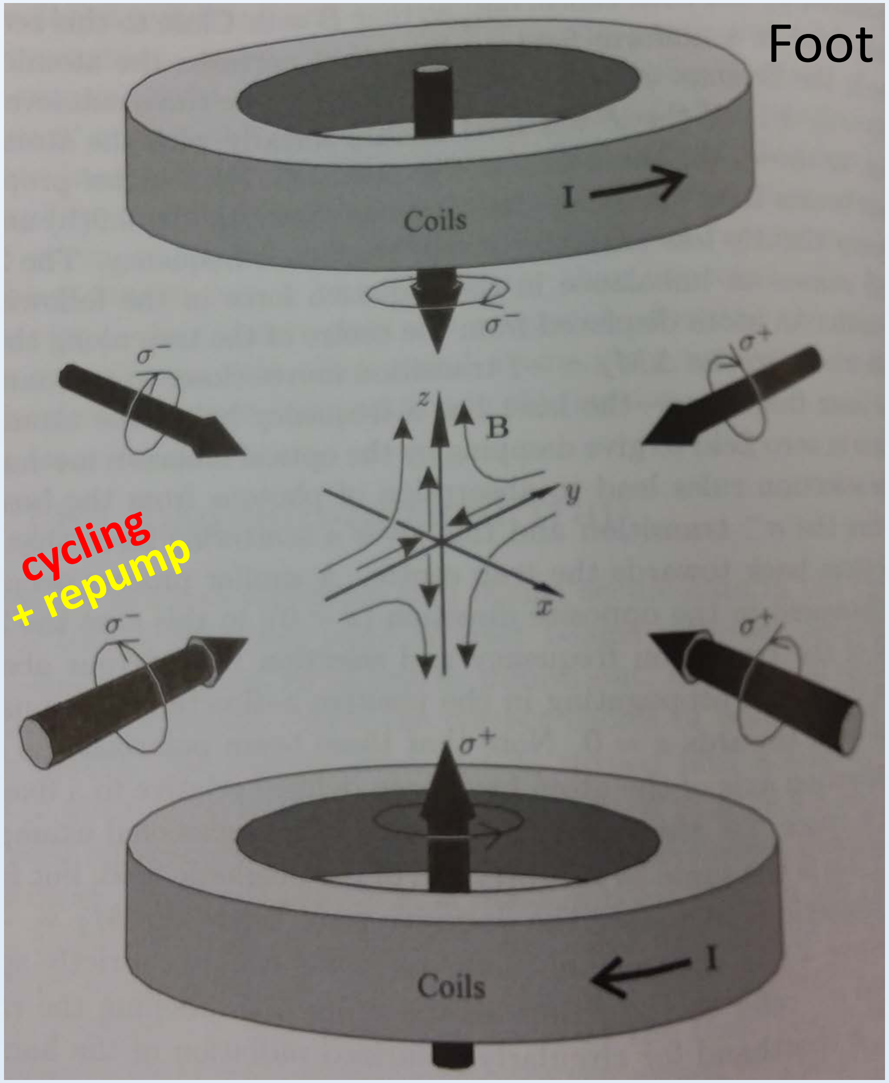
→ add a B-field gradient

The magneto-optical trap (MOT)

- 3D molasses + B-field gradient
  > spatially varying force

- working horse of cold atom experiments
  > simple, effective,
  much larger capture velocities

First MOT demonstration
Bagnato, et al., Pritchard group (1987)



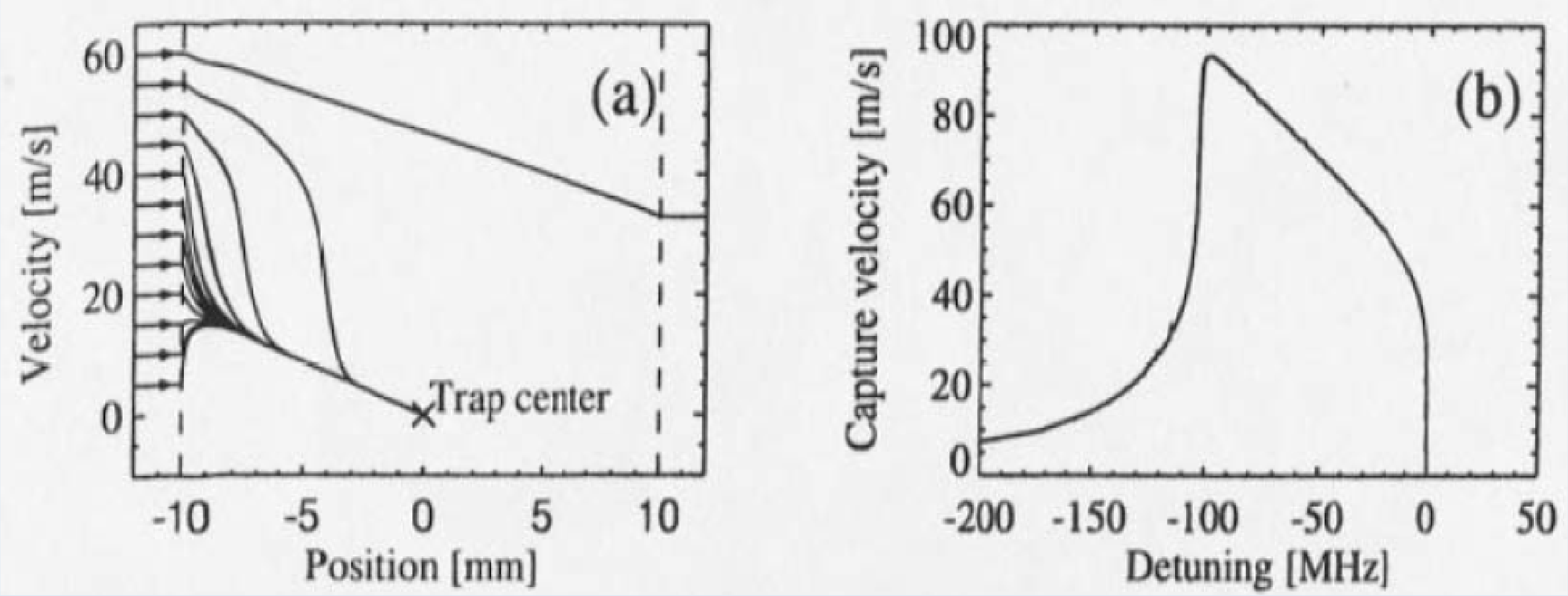
Foot

cycling
+ repump

anti-Helmholtz
coil pair

Loading a magneto-optical trap

1D simulation from Metcalf / van der Straten



$\delta = -5\Gamma \approx -2\pi \times 30$ MHz

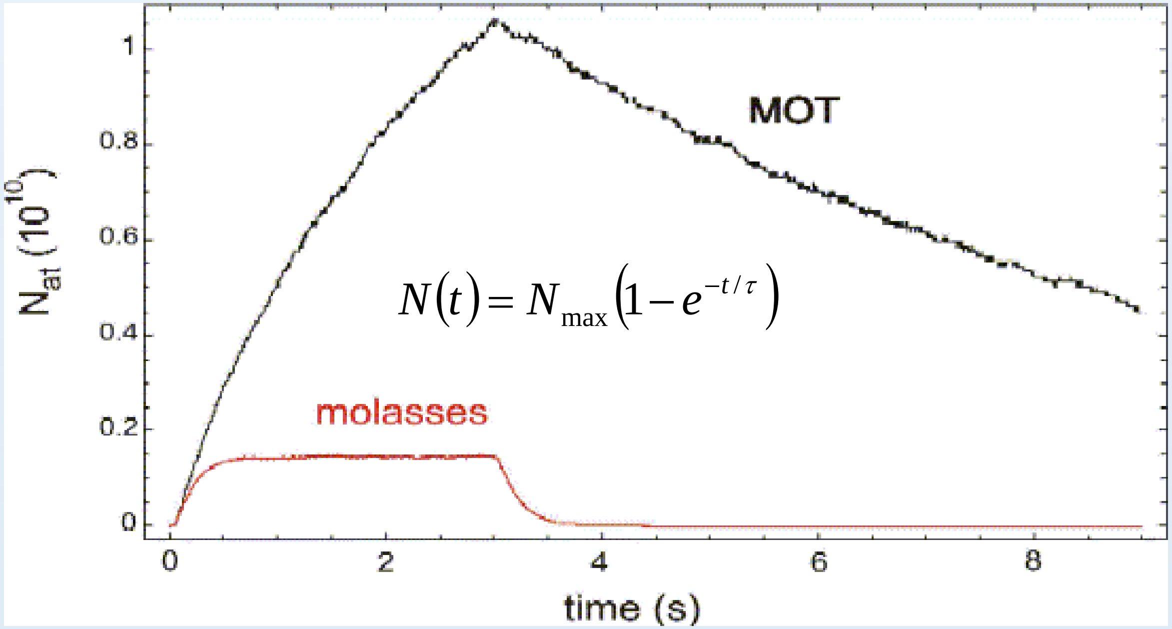
$s = 10, \sigma = 10$ mm

Loading a magneto-optical trap

strontium MOT, Killian group (Rice)

Typical MOT numbers ~ few × 10^8-10^{10}
Typical MOT temperatures ~ few × $T_{Doppler}$
Typical MOT dimensions ~ mm-scale

Loading a magneto-optical trap



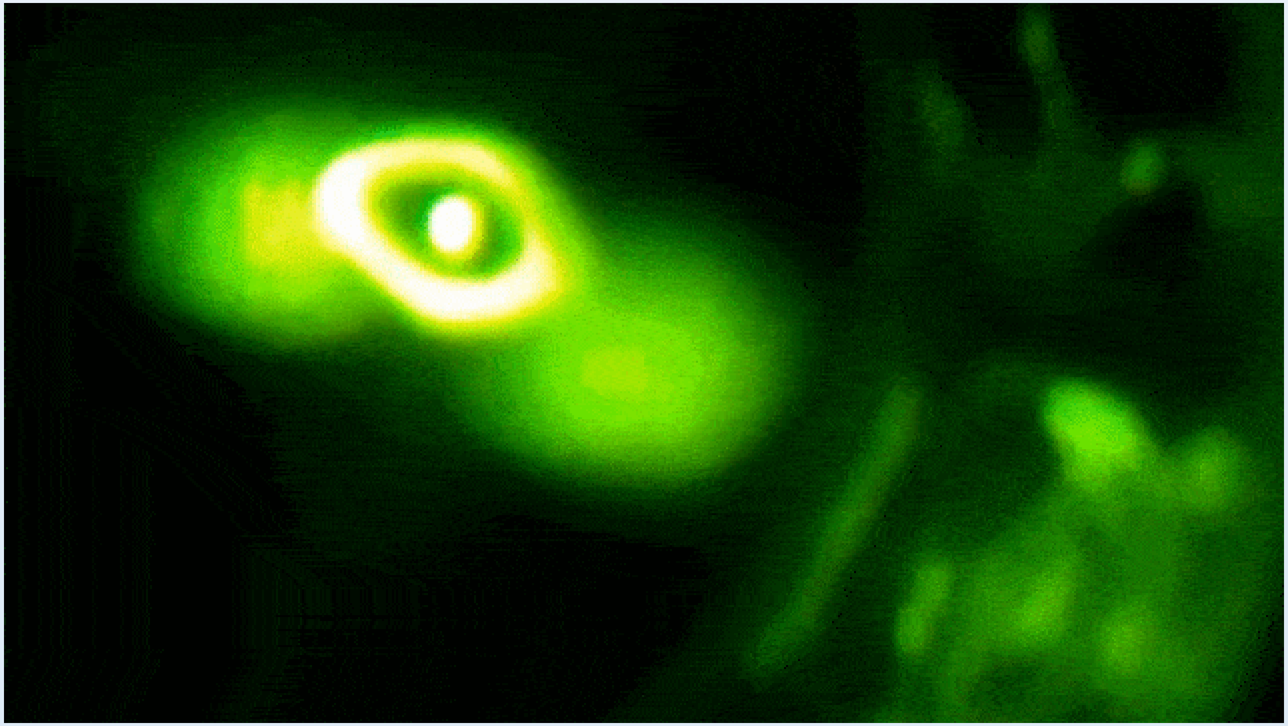
$$N(t) = N_{\max}\left(1 - e^{-t/\tau}\right)$$

Y. B. Ovchinnikov, *Opt. Comm.* **249**, 473 (2005)

MOT “charges” like a capacitor – gets filled by background atoms flying around, but those atoms also lead to loss (they have a lot of kinetic energy)

Funky MOTs

(sensitive to alignment, polarization, etc.)

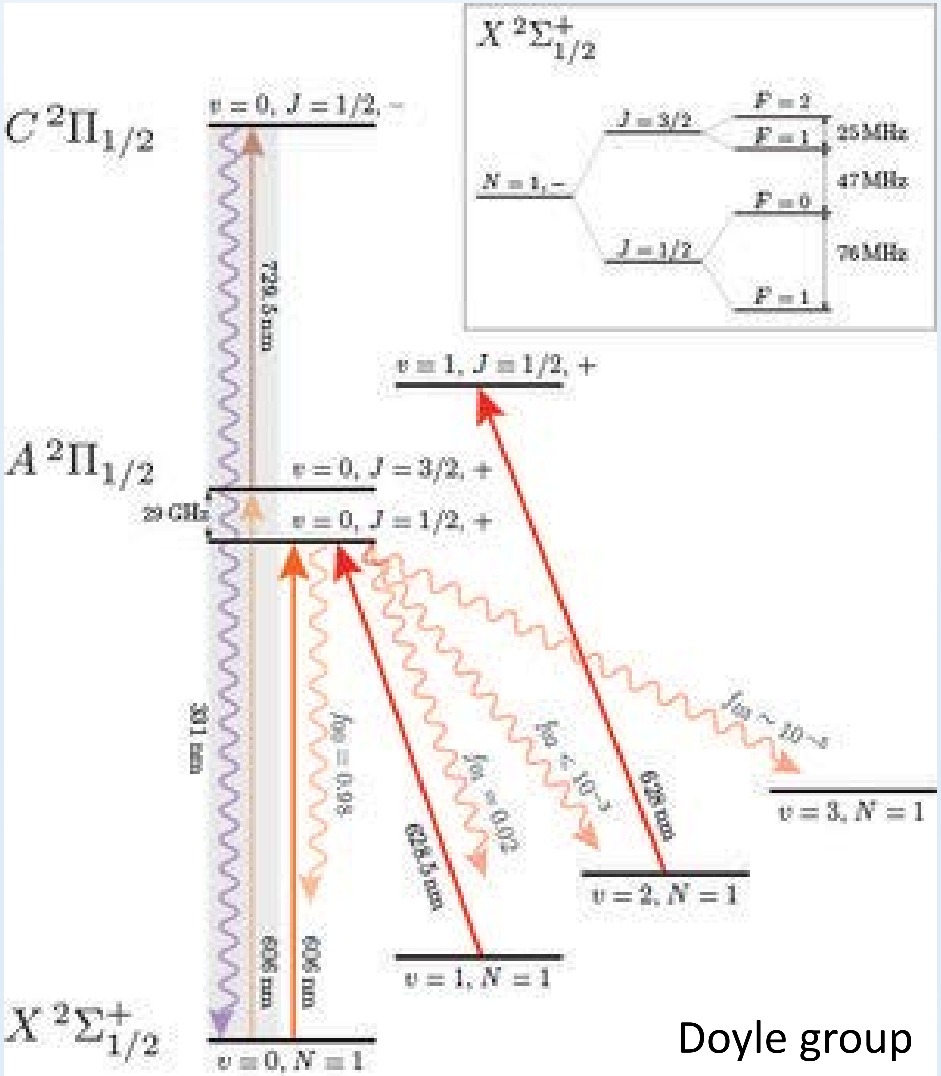


“racetrack MOT” - David Paredes, ICFO

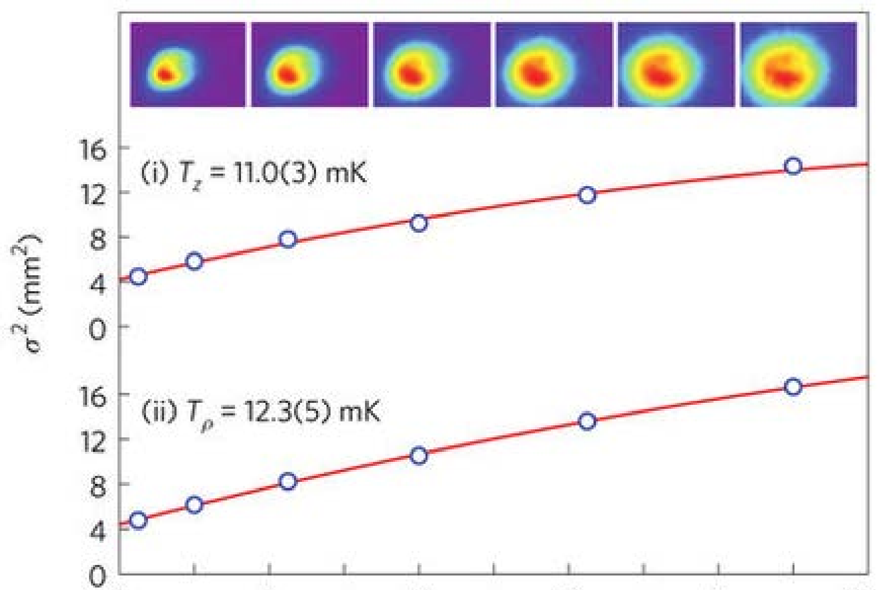
Laser-cooling

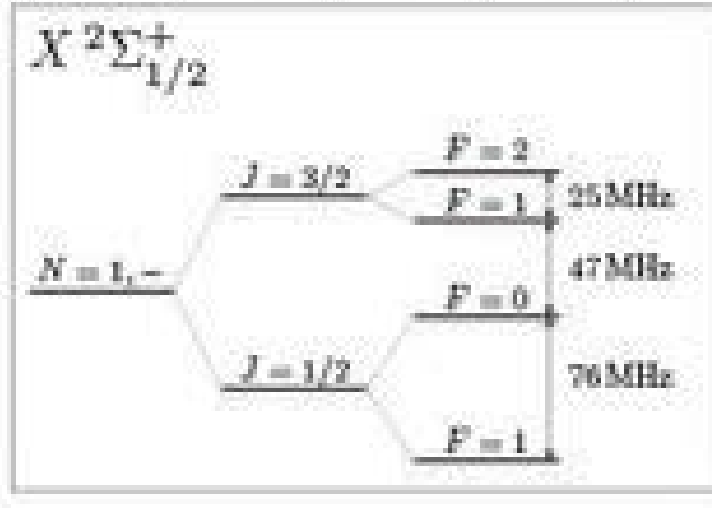
Laser-cooling of molecules

Tarbutt / Hinds group



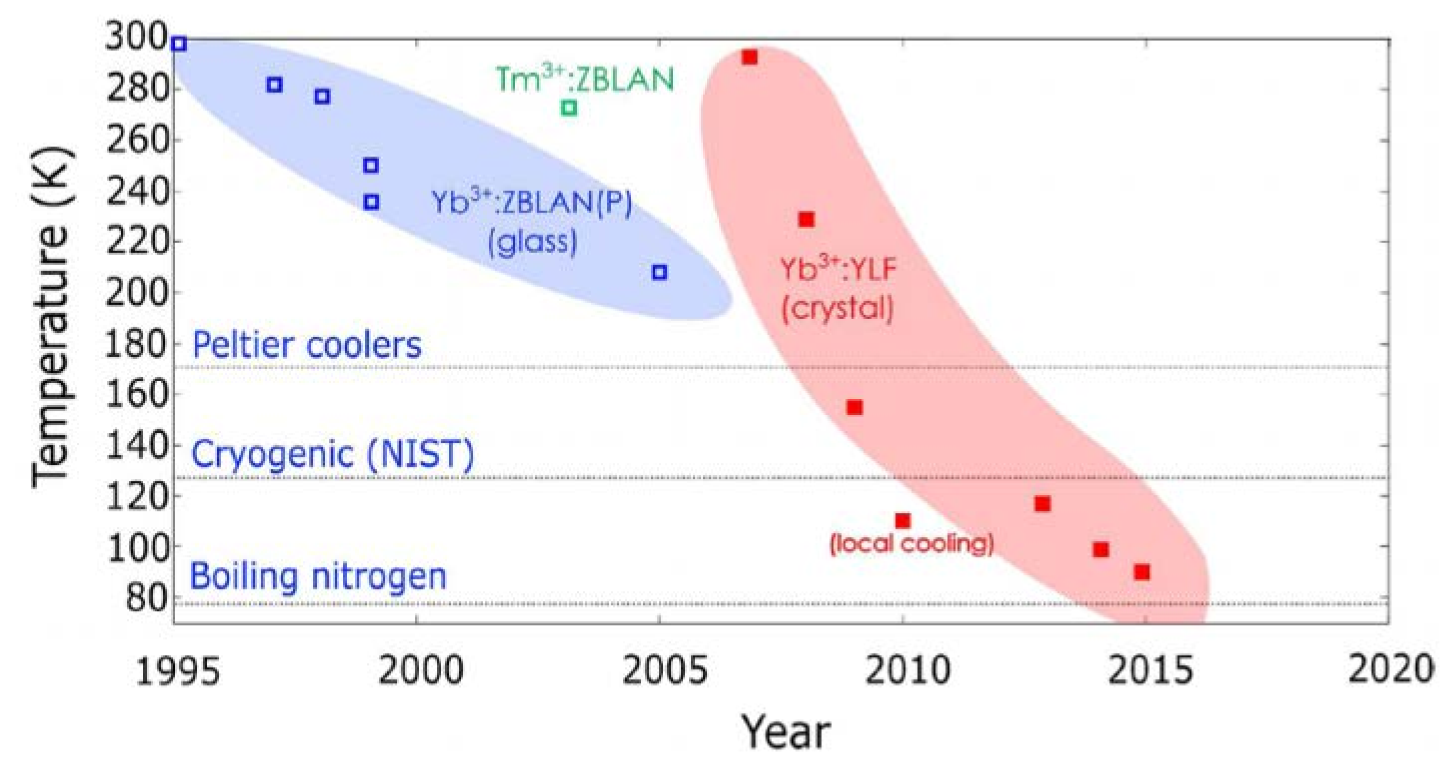
Doyle group





Laser-cooling of solids

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



Laser-cooling of solids

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