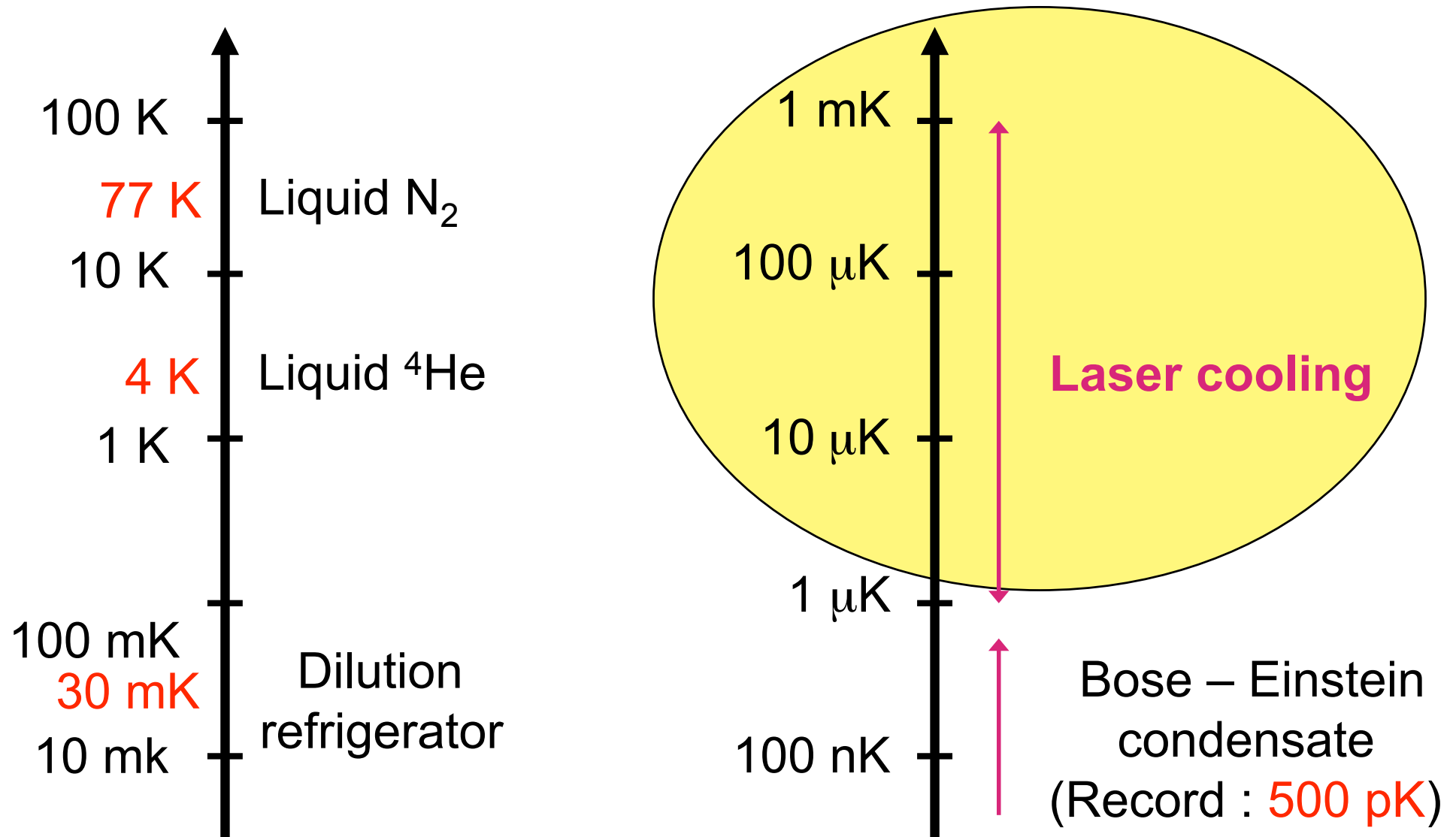


# Laser cooling and trapping

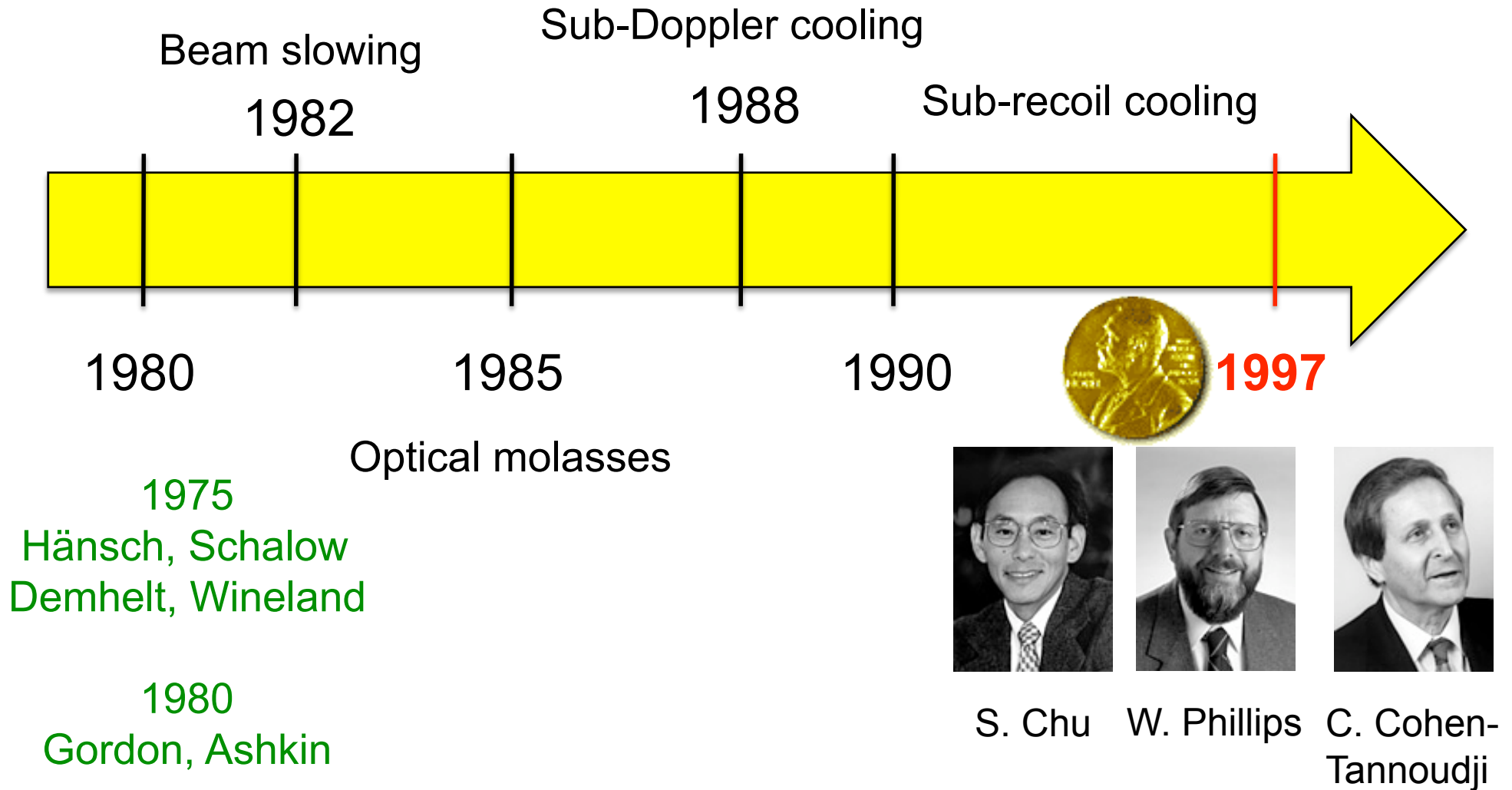
---

- Lecture 1** Light forces
- Lecture 2** Doppler cooling
- Lecture 3** Sub-Doppler cooling
- Lecture 4** Magneto-optical trap  
Evaporative cooling

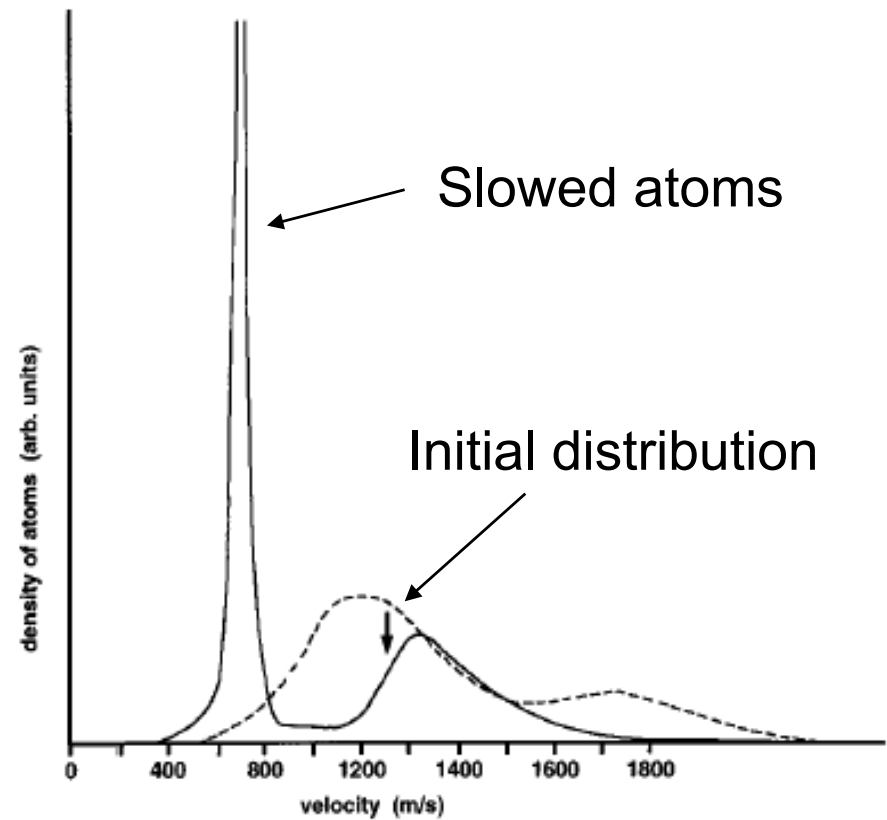
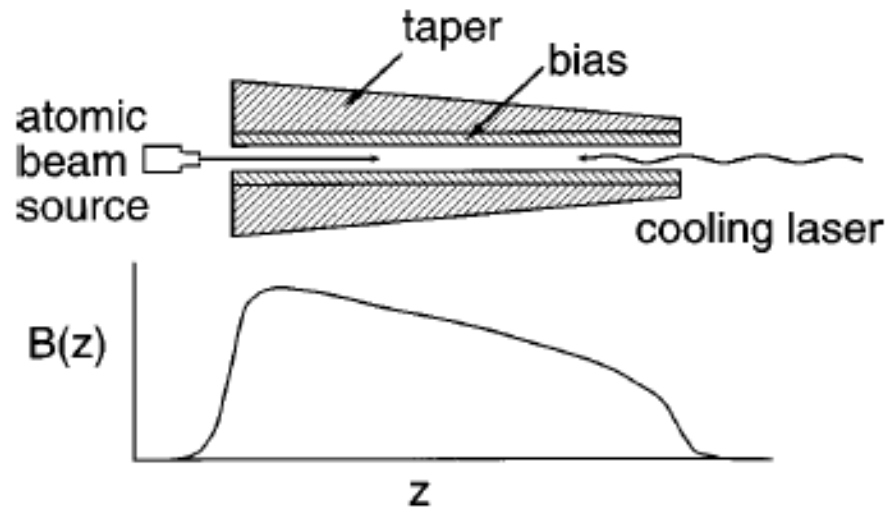
# How cold?



# (Very...) short history



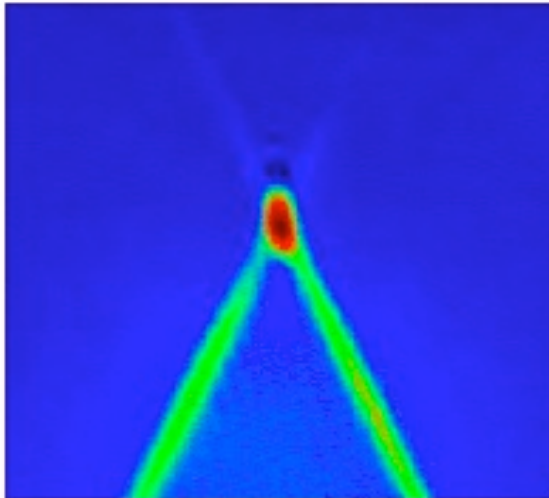
# Zeeman slowing



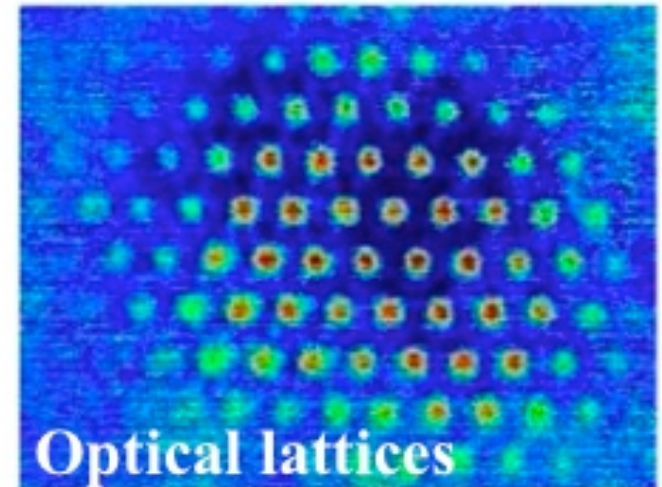
Phillips, PRL **48**, p. 596 (1982)

# Crossed dipole trap – crystal of light

---



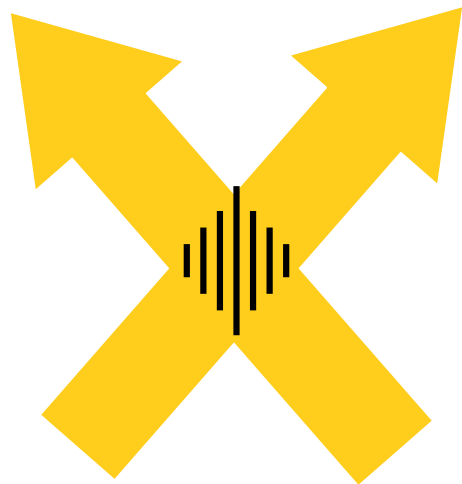
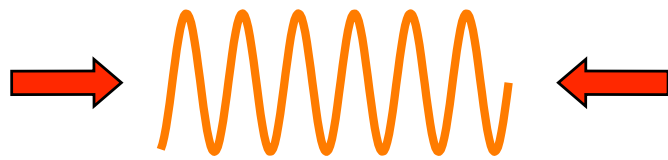
attraction towards  
large intensity  
regions



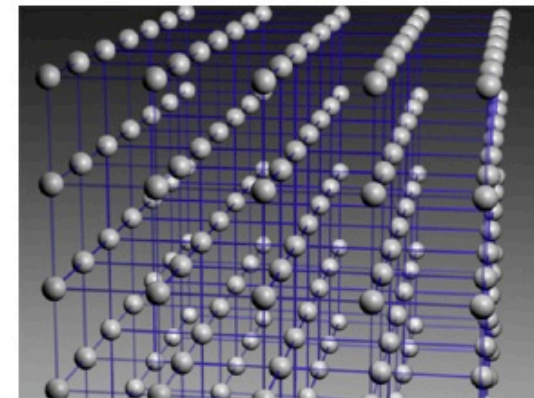
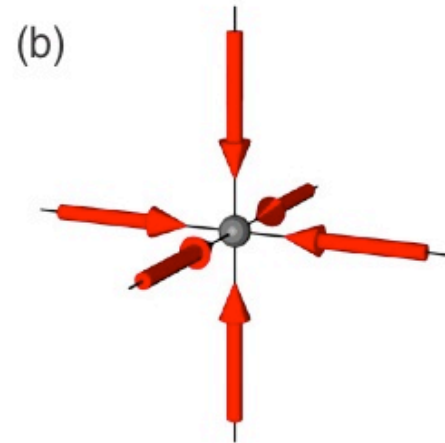
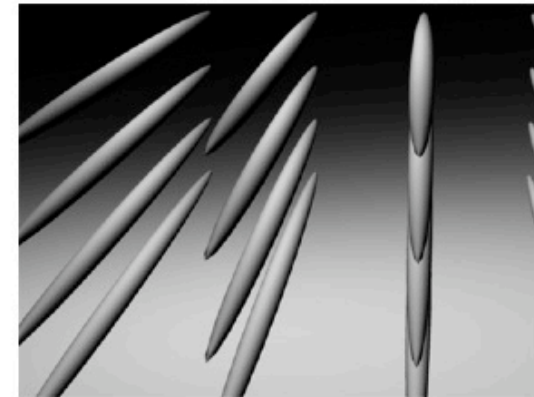
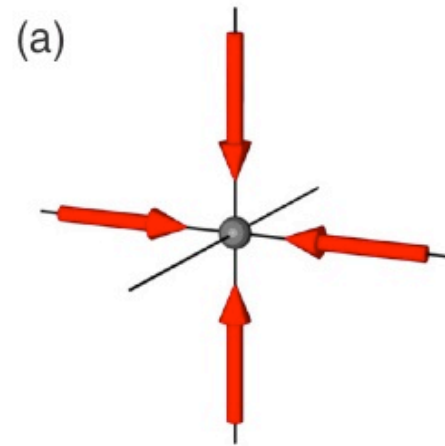
pictures from C. Salomon et al.

# Optical lattices

1 - d



2 - d



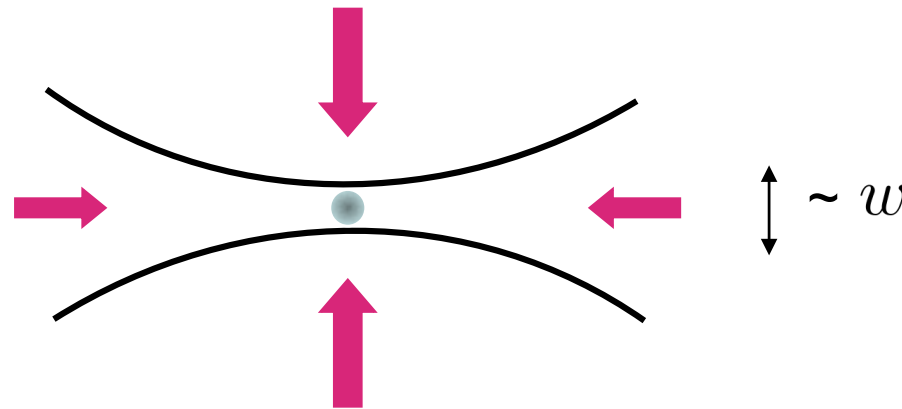
3 - d

(M. Greiner)

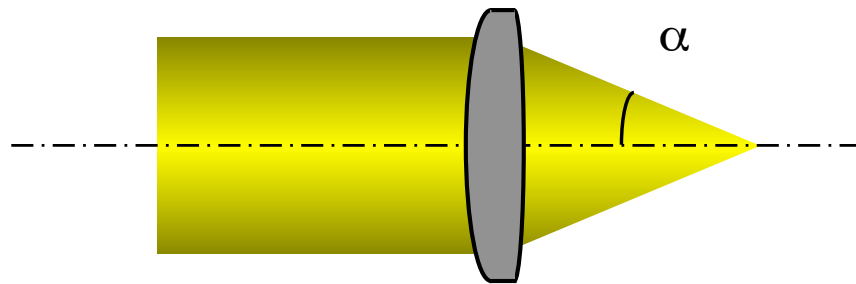
# Optical tweezers: trapping in 3 D

High field seekers  $\omega < \omega_0$

Gaussian beam



$$\sim z_R = \frac{\pi w^2}{\lambda}$$



Diffraction limited optics  $w \sim \lambda$

Trapping volume  $\sim \pi \lambda^3$

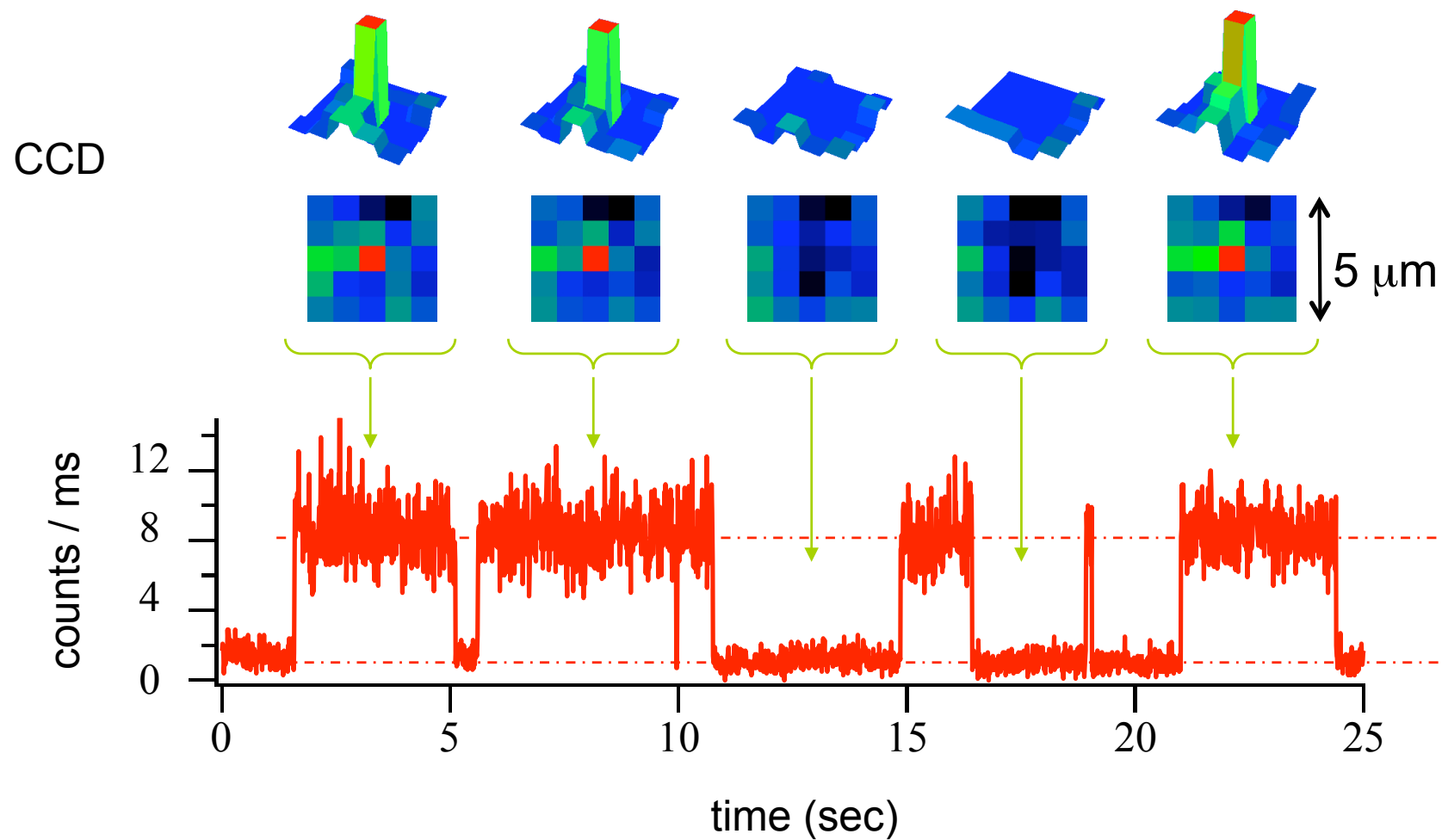
$$NA = \sin \alpha$$

$$w \sim \lambda/NA$$

Ex: 1 mW on 1  $\mu\text{m}$

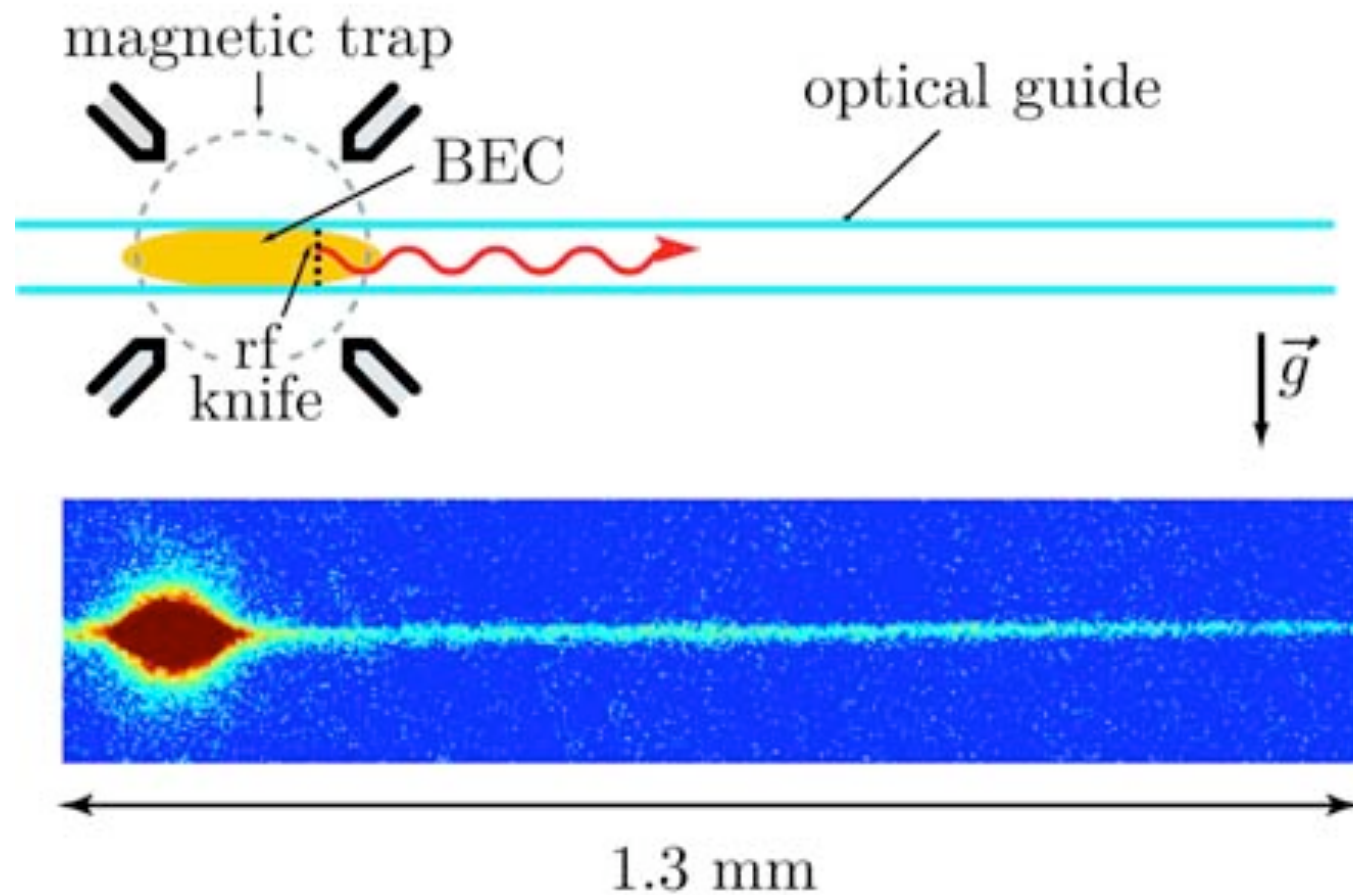
**Trap depth = 1 mK**

# Detecting a single atom

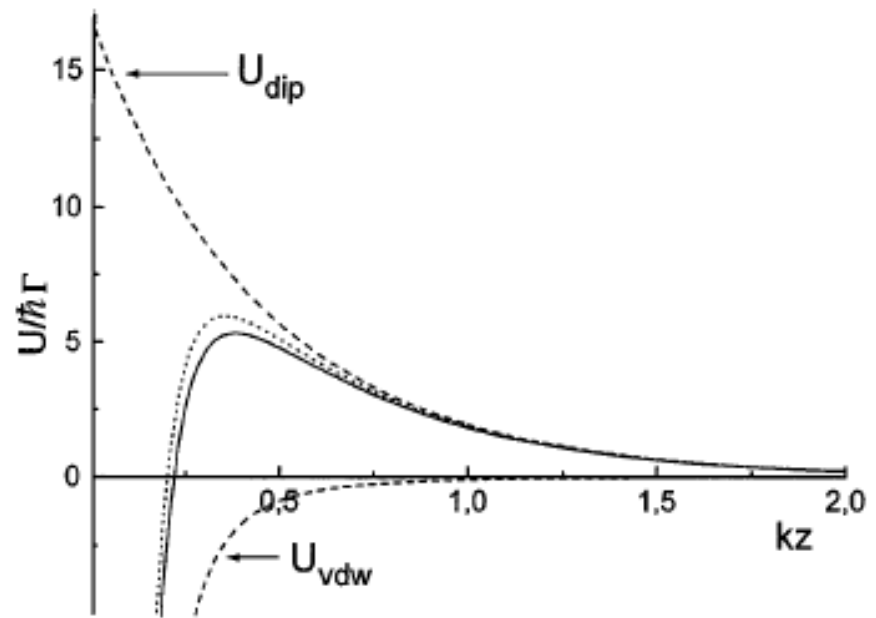
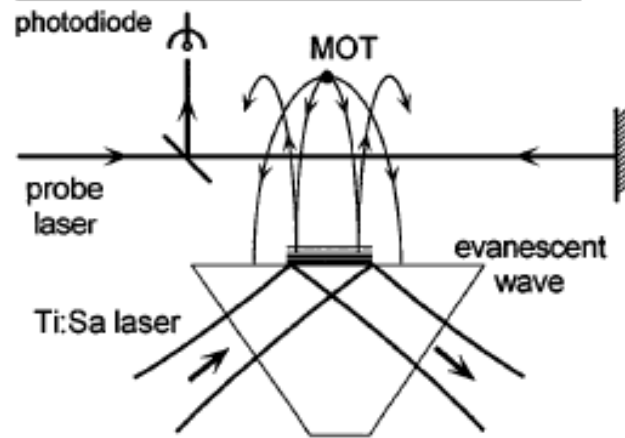
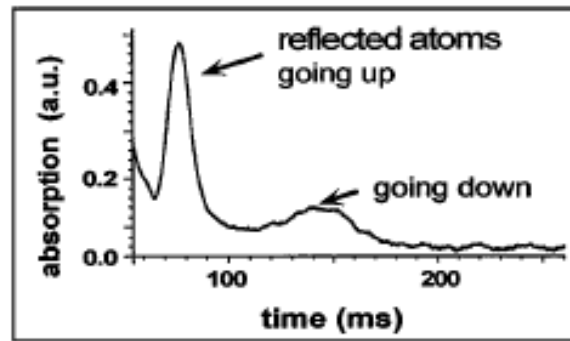




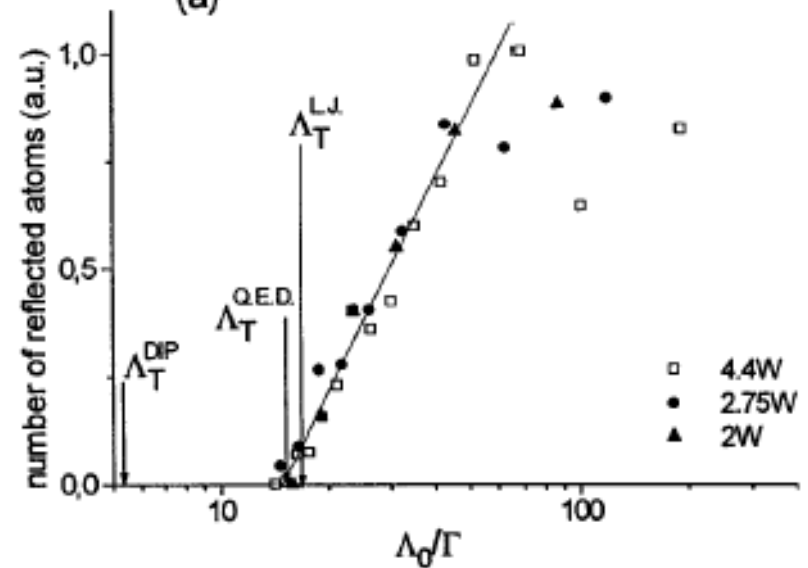
# Guiding an atom laser



# Bouncing atoms on a surface



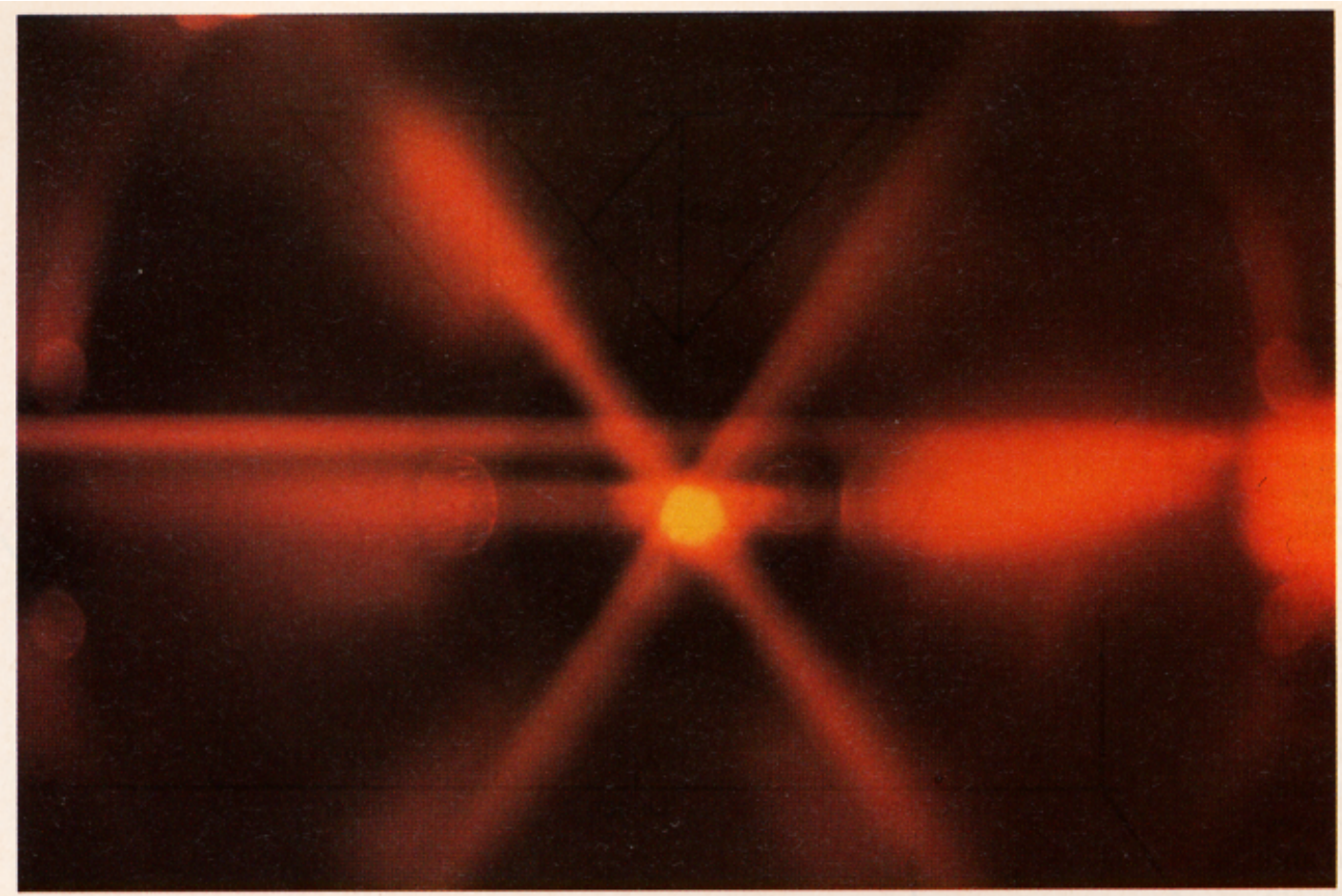
(a)



Institut d'Optique, 1996

## 3D optical molasses

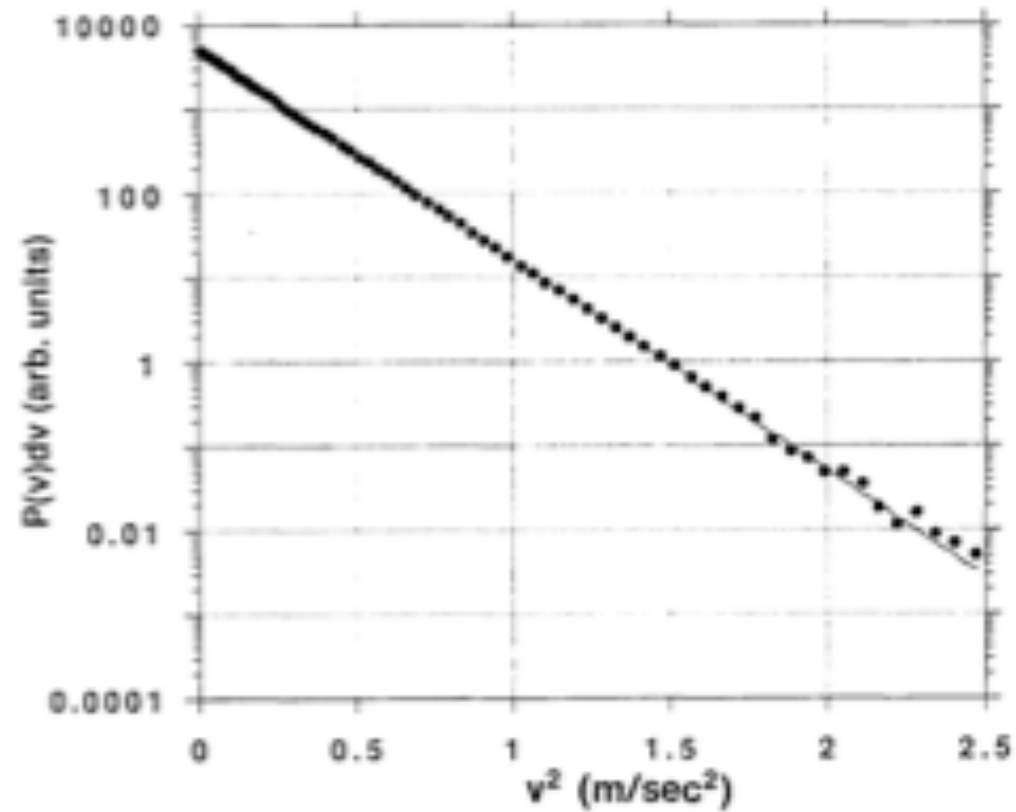
---



Chu (1985)

# Laser cooling and Maxwell Boltzman distribution

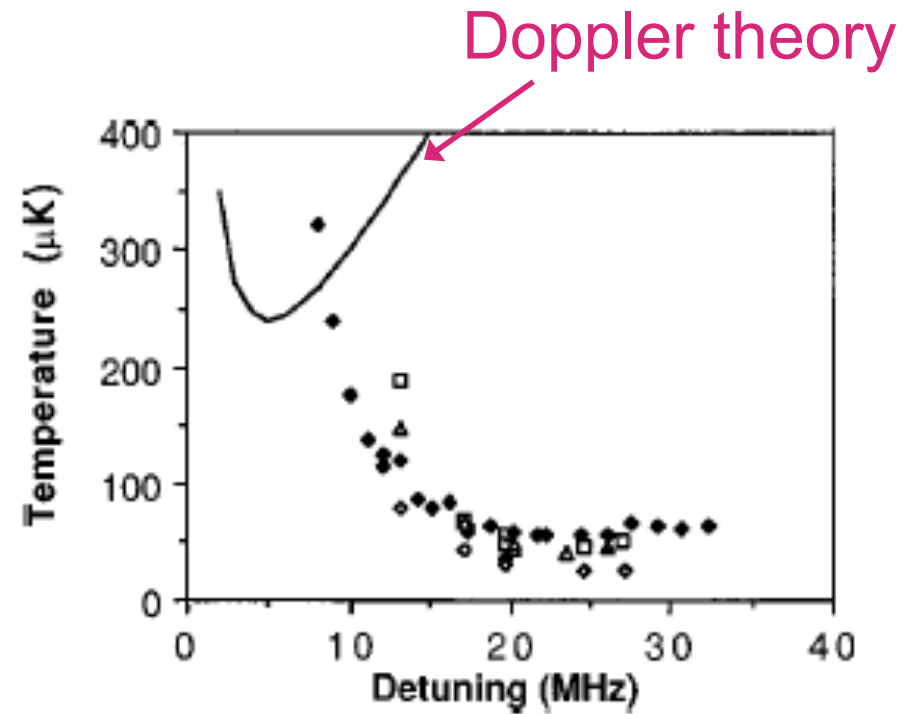
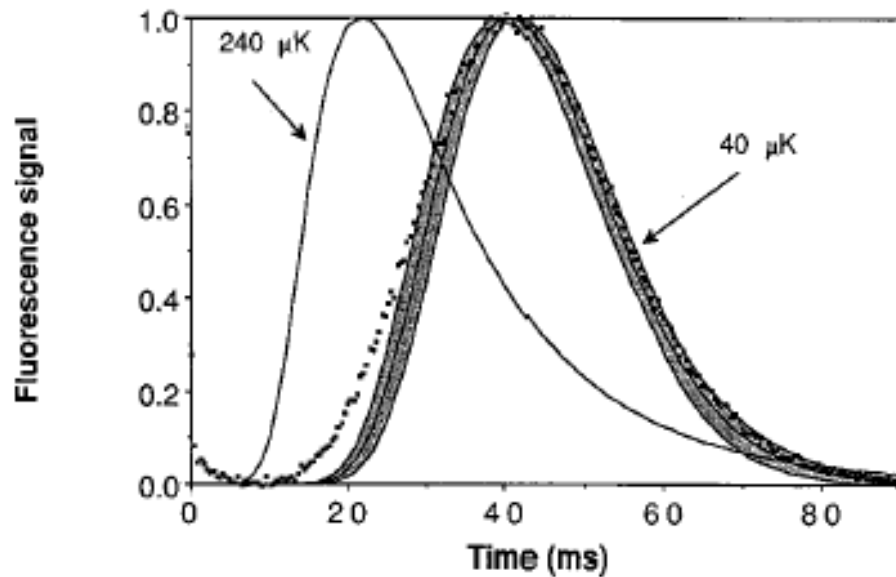
---



Lett *et al.*, JOSA B **11**, p. 2024 (1989)

# The results of Phillips *et al.* (1988)

## Time-of-flight measurement



For Na,  $T_D = 240 \mu\text{K}$

Lett, PRL **61**, p. 169 (1988)

# Laser cooled atoms (2010)

1	1											13	14	15	16	17	18	
1	H																	He
	1.0079																	4.0026
2	2	3											5	6	7	8	9	10
	Li	Be											B	C	N	O	F	Ne
	6.941	9.0122											10.811	12.011	14.007	15.999	18.998	20.180
3	11	12											13	14	15	16	17	18
	Na	Mg											Al	Si	P	S	Cl	Ar
	22.990	24.305											26.982	28.086	30.974	32.065	35.453	39.948
4	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
	39.098	40.078	44.956	47.867	50.942	51.996	54.938	55.845	58.933	58.693	63.546	65.39	69.723	72.64	74.922	78.96	79.904	83.80
5	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
	85.468	87.62	88.906	91.224	92.906	95.94	(98)	101.07	102.91	106.42	107.87	112.41	114.82	118.71	121.76	127.60	126.90	131.29
6	55	56	57-71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86
	Cs	Ba	La-Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
	132.91	137.33		178.49	180.95	183.84	186.21	190.23	192.22	195.08	196.97	200.59	204.38	207.2	208.98	(209)	(210)	(222)
7	87	88	89-103	104	105	106	107	108	109	110	111	112						
	Fr	Ra	Ac-Lr	Rf	Db	Sg	Bh	Hs	Mt	Uun	Uuu	Uub						
	(223)	(226)		(261)	(262)	(266)	(264)	(277)	(268)	(281)	(272)	(285)						
													114					
													Uuq					
													(289)					

Lanthanides	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71
	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
	138.91	140.12	140.91	144.24	(145)	150.36	151.96	157.25	158.93	162.50	164.93	167.26	168.93	173.04	174.97
Actinides	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103
	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr
	(227)	232.04	231.04	238.03	(237)	(244)	(243)	(247)	(247)	(251)	(252)	(257)	(258)	(259)	(262)

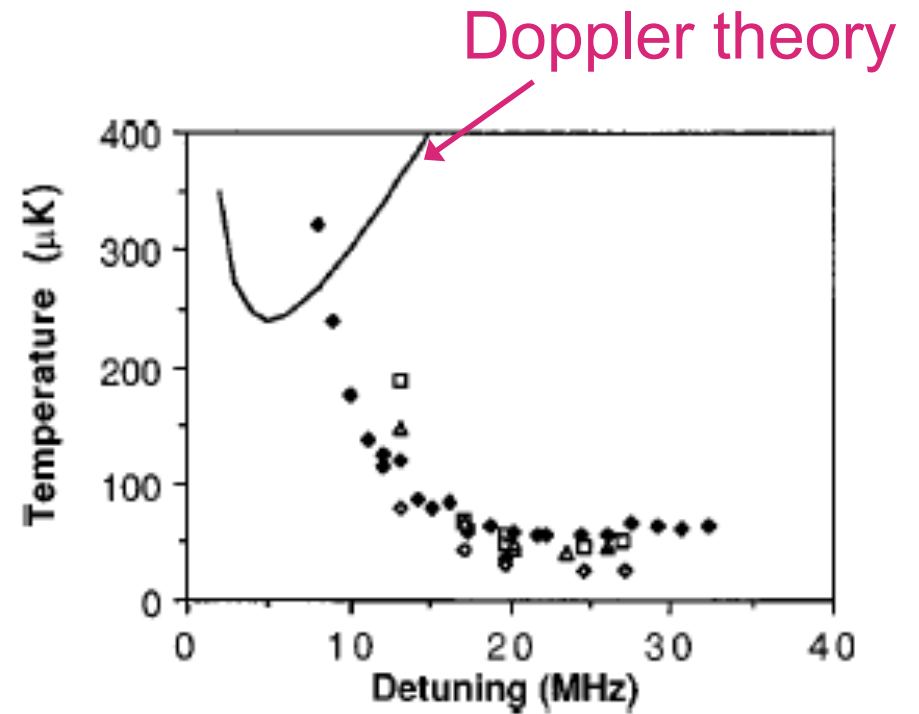
# Laser cooled atoms (2010)

1	1											13	14	15	16	17	18	
1	H																	He
	1.0079																	4.0026
2	2	3											5	6	7	8	9	10
	Li	Be											B	C	N	O	F	Ne
	6.941	9.0122											10.811	12.011	14.007	15.999	18.998	20.180
3	11	12											13	14	15	16	17	18
	Na	Mg											Al	Si	P	S	Cl	Ar
	22.990	24.305											26.982	28.086	30.974	32.065	35.453	39.948
4	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
	39.098	40.078	44.956	47.867	50.942	51.996	54.938	55.845	58.933	58.693	63.546	65.39	69.723	72.64	74.922	78.96	79.904	83.80
5	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
	85.468	87.62	88.906	91.224	92.906	95.94	(98)	101.07	102.91	106.42	107.87	112.41	114.82	118.71	121.76	127.60	126.90	131.29
6	55	56	57-71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86
	Cs	Ba	La-Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
	132.91	137.33		178.49	180.95	183.84	186.21	190.23	192.22	195.08	196.97	200.59	204.38	207.2	208.98	(209)	(210)	(222)
7	87	88	89-103	104	105	106	107	108	109	110	111	112						
	Fr	Ra	Ac-Lr	Rf	Db	Sg	Bh	Hs	Mt	Uun	Uuu	Uub						
	(223)	(226)		(261)	(262)	(266)	(264)	(277)	(268)	(281)	(272)	(285)						
													114					
													Uuq					
													(289)					

Lanthanides	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71
	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
	138.91	140.12	140.91	144.24	(145)	150.36	151.96	157.25	158.93	162.50	164.93	167.26	168.93	173.04	174.97
Actinides	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103
	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr
	(227)	232.04	231.04	238.03	(237)	(244)	(243)	(247)	(247)	(251)	(252)	(257)	(258)	(259)	(262)

# Discovery of sub-Doppler cooling (1988)

## Time-of-flight measurement

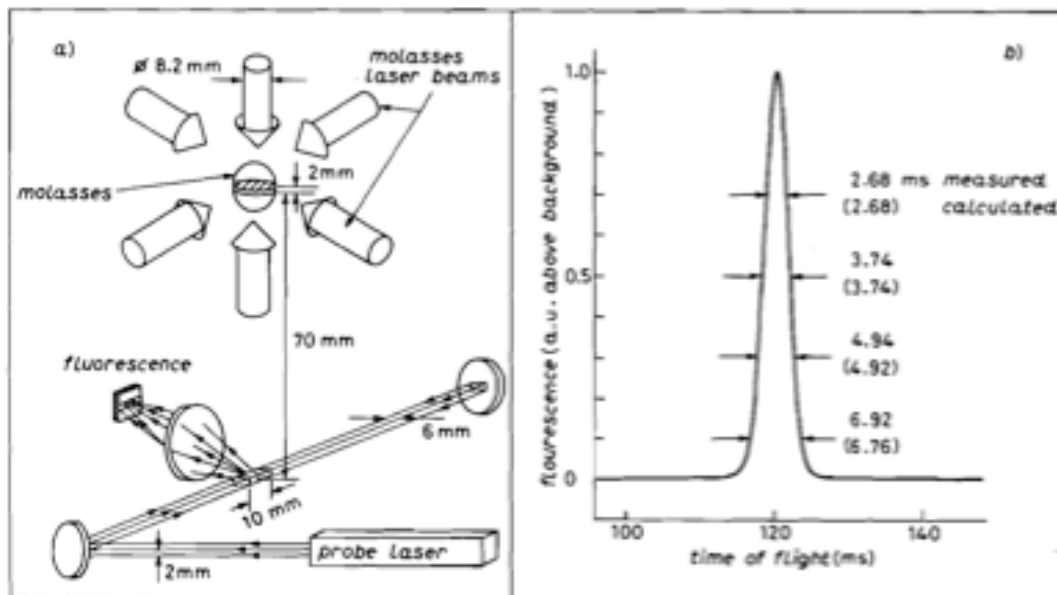


For Na,  $T_D = 240 \mu\text{K}$

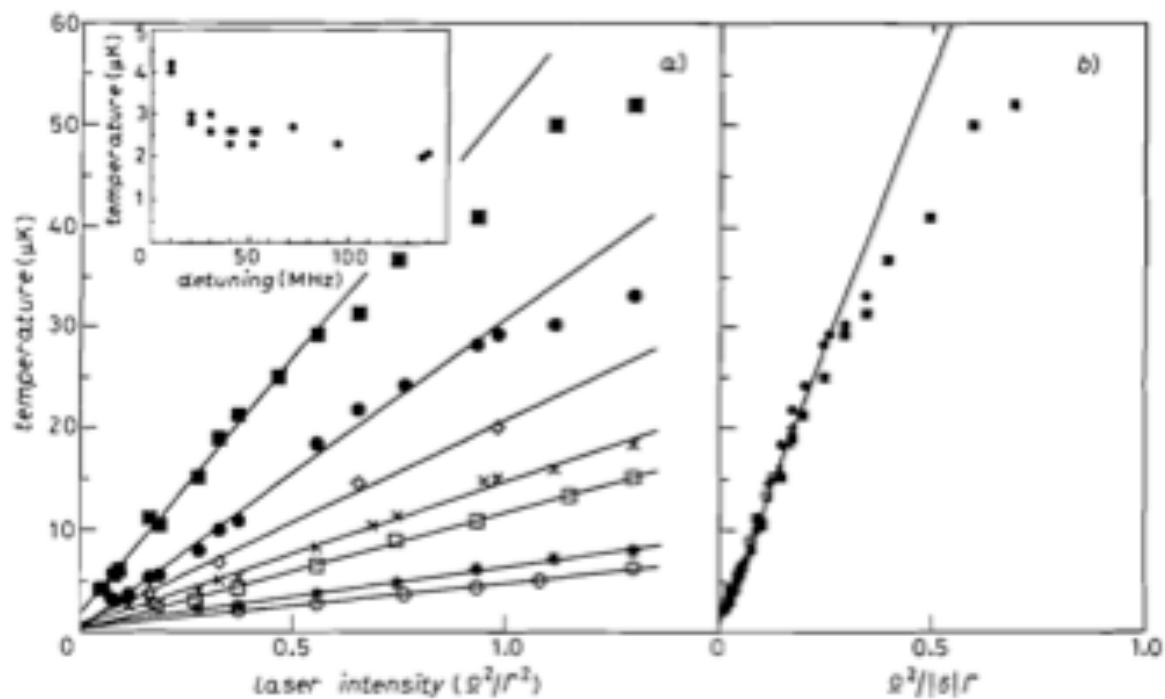
Lett, PRL **61**, p. 169 (1988)



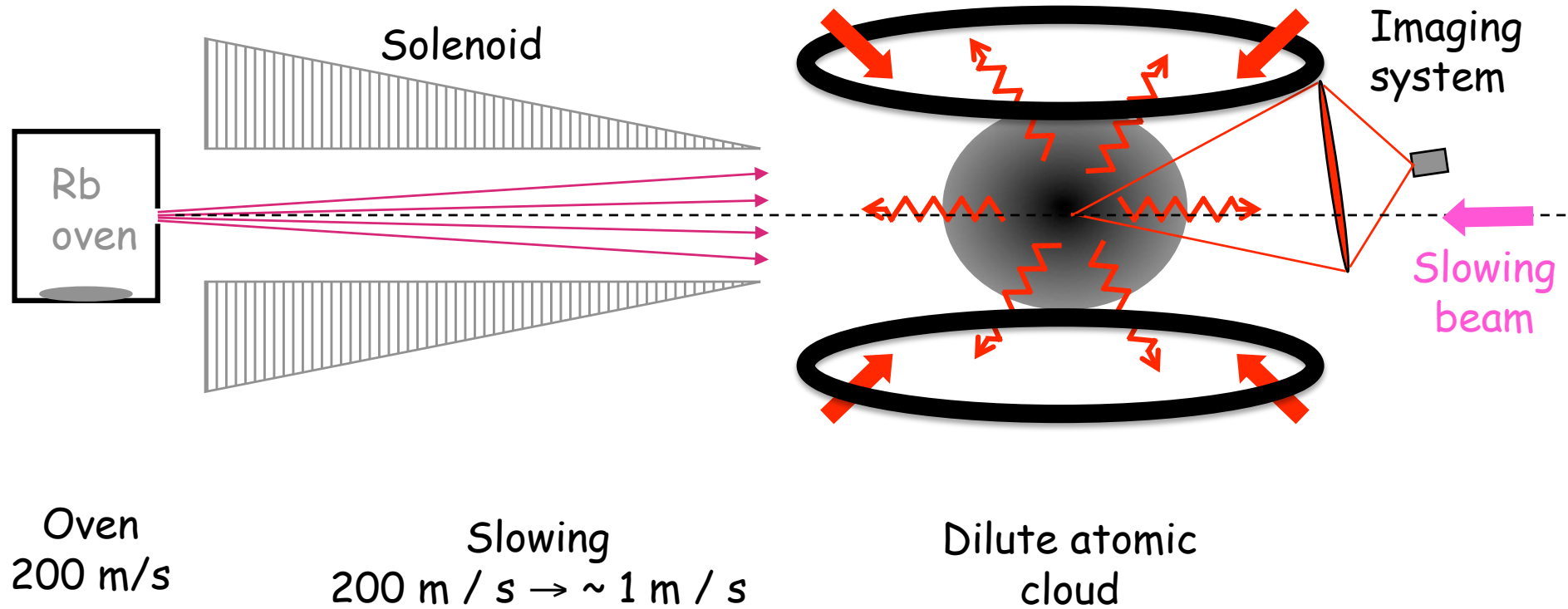
# Experimental verifications

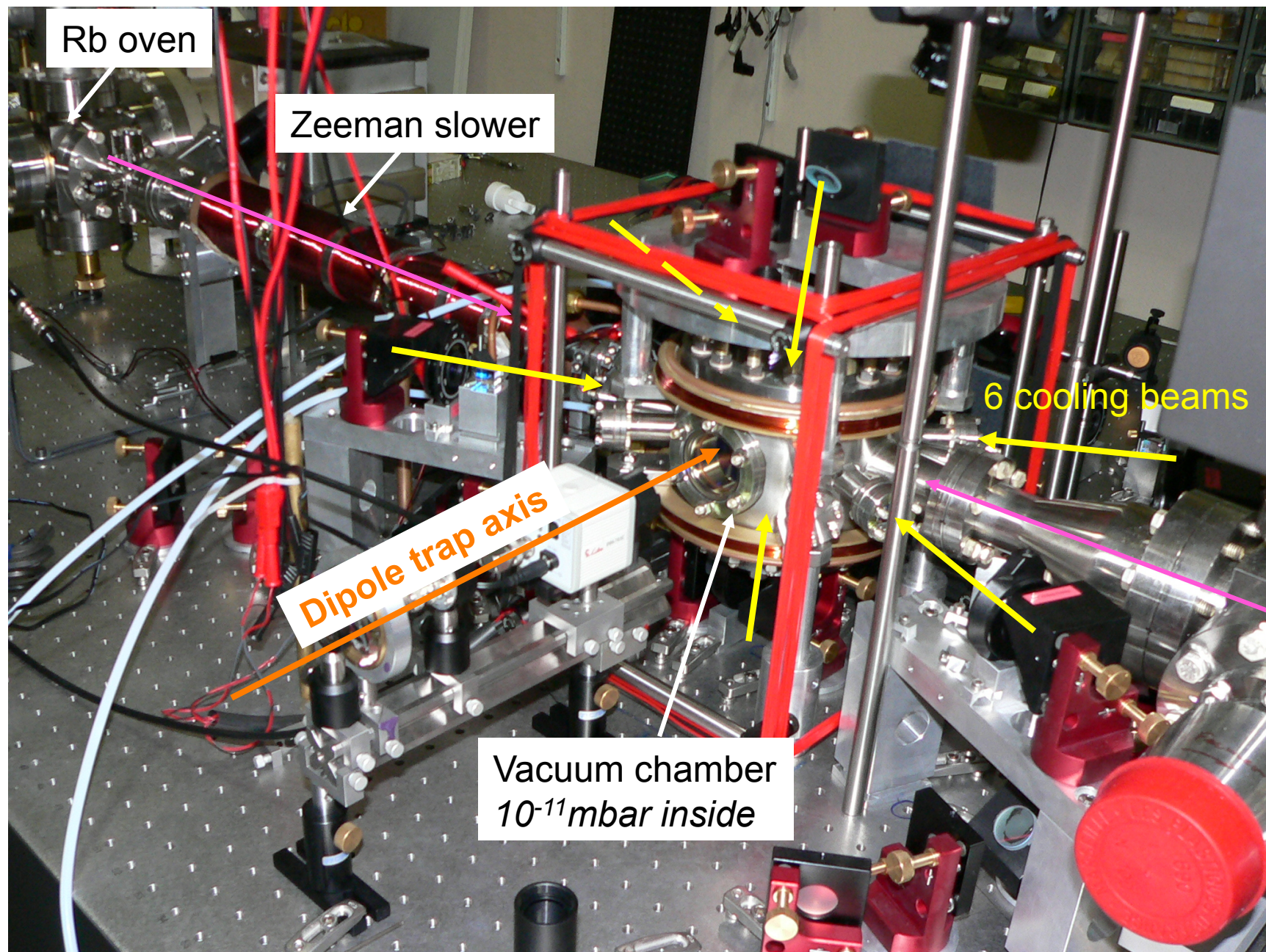


Salomon *et al.*,  
Euro. Phys. Lett. **12**, p. 683 (1990)



# Loading a MOT from a slowed beam





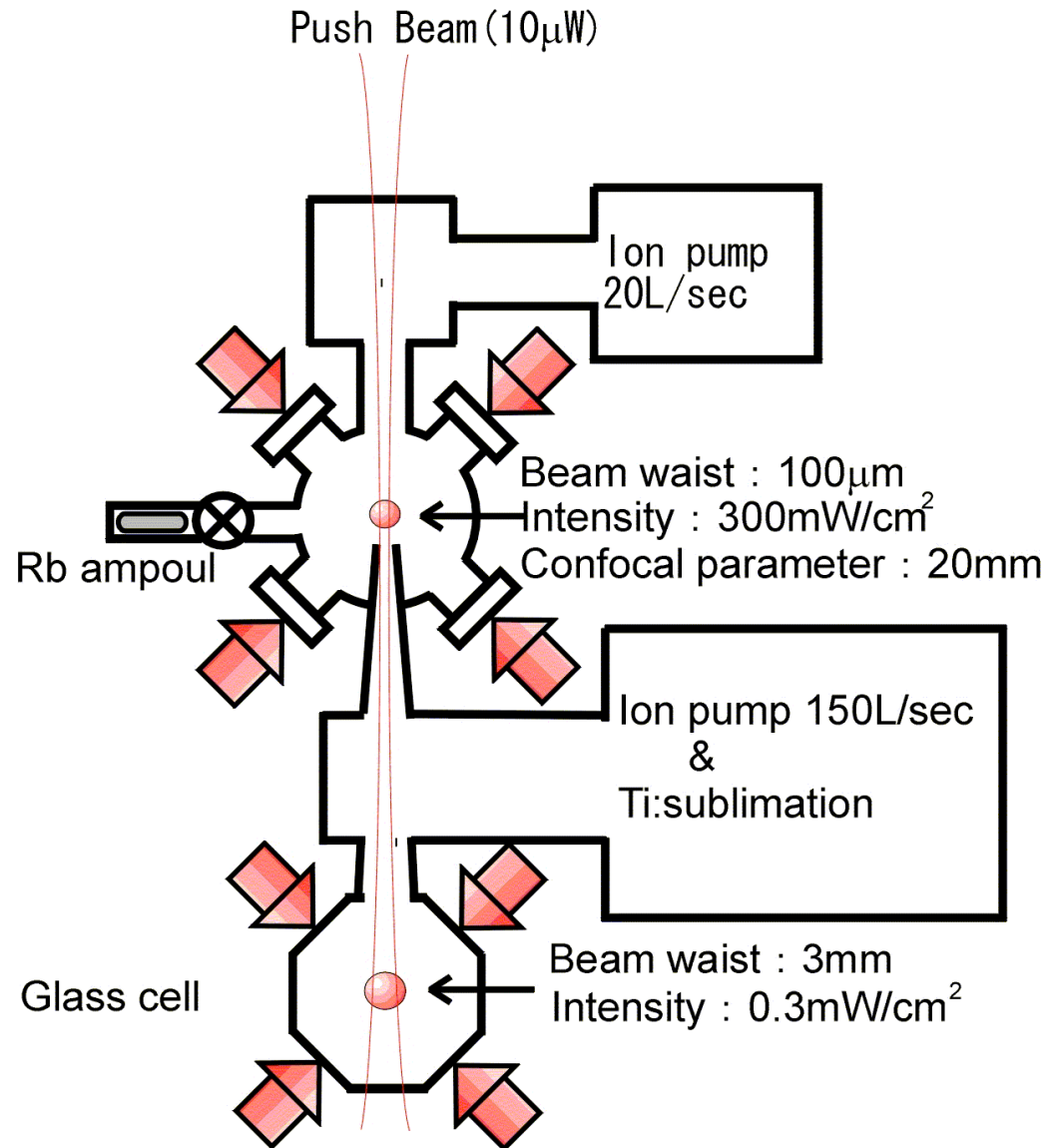
## A MOT trap of sodium

---



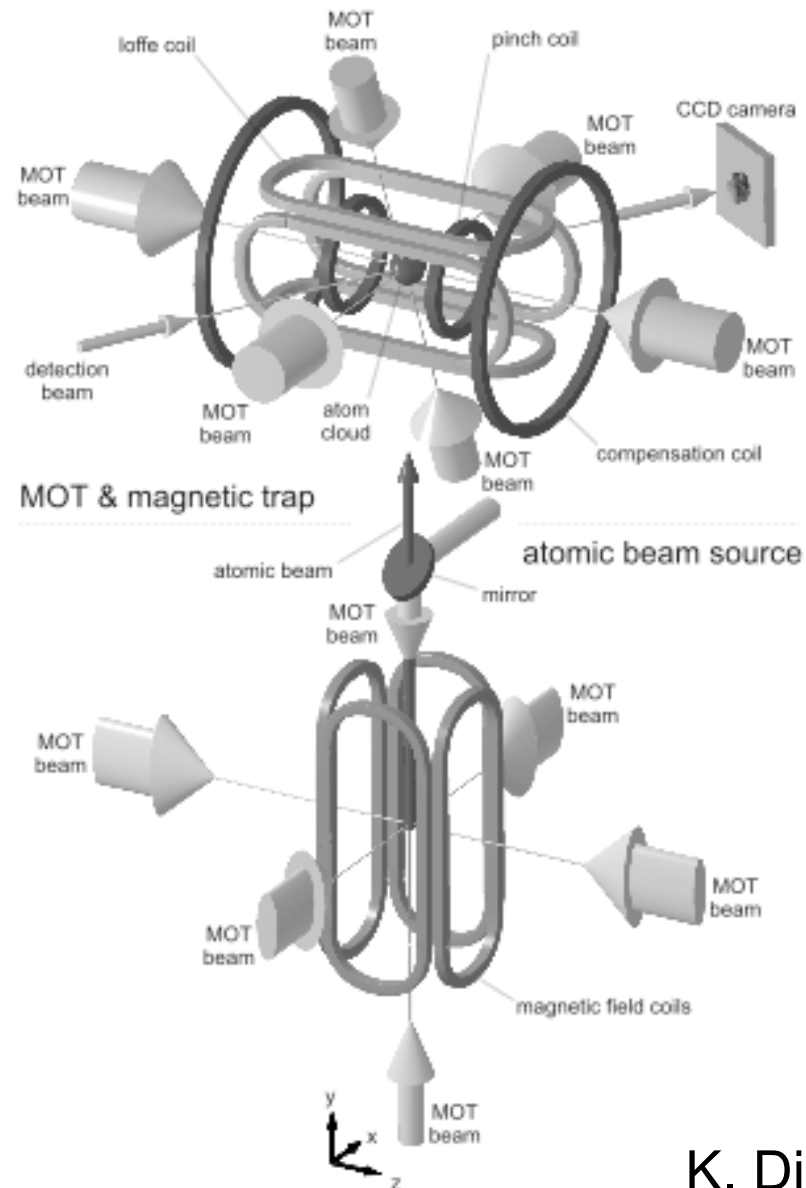
NIST, USA

# Double MOT system



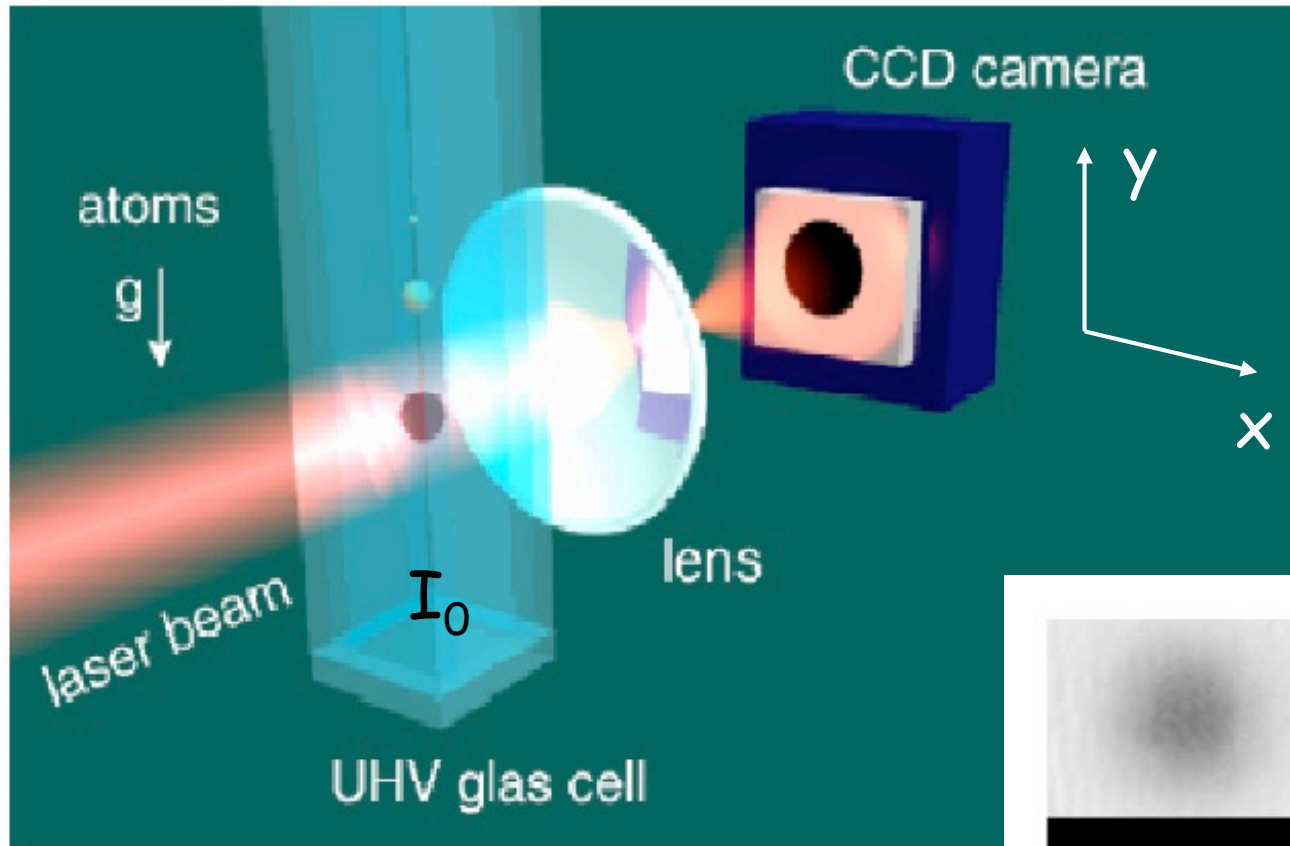
Gakushuin, Japan

# Loading from a 2D MOT



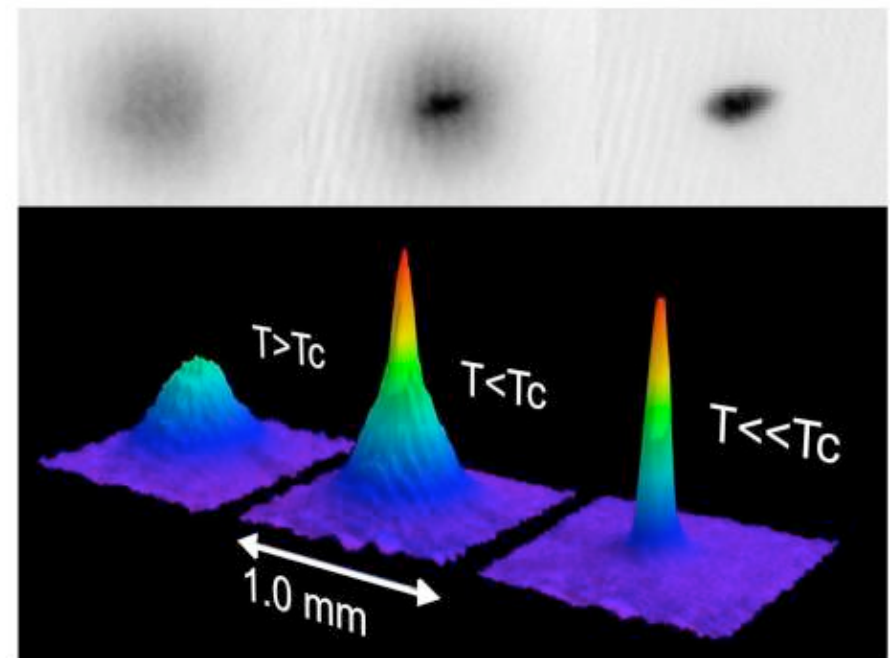
Amsterdam,  
K. Dieckmann thesis (2001)

# Absorption imaging



MIT

$$I(x,y) = I_0 e^{-n(x,y)\sigma L}$$



# Phase contrast imaging

---

