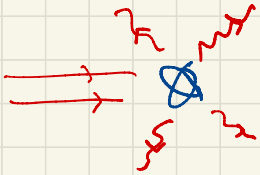
RAFFREDDAMENTO LASER e INTRAPPOLAMENTO

Idea originale 1975



$$\vec{\Delta p} = \hbar \vec{k}_L - \hbar \vec{k}_{es}$$

^{87}Rb $\quad \frac{\Delta p}{m} = \frac{\hbar k_L}{m} = v_{rinculo} \simeq 6 \text{ mm/s}$

$v_{termica}(300\,K) = \sqrt{\frac{k_B T}{m}} \simeq 240 \text{ m/s}$

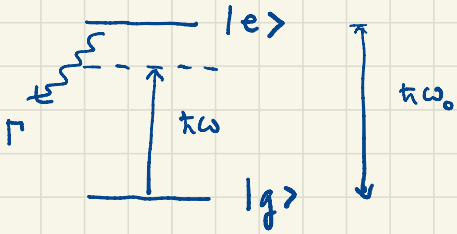
$$\vec{F} = \frac{\sum_i \vec{\Delta p_i}}{\Delta t} \simeq \hbar \vec{k}_L \cdot \underbrace{R_{ass}}_{\#\text{ fotoni assorbiti per unità di tempo}}$$

$\vec{k}_{es}$ si mediano a zero

$R_{ass} \sim 1/\tau \sim 10^7 \, s^{-1}$

$\frac{F}{m} = a \sim v_{rinculo} \cdot R_{ass} \sim 10^4 \, g$

Raffreddamento Doppler

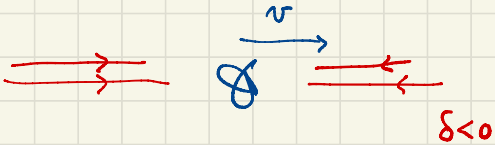


$$\hbar\delta = \omega - \omega_0 < 0$$

$$R_{ass} = \Gamma \cdot \rho_{ee} =$$

$$= \frac{1}{2} \frac{\Omega^2/2}{(\Omega^2/2) + (\Gamma/2)^2 + \delta^2} \Gamma$$

A $\delta = 0$, $R_{ass} = \frac{1}{2}\Gamma \frac{\Omega^2/2}{(\Omega^2/2) + (\Gamma/2)^2} < \frac{1}{2}\Gamma$



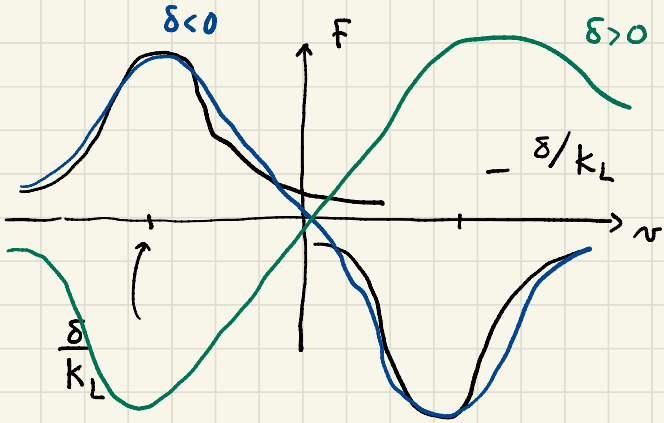
Sistema di rif. dell' atomo $\omega' = \omega - \vec{k}_L \cdot \vec{v}$

$k_L > 0$ per fascio da sx

$$F_+ = \hbar k_L \frac{\Gamma}{2} \frac{\Omega^2/2}{\Omega^2/2 + (\Gamma/2)^2 + (\delta - k_L v)^2}$$

forza media

$$F_- = - \hbar k_L \frac{\Gamma}{2} \frac{\Omega^2/2}{(\Omega^2/2) + (\Gamma/2)^2 + (\delta + k_L v)^2}$$



$\delta - k_L v = 0$

" Melasse ottiche "

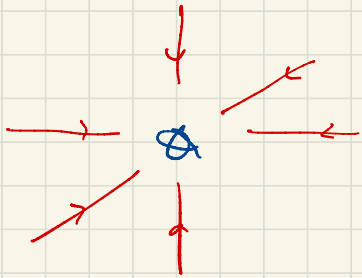
$\Omega \ll \Gamma$

$$f = F_+ + F_- = -\alpha v \qquad \text{per } |v| \ll \delta/k_L$$

Forza "viscosa" causa raffreddamento Doppler

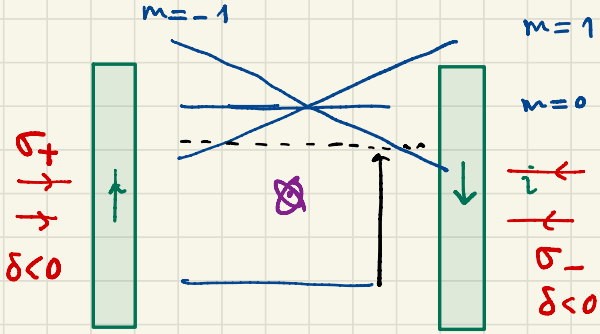
$$k_B T_D \simeq \hbar \frac{\Gamma}{2} = \frac{D}{\alpha} \simeq 150\ \mu K$$

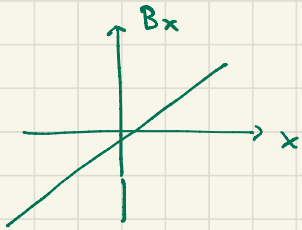
$$D \sim (\hbar k_L)^2 \Gamma$$



Trappola magneto-ottica

$$F = -\alpha v - \beta x$$





$\sigma_+ \qquad |g\rangle \leftrightarrow |e, m=1\rangle$

$\sigma_- \qquad |g\rangle \leftrightarrow |e, m=-1\rangle$

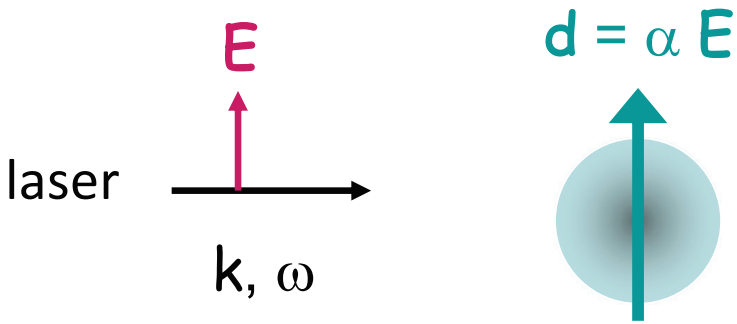
$N = 10^9$ atomi $\qquad \sim 10^6$ atomi $\quad (\Delta t < 1s)$

$L \simeq 5$ mm

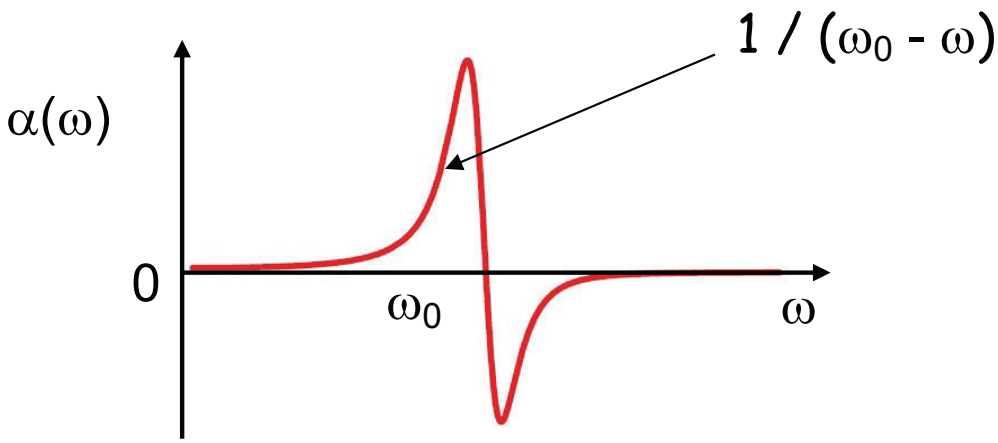
$T \simeq 100\,\mu K$

Optical dipole trap

Classical



Harmonic oscillator model



Interaction atom - light

$U(x) \sim -\alpha\, E(x)^2$

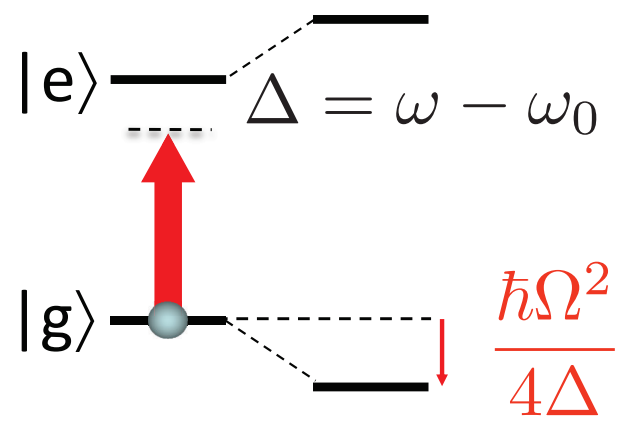
$\Rightarrow$ Conservative POTENTIAL

Quantum

$$\hbar\Omega = d.E$$

$$d = \langle e|\hat{D}|g\rangle$$

$\omega_0 > \omega$



Trap depth ~ 100 µK – 1 mK

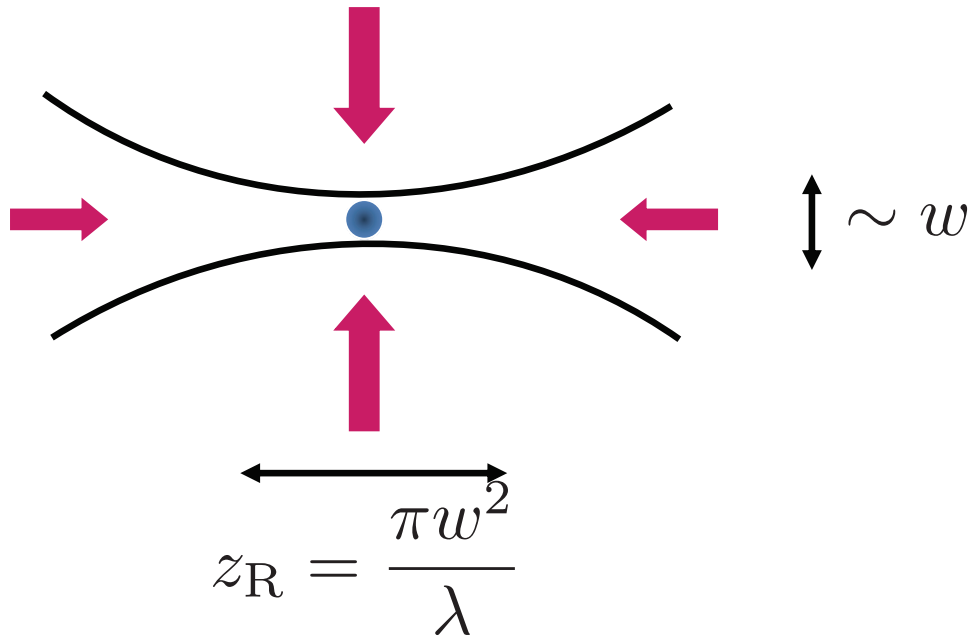
$\Rightarrow$ cold atoms

P ~ 1W ~ 100 µm

Optical tweezers: trapping in 3D

High field seekers $\omega < \omega_0$

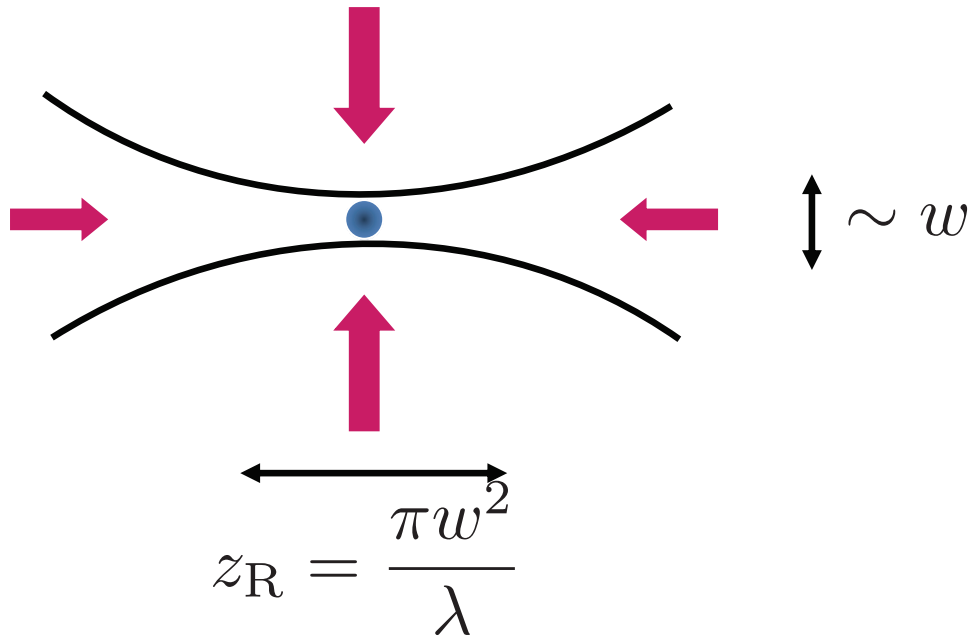
Gaussian beam

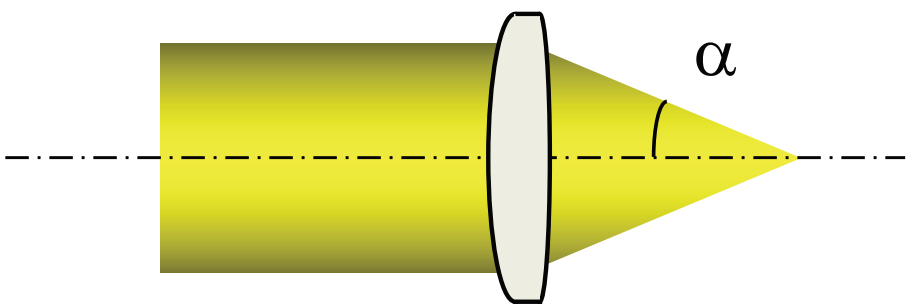


Optical tweezers: trapping in 3D

High field seekers $\omega < \omega_0$

Gaussian beam





NA = sin α
w ~ **λ/NA**

Diffraction limited optics $w \sim \lambda$

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

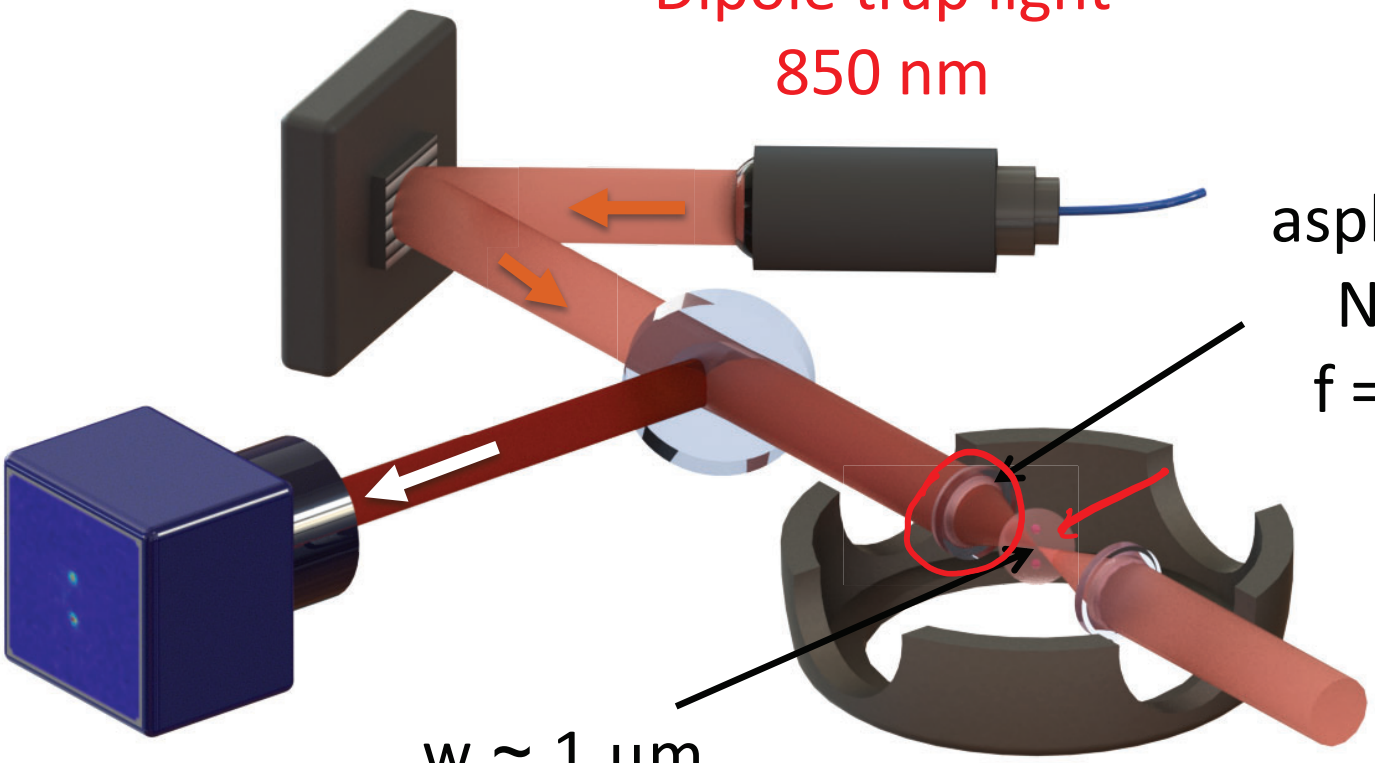
Ex: 1 mW on 1 µm

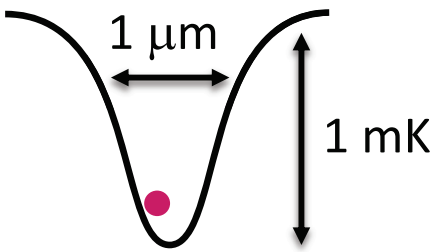
Trap depth = 1 mK

Optical tweezers: trapping in 3D

Schlosser, Nature (2001); Sortais, PRA (2007)

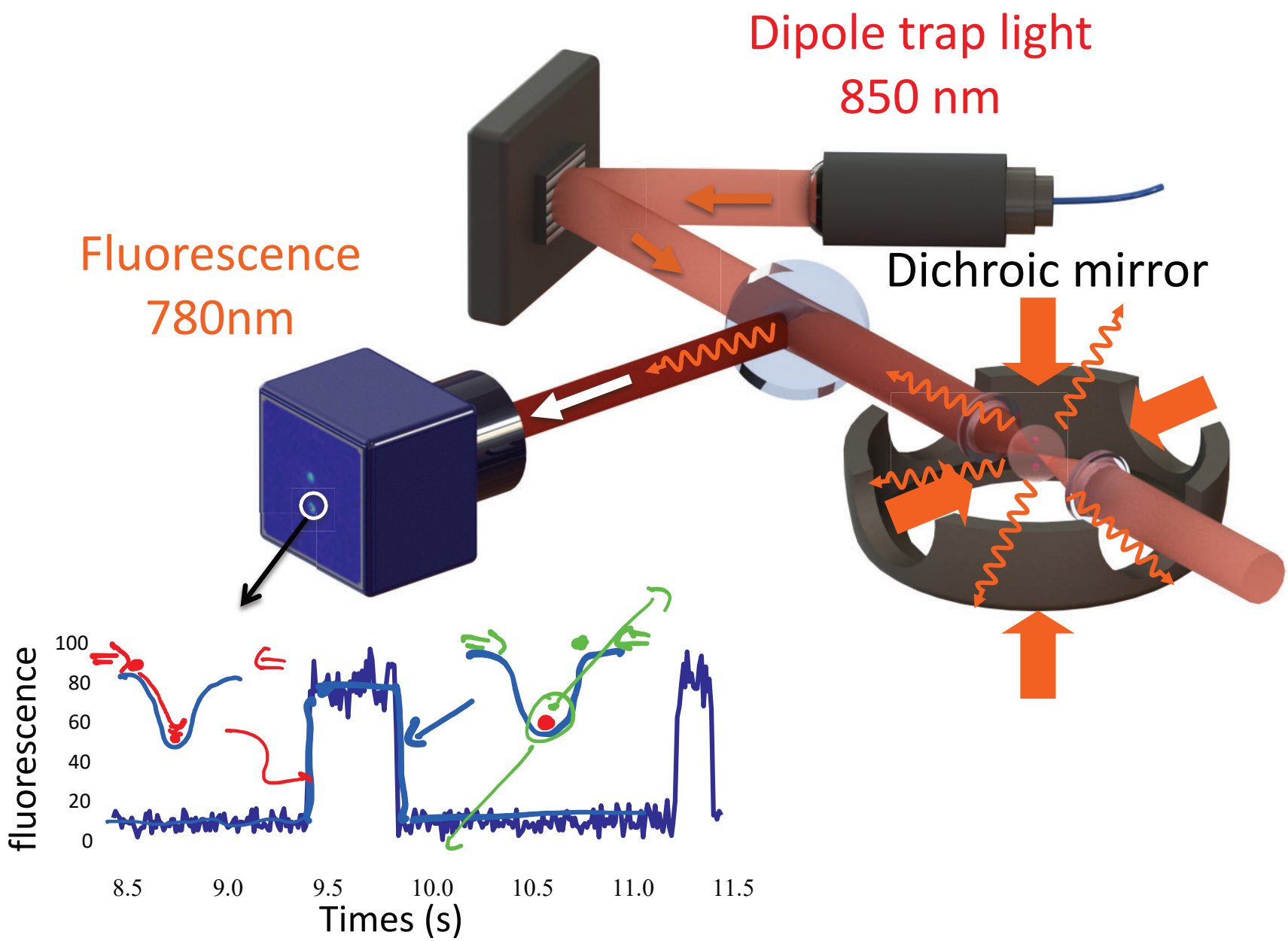
$w \sim \frac{\lambda}{2\,NA}$.



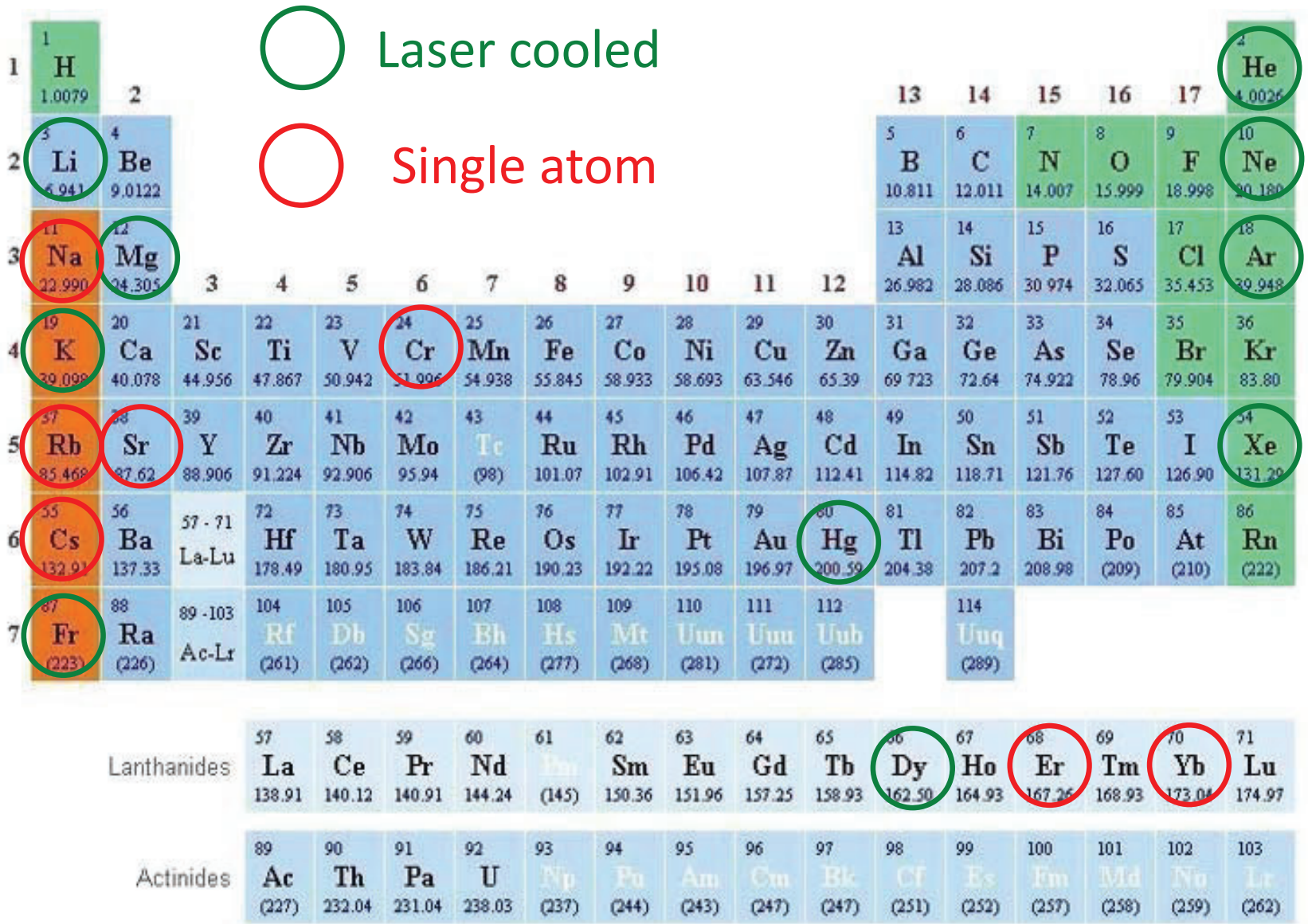


Single atoms in optical tweezers

Schlosser, Nature (2001); Sortais, PRA (2007)



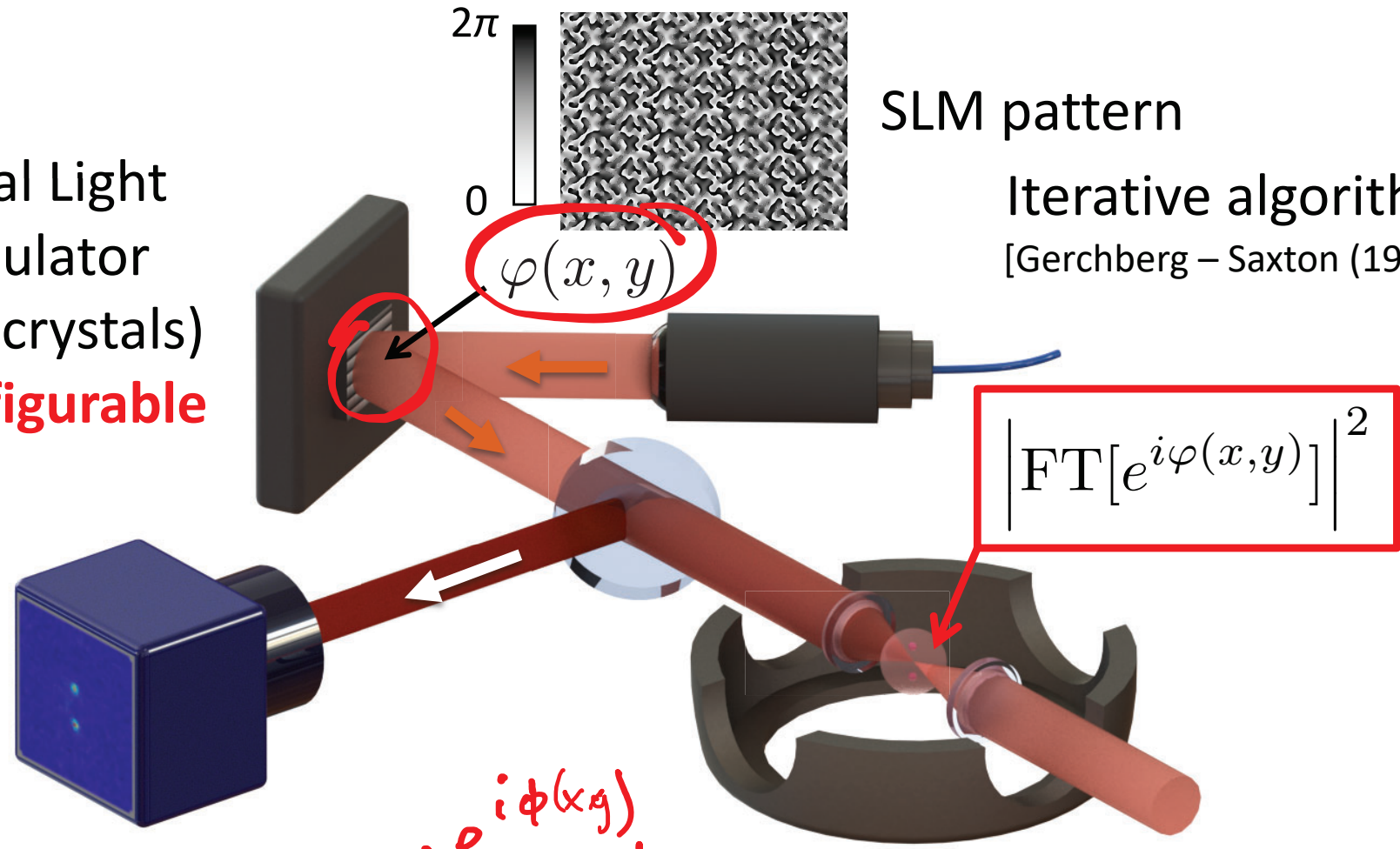
Which atoms?



Holographic 2D arrays of tweezers

Spatial Light Modulator (liquid crystals)

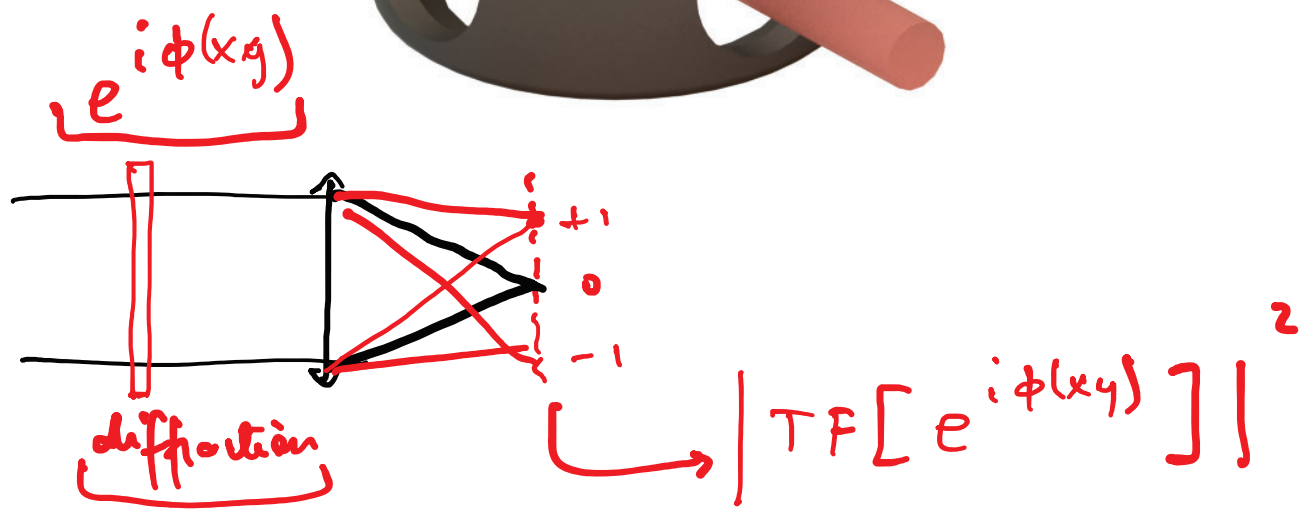
Reconfigurable



SLM pattern

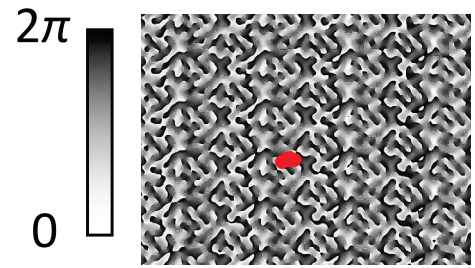
Iterative algorithm

[Gerchberg – Saxton (1972)]



Bergamini, JOSA B **21**, 1889 (2004)
Nogrette, PRX **4**, 021034 (2014)

Holographic 2D arrays of tweezers



SLM pattern

Iterative algorithm

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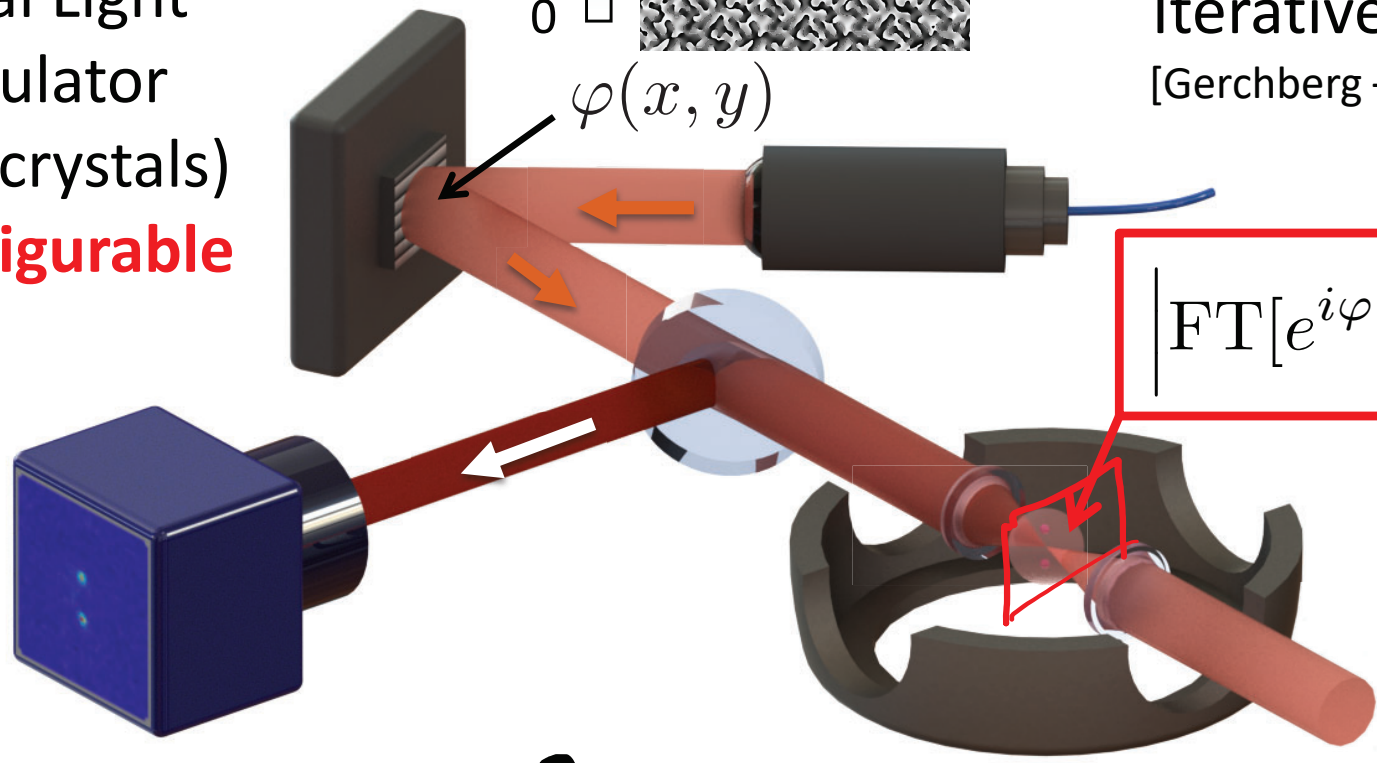
Spatial Light Modulator (liquid crystals)

Reconfigurable

$\varphi(x, y)$



$$\left|\mathrm{FT}[e^{i\varphi(x,y)}]\right|^2$$

D

λ

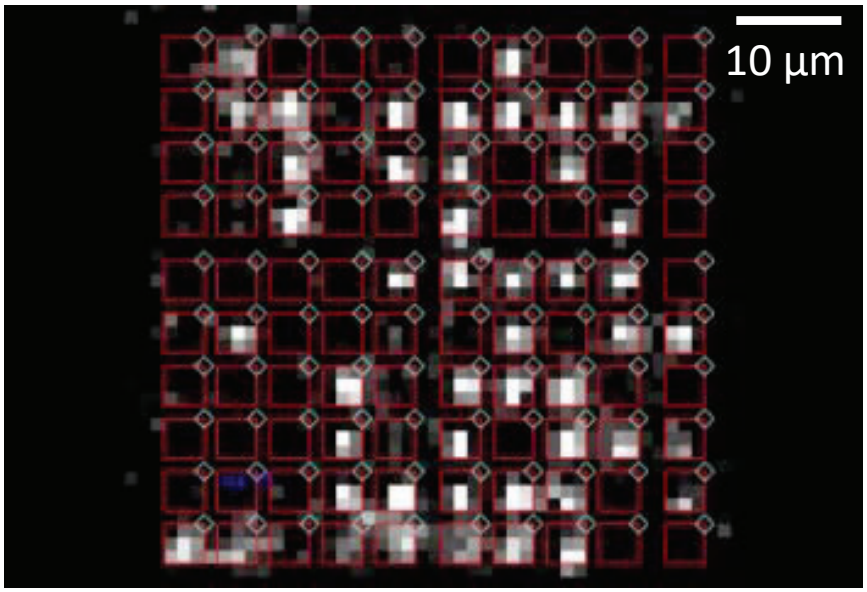
10 µm

2 - 20 µm

Bergamini, JOSA B **21**, 1889 (2004)

Nogrette, PRX **4**, 021034 (2014)

Atom-by-atom assembling of 2D arrays



Problem: stochastic loading ($p \sim 0.5$)

Solution: sort atoms in arrays

Miroshnychenko, Nature **442**, 151 (2006)

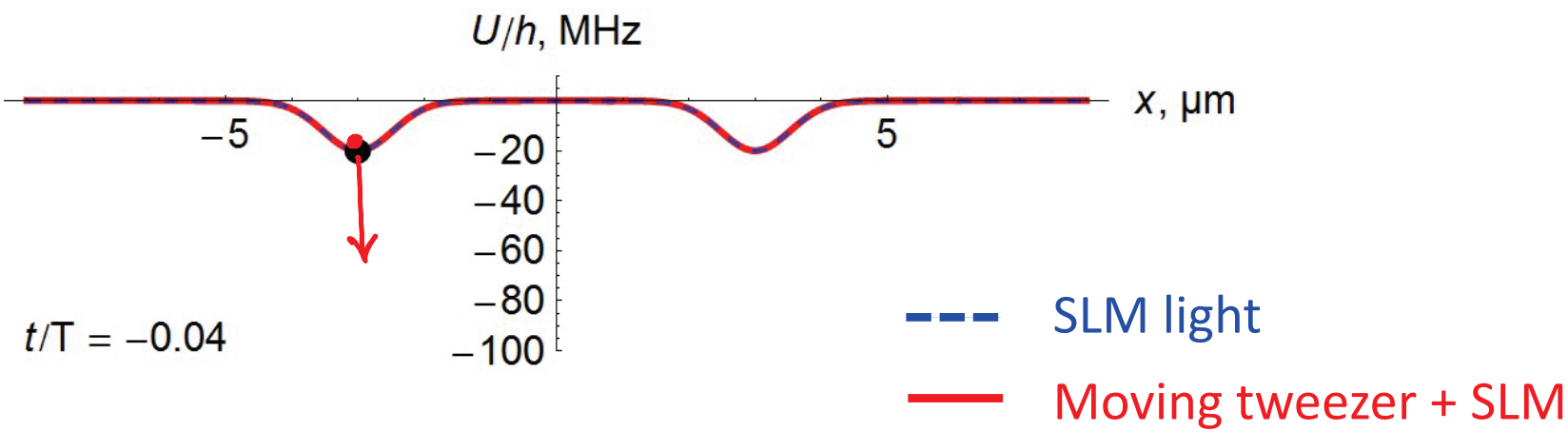
Atom-by-atom assembling of 2D arrays

Problem: stochastic loading ($p \sim 0.5$)

Solution: sort atoms in arrays

Miroshnychenko, Nature **442**, 151 (2006)

Moving atoms with a tweezers

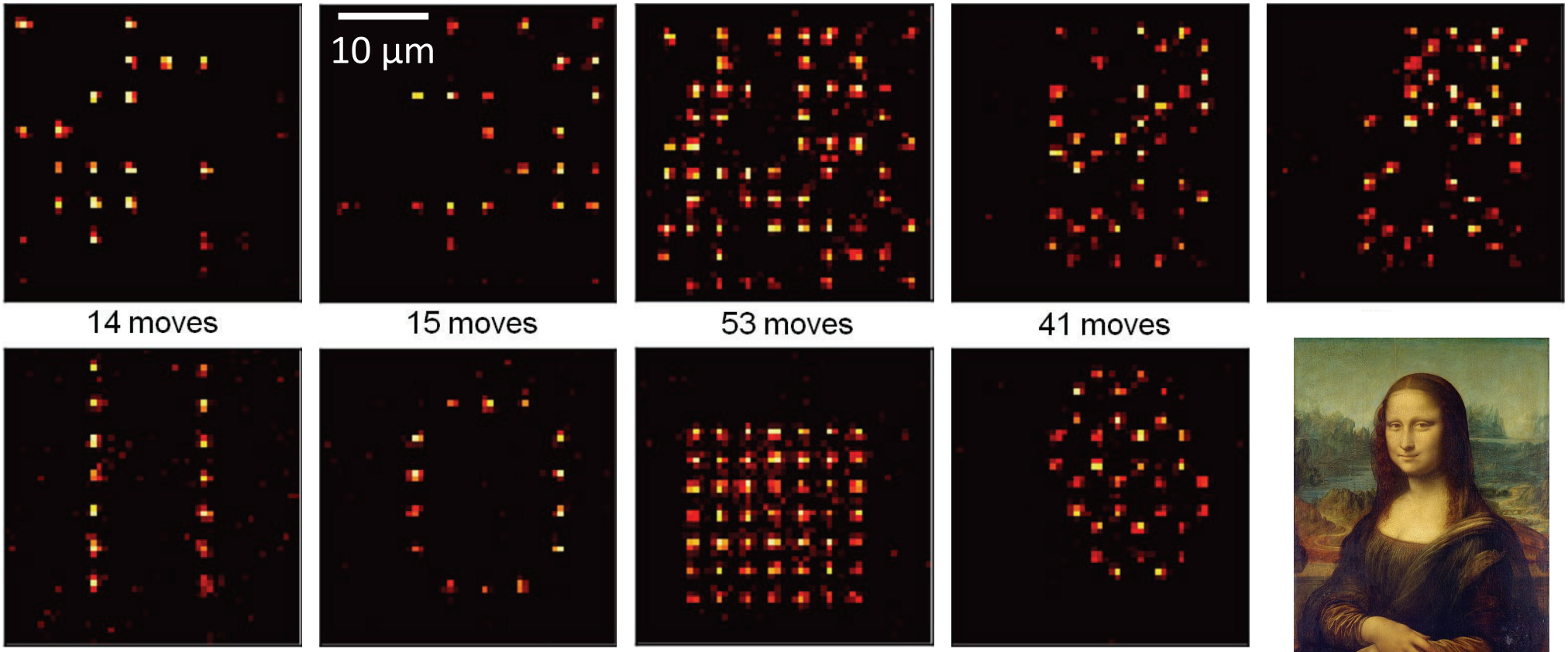


$p \sim 0.993(1)$

Gallery of assembled 2D arrays… (single-shot images…)

Initial

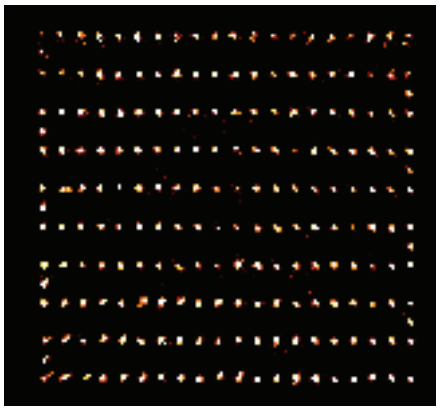
Final



Now ~ 200 atoms

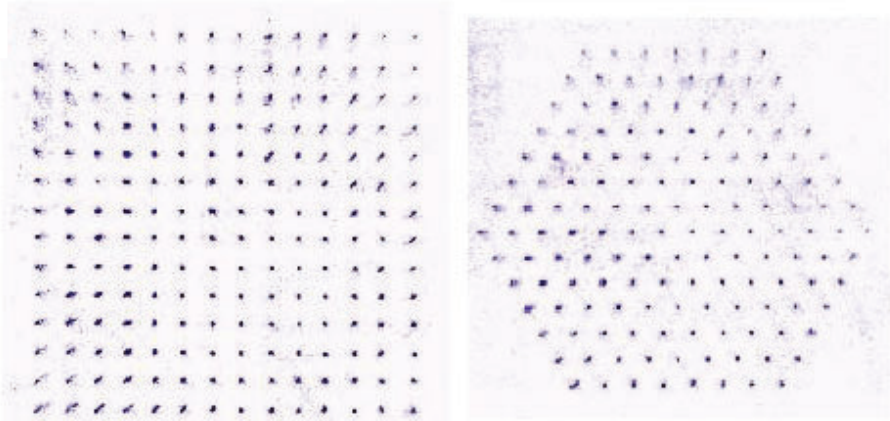
L. da Vinci

1D

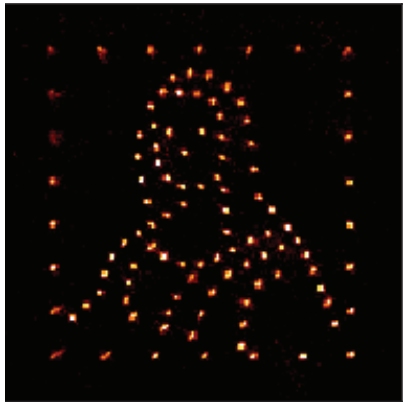


~100 µm

2D

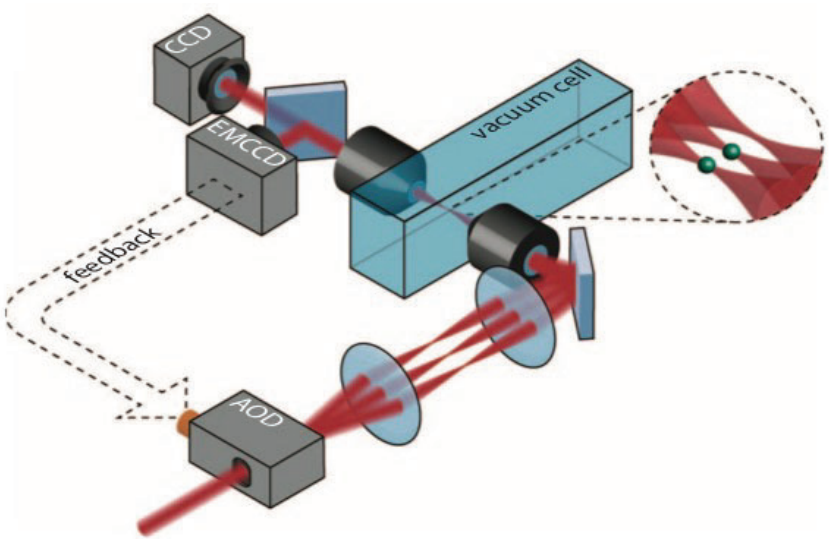


Schymik, PRA 2020



Now widely used,… with variants (1D, 2D & 3D)

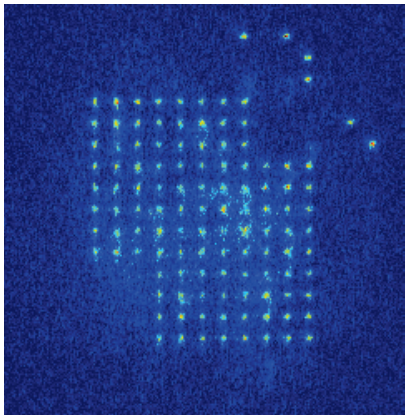
Lukin (Harvard), 2016



Rb

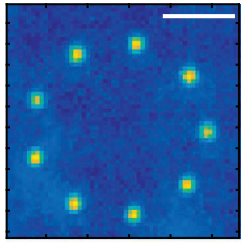
Birkl (Germany)

2D

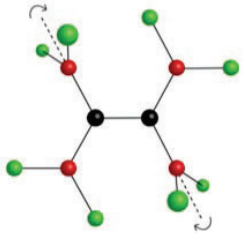


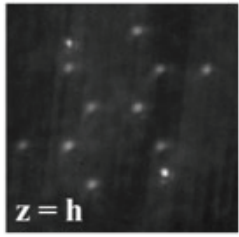
Ahn (Korea)

2D

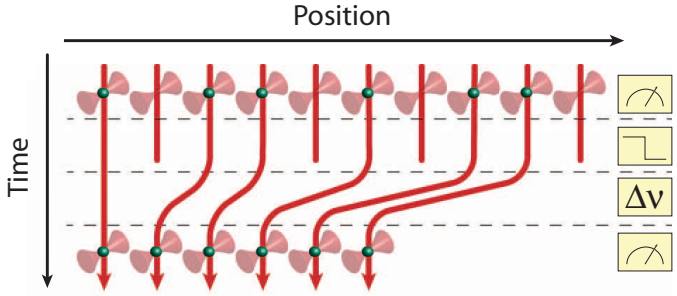


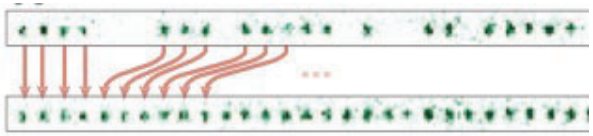
3D

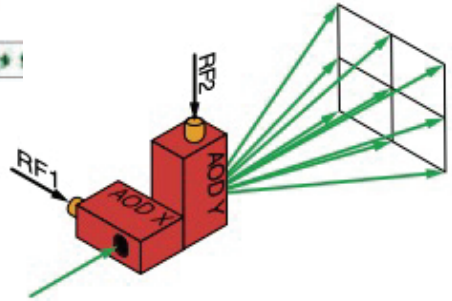




Rb



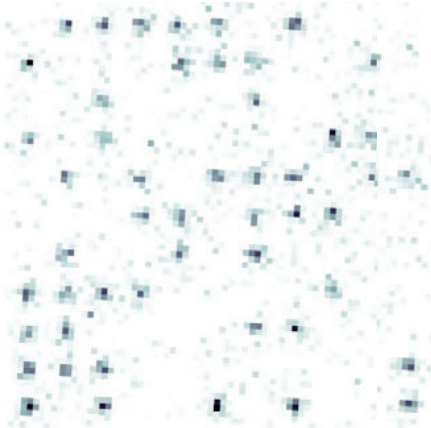




~300 atoms

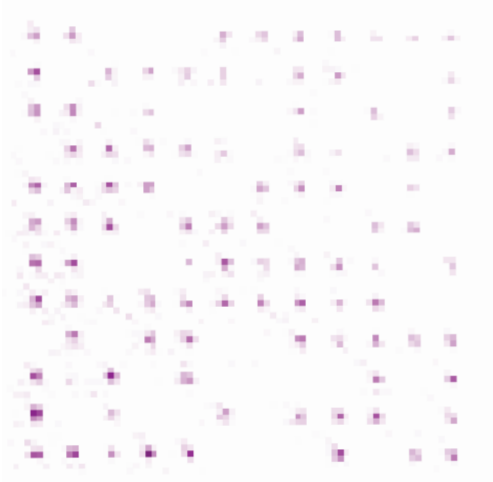
arXiv:2012.12281

Sr



Endres (Caltech)
Kauffman (JILA)
2018

Yb



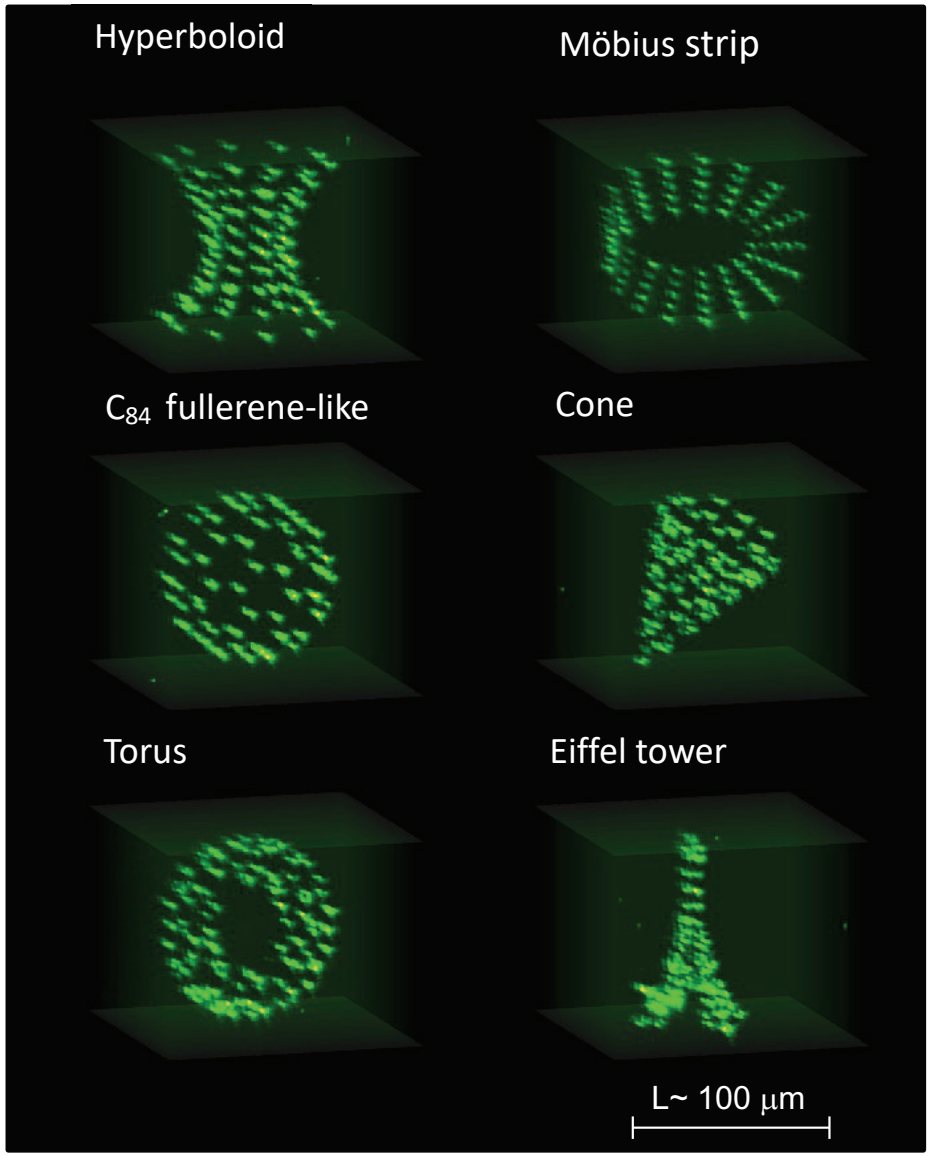
Thompson (Princeton)
2018

It also works in 3d!

Di Leonardo, Optics Express **15**, 1913 (2007)

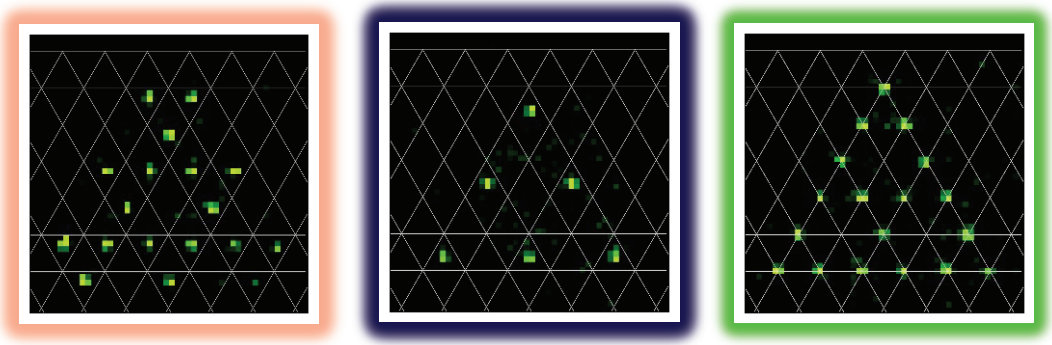
Averaged fluorescence

imaged "slice-by-slice"



Assembled Pyrochlore lattice

Plane 1 Plane 2 Plane 3

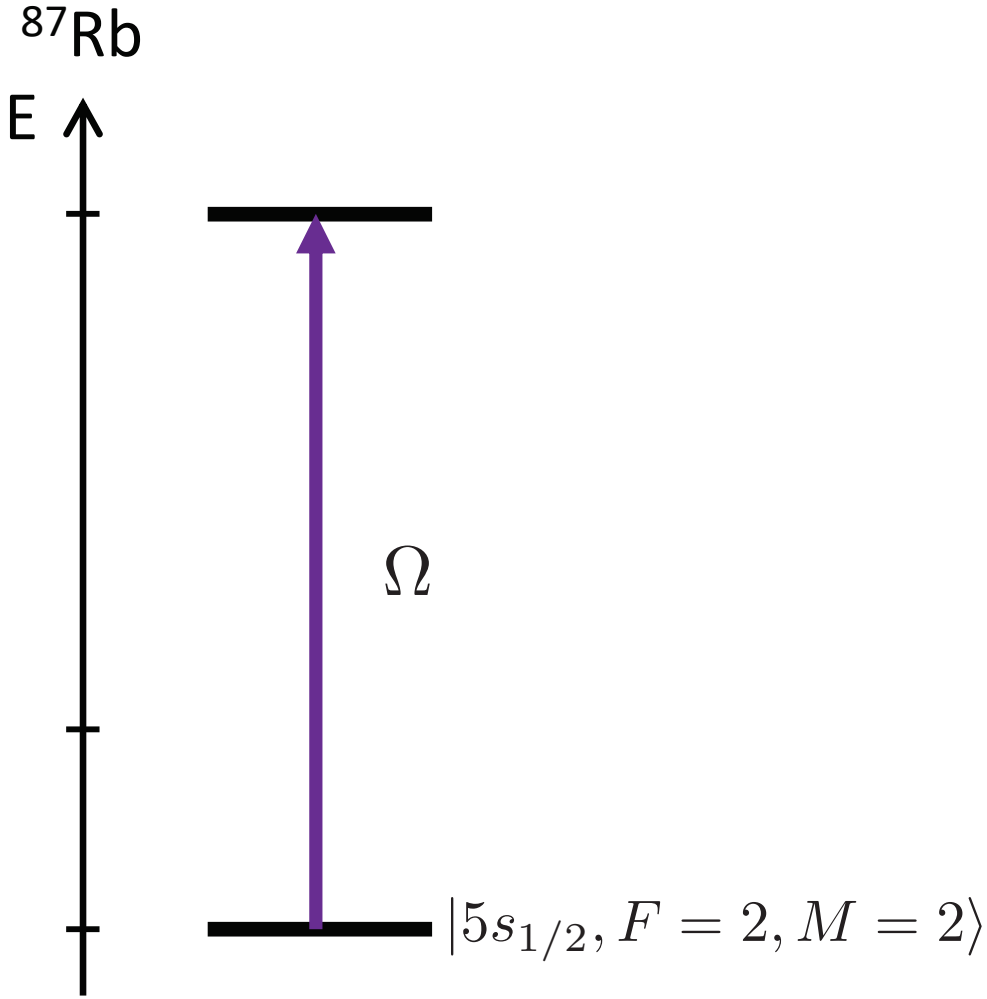


Front view Side view

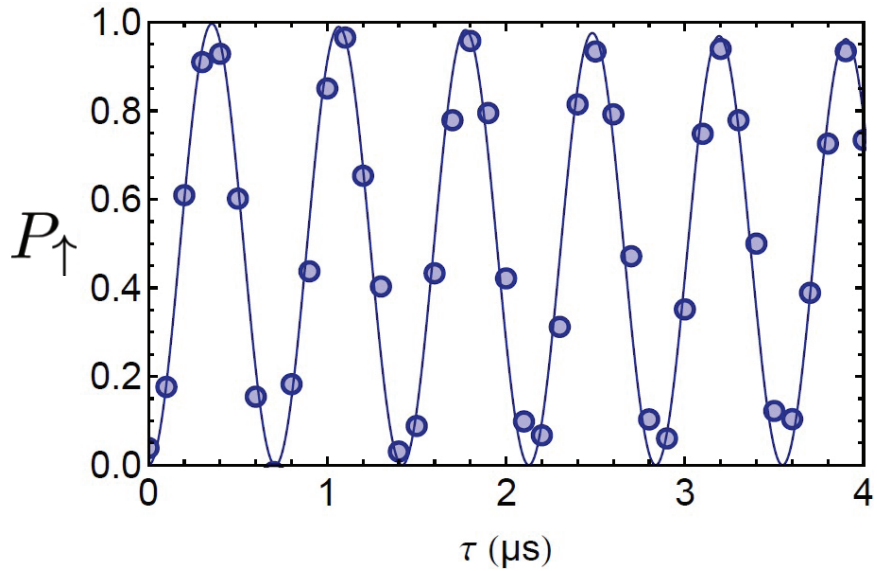
Barredo, Nature (2018)

Also: Weiss, Nature (2018); Ahn, Opt. Exp (2016)

Coherent optical Rydberg excitation (n = 50 – 100)



Optical excitation (Ω = 0.5 – 5 MHz)



Effective Rabi frequency:

Light-shift: