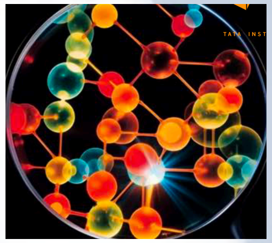
Lecture 2: Analog and digital quantum simulators from unitary dynamics to midcircuit measurements

Jed Pixley

ICTS Lecture Series:



Quantum Dynamics in the pre-fault tolerant era

6/5/2026

Lecture Series Overview

Quantum dynamics in the pre fault tolerant era

Lecture 1: From Classical and quantum chaos to thermalization in isolated quantum systems

Lecture 2: Analog and digital quantum simulators from unitary dynamics to midcircuit measurements.

Lecture 3: Monitored quantum dynamics in random quantum circuits

Lecture 4: Adaptive quantum circuits and control induced phase transitions

Lecture 5: Open quantum dynamics software tutorial

Lecture Series, learning goals

I. Lecture 1: Classical and Quantum Chaos, from single particle to many-body

II. Lecture 2: Quantum platforms

III. Lecture 3: Monitored dynamics, interplay of unitary and projective evolution.

IV. Lecture 4: Adaptive dynamics, controlling quantum dynamics

V. Lecture 5: Numerical approaches to adaptive quantum dynamics

Lecture 2: Learning Goals

What can the available quantum platforms do?

Understand the various quantum platforms

Cold atomic gases

Trapped ions

Neutral atoms

Superconducting qubits

**Nitrogen-vacancy centers in diamond

**Si based qubits **quantum dots

**topological qubits **Circuit QED

**=will not be covered

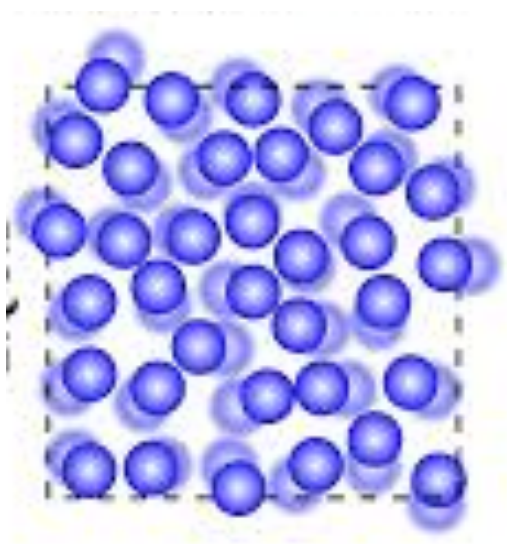
e.g. how they work, what they do, recent important experiments

Outline

I. Lecture series layout
II. Motivation to study quantum many-body systems
III. Platforms to study and control quantum many-body systems
IV. Experiments in unitary many-body dynamics
V. Measuring and manipulating many-body dynamics

Quantum Many Body Systems

To characterize condensed matter systems, want to understand the behavior of a large number of **interacting quantum mechanical** particles



described by a Hamiltonian operator

$$\hat{H}$$

with dynamics governed by unitary time evolution

$$|\Psi(t)\rangle = e^{-iHt}|\Psi_0\rangle$$

Quantum many-body wave function

Quantum Many Body Systems

Interactions of quantum particles in gases and solids allow a number of fascinating phases of matter to emerge

e.g. superfluids, superconductors, topological phases

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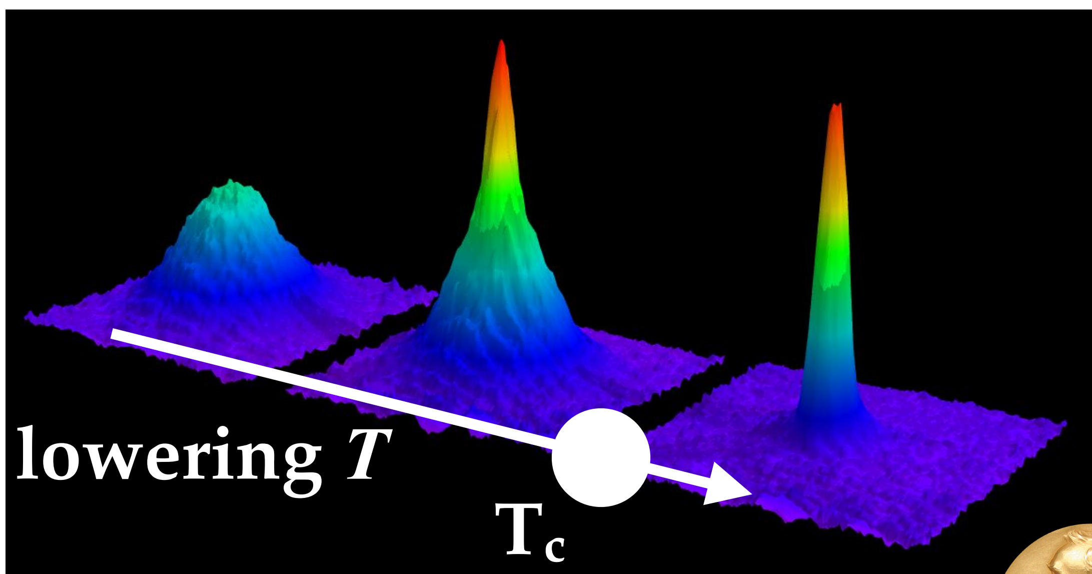

Davis et al., PRL (1995)

interacting Bose gas of ^{87}Rb

Quantum Many Body Systems

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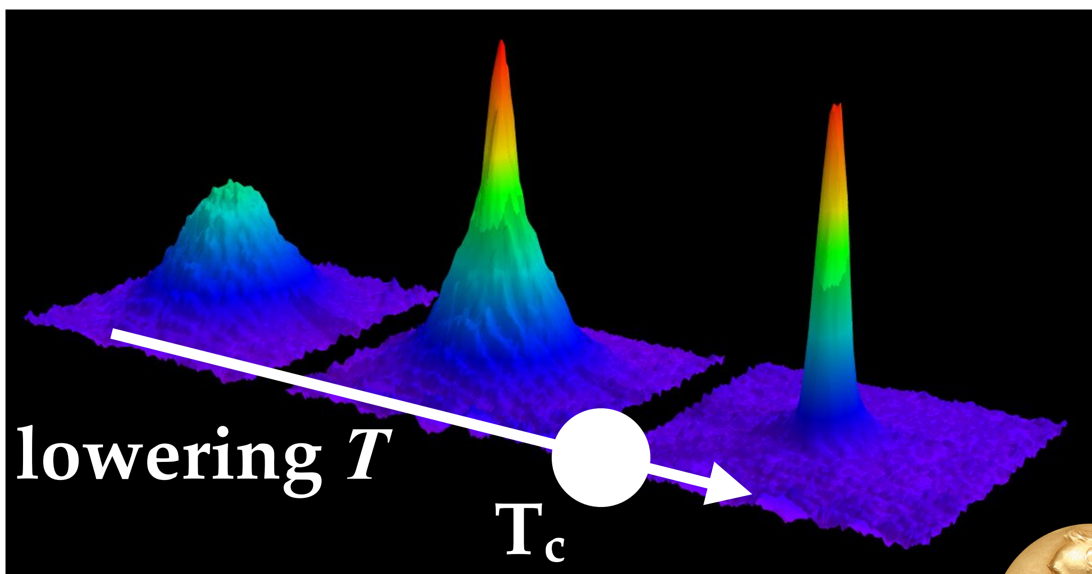
e.g. superfluids, **superconductors**, topological phases



Davis et al., PRL (1995)

Bednorz and Muller, (1986)

high temperature superconductor levitating above a strong magnet (Meissner effect)

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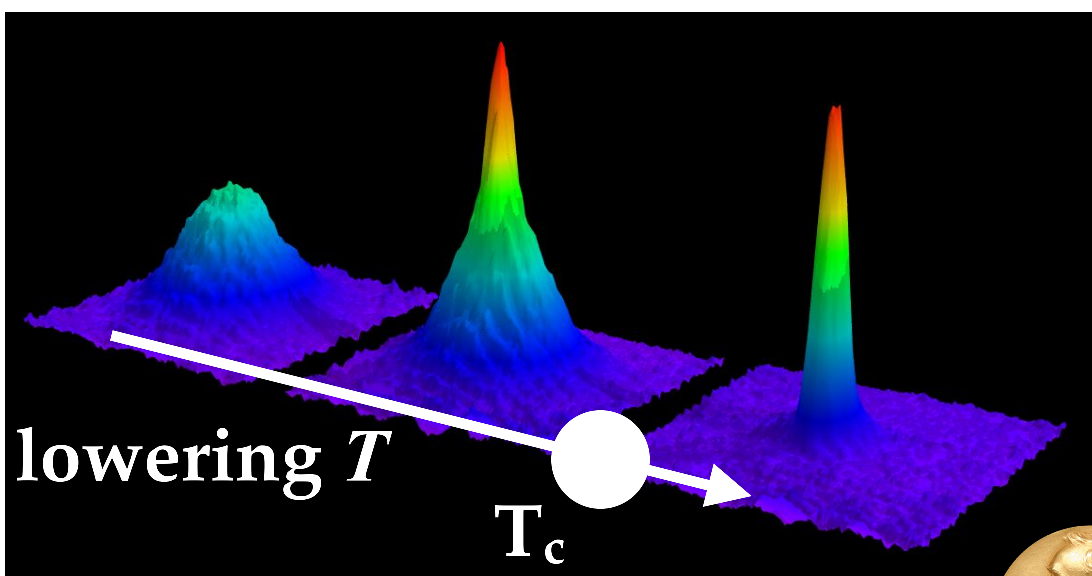

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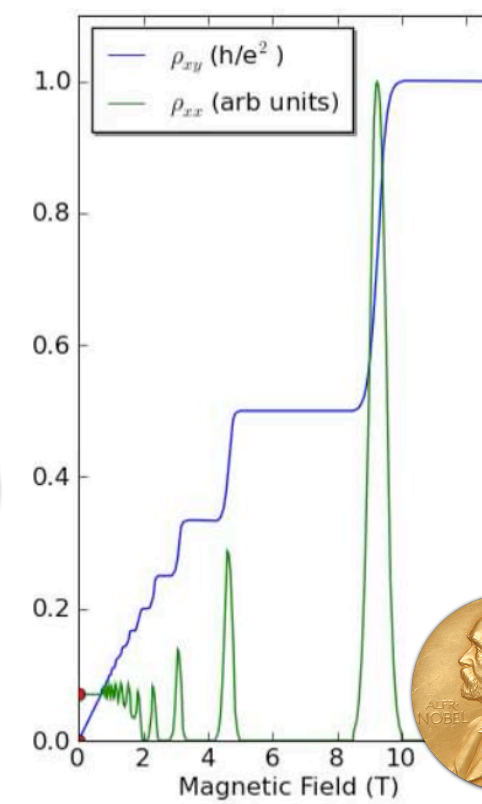

Klitzing, Dorda, Pepper PRL (1980)

2D electron gas in a magnetic field

(Quantum Hall effect!)

Quantum Many Body Systems

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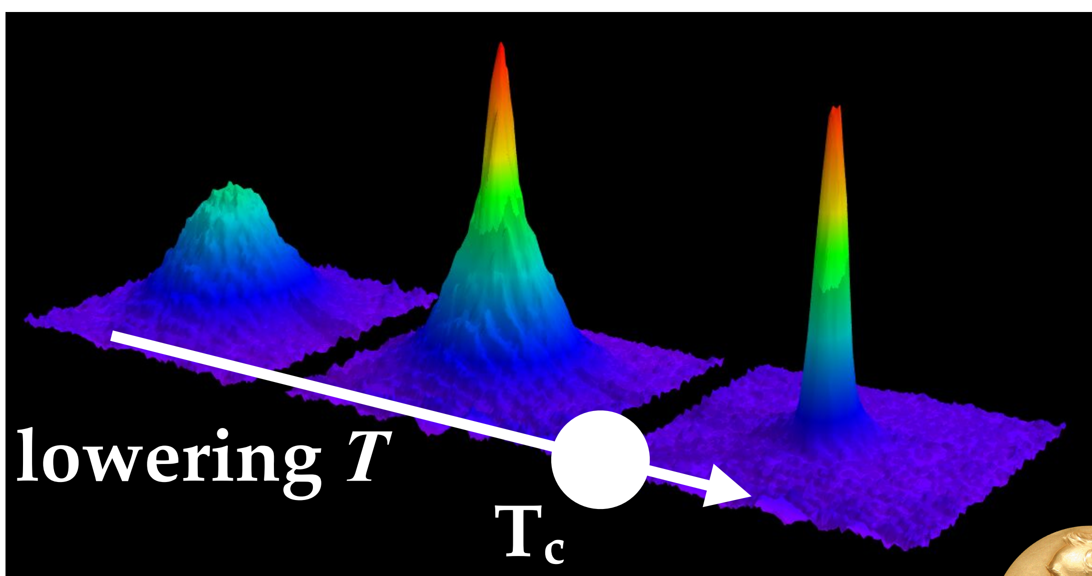

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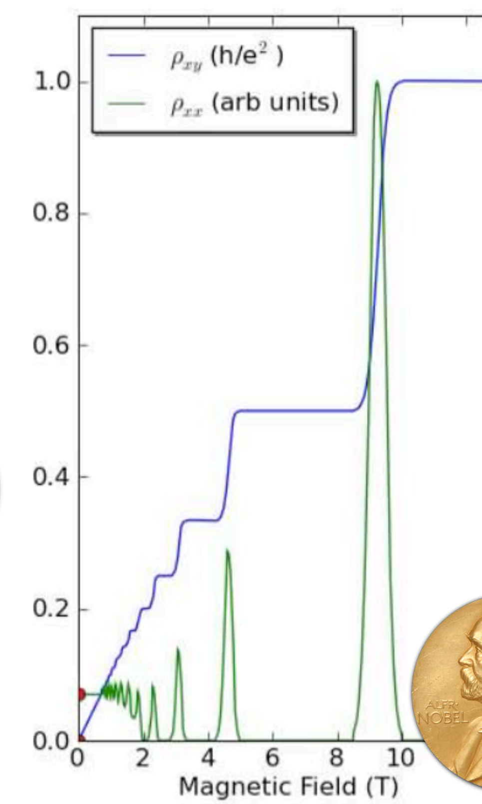

Klitzing, Dorda, Pepper PRL (1980)

Manipulating these phases of matter hold amazing promise for future technologies.

Emulating Quantum Many Body Systems

A way to `solve' for the properties of H is to "let nature do it" i.e. to emulate them

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"**Nature isn't classical, dammit**, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy."

Richard Feynman
Keynote talk at the 1st conference on Physics and Computation, MIT, 1981

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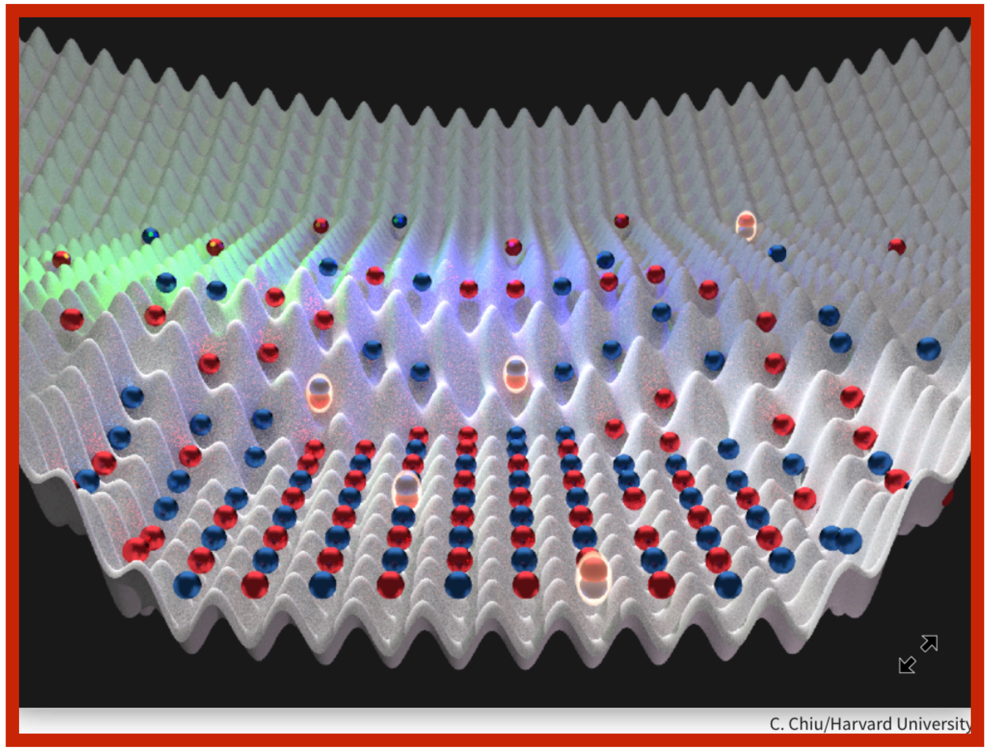
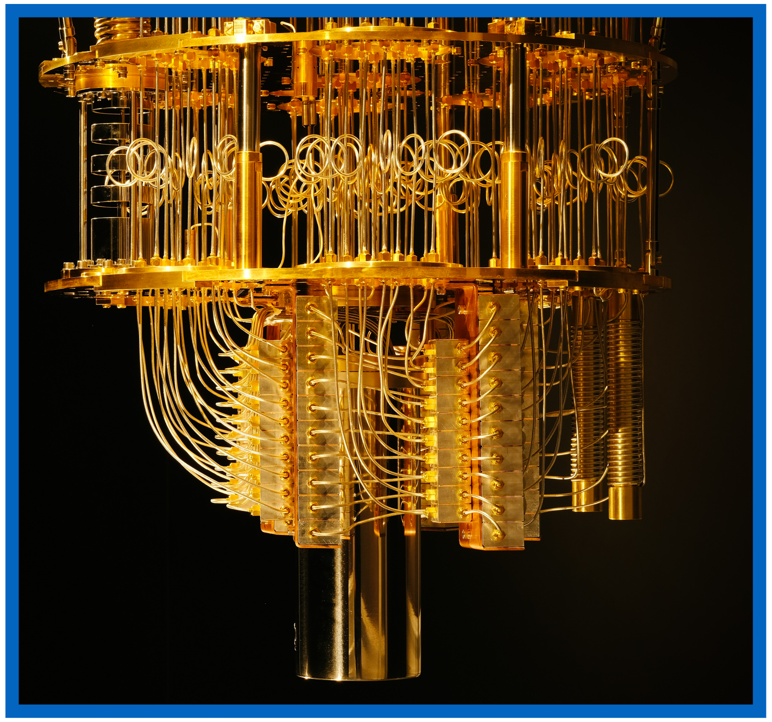
e.g. Build a "machine" that realizes H and let it run $|\Psi(t)\rangle = e^{-iHt}|\Psi_0\rangle$

Available Quantum Many Body Systems

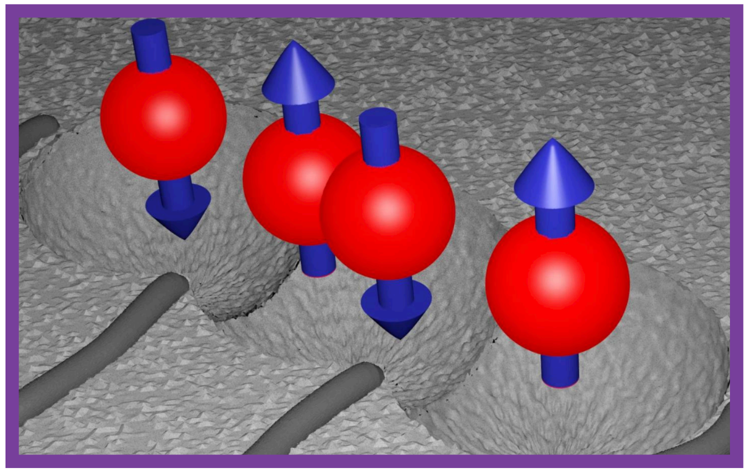
Now a number of available experimental platforms that are specifically designed to manipulate many body Hamiltonians:

Cold atoms, trapped ions, solid-state spins, superconducting qubits, quantum dots





IBM

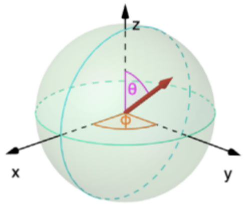


Maximilian Russ/Guido Burkard

These access quantum bits (qubits)

Classical bit $|0\rangle$ or $|1\rangle$

$$|q\rangle = \alpha|0\rangle + \beta|1\rangle$$



Manipulating Quantum Many Body Systems

Now a number of available experimental platforms that are specifically designed to emulate many body Hamiltonians:

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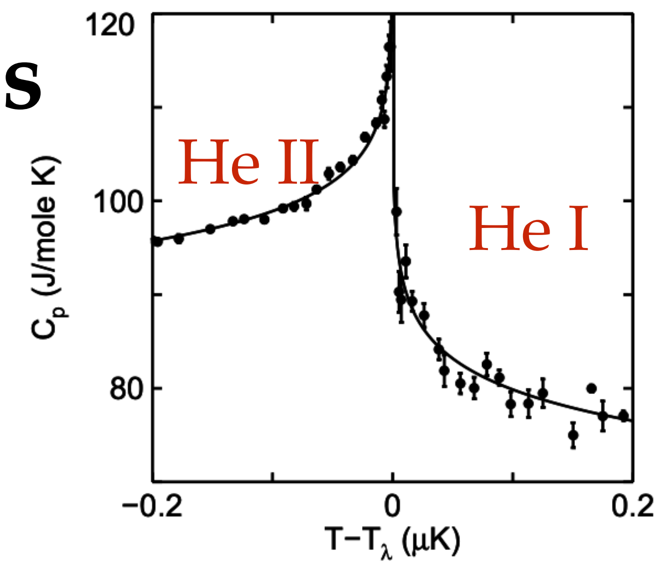
accessible in solid-state

superfluid transitions

the Hubbard model

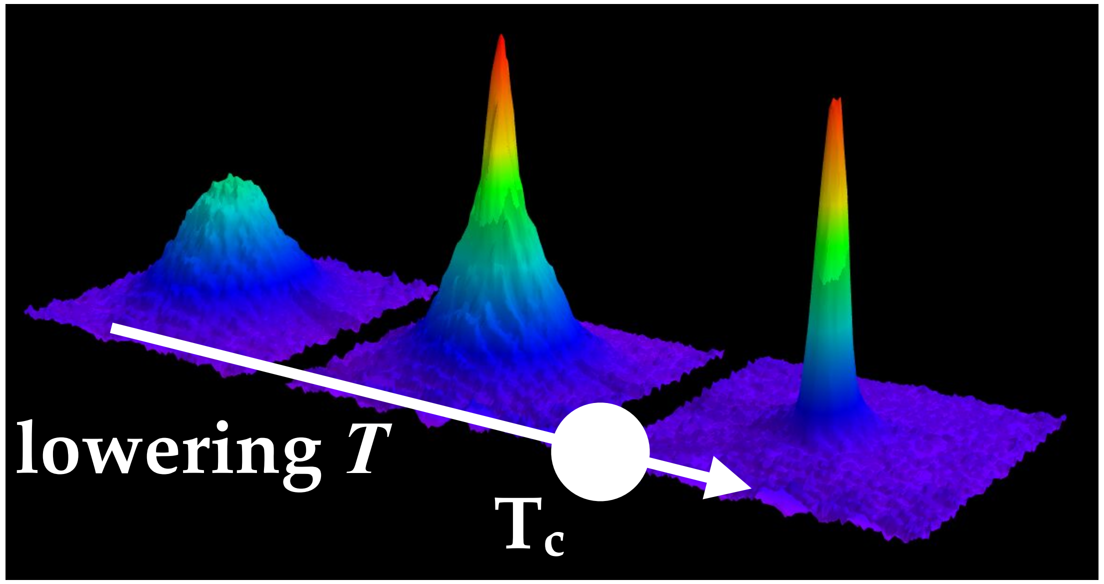
the Kondo effect

^4He



Lipa et al PRB (2003)

laser cooled gas of ^{87}Rb



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Manipulating Quantum Many Body Systems

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difficult (if not impossible)
in solid-state

Anderson localization
Many Body localization
Time Crystals

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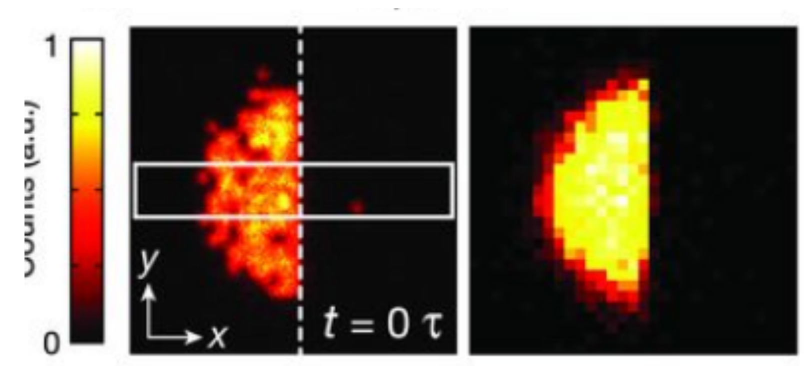
$|\Psi_0\rangle =$



Anderson localization

Many Body localization

Time Crystals

Construct H in the many-body localized phase

$$|\Psi(t)\rangle = e^{-iHt}|\Psi_0\rangle$$

Choi et al, Science (2016)

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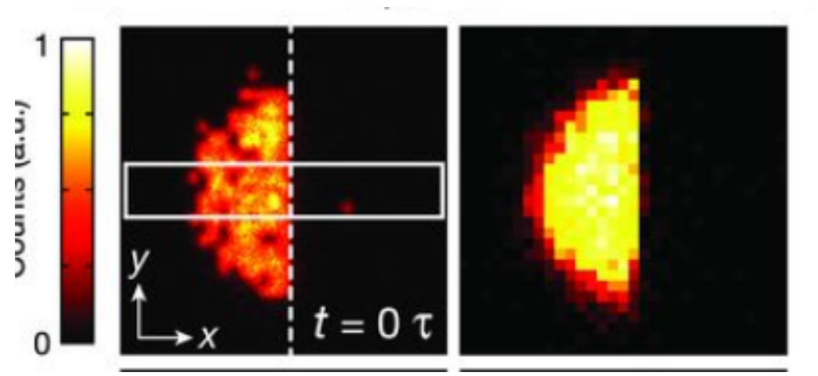

difficult (if not impossible) in solid-state

Can it thermalize?

Anderson localization
Many Body localization
Time Crystals

Wait long enough →

Choi et al, Science (2016)

Manipulating Quantum Many Body Systems

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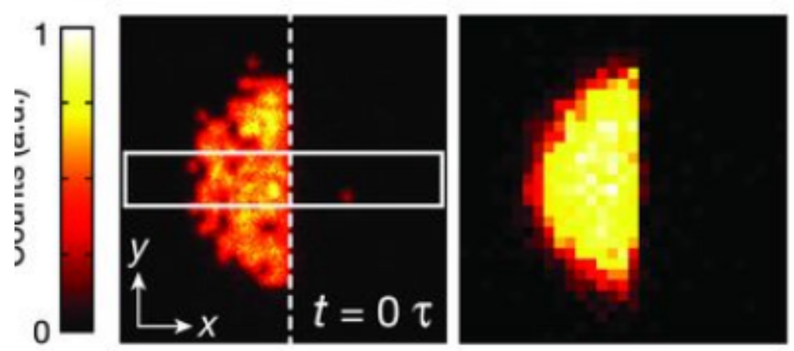
$$|\Psi_0\rangle =$$



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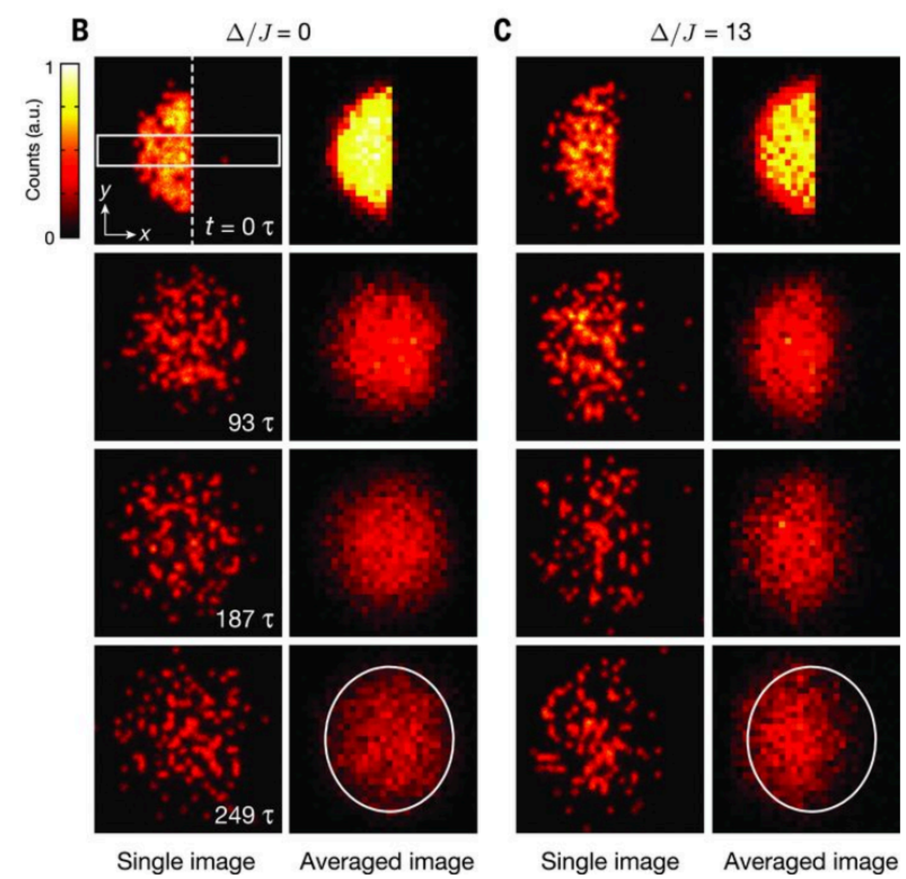
$$|\Psi(t)\rangle = e^{-iHt}|\Psi_0\rangle$$



Choi et al, Science (2016)

Characterizing Quantum Many Body Systems

A useful characterization for quantum many-body systems beyond correlations $\langle\Psi|\mathcal{O}(x,t)\mathcal{O}(0,0)|\Psi\rangle$ is the nature of their **entanglement structure**

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A useful characterization for quantum many-body systems beyond correlations $\langle\Psi|\mathcal{O}(x,t)\mathcal{O}(0,0)|\Psi\rangle$ is the nature of their **entanglement structure**

Recall from lecture 1

weakly entangled $S_E \sim L^{d-1}$

highly entangled $S_E \sim L^d$ "volume law"

Many-body quantum chaotic states are highly entangled

In *d=1*, critical states acquire a log-correction

$$S_E \sim \log L$$

Calabrese and Cardy, J. Stat. Mech (2004)

using Quantum Many Body Systems

This entanglement is a (necessary) resource to perform quantum computations

Worldwide race to build a quantum computer

USING QUANTUM MANY BODY SYSTEMS

This entanglement is a (necessary) resource to perform quantum computations

Worldwide race to build a quantum computer

Applications

Schor's factorization algorithm

Secure communication

Machine learning

Quantum Sensing

private sector

(Several more now)

Google AI Quantum

IBM Q

Microsoft

D-Wave The Quantum Computing Company™

Honeywell

IONQ

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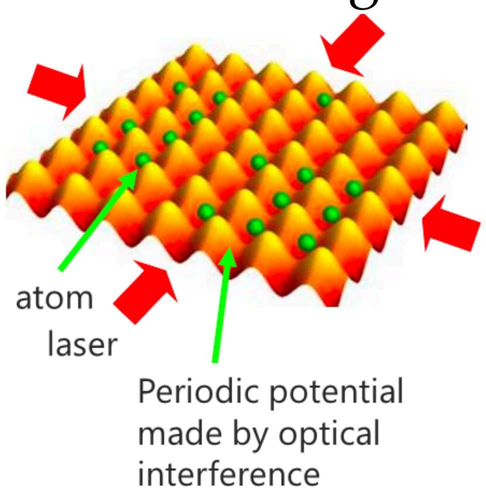
Quantum Platforms of Today

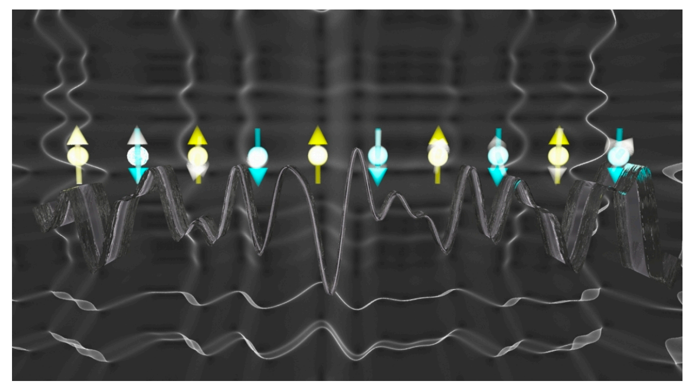
Several analog and digital quantum devices

Cold atomic gases



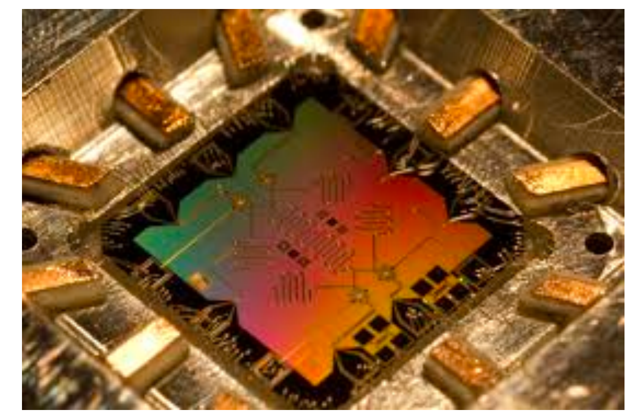
M. Kozuma group

Trapped ions



C. Monroe group

Superconducting qubits

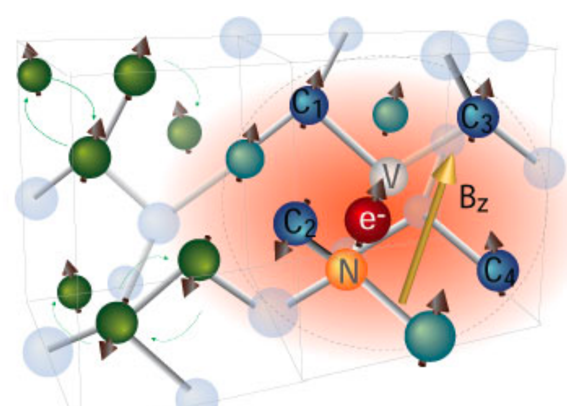


J. Martinis group

Neutral atoms

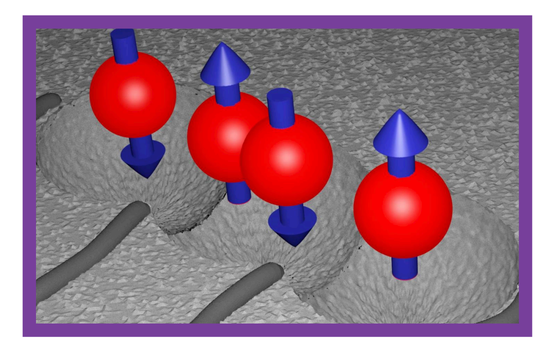
M. Endres group

Nitrogen-vacancy centers in diamond



P. Cappellaro group

Si qubits



Maximilian Russ/Guido Burkard

Quantum Platforms of Today

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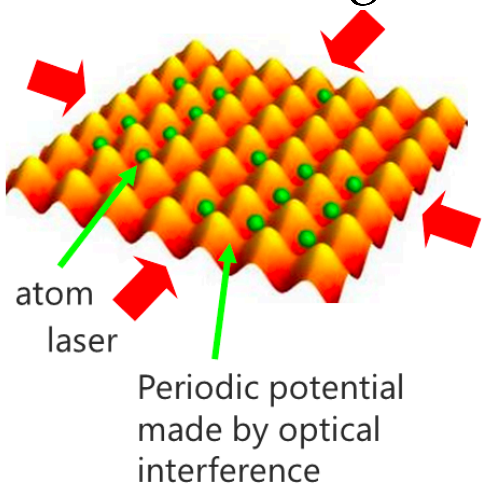

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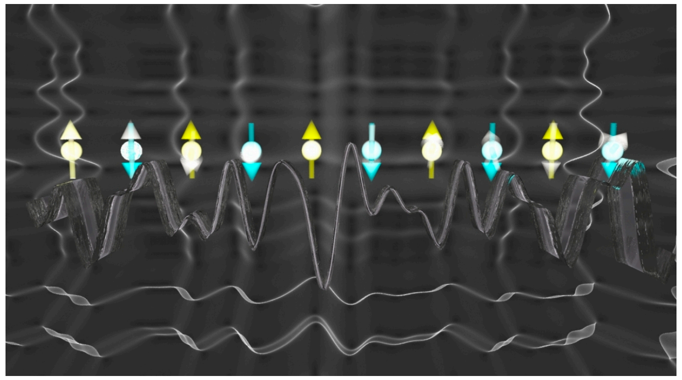

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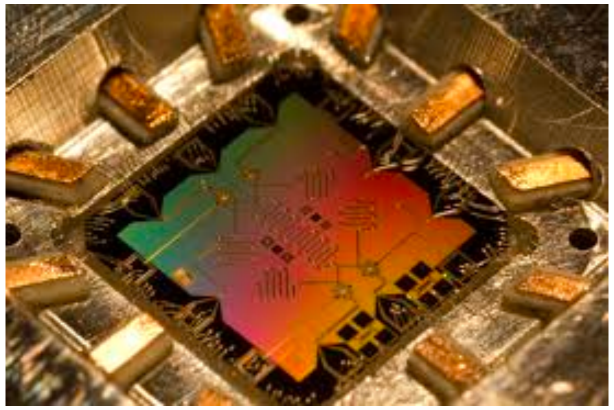
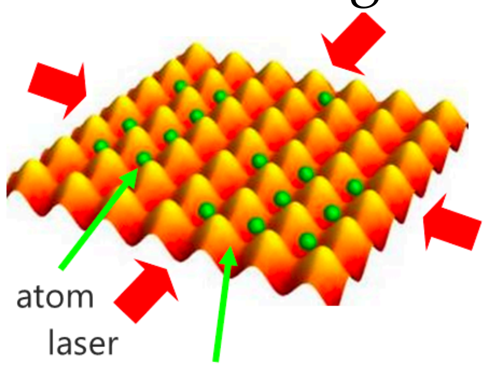


J. Martinis group

We will now consider each of these platforms in turn

Ultracold Atoms

Cold atomic gases



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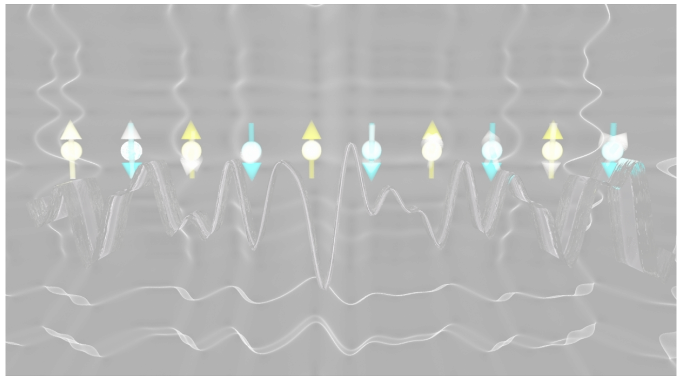

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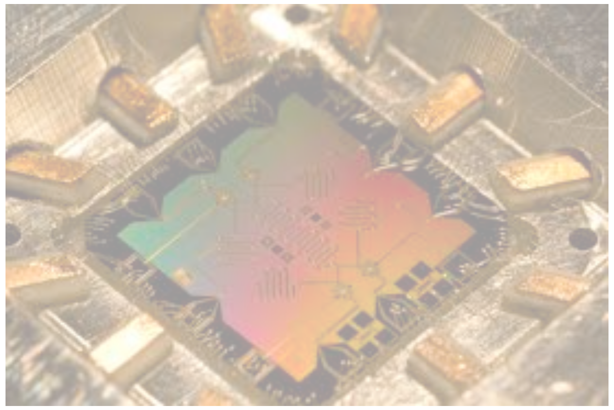

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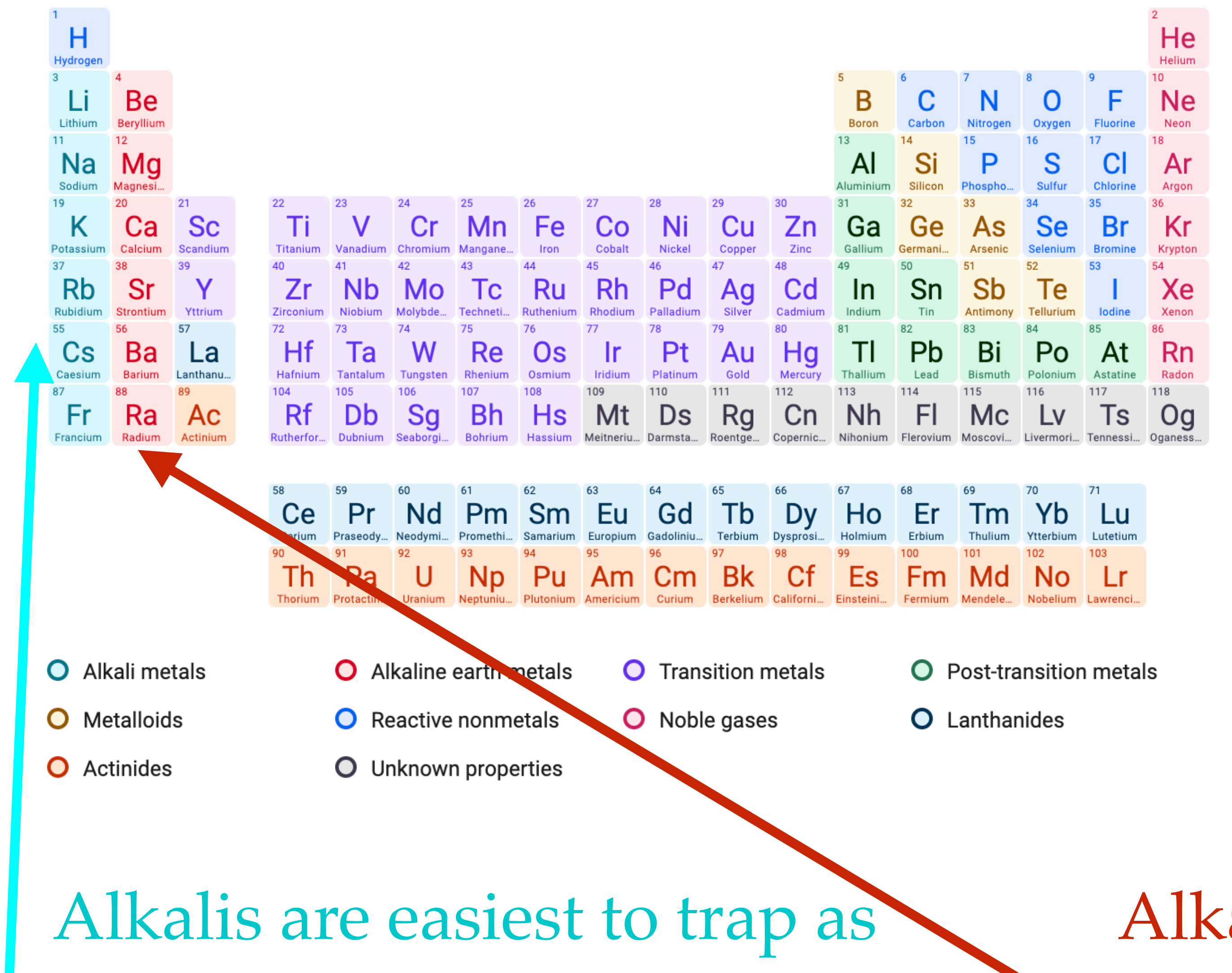
Ultracold Atoms

Periodic table



Alkalis are easiest to trap as the act like one electron atoms

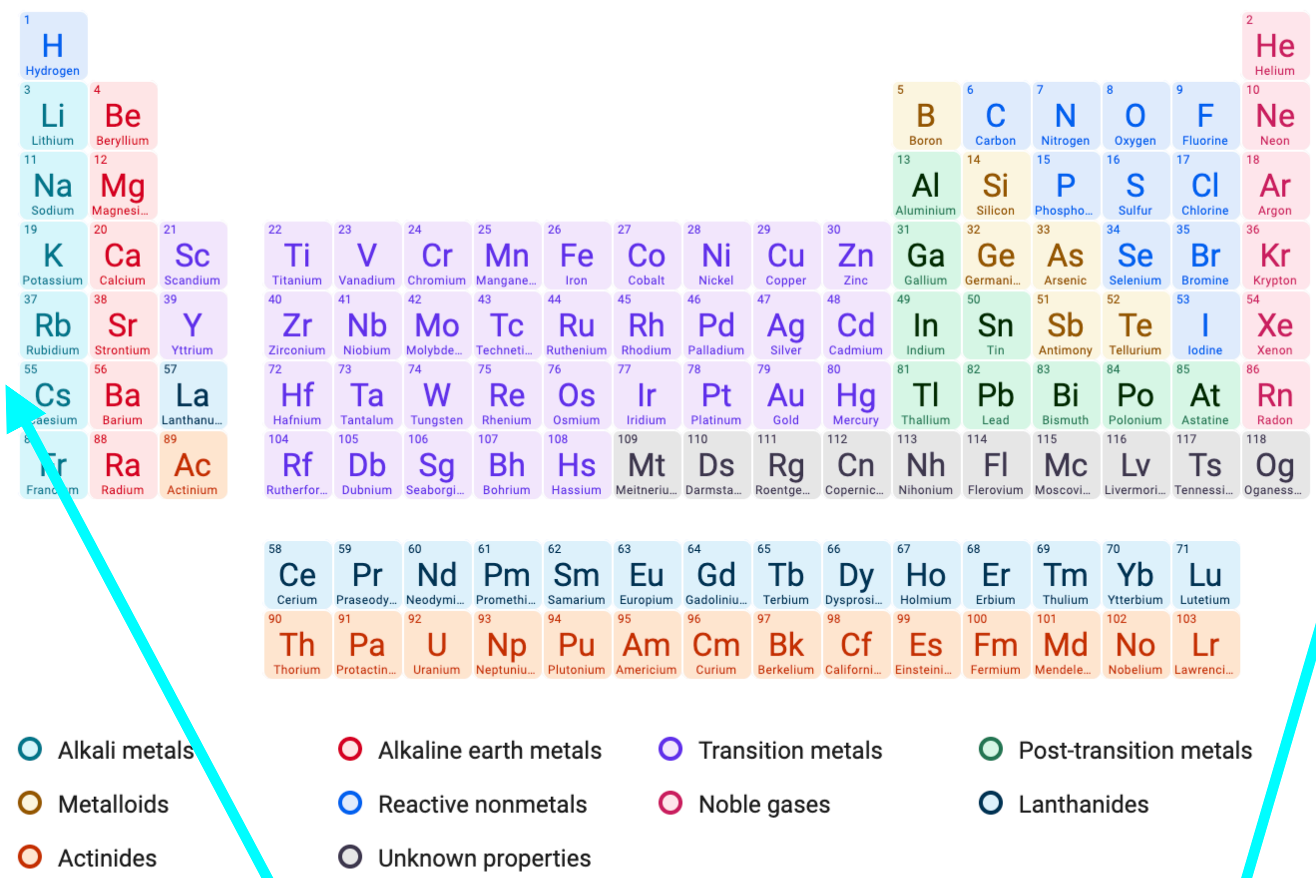
Alkali earths are harder but offer distinct capabilities

Atoms are charge neutral

Atomic Physics, Foot

Ultracold Atoms

Periodic table

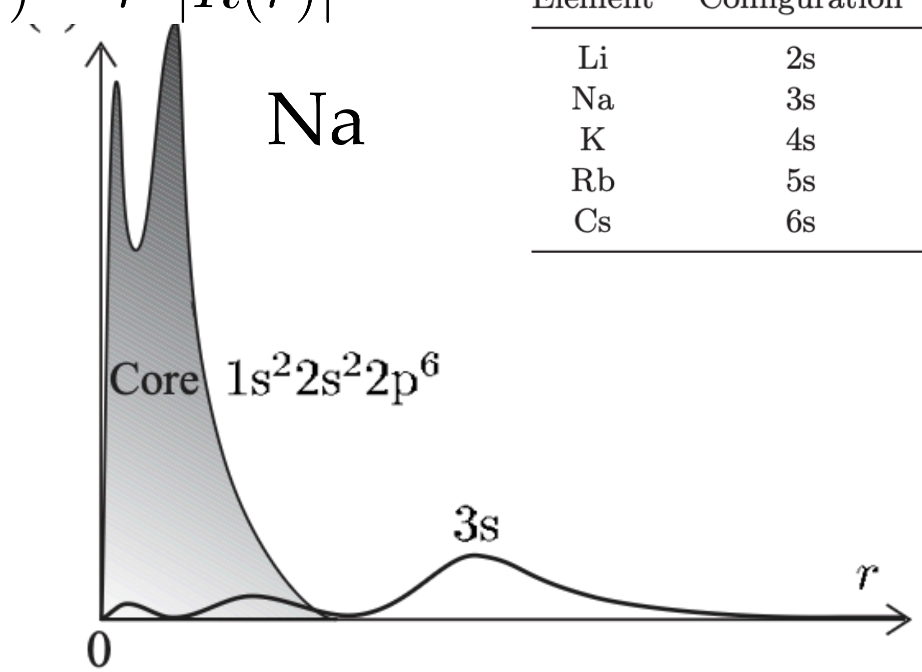


lithium	Li	$1s^2\ 2s$,
sodium	Na	$1s^2 2s^2 2p^6\ 3s$,
potassium	K	$1s^2 2s^2 2p^6 3s^2 3p^6\ 4s$,
rubidium	Rb	$1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6\ 5s$,
caesium	Cs	$1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 4d^{10} 5s^2 5p^6\ 6s$

Energies: Bohr like but with a quantum defect

$$E(n,l) = -hc\frac{R_\infty}{(n-\delta_l)^2}$$

$$P(r) = r^2|R(r)|^2$$



Element	Configuration	n^*	δ_s
Li	2s	1.59	0.41
Na	3s	1.63	1.37
K	4s	1.77	2.23
Rb	5s	1.81	3.19
Cs	6s	1.87	4.13

Alkalis are easiest to trap as the act like one electron atoms

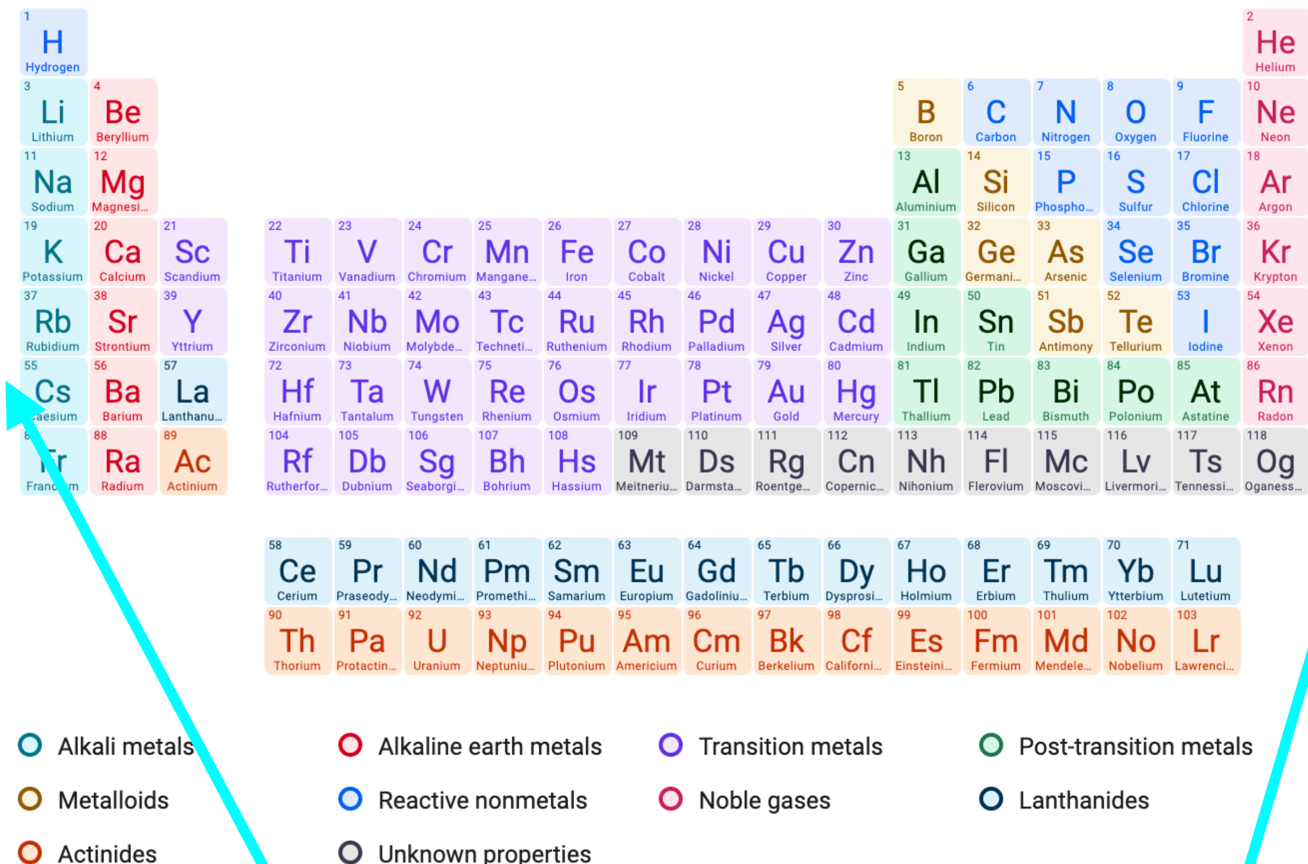
Focus on these for the following discussion

Atoms are charge neutral

Atomic Physics, Foot

Ultracold Atoms

Periodic table



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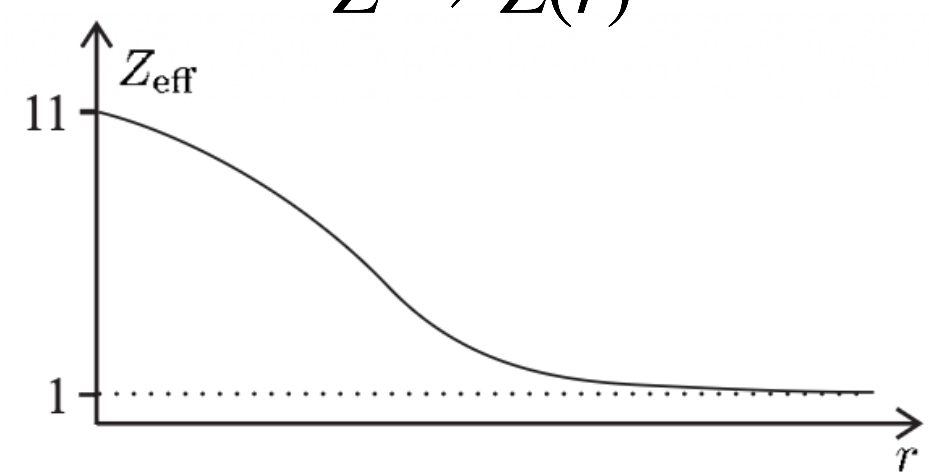
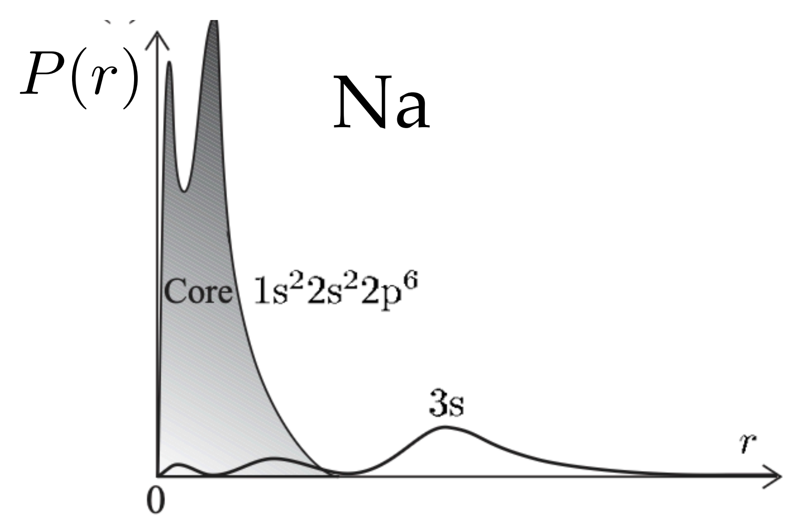
Wavefunctions: Let the atomic number

$Z \to Z(r)$





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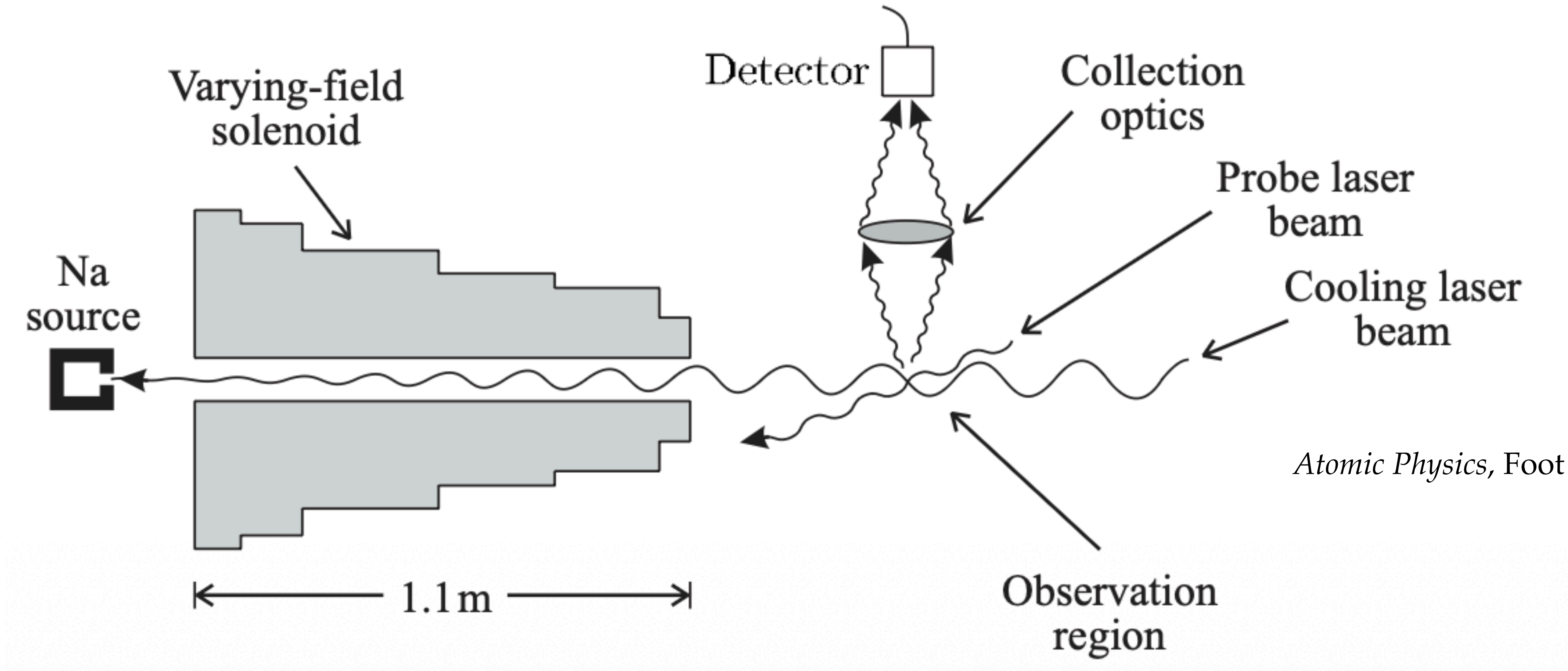
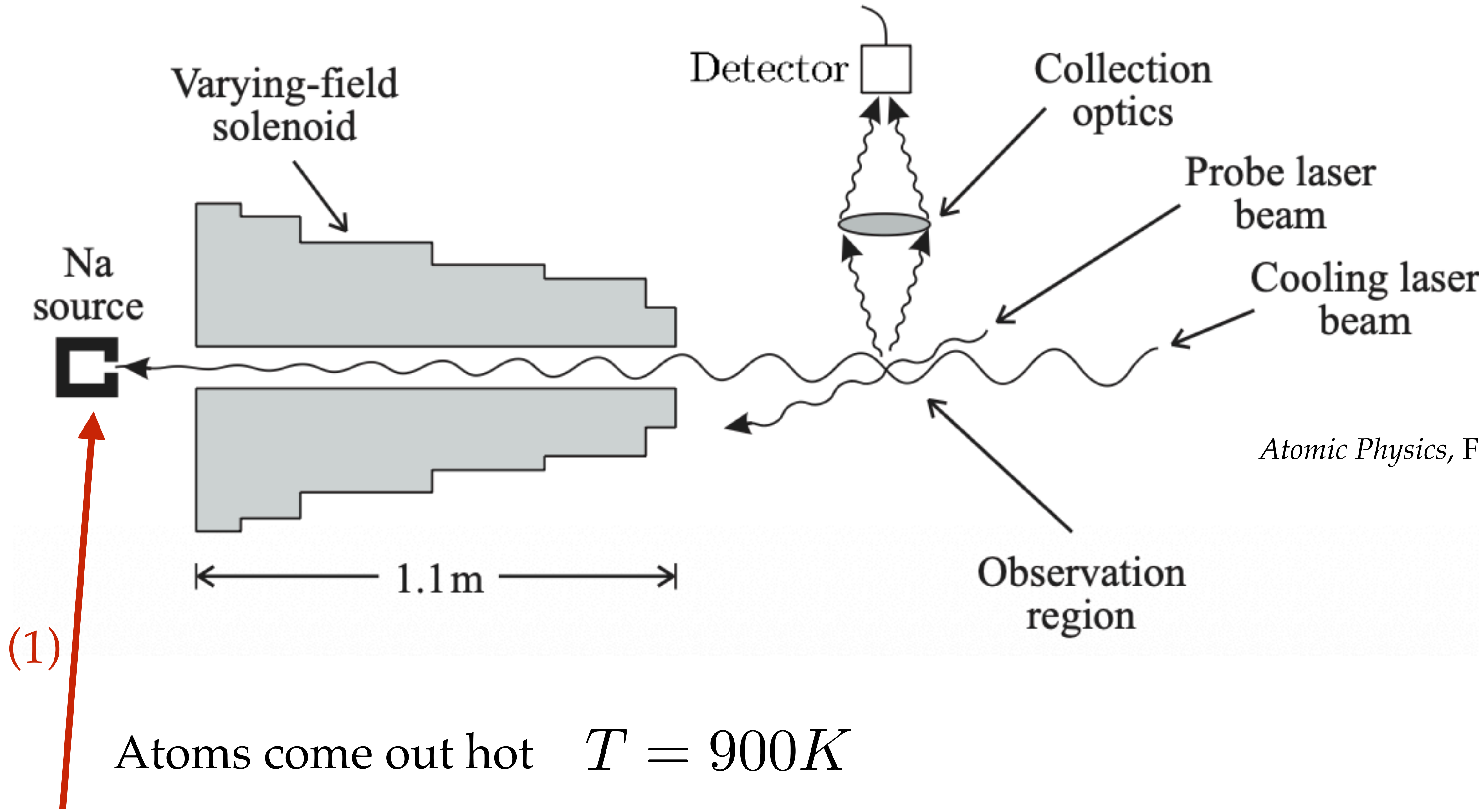


Atomic Physics, Foot

Atomic Physics, Foot

Ultracold Atoms



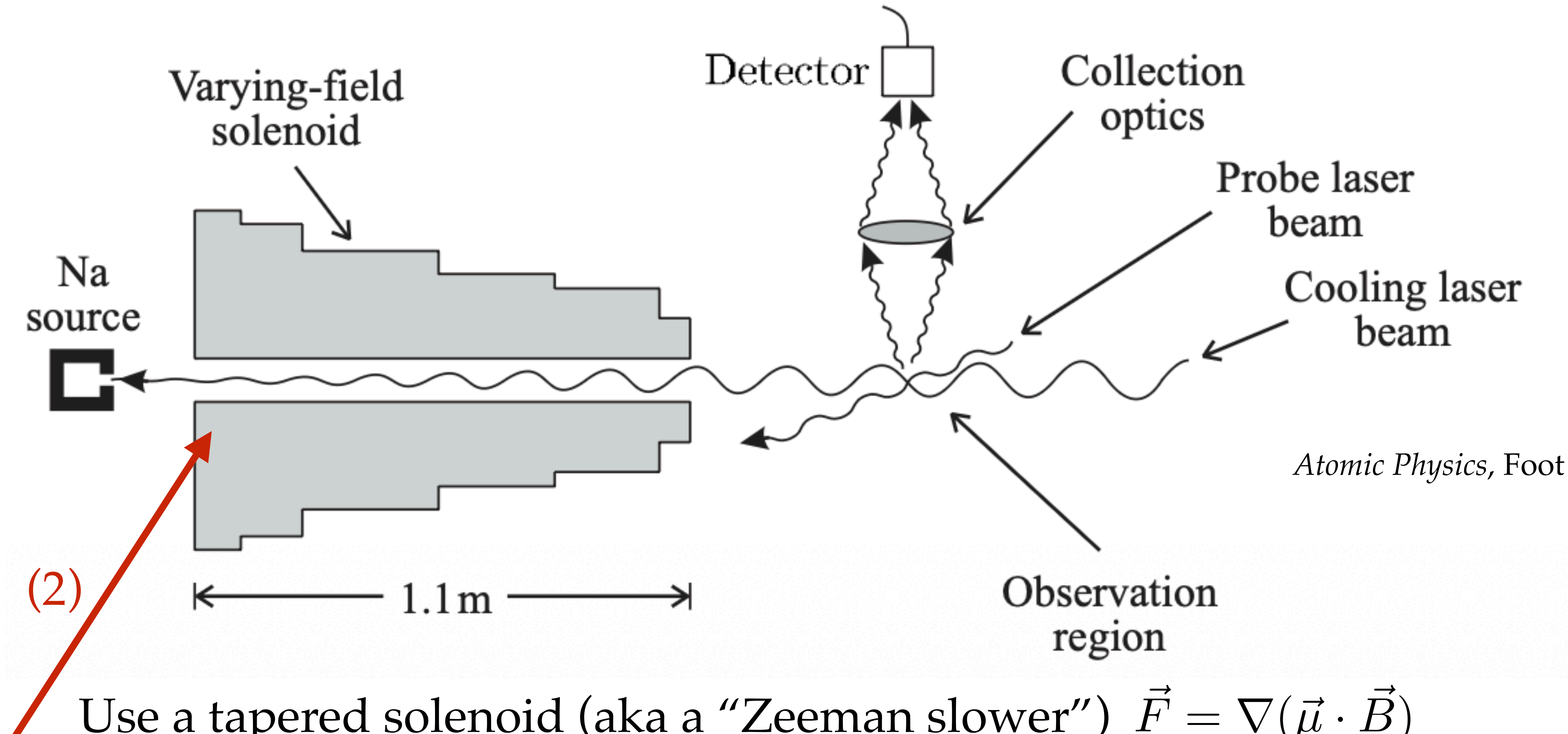
Atomic Physics, Foot

Atoms come out hot $T = 900K$

Most probable velocity is $v_0 \approx 1000\text{m/s}$

To fast to be stopped with lasers, need to first slow the atoms down

Ultracold Atoms

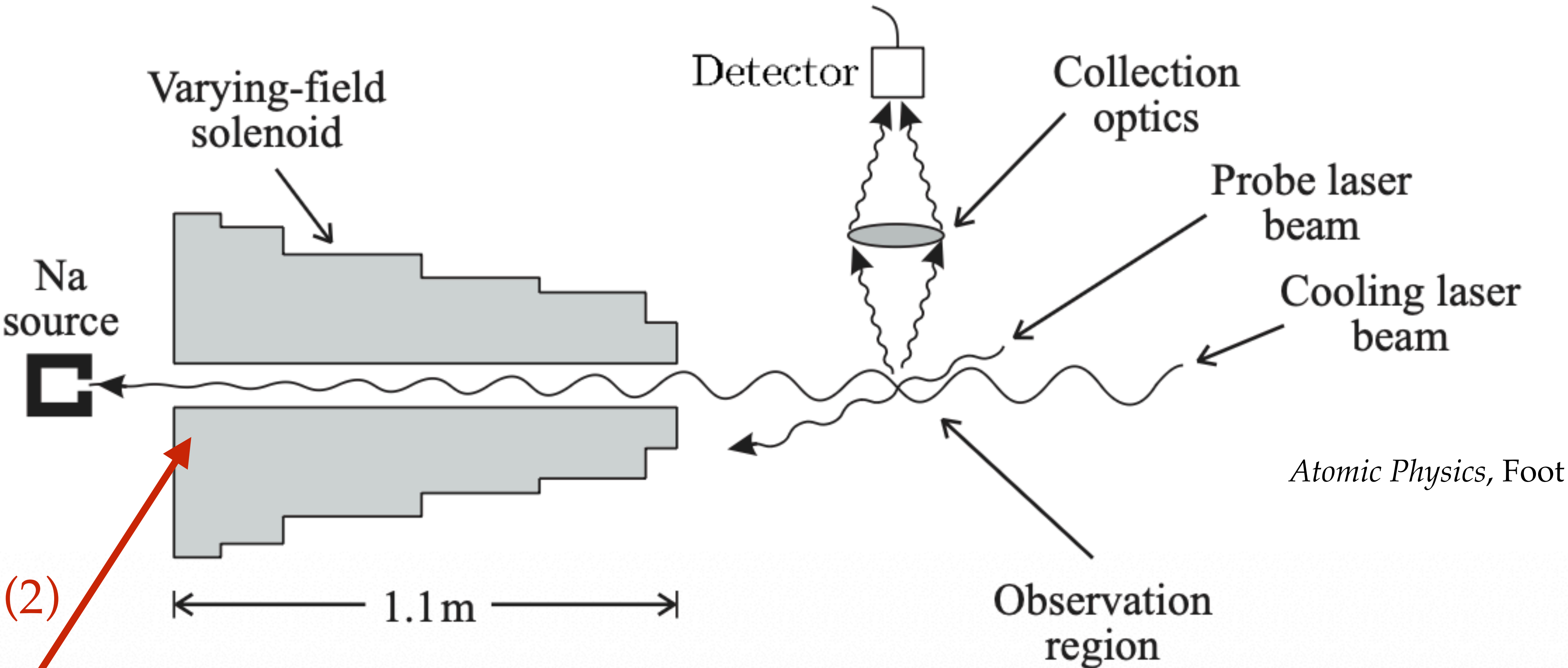


Atomic Physics, Foot

Use a tapered solenoid (aka a "Zeeman slower") $\vec{F} = \nabla(\vec{\mu} \cdot \vec{B})$

Under constant deceleration $v = v_0 \left(1 - \frac{z}{L_0}\right)^{1/2}$ Stopping distance $L_0 = \frac{{v_0}^2}{a_{\max}} \sim 1\text{m}$

Ultracold Atoms



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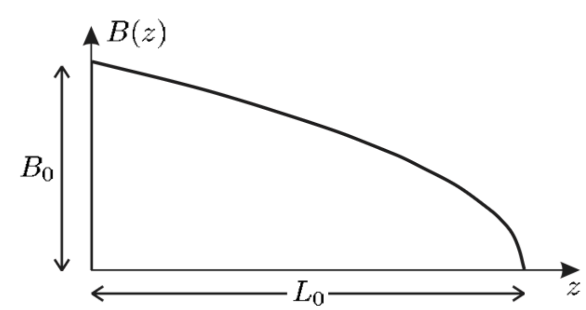
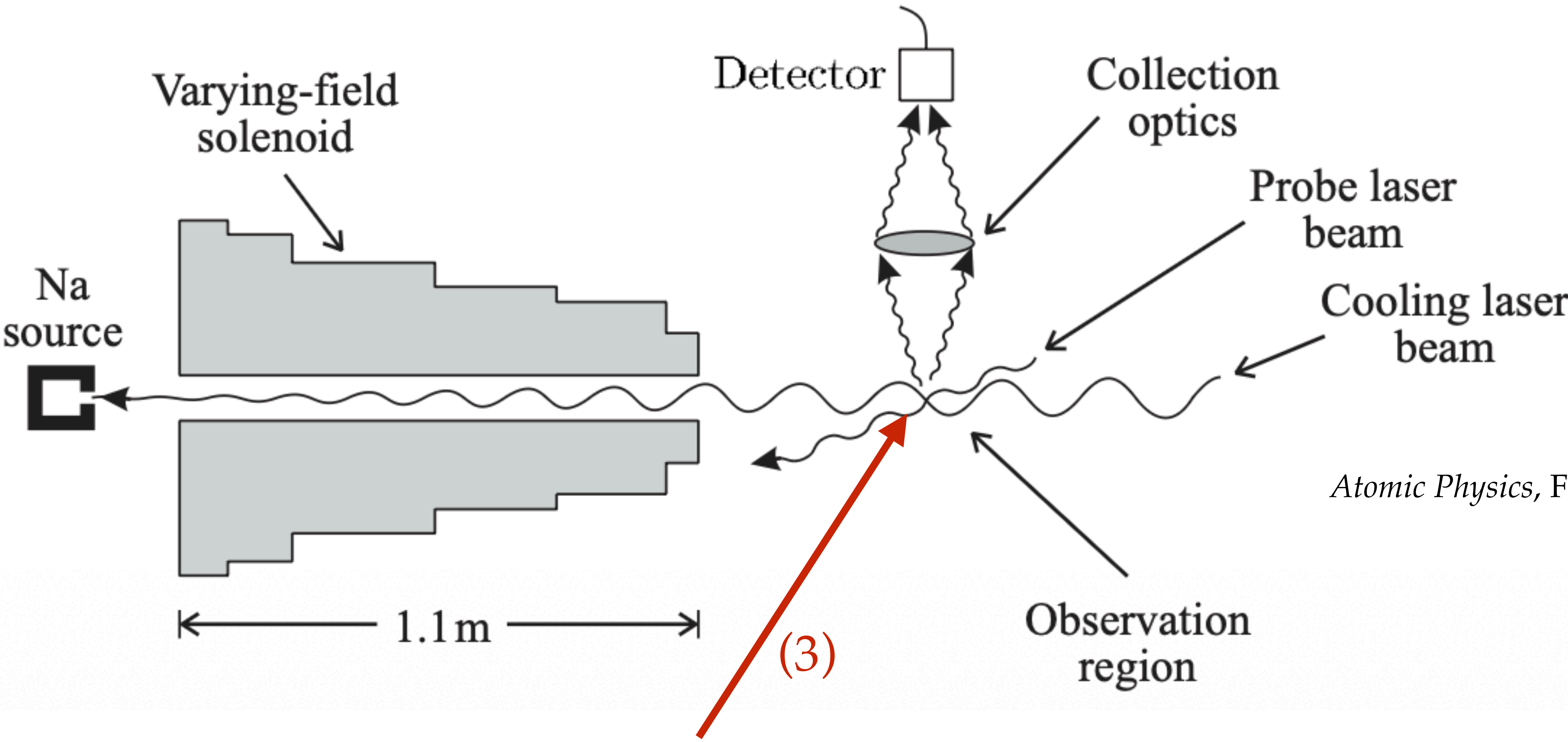
As the atoms slow down there energies change
and come out of resonance choose B to keep it on resonance

$$\omega_0 + \frac{\mu_B B(z)}{\hbar} = \omega + kv \qquad B(z) = B_0 \left(1 - \frac{z}{L_0}\right)^{1/2} + B_{\text{bias}}$$



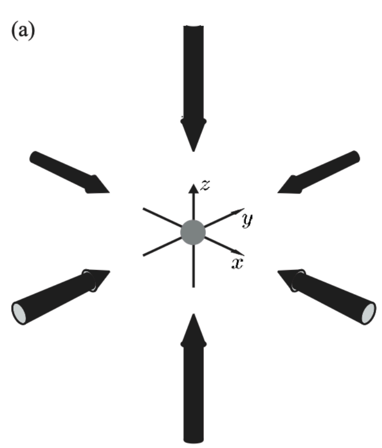
Ultracold Atoms



Atomic Physics, Foot

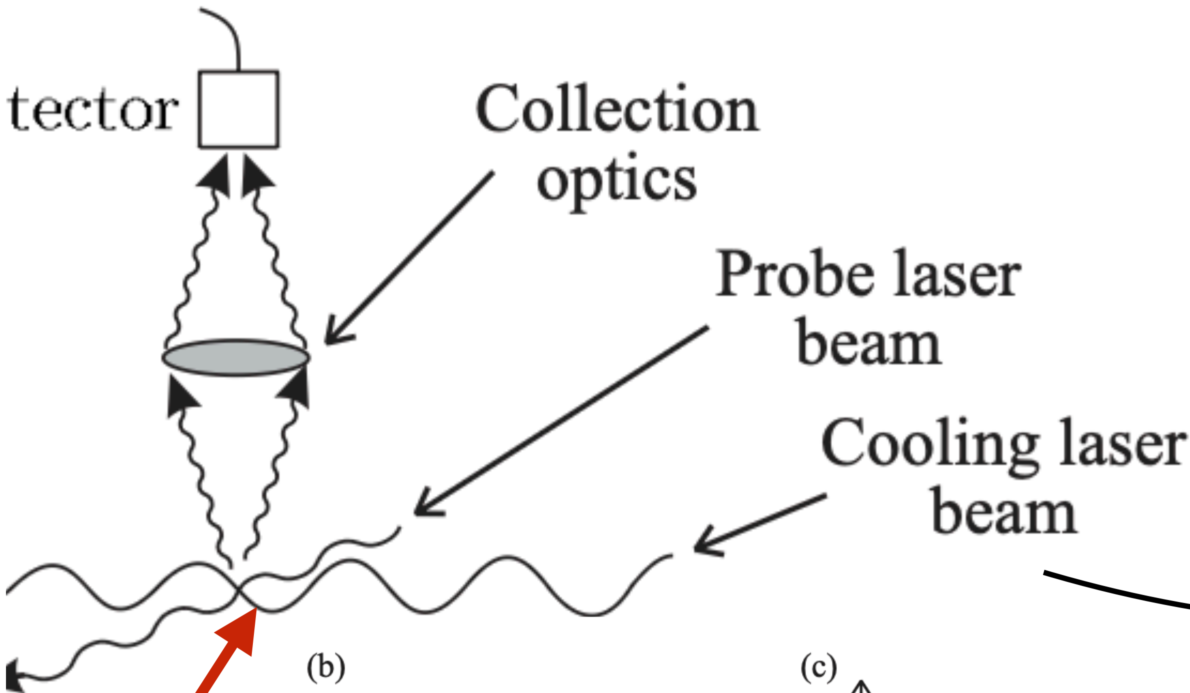
Atoms are now going slow enough to trap with optical forces

Optical molasses



Apply 6 counter propagating lasers

Ultracold Atoms



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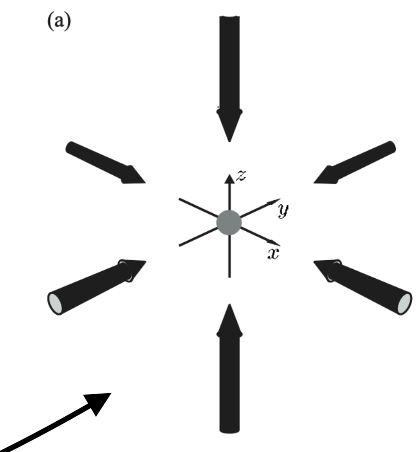
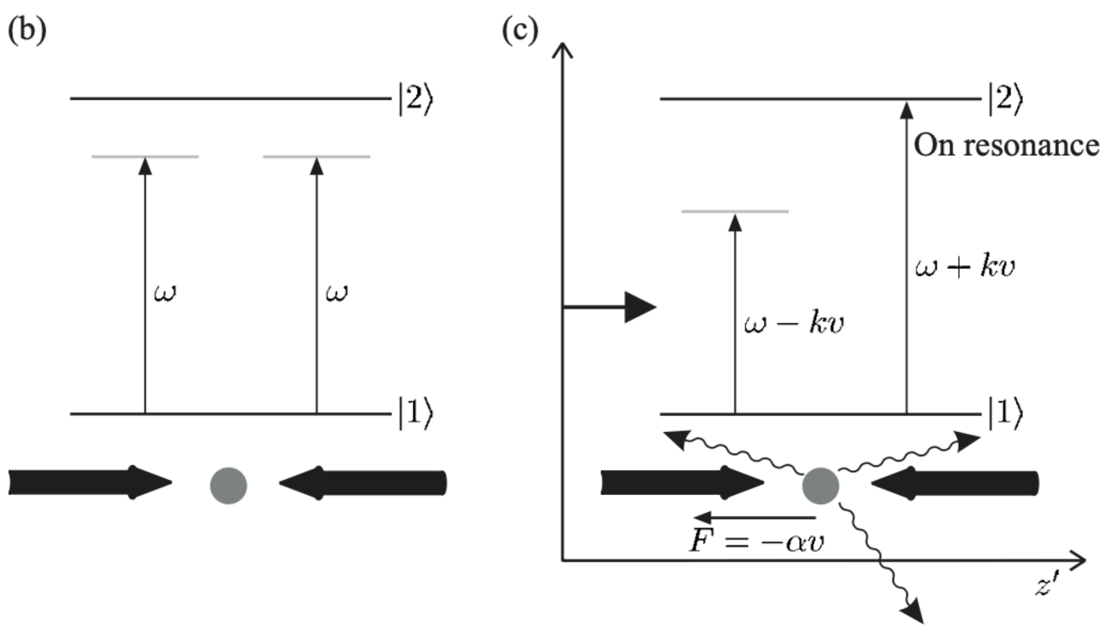
Optical molasses

Apply 6 counter propagating lasers





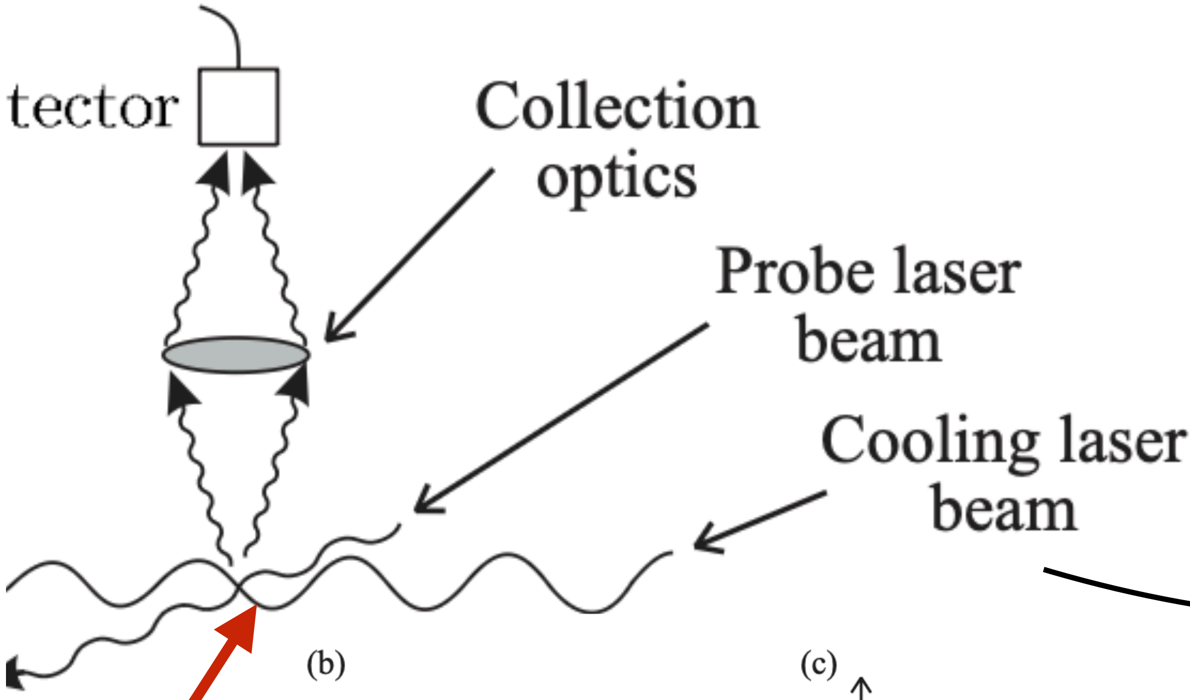
$F_{\text{scatt}} = (\text{photon momentum}) \times (\text{scattering rate})$

$$F_{\text{molasses}} = F_{\text{scatt}}\left(\omega - \omega_0 - kv\right) - F_{\text{scatt}}\left(\omega - \omega_0 + kv\right)$$

$$\simeq -2\frac{\partial F}{\partial \omega}kv = -\alpha v \qquad \alpha = 2k\frac{\partial F}{\partial \omega} = 4\hbar k^2 \frac{I}{I_{\text{sat}}} \frac{-2\delta/\Gamma}{\left[1 + (2\delta/\Gamma)^2\right]^2}$$

Atomic Physics, Foot

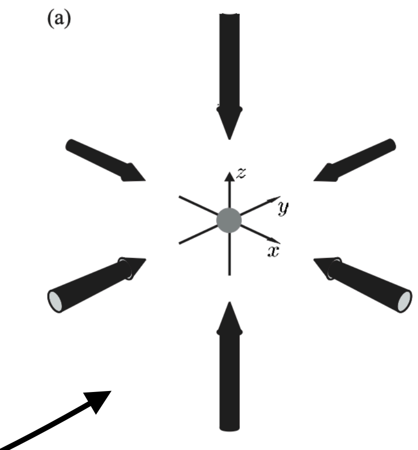
Ultracold Atoms

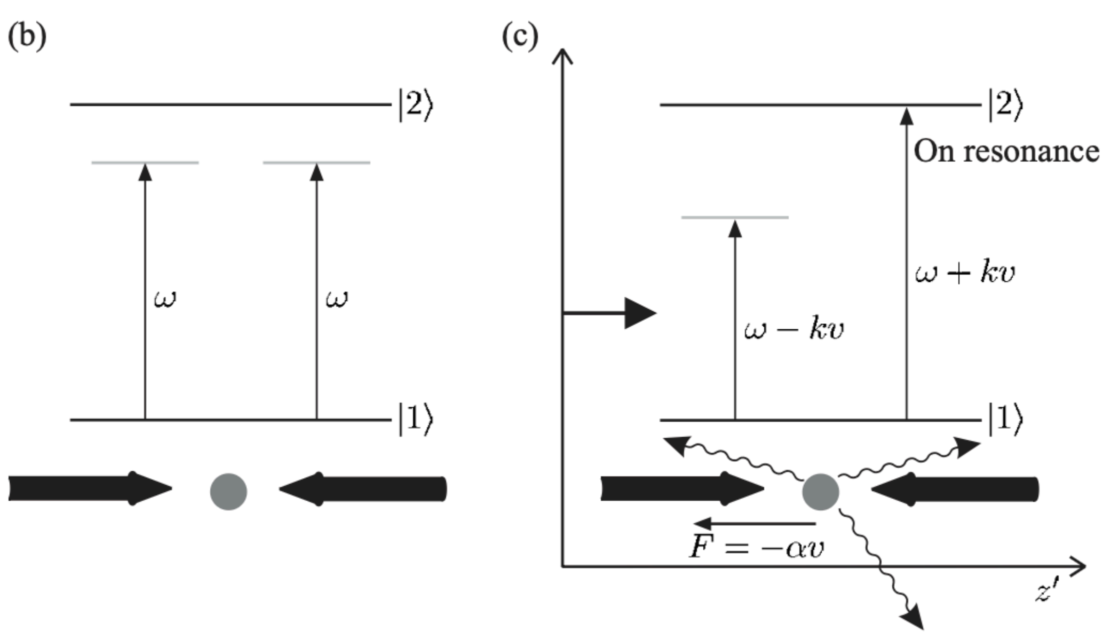


(3)

Optical molasses

Apply 6 counter propagating lasers





$F_{\text{scatt}} = (\text{photon momentum}) \times (\text{scattering rate})$

Laser intensity

detuning $\delta = \omega - \omega_0$

Spontaneous decay rate

$\Gamma_{Na} = 0.06(\text{ns})^{-1}$

$$F_{\text{molasses}} = F_{\text{scatt}}\left(\omega - \omega_0 - kv\right) - F_{\text{scatt}}\left(\omega - \omega_0 + kv\right)$$

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Atomic Physics, Foot

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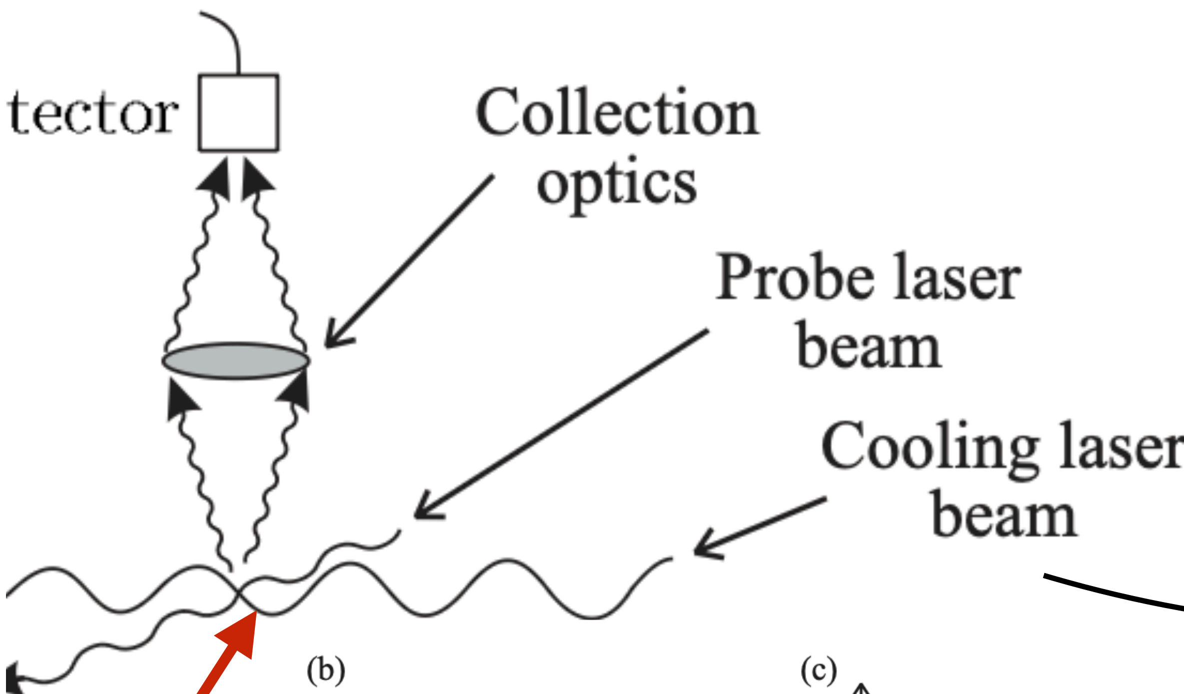

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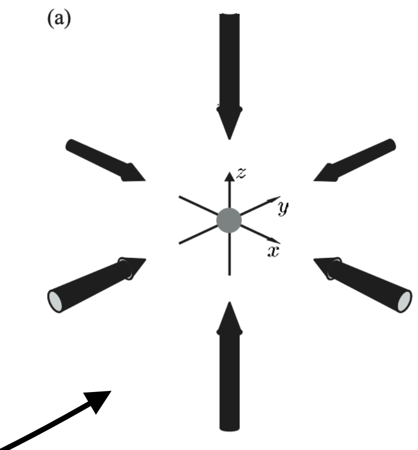
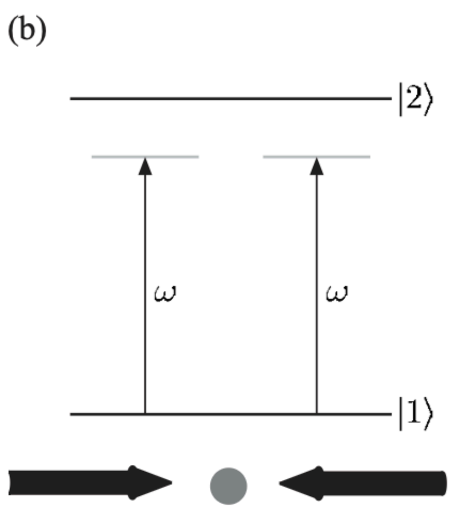
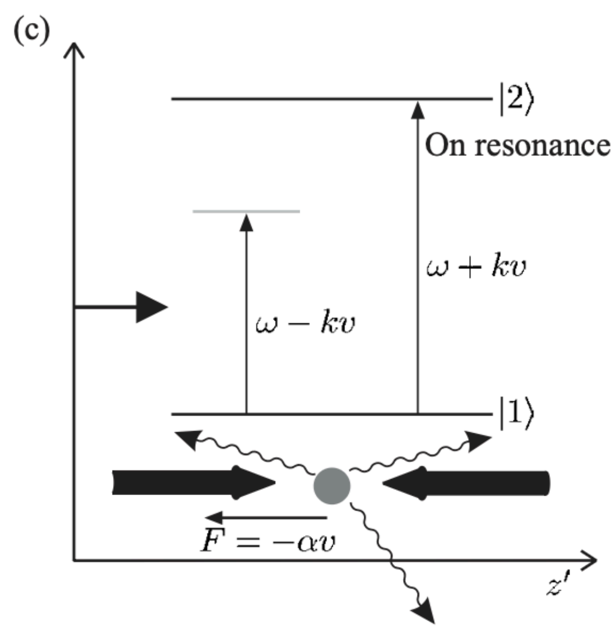
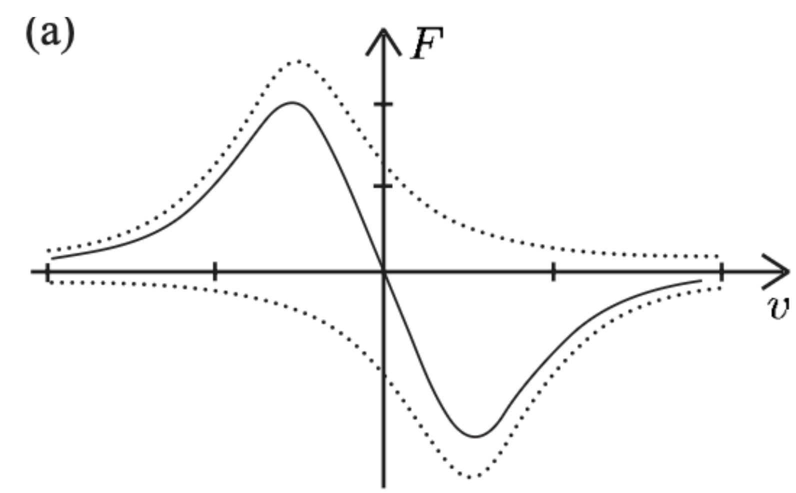


Creates a restoring force!

(3)







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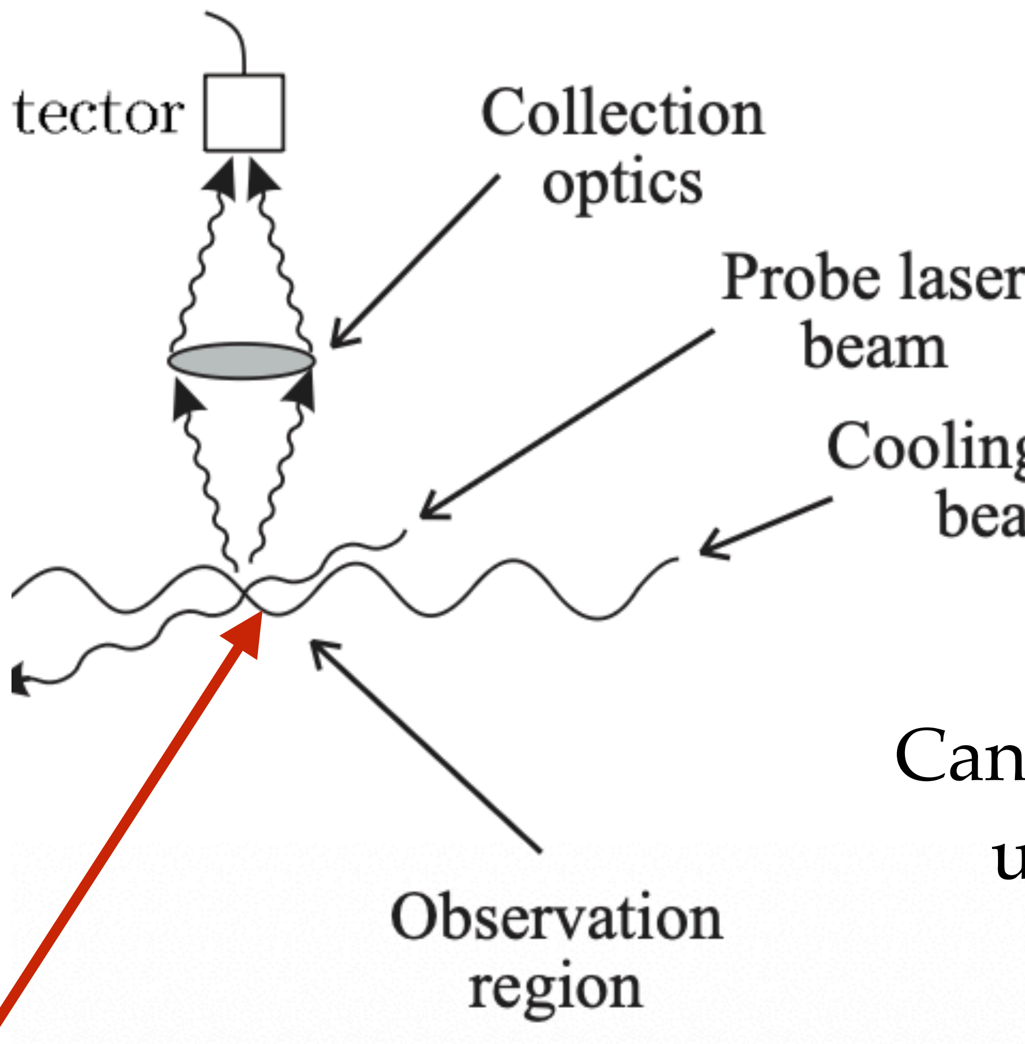
Atomic Physics, Foot

Ultracold Atoms



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Optical molasses

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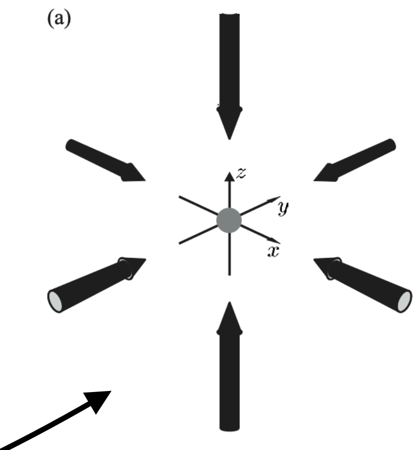
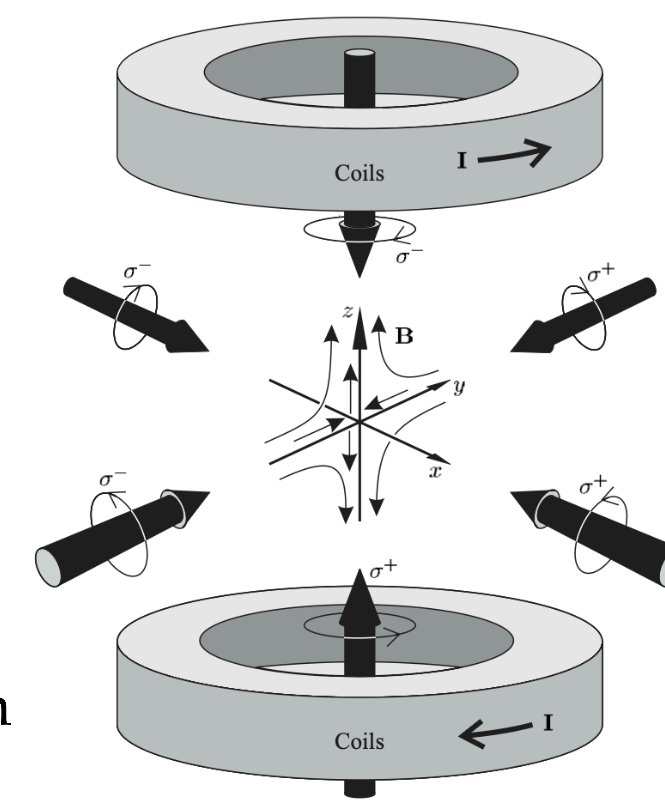


Magneto Optical Trap (MOT)

Can be further controlled using an additional magnetic field



$$F_{\mathrm{MOT}} = F_{\mathrm{scatt}}^{\sigma^+}\left(\omega - kv - (\omega_0 + \beta z)\right) - F_{\mathrm{scatt}}^{\sigma^-}\left(\omega + kv - (\omega_0 - \beta z)\right)$$

$$\simeq -2\frac{\partial F}{\partial \omega}kv + 2\frac{\partial F}{\partial \omega_0}\beta z$$

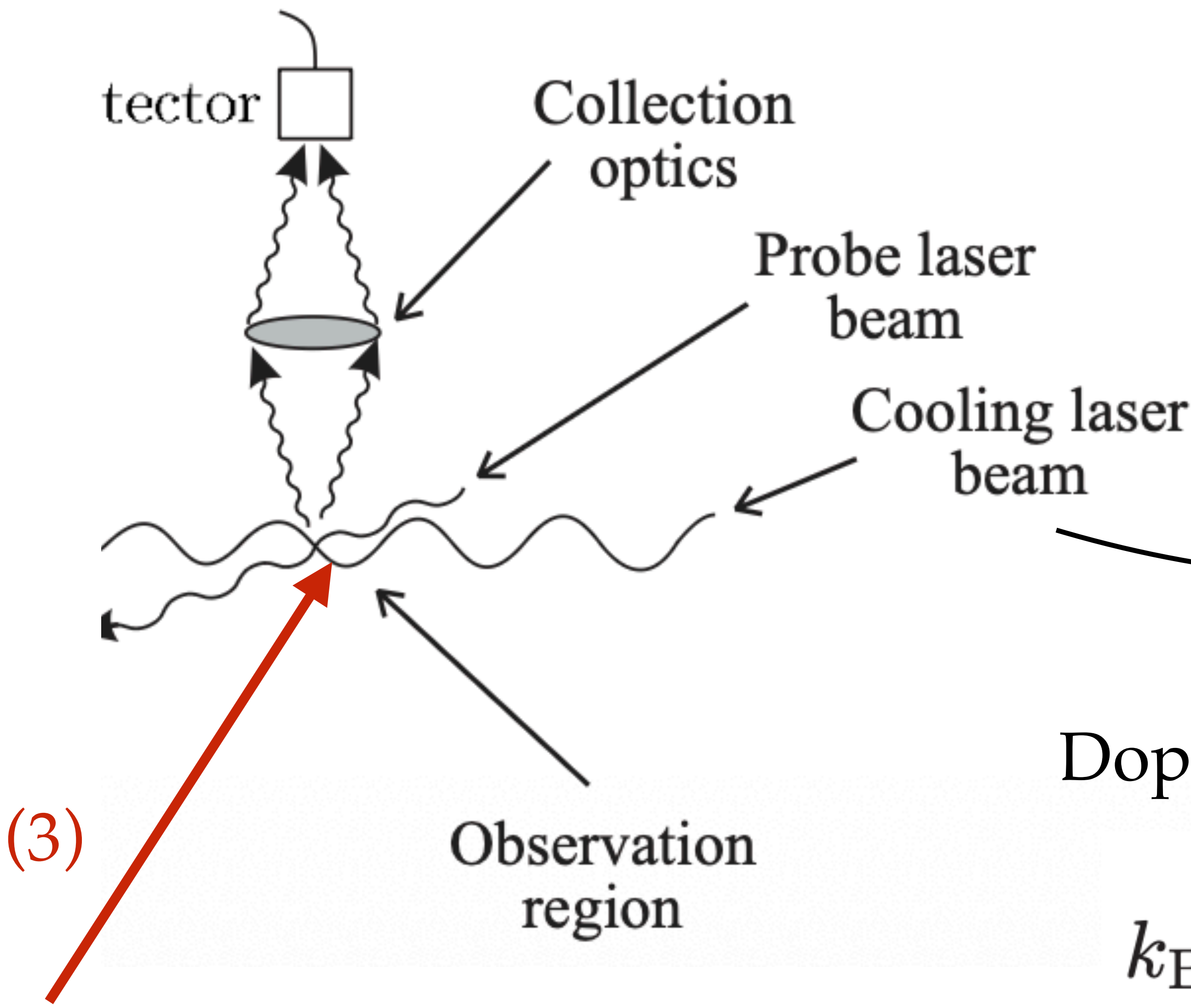
$$F_{\mathrm{MOT}} = -2\frac{\partial F}{\partial \omega}(kv + \beta z) \qquad \beta z = \frac{g\mu_{\mathrm{B}}}{\hbar}\frac{\mathrm{d}B}{\mathrm{d}z}z$$

$$= -\alpha v - \frac{\alpha\beta}{k}z\,.$$

This increases the density of trapped atoms as the MOT can trap some of the faster atoms

Atomic Physics, Foot

Ultracold Atoms



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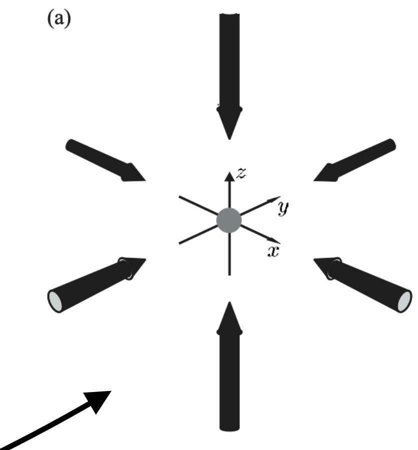


Doppler cooling limit

$$k_{\mathrm{B}}T_{\mathrm{D}} = \frac{\hbar\Gamma}{2} \qquad T_D^{\mathrm{Na}} = 240\mu\mathrm{K}$$

Theoretical limit

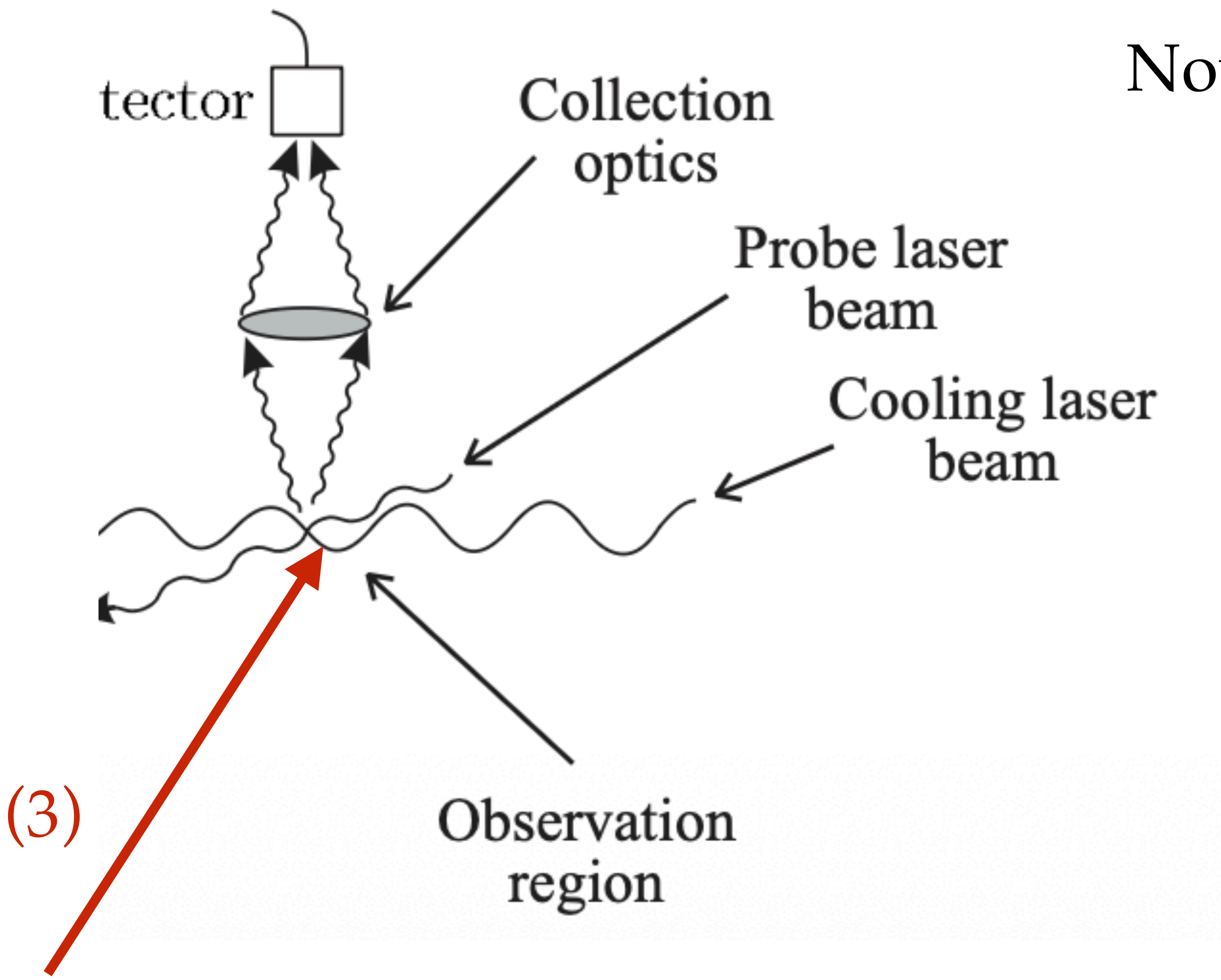
Turns out in reality the cooling mechanism is much more efficient (sub Doppler cooling)

$$T_{sD}^{\mathrm{Na}} = 2.4\mu\mathrm{K}$$

Sisyphus cooling

Atomic Physics, Foot

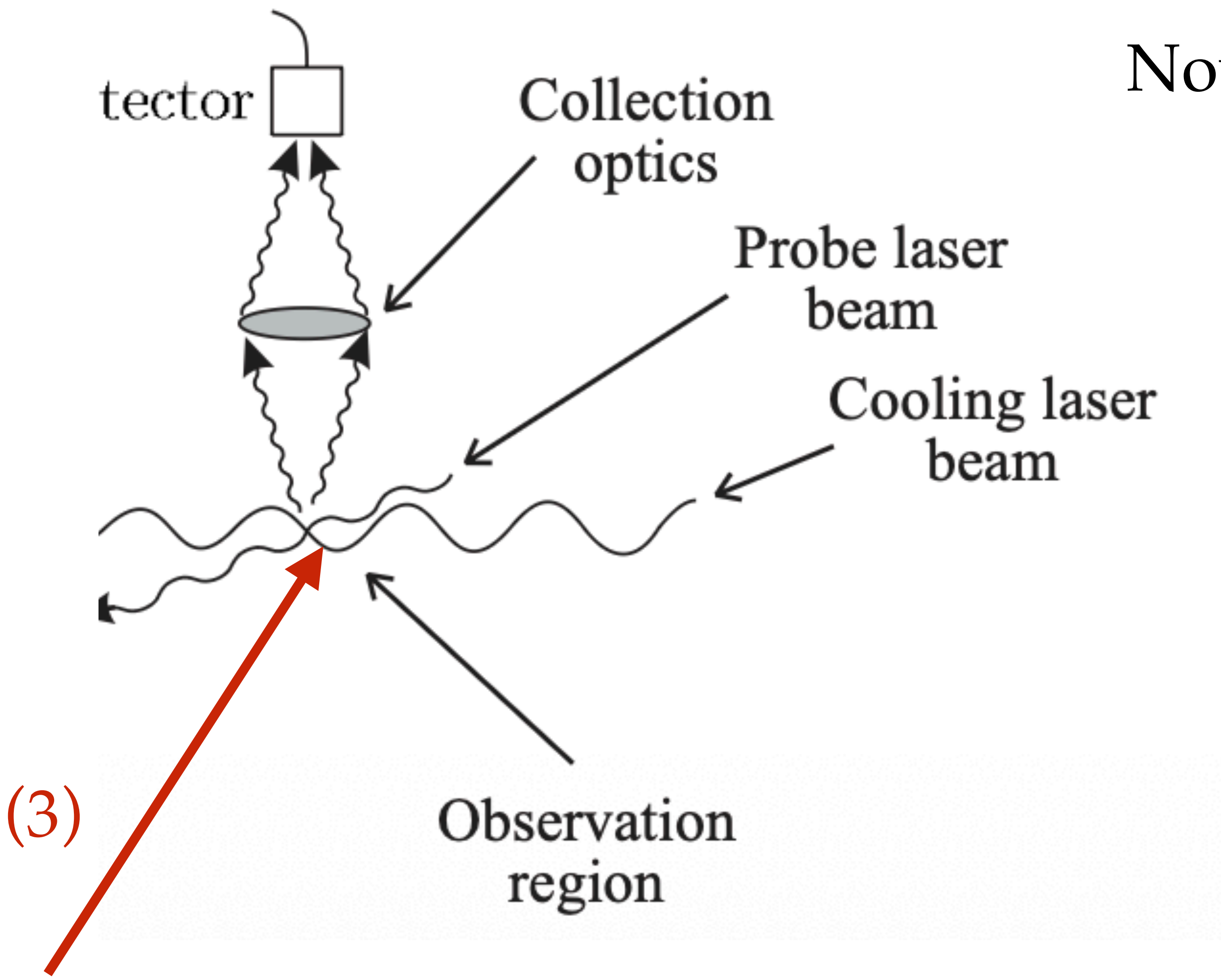
ULTRACOLD ATOMS



Now the atoms are moving slow enough to be loaded into a magnetic trap

Atomic Physics, Foot

Ultracold Atoms



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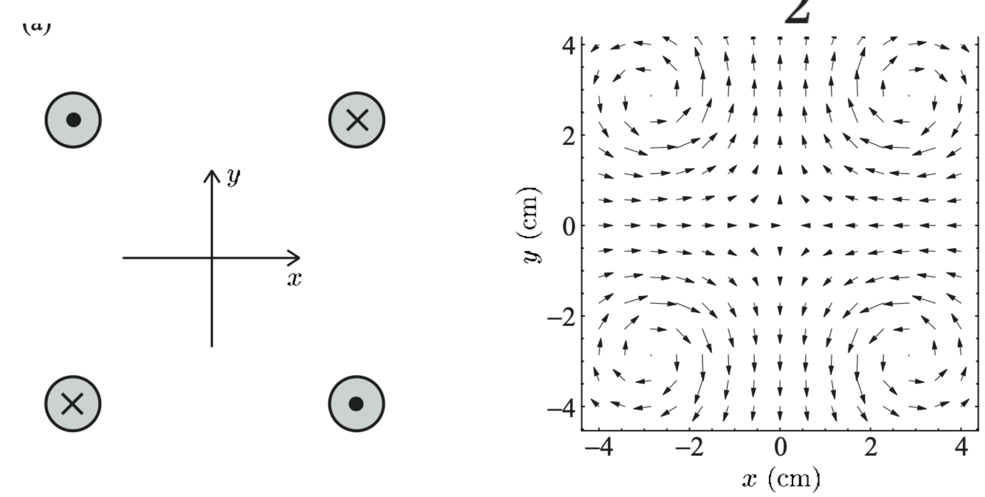
Radial confinement

$$\mathbf{B}(x,y) = b'\left(x\hat{\mathbf{e}}_x - y\hat{\mathbf{e}}_y\right) + \mathbf{B}_0 \qquad \mathbf{B}_0 = B_0\hat{\mathbf{e}}_z$$

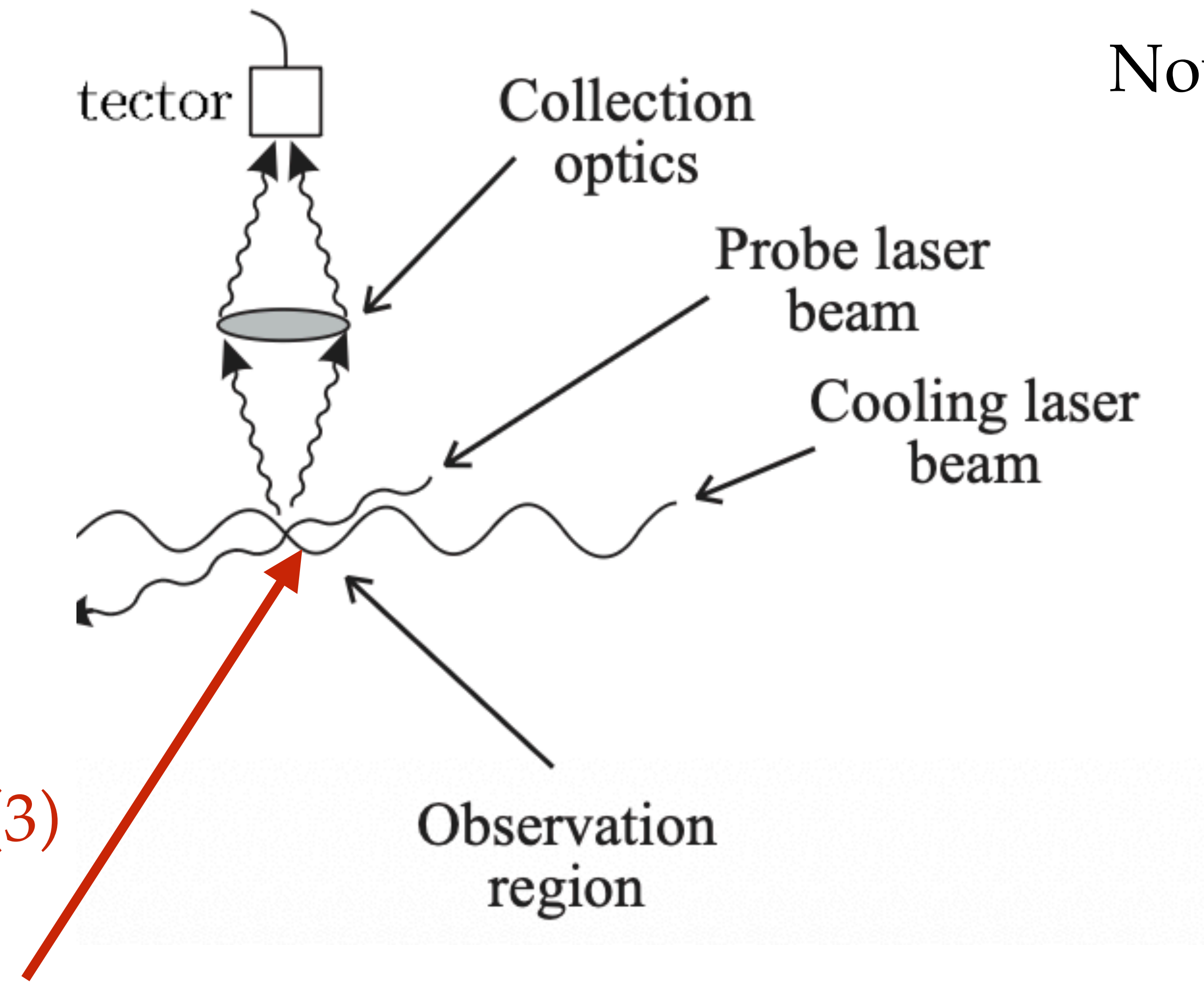
$$\mathbf{F} = -\nabla V \qquad V(r) = V_0 + \frac{1}{2}M\omega_r^2 r^2$$



Atomic Physics, Foot

Ultracold Atoms

(3)



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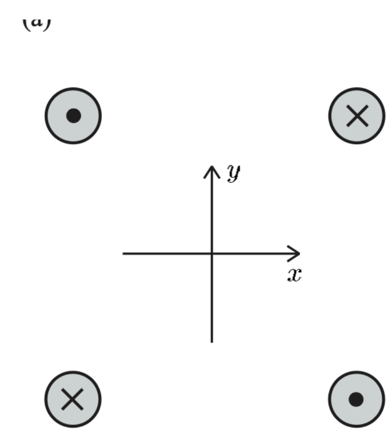
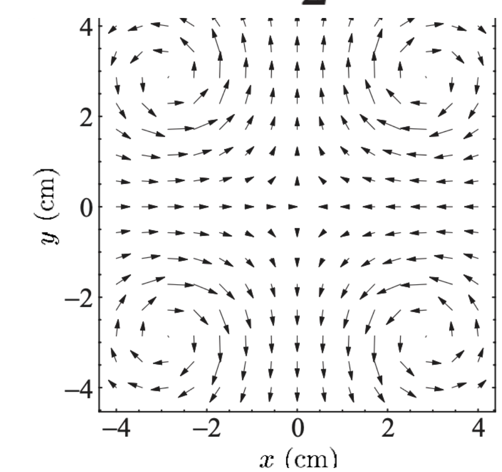
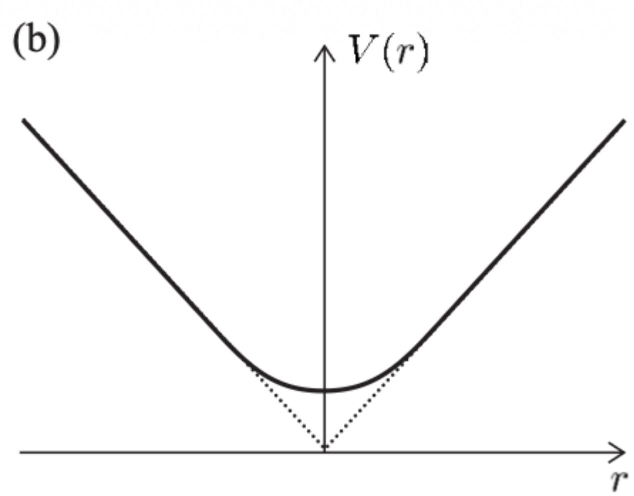
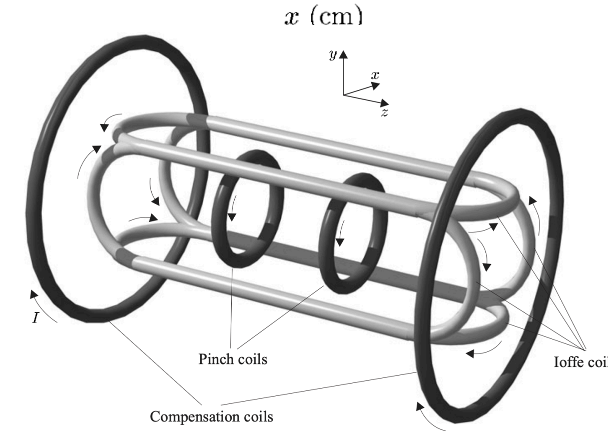






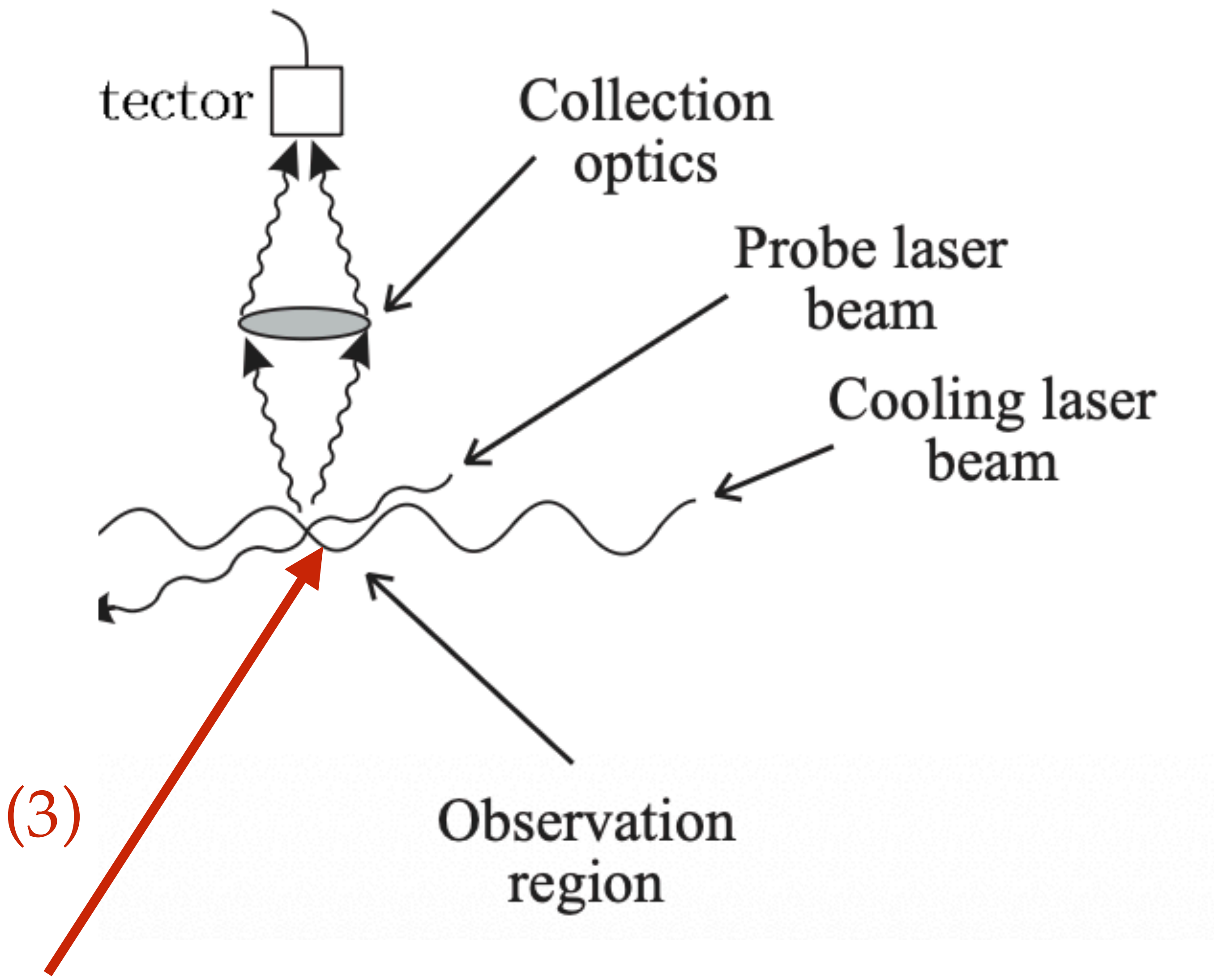
Axial confinement



$$V(r,z) = V_0 + \frac{M}{2}(\omega_r^2 r^2 + \omega_z^2 z^2)$$

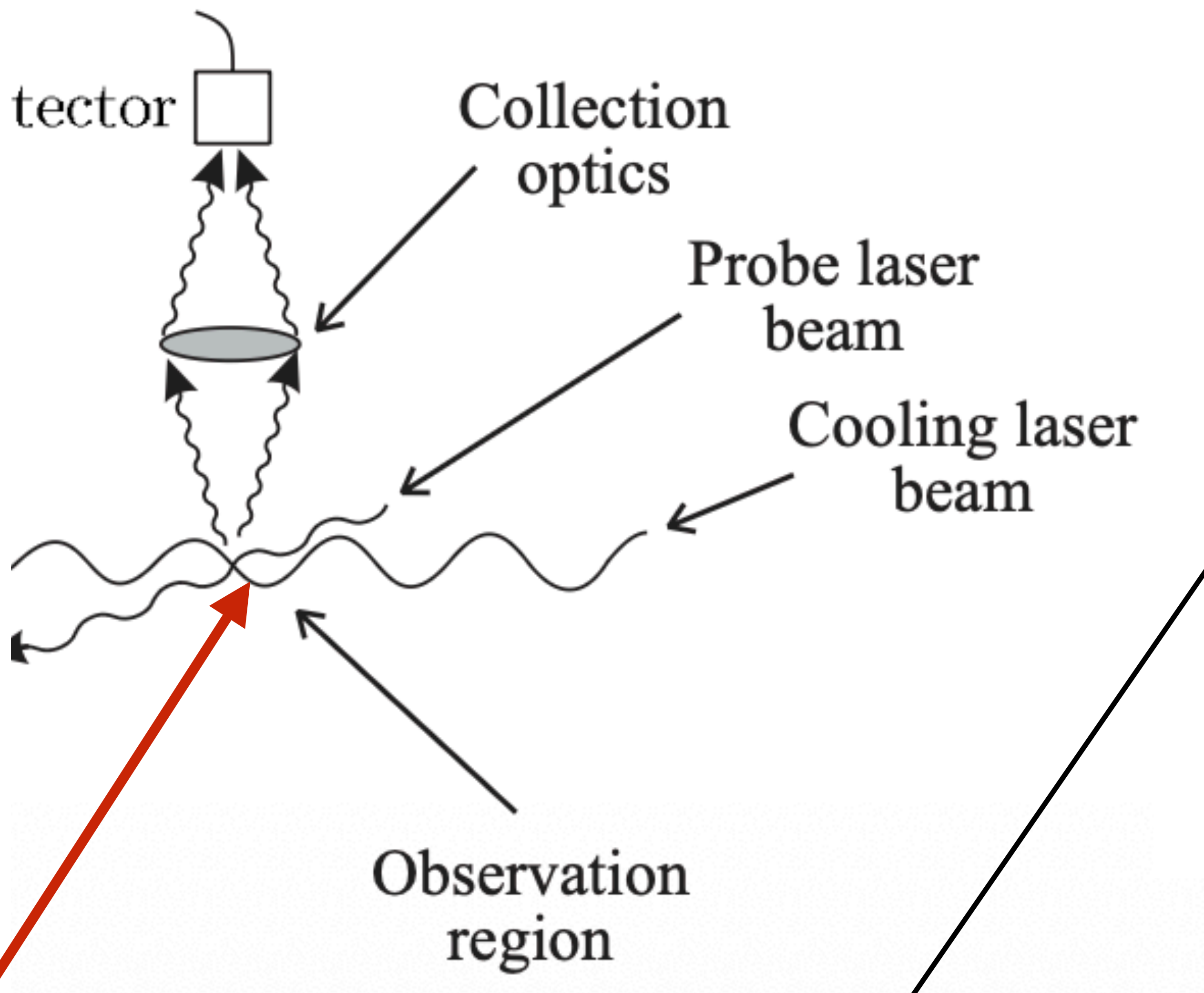
Atomic Physics, Foot

Ultracold Atoms



With the atoms in the trap,
they can now be cooled to quantum degeneracy using evaporative cooling

ULTRACOLD ATOMS



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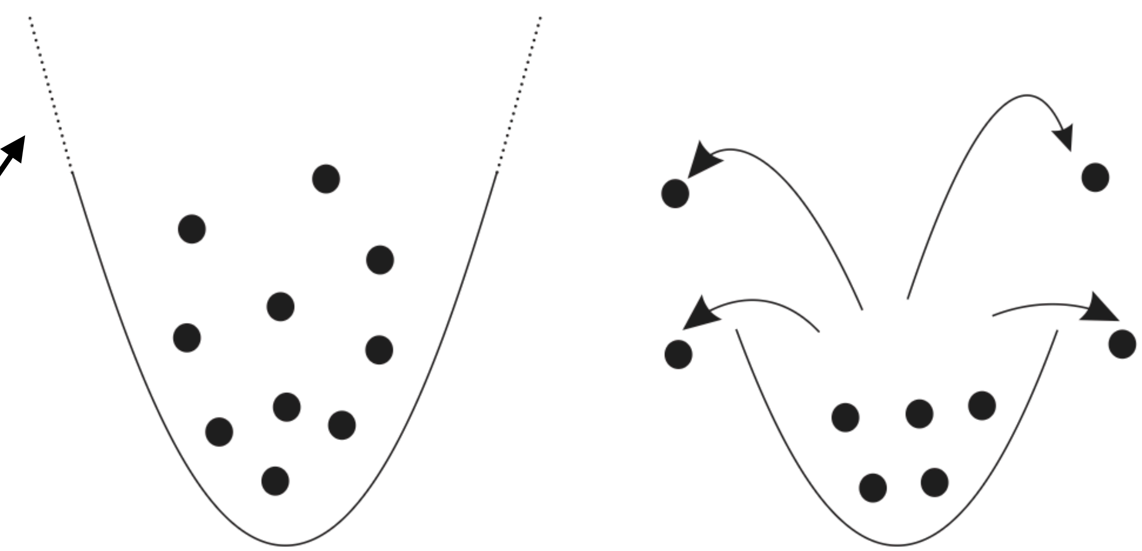
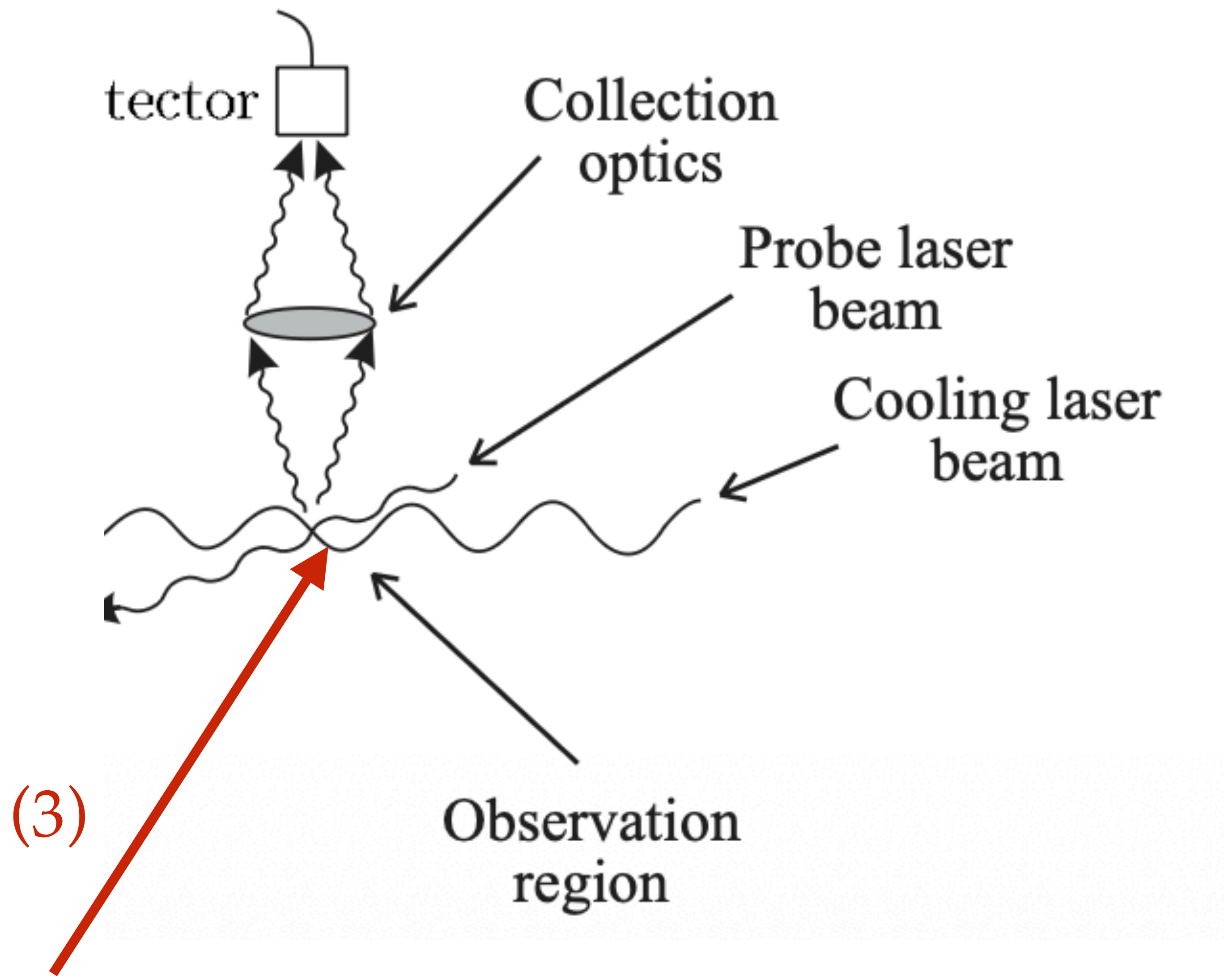


Evaporative cooling Has no lower limit, has reached below 10nK

Lowering the tops of the trap allows the most energetic fastest/hottest atoms to leave, lowering the overall temperature.

Atomic Physics, Foot

Ultracold Atoms



Strong correlations are introduced through an optical lattice

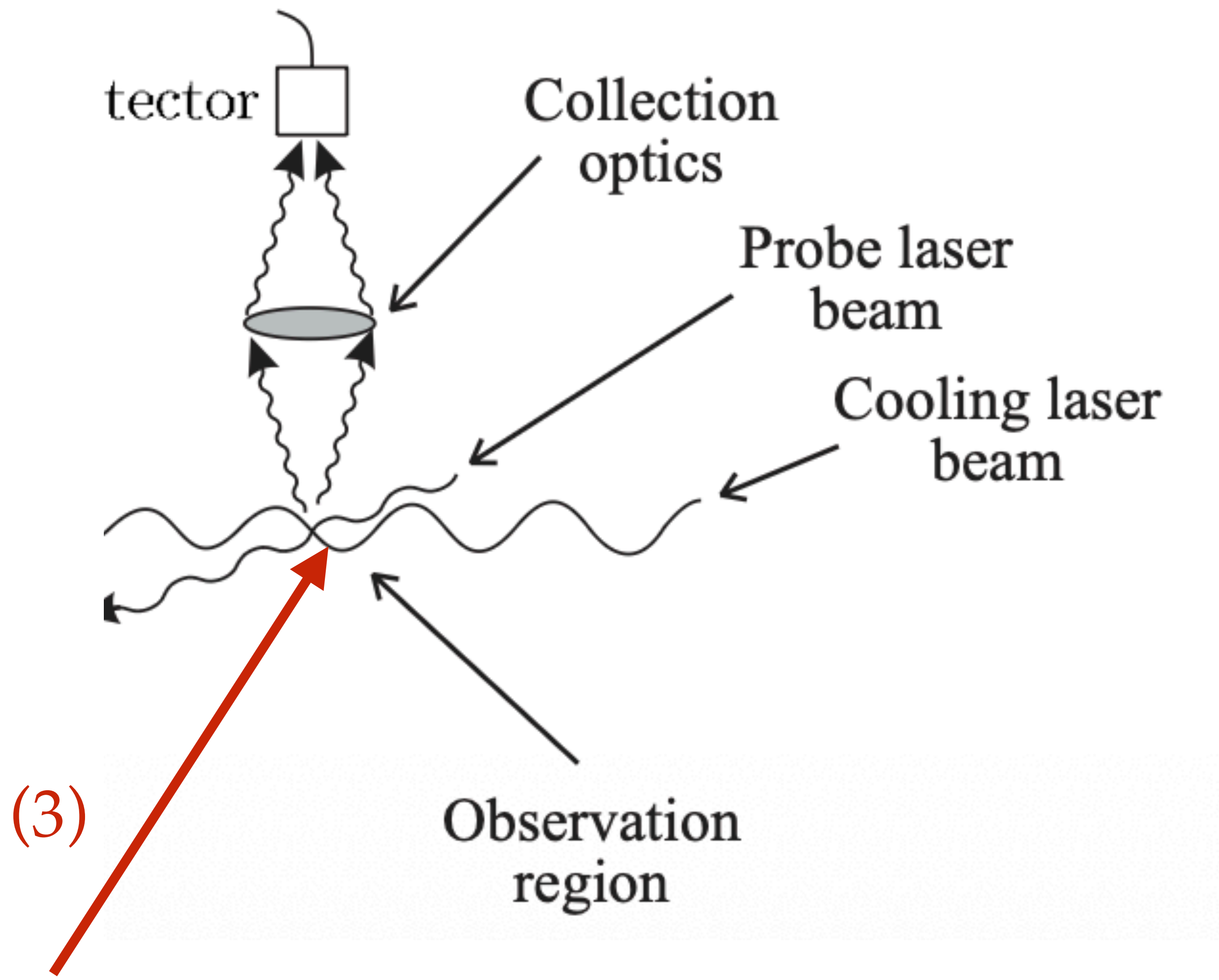
In an electric field
each atom acts like an electric dipole

$$U = -\frac{1}{2}\epsilon_0 \chi_{\mathrm{a}} E^2 = \frac{1}{2} e\mathbf{r} \cdot \mathbf{E}$$

$$F_z = -\frac{\partial U}{\partial z} = \epsilon_0 \chi_{\mathrm{a}} E \frac{\partial E}{\partial z}$$

Atomic Physics, Foot

Ultracold Atoms



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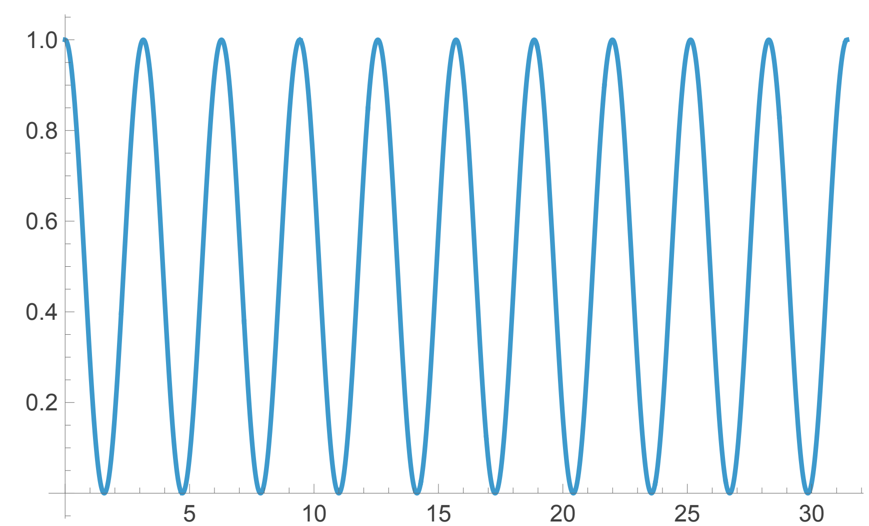
$$F_z = -\frac{\partial U}{\partial z} = \epsilon_0 \chi_a E \frac{\partial E}{\partial z}$$

Using the electric field of a standing wave

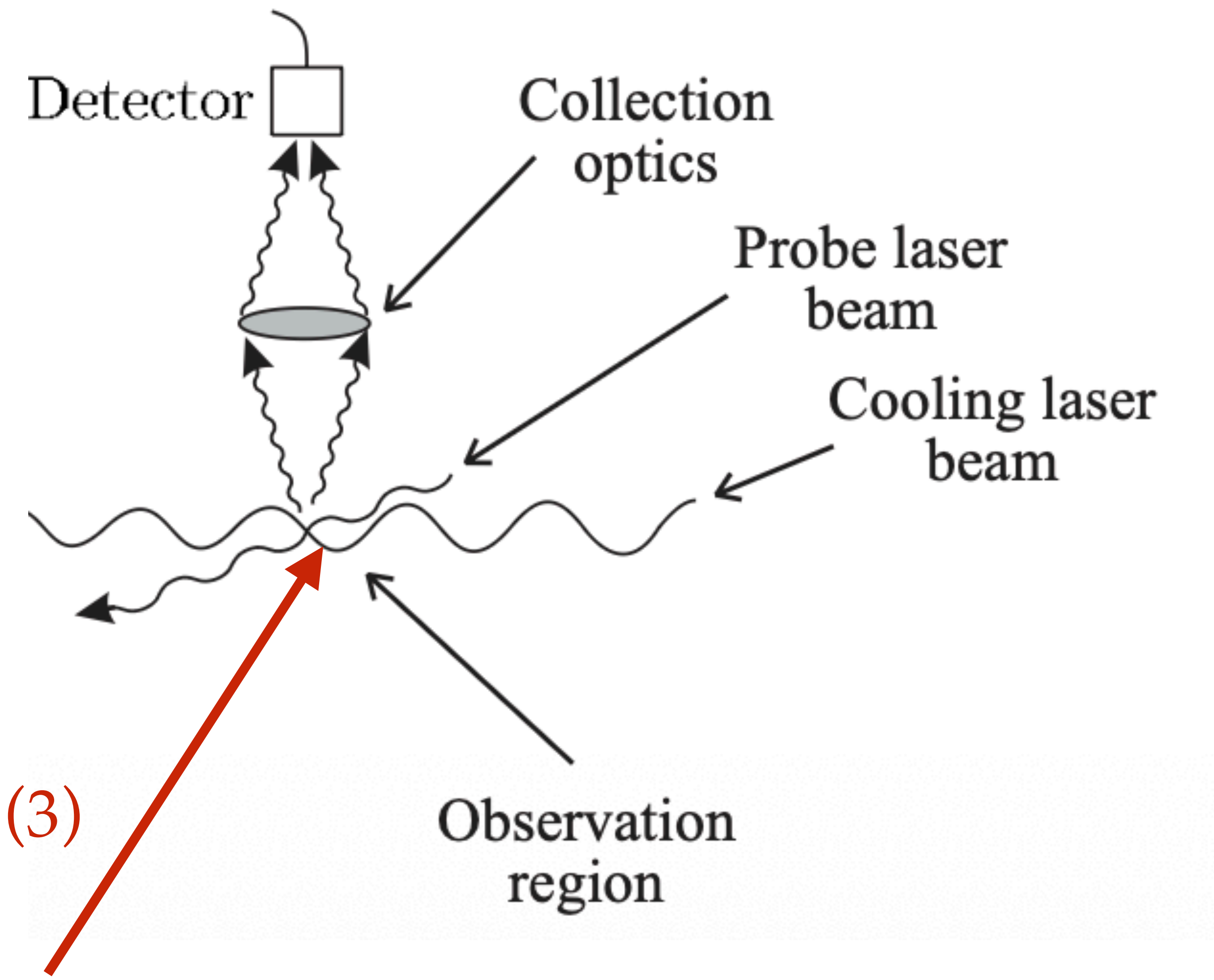
$$\begin{aligned}\mathbf{E} &= E_0\left\{\cos\left(\omega t - kz\right) + \cos\left(\omega t + kz\right)\right\}\widehat{\mathbf{e}}_x \\ &= 2E_0 \cos\left(kz\right)\cos\left(\omega t\right)\widehat{\mathbf{e}}_x\ .\end{aligned}$$

$$U_{\text{dipole}} = U_0 \cos^2\left(kz\right)$$



Atomic Physics, Foot

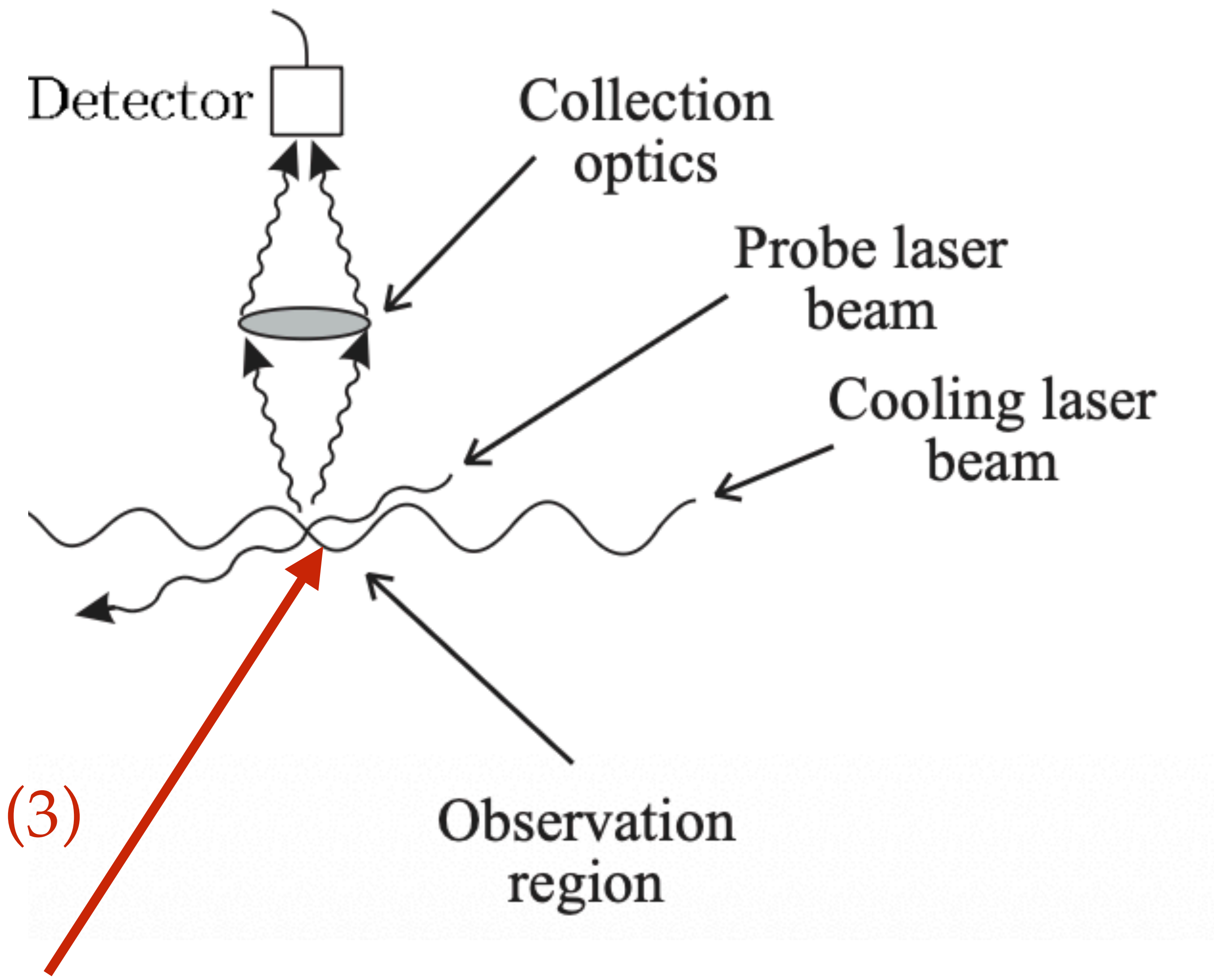
Ultracold Atoms



Now to make measurements

Time of flight imaging

Ultracold Atoms



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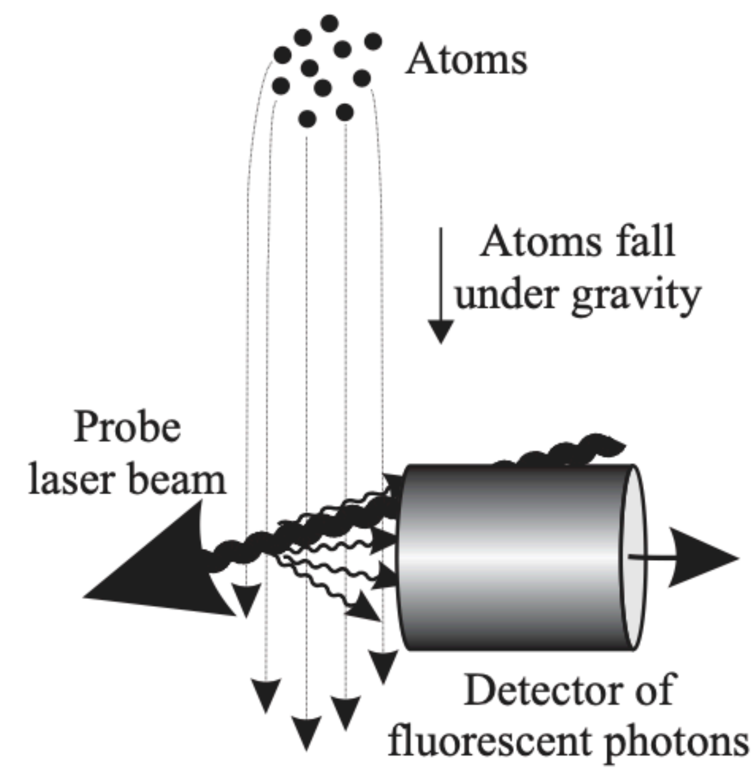


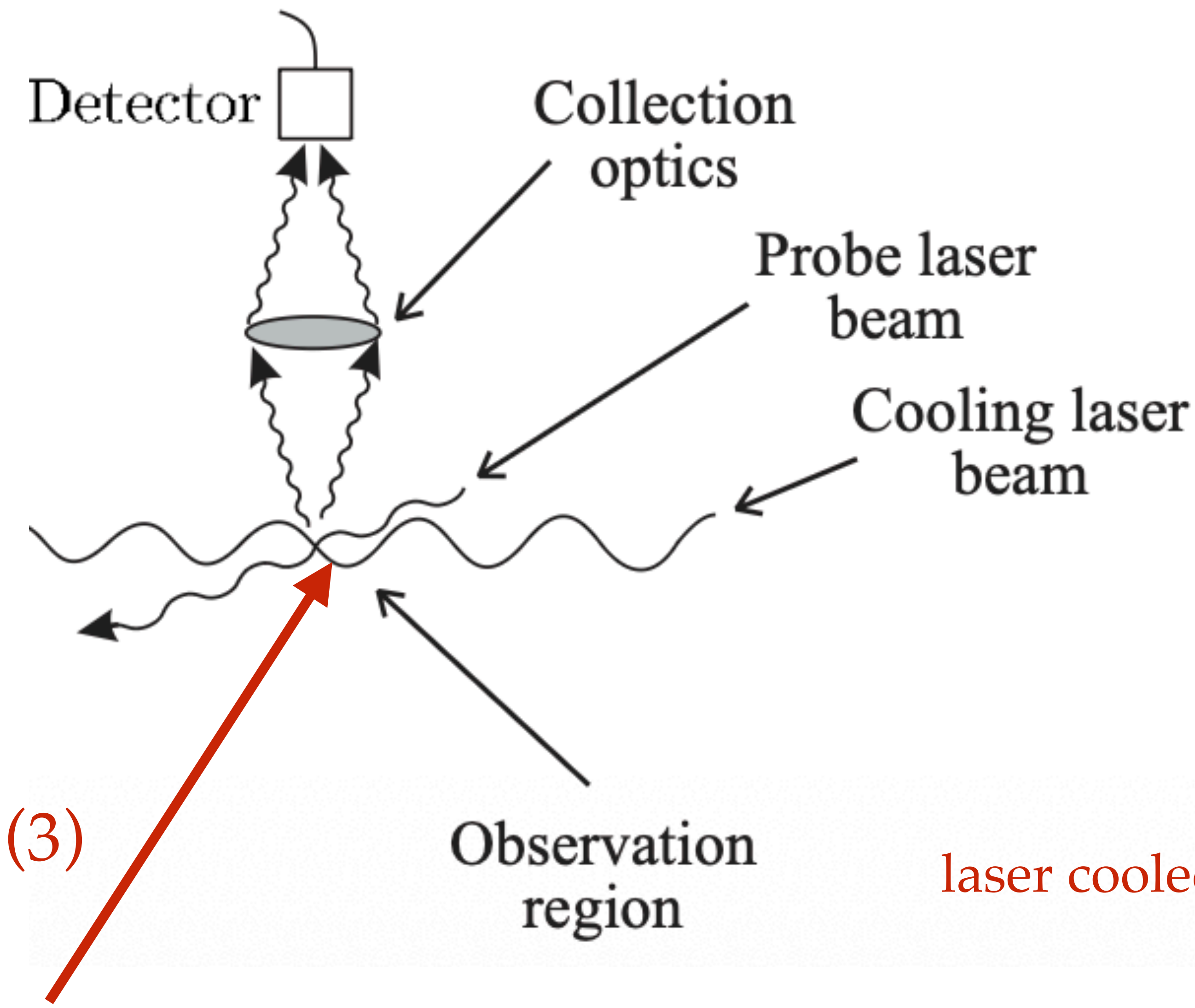
Pump-probe experiments
also accessible

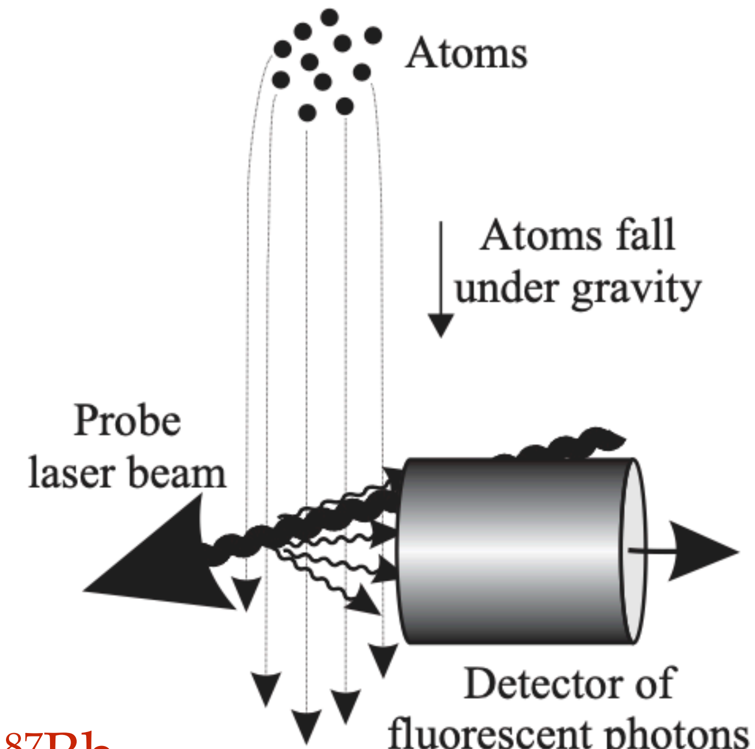
Atomic Physics, Foot

Ultracold Atoms

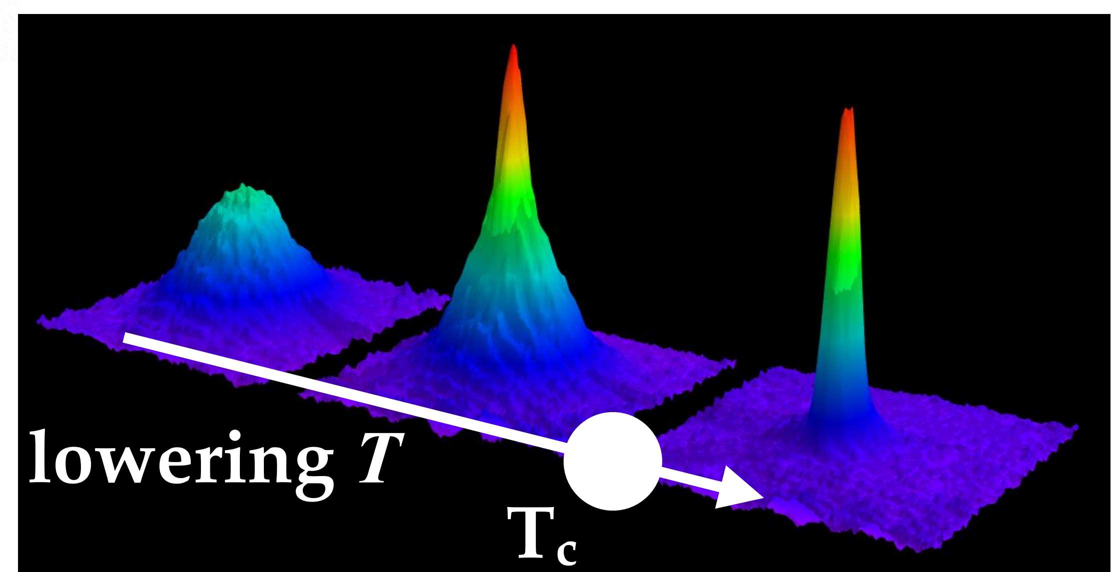
Now to make measurements

Time of flight imaging





laser cooled gas of ^{87}Rb



Davis et al., PRL (1995)

Pump-probe experiments also accessible

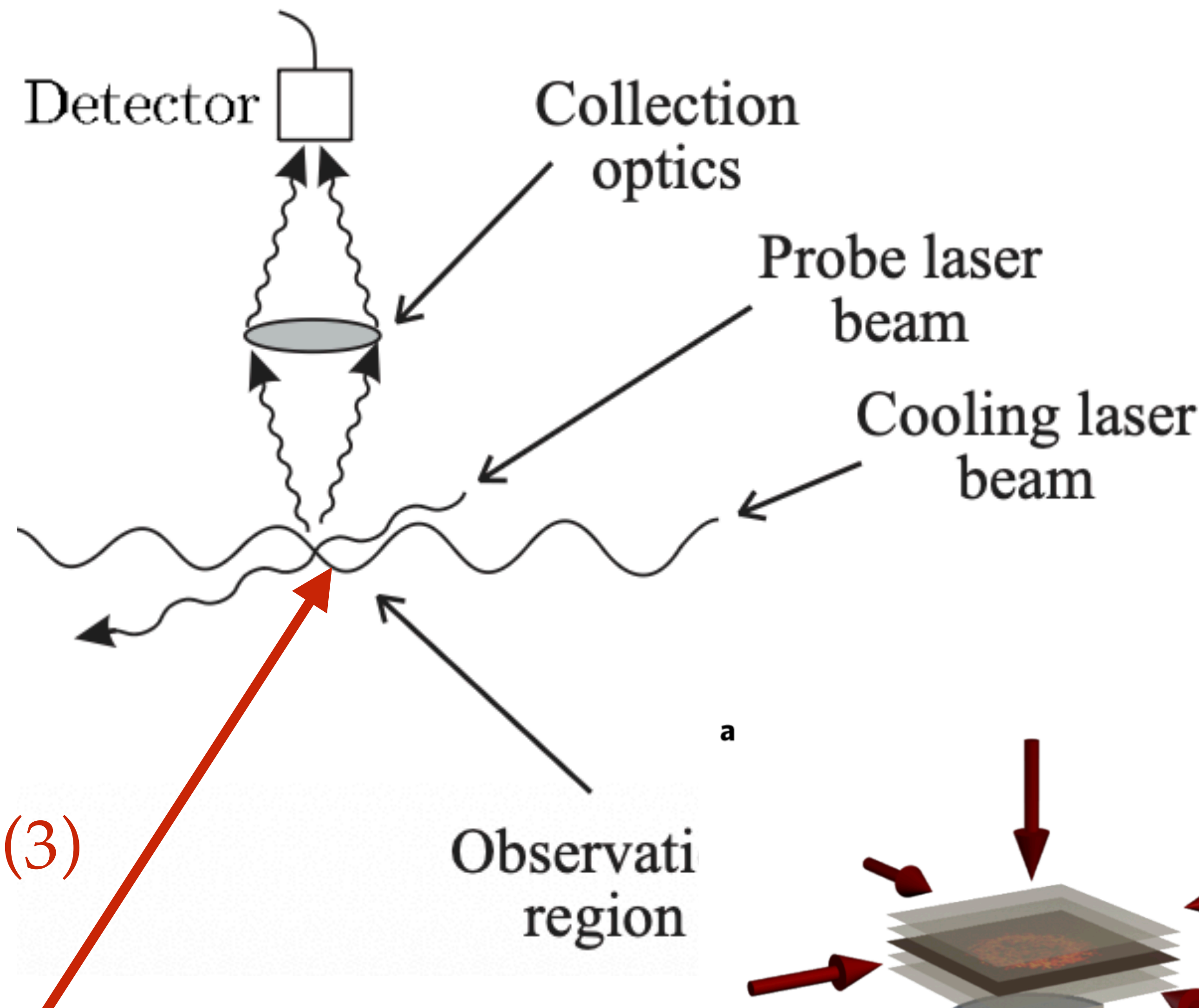
Atomic Physics, Foot

Ultracold Atoms

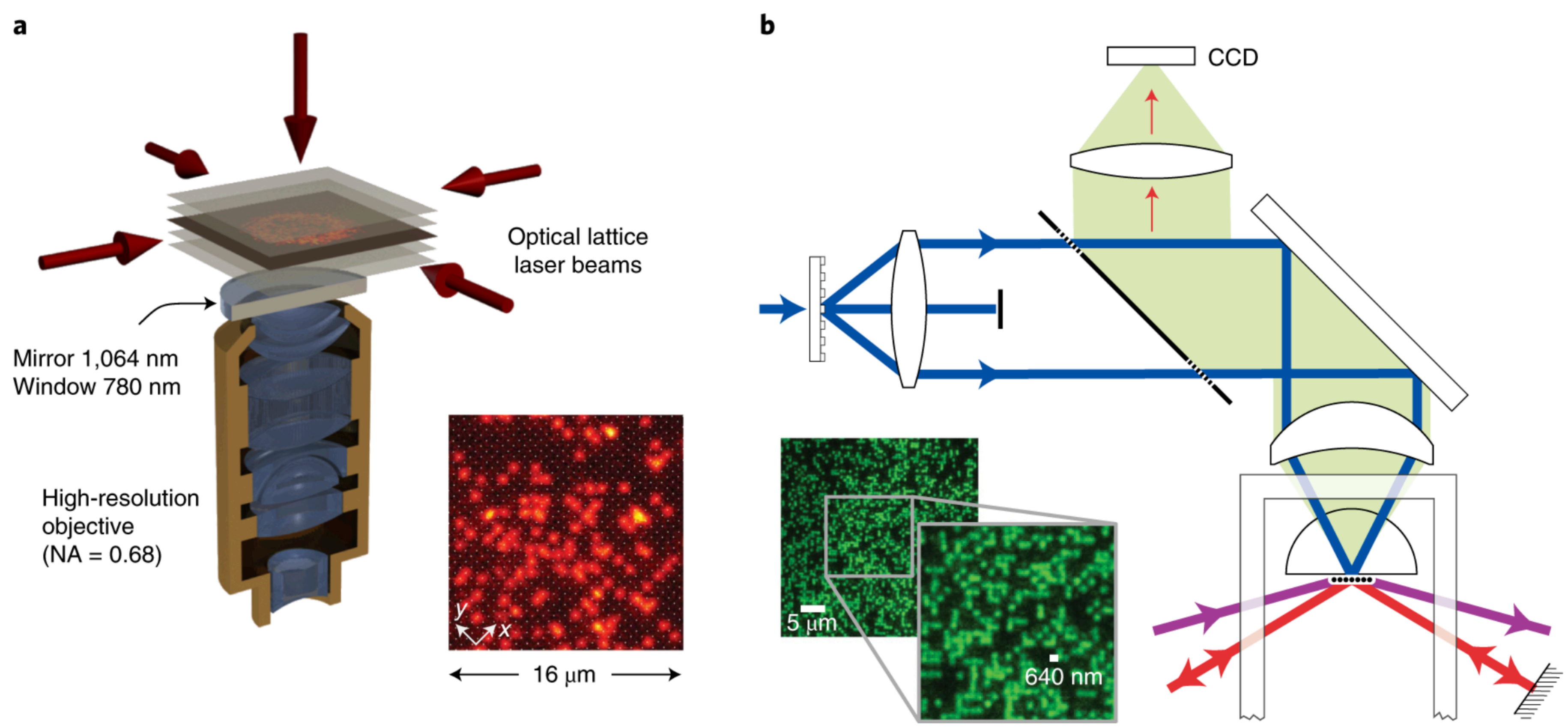
Now to make measurements

Quantum Gas Microscope:
Single site imaging

Gross and Bakr, Nature Physics (2021)



Atomic Physics, Foot



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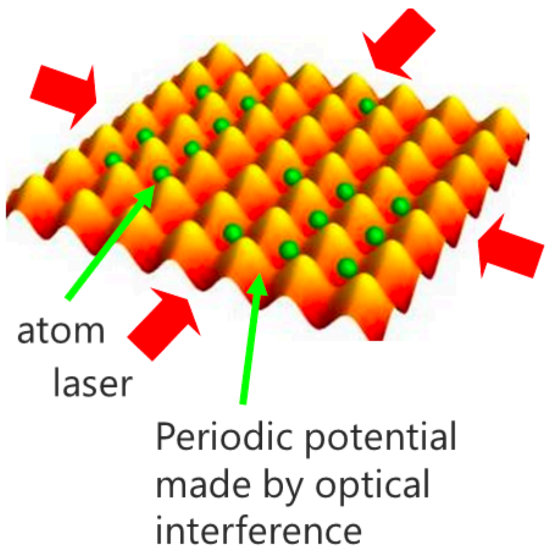
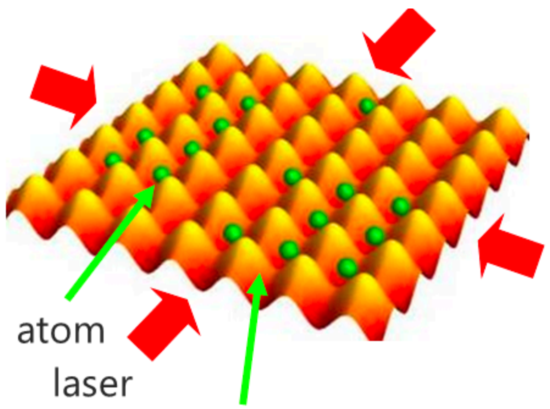


Is well suited for probing the dynamics of quantum many body systems, **analog quantum simulator**

Can watch simple initial states relax and interfere

control inter particle interactions via the Feshbach resonance

Ultracold Atoms



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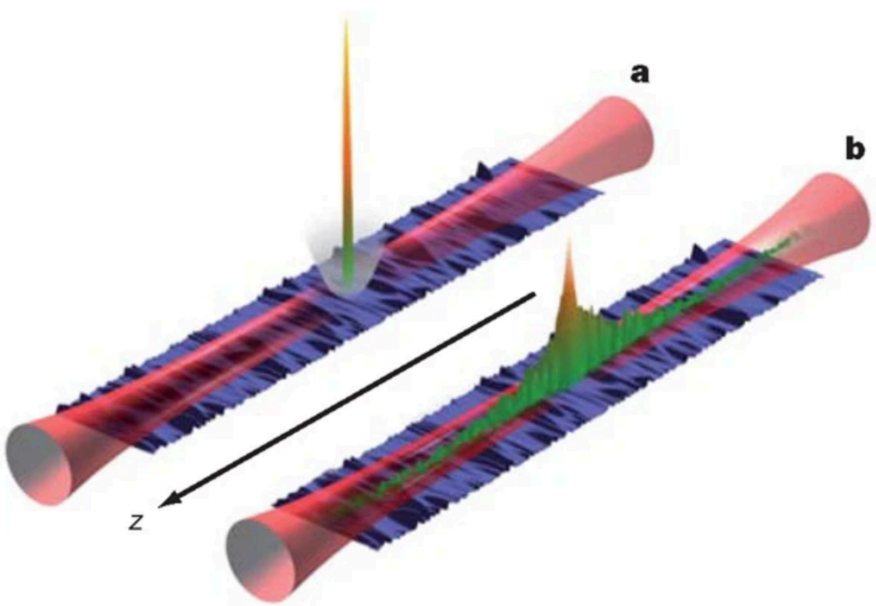
Direct observation of
Anderson localization

Billy et al, Nature (2008)



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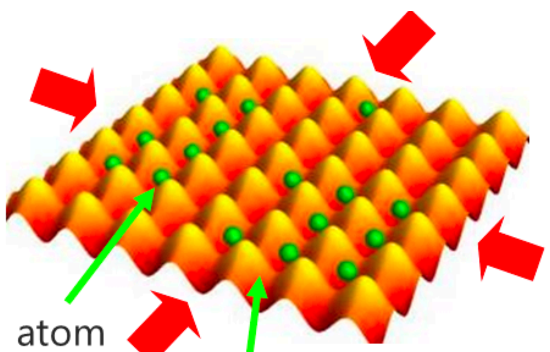

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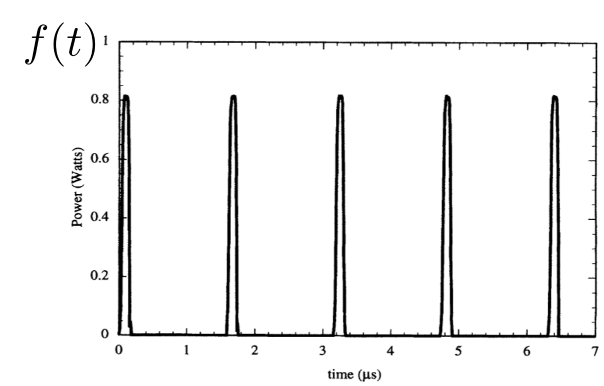
Ideal for Floquet dynamics as optical pulses can be applied periodically.

Lecture 1

Direct realization of the quantum kicked rotor: $U_{KR} = e^{-i\hat{p}^2 T/2I} e^{-ik\cos(\hat{\theta})}$

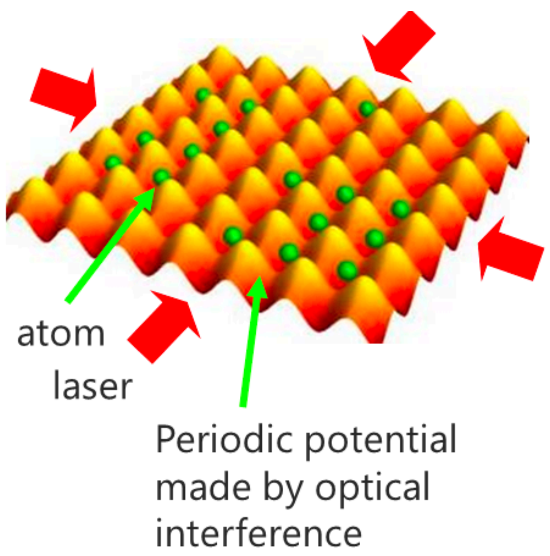
Apply a standing wave for time T, then switch it off $\mathbf{E} = 2E_0 \cos(kz) f(t)$

Apply free particle evolution for time T $p^2/2m$



Moore et al, Raizen, PRL (1995)

Ultracold Atoms



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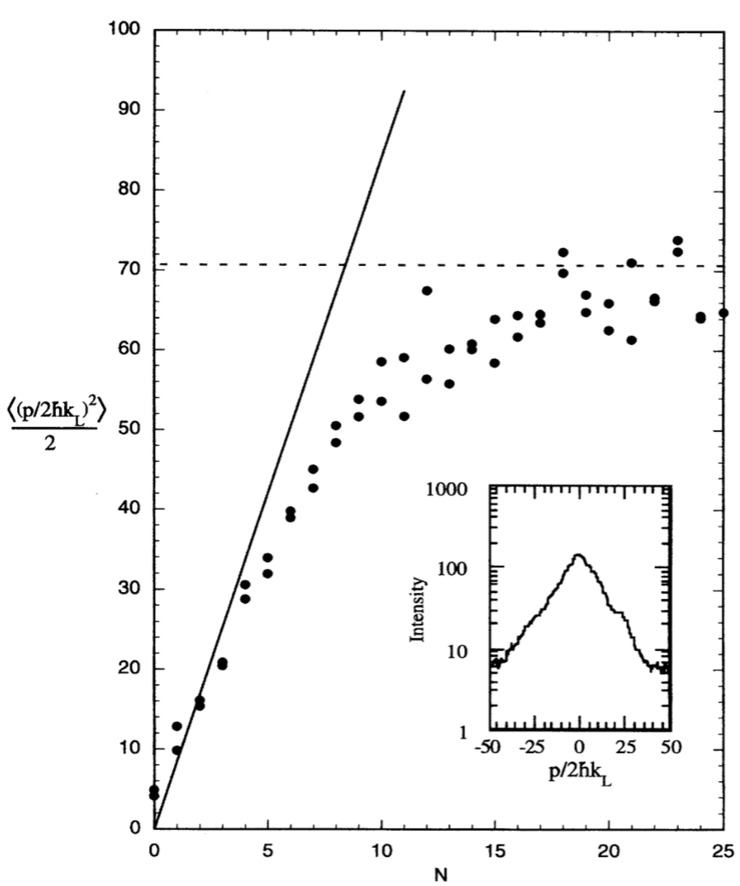

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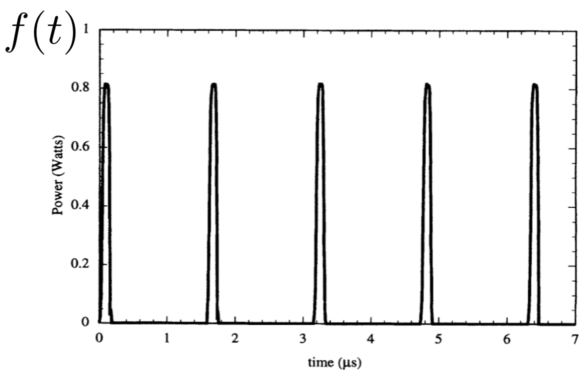
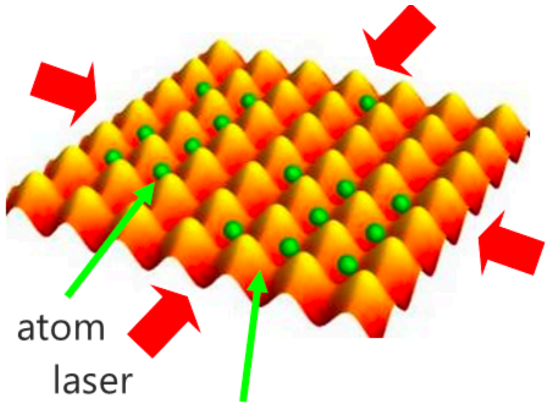


Gas of ultra cold Na atoms

observation of dynamical localization!

Moore et al, Raizen, PRL (1995)

Ultracold Atoms



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Trapping a single ^{133}Cs atom in the *F*=3 hyperfine state (has a large magnetic dipole moment)

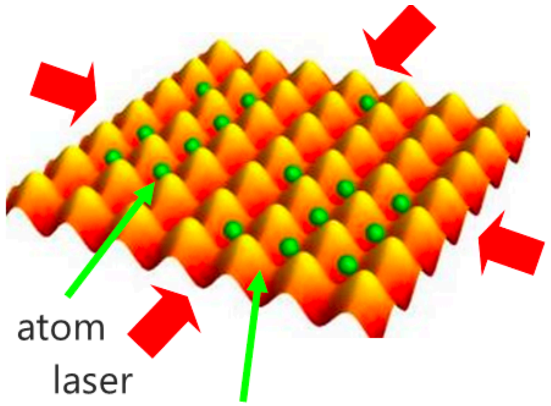
Then this atom has a magnetic moment $\mathbf{J} \to \mathbf{F}$

First apply a short magnetic field pulse to rotate F about the y-axis by α/T

Now we have to rotate **F** about the z-axis by an amount $kJ_z/(2S)$, this can be achieve via the AC stark shift

Chaudhury, et al, Nature (2009)

Ultracold Atoms



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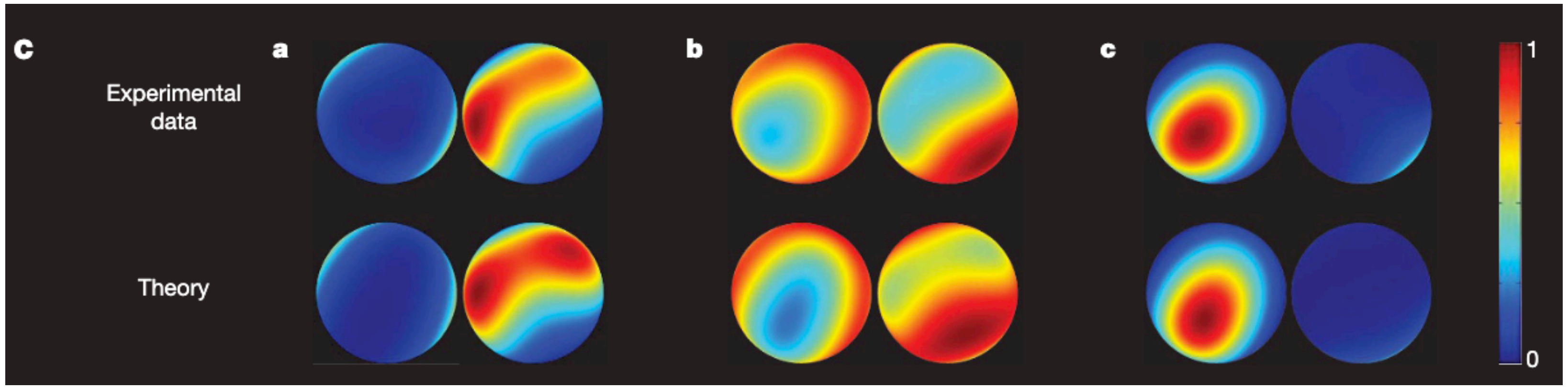
Hussimi distributions

$$Q(\theta,\phi) = (2F+1)\langle\theta,\phi|\rho|\theta,\phi\rangle/4\pi$$



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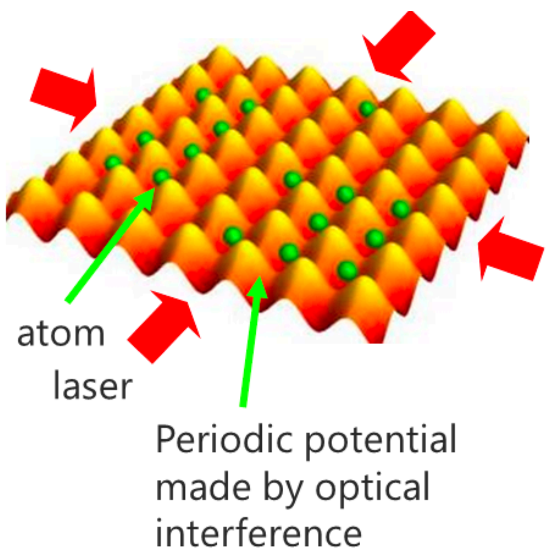

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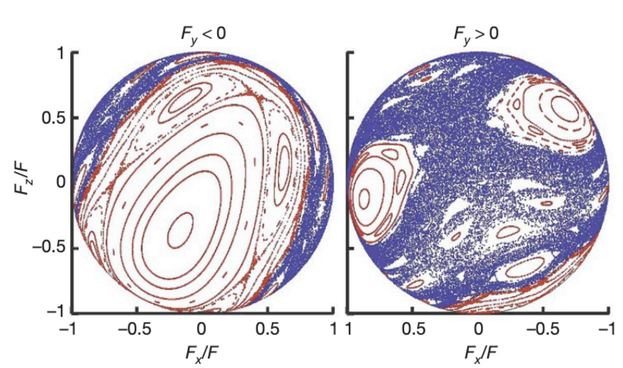
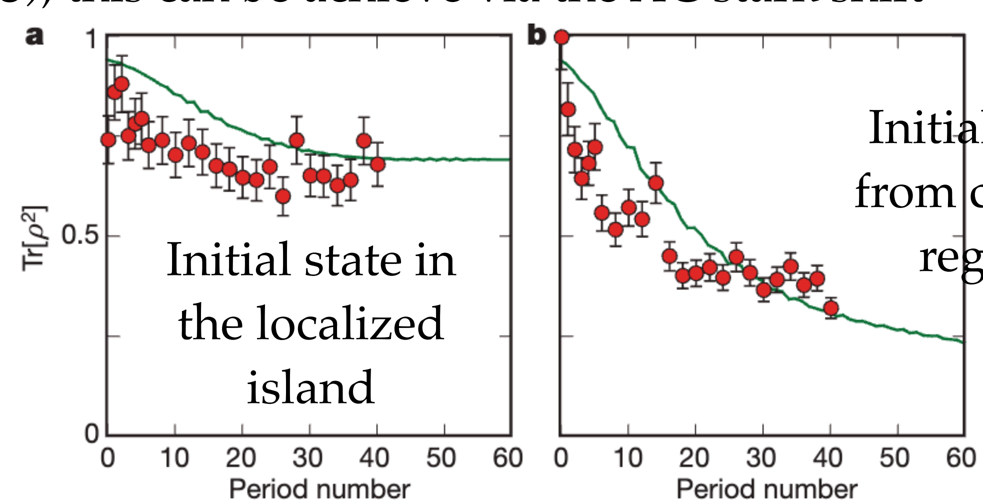
Then this atom has a magnetic moment $\mathbf{J} \rightarrow \mathbf{F}$

First apply a short magnetic field pulse to rotate F about the y-axis by α/T

Now we have to rotate **F** about the z-axis by an amount $kJ_z/(2S)$, this can be achieve via the AC stark shift

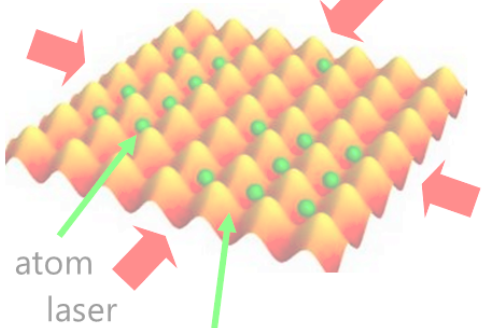




Chaudhury, et al, Nature (2009)

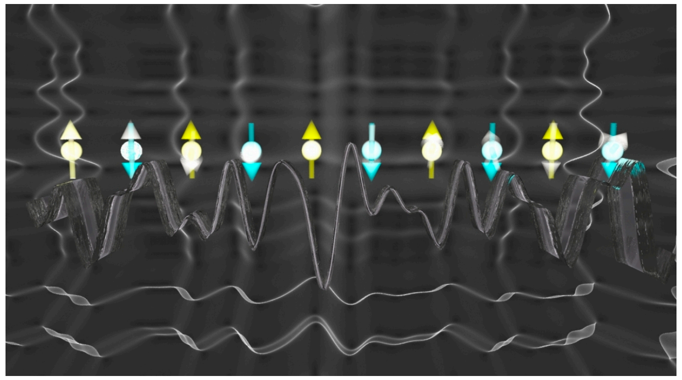
Trapped Ions

Cold atomic gases



M. Kozuma group

Trapped ions

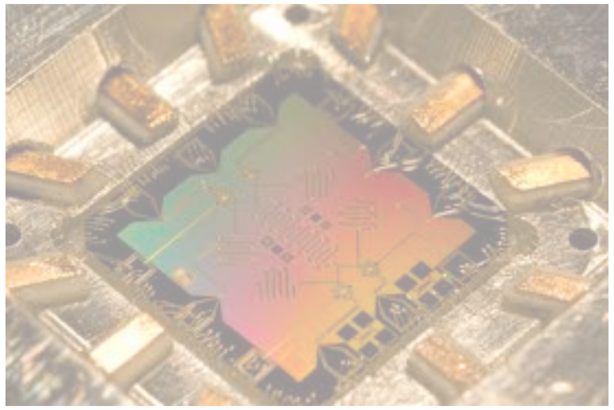


C. Monroe group

Neutral atoms

M. Endres group

Superconducting qubits



J. Martinis group

We will now consider each of these platforms in turn

Trapped Ions

Charged particles experience much larger forces then neutral atoms

Magnetic forces on neutrals

$$\mathrm{d}B/\mathrm{d}z = 10\,\mathrm{T\,m^{-1}} \qquad F_{\mathrm{neutral}} = \boldsymbol{\mu}_{\mathrm{B}} \left| \frac{\mathrm{d}B}{\mathrm{d}z} \right| \simeq 10^{-22}\,\mathrm{N}$$

Electric forces on ions

$$e = 1.6 \times 10^{-19}\,\mathrm{C} \qquad E = 10^5\,\mathrm{V\,m^{-1}} \qquad F_{\mathrm{ion}} = eE \approx 10^{-14}\,\mathrm{N}$$

Forces on ions are 10^8 greater then on neutrals!

Atomic Physics, Foot

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Forces on ions are 10^8 greater then on neutrals!

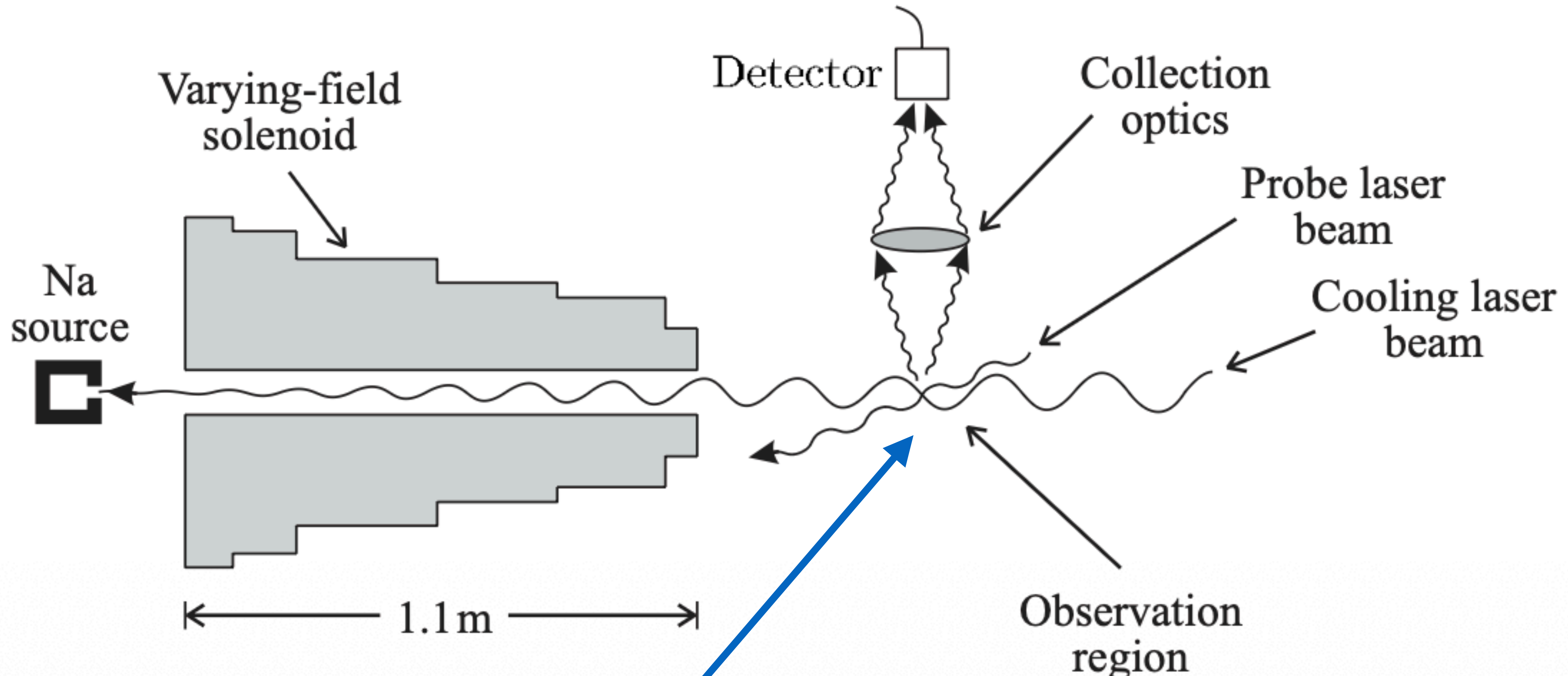
The traps are also a lot deeper for ions for $V_0 = 500\,\mathrm{V}$ $T_{\mathrm{depth}} \sim 10^{6}\mathrm{K}$

Compared with neutrals $T_{\mathrm{depth}} \sim 0.07\mathrm{K}$

This is important to trap ions as they are created by ionizing neutral atoms

Atomic Physics, Foot

Trapped Ions



(1) We now add an electron beam to ionize the atoms, by knocking off the outer electron on some fraction of the atoms

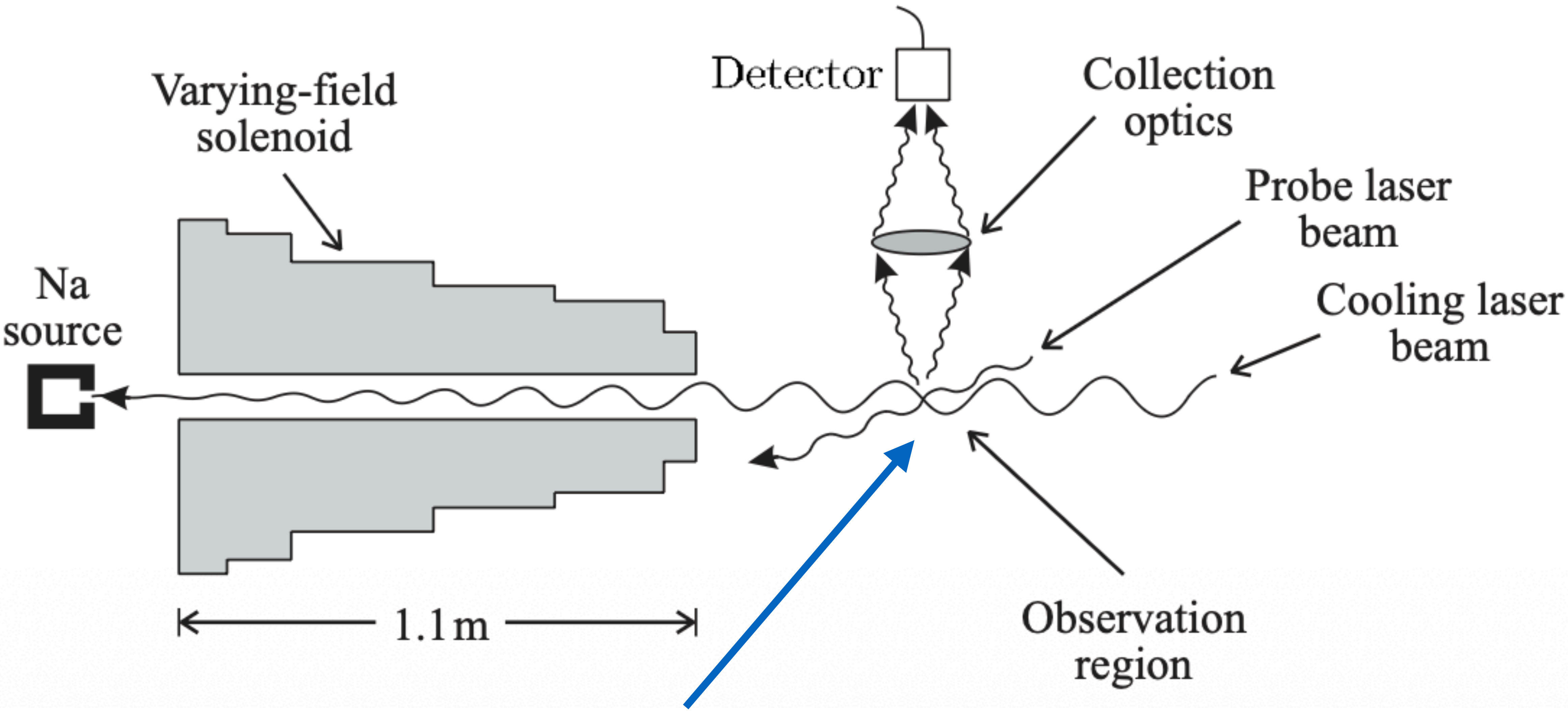
Ions that can be easily trapped have one valence electron outside a closed shell, these include

Yb^+, Ca^+, Sr^+, Ba^+, Be^+, Mg^+, Al^+, Hg^+, In^+

This makes the cooling process easier

Atomic Physics, Foot

Trapped Ions



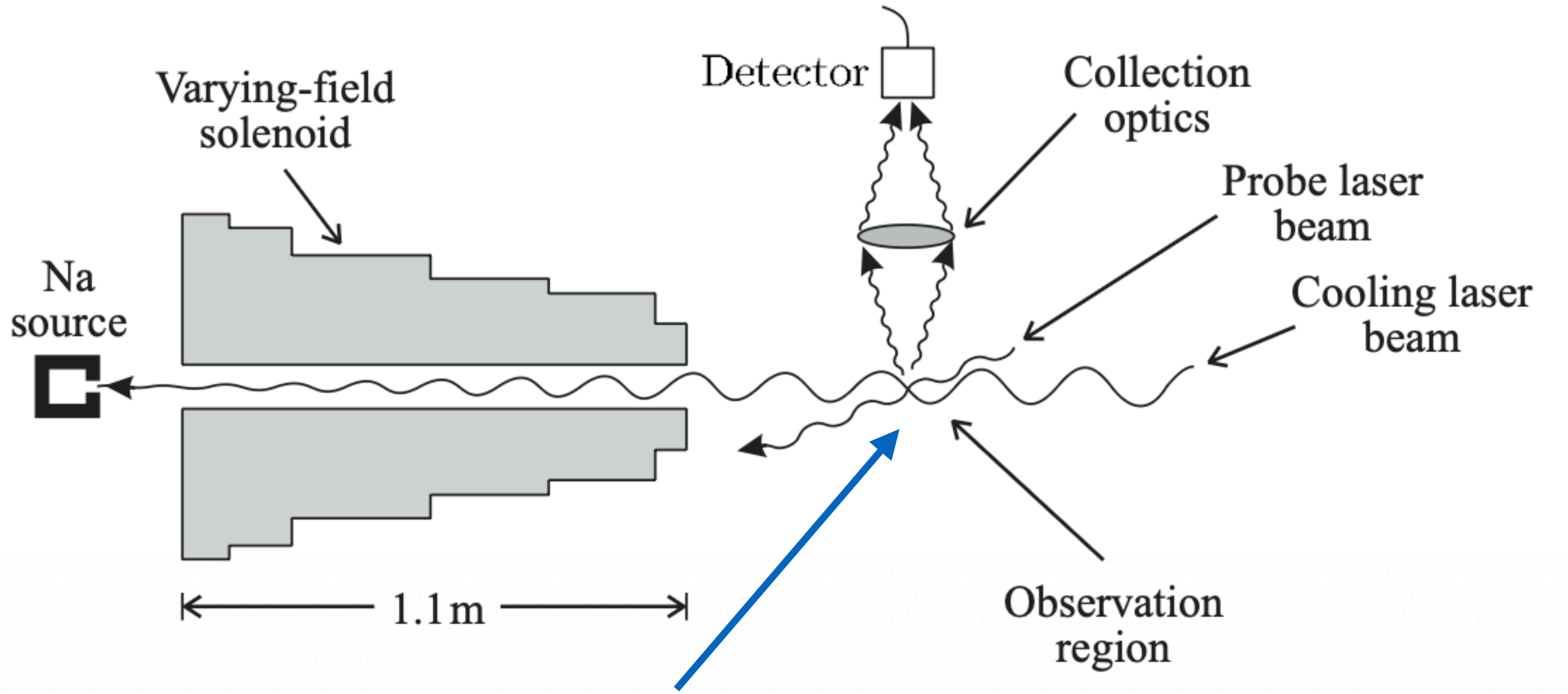
(1) We now add an electron beam to ionize the atoms, by knocking off the outer electron on some fraction of the atoms

(2) The ions now have a large recoil energy due to the ionization process. This gives them much larger kinetic energy then thermal motion.

$T_{\text{depth}} \sim 10^6\text{K}$ The deep trap is sufficient to capture these ions

Atomic Physics, Foot

Trapped Ions



(3) We now want to cool the ions

Buffer gas cooling: small density of background helium gas can scatter and cool the hottest atoms

Then Doppler cooled to $k_B T_D = \frac{\hbar\Gamma}{2}$

Ions that can be easily trapped have one valence electron outside a closed shell, these include

Yb^+, Ca^+, Sr^+, Ba^+, Be^+, Mg^+, Al^+, Hg^+, In^+

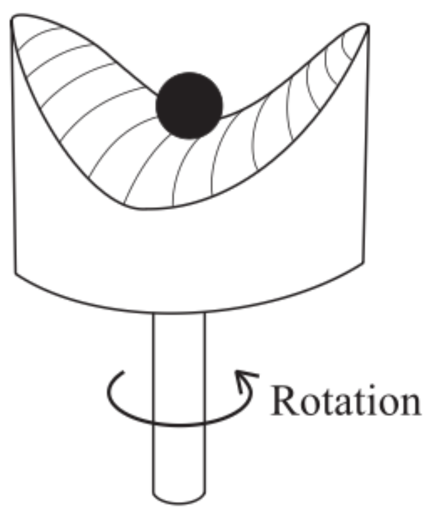
Atomic Physics, Foot

Trapped Ions

Need to trap them in electric field, but we cannot do this with electrostatics

Earnshaw's theorem: A charged particle acted on by electrostatic force cannot come to rest at a stable equilibrium.

First consider a mechanical analog



A ball of mass m sitting on a rotating saddle

$$V = \frac{V_0}{2}\left[(r\cos(\Omega t))^2 - (r\sin(\Omega t))^2\right]$$

Atomic Physics, Foot

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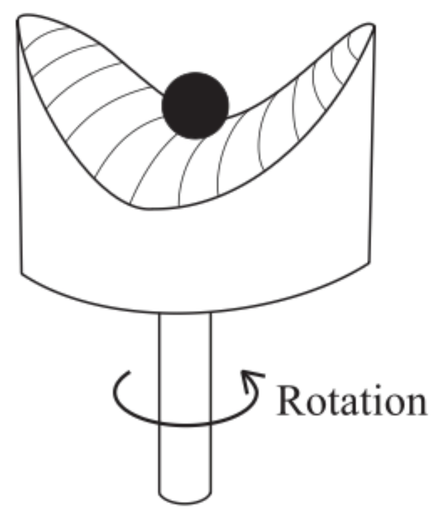

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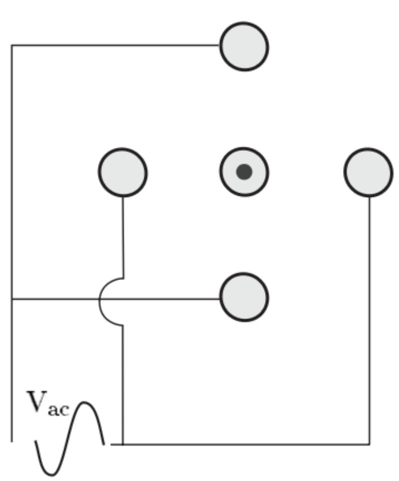
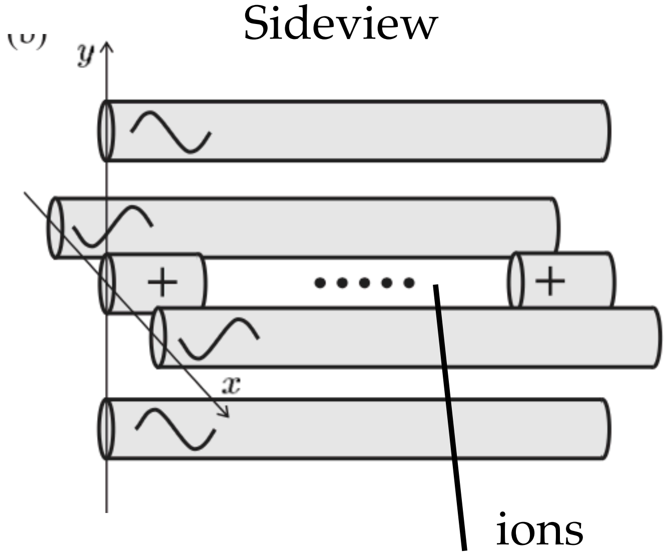
The Paul trap

Birds Eye view



Sideview



$$\mathbf{E}(x,y,t) = -\nabla\phi(x,y,t)$$

$$= -\frac{V_0}{r_0^2}\cos(\Omega t)\,(x\hat{\mathbf{e}}_x - y\hat{\mathbf{e}}_y)$$

$$\phi = \phi_0 + \frac{V_0}{2r_0^2}\cos(\Omega t)\,(x^2 - y^2)$$

Atomic Physics, Foot

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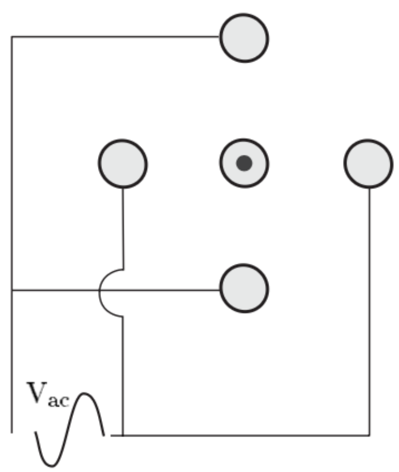

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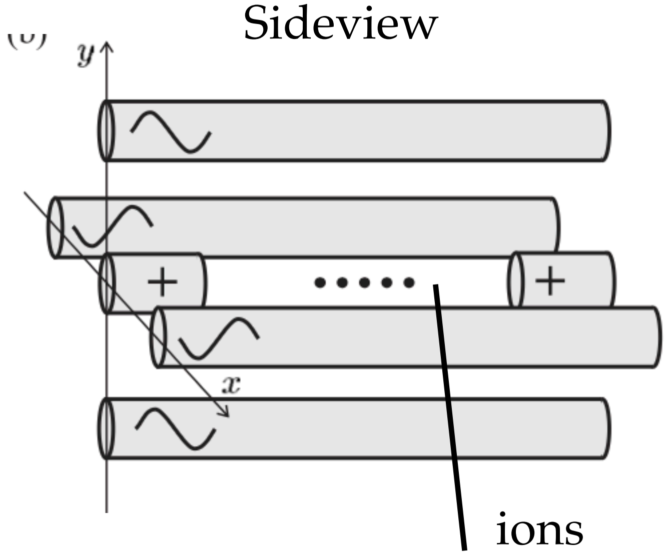

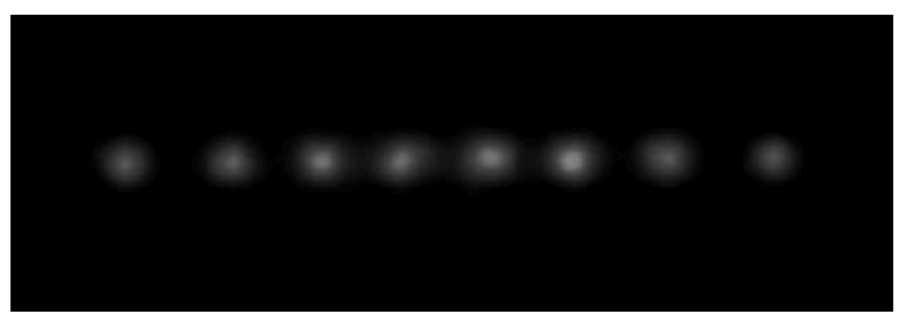

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Atomic Physics, Foot

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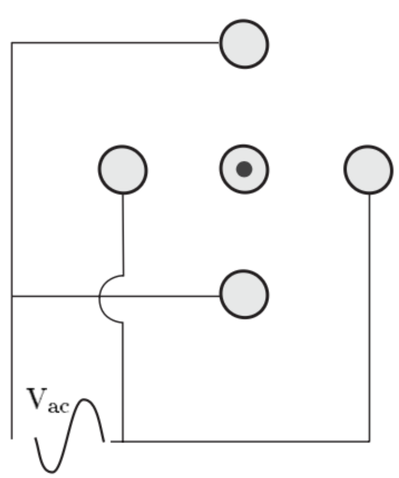

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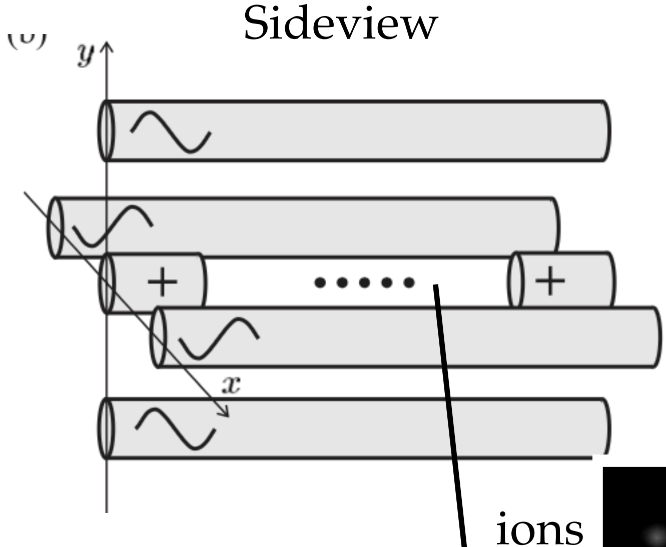

ions

$$\mathbf{E}(x,y,t) = -\nabla\phi(x,y,t)$$

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Equation of motion $$M\frac{\mathrm{d}^2x}{\mathrm{d}t^2} = -\frac{eV_0}{r_0^2}\cos(\Omega t)\,x \qquad \tau = \Omega t/2$$

$$x = x_0\cos\left(\frac{q_x\tau}{\sqrt{2}} + \theta_0\right)\left\{1 + \frac{q_x}{2}\cos 2\tau\right\} \qquad q_x = \frac{2eV_0}{\Omega^2 M r_0^2}$$

The ions remain trapped if $q_x \leqslant 0.9$

$$\omega_x = \frac{q_x\Omega}{2\sqrt{2}} = \frac{eV_0}{\sqrt{2}\Omega M r_0^2}$$

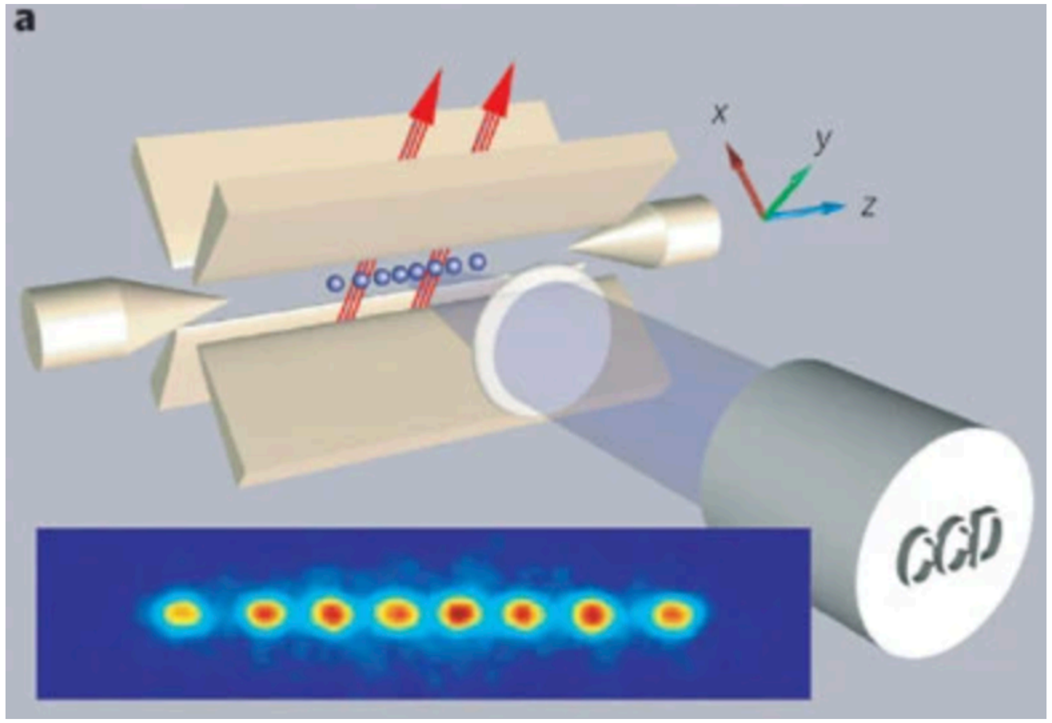
Slower oscillations

Fast oscillation, micromotion

Atomic Physics, Foot

Trapped Ions

During the cooling process the ions
emit photons that for some ions
can be seen with naked eye to (e.g. Ba^{+})



Blatt and Wineland, Nature Physics (2008)

This gives rise to a chain of trapped ions that are stable for quite a long time, e.g. for several days is quite common.

Atomic Physics, Foot

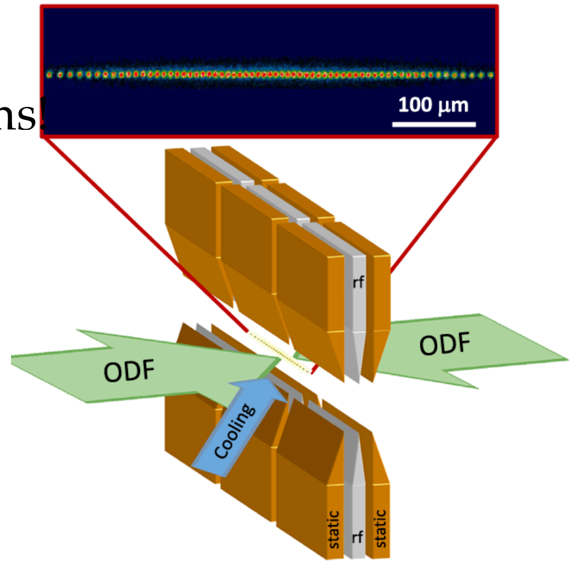
Trapped Ions

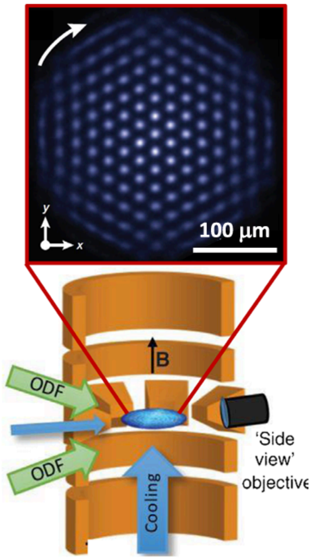
Trapped ion experiments can probe many body physics that results from the interactions between the ions.

Schneider, Porras, Schaetz, IOP (2012)   Monroe et al, Rev. Mod Phys (2021)

1D and 2D traps are possible

60 atoms





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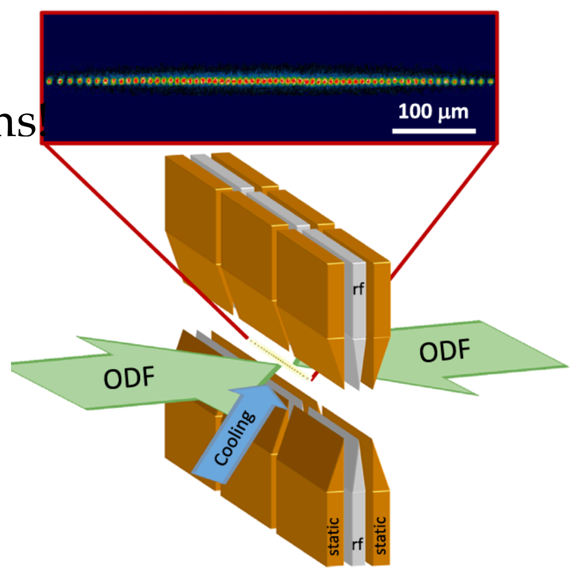
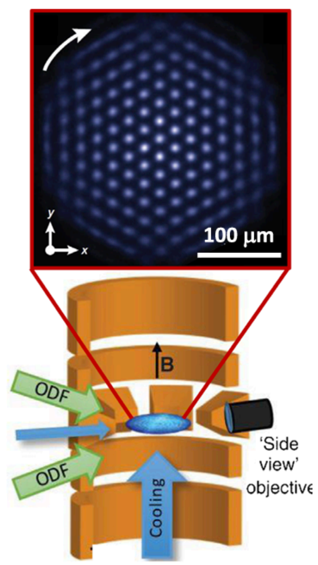
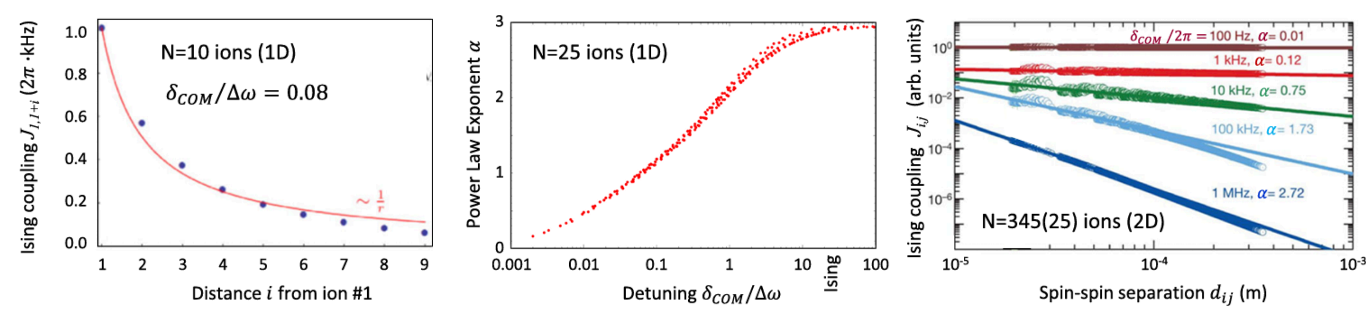




Accessible many-body Hamiltonians

$$H_{J_\theta} = \sum_{i<j} J_{ij}\sigma^i_{\theta_i}\sigma^j_{\theta_j}, \qquad J_{ij} = \frac{J_0}{|i-j|^\alpha}$$



$$H_{TI} = \sum_{i<j} J_{ij}\sigma^i_x\sigma^j_x + B_y\sum_i \sigma^i_y$$

$$H = \sum_{i<j} J_{ij}(S^i_xS^j_x + S^i_yS^j_y + \lambda S^i_zS^j_z) + D\sum_i (S^i_z)^2 \qquad \text{Spin-1}$$

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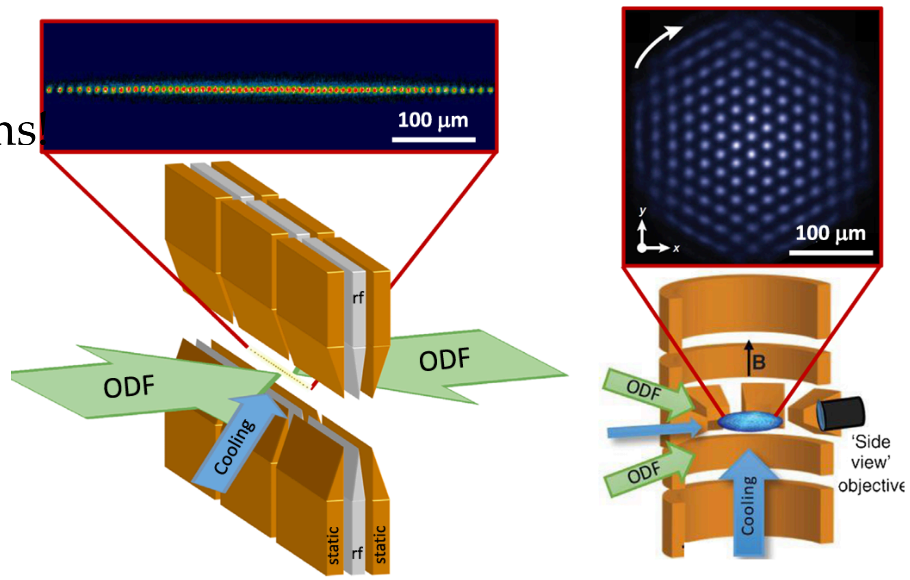

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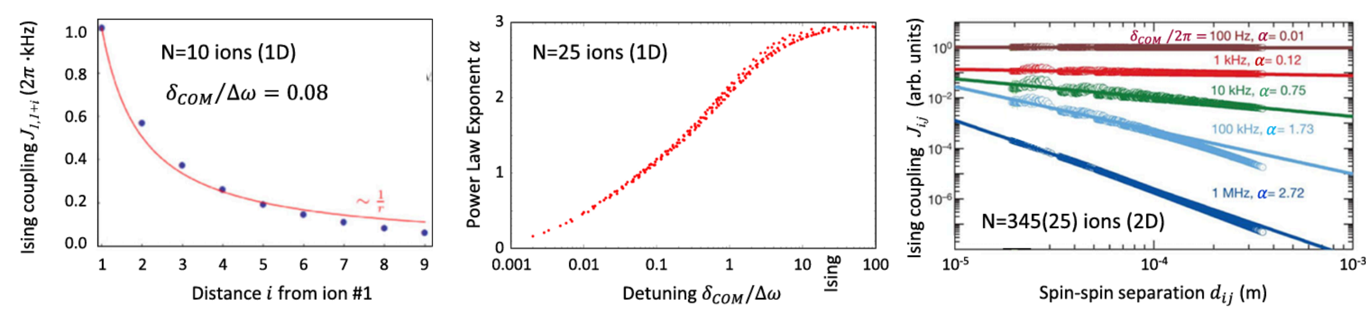
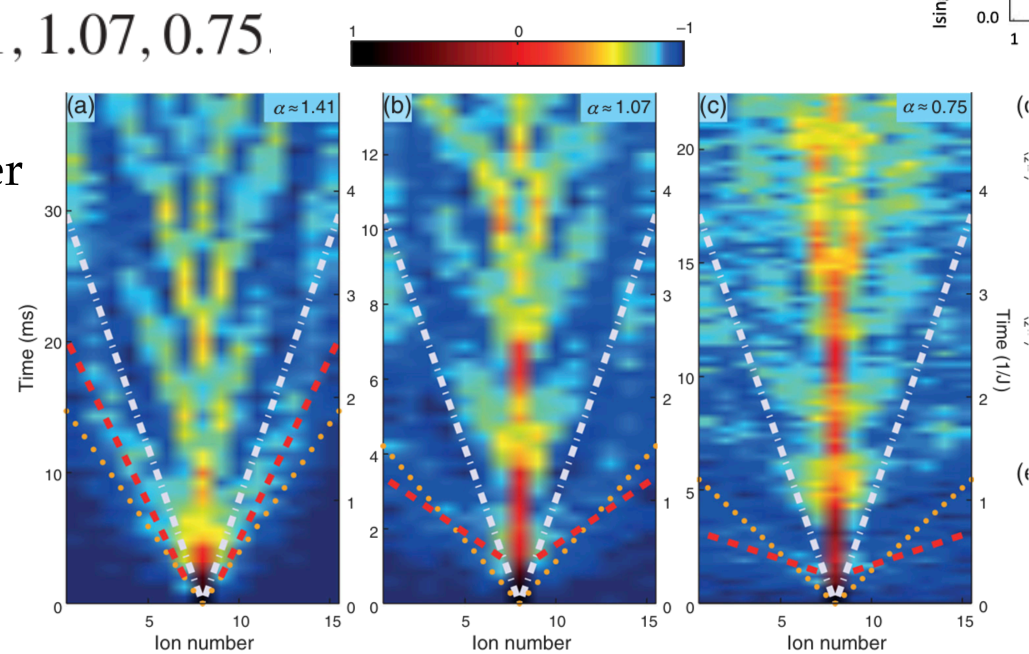


$\alpha \approx 1.41, 1.07, 0.75$

Magnetization after a local quench



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Atomic Physics, Foot

Trapped Ions

VOLUME 74, NUMBER 20 PHYSICAL REVIEW LETTERS 15 MAY 1995

Quantum Computations with Cold Trapped Ions

J. I. Cirac and P. Zoller*
Institut für Theoretische Physik, Universiät Innsbruck, Technikerstrasse 25, A-6020 Innsbruck, Austria
(Received 30 November 1994)

A quantum computer can be implemented with cold ions confined in a linear trap and interacting with laser beams. Quantum gates involving any pair, triplet, or subset of ions can be realized by coupling the ions through the collective quantized motion. In this system decoherence is negligible, and the measurement (readout of the quantum register) can be carried out with a high efficiency.

Universal quantum computation is accessible with trapped ions

Optical pulses are used to make one and two qubit gates by directly coupling the ions together through forces that depends on the spin state of the ions

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One qubit gates

$$R^C(\theta,\phi) = \exp\left(i\theta/2\left(e^{i\varphi}\sigma_+ + e^{-i\varphi}\sigma_-\right)\right)$$
$$= \begin{pmatrix} \cos\theta/2 & ie^{i\varphi}\sin\theta/2 \\ ie^{-i\varphi}\sin\theta/2 & \cos\theta/2 \end{pmatrix},$$

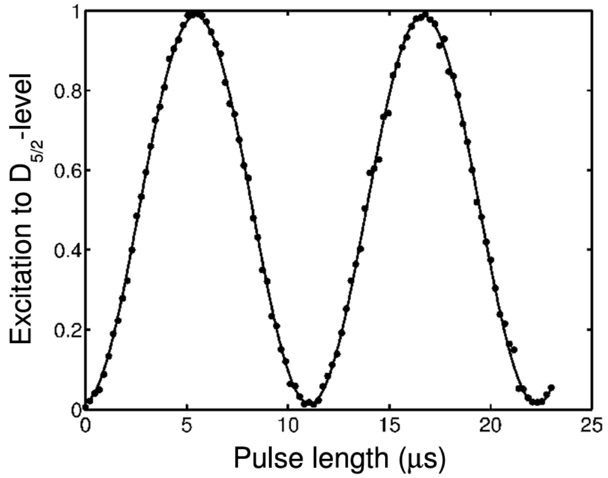

Fig. 6. Rabi oscillations of a single Ca^+ ion. Each dot represents 1000 experiments, each consisting of initialization, application of laser light on the qubit transition and state detection.

Hafner, Roos, Blatt IOP (2008)

mic Physics, Foot

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Two qubit gates

Mølmer–Sørensen (MS) gates

$$XX(\theta) = e^{-i\theta(\sigma_{xi} \otimes \sigma_{xj})/2}$$

$$YY(\theta) = e^{-i\theta(\sigma_{yi} \otimes \sigma_{yj})/2}$$

$$ZZ(\theta) = e^{-i\theta(\sigma_{zi} \otimes \sigma_{zj})/2}$$

Hafner, Roos, Blatt IOP (2008)

Atomic Physics, Foot

Trapped Ions

Quantum computation with trapped ions (summary)

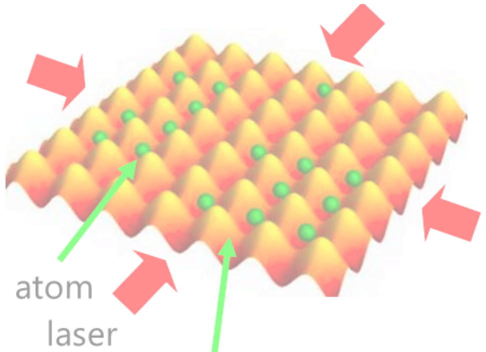
	Single qubit gates	Two qubit gates	Measurement \reset
Gate speeds	$1 - 20\mu s$	$10 - 200\mu s$	$100\mu s - 2ms$
Fidelity (typical)	99.96–99.997%	97.7–99.9%	99.5–99.8%

		Time to decay from excited state	dephasing time
Coherence times	IonQ	$T_1 \sim 10 - 100s$	$T_2 \sim 1s$
	Quantinuum	$T_1 > 1\text{min}$	$T_2 \sim 4s$

Atomic Physics, Foot

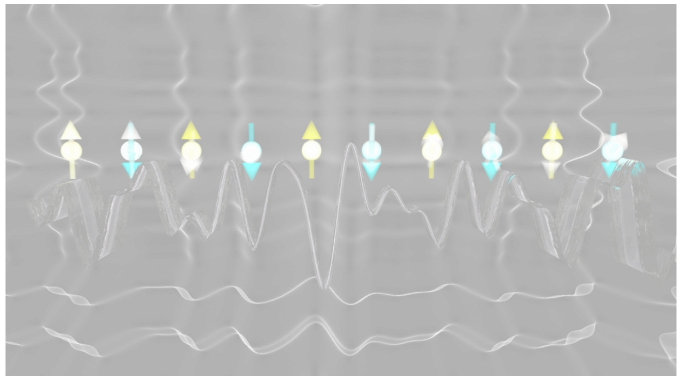
Neutral Atoms

Cold atomic gases



M. Kozuma group

Trapped ions



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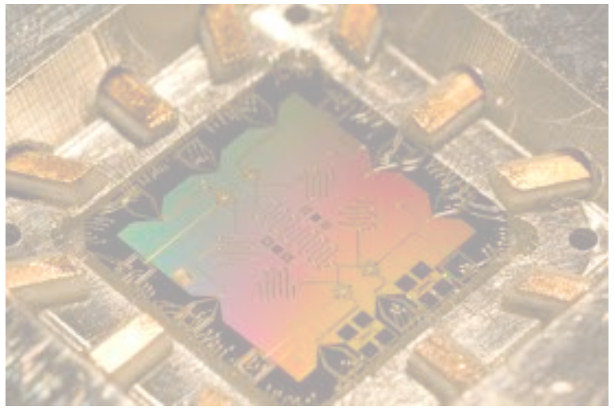

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Neutral Atoms

Starting from a gas of ultra cold atoms, the application of laser tuned close to a Rydberg level will dress the states.

Rydberg atoms: Hydrogen wave functions with large principal quantum number *n*

Rydberg atoms, Gallagher

n~30-150

Atomic radius $r_n \sim a_0 n^2$ e.g. $n = 30,\ r \sim 50nm$

$n = 137,\ r \sim 1\mu m$ Micron sized atoms!

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Creates a massive dipole moment in an electric field due to the large r

Two nearby Rydberg atoms interact strongly through the van der Walls electric dipole-dipole interaction

$$V(|\mathbf{r}_i - \mathbf{r}_j|) = \frac{C_6(n)}{|\mathbf{r}_i - \mathbf{r}_j|^6}$$

$C_6 \sim n^{11}$ Large interaction

Neutral Atoms

Starting from a gas of ultra cold atoms placed in a 1D optical lattice, the application of laser tuned close to a Rydberg level will dress the states.

Applying a laser with Rabi frequency Ω, couples the atoms ground state $|g\rangle \equiv |\downarrow\rangle$ to a chosen low lying Rydberg level $|r\rangle \equiv |\uparrow\rangle$

Weimer and Buchler, PRL (2010)   Lukin et al, PRL 2001   Lesanovsky and Katsura, PRB(R) (2012)

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Yields the Hamiltonian (after applying a rotating wave approximation)

$$H = \Omega \sum_{k=1}^{N-1} \sigma_k^x + \Delta \sum_{k=1}^{N-1} n_k + \sum_{k=1, m\neq k}^{N-1} V_{|k-m|} n_k n_m$$

$$\sigma_k^x = (|\uparrow_k\rangle\langle\downarrow_k| + |\downarrow_k\rangle\langle\uparrow_k|)$$

$$\sigma_k^z = (|\uparrow_k\rangle\langle\uparrow_k| - |\downarrow_k\rangle\langle\downarrow_k|)$$

$$n_k = (1 + \sigma_k^z) = |\uparrow_k\rangle\langle\uparrow_k|$$

Lattice spacing

$$V_{|k-m|} = \frac{C_6(n)/a^6}{|k-m|^6}$$

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$$V_{|k-m|} = \frac{C_6(n)/a^6}{|k-m|^6}$$

$$\sigma_k^x = (|\uparrow_k\rangle\langle\downarrow_k| + |\downarrow_k\rangle\langle\uparrow_k|) \quad \sigma_k^z = (|\uparrow_k\rangle\langle\uparrow_k| - |\downarrow_k\rangle\langle\downarrow_k|) \quad n_k = (1+\sigma_k^z) = |\uparrow_k\rangle\langle\uparrow_k|$$

$$C_6 \sim n^{11}$$

Focus on the regime where $|V_1| \gg |\Omega|, |\Delta|$

Weimer and Buchler, PRL (2010) Lukin et al, PRL 2001 Lesanovsky and Katsura, PRB(R) (2012)

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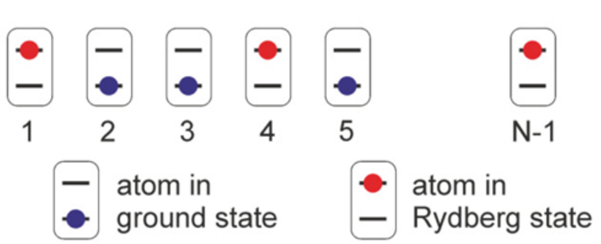
Yields the Hamiltonian (after applying a rotating wave approximation)

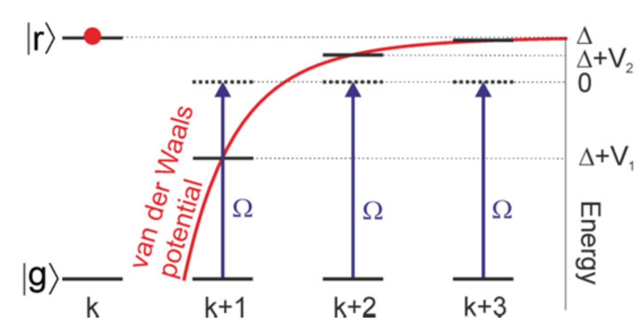
$$H = \Omega \sum_{k=1}^{N-1} \sigma_k^x + \Delta \sum_{k=1}^{N-1} n_k + \sum_{k=1, m\neq k}^{N-1} V_{|k-m|} n_k n_m \qquad V_{|k-m|} = \frac{C_6(n)/a^6}{|k-m|^6}$$

$$\sigma_k^x = (|\uparrow_k\rangle\langle\downarrow_k| + |\downarrow_k\rangle\langle\uparrow_k|) \qquad \sigma_k^z = (|\uparrow_k\rangle\langle\uparrow_k| - |\downarrow_k\rangle\langle\downarrow_k|) \qquad n_k = (1+\sigma_k^z) = |\uparrow_k\rangle\langle\uparrow_k| \qquad C_6 \sim n^{11}$$

Focus on the regime where $|V_1| \gg |\Omega|, |\Delta|$

Rydberg blockade: due to their large size and strong nearest neighbor interaction, its virtually impossible to excite two neighboring Rydberg atoms





Weimer and Buchler, PRL (2010)

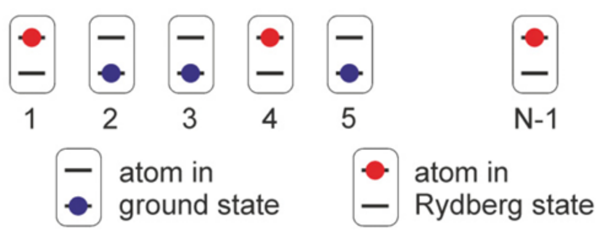
Lukin et al, PRL 2001

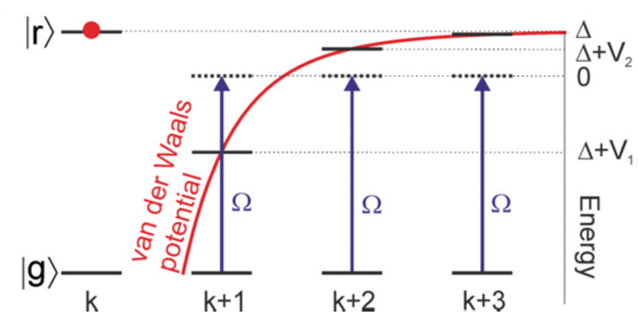
Lesanovsky and Katsura, PRB(R) (2012)

Neutral Atoms

Focus on the regime where $|V_1| \gg |\Omega|, |\Delta|$

Rydberg blockade: due to their large size and strong nearest neighbor interaction, its virtually impossible to excite two neighboring Rydberg atoms





This constrains the Hilbert space to a much smaller region $\mathcal{H}_{\text{Blockade}}$

Constraint $n_k n_{k+1} = 0$

The projector onto the ground state at site k is

$$P_k = |\downarrow_k\rangle\langle\downarrow_k| = 1 - |\uparrow_k\rangle\langle\uparrow_k|$$

And σ_k^x flips the spin at site k. Can only excite from $|\downarrow_k\rangle$ if the neighbors at $k-1$ and $k+1$ are in their ground state

Under this projection $\sigma_k^x \rightarrow P_{k-1}\sigma_k^x P_{k+1}$

Weimer and Buchler, PRL (2010) Lukin et al, PRL 2001 Lesanovsky and Katsura, PRB(R) (2012)

Neutral Atoms

Focus on the regime where $|V_1| \gg |\Omega|, |\Delta|$

Projection onto the constrained Hilbert space $\mathcal{H}_{\text{Blockade}}$

Under this projection $\sigma_k^x \to P_{k-1}\sigma_k^x P_{k+1}$

$$H = \Omega \sum_{k=1}^{N-1} \sigma_k^x + \Delta \sum_{k=1}^{N-1} n_k + \sum_{k=1, m\neq k}^{N-1} V_{|k-m|} n_k n_m$$

The Hamiltonian is projected to

$$\longrightarrow \quad H_{\text{eff}} = \Omega \sum_k P_k \sigma_{k+1}^x P_{k+2} + \Delta \sum_k n_k$$

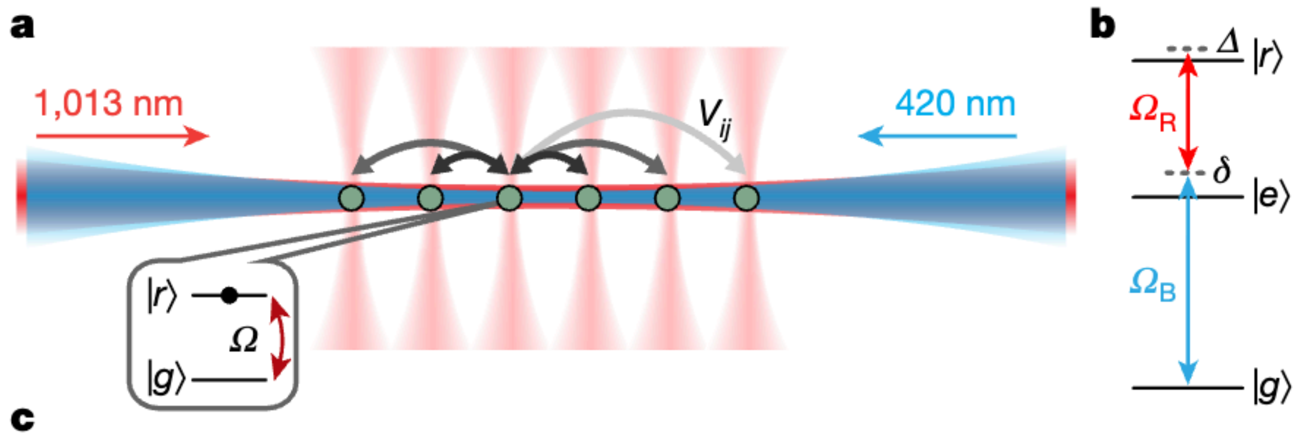
This is the PXP model, at resonance $\Delta = 0$

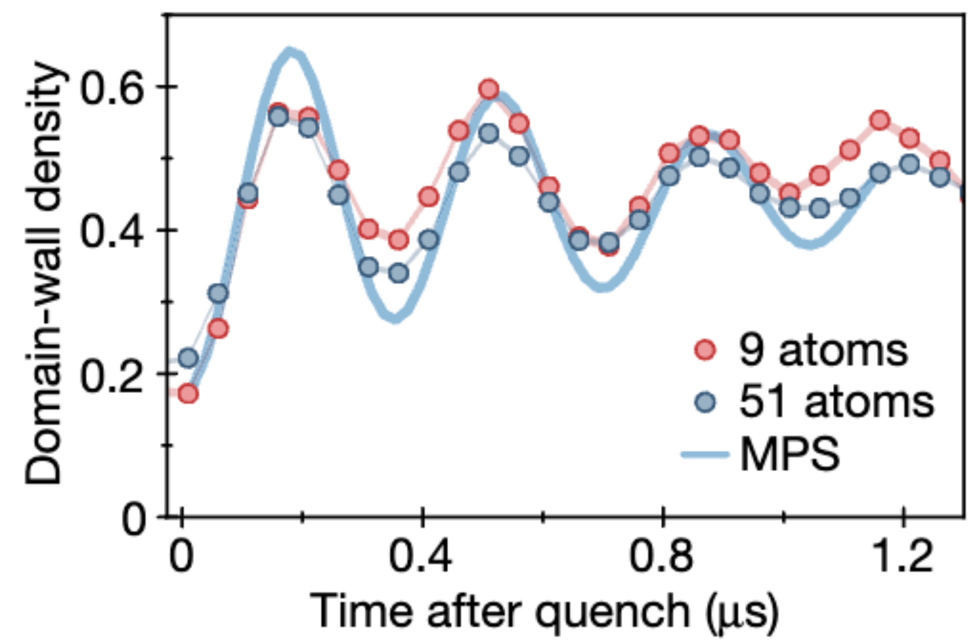
Weimer and Buchler, PRL (2010) Lukin et al, PRL 2001 Lesanovsky and Katsura, PRB(R) (2012)

Neutral Atoms

Analog Quantum Many Body Simulations

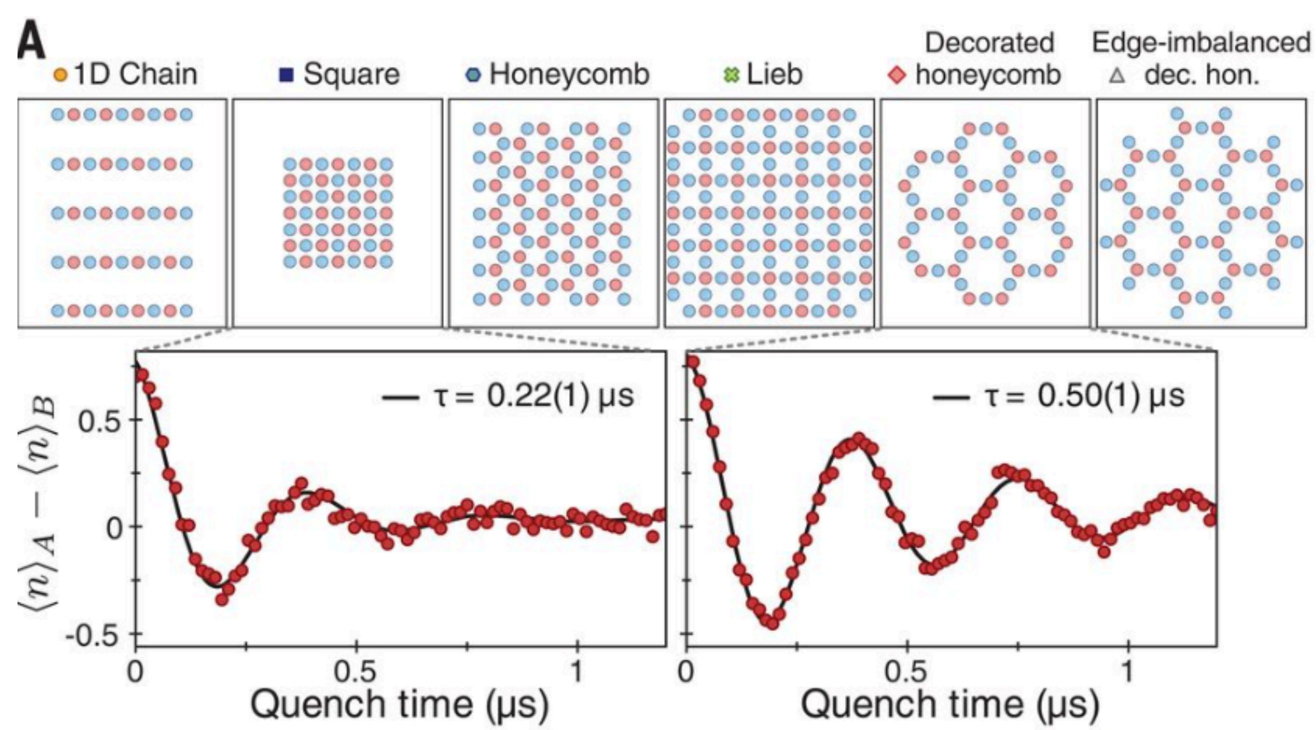
Observation of scar states in the PXP model (Lecture 1)





Bernien et al Nature (2017) Turner et al Nature Physic (2018)

Was then extended to multiple dimensions and ~200 atoms



Bluvstein et al Science (2021)

Neutral Atoms

Optical tweezer arrays: Individual atoms trapped in tunable two-dimensional arrays of optical microtraps, when coupled with the Rydberg level produce strong correlations between the atoms.

Neutral Atoms

Optical tweezer arrays: Individual atoms trapped in tunable two-dimensional arrays of optical microtraps, when coupled with the Rydberg level produce strong correlations between the atoms.

LETTER

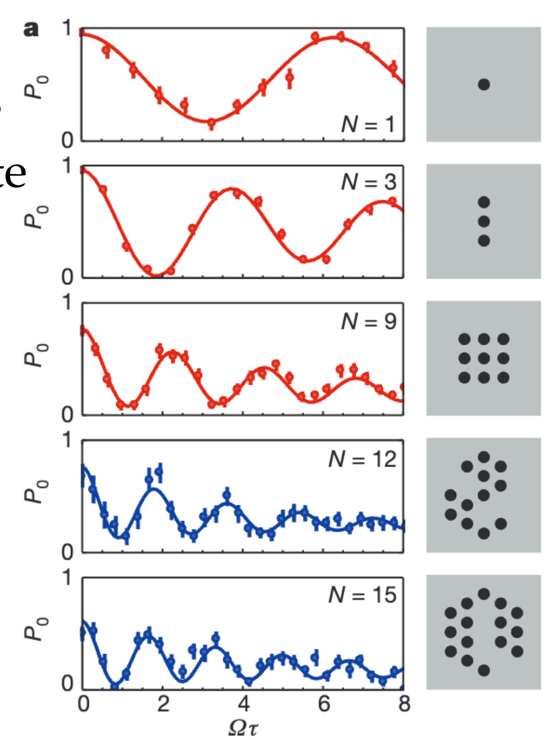
doi:10.1038/nature18274

Tunable two-dimensional arrays of single Rydberg atoms for realizing quantum Ising models

Henning Labuhn[1]*, Daniel Barredo[1]*, Sylvain Ravets[1], Sylvain de Léséleuc[1], Tommaso Macrì[2], Thierry Lahaye[1] & Antoine Browaeys[1]

$$g^{(2)}(k) = \frac{1}{N_t} \sum_i \frac{\langle n_i n_{i+k} \rangle}{\langle n_i \rangle \langle n_{i+k} \rangle}$$

Probability to be in the ground state

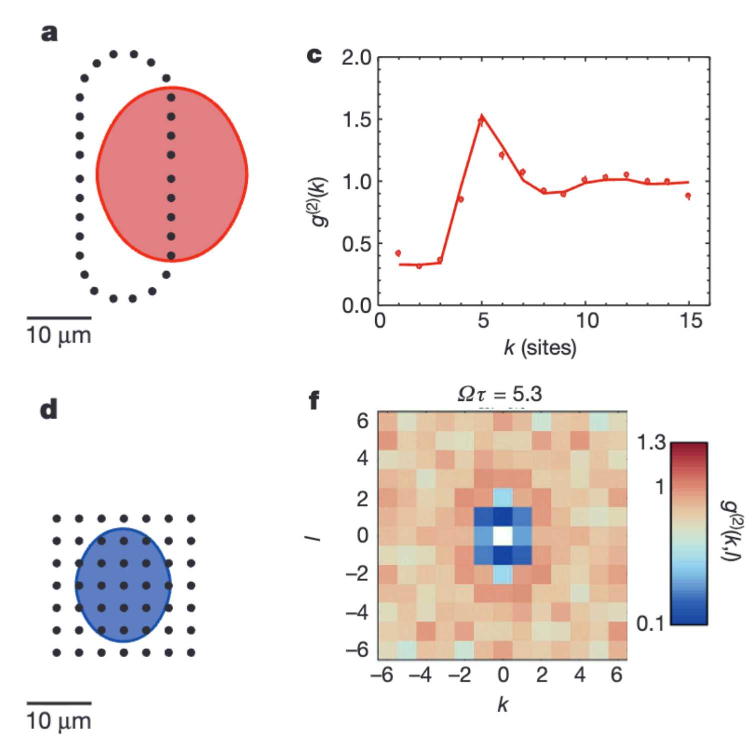


$$H = \sum_i \frac{\hbar\Omega}{2} \sigma^i_x + \sum_{i<j} V_{ij} n^i n^j$$

$$\sigma^x_k = (|\uparrow_k\rangle\langle\downarrow_k| + |\downarrow_k\rangle\langle\uparrow_k|)$$

$$n_k = (1 + \sigma^z_k)$$

Realizing a transverse field Ising model



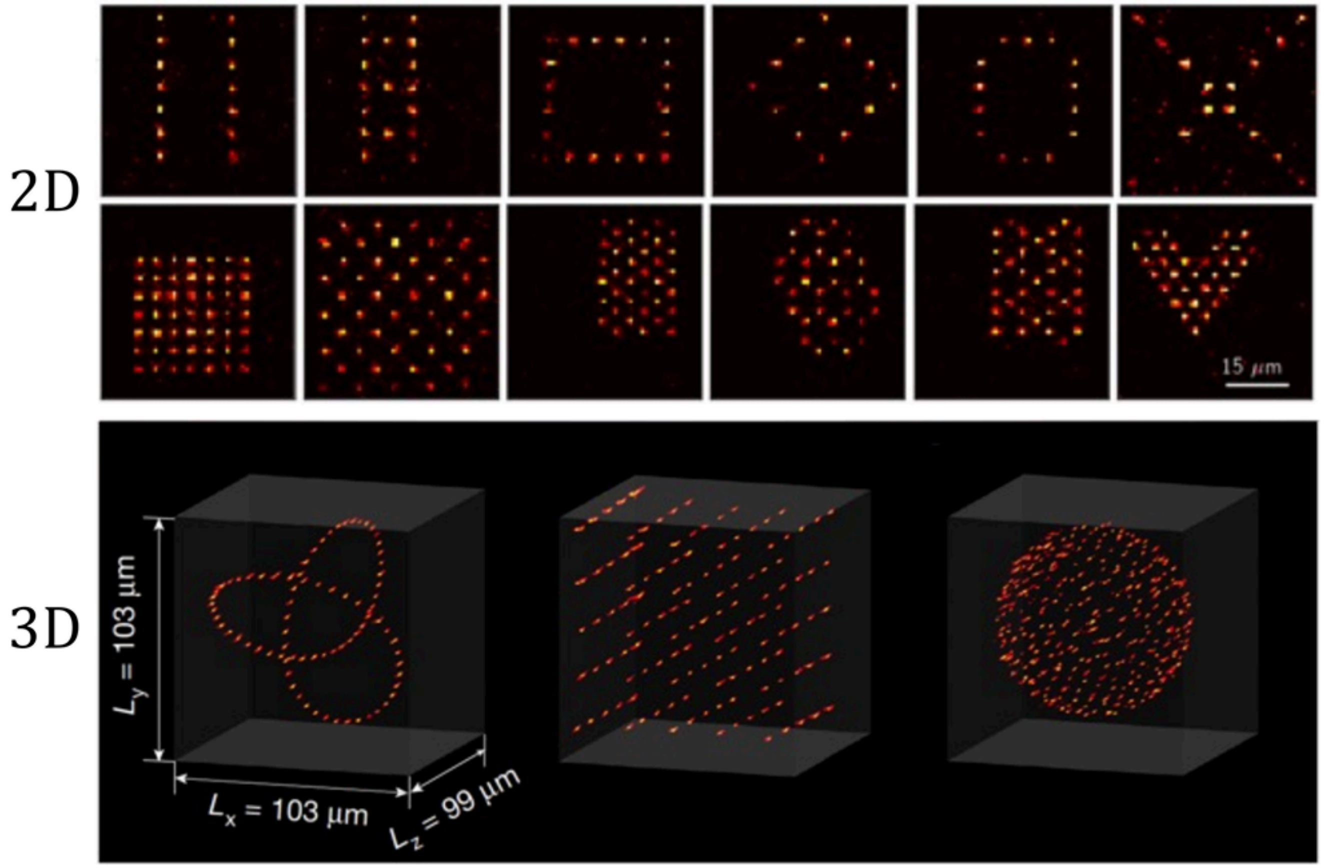
Neutral Atoms

Optical tweezer arrays: Individual atoms trapped in tunable two-dimensional arrays of optical microtraps, when coupled with the Rydberg level produce strong correlations between the atoms.

Letter | Published: 05 September 2018

Synthetic three-dimensional atomic structures assembled atom by atom

Daniel Barredo, Vincent Lienhard, Sylvain de Léséleuc, Thierry Lahaye & Antoine Browaeys



Neutral Atoms

Analog Quantum Many Body Simulations of quantum magnetism

Article | Published: 07 July 2021

Quantum phases of matter on a 256-atom programmable quantum simulator

Sepehr Ebadi, Tout T. Wang, Harry Levine, Alexander Keesling, Giulia Semeghini, Ahmed Omran, Dolev Bluvstein, Rhine Samajdar, Hannes Pichler, Wen Wei Ho, Soonwon Choi, Subir Sachdev, Markus Greiner, Vladan Vuletić & Mikhail D. Lukin

Article | Published: 07 July 2021

Quantum simulation of 2D antiferromagnets with hundreds of Rydberg atoms

Pascal Scholl, Michael Schuler, Hannah J. Williams, Alexander A. Eberharter, Daniel Barredo, Kai-Niklas Schymik, Vincent Lienhard, Louis-Paul Henry, Thomas C. Lang, Thierry Lahaye, Andreas M. Läuchli & Antoine Browaeys

Neutral Atoms

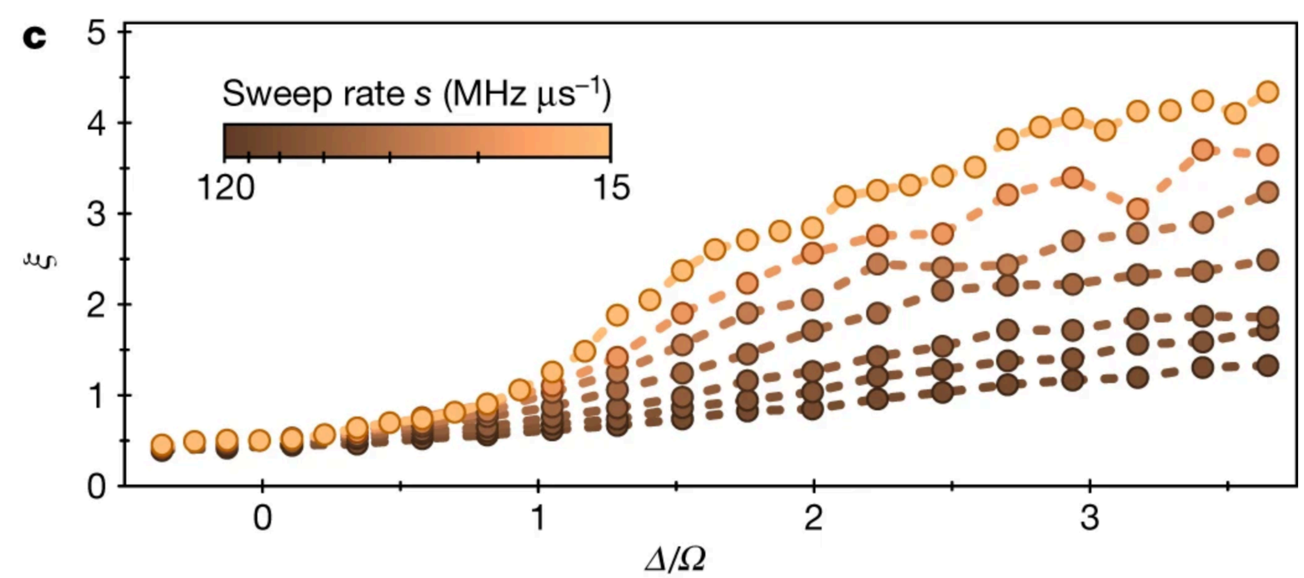
Analog Quantum Many Body Simulations of quantum magnetism

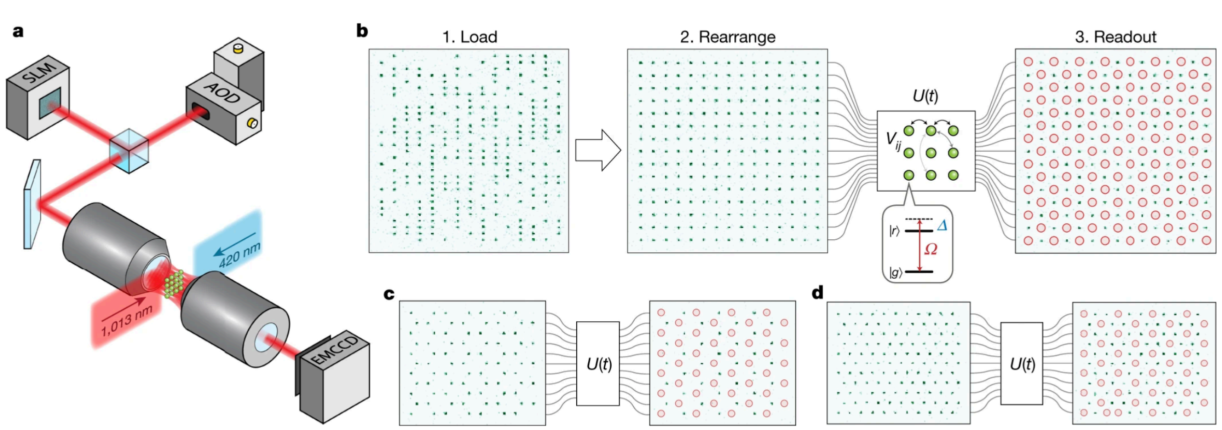
Observation of the (2+1)d Ising quantum phase transition

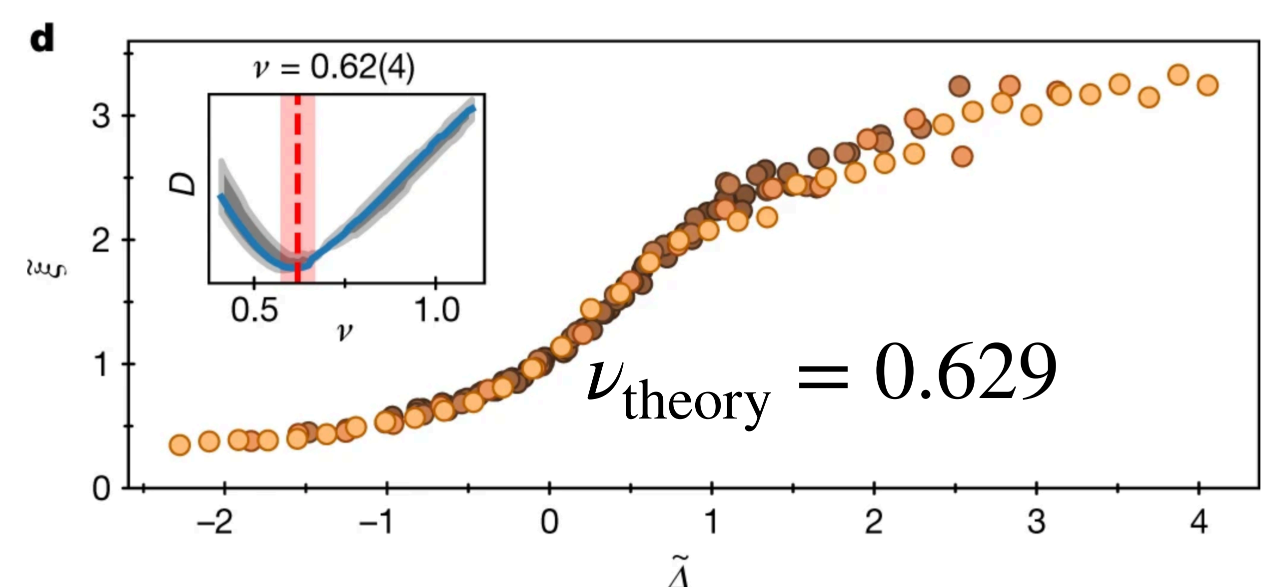
Article | Published: 07 July 2021

Quantum phases of matter on a 256-atom programmable quantum simulator

Sepehr Ebadi, Tout T. Wang, Harry Levine, Alexander Keesling, Giulia Semeghini, Ahmed Omran, Dolev Bluvstein, Rhine Samajdar, Hannes Pichler, Wen Wei Ho, Soonwon Choi, Subir Sachdev, Markus Greiner, Vladan Vuletić & Mikhail D. Lukin







Neutral Atoms

Quantum Computation with neutral (i.e. Rydberg dressed) atoms

VOLUME 85, NUMBER 10 PHYSICAL REVIEW LETTERS 4 SEPTEMBER 2000

Fast Quantum Gates for Neutral Atoms

D. Jaksch, J. I. Cirac, and P. Zoller
Institut für Theoretische Physik, Universität Innsbruck, Technikerstrasse 25, A-6020 Innsbruck, Austria

S. L. Rolston
National Institute of Standards and Technology, Gaithersburg, Maryland 20899

R. Côté[1] and M. D. Lukin[2]
[1]*Physics Department, University of Connecticut, 2152 Hillside Road, Storrs, Connecticut 06269-3046*
[2]*ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138*
(Received 7 April 2000)

We propose several schemes for implementing a fast two-qubit quantum gate for neutral atoms with the gate operation time much faster than the time scales associated with the external motion of the atoms in the trapping potential. In our example, the large interaction energy required to perform fast gate operations is provided by the dipole-dipole interaction of atoms excited to low-lying Rydberg states in constant electric fields. A detailed analysis of imperfections of the gate operation is given.

VOLUME 87, NUMBER 3 PHYSICAL REVIEW LETTERS 16 JULY 2001

Dipole Blockade and Quantum Information Processing in Mesoscopic Atomic Ensembles

M. D. Lukin,[1] M. Fleischhauer,[1,2] and R. Cote[3]
[1]*ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138*
[2]*Fachbereich Physik, Universität Kaiserslautern, D-67663 Kaiserslautern, Germany*
[3]*Physics Department, University of Connecticut, Storrs, Connecticut 06269*

L. M. Duan, D. Jaksch, J. I. Cirac, and P. Zoller
Institut für Theoretische Physik, Universität Innsbruck, A-6020 Innsbruck, Austria
(Received 7 November 2000; published 26 June 2001)

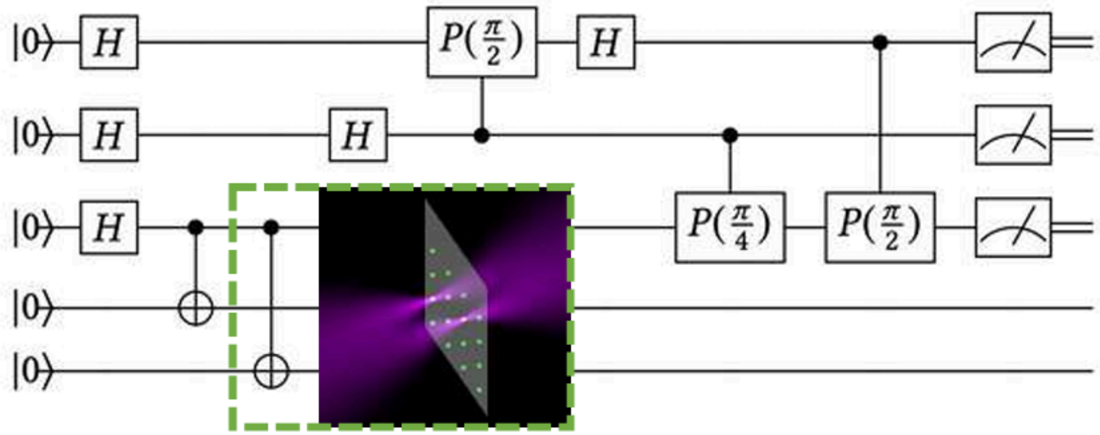
We describe a technique for manipulating quantum information stored in collective states of mesoscopic ensembles. Quantum processing is accomplished by optical excitation into states with strong dipole-dipole interactions. The resulting "dipole blockade" can be used to inhibit transitions into all but singly excited collective states. This can be employed for a controlled generation of collective atomic spin states as well as nonclassical photonic states and for scalable quantum logic gates. An example involving a cold Rydberg gas is analyzed.

Neutral Atoms

QUANTUM COMPUTING WITH NEUTRAL ATOMS

Loïc Henriet[1], Lucas Beguin[1], Adrien Signoles[1], Thierry Lahaye[2,1], Antoine Browaeys[2,1], Georges-Olivier Reymond[1], and Christophe Jurczak[1,3]

One and two qubit gates are created by applying lasers to individually chosen atoms



Neutral Atoms

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Loïc Henriet[1], Lucas Beguin[1], Adrien Signoles[1], Thierry Lahaye[2,1], Antoine Browaeys[2,1], Georges-Olivier Reymond[1], and Christophe Jurczak[1,3]

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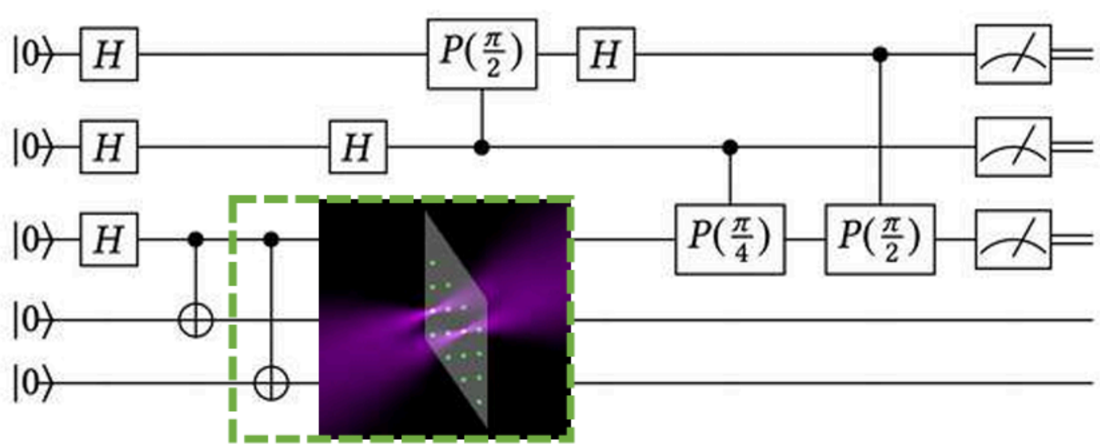

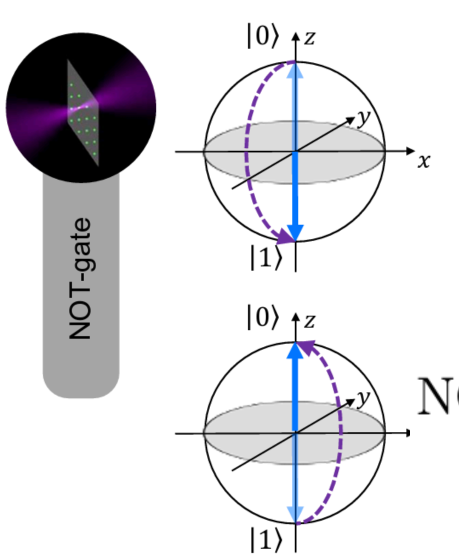

Any one qubit gate accessible

$$\mathrm{NOT} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \qquad \mathrm{H} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

Neutral Atoms

QUANTUM COMPUTING WITH NEUTRAL ATOMS

Loïc Henriet[1], Lucas Beguin[1], Adrien Signoles[1], Thierry Lahaye[2,1], Antoine Browaeys[2,1], Georges-Olivier Reymond[1], and Christophe Jurczak[1,3]

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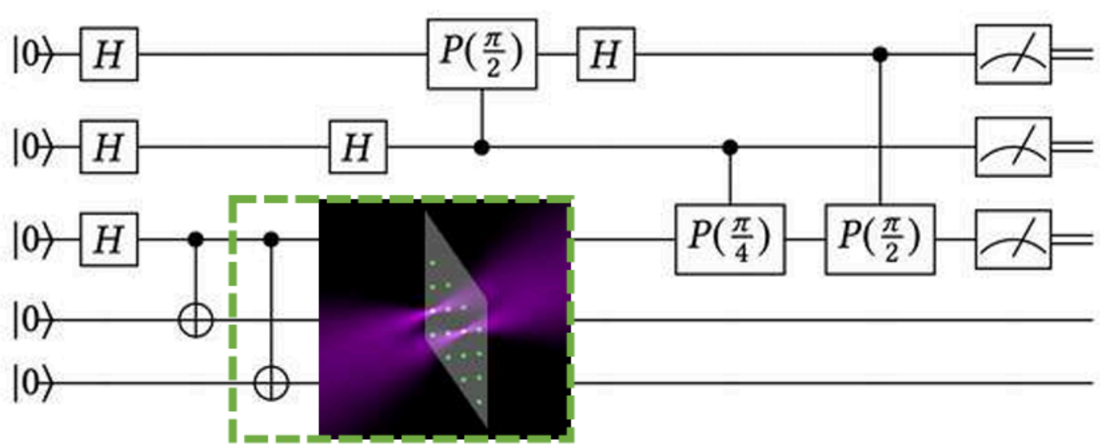
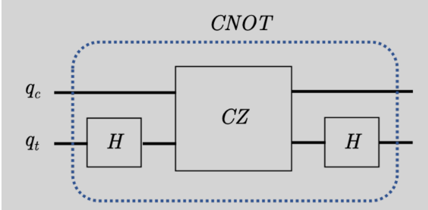


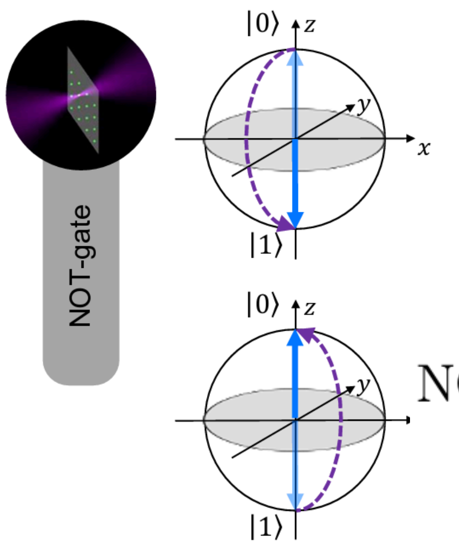
The 2-qubit CZ gate is naturally accessible

$$e^{i\pi}\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & -1\end{bmatrix} = e^{i\pi}\mathrm{CZ}$$

Combined with Hadamard, makes an entangling CNOT

$$\mathrm{CNOT} = \begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 1\\ 0 & 0 & 1 & 0\end{bmatrix}$$





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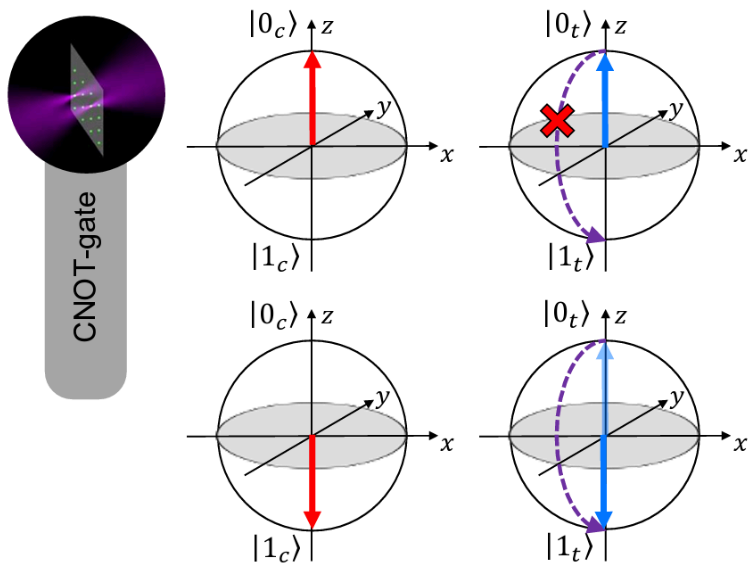


Neutral Atoms

Quantum computation with neutral atoms (summary)

	Single qubit gates	Two qubit gates	Measurement \ reset
Gate speeds	~0.1–10 μs	~0.4–1 μs CZ-gates	5-50 μs
Fidelity (typical)	99.9–99.97%	99.85–99.86%	98–99.8%

Coherence times

QuEra Aquila

Time to decay from excited state

$T_1 \sim$ 1-10 Seconds

Hyperfine qubits

Ramsey coherence time

$T_2^* \sim 10\mu s$

Used to interact two qubits

Article | Open access | Published: 15 September 2025

Continuous operation of a coherent 3,000-qubit system

Neng-Chun Chiu, Elias C. Trapp, Jinen Guo, Mohamed H. Abobeih, Luke M. Stewart, Simon Hollerith, Pavel L. Stroganov, Marcin Kalinowski, Alexandra A. Geim, Simon J. Evered, Sophie H. Li, Xingjian Lyu, Lisa M. Peters, Dolev Bluvstein, Tout T. Wang, Markus Greiner, Vladan Vuletić & Mikhail D. Lukin

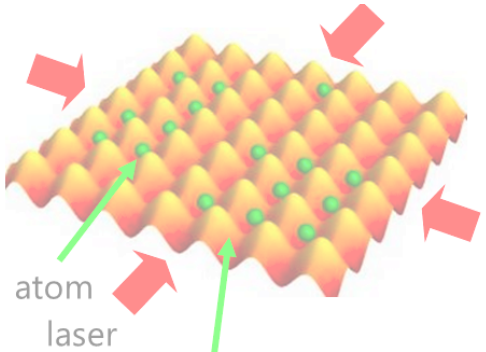
Can store atoms a long time

Worked for 2 hrs!

Atomic Physics, Foot

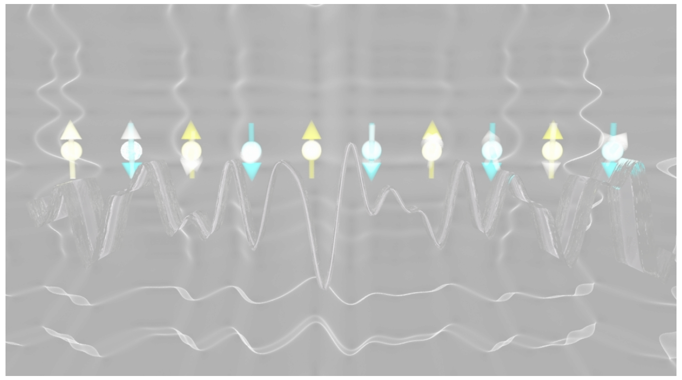
Neutral Atoms

Cold atomic gases



M. Kozuma group

Trapped ions

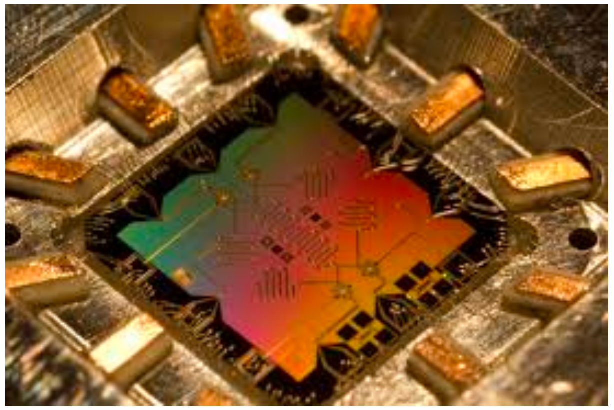


C. Monroe group

Neutral atoms

M. Endres group

Superconducting qubits



J. Martinis group

We will now consider each of these platforms in turn

Superconducting (Transmon) Qubits

2025 Nobel prize in Physics given for the discovery of superconducting qubits, known as the transmon qubit

Ill. Niklas Elmehed © Nobel Prize Outreach
John Clarke

Ill. Niklas Elmehed © Nobel Prize Outreach
Michel H. Devoret

Ill. Niklas Elmehed © Nobel Prize Outreach
John M. Martinis

VOLUME 53, NUMBER 13 PHYSICAL REVIEW LETTERS 24 SEPTEMBER 1984

Resonant Activation from the Zero-Voltage State of a Current-Biased Josephson Junction

Michel H. Devoret,[a] John M. Martinis, Daniel Esteve,[a] and John Clarke
Department of Physics, University of California, Berkeley, California 94720, and Materials and Molecular Research Division, Lawrence Berkeley Laboratory, Berkeley, California 94720

(Received 26 July 1984)

Superconducting (Transmon) Qubits

We now move away from the "atom is the qubit" perspective to using a coherent macroscopic quantum state (i.e. a superconductor) as a qubit

Introduction to Many-Body Physics, Coleman

Superconducting (Transmon) Qubits

We now move away from the "atom is the qubit" perspective to using a coherent macroscopic quantum state (i.e. a superconductor) as a qubit

Conventional $s-$wave superconductors made of Al

	T_c(K)	2Δ (GHz)
Al	1.175	82.2
Pb	7.2	660
Hg	4.15	399
Nb	9.2	738.5
YBCO	70-90K	—

Srivatsan Chakram, Lecture Notes

Introduction to Many-Body Physics, Coleman

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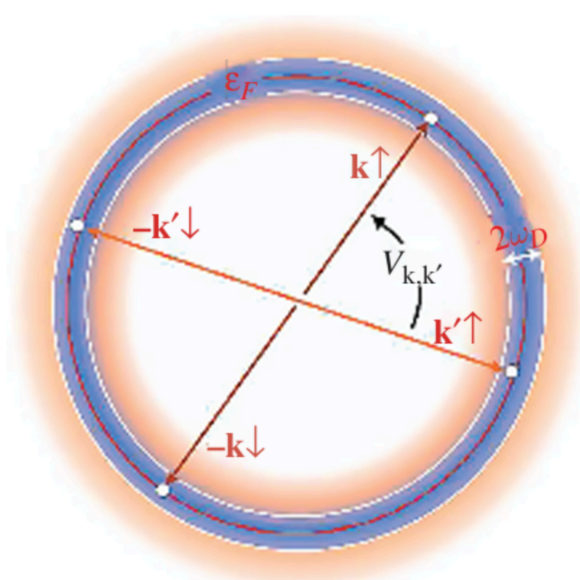
YBCO	70-90 K	—

Srivatsan Chakram, Lecture Notes

BCS Hamiltonian

$$H = \sum_{\mathbf{k}\sigma} \epsilon_{\mathbf{k}\sigma} c^\dagger_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \sum_{\mathbf{k},\mathbf{k}'} V_{\mathbf{k},\mathbf{k}'} c^\dagger_{\mathbf{k}\uparrow} c^\dagger_{-\mathbf{k}\downarrow} c_{-\mathbf{k}'\downarrow} c_{\mathbf{k}'\uparrow}$$



Introduction to Many-Body Physics, Coleman

Phonon mediated attractive interaction around the Fermi surface

$$V_{\mathbf{k},\mathbf{k}'} = \begin{cases} -g_0/V & (|\epsilon_{\mathbf{k}}| < \omega_D) \\ 0 & \text{(otherwise)}. \end{cases}$$

Superconducting order parameter

$$\Delta = |\Delta| e^{i\phi} = -g_0 \int_{|\epsilon_{\mathbf{k}}|<\omega_D} \frac{d^3k}{(2\pi)^3} \langle c_{-\mathbf{k}\downarrow} c_{\mathbf{k}\uparrow} \rangle$$

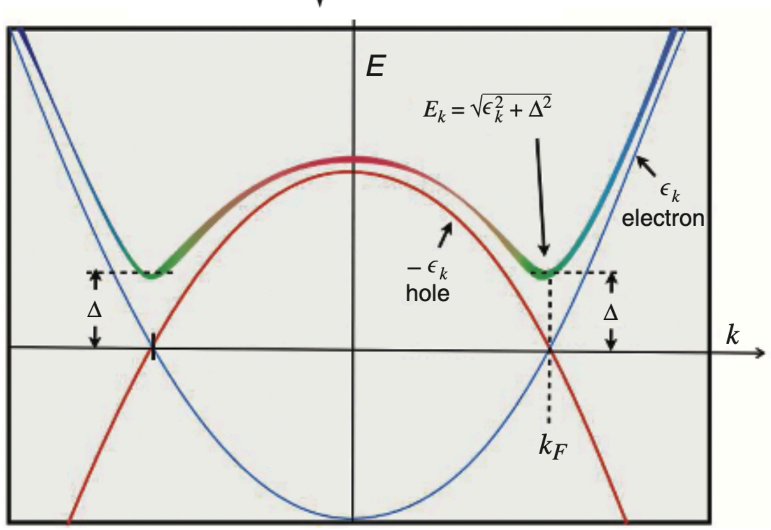
Superconducting (Transmon) Qubits

Conventional $s-$wave superconductors made of Al

$$H_{MFT} = \sum_{\mathbf{k}\sigma} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \sum_{\mathbf{k}} \left[\bar{\Delta} c_{-\mathbf{k}\downarrow} c_{\mathbf{k}\uparrow} + c^{\dagger}_{\mathbf{k}\uparrow} c^{\dagger}_{-\mathbf{k}\downarrow} \Delta \right] + \frac{V}{g_0} \bar{\Delta}\Delta$$

The superconducting excitations are gapped

$$E_{\mathbf{k}} = \sqrt{\epsilon_{\mathbf{k}}^2 + |\Delta|^2}.$$



Self consistent equation for the superconducting order parameter

$$\Delta = \frac{g_0}{V} \sum_{\mathbf{k}} \frac{1}{2} \sin\theta_{\mathbf{k}} = g_0 \int_{|\epsilon_{\mathbf{k}}| < \omega_D} \frac{d^3k}{(2\pi)^3} \frac{\Delta}{2\sqrt{\epsilon_{\mathbf{k}}^2 + \Delta^2}}.$$

Introduction to Many-Body Physics, Coleman

Superconducting (Transmon) Qubits

Conventional $s-$wave superconductors made of Al

$$H_{MFT} = \sum_{\mathbf{k}\sigma} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \sum_{\mathbf{k}} \left[\bar{\Delta} c_{-\mathbf{k}\downarrow} c_{\mathbf{k}\uparrow} + c^{\dagger}_{\mathbf{k}\uparrow} c^{\dagger}_{-\mathbf{k}\downarrow} \Delta \right] + \frac{V}{g_0} \bar{\Delta} \Delta$$

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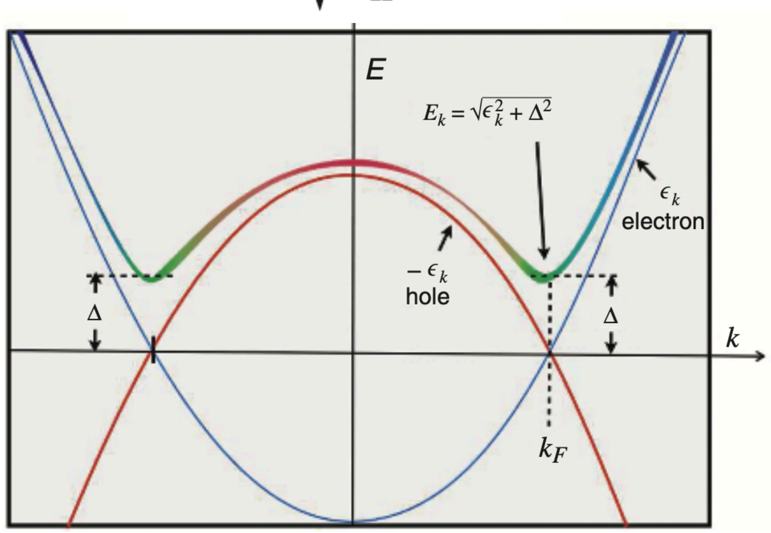

Self consistent equation for the superconducting order parameter

$$\Delta = \frac{g_0}{V} \sum_{\mathbf{k}} \frac{1}{2} \sin\theta_{\mathbf{k}} = g_0 \int_{|\epsilon_{\mathbf{k}}| < \omega_D} \frac{d^3k}{(2\pi)^3} \frac{\Delta}{2\sqrt{\epsilon_{\mathbf{k}}^2 + \Delta^2}}.$$

With the solution at $T = 0$

$$\Delta = 2\omega_D e^{-\frac{1}{g_0 N(0)}}.$$

And the ground state wave function is

$$|BCS\rangle = \prod_{\mathbf{k}} \left(u_{\mathbf{k}} + \mathrm{v}_{\mathbf{k}} c^{\dagger}_{-\mathbf{k}\downarrow} c^{\dagger}_{\mathbf{k}\uparrow} \right) |0\rangle$$

$$u_{\mathbf{k}} = \sqrt{\frac{1}{2}\left[1 + \frac{\epsilon_{\mathbf{k}}}{E_{\mathbf{k}}}\right]}$$

$$\mathrm{v}_{\mathbf{k}} = \sqrt{\frac{1}{2}\left[1 - \frac{\epsilon_{\mathbf{k}}}{E_{\mathbf{k}}}\right]}.$$

Introduction to Many-Body Physics, Coleman

Superconducting (Transmon) Qubits

The ground state wave function is

$$|BCS\rangle = \prod_{\mathbf{k}} \left(u_{\mathbf{k}} + v_{\mathbf{k}} c^{\dagger}_{-\mathbf{k}\downarrow} c^{\dagger}_{\mathbf{k}\uparrow} \right) |0\rangle$$

$$u_{\mathbf{k}} = \sqrt{\frac{1}{2}\left[1 + \frac{\epsilon_{\mathbf{k}}}{E_{\mathbf{k}}}\right]}$$

$$v_{\mathbf{k}} = \sqrt{\frac{1}{2}\left[1 - \frac{\epsilon_{\mathbf{k}}}{E_{\mathbf{k}}}\right]}.$$

Ignoring the normalization, we can write this as a coherent state

$$|BCS\rangle = \prod_{\mathbf{k}} \left(1 + \phi_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\uparrow} c^{\dagger}_{-\mathbf{k}\downarrow} \right) |0\rangle\rangle = \exp\left[\sum_{\mathbf{k}} \phi_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\uparrow} c^{\dagger}_{-\mathbf{k}\downarrow} \right] |0\rangle = \exp\left[\Lambda^{\dagger}\right] |0\rangle$$

$$\phi_{\mathbf{k}} = -\frac{v_{\mathbf{k}}}{u_{\mathbf{k}}}$$

$$|BCS\rangle = \sum_{n} \frac{1}{n!} (\Lambda^{\dagger})^{n} |0\rangle = \sum_{n} \frac{1}{\sqrt{n!}} |n\rangle$$

← n Cooper pairs

Introduction to Many-Body Physics, Coleman

Superconducting (Transmon) Qubits

The ground state wave function is

$$|BCS\rangle = \prod_{\mathbf{k}} \left(u_{\mathbf{k}} + v_{\mathbf{k}} c^{\dagger}_{-\mathbf{k}\downarrow} c^{\dagger}_{\mathbf{k}\uparrow} \right) |0\rangle$$

$$u_{\mathbf{k}} = \sqrt{\frac{1}{2}\left[1 + \frac{\epsilon_{\mathbf{k}}}{E_{\mathbf{k}}}\right]}$$

$$v_{\mathbf{k}} = \sqrt{\frac{1}{2}\left[1 - \frac{\epsilon_{\mathbf{k}}}{E_{\mathbf{k}}}\right]}.$$

Ignoring the normalization, we can write this as a coherent state

$$|BCS\rangle = \prod_{\mathbf{k}} \left(1 + \phi_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\uparrow} c^{\dagger}_{-\mathbf{k}\downarrow}\right) |0\rangle) = \exp\left[\sum_{\mathbf{k}} \phi_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\uparrow} c^{\dagger}_{-\mathbf{k}\downarrow}\right] |0\rangle = \exp\left[\Lambda^{\dagger}\right] |0\rangle$$

$$\phi_{\mathbf{k}} = -\frac{v_{\mathbf{k}}}{u_{\mathbf{k}}}$$

n Cooper pairs

$$|BCS\rangle = \sum_{n} \frac{1}{n!} (\Lambda^{\dagger})^{n} |0\rangle = \sum_{n} \frac{1}{\sqrt{n!}} |n\rangle$$

Applying the gauge transformation

$$c^{\dagger}_{\mathbf{k},\sigma} \to e^{i\varphi} c^{\dagger}_{\mathbf{k},\sigma} \quad \Delta \to e^{i2\varphi} \Delta$$

$$|BCS(\varphi)\rangle = \prod_{\mathbf{k}} (1 + e^{i2\varphi} \phi_{\mathbf{k}} c^{\dagger}_{\mathbf{k},\uparrow} c^{\dagger}_{-\mathbf{k},\downarrow}) |0\rangle$$

$$= \sum_{n} \frac{e^{i2n\varphi}}{\sqrt{n!}} |n\rangle$$

Introduction to Many-Body Physics, Coleman

Superconducting (Transmon) Qubits

The ground state wave function is

$$|BCS\rangle = \prod_{\mathbf{k}} \left(u_{\mathbf{k}} + v_{\mathbf{k}} c^{\dagger}_{-\mathbf{k}\downarrow} c^{\dagger}_{\mathbf{k}\uparrow} \right) |0\rangle$$

$$u_{\mathbf{k}} = \sqrt{\frac{1}{2}\left[1 + \frac{\epsilon_{\mathbf{k}}}{E_{\mathbf{k}}}\right]}$$

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$$= \sum_{n} \frac{e^{i2n\varphi}}{\sqrt{n!}} |n\rangle$$

Consider the action of number operator

$$\hat{N} = \sum_{\mathbf{k},\sigma} c^{\dagger}_{\mathbf{k},\sigma} c_{\mathbf{k},\sigma} \qquad \hat{N} |BCS(\varphi)\rangle = \sum_{n} 2n \frac{e^{i2n\varphi}}{\sqrt{n!}} |n\rangle \quad \longrightarrow \quad \hat{N} = -i \frac{d}{d\varphi}$$

Introduction to Many-Body Physics, Coleman

Superconducting (Transmon) Qubits

The phase of the wavefunction and the particle number are canonically conjugate variables

$$\hat{N} = -i\frac{d}{d\varphi}$$

φ is like position and N is like momentum

$$[\hat{\varphi}, \hat{N}] = i$$

Circuit QED, Girvin

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Superconducting (Transmon) Qubits

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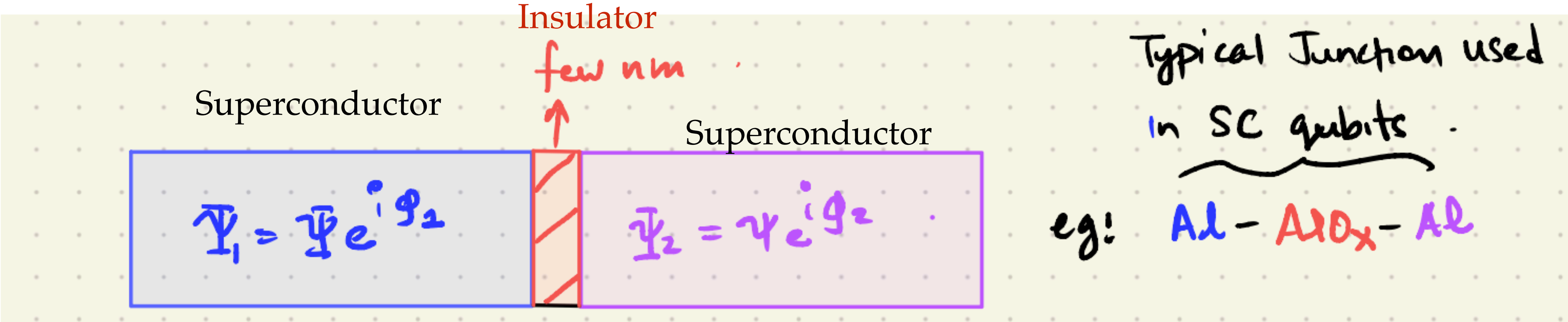
Josephson tunneling: Two identical superconductors separated by an insulating barrier



Srivatsan Chakram, Lecture Notes

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Superconducting (Transmon) Qubits

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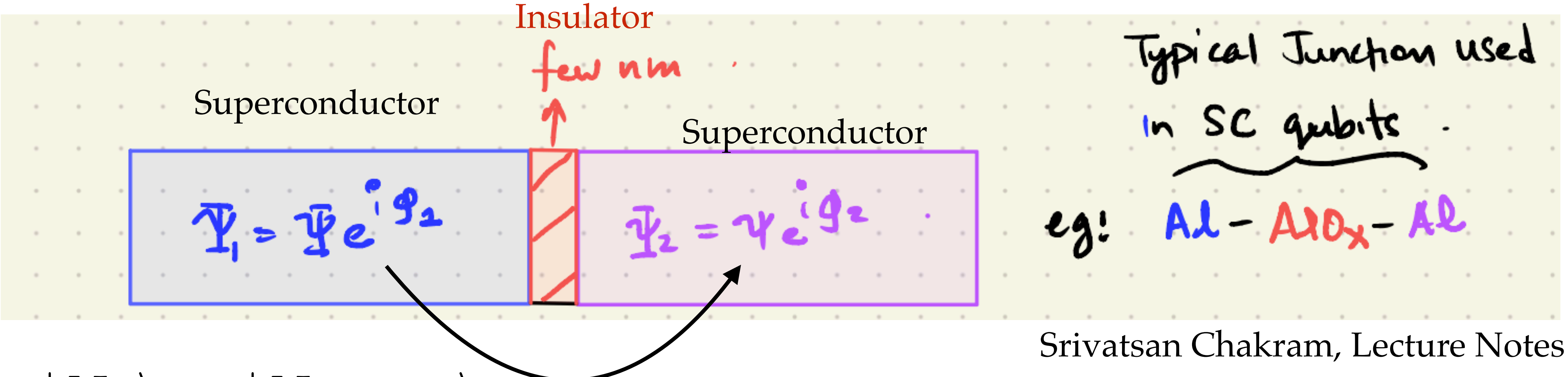

Srivatsan Chakram, Lecture Notes

$$|N_L\rangle \to |N_L - m\rangle \qquad |N_R\rangle \to |N_R + m\rangle$$

Applying a voltage bias, Cooper pairs tunnel from Left to Right

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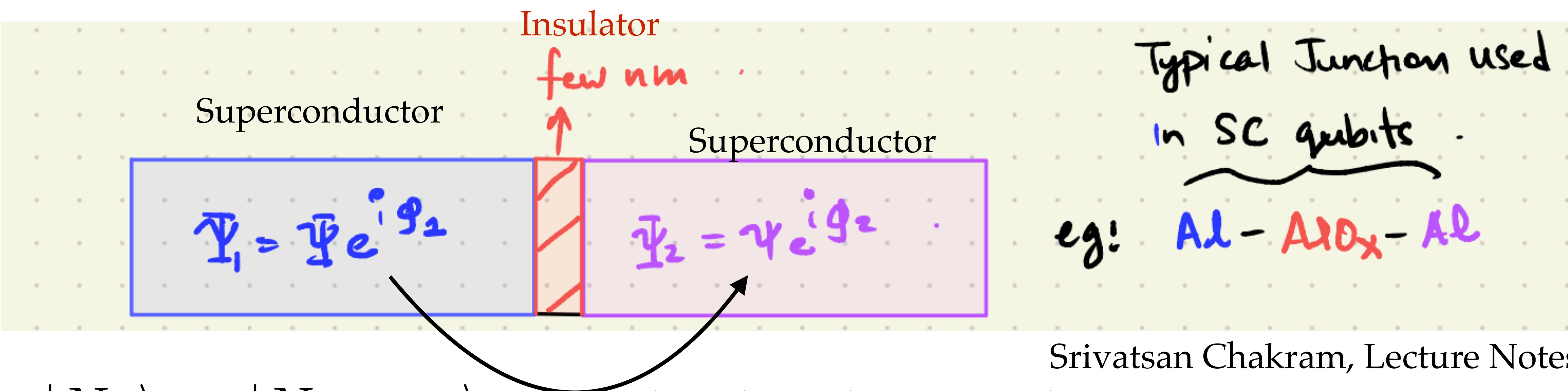
Superconducting (Transmon) Qubits

Josephson tunneling: Two identical superconductors separated by an insulating barrier



Srivatsan Chakram, Lecture Notes

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Applying a voltage bias, Cooper pairs tunnel from Left to Right

$$|m\rangle \equiv |N_L - m\rangle \otimes |N_R + m\rangle$$

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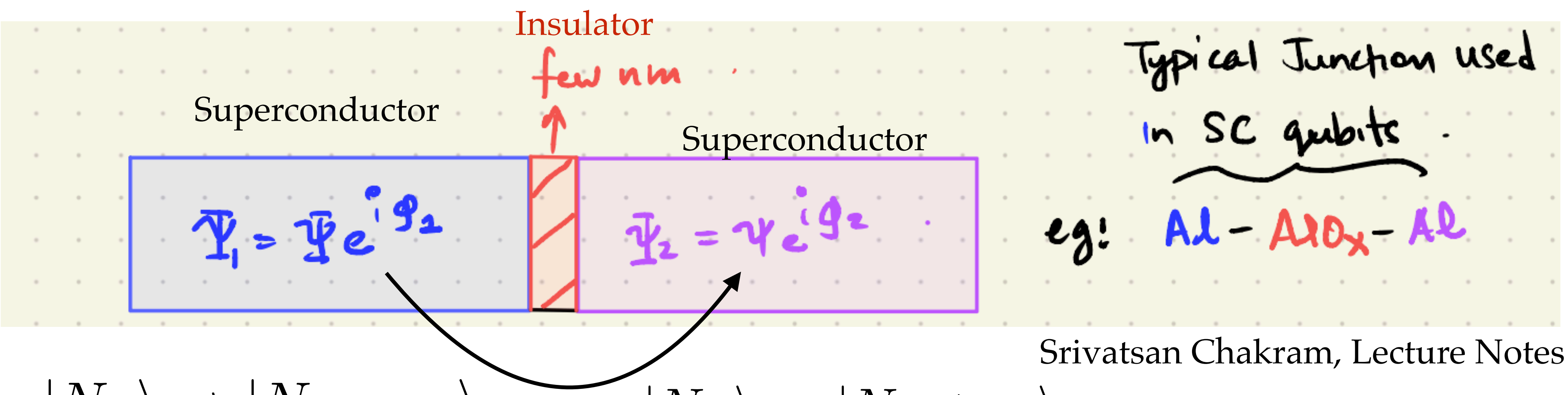
Superconducting (Transmon) Qubits

Josephson tunneling: Two identical superconductors separated by an insulating barrier



Srivatsan Chakram, Lecture Notes

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Applying a voltage bias, Cooper pairs tunnel from Left to Right

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We therefore include a tunneling term

$$H_{\mathrm{T}} = -\frac{1}{2}E_{\mathrm{J}}\sum_m \{|m\rangle\langle m+1| + |m+1\rangle\langle m|\}$$

Josephson coupling energy $E_{\mathrm{J}} = \frac{1}{2}\frac{h}{(2e)^2}G_{\mathrm{N}}\Delta$ ← Normal state conductance

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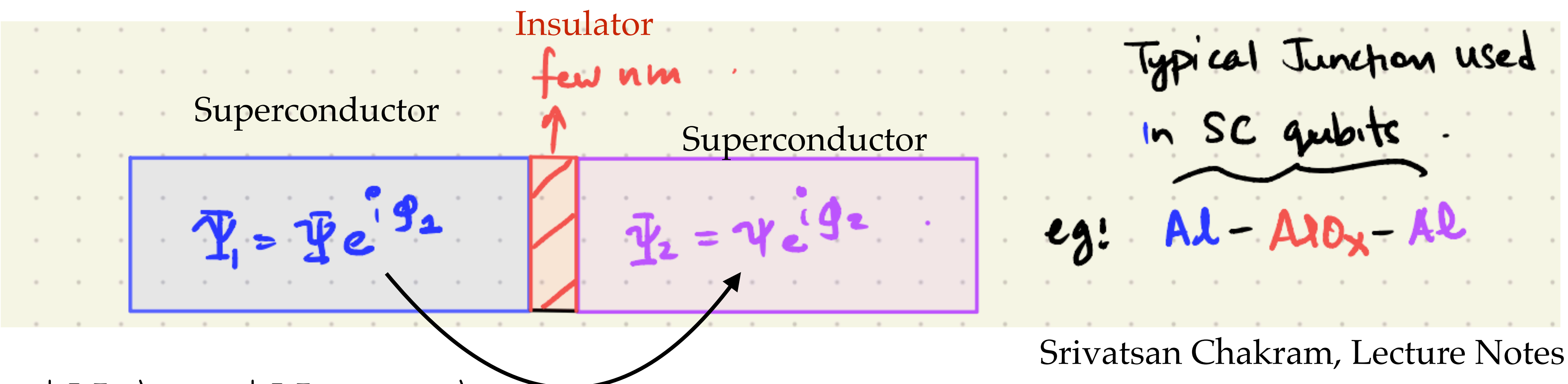
SUPERCONDUCTING (TRANSMON) QUBITS

Josephson tunneling: Two identical superconductors separated by an insulating barrier



Srivatsan Chakram, Lecture Notes

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H_T has plane wave solutions

$$|\varphi\rangle = \sum_{m=-\infty}^{+\infty} e^{+im\varphi} |m\rangle$$

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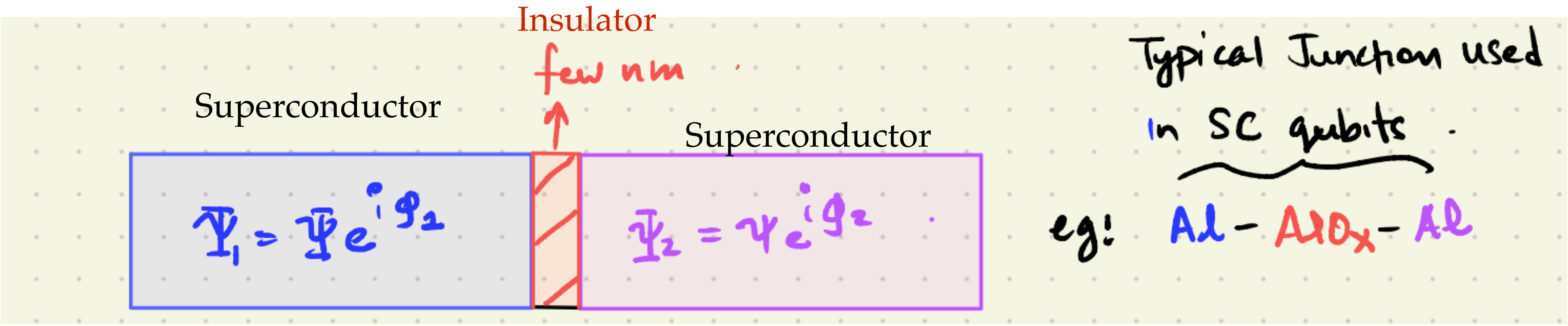
Superconducting (Transmon) Qubits

Josephson tunneling: Two identical superconductors separated by an insulating barrier



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Srivatsan Chakram, Lecture Notes

$$H_{\mathrm{T}} = -\frac{1}{2}E_{\mathrm{J}}\sum_m \{|m\rangle\langle m+1| + |m+1\rangle\langle m|\} \qquad E_{\mathrm{J}} = \frac{1}{2}\frac{h}{(2e)^2}G_{\mathrm{N}}\Delta$$

H_T has plane wave solutions $\quad |\varphi\rangle = \sum_{m=-\infty}^{+\infty} e^{+im\varphi}|m\rangle$

$$H_T|\varphi\rangle = \frac{-E_J}{2}\sum_m e^{im\varphi}(|m+1\rangle + |m-1\rangle) = -E_J\cos\varphi|\varphi\rangle$$

$$\longrightarrow H_T = -\int \frac{d\varphi}{2\pi}E_J\cos\varphi|\varphi\rangle\langle\varphi| = -E_J\cos\hat{\varphi}$$

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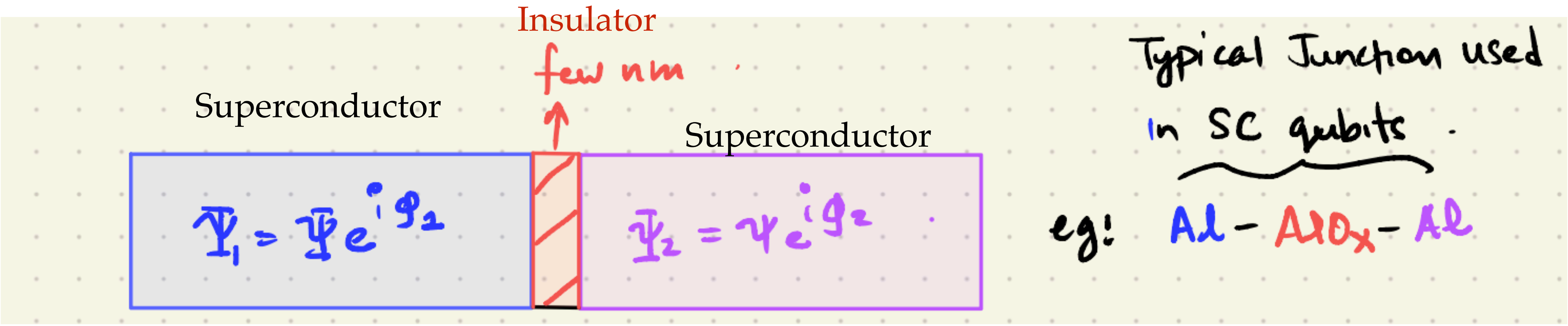
Superconducting (Transmon) Qubits

Josephson tunneling: Two identical superconductors separated by an insulating barrier



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$$H_T = -\int \frac{d\varphi}{2\pi} E_J \cos\varphi |\varphi\rangle\langle\varphi|$$

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Superconducting (Transmon) Qubits

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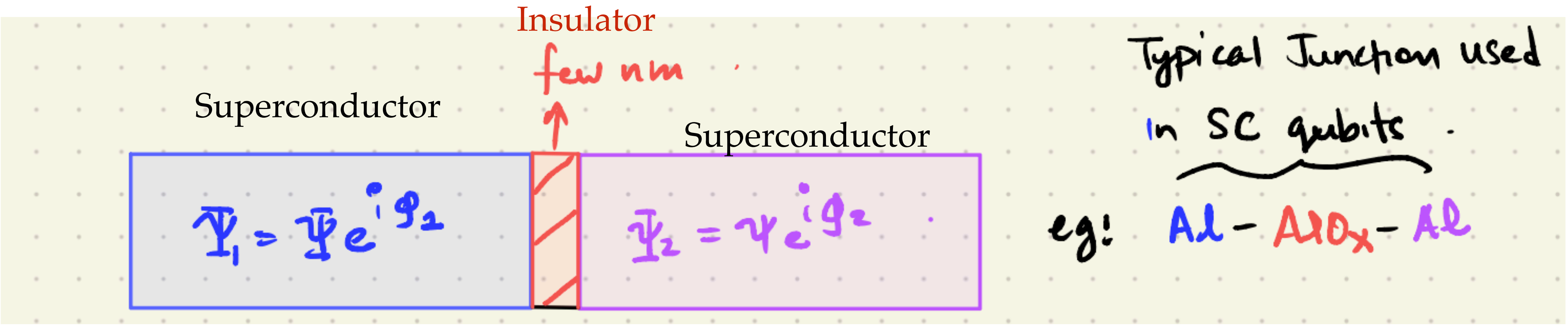

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$$H_T = -\int \frac{d\varphi}{2\pi} E_J \cos\varphi |\varphi\rangle\langle\varphi| \qquad E_J = \frac{1}{2}\frac{h}{(2e)^2} G_N \Delta$$

The equation of motion for the number of tunneling Cooper pairs is then

$$\dot{N}_T = \frac{1}{i\hbar}[N_T, H_T] = -\frac{1}{\hbar}\frac{dH_T}{d\varphi} = \frac{E_J}{\hbar}\sin\varphi$$

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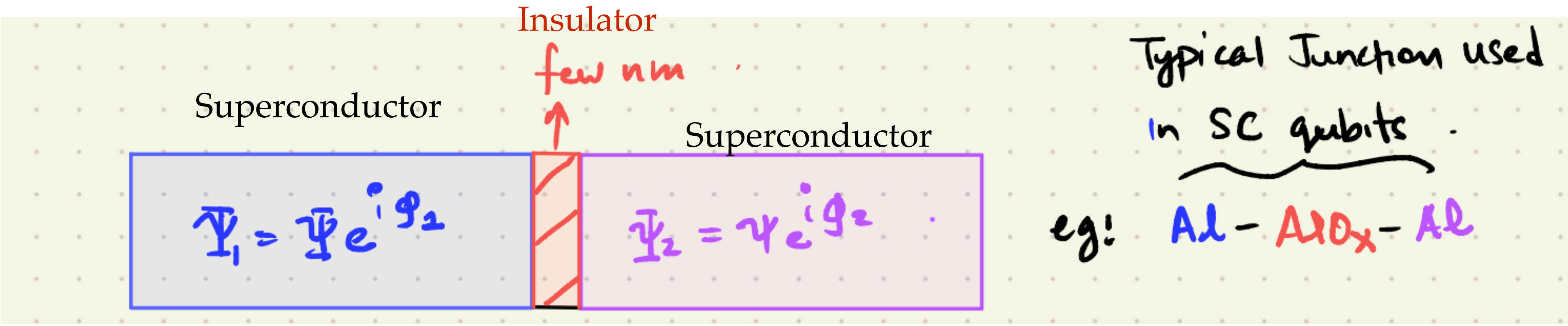
Superconducting (Transmon) Qubits

Josephson tunneling: Two identical superconductors separated by an insulating barrier



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Critical current, Maximum possible while remaining a superconductor

And we obtain the current $I = 2e\dot{N}_T = \frac{2eE_J}{\hbar}\sin\varphi \equiv I_c \sin\varphi$

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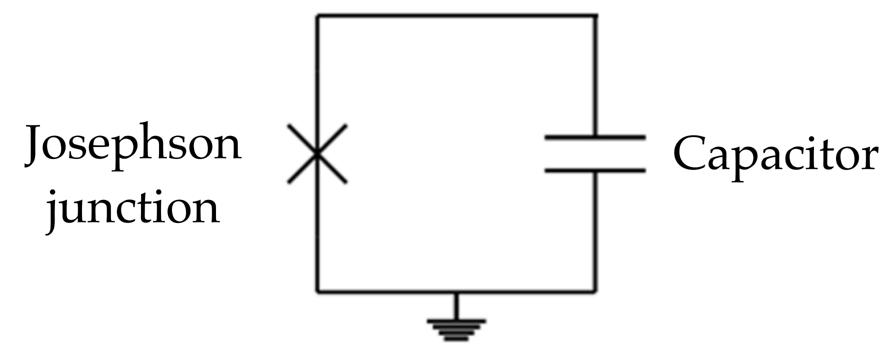
Superconducting (Transmon) Qubits

Put a Josephson junction in a circuit, **Cooper pair box**

$$H = H_C + H_T$$



$$H_C = 4E_C(\hat{N}_T - n_g)^2$$

Offset charge

The capacitor has a charging energy $E_C = \dfrac{e^2}{2C}$

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Superconducting (Transmon) Qubits

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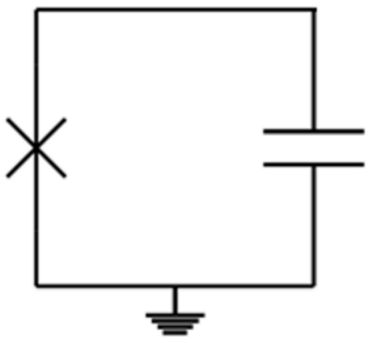

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Offset charge

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$$H = 4E_C(\hat{N}_T - n_g)^2 - E_J \cos\hat{\varphi}$$

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Superconducting (Transmon) Qubits

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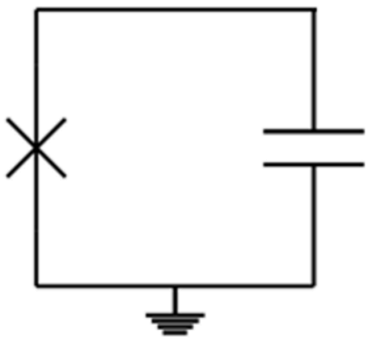

$$H = H_C + H_T$$

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Offset charge

The capacitor has a charging energy $E_C = \dfrac{e^2}{2C}$

$$H = 4E_C(\hat{N}_T - n_g)^2 - E_J \cos\hat{\varphi}$$

In the charge basis

$$H = \sum_N \left(4E_C(N - n_g)^2 |N\rangle\langle N| - \frac{E_J}{2}(|N\rangle\langle N+1| + |N+1\rangle\langle N|) \right)$$

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Superconducting (Transmon) Qubits

Put a Josephson junction in a circuit, **Cooper pair box**

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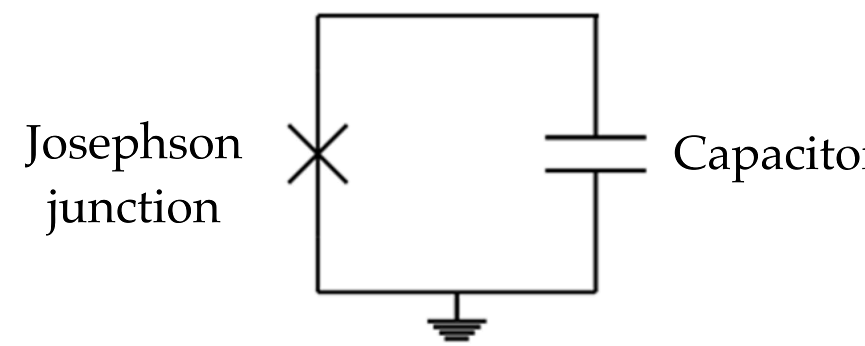
Focusing on $E_J \ll E_C$ the spectrum is analytically tractable



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Superconducting (Transmon) Qubits

Put a Josephson junction in a circuit, **Cooper pair box**

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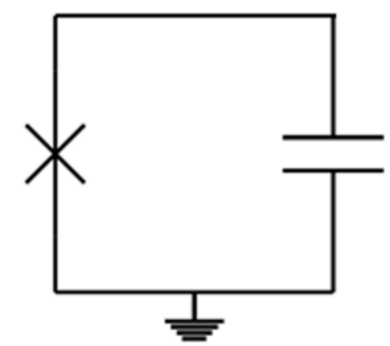

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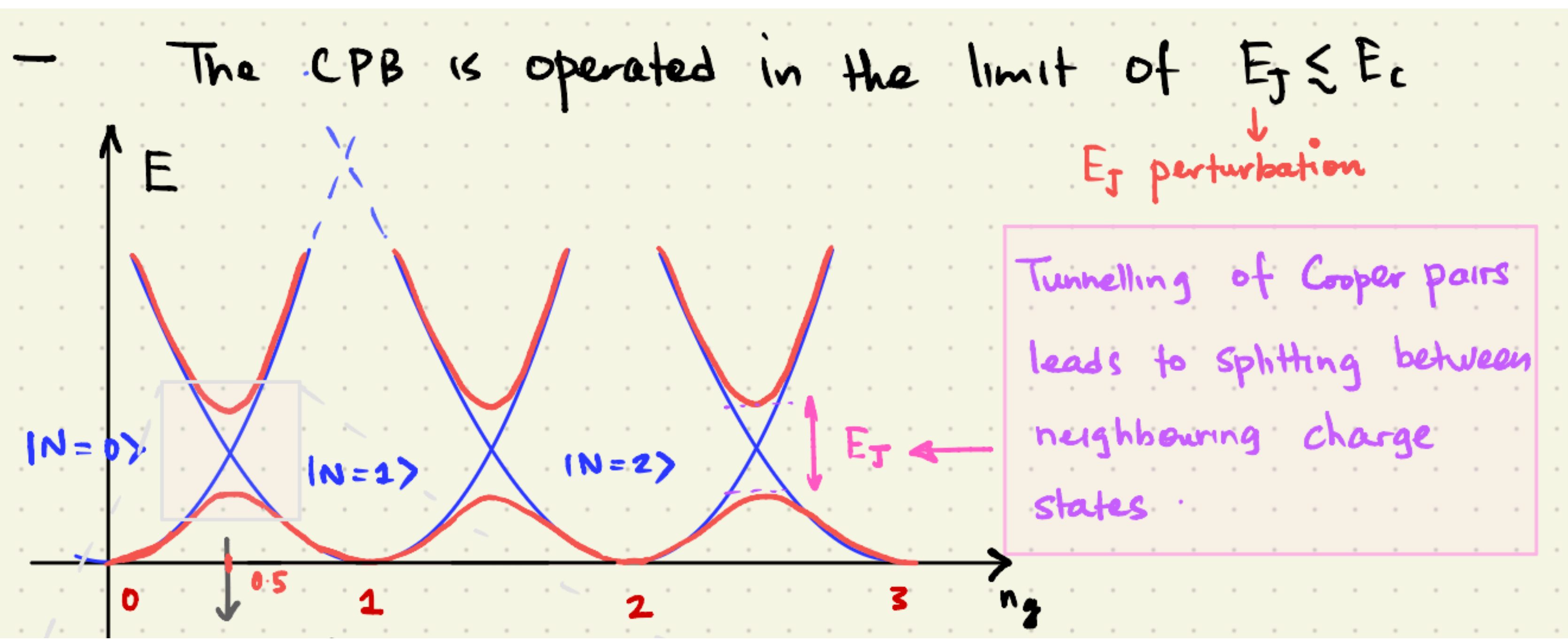

Gaps the excitations from $|0\rangle$ to $|1\rangle$

Superconducting (Transmon) Qubits

Put a Josephson junction in a circuit, **Cooper pair box**

$$H = \sum_N \left(4E_C (N - n_g)^2 |N\rangle\langle N| - \frac{E_J}{2}(|N\rangle\langle N+1| + |N+1\rangle\langle N|) \right)$$

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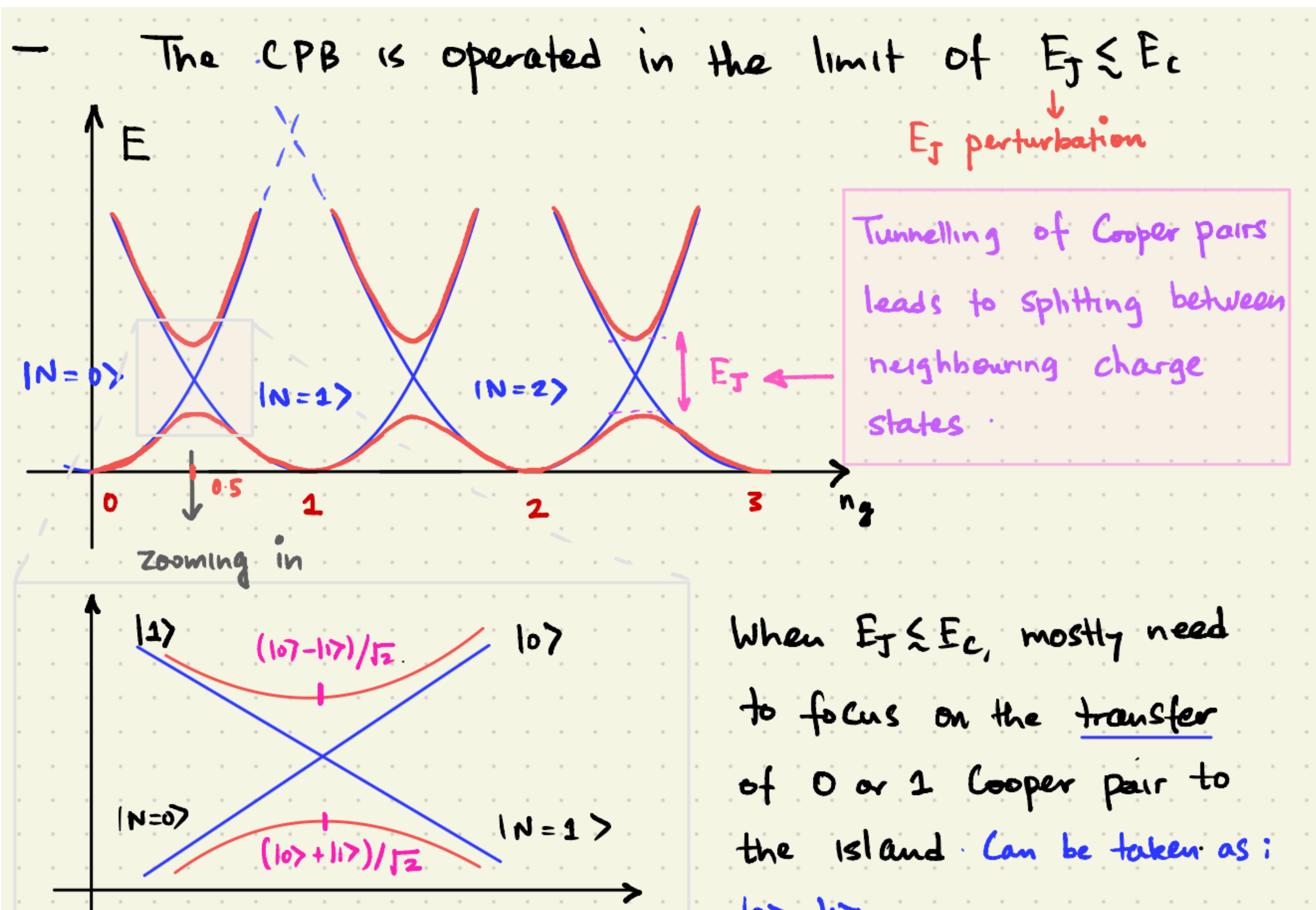
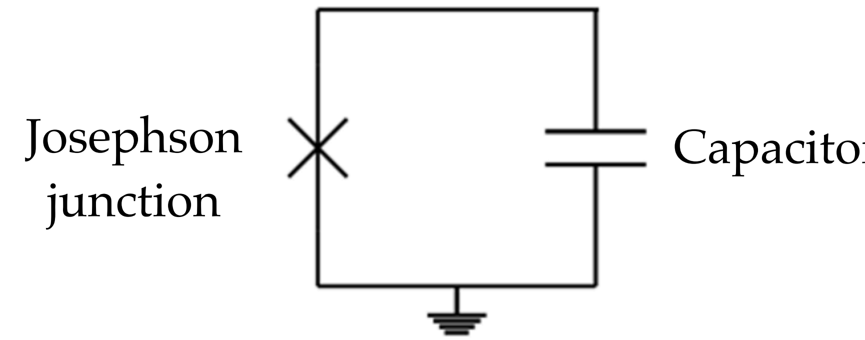


Srivatsan Chakram, Lecture Notes



Gaps the excitations from $|0\rangle$ to $|1\rangle$

We can truncate to $|0\rangle$ and $|1\rangle$

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Superconducting (Transmon) Qubits

Put a Josephson junction in a circuit, **Cooper pair box**

$$H = \sum_N \left(4E_C(N - n_g)^2 |N\rangle\langle N| - \frac{E_J}{2}(|N\rangle\langle N+1| + |N+1\rangle\langle N|) \right)$$

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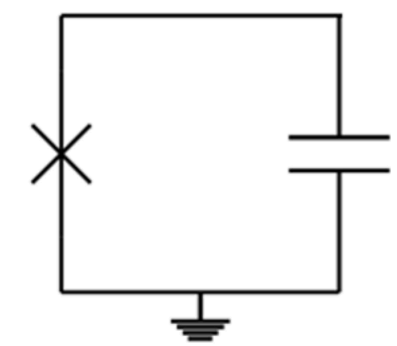


Truncating to $|0\rangle$ and $|1\rangle$ yields a qubit Hamiltonian!

$$H_{\text{eff}} = -4E_C(1/2 - n_g)\sigma_z - E_J/2\sigma_x$$

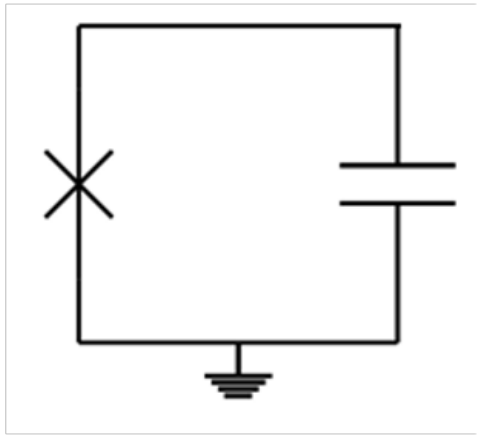
$$\sigma_z = |0\rangle\langle 0| - |1\rangle\langle 1| \qquad \sigma_x = |0\rangle\langle 1| + |1\rangle\langle 0|$$

With a spectrum $E_\pm = \pm\, 16\sqrt{E_C^2(1/2 - n_g)^2 + E_J^2/4} = \pm\, \omega_q$

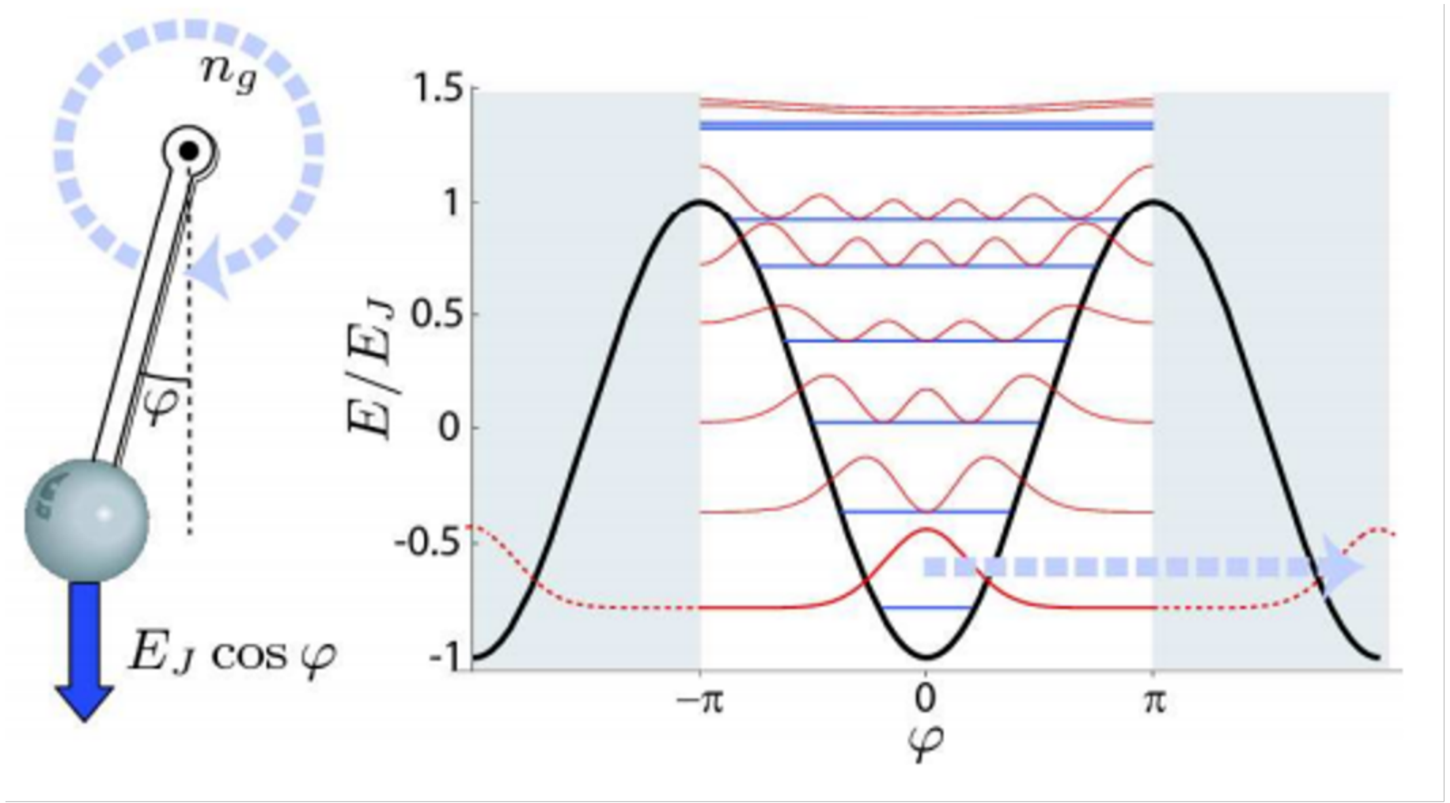
Single qubit rotations are performed by driving the gate voltage at ω_q

Summary: Superconducting (Transmon) Qubits

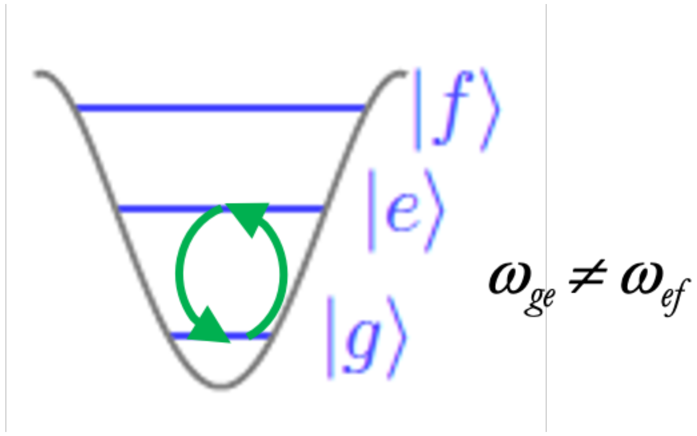
- Transmon is the simplest superconducting qubit
- Key element is the *Josephson Junction*
- Phase difference – macroscopic quantum DOF
- Junction acts as a nonlinear inductor



$$H = 4E_C(\hat{n} - n_g)^2 - E_J \cos(\hat{\varphi}) \text{ (anharmonic oscillator)}$$



- Lowest two levels form a qubit
- Transmon non-linearity used for cavity control



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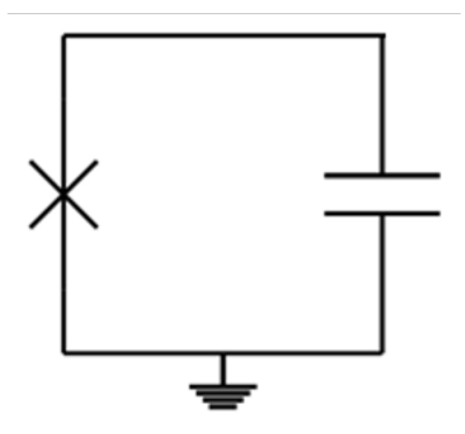
Superconducting Qubits

Lots of different types of superconducting qubits

Charge qubits

(what we have focused on)

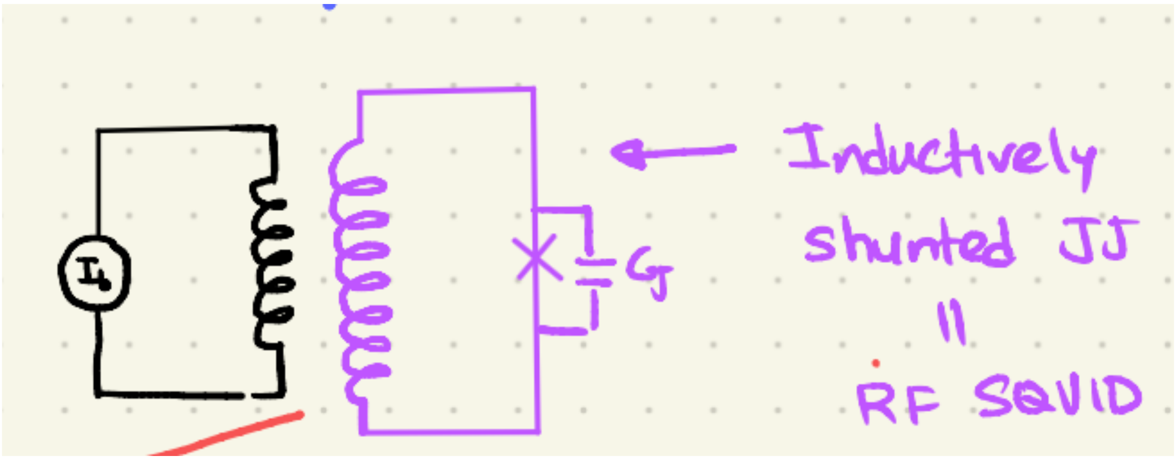


Cooper pair box
Quantronium
Transmon

Qubit is a superposition of charge states on an island

Inductively Shunted qubits

(Will not cover)



RF SQUID
Flux qubit
Phase qubit
Fluxonium qubit

Qubit is a superposition of persistent currents in a loop

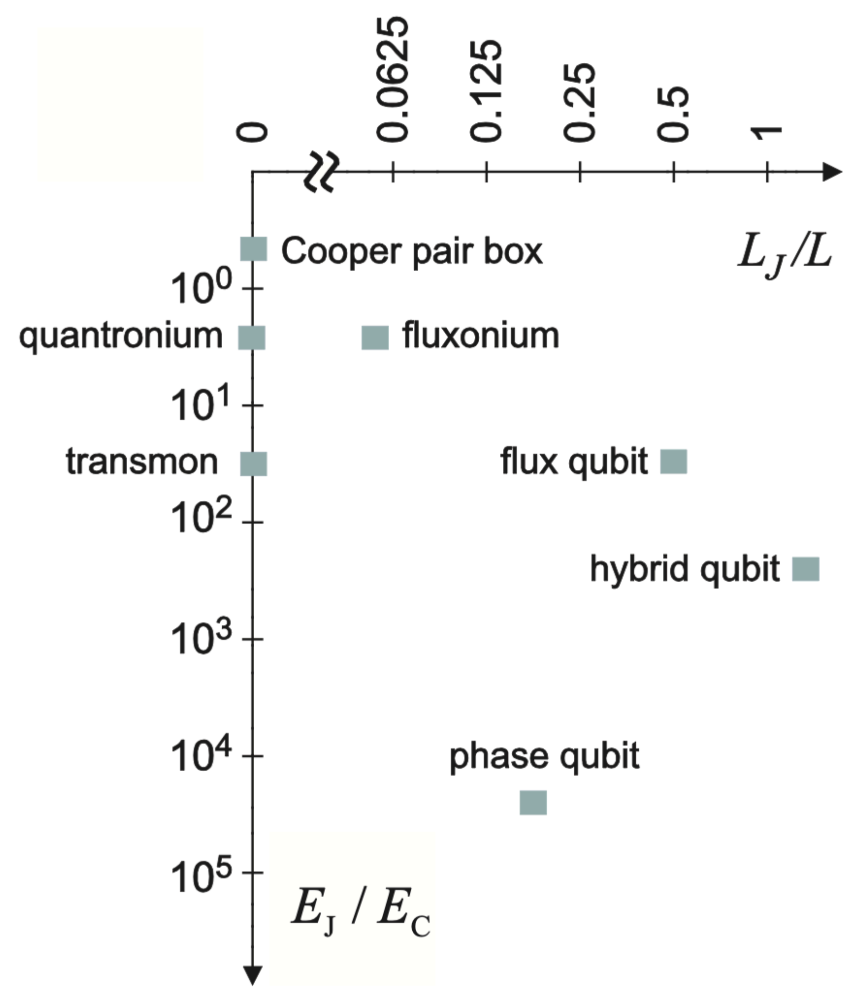
Superconducting Qubits

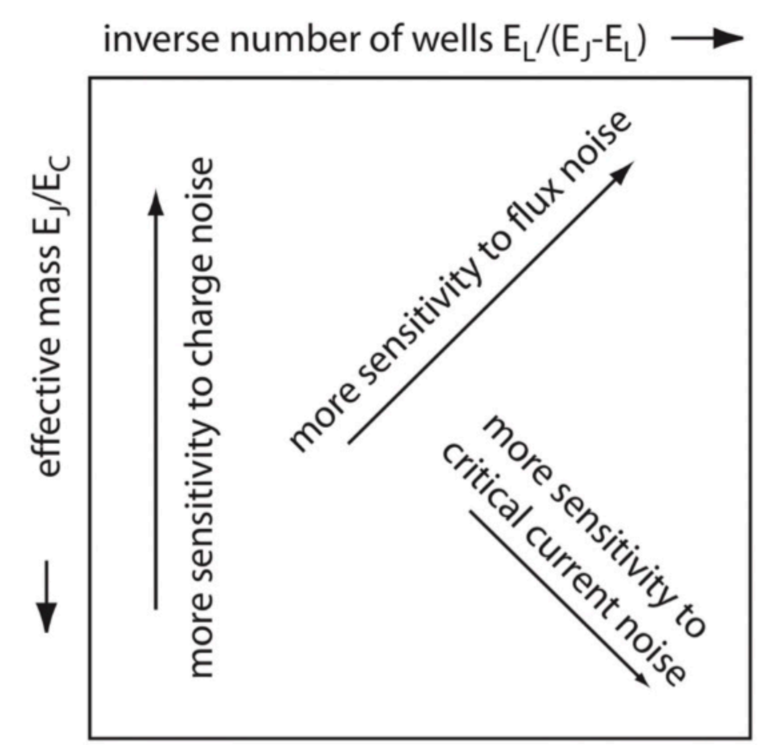
Lots of different types of superconducting qubits

Charge qubits
(what we have focused on)

Inductively Shunted qubits
(Will not cover)

"Periodic table" of superconducting qubits





Lots of different forms of 2 qubit gates (e.g. bring two capacitively coupled qubits in resonance)

Krantz et al, Applied Physics Reviews (2019)

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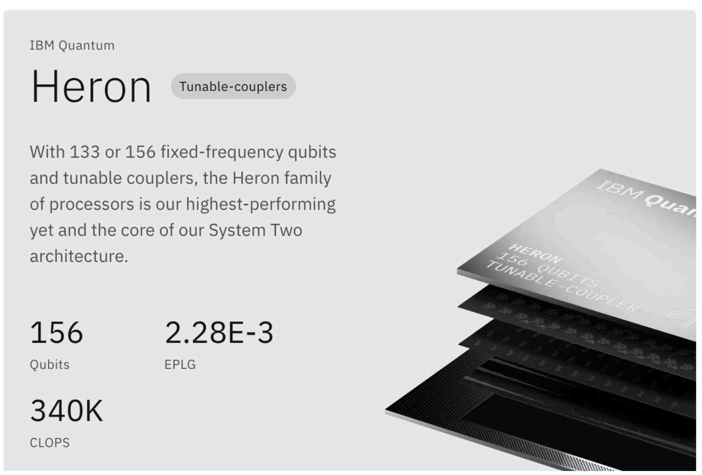
Superconducting Qubits

Major efforts to scale up superconducting qubits lead by IBM and Google

IBM



Google Quantum AI

IBM Quantum Platform | Search | us-east | Sign i

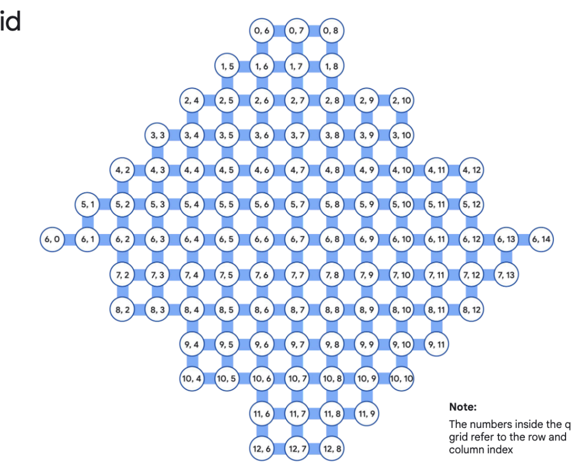
Search by name

Heron × | Reset filters

QPU name	Region	Qubits	Status	Pending jobs	Type	2Q error (median)	2Q error (layered)	Readout error (median)	CLOPS
ibm_boston	us-east	156	Online	0	Heron r3	1.16E-3	2.28E-3	5.371E-3	340K
ibm_kingston	us-east	156	Online	0	Heron r2	1.89E-3	3.42E-3	1.05E-2	340K
ibm_pittsburgh	us-east	156	Online	0	Heron r3	1.59E-3	3.37E-3	5.371E-3	330K
ibm_fez	us-east	156	Online	0	Heron r2	2.68E-3	4.88E-3	1.233E-2	320K
ibm_marrakesh	us-east	156	Online	0	Heron r2	2.71E-3	4.16E-3	1.276E-2	300K
ibm_aachen	eu-de	156	Online	1	Heron r3	1.67E-3	3.29E-3	7.568E-3	330K

Willow System Metrics	
Number of qubits	105
Average connectivity	3.47 (4-way typical)

Qubit grid



Superconducting Qubits

Quantum computation with superconducting qubits (Summary)

	Single qubit gates	Two qubit gates	Measurement \ reset
Gate speeds	~10–50 ns	~10–300 ns	~0.5–5 μs
Fidelity (typical)	99.9–99.99%	99.0–99.9%	97–99.5%

Coherence times

Time to decay from excited state: $T_1 \approx 50\text{-}125\mu s$

dephasing time: $T_2 \approx 70\text{-}150\mu s$

Superconducting Qubits

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In summary: Trapped ions and neutral atoms have long coherence times but are controlled via optical pulses and so the gate speeds are slow. Superconducting qubits have fast gate times but less coherence. Who will win the race??

Outline

I. Lecture series layout
II. Motivation to study quantum many-body systems
III. Platforms to study and control quantum many-body systems
IV. Experiments in unitary many-body dynamics
V. Measuring and manipulating many-body dynamics

Experiments Probing Many Body Chaos and Integrability

These quantum platforms have opened the door to perform experiments on the unitary evolution of quantum many body systems.

The theoretical questions we asked near the end of lecture 1 can now be explored experimentally. **Tests of ETH**

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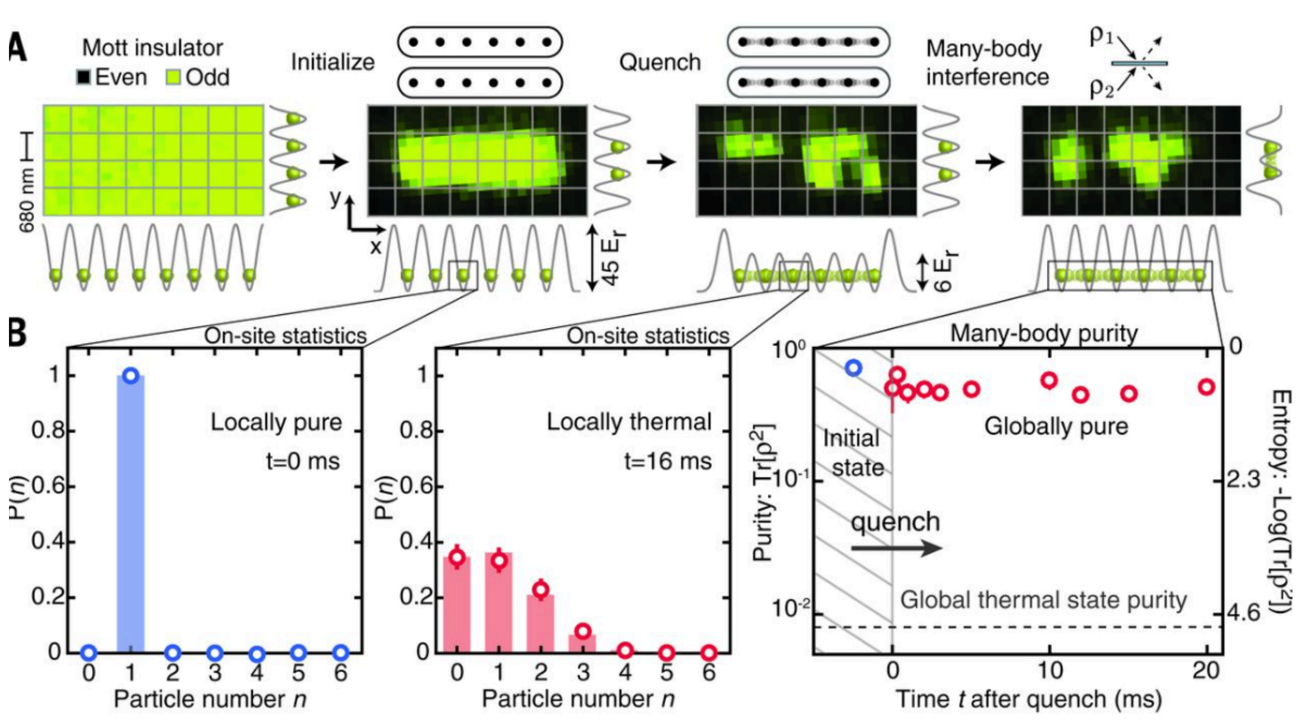
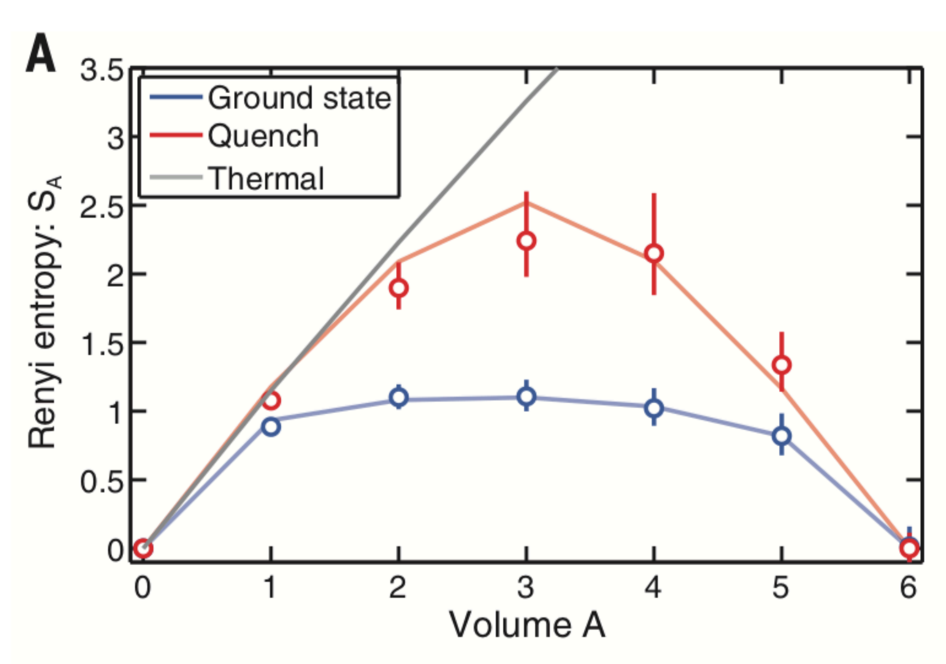
Quantum thermalization through entanglement in an isolated many-body system

Gas of ultracold ^{87}Rb

ADAM M. KAUFMAN, M. ERIC TAI, ALEXANDER LUKIN, MATTHEW RISPOLI, ROBERT SCHITTKO, PHILIPP M. PREISS, AND MARKUS GREINER Authors Info & Affiliations

SCIENCE • 19 Aug 2016 • Vol 353, Issue 6301 • pp. 794-800 • DOI: 10.1126/science.aaf6725





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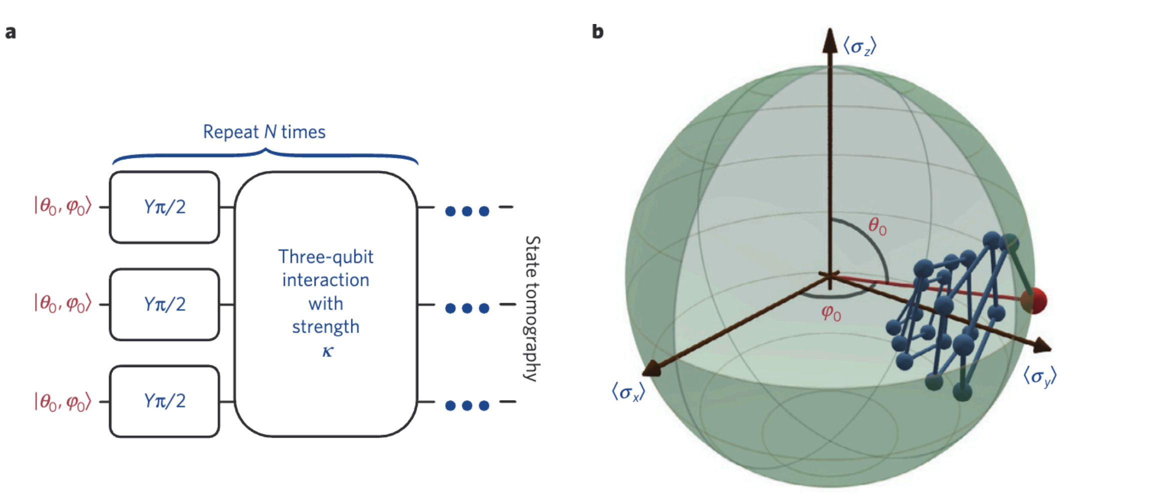
Ergodic dynamics and thermalization in an isolated quantum system

Superconducting qubits

C. Neill, P. Roushan, M. Fang, Y. Chen, M. Kolodrubetz, Z. Chen, A. Megrant, R. Barends, B. Campbell, B. Chiaro, A. Dunsworth, E. Jeffrey, J. Kelly, J. Mutus, P. J. J. O'Malley, C. Quintana, D. Sank, A. Vainsencher, J. Wenner, T. C. White, A. Polkovnikov & J. M. Martinis

Nature Physics **12**, 1037–1041 (2016) | Cite this article



Simulation of ergodicity in the quantum kicked top (lecture 1)

$$\mathcal{H}(t) = \frac{\pi}{2\tau} J_y + \frac{\kappa}{2j} J_z^2 \sum_{n=1}^{N} \delta(t - n\tau)$$

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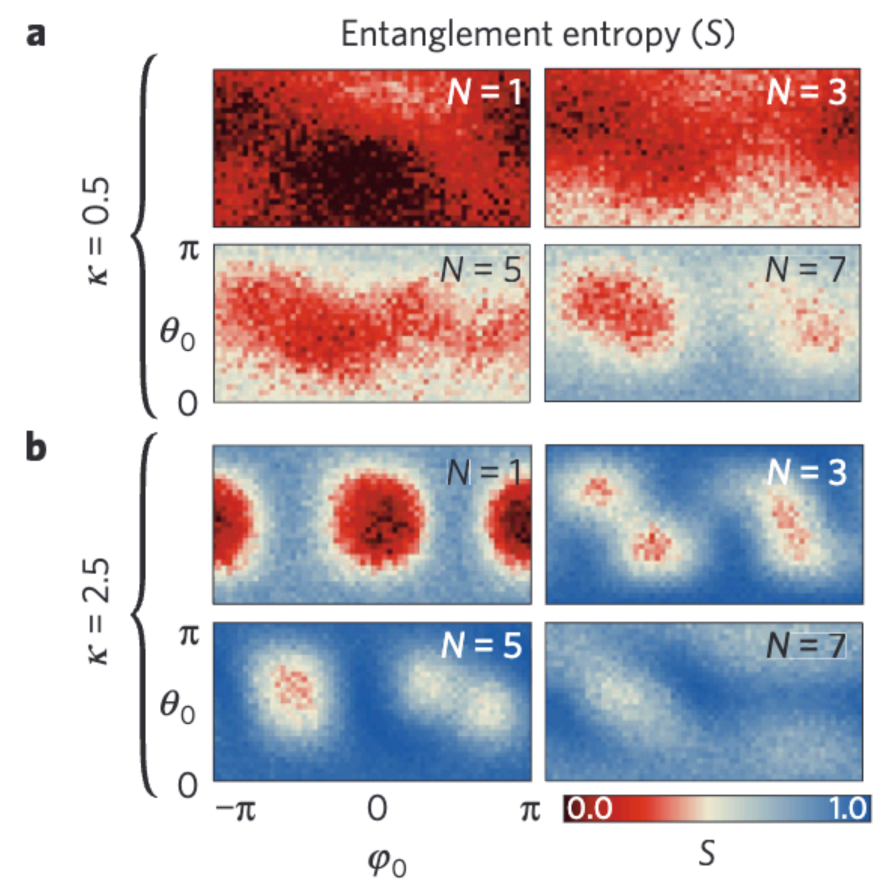

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Observation of prethermalization in long-range interacting spin chains

Trapped ions

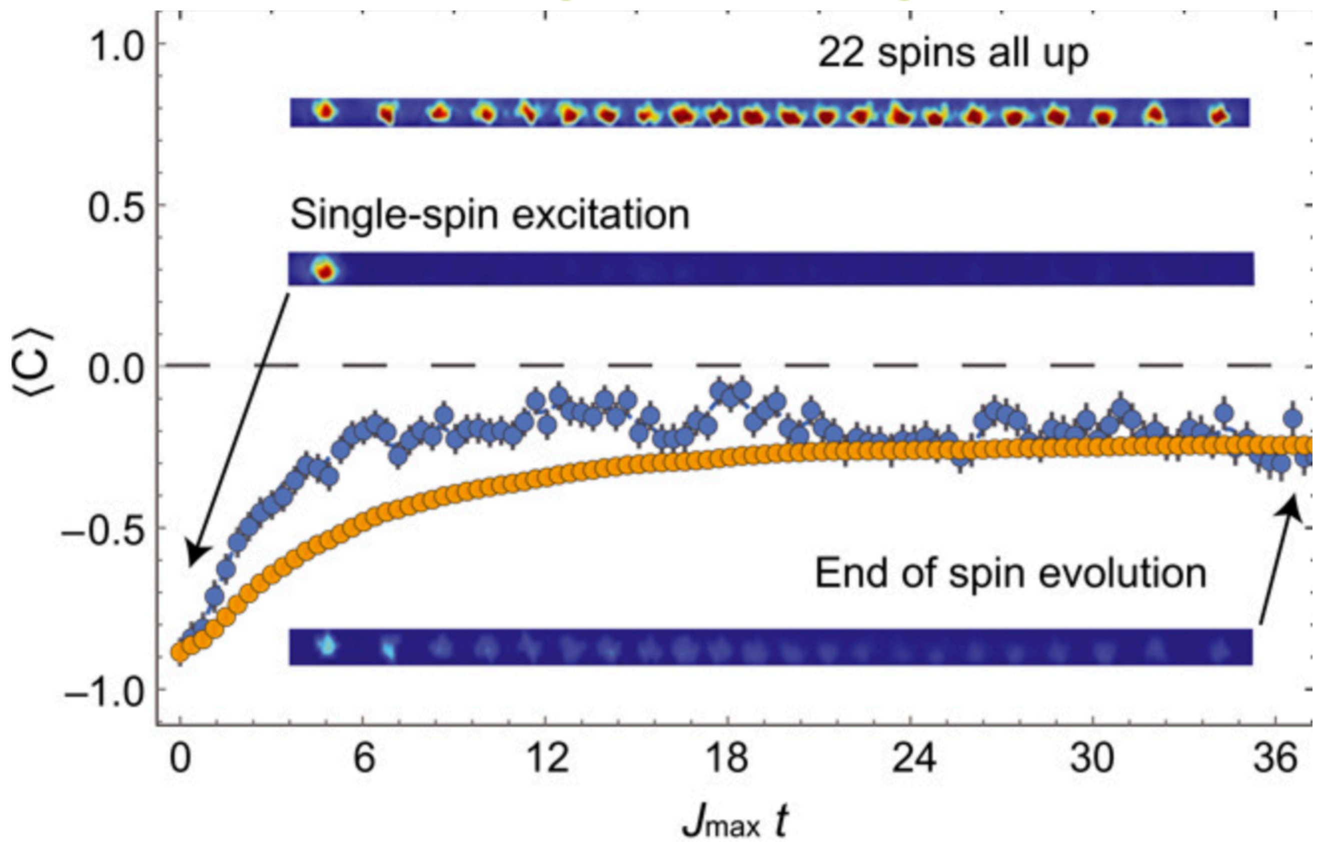
BRIAN NEYENHUIS, JIEHANG ZHANG, PAUL W. HESS, JACOB SMITH, AARON C. LEE, PHIL RICHERME, ZHE-XUAN GONG, ALEXEY V. GORSHKOV, AND CHRISTOPHER MONROE Authors Info & Affiliations

Close to an integrable model, slow thermalization

$$H = \sum_{i<j} J_{ij}\sigma_i^x\sigma_j^x + B\sum_i \sigma_i^z$$

Localization of the spin excitation

$$C = \sum_i \frac{2i - N - 1}{N-1}\frac{\sigma_i^z + 1}{2}$$



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Letter | Published: 13 April 2006

A quantum Newton's cradle

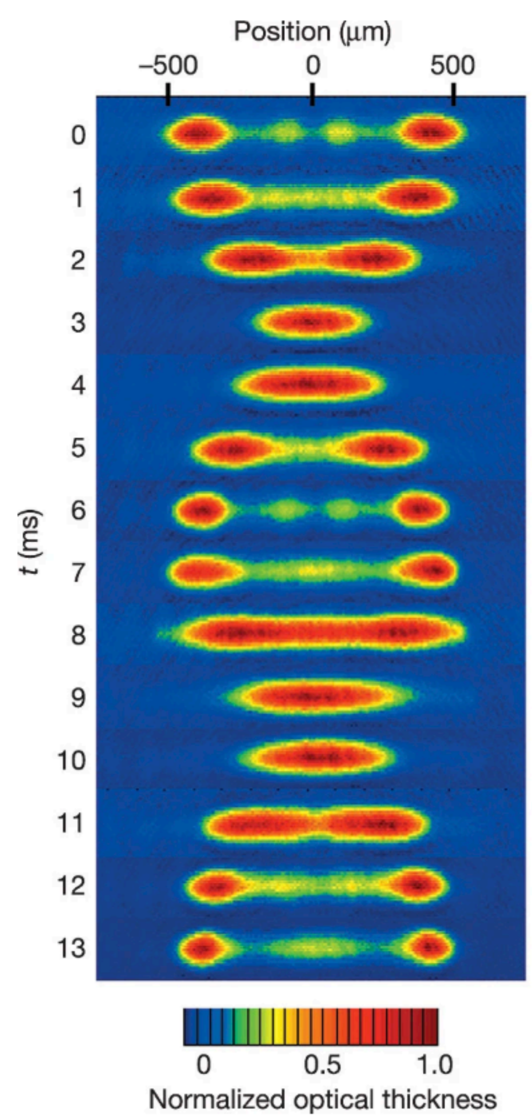
Toshiya Kinoshita, Trevor Wenger & David S. Weiss

Nature **440**, 900–903 (2006) | Cite this article

Gas of ultracold ^{87}Rb

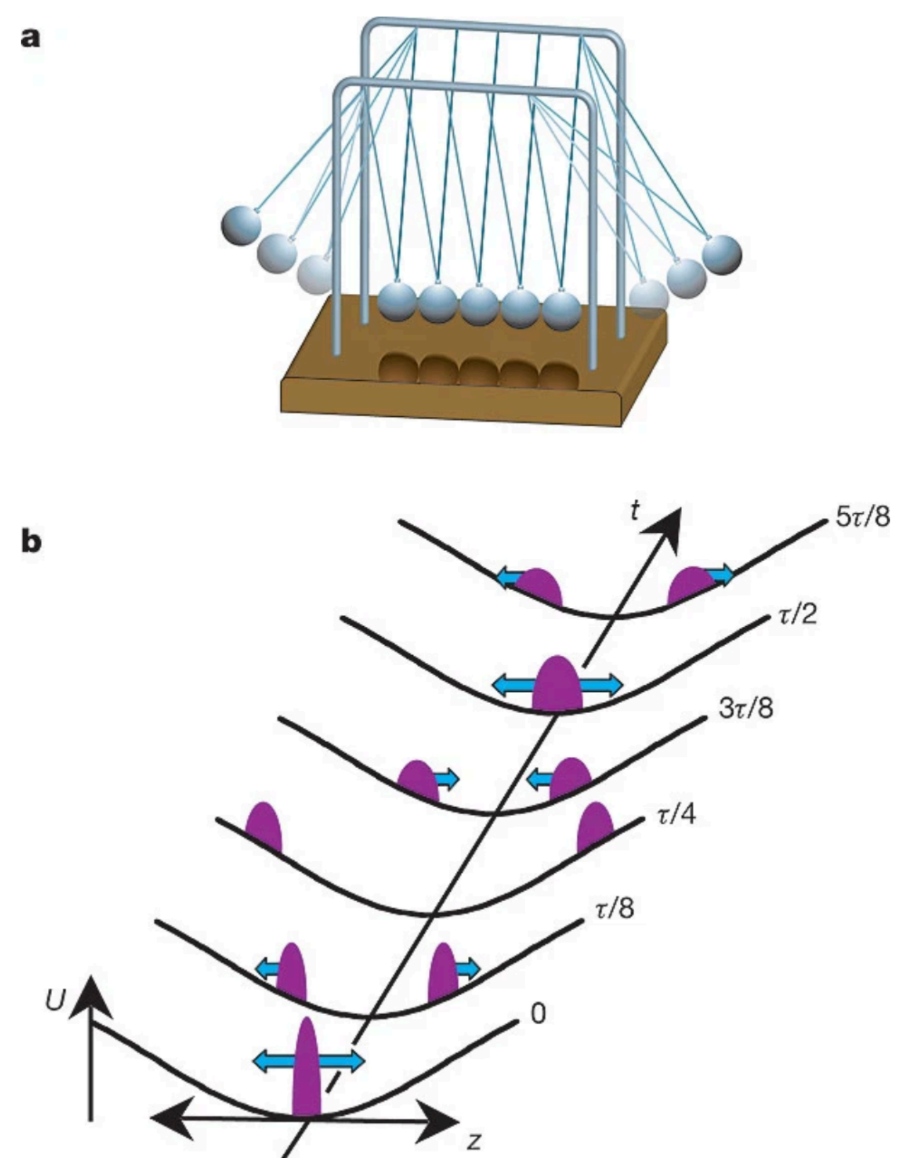
Realizing the Tonks-Giradau gas

$$i\hbar\frac{\partial\Psi_B}{\partial t}=\sum_{i=1}^{N}\left[-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x_i^2}+V\left(x_i,t\right)\right]\Psi_B + g_{1D}\sum_{1\leq i<j\leq N}\delta\left(x_i-x_j\right)\Psi_B,$$



Time of flight, absorption imaging

Integrable Dynamics



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Integrable Dynamics

Superconducting qubits

Dynamics of magnetization at infinite temperature in a Heisenberg spin chain

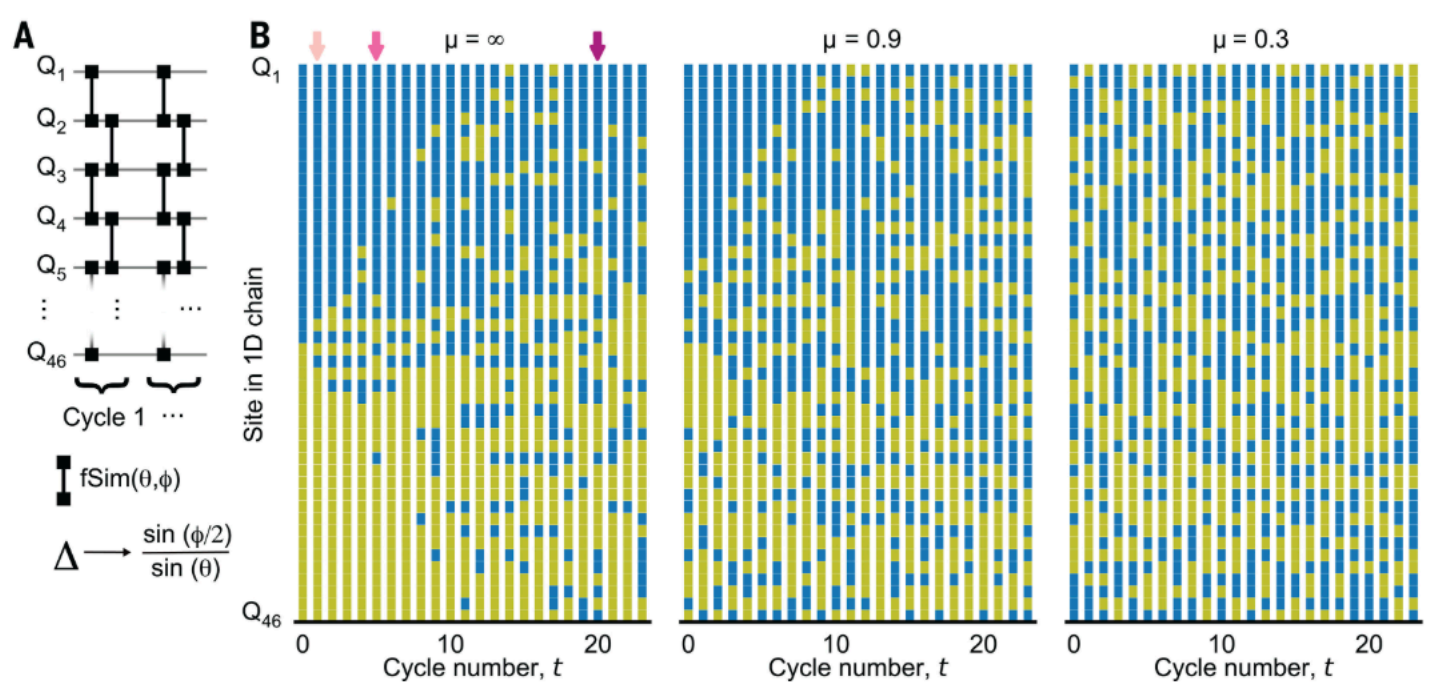
E. ROSENBERG, T. I. ANDERSEN, R. SAMAJDAR, A. PETUKHOV, J. C. HOKE, D. ABANIN, A. BENGTSSON, I. K. DROZDOV, C. ERICKSON, [...], AND P. ROUSHAN

+171 authors Authors Info & Affiliations

SCIENCE • 4 Apr 2024 • Vol 384, Issue 6691 • pp. 48-53 • DOI: 10.1126/science.adi7877

$$H = \sum_i \left(S_i^x S_{i+1}^x + S_i^y S_{i+1}^y + \Delta S_i^z S_{i+1}^z \right)$$

Domain wall dynamics Consistent with Bethe ansatz solution



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Observations of Many-Body Localization

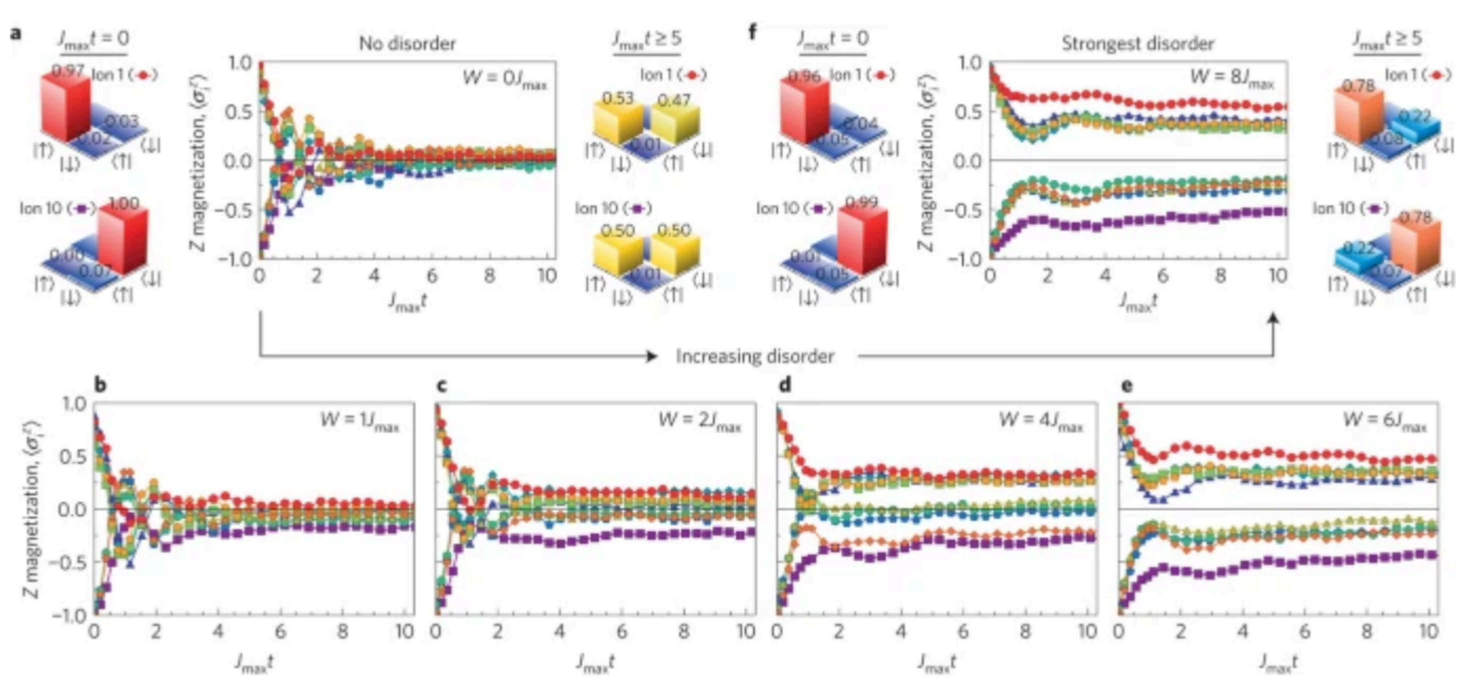
Trapped ions

Letter | Published: 06 June 2016

Many-body localization in a quantum simulator with programmable random disorder

J. Smith, A. Lee, P. Richerme, B. Neyenhuis, P. W. Hess, P. Hauke, M. Heyl, D. A. Huse & C. Monroe

Nature Physics **12**, 907–911 (2016) | Cite this article



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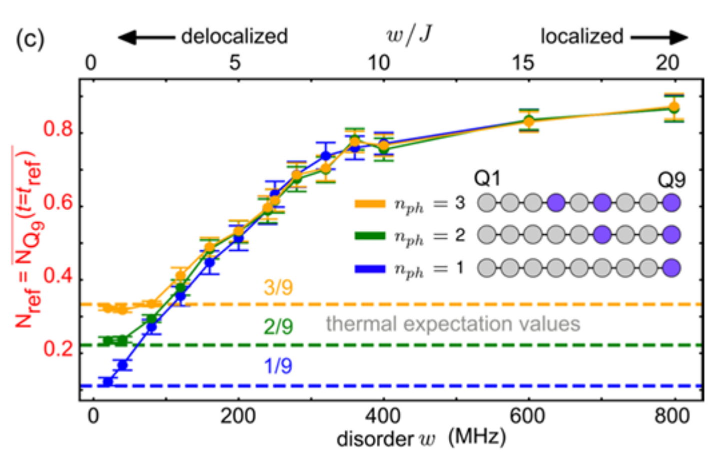
Observations of Many-Body Localization

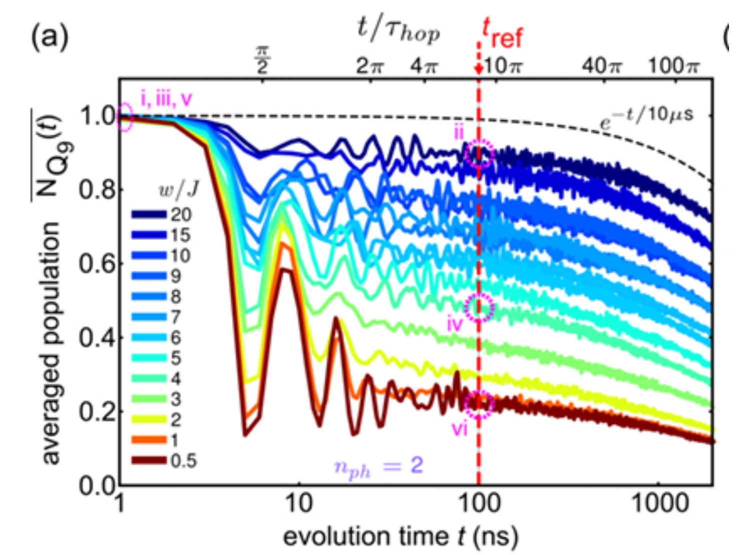
PHYSICAL REVIEW RESEARCH **4**, 013148 (2022)

Superconducting qubits

Direct measurement of nonlocal interactions in the many-body localized phase

B. Chiaro,[1,*] C. Neill,[2,*] A. Bohrdt,[3,4,*] M. Filippone,[5,*] F. Arute,[2] K. Arya,[2] R. Babbush,[2] D. Bacon,[2] J. Bardin,[2] R. Barends,[2] S. Boixo,[2] D. Buell,[2] B. Burkett,[2] Y. Chen,[2] Z. Chen,[2] R. Collins,[2] A. Dunsworth,[2] E. Farhi,[2] A. Fowler,[2] B. Foxen,[2] C. Gidney,[2] M. Giustina,[2] M. Harrigan,[2] T. Huang,[2] S. Isakov,[2] E. Jeffrey,[2] Z. Jiang,[2] D. Kafri,[2] K. Kechedzhi,[2] J. Kelly,[2] P. Klimov,[2] A. Korotkov,[2] F. Kostritsa,[2] D. Landhuis,[2] E. Lucero,[2] J. McClean,[2] X. Mi,[2] A. Megrant,[2] M. Mohseni,[2] J. Mutus,[2] M. McEwen,[2] O. Naaman,[2] M. Neeley,[2] M. Niu,[2] A. Petukhov,[2] C. Quintana,[2] N. Rubin,[2] D. Sank,[2] K. Satzinger,[2] T. White,[2] Z. Yao,[2] P. Yeh,[2] A. Zalcman,[2] V. Smelyanskiy,[2] H. Neven,[2] S. Gopalakrishnan,[6] D. Abanin,[7] M. Knap,[3,4] J. Martinis,[1,2] and P. Roushan[2,†]





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Measuring Quantum Many Body Systems

If we want to learn something about the quantum system or correct an error we need to **measure** it. To do so, we must couple the quantum system to the environment (measurement apparatus) producing an open quantum system

Local measurements then will be **part** of the dynamics,
As the system is running it will also be locally measured.
Referred to as *midcircuit measurements*

Open Quantum Many Body Systems

Global measurements will collapse the many-body wave function, destroying the entangled state

5th Solvay Conference of Physics, *Electrons and Photons* 1927

$$\hat{M}|\Psi\rangle \rightarrow |\Psi_{\text{final}}\rangle = \frac{\hat{M}|\Psi\rangle}{\sqrt{\langle\Psi|\hat{M}^{\dagger}\hat{M}|\Psi\rangle}}$$

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Example: 3 spin-1/2s $|\Psi\rangle = \sum_{\{\alpha_i\}} C_{\alpha_1,\alpha_2,\alpha_3}|\alpha_1,\alpha_2,\alpha_3\rangle \quad \alpha_i = \uparrow,\downarrow$

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A **global** measurement yields $\quad \uparrow,\uparrow,\downarrow$

$$|\Psi_{\text{final}}\rangle = |\uparrow,\uparrow,\downarrow\rangle$$

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A **local** measurement yields $\uparrow$ at site 2

$$|\Psi_{\text{final}}\rangle = \frac{\sum_{\alpha_1,\alpha_3} C_{\alpha_1,\uparrow,\alpha_3}|\alpha_1,\uparrow,\alpha_3\rangle}{\sqrt{\sum_{\alpha_1,\alpha_3}|C_{\alpha_1,\uparrow,\alpha_3}|^2}}$$

Open Quantum Many Body Systems

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A **local** measurement yields $\uparrow$ at site 2

$$|\Psi_{\text{final}}\rangle = \frac{\sum_{\alpha_1,\alpha_3} C_{\alpha_1,\uparrow,\alpha_3}|\alpha_1,\uparrow,\alpha_3\rangle}{\quad}$$

An entangled superposition remains!

Measuring Quantum Many Body Systems

Now experimentally accessible!

Several quantum platforms can now perform midcircuit measurements
superconducting qubits, Rydberg arrays, trapped ions

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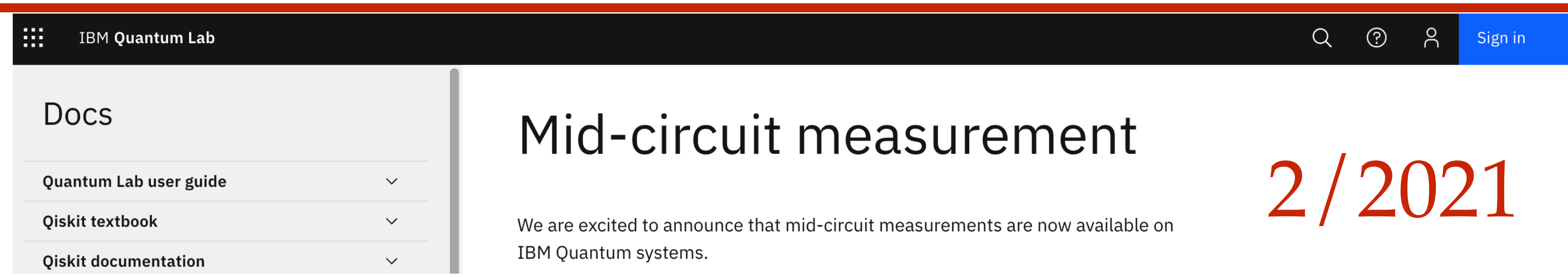
IBM Q



2/2021

Measuring Quantum Many Body Systems

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Several quantum platforms can now perform midcircuit measurements
superconducting qubits, Rydberg arrays, trapped ions

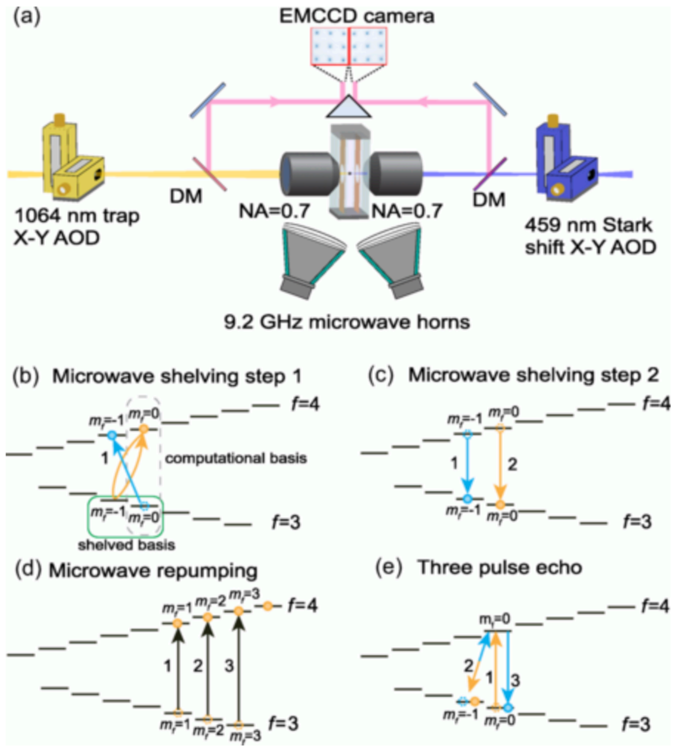
Midcircuit Measurements on a Single-Species Neutral Alkali Atom Quantum Processor

T. M. Graham[1], L. Phuttitarn[1], R. Chinnarasu[1], Y. Song[1,†], C. Poole[1], K. Jooya[1], J. Scott[1], A. Scott[1,‡], P. Eichler[1] *et al.*

Phys. Rev. X **13**, 041051 – **Published 15 December, 2023**

12/2023

Non-trivial with atoms as a measurement leads to the atom relaxing and emitting a photon disrupting nearby atoms. Have to "shelve" the qubit you want to measure so its far detuned from the rest.



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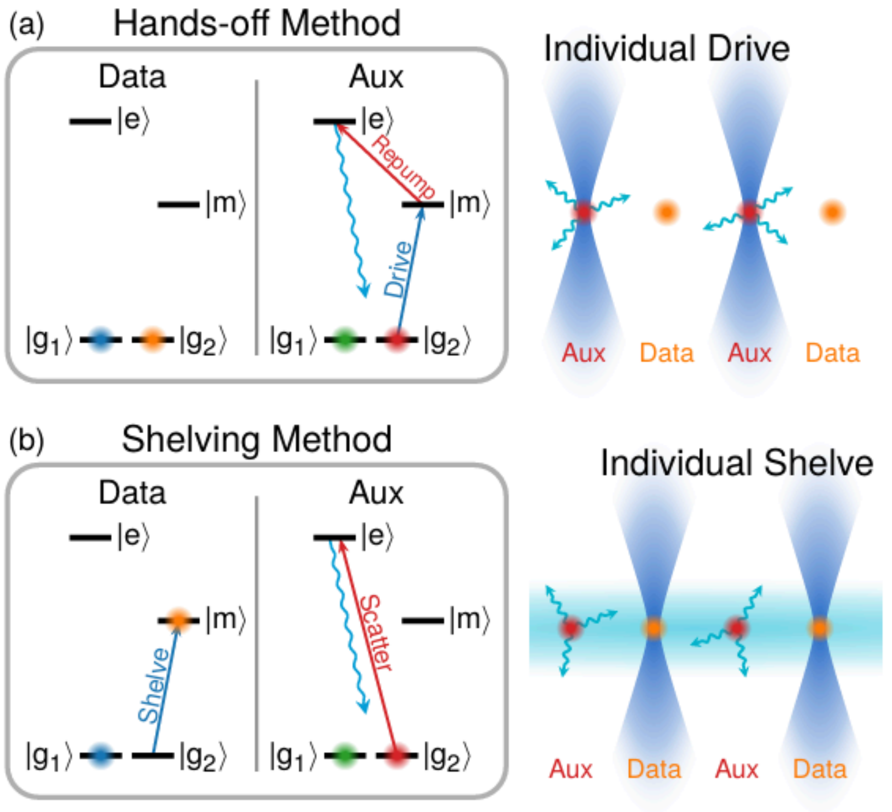
In-situ mid-circuit qubit measurement and reset in a single-species trapped-ion quantum computing system

arXiv:2504.12544 4/2025

Yichao Yu, Keqin Yan, Debopriyo Biswas, Vivian Ni Zhang, Bahaa Harraz, Crystal Noel, Christopher Monroe, Alexander Kozhanov

Non-trivial with atoms as a measurement leads to the atom relaxing and emitting a photon disrupting nearby atoms. Have to "shelve" the qubit you want to measure so its far detuned from the rest.



Measuring Quantum Many Body Systems

Can be used as a resource!

Measurement based quantum computation and measurement based state preparation.

Briegel, Browne, Dur, Raussendorf, Van den Nest, Nat. Phys. (2009).

Use measurements to prepare topological states

nature > articles > article

Article | Published: 14 February 2024

Non-Abelian topological order and anyons on a trapped-ion processor

Mohsin Iqbal, Nathanan Tantivasadakarn, Ruben Verresen, Sara L. Campbell, Joan M. Dreiling, Caroline Figgatt, John P. Gaebler, Jacob Johansen, Michael Mills, Steven A. Moses, Juan M. Pino, Anthony Ransford, Mary Rowe, Peter Siegfried, Russell P. Stutz, Michael Foss-Feig, Ashvin Vishwanath & Henrik Dreyer

Barvyi, Kim, Kliesch, Koenig arXiv (2022)

Tantivasadakarn, Thorngren, Vishwanath, Verresen arXiv (2023)

Measurement and Feedback in Quantum Many Body Systems

Now we want to use the outcome of the measurement to control the dynamics using real time feedback. This allows for quantum error correction, quantum state preparation, and the control of quantum chaos (Lecture 4).

Measurement and Feedback in Quantum Many Body Systems

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Article | Open access | Published: 22 February 2023

Suppressing quantum errors by scaling a surface code logical qubit

Google Quantum AI

Nature **614**, 676–681 (2023) | Cite this article

Use mid circuit measurements followed by a unitary operation to correct an unwanted error

25 cycles to reach a distance 5 surface code, a subextensive number of feedback operations

Measurement and Feedback in Quantum Many Body Systems

Now we want to use the outcome of the measurement to control the dynamics using real time feedback. This allows for quantum error correction, **quantum state preparation**, and the control of quantum chaos (Lecture 4).

Constant-Depth Quantum Circuits for Arbitrary Quantum State Preparation via Measurement and Feedback

Wei Zi,* Junhong Nie,† and Xiaoming Sun‡
State Key Lab of Processors, Institute of Computing Technology, Chinese Academy of Sciences, Beijing 100190, China and School of Computer Science and Technology, University of Chinese Academy of Sciences, Beijing 100049, China

The optimization of quantum circuit depth is crucial for practical quantum computing, as limited coherence times and error-prone operations constrain executable algorithms. Measurement and feedback operations are fundamental in quantum computing (e.g., quantum error correction); we develop a framework using them to achieve constant-depth implementations of essential quantum tasks. This includes preparing arbitrary quantum states with constant-depth circuits through measurement and feedback, breaking the linear-depth lower bound that is required without these operations. Our result paves the way for general quantum circuit compression using measurement and feedback.

Efficient preparation of the AKLT State with Measurement-based Imaginary Time Evolution

Tianqi Chen[1,2,3,4] and Tim Byrnes[1,5,6,7]

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Order from chaos with adaptive circuits on quantum hardware

Bibek Pokharel,[1,*] Haining Pan,[2,†] Kemal Aziz,[2] Luke C. G. Govia,[3] Sriram Ganeshan,[4,5] Thomas Iadecola,[6,7,8,9,10] Justin H. Wilson,[11,12] Barbara A. Jones,[3,‡] Abhinav Deshpande,[3] Jedediah H. Pixley,[2,13,§] and Maika Takita[1,¶]

arXiv:2509.18259

Conclusions

- Ultracold atoms are an ideal analog quantum simulator.
- Trapped ions can offer long range interactions for analog quantum simulation and can perform digital quantum gates for computation.
- Neutral (Rydberg) atoms offer an amazing amount of flexibility thanks to optical tweezer arrays for analog simulation and offer a new route to quantum computing.
- Superconducting qubits offer a macroscopic quantum tunneling process as the fundamental qubit. Lots of possibilities exist.
- Midcircuit measurements and feedback offer new routes to controlling quantum systems and exploring new forms of dynamcs.