Synthetic electromagnetism with neutral atoms

I. B. Spielman

Floquet topology

G. H. Reid, A. Pineiro, A. Fritsch, and M. Lu, **with Justyna Zwolak**

Synthetic Hall cylinder

M. Zhao, J. Tao, and Q. Liang

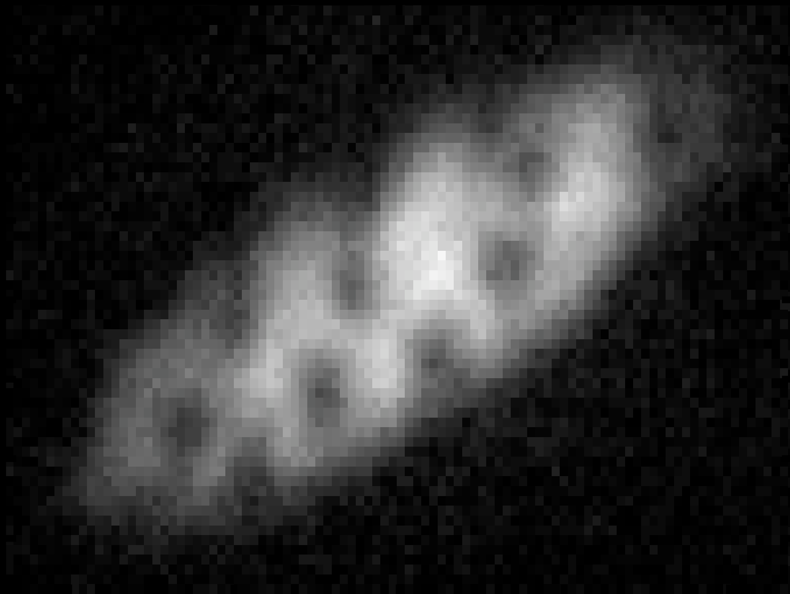
SOC, disorder, and weak measurement:

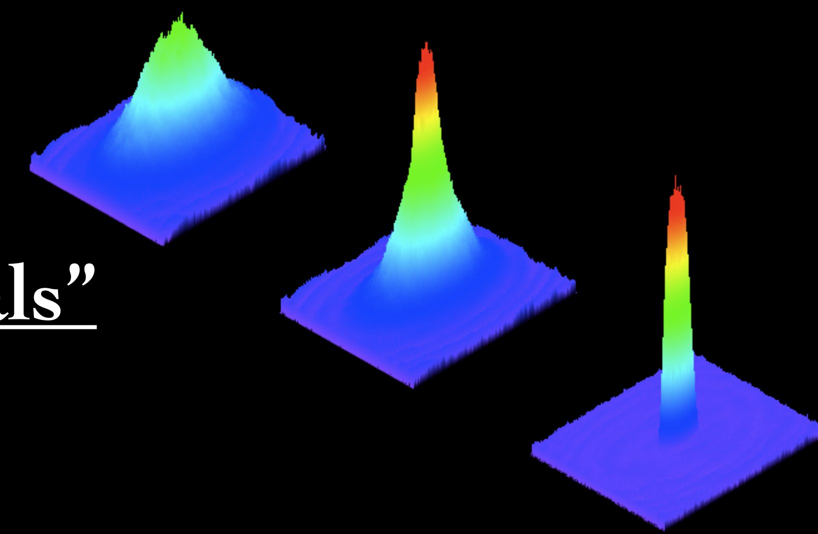
E. Altuntas

Support

NSF PFC@JQI, AFOSR Quantum Phases MURI, and NIST

Ultracold neutral atoms as a material system

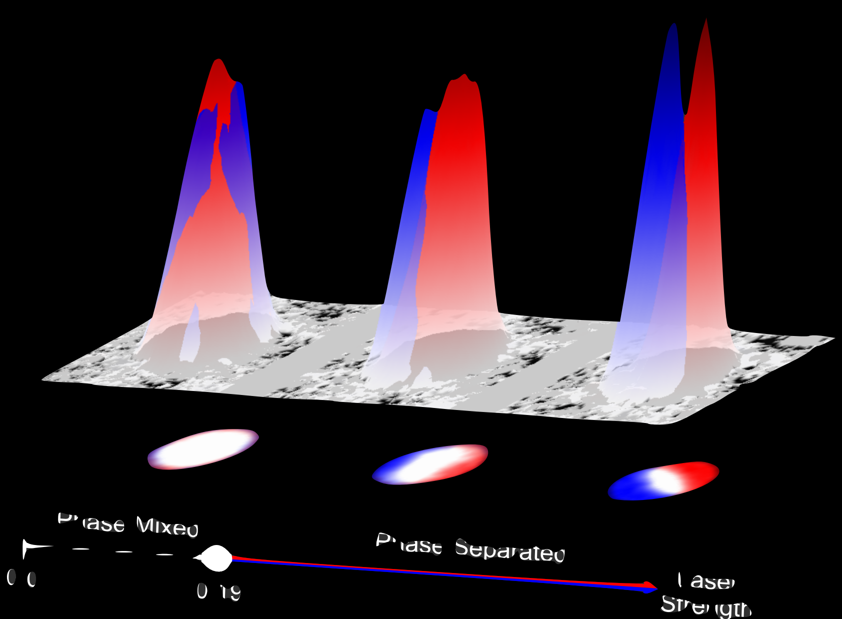




Cold atoms are good “materials”

Numerous properties can
be controlled and measured
on all relevant timescales and
in any lab

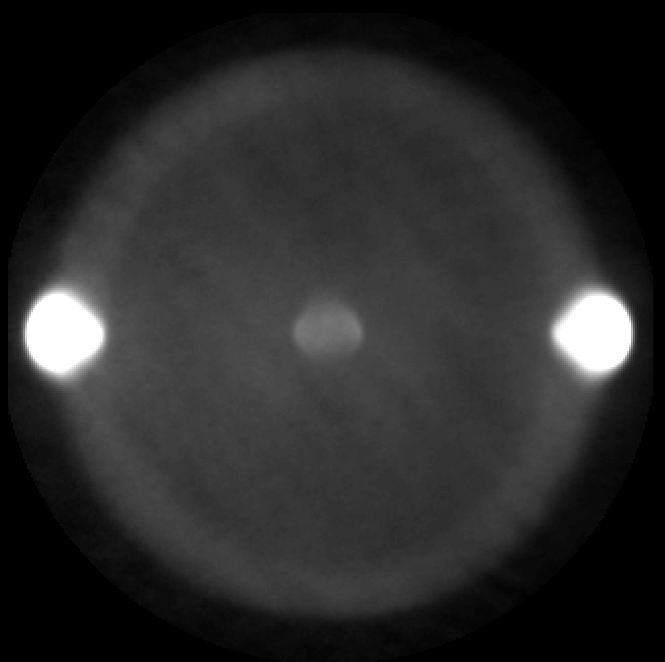
Very simple Hamiltonians



Cold atoms are bad “materials”

Short lived, and do so in vacuum

Interesting features **all** added
by hand (complex experiments).

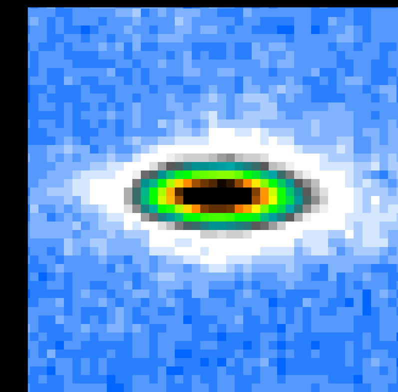


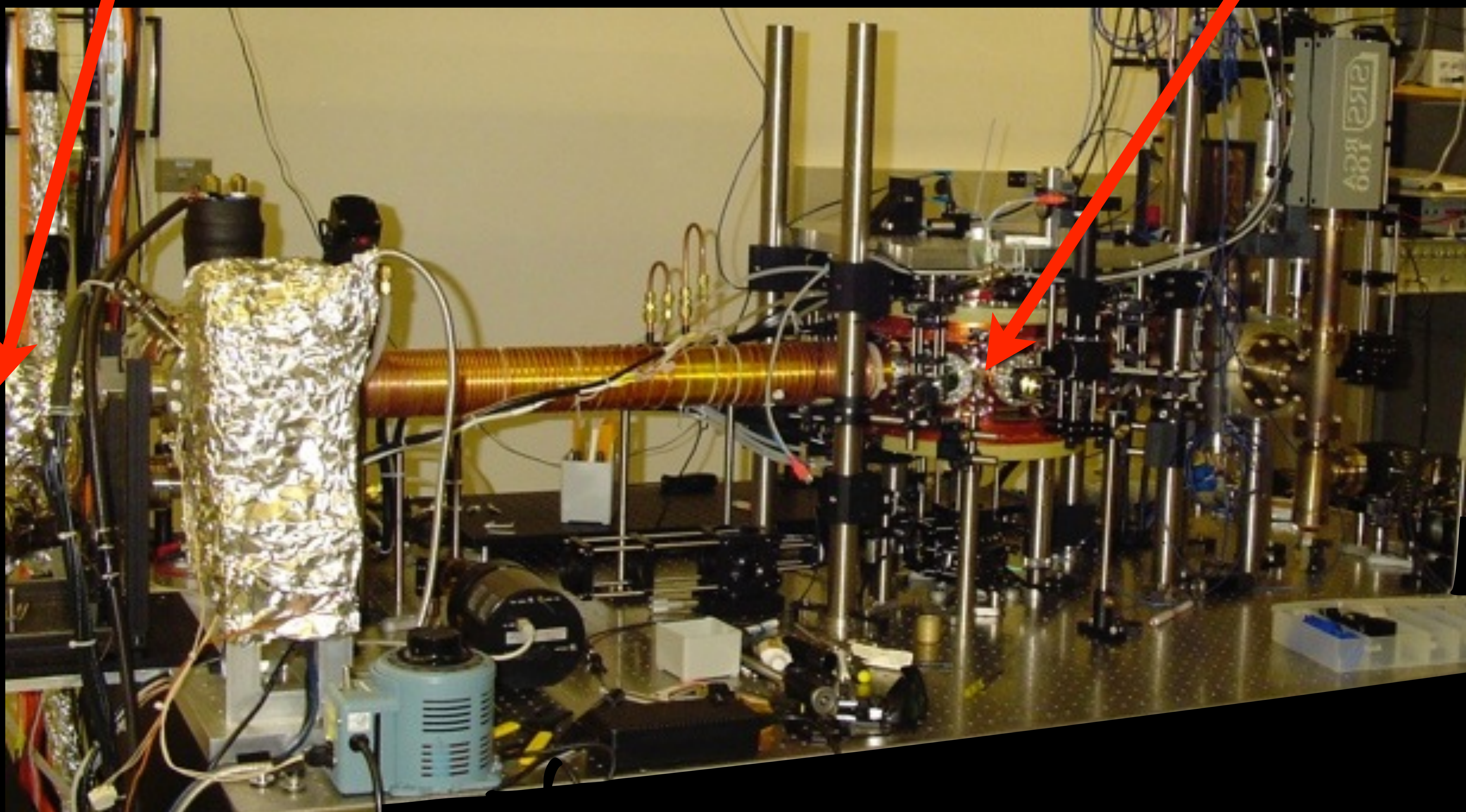
Starts like this

400 K

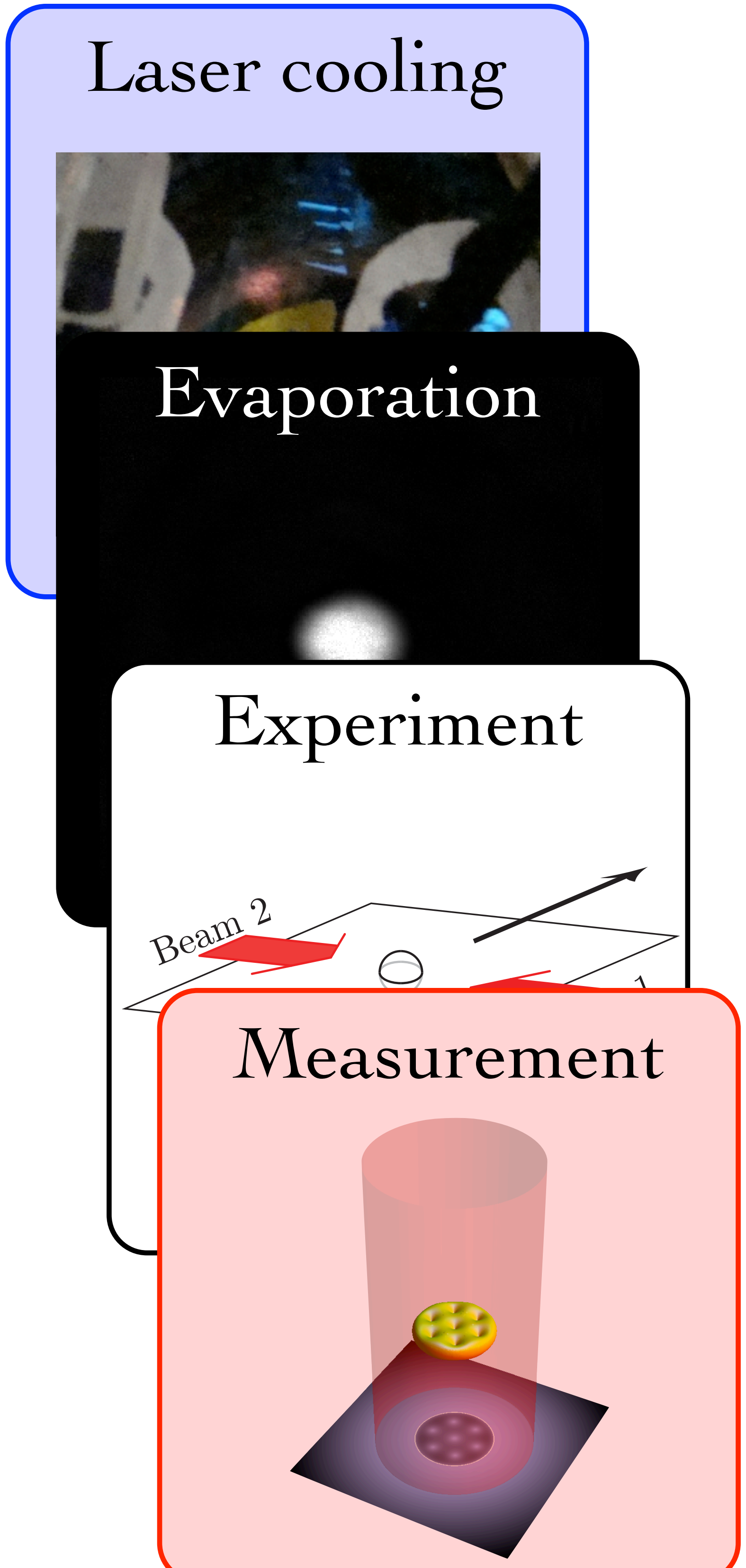
Ends here every 15 s

50 nK





Anatomy of an experiment



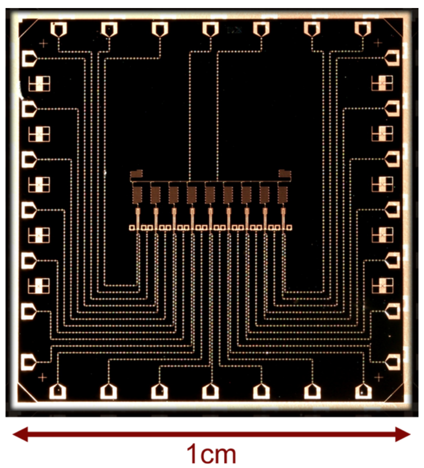
<u>Total cycle time is about 15 seconds</u>

We make a new BEC,
measure it,
destroy it,
and repeat.

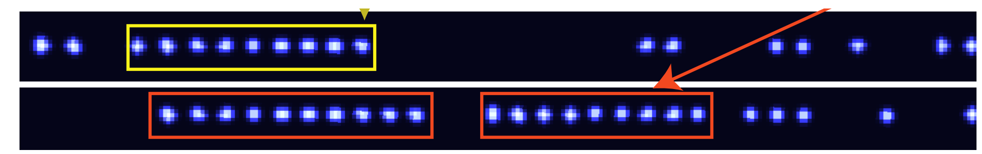
How to engineer atomic quantum (and photonic) systems

Bottom-up engineering (Micromanaging quantum systems)

Build the system up from well controlled quantum building blocks, e.g., qbits.



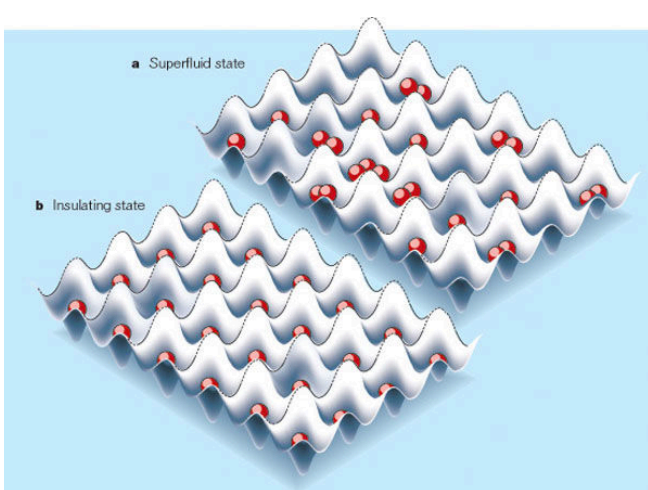
Martinis group / google; Science (2017)



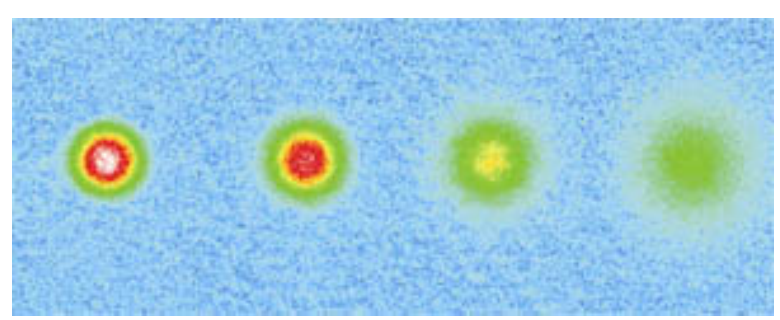
Monroe group; Nature (2017)

Hamiltonian engineering (Coaching quantum systems)

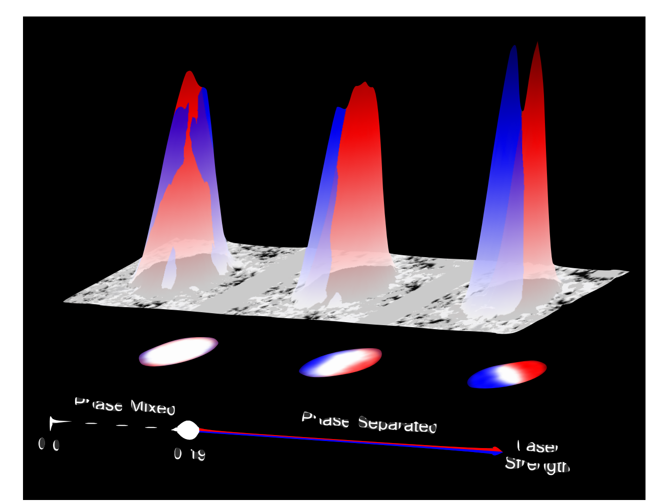
Build the Hamiltonian up with well calibrated control techniques



Bloch group; Nature (2002)



Jin group; Nature (2003)



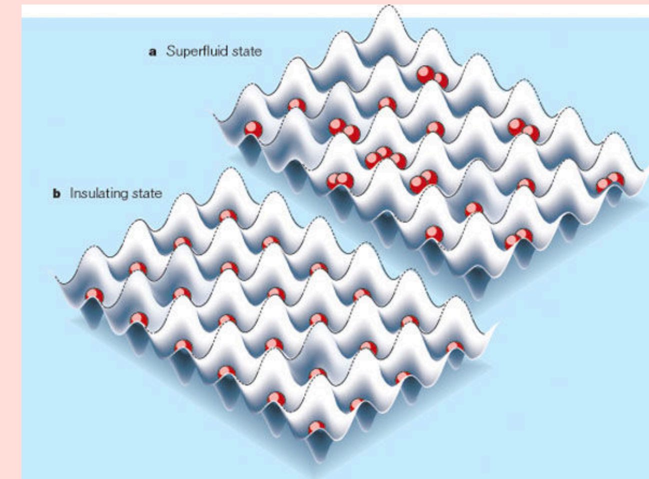
Lin et al; Nature (2011)

Our tools

Optical lattices

e.g., adding potentials

$$H = \frac{\hbar^2 \mathbf{k}^2}{2m} + \frac{V}{2}\cos(2k_r x) + \ldots.$$

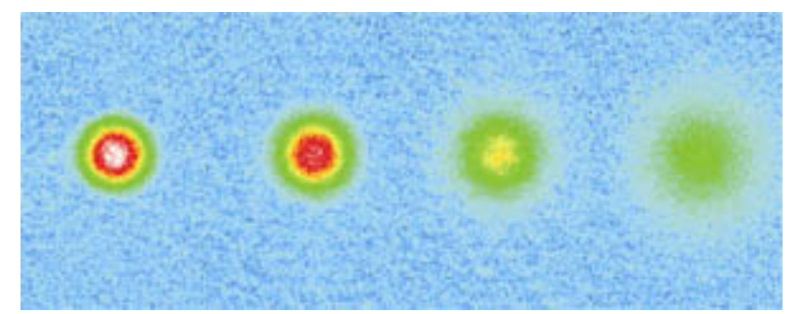


Interaction tuning

e.g., Feshbach resonances

$$H = \ldots. + g_{3\mathrm{D}}\delta(\mathbf{r}_i - \mathbf{r}_j) + \ldots$$

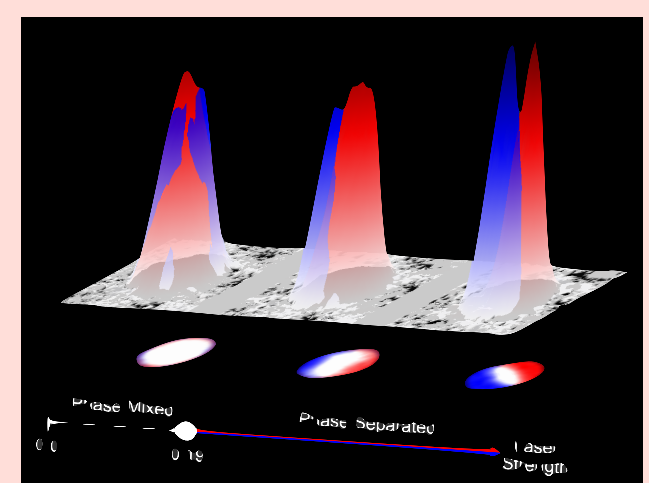
(really a regularized delta function…)



Gauge fields / SOC

e.g., laser induced motion

$$H = \frac{\left[\mathbf{k} - \hat{\mathcal{A}}(\mathbf{x})\right]^2}{2m} + \ldots.$$

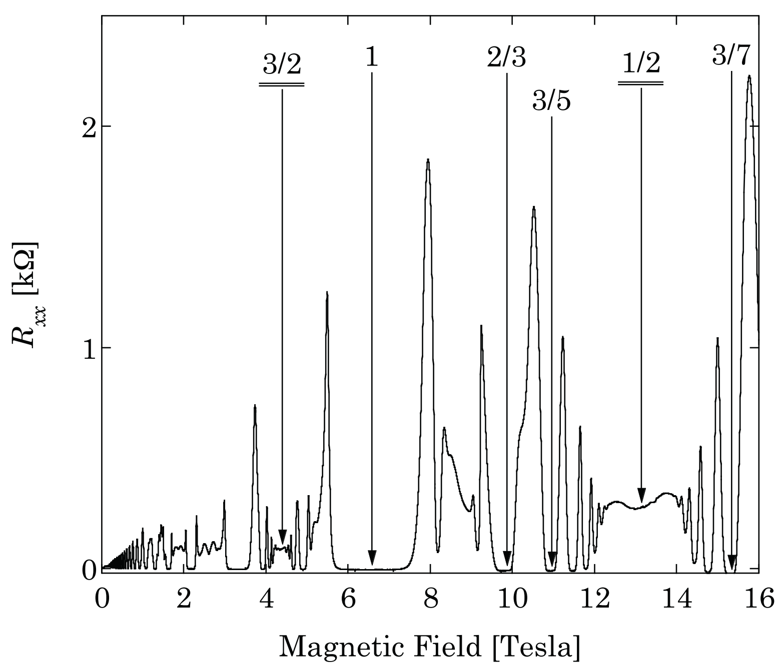


Lattice and gauge fields: why?

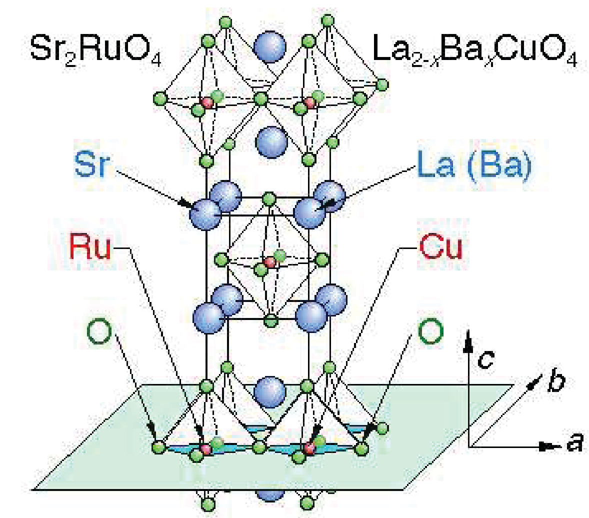
Fundamental physics of novel matter

Quantum Hall (bosons or fermions, **magnetic field**),
Quantum magnets (**spin-spin interactions, non-zero range**)
p-wave superconductors (fermions, spin polarized **p-wave interactions**)
Topological insulators (generally with **spin-orbit coupling**)
(almost!) chaos

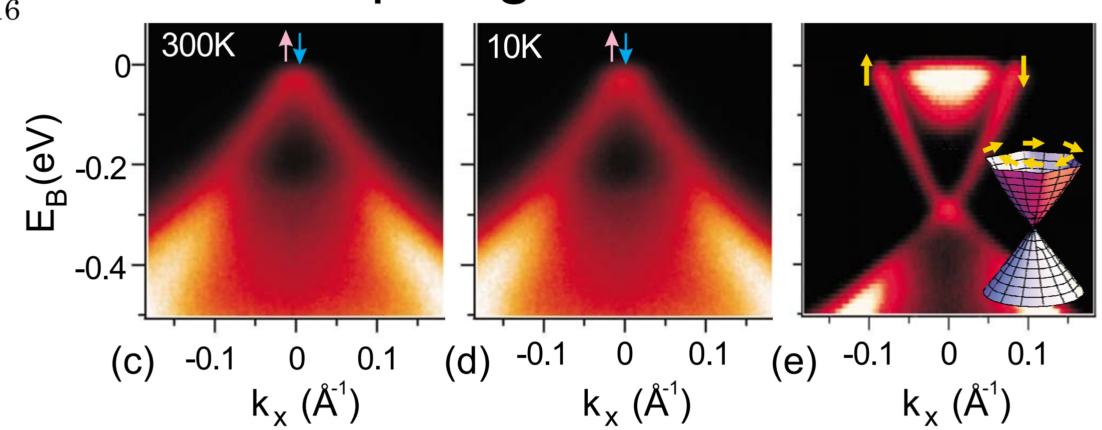
FQHE Systems



p-wave superconductivity



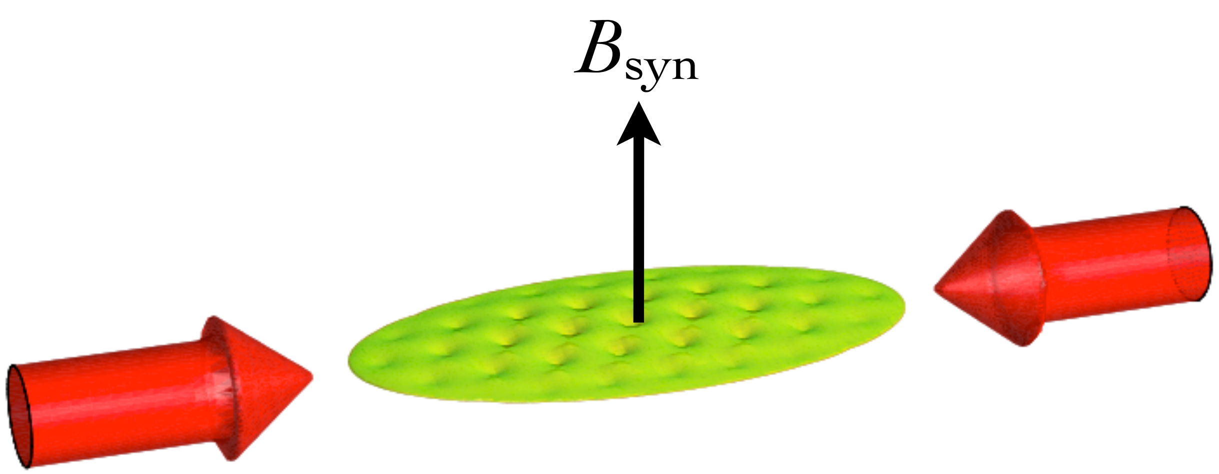
Topological insulators

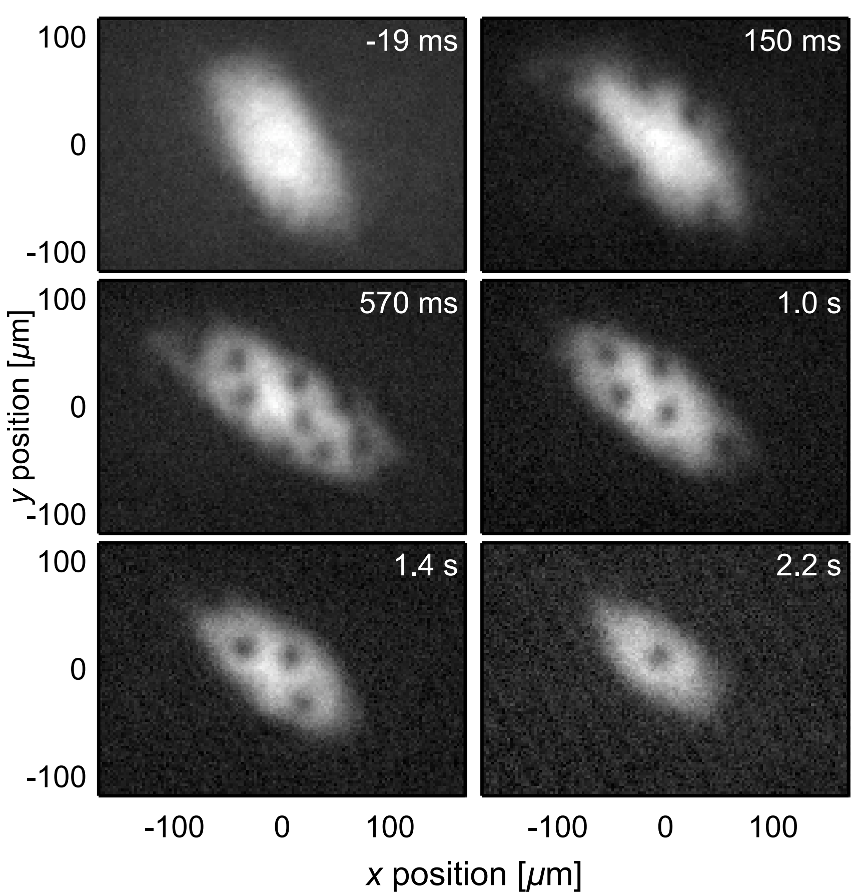


R. B. Laughlin. PRL (1983); A. Y. Kitaev, Ann. Phys. (2006); Hassan and Kane, RMP (2010)

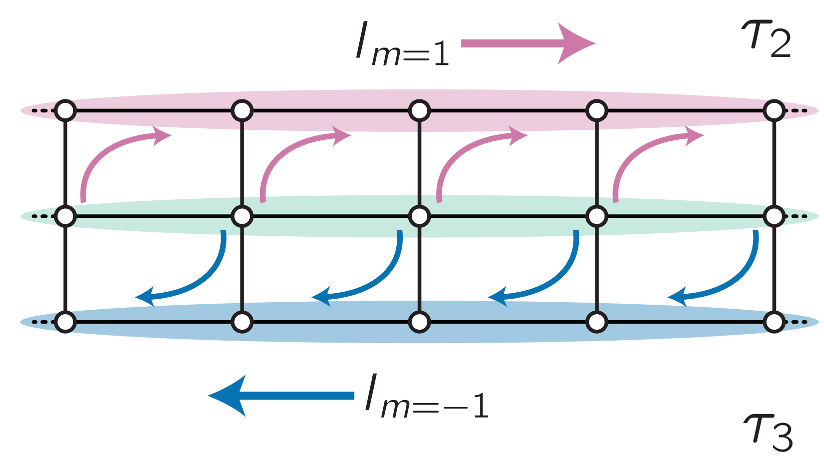
Outline

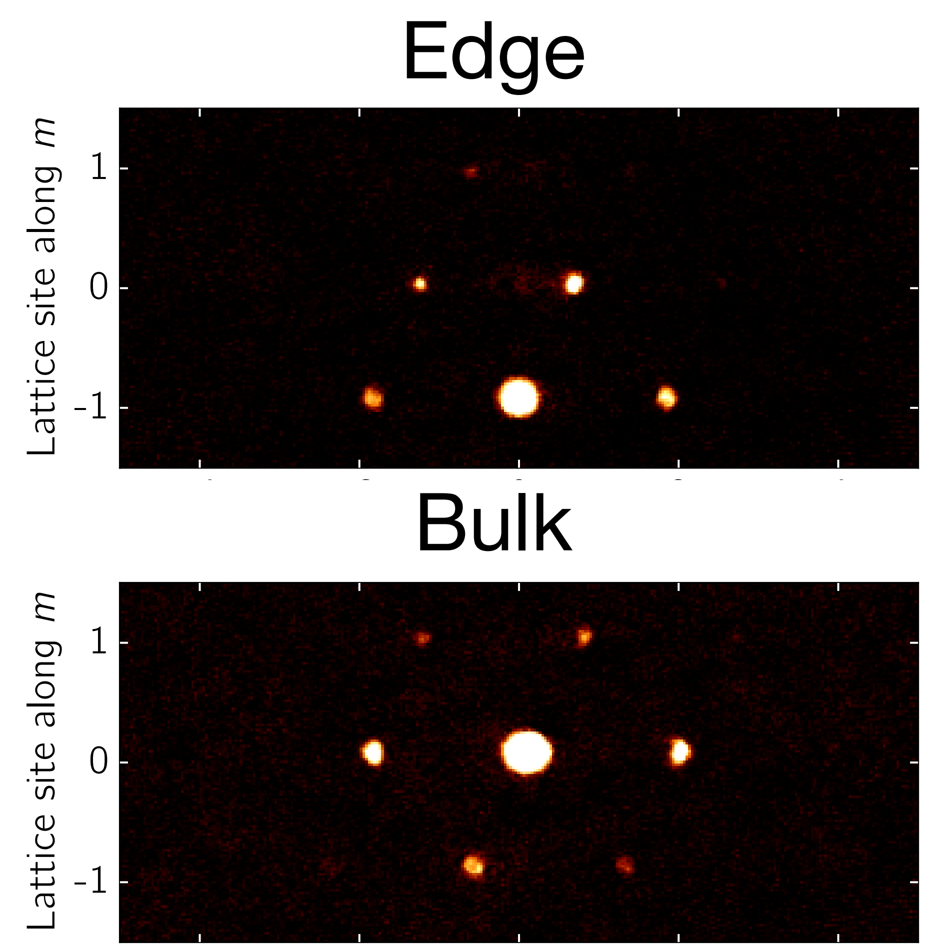
Fields in free space



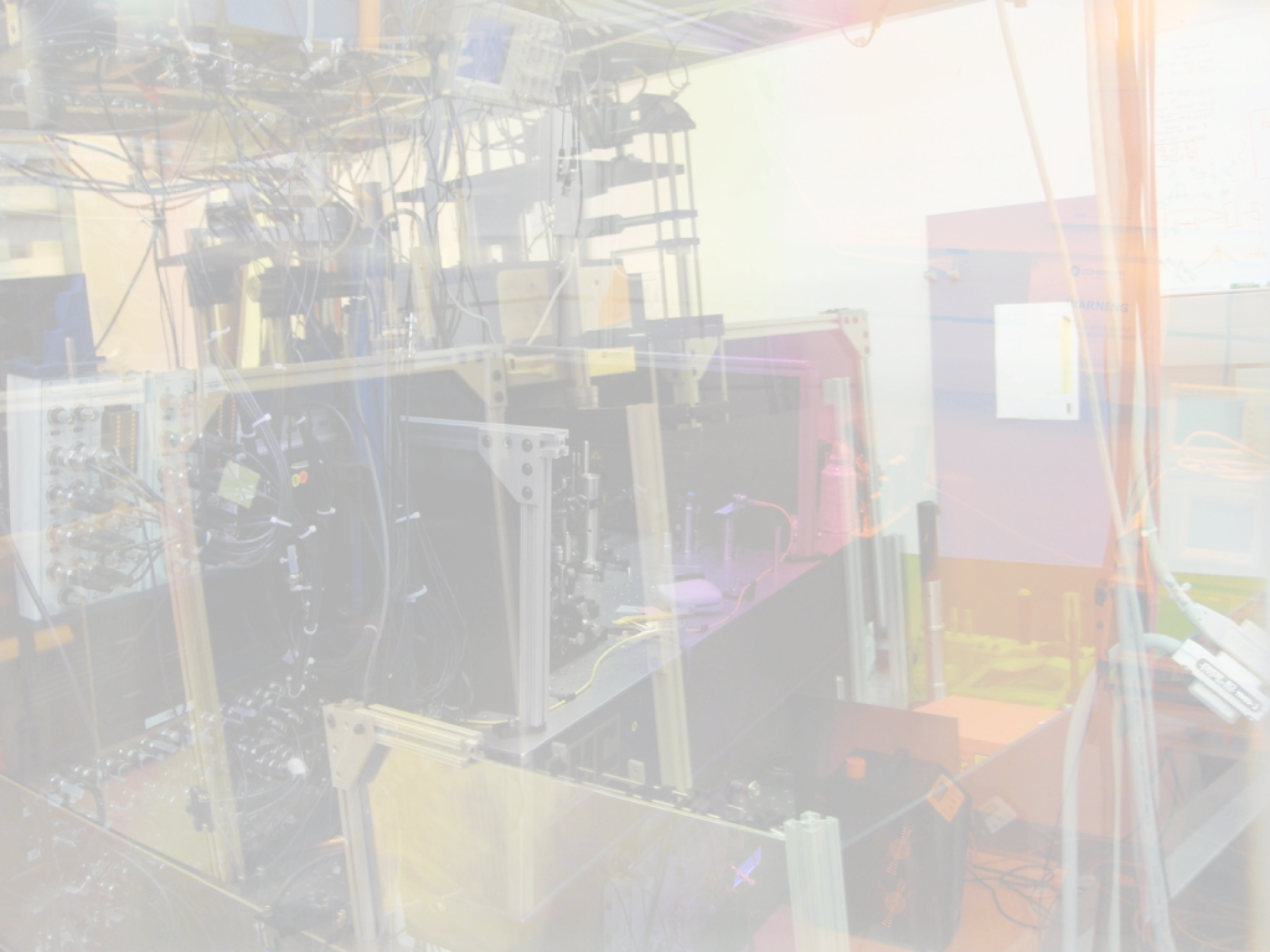


Fields in synthetic dimensions





B. Stuhl and Hsin-I Lu, et al. Science (2015)



Synthetic electromagnetism with neutral atoms

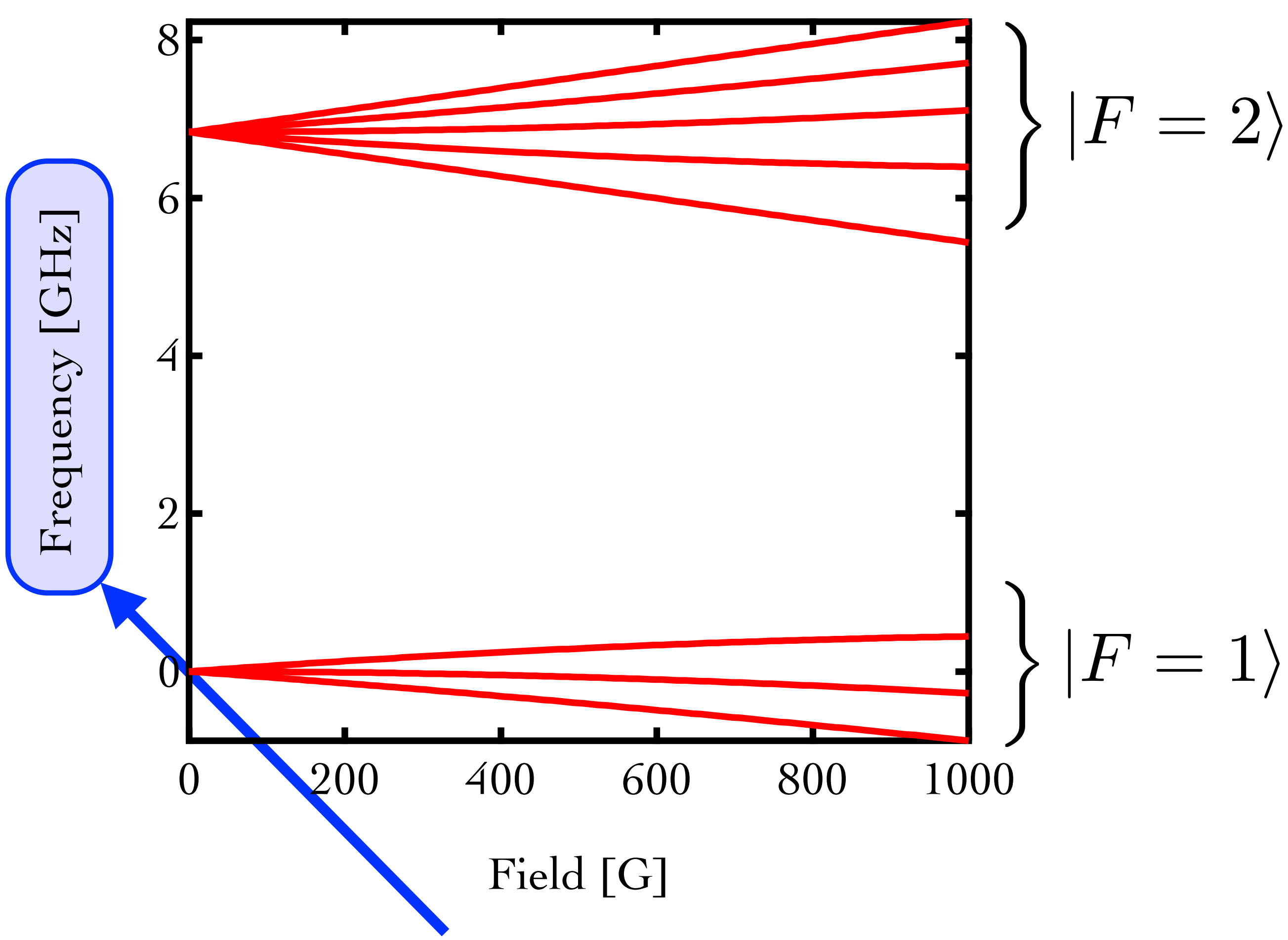
In this talk we will study the behavior of quantum matter in the presence of *static* magnetic fields

NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

What do magnetic fields do?

To spins

Zeeman effect, example of ^{87}Rb



Energy in dimensions of Hz

To charges

1. Freshman mechanics

Mechanical variables and forces

$$\mathbf{F} = q\mathbf{v} \times \mathbf{B}$$

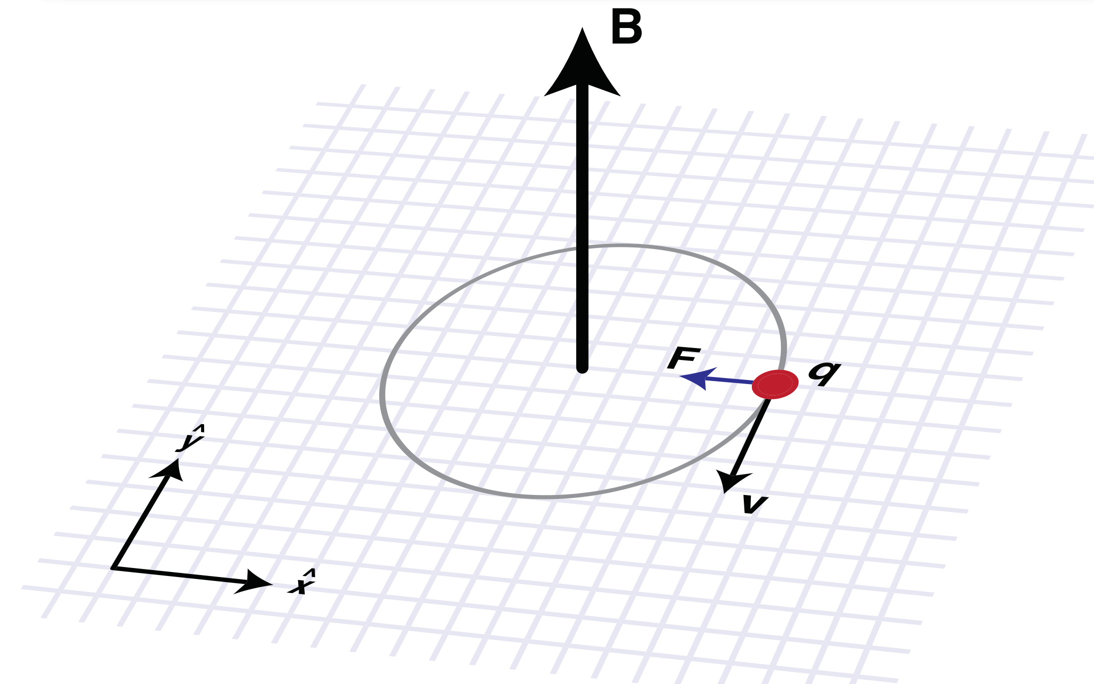
2. Junior mechanics

Canonical variables and vector potential

$$\mathbf{B} = \nabla \times \mathbf{A} \qquad \text{e.g.,} \;\; \mathbf{A} = \frac{B}{2}(x\hat{y} - y\hat{x})$$

$$H = \frac{(\mathbf{p} - q\mathbf{A})^2}{2m}$$

$$\dot{p}_j = -\frac{\partial}{\partial x_i}H, \;\; \dot{x}_j = \frac{\partial}{\partial p_i}H$$



What we want to create for neutral atoms

Single particle hamiltonian

$$\hat{H} = \frac{\hbar^2}{2m}\left[\left(k_x - \frac{qA_x}{\hbar}\right)^2 + \left(k_y - \frac{qA_y}{\hbar}\right)^2\right] + V(\mathbf{x})$$

How to control the *kinetic* energy term coupling between internal, spin, degrees of freedom.

Here I will be interested in a synthetic field normal to a 2D plane.
Some common gauge choices are:

$$A = \left\{-\frac{By}{2}, \frac{Bx}{2}, 0\right\}$$

Symmetric gauge: natural for rotating systems

$$A = \{0, Bx, 0\}$$

Landau gauge: relevant here

<u>Expect the usual relations for fields</u>

$$\mathbf{E} = -\nabla\Phi - \frac{\partial \mathbf{A}}{\partial t} \qquad B = \nabla \times A$$

<u>References</u>
J. C. Maxwell (1873)

Synthetic electromagnetism with neutral atoms

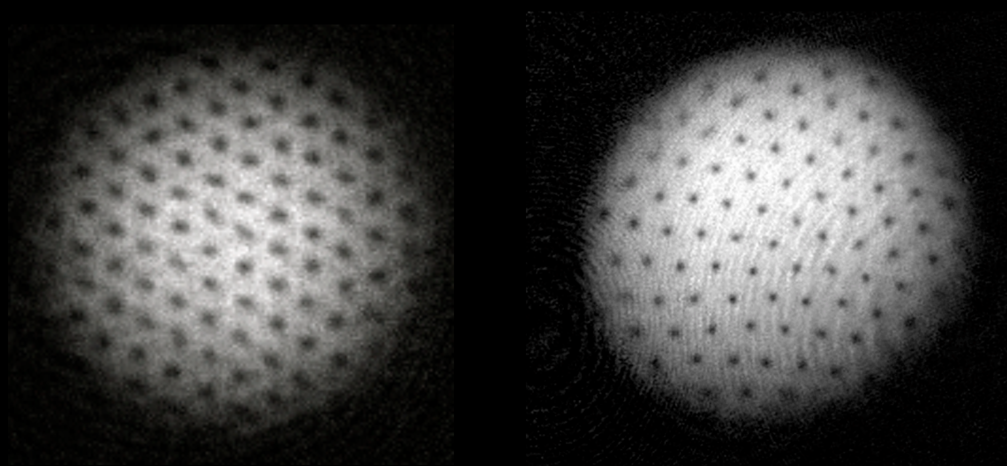
But wait our *neutral* atoms are
charge neutral!

National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

How to "charge" neutral particles

Rotation

$$H_r = \frac{\hbar^2}{2m}\left[\left(\hat{k}'_x - \frac{m\Omega}{\hbar}y\right)^2 + \left(\hat{k}'_y + \frac{m\Omega}{\hbar}x\right)^2\right] + \frac{m\left(\omega^2 - \Omega^2\right)}{2}\mathbf{r}^2$$



JILA MIT

Raman Dressing

How to simulate magnetic fields

(1) Rotation: the Hamiltonian in the rotating frame has an effective field. For high fields fine tuning is required.

References: V. Schweikhard et al PRL **92** 040404 (2004), J. R. Abo-Shaeer, C. Raman, and W. Ketterle PRL **88** 070409 (2002), K.W. Madison et al PRL **84** 806 (2000)

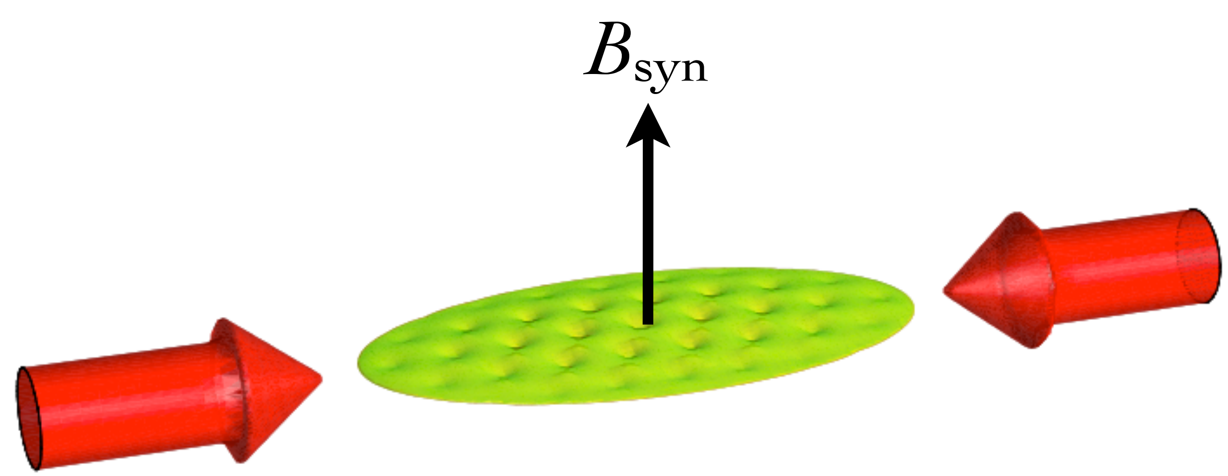
(2) Stroboscopic proposals.

(3) Immersions and others

References: A. Sørensen, et al PRL **94** p086803 (2005), A. Klein and D. Jaksch EPL, **85** 13001 (2009)

Our approach

(4) Raman techniques.



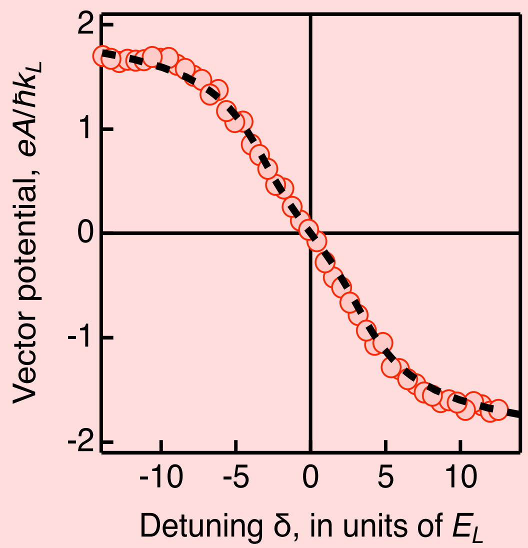
Reference: G. Juzeliñuas et al PRA **73** p025602 (2006)

Today's outline

A synthetic vector potential, created

Generate a synthetic vector potential

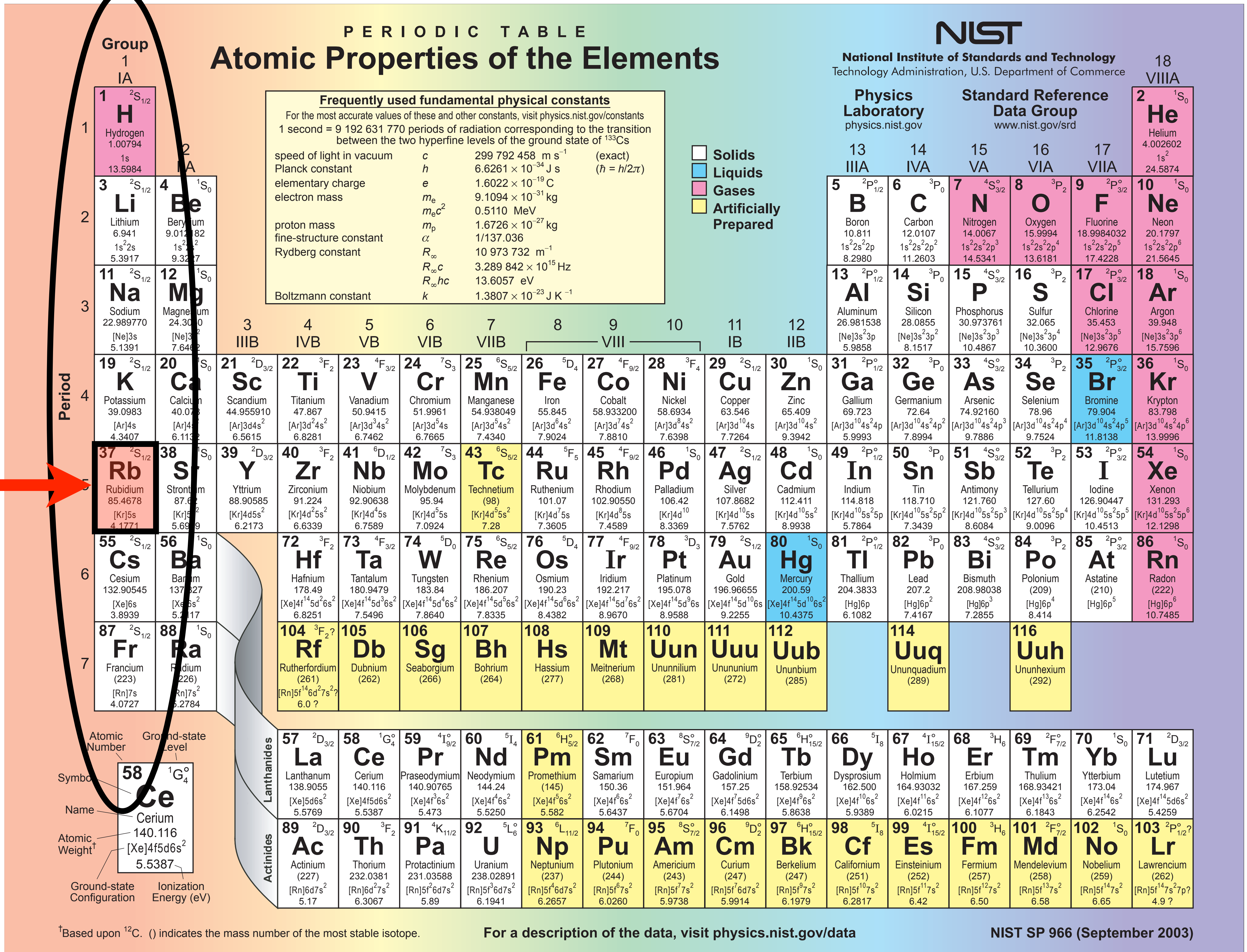
$$\hat{H} = \frac{\hbar^2}{2m}\left[\left(k_x - \frac{qA_x}{\hbar}\right)^2 + \left(k_y - \frac{qA_y}{\hbar}\right)^2\right] + V(\mathbf{x})$$



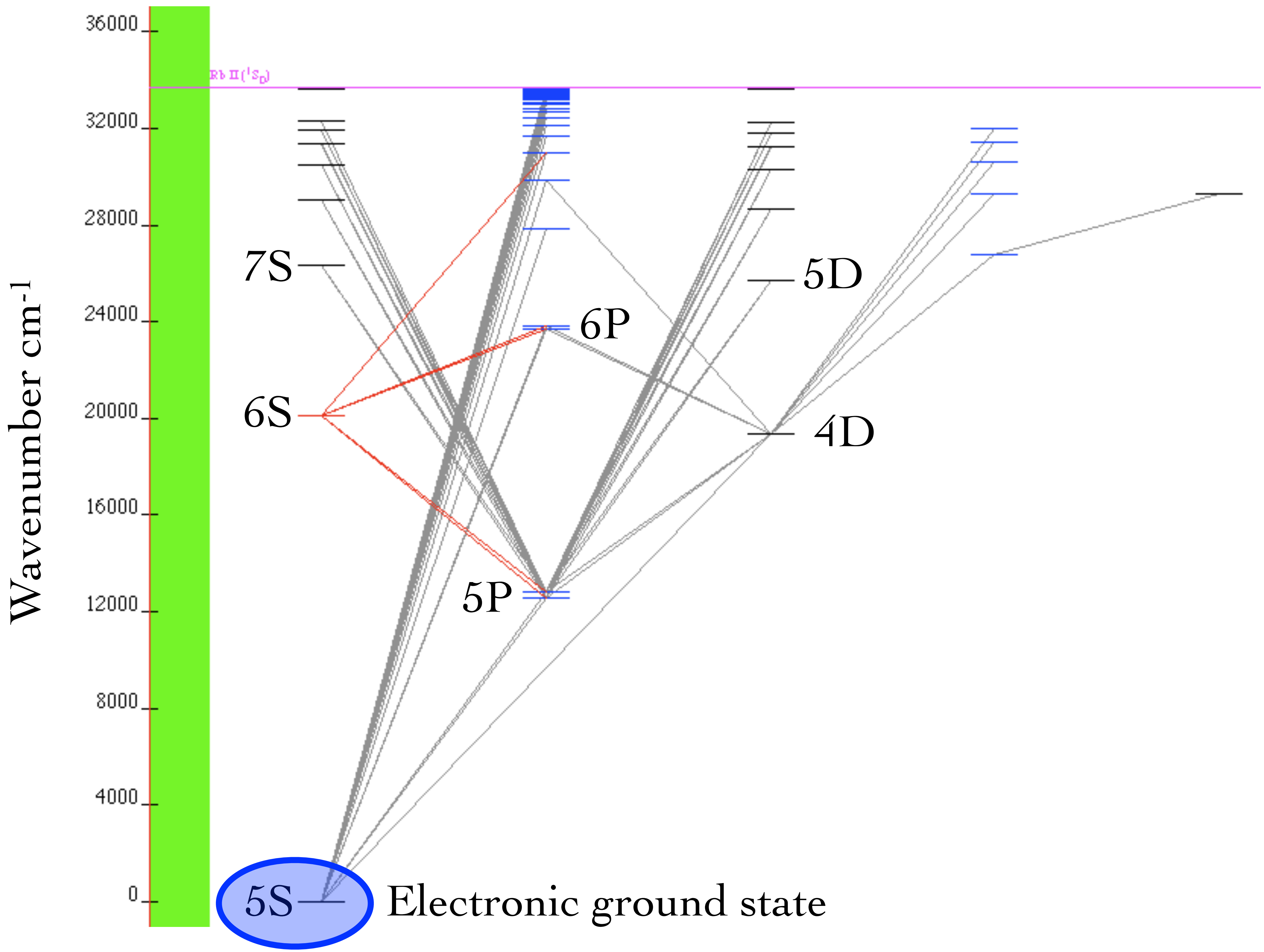
A electric and magnetic fields, revealed

Spatial variation of A gives rise to a magnetic field

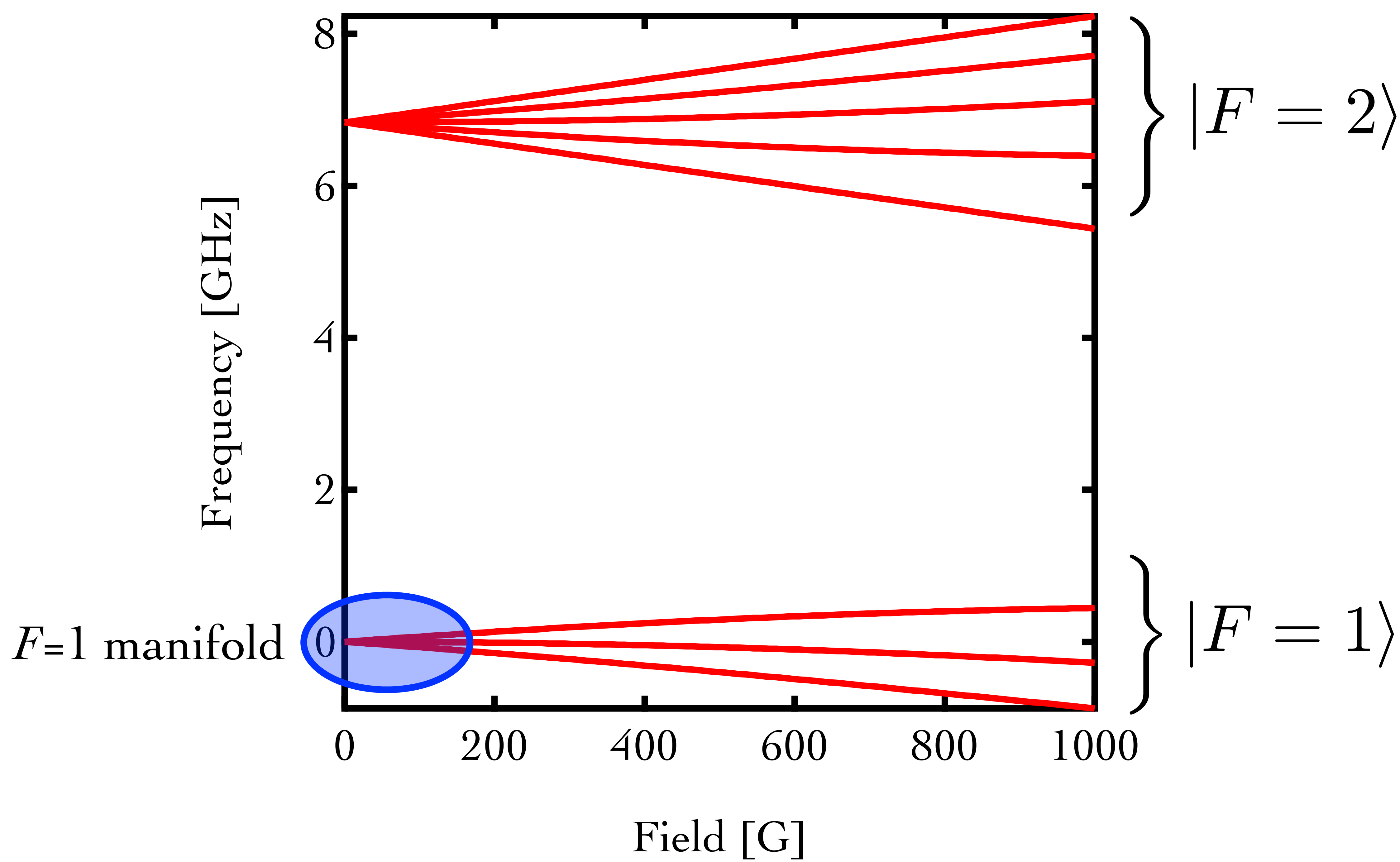
Rubidium 87


PERIODIC TABLE
Atomic Properties of the Elements
NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce
Physics Laboratory
physics.nist.gov
Standard Reference Data Group
www.nist.gov/srd
Frequently used fundamental physical constants
For the most accurate values of these and other constants, visit physics.nist.gov/constants
1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of 133Cs
speed of light in vacuum c 299 792 458 m s-1 (exact)
Planck constant h 6.6261 × 10-34 J s (ħ = h/2π)
elementary charge e 1.6022 × 10-19 C
electron mass me 9.1094 × 10-31 kg
mec2 0.5110 MeV
proton mass mp 1.6726 × 10-27 kg
fine-structure constant α 1/137.036
Rydberg constant R∞ 10 973 732 m-1
R∞c 3.289 842 × 1015 Hz
R∞hc 13.6057 eV
Boltzmann constant k 1.3807 × 10-23 J K-1
Solids
Liquids
Gases
Artificially Prepared
Group
Period
37 Rb Rubidium 85.4678 [Kr]5s 4.1771
Atomic Number
Ground-state Level
Symbol
Name
Atomic Weight†
Ground-state Configuration
Ionization Energy (eV)
58 Ce Cerium 140.116 [Xe]4f5d6s2 5.5387
Lanthanides
Actinides
†Based upon 12C. () indicates the mass number of the most stable isotope.
For a description of the data, visit physics.nist.gov/data
NIST SP 966 (September 2003)

Rubidium 87: Level structure



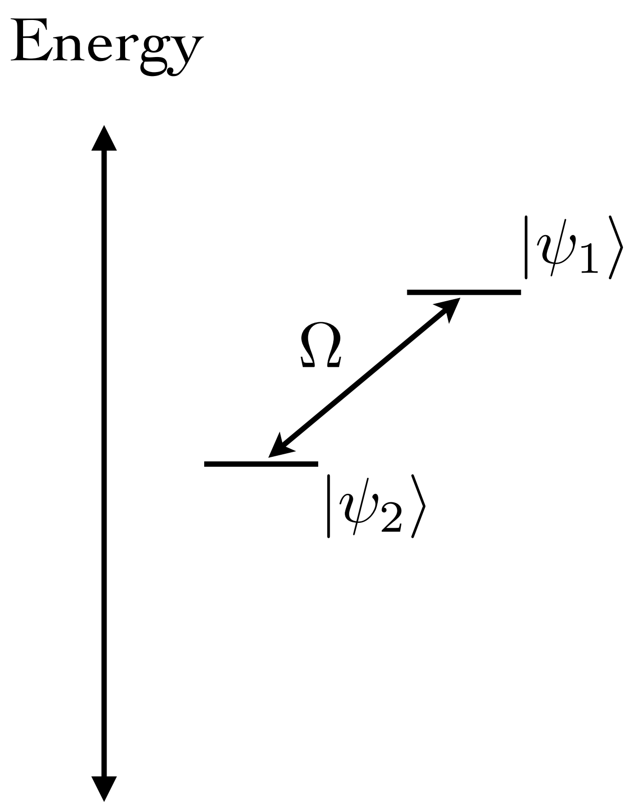
Rubidium 87: $5S_{1/2}$ ground state



All the atomic physics you need to know

Schematic

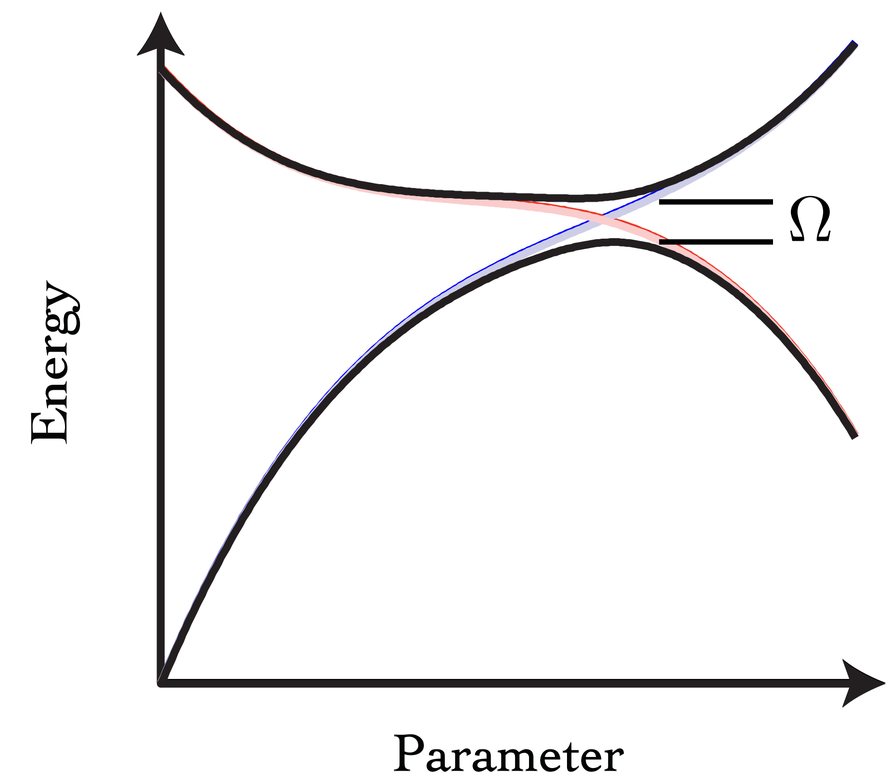
Two levels coupled together



$$H = \begin{pmatrix} E_1 & \Omega/2 \\ \Omega/2 & E_2 \end{pmatrix}$$

Graphic result

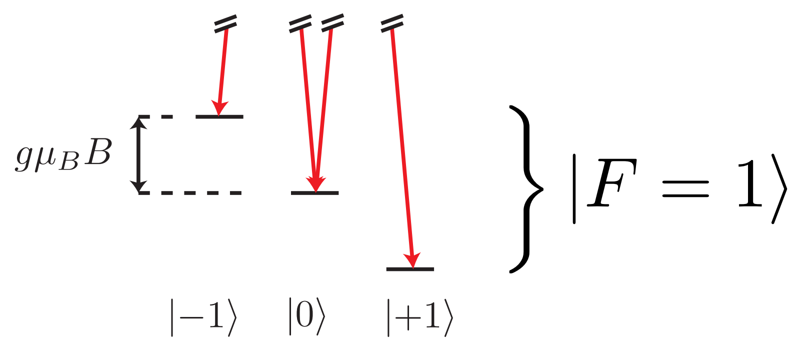
Avoided crossings

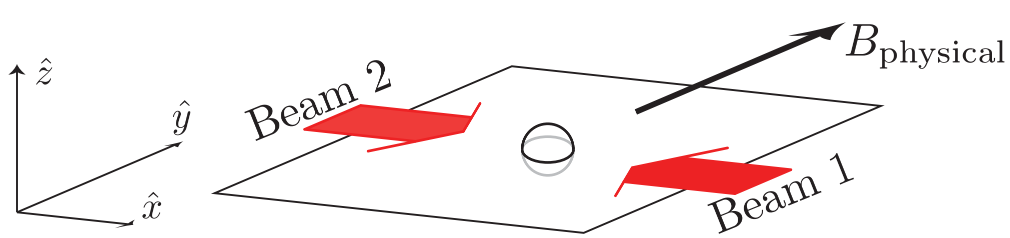


Atom light interaction: pictures

Atom light interaction

Given the following geometry and levels



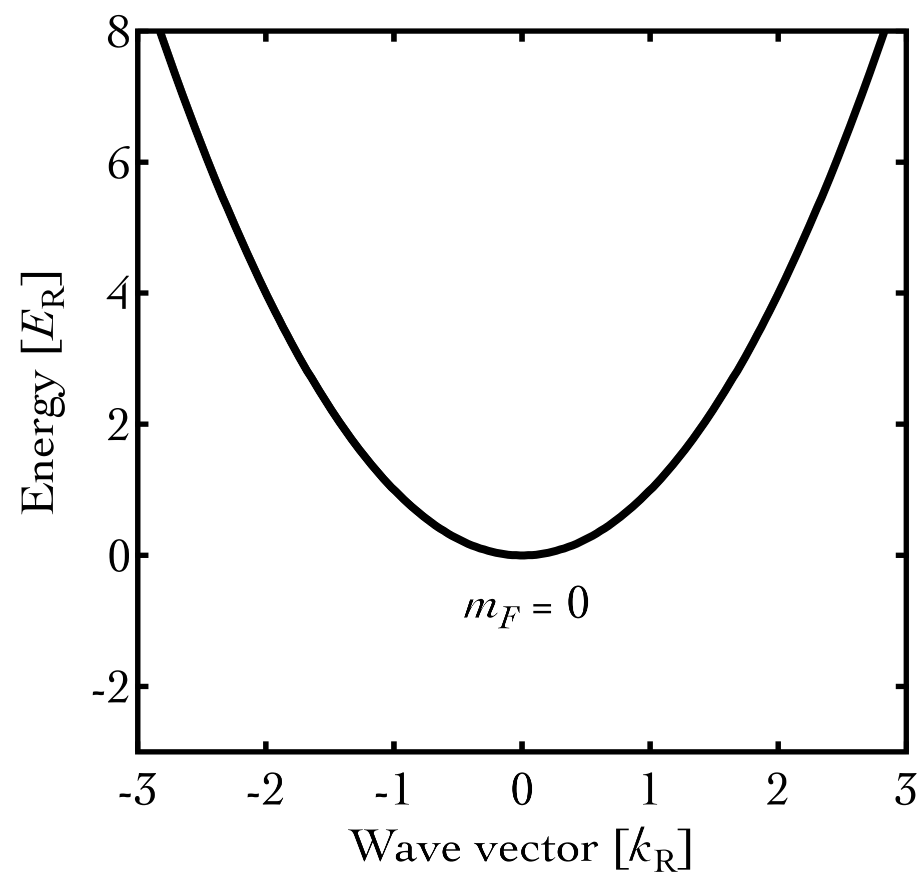


Dimensions

$$k_R = \frac{2\pi}{\lambda}, \ E_R = \frac{\hbar^2 k_R^2}{2m}$$

$$E_R \approx h \times 3\ \text{kHz} = k_\text{B} \times 140\ \text{nK}$$

Coupled States



References

[1] Juzeliūnas, et al., PRA 025602 **73** (2006), + earlier pubs

[2] S.-L. Zhu, et al., PRL 240401 **97** (2006)

[3] Günter et al, PRA **79** 011604 (2009)

[4] IBS, PRA 063613 **79** (2009)

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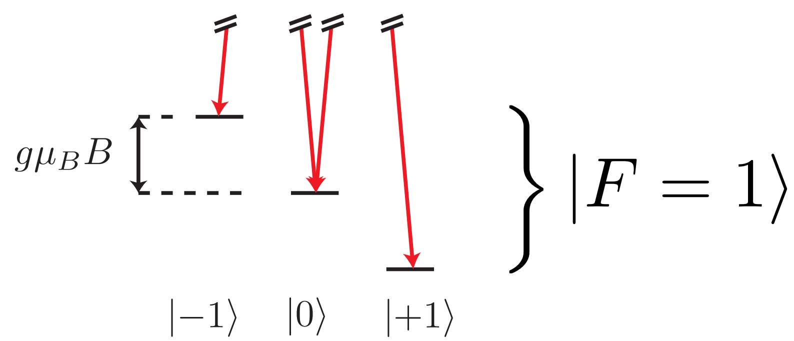

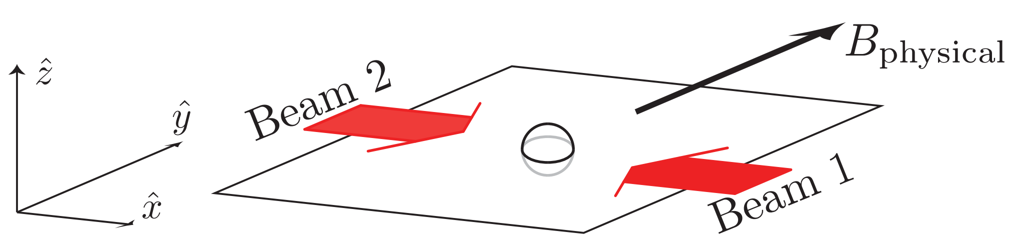

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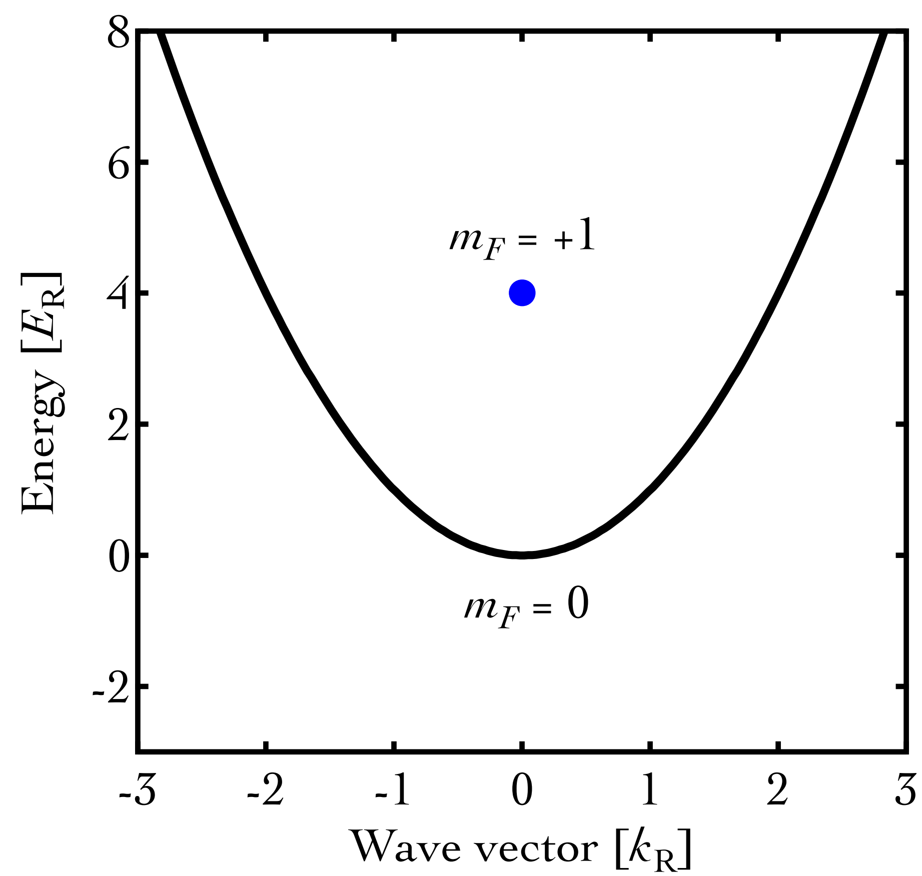

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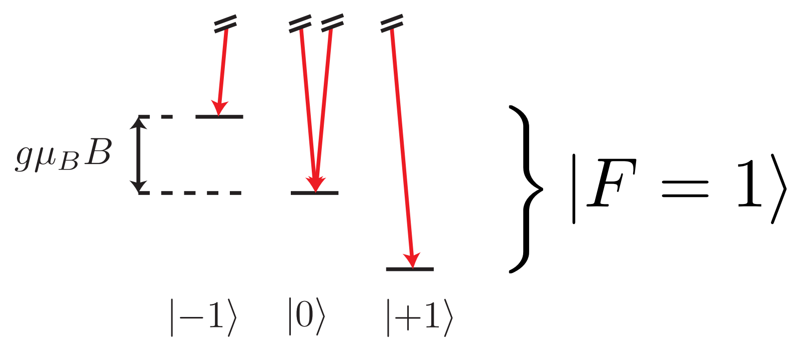

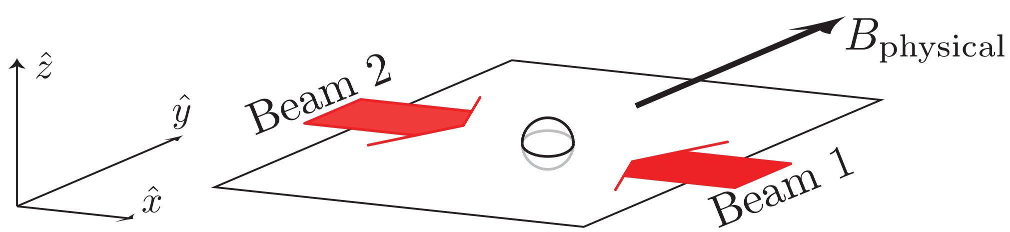

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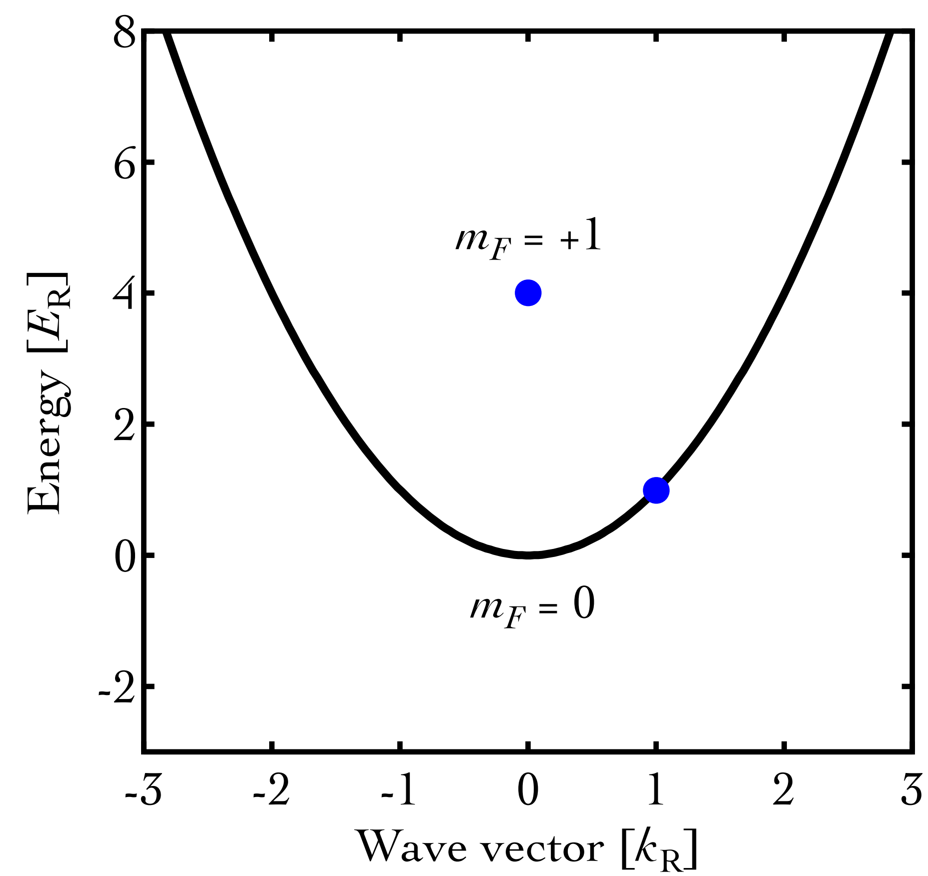
Coupled States



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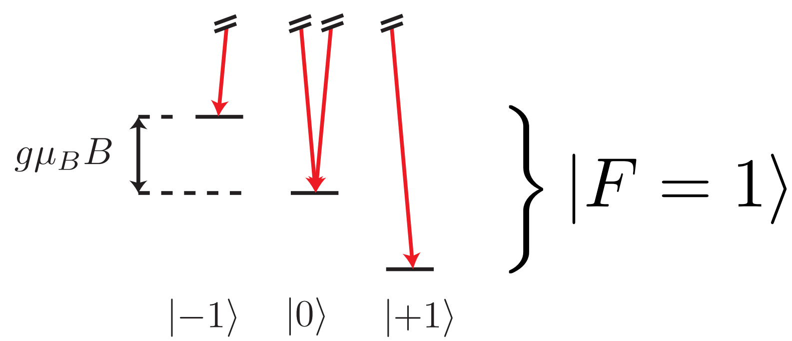

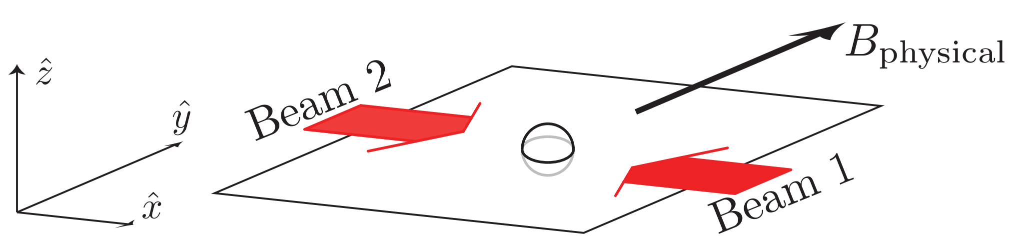

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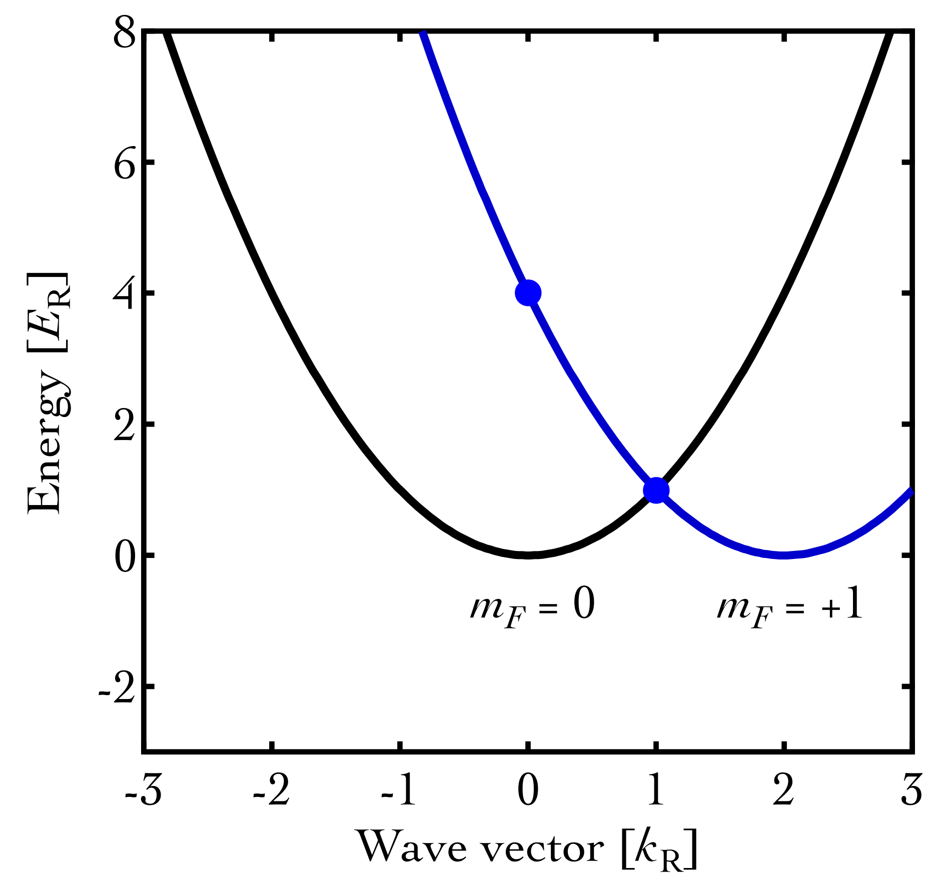

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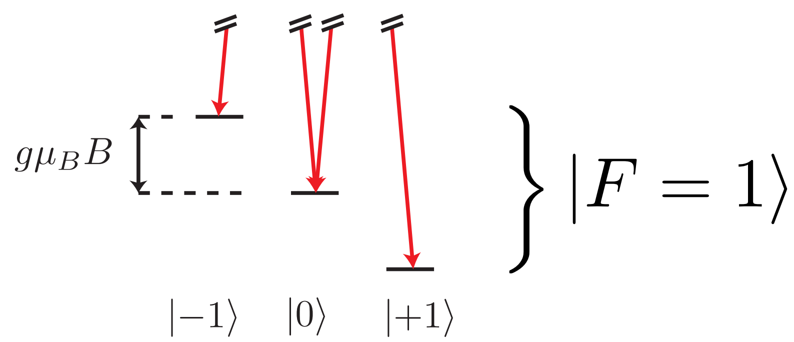

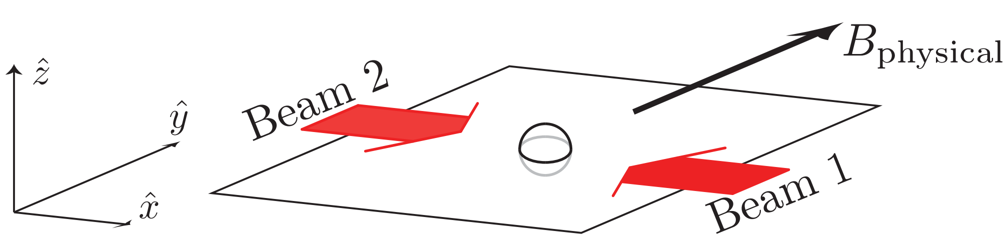

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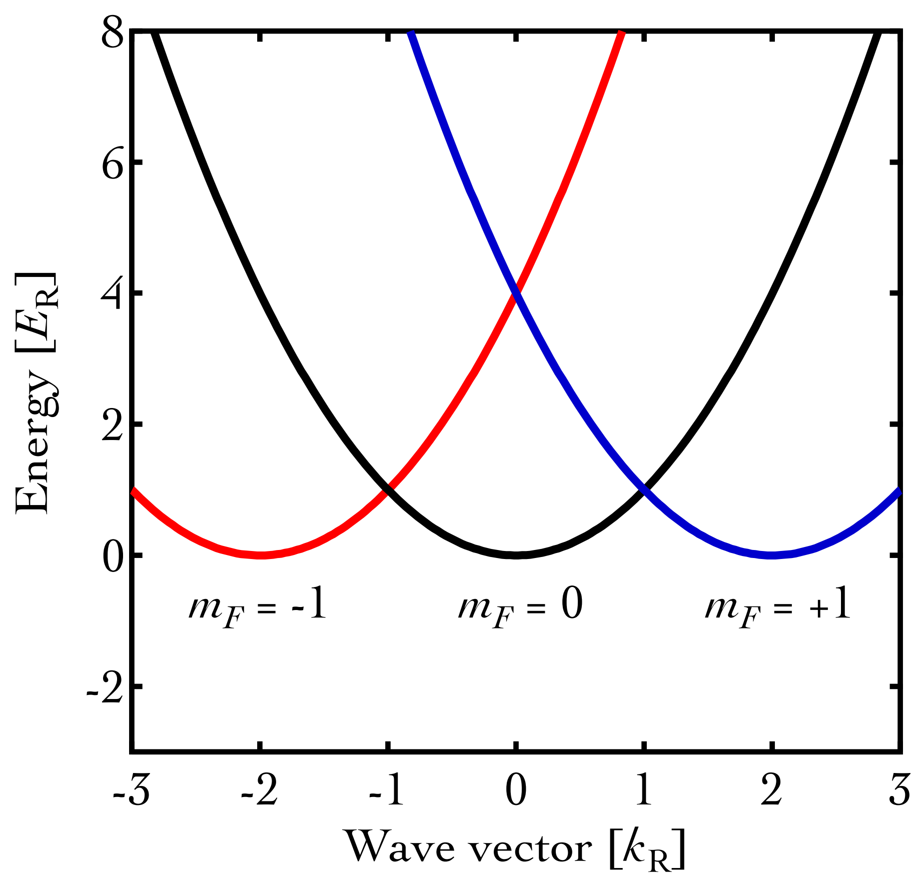
$$E_R \approx h \times 3\ \text{kHz} = k_\text{B} \times 140\ \text{nK}$$

Coupled States



References

[1] Juzeliūnas, et al., PRA 025602 **73** (2006), + earlier pubs

[2] S.-L. Zhu, et al., PRL 240401 **97** (2006)

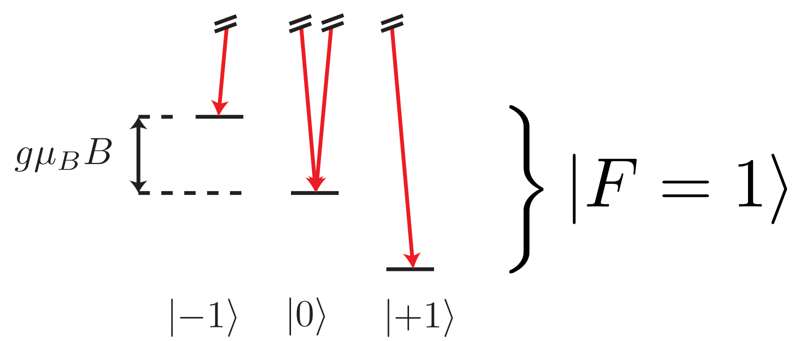
[3] Günter et al, PRA **79** 011604 (2009)

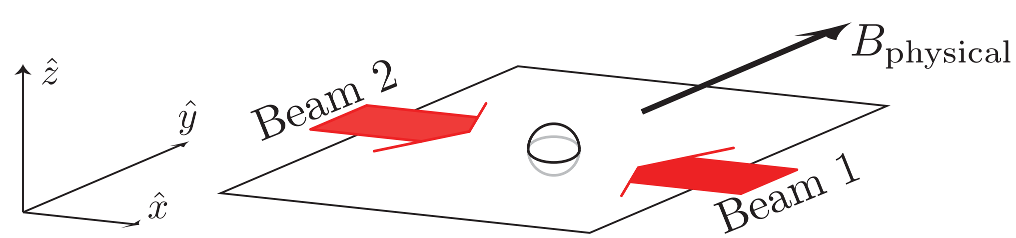
[4] IBS, PRA 063613 **79** (2009)

Atom light interaction: pictures

Atom light interaction

Given the following geometry and levels





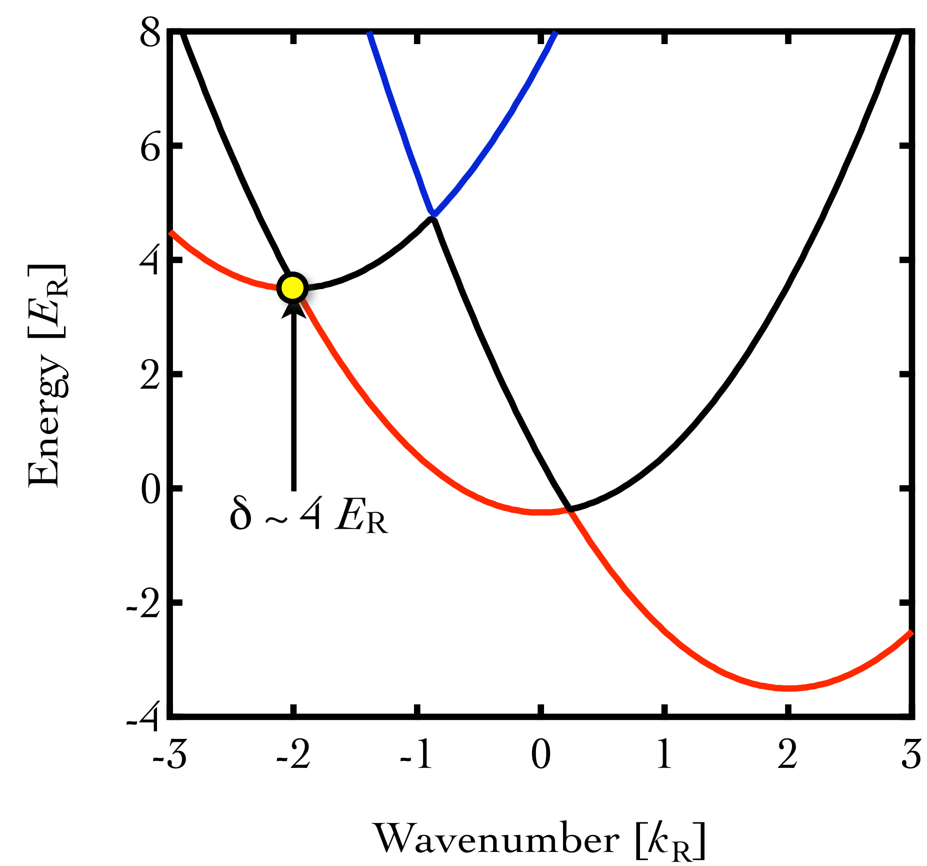
Dimensions

$$k_R = \frac{2\pi}{\lambda}, \;\; E_R = \frac{\hbar^2 k_R^2}{2m}$$

$$E_R \approx h \times 3\ \text{kHz} = k_{\text{B}} \times 140\ \text{nK}$$

Coupled States

States will be labeled by:
(1) the "band index" and by
(2) a quasi-momentum k



References

[1] Juzeliūnas, et al., PRA 025602 **73** (2006), + earlier pubs

[2] S.-L. Zhu, et al., PRL 240401 **97** (2006)

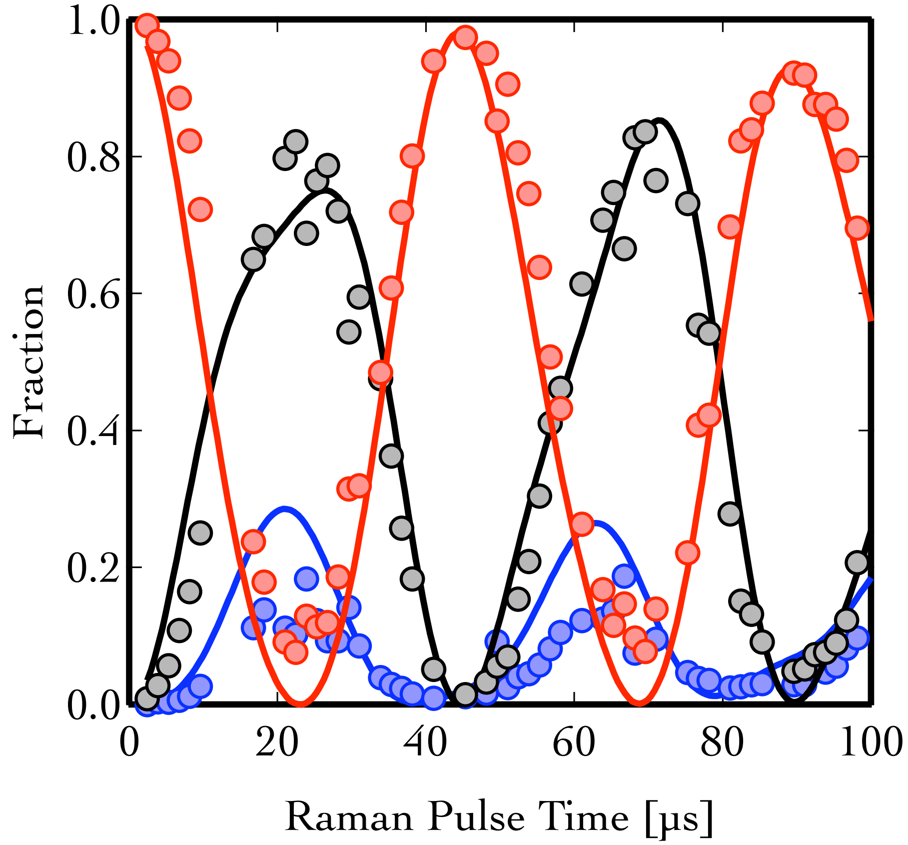
[3] Günter et al, PRA **79** 011604 (2009)

[4] IBS, PRA 063613 **79** (2009)

Atom light interaction: pictures

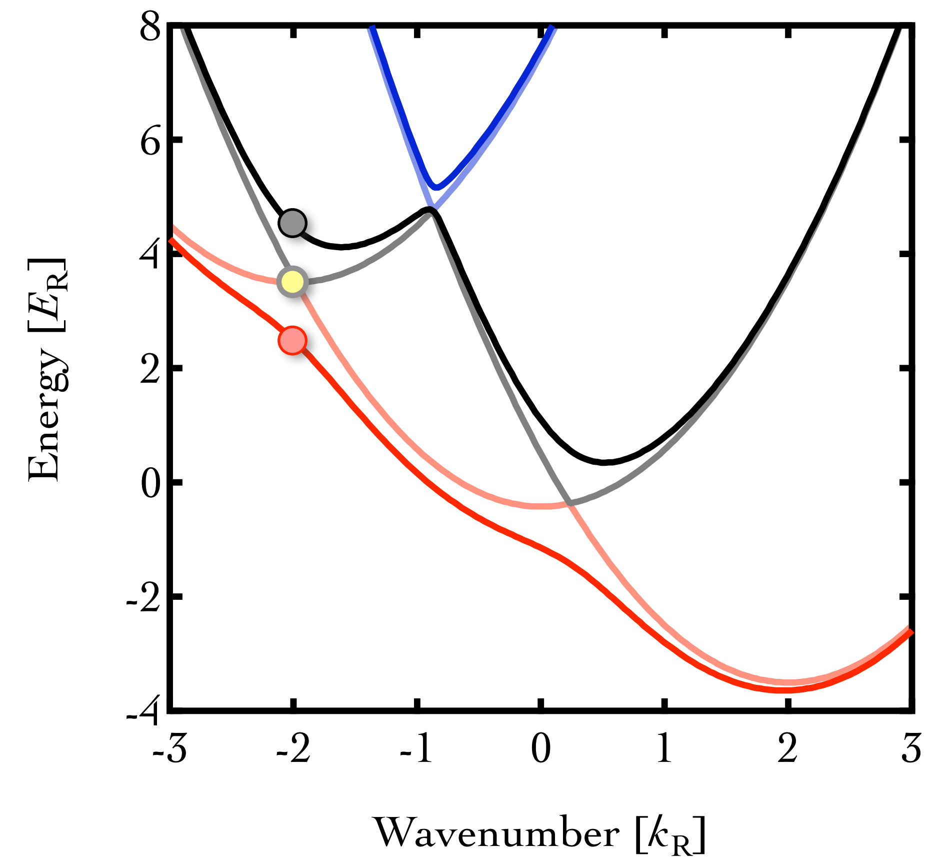
Time evolution

In the sudden limit (Raman-Nath)
Population oscillations yield coupling



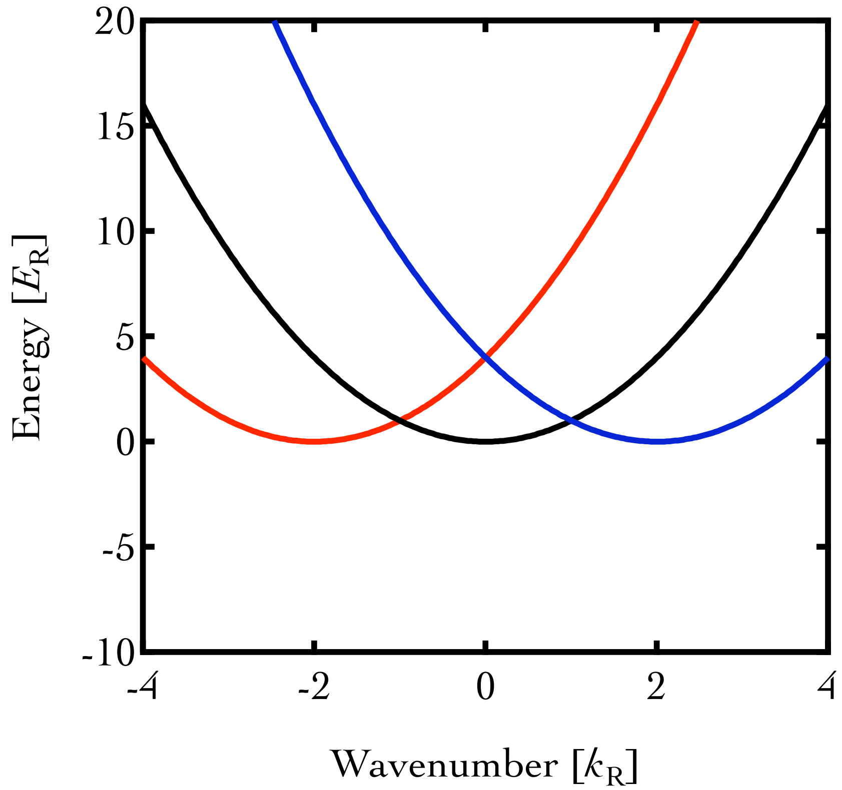
Coupled States

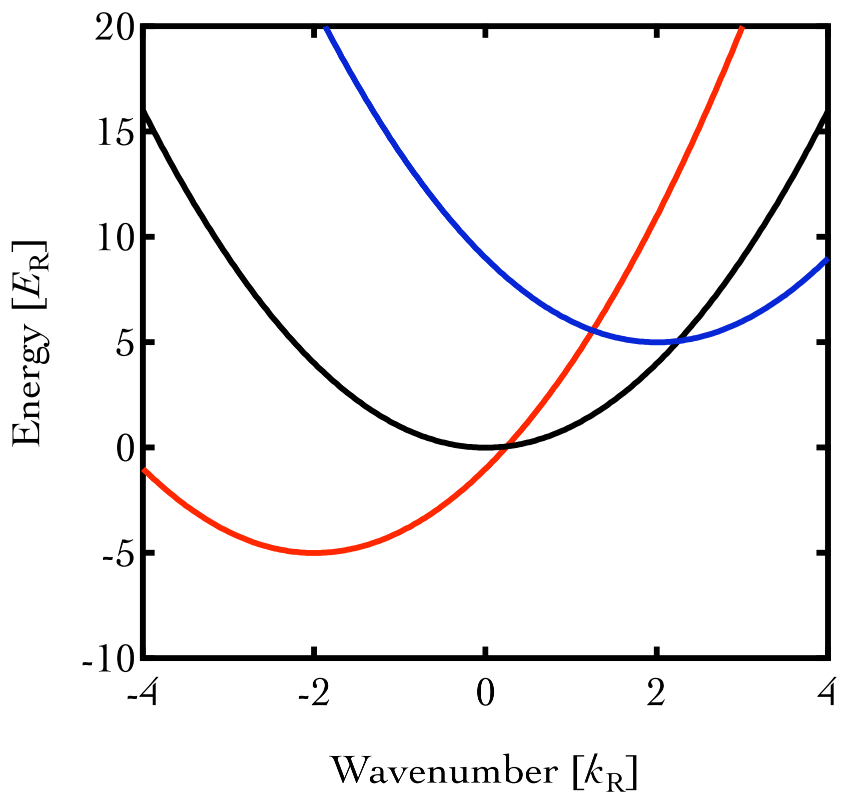
States will be labeled by:
(1) a "band index" and by
(2) a momentum k



Y.-J. Lin et al, PRL **102** 130401 (2009)

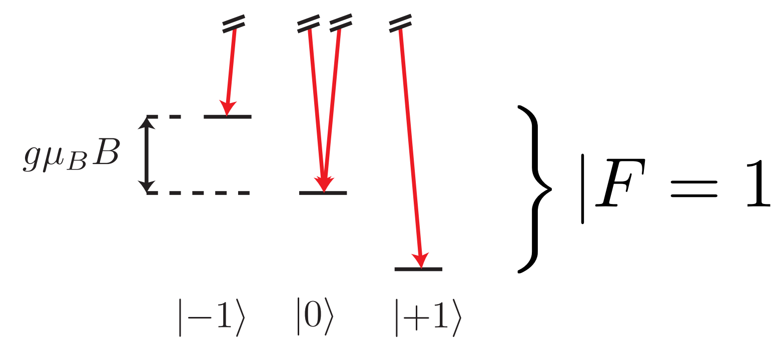
Atom light interaction: vector potential

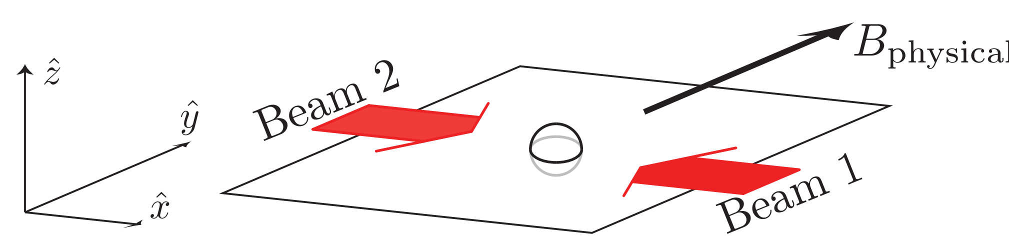




Atom light interaction

Given the following geometry and levels



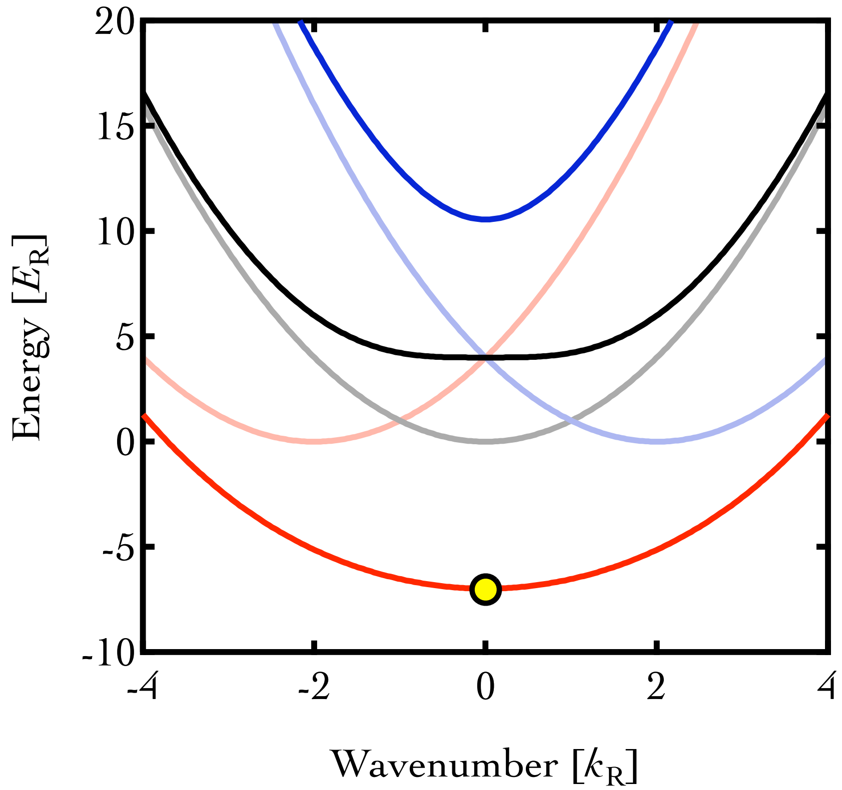


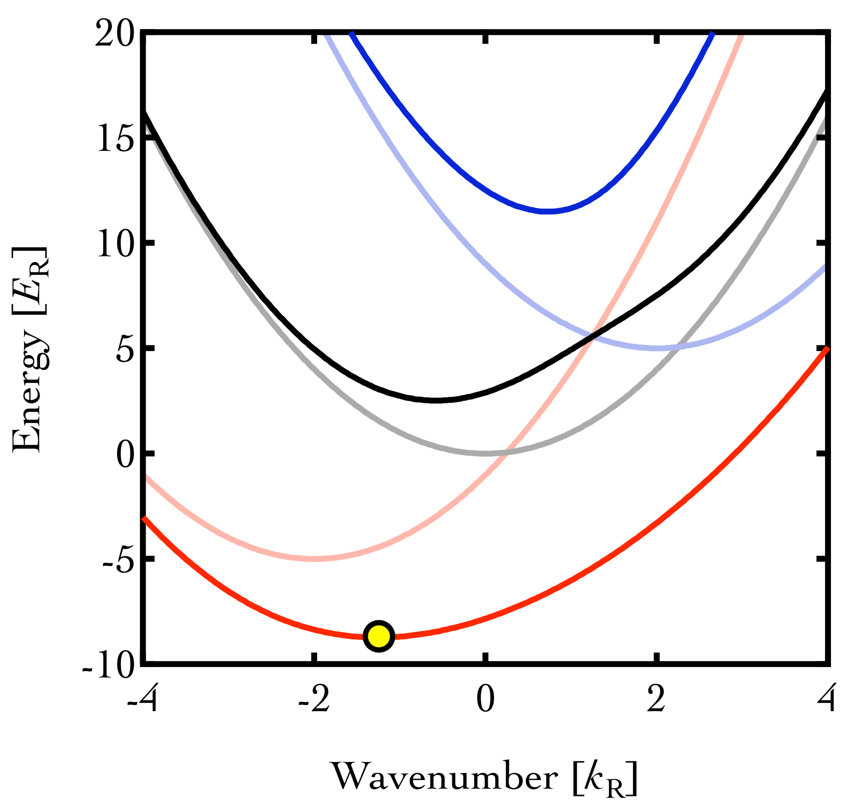
Dimensions

$$k_R = \frac{2\pi}{\lambda},\ \ E_R = \frac{\hbar^2 k_R^2}{2m}$$

$$E_R \approx h \times 3\ \mathrm{kHz} = k_{\mathrm{B}} \times 140\ \mathrm{nK}$$

Atom light interaction: vector potential



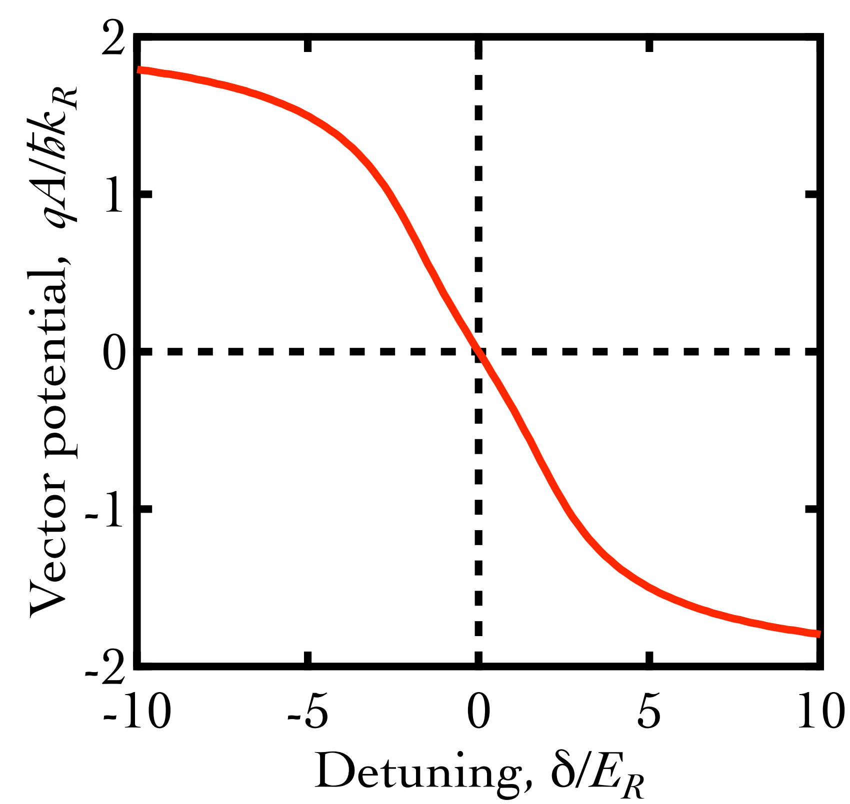


Coupling Hamiltonian

$$H(k) = |\Psi(k)\rangle \begin{pmatrix} (\tilde{k_x}-2)^2+\delta & \Omega/2 & 0 \\ \Omega/2 & (\tilde{k_x})^2 & \Omega/2 \\ 0 & \Omega/2 & (\tilde{k_x}+2)^2-\delta \end{pmatrix} \langle\Psi(k)|$$

Engineered vector potential

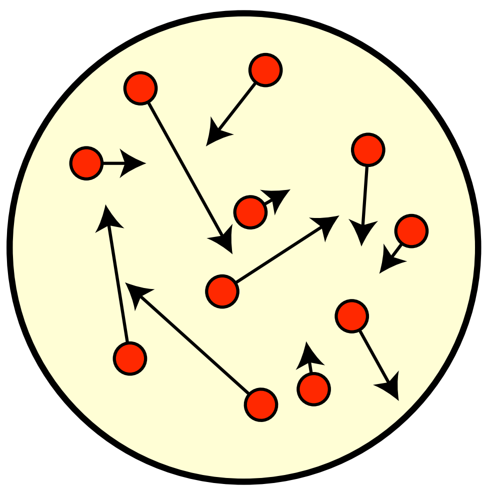
$$\hat{H} = \frac{\hbar^2}{2m}\left[\boxed{\left(k_x - \frac{qA_x}{\hbar}\right)^2} + \left(k_y - \cancel{\frac{qA_y}{\hbar}}\right)^2\right] + V(\mathbf{x})$$



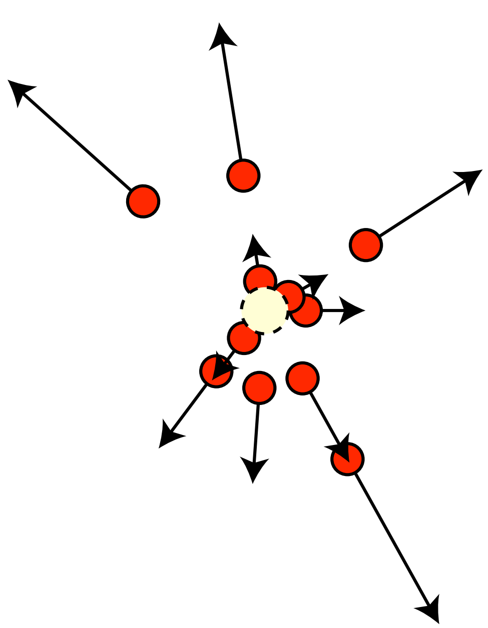
Measurement: Time-of-flight and Stern-Gerlach

Camera's point of view

Before TOF

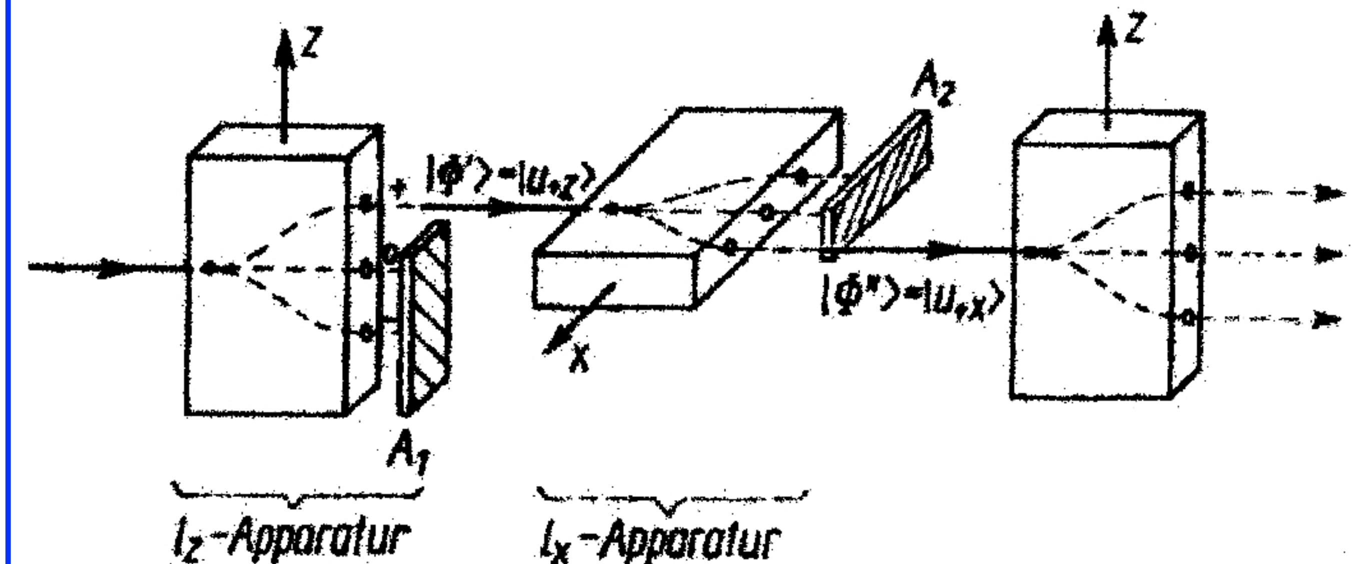


After TOF



Magnetic field gradient $B_y = B' y$

Field gradient along the *y* direction

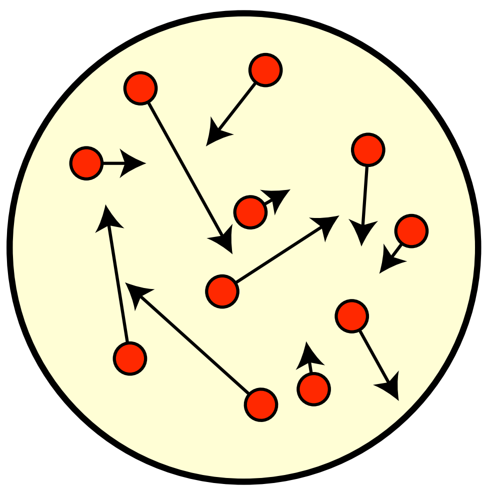


W. Gerlach and O. Stern Zeitschrift für Physik A (1922)

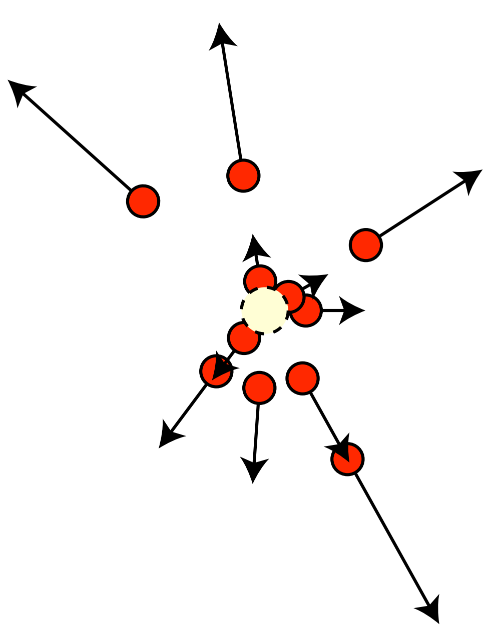
Measurement: Time-of-flight and Stern-Gerlach

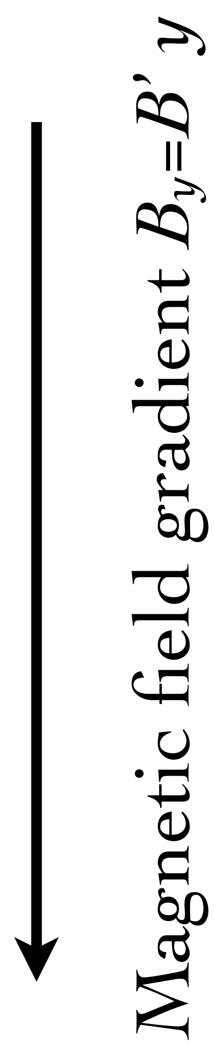
Camera's point of view

Before TOF

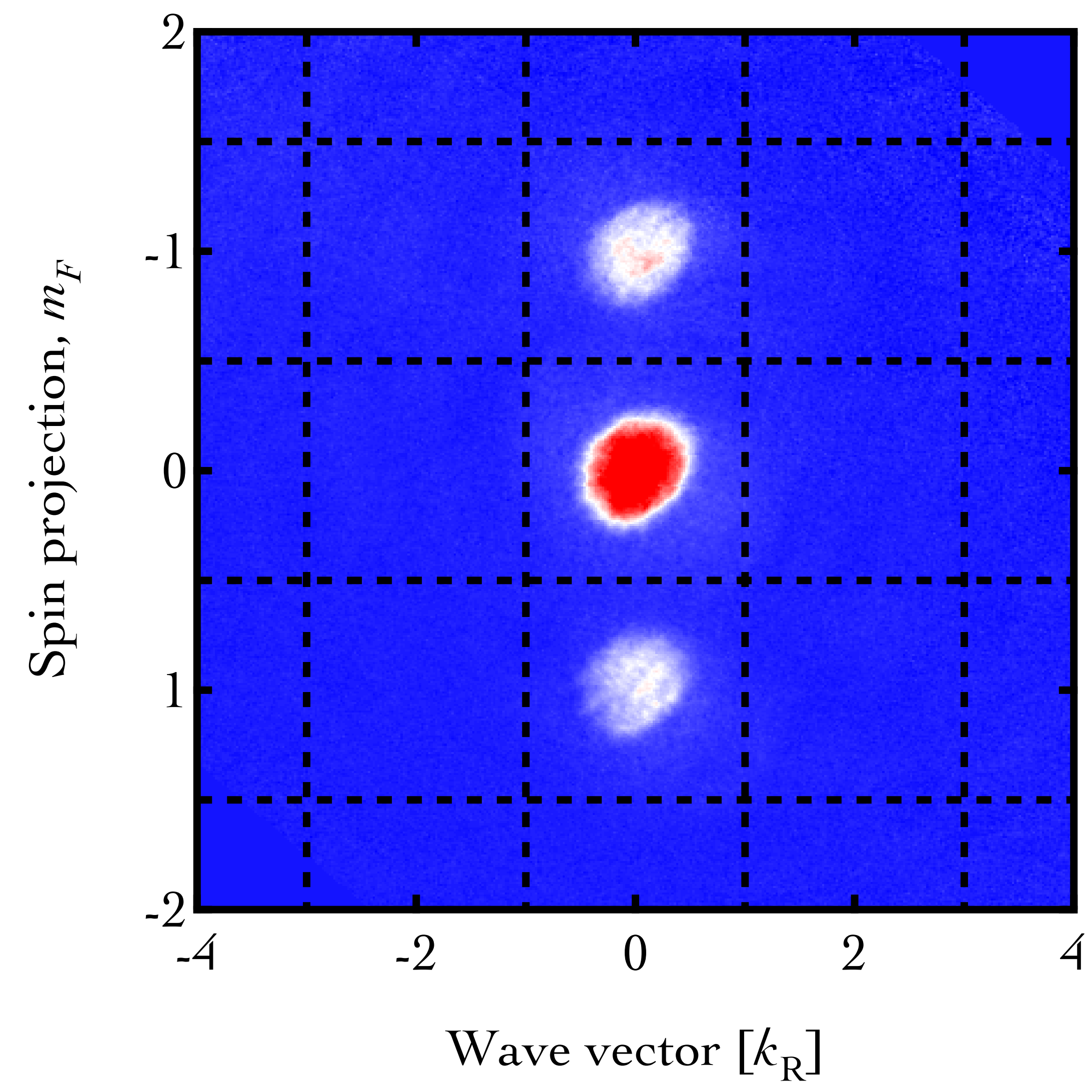


After TOF





Field gradient along the y direction



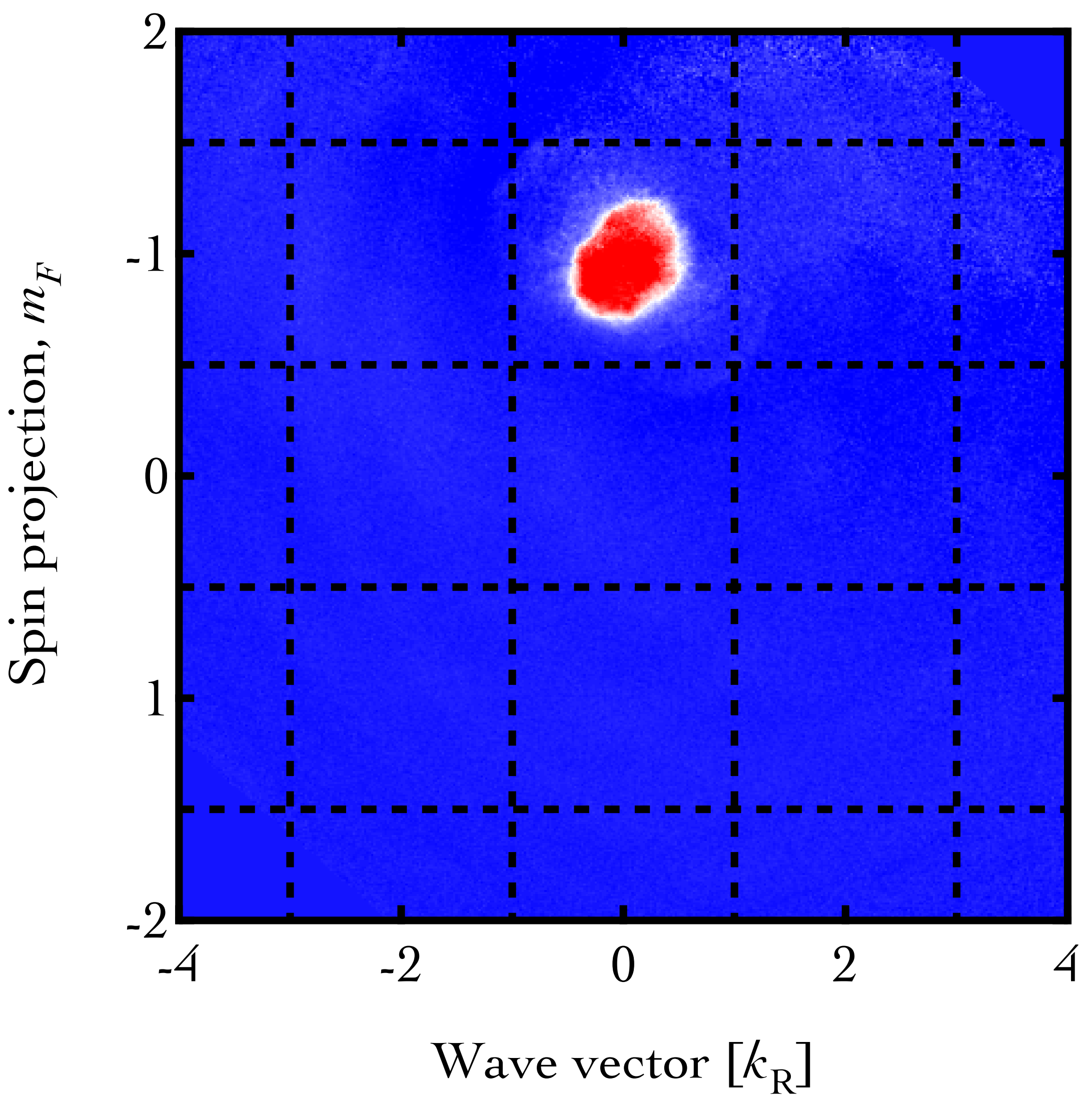
In the lab

Adiabatic manipulation of atoms

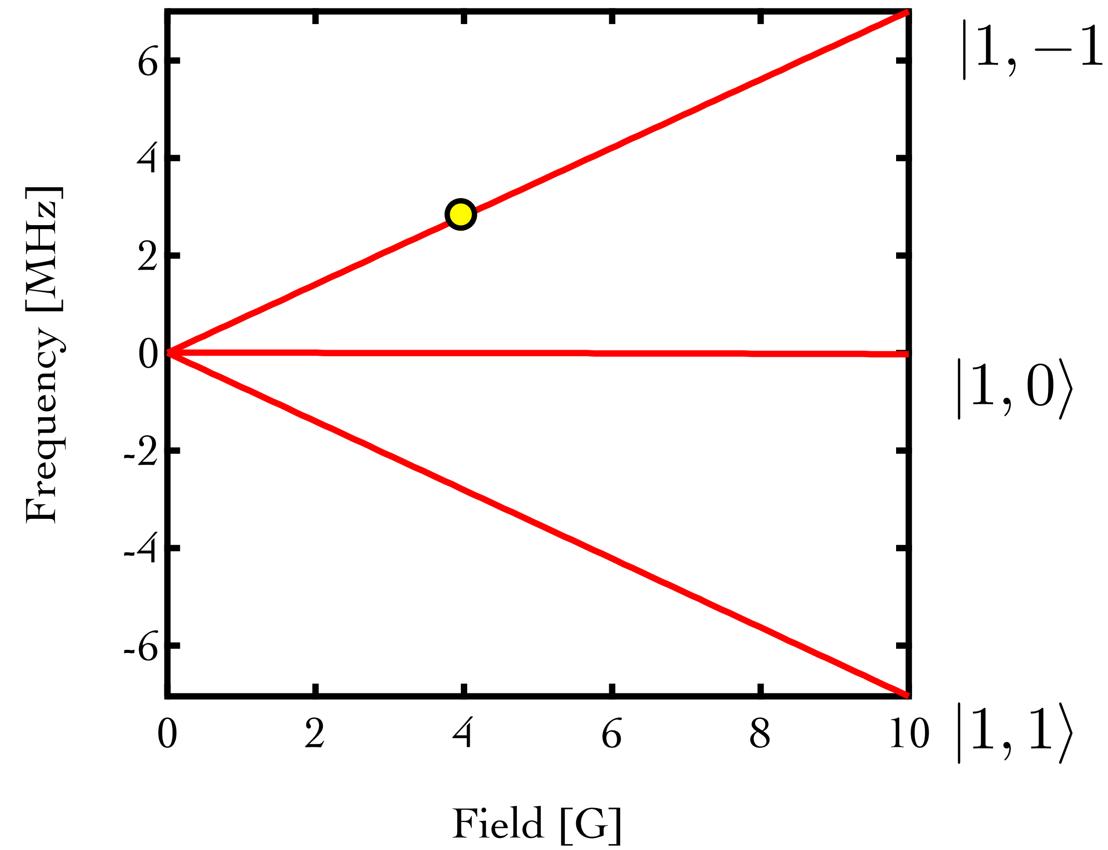
Initial state $|F=1, m_F=-1\rangle$

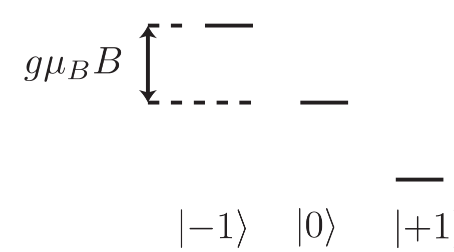
Suddenly turn off dipole trap, then TOF

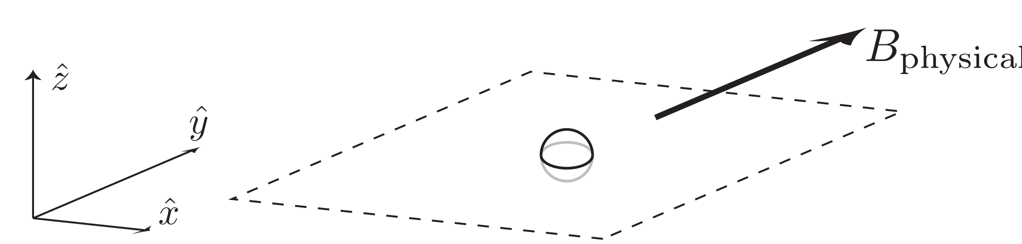
B field gradient



Zeeman shift







Loading: momentum

Adiabatic manipulation of atoms

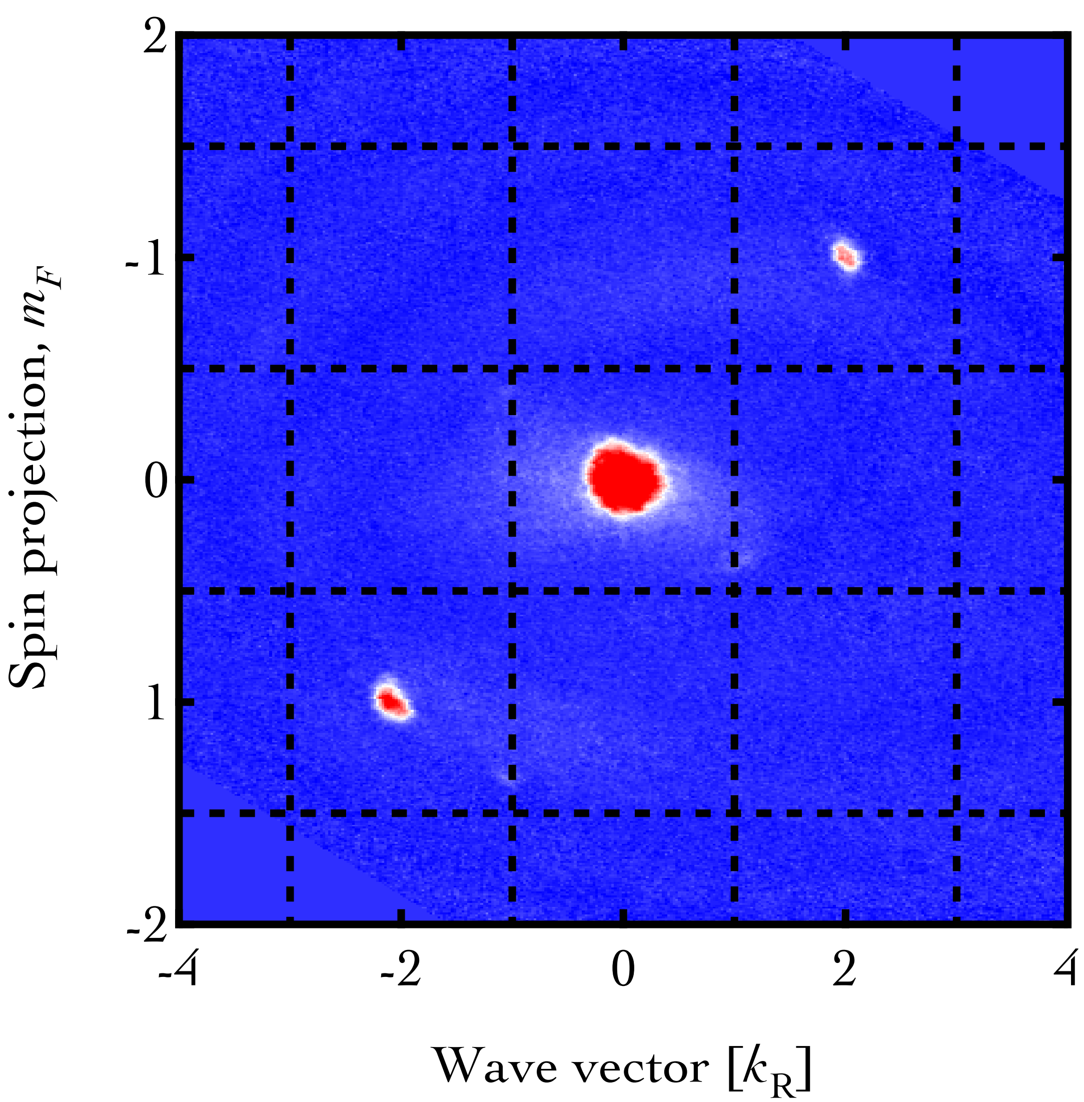
Initial state $|F=1, m_F=-1\rangle$

RF dressed state (RF on, ramp B to resonance)

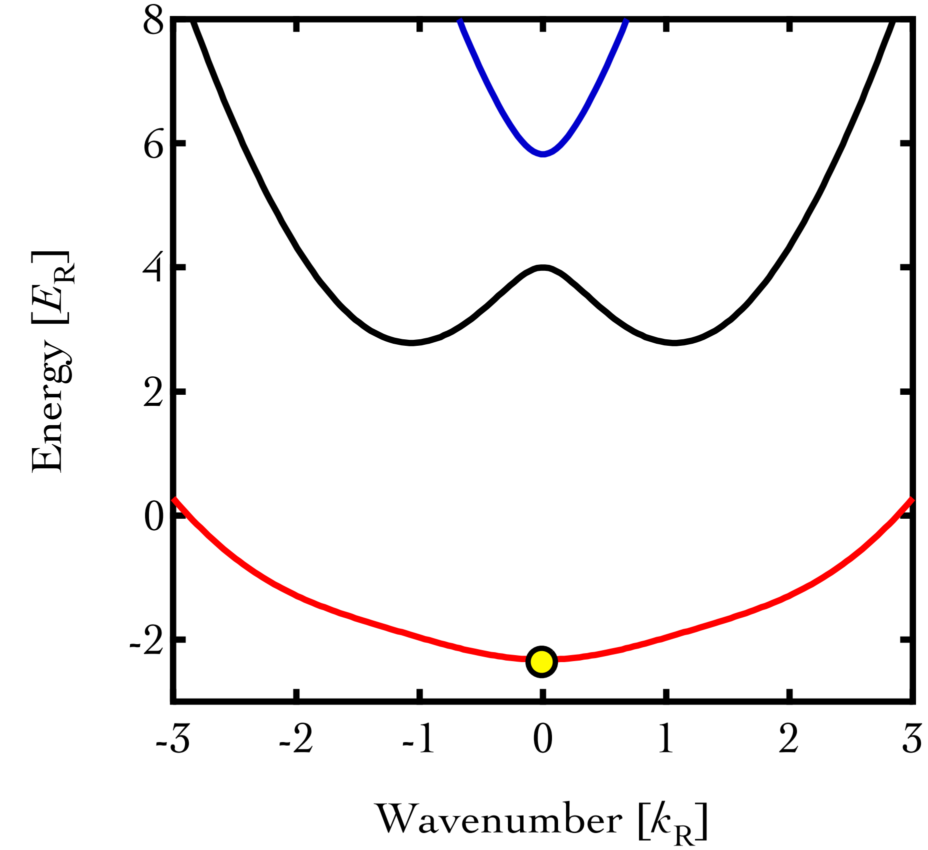
Raman + RF dressed state (Ramp Raman on)

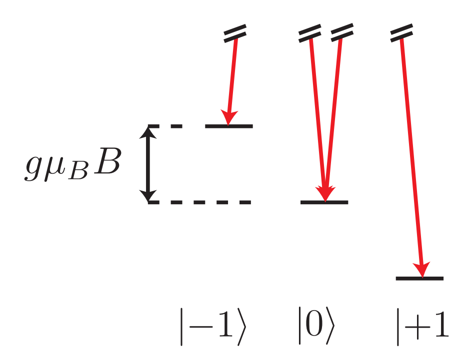
Raman only dressed state (Ramp RF off)

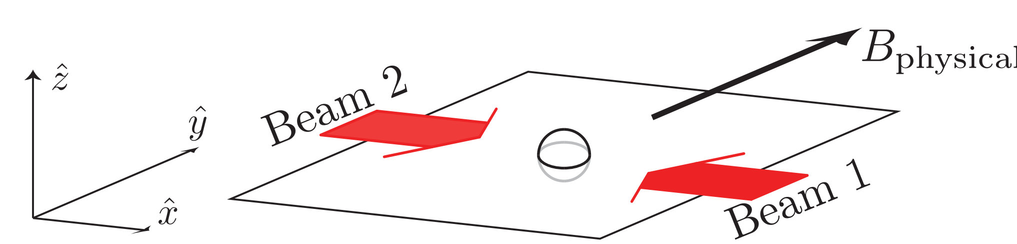
Suddenly turn off Raman + dipole trap, TOF



Raman Dressed





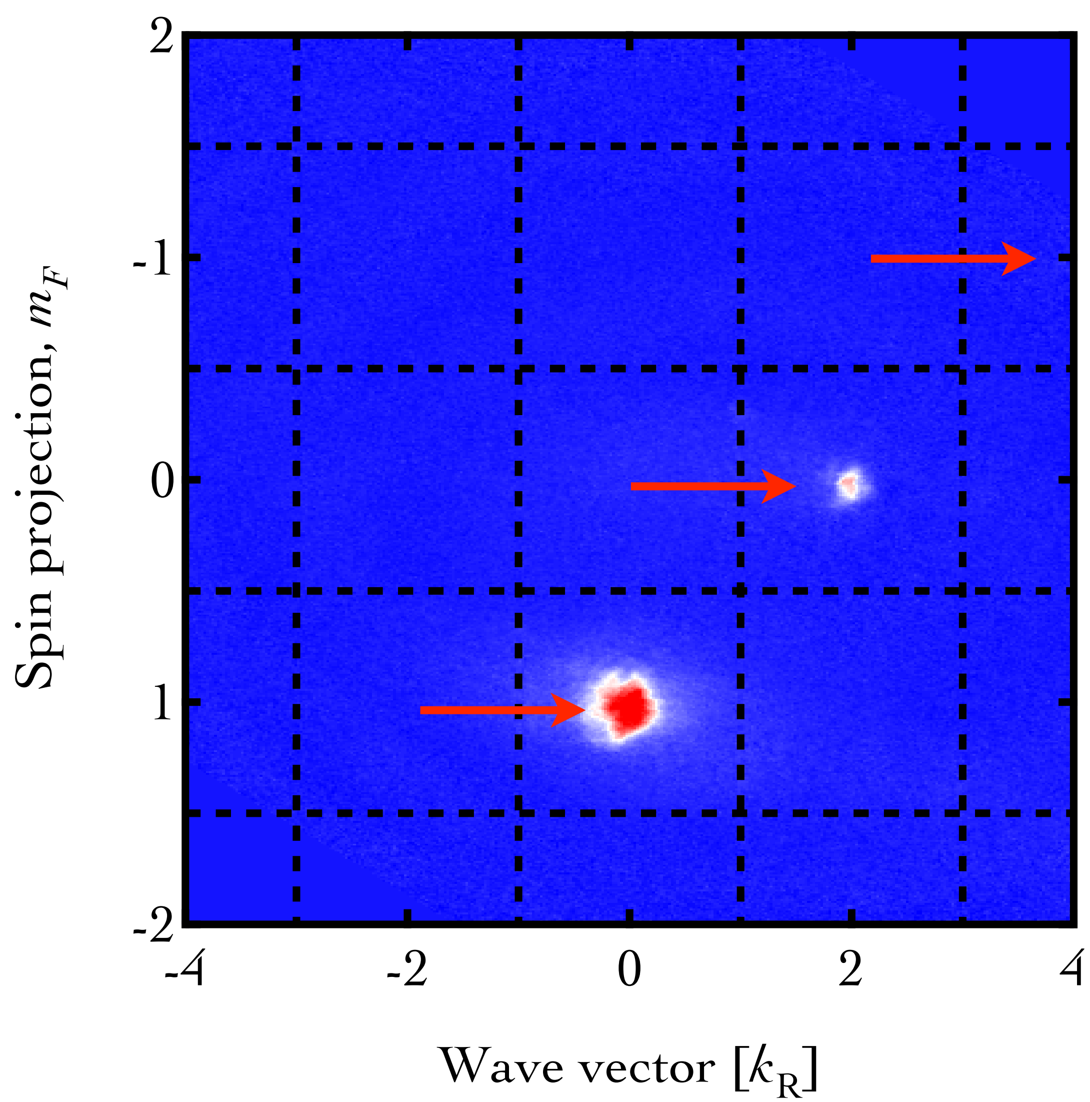


Displaced momentum distribution

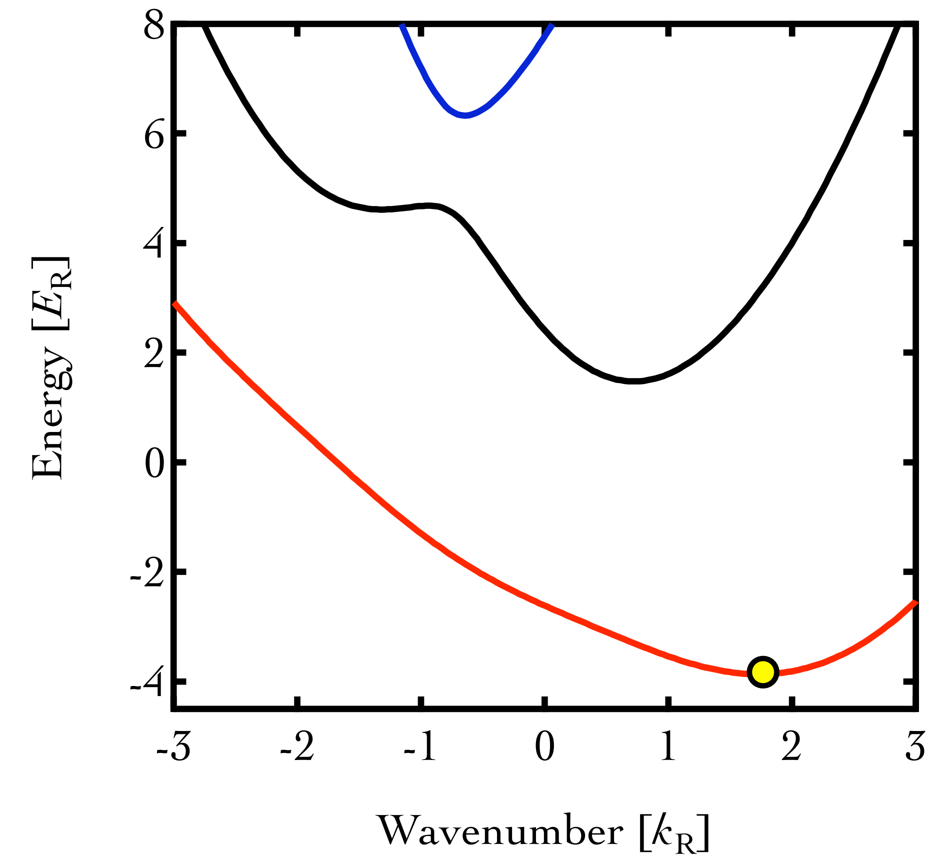
Conserved

Abrupt turnoff conserves mechanical velocity

Mechanical velocity is averaged over all orders and is zero in equilibrium (of course).



Raman Dressed



1. Junior mechanics

Canonical variables and vector potential

$$H = \frac{(\mathbf{p} - q\mathbf{A})^2}{2m}$$

$$\dot{p}_j = -\frac{\partial}{\partial x_i} H, \;\; \dot{x}_j = \frac{\partial}{\partial p_i} H$$

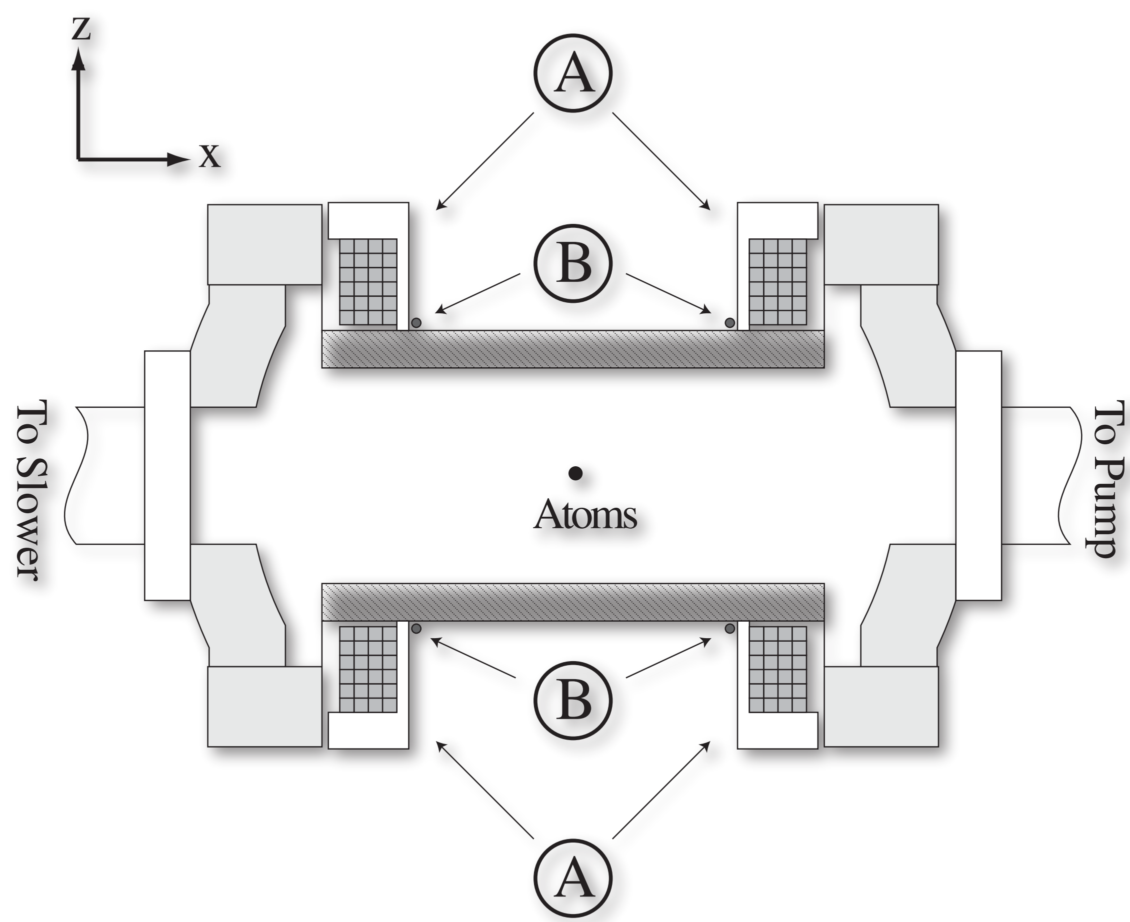
$$\dot{x}_j = v_j = \frac{p - qA_j}{m}$$

A laboratory tunable vector potential

Idea

We can control the *engineered* vector potential in time and space giving *synthetic* ***E*** and ***B*** fields.

Bias and quadrupole ***B*** fields = offset and gradient in detuning.

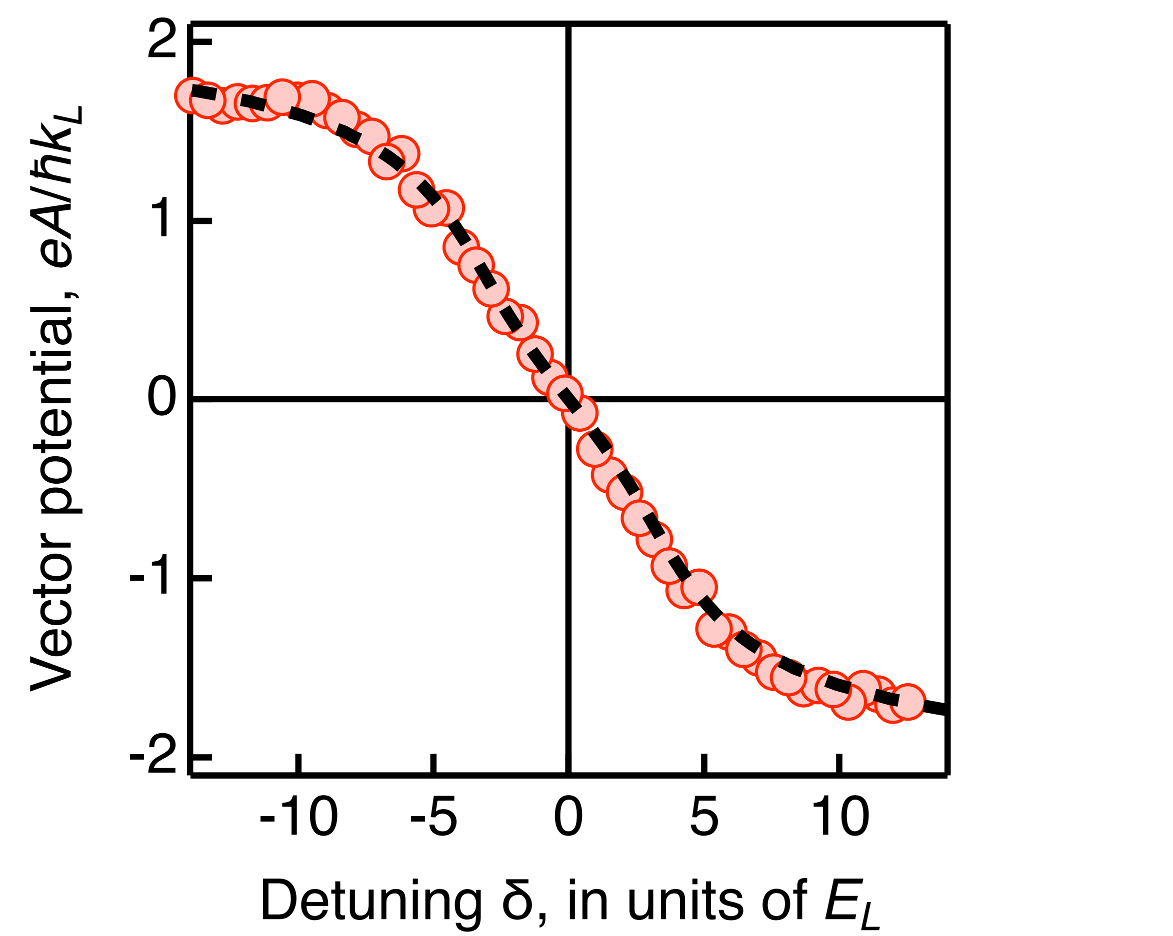


Transfer function

$$\hat{H} = \frac{\hbar^2}{2m}\left\{\left[k_x - \frac{qA_x(\delta,\Omega)}{\hbar}\right]^2 + k_y^2\right\} + V(\mathbf{x})$$

where $\delta(x,y,t)$ and $\Omega(x,y,t)$

The detuning and coupling specify the local synthetic vector potential



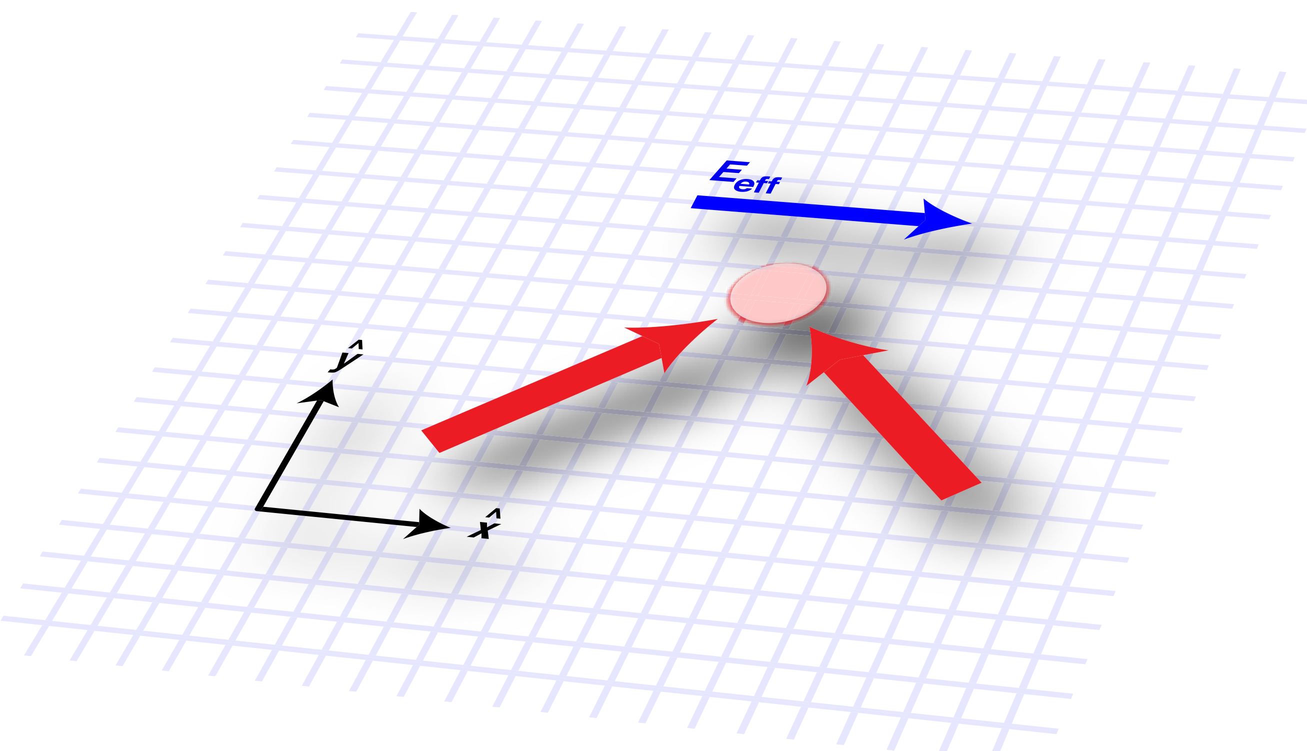
References

[1] Y.-J. Lin et al, PRA **79** 063631 (2009)

Electric fields: time dependence

Complete disclosure

Our beams now intersect at 90°
Not for physics reasons.

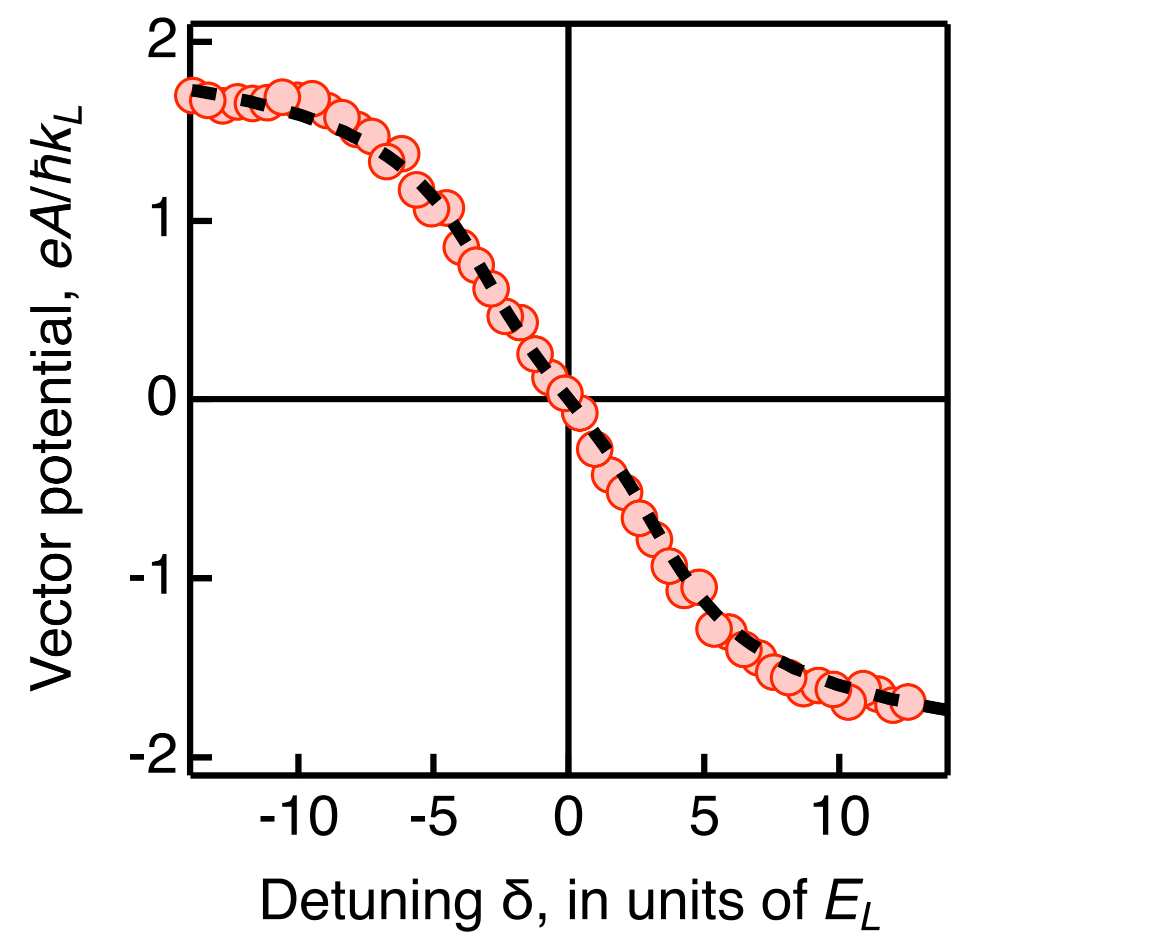


Transfer function

$$\hat{H} = \frac{\hbar^2}{2m}\left\{\left[k_x - \frac{qA_x(\delta,\Omega)}{\hbar}\right]^2 + k_y^2\right\} + V(\mathbf{x})$$

where $\delta(x,y,t)$ and $\Omega(x,y,t)$

The detuning and coupling specify the local synthetic vector potential



Synthetic Electric Field

A uniform vector potential: forces

Time dependence gives electric fields and forces
Usual "quasi-static assumptions"

1. Freshman version

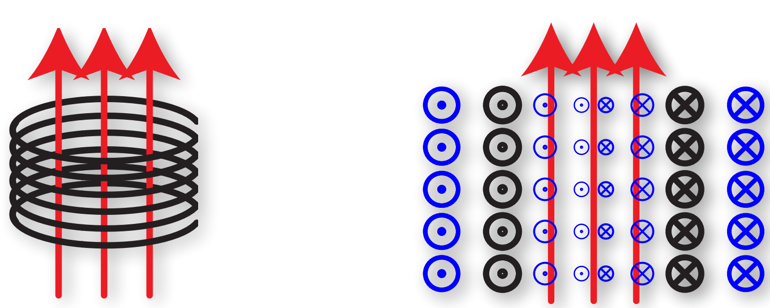
$$\mathbf{E} = -\nabla\Phi - \frac{\partial \mathbf{A}}{\partial t}$$

$$\frac{m\Delta\dot{\mathbf{x}}}{\hbar} = \frac{e}{\hbar}\int \mathbf{E}dt = -\frac{e}{\hbar}\Delta\mathbf{A}$$

2. Junior version

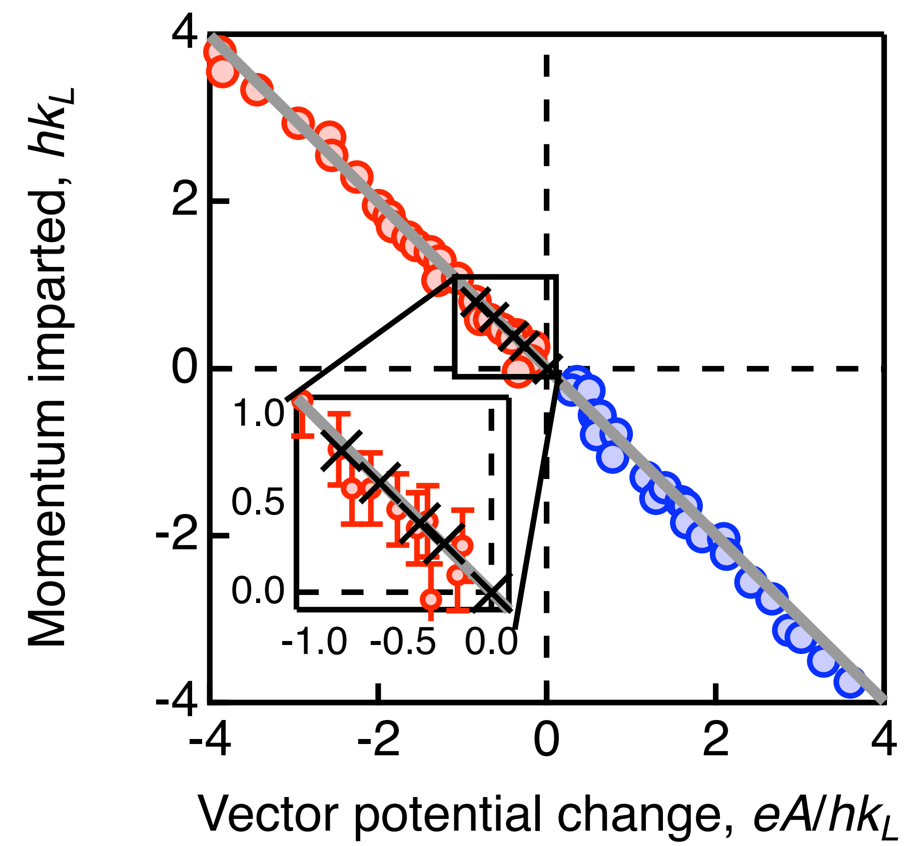
$$\frac{m\dot{x}_j}{\hbar} = k_j - \frac{qA_j}{\hbar}, \;\; \dot{k}_j = -\frac{1}{\hbar}\frac{\partial}{\partial x_i}H = 0$$

Geometric example



Realization with dressed states

Yes! Atoms acquire expected -2 k_{R} mechanical momentum kick.



Our synthetic vector potential behaves just like the real thing

References
Y.-J. Lin et al Nat. Phys. (2011)

Synthetic magnetic field

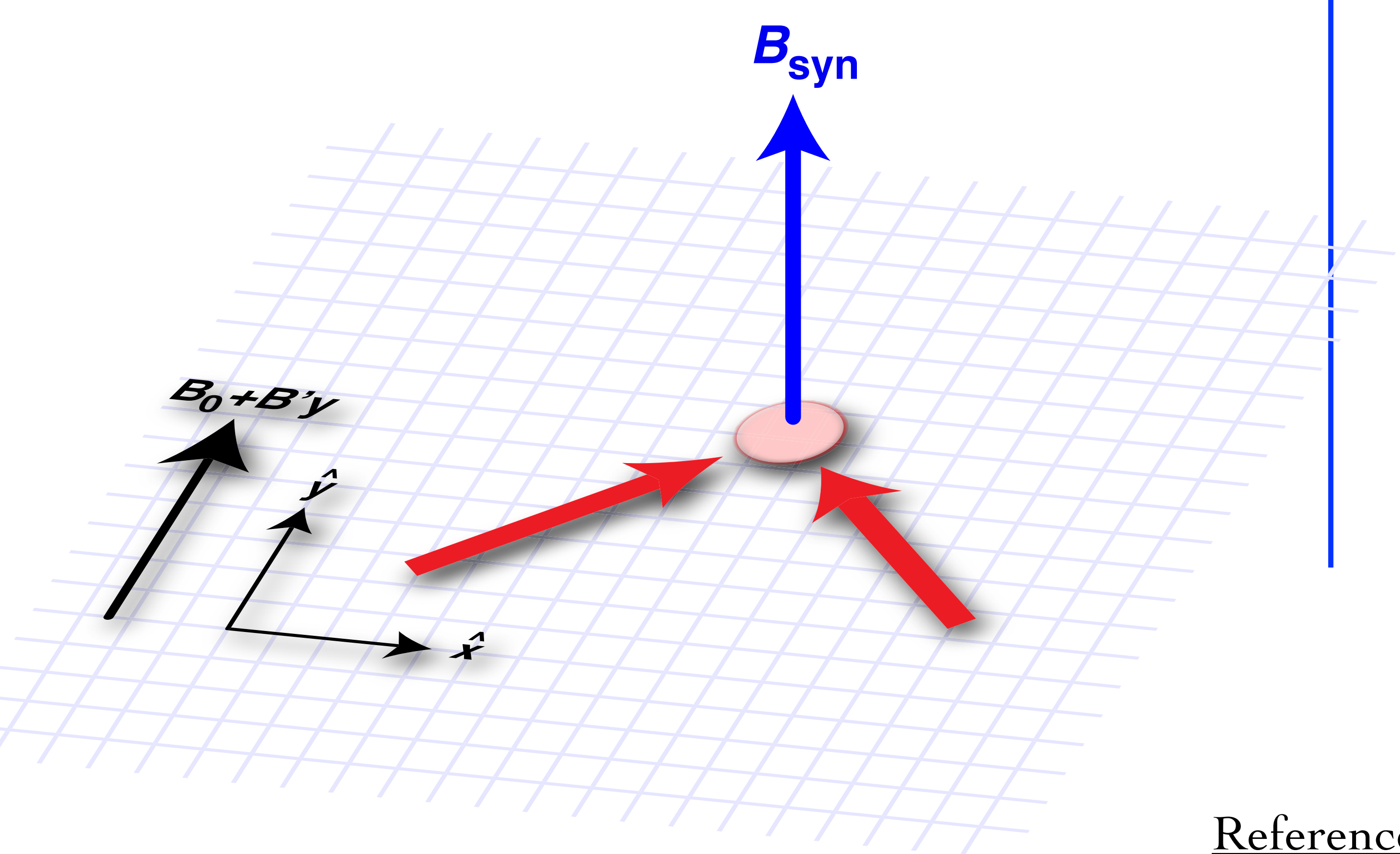
Loading procedure

Initial state
RF dressed state (RF on, ramp B to resonance)
Raman + RF dressed state (Ramp Raman on)
Raman only dressed state (Ramp RF off)

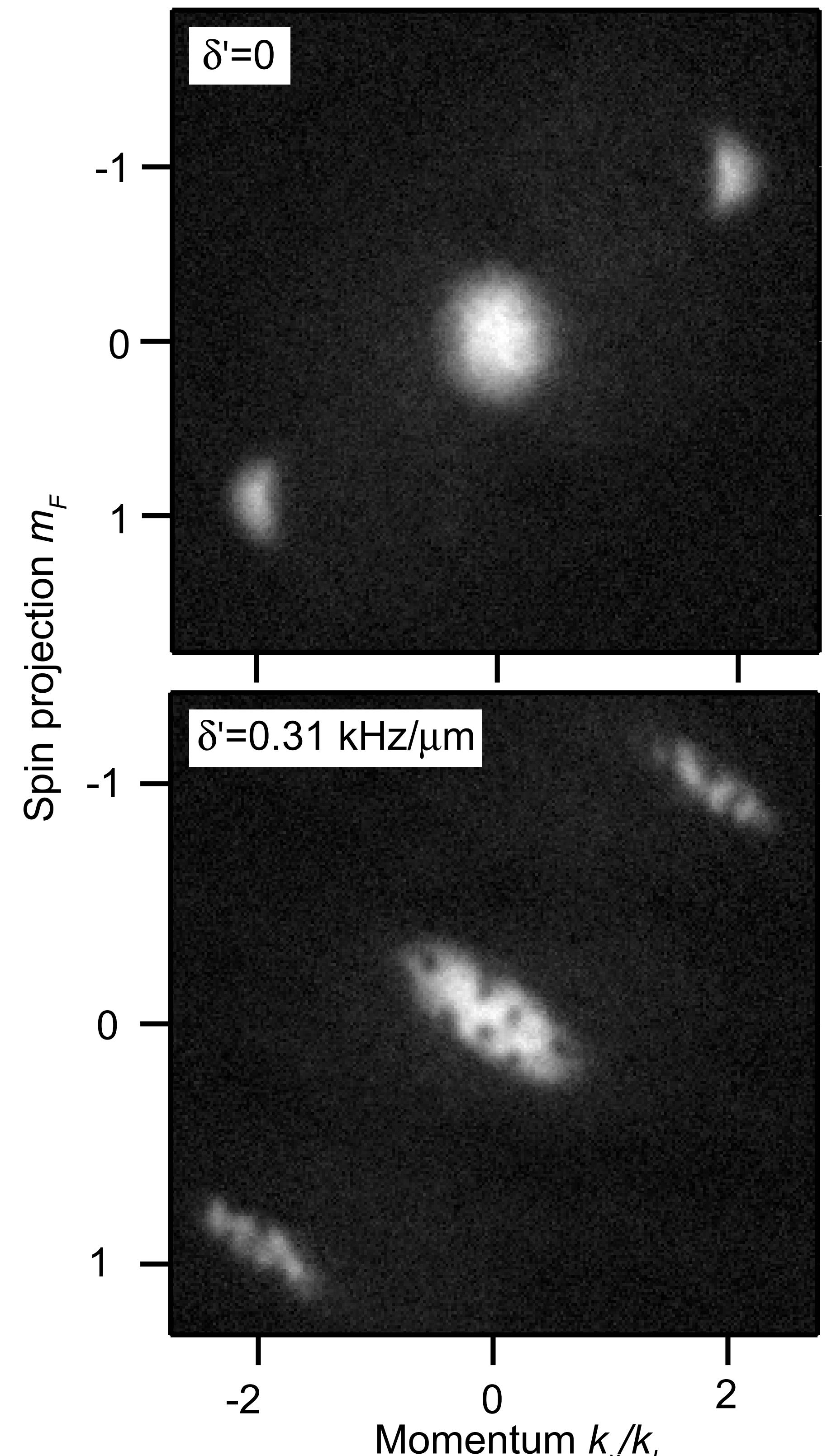
Ramp field gradient on (from 0 to 500 Hz/μm)

Equilibrate for 500 ms

TOF imaging



Outcome

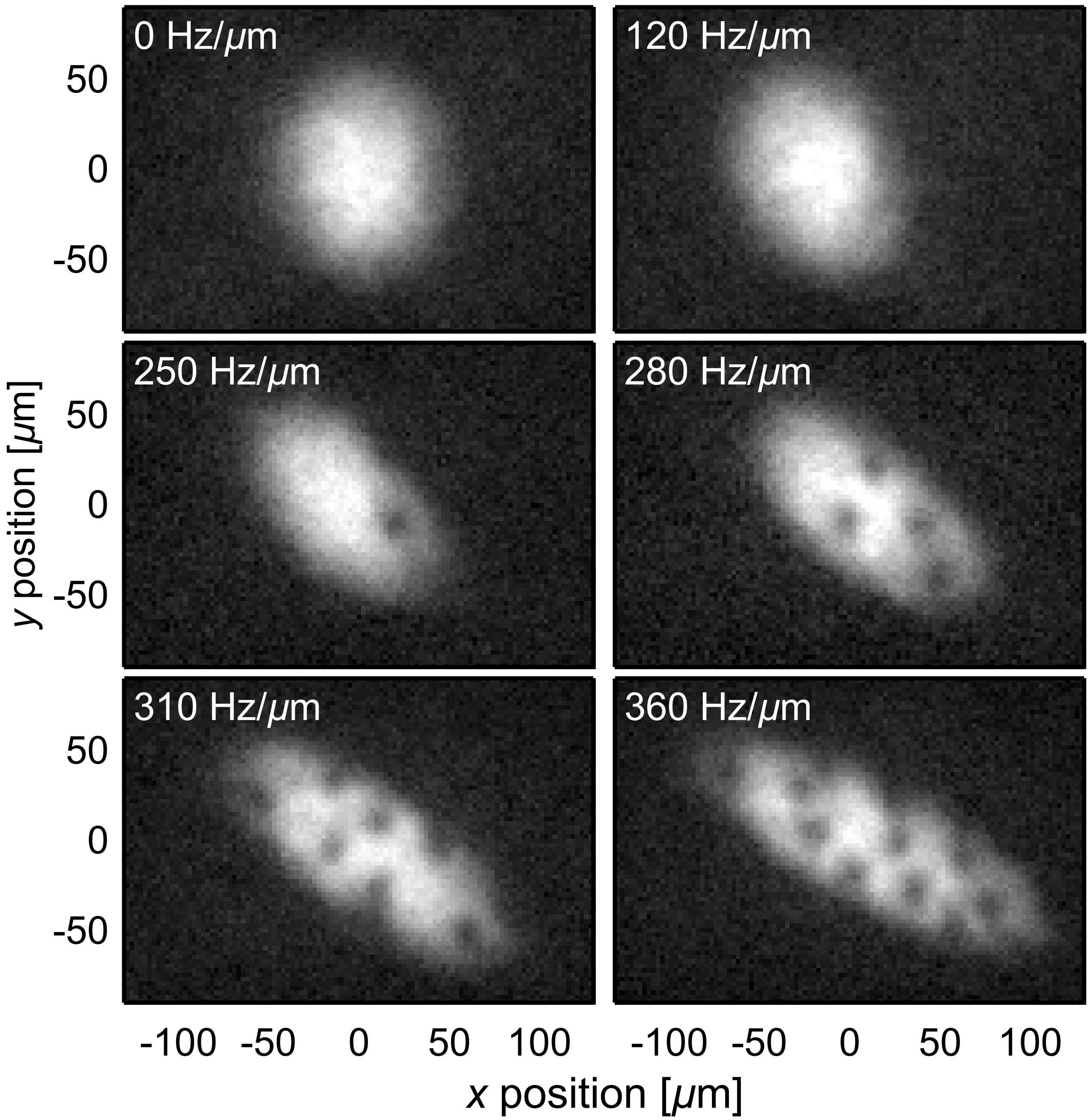


References
Y.-J. Lin *et al* Nature (2009)

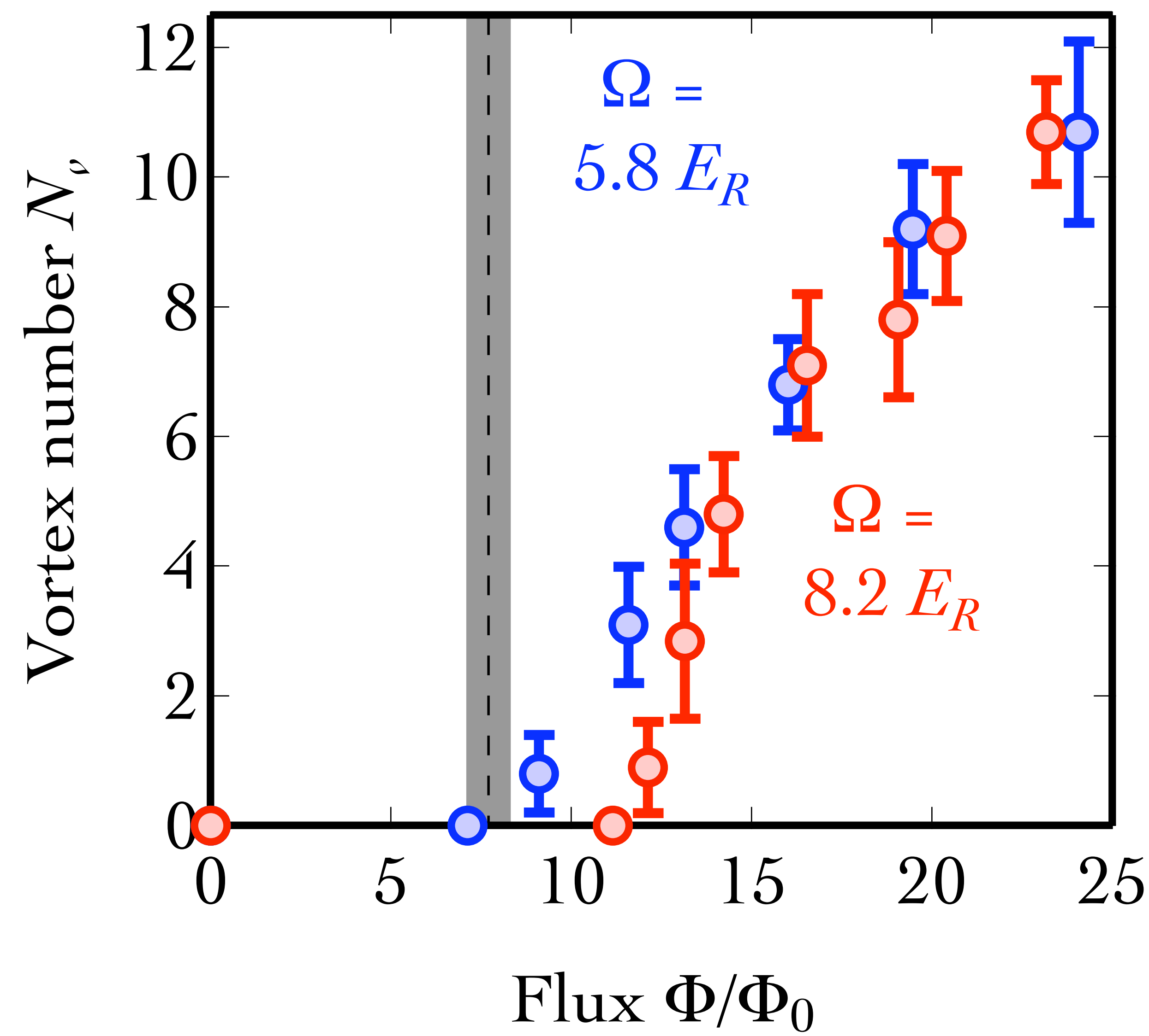
But that not what happened...

Vortex number

Spatial dependence gives magnetic fields and forces



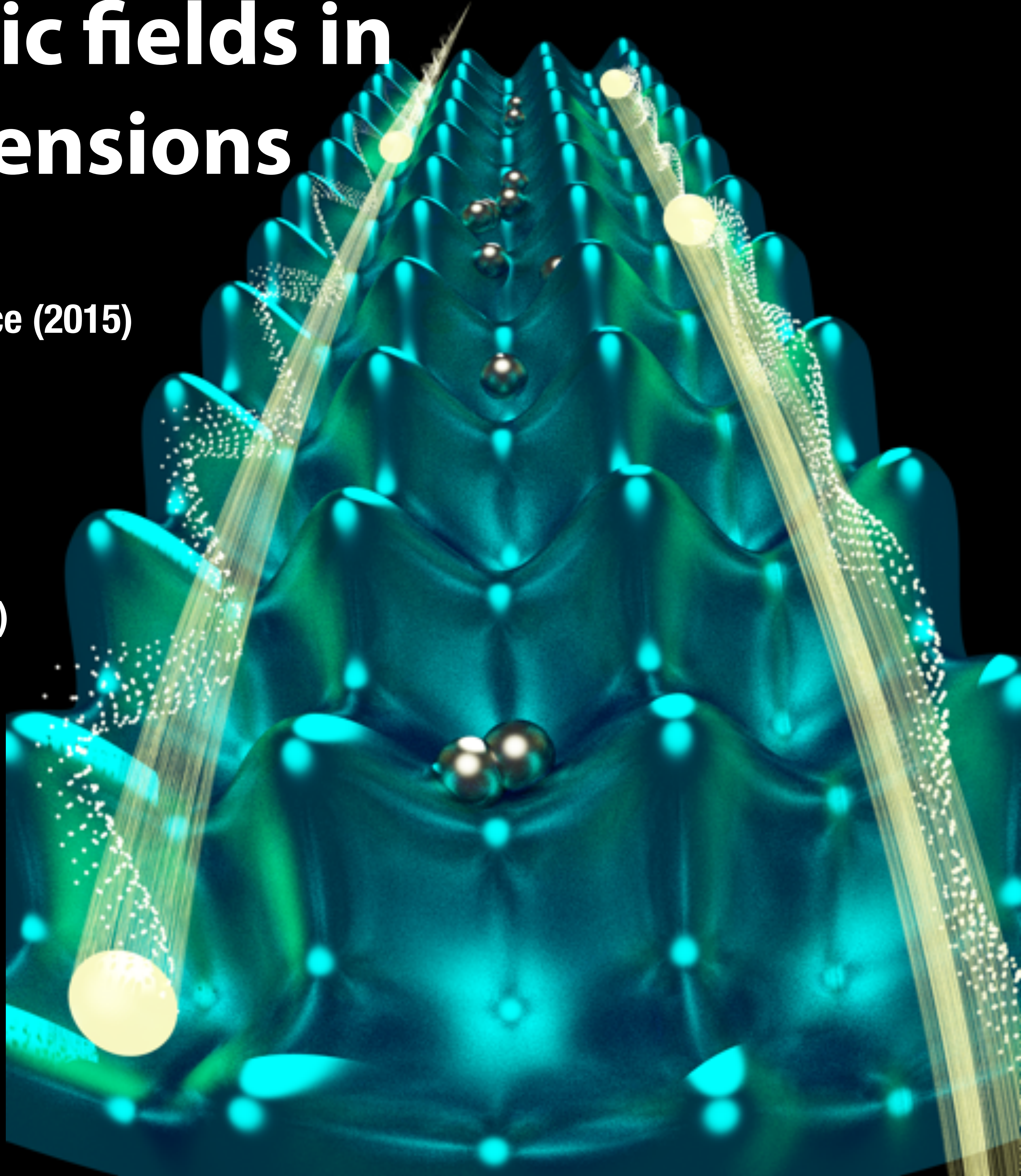
Critical field for vortex formation



References

Extensive review: A.L. Fetter, RMP **81** 647 (2009)

Large magnetic fields in synthetic dimensions



JQI:
B. Stuhl and Hsin-I Lu, et al. Science (2015)

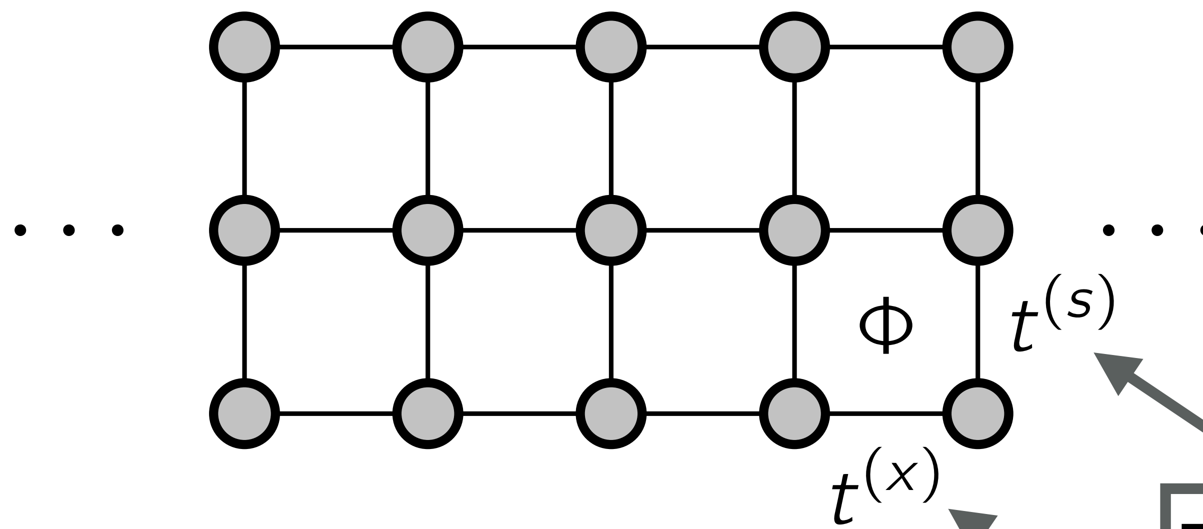
Florence
M. Mancini et al. Science (2015)

THEORY PROPOSAL:
Celi, A. et al. Phys. Rev. Lett. (2014)

Where we are going:

Large magnetic fields in a 2D lattice

$\Phi \approx 1/3$



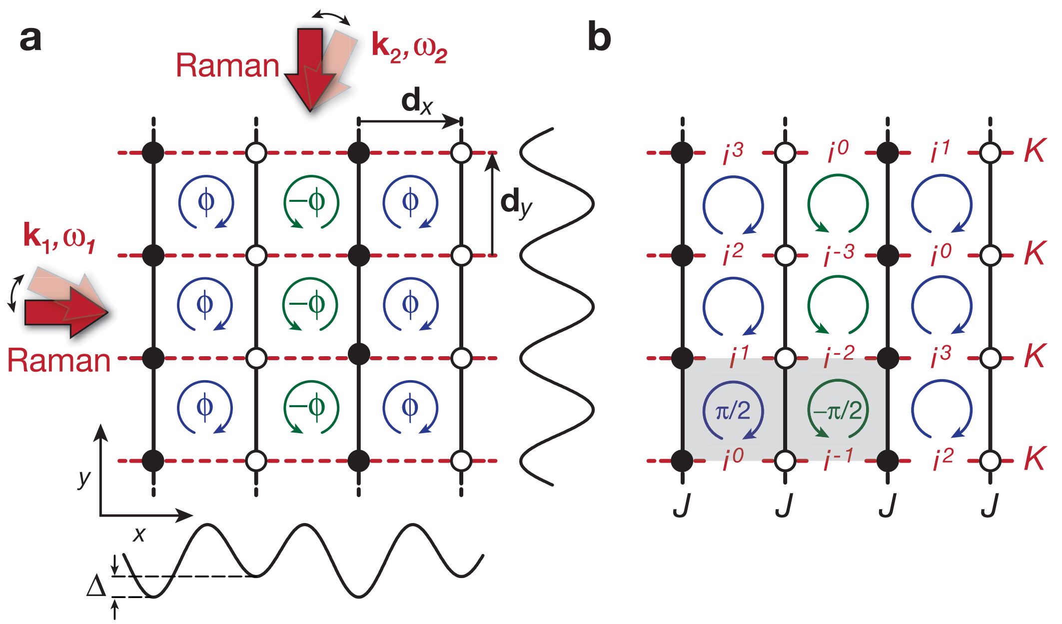
Tunneling also gives phases such that the acquired phase gives an effective Aharonov-Bohm phase

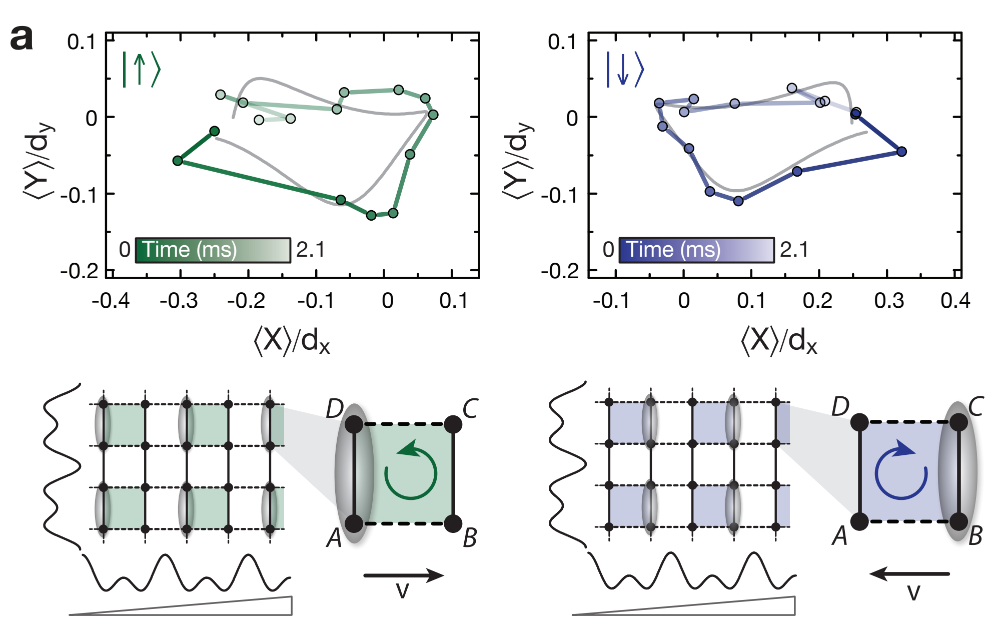
References

B. Stuhl, et al. Science (2015); Celi, A. et al. Phys. Rev. Lett. (2014);

AMO: fields in lattices

Light assisted hopping I: Munich

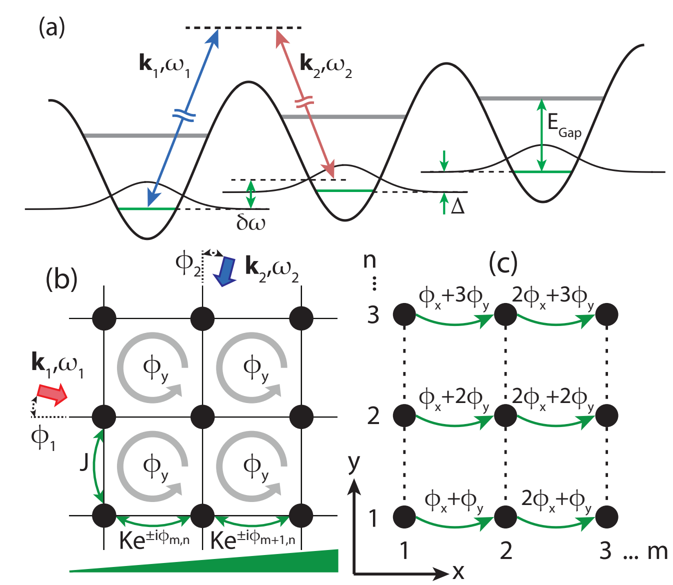


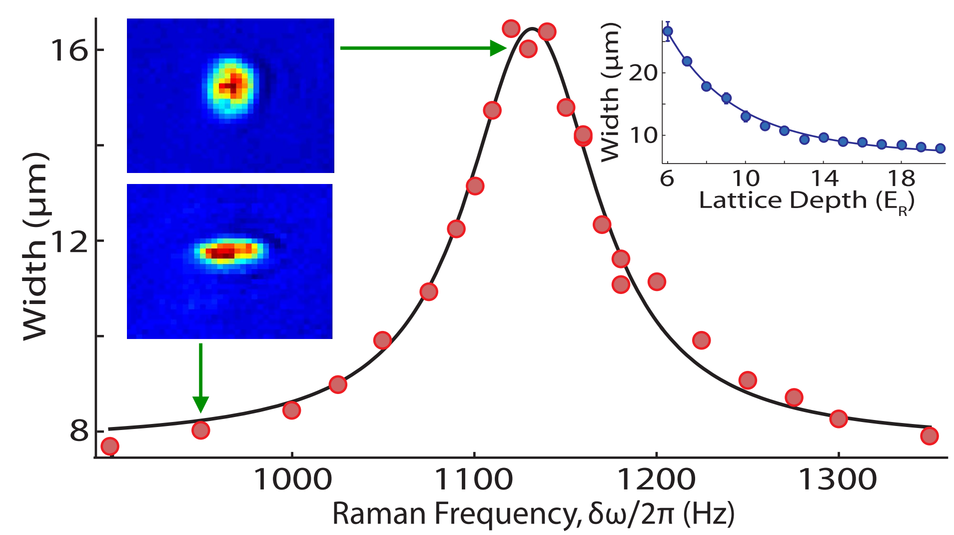


References

M. Aidelsburger *et al* PRL (2011), M. Aidelsburger et al PRL (2013)

Light assisted hopping II: MIT



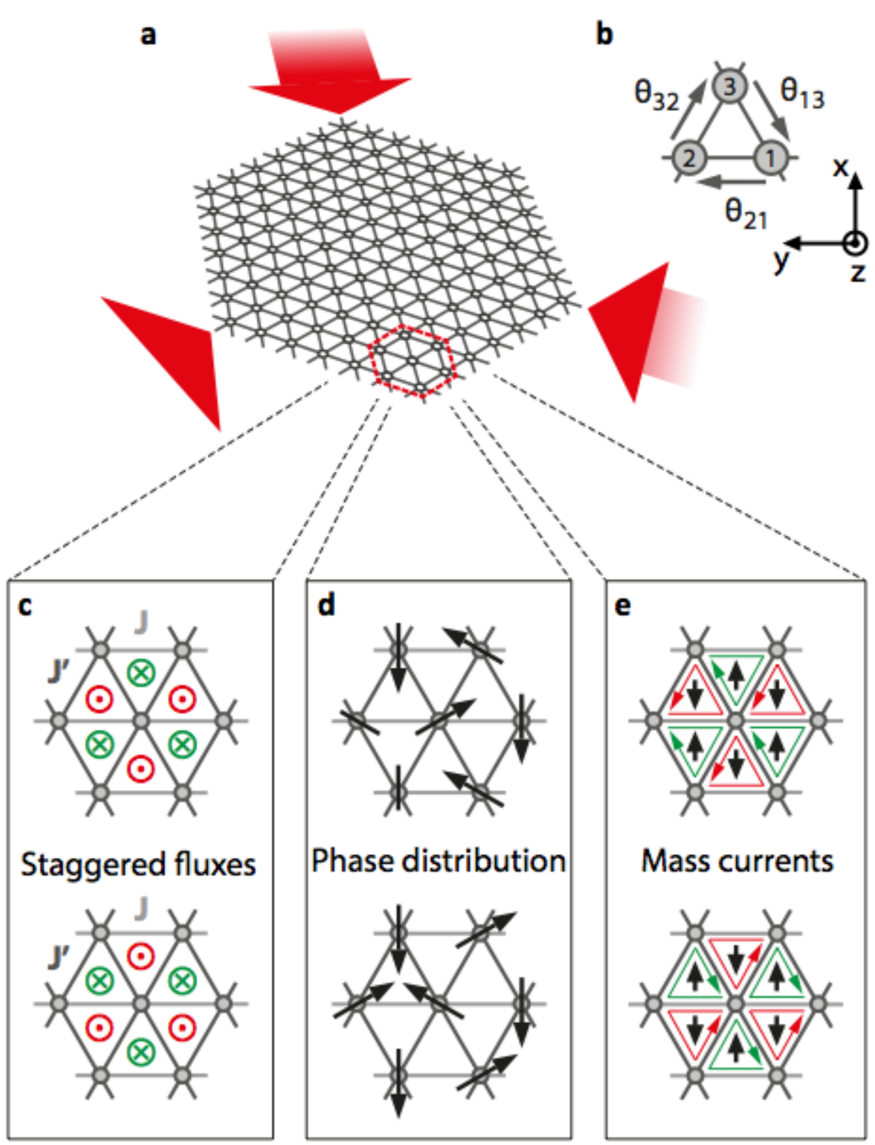


References

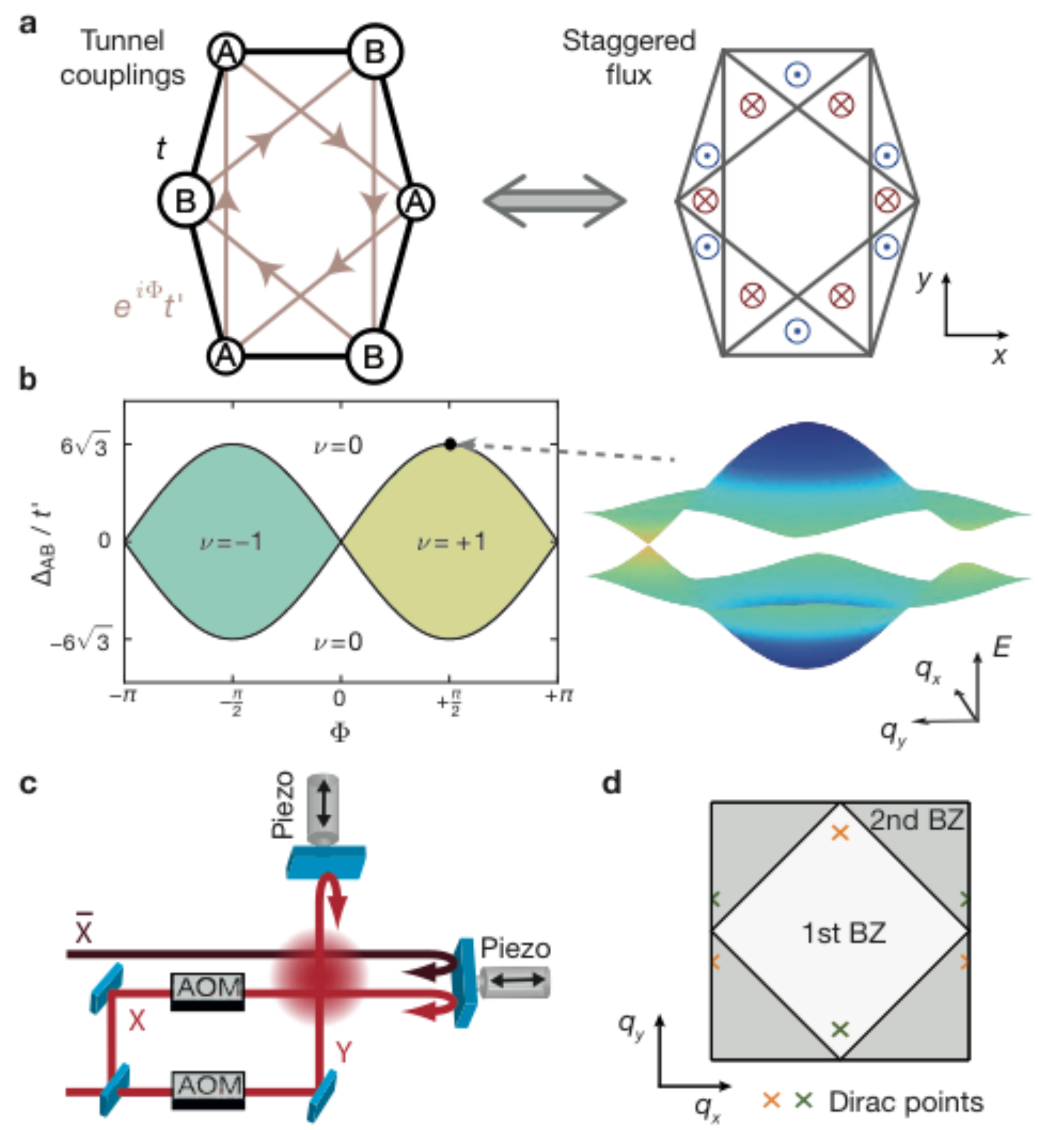
C. J. Kennedy, et al Nat. Phys (2015), H. Miyake *et al* PRL (2013)

AMO: exotic lattices

Modulation I: Hamburg



Modulation II: Zurich



References

J. Struck *et at* N. Physics (2013)

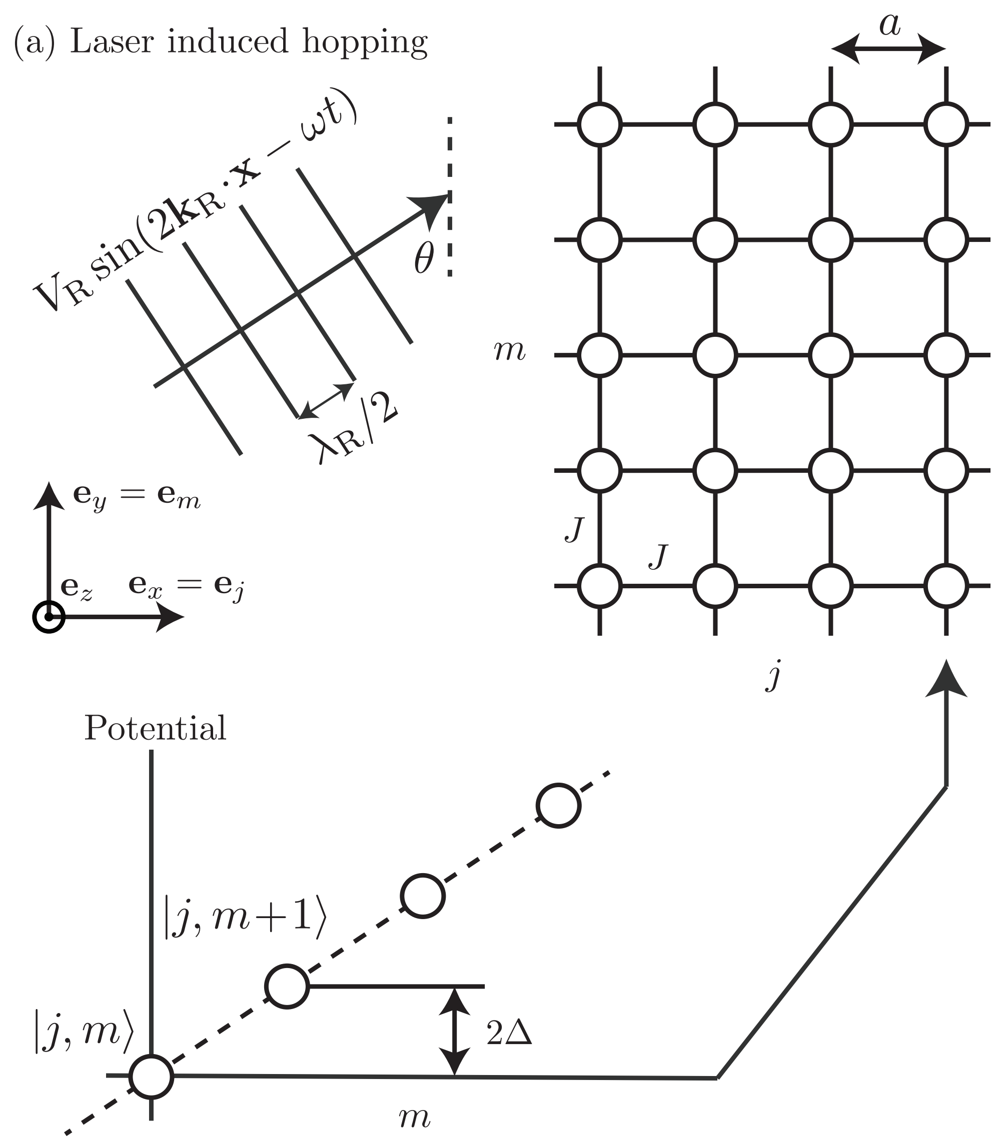
References

J. Gotzu *at al* Nature (2014)

Backdrop

Basic idea: laser induced hopping

$$H = -\sum_{\mathrm{j}} \left[t^{(x)} e^{-i2\pi\Phi j_y} |\mathbf{j}+\mathbf{e}_x\rangle\langle\mathbf{j}| + t^{(y)} |\mathbf{j}+\mathbf{e}_y\rangle\langle\mathbf{j}| + \mathrm{h.c.} \right]$$

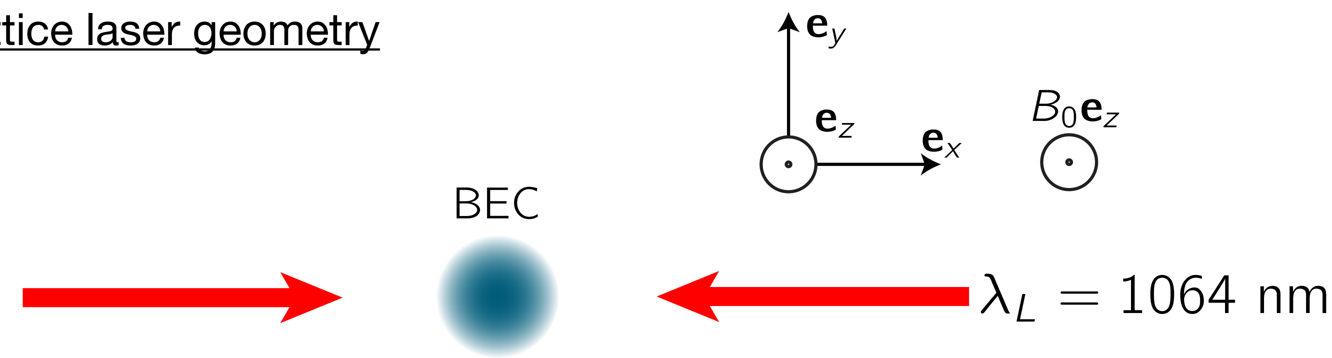


References

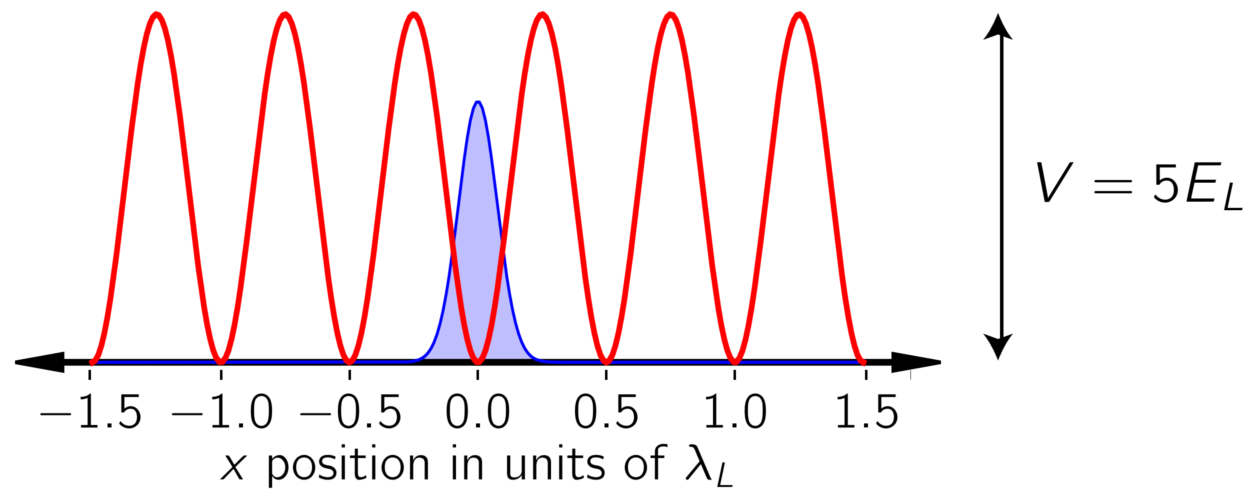
D. Jaksch and P. Zoller; New Journal of Physics (2003).

Building a magnetic lattice

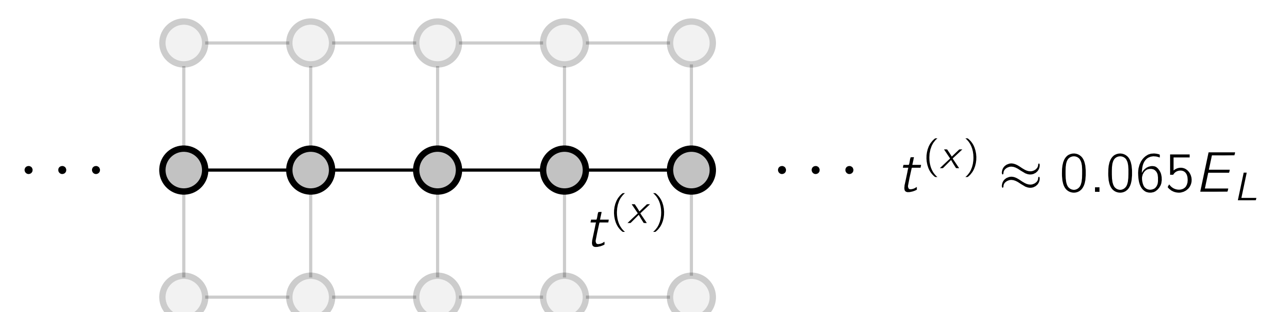
Lattice laser geometry



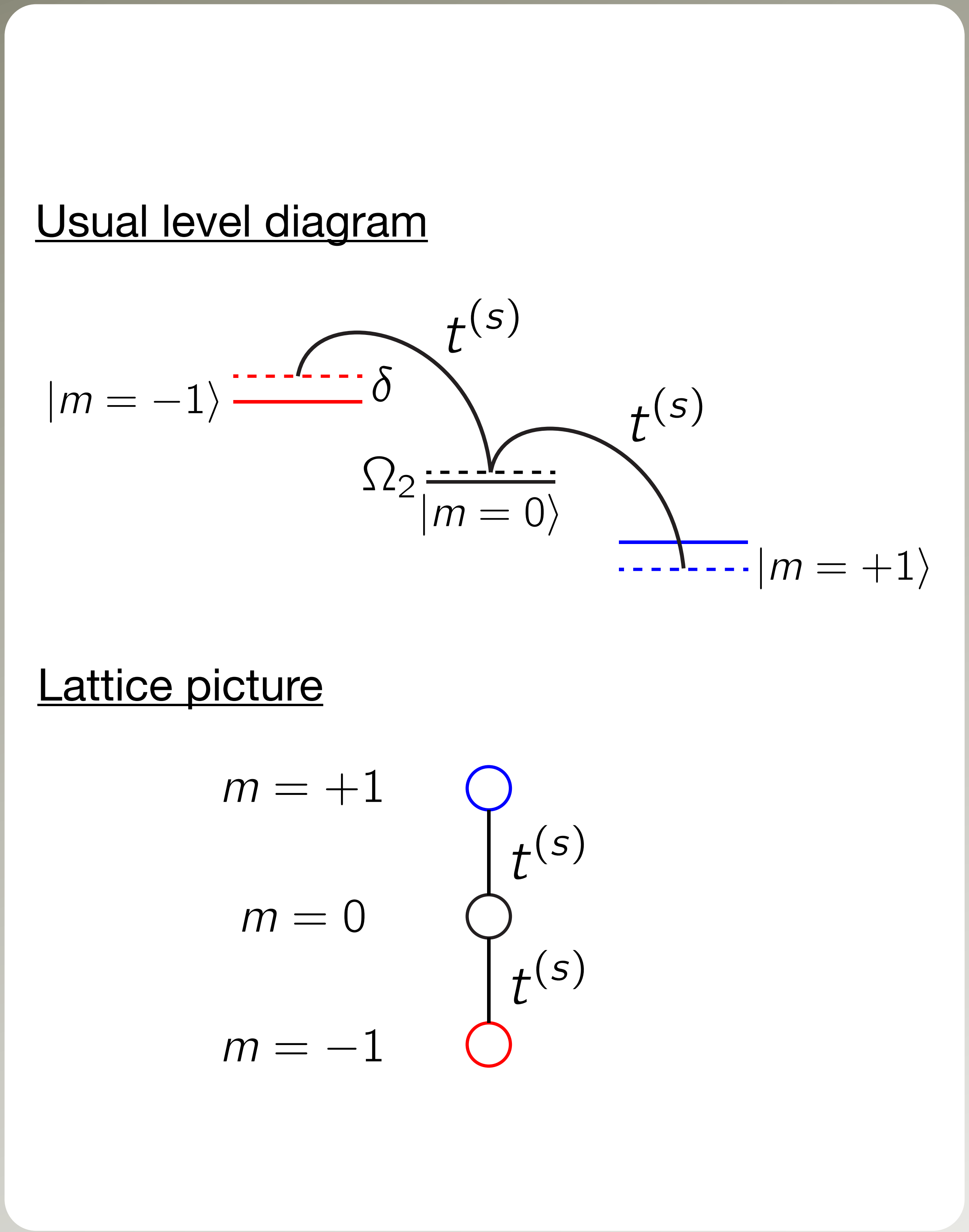
Lattice potential



Tight binding model



Building a magnetic lattice

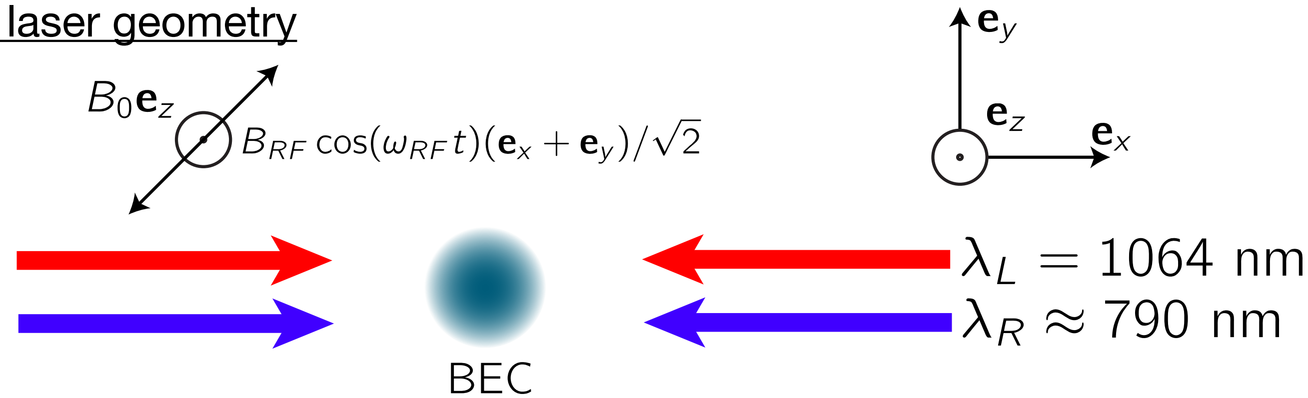


Reference

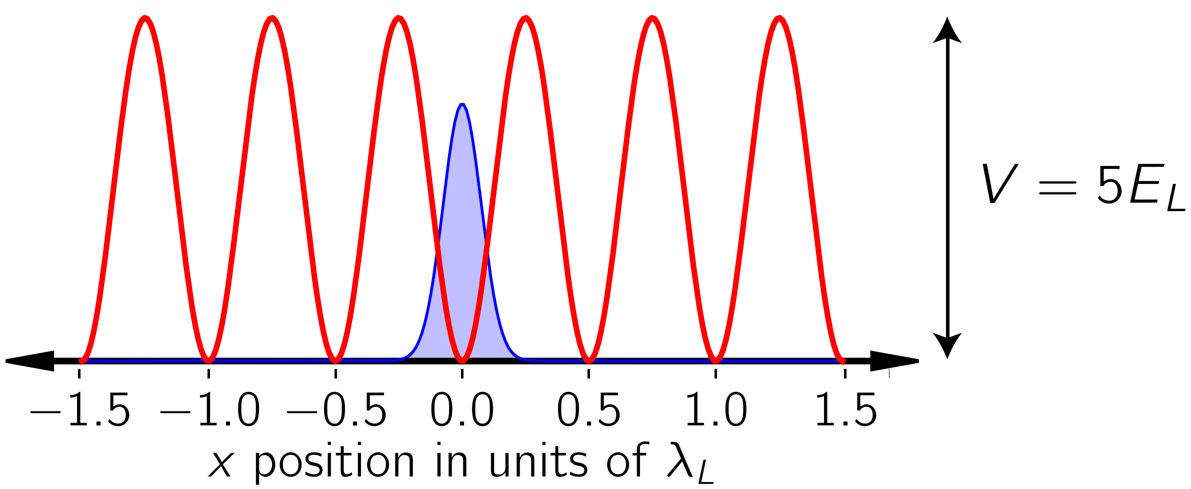
Celi, A. et al. Phys. Rev. Lett. (2014).

All together: Full lattice

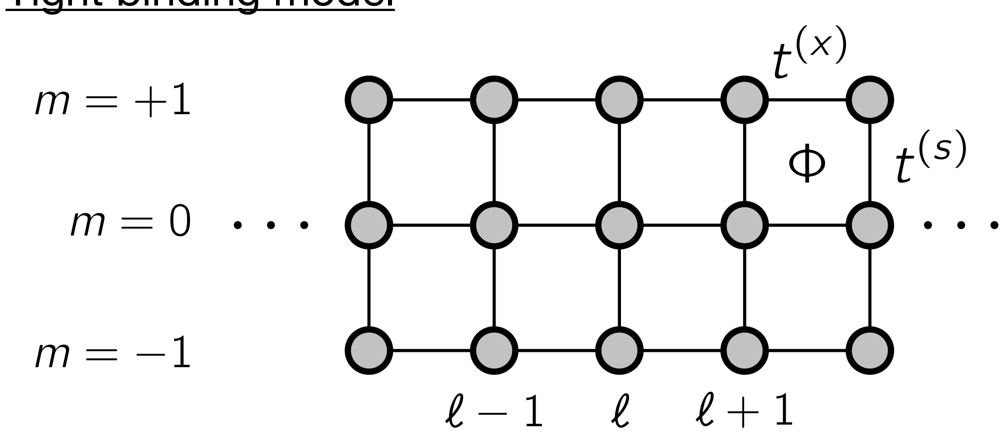
Lattice laser geometry



Lattice potential



Tight binding model



$t^{(x)} \approx 0.065E_L$

$|t^{(s)}| = 0.5t^{(x)}$ to $5t^{(x)}$

Synthetic hopping

$$t^{(s)} = \frac{\Omega_R}{\sqrt{2}}e^{i2k_Rx} = \frac{\Omega_R}{\sqrt{2}}e^{i(2\pi\Phi)\ell}$$

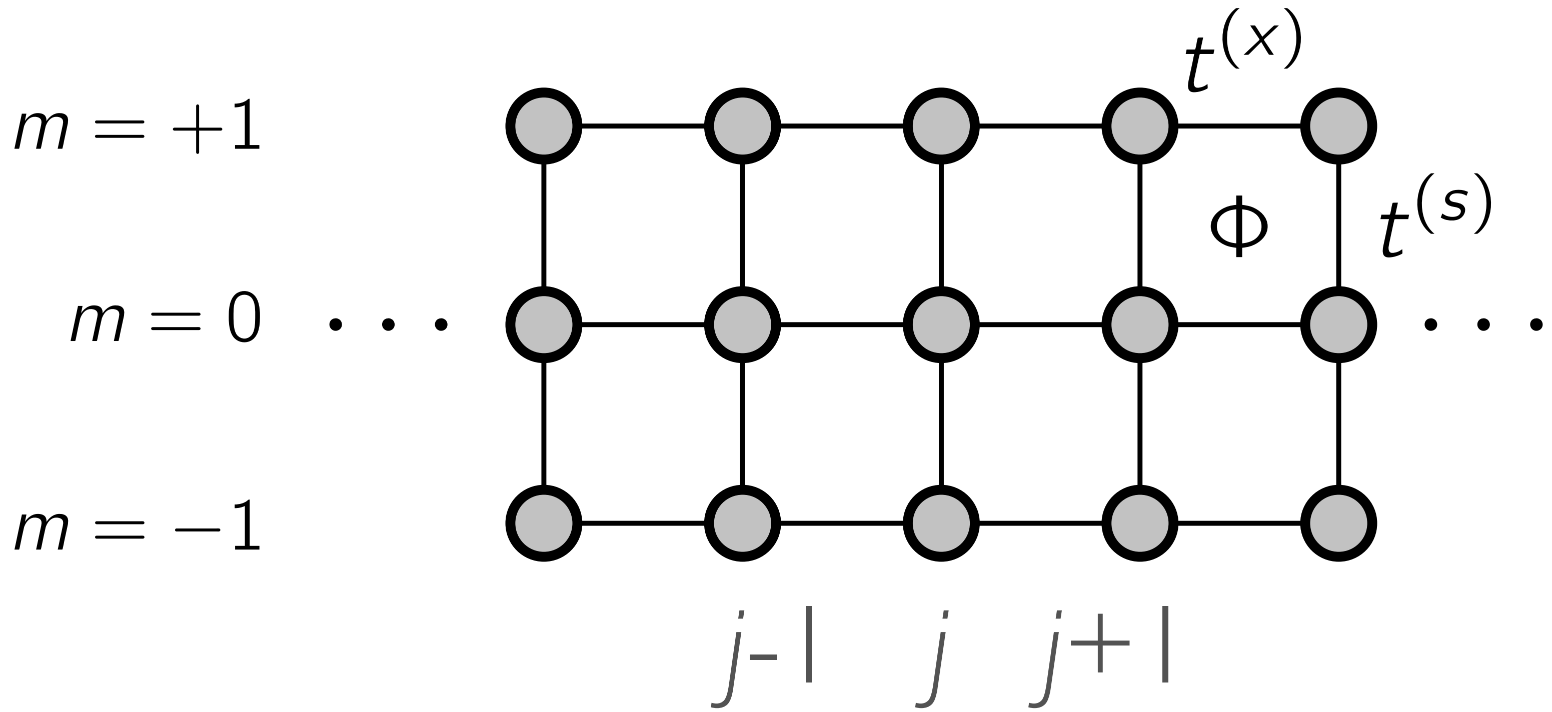
$$\text{with } \Phi = \frac{\lambda_L}{\lambda_R} \approx 1.32$$

References

Celi, A. et al. Phys. Rev. Lett. (2014); 3-site dual to: M. Atala et al. Nat. Phys. (2014)

All together: Full lattice

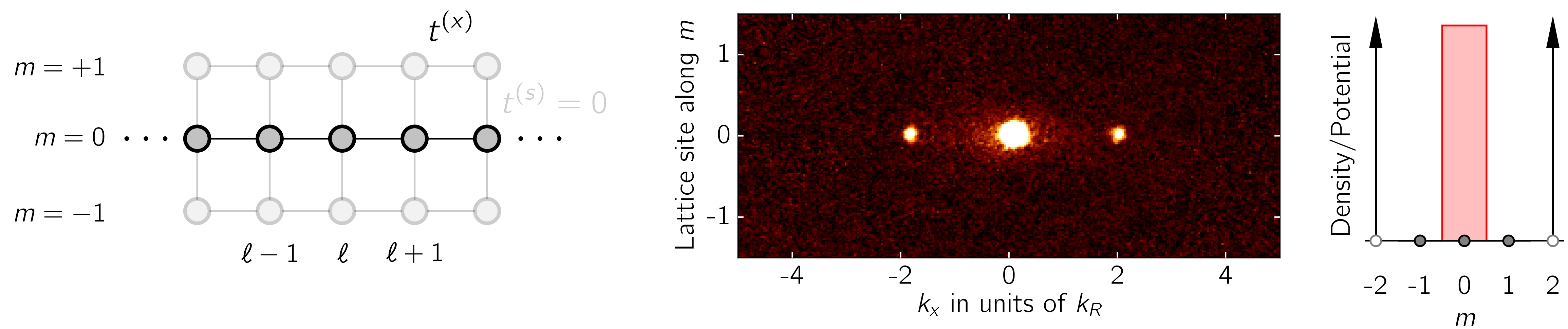
$$H = -\sum_{j,m}\left[t_j\,|j+1,m\rangle\langle j,m| + t_s e^{i(\Phi j+\varphi)}\,|j,m+1\rangle\langle j,m| + \text{c.c}\right]$$

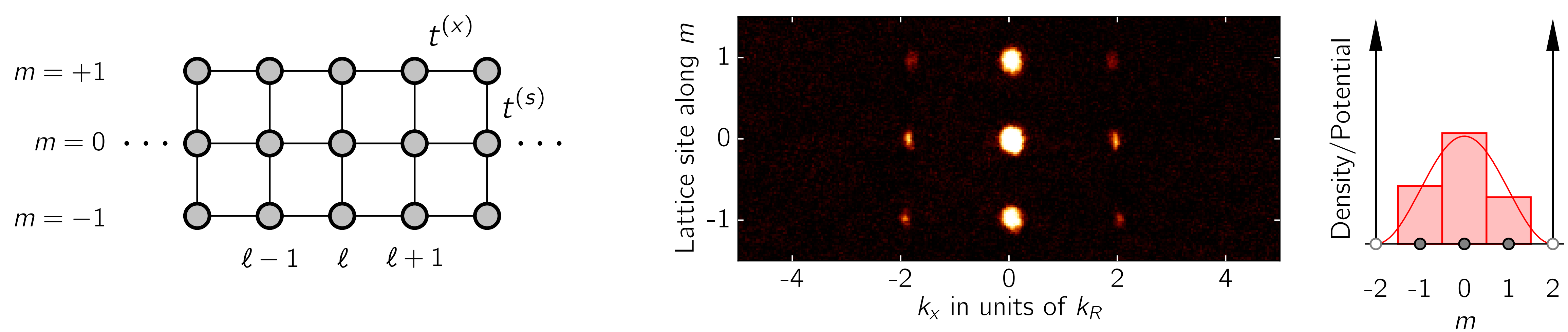


References

Celi, A. et al. Phys. Rev. Lett. (2014); 3-site dual to: M. Atala et al. Nat. Phys. (2014)

Interpreting data

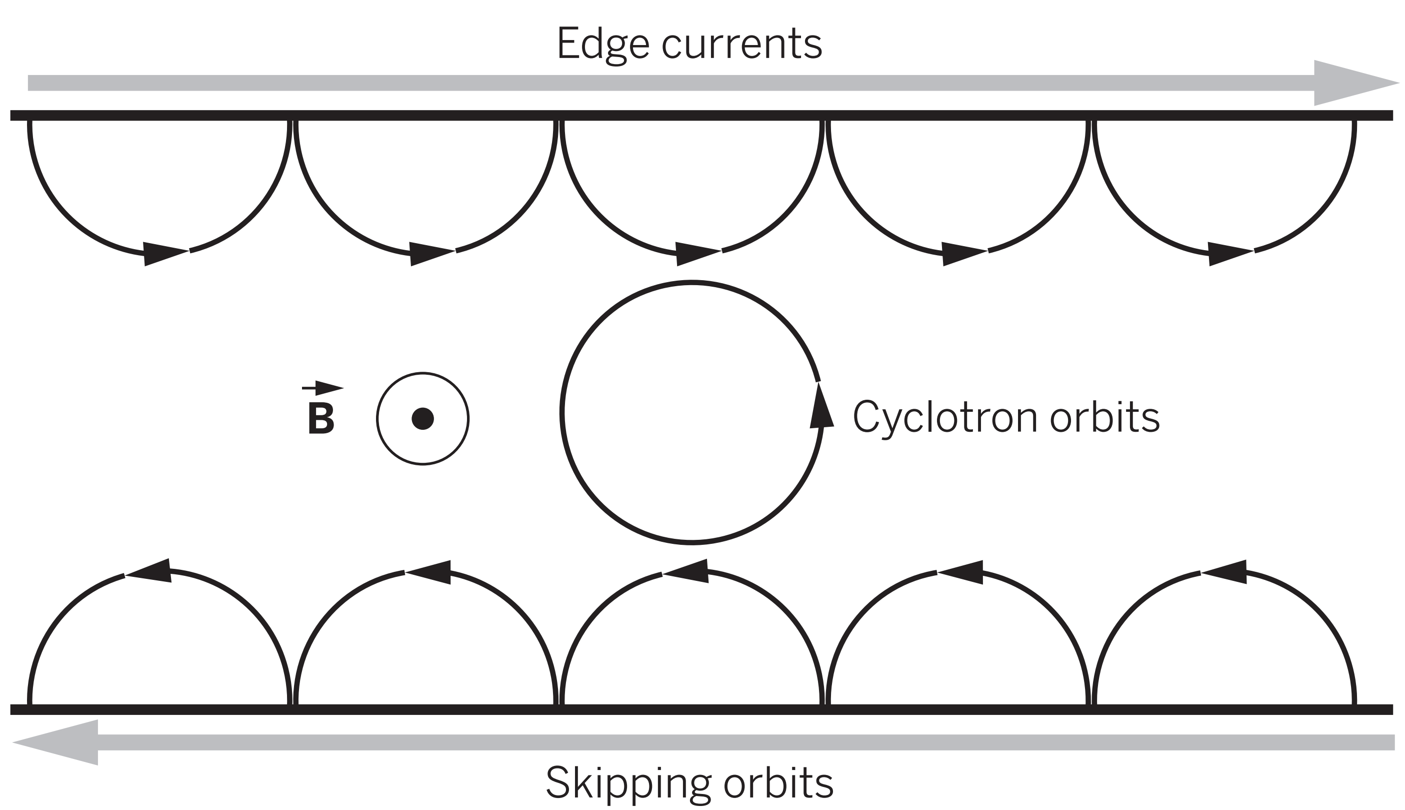




Continuum magnetic fields

Single-particle eigenstate structure: **Landau gauge**

$$H = \frac{\hbar^2}{2m}\left[\left(k_x + \frac{qBy}{\hbar}\right)^2 + k_y^2\right], \quad \text{from} \quad \mathbf{A} = -By\mathbf{e}_x \quad \text{with} \quad \ell_B = \sqrt{\frac{\hbar}{qB}}$$

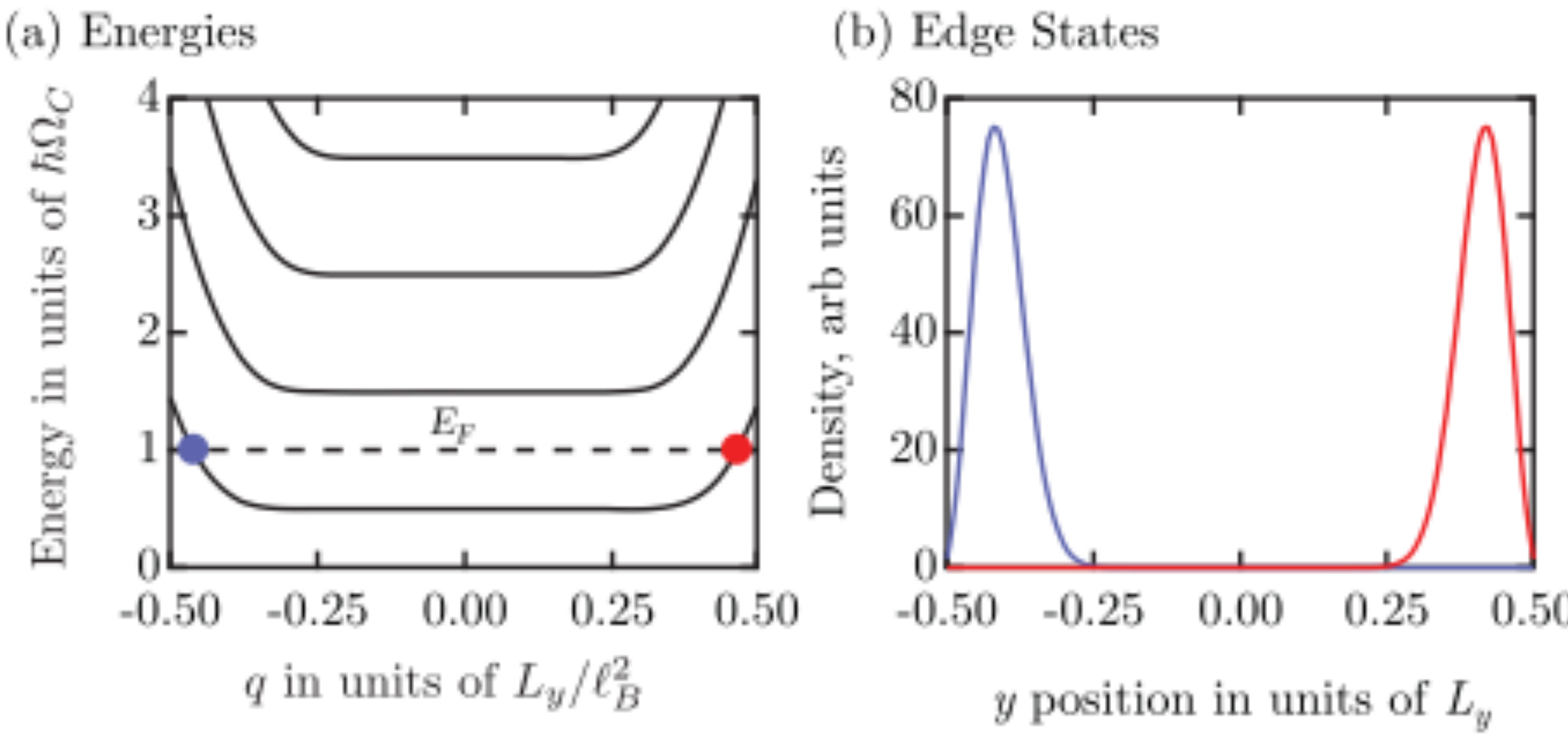


References

Figure From: A. Cili and L. Tarruell, Science Perspective (2015)

QHE systems: Edge states

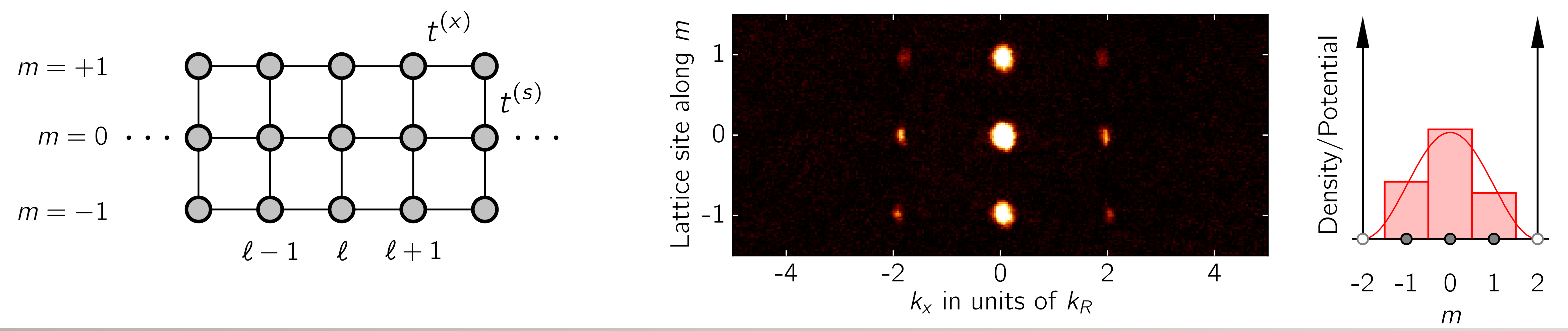
Edge states in QHE systems



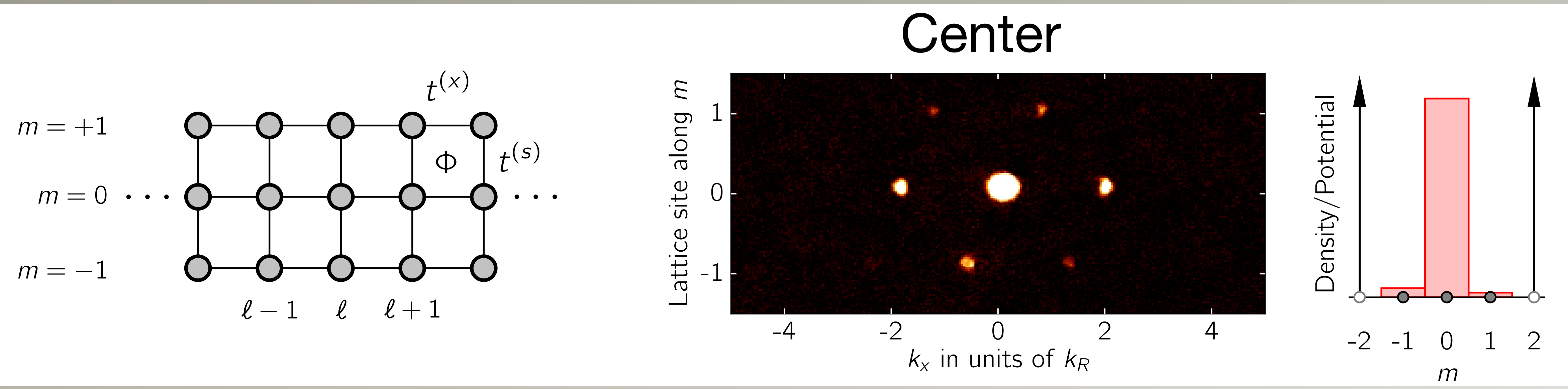
References

I. B. Spielman Ann. der Phy. (2013).

Interpreting data: zero flux

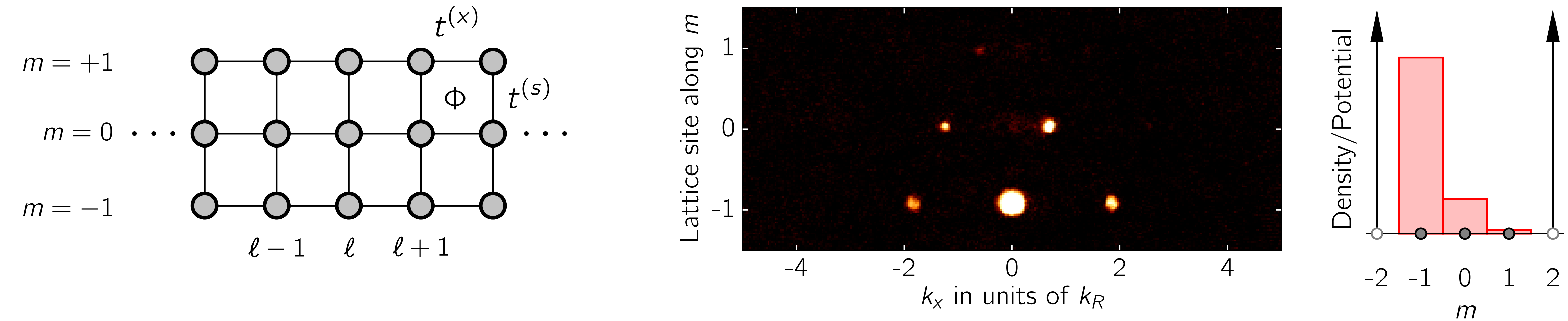


Interpreting data: +1/3 flux quantum

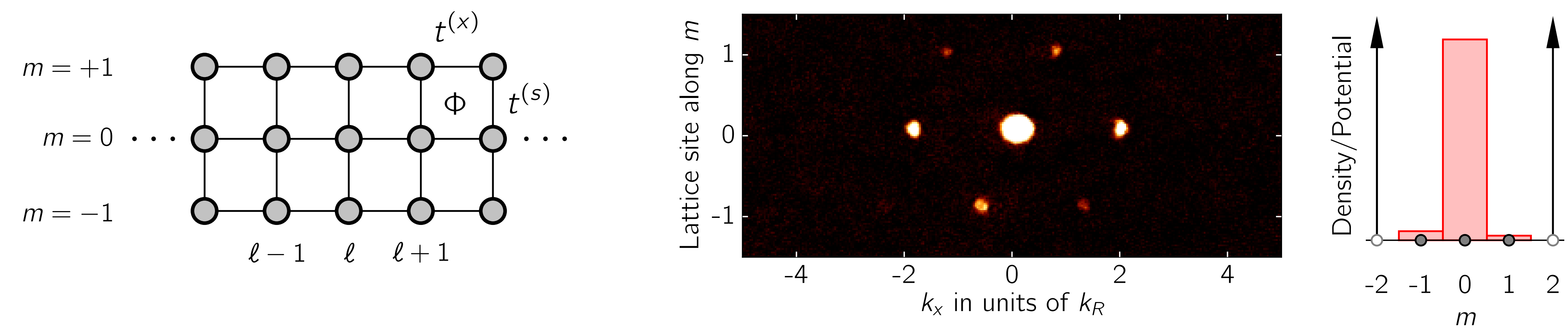


Interpreting data: +1/3 flux quantum

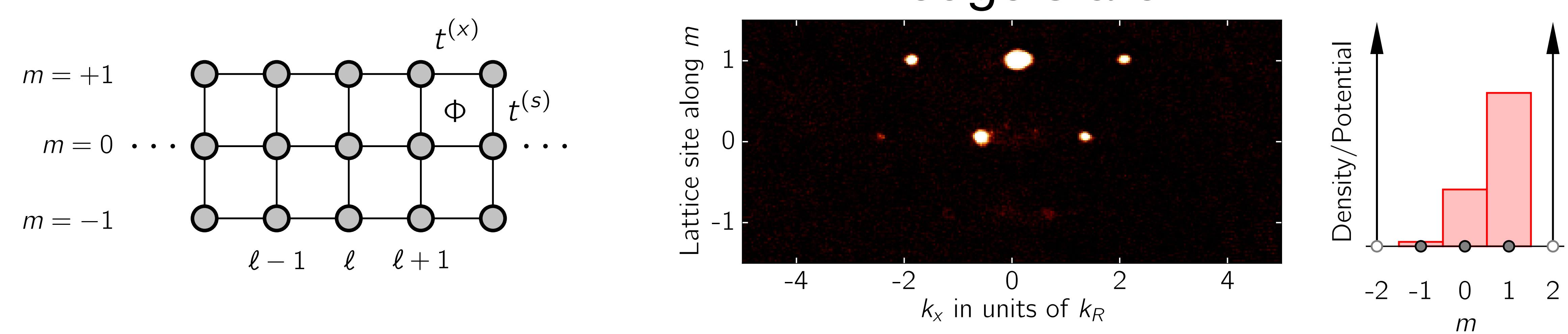
-1 edge state



Center

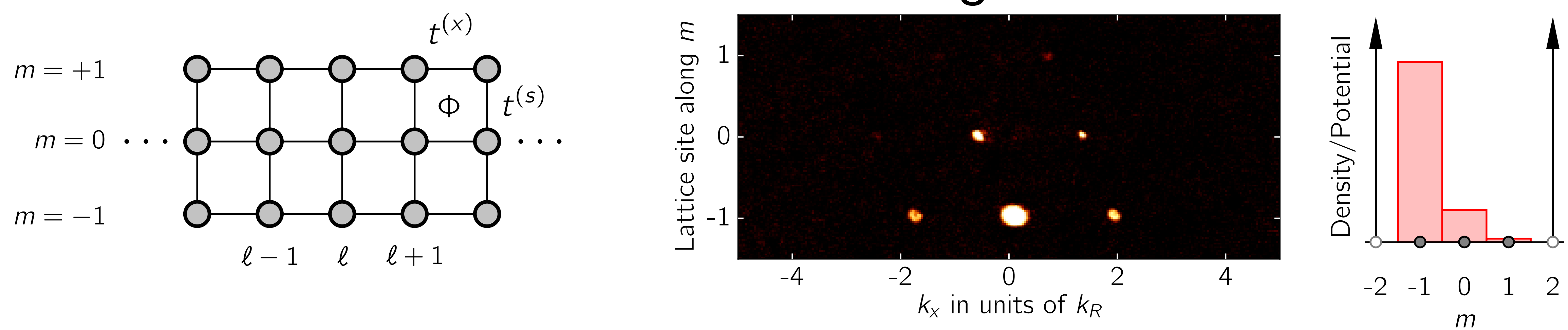


+1 edge state



Interpreting data: -1/3 flux quantum

-1 edge state



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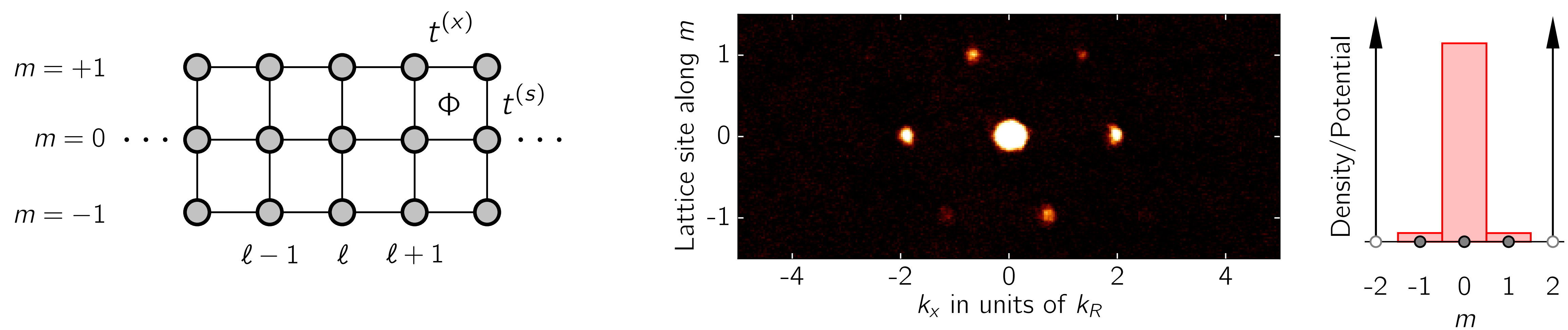
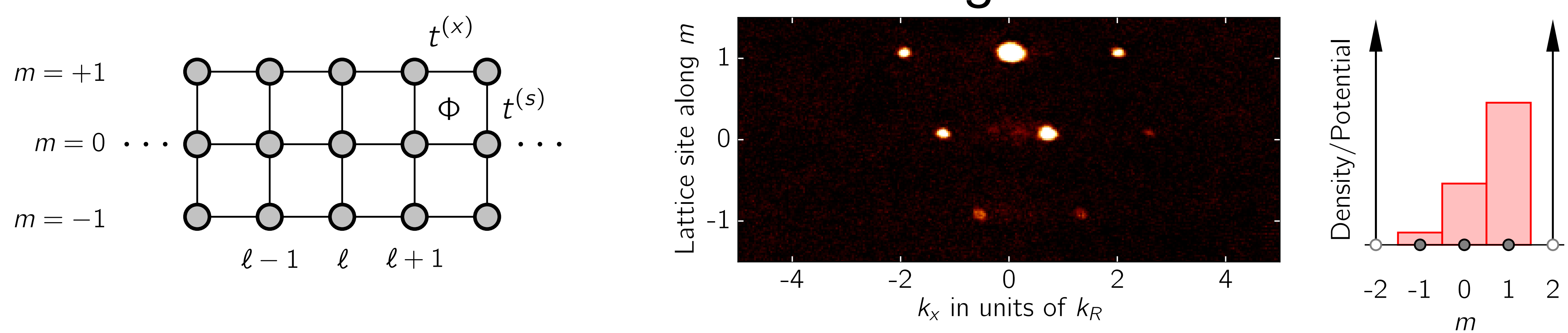
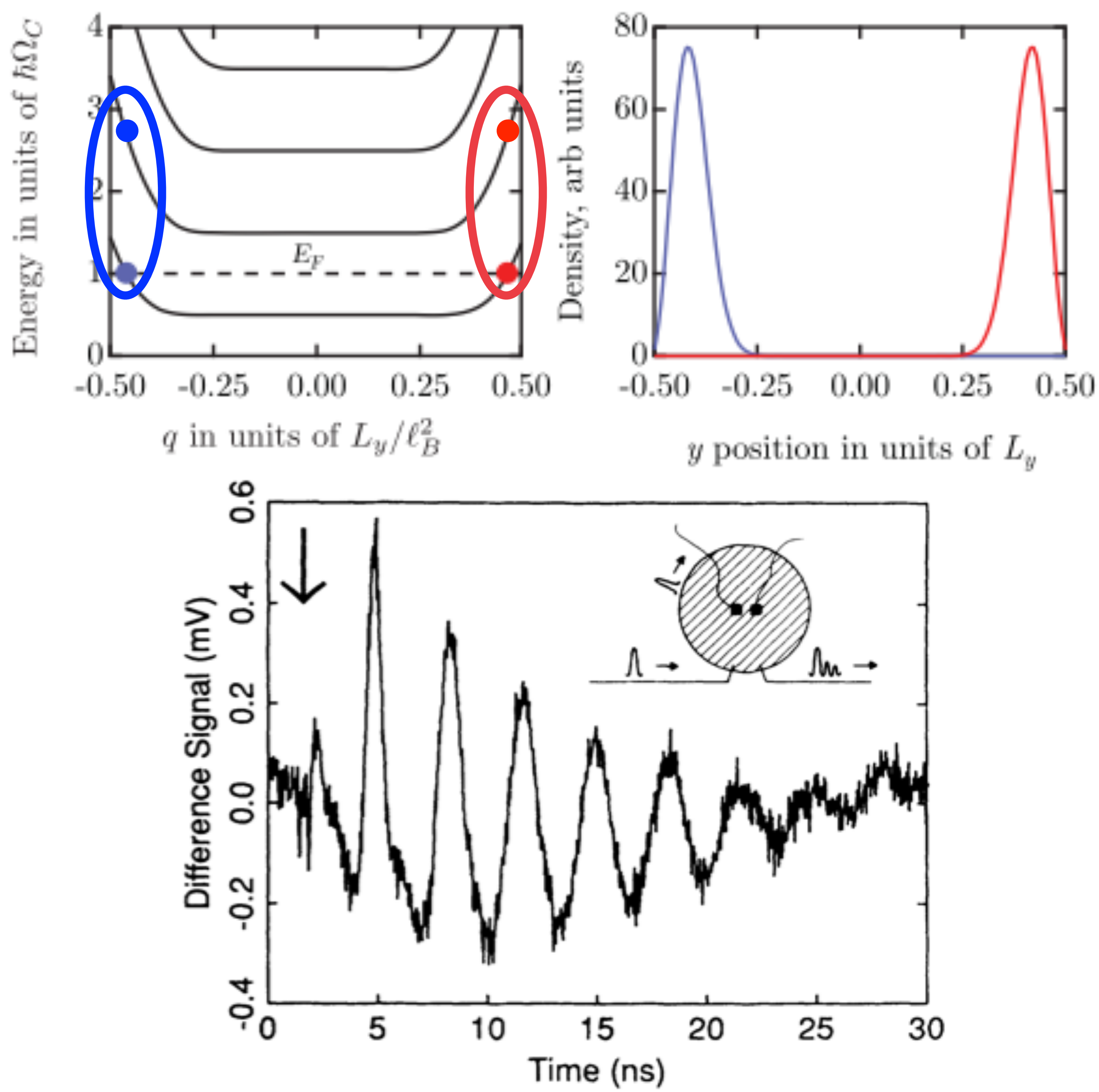


+1 edge state



QHE systems: edge states, skipping?

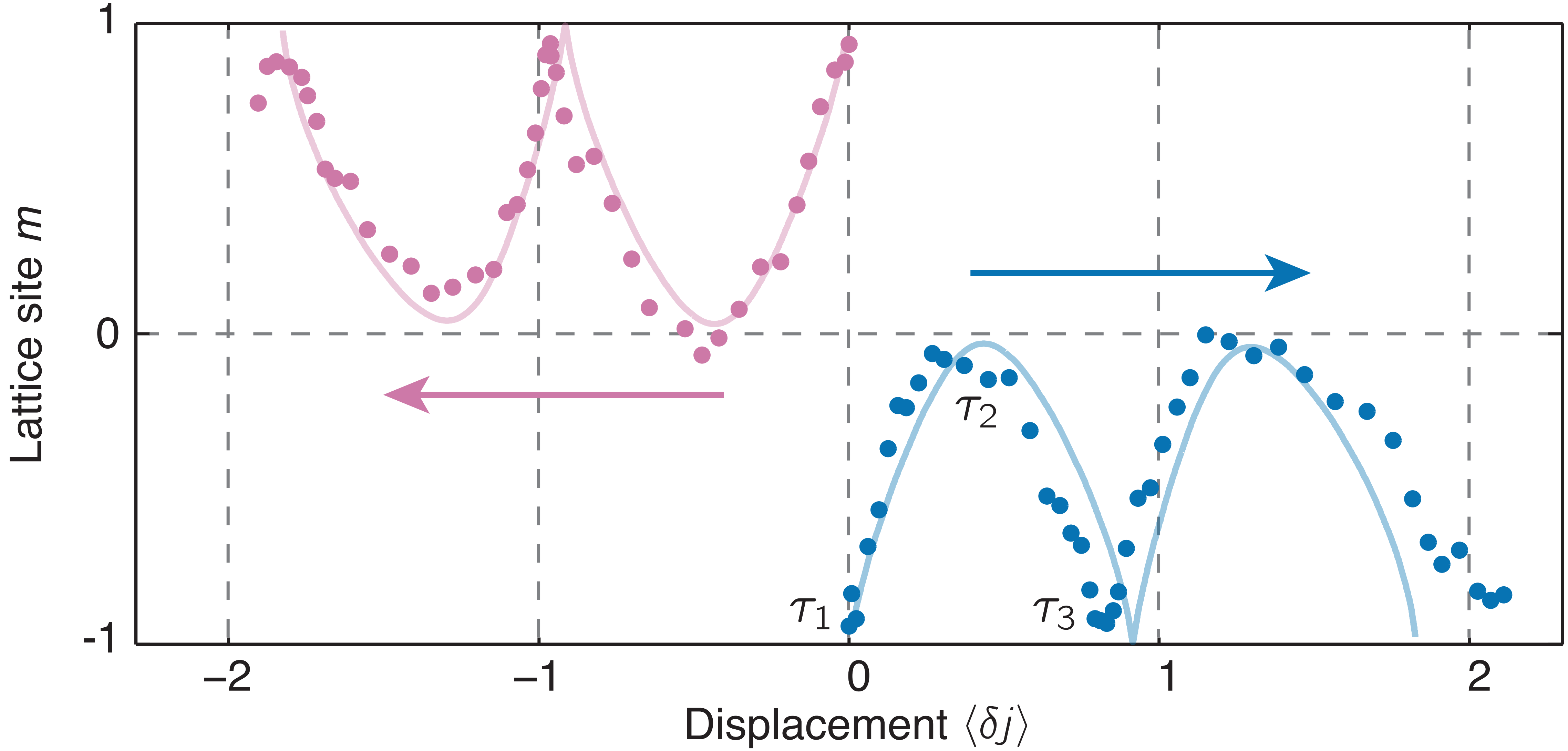
Edge excitations in QHE systems

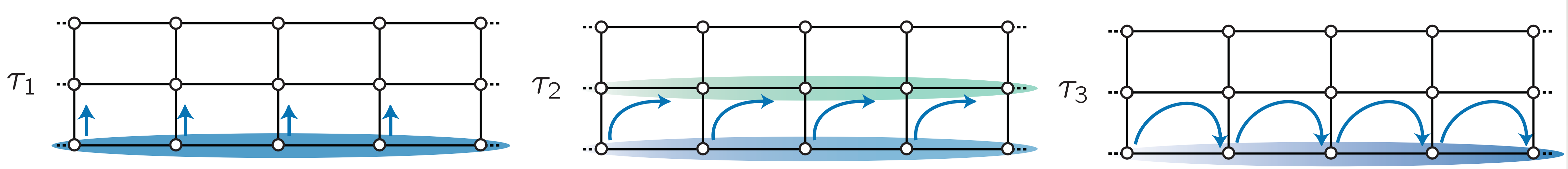


References

R. Ashoori, et al., Phys. Rev. B 45, 3894–3897 (1992).

Dynamics: edge magnetoplasmons



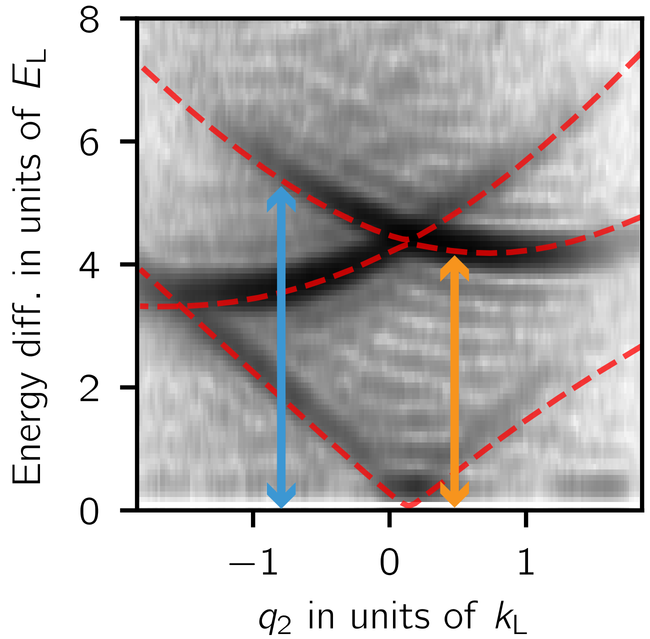


References

B. Stuhl and H.-I Lu, et al., Science (2015); M. Mancini, et al., Science (2015)

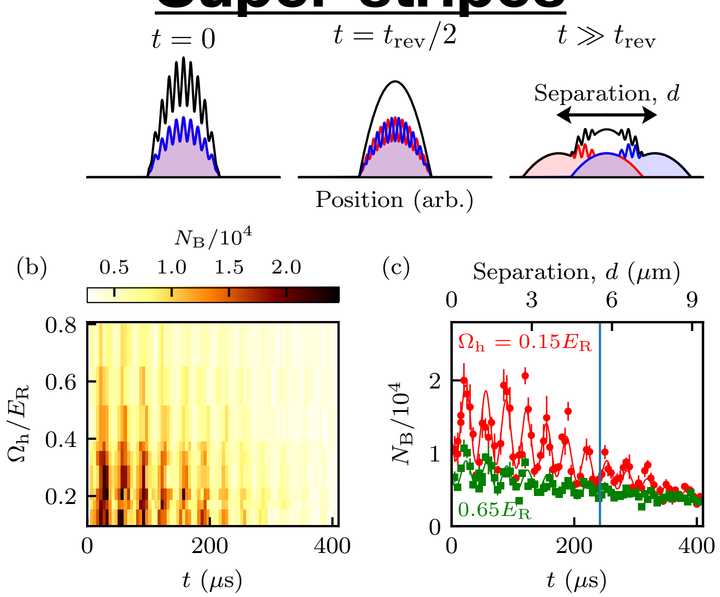
Other recent work

Rashba SOC



A. Valdés-Curiel et al Nat. Comm. (2021)

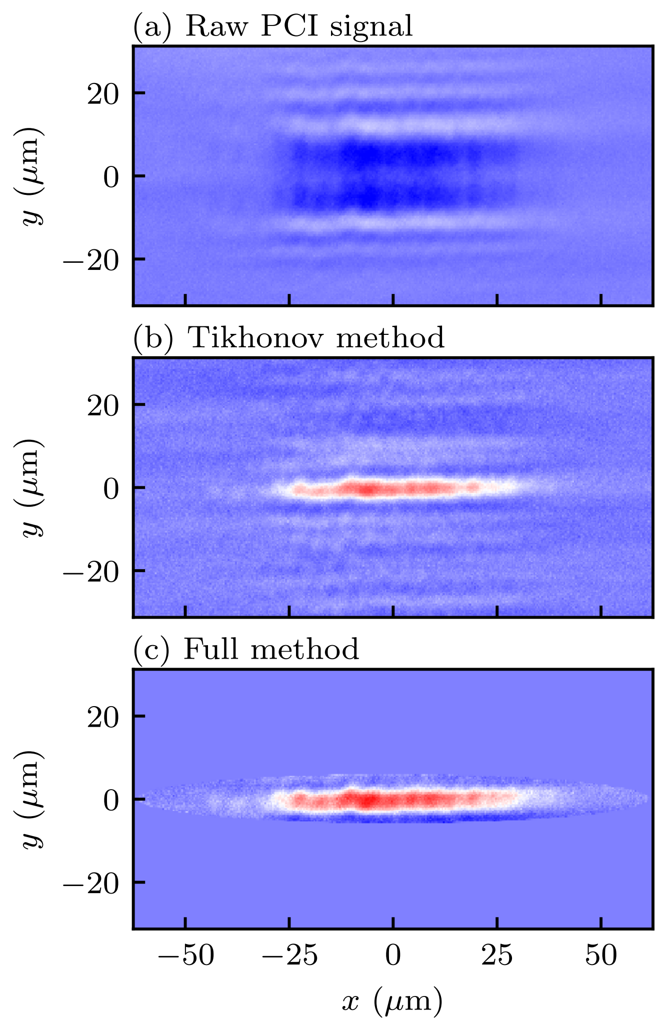
Super-stripes



A. Putra et al.; PRL (2020)

Fancy image processing

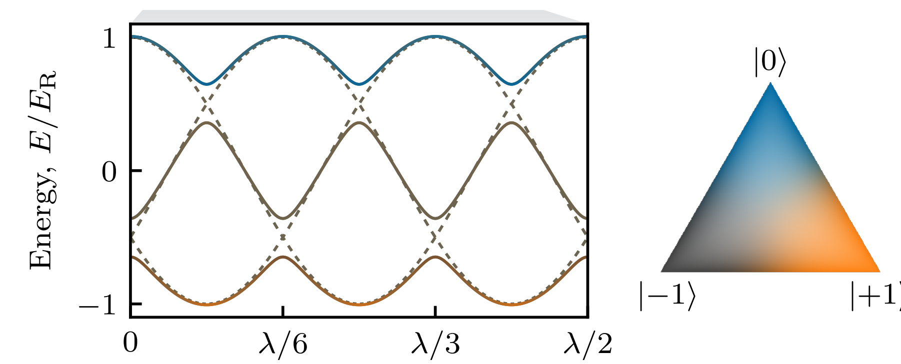
Recover images from imperfect data



E. Altuntas and IBS
(2021 in preparation)

Sub-wavelength lattice

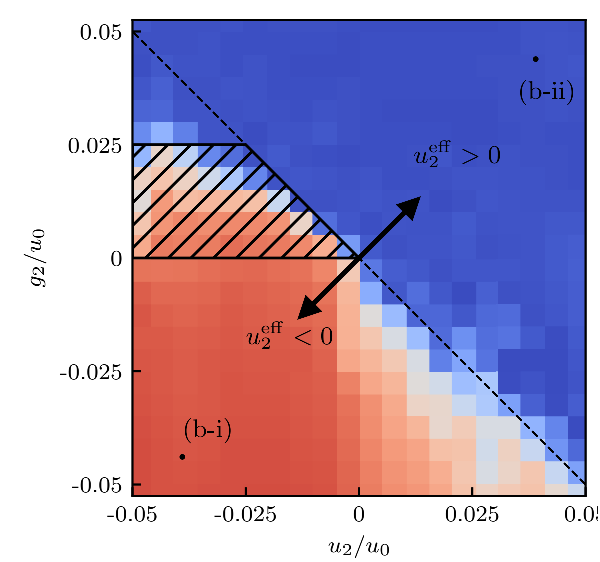
Ring coupling w/o added lattice



R. Anderson et al
PR Research (2020)

Theory: effective interactions

Weak measurement + classical feedback in spinor systems



H. M. Hurst, and IBS; PRR (2020)