# Synthetic gauge fields for ultracold atoms

Joint Quantum Institute

R. A. Williams, K. Jiménez-García, L. J. LeBlanc,
M. C. Beeler, A. R. Perry, W. D. Phillips
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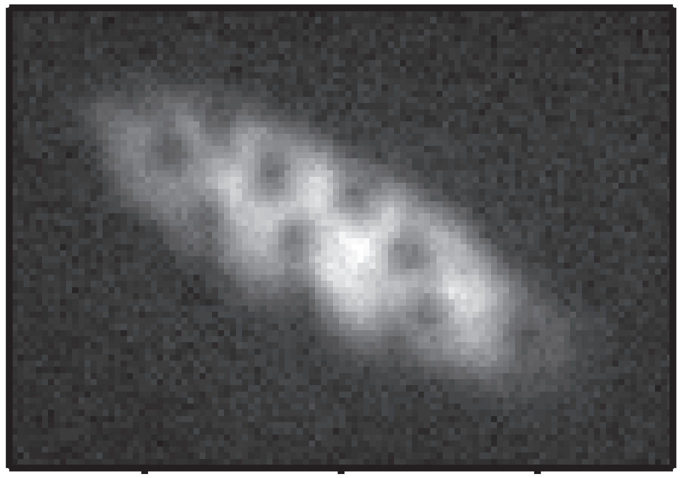
NIST

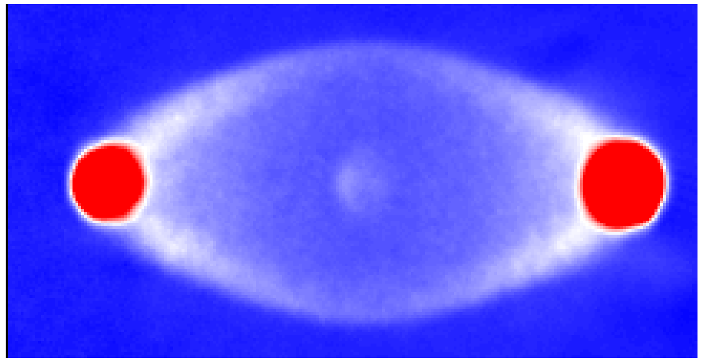
University of Maryland 1856

# Outline

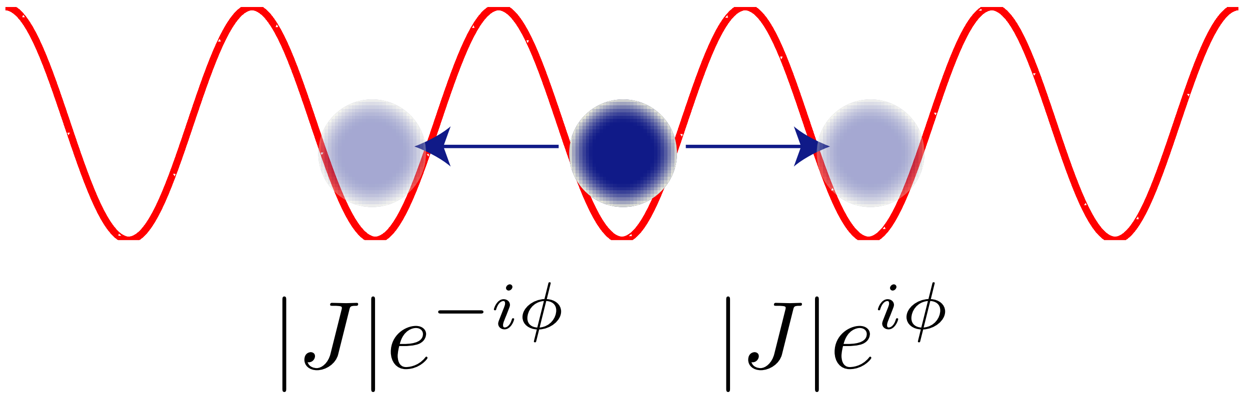


- Experimental arrangement and brief overview of previous work on synthetic gauge fields for ultracold atoms.

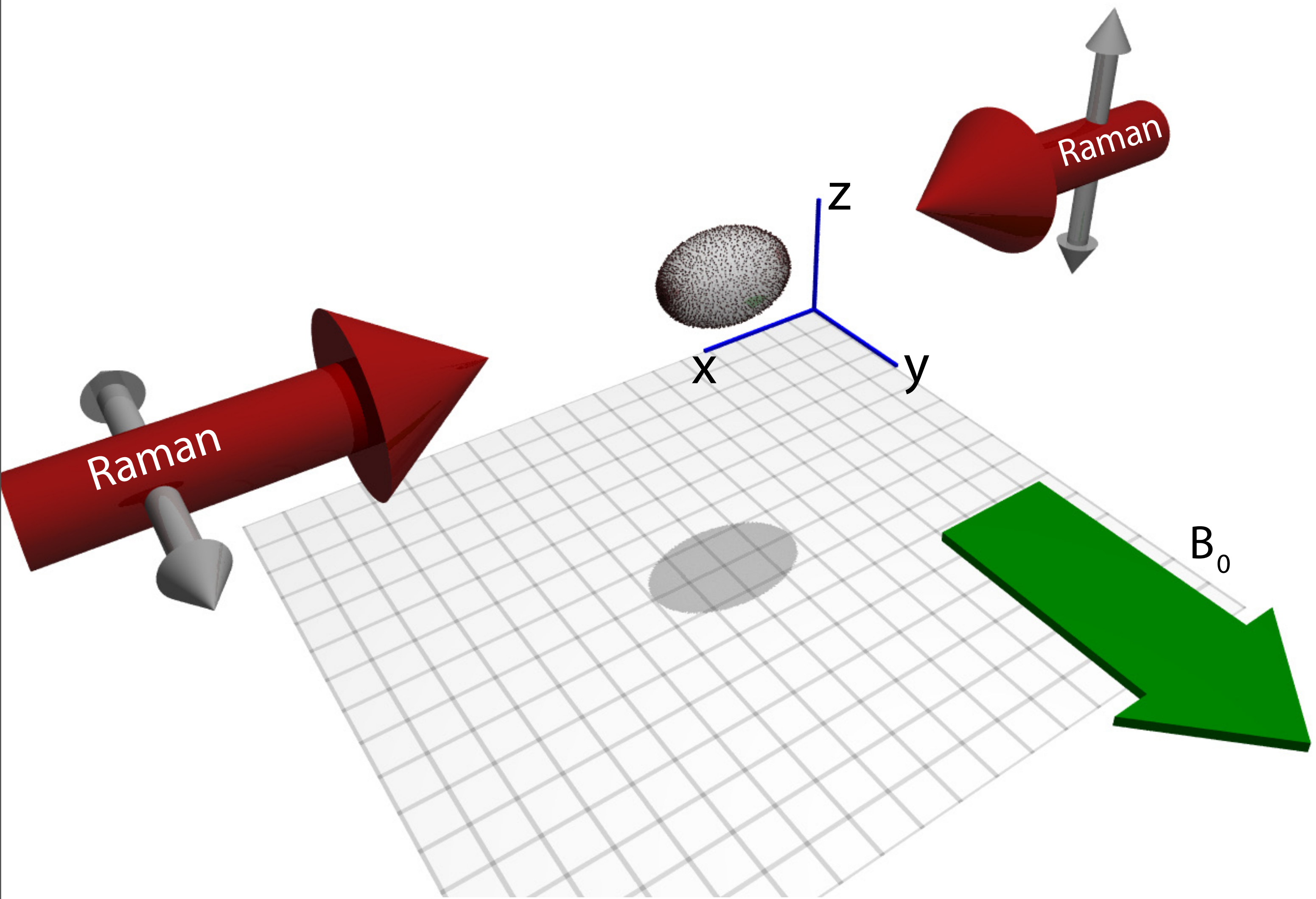
- Synthetic partial waves for ultracold atomic collisions

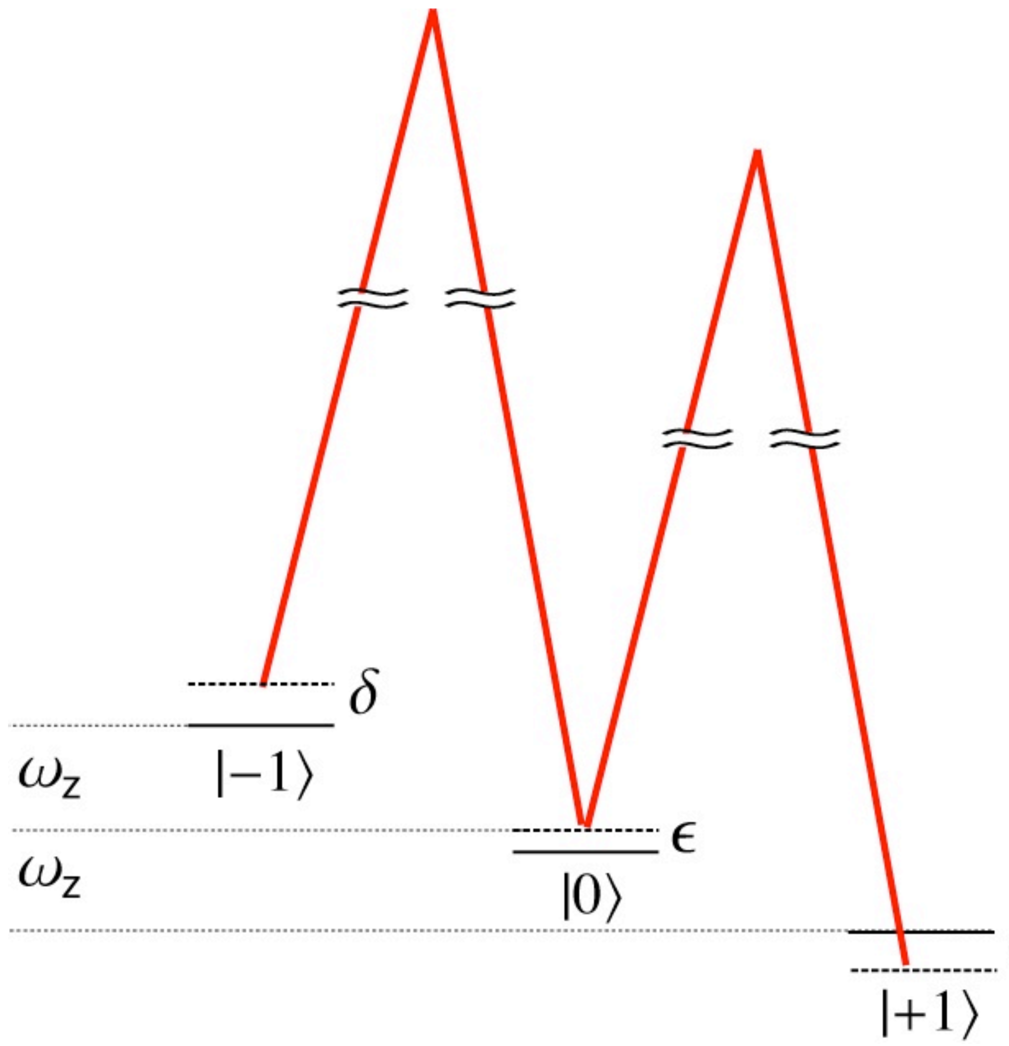


- Peierls substitution in an engineered lattice potential



# Experimental arrangement



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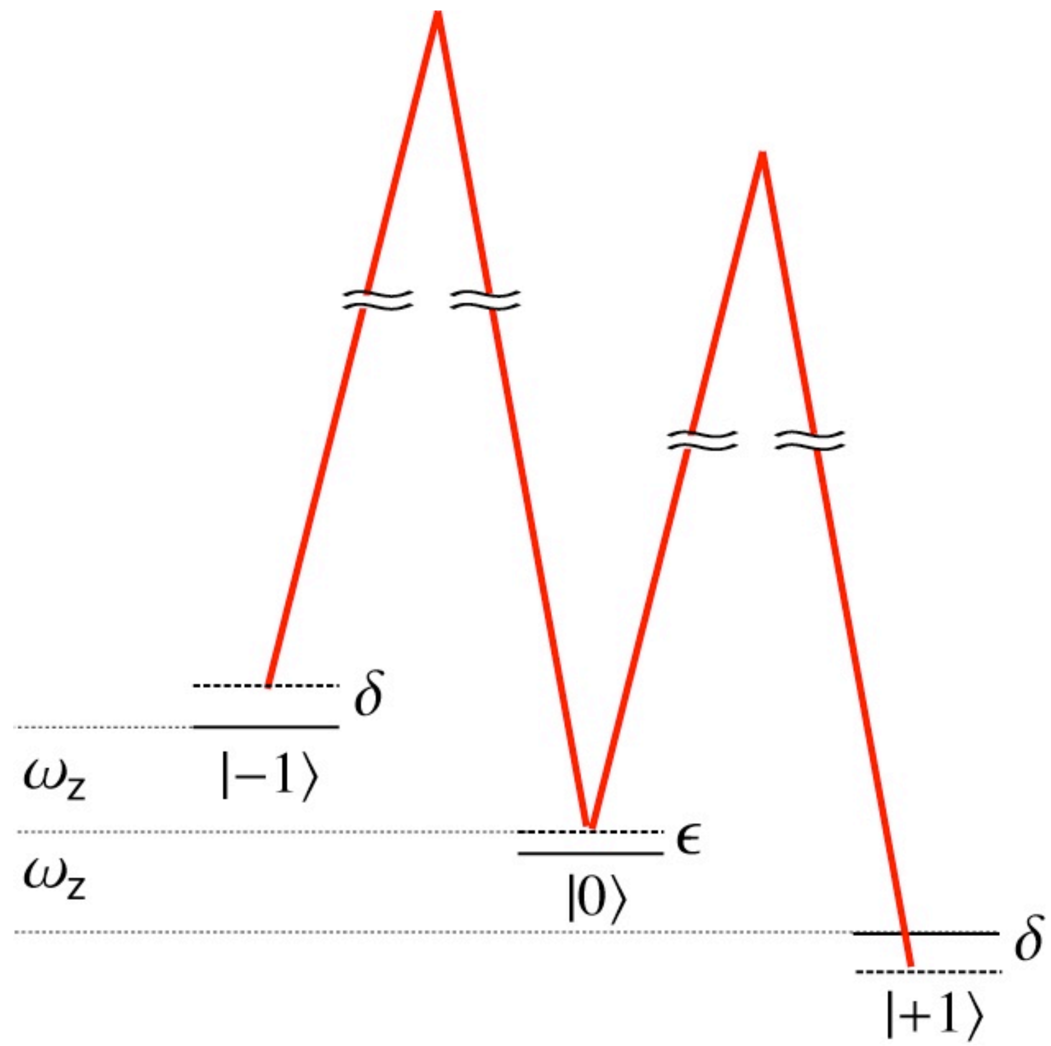
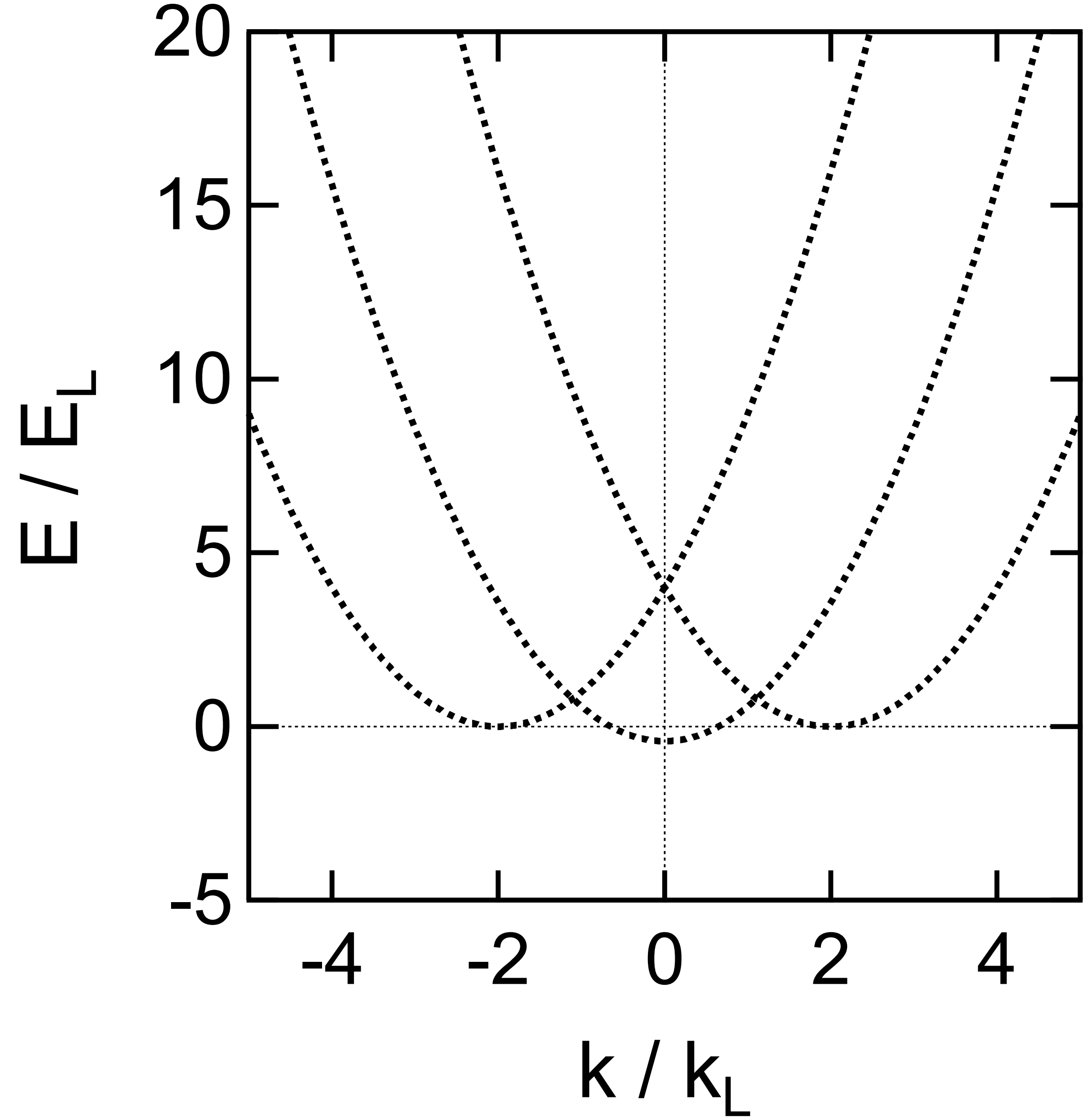



$$H/\hbar = \begin{pmatrix} \frac{\hbar}{2m}(k_x + 2k_L)^2 - \delta & \Omega_R/2 & 0 \\ \Omega_R/2 & \frac{\hbar}{2m}k_x^2 - \epsilon & \Omega_R/2 \\ 0 & \Omega_R/2 & \frac{\hbar}{2m}(k_x - 2k_L)^2 + \delta \end{pmatrix}$$

# Experimental arrangement

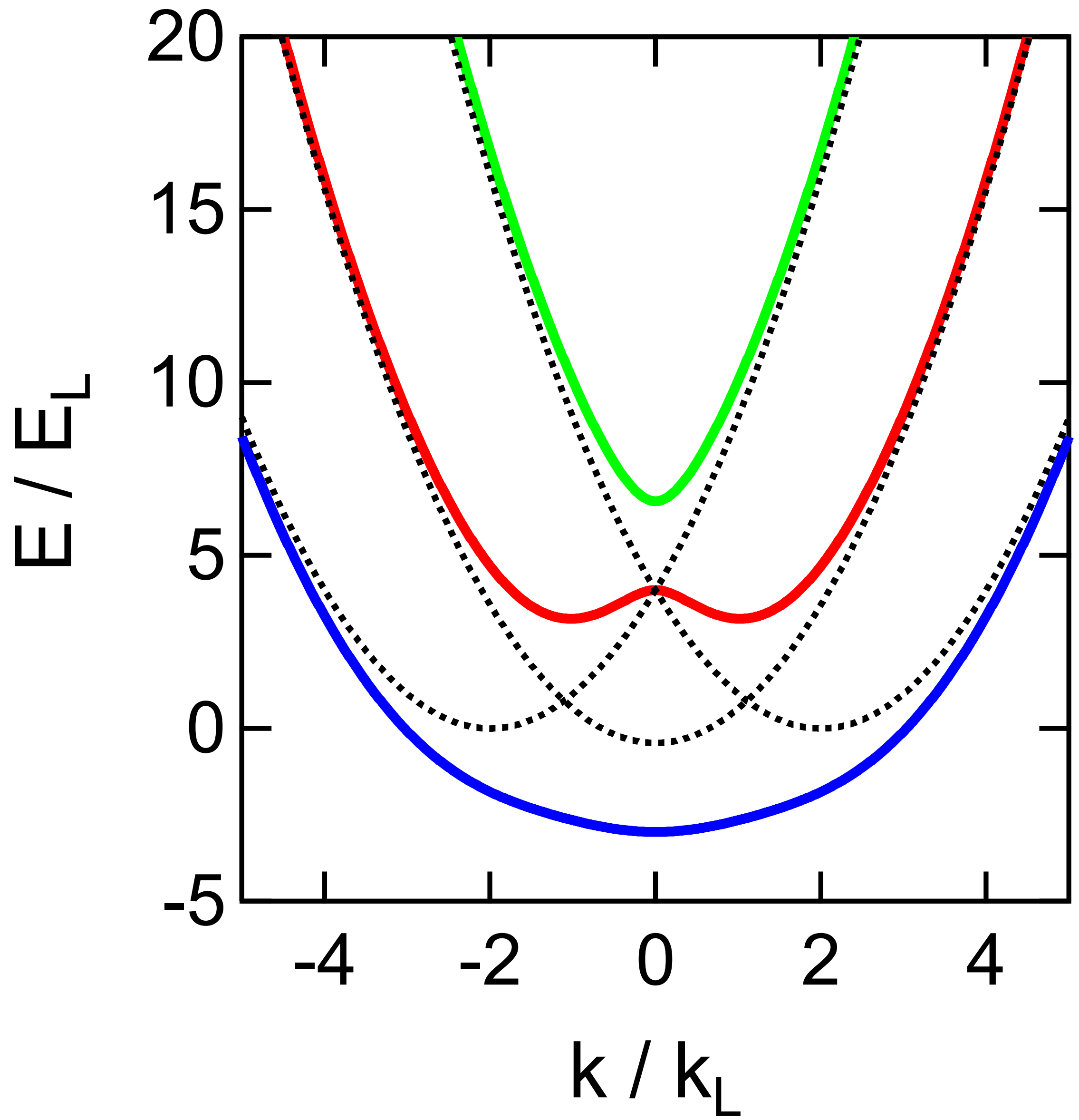



$\hbar\delta = 0$

$\hbar\epsilon = 0.42 E_L$

$$H/\hbar = \begin{pmatrix} \frac{\hbar}{2m}(k_x + 2k_L)^2 - \delta & \Omega_R/2 & 0 \\ \Omega_R/2 & \frac{\hbar}{2m}k_x^2 - \epsilon & \Omega_R/2 \\ 0 & \Omega_R/2 & \frac{\hbar}{2m}(k_x - 2k_L)^2 + \delta \end{pmatrix}$$

# Experimental arrangement



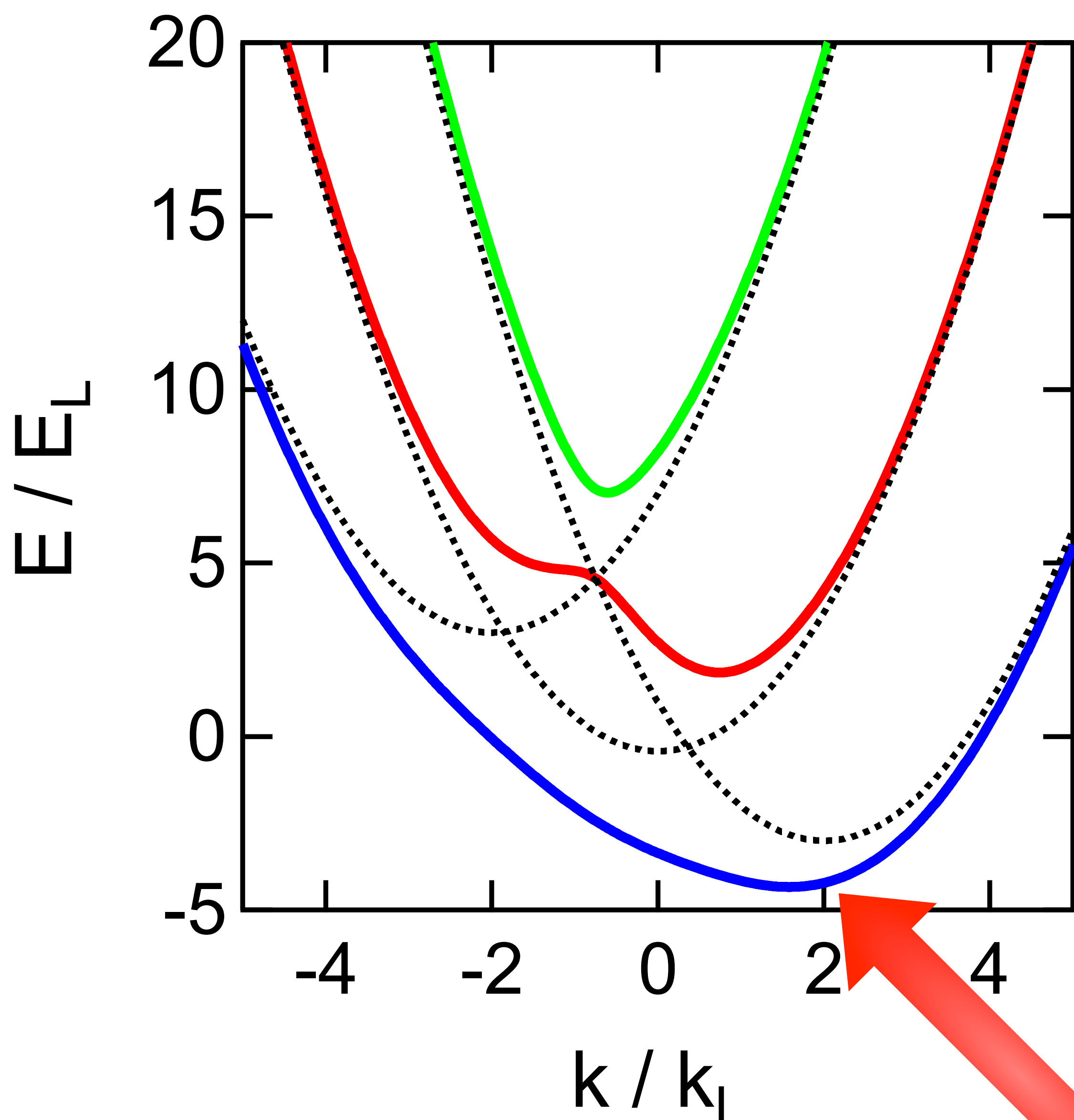

$$\hbar\delta = 0$$

$$\hbar\epsilon = 0.42 E_L$$

$$\hbar\Omega_R = 6 E_L$$

$$H/\hbar = \begin{pmatrix} \frac{\hbar}{2m}(k_x + 2k_L)^2 - \delta & \Omega_R/2 & 0 \\ \Omega_R/2 & \frac{\hbar}{2m}k_x^2 - \epsilon & \Omega_R/2 \\ 0 & \Omega_R/2 & \frac{\hbar}{2m}(k_x - 2k_L)^2 + \delta \end{pmatrix}$$

# Effective vector potential




$$\hbar\delta = -3E_L$$

$$\hbar\epsilon = 0.42E_L$$

$$\hbar\Omega_R = 6E_L$$

Minimum of dispersion relation shifted to finite momentum

Uniform vector potential

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

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

Uniform vector potential

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

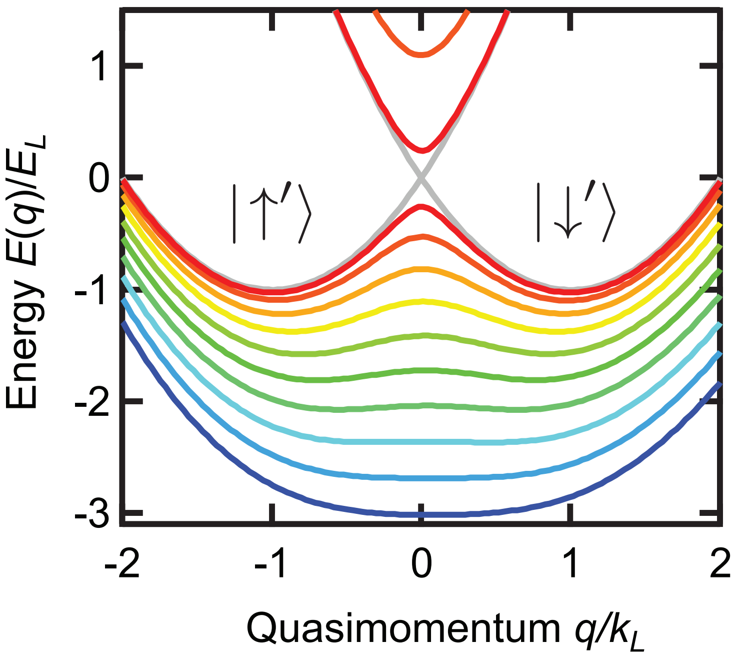
$$\mathbf{A} = \mathbf{A}(t)$$

Electric fields for neutral atoms!

Y.-J. Lin *et al*, Nature Physics (2011)

Raman-dressing

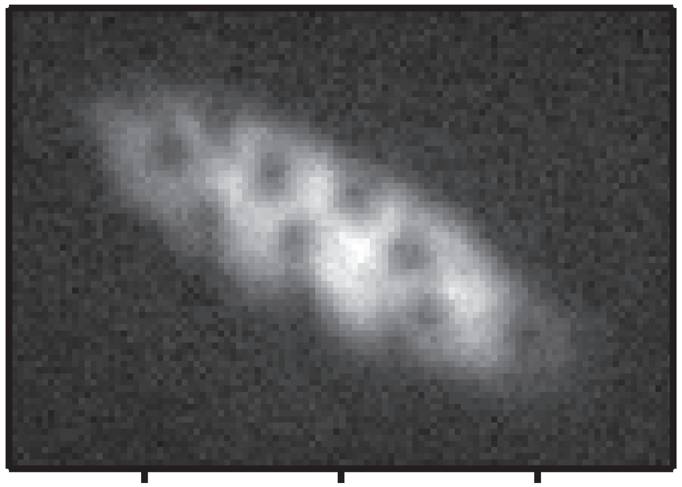
Synthetic gauge fields




$$\hat{H} \propto k_x \sigma_y$$

First ever spin-orbit coupling for bosons!

Y.-J. Lin *et al*, Nature (2011)



$$\nabla \times \mathbf{A} \neq 0$$

Magnetic fields for neutral atoms!

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

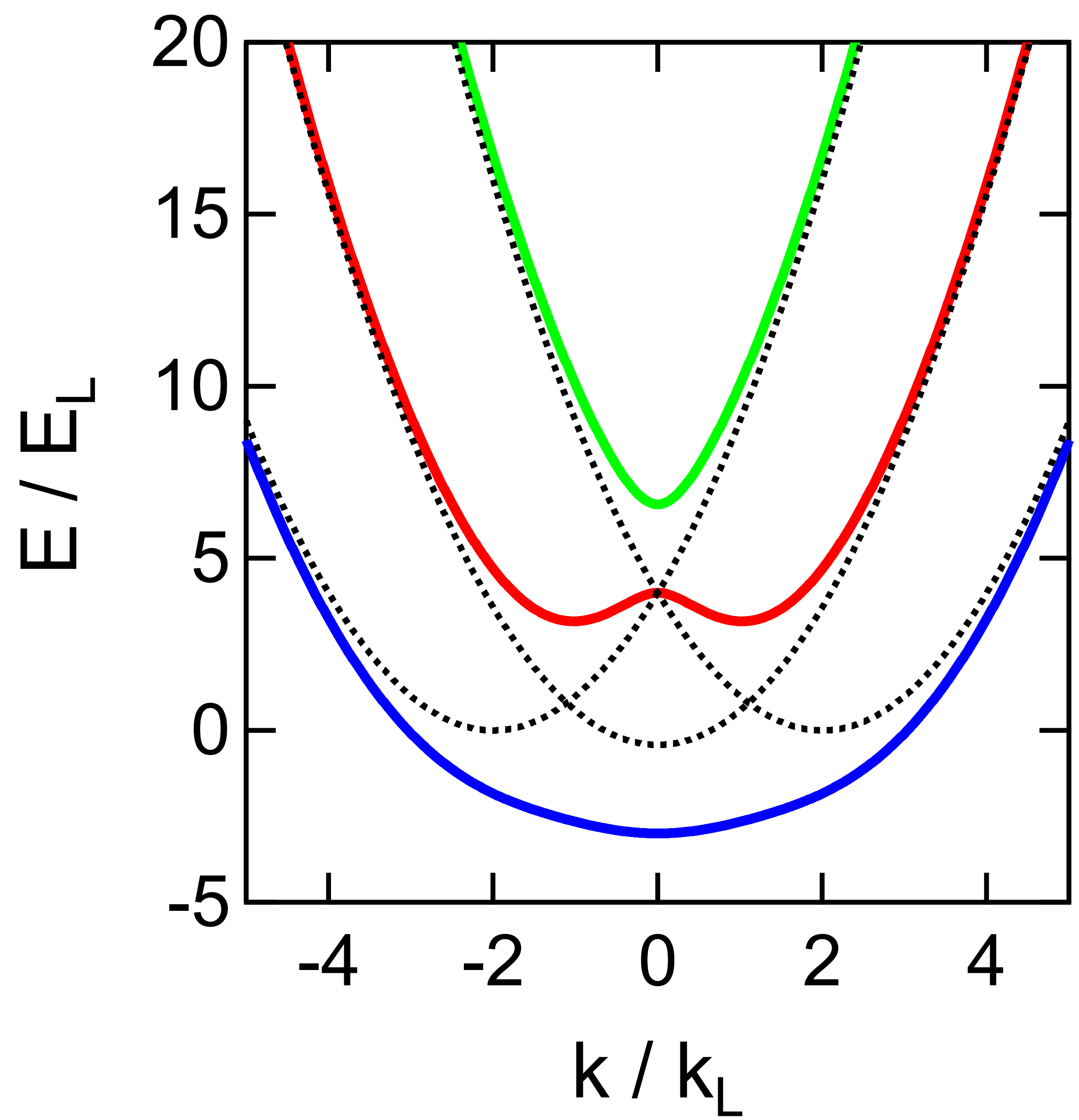
## Recent other work on spin-orbit coupling at

- Shanxi University, China
- Hefei University of Science and Technology of China
- MIT
- Washington State,  Purdue ...

# Synthetic partial waves for ultracold atomic collisions

R. A. Williams et al, Science, **335**, 314-317 (2012)

# Experimental arrangement

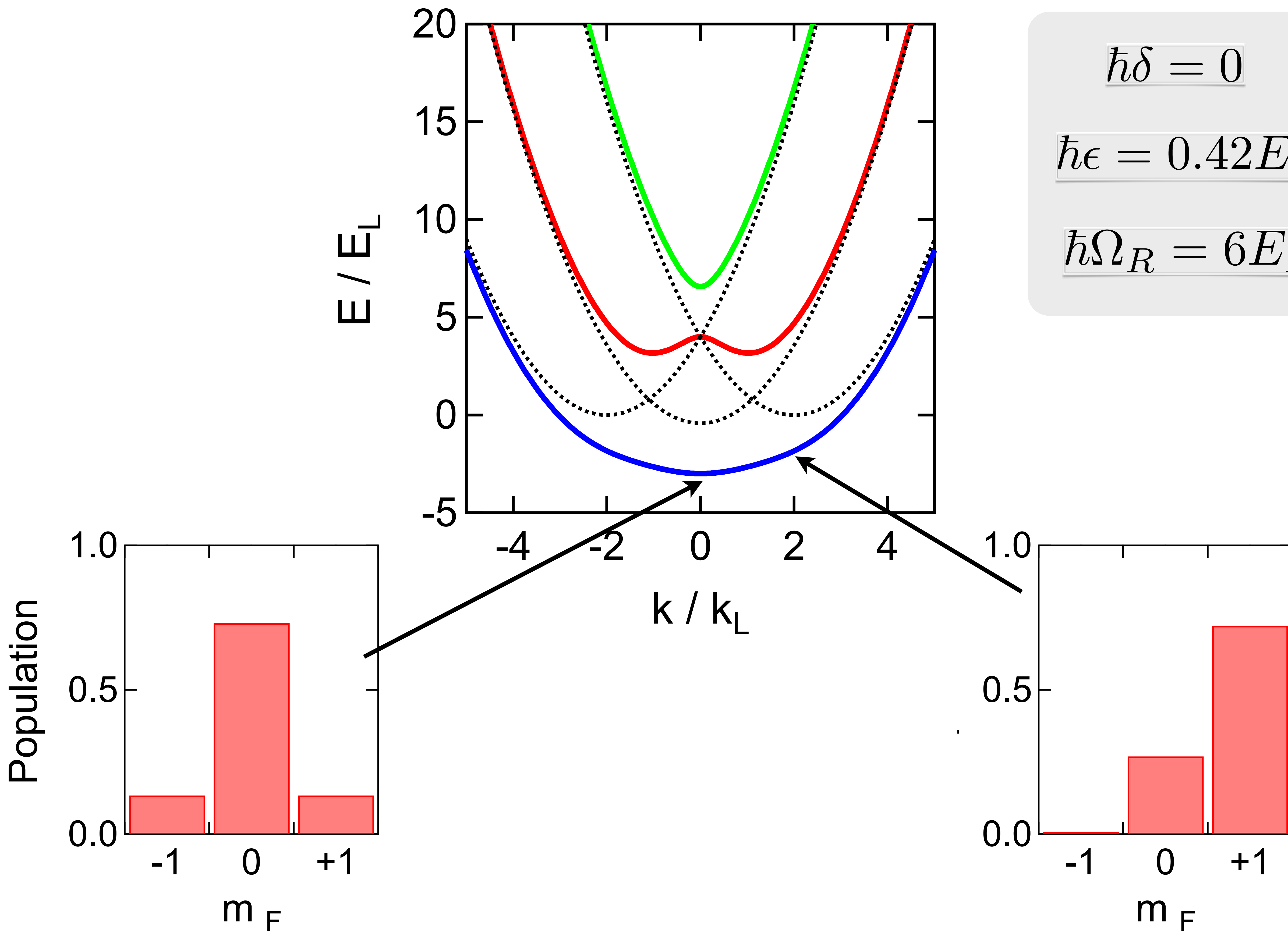



$$\hbar\delta = 0$$

$$\hbar\epsilon = 0.42E_L$$

$$\hbar\Omega_R = 6E_L$$

# Experimental arrangement

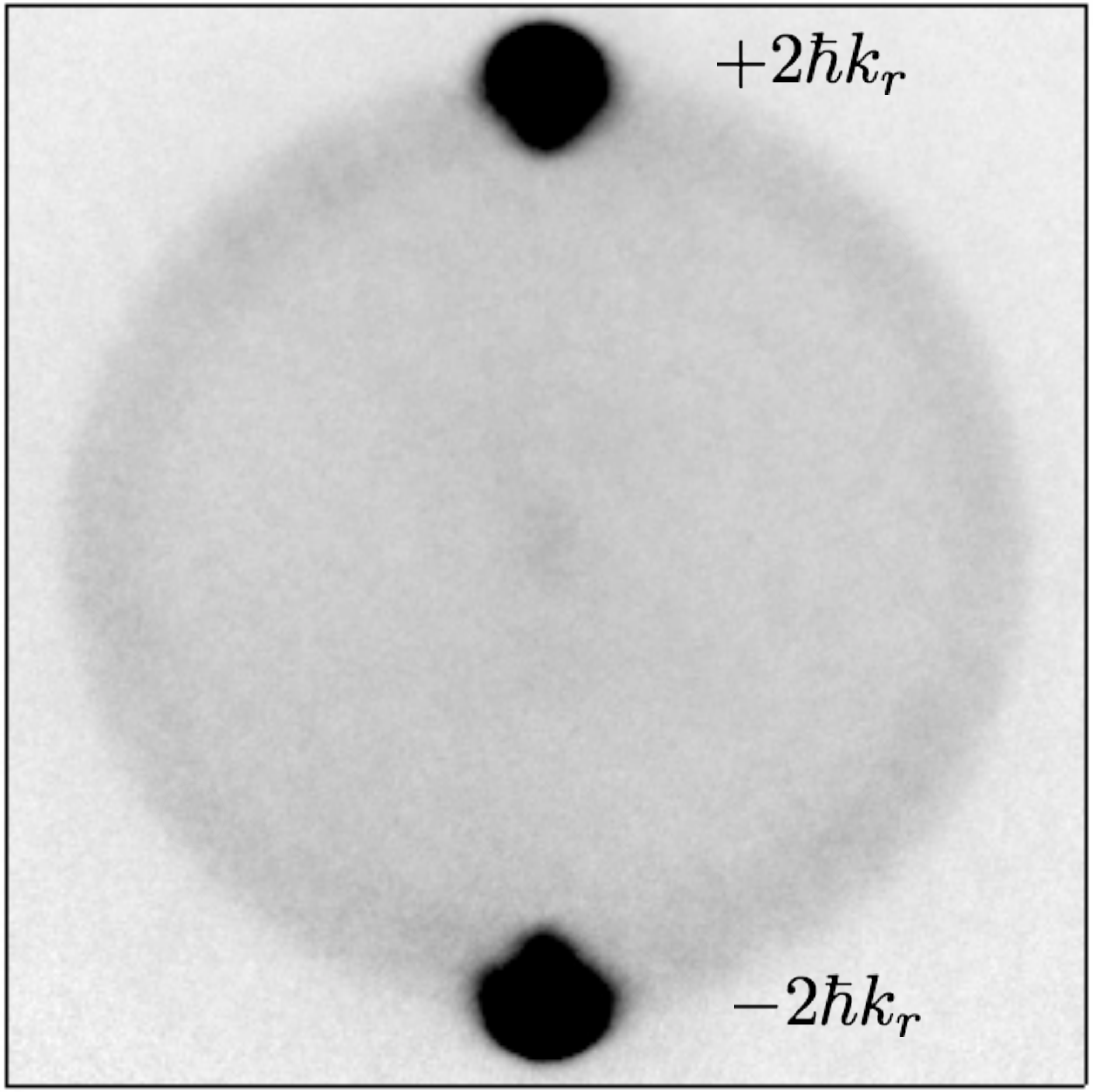



$\hbar\delta = 0$

$\hbar\epsilon = 0.42 E_L$

$\hbar\Omega_R = 6 E_L$

# s-wave scattering halo



# Imaging of *s* and *d* Partial-Wave Interference in Quantum Scattering of Identical Bosonic Atoms

Nicholas R. Thomas,[1] Niels Kjærgaard,[1,*] Paul S. Julienne,[2] and Andrew C. Wilson[1]
[1]*Department of Physics, University of Otago, Dunedin, New Zealand*
[2]*National Institute of Standards and Technology, 100 Bureau Drive, Stop 8423, Gaithersburg, Maryland, 20899-8423 USA*
(Received 19 May 2004; published 22 October 2004)

We report on the direct imaging of *s* and *d* partial-wave interference in cold collisions of atoms. Two ultracold clouds of $^{87}$Rb atoms were accelerated by magnetic fields to collide at energies near a *d*-wave shape resonance. The resulting halos of scattered particles were imaged using laser absorption. By scanning across the resonance we observed a marked evolution of the scattering patterns due to the energy dependent phase shifts for the interfering *s* and *d* waves. Since only two partial-wave states are involved in the collision process the scattering yield and angular distributions have a simple interpretation in terms of a theoretical model.

DOI: 10.1103/PhysRevLett.93.173201 PACS numbers: 34.50.–s, 03.65.Nk, 32.80.Pj, 39.25.+k

VOLUME 93, NUMBER 17 PHYSICAL REVIEW LETTERS week ending 22 OCTOBER 2004

# Interferometric Determination of the *s* and *d*-Wave Scattering Amplitudes in $^{87}$Rb

Ch. Buggle, J. Léonard, W. von Klitzing, and J. T. M. Walraven
*FOM Institute for Atomic and Molecular Physics, Kruislaan 407, 1098 SJ Amsterdam, The Netherlands*
*and Van der Waals–Zeeman Institute of the University of Amsterdam, Valckenierstraat 65/67, 1018 XE The Netherlands*
(Received 4 June 2004; published 22 October 2004)

We demonstrate an interference method to determine the low-energy elastic scattering amplitudes of a quantum gas. We linearly accelerate two ultracold atomic clouds up to energies of 1.2 mK and observe the collision halo by direct imaging in free space. From the interference between *s*- and *d*- partial waves in the differential scattering pattern we extract the corresponding phase shifts. The method does not require knowledge of the atomic density. This allows us to infer accurate values for the *s*- and *d*-wave scattering amplitudes from the zero-energy limit up to the first Ramsauer minimum using only the van der Waals $C_6$ coefficient as theoretical input. For the $^{87}$Rb triplet potential, the method reproduces the scattering length with an accuracy of 6%.

DOI: 10.1103/PhysRevLett.93.173202 PACS numbers: 34.50.–s, 03.65.Sq, 03.75.–b, 32.80.Pj

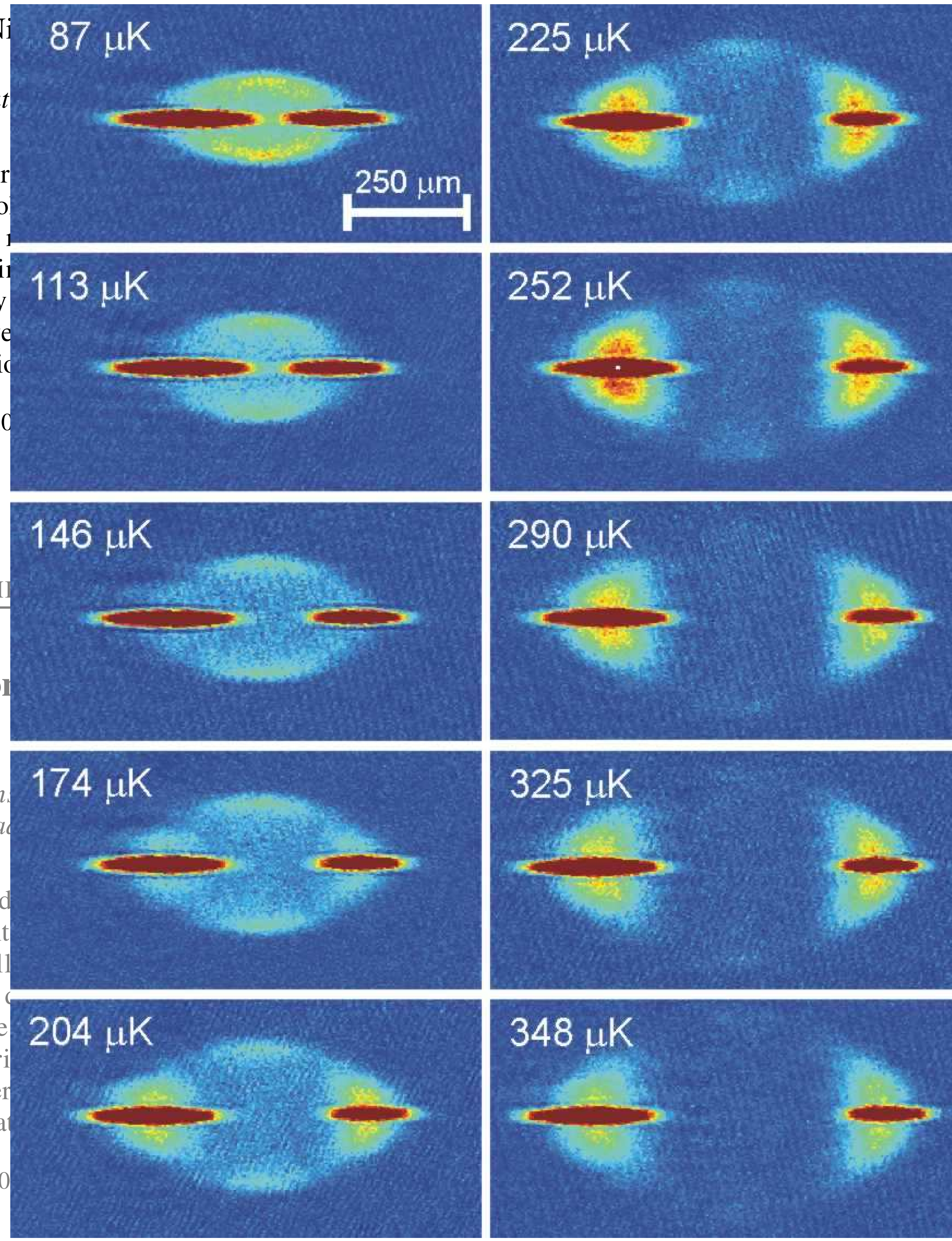
# Imaging of *s* and *d* Partial-Wave Interference in Quantum Scattering of Identical Bosonic Atoms

Ni … ilson[1]

[2]*National Institut … and, 20899-8423 USA*

We r … atoms. Two
ultraco … ar a *d*-wave
shape … orption. By
scanni … due to the
energy … e states are
involve … mple inter-
pretatic …

DOI: 10 … Pj, 39.25.+k



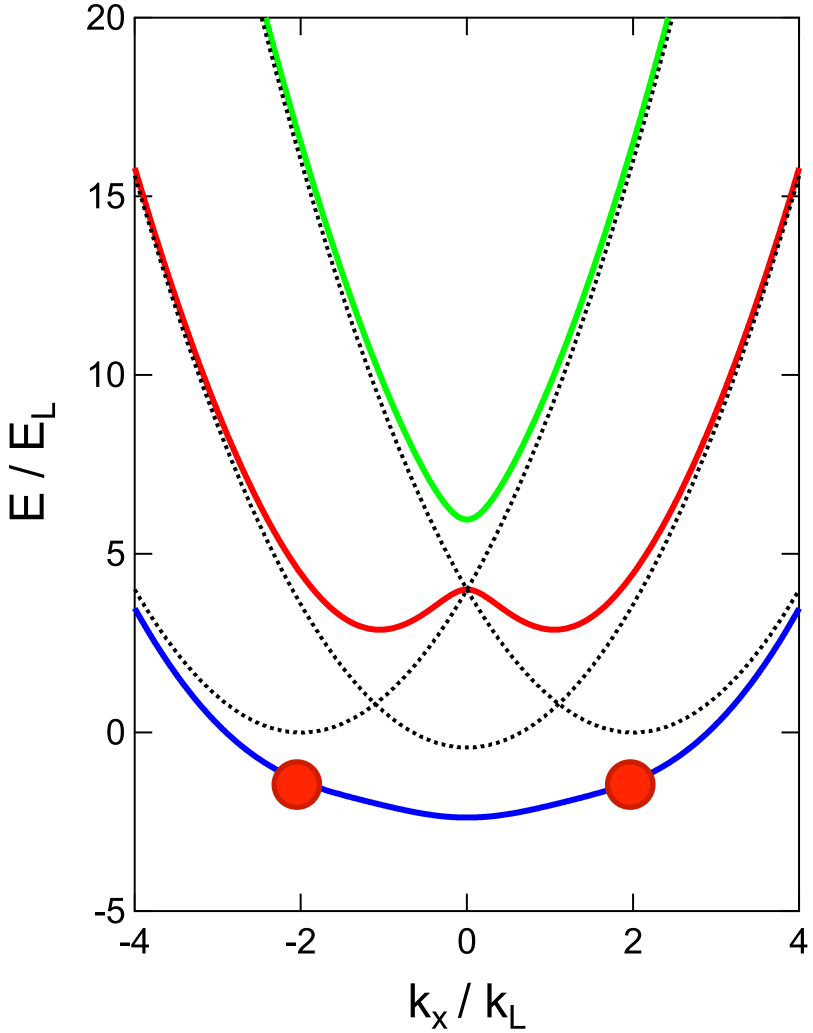



## Interferon … udes in $^{87}$Rb

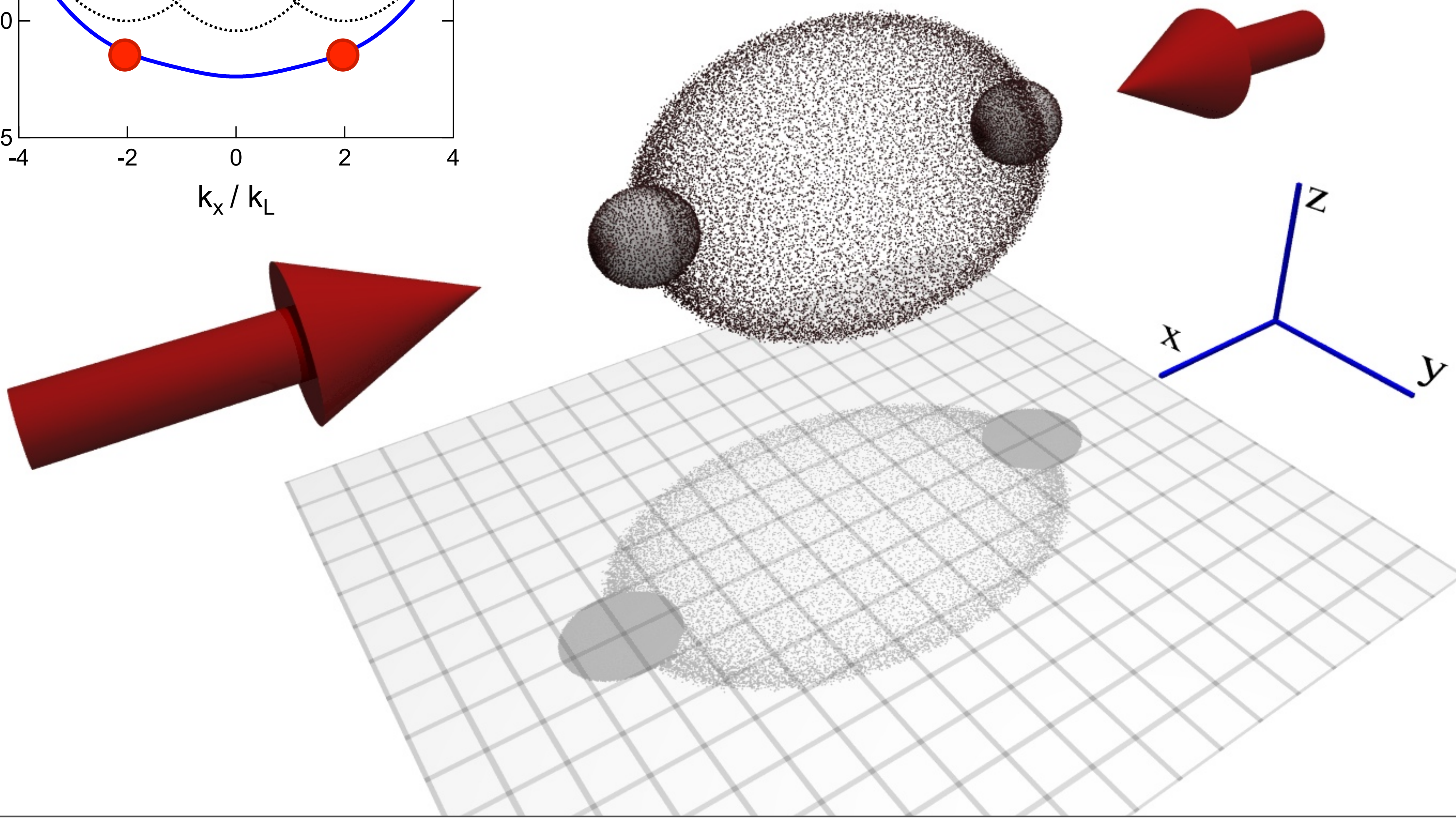
*FOM In … Netherlands*
*and Van der Wa … XE The Netherlands*

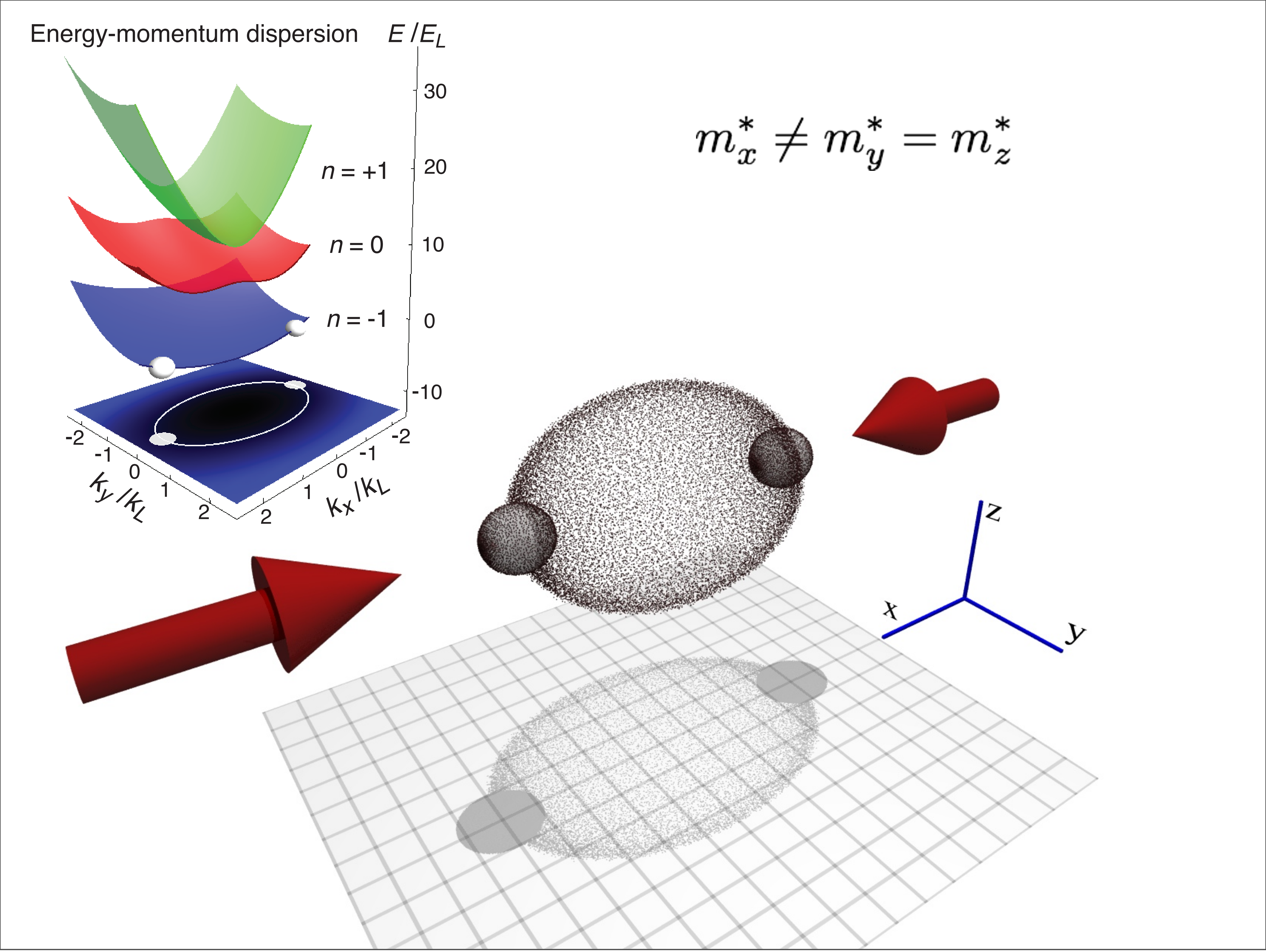
We d … nplitudes of
a quant … nd observe
the coll … rtial waves
in the … d does not
require … nd *d*-wave
scatteri … g only the
van der … reproduces
the scat …

DOI: 10 … –b, 32.80.Pj

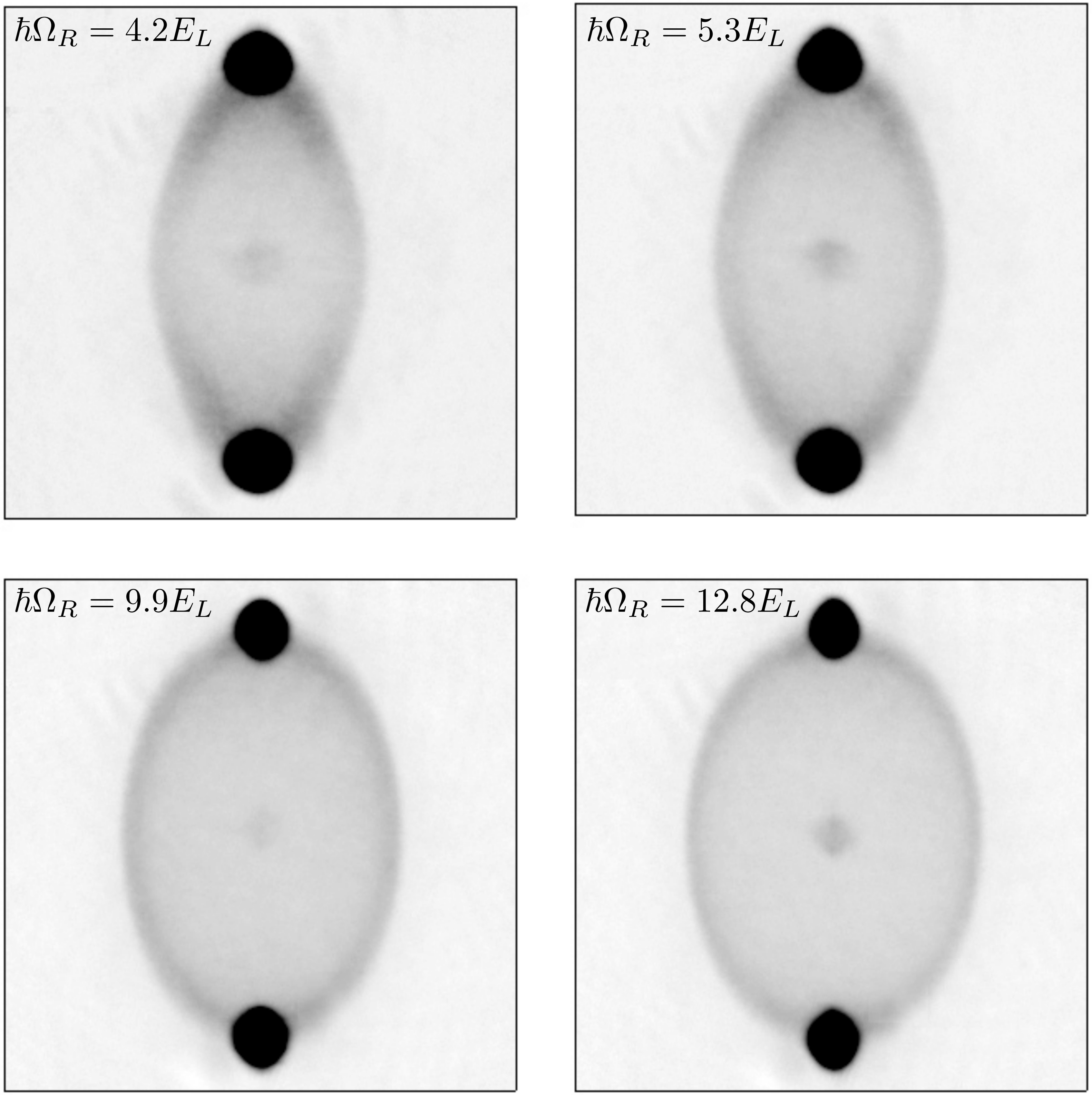



$$m_x^* \neq m_y^* = m_z^*$$

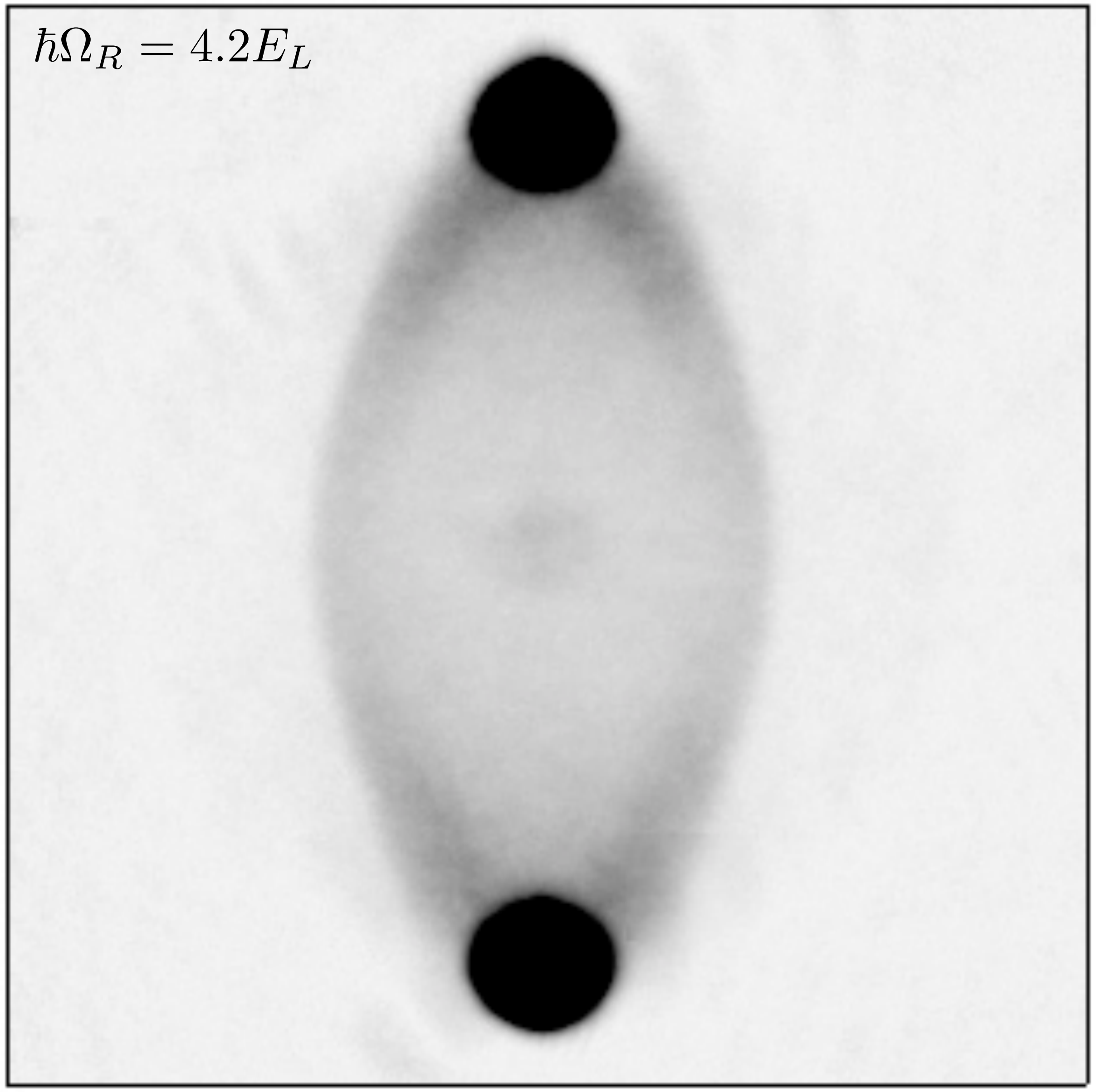


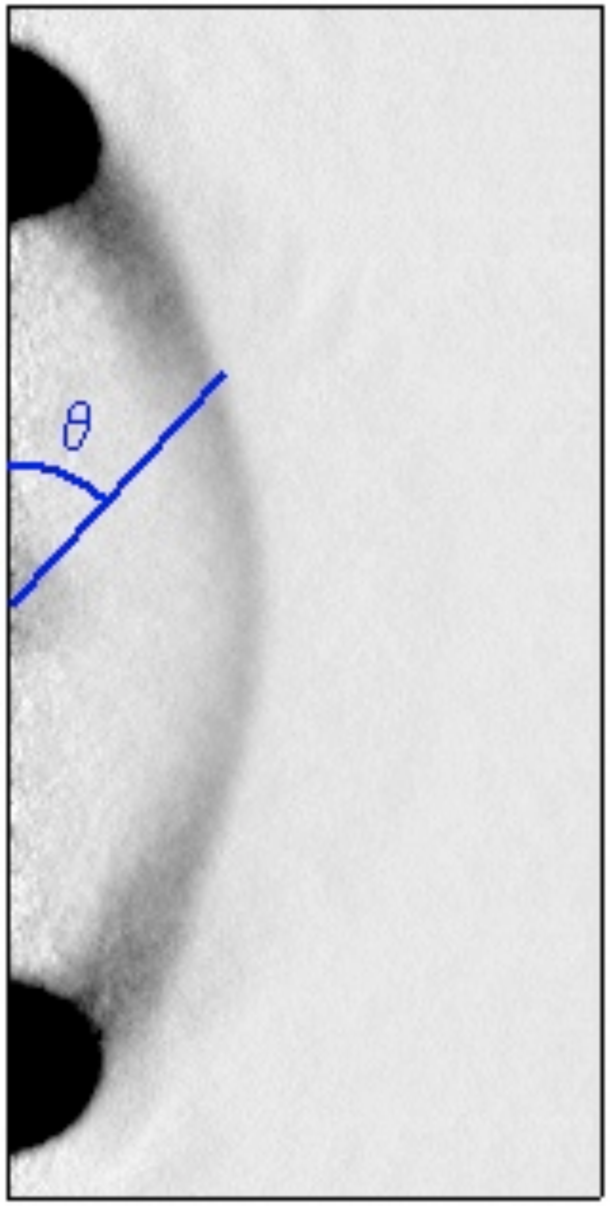

Energy-momentum dispersion
$E/E_L$
30
20
10
0
-10
$n = +1$
$n = 0$
$n = -1$
-2
-1
0
1
2
$k_y/k_L$
$k_x/k_L$
$m_x^* \neq m_y^* = m_z^*$
z
x
y

# Dressed particle scattering



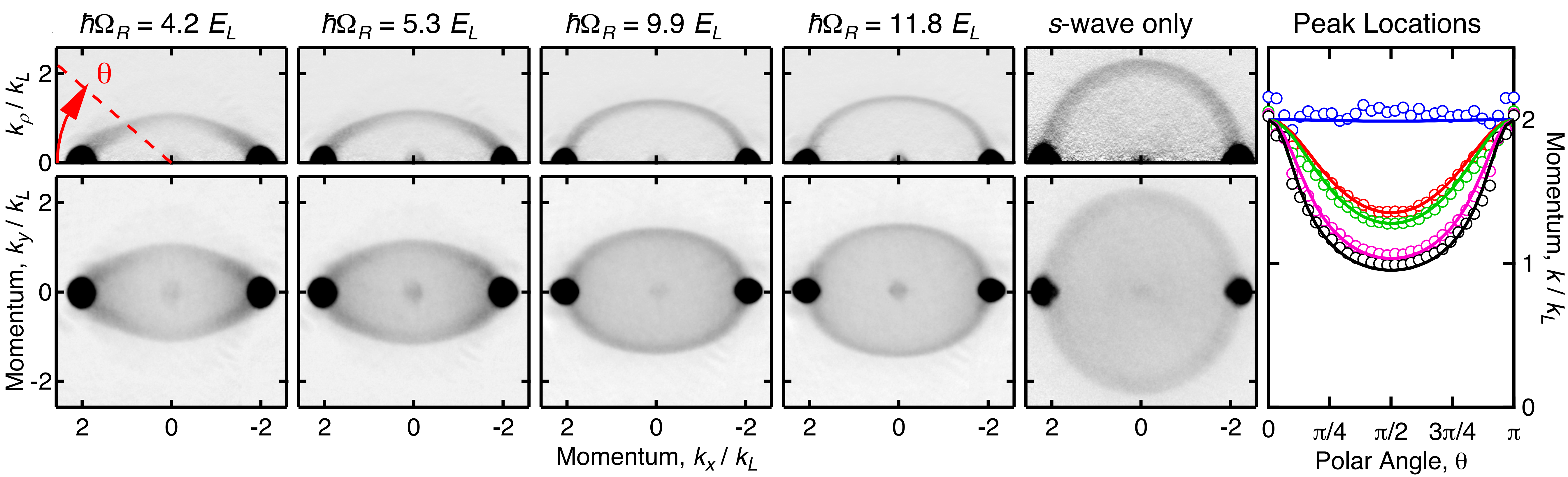
# Inverse Abel transform



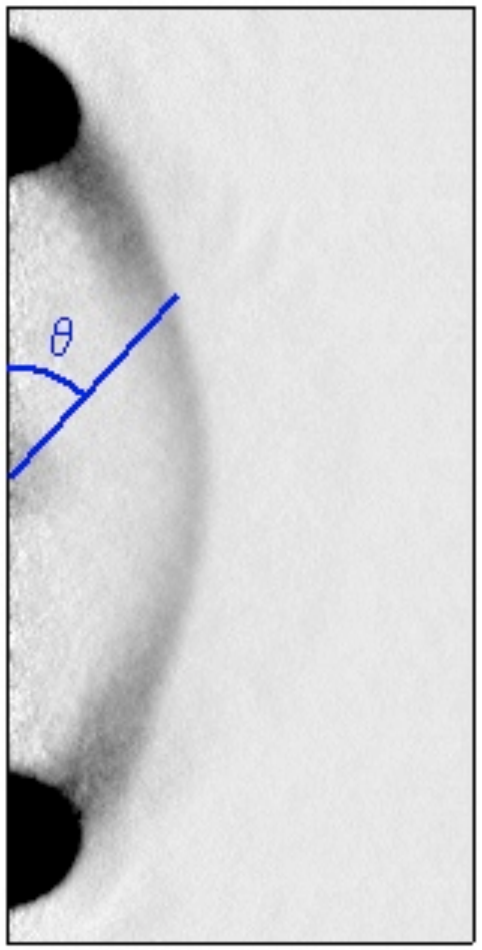




$n(x, y)$ → Inverse Abel transform → $n(\rho, x)$

# Shape of the scattering halo

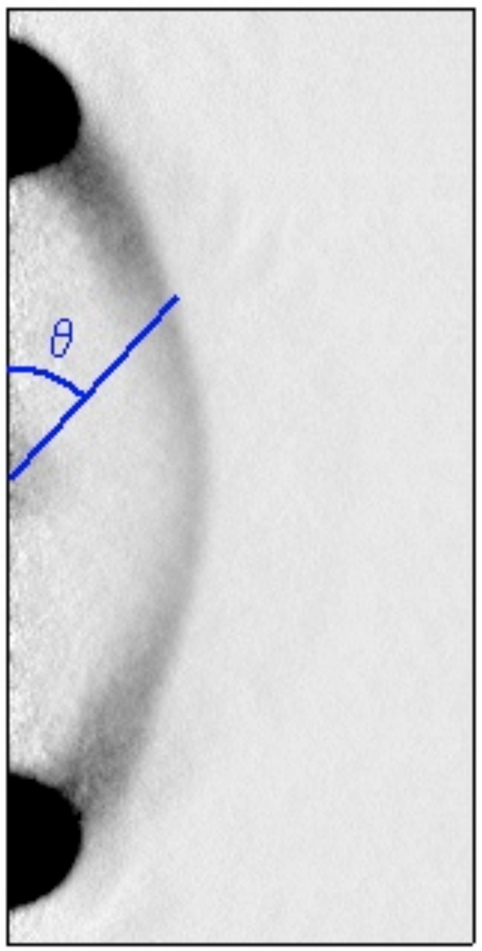


# Atomic distribution on scattering halo

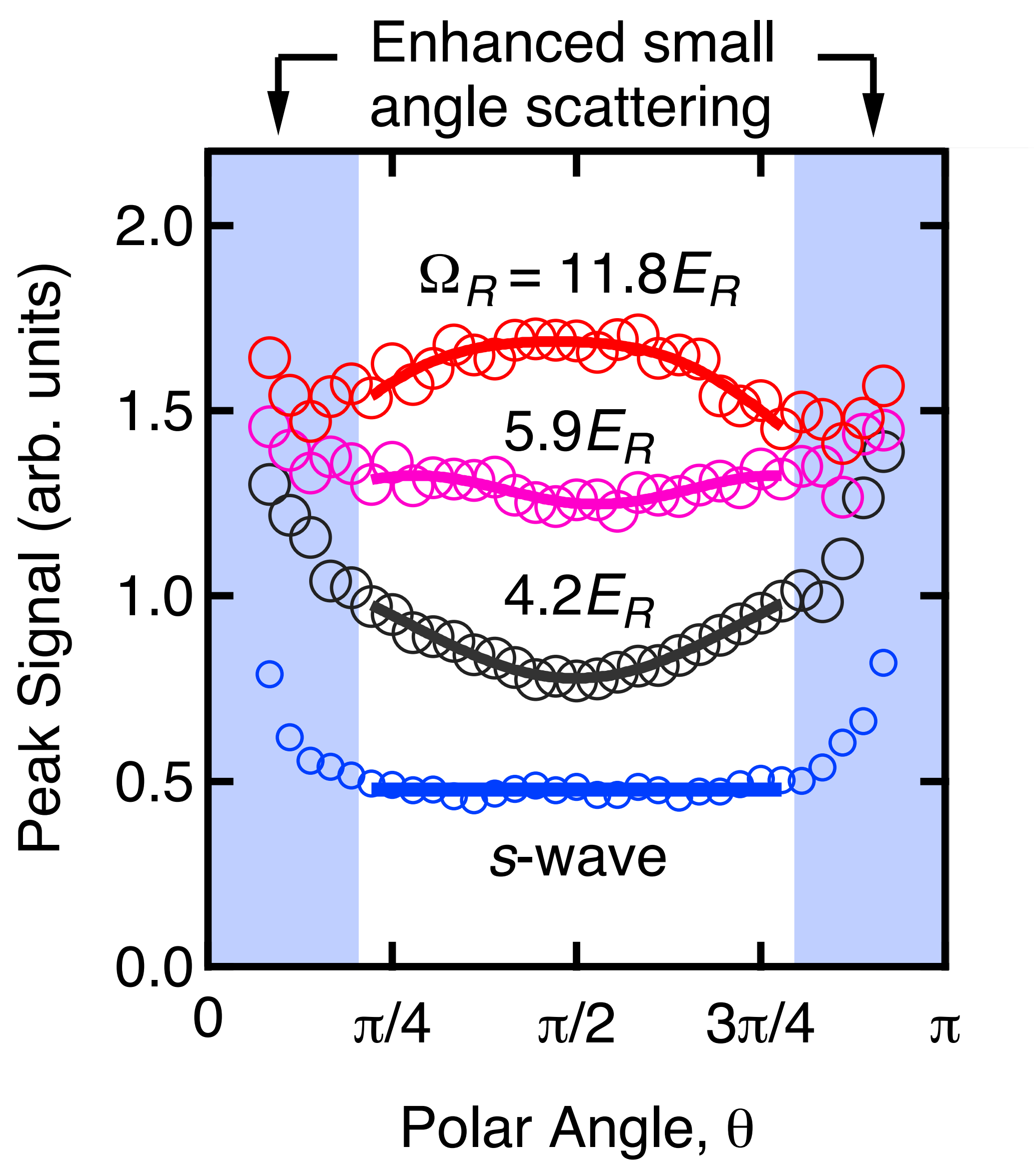



$$n(\rho, x)$$

# Atomic distribution on scattering halo




$$n(\rho, x)$$



# Effective higher order partial waves

Microscopic view → Contact interactions $V(\mathbf{r}_1 - \mathbf{r}_2) = g\,\delta(\mathbf{r}_1 - \mathbf{r}_2)$

$$\hat{H}_{\mathrm{int}} = \frac{g}{2}\int d^3\mathbf{r} \sum_{\sigma_1,\sigma_2} \hat{\psi}^\dagger_{\sigma_1}(\mathbf{r})\hat{\psi}^\dagger_{\sigma_2}(\mathbf{r})\hat{\psi}_{\sigma_1}(\mathbf{r})\hat{\psi}_{\sigma_2}(\mathbf{r})$$

$$= \frac{g}{2}\int \frac{d^3\mathbf{k}_1}{(2\pi)^3}\cdots\frac{d^3\mathbf{k}_4}{(2\pi)^3} \sum_{\sigma_1,\sigma_2} \hat{\phi}^\dagger_{\sigma_1}(\mathbf{k}_4)\hat{\phi}^\dagger_{\sigma_2}(\mathbf{k}_3)\hat{\phi}_{\sigma_1}(\mathbf{k}_2)\hat{\phi}_{\sigma_2}(\mathbf{k}_1)\;\delta^{(3)}(\mathbf{k}_1 + \mathbf{k}_2 - \mathbf{k}_3 - \mathbf{k}_4)$$

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Dressed states are related to bare states by a momentum dependent unitary transformation, U(**k**).

$$\phi'_n(\mathbf{k}) = \sum_{\sigma'} U_{n,\sigma'}(\mathbf{k})\phi_{\sigma'}(\mathbf{k})$$

# Effective higher order partial waves

Microscopic view → Contact interactions $V(\mathbf{r}_1-\mathbf{r}_2)=g\,\delta(\mathbf{r}_1-\mathbf{r}_2)$

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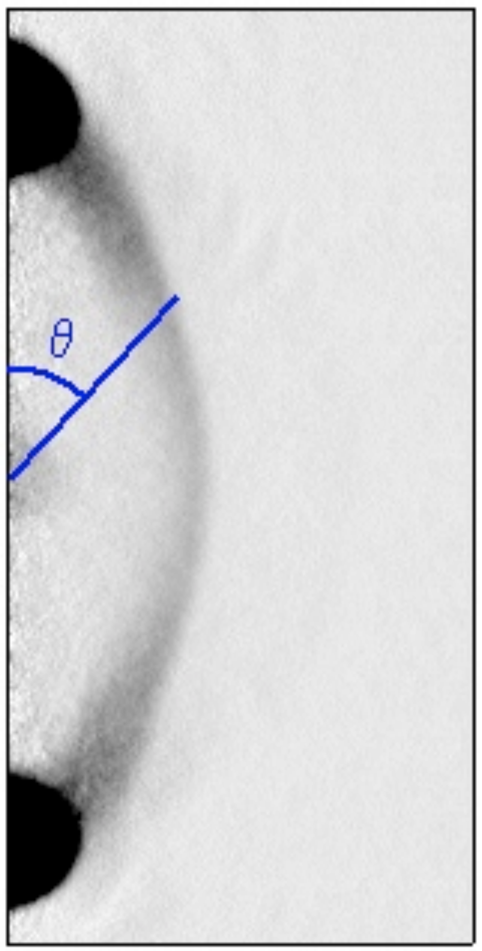
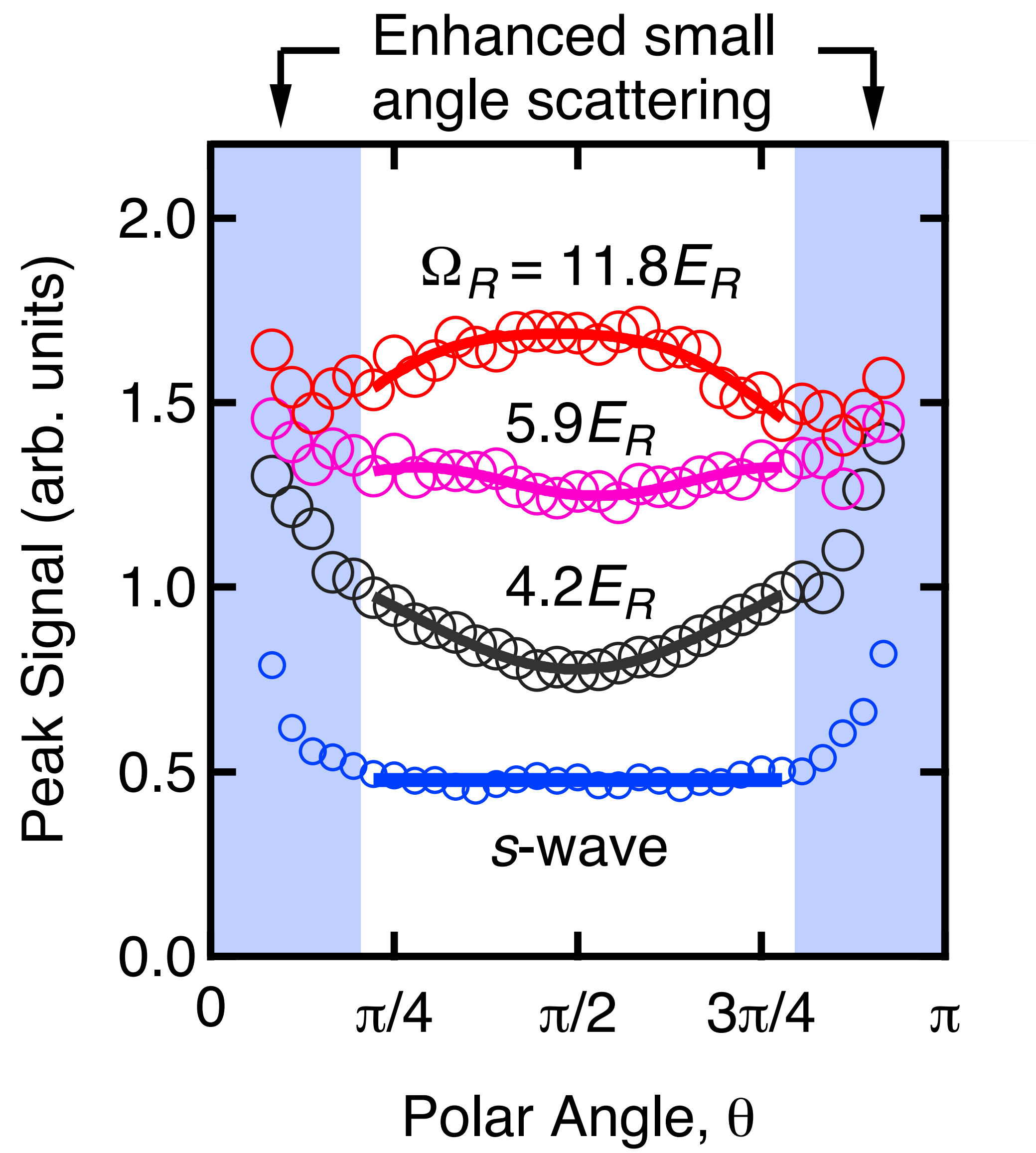
$$\hat{H}_{\rm int}=\frac{g}{2}\int\frac{d^3\mathbf{k}_1}{(2\pi)^3}\cdots\frac{d^3\mathbf{k}_4}{(2\pi)^3}\sum_{n_1,n_2,n'_1,n'_2}\hat{\phi}'^\dagger_{n_1}(\mathbf{k}_4)\hat{\phi}'^\dagger_{n_2}(\mathbf{k}_3)\hat{\phi}'_{n'_1}(\mathbf{k}_2)\hat{\phi}'_{n'_2}(\mathbf{k}_1)$$

$$\times\boxed{\left[\sum_{\sigma_1,\sigma_2}U_{n_1,\sigma_1}(\mathbf{k}_4)U^\dagger_{\sigma_1,n'_1}(\mathbf{k}_2)U_{n_2,\sigma_2}(\mathbf{k}_3)U^\dagger_{\sigma_2,n'_2}(\mathbf{k}_1)\right]}\times\delta^{(3)}(\mathbf{k}_1+\mathbf{k}_2-\mathbf{k}_3-\mathbf{k}_4)$$

# Atomic distribution on scattering halo




$$n(\rho, x)$$



# Partial wave decomposition

$$\left| \sum_l (\exp 2i\eta_l - 1)(2l+1) P_l(\cos(\theta)) \right|^2$$

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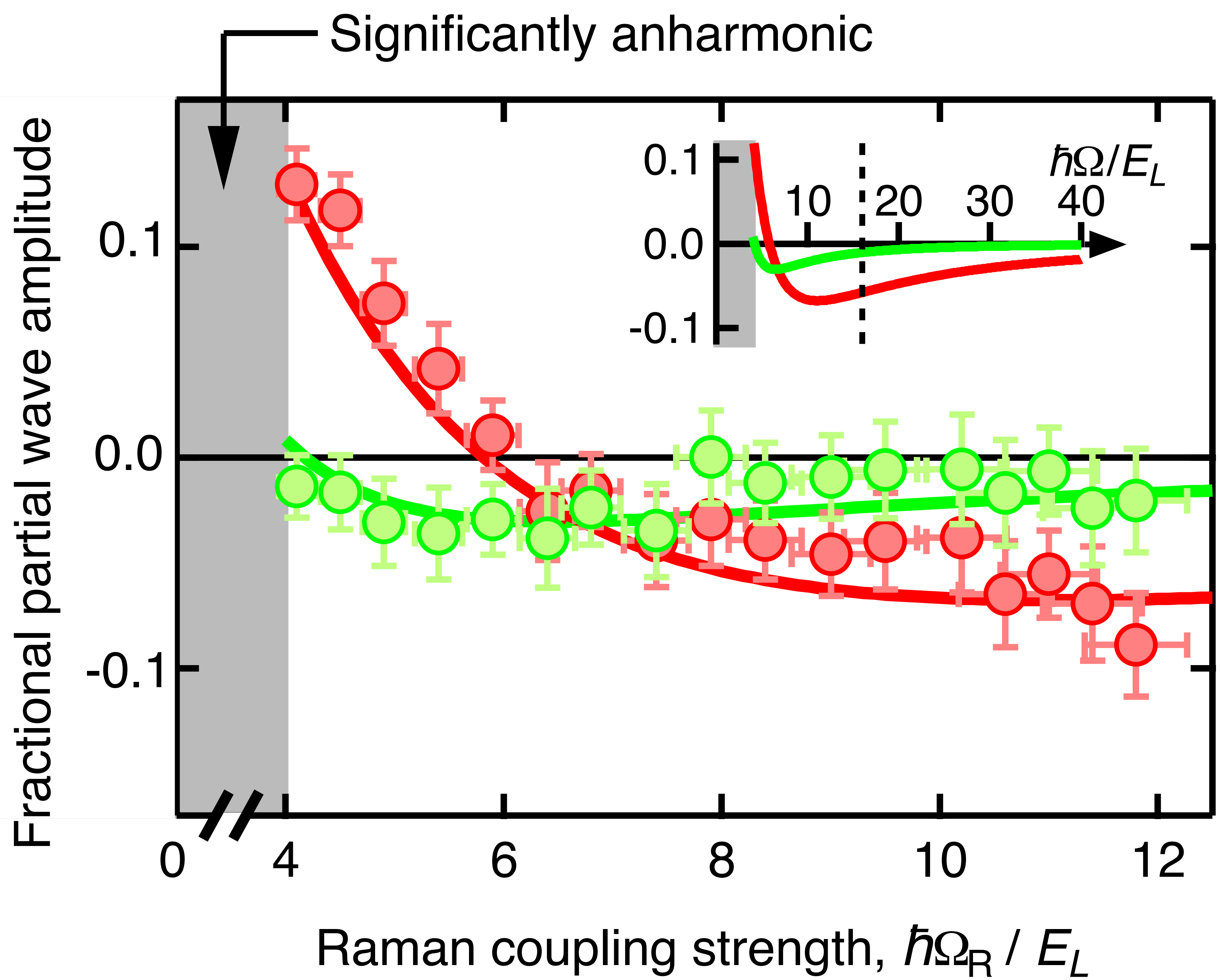


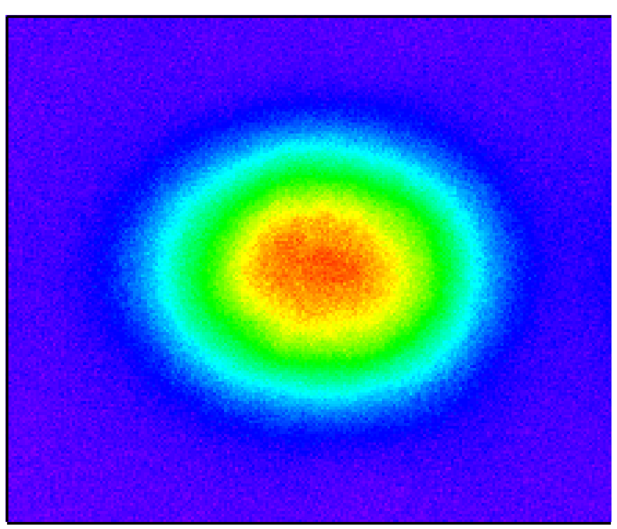
# Future directions

Particularly interesting with fermions:

C. Zhang et al, PRL 101, 160401 (2008)

K. Seo, L. Han, C. A. R. Sa de Melo, arXiv:1110:6364 (2011),
arXiv:1201:0177 (2011)

Could lead to p-wave superfluidity, Majorana fermions...



Fermions at NIST!

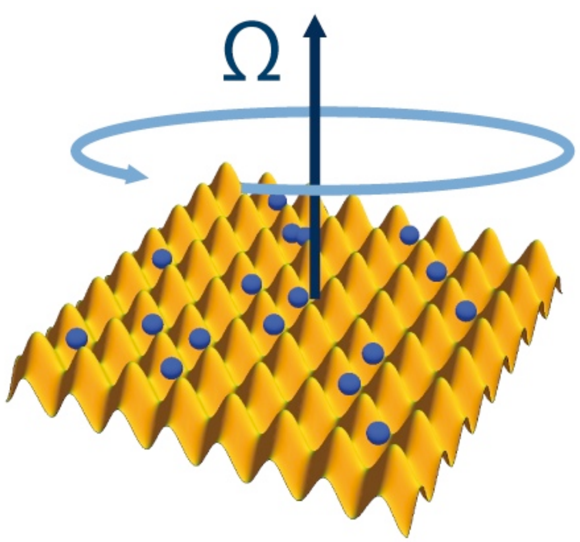
# Peierls substitution in an engineered lattice potential

K. Jiménez-García et al, PRL, **108**, 225303 (2012)

# Artificial magnetic fields in optical lattices

$$H = -J \sum_{\langle i,j \rangle} \left( \hat{a}_i^\dagger \hat{a}_j e^{i\phi_{ij}} + \hat{a}_j^\dagger \hat{a}_i e^{-i\phi_{ij}} \right) \quad \text{, where} \quad \phi_{ij} = (q/\hbar) \int_{\mathbf{r}_i}^{\mathbf{r}_j} \mathbf{A} \cdot \mathrm{d}\mathbf{r}$$

Theory: Jaksch and Zoller, NJP (2003)




Rotating optical lattices:

- S. Tung et al, PRL, **97**, 240402, (2006) JILA
- R. A. Williams et al, PRL, **104**, 050404, (2010) Oxford

Light-induced vector potential:

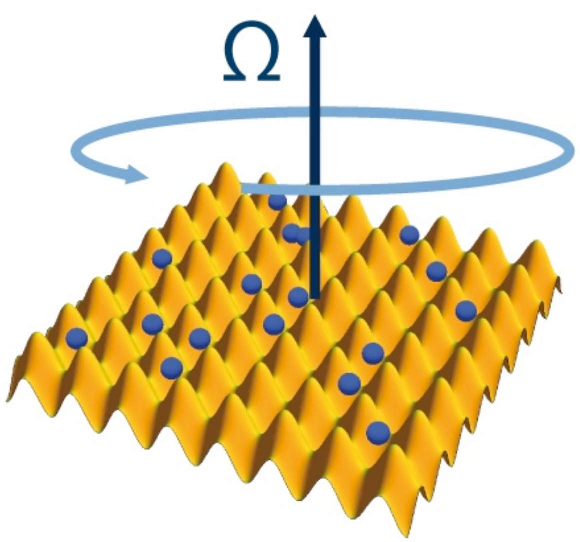
- M. Aidelsburger et al, PRL, **107**, 255301 (2011) Munich
- K. Jiménez-García et al, PRL, **108**, 225303 (2012) NIST
- J. Struck et al, PRL, **108**, 225304 (2012) Hamburg

Talk tomorrow morning

# Artificial magnetic fields in optical lattices

$$H = -J \sum_{\langle i,j \rangle} \left( \hat{a}_i^\dagger \hat{a}_j e^{i\phi_{ij}} + \hat{a}_j^\dagger \hat{a}_i e^{-i\phi_{ij}} \right) \quad , \text{ where } \quad \phi_{ij} = (q/\hbar) \int_{\mathbf{r}_i}^{\mathbf{r}_j} \mathbf{A} \cdot d\mathbf{r}$$

Theory: Jaksch and Zoller, NJP (2003)

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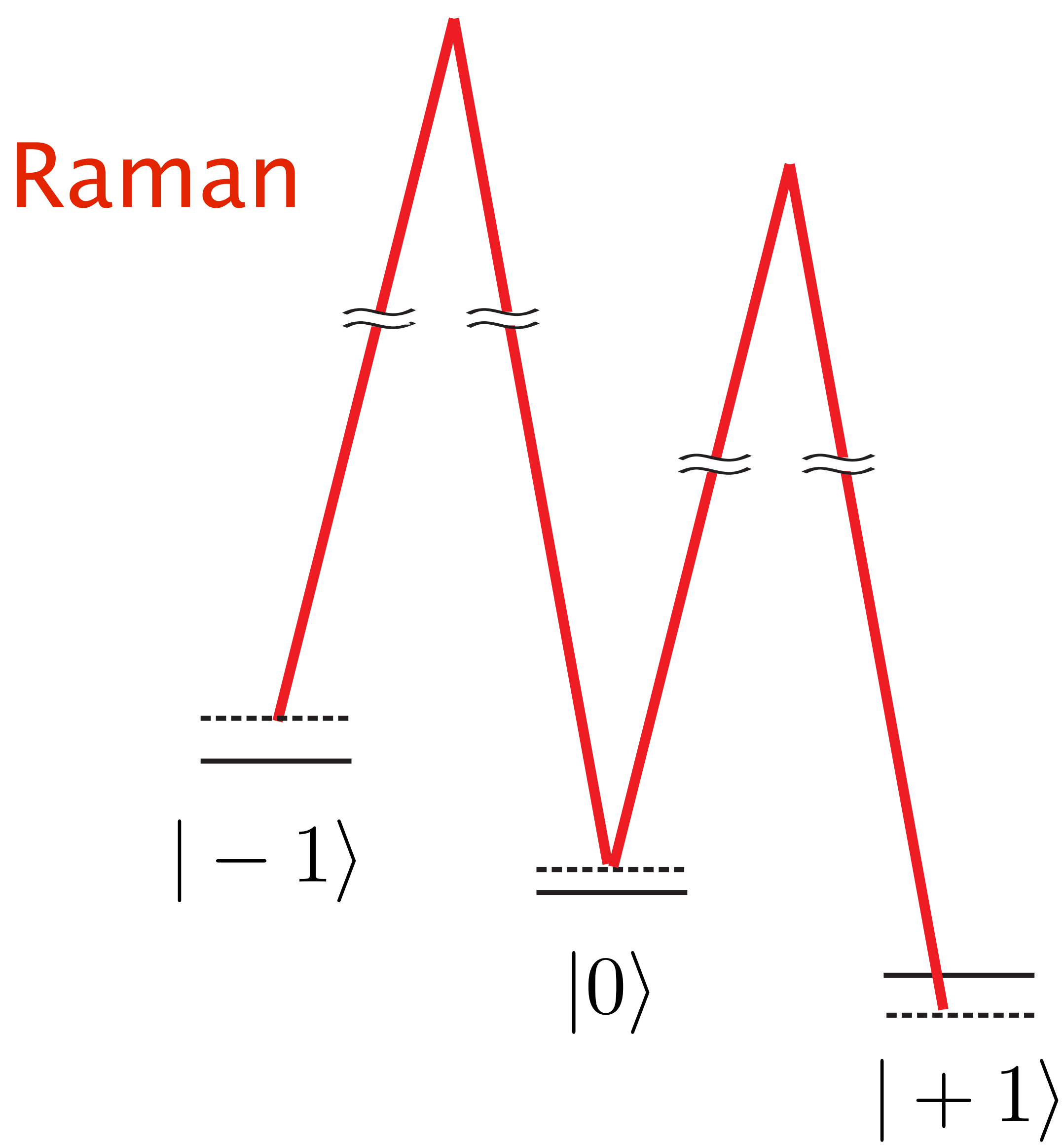
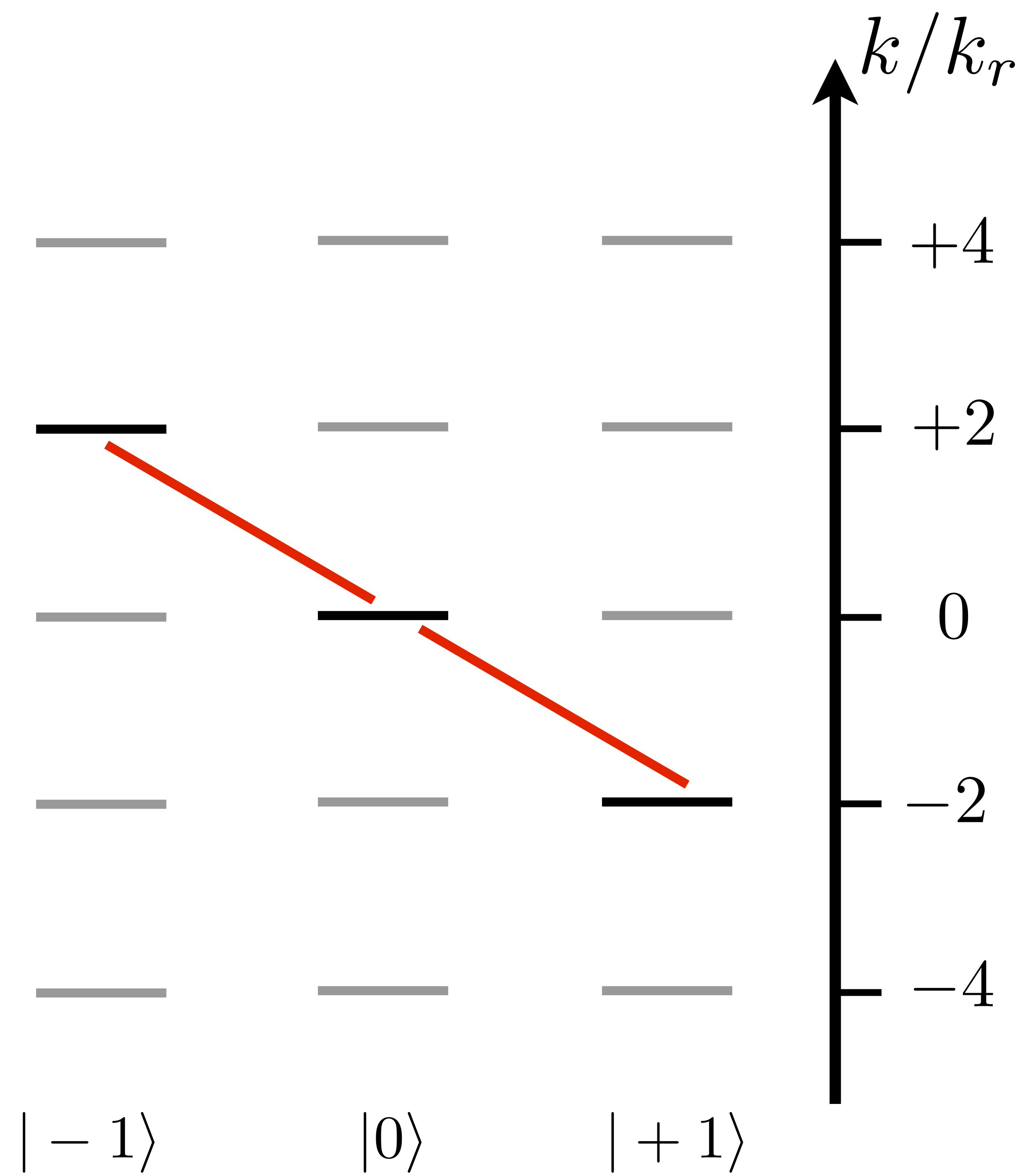
- J. Struck et al, PRL, **108**, 225304 (2012) Hamburg

Talk tomorrow morning

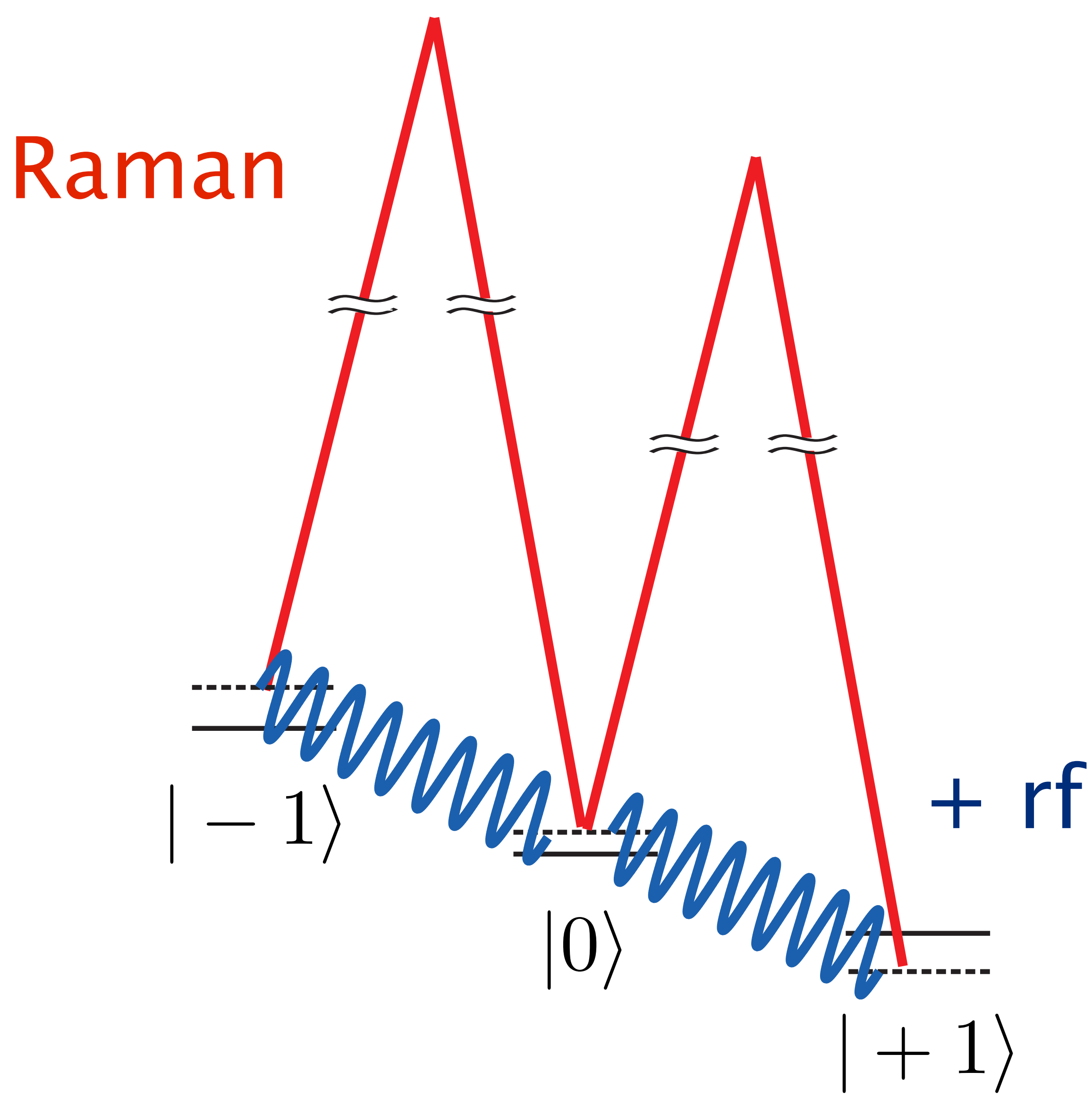
Flux lattices: N. Cooper, PRL **106**, 175301 (2011)

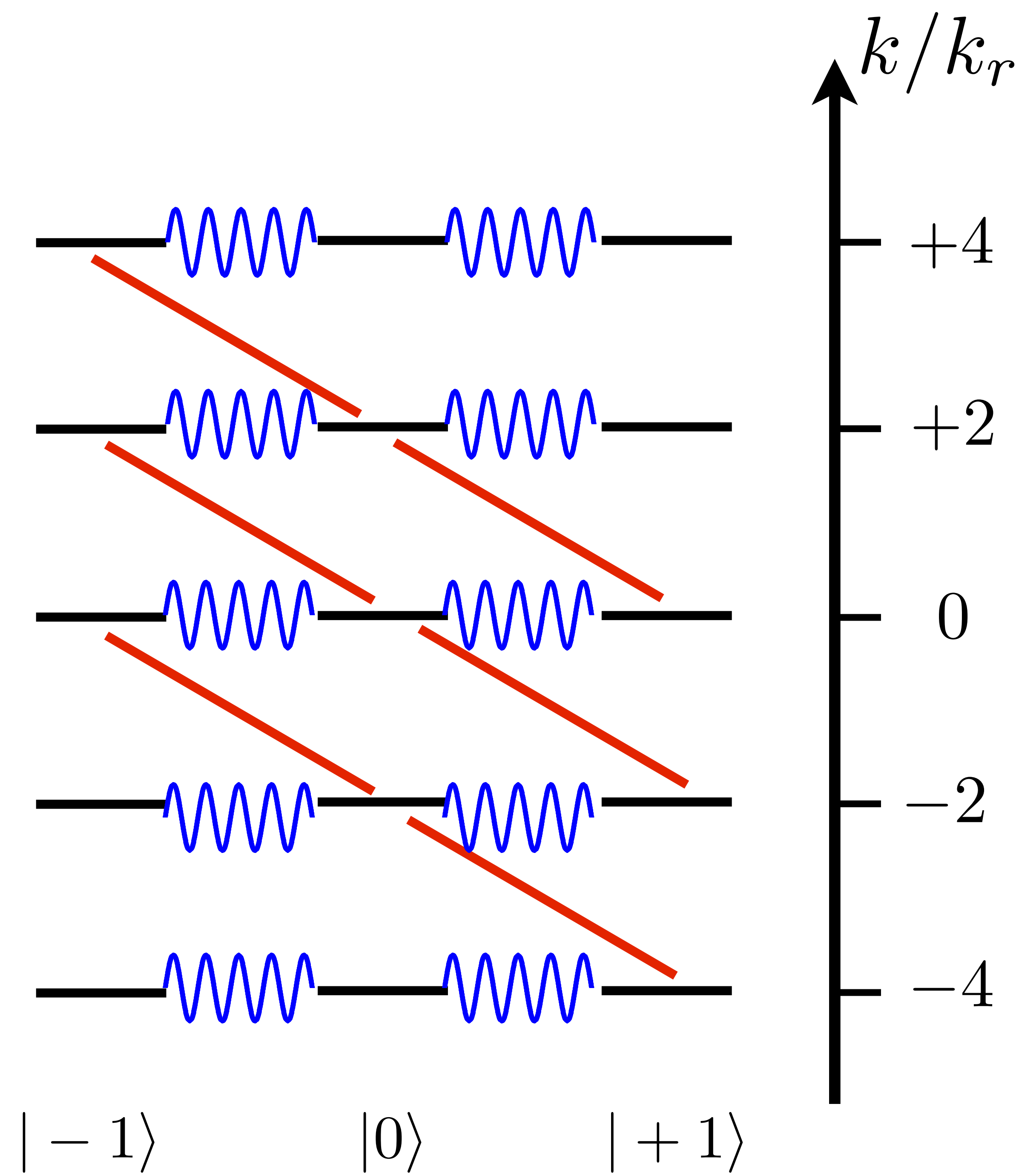
# rf + Raman Lattice



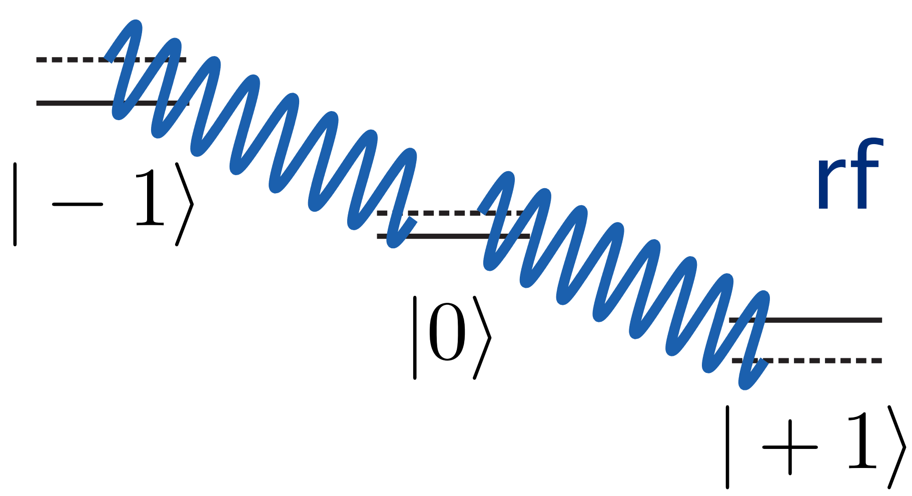



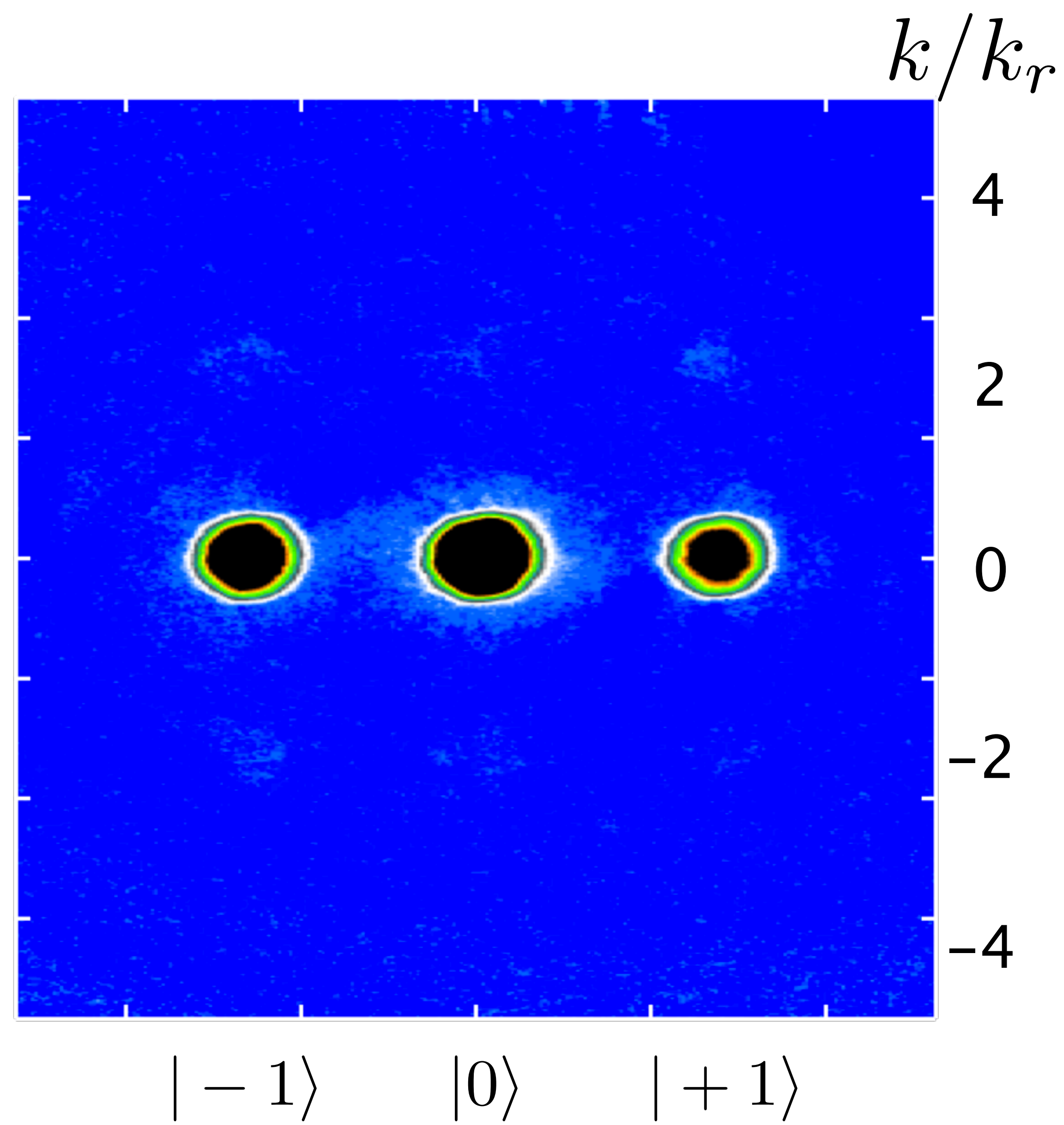
# rf + Raman Lattice



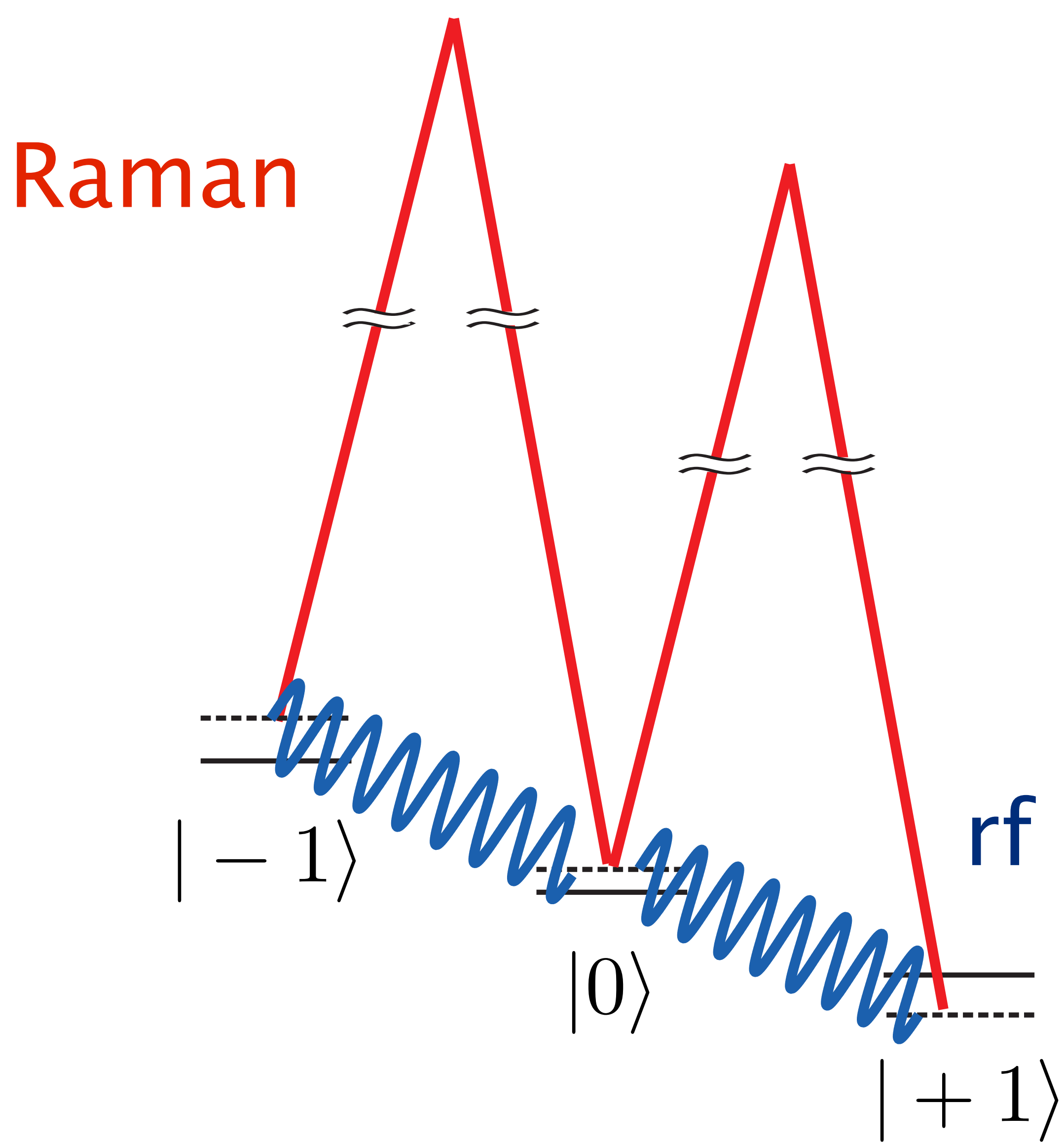



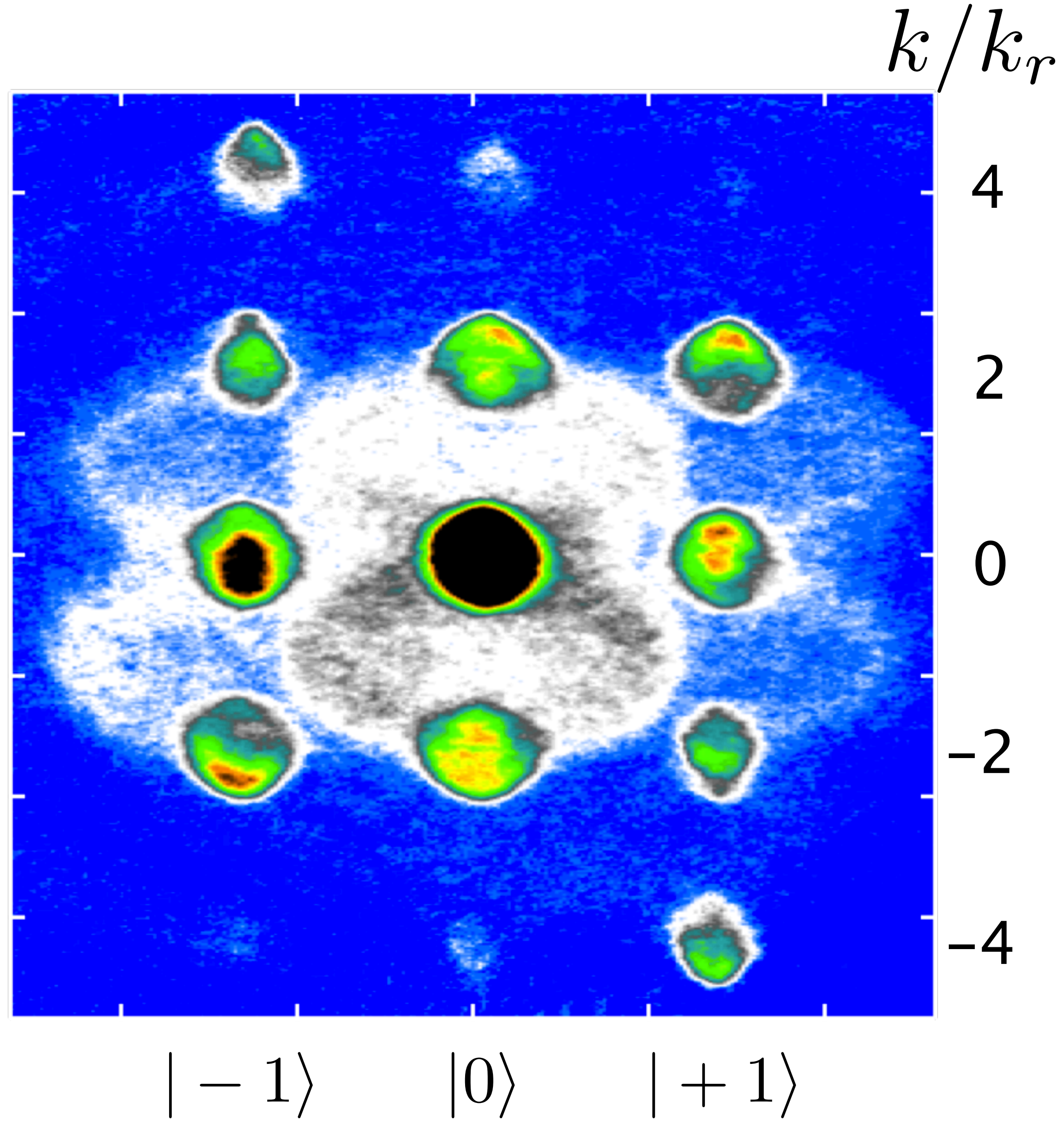
# rf + Raman Lattice



# rf + Raman Lattice

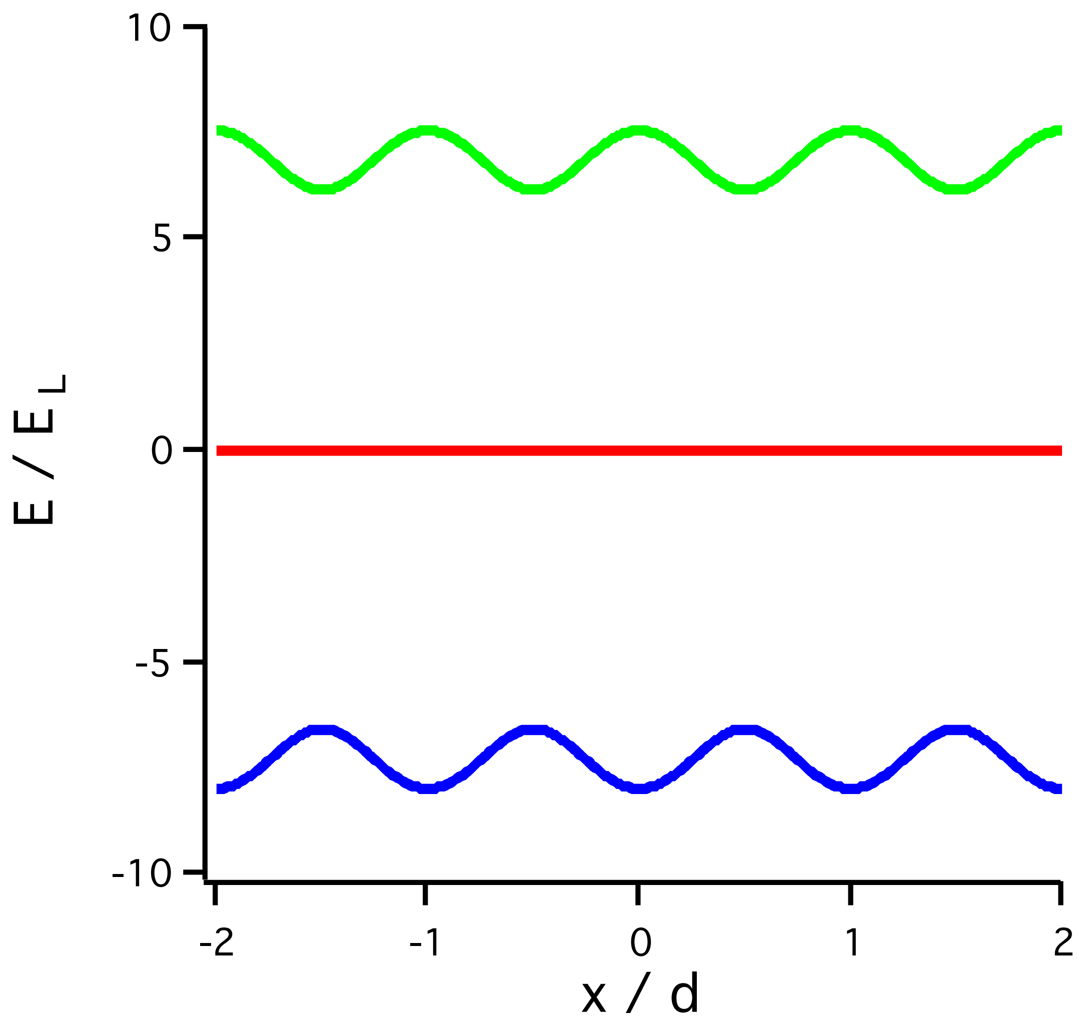


# rf + Raman Lattice

Hamiltonian in basis $|-1\rangle,\ |0\rangle,\ |+1\rangle$

$$H/\hbar = \frac{1}{2}\begin{pmatrix} -2\delta & \Omega_{rf} + \Omega_R e^{i2k_L x} & 0 \\ \Omega_{rf} + \Omega_R e^{i2k_L x} & -2\epsilon & \Omega_{rf} + \Omega_R e^{i2k_L x} \\ 0 & \Omega_{rf} + \Omega_R e^{i2k_L x} & 2\delta \end{pmatrix}$$




$$\hbar\Omega_{rf} = 1\ E_L$$

$$\hbar\Omega_R = 10\ E_L$$

$$\hbar\delta = 2E_L$$

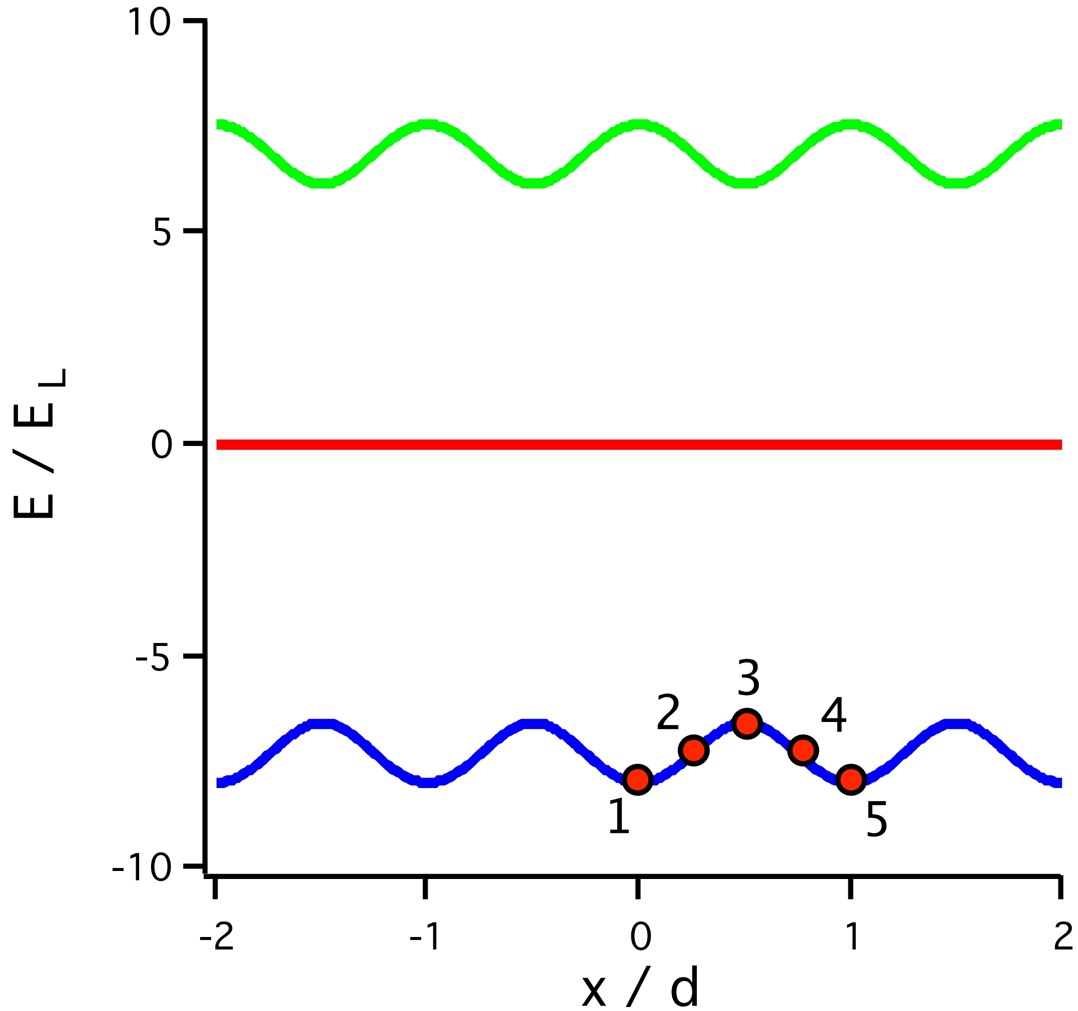
$$\hbar\epsilon = 0.42\ E_L$$

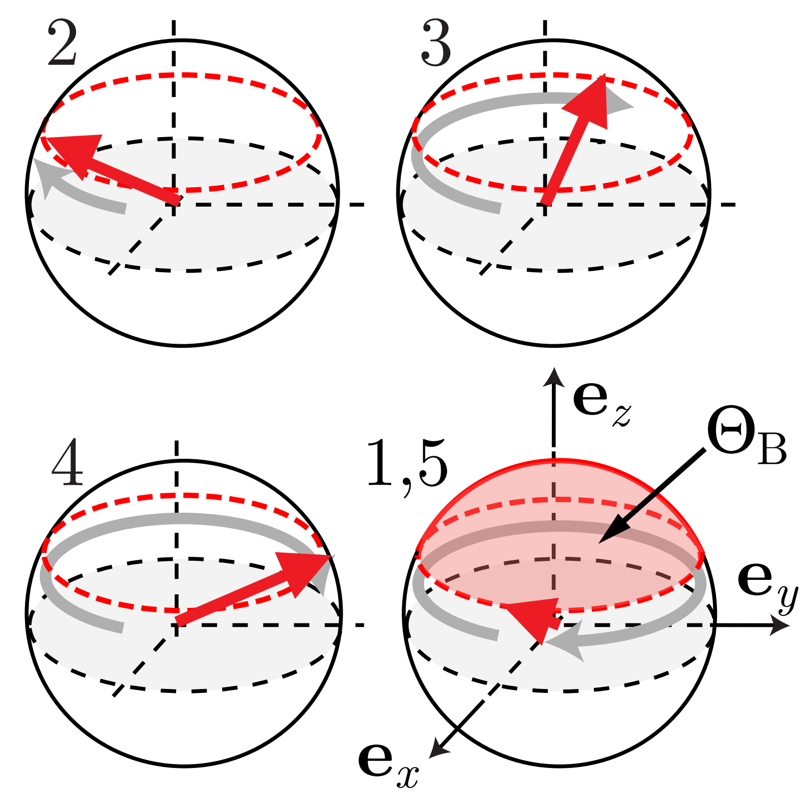
# rf + Raman Lattice

Hamiltonian in basis $|-1\rangle,\ |0\rangle,\ |+1\rangle$

$$H_{\mathrm{rf+R}} = \boldsymbol{\Omega}(x)\cdot\mathbf{F} + H_{\mathrm{Q}}$$

$$\boldsymbol{\Omega}(x) = \frac{1}{\sqrt{2}}\begin{pmatrix}\Omega_{rf}+\Omega_R\cos 2k_L x\\ -\Omega_R\sin 2k_L x\\ \sqrt{2}\delta\end{pmatrix}$$



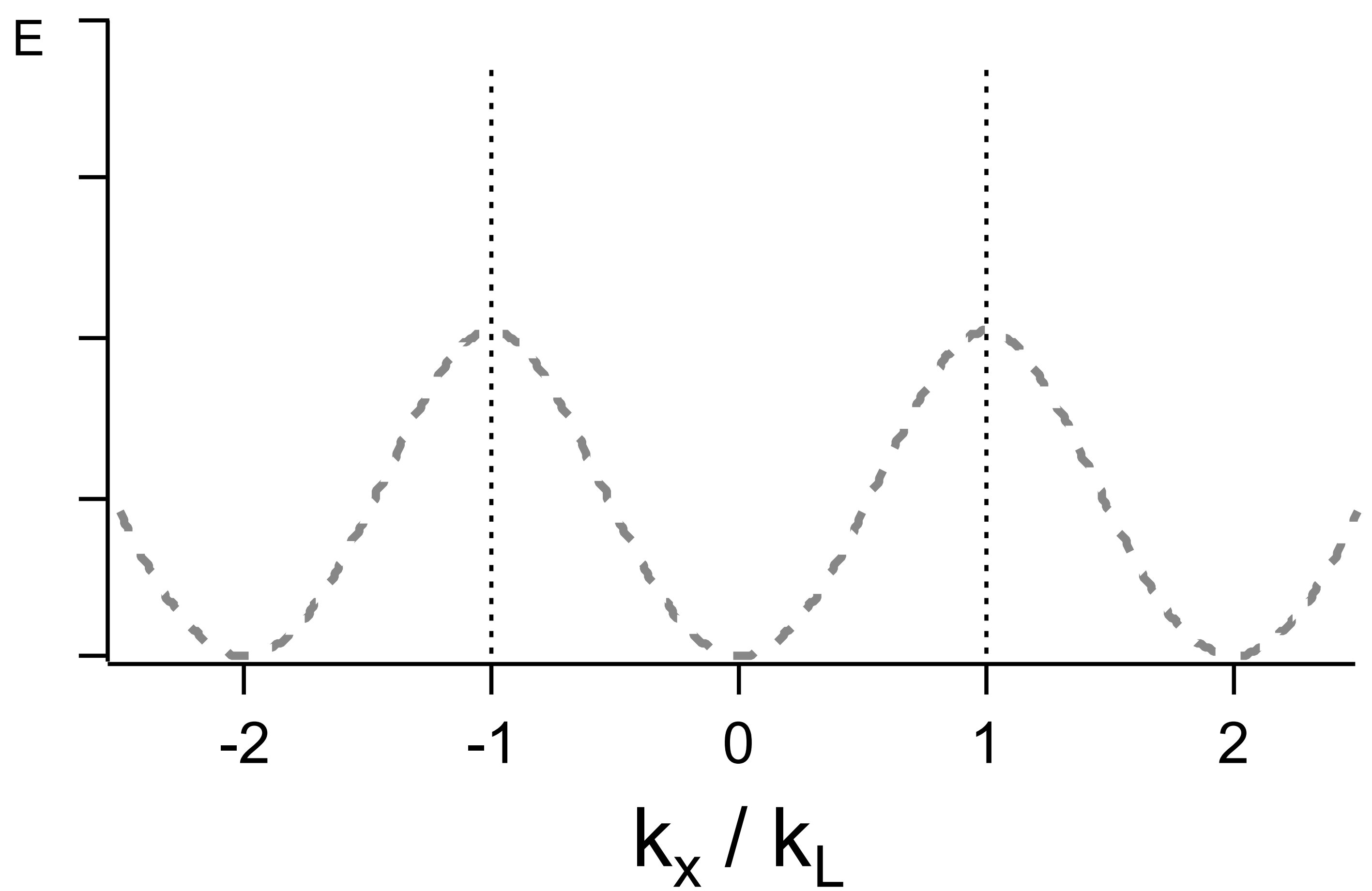



# rf + Raman Lattice

$$H = -J \sum_{\langle i,j \rangle} \left( \hat{a}_i^\dagger \hat{a}_j e^{i\phi_{ij}} + \hat{a}_j^\dagger \hat{a}_i e^{-i\phi_{ij}} \right)$$

Bandstructure in the presence of a vector potential

$$E(k) = -2J\cos(ka - \phi)$$

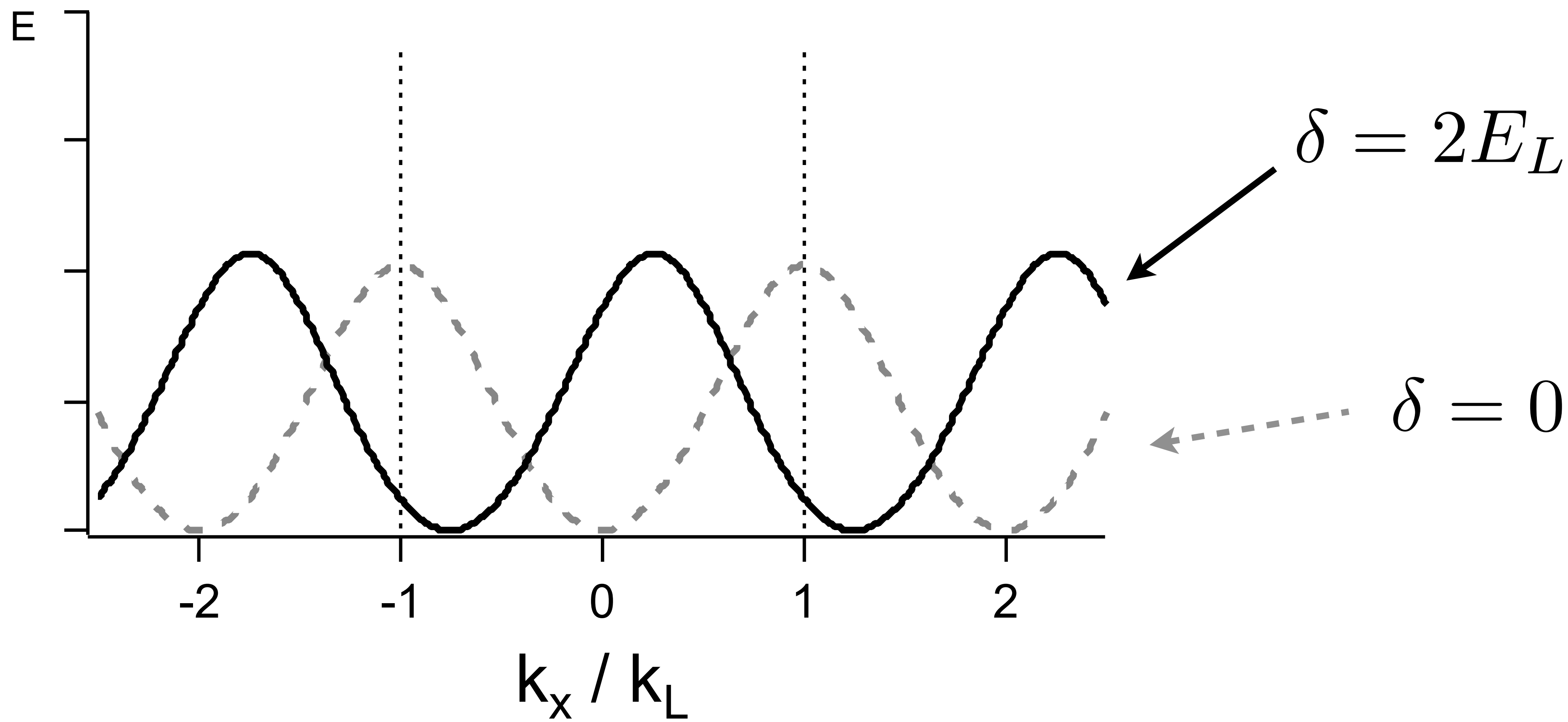



$\delta = 0$

# rf + Raman Lattice

$$H = -J \sum_{\langle i,j \rangle} \left( \hat{a}_i^\dagger \hat{a}_j e^{i\phi_{ij}} + \hat{a}_j^\dagger \hat{a}_i e^{-i\phi_{ij}} \right)$$

Bandstructure in the presence of a vector potential $\Rightarrow$ $E(k) = -2J\cos(ka - \phi)$

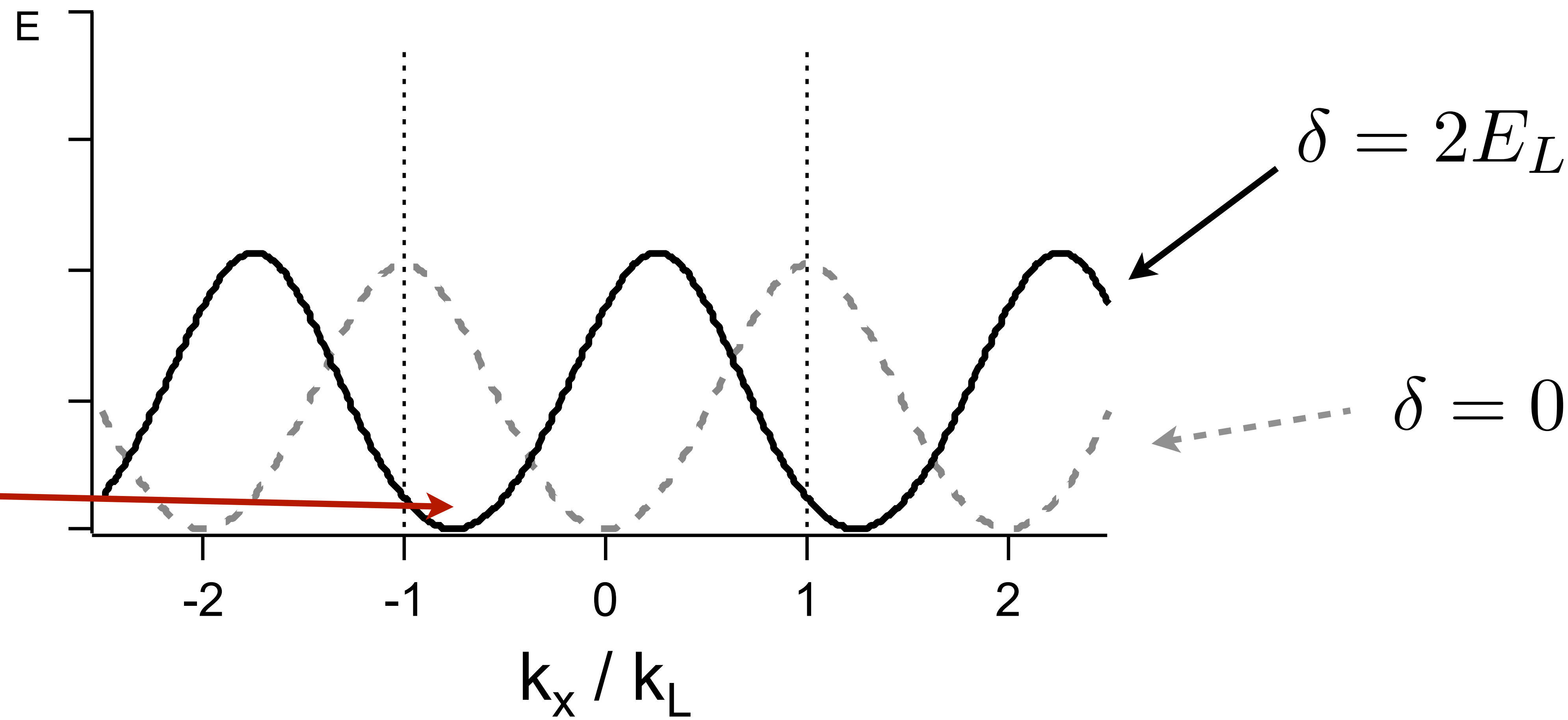


# rf + Raman Lattice

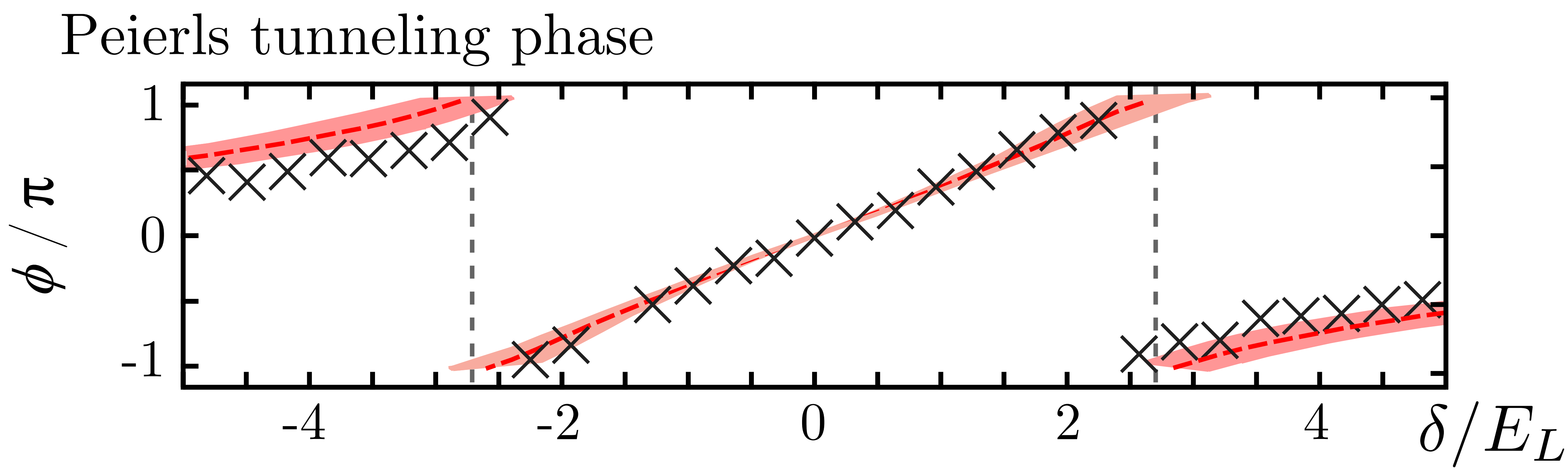
$$H = -J \sum_{\langle i,j \rangle} \left( \hat{a}_i^\dagger \hat{a}_j e^{i\phi_{ij}} + \hat{a}_j^\dagger \hat{a}_i e^{-i\phi_{ij}} \right)$$

Bandstructure in the presence of a vector potential $\Rightarrow$ $E(k) = -2J\cos(ka - \phi)$

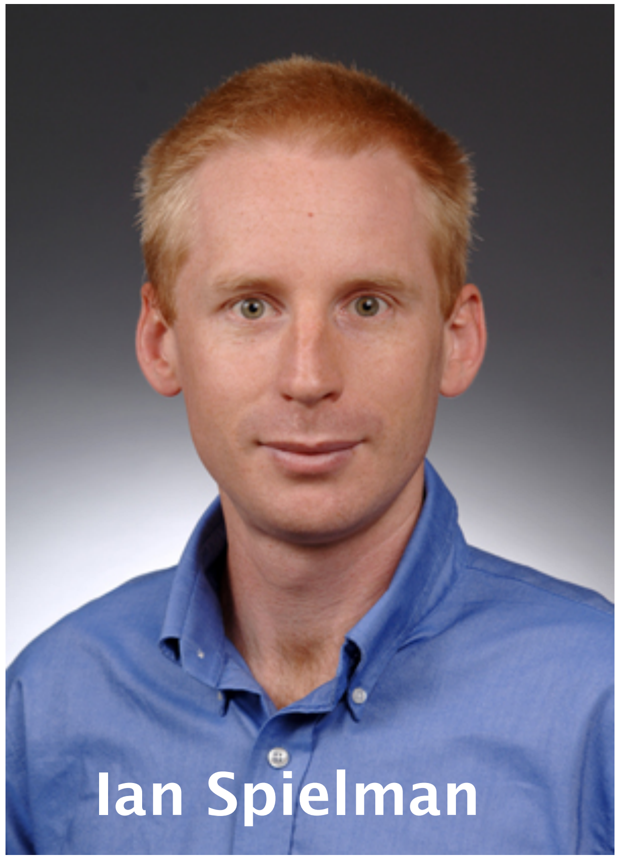
$$\frac{k_{\min}}{k_L} = \frac{\phi}{\pi}$$



# rf + Raman Lattice

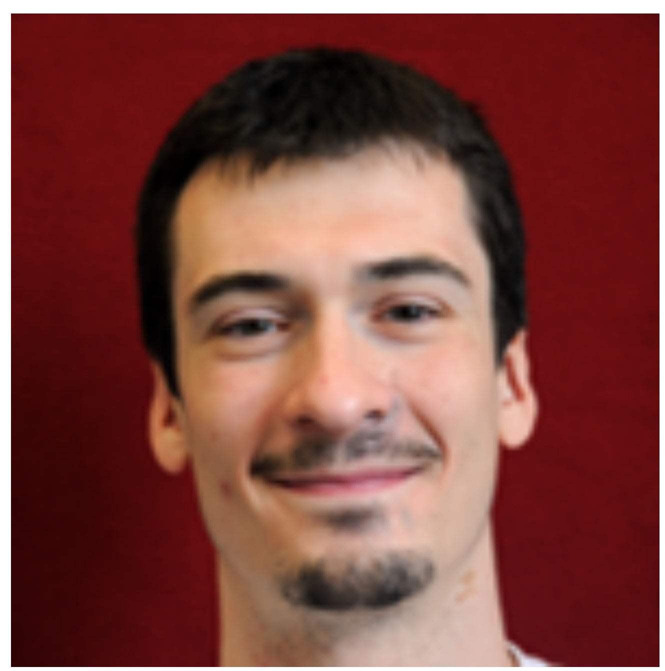


# Acknowledgements




Karina Jiménez-García





Matthew Beeler