Ultracold atoms: spin orbit coupling and engineered interactions

I. B. Spielman

Current team

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Alum

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Senior coworkers

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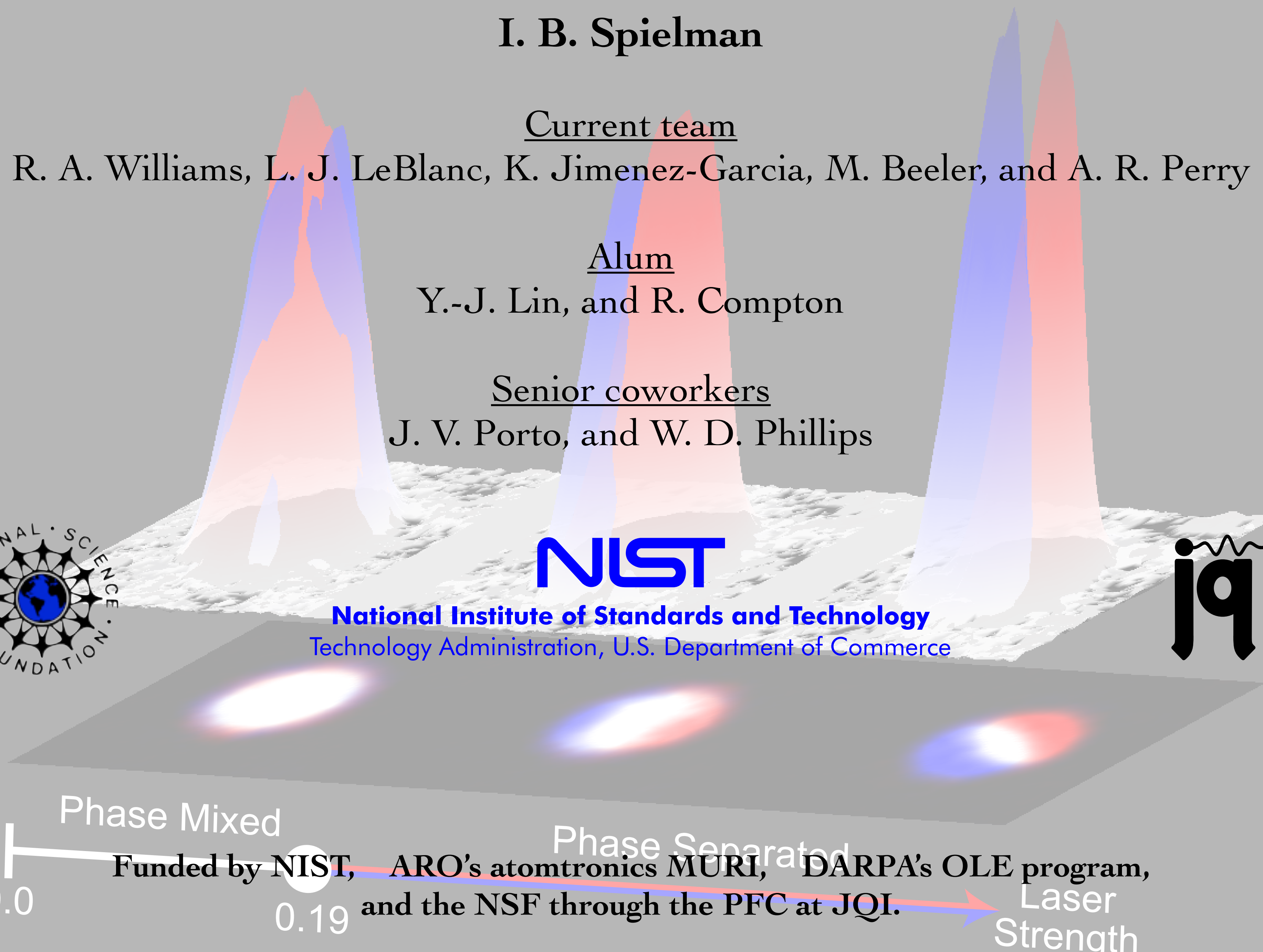

NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

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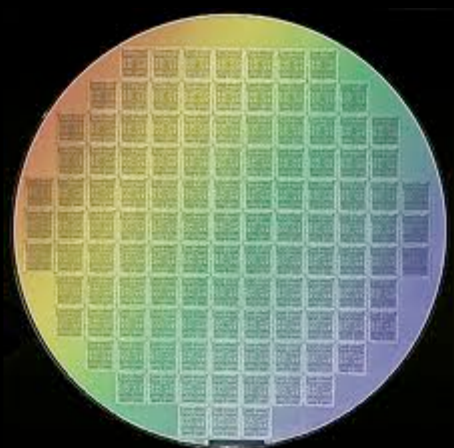
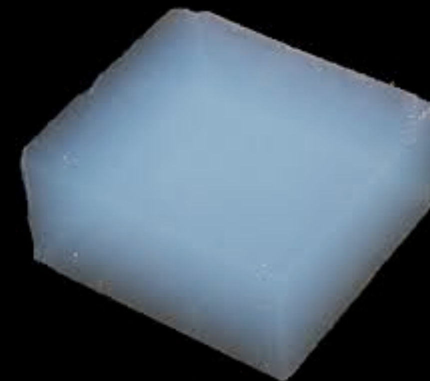
What are materials?



Si
$2.3\ g/cm^3$



Aerogel
$1\ mg/cm^3$

Ian's answer I: "chunks of stuff."

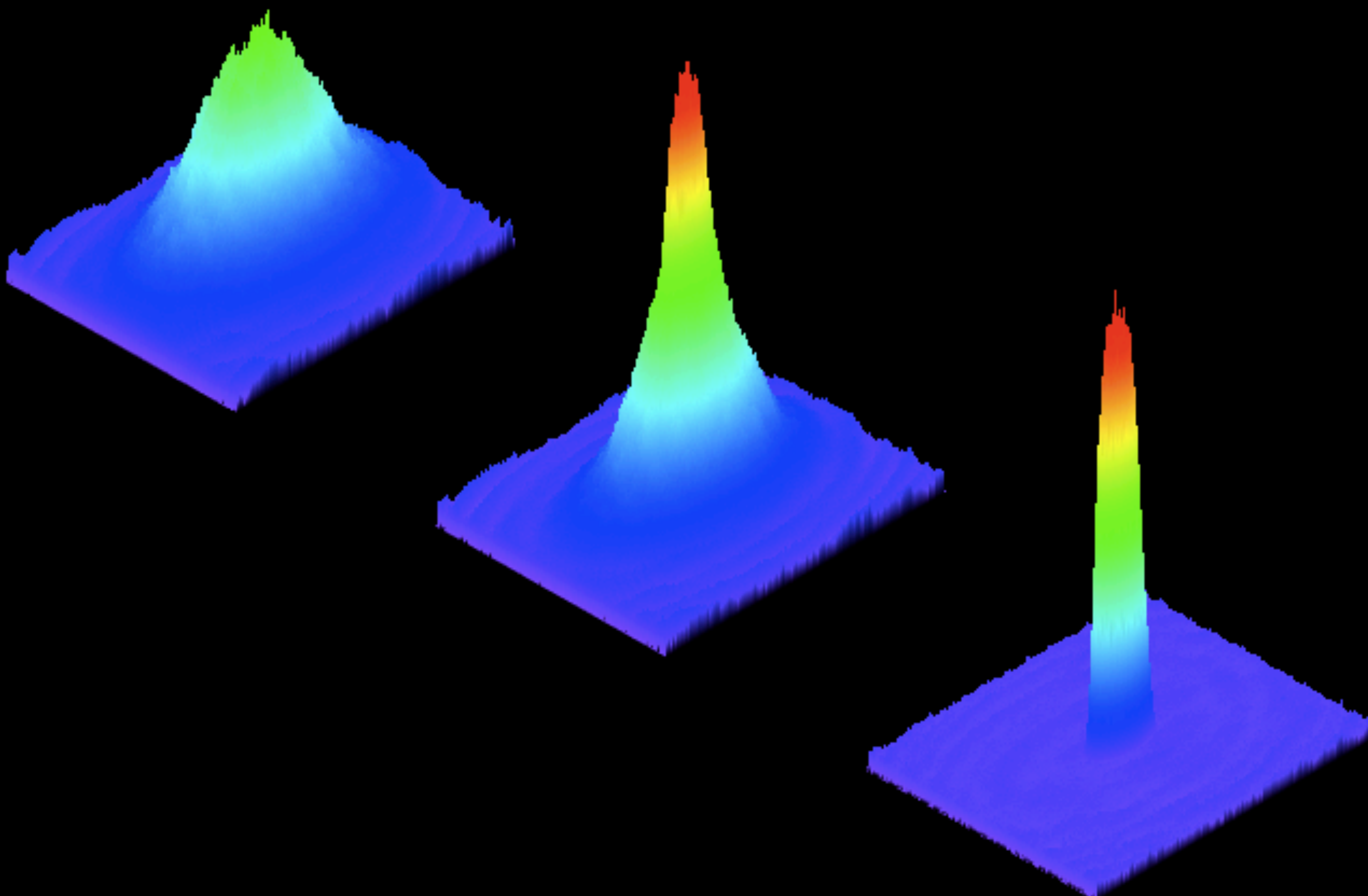
Liquid Helium
$125\ mg/cm^3$

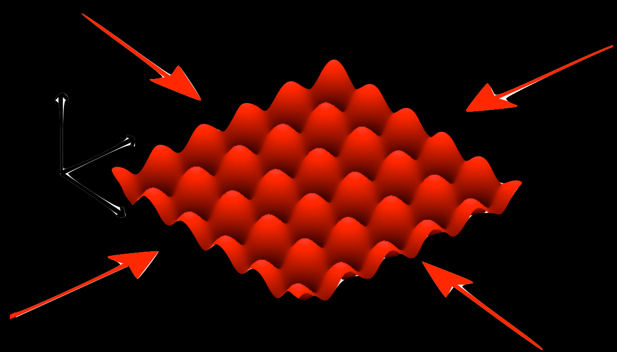
Ultracold neutral atoms

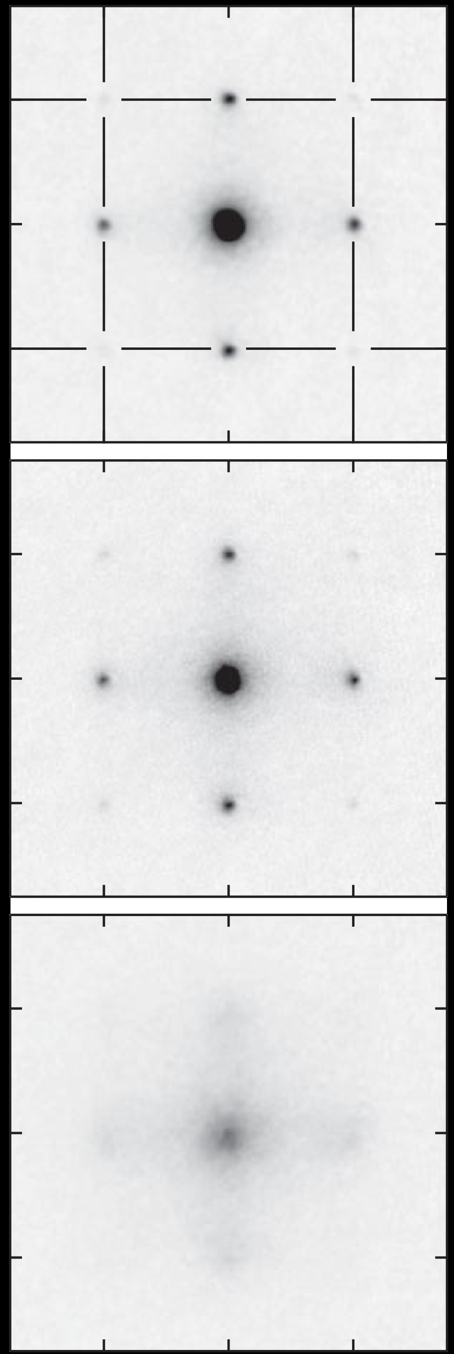
~10^{14} cm^{-3} or 100 ng/cm^3

(air is ~1 mg/cm^3)

Are these materials?







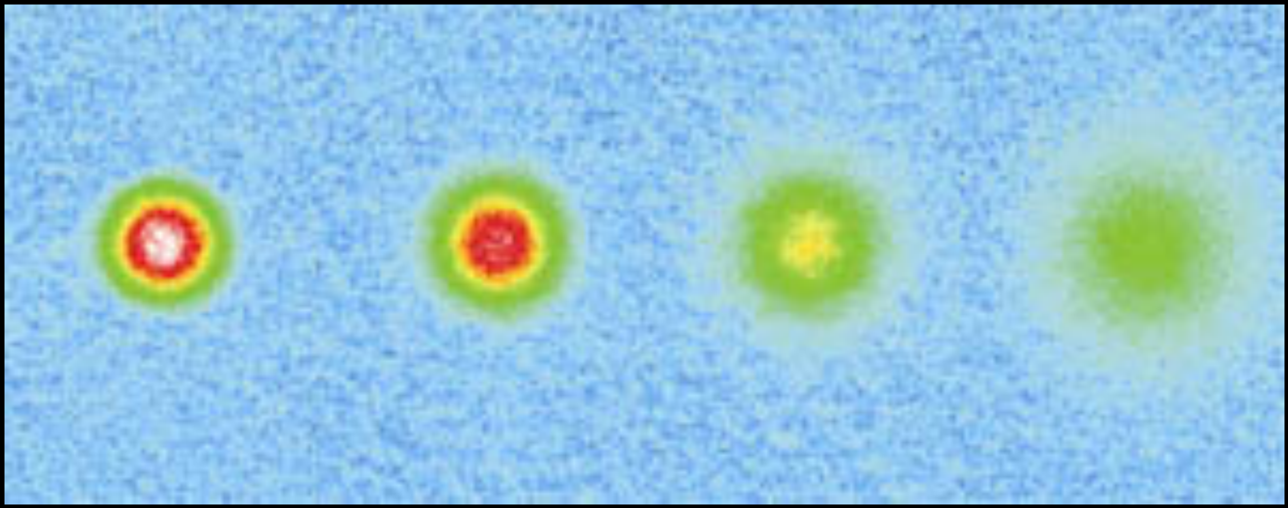
They can be fluids

They can be insulators

first: Greiner et al Nature (2002)

They can be bosons

They can be fermions

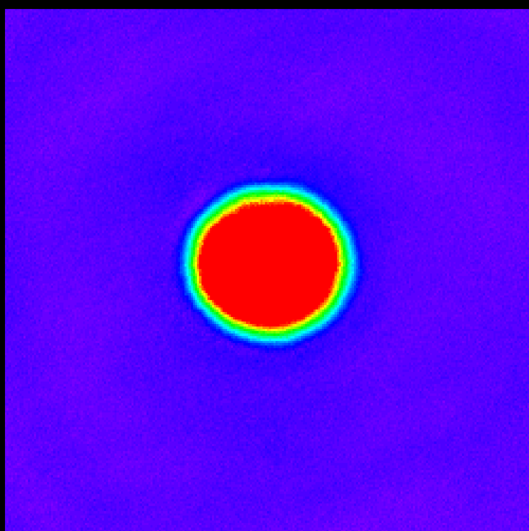


They can be molecules

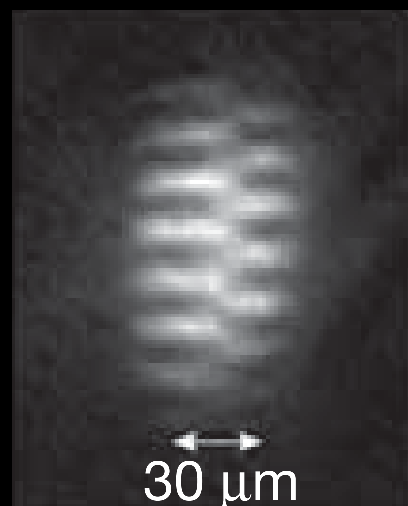
They can be atoms

e.g., Regal Nature (2003)

They can be 3D

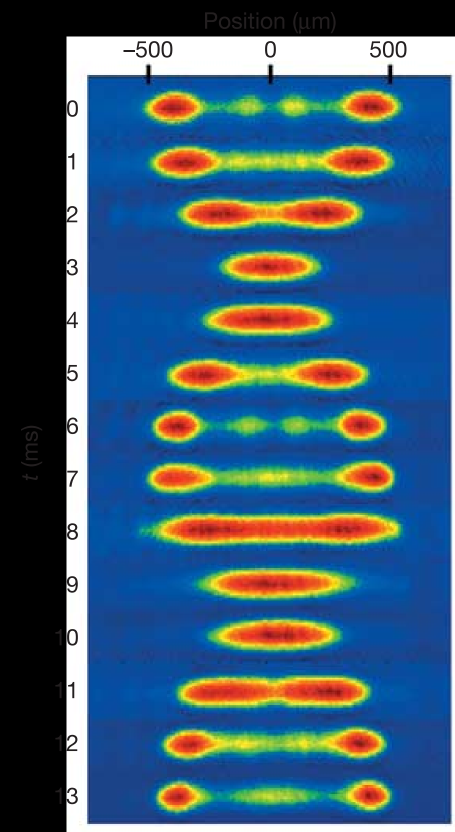


They can be 2D



e.g., Hadzibabic Nature (2006)

They can be 1D



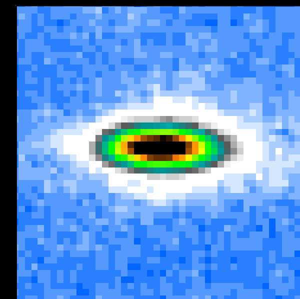
e.g., Kinoshita Nature (2006)

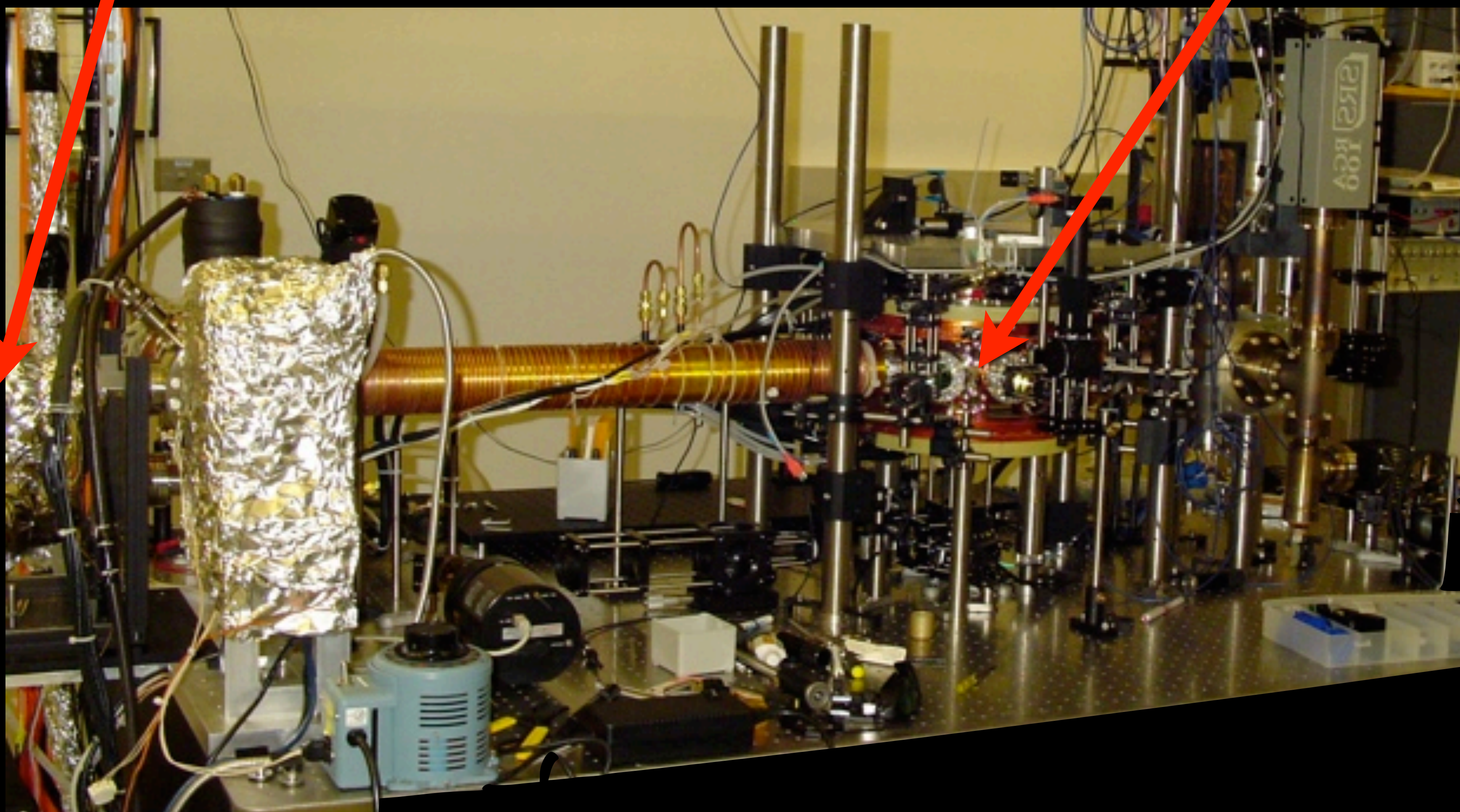
Starts like this

400 K

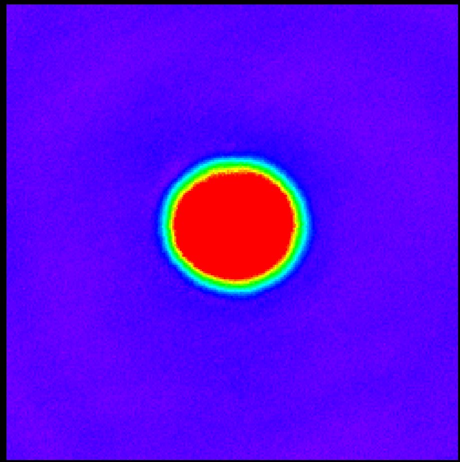
Ends here every 20 s

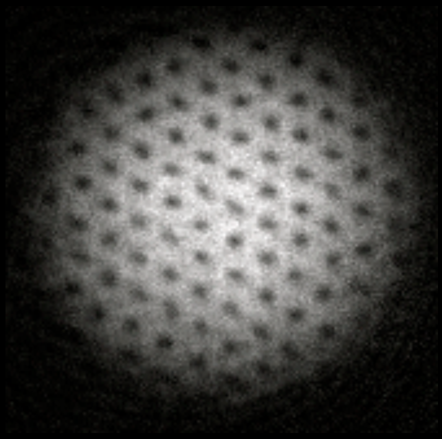
50 nK





What are materials?





Ian's answer: "stuff"

In a finite volume of space

Have "mechanical properties"

Or "fluid properties"

Cold atoms are: good materials

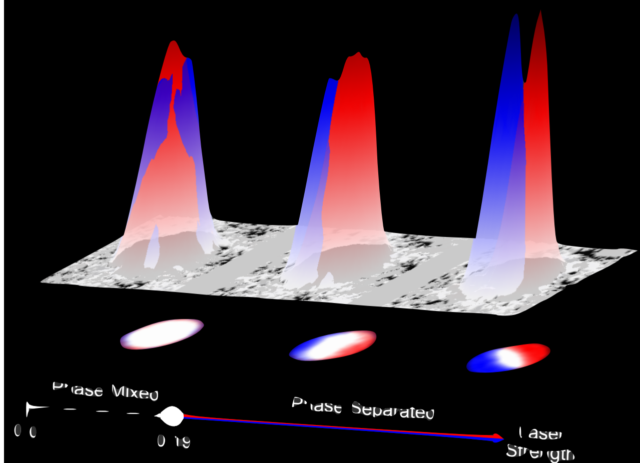
Numerous properties can
be controlled on many timescales

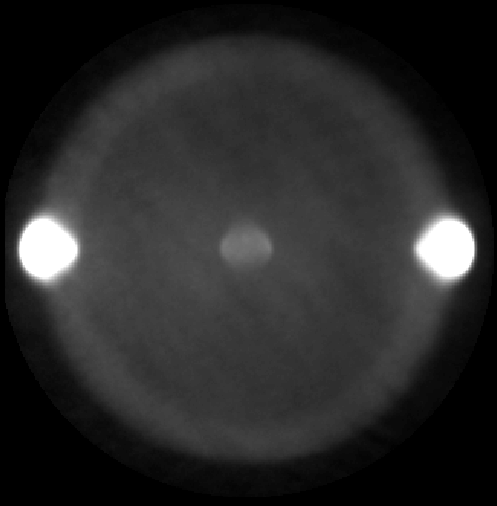
Very simple Hamiltonian

Cold atoms are: bad materials

Short lived

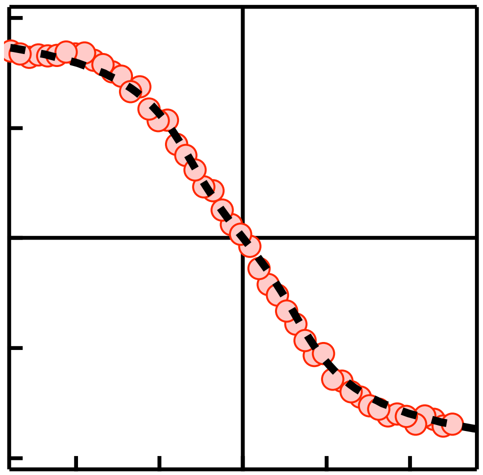
Interesting features **all** added
by hand (complex experiments).



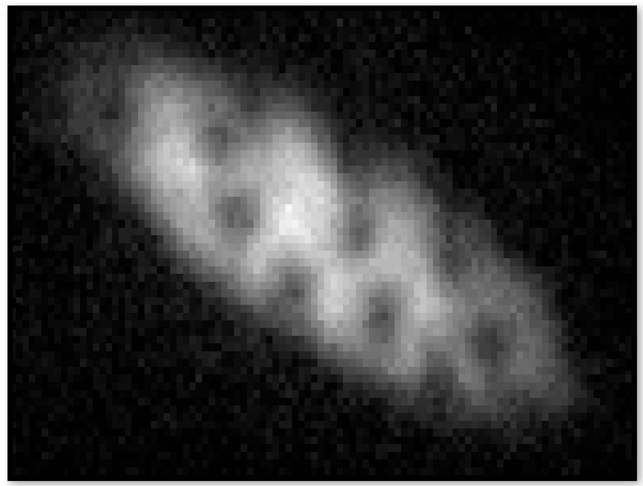


Artificial gauge fields

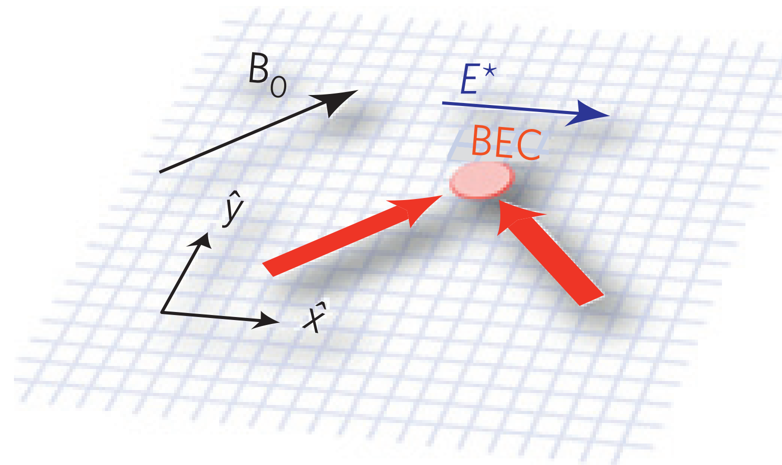
Vector potential



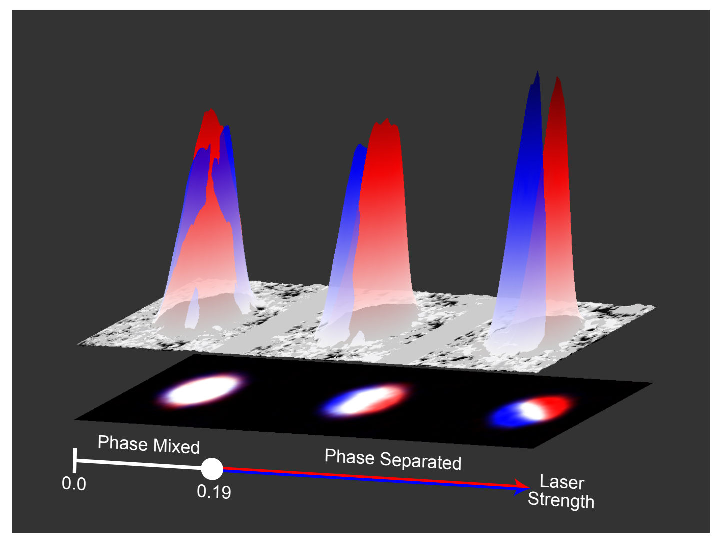
Magnetic field



Electric field



Spin Orbit coupling



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

Can be a matrix

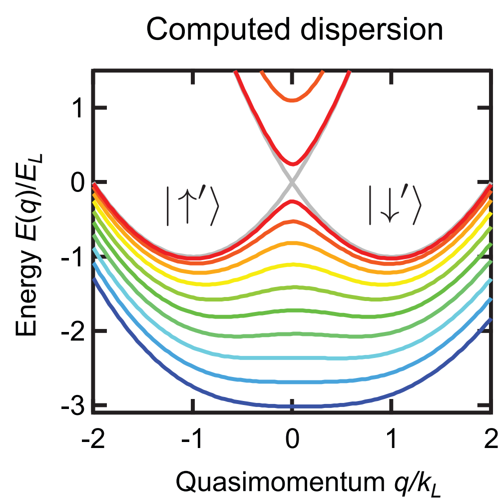
Spin orbit coupling of pseudo spin-1/2 atoms

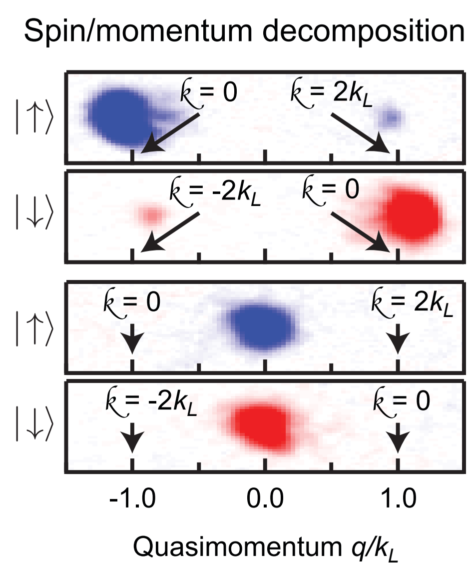
Current experiments with Bosons

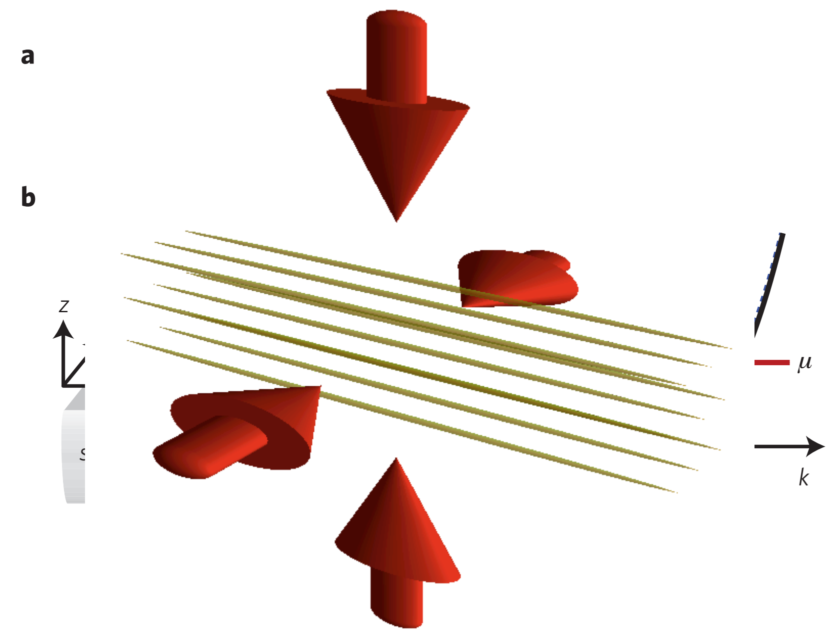
Spin orbit coupling for pseudo spin 1/2 **Bosons** (testbed platform)

$$\hat{\mathcal{H}} = \hat{\Psi}^\dagger(\mathbf{x}) \left(\frac{\hbar^2 \hat{\mathbf{k}}^2}{2m} \check{1} + \frac{\hbar^2 k_R}{m} \hat{k}_x \check{\sigma}_y + \frac{\Omega}{2} \check{\sigma}_z \right) \hat{\Psi}(\mathbf{x}) + \frac{g}{2} \sum_{s,s'} \hat{\psi}_s^\dagger(\mathbf{x}) \hat{\psi}_{s'}^\dagger(\mathbf{x}) \hat{\psi}_{s'}(\mathbf{x}) \hat{\psi}_s(\mathbf{x})$$

$$\text{for } \Psi^\dagger(\mathbf{x}) = \left\{ \psi_\uparrow^\dagger(\mathbf{x}), \psi_\downarrow^\dagger(\mathbf{x}) \right\}$$







Refs.

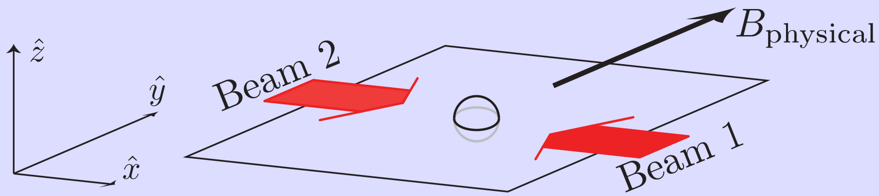
Cold atom experiments: Y.-J. Lin et al Nature (2011), R. A. Williams Science (accepted, 2011)

Theory: C. Zhang et al, PRL (2008), J. D. Sau et al, PRL (2010), J. Alicea et al, N. Physics (2011)

Spin orbit coupling with ultracold atoms

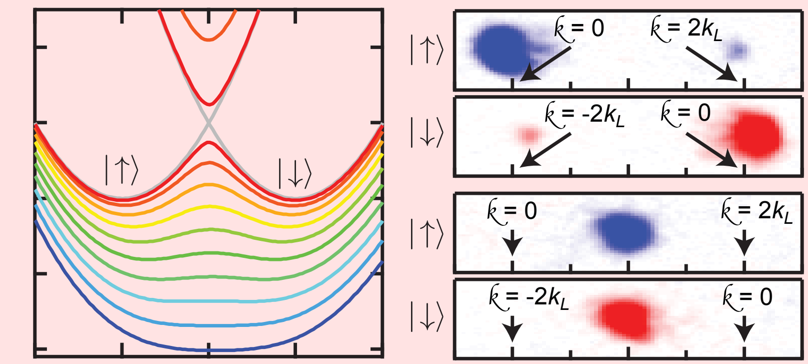
Raman dressed states

Concept



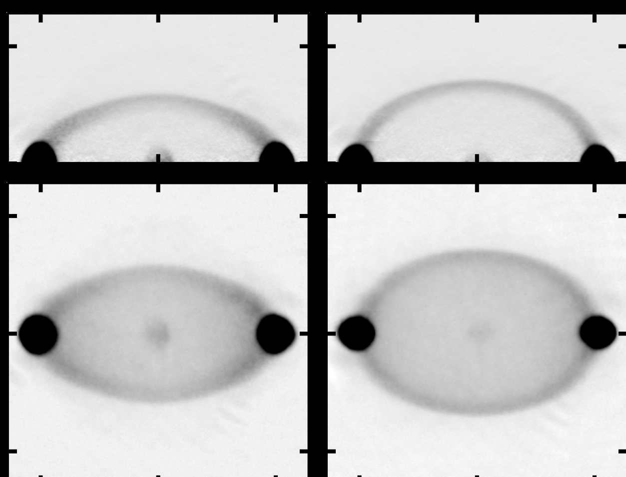
Spin orbit coupling, engineered

$$\hat{H} = \frac{\hbar^2\hat{\mathbf{k}}^2}{2m}\check{1} - \left[\mathbf{B} + \mathbf{B}_{\mathrm{SO}}\left(\hat{\mathbf{k}}\right)\right]\cdot\boldsymbol{\mu} = \frac{\hbar^2\hat{\mathbf{k}}^2}{2m}\check{1} + \frac{\Omega}{2}\check{\sigma}_z + \frac{\delta}{2}\check{\sigma}_y + 2\alpha\hat{k}_x\check{\sigma}_y$$

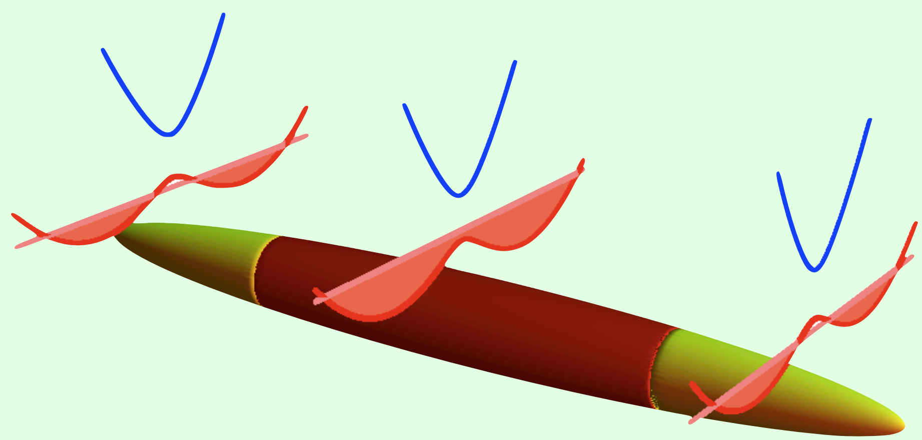


Interactions, rearranged

effective d- and g- wave interactions in bosons



Fermions, the future

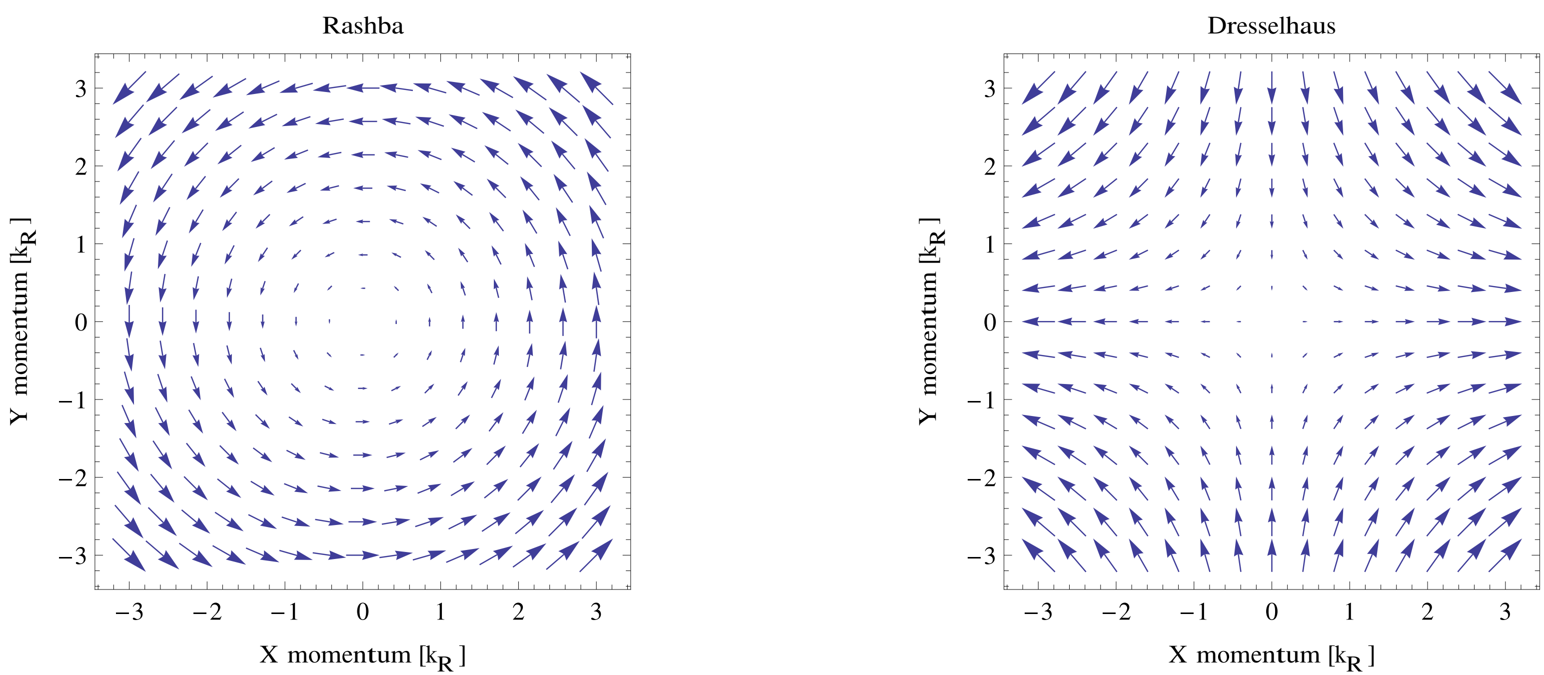


Spin orbit coupling: what do we desire?

Spin-orbit coupling

$$H = \frac{\hbar^2 \mathbf{k}^2}{2m}\check{1} + \frac{\delta}{2}\check{\sigma}_z + \alpha\left(k_x\check{\sigma}_y - k_y\check{\sigma}_x\right) + \beta\left(k_x\check{\sigma}_x - k_y\check{\sigma}_y\right).$$

α gives the strength of the Rashba coupling; β yields the linear Dresselhaus coupling; and δ produces a Zeeman splitting

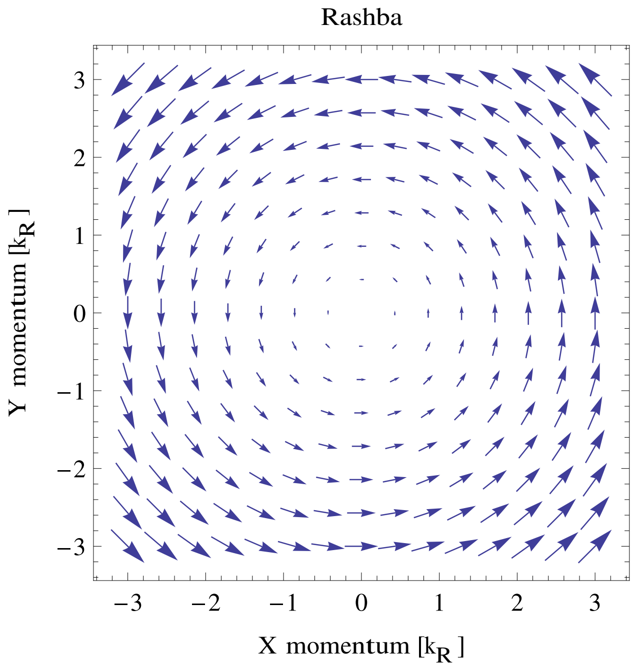


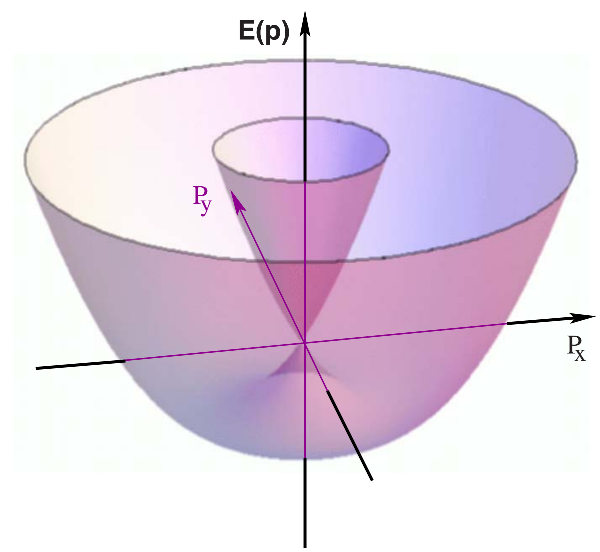
Spin-orbit coupling: Rashba

Spin-orbit coupling

$$H = \frac{\hbar^2 \mathbf{k}^2}{2m}\check{1} + \frac{\delta}{2}\check{\sigma}_z + \alpha\left(k_x\check{\sigma}_y - k_y\check{\sigma}_x\right) + \beta\left(k_x\check{\sigma}_x - k_y\check{\sigma}_y\right).$$

Pure Rashba: $\beta = 0$





Cold atom Refs.

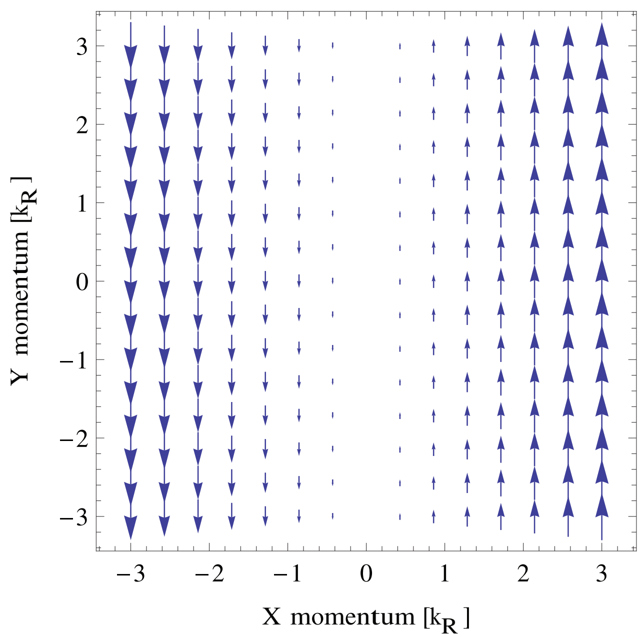
T. D. Stanescu and B. Anderson and V. Galitski PRA (2008)

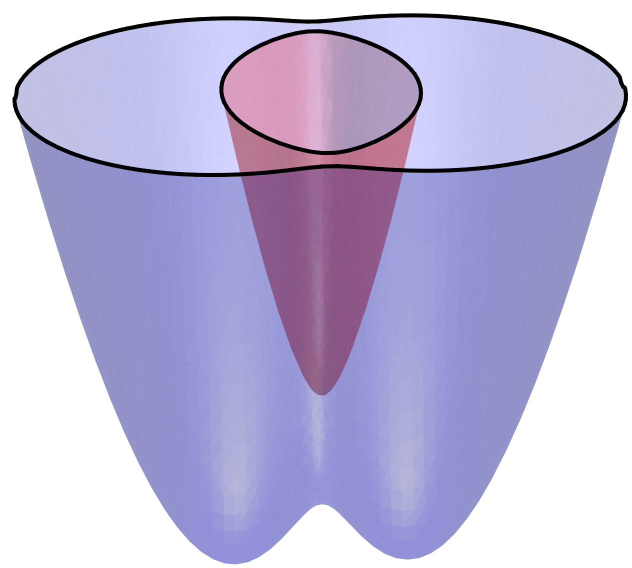
Spin-orbit coupling: Rashba = Dresselhaus

<u>Spin-orbit coupling</u>

$$\hat{H} = \frac{\hbar^2 \hat{\mathbf{k}}^2}{2m}\check{1} + 2\alpha k_x \check{\sigma}_y + \frac{\Omega}{2}\check{\sigma}_z$$

Equal Rashba and Dresselhaus: $\alpha = \beta$





<u>GaAs Refs.</u>

J. D. Koralek et al, Nature (2009); C. H. L. Quay et al, Nat. Phys. (2010)

Non-abelian gauge fields and Spin-Orbit coupling

Spin-orbit coupling

$$H = \frac{\hbar^2 \mathbf{k}^2}{2m}\check{1} + \frac{\delta}{2}\check{\sigma}_z + \alpha\left(k_x\check{\sigma}_y - k_y\check{\sigma}_x\right) + \beta\left(k_x\check{\sigma}_x - k_y\check{\sigma}_y\right).$$

Uniform Non-abelian gauge field

$$\check{H} = \frac{\hbar^2}{2m}\left[\left(k_x\check{1} - \frac{q}{\hbar}\check{A}_x\right)^2 + \left(k_y\check{1} - \frac{q}{\hbar}\check{A}_y\right)^2\right] + \frac{\delta}{2}\check{\sigma}_z + E_0\check{1}$$

Spin-orbit coupling *is* a (sometimes) non-abelian gauge field!

$$\check{H} = \frac{\hbar^2}{2m}\left\{\left[(k_x\check{1} + \frac{1}{2}\left(\alpha\check{\sigma}_y + \beta\check{\sigma}_x\right)\right]^2 + \left[(k_y\check{1} - \frac{1}{2}\left(\alpha\check{\sigma}_x + \beta\check{\sigma}_y\right)\right]^2\right\} + \frac{\delta}{2}\check{\sigma}_z + E_0\check{1}$$

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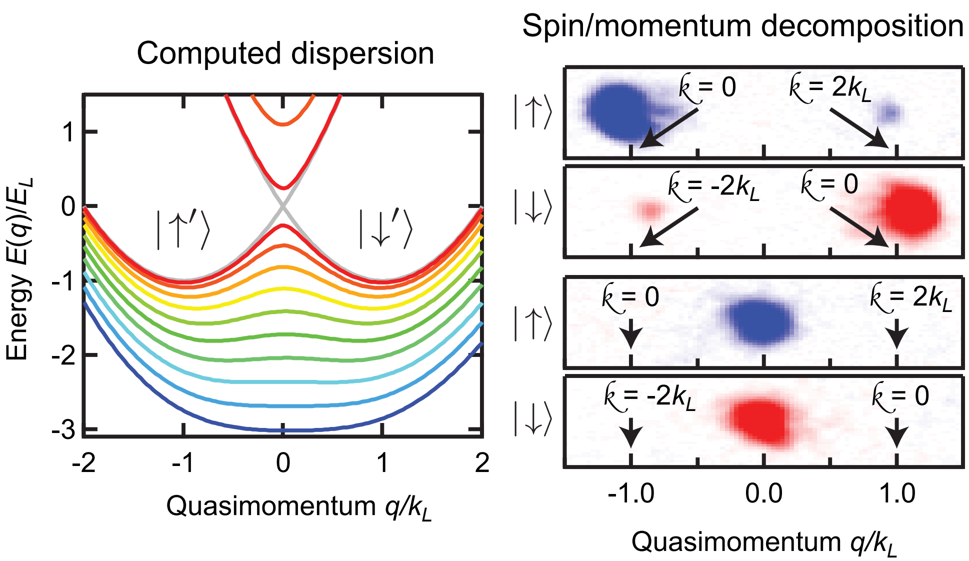
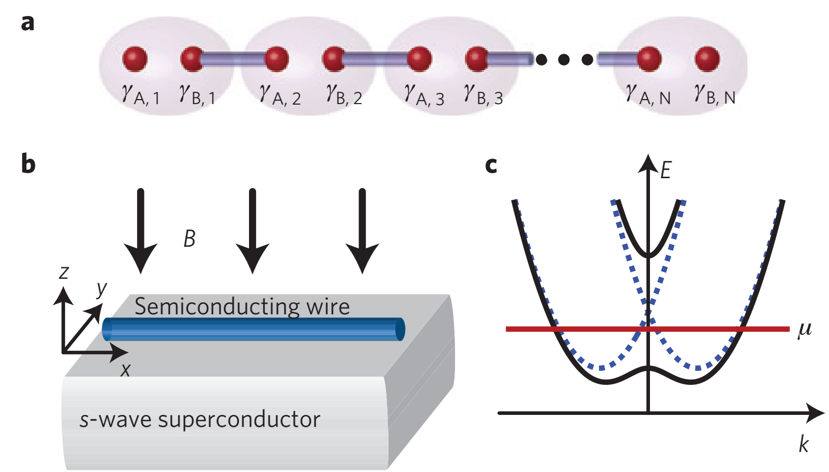
$$\text{for } \Psi^\dagger(\mathbf{x}) = \left\{\psi_\uparrow^\dagger(\mathbf{x}), \psi_\downarrow^\dagger(\mathbf{x})\right\}$$





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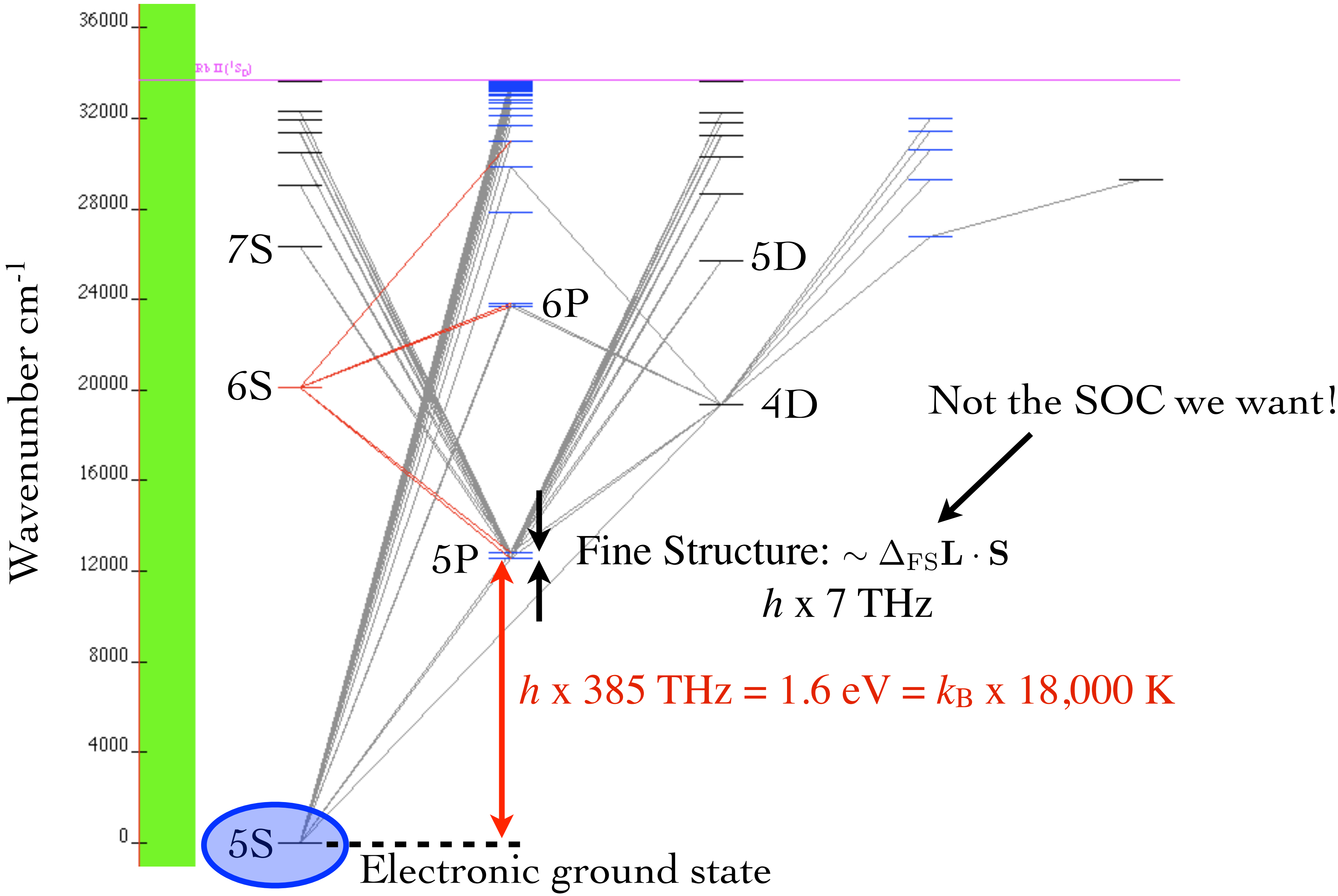
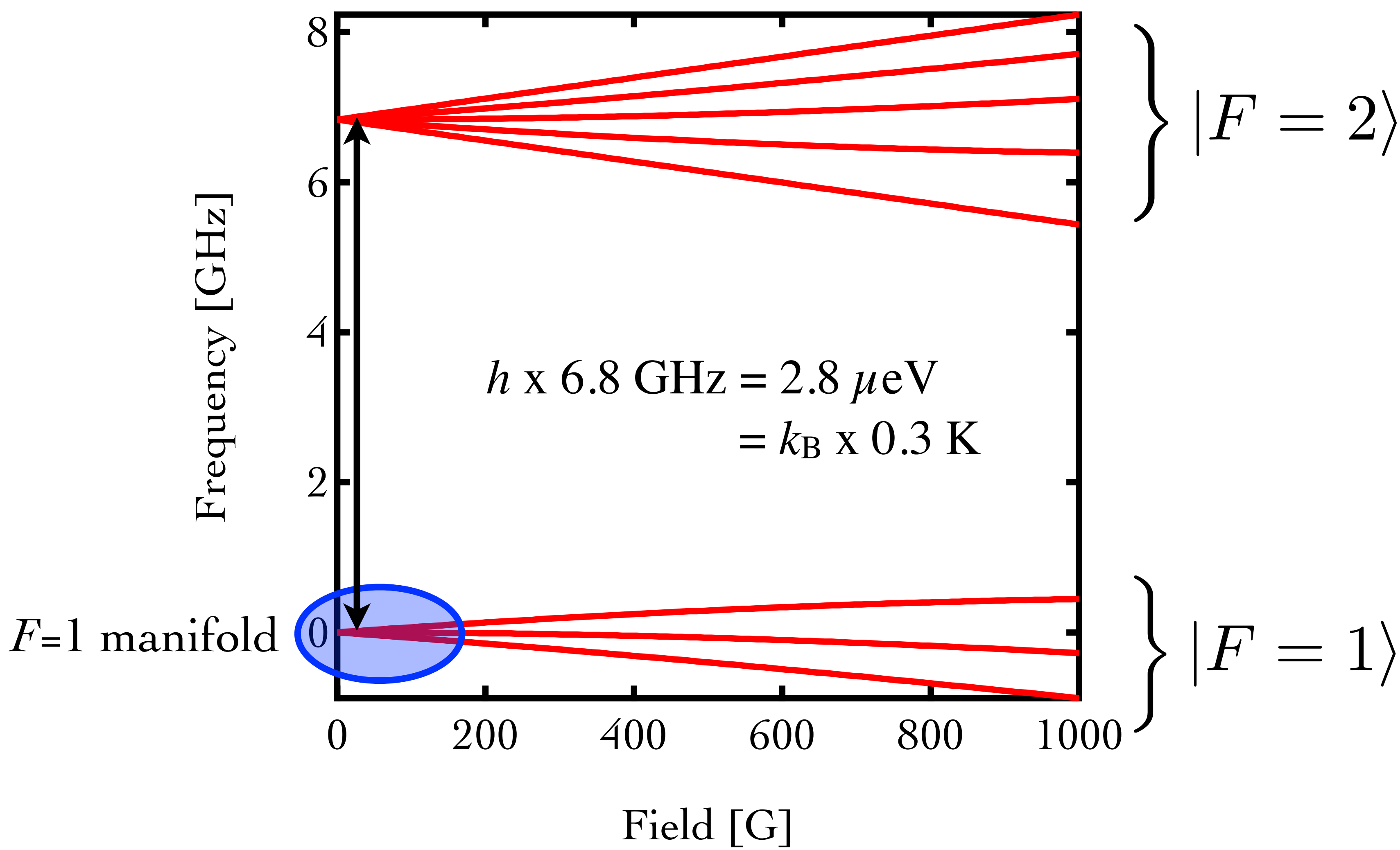
Rubidium 87: “The GaAs of atoms”



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

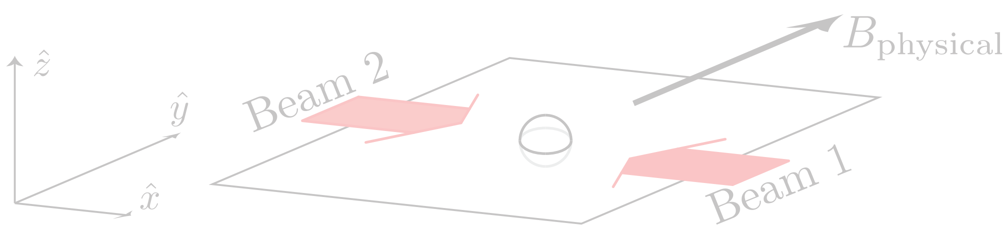


Engineered spin-orbit coupling

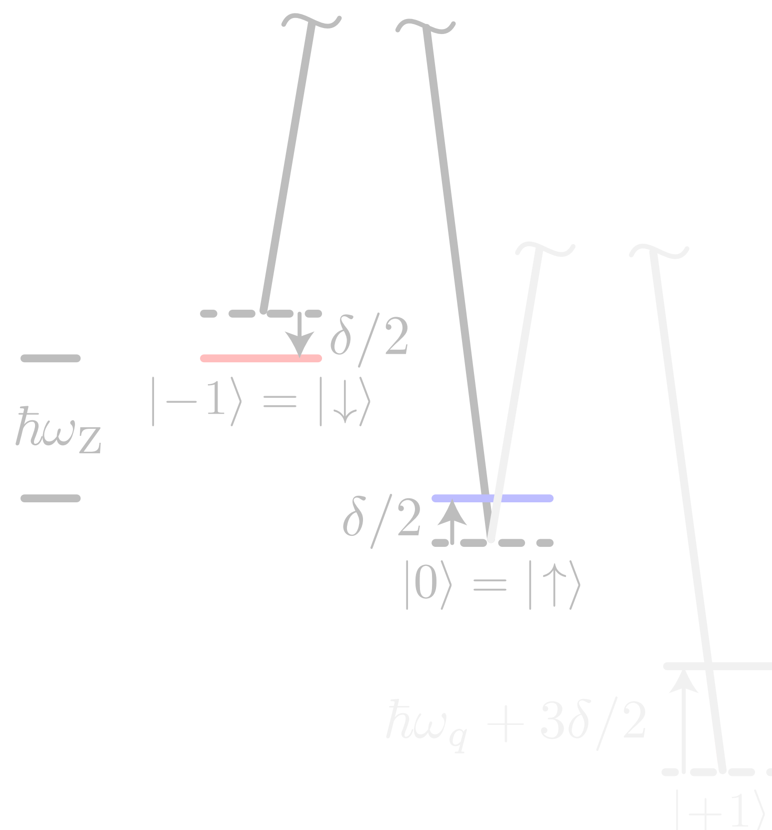
Momentum representation

$$H = \sum_k \left\{ \begin{pmatrix} \langle k-1,\uparrow | & \langle k+1,\downarrow | \end{pmatrix} \begin{pmatrix} (\tilde{k}_x - 1)^2 + \delta/2 & \Omega_R/2 \\ \Omega_R/2 & (\tilde{k}_x + 1)^2 - \delta/2 \end{pmatrix} \begin{pmatrix} |k-1,\uparrow\rangle \\ |k+1,\downarrow\rangle \end{pmatrix} \right\}$$

Geometry



Levels



Natural dimensions

Length: $\lambda \approx 790$ nm

Momentum: $\hbar k_r = 2\pi/\lambda$

Energy: $E_r = \dfrac{\hbar^2 k_r^2}{2m} \approx h \times 3.4\ \text{kHz} = 14\ \text{peV}$

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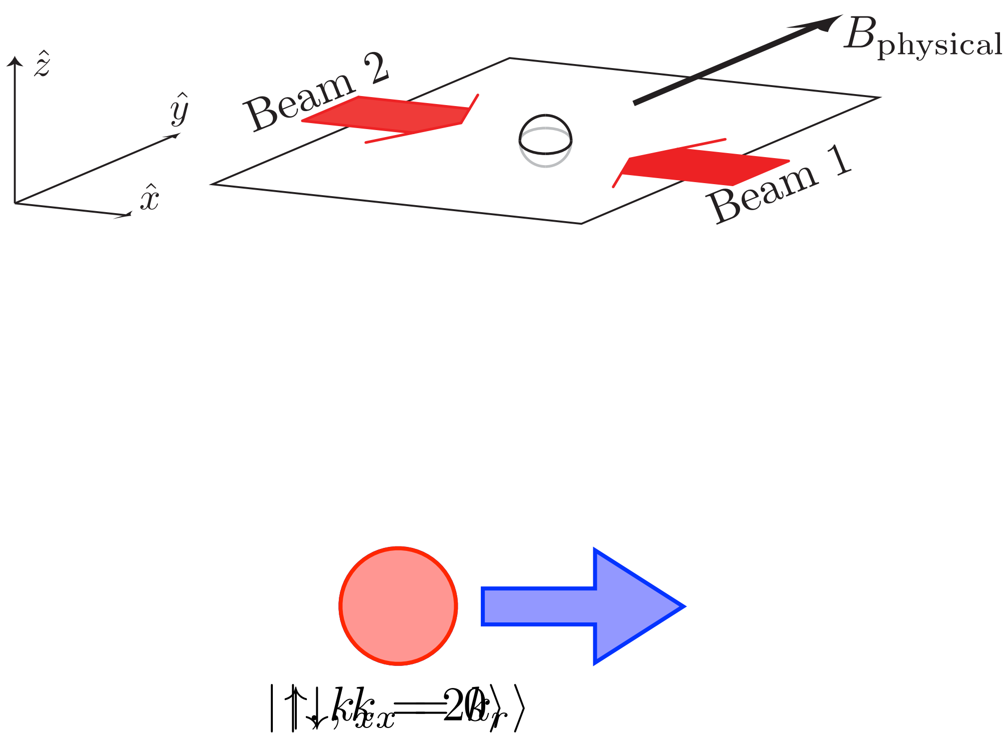
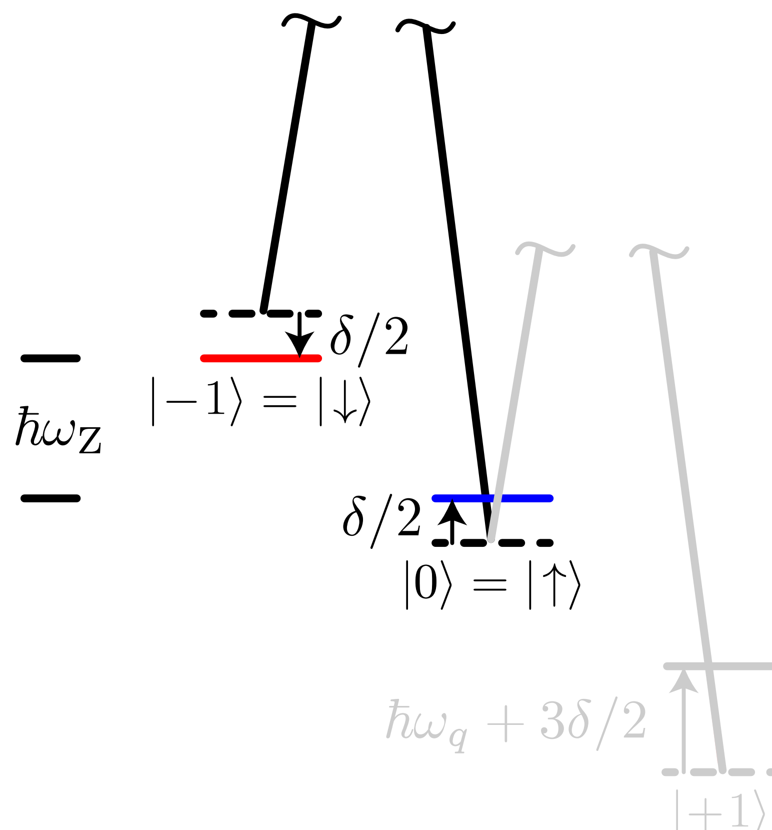
Geometry



Levels

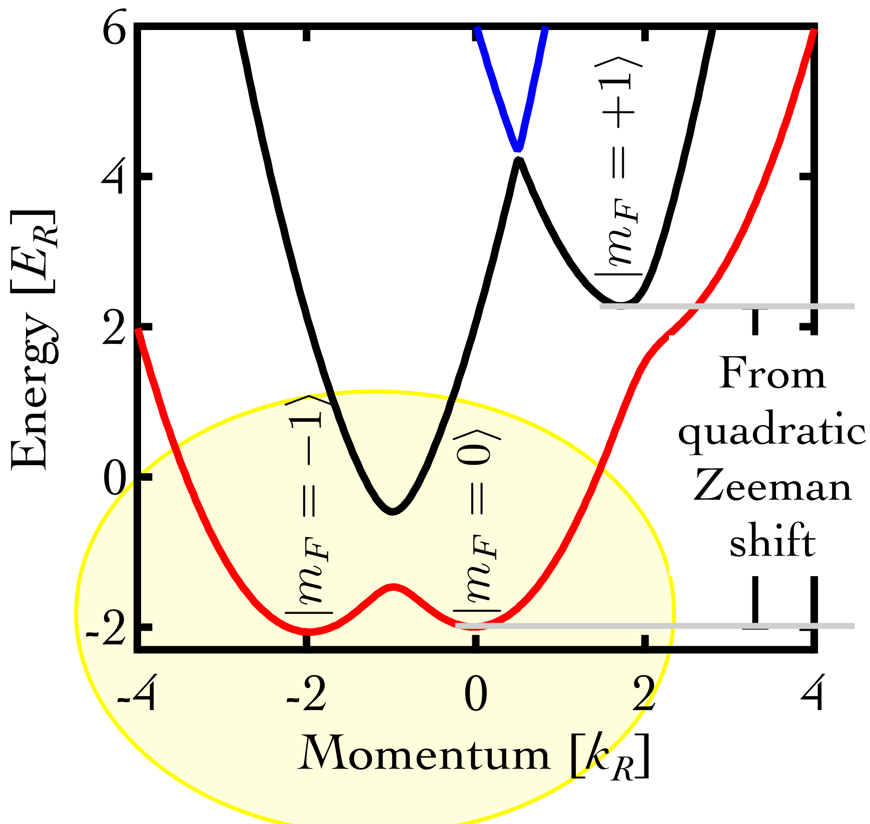


Spin orbit coupling: origin

Momentum representation

$$H = \sum_k \left\{ \left(\langle k-1,\uparrow| \quad \langle k+1,\downarrow| \right) \begin{pmatrix} (\tilde{k_x}-1)^2+\delta/2 & \Omega_R/2 \\ \Omega_R/2 & (\tilde{k_x}+1)^2-\delta/2 \end{pmatrix} \begin{pmatrix} |k-1,\uparrow\rangle \\ |k+1,\downarrow\rangle \end{pmatrix} \right\}$$

Spin 1/2 bosons????



Transform to

$$\hat{H} = \frac{\hbar^2\hat{\mathbf{k}}^2}{2m}\check{1} + \left(\frac{\delta}{2} + \frac{\hbar^2 k_R}{m}\hat{k}_x\right)\check{\sigma}_y + \frac{\Omega}{2}\check{\sigma}_z + \Delta E\check{1}$$
$$= \frac{\hbar^2}{2m}\left[\left(\hat{k}_x\check{1} + k_R\check{\sigma}_y\right)^2 + \left(\hat{k}_y\check{1} - 0\right)^2\right] + \frac{\delta}{2}\check{\sigma}_y + \frac{\Omega}{2}\check{\sigma}_z$$

NOTICE

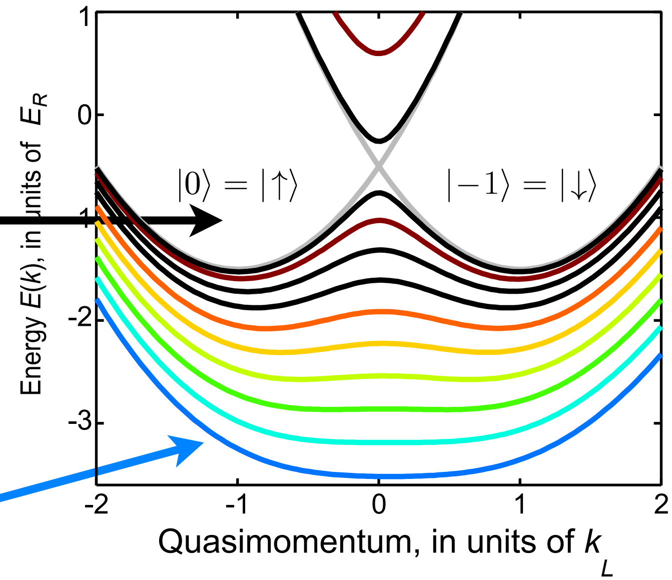
Written as a "2x2" vector potential, this S-O coupling is Abelian, $A_y = 0$: so $[A_x, A_y]=0$.

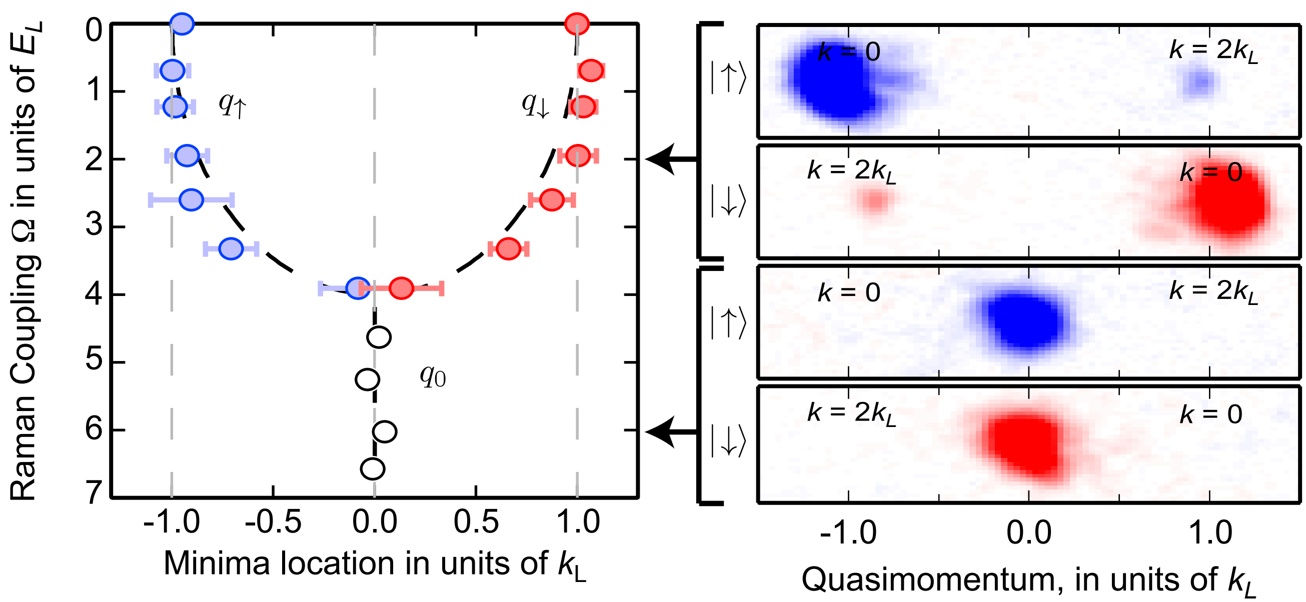
However, the Hamiltonian *is* non-trivial owing to the Zeeman field along z.

Typical data

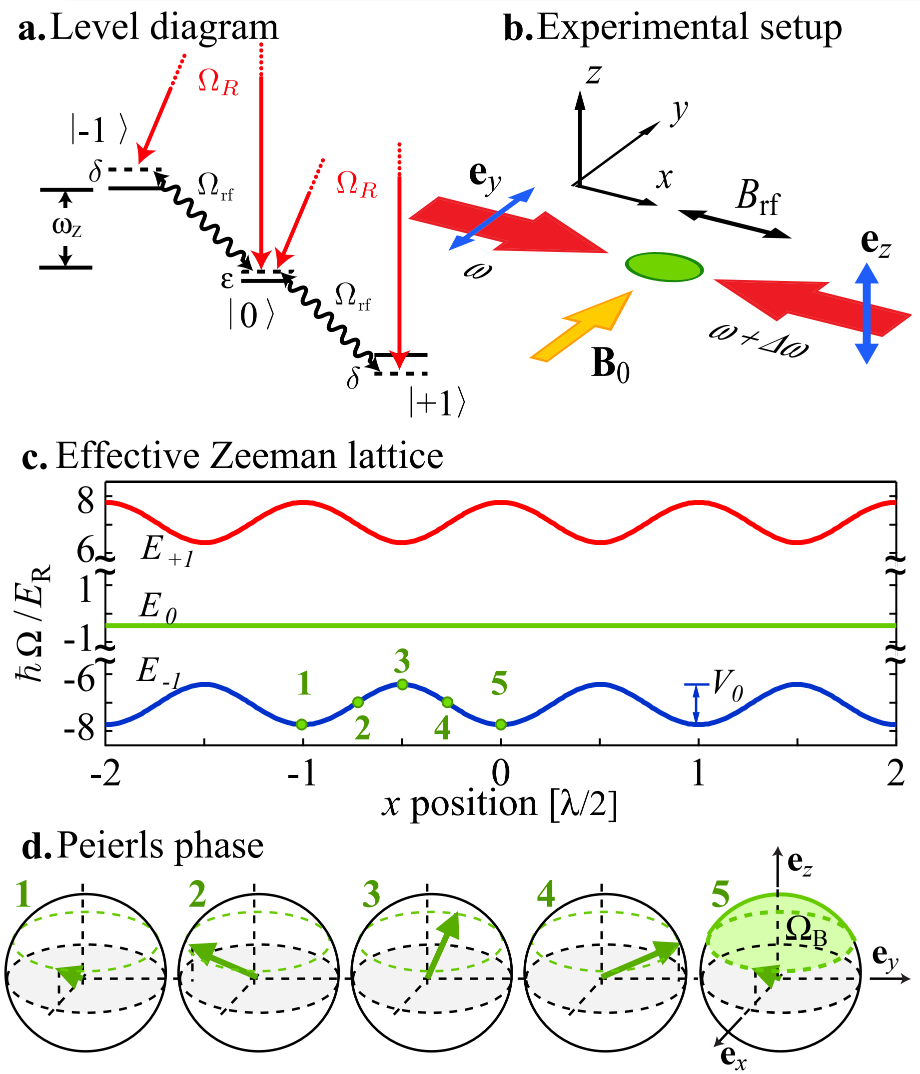
Double Well
"Spin-orbit limit"

Single minimum
"vector potential limit"



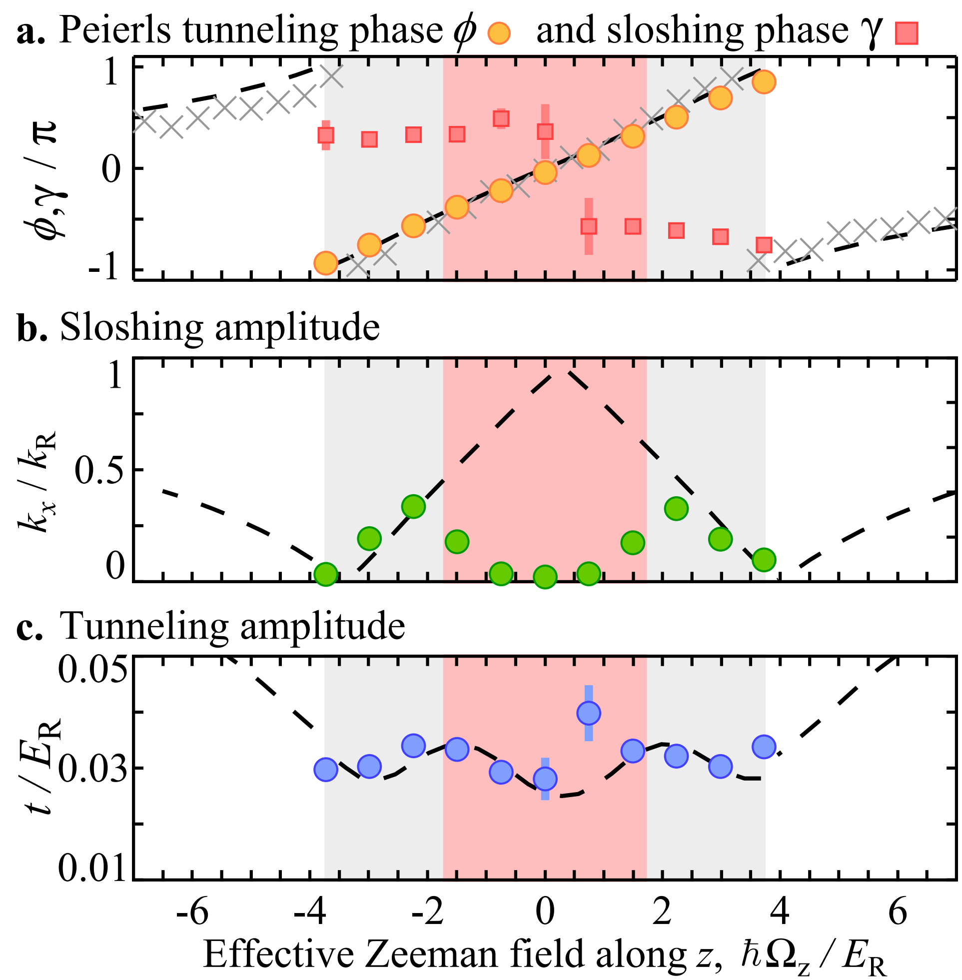


Peierls lattice



$$H(x) = \mathbf{\Omega} \cdot \mathbf{F} + H_Q$$

$$\mathbf{\Omega} = \{\Omega_{rf} + \Omega_R \cos(2k_R x), -\Omega_R \sin(2k_R x), \sqrt{2}\delta\}$$



$$H = \sum_j [t \exp(i\phi) \hat{a}^\dagger_{j+1} \hat{a}_j + \text{h.c.}]$$

Refs.

K. Jimenez-Garcia *et al* (in preparation)

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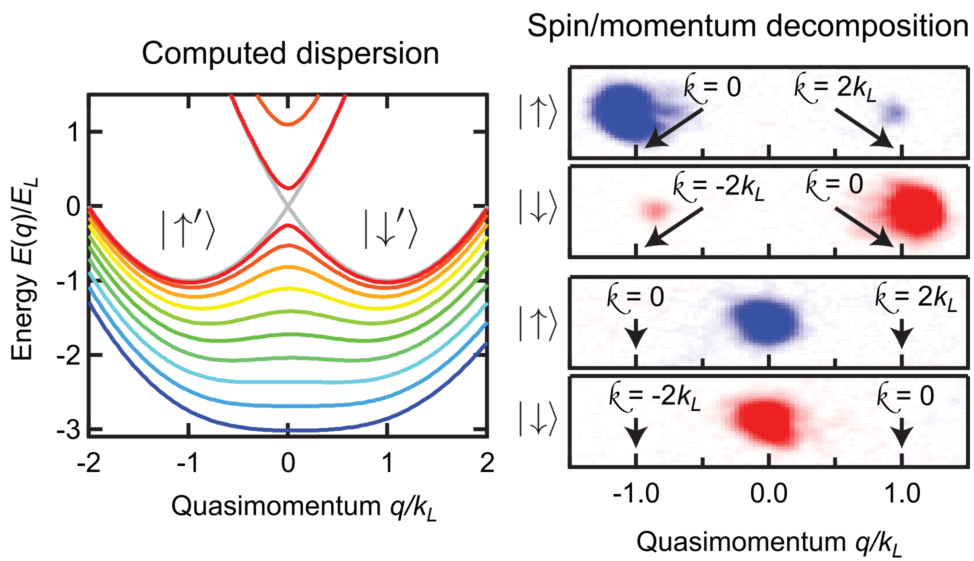
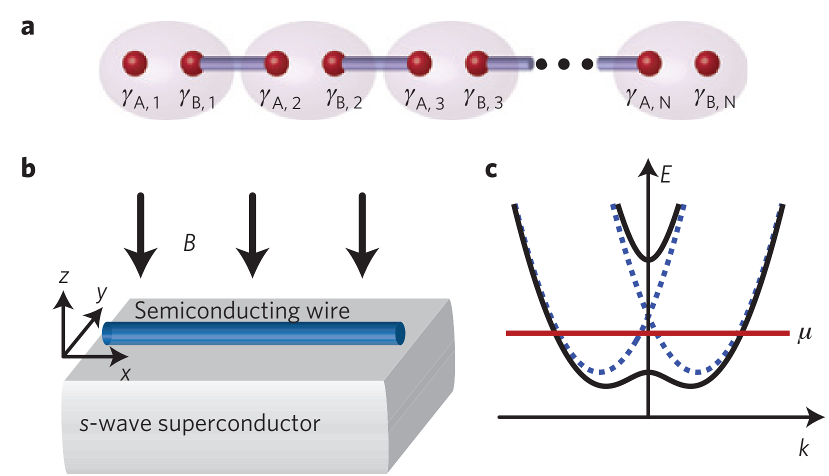
$$\text{for } \Psi^\dagger(\mathbf{x}) = \left\{ \psi_\uparrow^\dagger(\mathbf{x}), \psi_\downarrow^\dagger(\mathbf{x}) \right\}$$





Refs.

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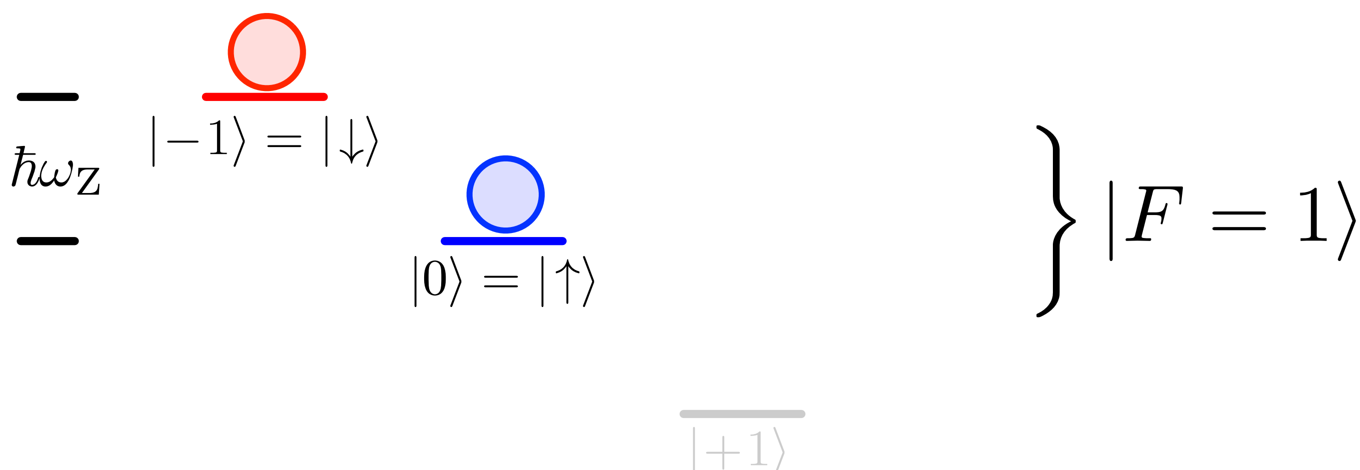
Theory: C. Zhang et al, PRL (2008), **J. D. Sau et al, PRL (2010), J. Alicea et al, N. Physics (2011)**

Effective Hamiltonian for dressed spins

Two pseudo-spin contact interactions

$$\hat{H}_{\text{int}} = \frac{1}{2}\int d^3r : \left[\left(c_0 + \frac{c_2}{2}\right)(\hat{\rho}_\downarrow + \hat{\rho}_\uparrow)^2 + \frac{c_2}{2}\left(\hat{\rho}_\downarrow^2 - \hat{\rho}_\uparrow^2\right) + c_2 \hat{\rho}_\downarrow \hat{\rho}_\uparrow\right] :$$



Effective Hamiltonian for dressed spins

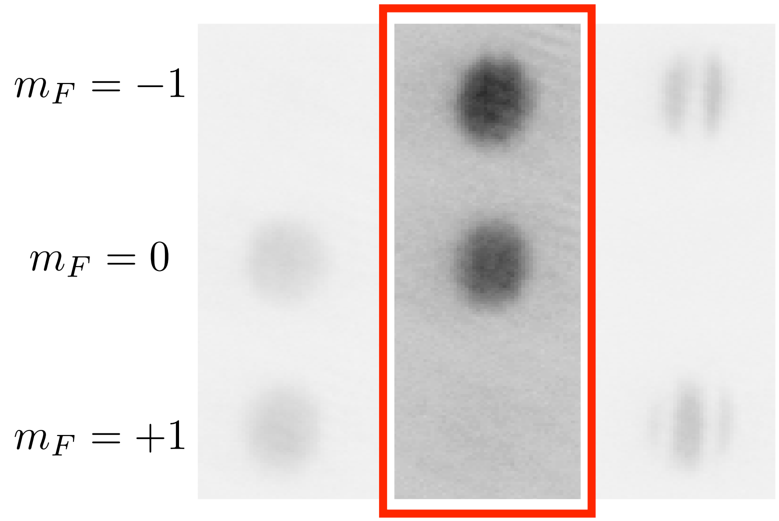
Two pseudo-spin contact interactions

$$\hat{H}_{\mathrm{int}} = \frac{1}{2}\int d^3r : \left[\left(c_0 + \frac{c_2}{2}\right)\left(\hat{\rho}_\downarrow + \hat{\rho}_\uparrow\right)^2 + \frac{c_2}{2}\left(\hat{\rho}_\downarrow^2 - \hat{\rho}_\uparrow^2\right) + c_2 \hat{\rho}_\downarrow \hat{\rho}_\uparrow\right] :$$

$$c_0 = 7.8 \times 10^{-12}\ \mathrm{Hz} \cdot \mathrm{cm}^3$$

$$c_2 = -3.6 \times 10^{-14}\ \mathrm{Hz} \cdot \mathrm{cm}^3$$

m_F = -1, m_F = 0 mixture: miscible for ^{87}Rb



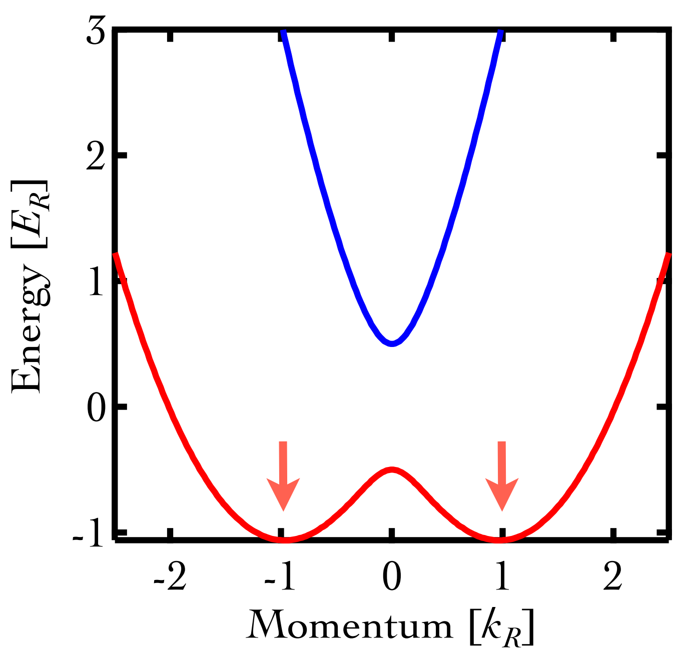
Ph.D. Thesis of Ming-Shien Chang
(Chapman group)

Effective Hamiltonian for dressed spins

Two pseudo-spin contact interactions

$$\hat{H}_{\rm int} = \frac{1}{2}\int d^3r : \left[\left(c_0 + \frac{c_2}{2}\right)\left(\hat{\rho}_\downarrow + \hat{\rho}_\uparrow\right)^2 + \frac{c_2}{2}\left(\hat{\rho}_\downarrow^2 - \hat{\rho}_\uparrow^2\right) + c_2\hat{\rho}_\downarrow\hat{\rho}_\uparrow\right] :$$

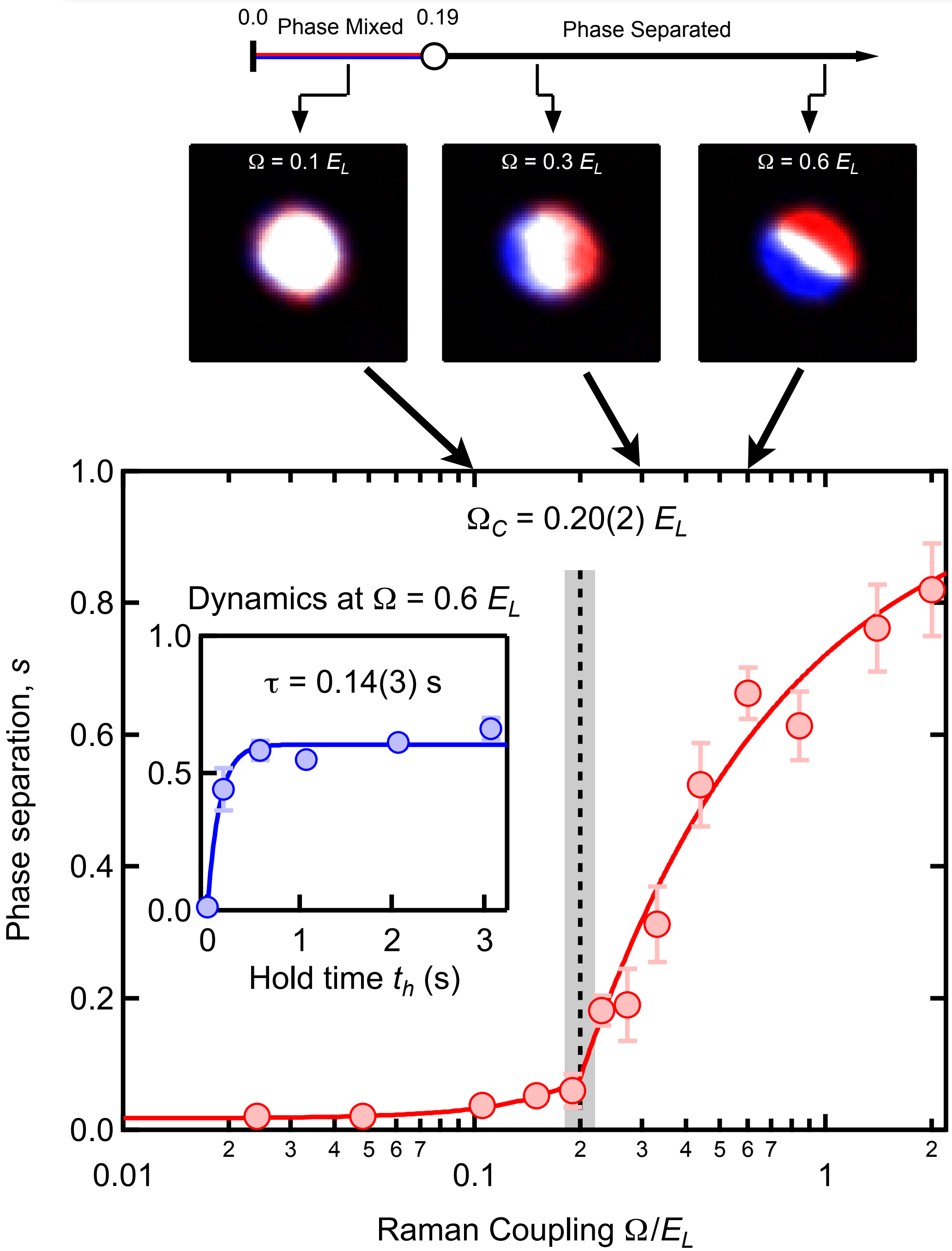
$$\rightarrow \frac{1}{2}\int d^3r : \left[\left(c_0 + \frac{c_2}{2}\right)\left(\hat{\rho}_{\downarrow'} + \hat{\rho}_{\uparrow'}\right)^2 + \frac{c_2}{2}\left(\hat{\rho}_{\downarrow'}^2 - \hat{\rho}_{\uparrow'}^2\right) + \left(c_2 + c'_{\uparrow,\downarrow}\right)\hat{\rho}_{\downarrow'}\hat{\rho}_{\uparrow'}\right] :$$



Spin-orbit term

$$c'_{\uparrow,\downarrow} \approx c_0 \frac{\Omega_R^2}{8}$$

Transition from miscible to immiscible



<u>A quantum phase transition</u>

Previously unexpected

<u>Our MFT prediction</u>

Phase separation at $\Omega = 0.19\ E_L$

<u>Ref.</u>

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

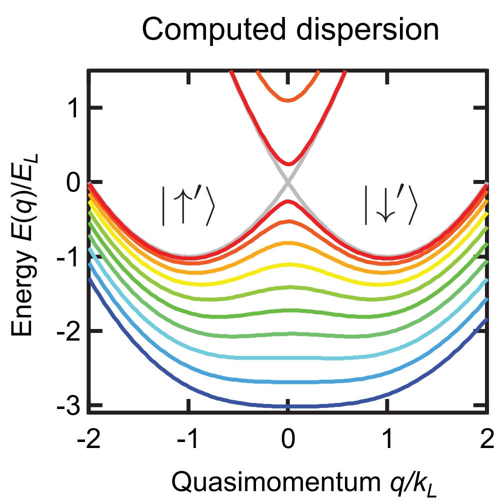
Spin orbit coupling of pseudo spin-1/2 atoms

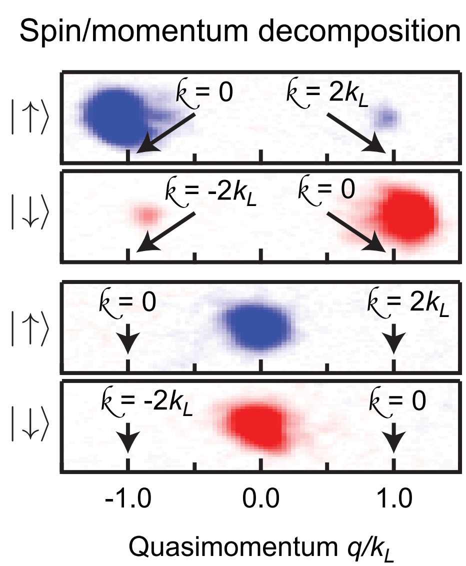
Current experiments with Bosons

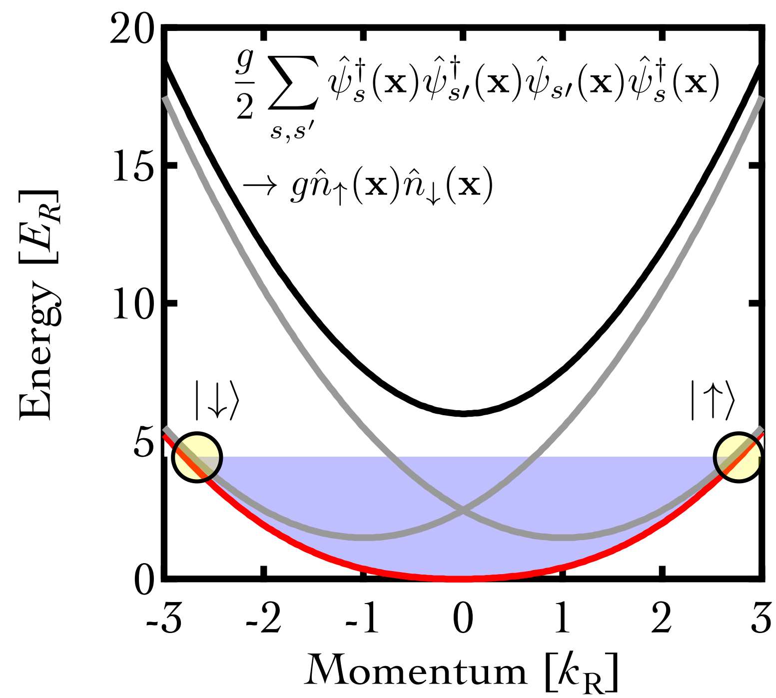
Spin orbit coupling for pseudo spin 1/2 **Bosons** (testbed platform)

$$\hat{\mathcal{H}} = \hat{\Psi}^\dagger(\mathbf{x})\left(\frac{\hbar^2\hat{\mathbf{k}}^2}{2m}\check{1} + \frac{\hbar^2 k_R}{m}\hat{k}_x\check{\sigma}_y + \frac{\Omega}{2}\check{\sigma}_z\right)\hat{\Psi}(\mathbf{x}) + \frac{g}{2}\sum_{s,s'}\hat{\psi}_s^\dagger(\mathbf{x})\hat{\psi}_{s'}^\dagger(\mathbf{x})\hat{\psi}_{s'}(\mathbf{x})\hat{\psi}_s(\mathbf{x})$$

$$\text{for } \Psi^\dagger(\mathbf{x}) = \left\{\psi_\uparrow^\dagger(\mathbf{x}), \psi_\downarrow^\dagger(\mathbf{x})\right\}$$







Refs.

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Theory: **C. Zhang et al, PRL (2008)**, J. D. Sau et al, PRL (2010), J. Alicea et al, N. Physics (2011)

Modified interactions: optical screening

Interacting fermions in a **single component** gas
Effective p-wave interactions!!

Test with Bosons, look for d- and g- wave interactions

$$\hat{\mathcal{H}} = \hat{\Psi}^\dagger(\mathbf{x}) \left(\frac{\hbar^2 \hat{\mathbf{k}}^2}{2m} \check{1} + \frac{\hbar^2 k_R}{m} \hat{k}_x \check{\sigma}_y + \frac{\Omega}{2} \check{\sigma}_z \right) \hat{\Psi}(\mathbf{x}) + \frac{g}{2} \sum_{s,s'} \hat{\psi}_s^\dagger(\mathbf{x}) \hat{\psi}_{s'}^\dagger(\mathbf{x}) \hat{\psi}_{s'}(\mathbf{x}) \hat{\psi}_s(\mathbf{x})$$

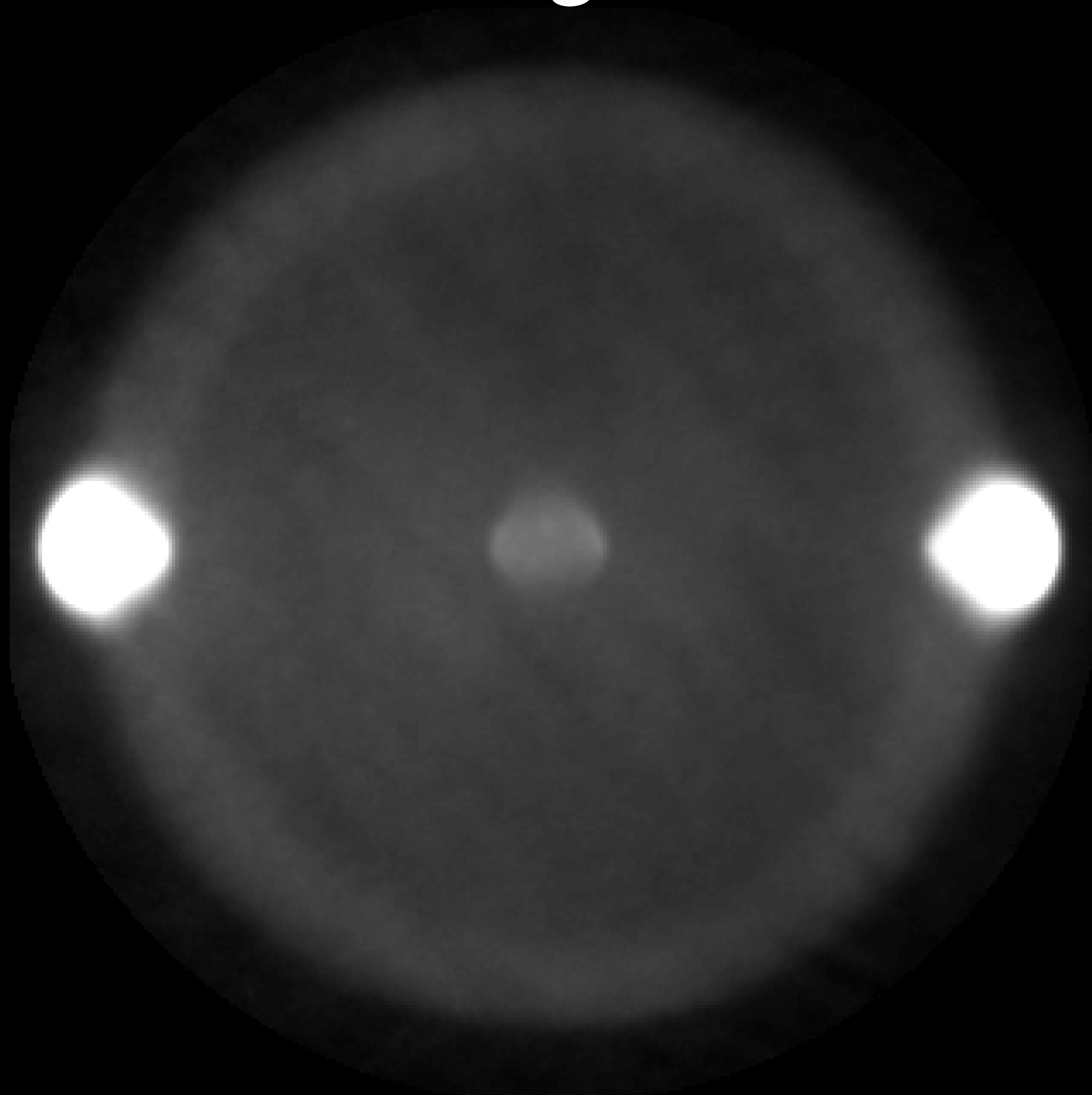
A dielectric function

$$V_{\text{eff}} = g \boxed{\sum_{\sigma_1,\sigma_2} U_{-,\sigma_1}(\mathbf{k}_1) U^\dagger_{\sigma_1,-}(\mathbf{k}_3) U_{-,\sigma_2}(\mathbf{k}_2) U^\dagger_{\sigma_2,-}(\mathbf{k}_4)}$$

$$= V(\mathbf{k}_1 - \mathbf{k}_3)\chi(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3, \mathbf{k}_4)$$

$$V_{\text{eff}}(\mathbf{x}) \approx g \frac{\Omega|x| + 2}{16} \left(e^{-\Omega|x|/2} \right) \delta(y)\delta(z)$$

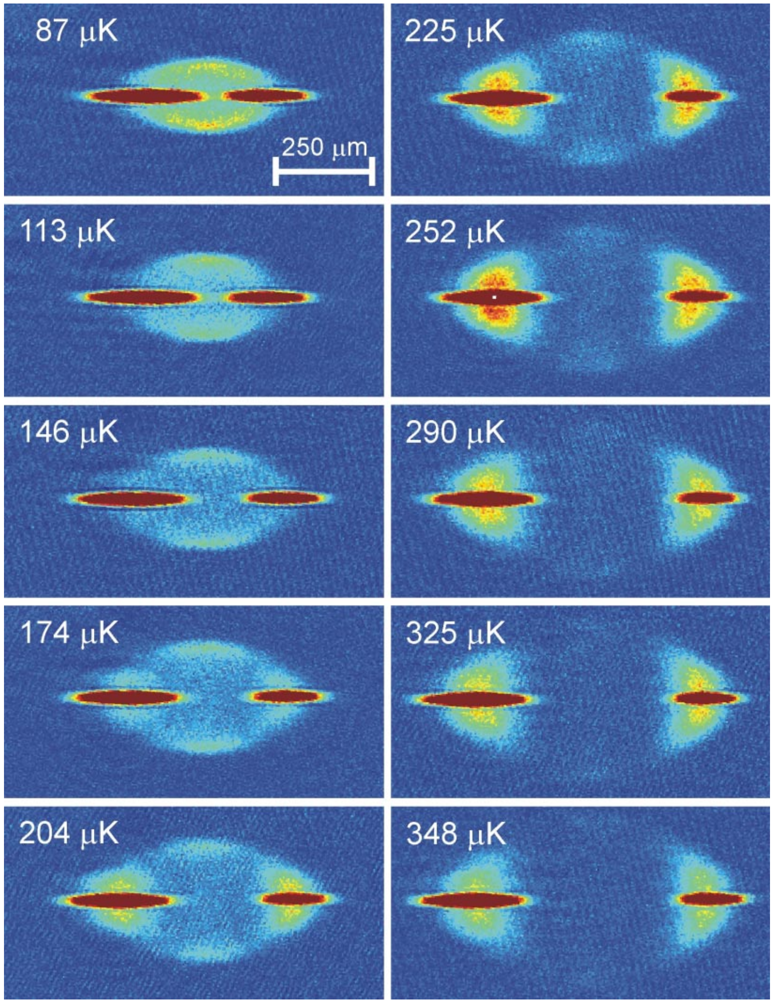
Colliding BEC's



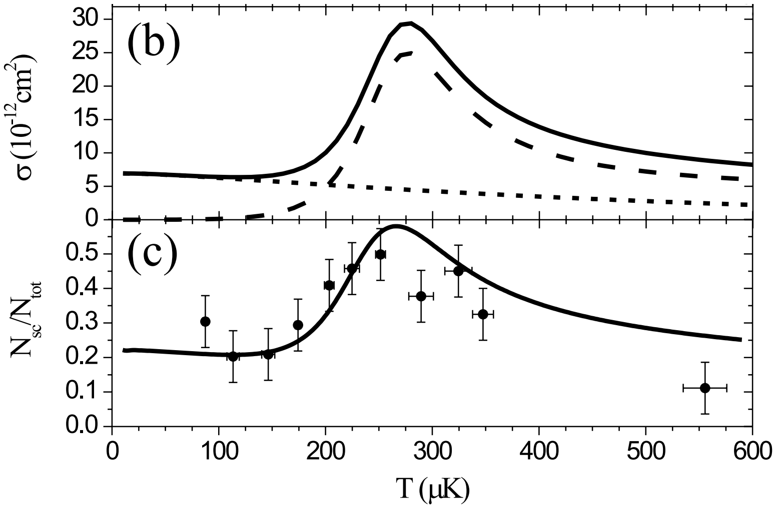
Collisions as a probe of interatomic potentials

Colliding BEC's

All s-wave

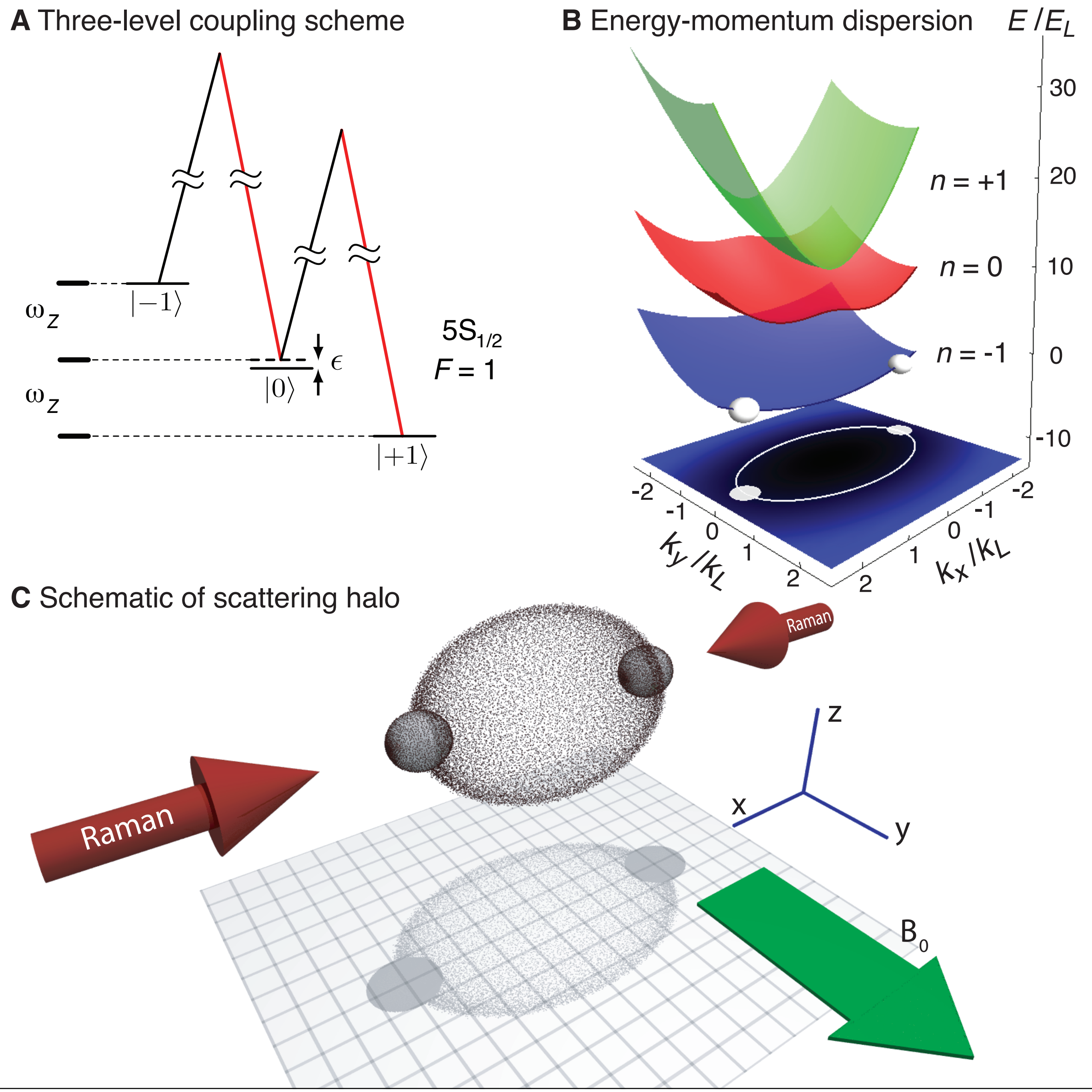


lots of d-wave



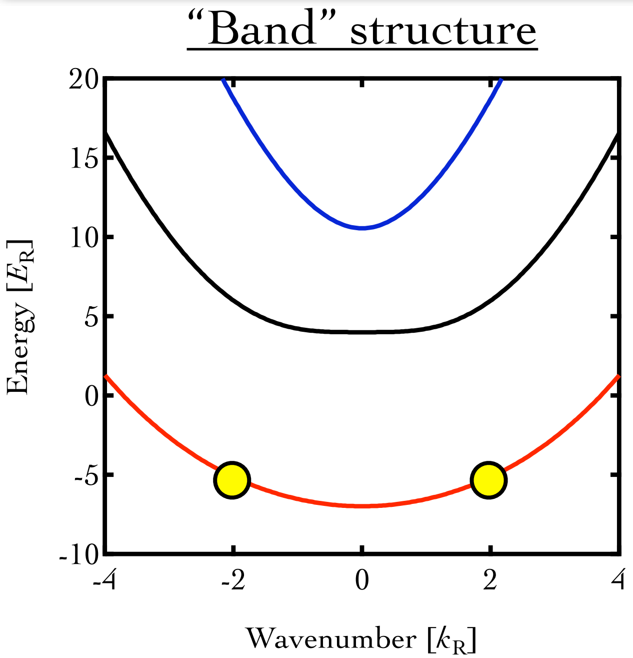
Thomas et al PRL (2004); Ch. Buggle PRL (2004)

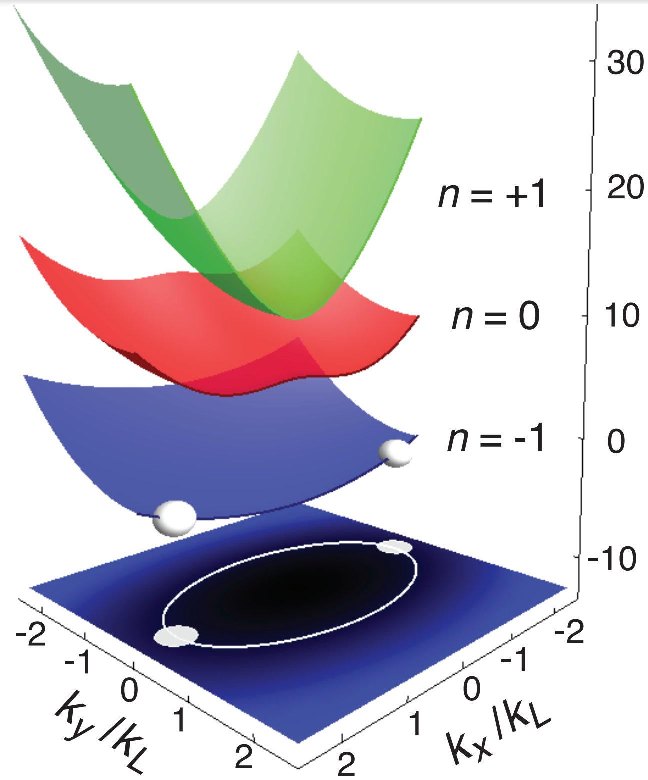
Schematic

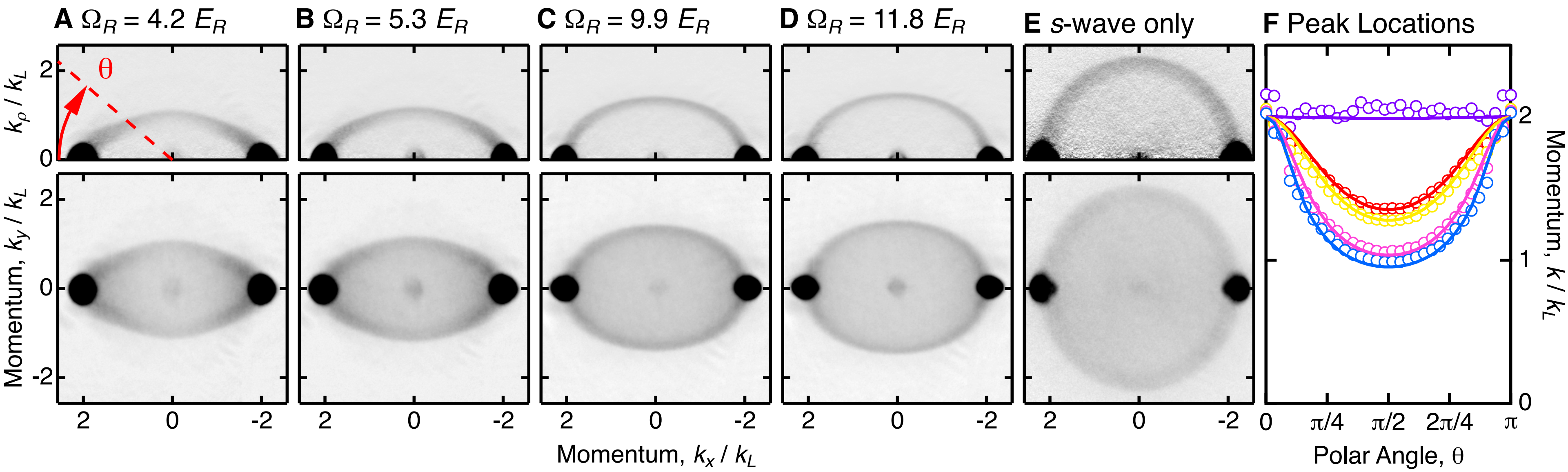


A Three-level coupling scheme
ωz
ωz
|−1⟩
|0⟩
|+1⟩
ϵ
5S1/2
F = 1
B Energy-momentum dispersion
E / EL
30
20
10
0
-10
n = +1
n = 0
n = -1
ky / kL
kx / kL
-2
-1
0
1
2
C Schematic of scattering halo
Raman
Raman
z
x
y
B0

Effective mass effect

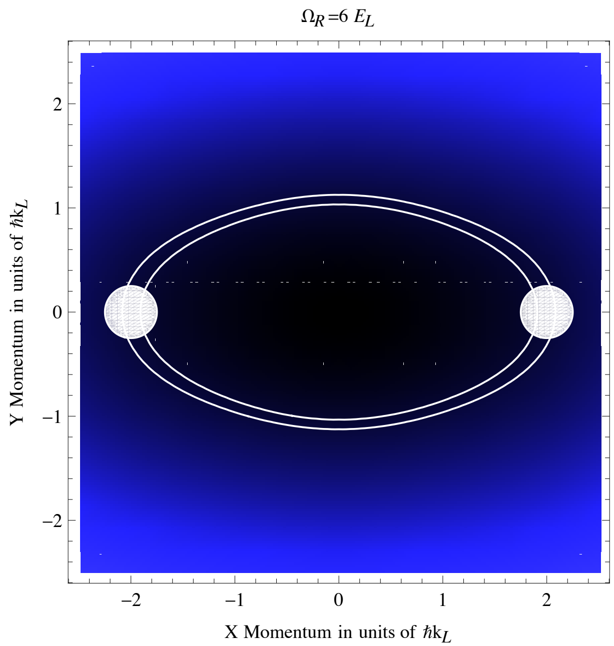


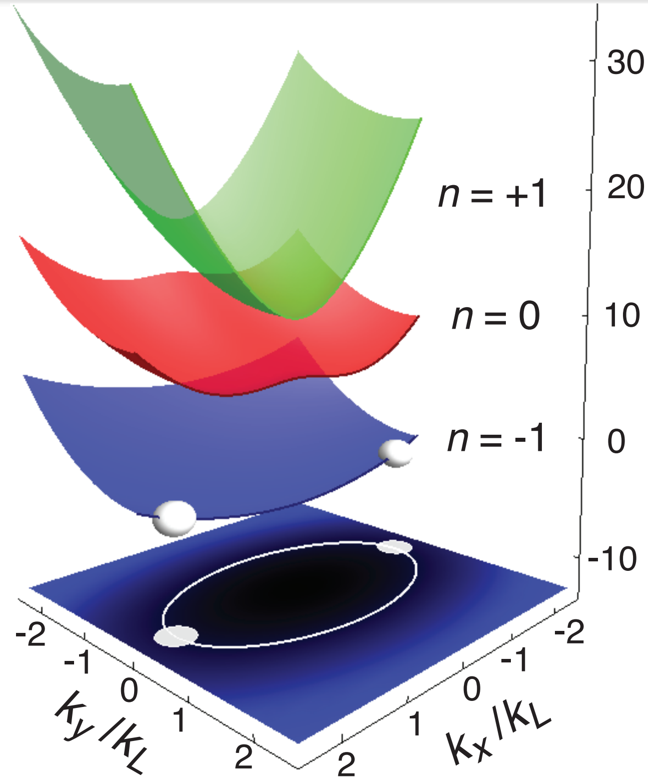


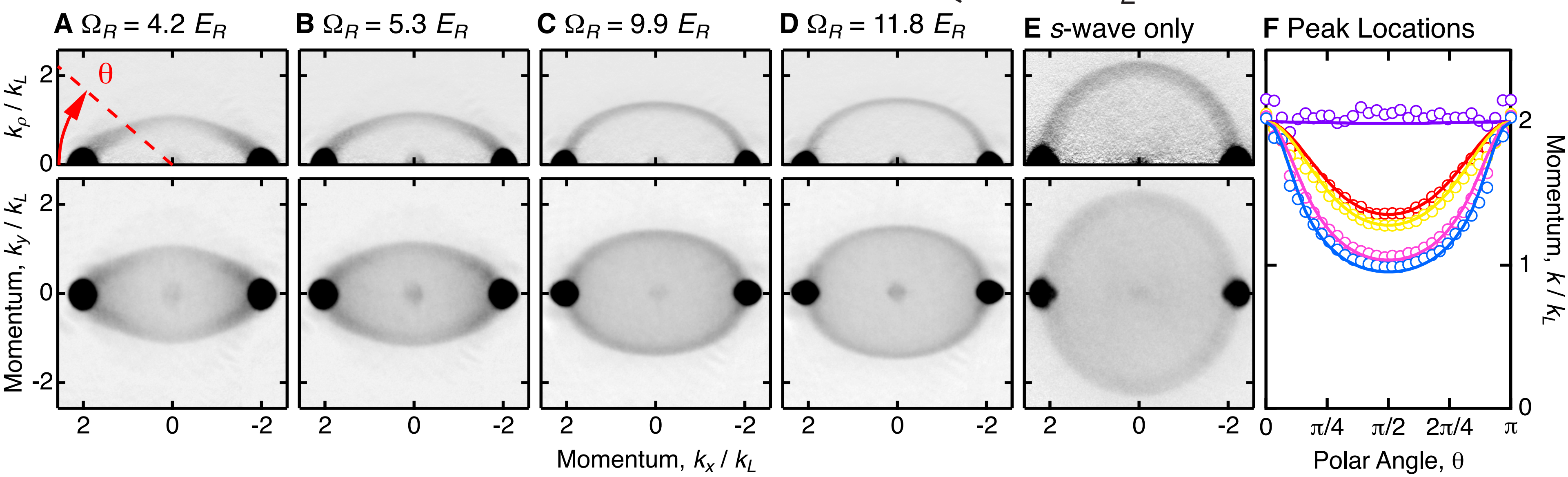


Density of states effect

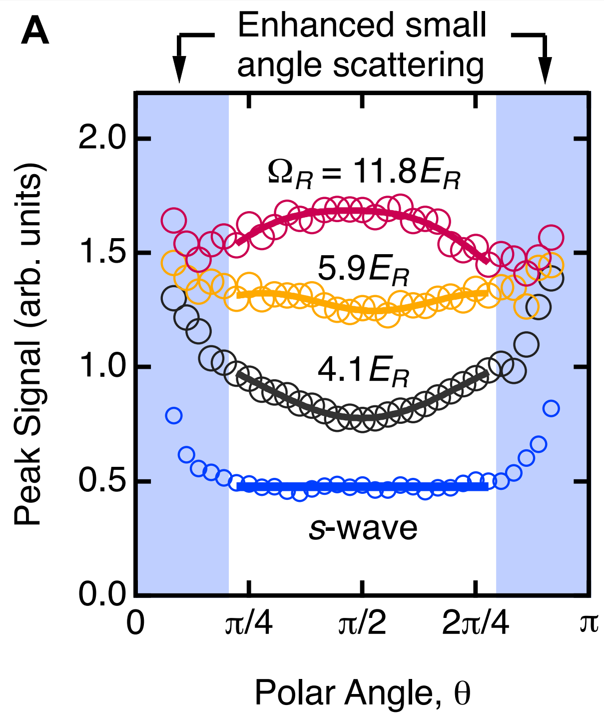
$$g(E)\delta E = N(E+\delta E) - N(E)$$







Modified collisions

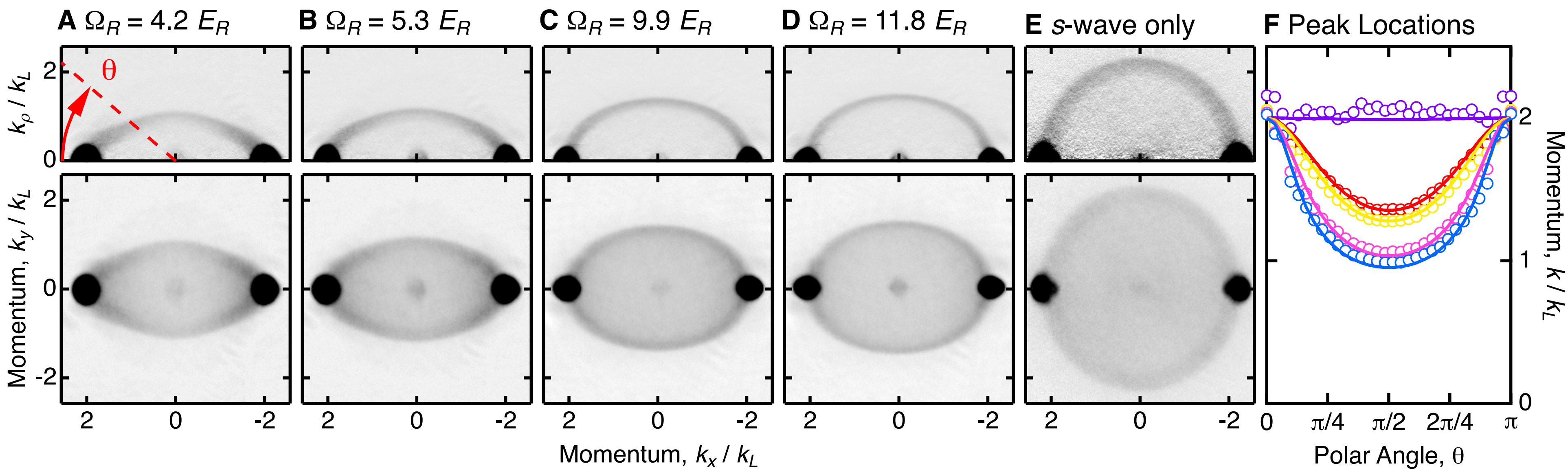


Remove density of states effect

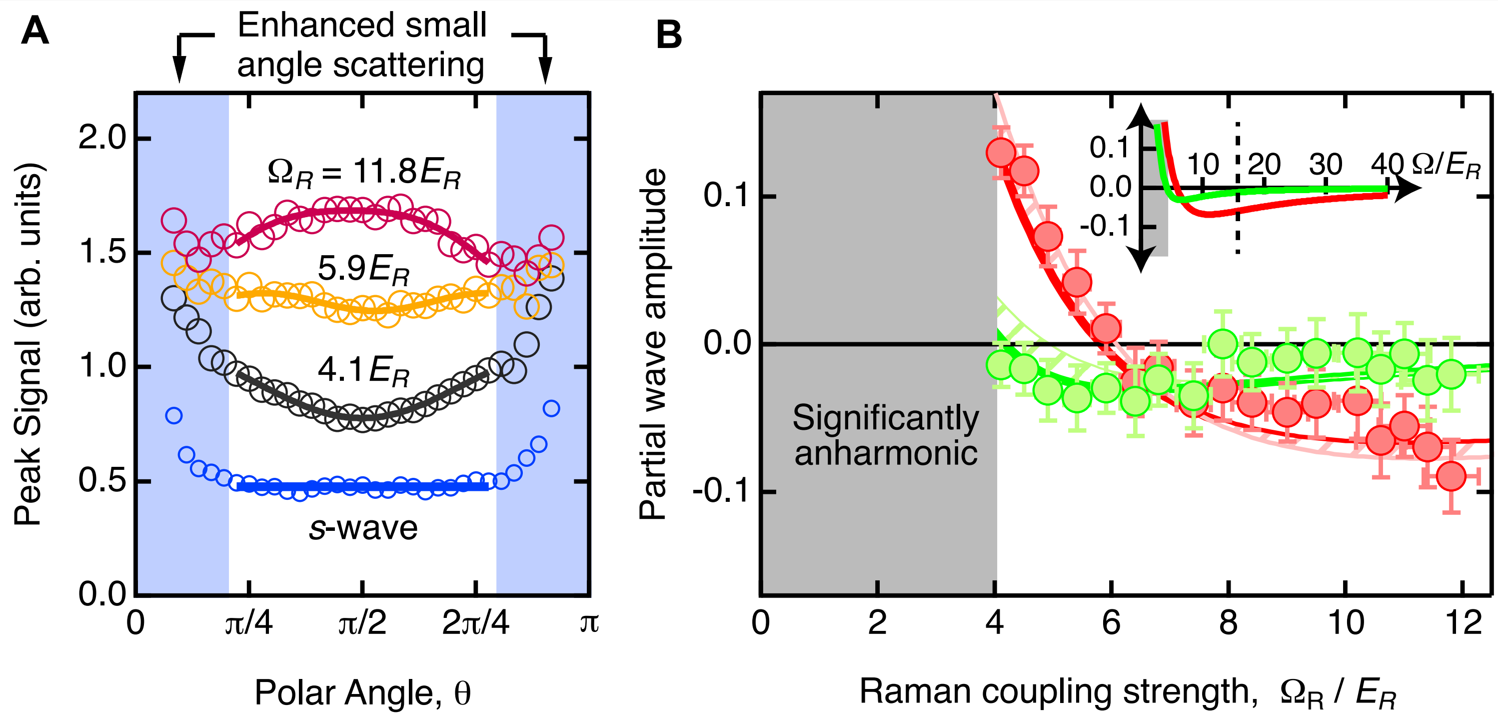
$$\Gamma_i = \frac{2\pi}{\hbar} \int_{S_i} \frac{dS_k}{(2\pi)^2} \frac{|\langle i|\hat{V}|S_k\rangle|^2}{|\nabla_k E(S_k)|}$$

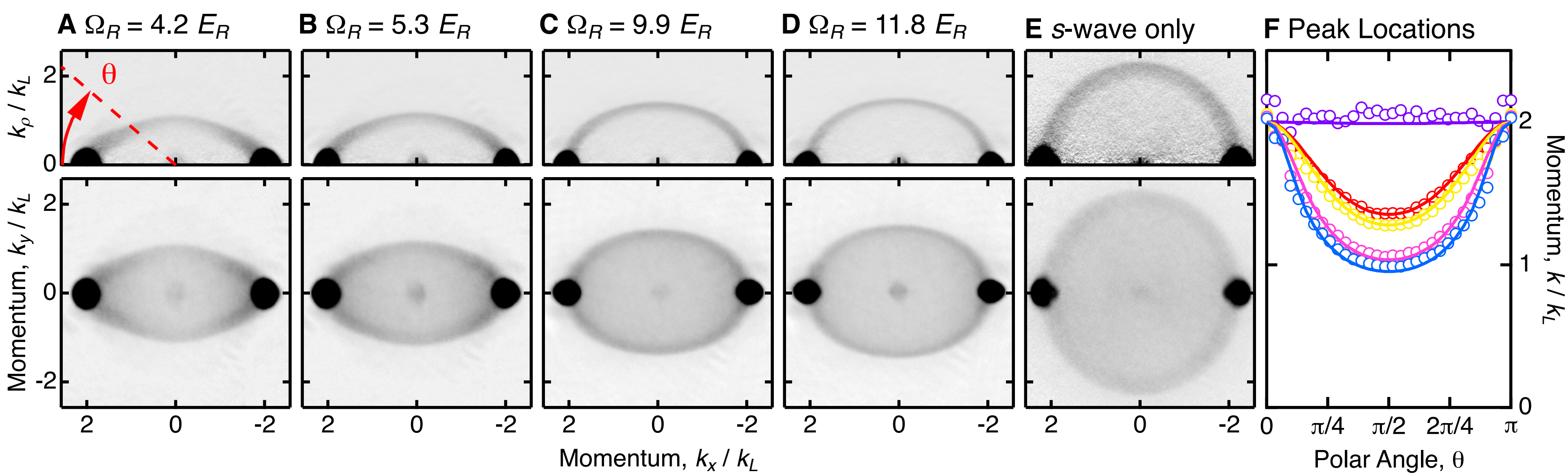
Then fit to partial wave expansion

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



Modified matrix element effect



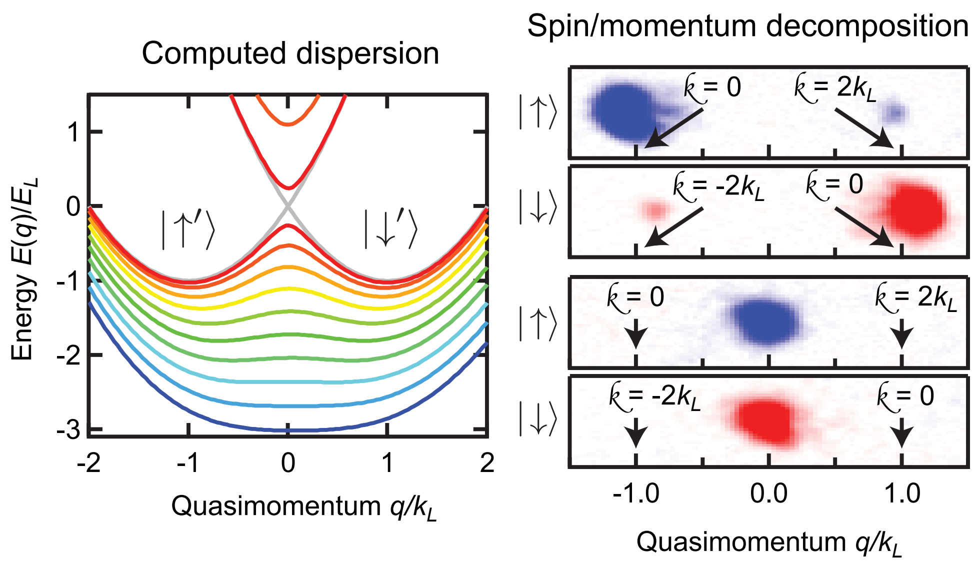


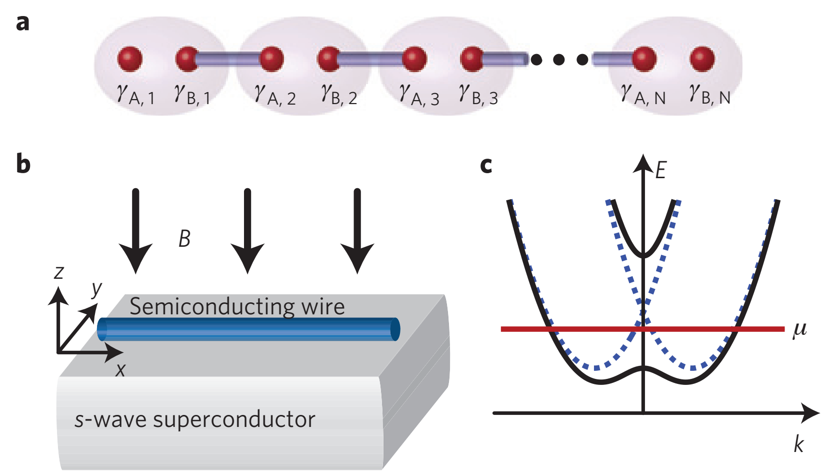
Spin orbit coupling of pseudo spin-1/2 atoms

Moving forward to Fermions

$$\hat{\mathcal{H}} = \hat{\Psi}^\dagger(\mathbf{x}) \left(\frac{\hbar^2 \hat{\mathbf{k}}^2}{2m} \check{1} + \frac{\hbar^2 k_R}{m} \hat{k}_x \check{\sigma}_y + \frac{\Omega}{2} \check{\sigma}_z \right) \hat{\Psi}(\mathbf{x}) + \frac{g}{2} \sum_{s,s'} \hat{\psi}_s^\dagger(\mathbf{x}) \hat{\psi}_{s'}^\dagger(\mathbf{x}) \hat{\psi}_{s'}(\mathbf{x}) \hat{\psi}_s(\mathbf{x})$$

$$\text{for } \Psi^\dagger(\mathbf{x}) = \left\{ \psi_\uparrow^\dagger(\mathbf{x}), \psi_\downarrow^\dagger(\mathbf{x}) \right\}$$





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Theory: C. Zhang et al, PRL (2008), J. D. Sau et al, PRL (2010), J. Alicea et al, N. Physics (2011)

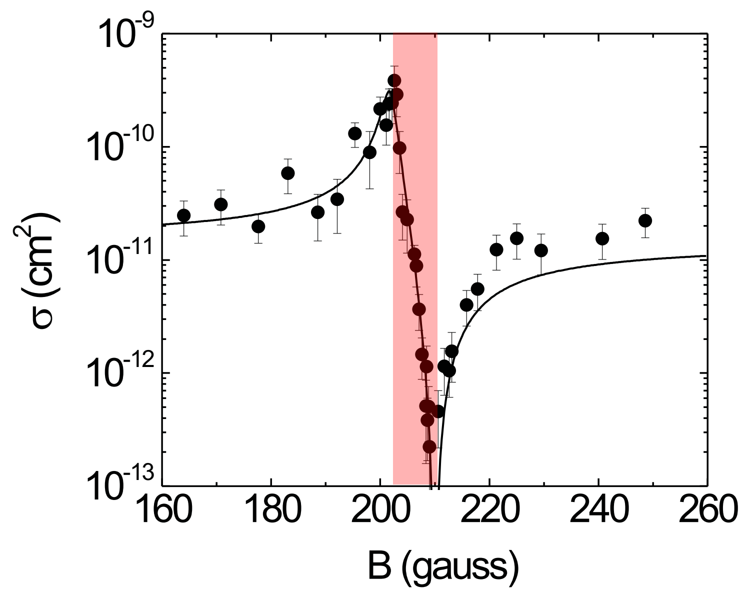
Pairing: ^{40}K

$$\hat{\mathcal{H}} = \hat{\Psi}^\dagger(\mathbf{x}) \left(\frac{\hbar^2 \hat{\mathbf{k}}^2}{2m} \check{1} + \frac{\hbar^2 k_R}{m} \hat{k}_x \check{\sigma}_y + \frac{\Omega}{2} \check{\sigma}_z \right) \hat{\Psi}(\mathbf{x}) + \left[\Delta \hat{\Psi}_\uparrow(\mathbf{x}) \hat{\Psi}_\downarrow(\mathbf{x}) + \text{h.c.} \right]$$

$$E_{B,1D} \propto g^2$$

$$E_{B,3D} \propto e^{-\pi/k_F|a|}, \text{ with } g = 2\pi\hbar^2 a/m$$

In 1D and 2D robust pairing (at single particle level)
at all attractive coupling strengths



<u>Refs.</u>

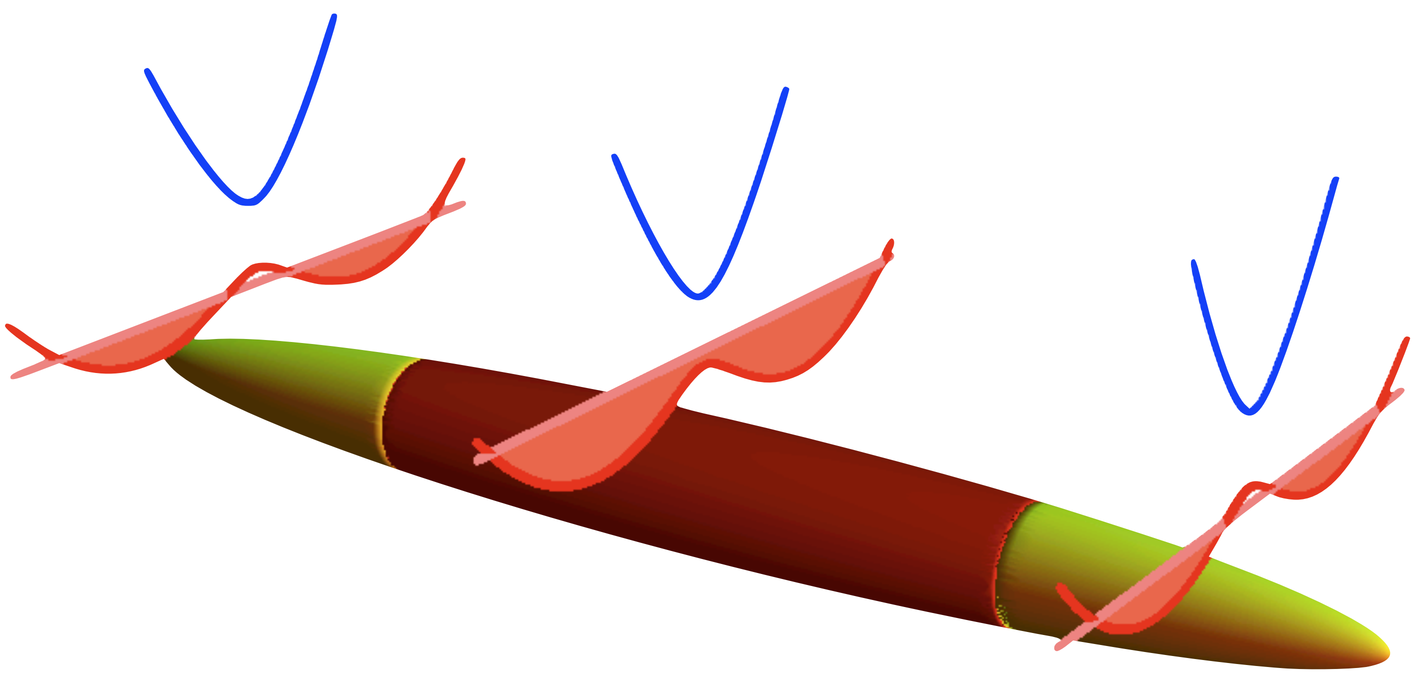
C. Regal (Ph.D. thesis); Bloch, I., Dalibard, J. & Zwerger, Rev. Mod. Phys. 80, 885–964 (2008).

Theory questions

Pairing gap is *intrinsic* not from proximity effect

$$\hat{\mathcal{H}} = \hat{\Psi}^\dagger(\mathbf{x}) \left(\frac{\hbar^2 \hat{\mathbf{k}}^2}{2m} \check{1} + \frac{\hbar^2 k_R}{m} \hat{k}_x \check{\sigma}_y + \frac{\Omega}{2} \check{\sigma}_z \right) \hat{\Psi}(\mathbf{x}) + \frac{g}{2} \sum_{s,s'} \hat{\psi}_s^\dagger(\mathbf{x}) \hat{\psi}_{s'}^\dagger(\mathbf{x}) \hat{\psi}_{s'}(\mathbf{x}) \hat{\psi}_s(\mathbf{x})$$

for $\Psi^\dagger(\mathbf{x}) = \left\{ \psi_\uparrow^\dagger(\mathbf{x}), \psi_\downarrow^\dagger(\mathbf{x}) \right\}$



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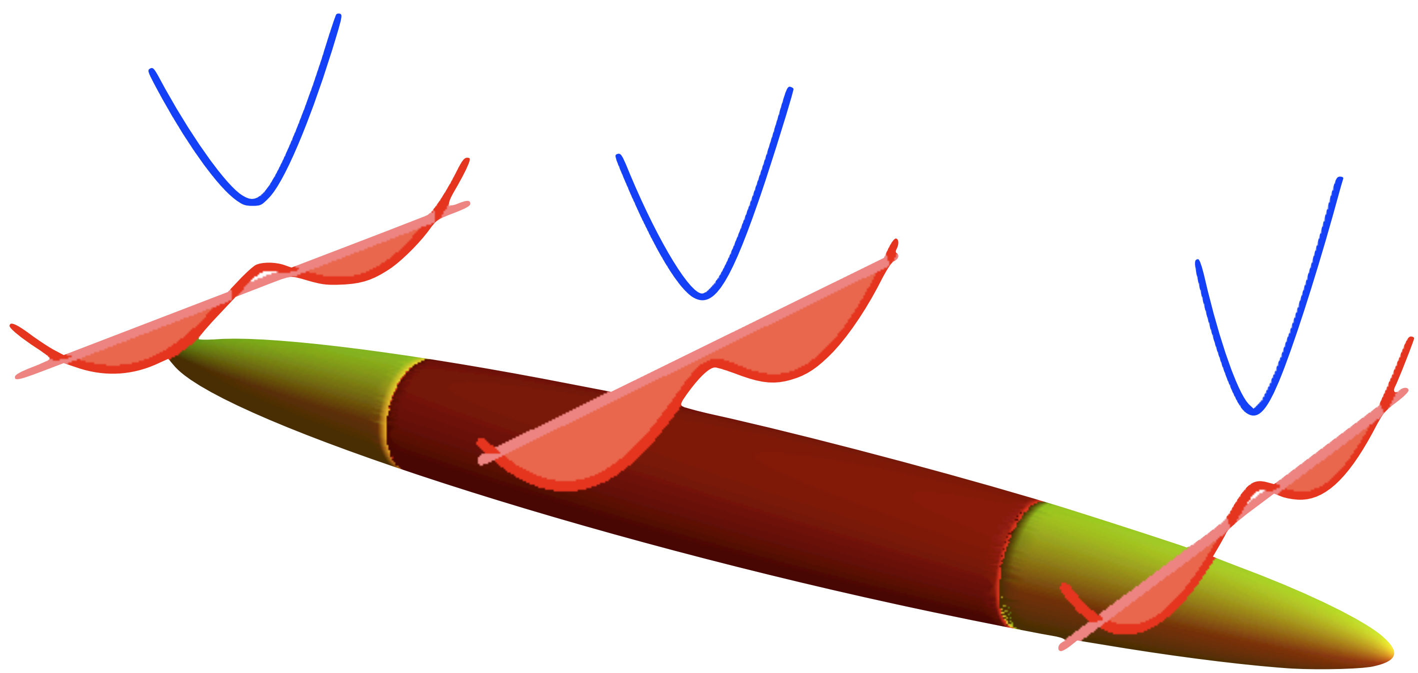
for $\Psi^\dagger(\mathbf{x}) = \left\{ \psi_\uparrow^\dagger(\mathbf{x}), \psi_\downarrow^\dagger(\mathbf{x}) \right\}$



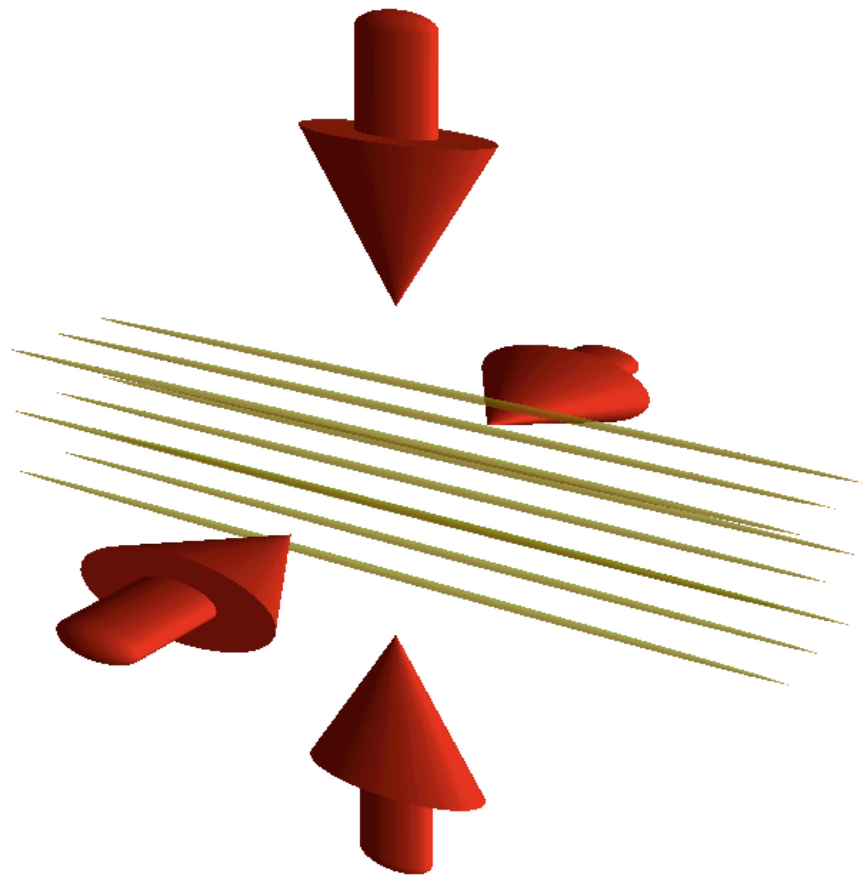
Theory questions

Pairing gap is *intrinsic* not from proximity effect

Coupling between needles important? Finite size important?

$$\hat{\mathcal{H}} = \hat{\Psi}^{\dagger}(\mathbf{x}) \left(\frac{\hbar^2 \hat{\mathbf{k}}^2}{2m} \check{1} + \frac{\hbar^2 k_R}{m} \hat{k}_x \check{\sigma}_y + \frac{\Omega}{2} \check{\sigma}_z \right) \hat{\Psi}(\mathbf{x}) + \left[\Delta e^{i\varphi} \hat{\psi}_{\uparrow}(\mathbf{x}) \hat{\psi}_{\downarrow}(\mathbf{x}) + \text{h.c.} \right]$$

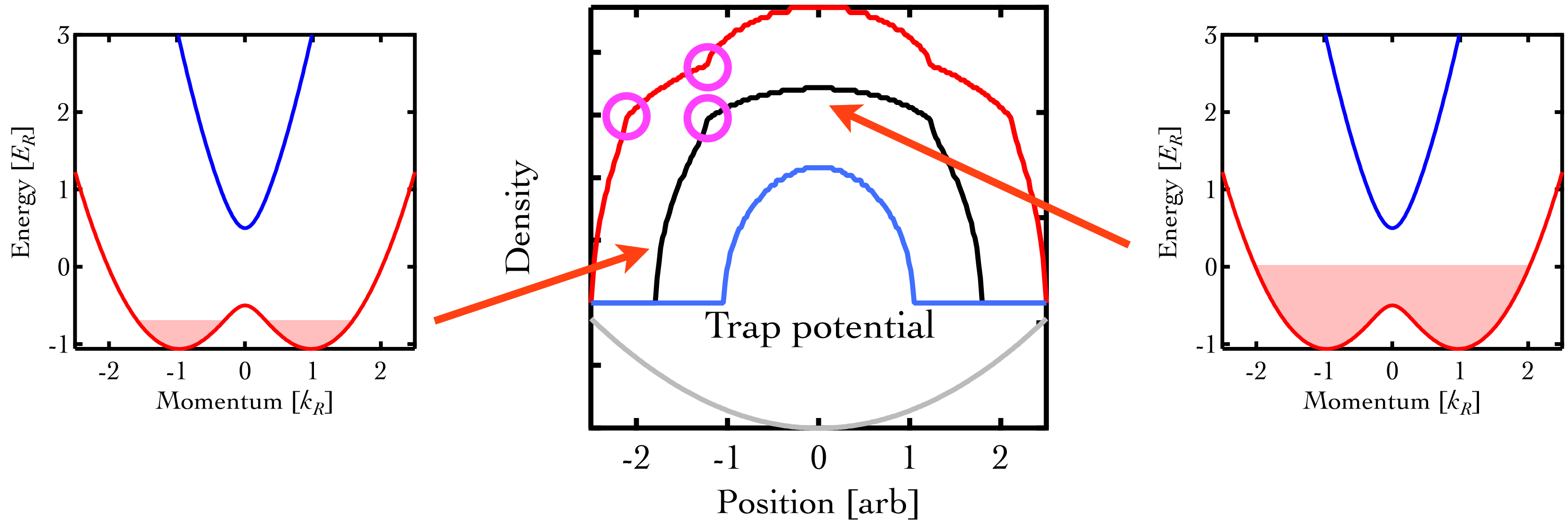
for $\Psi^{\dagger}(\mathbf{x}) = \left\{ \psi_{\uparrow}^{\dagger}(\mathbf{x}), \psi_{\downarrow}^{\dagger}(\mathbf{x}) \right\}$



Theory questions

Pairing gap is *intrinsic* not from proximity effect
Coupling between needles important? Finite size important?

What happens at μ smoothy changes and crosses from
TSC to SC phases?



If Majorana fermions's do form at these interfaces, how to detect?

The ugly: ^{40}K

Lifetime, lifetime, stability

Spontaneous emission
(lights scattering)
t ~ 0.5 - 1 s (double well)
t ~ 0.1 s (single well)

Feshbach losses
(molecule formation)
t ~ 1 s ($1/k_F a \sim -1$)
t ~ 0.1 s ($1/k_F a \sim 0$)

~ 200 μG absolute
stability at 200 G
(1 ppm)


Gauge fields

Mixtures