Strongly Interacting Fermi Gases

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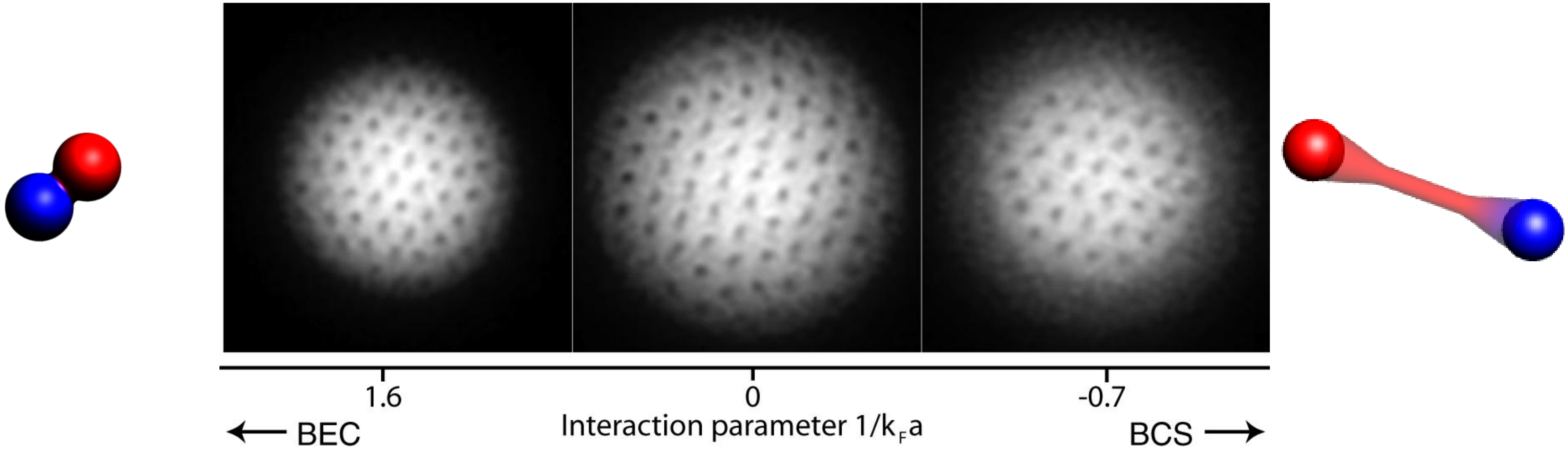


Massachusetts Institute of Technology

Center for Ultracold Atoms at MIT and Harvard

Biblio- (or Webo-)graphy

Varenna Notes:
on Fermi Gases:
Ketterle, Zwierlein, *Making, Probing and Understanding Ultracold Fermi Gases*
http://arxiv.org/abs/0801.2500

on BEC:
Ketterle, Durfee, Stamper-Kurn, *Making, Probing and Understanding BEC*
http://cua.mit.edu/ketterle_group/Projects_1999/Pubs_99/kett99varenna.pdf

Stefano Giorgini, Lev P. Pitaevskii, Sandro Stringari
The theory of Fermi gases
http://arxiv.org/abs/0706.3360

Immanuel Bloch, Jean Dalibard, Wilhelm Zwerger
Many-Body Physics with Ultracold Gases:
http://arxiv.org/abs/0704.3011

Lecture Notes “The BEC-BCS crossover and the Unitary Fermi Gas”
Edited by W. Zwerger, Springer, 2012

Indistinguishable Particles

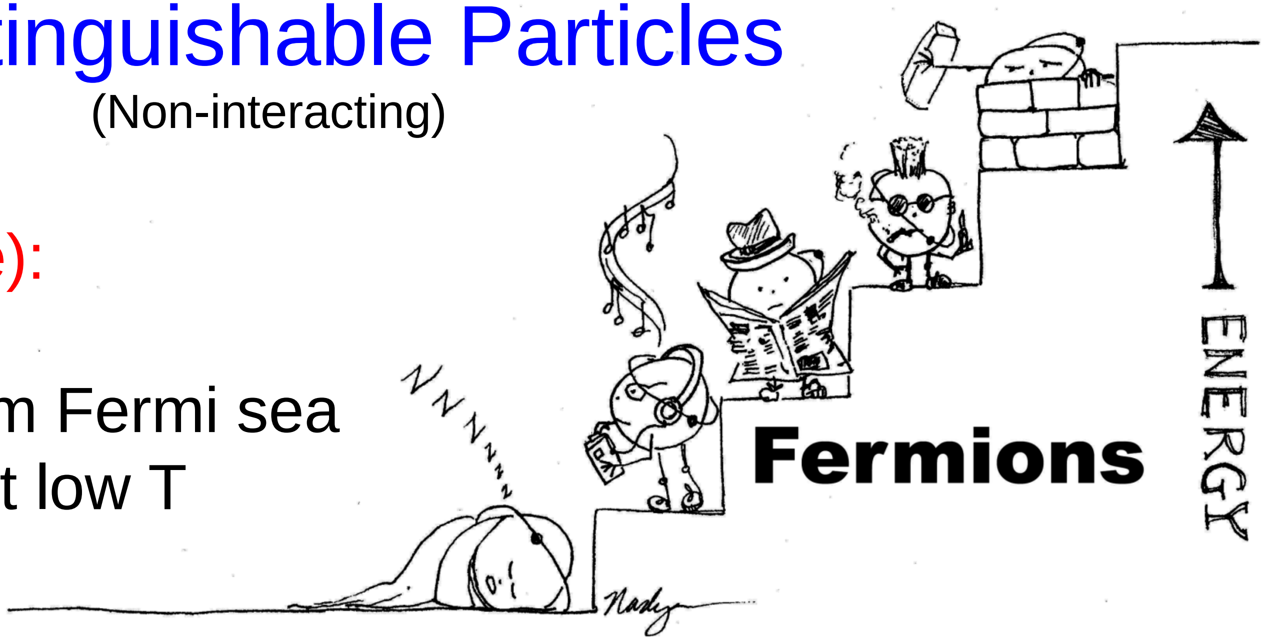
(Non-interacting)

Fermions (unsociable):

Half-Integer Spin

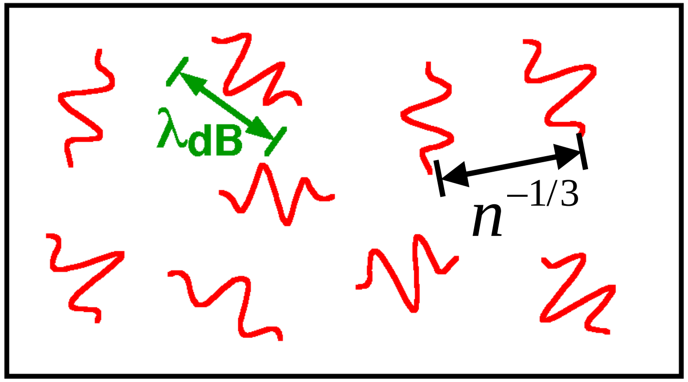
Pauli blocking → Form Fermi sea

No phase transition at low T



Degenerate gases

de Broglie wavelength ~ Interparticle spacing



$$\lambda_{dB} \approx n^{-1/3}$$

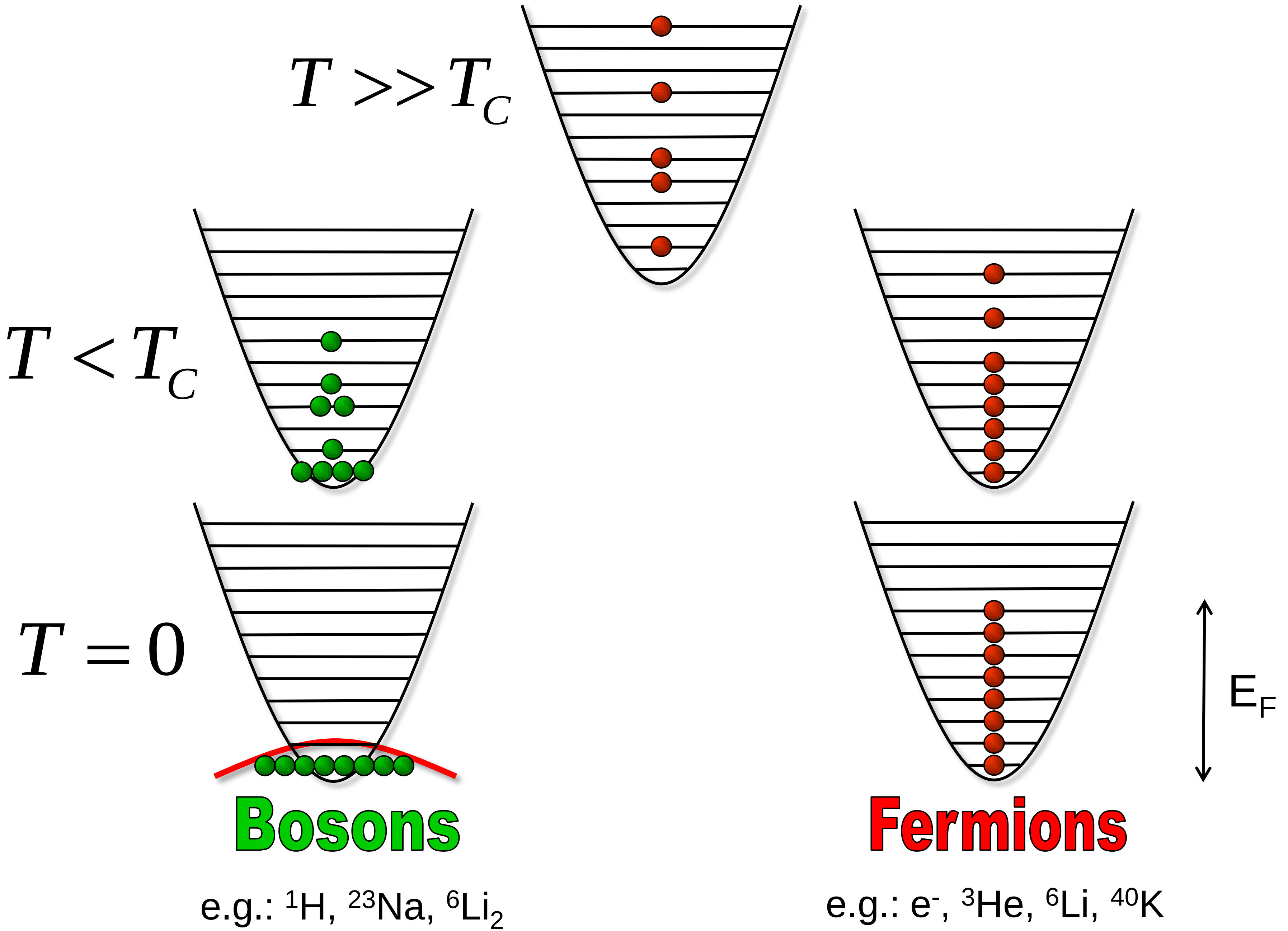
Want lifetime > 1s $\Rightarrow n < 10^{15}\,\mathrm{cm}^{-3}$ *Ultradilute*

$$T_F \approx \frac{\hbar^2}{k_B m} n^{2/3} \approx 1\,\mu\mathrm{K}$$ *Ultracold*

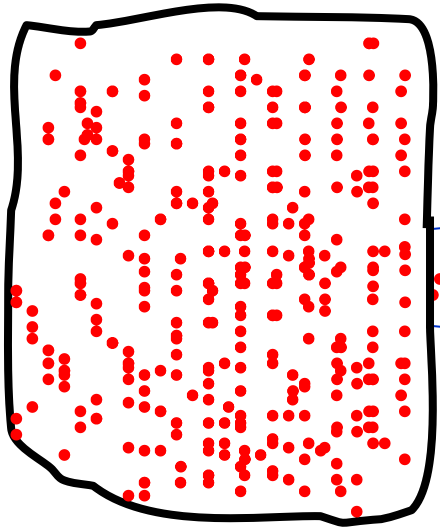
Good news: ***Bosons*** condense at

$$T_C \approx T_F$$

Bosons vs Fermions

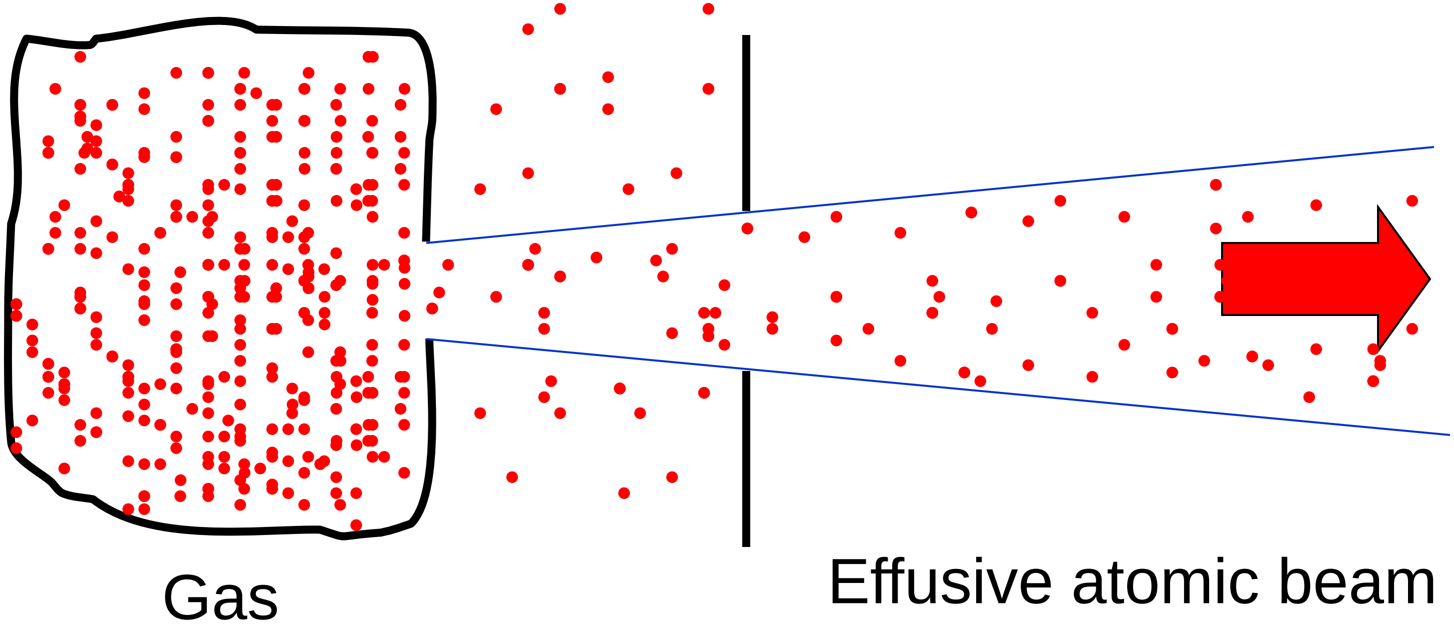


How to measure temperature?

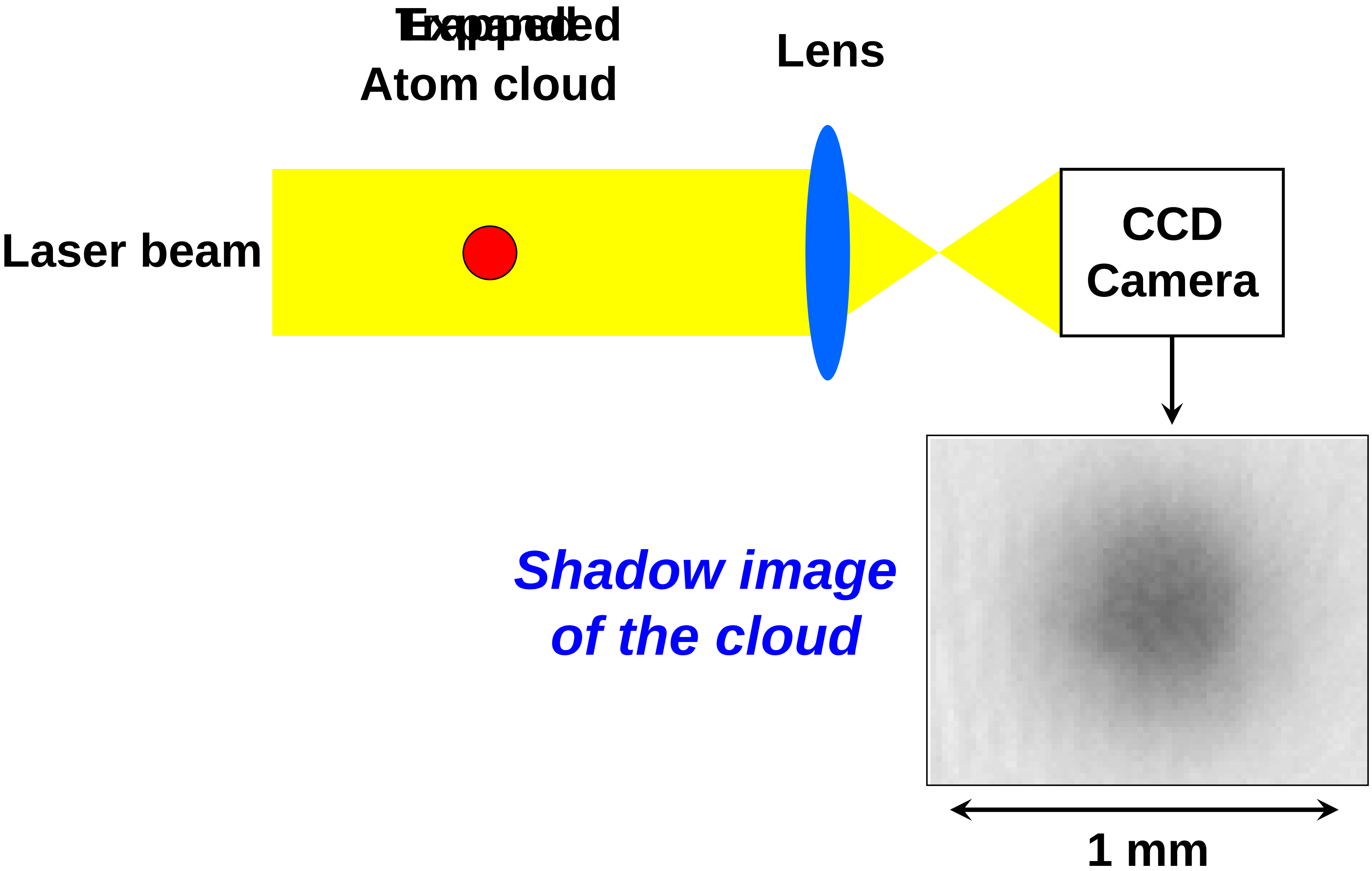


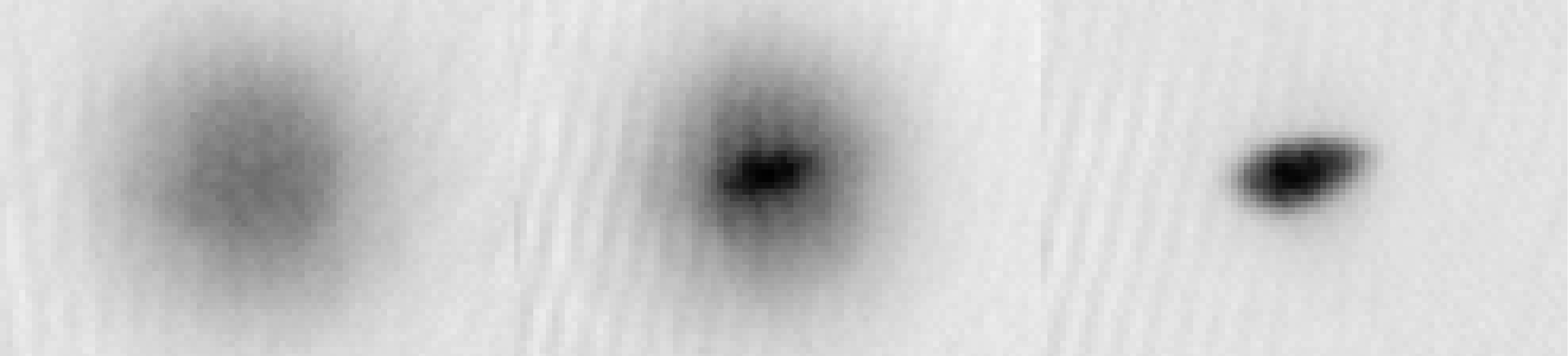
Gas

How to measure temperature?

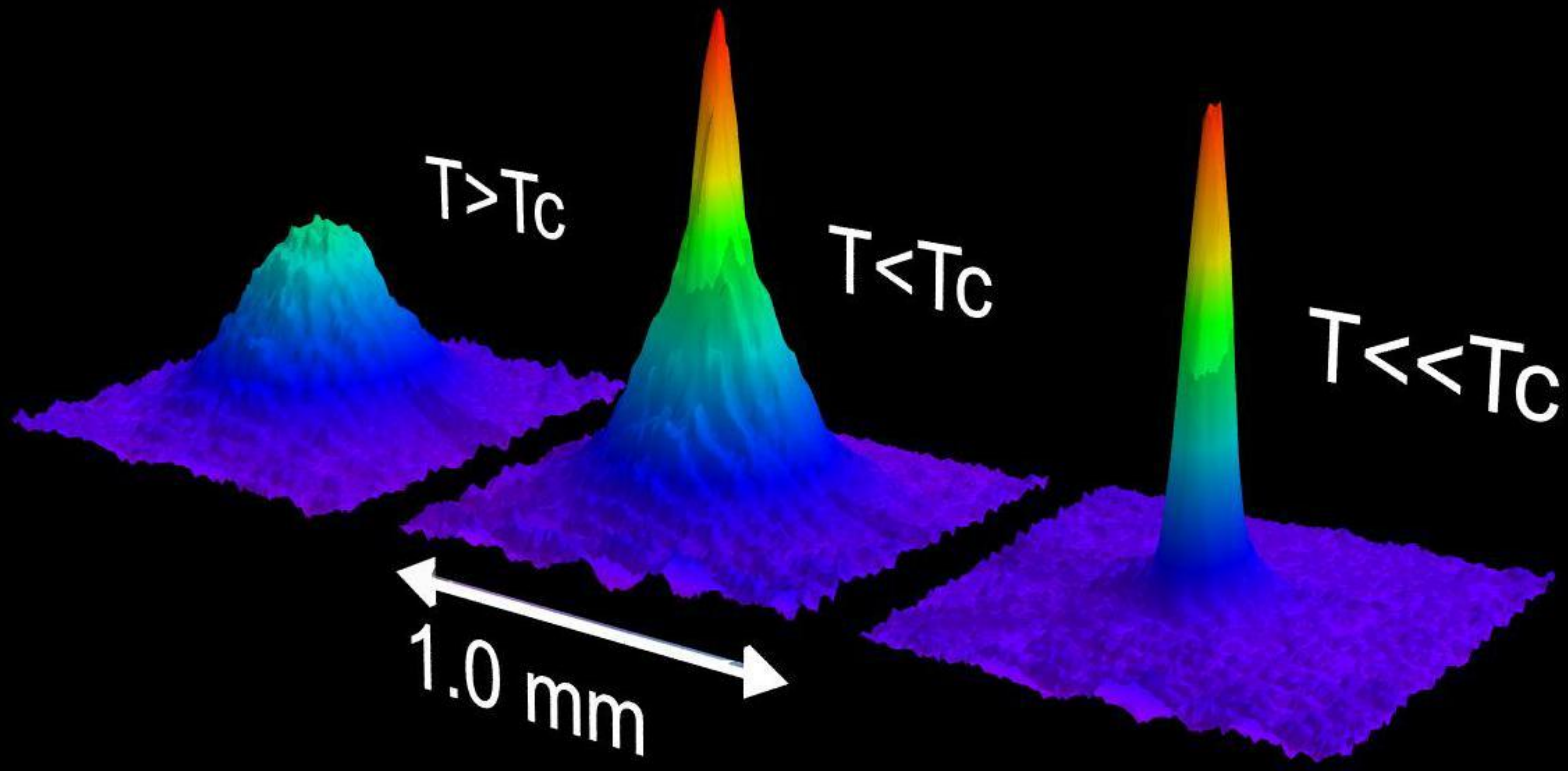


Observation of the atom cloud

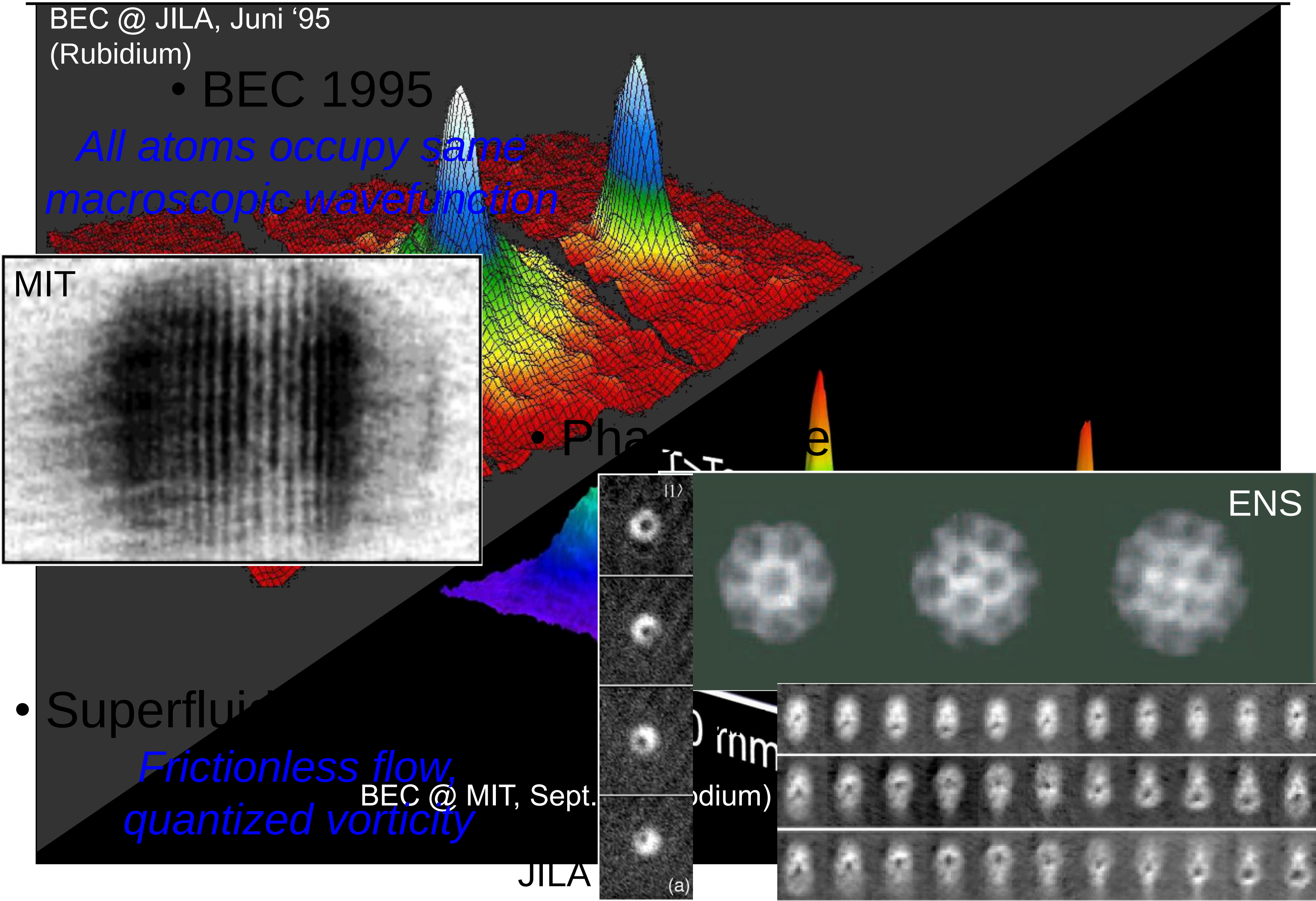




BEC @ MIT, 1995 (Sodium)

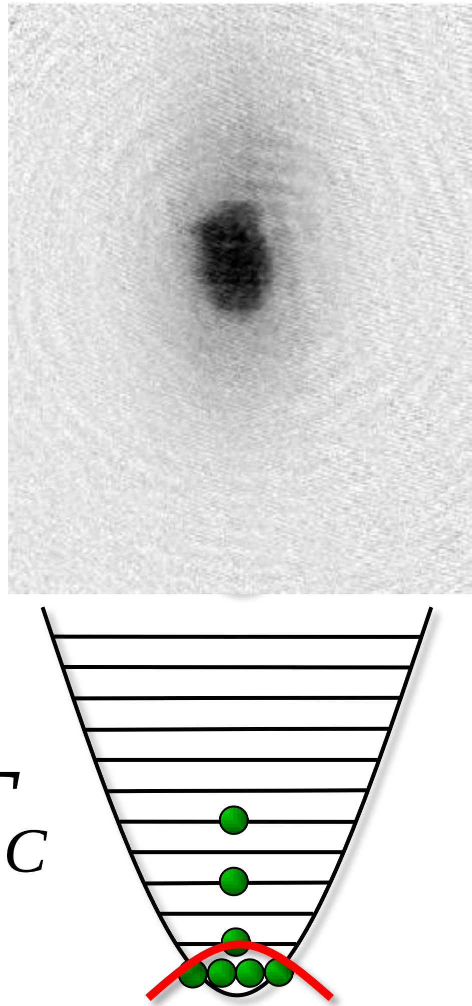


Superfluidity in Bosonic Gases

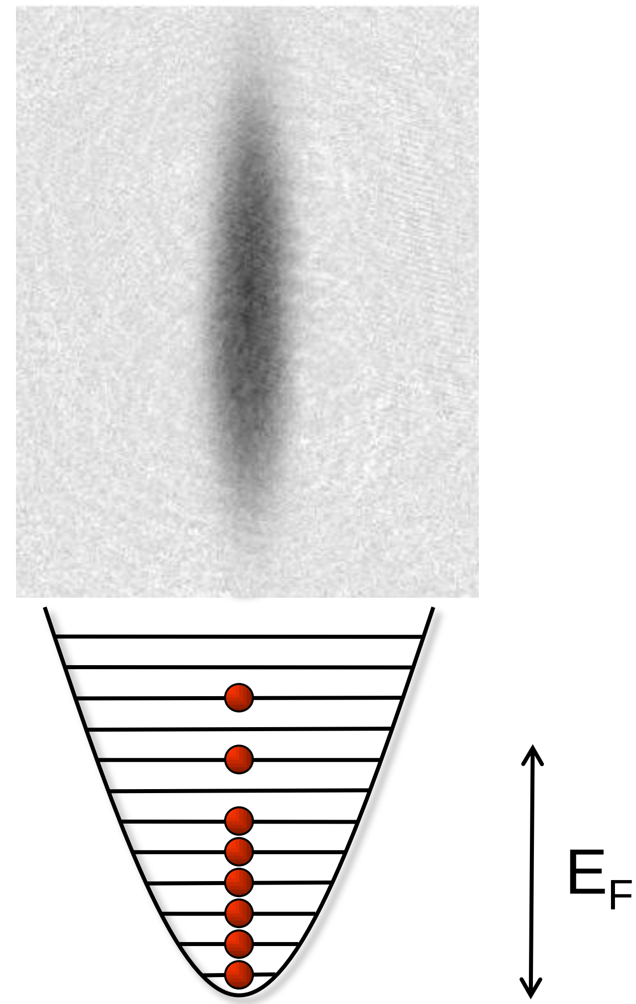


Bosons vs Fermions

^{23}Na



^{6}Li



$$T < T_C$$

Bosons

e.g.: ^{1}H, ^{23}Na, $^{6}Li_2$

Fermions

e.g.: e^-, ^{3}He, ^{6}Li, ^{40}K

Non-interacting Fermi gas

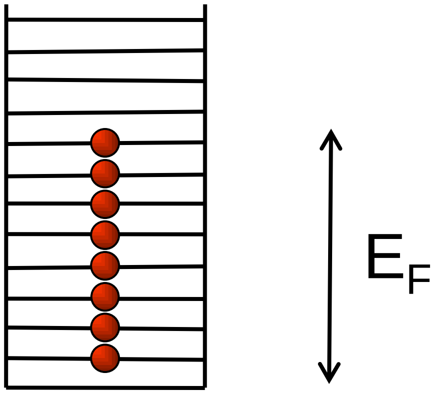
- Fermi-Dirac Statistics:

$$f(\epsilon) = \frac{1}{e^{\beta(\epsilon-\mu)}+1}$$

At T = 0:

$$f(\epsilon) \to \theta(E_F - \epsilon)$$

- Fermi gas in a box:



$$\epsilon = \frac{\hbar^2 k^2}{2m}$$

$$N = \int d^3x \int \frac{d^3k}{(2\pi)^3}\theta\left(E_F - \frac{\hbar^2 k^2}{2m}\right)$$

$$n = \frac{1}{(2\pi)^3}\text{Volume of sphere in k-space with radius } k_F$$

$$= \frac{1}{6\pi^2}k_F^3$$

$$E_F = \frac{\hbar^2 k_F^2}{2m}$$

$$k_F = (6\pi^2 n)^{-1/3} \sim 1/\text{Interparticle spacing}$$

Non-interacting Fermi gas

- Fermi-Dirac Statistics:

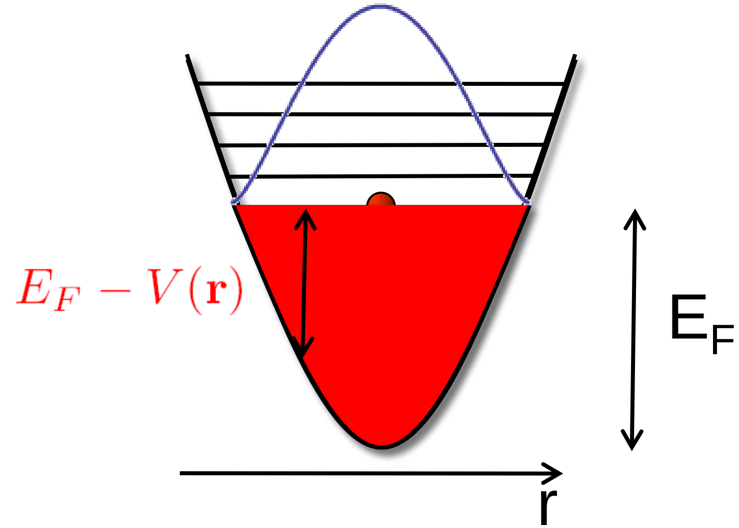
$$f(\epsilon) = \frac{1}{e^{\beta(\epsilon-\mu)}+1}$$

At T = 0:

$$f(\epsilon) \rightarrow \theta(E_F - \epsilon)$$

- Fermi gas in a trap:

$$\epsilon_F(\mathbf{r}) = E_F - V(\mathbf{r})$$

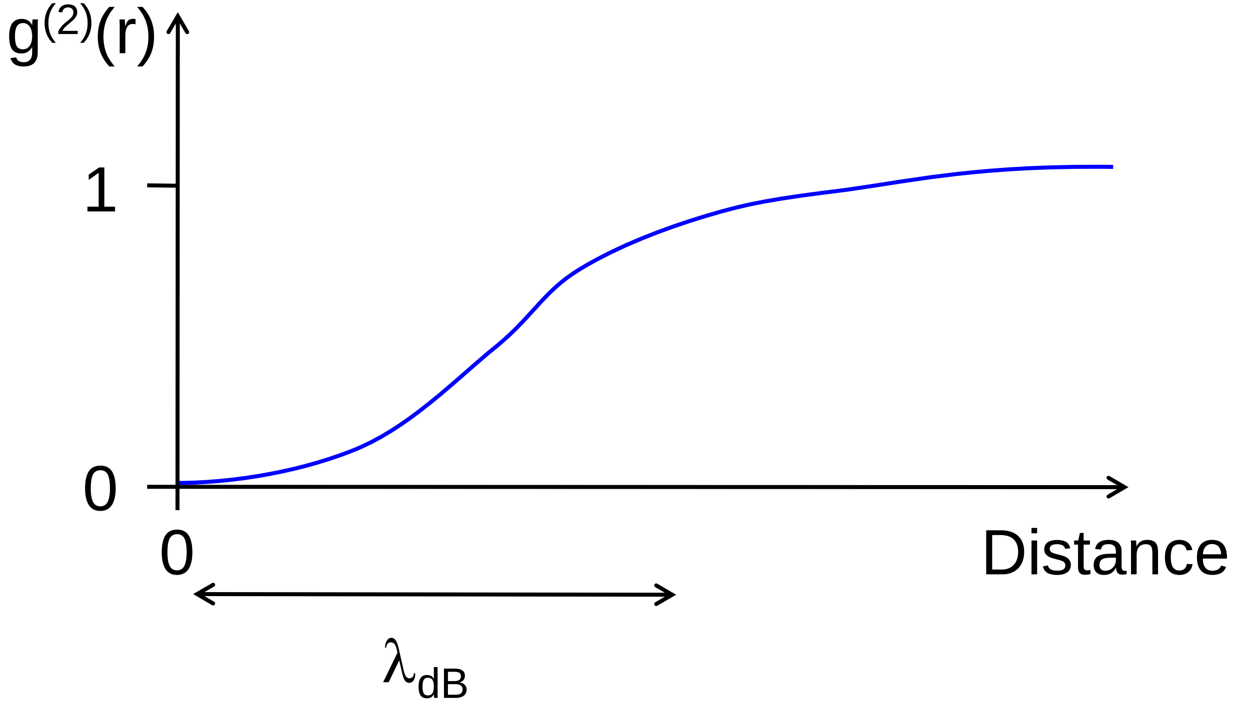


$$n(\mathbf{r}) = \frac{1}{6\pi^2} k_F(\mathbf{r})^3 = \frac{1}{6\pi^2\hbar^3}\left(2m(E_F - V(\mathbf{r}))\right)^{3/2}$$

(Local density approximation)

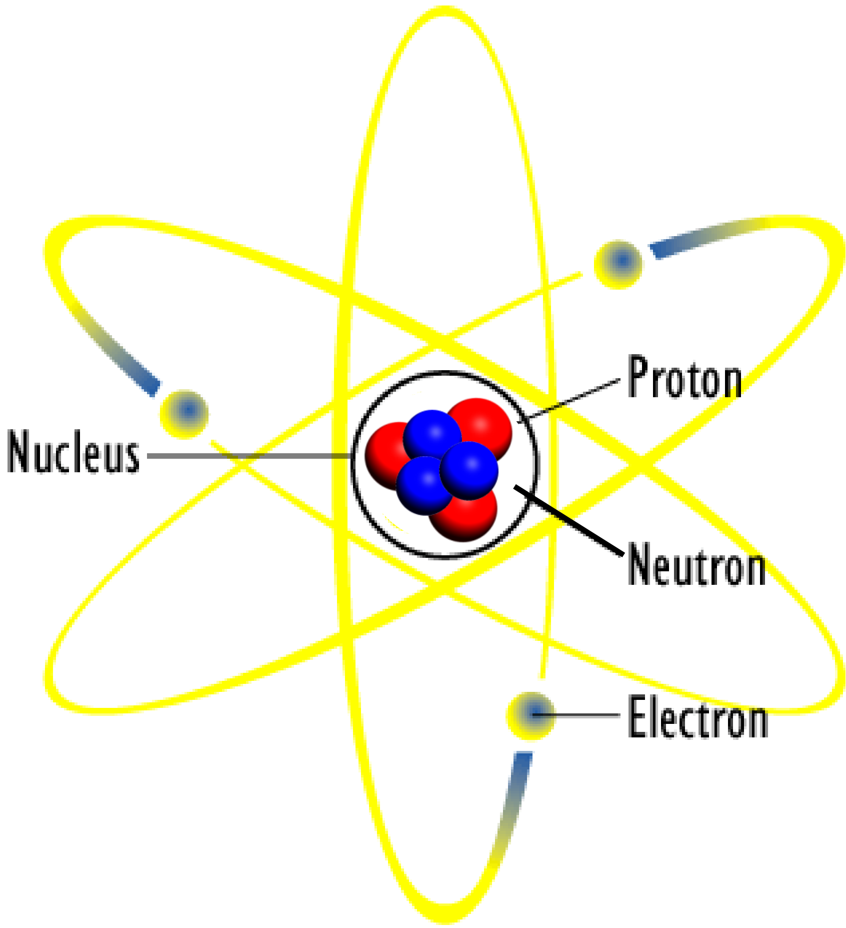
Freezing out of collisions

Pair correlations in a Fermi gas:

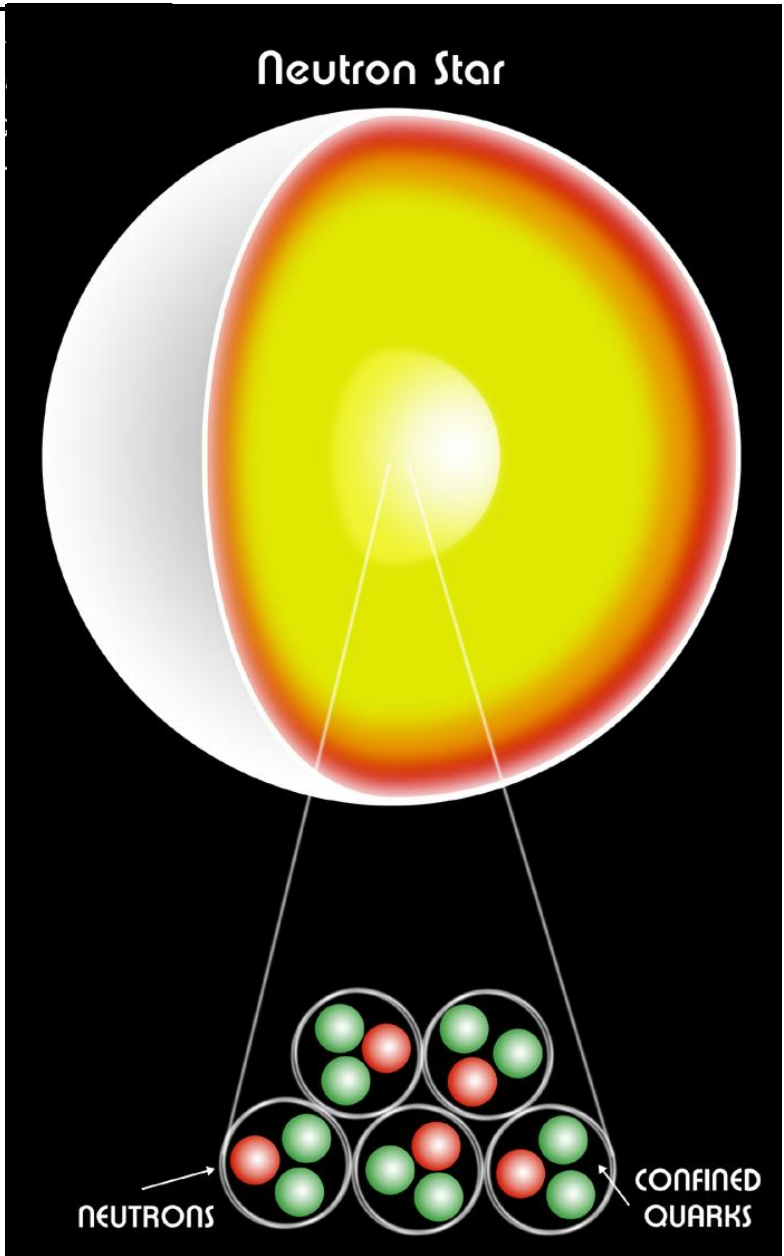


No interactions if range of potential is < λ_{dB}

Fermions – The Building Blocks of Matter



Lithium-6



Harvard-Smithsonian Center for Astrophysics

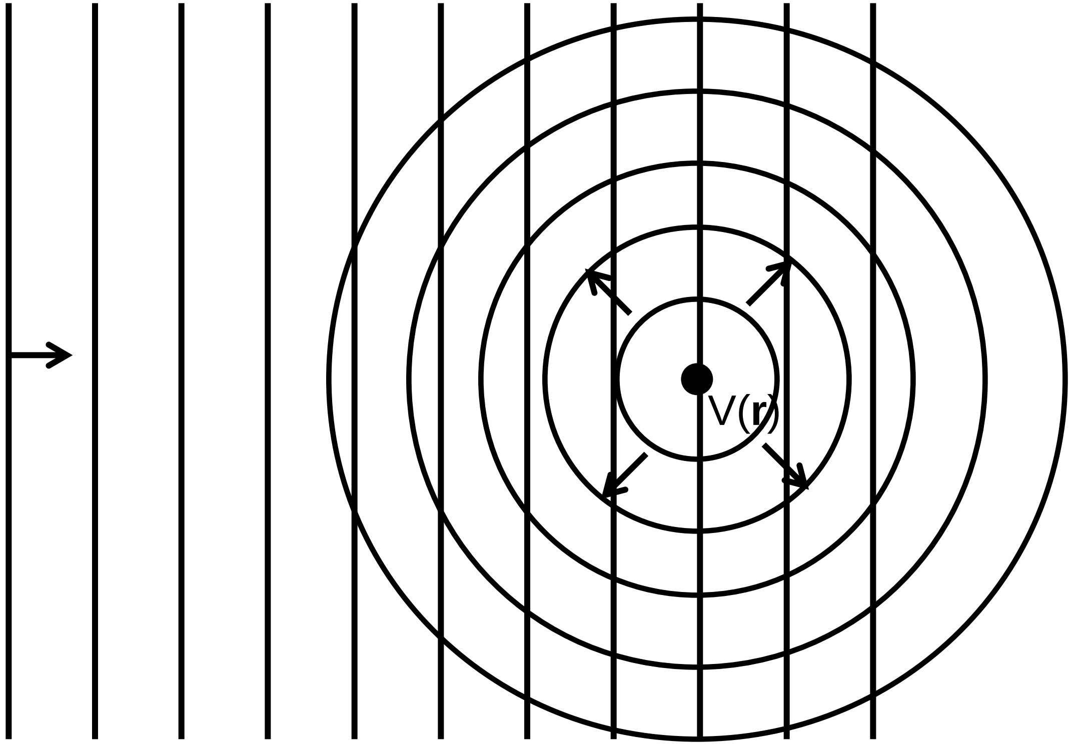
Scattering Theory

Incoming plane wave

$e^{ikz-i\omega t}$

Radially outgoing wave

$$f_k(\vartheta,\varphi)\frac{1}{r}e^{ikr-i\omega t}$$



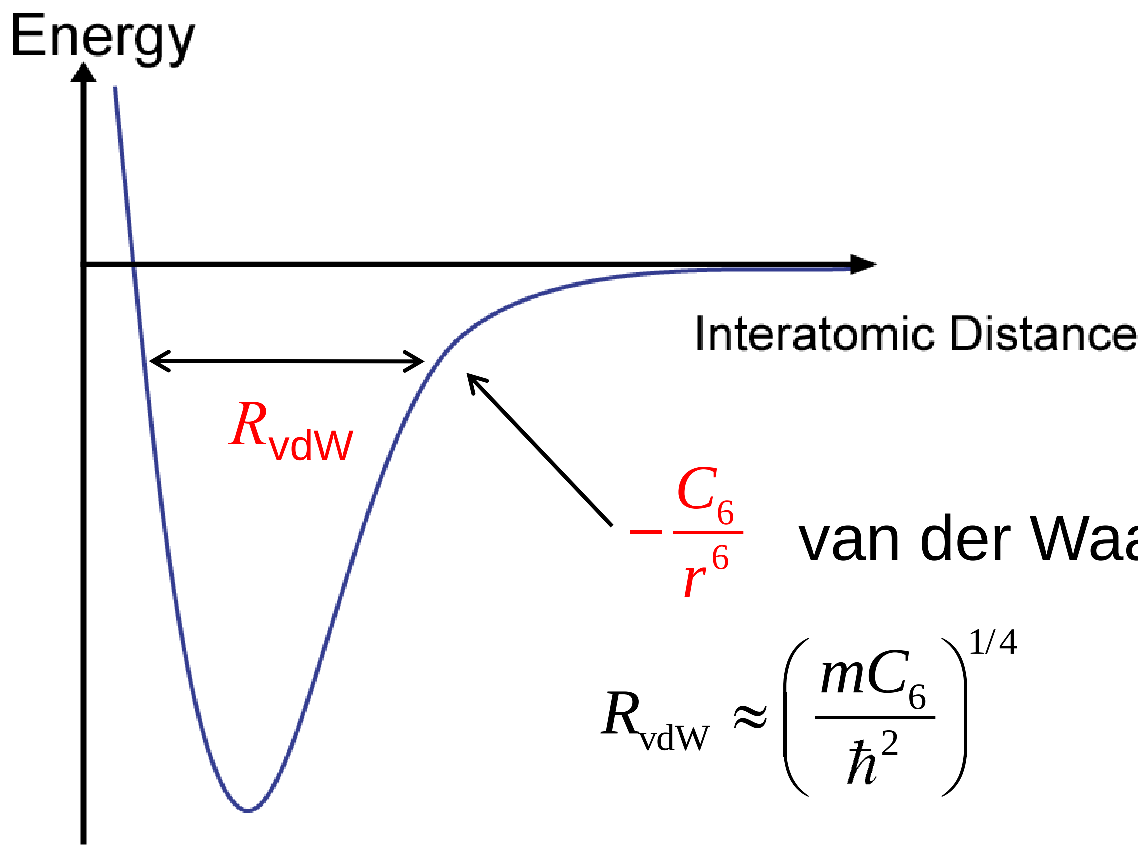
For s-wave:

$$f_k\frac{1}{r}e^{ikr-i\omega t}$$

$$e^{ikz}+f_k\frac{1}{r}e^{ikr}\approx\frac{1}{kr}e^{i\delta(k)}\sin(kr+\delta(k))$$

$$f_k=\frac{1}{k}e^{i\delta(k)}\sin(\delta(k))$$

Interatomic interactions



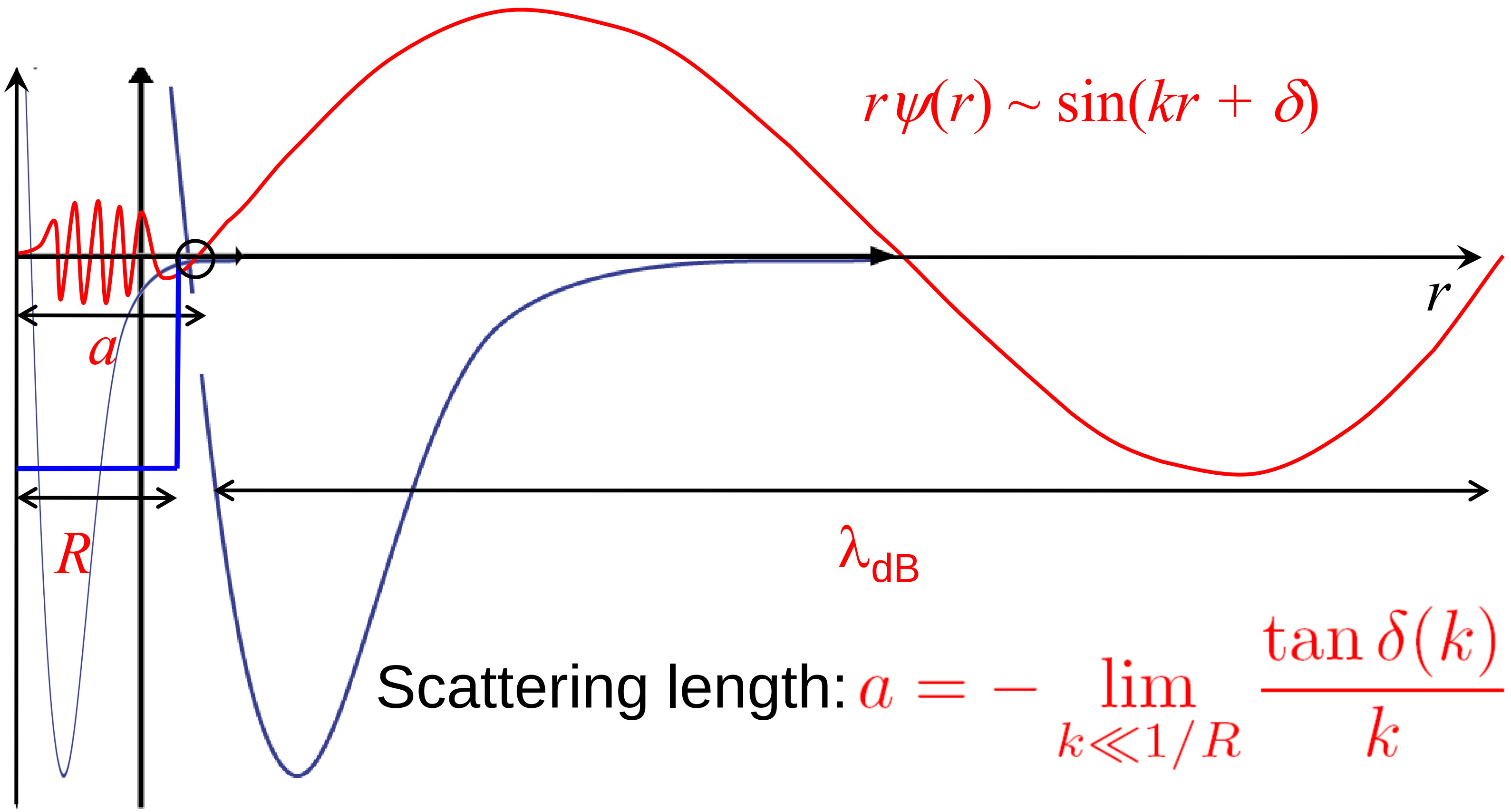
van der Waals potential

$$R_{\text{vdW}} \approx \left(\frac{mC_6}{\hbar^2}\right)^{1/4}$$

- For Alkali atoms: $R_{\text{vdW}} \sim$ 50-200 a_0
- Ultracold collisions: $\lambda_{dB} \approx 1\mu m >> R$

→ atoms do not probe the details of the potential

Interatomic interactions

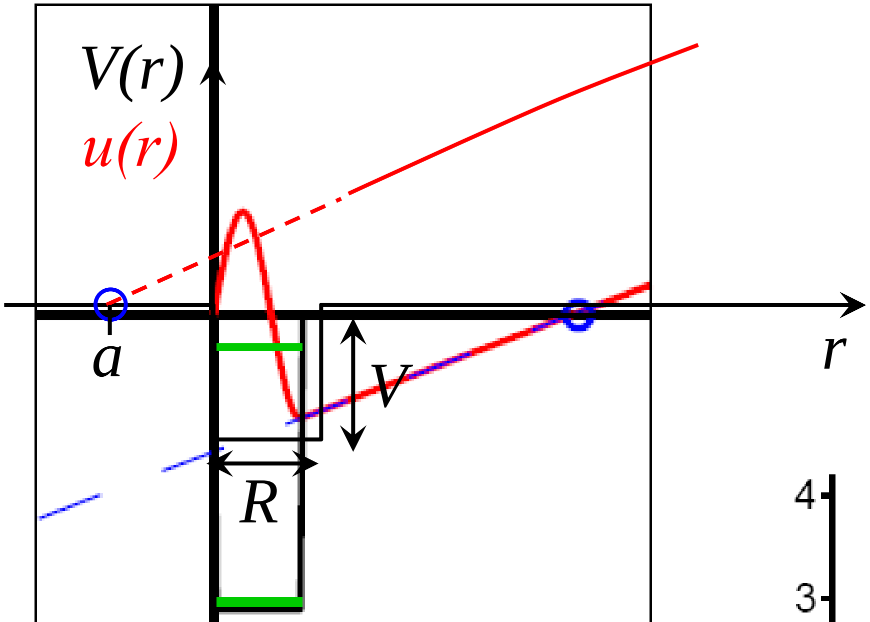


Scattering length: $a = -\lim_{k \ll 1/R} \frac{\tan\delta(k)}{k}$

- For Alkali atoms: R_{vdW} ~ 50-200 a_0
- Ultracold collisions: $\lambda_{dB} \approx 1\mu m >> R$

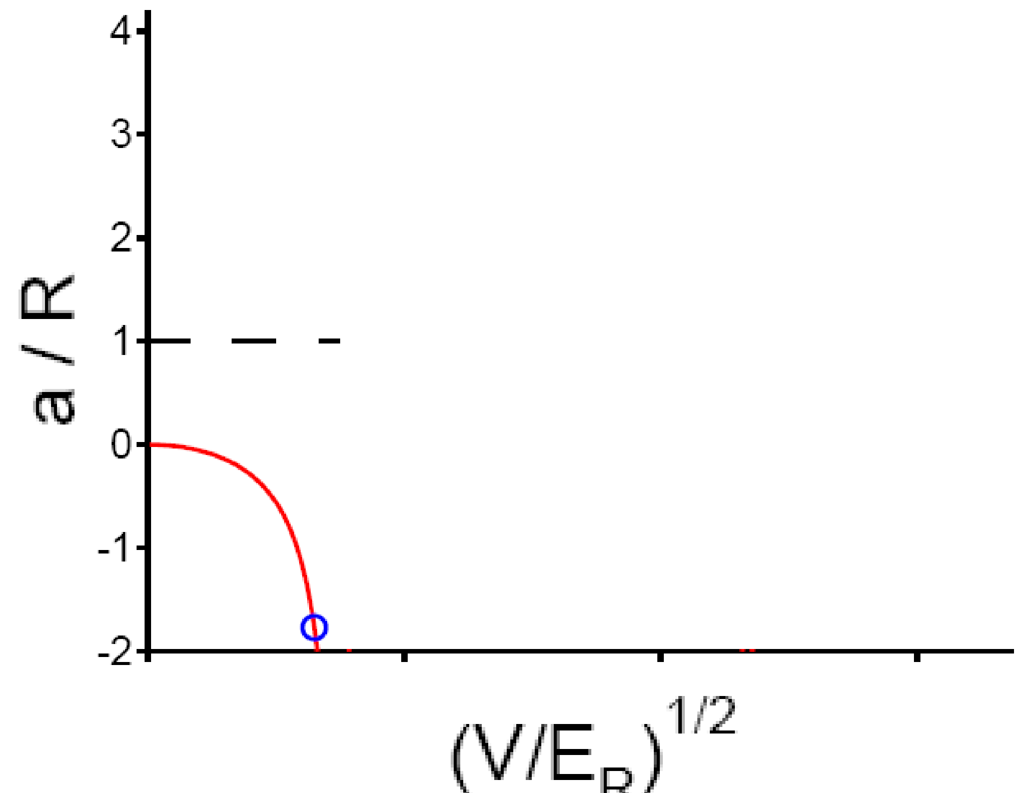
→ atoms do not probe the details of the potential

Scattering Resonances



$$u(r) \overset{r>R}{=} \sin(k(r-a))$$

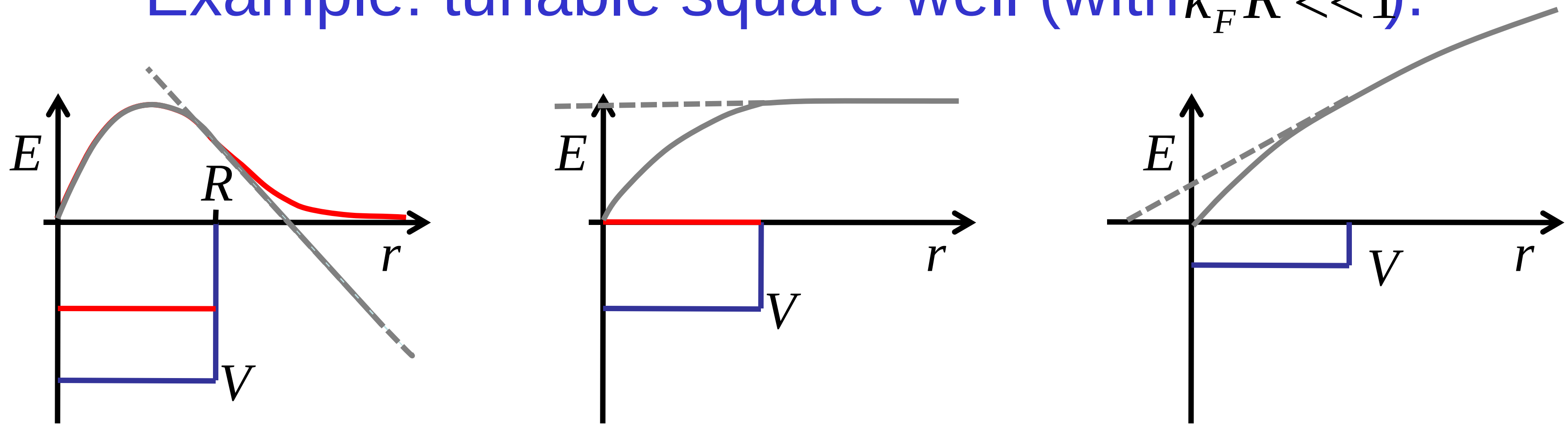
(s-wave) scattering length



Tunable Interactions

Vary interaction strength between spin up and spin down

Example: tunable square well (with $k_F R << 1$):



strong attraction	Resonance	weak attraction
deep bound state	*bound state appears*	*no bound state*

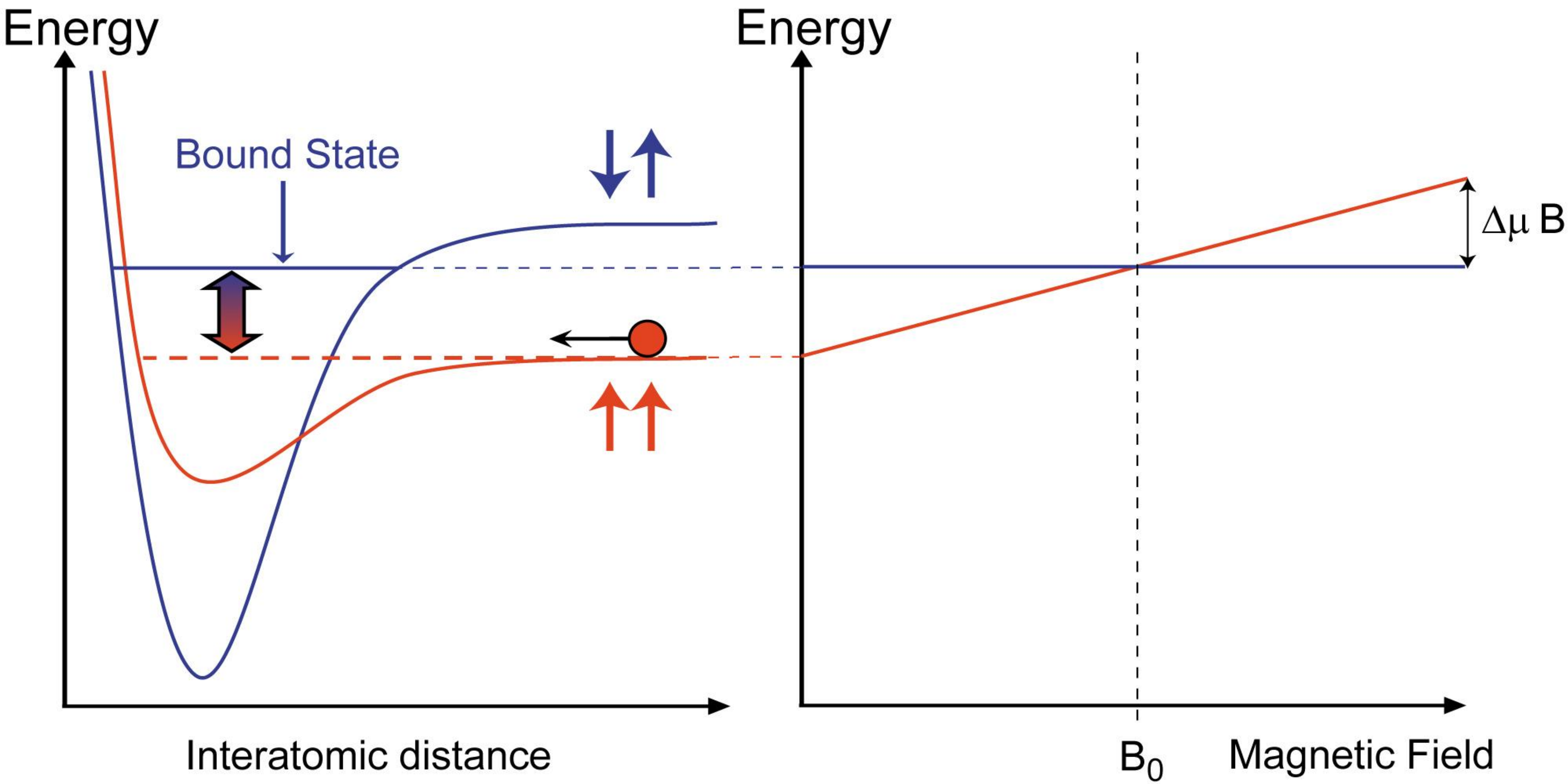
scattering length

$a > 0$	$a \to \pm\infty$	$a < 0$

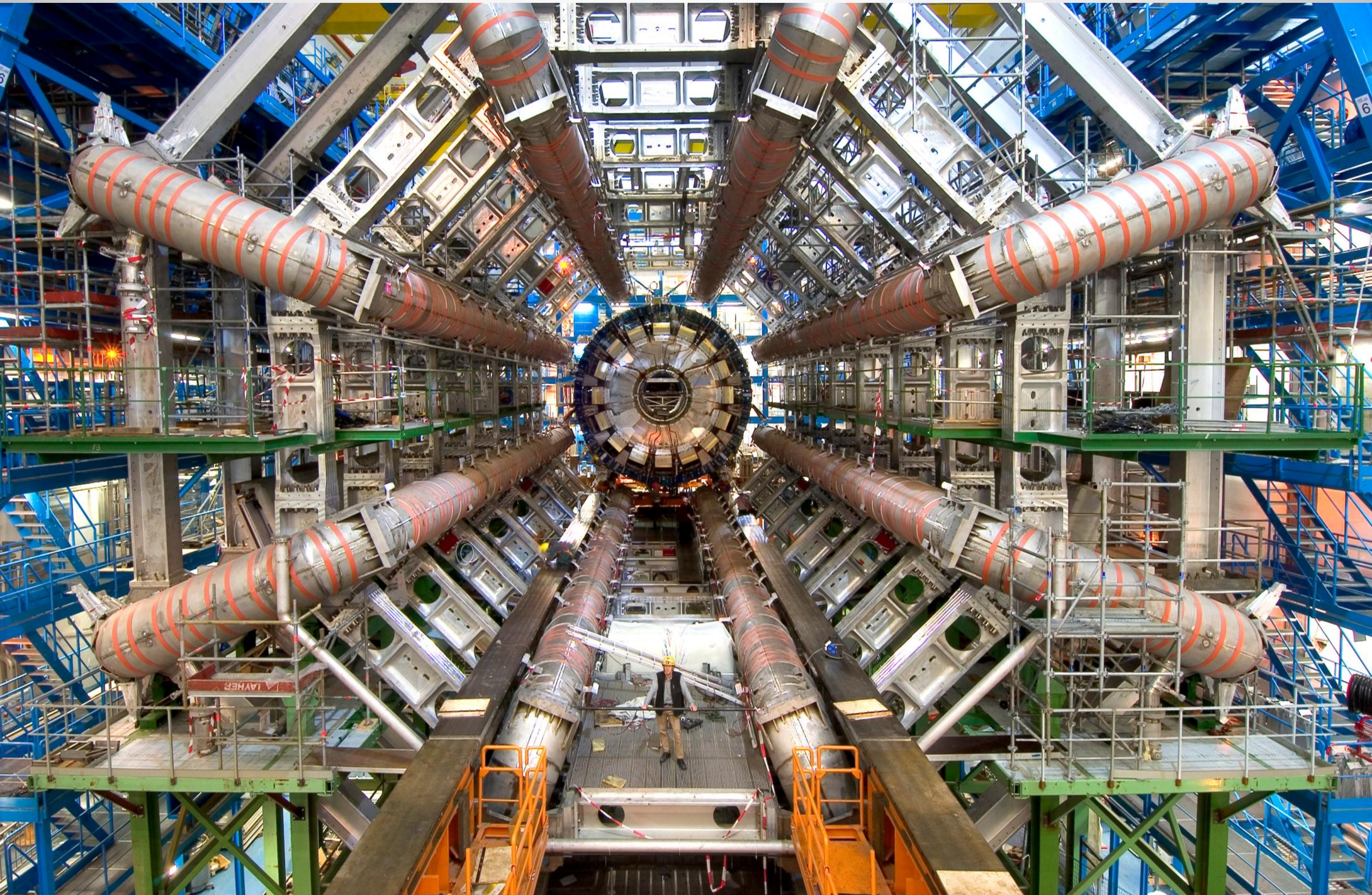
Important for Many-Body Physics:

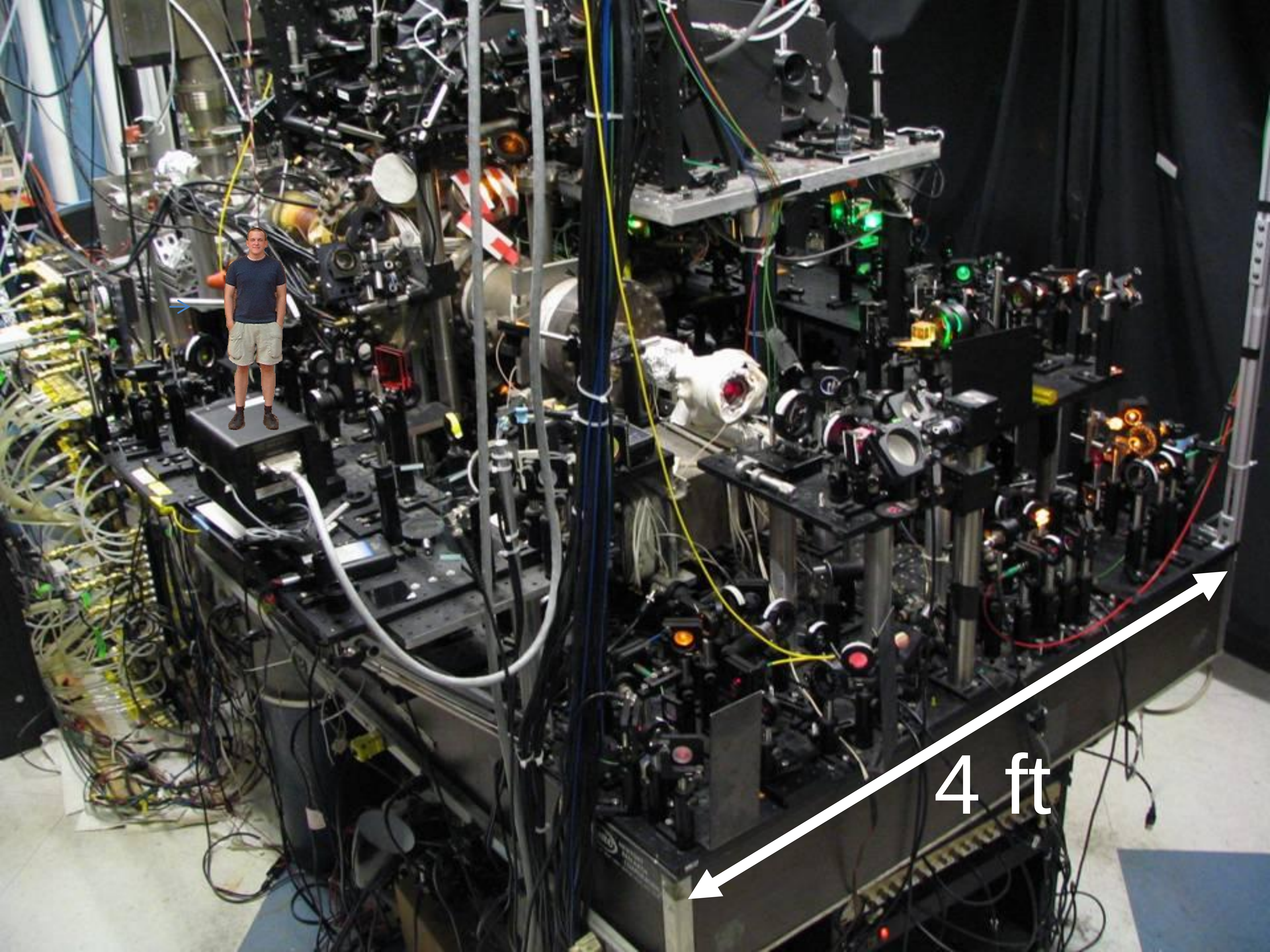
$$\frac{\text{Interparticle distance}}{\text{Scattering length}} = \frac{1}{k_F a}$$

Feshbach resonances: Tuning the interactions



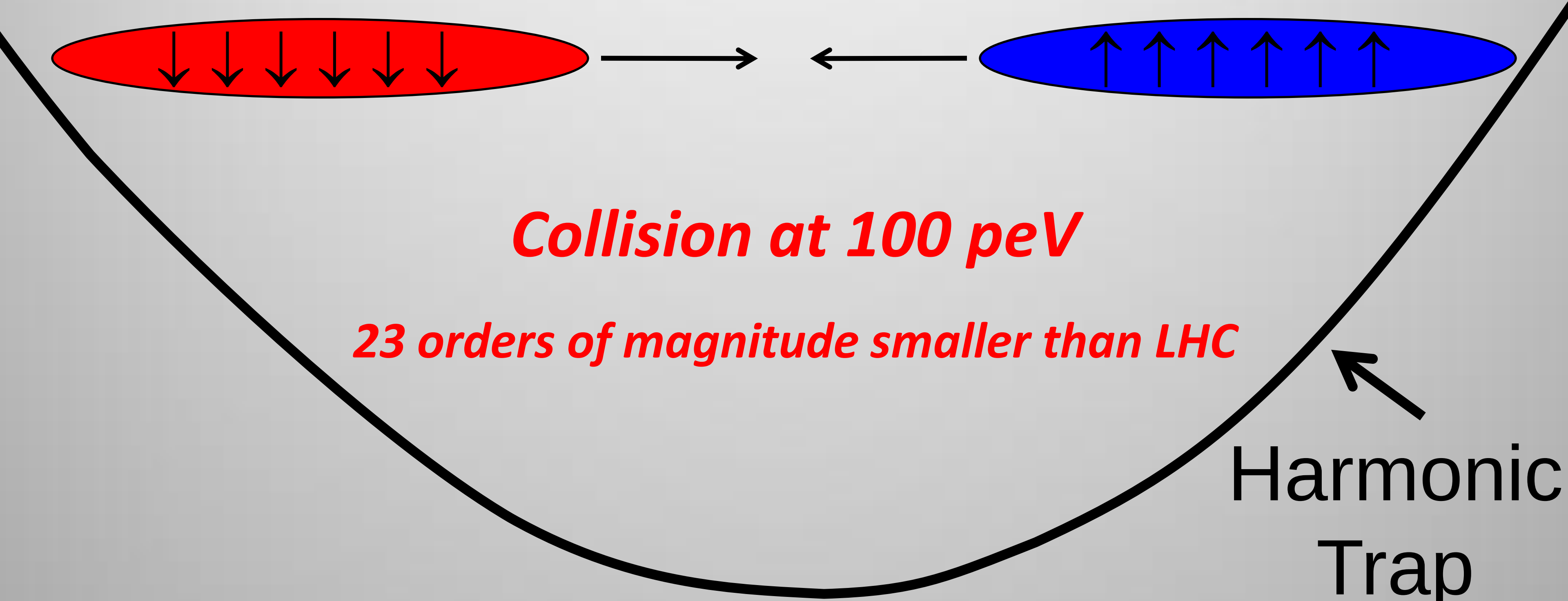
Large Hadron Collider (LHC)




4 ft

Little Fermi Collider (LFC)

A ↓ Fermi gas collides with a ↑ cloud with resonant interactions



Collision at 100 peV

23 orders of magnitude smaller than LHC

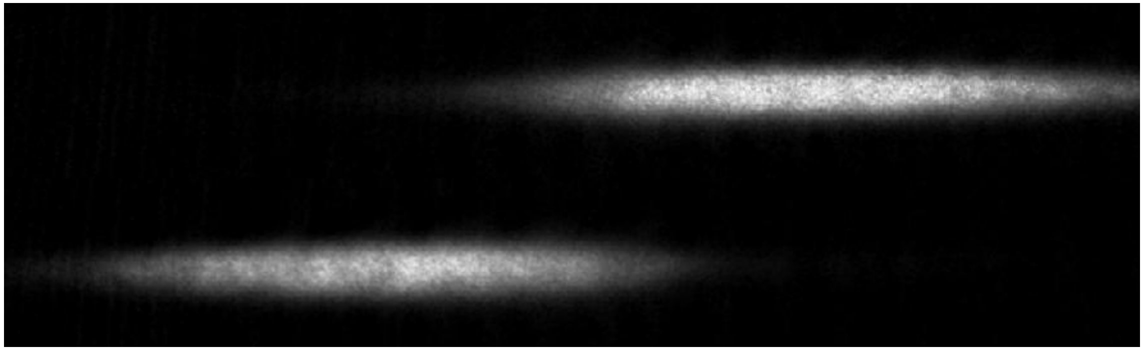
A.T. Sommer, M.J.H. Ku, G. Roati, M.W. Zwierlein, Nature 472, 201 (2011)

First study of spin currents in degenerate Fermi gases: Jin, DeMarco, 2001

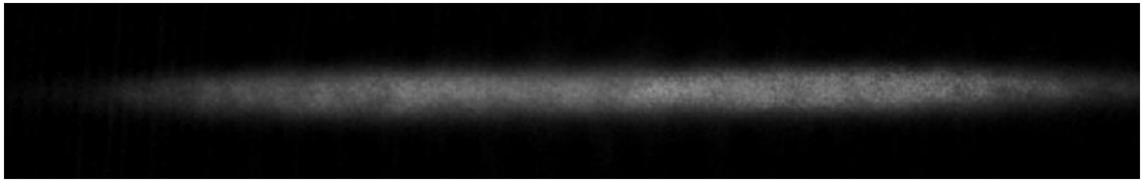
Little Fermi Collider

Preparation: Mix, cool, kick, and rush to resonance

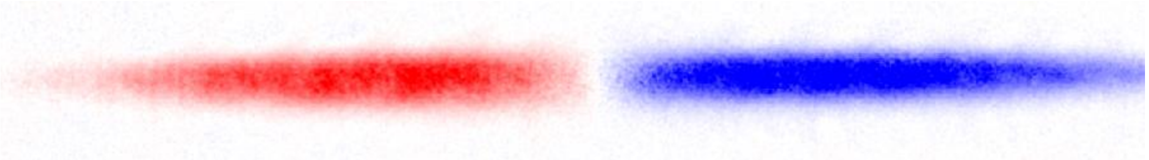
Rapid (10 us) probing of spin up and down



Total OD



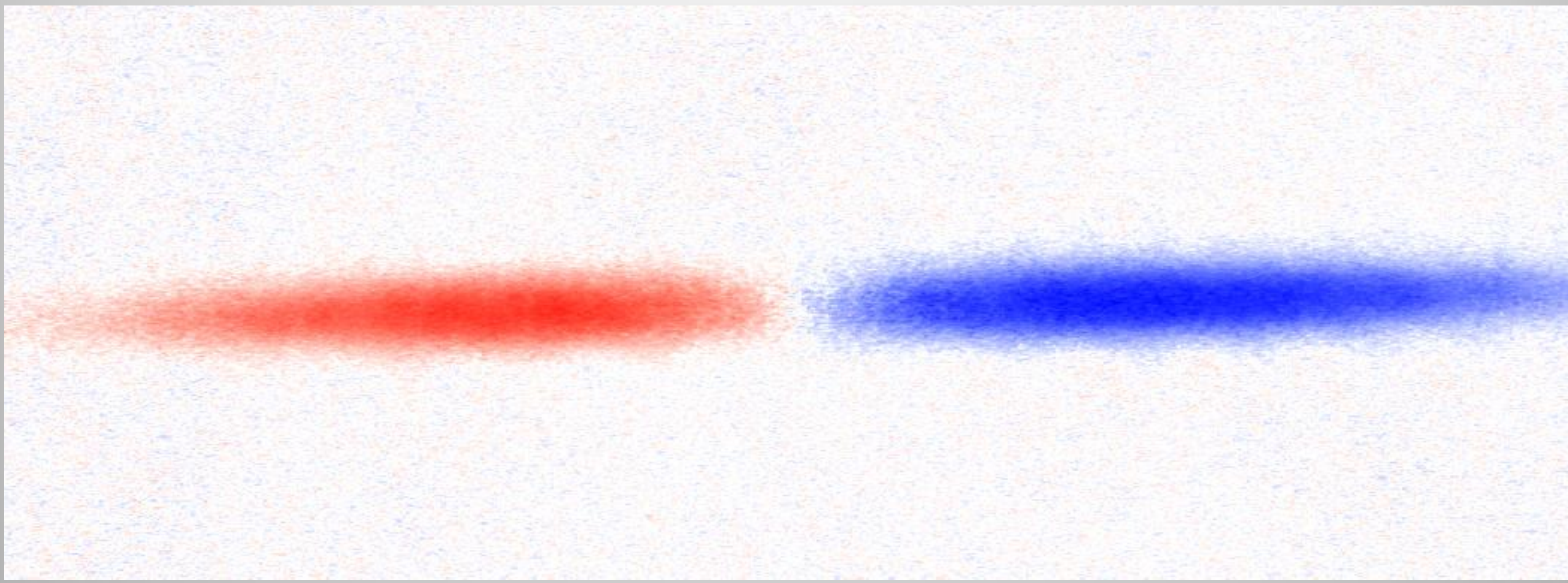
Difference



Earlier spin excitation experiments: DeMarco and Jin, PRL 88, 040405 (2002)

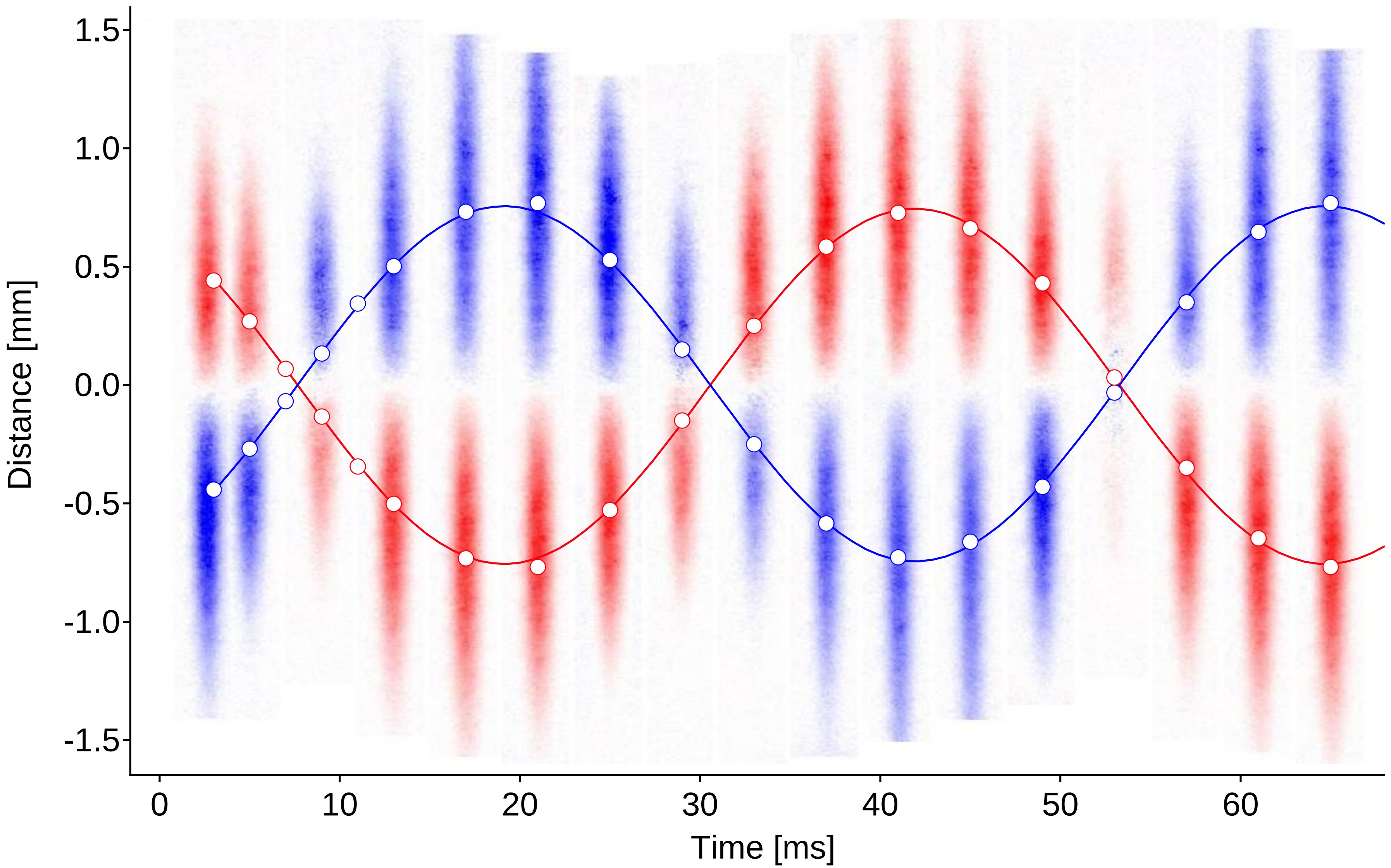
Little Fermi Collider (LFC)

Without Interactions



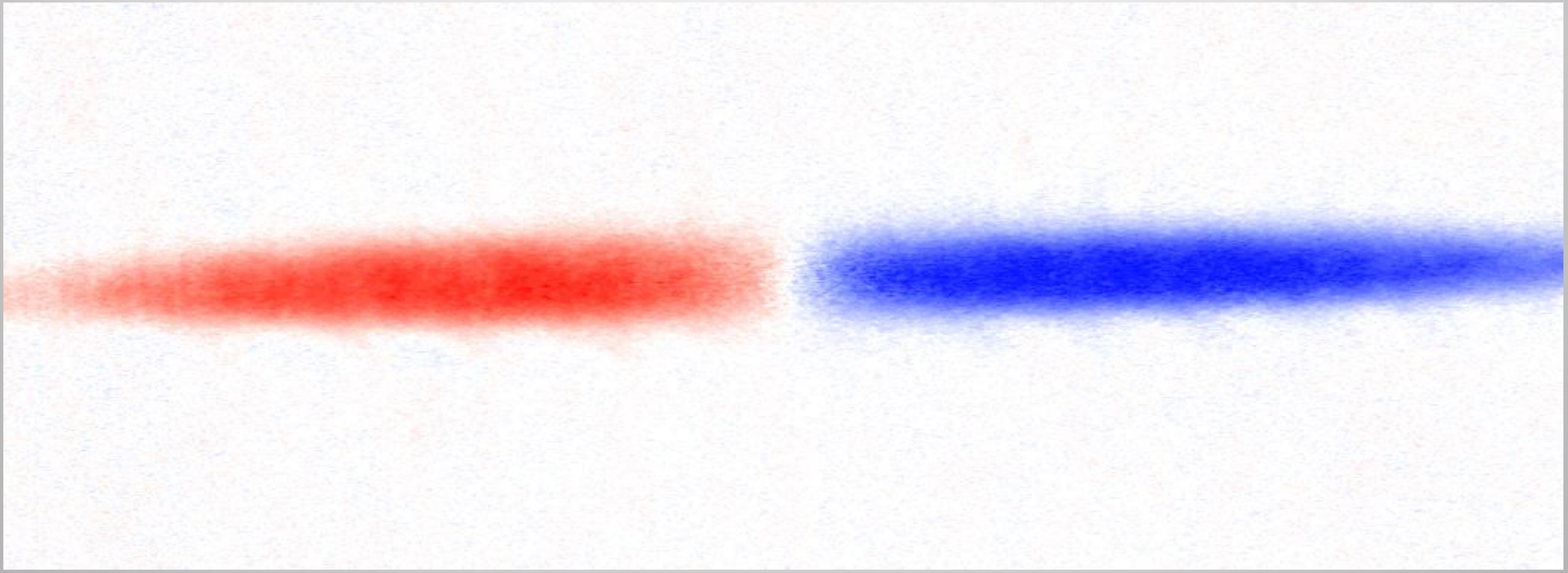
A.T. Sommer, M.J.H. Ku, G. Roati, M.W. Zwierlein, Nature 472, 201 (2011)

Evolution without interactions



Little Fermi Collider (LFC)

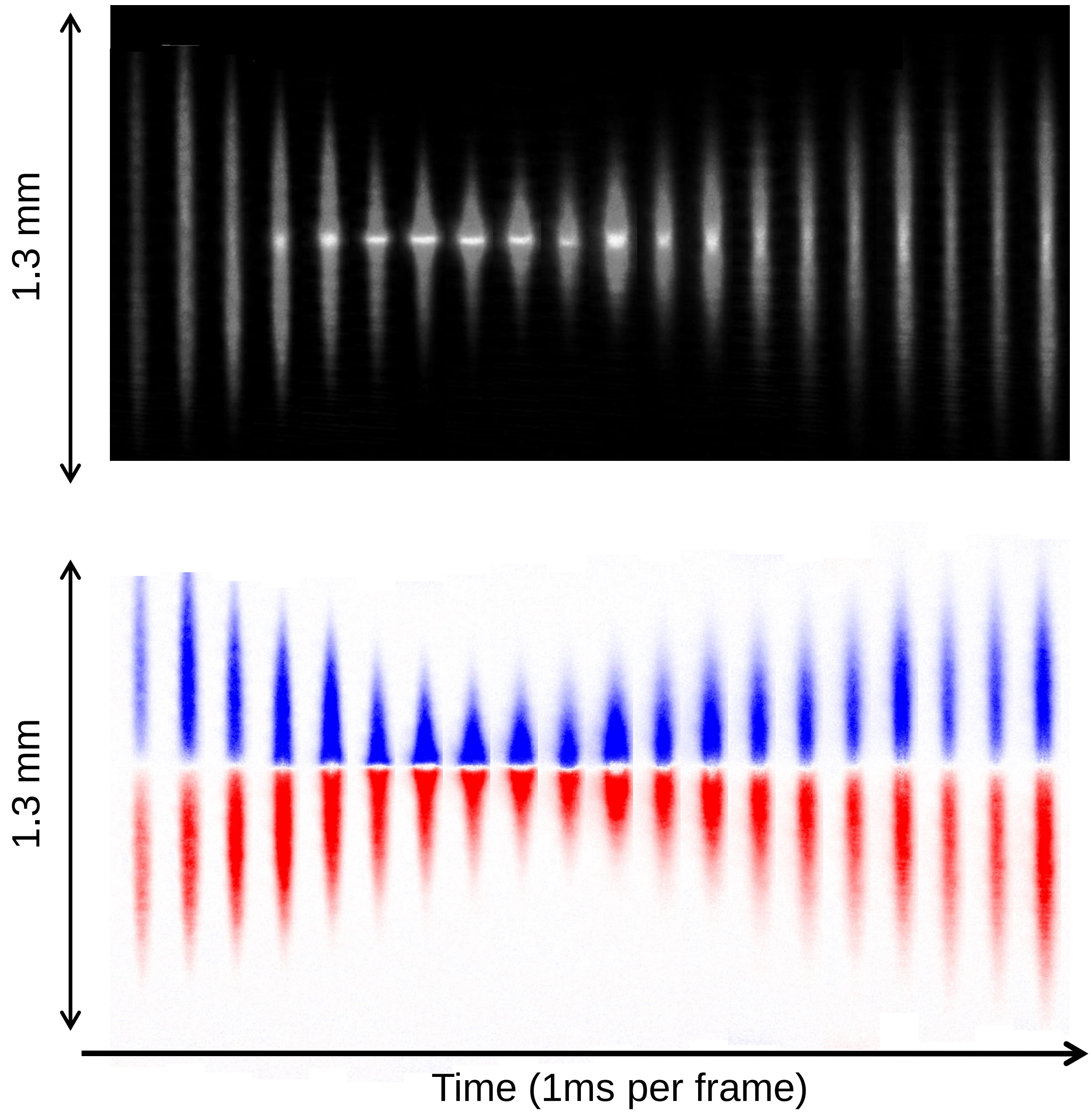
With resonant interactions



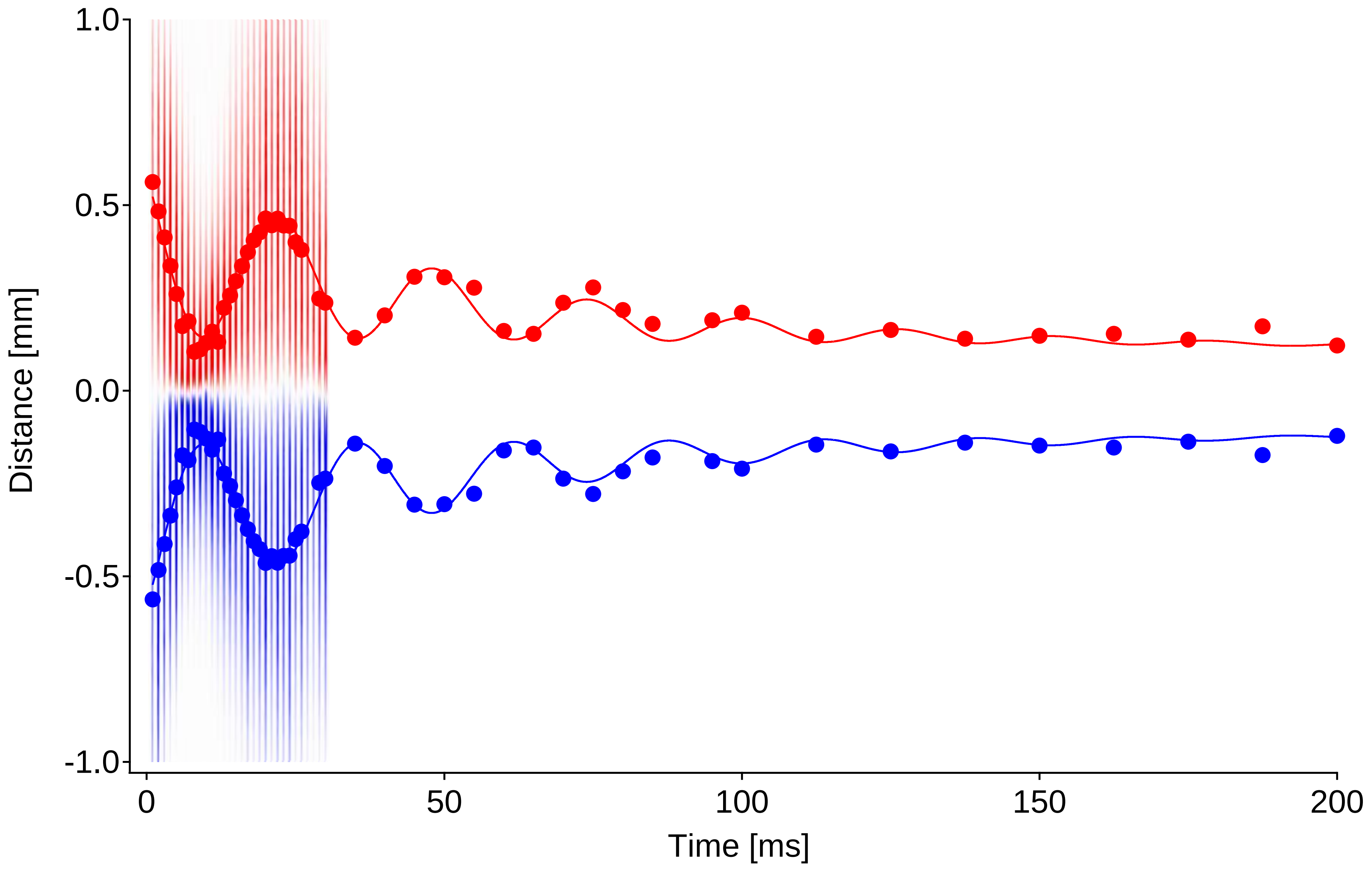
A.T. Sommer, M.J.H. Ku, G. Roati, M.W. Zwierlein, Nature 472, 201 (2011)

First collision

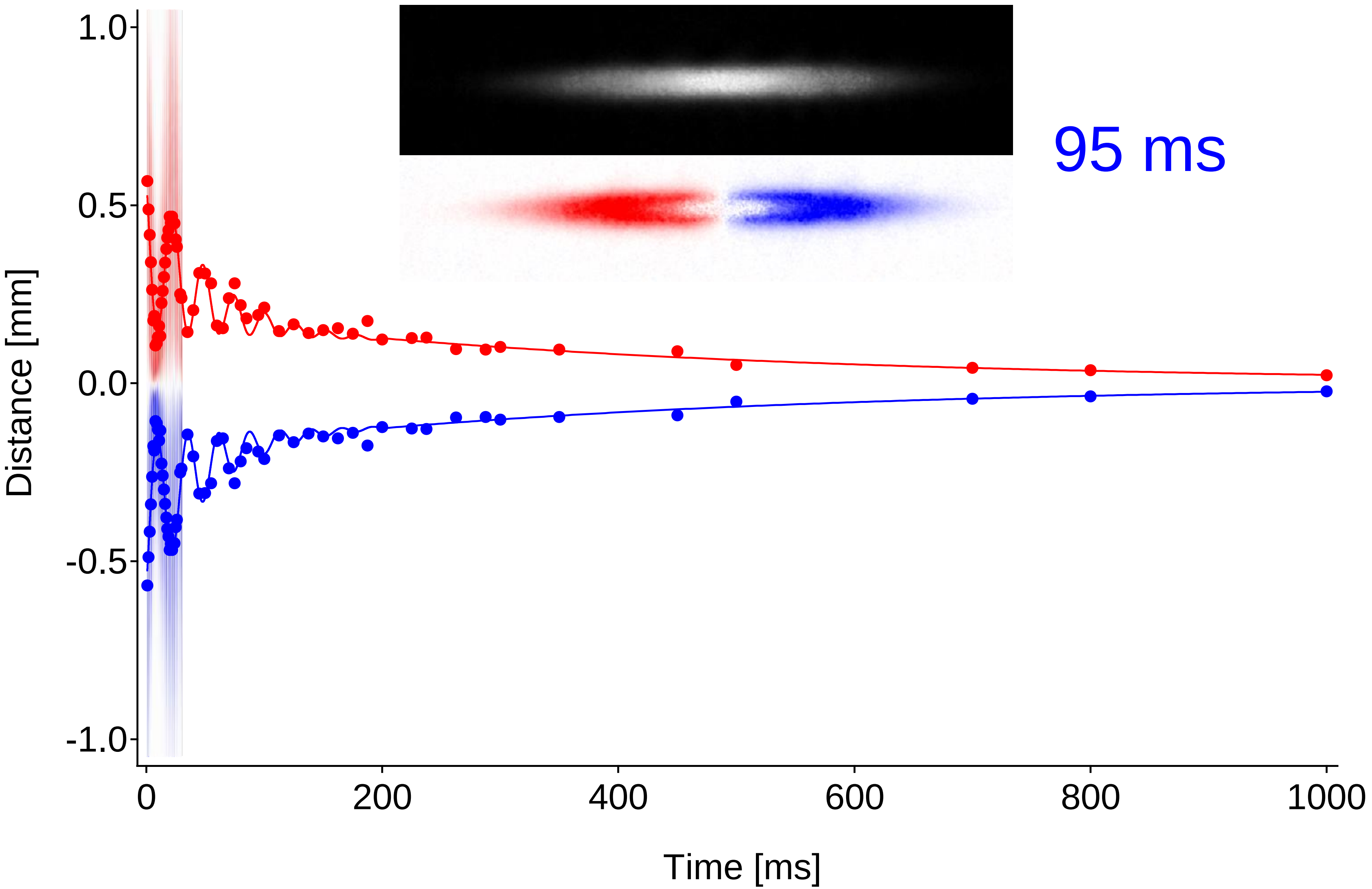
initial 20 ms



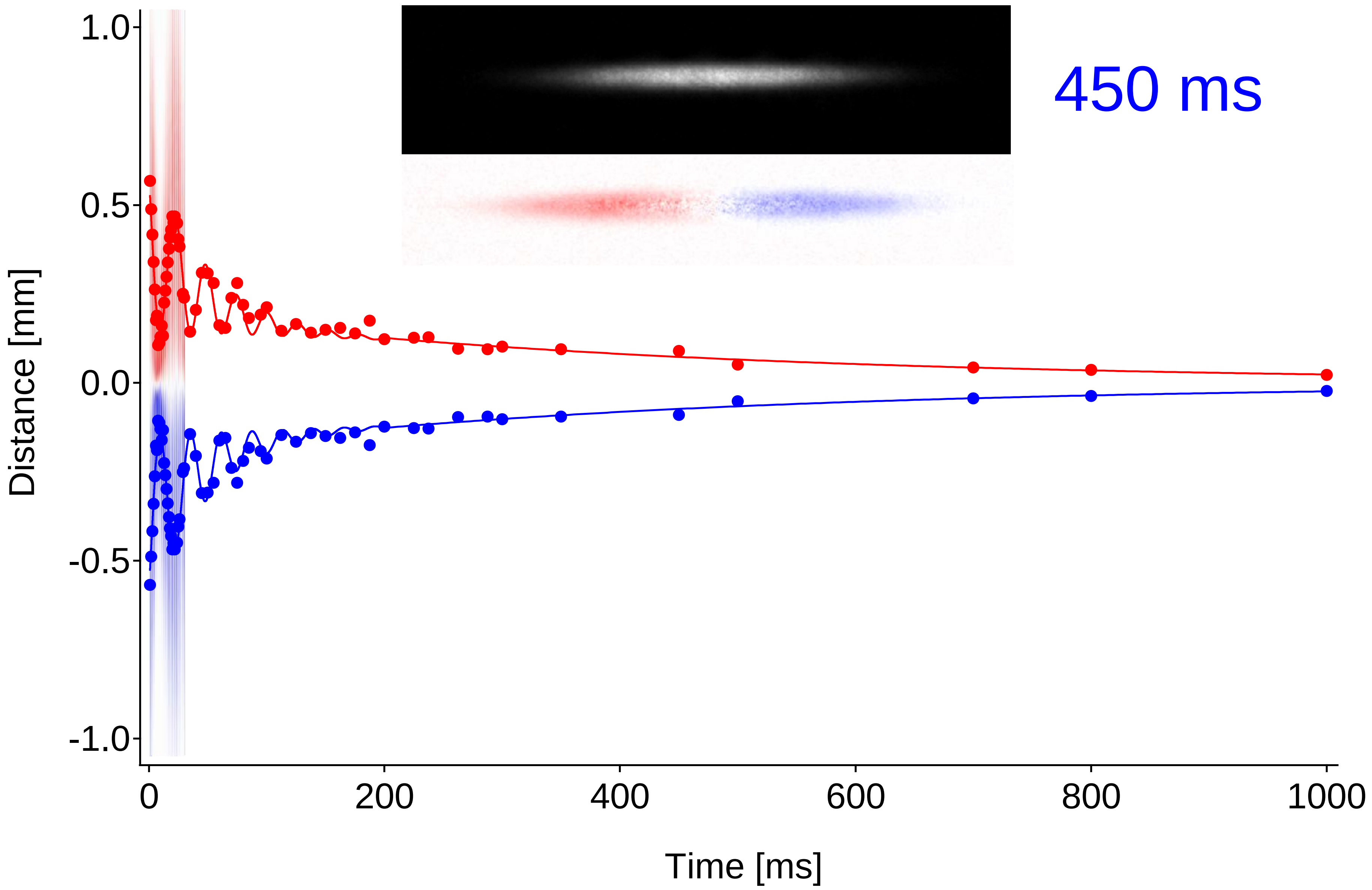
Later times



Much later times



Much later times



Universal Spin Transport

Relaxation of spin current only due to ↓↑ collisions

Resonant scattering cross section: $\sigma \sim \frac{1}{k_F^2}$

Mean free path: $l = \frac{1}{n\sigma} \sim \frac{1}{k_F}$ = interparticle spacing

"A perfect liquid"

Spin drag coefficient (∝ Collision rate) $\Gamma_{SD} \sim n\sigma v \sim \frac{\hbar}{m} k_F^2 \sim E_F / \hbar$

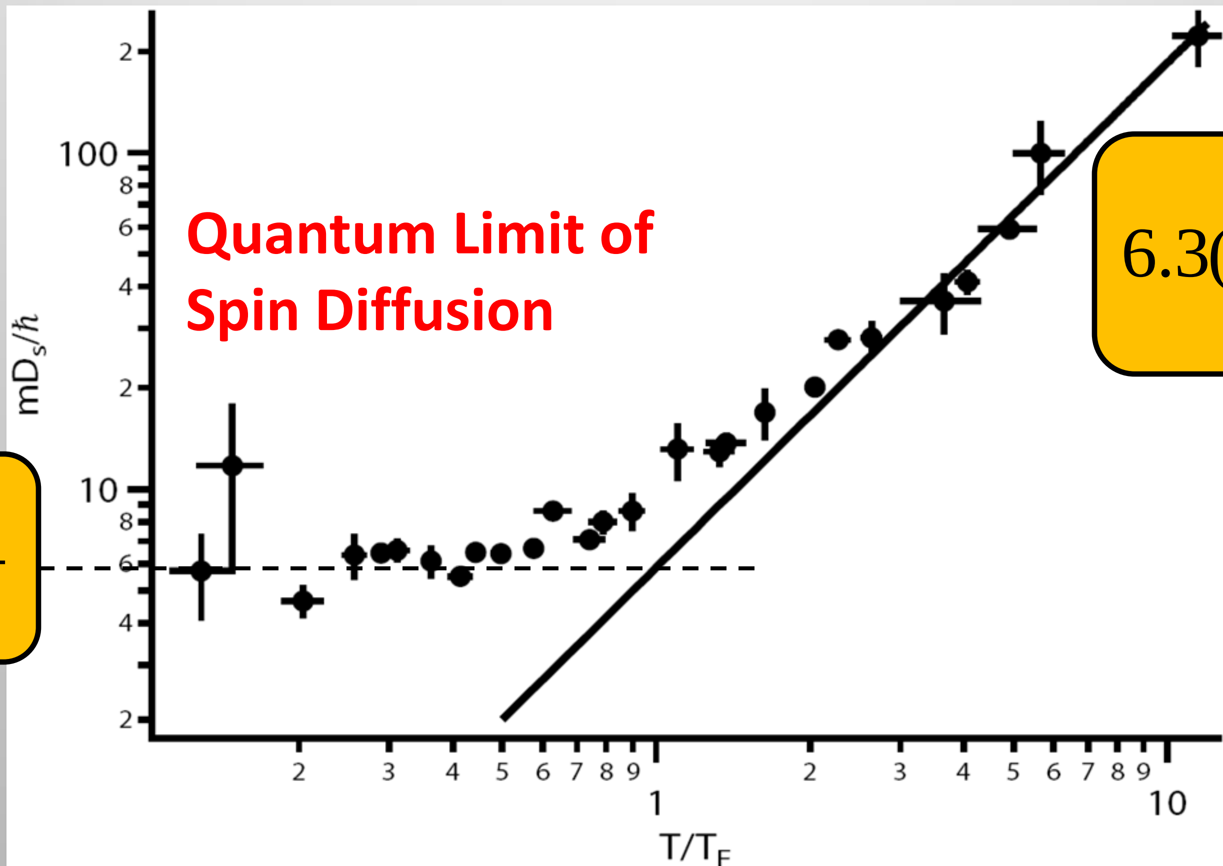
Diffusion constant: $D \sim \frac{(\text{mean free path})^2}{\text{collision time}} \sim \frac{\hbar}{m}$

$$\frac{\hbar}{m} = \frac{(100\ \mu\text{m})^2}{1\ \text{s}}$$

Spin Diffusion vs Temperature

Spin current = -D · Spin density gradient

Universal high-T behavior:



$$6.3(3)\,\frac{\hbar}{m}\left(\frac{T}{T_F}\right)^{3/2}$$

$$5.8\,\frac{\hbar}{m}$$

A.T. Sommer, M.J.H. Ku, G. Roati, M.W. Zwierlein, Nature 472, 201 (2011)

Can Fermi Gases become superfluid?

Superconductivity

Electrons are Fermions

Discovery of superconductivity 1911

Heike Kamerlingh-Onnes 1911

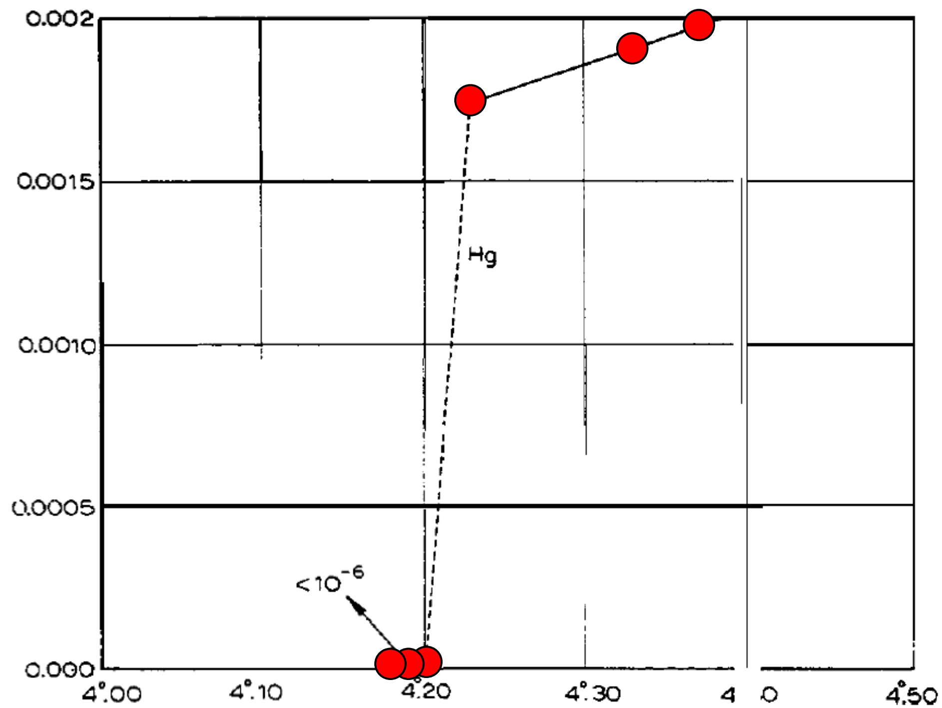


Fig. 17.

Fermionic Superfluidity

Condensation of Fermion Pairs

- Helium-3 (Lee, Osheroff, Richardson 1971)
- Superconductors: *Charged* superfluids of electron pairs

Frictionless flow ⇔ Resistance-less current

John Bardeen

Leon N. Cooper

John R. Schrieffer

- Neutron stars

In the core: Quark superfluid

BCS Wavefunction

- Many-body wavefunction for a condensate of Fermion Pairs:

$$\Psi(\mathbf{r}_1, \ldots, \mathbf{r}_N) = \varphi(|\mathbf{r}_1 - \mathbf{r}_2|)\chi_{12} \ldots \varphi(|\mathbf{r}_{N-1} - \mathbf{r}_N|)\chi_{N-1,N}$$

Spatial pair wavefunction

Spin wavefunction

$$\chi_{ij} = \frac{1}{\sqrt{2}}\left(|\uparrow\rangle_i |\downarrow\rangle_j - |\downarrow\rangle_i |\uparrow\rangle_j\right)$$

- Second quantization:

$$|\Psi\rangle_N = \int \prod_i d^3 r_i \, \varphi(\mathbf{r}_1 - \mathbf{r}_2)\Psi_\uparrow^\dagger(\mathbf{r}_1)\Psi_\downarrow^\dagger(\mathbf{r}_2) \ldots \varphi(\mathbf{r}_{N-1} - \mathbf{r}_N)\Psi_\uparrow^\dagger(\mathbf{r}_{N-1})\Psi_\downarrow^\dagger(\mathbf{r}_N)\,|0\rangle$$

- Fourier transform: Pair wavefunction: $\varphi(\mathbf{r}) = \sum_k \varphi_k \frac{e^{i\mathbf{k}\cdot\mathbf{r}}}{\sqrt{\Omega}}$

  Operators: $\Psi_\sigma^\dagger(\mathbf{r}) = \sum_k c_{k\sigma}^\dagger \frac{e^{-i\mathbf{k}\cdot\mathbf{r}}}{\sqrt{\Omega}}$

- Pair creation operator: $b^\dagger = \sum \varphi_k c_{k\uparrow}^\dagger c_{-k\downarrow}^\dagger$

- Many-body wavefunction: $|\Psi\rangle_N = {b^\dagger}^{N/2}\,|0\rangle$

  a fermion pair condensate

$|\Psi\rangle_N$ is not a Bose condensate

$$|\Psi\rangle_N = b^{\dagger\, N/2}|0\rangle$$

- Commutation relations for pair creation/annihilation operators

$$[b^\dagger, b^\dagger]_- = \sum_{kk'} \varphi_k \varphi_{k'} \left[c^\dagger_{k\uparrow} c^\dagger_{-k\downarrow}, c^\dagger_{k'\uparrow} c^\dagger_{-k'\downarrow}\right]_- = 0 \quad ✓$$

$$[b, b]_- = \cdots = 0 \quad ✓$$

$$[b, b^\dagger]_- = \cdots = \sum_k |\varphi_k|^2 (1 - n_{k\uparrow} - n_{k\downarrow}) \neq 1 \quad ✗$$

Occupation of momentum k

- pairs do not obey Bose commutation relations, *unless* $n_k \ll 1$

$$[b, b^\dagger]_- \approx \sum_k |\varphi_k|^2 = 1$$

BEC limit of tightly bound molecules

BCS Wavefunction

- Introduce coherent state / switch to grand-canonical description:

$$
\begin{aligned}
\mathcal{N}\,|\Psi\rangle &= \sum_{J_{\text{even}}} \frac{N_p^{J/4}}{(J/2)!}\,|\Psi\rangle_J \quad = \sum_M \frac{1}{M!} N_p^{M/2}\, b^{\dagger\,M}\,|0\rangle \\
&= e^{\sqrt{N_p}\, b^\dagger}\,|0\rangle \\
&= \prod_k e^{\sqrt{N_p}\,\varphi_k c^\dagger_{k\uparrow} c^\dagger_{-k\downarrow}}\,|0\rangle \\
&= \prod_k \left(1 + \sqrt{N_p}\,\varphi_k\, c^\dagger_{k\uparrow} c^\dagger_{-k\downarrow}\right)|0\rangle
\end{aligned}
$$

$c^\dagger_k$ and $c^\dagger_{k'}$ commute

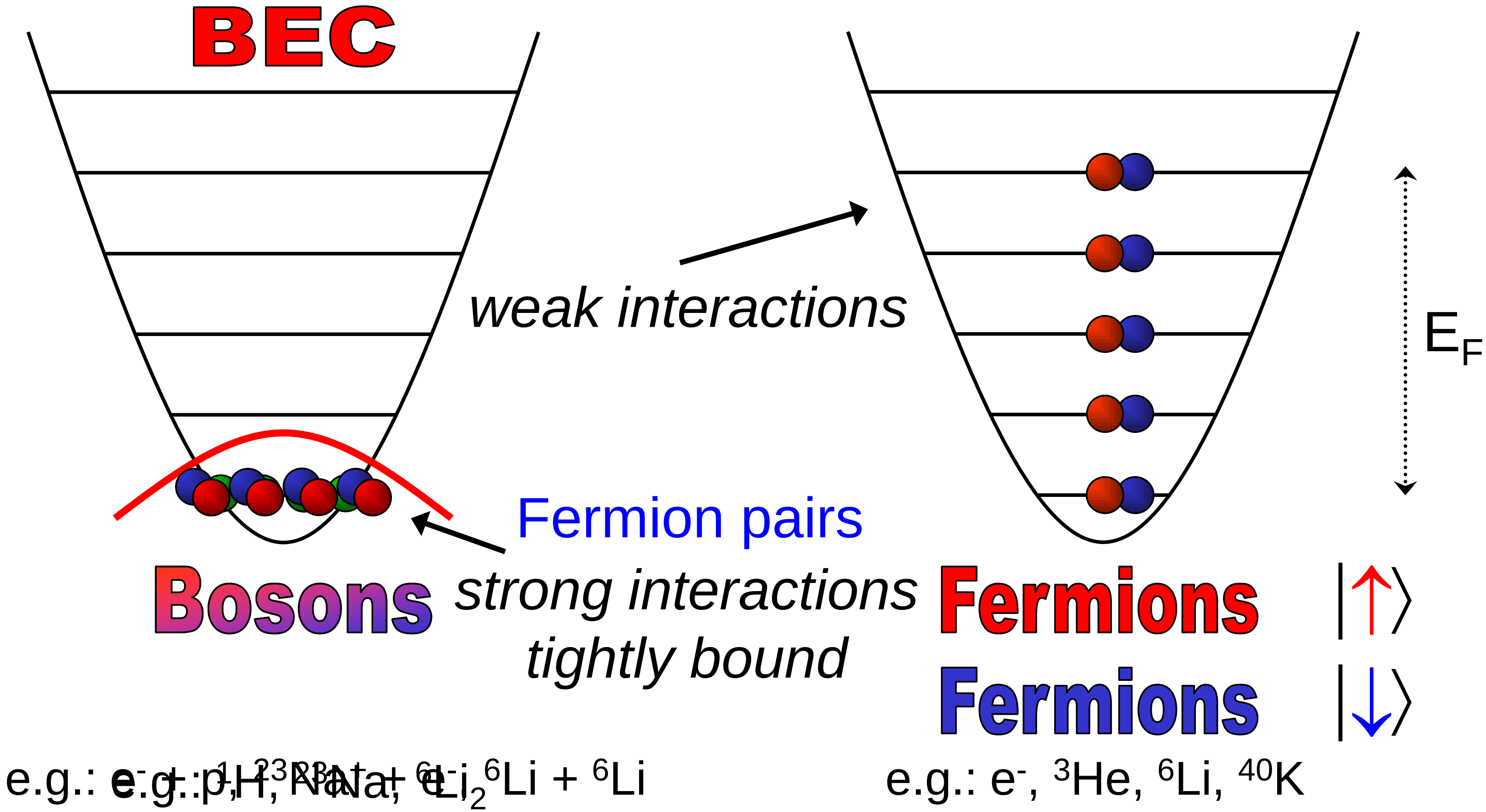
because $c^{\dagger 2}_k = 0$

- Normalization: $\mathcal{N} = \prod_k \frac{1}{u_k} = \prod_k \sqrt{1 + N_p |\varphi_k|^2}$

- BCS wavefunction: $$|\Psi_{\text{BCS}}\rangle = \prod_k \left(u_k + v_k c^\dagger_{k\uparrow} c^\dagger_{-k\downarrow}\right)|0\rangle$$

with $v_k = \sqrt{N_p}\,\varphi_k u_k$ and $|u_k|^2 + |v_k|^2 = 1$

Bosons vs Fermions



$$T_C \approx T_F$$

Interatomic interactions

- Mean-field interaction energy: $$E_{\mathrm{MF}} = \frac{4\pi\hbar^2 na}{m}$$
- Weak or strong interaction? $$\frac{E_{\mathrm{MF}}}{E_F} \simeq k_F a$$

$$k_F = (6\pi^2 n)^{1/3} \sim 1/2000 a_0$$

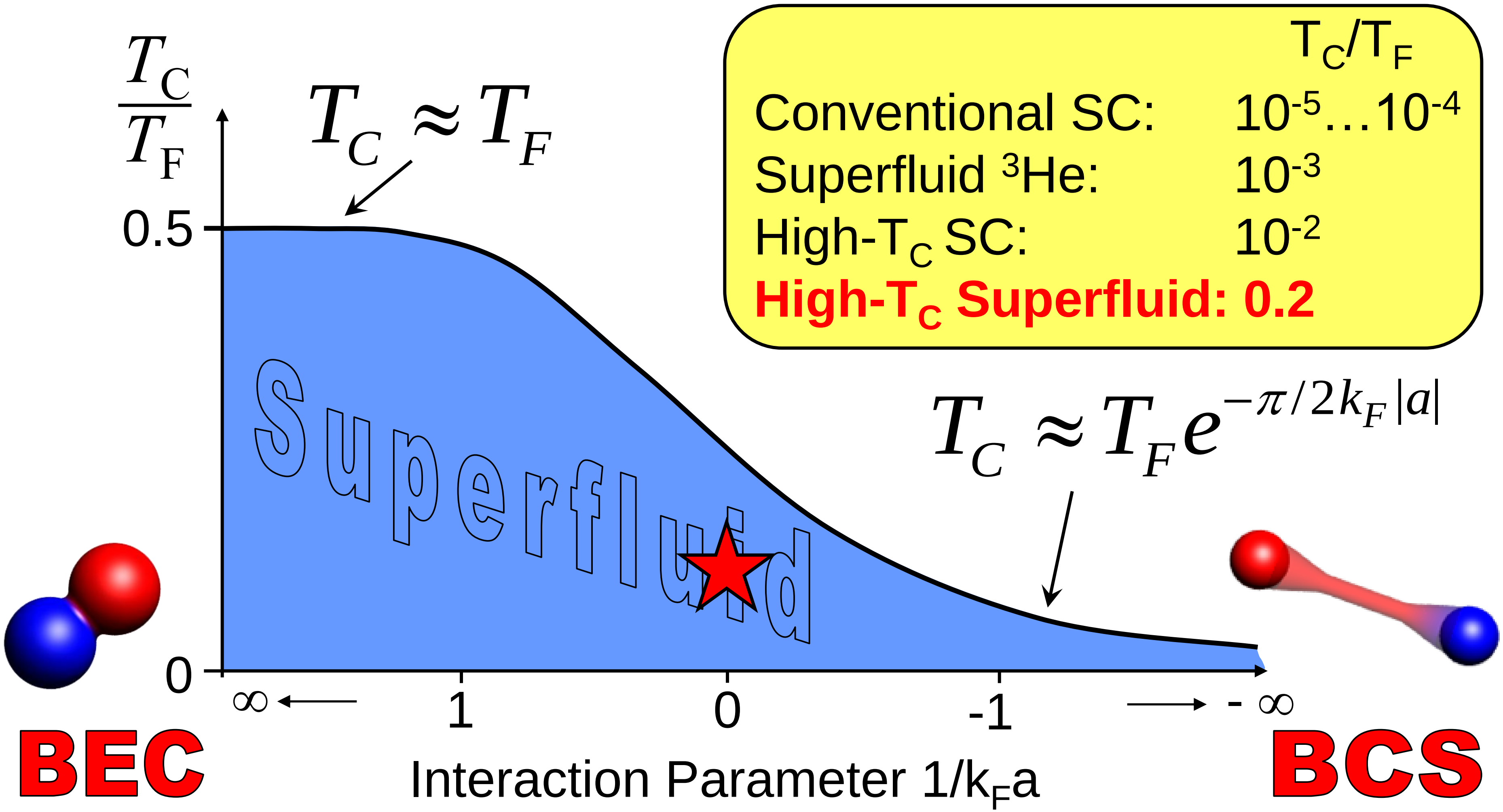
$$a \sim 50 - 100 a_0$$

$$k_F a \lesssim 5\%$$

- Typically weak interaction
- Superconductors: Electron-Phonon interaction also weak: $$\frac{\hbar\omega_D}{E_F} = \frac{100\ \mathrm{K}}{10\,000\ \mathrm{K}} \sim 1\%$$

How can we have atom pairs with arbitrarily weak interaction?

Critical Temperature for Fermionic Superfluidity



Scaled to the density of electrons in solids:

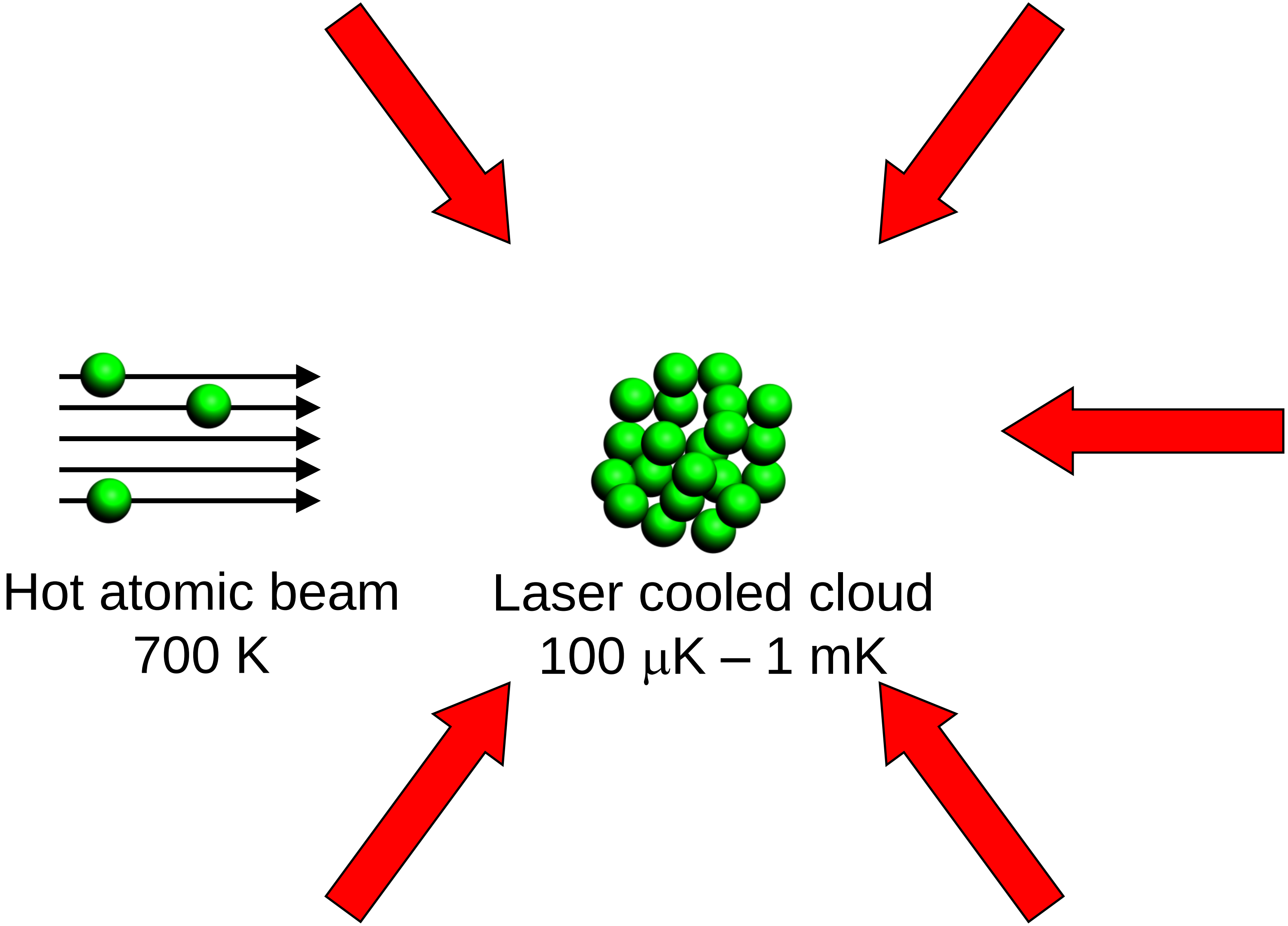
Superconductivity far above room temperature!

Experimental realization of the BEC-BCS Crossover

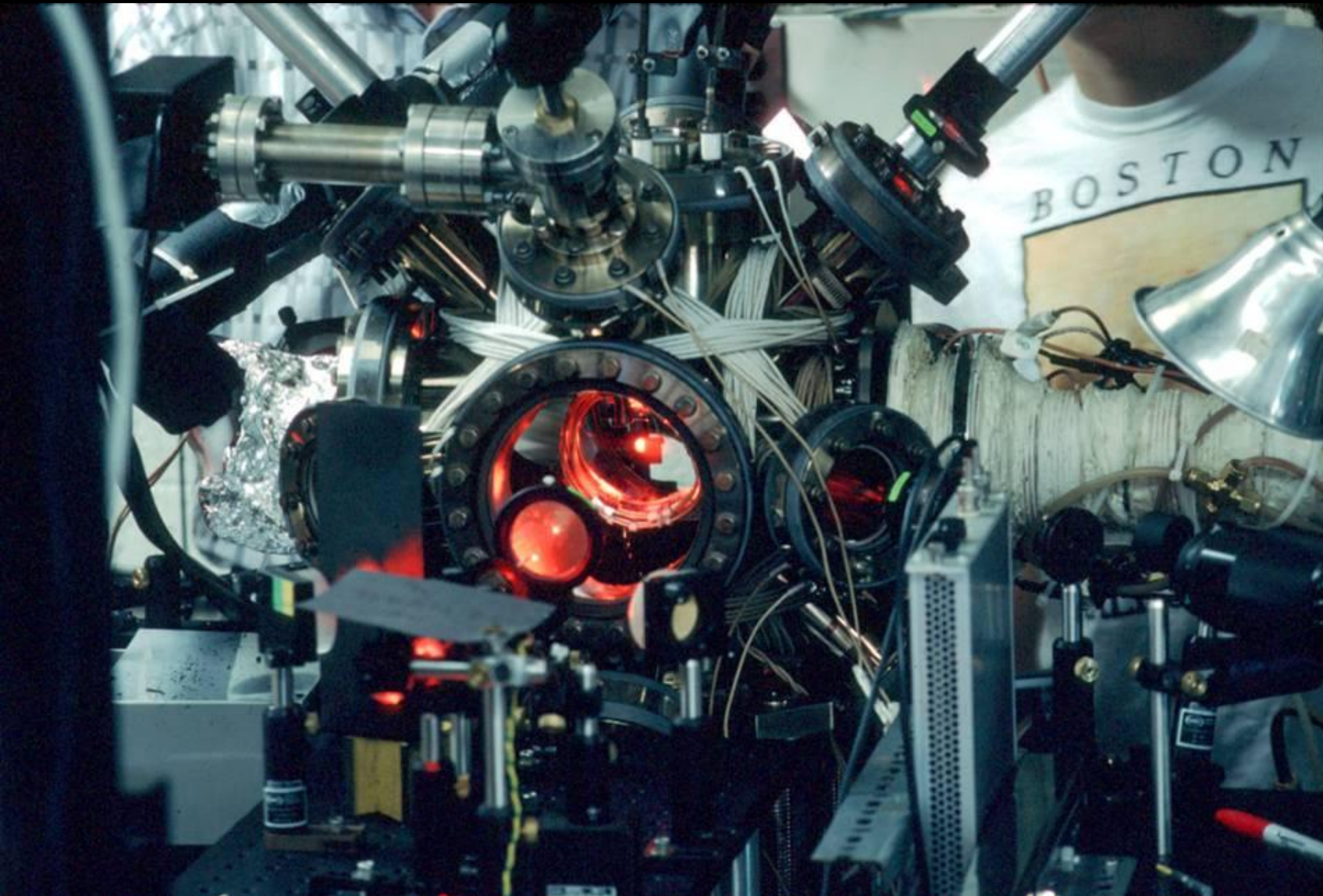
The cooling methods

- Laser cooling
- Evaporative cooling

Techniques: Laser cooling

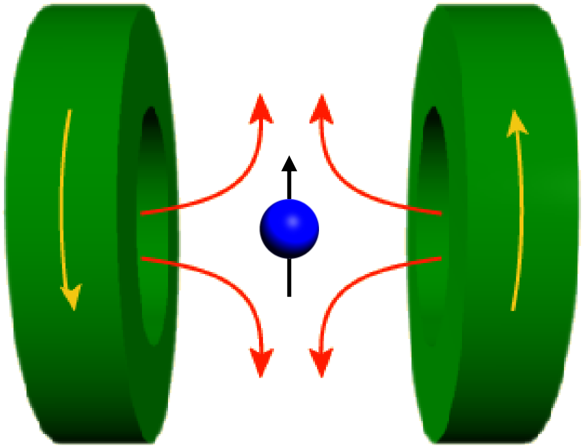


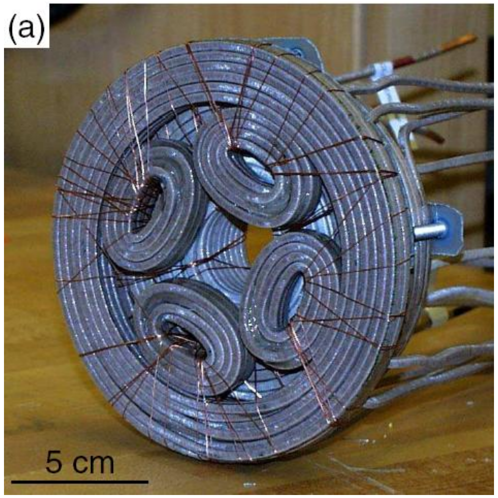
Chu, Cohen-Tannoudji, Phillips, Pritchard, Ashkin, Lethokov, Hänsch,
Schawlow, Wineland …


BOSTON

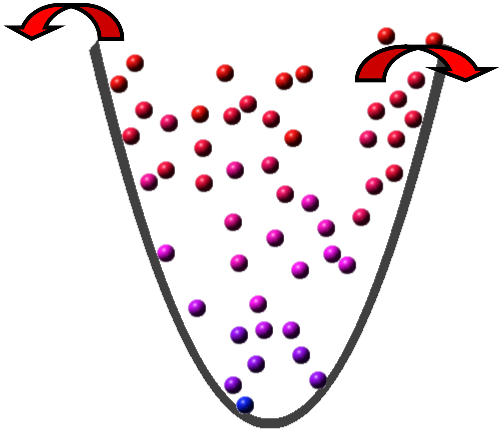
Techniques

Magnetic Trapping





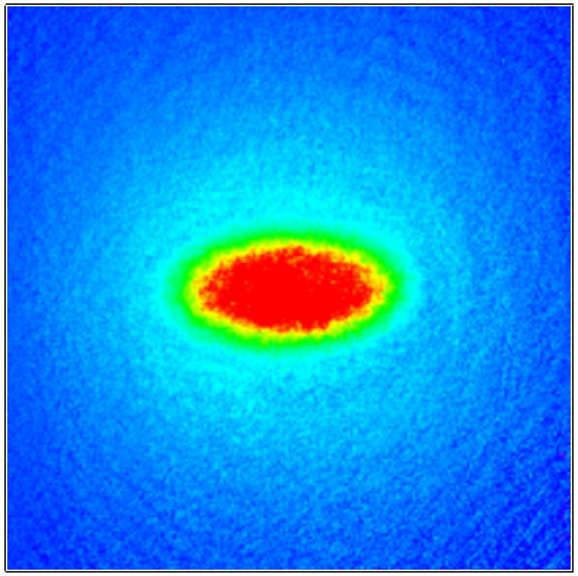
Evaporative Cooling



Source of ultracold fermions

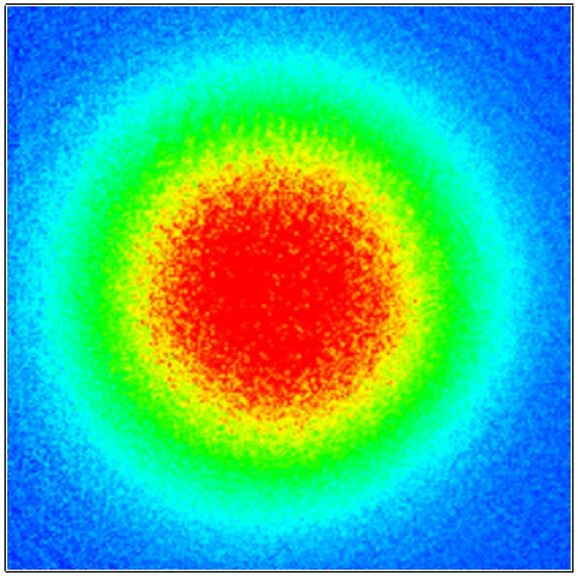
Cool fermionic lithium-6
using sodium as a refrigerator

10^7 atoms in BEC (w/o Li)



Bosons

5 x 10^7 Li atoms at $\frac{T}{T_F} < 0.3$

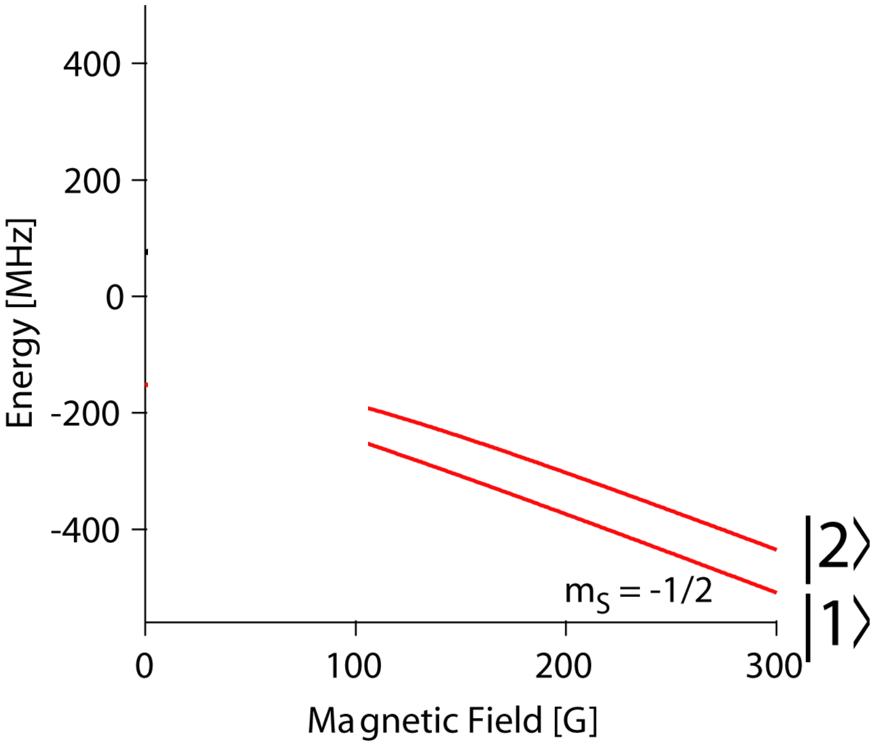


Fermions

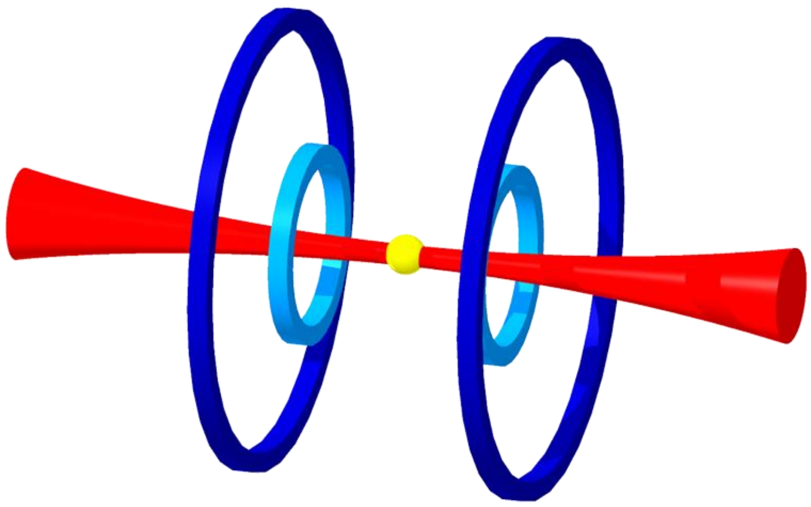
Z. Hadzibabic *et.al.*, PRL **91**, 160401 (2003)

Preparation of an interacting Fermi system in Lithium-6

Electronic spin: S = ½, Nuclear Spin: I = 1
→ (2I+1)(2S+1) = 6 hyperfine states



Optical trapping @ 1064 nm

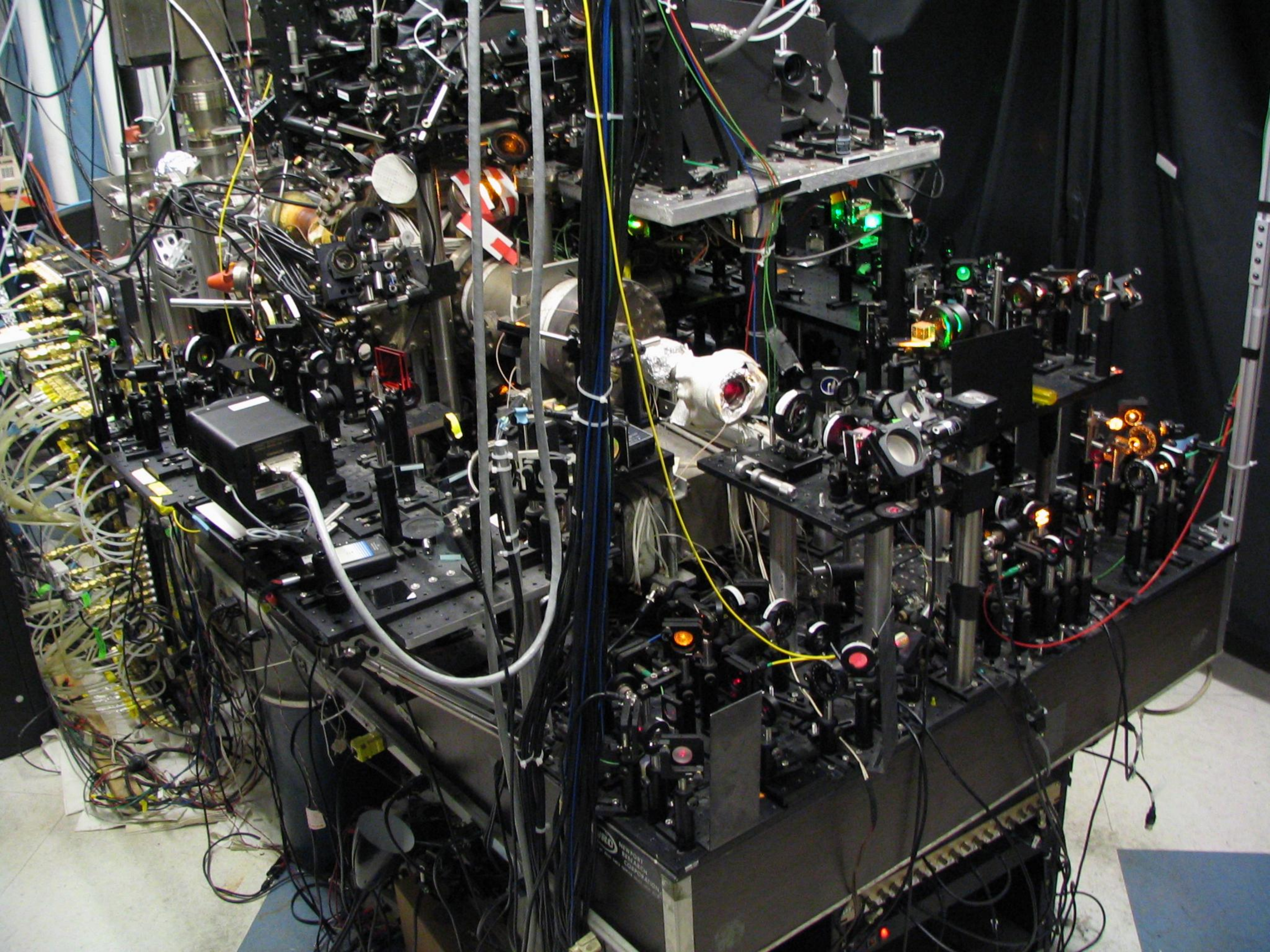


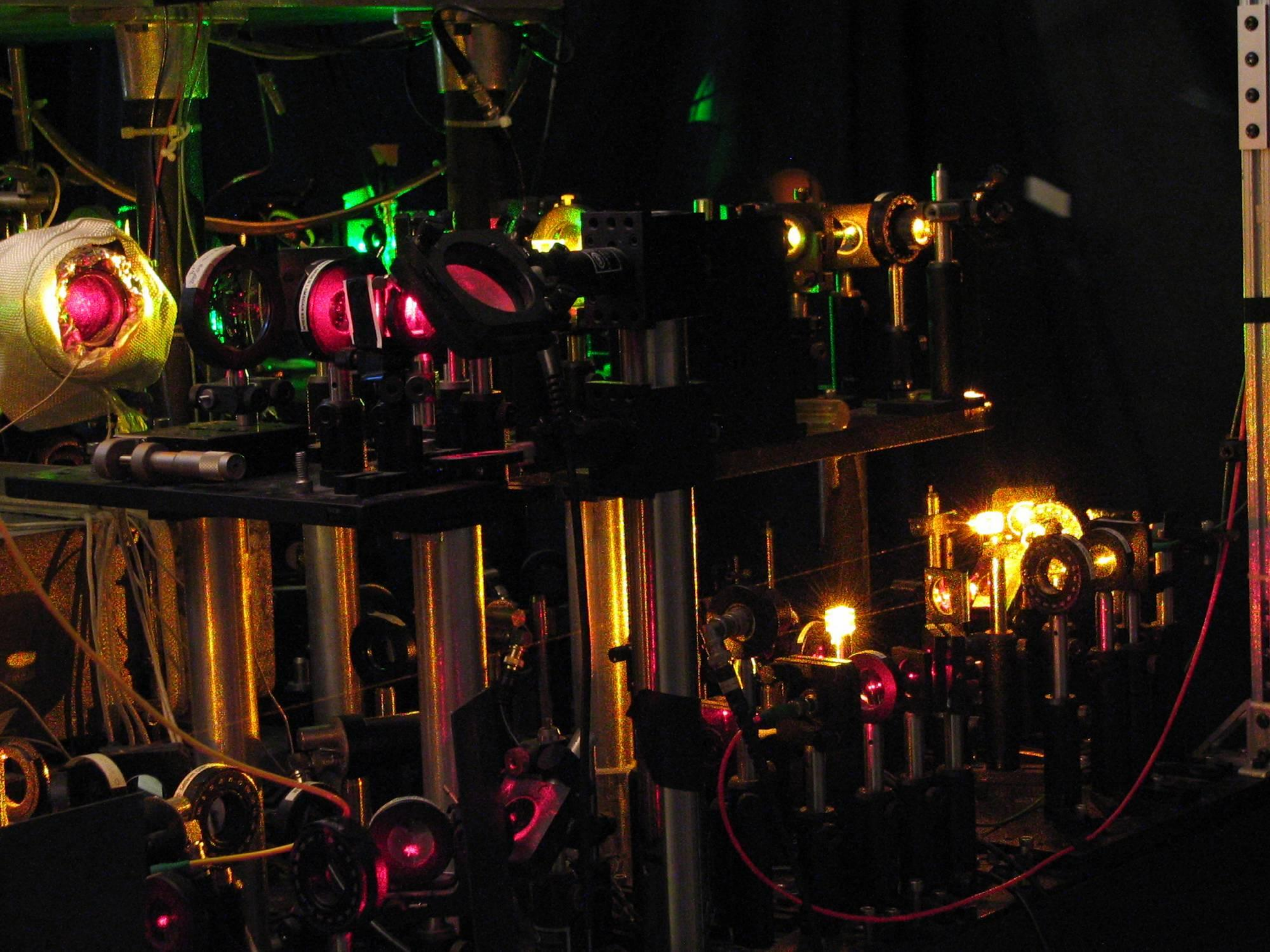
ν_{axial} = 10-20 Hz
ν_{radial} = 50–200 Hz
E_{trap} = 0.5 - 5 μK

At high fields, states |1> and |2> have large and negative scattering length

$$a_{12} = -2100\ a_0$$

High T_C !

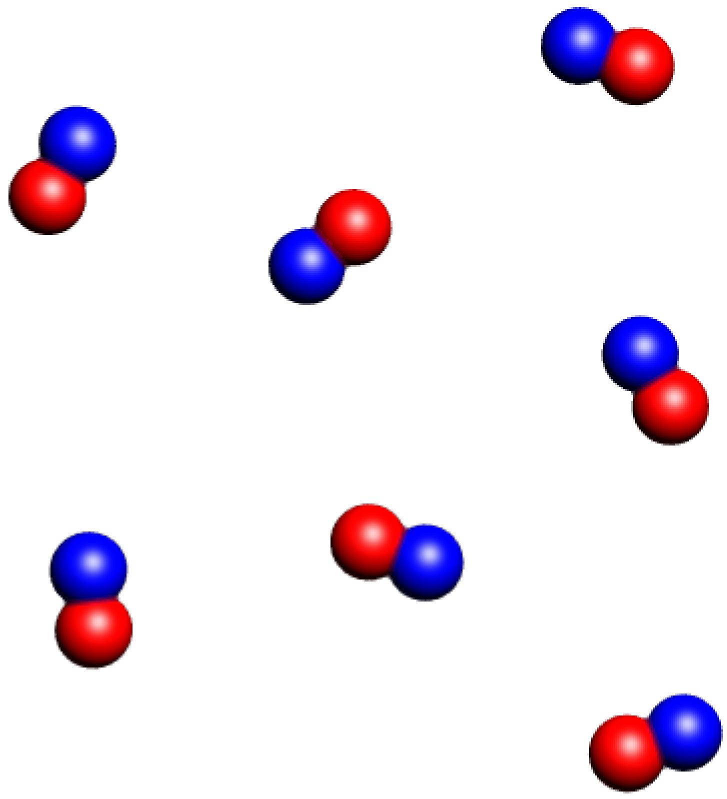




Feshbach resonances: Tuning the interactions

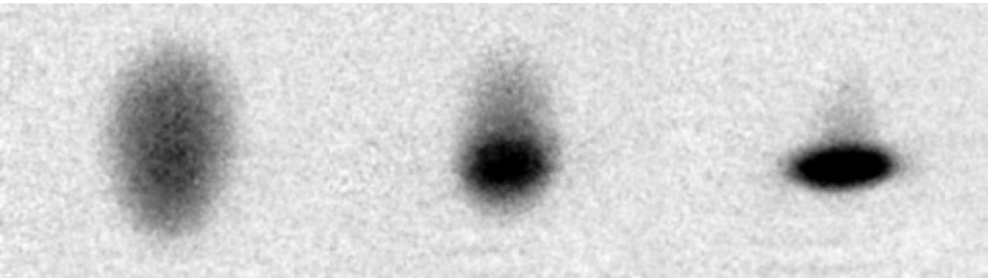
$$T_C \approx T_F$$

Tune!



Disclaimer: That's a cartoon picture

BEC of Fermion Pairs (Molecules)

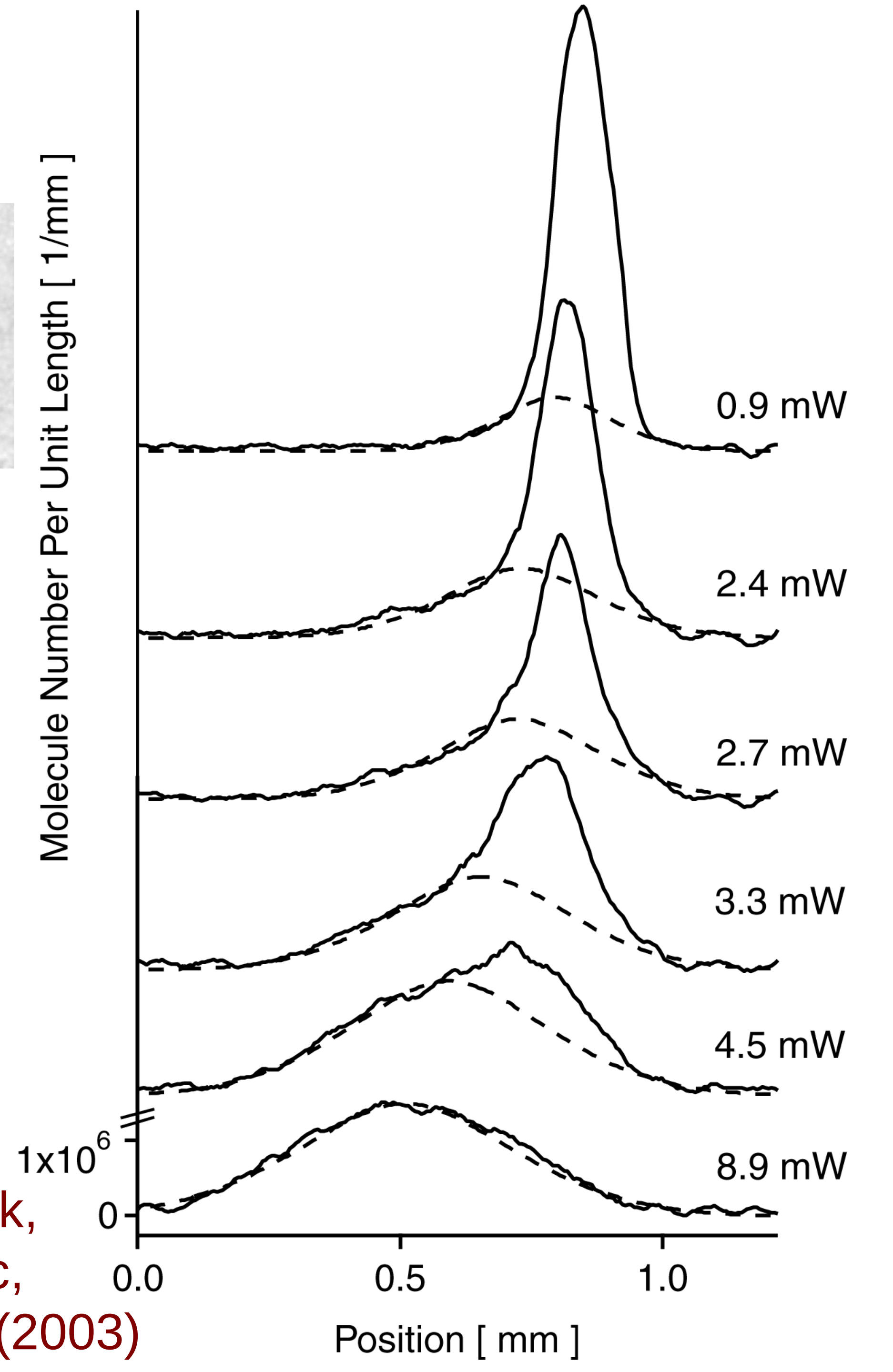


$T > T_C$ $T < T_C$ $T \ll T_C$

These days: Up to 10 million condensed molecules

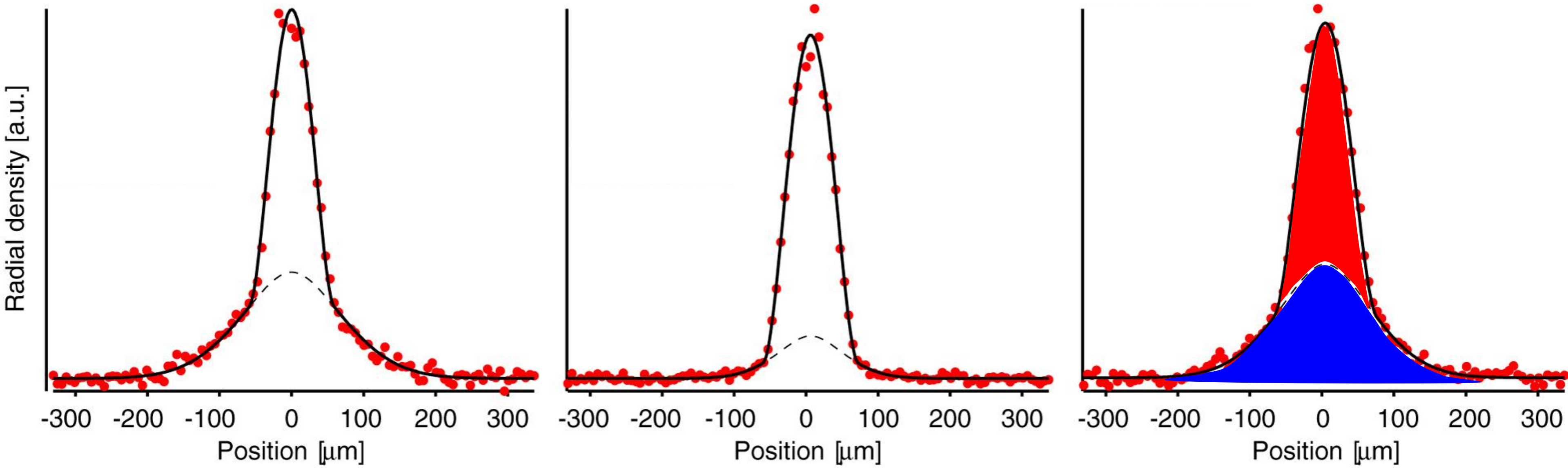
Boulder	Nov '03
Innsbruck	Nov '03, Jan '04
MIT	Nov '03
Paris	March '04
Rice, Duke	

M.W. Zwierlein, C. A. Stan, C. H. Schunck, S.M.F. Raupach, S. Gupta, Z. Hadzibabic, W. Ketterle, Phys. Rev. Lett. 91, 250401 (2003)



Observation of Pair Condensates

BEC-Side | Resonance | BCS-Side (above dissociation limit for molecules)

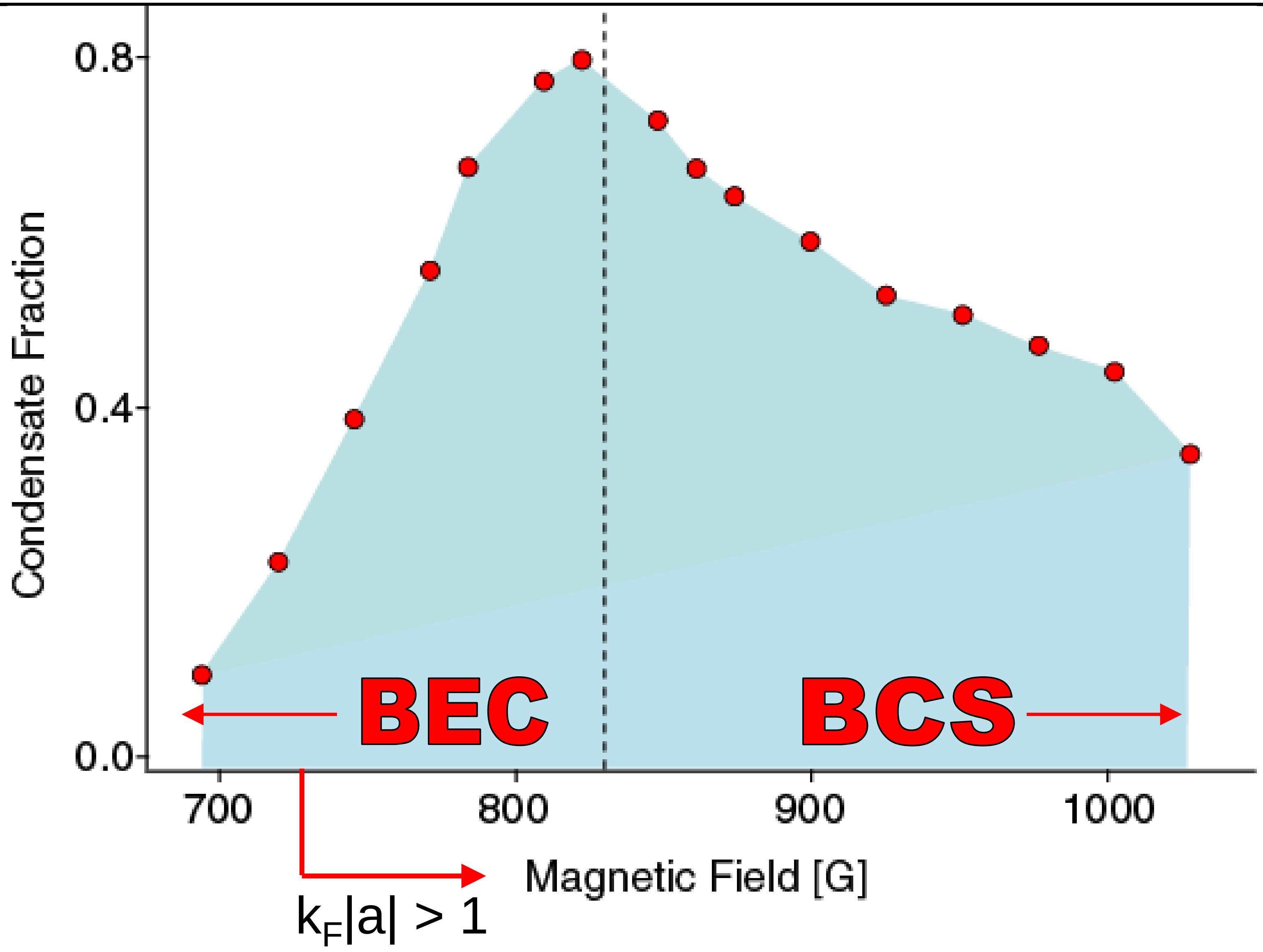


Thermal + condensed pairs

First observation: C.A. Regal et al., Phys. Rev. Lett. **92**, 040403 (2004)

M.W. Zwierlein, C.A. Stan, C.H. Schunck, S.M.F. Raupach, A.J. Kerman, W. Ketterle, Phys. Rev. Lett. **92**, 120403 (2004).

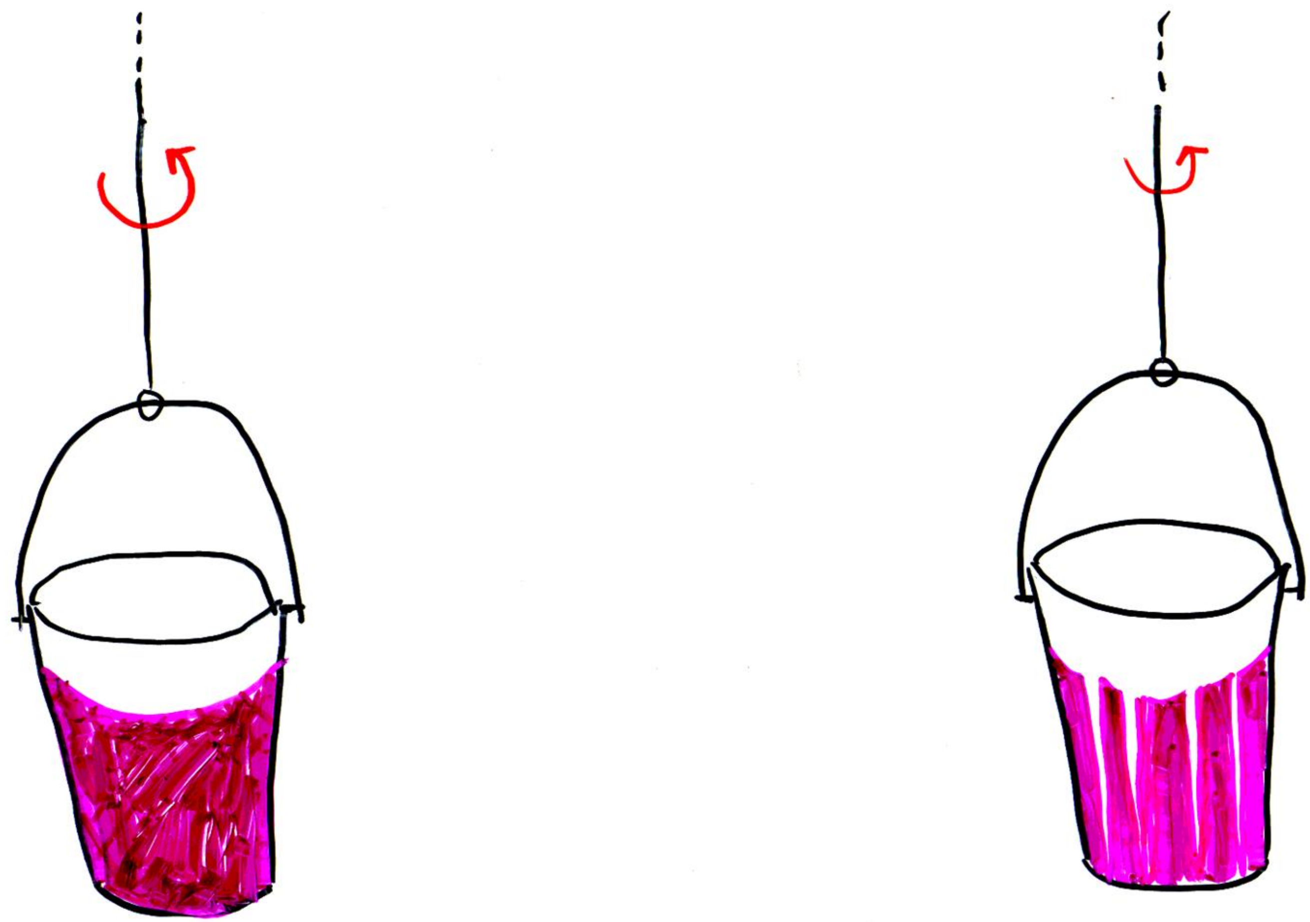
Condensate Fraction vs Magnetic Field



M.W. Zwierlein, C.A. Stan, C.H. Schunck, S.M.F. Raupach, A.J. Kerman, W. Ketterle, Phys. Rev. Lett. **92**, 120403 (2004).

How can we show that these gases are superfluid?

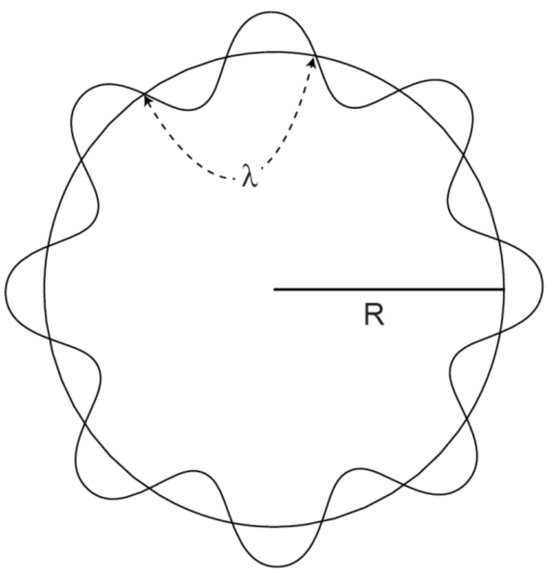
Rotating Fluids



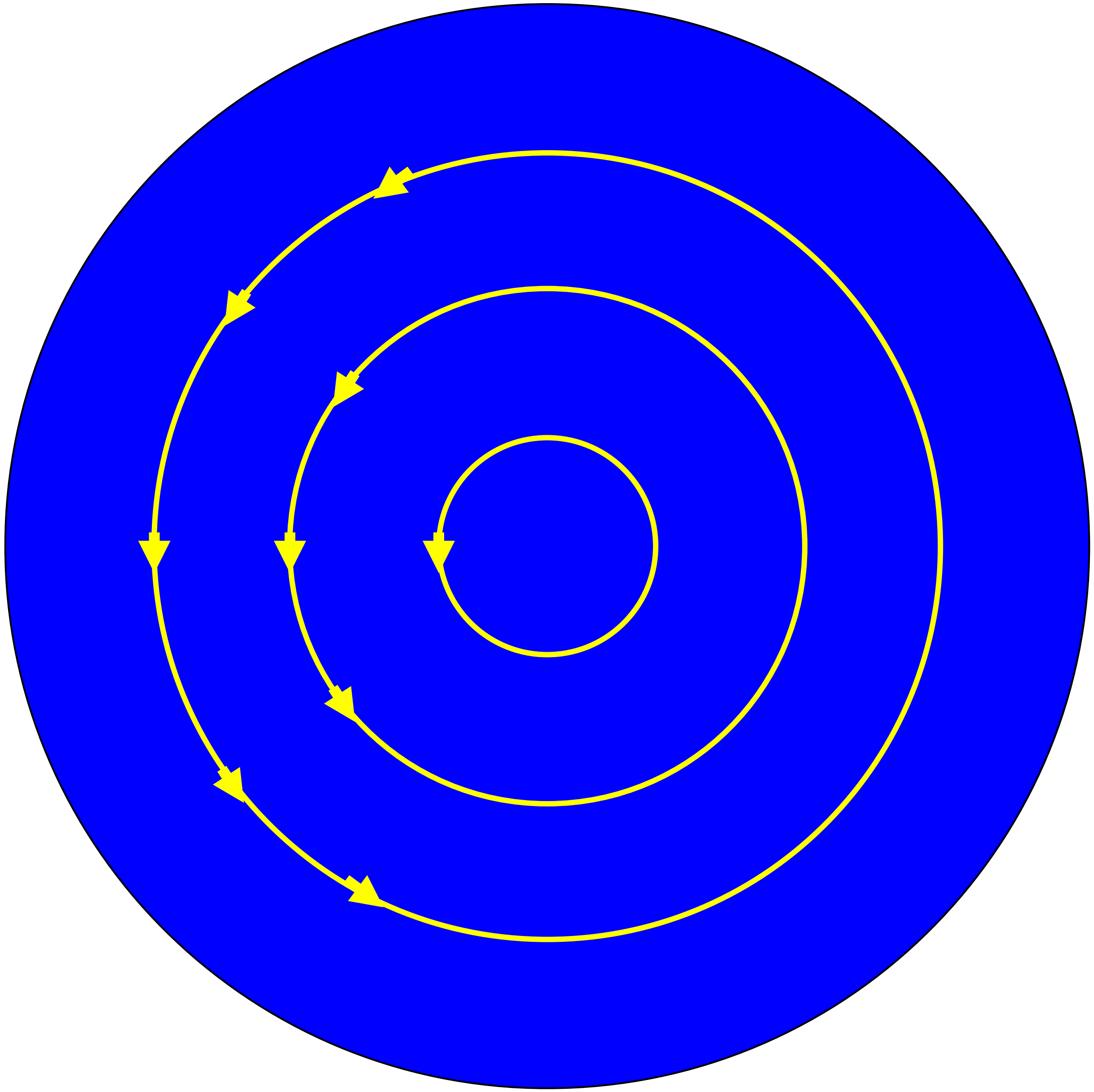
Normal Quantum

Fluid

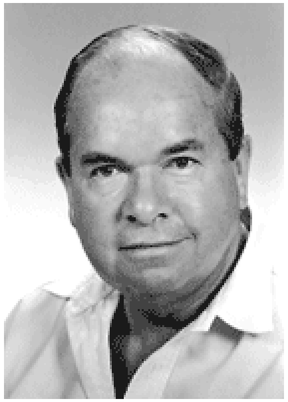
Rotating superfluid



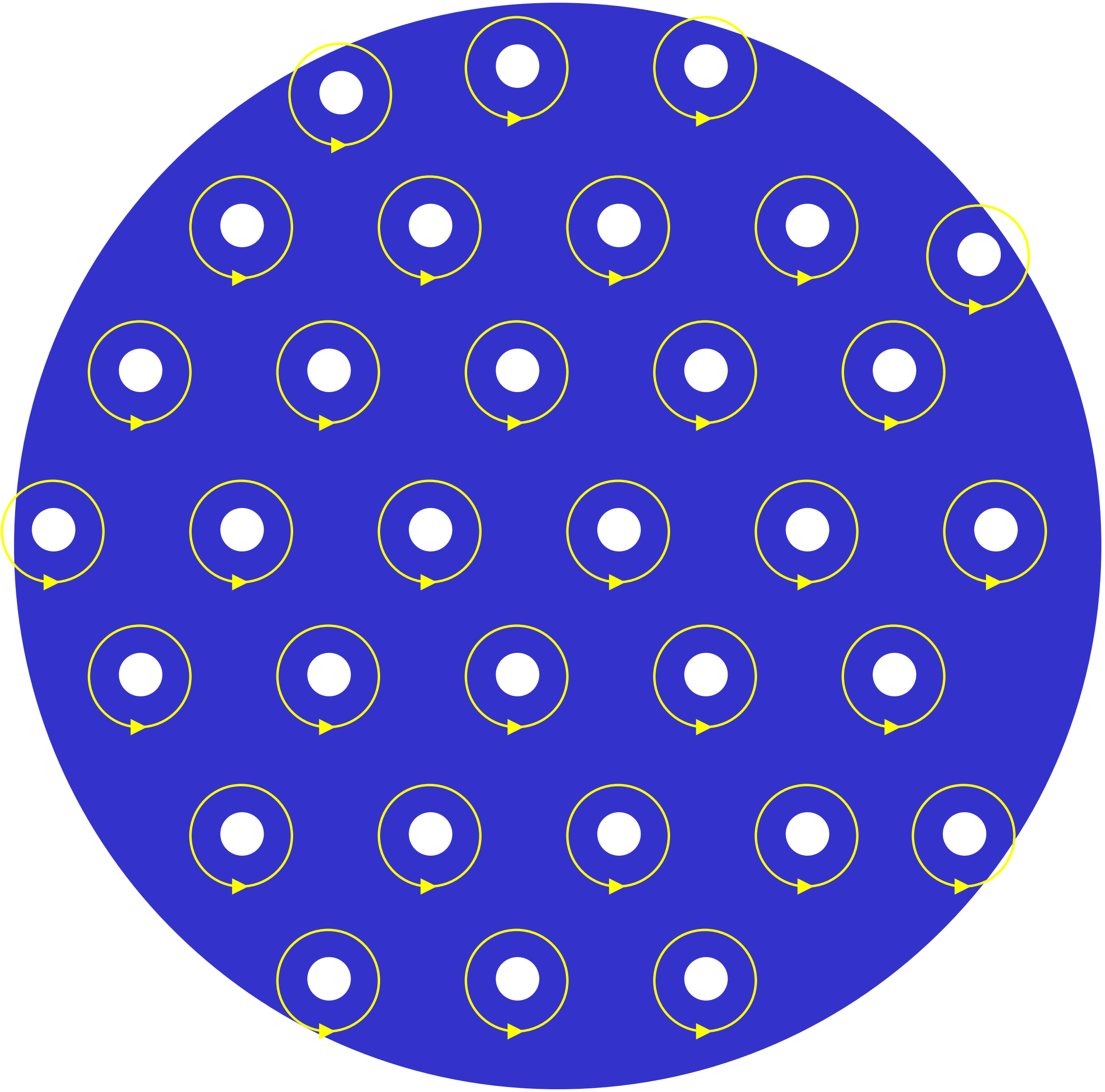
Look from top into the bucket



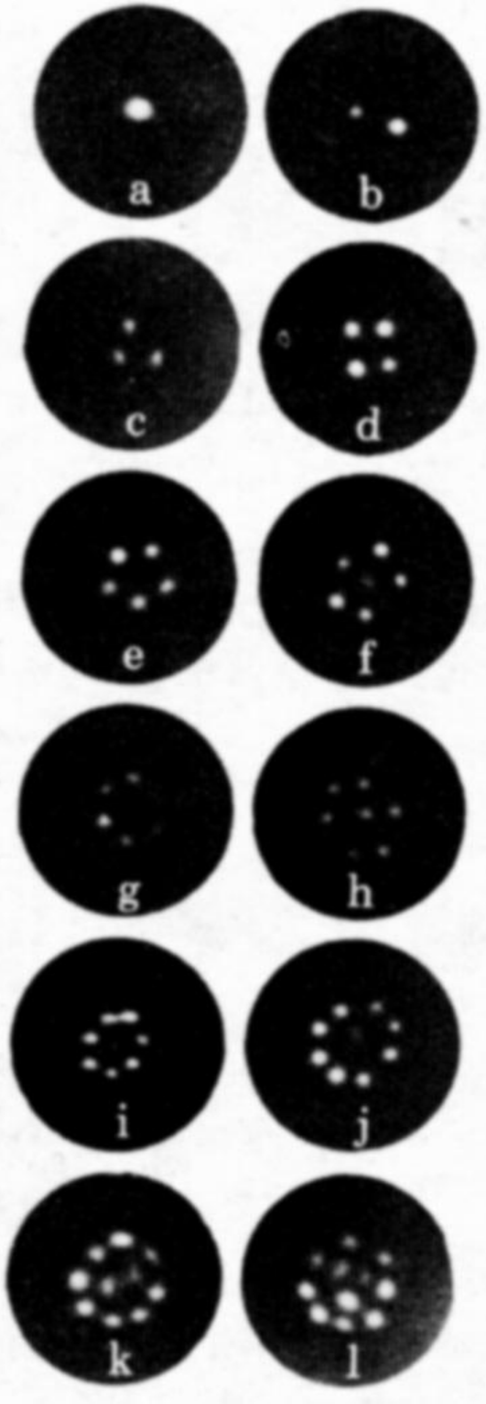
Look from top into the bucket



Aleksei A. Abrikosov



Abrikosov lattice (honeycomb lattice)

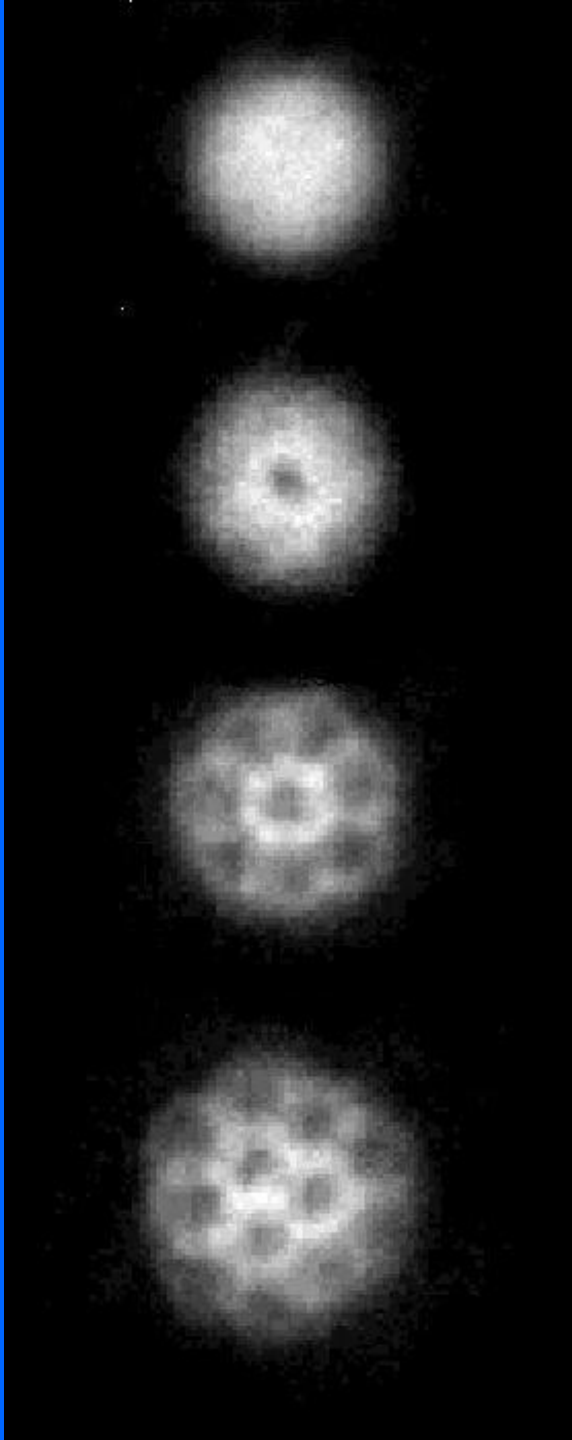


Vortex Arrays in Bosonic Gases / Fluids

Berkeley
(R.E. Packard, 1979)
Helium-4

ENS
(J. Dalibard, 2000)
Rubidium BEC

Also: Phase engineering of single vortices in BEC: JILA (1999)



THE DIRECT OBSERVATION OF INDIVIDUAL FLUX LINES IN TYPE II SUPERCONDUCTORS

U. ESSMANN and H. TRÄUBLE

Institut für Physik am Max-Planck-Institut für Metallforschung, Stuttgart and Institut für theoretische und angewandte Physik der Technischen Hochschule Stuttgart

Received 4 April 1967

Neutral superfluids under rotation

$$\vec{F} = 2m\vec{v} \times \vec{\omega}$$

Coriolis force in rotating frame

$$\Leftrightarrow$$

Superconductors in magnetic field

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

Lorentz Force

U. Essmann and H. Träuble,
Physics Letters A, **24**, 526 (1967)

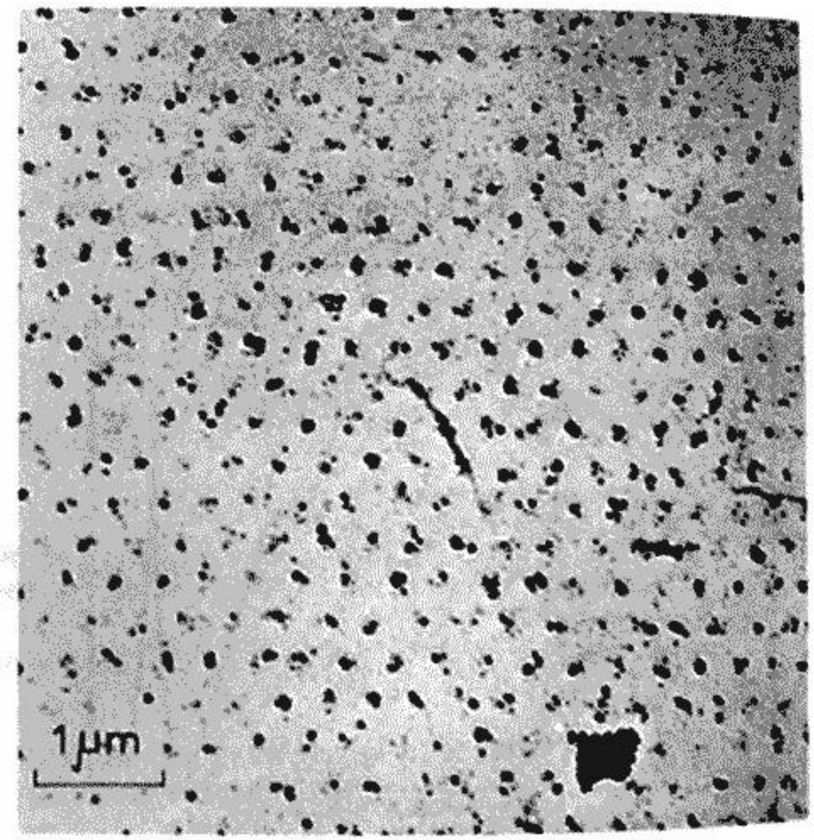
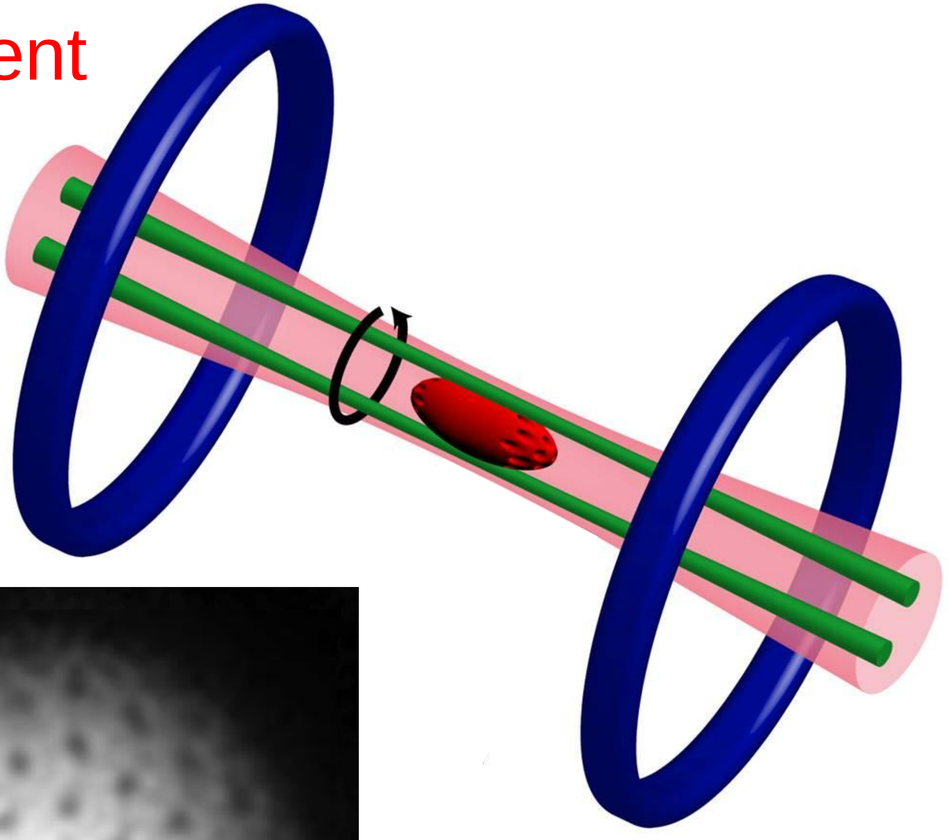
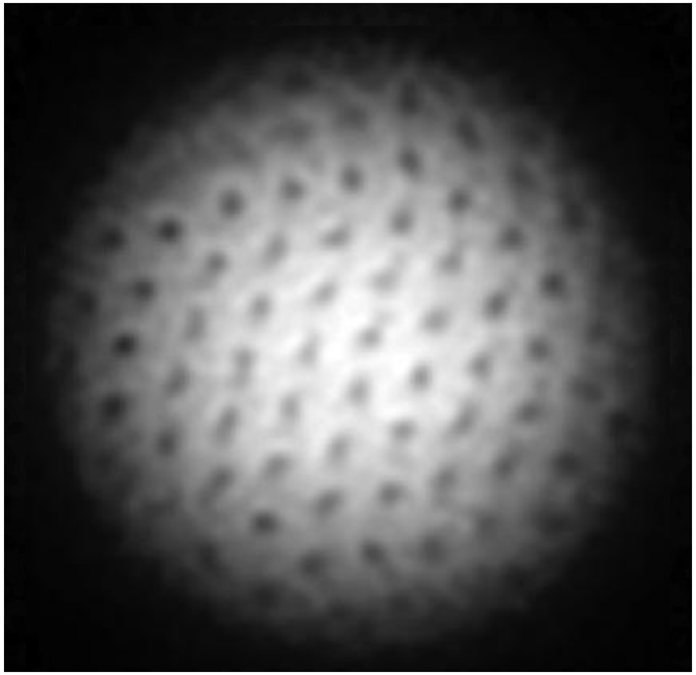


Fig. 1. "Perfect" triangular lattice of flux lines on the surface of a lead-4at% indium rod at 1.1°K. The black dots consist of small cobalt particles which have been stripped from the surface with a carbon replica.

Spinning a strongly interacting Fermi gas

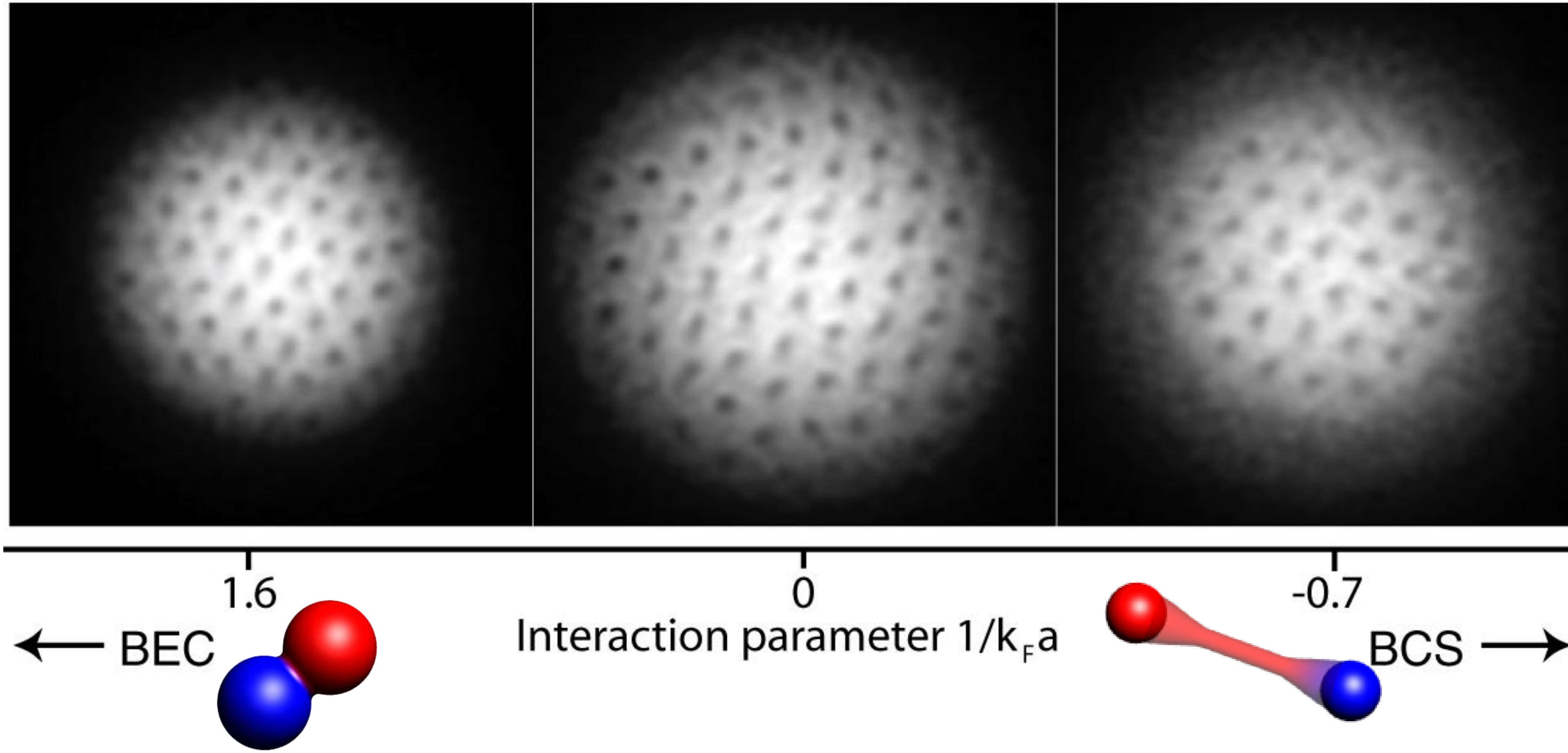
The rotating bucket experiment with a strongly interacting Fermi gas, a million times thinner than air





Vortex lattices in the BEC-BCS crossover

Establishes *superfluidity* and *phase coherence* in gases of fermionic atom pairs



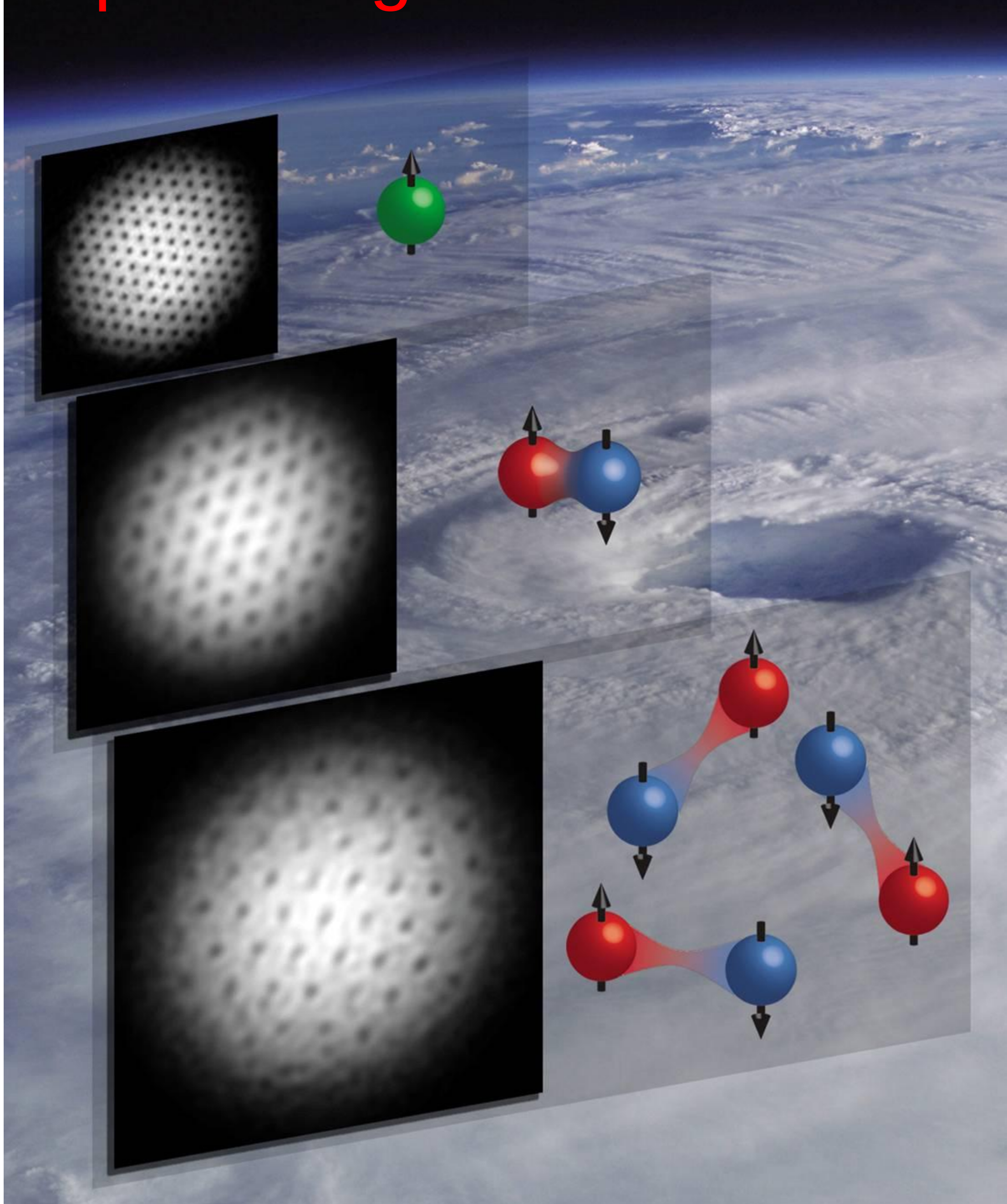
M.W. Zwierlein, J.R. Abo-Shaeer, A. Schirotzek, C.H. Schunck, W. Ketterle, Nature 435, 1047-1051 (2005)

Gallery of superfluid gases

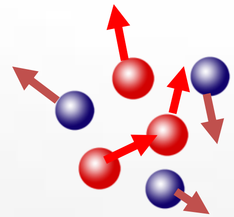
Atomic Bose-Einstein condensate (sodium)

Molecular Bose-Einstein condensate (lithium $^{6}Li_2$)

Pairs of fermionic atoms (lithium-6)

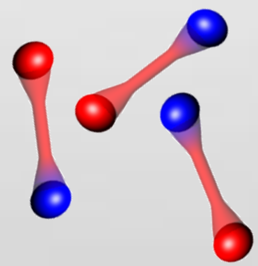


Thermodynamics



Classical gas Equation of State (EoS):

$$P = nk_B T$$



Jason asks:

What is the EoS of a strongly interacting Fermi gas?

$$P(n,T)$$

Lots of expts.: Thomas, Jin, Salomon, Grimm, Ketterle, Hulet, Mukaiyama, Vale, ...

Influential proposal: Tin-Lun Ho, Qi Zhou, Nature Physics 6, 131 (2010)

Thermodynamics

Equilibrium Thermodynamics
as baseline for non-equilibrium studies

→ Establish Equation of State

Classical gas $P = nk_BT$

Generally need $P(n,T)$

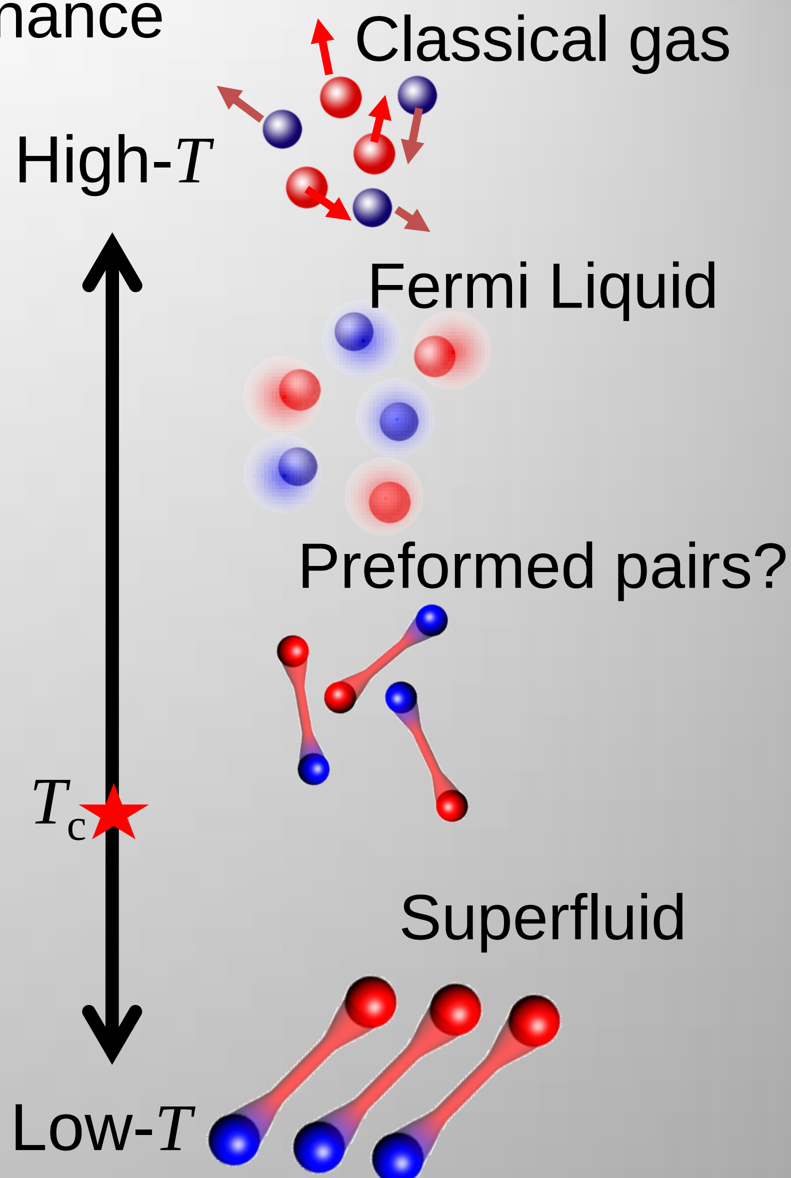
Or fixing chemical potential $P(\mu,T)$

Or replacing $n = \left.\frac{\partial P}{\partial \mu}\right|_{T,a,\ldots}$ $n(\mu,T)$

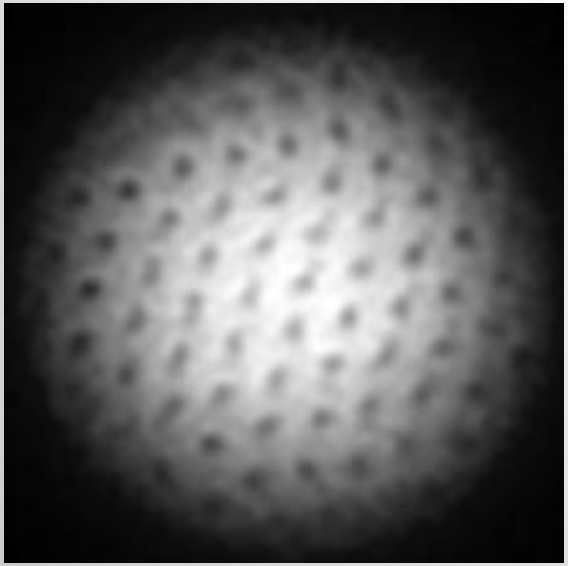
Thermodynamics of the Unitary Fermi Gas

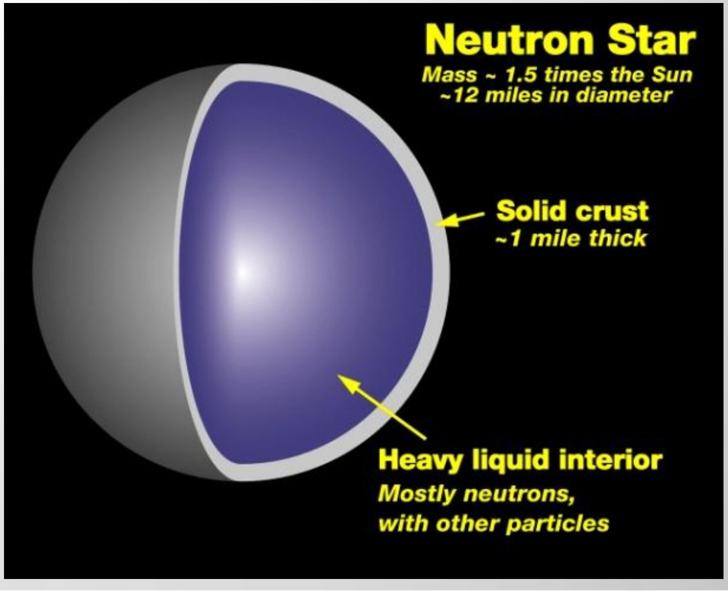
Spin ½ - Fermi gas at a Feshbach resonance

- *Normal state:*
  - Is it a Fermi liquid?
  - Are there preformed pairs (pseudogap regime)?
- *Superfluid properties*:
  - Transition temperature
  - Critical Entropy
  - Energy of the superfluid
  - ...



Relation to equation of state of a neutron star





Property	Atoms	Neutrons
Spin	Pseudospin ½	Spin ½
Interparticle distance $n^{-1/3}$	1 μm	1 fm
Density	10^{13} cm^{-3}	10^{38} cm^{-3}
Fermi Energy	1 μK = 10^{-10} eV	10^{12} K = 150 MeV
Scattering length a	freely tunable	-19 fm

Both systems lie in universal regime: $a \gg n^{-1/3}$

small print: neglecting effective range

Measuring the Equation of State

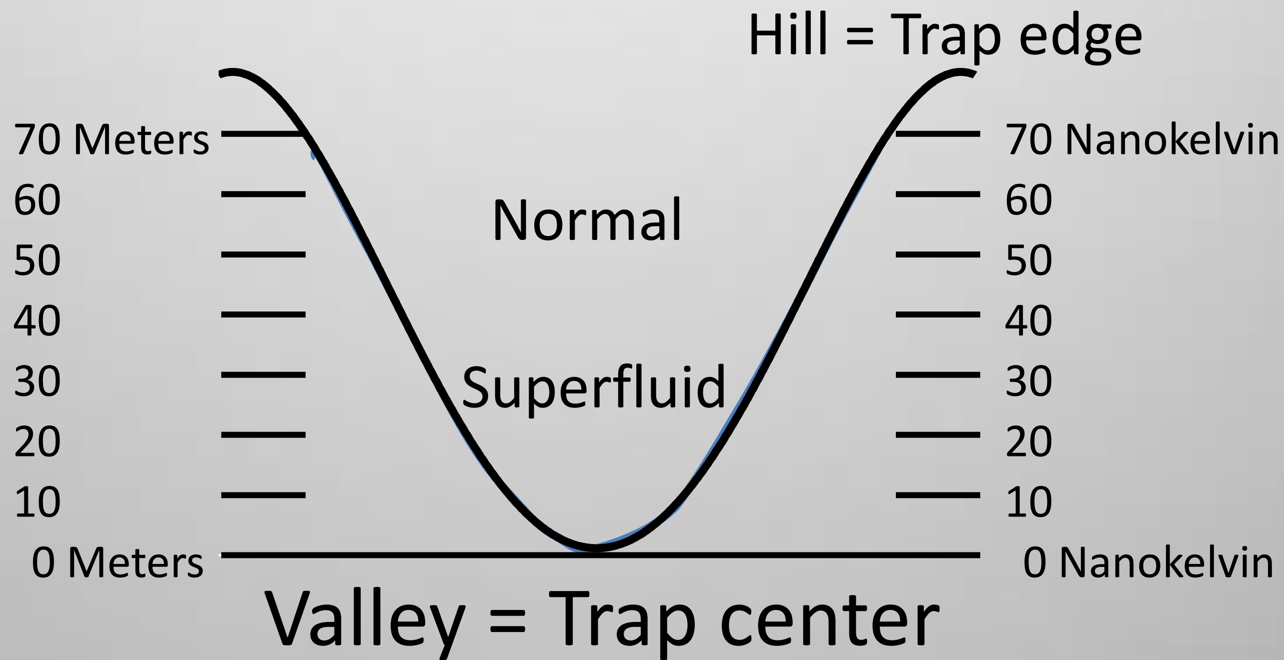
When climbing a mountain, the air gets thinner...

Equation of state → density as a function of height

The inverse works as well!

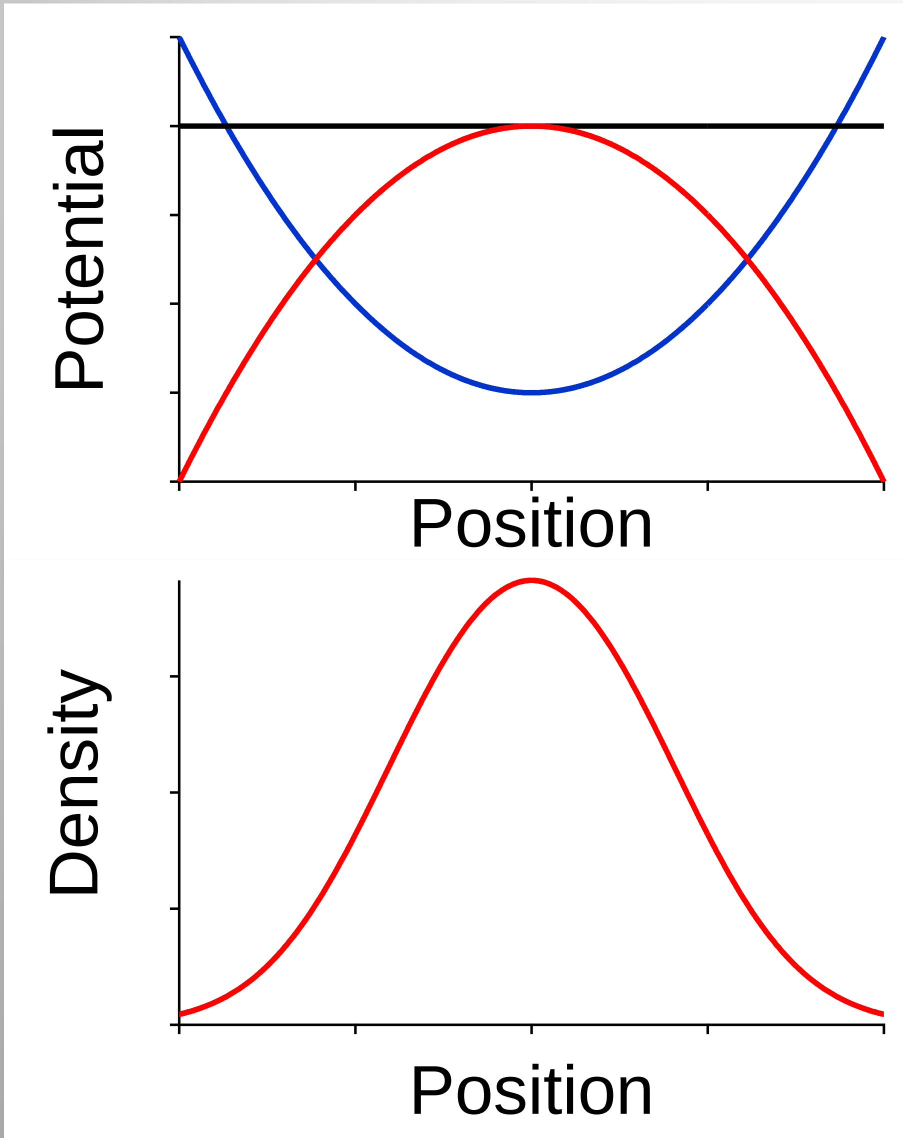
Density as a function of height → equation of state

Atoms in our trapping potential $\hat{=}$ air particles in gravitational potential



Equation of State

Equation of state from density distribution in a trap



$V(\mathbf{r})$

μ_0

Local chemical potential

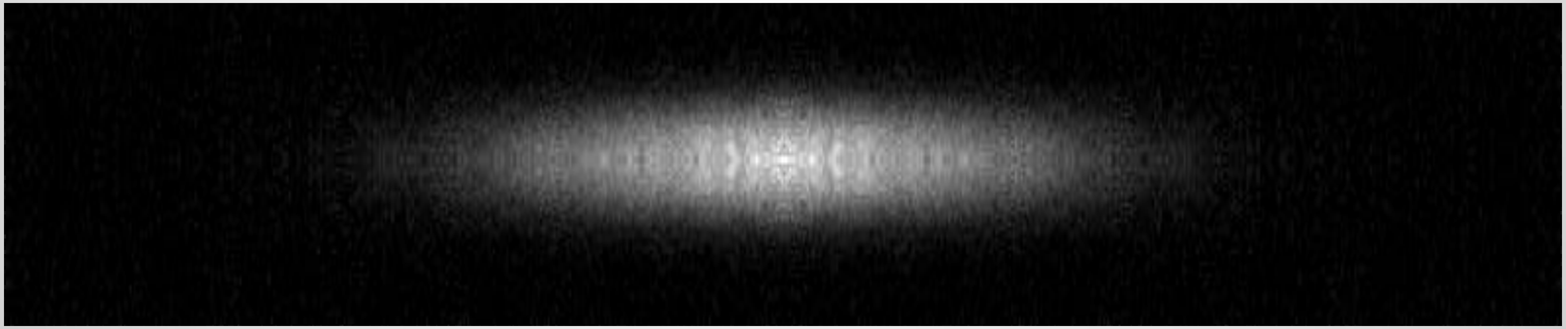
$$\mu(\vec{r}) = \mu_0 - V(\vec{r})$$

Local density

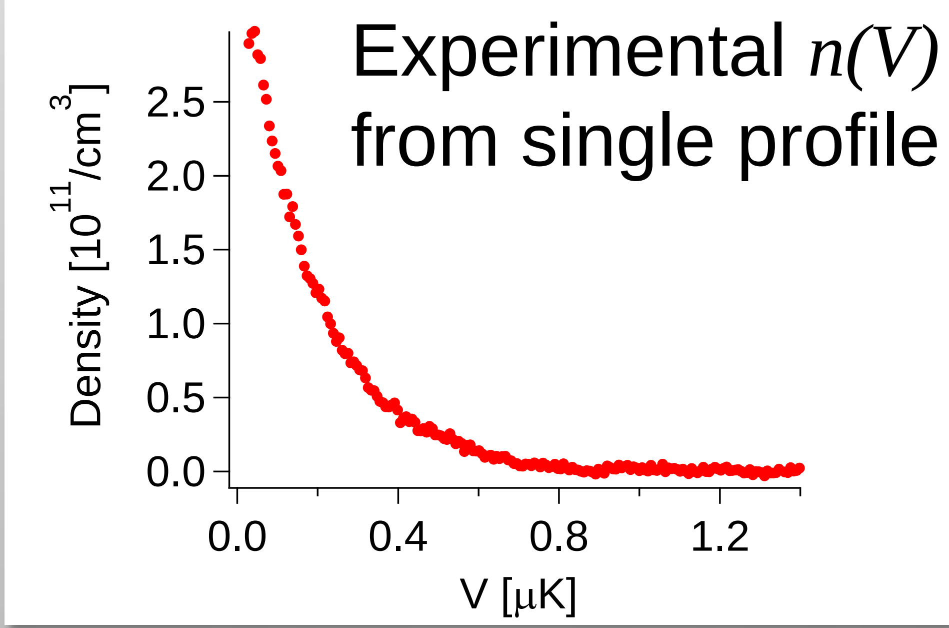
$$n(V) = n(\mu_0 - V, T)$$

Density profile provides a scan through the equation of state

Equation of State: Measuring density



Exploiting cylindrical symmetry and careful characterization of trapping potential:



Equation of State: Measuring pressure

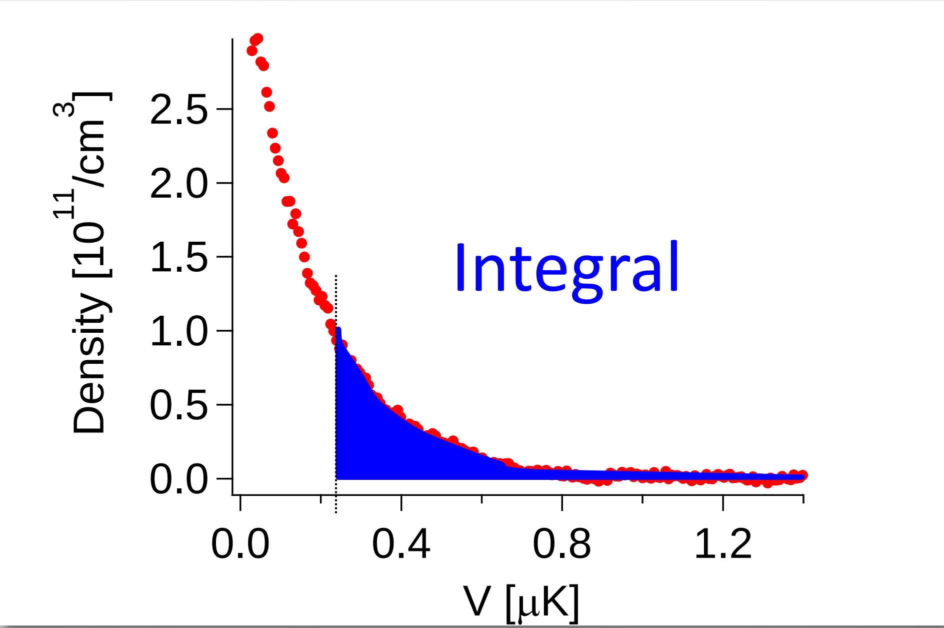
Pressure = weight / unit area of air above you

For atom trappers: replace m g h → V

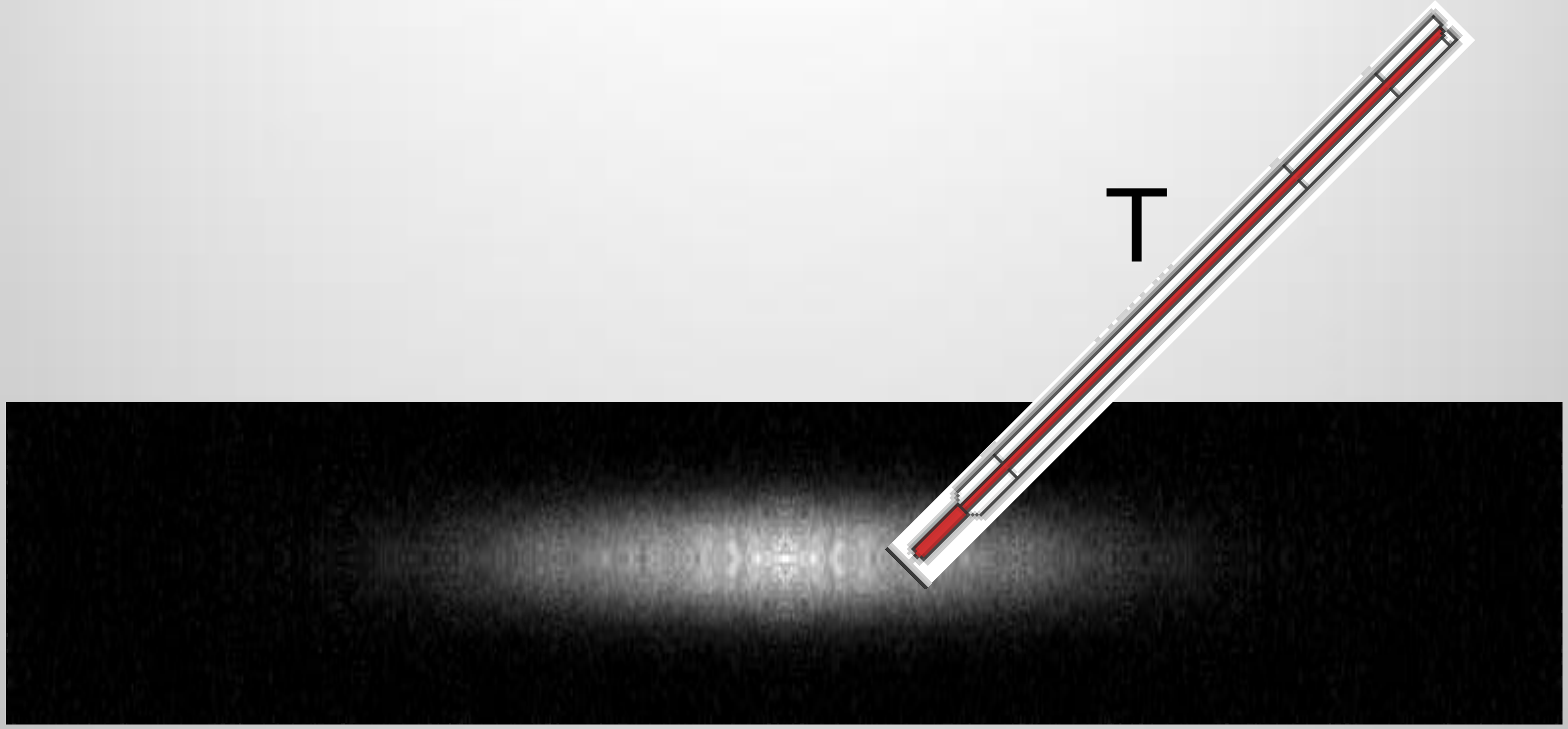
Pressure = integrated density over potential

Local pressure

$$P = \int_V^\infty \mathrm{d}V' \; n(V')$$



How to get T?

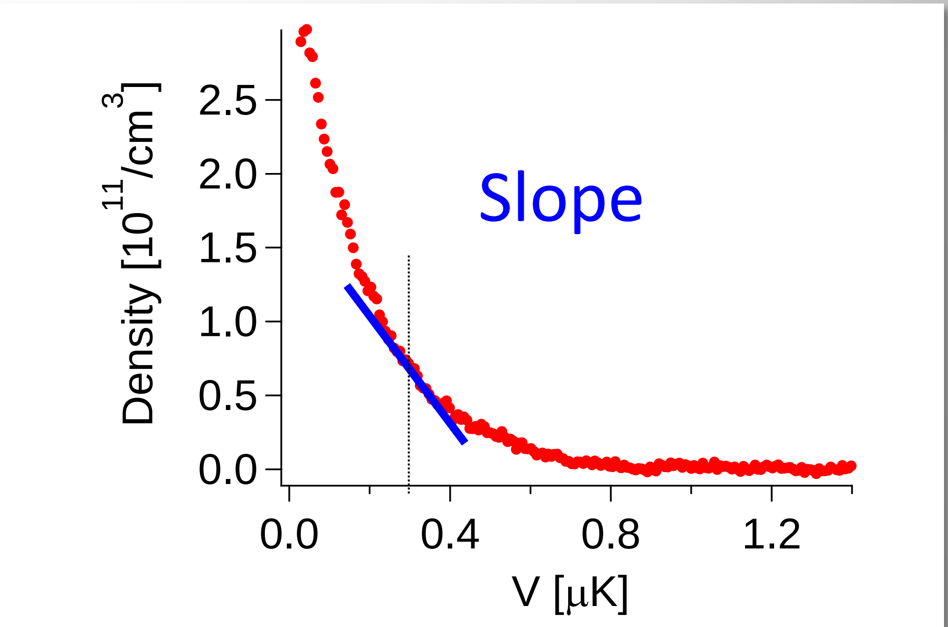


...Not impossible, but it’s very difficult, so...

Don't! Instead:

Local compressibility

$$\kappa = -\frac{1}{n^2}\frac{\mathrm{d}n}{\mathrm{d}V}$$



Compressibility Equation of State

$$\kappa(n, P)$$

All other thermodynamic quantities follow!

Mark J. H. Ku, Ariel T. Sommer, Lawrence W. Cheuk, Martin W. Zwierlein
Science **335**, 563-567 (2012)

No-fit Equation of State

Normalize compressibility & pressure via known density:

$$\tilde{\kappa} = \frac{\kappa}{\kappa_0} = \frac{\mathrm{d}\varepsilon_F}{\mathrm{d}\mu} = -\frac{\mathrm{d}\varepsilon_F}{\mathrm{d}V}$$

$$\tilde{P} = \frac{P}{P_0}$$

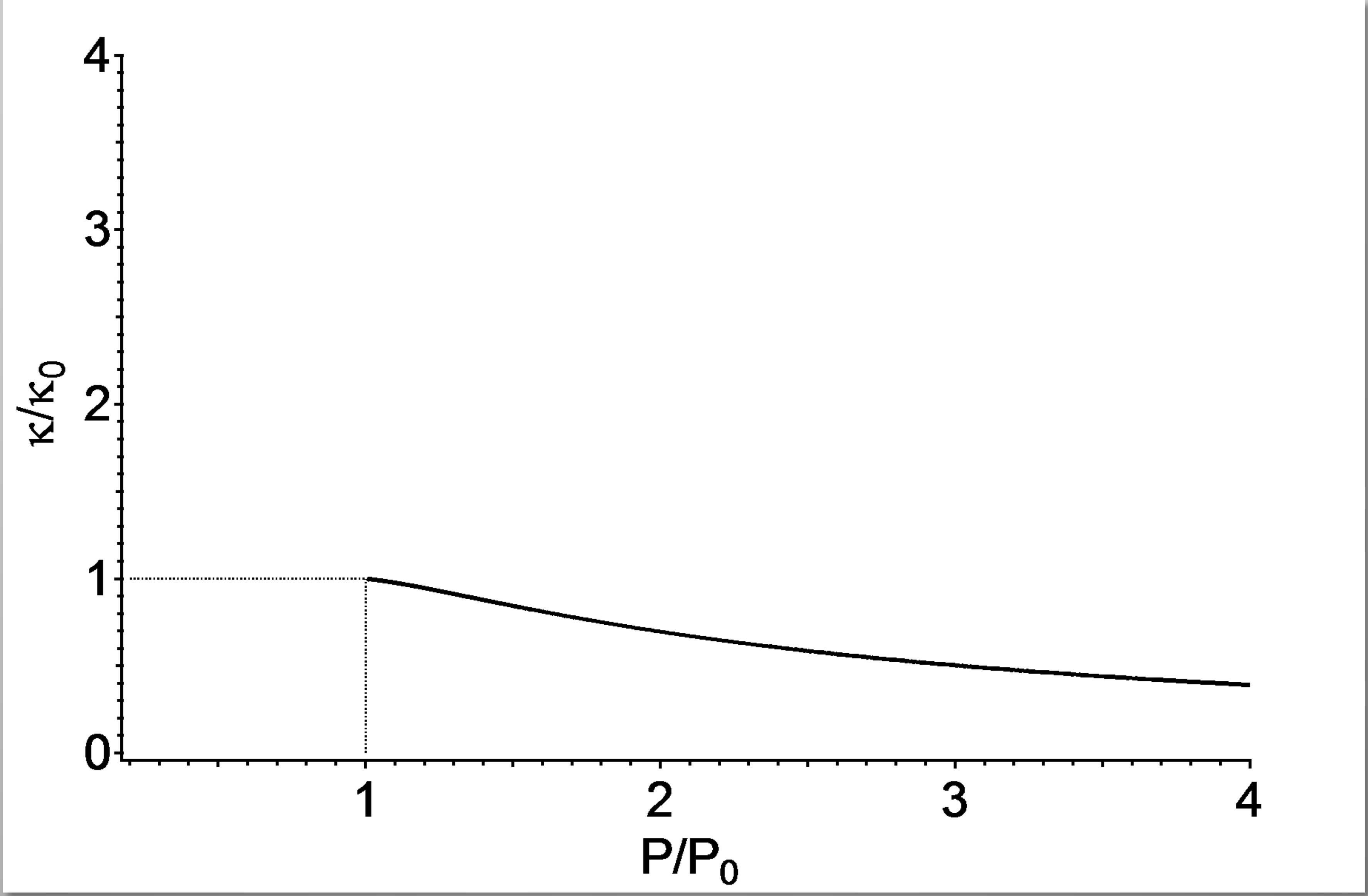
$$\kappa_0 = \frac{3}{2}\frac{1}{n\varepsilon_F}$$

$$P_0 = \frac{2}{5} n\varepsilon_F$$

For a scale-invariant system

$$\tilde{\kappa} = \tilde{\kappa}(\tilde{p})$$

Compressibility Equation of State



Mark J. H. Ku, Ariel T. Sommer, Lawrence W. Cheuk, Martin W. Zwierlein
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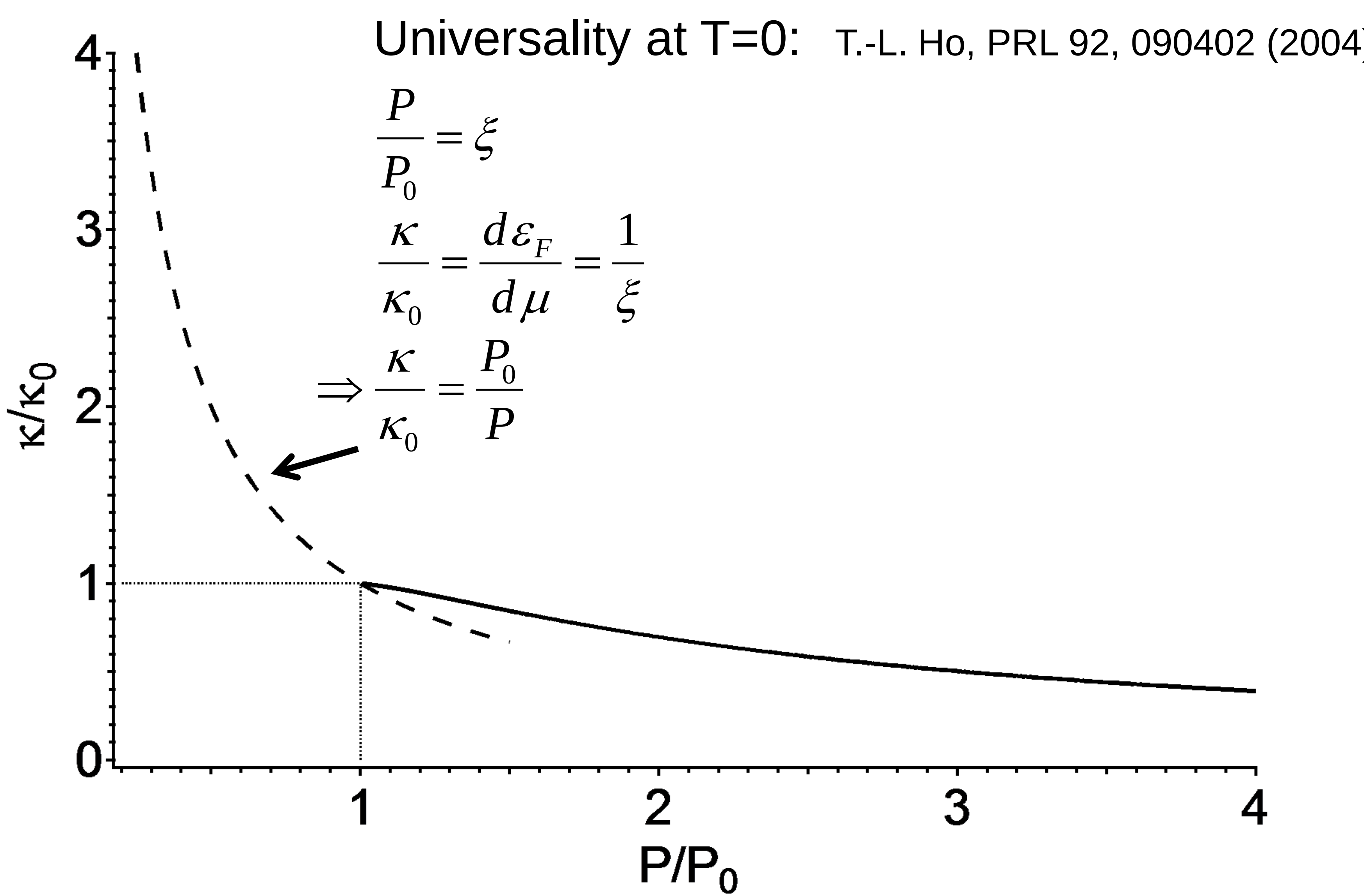
Compressibility Equation of State



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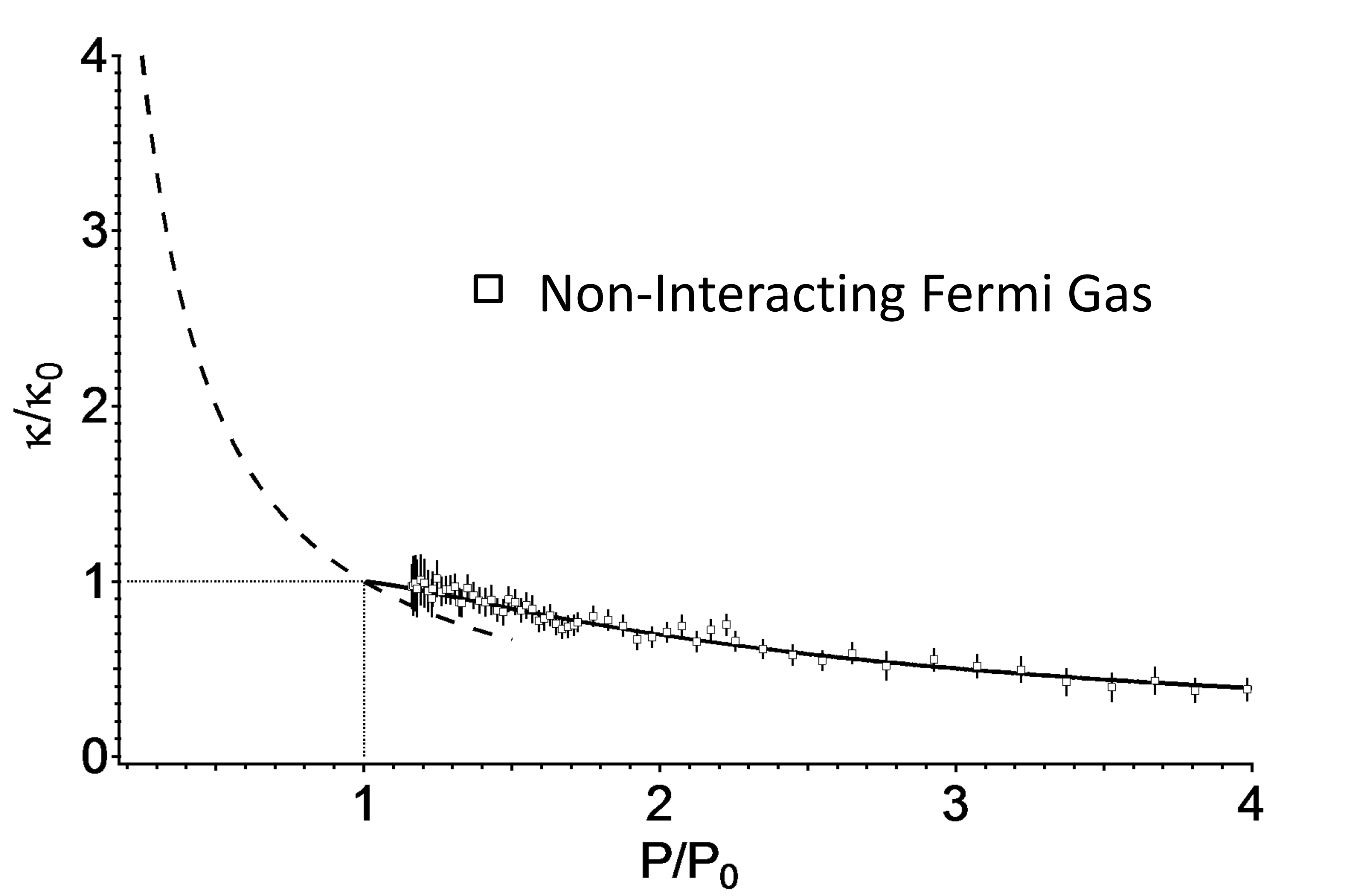
Compressibility Equation of State



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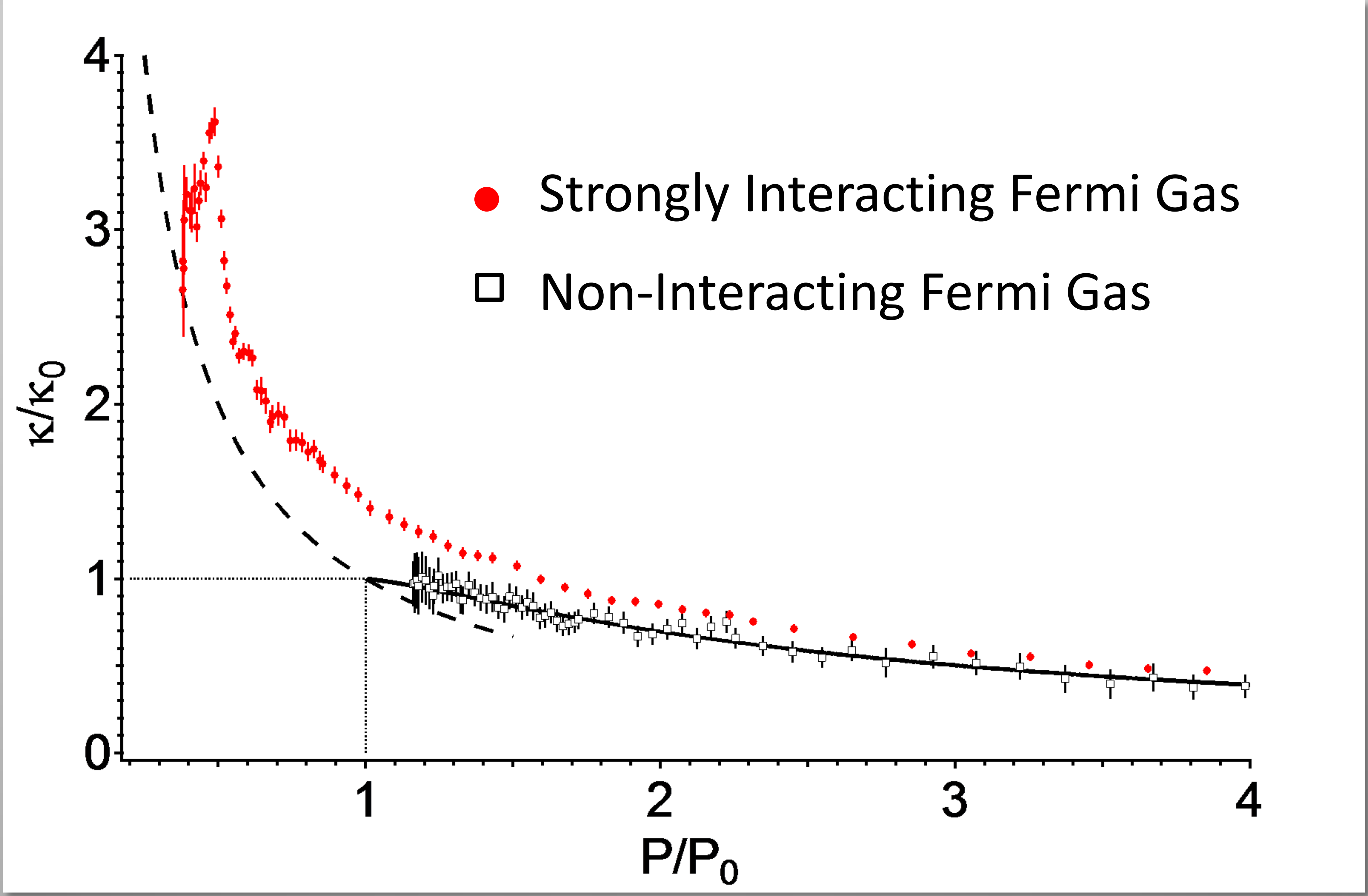
Compressibility Equation of State



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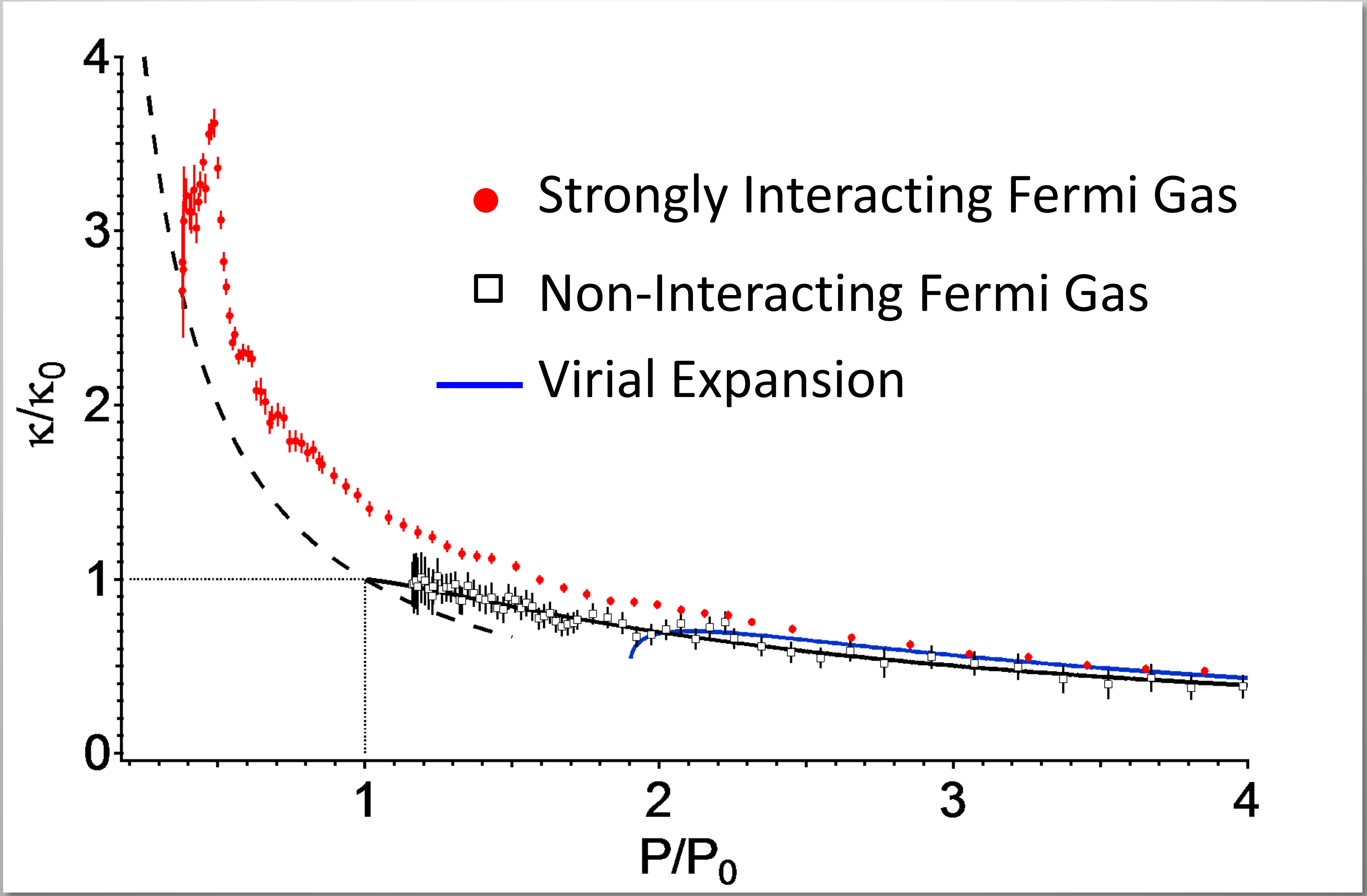
Compressibility Equation of State



Mark J. H. Ku, Ariel T. Sommer, Lawrence W. Cheuk, Martin W. Zwierlein
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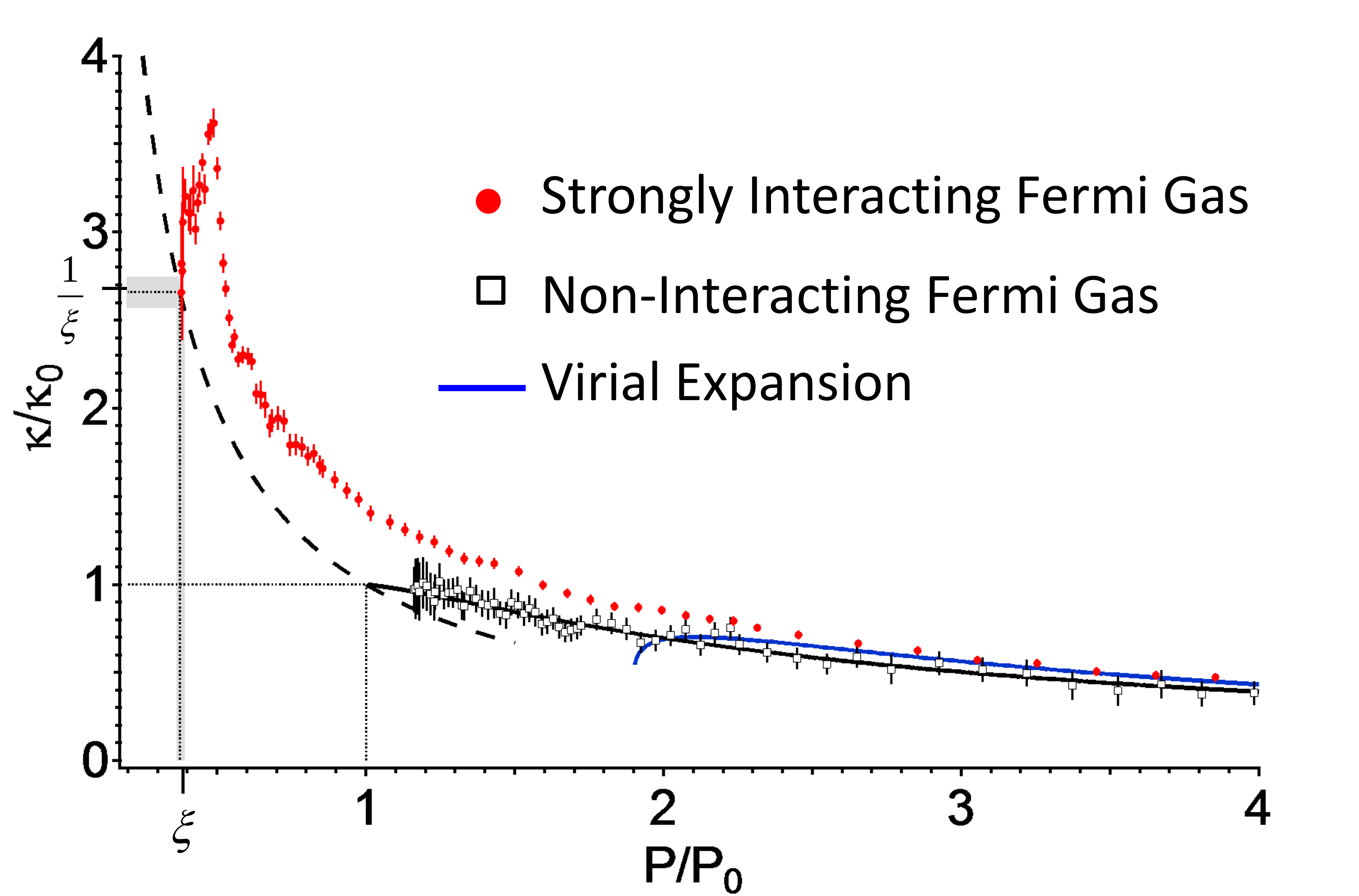
Compressibility Equation of State



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Science **335**, 563-567 (2012)

Compressibility Equation of State

$$\kappa(n,P) \longrightarrow \kappa(n,T)$$

Getting the temperature scale:

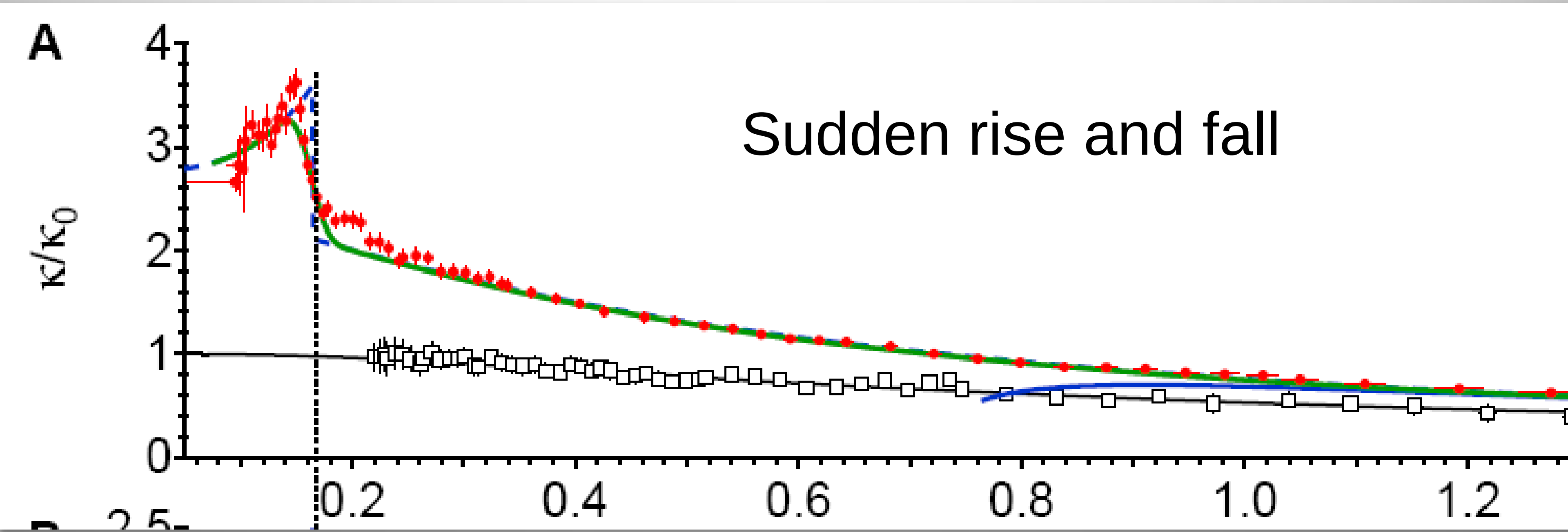
$$\left.\frac{\mathrm{d}(P/P_0)}{\mathrm{d}(T/T_F)}\right|_T = \frac{5}{2}\frac{T_F}{T}\left(\frac{P}{P_0} - \frac{\kappa_0}{\kappa}\right)$$

$$\frac{T}{T_F} = \frac{T_i}{T_F}\exp\left\{\frac{2}{5}\int_{\tilde{p}_i}^{\tilde{p}} d\tilde{p}\,\frac{1}{\tilde{p} - \frac{1}{\tilde{\kappa}}}\right\}$$

Mark J. H. Ku, Ariel T. Sommer, Lawrence W. Cheuk, Martin W. Zwierlein
Science **335**, 563-567 (2012)

Compressibility Equation of State

Compressibility

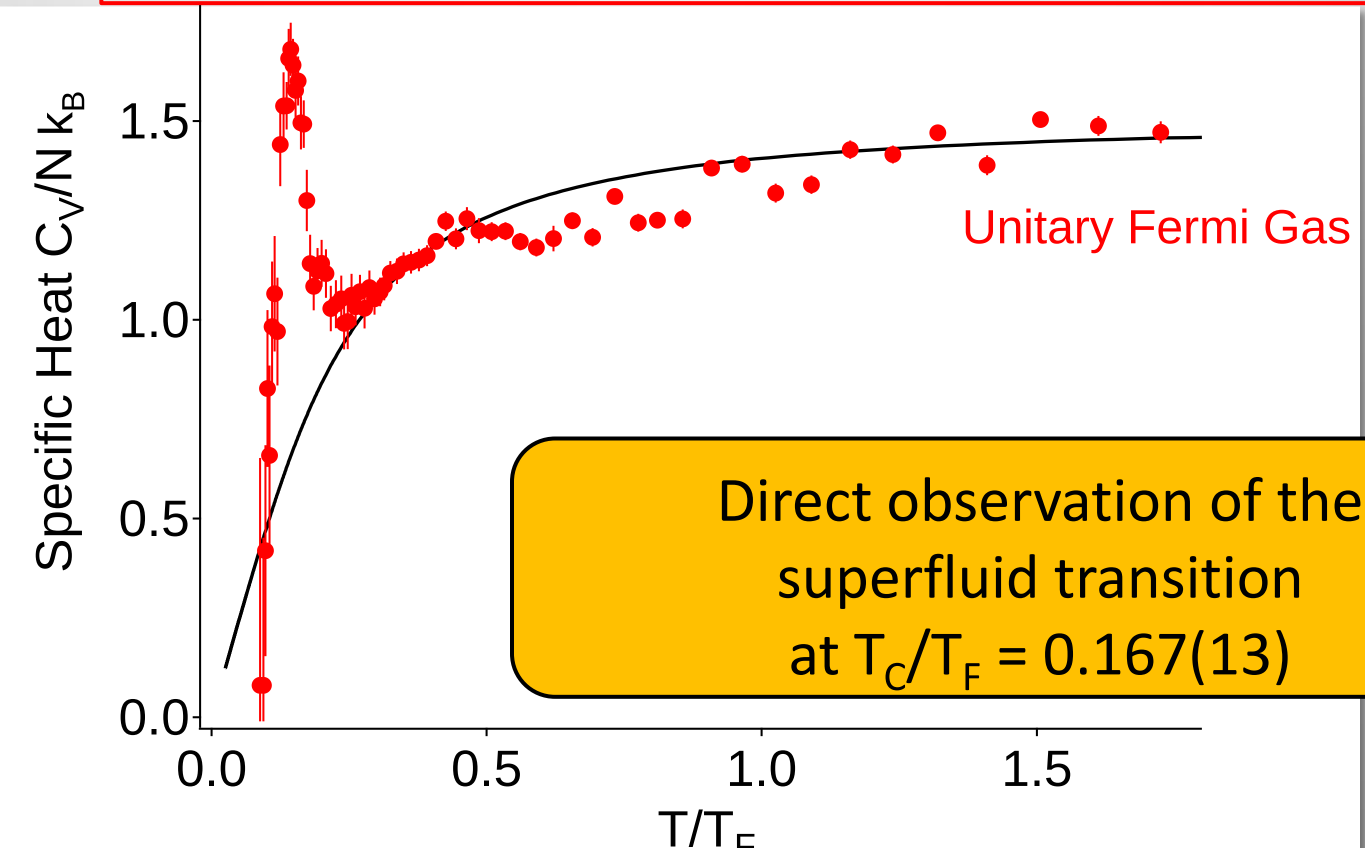


Heat capacity

For a resonant gas:

$$P = \frac{2}{3}\frac{E}{V}$$

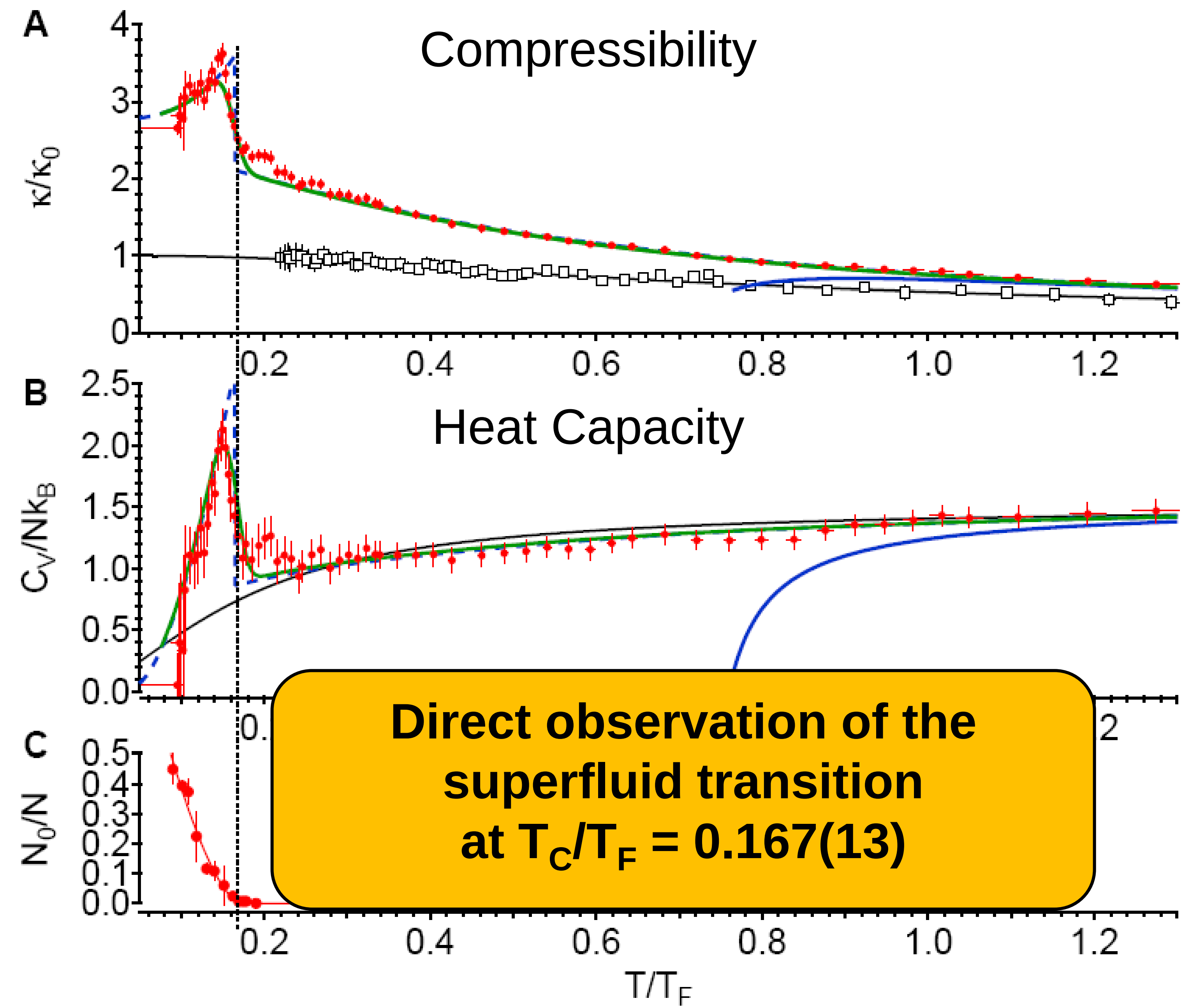
$$\frac{C_V}{Nk_B} = \frac{d(E/Nk_B)}{dT}\bigg|_{N,V} = \frac{d(P/nE_F)}{d(T/T_F)} = \frac{3}{2}\frac{T_F}{T}\left(\frac{P}{P_0} - \frac{\kappa_0}{\kappa}\right)$$



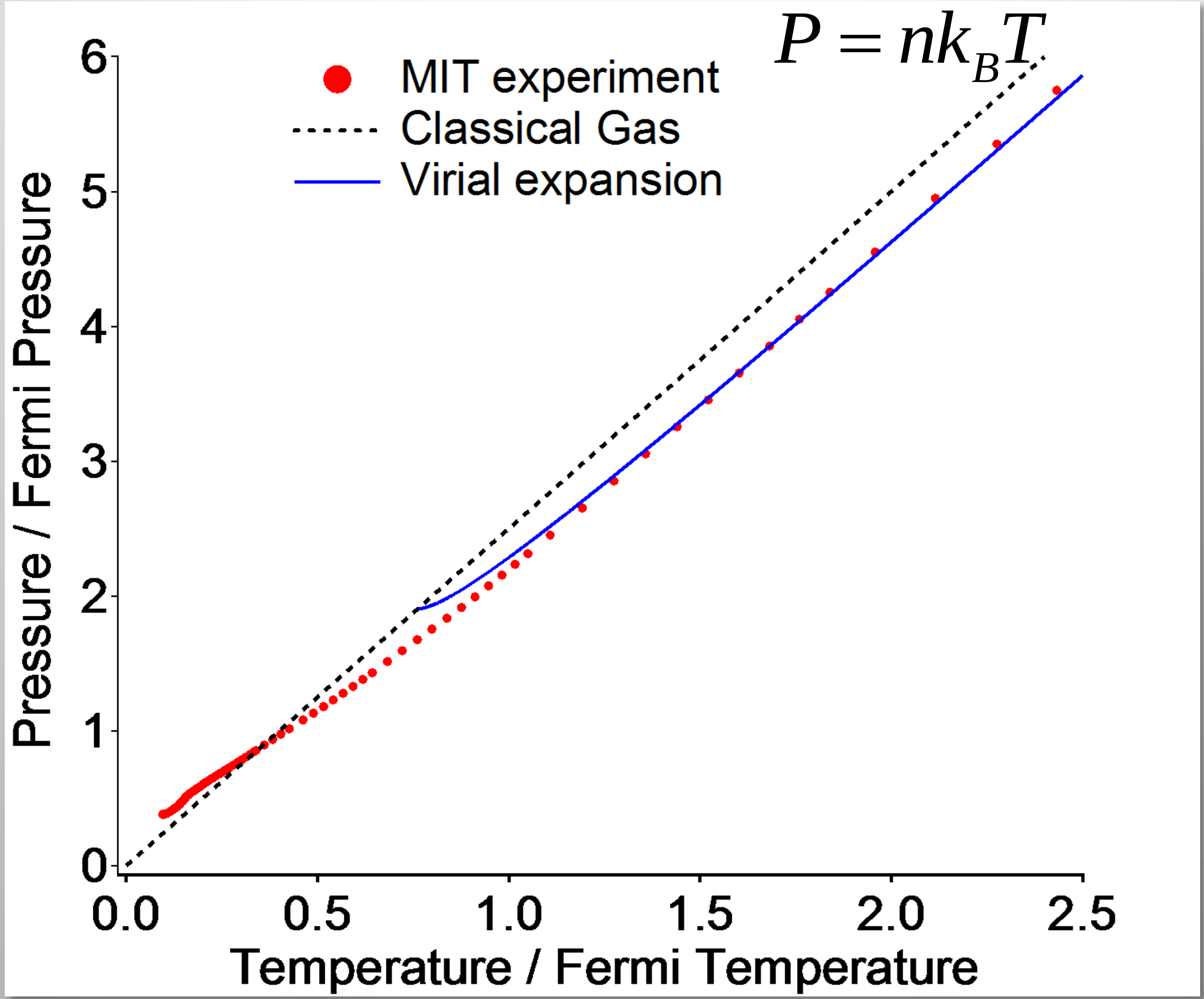
Direct observation of the superfluid transition at $T_C/T_F = 0.167(13)$

Scaled to the density of electrons in a solid, superfluidity would occur far above room temperature

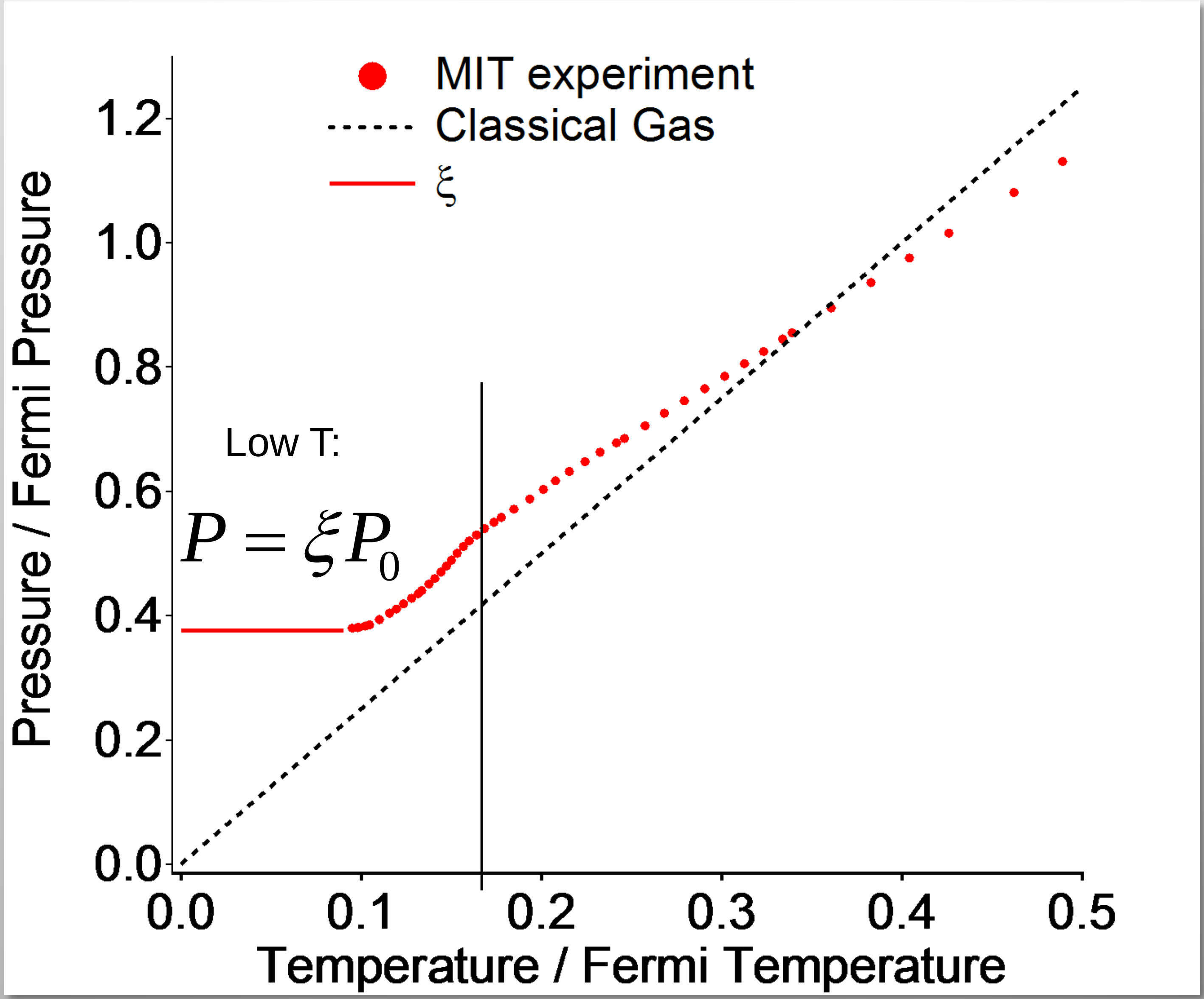
Compressibility, Heat Capacity, Condensates



Equation of state of a resonant Fermi gas



Equation of state of a resonant Fermi gas



New value for ξ: $\xi = 0.376(5)[8]$

Compressibility Equation of State

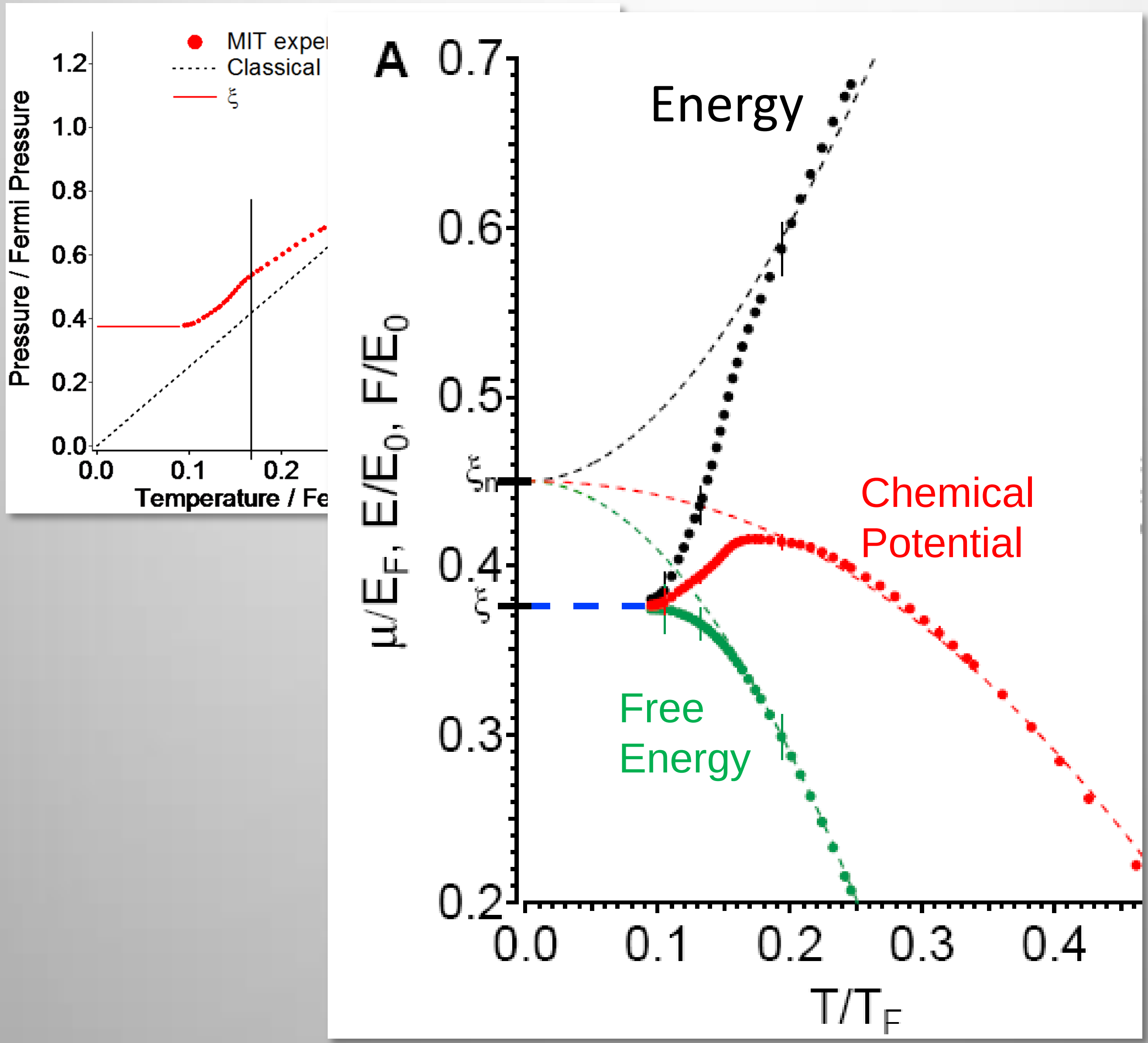
Going back to Density Equation of State

$$\tilde{\kappa} = \frac{\mathrm{d}\varepsilon_F}{\mathrm{d}\mu} = -\frac{T_F^2}{T^2}\frac{\mathrm{d}(T/T_F)}{\mathrm{d}(\beta\mu)}$$

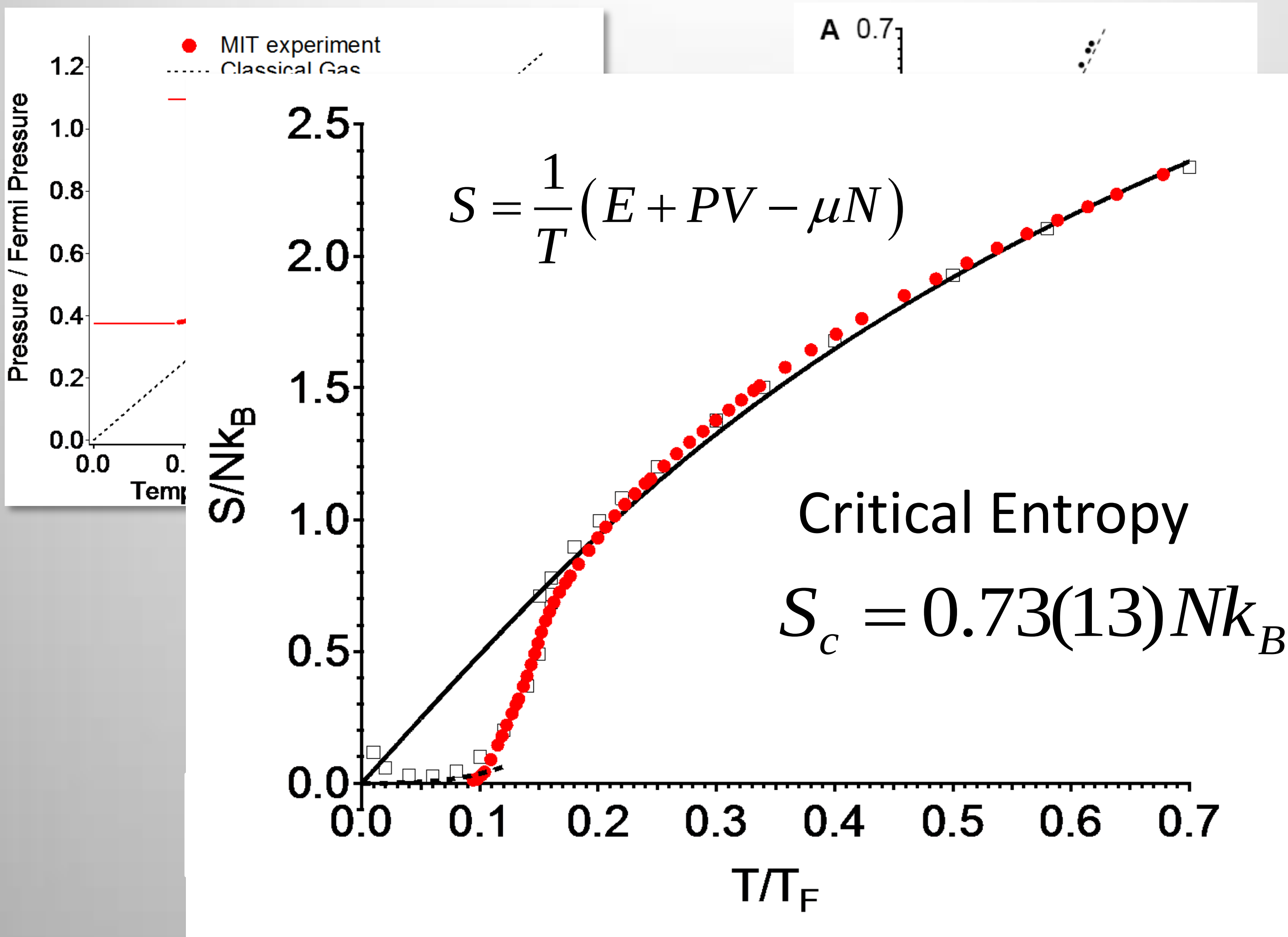
$$\beta\mu = \beta\mu_i - \int_{T_i/T_F}^{T/T_F} d(T/T_F)\frac{T_F^2}{T^2}\frac{1}{\tilde{\kappa}}$$

with $\beta\mu_i$ and T_i known at high temperatures

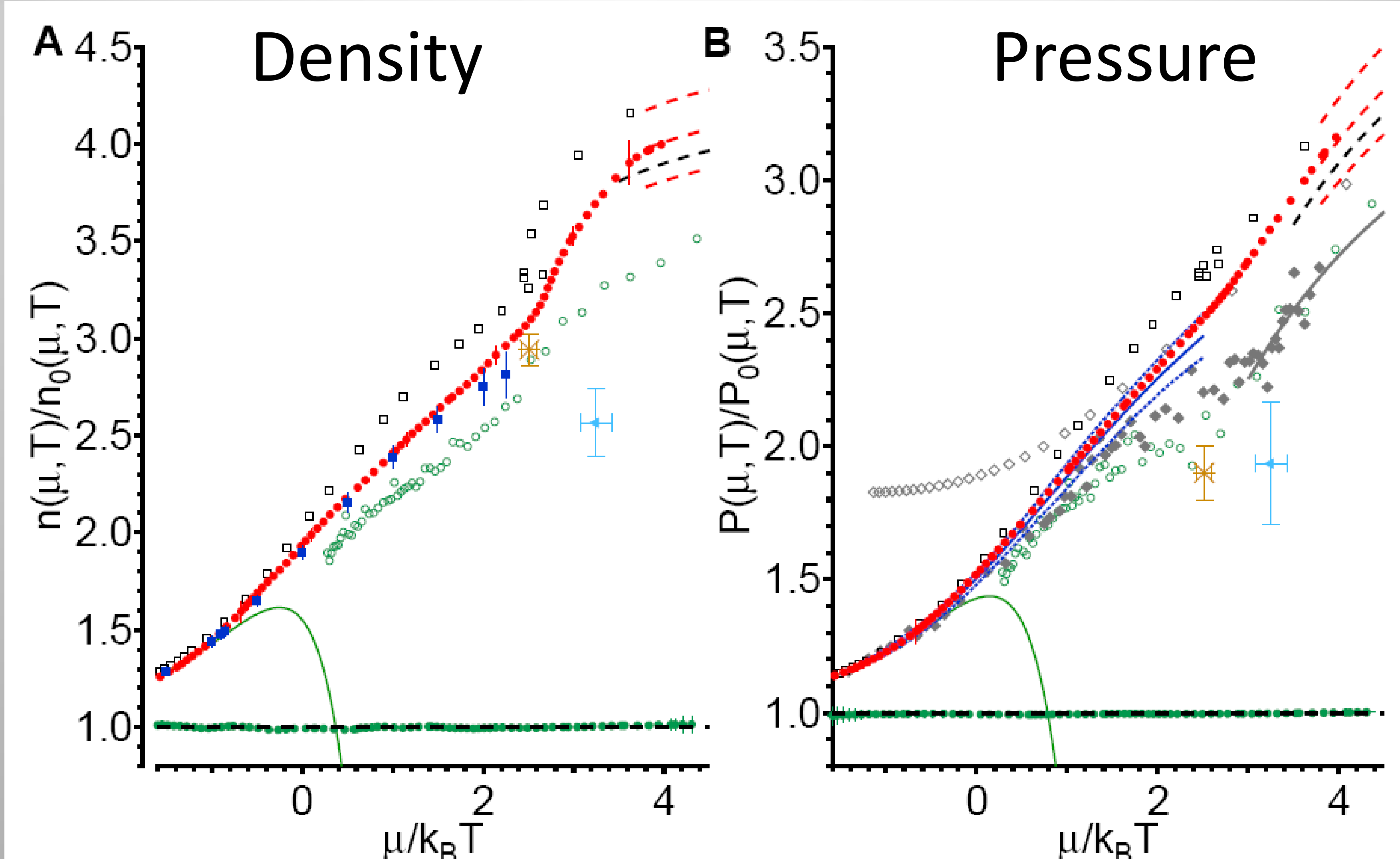
Equation of state of a resonant Fermi gas



Equation of state of a resonant Fermi gas



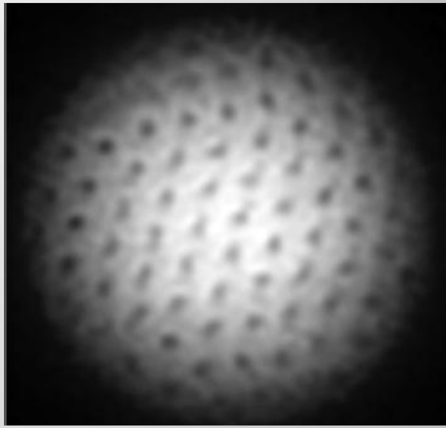
Equation of state of a resonant Fermi gas



Mark Ku, Ariel Sommer, Lawrence Cheuk, MWZ, Science **335**, 563-567 (2012)
K. Van Houcke, F. Werner, E. Kozik, N. Prokofev, B. Svistunov,
M. Ku, A. Sommer, L. Cheuk, A. Schirotzek, MWZ, Nature Physics **8**, 366 (2012)

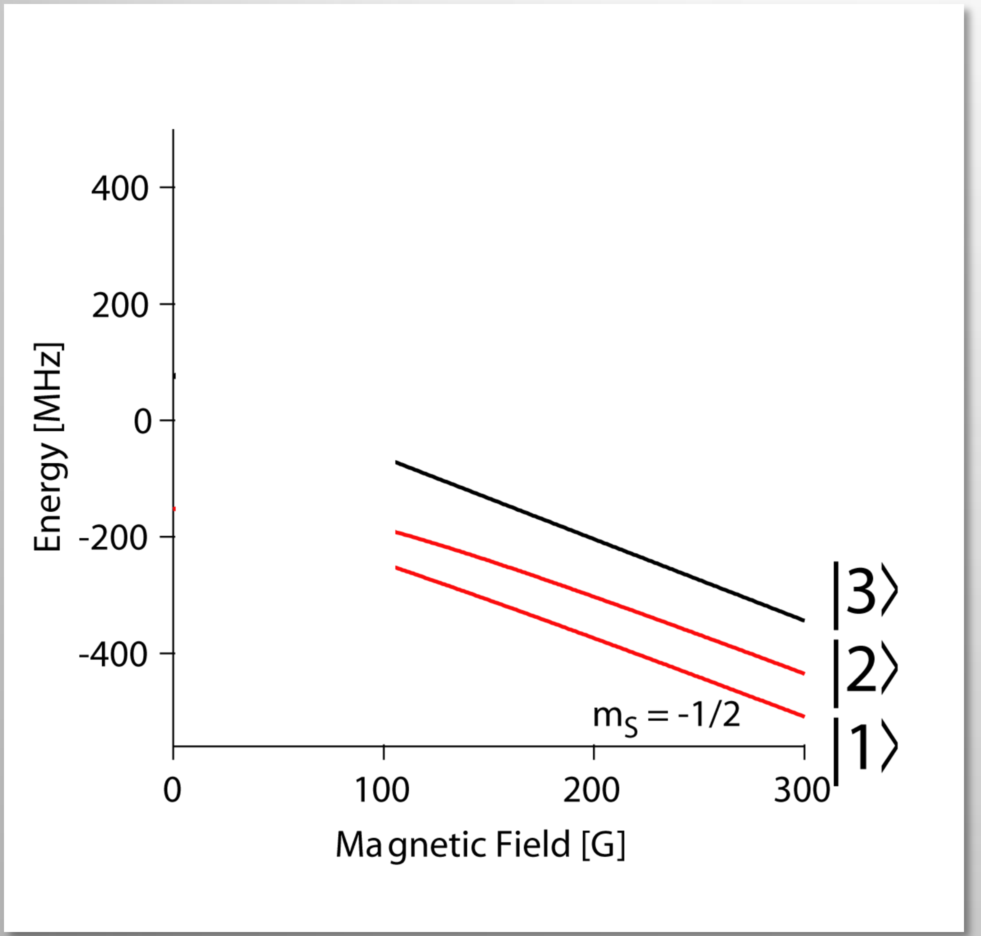
Binding Energy of Pairs

A Gedanken experiment



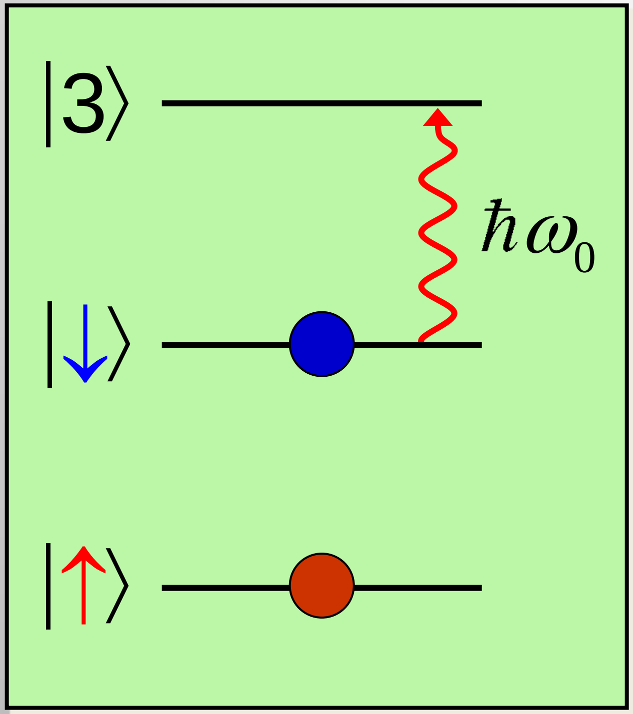
What is the energy cost of removing one fermion from the superfluid?

Radiofrequency spectroscopy

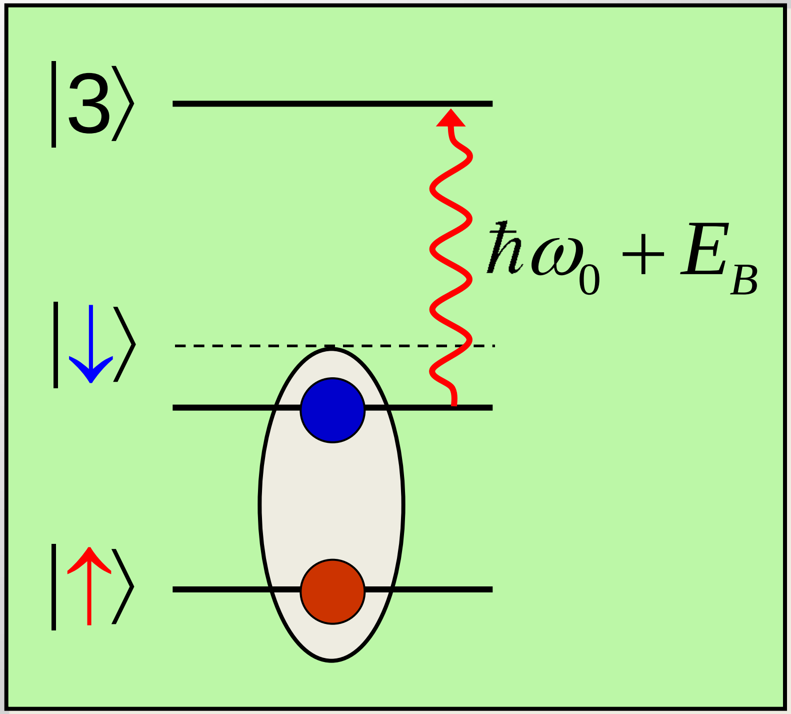


Radiofrequency spectroscopy

No interactions



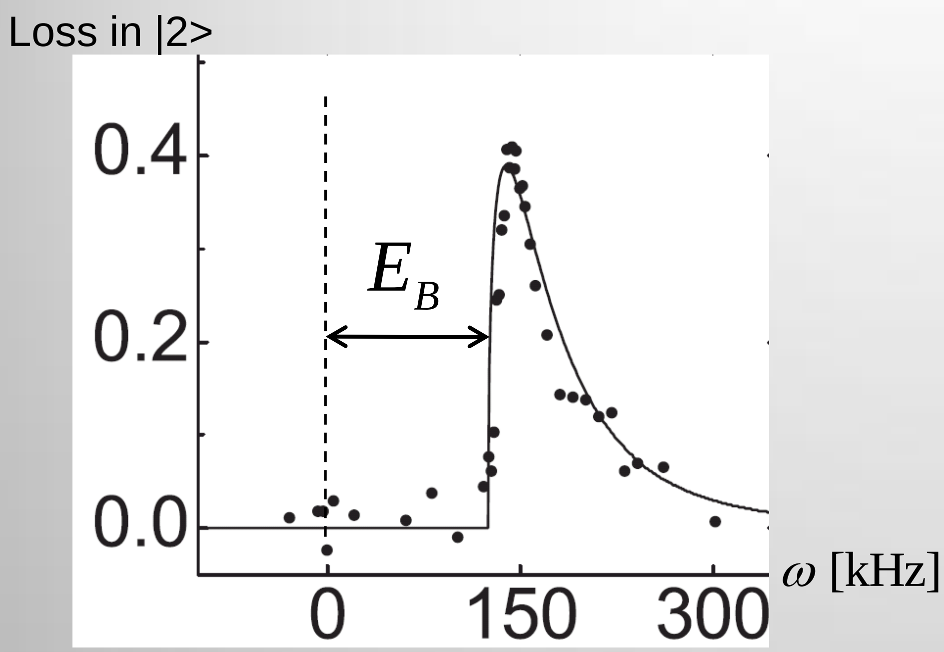
Molecular Pairing



Photon energy = Zeeman + Binding + Kinetic energy

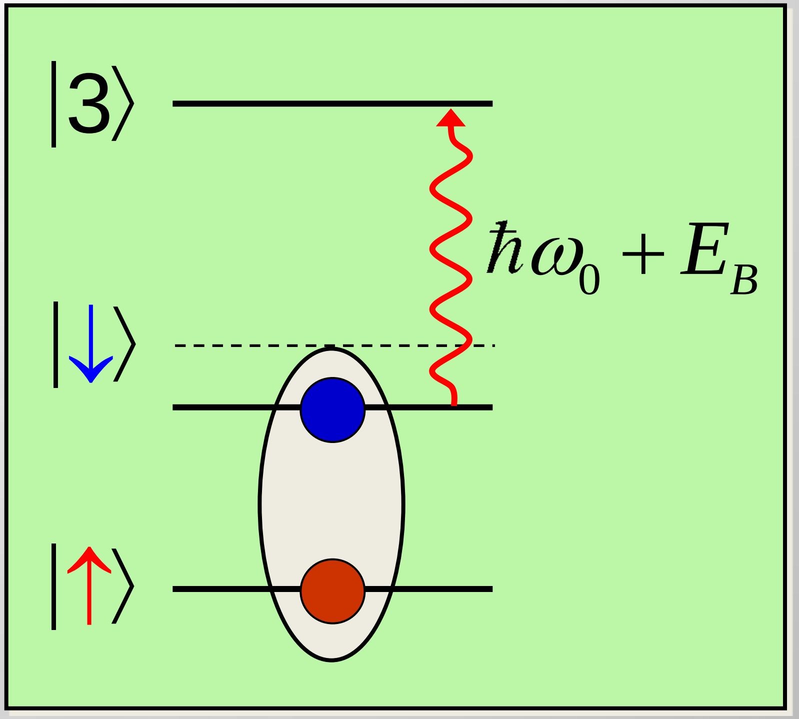
$$\hbar\omega = \hbar\omega_0 + E_B + 2\varepsilon_k$$

Radiofrequency spectroscopy



C.Chin et al. Science, **305**, 1128 (2004)

Molecular Pairing

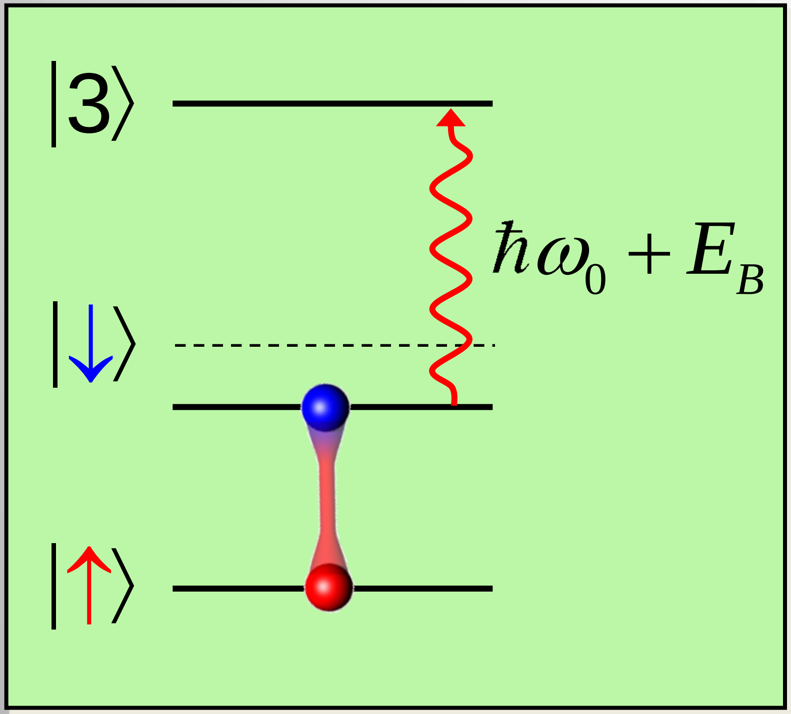


Photon energy = Zeeman + Binding + Kinetic energy

$$\hbar\omega = \hbar\omega_0 + E_B + 2\varepsilon_k$$

Radiofrequency spectroscopy

BCS pairing is a many-body affair. Does the picture still hold?



Energy gain due to pairing (BCS):

$$\delta E(N) = E_{SF}(N) - E_{Normal}(N) = -\frac{3}{8} N \frac{\Delta^2}{E_F}$$

Binding energy per particle:

$$E_B = \frac{\delta E(N+2) - \delta E(N)}{2} = -\frac{\Delta^2}{2E_F}$$

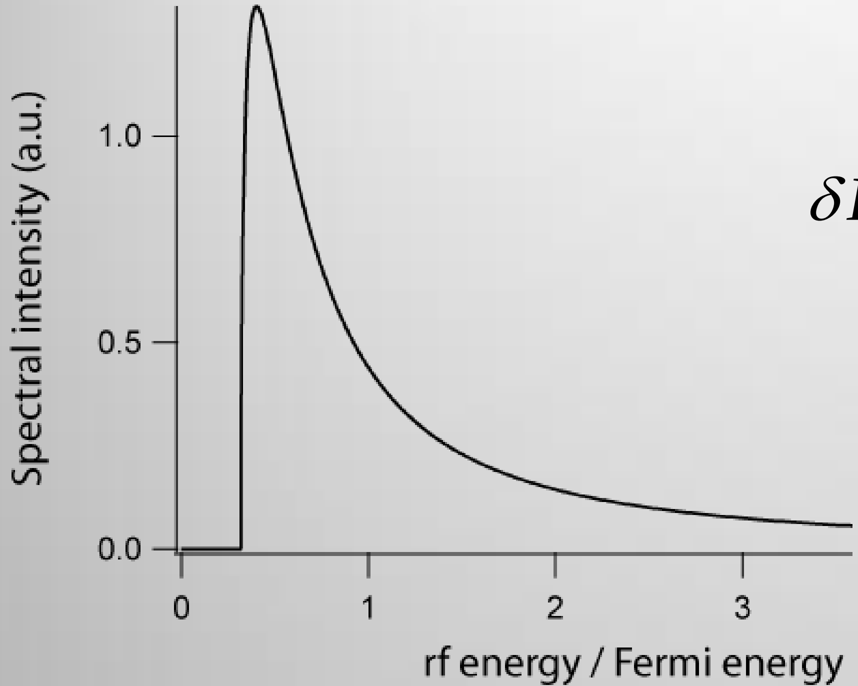
Photon energy = Zeeman + Quasiparticle + Kinetic energy

$$\hbar\omega = \hbar\omega_0 + E_k - \mu + \varepsilon_k$$

Onset at $$\hbar\omega = \hbar\omega_0 + \frac{\Delta^2}{2E_F}$$

Radiofrequency spectroscopy

BCS pairing is a many-body affair. Does the picture still hold?



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Onset at $$\hbar\omega = \hbar\omega_0 + \frac{\Delta^2}{2E_F}$$

Radiofrequency spectroscopy

Fermi's Golden Rule:

$$\Gamma(\omega) \equiv \frac{2\pi}{\hbar} \sum_f \left| \left\langle f \left| \hat{V} \right| \Psi_{\mathrm{BCS}} \right\rangle \right|^2 \delta\left(\hbar\omega - E_f\right)$$

Interaction:

$$\hat{V} = V_0 \sum_k c^\dagger_{k3} c_{k\uparrow} + c^\dagger_{k\uparrow} c_{k3}$$

Insert quasiparticle operators:

$$c_{k\uparrow} = u_k \gamma_{k\uparrow} + v_k \gamma^\dagger_{-k\downarrow}$$

Act on BCS-state:

$$c^\dagger_{k3} c_{k\uparrow} \left|\Psi_{\mathrm{BCS}}\right\rangle = v_k c^\dagger_{k3} \gamma^\dagger_{-k\downarrow} \left|\Psi_{\mathrm{BCS}}\right\rangle$$

And thus:

$$\hat{V} \left|\Psi_{\mathrm{BCS}}\right\rangle = V_0 \sum_k v_k c^\dagger_{k3} \gamma^\dagger_{-k\downarrow} \left|\Psi_{\mathrm{BCS}}\right\rangle$$

Radiofrequency spectroscopy

Fermi's Golden Rule:

$$\Gamma(\omega) \equiv \frac{2\pi}{\hbar} \sum_f \left| \left\langle f \left| \hat{V} \right| \Psi_{\mathrm{BCS}} \right\rangle \right|^2 \delta\left(\hbar\omega - E_f\right)$$

Possible final states: $|k\rangle \equiv c^\dagger_{k3}\gamma_{-k\uparrow}\,|\Psi_{\mathrm{BCS}}\rangle$

RF Photon provides: $\hbar\Omega(k) = \hbar\omega_{\uparrow 3} + E_k + \epsilon_k - \mu$

Invert: $\hbar\Omega(k) = \hbar\omega_{\uparrow 3} + E_k + \epsilon_k - \mu$ to get ϵ_k in terms of ω

Then: $\delta(\hbar\omega - \hbar\Omega(k)) = \frac{1}{\hbar}\frac{d\epsilon_k}{d\Omega}\,\delta(\epsilon_k - \epsilon(\omega))$

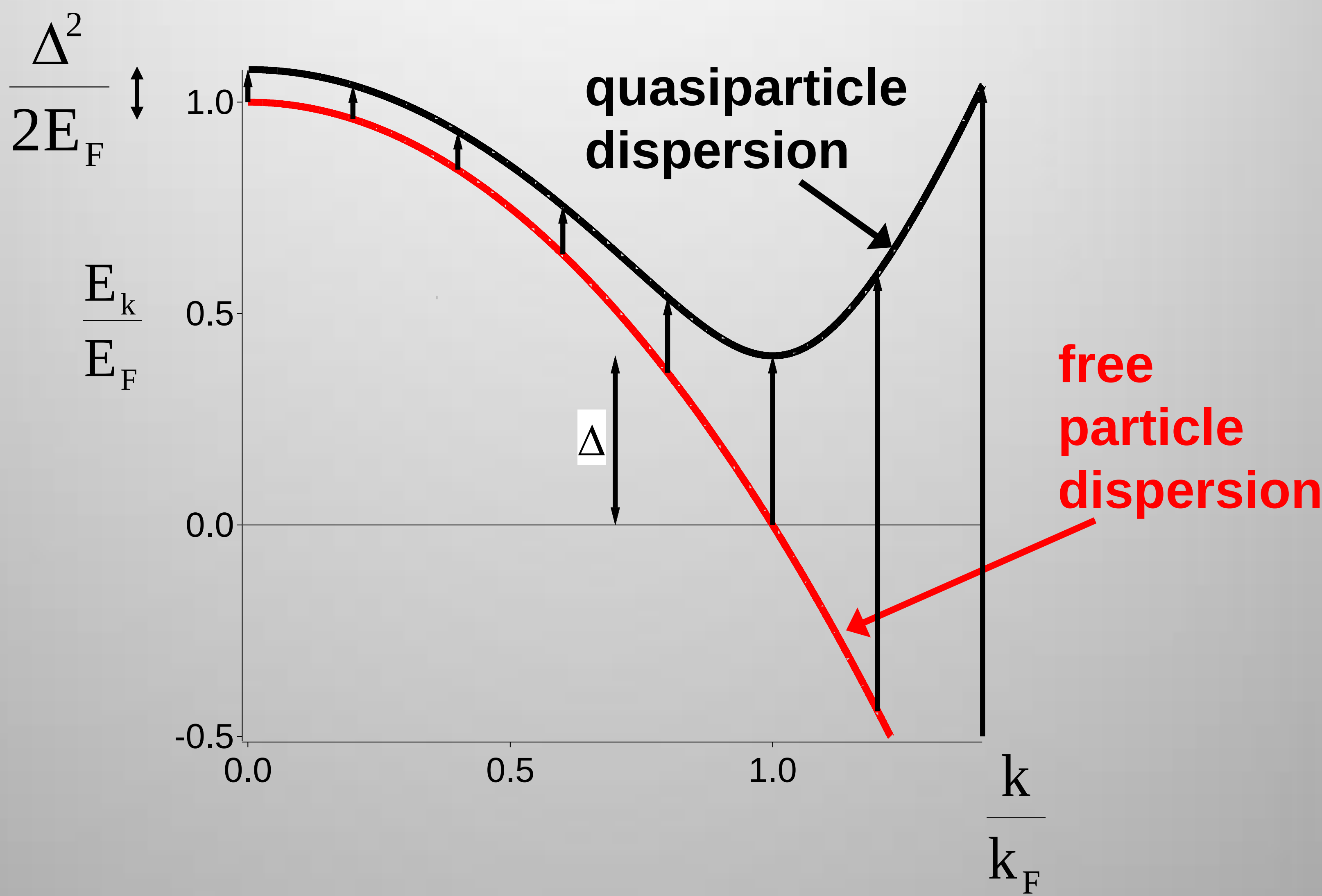
But: $\frac{d\Omega}{d\epsilon_k} = \frac{\xi_k}{E_k} + 1 = 2u_k^2$

And the final RF spectrum becomes:

$$\Gamma(\omega) = \frac{\pi}{\hbar} V_0^2\, \rho(\epsilon_k)\ \left.\frac{v_k^2}{u_k^2}\right|_{\epsilon_k = \epsilon(\omega)} = \pi N_p\, V_0^2\, \rho(\epsilon_k)\ \left.|\varphi_k|^2\ \right|_{\epsilon_k = \epsilon(\omega)}$$

Radiofrequency spectroscopy

$$\hbar\Omega = \hbar\omega_{\uparrow 3} + E_k \; - (\mu - \varepsilon_k)$$



Radiofrequency spectroscopy

$$\Gamma(\omega) = \pi N_p V_0^2 \rho(\epsilon_k) \ |\varphi_k|^2 \ \Big|_{\epsilon_k=\epsilon(\omega)}$$

$$\hbar\omega_{\mathrm{th}} = \sqrt{\mu^2+\Delta^2} - \mu \rightarrow \begin{cases} \frac{\Delta^2}{2E_F} & \text{in the BCS-limit} \\ 0.31 E_F & \text{on resonance} \\ |E_B| = \frac{\hbar^2}{ma^2} & \text{in the BEC-limit} \end{cases}$$

Explicitely:

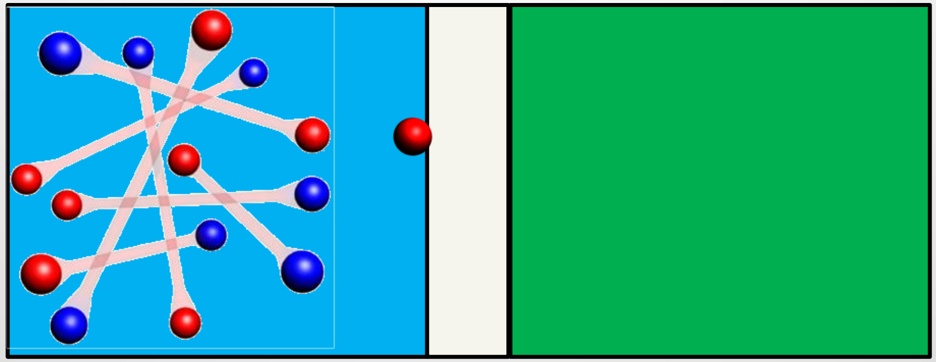
$$\Gamma(\omega) = \frac{3\pi}{4\sqrt{2}\hbar} \frac{N V_0^2 \Delta^2}{E_F^{3/2}} \frac{\sqrt{\hbar\omega - \hbar\omega_{\mathrm{th}}}}{\hbar^2\omega^2} \sqrt{1 + \frac{\omega_{\mathrm{th}}}{\omega} + \frac{2\mu}{\hbar\omega}}$$

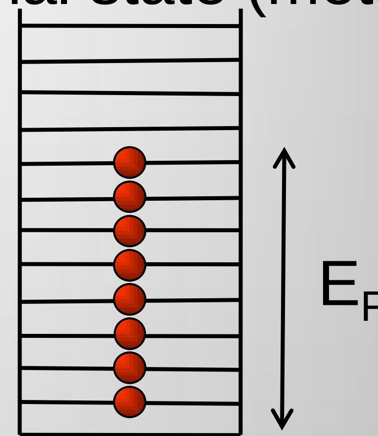
BEC-limit:

$$\Gamma_{\mathrm{BEC}}(\omega) = \frac{4}{\hbar} N_M V_0^2 \sqrt{|E_B|} \frac{\sqrt{\hbar\omega - |E_B|}}{\hbar^2\omega^2}$$

Connection to tunneling experiments

Final state (metal):

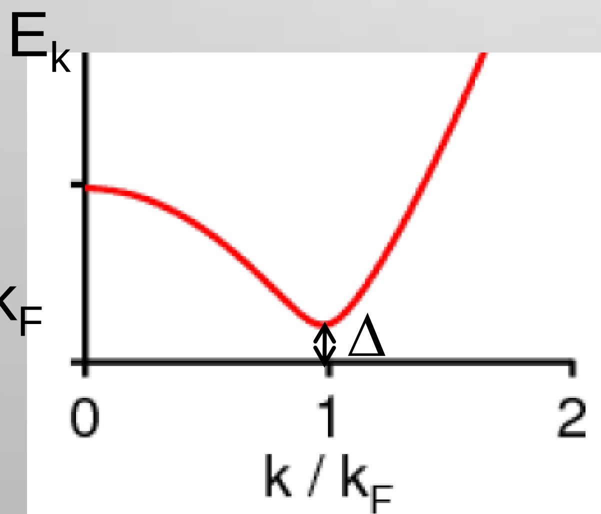


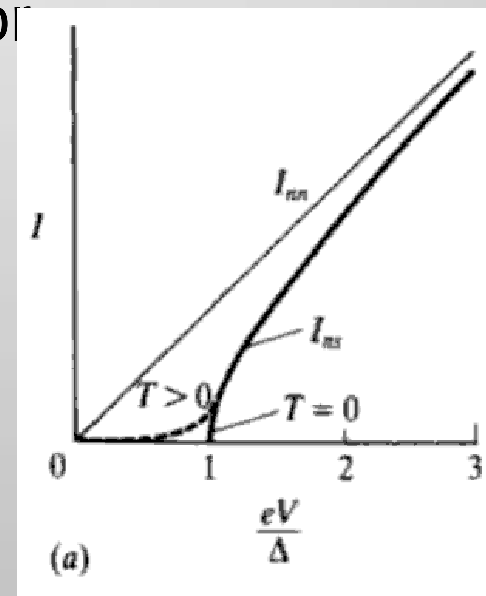


Superconductor ↑ Normal metal

Insulator

Transfer at Fermi surface $k=k_F$

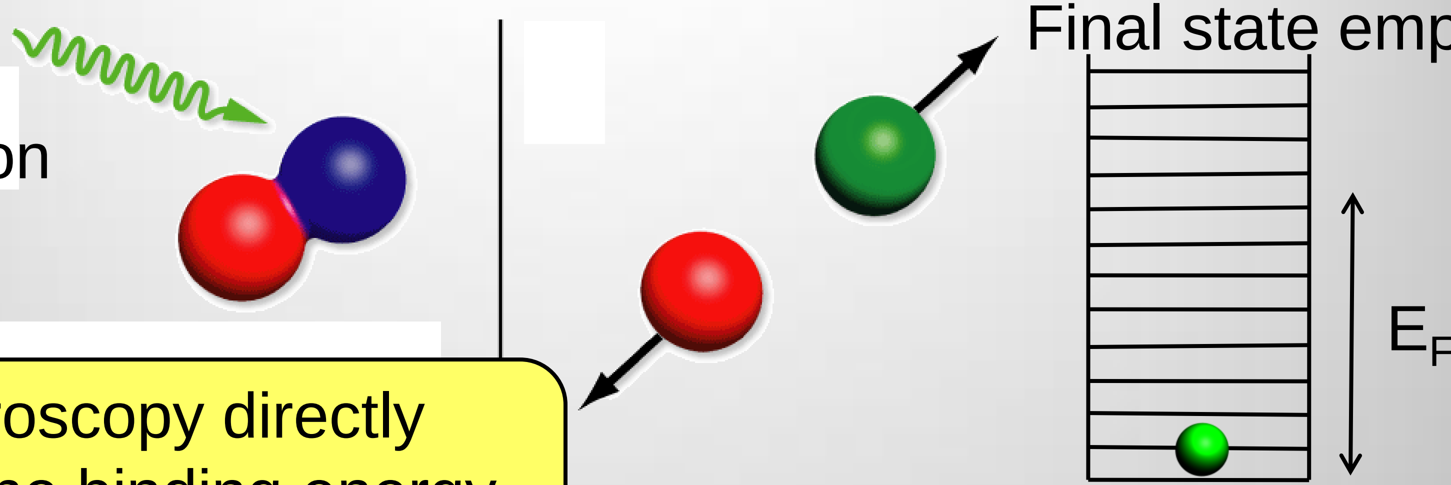




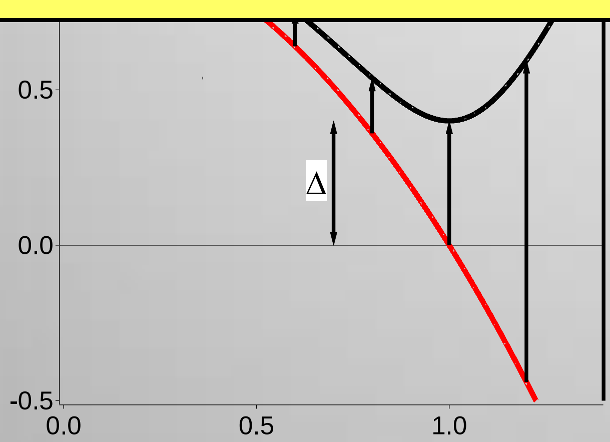
Onset at: $$eV = \Delta$$

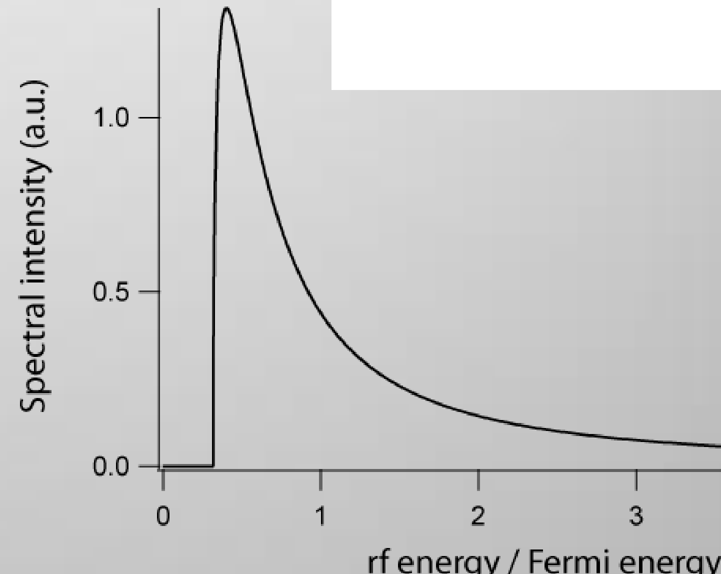
Source: Tinkham, Introduction to Superconductivity

Connection to tunneling experiments



RF spectroscopy directly measures the binding energy of fermion pairs (not the gap)

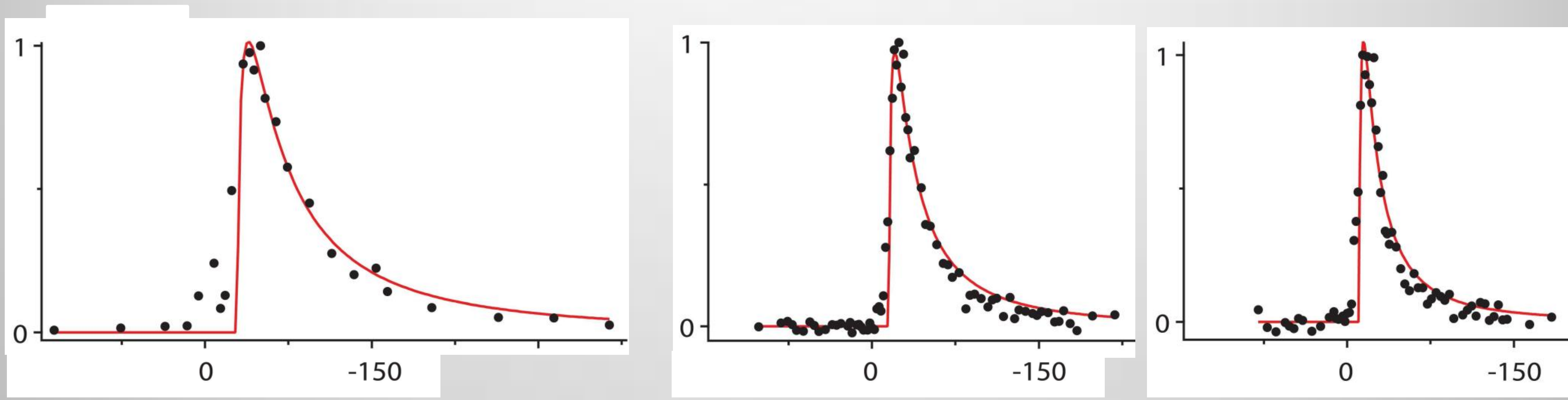




BCS limit, onset at: $$\hbar\omega - \hbar\omega_0 = \frac{\Delta^2}{2E_F}$$

Rf Spectra in the BEC-BCS Crossover

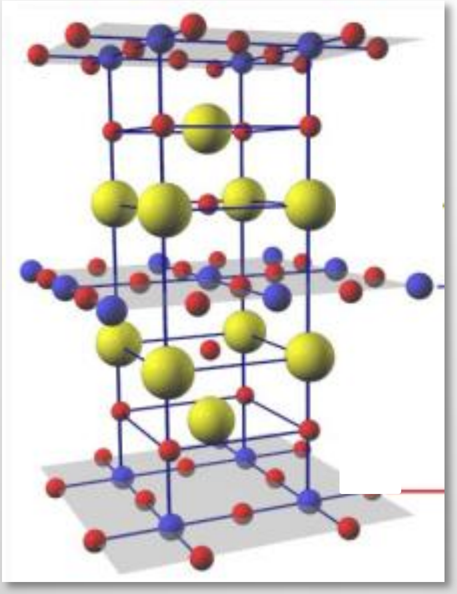
BEC **Unitarity** **BCS**



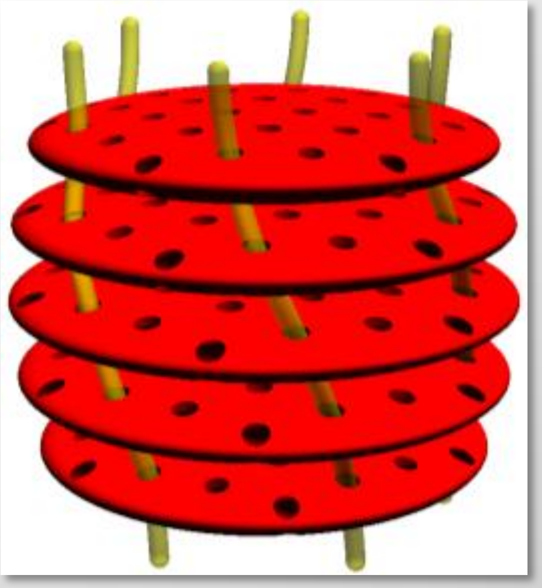
- Determine binding energy spectroscopically
- Infer size of the pairs at unitarity:
  about half the interparticle spacing

Christian H. Schunck, Yong-il Shin, Andre Schirotzek, Wolfgang Ketterle, Nature **454**, 739 (2008)

Fermions entering Flatland



High-T_c Superconductor with stacks of CuO planes



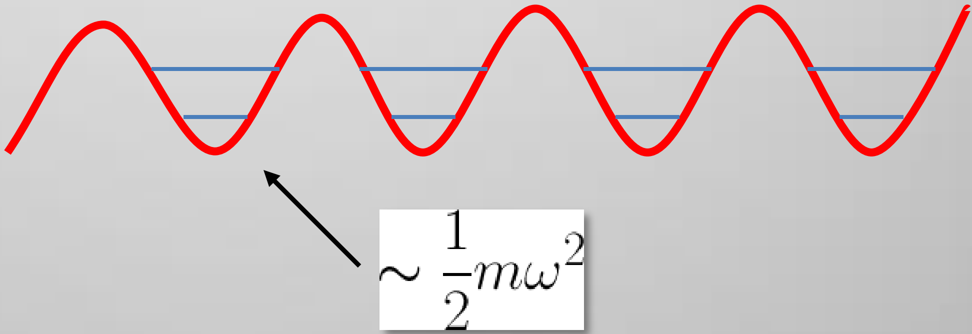
Stacks of 2D coupled fermionic superfluids

- 2D Fermi Gases: A paradigm of condensed matter physics
- Access physics of layered superconductors
- Evolution of Fermion Pairing from 3D to 2D
- Study superfluidity in lower dimensions

Expts on 2D Bose gases: Ketterle, Dalibard, Cornell, Phillipps, Chin
Expts on 2D Fermi gases: Turlapov, Koehl, Thomas, Vale

Making quasi-2D Fermi gases

- Confine atoms tightly in one direction
  until only the ground state is occupied
- Our setup: 1D lattice (retro-reflected laser beam)
- 2D-ness tuned by lattice depth
- Deep lattice: $\frac{\varepsilon_F}{\hbar\omega} \sim 0.1$, aspect ratio of ~1:1000

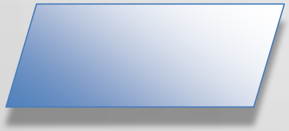


Pairing in 1D, 2D, 3D

- In 1D

Two particles bind for the slightest attraction

- In 2D

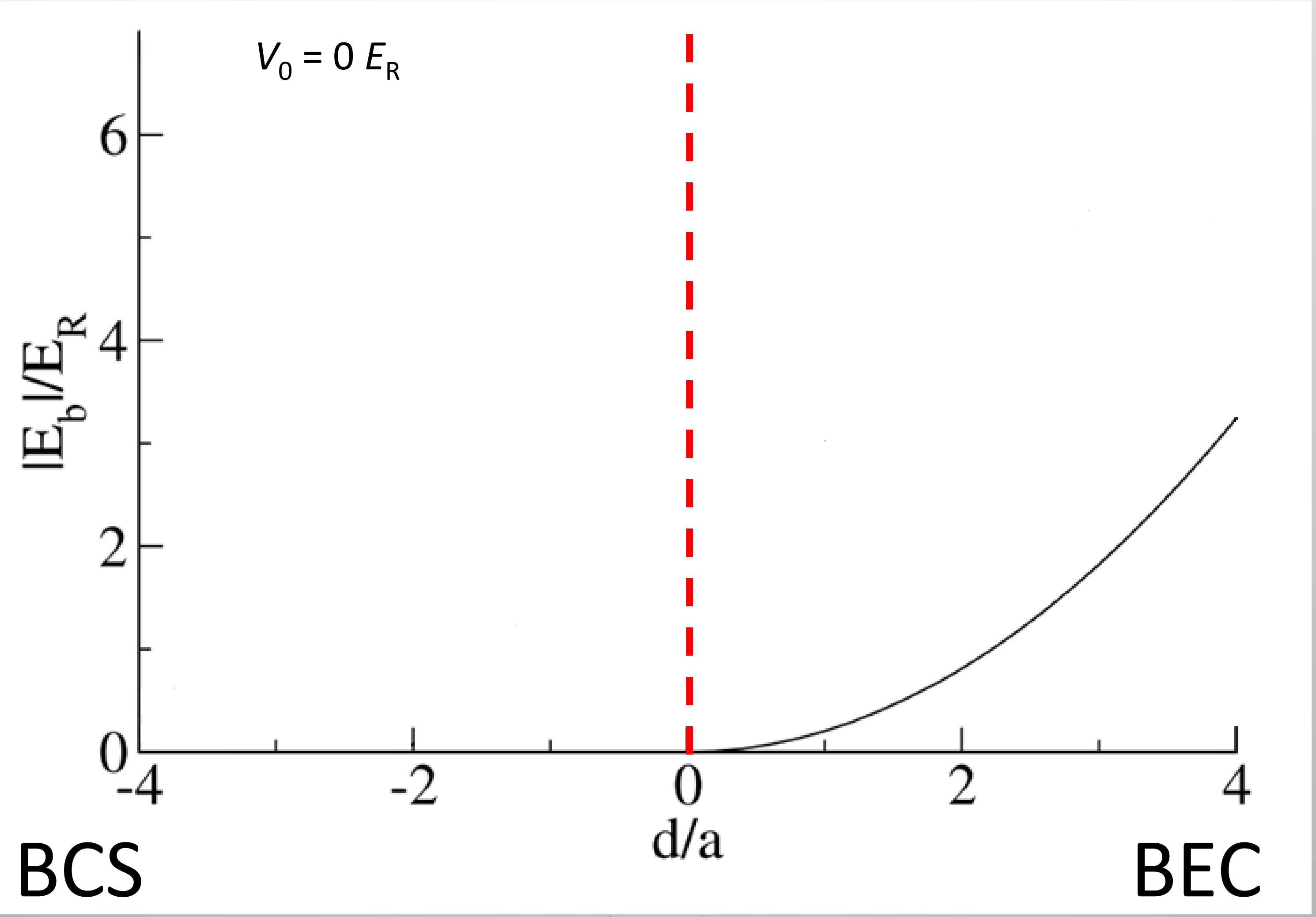


Two particles bind for the slightest attraction
... but binding is exponentially weak

- In 3D

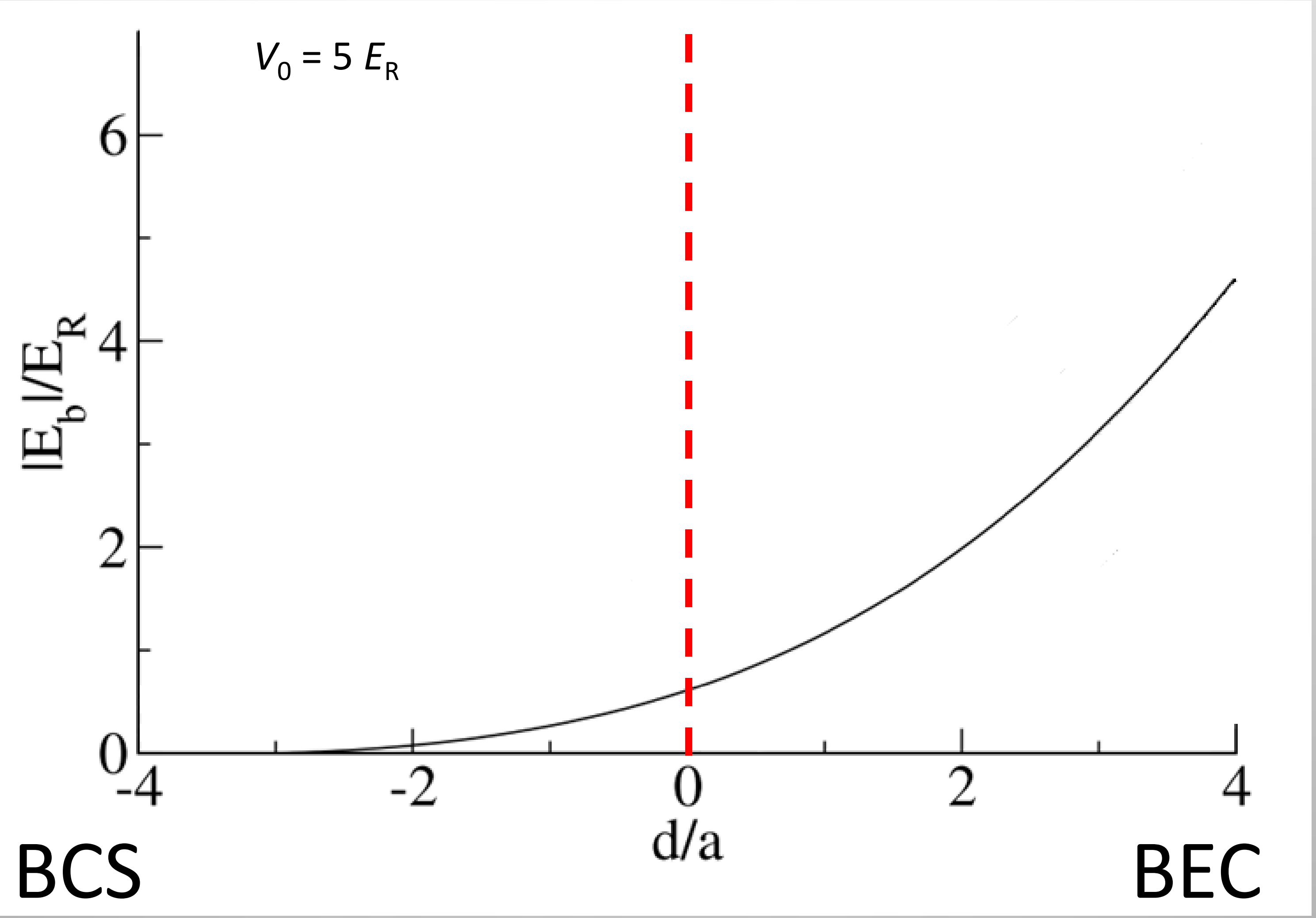
Pairing requires strong attraction, or many-body physics:
The presence of a Fermi sea (Cooper pairing)

Binding Energy from 3D to 2D (1D lattice)



Orso & Wouters. PRL **95** 060402 (2005)

Binding Energy from 3D to 2D (1D lattice)



Orso & Wouters. PRL **95** 060402 (2005)

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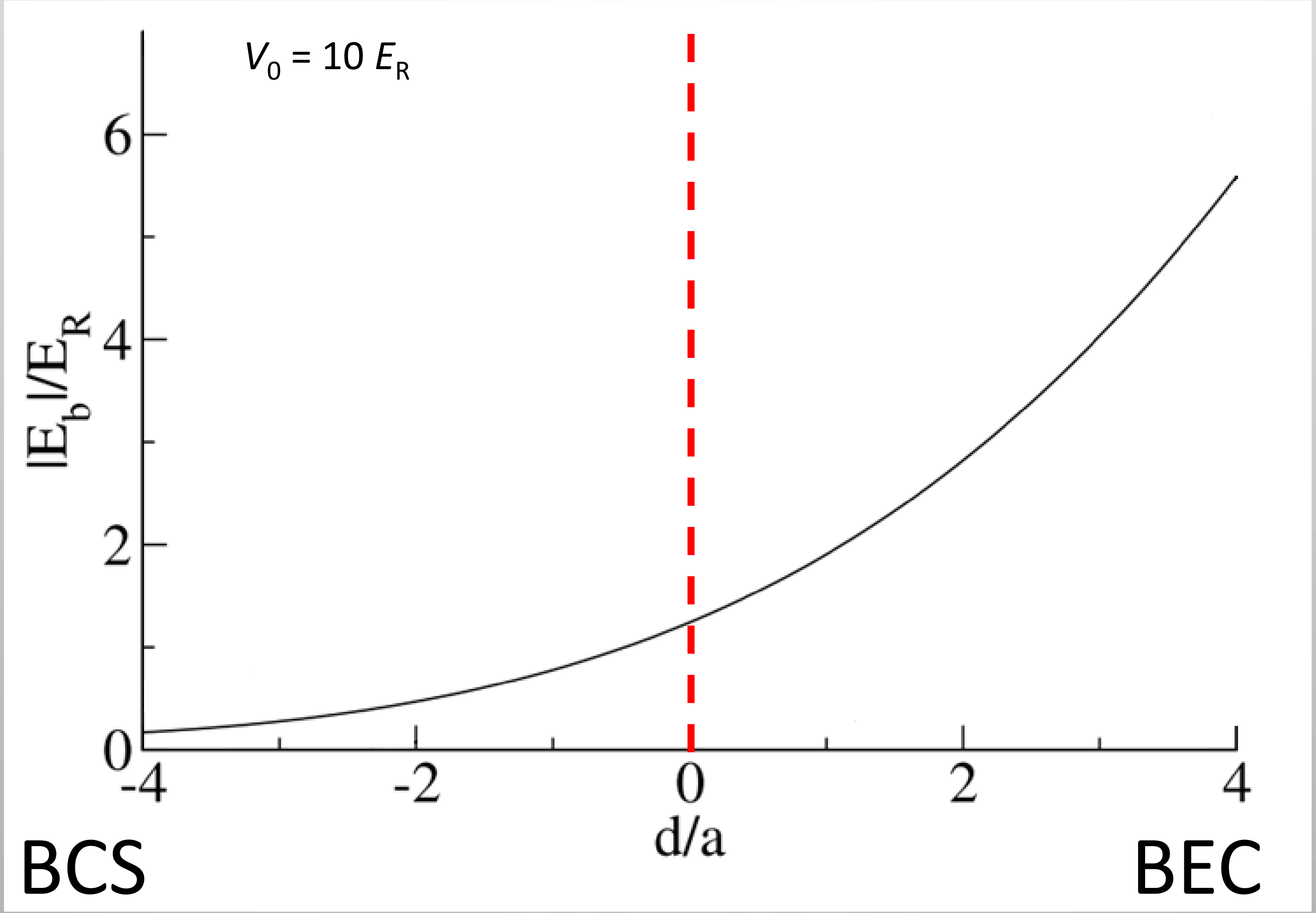

Orso & Wouters. PRL **95** 060402 (2005)

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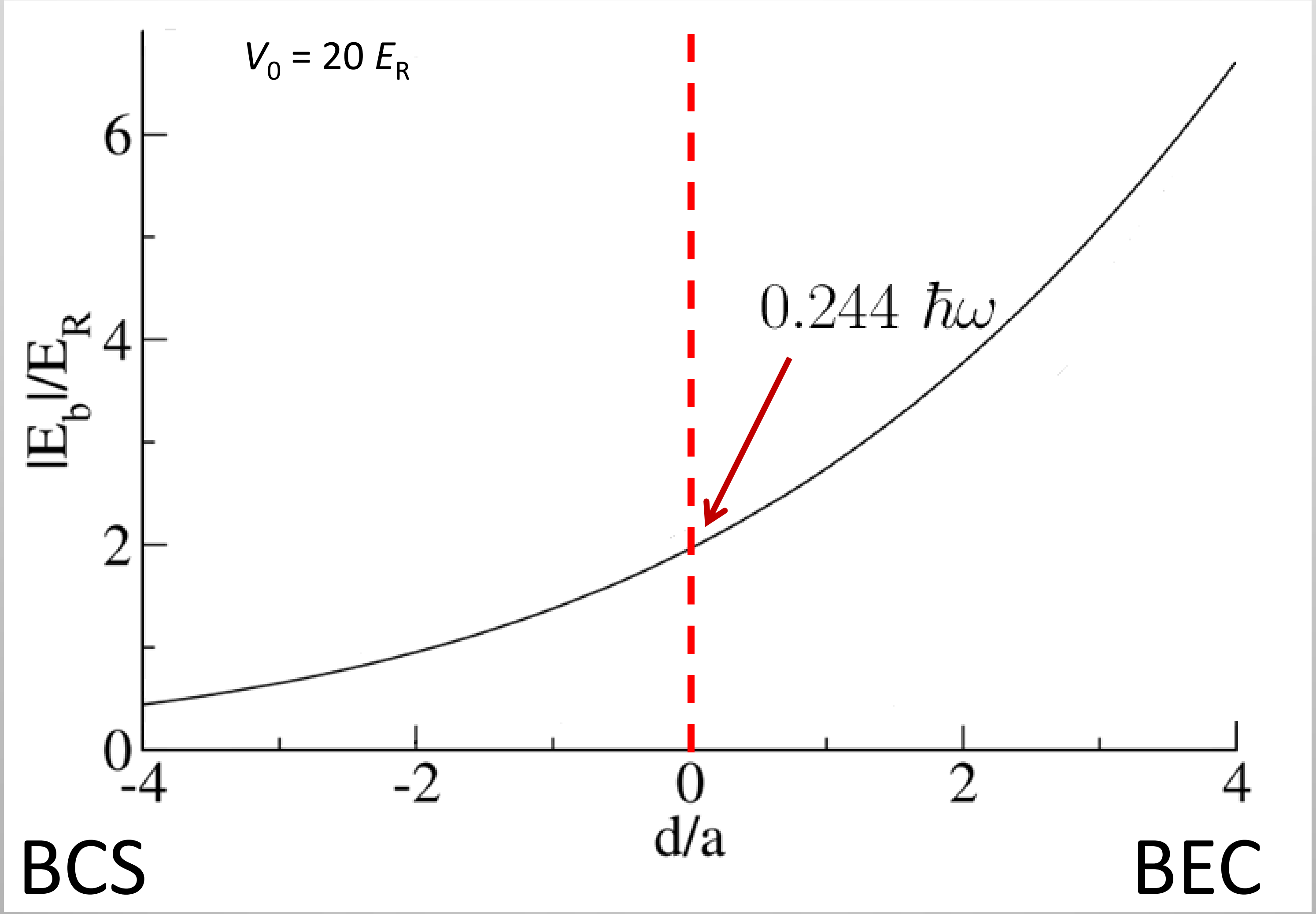
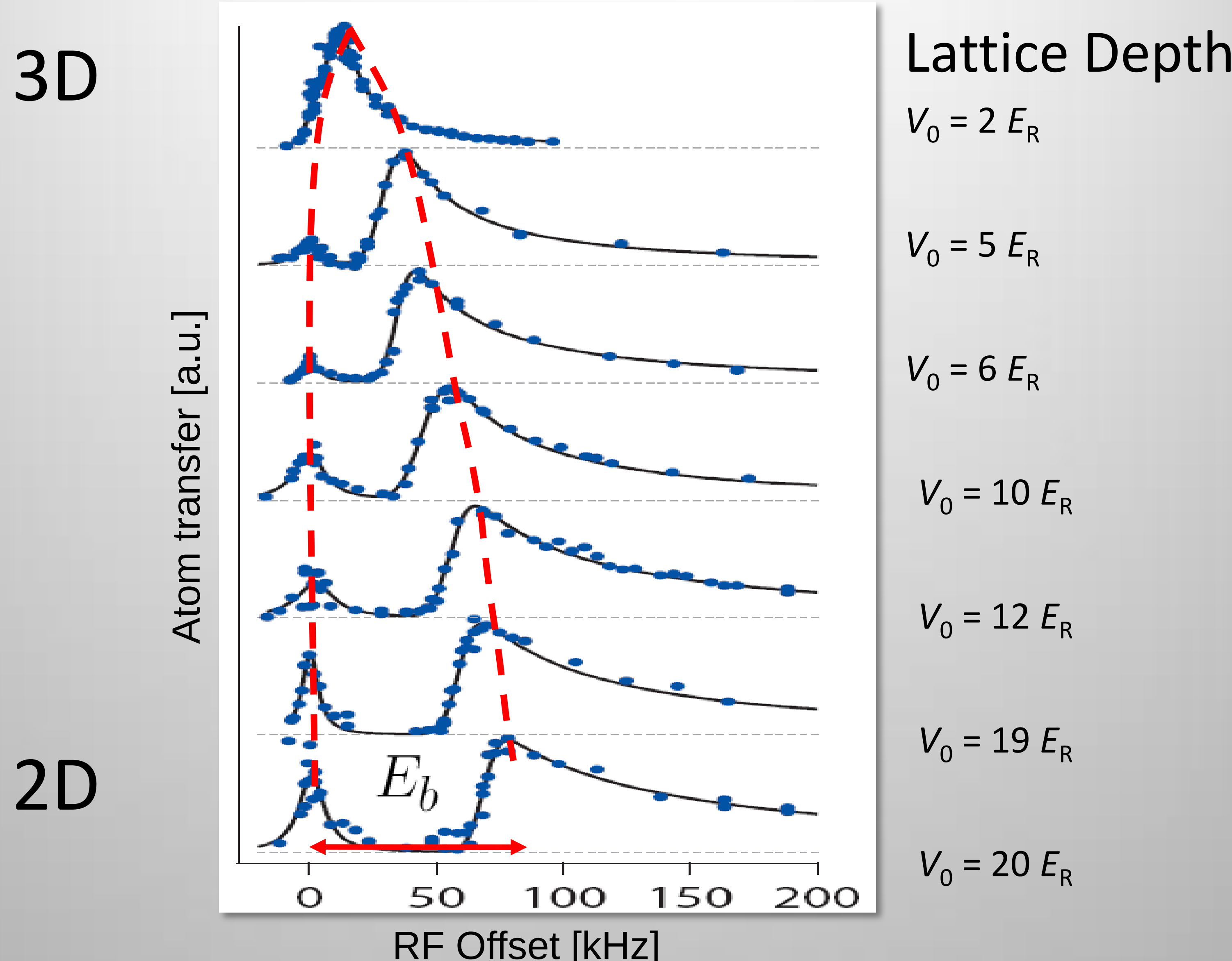


Orso & Wouters. PRL **95** 060402 (2005)

Evolution of Fermion Pairing from 3D to 2D

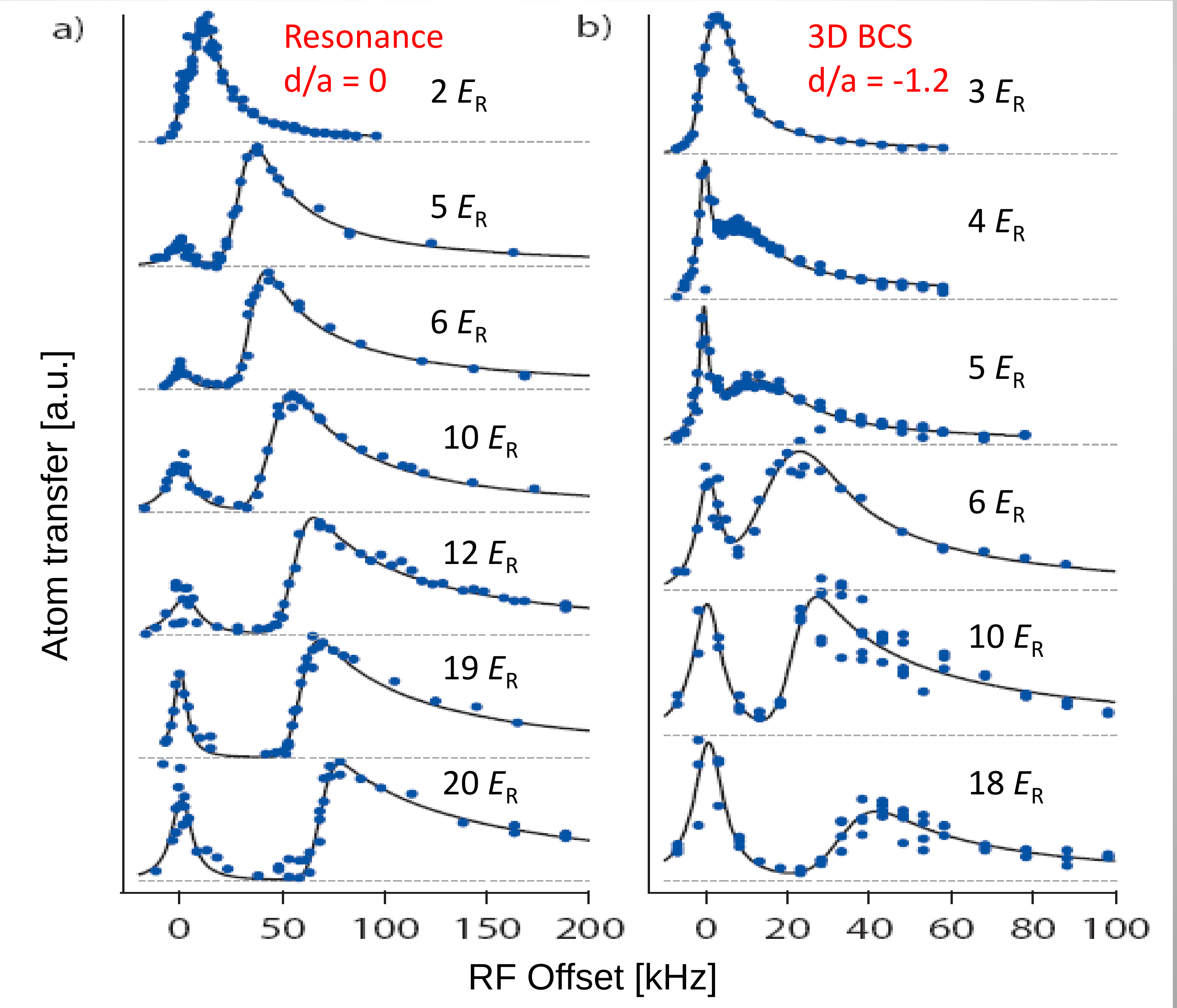


A. T. Sommer, L. W. Cheuk, M. J.-H. Ku, W. S. Bakr, M. W. Zwierlein
PRL **108**, 045302 (2012) Selected for Viewpoint in Physics, Jan '12

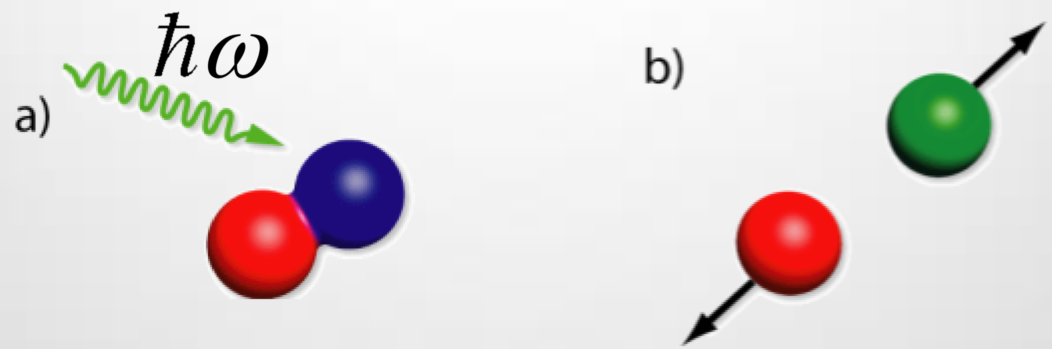
Evolution of Fermion Pairing from 3D to 2D

3D

2D



RF spectrum of fermion pairs



$$I(\omega) \sim \rho(\varepsilon_k)\,|\psi(k)|^2\Big|_{\varepsilon_k=\varepsilon(\omega)}$$

Density of States: 3D $\sim \sqrt{\varepsilon}$

2D *const.*

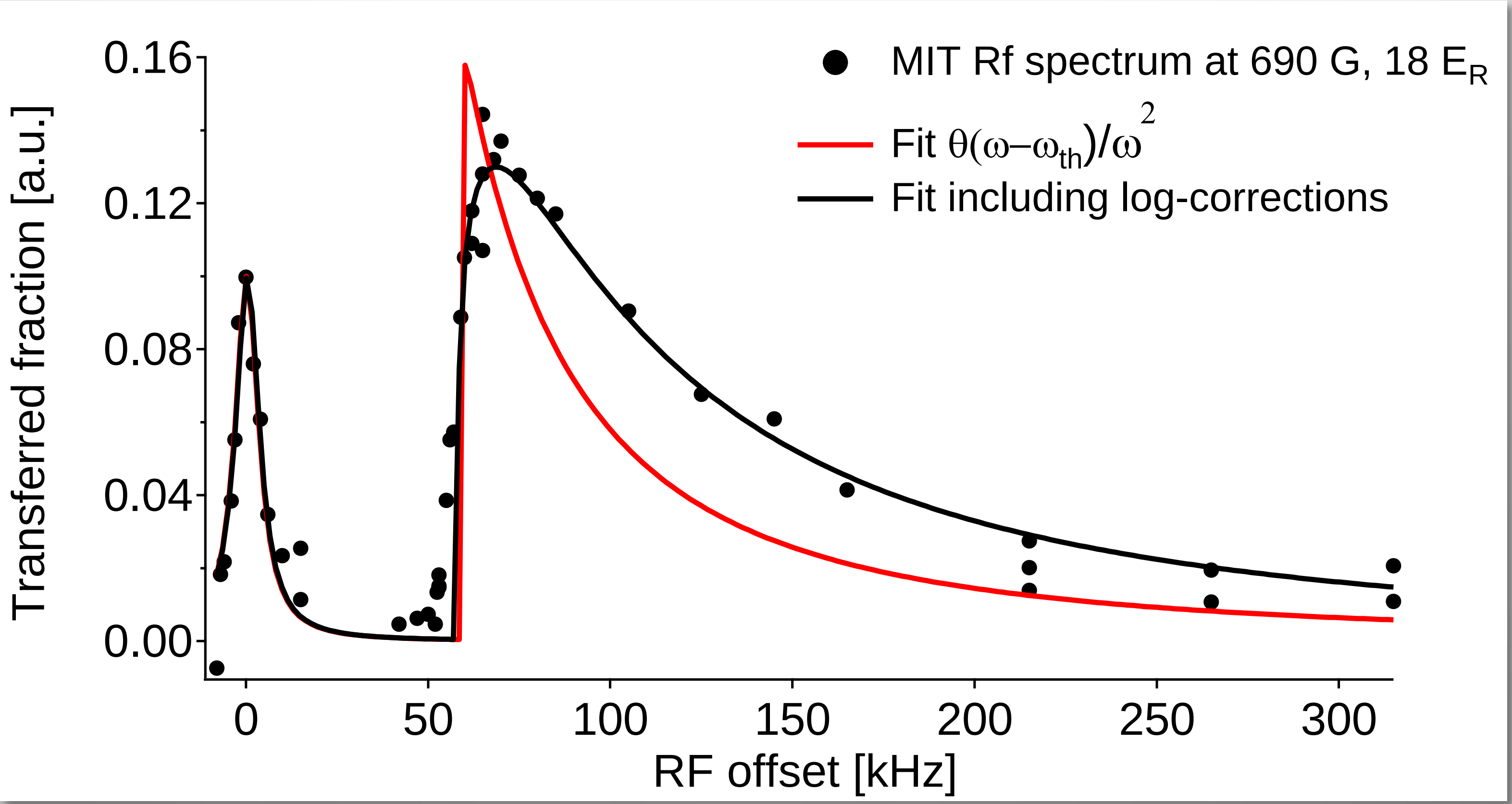
3D: $I(\omega) \sim \dfrac{\sqrt{\omega-\omega_{th}}}{\omega^2}$

Interactions in final state:
Langmack, Barth, Zwerger, Braaten
Phys. Rev. Lett. **108**, 060402 (2012)

2D: $I(\omega) \sim \dfrac{\theta(\omega-\omega_{th})}{\omega^2}\;\dfrac{\ln^2(E_b^f/E_b)}{\ln^2((\omega-E_b)/E_b^f)+\pi^2}$

Logarithmic Corrections in 2D Spectra

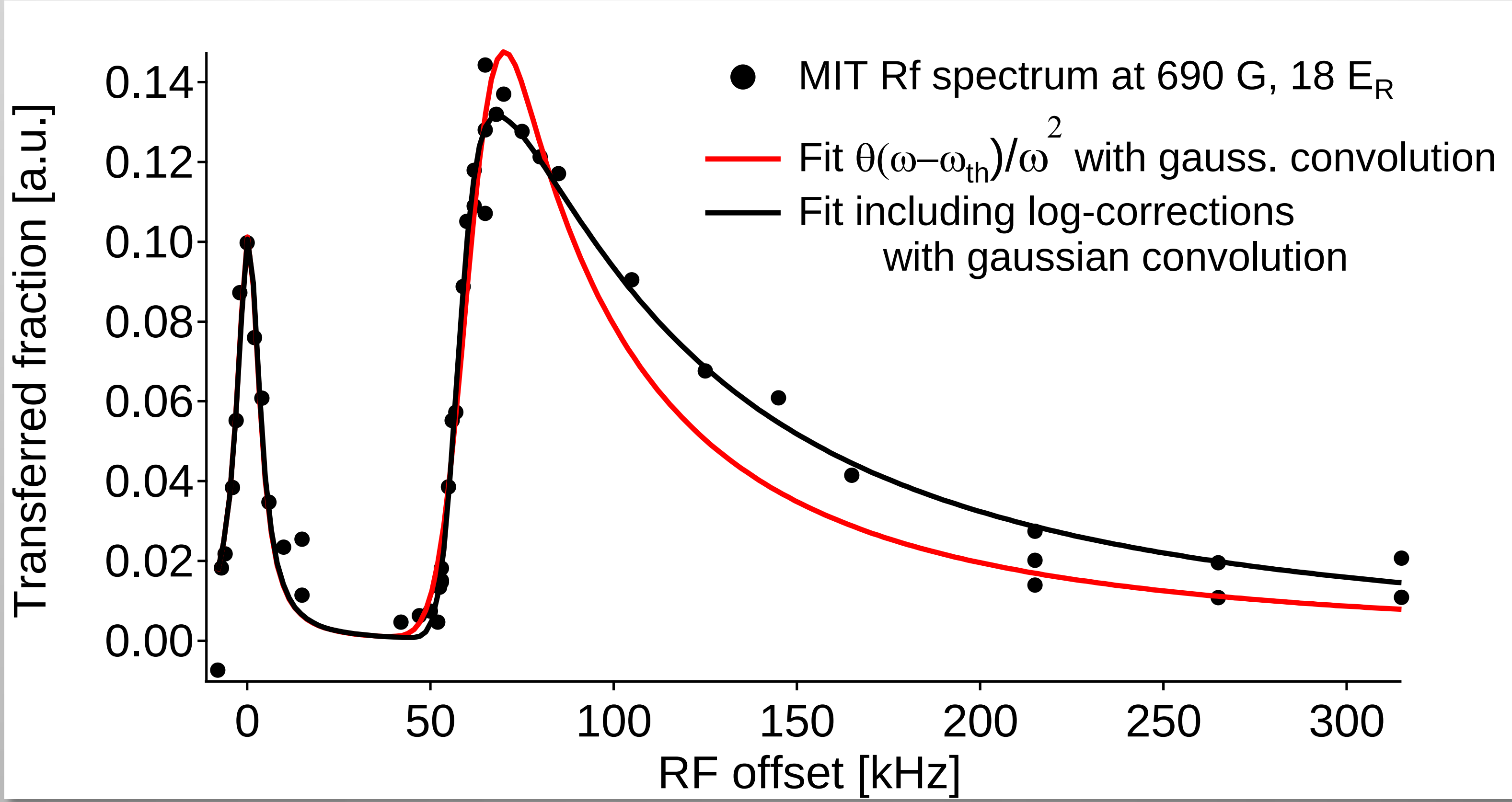
2D nature of interactions strongly influence “naïve” spectra



$$I_{Pair}(\omega) \sim \frac{\theta(\omega-\omega_{th})}{\omega^2} \frac{\ln^2(E_b^f / E_b)}{\ln^2((\omega - E_b)/E_b^f) + \pi^2}$$

Logarithmic Corrections in 2D Spectra

2D nature of interactions strongly influence "naïve" spectra

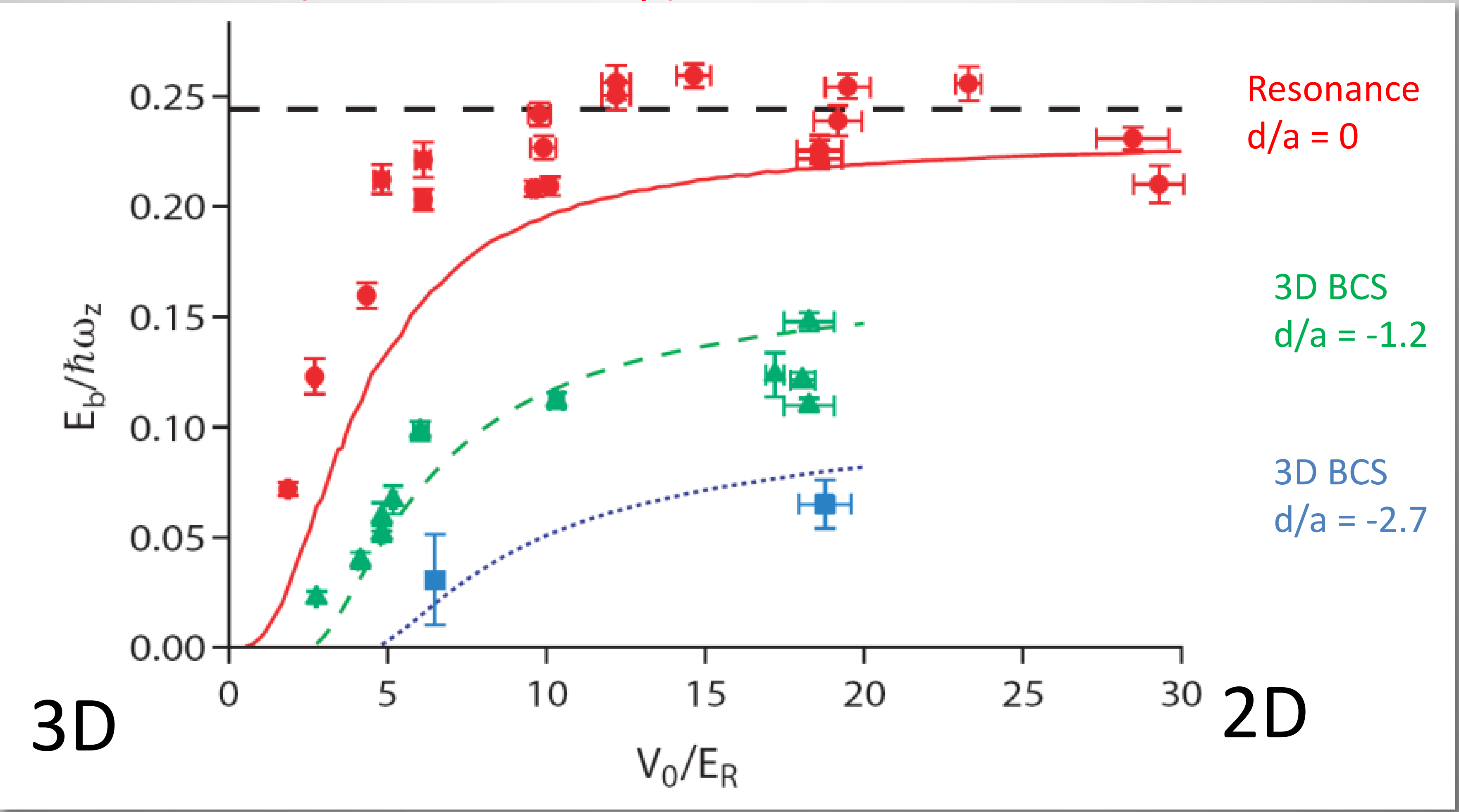


$$I_{Pair}(\omega) \sim \frac{\theta(\omega-\omega_{th})}{\omega^2} \frac{\ln^2(E_b^f / E_b)}{\ln^2((\omega - E_b)/E_b^f) + \pi^2}$$

Evolution of Fermion Pairing from 3D to 2D

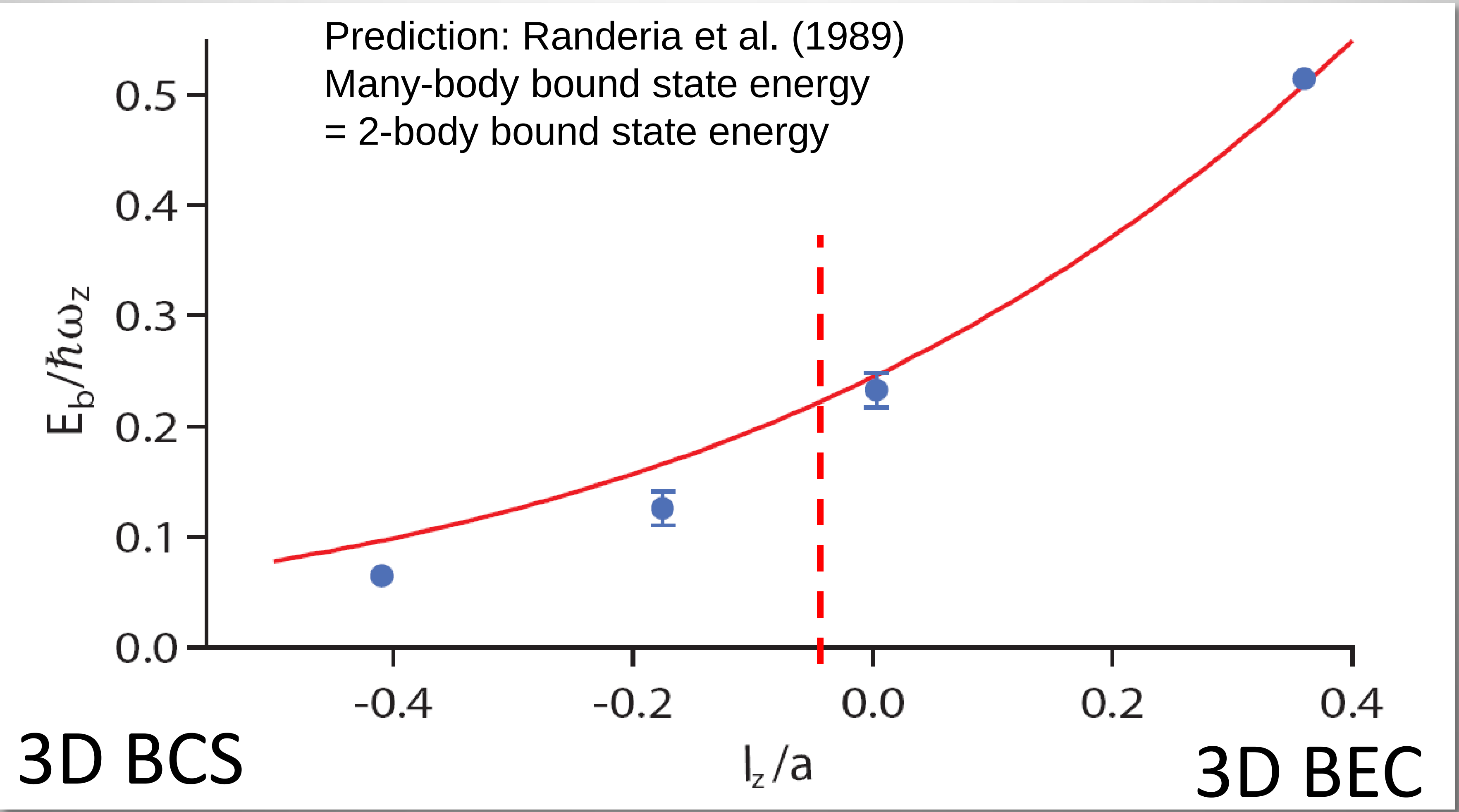
On Resonance
(in harmonic trap):

$$E_{B,th} = 0.244\hbar\omega_z$$



A. T. Sommer, L. W. Cheuk, M. J.-H. Ku, W. S. Bakr, M. W. Zwierlein
PRL **108**, 045302 (2012) Selected for Viewpoint in Physics, Jan '12

Deep 2D regime
Comparison with mean-field BEC-BCS in 2D



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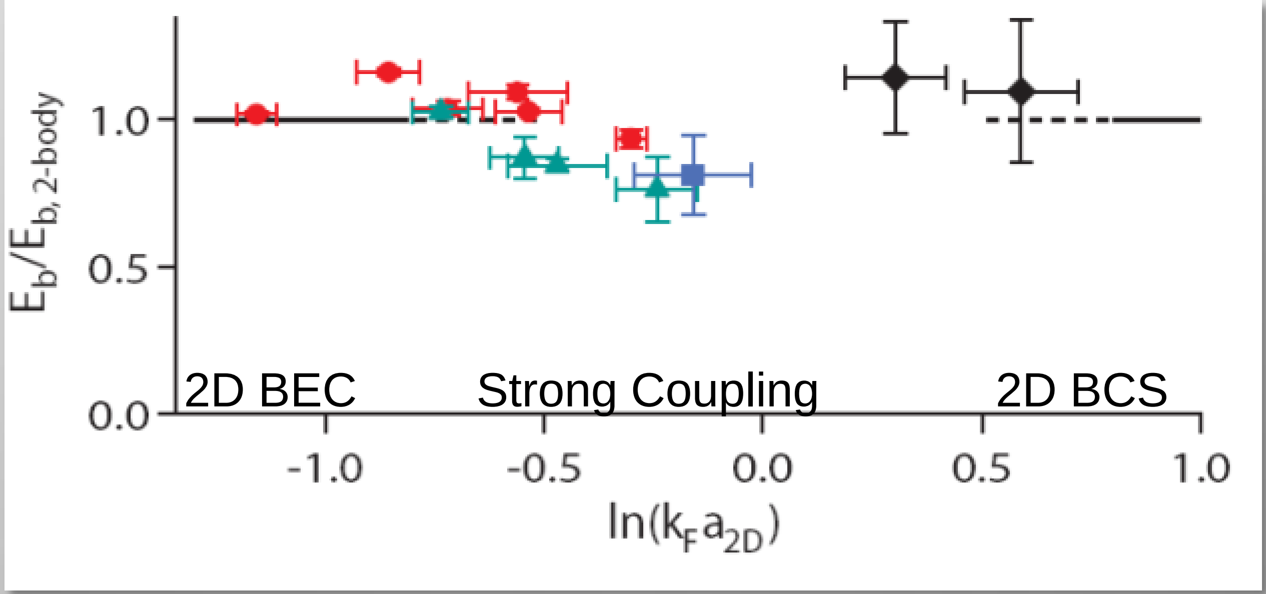
PRL **108**, 045302 (2012) Selected for Viewpoint in Physics, Jan '12

Deep 2D regime
Comparison with mean-field BEC-BCS in 2D

Prediction: Randeria et al. (1989)
Many-body bound state energy
= 2-body bound state energy



Only small deviation observed between many-body and 2-body bound-state energy

Same conclusion in M. Koehl group: Feld et al., Nature 480, 75 (2011)

A. T. Sommer, L. W. Cheuk, M. J.-H. Ku, W. S. Bakr, M. W. Zwierlein
PRL **108**, 045302 (2012) Selected for Viewpoint in Physics, Jan ‘12

Spin-Orbit Coupled Fermi Gases

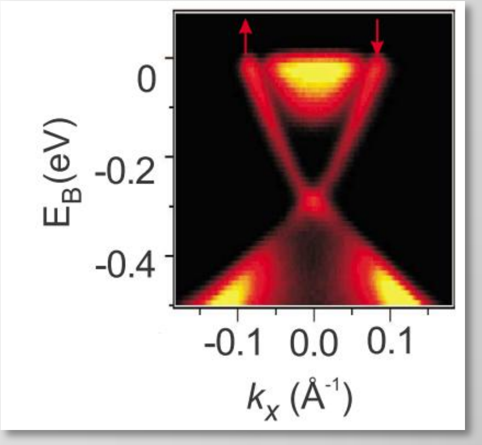
Spin-Orbit Coupling

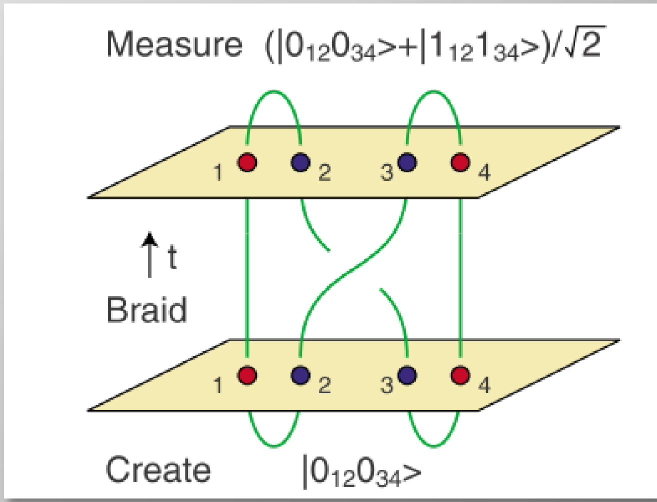
Motivation:

- Possible Ingredient for Topological Phases of Matter
- Induces p- (and higher-order) partial wave interactions + p-wave pairing
  - Topological Superconductors: → Majorana Edge States

Topological protection

→ Quantum computation with Majorana fermions (Kitaev)





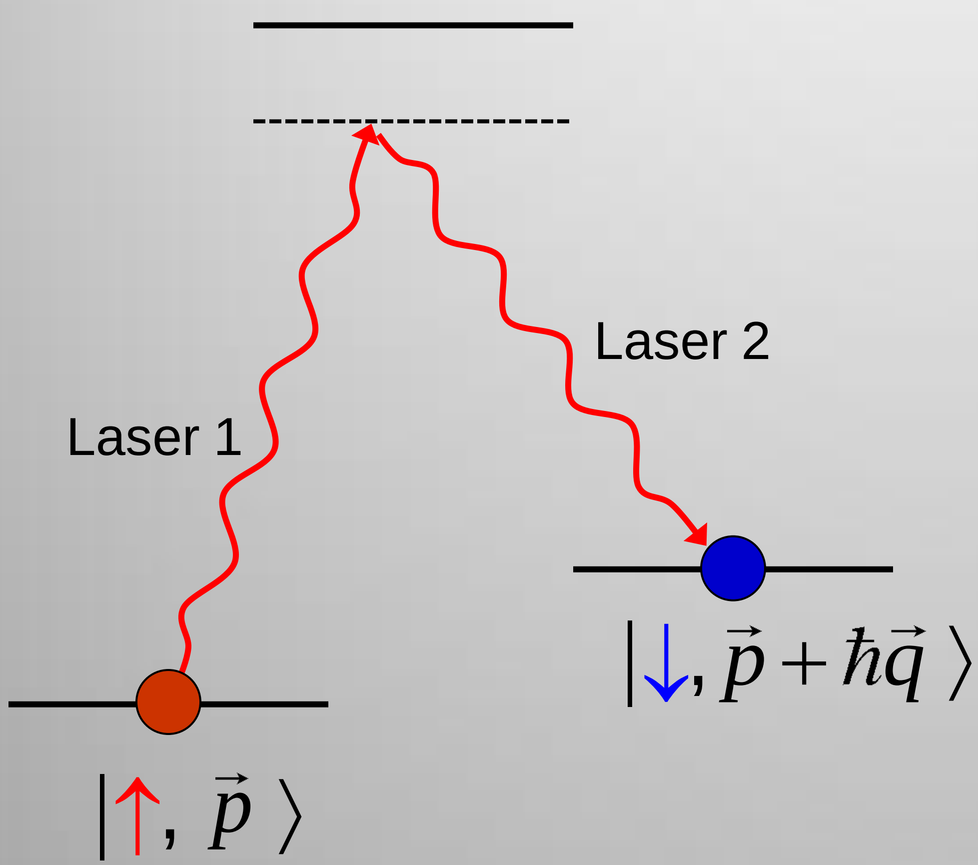
M.Z. Hasan and C.L. Kane
RMP **82**, 3045 (2010)

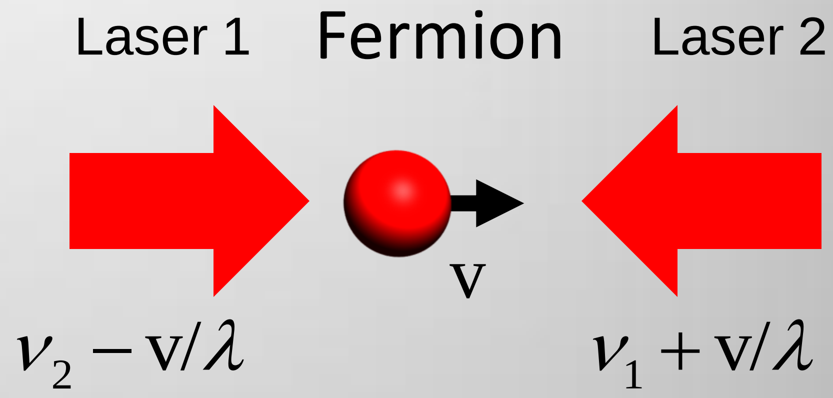
Spin-Orbit Coupling

Raman transition:

Couple different spin (hyperfine) states

Doppler effect causes momentum-dependent coupling





Pioneering work with bosons:

Ian Spielman, NIST

Recent work with fermions:

Zhang et al., Shanxi

The spin-orbit Hamiltonian

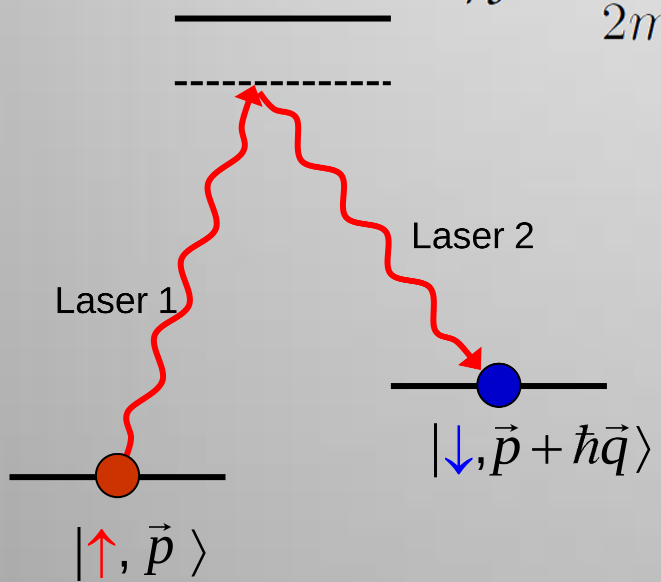
- The SO Hamiltonian

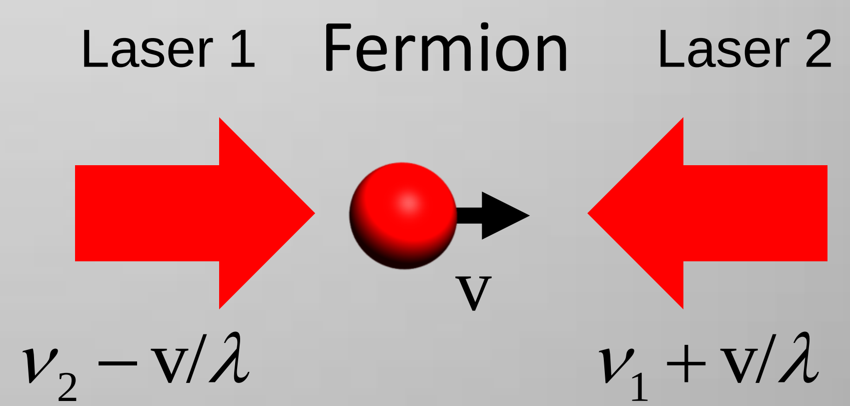
$$\mathcal{H} = \frac{\hbar^2 k^2}{2m} - \frac{g\mu_B}{\hbar}\mathbf{S}\cdot(\mathbf{B}^{(D)} + \mathbf{B}^{(R)} + \mathbf{B}^{(Z)})$$

$$\mathbf{B}^{(R)} = \alpha(k_y, -k_x, 0) \qquad \mathbf{B}^{(D)} = \beta(k_y, k_x, 0)$$

- 1D SO Hamiltonian

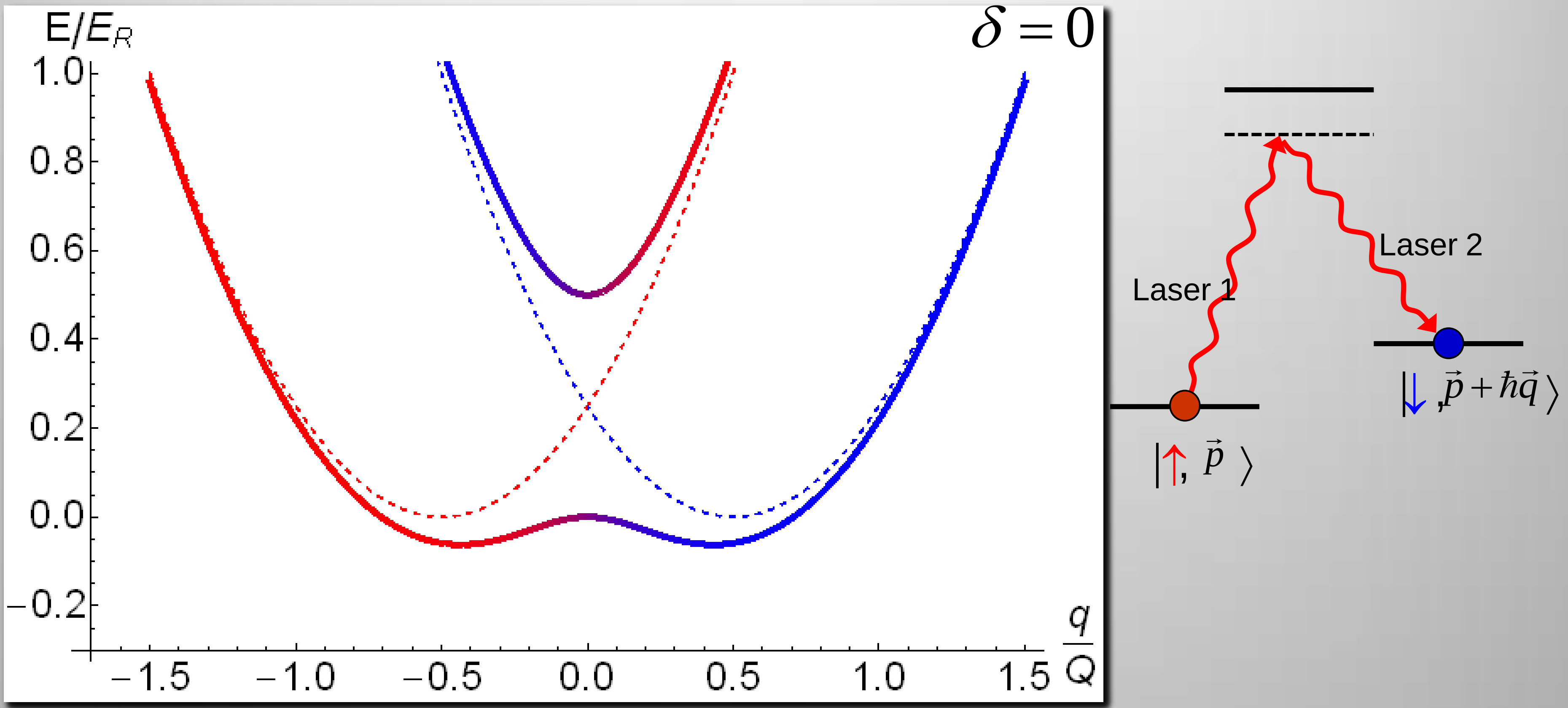
$$\mathcal{H} = \frac{\hbar^2 k^2}{2m} + 2\alpha k \sigma_z + \frac{\delta}{2}\sigma_z + \frac{\hbar\Omega_R}{2}\sigma_x$$



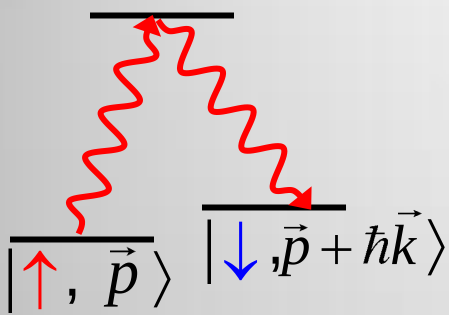


The spin-orbit gap

$$\mathcal{H} = \frac{\hbar^2 k^2}{2m} + 2\alpha k \sigma_z + \frac{\delta}{2}\sigma_z + \frac{\hbar\Omega_R}{2}\sigma_x$$

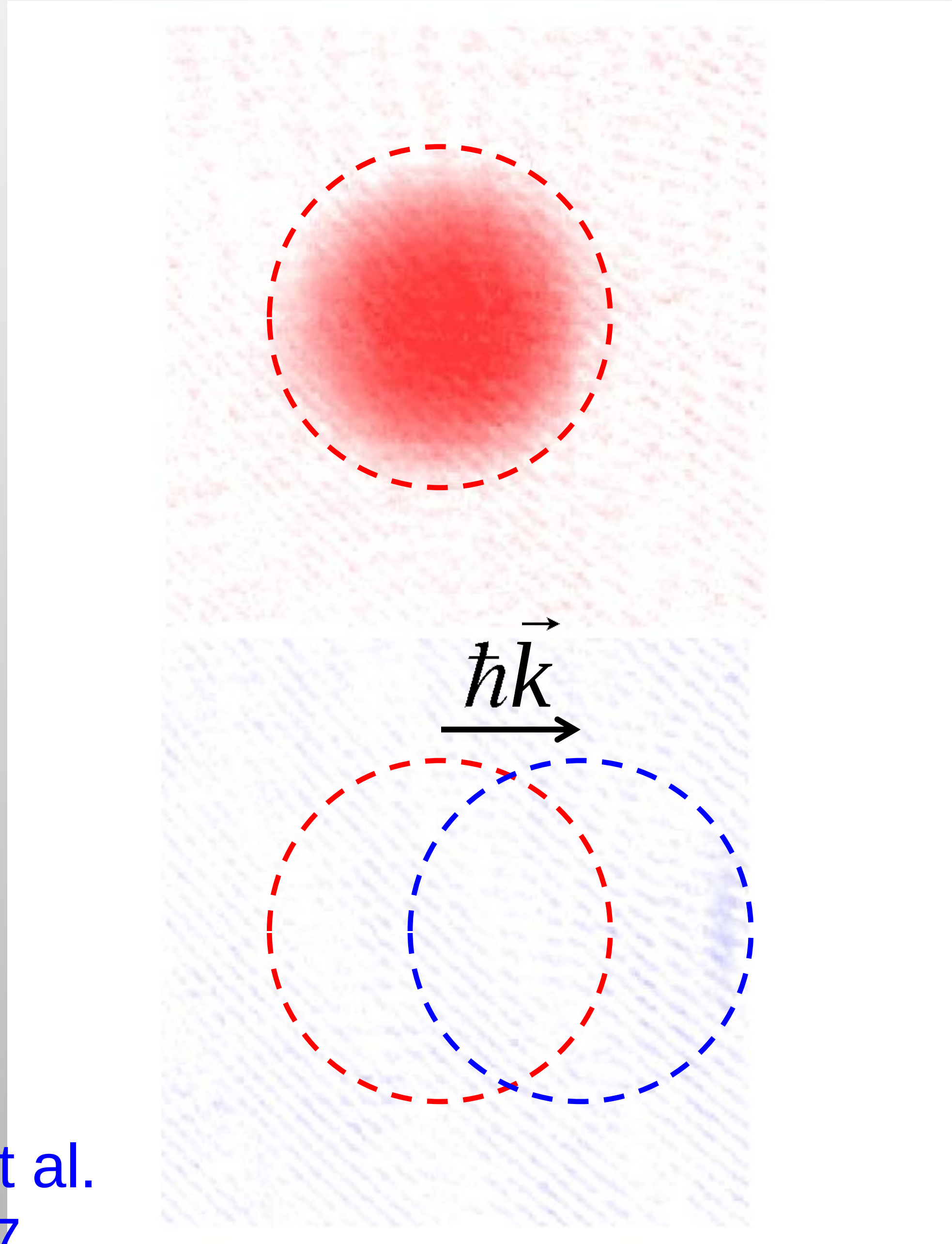


Coupling Spin and Momentum via Raman



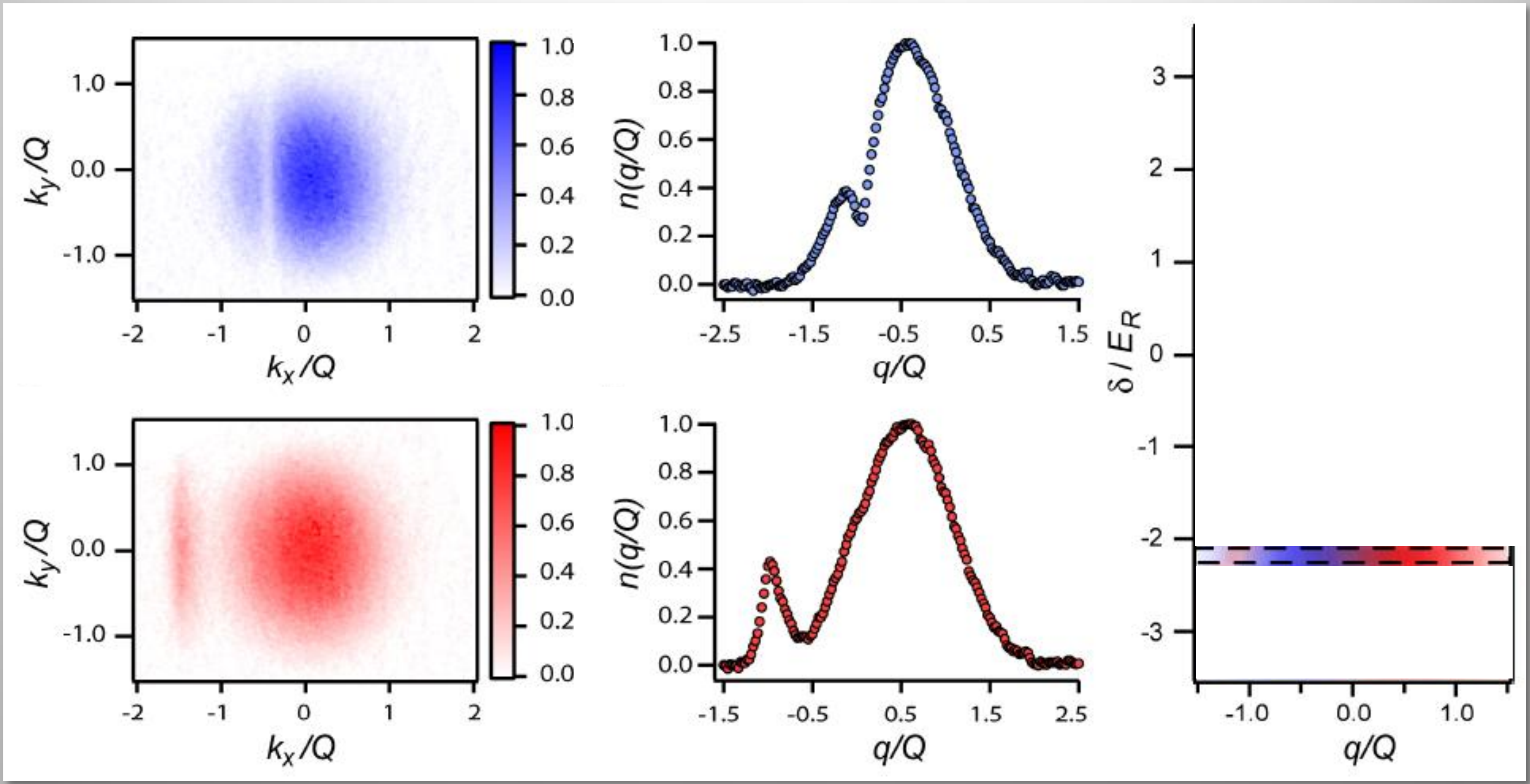
Vary detuning

Short pulse



ee also: Zhang et al.
arXiv:1204.1887

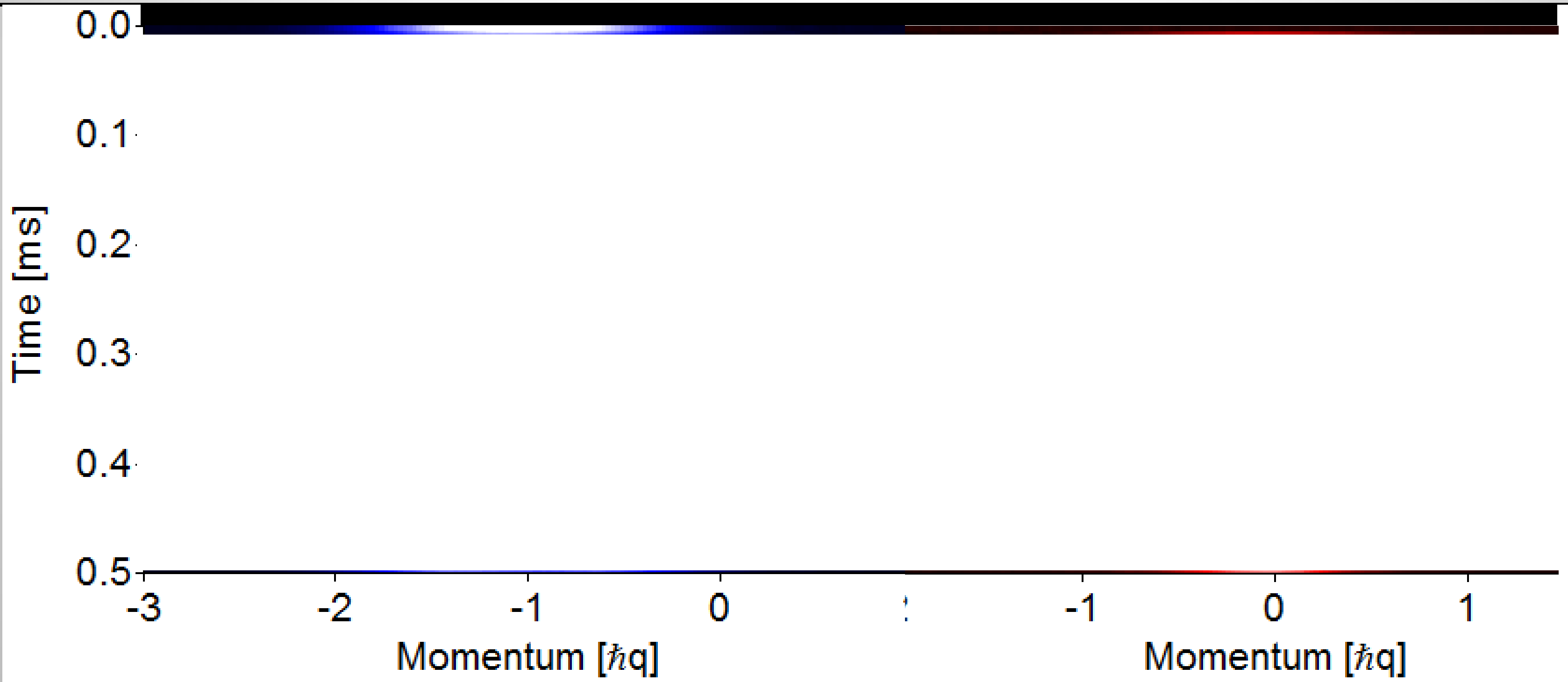
Coupling Spin and Momentum via Raman



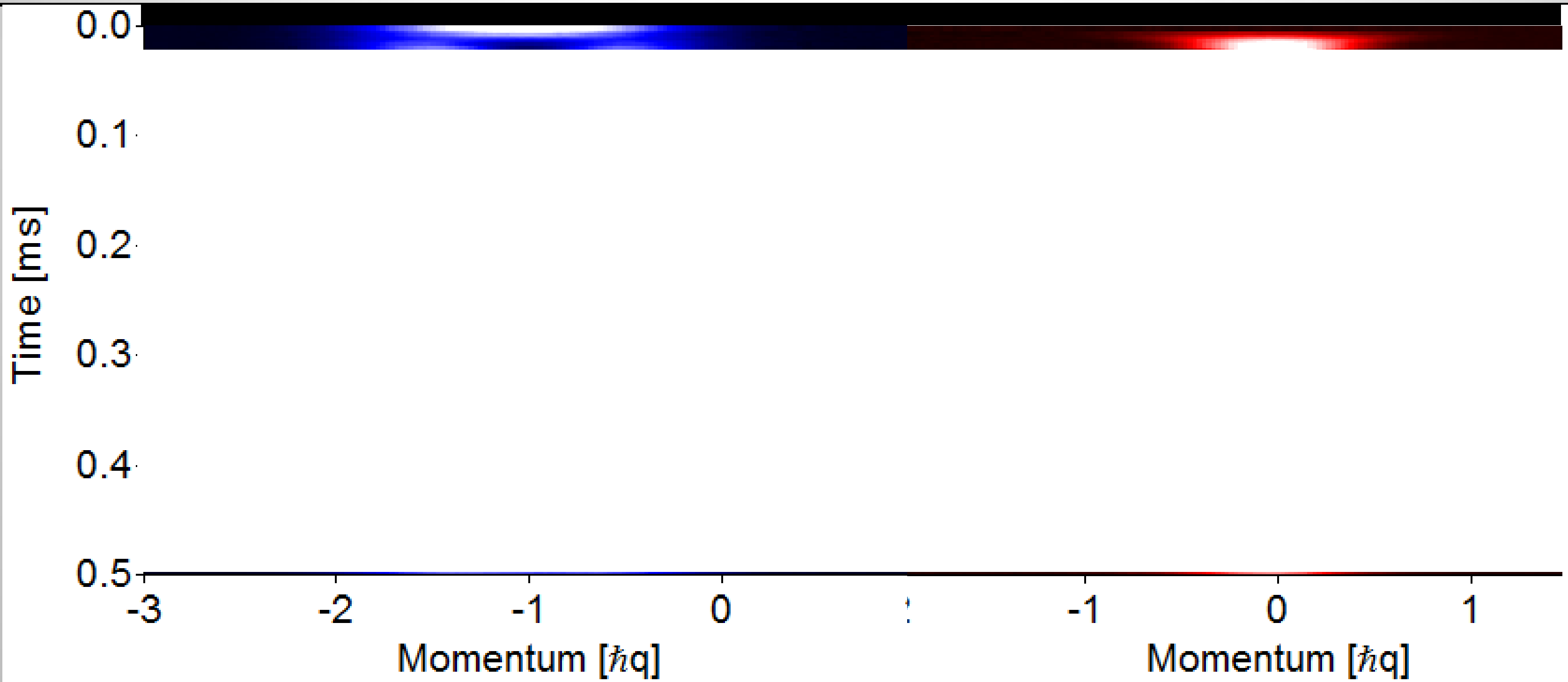
$$\left|\tilde{k}\right\rangle$$

$$= \alpha_k \left|k, \uparrow\right\rangle + \beta_k \left|k + q, \downarrow\right\rangle$$

Rabi Oscillations of Spin-Momentum Coupled States



Rabi Oscillations of Spin-Momentum Coupled States



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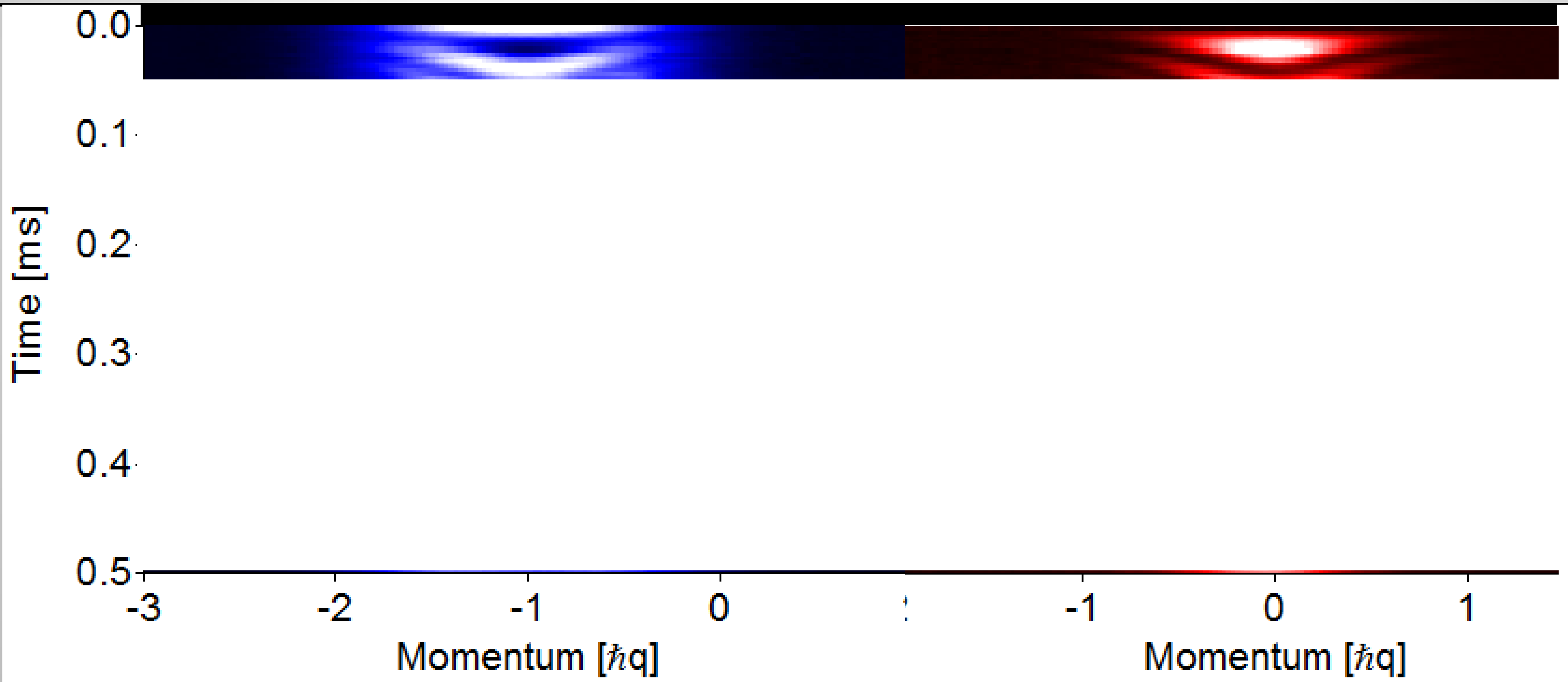

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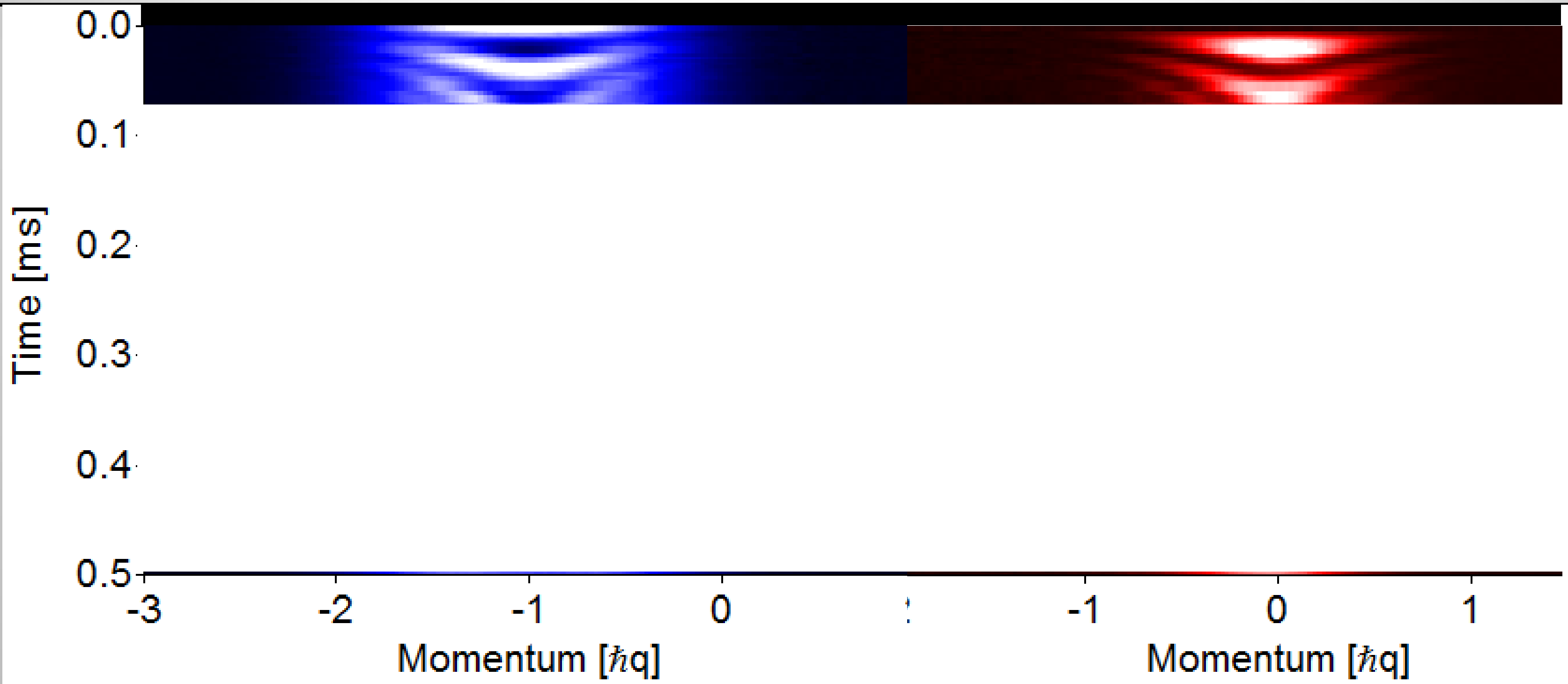
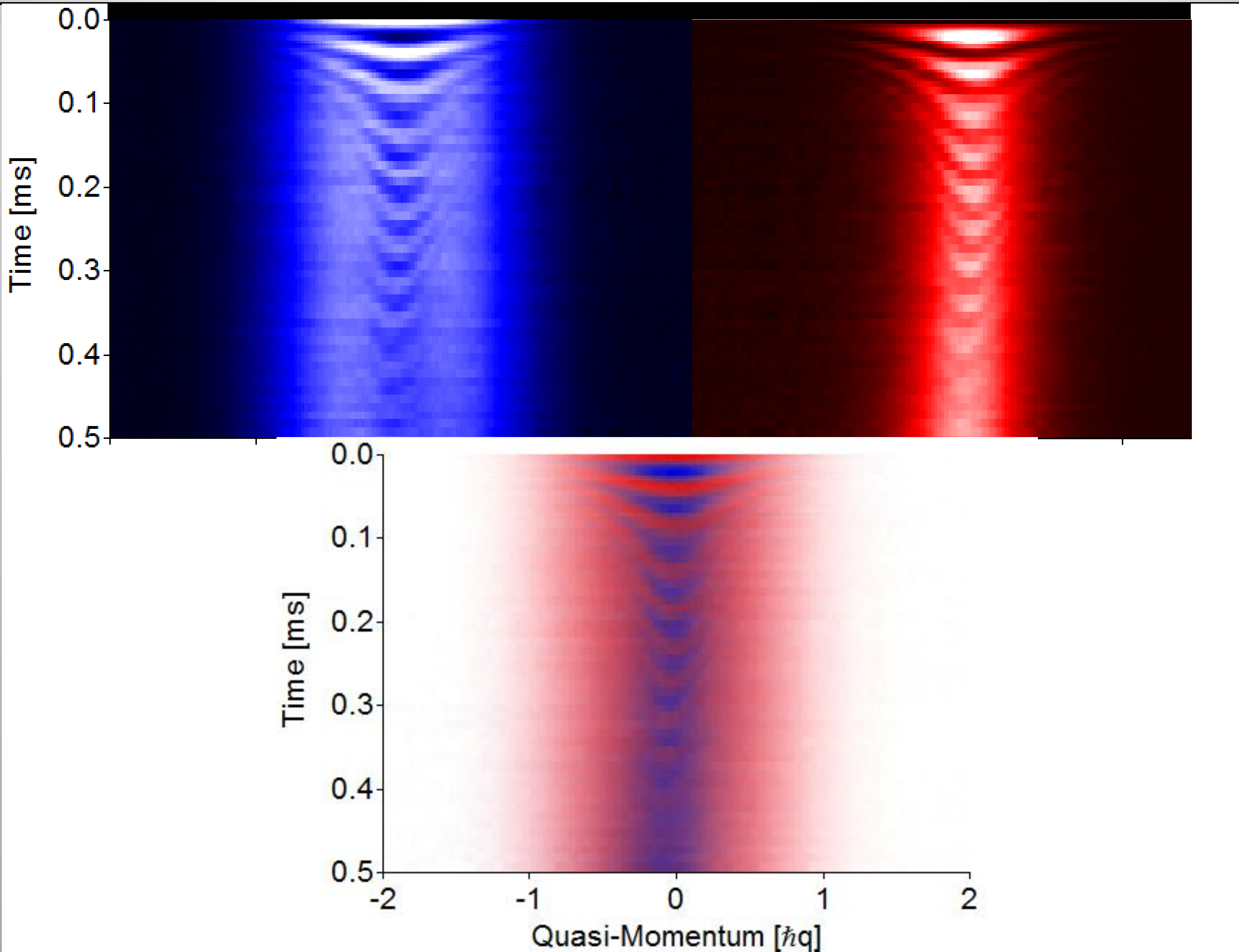
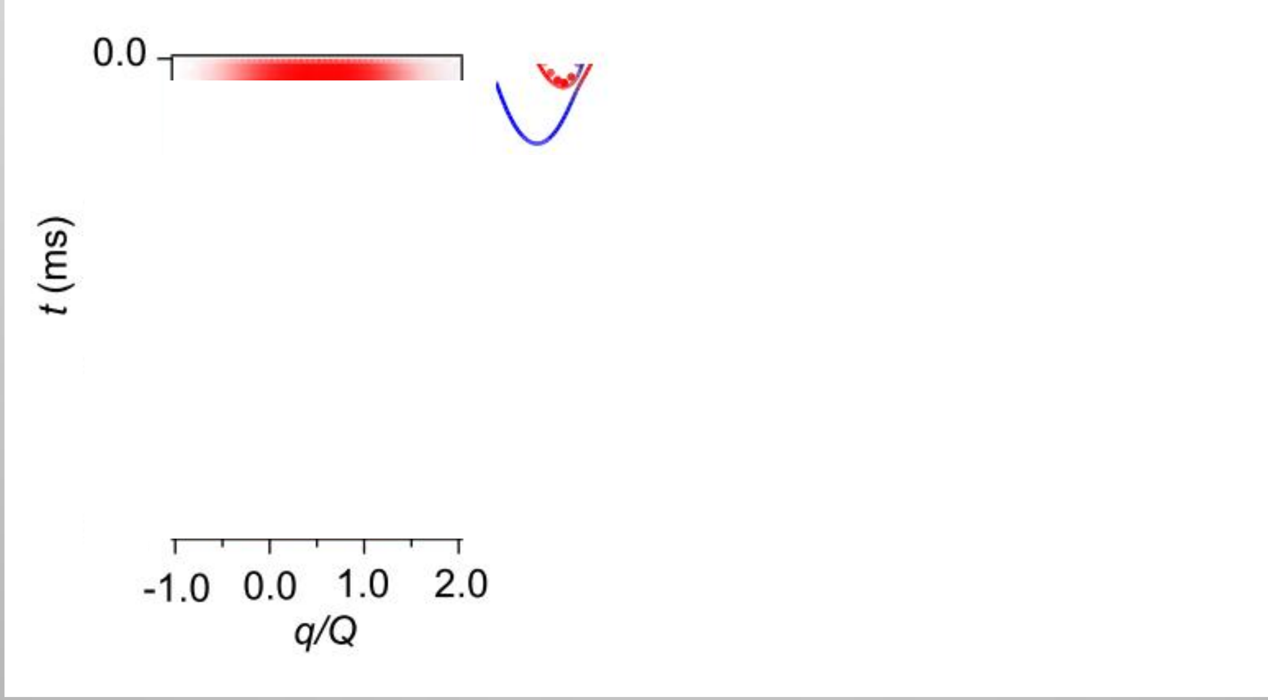


Rabi Oscillations of Spin-Momentum Coupled States



Raman Dressing

- When SO coupling is ramped slowly:
  - Spin composition follows effective magnetic field
  - Process is reversible
  - By changing detuning, dress either into upper band or lower band



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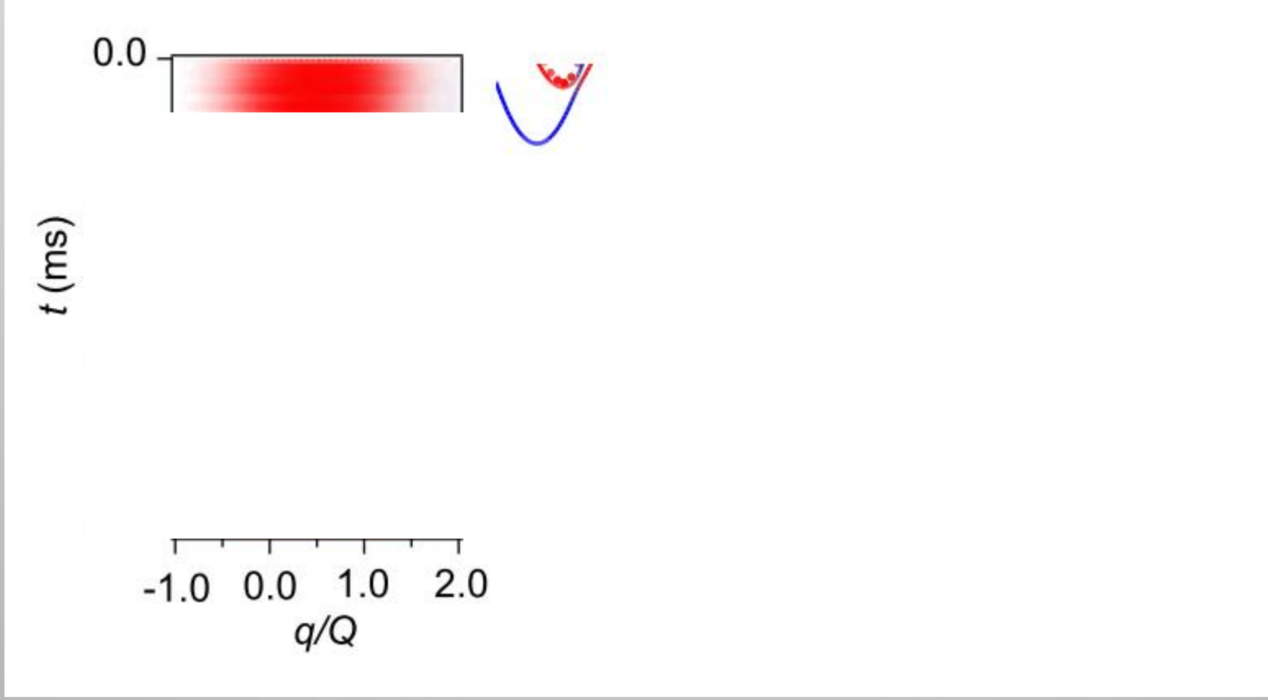

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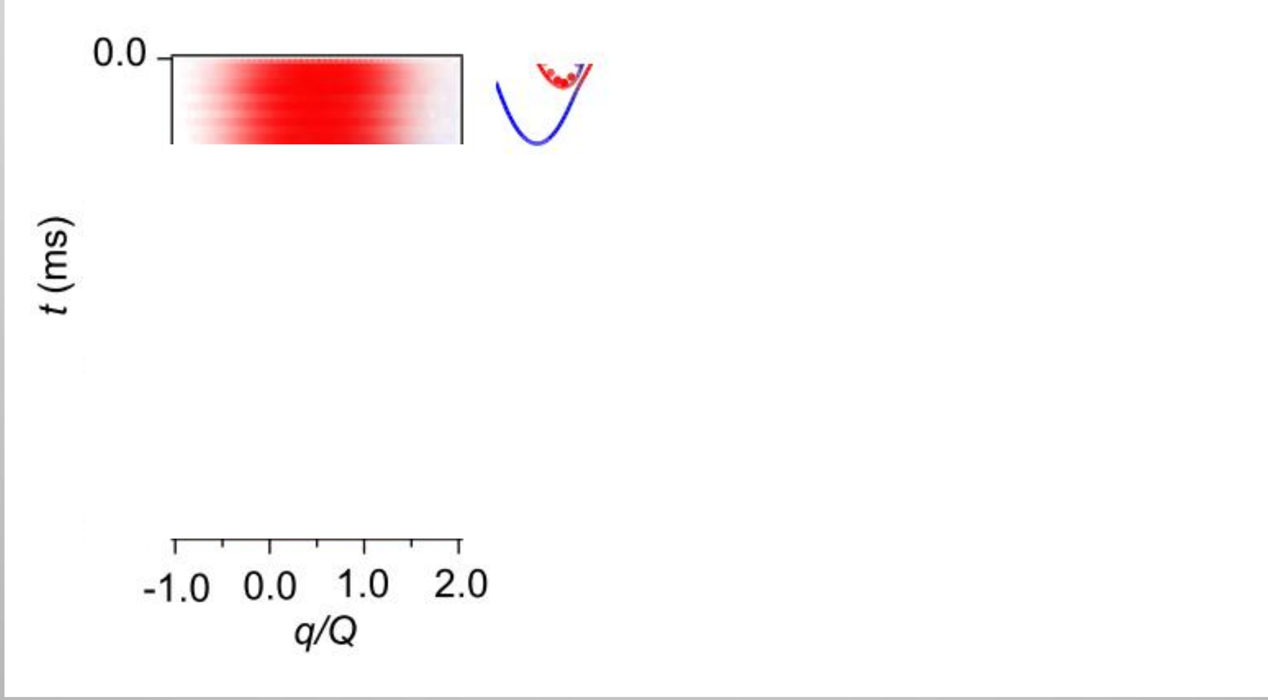

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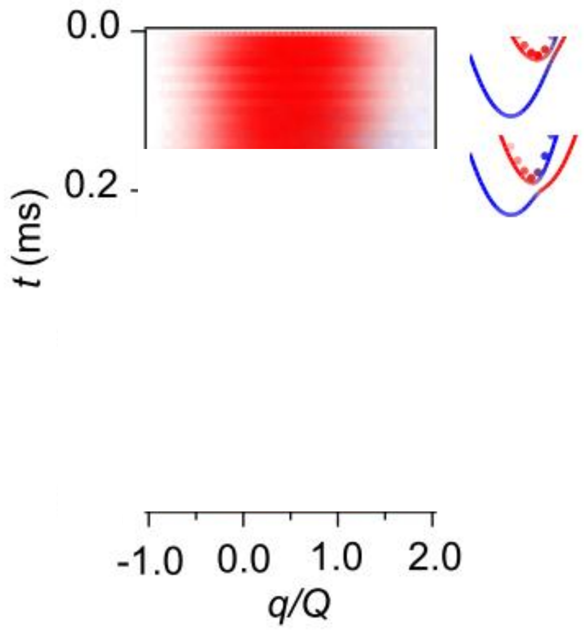

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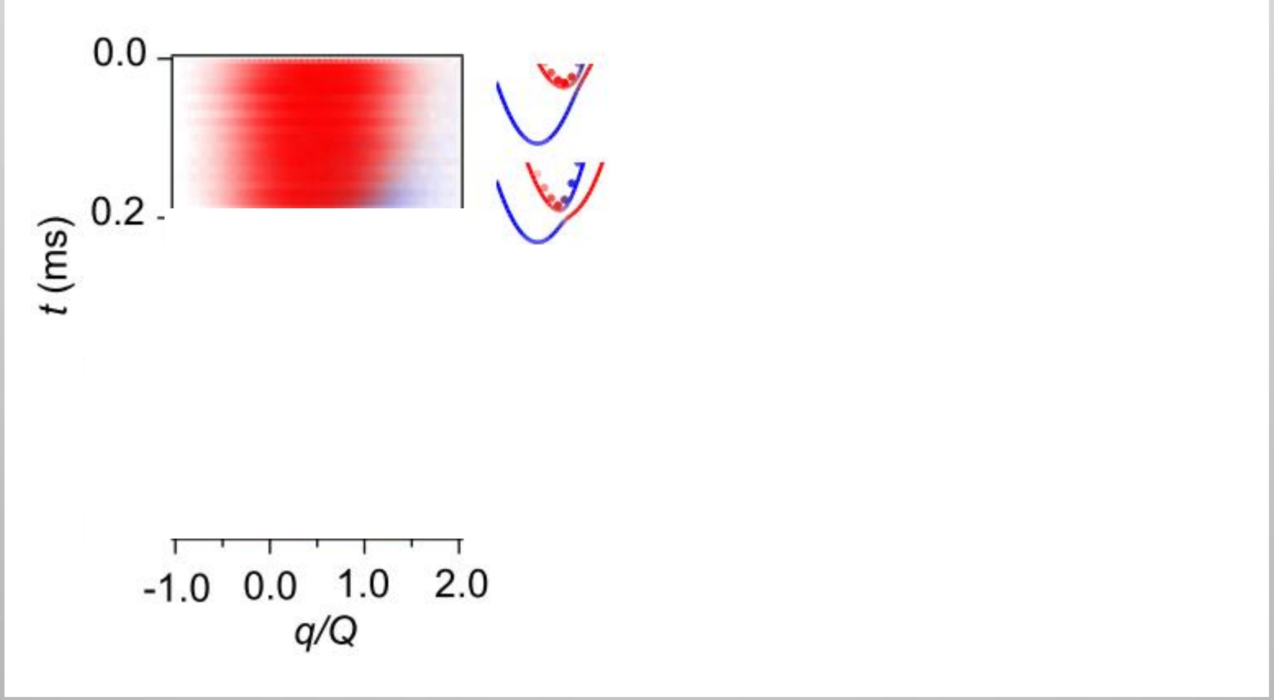

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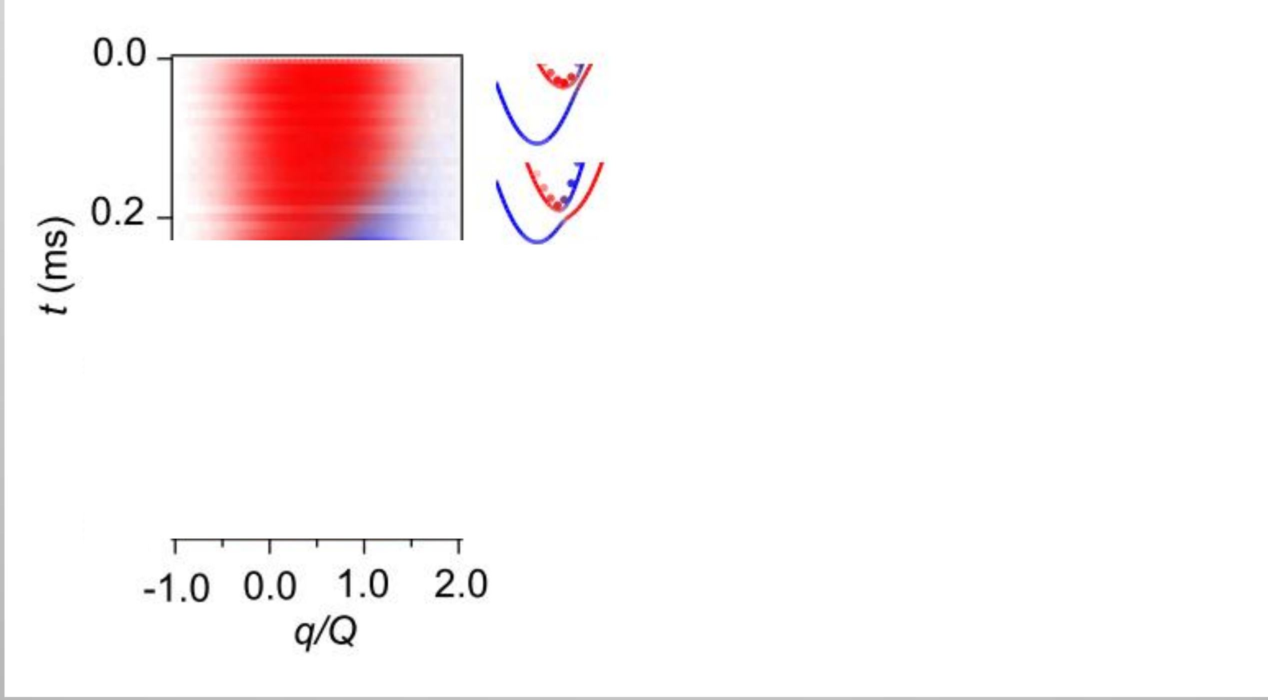

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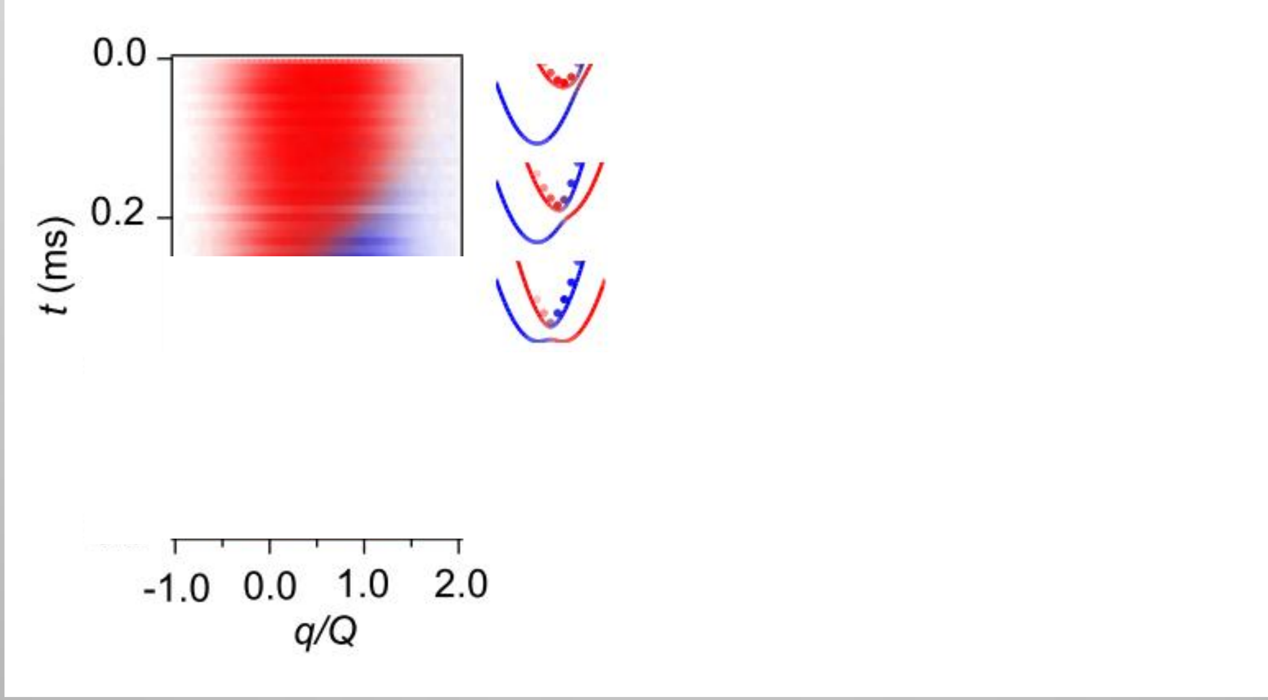

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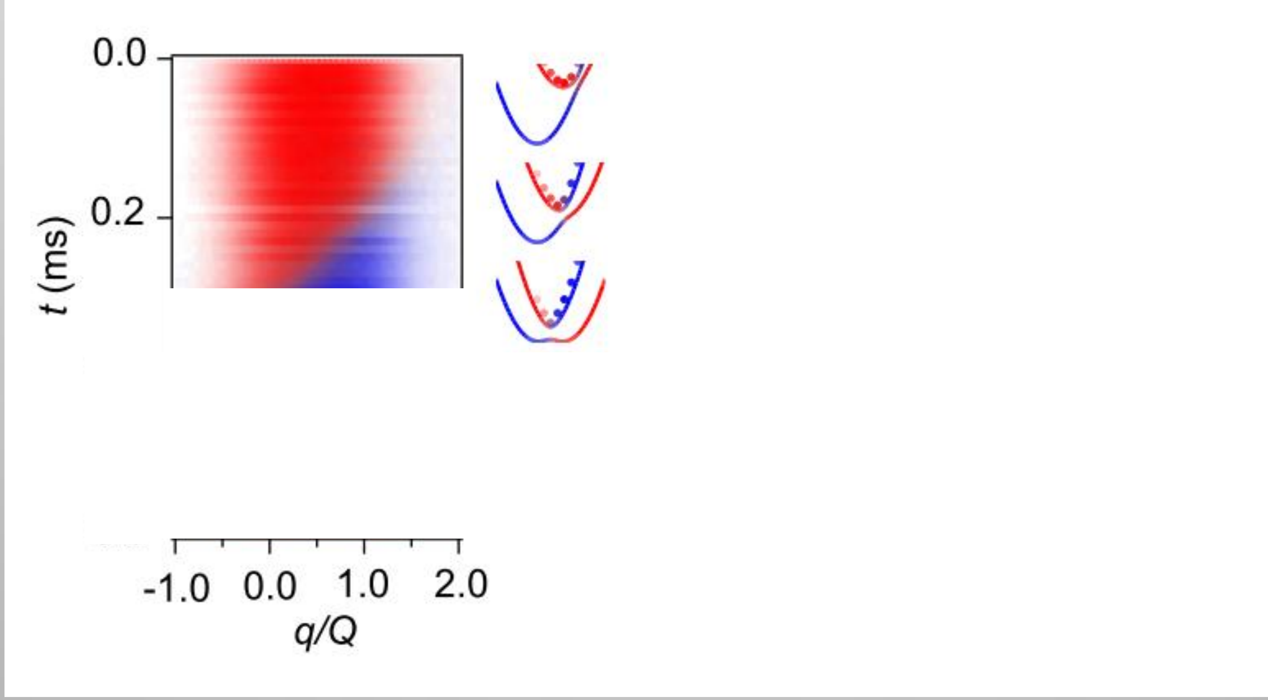

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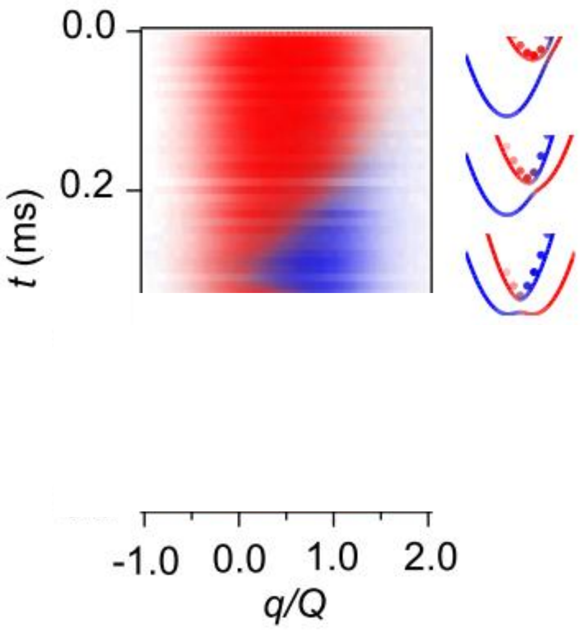

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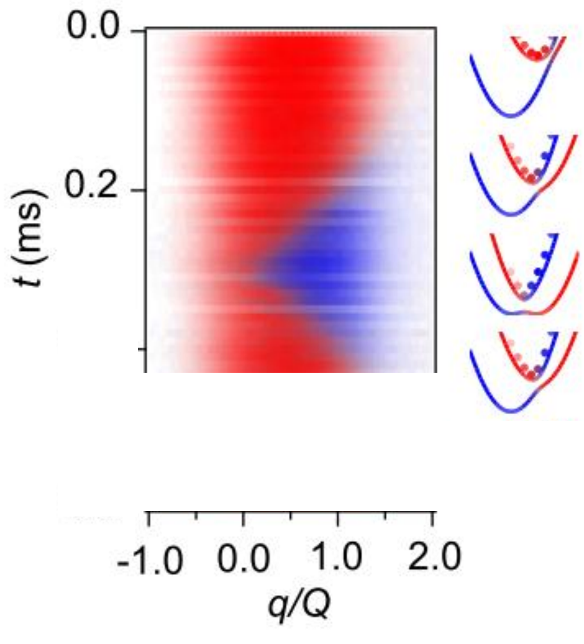

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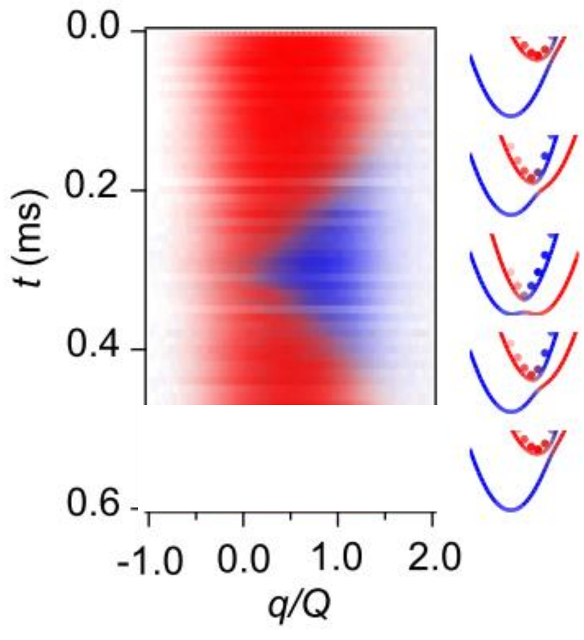

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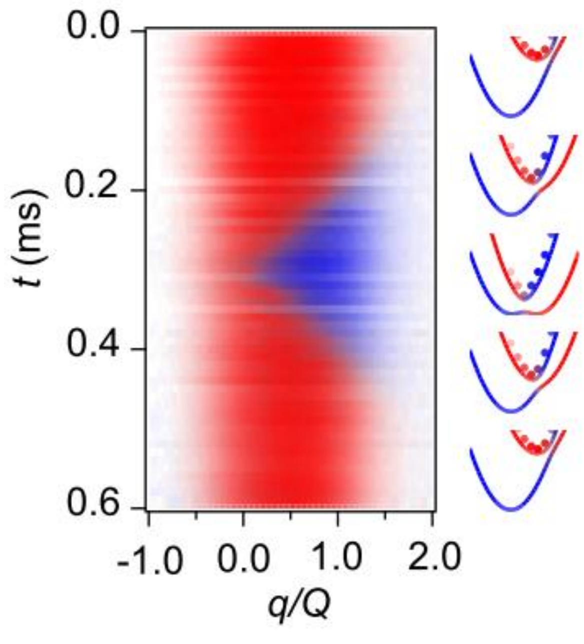

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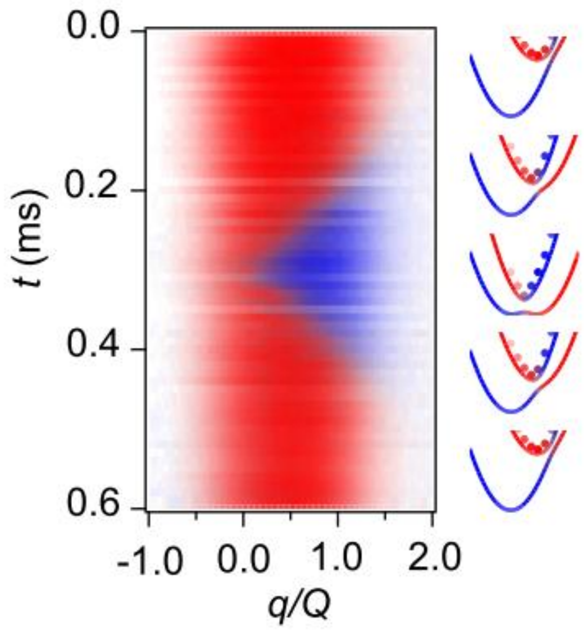
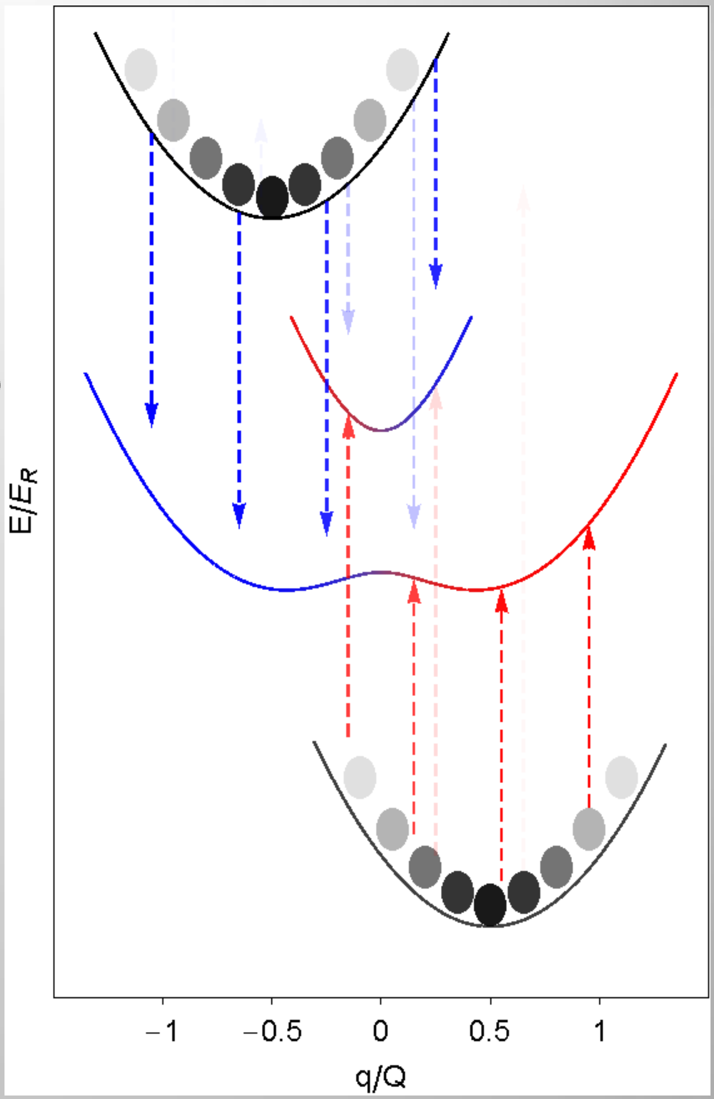


Spin-injection spectroscopy

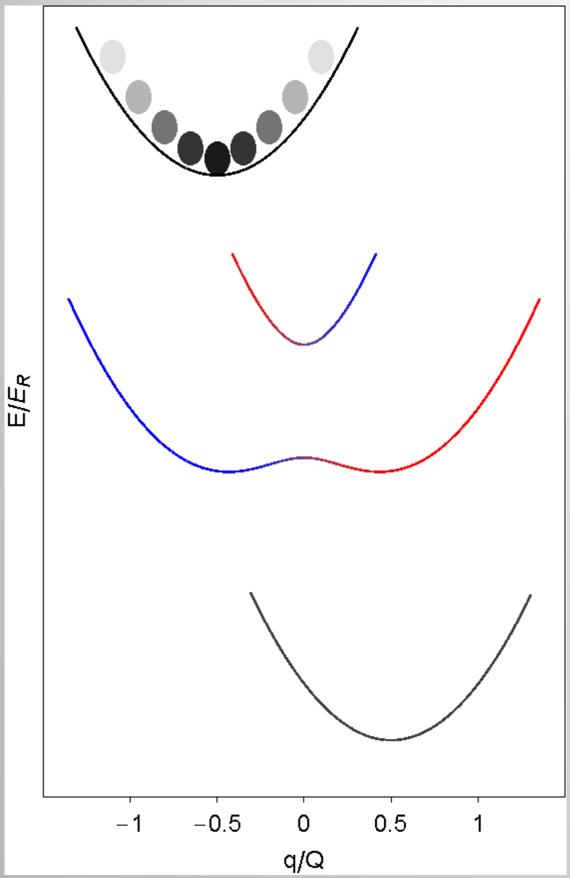
- How to characterize Hamiltonian?
  - Can topology be measured?
- Condensed matter: transport, (spin-)ARPES, STM …
- Cold atom analog: momentum resolved RF (Jin, Koehl)
  (=photoemission spectroscopy)
- Photoemission Spectroscopy probes dispersion *E(k)*

Spin-injection spectroscopy

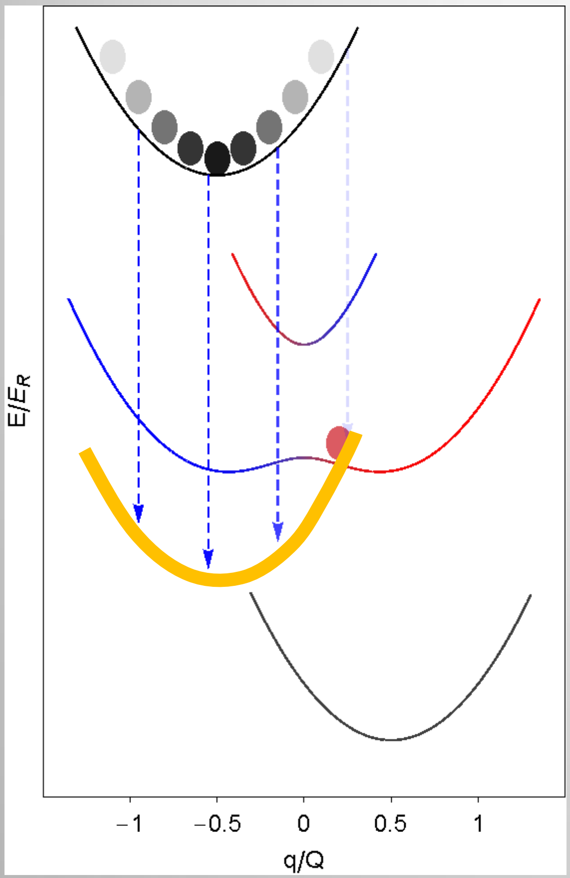
- Spin-injection spectroscopy
  - Measures *E*(*k*) and spin texture.
  - Start from reservoir states: $|\uparrow\rangle_R$,$|\downarrow\rangle_R$
  - Transfer into SO coupled system with RF pulse
  - Project into free space, give TOF
  - Spin-selective imaging gives spin/momentum
  - Reconstruct *E(k)* along with “color” of band

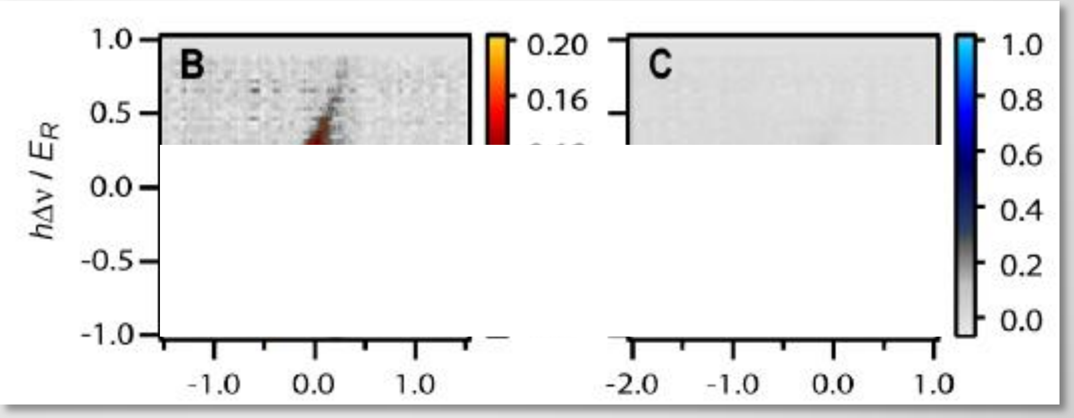


Spin-injection spectroscopy



Spin-injection spectroscopy





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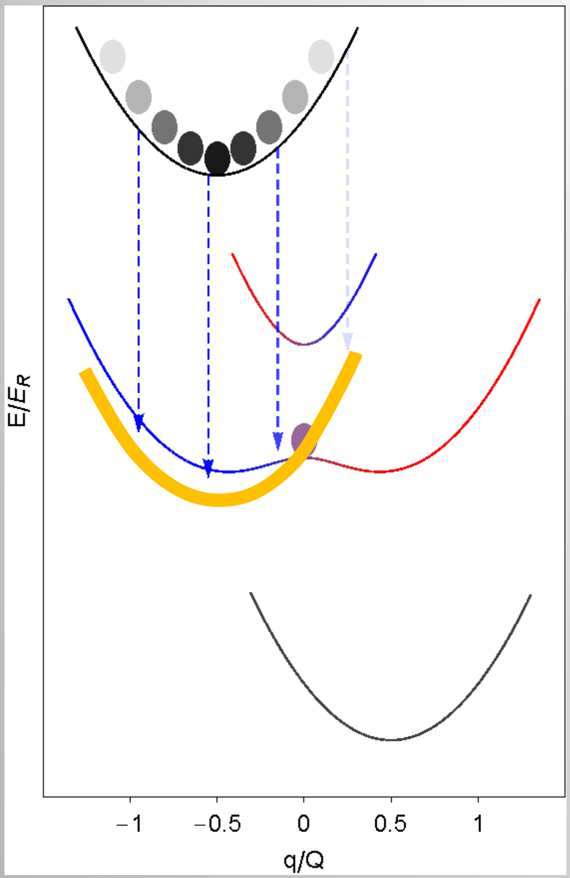

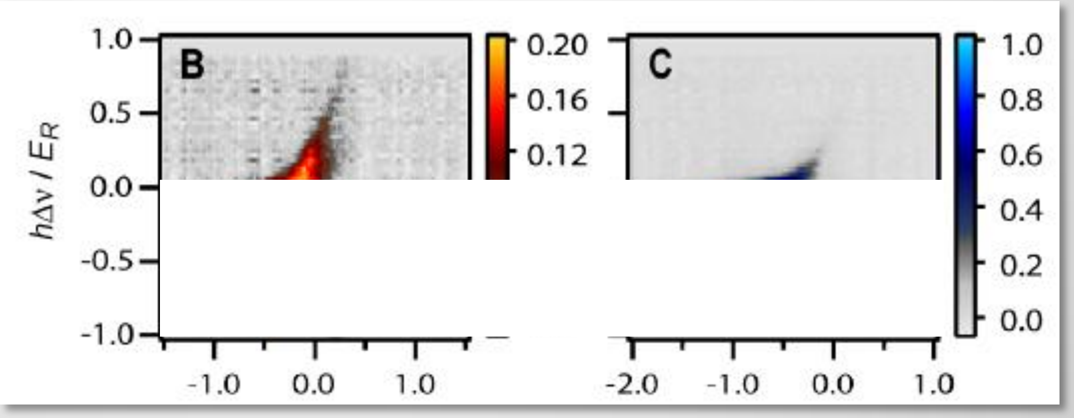

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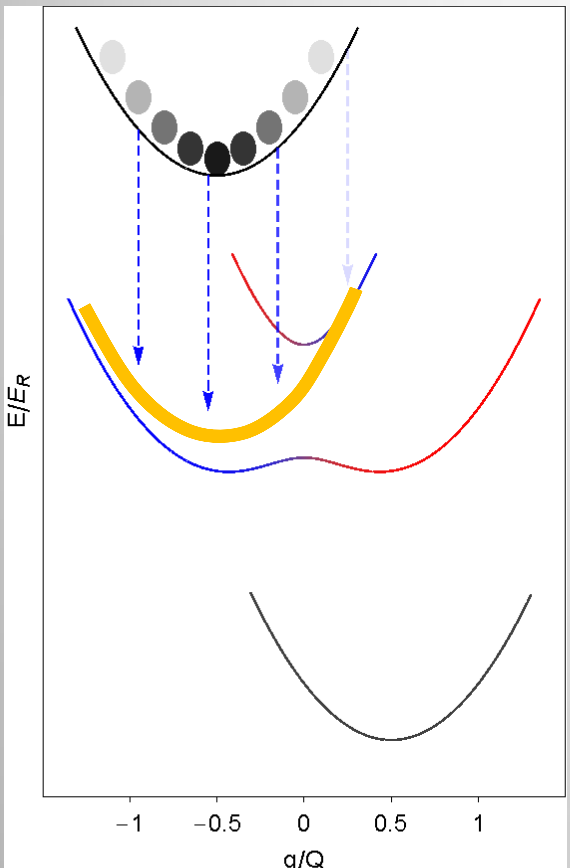

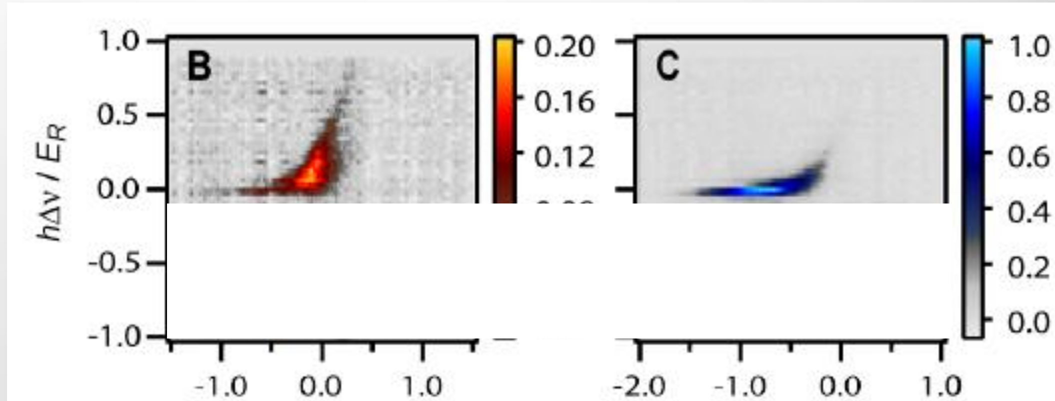

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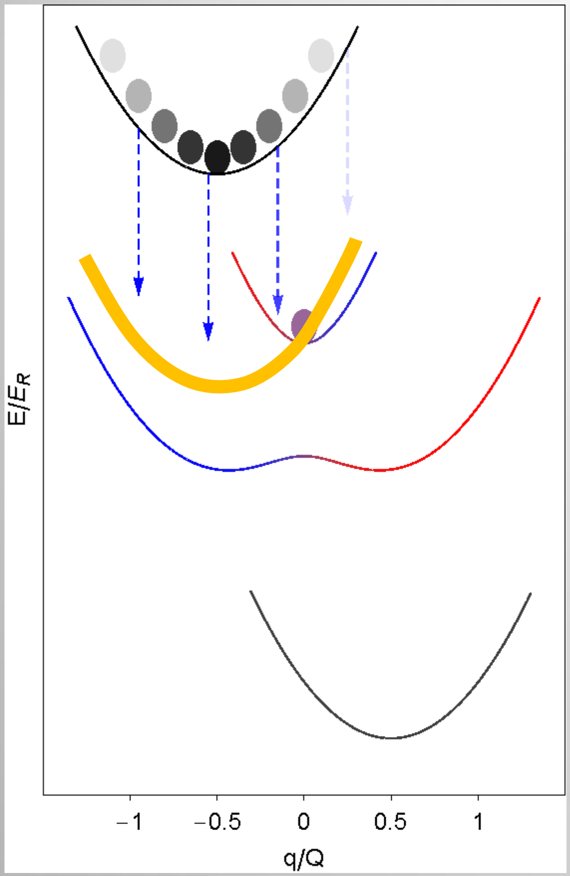

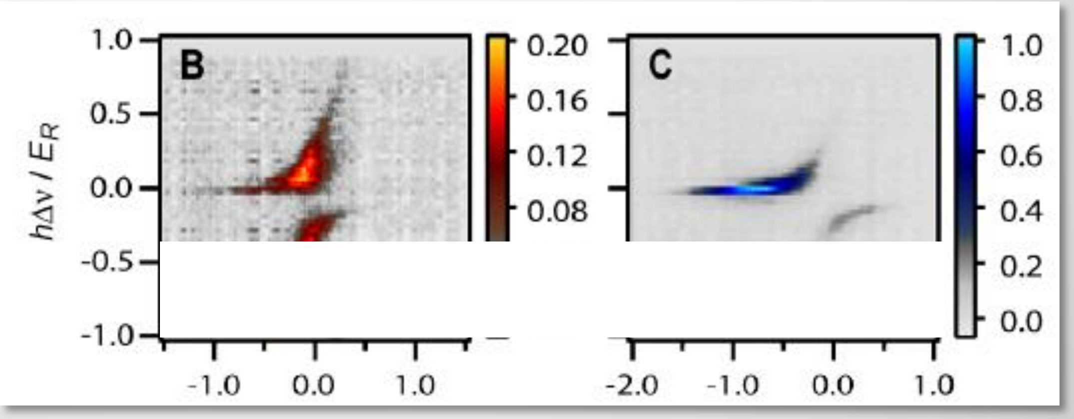

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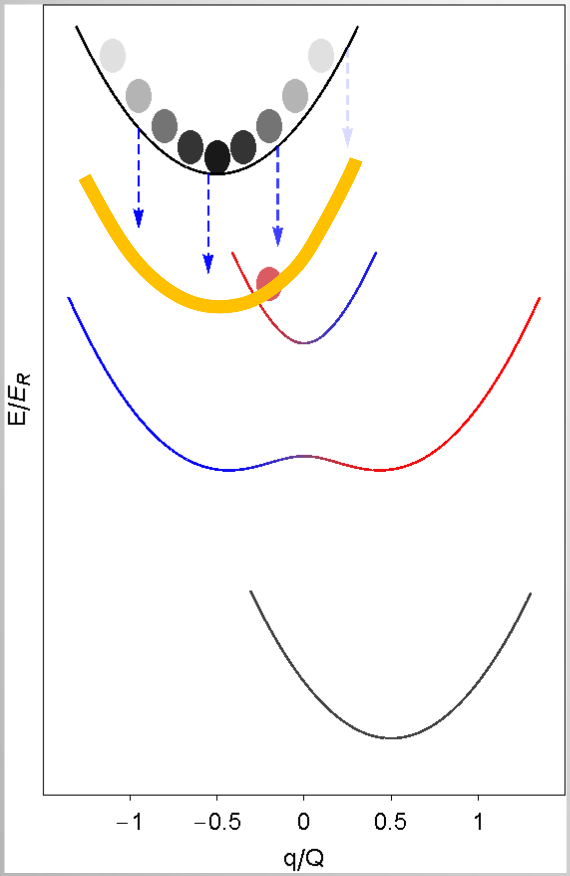

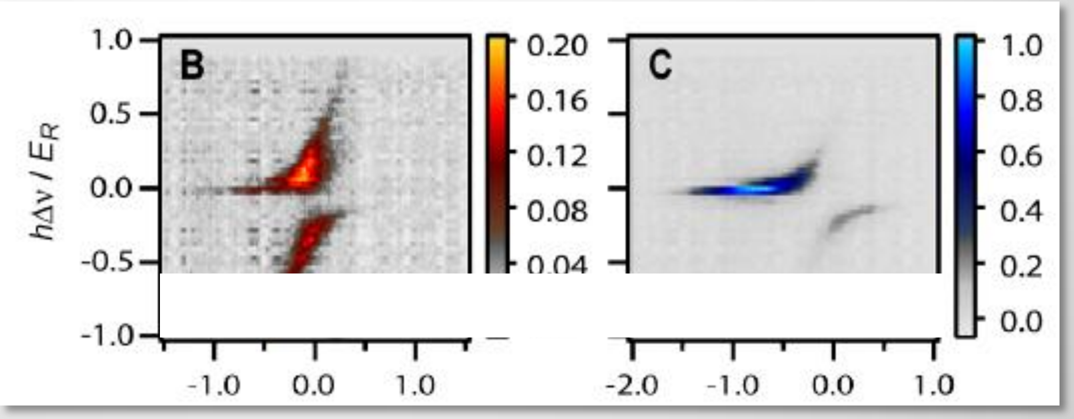

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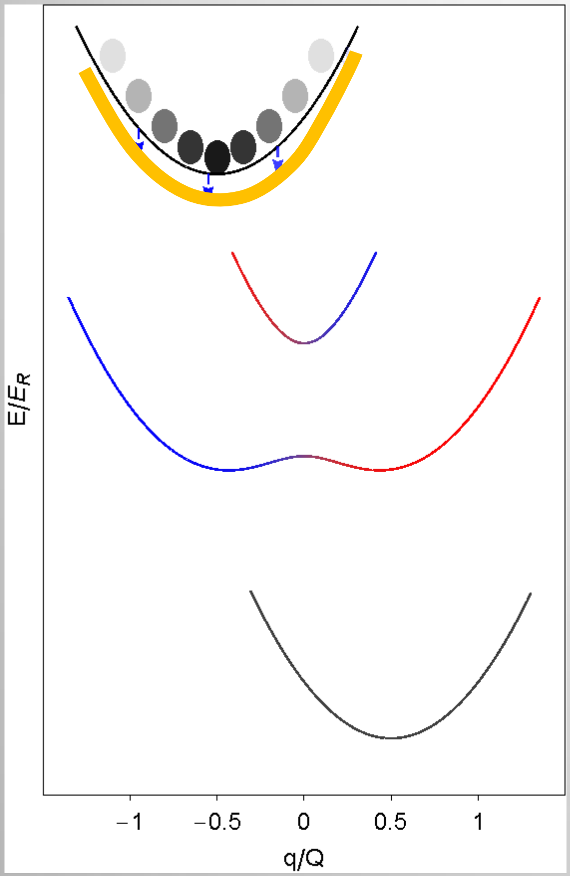

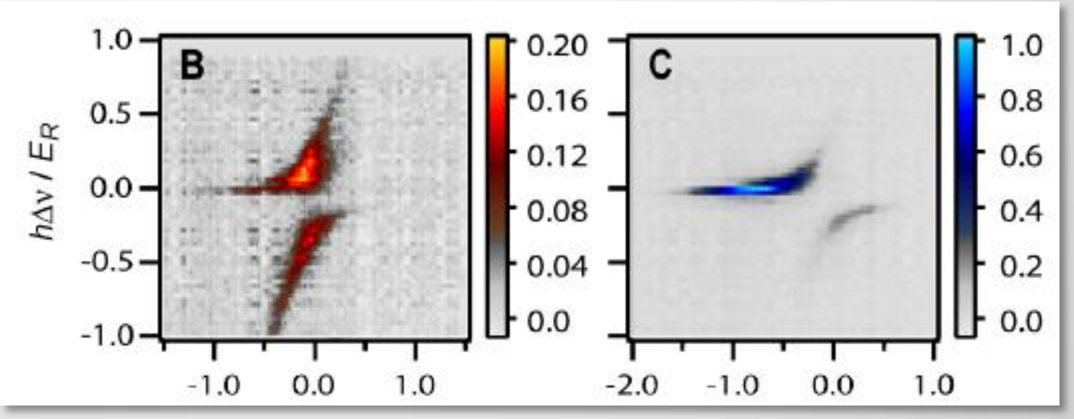

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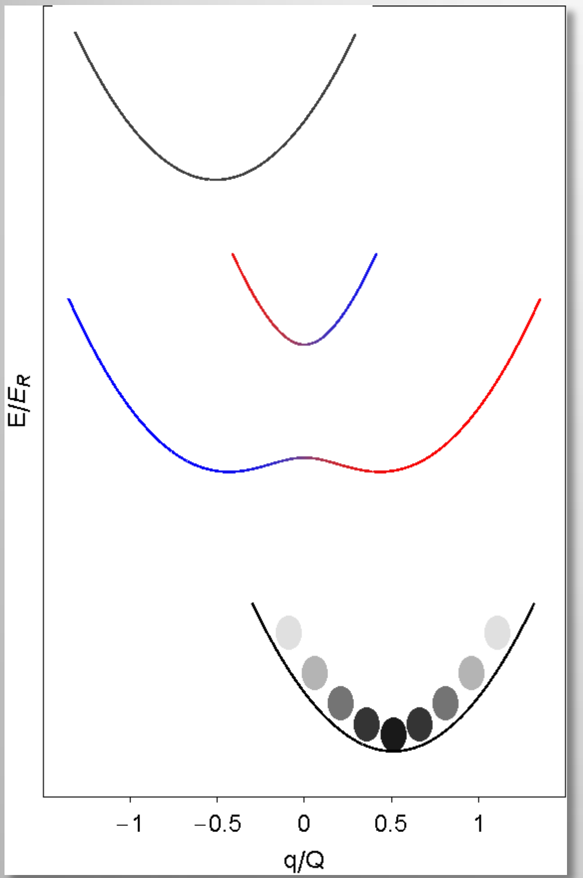
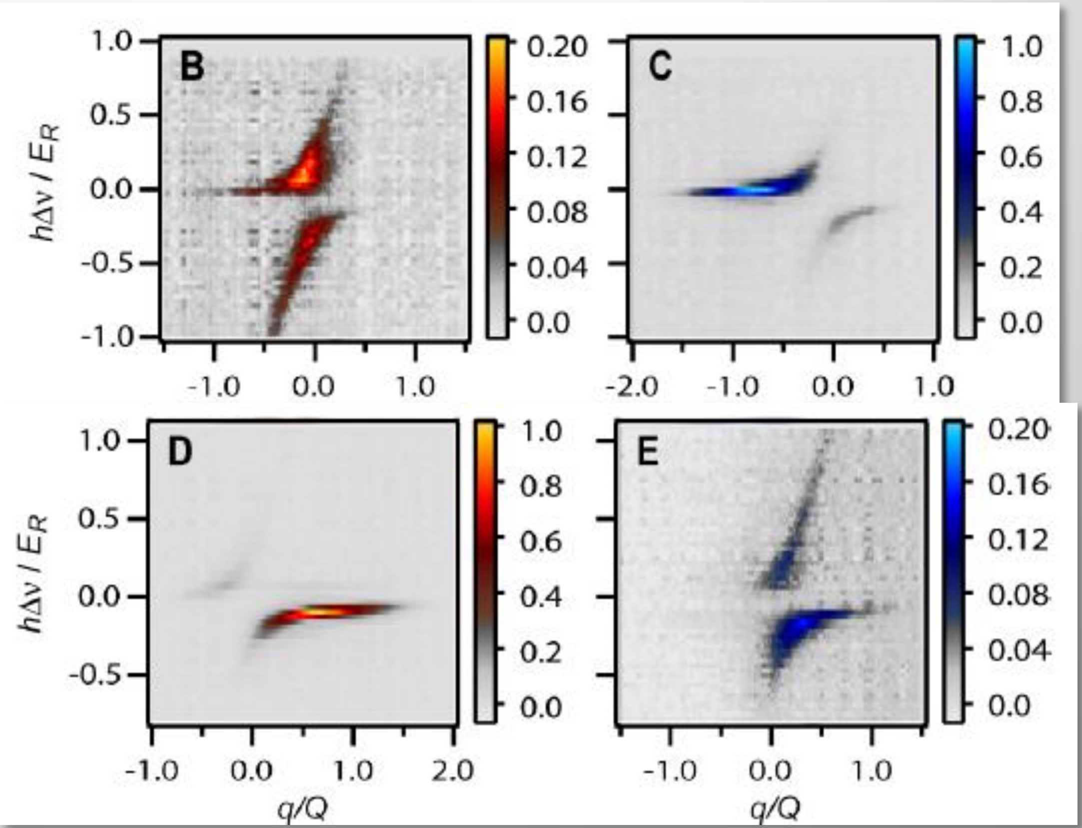
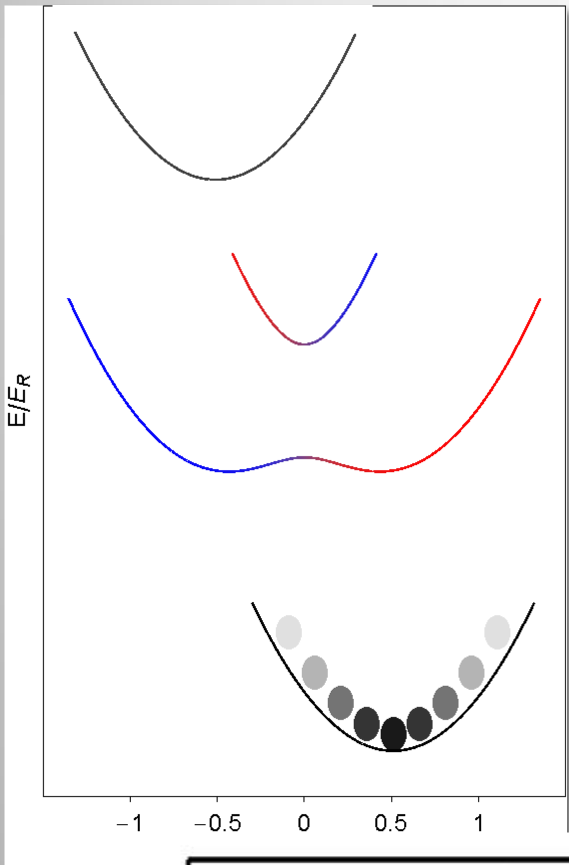
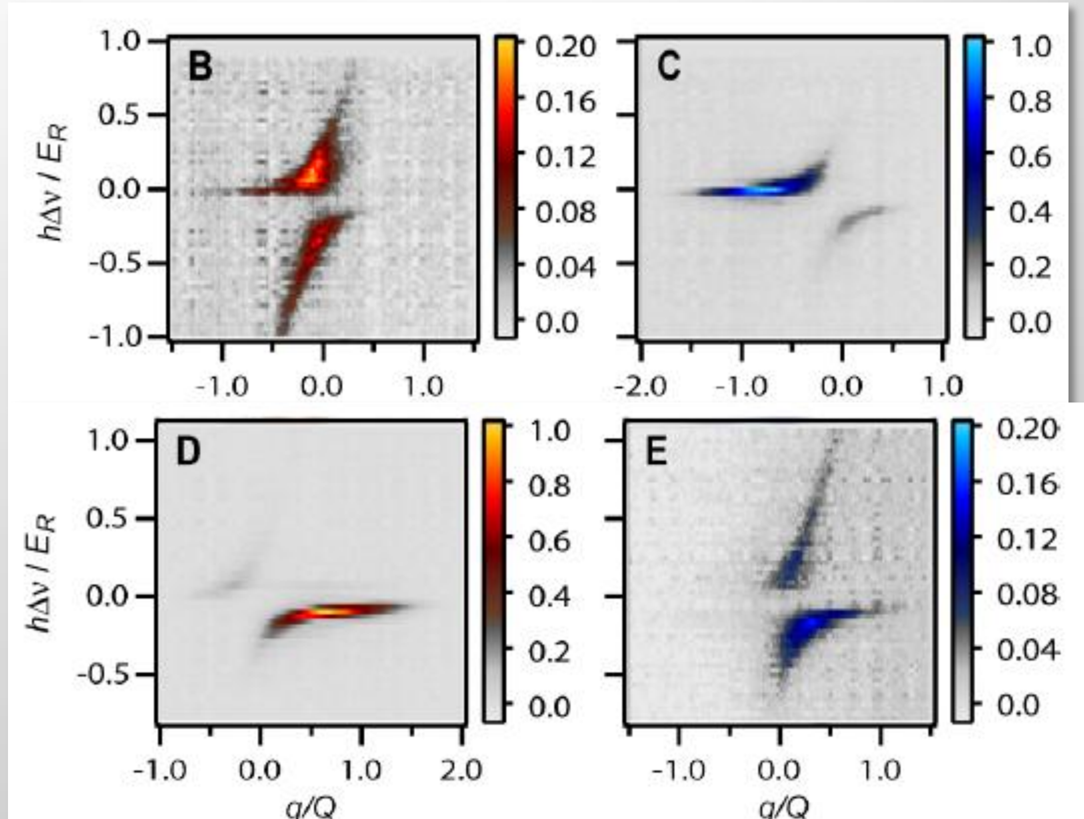
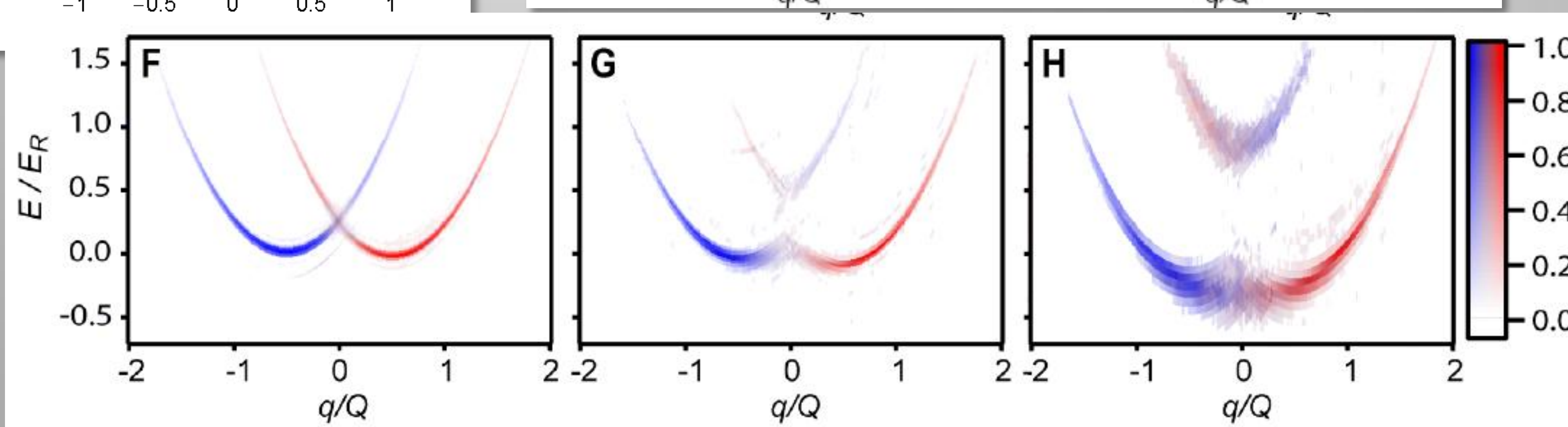




Direct Observation of the Spin-Orbit Gap

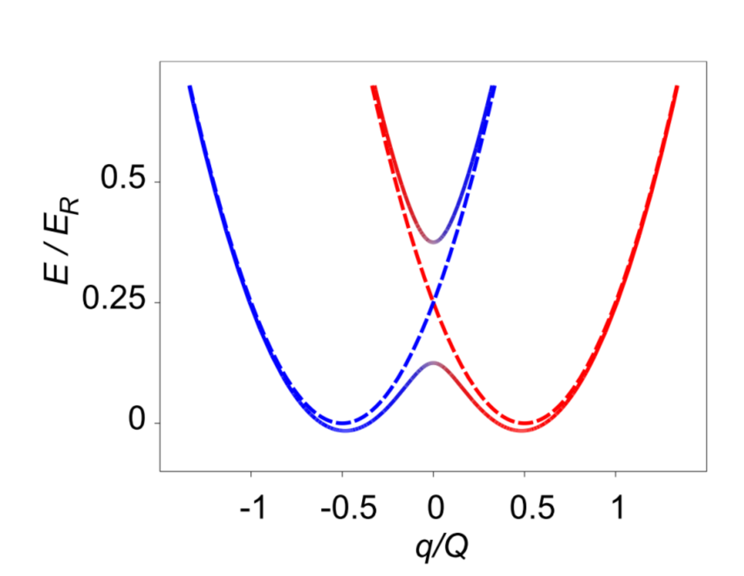


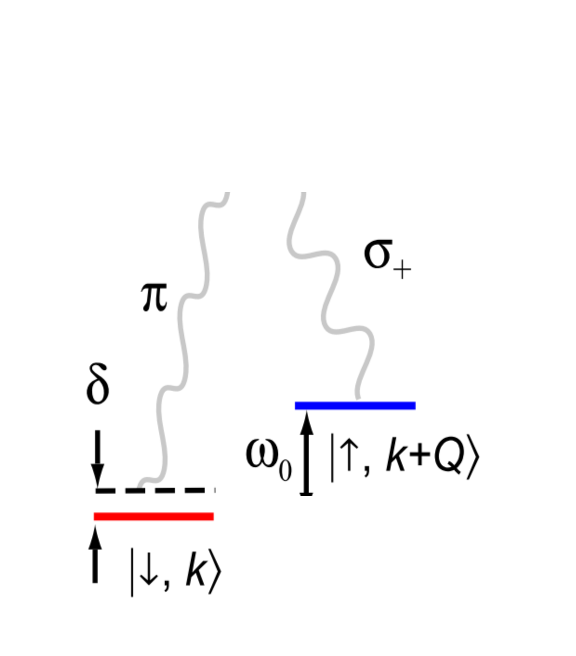




Creating a spinful lattice

- With both Raman and RF, we obtain a spin-orbit coupled lattice (see Jiménez-García et al., arXiv:1201.6630 (2012))





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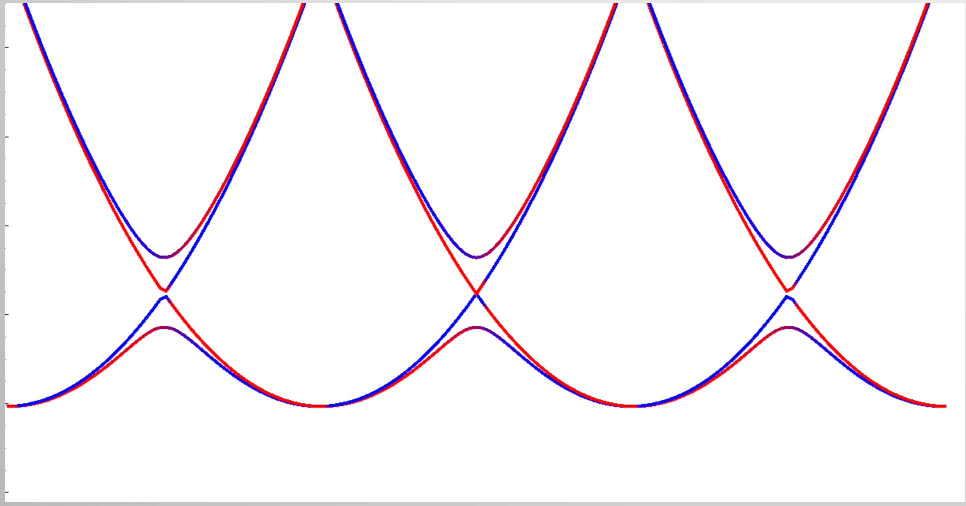
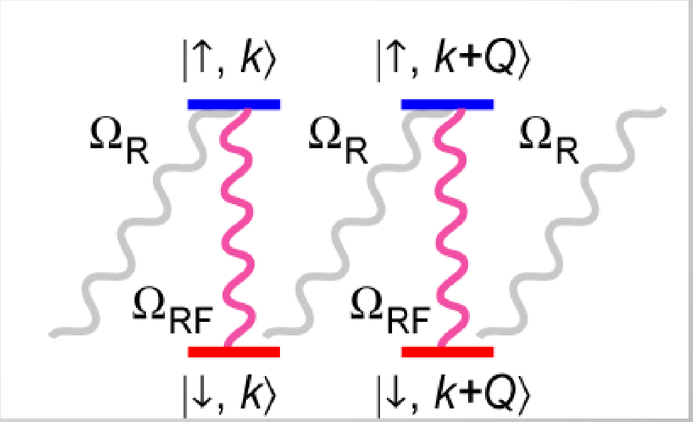
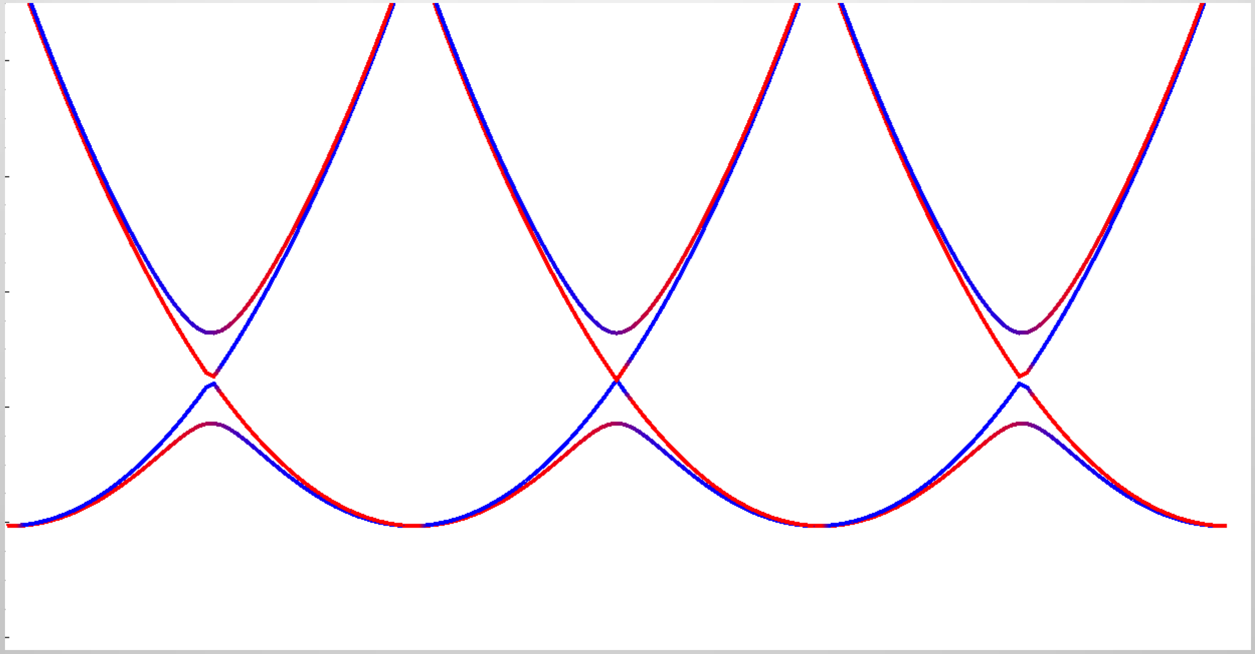
Repeated scheme:





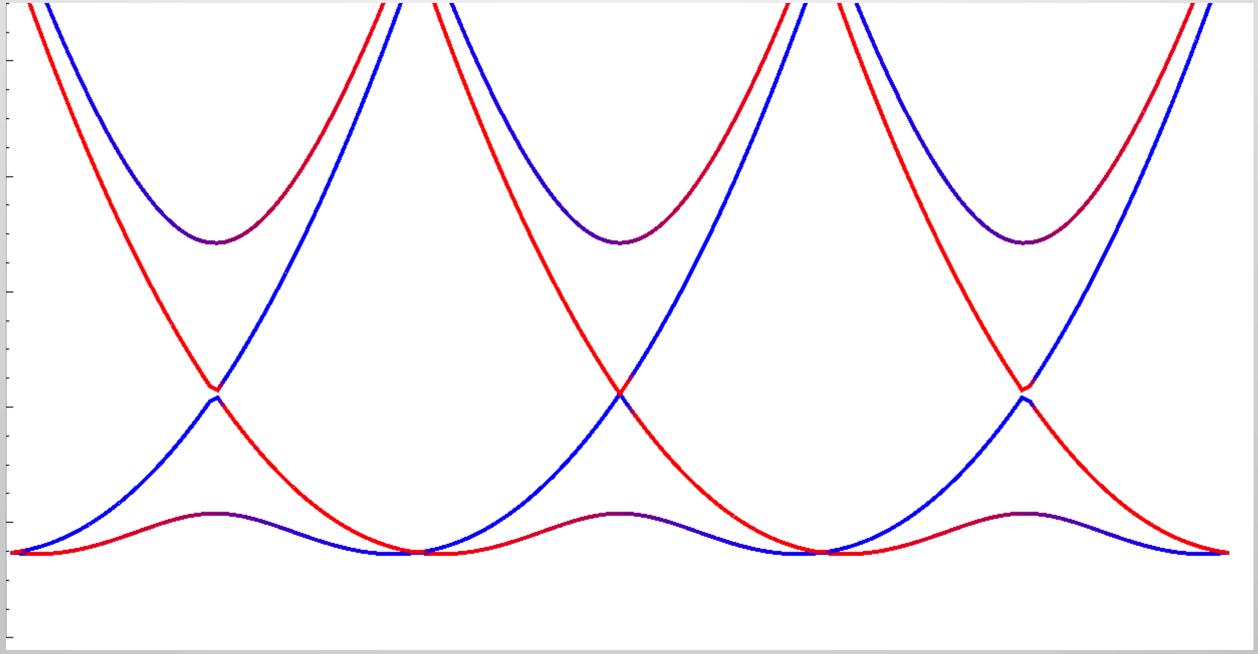
Creating a spinful lattice

- In repeated scheme



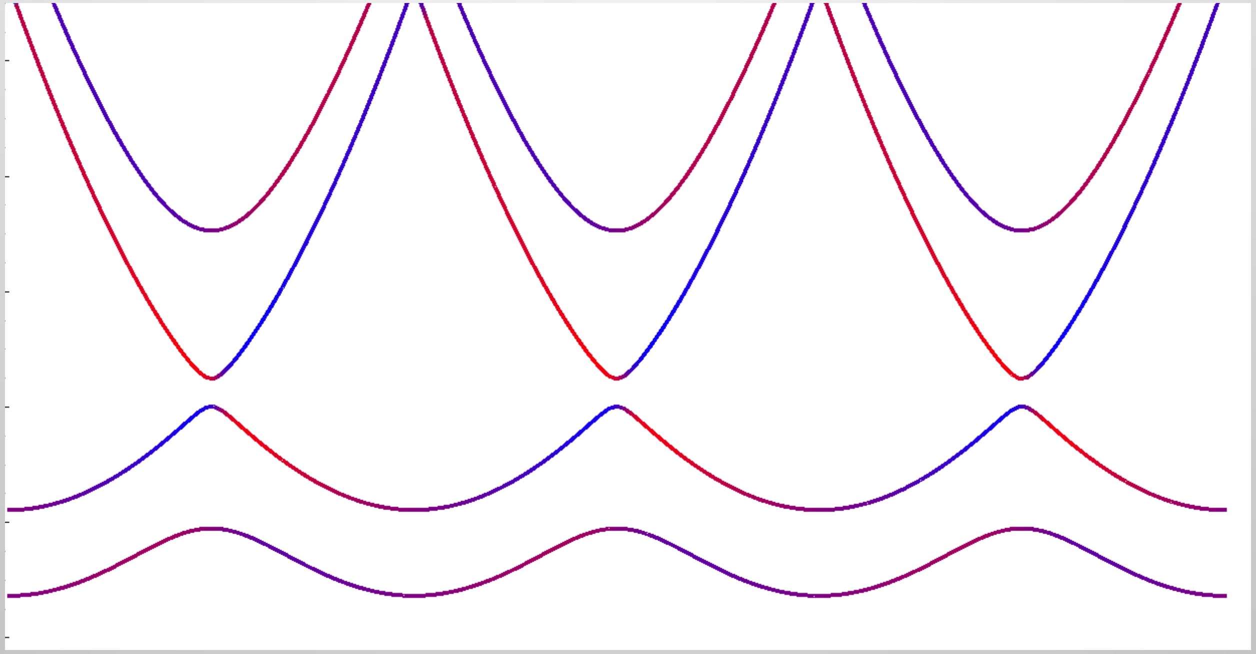
Creating a spinful lattice

- Degenerate point inside spin orbit gap



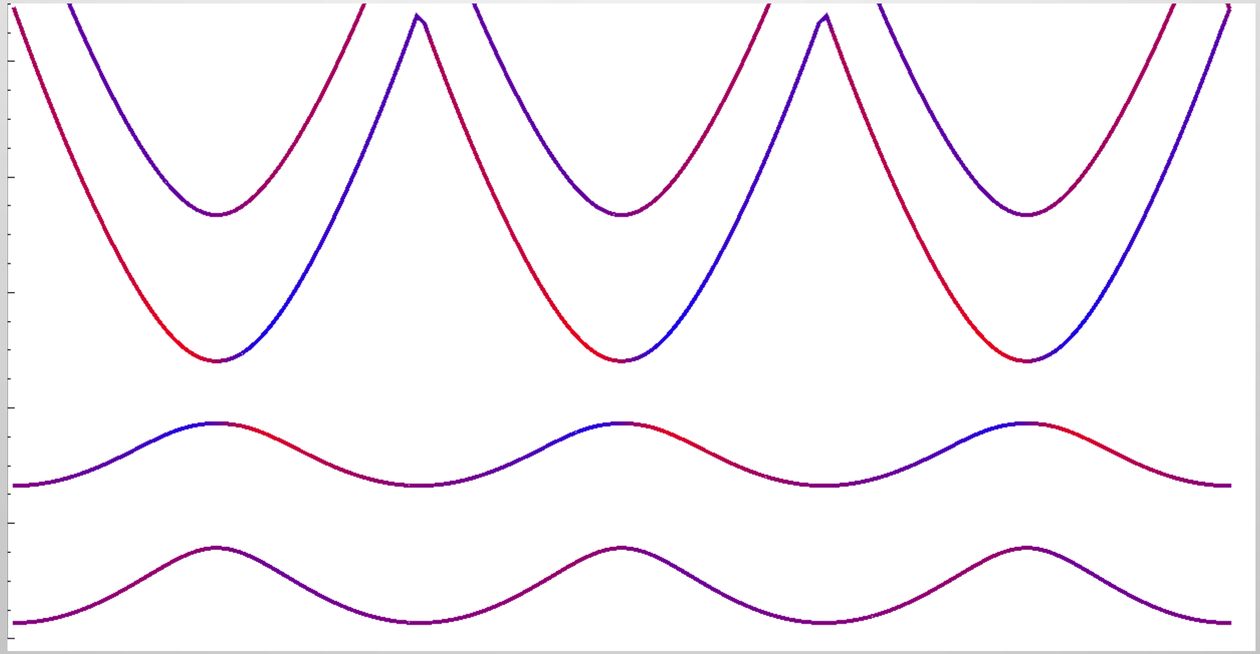
Creating a spinful lattice

- Bandgap opens between 2nd and 3rd band

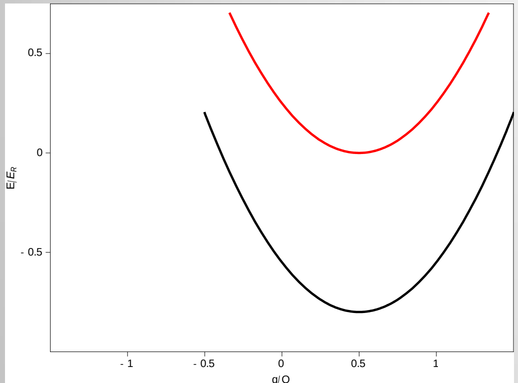


Creating a spinful lattice

- Larger RF, gap between lowest bands



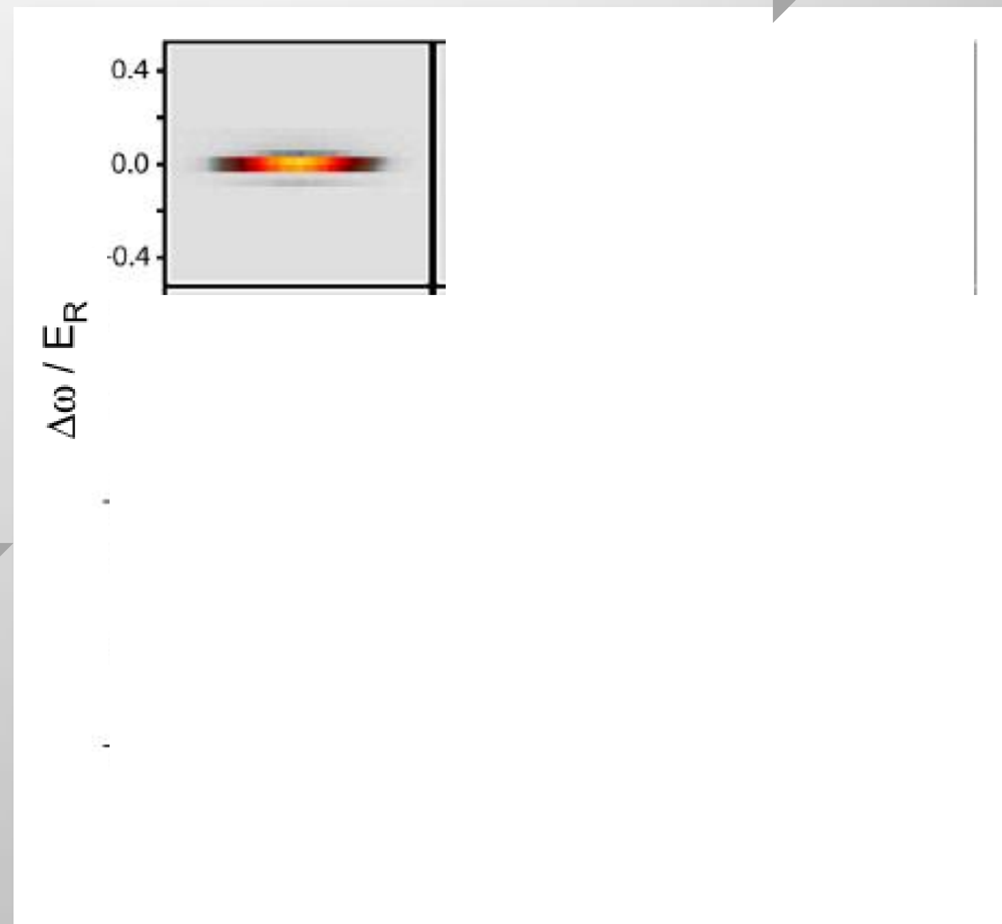
Spin-injection spectroscopy



- Transition at hyperfine splitting

Increasing Raman Intensity

Increasing RF Intensity



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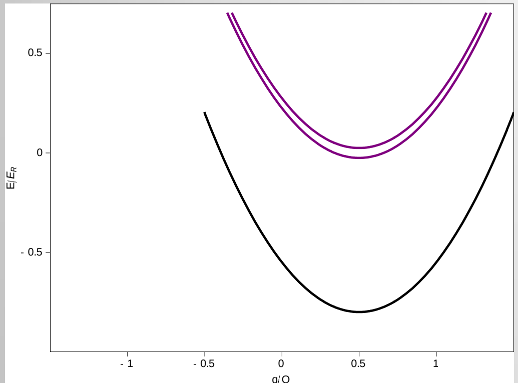
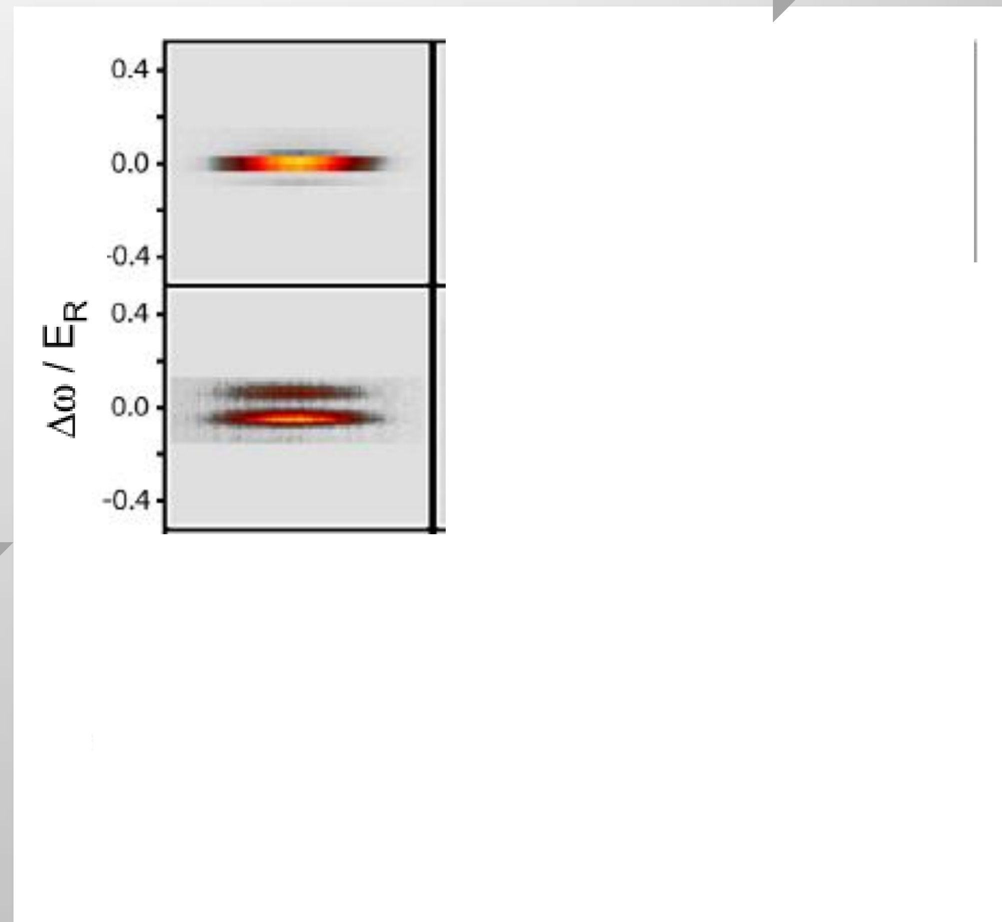


- Autler-Townes doublet

Increasing Raman Intensity

Increasing RF Intensity



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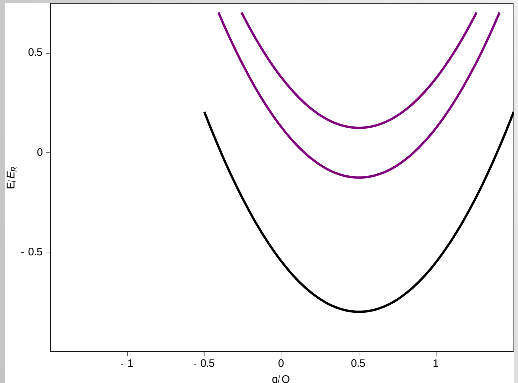

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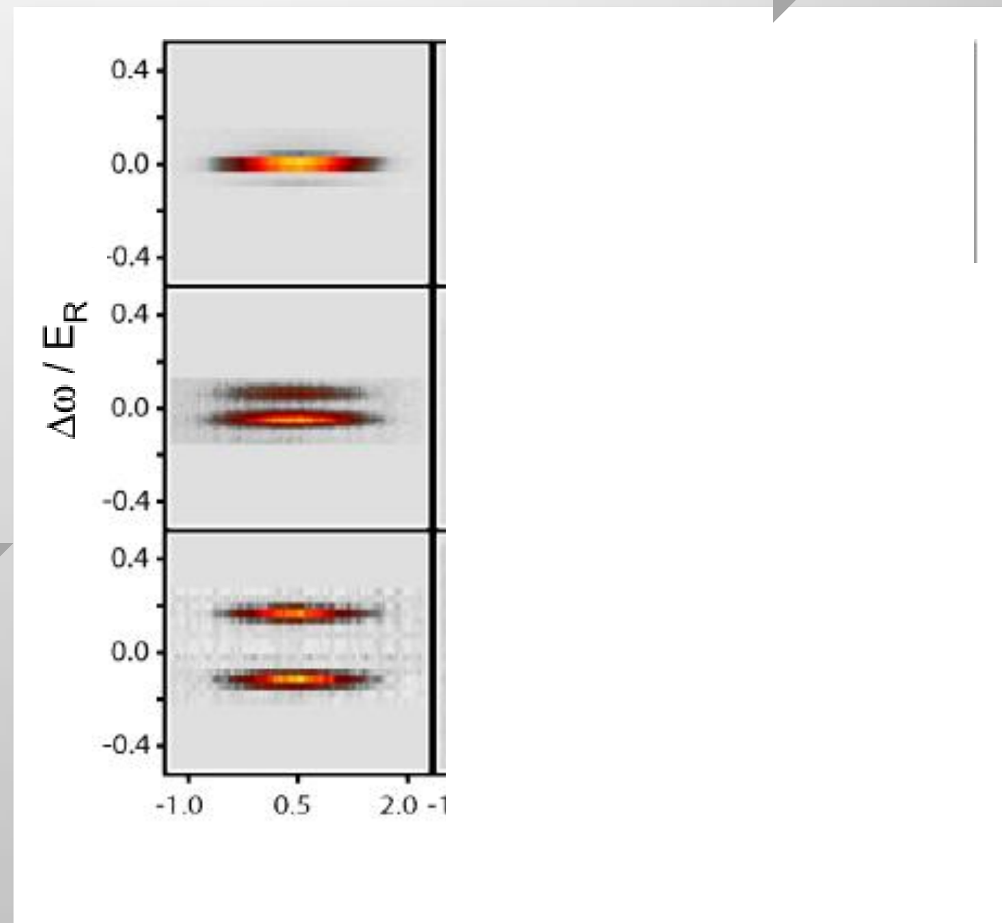
Increasing RF Intensity



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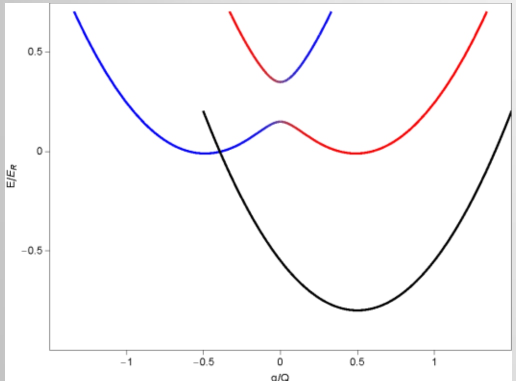
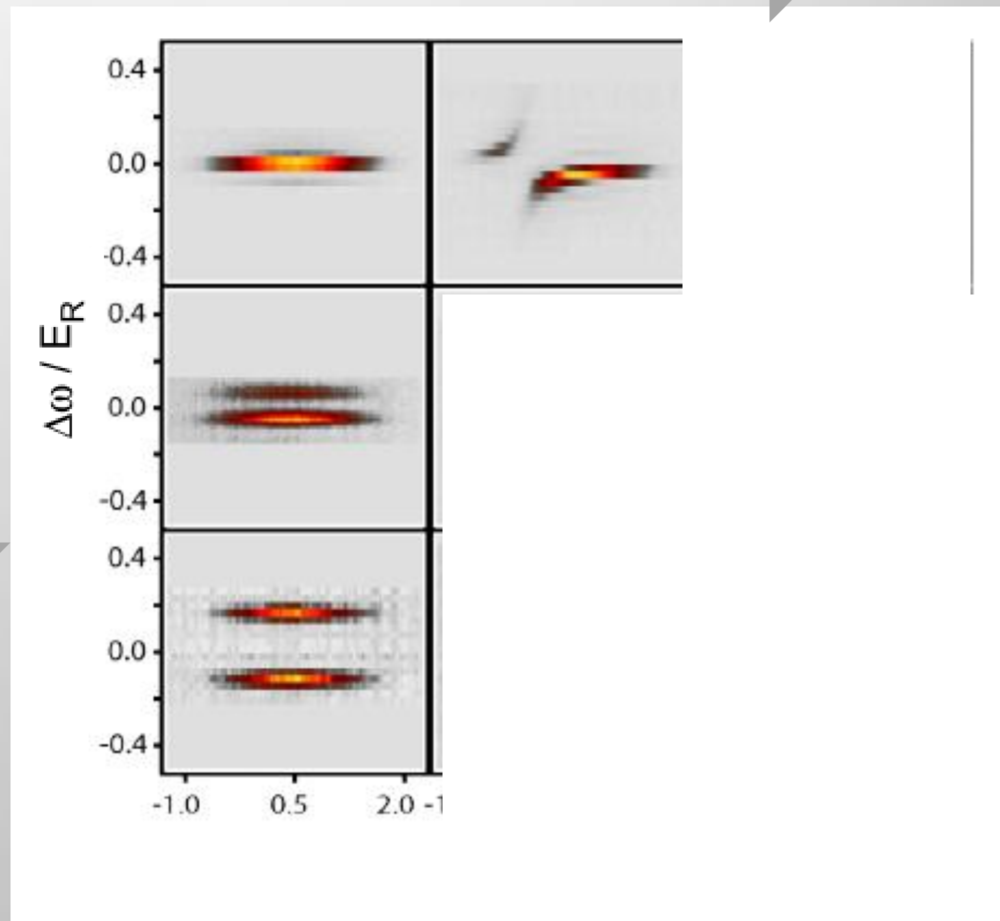


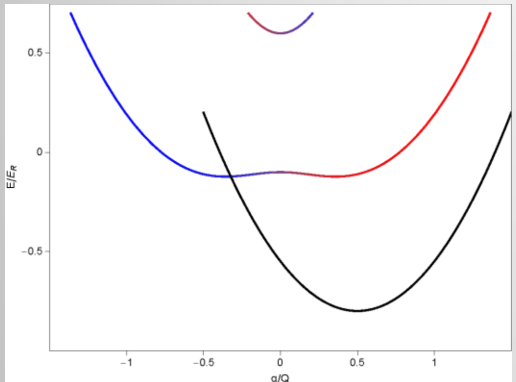
- Momentum-dependent Autler-Townes doublet

Increasing Raman Intensity

Increasing RF Intensity



Spin-injection spectroscopy of spinful lattice



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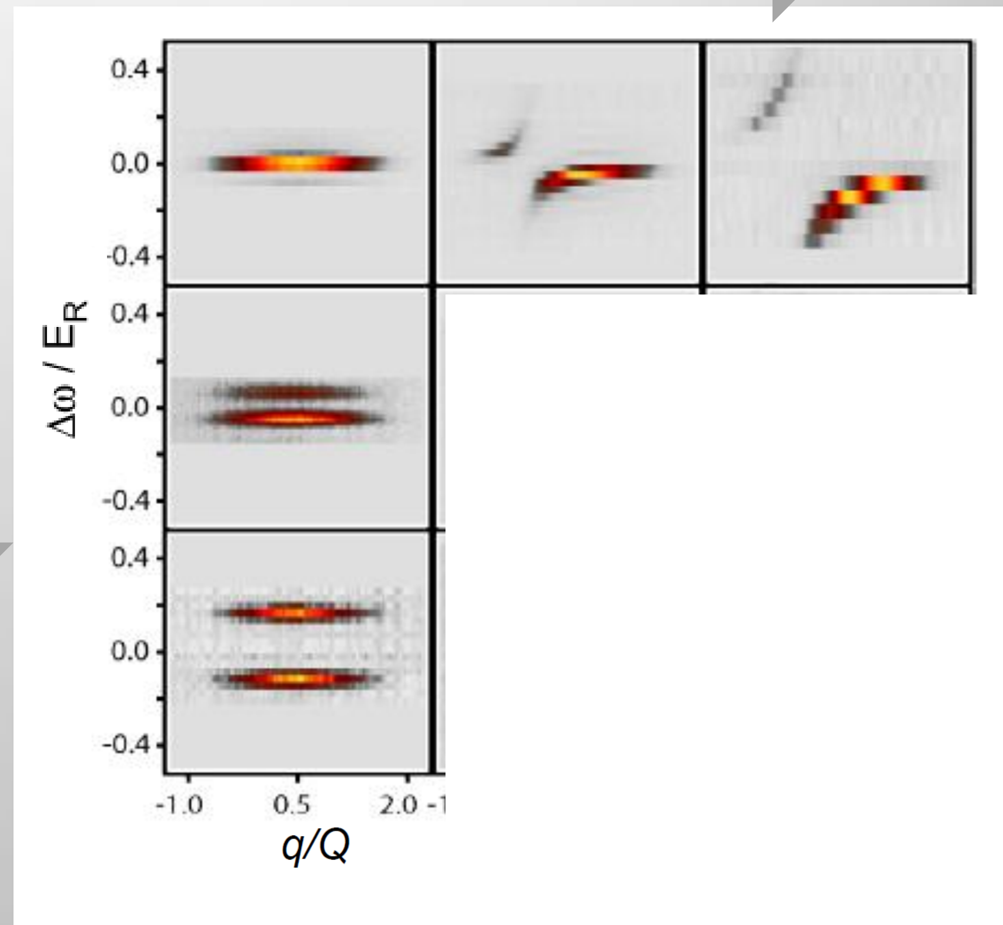

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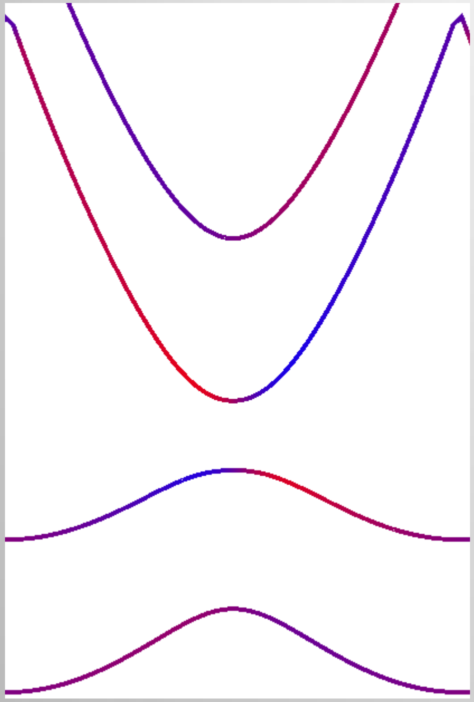
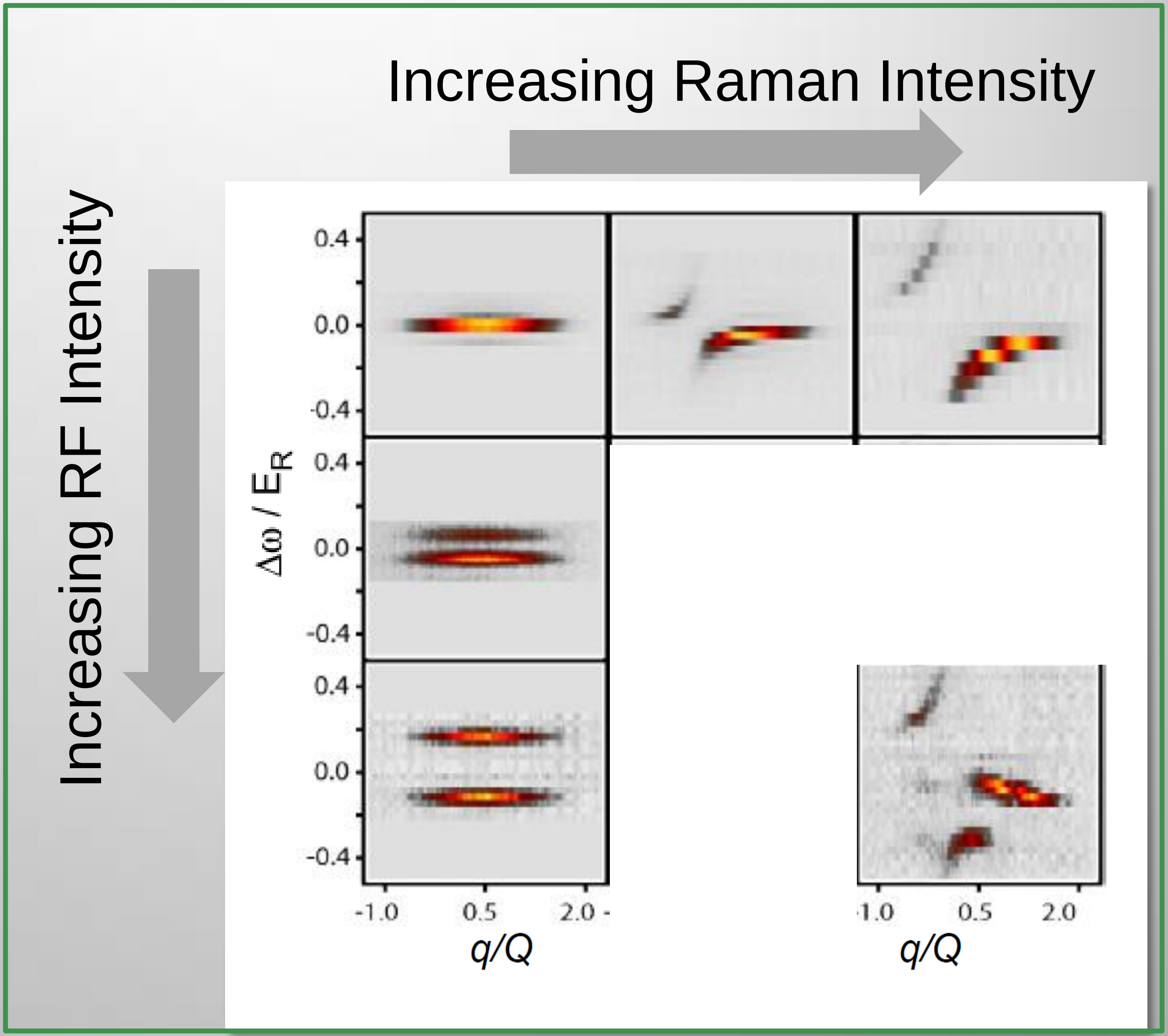
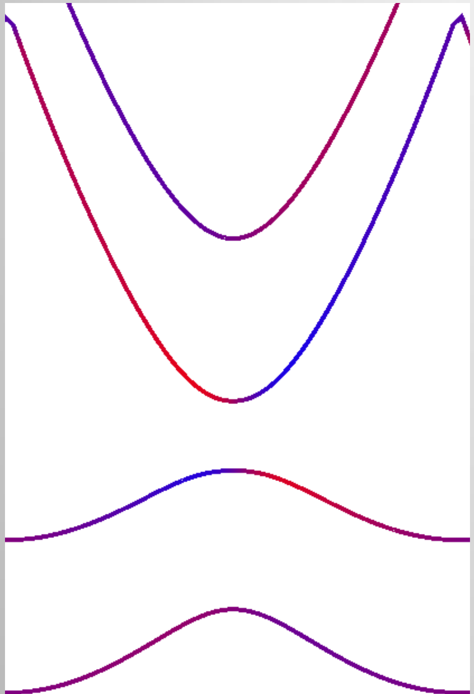
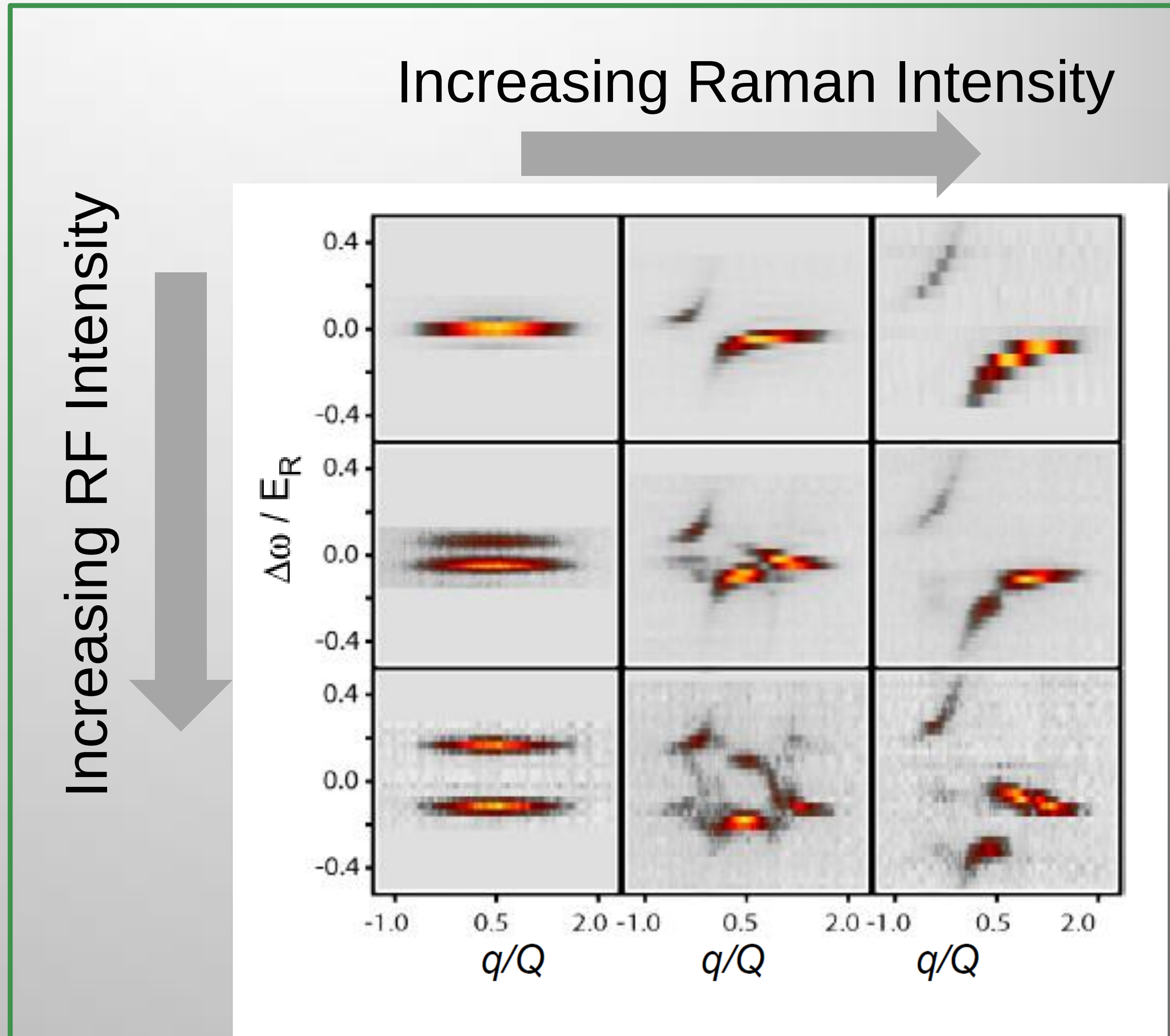


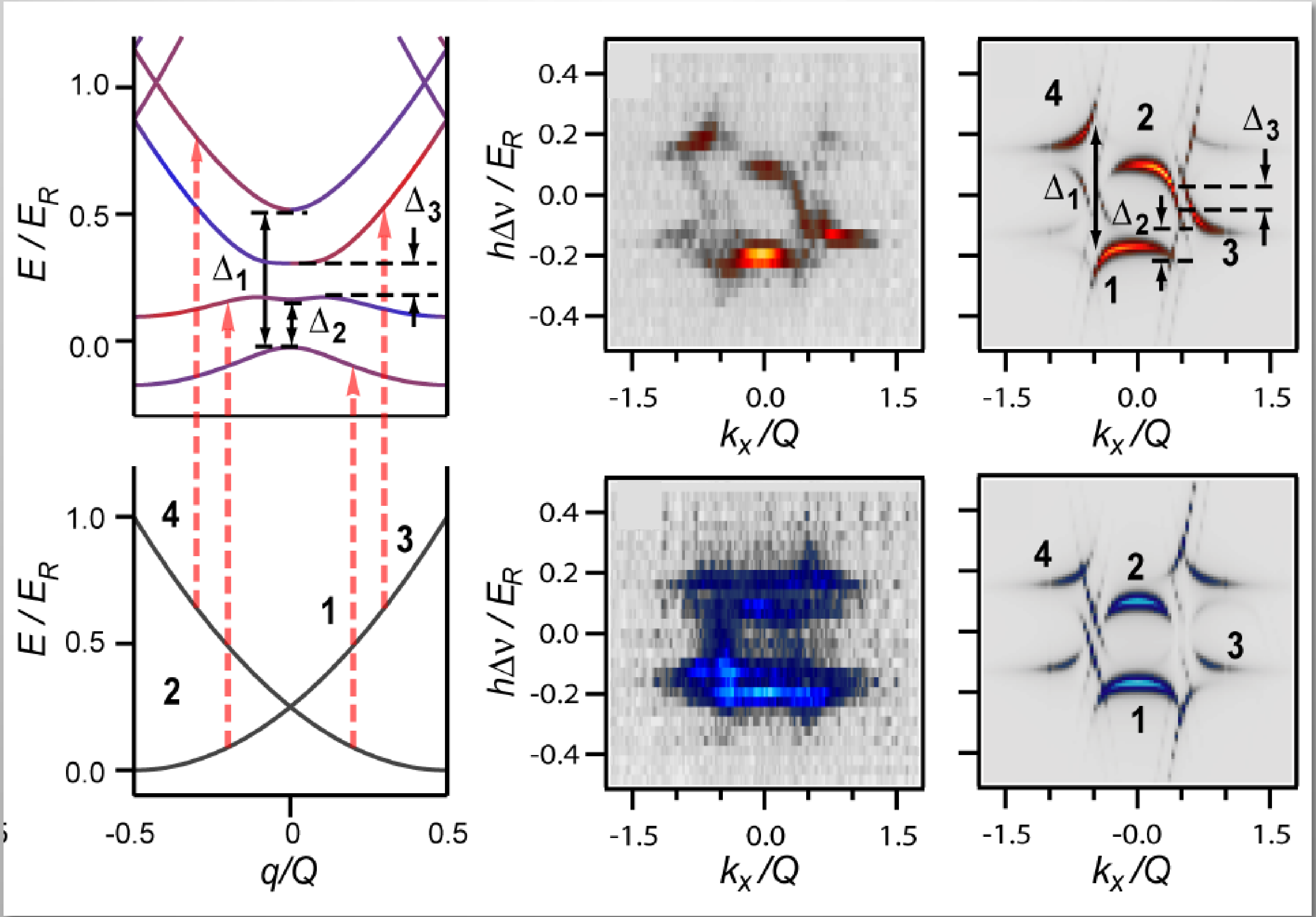


Spin-injection spectroscopy of spinful lattice

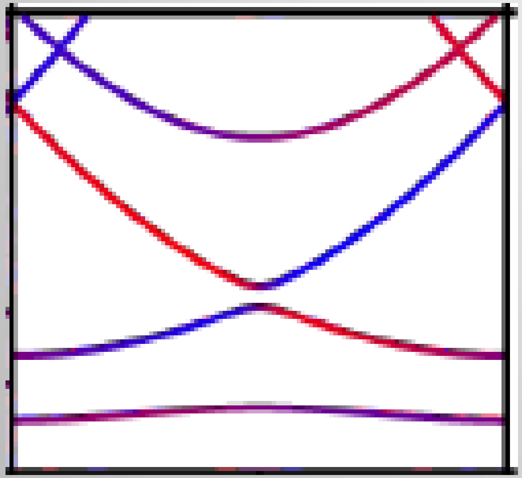


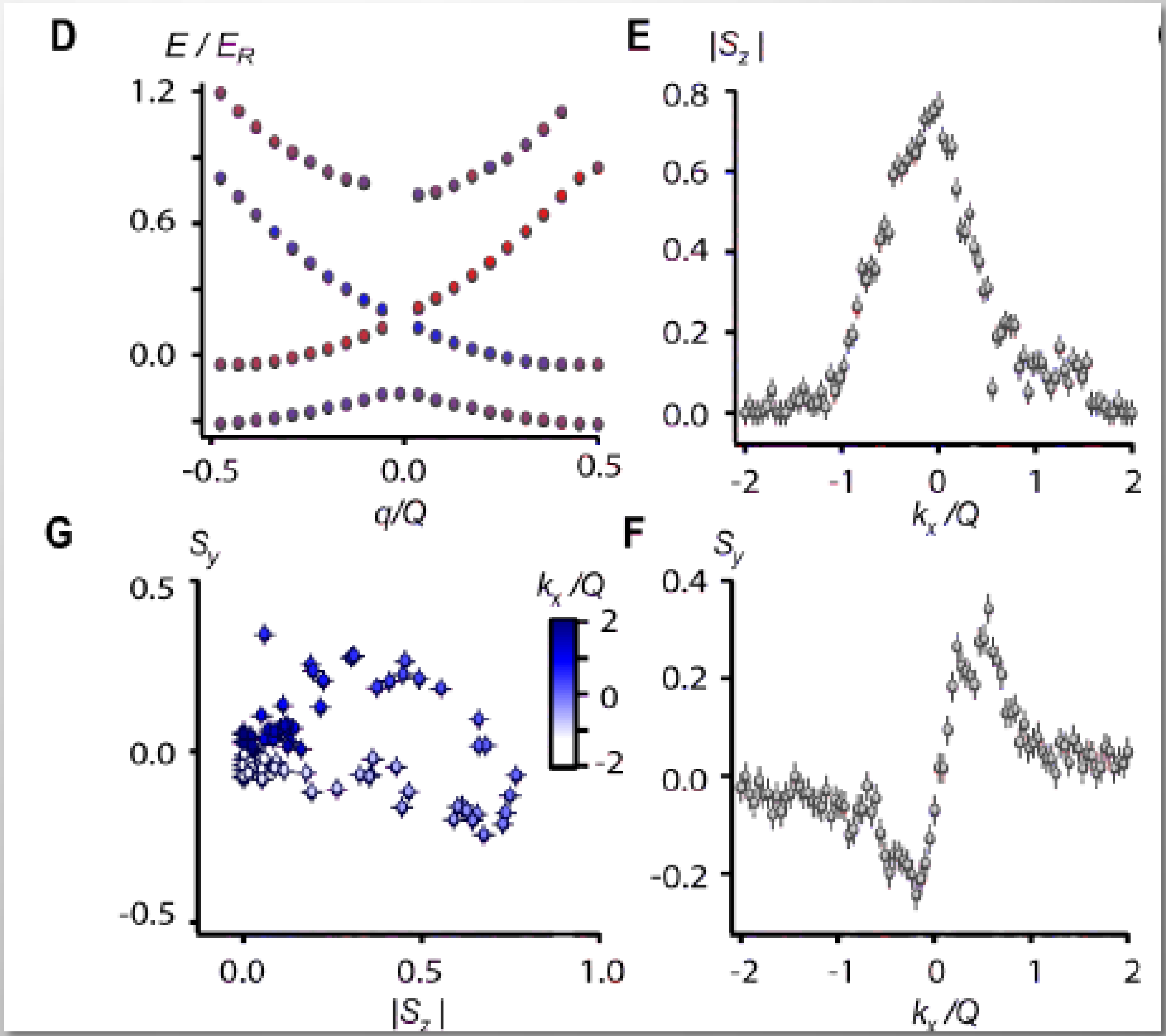


Spin-injection spectroscopy of spinful lattice

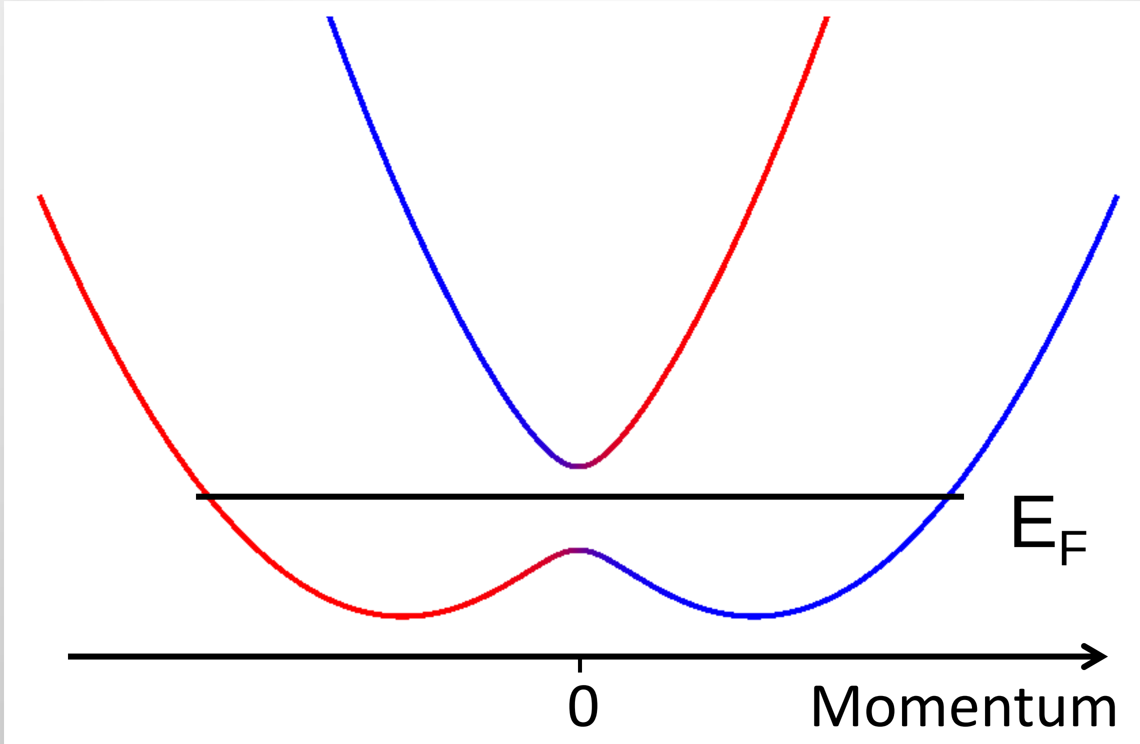


Determination of Spinful Band Structure





Spin-orbit Coupling of a Fermi sea



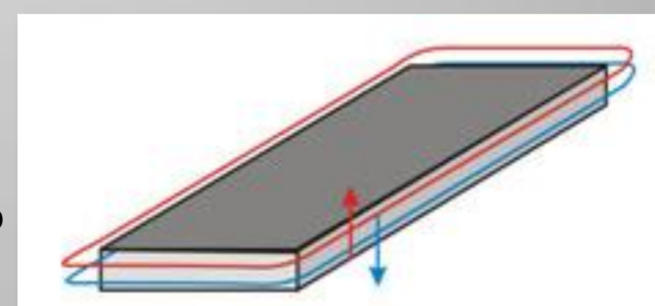
Spin-Orbit coupled Fermi sea $|\uparrow\rangle$ moves to the left, and $|\downarrow\rangle$ to the right

With extensions of these techniques:

Topological insulators, edge states

With interactions:

Topological superfluids, majorana fermions?



Fermions and Bosons

BEC I

Fermi Gases in 3D and 2D

Synthetic Gauge Fields

A.T. Sommer

M.J.H. Ku

L.W. Cheuk

Dr. T. Yefsah

Dr. W. Bakr

Fermi I

LiNaK

Bose-Fermi-Fermi mixtures

C.-H. Wu

J.W. Park

I. Santiago

S. Will

Fermi II

Fermi Gas

Microscope

T. Gersdorf

D. Reens

M. Okan

V. Ramasesh

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sitor spring 2012: Zoran Hadzibabic

ction: Felix Werner, Kris van Houcke, Evgeny Kozik,
Nikolay Prokof'ev, Boris Svistunov