Strongly Correlated Systems of Cold Atoms

Detection of many-body quantum phases by measuring correlation functions

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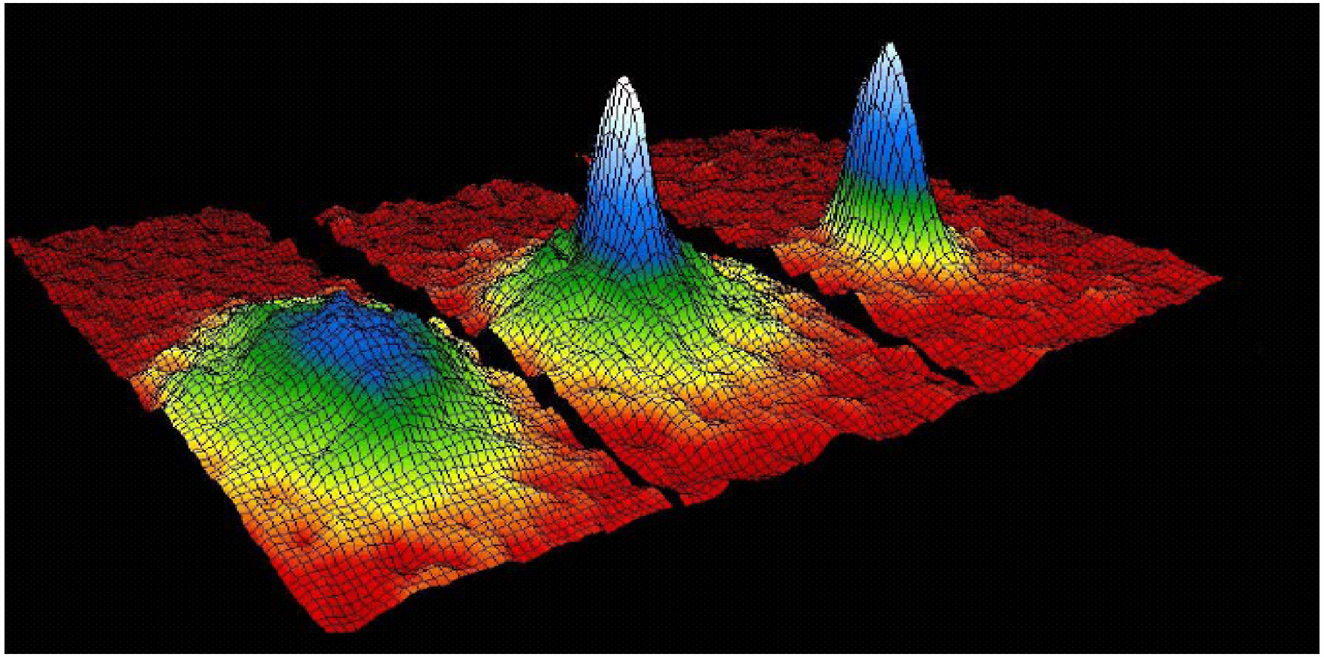
Thanks to: J. Schmiedmayer, M. Oberthaler, V. Vuletic,
M. Greiner, M. Oshikawa

Bose-Einstein condensation



Cornell et al., Science 269, 198 (1995)

$$n \sim 10^{14}\mathrm{cm}^3 \quad T_{\mathrm{BEC}} \sim 1\mu\mathrm{K}$$

Ultralow density condensed matter system

Interactions are weak and can be described theoretically from first principles

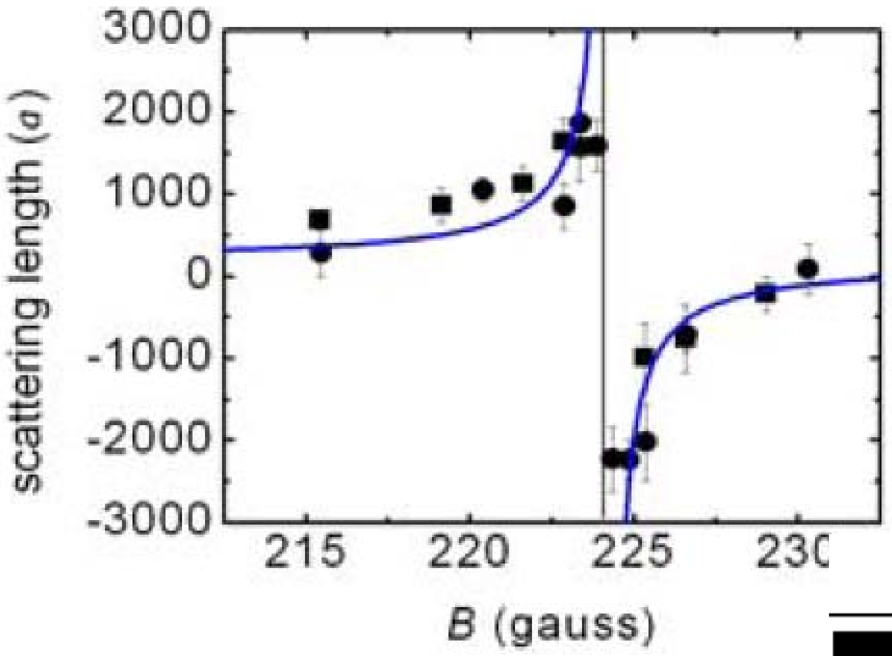
New Era in Cold Atoms Research

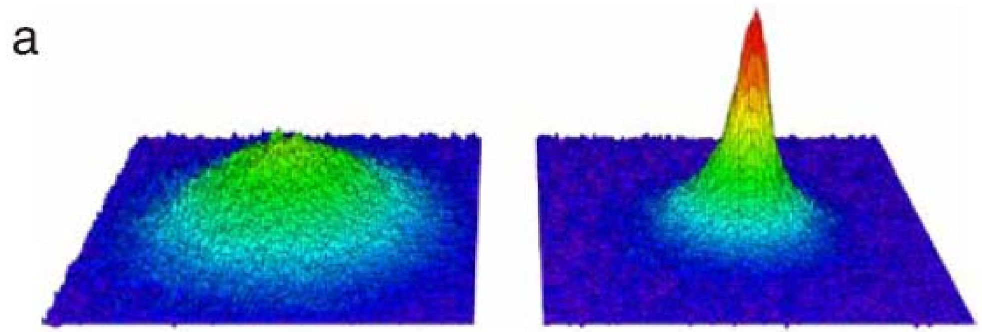
Focus on Systems with Strong Interactions

- Feshbach resonances
- Rotating systems
- Low dimensional systems
- Atoms in optical lattices
- Systems with long range dipolar interactions

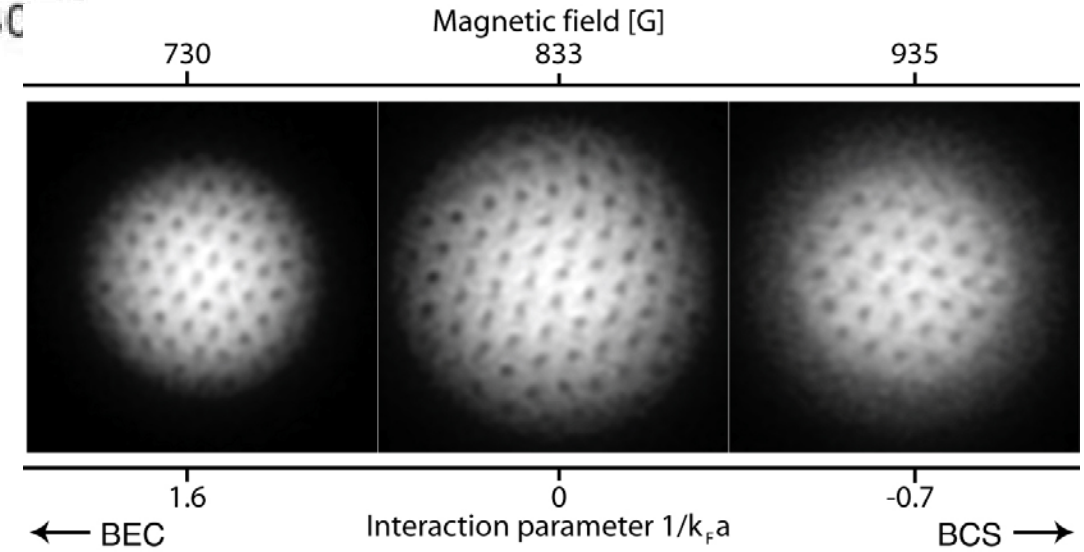
Feshbach resonance and fermionic condensates

Greiner et al., Nature 426:537 (2003); Ketterle et al., PRL 91:250401 (2003)

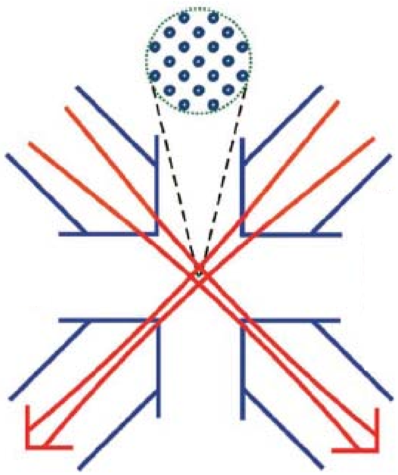




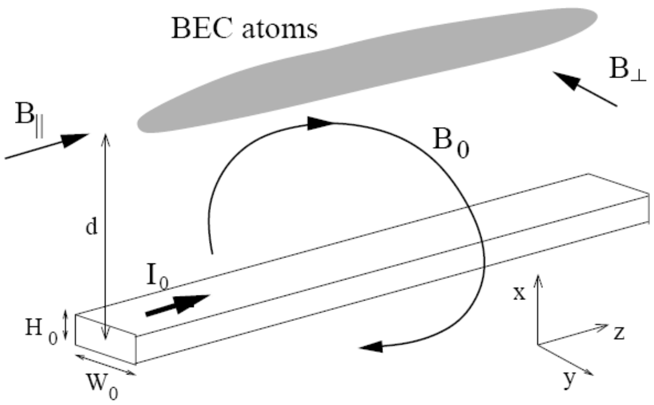
Ketterle et al.,
Nature 435, 1047-1051 (2005)



One dimensional systems



1D confinement in optical potential
Weiss et al., Science (05);
Bloch et al.,
Esslinger et al.,



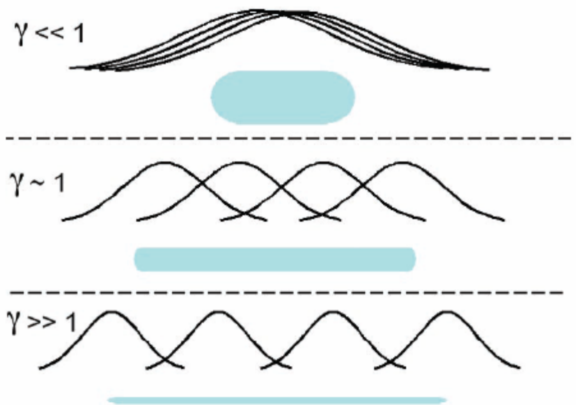
One dimensional systems in microtraps.
Thywissen et al., Eur. J. Phys. D. (99);
Hansel et al., Nature (01);
Folman et al., Adv. At. Mol. Opt. Phys. (02)

$$\mathrm{E_{kin}} \sim \frac{\hbar^2}{m\,d^2} \sim \frac{\hbar^2\,n^2}{m}$$

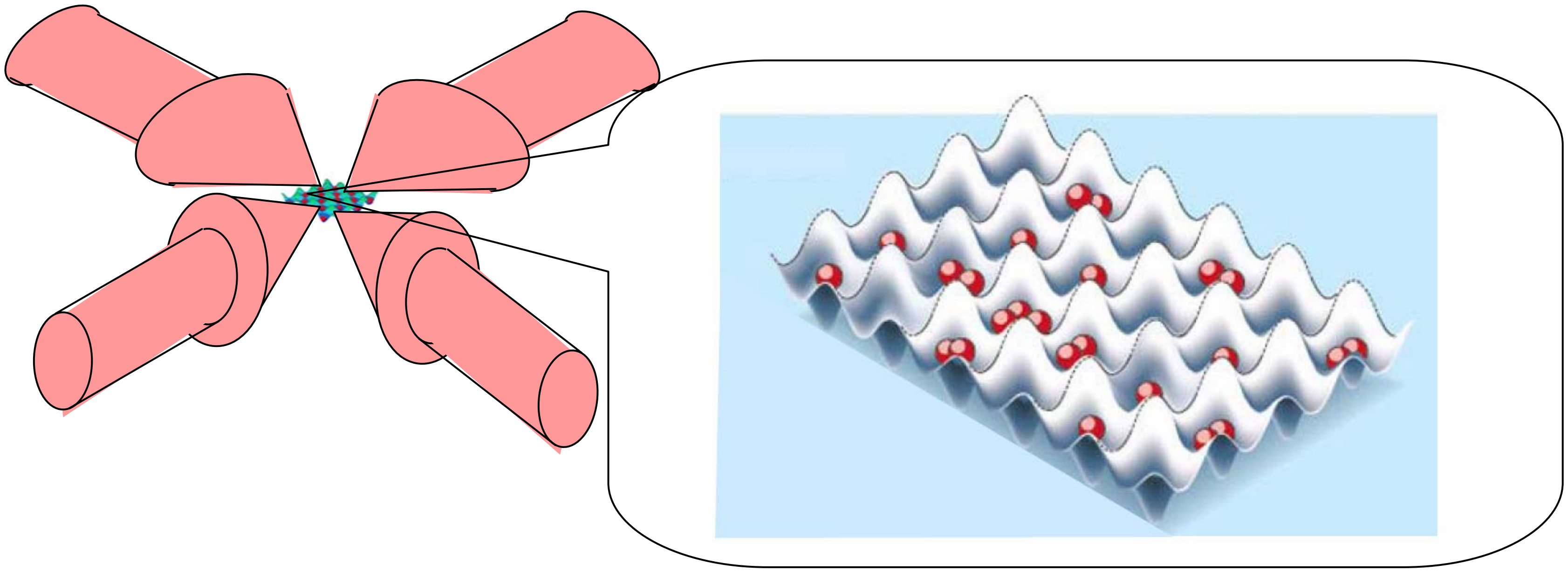
$$\mathrm{E_{int}} \sim g\,n$$

$$\gamma = \frac{\mathrm{E_{int}}}{\mathrm{E_{kin}}} \sim \frac{g\,m}{\hbar^2\,n}$$

Strongly interacting regime can be reached for low densities



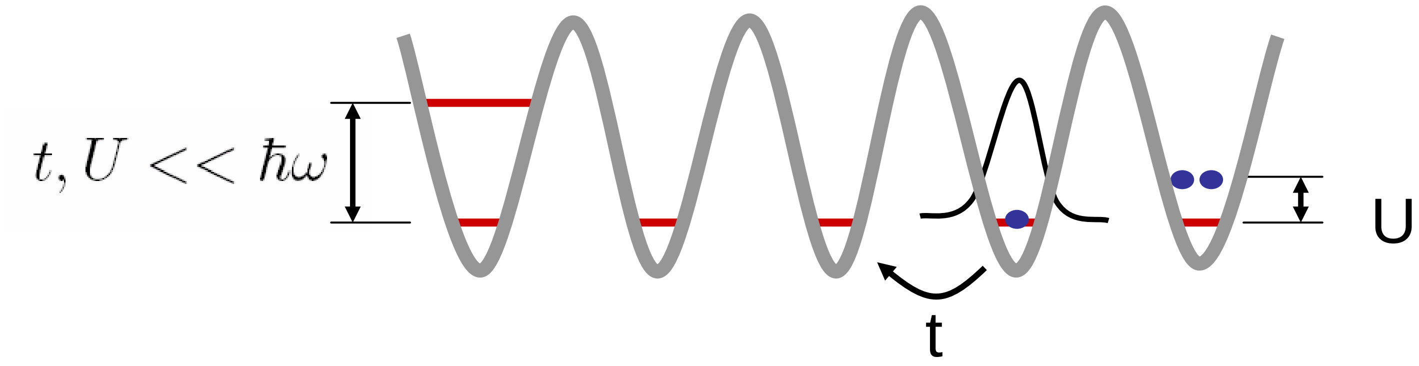
Atoms in optical lattices



Theory: Jaksch et al. PRL (1998)

Experiment: Kasevich et al., Science (2001);
Greiner et al., Nature (2001);
Phillips et al., J. Physics B (2002)
Esslinger et al., PRL (2004);
and many more …

Bose Hubbard model

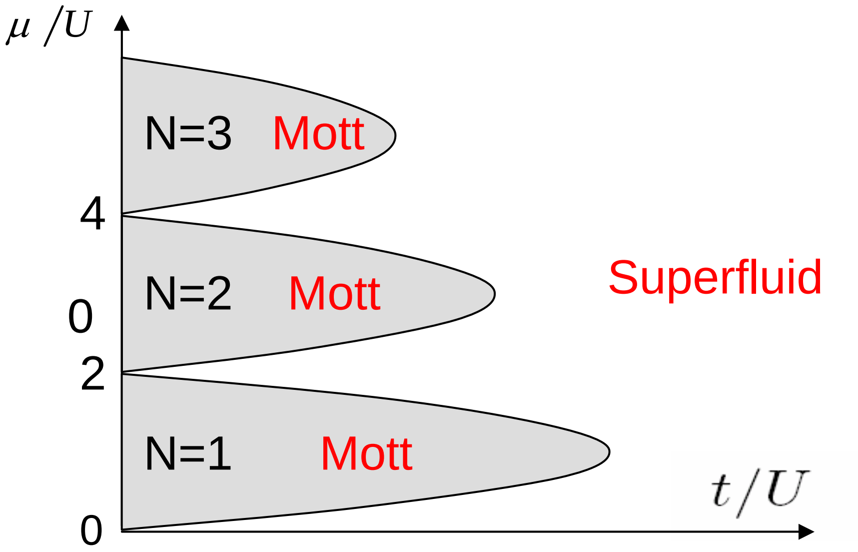


$$\mathcal{H} = -t \sum_{\langle ij \rangle} b_i^\dagger b_j + U \sum_i n_i (n_i - 1) - \mu \sum_i n_i$$

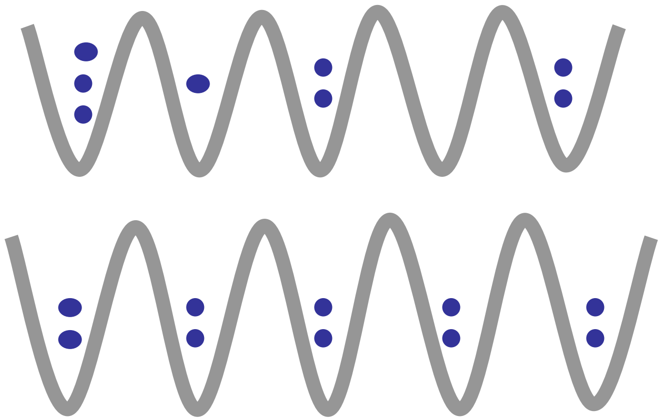
t – tunneling of atoms between neighboring wells

U – repulsion of atoms sitting in the same well

Bose Hubbard model. Mean-field phase diagram



M.P.A. Fisher et al.,
PRB40:546 (1989)



$$U << Nt$$

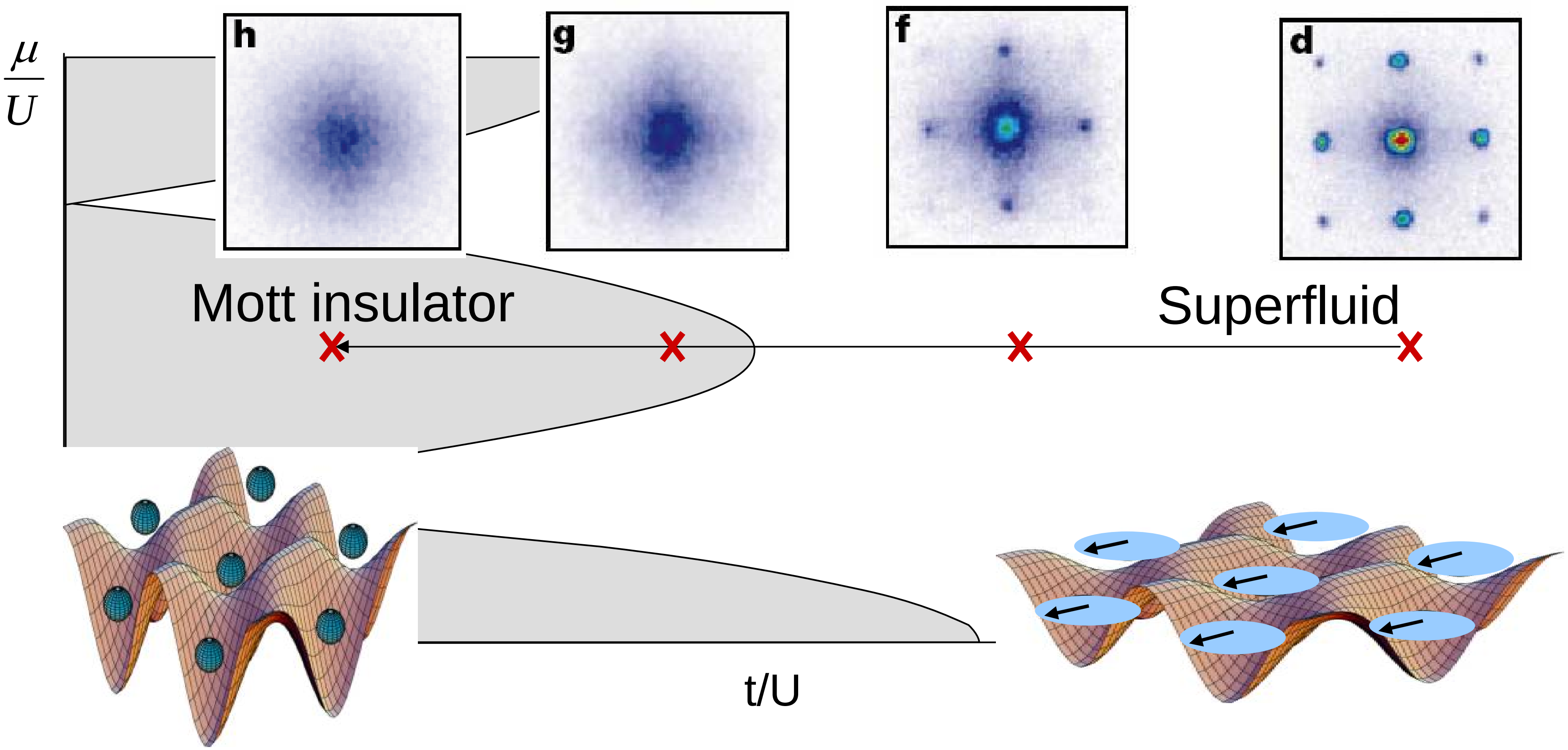
Superfluid phase
Weak interactions

$$U >> Nt$$

Mott insulator phase
Strong interactions

Superfluid to insulator transition in an optical lattice

Greiner et al., Nature 415 (2002)
See also Ketterle et al. cond-mat/0507288



New Era in Cold Atoms Research

Focus on Systems with Strong Interactions

Goals

- Resolve long standing questions in condensed matter physics
  (e.g. origin of high temperature superconductivity)

- Resolve matter of principle questions
  (e.g. existence of spin liquids in two and three dimensions)

- Study new phenomena in strongly correlated systems
  (e.g. coherent far from equilibrium dynamics)

This talk:

Detection of many-body quantum phases by measuring correlation functions

Outline

Measuring correlation functions in intereference experiments

1. Interference of independent condensates
2. Interference of interacting 1D systems
3. Full counting statistics of intereference experiments.
   Connection to quantum impurity problem
4. Interference of 2D systems

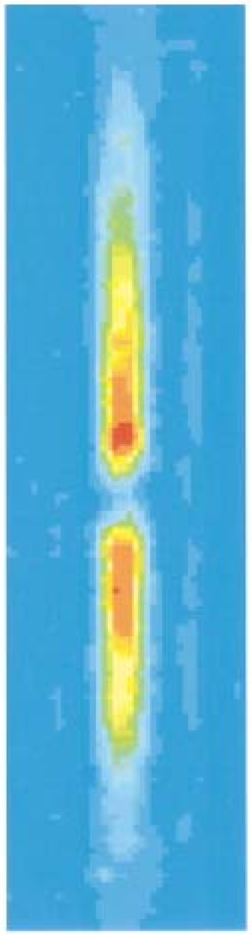
Quantum noise interferometry in time of flight experiments

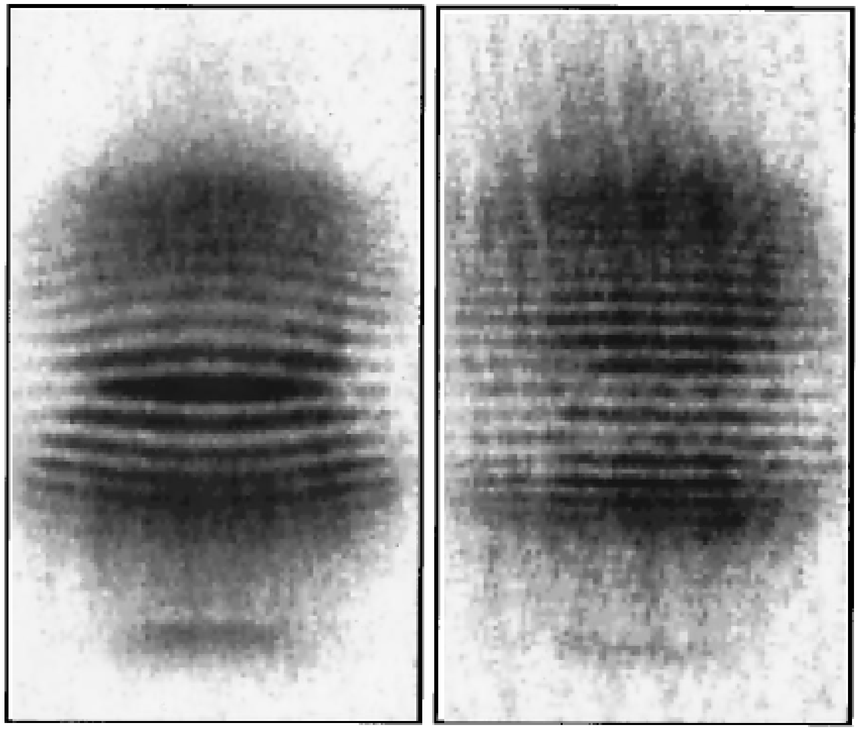
1. Detection of magnetically ordered Mott states in
   optical lattices
2. Observation of fermion pairing

Measuring correlation functions in intereference experiments

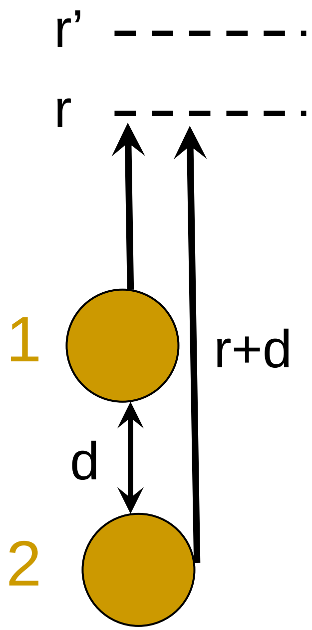
Interference of two independent condensates

Andrews et al., Science 275:637 (1997)





Interference of two independent condensates



$$\rho_{\text{int}}(r) = a_1^\dagger(r)\, a_2(r) + \text{c.c.}$$

$$a_1(r) = e^{i\phi_1 + i k_1 r} \qquad k_1 = \frac{m v_1}{\hbar} = \frac{m r}{\hbar t}$$

$$a_2(r) = e^{i\phi_2 + i k_2 r} \qquad k_2 = \frac{m v_2}{\hbar} = \frac{m(r+d)}{\hbar t}$$

$$\rho_{\text{int}}(r) = e^{i(k_2 - k_1) r}\, e^{i(\phi_2 - \phi_1)} + \text{c.c.}$$

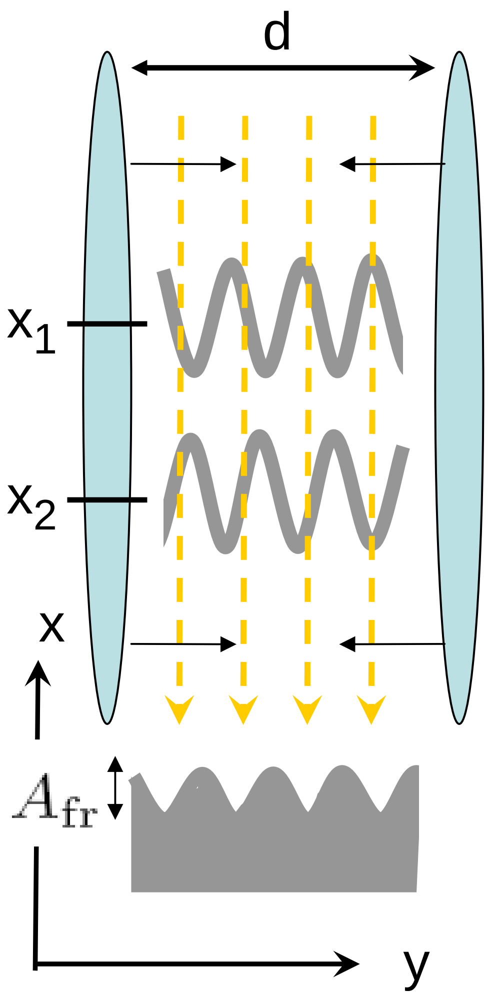
$$\rho_{\text{int}}(r) = e^{i \frac{m d r}{\hbar t}}\, e^{i(\phi_2 - \phi_1)} + \text{c.c.}$$

Clouds 1 and 2 do not have a well defined phase difference.
However each individual measurement shows an interference pattern

$$\langle \rho_{\text{int}}(r) \rangle = 0$$

$$\langle \rho_{\text{int}}(r)\, \rho_{\text{int}}(r') \rangle = e^{i \frac{m d}{\hbar t}(r - r')} + \text{c.c.}$$

Interference of one dimensional condensates



Experiments: Schmiedmayer et al., Nature Physics 1 (05)

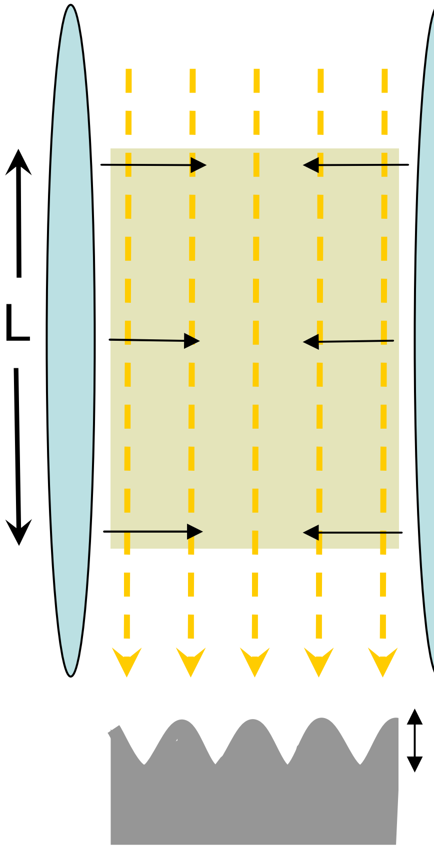
Amplitude of interference fringes, $A_{\rm fr}$,
contains information about phase fluctuations
within individual condensates

$$d\rho_{\rm int}(x,y) = (e^{i\frac{mdy}{\hbar t}} a_1^\dagger(x) a_2(x) + \text{c.c.})\, dx$$

$$\rho_{\rm int}(y) = e^{i\frac{mdy}{\hbar t}} \int_0^L dx\, a_1^\dagger(x) a_2(x) + \text{c.c.}$$

$$\rho_{\rm int}(y) = A_{\rm fr}\, e^{i\Delta\phi + i\frac{mdy}{\hbar t}} + \text{c.c.}$$

Interference amplitude and correlations



$$A_{\rm fr}\, e^{i\Delta\phi} = \int_0^L dx\, a_1^\dagger(x)\, a_2(x)$$

$$\langle |A_{\rm fr}|^2 \rangle = \int_0^L \int_0^L dx\, dy\, \langle a_1^\dagger(x)\, a_2(x)\, a_2^\dagger(y)\, a_1(y) \rangle$$

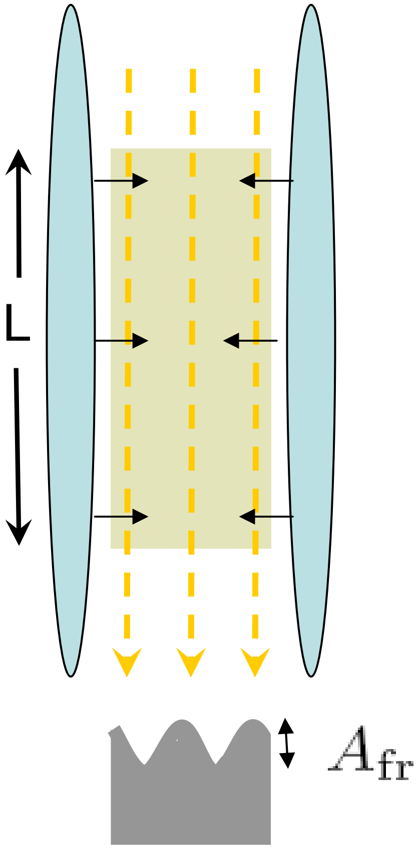
$$\simeq L \int_0^L dx\, \langle a_1(x)\, a_1^\dagger(0) \rangle \langle a_2(0) a_2^\dagger(x) \rangle$$

For identical condensates

$$\langle |A_{\rm fr}|^2 \rangle = L \int_0^L dx\, (G(x))^2$$

Instantaneous correlation function $G(x) = \langle a(x)\, a^\dagger(0) \rangle$

Interference between Luttinger liquids



Luttinger liquid at T=0

$$G(x) \sim \rho \left(\frac{\xi_h}{x} \right)^{2-1/K}$$

K – Luttinger parameter

$$\langle |A_{\rm fr}|^2 \rangle \sim (\rho \xi_h)^{1/K} (L\rho)^{2-1/K}$$

For non-interacting bosons $K = \infty$ and $A_{\rm fr} \sim L$

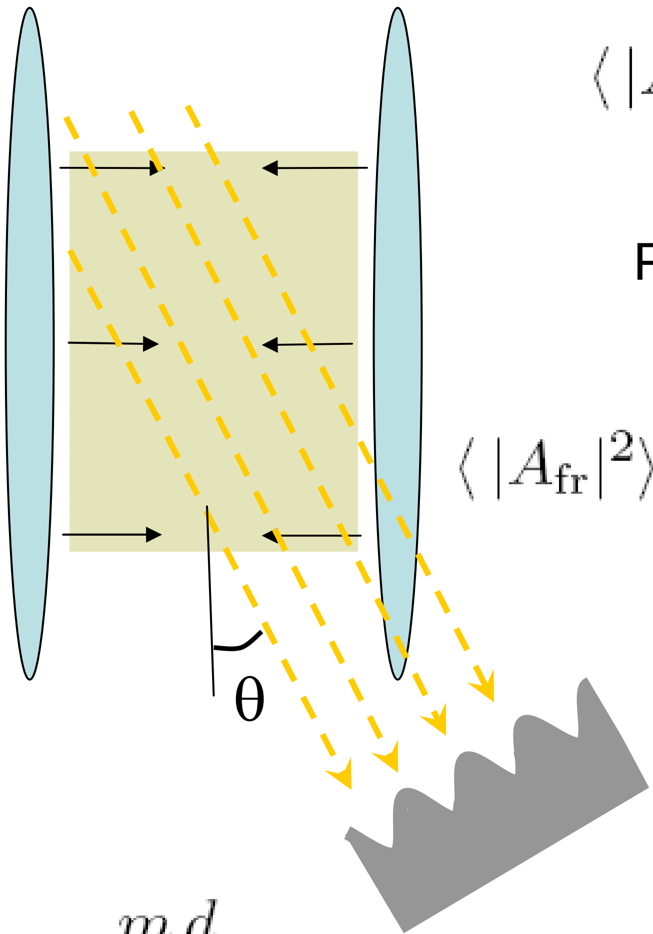
For impenetrable bosons $K = 1$ and $A_{\rm fr} \sim \sqrt{L}$

Luttinger liquid at finite temperature

$$\langle |A_{\rm fr}|^2 \rangle \sim L \rho^2 \xi_h \left(\frac{\hbar^2}{m \xi_h^2} \frac{1}{T} \right)^{1-1/K}$$

Luttinger parameter *K* may be extracted from the *L* or *T* dependence of $A_{\rm fr}$

Rotated probe beam experiment



$$q = \frac{m\,d}{\hbar\,t}\,\tan\theta$$

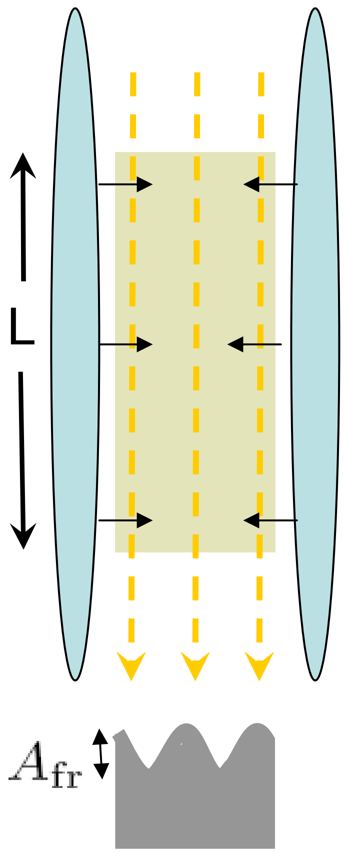
$$\langle\,|A_{\rm fr}|^2\rangle = L\int_0^L dx\;\cos(\,qx\,)\,(\,G\,(x)\,)^2$$

For large imaging angle, $q\,L >> 1$

$$\langle\,|A_{\rm fr}|^2\rangle \sim L\,\rho^2\,\xi_h\,\sin(\,\frac{\pi}{K}\,)\,\Gamma(\,1 - \frac{2}{K}\,)\,(\,\xi_h\,q\,)^{1/K-1}$$

Luttinger parameter *K* may be extracted from the angular dependence of $A_{\rm fr}\,(\,\theta\,)$

Higher moments of interference amplitude



$A_{\rm fr}$ is a quantum operator. The measured value of $|A_{\rm fr}|$ will fluctuate from shot to shot.
Can we predict the distribution function of $|A_{\rm fr}|$?

Higher moments

$$\langle\, |A_{\rm fr}|^{2n} \rangle \;=\; \int_0^L dz_1 \ldots dz_n' \, |\langle\, a^\dagger(z_1) \ldots a^\dagger(z_n)\, a(z_1') \ldots a(z_n')\, \rangle|^2$$

Changing to periodic boundary conditions (long condensates)

$$\langle\, |A_{\rm fr}|^{2n} \rangle \;=\; \langle\, |A_{\rm fr}|^2 \rangle^n \times Z_{2n}$$

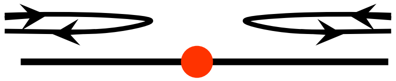
$$Z_{2n} = \prod_{ij} \int_0^{2\pi} \cdots \int_0^{2\pi} \frac{du_i}{2\pi} \frac{dv_j}{2\pi} \left| \frac{\prod_{i<j} 2\sin\left(\frac{u_i - u_j}{2}\right) \prod_{i<j} 2\sin\left(\frac{v_i - v_j}{2}\right)}{\prod_{ij} 2\sin\left(\frac{u_i - v_j}{2}\right)} \right|^{1/K}$$

Explicit expressions for Z_{2n} are available but cumbersome

Fendley, Lesage, Saleur, J. Stat. Phys. 79:799 (1995)

Full counting statistics of interference experiments

Impurity in a Luttinger liquid



$$S = \frac{\pi K}{2} \int dx\, d\tau \, [\, (\partial_\tau \phi)^2 + (\partial_x \phi)^2 \,] + 2g \int d\tau \, \cos\phi\,(x=0\,,\tau)$$

Expansion of the partition function in powers of *g*

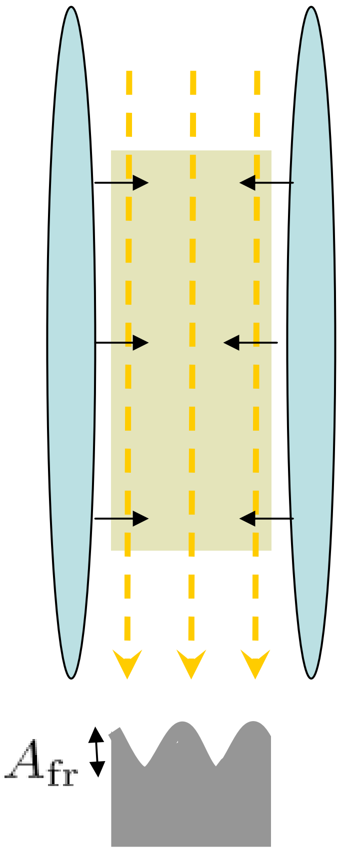
$$Z_{\text{imp}} = \sum_n \frac{g^{2n}}{(2n)!} \int d\tau_1 \ldots d\tau_n \, (e^{i\phi} + e^{-i\phi})_{\tau_1} \ldots (e^{i\phi} + e^{-i\phi})_{\tau_{2n}}$$

$$Z_{\text{imp}} = \sum \frac{g^{2n}}{(n!)^2} Z_{2n}$$

$$Z_{2n} = \prod_{ij} \int_0^{2\pi} \cdots \int_0^{2\pi} \frac{du_i}{2\pi} \frac{dv_j}{2\pi} \left| \frac{\prod_{i<j} 2\,\sin(\frac{u_i-u_j}{2}) \prod_{i<j} 2\,\sin(\frac{v_i-v_j}{2})}{\prod_{ij} 2\,\sin(\frac{u_i-v_j}{2})} \right|^{1/K}$$

Partition function of the impurity contains correlation functions taken at the same point and at different times. Moments of interference experiments come from correlations functions taken at the same time but in different points. Lorentz invariance ensures that the two are the same

Relation between quantum impurity problem and interference of fluctuating condensates



Normalized amplitude of interference fringes $a^2 = |A_{\rm fr}|^2 / \langle\, |A_{\rm fr}|^2 \rangle$

Distribution function of fringe amplitudes $W(\,K,\, a^2\,)$

Relation to the impurity partition function

$$Z_{\rm imp}(\,K,\,g\,) = \int_0^\infty da^2\, W(\,K\,,\,a^2\,)\, I_0(\,2g\,a\,)$$

Distribution function can be reconstructed from $Z_{\rm imp}(\,K,\,g\,)$ using completeness relations for Bessel functions

$$W(K,a^2) = 2\int_0^\infty g\,dg\, Z_{\rm imp}(K,ig) J_0(2ga^2)$$

Bethe ansatz solution for a quantum impurity

$Z_{\rm imp}(K, g)$ can be obtained from the Bethe ansatz following
Zamolodchikov, Phys. Lett. B 253:391 (91); Fendley, et al., J. Stat. Phys. 79:799 (95)
Making analytic continuation is possible but cumbersome

Interference amplitude and spectral determinant

$Z_{\rm imp}(K, ig)$ is related to a Schroedinger equation

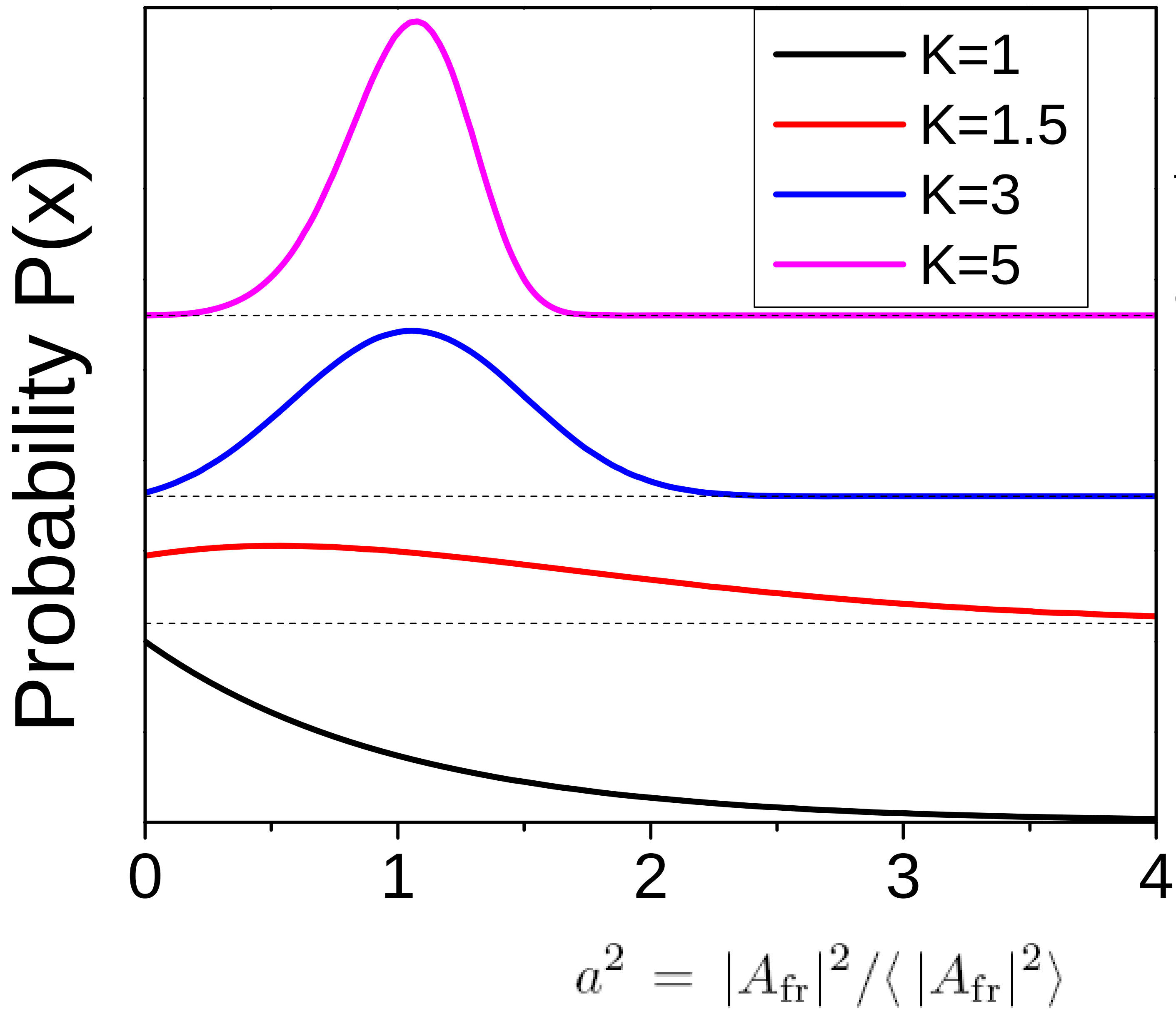
Dorey, Tateo, J.Phys. A. Math. Gen. 32:L419 (1999)
Bazhanov, Lukyanov, Zamolodchikov, J. Stat. Phys. 102:567 (2001)

$$-\frac{d^2\Psi}{dx^2} + \left(x^{4K-2} + \frac{3}{4x^2} \right)\Psi = E\Psi$$

Spectral determinant $D(E) = \prod_{n=1}^{\infty} \left(1 - \frac{E}{E_n}\right)$

$$\boxed{Z_{\rm imp}(K, ig) = D\left(\frac{g^2}{\pi^2} (4K)^{2-K^{-1}} [\Gamma(1 - \frac{1}{2K})]^2 \sin^2(\frac{\pi}{2K}) \right)}$$

Evolution of the distribution function



Narrow distribution for $K \to \infty$. Distribution width approaches

$$\sigma = \frac{\pi}{6K}$$

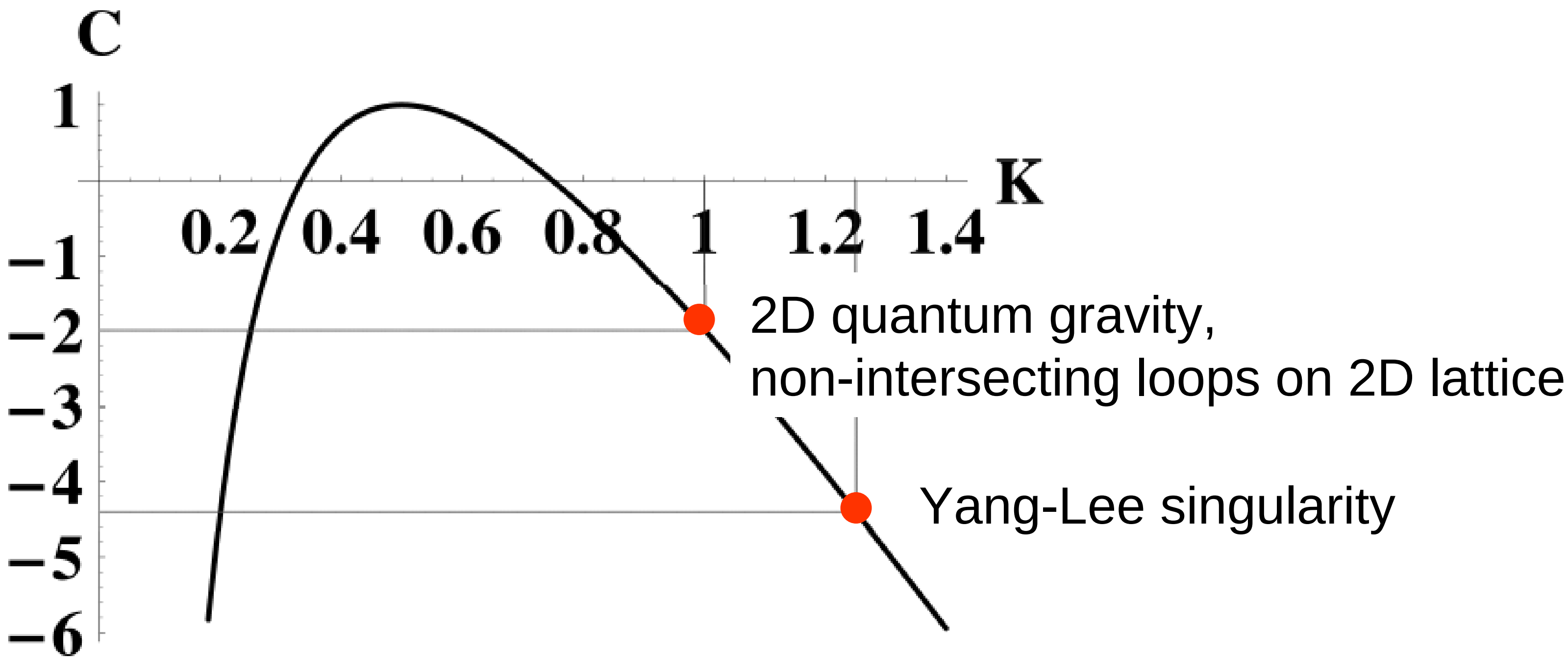
Wide Poissonian distribution for $K \to 1$

From interference amplitudes to conformal field theories

$Z_{\mathrm{imp}}(K, ig)$ correspond to vacuum eigenvalues of *Q* operators of CFT

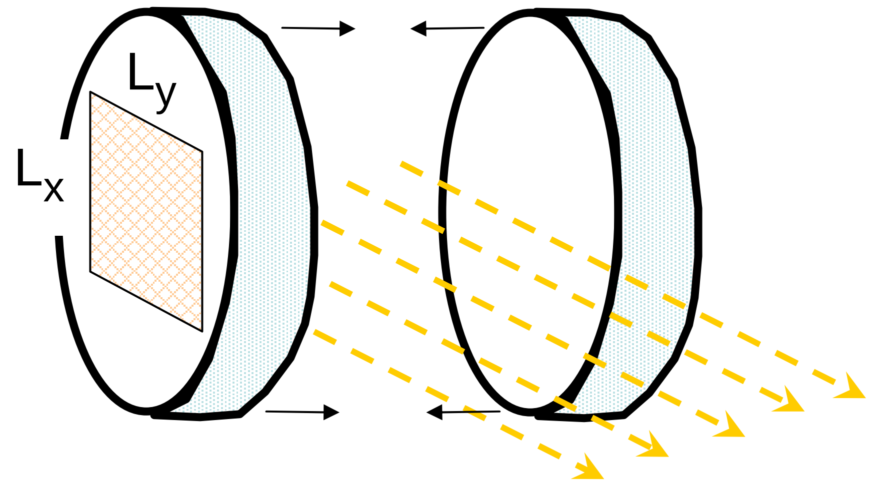
Bazhanov, Lukyanov, Zamolodchikov, Comm. Math. Phys.1996, 1997, 1999

When K>1, $Z_{\mathrm{imp}}(K, ig)$ is related to Q operators of CFT with c<0. This includes 2D quantum gravity, non-intersecting loop model on 2D lattice, growth of random fractal stochastic interface, high energy limit of multicolor QCD, …

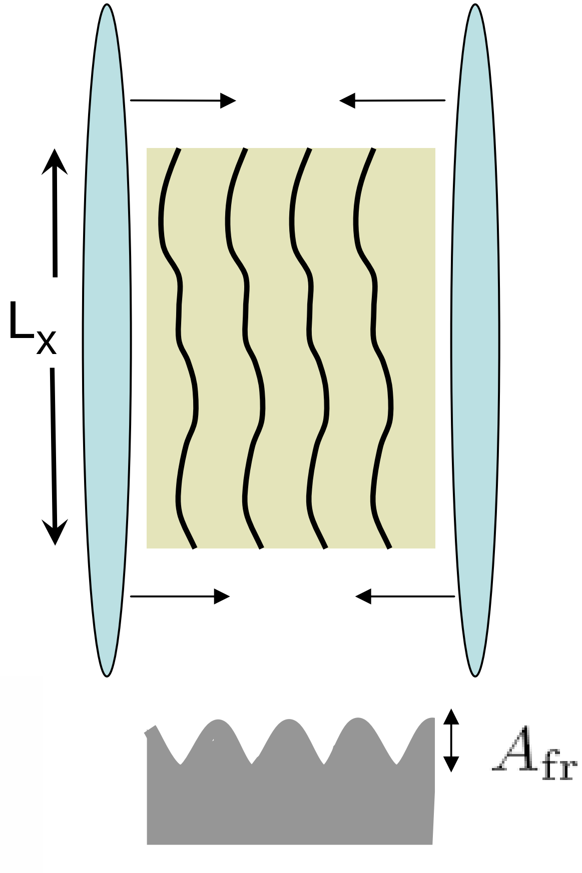


Interference of two dimensional condensates

Experiments: Stock et al., cond-mat/0506559



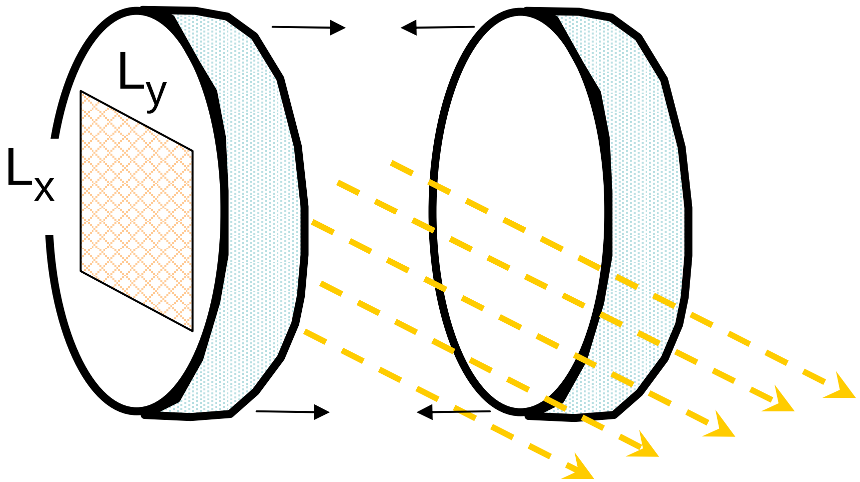
Probe beam parallel to the plane of the condensates



$$\langle |A_{\rm fr}|^2 \rangle = L_x L_y \int_0^{L_x} \int_0^{L_y} d^2\vec{r} \, (G(\vec{r}))^2$$

$$G(\vec{r}) = \langle a(\vec{r}) \, a^\dagger(0) \rangle$$

Interference of two dimensional condensates. Quasi long range order and the KT transition



Above KT transition

$$G(r) \sim e^{-r/\xi}$$

$$\langle |A_{\text{fr}}|^2 \rangle \sim L_x L_y$$

$$\log \xi(T) \sim 1/\sqrt{T - T_{\text{KT}}}$$

Below KT transition

$$G(r) \sim \rho \left(\frac{\xi_h}{r} \right)^{\alpha}$$

$$\alpha(T) = \frac{m T}{2 \pi \rho_s(T) \hbar^2}$$

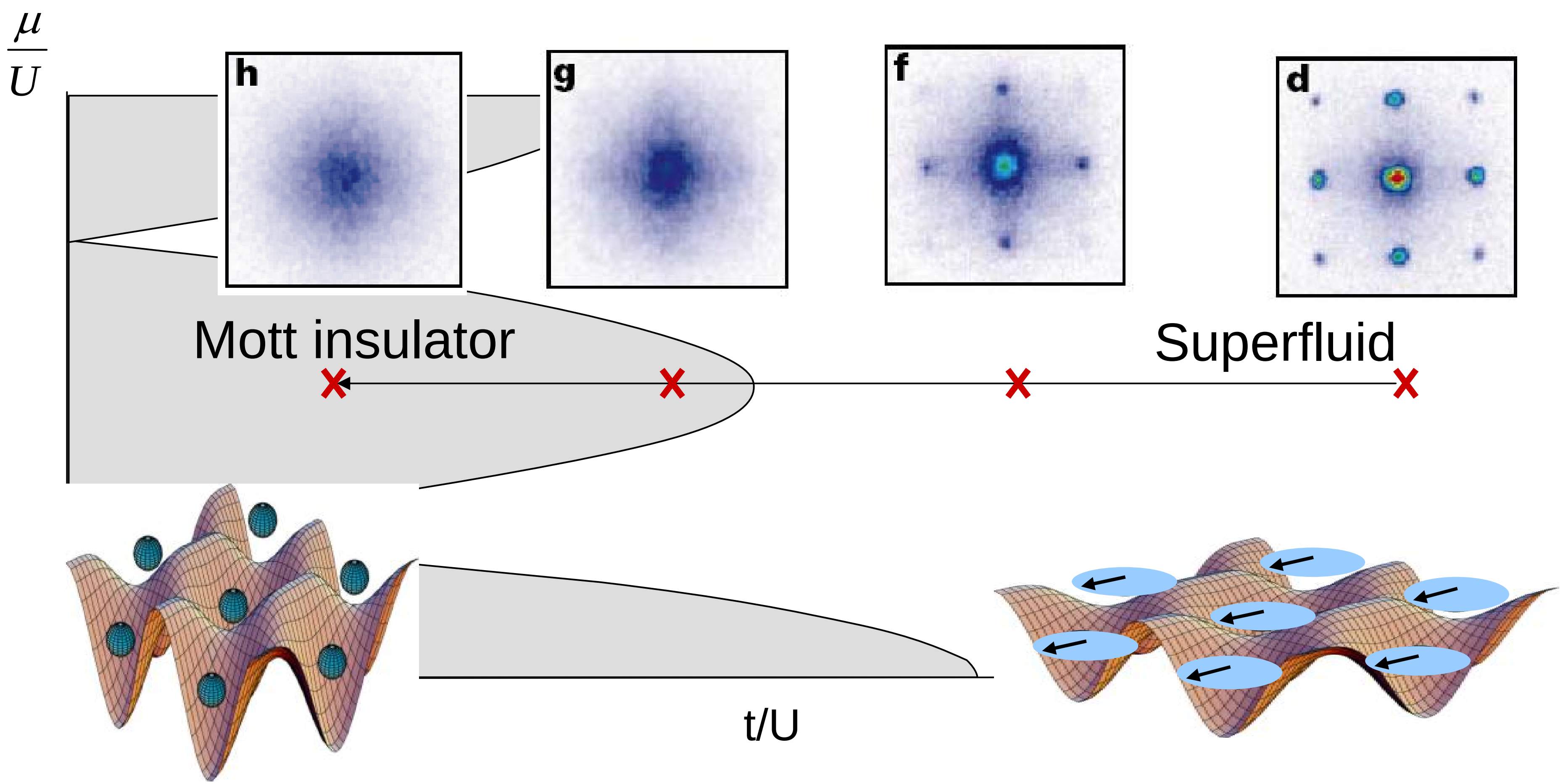
$$\langle |A_{\text{fr}}|^2 \rangle \sim (L_x L_y)^{2-\alpha}$$

One can also use rotated probe beam experiments to extract α from the angular dependence of A_{fr}

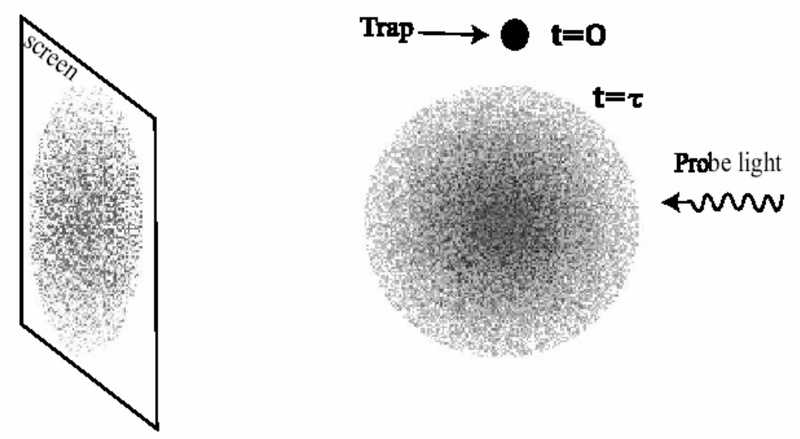
Quantum noise interferometry in time of flight experiments

Atoms in an optical lattice. Superfluid to Insulator transition

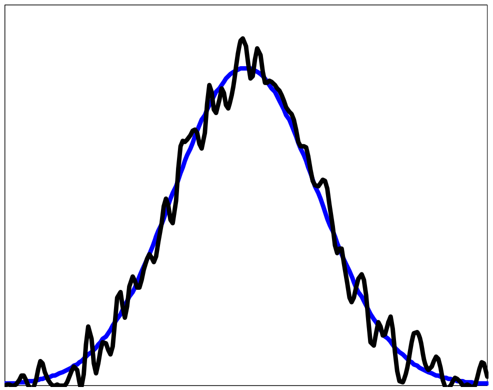
Greiner et al., Nature 415:39 (2002)

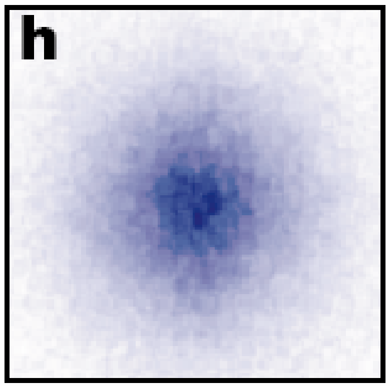


Time of flight experiments



Quantum noise interferometry of atoms in an optical lattice



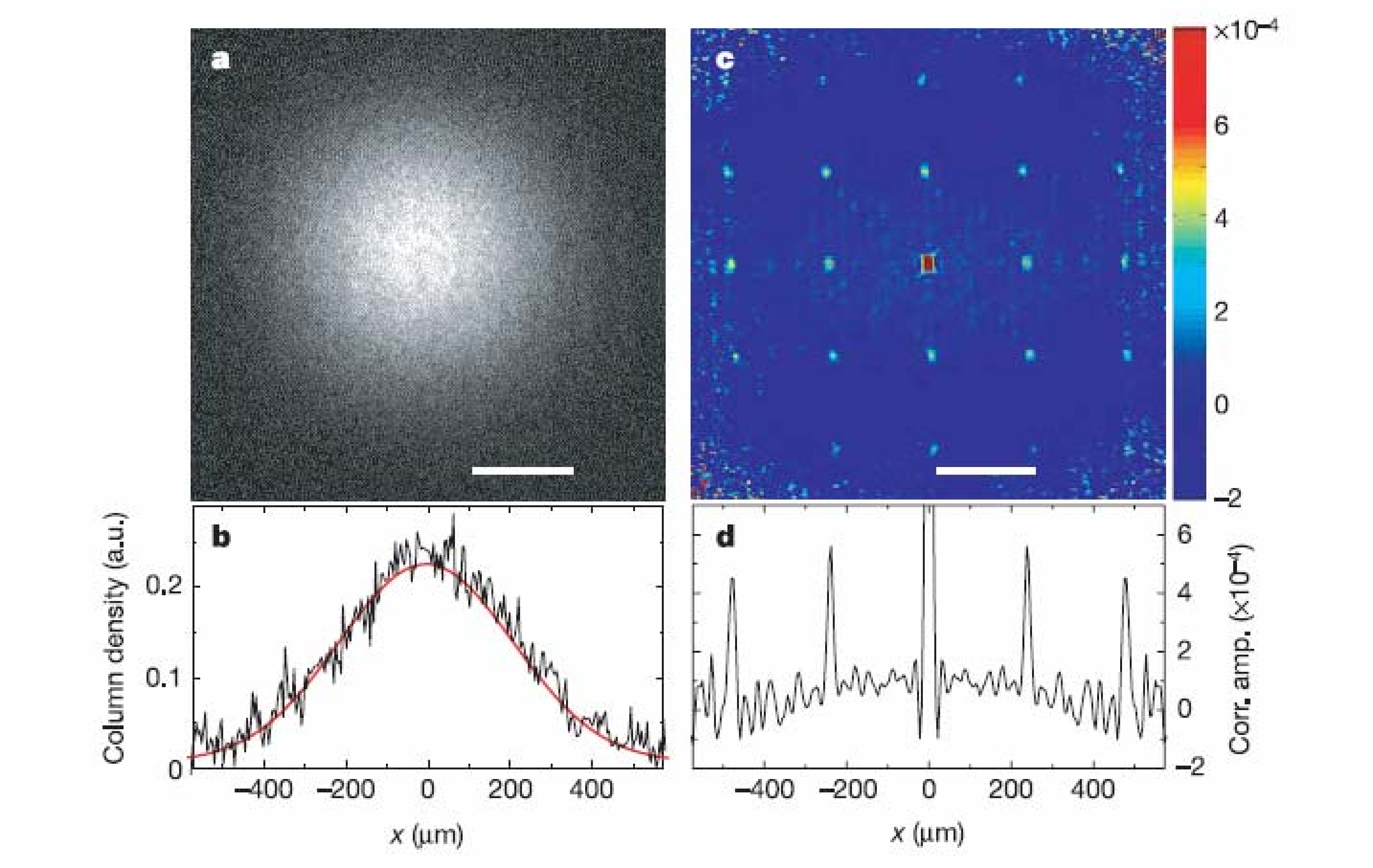


Second order coherence $G(r_1, r_2) = \langle n(r_1) n(r_2) \rangle - \langle n(r_1) \rangle \langle n(r_2) \rangle$

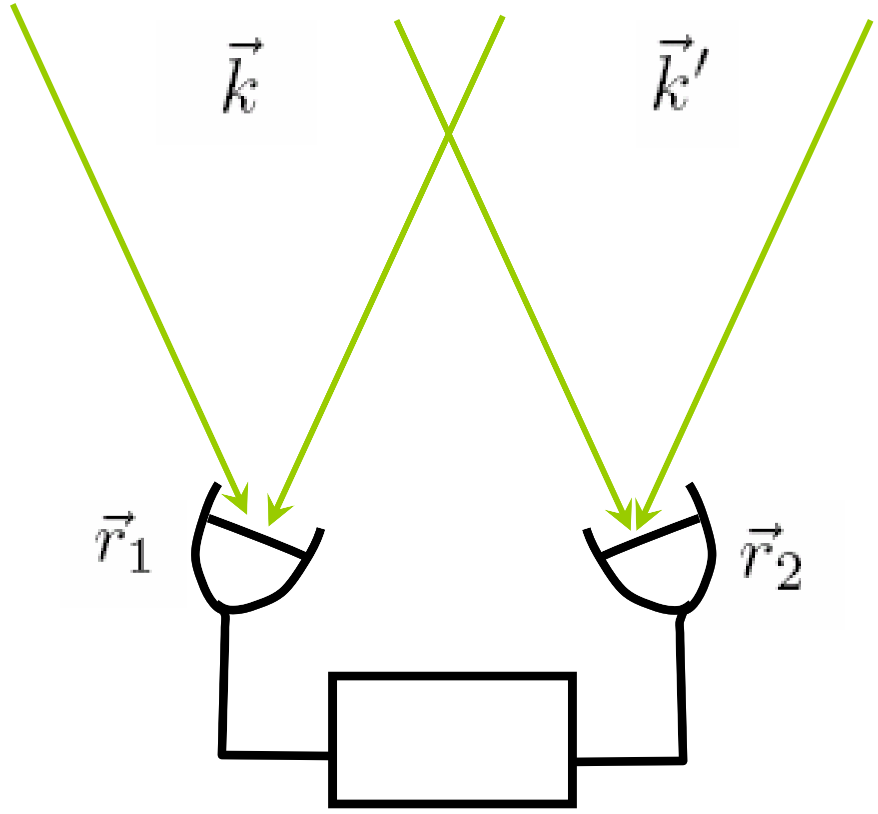
Second order coherence in the insulating state of bosons. Hanburry-Brown-Twiss experiment

Theory: Altman et al., PRA 70:13603 (2004)

Experiment: Folling et al., Nature 434:481 (2005)

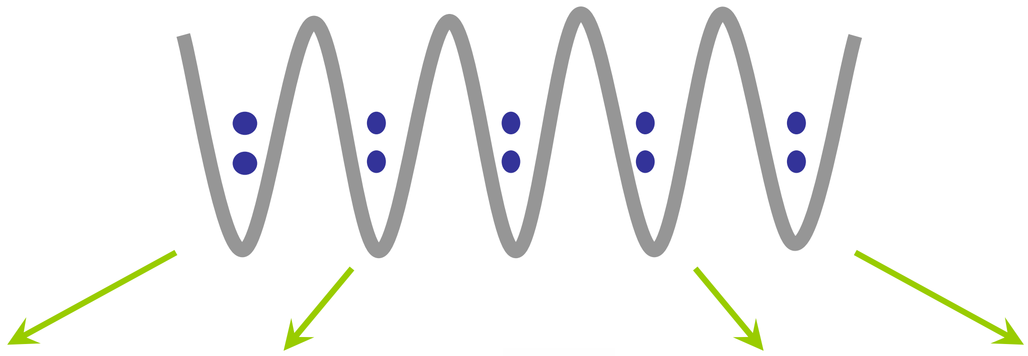


Hanburry-Brown-Twiss stellar interferometer



$$\langle\, I(\vec{r}_1)\; I(\vec{r}_2)\rangle = A + B\;\cos\Big((\vec{k}-\vec{k}')\;(\vec{r}_1-\vec{r}_2)\Big)$$

Second order coherence in the insulating state of bosons



Bosons at quasimomentum $\vec{k}$ expand as plane waves

with wavevectors $\vec{k},\ \vec{k}+\vec{G}_1,\ \vec{k}+\vec{G}_2$

First order coherence: $\langle\ \rho(\vec{r})\ \rangle$

Oscillations in density disappear after summing over $\vec{k}$

Second order coherence: $\langle\ \rho(\vec{r}_1)\ \rho(\vec{r}_2)\ \rangle$

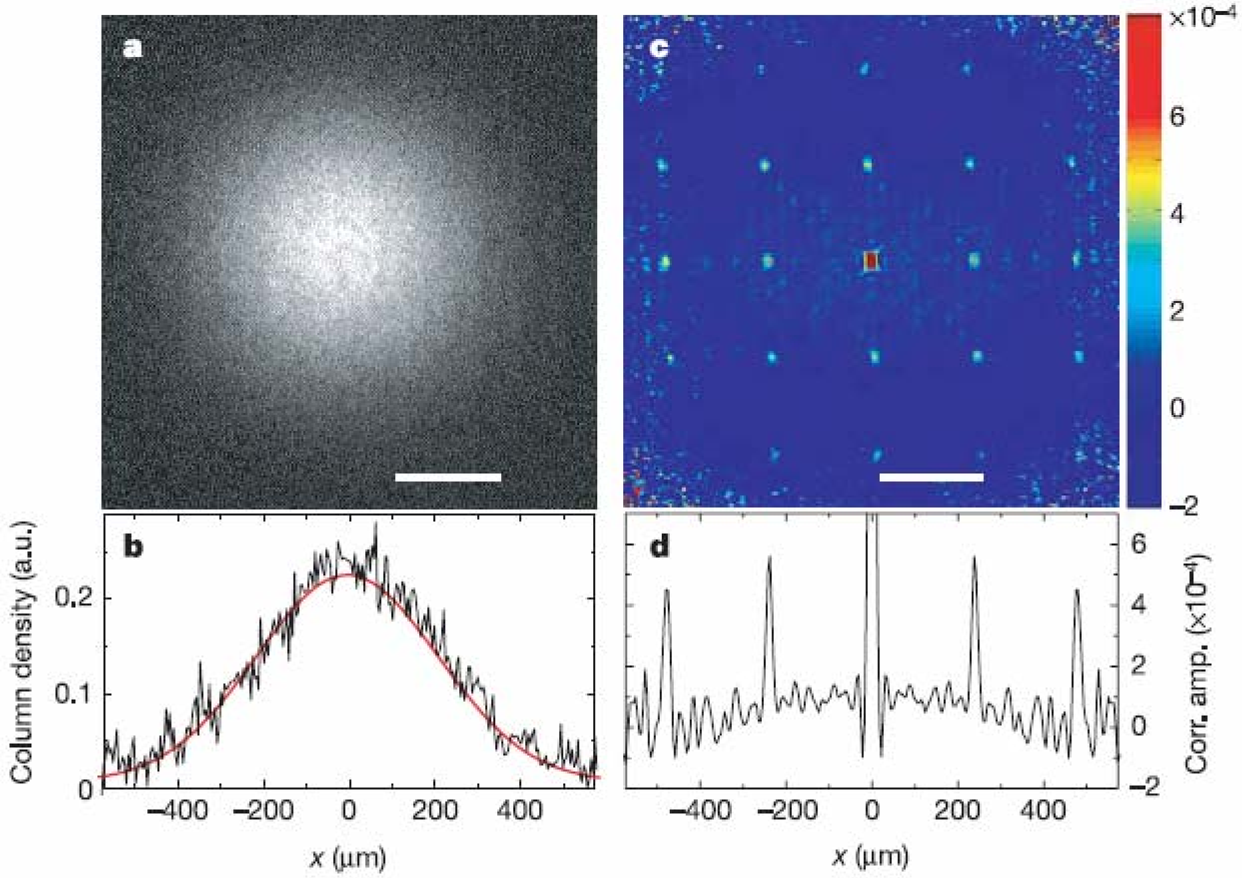
Correlation function acquires oscillations at reciprocal lattice vectors

$$\langle\ \rho(\vec{r}_1)\ \rho(\vec{r}_2)\ \rangle = A_0 + A_1\ \cos\Big(\ \vec{G}_1(\vec{r}_1-\vec{r}_2)\ \Big) + A_2\ \cos\Big(\ \vec{G}_2(\vec{r}_1-\vec{r}_2)\ \Big) + \ldots$$

Second order coherence in the insulating state of bosons. Hanburry-Brown-Twiss experiment

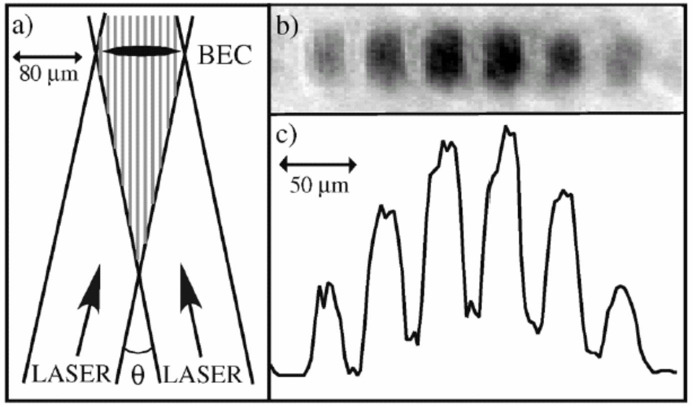
Theory: Altman et al., PRA 70:13603 (2004)

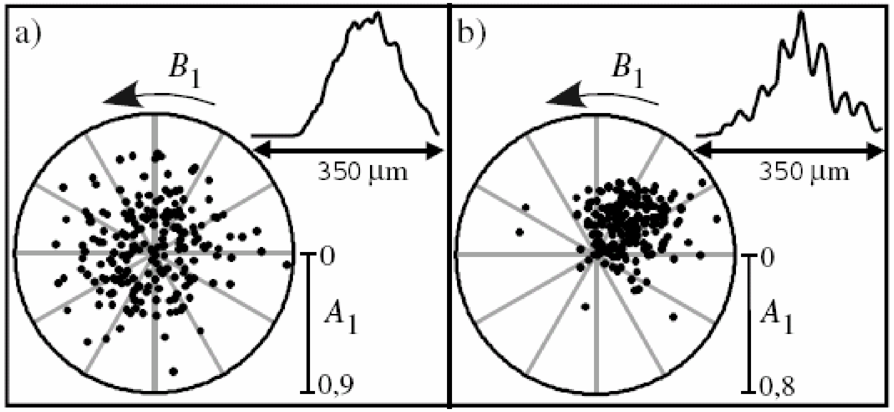
Experiment: Folling et al., Nature 434:481 (2005)



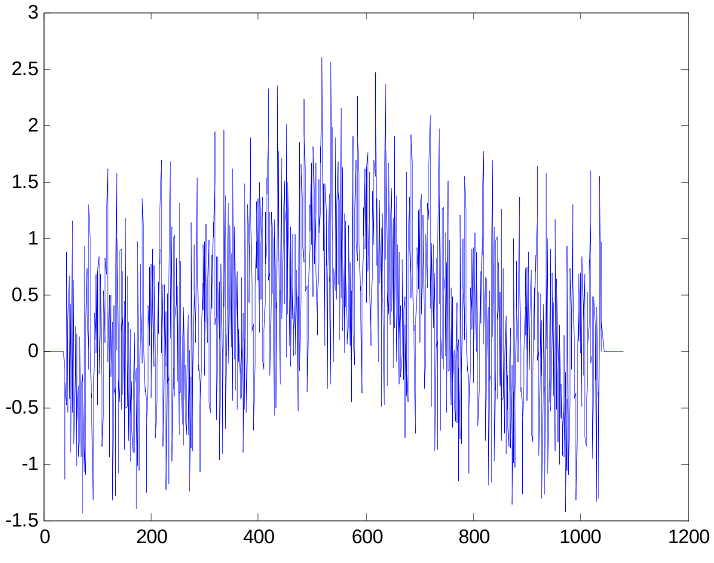
Interference of an array of independent condensates

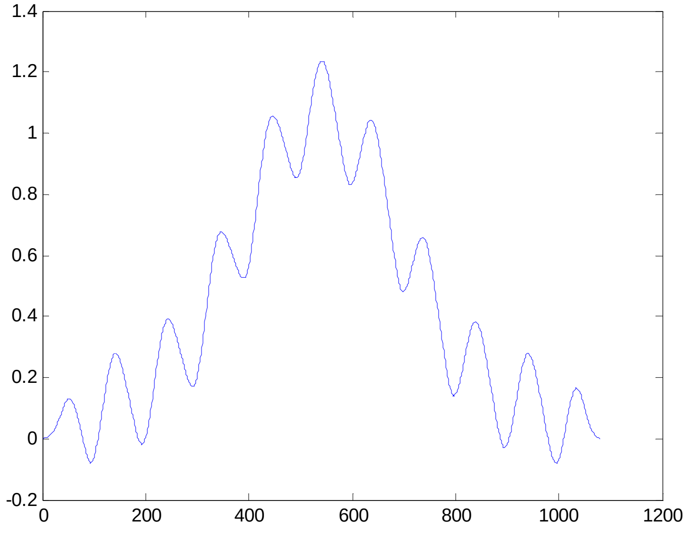
Hadzibabic et al., PRL 93:180403 (2004)





Smooth structure is a result of finite experimental resolution (filtering)



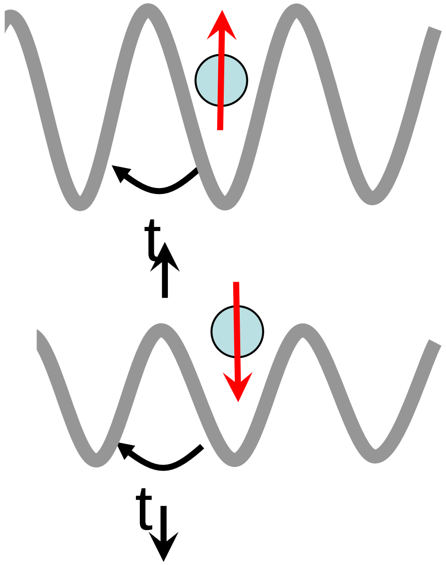


Applications of quantum noise interferometry

Spin order in Mott states of atomic mixtures

Two component Bose mixture in optical lattice

Example: $^{87}\mathrm{Rb}$. Mandel et al., Nature 425:937 (2003)



$$|\uparrow\rangle = |F=1, m_F=-1\rangle$$

$$|\downarrow\rangle = |F=2, m_F=-2\rangle$$

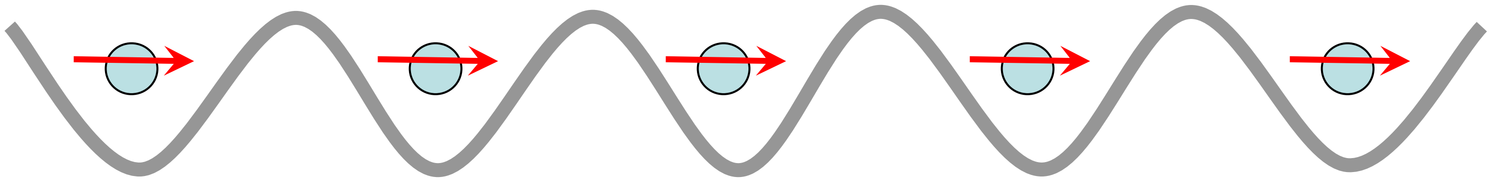
Two component Bose Hubbard model

$$\mathcal{H} = -\ t_\uparrow \sum_{\langle ij\rangle} b^\dagger_{i\uparrow} b_{j\uparrow} - t_\downarrow \sum_{\langle ij\rangle} b^\dagger_{i\downarrow} b_{j\downarrow} + U_{\uparrow\uparrow} \sum_i n_{i\uparrow}(n_\uparrow - 1)$$
$$+\ U_{\downarrow\downarrow} \sum_i n_{i\downarrow}(n_\downarrow - 1) + U_{\uparrow\downarrow} \sum_i n_{i\uparrow} n_\downarrow$$

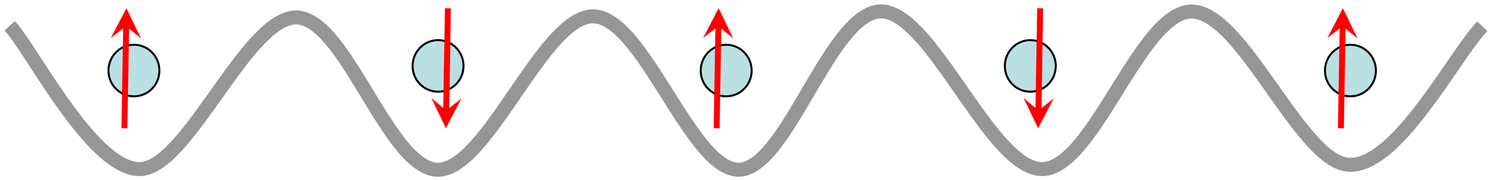
Two component Bose mixture in optical lattice. Magnetic order in an insulating phase

Insulating phases with N=1 atom per site. Average densities $n_\uparrow = n_\downarrow = \frac{1}{2}$

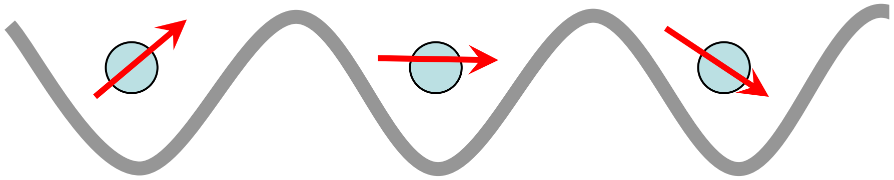
Easy plane ferromagnet $| \Psi \rangle = \prod_i \left(b^\dagger_{i\uparrow} + e^{i\phi} b^\dagger_{i\downarrow} \right) | 0 \rangle$



Easy axis antiferromagnet $| \Psi \rangle = \prod_{i \in A} b^\dagger_{i\uparrow} \prod_{i \in B} b^\dagger_{i\downarrow}$



Quantum magnetism of bosons in optical lattices



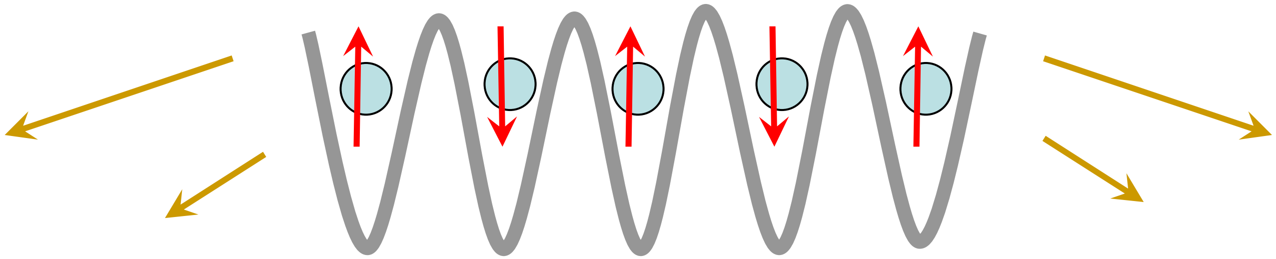
Duan, Lukin, Demler, PRL (2003)

$$\mathcal{H} = J_z \sum_{\langle ij \rangle} \sigma_i^z \sigma_j^z + J_\perp \sum_{\langle ij \rangle} \left(\sigma_i^x \sigma_j^x + \sigma_i^y \sigma_j^y \right)$$

$$J_z = \frac{t_\uparrow^2 + t_\downarrow^2}{2U_{\uparrow\downarrow}} - \frac{t_\uparrow^2}{U_{\uparrow\uparrow}} - \frac{t_\downarrow^2}{U_{\downarrow\downarrow}} \qquad J_\perp = -\frac{t_\uparrow t_\downarrow}{U_{\uparrow\downarrow}}$$

- Ferromagnetic $\quad U_{\uparrow\downarrow} >> U_{\uparrow\uparrow},\ U_{\downarrow\downarrow}$
- Antiferromagnetic $\quad U_{\uparrow\downarrow} << U_{\uparrow\uparrow},\ U_{\downarrow\downarrow}$

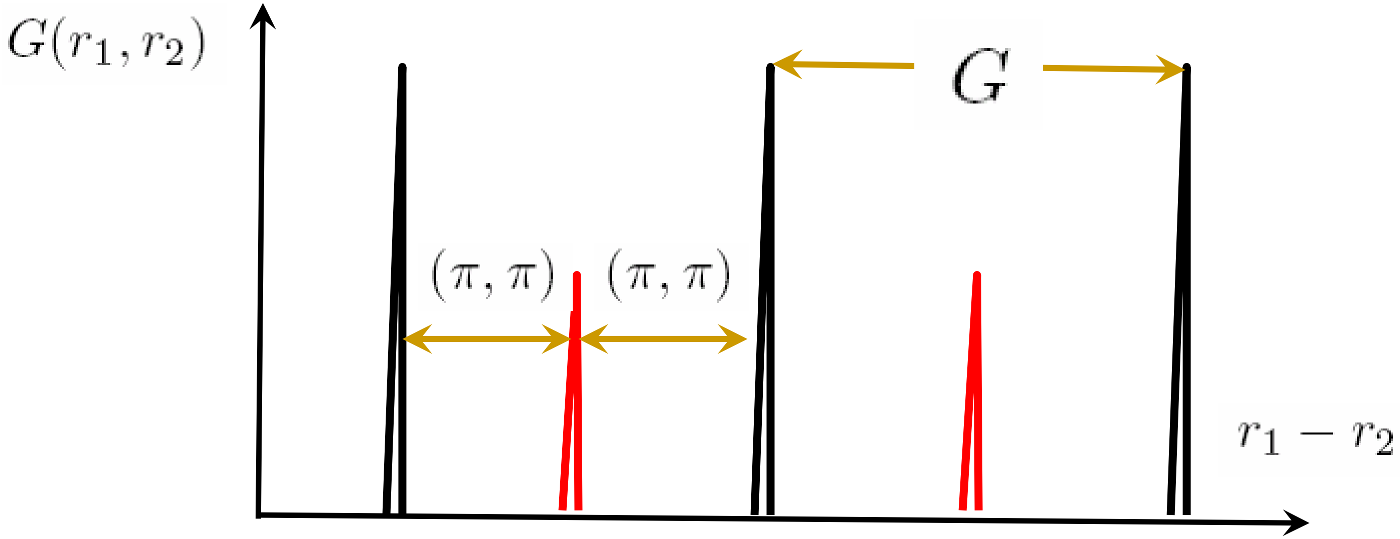
Probing spin order of bosons



$$r = \frac{\hbar\, k\, t}{m}$$

Correlation Function Measurements

$$\begin{aligned} G(r_1, r_2) &= \langle\, n(r_1)\; n(r_2)\, \rangle_{\mathrm{TOF}} - \langle\, n(r_1)\, \rangle_{\mathrm{TOF}}\, \langle\, n(r_2)\, \rangle_{\mathrm{TOF}} \\ &\sim \langle\, n(k_1)\; n(k_2)\, \rangle_{\mathrm{LAT}} - \langle\, n(k_1)\, \rangle_{\mathrm{LAT}}\, \langle\, n(k_2)\, \rangle_{\mathrm{LAT}} \end{aligned}$$



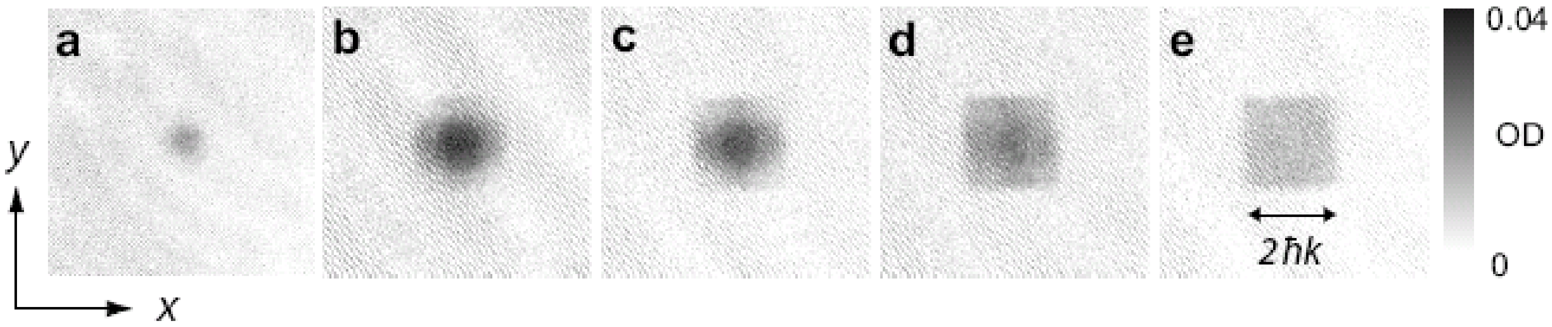
Extra Bragg peaks appear in the second order correlation function in the AF phase

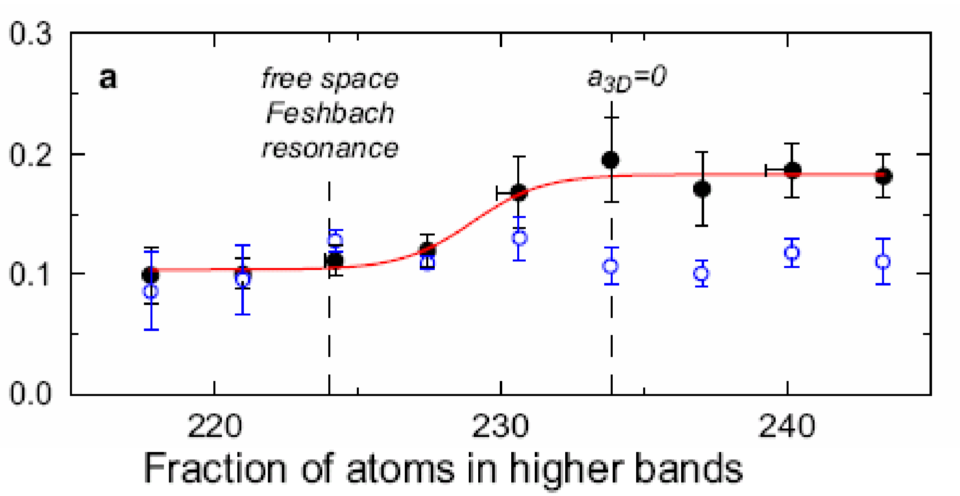
Applications of quantum noise interferometry

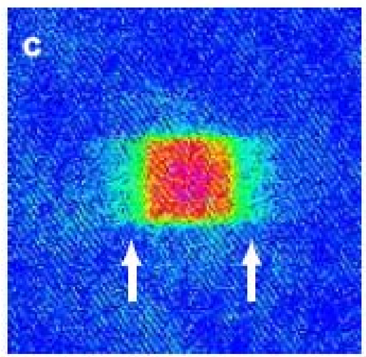
Detection of fermion pairing

Fermionic atoms in an optical lattice

Kohl et al., PRL 94:80403 (2005)

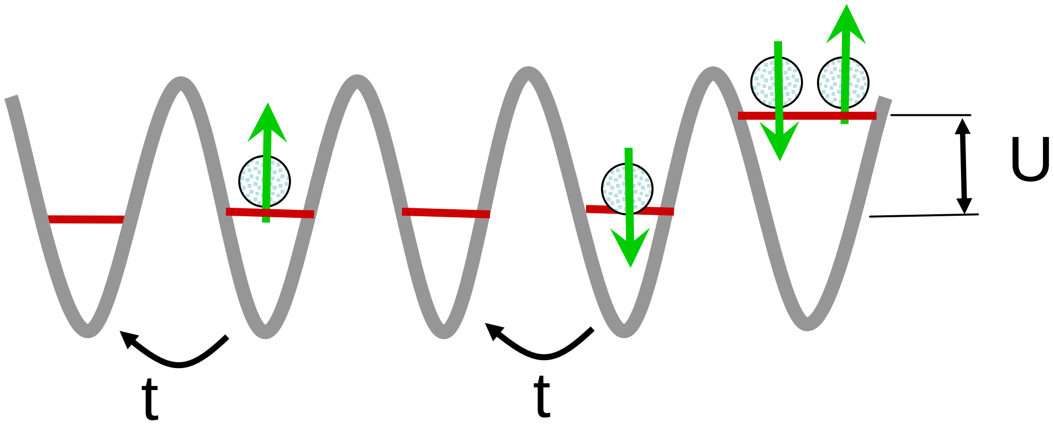




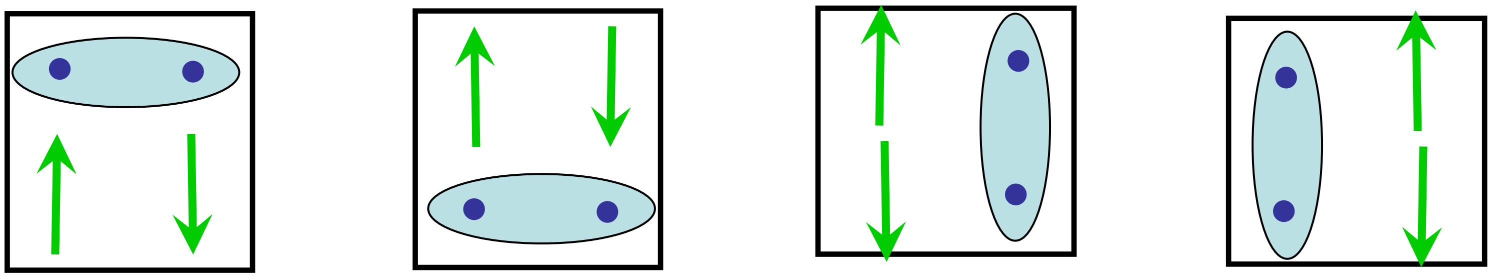


Fermions with repulsive interactions

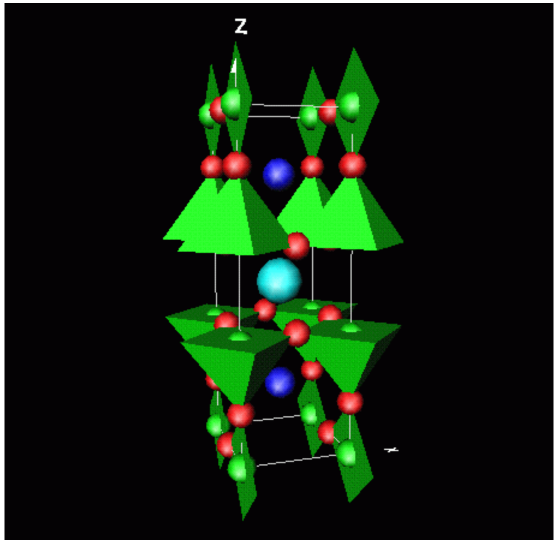
$$\mathcal{H} = -t \sum_{\langle ij \rangle \, \sigma} c^{\dagger}_{i\sigma} c_{j\sigma} + U \sum_i n_{i\uparrow} n_{i\downarrow} - \mu \sum_i n_i$$



Possible d-wave pairing of fermions

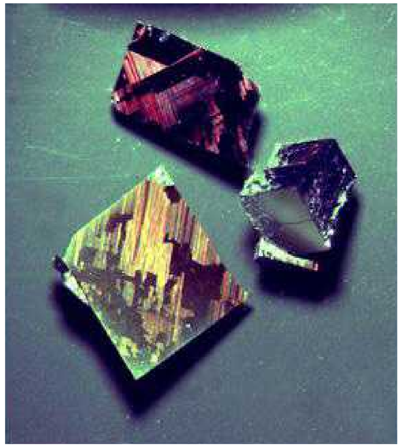


High temperature superconductors



$YBa_2Cu_3O_7$

Superconducting
Tc 93 K



Picture courtesy of UBC Superconductivity group

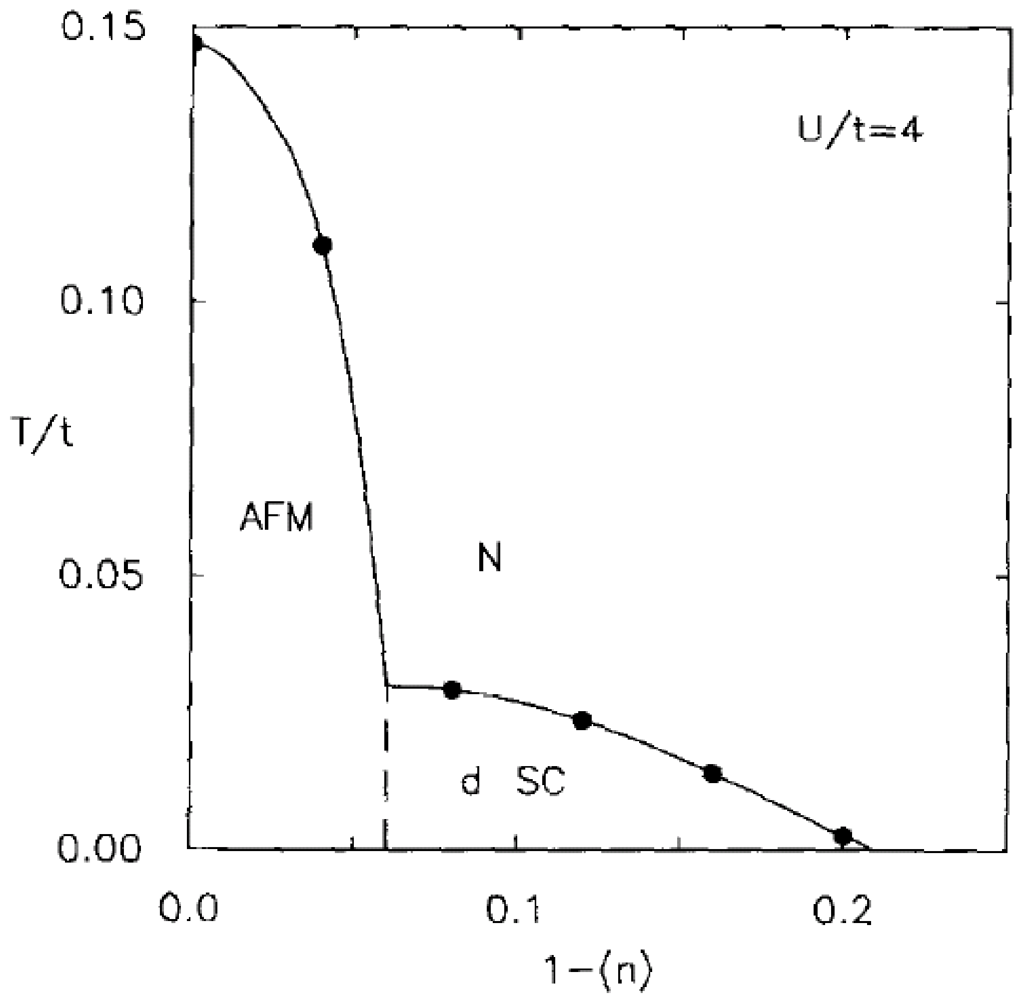
Hubbard model – minimal model for cuprate superconductors

P.W. Anderson, cond-mat/0201429

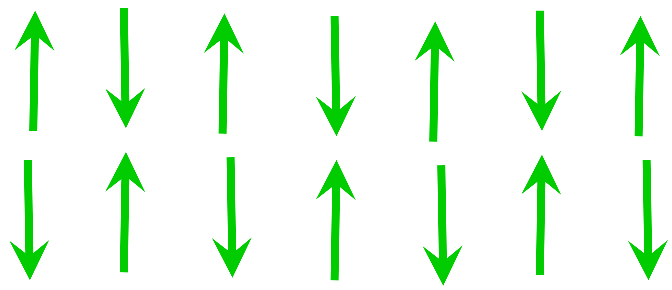
After twenty years of work we still do not understand the fermionic Hubbard model

Positive U Hubbard model

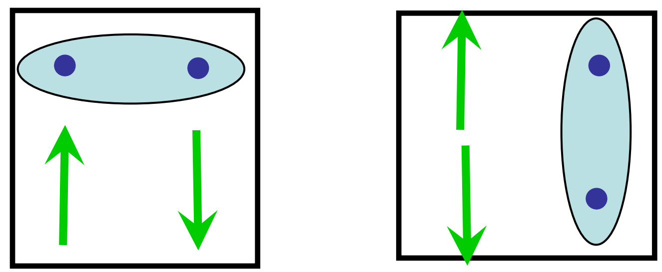
Possible phase diagram. Scalapino, Phys. Rep. 250:329 (1995)



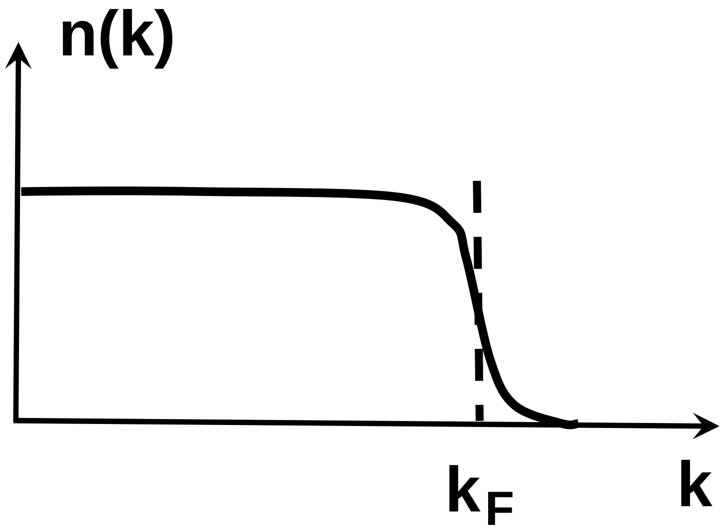
Antiferromagnetic insulator

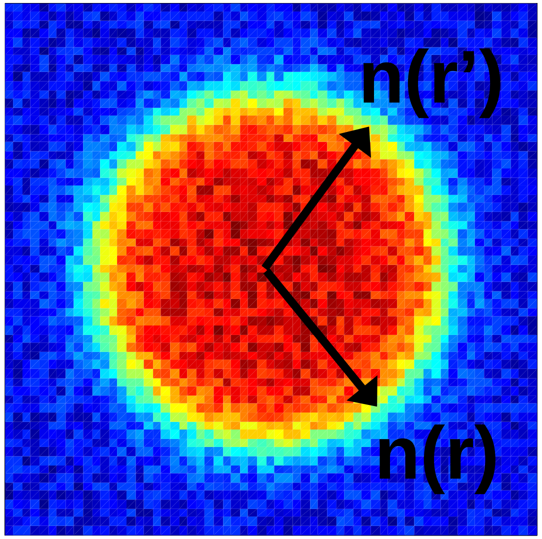


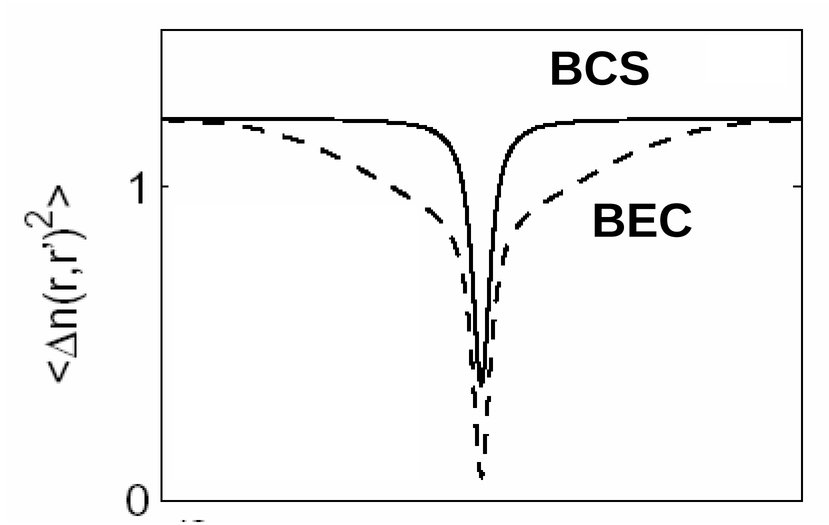
D-wave superconductor



Second order interference from a BCS superfluid





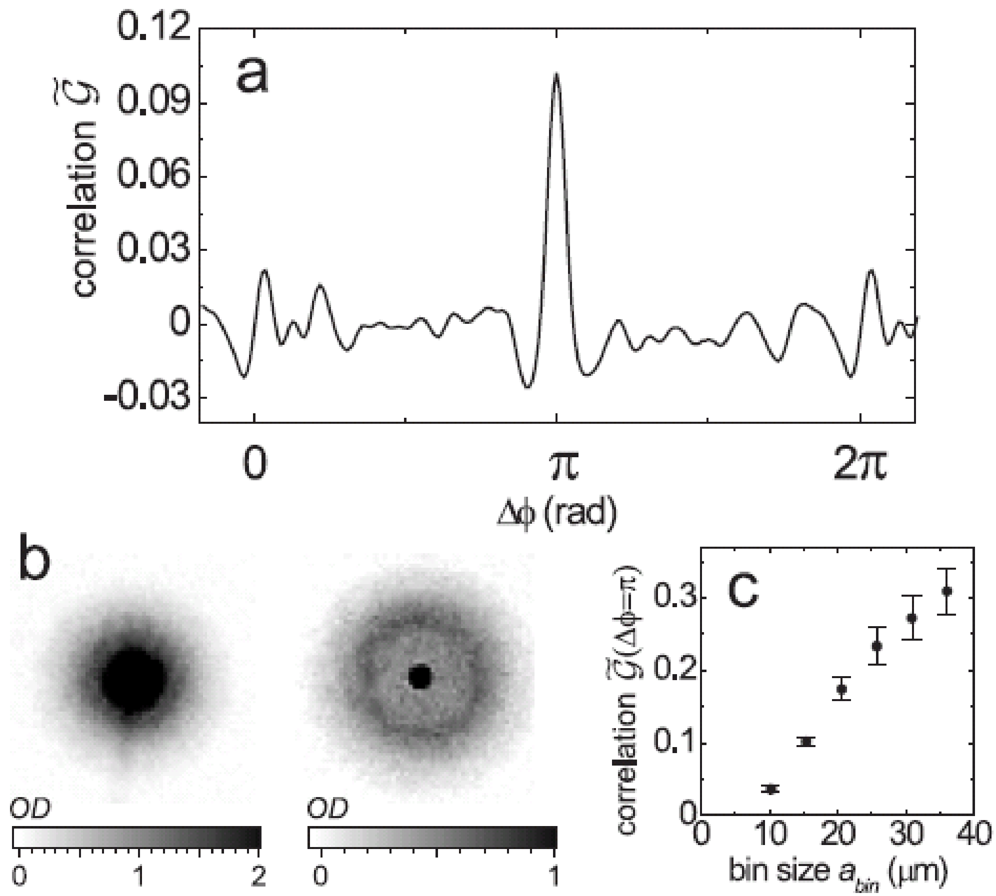


$$\Delta n(\mathbf{r},\mathbf{r}') \equiv n(\mathbf{r}) - n(\mathbf{r}')$$

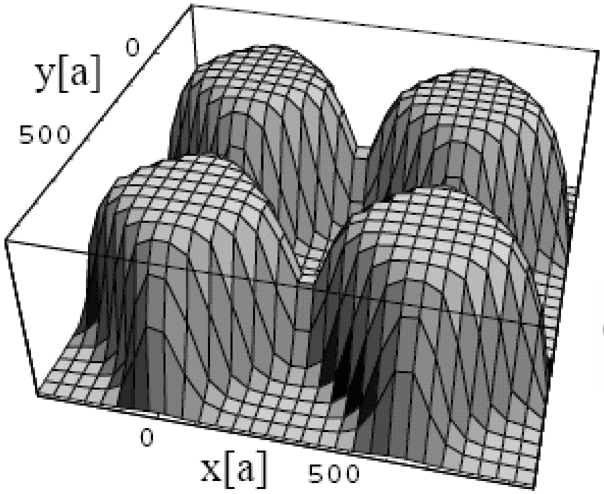
$$\Delta n(\mathbf{r},-\mathbf{r}) \left| \Psi_{BCS} \right\rangle = 0$$

Momentum correlations in paired fermions

Theory: Altman et al., PRA 70:13603 (2004)
Experiment: Greiner et al., PRL 94:110401 (2005)



Fermion pairing in an optical lattice



Second Order Interference
In the TOF images

$$G(r_1, r_2) = \langle n(r_1) n(r_2) \rangle - \langle n(r_1) \rangle \langle n(r_2) \rangle$$

Normal State

$$G_{\mathrm{N}}(r_1, r_2) = \delta(r_1 - r_2)\rho(r_1) - \rho^2(r_1) \sum_G \delta(r_1 - r_2 - \frac{G\hbar t}{m})$$

Superfluid State

$$G_{\mathrm{S}}(r_1, r_2) = G_{\mathrm{N}}(r_1, r_2) + \Psi(r_1) \sum_G \delta(r_1 + r_2 + \frac{G\hbar t}{m})$$

$\Psi(r) = |u(Q(r))v(Q(r))|^2$ **measures the Cooper pair wavefunction**

$$Q(r) = \frac{mr}{\hbar t}$$

One can identify unconventional pairing

Conclusions

We understand well: electron systems in semiconductors and simple metals. Interaction energy is smaller than the kinetic energy. Perturbation theory works

We do not understand: strongly correlated electron systems in novel materials. Interaction energy is comparable or larger than the kinetic energy. Many surprising new phenomena occur, including high temperature superconductivity, magnetism, fractionalization of excitations

Ultracold atoms have energy scales of 10^{-6}K, compared to 10^{4} K for electron systems. However, by engineering and studying strongly interacting systems of cold atoms we should get insights into the mysterious properties of novel quantum materials

Our big goal is to develop a general framework for understanding strongly correlated systems. This will be important far beyond AMO and condensed matter

Developing new detection methods is an important problem in the area of strongly correlated atoms. Interference experiments and analysis of quantum noise in time of flight experiments are powerful tools for analyzing many-body states