Scattering of atoms in collision of quasi - condensates

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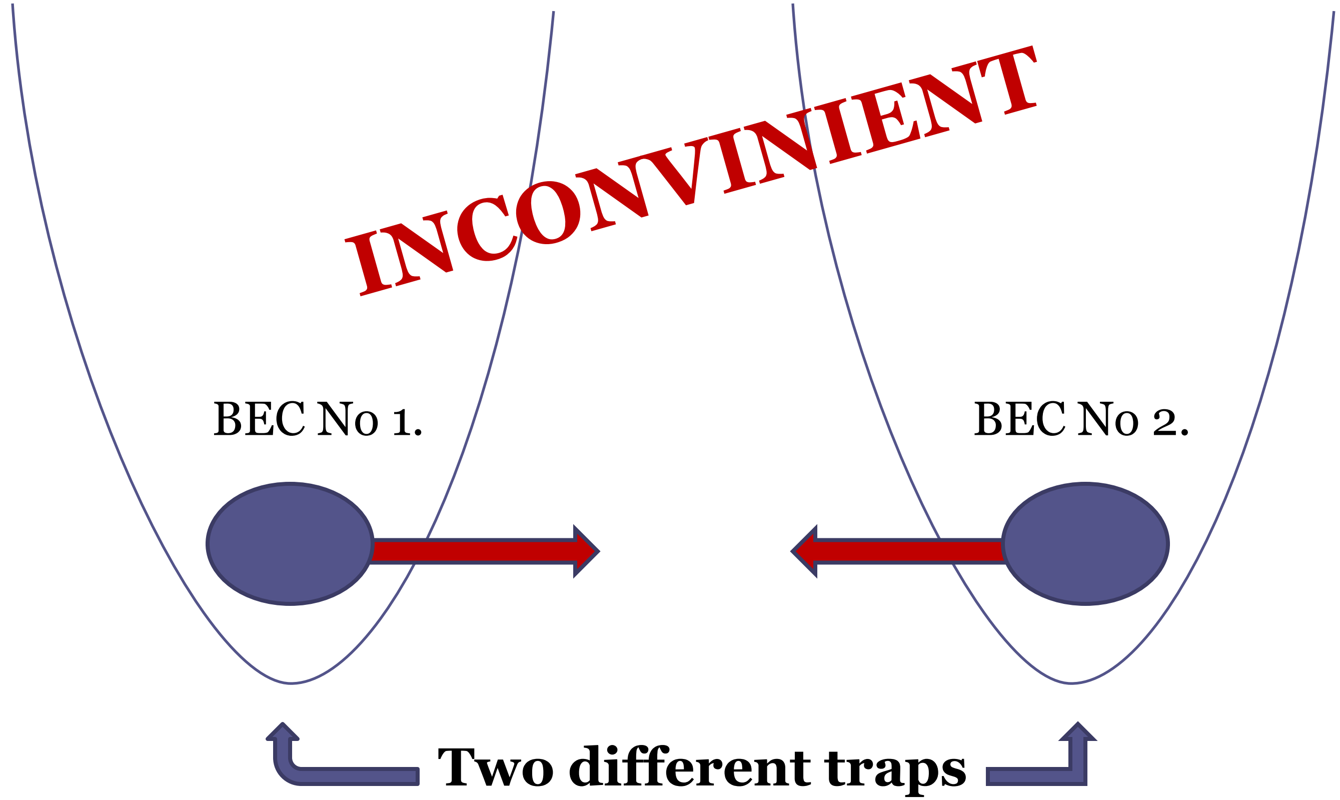
Plan of the talk

- ***Collision of two Bose-Einstein Condensates***
  Experimental realization
- ***Theoretical description - model***
  Dynamical Bogoliubov theory
- ***Phase fluctuations***
  Important feature of elongated condensates
- ***BEC vs. quasi-BEC correlations***
- ***Summary***

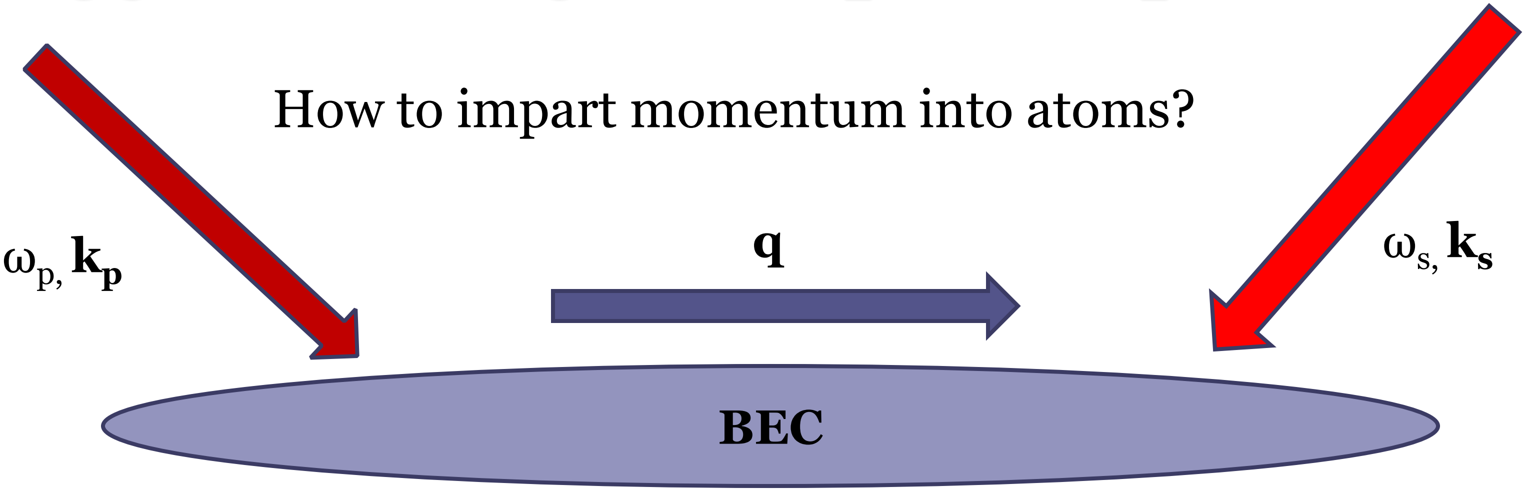
Collision of two Bose-Einstein Condensates

How to collide two ultracold atomic clouds?



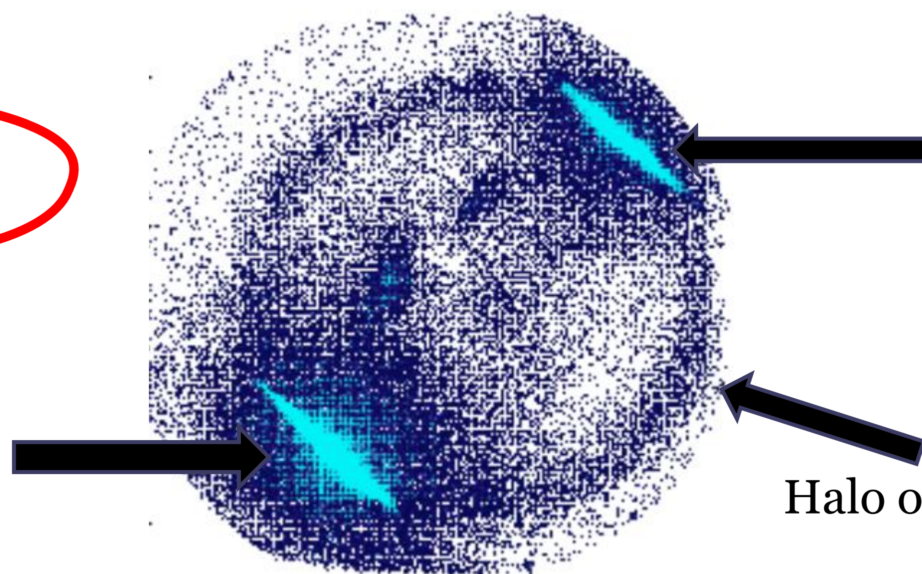
Bragg Scattering – two photon process

How to impart momentum into atoms?



Single atom gains momentum $\mathbf{q}$.

HALF-COLLISION

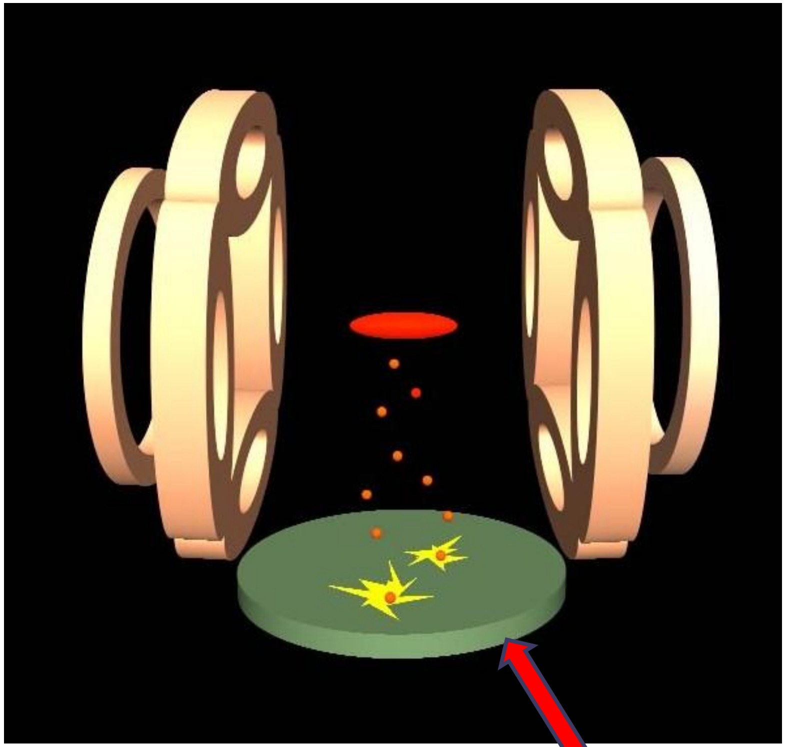


arXiv:quant-ph/0609019v1

Experiments with metastable helium atoms

Group in France: Denis Boiron, Chris Westbrook, Alain Aspect

Possibility of measuring correlations between scattered atoms.



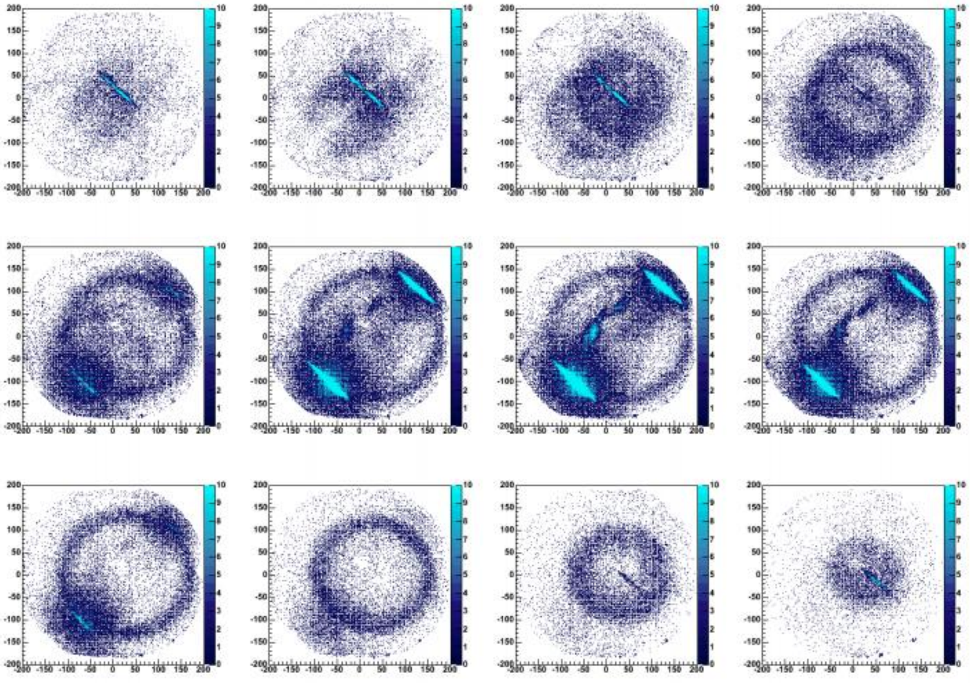


FIGURE 2. Images of the collision of two condensates. Each frame represents successive slices of the atomic cloud as it passes the plane of the detector. The two colliding condensates and the s-wave collision sphere are clearly visible.

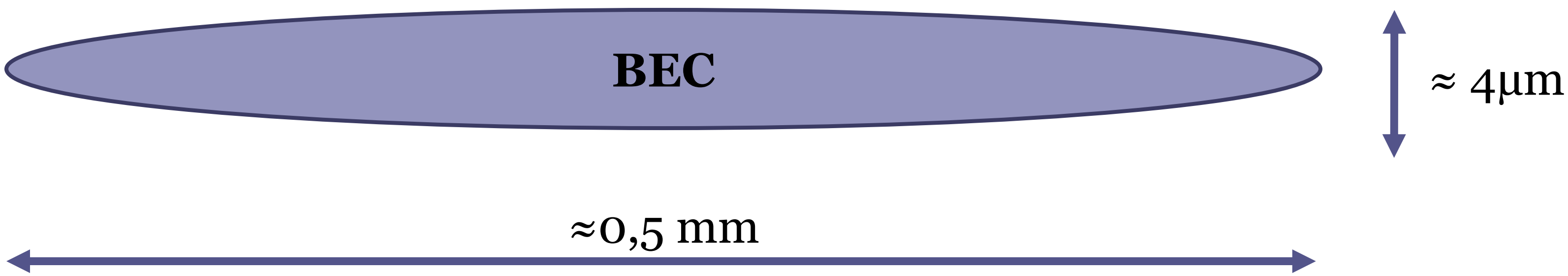
Detector: microchannel plate

C.I. Westbrook *et al.*, *Producing and Detecting Correlated Atoms*, arXiv:quant-ph/0609019v1

Experiments with metastable helium atoms

BEC in experimental situation:

cylindrical symmetry



In simulations:
Imaginary time method - BEC ground state in trap obtained from GP equation.

Theoretical description

- ***Hamiltionan of the many-body system***

$$\hat{H} = \int d\mathbf{r}\ \hat{\Psi}^\dagger(\mathbf{r}) \left(-\frac{\hbar^2 \Delta}{2m} + V(\mathbf{r}) \right) \hat{\Psi}(\mathbf{r}) + \frac{g}{2} \int d\mathbf{r}\ \hat{\Psi}^\dagger(\mathbf{r}) \hat{\Psi}^\dagger(\mathbf{r}) \hat{\Psi}(\mathbf{r}) \hat{\Psi}(\mathbf{r})$$

- ***Bogoliubov approximation of field operator***

$$\hat{\Psi}(\mathbf{r}) = \psi(\mathbf{r}) + \hat{\delta}(\mathbf{r})$$

$$\psi(\mathbf{r}) = \psi_{+Q}(\mathbf{r}) + \psi_{-Q}(\mathbf{r})$$

BEC wavefunction

describes atoms out of the condensate

Dynamical equations

- ***Gross-Pitaevskii equation:***

$$i\hbar\partial_t\psi = \left(-\frac{\hbar^2\Delta}{2m} + g|\psi|^2\right)\psi$$

- ***Linear equation for field of scattered atoms:***

$$i\hbar\partial_t\hat{\delta}(\mathbf{r},t) = H_0(\mathbf{r},t)\hat{\delta}(\mathbf{r},t) + B(\mathbf{r},t)\hat{\delta}^\dagger(\mathbf{r},t)$$

source term

$$H_0(\mathbf{r},t) \;=\; -\frac{\hbar^2}{2m}\triangle + 2g|\psi(\mathbf{r},t)|^2$$

$$B(\mathbf{r},t) \approx 2g\psi_Q(\mathbf{r},t)\psi_{-Q}(\mathbf{r},t)$$

Description of halo

- ***First order correlation function***

$$G^{(1)}(\mathbf{k}_1,\mathbf{k}_2,t)=\langle\hat{\delta}^\dagger(\mathbf{k}_1,t)\hat{\delta}(\mathbf{k}_2,t)\rangle$$

- ***Second order correlation function***

$$G^{(2)}(\mathbf{k}_1,\mathbf{k}_2,t)=\langle\hat{\delta}^\dagger(\mathbf{k}_1,t)\hat{\delta}^\dagger(\mathbf{k}_2,t)\hat{\delta}(\mathbf{k}_2,t)\hat{\delta}(\mathbf{k}_1,t)\rangle$$

Local correlations

Back-to-back correlations

Approximations

- ***Neglect mean field effects in all equations:***

$$\cancel{g|\psi|^2}$$

- ***Number of scattered atoms is small – expand field operator in perturbation series:***

$$\hat{\delta} = \boxed{\hat{\delta}^{(0)}} + \boxed{\hat{\delta}^{(1)}} + \ldots$$

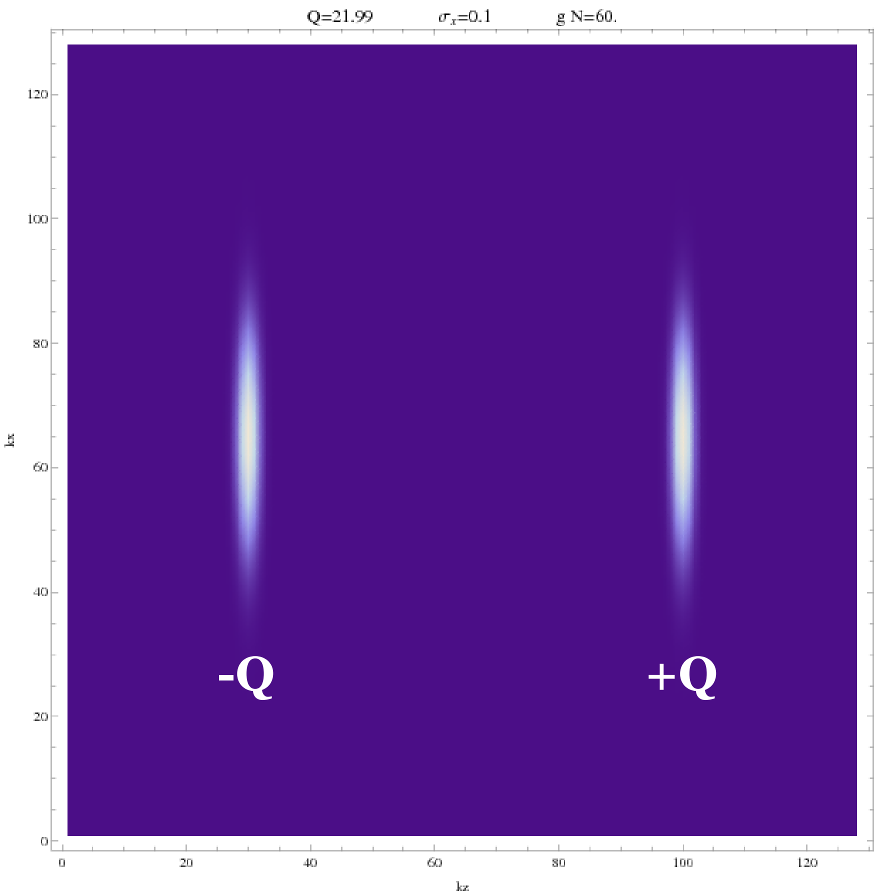
Propagate without
the source term.

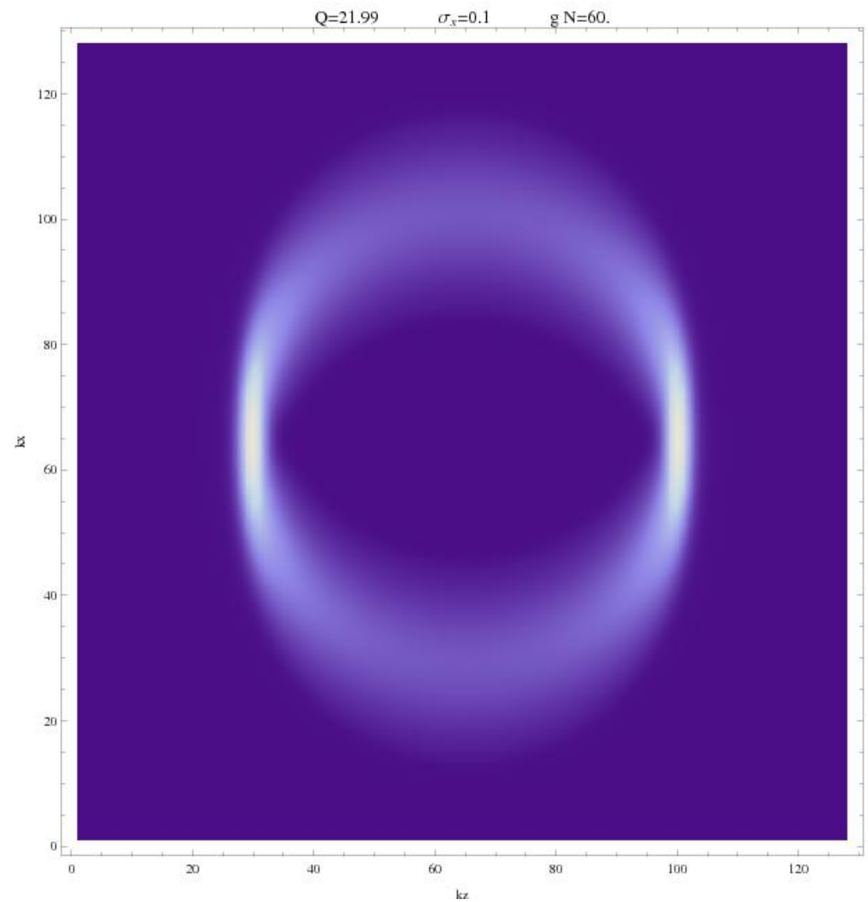
Propagate.
Atoms are produced by zeroth-term.

Resutls

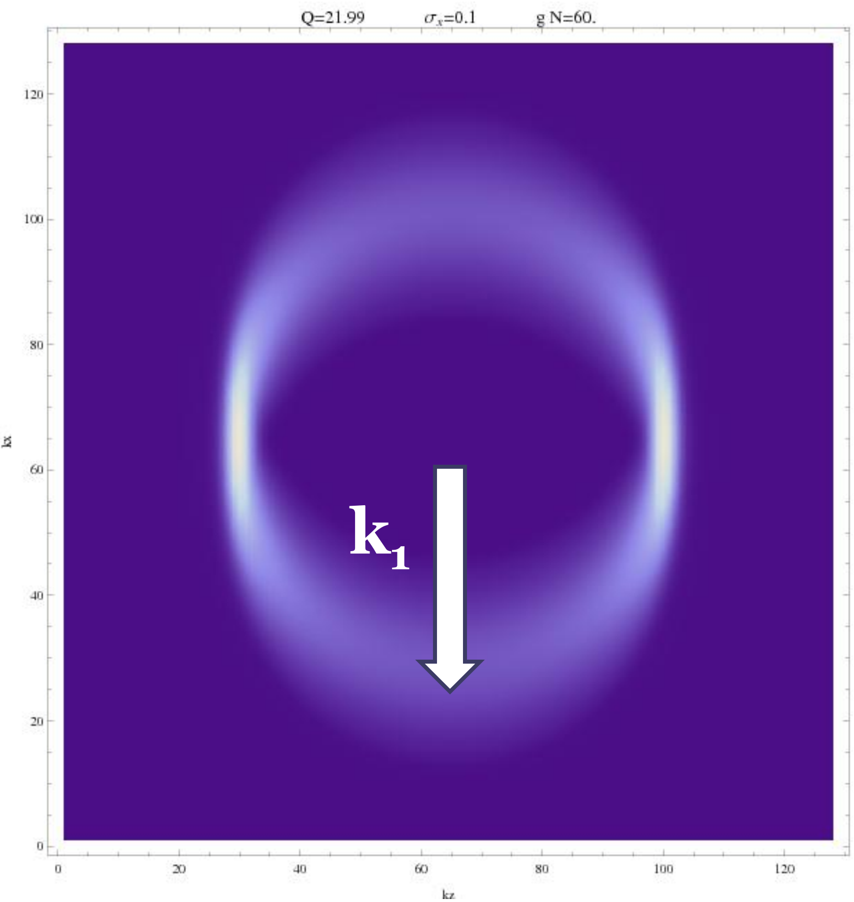
Two BECs
in wavevector space **k**.

Density of scattered atoms
in wavevector space **k**.

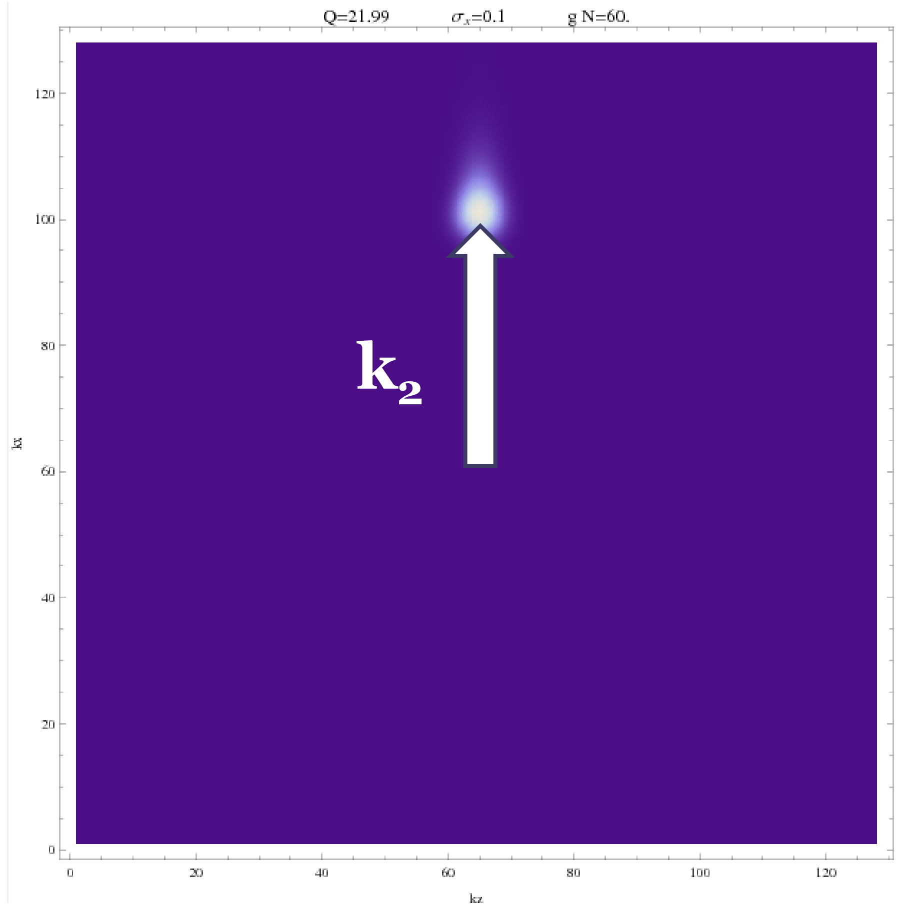




Back-to-back correlations

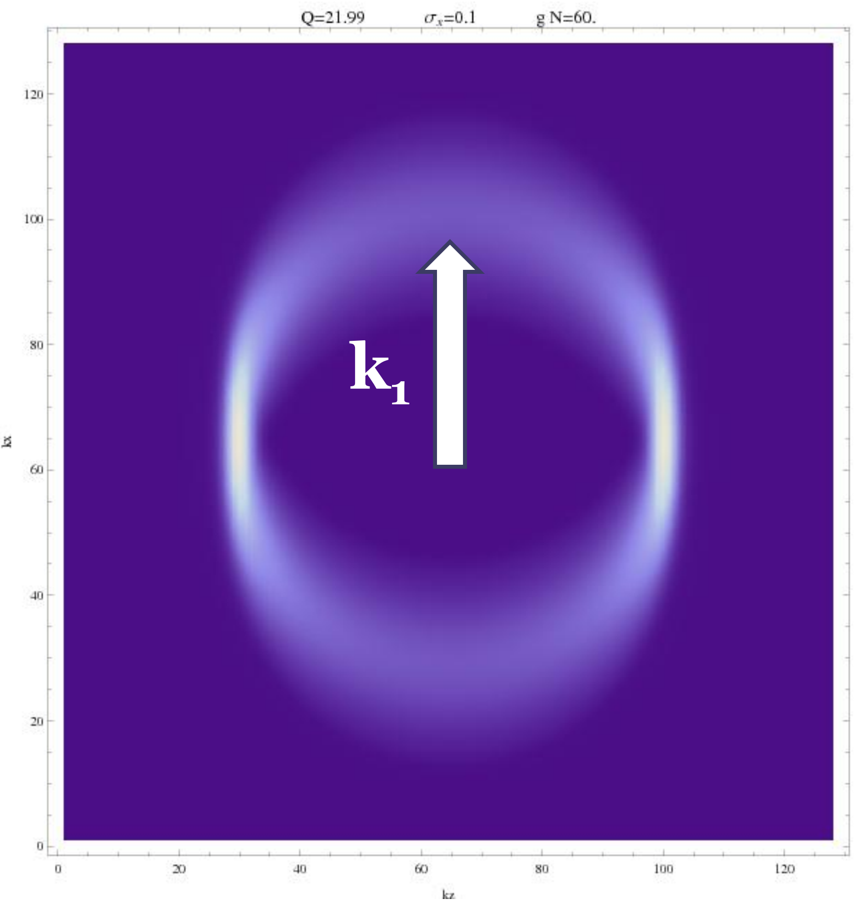


Nonvanishing
if $\mathbf{k_2}$ ~ - $\mathbf{k_1}$ and if $|\mathbf{k_2}|$ ~ $|\mathbf{k_1}|$~Q

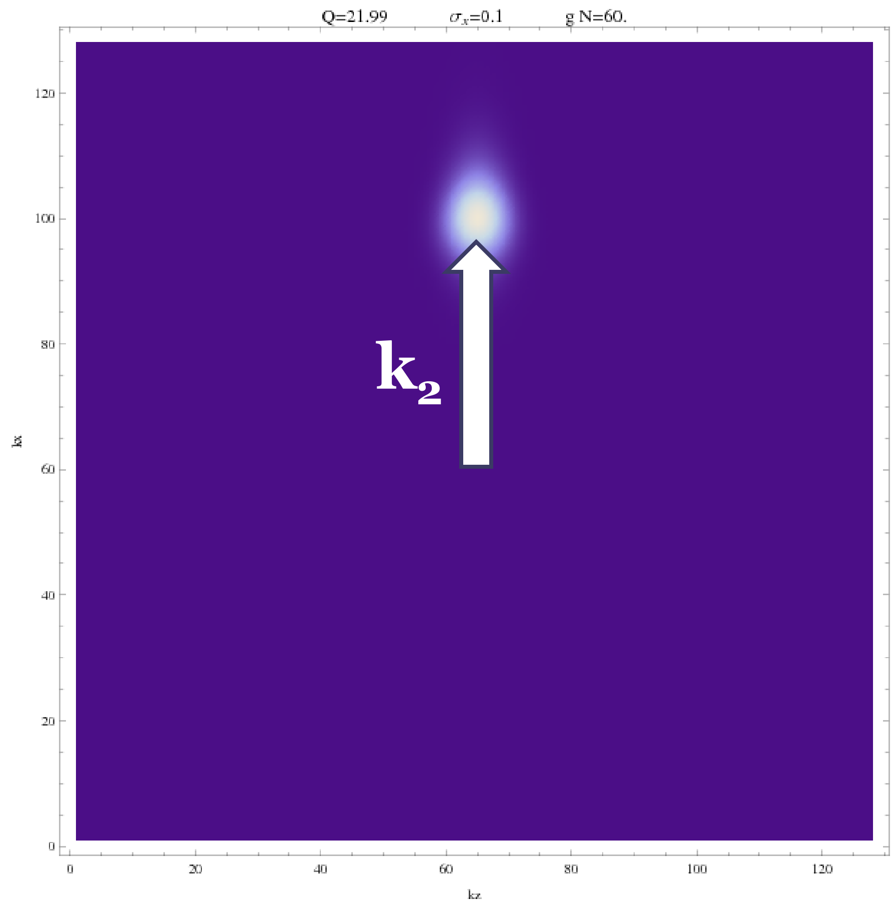


What are possible $\mathbf{k_2}$ vectors when $\mathbf{k_1}$ is fixed and set $\mathbf{k_1}$=-Q $\mathbf{e_x}$?

Local correlations



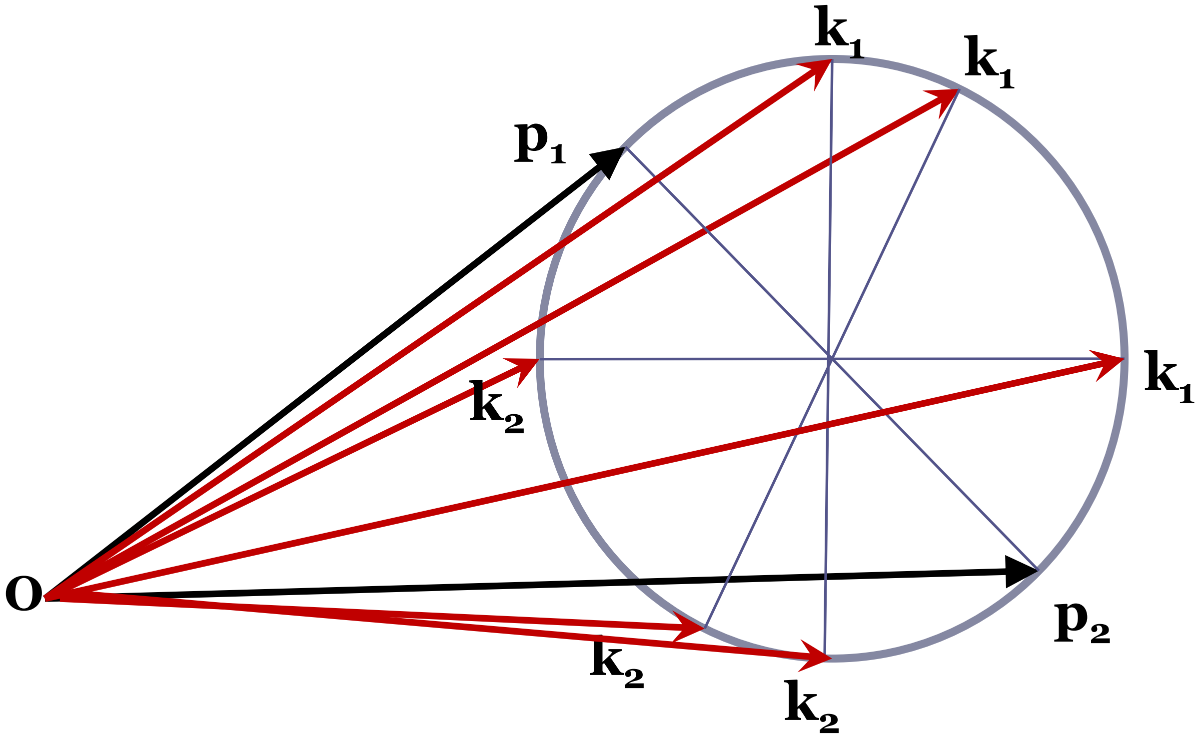
Nonvanishing
if $\mathbf{k_2} \sim + \mathbf{k_1}$ and if $|\mathbf{k_2}| \sim |\mathbf{k_1}| \sim Q$



What are possible $\mathbf{k_2}$ vectors when $\mathbf{k_1}$ is fixed and set $\mathbf{k_1}$=+Q $\mathbf{e_x}$?

Physical intuition

- ***How can one <u>understand</u> the results?*** *Every occupied mode in momentum space is a result of an elementary collision between two particles from the condensate:*

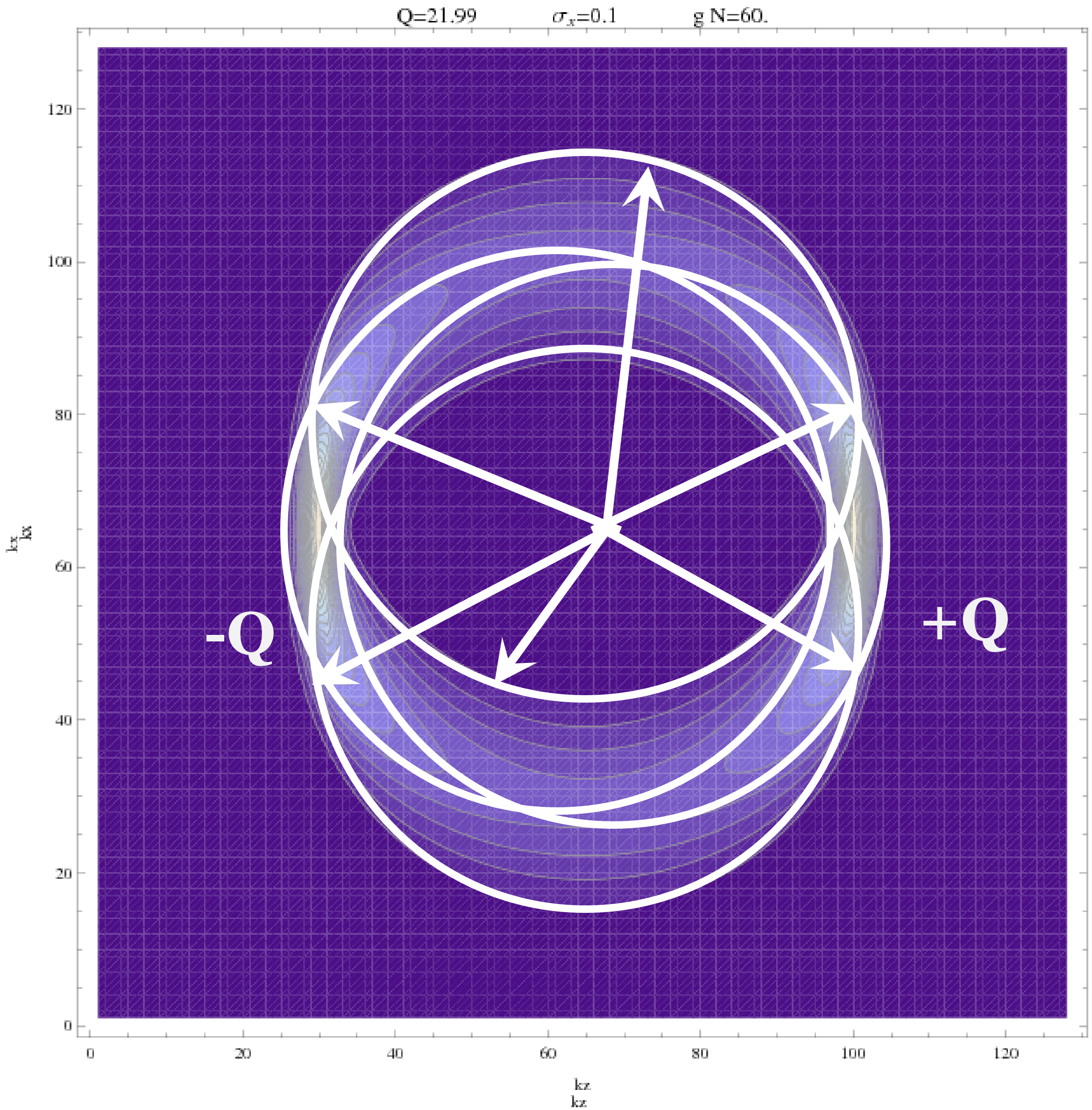


Conservation laws:

$$\mathbf{p}_1 + \mathbf{p}_2 = \mathbf{k}_1 + \mathbf{k}_2$$

$$\mathbf{p}_1^2 + \mathbf{p}_2^2 = \mathbf{k}_1^2 + \mathbf{k}_2^2$$

Halo of scattered atoms



Phase Fluctuations

If one of the dimension of BEC is much larger than others
(in experimental case aspect ratio is 125) the **phase fluctuates**.

How to describe phase fluctuations? Start with field operator:

$$\hat{\psi}(\mathbf{r}) = \sqrt{n(\mathbf{r})}\,\exp[i\hat{\phi}(\mathbf{r})]$$

Density of BEC from Gross-Pitaevskii eqn.

Phase operator

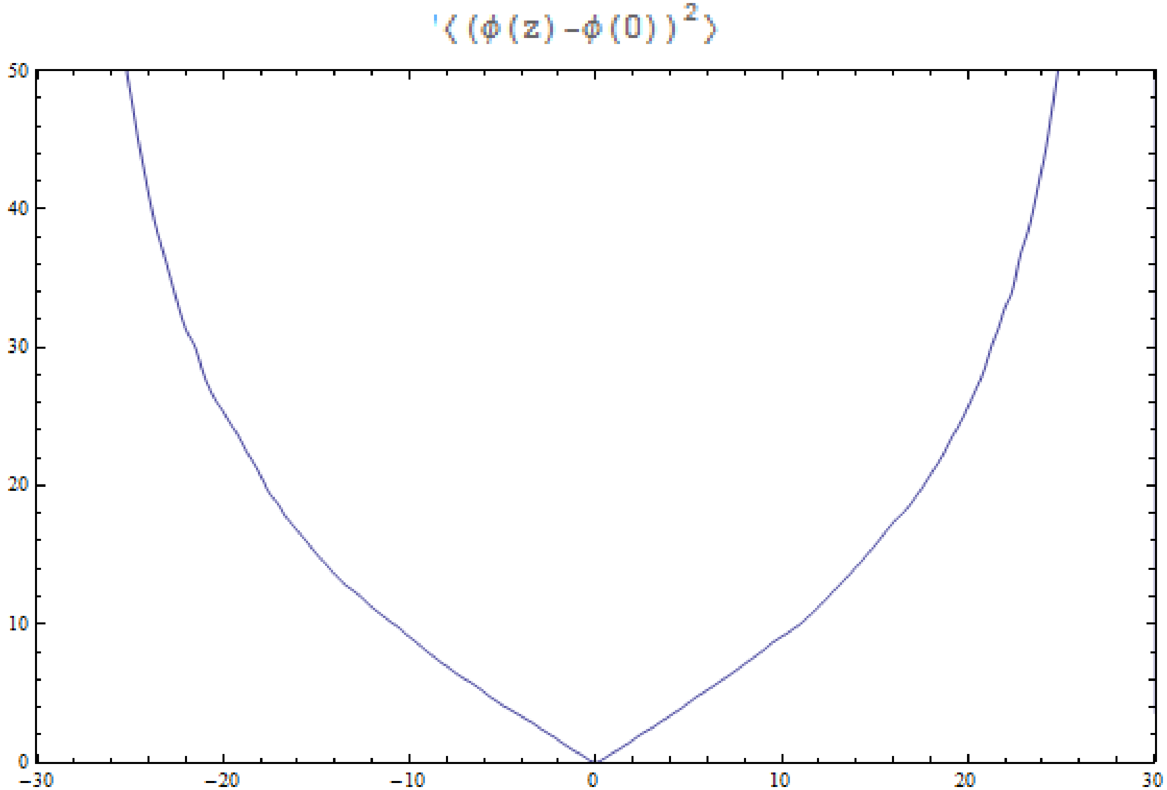
Describes fluctuations of the phase of the BEC.

Depends only on **z** coordinate.

Condensate with fluctuating phase $=$ Quasi-condensate

Phase Fluctuations

Fluctuations of BEC **phase**

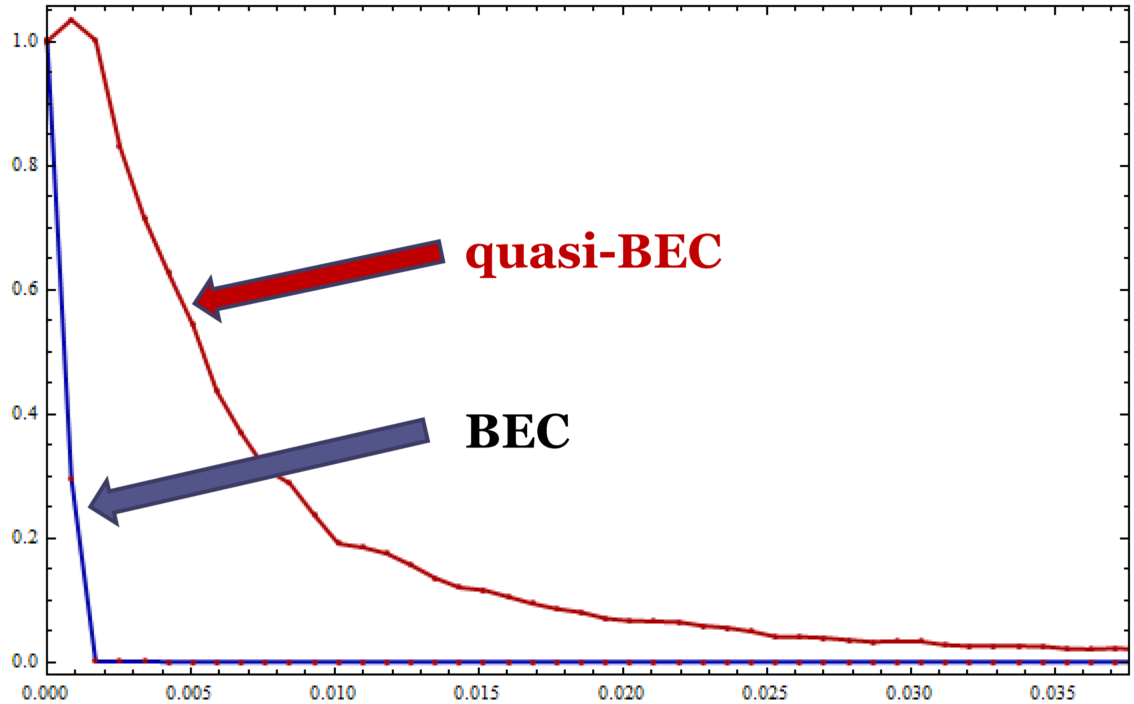


T = 960 nK

z/a$_{ho,z}$

Phase Fluctuations

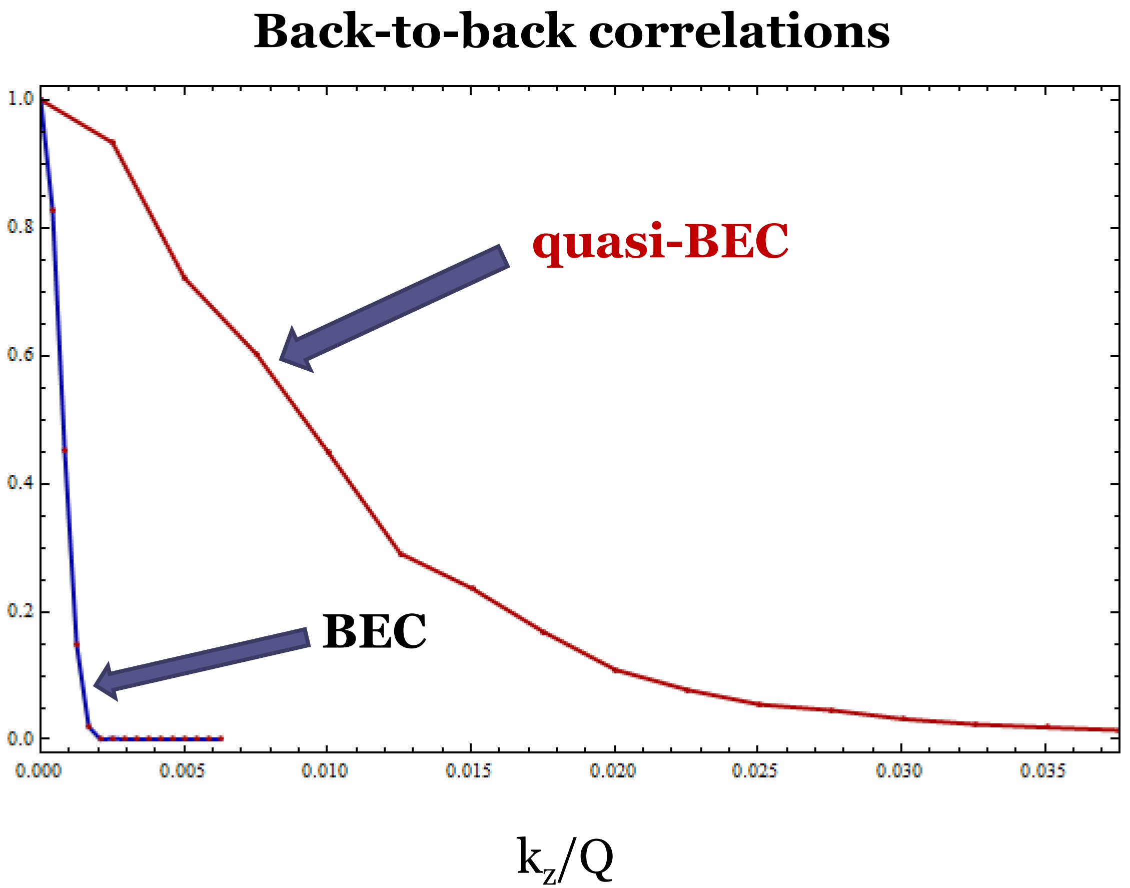
Mean momentum distribution



k_z/Q

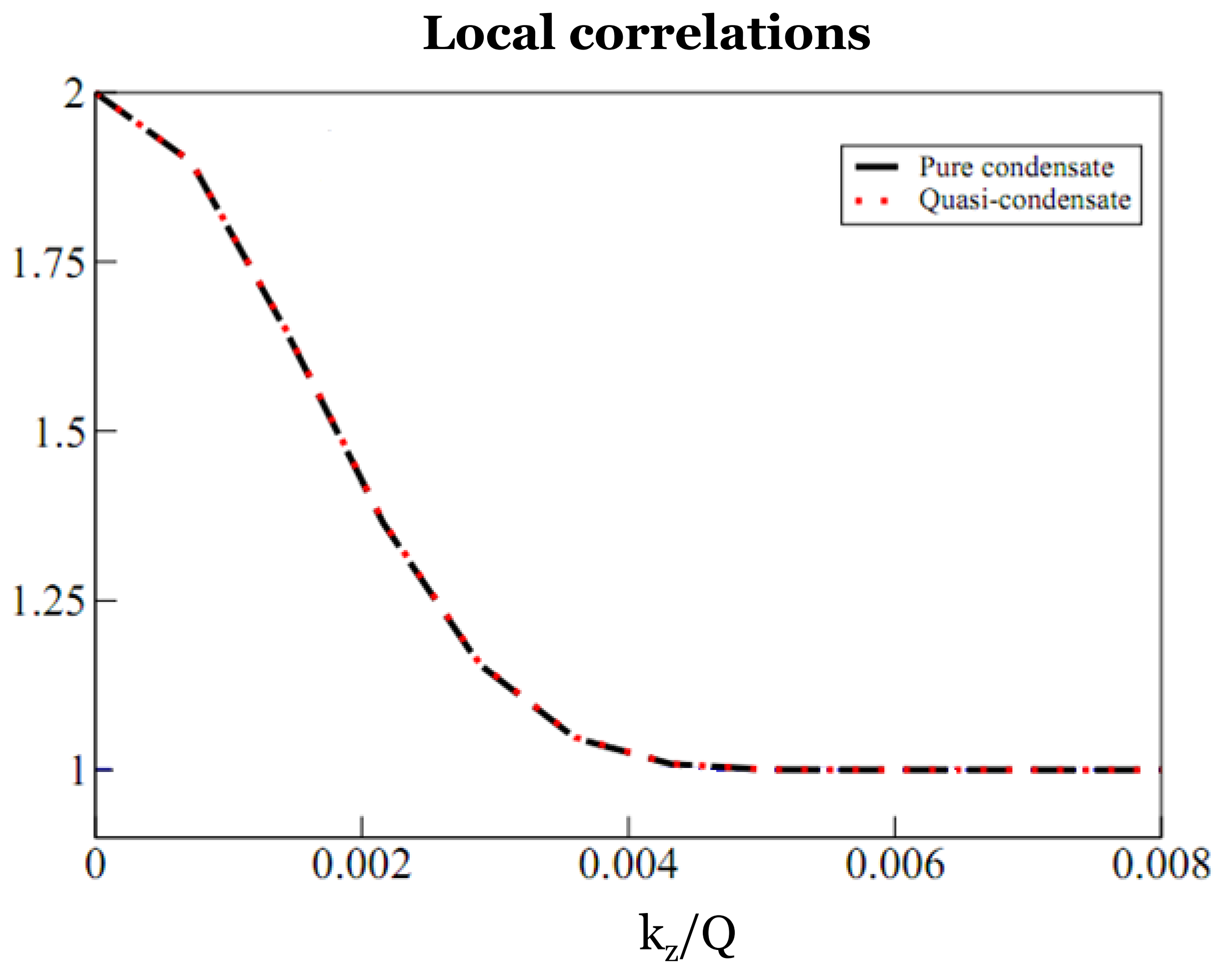
T = 960 nK

BEC vs. quasi-BEC correlations



T = 960 nK

BEC vs. quasi-BEC correlations



T = 960 nK

Research goals

- Estimation of the quasi-BEC temperature.

- Experiment not in far field.

- Second method of temperature estimation – Raman process.

- What is *classical* and what is *quantum* in the collision?

Work in progress . . . .

Summary

- **Halo of scattered atoms** - due to the collision some of the atoms are scattered away.
- **Model of the collision** - we introduced approximate model to describe the properties of the halo.
- **Correlations** – within the model correlation functions are calculated.
- **Energy and momentum conservation** are important in describing the properties of halo.
- **Phase fluctuations** of BEC must be taken into account in elongated configurations.

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Thank you