Quantum quenches of dilute Bose gases in 1D, 2D, 3D, at zero and finite temperatures

T. Świsłocki, M. Stobińska, P. Deuar

Institute of Physics, Polish Academy of Sciences, Warsaw, Poland

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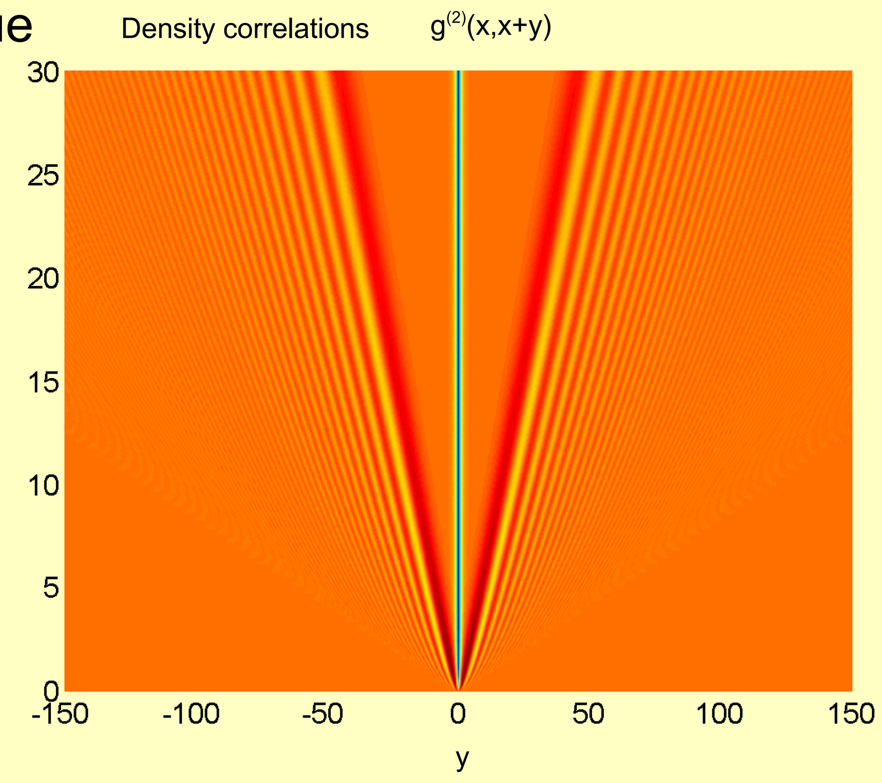
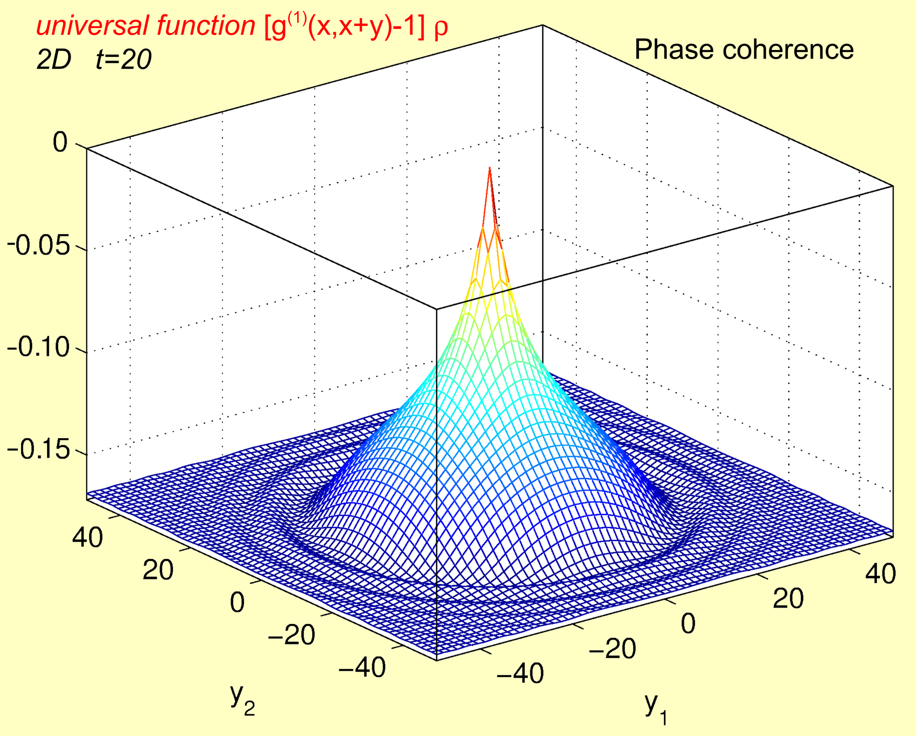
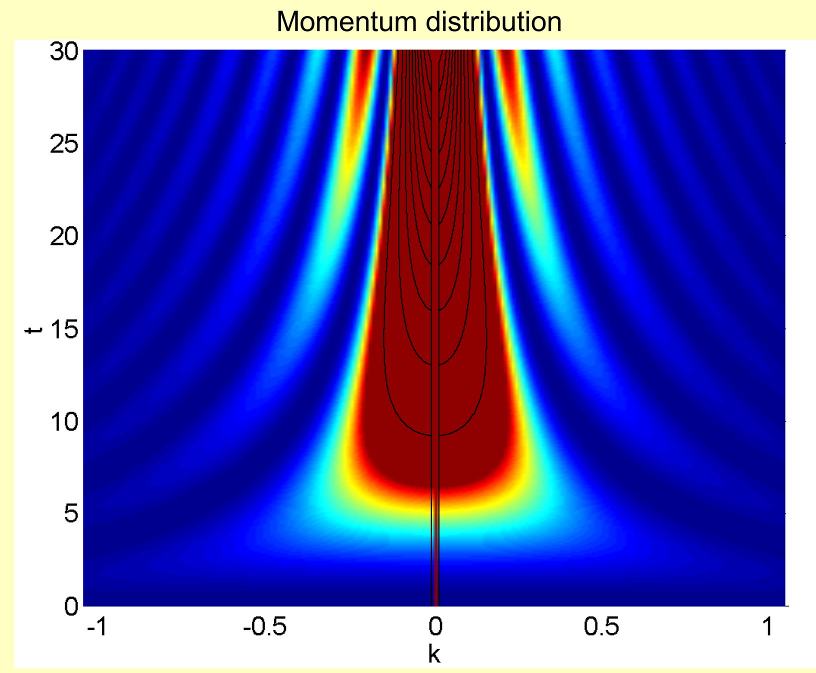
- Initially g=0, $\gamma \lesssim 1$
  (coherent ground state at T=0)
- At $t > 0$, we quench g to a positive value
- A prototype of various phenomena:
  - *turning on a Feshbach resonance*
  - *changes of the transverse trapping*
- One essential parameter: $\rho = \frac{1}{\sqrt{2\gamma}}$
  (= density per healing length ξ)
- *Physically relevant units:*
  $\hbar = 1, \quad m = 1, \quad \xi = \hbar/\sqrt{2mng} = 1.$
- *Treat with number-conserving Bogoliubov method as per*
  Y. Castin, R. Dum, Phys. Rev. A 57, 3008 (1998)

Quantum quench of interaction g in a uniform gas at T=0







$$g^{(1)}(x,x+y) = \frac{\langle \widehat{\Psi}^\dagger(x)\widehat{\Psi}(x+y)\rangle}{N} = 1 - \frac{1}{8N}\sum_{k\neq 0}\frac{1}{\omega_k^2}\left[1-\cos 2\omega_k t - \cos ky + \cos(ky+2\omega_k t)\right]$$

$$\omega_k = \sqrt{\frac{k^2}{2}\left(\frac{k^2}{2}+1\right)}$$

$$g^{(2)}(x,x+y) = 1 - \frac{1}{4N}\sum_{k\neq 0}\frac{k^2}{\omega_k^2}\left[\cos ky - \cos(ky+2\omega_k t)\right]$$

continuum:

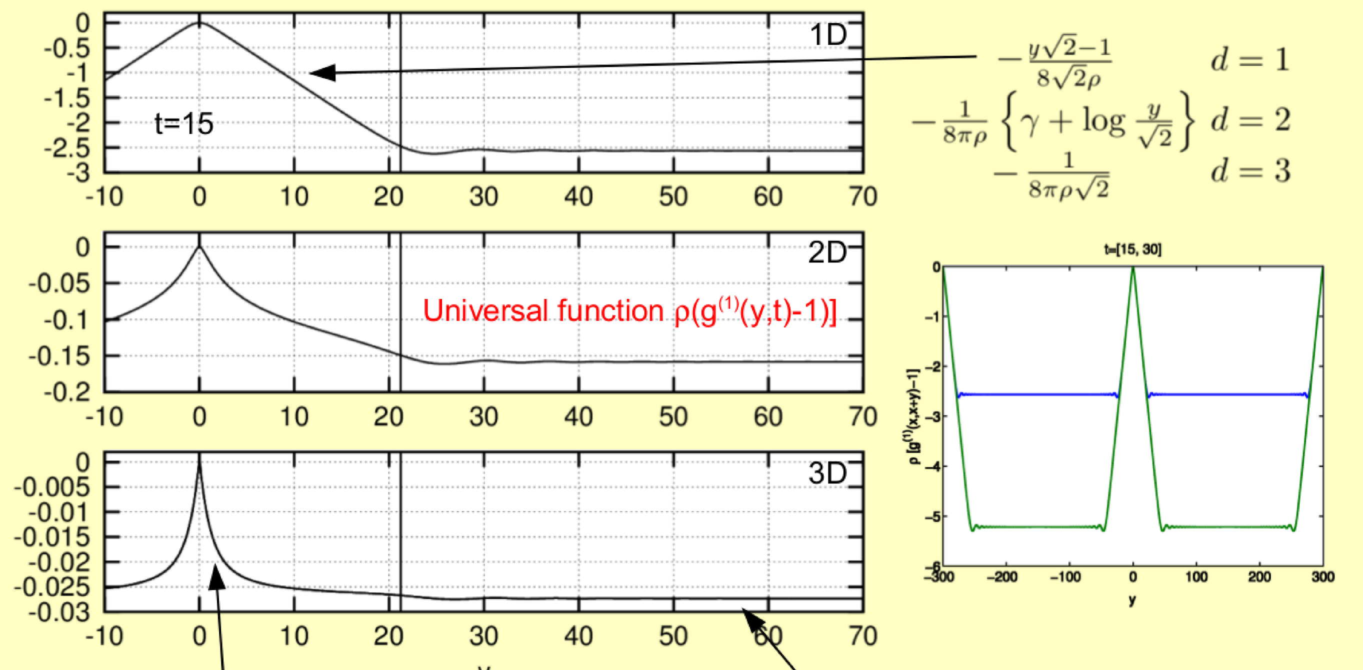
$$g^{(1)}(0,y)(t) = 1 - \frac{1}{\rho}\int_0^{k_{\max}} dk\,\left(\frac{1-\cos 2\omega_k t}{2+k^2}\right)\begin{cases}\frac{1}{2\pi k^2}\,(1-\cos ky) & \text{1D}\\ \frac{1}{4\pi k}\,(1-J_0[k|y|]) & \text{2D}\\ \frac{1}{4\pi^2}\left(1-\frac{\sin ky}{ky}\right) & \text{3D}\end{cases}$$

$$\rho_k = \langle \widehat{\Psi}_k^\dagger \widehat{\Psi}_k\rangle = \frac{1}{4\Delta k}\left(\frac{\sin\omega_k t}{\omega_k}\right)^2 \quad \forall k\neq 0$$

continuum:

$$g^{(2)}(0,y)(t) = 1 - \frac{1}{\rho}\int_0^{k_{\max}} dk\,\left(\frac{1-\cos 2\omega_k t}{2+k^2}\right)\begin{cases}\frac{1}{\pi}\cos ky & \text{1D}\\ \frac{k}{2\pi}\,J_0[k|y|] & \text{2D}\\ \frac{k^2}{2\pi^2}\,\frac{\sin ky}{ky} & \text{3D}\end{cases}$$

Phase coherence



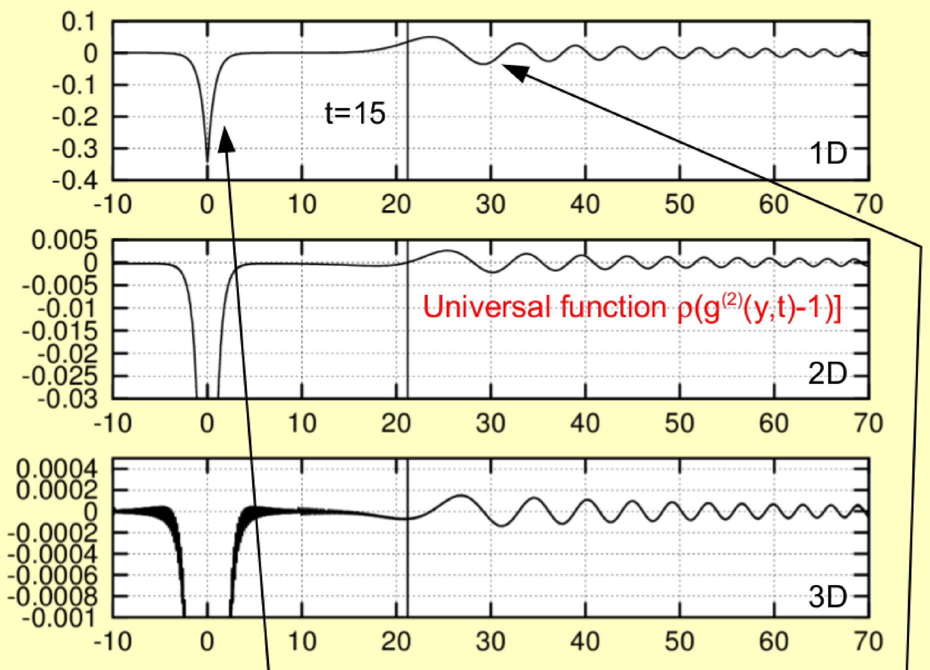
$$\begin{cases} -\frac{y\sqrt{2}-1}{8\sqrt{2}\rho} & d=1\\ -\frac{1}{8\pi\rho}\left\{\gamma+\log\frac{y}{\sqrt{2}}\right\} & d=2\\ -\frac{1}{8\pi\rho\sqrt{2}} & d=3\end{cases}$$

$$\begin{cases} -\frac{y^2}{8\sqrt{2}\rho} & d=1\\ -\frac{y^2}{16\pi\rho}\left\{1-\gamma-\log\frac{y}{\sqrt{2}}\right\} & d=2\\ -\frac{y}{16\pi\rho} & d=3\end{cases}$$

$$g^{(1)}(\infty,t) = 1-\Delta(t)$$

where $\Delta(\text{long } t) \approx \begin{cases} \frac{2t-1}{8\rho\sqrt{2}} & d=1\\ \frac{1}{8\pi\rho}\{c_1+\log t\} & d=2\\ \frac{1}{8\pi\rho\sqrt{2}}\left(\frac{2}{\pi}\tan^{-1}\frac{k_{\max}}{\sqrt{2}}+c_2 e^{-c_3 t}\right) & d=3\end{cases}$

Density correlations



Local antibunching $-\begin{cases} \frac{e^{-y\sqrt{2}}}{2\sqrt{2}\rho} & d=1\\ \frac{K_0[y\sqrt{2}]}{2\pi\rho} & d=2\\ \frac{e^{-y\sqrt{2}}}{4\pi\rho y} & d=3\end{cases}$

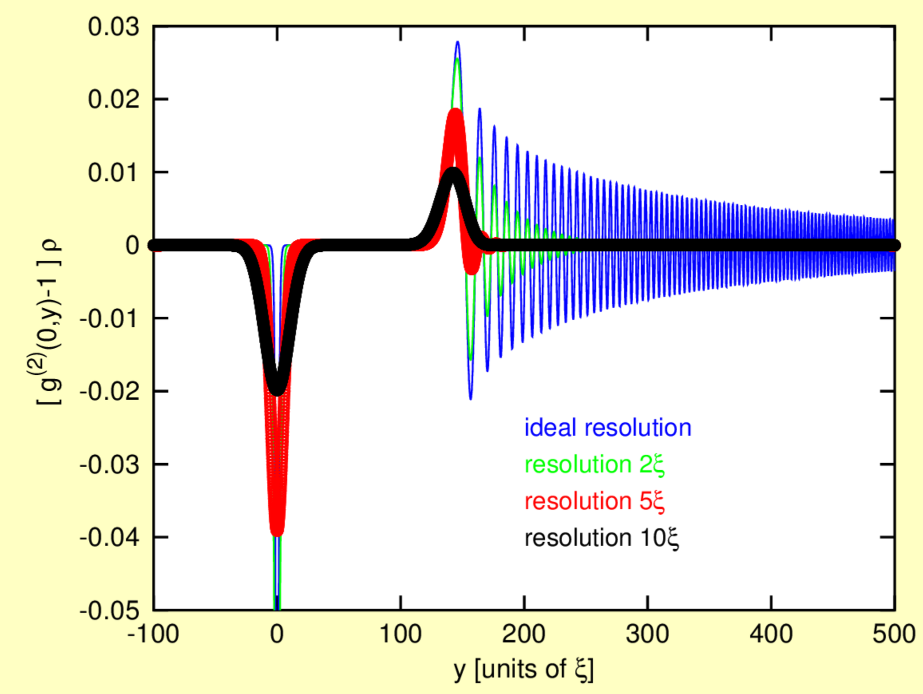
$$\begin{cases} -\frac{1}{\rho\sqrt{8}(3t)^{1/3}}\mathrm{Ai}[x] & d=1\\ \frac{2^{1/4}}{4\sqrt{\pi y}(3t)^{1/2}}F_2[x] & d=2\\ \frac{1}{4\pi y(3t)^{2/3}}F_3[x] & d=3\end{cases}$$

where $x = \frac{-(y-t\sqrt{2})\sqrt{2}}{(3t)^{1/3}}$

Observing density correlations

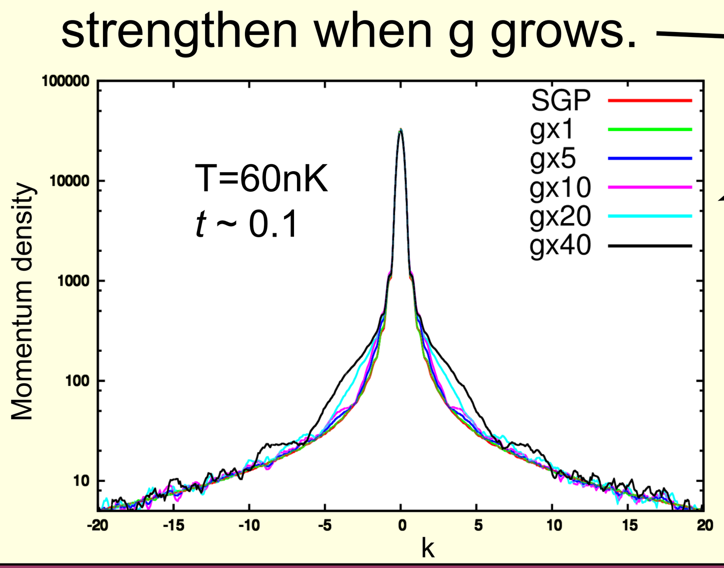
Most structures are of healing length size ξ but experiments do not resolve this.

However...

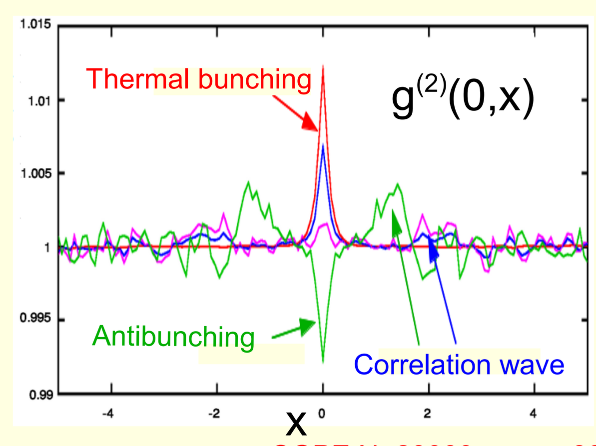


T>0 quench

- At *t=0,* start with an SGPE thermal ensemble in the quasicondensate regime.
- Evolve
  hybrid SGPE / positive-P equations
- This corresponds to turning on beyond-mean-field effects at *t>0*
- Observe:
  - quantum quench effects as above,
  - intermingled with thermal correlations
- *Additional depletion*
- *Antibunching locally,*
- *At large distances: correlation waves*
- Scaling with interaction strength
  - SGPE description is invariant when gN is kept constant
  - However, beyond-mean-field effects strengthen when g grows.

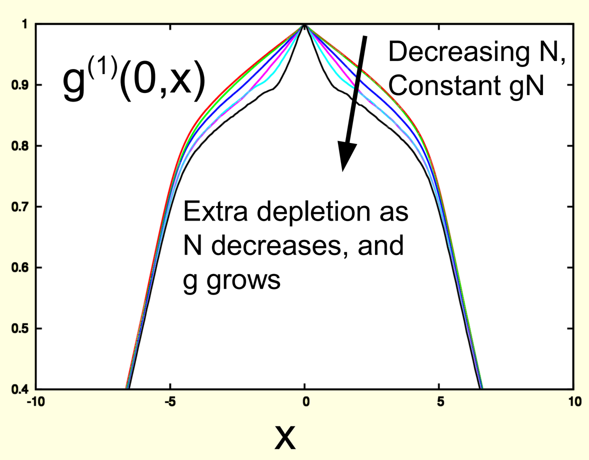


Variation with g

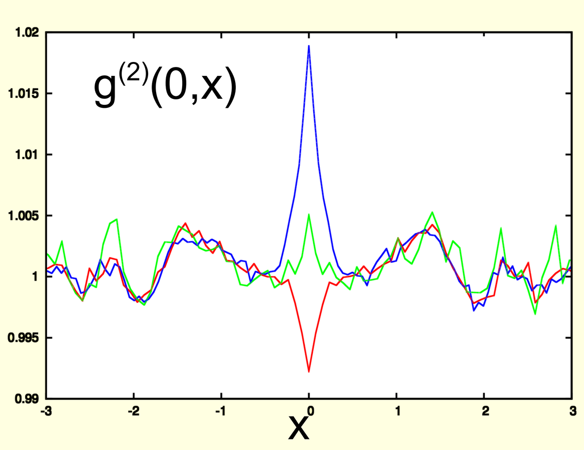


T=60nK, $t \sim 0.1$

SGPE N=20000 ω_{perp} = 32 Hz
N=4000 ω_{perp} = 71.6 Hz
N=2000 ω_{perp} = 101 Hz
N=1000 ω_{perp} = 143 Hz

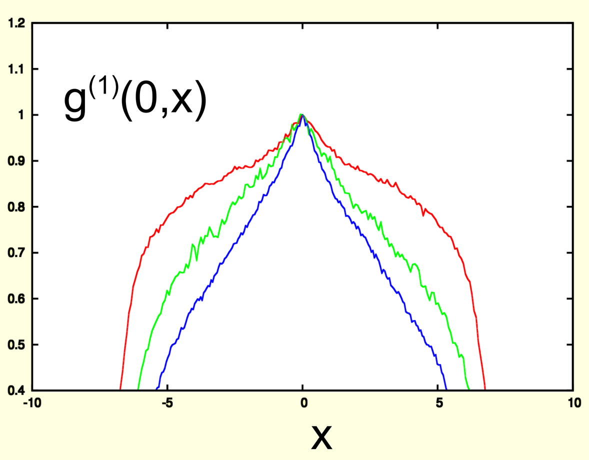


Variation with T



T= 60nK
T=120nK
T=185nK

N=1000, ω=9x143x143 Hz
t=0.12



87^{Rb}, trap units(x), μ=22.4 coupling γ=0.01 N=20000 atoms ω = 9x32x32 Hz

$$i\hbar\frac{\partial\Psi_p}{\partial t} = (1-i\gamma)\left(-\frac{\hbar^2\nabla^2}{2m}+V_{trap}-\mu+g\Psi_p\tilde{\Psi}_p^* + \sqrt{ig}\xi\right)\Psi_p + \sqrt{\gamma T}\eta,$$

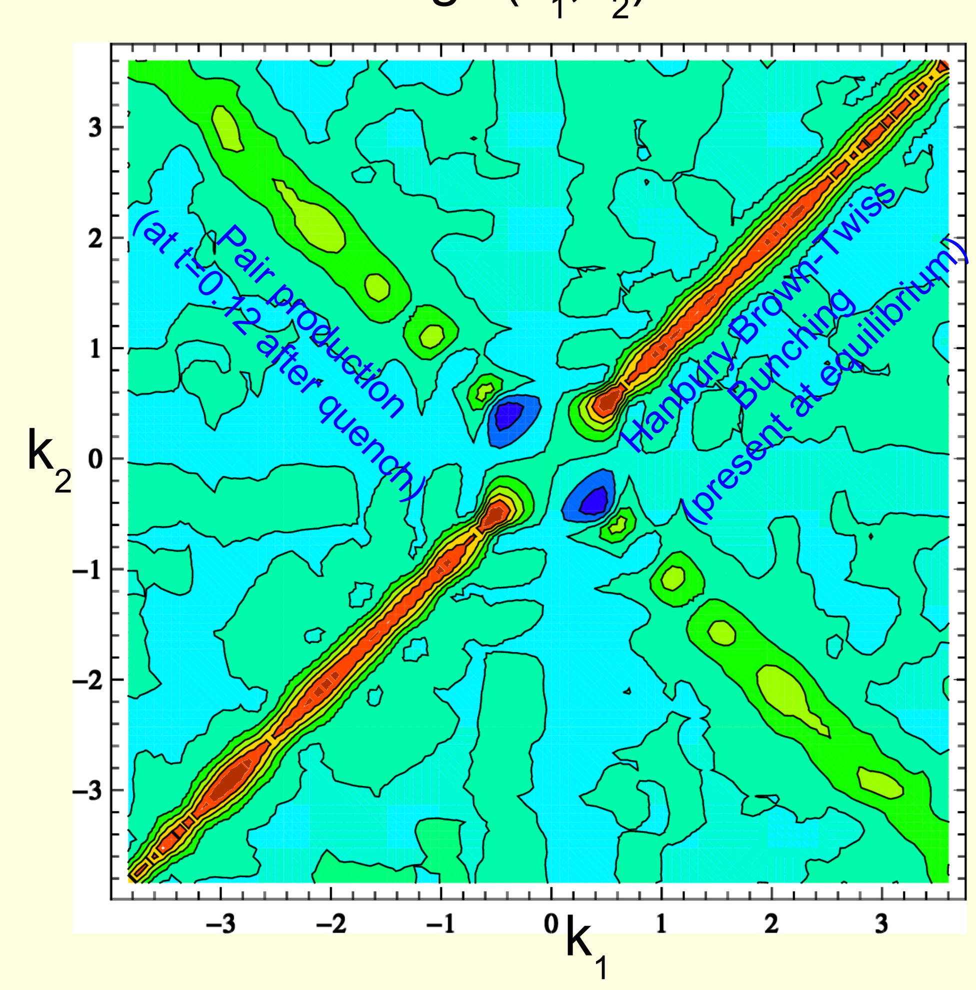
Added noise terms

$$i\hbar\frac{\partial\tilde{\Psi}_p}{\partial t} = (1-i\gamma)\left(-\frac{\hbar^2\nabla^2}{2m}+V_{trap}-\mu+g\tilde{\Psi}_p\Psi_p^* + \sqrt{ig}\xi\right)\tilde{\Psi}_p + \sqrt{\gamma T}\eta.$$

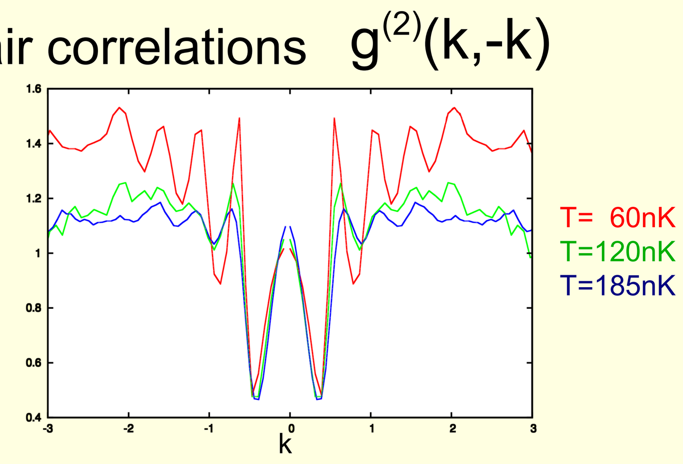
HBT and pair production

N=1000, ω=9x143x143 Hz t=0.12

$g^{(2)}(k_1,k_2)$



Pair correlations $g^{(2)}(k,-k)$



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