Quasicondensate dynamics with both classical field and quantum fluctuations included

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Abstract

We obtain a description of the dynamics of ultracold Bose gases that includes both classical and quantum fluctuations and is applicable at temperatures too high for a Bogoliubov description, e.g. quasicondensates. Such calculations have been elusive in the past because existing methods for higher temperature gases such as the Stochastic Gross-Pitaevskii (SGPE) method omit quantum field effects like pairing and quantum depletion. To overcome this, we developed a hybrid description that combines the thermal fluctuations of the SGPE with the quantum effects of the positive-P representation. As a demonstration, we track the appearance and stabilization of quantum fluctuation effects after turning on the hybrid description in trapped quasicondensates with pre-existing thermal excitations. We observe counter-propagating atom pairs, additional loss of the coherence like in a quantum quench, antibunching, as well as density correlation waves.

Hamiltonian of the system

Stochastic Gross-Pitaevskii equation

$$i\hbar\frac{\partial\Psi(x,t)}{\partial t}=(1-i\gamma)\left(-\frac{\hbar^2\nabla^2}{2m}+V(x)-\mu+g\,|\Psi(x,t)|^2\right)\Psi(x,t)+\sqrt{2\hbar\gamma k_BT}\,\eta(x,t)$$

Positive-P representation

$$i\hbar\frac{\partial\Psi(x,t)}{\partial t}=\left(-\frac{\hbar^2\nabla^2}{2m}+V(x)+g\Psi(x,t)\tilde{\Psi}^*(x,t)+\sqrt{ig}\,\xi(x,t)\right)\Psi(x,t)$$

$$i\hbar\frac{\partial\tilde{\Psi}(x,t)}{\partial t}=\left(-\frac{\hbar^2\nabla^2}{2m}+V(x)+g\tilde{\Psi}(x,t)\Psi^*(x,t)+\sqrt{ig}\,\tilde{\xi}(x,t)\right)\tilde{\Psi}(x,t)$$

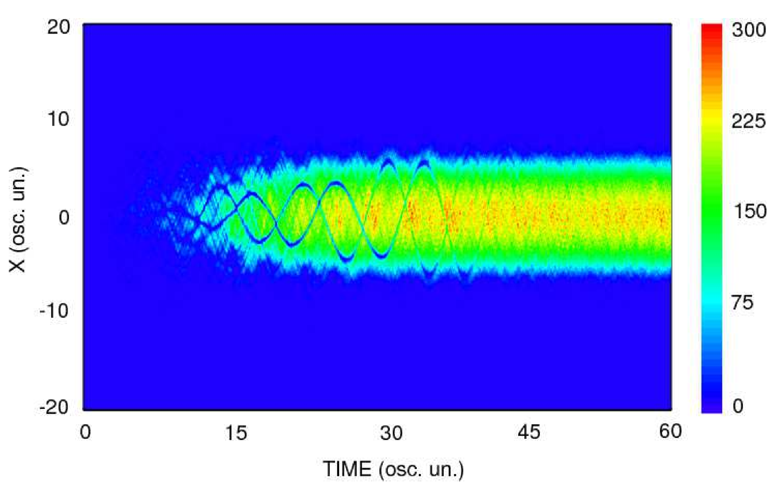
Hybrid equations

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

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

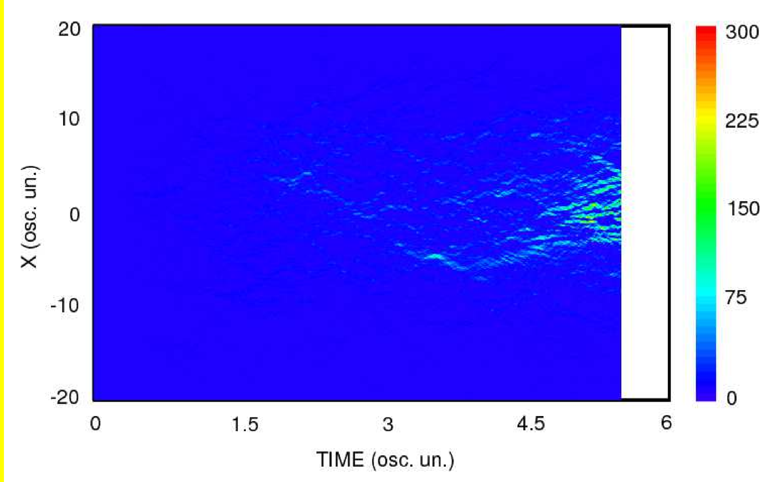
$$\langle\eta^*(x,t)\eta(x',t')\rangle=\delta(x-x')\delta(t-t')\qquad\langle\xi^*(x,t)\xi(x',t')\rangle=\delta(x-x')\delta(t-t')$$

Single realization of the SGPE



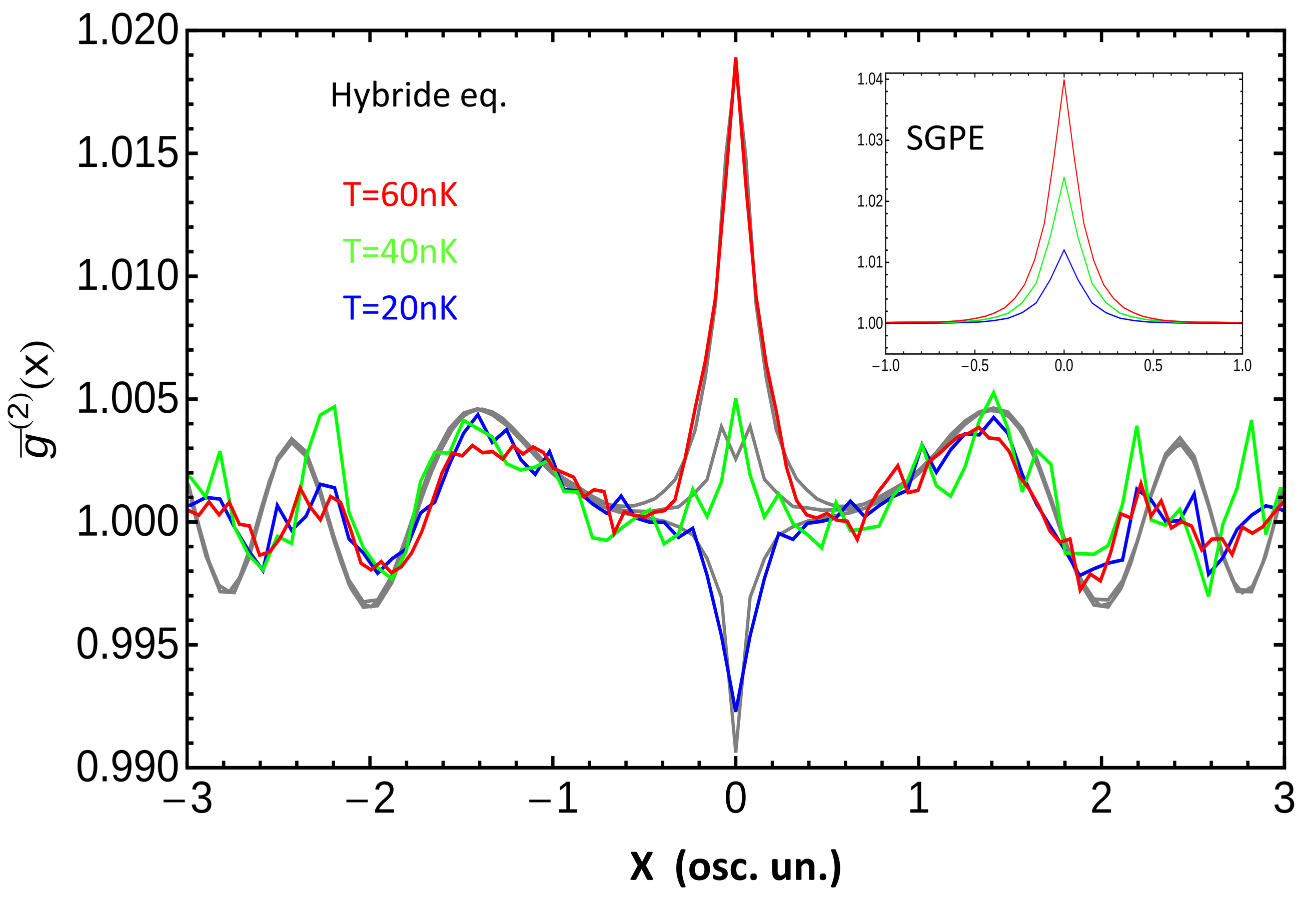
The generation of a single sample Ψ(x) of the thermal equilibrium ensemble for a harmonically trapped 1D Bose gas. Color shows the local density $n(x, t)$ =|(x, t)|^2 of the gas during its time evolution. Thermal cloud bath parameters are T = 13.89, μ = 22.41, g = 0.1, and = 0.01. Note the generation of spontaneous soliton defects.

Single realization of the hybride equations

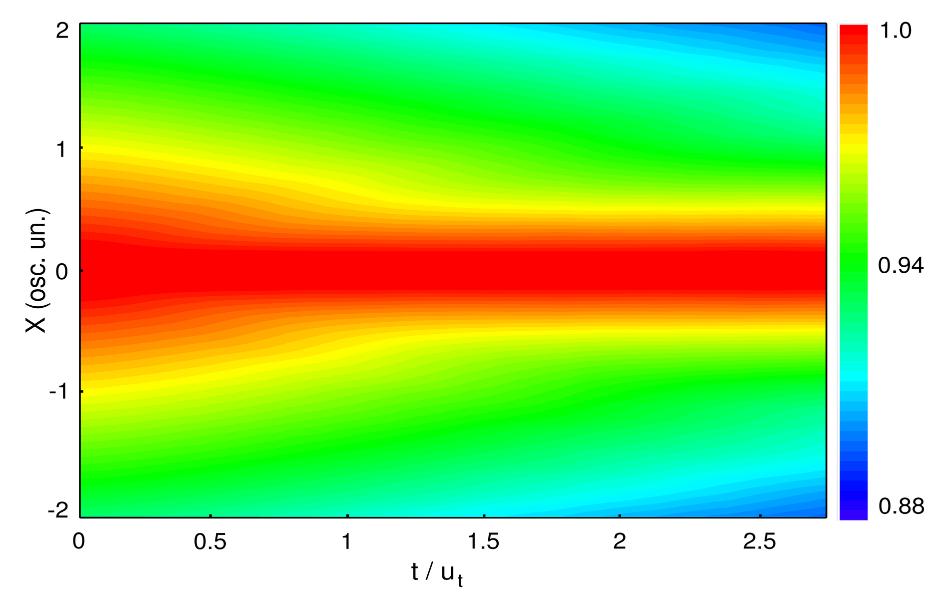


An attempt to generate a sample of the thermal equilibrium ensemble with the hybrid equations. All parameters like in SGPE case, except for the markedly shorter timescale. The white space on the right indicates the onset of catastrophic noise amplification.

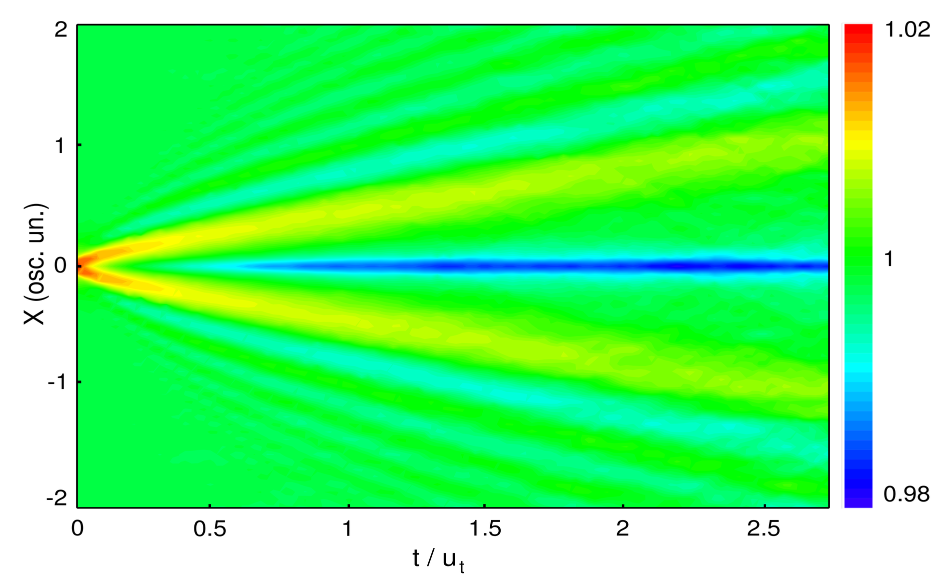
SGPE vs hybride equations – density correlation functions



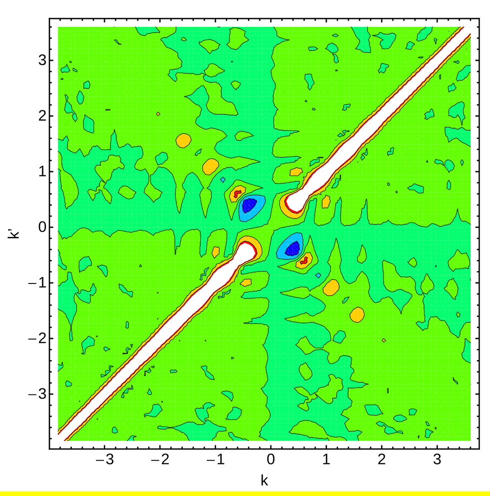
Thermal fluctuations dominate over antibunching at high temperatures, while it emerges at lower T. Correlation waves are mostly unafected by temperature. The gray lines show estimates based on the SGPE and a T=0 quantum quench *arXiv:1310.1301*.



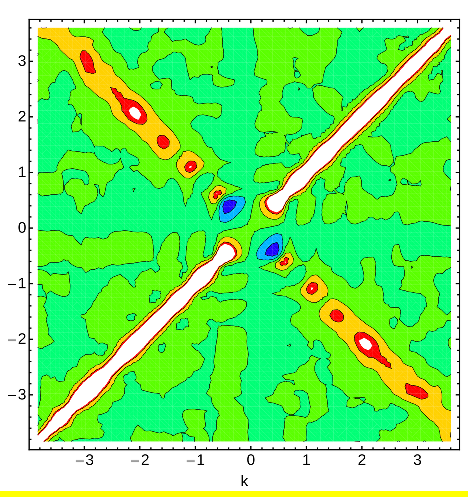
Time dependence of the **phase correlation** function after the inclusion of quantum fluctuations. Note the initial reduction of phase coherence due to quantum fluctuations, and later stabilization of the correlation over a progressively larger region with time. The changeover is evidenced by a „kink" in the color contours.



Time dependence of the **density correlation** function after the inclusion of quantum fluctuations. Long-lived correlation waves form, then move away from the small *„X" region,* where only local antibunching stabilises.



Correlation function $g^{(2)}(k, k')$ in the SGPE ensemble for T = 0.155T and μ = 22.41. Contours are at intervals of 0.2, white color indicates $g^{(2)} > 1.6$. Hanbury Brown-Twiss bunching at equilibrium is visible, but no pair production.



Correlation function $g^{(2)}(k, k')$ after t = 2.7ut evolution with the **hybrid** equations for T = 0.155T, μ = 22.41, and g = 0.2. A strong counter-propagating ($k' = -k$) pair signal has appeared. Contours are at intervals of 0.2, white color indicates $g^{(2)} > 1.6$.

arXiv:1409.0146

In conclusion

- A description of the dynamics of ultracold Bose gases that includes both classical and quantum fluctuations together was Developed.
- Such as dynamics in a quasicondensate, including the creation of atom pairs at temperatures too high for a Bogoliubov description.
- Time of the simulations is limited because of noise amplification.
- We observe counter-propagating atom pairs, additional loss of the coherence like in a quantum quench, antibunching, as well as density correlation waves.

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