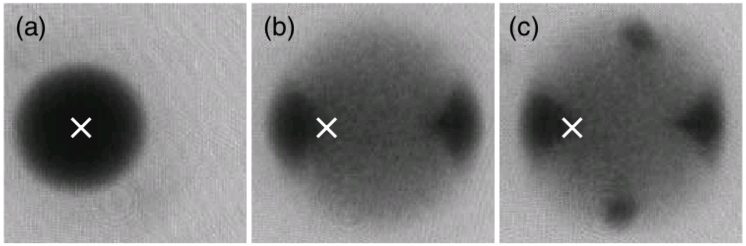
Bogoliubov quantum dynamics at T>=0 (even without a condensate)

Piotr Deuar

Institute of Physics, Polish Academy of Sciences, Warsaw

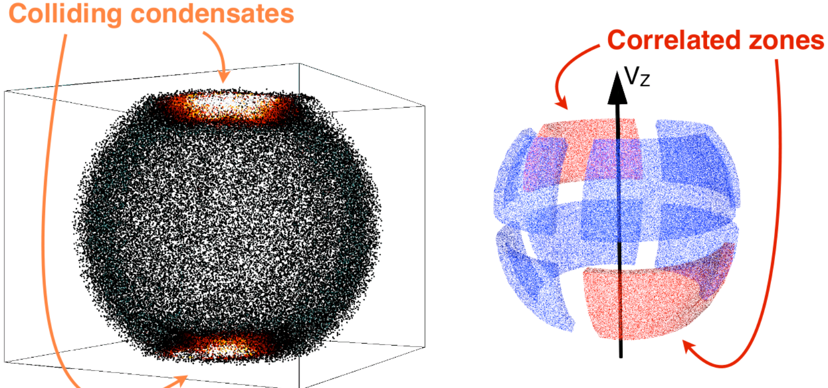
1. Supersonic pair creation
2. Palaiseau BEC collision experiment
3. Simulation of scattered pair dynamics at T=0
4. Quasicondensate 0<T<Tc
5. T>Tc?

Supersonic pair creation

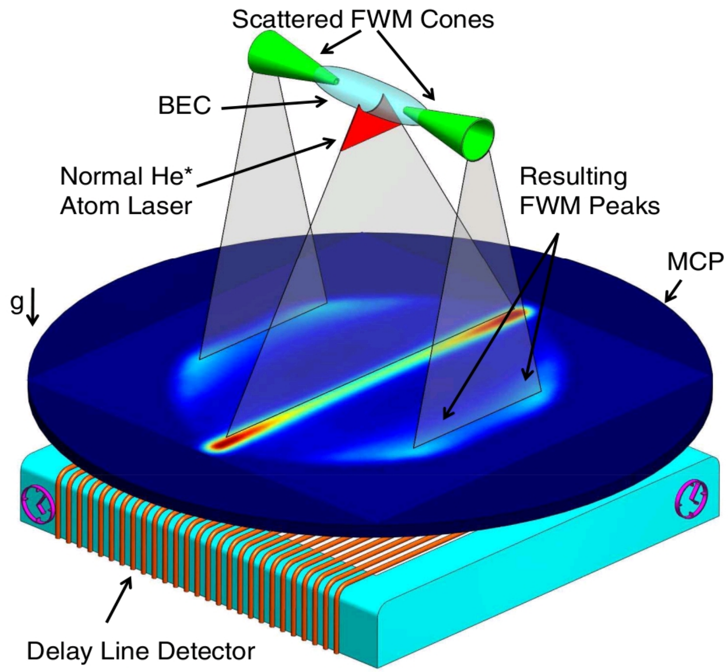


J.Vogels *et al*, PRL **89,** 020401 (2002)

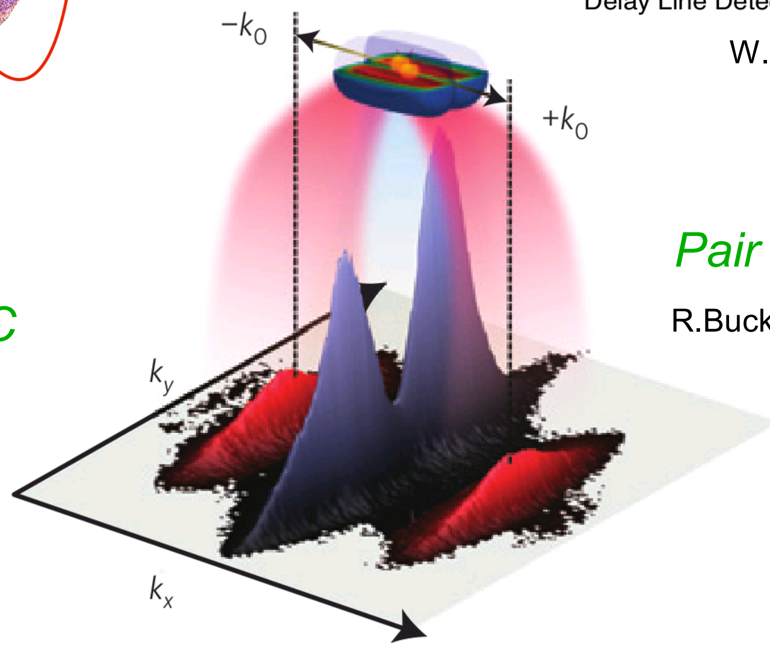
BEC Collisions



J-C.Jaskula *et al*, PRL **105,** 190402 (2010)



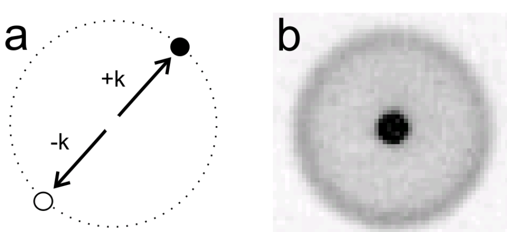
W. RuGway *et al*, PRL **107,** 075301 (2011)



Pair emission from a 1D gas

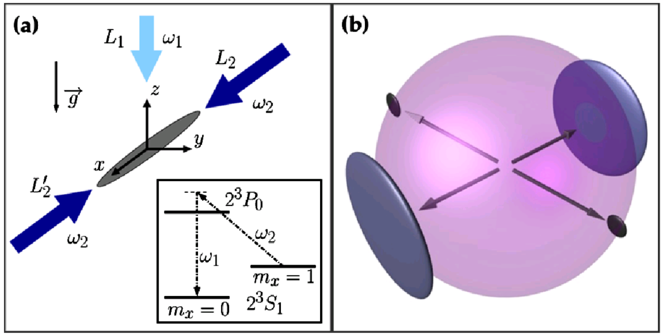
R.Bucker *et al*, Nature Phys. **7,** 608 (2011)

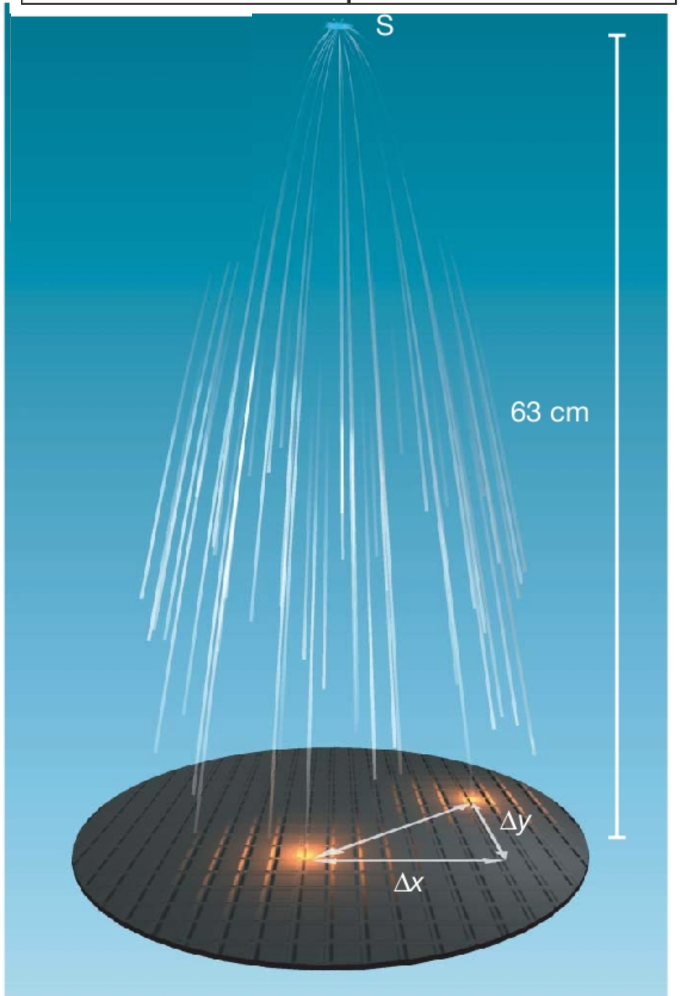
Dissociation of molecular BEC



M. Greiner *et al*, PRL **94,** 110401 (2005)

BEC collision – Palaiseau experiment





Experiment:

INSTITUT d'OPTIQUE GRADUATE SCHOOL

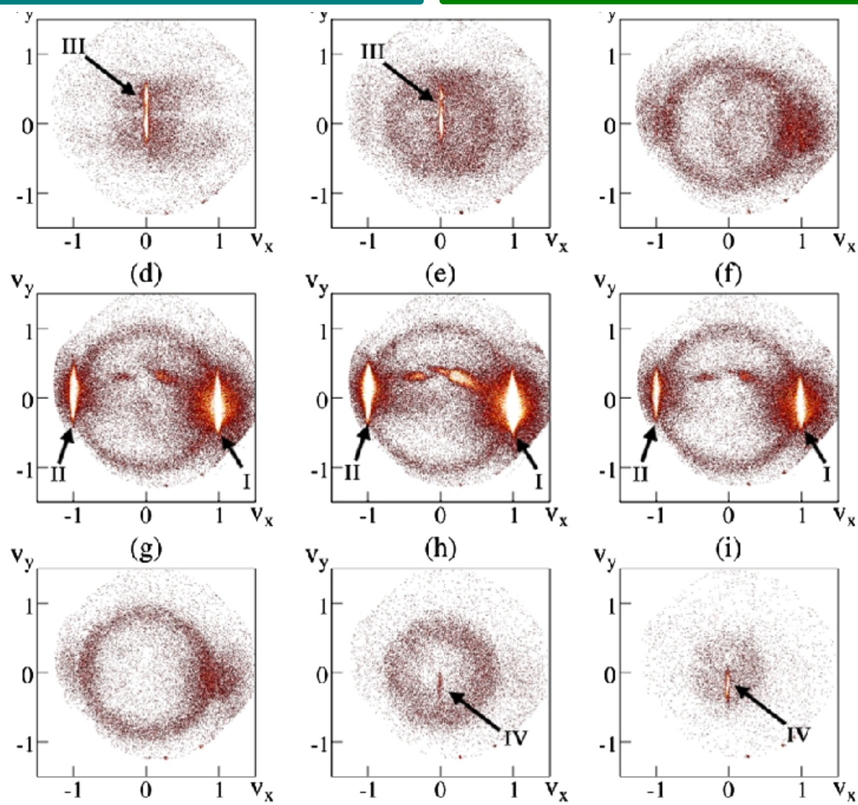
Chris Westbrook
Denis Boiron
Jean-Christophe Jaskula
Valentina Krachmalnicoff
Marie Bonneau
Vanessa Leung
Guthrie Partridge
Alain Aspect

Theory:

Piotr Deuar (Warsaw)

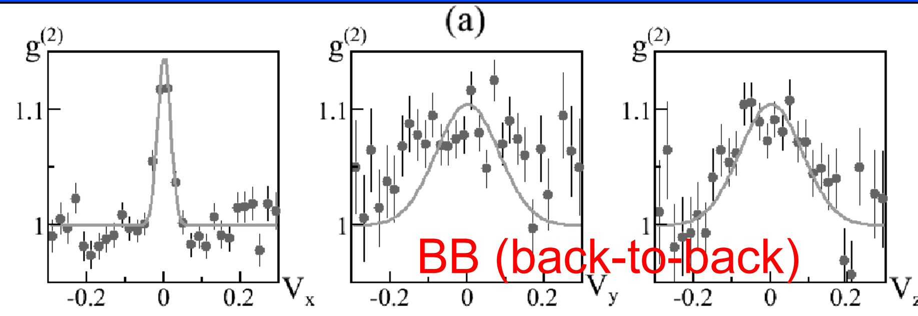
Karen Kheruntsyan (Queensland)

Marek Trippenbach (Warsaw)
Jan Chwedeńczuk
Tomasz Wasak
Paweł Ziń

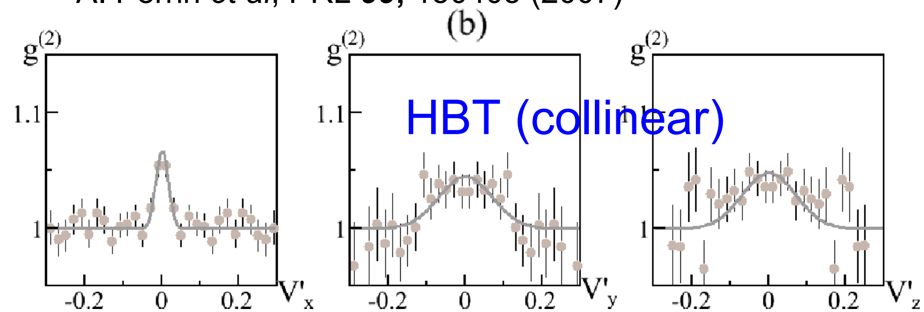


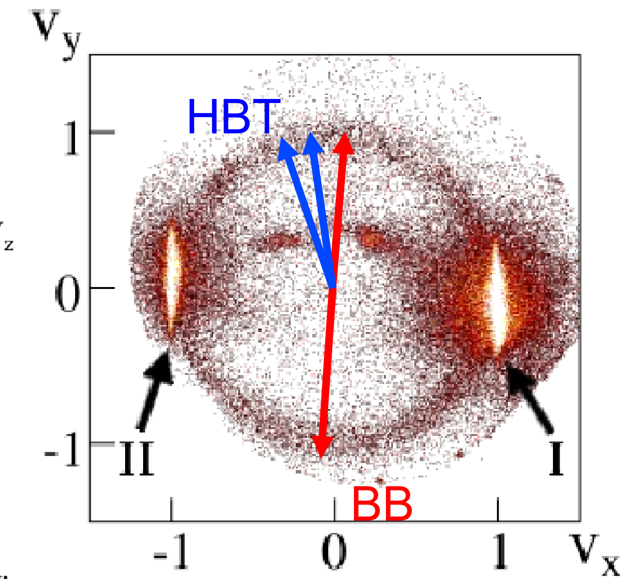
A. Perrin *et al*, PRL **99,** 150405 (2007)

Pairing and density correlations

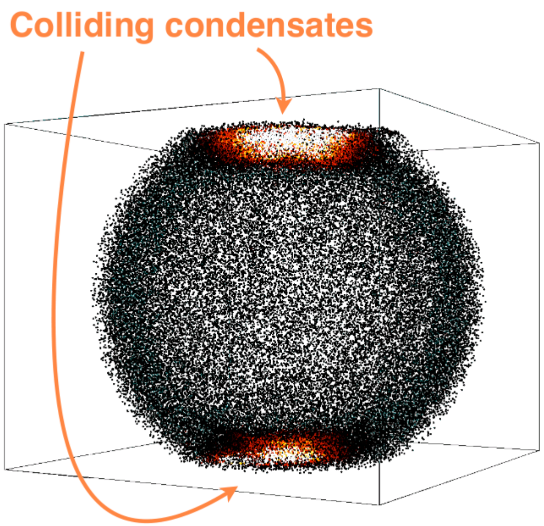


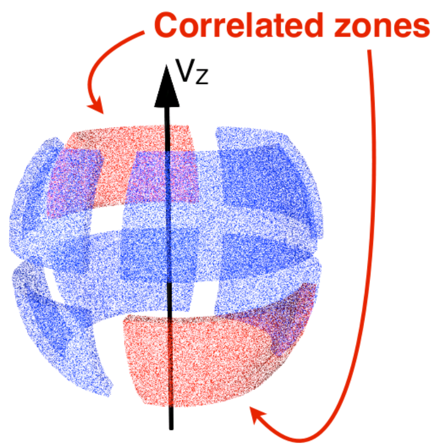
A. Perrin *et al*, PRL **99,** 150405 (2007)

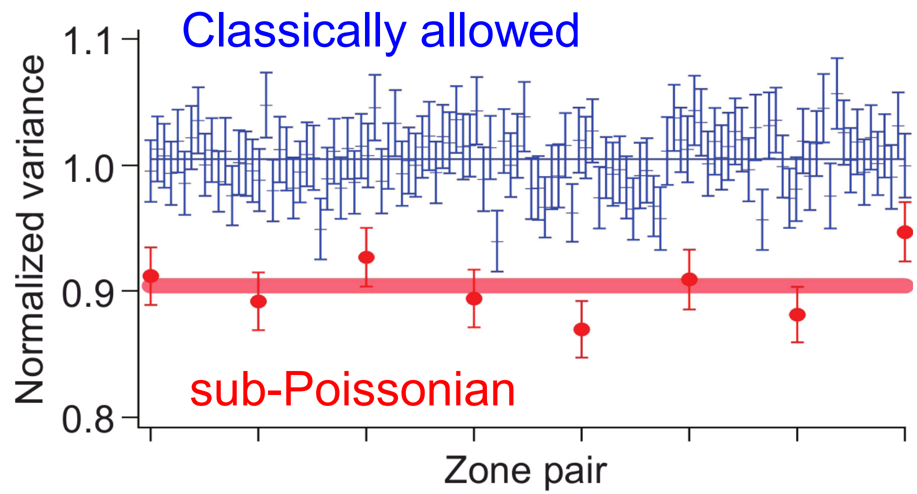




Squeezing of relative particle number between zones







J-C.Jaskula *et al*, PRL **105,** 190402 (2010)

Positive-P representation

$$\hat{H} = \int dx \left\{ \hat{\Psi}^\dagger(x) \left[V(x) - \frac{\hbar^2}{2m}\nabla^2 \right] \hat{\Psi}(x) + \frac{g}{2}\hat{\Psi}^\dagger(x)^2 \hat{\Psi}(x)^2 \right\}$$

$H_0(x)$

$$\widehat{\rho} = \int P\left[\psi, \widetilde{\psi}\right] |\psi\rangle \langle\widetilde{\psi}| \, \mathcal{D}^2\psi(\vec{x})\mathcal{D}^2\widetilde{\psi}(\vec{x})$$

Probability distribution of bra & ket coherent fields $\psi(x), \ \widetilde{\psi}(x)$

dynamics

$$i\hbar\frac{d\psi(x)}{dt} = \left\{ H_0(x) + g\widetilde{\psi}^*(x)\psi(x) + \sqrt{i\hbar g}\,\xi(x,t) \right\} \psi(x)$$

$$i\hbar\frac{d\widetilde{\psi}(x)}{dt} = \left\{ H_0(x) + g\psi^*(x)\widetilde{\psi}(x) + \sqrt{i\hbar g}\,\widetilde{\xi}(x,t) \right\} \widetilde{\psi}(x)$$

Gaussian real white noise $\xi(x,t), \ \widetilde{\xi}(x,t)$

However:

intractable after an inconvenient time

Positive-P Bogoliubov

PD *et al*, PRA **83,** 063625 (2011)

$$\widehat{\Psi}(\mathbf{x},t) = \phi(\mathbf{x},t) + \widehat{\delta}(\mathbf{x},t)$$

(symmetry breaking version)

condensate

Bogoliubov fluctuation field – *MUST BE "small"*

Treat only $\widehat{\delta}(\mathbf{x},t)$ using positive-P representation

$$i\hbar\frac{d\phi(x)}{dt} = \left[H_0(x) + g|\phi(x)|^2\right]\phi(x)$$

Mean field

$$i\hbar\frac{d\psi(x)}{dt} = \left\{H_0(x) + 2g|\phi(x)|^2\right\}\psi(x) + g\phi(x)^2\widetilde{\psi}(x)^* + \sqrt{i\hbar g}\,\phi(x)\xi(x,t)$$

$$i\hbar\frac{d\widetilde{\psi}(x)}{dt} = \left\{H_0(x) + 2g|\phi(x)|^2\right\}\widetilde{\psi}(x) + g\phi(x)^2\psi(x)^* + \sqrt{i\hbar g}\,\phi(x)\widetilde{\xi}(x,t)$$

Now equations are linear ------> no blow-up of noise :)

Can use plane wave basis ---> no diagonalizing of 10^6 X 10^6 matrices :)

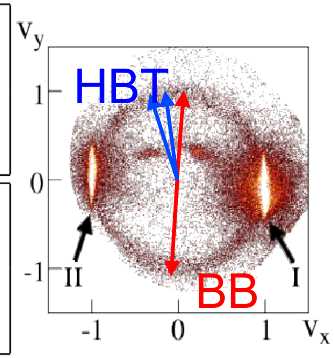
1st generation experiment: ***good agreement***

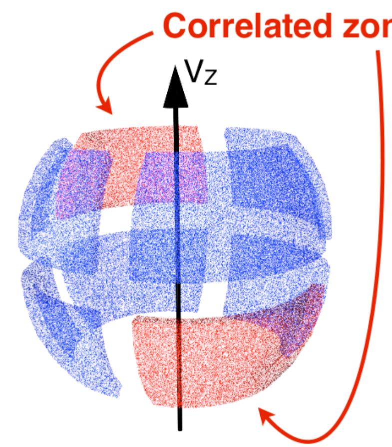
V. Krachmalnicoff *et al*, PRL **104,** 150402 (2010)

Second generation experiment: something suspicious

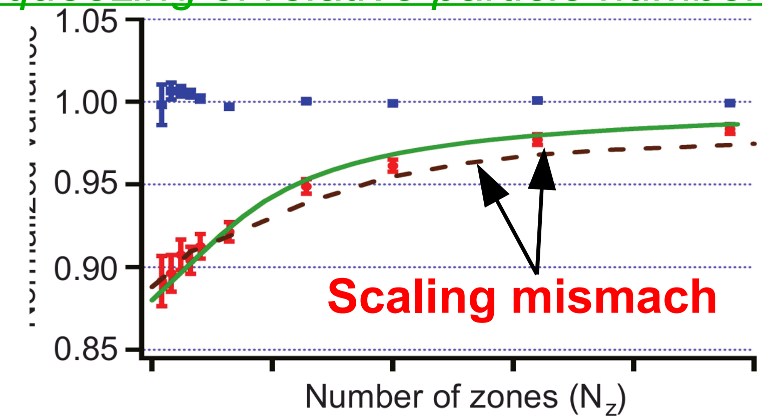
Pair correlations along long axis $g^{(2)}(\Delta k_z)$

	experiment		numerics	
	$\frac{\text{BB width}}{\text{HBT width}}$	$\frac{\text{BB height}}{\text{HBT height}}$	$\frac{\text{BB width}}{\text{HBT width}}$	$\frac{\text{BB height}}{\text{HBT height}}$
1st generation	1.1	2.1	1	2.2
2nd generation	18	0.5	1	2.2





Squeezing of relative particle number



The suspect:

A quasicondensate

experiment	ω_z	ω_r	aspect
1st generation	47	1150	24.5
2nd generation	7.5	1500	200

1st generation ← ~ elongated 3d bec

2nd generation ← Quasicondensate at our temperatures condensate fraction ~5%

Classical field /PGPE/SGPE/... for quasiBEC

e.g. free space : plane wave basis

Full quantum field

c-fields

$$\Psi(\mathbf{r}) = \sum_{\mathbf{k}} a_{\mathbf{k}} \frac{1}{\sqrt{V}} e^{i\mathbf{kr}} \longrightarrow \Phi(\mathbf{r}) = \sum_{|\mathbf{k}|\leqslant \mathbf{K}_{\max}} \alpha_{\mathbf{k}} \frac{1}{\sqrt{V}} e^{i\mathbf{kr}}$$

Replace mode amplitude operators $a_{\mathbf{k}}$
with complex number amplitudes $\alpha_{\mathbf{k}}$

Thermal initial state:

- $|\alpha_{\mathbf{k}}|^2$ Distributed according to Bose-Einstein distribution
- Phase of $\alpha_{\mathbf{k}}$ is random
- Use many realizations to get thermal ensemble

Used to model our quasicondensate

Useful papers: D. Petrov *et al*, PRL **87**, 050404 (2001)
M. Brewczyk *et al,* J. Phys B **40,** R1 (2007)
P. Blakie *et al.* Adv. Phys. **57**, 363 (2008)
N. Proukakis, B. Jackson, J. Phys A **41,** 203002 (2008)

First Trick: each realization is independent

INITIAL STATE t=0

Treat $\alpha_{CF}(x)$ as condensates

$$\phi(x) = \alpha_{CF}(x)$$

$\alpha_{CF}(x)$ Classical field realization 1

- $\psi(x),\ \widetilde{\psi}(x)$ Bogoliubov realization 1A
- $\psi(x),\ \widetilde{\psi}(x)$ Bogoliubov realization 1B
- $\psi(x),\ \widetilde{\psi}(x)$ Bogoliubov realization 1C

$\alpha_{CF}(x)$ Classical field realization 2

- $\psi(x),\ \widetilde{\psi}(x)$ Bogoliubov realization 2A
- $\psi(x),\ \widetilde{\psi}(x)$ Bogoliubov realization 2B
- $\psi(x),\ \widetilde{\psi}(x)$ Bogoliubov realization 2C

$\alpha_{CF}(x)$ Classical field realization 3

- $\psi(x),\ \widetilde{\psi}(x)$ Bogoliubov realization 2A
- $\psi(x),\ \widetilde{\psi}(x)$ Bogoliubov realization 2B
- $\psi(x),\ \widetilde{\psi}(x)$ Bogoliubov realization 2C

2nd Trick: each realization is independent

INITIAL STATE *t=0*

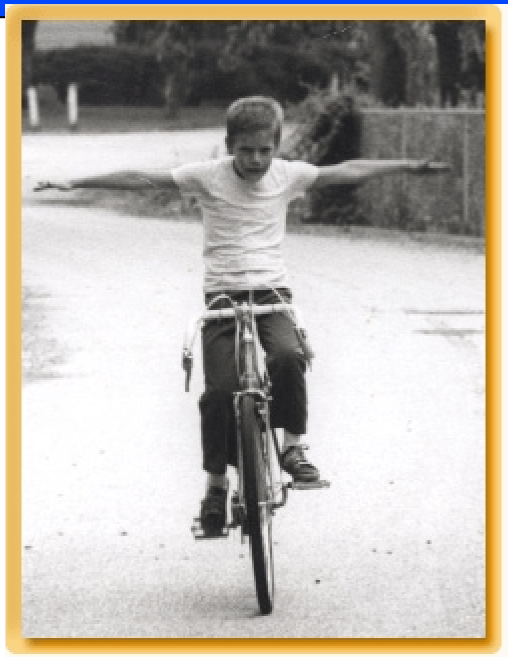
Treat $\alpha_{CF}(x)$ as condensates
$\phi(x) = \alpha_{CF}(x)$

$\alpha_{CF}(x)$ Classical field realization 1 → $\psi(x),\ \widetilde{\psi}(x)$ Bogoliubov realization 1

$\alpha_{CF}(x)$ Classical field realization 2 → $\psi(x),\ \widetilde{\psi}(x)$ Bogoliubov realization 2

$\alpha_{CF}(x)$ Classical field realization 3 → $\psi(x),\ \widetilde{\psi}(x)$ Bogoliubov realization 2

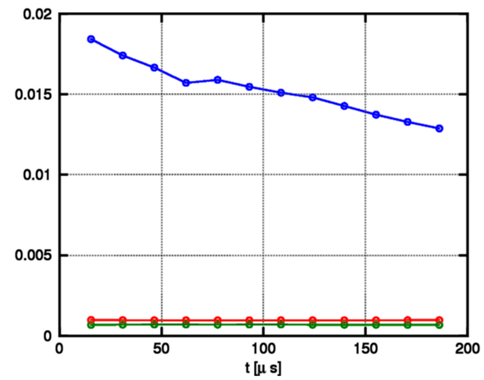
Look mum, no condensate! ($n_0 \sim 0.05$)



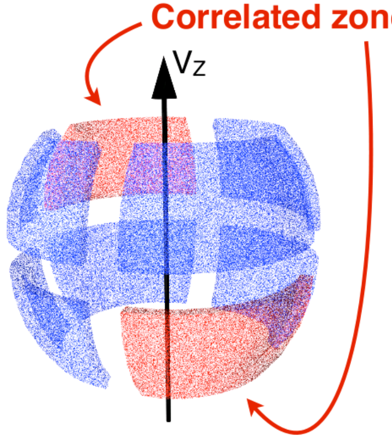
Look mum, no hands!

Pair correlations $g^{(2)}(\Delta k_z)$

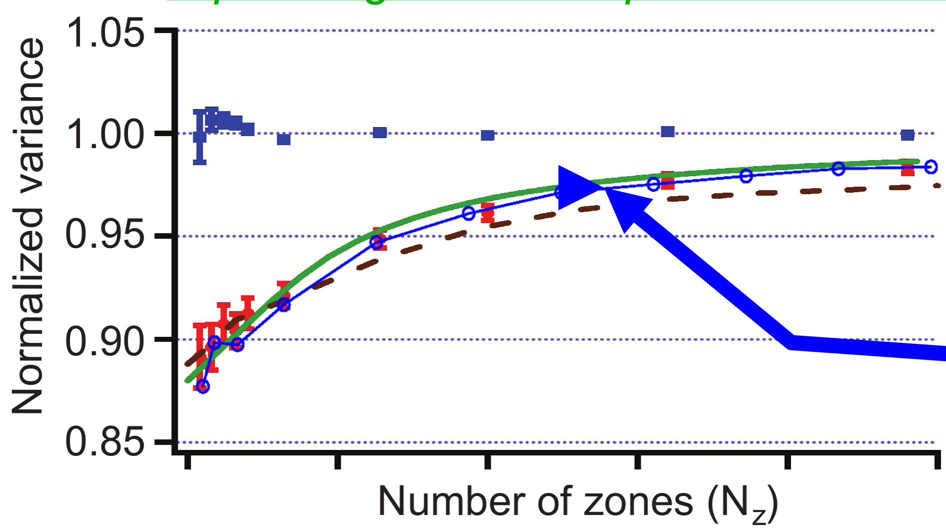
	experiment		numerics	
	$\frac{\text{BB width}}{\text{HBT width}}$	$\frac{\text{BB height}}{\text{HBT height}}$	$\frac{\text{BB width}}{\text{HBT width}}$	$\frac{\text{BB height}}{\text{HBT height}}$
1st generation	1.1	2.1	1	2.2
2nd generation	18	0.5	~~1~~ 16	~~2.2~~ 0.3



Visible effect of Quasicondensate on pairing



Squeezing of relative particle number



Surprise!
improved match

Caveats

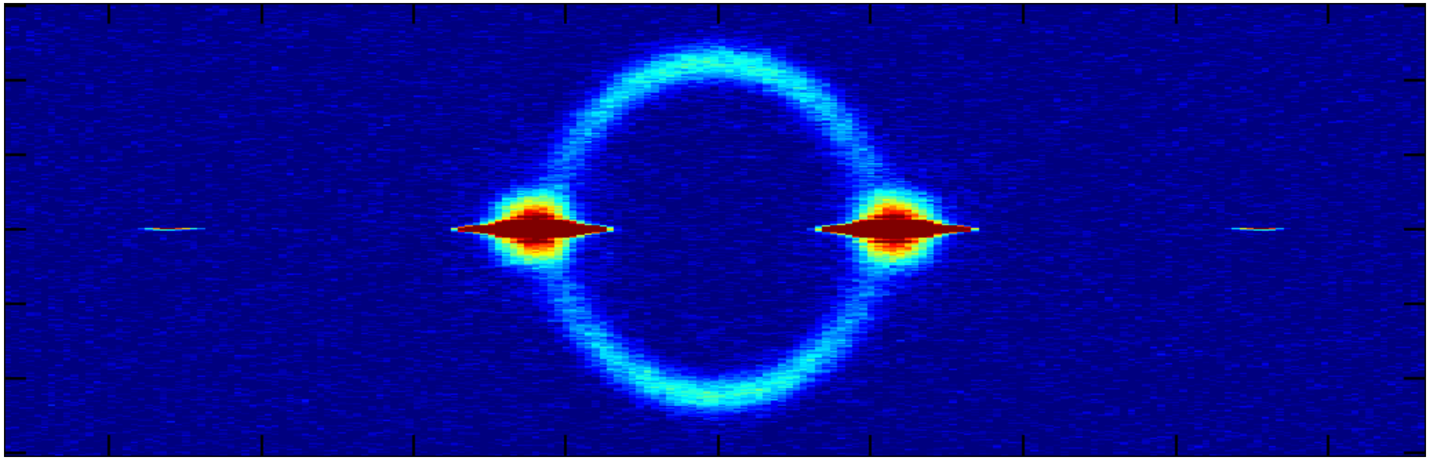
<u>Caveat 1:</u> need *additional t>0* depletion to be small

(initial depletion is apparently irrelevant)

<u>Caveat 2:</u> don't look at the condensate regions

(plane waves are not orthogonal to the condensate)

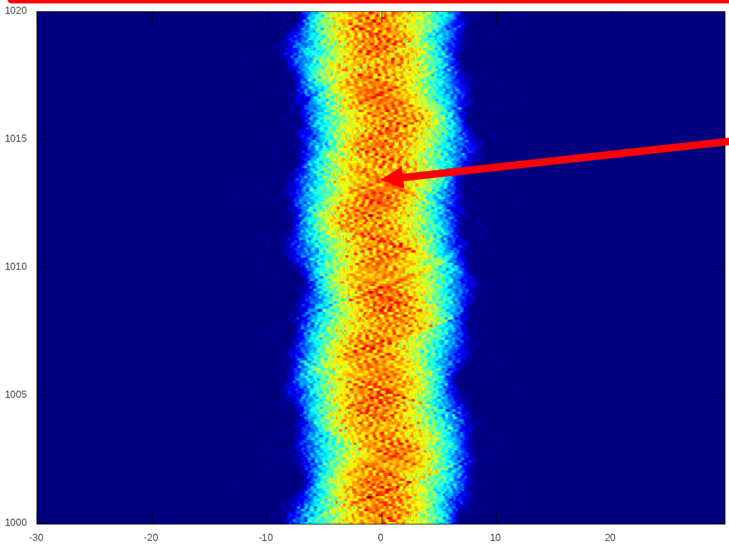
-----> mix-up of Bogoliubov modes and condensate there



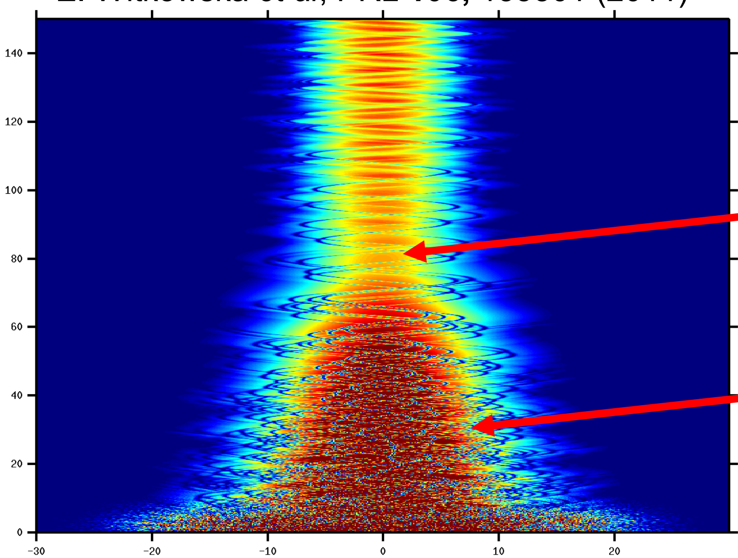
Even less condensate?

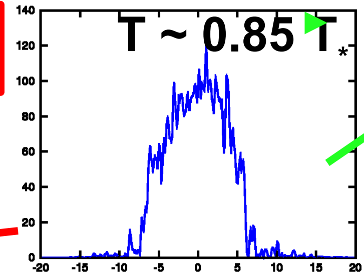
Classical field simulation of
1D evaporative cooling

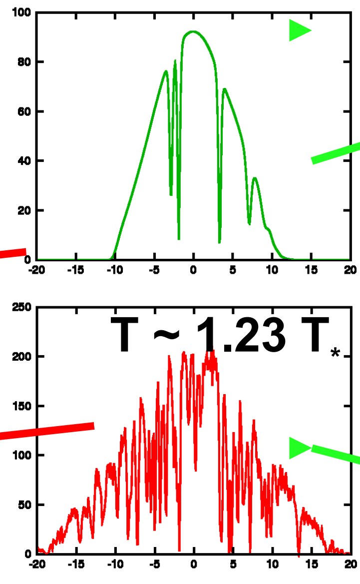
See poster: Emilia Witkowska



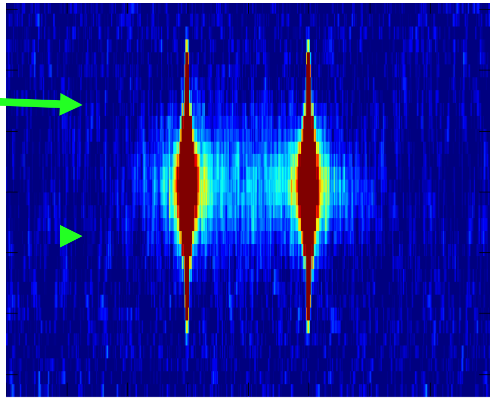
E. Witkowska *et al*, PRL **106,** 135301 (2011)

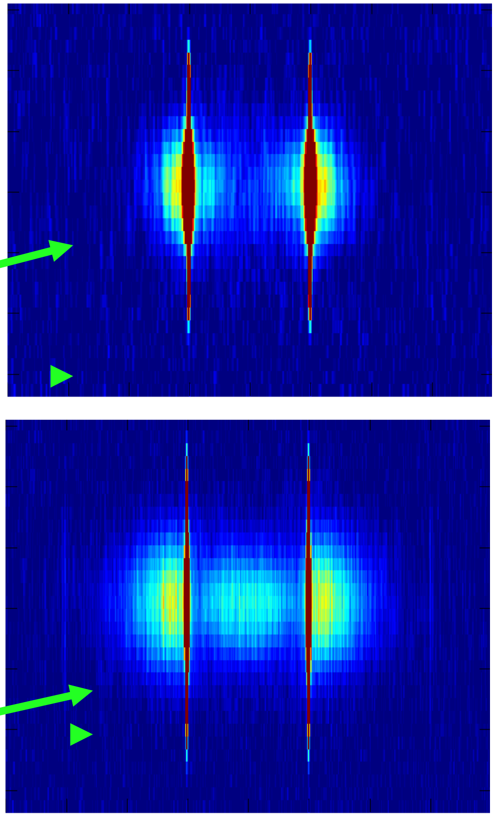






RELEASE 1D CONFINEMENT AND COLLIDE





Summary

- Quantitative simulation of dynamics of pair scattering

  With positive-P treatment of Bogoliubov field

- Bogoliubov dynamics made tractable for large systems

  By use of plane wave modes + stochastic noise

- Treat classical field realizations as condensates

  Apparently works even with no true condensate

- Need to work on number-conserving Bogoliubov version