Quantum systems of ultracold atoms
New probes of many-body correlations

Analysis of quantum noise

Interference of fluctuating condensates and correlation functions

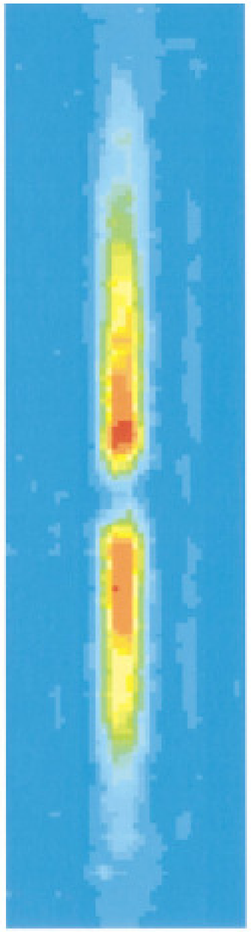
From quantum noise to high order correlation functions

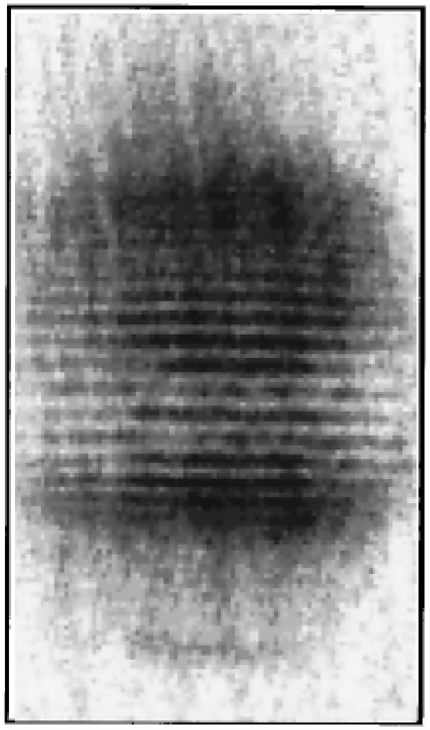
Analysis of magnetization fluctuations in lattice models

MURI
Program in
Optical Lattices

Interference of two independent condensates

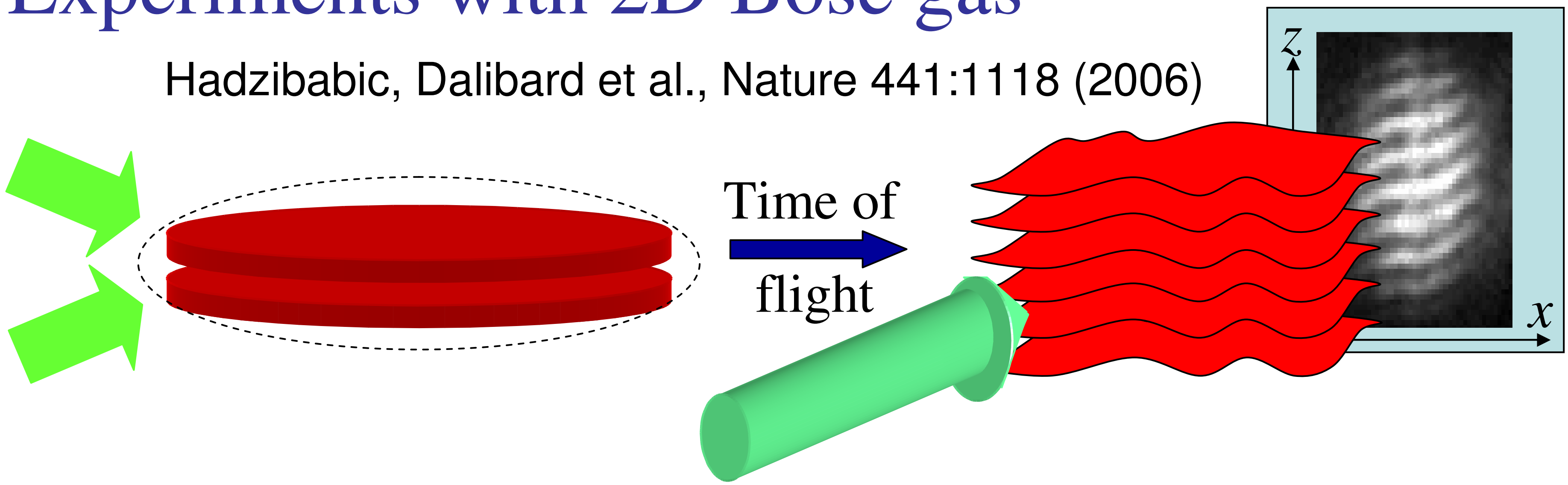
Andrews et al., Science 275:637 (1997)



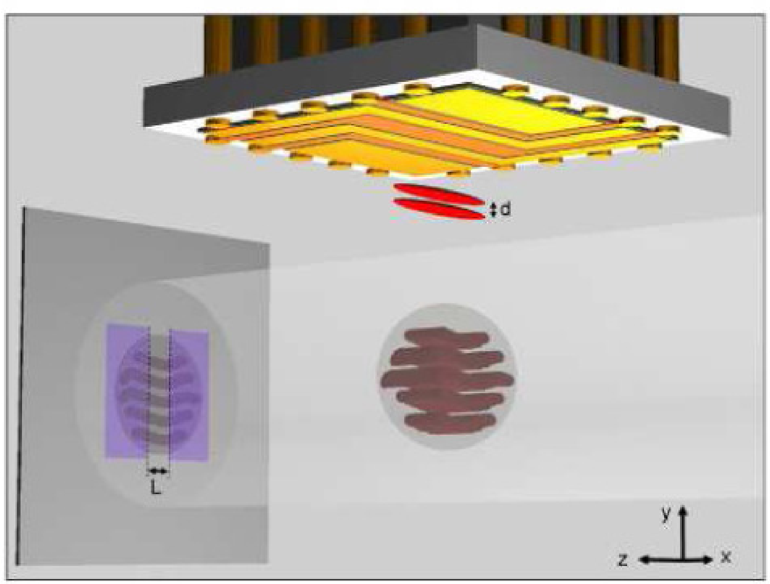


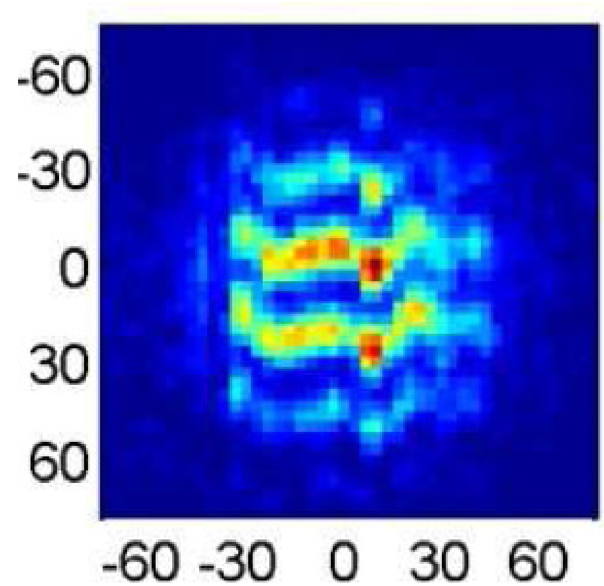
Experiments with 2D Bose gas

Hadzibabic, Dalibard et al., Nature 441:1118 (2006)



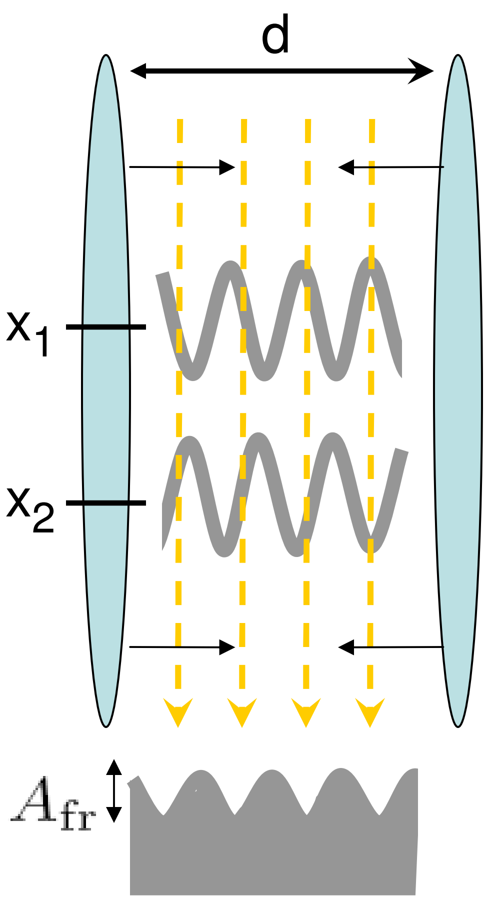
Experiments with 1D Bose gas S. Hofferberth et al. arXiv0710.1575





Interference of fluctuating condensates

Polkovnikov, Altman, Demler, PNAS 103:6125(2006)



Amplitude of interference fringes, $A_{\rm fr}$

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

For independent condensates A_{fr} is finite but $\Delta\phi$ is random

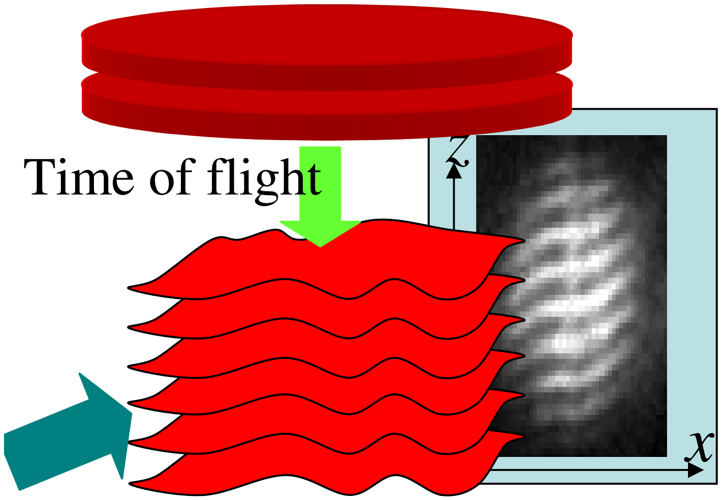
$$\langle |A_{\rm fr}|^2 \rangle = \int_0^L \int_0^L dx\, dy\, \langle a_1^\dagger(x)\, a_2(x)\, a_2^\dagger(y)\, a_1(y) \rangle$$

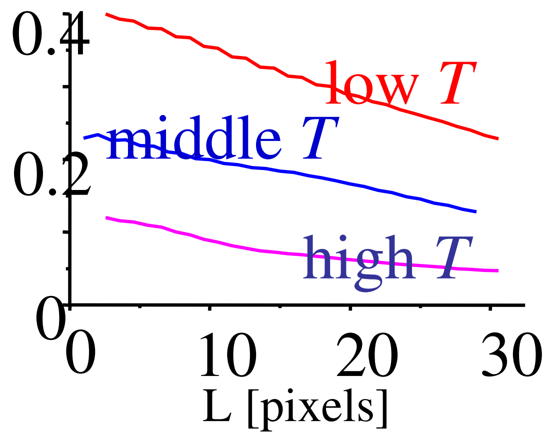
$$\simeq L \int_0^L dx\, \langle a_1(x)\, a_1^\dagger(0) \rangle \langle a_2(0) a_2^\dagger(x) \rangle$$

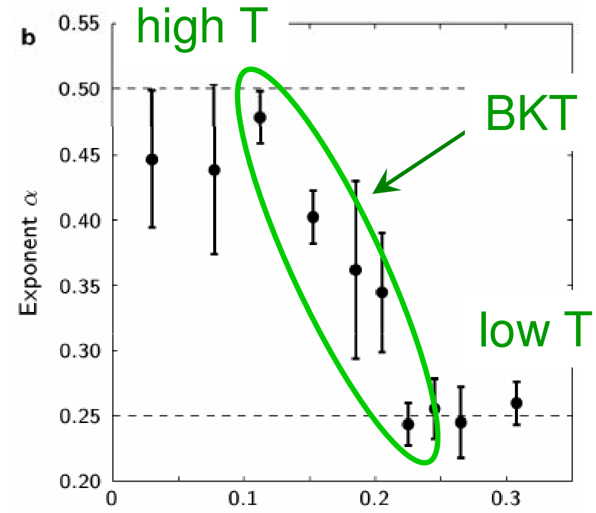
For identical condensates $\langle |A_{\rm fr}|^2 \rangle = L \int_0^L dx\, (G(x))^2$

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

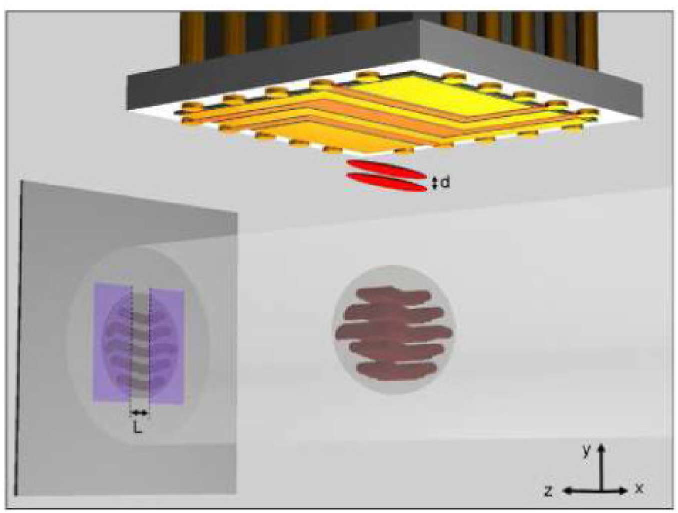
Interference between fluctuating condensates

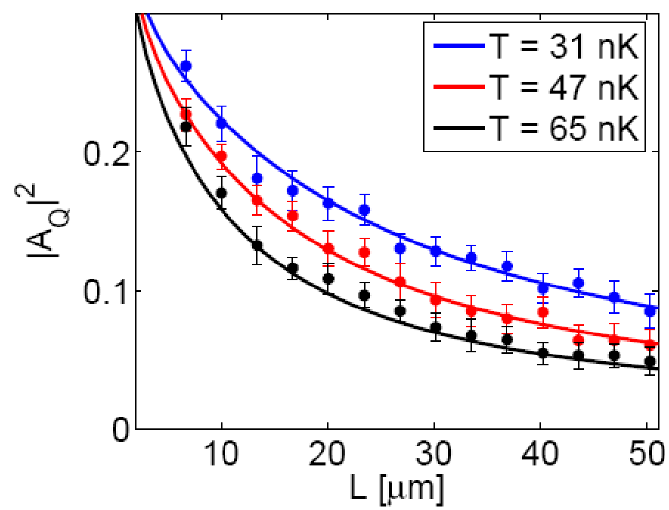






2d: BKT transition, Hadzibabic et al, 2006

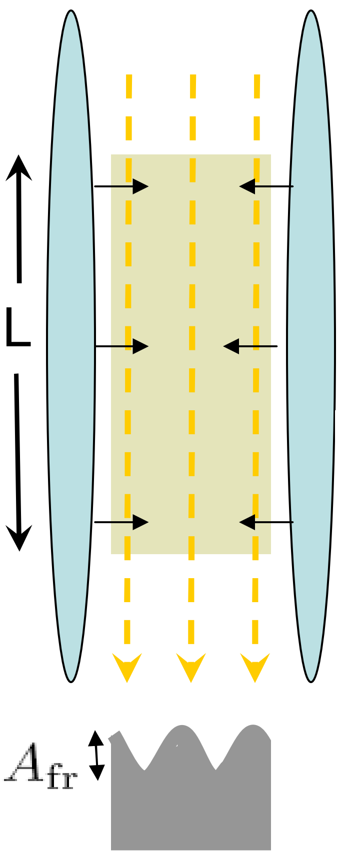




1d: Luttinger liquid, Hofferberth et al., 2007

Distribution function of fringe amplitudes for interference of fluctuating condensates

Gritsev, Altman, Demler, Polkovnikov, Nature Physics 2006
Imambekov, Gritsev, Demler, cond-mat/0612011



$A_{\rm fr}$ is a quantum operator. The measured value of $|A_{\rm fr}|$ will fluctuate from shot to shot.

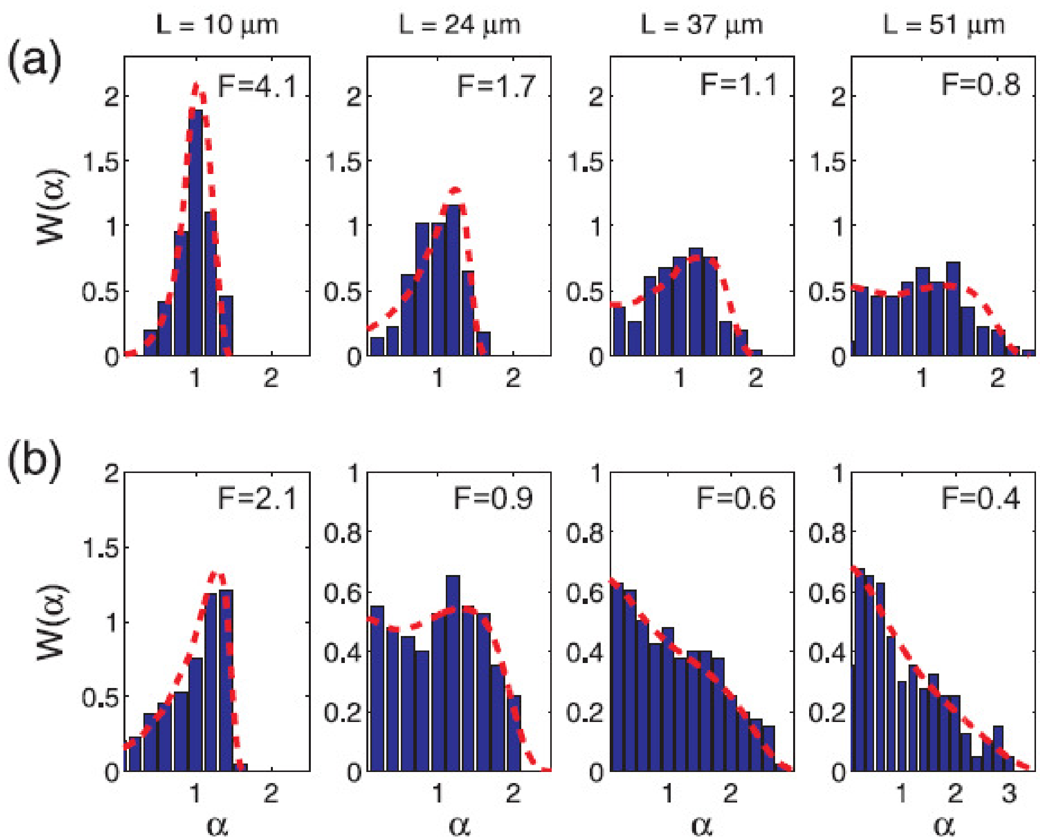
$$\langle\, |A_{\rm fr}|^{2n} \rangle \; = \int_0^L dz_1 \, \ldots \, dz_n' \, |\langle\, a^\dagger(z_1) \, \ldots a^\dagger(z_n) \, a(z_1') \, \ldots a(z_n') \,\rangle|^2$$

Higher moments reflect higher order correlation functions

We need the full distribution function of $|A_{\rm fr}|$

Distribution function of interference fringe contrast

Experiments: Hofferberth et al., arXiv0710.1575
Theory: Imambekov et al. , cond-mat/0612011



Quantum fluctuations dominate:
asymetric Gumbel distribution
(low temp. T or short length L)

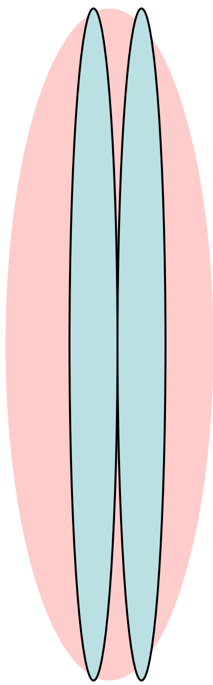
Thermal fluctuations dominate:
broad Poissonian distribution
(high temp. T or long length L)

Intermediate regime:
double peak structure

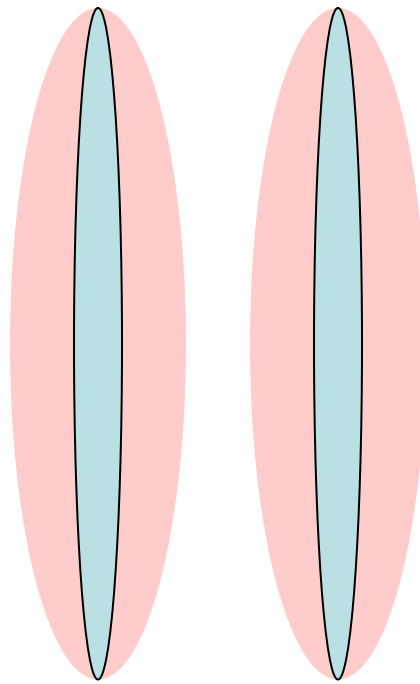
Comparison of theory and experiments: no free parameters
Higher order correlation functions can be obtained

Studying coherent dynamics of strongly interacting systems in interference experiments

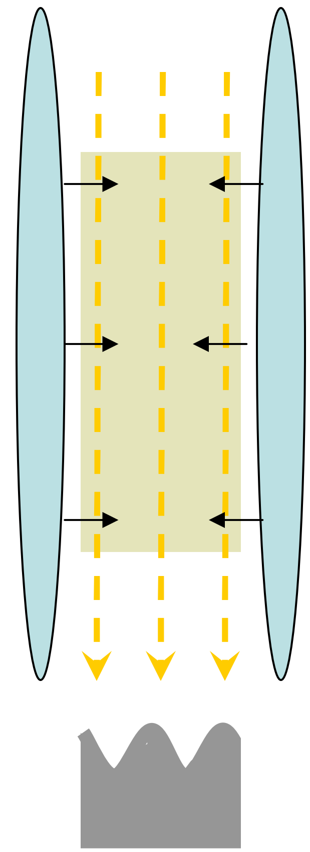
Studying dynamics using interference experiments



Prepare a system by
splitting one condensate



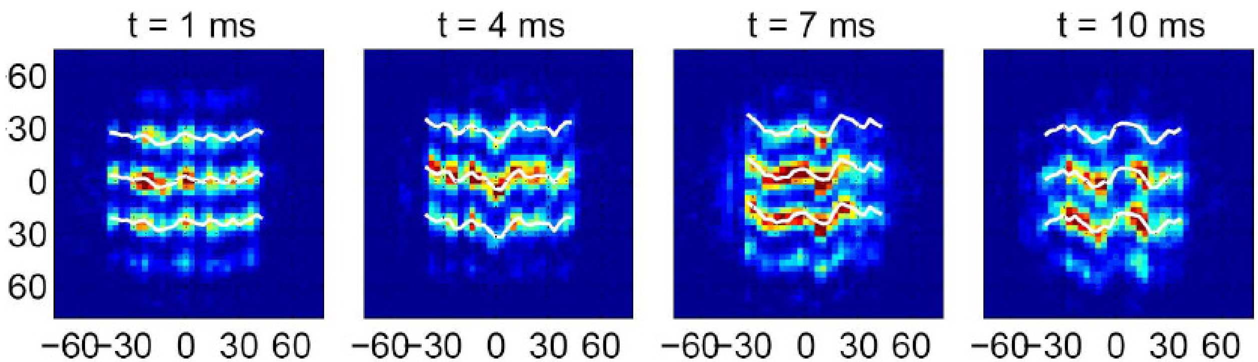
Take to the regime of
zero tunneling

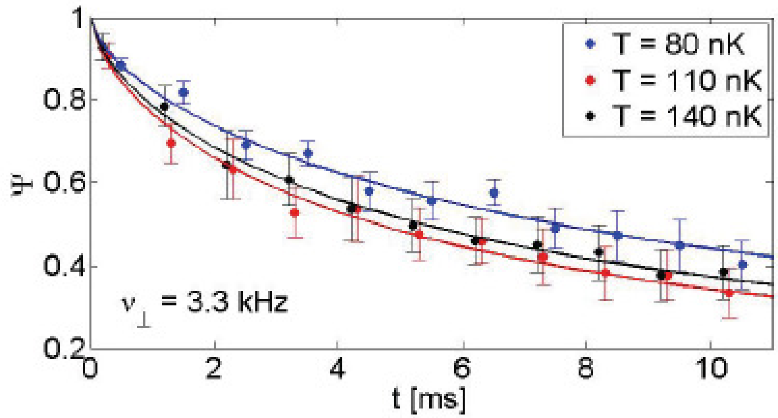


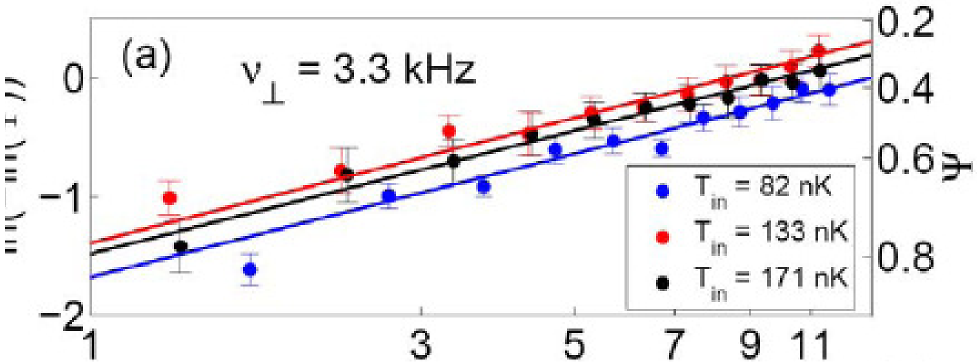
Measure time evolution
of fringe amplitudes

Dynamics of split condensates

Theory: Burkov et al., PRL 2007
Experiment: Hofferberth et al,. Nature 2007







Theoretical prediction

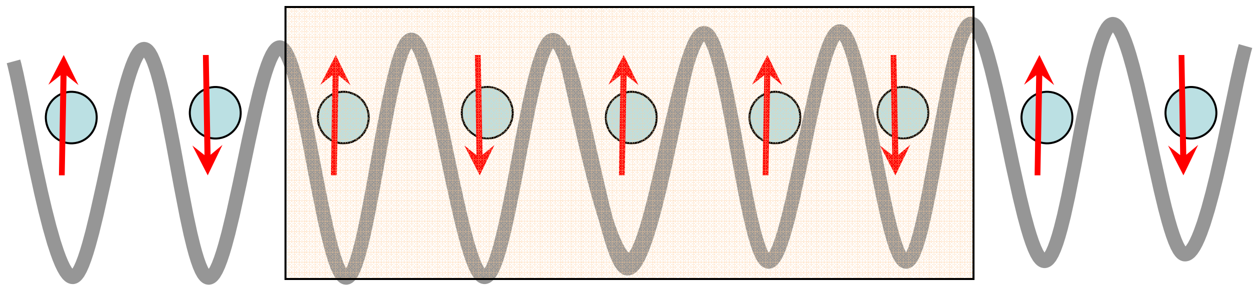
$$\boxed{\langle e^{i\phi(t)} \rangle \sim e^{-\left(\frac{t}{t_{\mathrm{T}}}\right)^{2/3}}}$$

T_{in} $[nK]$	$n_{1\mathrm{d}}$ $[1/\mu\mathrm{m}]$	$\frac{\omega_\perp}{2\pi}$ $[\mathrm{kHz}]$	α
82(28)	20(4)	3.3	0.64(8)
133(25)	34(5)	3.3	0.65(7)
171(19)	52(4)	3.3	0.64(4)
81(31)	22(4)	4.0	0.65(3)
128(23)	37(4)	4.0	0.66(3)
175(20)	51(5)	4.0	0.64(6)

Probing spin systems using distribution function of magnetization

Probing spin systems using distribution function of magnetization

Cherng, Demler, New J. Phys. 9:7 (2007)



Magnetization in a finite system $$M^z_{\text{tot}} = \sum_{i=1}^{L} M^z(i)$$

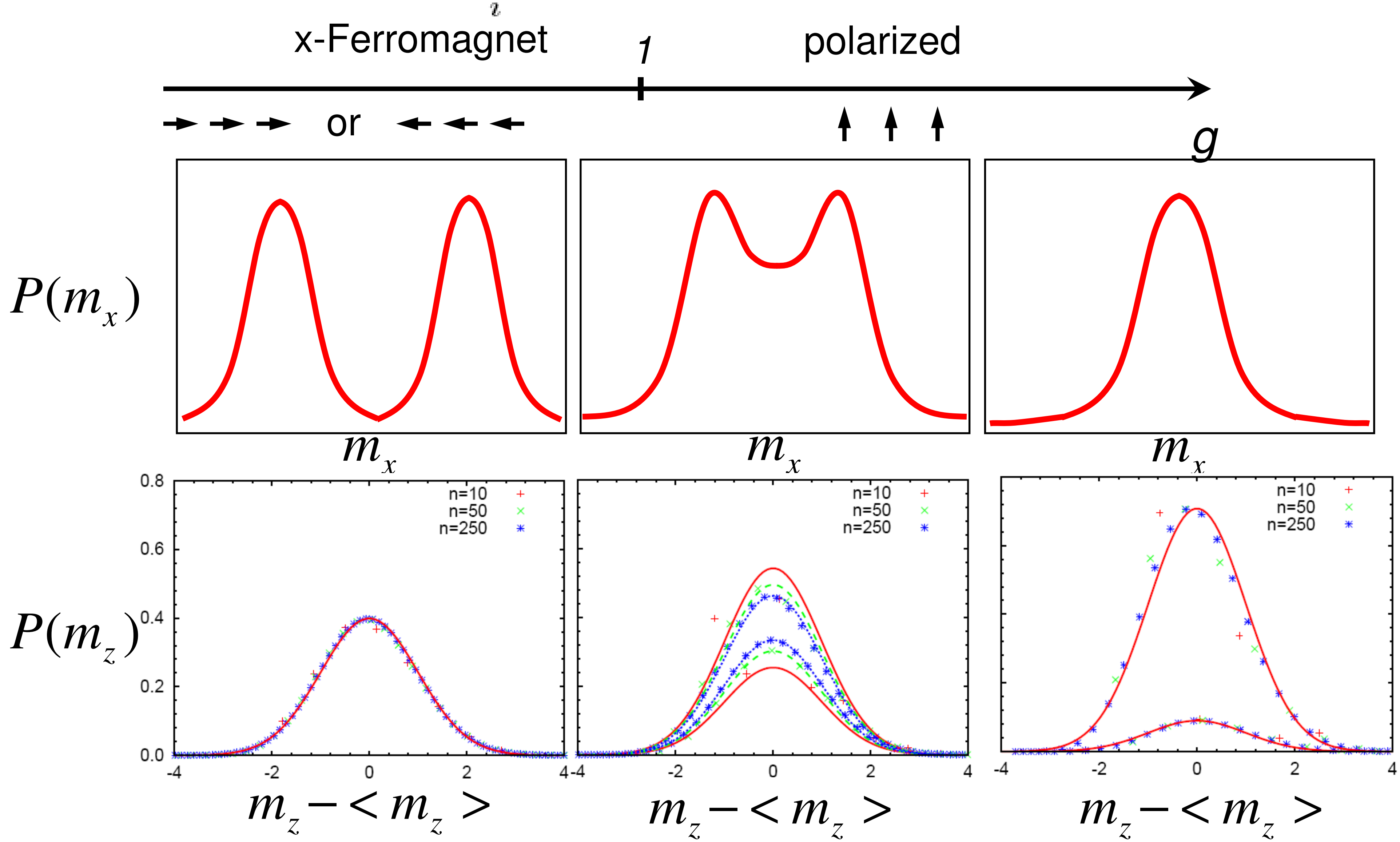
Average magnetization $$\langle M^z_{\text{tot}} \rangle = L \langle M^z \rangle$$

Higher moments of M^z_{tot} contain information about higher order correlation functions

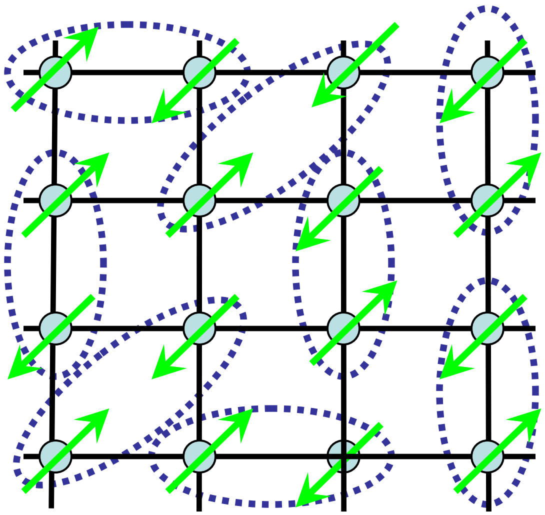
$$\langle (M^z_{\text{tot}} - \langle M^z_{\text{tot}} \rangle)^2 \rangle = L \sum_{ij} \langle (M_z(i) - \langle M^z \rangle) (M^z(j) - \langle M^z \rangle) \rangle$$

Distribution Functions

$$\mathcal{H} = -J \sum_i \left[2S^x(i)S^x(i+1) + gS^z(i) \right]$$



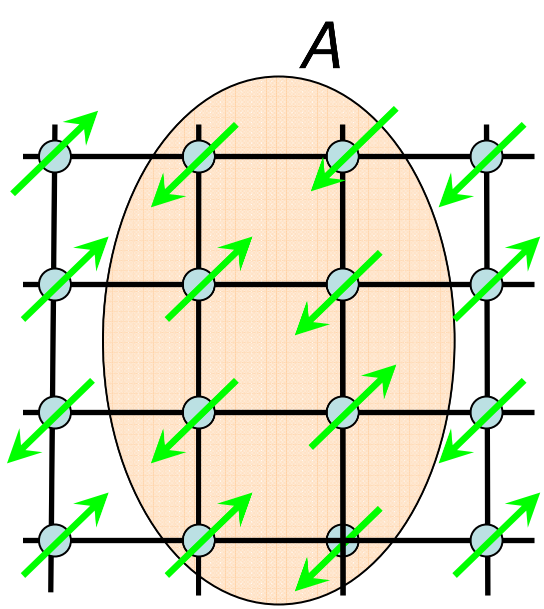
Using noise to detect spin liquids



Spin liquids have no broken symmetries
No sharp Bragg peaks

Algebraic spin liquids have long range spin correlations

$$\langle S_i \, S_j \rangle = \frac{e^{i\,Q\,r_{ij}}}{|\, r_i - r_j \,|^{1+\eta}}$$



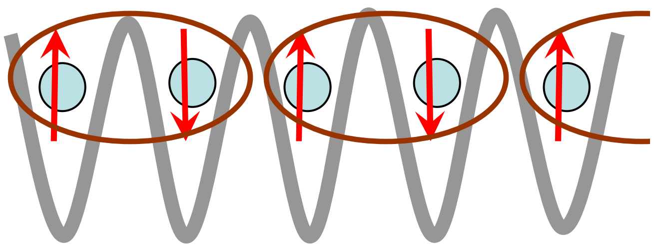
No static magnetization $\langle S_{\mathrm{A}} \rangle = 0$

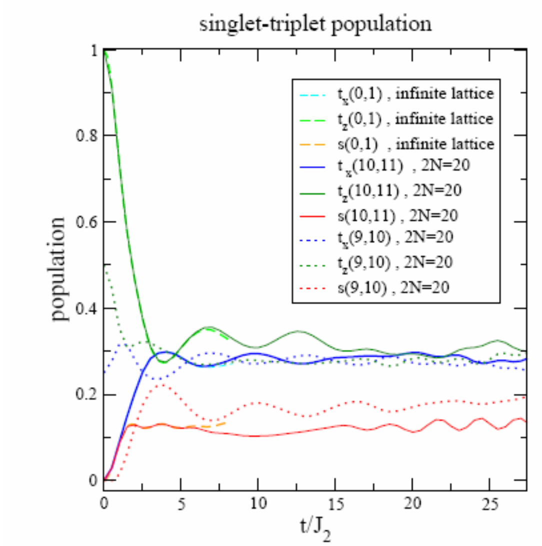
Noise in magnetization exceeds shot noise

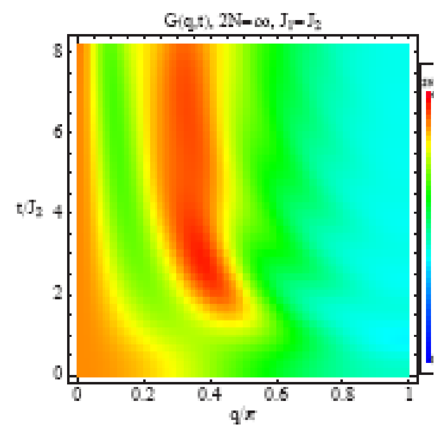
$$\langle S_{\mathrm{A}}^2 \rangle = \sum_{ij} \langle S_i \, S_j \rangle \sim A \int_{\mathrm{A}} \frac{r\,dr}{|\, r \,|^{1+\eta}} \sim A^{1+\frac{1-\eta}{2}}$$

Work in progress on theoretical milestones for MURI

Investigate coherent quantum dynamics of strongly interacting spin systems and superfluids







Investigate experimental requirements for reaching and detecting the antiferromagnetic phase
(Long lived doublon states)

Investigate theoretically new approaches to realizing and detecting of spin liquid states and anyon statistics
(Measuring spin loop operators using coupling to cavity)

MURI quantum simulation project

Phase I

Validation and Verification

Simulate solvable Hamiltonians. Compare with calculations.
Examples: low dimensional systems, precision study of Mott insulator phases, superexchange interactions, fermionic superfluidity in optical lattice.

New tools for detection and caracterization of strongly correlated states

Optical addressability → Quantum gas microscope

Critical velocity in moving superfluids

Bragg spectroscopy in optical lattices

Quantum noise analysis

Phase II

Combine all tools and methods developed during phase I to tackle goals of this MURI project:

Quantum magnetism

Fermionic superfluidity in systems with repulsive interactions

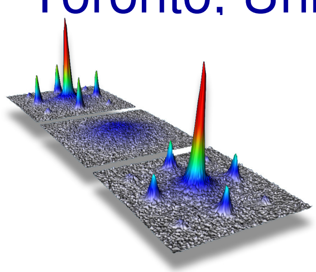
Ultimate goal: use the results of quantum analogue simulations to identify new solid state systems with favorable properties

Quantum Simulations of Condensed Matter Systems using Ultracold Atomic Gases

FY07 MURI Topic #18

Markus Greiner (principal investigator), Eugene Demler, John Doyle, Luming Duan, Mark Kasevich, Wolfgang Ketterle, Mikhail Lukin, Subir Sachdev, Martin Zwierlein, Joseph Thywissen,Immanuel Bloch, Peter Zoller

Collaborating Universities: Harvard, MIT, Stanford, Michigan, Toronto, University of Mainz, Germany, University of Innsbruck,



MURI
Program in
Optical Lattices