Probing many-body systems of ultracold atoms

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Collaboration with experimental groups of
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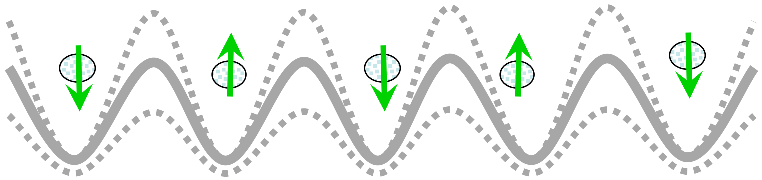
Harvard-MIT CUA

$$ NSF, MURI, DARPA, AFOSR

Outline

- Lattice modulation
- experiments with
- fermions



Also yesterday's talks by Henning Moritz and Andreas Ruegg

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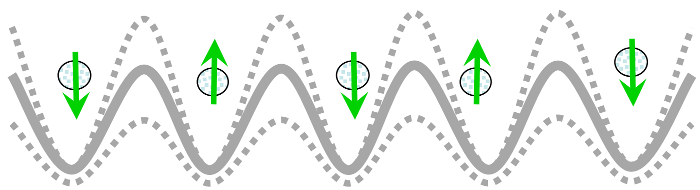
- Ramsey interference
- experiments in 1d

Lattice modulation experiments with fermions in optical lattice.



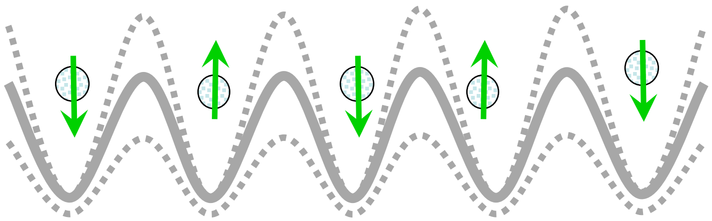
Probing the Mott state of fermions

Expts: Joerdens et al., Nature (2008)
Greif, Tarruell, Strohmaier, Moritz, Esslinger et al.

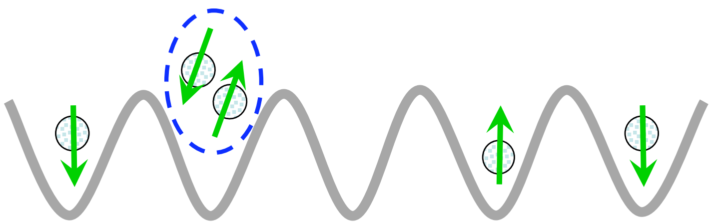
Theory: Kollath et al., PRA (2006)
Huber, Ruegg, PRA (2009)
Sensarma et al. PRL 2009
Pollet, Pekker, Demler, unpublished

Yesterday’s talks by Henning Moritz and Andreas Ruegg

Lattice modulation experiments
Probing dynamics of the Hubbard model



Modulate lattice potential V_0



Measure number of doubly occupied sites

$$t \sim \exp(-\sqrt{V_0/E_R}) \qquad U \sim \left(\frac{V_0}{E_R}\right)^{3/4}$$

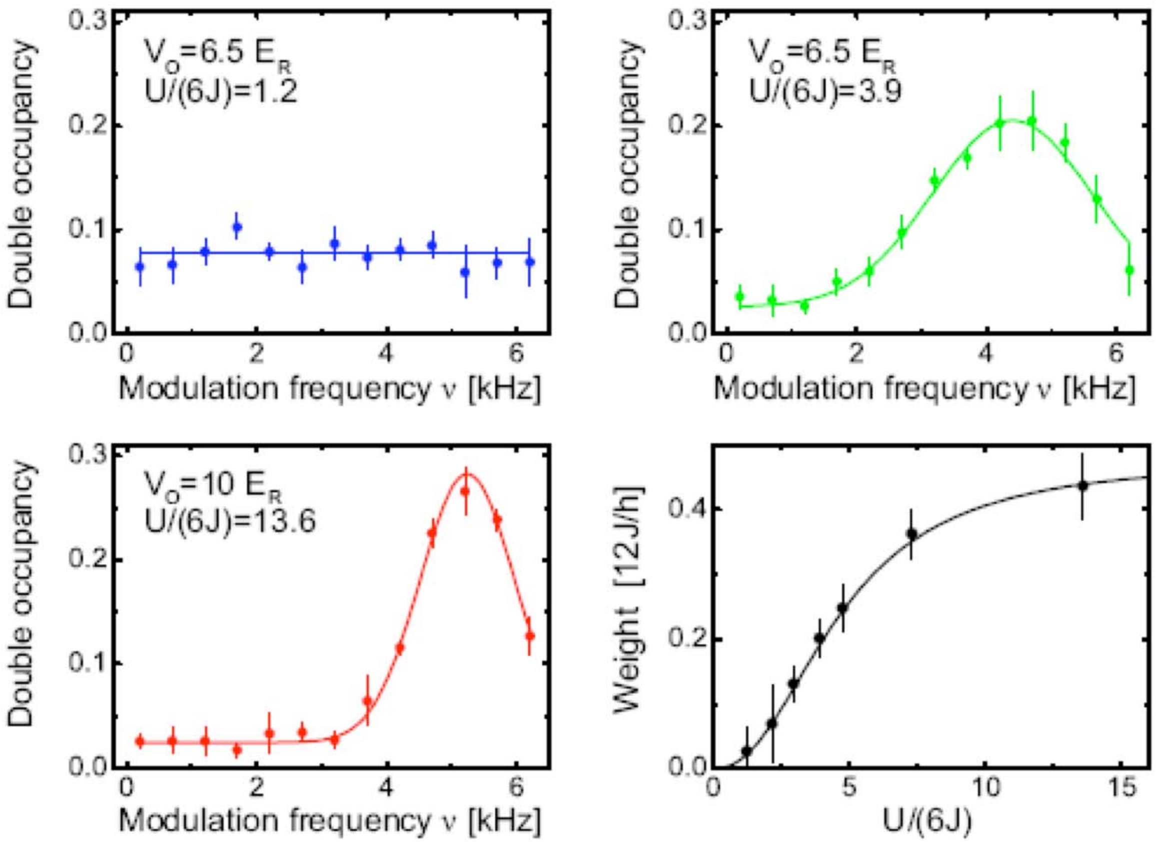
Main effect of shaking: modulation of tunneling

$$\mathcal{H}_{\text{pert}}(\tau) = \lambda t \cos\omega\tau \sum_{\langle ij\rangle\sigma} c^\dagger_{i\sigma} c_{j\sigma}$$

Doubly occupied sites created when frequency W matches Hubbard U

Lattice modulation experiments
Probing dynamics of the Hubbard model

R. Joerdens et al., Nature 455:204 (2008)



Mott state

Regime of strong interactions *U>>t.*

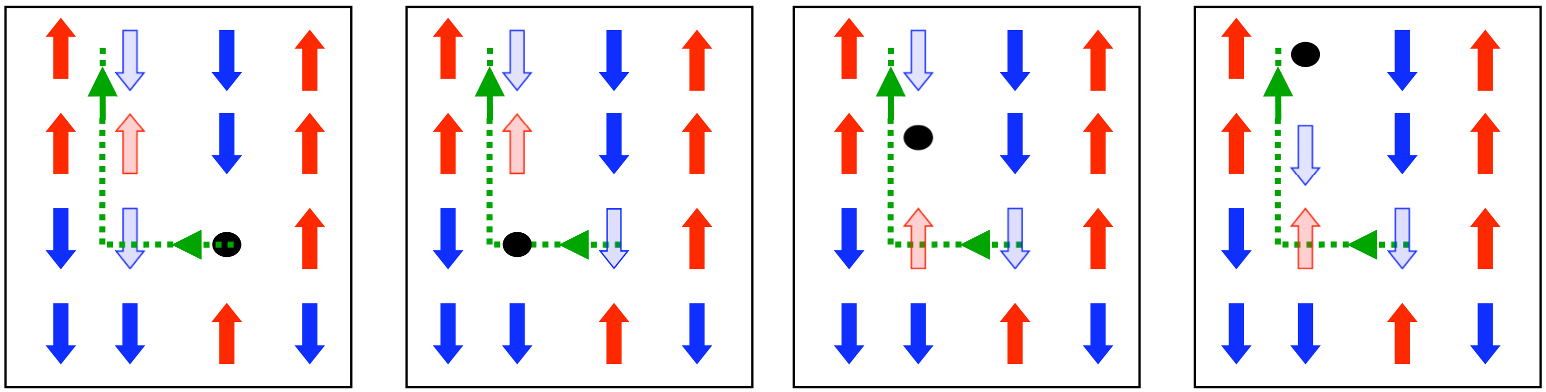
Mott gap for the charge forms at $T \sim U$

Antiferromagnetic ordering at $T_N \sim J = \frac{4t^2}{U}$

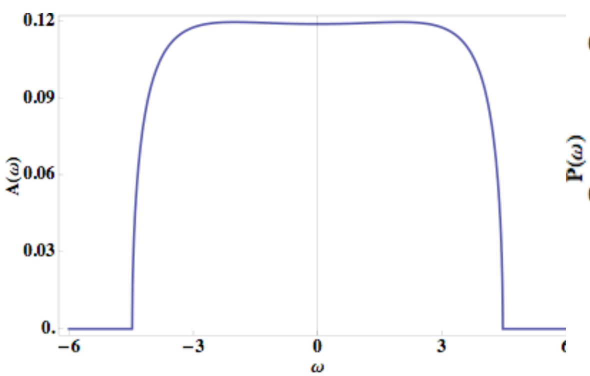
"High" temperature regime $T_N << T << U$

All spin configurations are equally likely.
Can neglect spin dynamics.

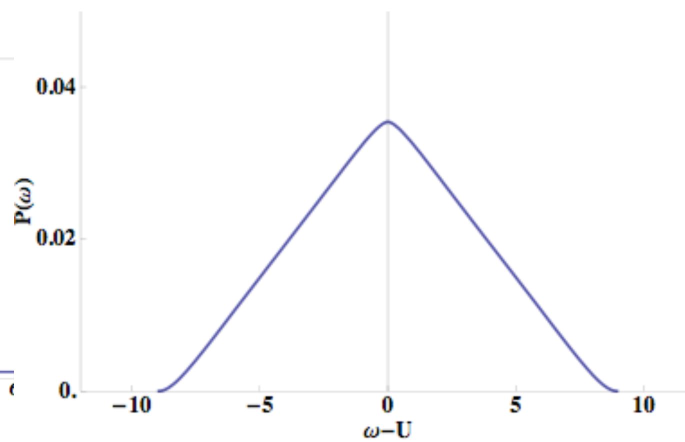
Doublon production rate depends on propagation of doublons and holes



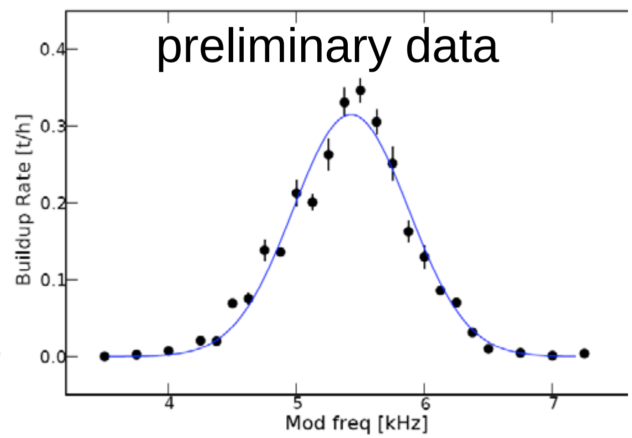
Retraceable Path Approximation *Brinkmann & Rice, 1970*



Spectral Fn. of single hole



Doublon Production Rate



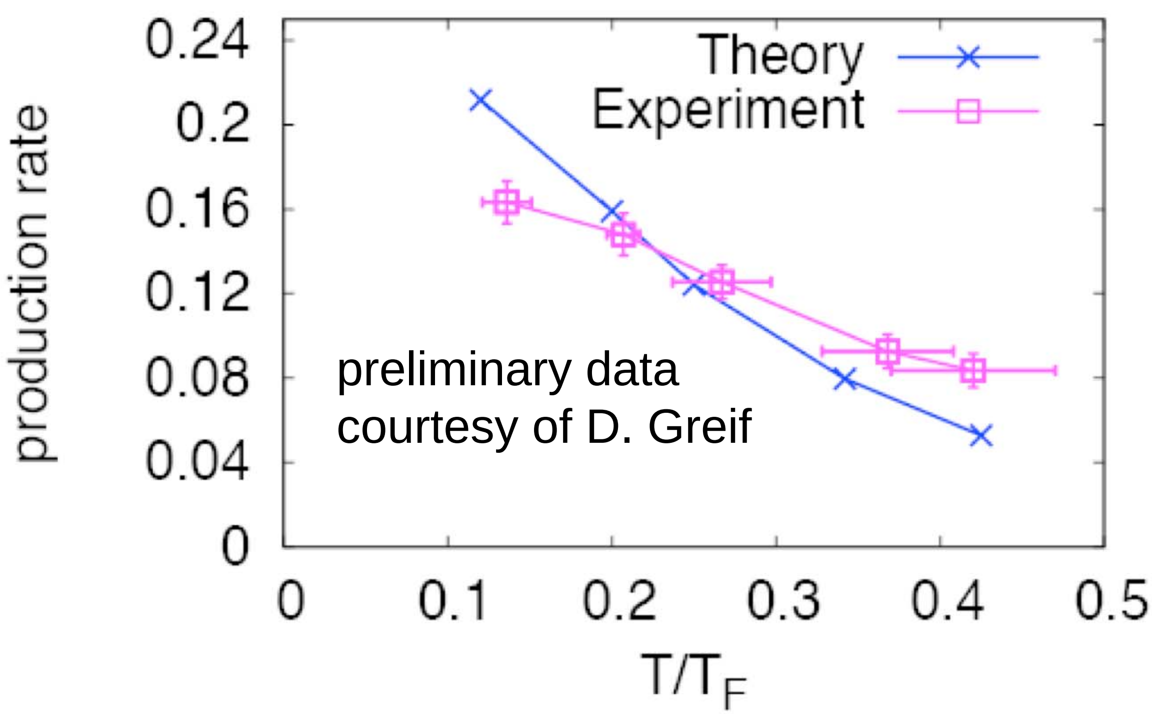
Experimental data courtesy of D. Greif

Lattice modulation experiments. Sum rule

$$P_d(\omega) = \frac{\pi^3}{2} t^2 \lambda^2 \sum_{r\delta\delta'} \int d\omega' A^d(r+\delta, \omega') A^h(r+\delta', \omega - U - \omega')$$

$A^{d(h)}$ is the spectral function of a single doublon (holon)

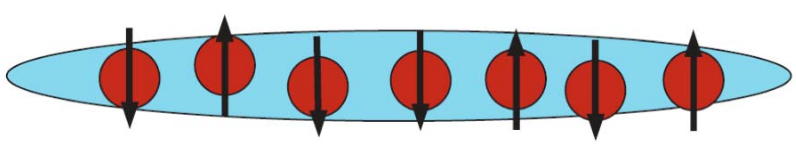
Sum Rule : $$\boxed{\int d\omega P_d(\omega) = \frac{\pi^3}{2} t^2 \lambda^2 z}$$ T-independent ?



Simple model to include temperature dependence and trap: multiply production rate by the average fraction of nearest neighbors with opposite spins

Ramsey Interference in one dimensional systems

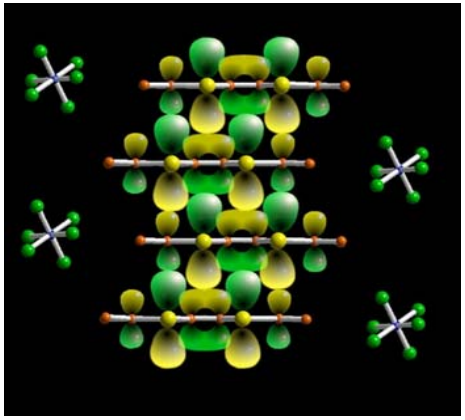
Using quantum noise to study many-body dynamics



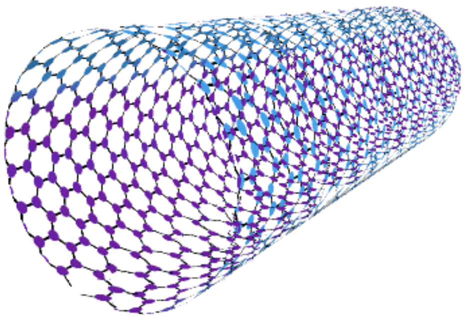
One dimensional systems in condensed matter

Non-perturbative effects of interactions:
Absense of long range order
Electron fractionalization

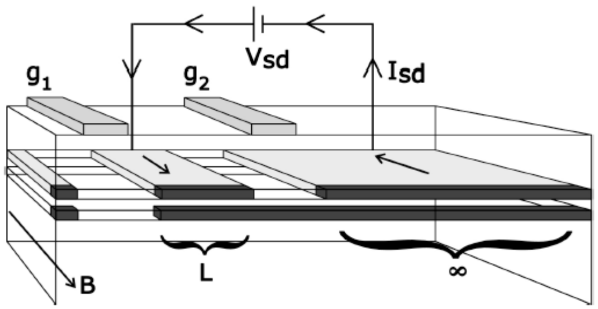
1d organics



carbon
nanotubes



GaAs/AlGaAs
Heterostructures

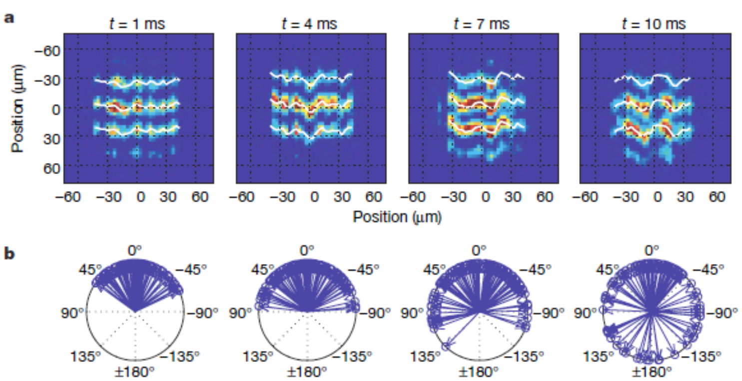


Emphasis on equilibrium properties and linear response

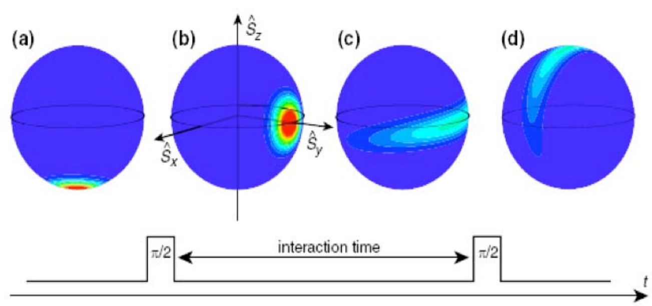
1d systems of ultracold atoms: analysis of nonequilibrium dynamics

Time evolution of coherence in split condensates
S. Hofferberth et al., Nature (2007)

S. Hofferberth[1,2], I. Lesanovsky[3], B. Fischer[1], T. Schumm[2] & J. Schmiedmayer[1,2]



1D Ramsey Interferometry (Widera, et.al PRL 2008)

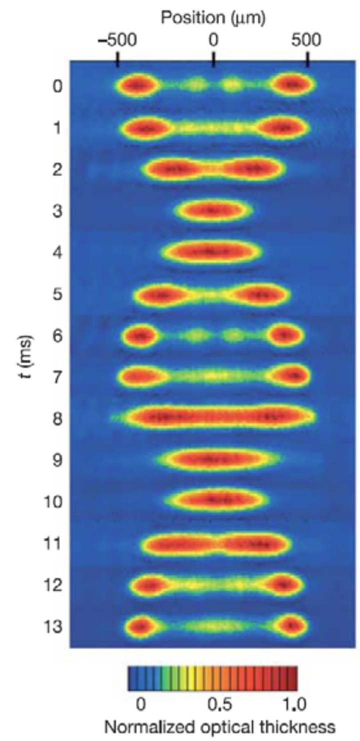


nature

LETTERS

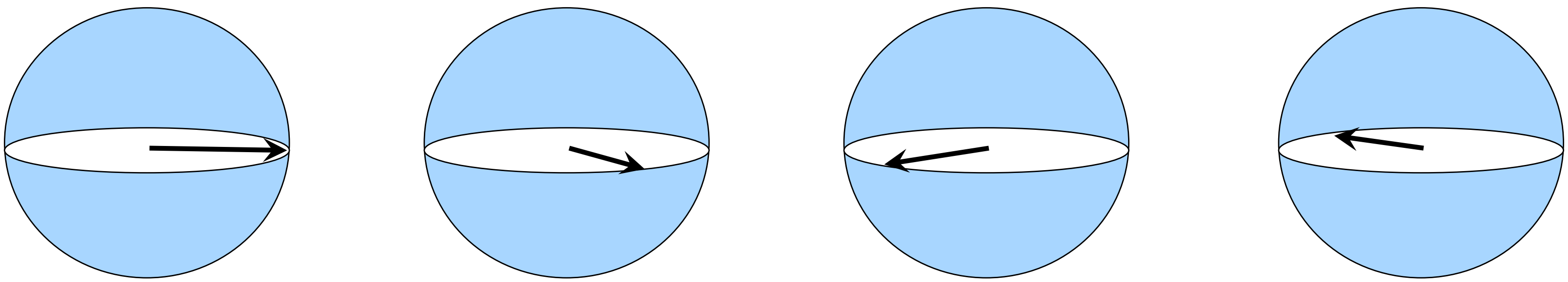
A quantum Newton's cradle

Toshiya Kinoshita[1], Trevor Wenger[1] & David S. Weiss[1]

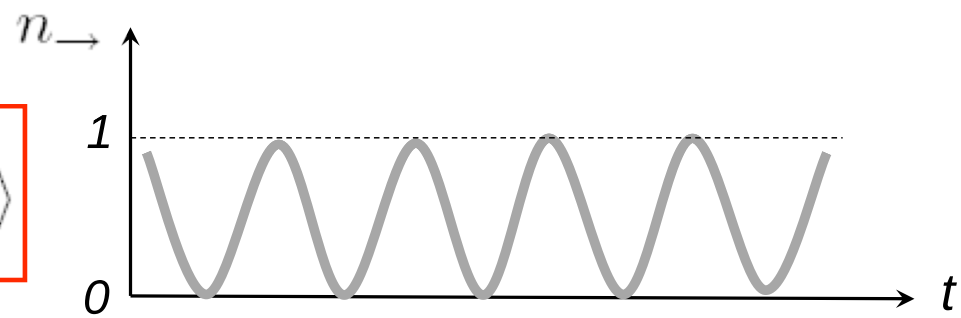


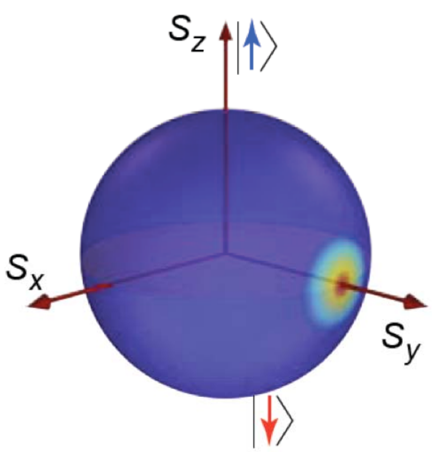
Introduction:
Ramsey Interference

Ramsey interference



$$|\Psi\rangle = e^{-iE_1 t}|\uparrow\rangle + e^{-iE_2 t}|\downarrow\rangle$$





Atomic clocks and Ramsey interference:
Working with *N* atoms improves the precision by $\sqrt{N}$.

Ramsey Interference with BEC

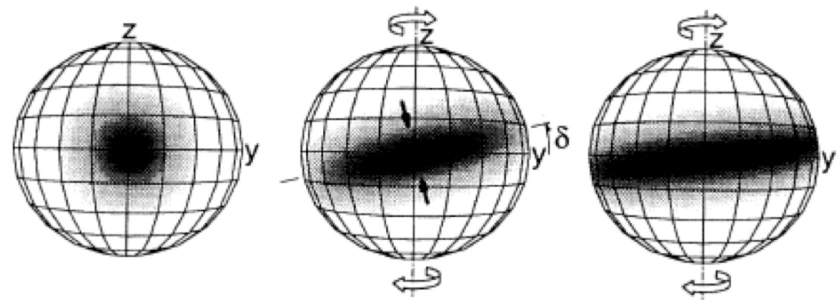
Single mode approximation

$$H = gS_z^2$$

M.Kitagawa, M.Ueda, PRA(1993)

$$|\psi(t=0)\rangle = \frac{1}{\sqrt{2^n}}\sum_m \binom{n}{m} |m\uparrow, n-m\downarrow\rangle$$

$$|\psi(t)\rangle = \frac{1}{\sqrt{2^n}}\sum_m \binom{n}{m} e^{-itg(2m-n)^2/4}|m\uparrow, n-m\downarrow\rangle$$



(a) (b) (c)

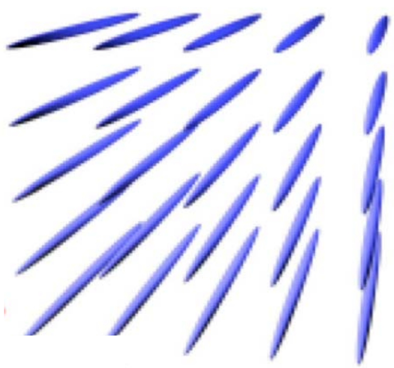
Gaussian distribution of S_z

Spin squeezing: possible application in quantum enhanced metrology

Sorensen, Moller, Cirac, Zoller, Lewensstein, …

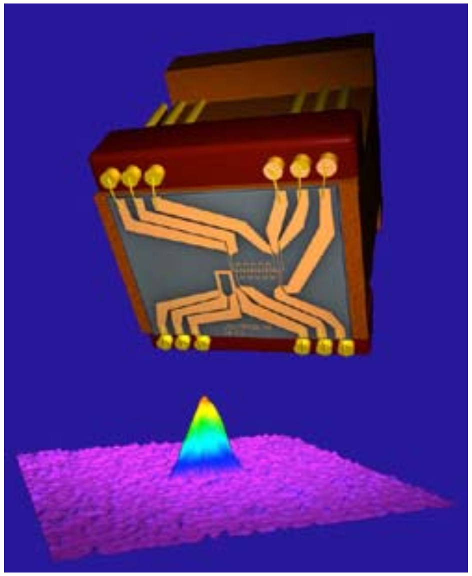
Ramsey Interference with 1d BEC

1d systems in optical lattices



Ramsey interference in 1d tubes:
A.Widera et al.,
B. PRL 100:140401 (2008)

1d systems in microchips



Two component BEC in microchip

Treutlein et.al, PRL 2004

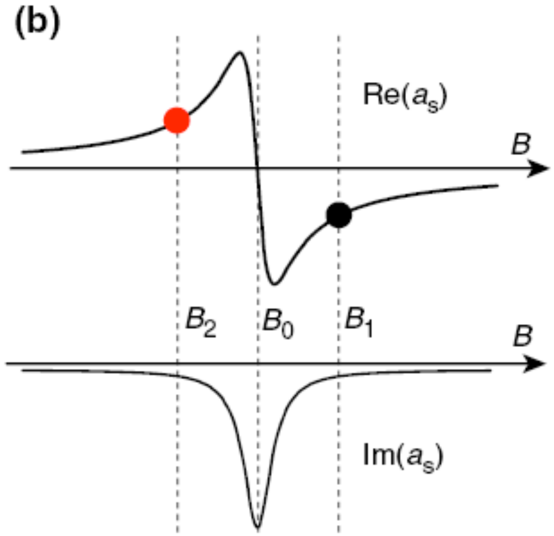
Ramsey Interference in 1d:
a probe of many-body dynamics

Ramsey interference in 1d condensates

Spin echo experiments

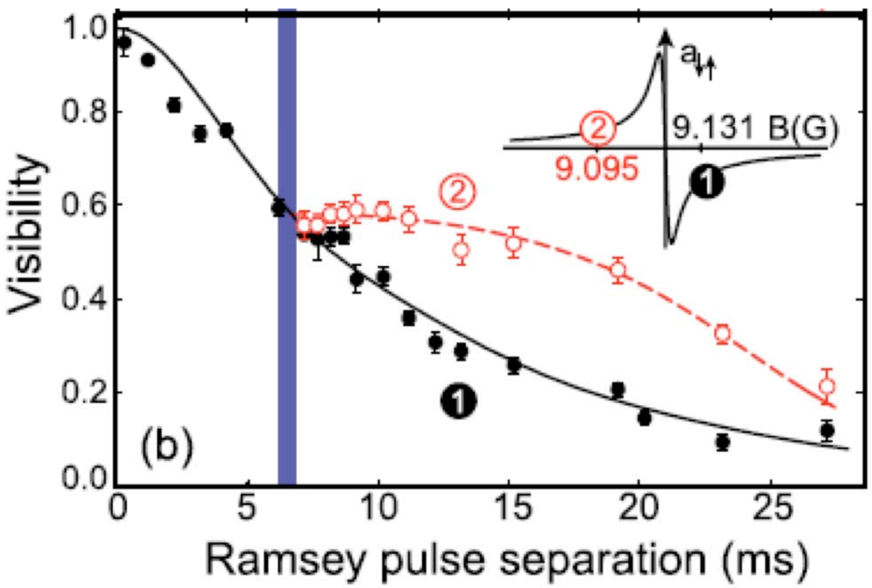
$$H = gS_z^2$$

$$g \to -g$$



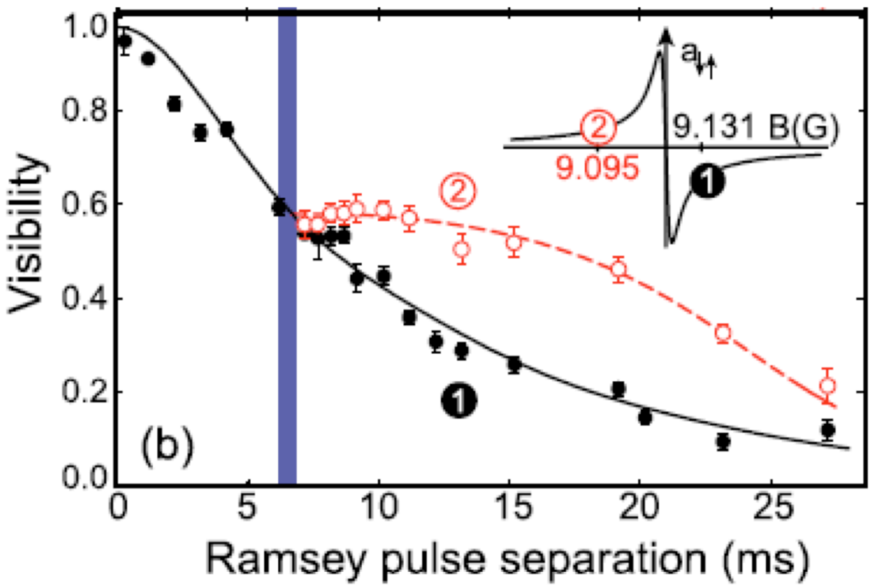
Expect full revival of fringes

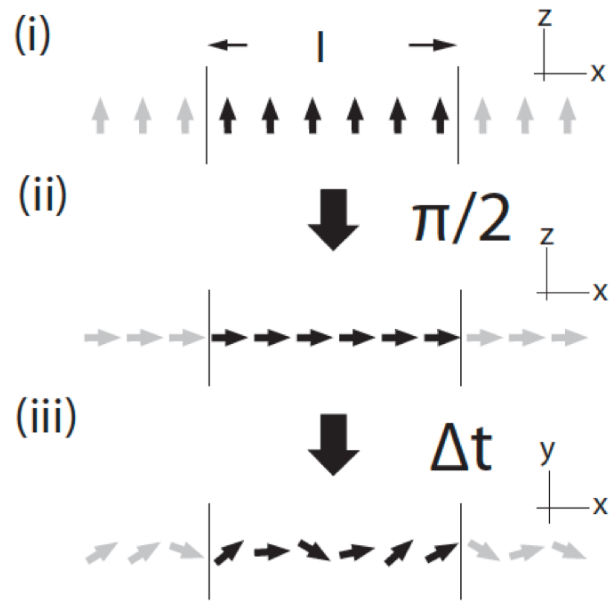
A. Widera, et al, PRL 2008



Only partial revival
after spin echo!

Spin echo experiments in 1d tubes



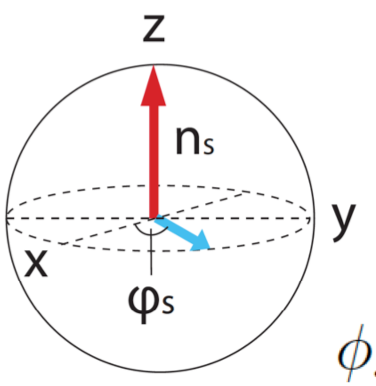


Single mode approximation does not apply.
Need to analyze the full model

$$\mathcal{H} = \int dx \left[g_c (n_1 + n_2)^2 + g_s (n_1 - n_2)^2 + \frac{|\nabla \Psi_1|^2}{2m} + \frac{|\nabla \Psi_2|^2}{2m} \right]$$

Low energy effective Hamiltonian for spin dynamics

Bosonization



$$
\begin{aligned}
S_x(r) &= \rho\cos\phi_s(r) \\
S_y(r) &= \rho\sin\phi_s(r) \\
S_z(r) &= n_s(r)
\end{aligned}
$$

ϕ_s and n_s are canonically conjugate variables.

Tomonaga-Luttinger Hamiltonian

$$
\begin{aligned}
H_s &= \int dr \left[\frac{\rho}{2m}(\nabla\phi_s)^2 + g_s n_s^2\right] \\
&= \sum_{k\neq 0} c_s |k| b^\dagger_{s,k} b_{s,k} + g_s n_{s,0}^2
\end{aligned}
$$

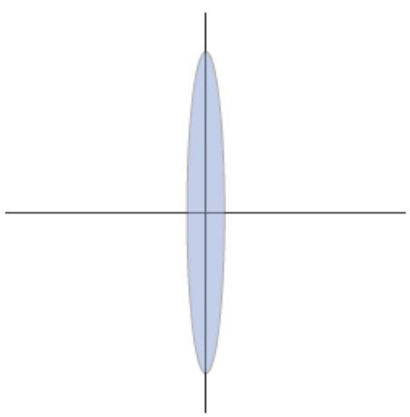
Ramsey interference: Initial State

After p/2 pulse, spins point in x direction

$$S_x(r) \;=\; \rho \,\cos\phi_s(r)$$

Small uncertainty in $\phi_s(r)$

Initial state: squeezed state in f_s



$$|\psi(t=0)\rangle \;=\; \exp\left(\sum_k W_k b_k^\dagger b_{-k}^\dagger\right)|0\rangle$$

W_k determined from

$$\langle S^z(r) S^z(r')\rangle = \rho\delta(r-r')$$

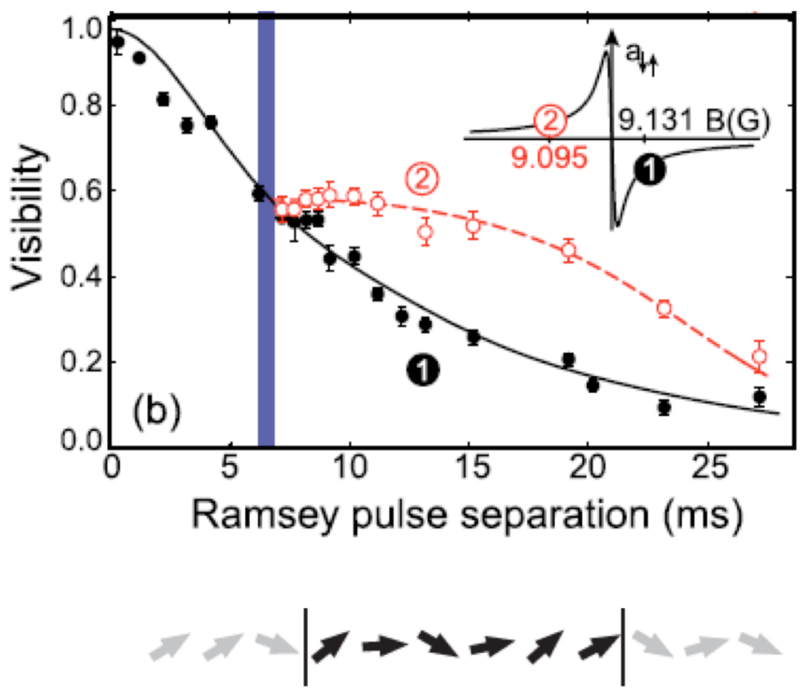
Short distance cut-off at spin healing length

related argument in Bistrizer, Altman, PNAS (2008)

Ramsey interference in 1d
Time evolution

$$|\Psi(t)\rangle \;=\; \exp\left(W_k \, e^{iE_k t} \, b_k^\dagger \, b_{-k}^\dagger \right)$$

Luttinger liquid provides good agreement with experiments.
A. Widera et al., PRL 2008. Theory: V. Gritsev

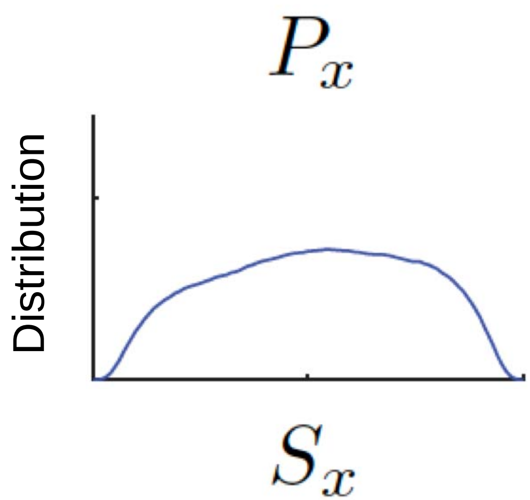


Technical noise could also lead to the absence of echo

Need “smoking gun” signatures of many-body decoherece

Distribution functions of Ramsey amplitude

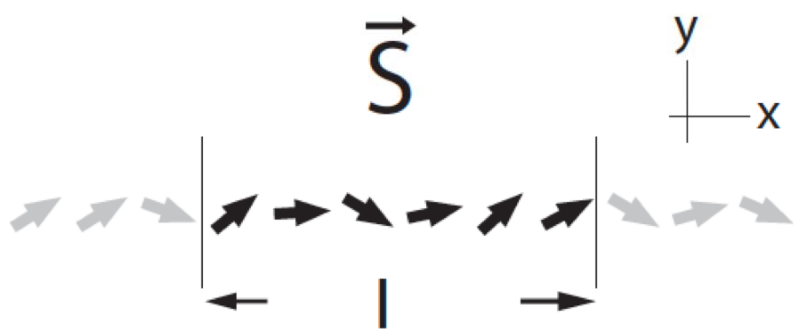
Probing spin dynamics through distribution functions



Distribution function contains information about higher order correlations

Joint distribution function can also be obtained

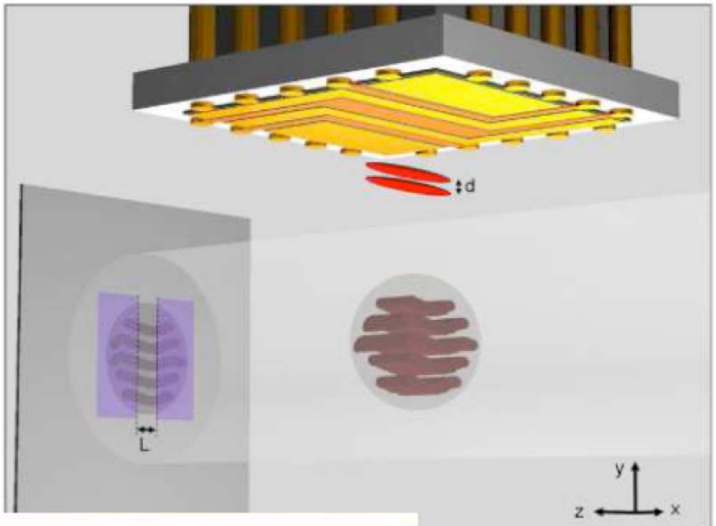
$$
\begin{aligned}
S_x(r) &= \rho \cos \phi_s(r) \\
S_y(r) &= \rho \sin \phi_s(r)
\end{aligned}
$$

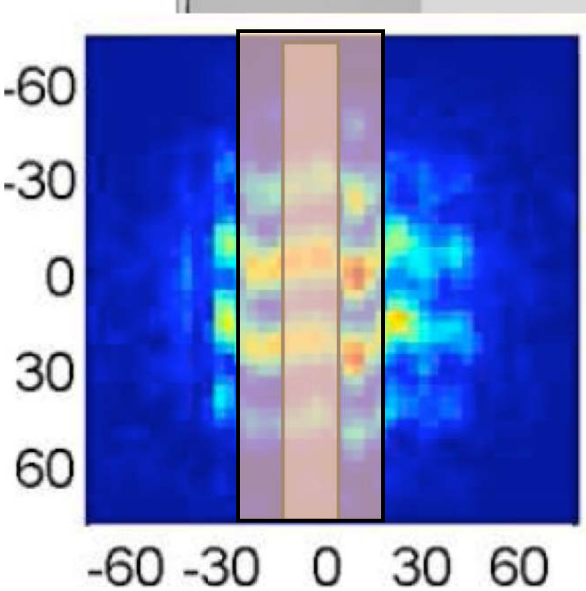


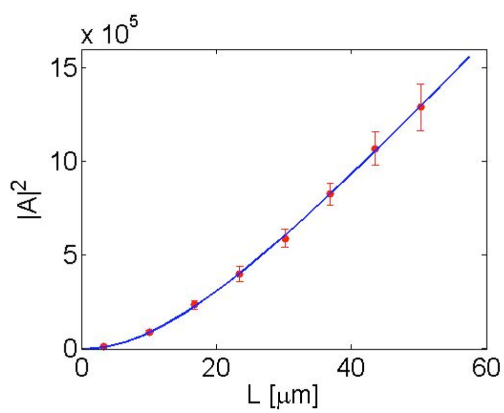
Interference of independent 1d condensates

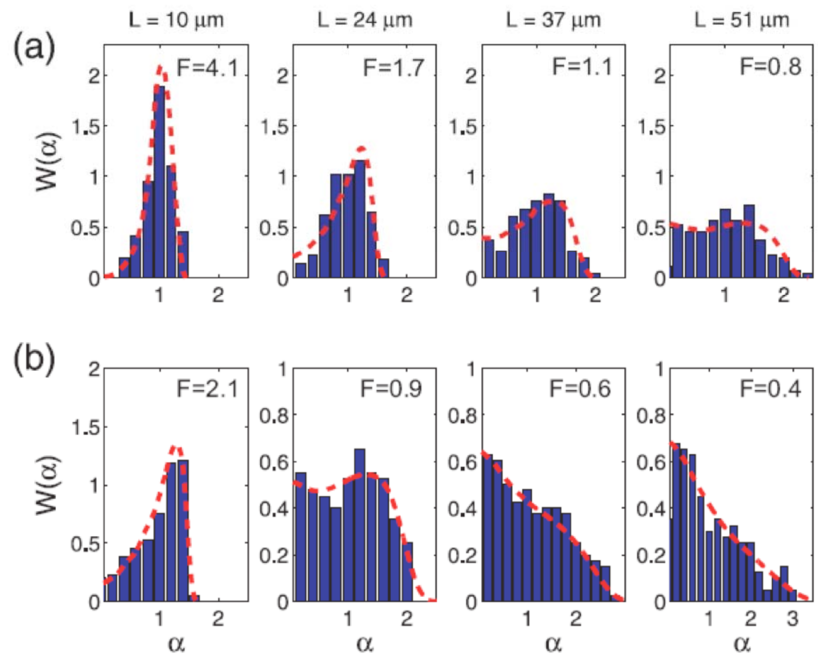
S. Hofferberth, I. Lesanovsky, T. Schumm, J. Schmiedmayer,
A. Imambekov, V. Gritsev, E. Demler, Nature Physics (2008)

Higher order correlation functions probed by noise in interference









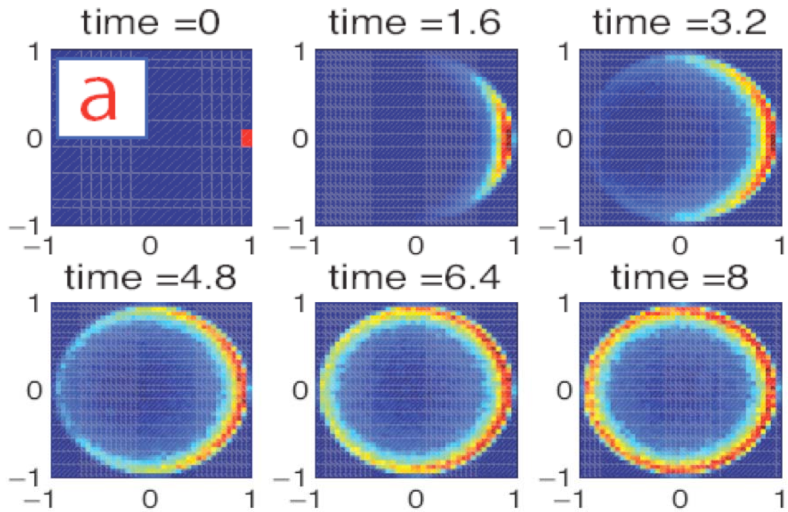
Joint distribution functions

Short segments

|S|^2 does not change

but Sx decays

$$\frac{\pi^2 l}{4\,K_s\,\xi_s} << 1$$

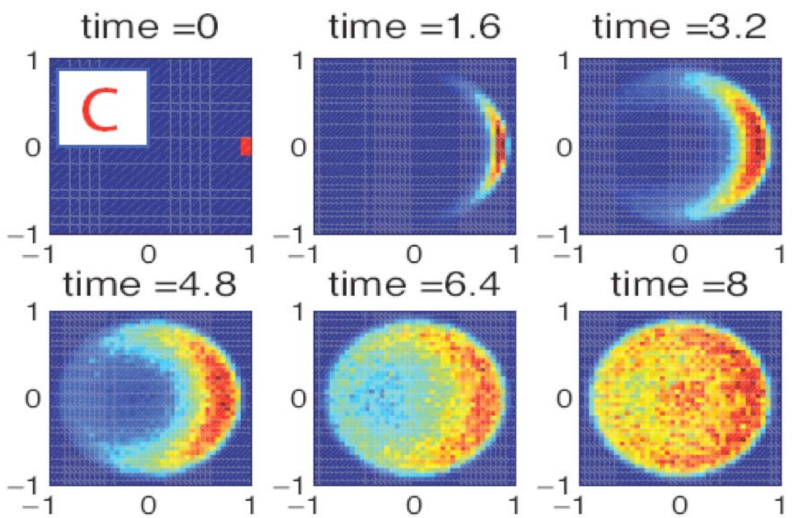


S_x

Long segments

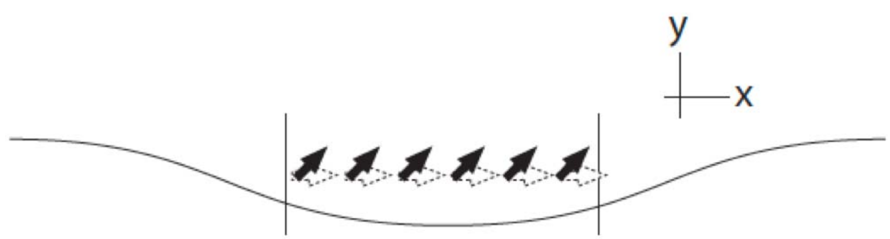
both Sx and |S|^2 decay

$$\frac{\pi^2 l}{4\,K_s\,\xi_s} >> 1$$

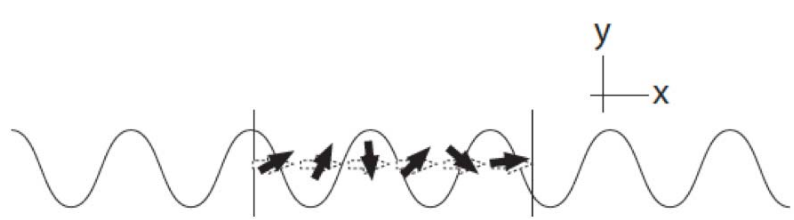


Two regimes of spin dynamics

Modes with λ>l leads to the decay of Sx but not |S|

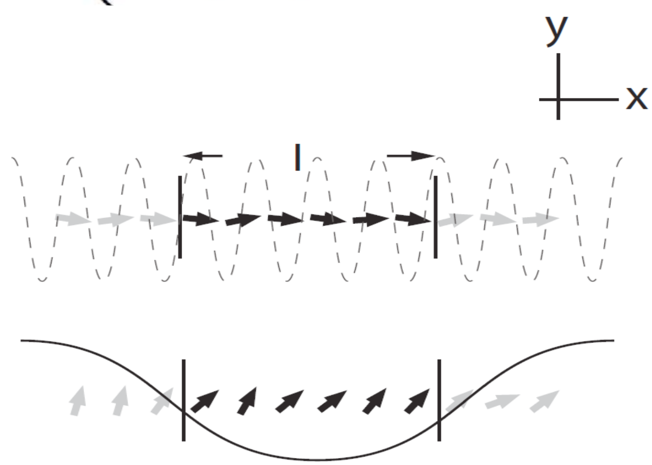


Modes with λ<l leads to the decay of both Sx and |S|



Analytic solution for the distribution function

$$P_l^{x,y}(\alpha,t) = \int_{-\infty}^{\infty}\int_{-\pi}^{\pi}\prod_k e^{-\lambda_{rsk}^2/2}d\lambda_{rsk}d\lambda_{\theta sk}$$
$$\delta\left(\alpha-\rho\int_{-l/2}^{l/2}dre^{i\chi(r,t,\{\lambda_{jsk}\})}\right)$$
$$\chi(r,t,\{\lambda_{jsk}\}) = \frac{1}{\sqrt{L}}\sum_k \lambda_{rsk}\sqrt{\langle|\phi_{s,k}(t)|^2\rangle}\sin(kr+\lambda_{\theta sk})$$
$$\frac{\langle|\phi_{s,k}|^2\rangle}{L} = \frac{1}{2N}\left\{\left(\frac{\pi\rho}{|k|K_s}\right)^2\sin^2(c_s|k|t)+\cos^2(c_s|k|t)\right\}$$



Summary

- Suggested unique signatures of the multimode decoherence of Ramsey fringes in 1d
- Ramsey interferometer combined with study of distribution function is a useful tool to probe many-body dynamics
- Joint distribution functions provide simple visualization of complicated many-body dynamics