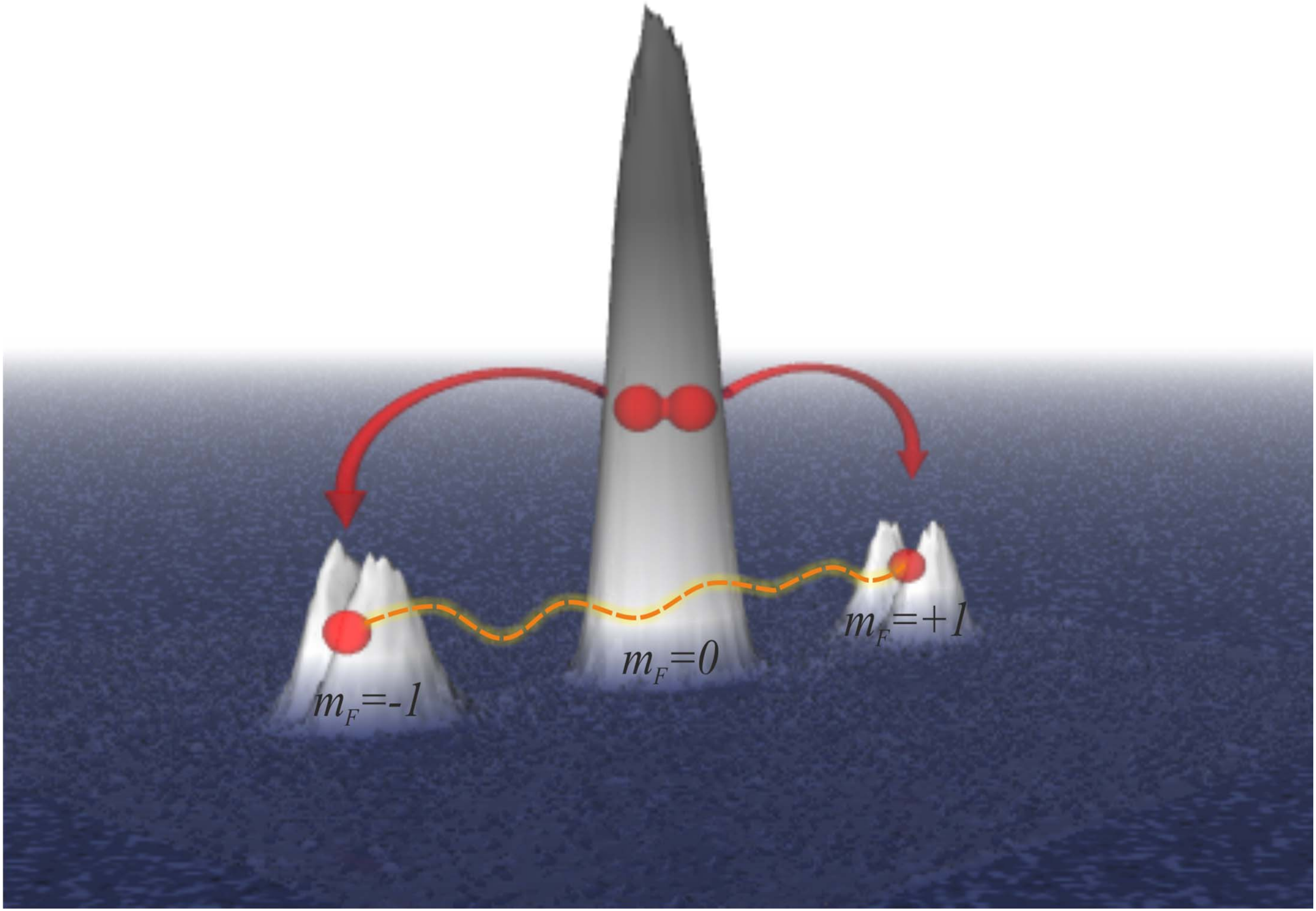
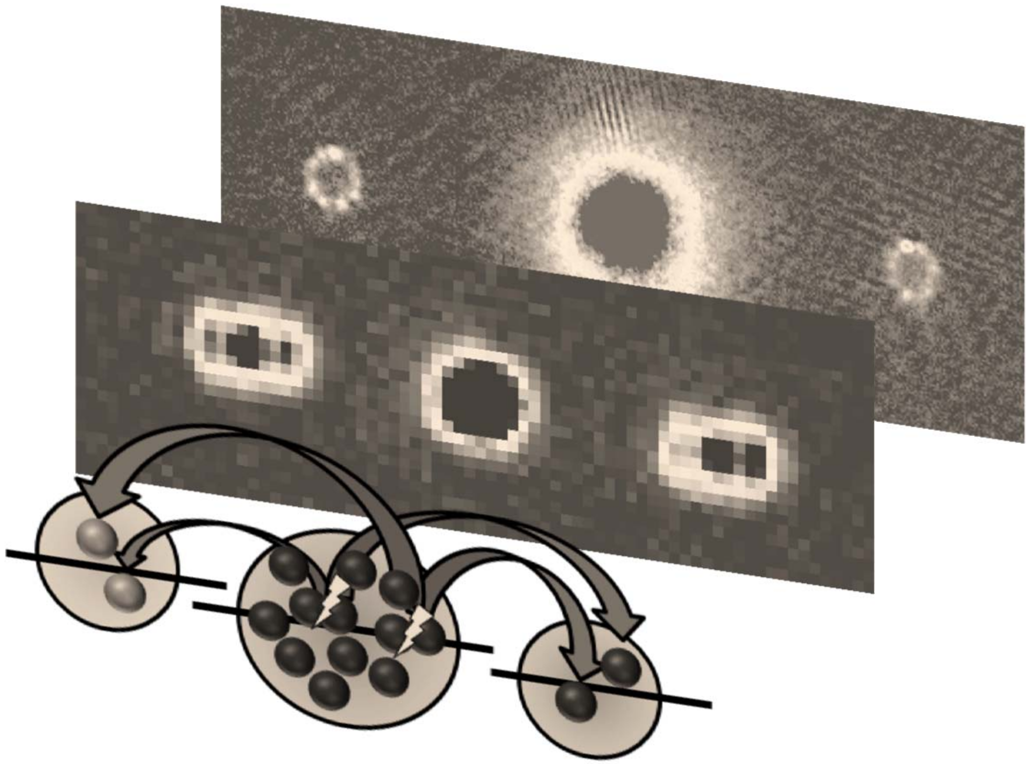


m_F=-1
m_F=0
m_F=+1

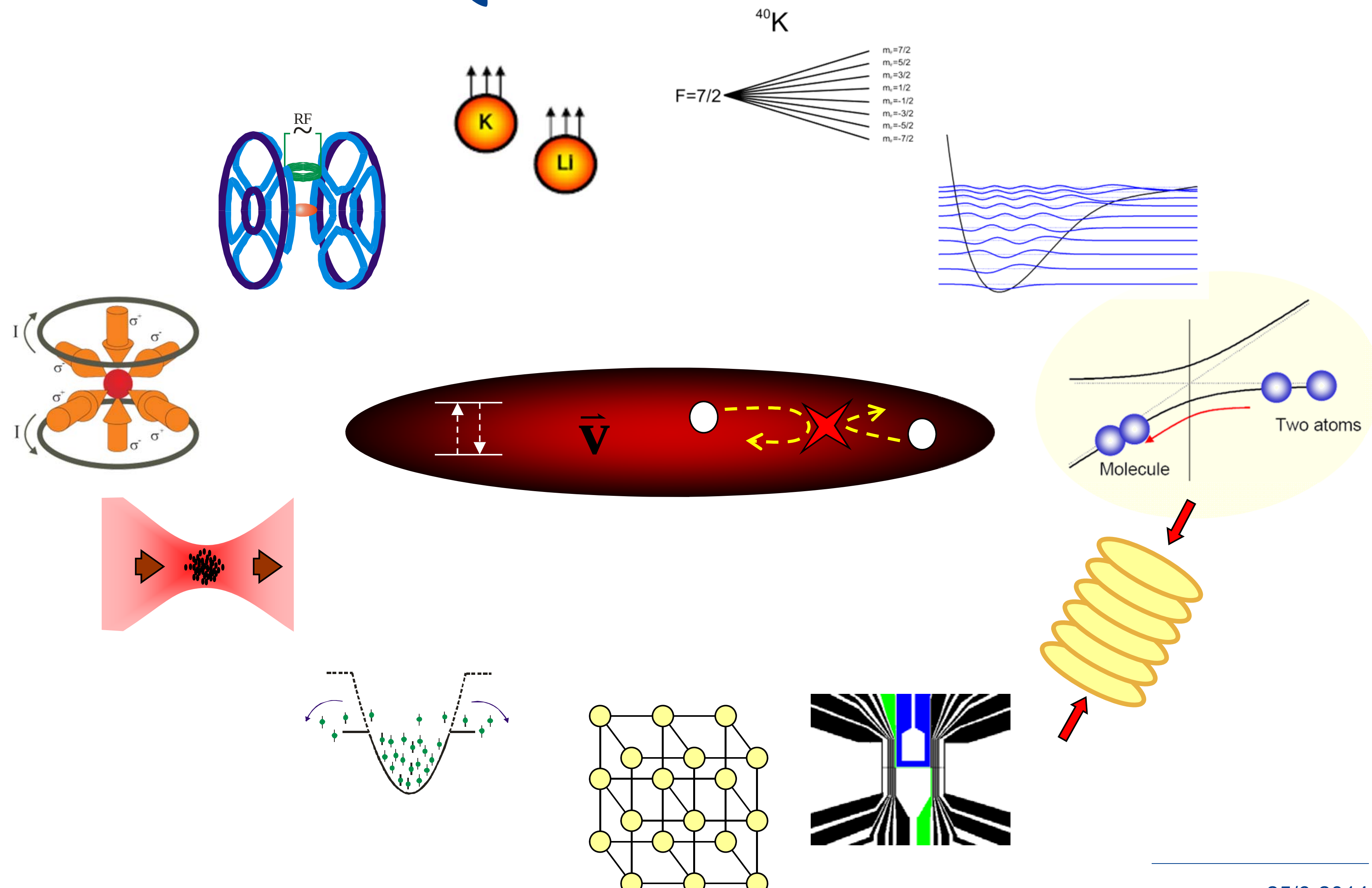
AARHUS UNIVERSITET

Correlations and entanglement in spinor quantum gasses

J. Arlt

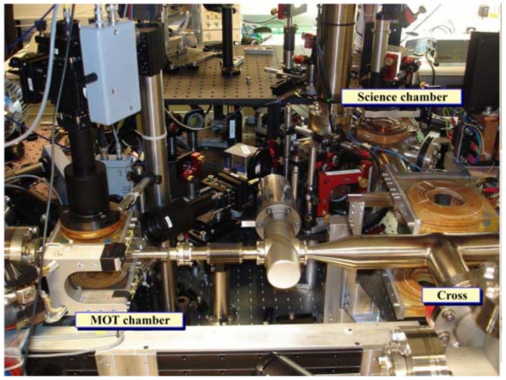


ULTRACOLD QUANTUM GASES GROUP



Experiments:

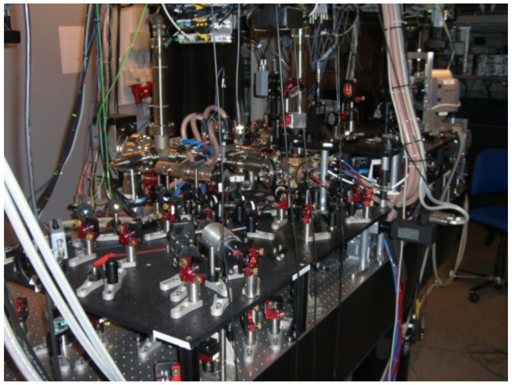
Ultracold Bosons in Optical Lattices



- Quantum optics with matter waves
- Spinor dynamics in 2D
- Faraday detection

Andrew Hilliard | Poul Pedersen | Miroslav Gajdacz

Multi Species Quantum Gases

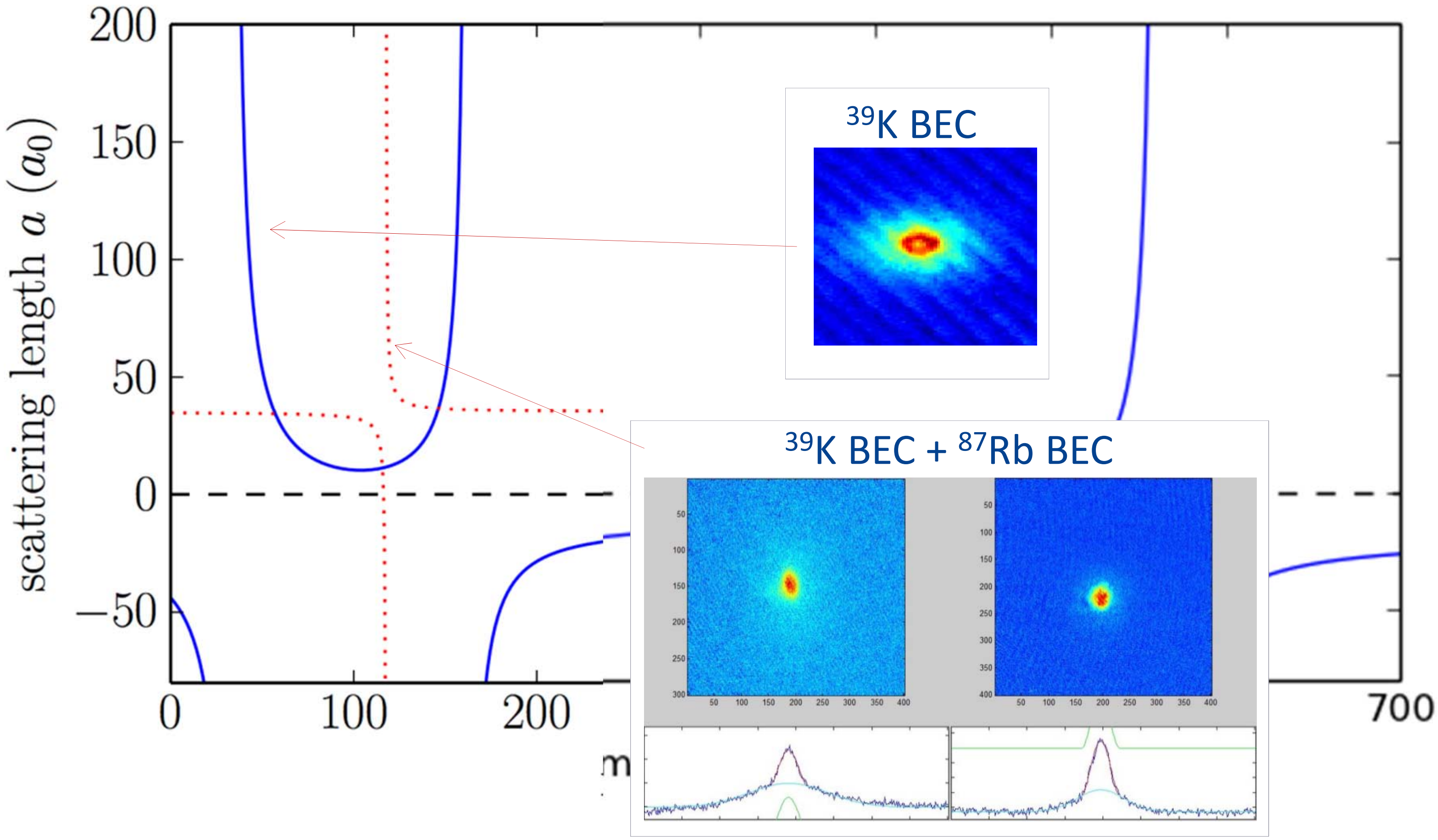


- multi-species quantum gases
- phases in tuneable mixtures
- bosonic polaron physics

Nils Winter | Lars Wacker | Nils Jørgensen

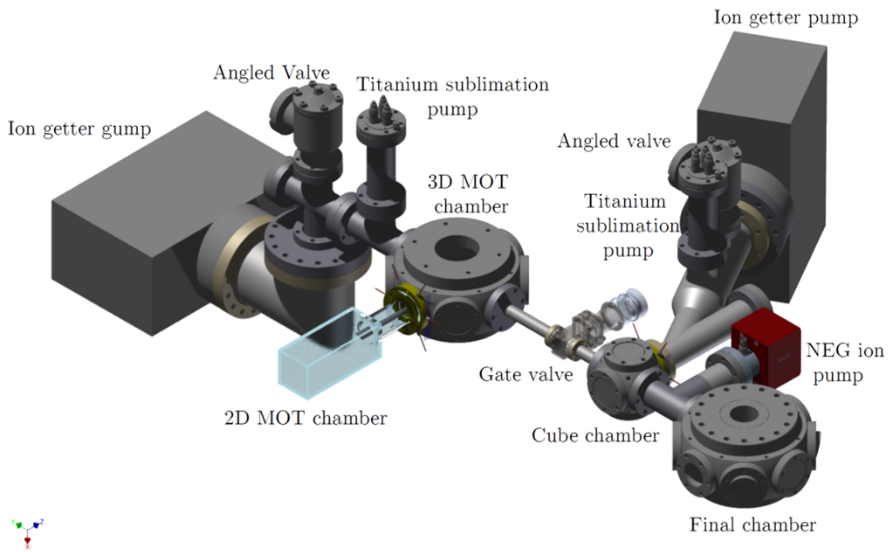
AARHUS UNIVERSITET

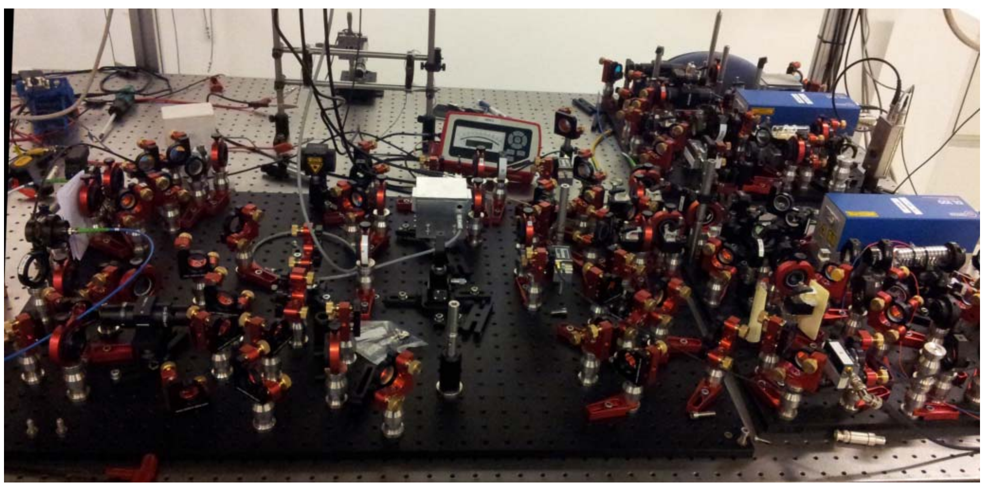
Mix - Multi Species Quantum Gases



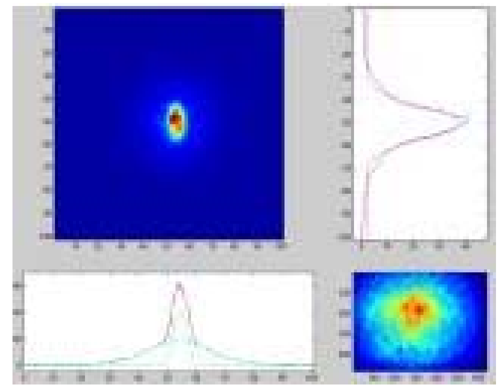
Potassium in $|F = 1, m_F = -1\rangle$

HiRes - High Resolution Experiment





Jacob Sherson



Romain Mueller

Robert Heck

PostDocs: Mark Bason, Wenzhuo Zhang, Mario Napolitano

Laboratory visits:

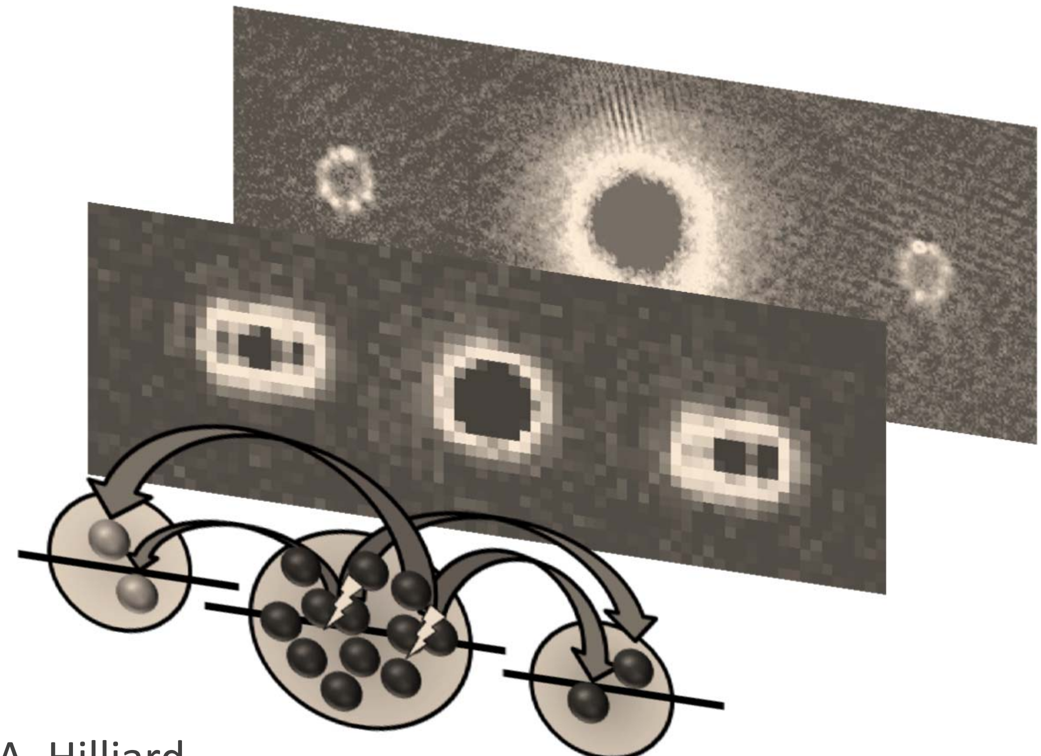
Thursday (tomorrow) at 13:00 !

We will leave together from AIAS.
The labs are within walking
distance.

AARHUS UNIVERSITET

Correlations and entanglement in spinor quantum gasses

J. Arlt



P. Pedersen, M. Gajdacz, J. Sherson, A. Hilliard
Aarhus Universitet

B. Lücke, J. Peise, F. Deuretzbacher, W. Ertmer, L. Santos, C. Klempt
Leibniz Universität Hannover

G. Vitagliano, G. Tóth
University of the Basque Country

AARHUS UNIVERSITET

Precision Measurements in Physics

Length

...

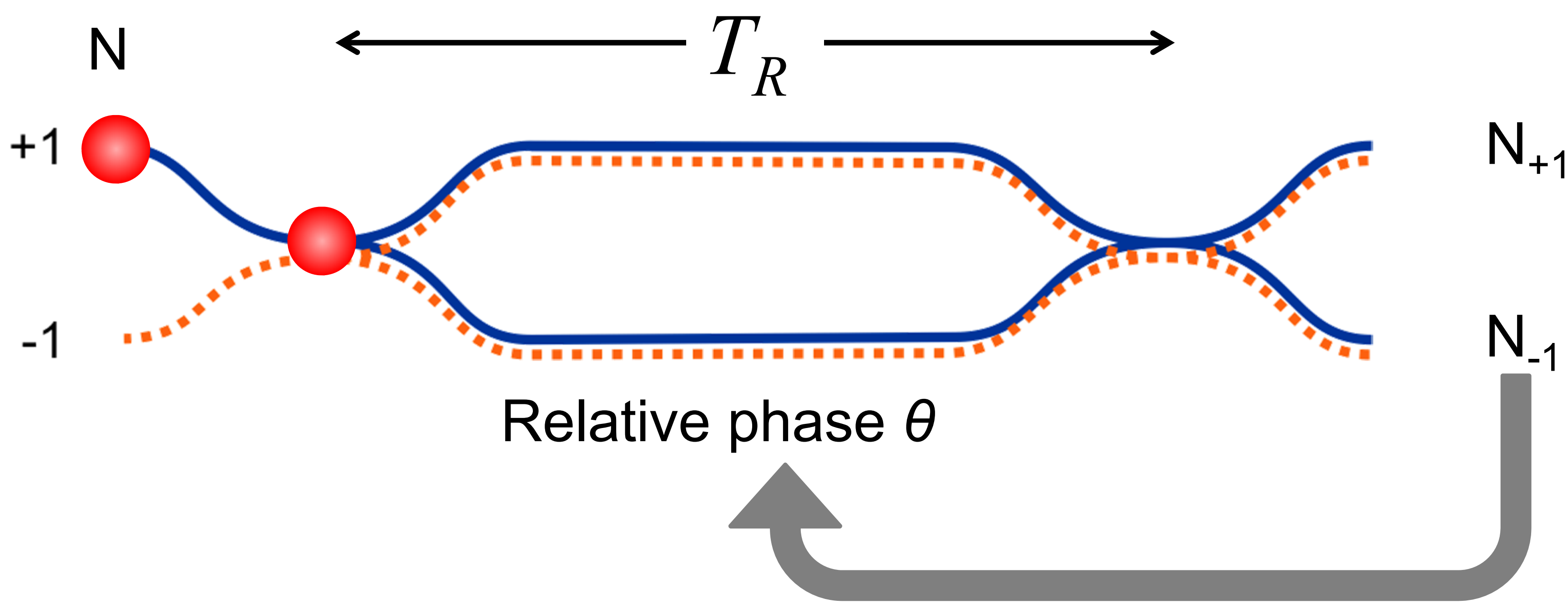
Gravitational Wave Detector

Time

...

Atomic Clock

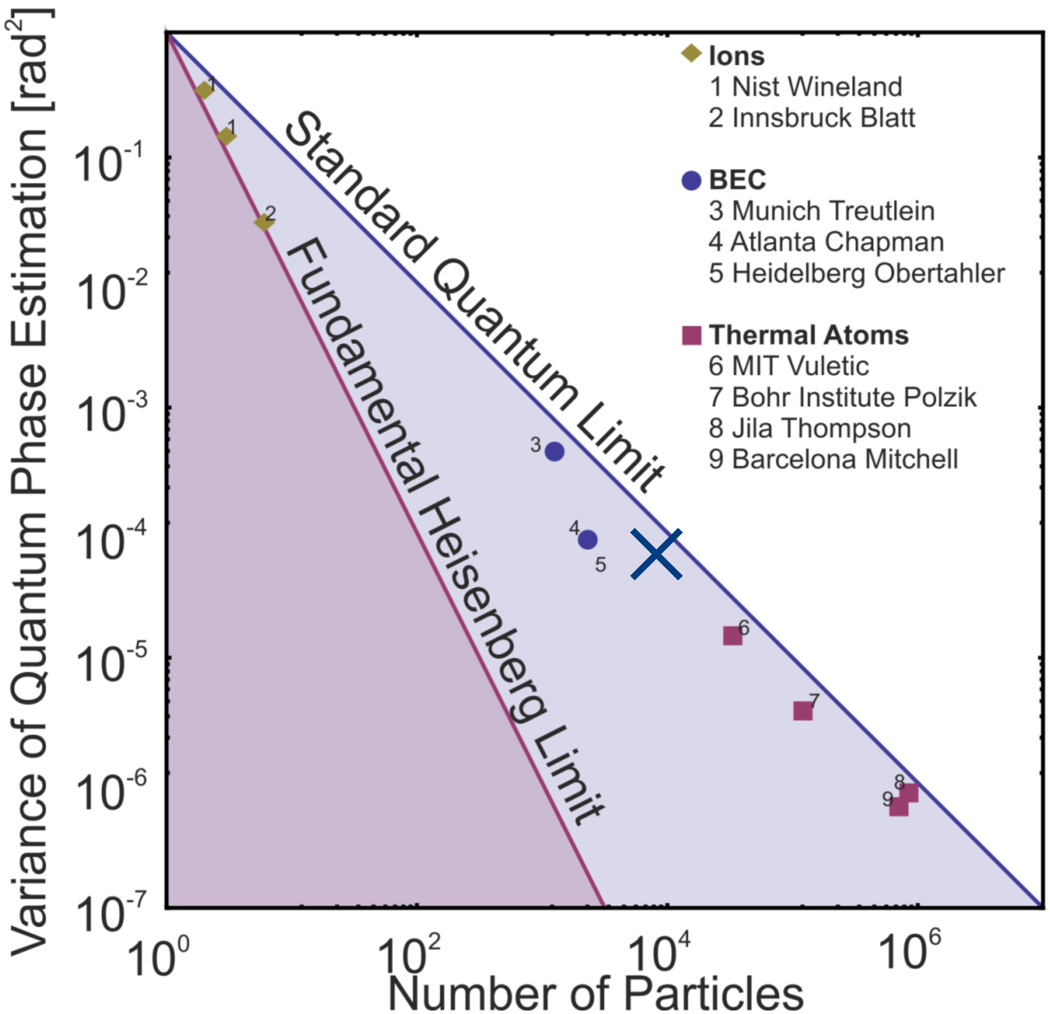
Atom interferometry



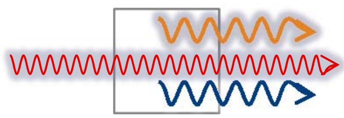
Phase estimation uncertainty:

$$\frac{\Delta\theta}{\theta}(\tau) = \frac{1}{\omega_0 T_{\mathrm{R}} \sqrt{N}} \sqrt{\frac{T_{\mathrm{prep}} + T_{\mathrm{R}}}{\tau}}$$

Solution: Sub-shot-noise Interferometry



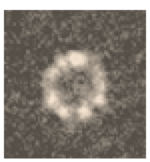
Content



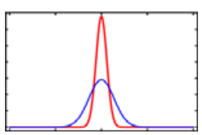
Introduction

Creation of correlated states

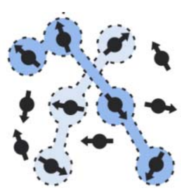
External mode control



2D correlated spinor gasses

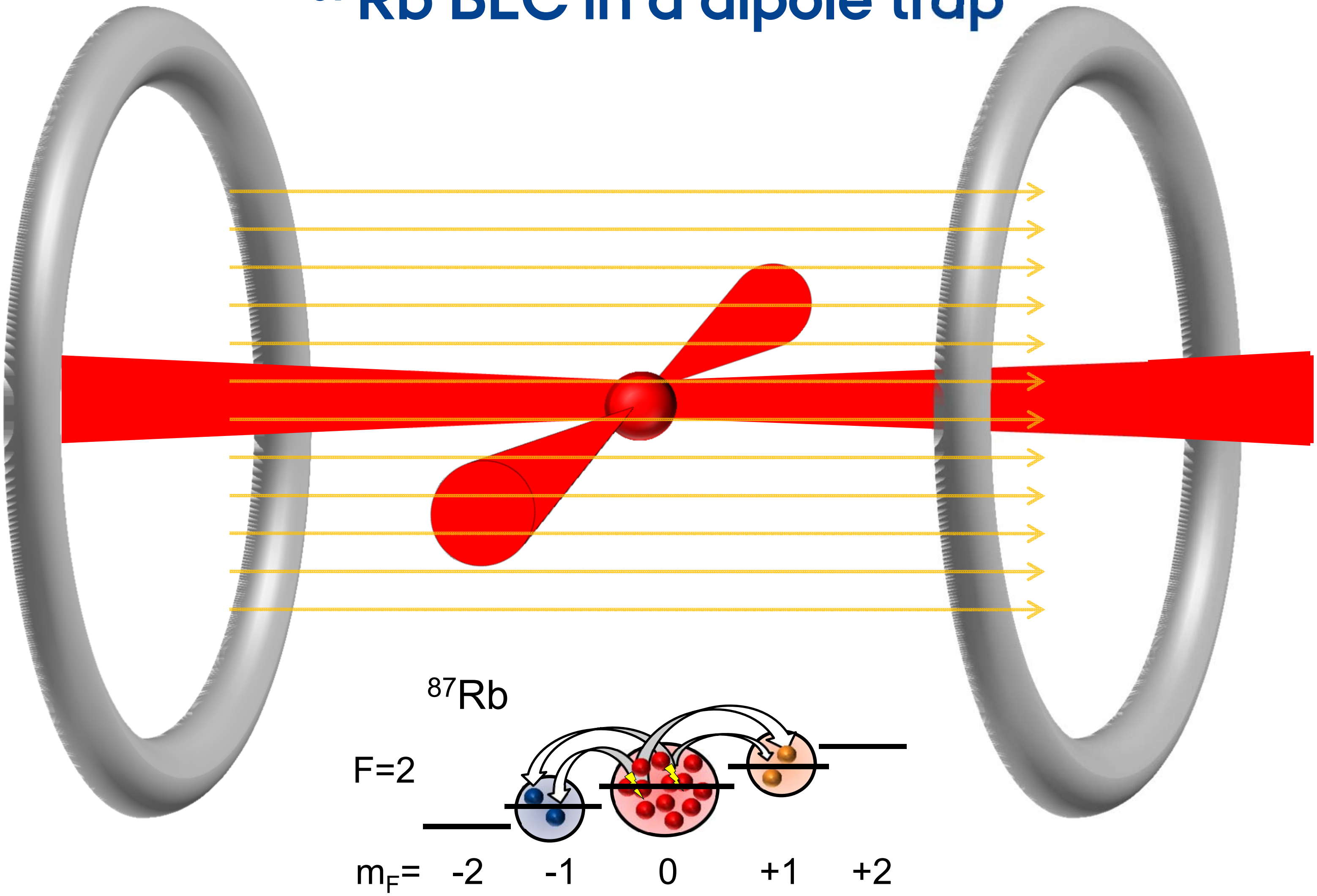


Dicke states for interferometry



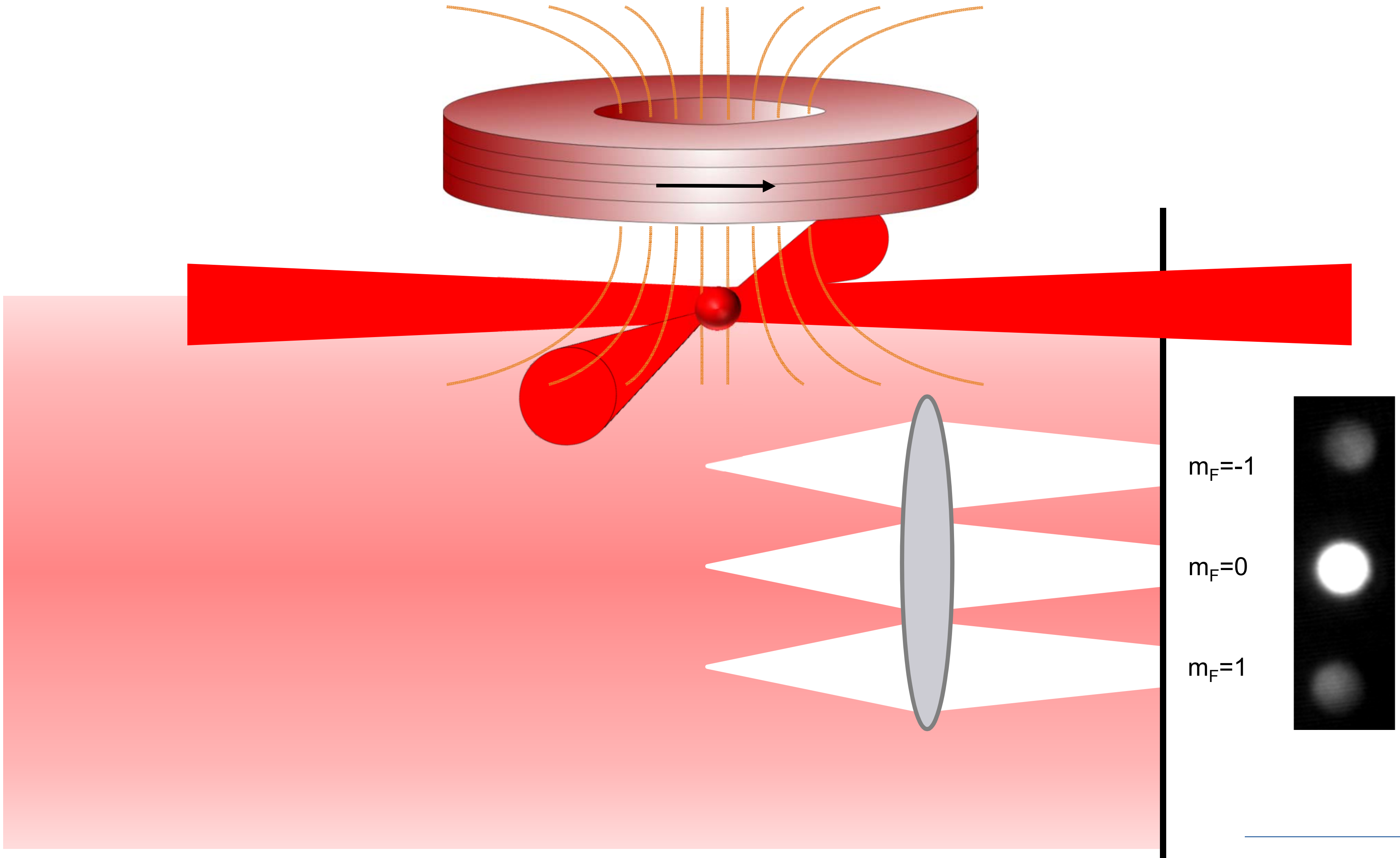
Multi-particle entanglement

^{87}Rb BEC in a dipole trap



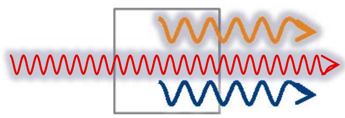
AARHUS UNIVERSITET

Absorption detection



AARHUS
UNIVERSITET

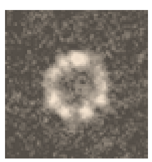
Content



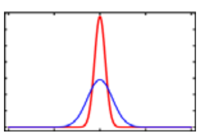
Introduction

Creation of correlated states

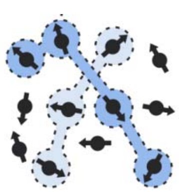
External mode control



2D correlated spinor gasses



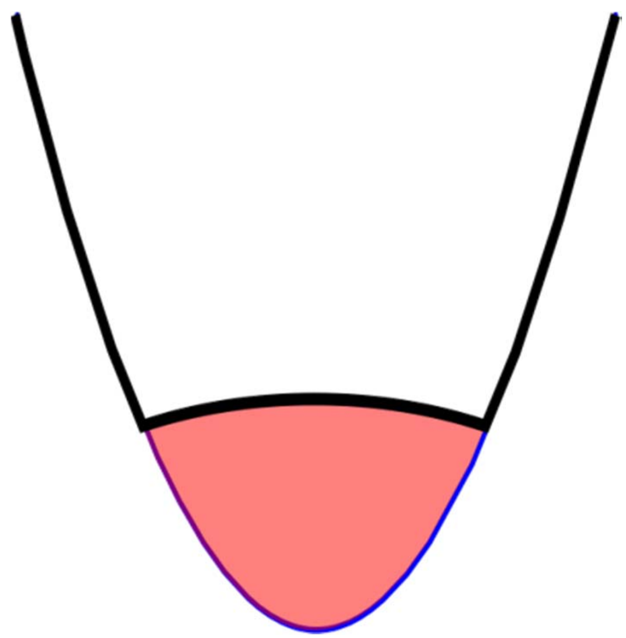
Dicke states for interferometry



Multi-particle entanglement

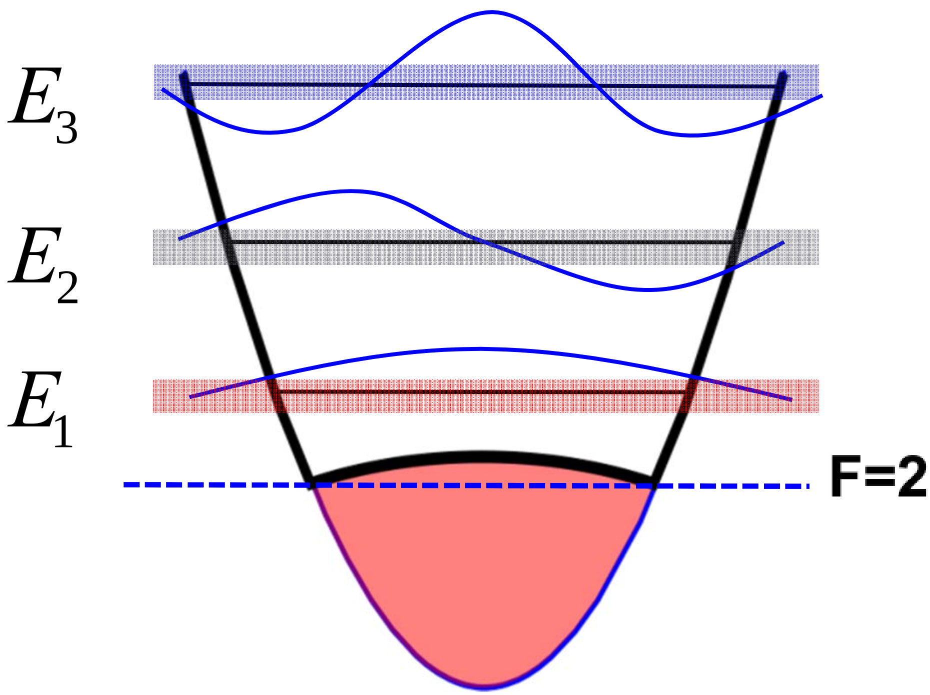
Simplified model for spin dynamics

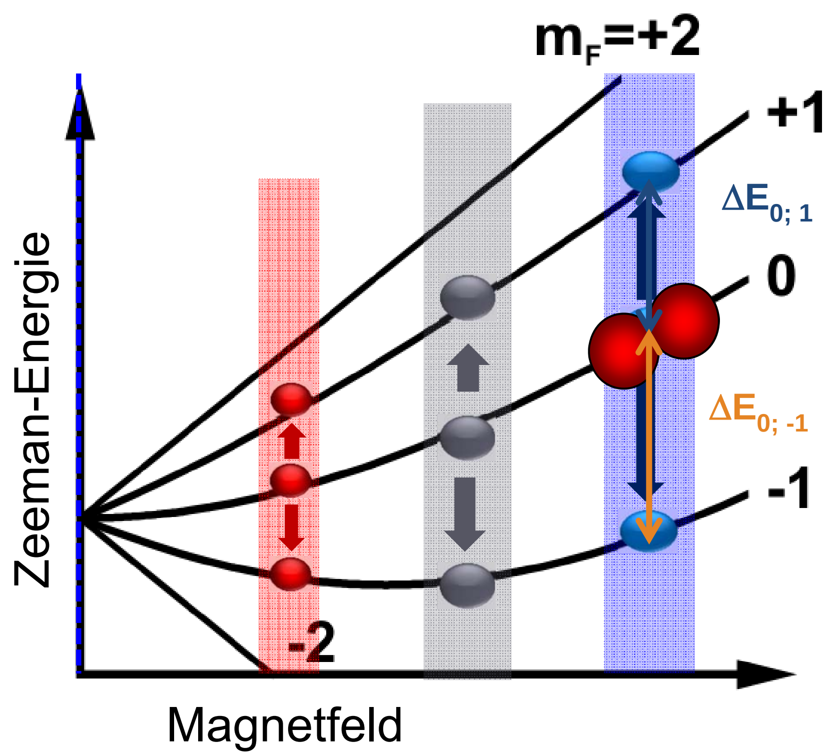
Effective potential for mF=+/-1 atoms



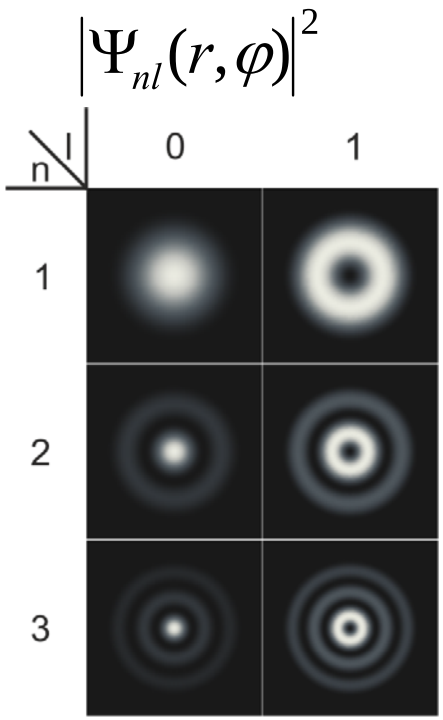
Simplified model for spin dynamics

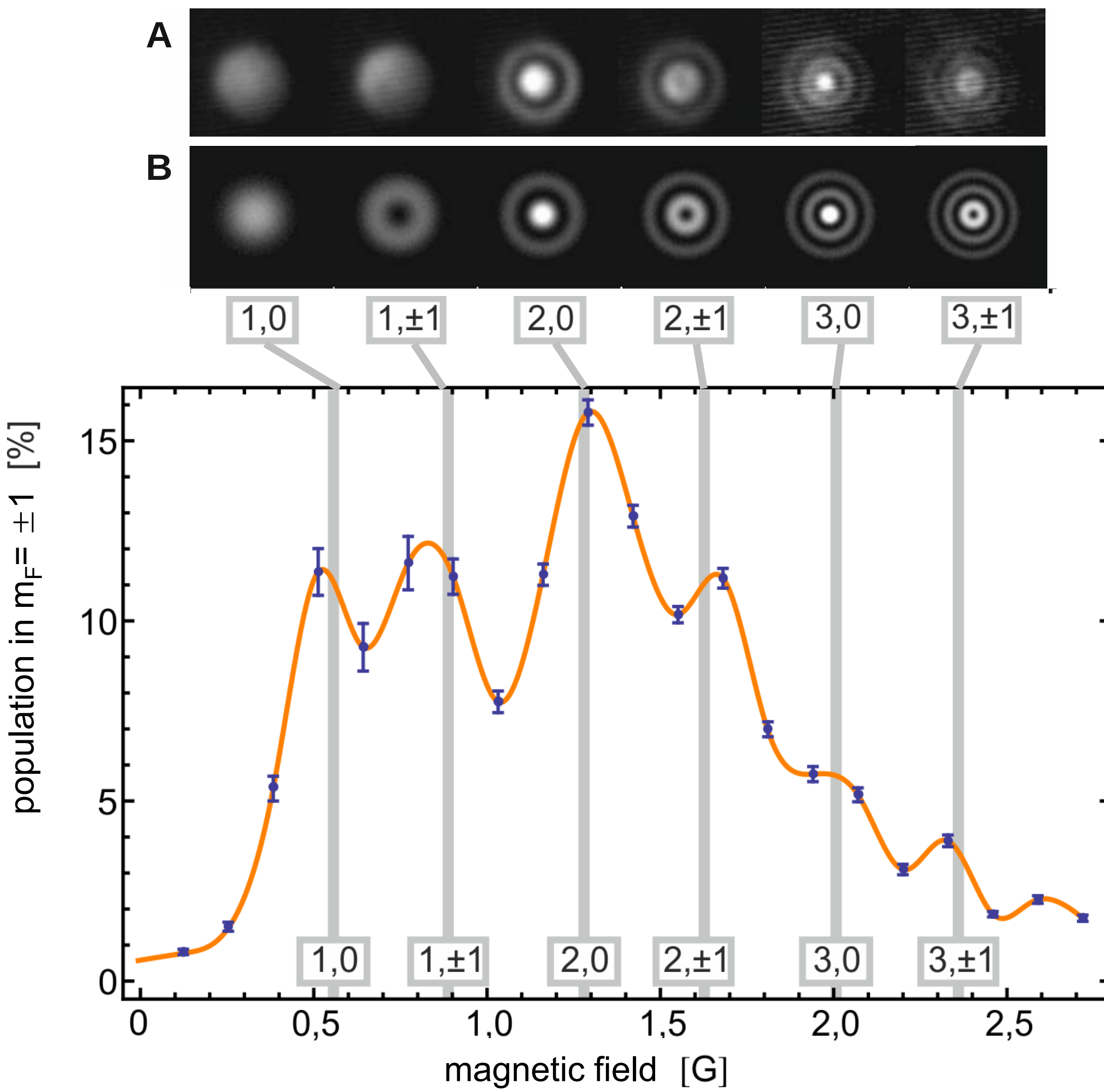
Effective potential for mF=+/-1 atoms





Multiresonant spinor dynamics in a Bose-Einstein condensate,
Phys. Rev. Lett. 103, 195302 (2009)

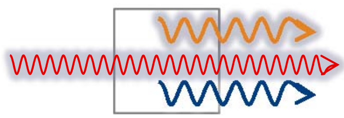




Parametric Amplification of Vacuum Fluctuations in a Spinor Condensate
Phys. Rev. Lett. 104, 195303 (2010)

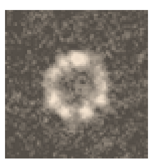
AARHUS UNIVERSITET

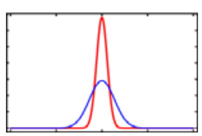
Content

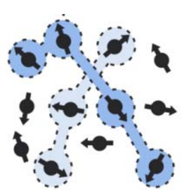

Introduction


Creation of correlated states


External mode control

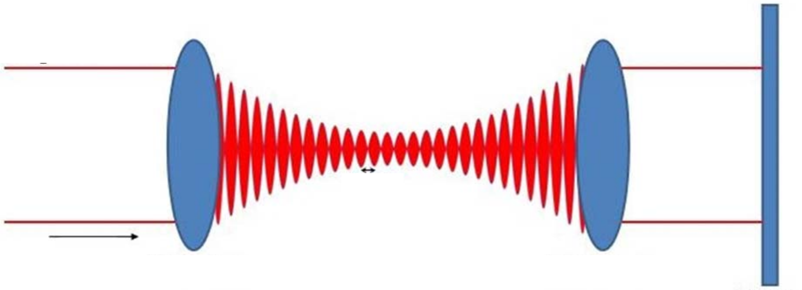

2D correlated spinor gasses

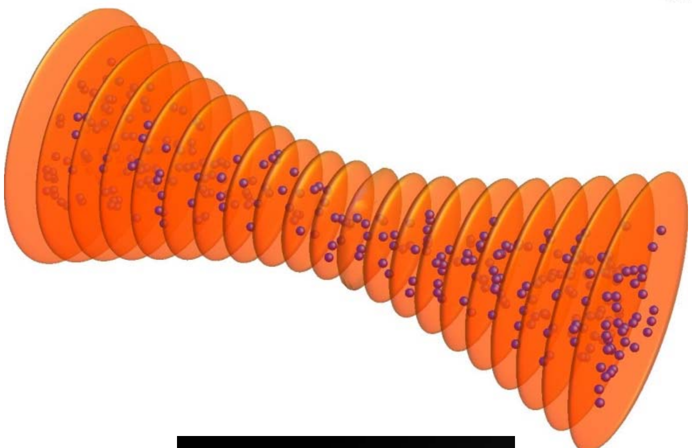

Squeezed and Dicke states

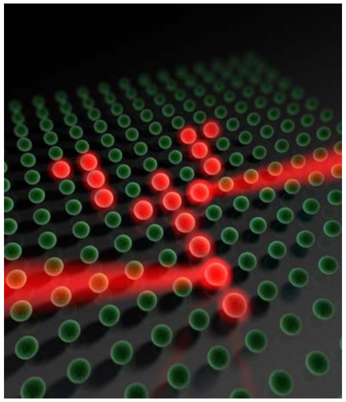

Multi-particle entanglement

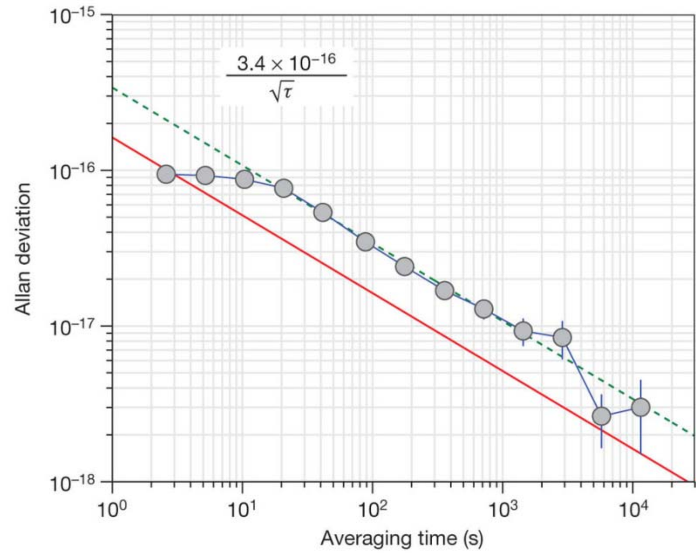
AARHUS
UNIVERSITET

Optical lattices





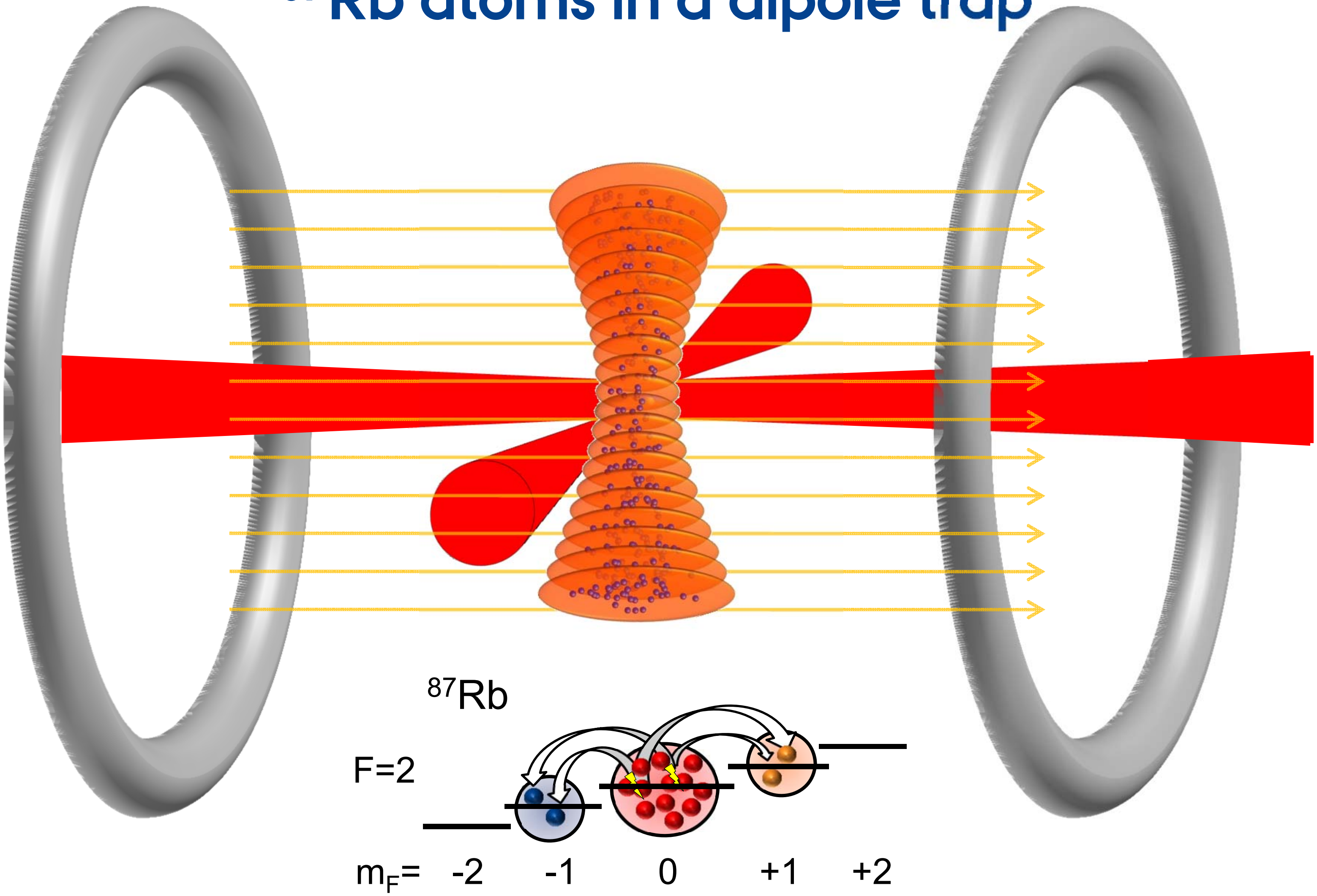




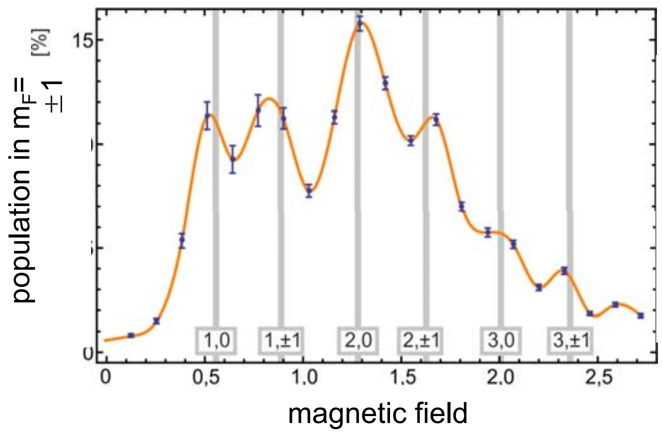
J. Ye group, Nature 506, 71–75 (2014)

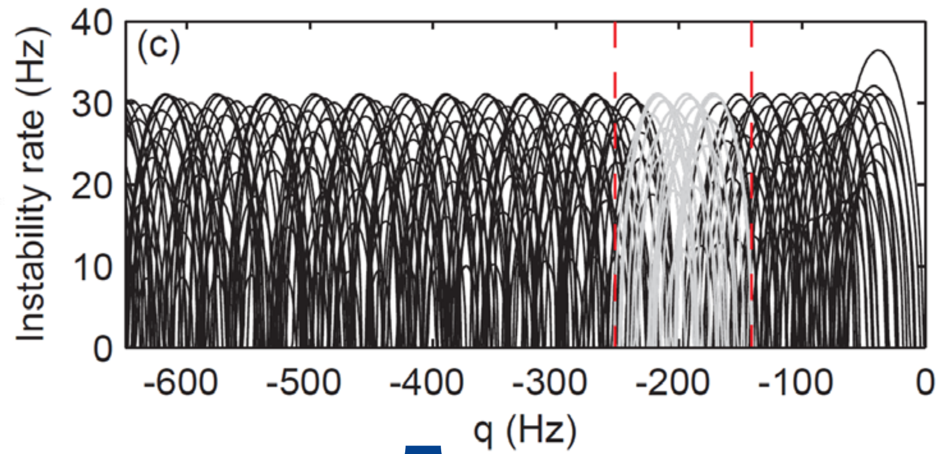
AARHUS UNIVERSITET

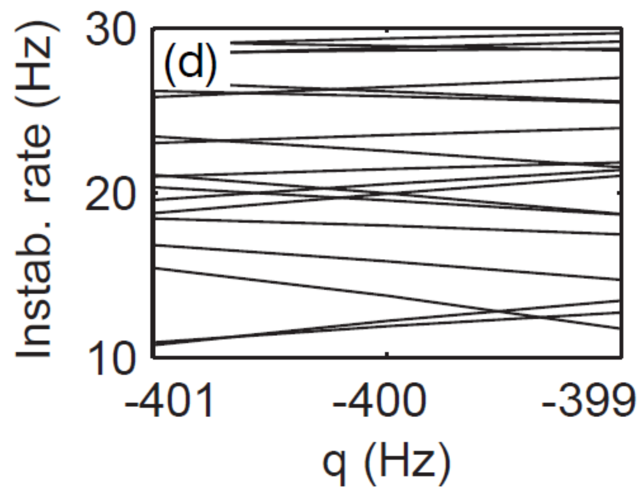
^{87}Rb atoms in a dipole trap



External modes in 2D

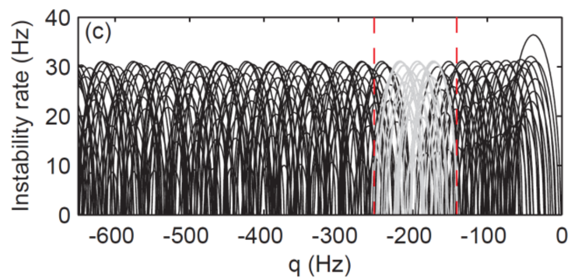


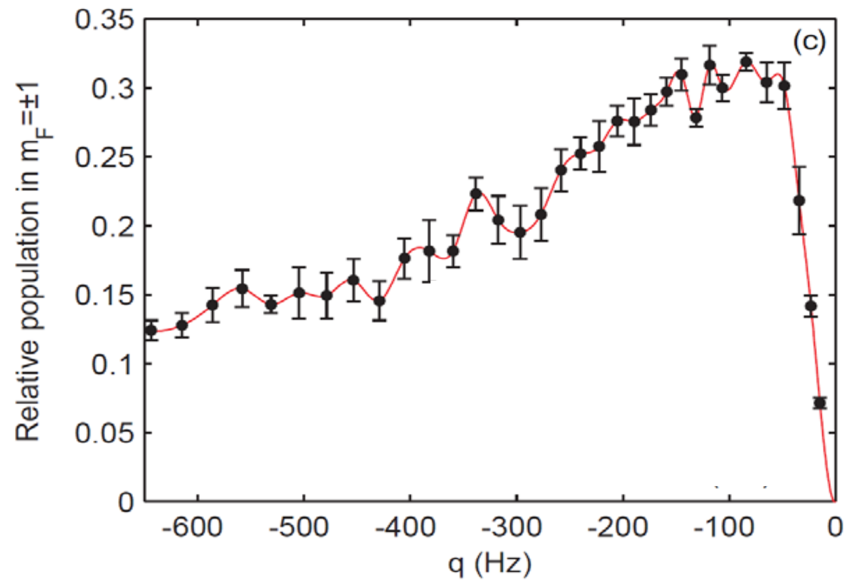


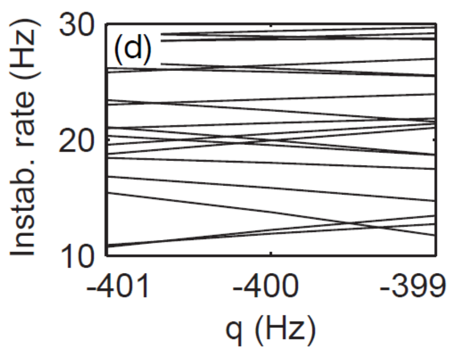


Multimode dynamics expected!

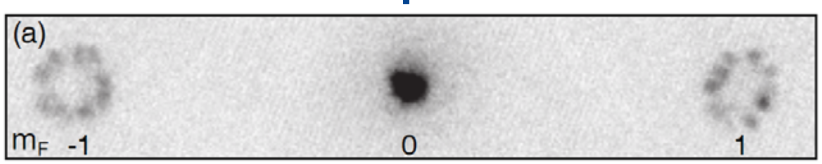
External modes in 2D





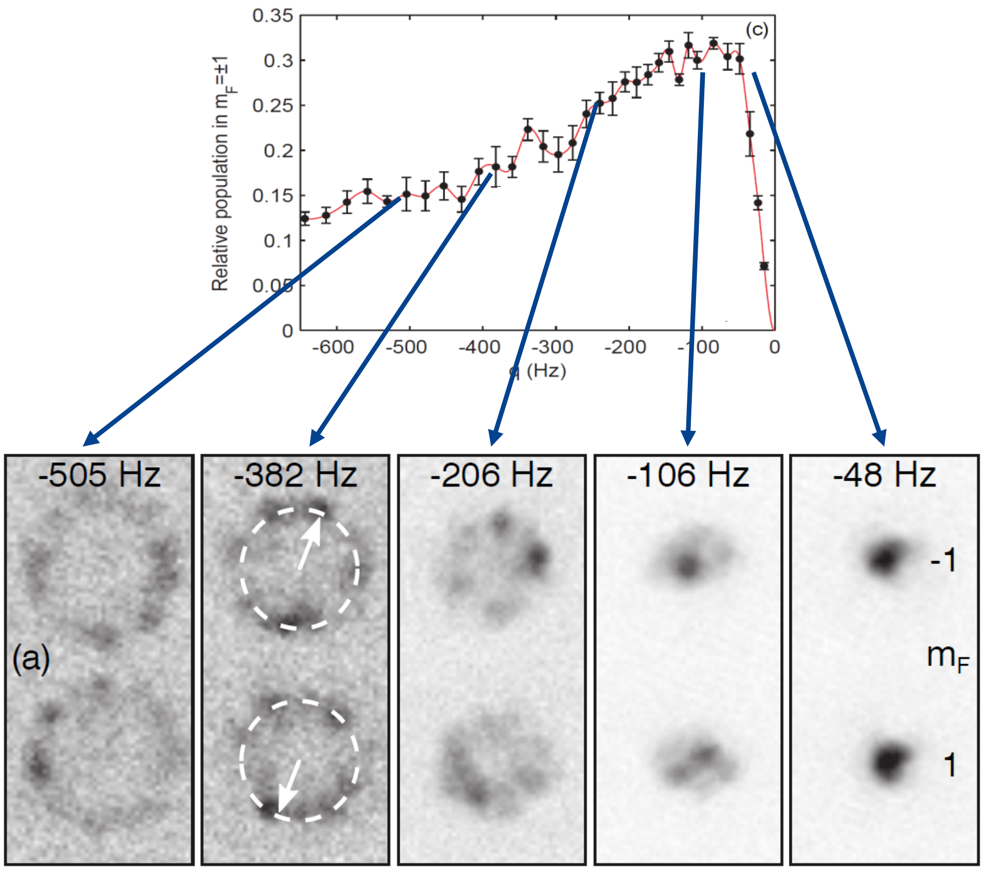


Multimode spinor clouds!

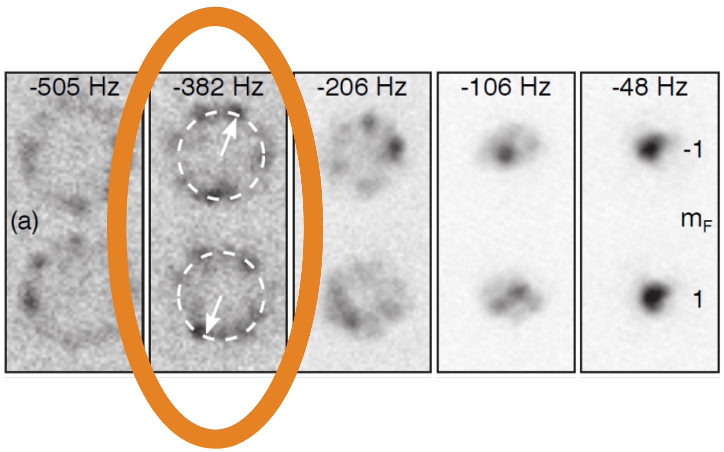


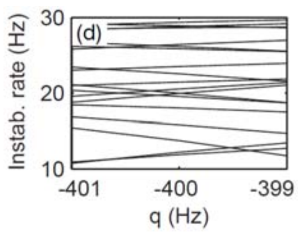
AARHUS
UNIVERSITET

Observation of “correlated rings” in TOF

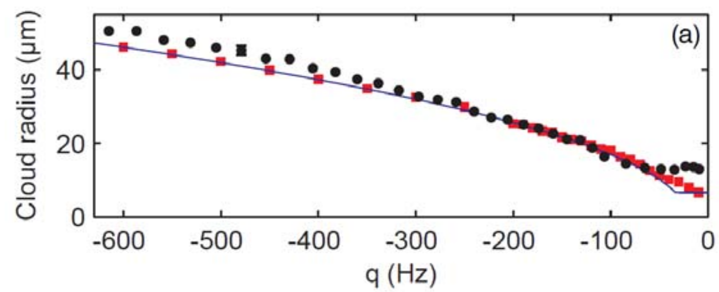


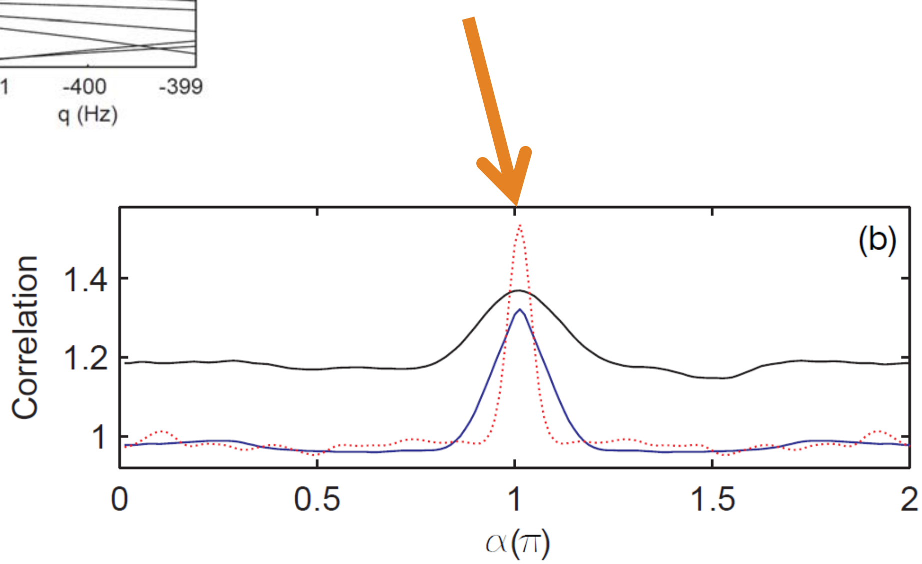
Understanding “correlated rings” in TOF





Radius well understood.!

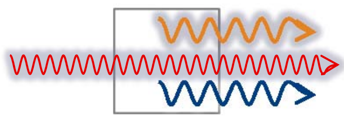




- Correlated clouds
- Squeezed relative atom number
- EPR pairs?

Spin dynamics in a two dimensional quantum gas, Phys. Rev. A 89 (2014), 051603(R)

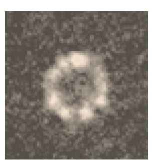
Content



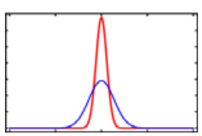
Introduction

Creation of correlated states

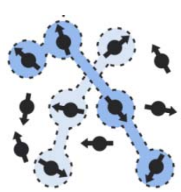
External mode control



2D correlated spinor gasses



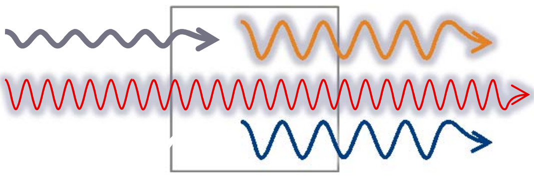
Dicke states for interferometry



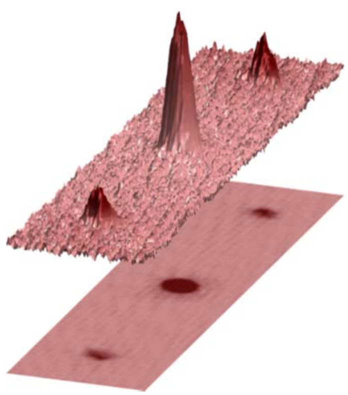
Multi-particle entanglement

Two possibilities for triggering:

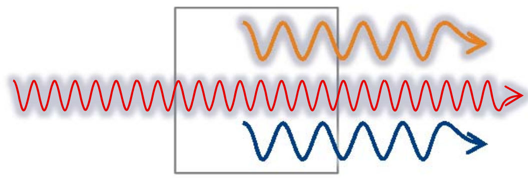
1) classical seed



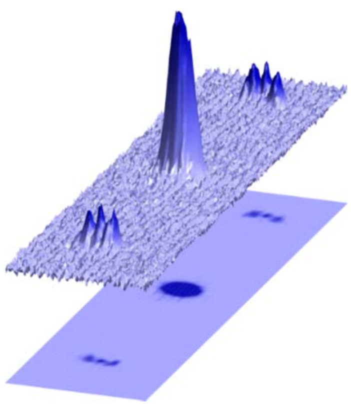
Seed atoms in $m_F=\pm1$ in the spatial mode of the initial BEC



2) vacuum fluctuations



No atoms present in $m_F=\pm1$ in the excited spatial mode



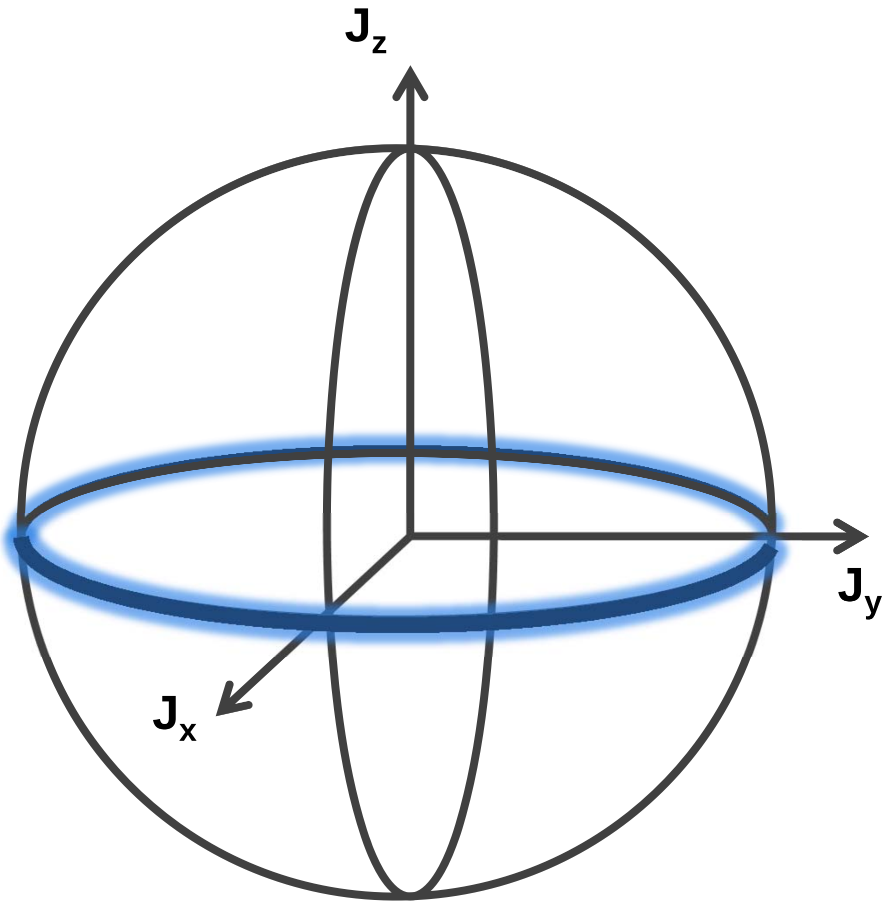
Parametric amplification of vacuum fluctuations in a spinor condensate, Phys. Rev. Lett. 104, 195303 (2010).

Dicke states

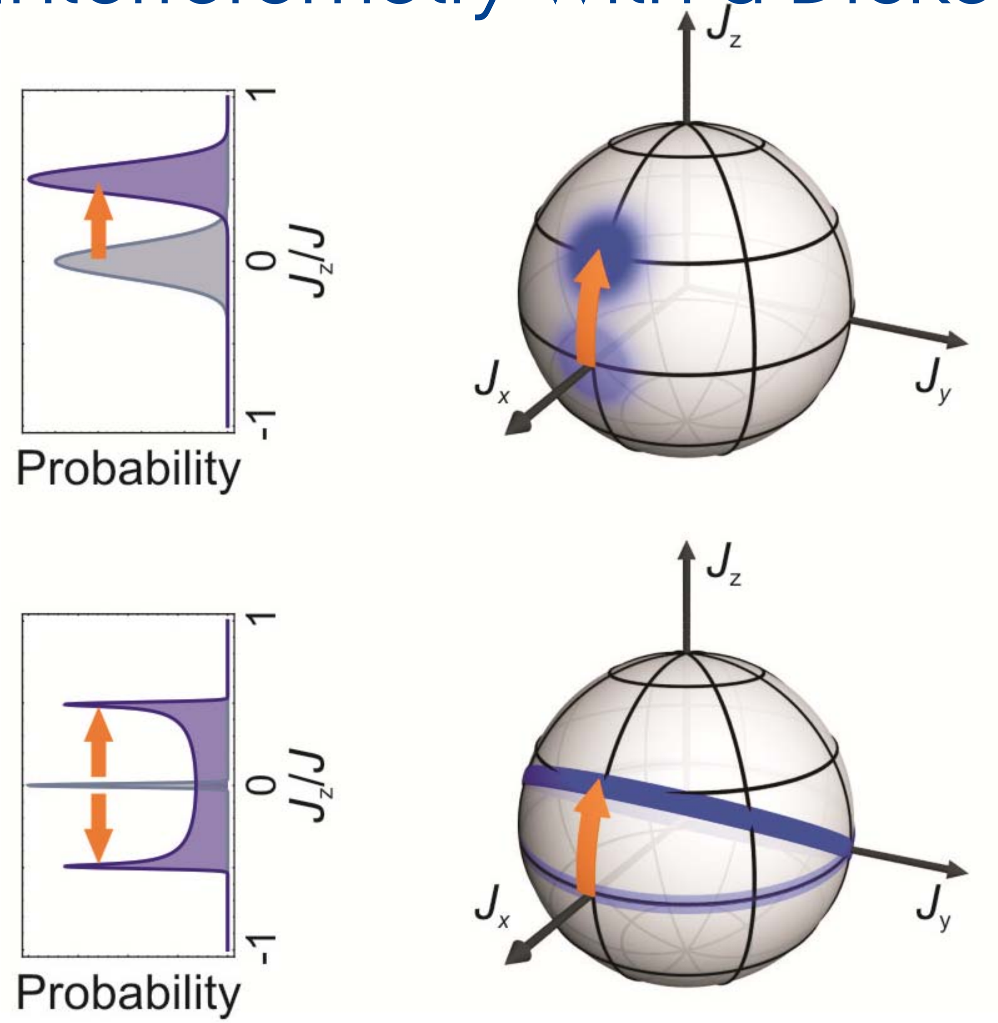
Ideally, spin dynamics produces a Dicke state with the following properties:

$\Delta J_Z = 0$

$\langle J_x \rangle = \langle J_y \rangle = 0$

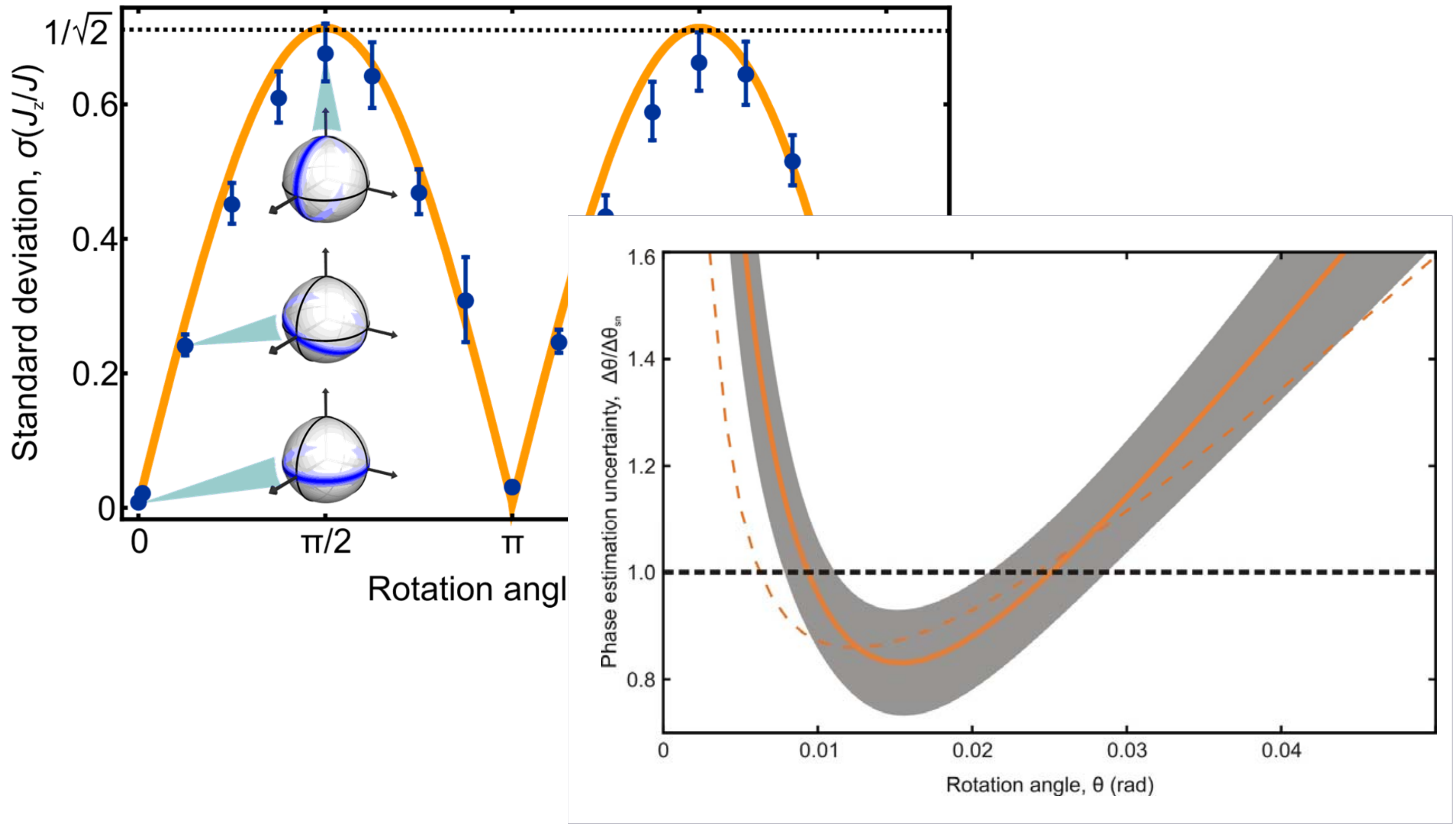


Interferometry with a Dicke state



Observable: $\sigma(J_z)$

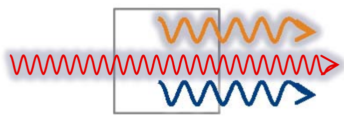
Standard deviation after rotation



Twin Matter Waves for Interferometry Beyond the Classical Limit
Lücke et al., Science **334**, 773 (2011)

AARHUS UNIVERSITET

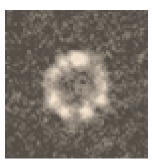
Content



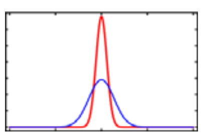
Introduction

Creation of correlated states

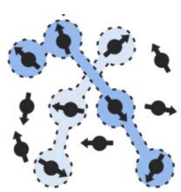
External mode control



2D correlated spinor gasses

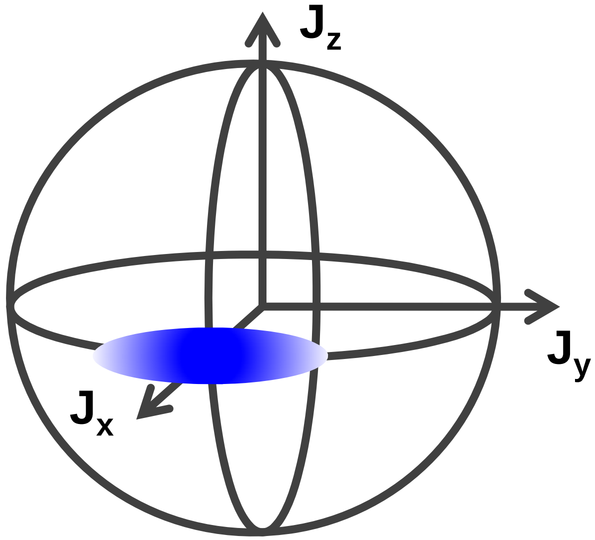


Dicke states for interferometry



Multi-particle entanglement

Squeezing parameters and entanglement

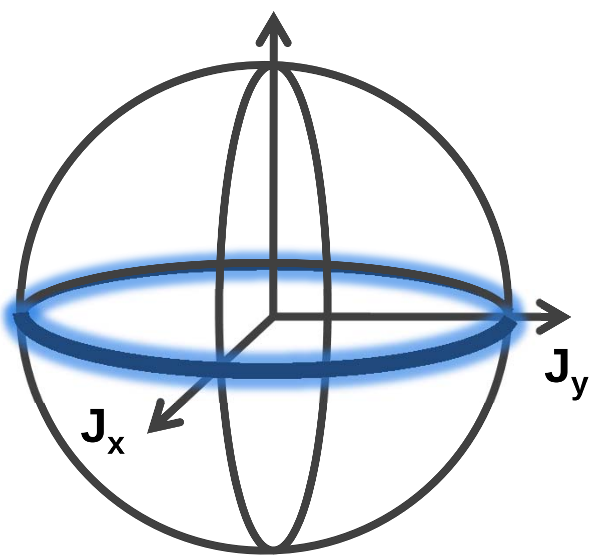


Spin squeezing parameter

$$\xi^2 = N\frac{(\Delta J_z)^2}{\langle J_x\rangle^2 + \langle J_y\rangle^2}$$

$\xi < 1$ proves entanglement

D.J.Wineland, J.J.Bollinger and W.M.Itano, *Squeezed atomic states and projection noise in spectroscopy*, Phys. Rev. A 50, 67–88 (1994)



Generalized squeezing parameter

$$\xi_{\mathrm{gen}}^2 = (N-1)\frac{(\Delta J_z)^2}{\boxed{\langle J_x^2\rangle + \langle J_y^2\rangle} - N/2}$$

$\xi < 1$ proves entanglement

Effective spin length J_{eff}

G. Vitaliano, P

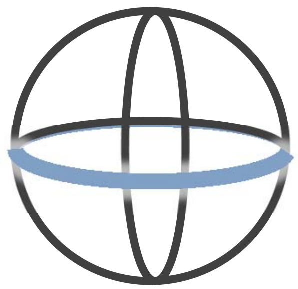
arbitrary spin F

G. Vitaliano, I.

entanglement

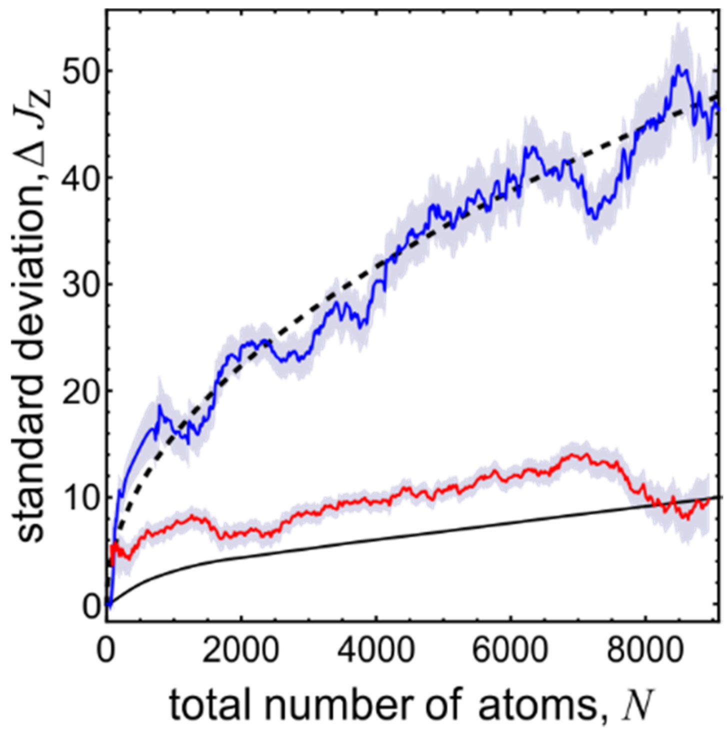
AARHUS
UNIVERSITET

Fluctuations in J_z



Generalized squeezing parameter

$$\xi^2_{\text{gen}} = (N-1)\frac{\boxed{(\Delta J_z)^2}}{\langle J_x^2\rangle + \langle J_y^2\rangle - N/2}$$

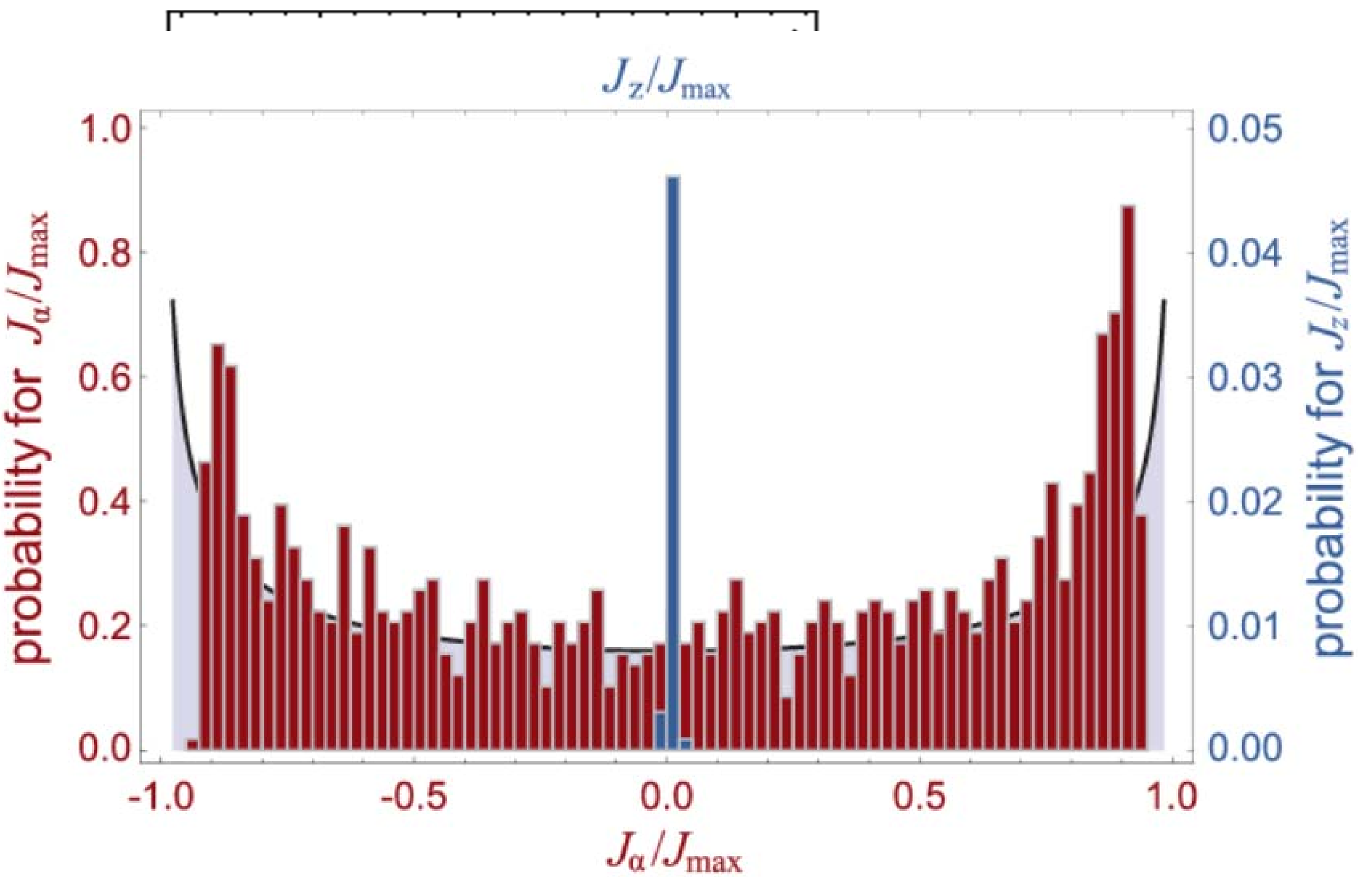


number squeezing:
-12.4 ±1.2 dB

Fluctuations in J_{eff}

Generalized squeezing parameter

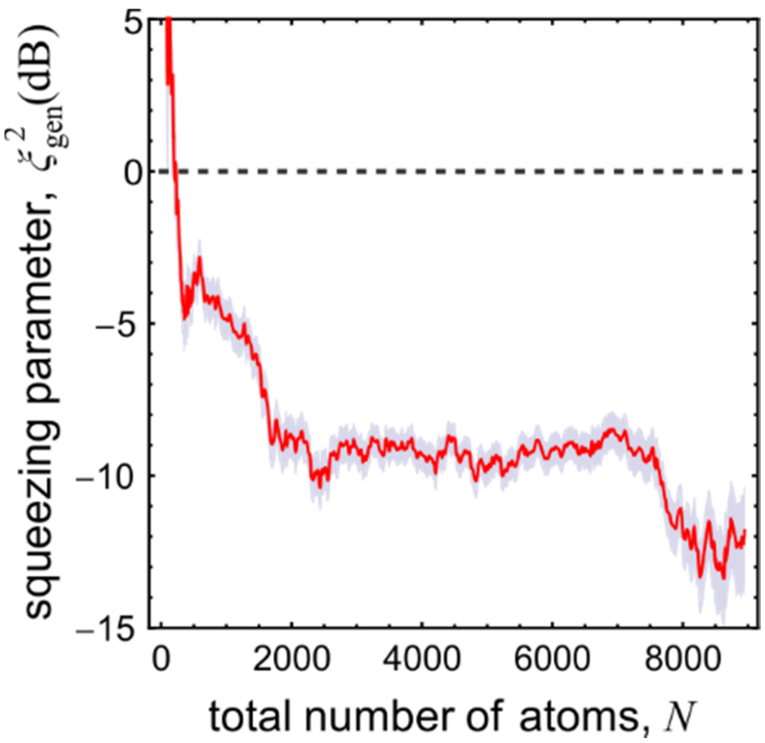
$$\xi_{\mathrm{gen}}^2 = (N-1)\frac{(\Delta J_z)^2}{\boxed{\langle J_x^2\rangle + \langle J_y^2\rangle} - N/2}$$



Generalized spin squeezing

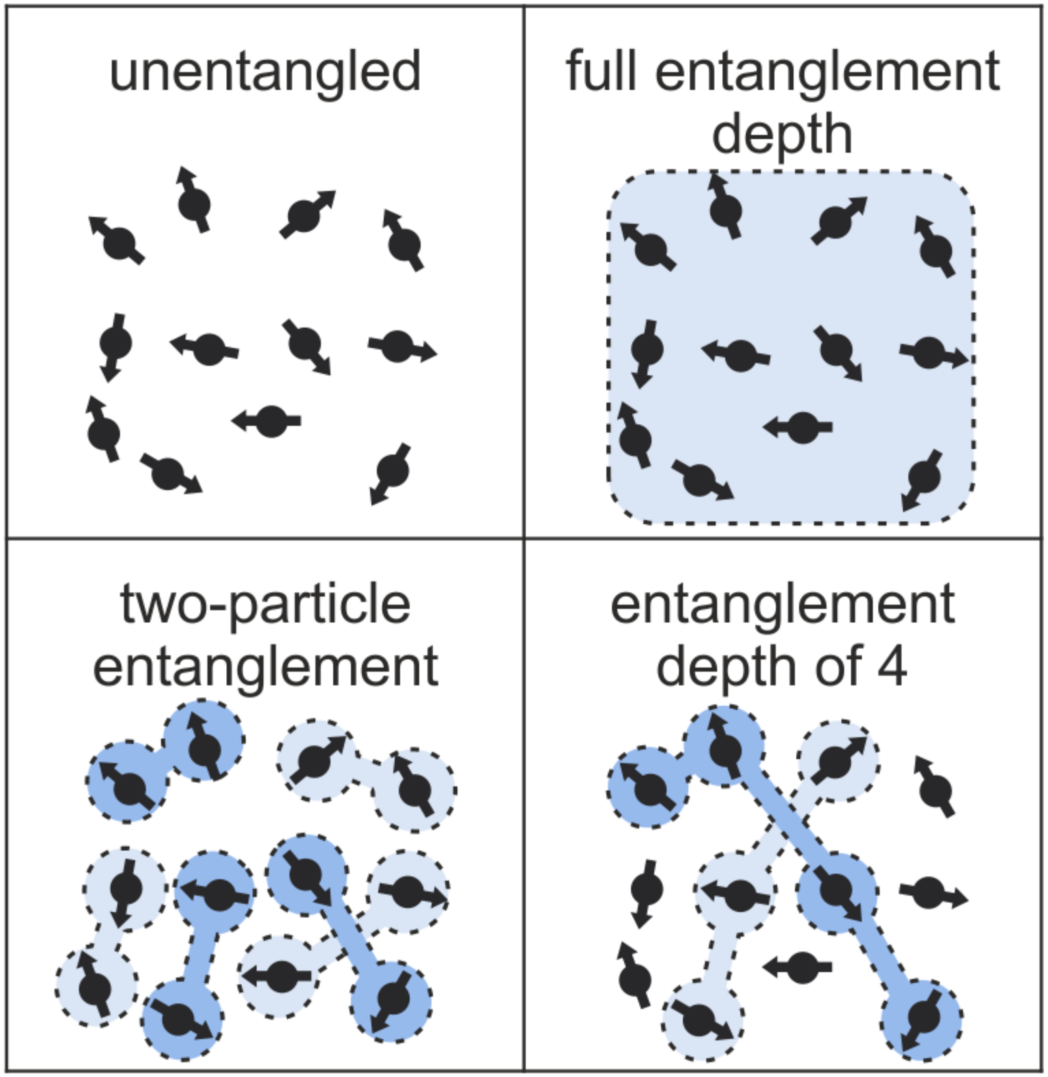
Generalized squeezing parameter

$$\boxed{\xi^2_{\mathrm{gen}}} = (N-1)\frac{(\Delta J_z)^2}{\langle J_x^2\rangle + \langle J_y^2\rangle - N/2}$$



generalized squeezing:
-11.4(5) dB at 8000 atoms

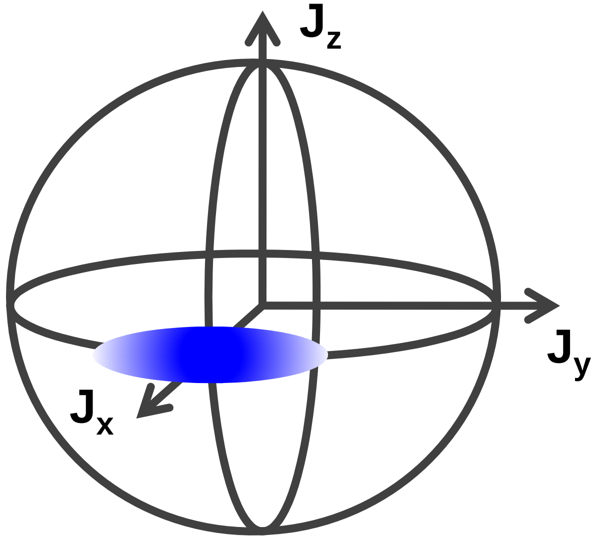
Entanglement depth

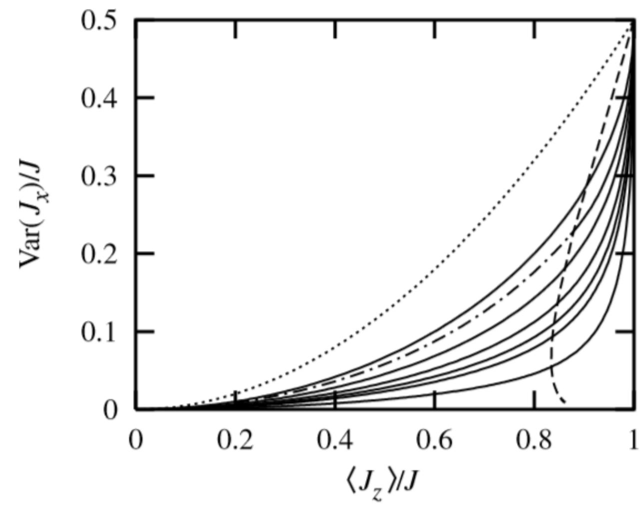


Entanglement depth according to **O.Gühne et al., New J. Phys. 7 229 (2005).**

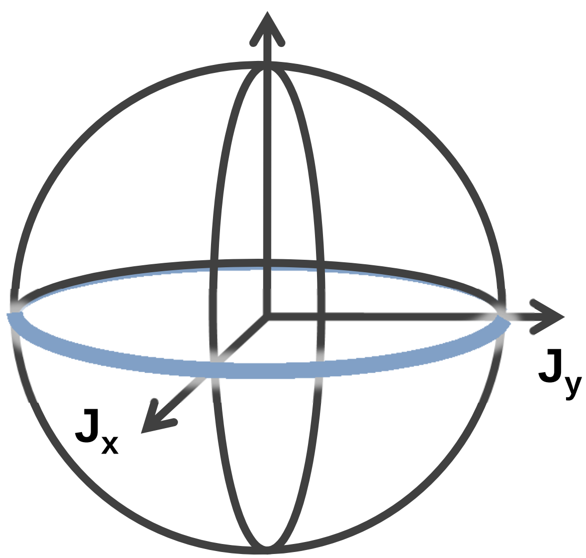
AARHUS UNIVERSITET

Entanglement depth



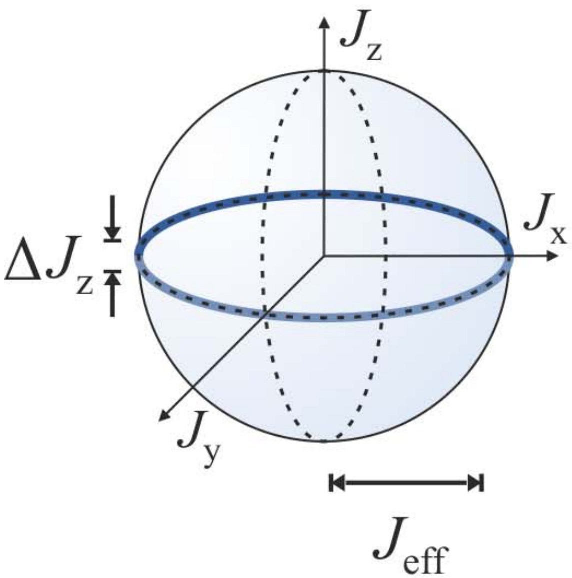


A. Sørensen and K. Mølmer, Phys. Rev. Lett. **86**, 4431 (2001).



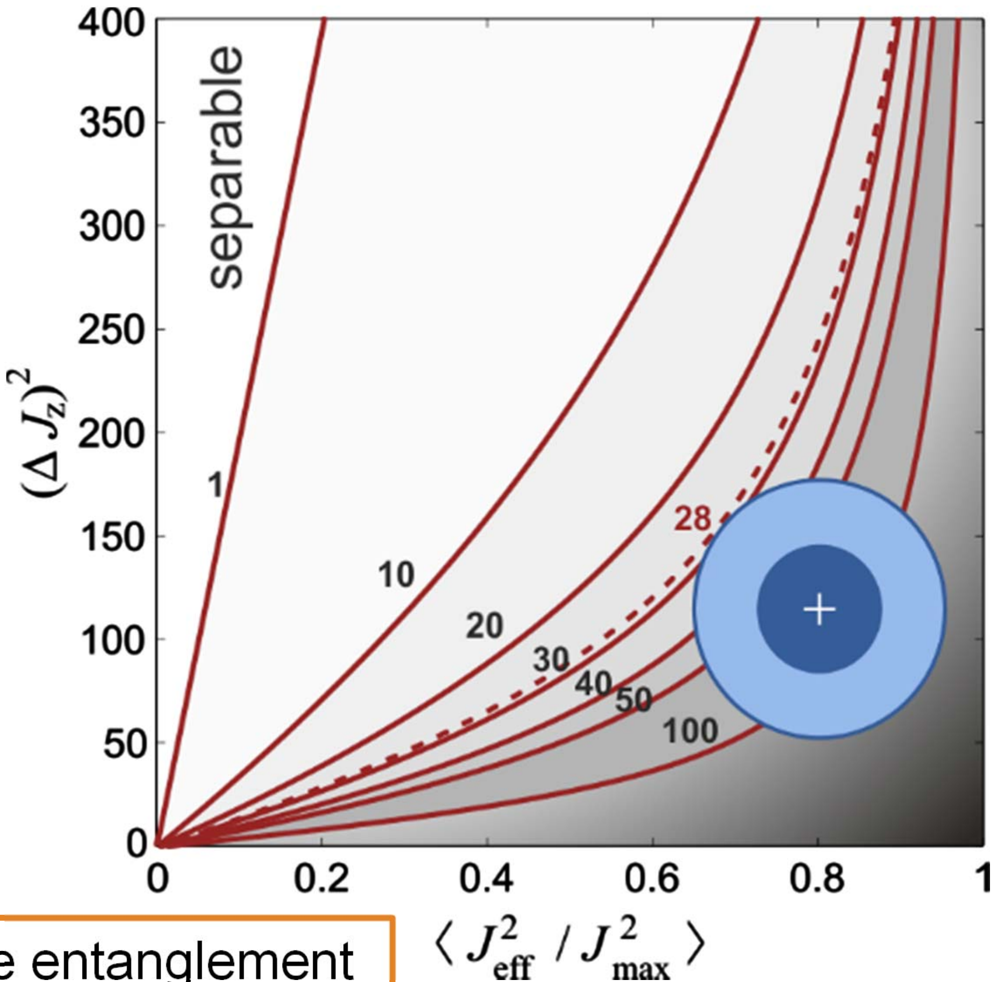
?

Measurement of the entanglement depth



$$J_{eff}^2 = \langle J_x^2 + J_y^2 \rangle$$

Total number N = 8000.



Center:	**68**-particle entanglement
Two std. dev.:	**28**-particle entanglement

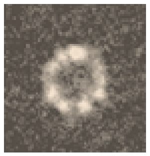
Detecting multiparticle entanglement of Dicke states
Bernd Lücke et al., **Phys. Rev. Lett. 112, 155304 (2014)**

AARHUS
UNIVERSITET

Conclusion

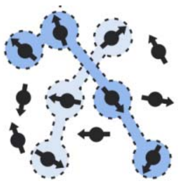
Creation of correlated states

External mode control



2D correlated spinor gasses

- observation in single planes
- EPR state preparation



Multi-particle entanglement

- interferometry with heralded Fock states
- deterministic preparation of Dicke states

Thank you for your attention.

P. Pedersen, M. Gajdacz, J. Sherson, A. Hilliard
Aarhus Universitet

B. Lücke, J. Peise, F. Deuretzbacher,
W. Ertmer, L. Santos, C. Klempt
Leibniz Universität Hannover

G. Vitagliano, G. Tóth
University of the Basque Country