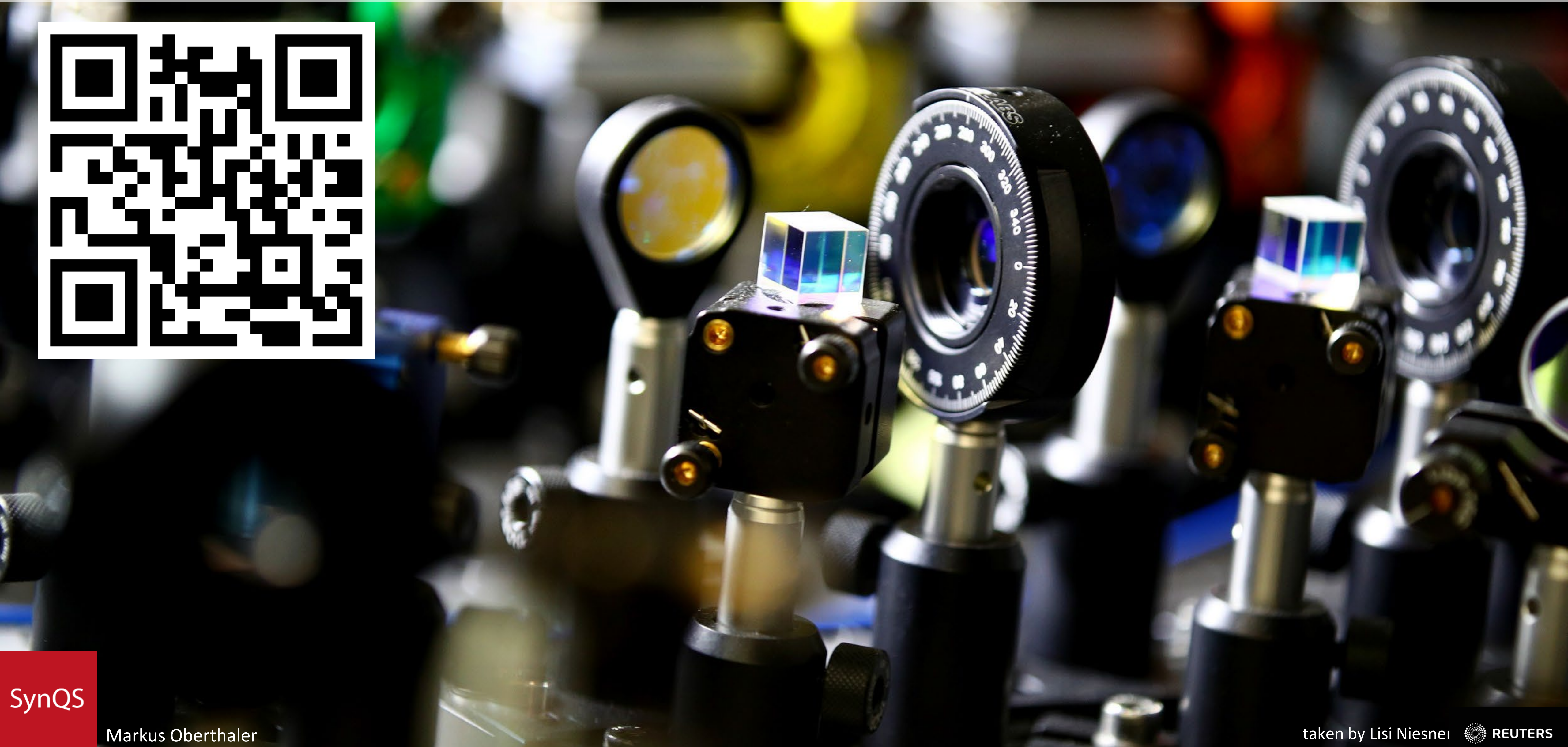
Quantum Mixtures @ Synthetic Quantum Systems/Heidelberg University

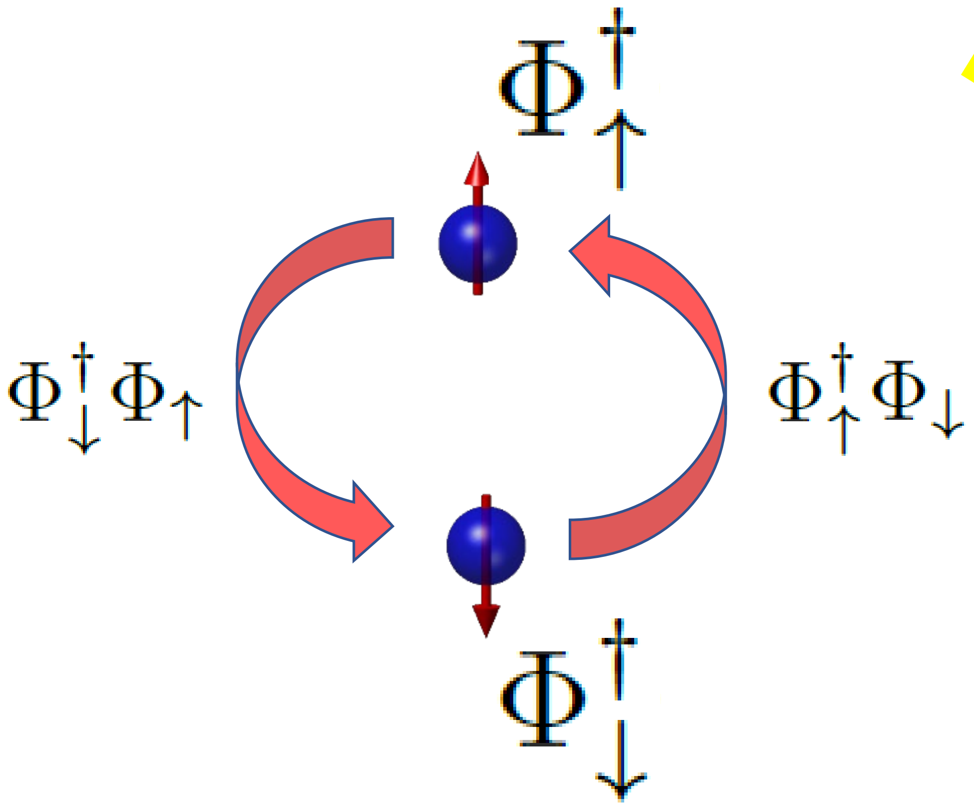


SynQS

Markus Oberthaler

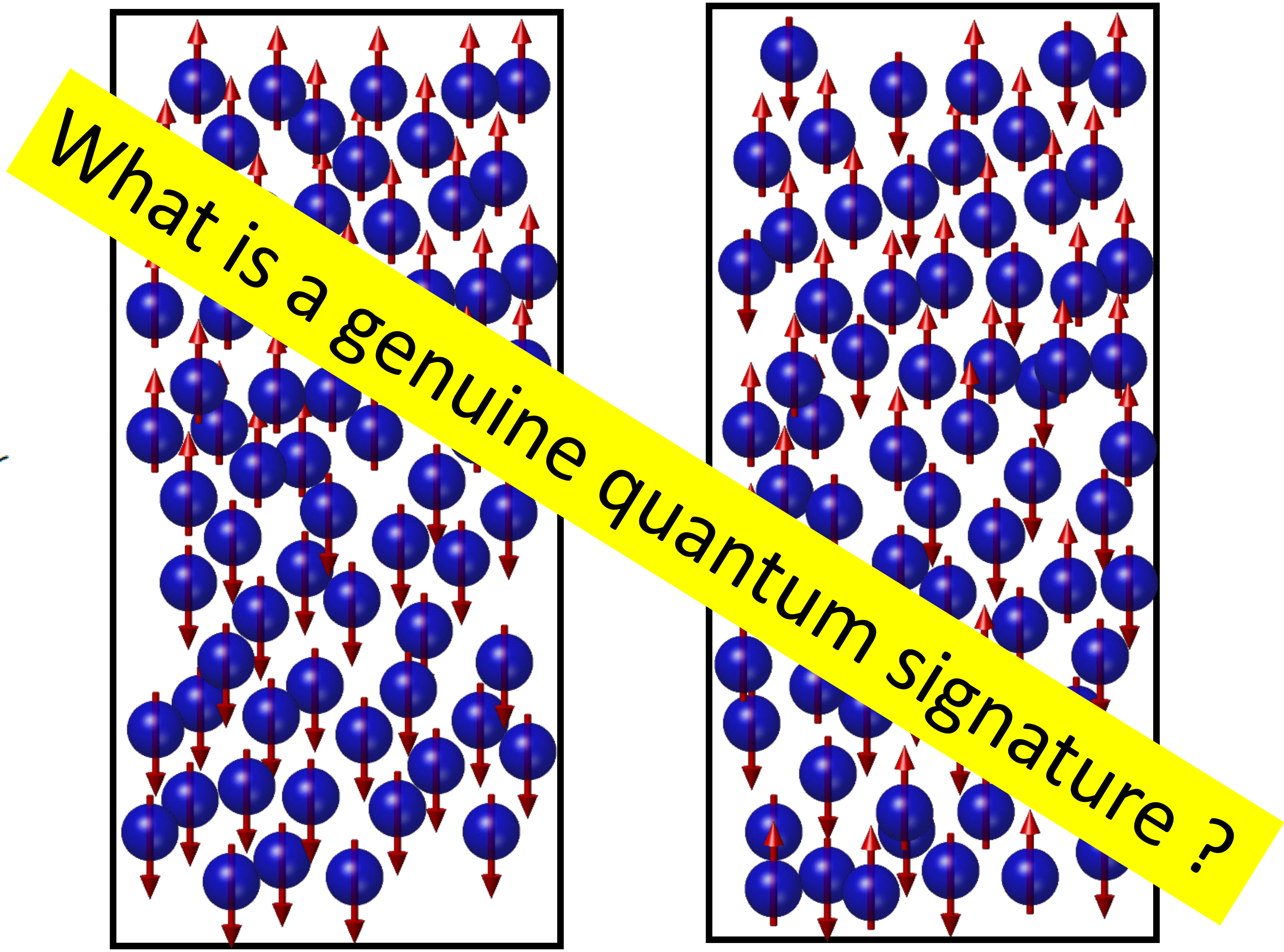
taken by Lisi Niesner REUTERS

Coherent Quantum Mixtures

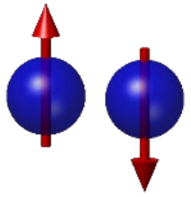


phase separation - immiscible

coexistence - miscible



Coherent mixtures with increasing complexity



pseudo spin ½

one dimensional

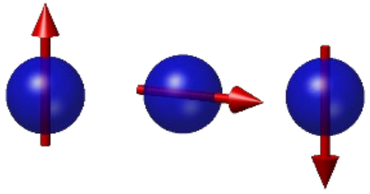
miscible to immiscible transition via linear coupling

critical scaling after a quench towards a quantum critical point

quantum features in zero dimensional situation (no motion)

introduce collective spin dynamics

squeezing and quantum bifurcation



spin 1

non-local entanglement

EPR correlation from 0d to 1d

one dimensional

POVM readout

universal dynamics

topological excitations such as solitons

Question

Experimental details

Please bear with me

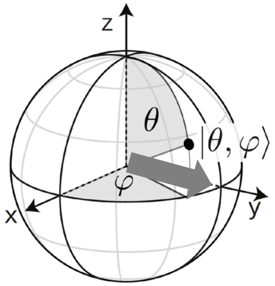
Genuine quantum feature: Entanglement

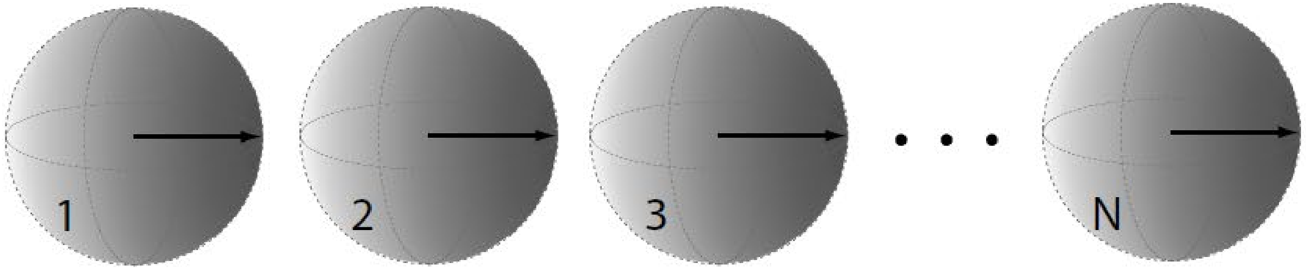
$$\rho \neq \sum_k p_k \rho_k^{(1)} \otimes \rho_k^{(2)} \otimes \cdots \otimes \rho_k^{(N)}$$

separable density matrix

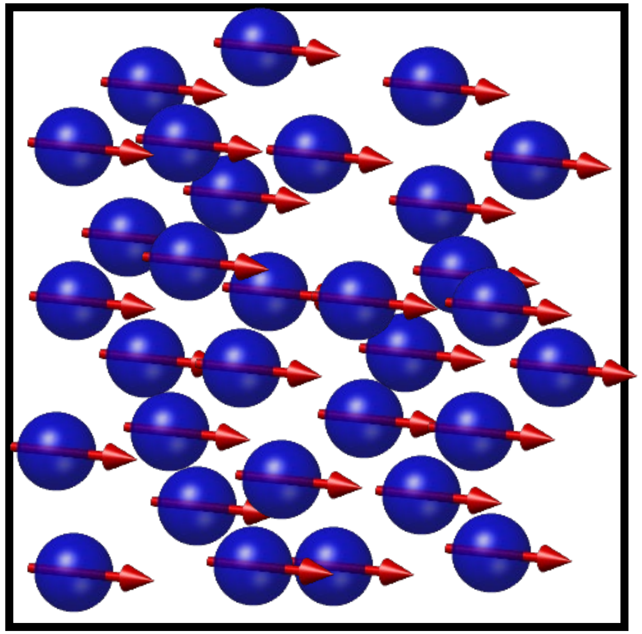
$\sigma^{(i)} = \frac{1}{2}$

$\Delta\sigma_{\perp}^{(i)} = \frac{1}{2}$





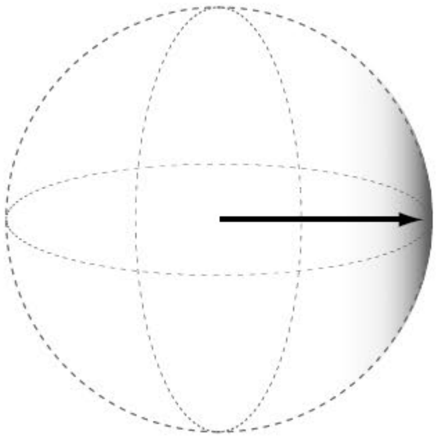
Indistinguishable uncorrelated bosons



$$J_{x,y,z} = \sum_i^N S_{x,y,z}^{(i)}$$

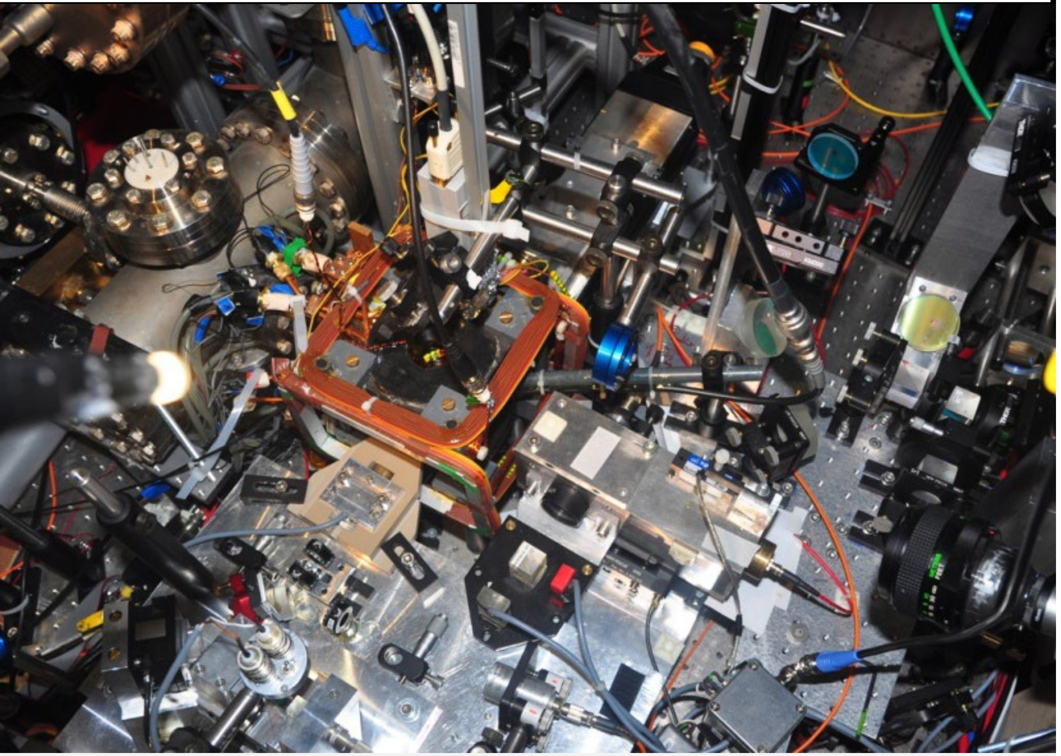
Schwinger – collective spin:

Suppression of fluctuations as witness for entanglement

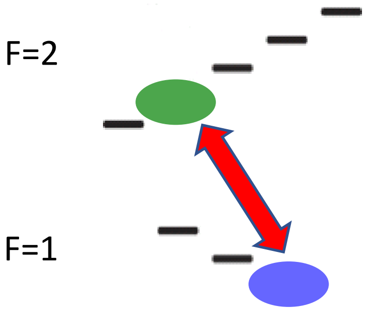


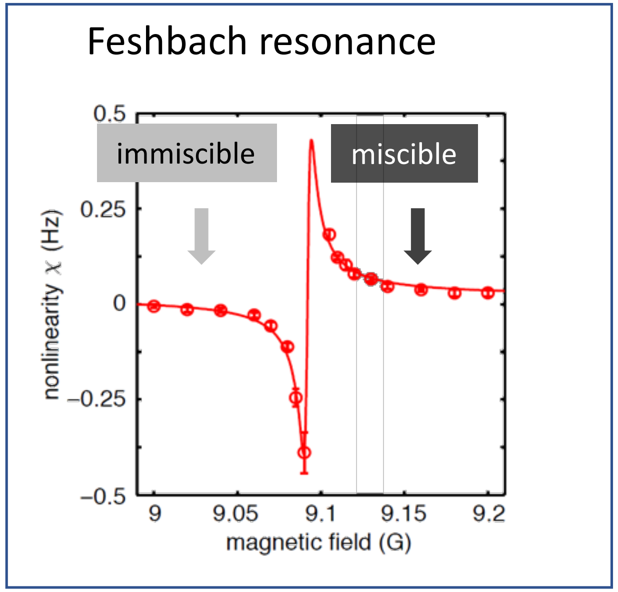
$J = N \cdot \frac{1}{2}$

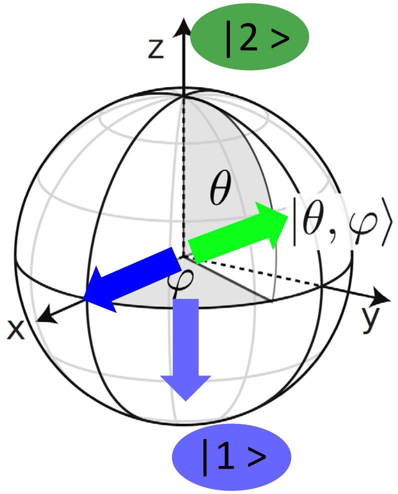
Vacuum since 2000, with one day break



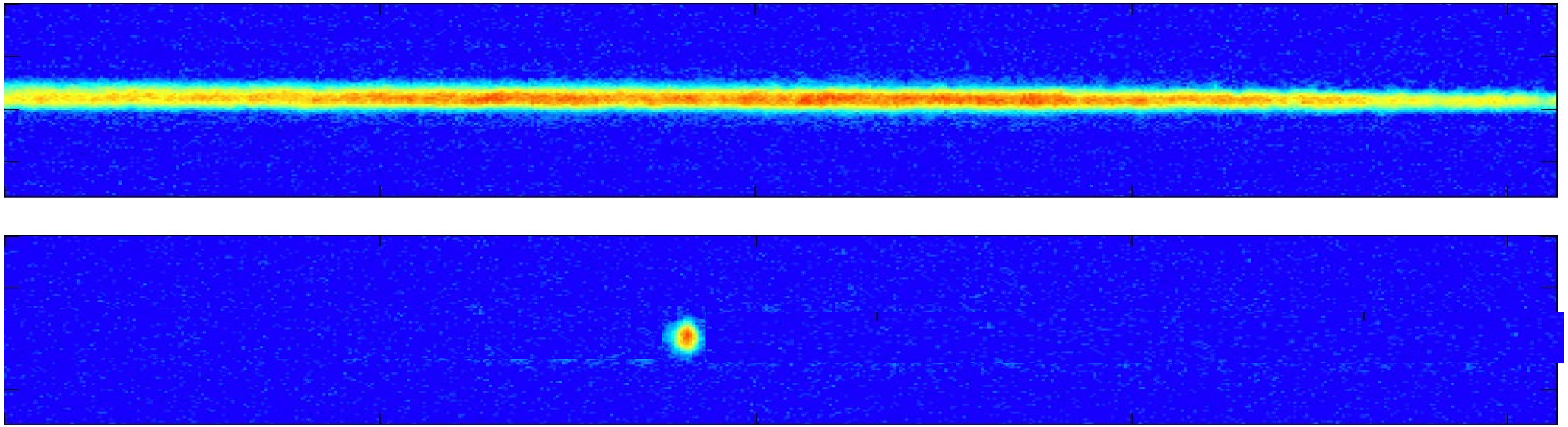
Rubidium BEC





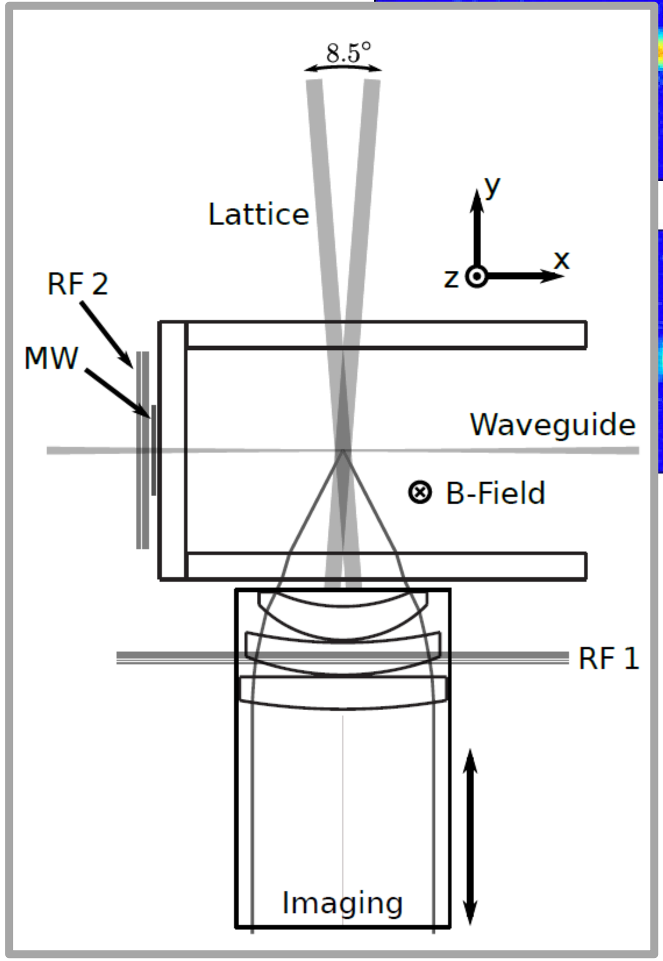


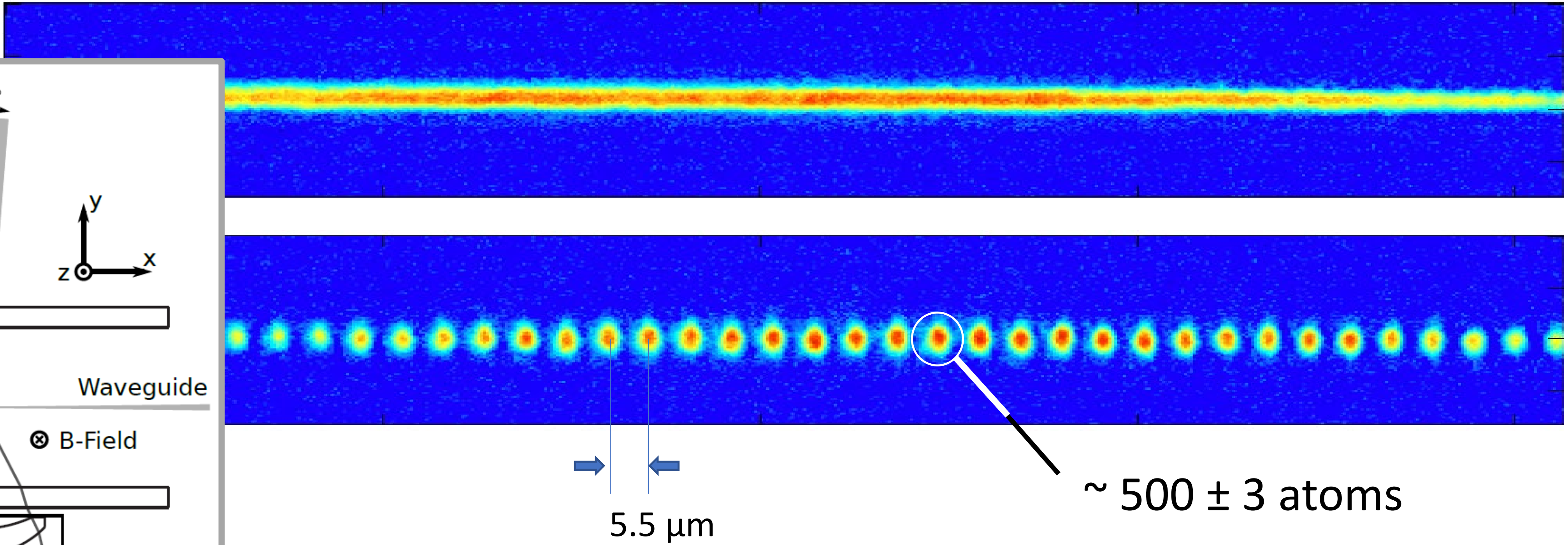
1D many mode situation $\rightarrow$ 0D single mode situation



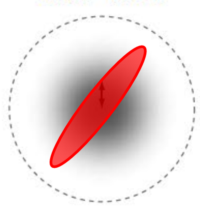
Experimental details

1D many mode situation → many 0D realizations





Good statistics due to 60 000 BECs per day running 24h/7d

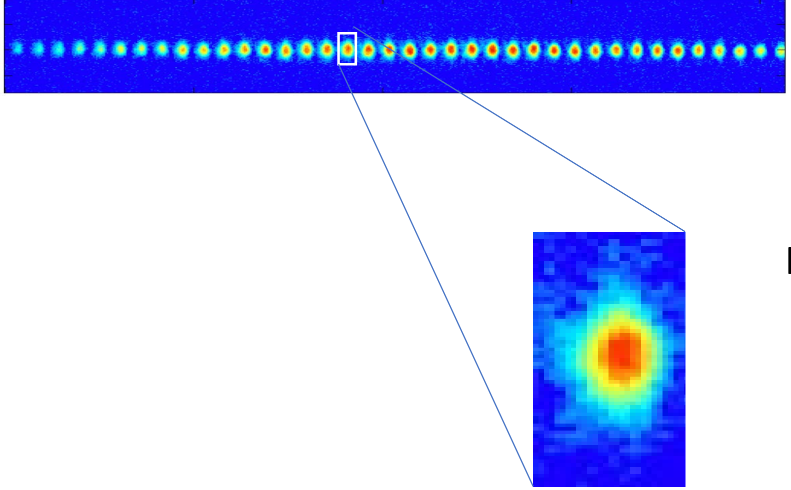


$$\Delta J_\perp = \sqrt{N/2}$$

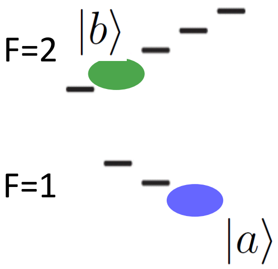
Quantum physics is revealed by characteristic fluctuations

Experimental details

single mode/ 0d approximation without coherent coupling



Rubidium BEC



$$\mathcal{H} = \mathcal{H}_a + \mathcal{H}_b + \mathcal{H}_{ab}$$

$$\mathcal{H}_a = \int \mathrm{d}^3\mathbf{x}\, \hat{\psi}_a{}^\dagger(\mathbf{x}) \left(-\frac{\hbar^2}{2m}\nabla^2 + V_a(\mathbf{x}) + \frac{4\pi a_{aa}}{2m} \hat{\psi}_a^\dagger(\mathbf{x})\hat{\psi}_a(\mathbf{x}) \right) \hat{\psi}_a(\mathbf{x})$$

$$\mathcal{H}_{ab} = \frac{4\pi a_{ab}}{m} \int \mathrm{d}^3\mathbf{x}\, \hat{\psi}_a^\dagger(\mathbf{x})\hat{\psi}_b^\dagger(\mathbf{x})\hat{\psi}_a(\mathbf{x})\hat{\psi}_b(\mathbf{x}).$$

0d assumption

$$\hat{\psi}_b^\dagger(\mathbf{x}) = \hat{a}_b^\dagger \phi_b(\mathbf{x})$$

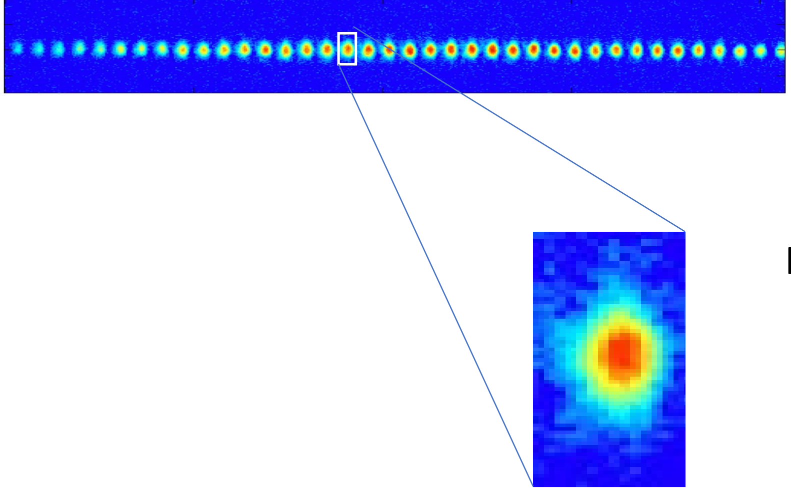
$$\hat{\psi}_a^\dagger(\mathbf{x}) = \hat{a}_a^\dagger \phi_a(\mathbf{x})$$

$$[\hat{a}_i, \hat{a}_j^\dagger] = \delta_{ij}$$

$$\mathcal{H}_a + \mathcal{H}_b = \frac{1}{2}\int \mathrm{d}^3\mathbf{x}\, \Big[\phi_a(\mathbf{x})\omega_a\phi_a(\mathbf{x})\hat{a}_a^\dagger\hat{a}_a + g_{aa}|\phi_a(\mathbf{x})|^4\hat{a}_a^\dagger\hat{a}_a^\dagger\hat{a}_a\hat{a}_a + \phi_b(\mathbf{x})\omega_b\phi_b(\mathbf{x})\hat{a}_b^\dagger\hat{a}_b + g_{bb}|\phi_b(\mathbf{x})|^4\hat{a}_b^\dagger\hat{a}_b^\dagger\hat{a}_b\hat{a}_b\Big],$$

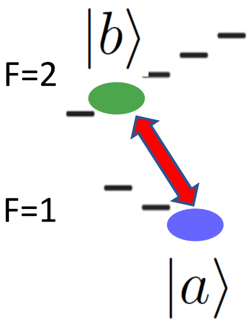
$$\mathcal{H}_{ab} = \int \mathrm{d}^3\mathbf{x}\, g_{ab}|\phi_a(\mathbf{x})|^2|\phi_b(\mathbf{x})|^2 \cdot \hat{a}_a^\dagger\hat{a}_b^\dagger\hat{a}_a\hat{a}_b$$

single mode/ 0d approximation with coherent coupling



5 µm

Rubidium BEC



$$\tilde{\omega}_i = \int \mathrm{d}^3\mathbf{x}\, \phi_i(\mathbf{x})\omega_i\phi_i(\mathbf{x}), \qquad \omega_i = -\frac{\hbar^2}{2m}\nabla^2 + V_i(\mathbf{x})$$

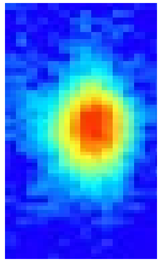
$$\chi_{ij} = \int \mathrm{d}^3\mathbf{x}\, g_{ij}|\phi_i(\mathbf{x})|^2|\phi_j(\mathbf{x})|^2$$

$$\mathcal{H} = \tilde{\omega}_a\hat{a}_a^\dagger\hat{a}_a + \tilde{\omega}_b\hat{a}_b^\dagger\hat{a}_b + \frac{\chi_{aa}}{2}\hat{a}_a^\dagger\hat{a}_a^\dagger\hat{a}_a\hat{a}_a + \frac{\chi_{bb}}{2}\hat{a}_b^\dagger\hat{a}_b^\dagger\hat{a}_b\hat{a}_b + \chi_{ab}\hat{a}_a^\dagger\hat{a}_b^\dagger\hat{a}_a\hat{a}_b$$

$$\mathcal{H}_{\mathrm{cpl}} = -\frac{\hbar\Omega_r}{2}\int d^3\mathbf{x}\left(\hat{\psi}_a(\mathbf{x})\hat{\psi}_b^\dagger(\mathbf{x})\mathrm{e}^{-\mathrm{i}(\delta_c t+\varphi_0)} + \mathrm{h.c.}\right) \Rightarrow \mathcal{H}_{\mathrm{cpl}} = -\frac{\hbar\tilde{\Omega}}{2}\left(\hat{a}_a\hat{a}_b^\dagger\mathrm{e}^{-\mathrm{i}(\delta_c t+\varphi_0)} + \mathrm{h.c.}\right)$$

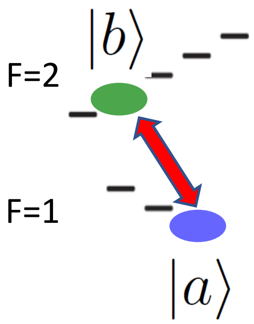
$$\tilde{\Omega} = \Omega_r\int d^3\mathbf{x}\,\phi_a(\mathbf{x})\phi_b(\mathbf{x})$$

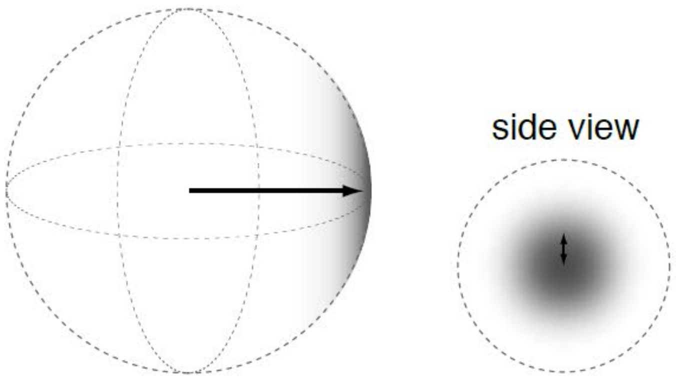
Schwinger collective spins simplifies H significantly



5 µm

Rubidium BEC





$J = N \cdot \frac{1}{2}$ $\Delta J_{\perp} = \sqrt{N/2}$

$$J_{x,y,z} = \sum_{i}^{N} S_{x,y,z}^{(i)}$$

Schwinger – collective spin:

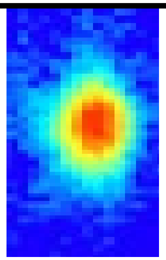
$$\hat{J}_x = \frac{1}{2}(\hat{a}_a^{\dagger}\hat{a}_b + \hat{a}_b^{\dagger}\hat{a}_a) \qquad \hat{J}_y = \frac{1}{2i}(\hat{a}_b^{\dagger}\hat{a}_a - \hat{a}_a^{\dagger}\hat{a}_b) \qquad \hat{J}_z = \frac{1}{2}(\hat{a}_b^{\dagger}\hat{a}_b - \hat{a}_a^{\dagger}\hat{a}_a)$$

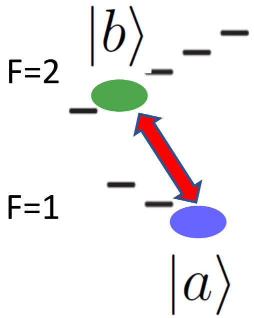
$$[\hat{J}_i, \hat{J}_j] = \mathrm{i}\epsilon_{ijk}\hat{J}_k.$$

$$[\hat{a}_i, \hat{a}_j^{\dagger}] = \delta_{ij}$$

Lipkin-Meshkov-Glick Hamiltonian
Two mode Bose Hubbard
Quantum dimer
Fully connected transverse field Ising model

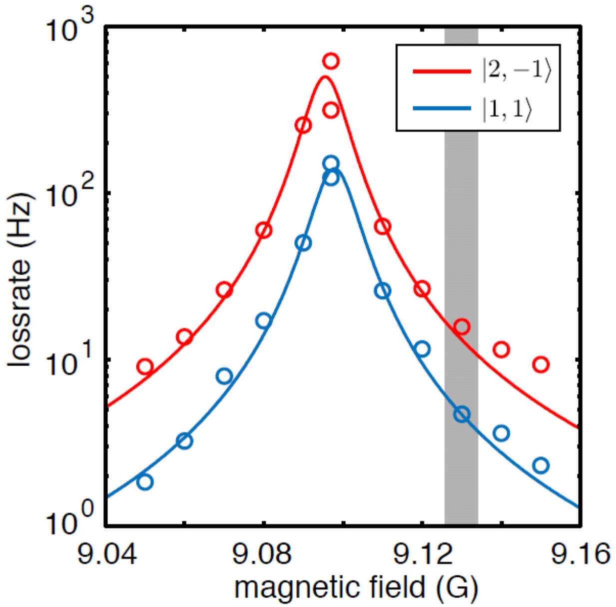
The Hamiltonian and the energy scales



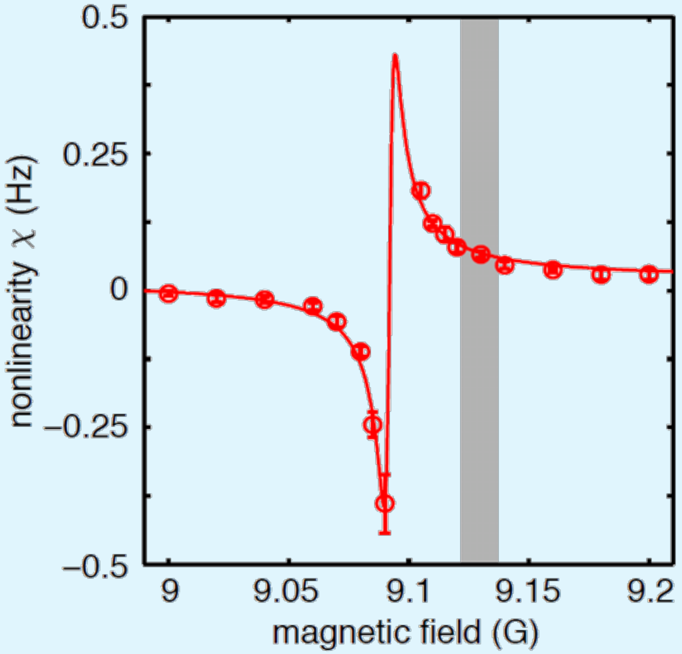


$$\hat{H} = \chi \hat{J}_z^{\,2} - \Omega \hat{J}_x + [\Delta + (g_{11} - g_{22})N]\hat{J}_z$$

Feshbach resonance -loss



Feshbach resonance



±1Hz

Magnetic field

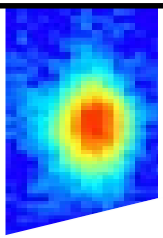
± 100µG

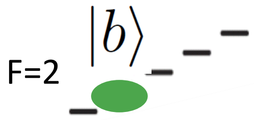
Total atom number fluctuations

N = 400 ± 40

The Hamiltonian and the energy scales

Lipkin-Meshkov-Glick Hamiltonian
Two mode Bose Hubbard
Quantum dimer
Fully connected transverse field Ising model





1.C

Nuclear Physics 62 (1965) 188—198; © North-Holland Publishing Co., Amsterdam

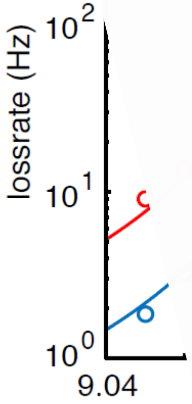
VALIDITY OF MANY-BODY APPROXIMATION METHODS FOR A SOLVABLE MODEL

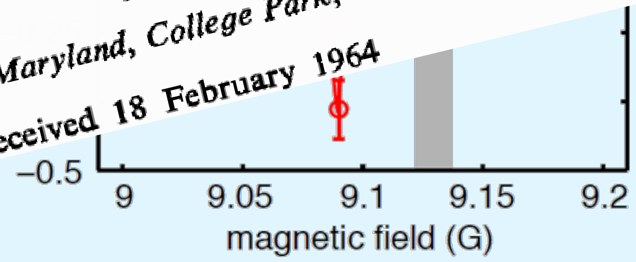
(I). Exact Solutions and Perturbation Theory

H. J. LIPKIN,
Weizmann Institute of Science, Rehovoth, Israel

N. MESHKOV and A. J. GLICK †
Weizmann Institute of Science, Rehovoth, Israel
and
University of Maryland, College Park, Maryland ††

Received 18 February 1964





$$[\Delta+(g_{11}-g_{22})N]\hat{J}_z$$

±1Hz

Magnetic field

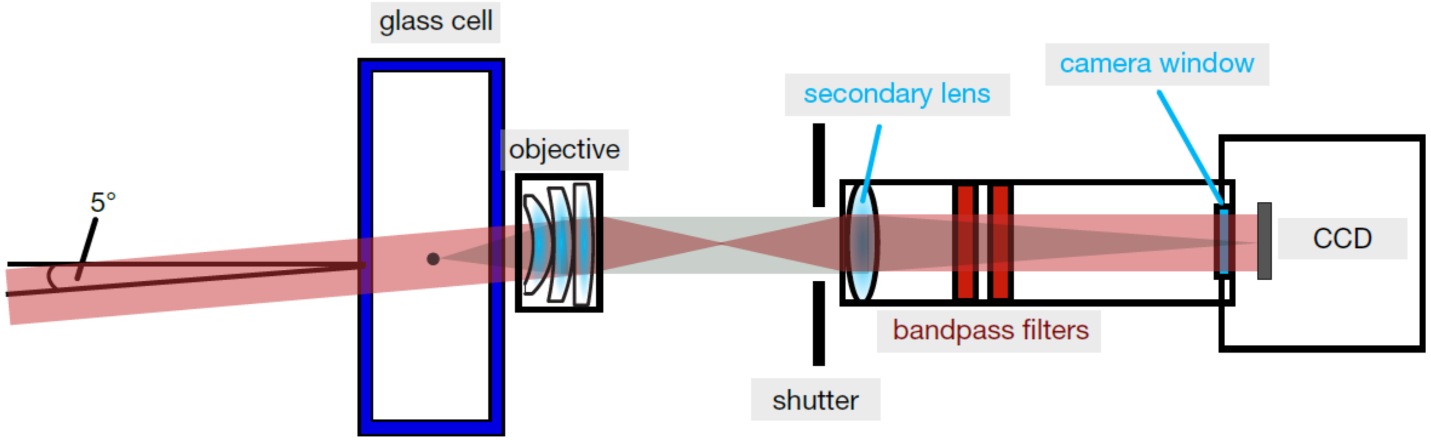
± 100μG

Total atom number fluctuations

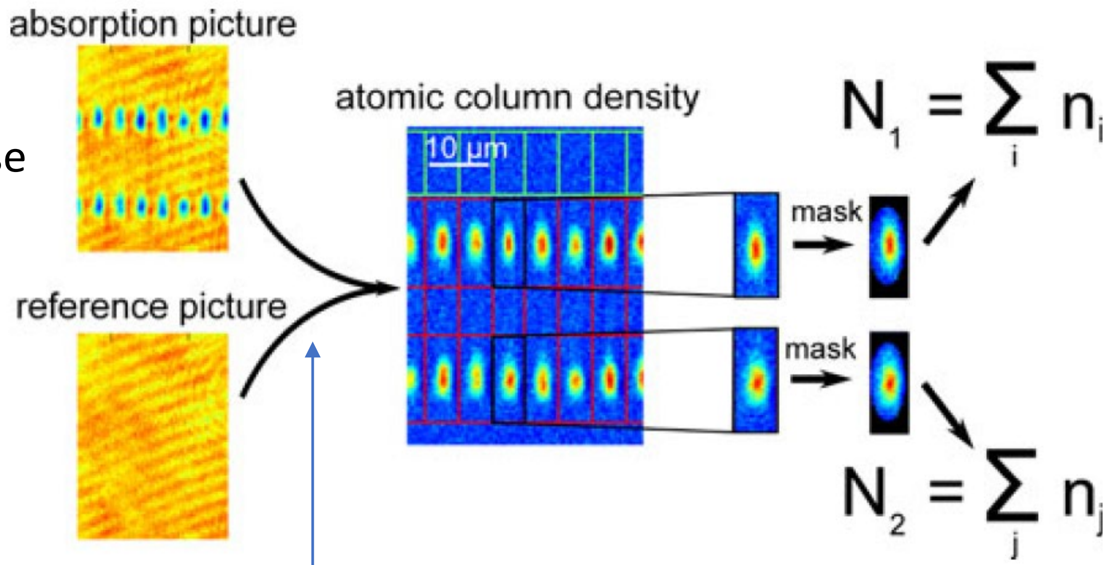
N = 400 ± 40

Imaging @ ±3atoms

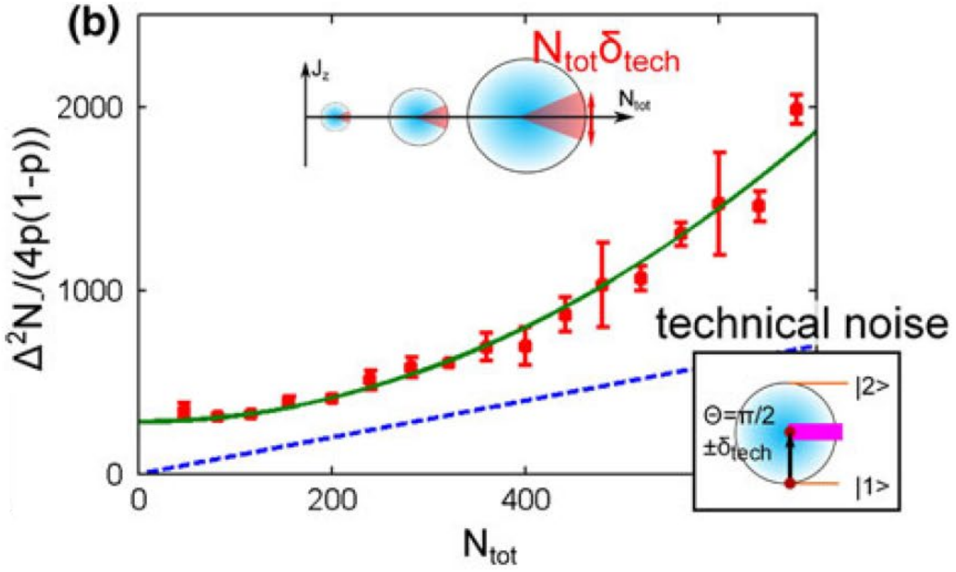
App. Phys. B 113, 69 (2013)

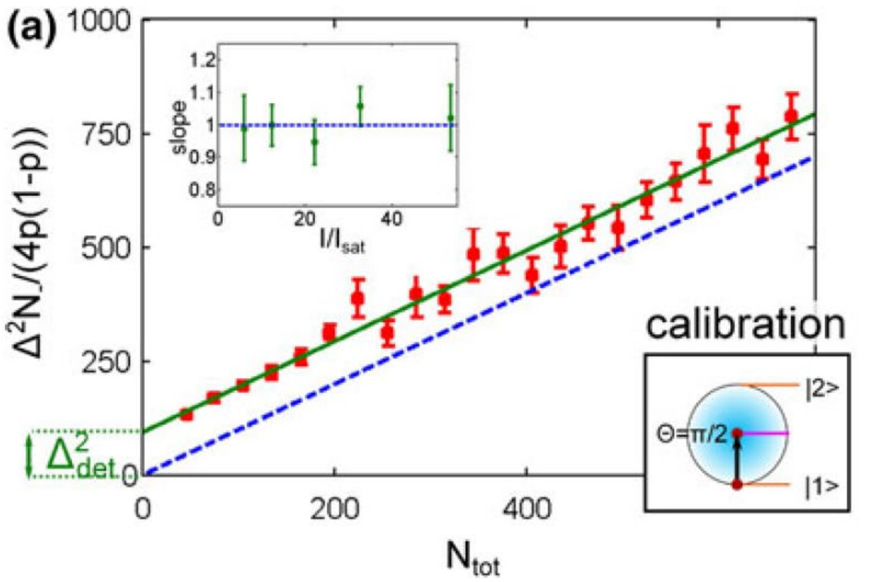


$\pi/2$ pulse



$$n_c = \int n \mathrm{d}z = -\frac{1}{\sigma_0}\left[\alpha \cdot \ln\left(\frac{I_\mathrm{f}}{I_\mathrm{i}}\right) + \frac{I_\mathrm{f} - I_\mathrm{i}}{I_\mathrm{sat}}\right]$$





What has Trinitrotoluol (TNT) to do with quantum mixtures ?

PRL 113, 103004 (2014); PRA 91, 013412 (2015)

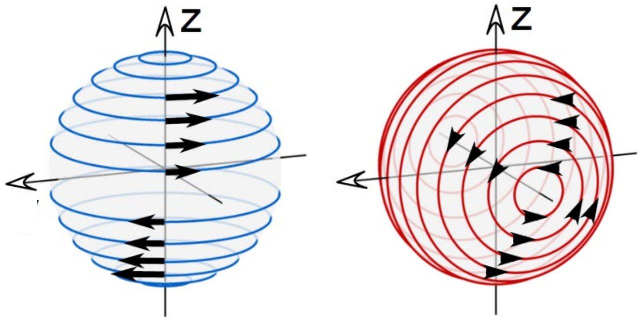
$$\hat{H} = \chi \hat{J}_z^{\,2} - \Omega \hat{J}_x$$

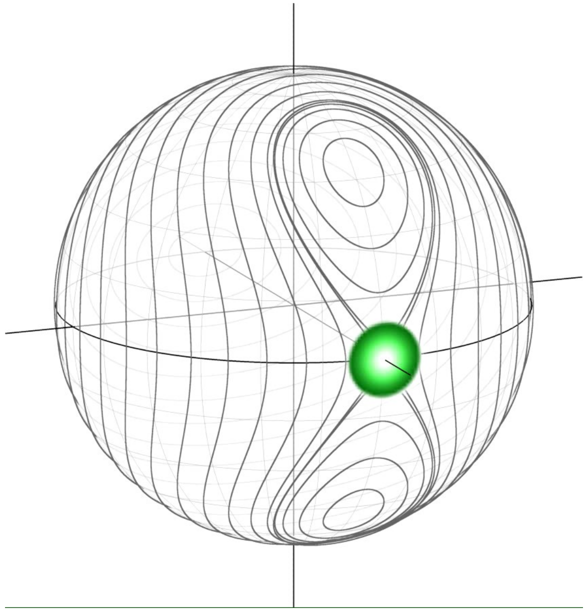
rotation z axis

$$e^{\frac{-i\chi t}{\hbar}\hat{J}_z\hat{J}_z}$$

rotation x axis

$$e^{\frac{-i\,\Omega\, t}{\hbar}\hat{J}_x}$$





e.g. A. Micheli et al. Phys.Rev. A **67** , 013607 (2003)

Wolfgang Muessel

generating non-classical states – Twist aNd Turn

What about the classical limit of complex order parameter ?

$$H = \chi J_z^2 - \Omega J_x$$

classical →

$$H = \frac{\Lambda}{2}\Delta n^2 - \sqrt{1-\Delta n^2}\cos\varphi \qquad \Lambda = \frac{N\chi}{\Omega}$$

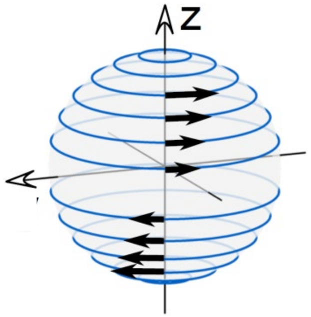
$$\hat{a}^+ = \sqrt{n_a}\, e^{i\varphi_a}$$

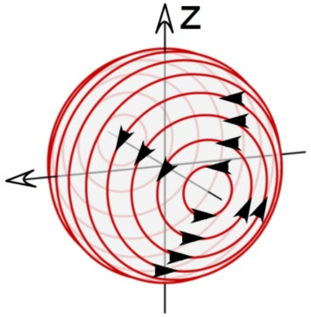
rotation z axis

$$e^{\frac{-i\chi t}{\hbar}\hat{J}_z\hat{J}_z}$$

rotation x axis

$$e^{\frac{-i\,\Omega\, t}{\hbar}\hat{J}_x}$$





$$\hat{J}_x = \frac{1}{2}\left(\hat{a}^+\hat{b} + \hat{b}^+\hat{a}\right)$$

$$\hat{J}_y = \frac{1}{2i}\left(\hat{a}^+\hat{b} - \hat{b}^+\hat{a}\right)$$

$$\hat{J}_z = \frac{1}{2}\left(\hat{a}^+\hat{a} - \hat{b}^+\hat{b}\right)$$

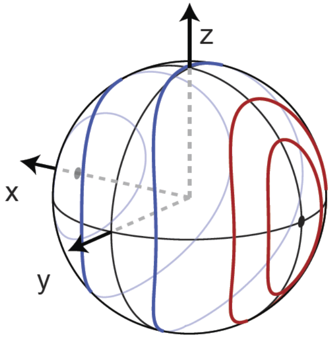
Schwinger spin

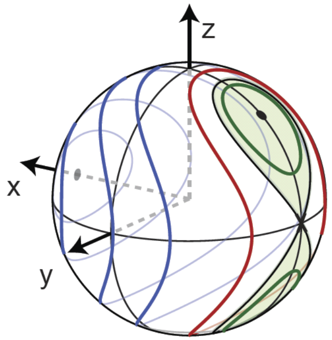
$$\hat{J}_x \cong \sqrt{n_a n_b}\cos\varphi$$

$$\hat{J}_y \cong \sqrt{n_a n_b}\sin\varphi$$

$$\hat{J}_z \cong \frac{n_a - n_b}{2}$$

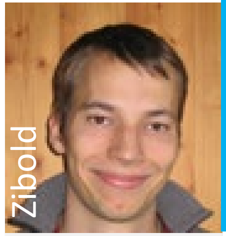
Classical description

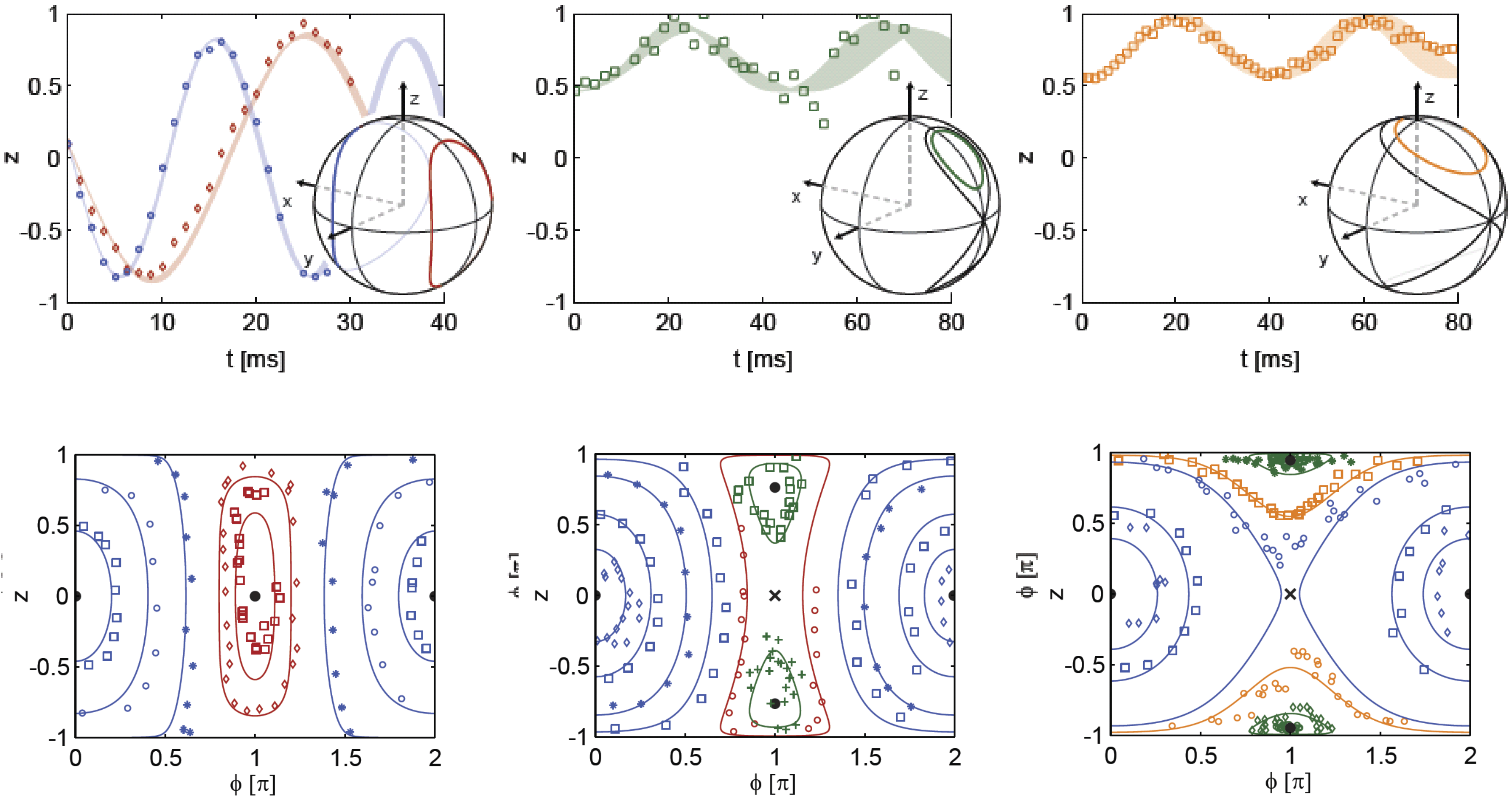




Dynamics

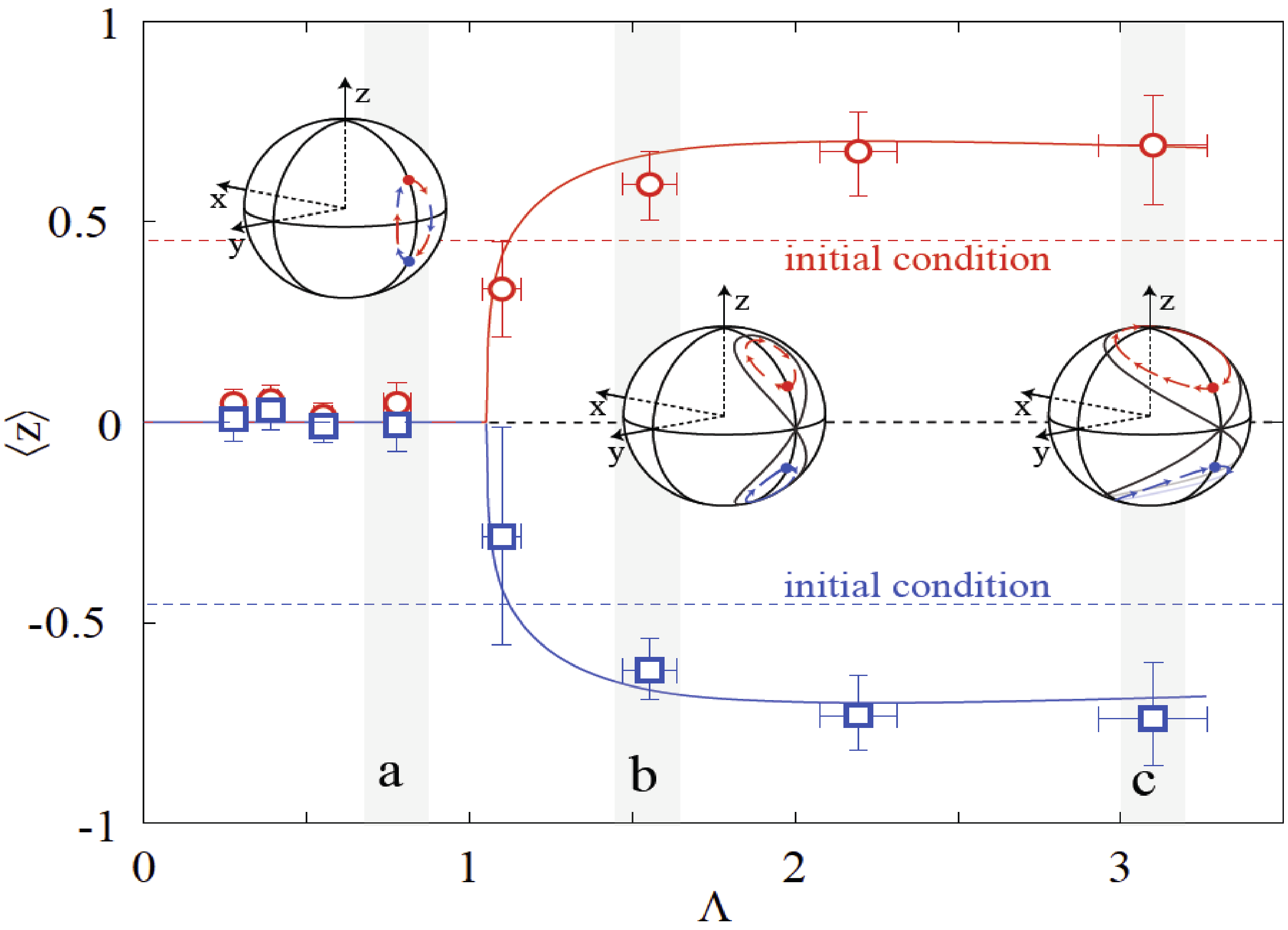
PRL 105, 204101 (2010)





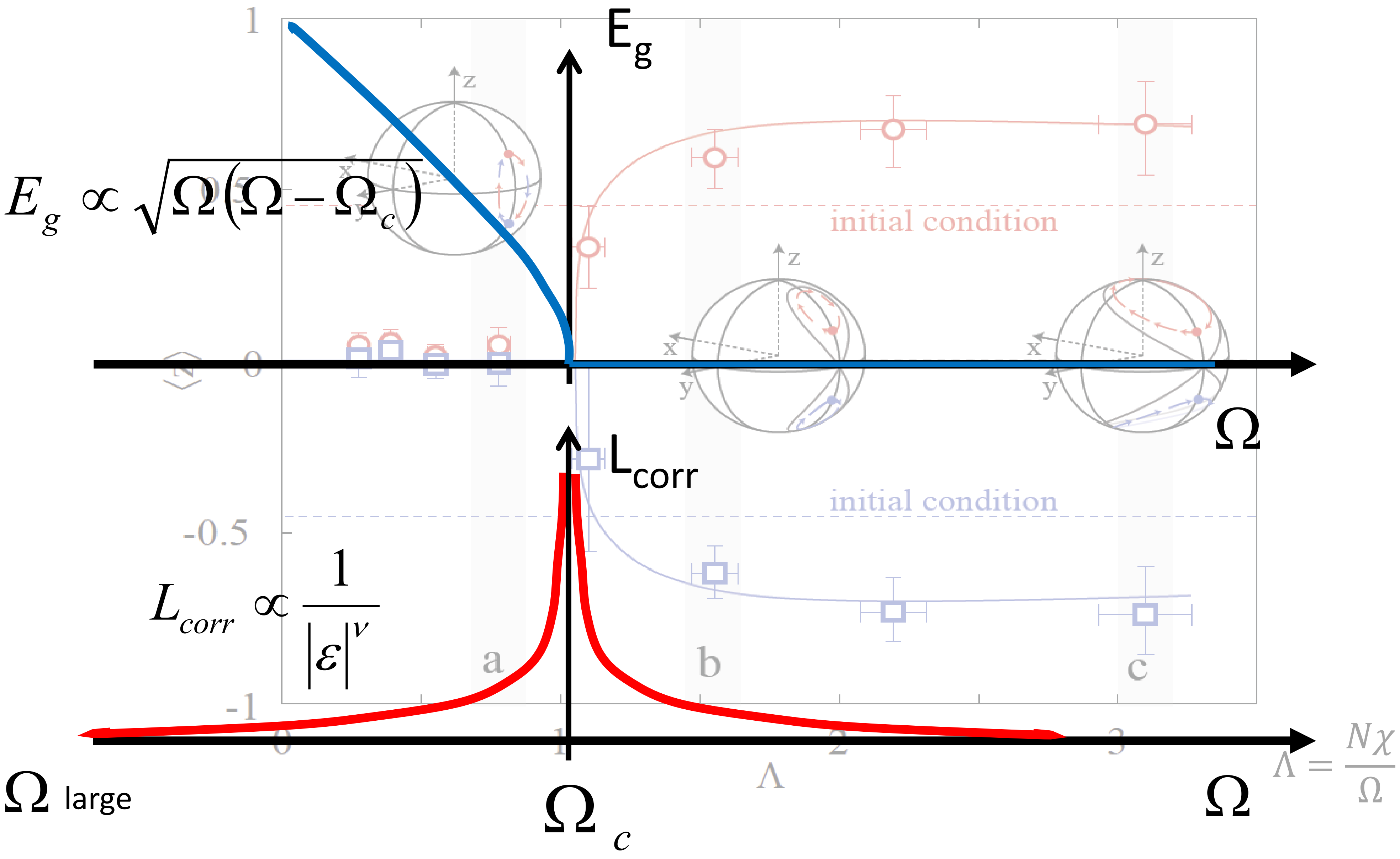
increasing interactions

Quantum bifurcation – quantum phase transition



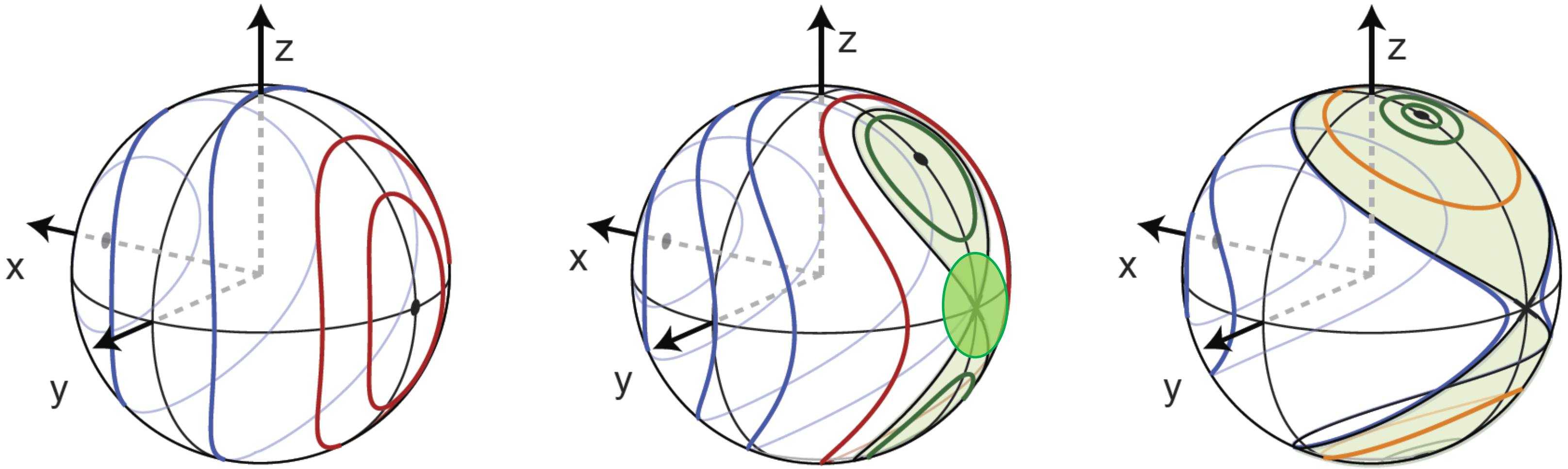
$$\Lambda = \frac{N\chi}{\Omega}$$

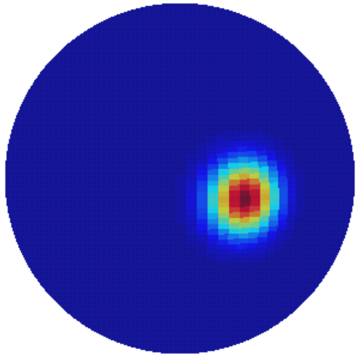
Quantum bifurcation – quantum phase transition

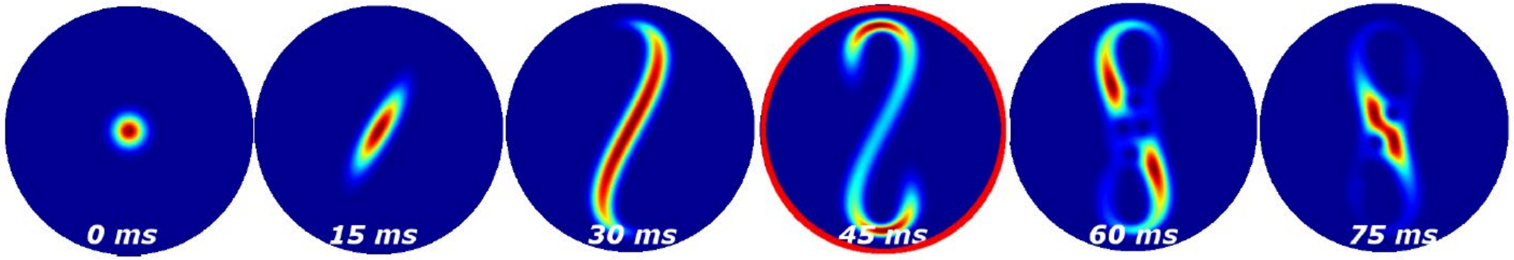


,interesting‘ many particle states

squeezing ➡ non Gaussian state







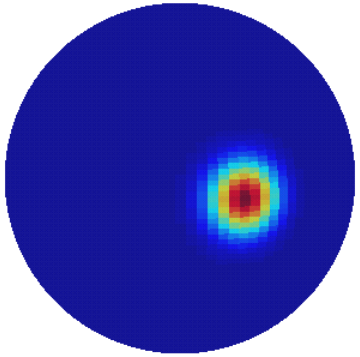
‚interesting‘ many particle states

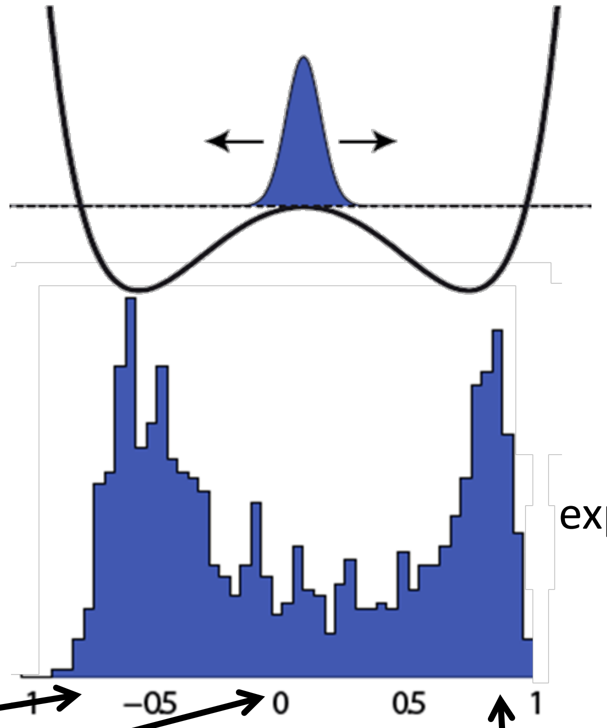
squeezing ➡ non Gaussian state

PHYSICAL REVIEW A 78, 023611 (2008)

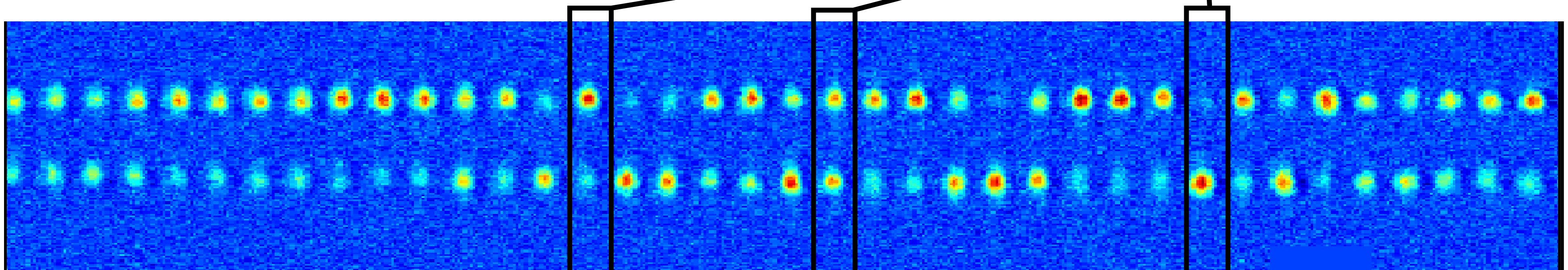
Fock-space WKB method for the boson Josephson model describing a Bose-Einstein condensate trapped in a double-well potential

V. S. Shchesnovich[1] and M. Trippenbach[2]



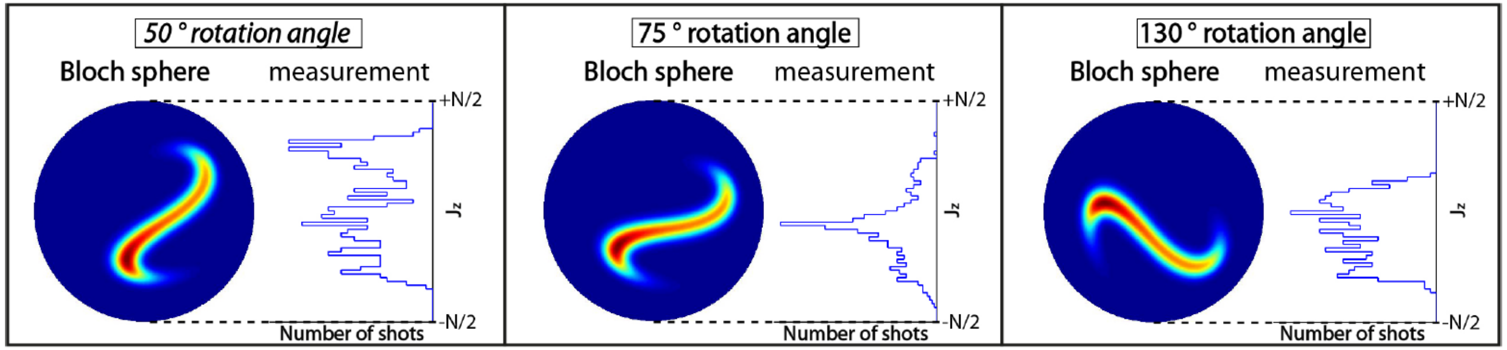


experiment

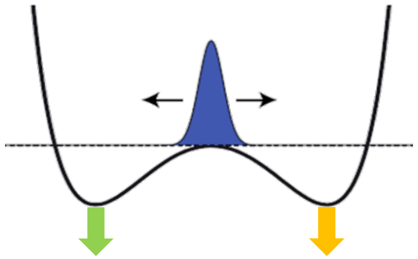


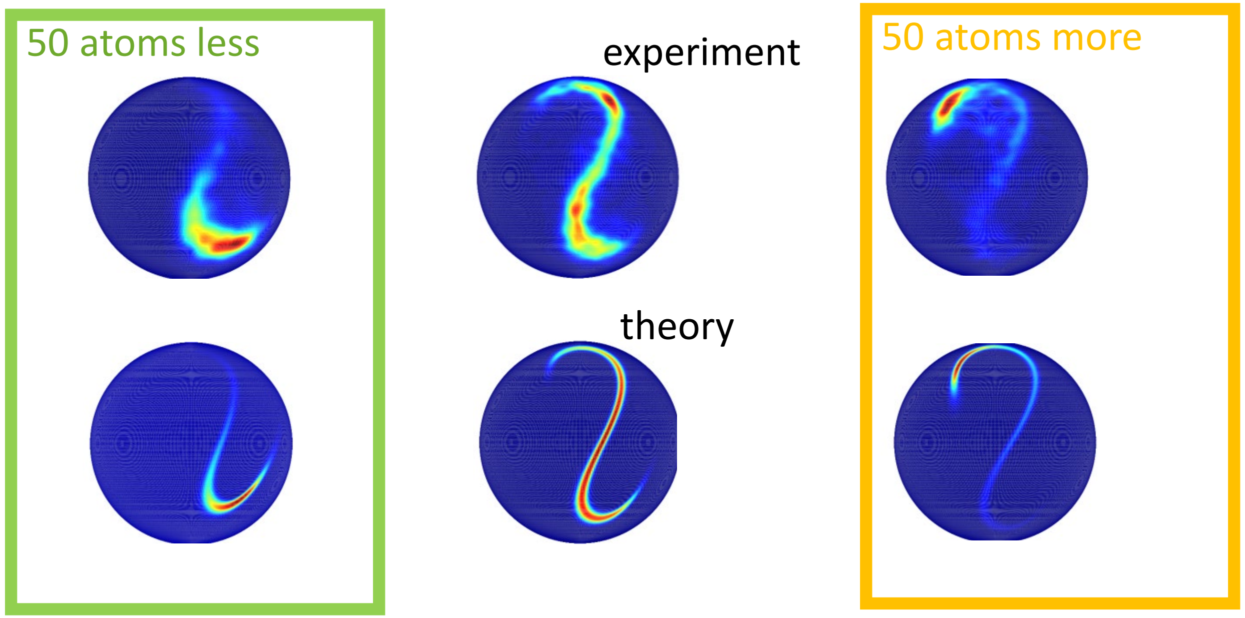
Tomography with 90000 BECs

90000 BEC experiments !

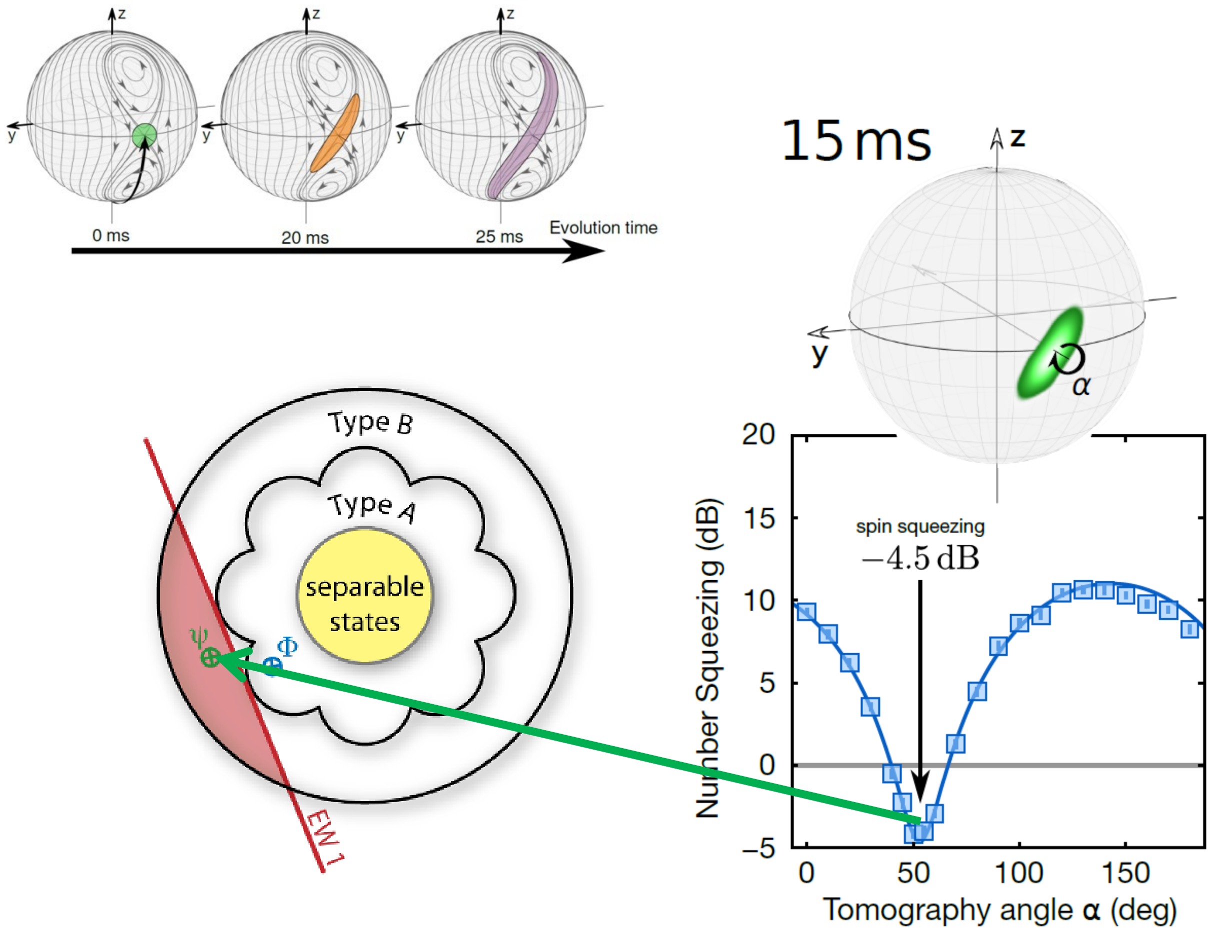


postselected: 340 ± 10 atoms



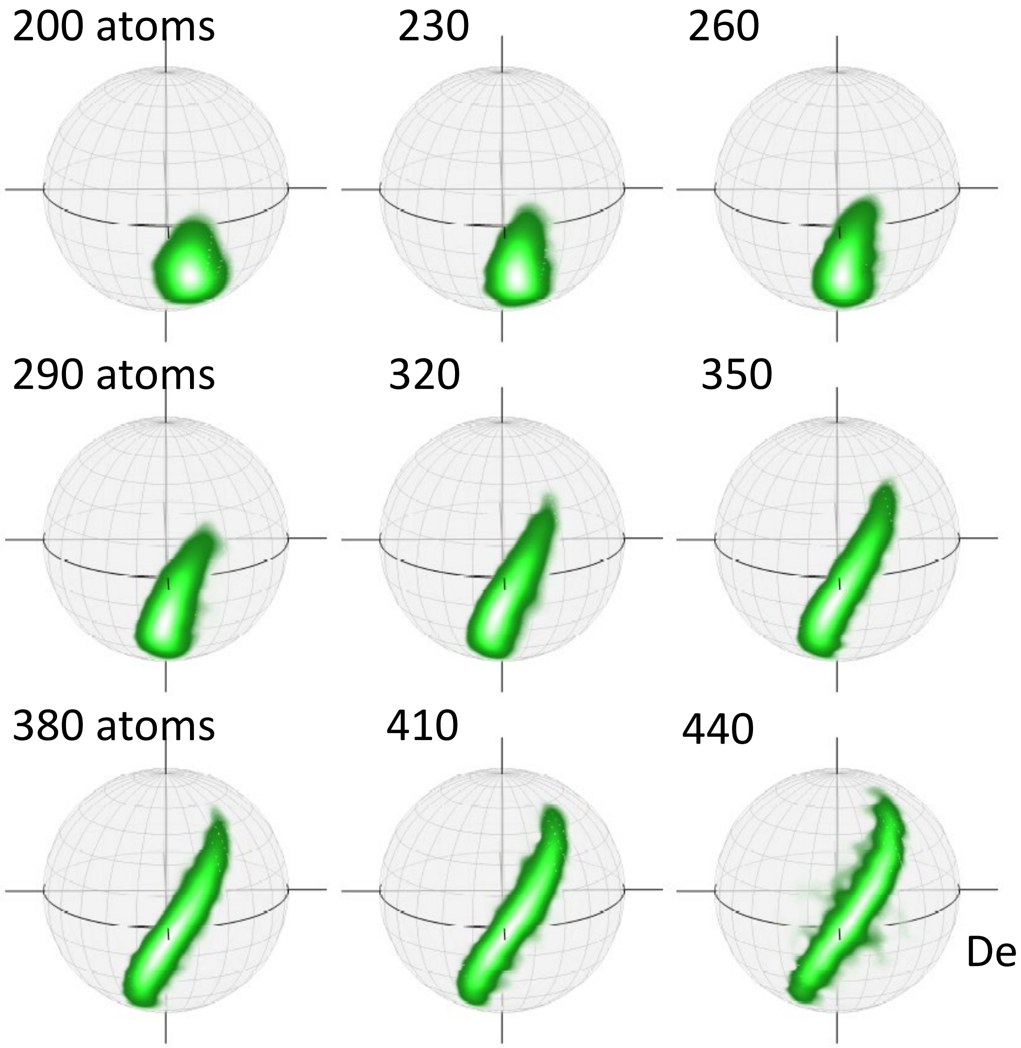


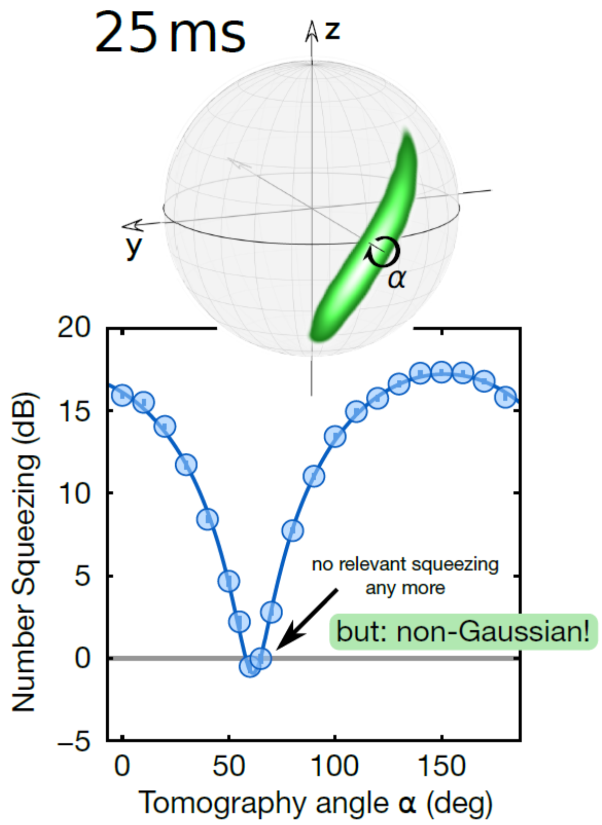
See also: Schmied, Treutlein New J. Phys. 13:065019, (2011)



z
y
0 ms
20 ms
25 ms
Evolution time
15 ms
z
y
α
Type B
Type A
separable states
Ψ
Φ
EW 1
spin squeezing
−4.5 dB
Number Squeezing (dB)
20
15
10
5
0
−5
0
50
100
150
Tomography angle α (deg)

experimentally reconstructed after 25ms with >100.000 BECs



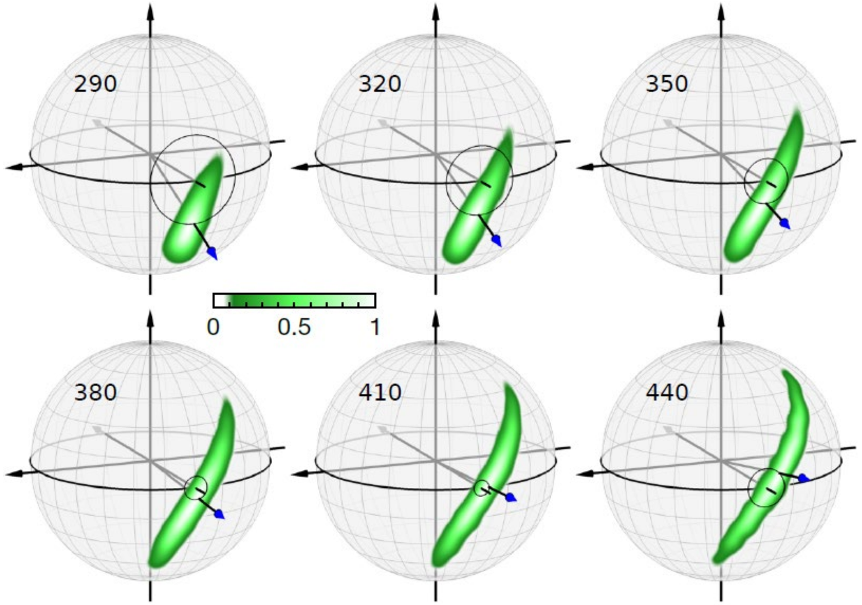


Demonstrate entanglement via quantum enhanced metrology

Fisher information and entanglement of non-Gaussian spin states
H. Strobel, W. Muessel, D. Linnemann, T. Zibold, D. B. Hume, L. Pezzè, A. Smerzi, M. K. Oberthaler
SCIENCE, 2014, Vol. 345 , 424-427

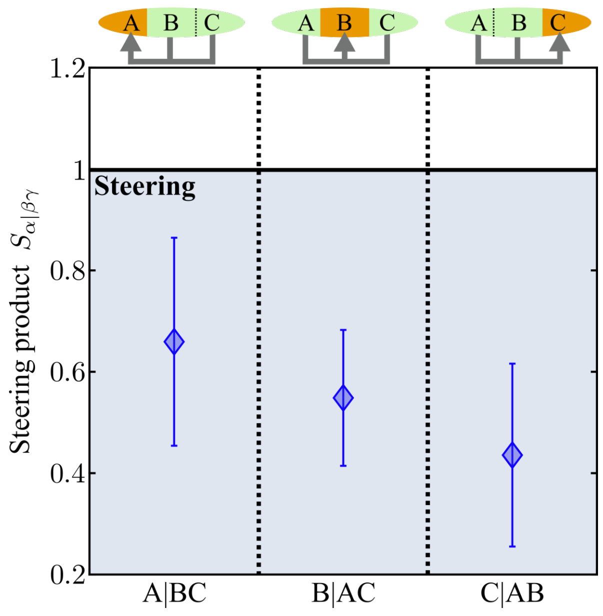
SUMMARY

worth 100.000 BECs



Ultracold coherent mixtures reveal quantum entanglement
from squeezed to non-Guassian states

Spinor Bose gases
an ideal platform for quantum many body physics



REVIEWS OF MODERN PHYSICS, VOLUME 90, JULY–SEPTEMBER 2018

Quantum metrology with nonclassical states of atomic ensembles

Luca Pezzè and Augusto Smerzi
QSTAR, INO-CNR and LENS, Largo Enrico Fermi 2, 50125 Firenze, Italy

Markus K. Oberthaler
Kirchhoff-Institut für Physik, Universität Heidelberg,
Im Neuenheimer Feld 227, 69120 Heidelberg, Germany

Roman Schmied and Philipp Treutlein
Department of Physics, University of Basel,
Klingelbergstrasse 82, 4056 Basel, Switzerland

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