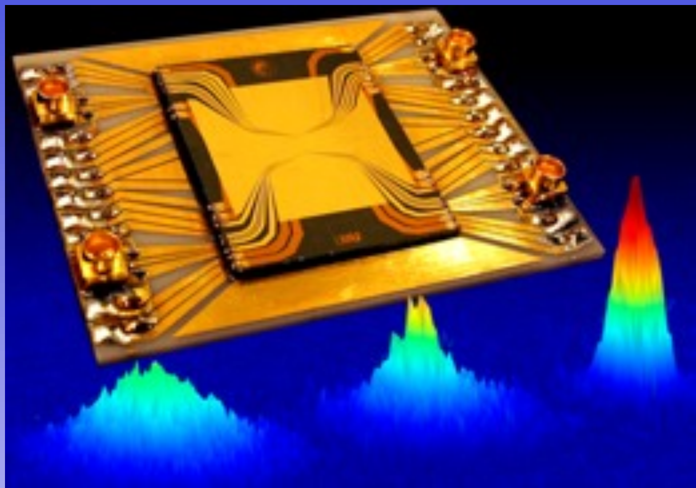
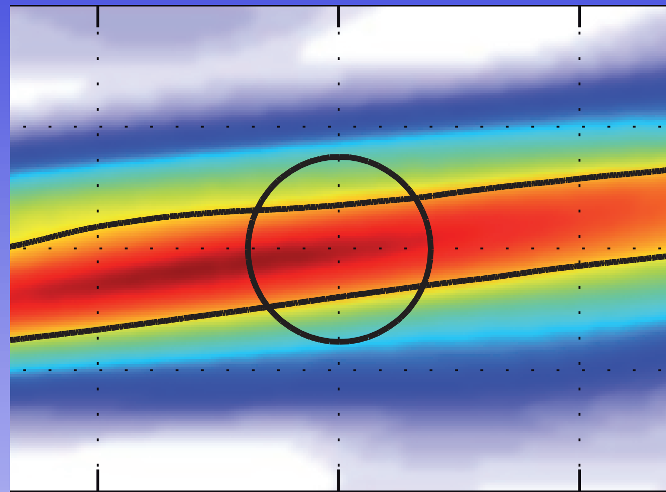
Atom-chip-based generation of entanglement for quantum metrology





Philipp Treutlein

Max F. Riedel, Pascal Böhi, Jad C. Halimeh,
Roman Schmied, and Theodor W. Hänsch

theory collaboration: Yun Li and Alice Sinatra (LKB/ENS)

LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN
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MAX-PLANCK-INSTITUT FÜR QUANTENOPTIK MPQ

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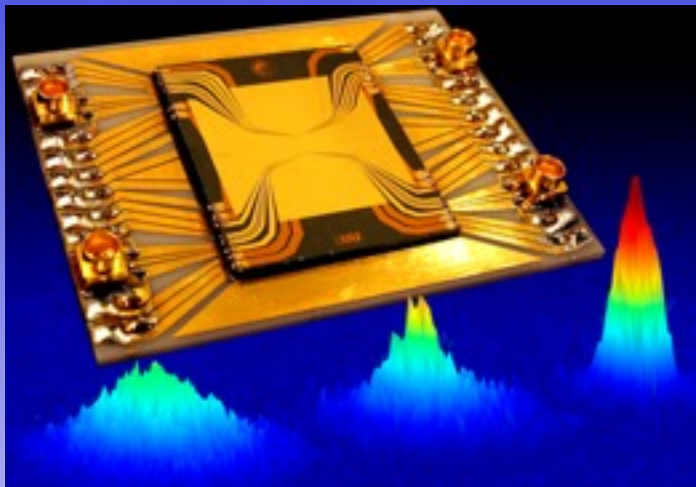

see poster by
Alice Sinatra

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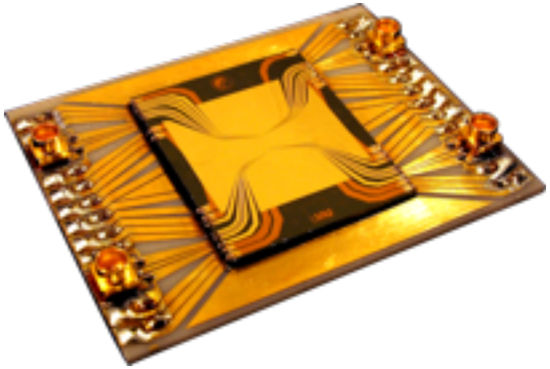
September 2010: move to the UNIVERSITY OF BASEL Switzerland

Outline



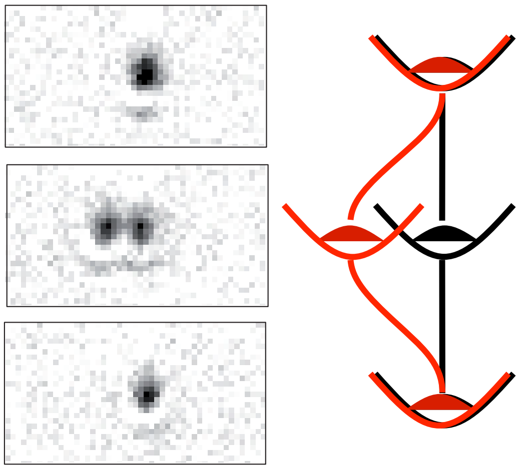
Ultracold atoms on atom chips

- basic principles
- experimental setup

Chip-based atomic clocks and interferometers

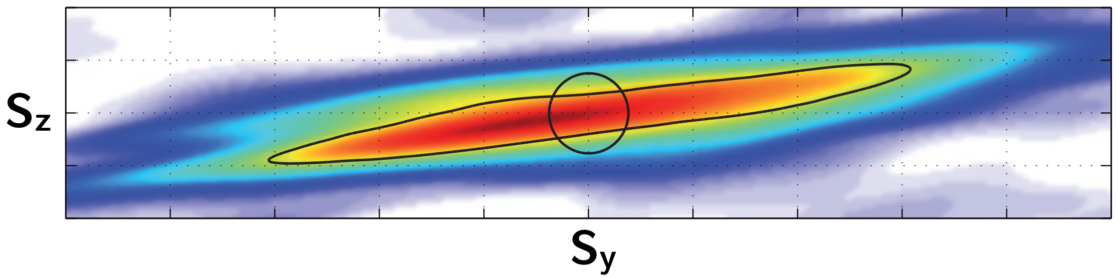
- BEC interferometer with internal-state labeling

P. Böhi et al., Nature Physics 5, 592 (2009).



Spin-squeezing and multi-particle entanglement

- control of collisions in state-dependent potential
- spin-squeezing on the clock transition
- Wigner function reconstruction
- experimental test of multi-particle entanglement

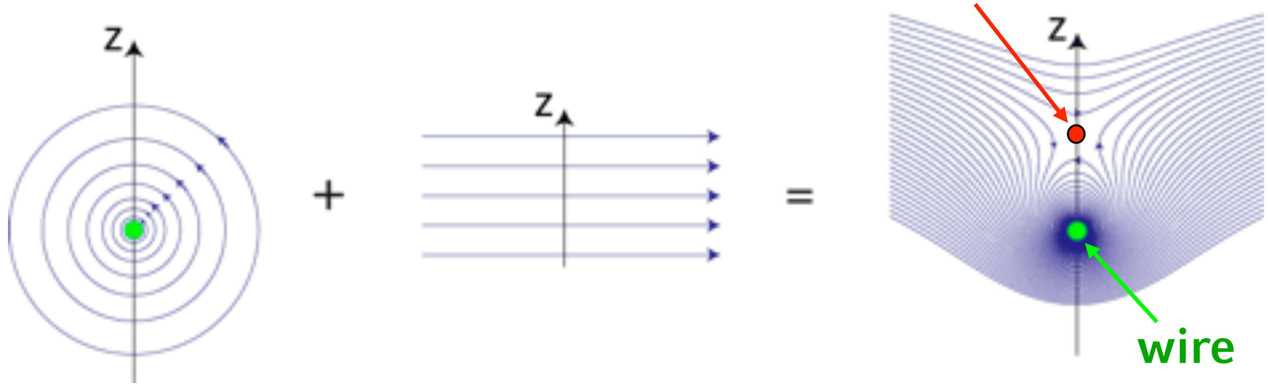


M. F. Riedel et al.,
Nature 464, 1170 (2010).

Atom chips

Basic principle: the wire trap

atoms are trapped in
B-field minimum



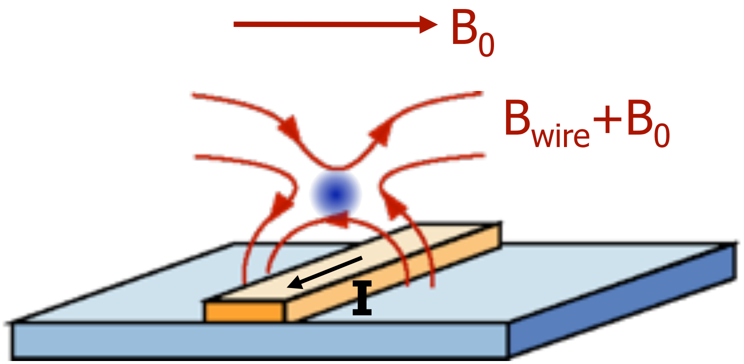
magnetic field of wire | homogeneous field | trap (2D)

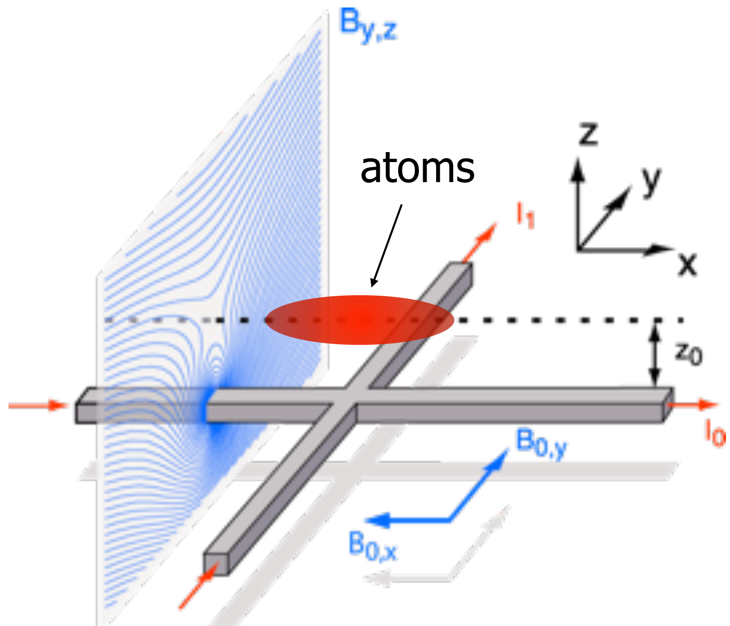
Zeeman interaction

$$H_Z = -\boldsymbol{\mu} \cdot \mathbf{B}$$

Wire field gradient

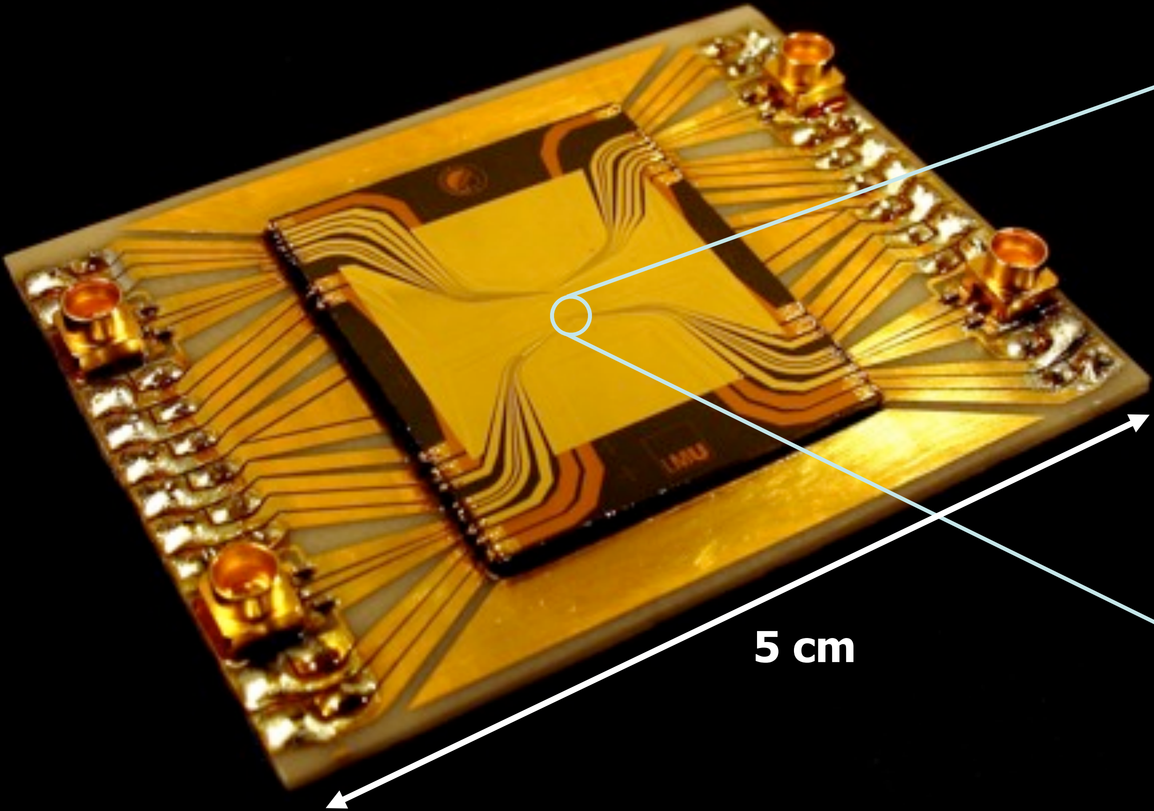
$$\frac{\partial B}{\partial z} = -\frac{\mu_0}{2\pi} \cdot \frac{I}{z^2}$$

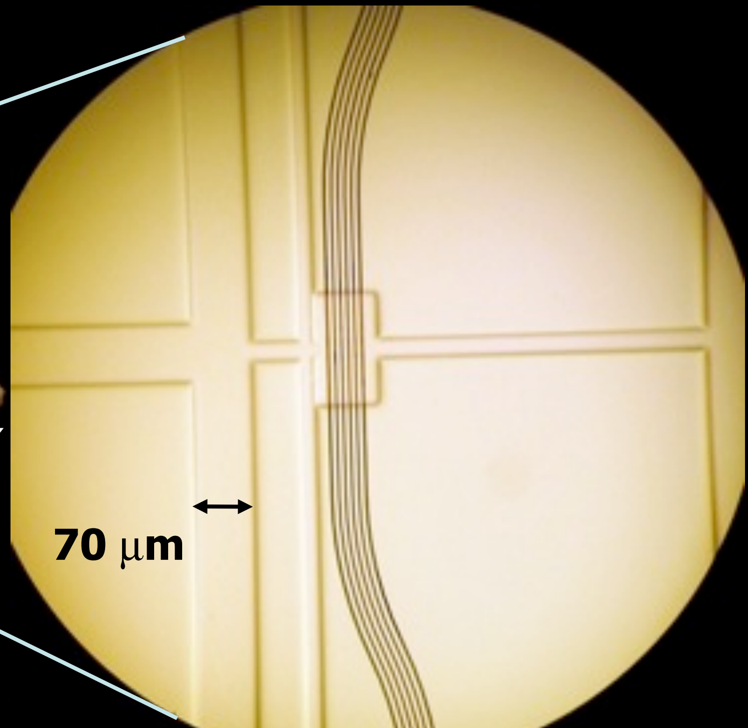




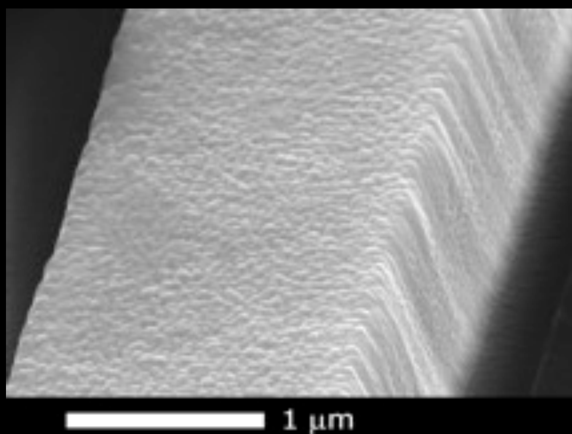
high trap frequencies: up to 1 MHz
small atom-surface distance: < 1 μm possible

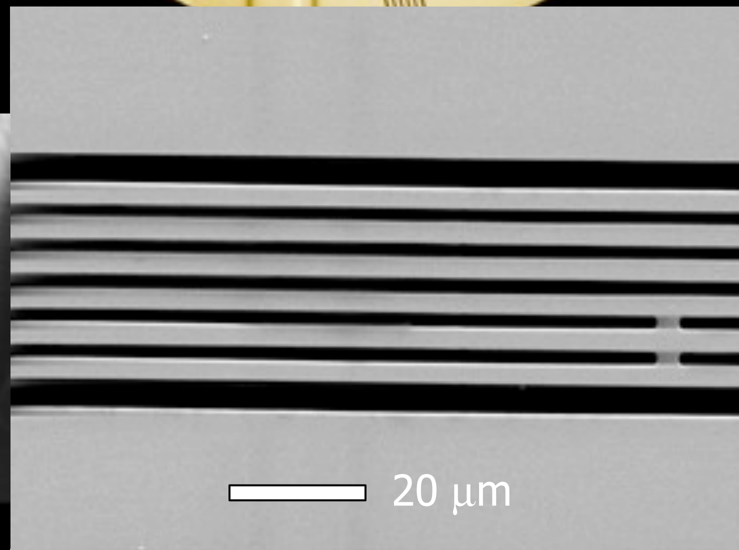
State of the art: multi-layer atom chips





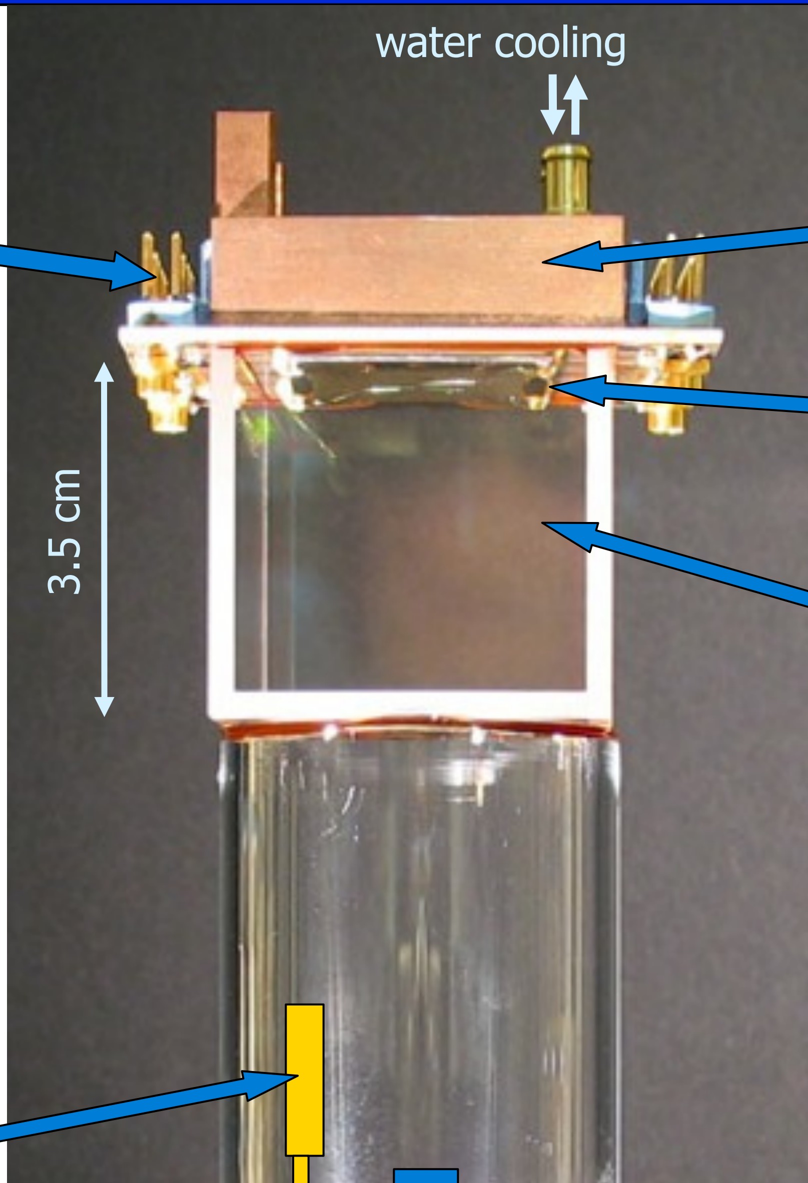
We gratefully acknowledge the Kotthaus group at CeNS, LMU Munich for cleanroom access





Compact glass cell vacuum chamber

wire connectors



copper block

atom chip with
mirror surface

base pressure
in glass cell:
3×10^{-10} mbar
at T = 300 K

(trap lifetime ≈ 5 s
with dispenser on)

Rb dispenser

to ion pump

Production of Bose-Einstein condensates

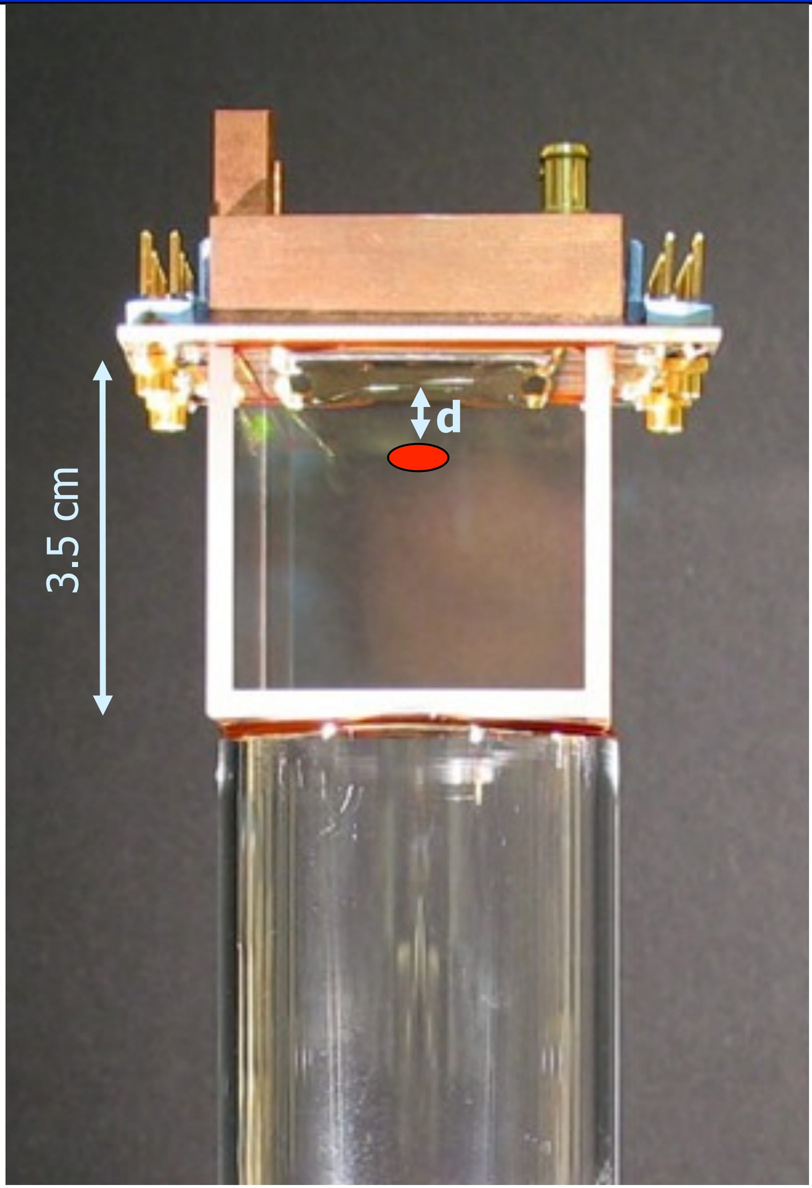
BEC sequence:

- mirror-MOT
- optical molasses
- optical pumping
- magnetic trap
- transport atoms
- evaporative cooling to BEC

all inside the same glass cell

pressure:
3×10^{-10} mbar

experimental cycle: 10 s



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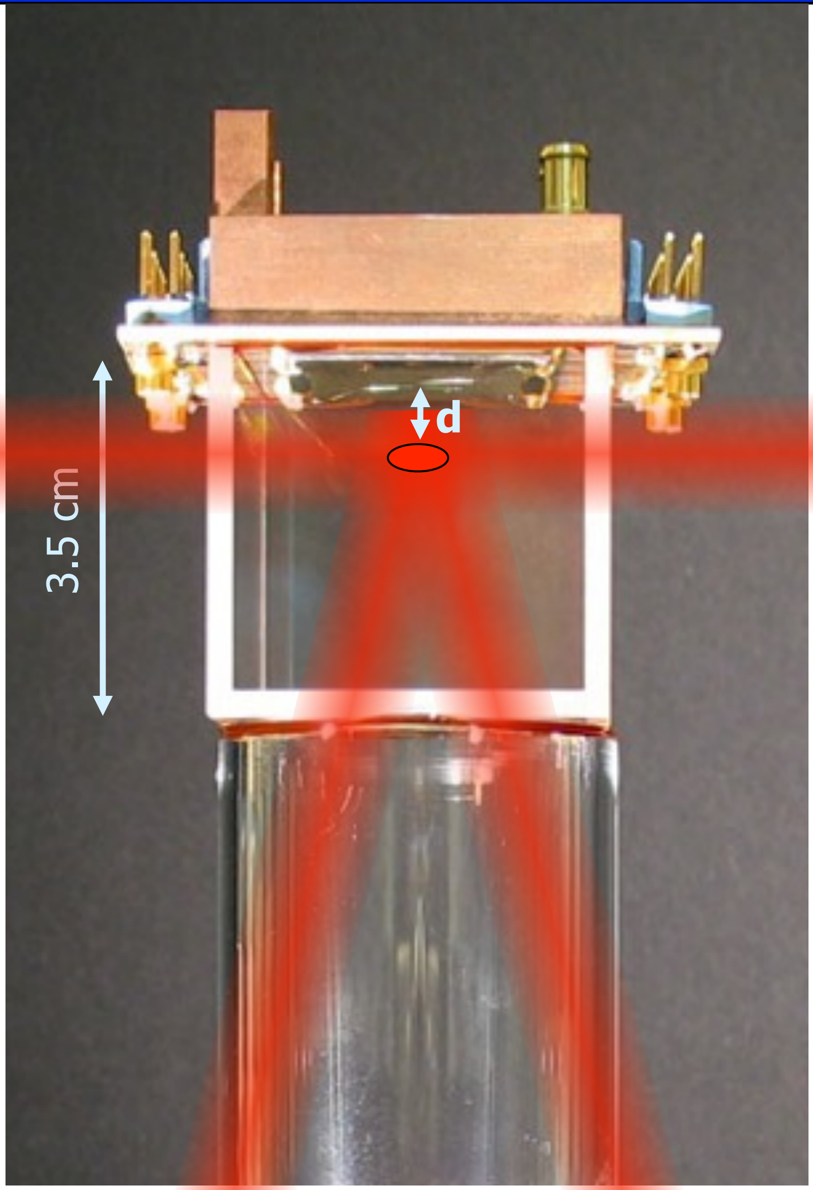
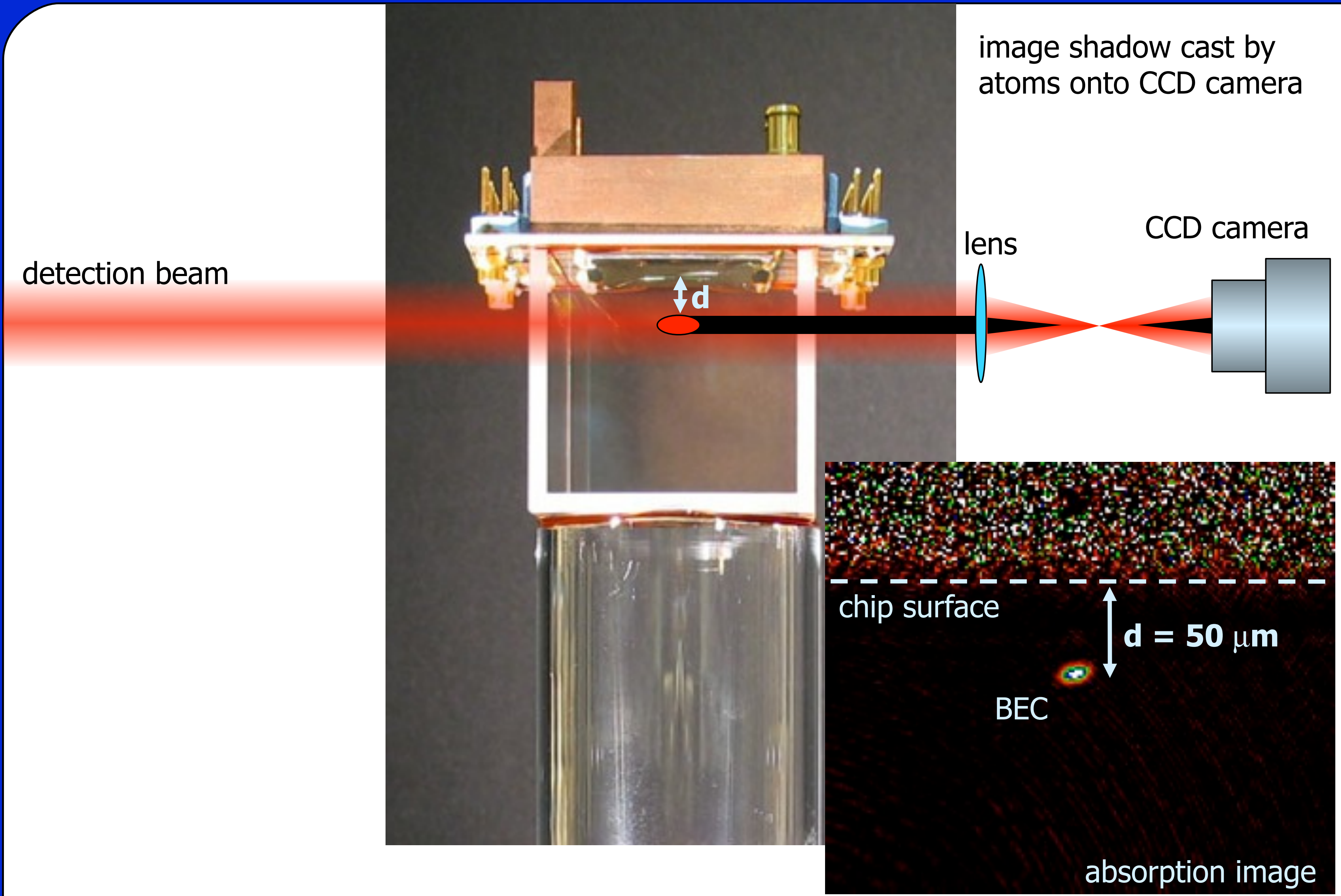


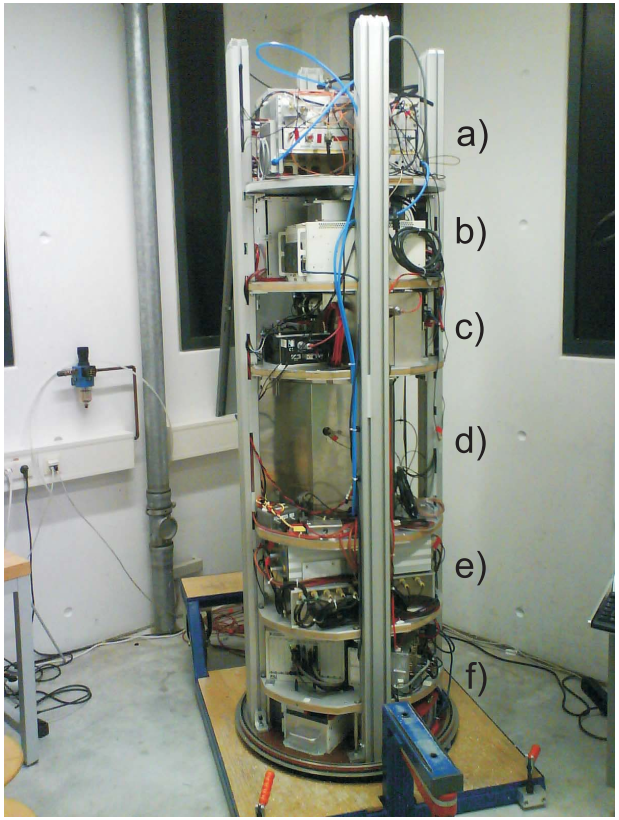
Absorption imaging



Portable atom-chip setups

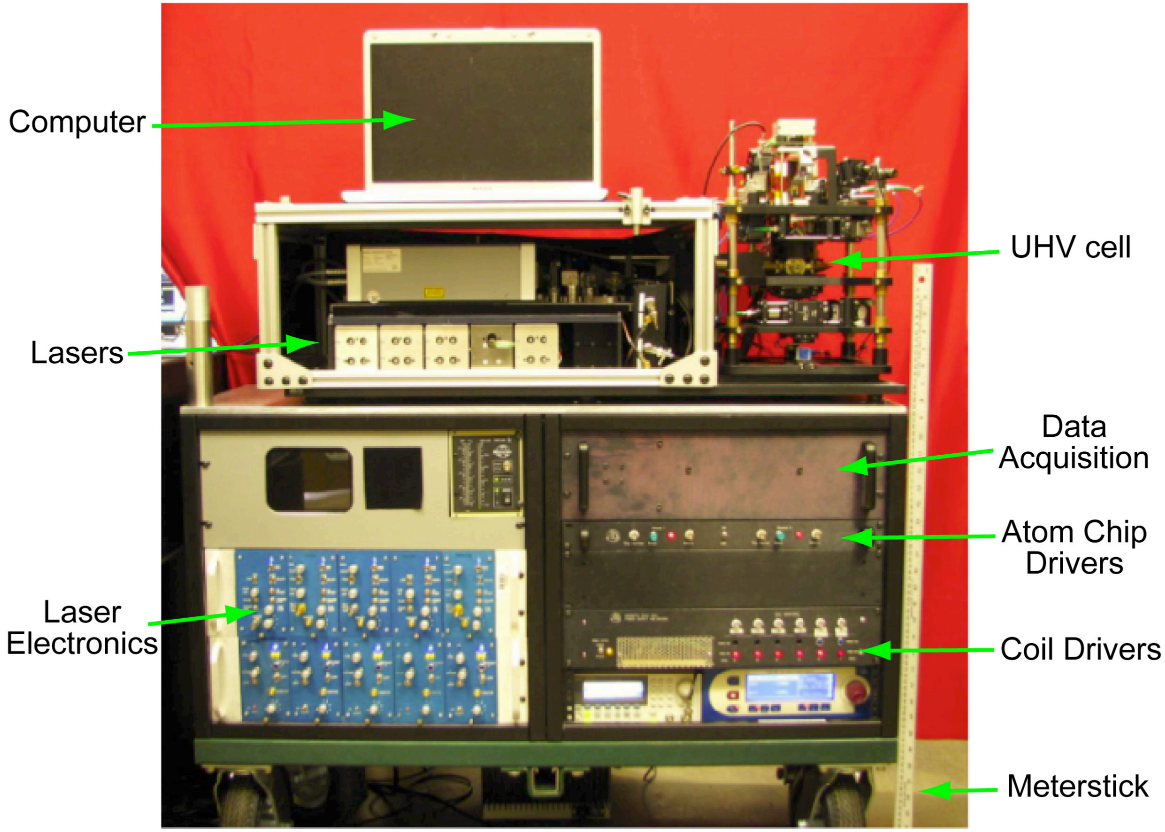
QUANTUS project

A. Vogel et al.,
Appl. Phys. B 84, 663 (2006).



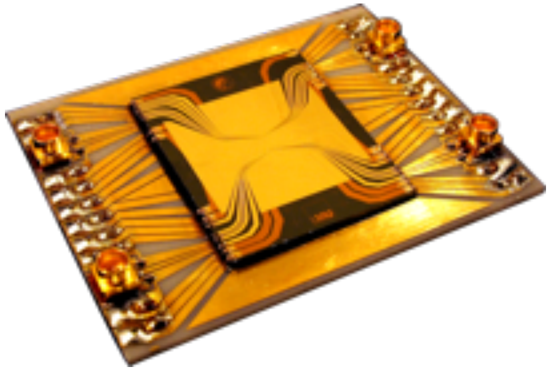
D. Anderson’s group, Boulder

D. M. Farkas et al., arXiv:0912.0533 (2009).



Key components commercially available: ColdQuanta www.coldquanta.com

Outline



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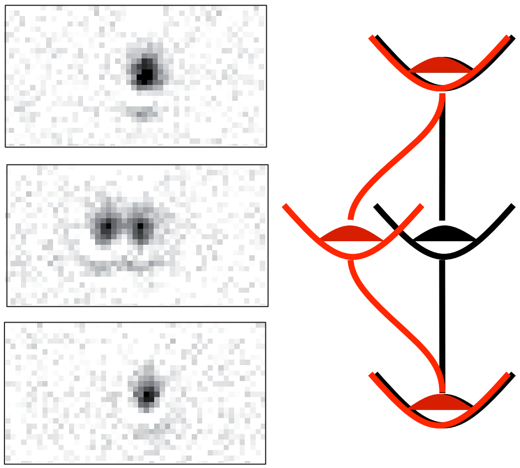

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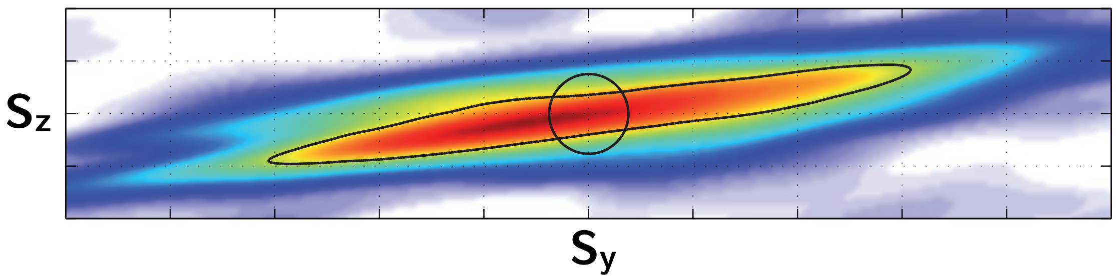
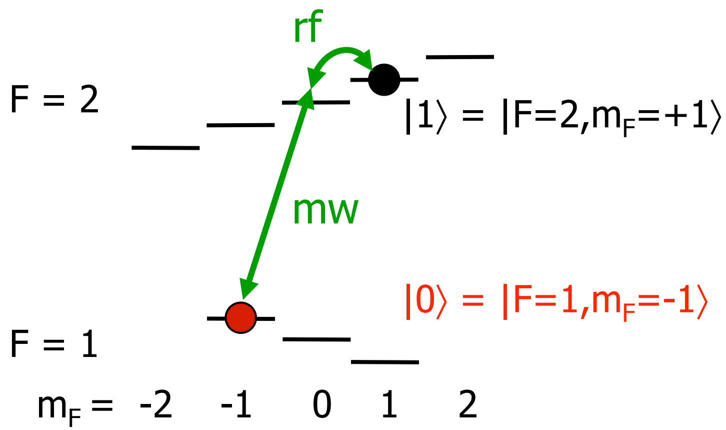
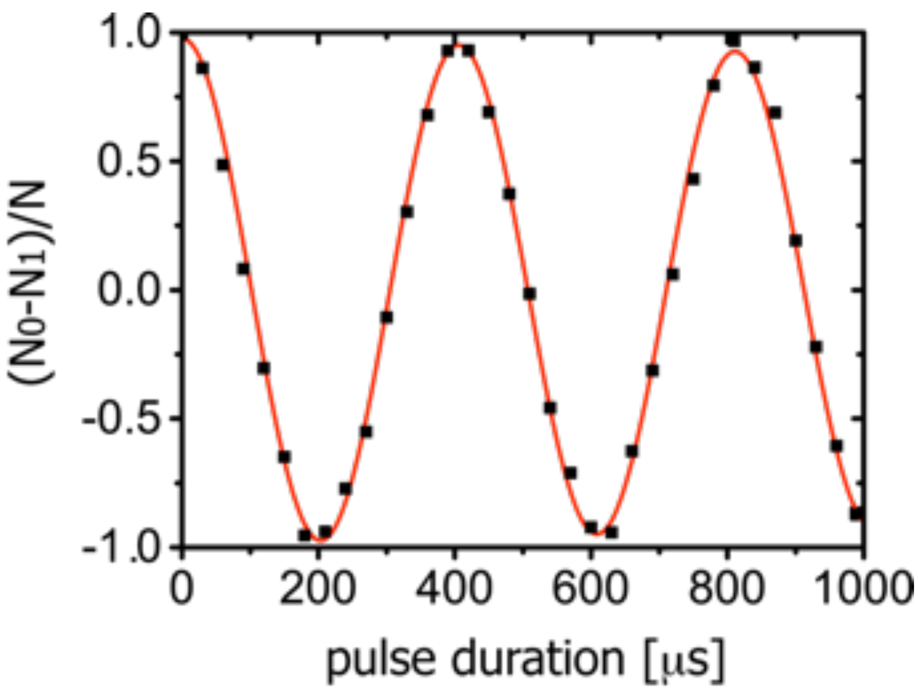


Clock states of ^{87}Rb in a magnetic trap





Qubit / clock states of ^{87}Rb

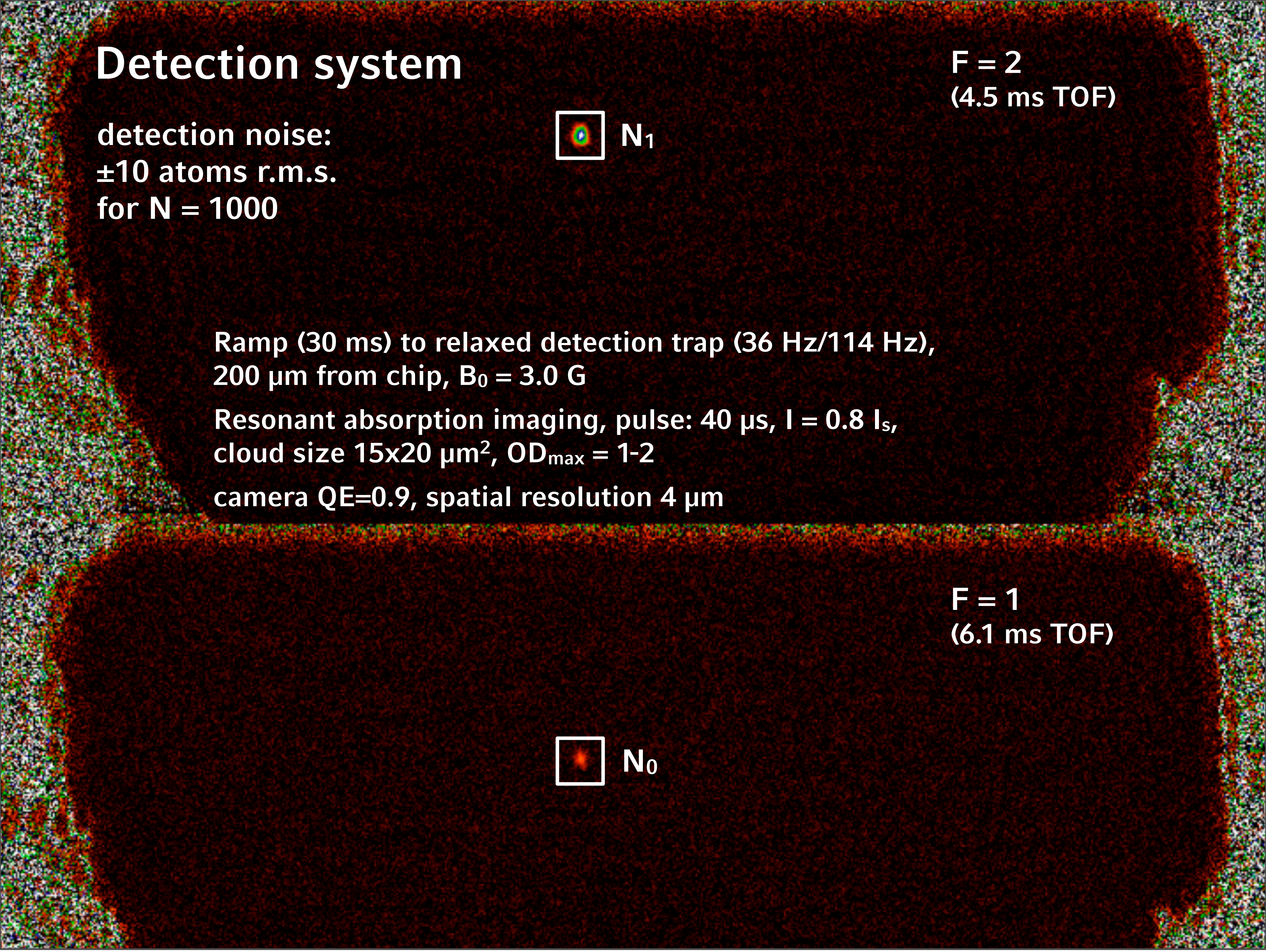
- both magnetically trappable
- nearly identical potentials
- coherence lifetime > 5 s possible
  (chip-based clock, thermal atoms)
- limitation: 2-body loss in |2,1>
  (long lifetime only at low density)

Rabi oscillations on the two-photon transition

- atom number N = 1000
- image both states in one shot
  → normalize to total N
- observed contrast C = 0.98

Detection system

detection noise:
±10 atoms r.m.s.
for N = 1000



Ramp (30 ms) to relaxed detection trap (36 Hz/114 Hz), 200 μm from chip, $B_0 = 3.0$ G

Resonant absorption imaging, pulse: 40 μs, $I = 0.8\ I_s$, cloud size 15x20 μm^2, OD_{max} = 1-2

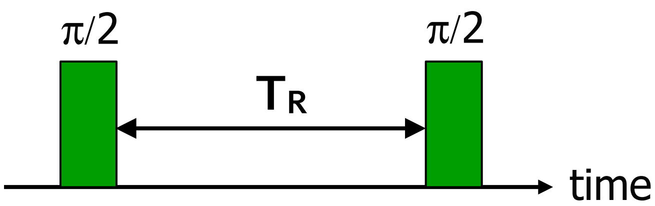
camera QE=0.9, spatial resolution 4 μm

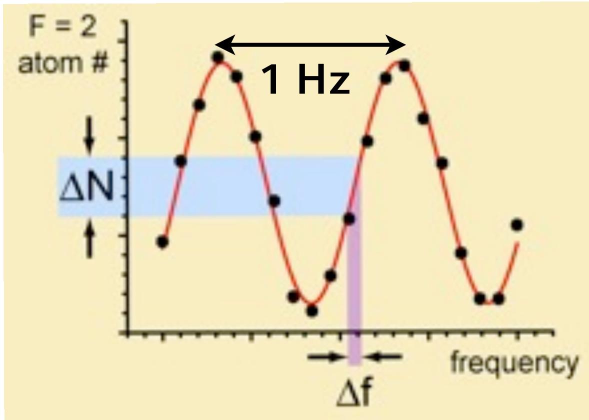
Chip-based atomic clock

Proof-of-principle experiment:

P. Treutlein et al., PRL 92, 203005 (2004).

Ramsey sequence





$T_R = 1$s

thermal atoms

frequency stability (Allan deviation):
1.7×10^{-11} @ 1 s

Dedicated precision experiment:

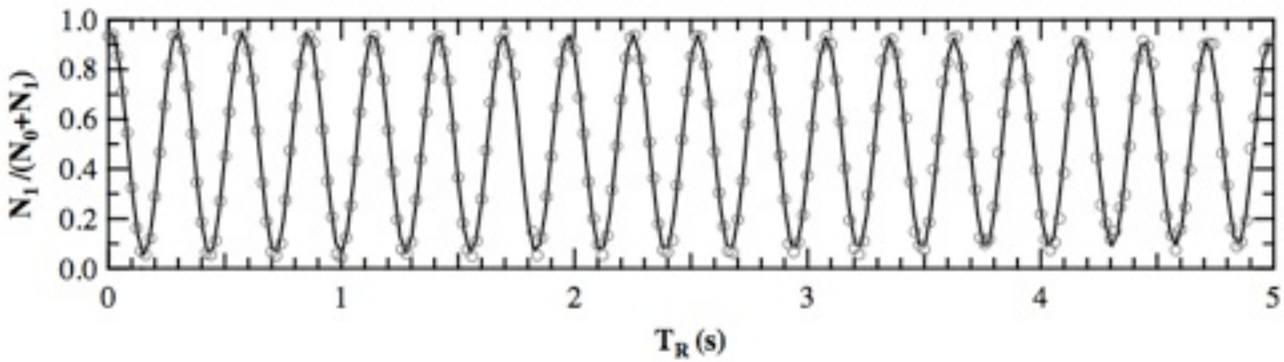
goal: stability 10^{-13} @ 1 s

- 10^4 - 10^5 atoms
- thermal atoms or BEC
- magnetic shielding
- improved detection

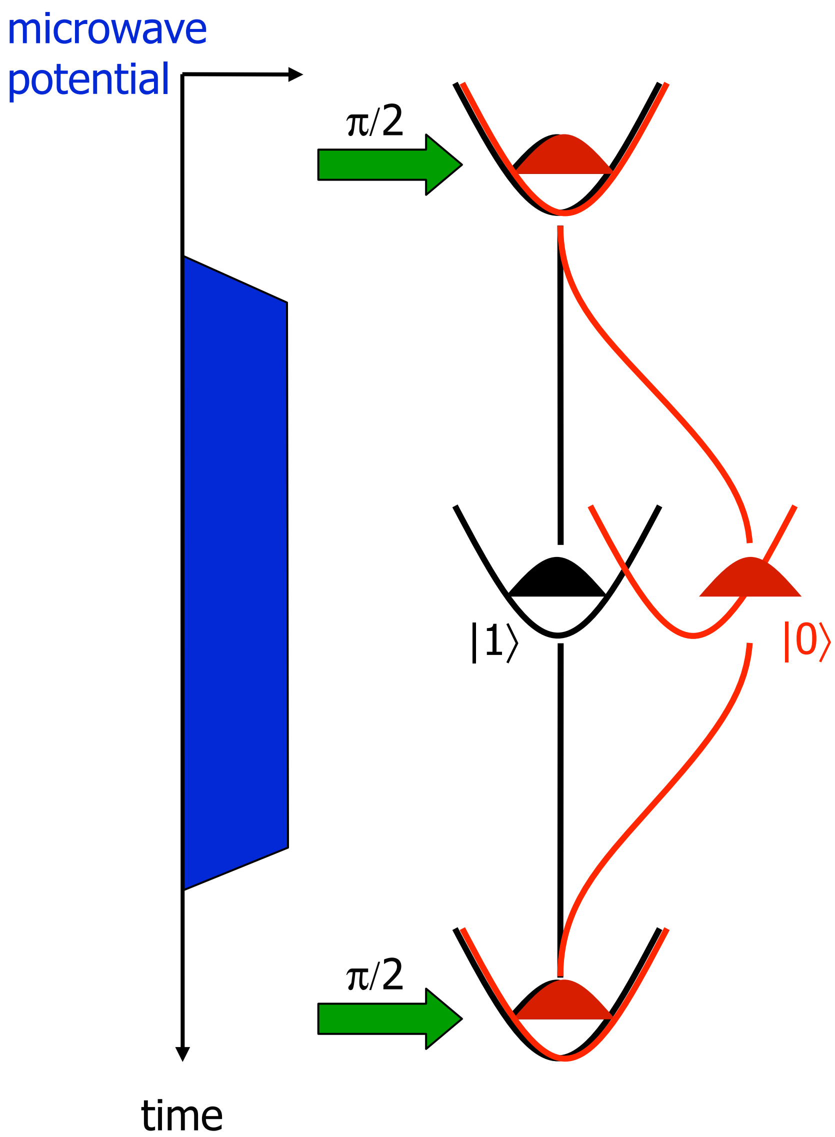
compact clock e.g. for satellite navigation

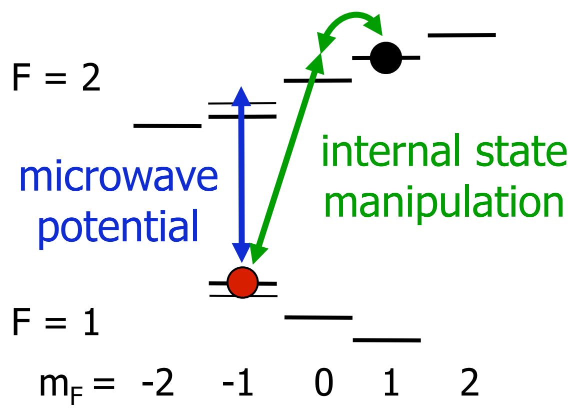
P. Rosenbusch/J. Reichel, Observatoire/SYRTE/LKB, Paris

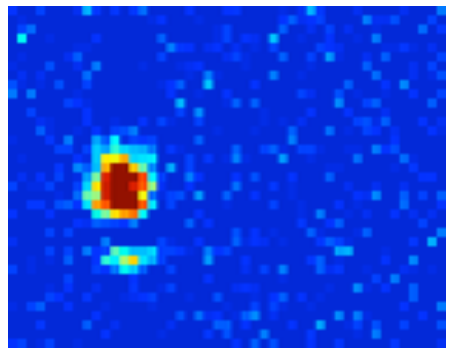
C. Deutsch et al., arXiv:1003.5925 (2010).



A trapped-atom interferometer on a chip







- movie shows in-situ images of BEC with 350 atoms during splitting
- detect both states (F=1 and F=2)

P. Böhi et al., Nature Physics 5, 592 (2009).

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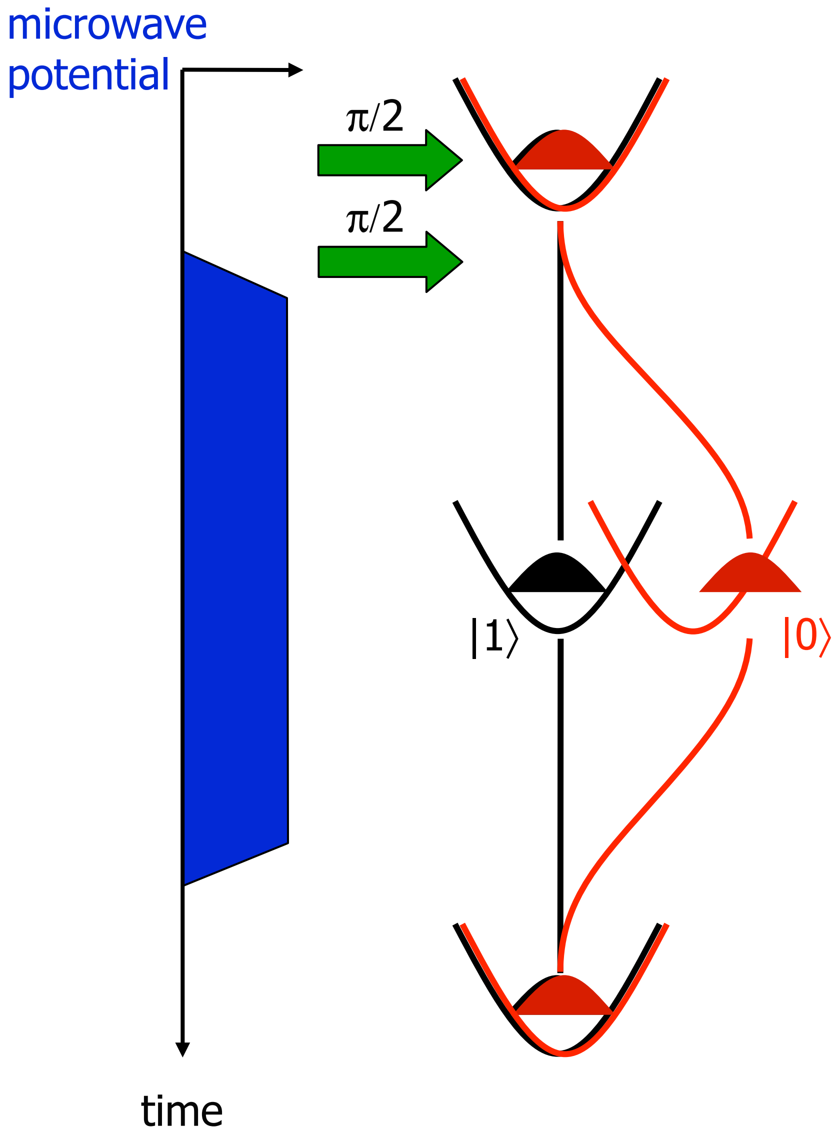
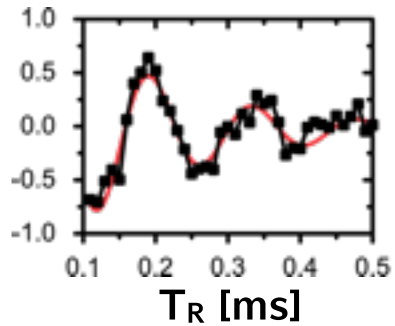
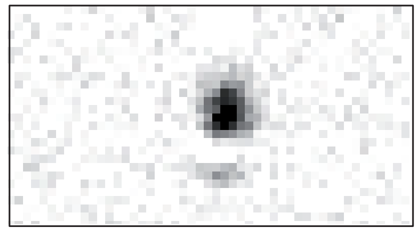


Ramsey fringes



in-situ images



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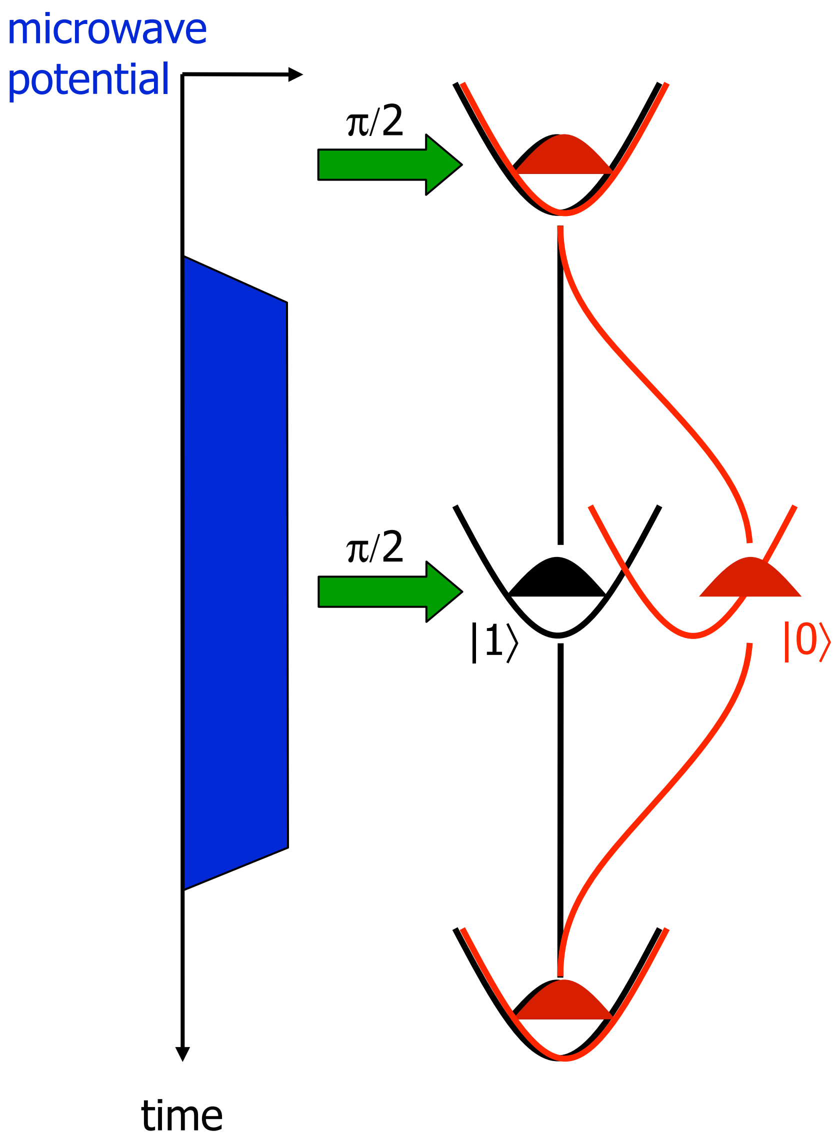

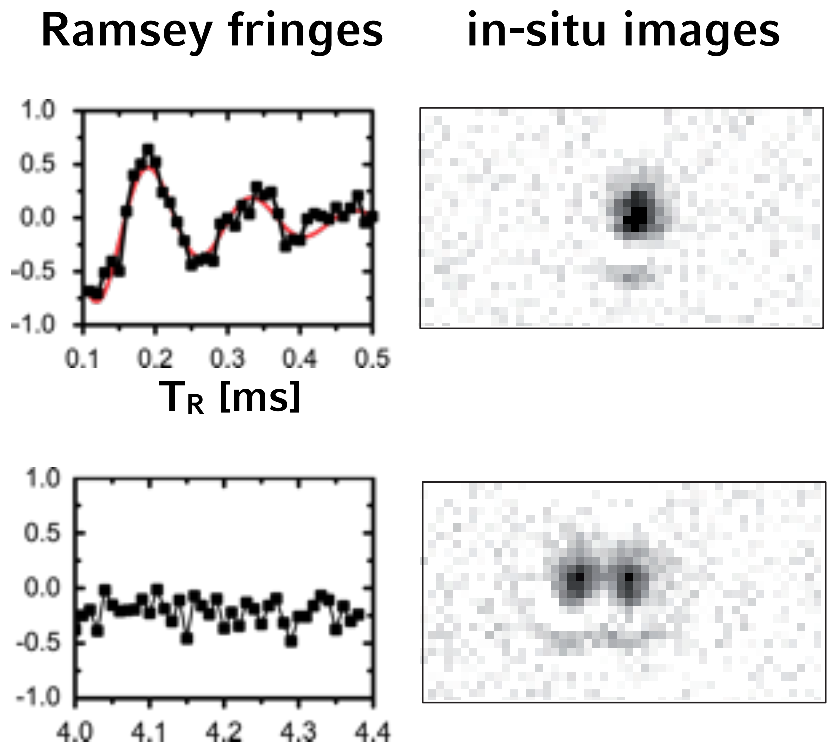

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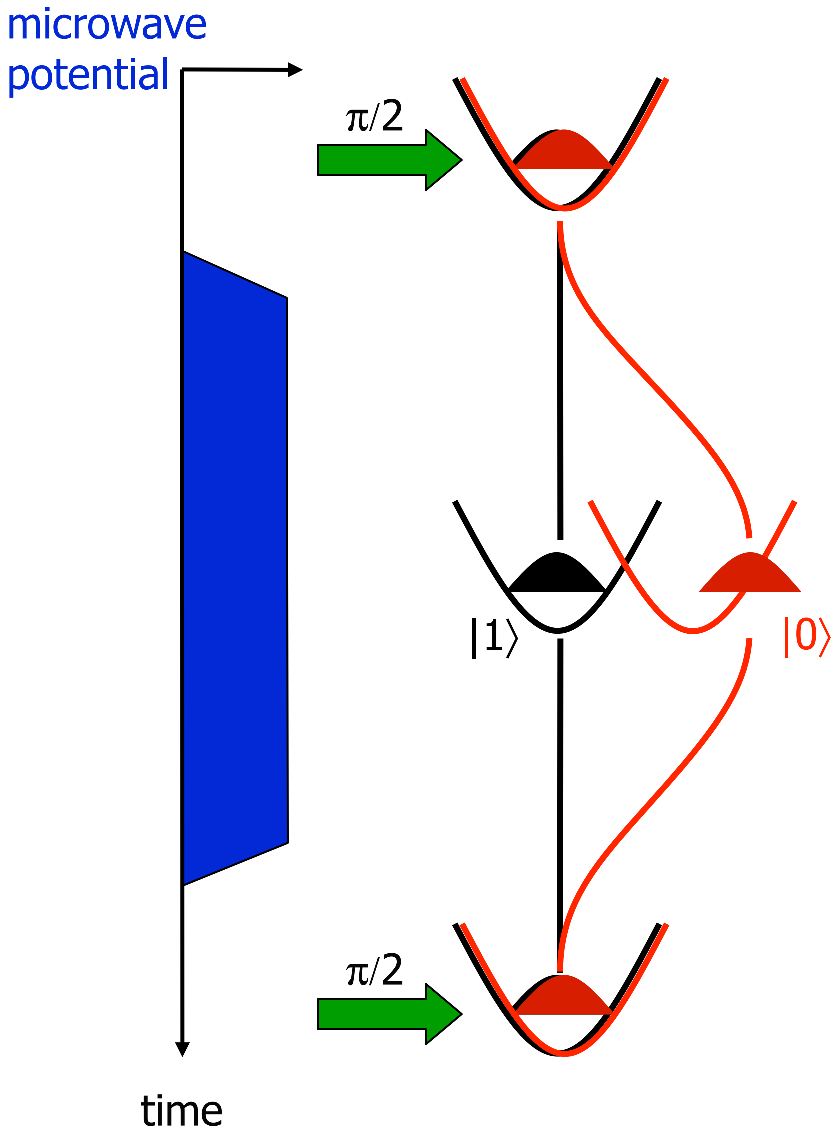
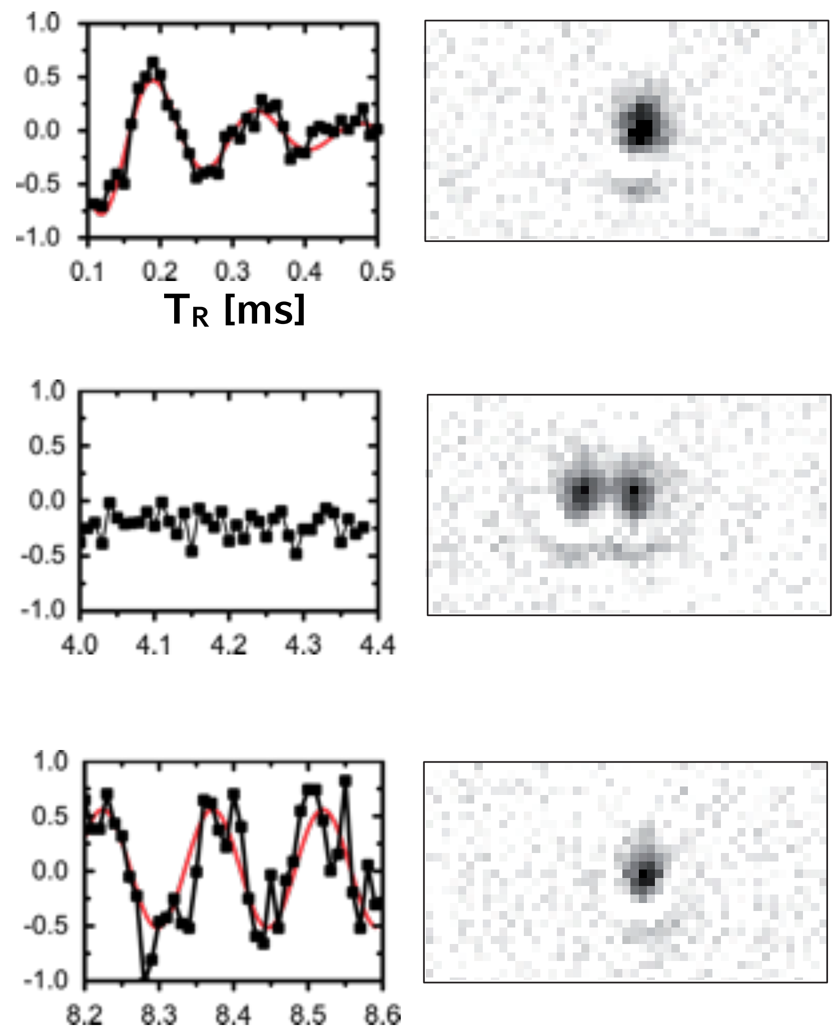


Ramsey fringes　　in-situ images



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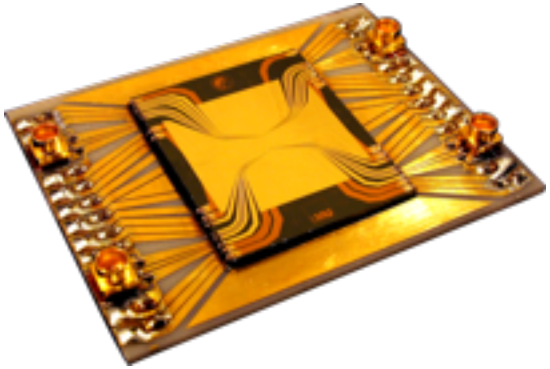
Outline



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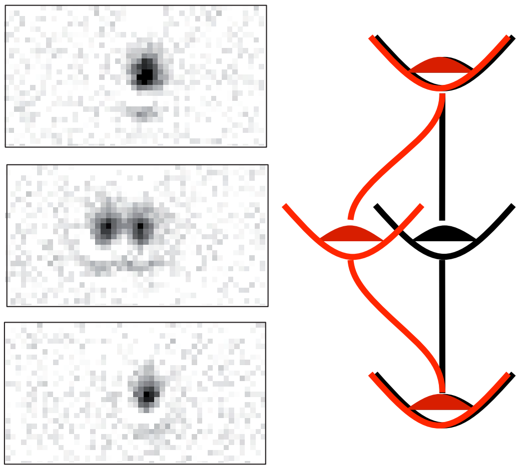

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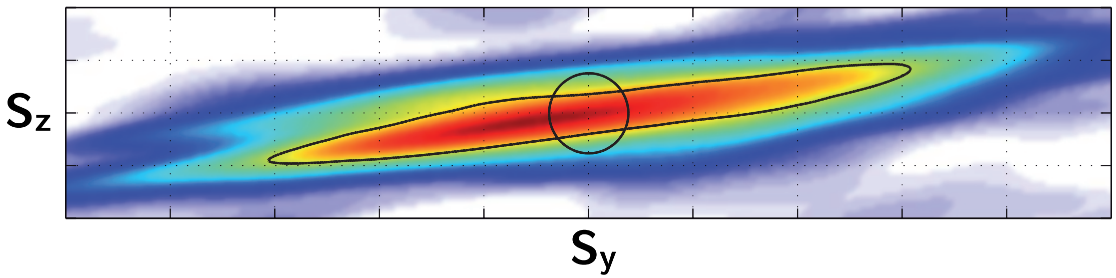


Two-component BEC as a collective spin

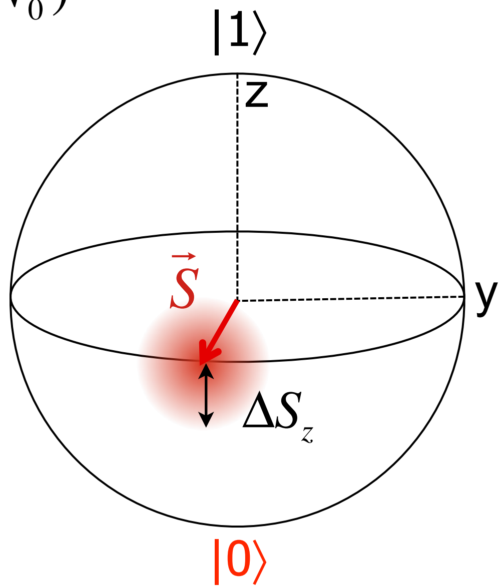
BEC internal state: collective spin

N × $|1\rangle$, $|0\rangle$ $\Rightarrow$ $\vec{S} = \sum_{i=1}^{N} \vec{s}_i$, $S = \frac{N}{2}$ $\quad S_z = \frac{1}{2}(N_1 - N_0)$

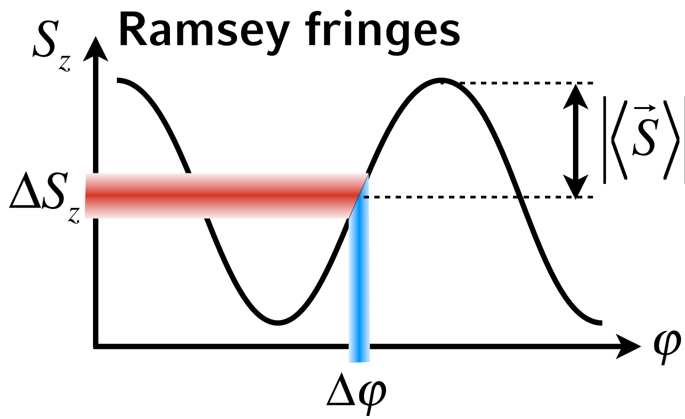
Coherent spin state (product state):

$$|\Psi\rangle \sim \left(|0\rangle + |1\rangle\right)^{\otimes N}, \quad \bar{N}_0 = \bar{N}_1 = N/2$$

$$\Rightarrow \quad \left|\langle S_x \rangle\right| = N/2, \quad \Delta S_z = \Delta S_y = \sqrt{N}/2$$



Quantum projection noise in a Ramsey interferometer



Spin squeezing and entanglement generation

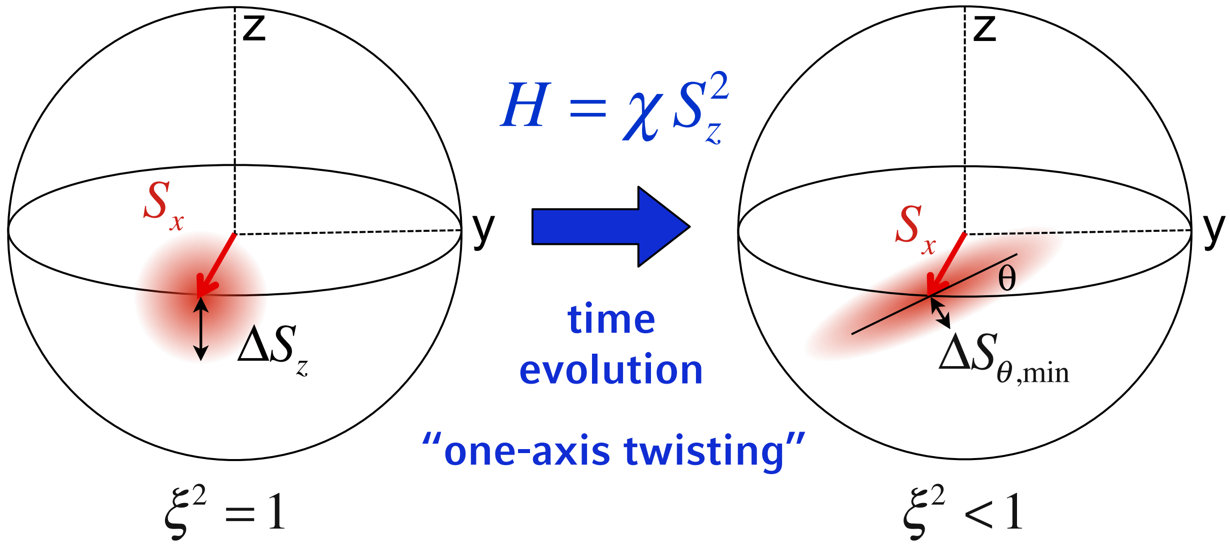
Spin squeezing/ entanglement through nonlinear dynamics

Kitagawa, Ueda (1993)

Sørensen, Duan, Cirac, Zoller (2001)

Sinatra, Castin (2000, 2008, 2009)

...



Squeezing/entanglement parameter (Wineland, 1994):

$$\xi^2 \equiv \frac{2S\left(\Delta S_{\theta,\min}\right)^2}{\langle S_x \rangle^2}$$

if $\xi^2 < 1$ ⇒

- **useful resource for interferometry beyond standard quantum limit**
- **atoms entangled**

to determine ξ, measure:

- **minimum fluctuations** $\Delta S_{\theta,\min}$
- **mean spin (Ramsey contrast)** $\langle S_x \rangle$

recent experiments: Oberthaler (BEC, double well 2008, int. state 2010)
Polzik, Vuletic (thermal atoms, int. state 2008/09/10), ...

Control nonlinearity by wave-function engineering

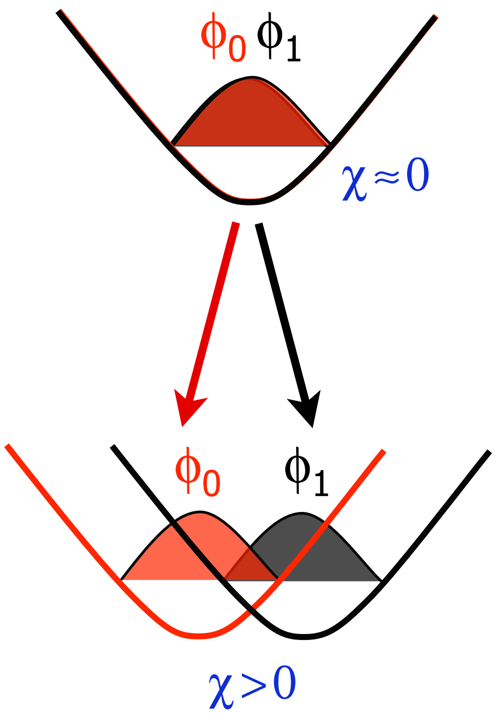
Hamiltonian:
(two-mode model)

$$H = \delta S_z + \Omega_R S_\varphi + \chi S_z^2$$

nonlinearity due to collisions

$$\chi \sim a_{00} \int |\phi_0|^4\, dr^3 + a_{11} \int |\phi_1|^4\, dr^3 - 2a_{01} \int |\phi_0|^2 |\phi_1|^2\, dr^3$$

(simplification: BEC mode functions ϕ_0, ϕ_1 independent of N_0, N_1)



but for ^{87}Rb: $a_{00} \sim a_{11} \sim a_{01} \Rightarrow \chi \approx 0$

no convenient Feshbach resonance in magnetic trap

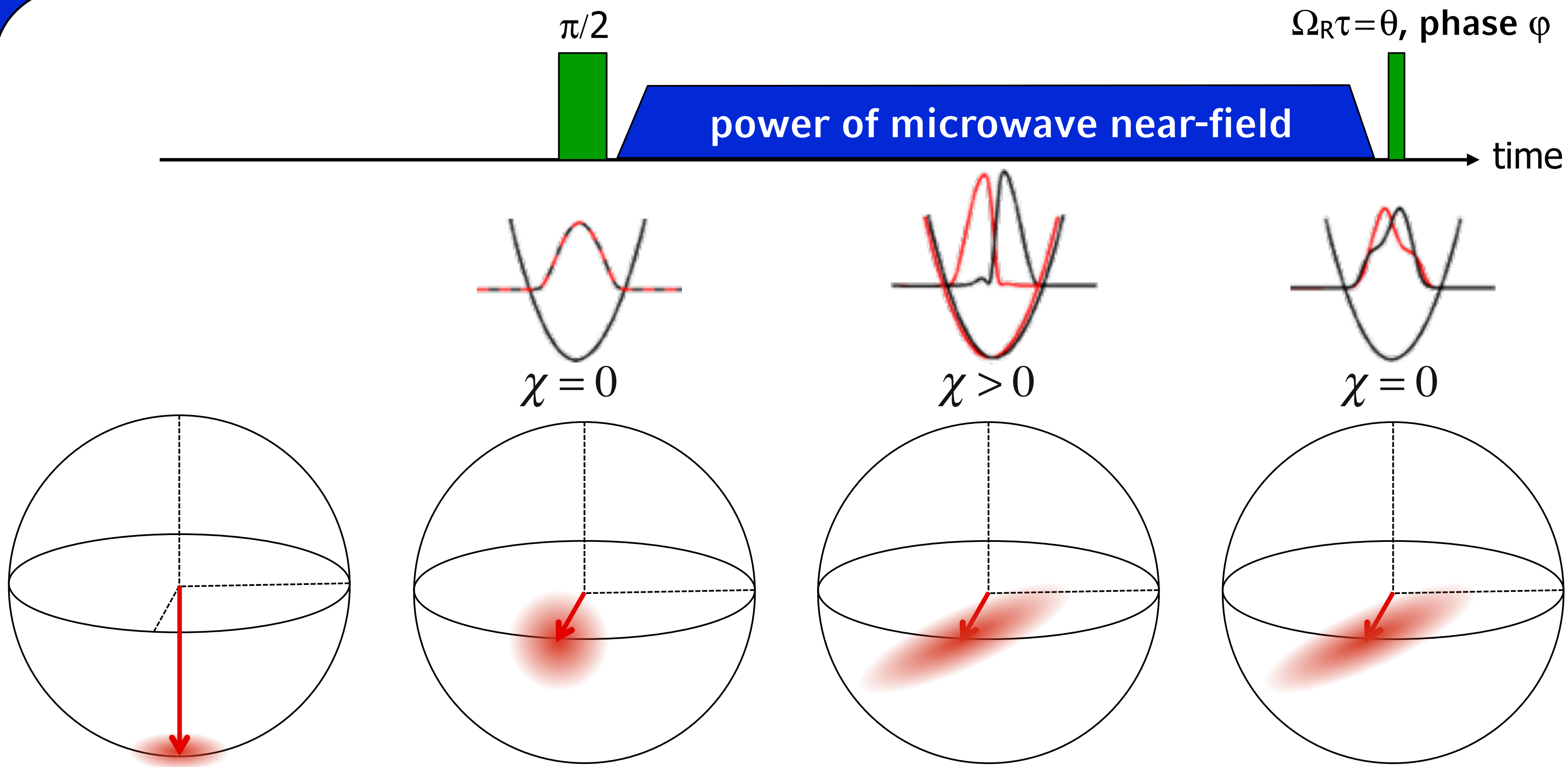
use state-dependent potential to control interactions via wave function overlap

(turn nonlinearity on for well-defined time, avoid oversqueezing)

Y. Li, P. Treutlein, J. Reichel, A. Sinatra, Eur. Phys. J. B 68, 365 (2009).

related idea for BEC in TOF: U. Poulsen and K. Mølmer, PRA 65, 033613 (2002).
related ideas for QIP with single atoms: T. Calarco et al., PRA 61, 022304 (2002).

Experimental sequence for spin squeezing



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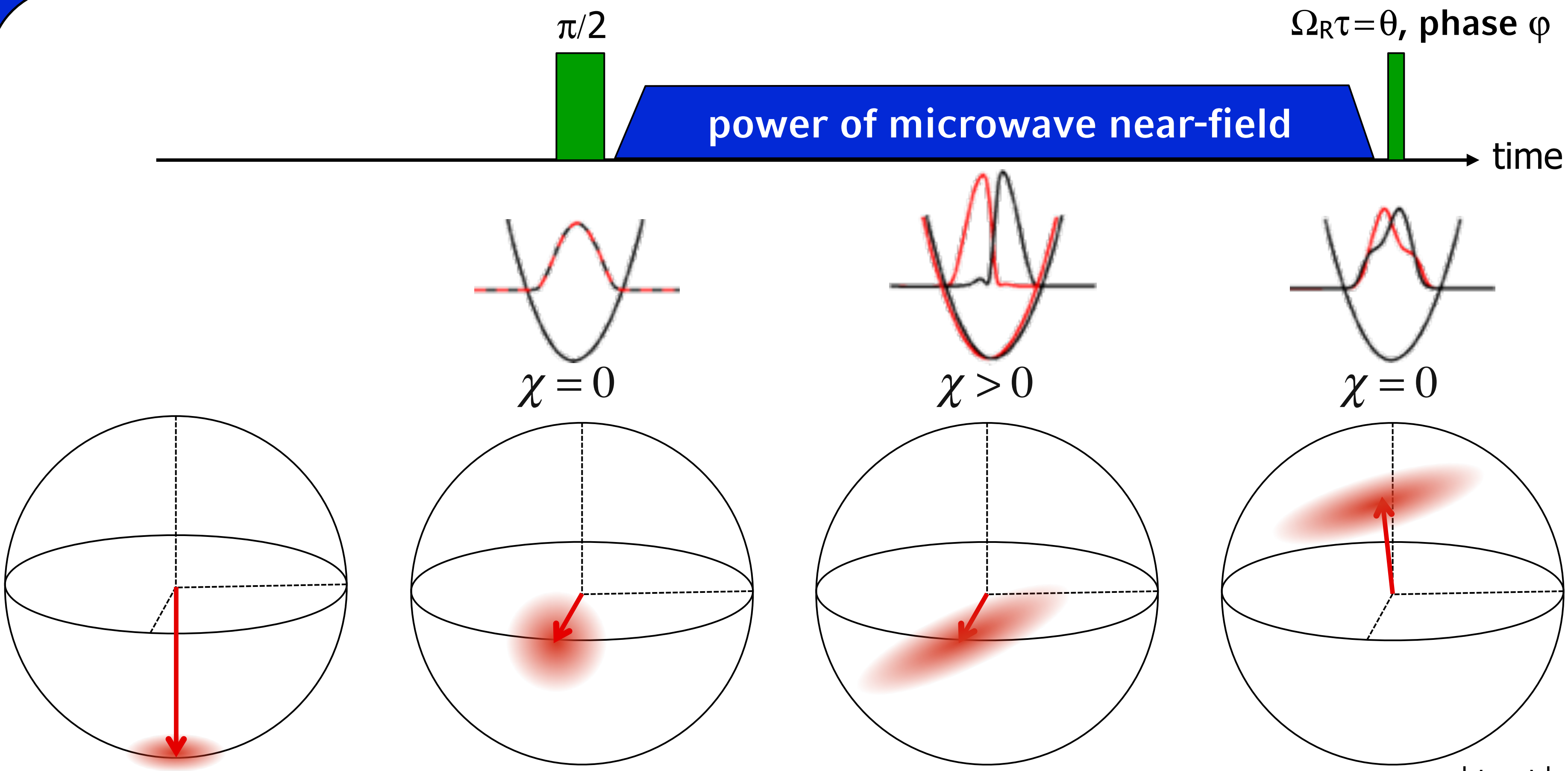

measure $\left|\langle S_x \rangle\right|$

(Ramsey contrast)

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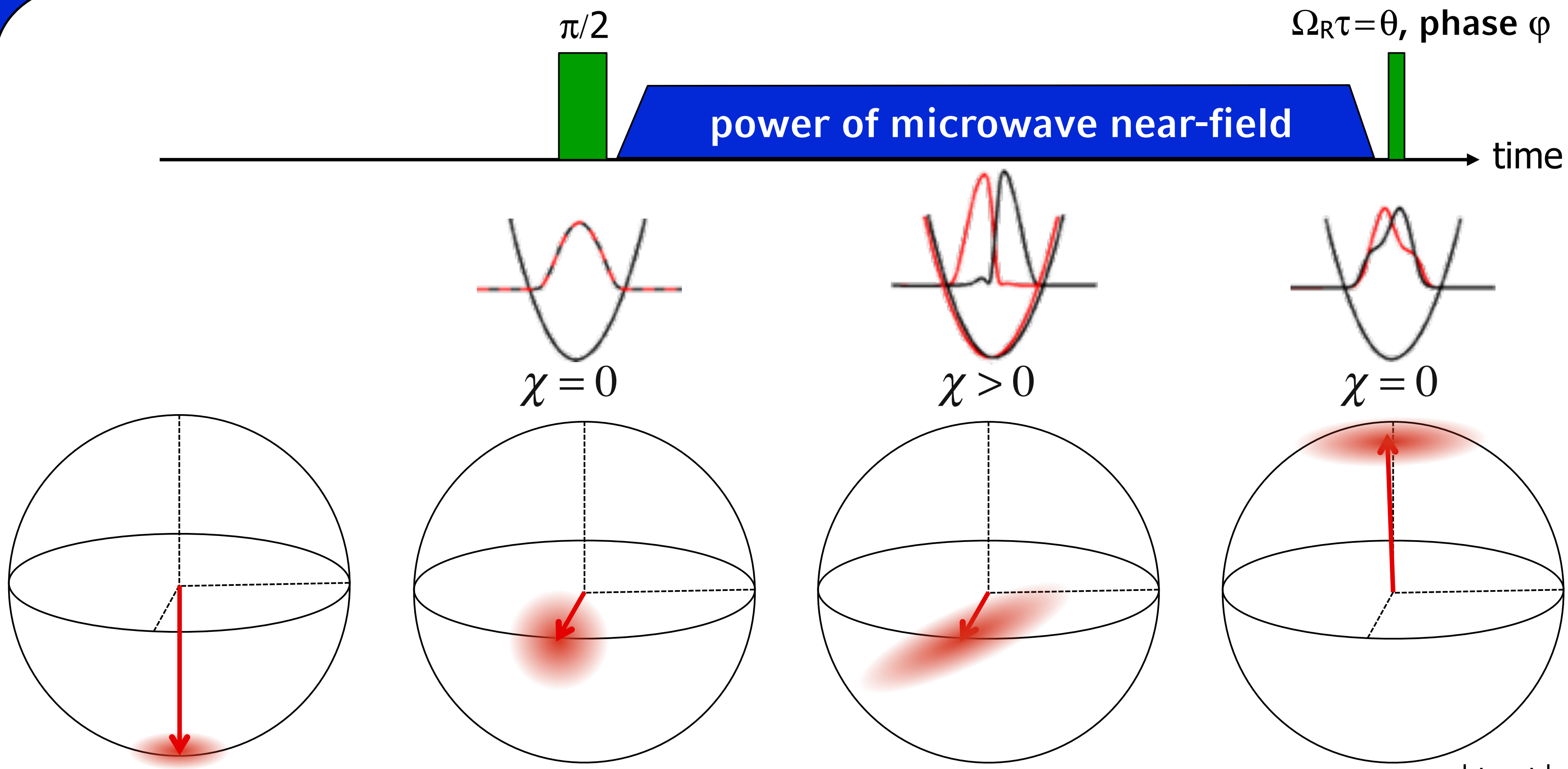

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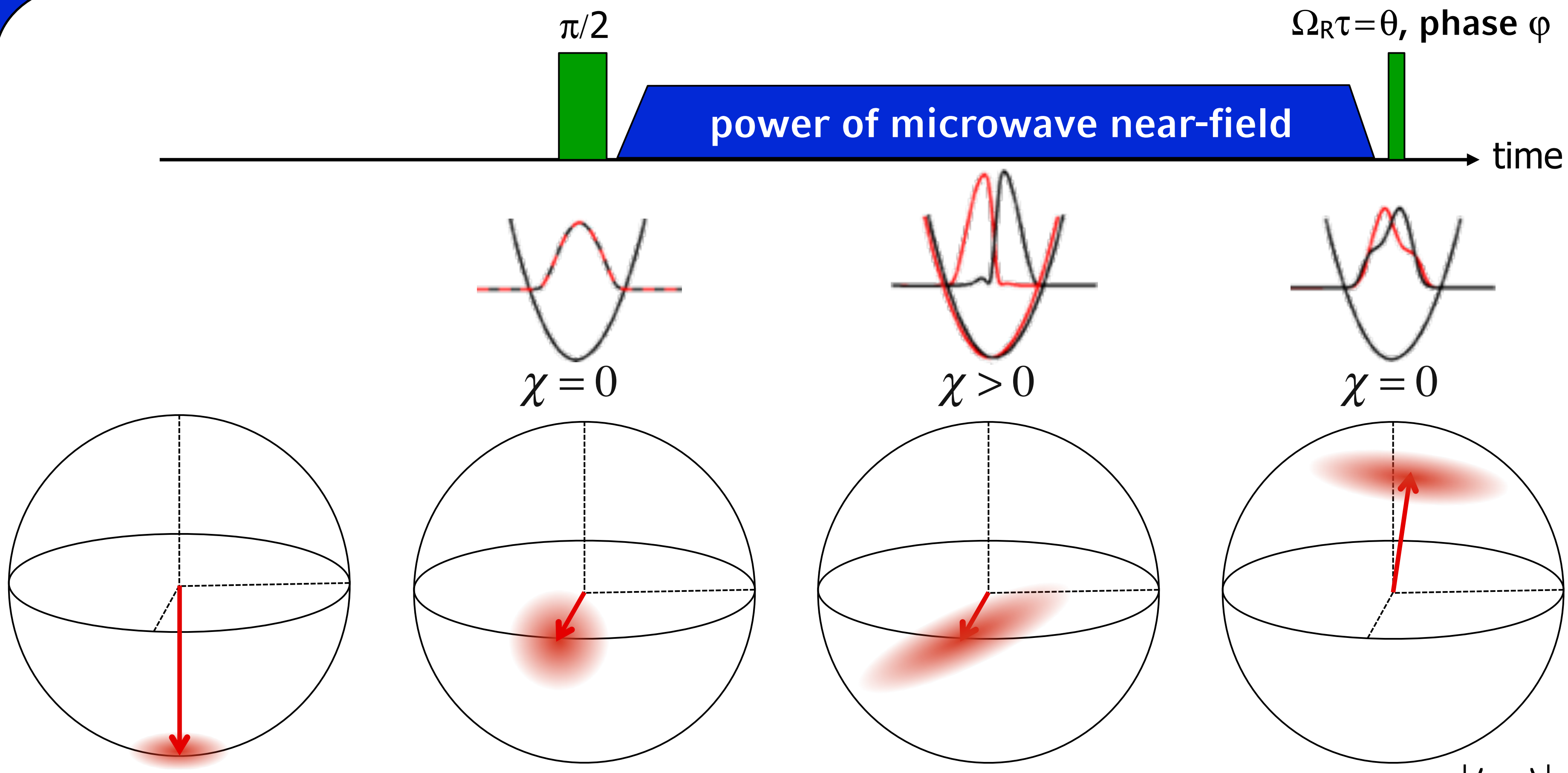

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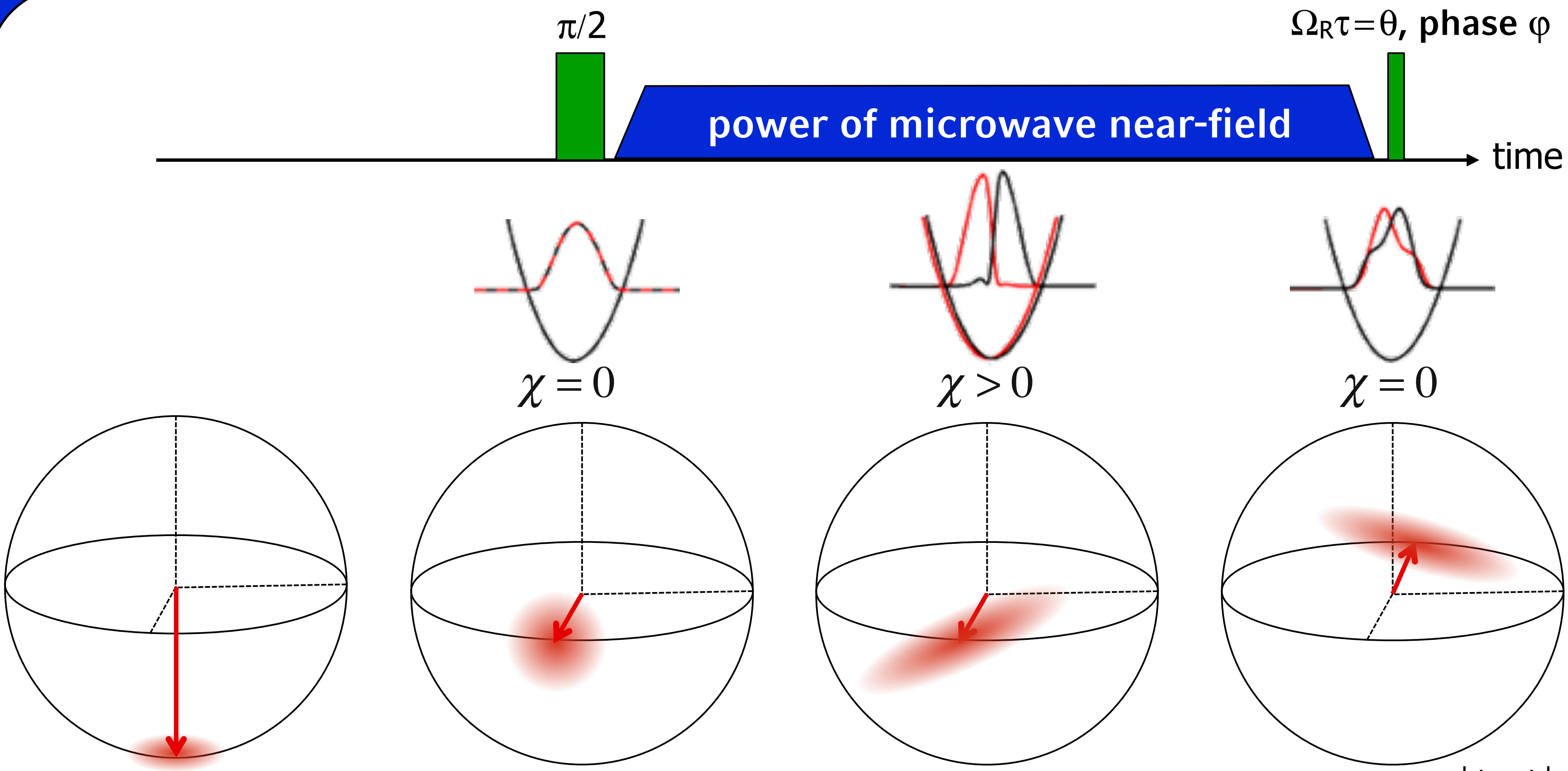

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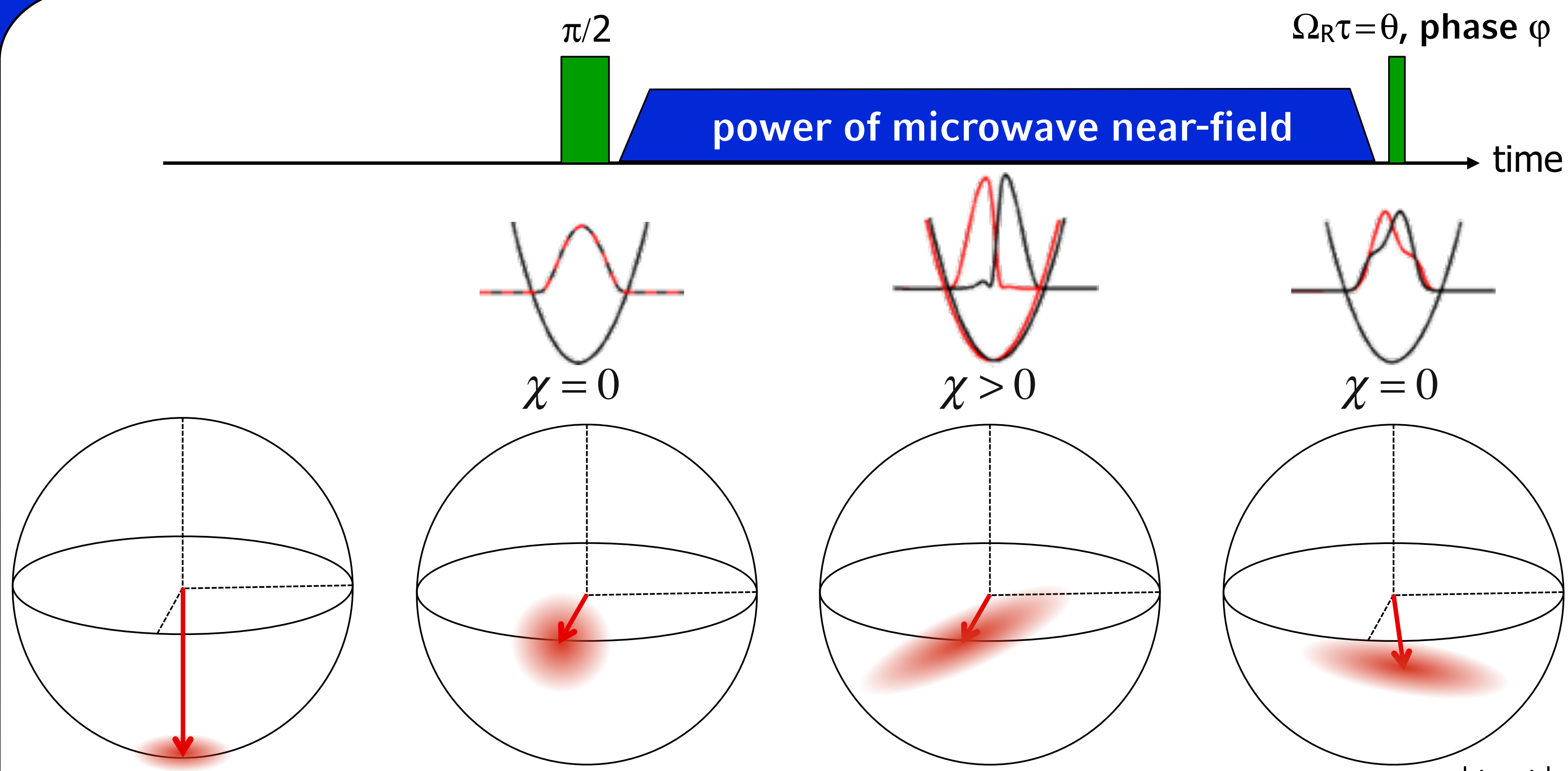
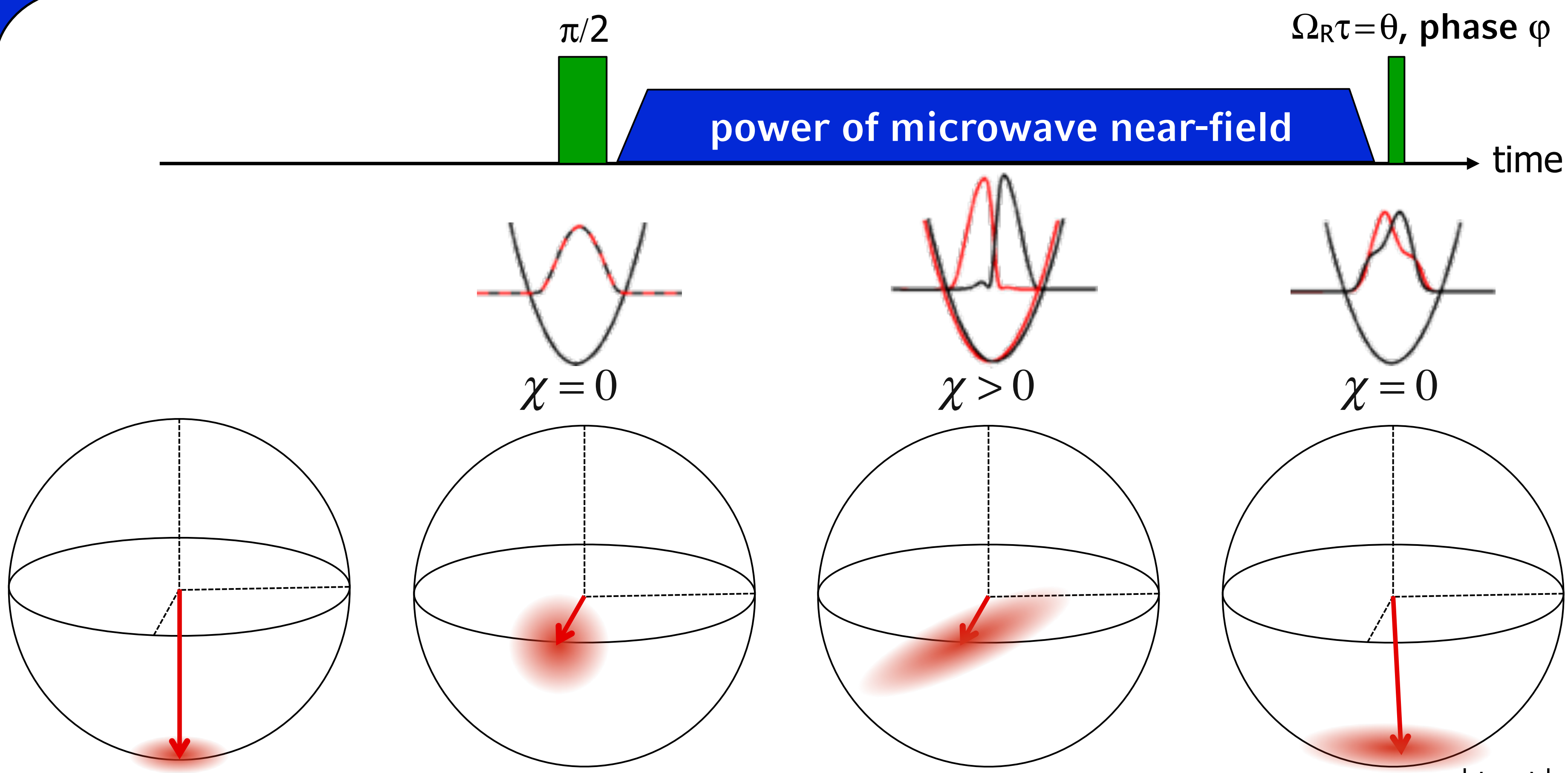


measure $\left|\langle S_x \rangle\right|$

(Ramsey contrast)

$$\xi^2 \equiv \frac{2S\left(\Delta S_{\theta,\min}\right)^2}{\langle S_x \rangle^2}$$

Experimental sequence for spin squeezing



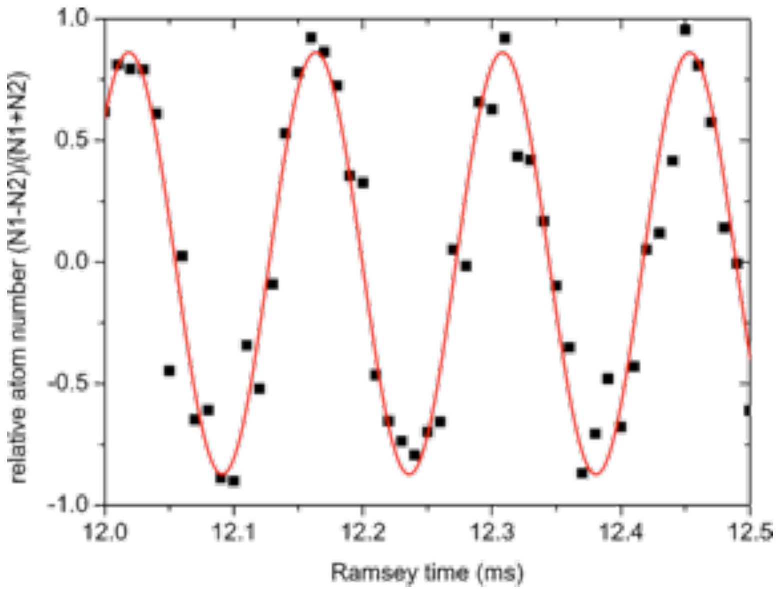
measure $\left|\langle S_x \rangle\right|$

(Ramsey contrast)

$$\xi^2 \equiv \frac{2S\left(\Delta S_{\theta,\min}\right)^2}{\langle S_x \rangle^2}$$

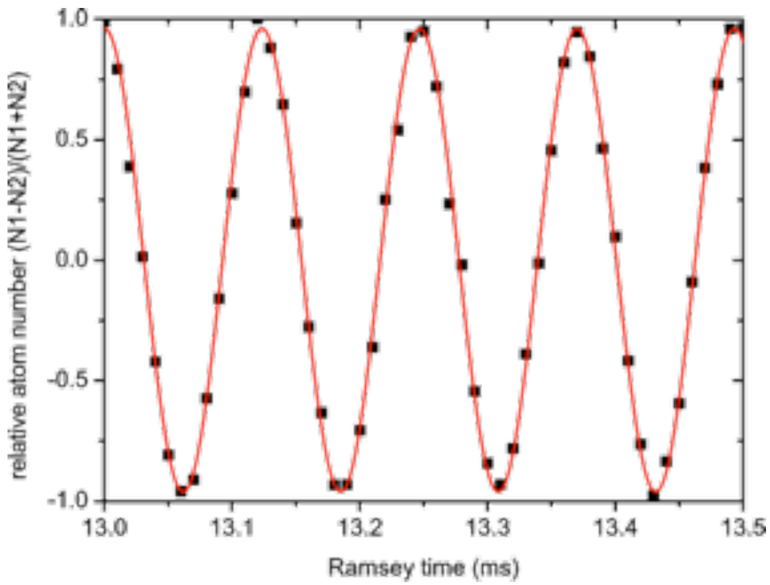
Contrast of Ramsey fringes

with splitting (χ>0, squeezing)



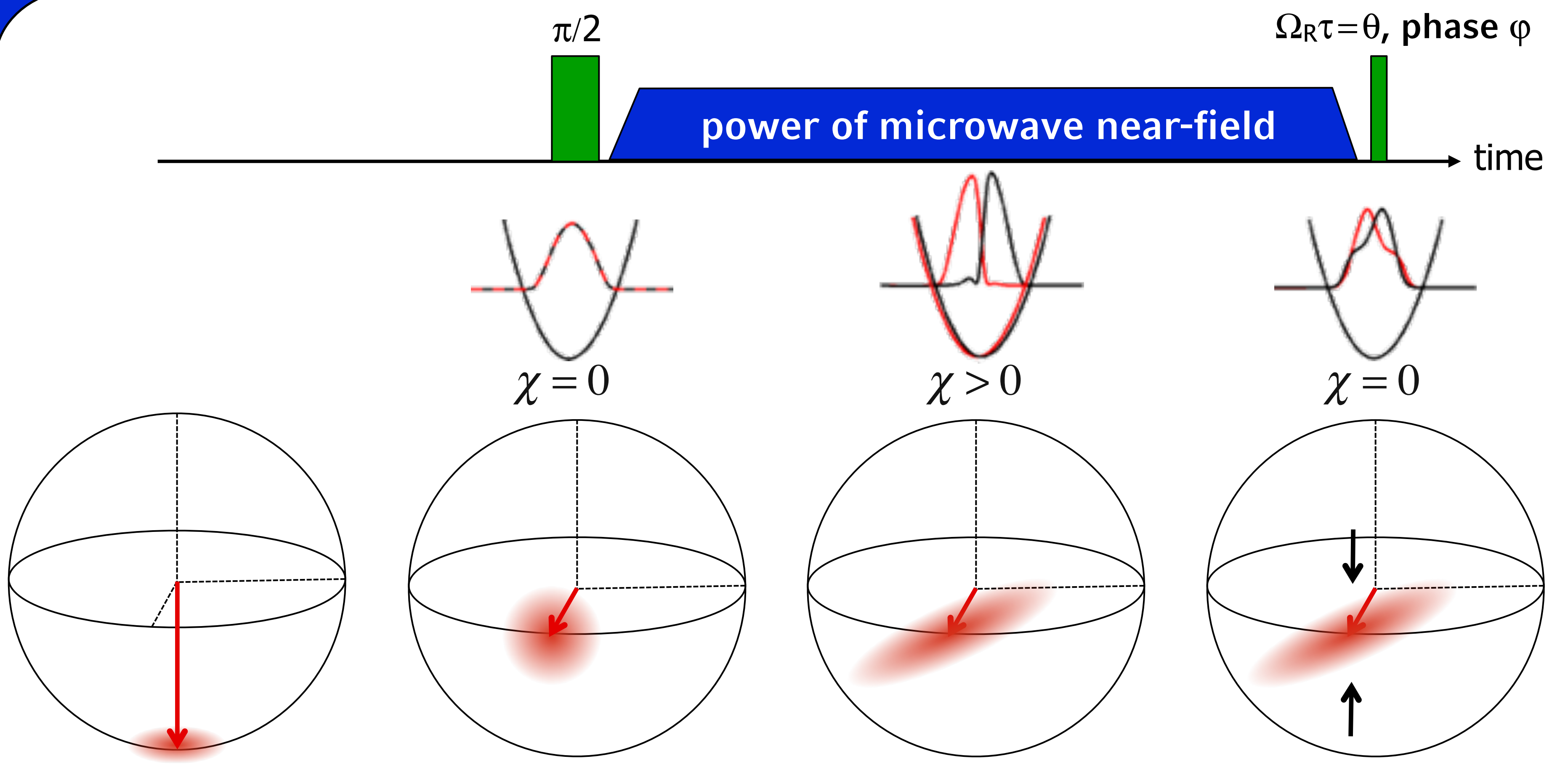
- Ramsey contrast C = 0.88 ± 0.03

without splitting (χ=0, reference)



- Ramsey contrast C = 0.96 ± 0.01
- |1,-1> trap lifetime ~ 4 s
- |2,1> trap lifetime ~ 200 ms
- superposition ~ 250 ms

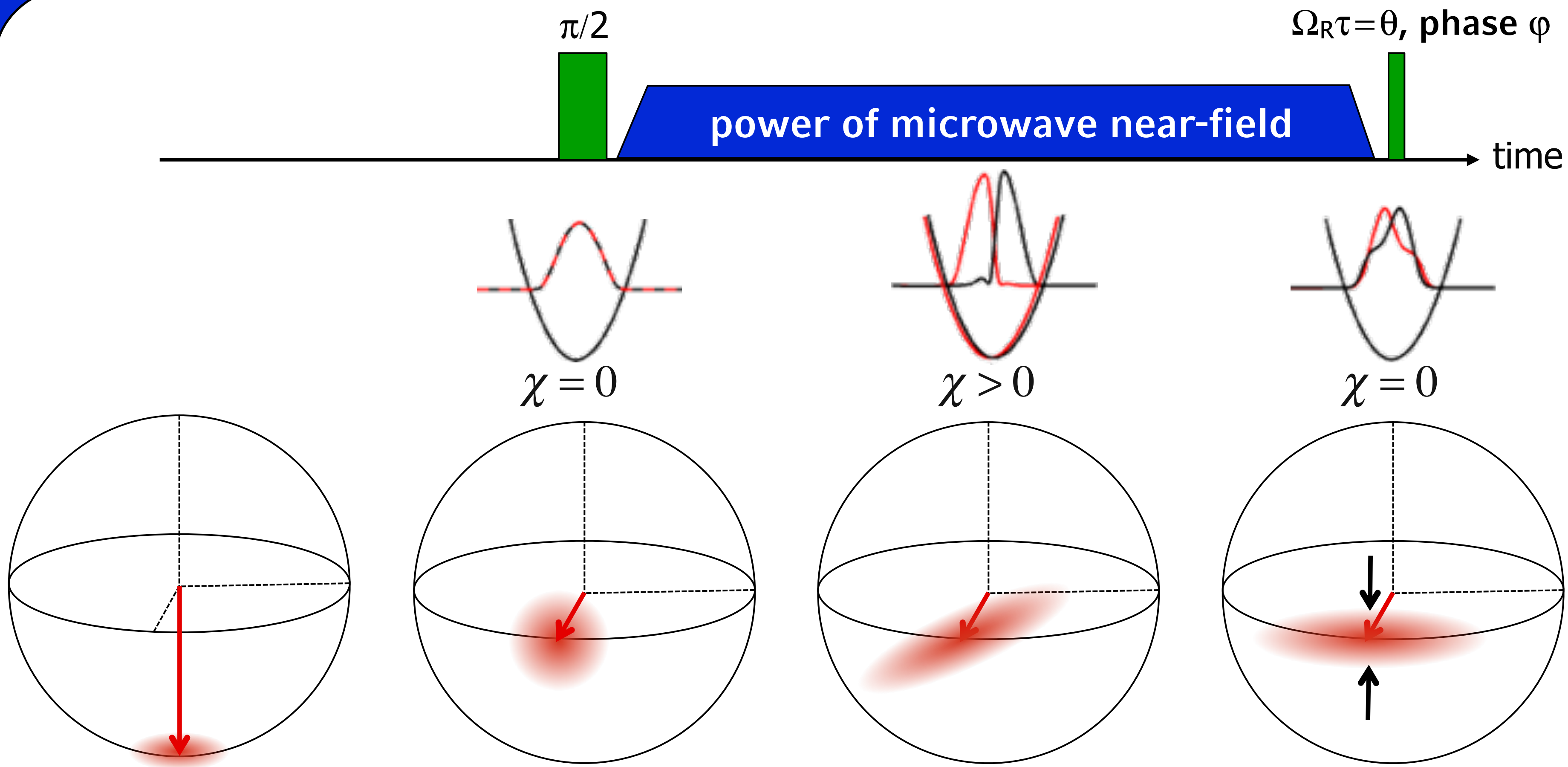
Experimental sequence for spin squeezing



$$\xi^2 \equiv \frac{2S\left(\Delta S_{\theta,\min}\right)^2}{\left\langle S_x \right\rangle^2}$$

State tomography:
measure ΔS_θ (projection noise) after turning for several angles θ

Experimental sequence for spin squeezing



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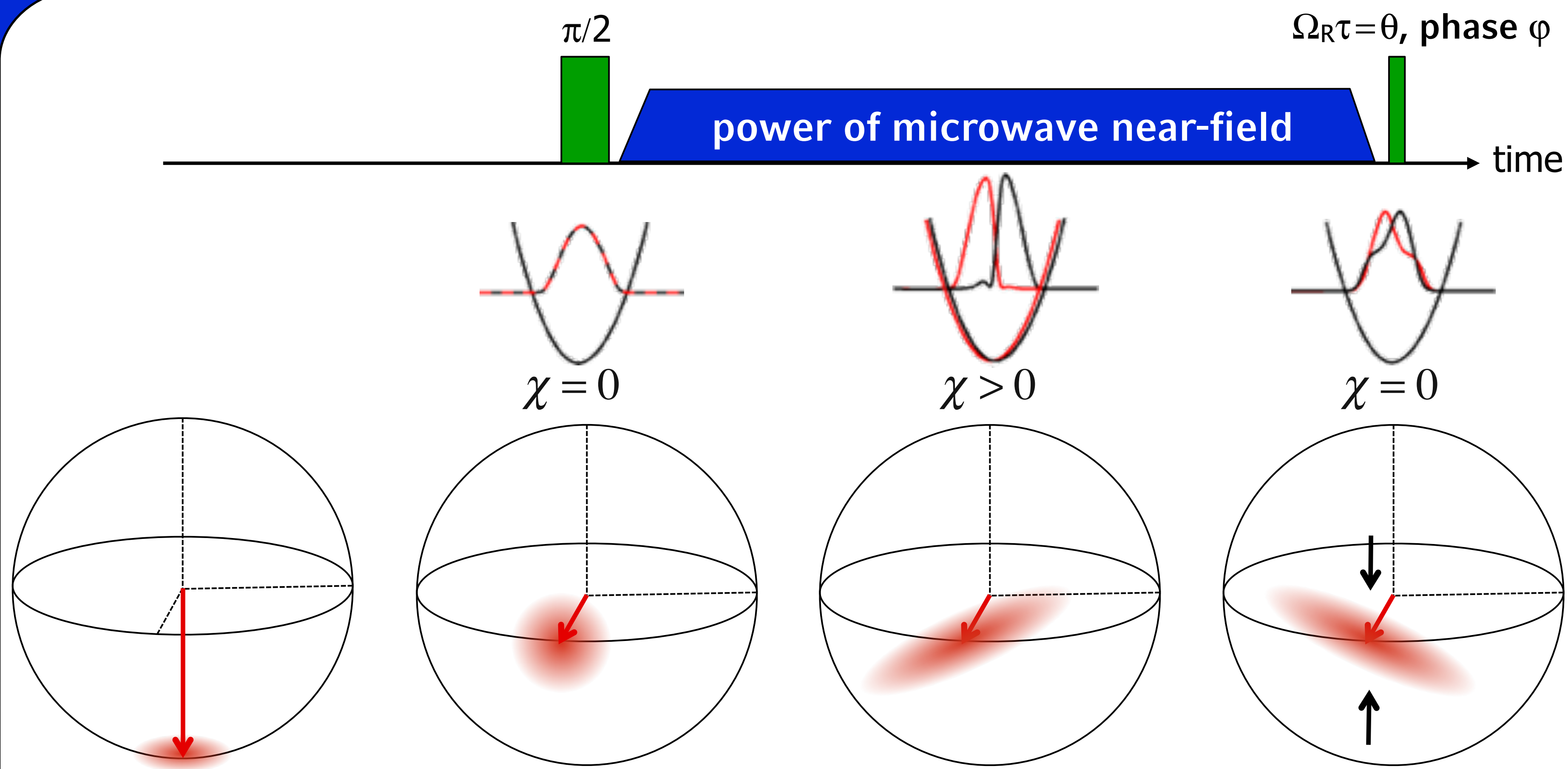

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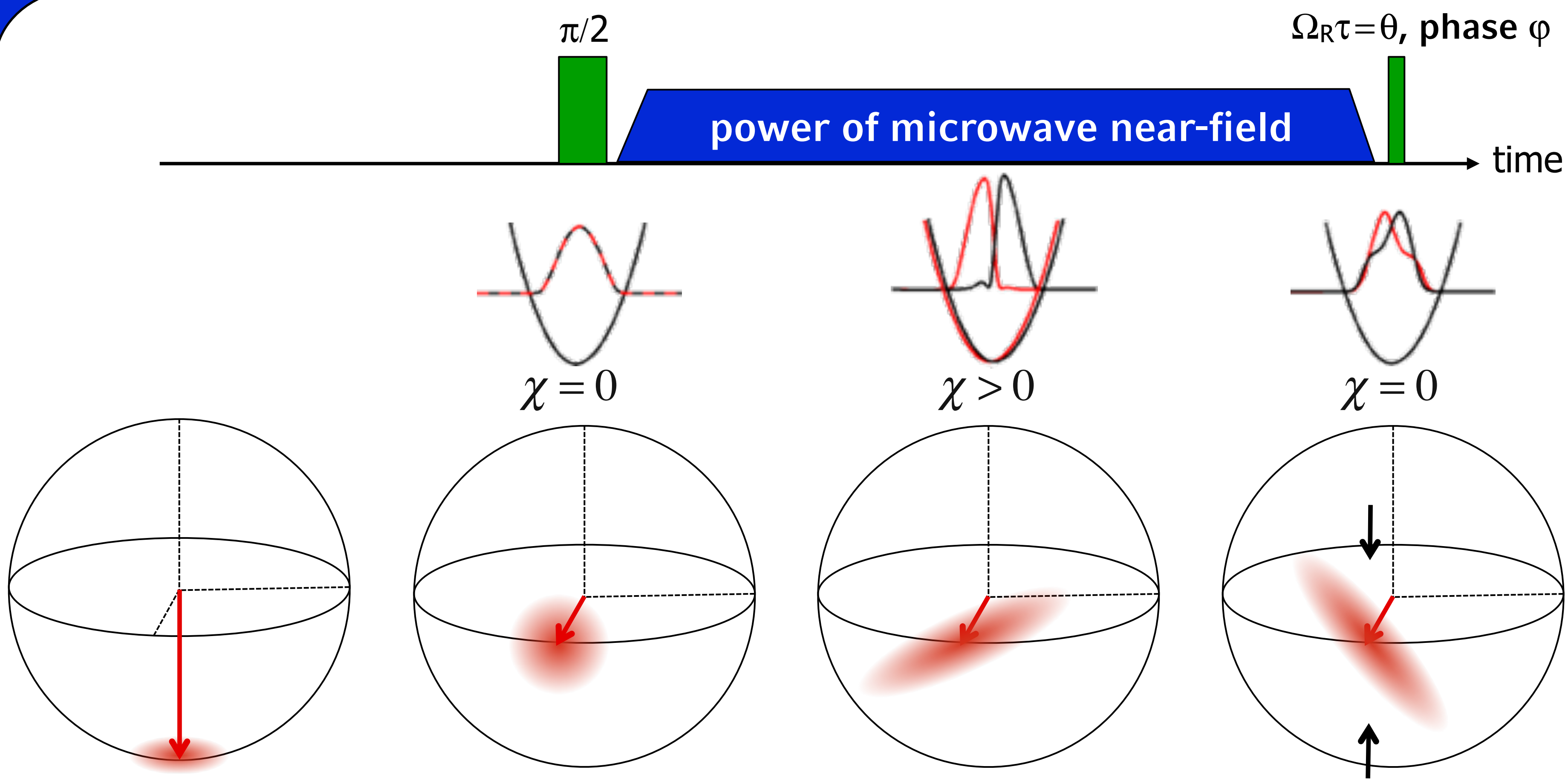

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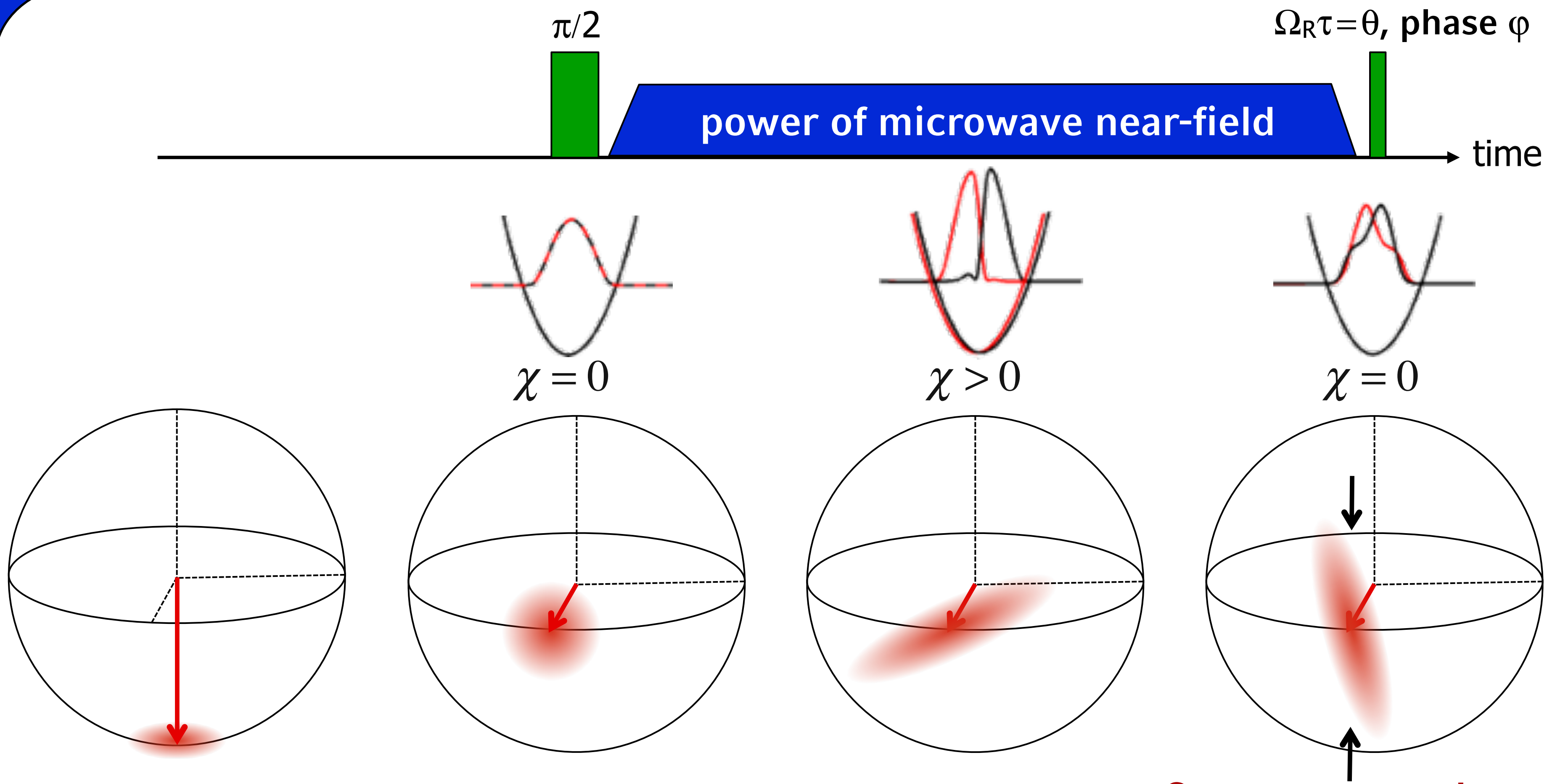

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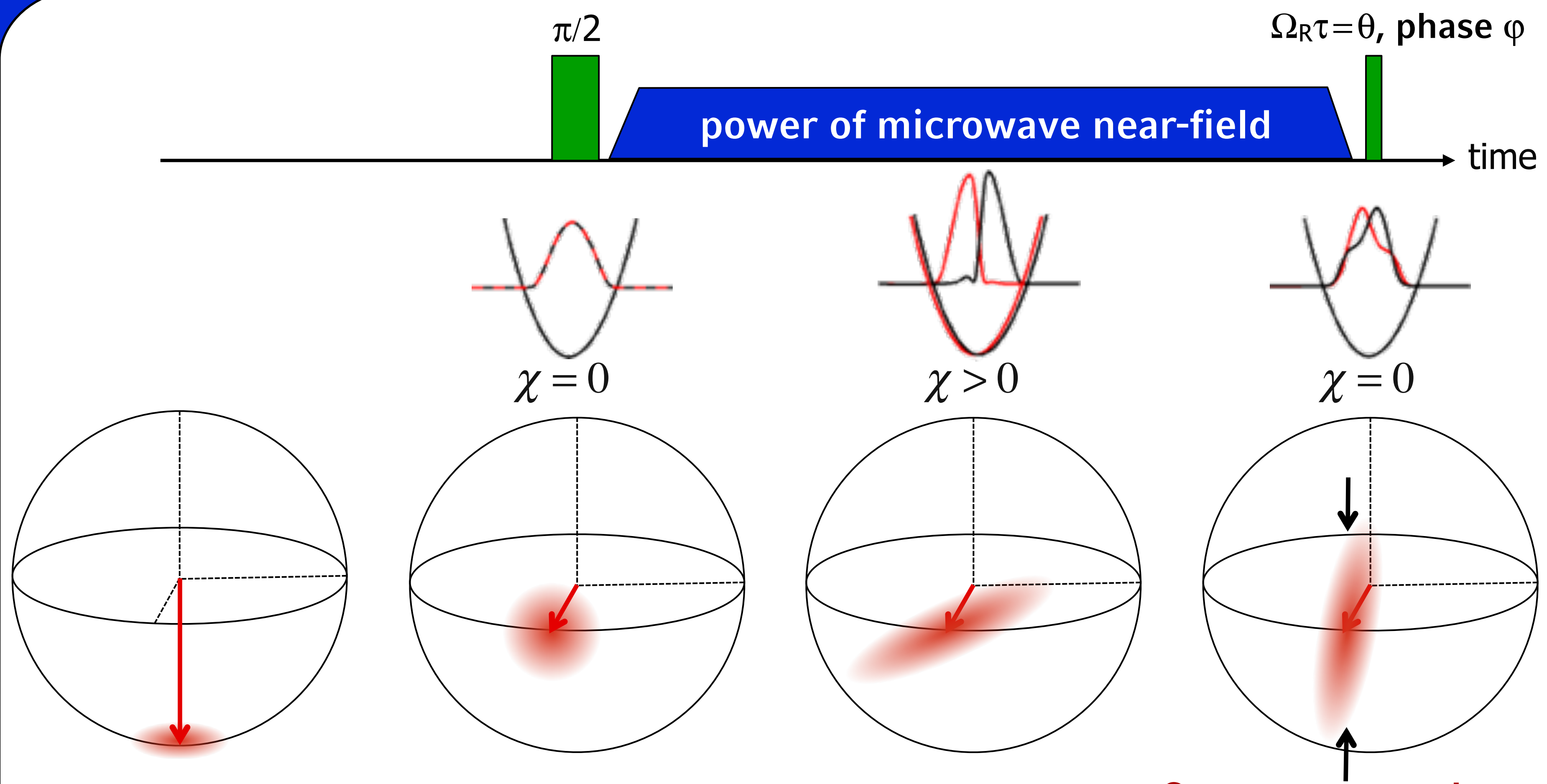

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State tomography:
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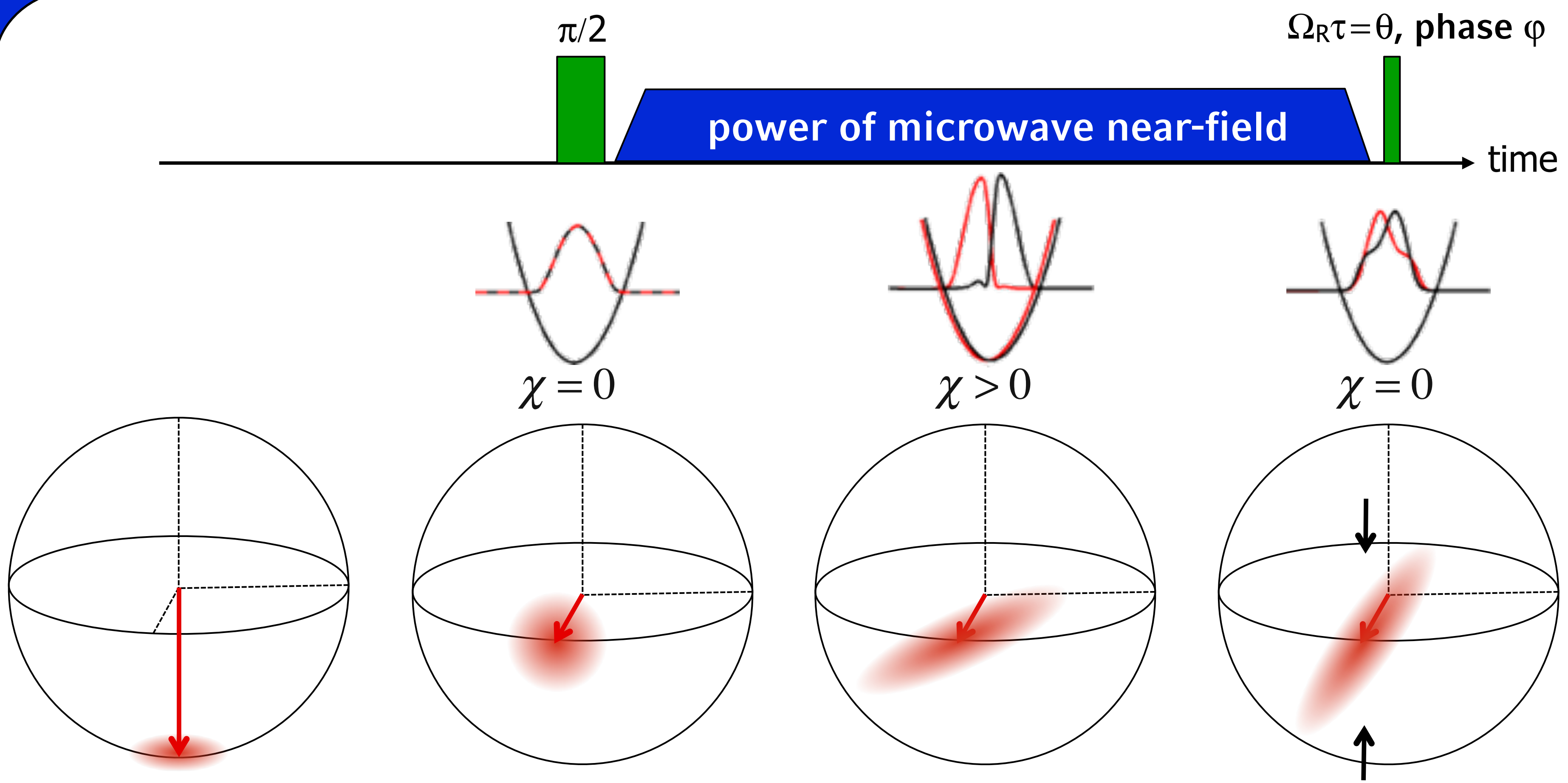
Experimental sequence for spin squeezing



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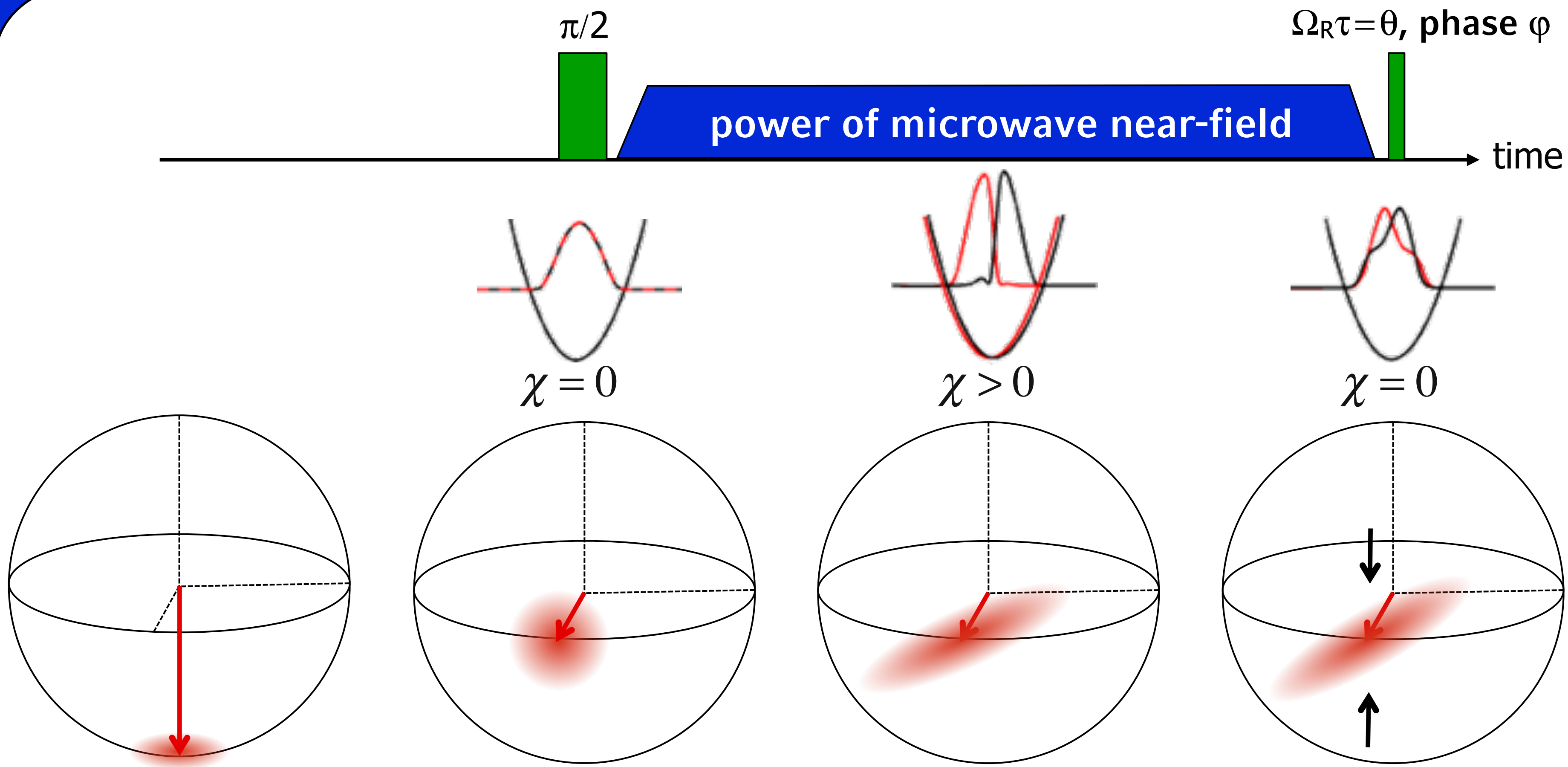
Experimental sequence for spin squeezing



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State tomography:
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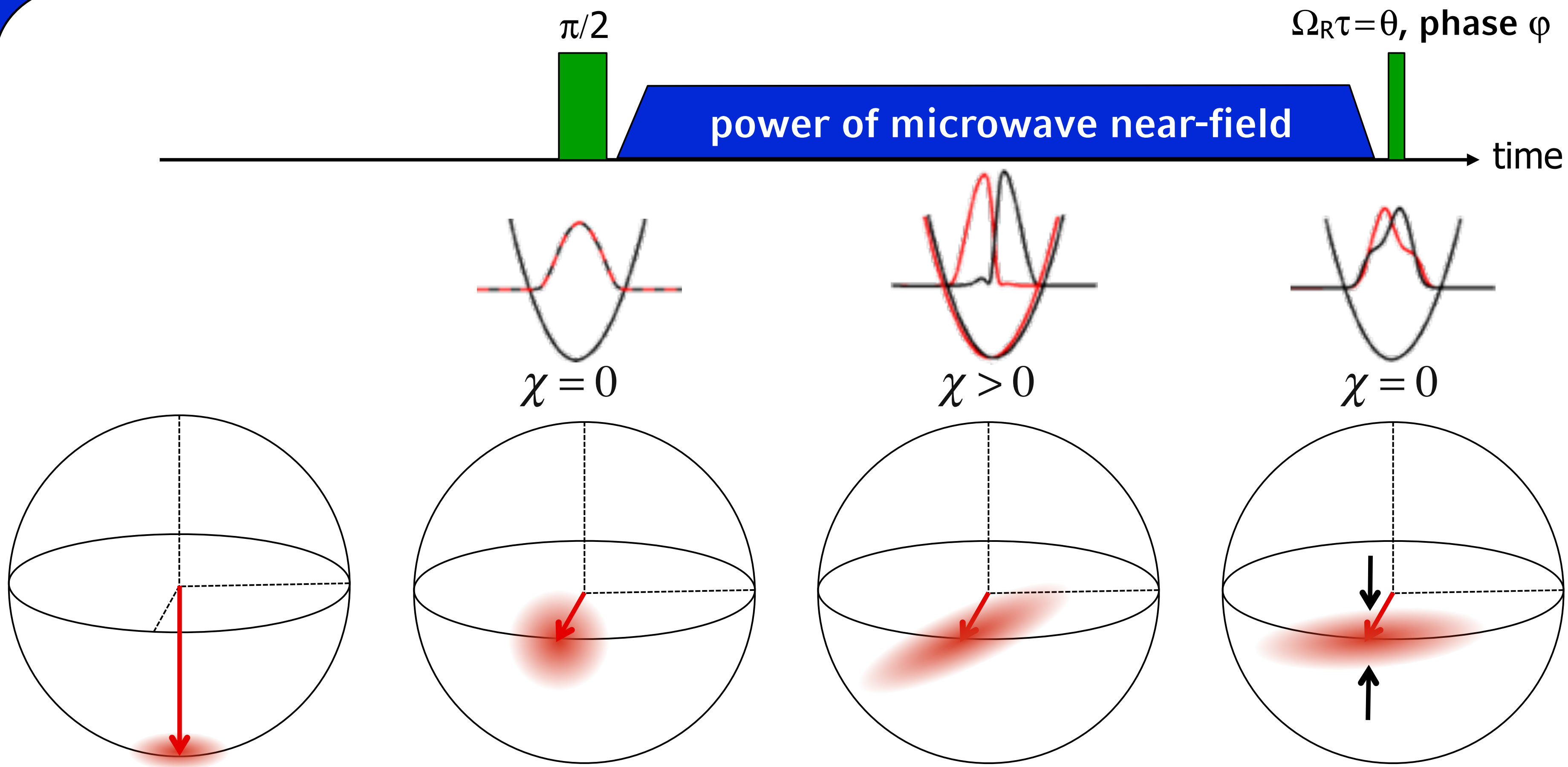
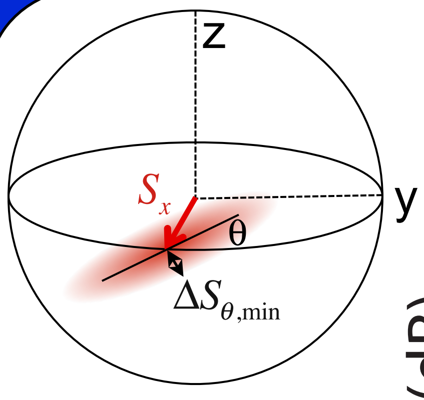
Experimental sequence for spin squeezing



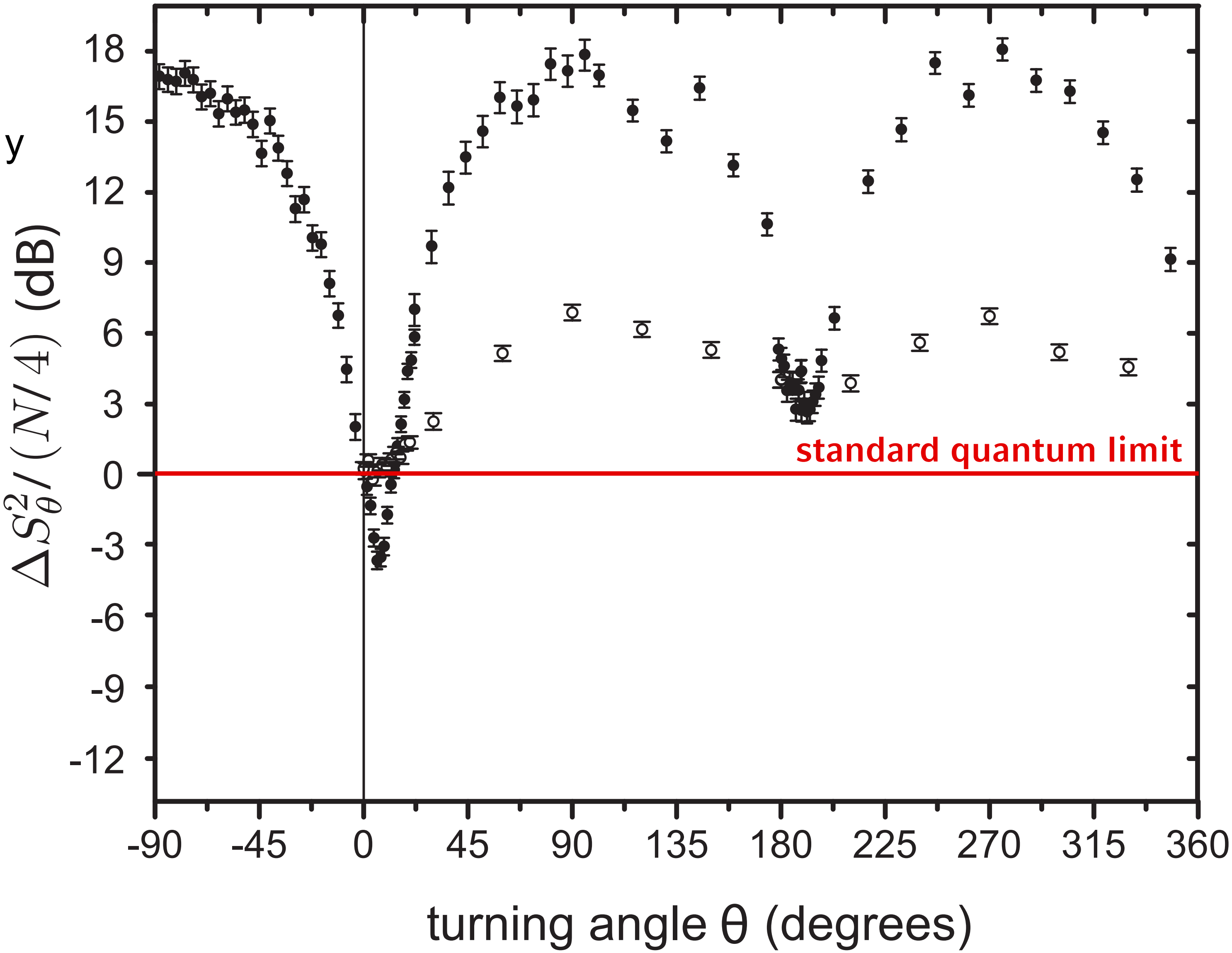
$$\xi^2 \equiv \frac{2S\left(\Delta S_{\theta,\min}\right)^2}{\langle S_x \rangle^2}$$

State tomography:
measure ΔS_θ (projection noise) after turning for several angles θ

Spin squeezing: data

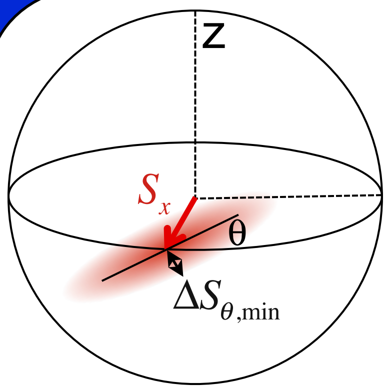


N = 1250

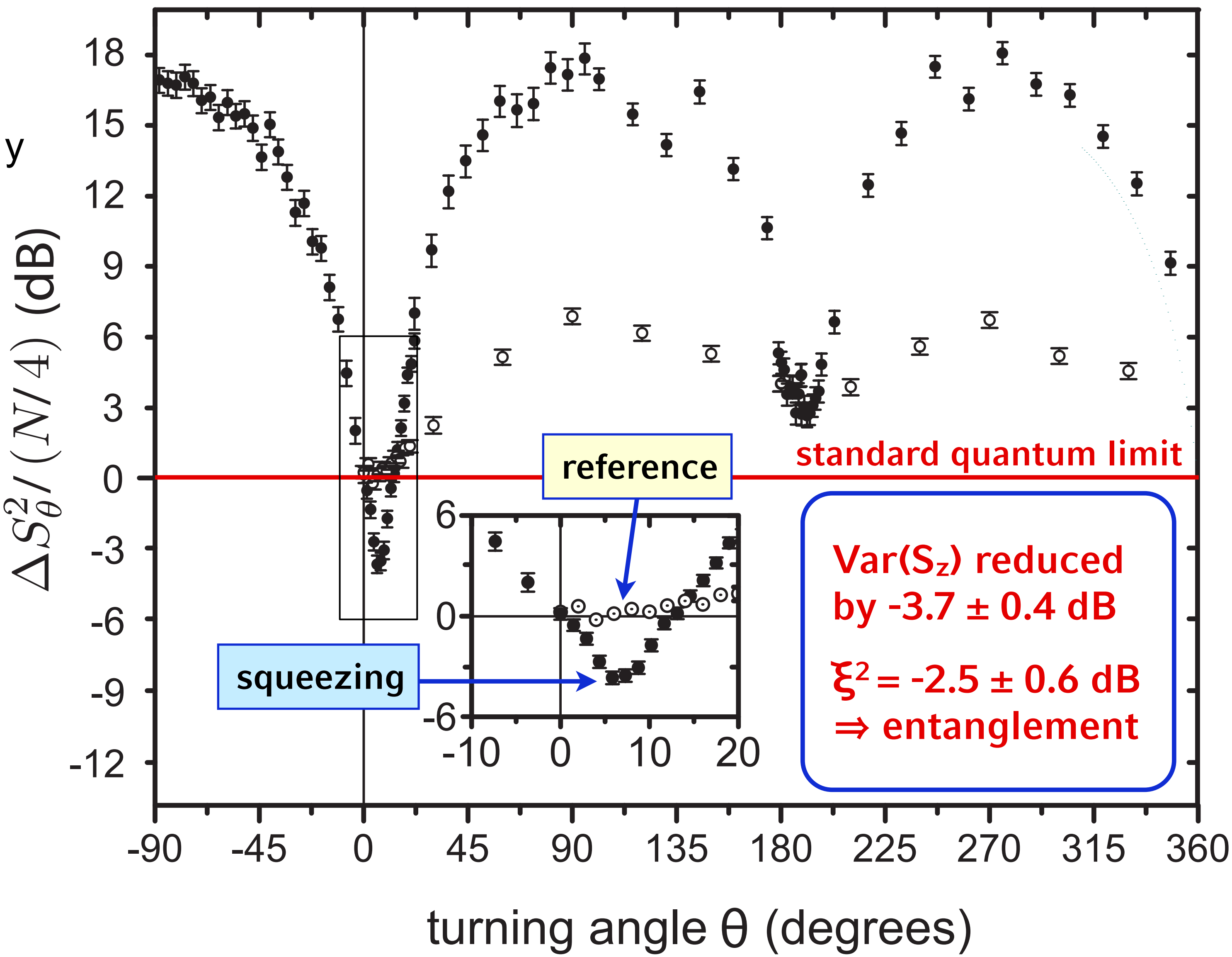


statistics:
370 shots per datapoint

Spin squeezing: data

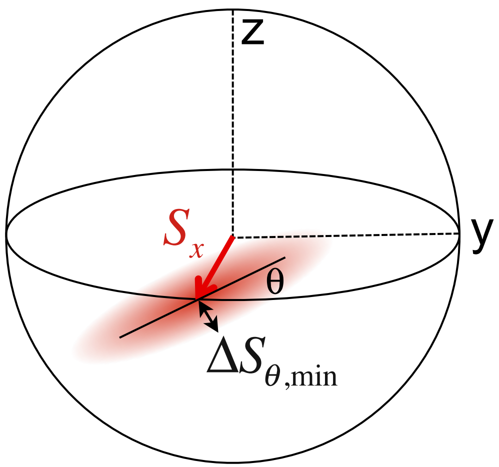


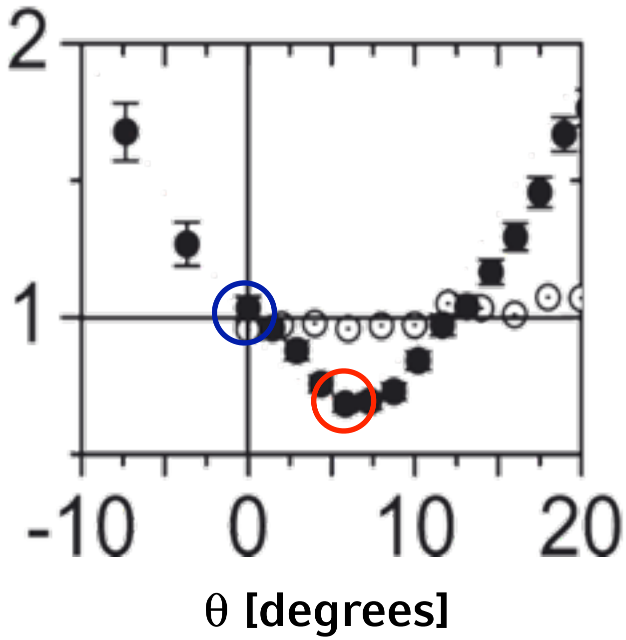
N = 1250

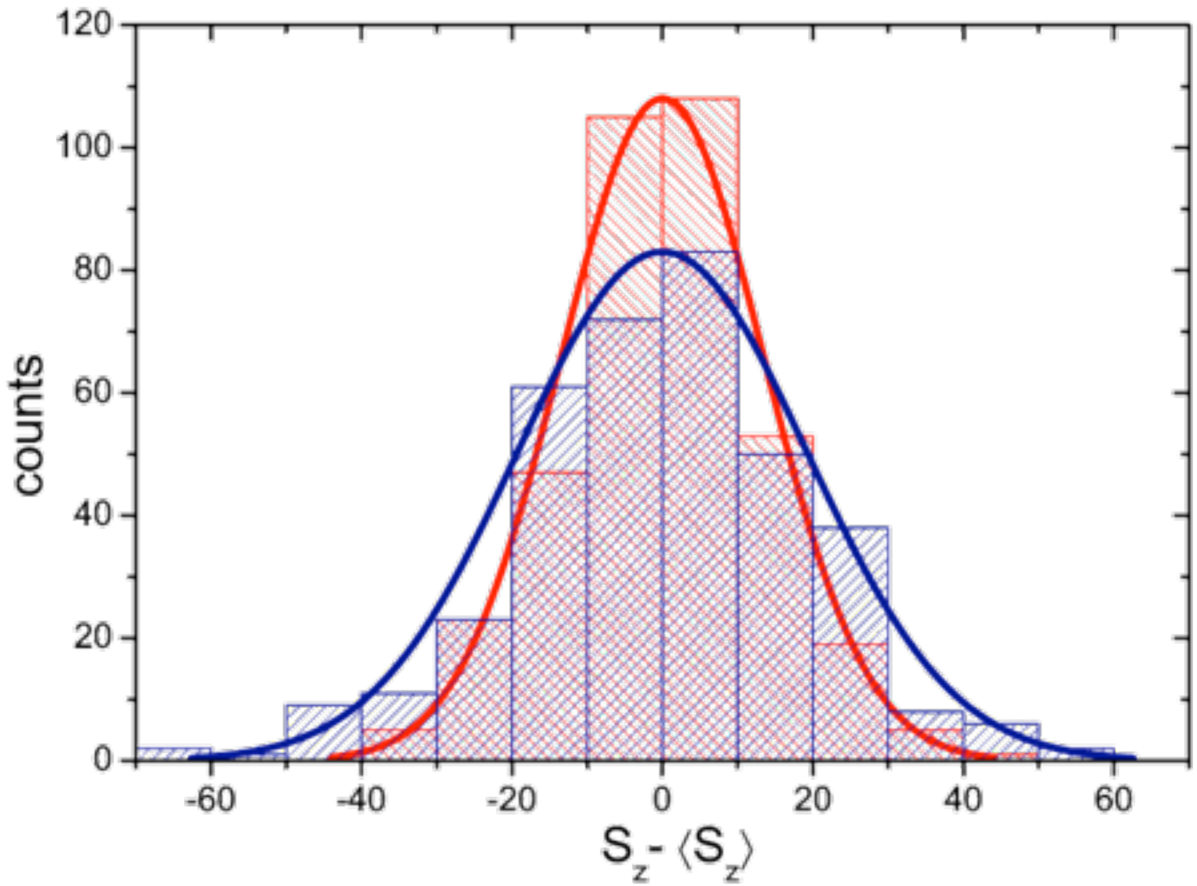


statistics: 370 shots per datapoint

Marginals of the Wigner function





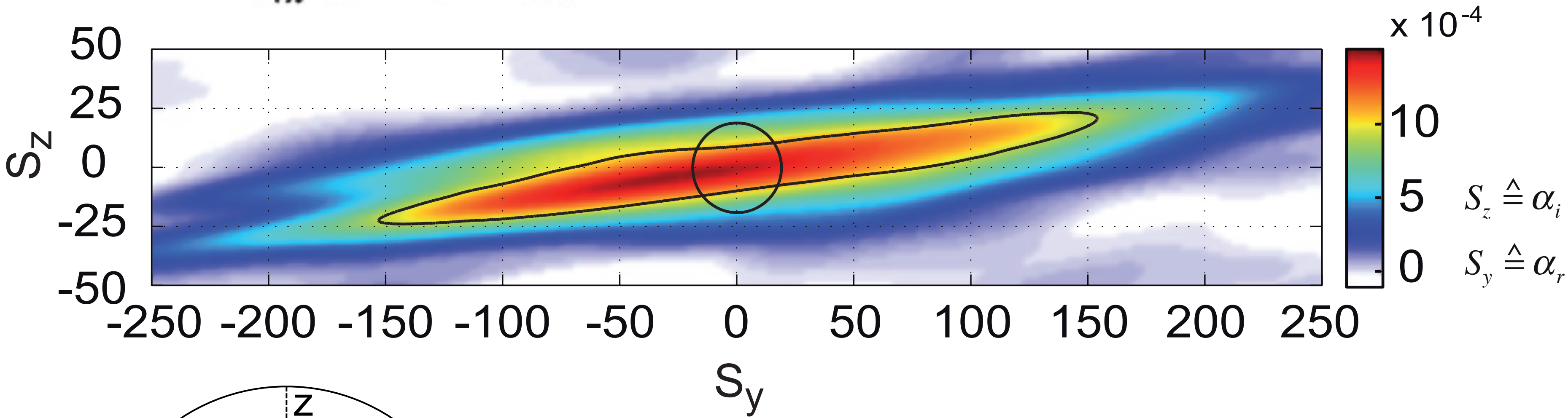


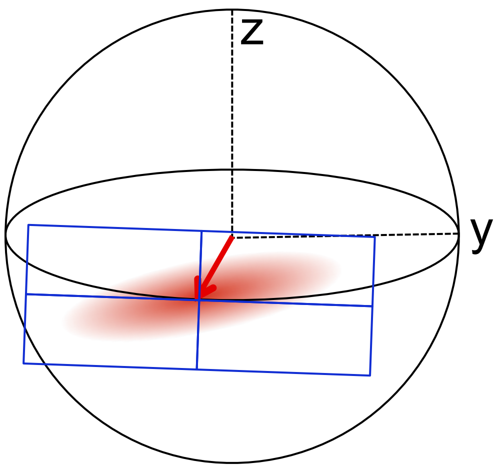
Quantum state tomography

Quantum state reconstruction

Wigner function - obtained by inverse Radon transform

$$W(\alpha_r,\alpha_i,s)=\frac{1}{4\pi^2}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\int_0^{\pi} w(x,\theta)\exp[s\eta^2/8+i\eta(x-\alpha_r\cos\theta-\alpha_i\sin\theta)]\,|\eta|\,dx\,d\eta\,d\theta\,.$$





local approximation of Bloch sphere by plane

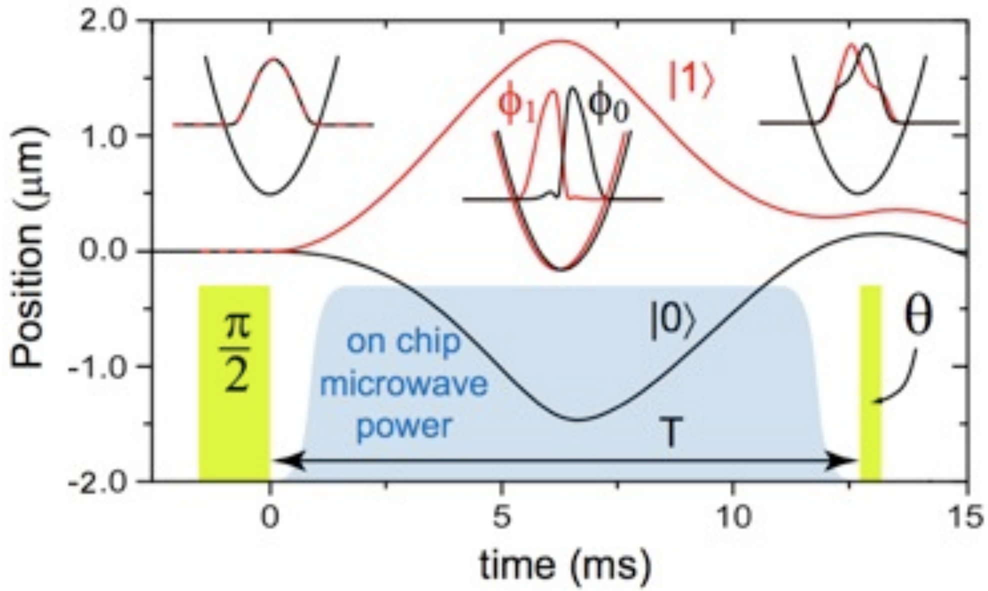
limited resolution due to

- finite angular resolution
- finite resolution in atom number (imaging noise)
- limited amount of data for histograms

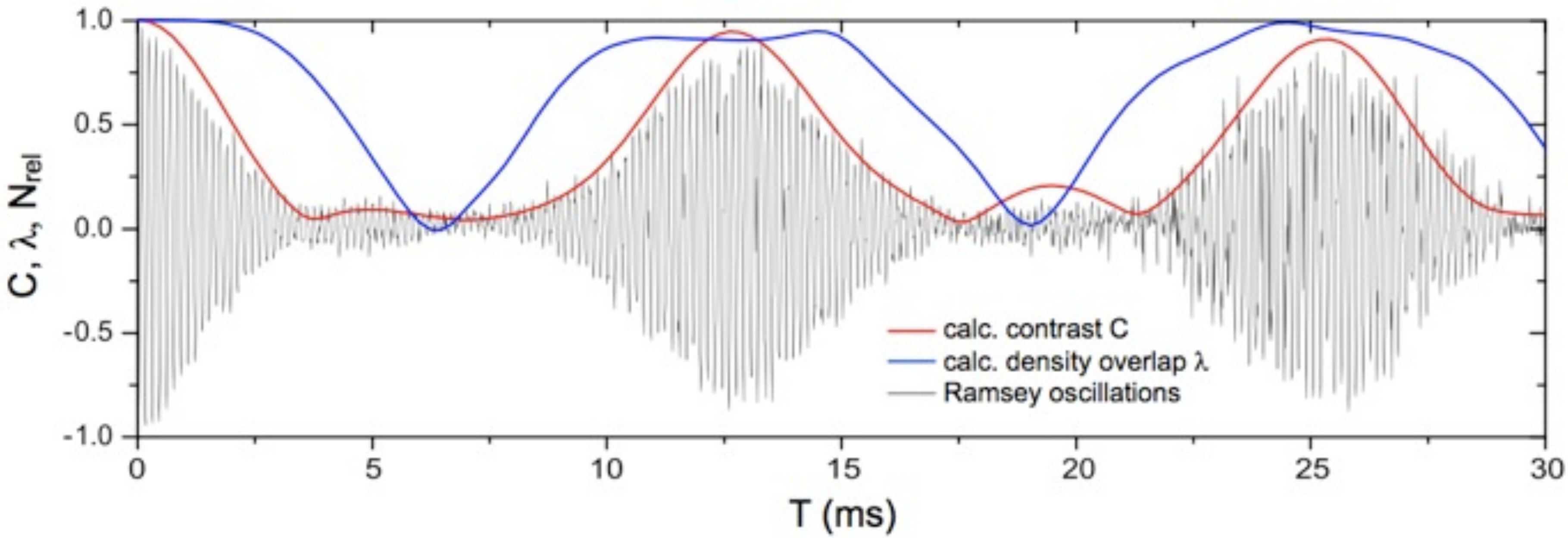
Simulation: Li Yun and A. Sinatra, ENS Paris

Yun Li et al.,
EPJB 68, 365 (2009).

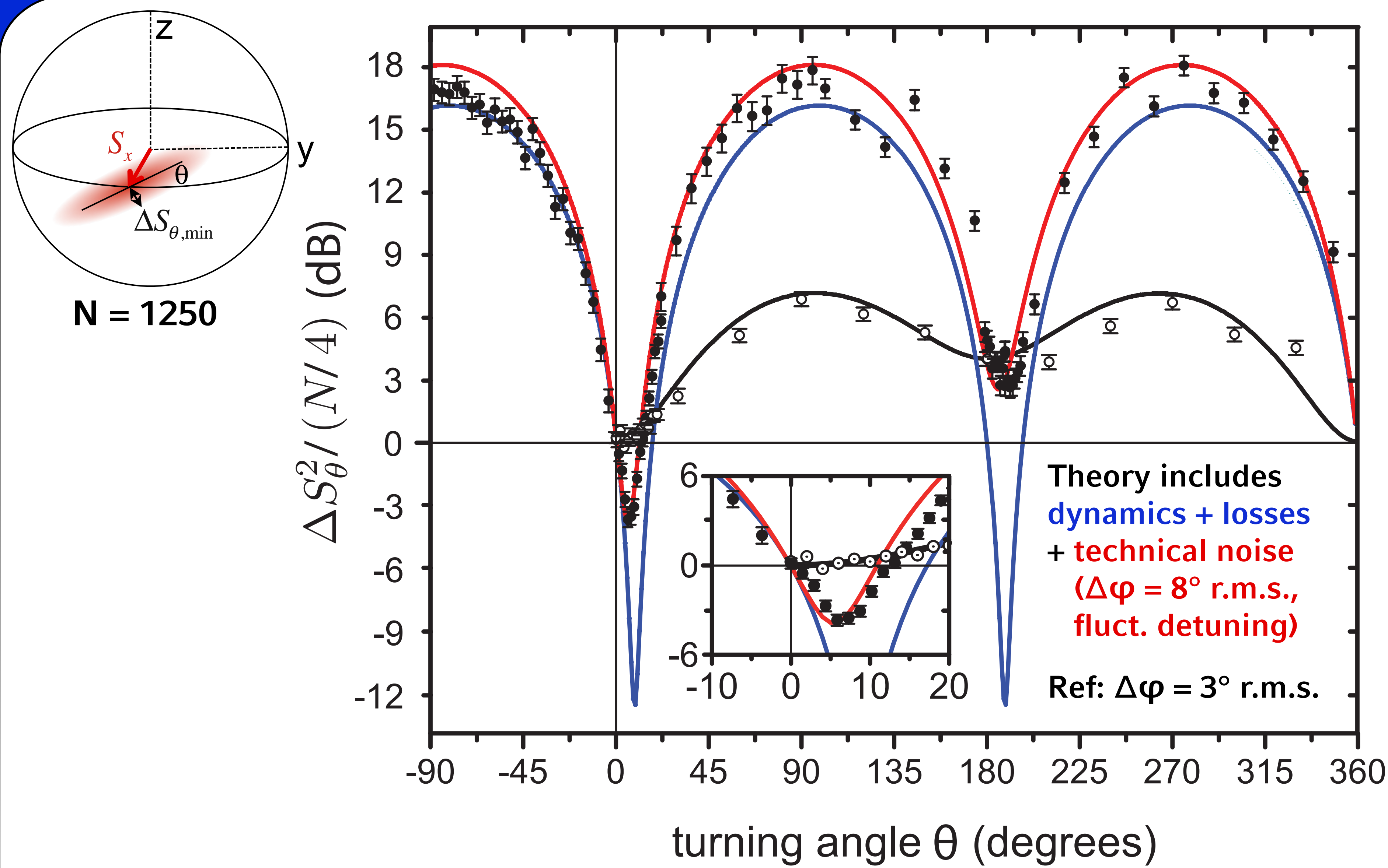
Spatial evolution of the two states
(ϕ_0, ϕ_1 for $N_0=N_1=N/2$)



Ramsey contrast
(theory vs. experiment)



Spin squeezing: data + theory

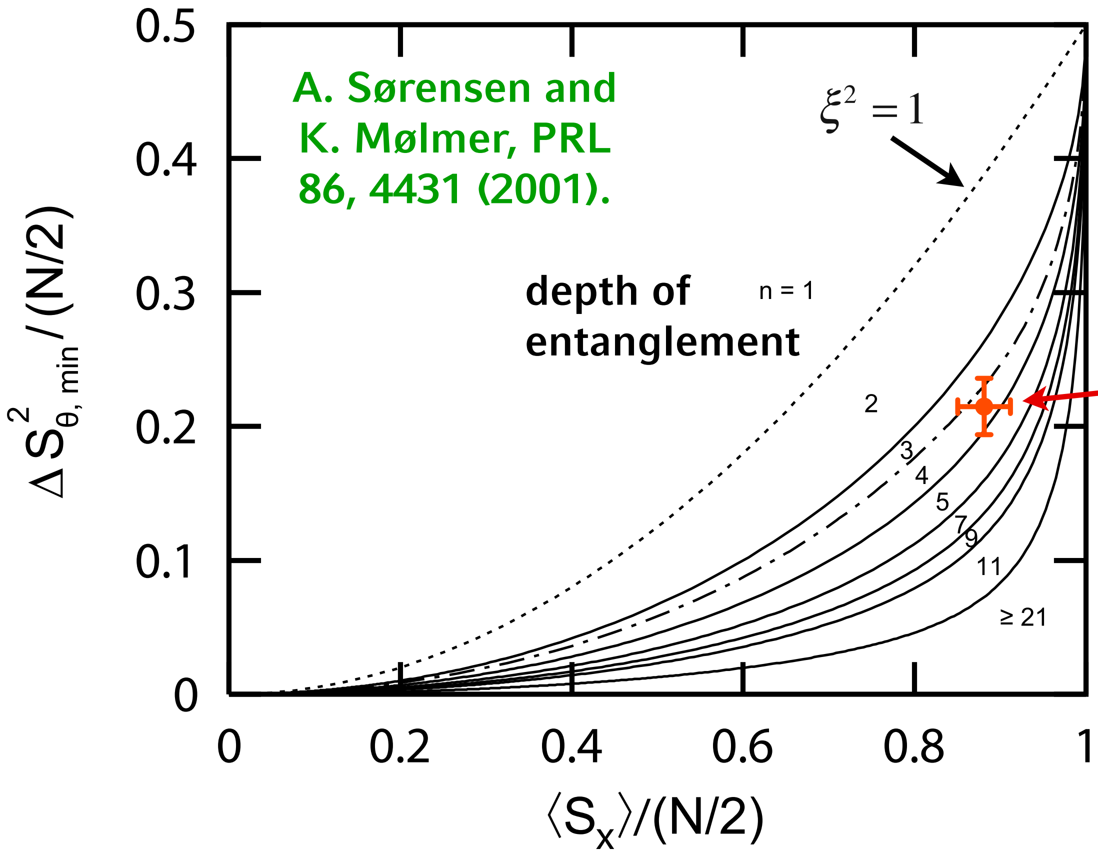


Depth of entanglement in the squeezed BEC

Separable state of N atoms: $\rho = \sum_k P_k \rho_k^{(1)} \otimes \rho_k^{(2)} \otimes \ldots \otimes \rho_k^{(N)} \Rightarrow \xi^2 \geq 1$

A. Sørensen et al., Nature 409, 63 (2001).

How large are the clusters of entangled atoms in the BEC at least? $\Rightarrow$ **depth of entanglement**



our data

$\Rightarrow$ clusters of ≥ 4 entangled particles

Outlook

- improve squeezing (decrease technical noise)
- study scaling with atom number and temperature
- use squeezed states in atomic clock on a chip
  (relax magnetic trap after squeezing to turn off nonlinearity: squeezing survives for ~ 0.6 s in presence of loss and residual phase diffusion)

P. Rosenbusch/J. Reichel, Observatoire, Paris

- characterize multi-particle entanglement (quantum Fisher information...)

A. Smerzi et al., Trento

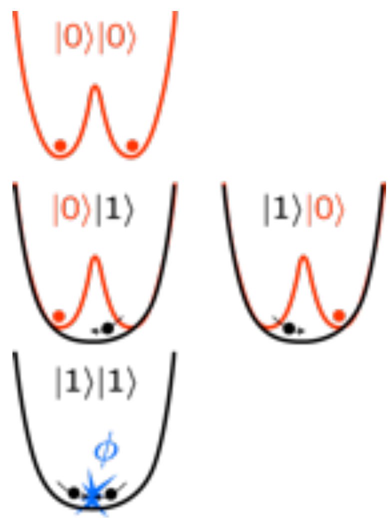
- entanglement of several BECs through collisions
- QIP with single atoms on atom chips

T. Calarco et al., PRA 61, 022304 (2002).

P. Treutlein et al., PRA 94, 022312 (2006).

P. Treutlein et al., Fortschr. Phys. 54, 702 (2006).

$$
\begin{aligned}
|0\rangle|0\rangle &\Rightarrow \quad |0\rangle|0\rangle \\
|0\rangle|1\rangle &\Rightarrow \quad |0\rangle|1\rangle \\
|1\rangle|0\rangle &\Rightarrow \quad |1\rangle|0\rangle \\
|1\rangle|1\rangle &\Rightarrow e^{i\phi}|1\rangle|1\rangle
\end{aligned}
$$



Munich atom chip team - P. Treutlein / T. W. Hänsch

Collaborations: L. Yun, A. Sinatra, and J. Reichel (ENS Paris), M. Lukin (Harvard), D. König and J. Kotthaus (LMU Munich), M. Ludwig and F. Marquardt (LMU), K. Hammerer, K. Stannigel, C. Genes, M. Wallquist, and P. Zoller (Innsbruck)