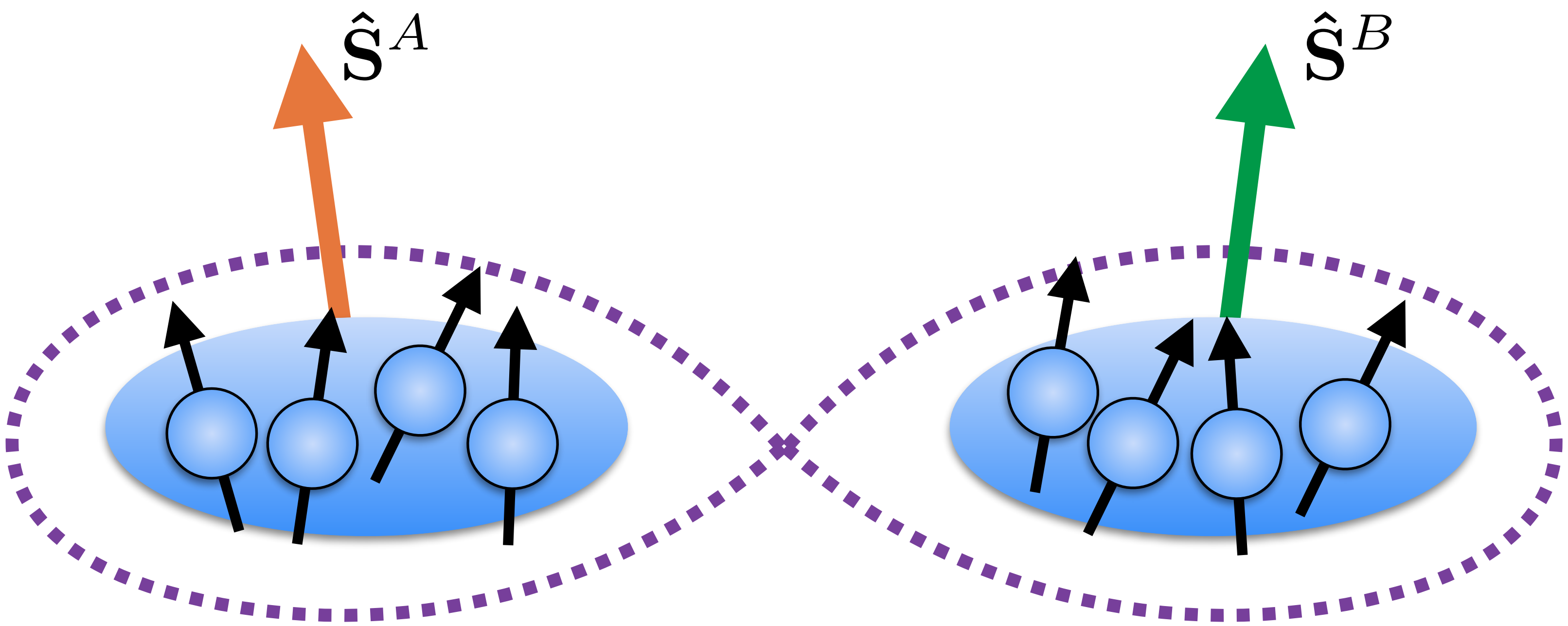
Einstein-Podolsky-Rosen experiment with two Bose-Einstein condensates



University of Basel

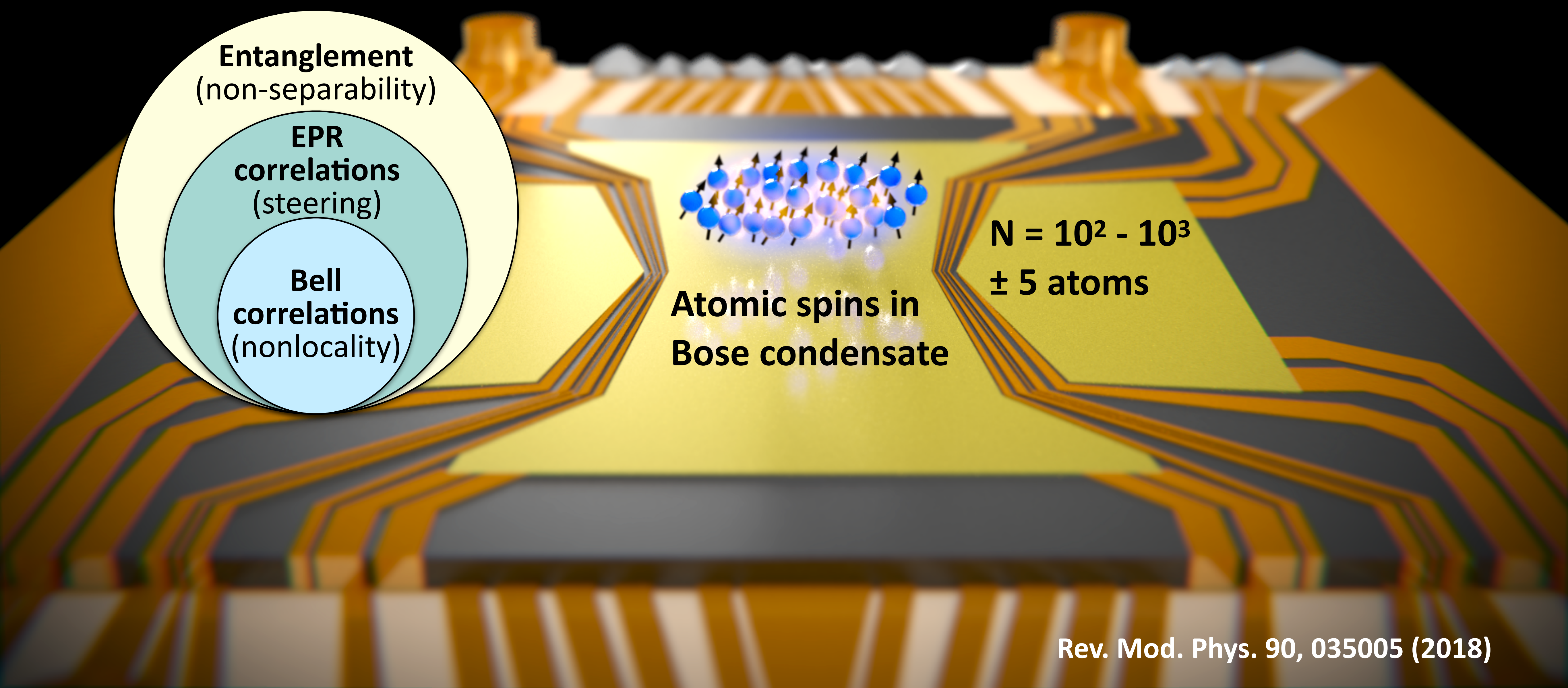
Many-particle entanglement and quantum metrology

Fundamental questions

- how to create and detect it
- how to quantify it
- classes of entangled states
- usefulness, robustness

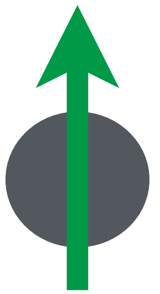
Quantum metrology

- interferometry beyond standard quantum limit (SQL)
- field&force sensing on micrometer scale
- field imaging



Rev. Mod. Phys. 90, 035005 (2018)

Einstein-Podolsky-Rosen experiment



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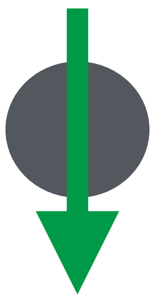

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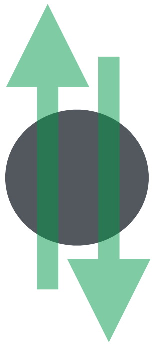
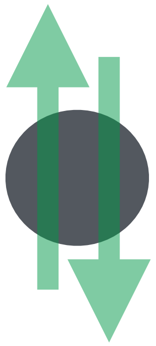


$$\frac{1}{\sqrt{2}}\left(|\uparrow\rangle + |\downarrow\rangle\right)$$

Einstein-Podolsky-Rosen experiment

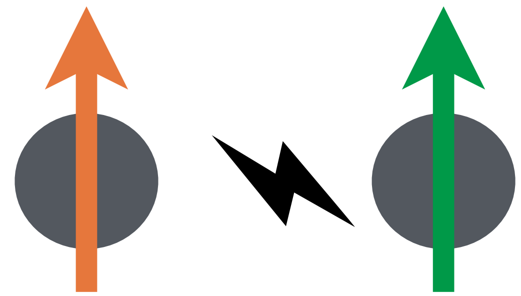


$$\frac{1}{\sqrt{2}}\left(|\uparrow\rangle + |\downarrow\rangle\right)$$

$$\mathrm{var}(S_y)\mathrm{var}(S_z) \geq \frac{1}{4}|\langle S_x\rangle|$$

Einstein-Podolsky-Rosen experiment

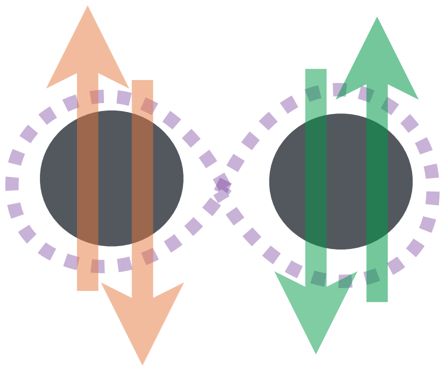
interaction



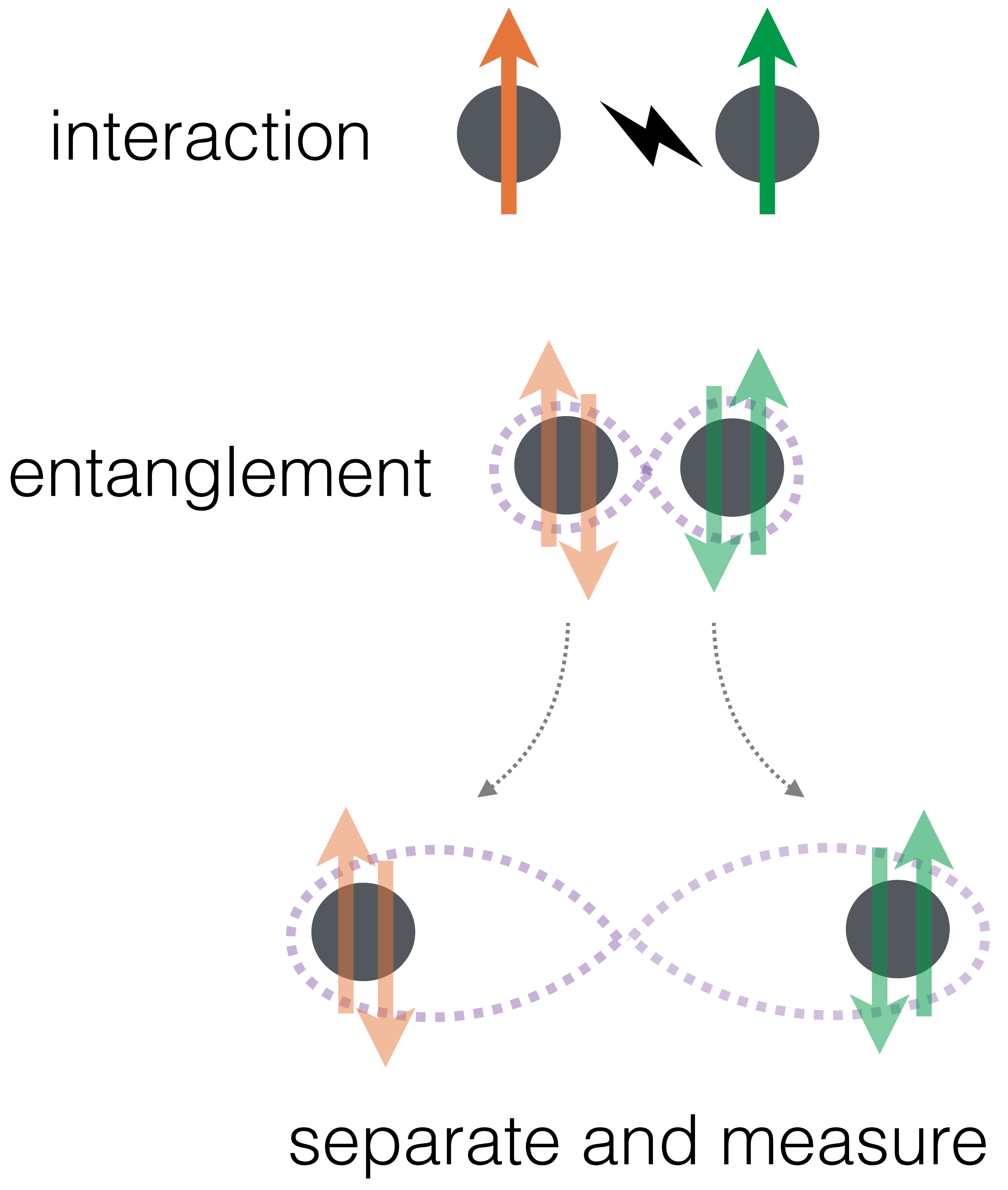
Einstein-Podolsky-Rosen experiment

interaction

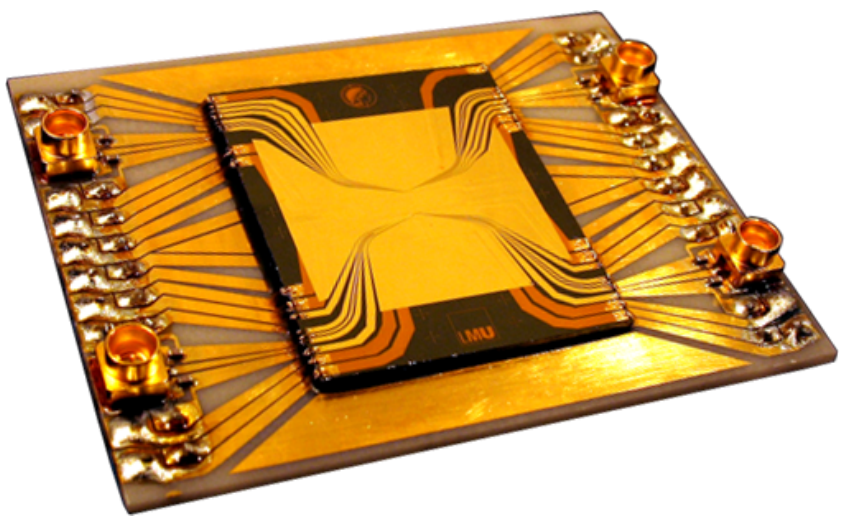
entanglement

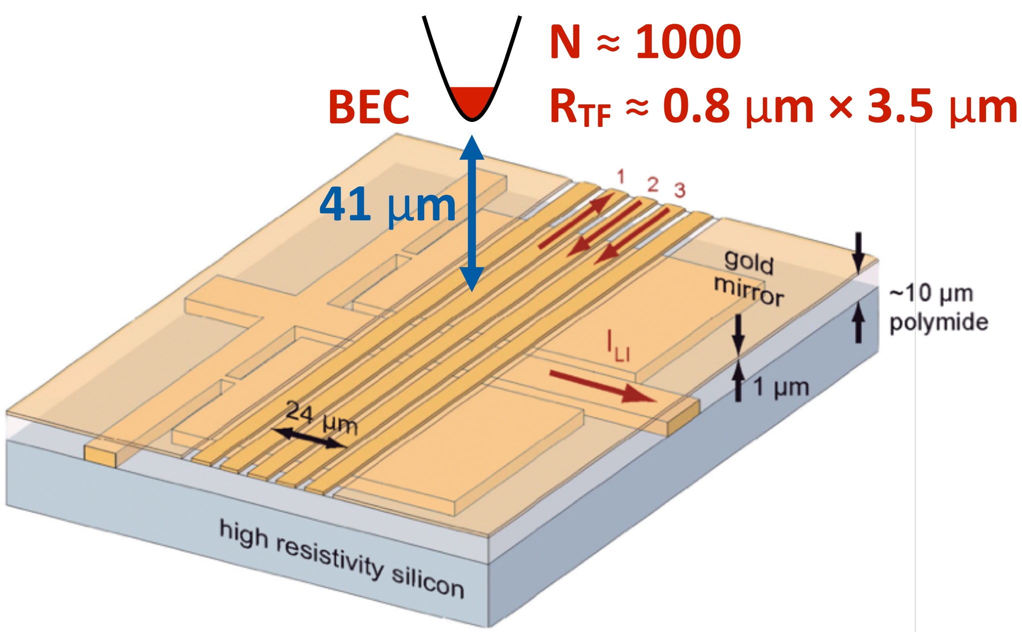


Einstein-Podolsky-Rosen experiment

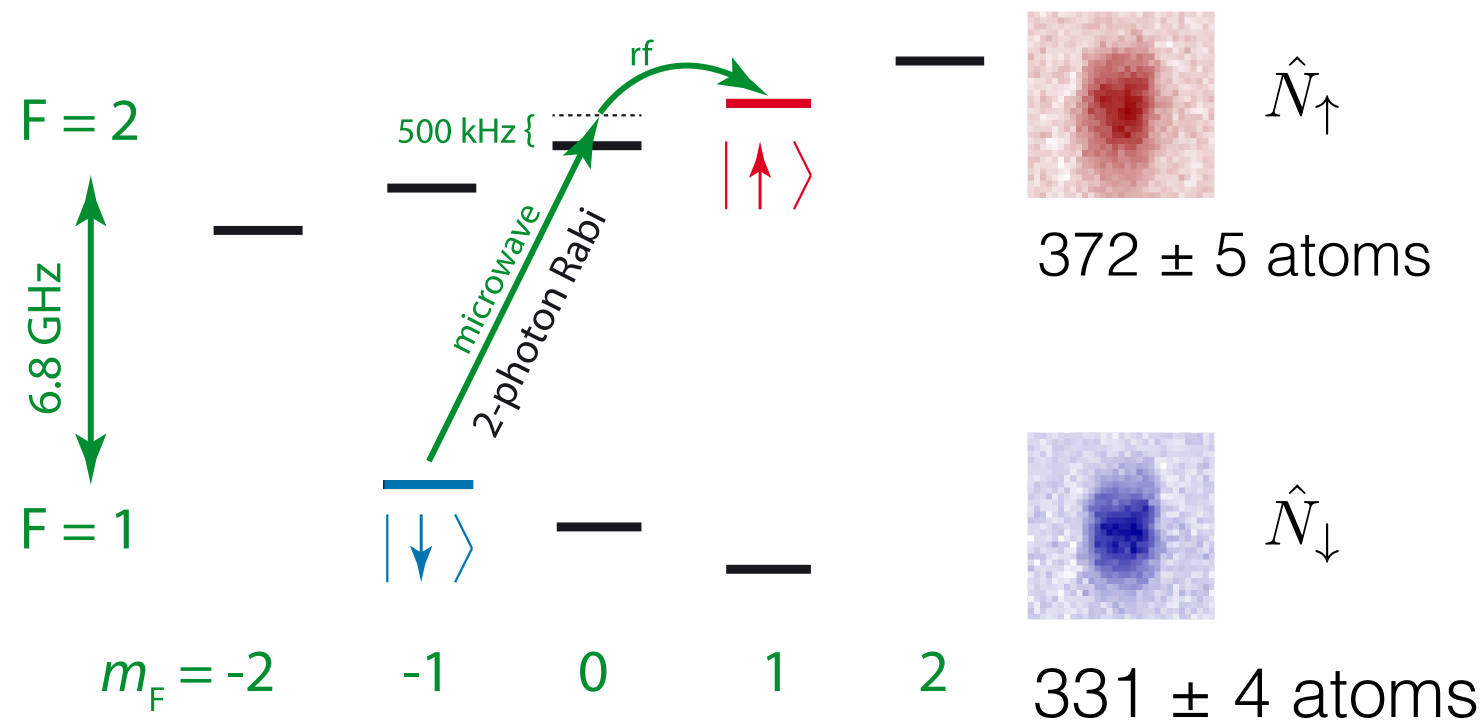


Two-component ^{87}Rb BEC on an atom chip



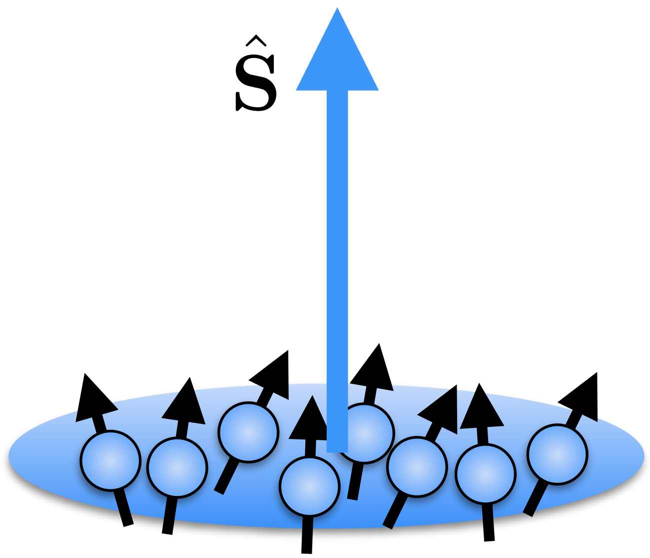


^{87}Rb ground state hyperfine structure:



- single spatial mode
- low susceptibility to magnetic field fluctuations
- spin rotations with very high fidelity
- very long coherence times (TACC, Syrte, Paris)
  Li et al. PRL 125, 123402 (2020)

Spin-squeezing through atomic interactions

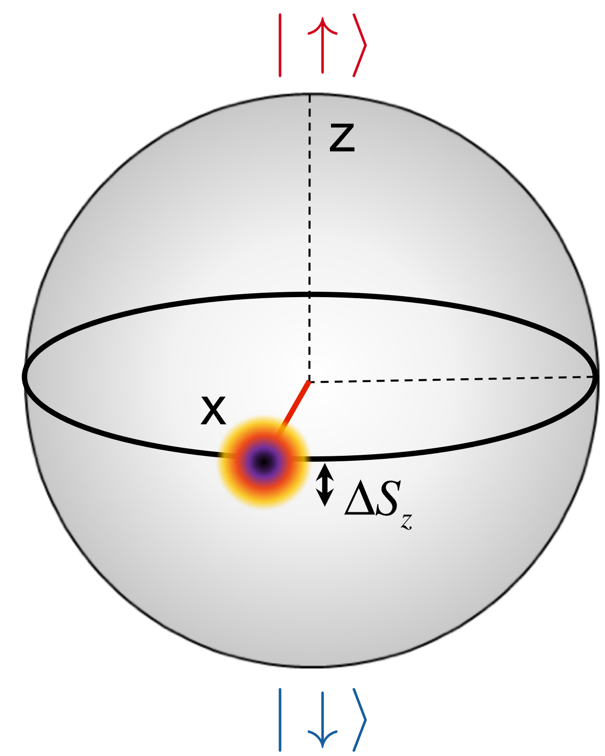


Ensemble of spins

Collective spin:

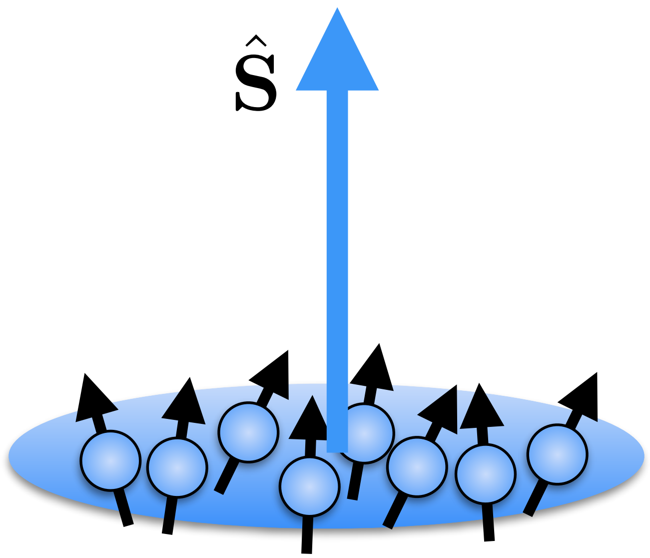
$$\hat{\mathbf{S}} = \sum_{i=1}^{N} \hat{\mathbf{s}}_i, \quad S = \frac{N}{2}$$

$$\hat{S}_z = \frac{1}{2}(\hat{N}_\uparrow - \hat{N}_\downarrow)$$



$$\Delta S_z = \frac{\sqrt{N}}{2}$$

Spin-squeezing through atomic interactions



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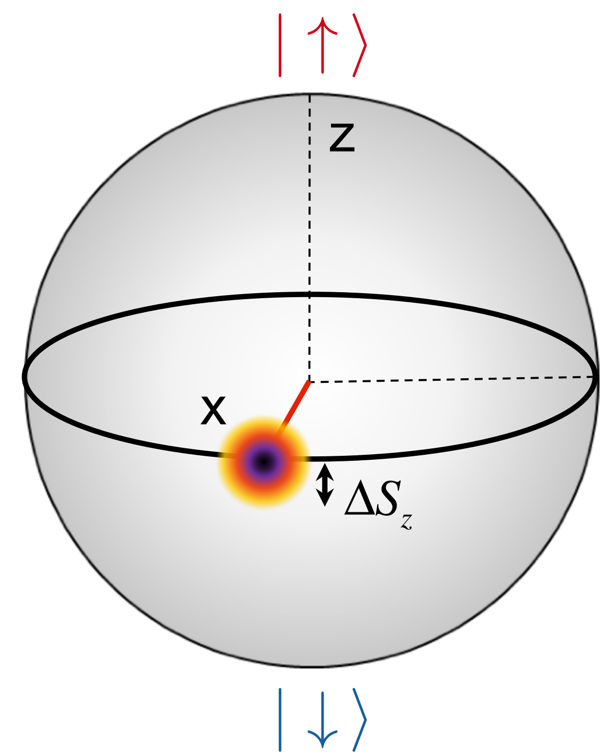
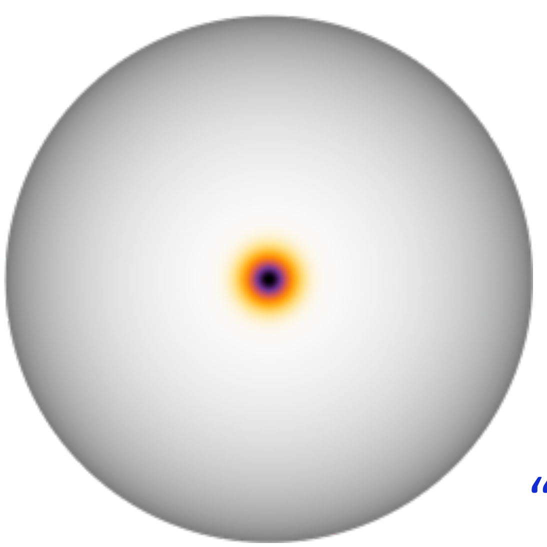


$$\Delta S_z = \frac{\sqrt{N}}{2}$$

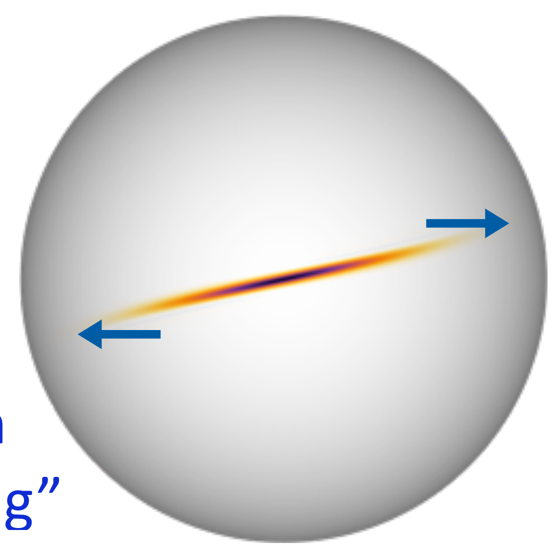
Atomic collisions create spin squeezing



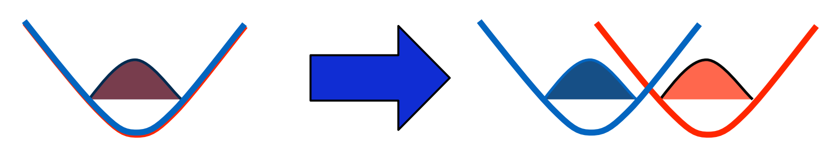
coherent spin state

$$\hat{\mathcal{H}} = \chi \hat{S}_z^2$$

time evolution
“one-axis twisting”



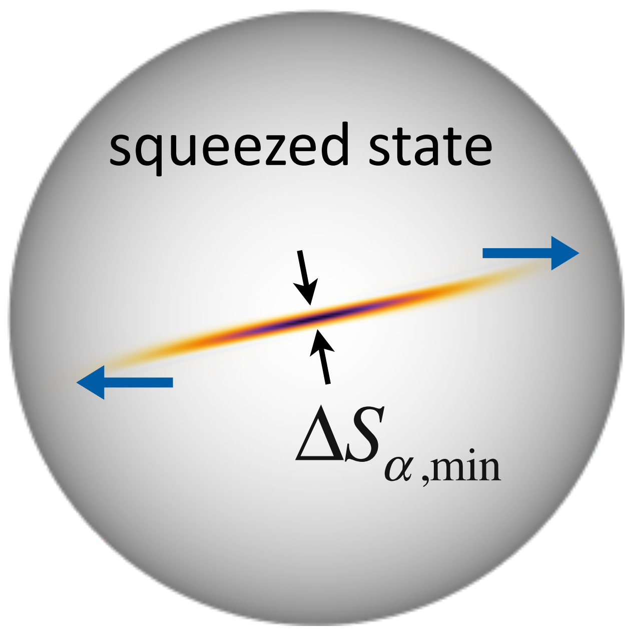
squeezed spin state



interaction tuning by
state dependent potentials

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

Entanglement in spin squeezed states



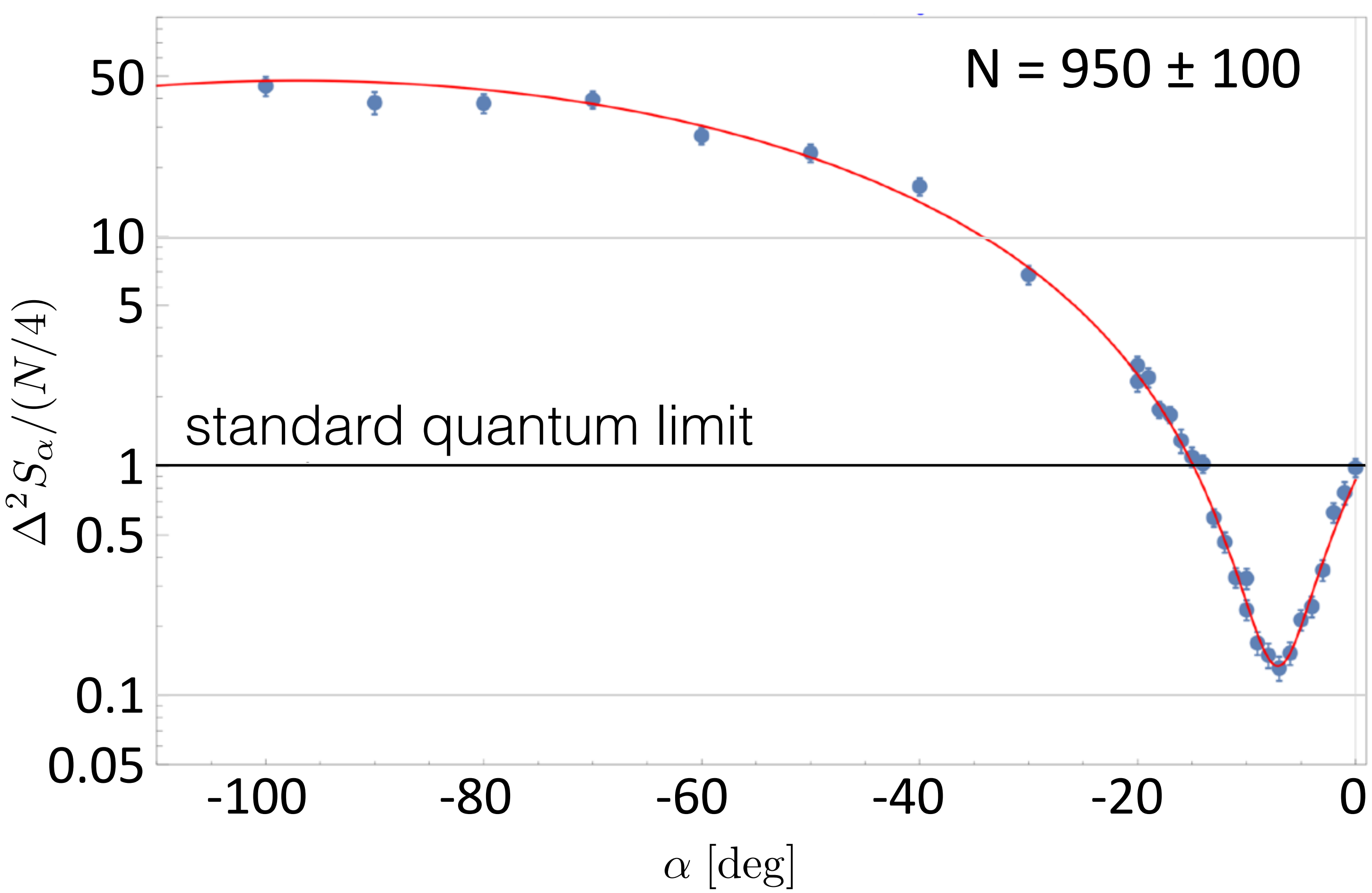
$\xi^2 < 1$

Spin-squeezing parameter

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

entanglement witness

Kitagawa & Ueda PRA 47, 5138,1993
Wineland et al. PRA 50, 67,1994
Sørensen et al. Nature 409, 63–66, 2001



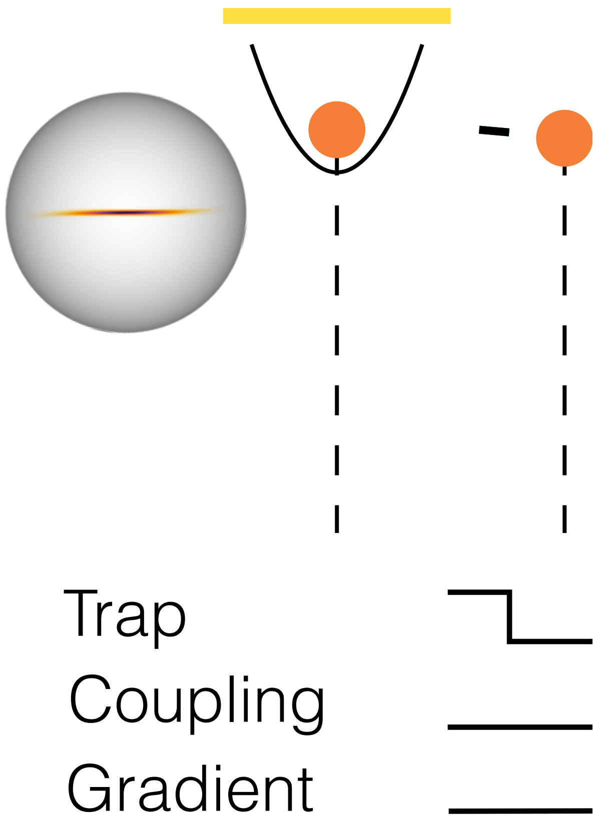
ξ^2 = -8.2 ± 0.5 dB

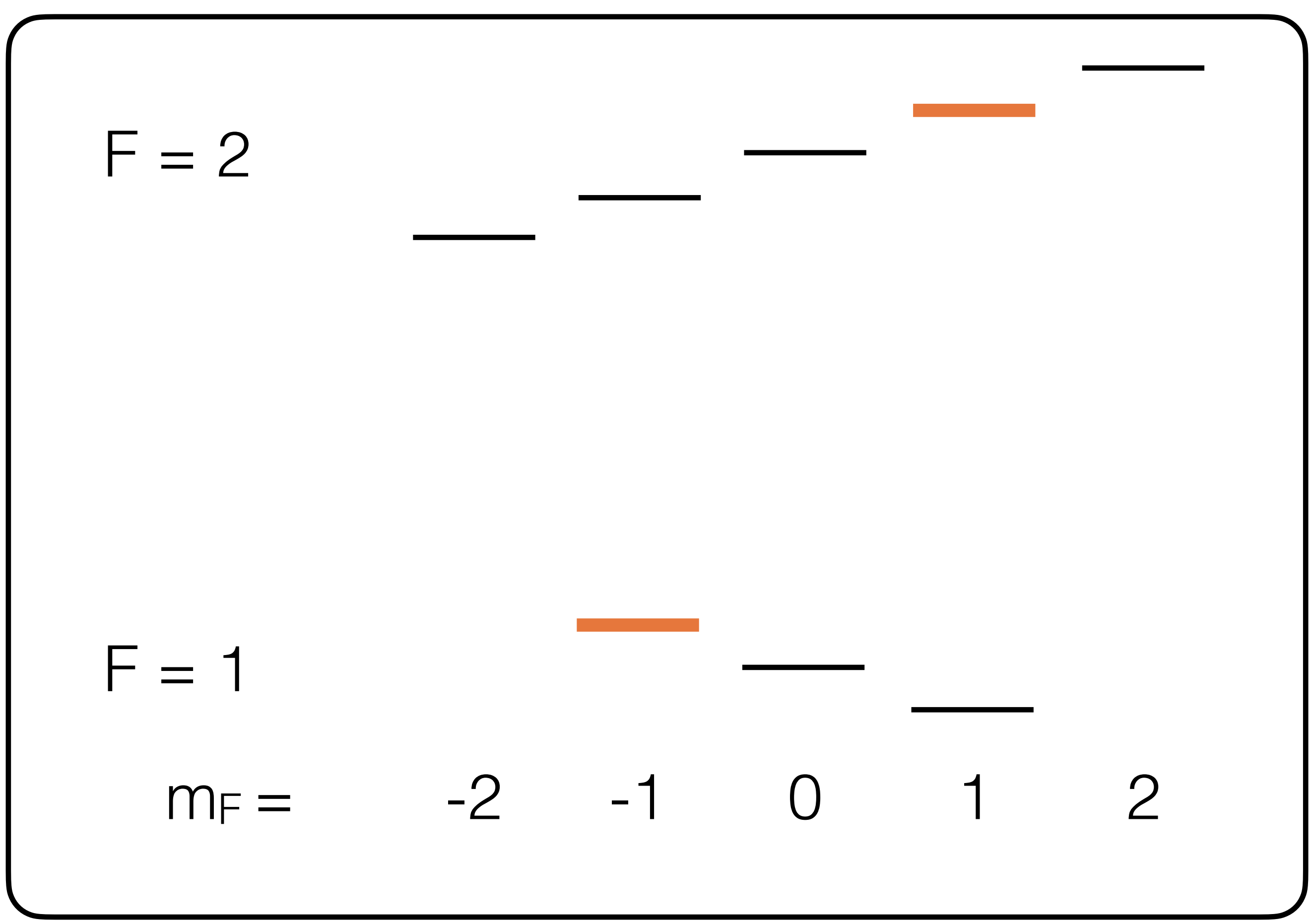
⇒ entanglement

(Noise reduced by -8.7 ± 0.5 dB, contrast C = 94.9 %)

Spin squeezed states possess EPR-Entanglement and Bell correlations:
Fadel et al. Science 360, 409 (2018)
Kunkel et al. Science 360, 413 (2018)
Lange et al. Science 360 , 416 (2018)
Schmied et al. Science 352, 441 (2016)

Splitting a BEC in two





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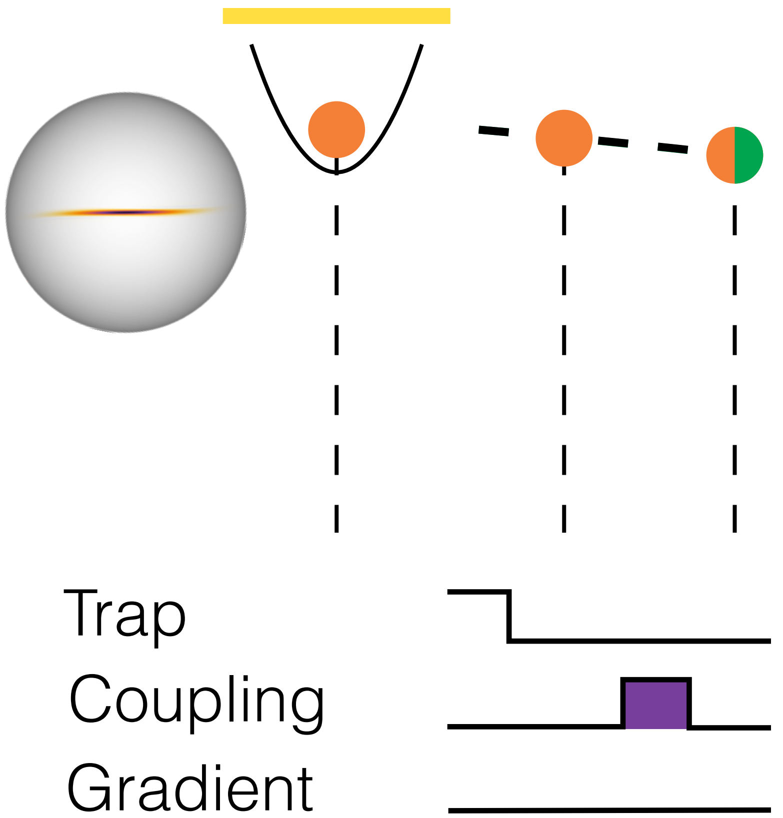

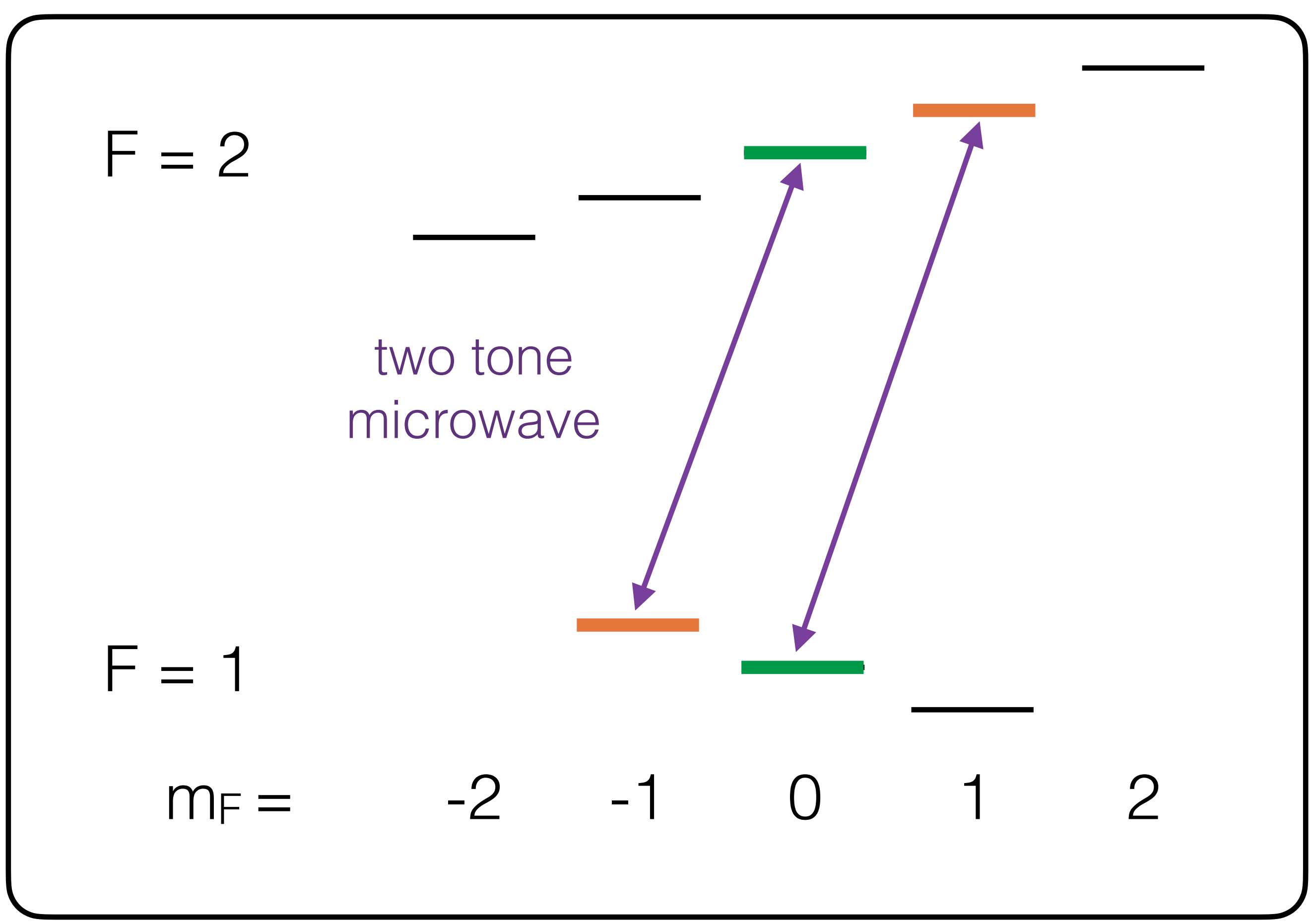

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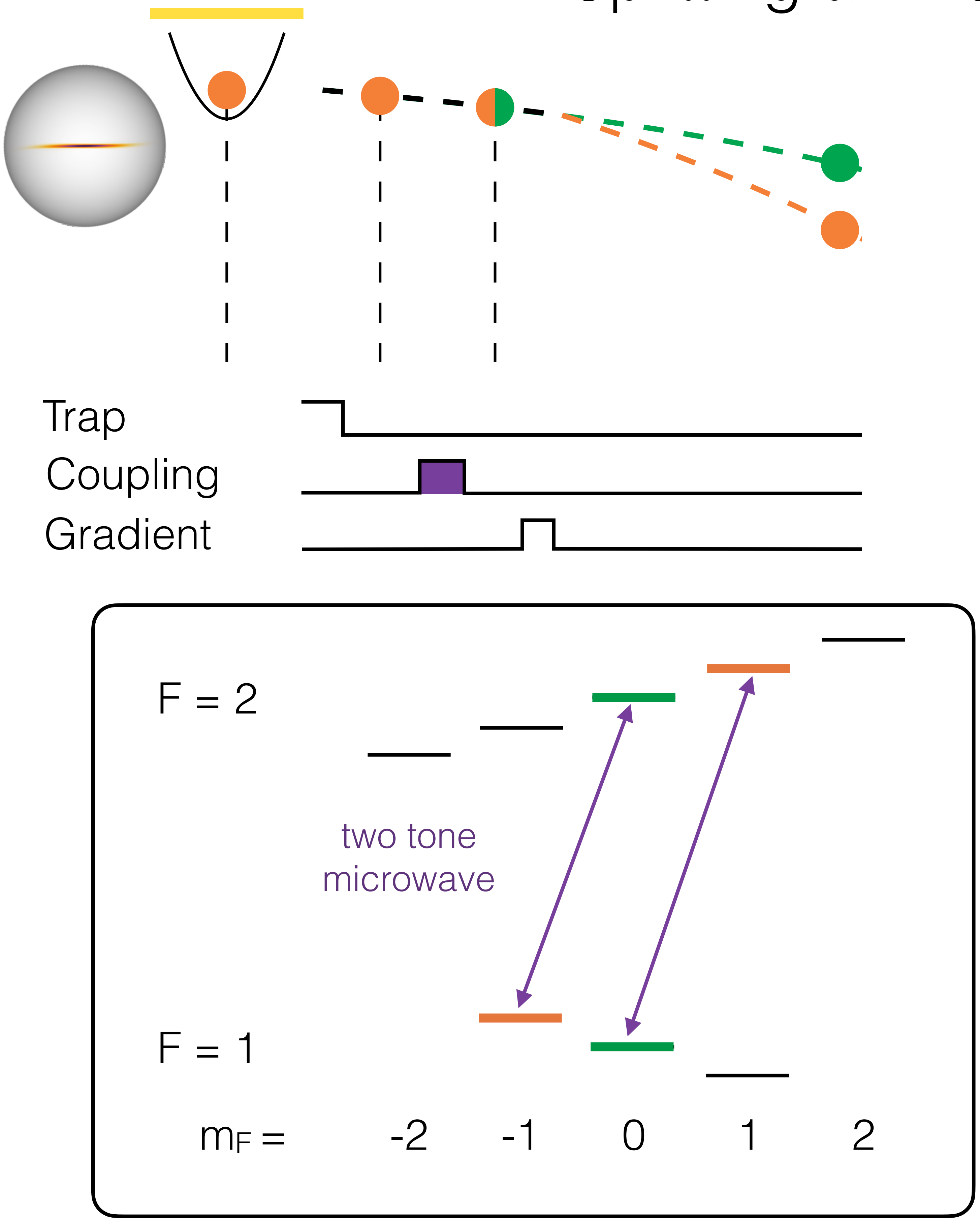

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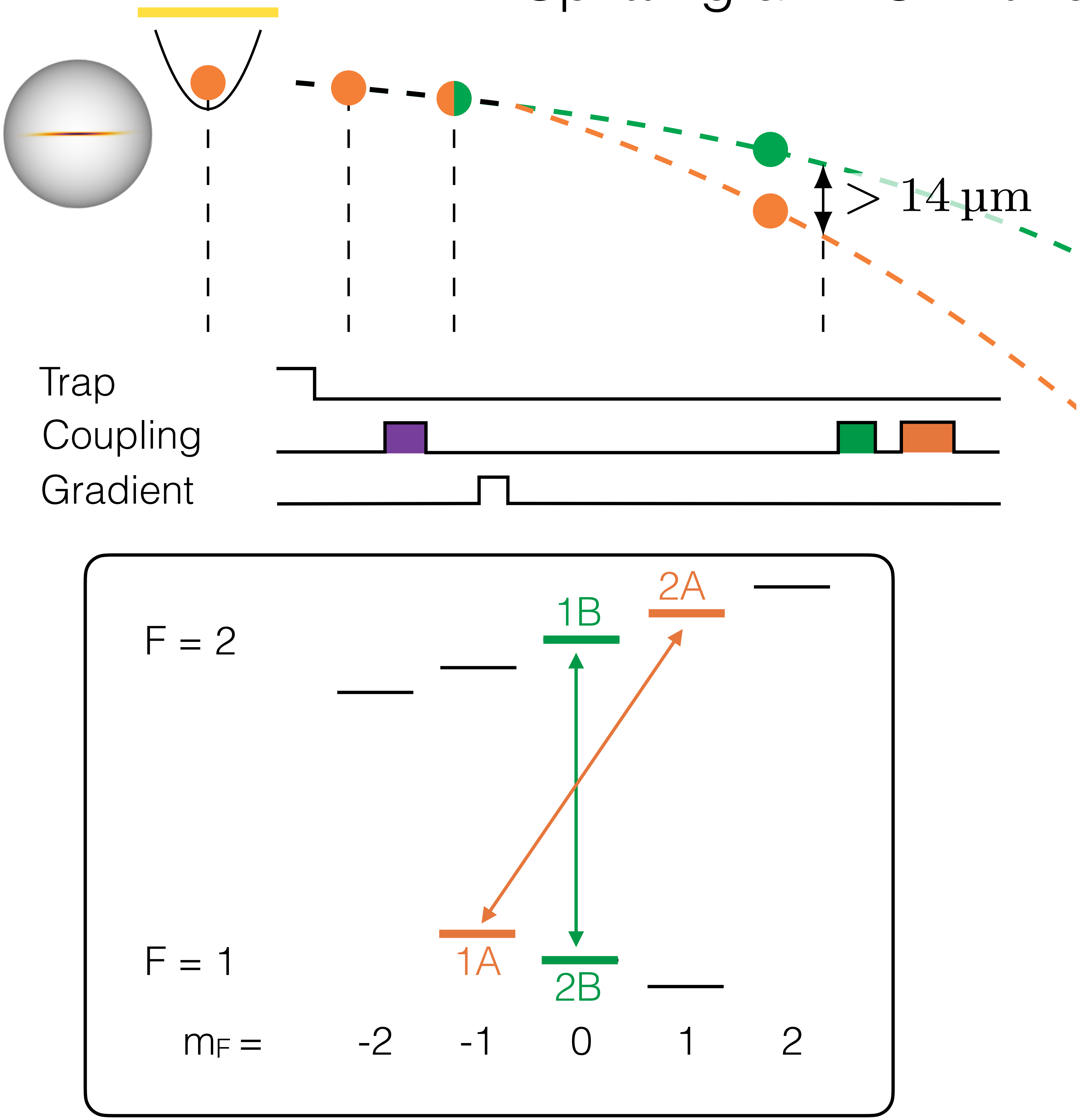

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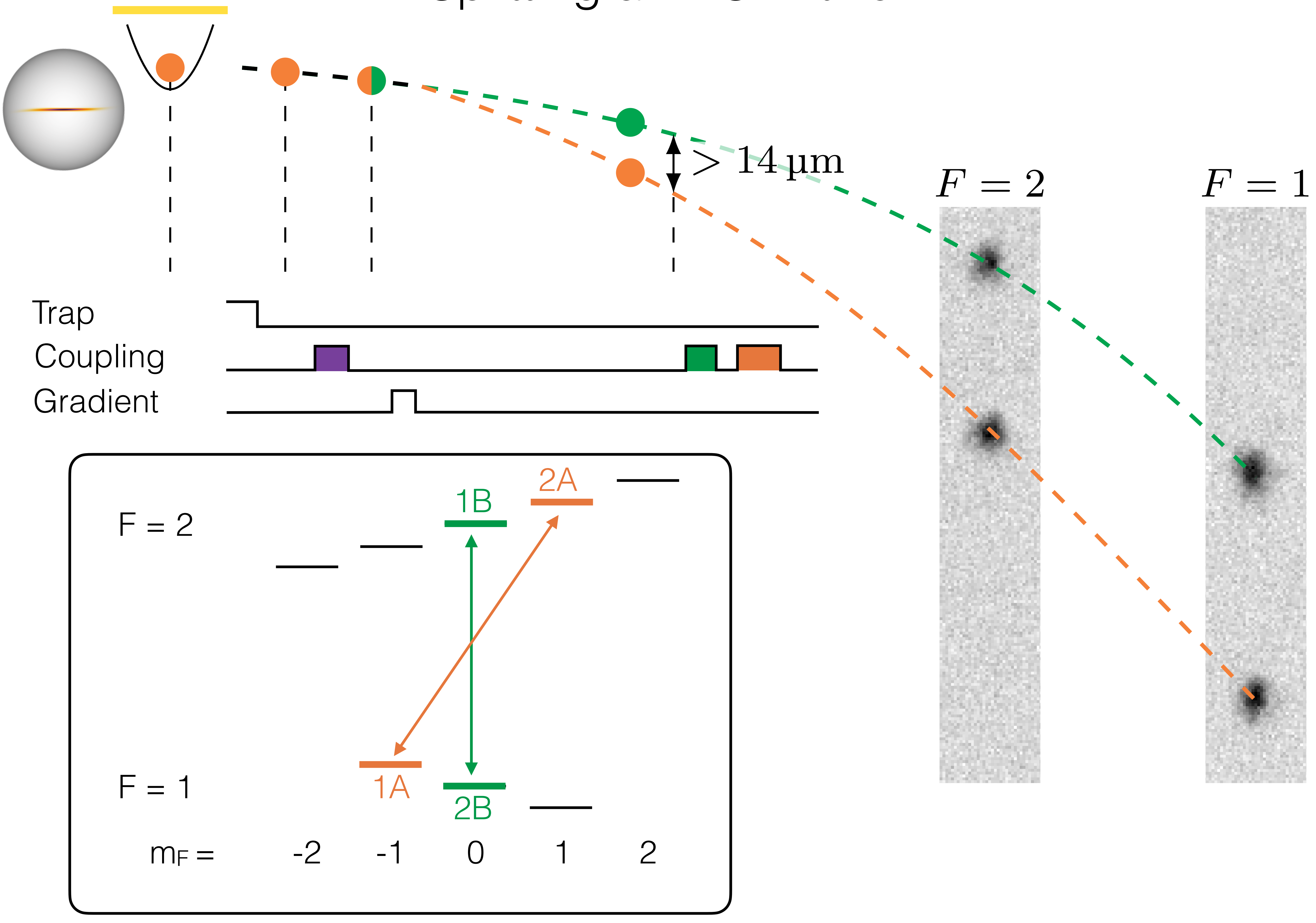
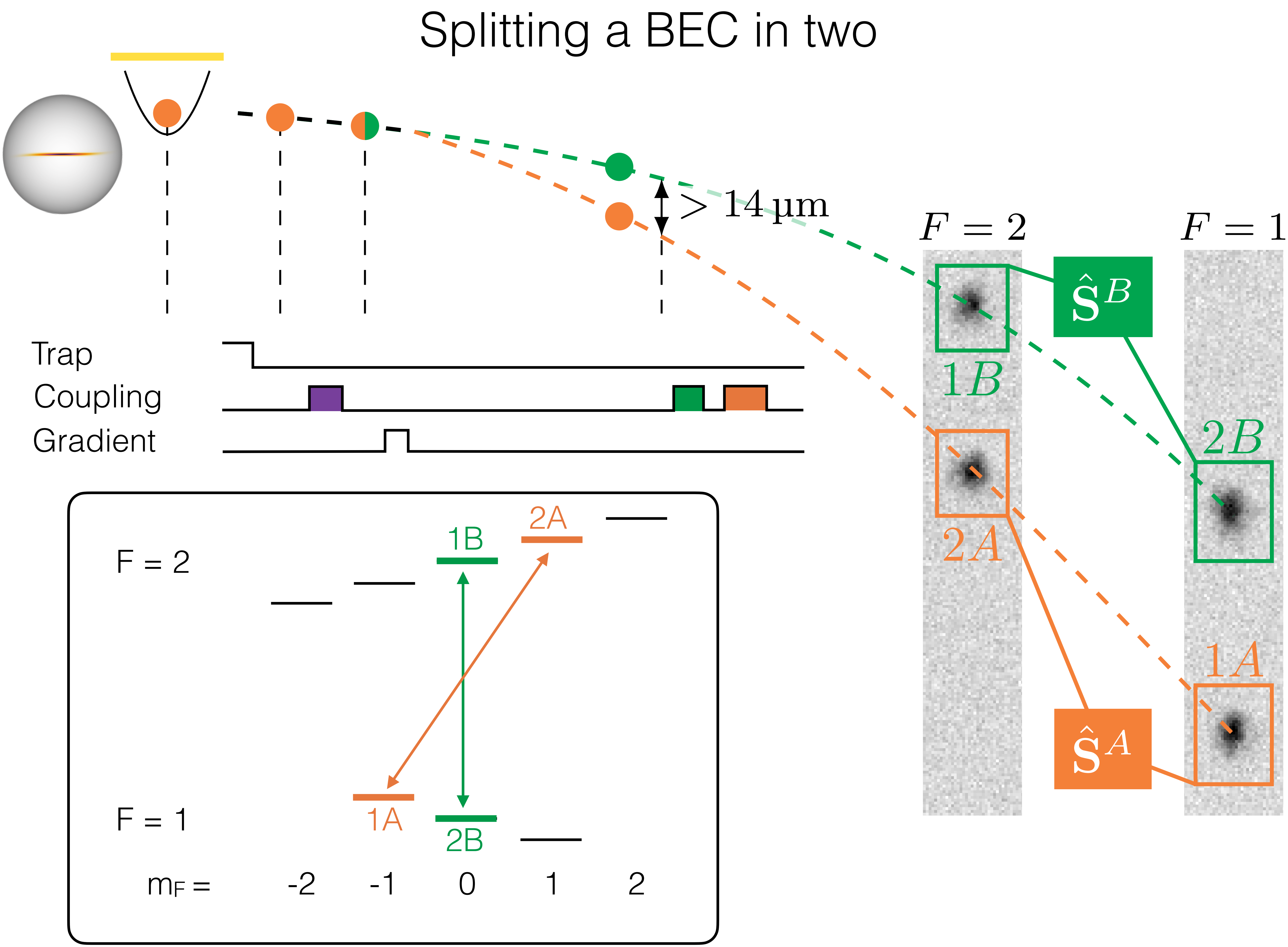
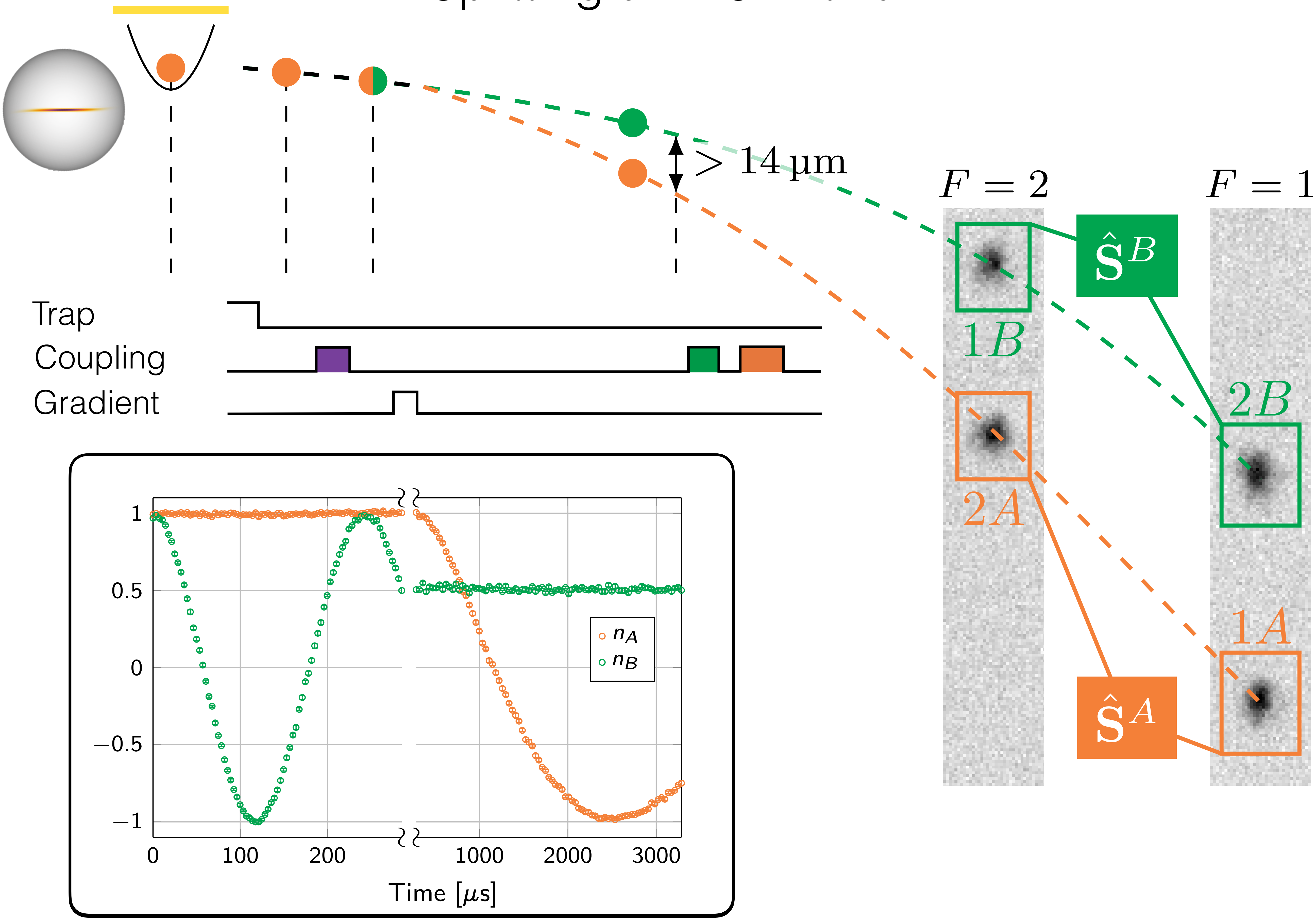


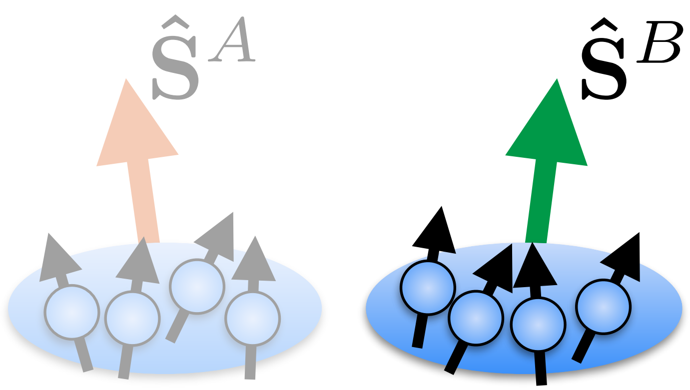


Splitting a BEC in two
> 14 µm
F = 2
F = 1
$\hat{\mathbf{S}}^B$
1B
2B
2A
1A
$\hat{\mathbf{S}}^A$
Trap
Coupling
Gradient
F = 2
F = 1
1B
2A
1A
2B
m_F =
-2
-1
0
1
2

Splitting a BEC in two



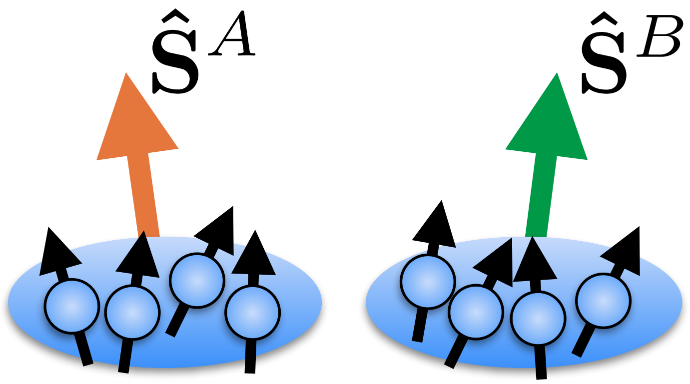
Einstein-Podolsky-Rosen entanglement



Heisenberg uncertainty relation for System **B**:

$$\mathrm{Var}(\hat{S}_z^B)\mathrm{Var}(\hat{S}_y^B) \geq \frac{1}{4}|\langle \hat{S}_x^B \rangle|^2$$

Einstein-Podolsky-Rosen entanglement



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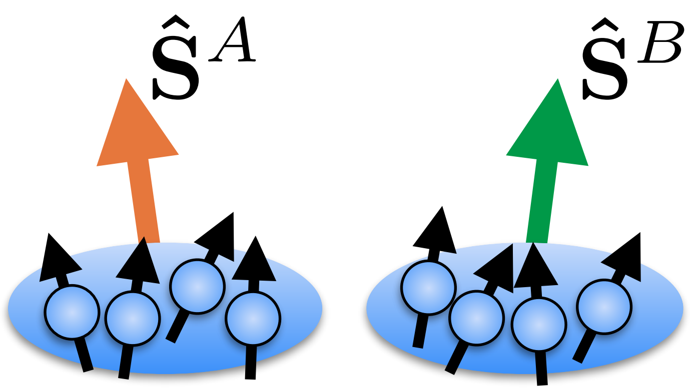
inferred variance

Einstein-Podolsky-Rosen entanglement



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inferred variance

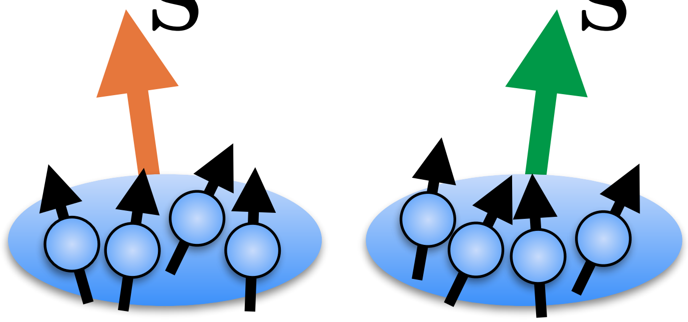
EPR paradox:

$$\mathrm{Var}_{\mathrm{inf}}(\hat{S}_z^B)\mathrm{Var}_{\mathrm{inf}}(\hat{S}_y^B) < \frac{1}{4}|\langle \hat{S}_x^B \rangle|^2$$

inferred uncertainty product can beat the Heisenberg limit

Einstein, Podolsky, and Rosen, Phys. Rev. 47, 777 (1935)
Schrödinger, Math. Proc. Cambridge Philos. Soc. 31, 555 (1935)

Einstein-Podolsky-Rosen entanglement



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EPR criterion:

$$\mathcal{E}_{\mathrm{EPR}} = \frac{4\mathrm{Var}(g_z \hat{S}_z^A + \hat{S}_z^B)\mathrm{Var}(g_y \hat{S}_y^A + \hat{S}_y^B)}{|\langle \hat{S}_x^B \rangle|^2} \geq 1$$

Einstein, Podolsky, and Rosen, Phys. Rev. 47, 777 (1935)
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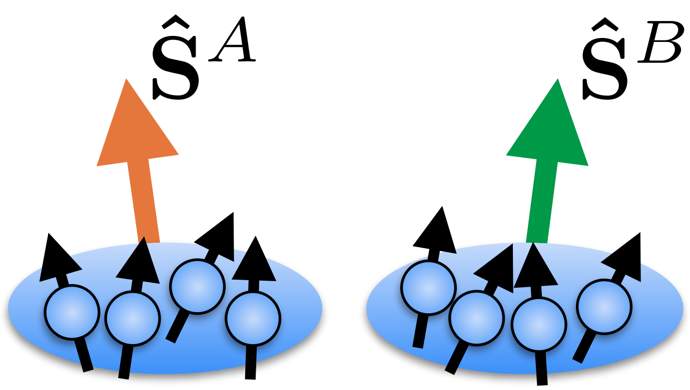
Einstein-Podolsky-Rosen entanglement



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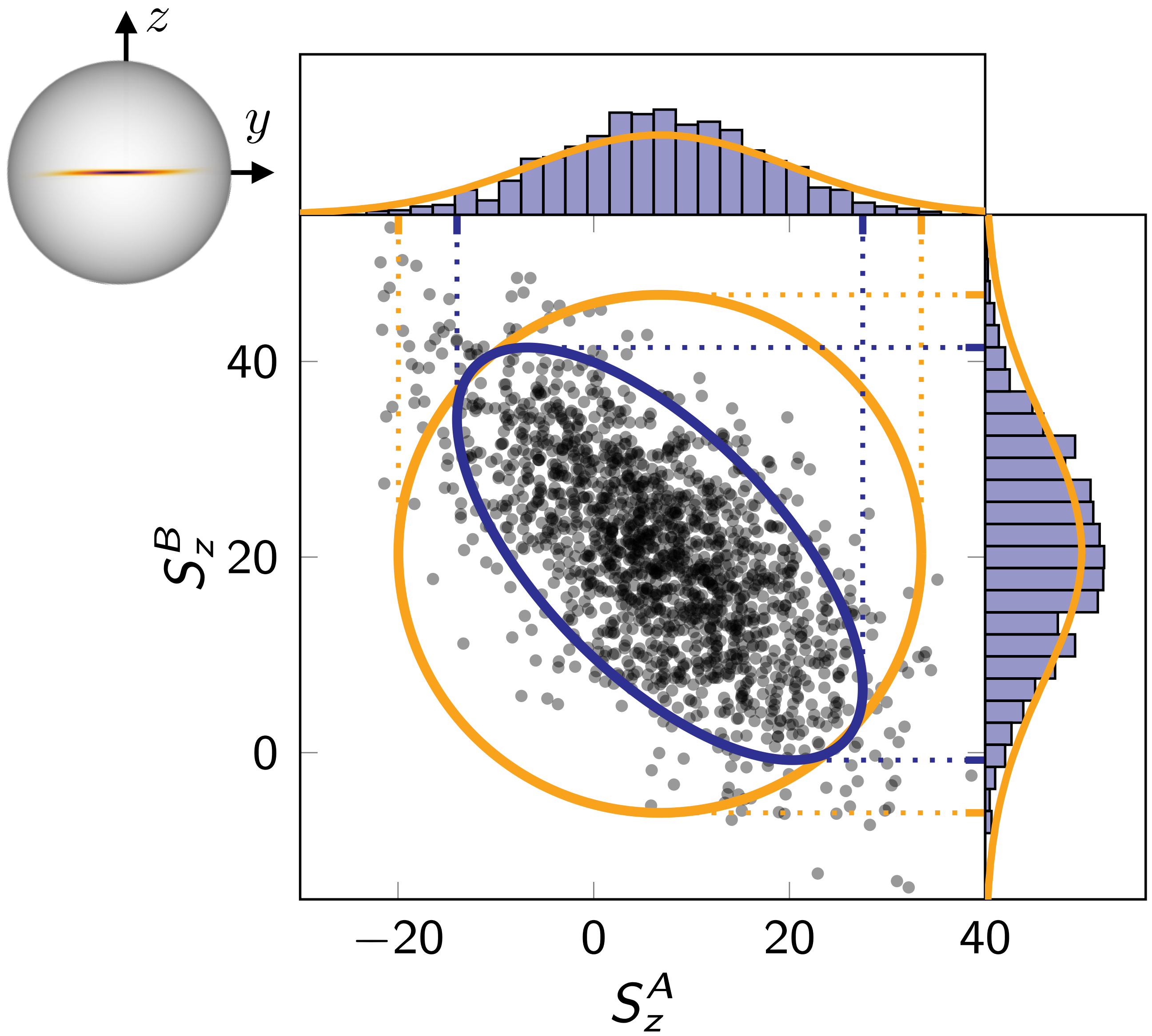
Entanglement criterion:

$$\mathcal{E}_{\mathrm{Ent}} = \frac{4\mathrm{Var}(g_z\hat{S}_z^A + \hat{S}_z^B)\mathrm{Var}(g_y\hat{S}_y^A + \hat{S}_y^B)}{\left(|g_z g_y||\langle \hat{S}_x^A \rangle| + |\langle \hat{S}_x^B \rangle|\right)^2} \geq 1$$

Einstein, Podolsky, and Rosen, Phys. Rev. 47, 777 (1935)
Schrödinger, Math. Proc. Cambridge Philos. Soc. 31, 555 (1935)

Giovannetti, et al. PRA 67, 022320 (2003)
Reid et al, Rev. Mod. Phys. 81, 1727 (2009)
Peise et al, Nat. Comm. 6, 8984 (2015)

Correlations reveal entanglement between the two BECs



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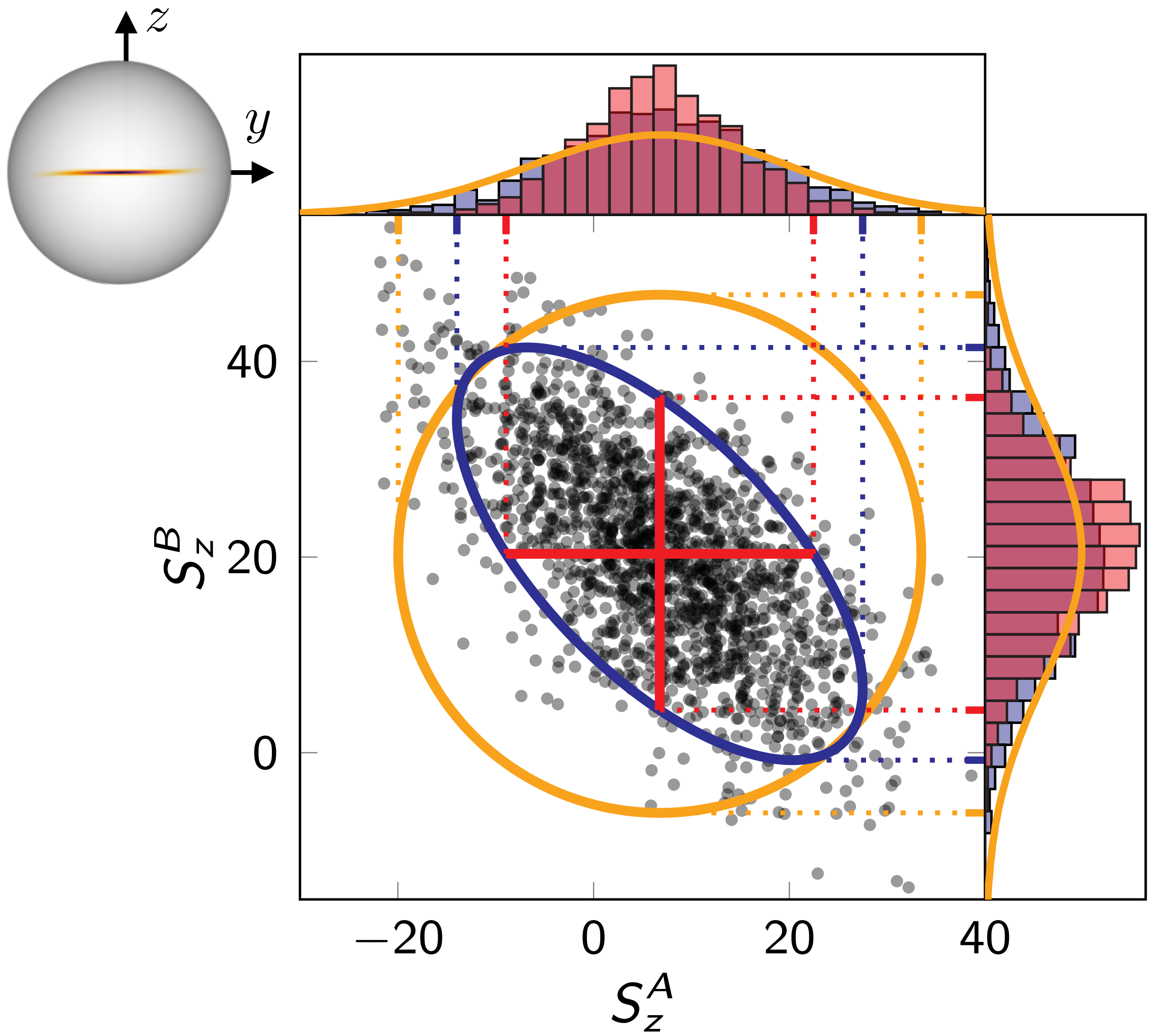
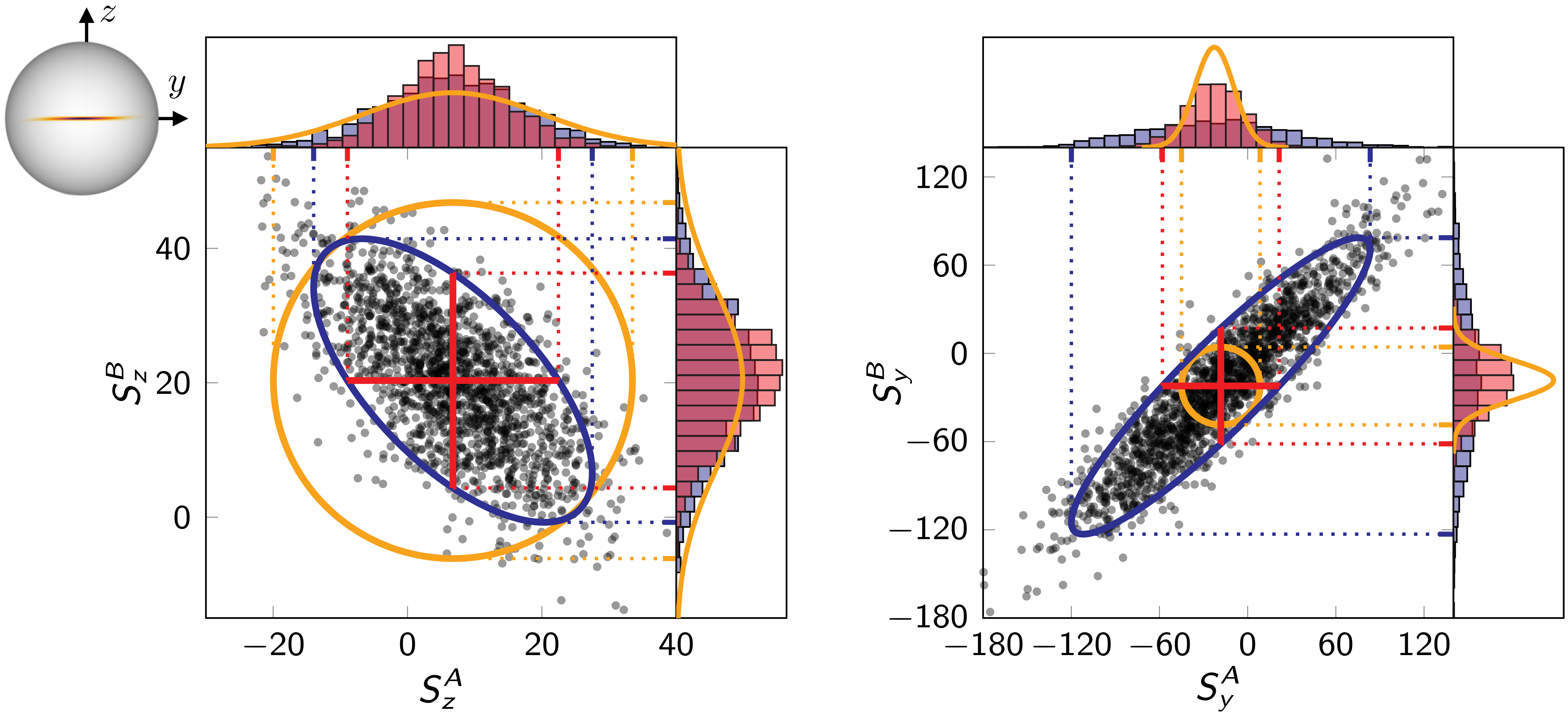


Correlations reveal entanglement between the two BECs



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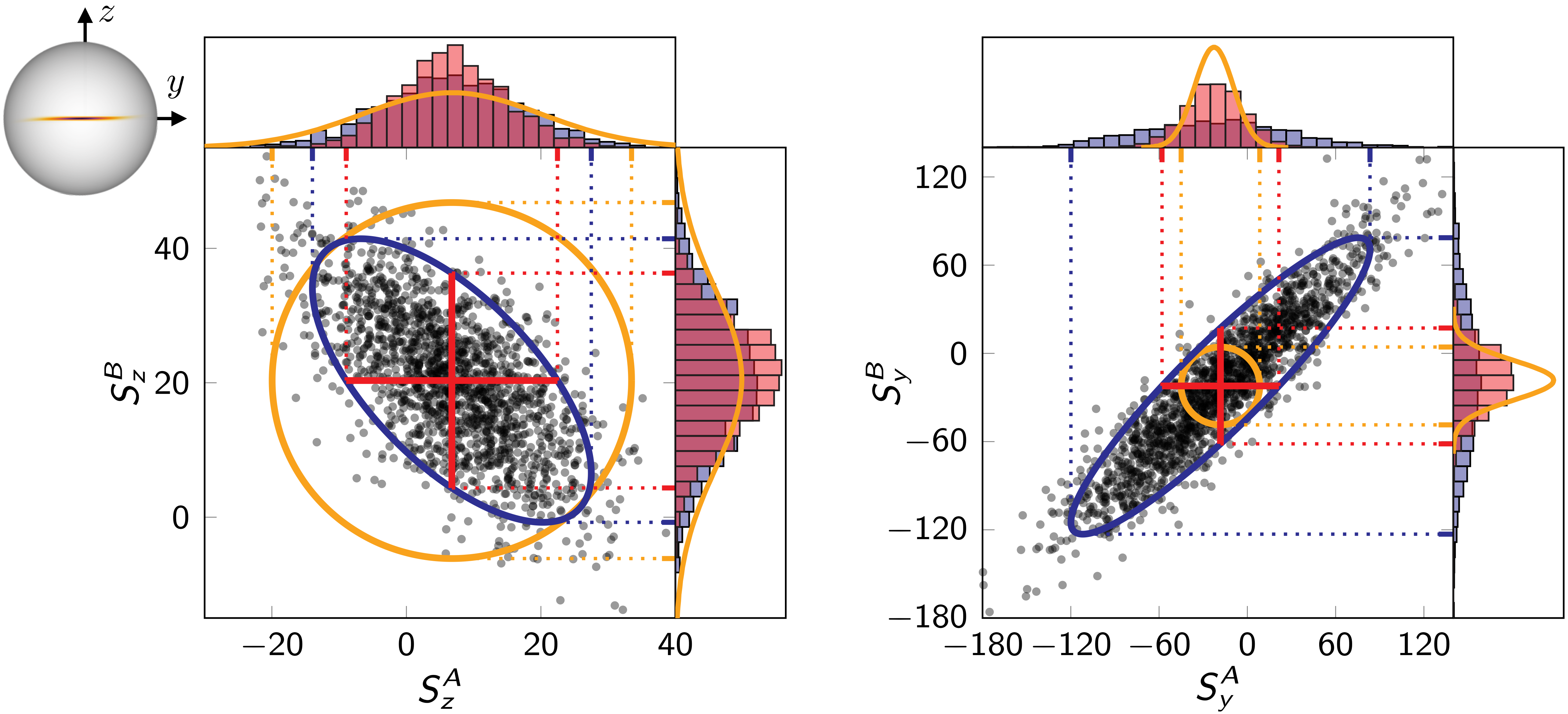
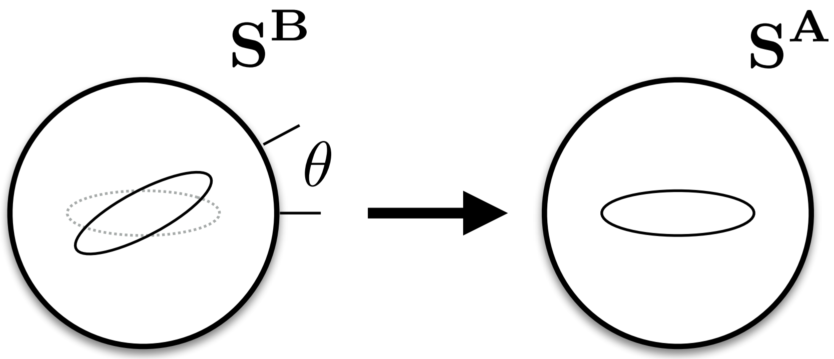


- initial spin squeezing $\xi^2 \approx -7$ dB
- split spins are still squeezed
- contrast in S_x^A and S_x^B about 96%

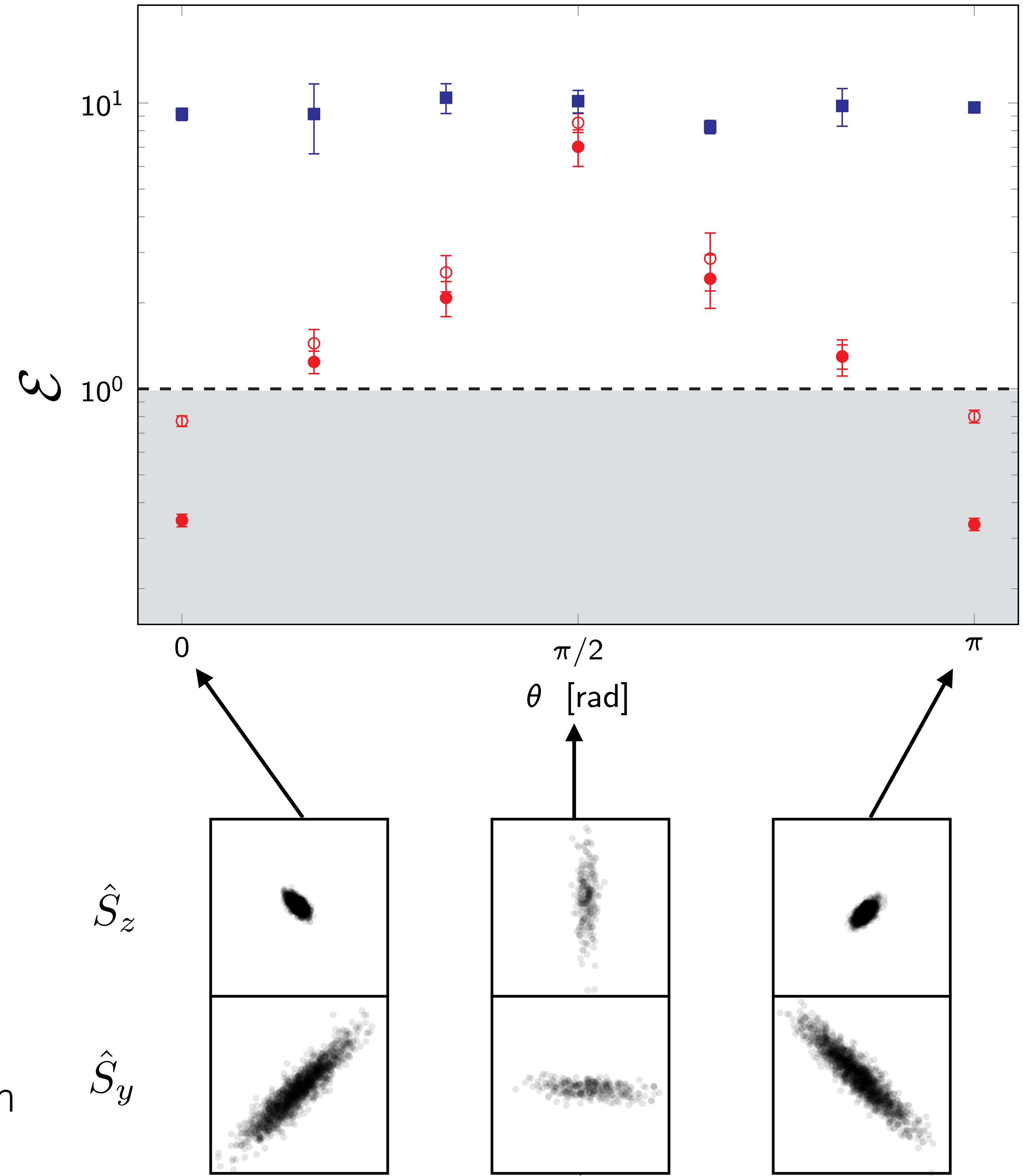
Entanglement and EPR steering detected:

	$A \to B$	$B \to A$
$\mathcal{E}_{\mathrm{Ent}}$	0.35 ± 0.01	
$\mathcal{E}_{\mathrm{EPR}}$	0.81 ± 0.03	0.77 ± 0.03
$H.l.$	10.2 ± 0.4	9.2 ± 0.5

Individual manipulation of the two BECs



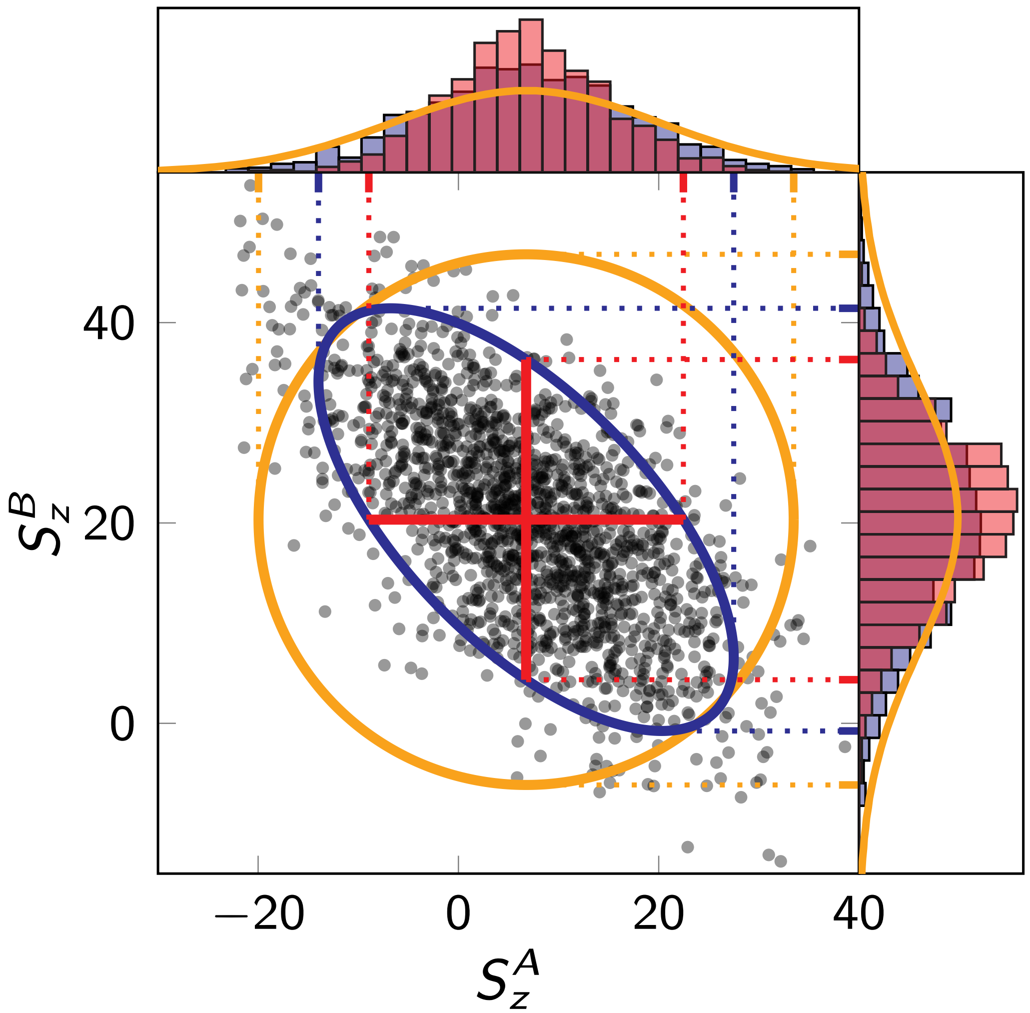
$\hat{S}_z$	θ	0
$\hat{S}_y$	$\pi/2+\theta$	$\pi/2$

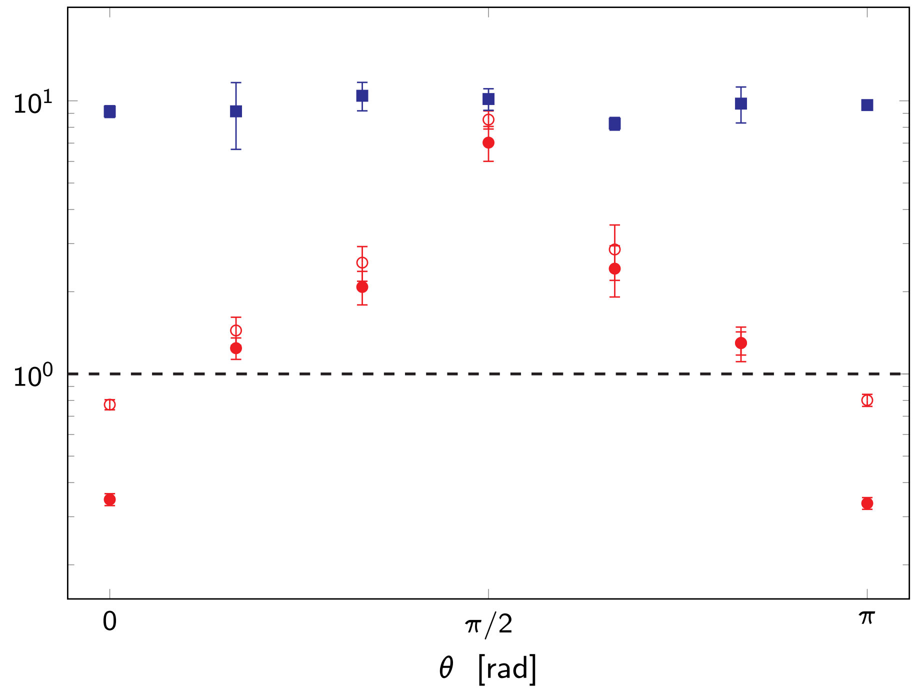


- correlations vanish for $\theta = \pi/2$
- for $\theta = \pi$ correlations become anticorrelations and vice versa (gains g_z, g_y change sign)
- manipulation of spin B does not destroy the entanglement
- individual control important for: quantum key distribution, teleportation etc.

Summary

- EPR Paradox between two Bose-Einstein condensates containing each about 700 atoms
- microwave control to realize a BEC beam splitter



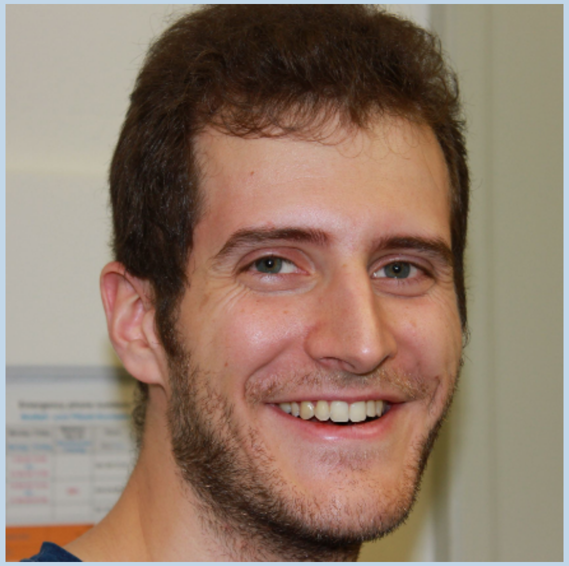


- individual control of two macroscopic spins
- future applications in quantum metrology

PRX 13, 021031 (2023)

M.D. Reid, Physics 16, 92 (2023)

Quantum Atom Optics group in Basel



Paolo Colciaghi

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