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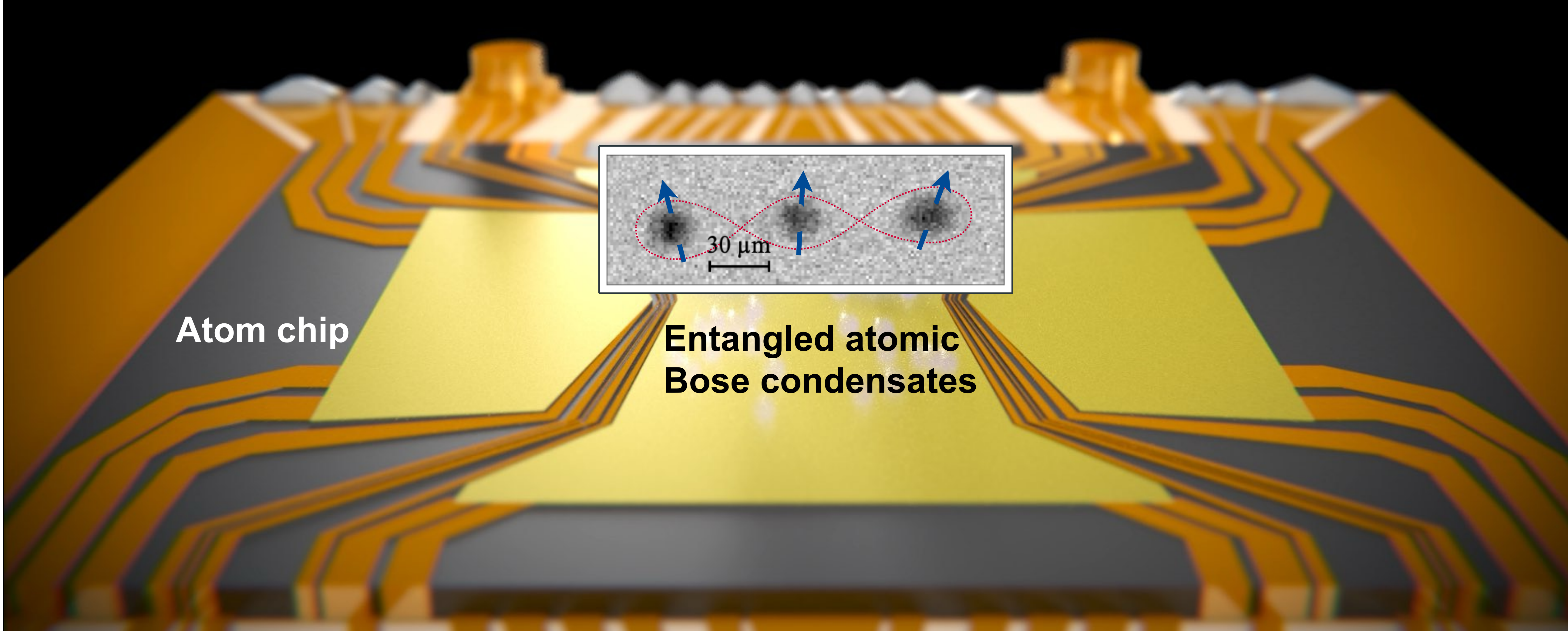
Multiparameter quantum metrology with EPR entangled BECs

Philipp Treutlein

atom.physik.unibas.ch

Colciaghi et al, PRX 13, 021031 (2023)



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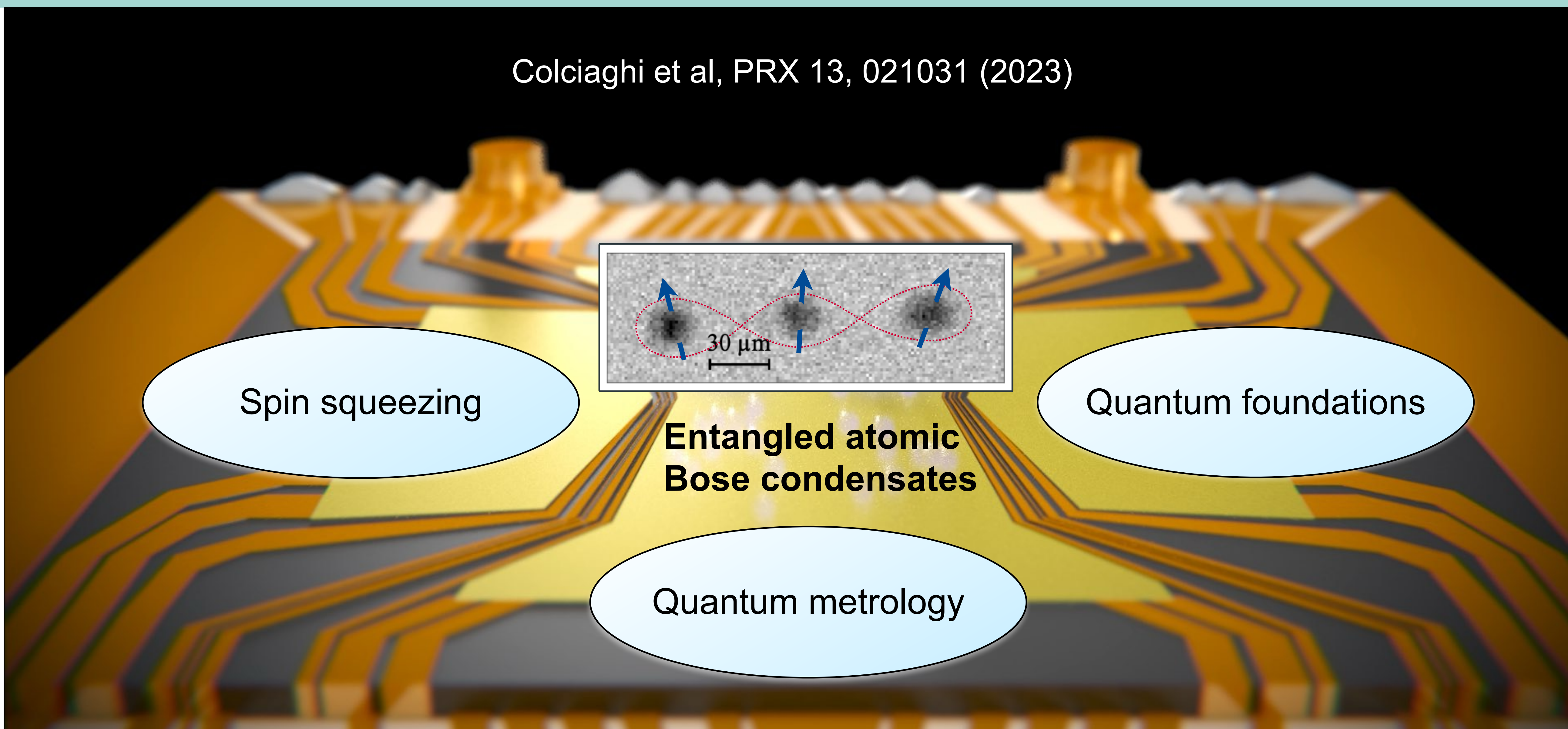
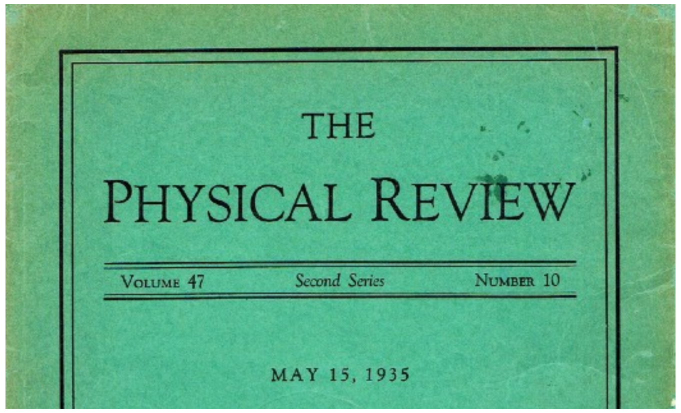
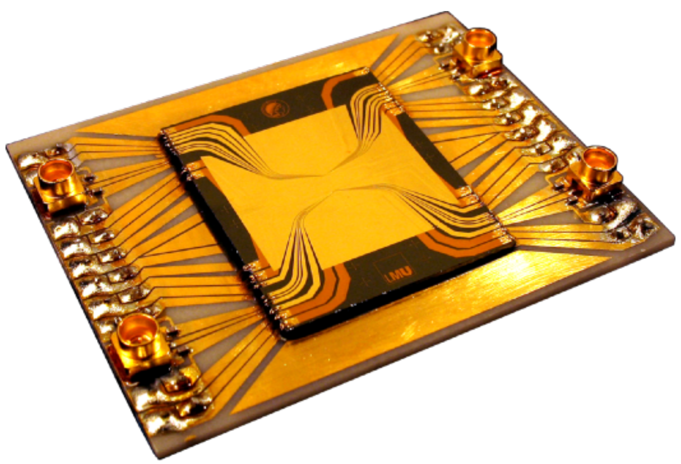


Outline



The Einstein-Podolsky-Rosen paradox

Einstein, Podolsky, Rosen, Phys Rev 47, 777 (1935)



Two-component Rb BEC on atom chip

Spin-squeezing, quantum metrology

Riedel et al, Nature 464, 1170 (2010)
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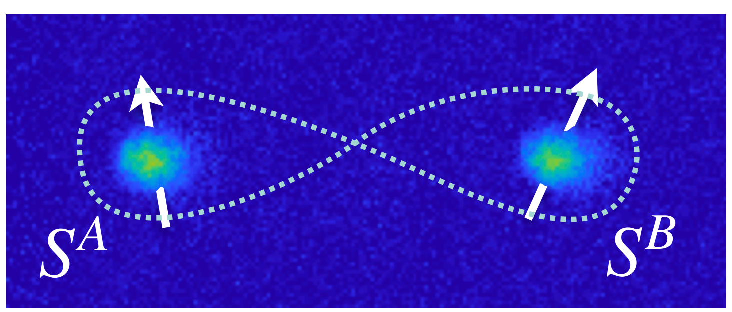
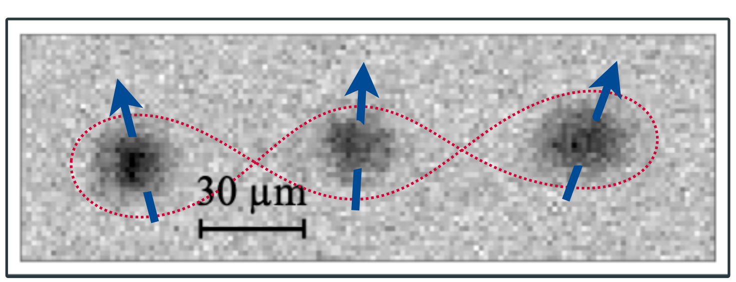
Schmied et al, Science 352, 441 (2016)
Fadel et al, Science 360, 409 (2018)



EPR paradox between two spatially separated and addressable BECs

Colciaghi et al, PRX 13, 021031 (2023)



Multiparameter estimation with an array of entangled atomic sensors

collaboration: Y. Baamara, A. Sinatra

The Einstein-Podolsky-Rosen paradox

Heisenberg uncertainty relation for system B:

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

Entanglement: measurement outcomes in A allow to predict ("infer") measurement outcomes in B

$$\hat{S}_{y,\mathrm{inf}}^B = g_y \hat{S}_y^A + c_y$$ linear estimate

$$\mathrm{Var}_{\mathrm{inf}}\left(\hat{S}_y^B\right) = \mathrm{Var}\left(\hat{S}_y^B - \hat{S}_{y,\mathrm{inf}}^B\right)$$ "inferred variance"

EPR paradox

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

Inferred uncertainty product below the Heisenberg relation

Einstein, Podolsky, and Rosen, Phys. Rev. 47, 777 (1935)
Schrödinger, Math. Proc. Cambridge Philos. Soc. 31, 555 (1935)
M. D. Reid et al, Rev. Mod. Phys. 81, 1727 (2009)

EPR steering and entanglement

EPR criterion

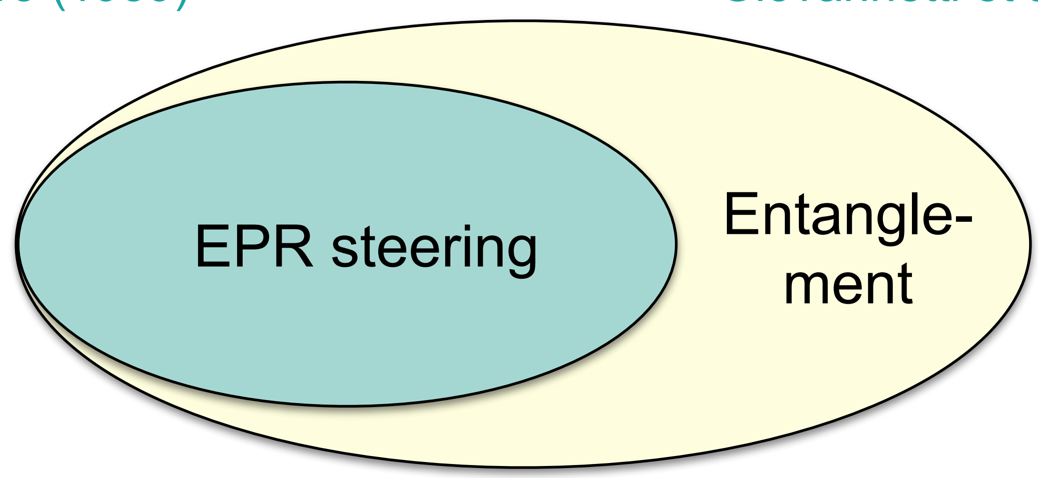
$$E_{EPR}^{A\to B} = \frac{4\,\mathrm{Var}\left(\hat{S}_y^B - g_y\hat{S}_y^A\right)\mathrm{Var}\left(\hat{S}_z^B - g_z\hat{S}_z^A\right)}{|\langle \hat{S}_x^B\rangle|^2} < 1$$

M. D. Reid, PRA 40, 913 (1989)

Entanglement criterion

$$E_{Ent} = \frac{4\,\mathrm{Var}\left(\hat{S}_y^B - g_y\hat{S}_y^A\right)\mathrm{Var}\left(\hat{S}_z^B - g_z\hat{S}_z^A\right)}{\left(|\langle \hat{S}_x^B\rangle| + |g_y g_z||\langle \hat{S}_x^A\rangle|\right)^2} < 1$$

Giovannetti et al, PRA 67, 022320 (2003)



Wiseman et al, PRL 98, 140402 (2007)

Experiments in optics: Ou et al, PRL 68, 3663 (1992), Silberhorn et al, PRL 86, 4267 (2001), Schori et al, PRA 66, 033802 (2002), Bowen et al, PRL 90, 043601 (2003), …

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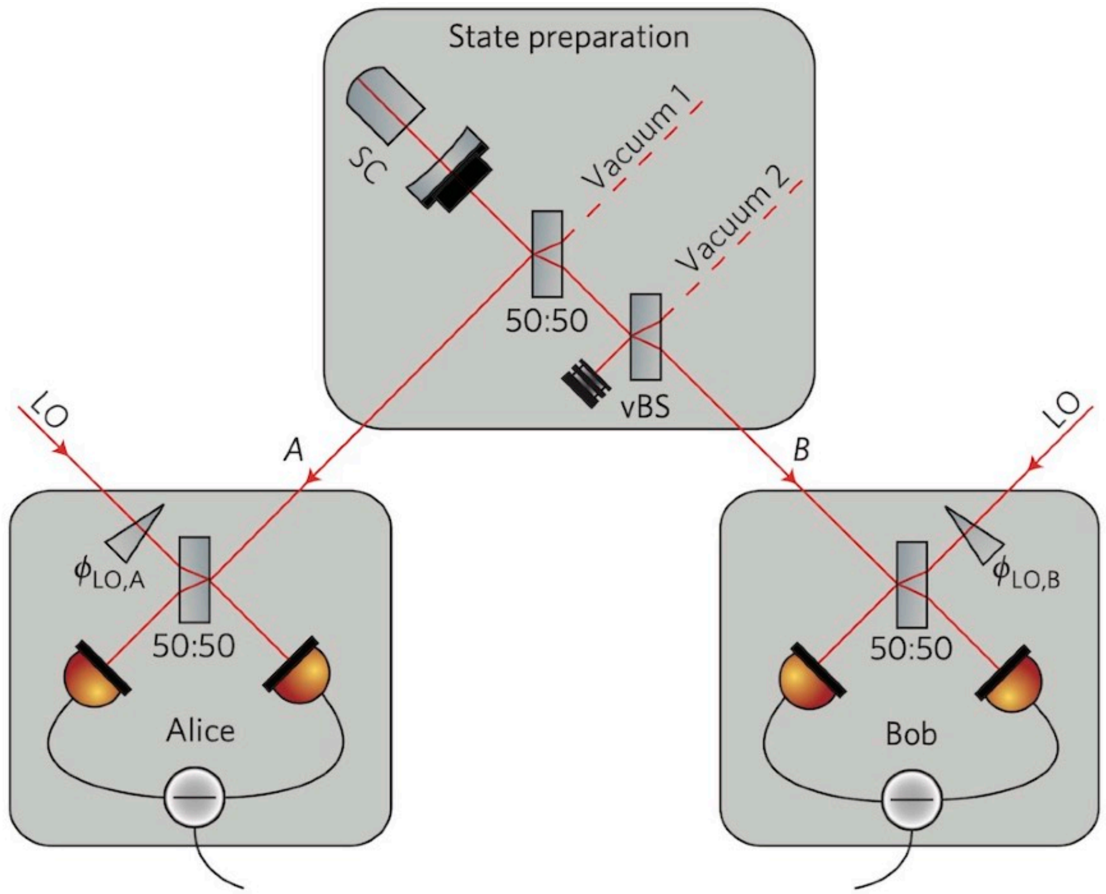
EPR experiments

Demonstrations of the EPR paradox



Optics
Ou et al, PRL 68, 3663 (1992)
Bowen et al, PRL 90, 043601 (2003)
Händchen et al, Nat Photon 6, 598 (2012)
Reid et al, Rev Mod Phys 81, 1727 (2009)

Bell tests

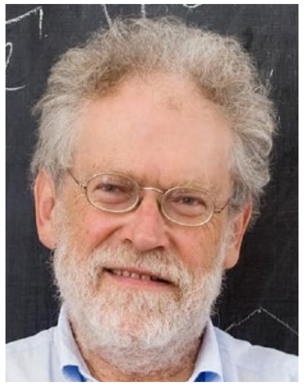
Bell, Physics 1, 195 (1964)

2 photons, 4 photons
2 ions, up to 14 ions
2 neutral atoms
2 superconducting qubits
2 solid-state spin qubits

Freedman, Clauser, PRL 28, 938 (1972)
Aspect et al, PRL 49, 1804 (1982)
Weihs et al, PRL 81, 5039 (1998)
…
Hensen et al, Nature 526, 682 (2015)
Giustina et al, PRL 115, 250401 (2015)
Shalm et al, PRL 115, 250402 (2015)
Rosenfeld et al, PRL 119, 195 (2017)

A. Aspect

J. F. Clauser



A. Zeilinger

The EPR paradox and nonlocality are firmly established in few-particle systems!

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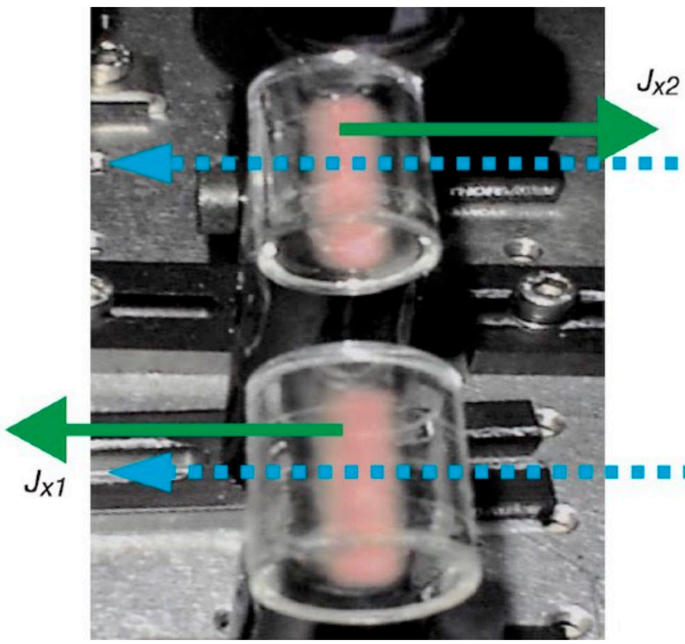
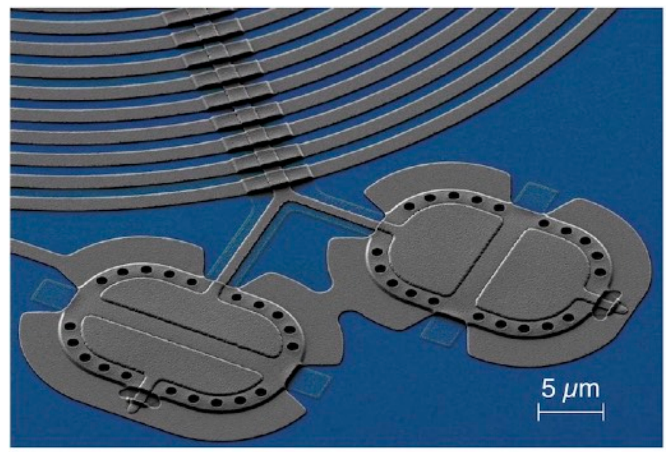
Entanglement and EPR in massive many-body systems

Entanglement between spatially separated systems





Atomic ensembles

Julsgaard et al, Nature 413, 400 (2001)
Chou et al, Nature 438, 828 (2005)
Lange et al, Science 360, 416 (2018)

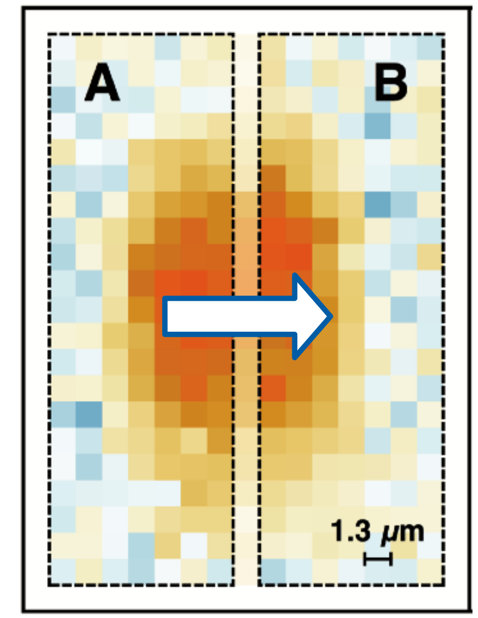
Mechanical oscillators

Kotler et al, Science 372, 622 (2021)
de Lépinay, Science 372, 625 (2021)

Hybrid systems

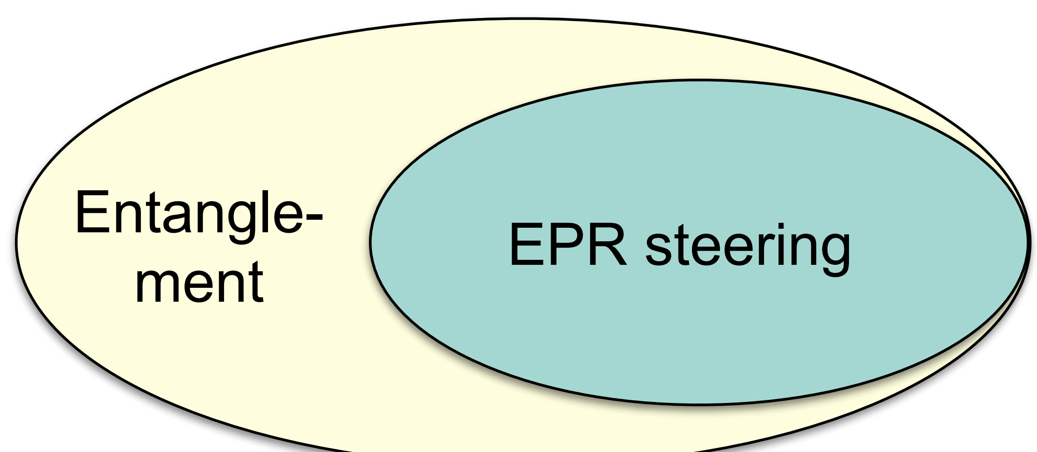
Lettner et al, PRL 106, 210503 (2011)
Thomas et al, Nat Phys 17, 228 (2021)

EPR steering in a single system



Atomic ensembles

Peise et al, Nat. Comm. 6, 8984 (2015)
Fadel et al, Science 360, 409 (2018)
Kunkel et al, Science 360, 413 (2018)



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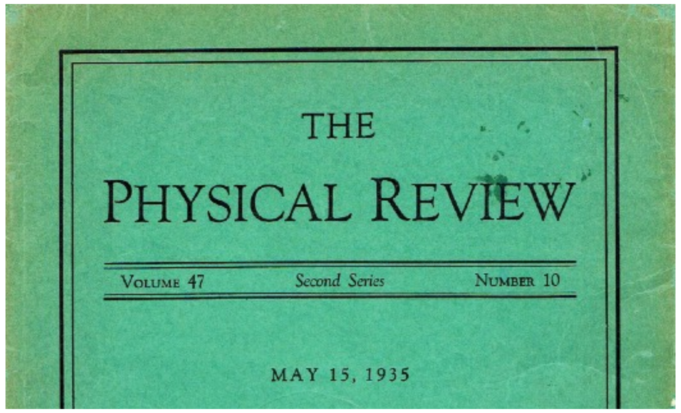

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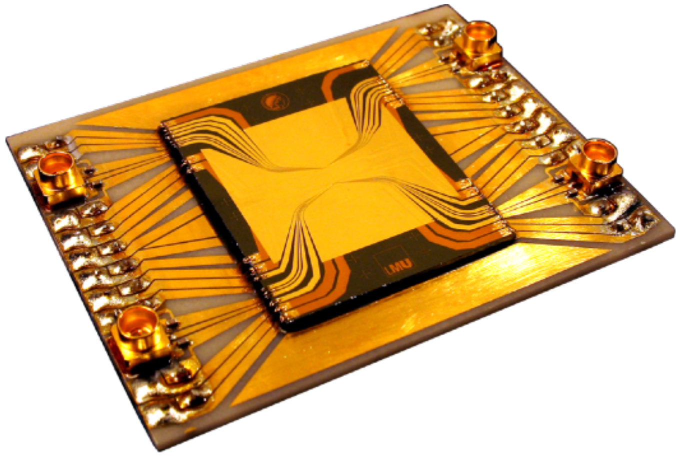

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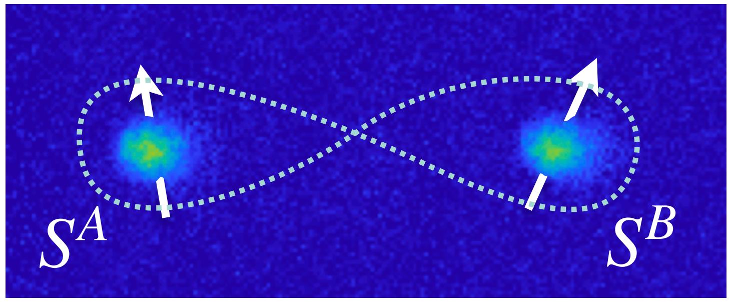

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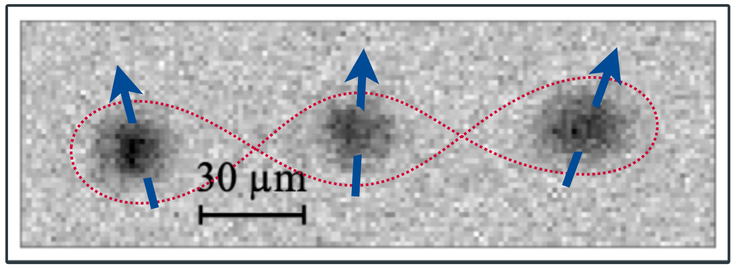

Multiparameter estimation with an array of entangled atomic sensors

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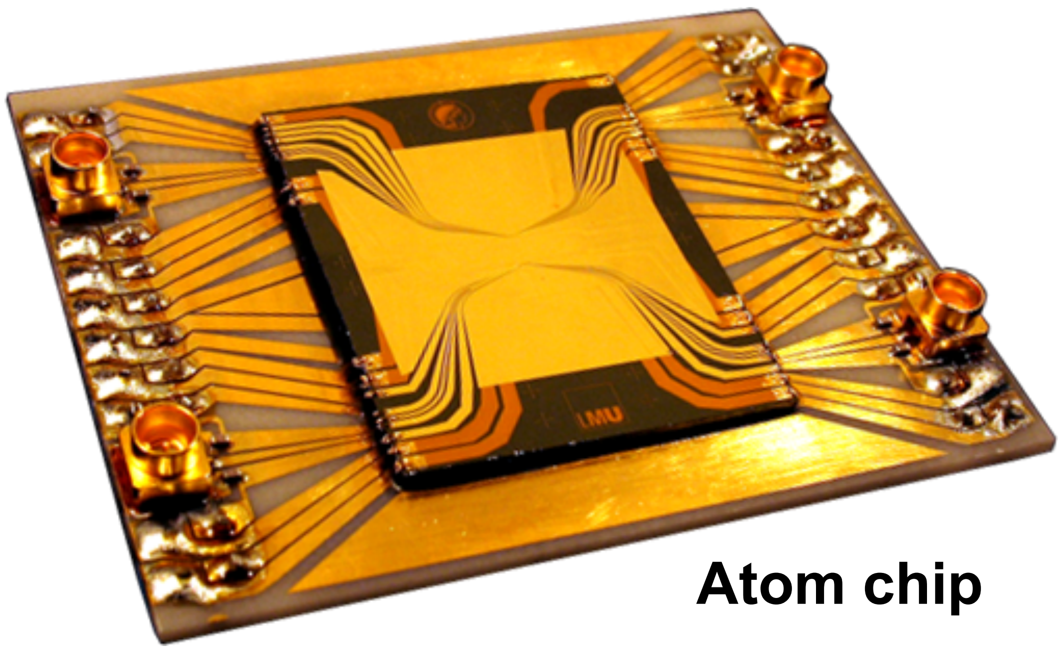
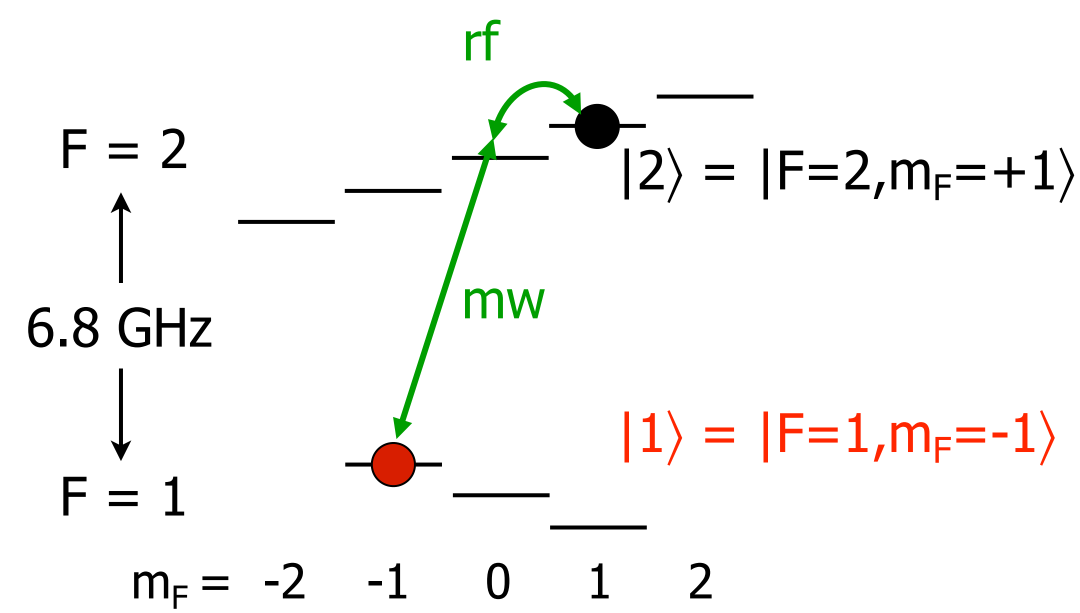
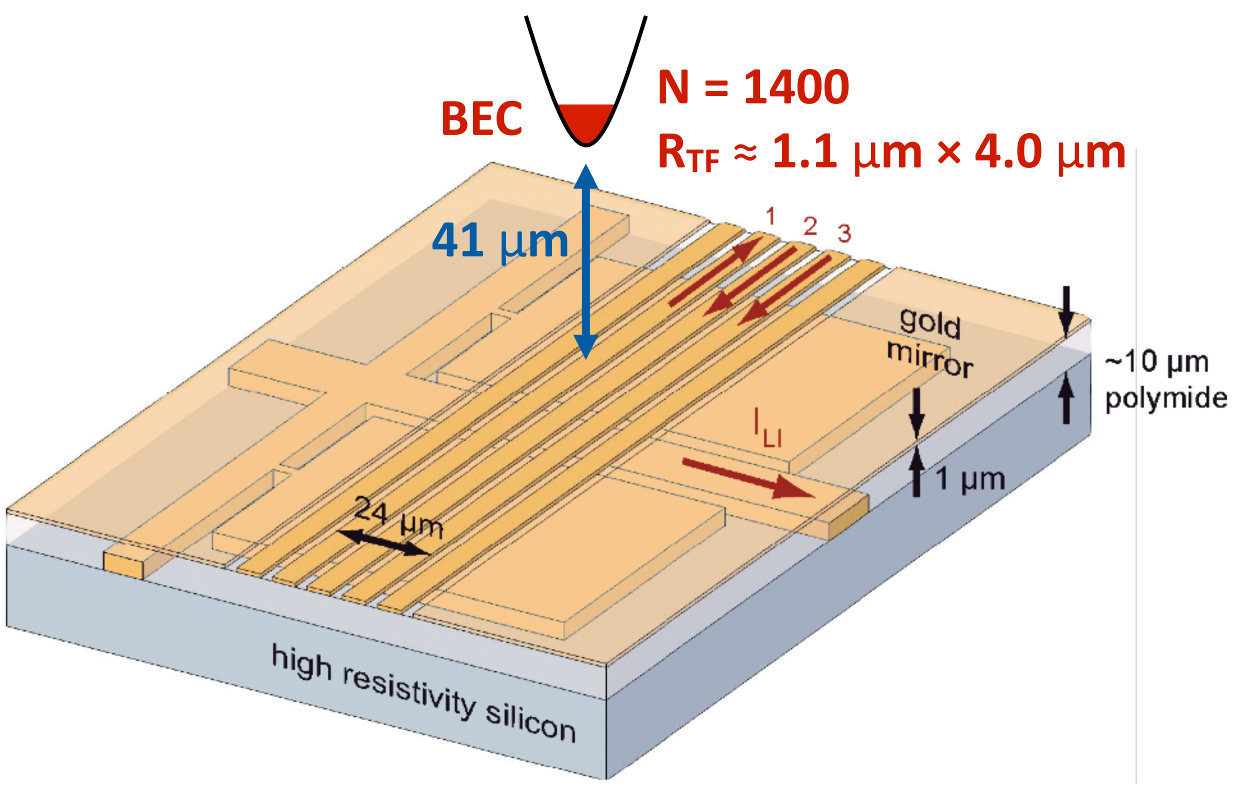
Two-component ^{87}Rb BEC on an atom chip



Atom chip

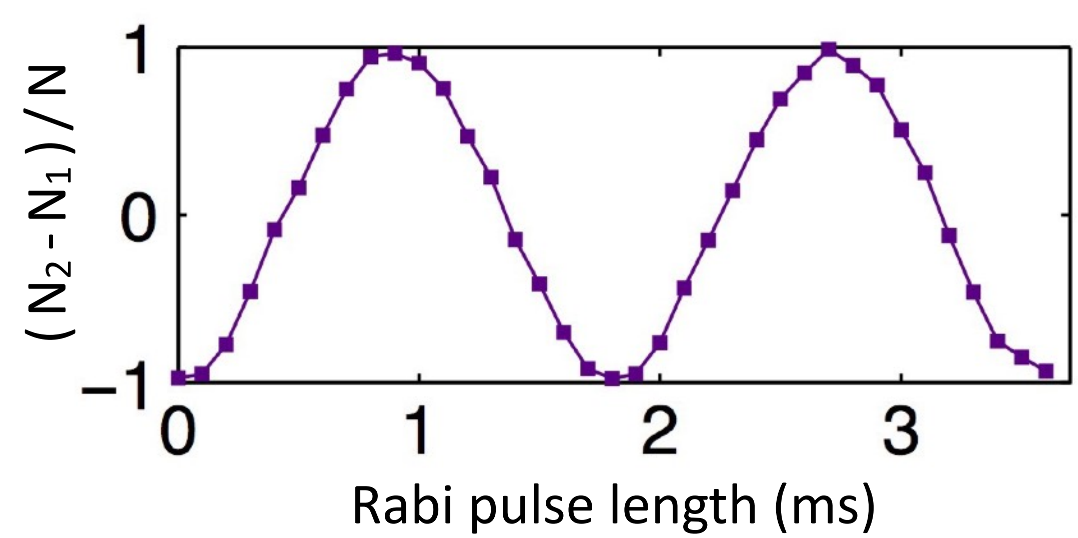
^{87}Rb ground-state hyperfine structure





Rabi oscillations

fidelity of π/2-pulse: (99.74±0.04)%



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

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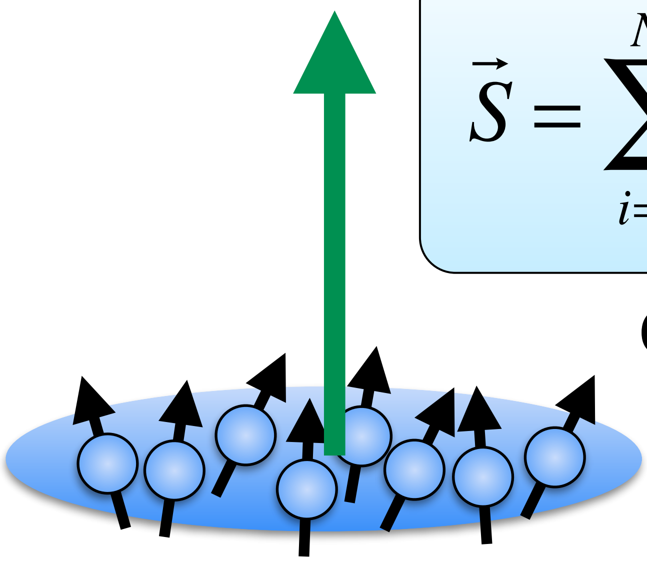
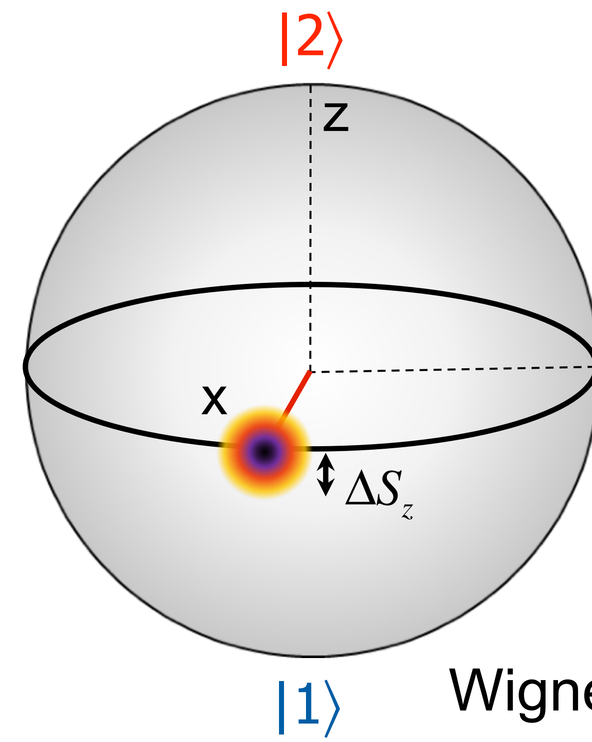
Collective spin description of BEC internal state



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

Collective spin

Ensemble of spins

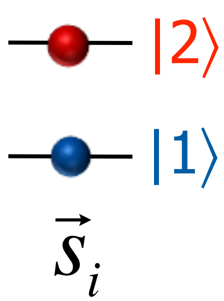


$$\Delta S_z = \frac{\sqrt{N}}{2}$$

Wigner function

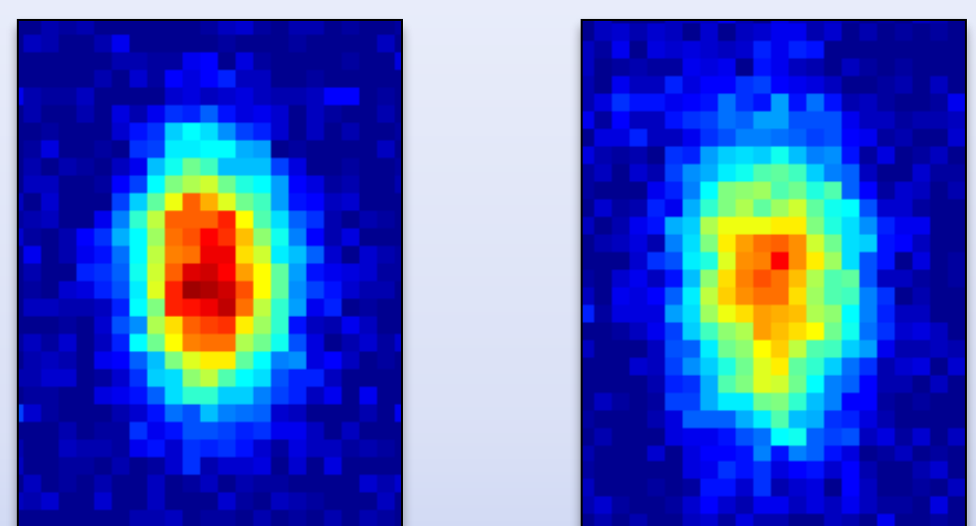
$$S_z = \tfrac{1}{2}(N_2 - N_1)$$

$N \times$



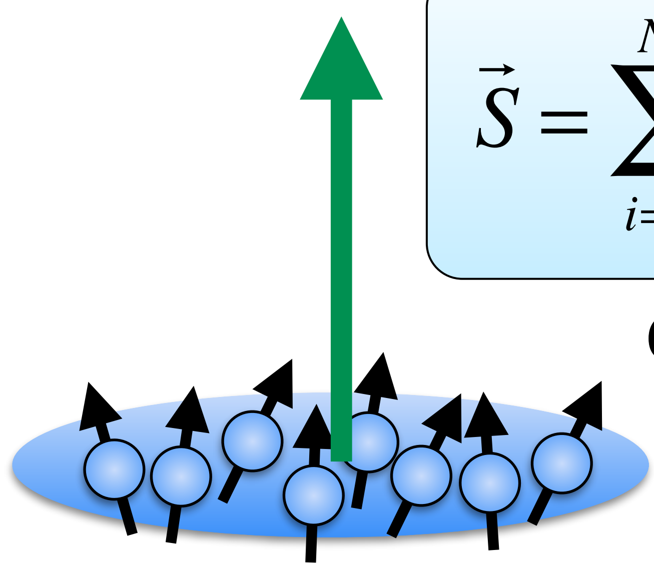
Absorption images of both states in single shot of experiment

F=2	F=1



578 ± 5 atoms | 663 ± 6 atoms

Spin-squeezing through collisions



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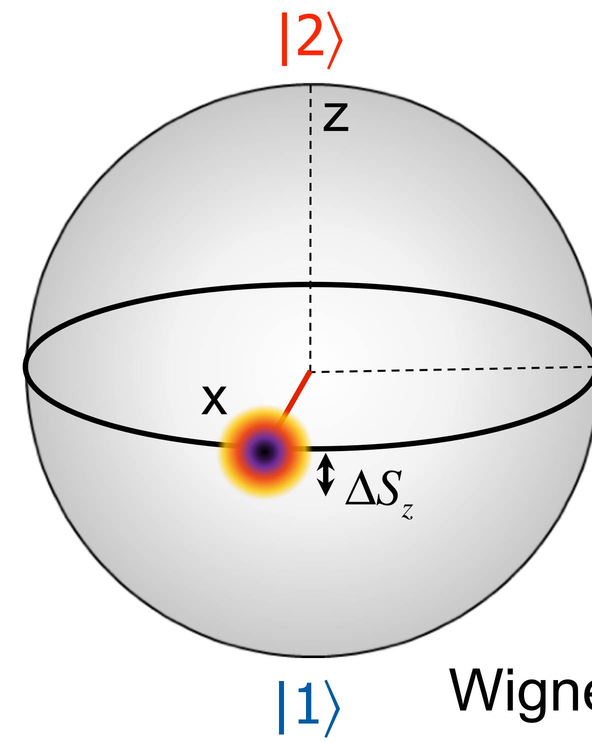
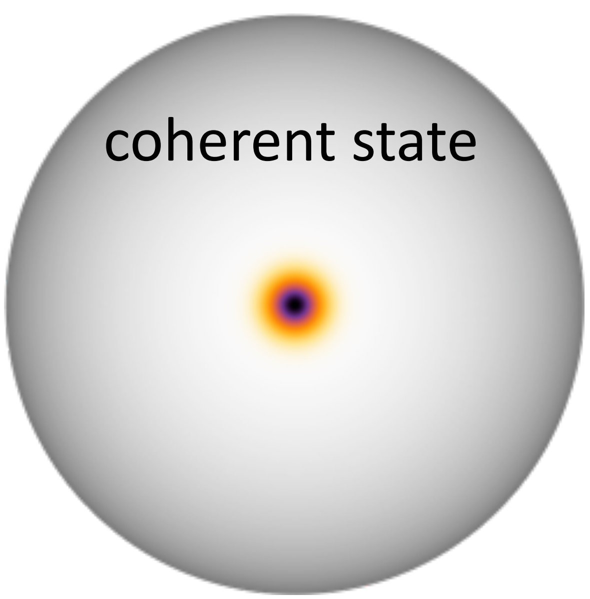


$$\Delta S_z = \frac{\sqrt{N}}{2}$$

Wigner function

Atomic collisions create entanglement



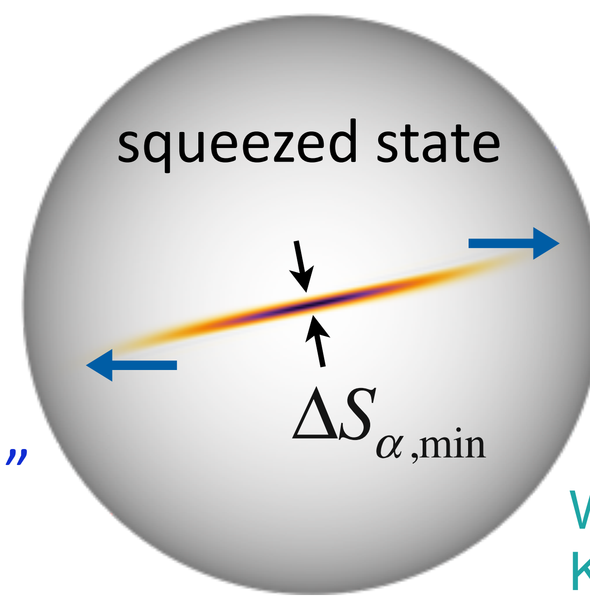
$$\xi^2 = 1$$

$$H = \chi S_z^2$$

time evolution

"one-axis twisting"

Riedel et al, Nature 464, 1170 (2010)



$$\xi^2 < 1$$

Spin-squeezing parameter

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

entanglement witness

Wineland, Bollinger, Itano (1992)
Kitagawa, Ueda (1993)
Sørensen, Duan, Cirac, Zoller (2001)

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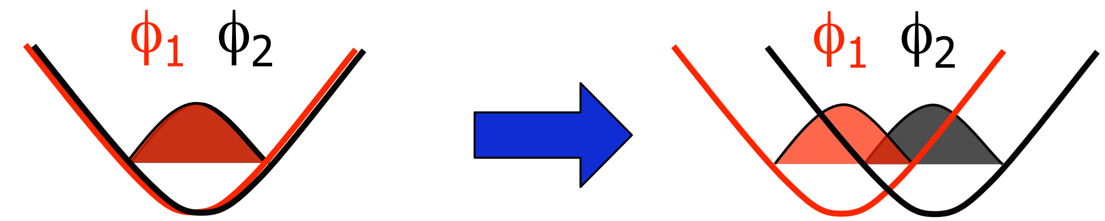
Controlled collisions in state-dependent potentials

How can we implement the squeezing Hamiltonian?

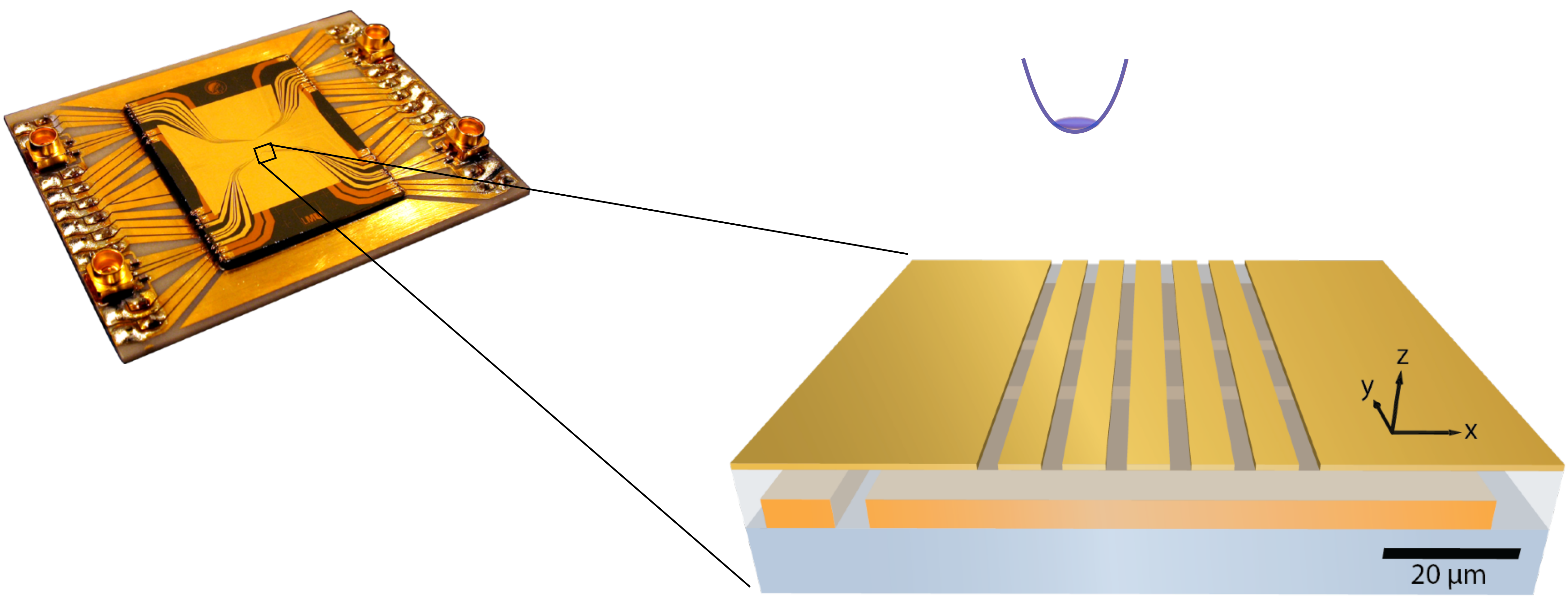
$$H = \chi S_z^2$$



$\chi = 2 \times 10^{-3}\ s^{-1}$ $\qquad$ $\chi = 3\ s^{-1}$

→ collisions between atoms in a state-dependent potential

$$\chi \sim a_{11} \int |\phi_1|^4 \, dr^3 + a_{22} \int |\phi_2|^4 \, dr^3 - 2a_{12} \int |\phi_1|^2 |\phi_2|^2 \, dr^3$$



Li, Treutlein, Reichel, Sinatra, Eur Phys J B 68, 365 (2009)
Treutlein, Hänsch, Reichel, Negretti, Cirone, Calarco, PRA 74, 022312 (2006)

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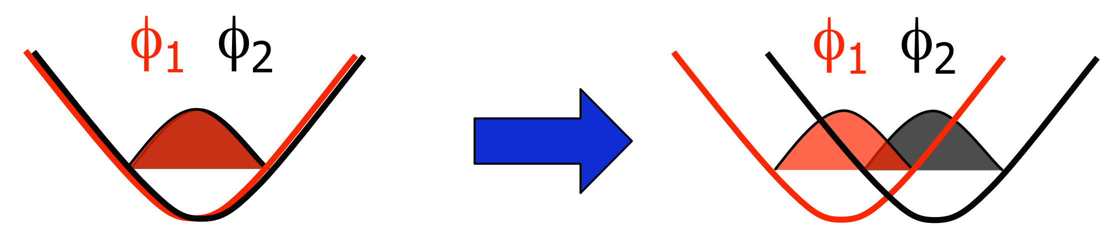
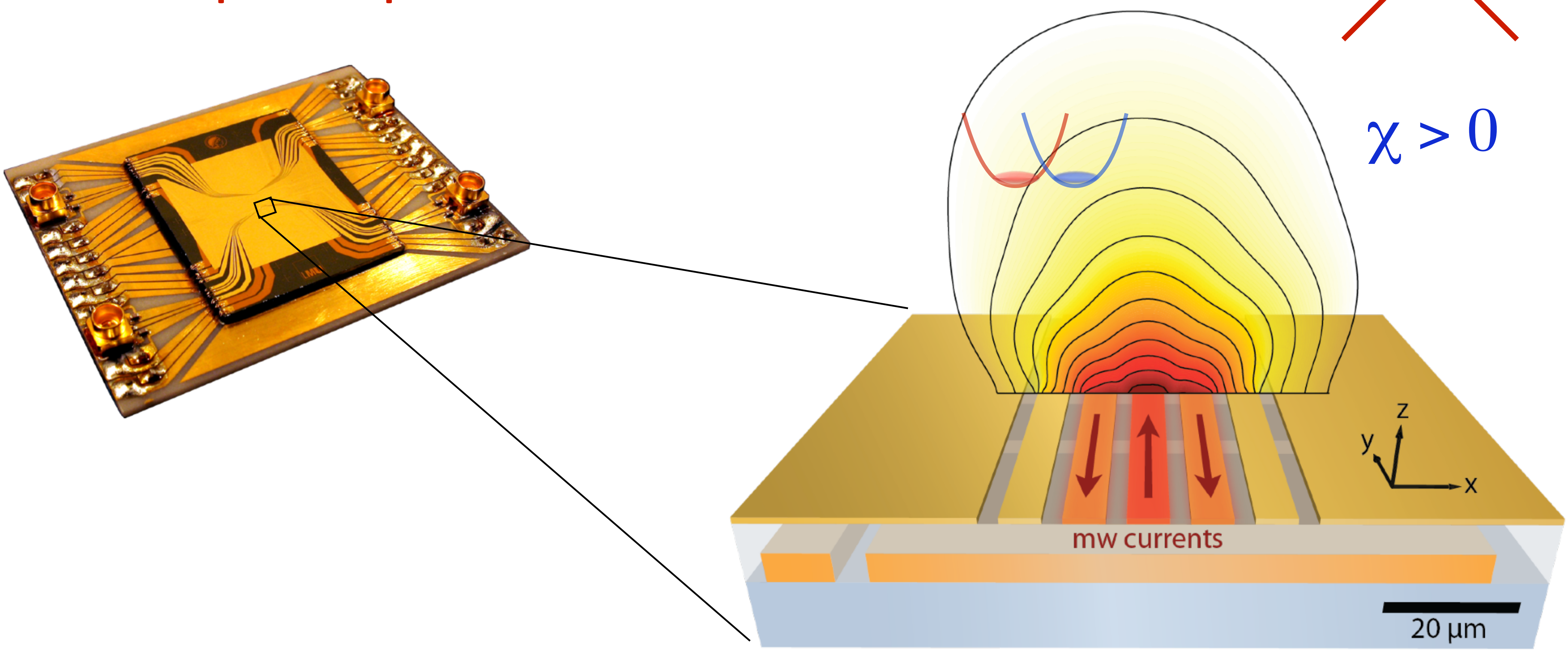


$\chi = 2 \times 10^{-3}\ \mathrm{s}^{-1}$ $\chi = 3\ \mathrm{s}^{-1}$

$$\chi \sim a_{11}\int|\phi_1|^4\,dr^3 + a_{22}\int|\phi_2|^4\,dr^3 - 2a_{12}\int\cancel{|\phi_1|^2|\phi_2|^2\,dr^3}$$



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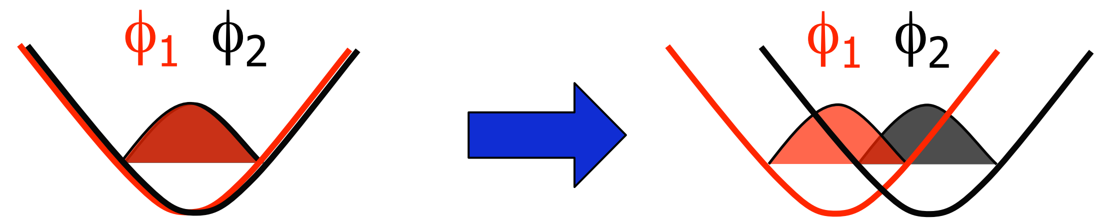

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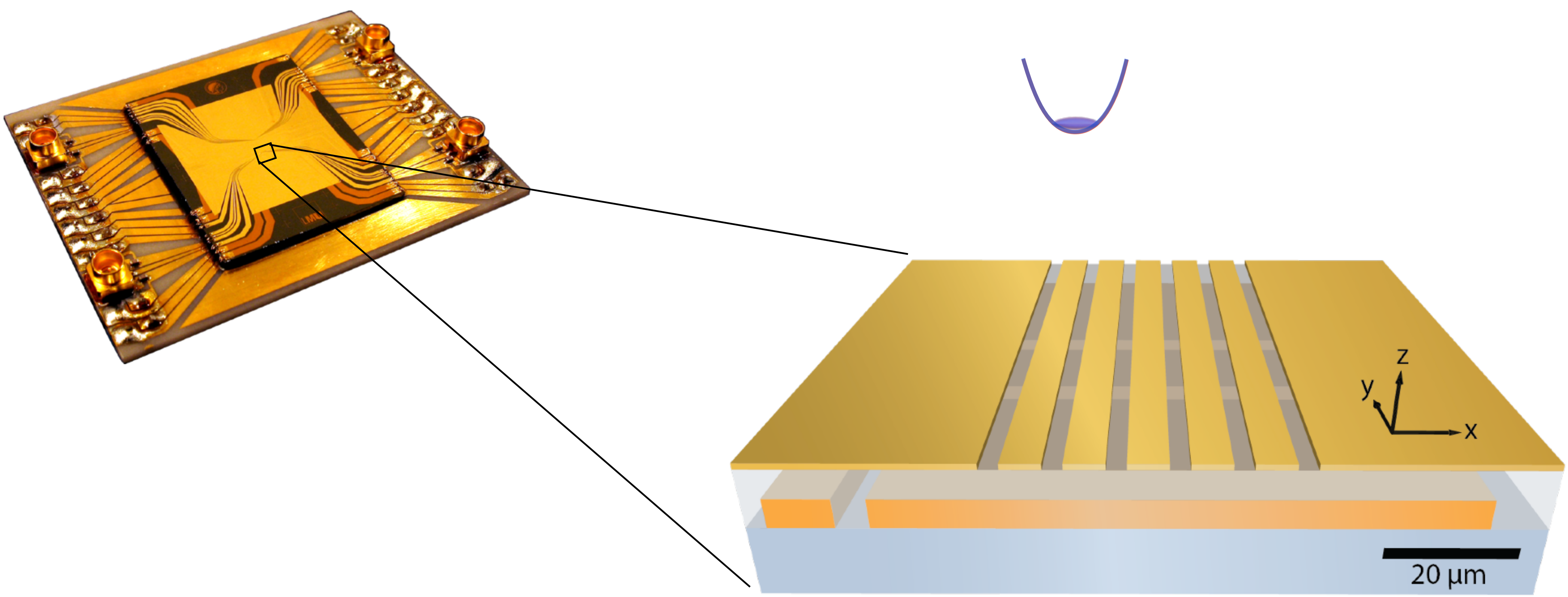

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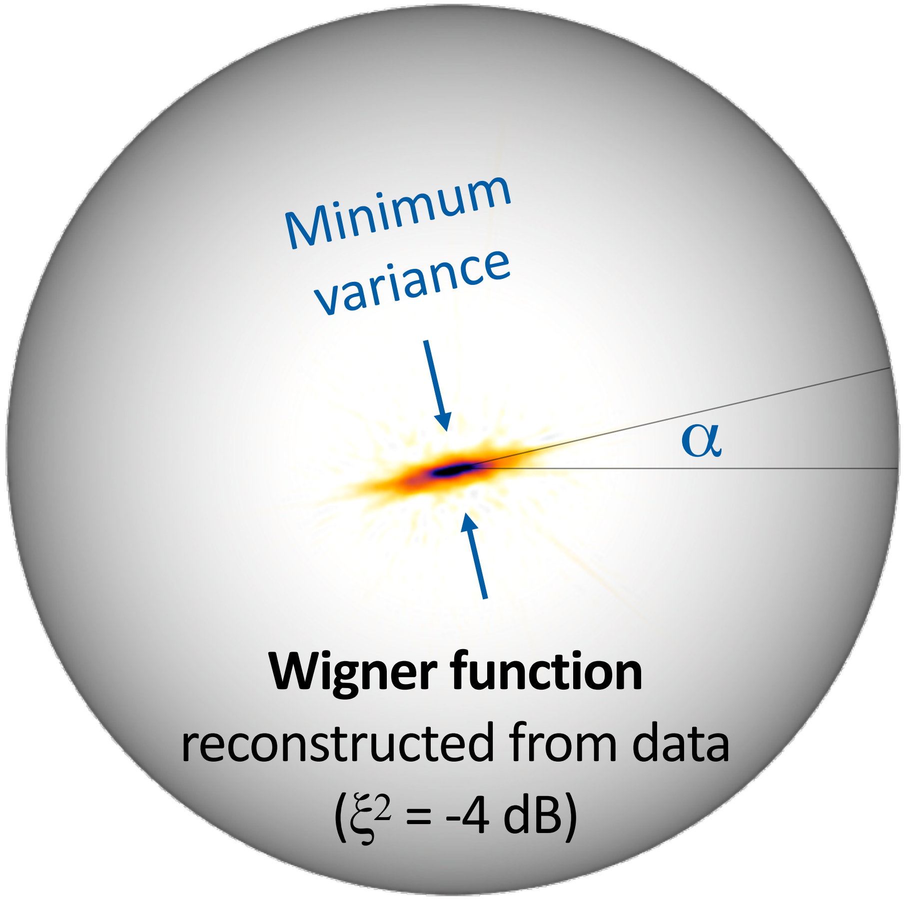
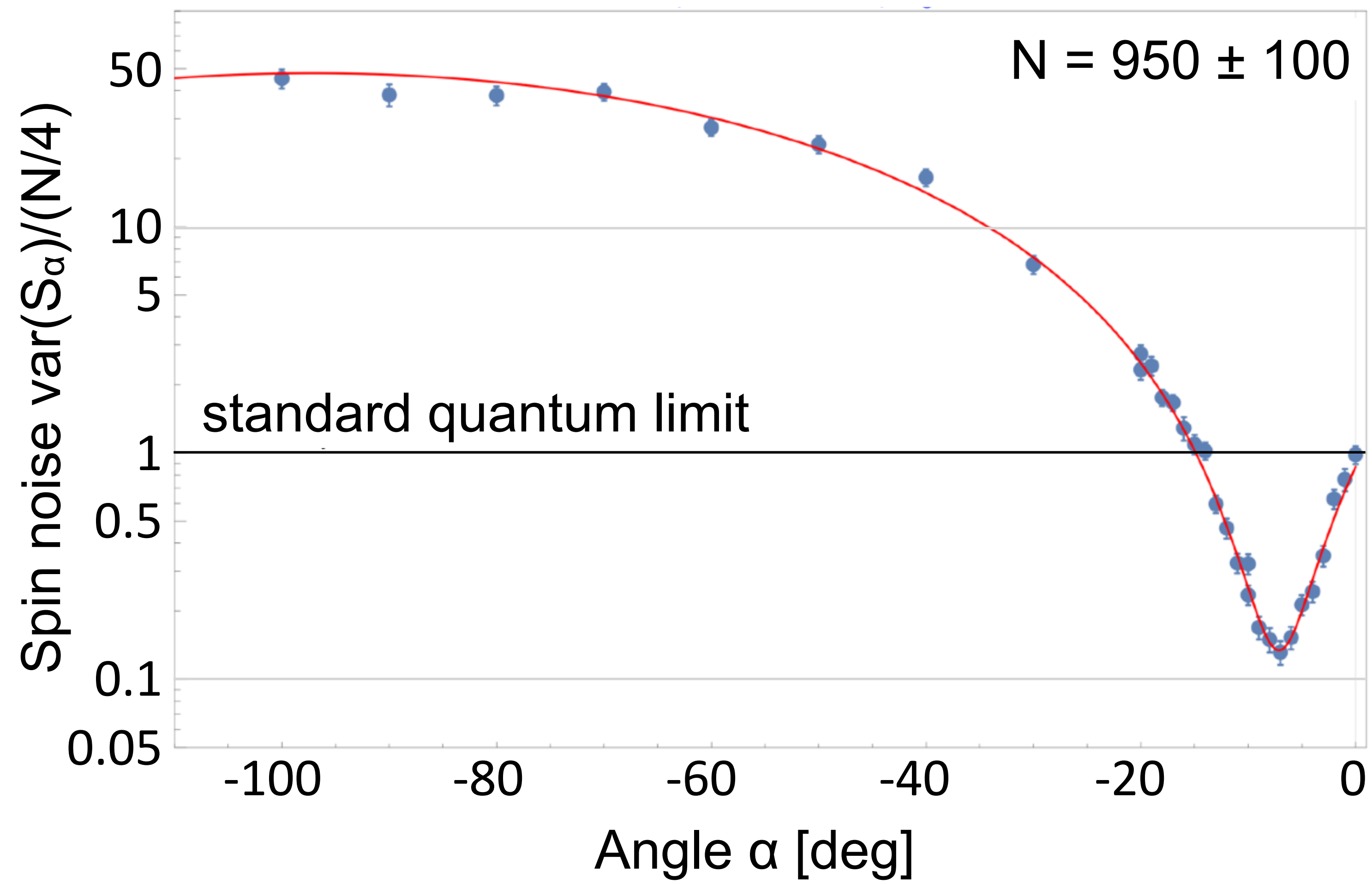
Tomography of spin-squeezed state





$$W(\vartheta,\varphi)=\sum_{k=0}^{2j}\sum_{q=-k}^{k}\rho_{kq}Y_{kq}(\vartheta,\varphi)$$

Squeezing and tomography

Riedel et al, Nature 464, 1170 (2010)
Schmied et al, New J Phys 13, 065019 (2011)

ξ^2 = -8.2 ± 0.5 dB
⇒ entanglement

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

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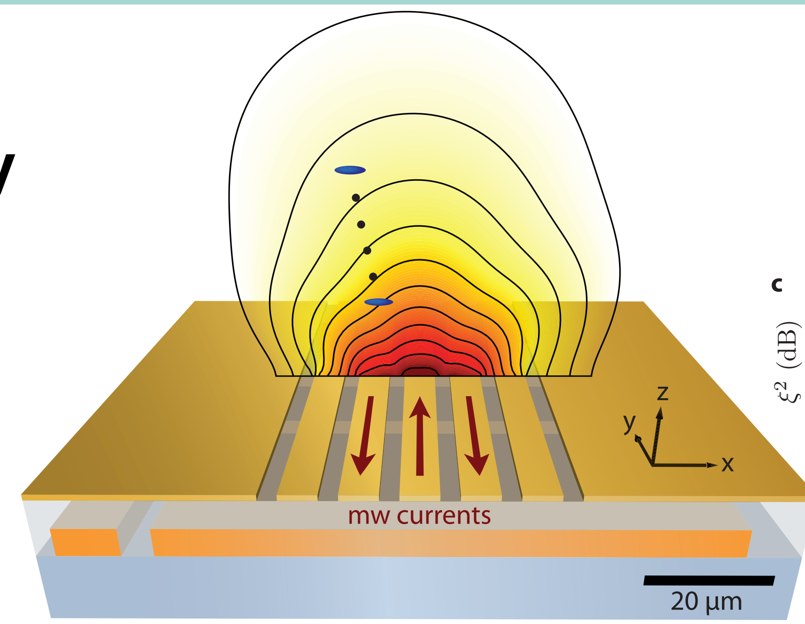
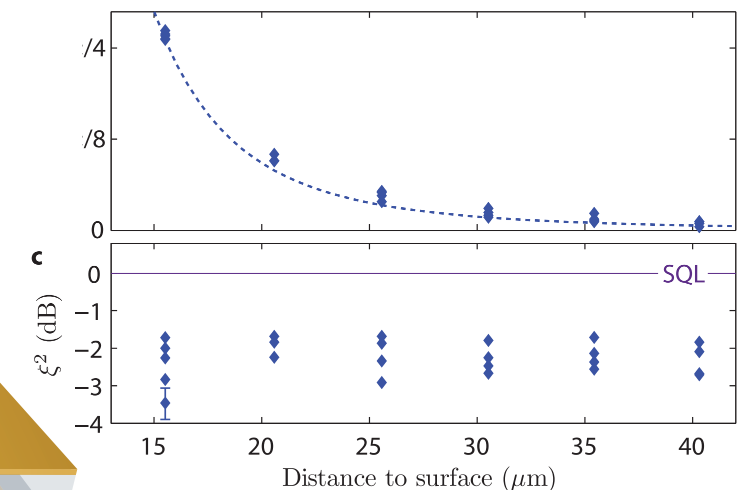
Experiments with spin-squeezed atoms

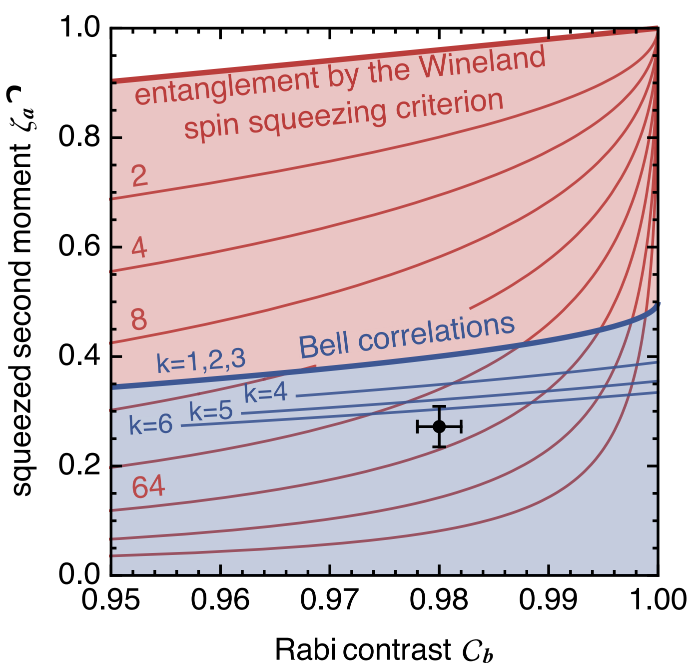




Quantum-enhanced interferometry

- mw field sensing close to chip surface
- enhancement of 7 dB beyond SQL

Riedel et al, Nature 464, 1170 (2010)
Ockeloen et al, PRL 111, 143001 (2013)



Many-particle Bell correlations

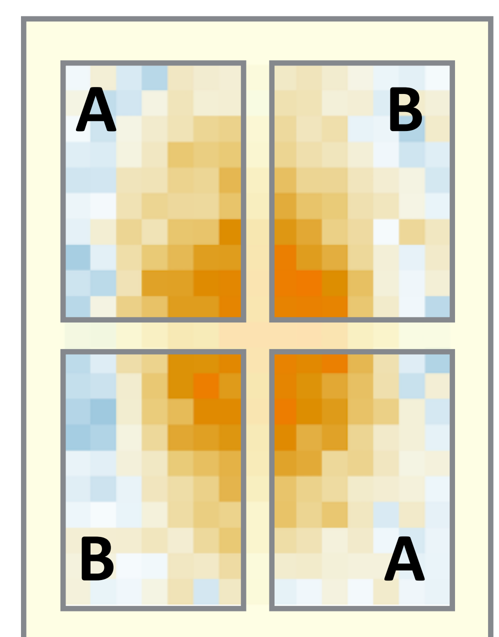
- Bell correlations in many-particle system detected by global measurements

Schmied et al, Science 352, 441 (2016)
Wagner et al, PRL 119, 170403 (2017)

Entanglement patterns

- Entanglement and steering between parts of BEC observed by high-resolution imaging

Fadel et al, Science 360, 409 (2018)



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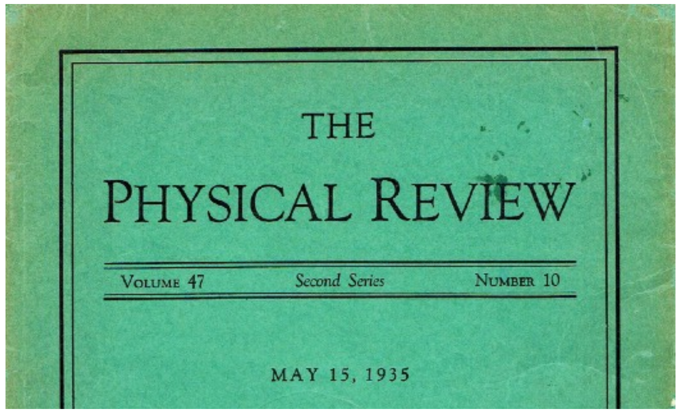
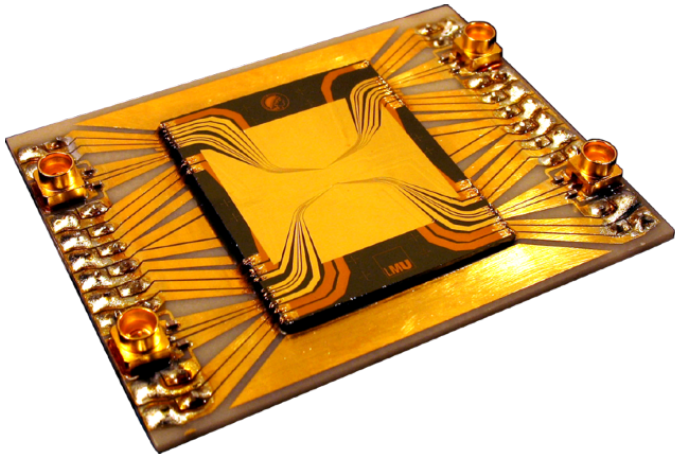


The Einstein-Podolsky-Rosen paradox

Einstein, Podolsky, Rosen, Phys Rev 47, 777 (1935)



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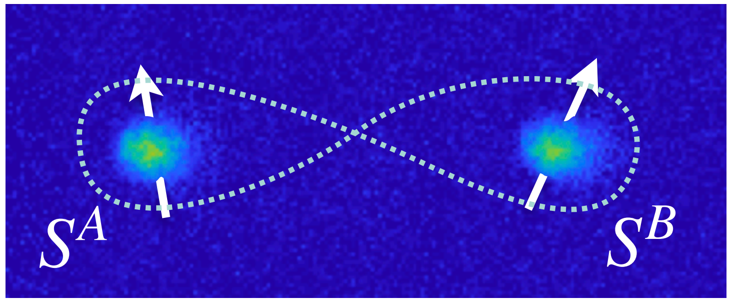

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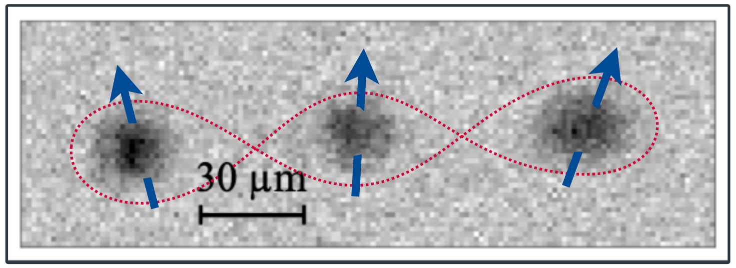

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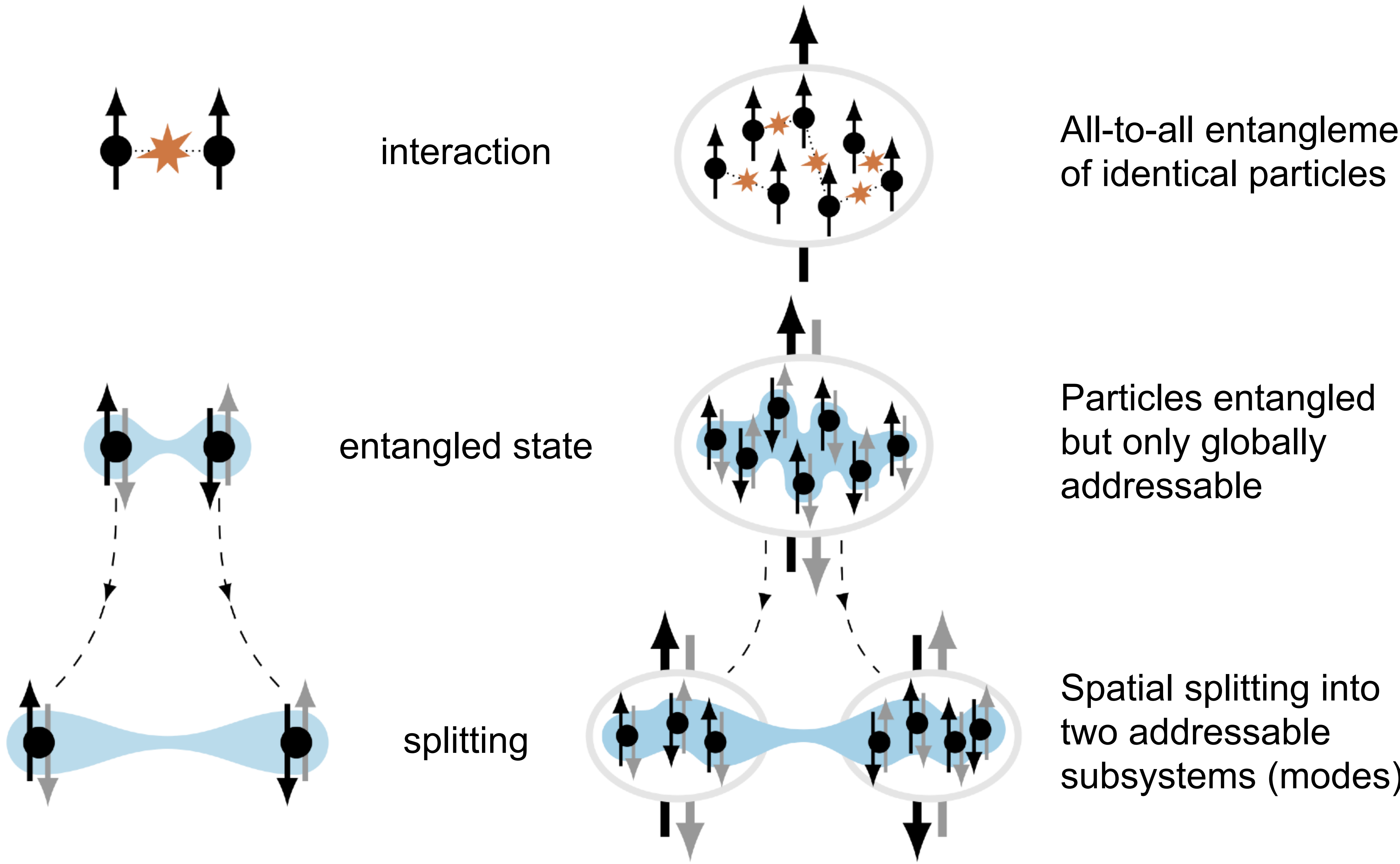
collaboration: Y. Baamara, A. Sinatra

An EPR experiment with a many-particle system



EPR, Phys Rev 47, 777 (1935)
Bohm, Quantum Theory (1951)

N. Killoran, M. Cramer, M. B. Plenio,
Extracting Entanglement from Identical Particles,
PRL 112, 150501 (2014)

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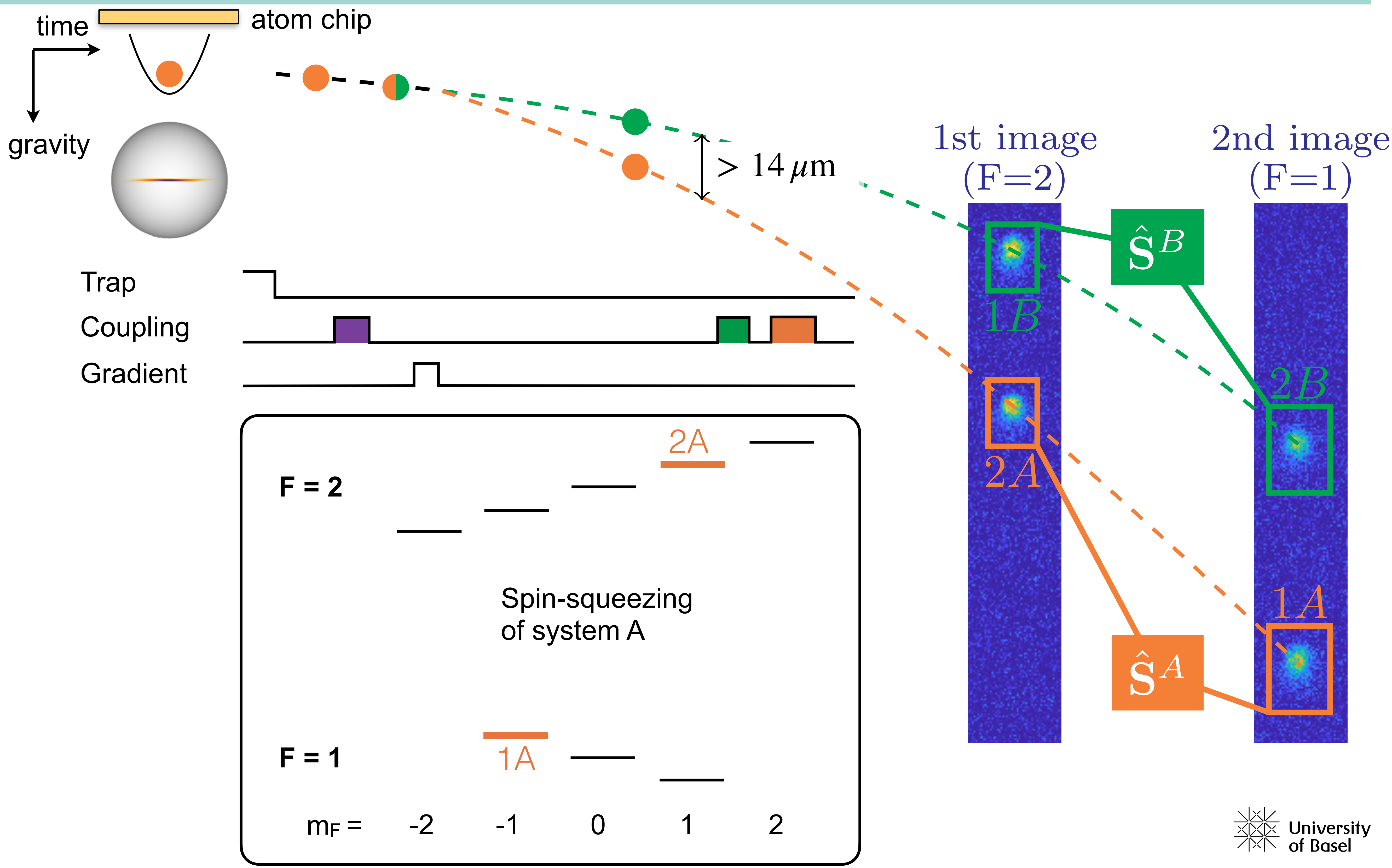
Coherent spatial splitting of two-component BEC



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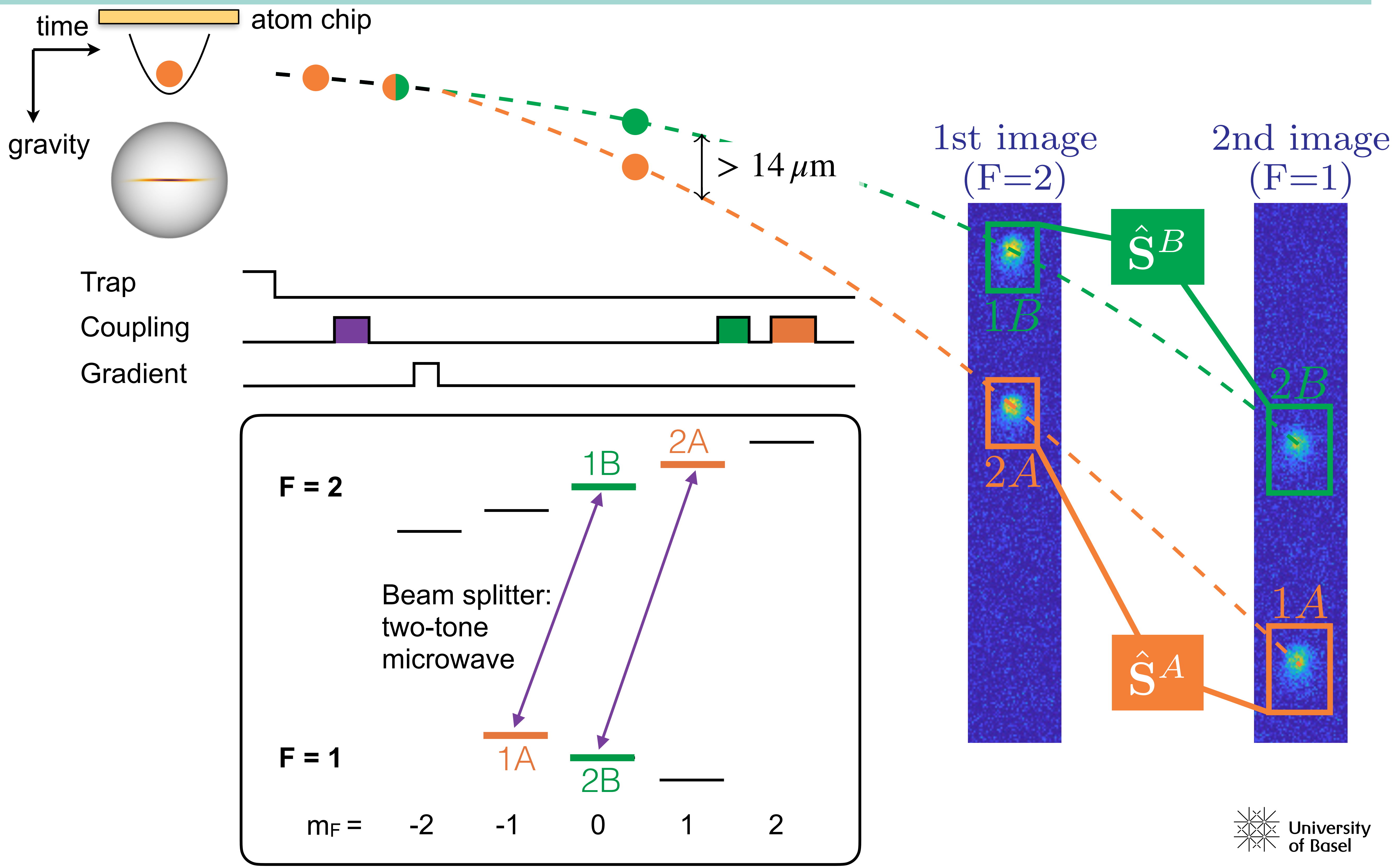

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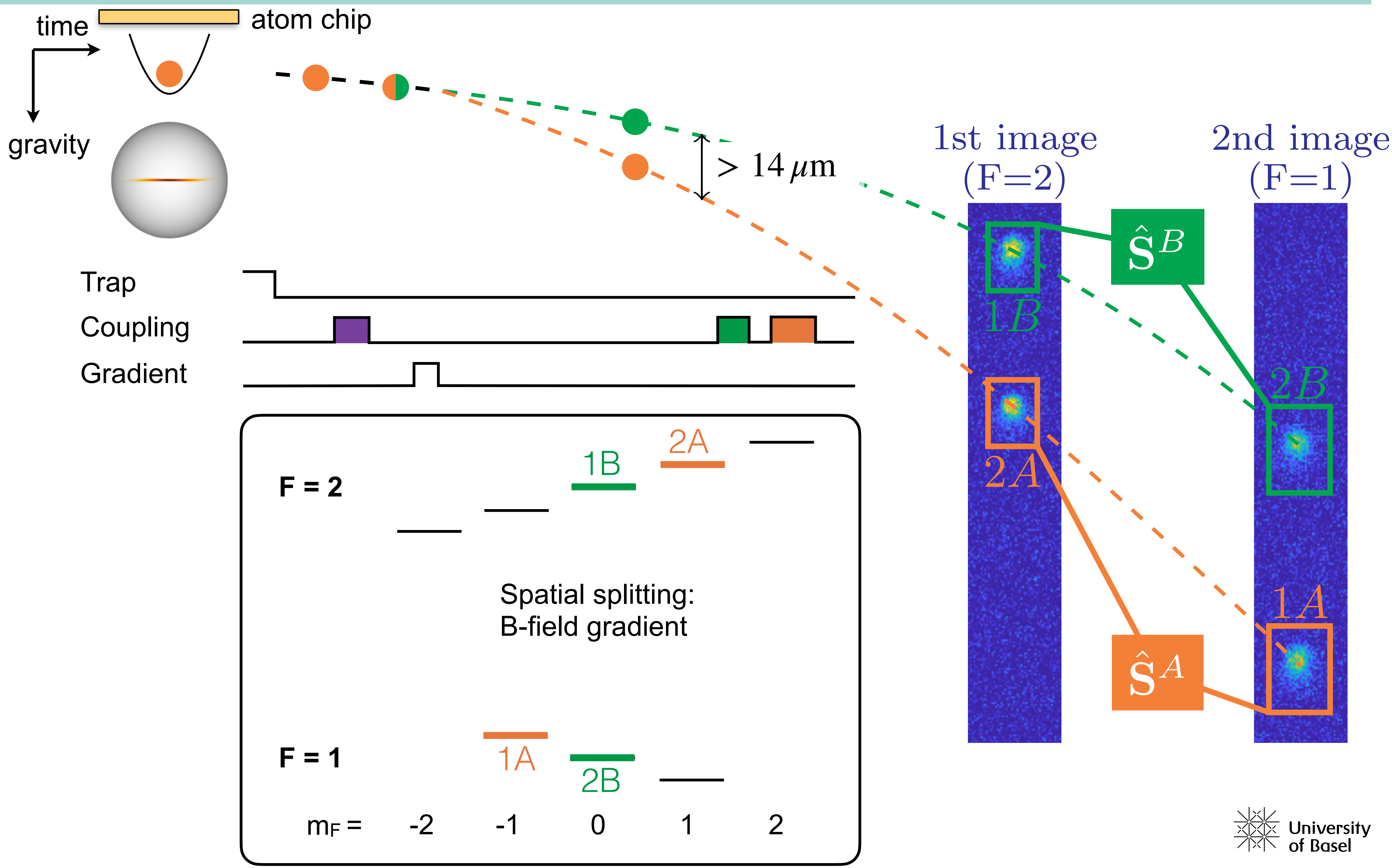

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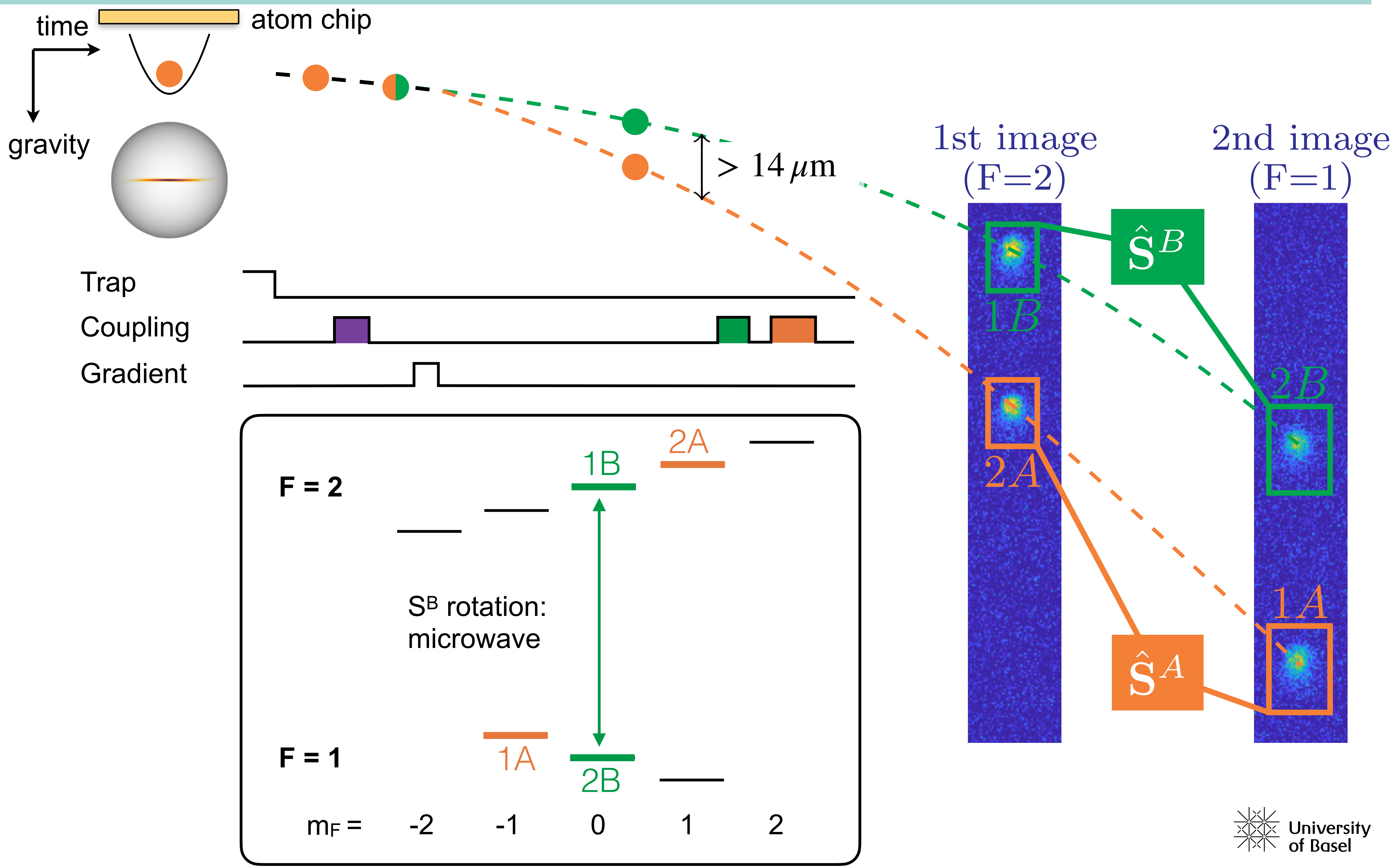
Coherent spatial splitting of two-component BEC



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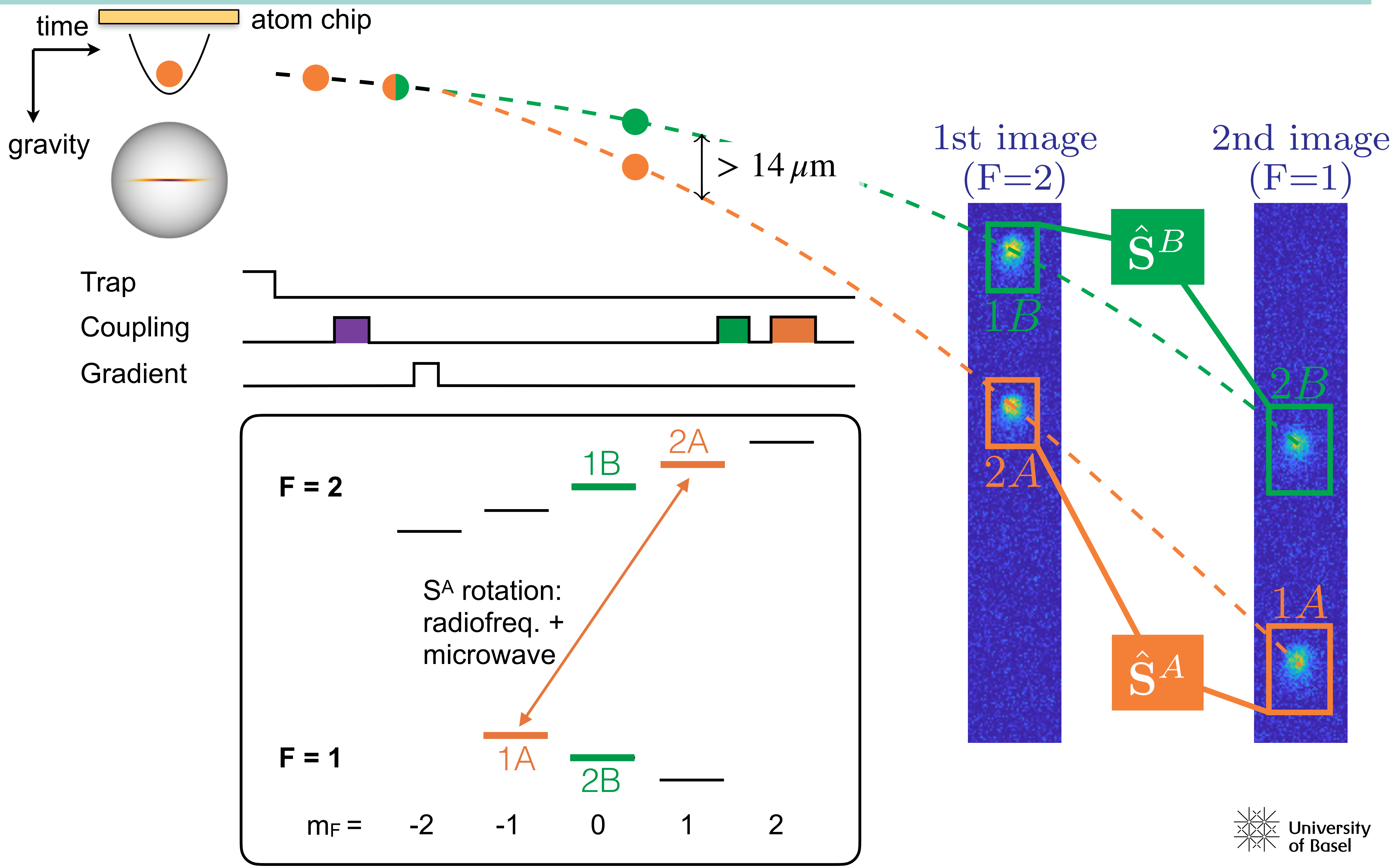
Coherent spatial splitting of two-component BEC



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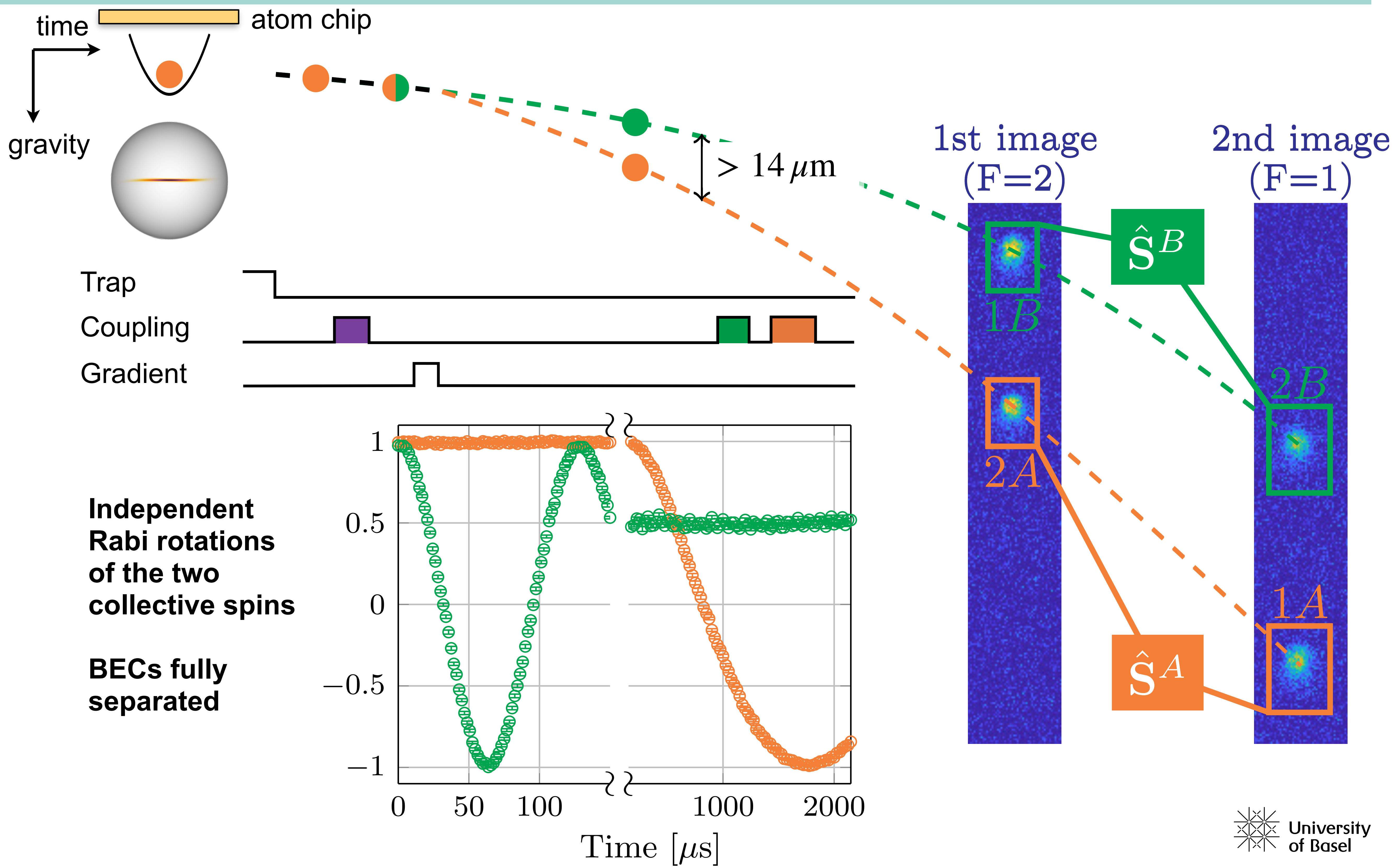
Independent spin rotations after splitting



Independent Rabi rotations of the two collective spins

BECs fully separated

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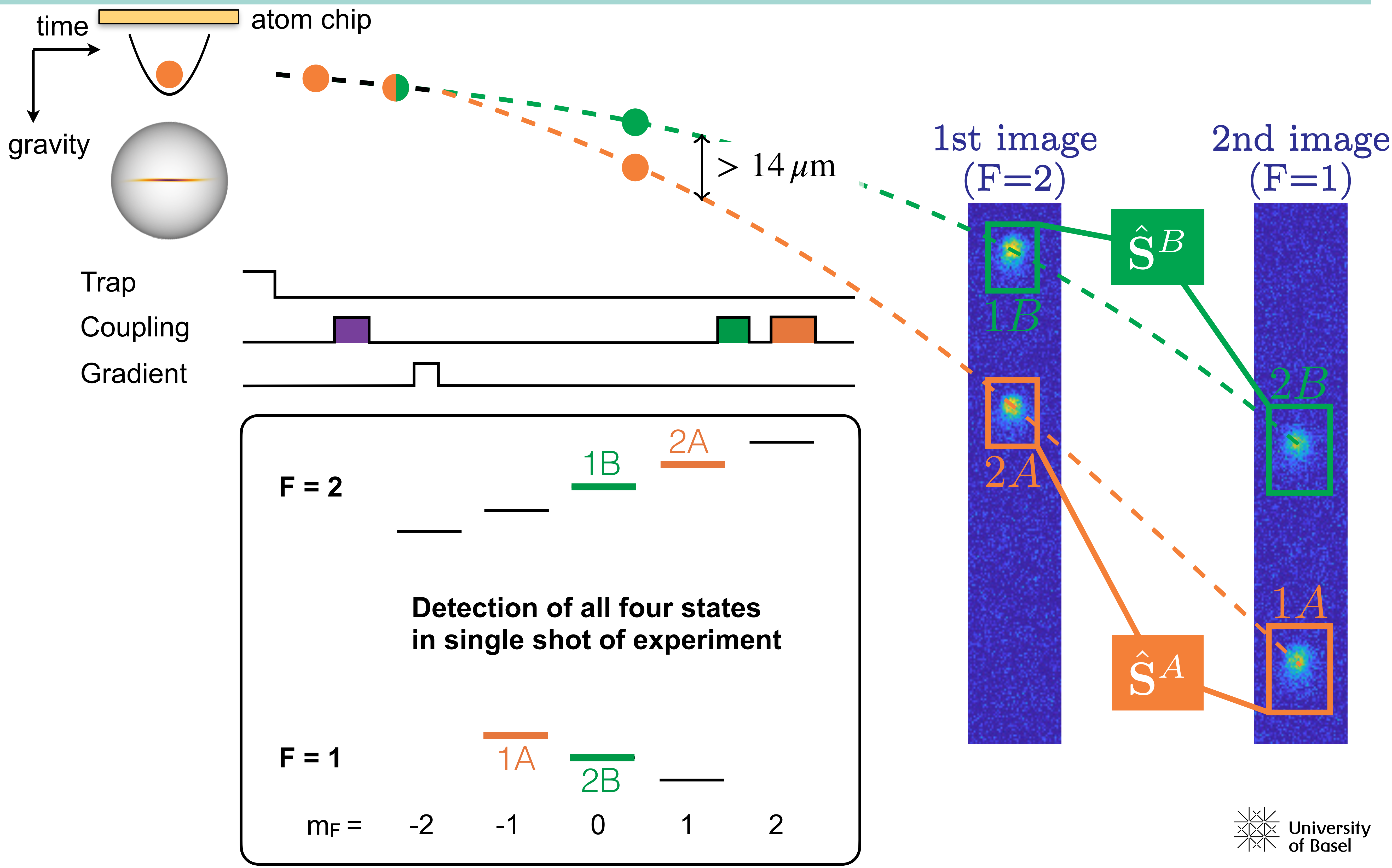
Independent spin rotations after splitting



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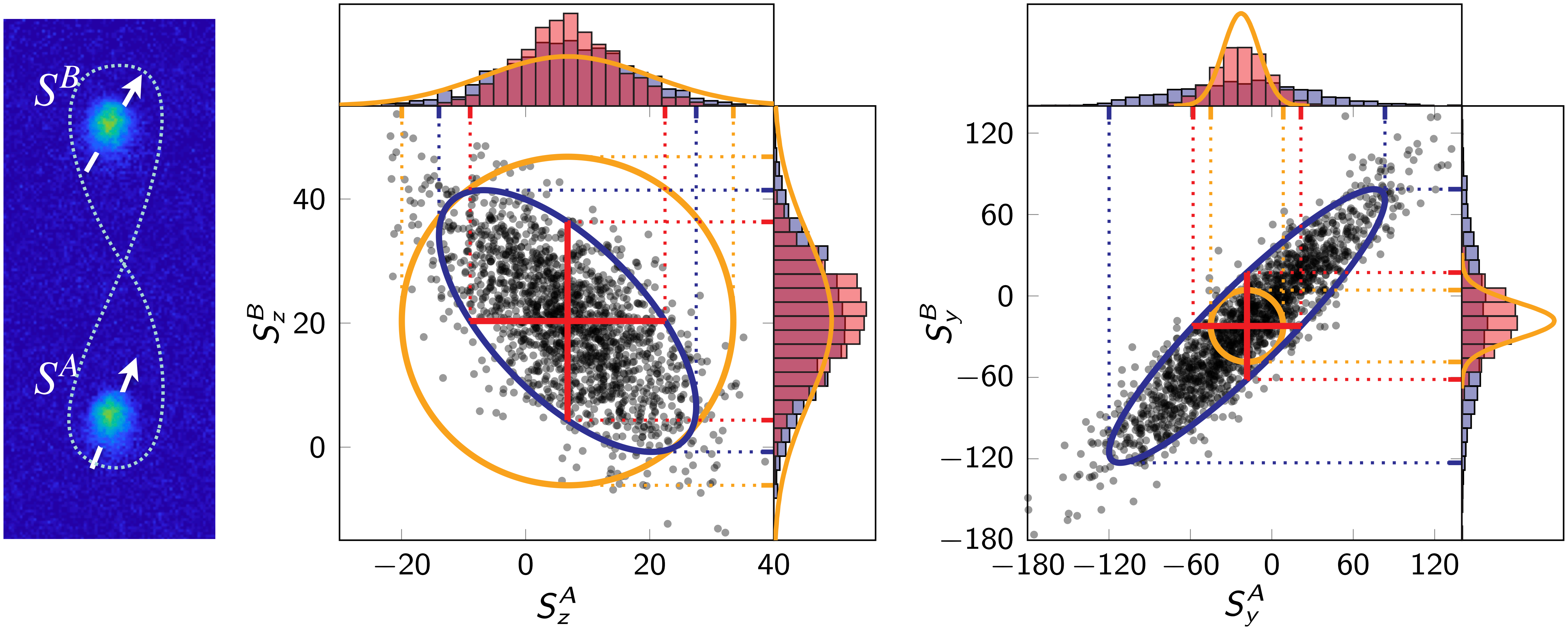
EPR paradox between two BECs



- $N \approx 1400$ atoms
- initial squeezing $\xi^2 \approx -7\,\mathrm{dB}$
- split spins are still squeezed
- contrast in S_x^A and S_x^B about 96%

EPR criterion

$$E_{EPR}^{A\to B} = \frac{4\,\mathrm{Var}\left(\hat{S}_y^B - g_y\hat{S}_y^A\right)\,\mathrm{Var}\left(\hat{S}_z^B - g_z\hat{S}_z^A\right)}{|\langle \hat{S}_x^B\rangle|^2} = 0.81(3) < 1$$

Colciaghi et al, PRX 13, 021031 (2023)

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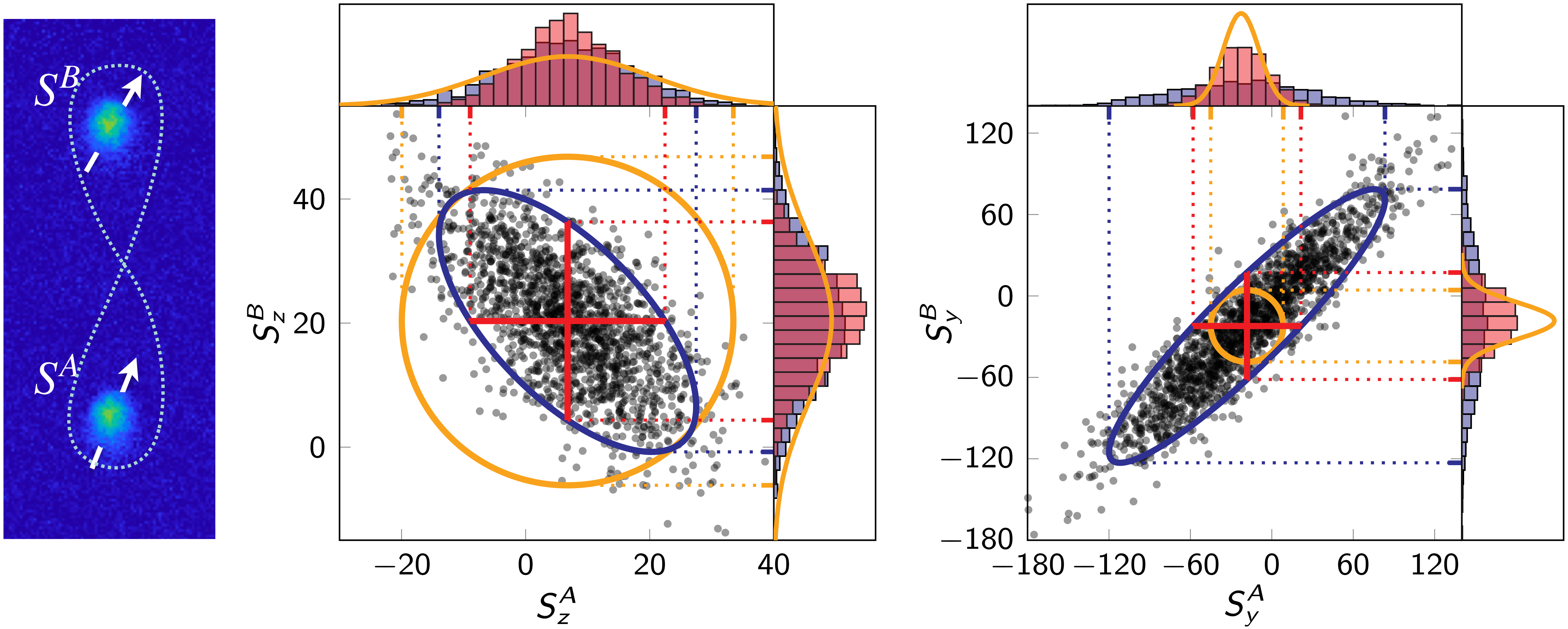
Entanglement criterion



- $N \approx 1400$ atoms
- initial squeezing $\xi^2 \approx -7\,\mathrm{dB}$
- split spins are still squeezed
- contrast in S_x^A and S_x^B about 96%

Entanglement criterion

$$E_{Ent} = \frac{4\,\mathrm{Var}\left(\hat{S}_y^B - g_y \hat{S}_y^A\right)\mathrm{Var}\left(\hat{S}_z^B - g_z \hat{S}_z^A\right)}{\left(|\langle \hat{S}_x^B \rangle| + |g_y g_z||\langle \hat{S}_x^A \rangle|\right)^2} = 0.35(2) < 1$$

Colciaghi et al, PRX 13, 021031 (2023)

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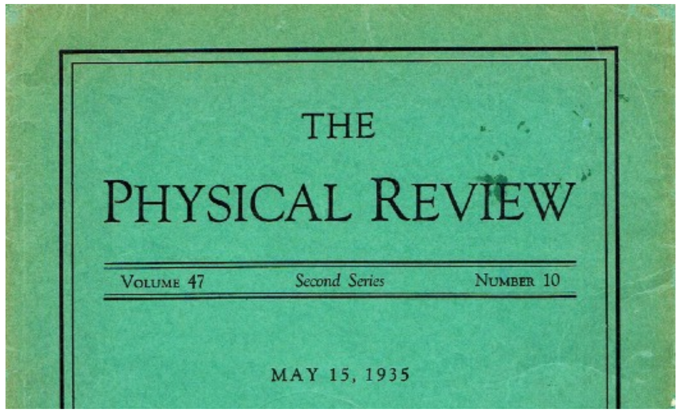
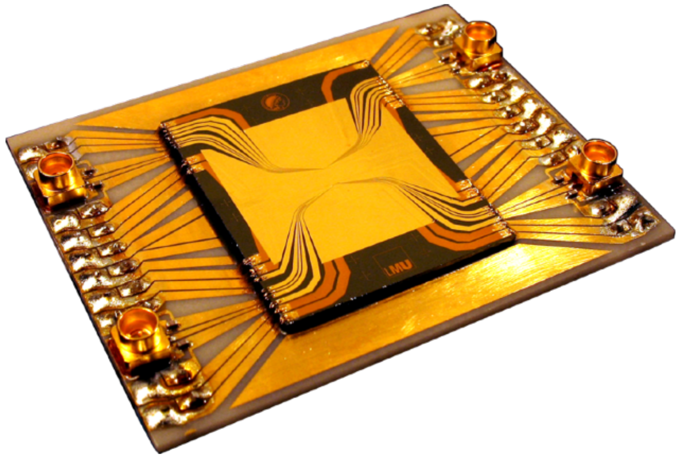
Outline



The Einstein-Podolsky-Rosen paradox

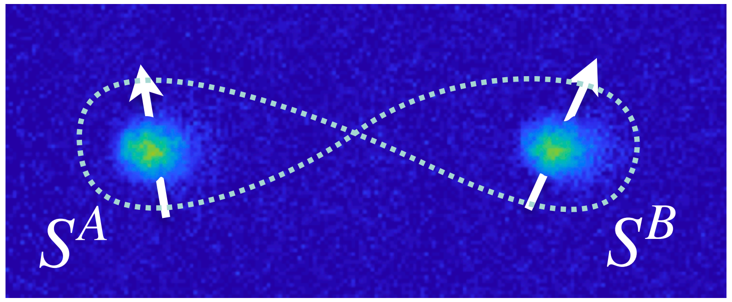
Einstein, Podolsky, Rosen, Phys Rev 47, 777 (1935)



Two-component Rb BEC on atom chip

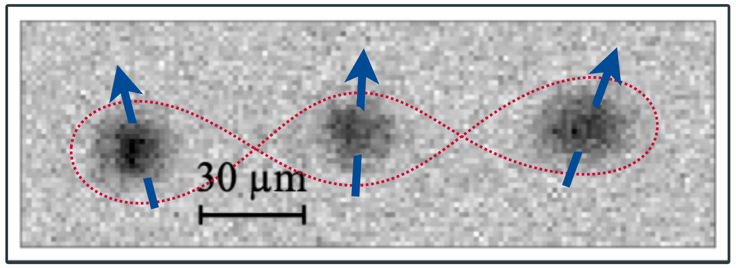
Spin-squeezing, quantum metrology

Riedel et al, Nature 464, 1170 (2010)
Ockeloen et al, PRL 111, 143001 (2013)
Schmied et al, Science 352, 441 (2016)
Fadel et al, Science 360, 409 (2018)



EPR paradox between two spatially separated and addressable BECs

Colciaghi et al, PRX 13, 021031 (2023)



Multiparameter estimation with an array of entangled atomic sensors

collaboration: Y. Baamara, A. Sinatra

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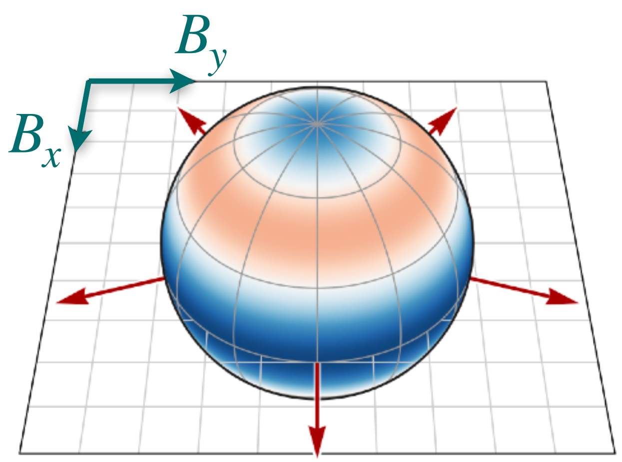
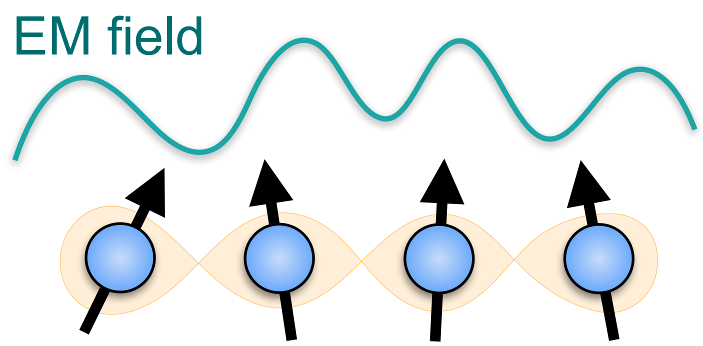
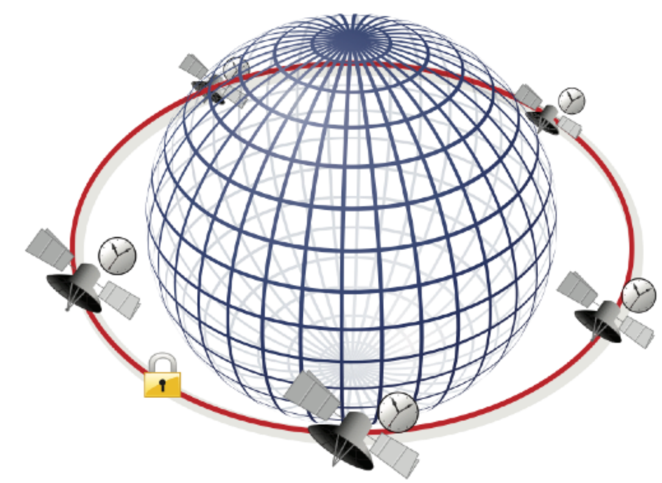
Multiparameter quantum metrology



Quantum compass
Vasilyev et al, arXiv:2404.14194



Sensor array for field imaging
Baamara et al, Scipost Phys 14, 050 (2023)



Quantum network of clocks
Kómár et al, Nat Phys 10, 582 (2014)

Multiparameter sensing tasks:

- vector field sensing
- sensing field distributions
- imaging
- networks of clocks/sensors

Conceptual challenges:

- measurement incompatibility $[S_i, S_j] = i\epsilon_{ijk}S_k$
- intra-sensor vs. inter-sensor entanglement
- quantum gain depends on resources considered (local vs. global detection, …)
- optimal strategy for given resources?

Szczykulska et al, Adv Phys: X, 1, 621 (2016); Gessner et al, PRL 121, 130503 (2018); Proctor et al, PRL 120, 080501 (2018); Sidhu et al, AVS Quantum Sci 2, 014701 (2020); Demkowicz-Dobrzański et al, *J Phys A: Math Theor* 53, 363001 (2020); Albarelli et al, Phys Lett A, 384, 126311 (2020), …

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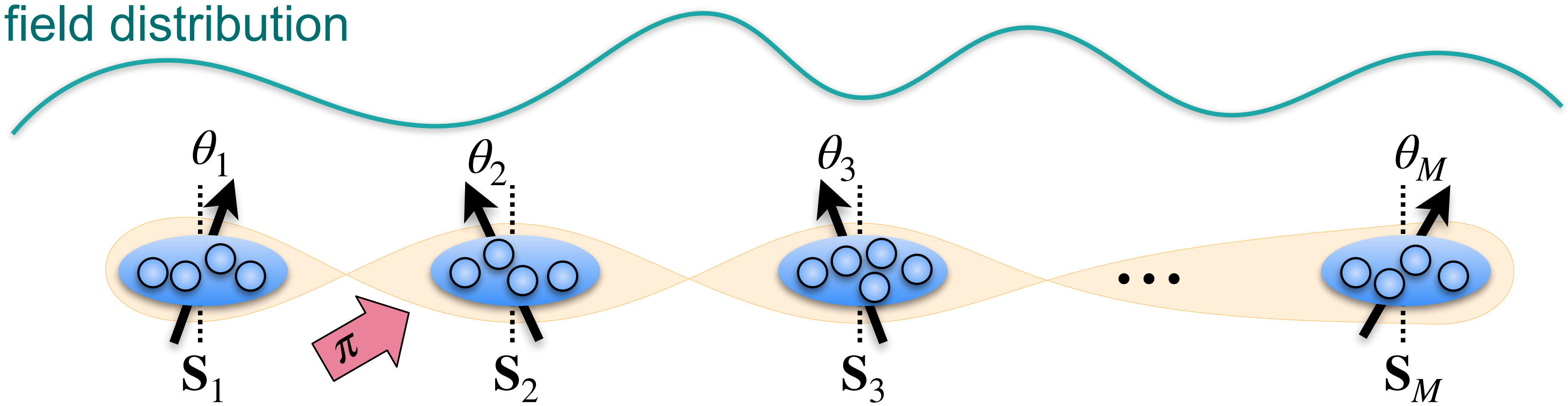
Multiparameter sensing with distributed entanglement

field distribution



array of entangled atomic ensembles

- fixed total N
- fixed total number of preparations μ

Global squeezing of all ensembles: $\mathbf{S} = \sum_k \mathbf{S}_k$ squeezed with $\xi < 1$

→ only symmetric mode has reduced noise

$$\theta_{\text{sym}} = (\theta_1 + \theta_2 + \ldots + \theta_M)/\sqrt{M} \qquad \Delta\theta_{\text{sym}} = \xi\, \Delta\theta_{\text{SQL}} \qquad \Delta\theta_{\text{SQL}} = \sqrt{\frac{M}{\mu N}}$$

Local spin rotations (π-pulses) transfer quantum enhancement to target Hadamard mode

e.g. $\theta_{\text{target}} = (\theta_1 \boxed{-\,\theta_2} + \ldots + \theta_M)/\sqrt{M}$ $\quad \boxed{\Delta\theta_{\text{target}} = \xi\, \Delta\theta_{\text{SQL}}}$

Prepare & measure complete set of target modes

→ all θ_i quantum enhanced

(optimal strategy saturating CR bound)

$$\boxed{\Delta\theta_i = \frac{\sqrt{M}\xi}{\sqrt{1 + (M-1)C^2\xi^2}}\Delta\theta_{\text{SQL}}}$$

Baamara et al, Scipost Phys 14, 050 (2023); Gessner Nat Commun 11, 3817 (2020), …

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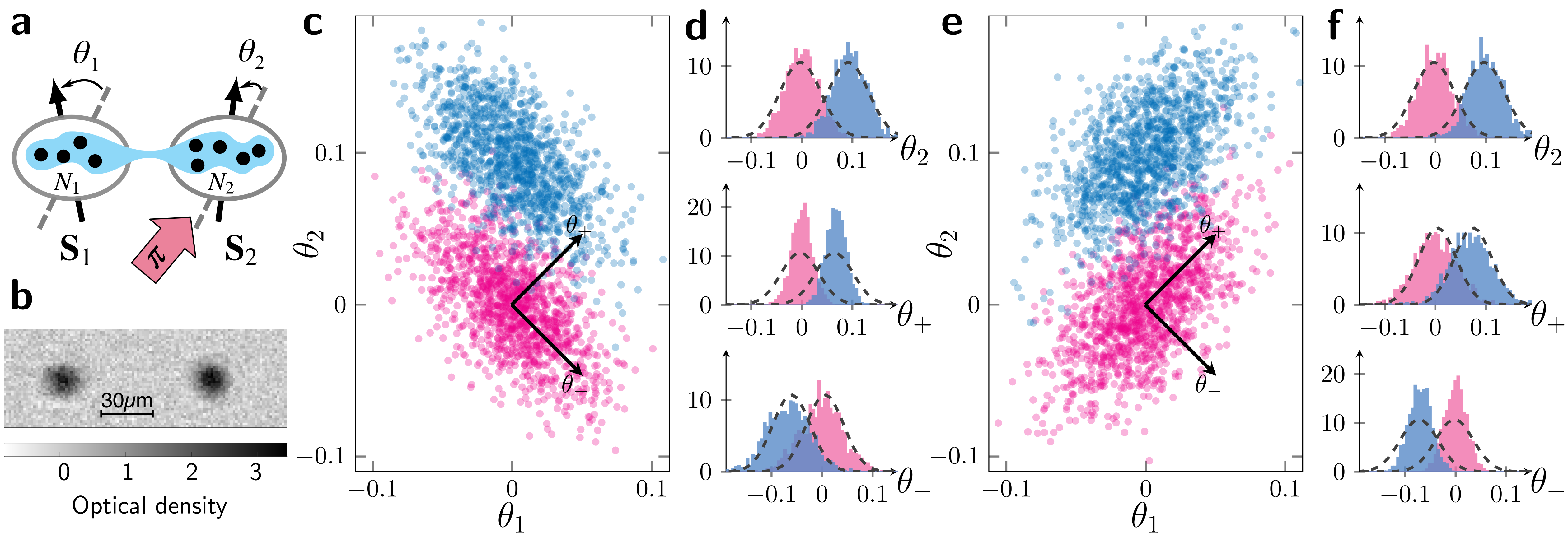
Two clouds: squeezing common and differential mode



exploit individual coherent control and detection of sensors

common mode:
$\theta_+ = (\theta_1 + \theta_2)/\sqrt{2}$

squeezed by -5.6(2) dB

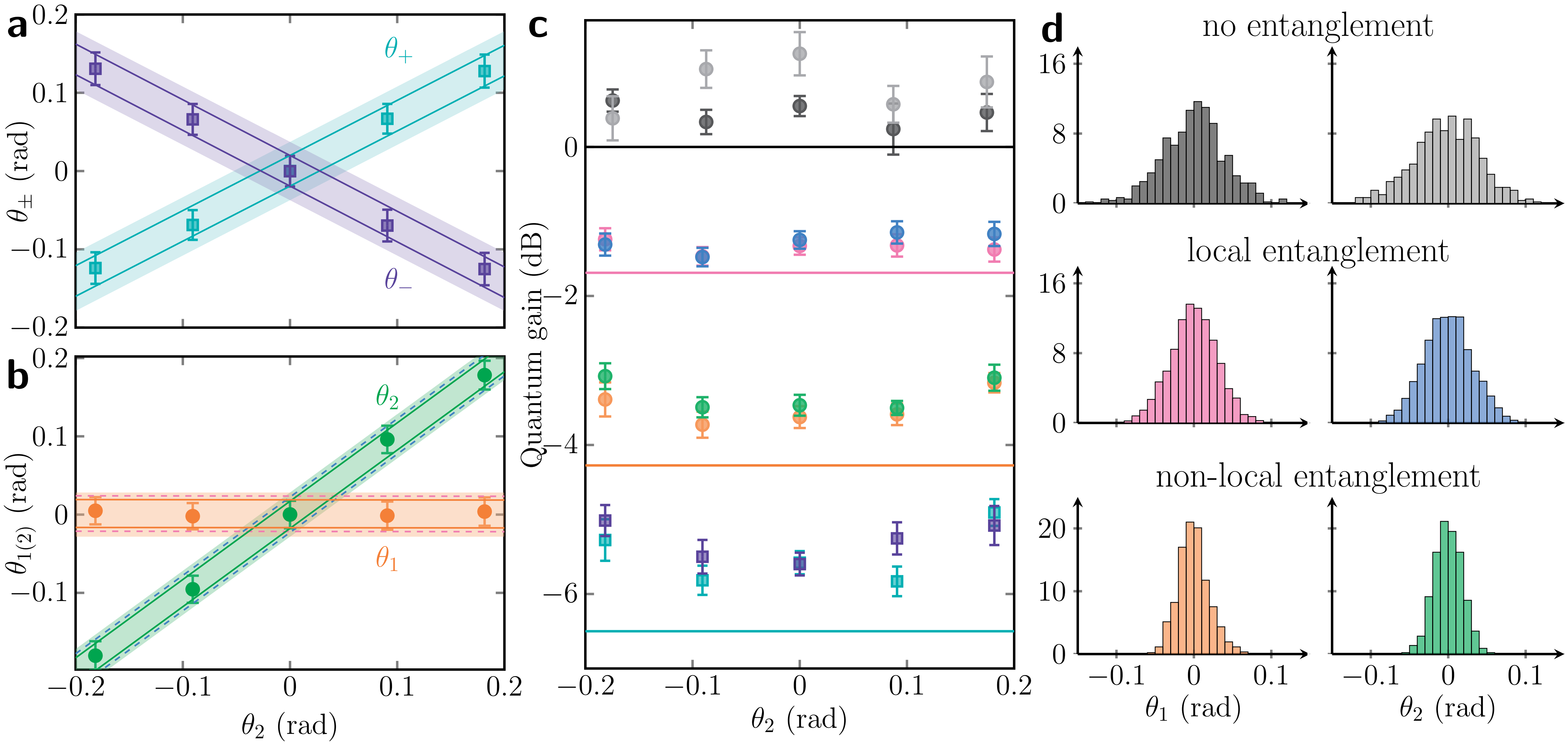
differential mode:
$\theta_- = (\theta_1 - \theta_2)/\sqrt{2}$

squeezed by -5.6(2) dB

see also: Malia et al, Nature 612, 661 (2022)

Li, Joosten, Baamara, Colciaghi, Sinatra, Treutlein, Zibold, to be published

Joint quantum enhancement for both parameters



Distributed entanglement results in ***joint*** quantum enhancement of ***both*** parameter estimates by 3.6(2) dB

$$\frac{(\Delta\theta_i)^2}{(\Delta\theta_{\mathrm{SQL}})^2} = \frac{2\xi^2}{1 + C^2\xi^2}$$

Li, Joosten, Baamara, Colciaghi, Sinatra, Treutlein, Zibold, to be published

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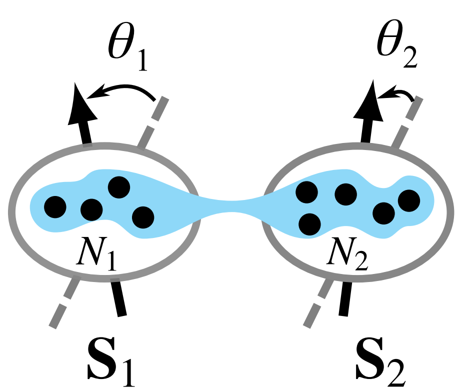
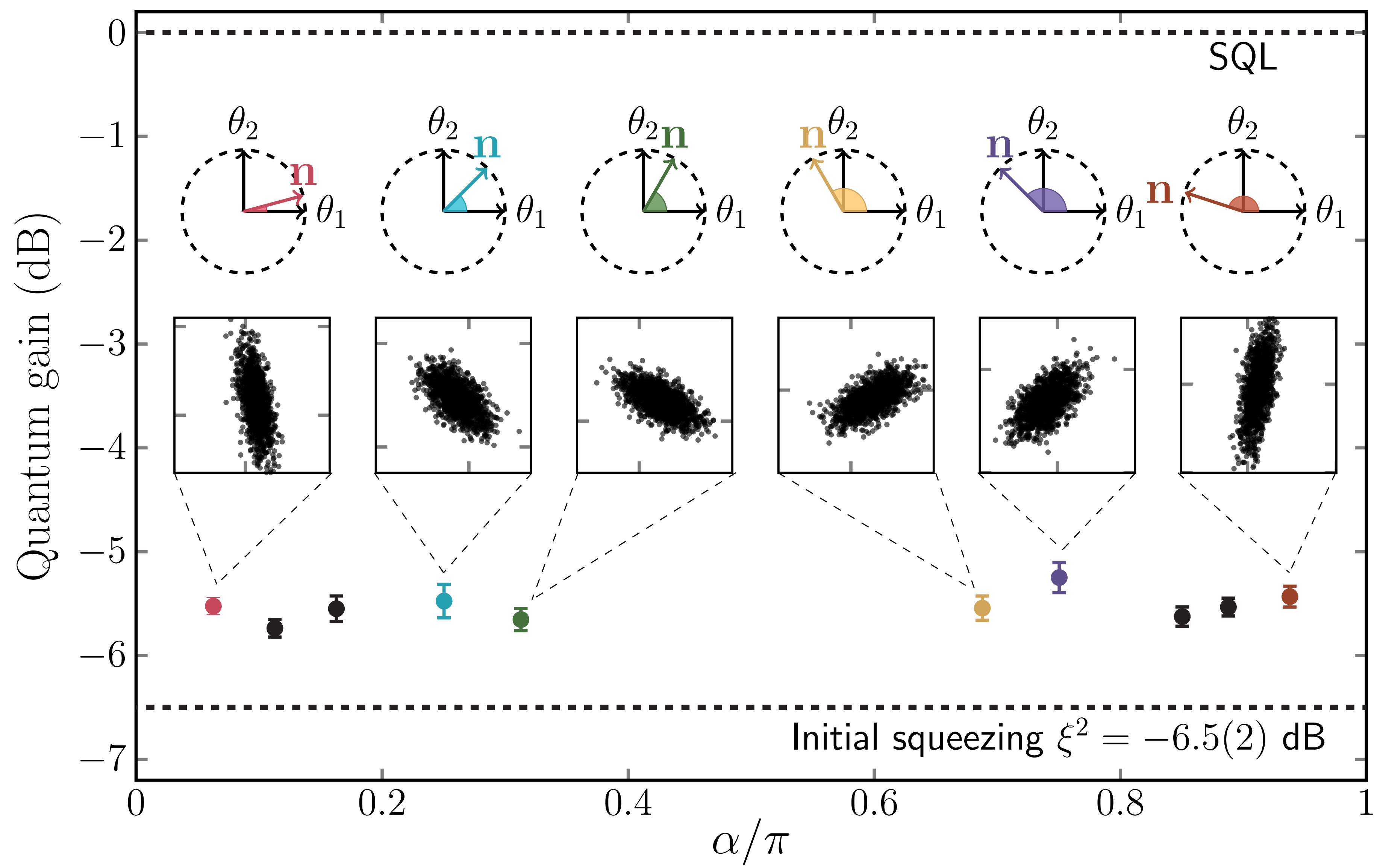
Squeezing arbitrary nonlocal parameter combinations



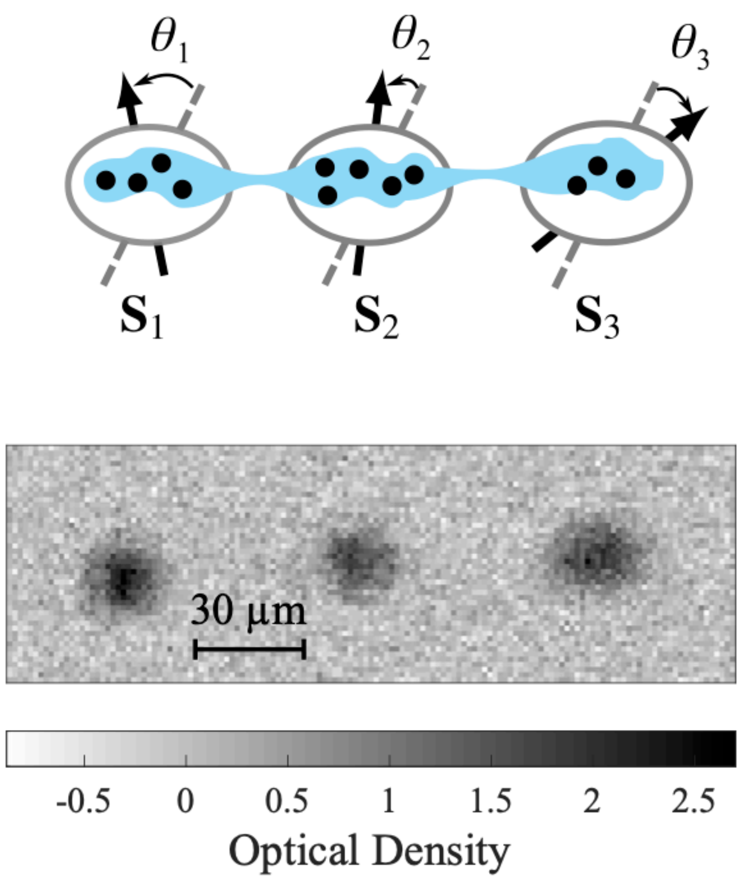
adjust N_1 and N_2 to match parameter combination



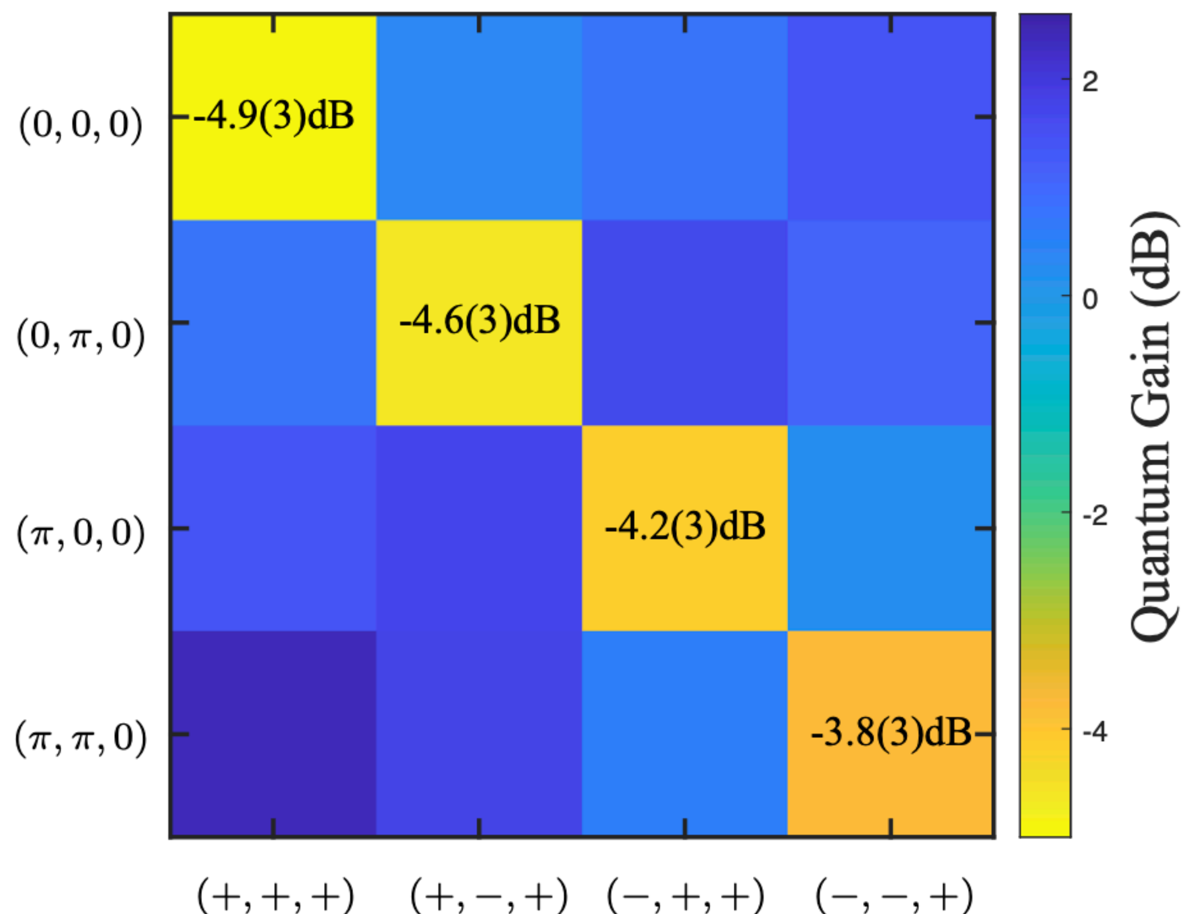
nonlocal parameter combinations: $\mathbf{n} \cdot \boldsymbol{\theta} = \cos(\alpha)\,\theta_1 + \sin(\alpha)\,\theta_2$

Li, Joosten, Baamara, Colciaghi, Sinatra, Treutlein, Zibold, to be published

Distributed sensing with three entangled ensembles



preparation of three entangled spinor BECs



quantum enhancement of four different modes

No Hadamard matrix for $M = 3 \rightarrow$ measure four modes for optimal estimation of all θ_i

Joint quantum gain for **multiple parameters** from distributed entanglement

Li, Joosten, Baamara, Colciaghi, Sinatra, Treutlein, Zibold, to be published

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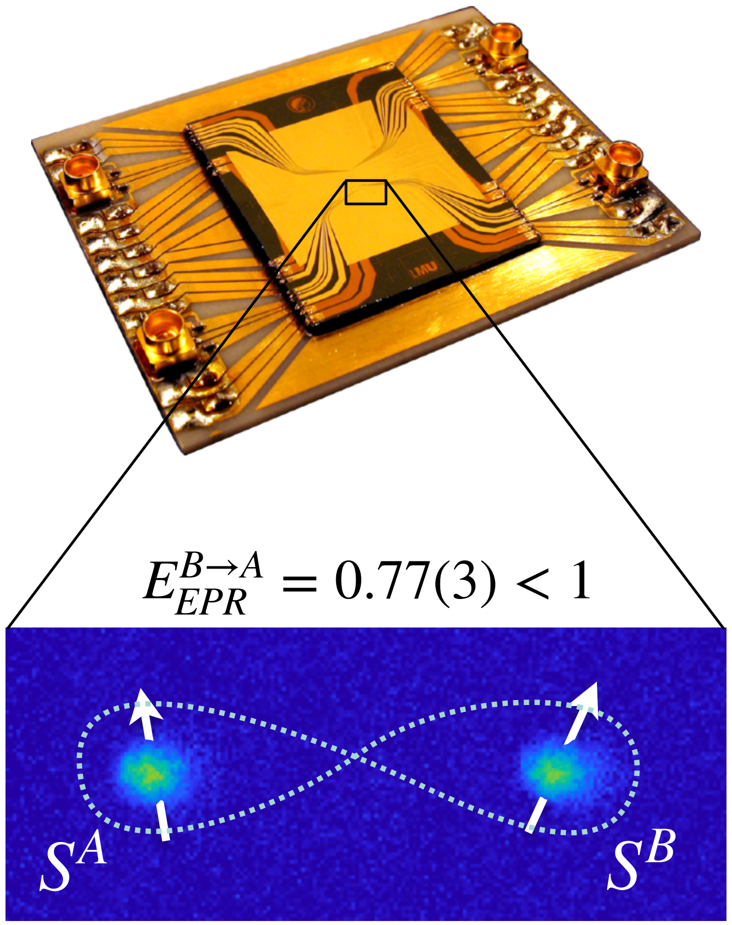
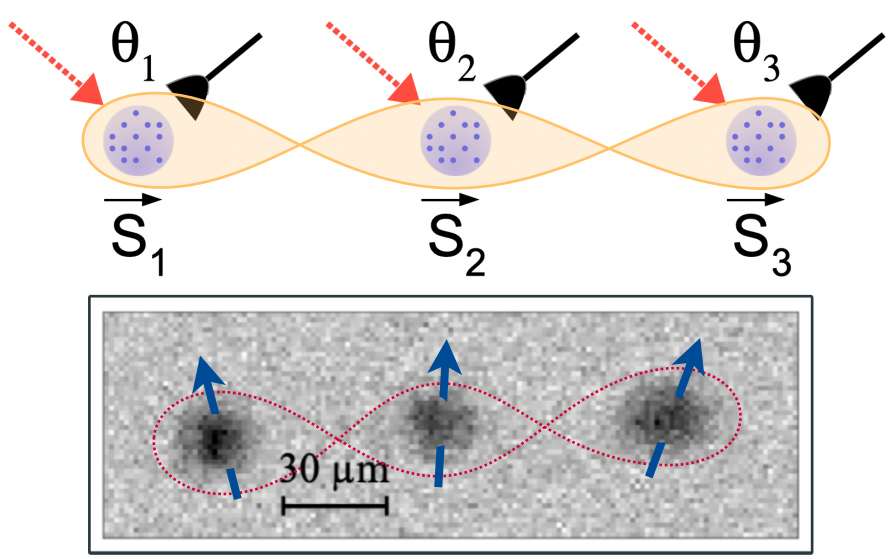
Outlook





Experiments on quantum foundations with massive many-particle systems

- Bell test with spatially separated BECs?
  → non-Gaussian states or measurements
  Oudot et al, New J Phys 21, 103043 (2019)
- Macroscopicity of many-particle EPR?
  Legget, J Phys A 40, 3141 (2007)
  Cavalcanti and Reid, J Mod Opt 54, 2373 (2007)
- Entanglement in tripartite systems

Multiparameter quantum metrology

- Imaging of field distributions close to chip
- Quantum gain for compressed sensing
  Baamara et al, Scipost Phys 14, 050 (2023)
- Networks of clocks

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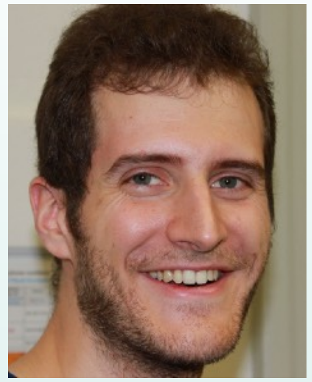
Quantum optics and atomic physics

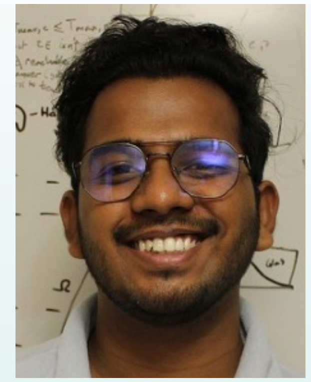
Positions available!


Manel Bosch

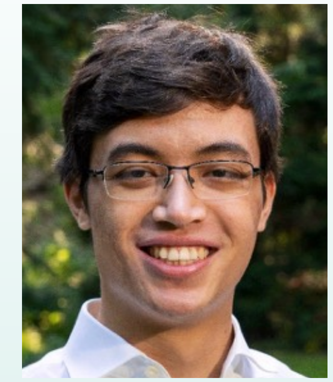

Gianni Buser


Paolo Colciaghi


Maryse Ernzer


Suyash Gaikwad

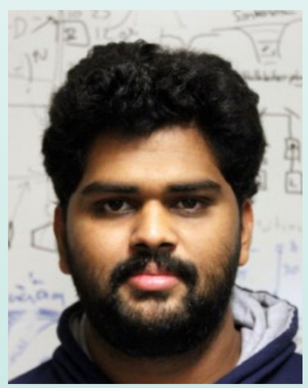

Alexandre Huot


Lex Joosten

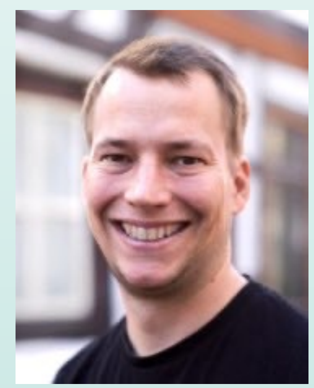

Yifan Li

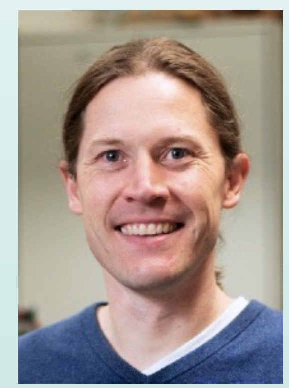

Roberto Mottola


Haroon Saeed


Madhav Saravanan


Gian-Luca Schmid


Tilman Zibold


Philipp Treutlein

theory collaborators


Alice Sinatra


Youcef Baamara