University of Basel

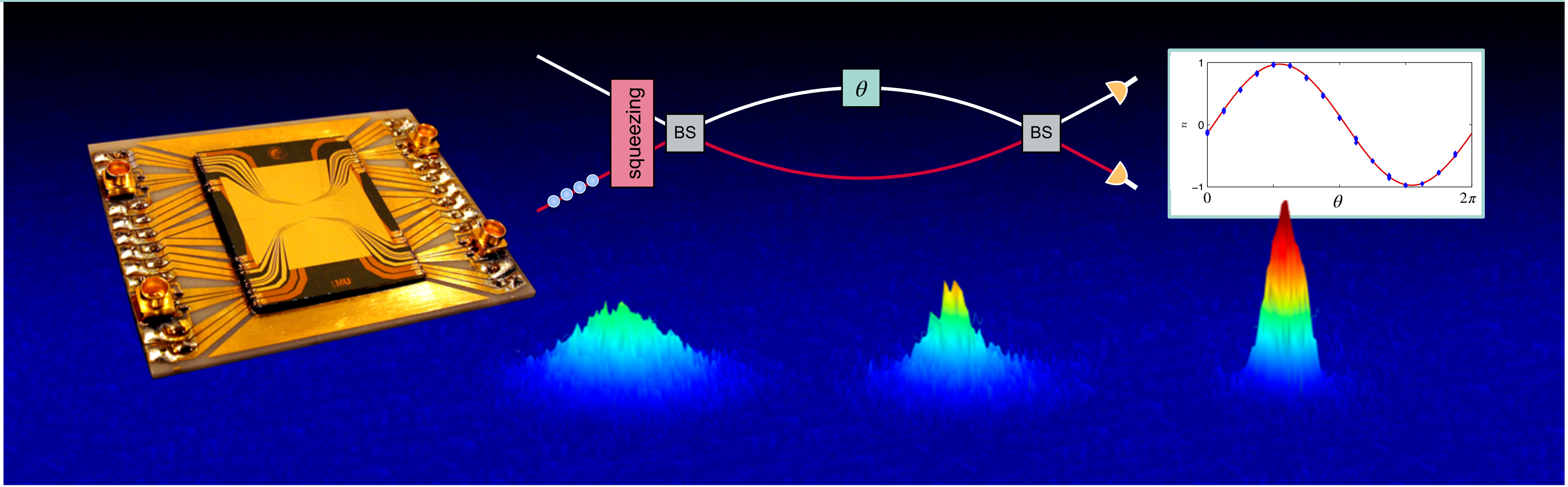
Basel Quantum Center

Swiss Nanoscience Institute

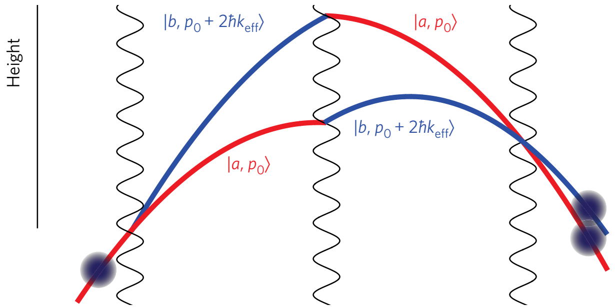
Wave-particle duality in atom interferometers

Precision measurements at the quantum limit

Philipp Treutlein

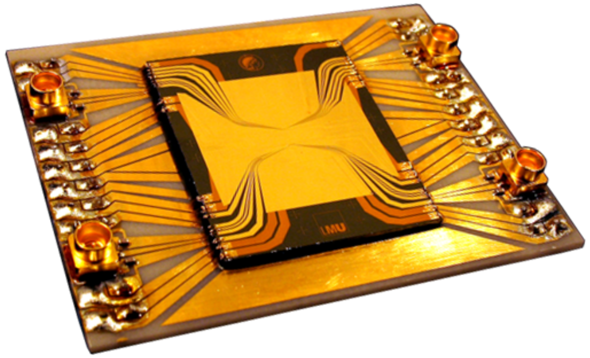


Outline

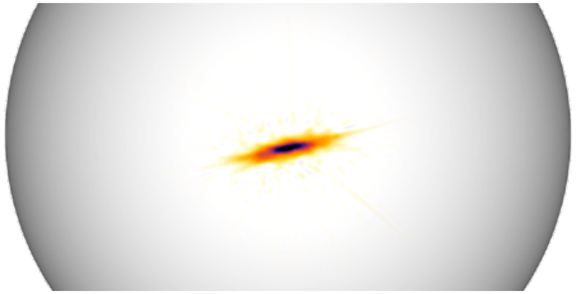


Atom interferometry:

Matter waves for precision measurements



An atom interferometer on a microchip



Quantum metrology:

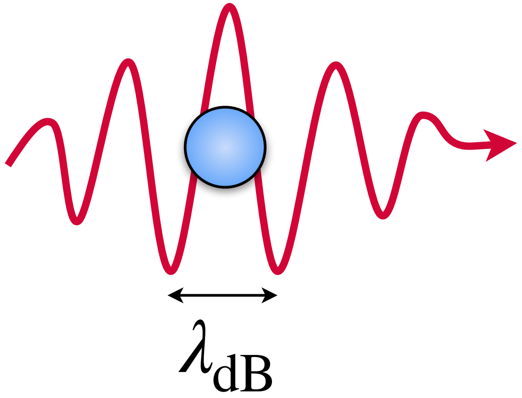
Entanglement-enhanced interferometers

Quantum foundations with many-particle systems

Louis de Broglie and the wave-particle duality of matter

Louis de Broglie

$$\lambda_{\mathrm{dB}} = \frac{h}{p} = \frac{h}{m \cdot v}$$



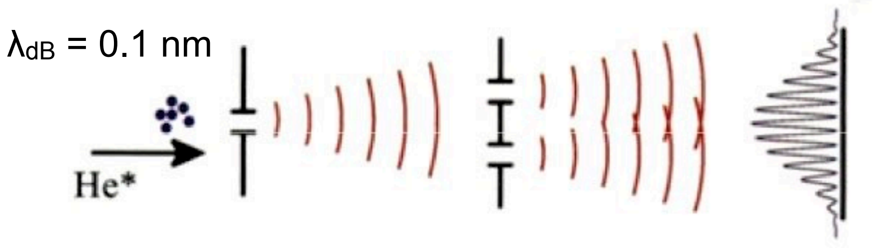
When I conceived the first basic ideas of wave mechanics in 1923–1924, I was guided by the aim to perform a ***real physical synthesis****, valid for all particles, of the* ***coexistence of the wave and of the corpuscular aspects*** *that Einstein had introduced for photons in his theory of light quanta in 1905.*

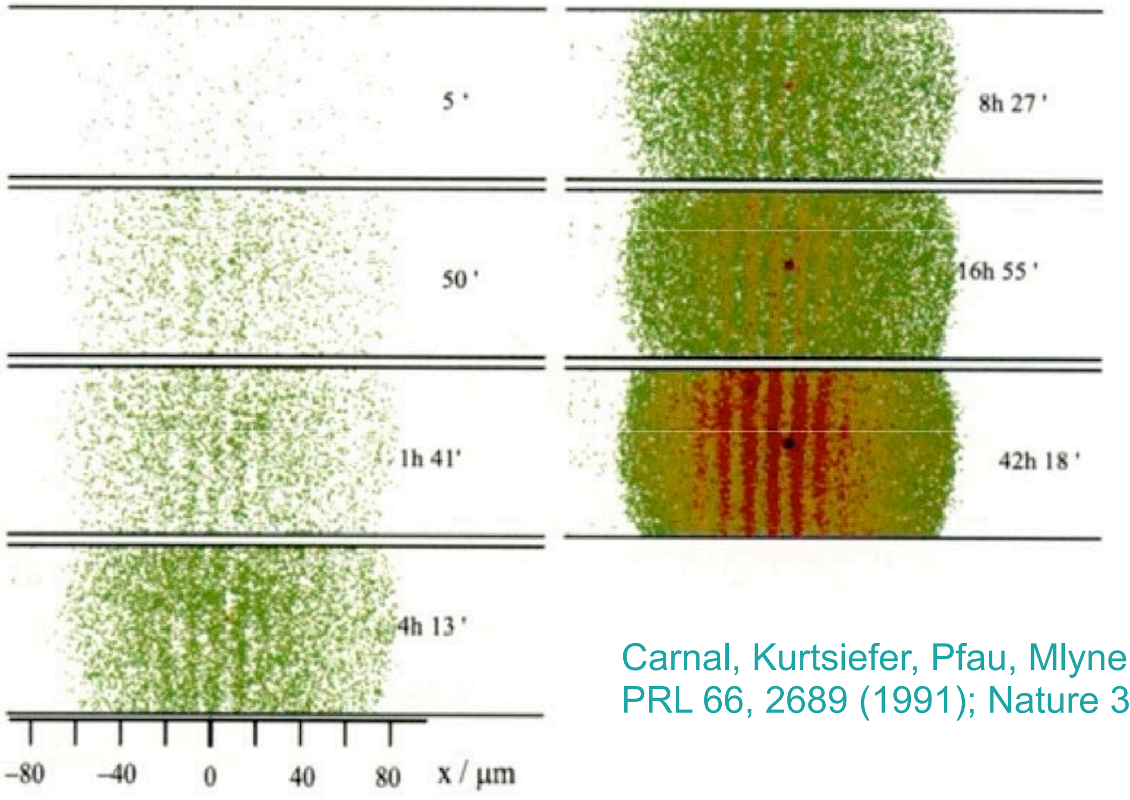
L. de Broglie, *The reinterpretation of wave mechanics*, Found. Phys. 1, 5 (1970).

L. de Broglie, *Ondes et quanta*, Comptes rendus 177, 507 (1923).

L. de Broglie, *Recherches sur la théorie des quanta*, Faculté des Sciences de Paris (1924).

Double slit interference of He* atoms





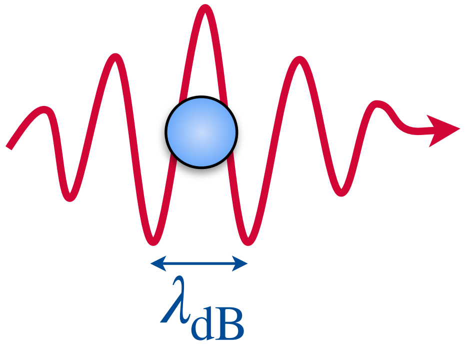
Carnal, Kurtsiefer, Pfau, Mlynek, see e.g.
PRL 66, 2689 (1991); Nature 386, 150 (1997).

Interference pattern appears atom by atom

Wave nature of atom → **interference**

Particle nature of atom → **quantum noise**

Examples of matter waves



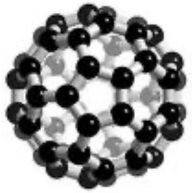
$$\lambda_{dB} = \frac{h}{p} = \frac{h}{m \cdot v}$$

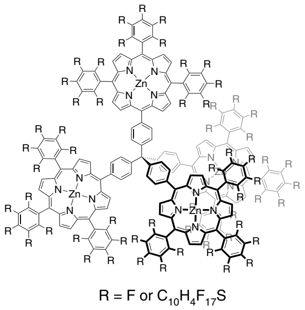
object	m [kg]	v [m/s]	λ_{dB} [m]
electron	9.1×10^{-31}	6×10^{6}	1×10^{-10}
neutron	1.7×10^{-27}	200	2×10^{-9}
^{87}Rb atom (300 K)	1.4×10^{-25}	270	2×10^{-11}
^{87}Rb atom (100 nK)	1.4×10^{-25}	0.005	1×10^{-6}
C_{60} molecule	1.2×10^{-24}	210	3×10^{-12}
oligoporphyrin	4×10^{-23}	260	6×10^{-14}
nanoparticles?	10^{-18}		
⋮	⋮	⋮	⋮
soccer ball	0.5	20	7×10^{-35}


electron


neutron

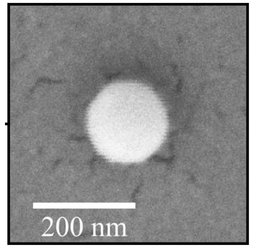

atom


C60



oligoporphyrin

Fein et al, Nat Phys 15, 1242 (2019)



nanoparticle

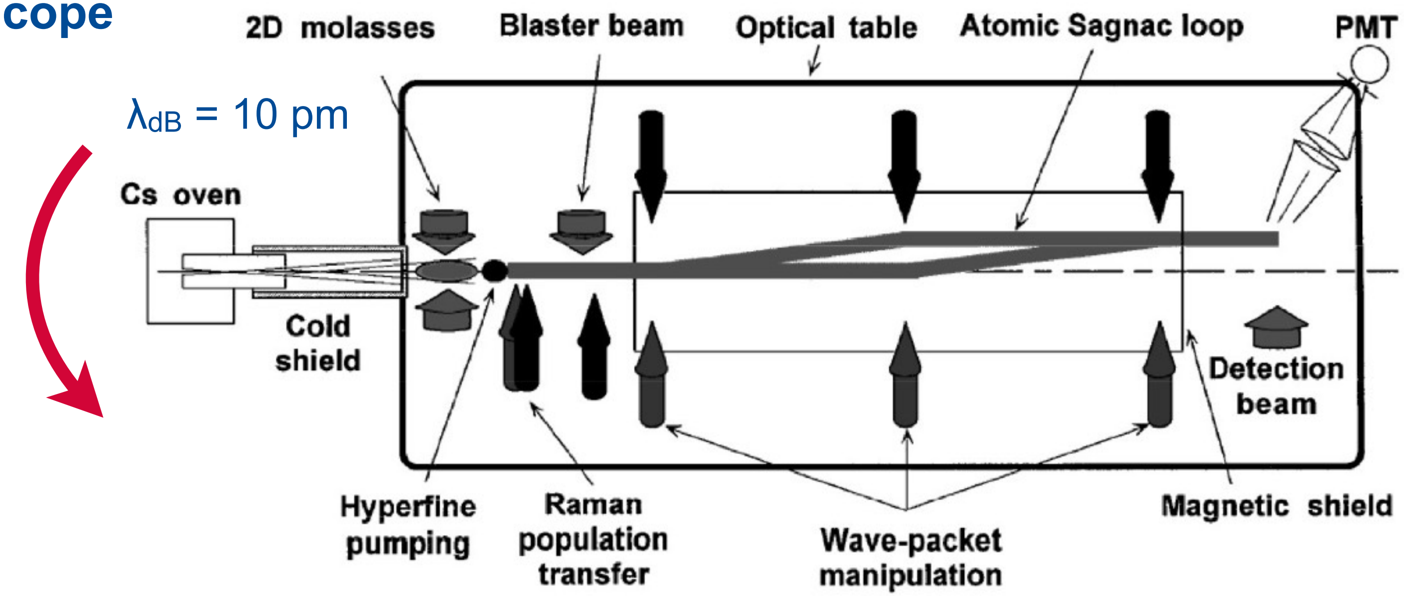
Delić et al, Science 367, 892 (2020)

Atom interferometry: matter waves for precision measurement

Gyroscope

λ_{dB} = 10 pm

Rotation Ω



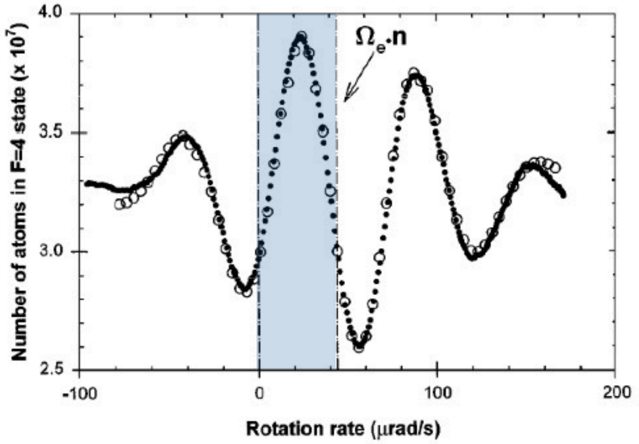
Gustavson et al, PRL 78, 2046 (1997)

Phase shift due to rotation

$$\Delta\phi = \frac{4\pi}{\lambda_{\mathrm{dB}} v}\,\Omega \cdot A$$

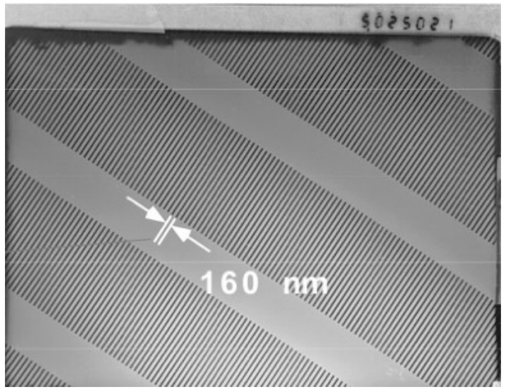
Sensitivity: $10^{-8}\,(\mathrm{rad/s})/\sqrt{\mathrm{Hz}}$

today: $10^{-10}\,(\mathrm{rad/s})/\sqrt{\mathrm{Hz}}$



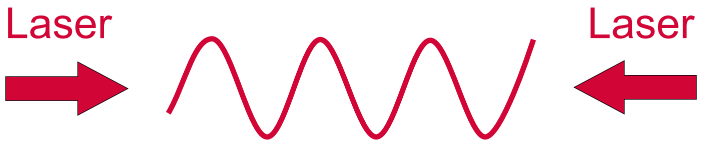
Beam splitter for atoms

Mechanical transmission grating



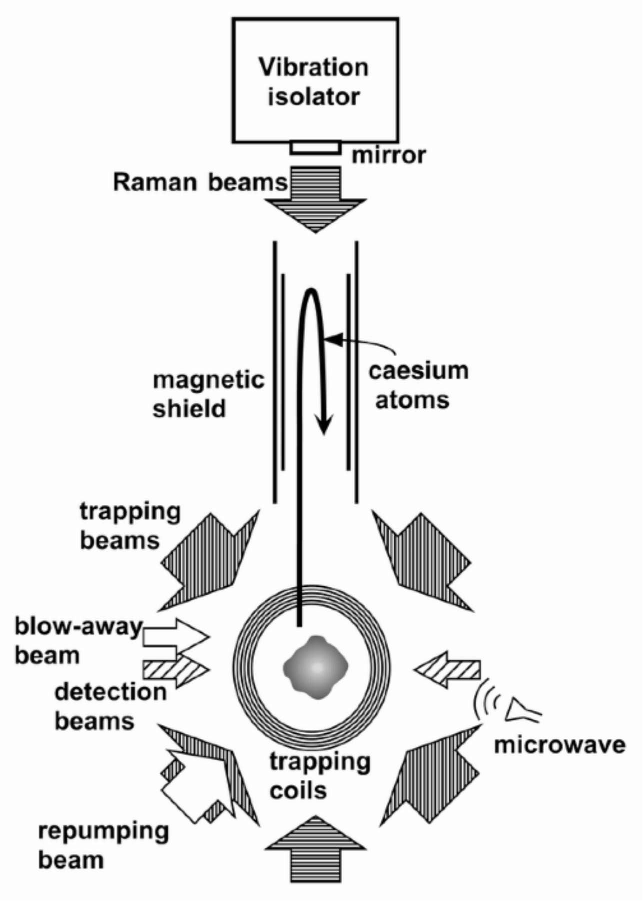
Pritchard et al.

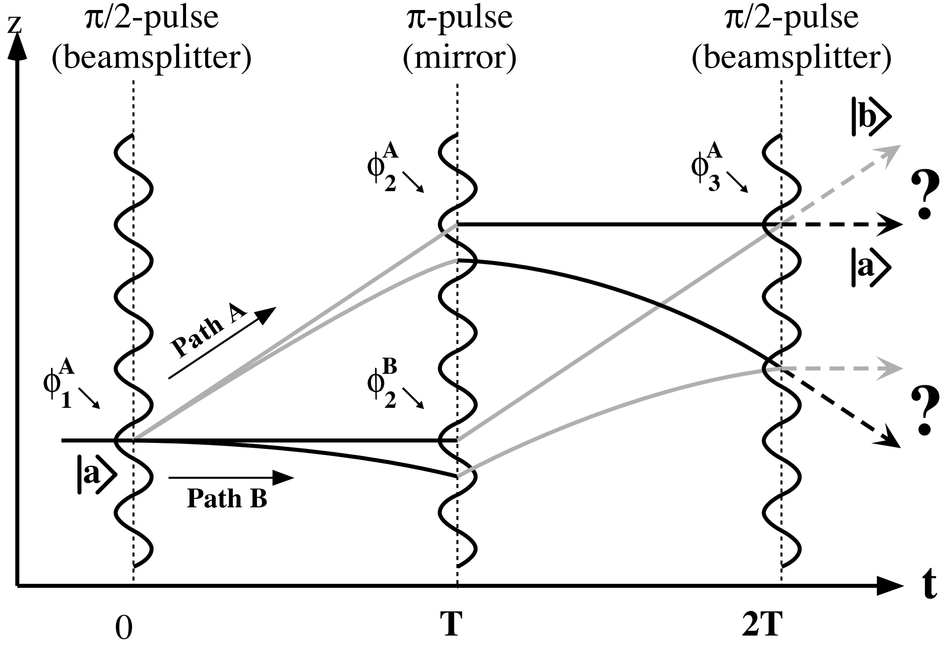
Counterpropagating laser beams



Bragg grating, Raman pulses, …

Atom interferometric measurement of gravity

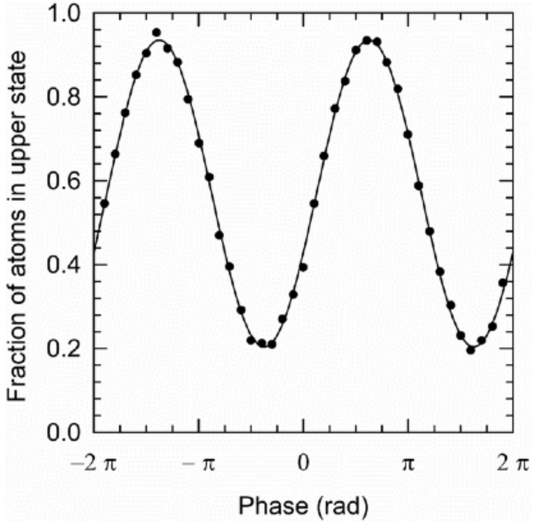


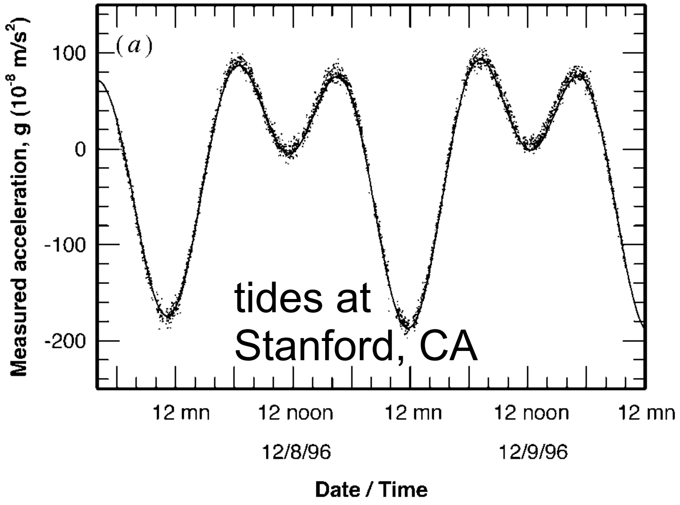


$$\Delta\phi = k_L g T^2$$

Phase shift due to gravitational acceleration g

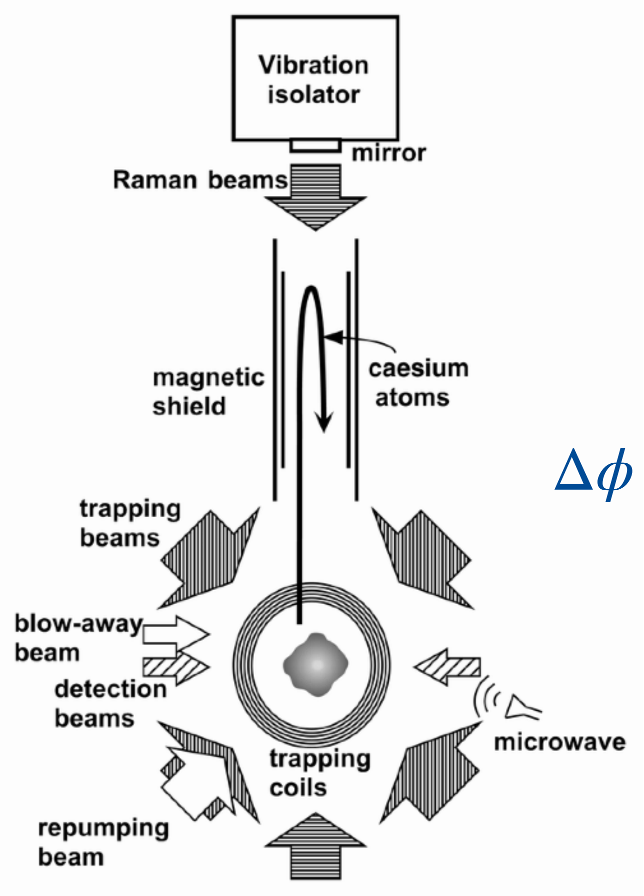
A. Peters et al, Nature 400, 849 (1999)





tides at Stanford, CA

Atom interferometric measurement of gravity



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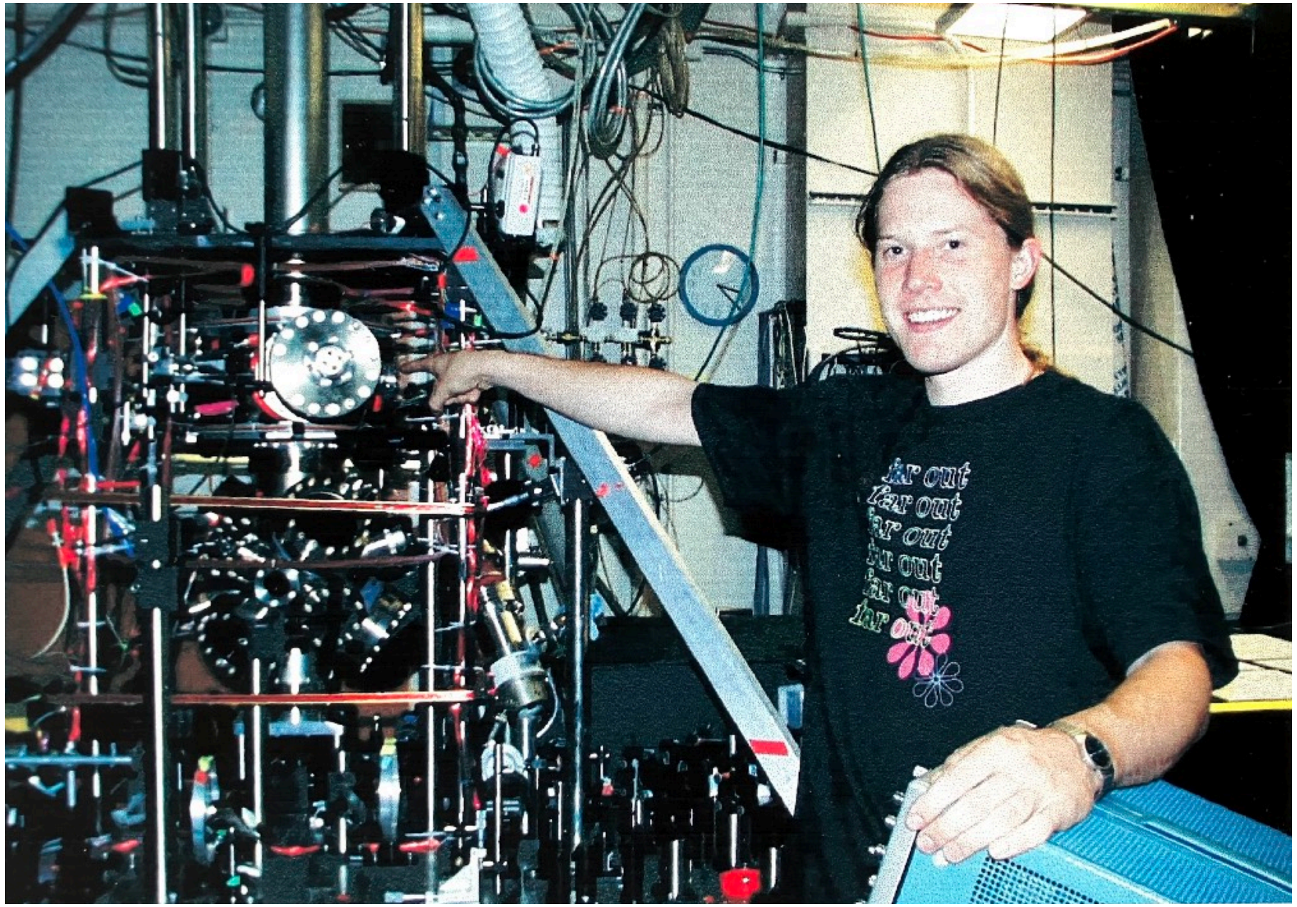


Stanford University, 2000

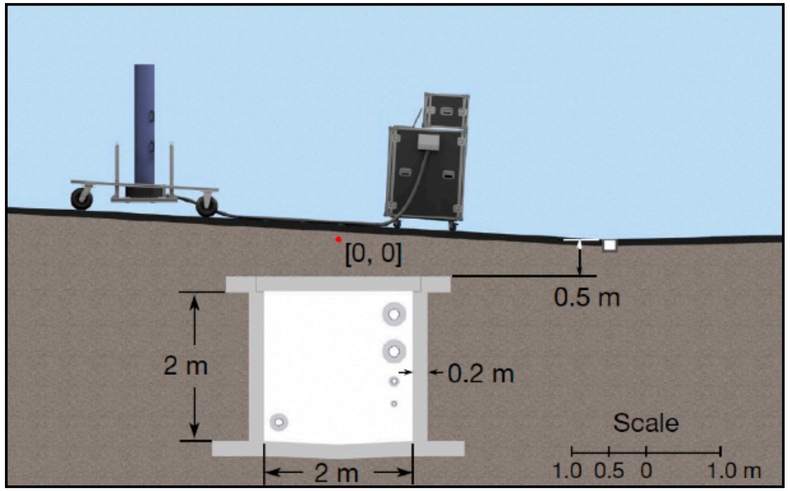
P. Treutlein, K.Y. Chung, and S. Chu, PRA 63, 051401 (2001)

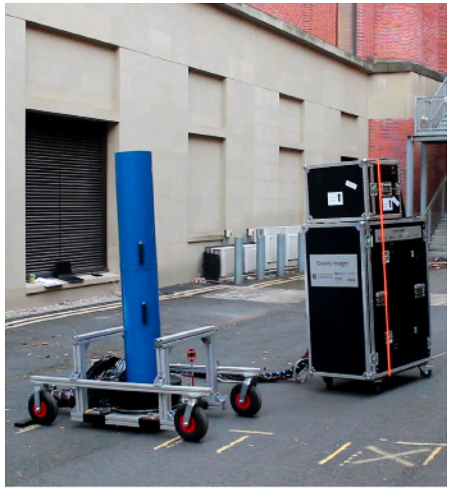
Applications: gravity cartography

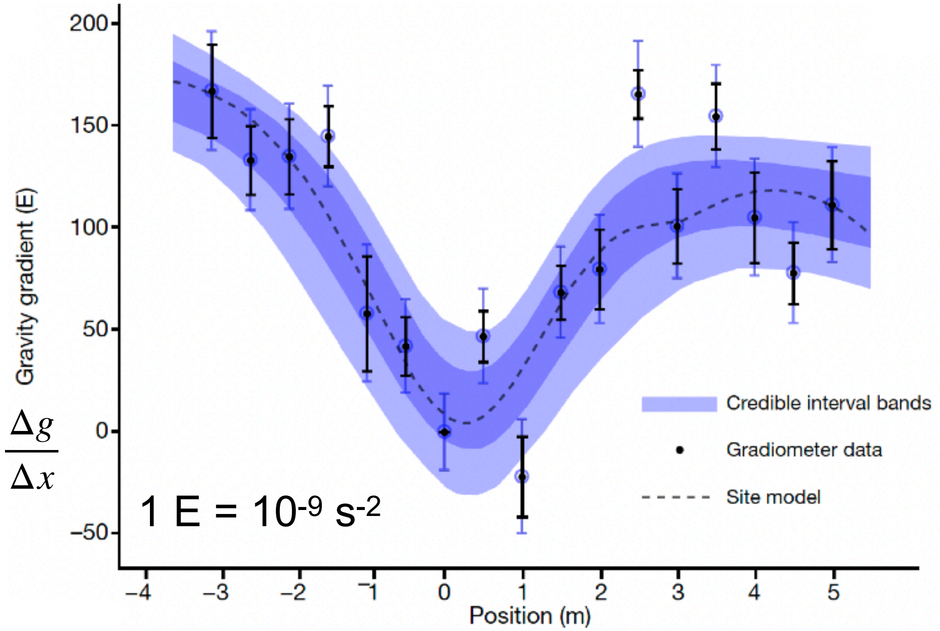
Detection of underground tunnel with an atom interferometer operated as a gravity gradiometer

Portable systems are commercially available

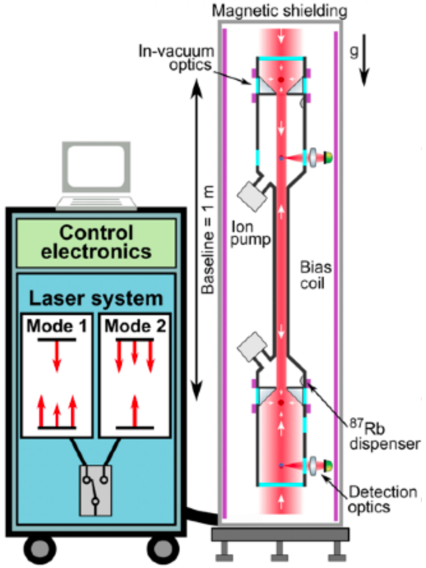
Stray et al, Nature 602, 590 (2020)



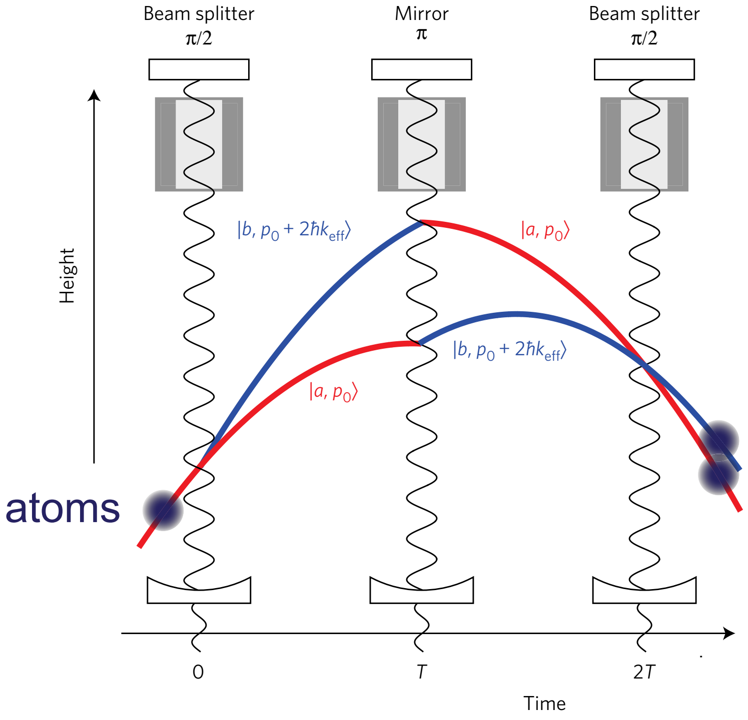




$1\ \mathrm{E} = 10^{-9}\ \mathrm{s}^{-2}$

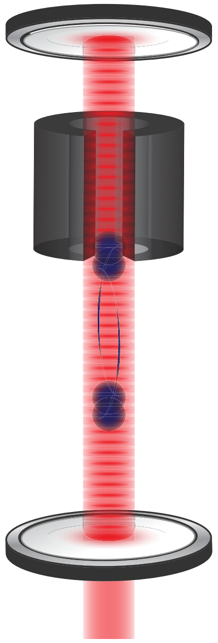


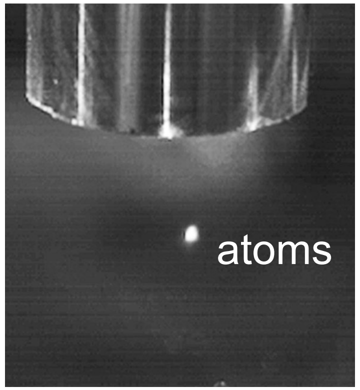
Search for new physics with atom interferometry

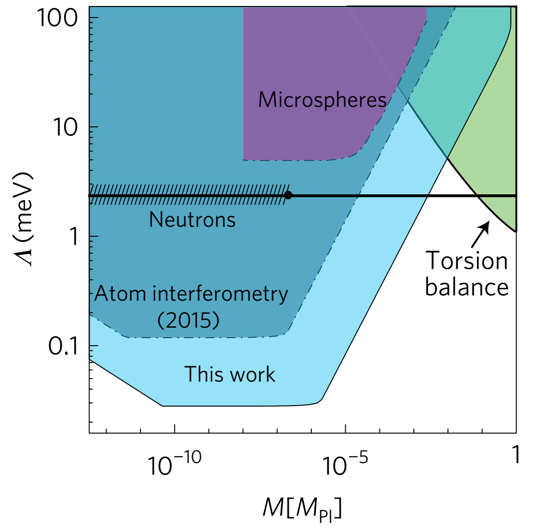


H. Müller and P. Haslinger,
Phys Unserer Zeit 49, 228 (2018)

$$\Delta\phi = k_{\text{eff}} a T^2$$







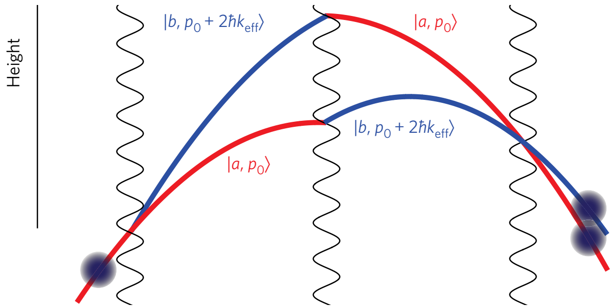
Chameleon scalar fields

Jaffe et al, Nat Phys 13, 938 (2017)

Search for new physics

- drifts of fundamental constants
- 5th force measurements
- dark energy models (chameleons, symmetrons…)
- Casimir Polder forces
- gravitational Aharonov-Bohm effect

Outline



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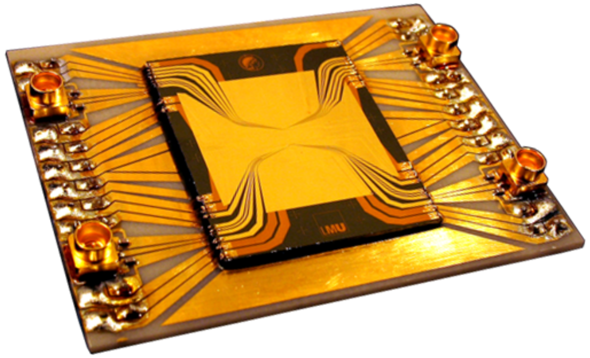
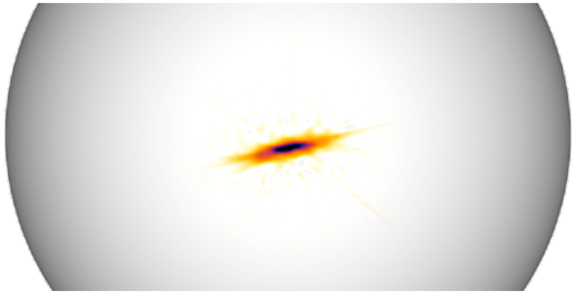


An atom interferometer on a microchip



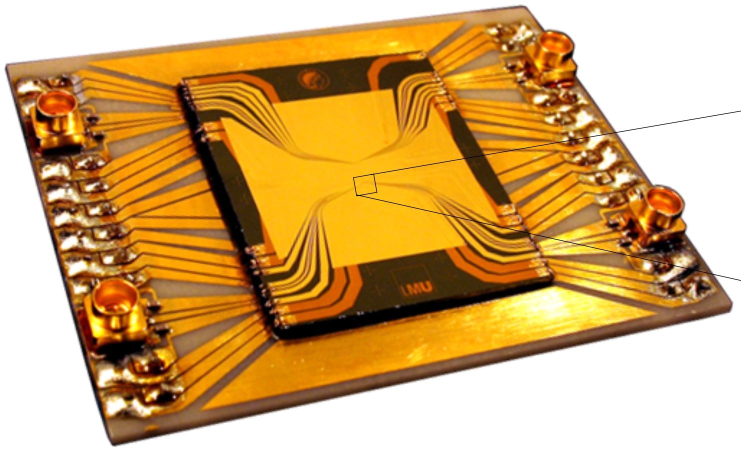
Quantum metrology:

Entanglement-enhanced interferometers

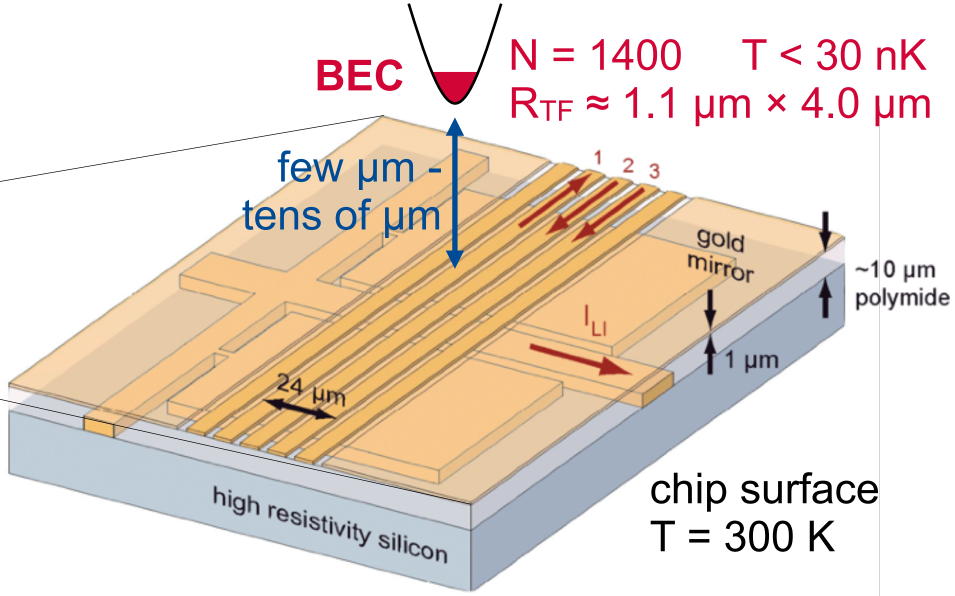
Quantum foundations with many-particle systems

Atom chips: a quantum laboratory on a microchip

Microfabricated wire pattern on a chip



Chip-based magnetic microtraps



Ultracold rubidium atoms at micrometer distance from a room-temperature chip surface

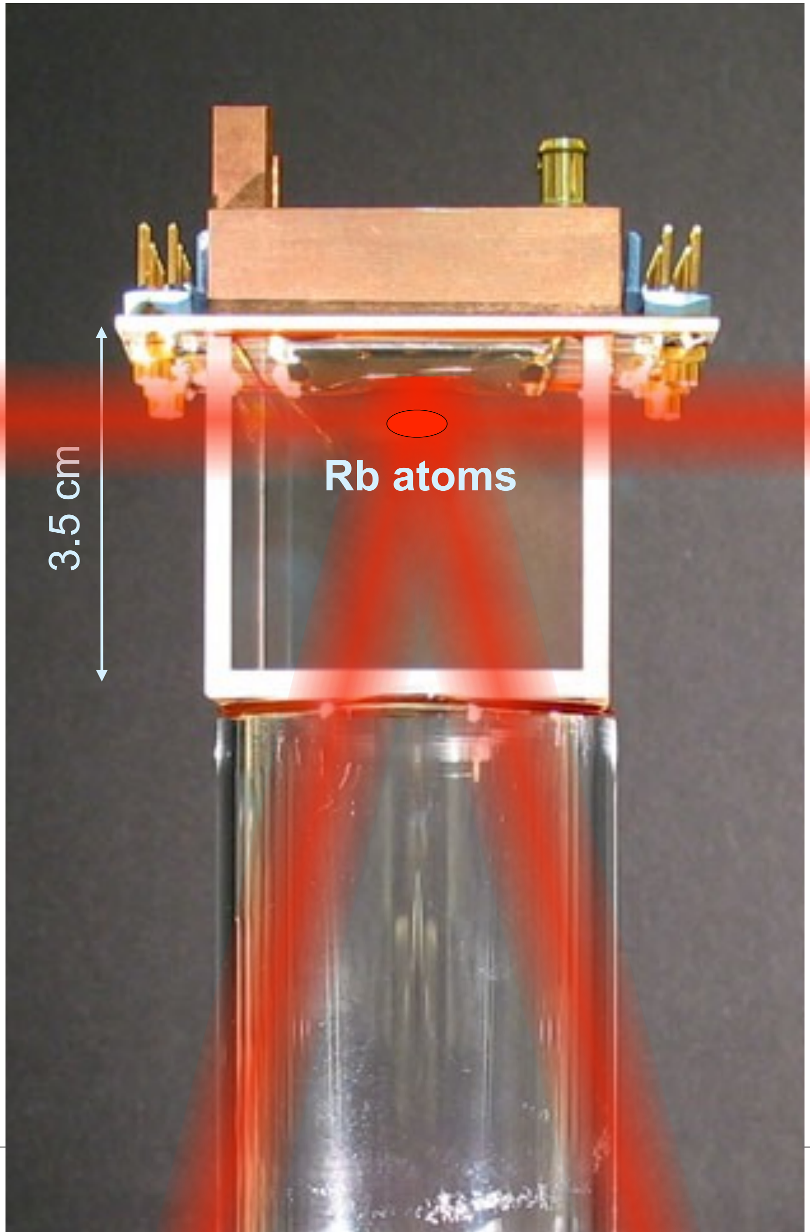
P. Treutlein et al, *Coherence in Microchip Traps*, Phys. Rev. Lett. 92, 203005 (2004).

Compact glass cell vacuum chamber

ultra-high vacuum
3 × 10^{-10} mbar

cooling laser beam

- mirror-MOT
- optical molasses
- optical pumping
- magnetic trap
- transport atoms
- evaporative cooling to Bose-Einstein condensation



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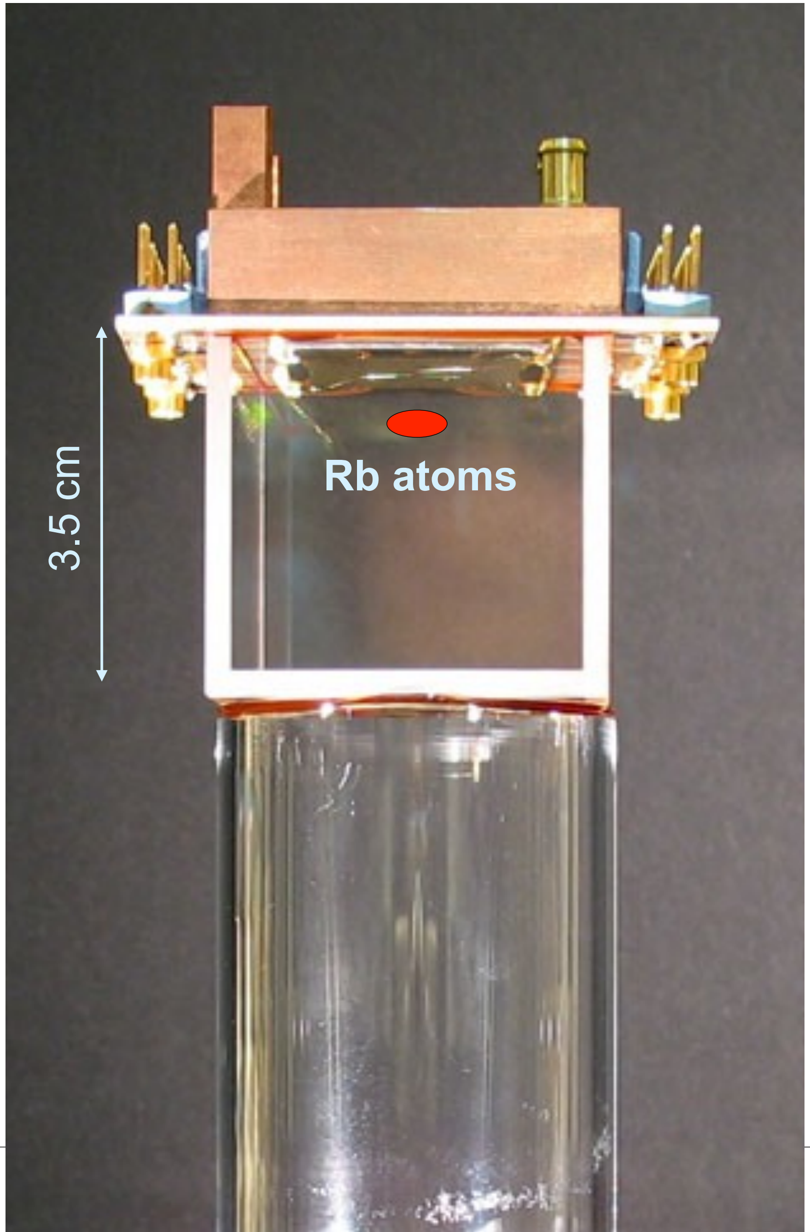
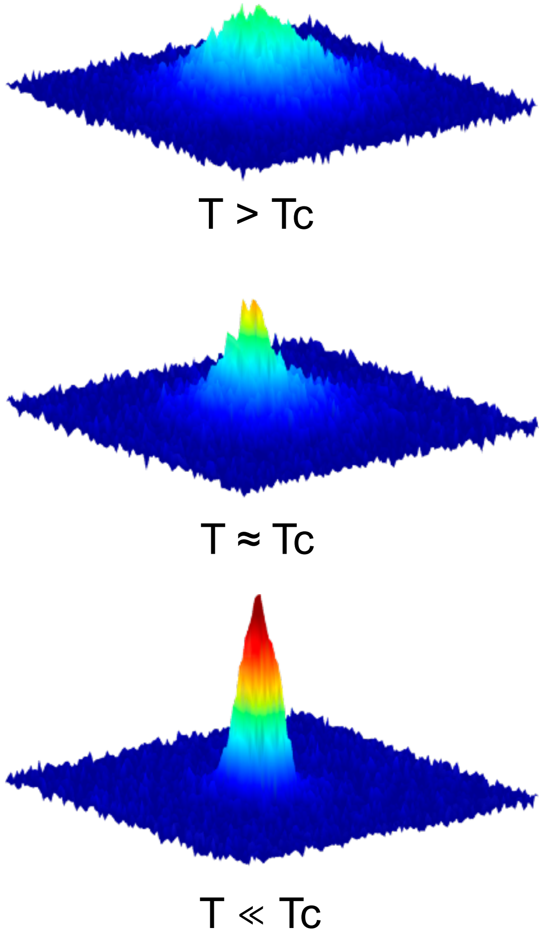




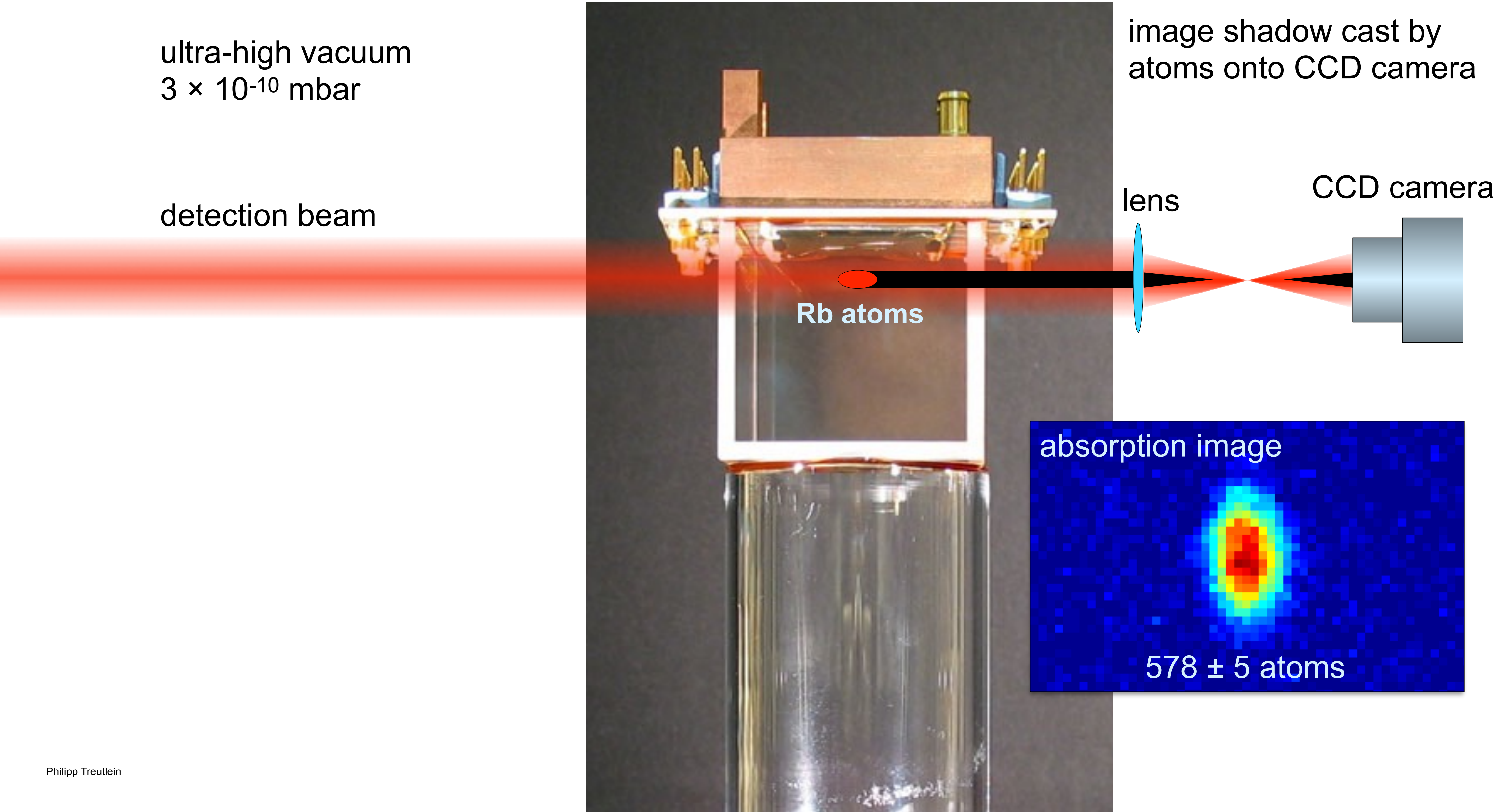
all degrees of freedom of atoms in well-defined quantum state

Detection: absorption imaging

ultra-high vacuum
3 × 10^{-10} mbar

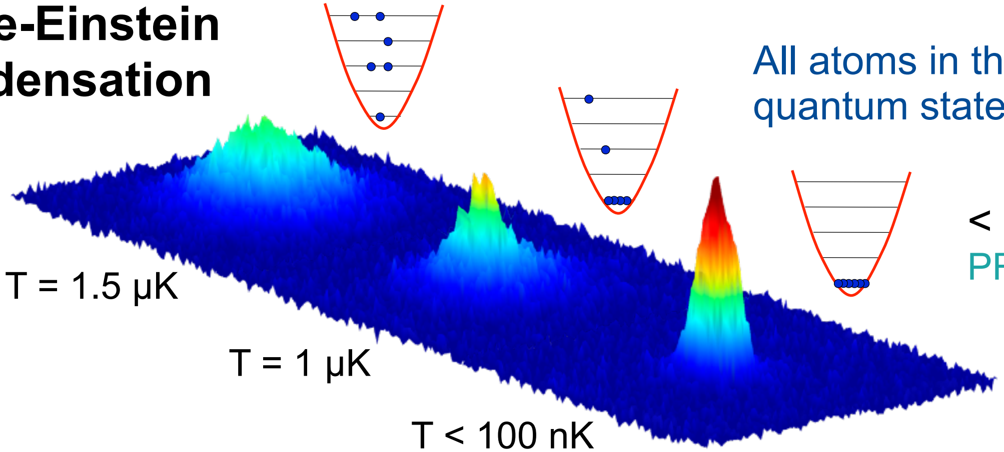
detection beam

image shadow cast by
atoms onto CCD camera



Two-component Bose-Einstein condensate of ^{87}Rb atoms

Bose-Einstein condensation

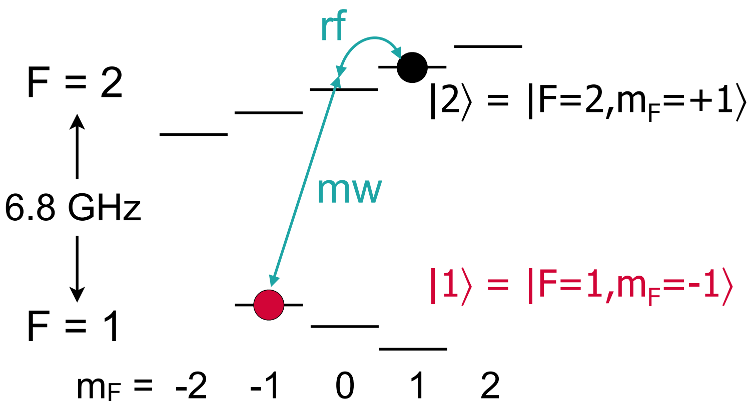


All atoms in the same quantum state

< 2% thermal fraction
PRA 93, 043624 (2016)

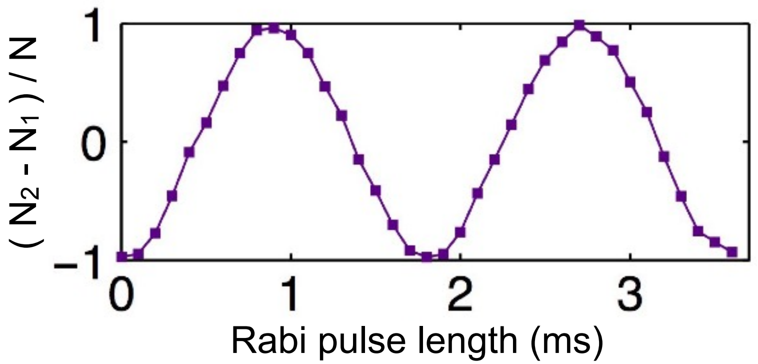
Quantum control of
- **internal state**
- **motion**
- **collisions**

^{87}Rb ground-state hyperfine structure



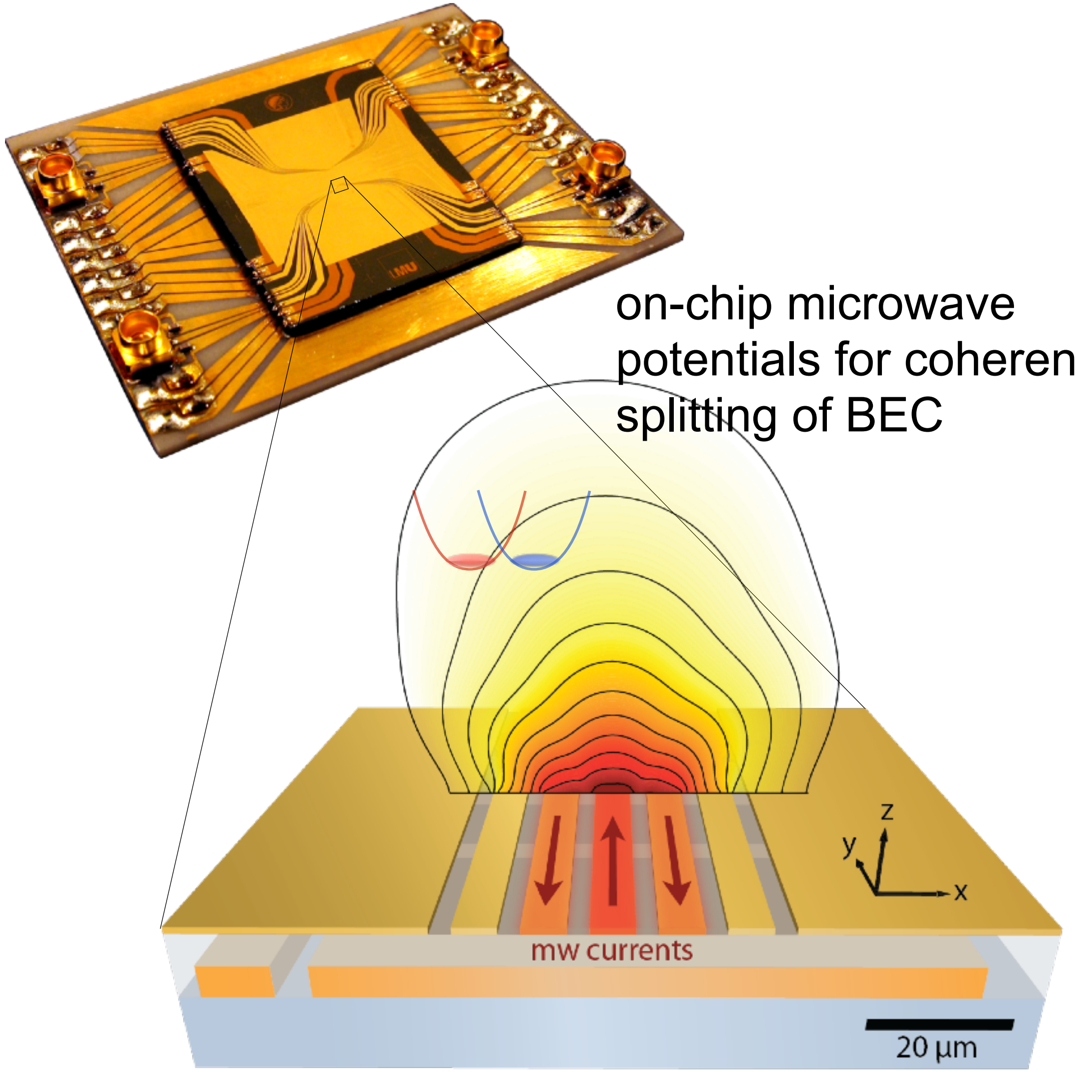
Rabi oscillations

fidelity of π/2-pulse: (99.74±0.04) %



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

An trapped-atom interferometer on a microchip



on-chip microwave potentials for coherent splitting of BEC

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

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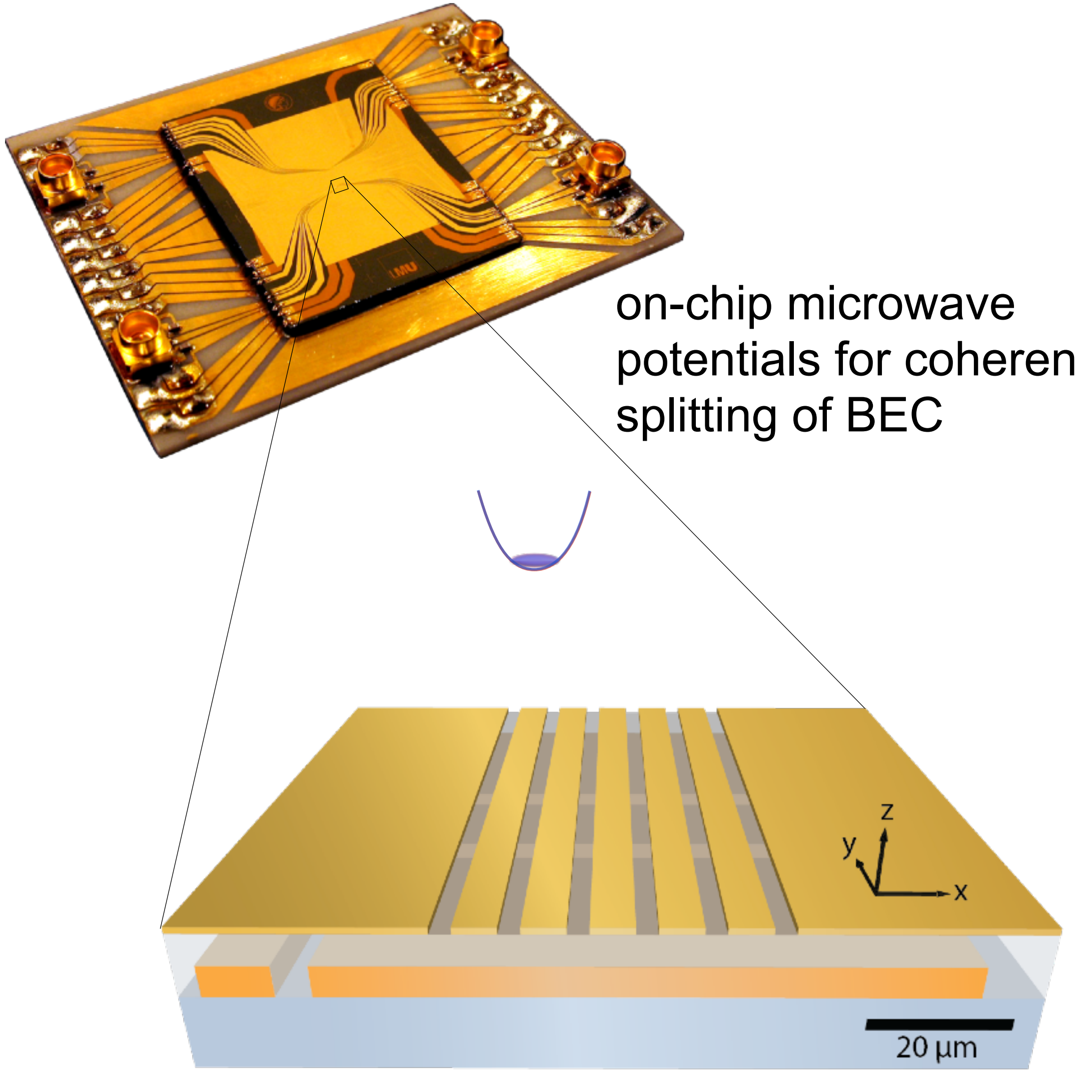

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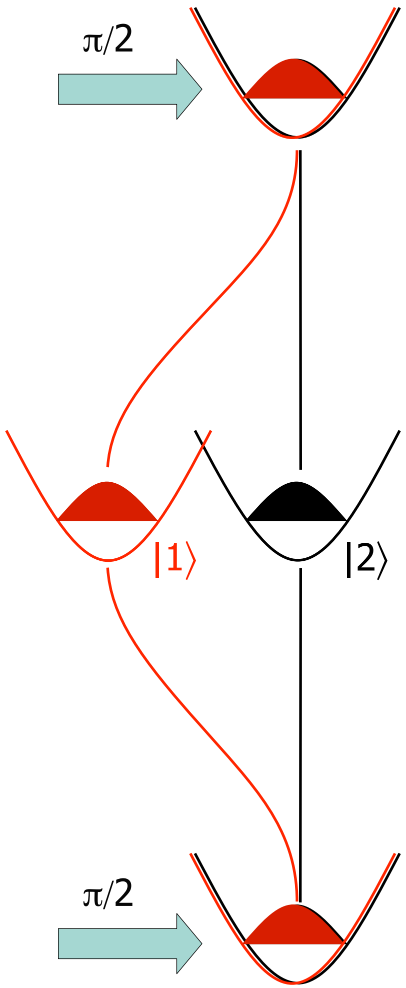
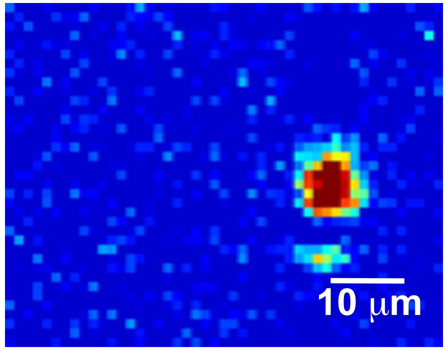
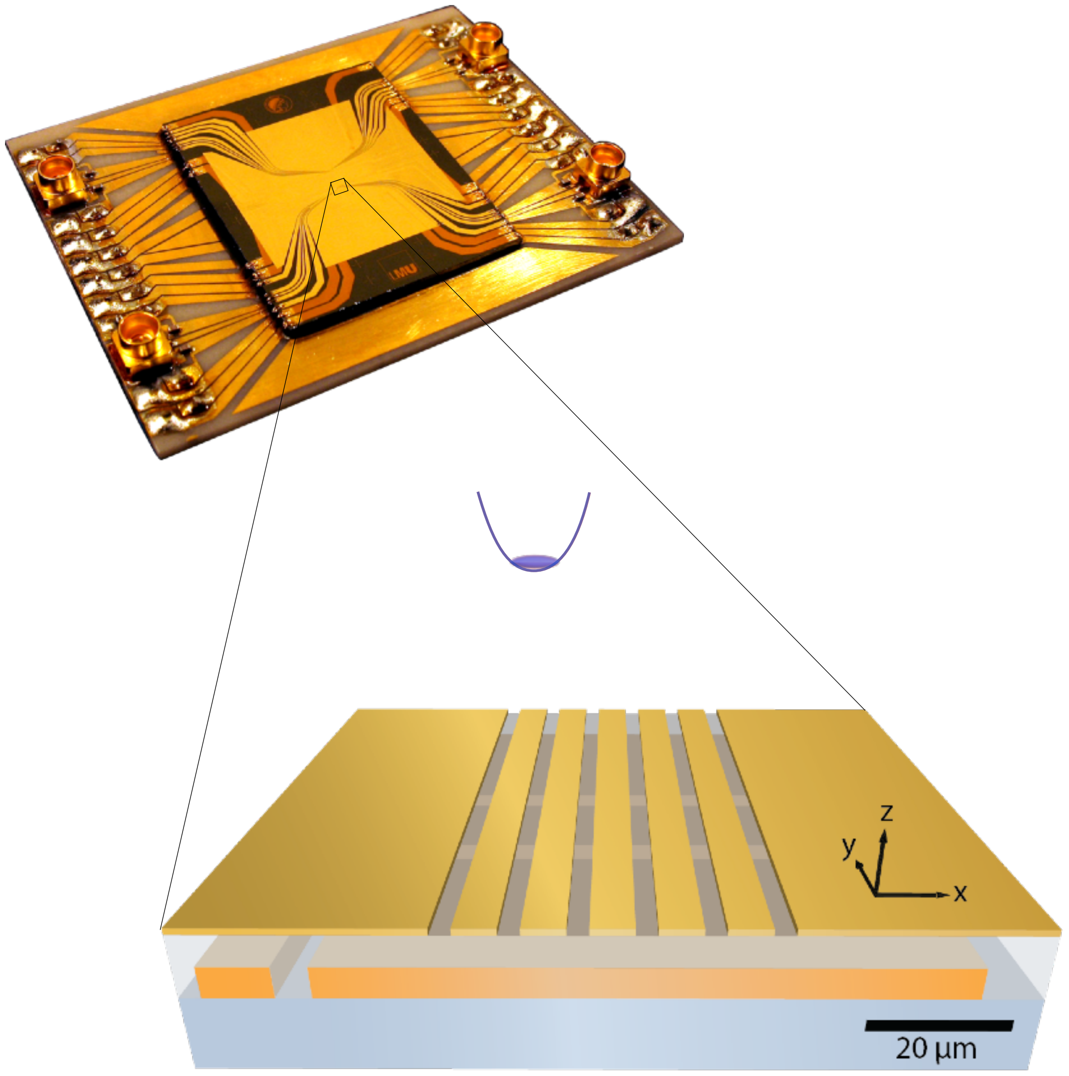


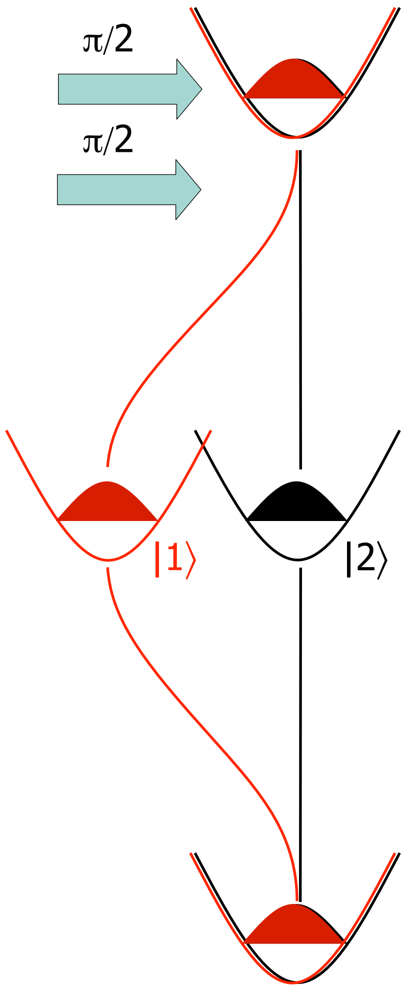


in-situ images of BEC with 350 atoms during splitting

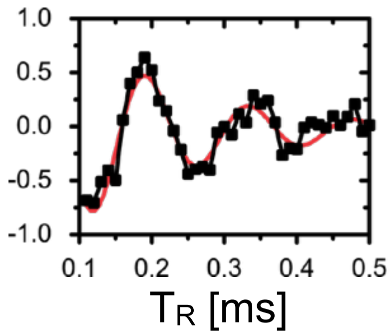
P. Böhi et al, Nature Physics 5, 592 (2009)

An atom interferometer on a microchip

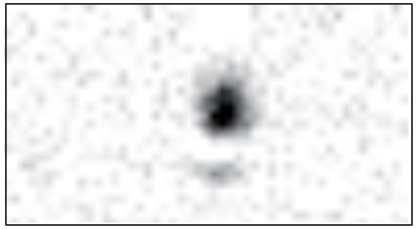




Ramsey fringes



in-situ images



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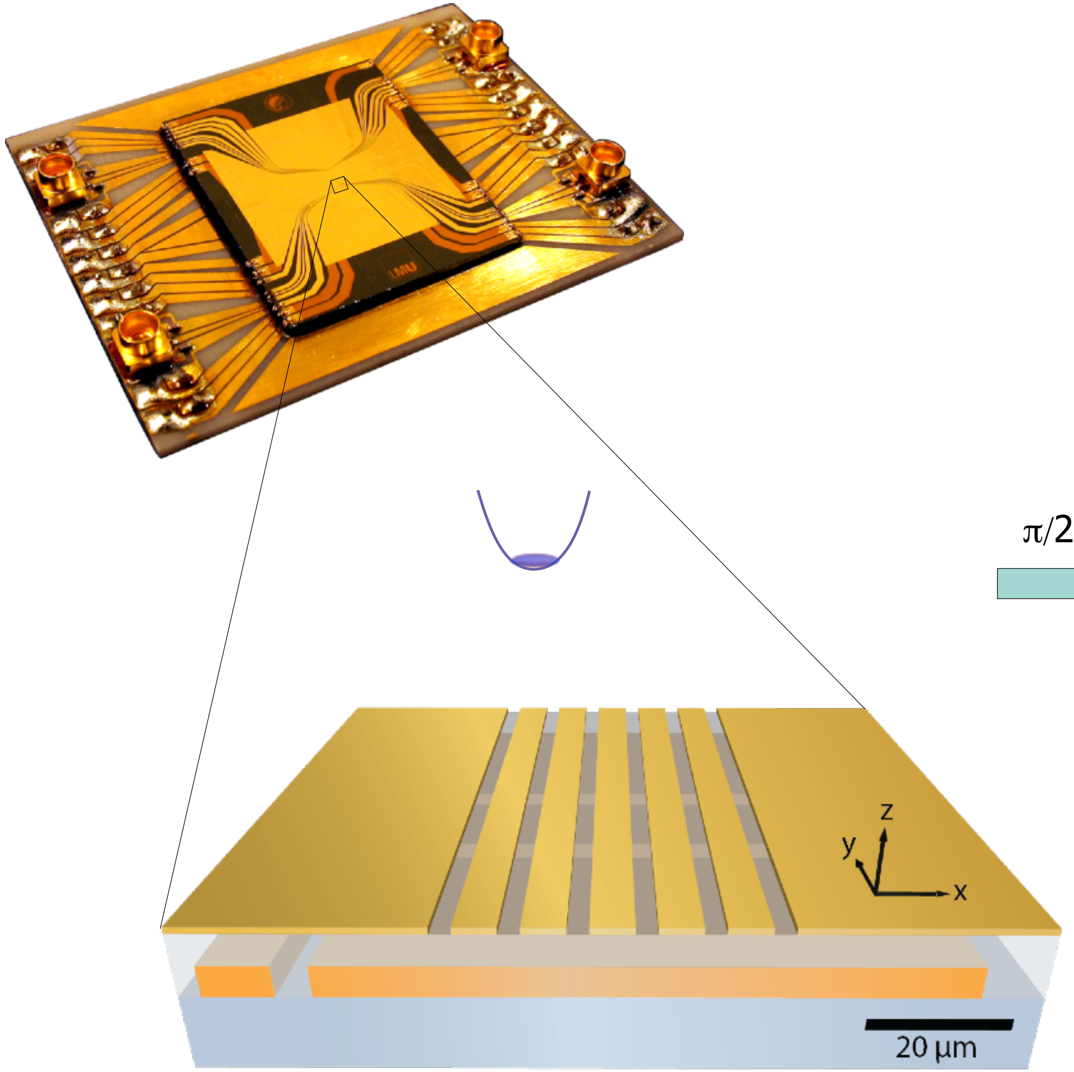

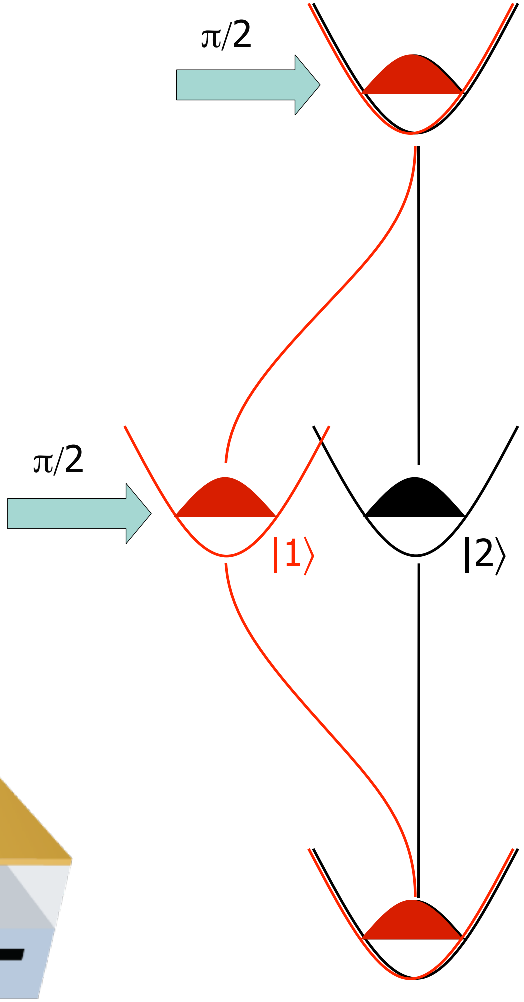

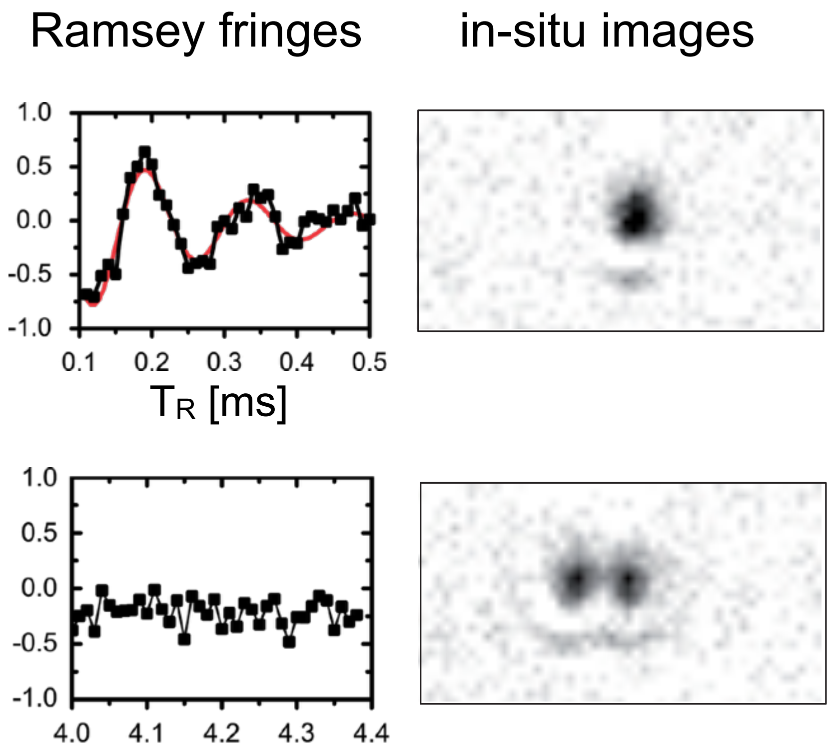

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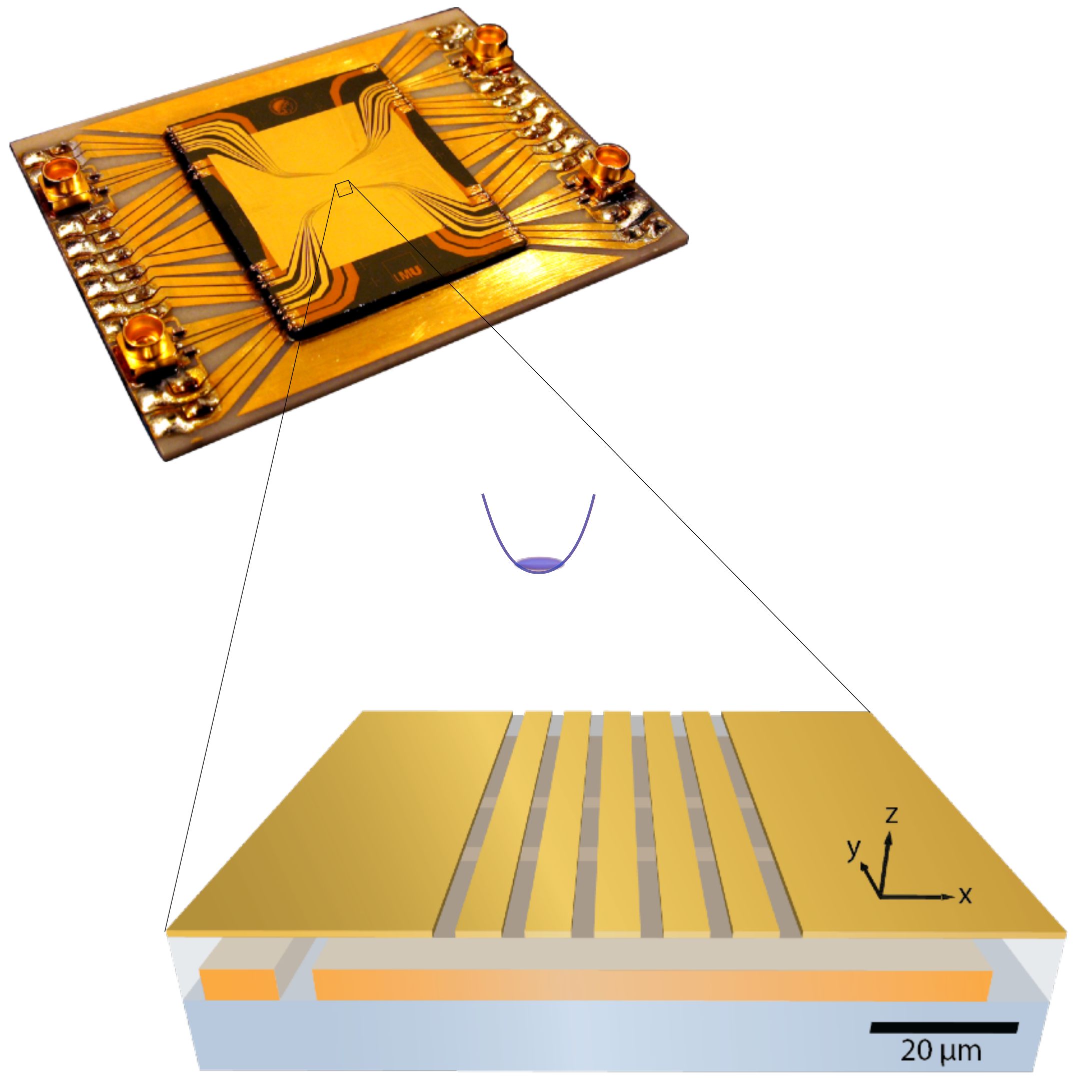

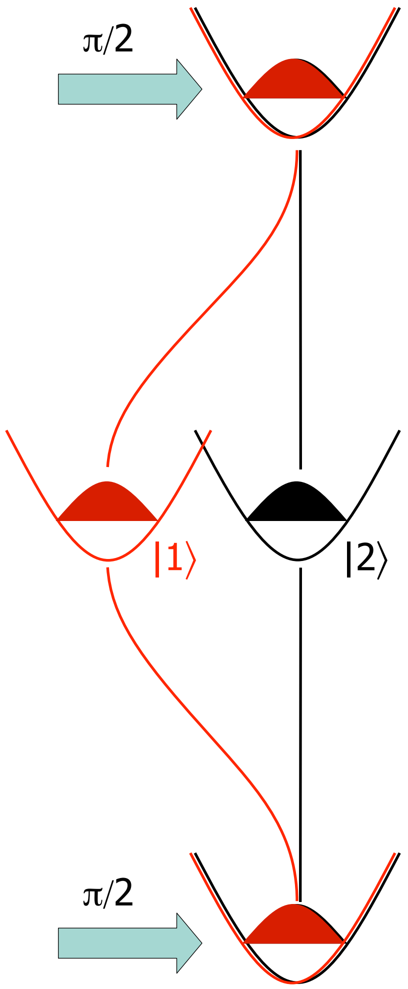

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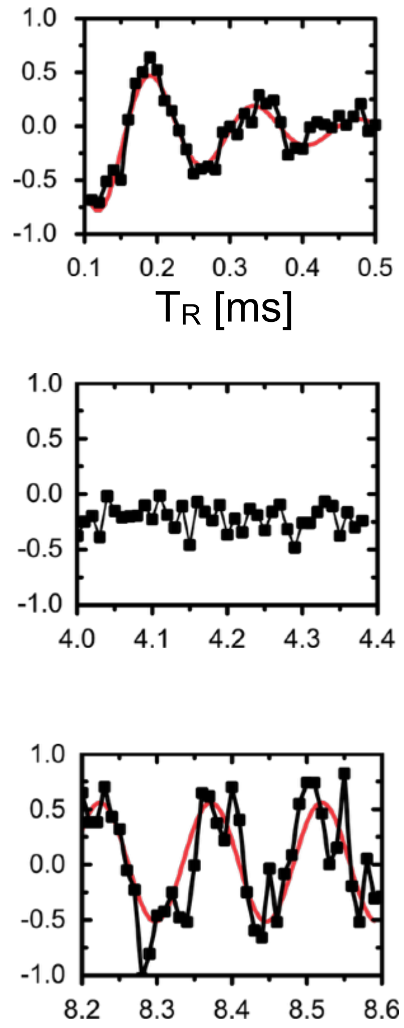

in-situ images

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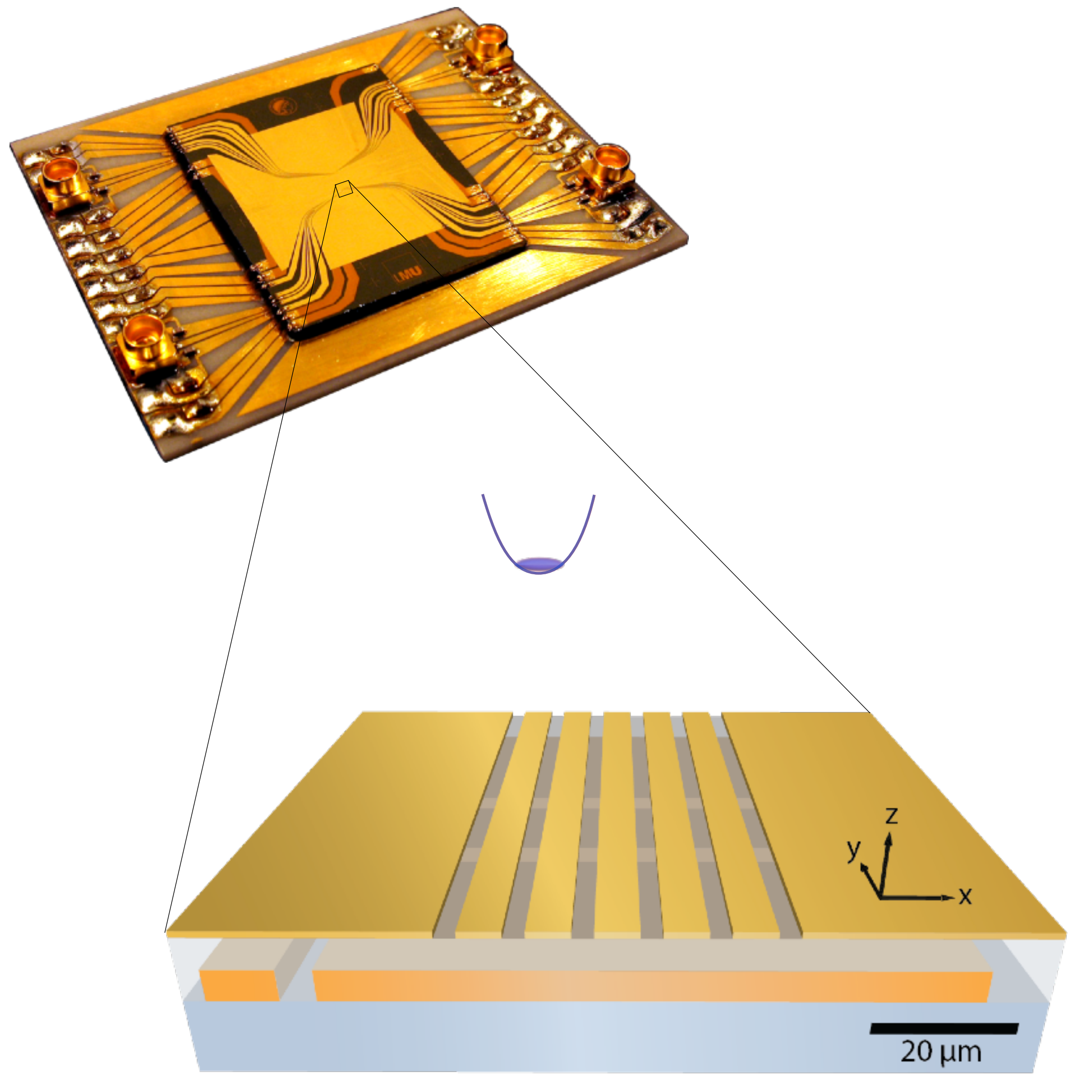

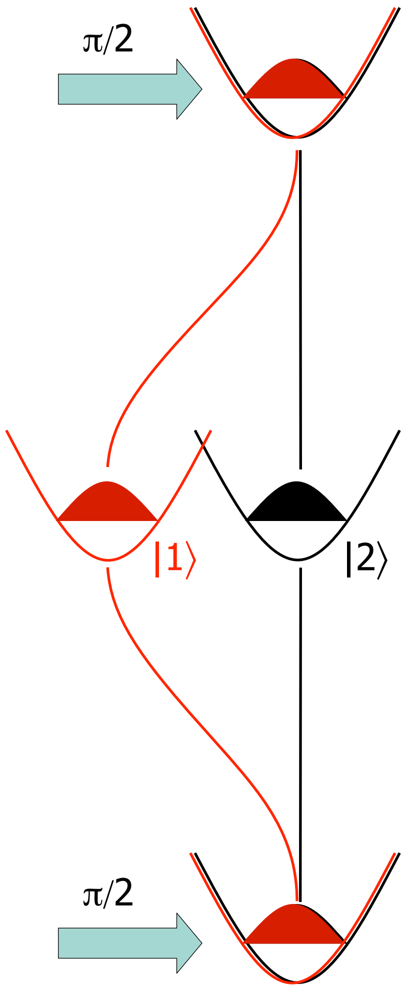

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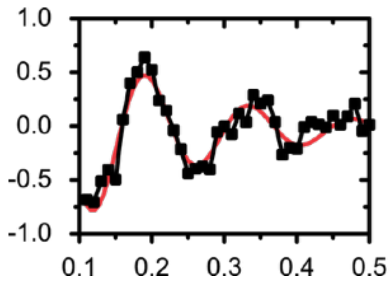
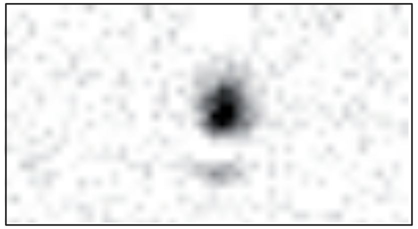
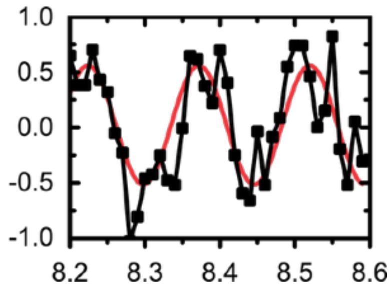
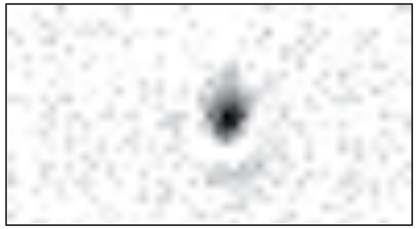




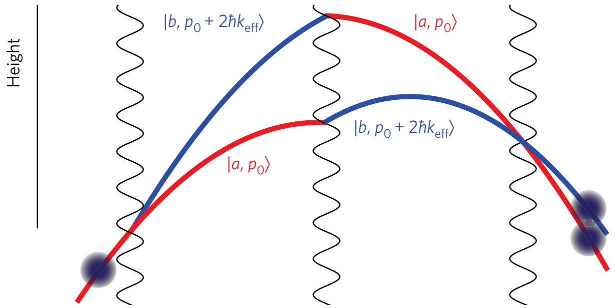
- compact setup
- high spatial resolution
- long interrogation times
- atom-atom interactions?





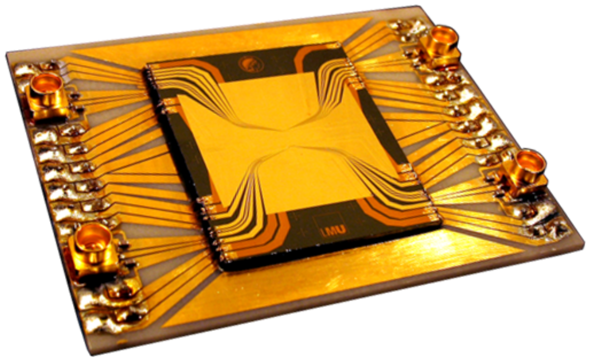
P. Böhi et al, Nature Physics 5, 592 (2009)

Outline

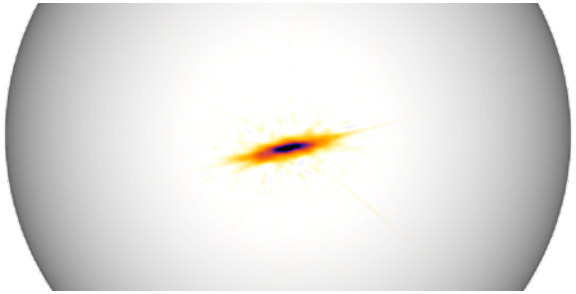


Atom interferometry:

Matter waves for precision measurements



An atom interferometer on a microchip

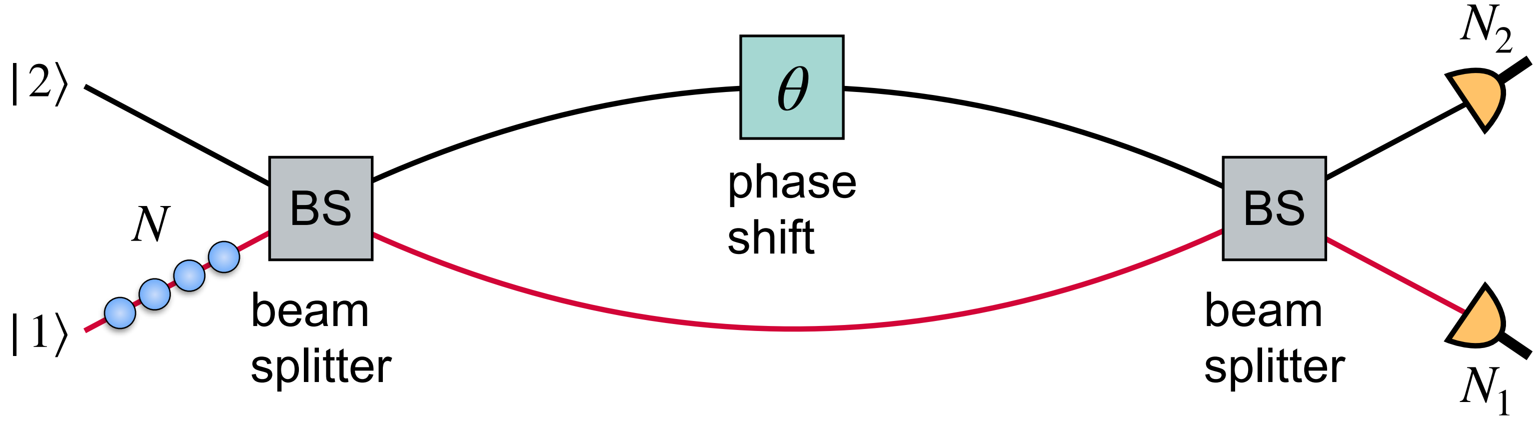


Quantum metrology:

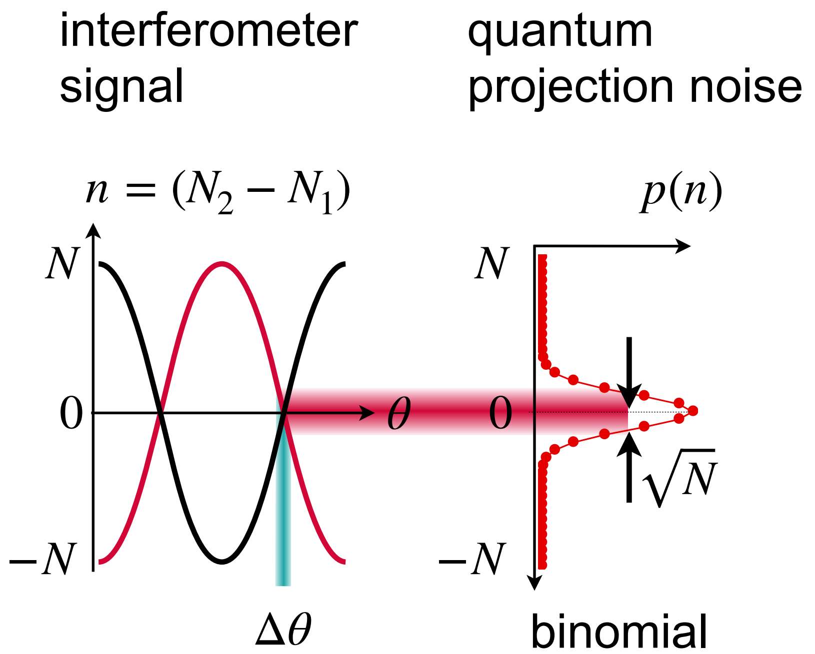
Entanglement-enhanced interferometers

Quantum foundations with many-particle systems

The standard quantum limit (SQL)



$$|1\rangle^N \qquad (|1\rangle + |2\rangle)^N \qquad (|1\rangle + e^{-i\theta}|2\rangle)^N \qquad \left(i\sin\frac{\theta}{2}|1\rangle + \cos\frac{\theta}{2}|2\rangle\right)^N$$



binomial distribution

"tossing a coin N times"

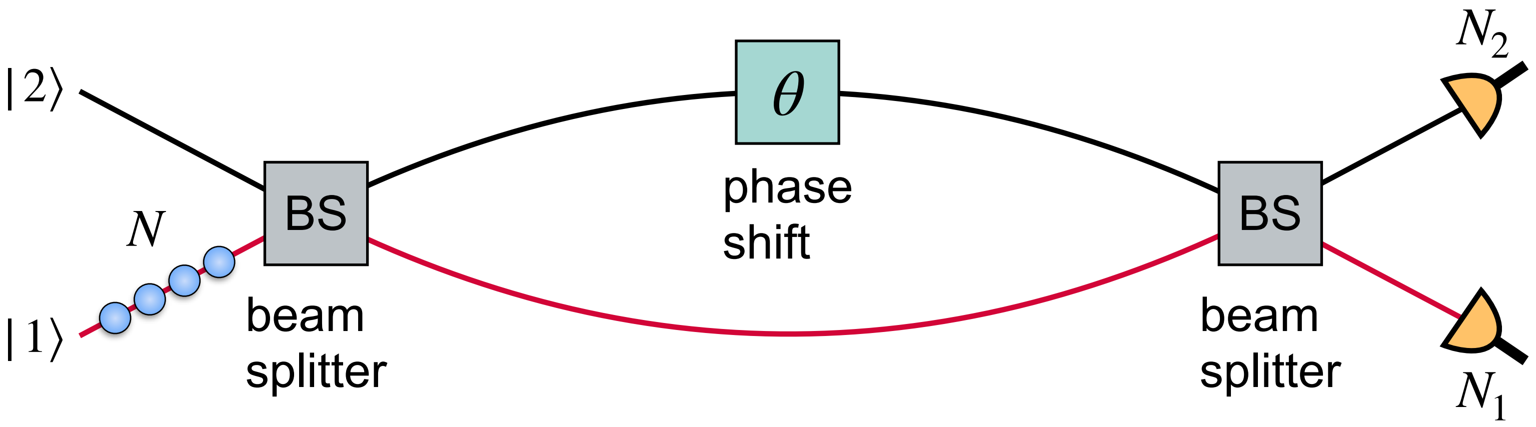
Phase uncertainty

$$\Delta\theta = \frac{\Delta n}{dn/d\theta} = \frac{1}{\sqrt{N}}$$

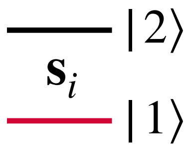
Standard quantum limit (SQL)

Pezzè, Smerzi, Oberthaler, Schmied, and Treutlein, Rev Mod Phys 90, 035005 (2018)

The standard quantum limit (SQL)

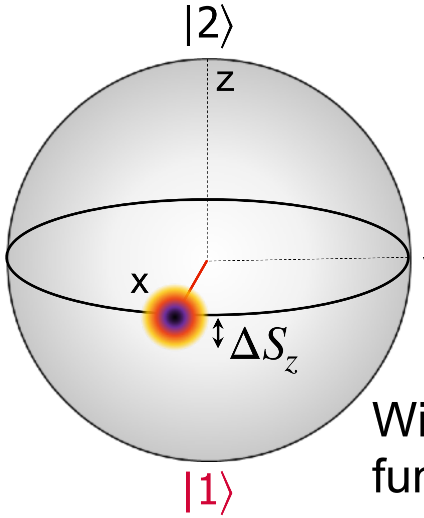


Collective spin description



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

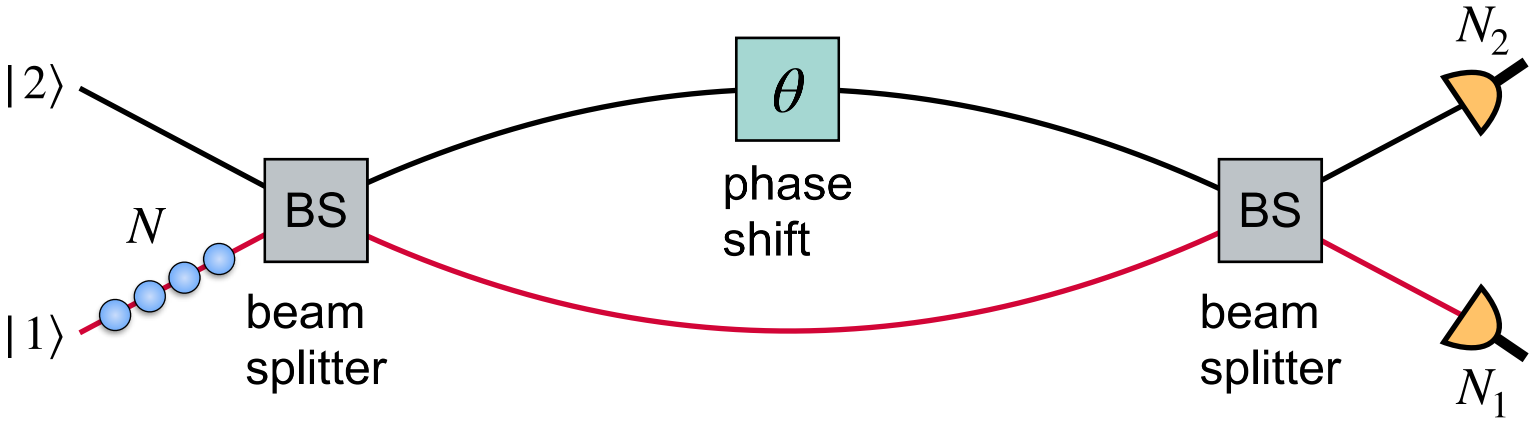
$$S_z = \frac{1}{2}(N_2 - N_1)$$



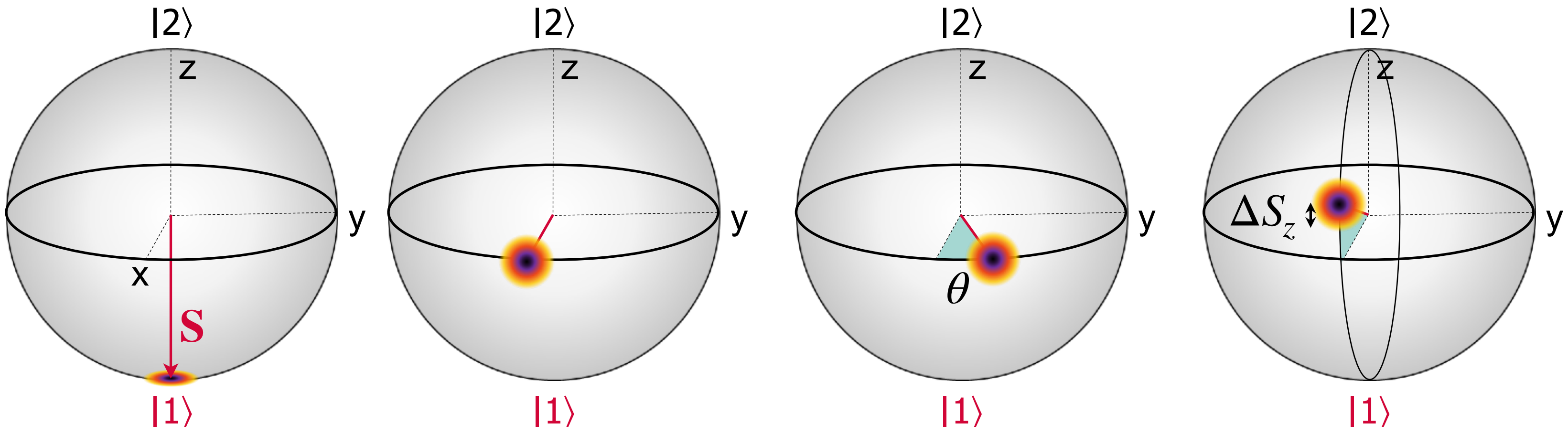
Wigner function

Pezzè, Smerzi, Oberthaler, Schmied, and Treutlein, Rev Mod Phys 90, 035005 (2018)

The standard quantum limit (SQL)



Collective spin description



Phase uncertainty

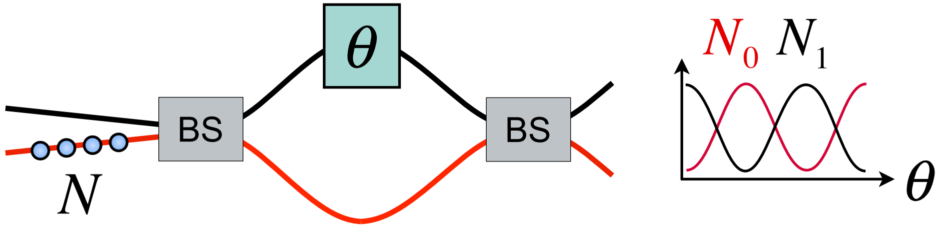
$$\Delta\theta \simeq \frac{\Delta S_z}{\langle S_x \rangle} = \frac{1}{\sqrt{N}}$$

Standard quantum limit (SQL)

Pezzè, Smerzi, Oberthaler, Schmied, and Treutlein, Rev Mod Phys 90, 035005 (2018)

Quantum metrology with entangled particles

Goal: use entanglement to improve interferometric measurements



Quantum metrology is useful if resources are limited:

- limited source brightness (limited N)
- systematic errors at large N
- small length scale → size limits N
- limited interrogation time T_R

Today's best atomic clocks and interferometers operate at or near the standard quantum limit

Standard quantum limit (SQL)

$$\Delta\theta \geq \frac{1}{\sqrt{N}}$$

independent particles

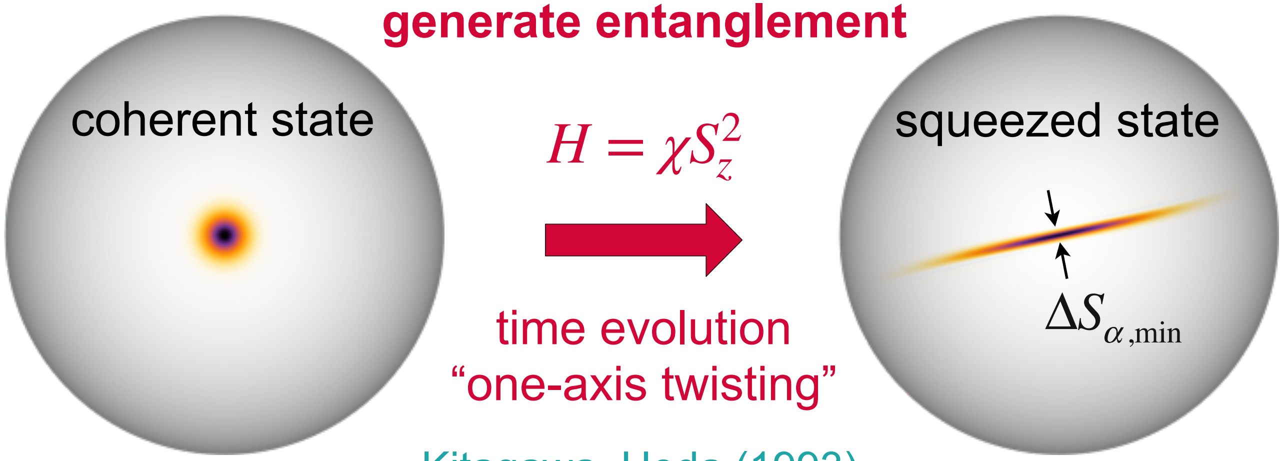
⇩

Heisenberg limit (HL)

$$\Delta\theta \geq \frac{1}{N}$$

entangled particles

Spin squeezing



atomic collisions generate entanglement

$H = \chi S_z^2$

time evolution
“one-axis twisting”

Kitagawa, Ueda (1993)

$\xi^2 = 1$

$\xi^2 < 1$

Spin-squeezing parameter
Wineland, Bollinger, Itano (1992)

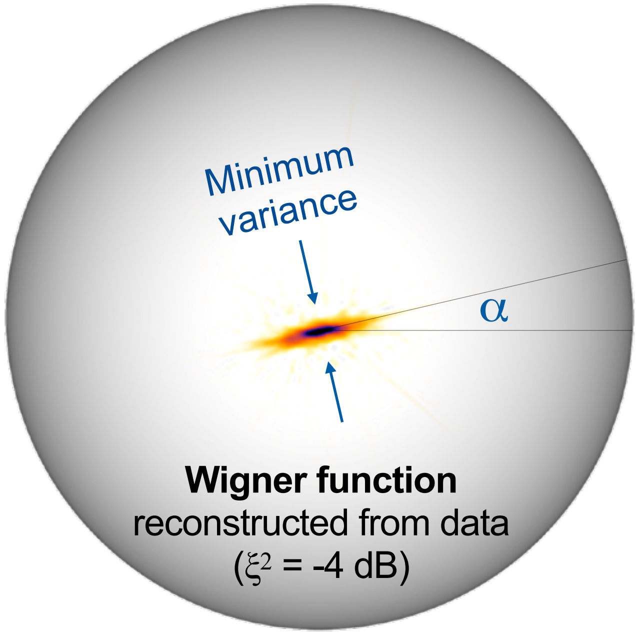
$$\boxed{\xi^2 \equiv \frac{N\left(\Delta S_{\alpha,\min}\right)^2}{\langle S_x\rangle^2}}$$

$$\xi^2 \propto \left(\frac{\text{Noise}}{\text{Signal}}\right)^2$$

$$\boxed{\Delta\theta = \frac{\xi}{\sqrt{N}}}$$

- useful resource for interferometry beyond standard quantum limit
- entanglement witness:
  $\xi^2 < 1$ → atoms entangled
  Sørensen, Duan, Cirac, Zoller (2001)

Tomography of spin-squeezed state

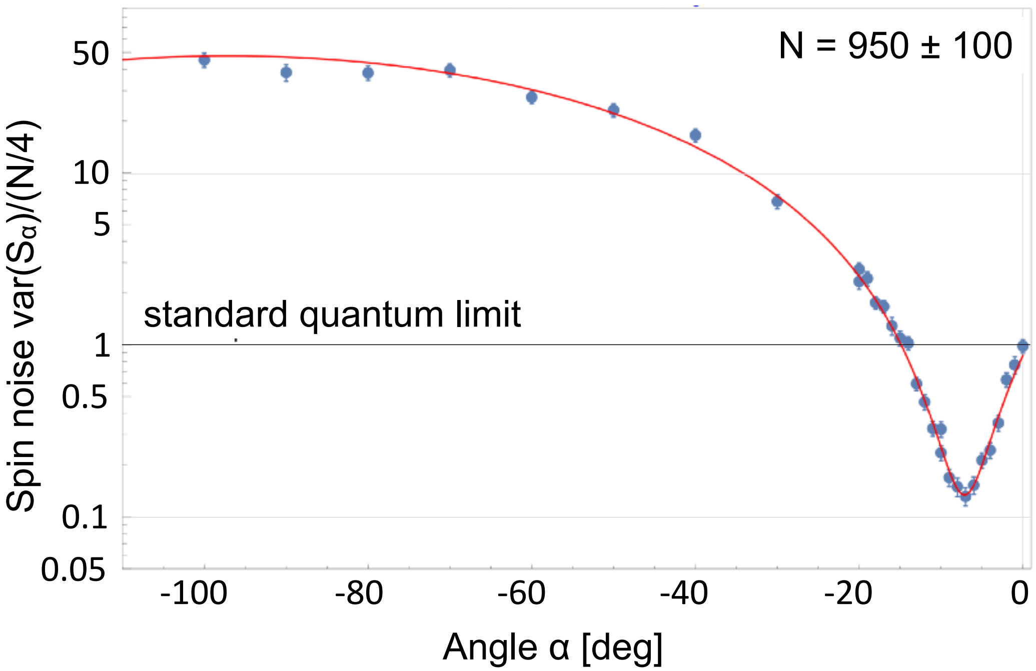


Wigner function
reconstructed from data
(ξ^2 = -4 dB)

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

Squeezing and tomography

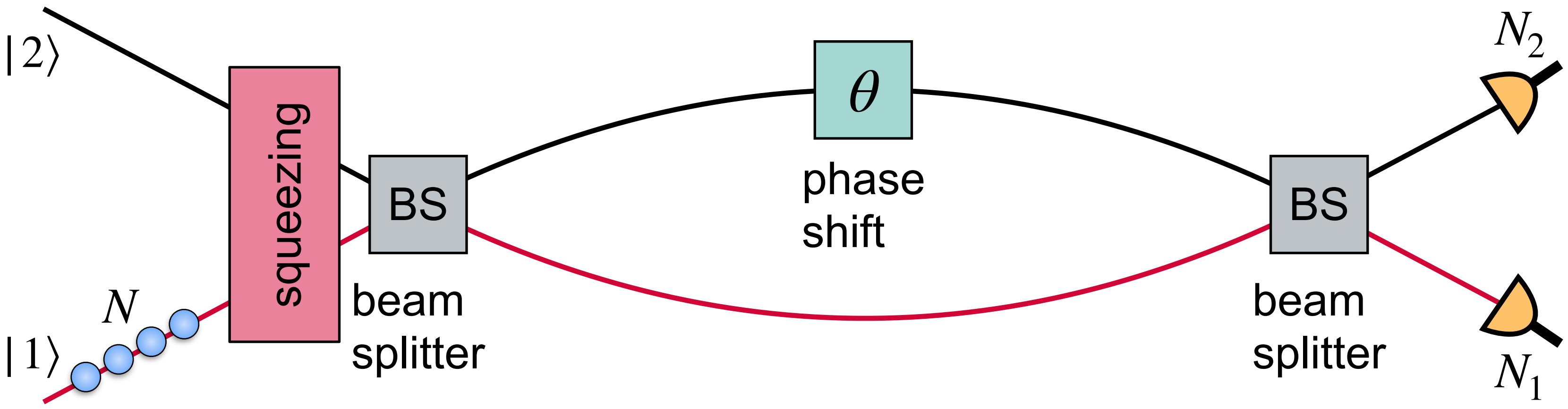
Riedel et al, Nature 464, 1170 (2010)
Schmied et al, New J Phys 13, 065019 (2011)

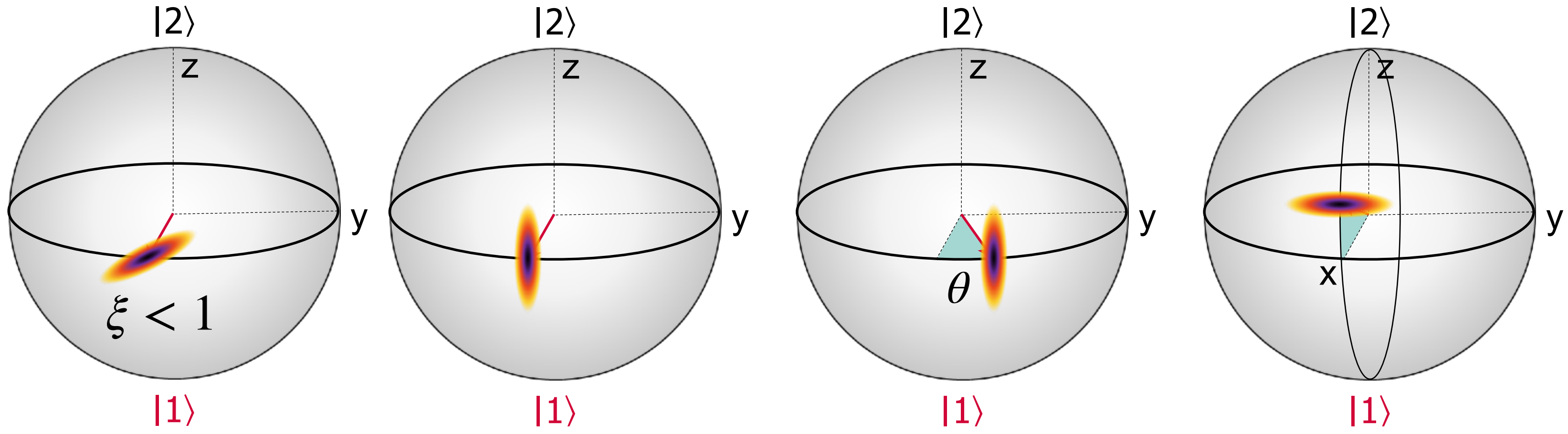


ξ^2 = -8.2 ± 0.5 dB
⇒ entanglement

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

Interferometer operating with a spin-squeezed state





Phase uncertainty

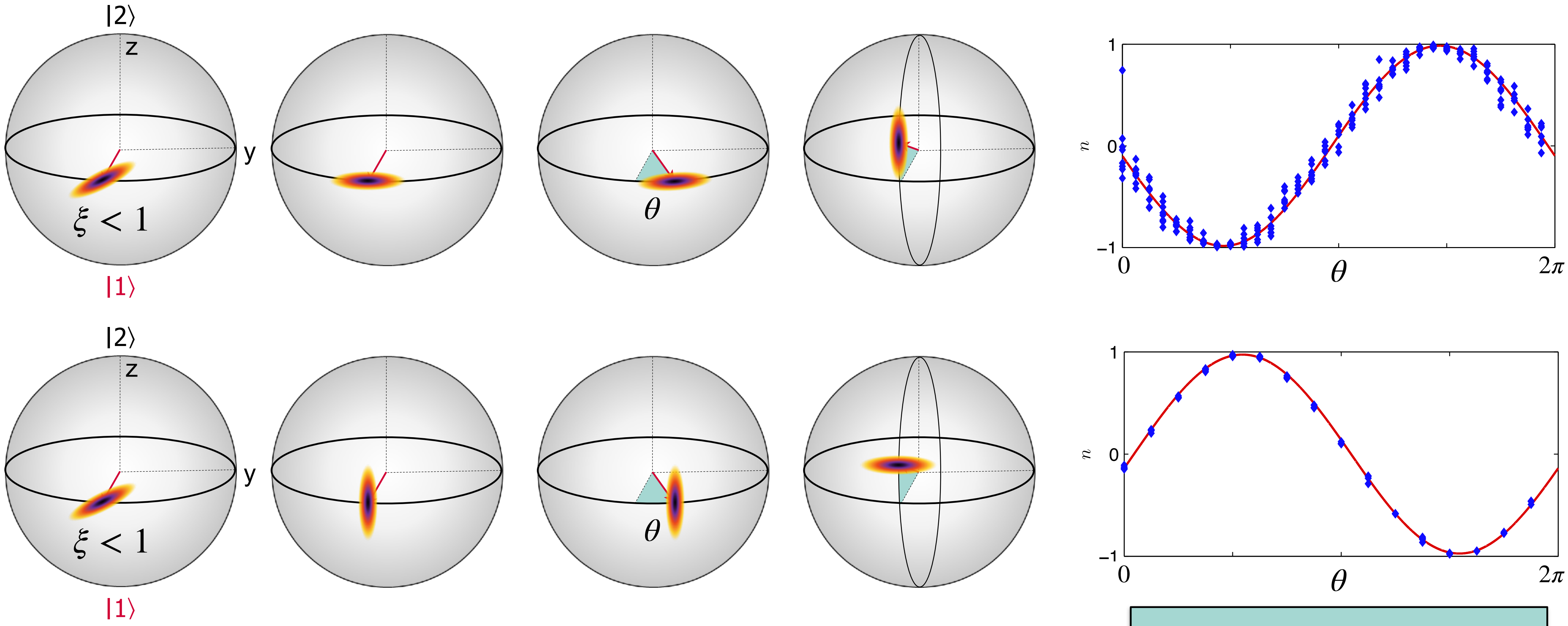
$$\Delta\theta \simeq \frac{\Delta S_z}{\langle S_x \rangle} = \frac{\xi}{\sqrt{N}}$$

Uncertainty below the SQL

$$\xi < 1$$

Pezzè, Smerzi, Oberthaler, Schmied, and Treutlein, Rev Mod Phys 90, 035005 (2018)

Interference fringes with spin-squeezed state

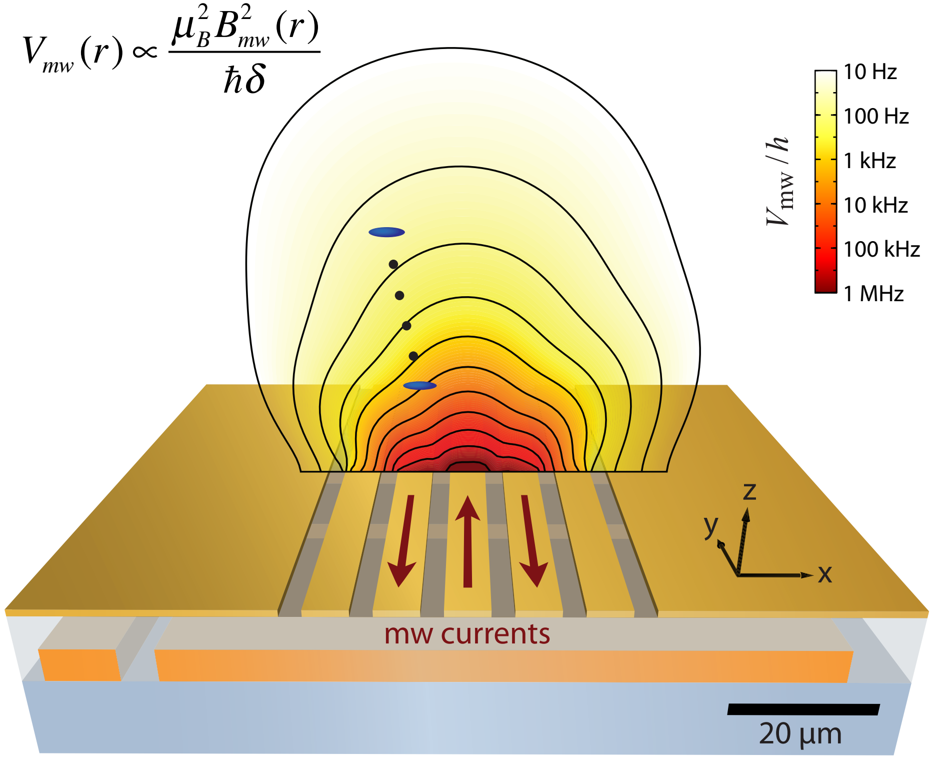


in the meantime improved to -7 dB below SQL

Ockeloen et al, Phys. Rev. Lett. 111, 143001 (2013)

Microwave field measurement beyond the SQL

$$V_{mw}(r) \propto \frac{\mu_B^2 B_{mw}^2(r)}{\hbar\delta}$$

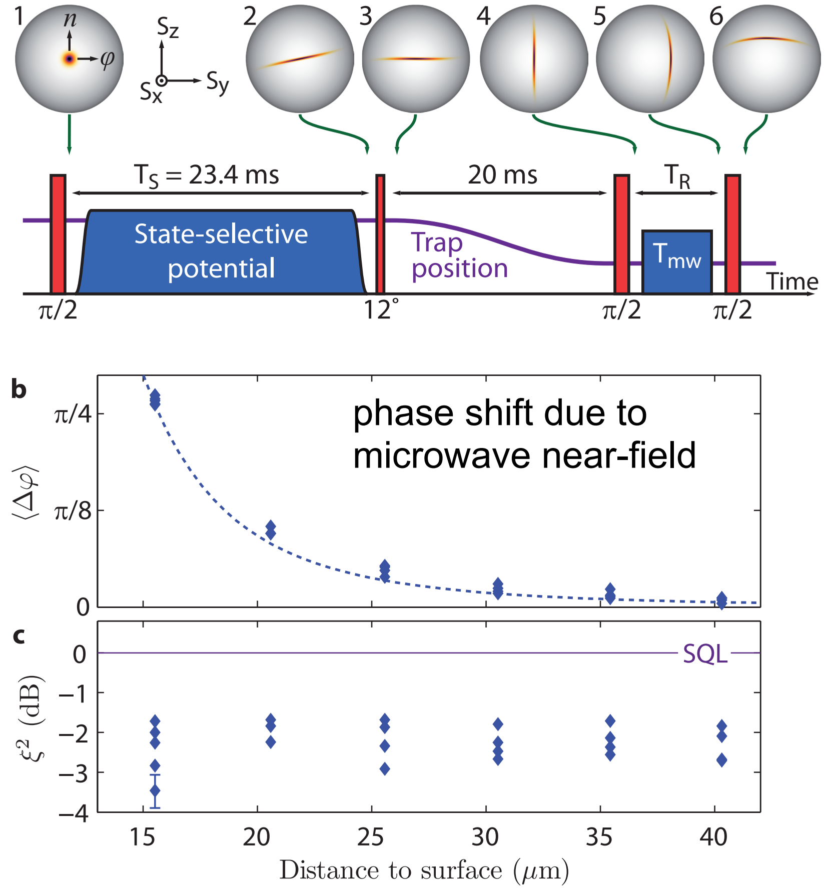


Sensitivity:

δB_{mw} = 77 pT @ 1 s
(near-resonant mw field)

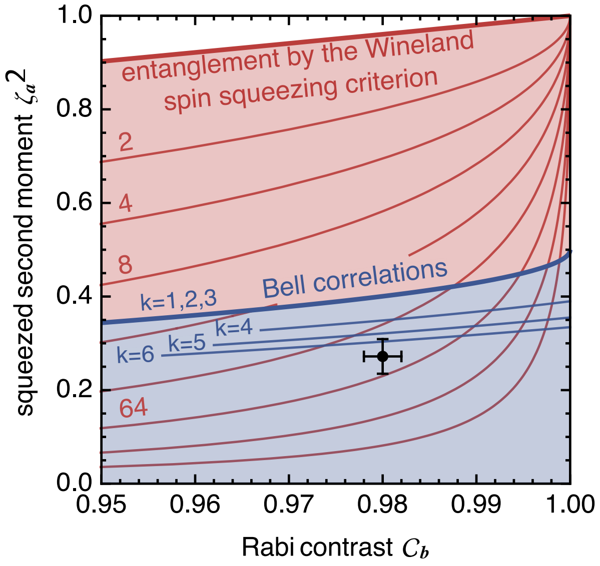
Probe volume: 20 µm^3

Interferometer with spin-squeezed state



Ockeloen et al, Phys. Rev. Lett. 111, 143001 (2013)

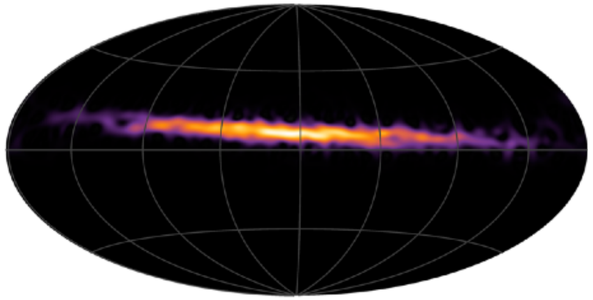
Exploring quantum foundations with massive many-particle systems



Spin-squeezing and many-particle entanglement

- genuine multipartite entanglement
- Wigner function tomography

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



Many-particle Bell correlations

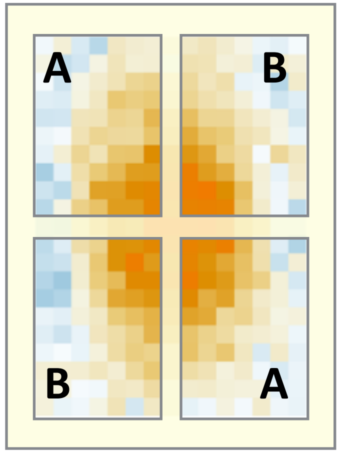
- Bell correlations in many-particle system detected by global measurements

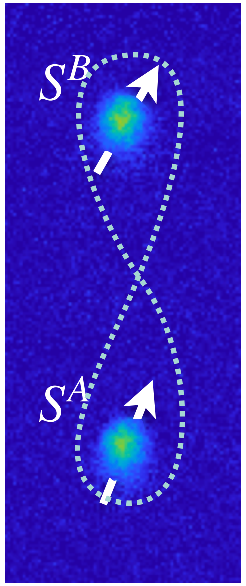
Schmied et al, Science 352, 441 (2016)
Wagner et al, PRL 119, 170403 (2017)

Einstein-Podolsky-Rosen paradox

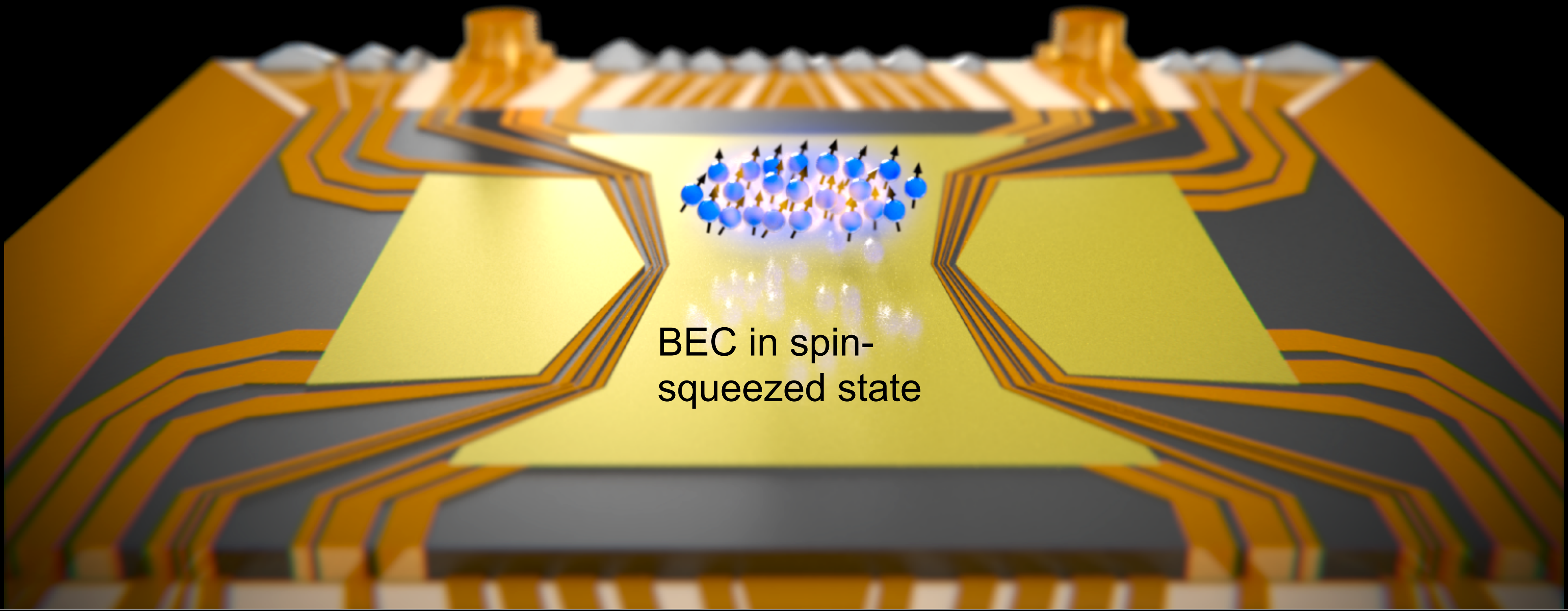
- Entanglement patterns, EPR steering
- EPR paradox between two BECs

Fadel et al, Science 360, 409 (2018)
Colciaghi et al, PRX 13, 021031 (2023)

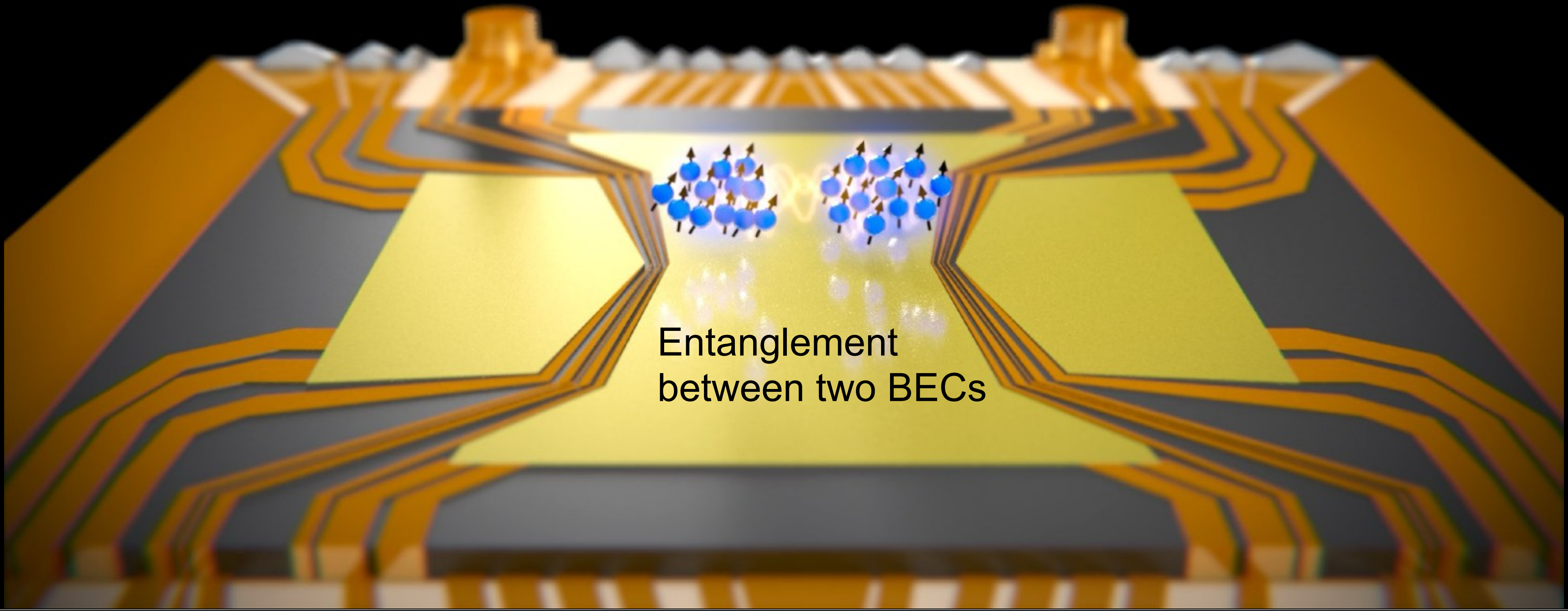




Spatial splitting of spin-squeezed BEC



Spatial splitting of spin-squeezed BEC

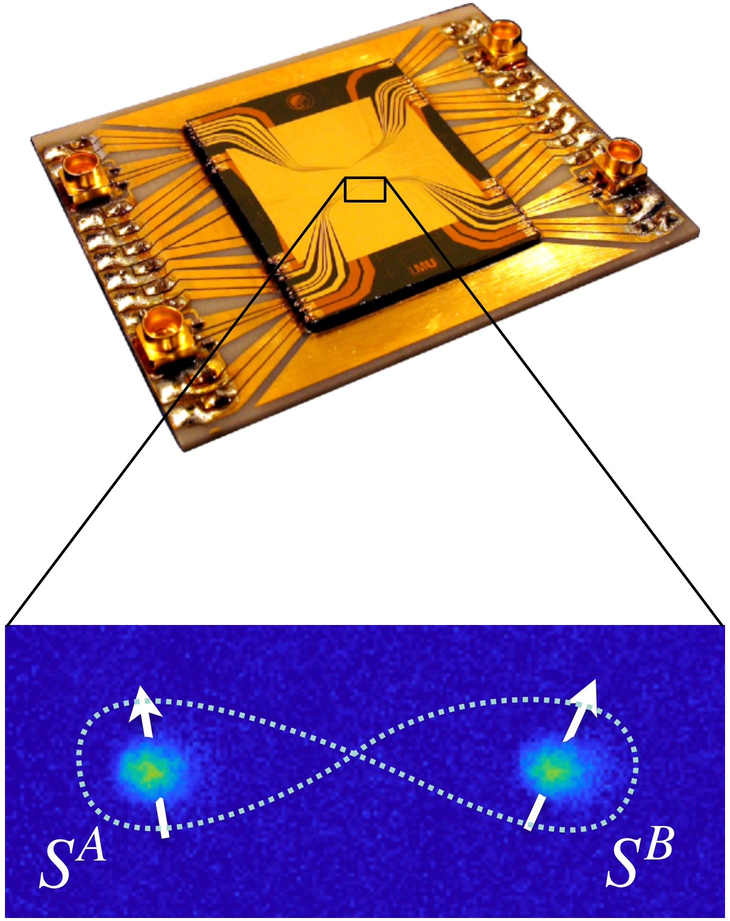


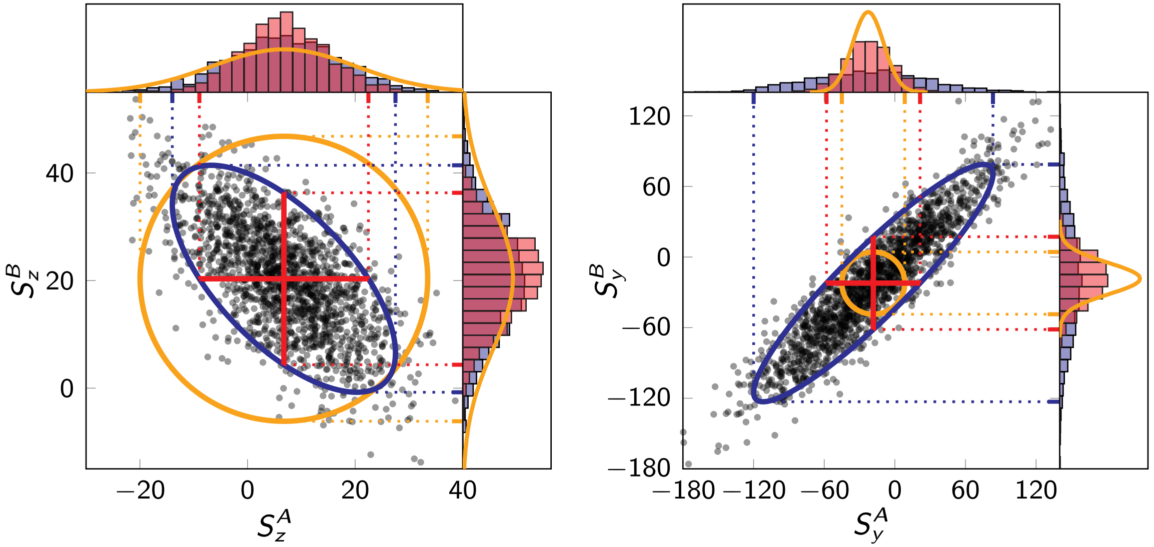
Entanglement
between two BECs

Einstein-Podolsky-Rosen experiment with two BECs

First observation of the EPR paradox with massive many-particle systems

Colciaghi et al, PRX 13, 021031 (2023)

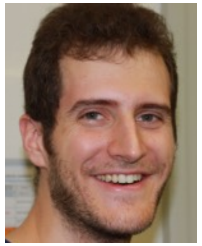




$$E_{EPR}^{A\to B} = \frac{4\,\mathrm{Var}(\hat{S}_y^B - g_y\hat{S}_y^A)\mathrm{Var}(\hat{S}_z^B - g_z\hat{S}_z^A)}{|\langle\hat{S}_x^B\rangle|^2} = 0.81(3) < 1$$

EPR criterion

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

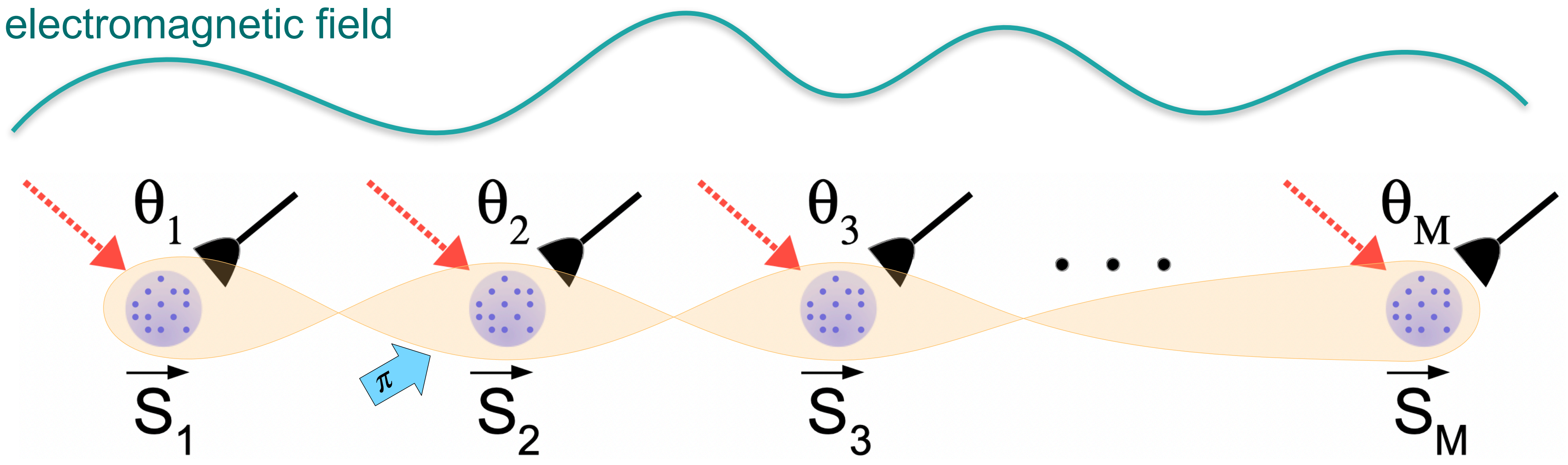


See Paolo Colciaghi's talk

SPS award winner

Thursday, 14:30, Room ETF E 1

New frontier: Multi-parameter quantum metrology



array of entangled atomic ensembles

- fixed total N
- fixed number of preparations

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

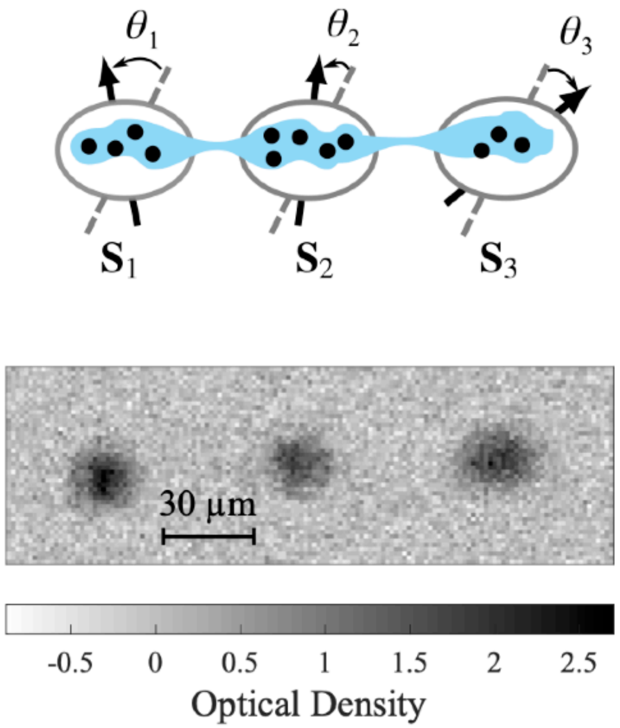
Local spin rotations (π-pulses) transfer quantum enhancement to target Hadamard mode

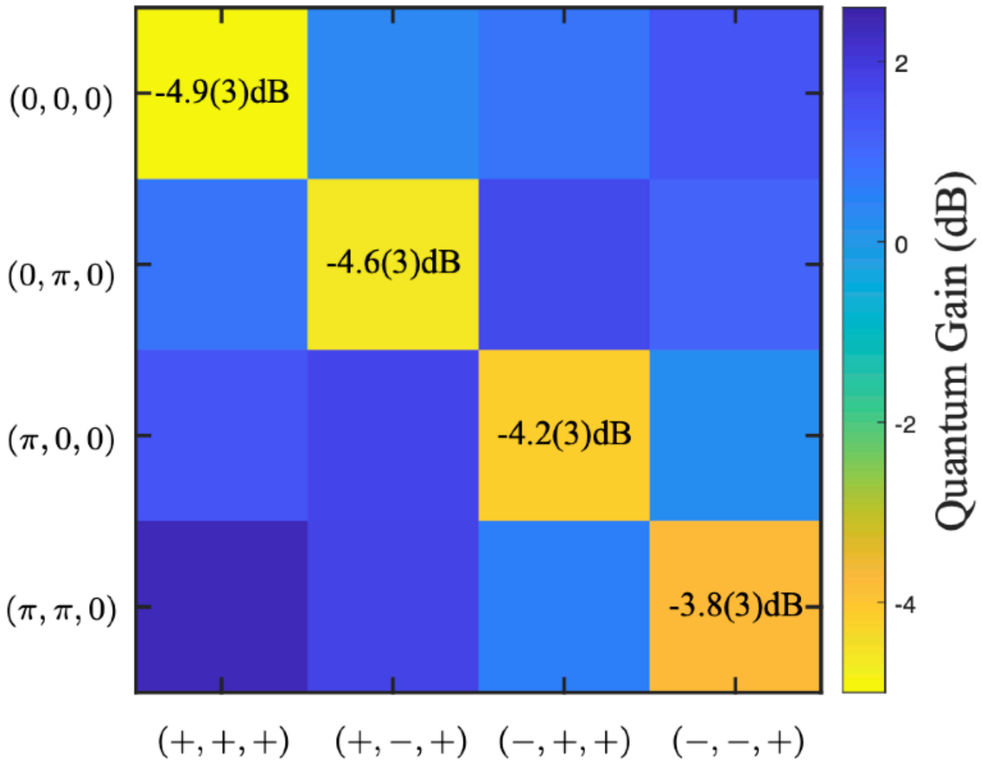
e.g. $\theta_{\text{target}} = (\theta_1 - \theta_2 + \ldots + \theta_M)/\sqrt{M}$ $\boxed{\Delta\theta_{\text{target}} = \xi\,\Delta\theta_{\text{SQL}}}$ $\Delta\theta_{\text{SQL}} = \sqrt{M/N}$

Prepare & measure complete set of modes → all θ_i quantum enhanced $\boxed{\Delta\theta_i \approx \xi\sqrt{M}\,\Delta\theta_{\text{SQL}}}$ for $N \gg 1$, $\xi\sqrt{M} \ll 1$

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

Multiparameter estimation with three entangled atomic ensembles





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

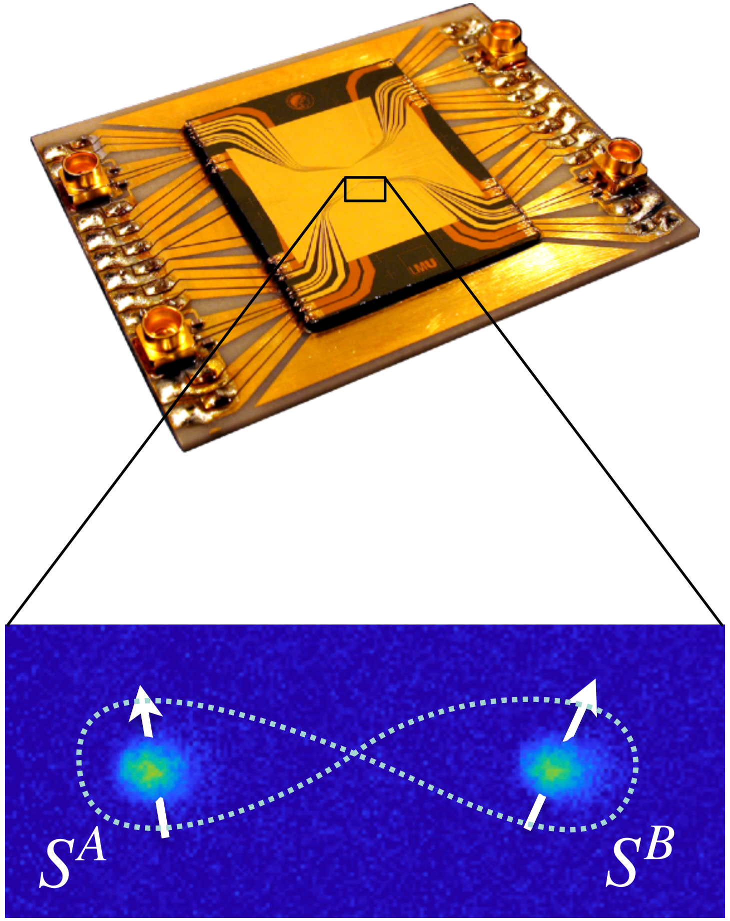
preparation of three entangled spinor BECs

quantum enhancement of four different modes

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

Conclusion and outlook

- **Atom interferometry**: from inertial sensing and geoscience to searches for new physics
- **de Broglie’s wave-particle duality** determines fundamental precision limits of interferometry
- Today’s best interferometers operate at this limit
- **Entanglement** can be harnessed to reduce quantum noise and improve precision
- **Quantum metrology**: an exciting research field where precision metrology meets quantum foundations



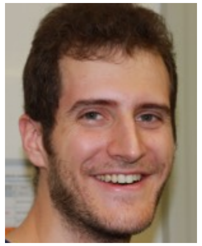
University of Basel

Quantum Optics and Atomic Physics

Positions available!

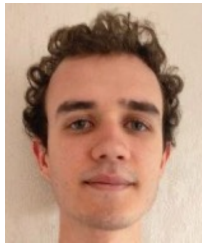

Manel Bosch


Gianni Buser


Paolo Colciaghi

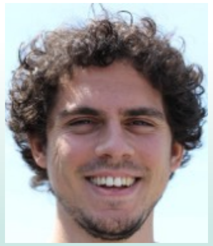

Maryse Ernzer


Suyash Gaikwad

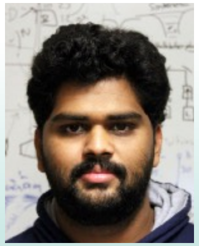

Alexandre Huot

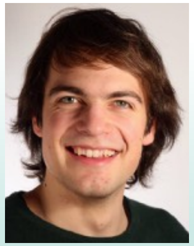

Lex Joosten

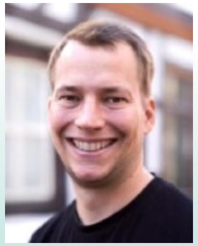

Yifan Li


Roberto Mottola


Haroon Saeed


Madhav Saravanan


Gian-Luca Schmid


Tilman Zibold


Philipp Treutlein

Theory collaborators


Alice Sinatra


Youcef Baamara