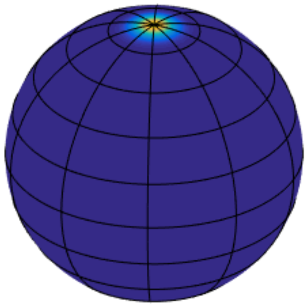
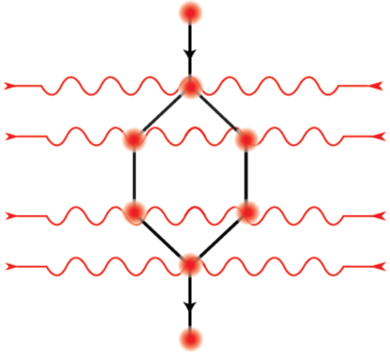
Progress towards a squeezed-state atom interferometer in a ring cavity





TVLBAI 2024

Onur Hosten

Institute of Science and Technology Austria

IST Austria

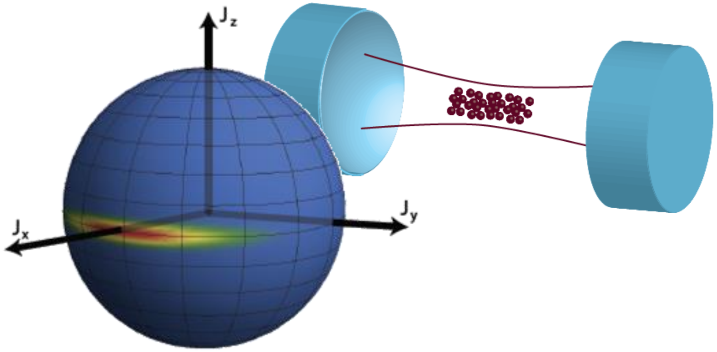
"Outskirts of Vienna" Klosterneuburg, Lower Austria

Hosten Group at IST Austria (since 2018):

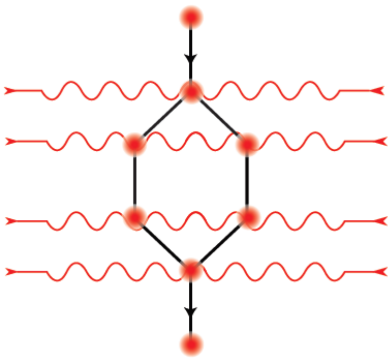
Quantum sensing with atoms and light
https://hostenlab.pages.ist.ac.at

Outline

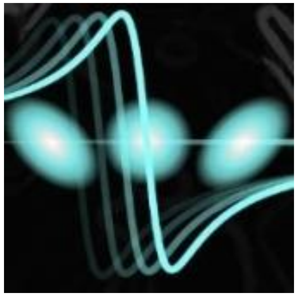
Cavity QED and spin squeezing



Towards squeezed inertial atom interferometers

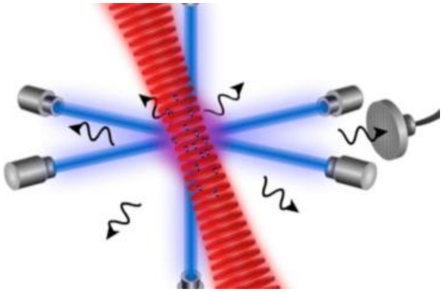


Special techniques



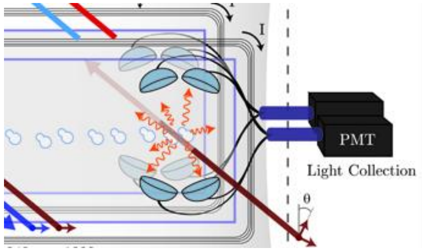
Squash locking

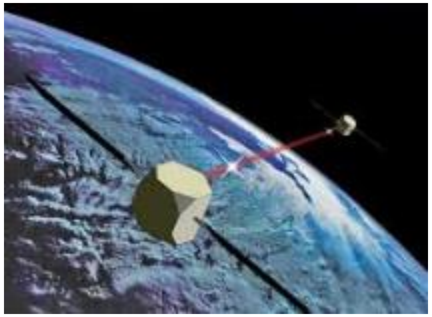
Precision sensing with atoms



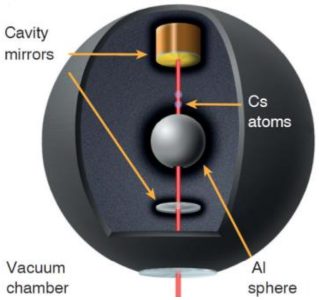
Atomic clocks
(resolve gravitational time dilation)

Molecules for Electron EDM searches
energy level shifts in E field
(constraining supersymmetry)





Atom interferometers
(Testing Einstein's equivalence principle)
(Gravitational wave detection)
(Searches of dark energy)
(Determination of fine structure const.)
(Gravimetry, inertial navigation)



In common:

- Reduce to sensing w/ two-level quantum system
- Can be improved via entanglement (spin squeezing)

Spin squeezing experiments

Illustrate the main experimental techniques with work we did back at Stanford

LETTER

doi:10.1038/nature16176

Measurement noise 100 times lower than the quantum-projection limit using entangled atoms

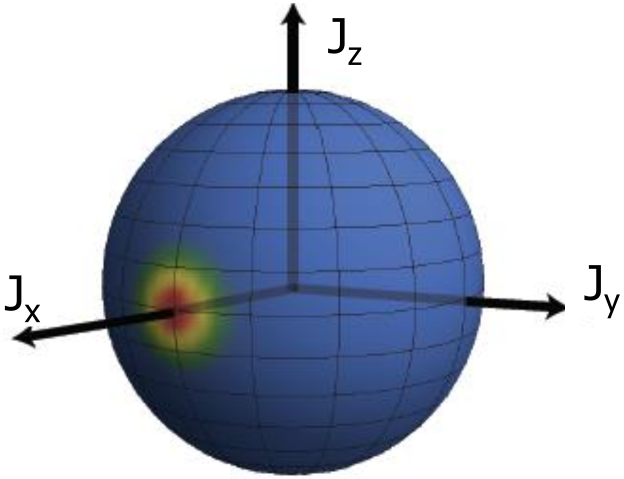
Onur Hosten[1], Nils J. Engelsen[1], Rajiv Krishnakumar[1] & Mark A. Kasevich[1]

- 20 dB spin squeezing and & atomic clock demonstration

A formal view for atomic sensors

2-level atoms: Spin ½ systems (^{87}Rb hyperfine clock states)

Spin N/2 system: Collective angular momentum vector **J**



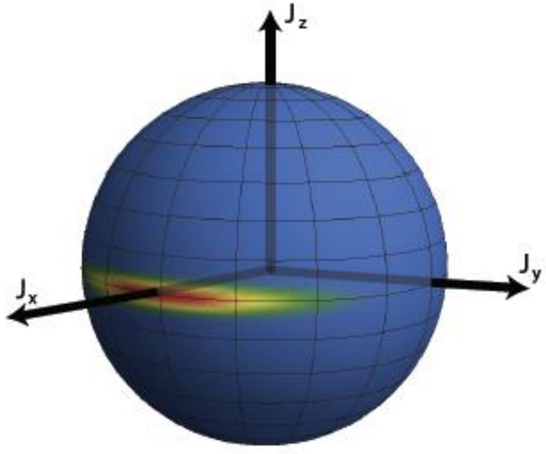
Coherent spin state (uncorrelated spins)
Representation on Bloch sphere (Wigner)

J_z : Population imbalance (-N/2 to N/2)
Arg[$J_x + i J_y$] : Phase difference between two levels

Uncertainty relation: $\Delta J_z \Delta J_y = N/4$
Shot noise: projection onto J_z axis $\sqrt{N}/2$

Spin Squeezed Atomic States

Spin squeezed states:

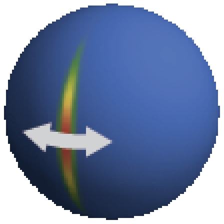


Reduced noise in ΔJ_z at the expense of ΔJ_y

$\Delta J_z < \sqrt{N}/2$

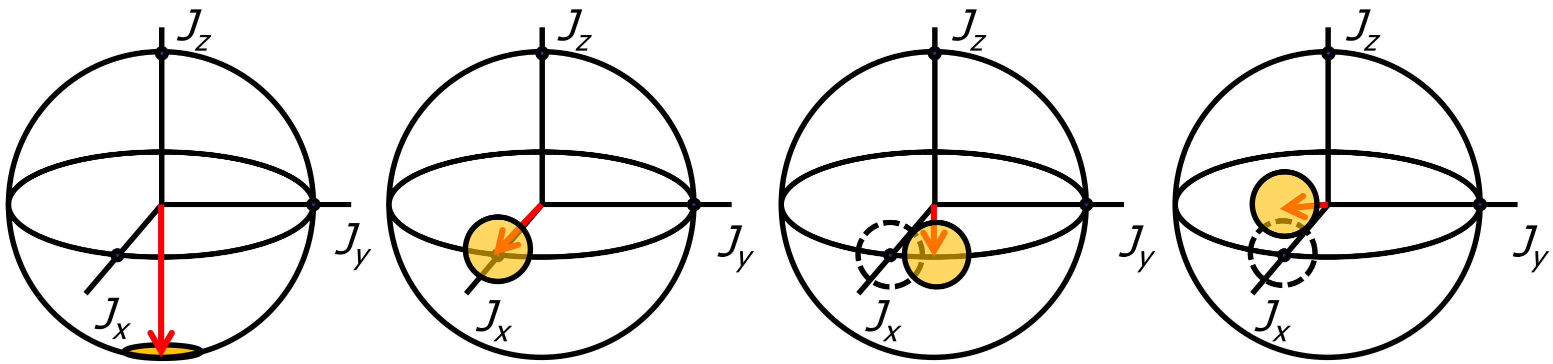
Necessarily implies entanglement

Can sense phase/population changes more accurately



Generic atom sensor

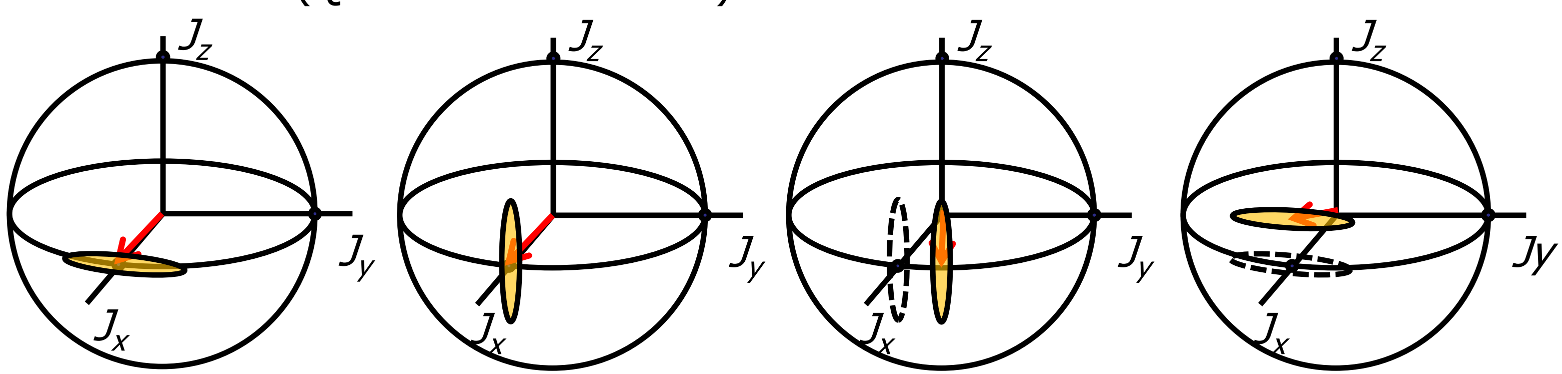
Ramsey sequence: $\pi/2$ – precession - π /2 – read J_z



θ phase

$\Delta\theta = 1/\sqrt{N}$
SQL

Squeezed states (Quantum correlations)



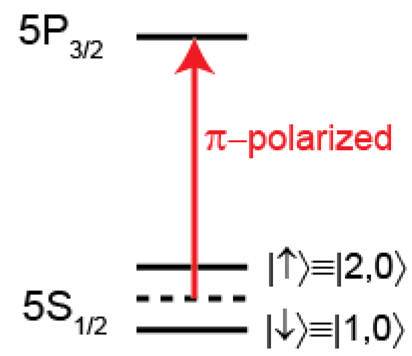
Number squeezed

Phase squeezed

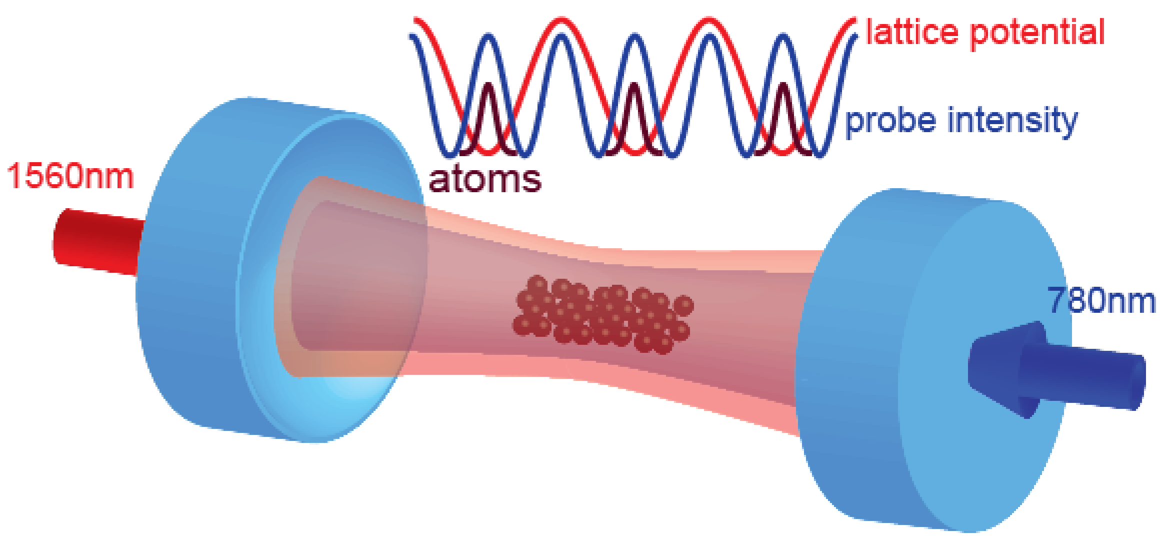
Reduced noise
$\Delta\theta \sim 1/N$ in principle

Many-atom cavity QED implementation

Population difference measurement:
Phase shifts imparted on light is proportional to J_z
(projects the atomic state)



175k finesse optical cavity:



Cavity resonance shift: 5.5 Hz per spin-flip (8kHz linewidth)
Technical noise floor: 3 spin-flips (out of 1M)

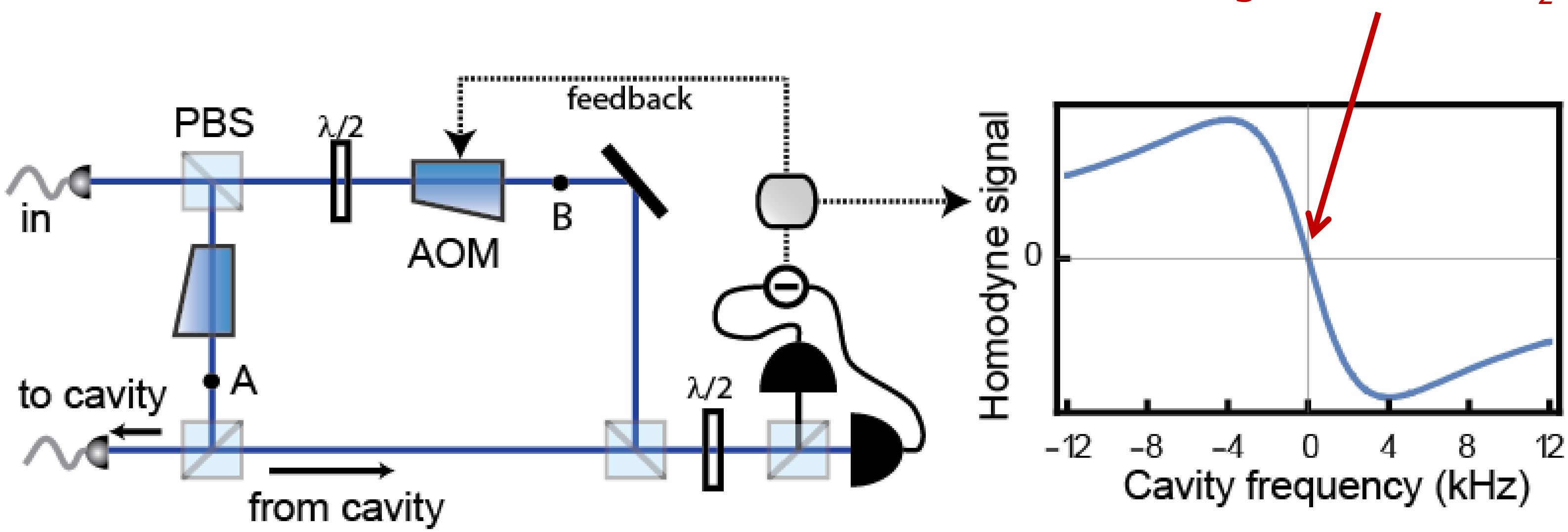
Sensing the cavity resonance shift

Homodyne detection:

10 nW path length stabilization sidebands

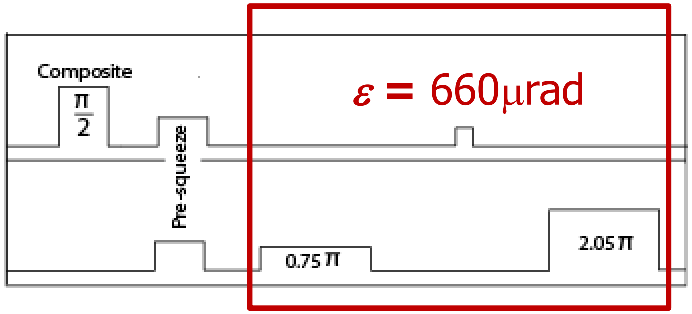
~10 pW probe (90 photons/pW)

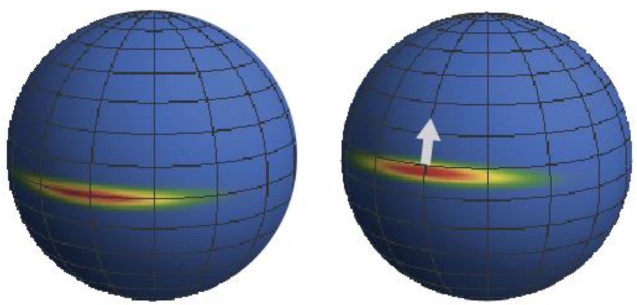
signal linear in J_z

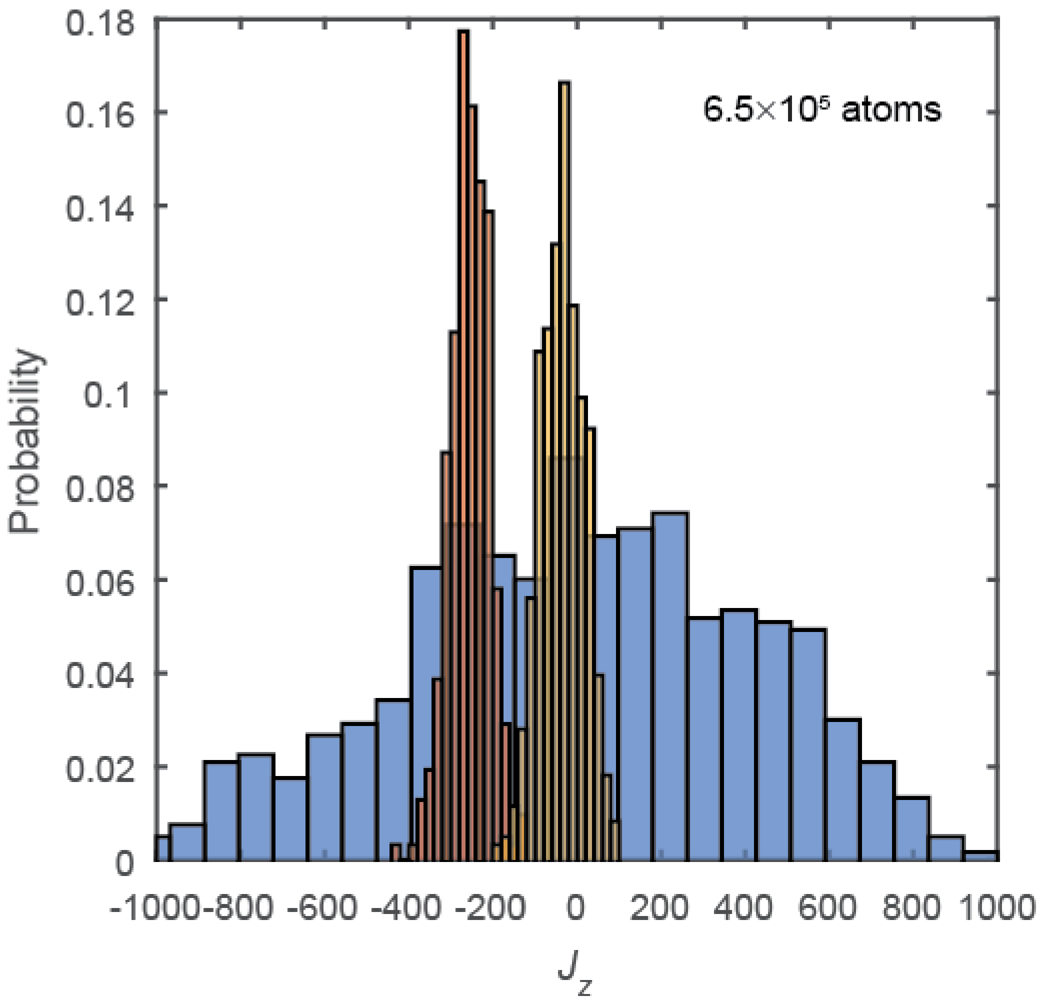


Homodyne system: Shot noise limited from 10Hz – 5MHz

Metrology demonstration: Tipping







140 μrad rms resolution
≡ 70× unentangled atoms

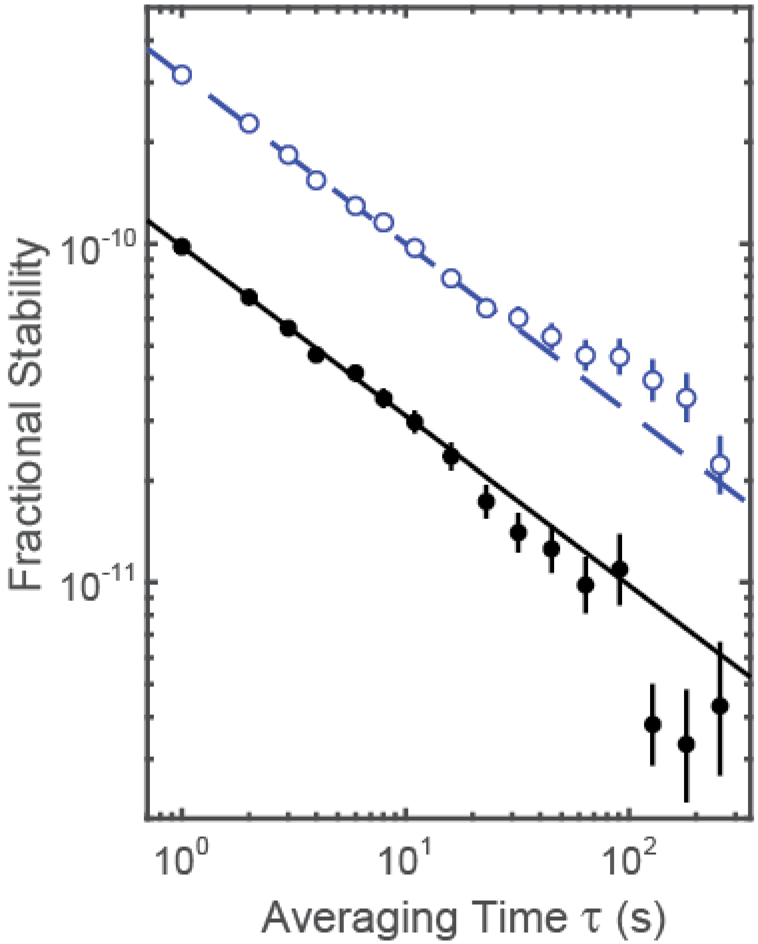
- 20 dB squeezed states, 18.5 dB direct metrology demo

Squeezed microwave clock

1×10^5 atoms
(10.5dB sqz.)

220μs Ramsey time

1s rep rate



Performance limit: μ-wave LO

10.5dB boost: 11 times faster averaging.

Key developments since...

Squeezed optical clock (2020)

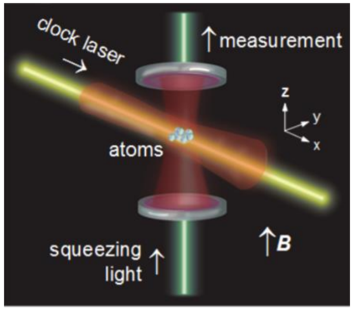
Entanglement-Enhanced Optical Atomic Clock

Edwin Pedrozo-Peñafiel,[1,*] Simone Colombo,[1,*] Chi Shu,[1,2,*] Albert F. Adiyatullin,[1] Zeyang Li,[1] Enrique Mendez,[1] Boris Braverman,[1,†] Akio Kawasaki,[1,‡] Daisuke Akamatsu,[1,3] Yanhong Xiao,[1,4] and Vladan Vuletić[1,§]

[1]*Department of Physics, MIT-Harvard Center for Ultracold Atoms and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

[2]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*

[3]*National Metrology Institute of Japan (NMIJ), National Institute of Advanced Industrial Science and Technology (AIST),*



Second-scale lifetime for squeezed states (2020)

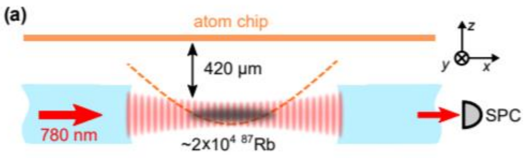
Self-amplifying spin measurement in a long-lived spin-squeezed state

Meng-Zi Huang[1], Jose Alberto de la Paz[2], Tommaso Mazzoni[2,*] Konstantin Ott[1,†] Alice Sinatra[1], Carlos L. Garrido Alzar[2], and Jakob Reichel[1‡]

[1]*Laboratoire Kastler Brossel, ENS-Université PSL, CNRS, Sorbonne Université, Collège de France, 24 rue Lhomond, 75005 Paris, France*

[2]*LNE-SYRTE, Observatoire de Paris-Université PSL, CNRS, Sorbonne Université, 61 Avenue de l'Observatoire, 75014 Paris, France*

(Dated: July 3, 2020)



Mapping of internal-to-momentum entanglement – twin fock states (2021)

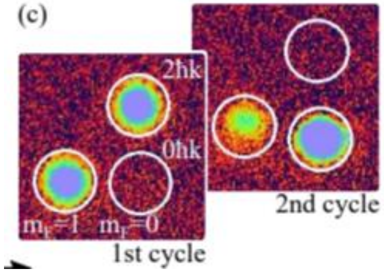
Momentum entanglement for atom interferometry

F. Anders[1], A. Idel[1], P. Feldmann[2], D. Bondarenko[2], S. Loriani[1], K. Lange[1], J. Peise[1], M. Gersemann[1], B. Meyer[1], S. Abend[1], N. Gaaloul[1], C. Schubert[1,3], D. Schlippert[1], L. Santos[2], E. Rasel[1], and C. Klempt[1,3]

[1] *Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, D-30167 Hannover, Germany*

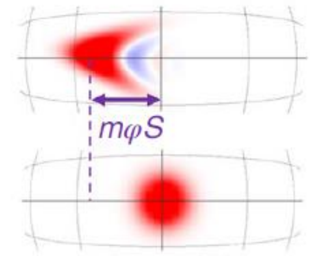
[2] *Institut für Theoretische Physik, Leibniz Universität Hannover, Appelstr. 2, D-30167 Hannover, Germany*

[3] *Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), Institut für Satellitengeodäsie und Inertialsensorik, c/o Leibniz Universität Hannover, DLR-SI, Callinstraße 36, 30167 Hannover, Germany*



Key developments since – cont.

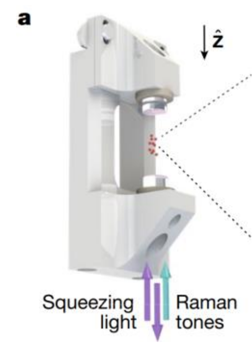
11.8 beyond SQL time reversal metrology (2022)



Time-reversal-based quantum metrology with many-body entangled states

Simone Colombo[1,4], Edwin Pedrozo-Peñafiel[1,4], Albert F. Adiyatullin[1,3,4], Zeyang Li[1], Enrique Mendez[1], Chi Shu[1,2] and Vladan Vuletić[1]

1.7 dB squeezed complete atom interferometry demo (2022)

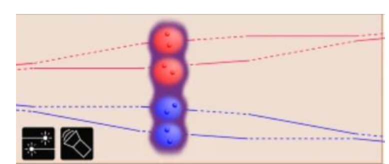


Entanglement-enhanced matter-wave interferometry in a high-finesse cavity

Graham P. Greve, Chengyi Luo, Baochen Wu & James K. Thompson

Nature 610, 472–477 (2022) | Cite this article

1.6 dB differential squeezing between two ~co-located atom interferometers (2022)



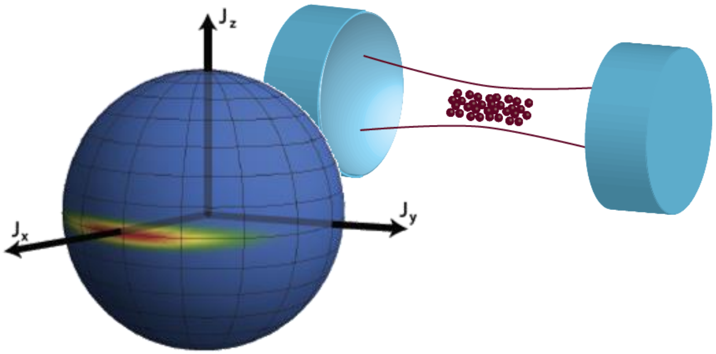
Distributed quantum sensing with mode-entangled spin-squeezed atomic states

Benjamin K. Malia, Yunfan Wu, Julián Martínez-Rincón & Mark A. Kasevich

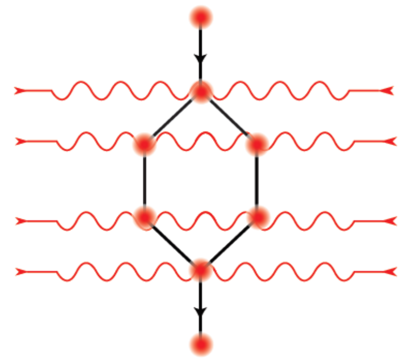
Nature 612, 661–665 (2022) | Cite this article

Outline

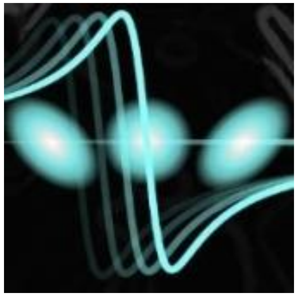
Cavity QED and spin squeezing



Towards squeezed inertial atom interferometers



Special techniques



Squash locking

Squeezed-state atom interferometry

Exploit squeezed states for force/acceleration sensing
through atom interferometry

Applied aspect: Improve sensitivity of inertial sensors
Fundamental aspect: Investigate large mass quantum superpositions

10^6 atoms + 20 dB squeezing:

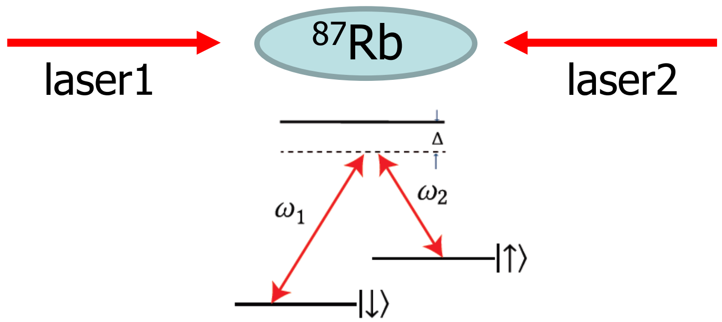
- Effectively equivalent to quantum interference with 10^6 atomic-mass unit collective object. (state of the art is 25000 amu)

Strategy:

Map spin squeezing onto spatial motion in a traveling wave cavity

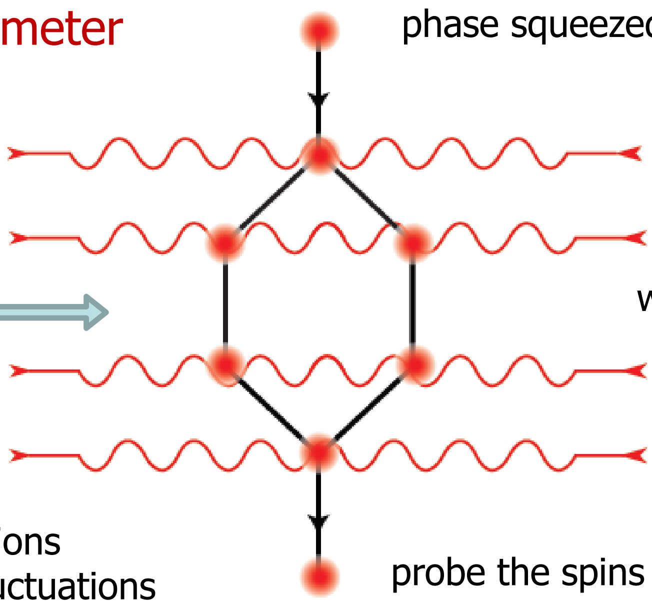
Mapping of entanglement to motional states

Raman-transitions: Spin-to-path mapping



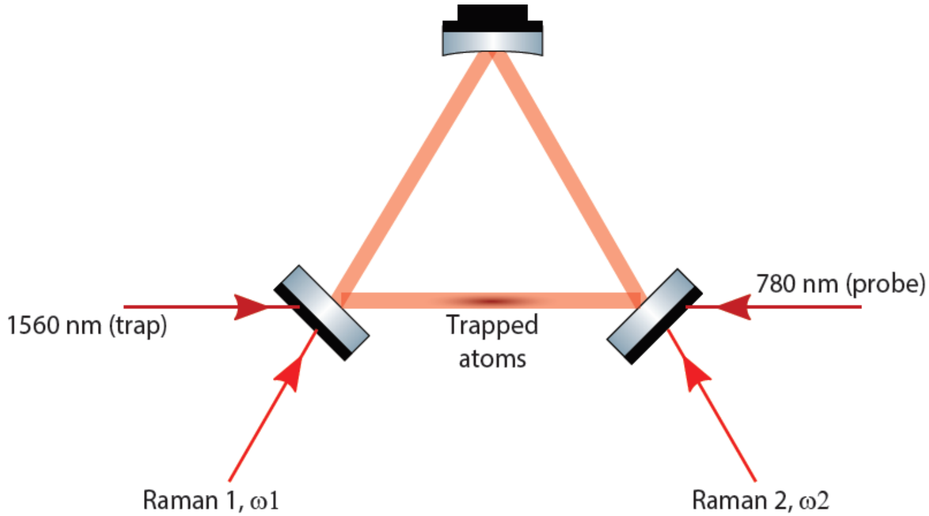
State dependent momentum transfer:
- Flip internal states
- Impart $\pm 2\hbar k$ momentum to atoms

A $4\text{-}\hbar k$ atom interferometer



Quantum correlations:
Reduced phase diff. fluctuations
Increased population diff. fluctuations

Traveling wave cavity



Role of the cavity

1) Radially trap atoms – 1560 nm
   (500 Hz radial trap freq., 1Hz axial…)
2) Generate and probe squeezed states
3) Assist spin-momentum mapping
   (6.834 GHz hyperfine split cavity modes)

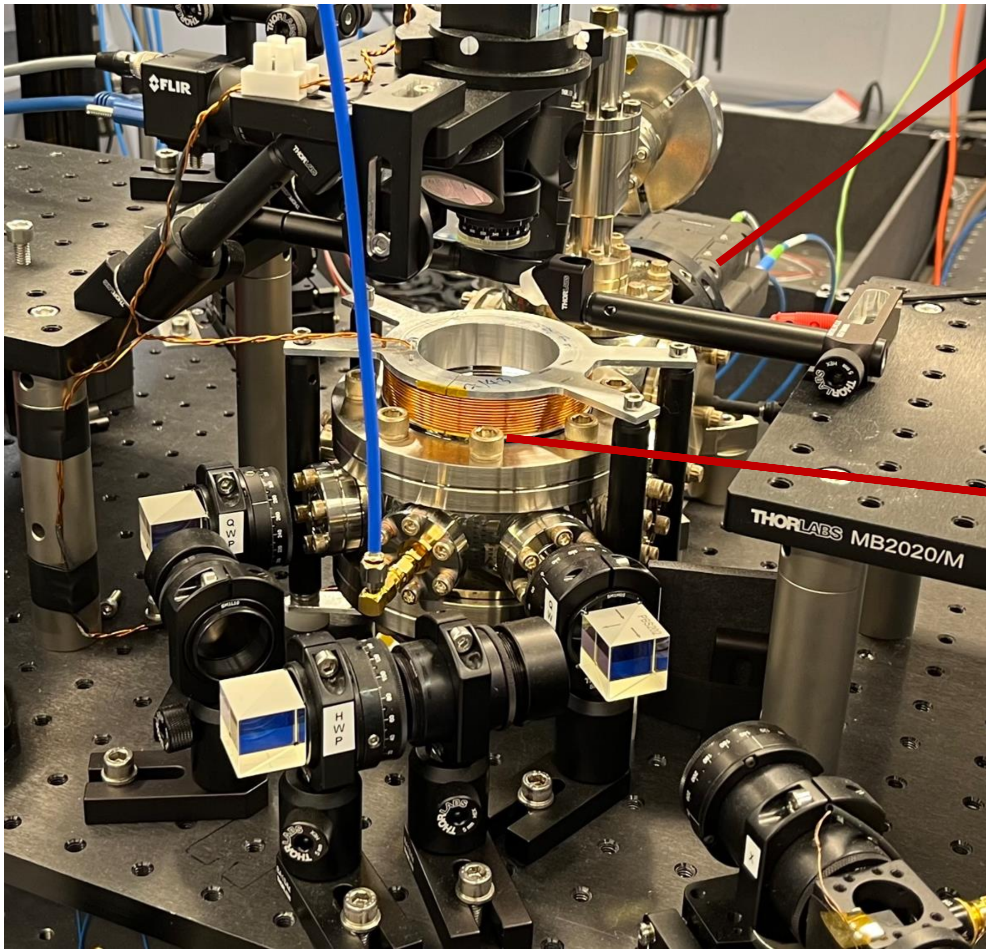
The constructed cavity

	780 nm, S-pol.	780 nm, P-pol.
Finesse	~36000	~2500
Full linewidth	83 kHz	1.2 MHz
FSR	3.05 GHz	3.05 GHz
Mirr. refl. phase	171°	140°

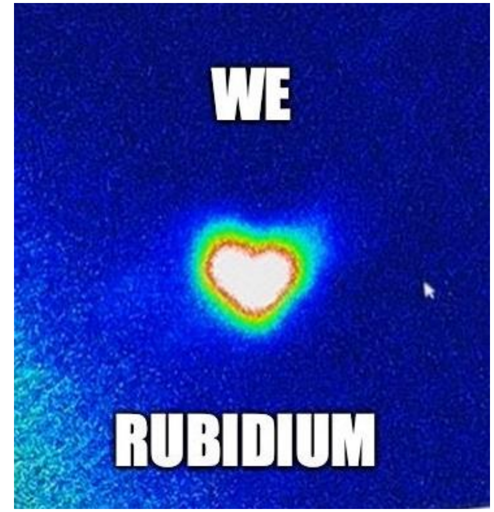
Finesse at 1560 nm: ~50000

Experimentally determined to obtain 6.834 GHz s- & p-polarization mode splitting

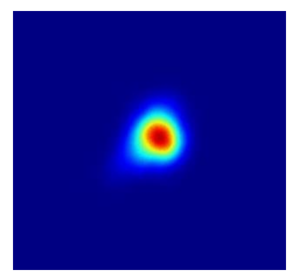
The cold atom machine



2D-MOT loads 20 M atoms

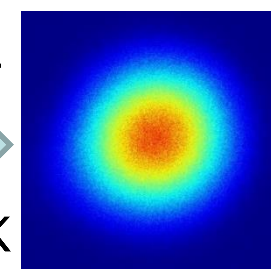


3D-MOT and molasses near cavity center



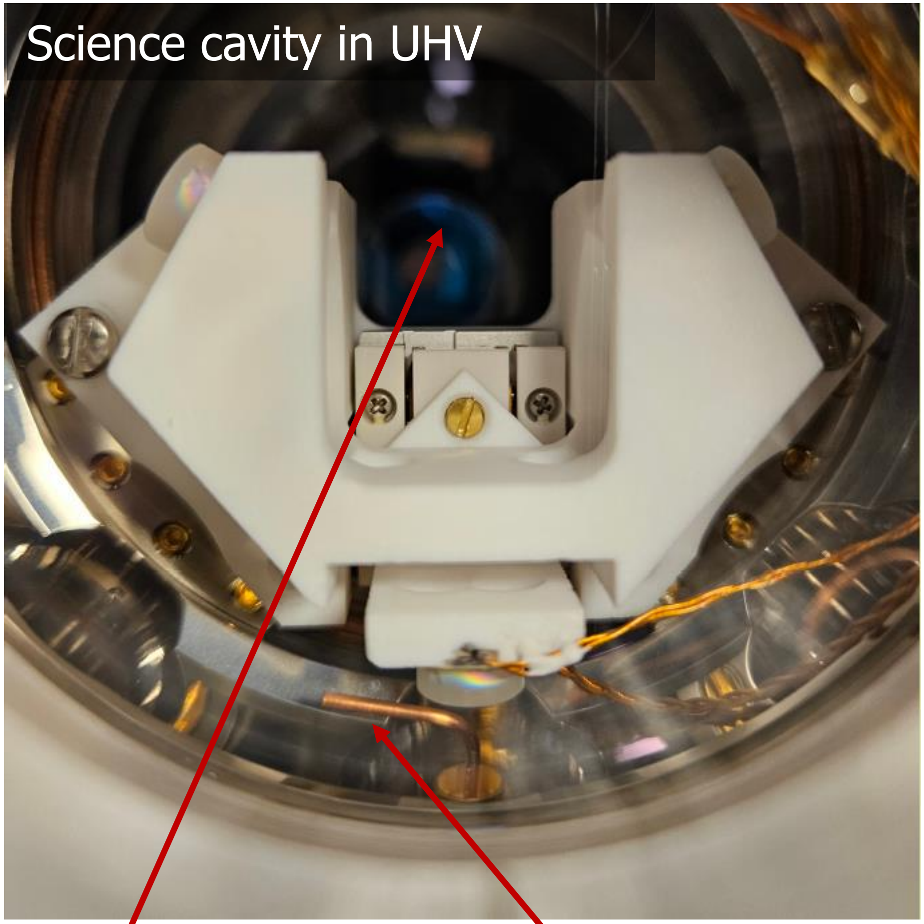
TOF

4 μK



to be loaded into cavity dipole trap

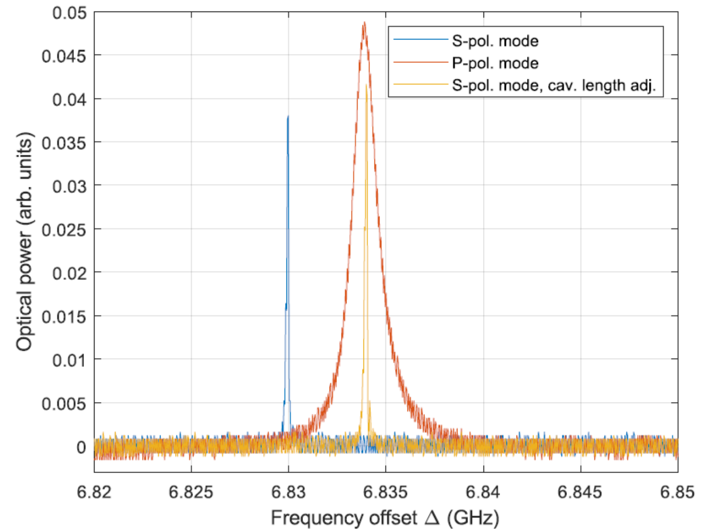
Traveling wave cavity – cont.



MOT location

in-vacuum μw antenna

The high and low finesse modes

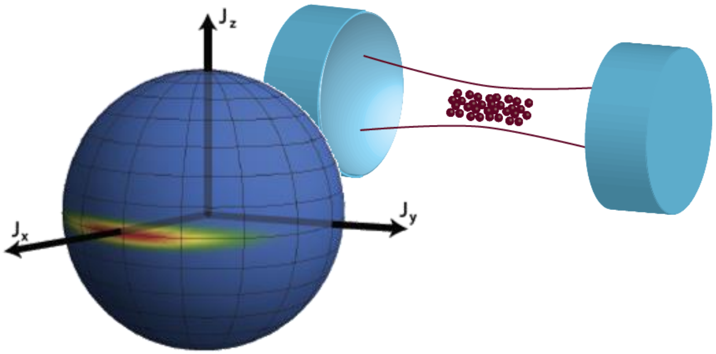


Cavity length adjustable up to 1mm through piezo stage to fine tune Raman modes.

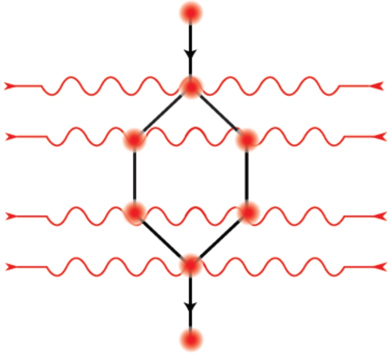
work in progress for interferometry and squeezing

Outline

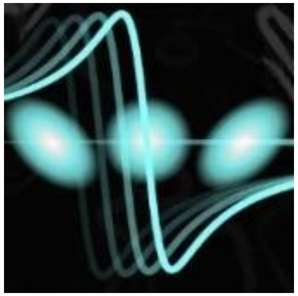
Cavity QED and spin squeezing



Towards squeezed inertial atom interferometers



Special techniques

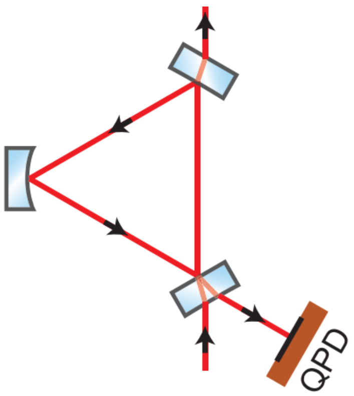


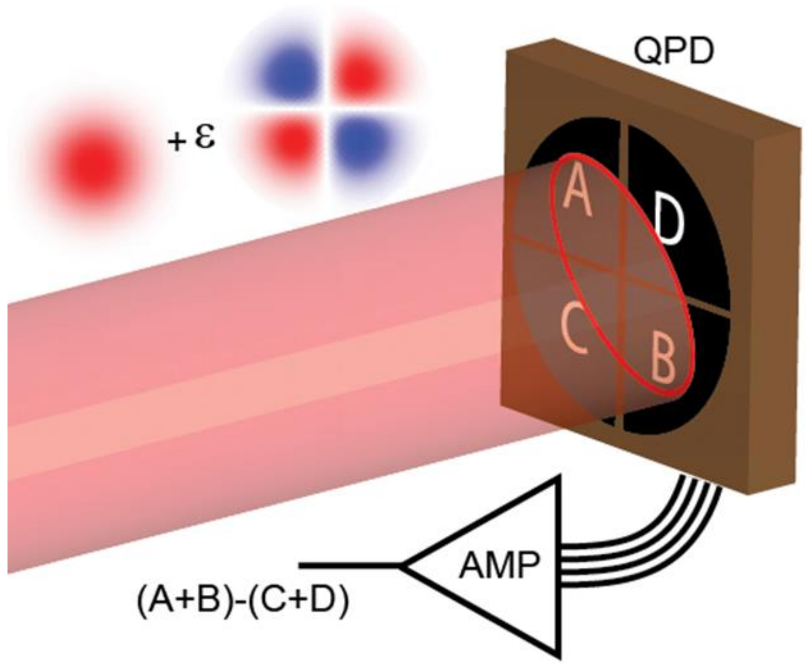
Squash locking

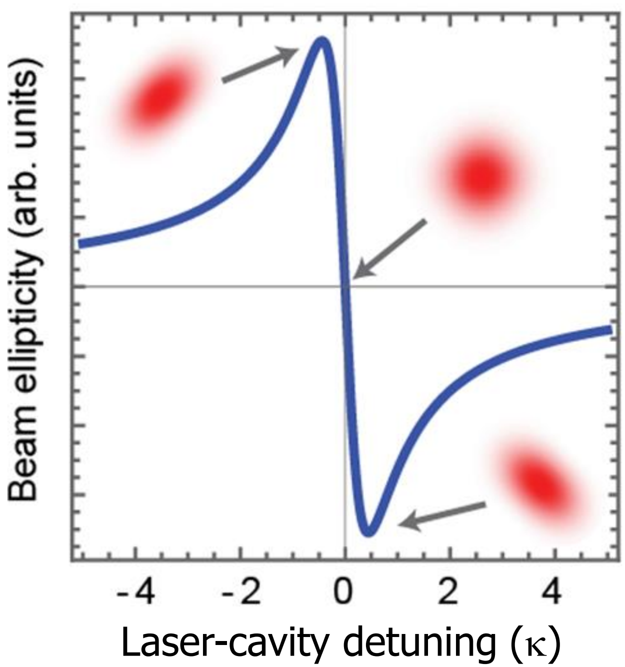
Squash locking – the idea

A competitive method for locking a laser to a cavity (and more)

- Measure the ellipticity of a laser beam reflecting form a cavity
- TEM00 + small amount TEM11 → elliptical beam
- Mode selective phase shift by the cavity near resonance

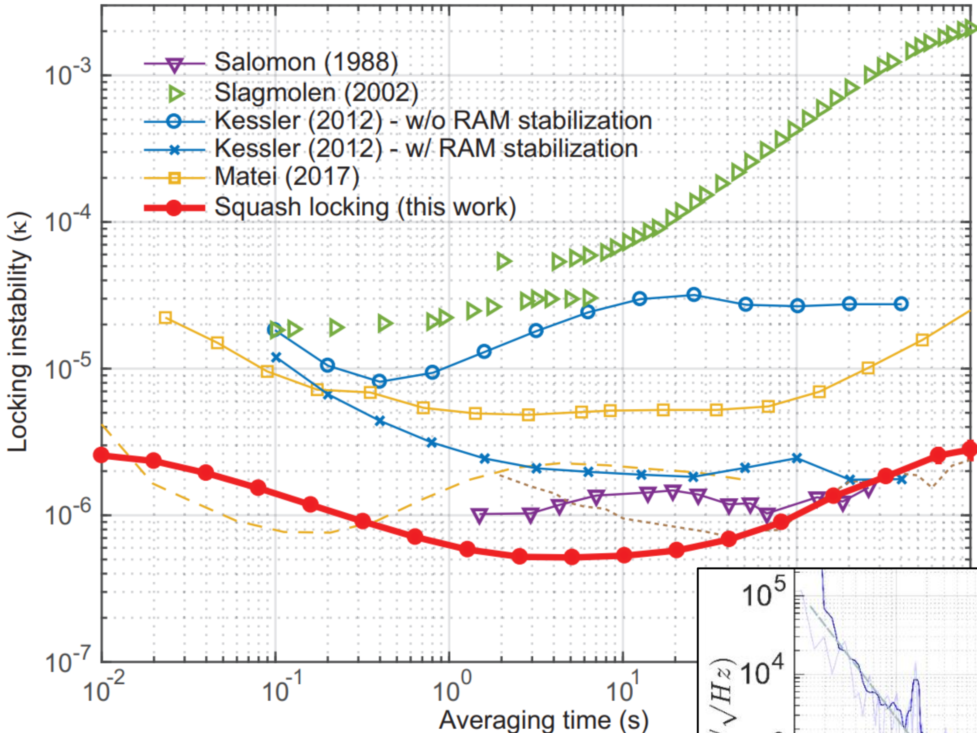






(also works for linear cavities)

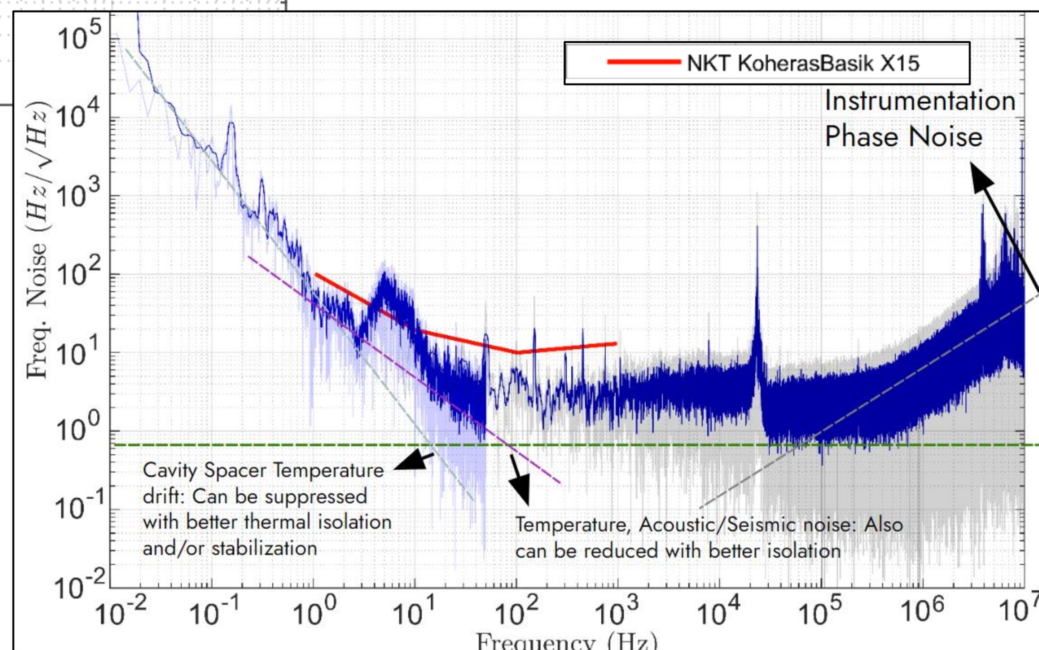
Performance



Ultra-tight laser frequency locking:

5x10^{-7}κ @ 5s wrt cavity linewidth

F. Diorico,…, O. Hosten, Optica (2024)



tulon PHOTONICS

Simplicity driven innovations:

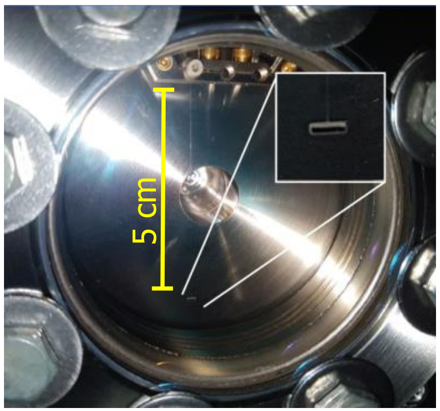
Self-injection locked lasers w/ sq. lock

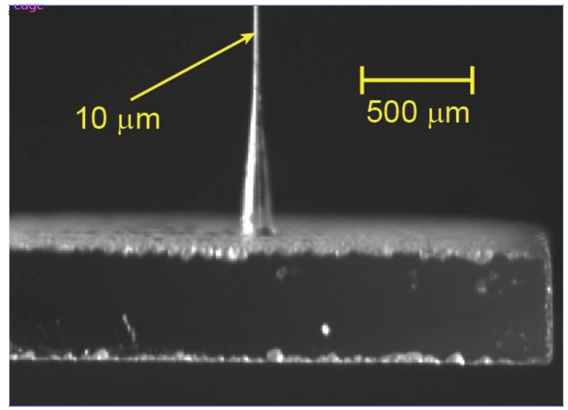
Currently ~1 Hz/rtHz, ~10Hz linewidth

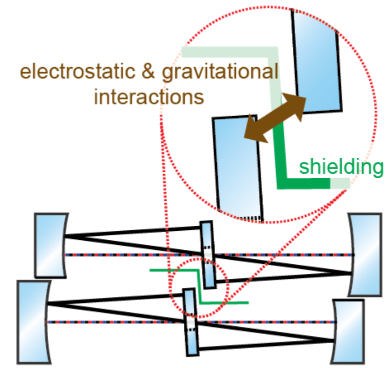
Bonus slide: A new direction in our group

Milligram scale optomechanics for gravitational and quantum physics

Towards generation of entanglement between two pendulums through gravity



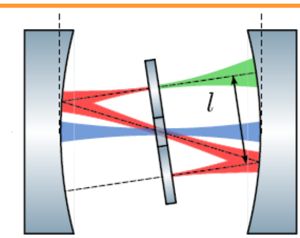




Zigzag optical cavity to interface torsional motion with light

- Exclusive yaw motion optomechanical coupling

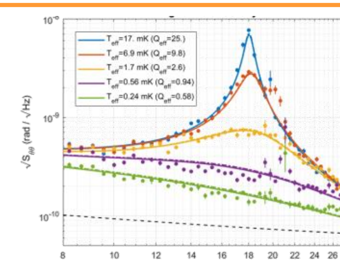
S. Agafonova, …, O. Hosten, PRResearch 2024



Optomechanical control of a 1 mg torsional pendulum

- Coldest oscillator from μg to kg: ~240 μK (prev. record: 6.9 mK)

S. Agafonova, ..., O. Hosten, in preparation



The group

Current group members

Fritz Diorico (Entrepreneur)
Vyacheslav Li (PhD student)
Sebastian Wald (PhD Student)
Sofia Agafonova (PhD Student)
Umang Mishra (PhD Student)
Edward Gheorghita (PhD Student)

Hosten Group at IST Austria:

Quantum sensing with atoms and light
https://hostenlab.pages.ist.ac.at

ISTA Institute of Science and Technology Austria