TACC – Trapped Atom Clock on a Chip: A testbed for the quantum physics of clocks

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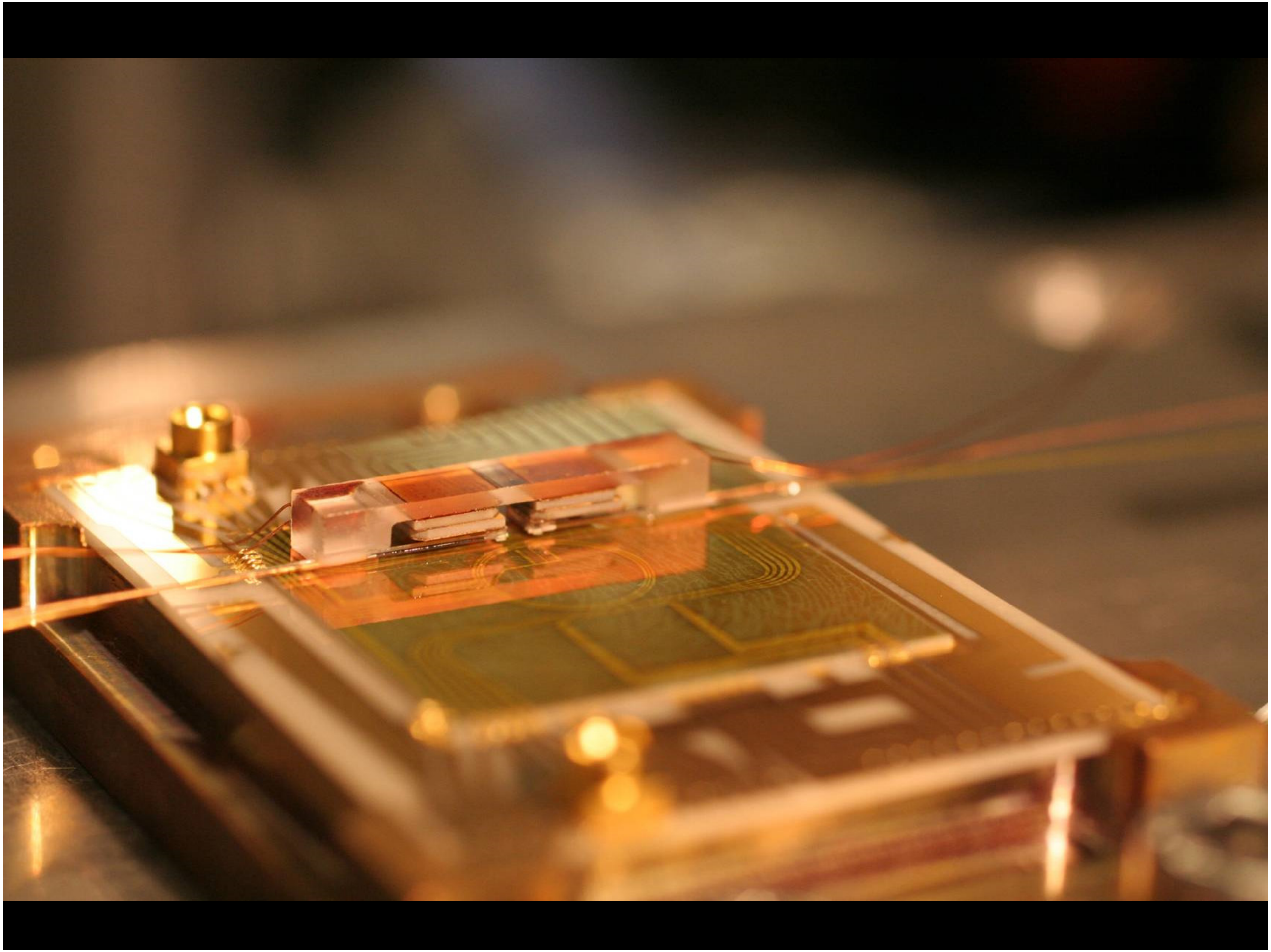
Laboratoire Kastler Brossel
Physique quantique et applications

l'Observatoire de Paris — SYRTE
Systèmes de Référence Temps-Espace

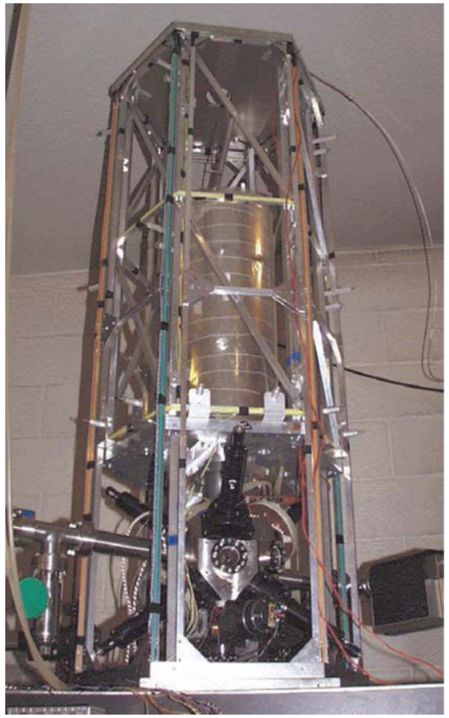


Existing standards: There's a gap

Stability: ~ 10^{-12} $s^{-1/2}$

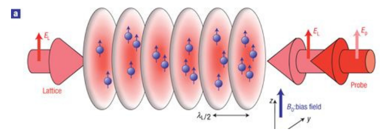
...

Stability <10^{-12} $s^{-1/2}$
and portable:
Interesting for applications



Stability: ~ 10^{-14} $s^{-1/2}$

Portable clocks beyond 10^{-12} $s^{-1/2}$



Optical lattice clocks

Trapped-atom clocks

- Interactions are important
- Many-body effects
- Quantum enhancement techniques are particularly promising

Outline

Part 1

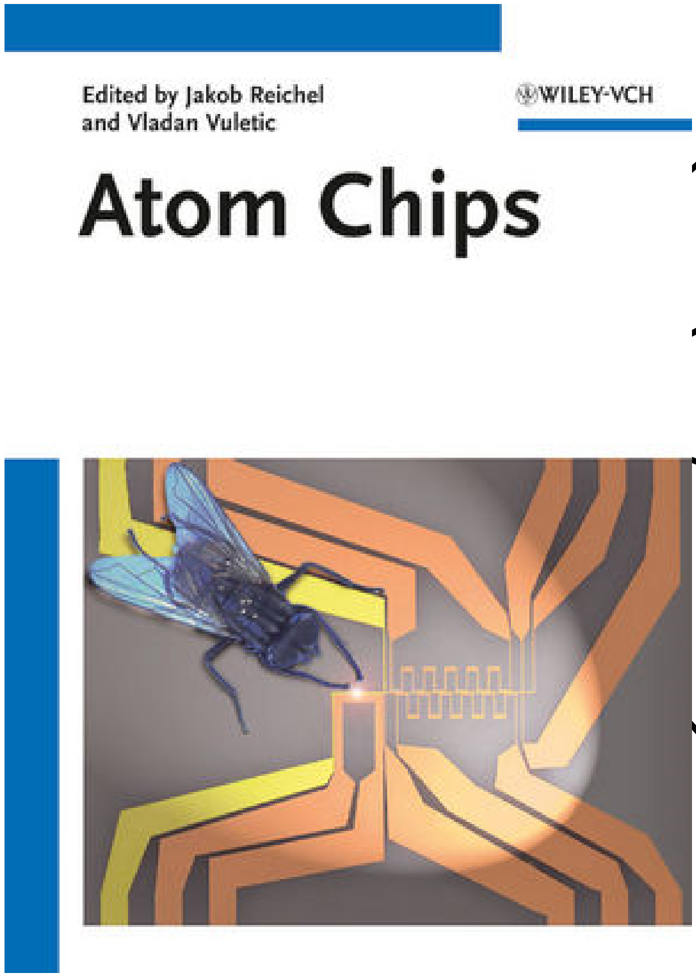
- Trapped-atom clock on a chip (TACC)
- Spin self-rephasing
- Clock stability

Part 2

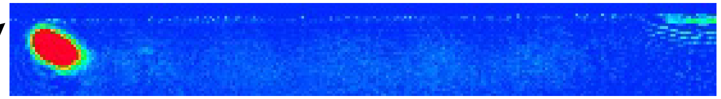
- Quantum enhancement techniques:
  QND detection and Spin Squeezing
- Spontanous spin squeezing
- ee-TACC: Towards quantum enhancement
  in a metrological environment

Trapped Atom Clock on a Chip – TACC

Atom Chips



Complex manipulation

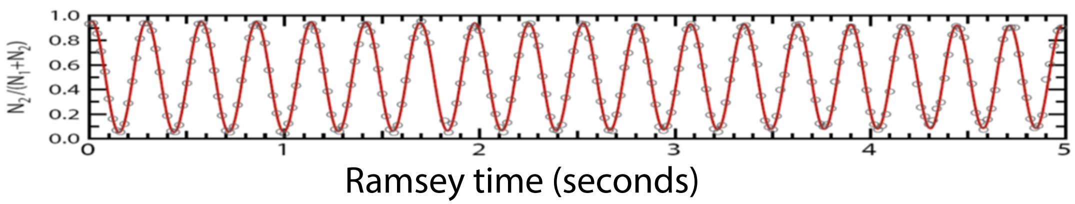


Compact setup,
fast BEC

ColdQuanta.com

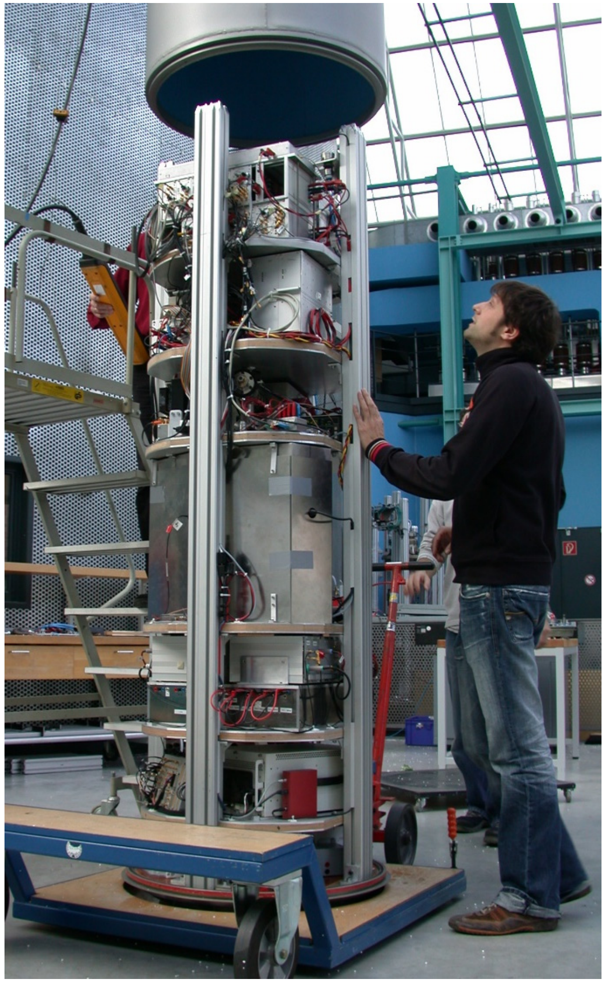
Drop tower proven!
Quantus collaboration

Long coherence time



Enabled by atom chip technology: BEC in microgravity

- 4.7 to 9 seconds free fall
- 110 meters falling height
- 3 drops per day
- 50 g max. at impact
- Payload area:
  173 cm height,
  60 cm diameter,
  234 kg max



Bremen drop tower (146m tall)

ZARM

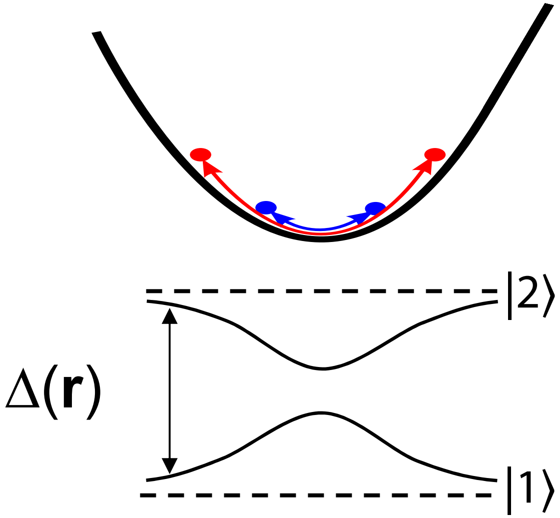
Complete BEC experiment

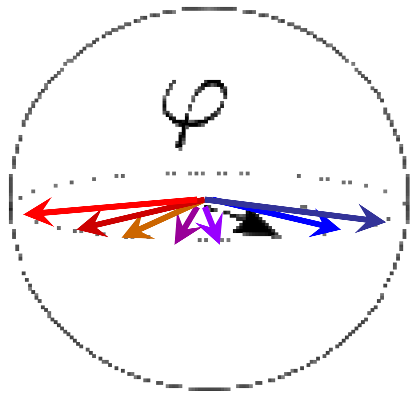
QUANTUS collaboration: Universities of Hannover, Ulm, Darmstadt, Hamburg, Birmingham, Berlin (HU), Bremen (ZARM), Munich (LMU), Paris (ENS).

That's cool, so
let's build a clock
on an atom chip!

OK, but what about
level shifts??

Trap shifts: Dephasing

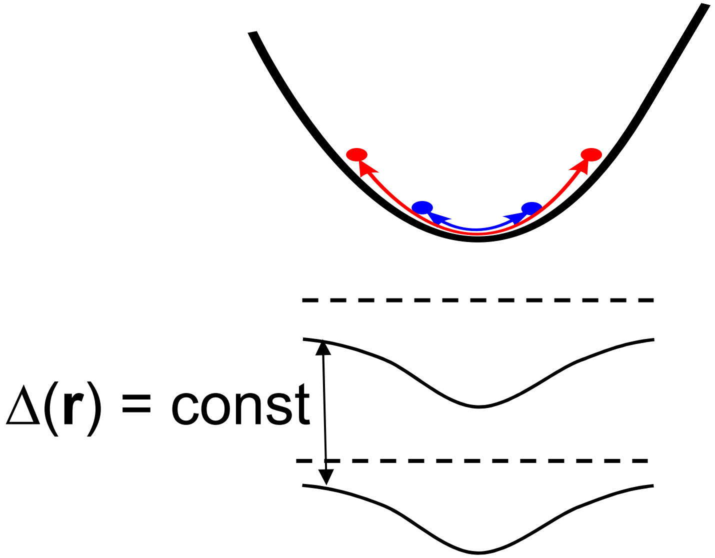


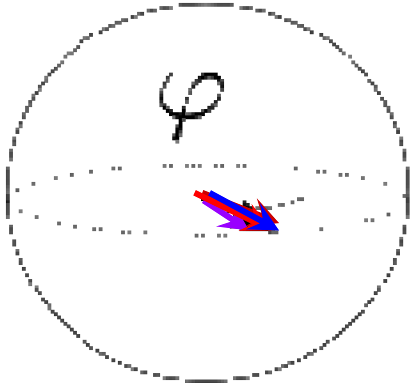


potential and interactions shift the energy levels

ensemble of atoms will dephase (inhomogeneous broadening)

Solution: "Magic" fields





There can be a shift, but it is constant in space.

An ensemble of atoms stays in phase.
Coherence is preserved.

Key idea in optical lattice clocks!

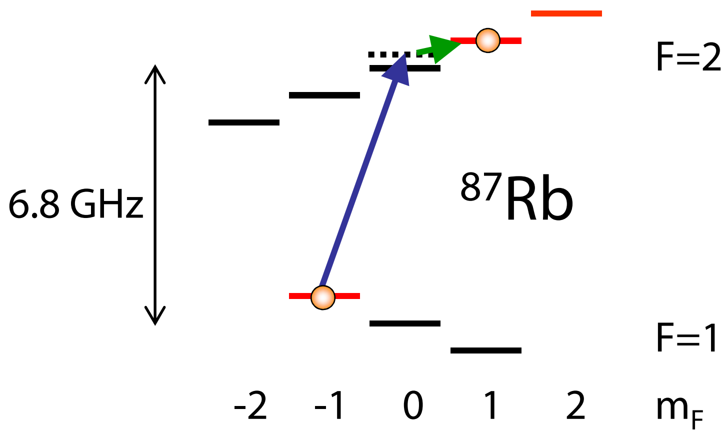
Long coherence time in a trap?

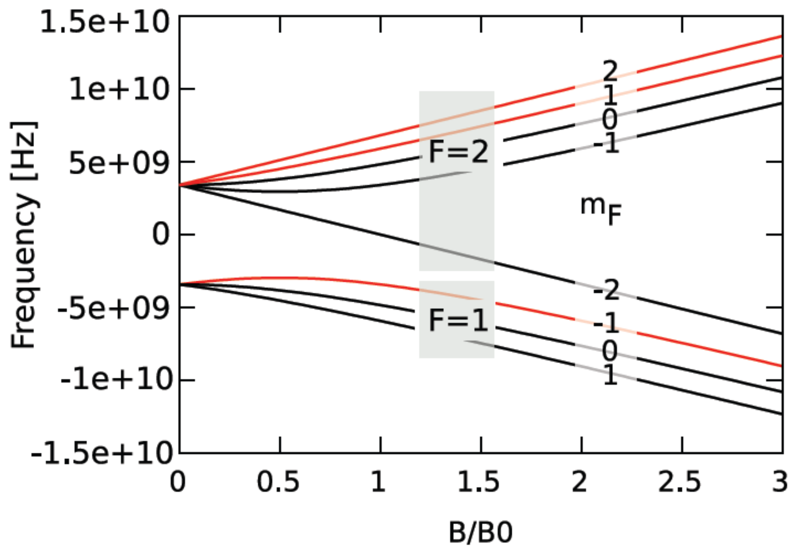
- Unperturbed clock frequency: ω_0
- Trapping potential perturbs transition:
  Differential Zeeman shift, $\omega_0 + \Delta(r)$
- Collisional interactions:
  density-dependent shift
- ***Minimize these perturbations?***

Seminal work, ^{87}Rb in a magnetic trap:

D. M. Harber, H. J. Lewandowski, J. M. McGuirk, and E. A. Cornell,
Effect of cold collisions on spin coherence and resonance shifts in a magnetically trapped ultracold gas,
PRA **66**, 053616 (2002).

Zeeman shifts





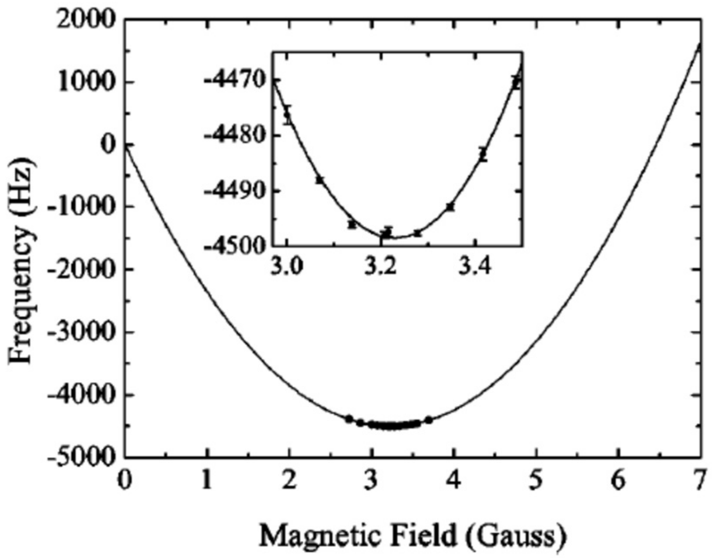
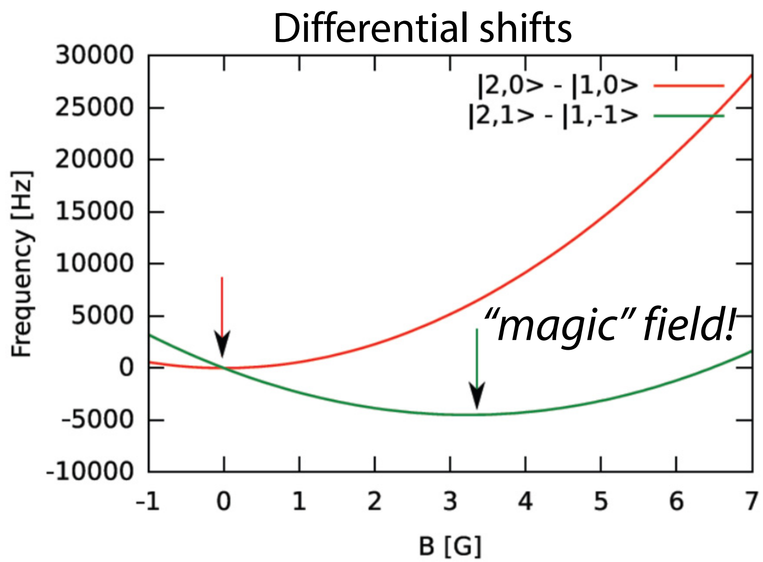


FIG. 1. Differential Zeeman shift at low magnetic fields for the $|1\rangle \rightarrow |2\rangle (|F=1, m_f=-1\rangle \rightarrow |F=2, m_f=1\rangle)$ transition. The solid



Second-order shift on |1,-1⟩ - |2,1⟩ is even weaker than on "canonical" |1,0⟩ - |2,0⟩ !

Collisional mean-field shift

- μK temperatures -> s-wave scattering
- In ^{87}Rb, all relevant scattering lengths nearly equal:

$$a_{22}=95.47a_0,\ a_{12}=98.09a_0,\ \text{and}\ a_{11}=100.44a_0$$

- Collisional shift proportional to density: $\Delta(r) \sim -n(\mathbf{r})$

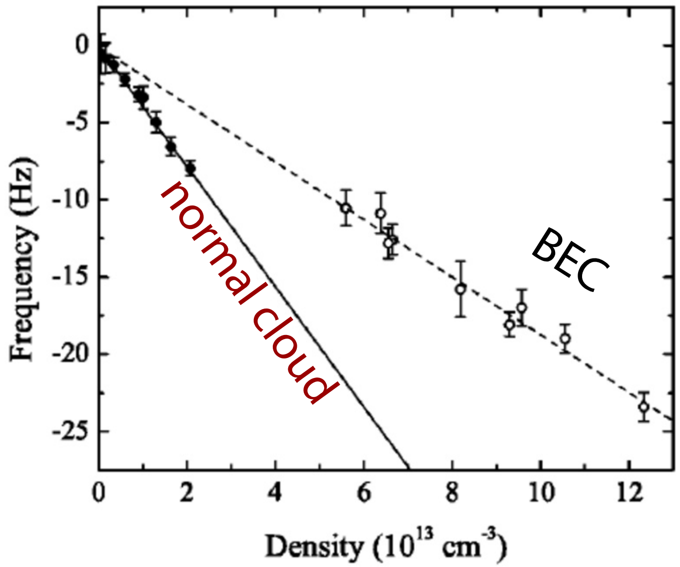
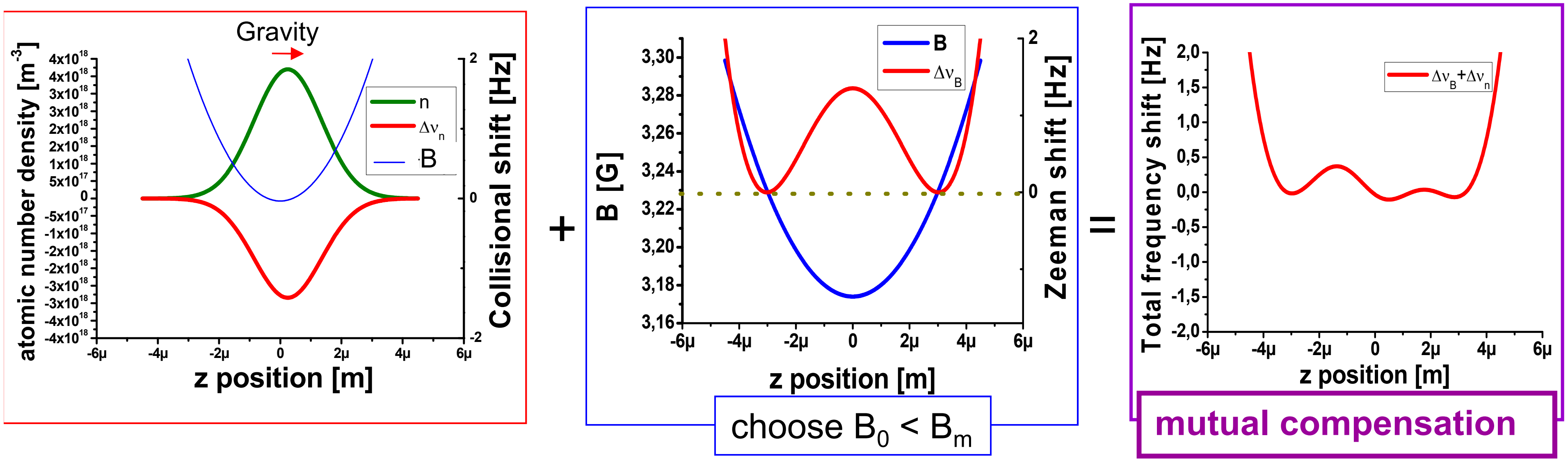


FIG. 2. Measurement of the cold collision shift. Solid and open circles represent measurements of the normal cloud and condensate, respectively. The solid line is a fit to the normal cloud data $\Delta\nu_{12} = 0.1(0.4) - 3.9(0.3)10^{-13}n$; the dashed line is a fit to the condensate data $\Delta\nu_{12} = -0.1(1.4) - 1.9(0.2)10^{-13}n$ where $\Delta\nu_{12}$ is in Hz and n is in cm^{-3}.

“Magic” field for ^{87}Rb

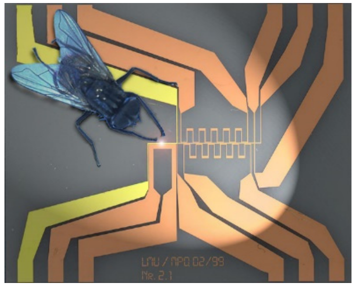
Lewandowski et al., PRL **88**, 070403 (2002)

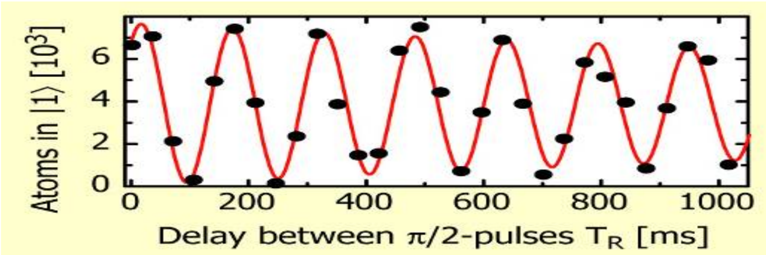


Can we do that on a chip?

Yes we can!

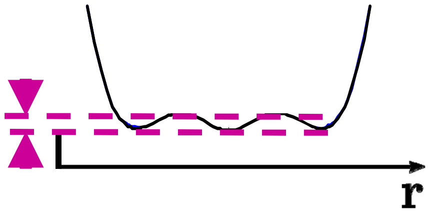
Ph. Treutlein *et al.*, PRL **92**, 203005 (2004).



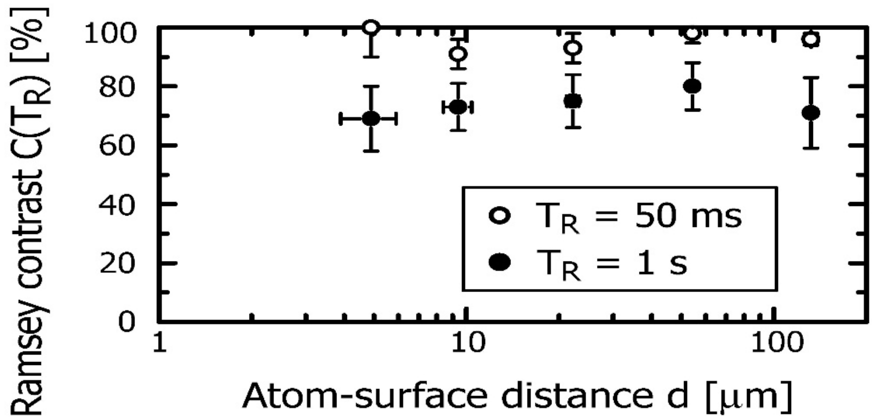


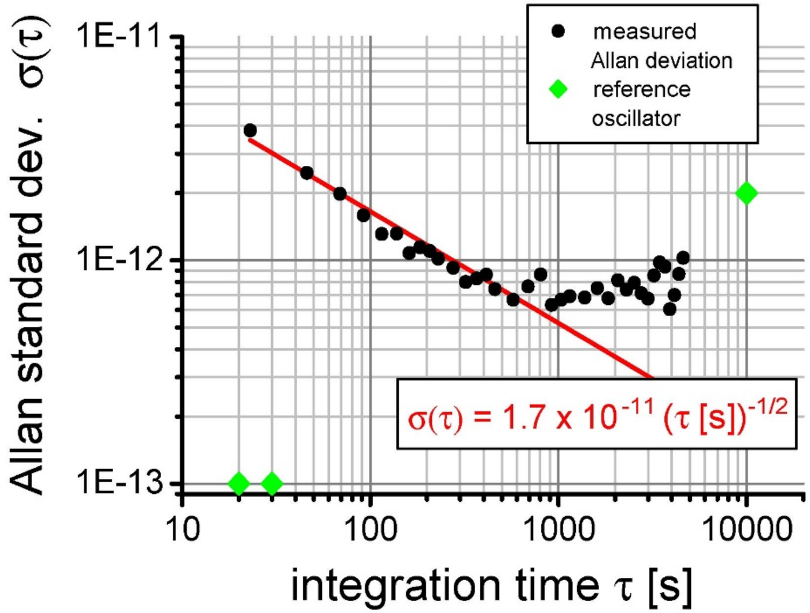
Coherence time $\tau_{coh} = 2.8$ s

…seemed to agree with predictions:



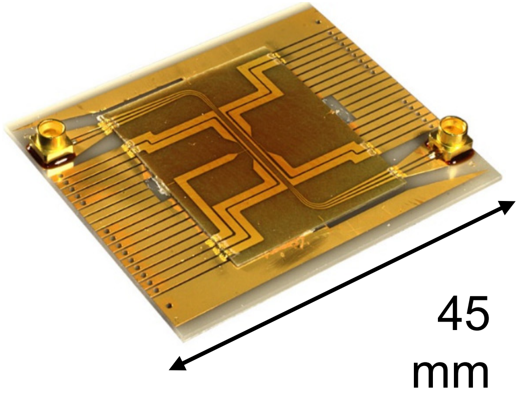
$$\left(\langle\Delta\ \ ^2\rangle - \langle\Delta\ \ \rangle^2\right)^{1/2} = 2\pi\cdot 0.08\ \mathrm{Hz}$$

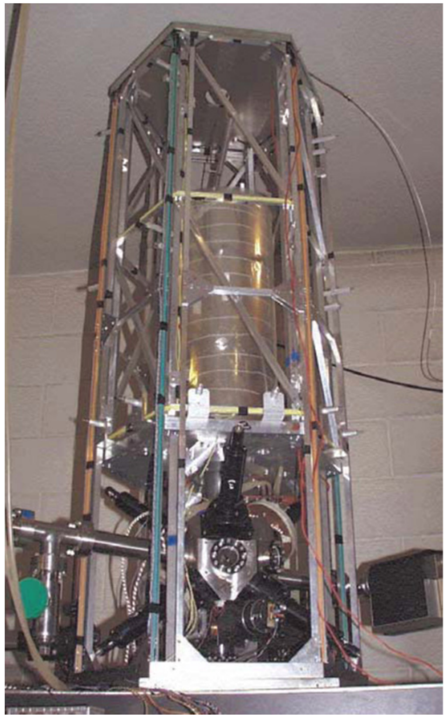




Short-term Allan variance dominated by ambient magnetic field fluctuations.

Can we reach a relevant range for compact clocks?



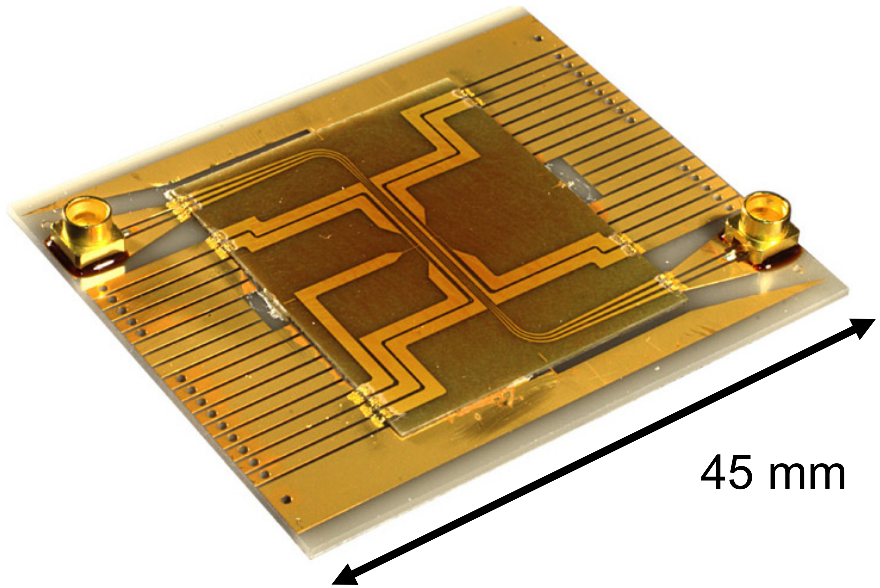


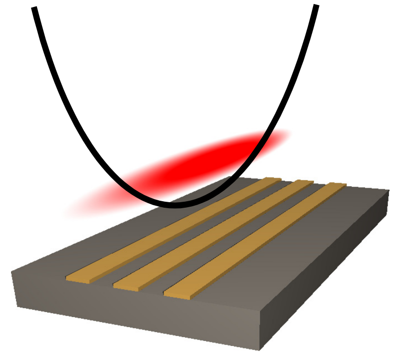
Stability: ~ 10^{-12} $s^{-1/2}$

Target stability: ~ 10^{-13} $s^{-1/2}$ range

Stability: ~ 10^{-14} $s^{-1/2}$

TACC: Trapped-Atom Clock on a Chip





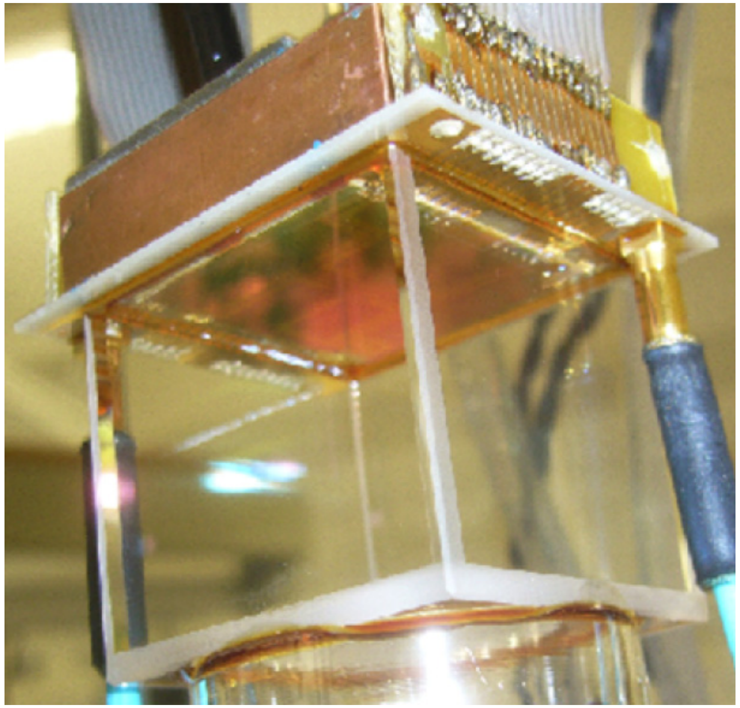
- Coplanar waveguide for microwave excitation
- Incorporate atomic clock know-how and techniques:
    - Two-layer magnetic shielding
    - Stable, low-noise current sources
    - Interrogation: homebuilt frequency chain with low phase noise, locked on H maser
    - + lots of SYRTE know-how

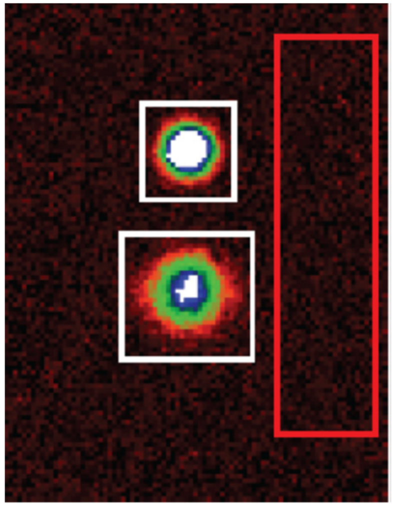
Laboratoire Kastler Brossel — Physique quantique et applications

IFRAF — Institut francilien de recherche sur les atomes froids — soutenu par la région ÎledeFrance

l'Observatoire de Paris — SYRTE — Systèmes de Référence Temps-Espace

TACC: Trapped-Atom Clock on a Chip

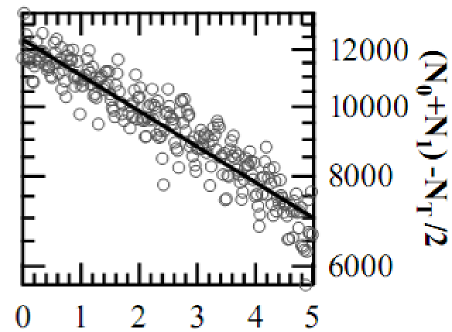


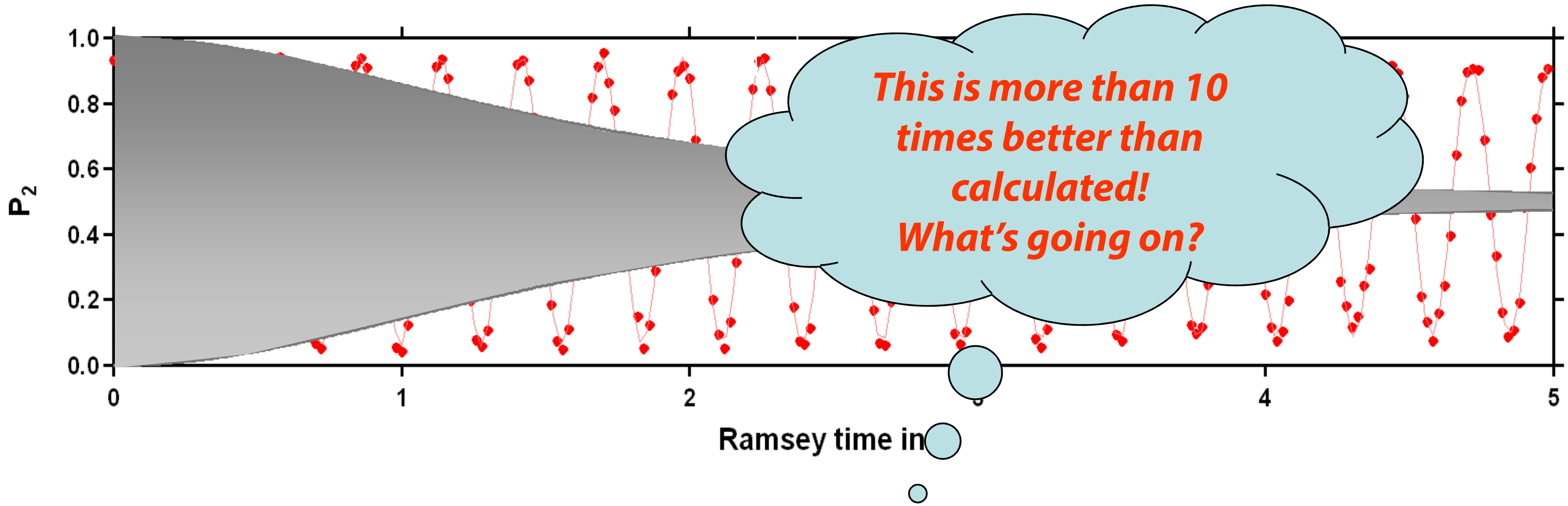


Ramsey measurement

C. Deutsch et al PRL **105**, 020401 (2010)

- Magnetic trap, $\{\omega_x, \omega_y, \omega_z\}/2\pi = \{32(1), 97.5(2.5), 121(1)\}$ Hz
- Evaporative cooling to 175nK (30nK above T_c)
- 25000 atoms
- Ramsey spectroscopy.
  Vary Ramsey time (but keep trapping time constant).





Contrast decay time τ_{coh} = 58 ±12 s

"Identical Spin Rotation Effect" (ISRE)

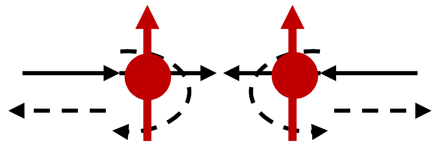
Origin: forward collisions of indistinguishable particles

E. P. Bashkin, JETP Lett. **33**, 8 (1981); C. Lhuillier and F. Laloe, J. Phys. **43**, 197 and 225 (1982)

spin-aligned collisions:

f/b scattering is indistinguishable

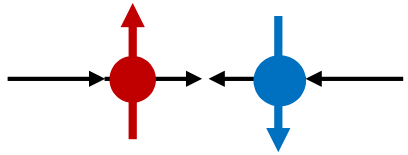
=> **2** x exchange interaction energy



anti-parallel spins:

f/b scattering is maximally distinguishable

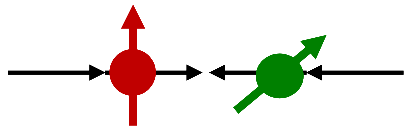
=> **1** x exchange interaction energy

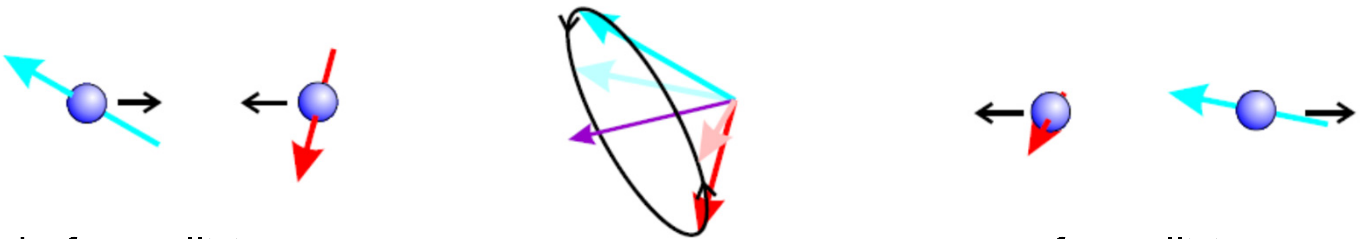


partially aligned spins:

calculate superposition of the above

=> exchange interaction energy creates torque on spins





before collision

after collision

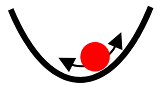
- ***A very general effect arising from indistinguishability***
- ***Known to cause spin waves***

PRL 88, 230404, 2002

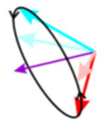
PRL 103, 010401, 2009

Interactions & Timescales

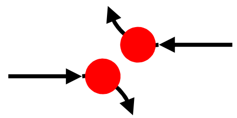
Trap frequency $\omega_x = 2\,\pi$ 30 Hz



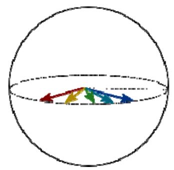
Exchange rate (ISRE rate): $\omega_{ex} = 2\,\pi$ 8 Hz



Lateral (elastic) collisions $\gamma_c = 2\,\pi$ 2 Hz



Dephasing rate: $\Delta_0 \sim 2\,\pi$ 0.08 Hz

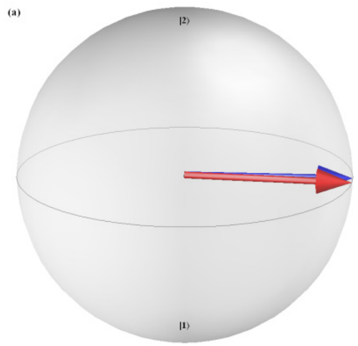


Conditions for tight spin synchronization

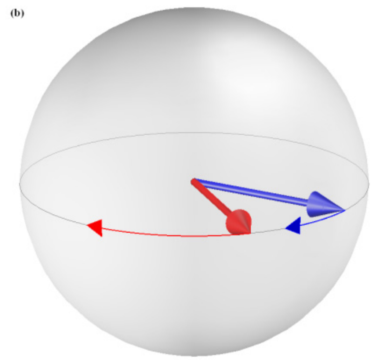
$$\begin{cases} \omega_{ex} \gg \Delta_0 \\ \omega_{ex}/\pi > \gamma_c \end{cases}$$

Spin self-rephasing

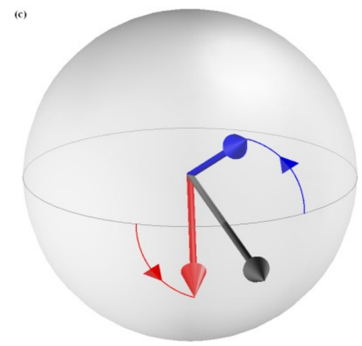
A quantum effect caused by particle statistics



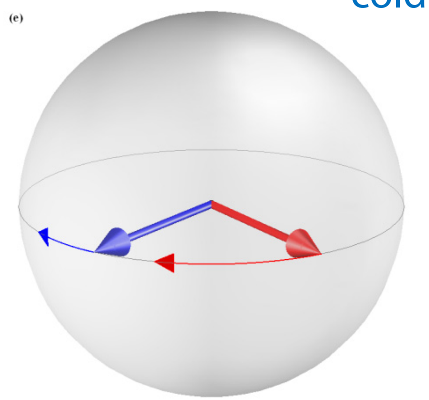
just after p/2
pulse



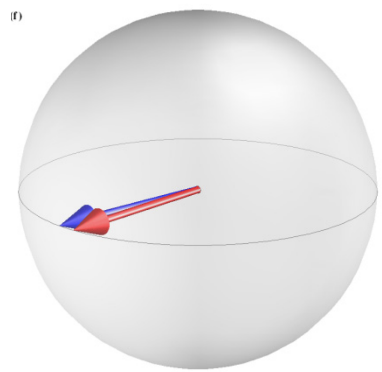
Free evolution: Hot atoms have stronger detuning, rotate faster than cold atoms.



ISRE rotates spins around their sum



After half a spin rotation, hot atoms are "behind" cold atoms and catch up => **synchronisation**



Atoms stay synchronised because opening angle is small.

C. Deutsch et al PRL **105**, 020401 (2010)

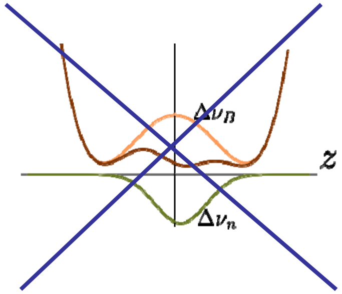
Full model

Collaboration with F. Laloë (ENS), J.-N. Fuchs & F. Piéchon (Paris-Sud)

- Motion treated semiclassically
- Full quantum treatment of spin
- Trap frequencies are fastest => Δ depends only on energy
- Interaction becomes "long-ranged in energy space"
- Results in a classically-looking equation for Bloch vector.
- **Three experimentally tunable parameters:**
  - **Inhomegeneity** $\Delta_0(T, \bar{n}, \ldots)$
  - **ISRE rate** $\omega_{\mathrm{ex}} \propto |a_{01}|\bar{n}$
  - **Lateral collision rate** $\gamma_c \propto a_{01}^2 \bar{n} \sqrt{T}$

- Prediction for our conditions:
  Contrast decay time 100 s
  (Experiment is limited by asymmetric loss of |0> and |1>)
- *Can make predictions for wide range of parameters*

Direct demonstration: contrast revivals



Go away from compensation!

Increase Δ (B0 + 500mG)

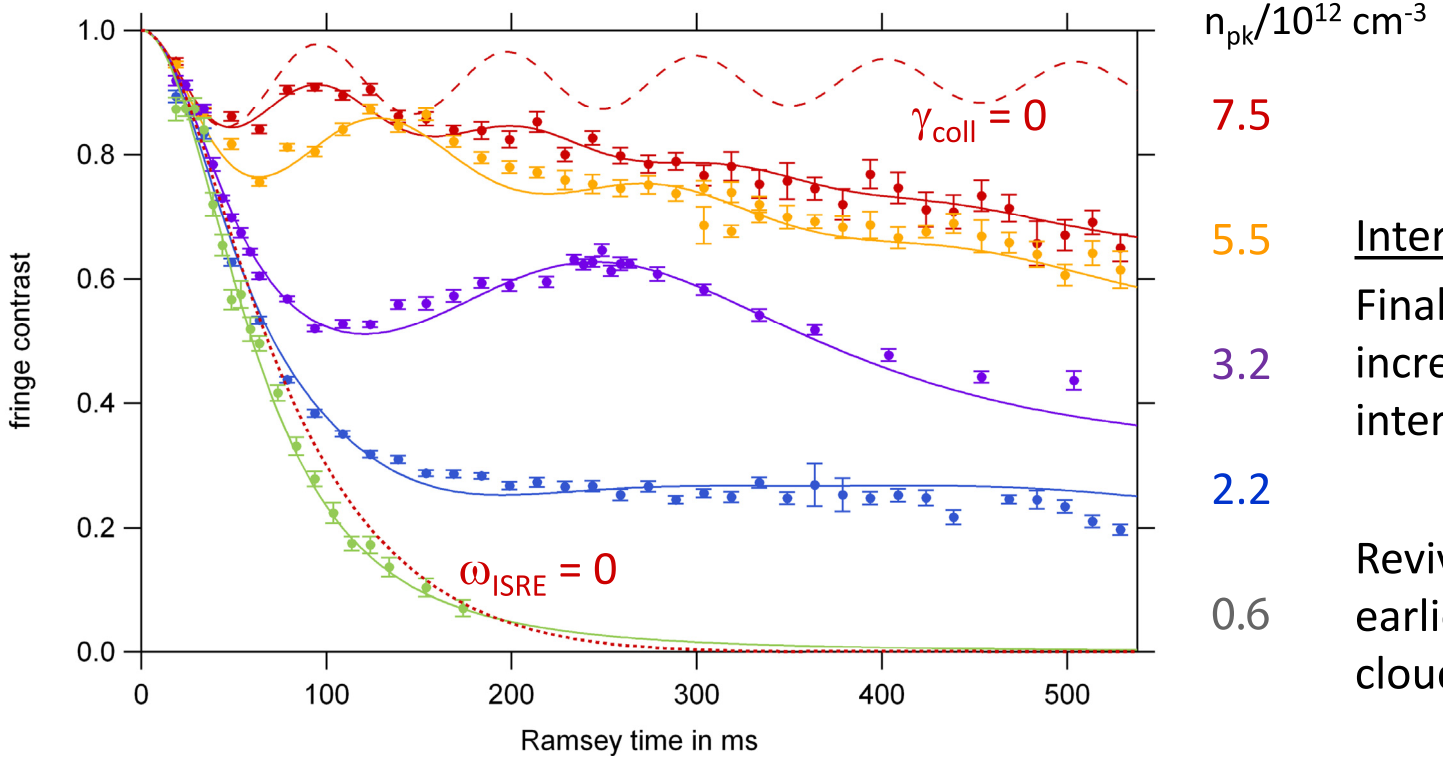
Tune ISRE via atom density

Go from $\omega_{ex} << \Delta$ to $\omega_{ex} \sim \Delta$

$\Delta(E) = 2\pi \cdot 2.0$ Hz x E/kT

$\gamma_{coll} = 2\pi \cdot 0.7$ Hz x $n_{pk}/10^{12}$ cm^{-3}

$\omega_{ex} = 2\pi \cdot 1.6$ Hz x $n_{pk}/10^{12}$ cm^{-3}



<u>Interaction effect:</u>

Final contrast increases with interaction

Revivals appear earlier for denser clouds

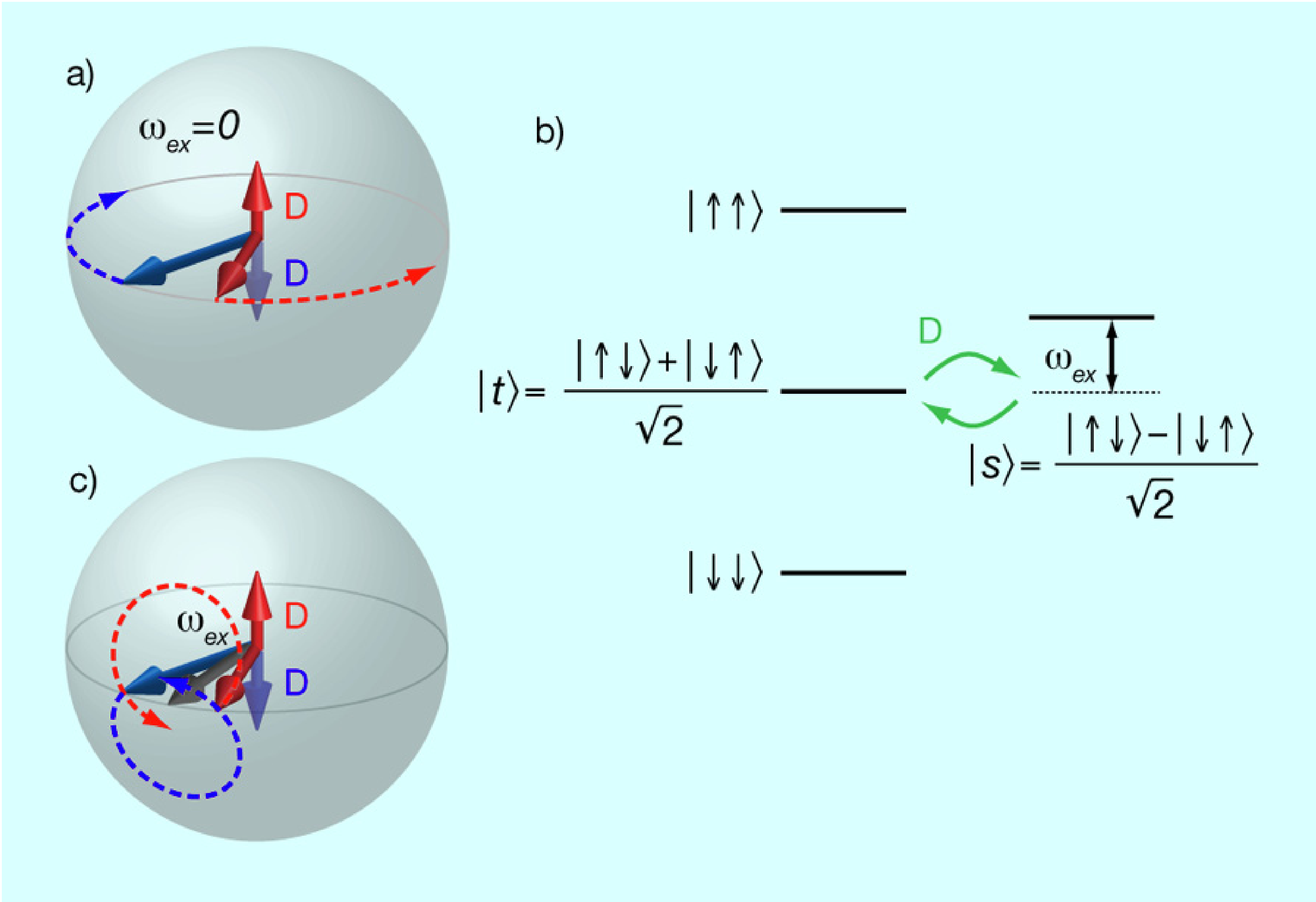
C. Deutsch et al., PRL (2010)

Alternative model: Singlet-triplet

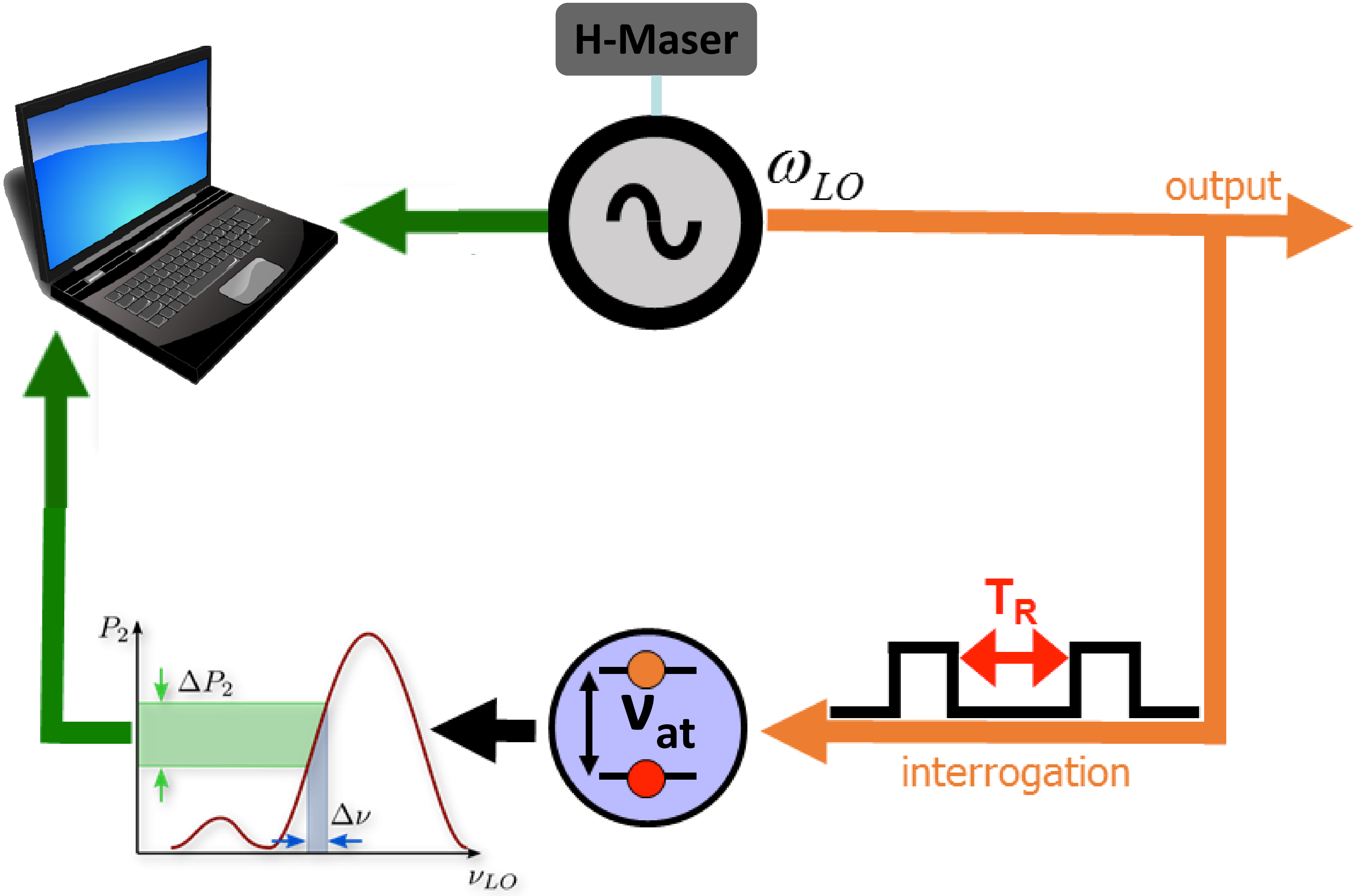
K. Gibble, Viewpoint on the Spin Self-Rephasing PRL (2010)

87Rb: Relevant scattering lengths are almost equal.

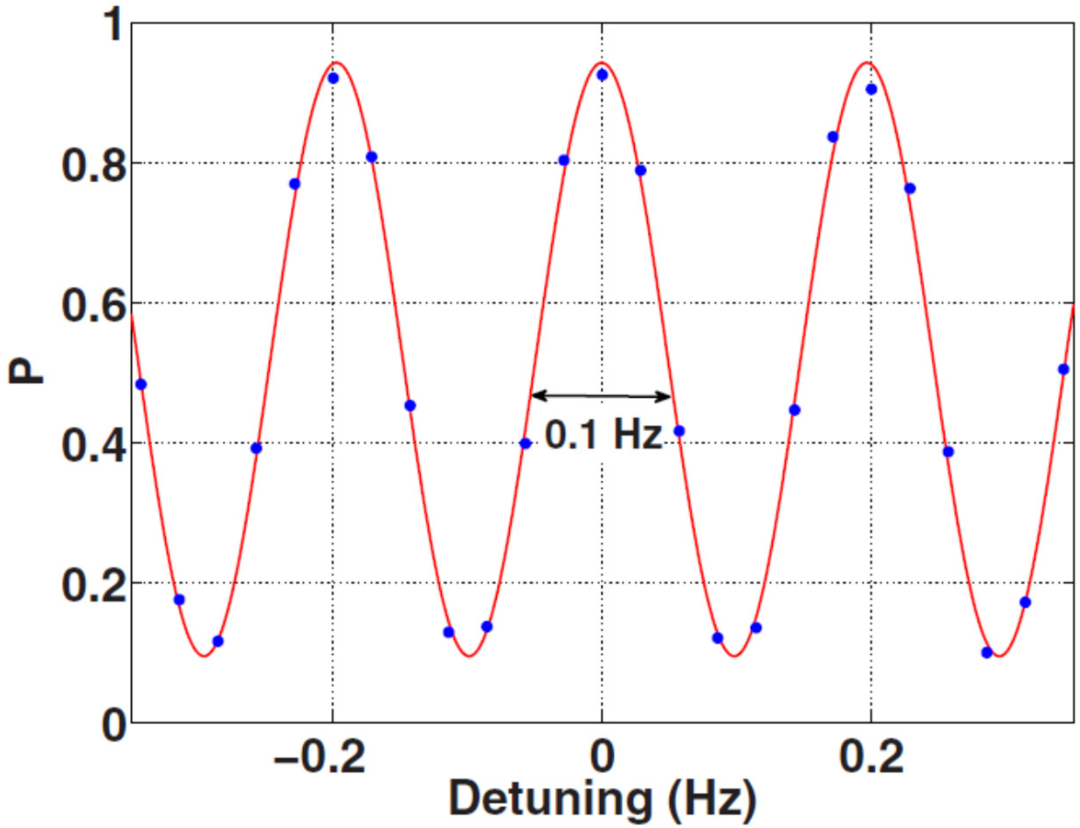
=> For two atoms: Singlet state shifted with respect to triplet state, as in fermions.



Clock stability measurement

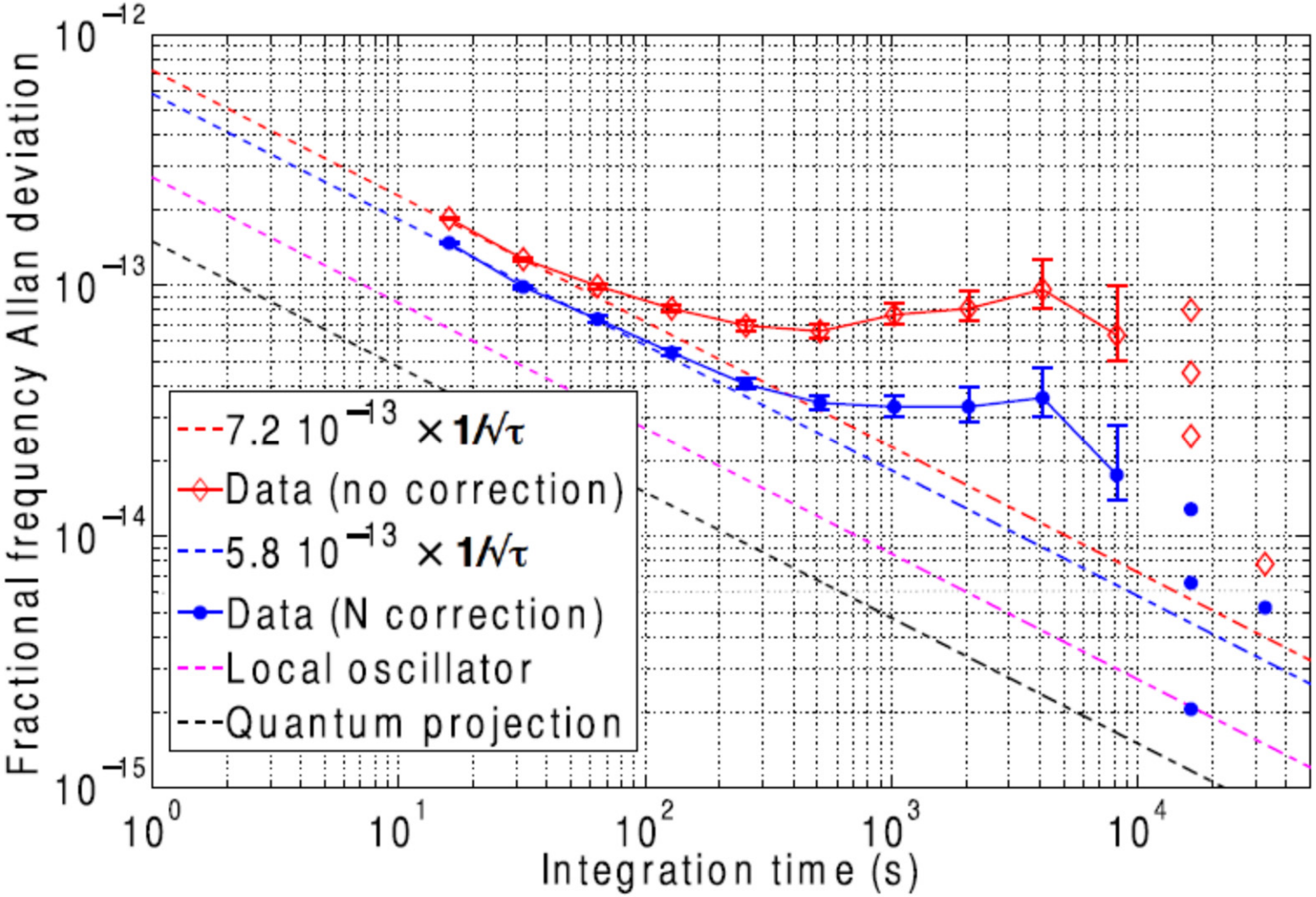


TACC Ramsey fringe



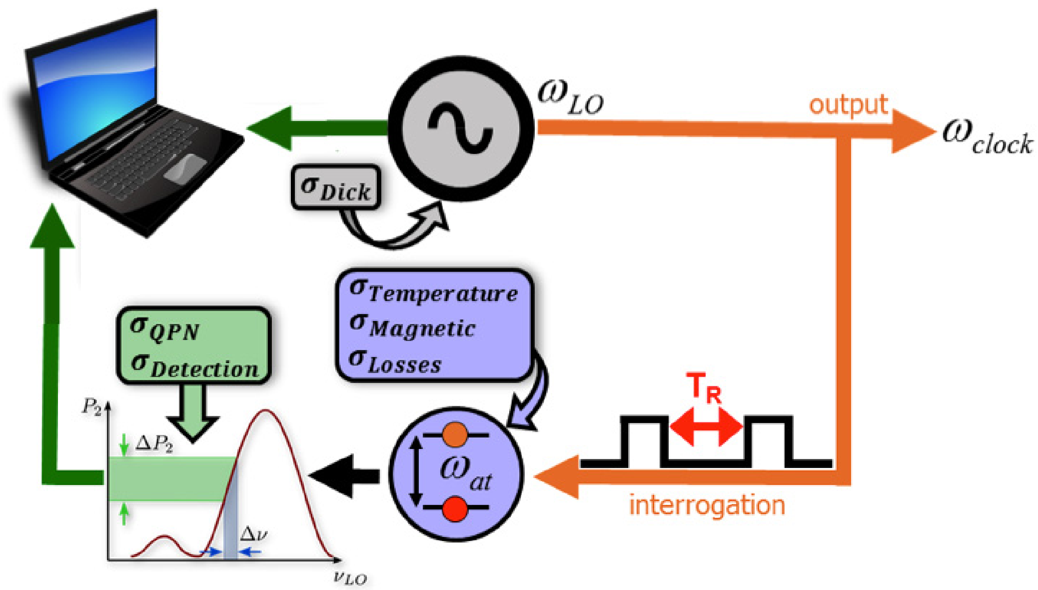
- ***Ramsey time: T_R=5s***
- ***Fourier-limited linewidth***
- ***85% contrast***

Allan variance



Stability: 5.8 10-13 $s^{-1/2}$

Stability budget

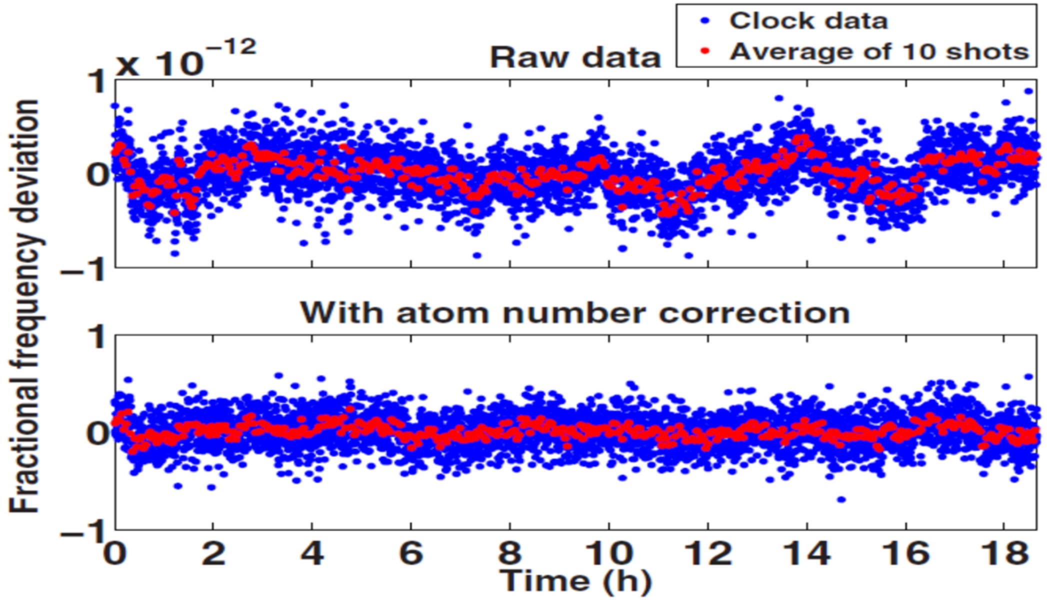


Relative frequency stability (10^{-13})	at 1 shot	at 1 sec
Measured	**1.5**	**5.8**
Temperature	**1.0**	**3.9**
Magnetic field	**0.7**	**2.6**
Local Oscillator	**0.7**	**2.7**
Quantum projection	**0.4**	**1.5**
N correction	**0.3**	**1.3**
Atom loss	**0.3**	**1.1**
Detection	**0.3**	**1.1**
Total estimate	**1.5**	**6.0**

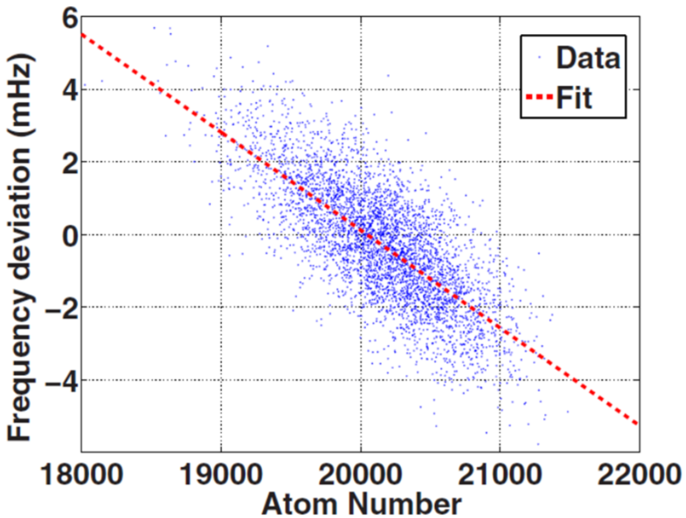
Stability of a trapped-atom clock on a chip, R.Szmuk, V. Dugrain, W. Maineult, J. Reichel and P. Rosenbusch, PRA **92**, 012106 (2015).

Clock frequency: Compensating the atom number dependence

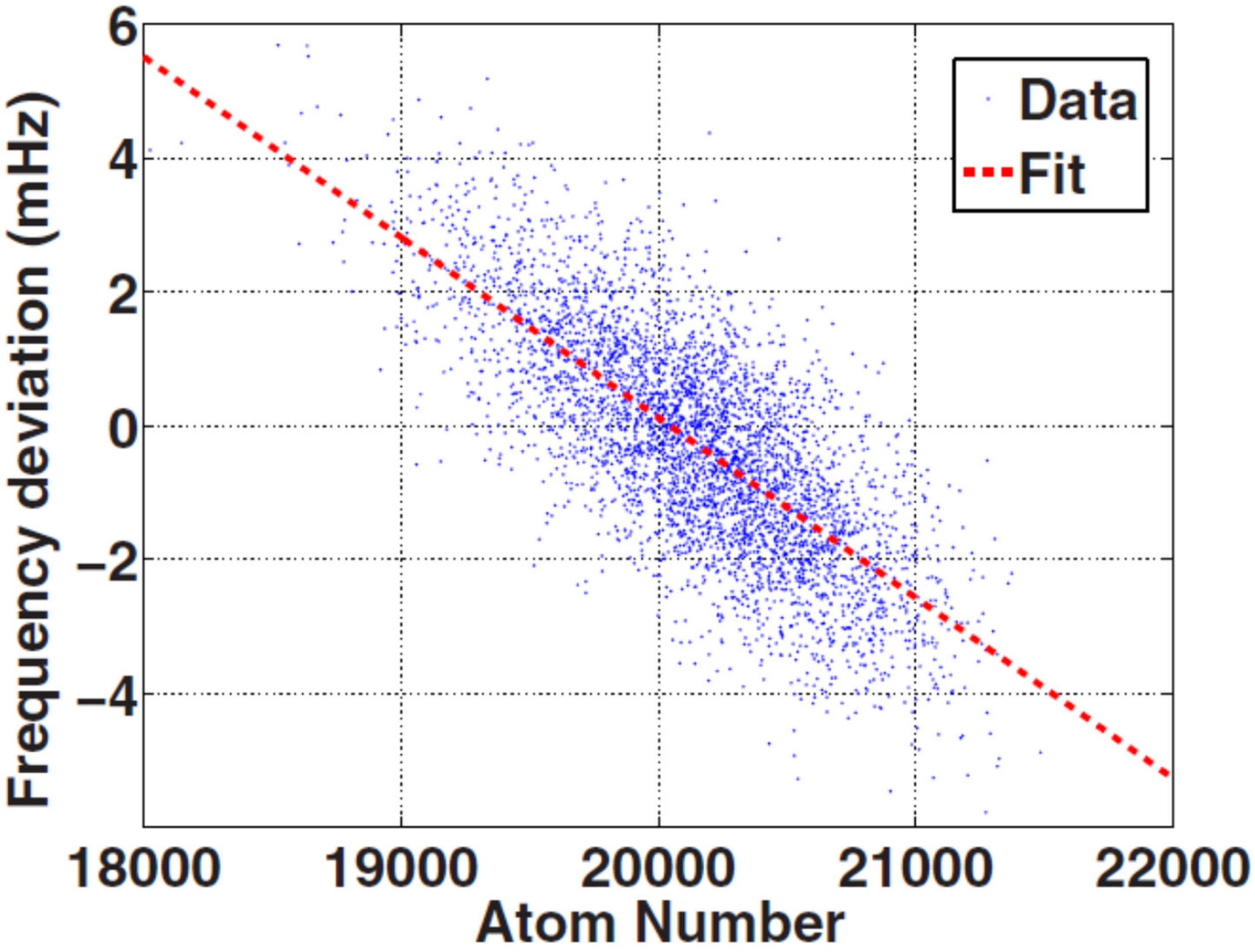
Relative frequency deviation over 18h



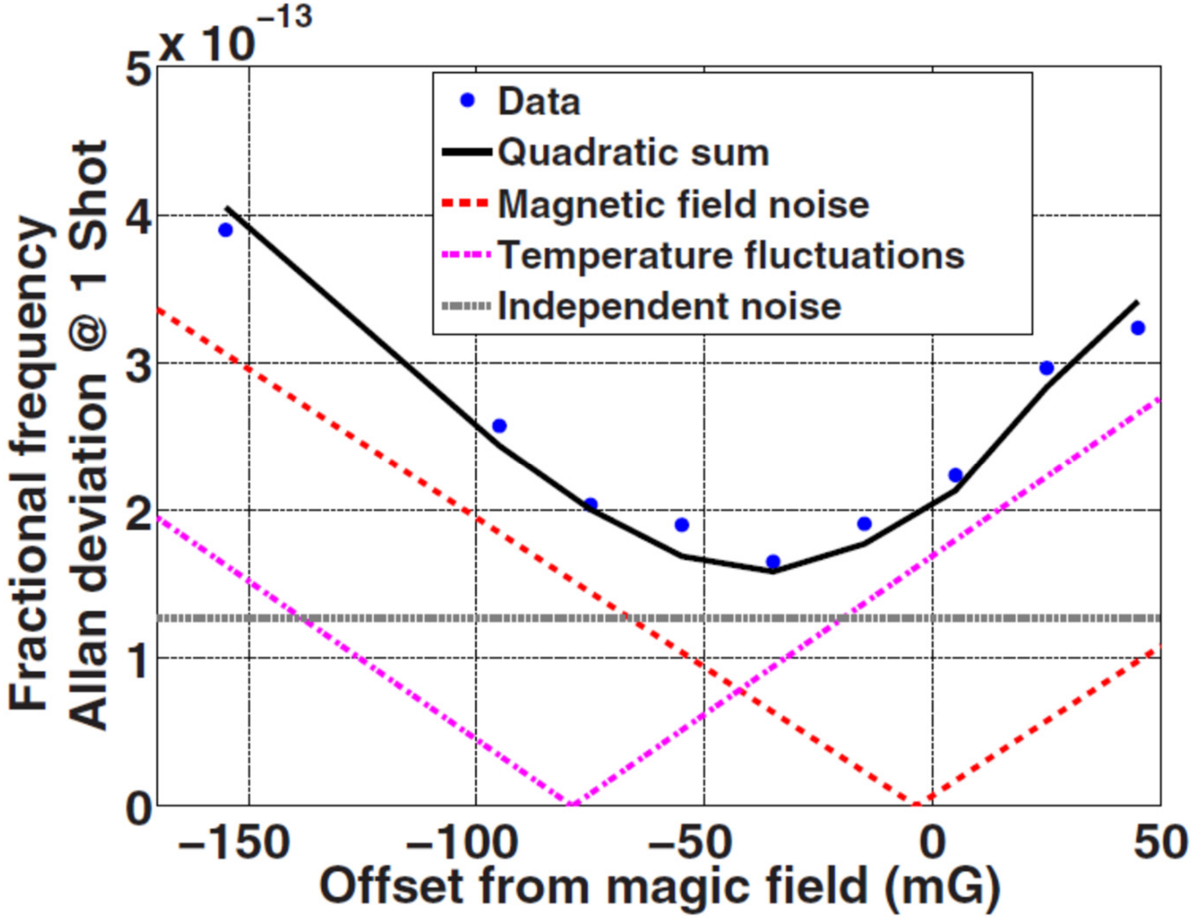
Reproducible dependence on N_{at}



Atom number – clock frequency correlation



Magnetic field dependence

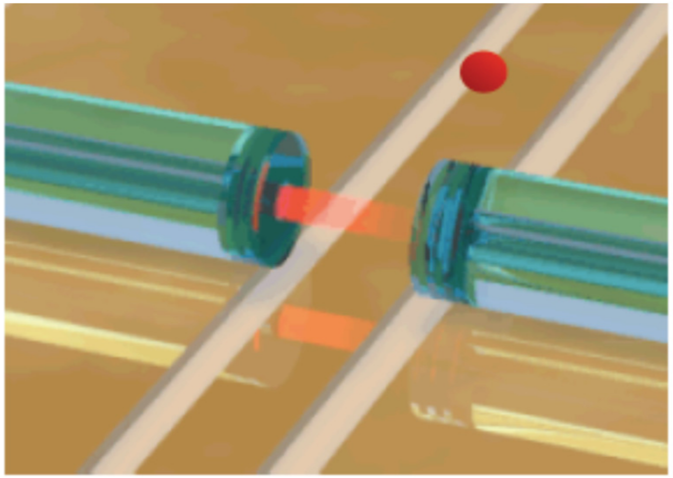


Magnetic field stability: 16 μG shot-to-shot

Temperature stability: 0.5 nK shot-to-shot

Perspectives

- **Some "easy" improvements:**
  - Reduce dead time (MOT loading)
  - Improve current source stability
- **eeTACC: Use quantum technologies**
  - Spin squeezing
  - Non-destructive detection



[redacted]

Quantum technologies for metrology

Two possible quantum enhancements

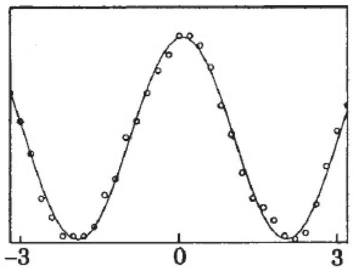
- **Spin squeezing: Detection beyond the standard quantum limit**
  - detection $\longrightarrow$ projective measurement $\longrightarrow$ QPN
  - For N uncorrelated atoms, coherent spin state, $\sigma \propto 1/\sqrt{N}$
  - Limiting is reached our primary frequency standards (fountain clocks)
    - Quantum correlations $\longrightarrow$ *spin squeezing*
  - **Particularly interesting when atom number is limited**

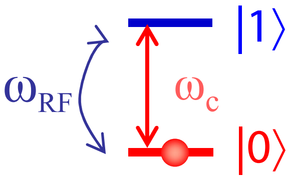
- **QND detection for reducing dead time**
  - Can reduce Dick effect:
    Local oscillator noise + dead time $\longrightarrow$ aliasing effect
  - Limiting compact clocks
    - *Quantum non-destructive (QND) detection*
      - Leading also to squeezing

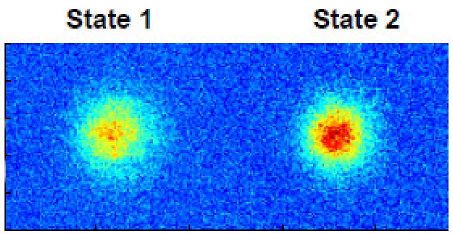
Tool for both: **Cavity-QED**

Readout: Continous parameter, but "digital" measurement

- *Always measure some kind of interference fringe: Ramsey fringe (internal state), matter wave interference (external state)…*







- *Desired observable is position on fringe (continuous value), but each atom is a two-level system, yielding only 1 bit of information.*

- *With independent atoms, this leads to binomial statistics, as in coin tossing:*

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

- *When all technical noise is eliminated, this is a fundamental limit to quantum measurement with two-level systems.*
- *…Unless entanglement is used!*

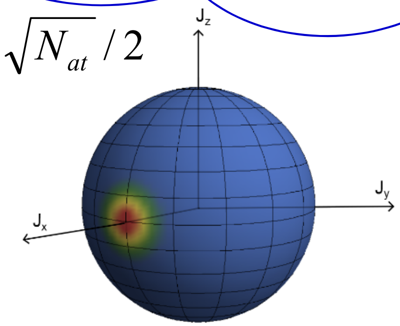
Spin squeezing

- Metrology in AMO systems (and beyond):
  Measuring an angle on a Bloch sphere
- Uncertainty relation constrains products of observables:

Spin-squeezed states are entangled!
Other entangled states with metrological gain exist as well.

Coherent spin state (CSS)

$$\Delta J_z = \Delta J_y = \sqrt{N_{at}}/2$$



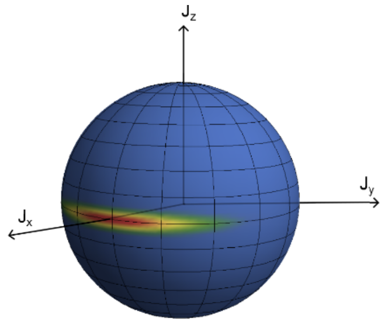
N independent atoms

Tensor product state

Projection noise limit:
$1/\sqrt{N_{at}}$

Spin-squeezed state

$$\xi^2 = \left(\frac{\sqrt{N_{at}}/2}{\Delta J_z} \frac{J_x}{N_{at}/2} \right)^2$$



Highly entangled state

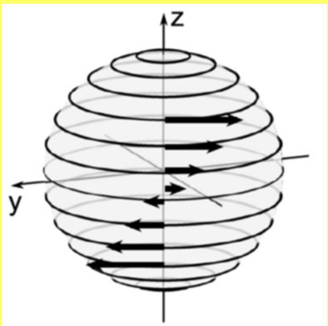
Noise: like CSS with ξ^2 times N_{at}

Ultimate (Heisenberg) limit: $1/N_{at}$

Create by interaction or QND measurement

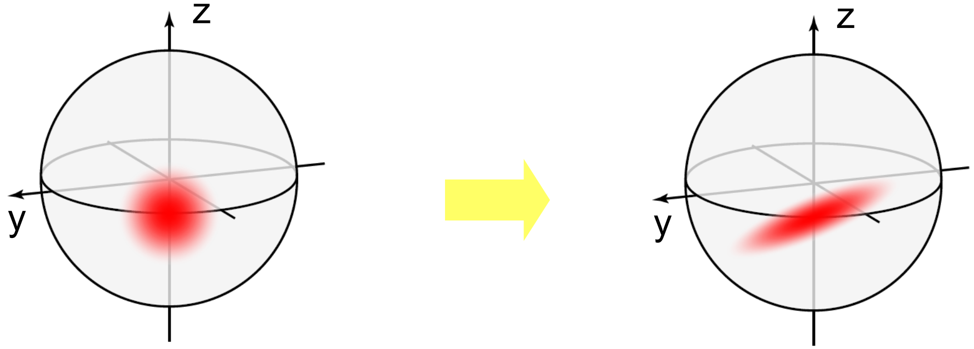
Creating spin-squeezed states

- ***Squeezing by interaction***



$$H = \chi S_z^2$$

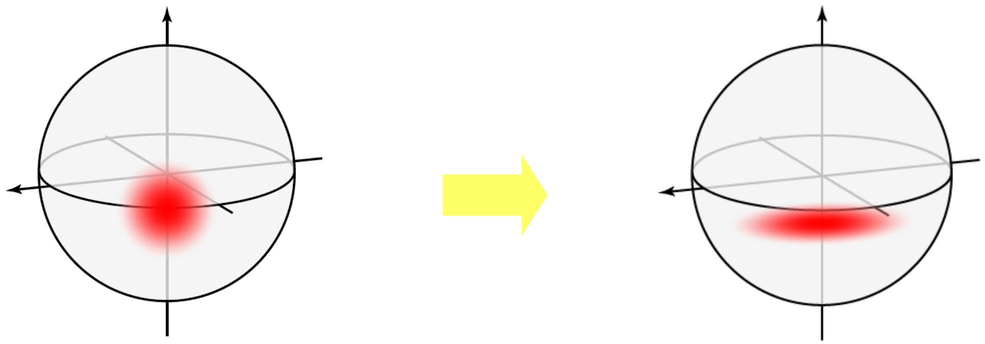
"One-axis twisting"



Implementation: collisional interaction or light shift in cavity

- ***Squeezing by nondestructive measurement***

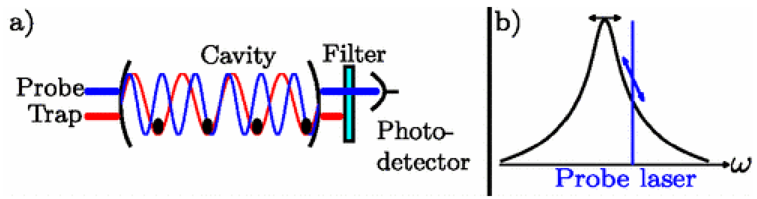
Measure N_2-N_1 with sub-shot noise resoution, without destroying their relative phase.



Implementation: two-color probe beams or cavity measurement

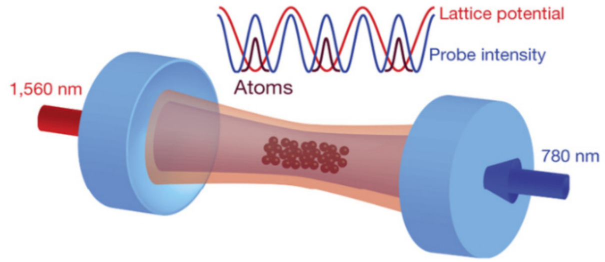
State of the art

Cavity feedback



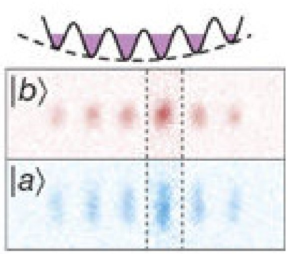
Leroux, PRL 104, 250801 (2010)

Non demolition measurement

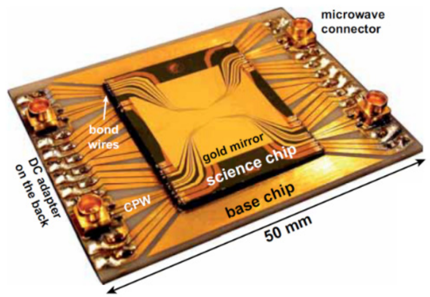


Hosten, Nature 529, 505-508 (2016)

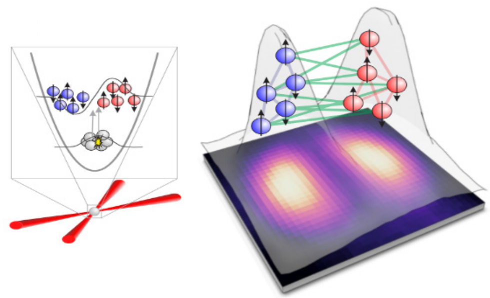
Collisional interactions in a BEC



Gross et al., Nature 464, 1165–1169 (2010)



Riedel, Nature 464, 1170-1173 (2010)



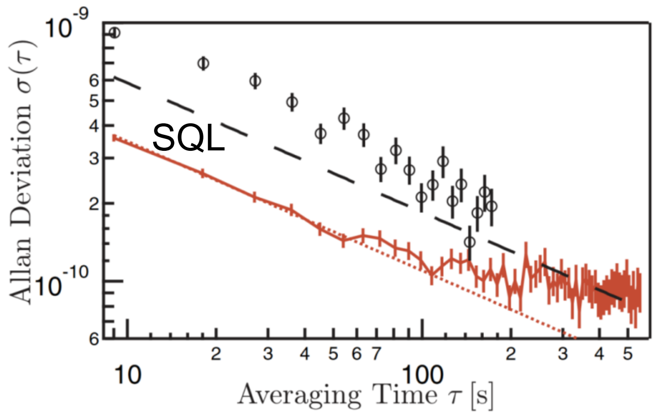
Lange, arXiv:1708.02480 (2017)

Applications are still at an elementary proof-of-principle level: 4.5dB clock improvement @ 10^{-9} $s^{-1/2}$.

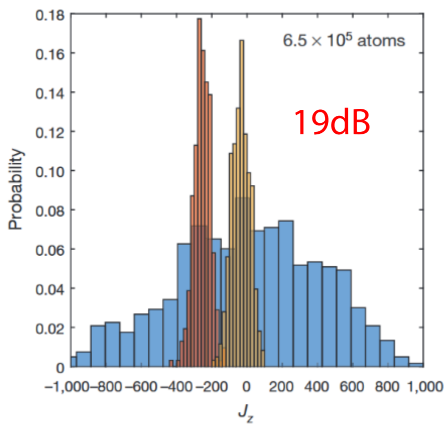
No metrology-grade experiments yet.

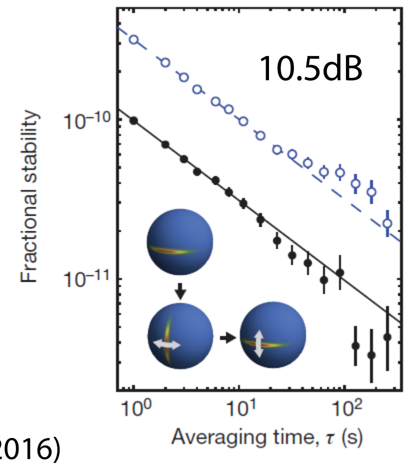
State of the art: Some results

5.6dB



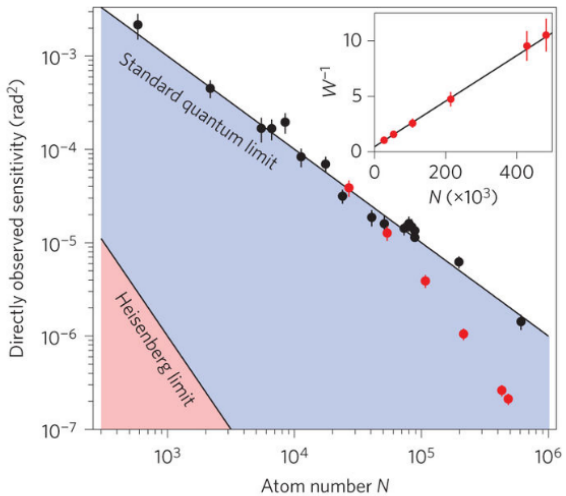
Leroux, et al. PRL 104, 250801(2010)





Hosten, et al. Nature 529, 505 (2016)

10dB



Bohnet, et al. *Nature Photonics* 8, 731 (2014)

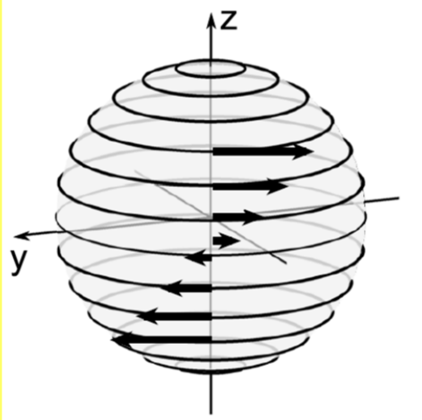
Other QND schemes

- Appel, et al., PNAS 106. 10960 (2009)
- Vanderbruggen, et al. PRL 110, 210503 (2013)
- Vallet, et al. New J. Phys. 19, 083002, (2017)

Spin squeezing and *QND detection* @ metrological level of precision 10^{-13} *range*

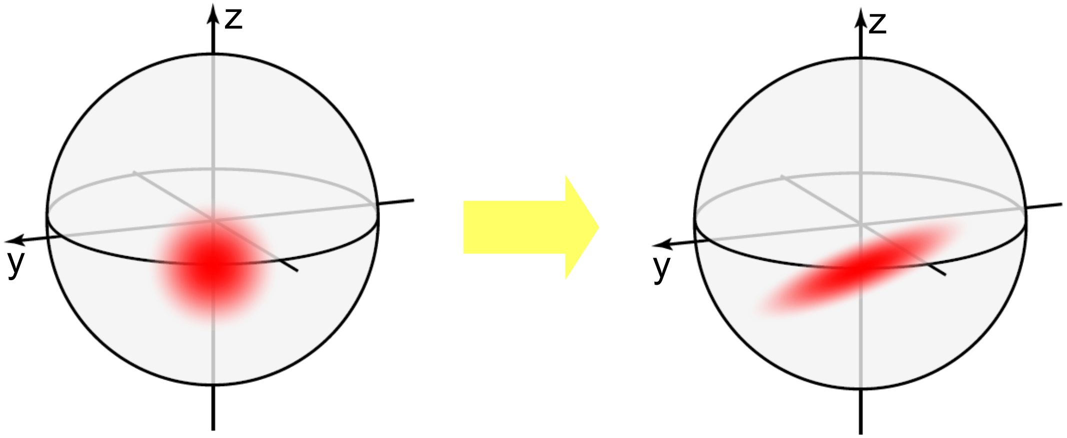
Interlude: Spontaneous spin squeezing in a Rb BEC

Spin squeezing by atomic interaction



$$H = \chi S_z^2$$

"One-axis twisting"



- ***Occurs naturally in BECs with two internal states*** $|\uparrow\rangle$, $|\downarrow\rangle$, ***due to interactions.***
  Sørensen et al, Nature (2001)
- χ ***depends on scattering lengths:*** $a_{\uparrow\uparrow}+a_{\downarrow\downarrow}-2a_{\uparrow\downarrow}$.

However, in ^{87}Rb, $a_{\uparrow\uparrow}\approx a_{\downarrow\downarrow}\approx 2a_{\uparrow\downarrow}$ **so that** $\chi\approx 0$.

Solutions so far:

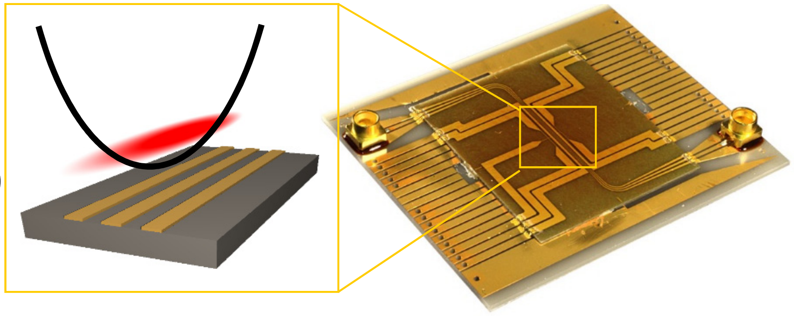
- **State-dependent potentials on atom chip** Riedel et al, Nature (2010)
- **Feshbach resonance in optical potential** Gross et al, Nature (2010)

Experiment

BEC in a highly anisotropic harmonic trap:

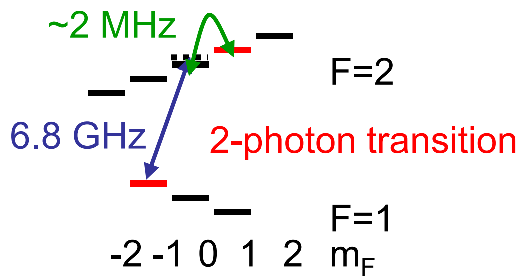
(2.7, 92, 74) Hz

“Pure” BEC, *N*~8000



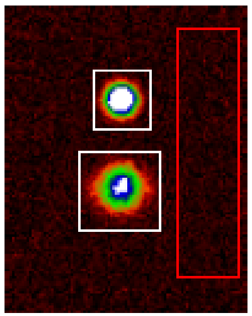
Two identically trapped states:

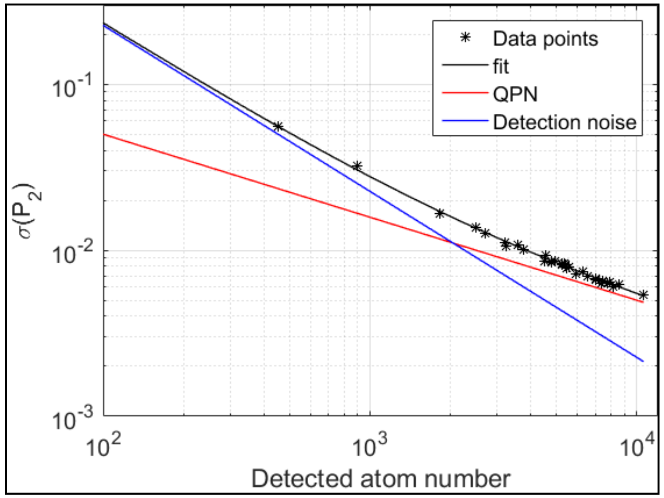
|↓⟩= |F=1,m=-1⟩, |↑⟩= |F=2,m=1⟩



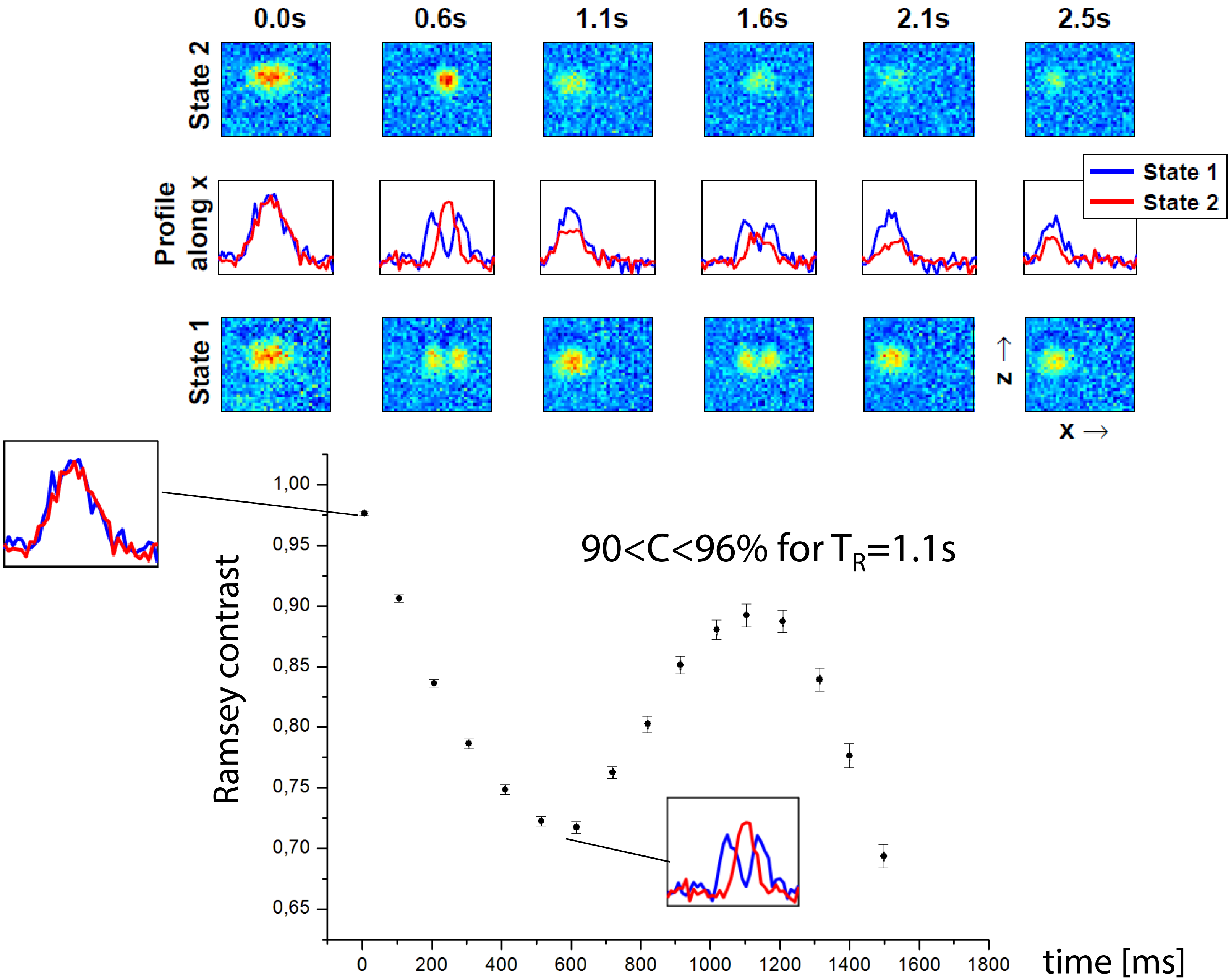
High-performance imaging:

- BE-DD camera for high QE
- ARP to untrapped state, transfer efficiency 99.9%.
- Image both clock states on same frame
  Fringe recomposition
- Careful calibration



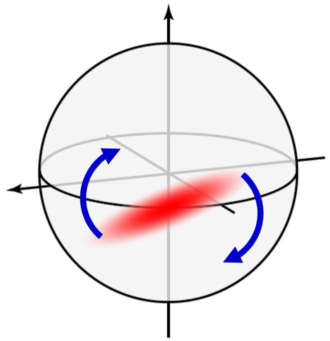


What's the trick?



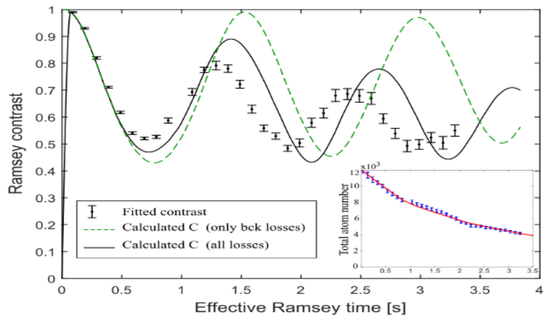
How to measure squeezing?

“Noise tomography”:



Repeat many times for every angle and compute standard deviation

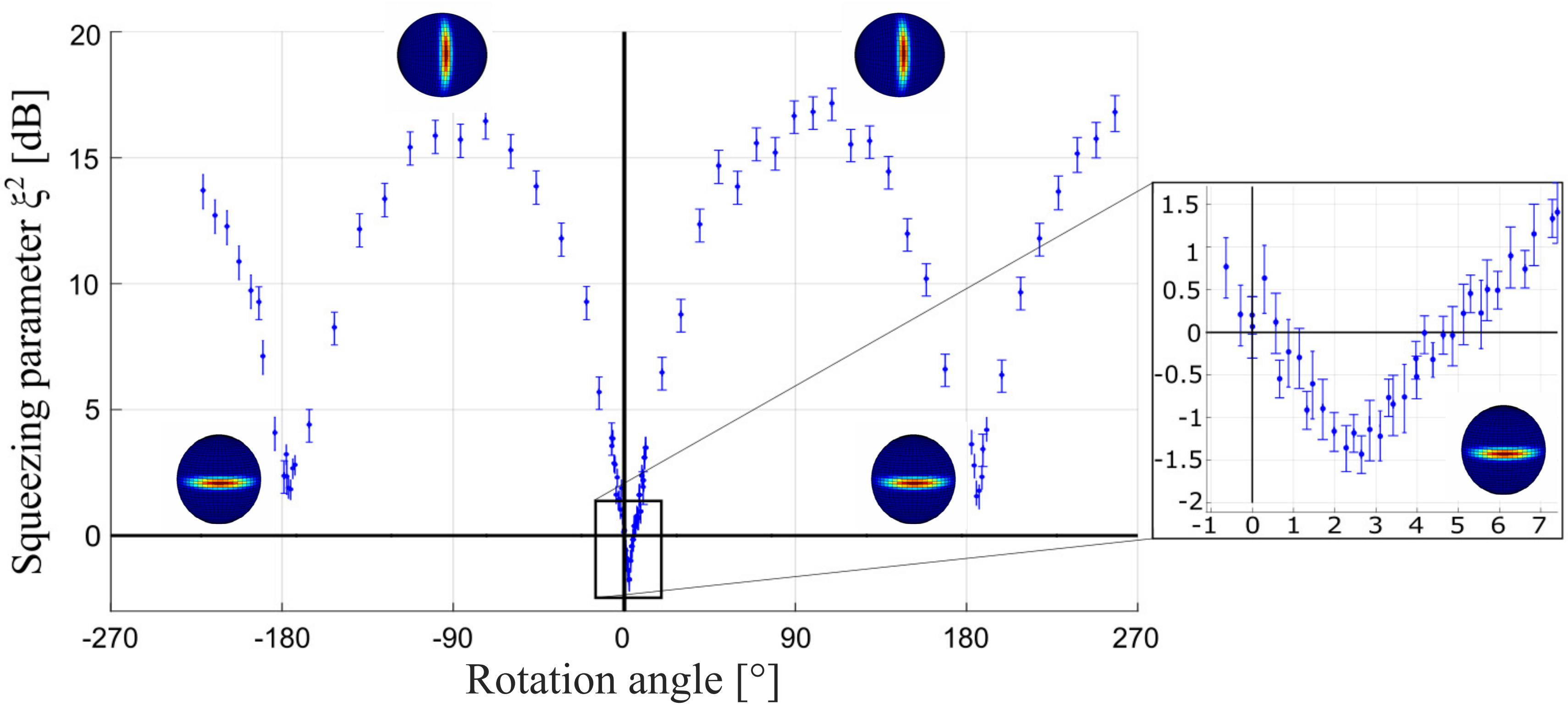
…and also measure contrast



…and deduce the spin squeezing factor (“Wineland factor”):

$$\xi^2 = \frac{N.\Delta S_z^2}{\langle S \rangle^2} = \frac{4\Delta S_z^2}{N.C^2}$$

Spontaneous Spin Squeezing Result in TACC



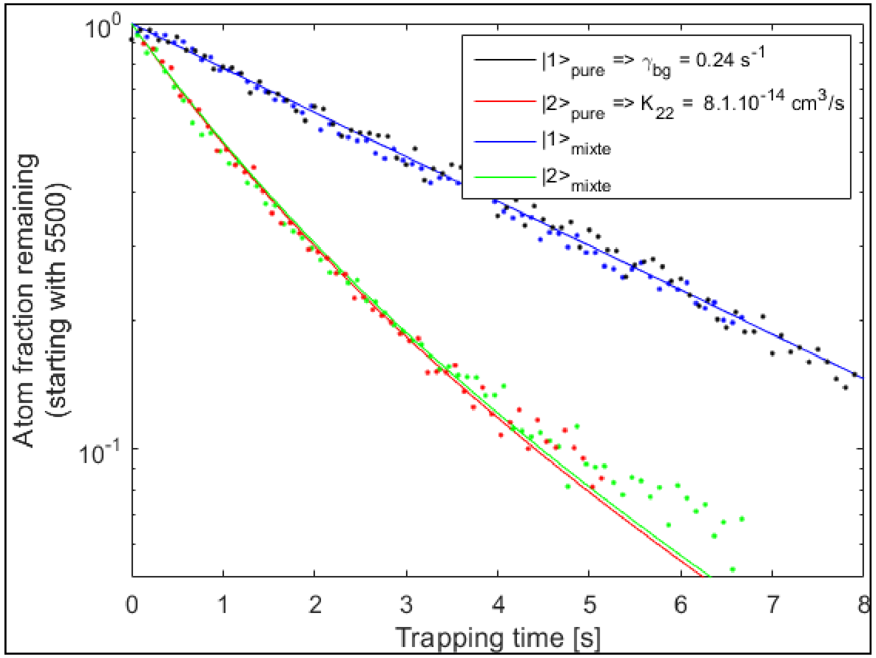
Squeezing parameter:

$$\xi^2 = \frac{N.\Delta S_z^2}{\langle S \rangle^2} = \frac{4\Delta S_z^2}{N.C^2} = -1.3 \pm 0.4 \text{ dB with } C = 90\%$$

Possible application: Atom interferometers with BEC source

Outlook for spontaneous spin squeezing

Limit: Asymmetric losses



Possible application:

Atom interferometers using BECs as a source state.

See for example S. Abend et al, Atom Chip Fountain Gravimeter, PRL **117**, 203003 (2016).

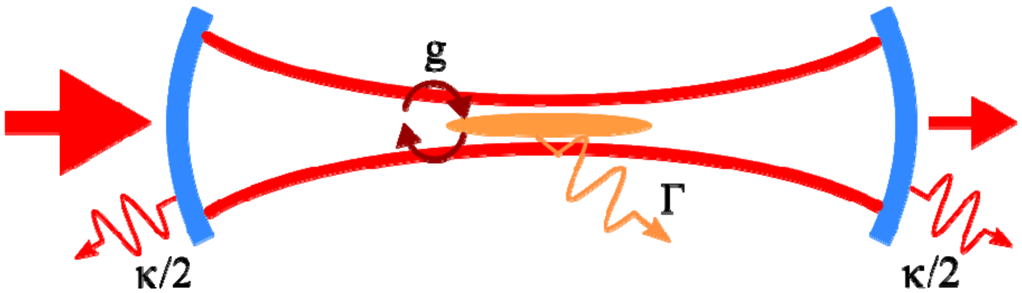
In such instruments, spontaneous squeezing comes for free!

Towards a squeezing-enhanced compact atomic clock

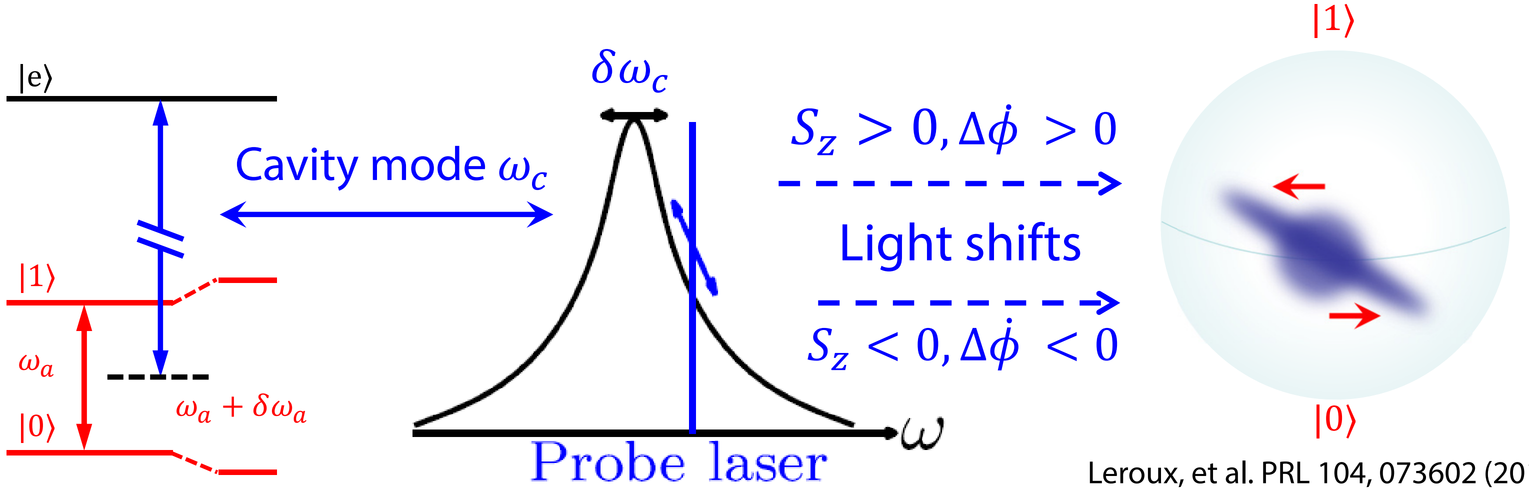
Spin squeezing in optical cavities

Atom-cavity interaction:

- Light shift of atomic transition ($\delta\omega_a \propto N_{\text{photon}}$)
- Cavity resonance shifted by spin population ($\delta\omega_c \propto S_z$)

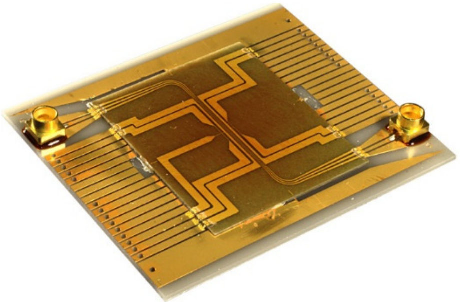


- ➢ One-axis twisting Hamiltonian $\mathcal{H} \propto S_z^2$
- ➢ spin population - phase shift correlation → squeezing of noise distribution

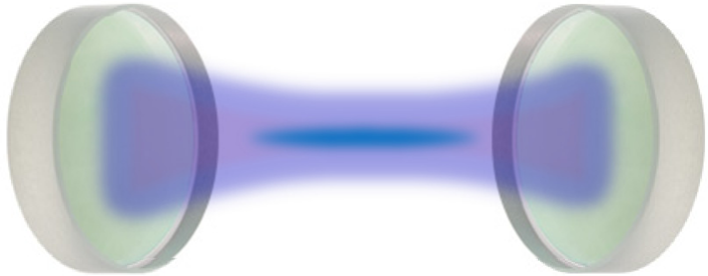


Leroux, et al. PRL 104, 073602 (2010)

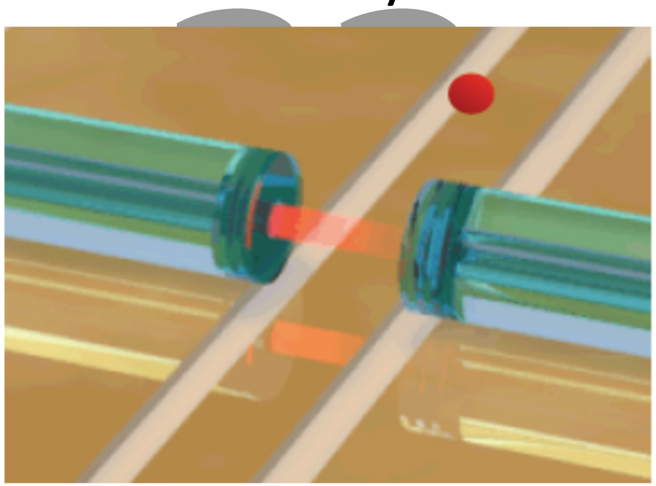
How to combine atom chip and Fabry-Perot cavity?



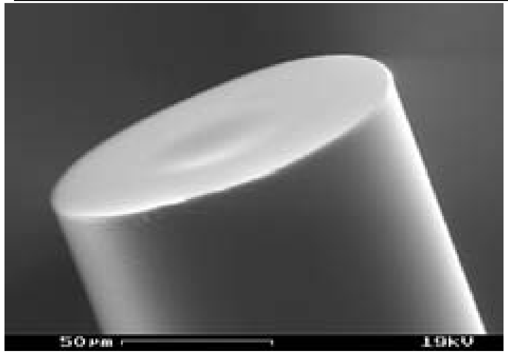
+



Solution: Fiber Fabry-Pérot cavities



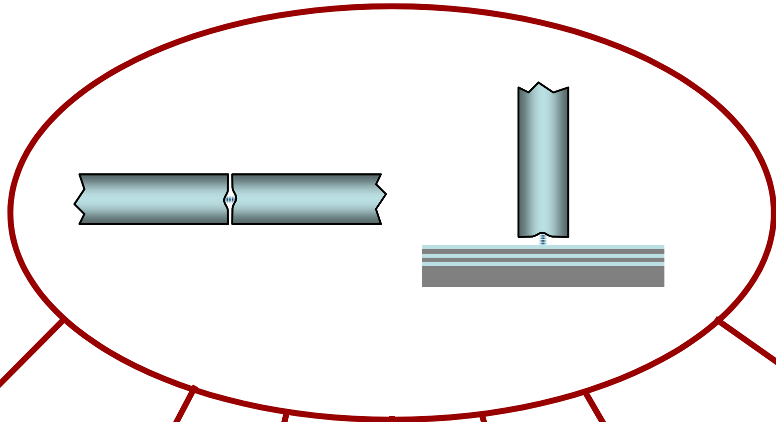
FFP: Fiber Fabry-Perot Microcavity



Laser-machined mirrors on optical fibers

Finesse F>200000
ROC R<10µm
Waist w<1.5µm

D. Hunger et al.,
New J Phys ***12****, 065038 (2010).*
AIP Advances ***2****, 012119 (2012).*



Neutral atoms
Paris, Cambridge,
Bonn, Munich (MPQ)

Cavity optomechanics
Yale, Paris, Konstanz

Ions
Innsbruck, Sussex,
Cambridge / Bonn,
Mainz, Boulder

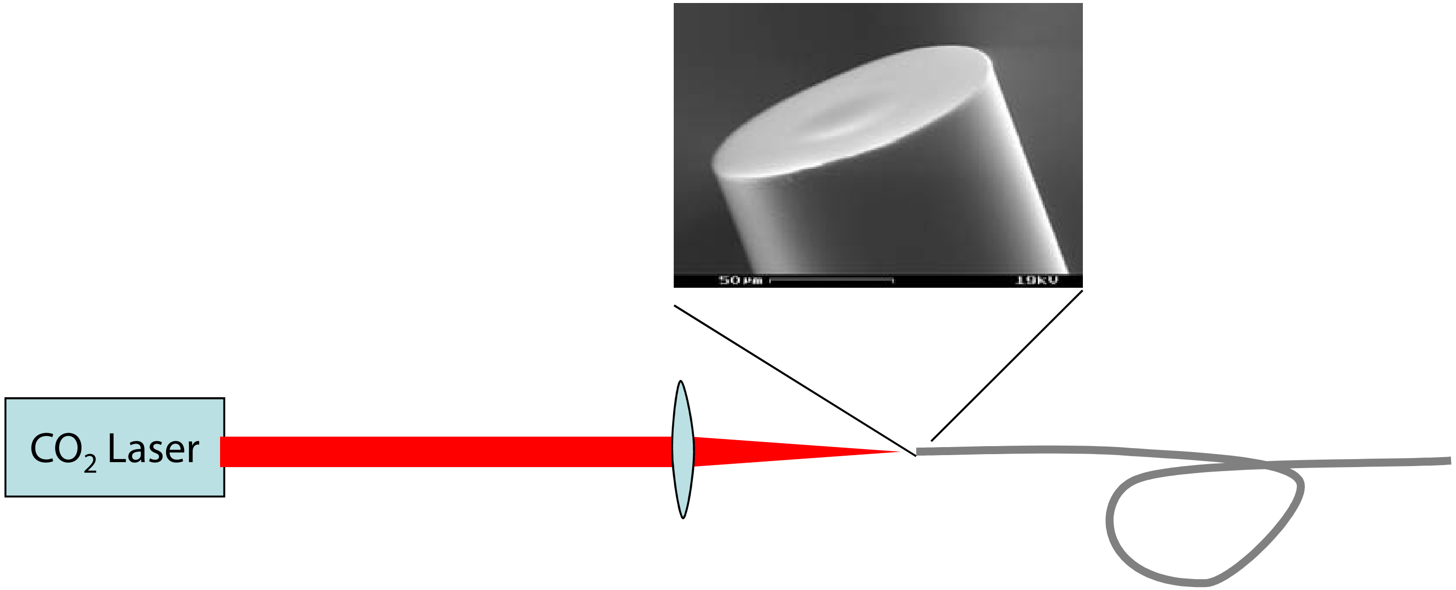
NV centers
Saarbrücken,
Munich (MPQ/LMU)

Quantum dots & wells
Paris&Zurich, NIST/JQI, Basel

CNTs
Paris (LPA&LKB)
Munich (LMU)

Molecules
ETH/
MPI Erlangen

Fiber Fabry-Perot cavities

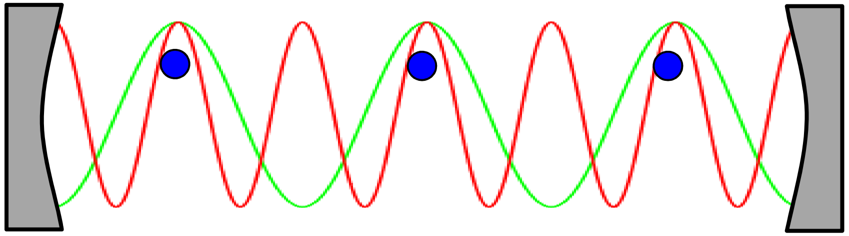


Material evaporation + surface melting occuring simultaneously.
D. Hunger et al., New J Phys 12, 065038 (2010).

D. Hunger et al., AIP Advances 2, 012119 (2012).

- Measured rms roughness (AFM): $\sigma_{sc} < 0.23$ nm
- From cavity measurement: $L = S+A \sim 15$ ppm!
- Measured finesse up to $F \sim 200000$ (Brandstätter et al., RMP 2013)
- Radius of curvature down to $R < 10\mu m$
- Mode waist down to $w_0 < 1.5\mu m$ (Mader et al., Nature Comm. 2015)
- Cooperativity $C > 100$

Couple *all* atoms to the cavity

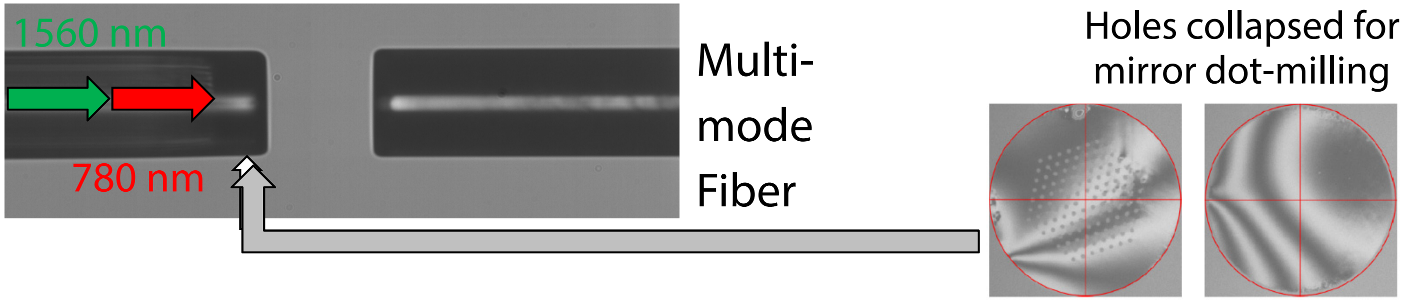


780 nm : probe

1560 nm : 1D optical lattice

Fiber cavity:

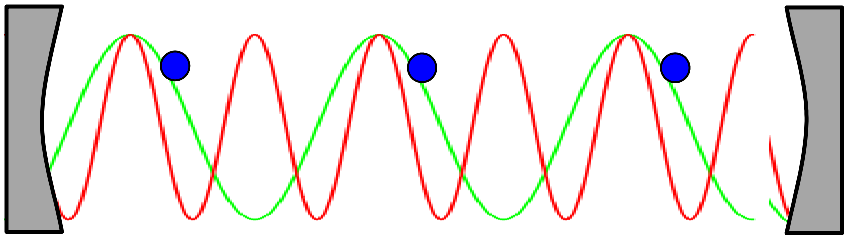
Endlessly single-mode PCF

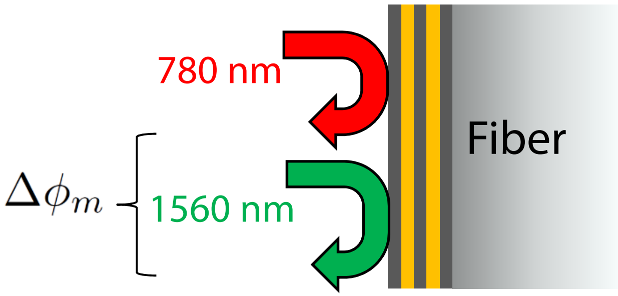


Multi-mode Fiber

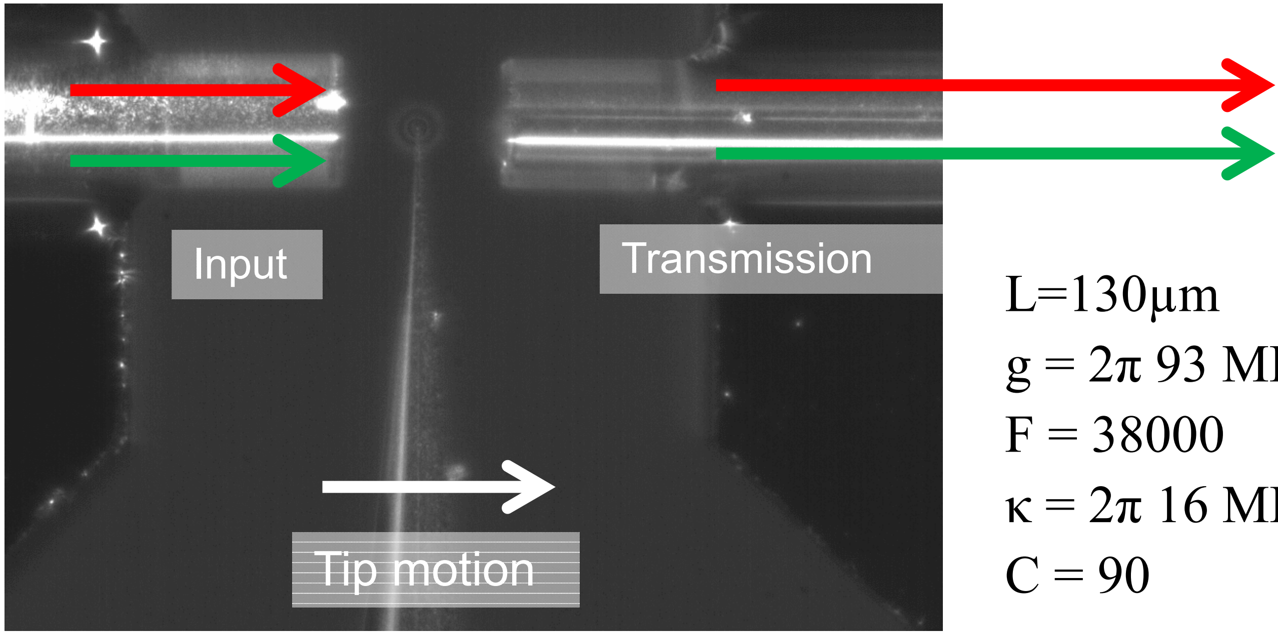
Holes collapsed for mirror dot-milling

Phase shift engineering:



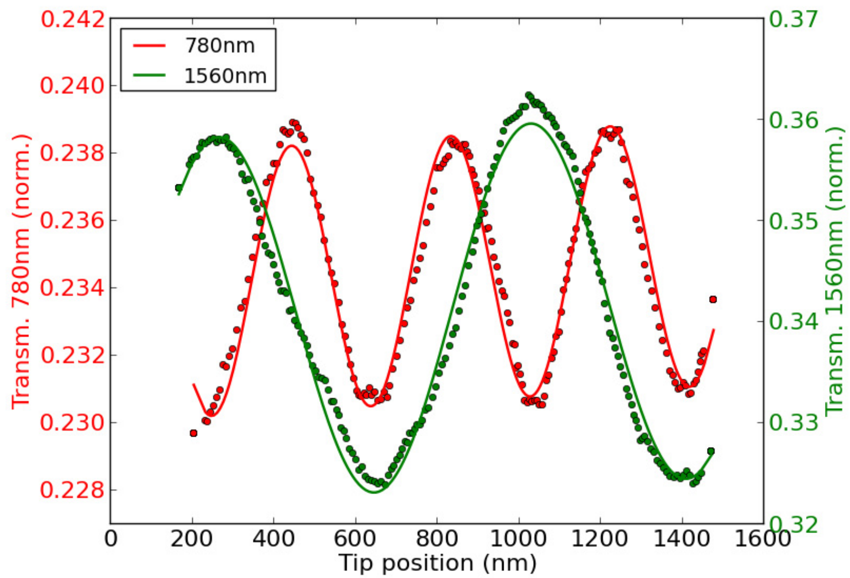


Mapping out the cavity modes with a SNOM tip



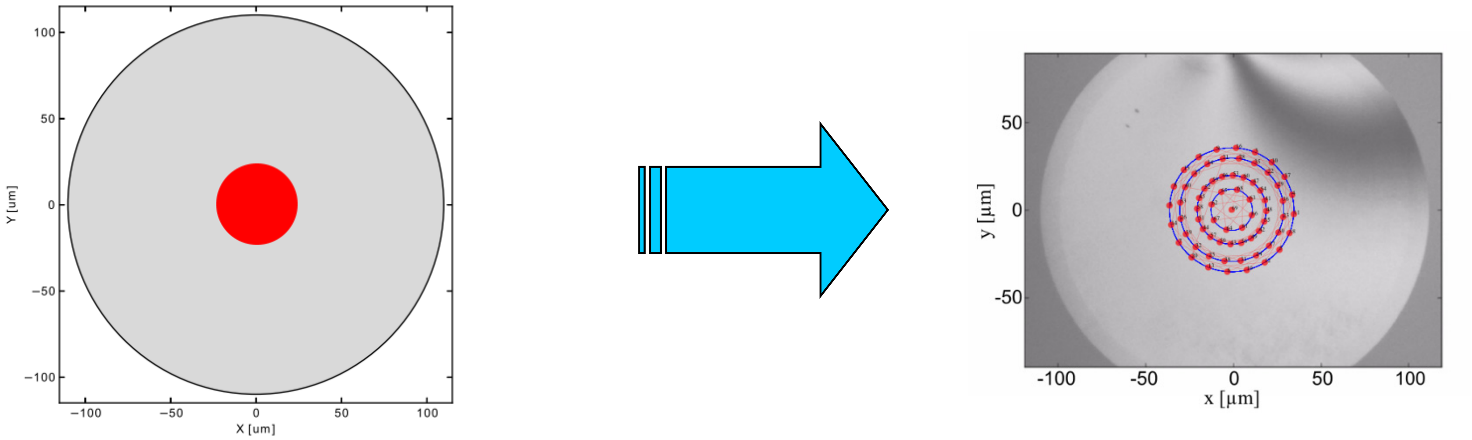
Transmission drops when the tip is at an antinode.

L=130μm
g = 2π 93 MHz
F = 38000
κ = 2π 16 MHz
C = 90



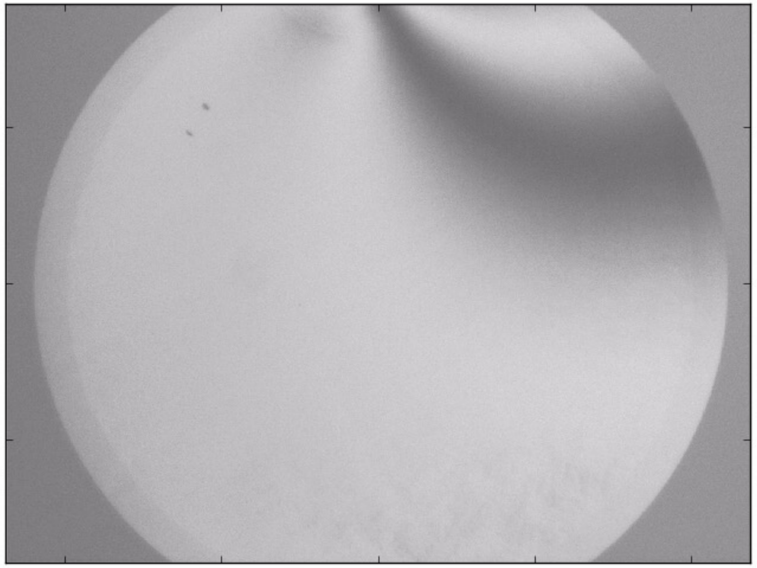
Make a *long* cavity: >1mm

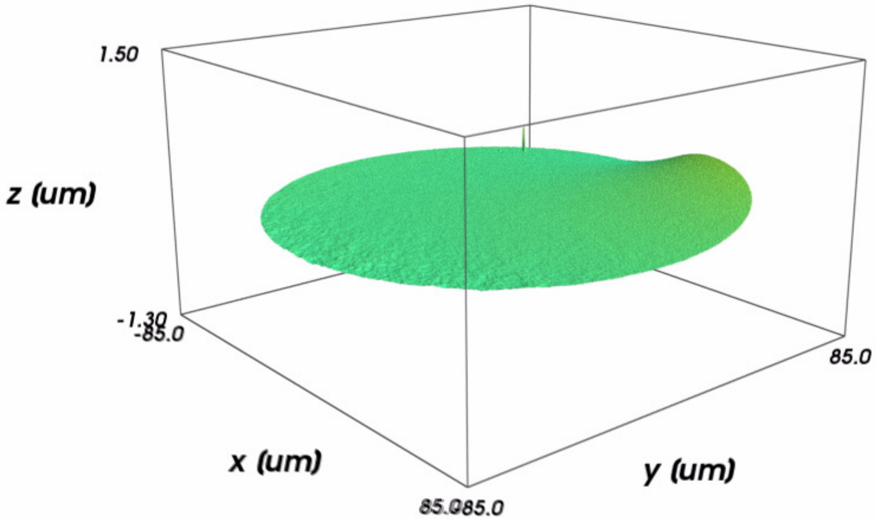
Use multiple laser shots: "Laser dot milling"



K. Ott *et al.,* Optics Express **24**, 9839 (2016)

CO2 laser dot milling at work





K. Ott, S. Garcia, R. Kohlhaas, K. Schüppert, P Rosenbusch, R. Long, J. Reichel, Opt. Express **24**, 261274 (2016)

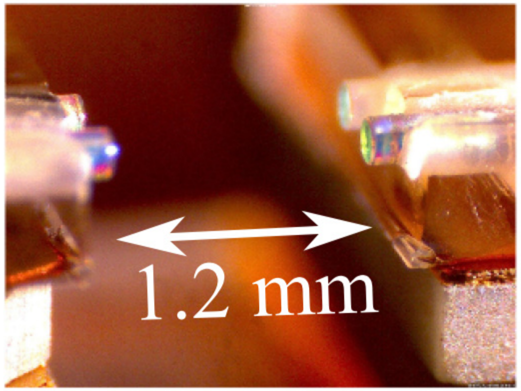
S. Garcia, F. Ferri, K. Ott, J. Reichel, R. Long, arXiv:1805.04089

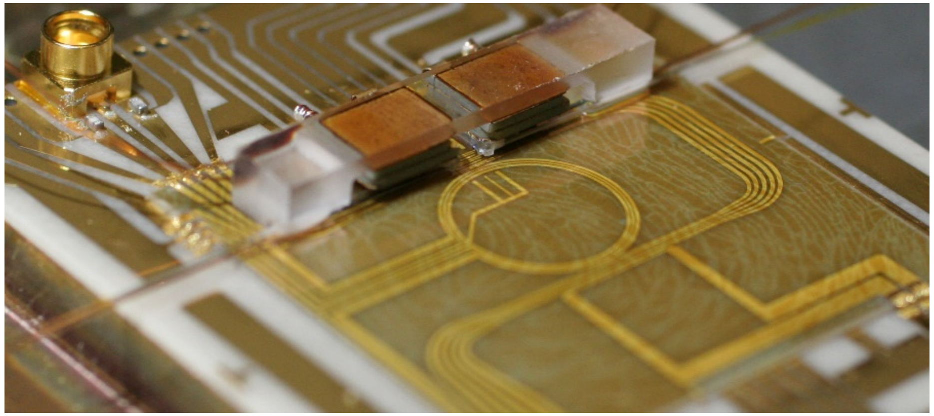
eeTACC: Fiber cavities on atom chip

2 fiber Fabry-Perot cavities integrated on chip

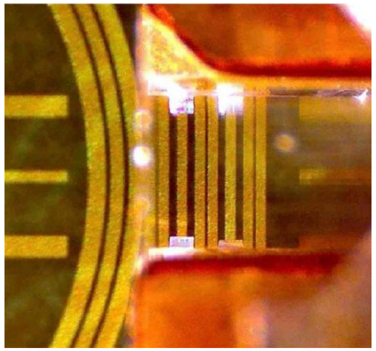
- Compatible with setup compactness
- Multi-shot CO_2 laser milling for large mirror radius
- New millimeter-size fiber cavities
- 780 nm and 1560 nm coatings
- Low- and high-finesse (3k and 38k) for weak- and strong-coupling regimes
- Same PZT for light-free cavity locking

K. Ott, et al. Optics Express 24, 9839 (2016)

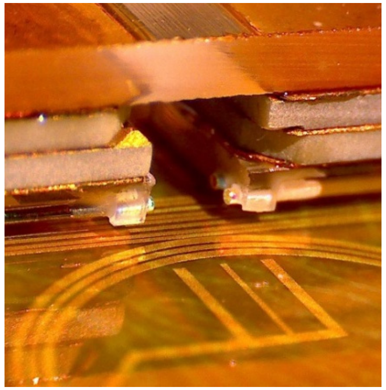




~500µm close

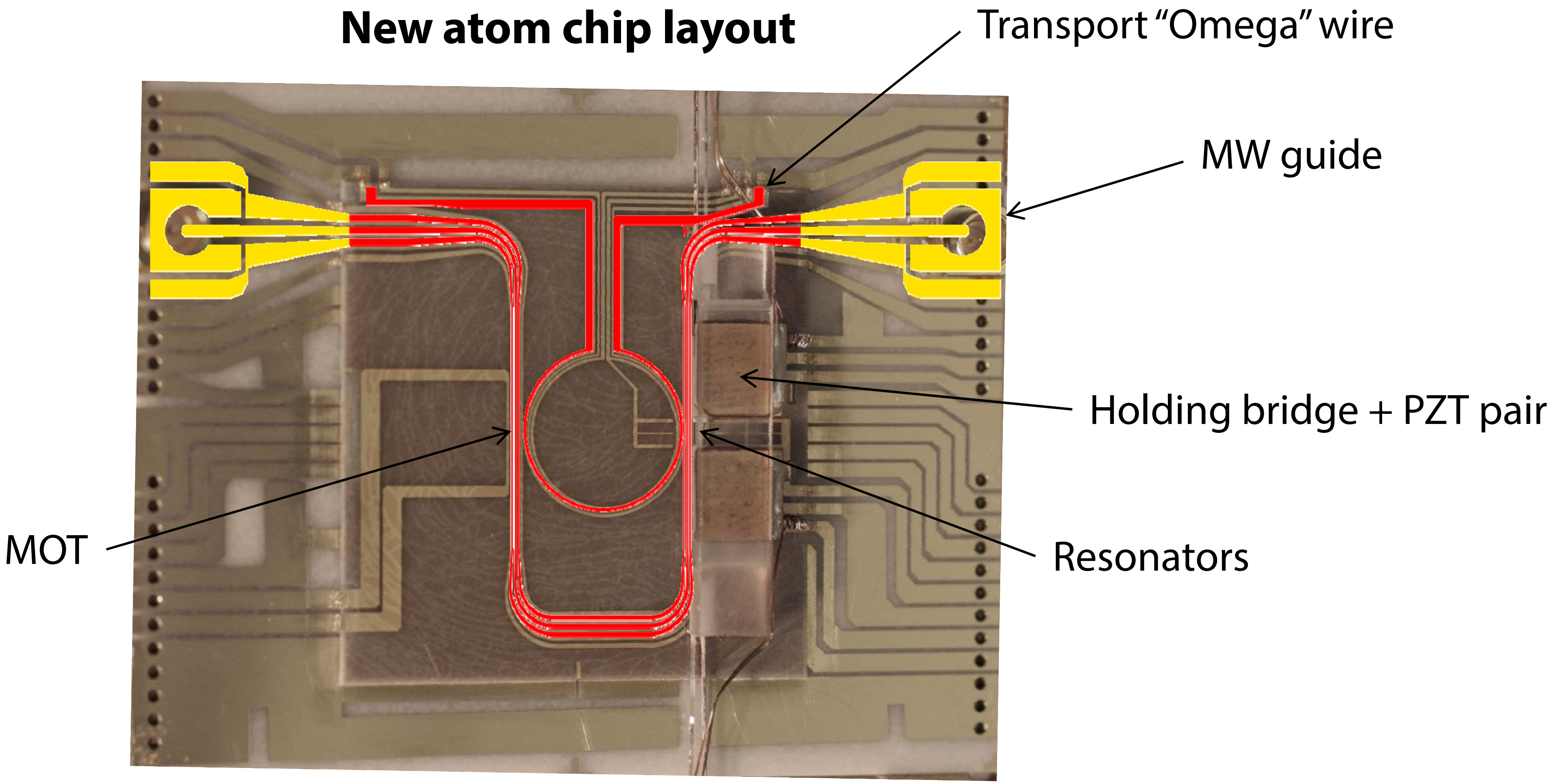


~400µm from chip surface

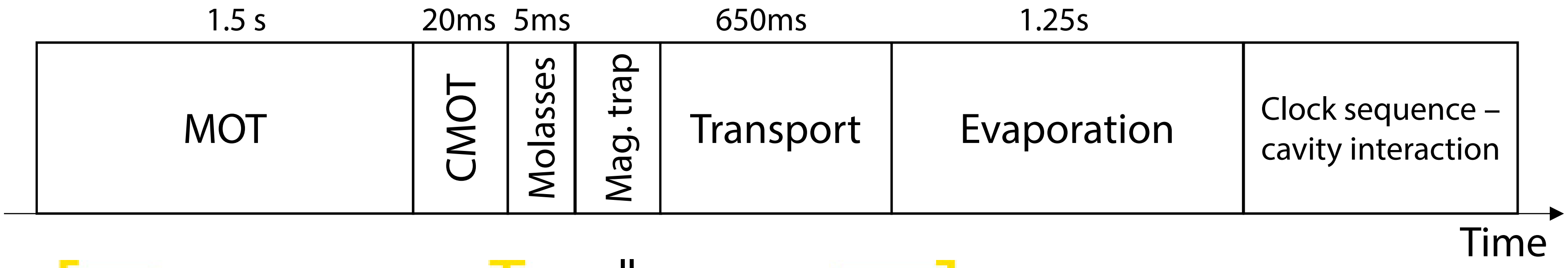


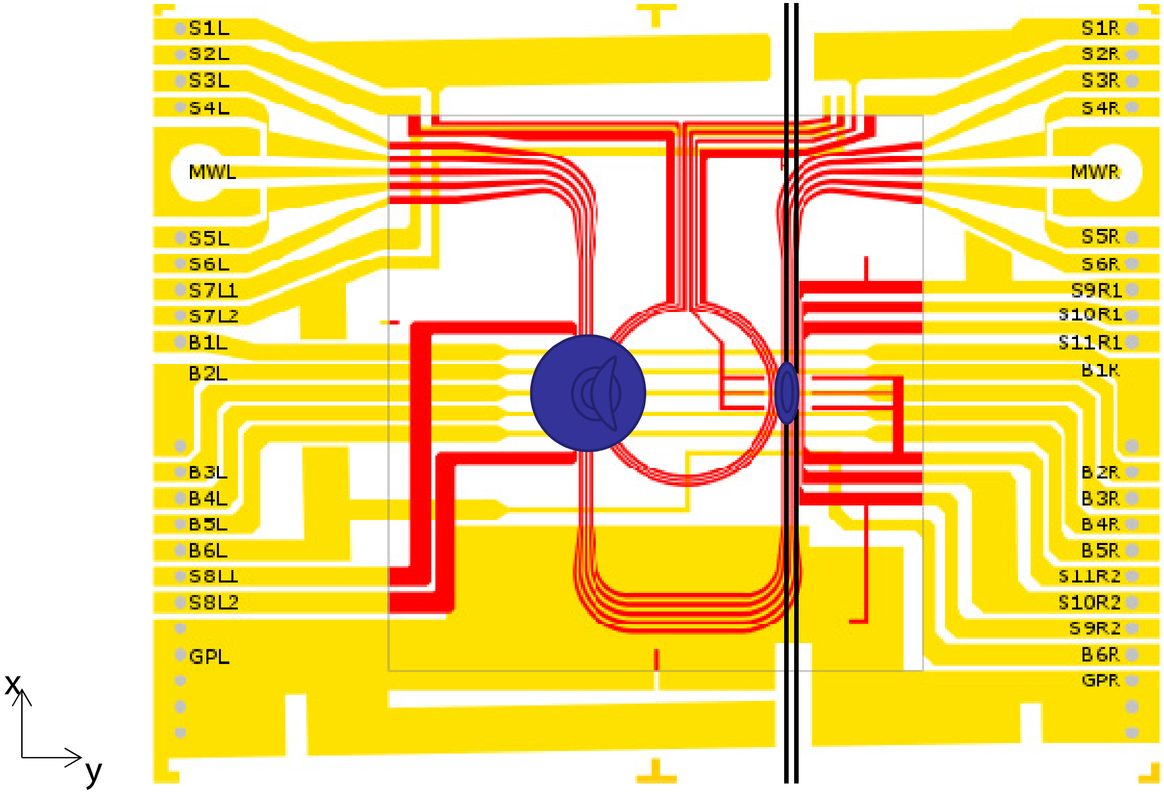
Cold atoms preparation on chip

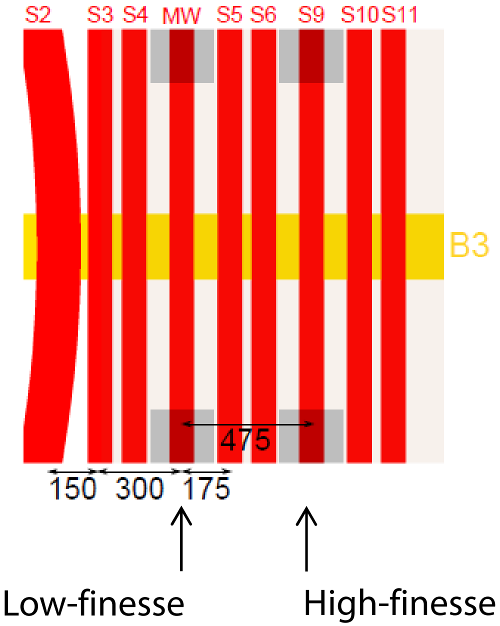
New atom chip layout



Cold atoms preparation on chip

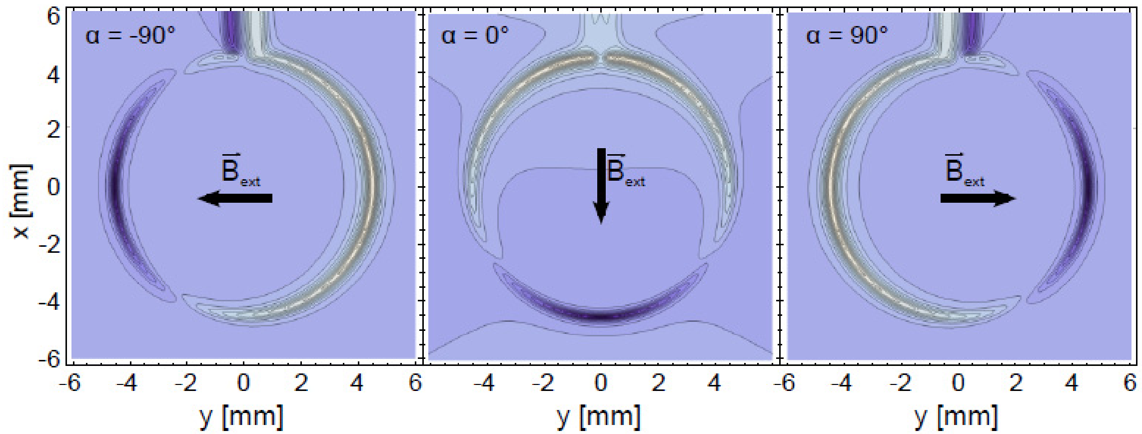




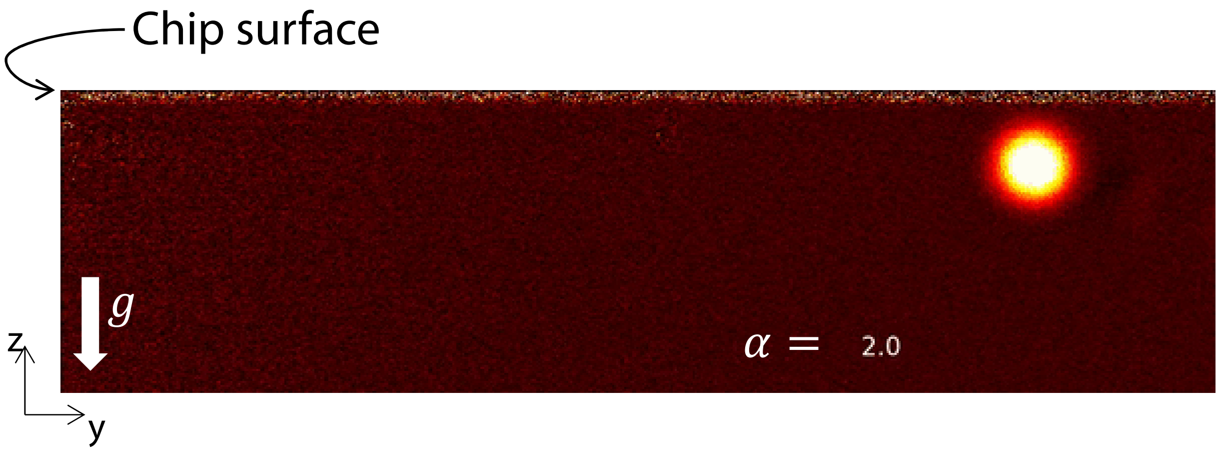


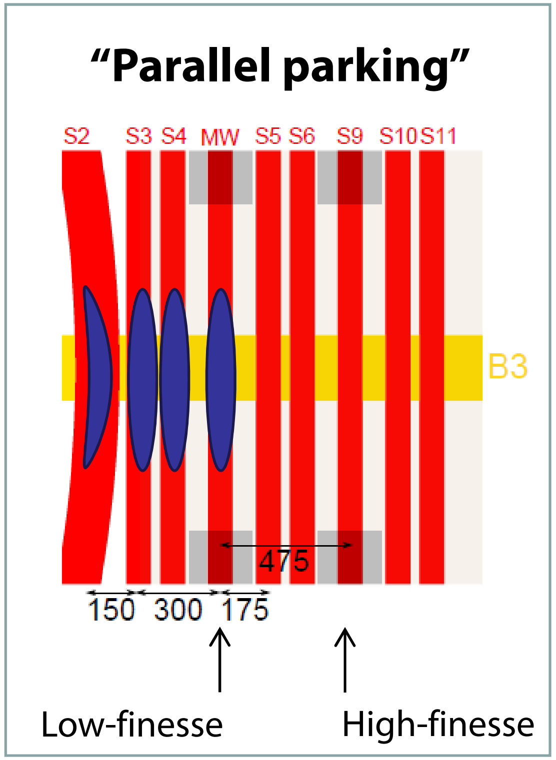
Atom transport

Rotation with "Omega" wire



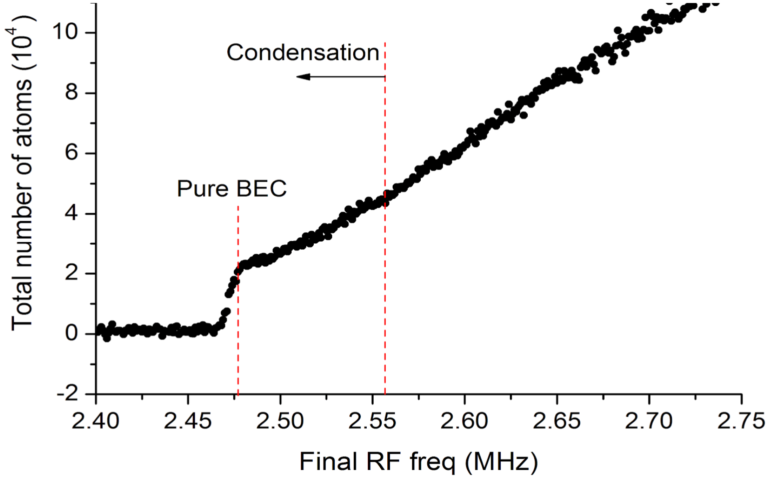
$$I_\Omega + \begin{cases} Bx = B_0 \cos(2\pi\alpha t) \\ By = B_0 \sin(2\pi\alpha t) \end{cases}$$

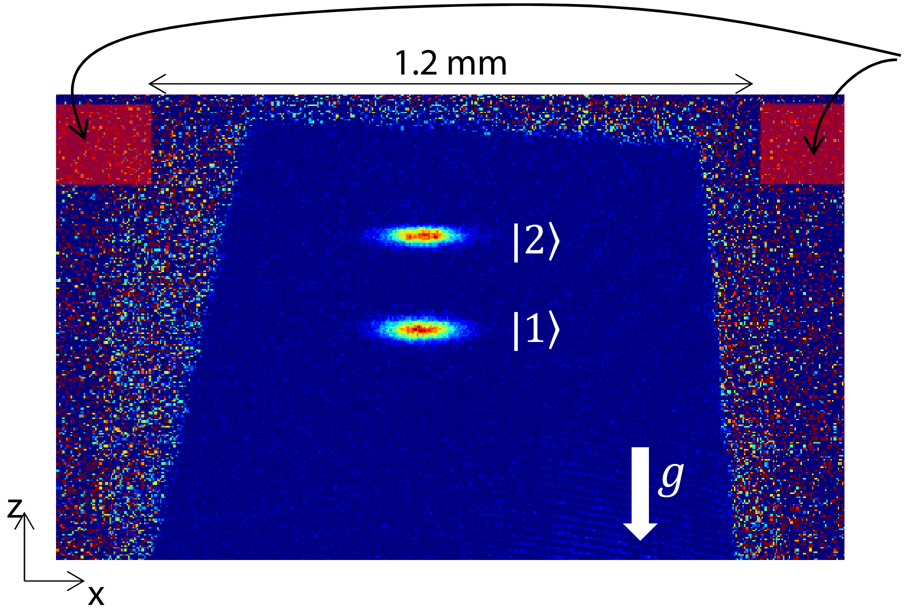




Cold atoms inside "Cavity" trap

- RF evaporation at resonator position
  - Tight magnetic trap
  - $(\omega x, \omega y, \omega z) = 2\pi\ (0.1, 3.3, 3.3)$ kHz
  - 1.25s exponential RF ramp
- ➢ Above BEC threshold: 4×10^4 atoms
  - Tz = 70 nK
  - Tx = 25 nK





Low-finesse cavity mirrors

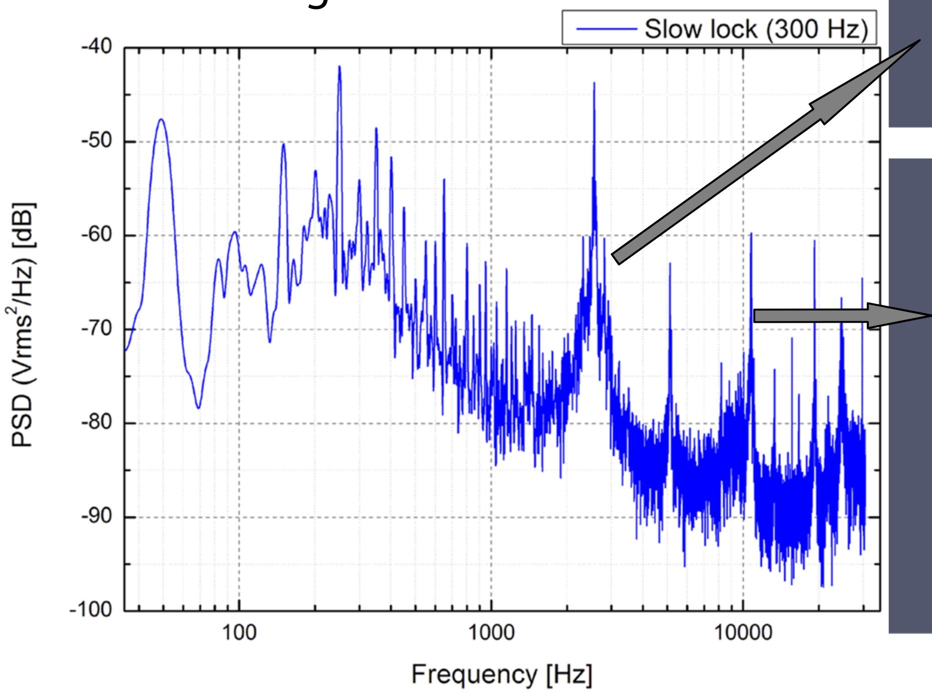
Cavity trap

- $(\omega x, \omega y, \omega z) = 2\pi\ (6, 60, 45)$ Hz
- 2.6s lifetime
- Trap center @ 400 µm from chip surf
- Overlap with optical cavity mode

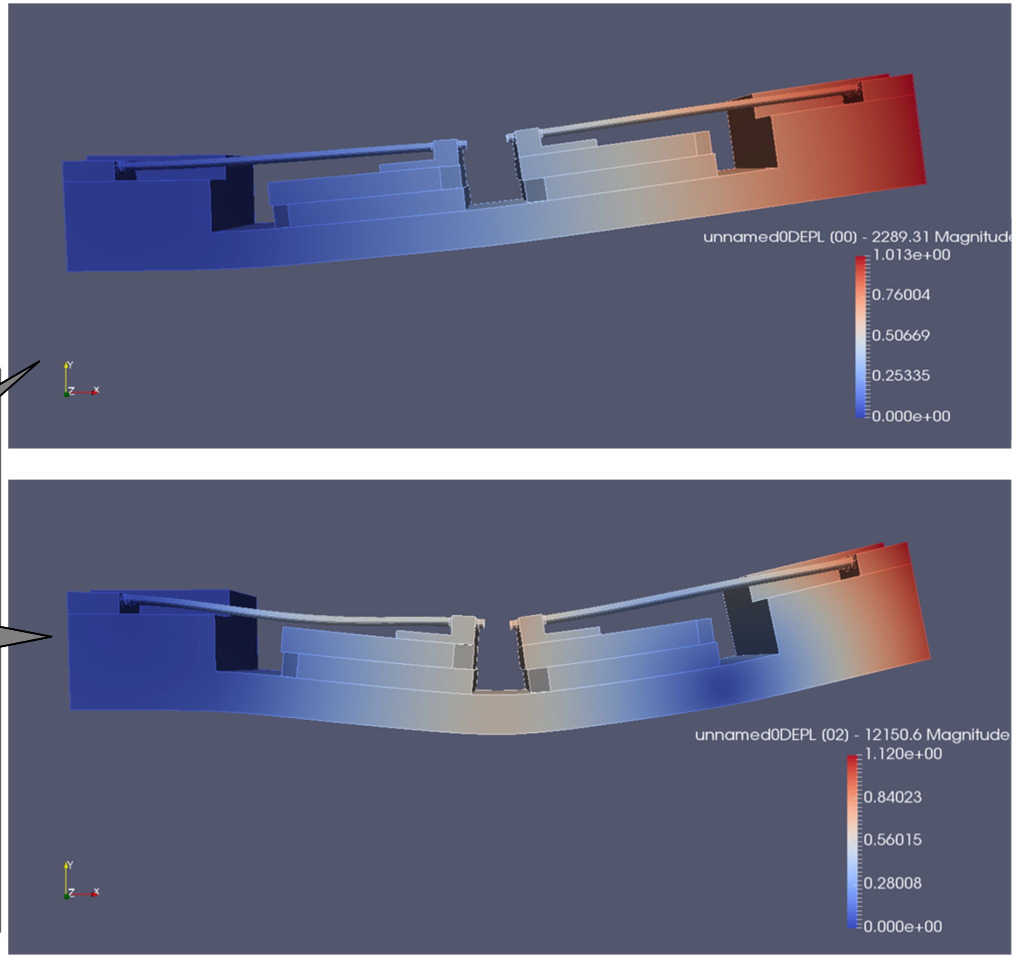
- Clock states detection with ARP pulse

Cavity locking

- High-Finesse cavity, 1560 nm
- PDH error signal
- Digital PI servo control (RedPitaya)
  - ➢ Locking bandwidth limited by strong mechanical resonances

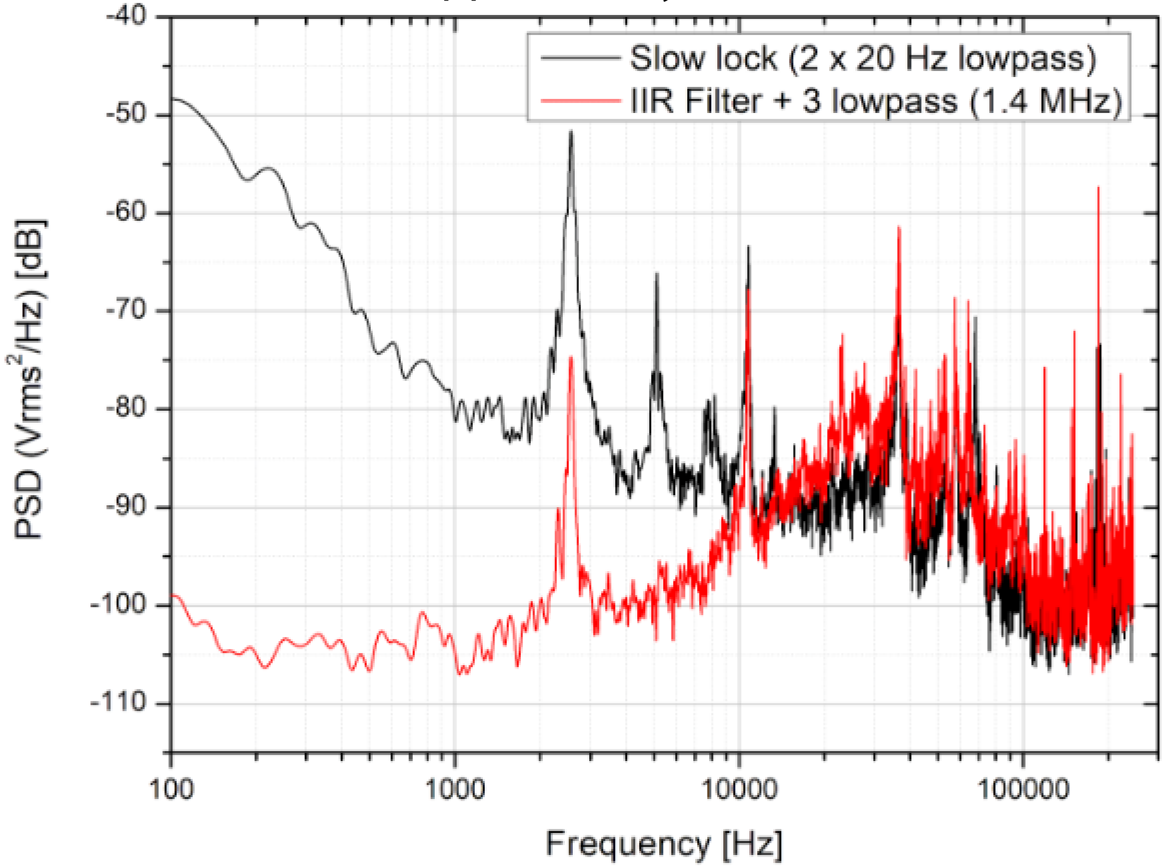


Finite elements simulations

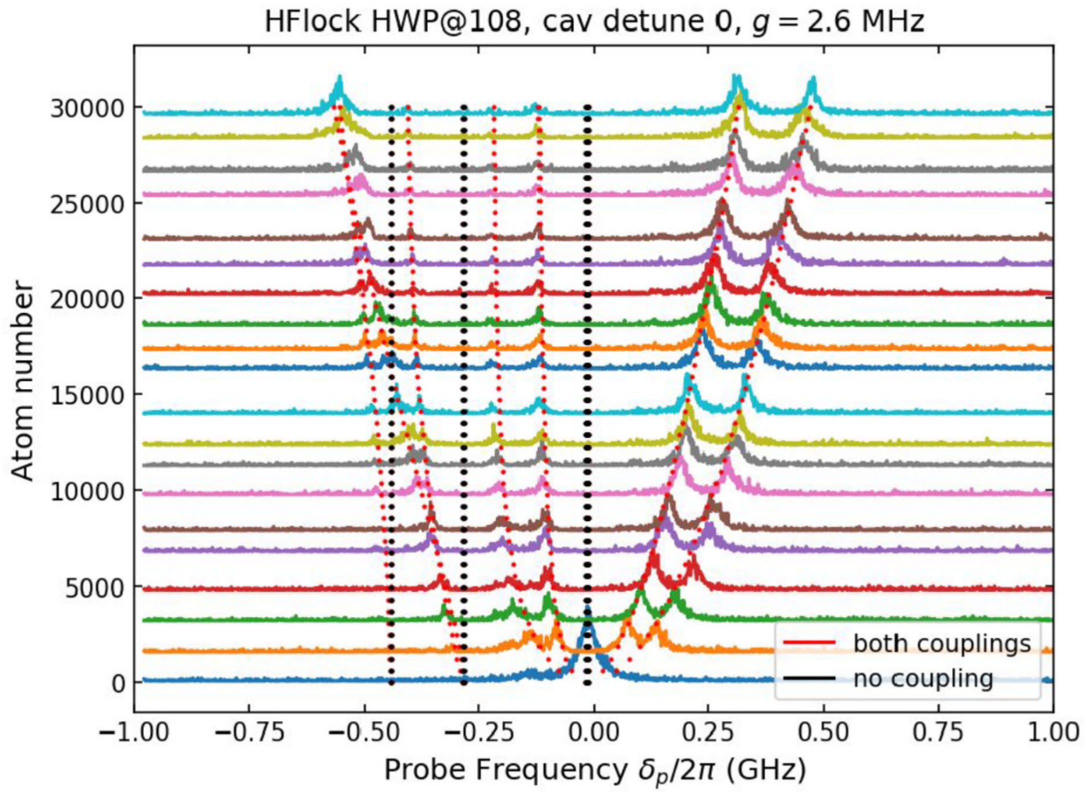


Locking bandwidth

- 12 pairs complex pole/zero implemented (up to 80 kHz)
- After PI optimization => Noise reduction up to 20kHz
- First mechanical resonance suppressed by more than 20 dB



Cavity QED signals!



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Laboratoire Kastler Brossel
Physique quantique et applications

PhD position available!

DGA

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Le progrès, une passion à partager

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erc

IFRAF