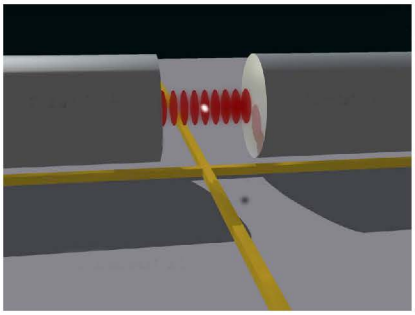
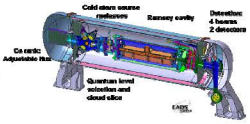


Spin squeezing for quantum metrology

Jakob Reichel
Laboratoire Kastler Brossel
ENS/CNRS/UPMC/CdF, Paris

Atomic clocks and sensors

Cs beam tube clock
(5 10^{-12} $s^{-1/2}$ stability,
~10^{-13} accuracy)

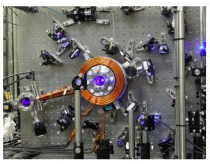


PHARAO space clock

absoute gravimeter
(www.muquans.com)

fountain clock

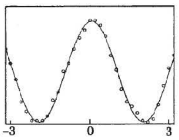
atomic magnetometer

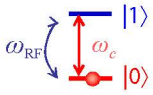


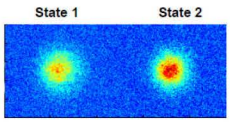
optical lattice clock
(~10-16 stability,
<10-17 accuracy)

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!*

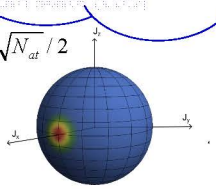
Spin squeezing

- Metrology in AMO systems beyond the standard quantum limit):
  Measuring angles on the Bloch sphere
- Uncertainty relations for angular momentum products of observables:

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

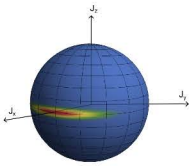
Coherent spin state (CSS)

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



Spin-squeezed state

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

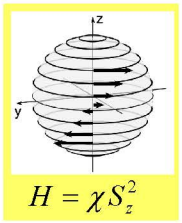


- ***N independent atoms***
- ***Tensor product state***
- ***Projection noise limit: $1/\sqrt{N_{at}}$***

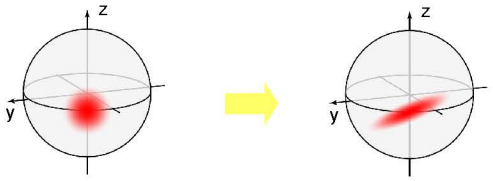
- ***Highly entangled state***
- ***Noise: like CSS with ξ^2 times N_{at}***
- ***Ultimate (Heisenberg) limit: $1/N_{at}$***
- ***Create by interaction or QND measurement***

Creating spin-squeezed states

- ***Squeezing by interaction***

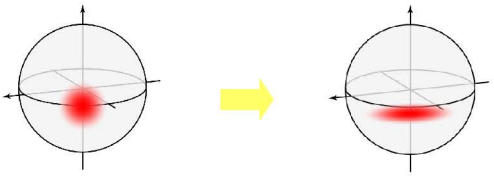


"One-axis twisting"



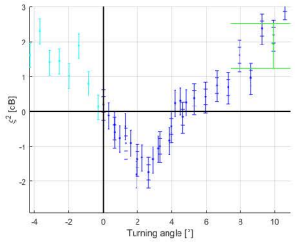
- ***Squeezing by nondestructive measurement***

Measure N_2-N_1 with sub-shot noise resoution, without destroying their relative phase.
(Difficult, but possible.)



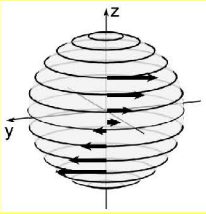
State of the art

- Not a magic wand, but **will improve clocks/sensors that are QPN-limited.**
- QPN limit **first reached in SYRTE fountain clock** (1999).
  As technology improves, more sensors reach this limit.
  Optical clocks expected to reach this limit soon.
- **Particularly important when atom N_{at} is restricted** (small probes…).
- Still at proof-of-principle level: 4.5dB clock improvement @ 10^{-9} $s^{-1/2}$.
  No metrology-grade experiments yet.

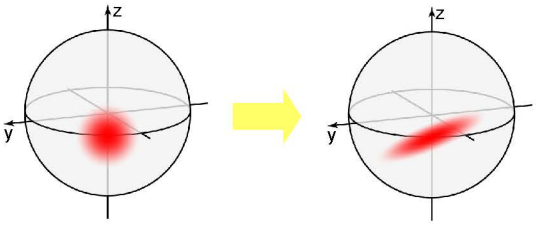


Spontaneous spin squeezing in a Rb BEC

Spin squeezing by atomic interaction



$$H = \chi S_z^2$$



"One-axis twisting"

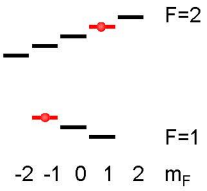
- ***Occurs naturally in BECs with two internal states*** $|\uparrow\rangle, |\downarrow\rangle$***, due to interactions.***
  Sørensen et al, Nature (2001)
- χ ***depends on scattering lengths:*** $a_{\uparrow\uparrow}+a_{\downarrow\downarrow}-2a_{\uparrow\downarrow}$.
- ***However, in*** ^{87}***Rb,*** $a_{\uparrow\uparrow}\approx a_{\downarrow\downarrow}\approx 2a_{\uparrow\downarrow}$ ***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

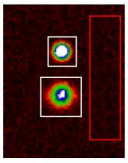
Highly anisotropic harmonic trap:

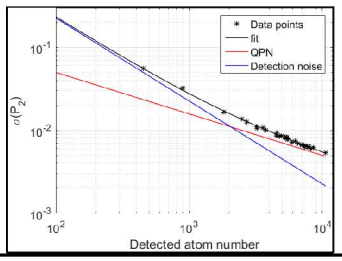
(2.7, 92, 74) Hz

Two identically trapped states:

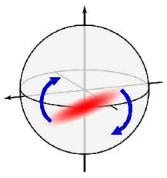


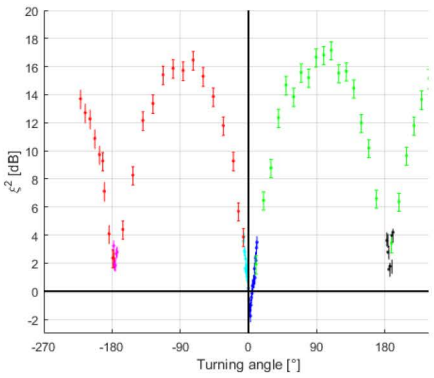
High-performance imaging:

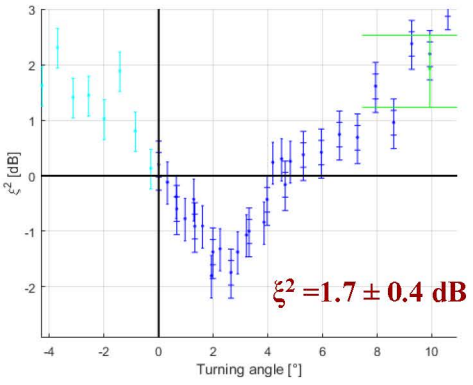




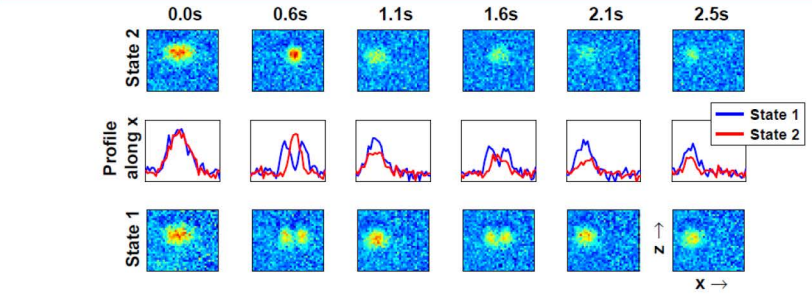
Timing sequence

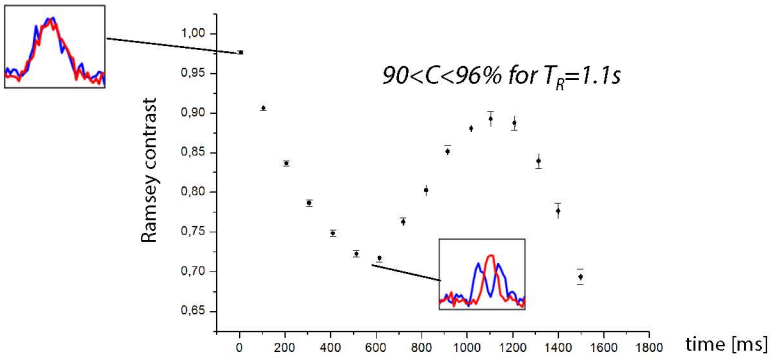






What's the trick?

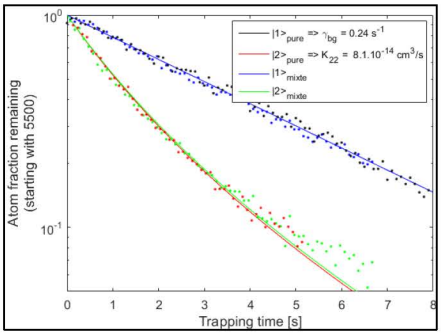




90<C<96% for T_R=1.1s

Outlook

Limit: Asymmetric losses



Possible application:

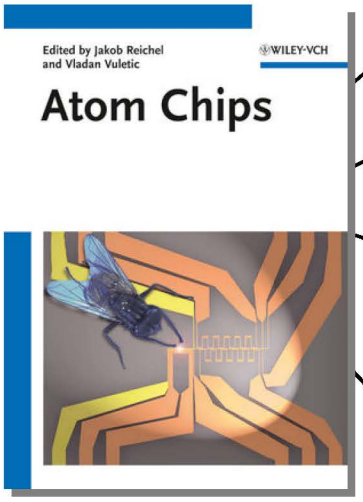
Atom interferometers using BECs as a source state.

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

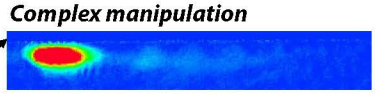
In such instruments, spontaneous squeezing comes for free!

Towards a squeezing-enhanced compact atomic clock

Atom Chips



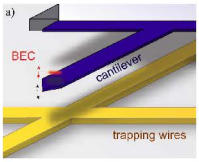
Complex manipulation



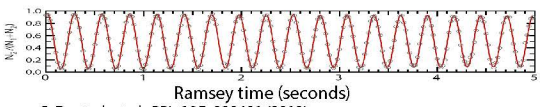
Compact setup, fast BEC

ColdQuanta.com

Interaction with surface



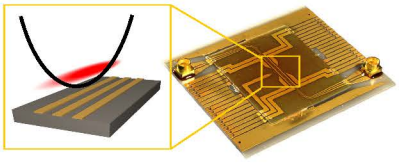
Long coherence time



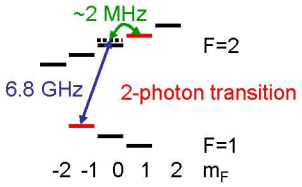
C. Deutsch et al., PRL **105**, 020401 (2010)

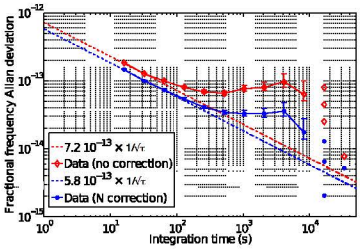
TACC: Trapped-Atom Clock on a Chip

Collaboration with SYRTE



Atom chip has coplanar waveguide for 2-photon clock transition.





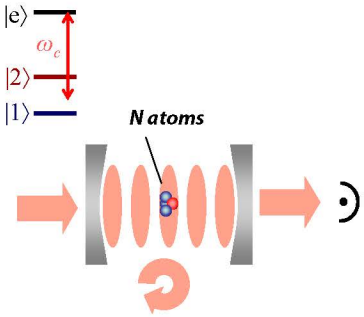
Measured stability: $5.8\ 10^{-13}\ s^{-1/2}$

Szmuk et al., *PRA*, **92**, 012106 (2015).

l'Observatoire de Paris | SYRTE

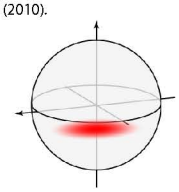
Laboratoire Kastler Brossel

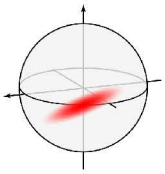
Generating spin squeezing with optical cavities



Detection projects N_2-N_1 state

Leroux, Schleier-Smith and Vuletic, PRL **104**, 073602 (2010).





State-dependent light intensity acts back on collective state

Schleier-Smith et al., PRL 104, 073604 (2010).

Now works very well: **>20dB**.

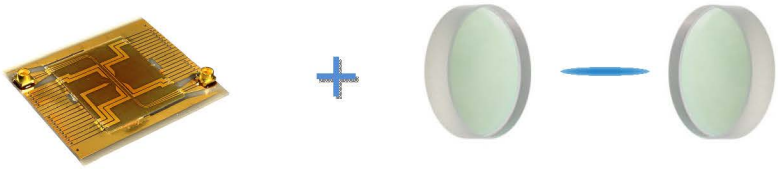
Hosten et al., Nature **529**, 505 (2016).

H. J. Kimble, Physica Scripta **176**, 127 (1998)

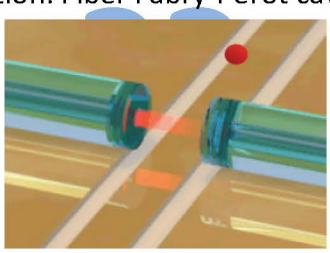
S. Haroche & J.-M. Raimond, *Exploring the Quantum*, Oxford (2006)

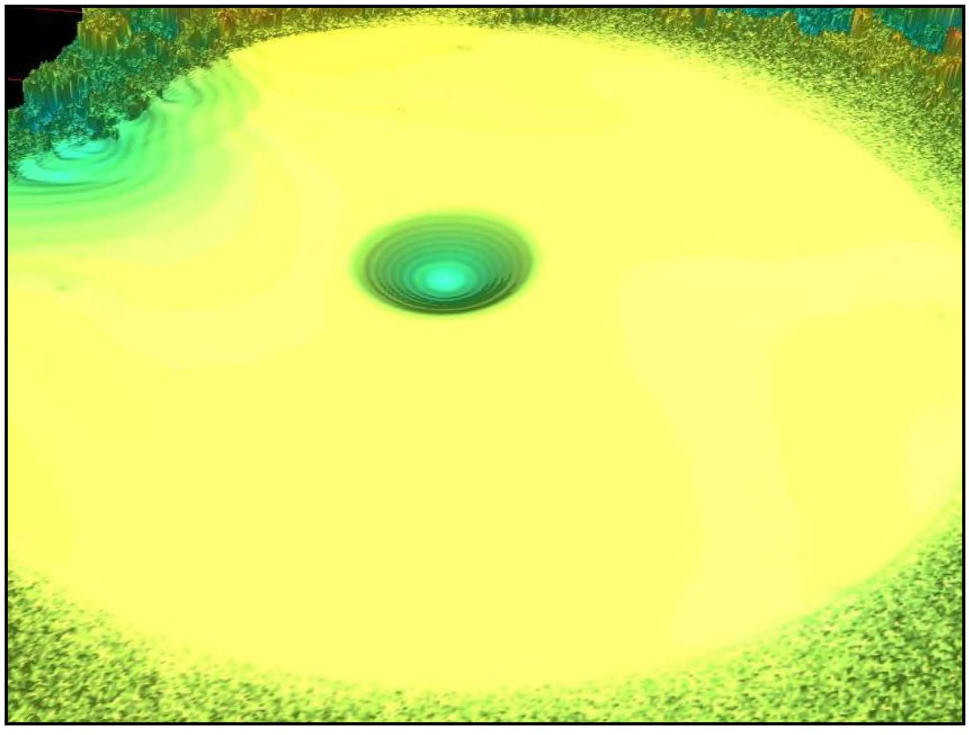
H. Tanji-Suzuki et al., Adv. At. Mol. Opt. Phys. **60**, 201, arXiv:1104.3594 (2011)

How to combine atom chip and Fabry-Perot cavity?

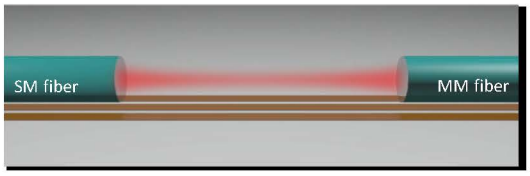


Solution: Fiber Fabry-Pérot cavities



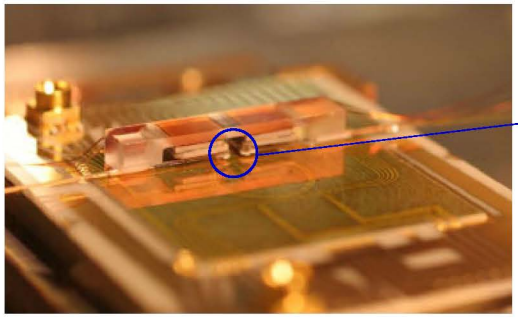


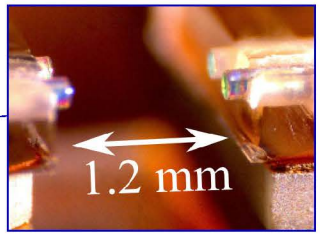
Experiment under way…



TACC 2.0 Design

L=1.5 mm FFP cavity, atom chip with microwave CPW.

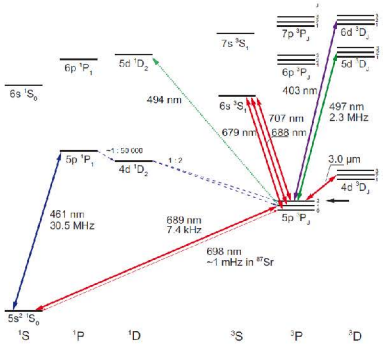




European Research Council

Outlook

- ***CQED with alkaline-earth atoms***



- ***Optical instead of microwave qubit:***
  Spontaneous emission no longer an issue!
  Limits will be completely different (and probably lower)!
- ***Optical lattice clocks use alkaline-earths.***

European Research Council

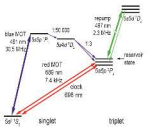
Future directions

Spin squeezed state: **One example** of metrological enhancement.

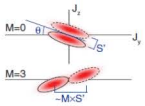
- **Metrological power of other entangled states?**
  - **Related to Fisher information.**
  - **Preparation, robustness, …**

Entanglement is a resource

- **Other atoms**
  - **So far, spin squeezing mostly limited to Rb.**
  - **Best lattice clocks: Sr…**



- **Advanced "quantum strategies" for metrology**
  - **Example: "quantum phase magnification".**



- Spin squeezing involves **powerful optical technologies** which can be **applied in other areas.**
  - **Example: Fiber Fabry-Perot cavities**