Long-lived Spin Squeezing in a Metrologically Relevant Regime

Jose Alberto de la Paz , Meng-zi Huang , Alice Sinatra , Carlos Garrido Alzar, and Jakob Reichel

- A trapped-atom clock on an atom chip with a fibre Fabry-Perot microcavity to generate spin squeezing.
- 8.1(9) dB of metrological squeezing with 2 x 10^4 ultracold alkali atoms by quantum non-demolition (QND) measurement.
- Lifetime on the order of a second, two orders of magnitude longer than previous experiments.
- Dynamics leading to a spin-orbit coupling that correlates cavity coupling with the spin state.
- Soon to be a clock

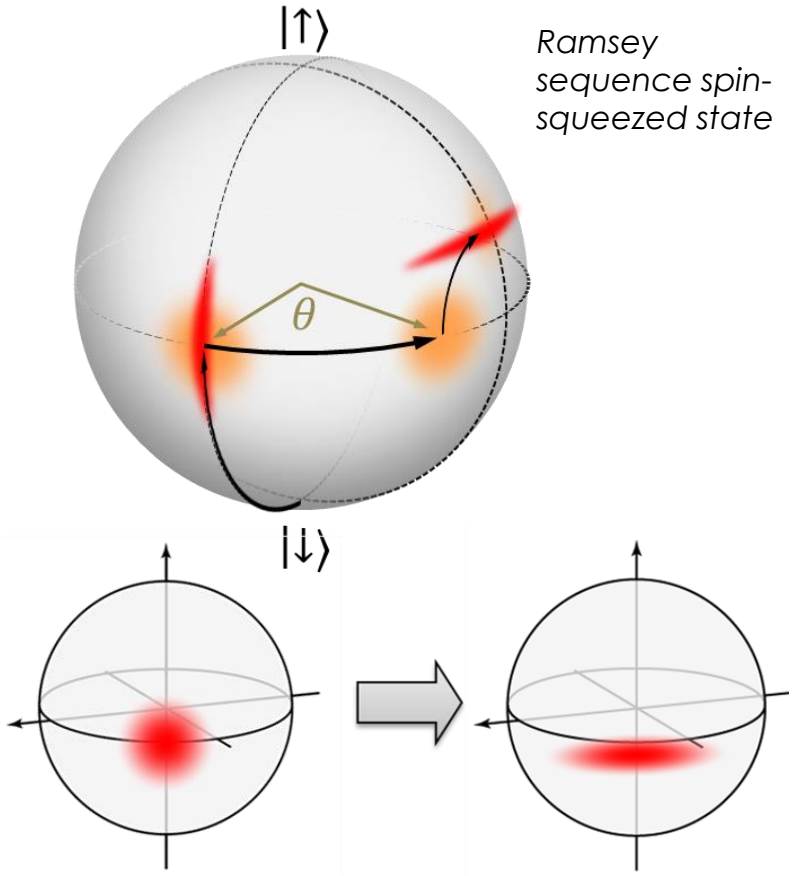
Detection beyond the SQL

- Quantum projection noise (QPN) for unentangled atoms $\Delta S_z = \Delta S_y = \sqrt{N}/2$ (SQL) is a major limitation for the best clocks.
- Spin squeezing can enable detection beyond the SQL.

Cavity-assisted Spin Squeezing

- Cavity detection serves as a QND measurement of S_z. The spin uncertainty is reduce to that of the measurement.
- Alternatively, a light-mediated S_z^2 interaction can produce entanglement as well.*

Spin Squeezing for Metrology



Ramsey sequence spin-squeezed state

* M. Scheleier-Smith, et al. Phys. Rev. Lett. 104, 073604 (2010)
* I. Leroux, et al., Phys. Rev. Lett. 104, 073602 (2010)

Relevance for clocks

Types of clocks

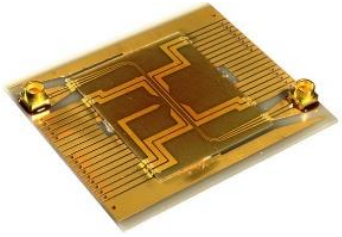
Chip-scale atomic clocks

~ 10^{-10} $s^{1/2}$

Commercial Rb clocks

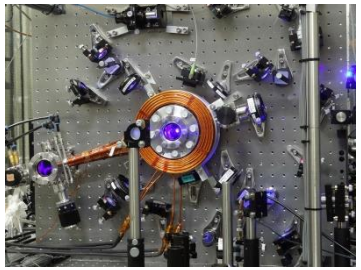
~ 10^{-12} $s^{1/2}$

Future compact clocks



10^{-13} $s^{1/2}$ range

Future primary clocks



~ 10^{-16} $s^{1/2}$

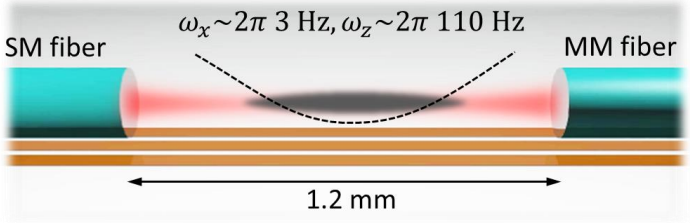
Pioneering spin squeezing experiment

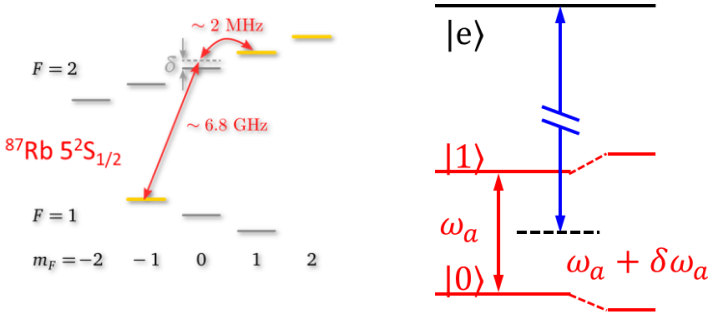
Spin-squeezed Ramsey measurements ("clocks")

- Vuletic lab (2010): 4.5dB below SQL, $\sigma(\tau) = 1.1 \times 10^{-9}\ \sqrt{s}/\sqrt{\tau}$
- Kasevich lab (2016): 10.5dB below SQL, $\sigma(\tau) = 9.7 \times 10^{-11}\ \sqrt{s}/\sqrt{\tau}$

Coherence lifetime in these experiments: ~10ms scale.

TACC 2: a highly stable cavity-QED platform

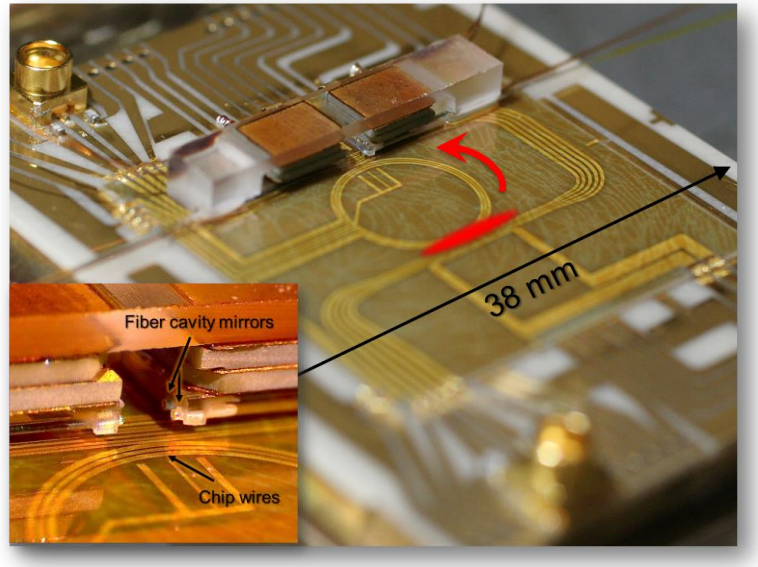




System Overview

- Two fibre Fabry-Perot cavities, closely glued on the same piezo stacks, have finesse 2.7e3 (science cav.) and 3.8e4
- Science cav. : waist 13.6 μm, linewidth 45 MHz, $C = {}^{4g^2}/_{\kappa\Gamma}$ =1.9 (anti-node), ~0.48 effective
- Clock frequency stability at $6 \times 10^{-13}\tau^{-1/2}$ without cavity interaction a T_R=1 s

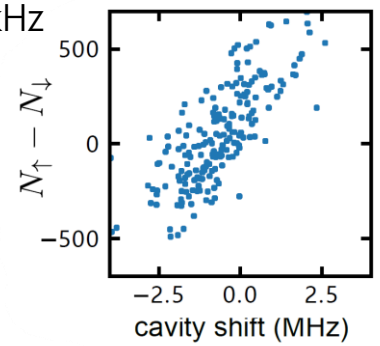
Meng-Zi Huang, et al. arXiv:2007.01964v1. (2020)



Interplay Between Squeezing And Spin Dynamics

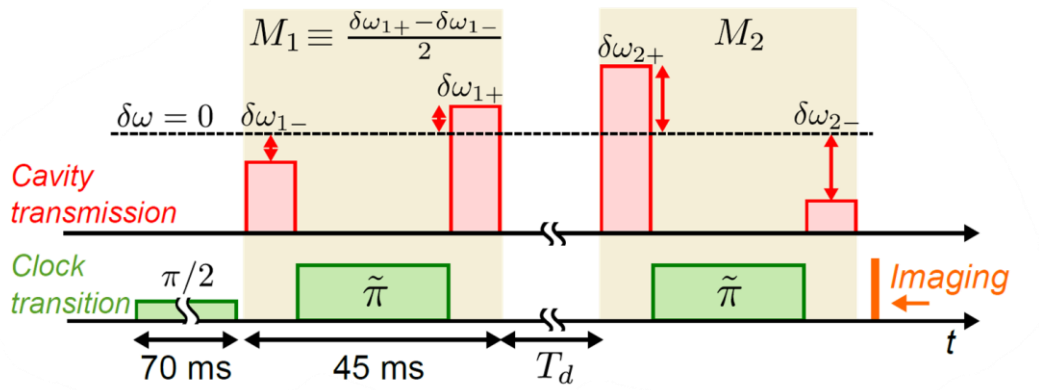
Strong coupling in dispersive regime

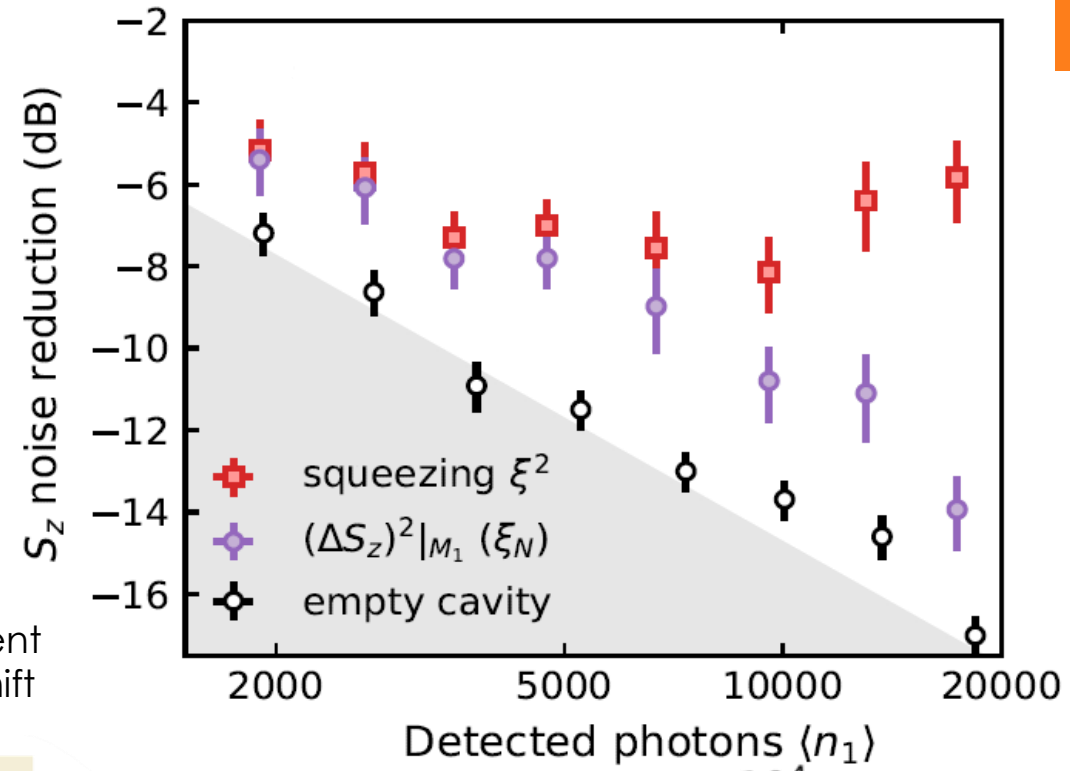
- Cavity shift: 16 kHz per spin.
- Imaging noise $\Delta_{img}(S_z)$~200, comparable to the SQL, (N~$2.3(1)\times10^4$).

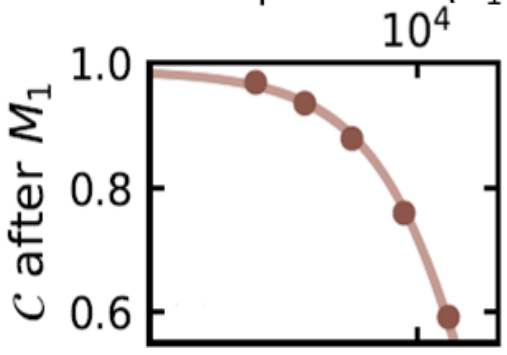


Composite measurement

- Spin echo in a composite measurement to compensate inhomogeneous light-shift

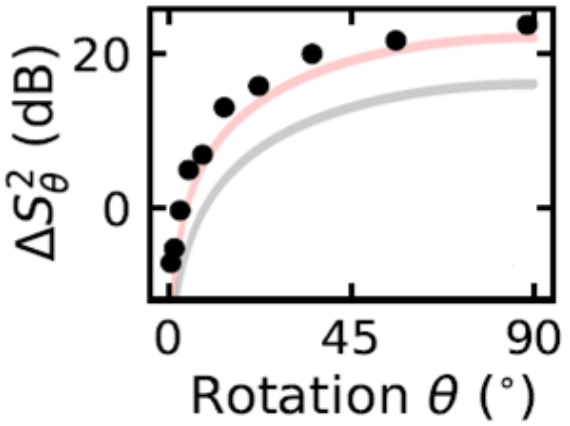






Conditional Squeezing

- Noise in empty cavity transmission is limited by PSN.
- Number squeezing is deduced from $Var\left(M_1 - \frac{M_2}{\alpha}\right)$
- Contrast measured independently.
- **Up to 8.1(9) dB metrological squeezing for ~10^4 photons.**

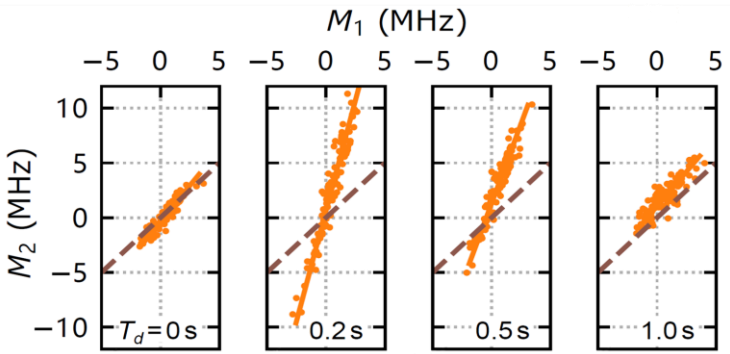


Meng-Zi Huang, et al. arXiv:2007.01964v1. (2020)

Spin Squeezing By QND Measurement: Results

Correlated non-identical measurements

- Longer delay: Correlated change in cavity shift
- Population difference fixed.
- Change in the effective cavity shift per spin



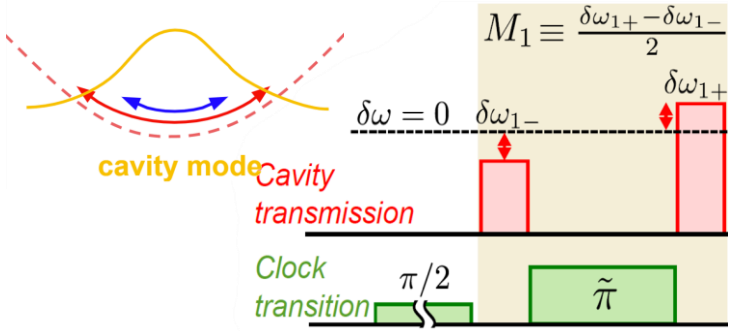
Amplification

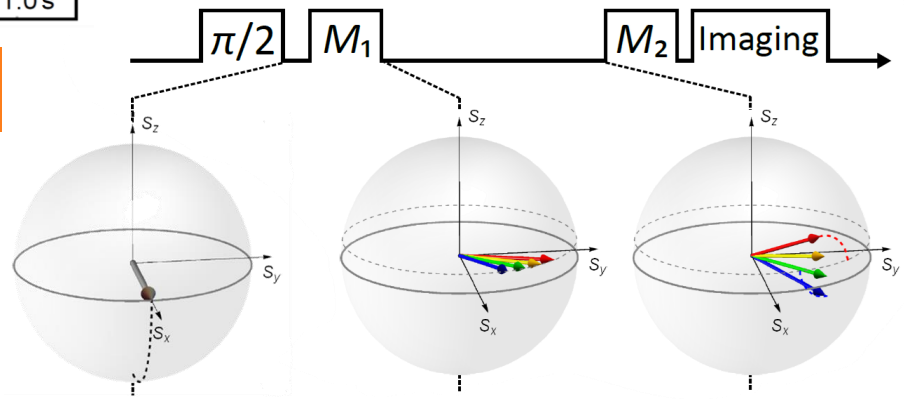
- Correlated dephasing turns into correlated population difference

$$\delta\omega_c = \alpha(t)\Omega S_z; \quad \alpha(t) \neq 1$$

Inhomogeneous light-shift

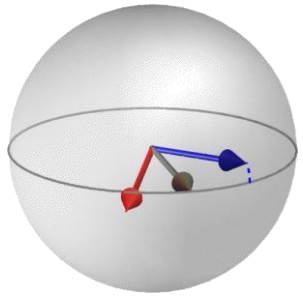
- Residual dephasing correlated with the 1st measurement

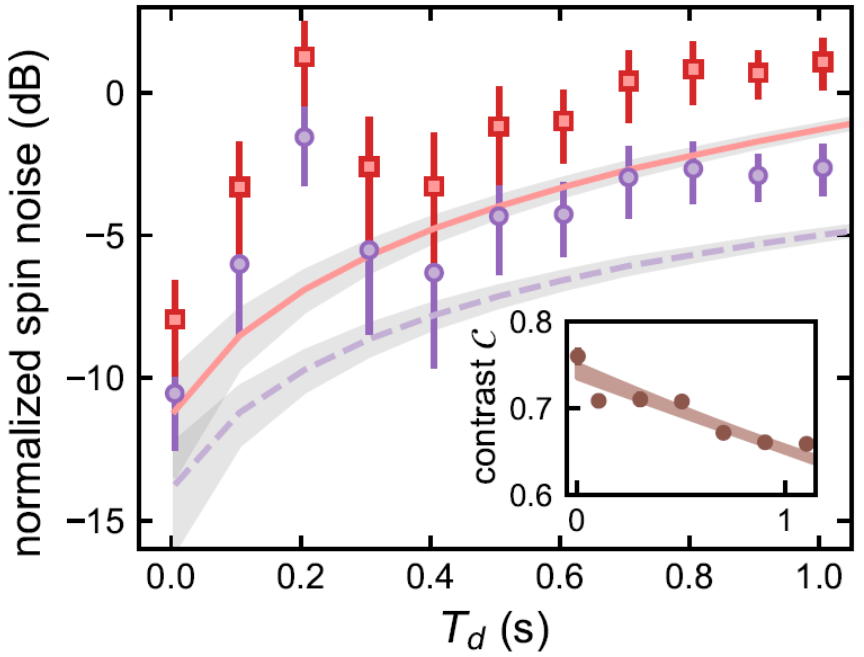




Identical Spin Rotation Effect (ISRE)

- Over forward collisions, two spins rotate around their sum.





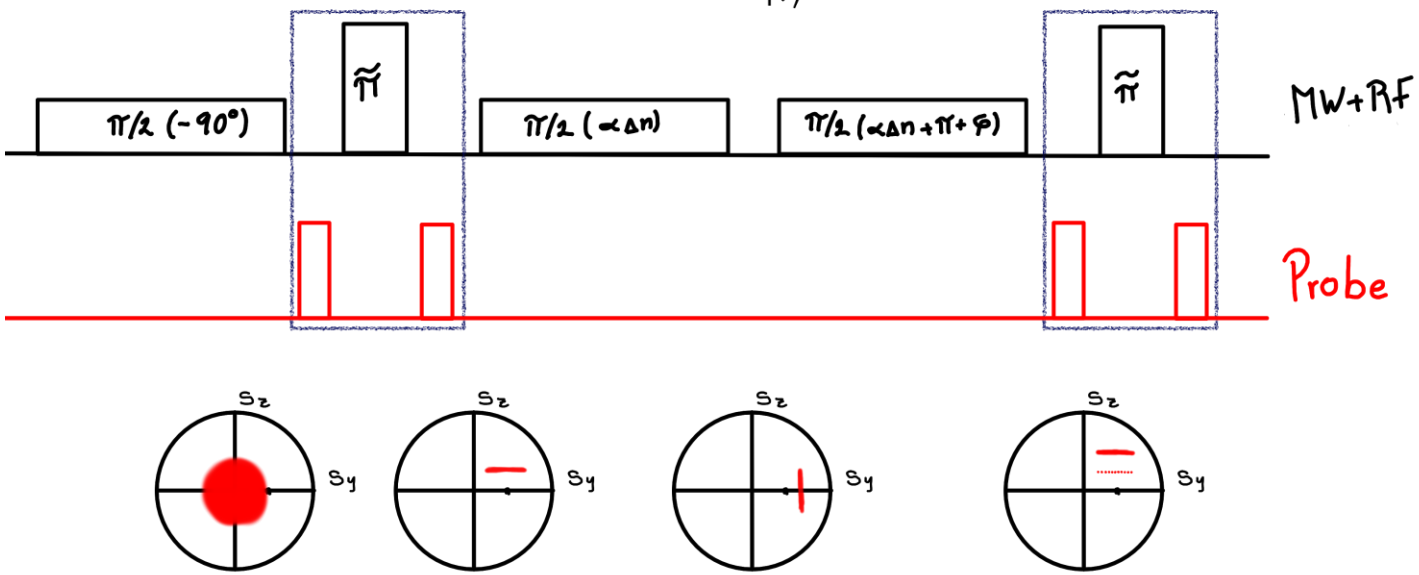
Meng-Zi Huang, et al. arXiv:2007.01964v1. (2020)

Squeezing and amplification in a clock

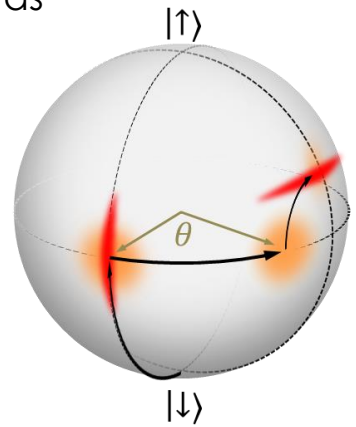
Complete clock sequence

A clock sequence would be divided as

- Squeezing of state
- Reorientation
- Phase accumulation
- Measurement



Amplification and Phase Accumulation



- Forward collisions are not expected to change the expectation value of the spin state
- Phase accumulation should translate simply to a shift in the second measurement of the clock

Preliminary resultd