ENTANGLEMENT-ENHANCED ATOMIC GRAVIMETER

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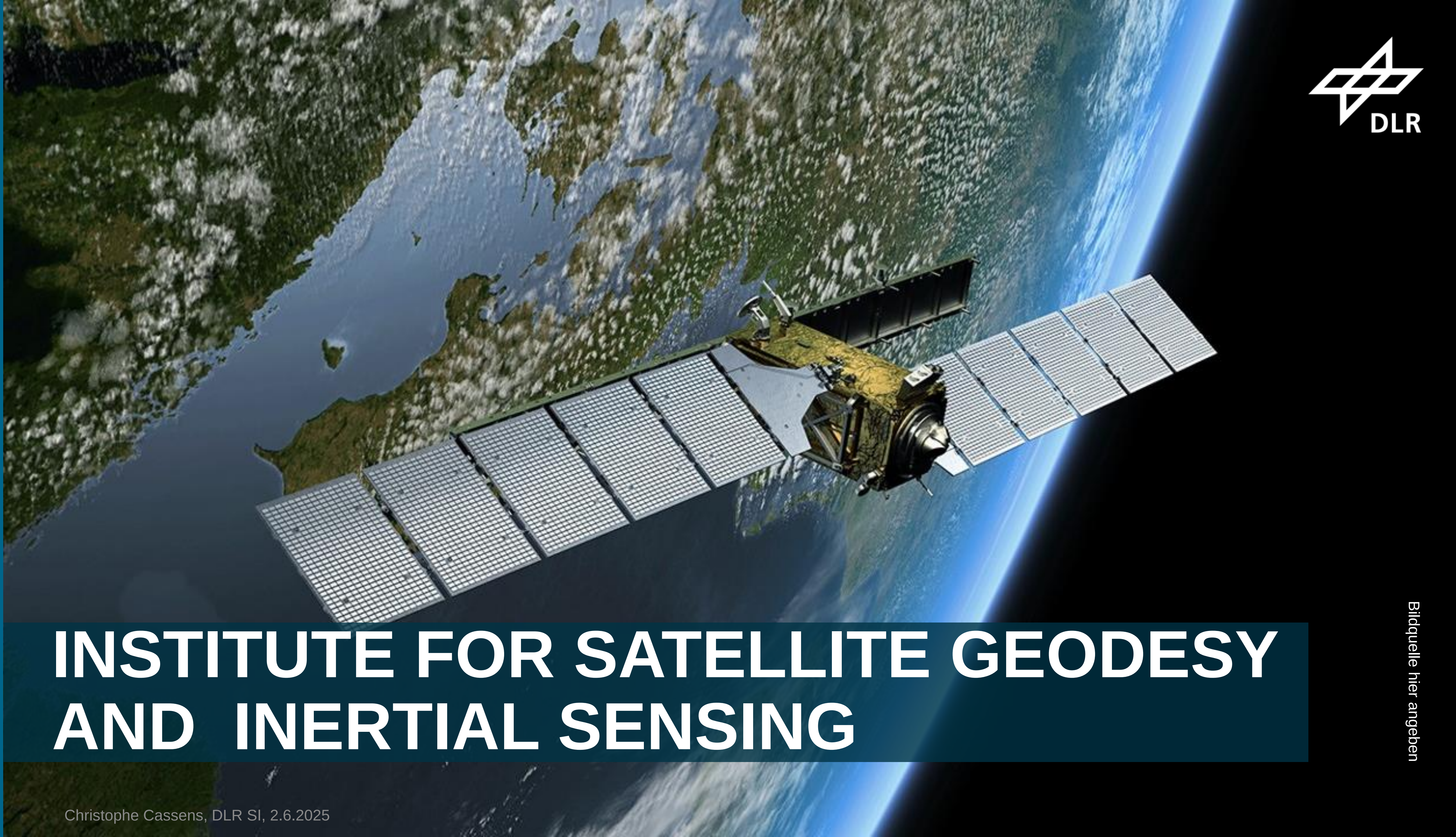


INSTITUTE FOR SATELLITE GEODESY AND INERTIAL SENSING

Bildquelle hier angeben

Atom interferometry - Gravimetry

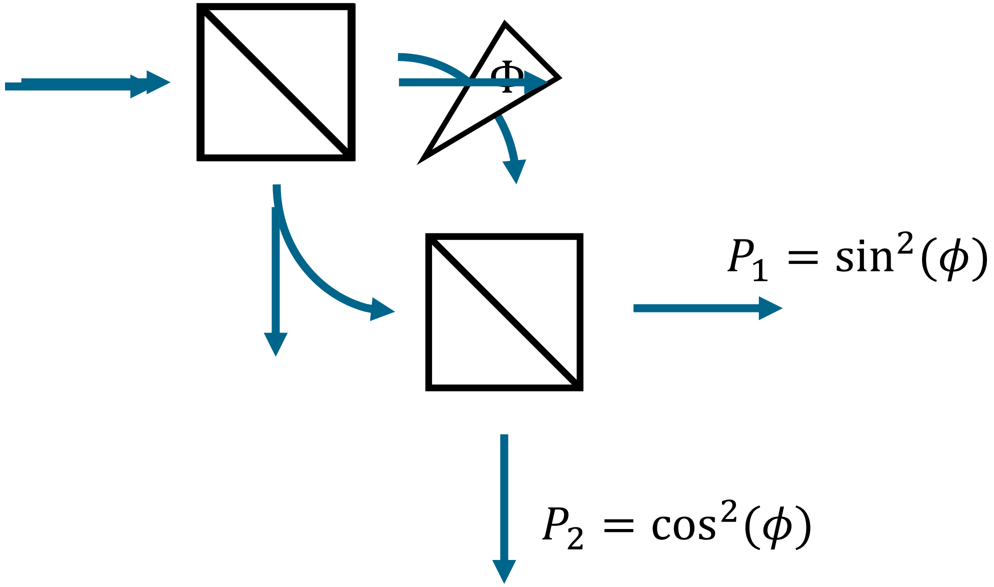
- Classical gravimeters can be very precise but suffer from drift over extended measurement times
- Atom interferometers combine high precision with long-term stability
- Atomic gravimeters have been demonstrated in many setups, even outside the lab [1]

[1] Stray et al, **Quantum sensing for gravity cartography**, Nature, 2022

Atom interferometry – light interferometry

- Similar to light interferometry

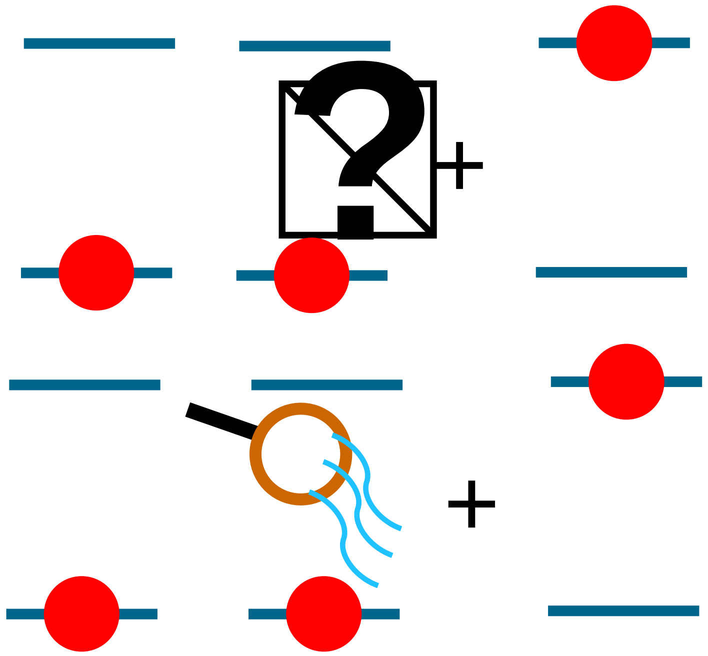
1. Superposition
2. Phase imprint
3. Interference



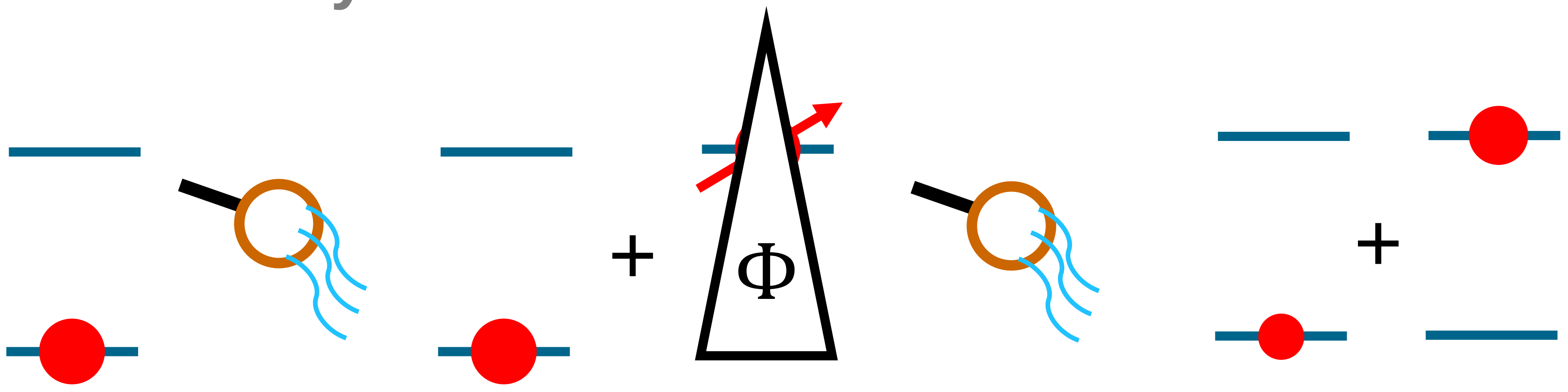
Atom interferometry - beamsplitter

- Two-path photon ≙ two-level atom (spin ½-system)
- What is a beamsplitter for atoms?

➢ e.g. Microwave radiation

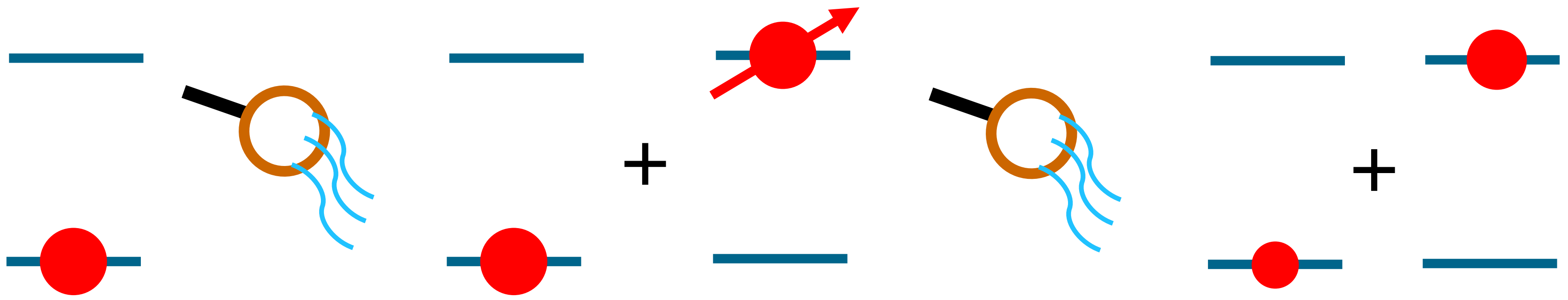


Atom interferometry



Determine Φ from final state of N atoms

Atom interferometry - Gravimetry



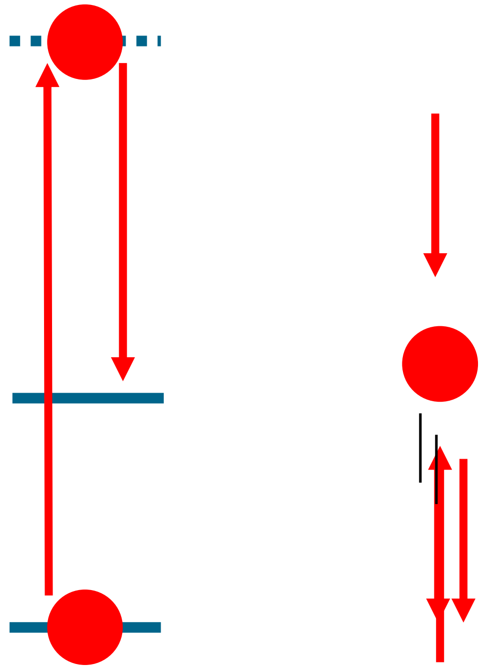
How can we imprint earths acceleration onto the phase?

Atom interferometry - Gravimetry

- Raman-light pulse couple states via two-photon transition

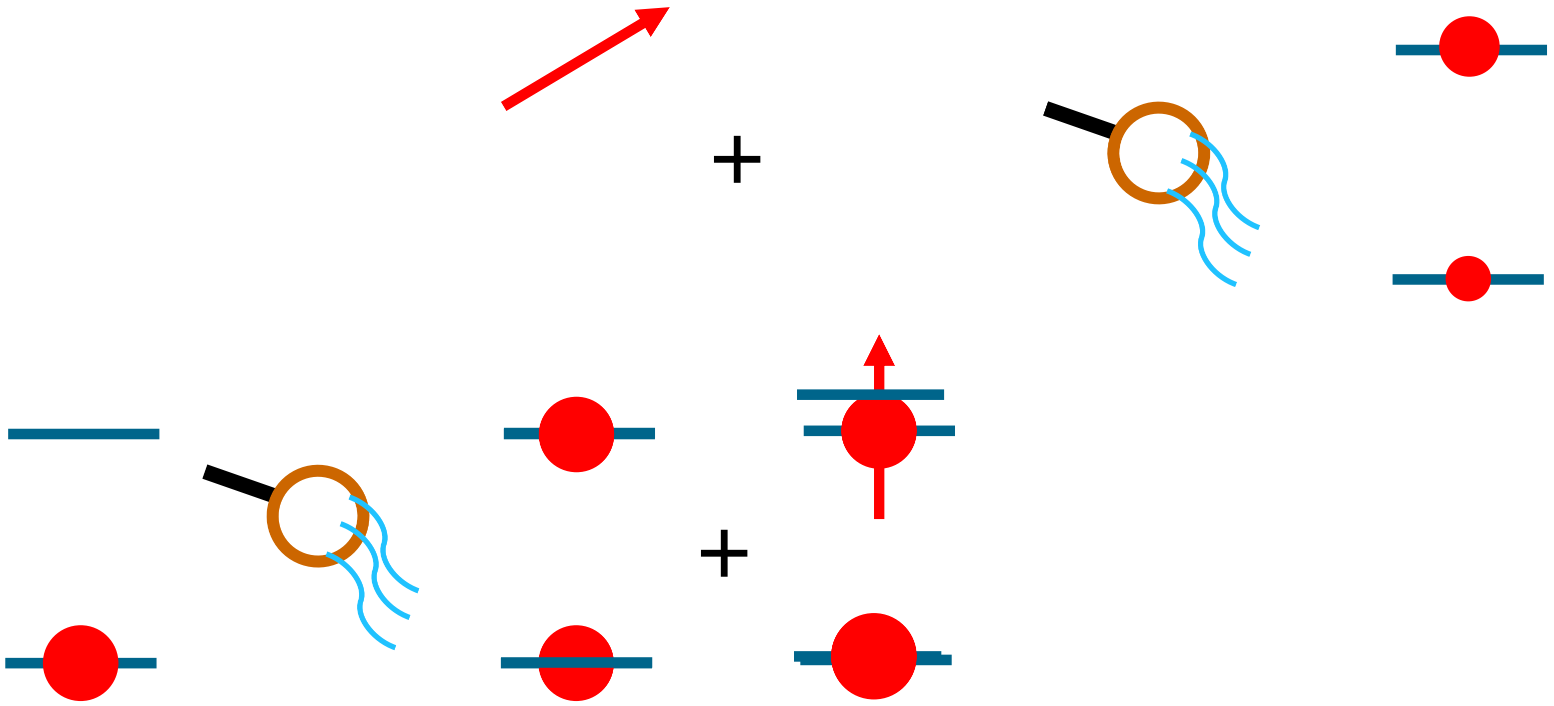
➢Changes spin state

➢Changes momentum state



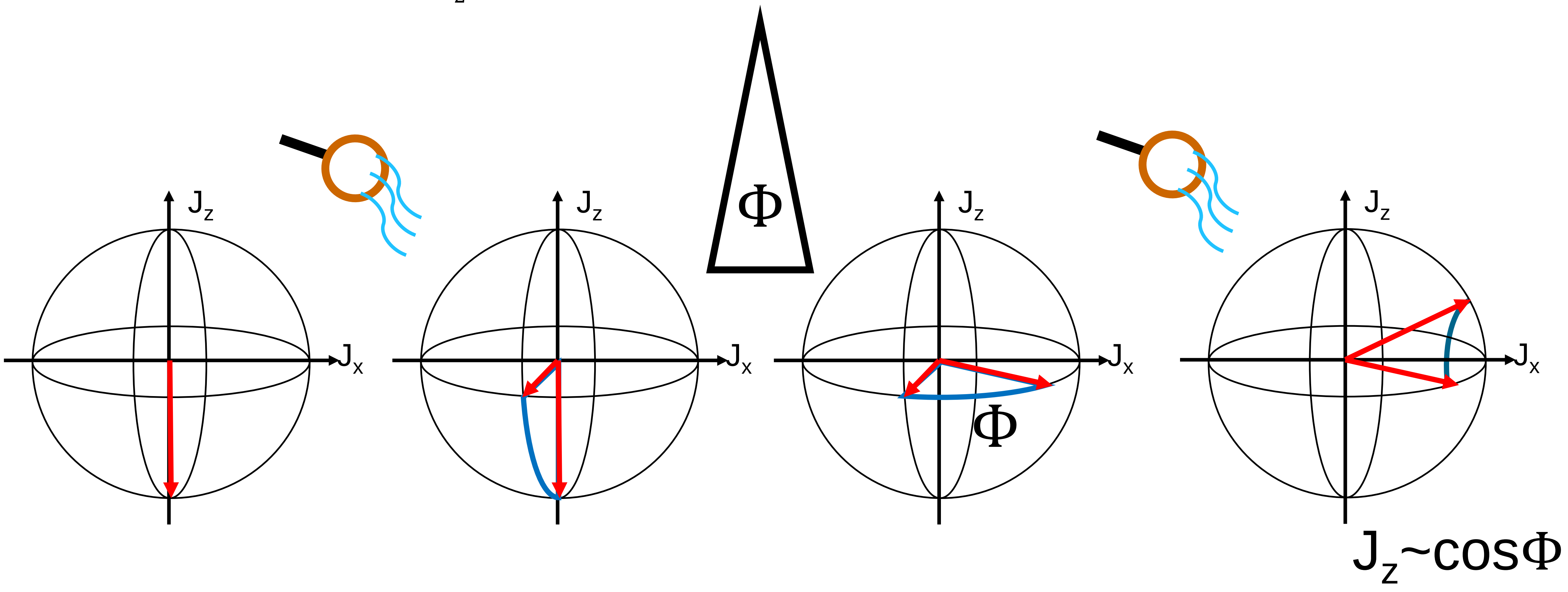
In free fall, phase imprint due to Doppler shift

Atom interferometry - Gravimetry



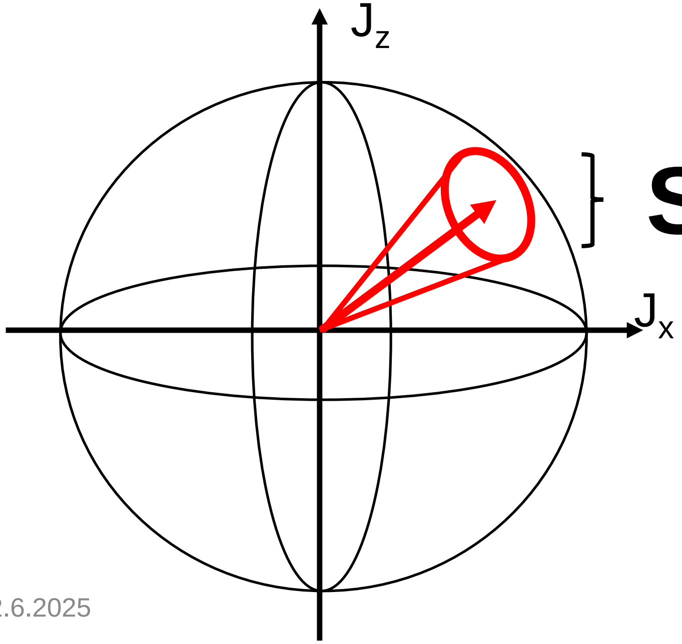
Atom interferometry – Bloch sphere representation

- Visualization on Bloch sphere
- Bloch sphere spanned by collective N-particle spin-1/2 operators J_x, J_y, J_z
- Measurement outcome: $J_z = \frac{1}{2}(N_\uparrow - N_\downarrow)$



Atom interferometry – Fundamental limit

- N Atoms are projected to output states independetly
  → N coin tosses
- Measurement outcome binomially distributed
  → limit to phase resolution

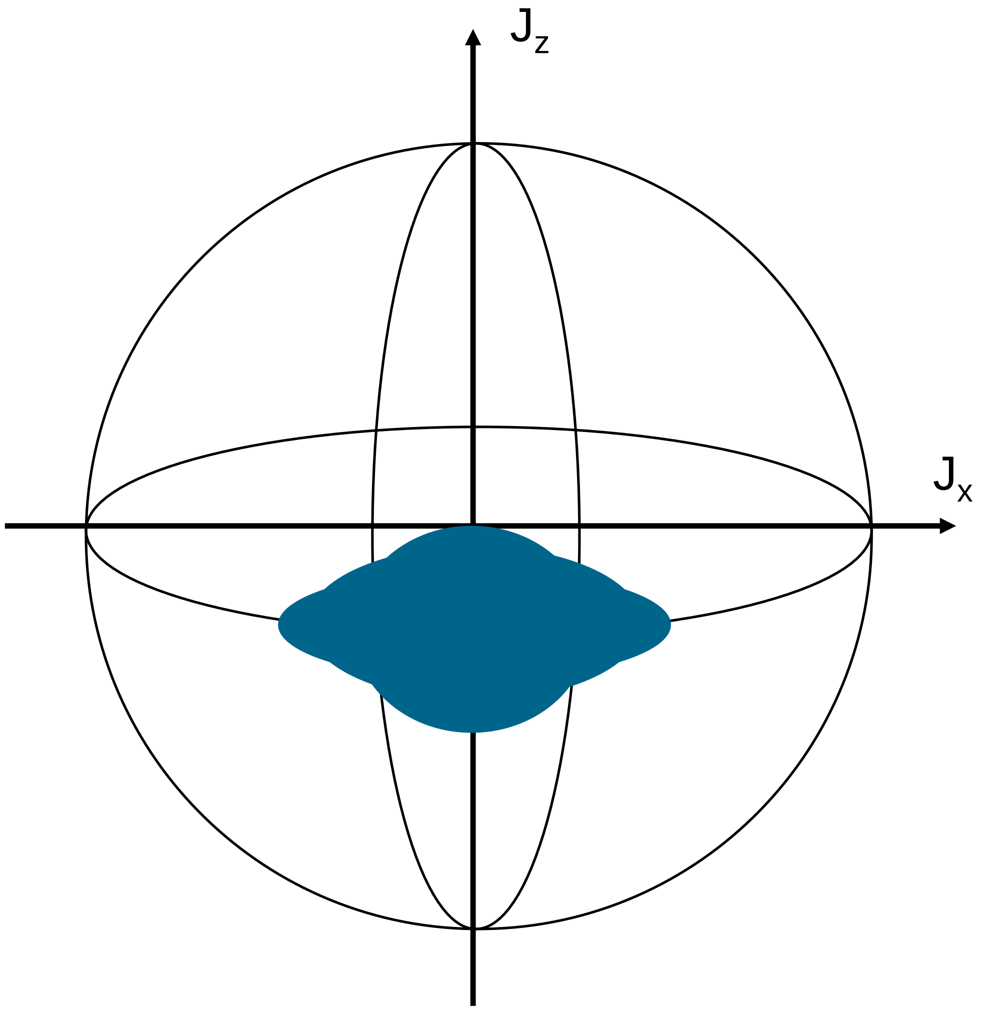


$$\textbf{SQL: } \Delta\Phi = \frac{1}{\sqrt{N}}$$

Atom interferometry – squeezed states

- How can we overcome the SQL?

➢ Create entanglement by non-linear interactions in BEC (spin-changing collisions) → squeezed state [1]



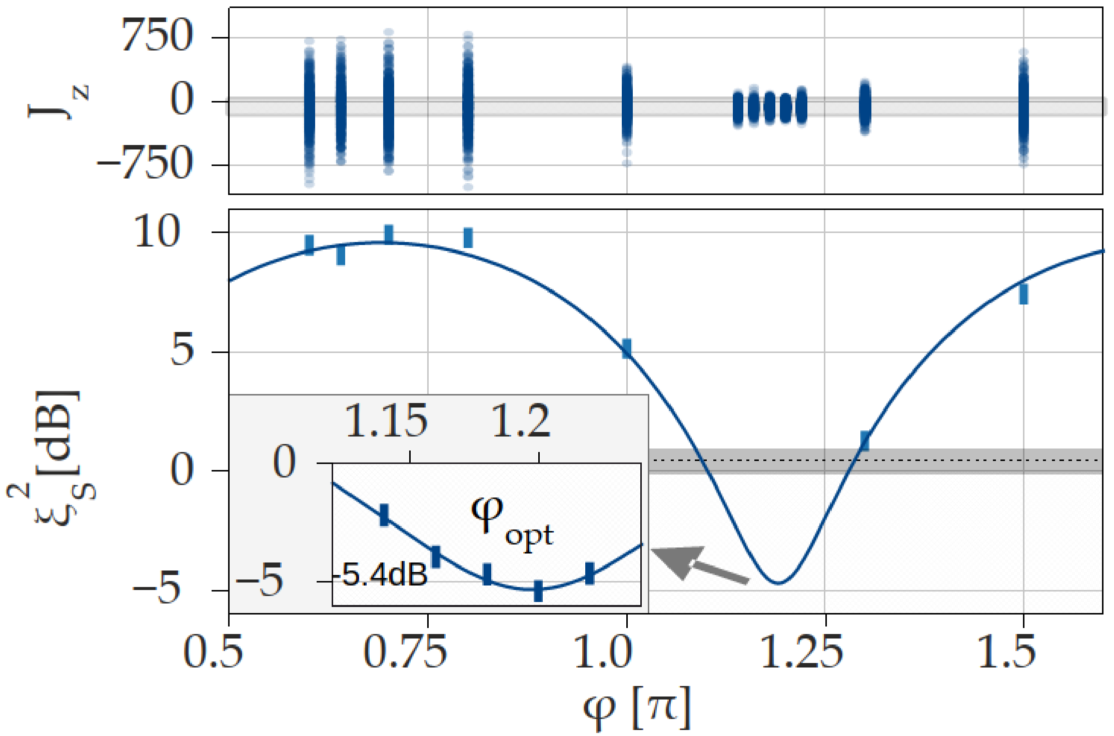
[1] Hamley et al, **Spin-nematic squeezed vacuum in a quantum gas**, Nature, 2012

Entanglement-enhanced atom interferometry

- Entanglement has shown improved phase sensitivity for clocks and magnetometer
- Towards entanglement: Malia et al[1], Greve et al[2] but no actual measurement yet

[1] Malia et al, **Distributed quantum sensing with mode-entangled spin-squeezed atomic states**, Nature, 2022
[2] Greve et al, **Entanglement-enhanced matter-wave interferometry in a high-finesse cavity**, Nature, 2022
[3] Abend et al, **Terrestrial very-long-baseline atom interferometry: Workshop summary**, AVS Quantum Sci., 2024

Atom interferometry – squeezed states



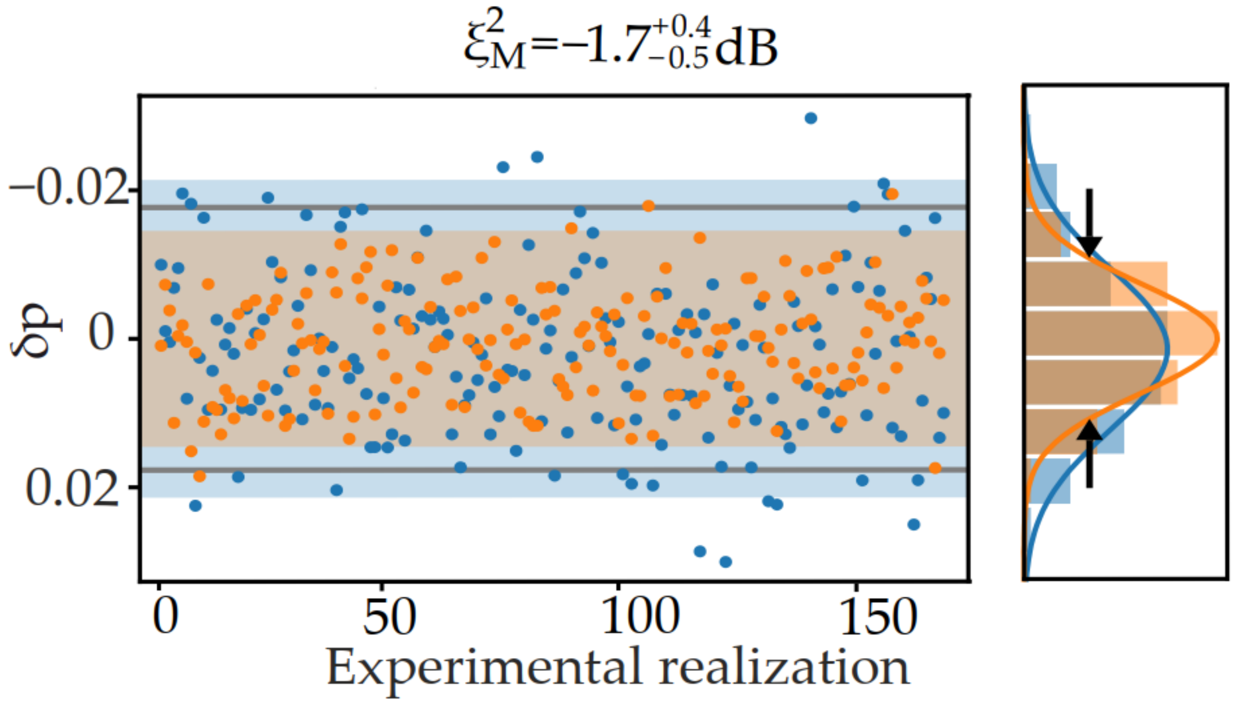
$$\xi_s = 4\frac{var(J_z)}{N}$$

We can use the squeezed state to overcome the SQL

Squeezed Gravimeter – Fluctuations below SQL?

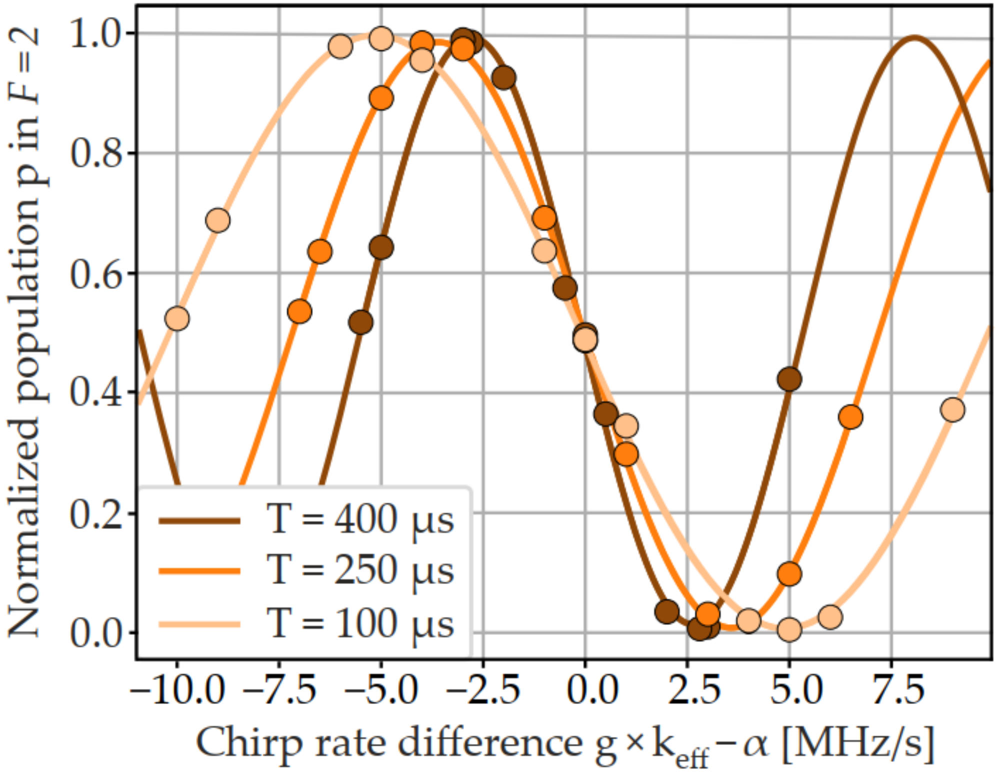
- Does the squeezed input state reduce quantum fluctuations?
- Yes, it does: Compared to unsqueezed state and compared to ideal SQL!

Noise reduction in variance



Squeezed Gravimeter – Signal (squeezed input state)

- Phase imprint depends on chirp rate α and time between Raman pulses T
  $\Phi = \left(g - \frac{\alpha}{k_{eff}}\right) S(T)$
- Chirp rate that cancels Doppler shift is independent of T



$$g_{exp} = 9.8118(16)\ m/s^2$$
$$g_{Hannover} = 9.8126\ m/s^2$$

Conclusion

- First realization of a squeezing-enhanced gravimeter (earlier works didn‘t measure g [1,2])
- Realization with BEC offers advantages for long interrogation as envisioned in gravitational wave detectors [3]

[1] Malia et al, **Distributed quantum sensing with mode-entangled spin-squeezed atomic states**, Nature, 2022
[2] Greve et al, **Entanglement-enhanced matter-wave interferometry in a high-finesse cavity**, Nature, 2022
[3] Abend et al, **Terrestrial very-long-baseline atom interferometry: Workshop summary**, AVS Quantum Sci., 2024

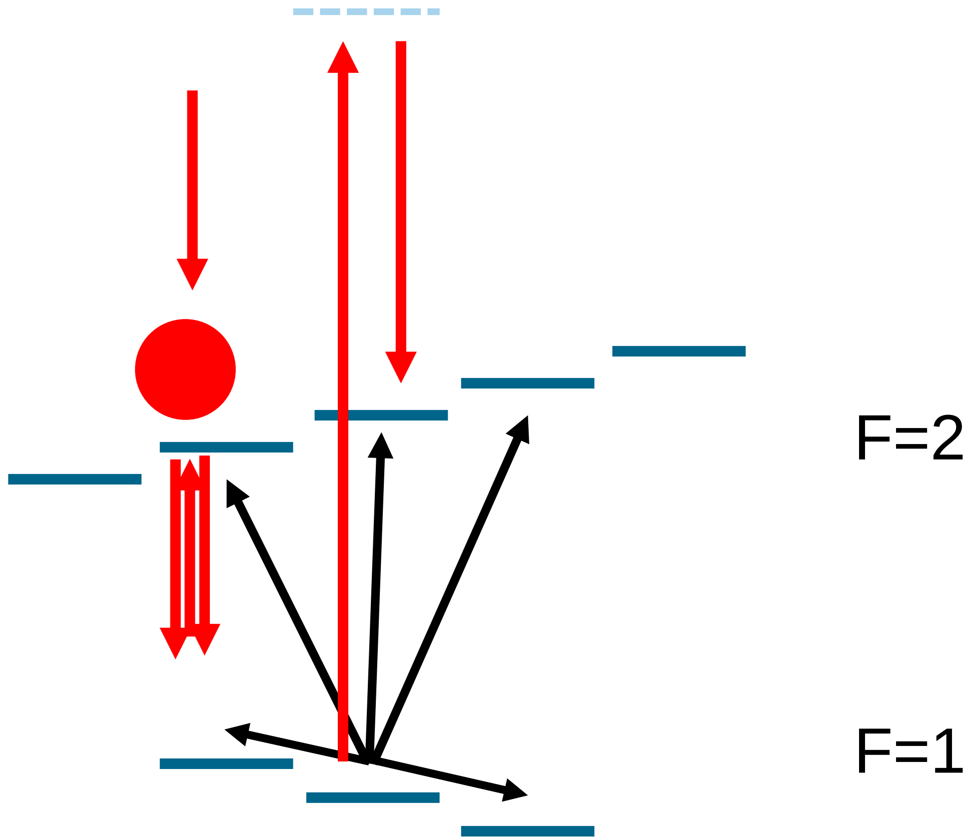
Backup - Experimental platform

- Our playground: F=1 and F=2 hyperfine levels
- State manipulation via:

➢mw pulses

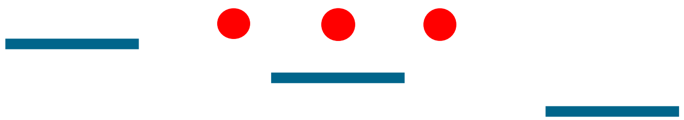
➢rf pulses

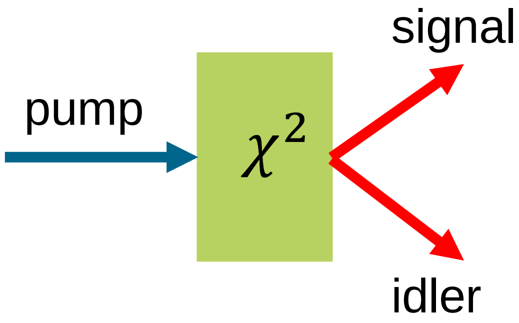
➢Raman pulses



Backup - Squeezing by spin-changing collisions

- Spin-changing collisions in $|\mathrm{F}=1, m=0\rangle$
- Create entangled pairs in $|F=1, m=\pm 1\rangle$
  → squeezed vacuum
- Photon analogue: Spontaneous parametric down-conversion

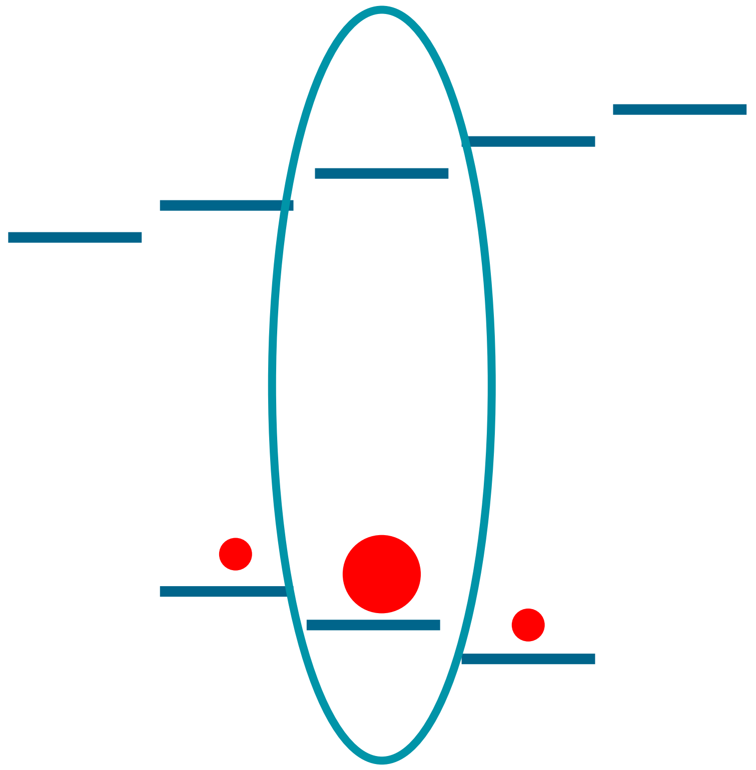




Backup - Magnetic field insensitive squeezed state

- Transfer squeezed state
  $|m = \pm 1\rangle \rightarrow |m = 0\rangle$

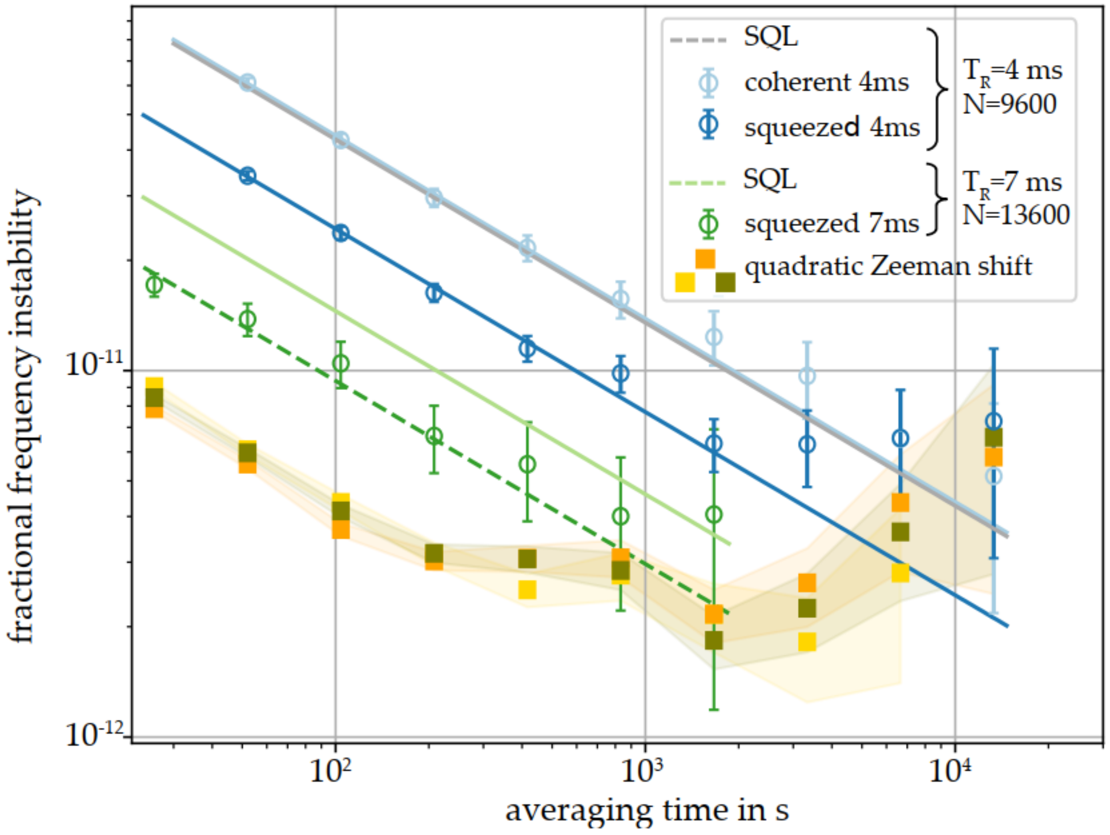
1. Mw pulse
2. Rf pulse



1st order magnetic field insensitive

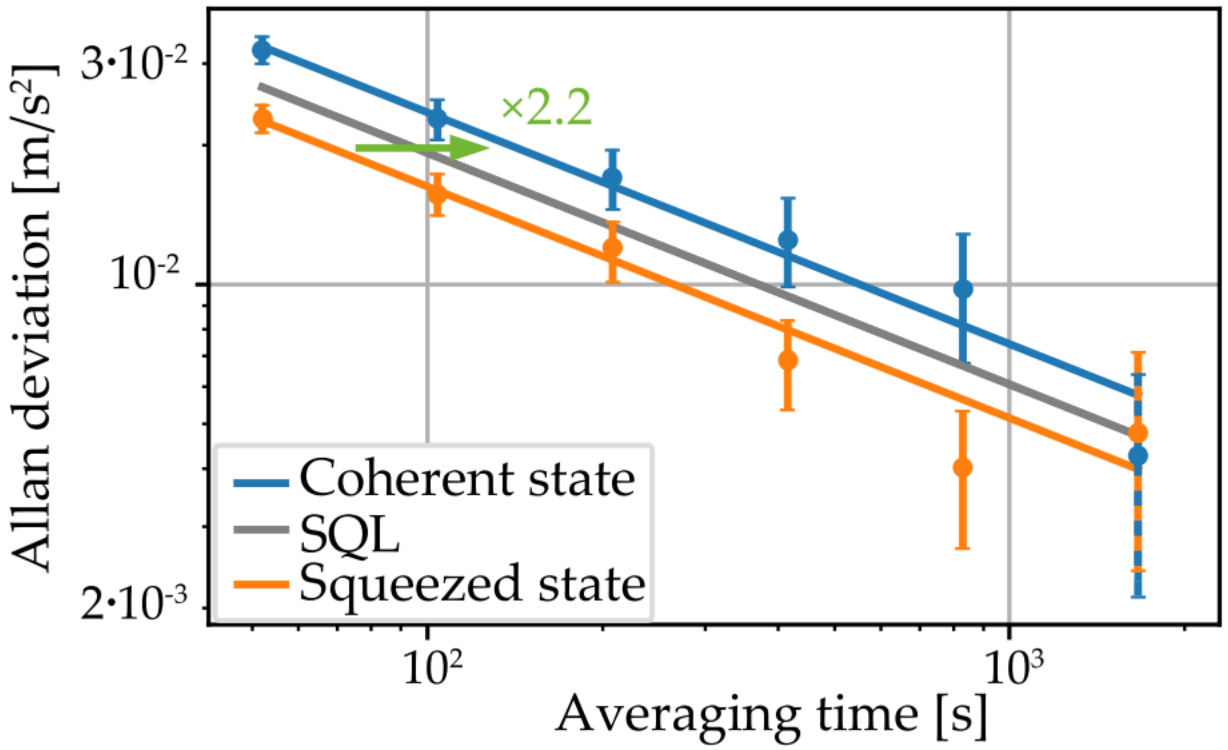
Backup – Squeezing-improved Clock and Magnetic field noise

- $\Delta B = 70\mu G$
- Magnetic field noise does not limit sensitivity for Ramsey times up to 7ms and averaging times < 1000s



Squeezed Gravimeter – Improvement in averaging

- How does the averaging behavior improve?
- Look at Allan deviation



Experimental platform

- Laser cooling ^{87}Rb
- Crossed-beam optical dipole trap
- BEC of 7k ^{87}Rb atoms in 26s