University of Copenhagen

Niels Bohr Institute

UNIVERSITY OF COPENHAGEN

Quantum Back-Action Evasion
for Future Gravitational Wave Detectors

IFD, Sestri Levante, 17 marzo 2025

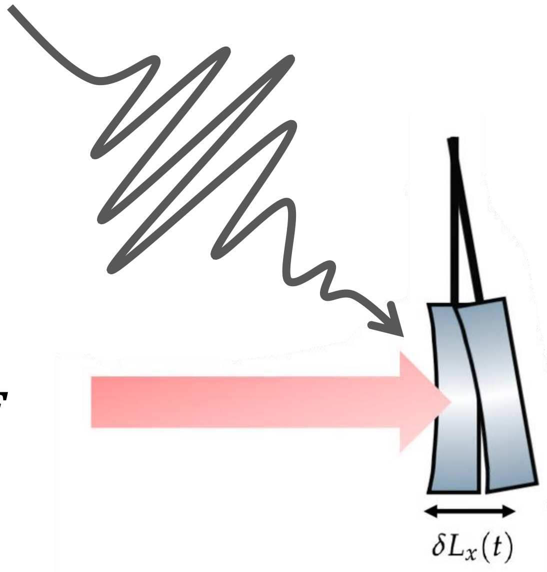
A.Grimaldi, V. Novikov, J. Jia, T.B. Brasil, M. Bocoum, M. Balabas, J. H. Müller, E. Zeuthen, E. S. Polzik

Phys. Rev. D **100**, 062004 https://doi.org/10.1103/PhysRevD.100.062004

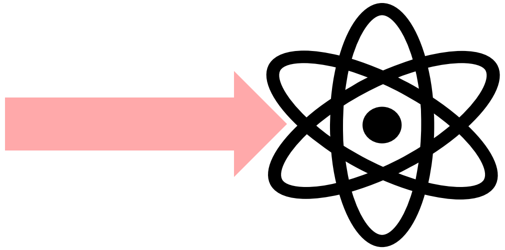
UNIVERSITY OF COPENHAGEN

Quantum Back-Action Evasion

Quantum limited detector $$q_{ITF} = \tilde{h}\sqrt{K_{ITF}} + p_1 + x_1 K_{ITF}$$



External quantum reference $$q_{Ref} = p_2 + x_2 K_{Ref}$$



Nat Commun **13**, 4815 (2022). https://doi.org/10.1038/s41467-022-32495-7

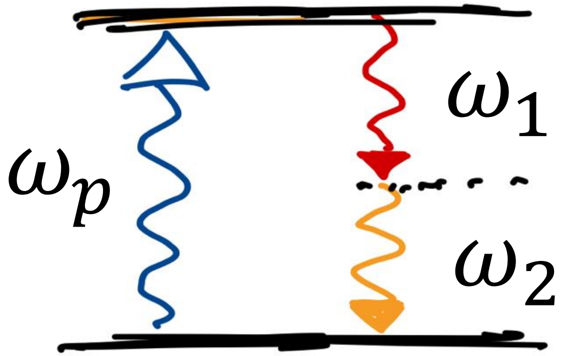
UNIVERSITY OF COPENHAGEN

Quantum Back-Action Evasion

Connection

Continuous variable entangled twin beams.

Non-linear crystal.



Parametric
down conversion

$$\omega_p = \omega_1 + \omega_2$$

Amplitude and phase are correlated

$$\Delta(x_1 - x_2)^2 \to 0$$

$$\Delta(p_1 + p_2)^2 \to 0$$

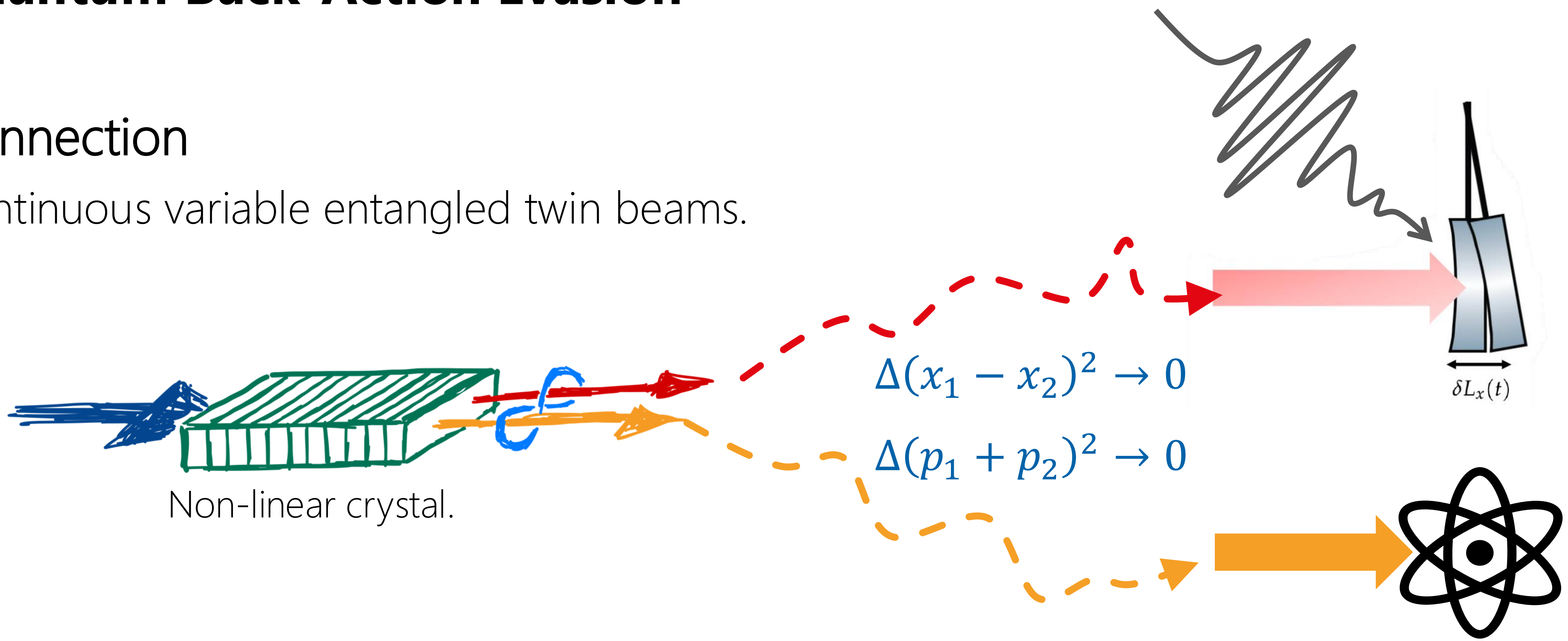
Nat Commun **13**, 4815 (2022). https://doi.org/10.1038/s41467-022-32495-7

UNIVERSITY OF COPENHAGEN

Quantum Back-Action Evasion

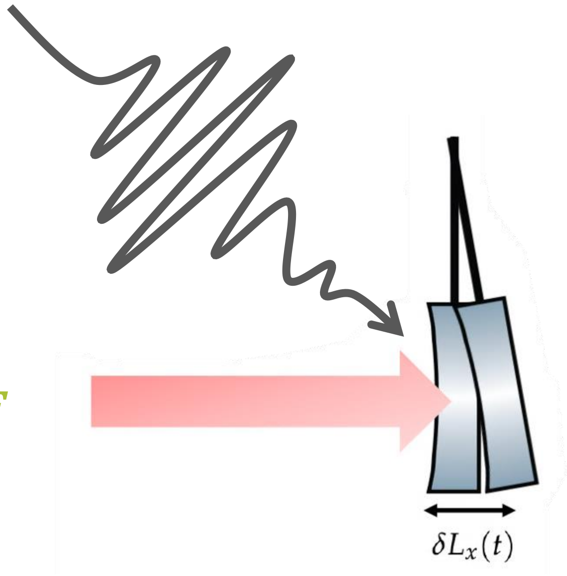
Connection

Continuous variable entangled twin beams.



Phys. Rev. D **100**, 062004 https://doi.org/10.1103/PhysRevD.100.062004

Quantum Back-Action Evasion

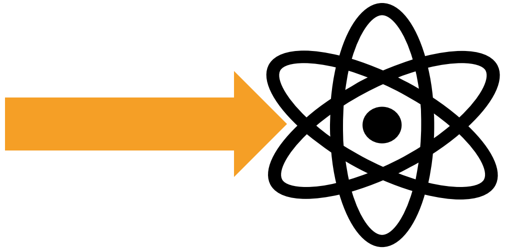


Quantum limited detector $\quad q_{ITF} = \tilde{h}\sqrt{K_{ITF}} + p_1 + x_1 K_{ITF}$

$\Delta(x_1 - x_2)^2 \rightarrow 0$

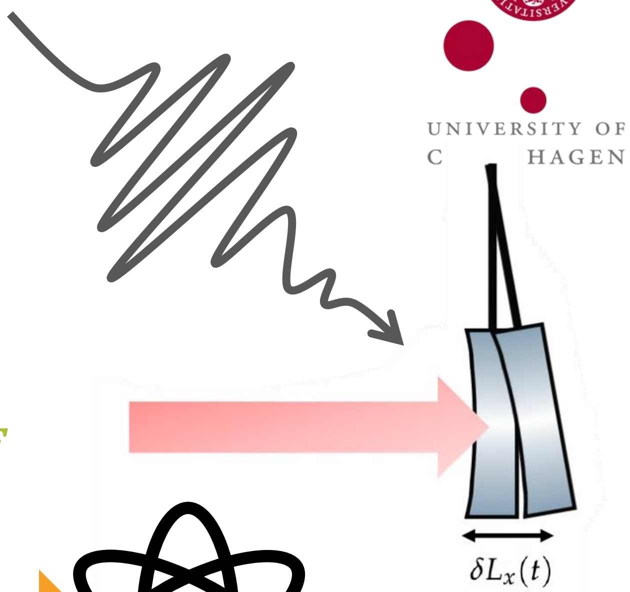
$\Delta(p_1 + p_2)^2 \rightarrow 0$

External quantum reference $\quad q_{Ref} = p_2 + x_2 K_{Ref}$



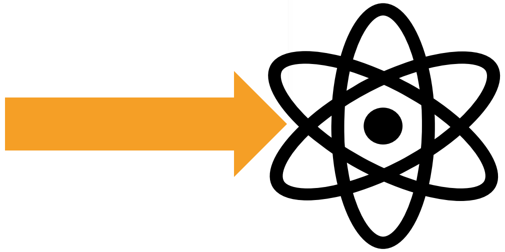
Phys. Rev. D **100**, 062004 https://doi.org/10.1103/PhysRevD.100.062004

Quantum Back-Action Evasion



Quantum limited detector $q_{ITF} = \tilde{h}\sqrt{K_{ITF}} + p_1 + x_1 K_{ITF}$

External quantum reference $q_{Ref} = p_2 + x_2 K_{Ref}$



$$\Delta(x_1 - x_2)^2 \to 0$$

$$\Delta(p_1 + p_2)^2 \to 0$$

$$\Delta(p_1 + p_2)^2 \to 0$$

$$q_{ITF} + q_{ITF} = \tilde{h}\sqrt{K_{ITF}} + p_1 + x_1 K_{ITF}(\Omega) + p_2 + x_2 K_{Ref}(\Omega)$$

Phys. Rev. D **100**, 062004 https://doi.org/10.1103/PhysRevD.100.062004

UNIVERSITY OF COPENHAGEN

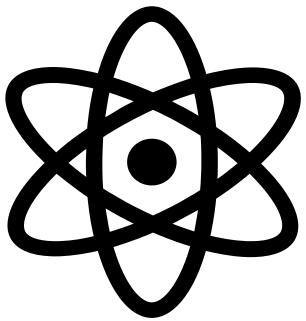
Quantum Back-Action Evasion

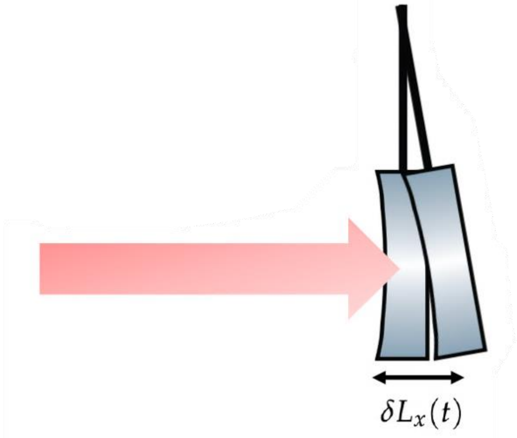
External (Quantum) Reference

$K_{Ref}(\Omega)$

$\Delta(x_1 - x_2)^2 \rightarrow 0$

$K_{ITF}(\Omega)$





Negative Mass Oscillator

Positive Mass Oscillator

Phys. Rev. D **100**, 062004 https://doi.org/10.1103/PhysRevD.100.062004

UNIVERSITY OF COPENHAGEN

Quantum Back-Action Evasion

External (Quantum) Reference

$K_{Ref}(\Omega)$ $\Delta(x_1 - x_2)^2 \rightarrow 0$ $K_{ITF}(\Omega)$

$$K_{Ref}(\Omega) \propto \frac{-P_{in}}{\Omega^2(\Omega^2 + \gamma^2)}$$

$$K_{ITF}(\Omega) \propto \frac{P_{in}}{\Omega^2(\Omega^2 + \gamma^2)}$$

Effective **Negative** Mass Oscillator

Positive Mass Oscillator

Nat Commun **14**, 6396 (2023). https://doi.org/10.1038/s41467-023-42059-y

UNIVERSITY OF COPENHAGEN

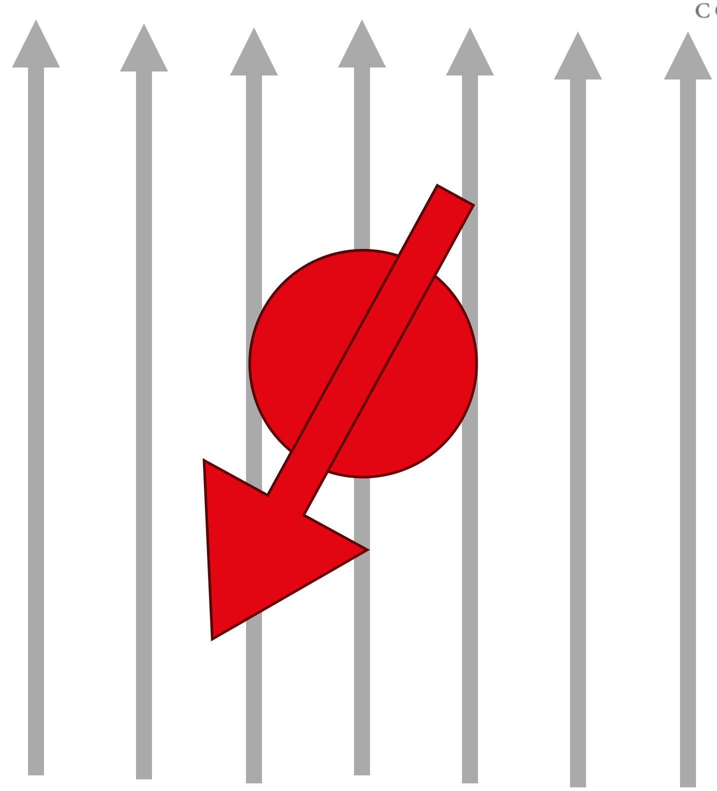
Quantum Back-Action Evasion

External (Quantum) Reference

$$K_{Ref}(\Omega)$$

$$K_{Ref}(\Omega) \propto \frac{-P_{in}}{\Omega^2(\Omega^2+\gamma^2)}$$

Effective **Negative** Mass Oscillator



Magnetic Field

$$H \propto -B \cdot J$$

Nat Commun **14**, 6396 (2023). https://doi.org/10.1038/s41467-023-42059-y

UNIVERSITY OF COPENHAGEN

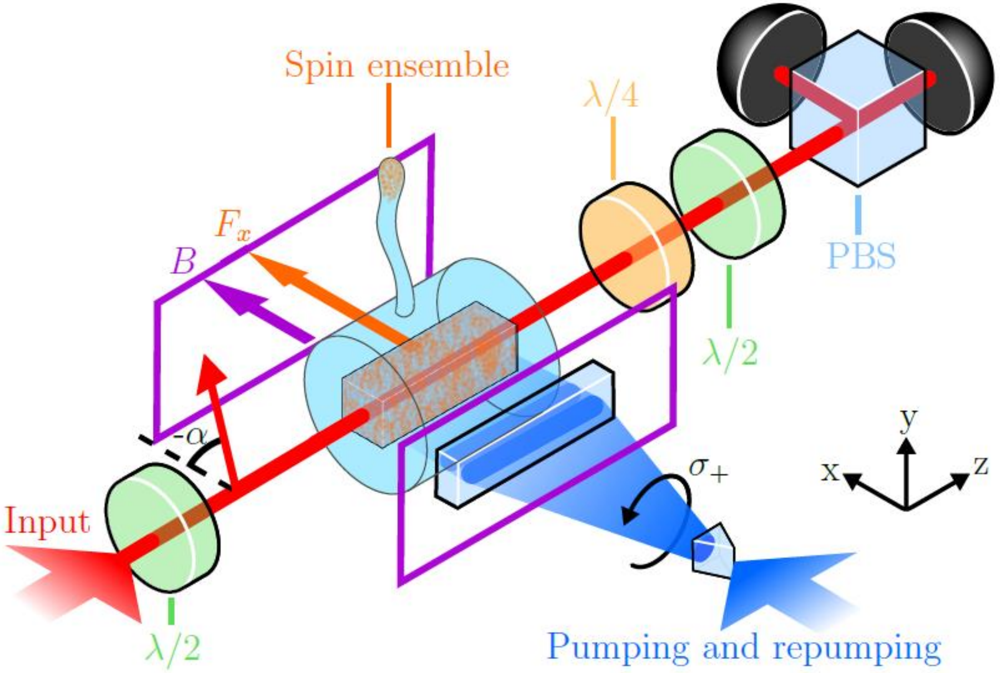
Quantum Back-Action Evasion

External (Quantum) Reference

$$K_{Ref}(\Omega)$$

$$K_{Ref}(\Omega) \propto \frac{-P_{in}}{\Omega^2(\Omega^2+\gamma^2)}$$

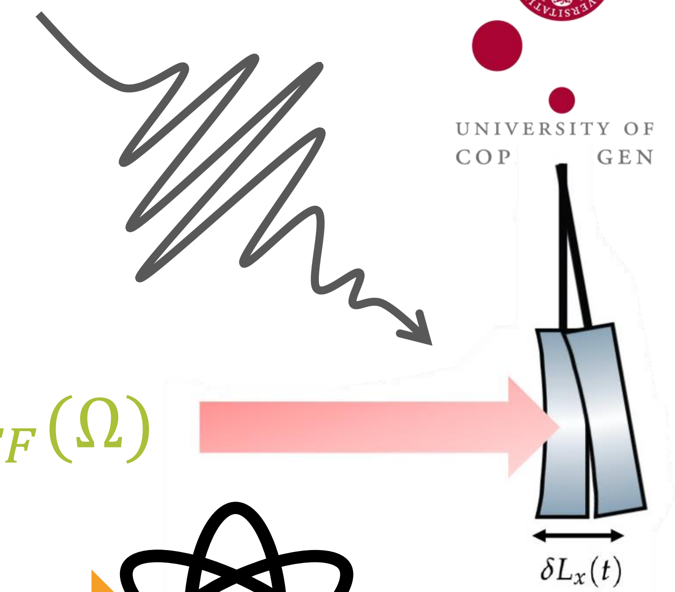
Effective **Negative** Mass Oscillator



Phys. Rev. D **100**, 062004 https://doi.org/10.1103/PhysRevD.100.062004

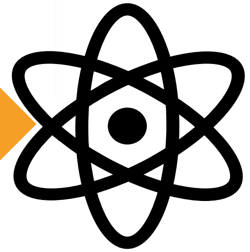
UNIVERSITY OF COPENHAGEN

Quantum Back-Action Evasion



Quantum limited detector $\quad q_{ITF} = \tilde{h}\sqrt{K_{ITF}} + p_1 + x_1 K_{ITF}(\Omega)$

External quantum reference $\quad q_{Ref} = p_2 + x_2 K_{Ref}(\Omega)$



$K_{Ref}(\Omega) \simeq -K_{ITF}(\Omega)$

$$q_{ITF} + q_{ITF} = \tilde{h}\sqrt{K_{ITF}} + p_1 + x_1 K_{ITF}(\Omega) + p_2 + x_2 K_{Ref}(\Omega)$$

$\Delta(p_1 + p_2)^2 \to 0$

Phys. Rev. D **100**, 062004 https://doi.org/10.1103/PhysRevD.100.062004

UNIVERSITY OF COPENHAGEN

Quantum Back-Action Evasion

Conditioning the $q_{ITF}(\Omega)$ based on the $q_{Ref}(\Omega)$, we can suppress the detector quantum noise

$$q_{ITF} + q_{ITF} = \tilde{h}\sqrt{K_{ITF}}$$

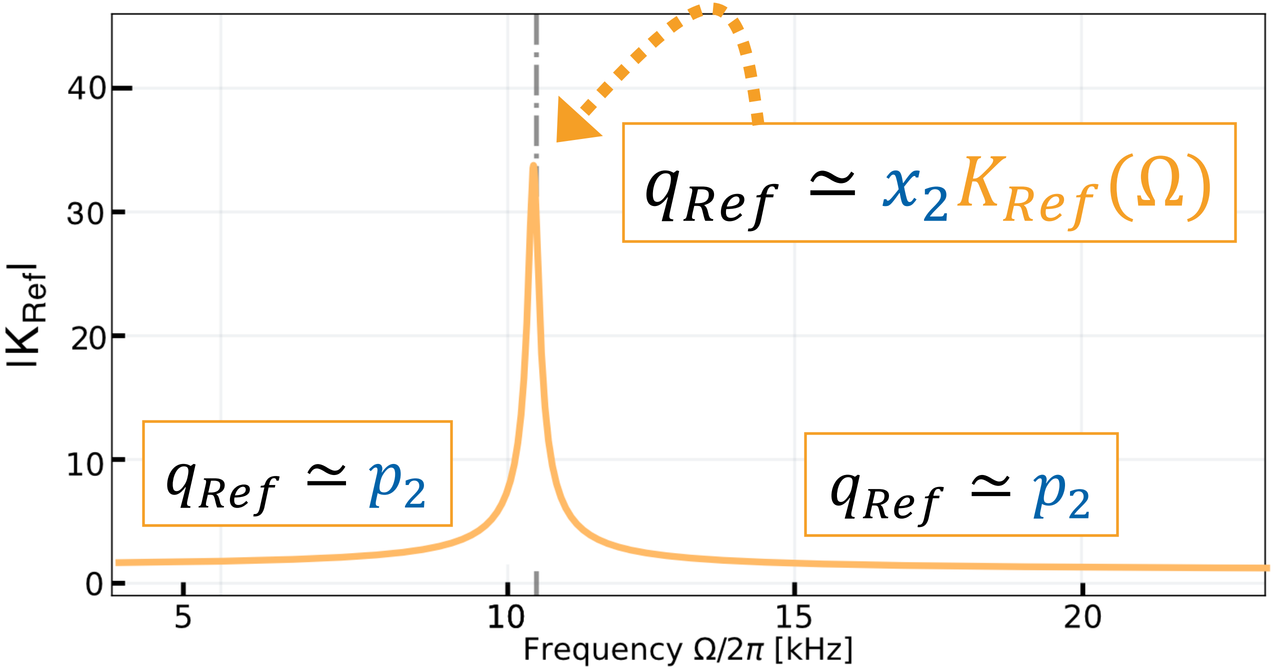
How did we demonstrate it?

UNIVERSITY OF COPENHAGEN

How did we demonstrate it?

One-axis twisting on the idler arm

$$q_{Ref} = p_2 + x_2 K_{Ref}(\Omega)$$



How did we demonstrate it?

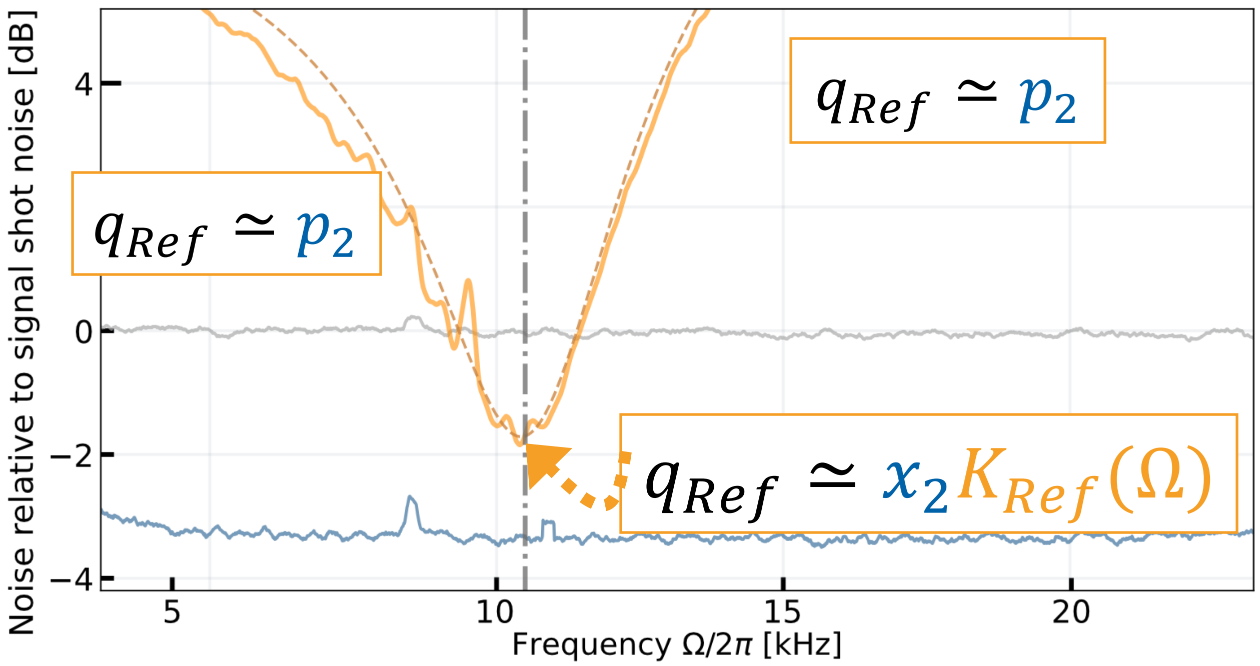
$\Delta(x_1 - x_2)^2 \rightarrow 0$

$\Delta(p_1 + p_2)^2 \rightarrow 0$

One-axis twisting on the idler arm

$$q_{Ref} = p_2 + x_2 K_{Ref}(\Omega)$$

$$q_1 = x_1$$



UNIVERSITY OF COPENHAGEN

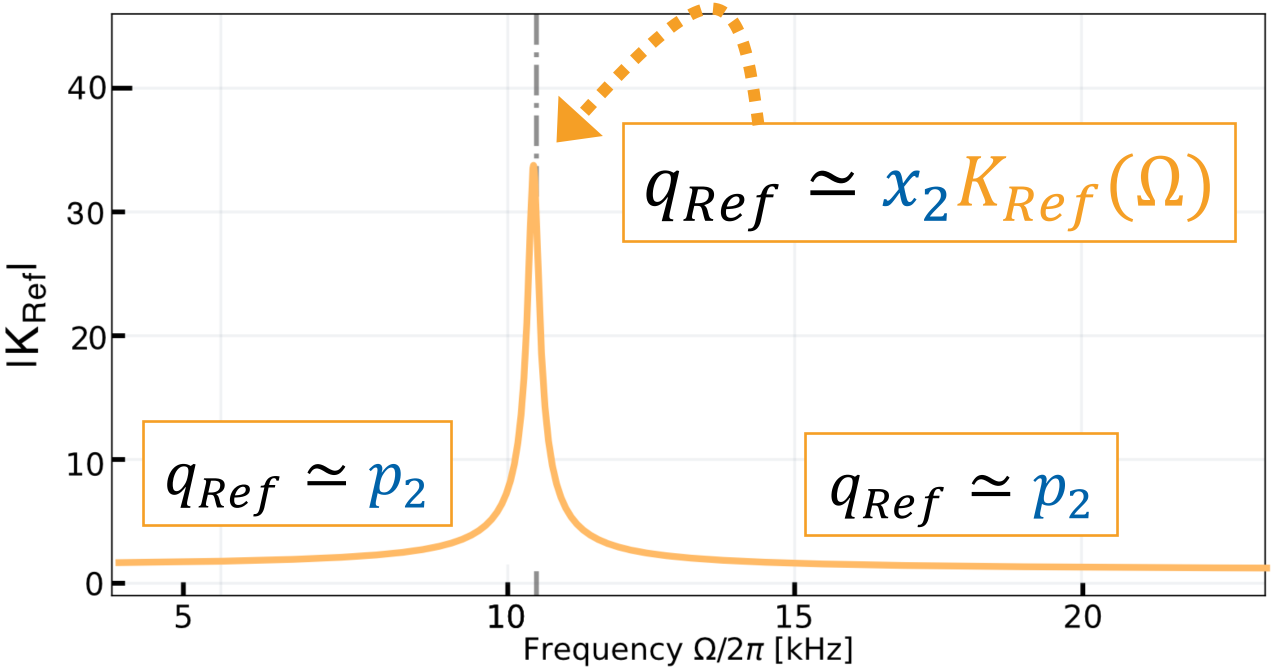
How did we demonstrate it?

One-axis twisting on the idler arm

$$q_{Ref} = p_2 + x_2 K_{Ref}(\Omega)$$

Phase Rotation

$$\Phi(\Omega) = \arctan[K_{Ref}(\Omega)]$$



$$q_{Ref}(\Omega) = N\,(\,p_2 \cos(\Phi(\Omega)) + x_2 \sin(\Phi(\Omega))\,)$$

$$\Delta(x_1 - x_2)^2 \to 0$$

$$\Delta(p_1 + p_2)^2 \to 0$$

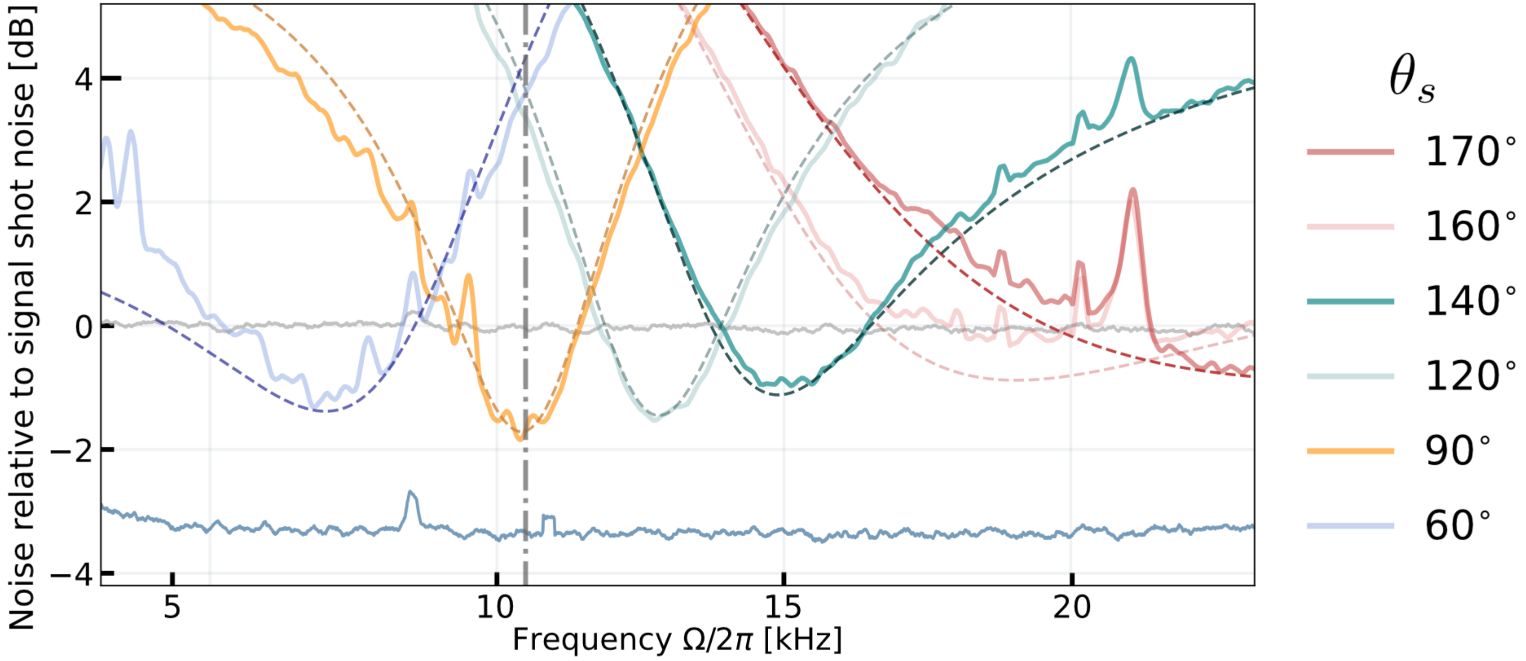
How did we demonstrate it?

One-axis twisting on the idler arm

$$q_{Ref} = p_2 + x_2 K_{Ref}(\Omega)$$

Phase Rotation

$$\Phi(\Omega) = \arctan[K_{Ref}(\Omega)]$$



$$q_1 = \sin(\theta_s) x_1 + \cos(\theta_s)\, p_1$$

$$q_{Ref}(\Omega) = N(\, p_2 \cos(\Phi(\Omega)) + x_2 \sin(\Phi(\Omega))\,)$$

How did we demonstrate it?

$$\Delta(x_1 - x_2)^2 \to 0$$

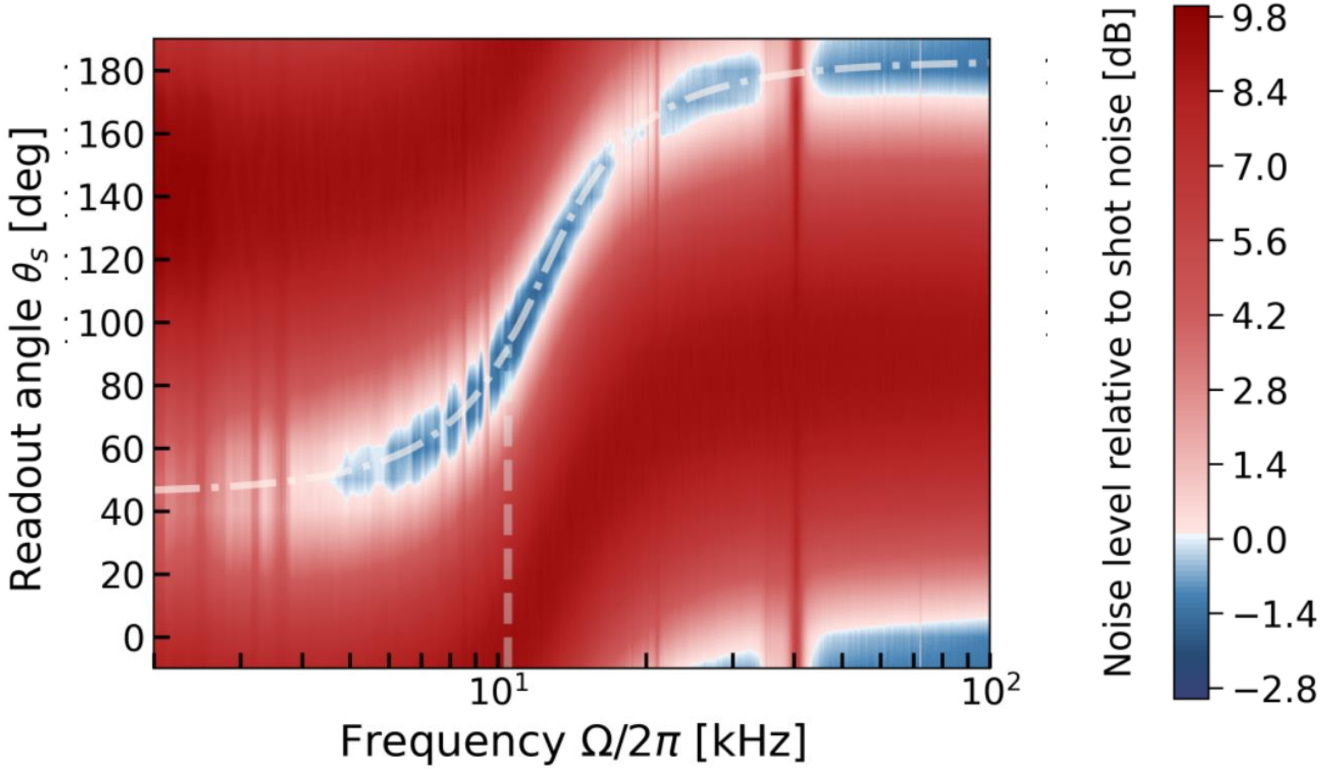
$$\Delta(p_1 + p_2)^2 \to 0$$

One-axis twisting on the idler arm

$$q_{Ref} = p_2 + x_2 K_{Ref}(\Omega)$$

Phase Rotation

$$\Phi(\Omega) = \arctan[K_{Ref}(\Omega)]$$



$$q_1 = \sin(\theta_s) x_1 + \cos(\theta_s)\, p_1$$

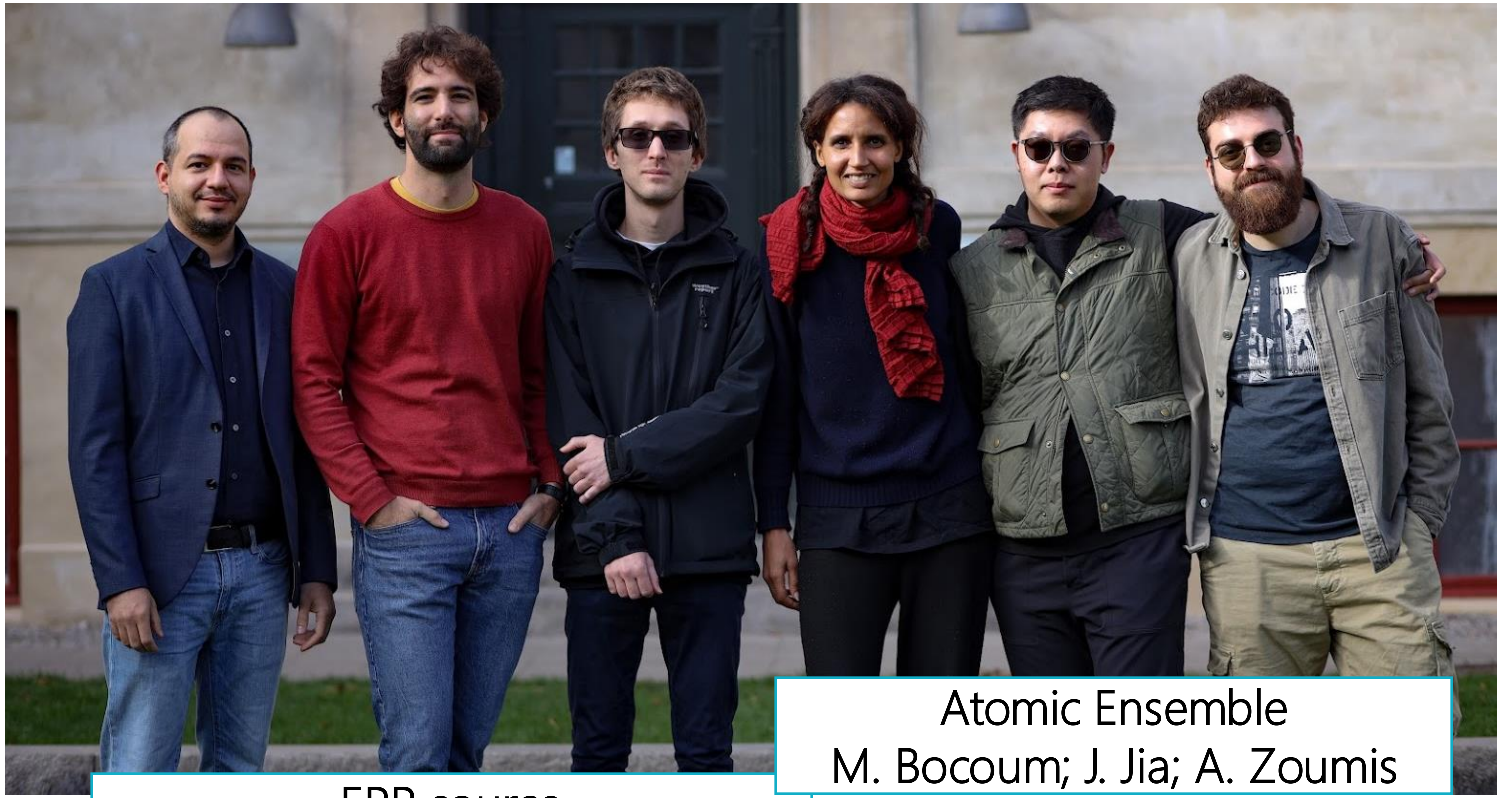
$$q_{Ref}(\Omega) = N(\, p_2 \cos(\Phi(\Omega)) + x_2 \sin(\Phi(\Omega))\,)$$

The Team
Niels Bohr Institute

UNIVERSITY OF COPENHAGEN

Prof. Polzik

Prof. Zeuthen



Atomic Ensemble
M. Bocoum; J. Jia; A. Zoumis

EPR source
T.B. Brasil; A. Grimaldi; V. Novikov;