University of Copenhagen

Niels Bohr Institute

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 **64**, 042006, **2001**

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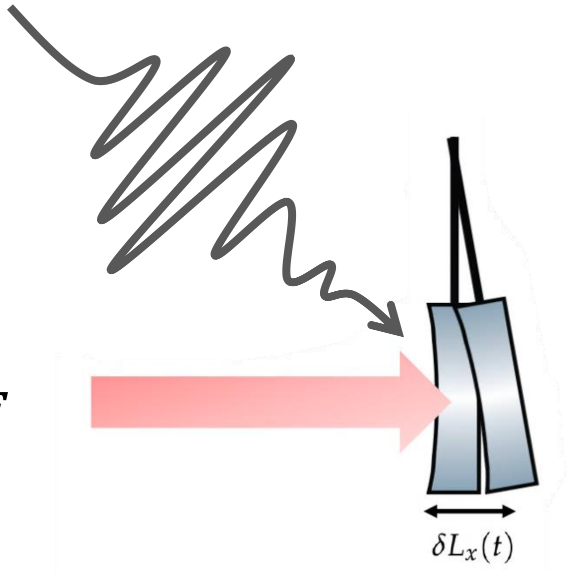
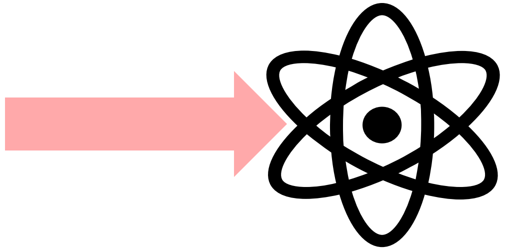
Quantum Back-Action Evasion



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

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



Change reference to Nature photonics paper

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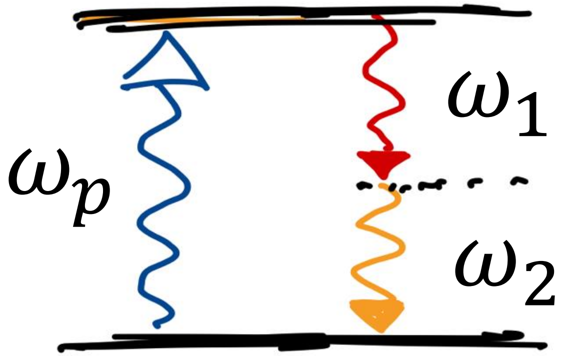
Quantum Back-Action Evasion

Connection

Continuous variable entangled twin beams.

Non-linear crystal.



Parametric
down conversion

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

Amplitude and phase are correlated

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

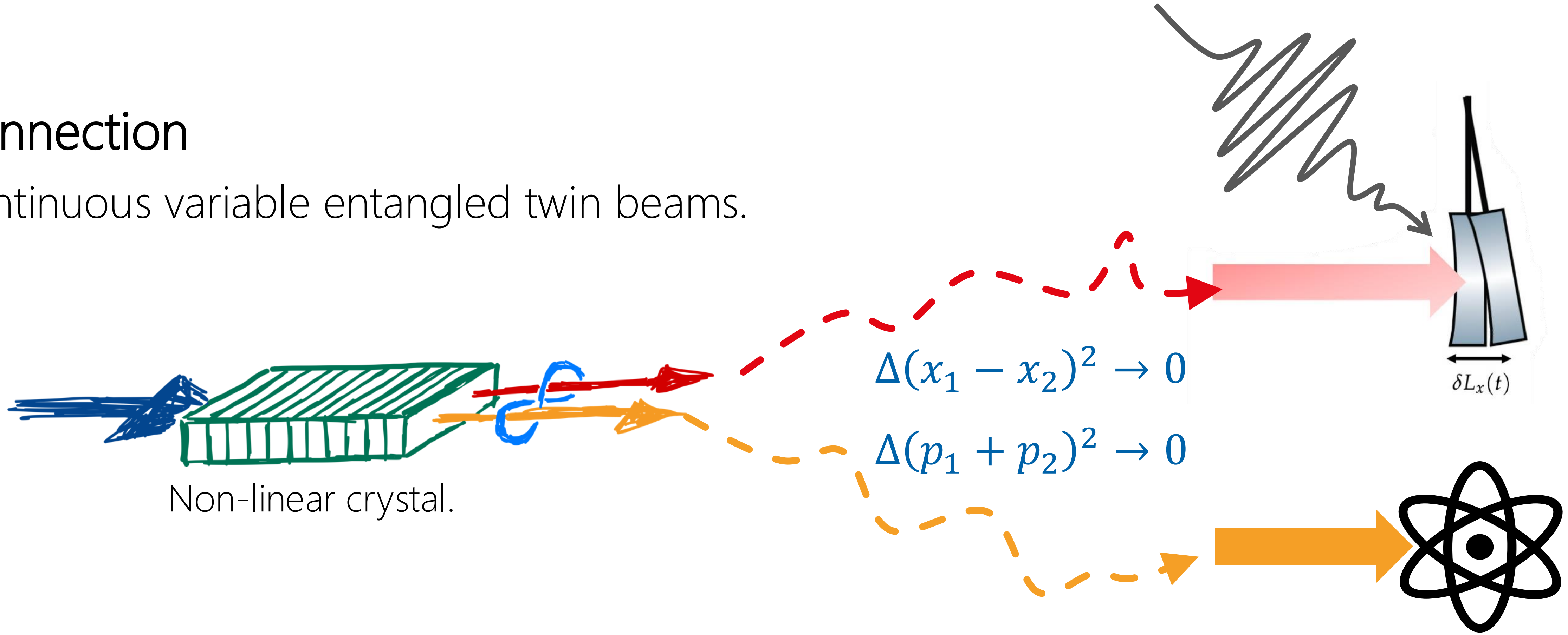
$$\Delta(p_1 + p_2)^2 \rightarrow 0$$

Change reference to Nature photonics paper

Quantum Back-Action Evasion

Connection

Continuous variable entangled twin beams.



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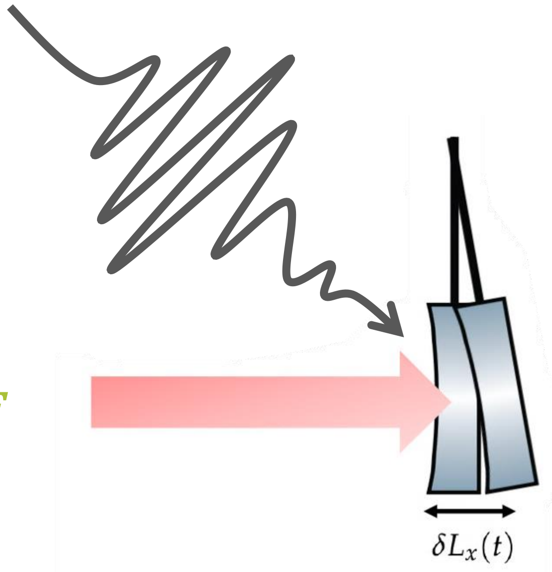
Quantum Back-Action Evasion

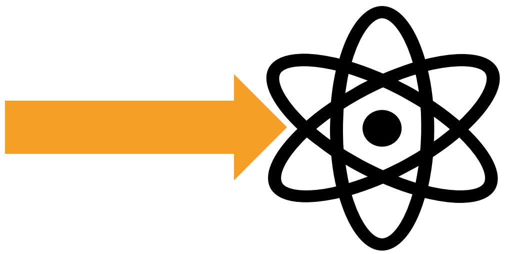


Quantum limited detector $\quad q_{ITF} = \tilde{h}\sqrt{K_{ITF}} + p_1 + x_1 K_{ITF}$

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

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

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



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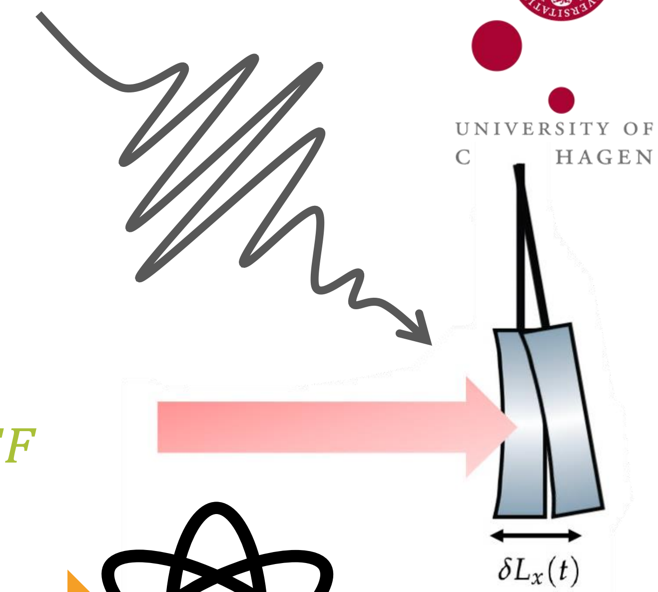

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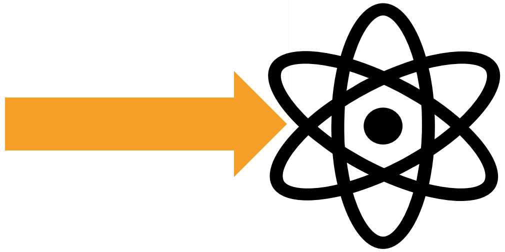


$$\Delta(x_1 - x_2)^2 \to 0$$

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

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

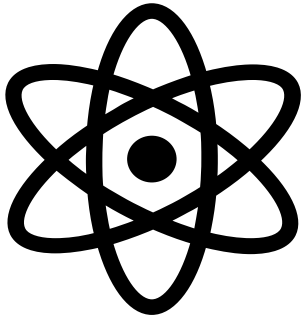
$$q_{ITF} + q_{ITF} = \tilde{h}\sqrt{K_{ITF}} + p_1 + x_1 K_{ITF}(\Omega) + p_2 + x_2 K_{Ref}(\Omega)$$

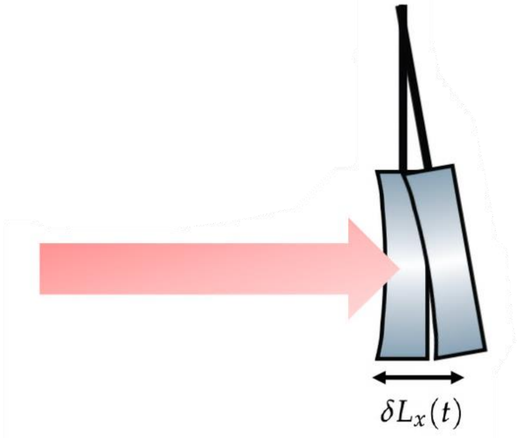
Change reference to Eguene/Emil papers

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

Change reference to Eguene/Emil papers

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

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Quantum Back-Action Evasion

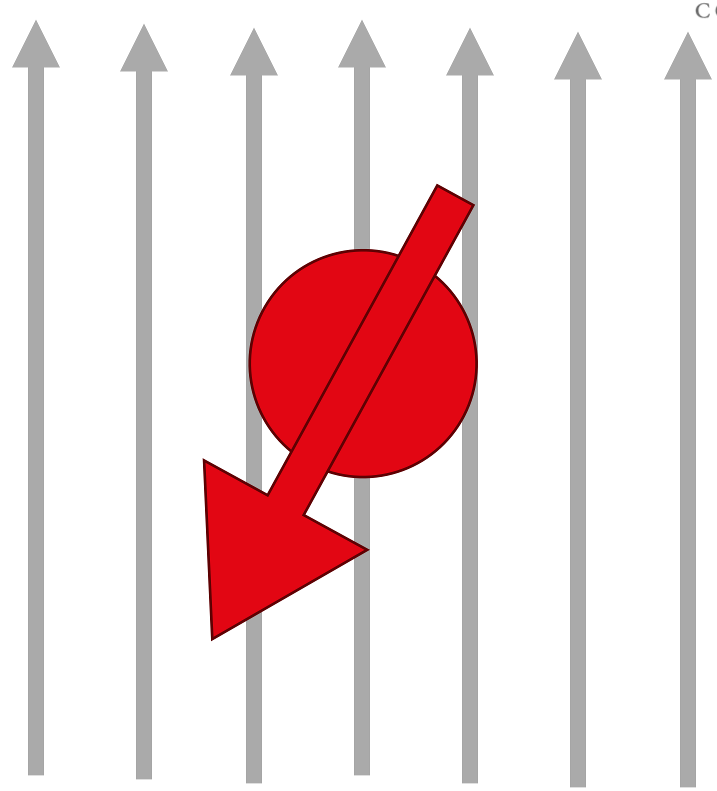
External (Quantum) Reference

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

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

Effective

Negative Mass Oscillator



Magnetic Field

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

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Quantum Back-Action Evasion

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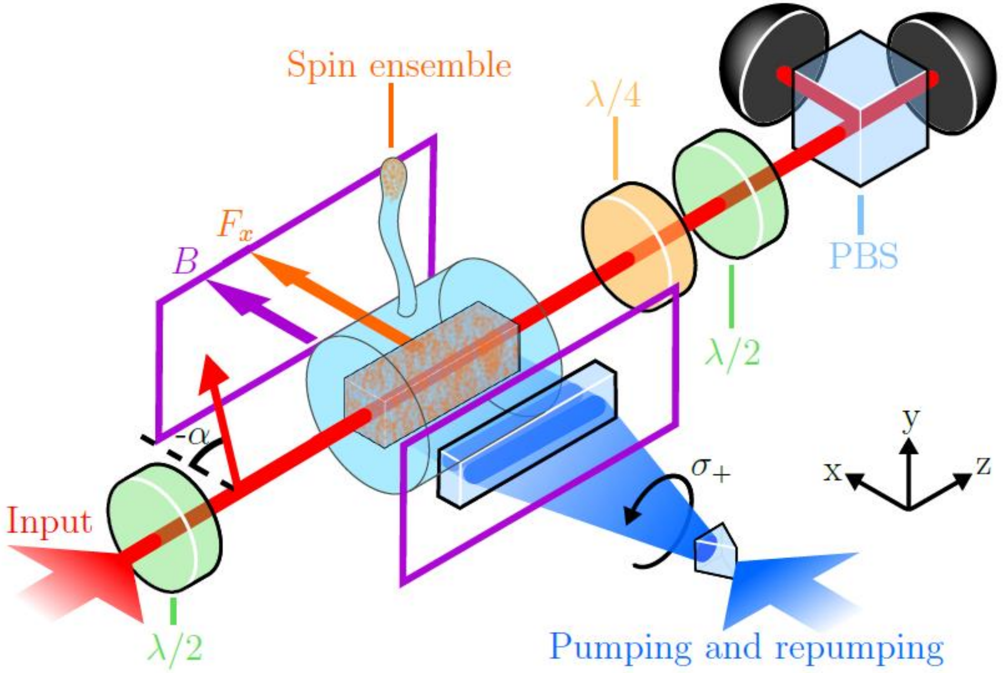
$$K_{Ref}(\Omega) \propto \frac{-P_{in}}{\Omega^2(\Omega^2+\gamma^2)}$$

Effective

Negative Mass Oscillator



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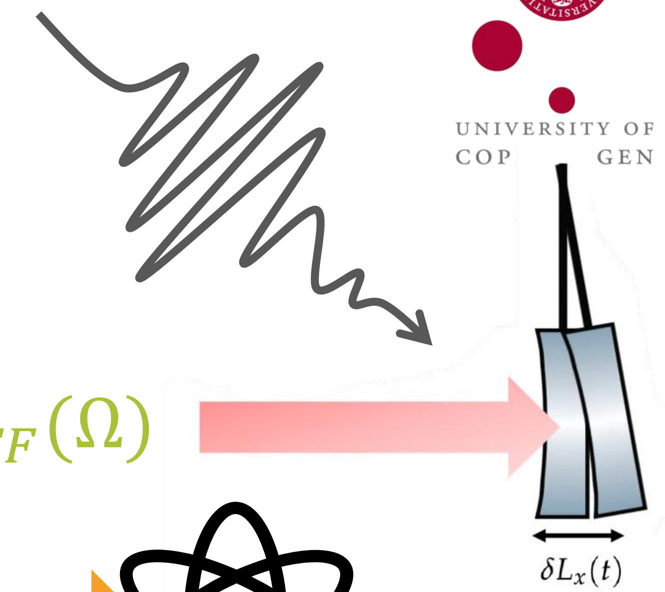
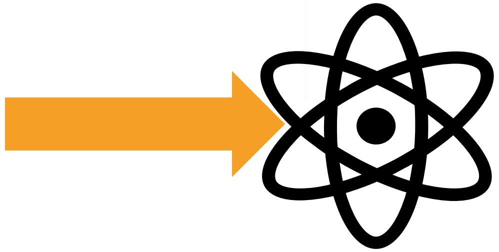
Quantum Back-Action Evasion



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

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



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

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

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

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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?

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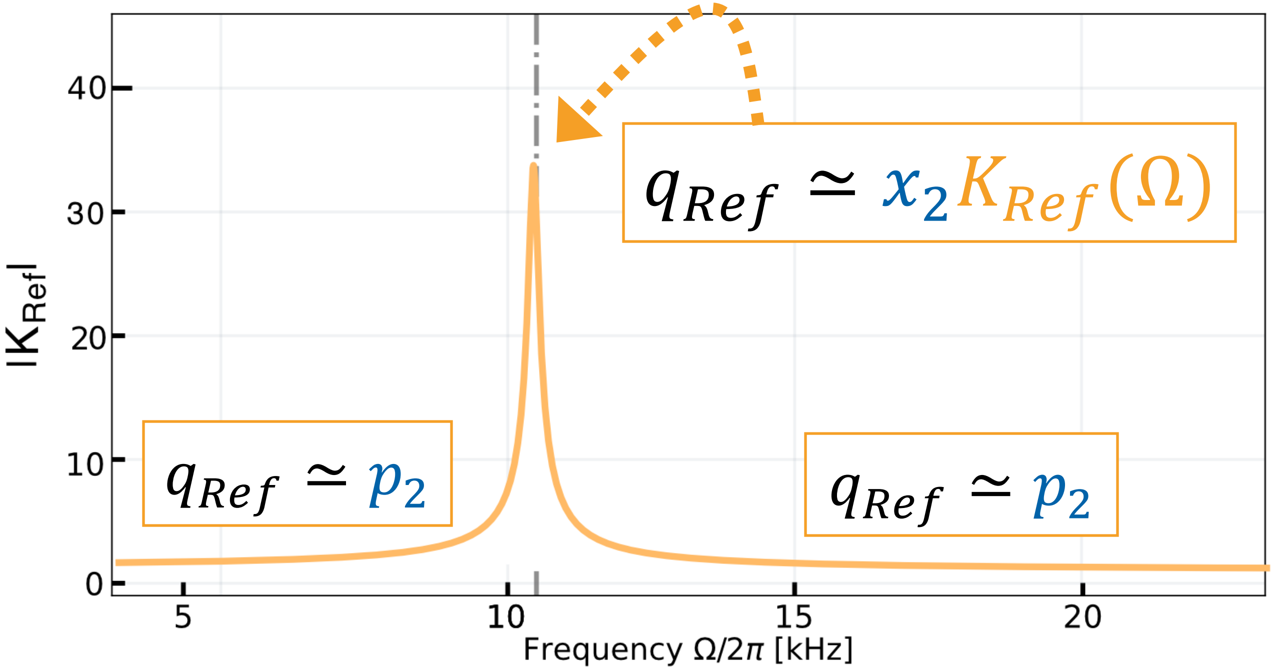
One-axis twisting on the idler arm

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



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

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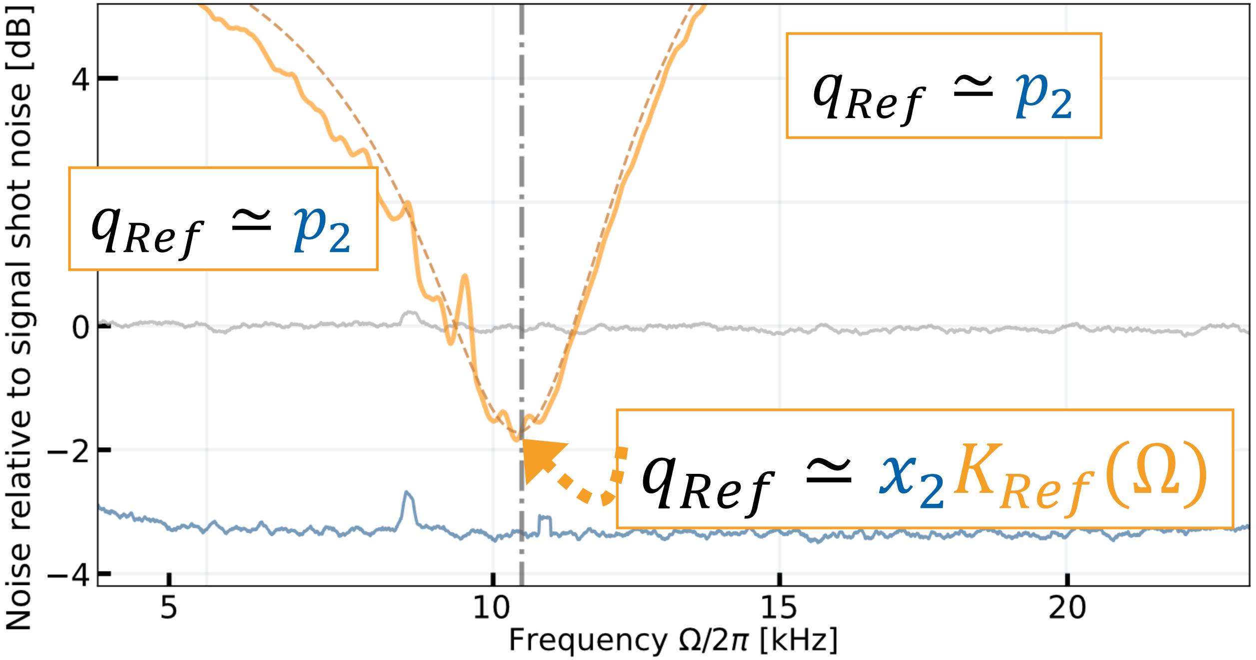
How did we demonstrate it?

One-axis twisting on the idler arm

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

$$q_1 = x_1$$



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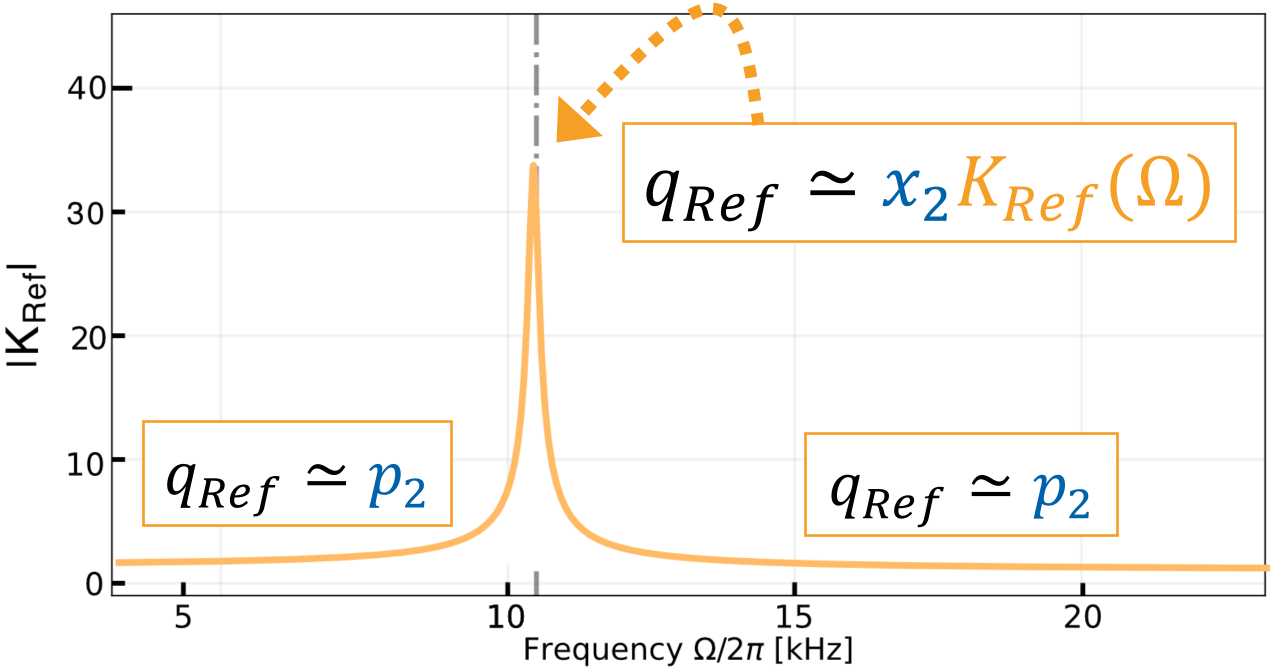
How did we demonstrate it?

One-axis twisting on the idler arm

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

Phase Rotation

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



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

How did we demonstrate it?

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

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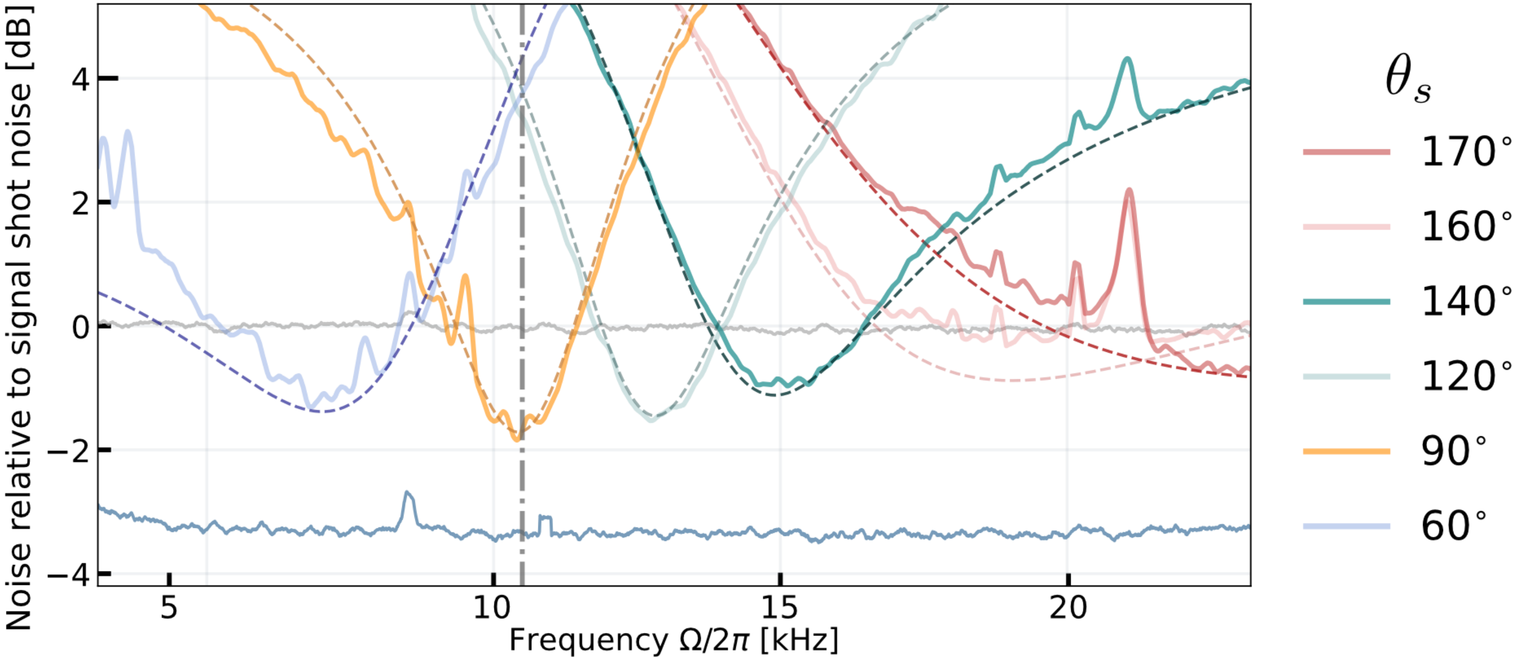

$$q_1 = \sin(\theta_s) x_1 + \cos(\theta_s)\, p_1$$

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

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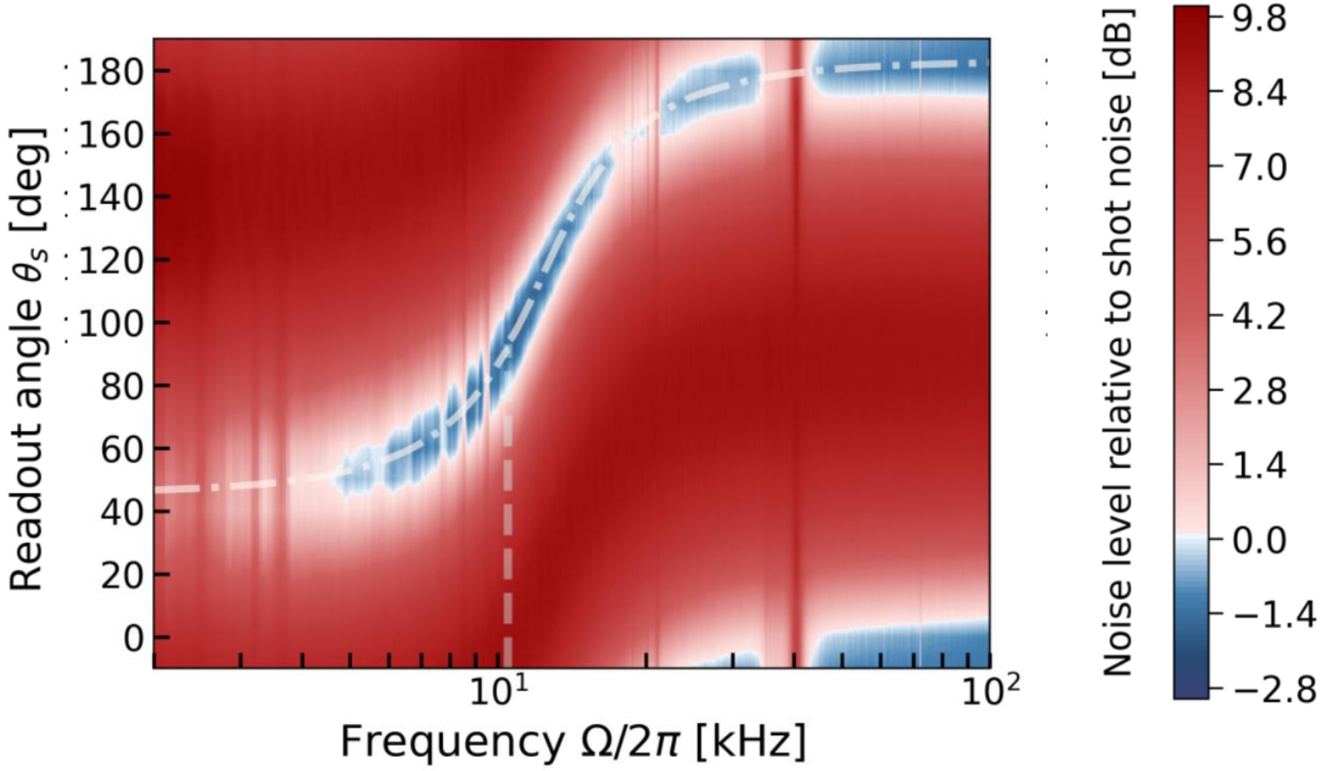

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The Team
Niels Bohr Institute

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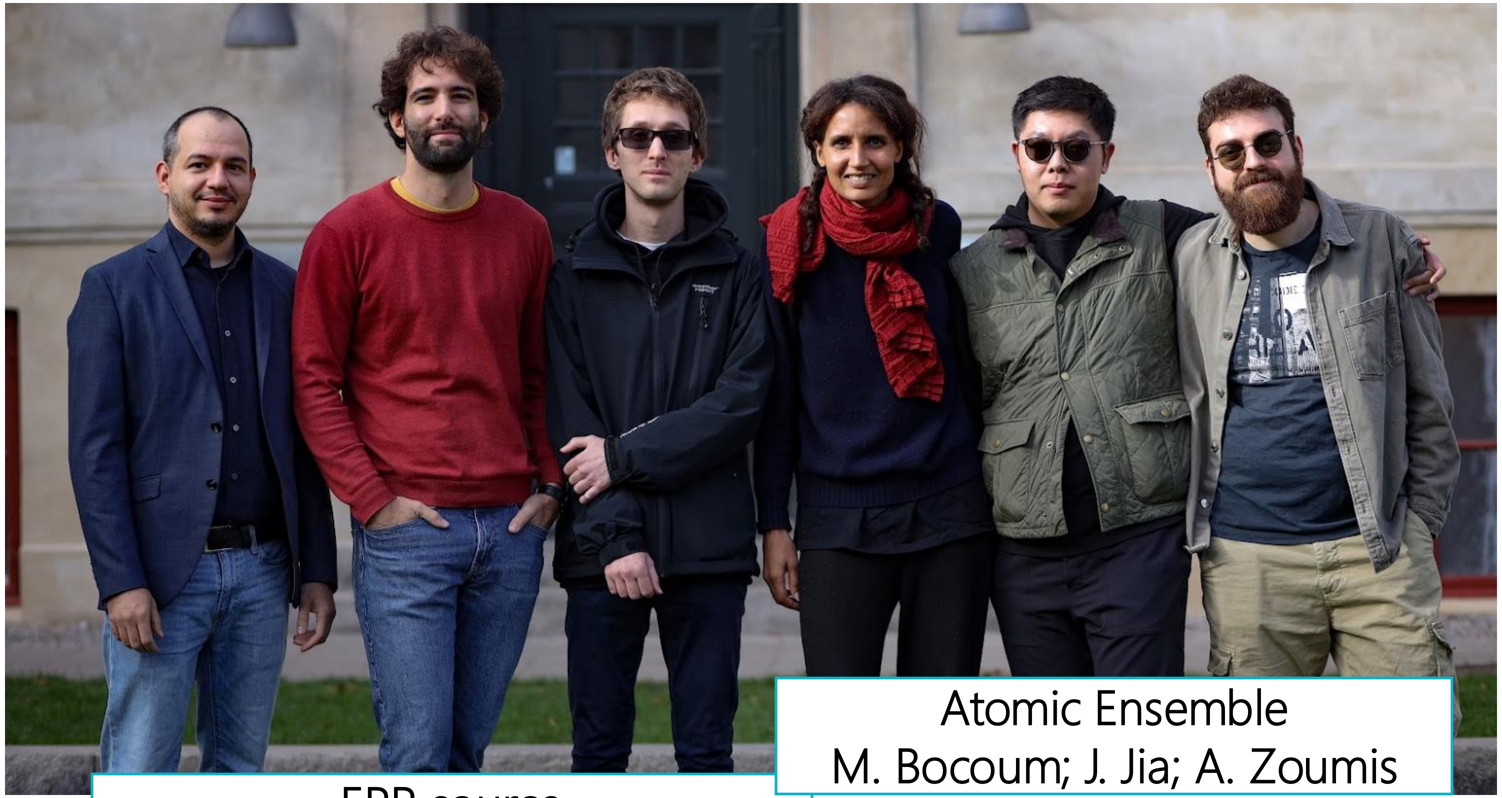
Prof. Polzik

Prof. Zeuthen



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

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