Quantum enhanced interferometry with squeezed light

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Take out messages

Goal of our study:

Improving the precision of multiphoton absorption measurements by using quantum state of light (squeezed light)

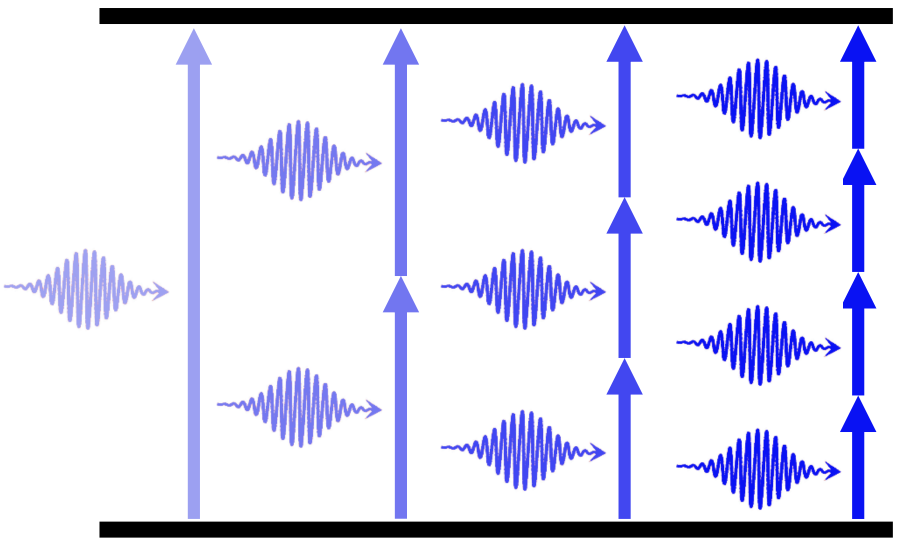
Results:

- Significant enhancement of the precision of multiphoton cross-section estimation
- Robustness of enhanced measurement precision against experimental imperfections
- Requiring nonlinear interferometers as platforms to achieve the enhancement

Multiphoton absorption

Definition: Simultaneous absorption of several photons by the sample

Features and applications:
- Large penetration depths
- Nonlinear dependence on the beam profile
- Surpassing single-photon diffraction limit
- Pushing resolution of optical microscopy to molecular scales



Limitation: Inherently weak light-matter interactions

Solutions:

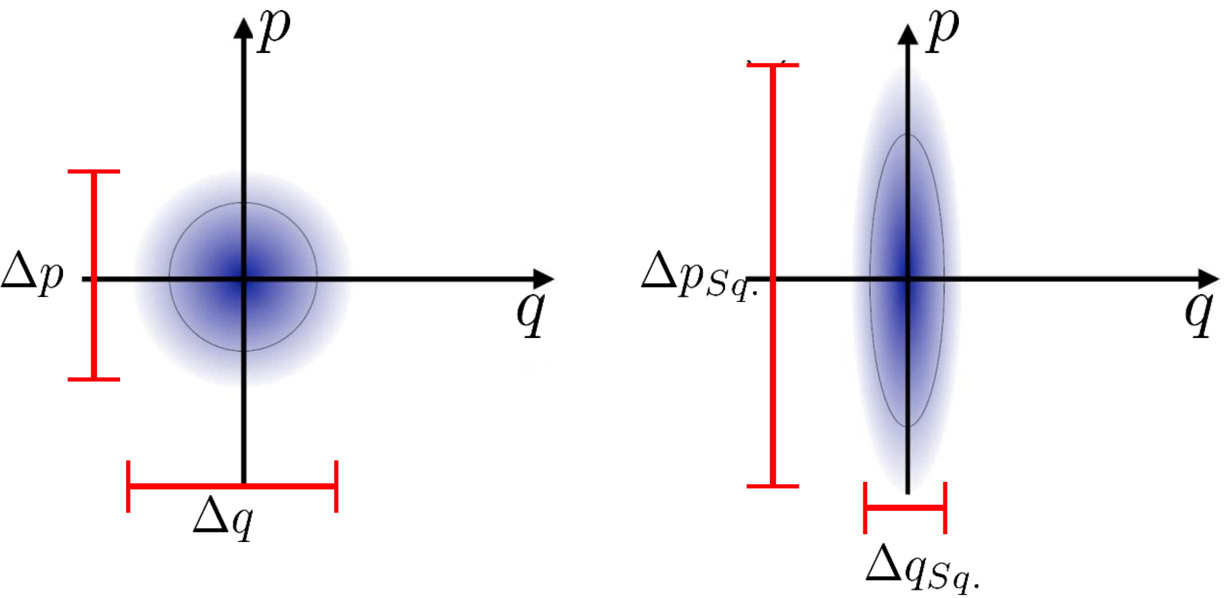
I. Utilization of strong ultrafast laser

II. Reduction of the shot-noise level by using quantum light fields

M. Rumi et al., Adv. Opt. Photonics 2, 451 (2010).
T. A. Klar et al., Proc. Natl. Acad. Sci. U.S.A. 97, 8206 (2000).
S. Bretschneider et al., Phys. Rev. Lett. 98, 218103 (2007).
S. J. Weishäupl et al., J. Mater. Chem. C 10, 6912 (2022).

Squeezed light

Definition: A quantum light with reduced statistical noise in one variable of a quantum field



$$\Delta q_{Sq.} < \Delta q$$

$$\Delta p_{Sq.} > \Delta p$$

Applications:

- Phase estimation
- Small displacement measurement
- Gravitational wave detection

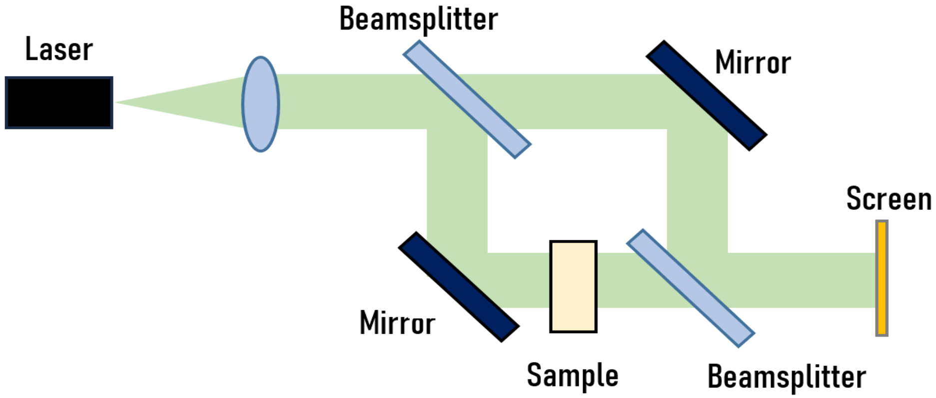
Production: Via down conversion processes

Engineered: Inside a nonlinear interferometer

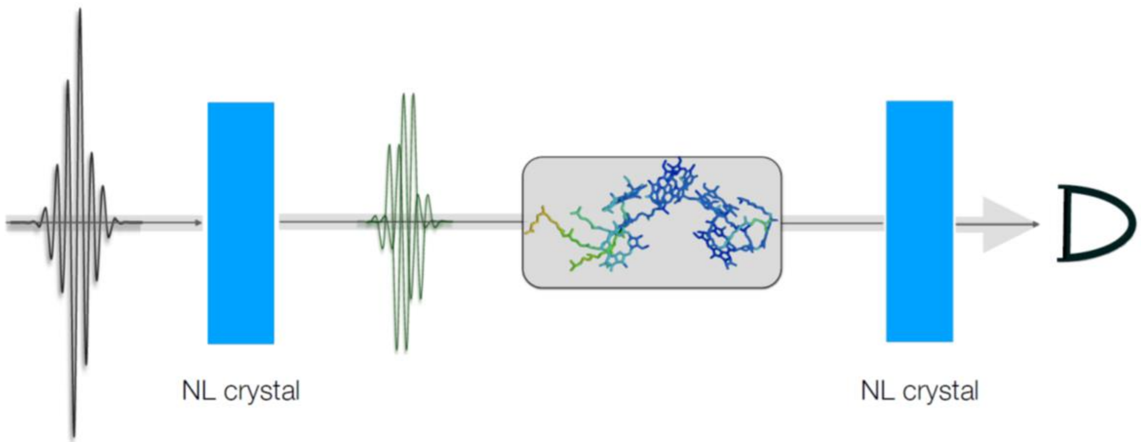
R. Schnabel, Physics Reports 684, 51 (2017).
SP, C. Muñoz, M. Chekhova, F. Schlawin, Phys. Rev. Lett. 130, 203604 (2023).

Nonlinear Interferometer

Linear interferometer: Known as Mach-Zendher interferometer made out of two beam splitters

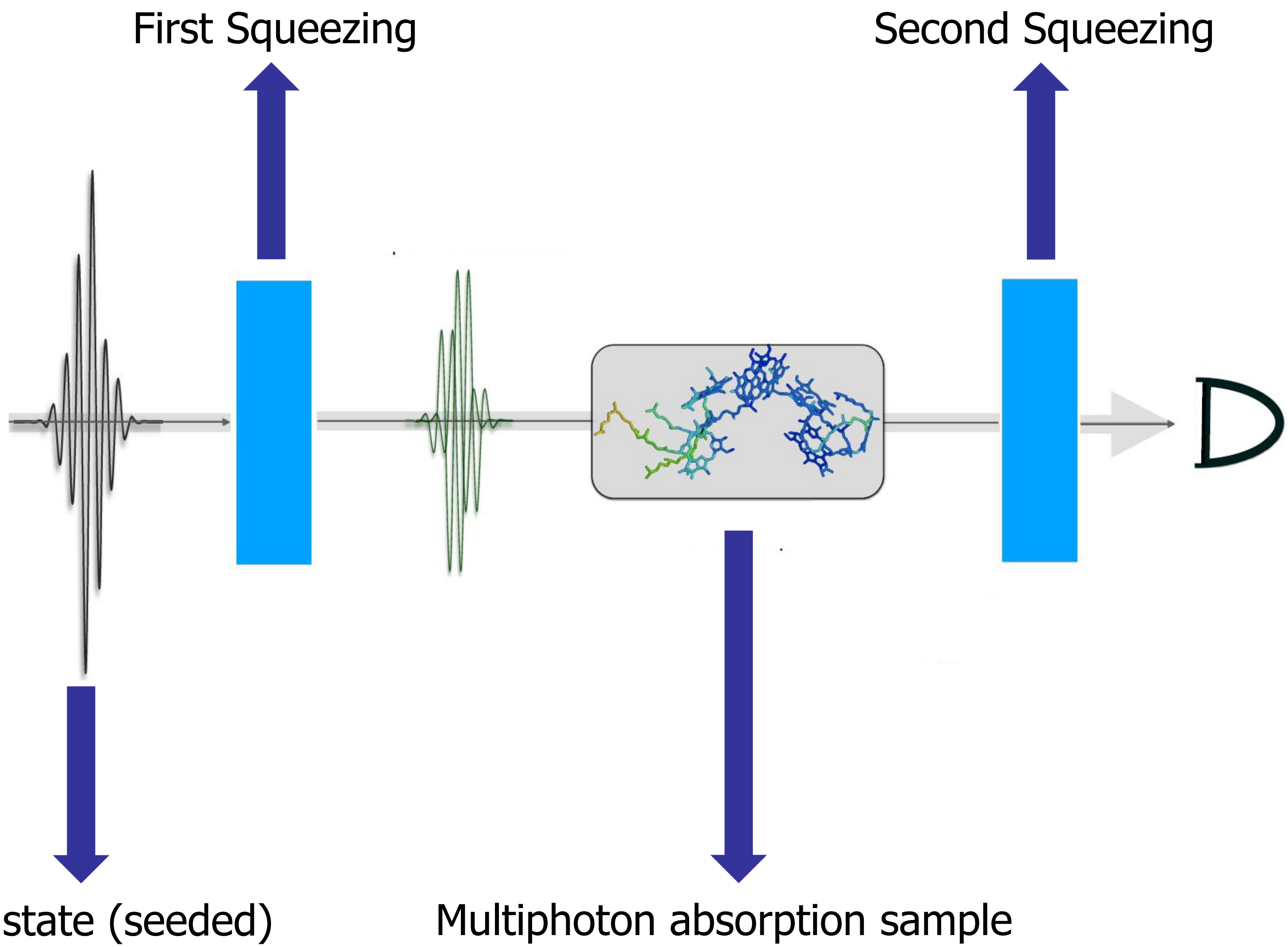


Nonlinear interferometer: Known as SU(1,1) interferometer made out of two nonlinear crystals



M. V. Chekhova and Z. Y. Ou, Adv. Opt. Photon. 8, 104 (2016).
C. M. Caves, Adv. Quant. Tech. 3, 1900138 (2020).

Setup



SP, C. Muñoz, M. Chekhova, F. Schlawin Phy. Rev. Lett. 130, 203604 (2023).

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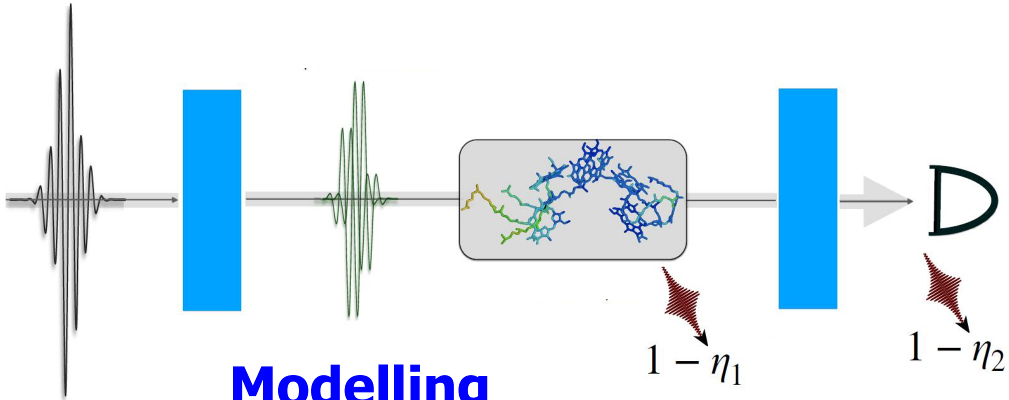
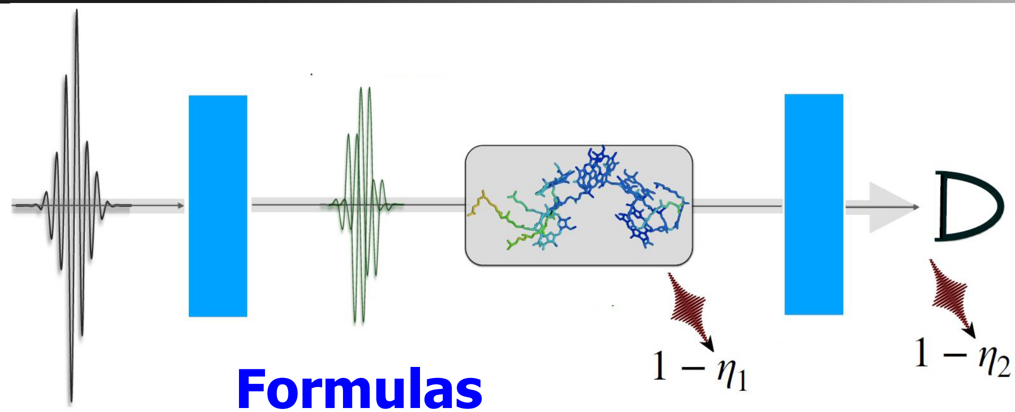


Parameters	Modelling
Seeding	Displacement operator (laser field)
Squeezing	Bogoliubov transformation
M-photon absorption	Markovian Lindblad master equation (open systems)
Single-photon loss	Beam splitter transformation
Observable	Photon number
Sensitivity	Via error-propagation

Setup



Parameters	Formulas
Seeding	$D^{\dagger}(\alpha)\rho D(\alpha)$
Squeezing	$e^{\mathcal{L}_{OPA\ k}}\rho \equiv U_{OPA\ k}\rho U^{\dagger}_{OPA\ k}$
M-photon absorption	$\frac{d}{dt}\rho = \frac{\gamma_{mPA}}{m}\left(2a^{m}\rho a^{\dagger m} - a^{\dagger m}a^{m}\rho - \rho a^{\dagger m}a^{m}\right)$
Single-photon loss	$e^{\mathcal{L}_{loss\ k}}\rho = U_{loss\ k}\rho U^{\dagger}_{loss\ k}$
Observable	$\hat{n} = a^{\dagger}a$
Sensitivity	$\Delta\varepsilon^2_{\hat{n}} = \frac{\mathrm{Var}\ (\hat{n})}{\left\lvert\frac{\partial\langle\hat{n}\rangle}{\partial\varepsilon}\right\rvert^2}$ $(\varepsilon \equiv t\gamma_{mPA} = n\ell\sigma)$

Setup

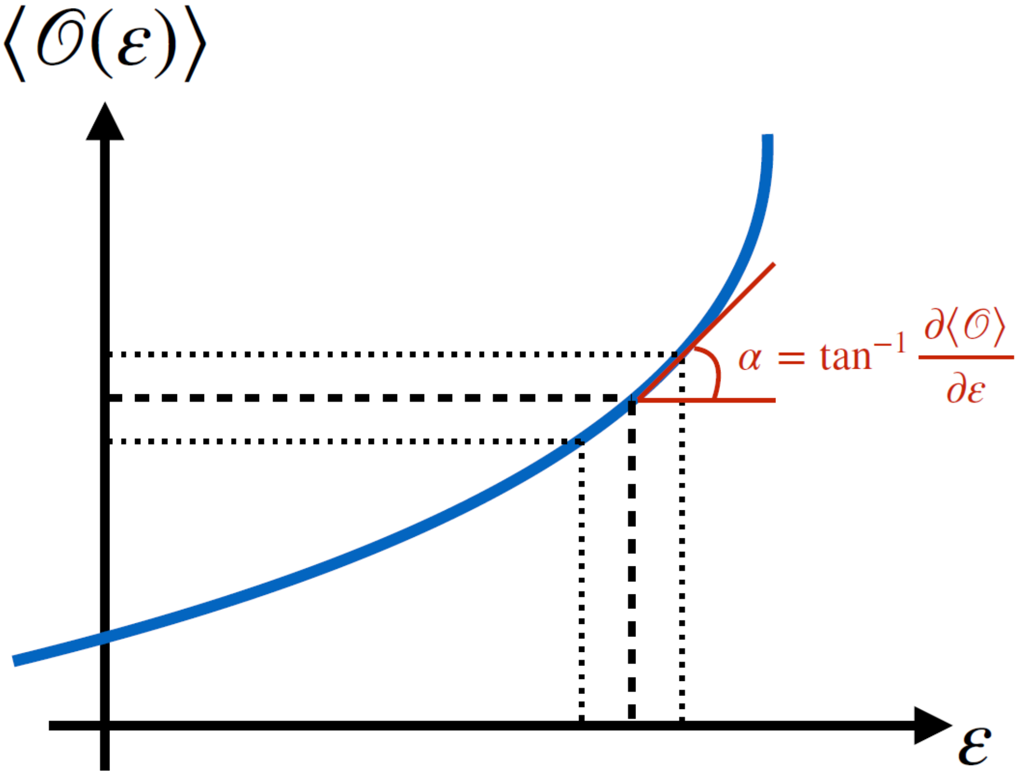
Sensitivity: Uncertainty in measuring a quantity (ε)

Measure the quantity with some observable:

$$< \mathcal{O} >=< \mathcal{O}(\varepsilon) >$$

The uncertainty is given by:

$$\Delta\varepsilon_{\mathcal{O}}^2 = \frac{\text{Var}\ (\mathcal{O})}{\left|\frac{\partial\langle\mathcal{O}\rangle}{\partial\varepsilon}\right|^2}$$



Setup

Goal of our study:

Improving the precision of multiphoton absorption measurements by using quantum state of light (squeezed light)

↓

The optimum sensitivity = Minimization of the uncertainty

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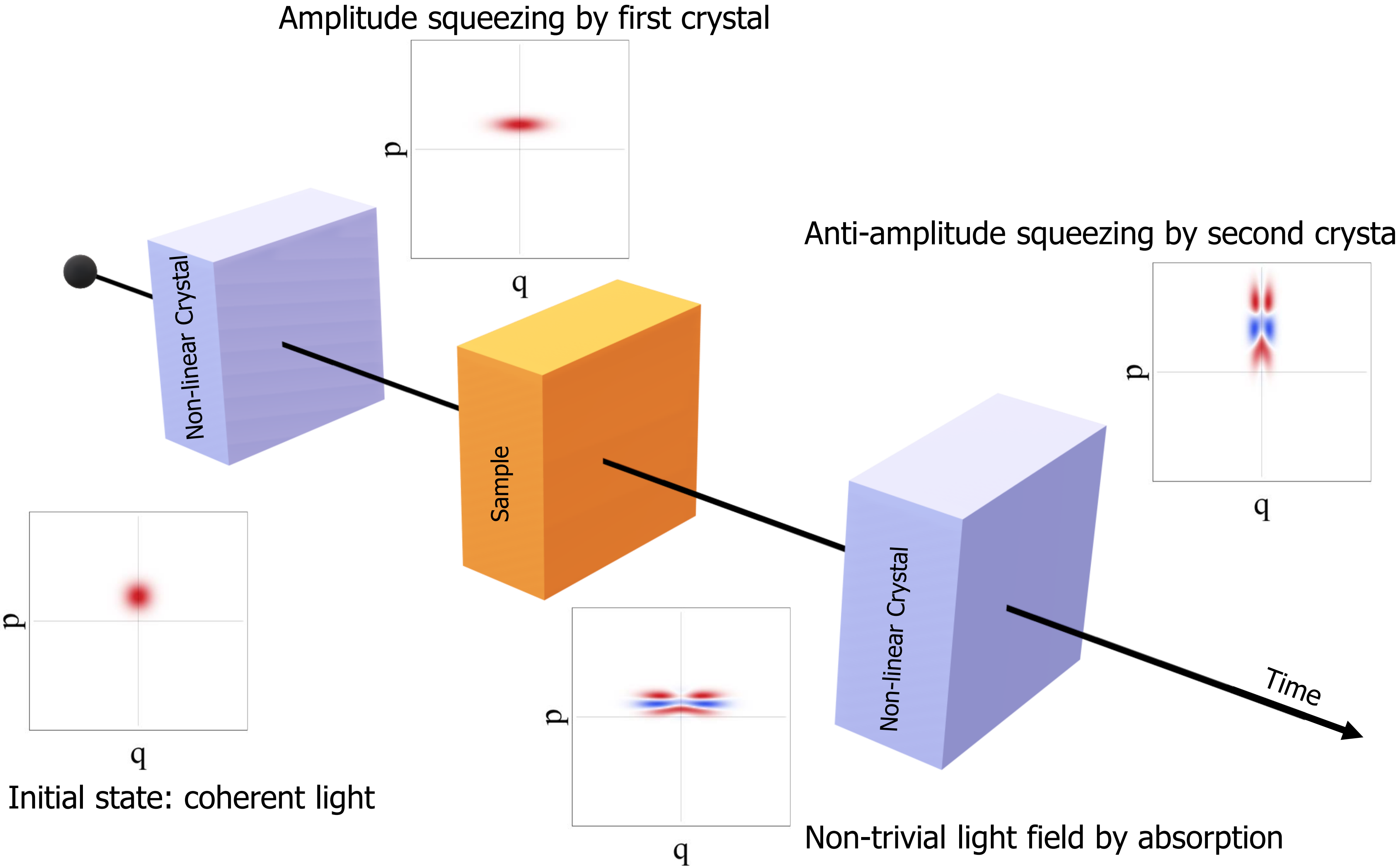
- Optimization of parameters
- Characterization of light fields
- Identification of parameter regimes
- Exploring the effects of error sources known as internal and external losses

Optimization

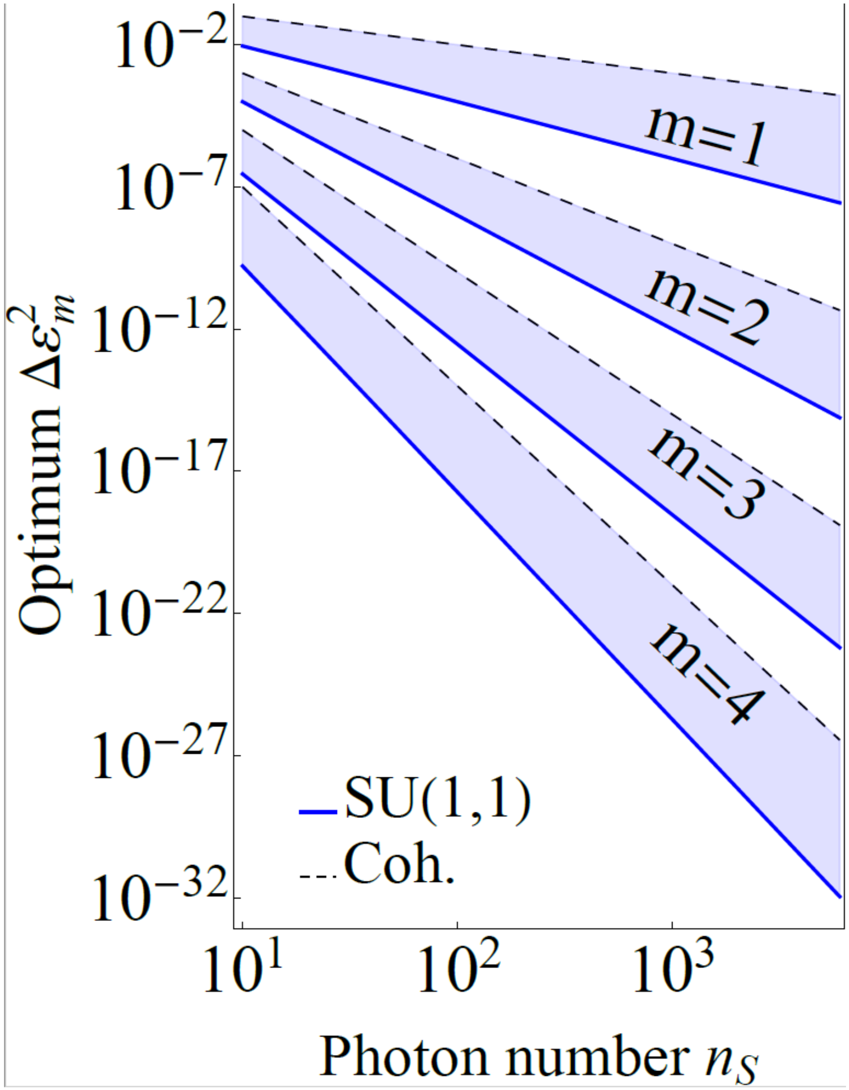


Optimization

Linear (coh.) vs SU(1,1) interferometer:

- Significant enhancement in sensitivity
- Superior scaling (one order of magnetite better)

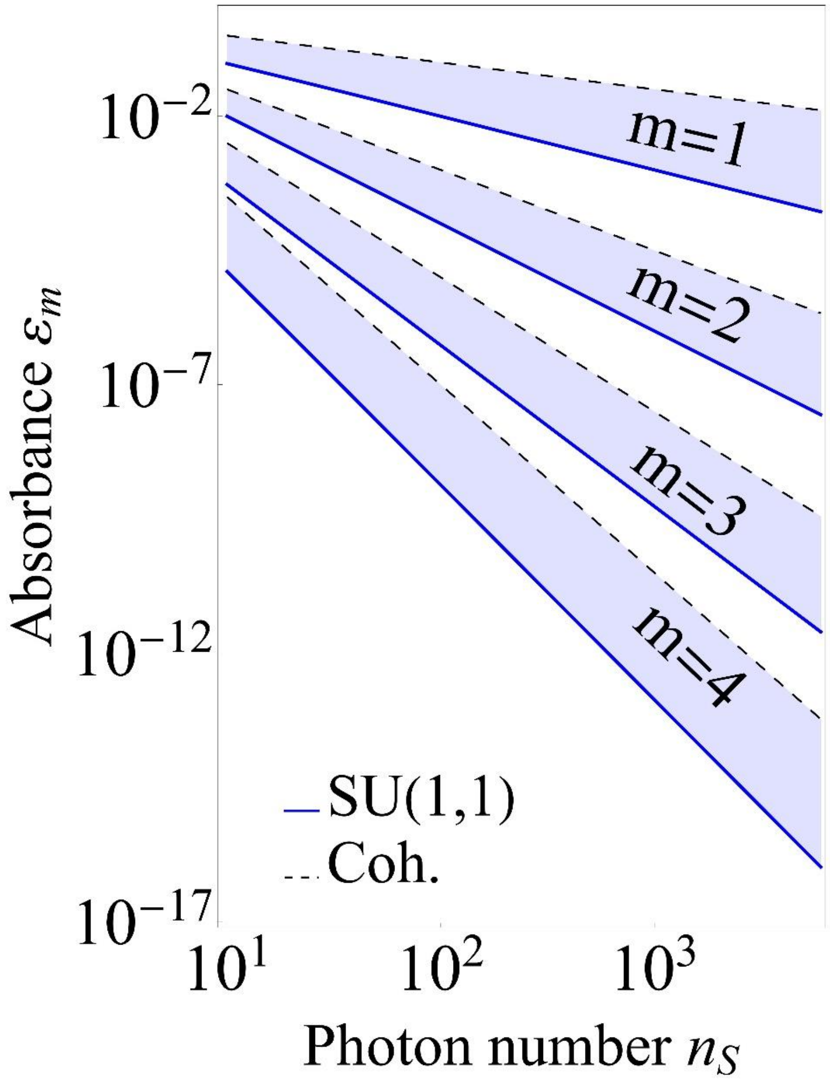
SU(1,1)	Coherent
$\Delta\varepsilon_m^2 \propto \frac{1}{n_S^{2m}}$	$\Delta\varepsilon_m^2 \propto \frac{1}{n_S^{2m-1}}$



Optimization

Linear (coh.) vs SU(1,1) interferometer:

- Significant enhancement in sensitivity
- Superior scaling (one order of magnetite better)
- Detection of m-photon absorption signal at significantly lower photon number



Optimization

Linear (coh.) vs SU(1,1) interferometer:

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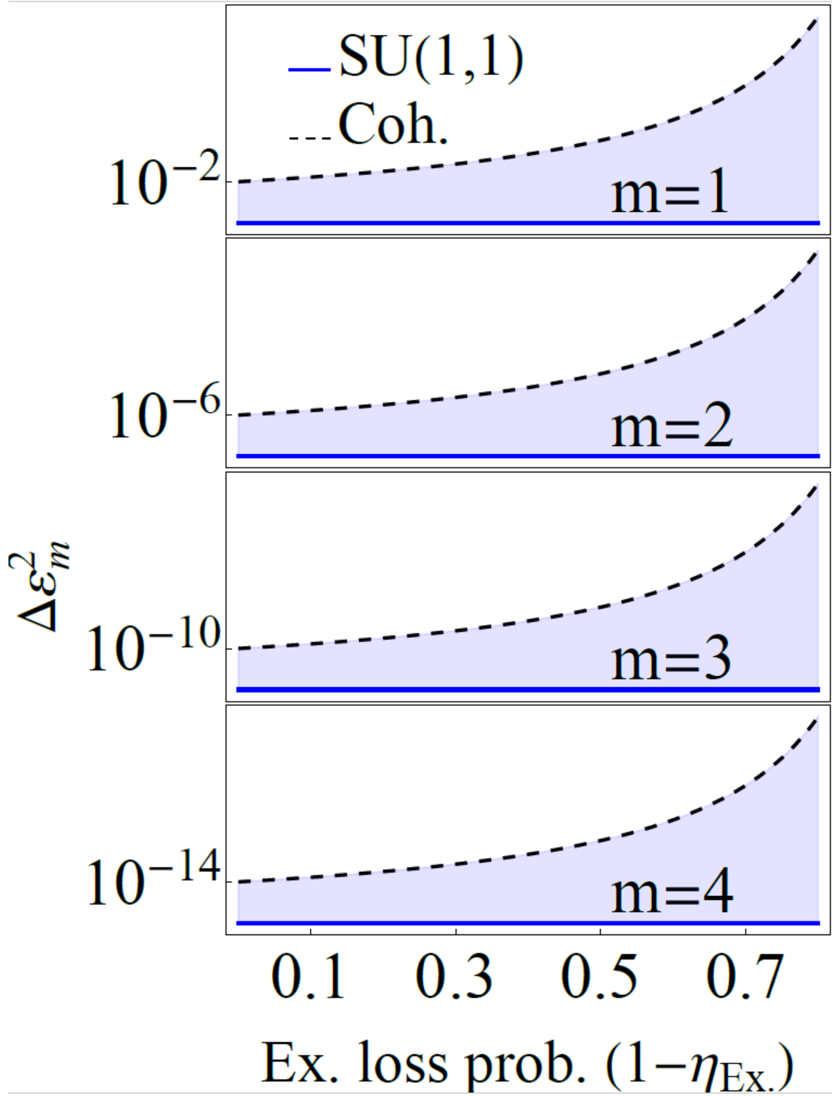
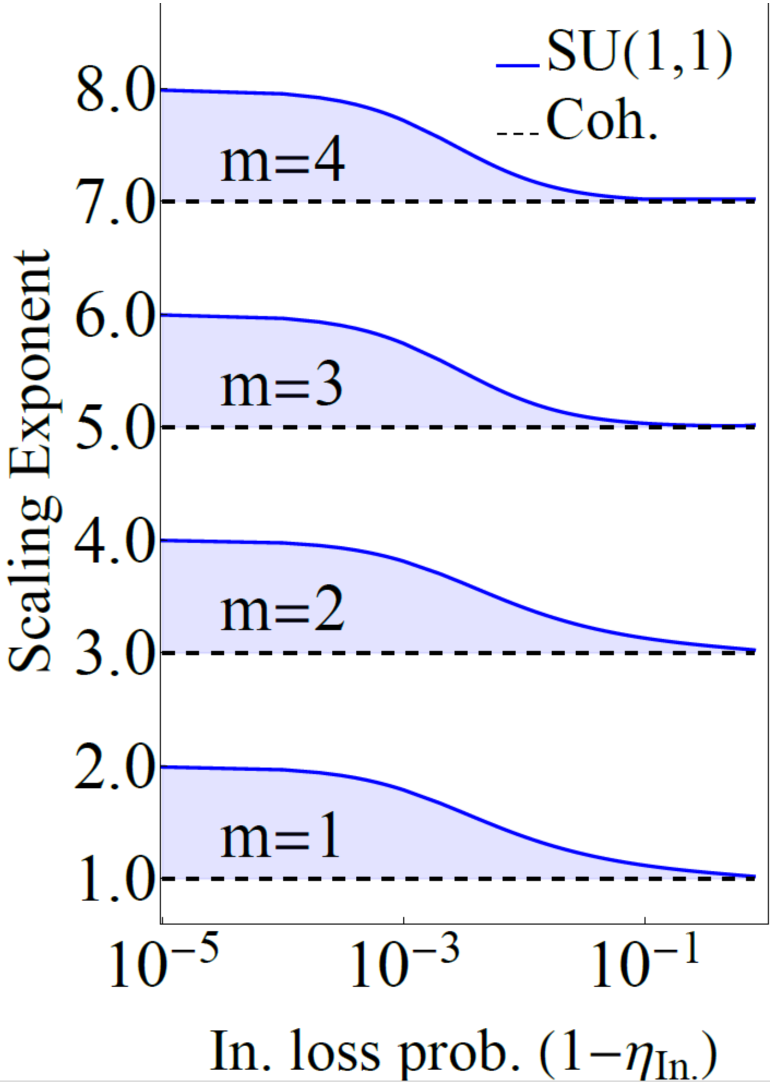
- Detection of m-photon absorption signal at significantly lower photon number
- External loss: Independent of it



Optimization

Linear (coh.) vs SU(1,1) interferometer:

- Significant enhancement in sensitivity
- Superior scaling (one order of magnetite better)
- Detection of m-photon absorption signal at significantly lower photon number
- External loss: Independent of it
- Internal loss: Scaling outperforms or equals to ideal linear interferometer



Summary

- Enhancement of the precision of multiphoton cross-section estimation in nonlinear interferometer (an order of magnitude compared to measurements by coherent light)

- Robustness of enhanced measurement precision against experimental imperfections

- Enhancement due to quantum light and optimal degree of squeezing created in the nonlinear interferometer

For more details, please see:

Phys. Rev. A 106, 043706 (2022).

Phys. Rev. Lett. 130, 203604 (2023).

Acknowledgment

CUI THE HAMBURG CENTRE FOR ULTRAFAST IMAGING

mpsd

Max-Planck-Institut für Struktur und Dynamik der Materie

Maria V. Chekhova

MPI Erlangen

Carlos S. Munoz

Universidad Autonoma Madrid

Frank Schlawin

CUI and *mpsd*

Thank you