Mitigation of back-scattered light by dual balanced-homodyne readout

Roman Schnabel

Institut für Laserphysik & Zentrum für Optische Quantentechnologien

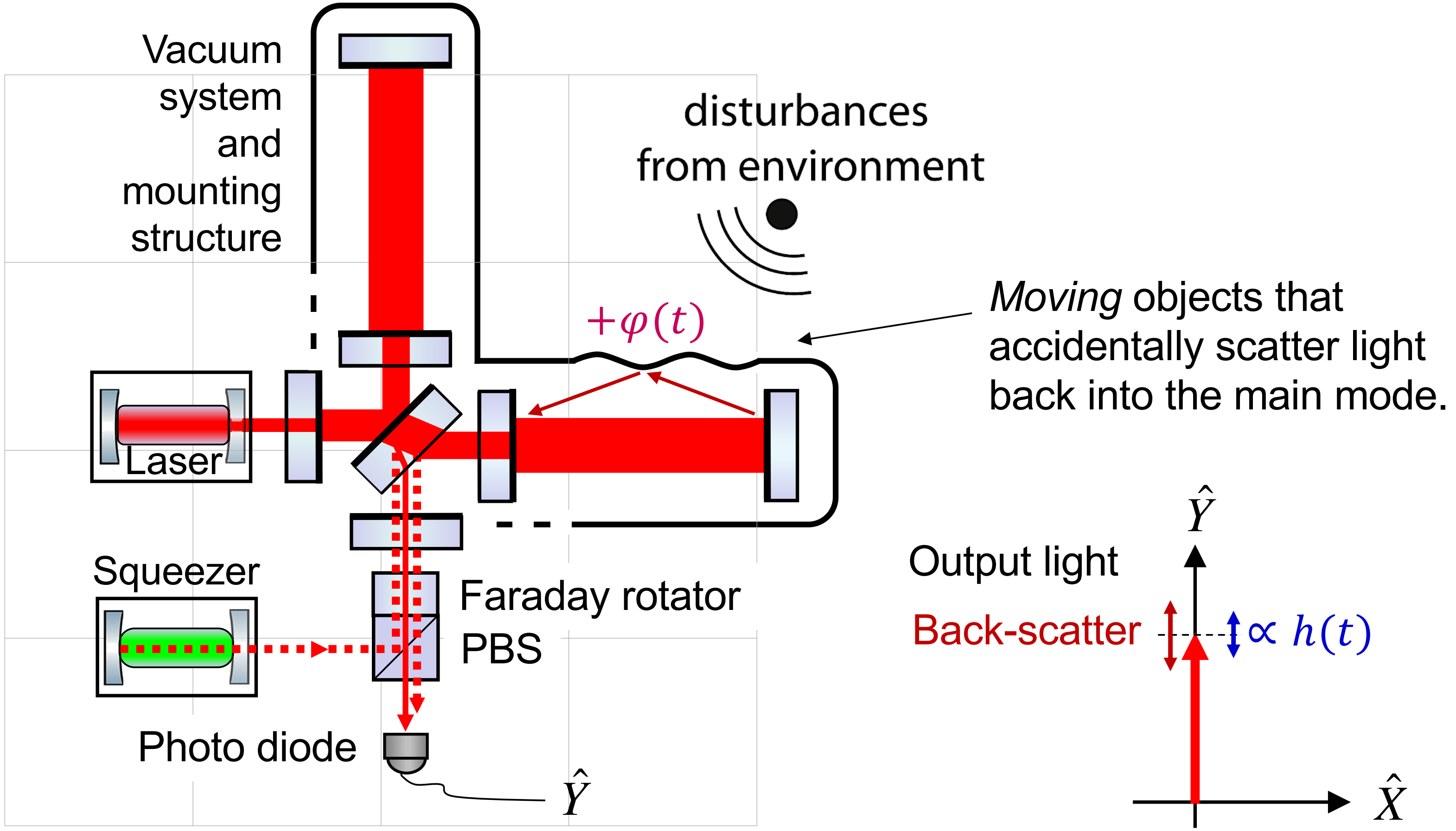
Melanie Ast, AEI Hannover

Sebastian Steinlechner, Maastricht University

Universität Hamburg

DER FORSCHUNG | DER LEHRE | DER BILDUNG

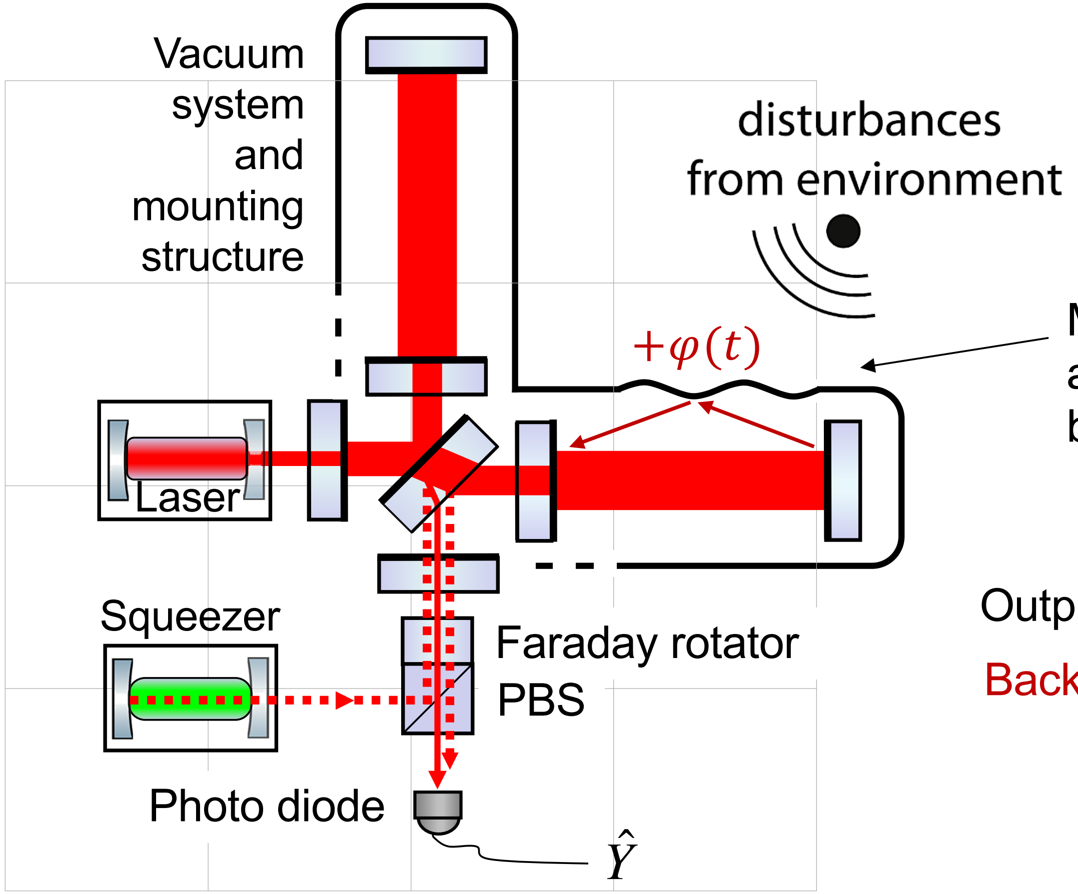
The back-scatter problem

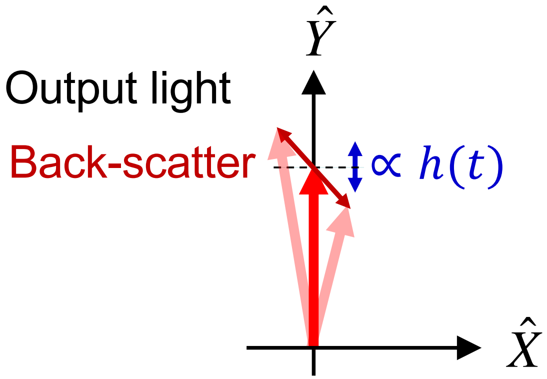


Back-scatter produces signals that cannot be distinguished from GW-signals.

Mitigating back-scattered light

The back-scatter problem

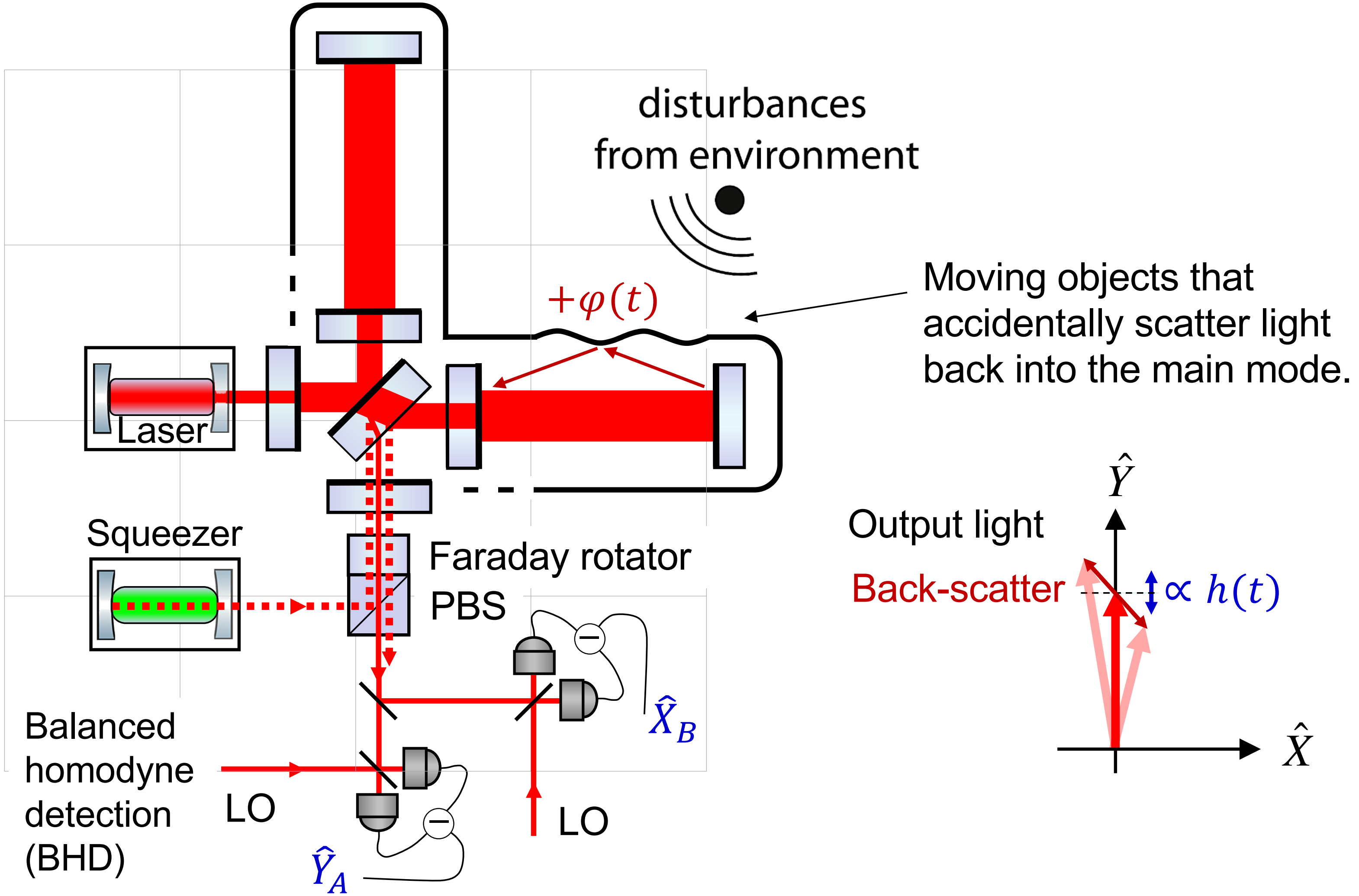




Back-scatter is never perfectly aligned along the quadrature of the GW-signals.
Back-scatter also shows up along $\hat{X}$. – GW-signals do not.

Mitigating back-scattered light

Dual Balanced-Homodyne Readout



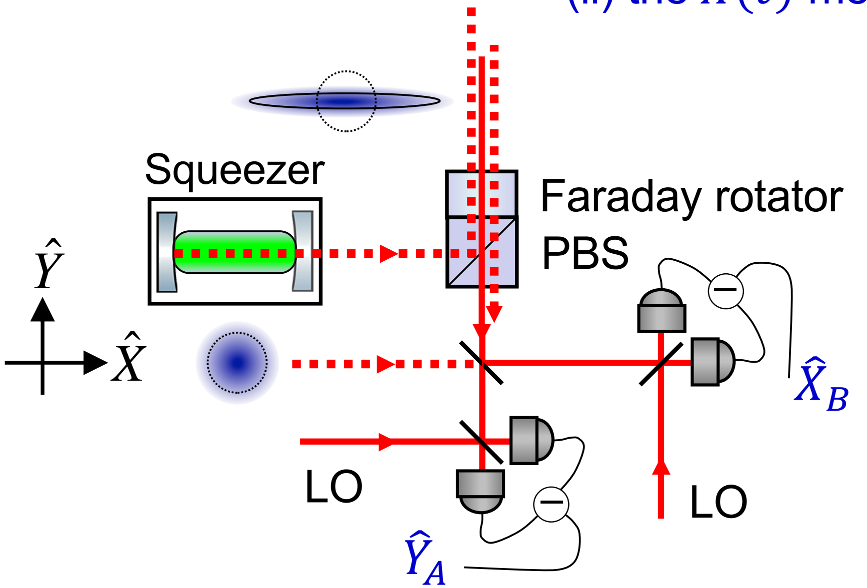
Mitigating back-scattered light

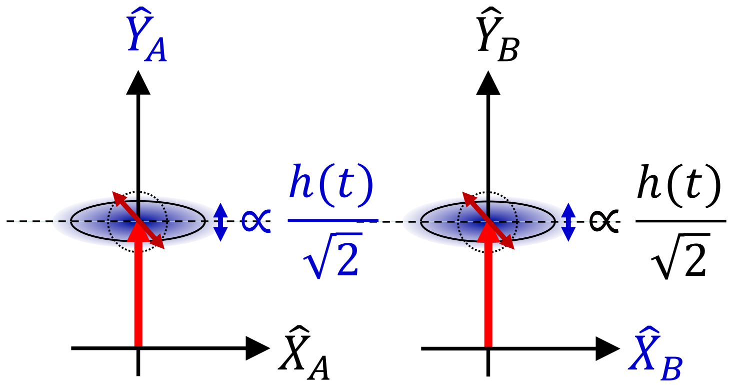
Simultaneous Measurements of $\hat{Y}$ and $\hat{X}$

$\hat{Y}(t)$ and $\hat{X}(t)$ are the output's amplitude modulation and phase quadrature modulation depths.
They do not commute and obey a Heisenberg uncertainty relation $\Delta^2\hat{X} \cdot \Delta^2 Y \geq \frac{1}{16}$.

They cannot be measured precisely at the same time (with a semi-classical device).

Even worse with squeezing: (i) the $\hat{Y}(t)$ measurement loses half of the squeezing
(ii) the $\hat{X}(t)$ measurement is anti-squeezed



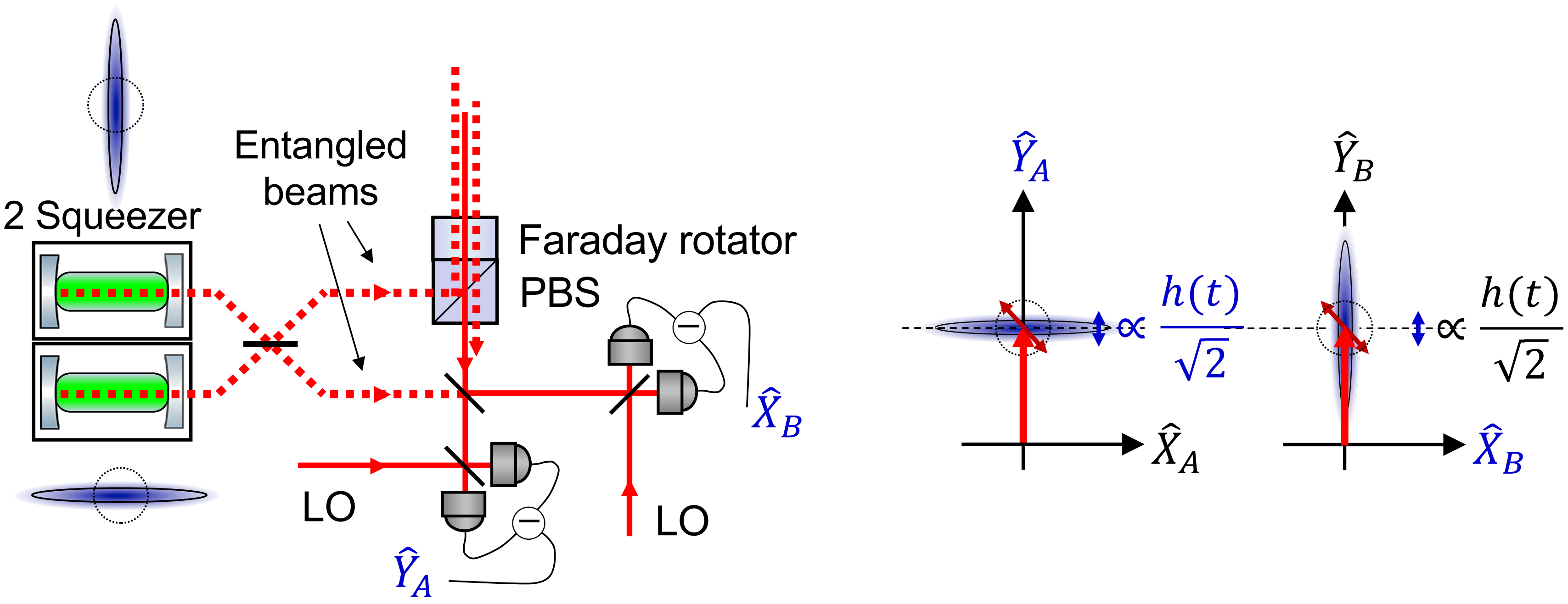


Mitigating back-scattered light

Entangled-Light Dual Balanced-HD

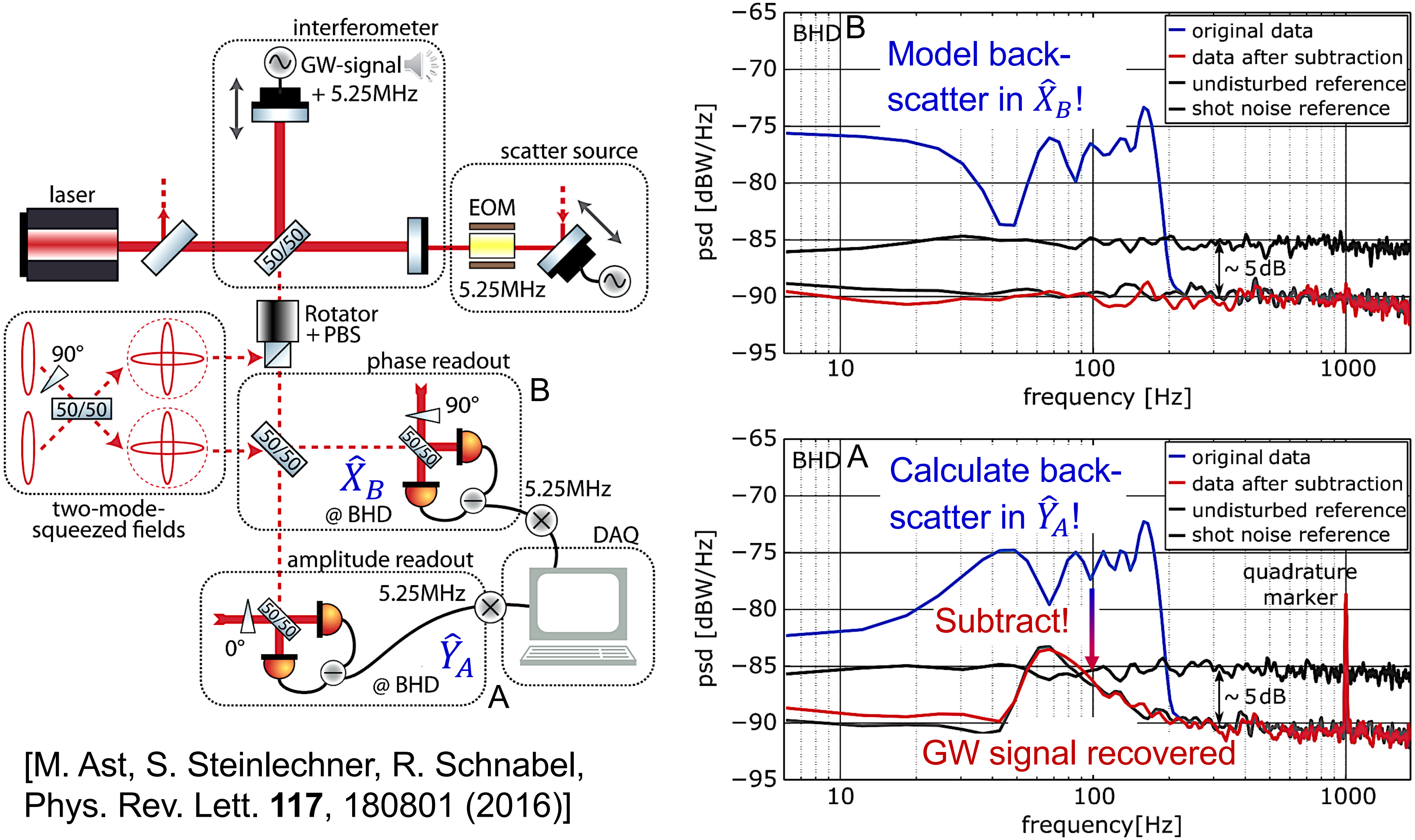
$\hat{X}(t)$ and $\hat{Y}(t)$ can be measured precisely at the same time using entanglement!

[G.M. D'Ariano, P. Lo Presti, M.G.A. Paris, *Using Entanglement Improves the Precision of Quantum Measurements*, Phys. Rev. Lett. **87**, 270404 (2001)]
W. Wasilewski *et al., Quantum noise limited and entanglement-assisted magnetometry,* Phys. Rev. Lett. **104**, 133601 (2010).
S. Steinlechner *et al., Quantum-dense metrology*, Nature Photonics **7**, 626 (2013).



Mitigating back-scattered light

Proof of principle demonstration

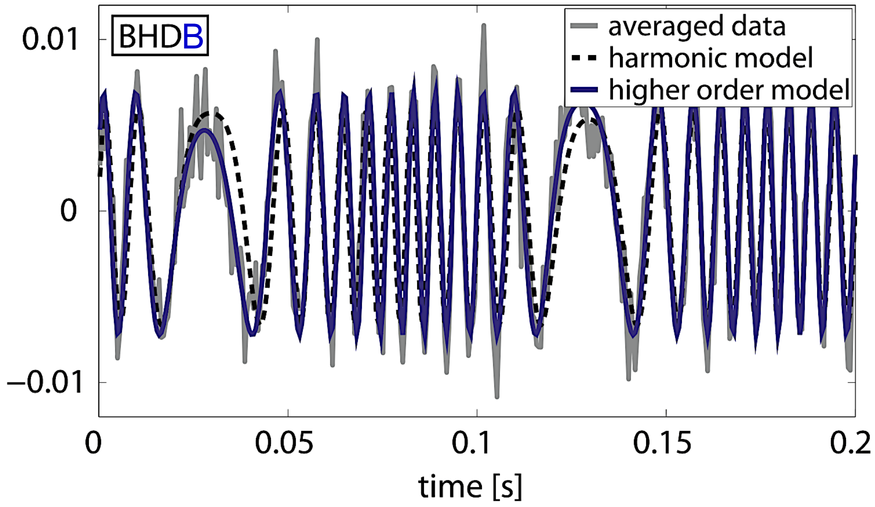


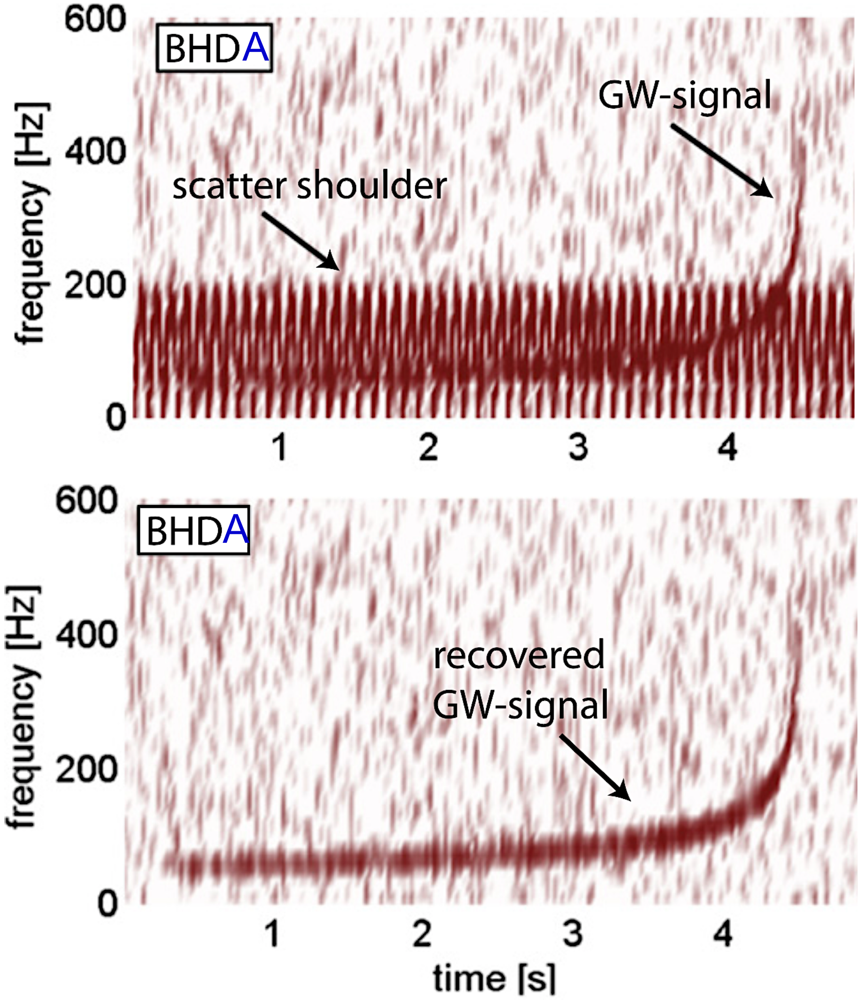
[M. Ast, S. Steinlechner, R. Schnabel, Phys. Rev. Lett. **117**, 180801 (2016)]

Mitigating back-scattered light

Proof of principle demonstration

Modelling the noise at B





Our model of the back-scatterer:
Anharmonic, damped oscillator

[M. Meinders, R. Schnabel,
Class. Quant. Grav. **32**, 195004 (2015)]

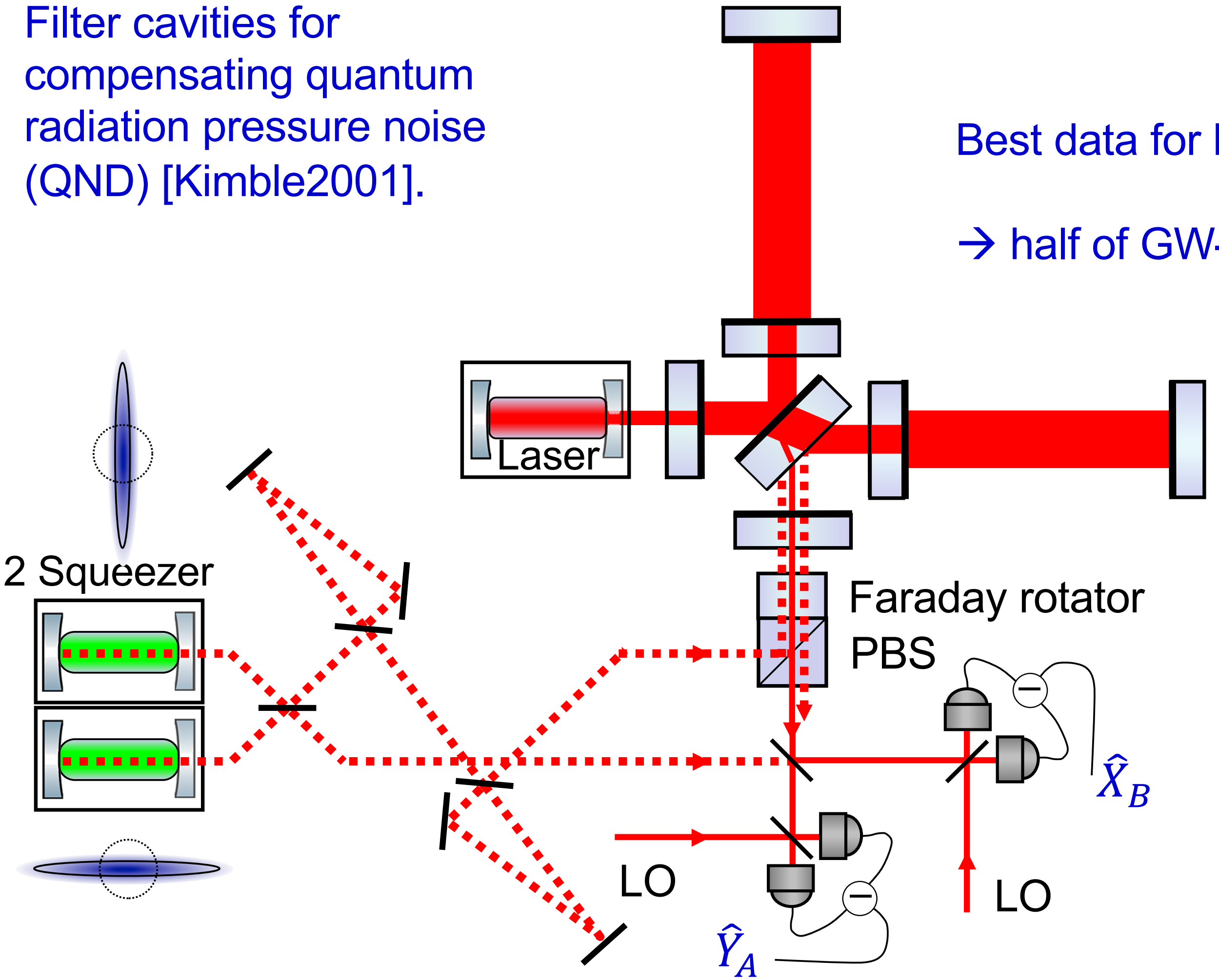
Mitigating back-scattered light

ET with Dual Balanced-Homodyne Readout

Filter cavities for compensating quantum radiation pressure noise (QND) [Kimble2001].

Best data for back-scatter modelling

→ half of GW-signal lost.



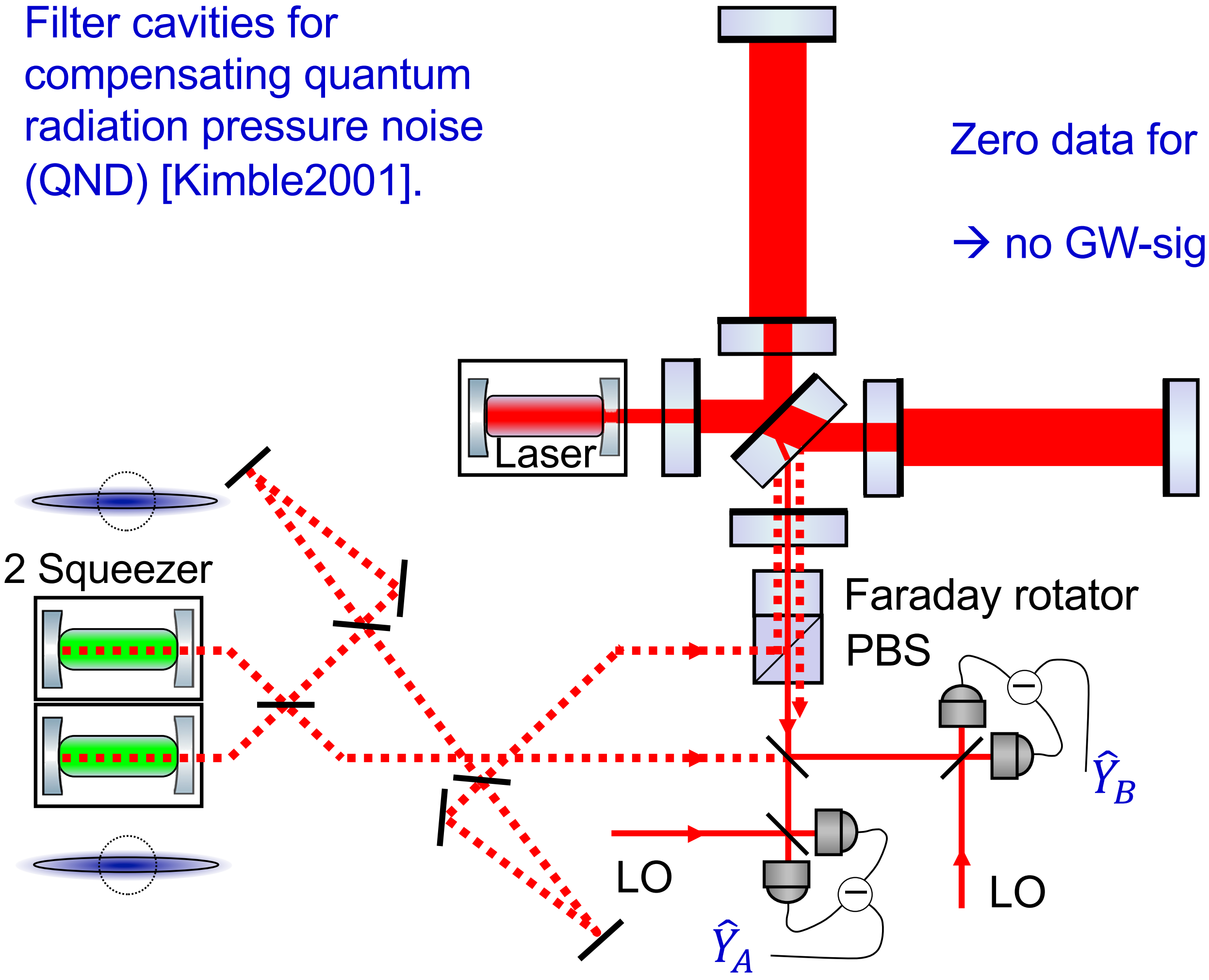
Mitigating back-scattered light

ET with Dual Balanced-Homodyne Readout

Filter cavities for compensating quantum radiation pressure noise (QND) [Kimble2001].

Zero data for back-scatter modelling

→ no GW-signal lost.



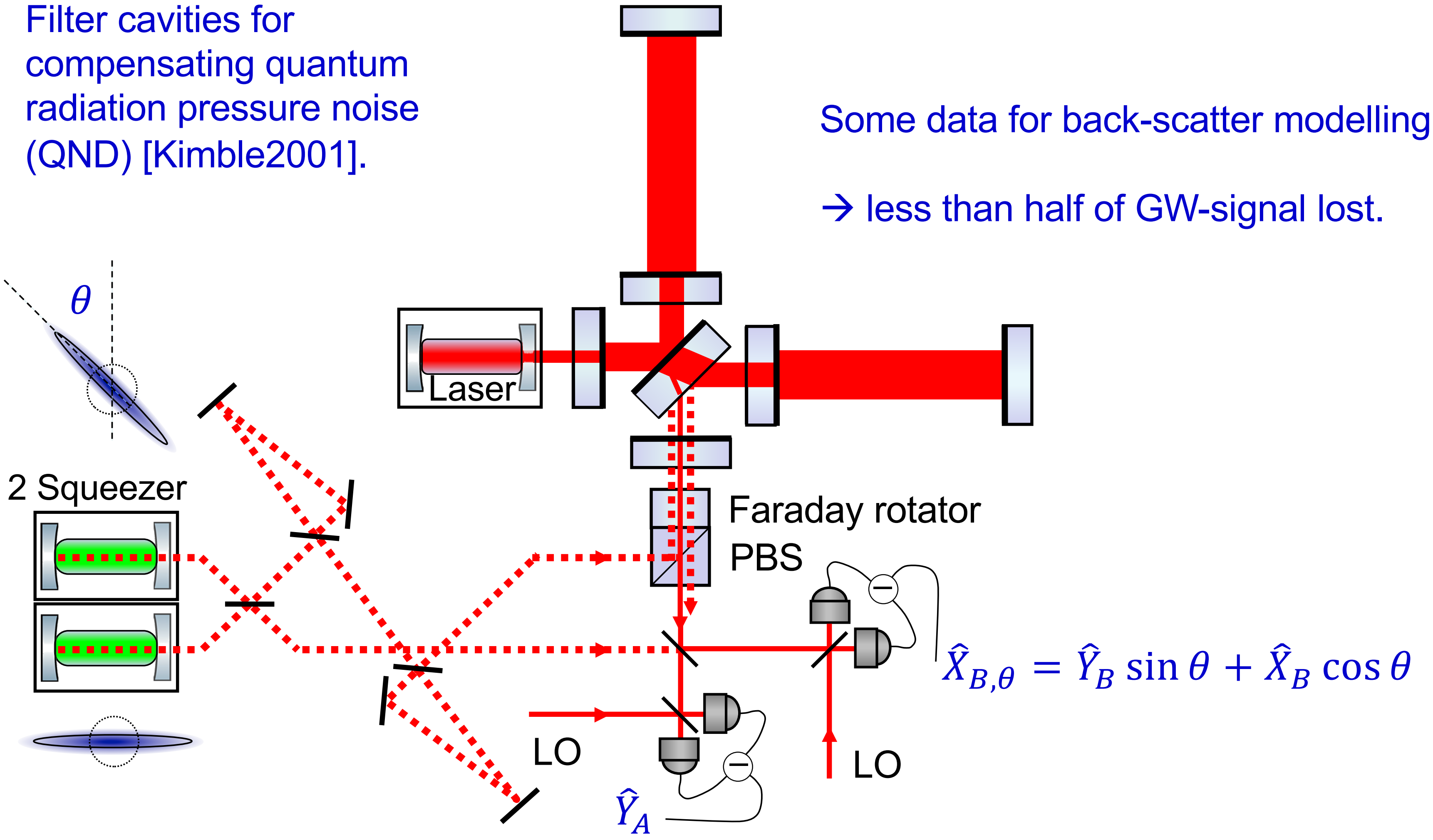
Mitigating back-scattered light

ET with Dual Balanced-Homodyne Readout

Filter cavities for compensating quantum radiation pressure noise (QND) [Kimble2001].

Some data for back-scatter modelling

→ less than half of GW-signal lost.



Mitigating back-scattered light

Summary

- *Entangled-light dual balanced-homodyne readout* is the cherry on the cake. All other means for reducing back-scatter are necessary!
- The entangled *external* beam serves as a quantum reference that allows for measuring the GW signal in $\hat{Y}(t)$ and the back-scatter in $\hat{X}(t)$ *simultaneously* with squeezed quantum noise (i.e. in theory with arbitrary precision).
- The additional information about the scatter may allow for subtracting back-scatter noise that is orders of magnitudes above quantum noise.
- "Just" up to half of the signal gets lost.
- Reading out $\hat{Y}_A$ and $\hat{X}_{B,\theta} = \hat{Y}_B \sin\theta + \hat{X}_B \cos\theta$ reduces the signal loss to $\frac{1}{2}\cos^2\theta$, (in power) while the quality of back-action subtraction reduces as well. θ can be frequency dependent. i.e. $\theta \rightarrow 0$ at higher frequencies without back-scatter problems.
- The *noise modelling* will continuously improve by using *machine learning* (AI).

Conclusion

- I highly recommend *entangled-light dual balanced-homodyne readout* for ET-low-f and other GW observatories targeting low frequencies.

Mitigating back-scattered light