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Fundamental quantum limit achieved by internal squeezing in cavity-enhanced sensors

Mikhail Korobko,
Sebastian Steinlechner, Jan Südbeck, Roman Schnabel

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University of Maastricht, Netherlands

GWADW 2023

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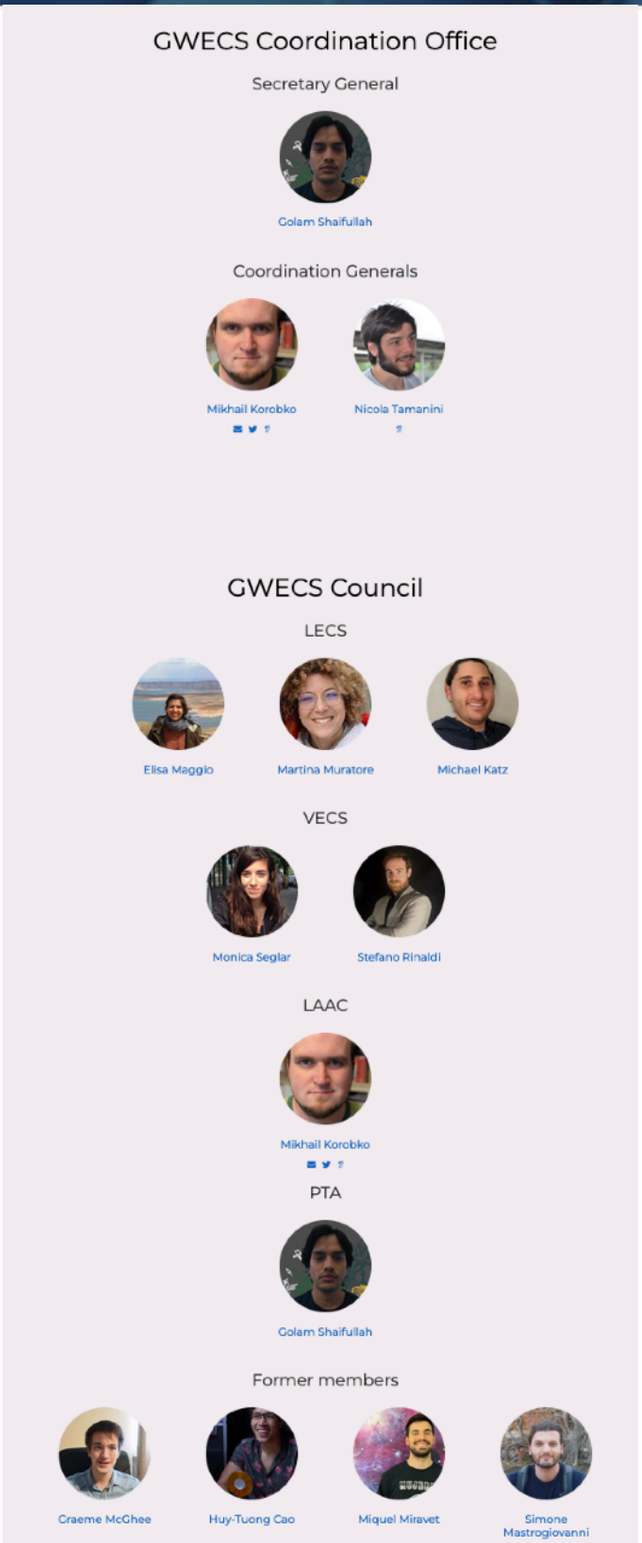

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Fundamental quantum limit achieved by internal squeezing in cavity-enhanced sensors

See preprint:
2303.09983

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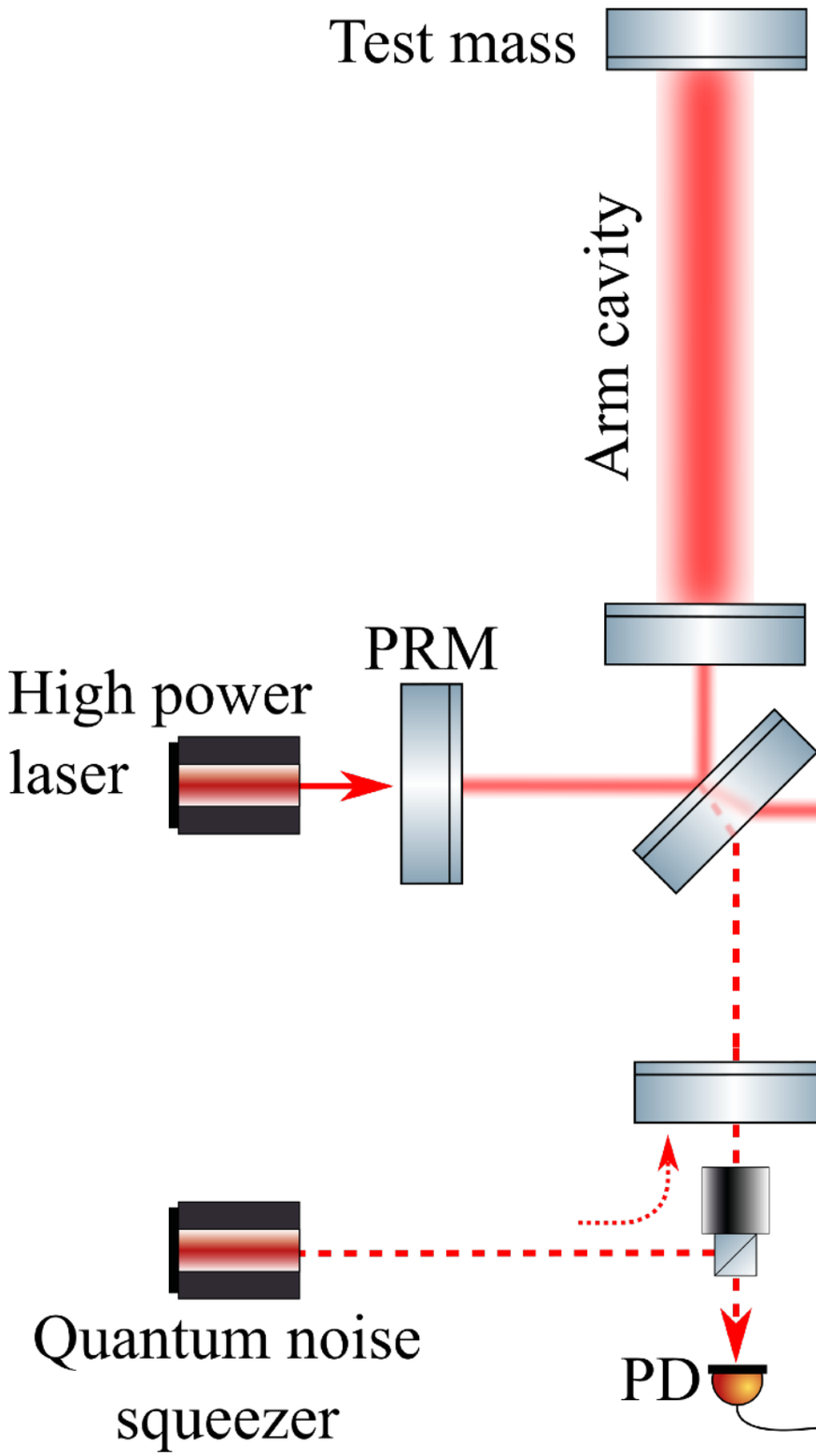
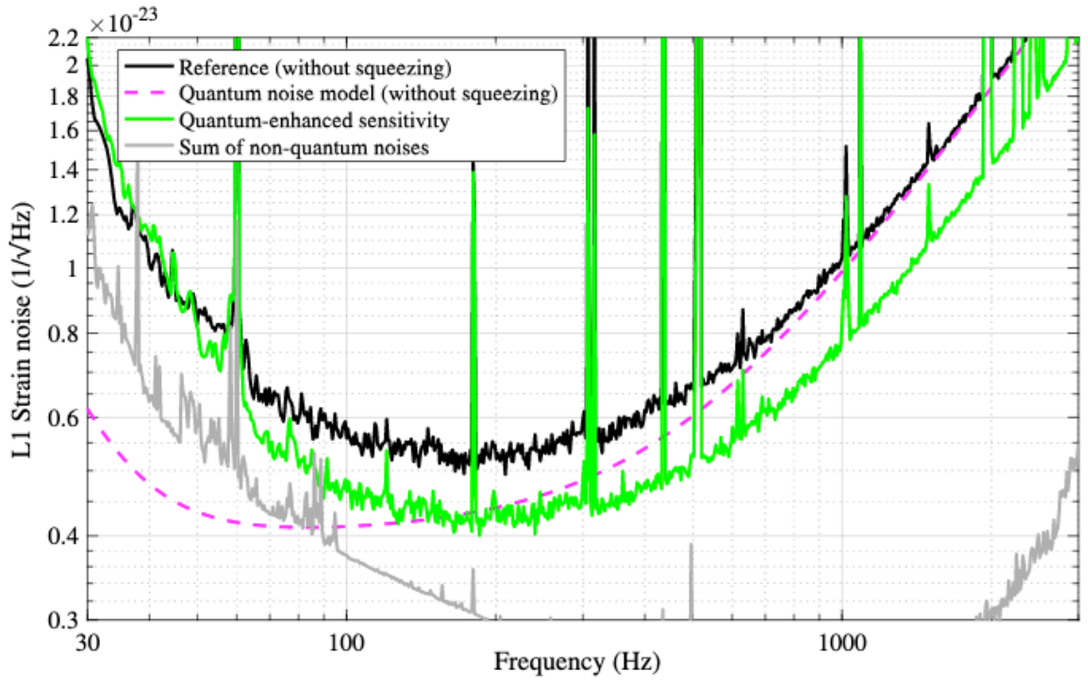
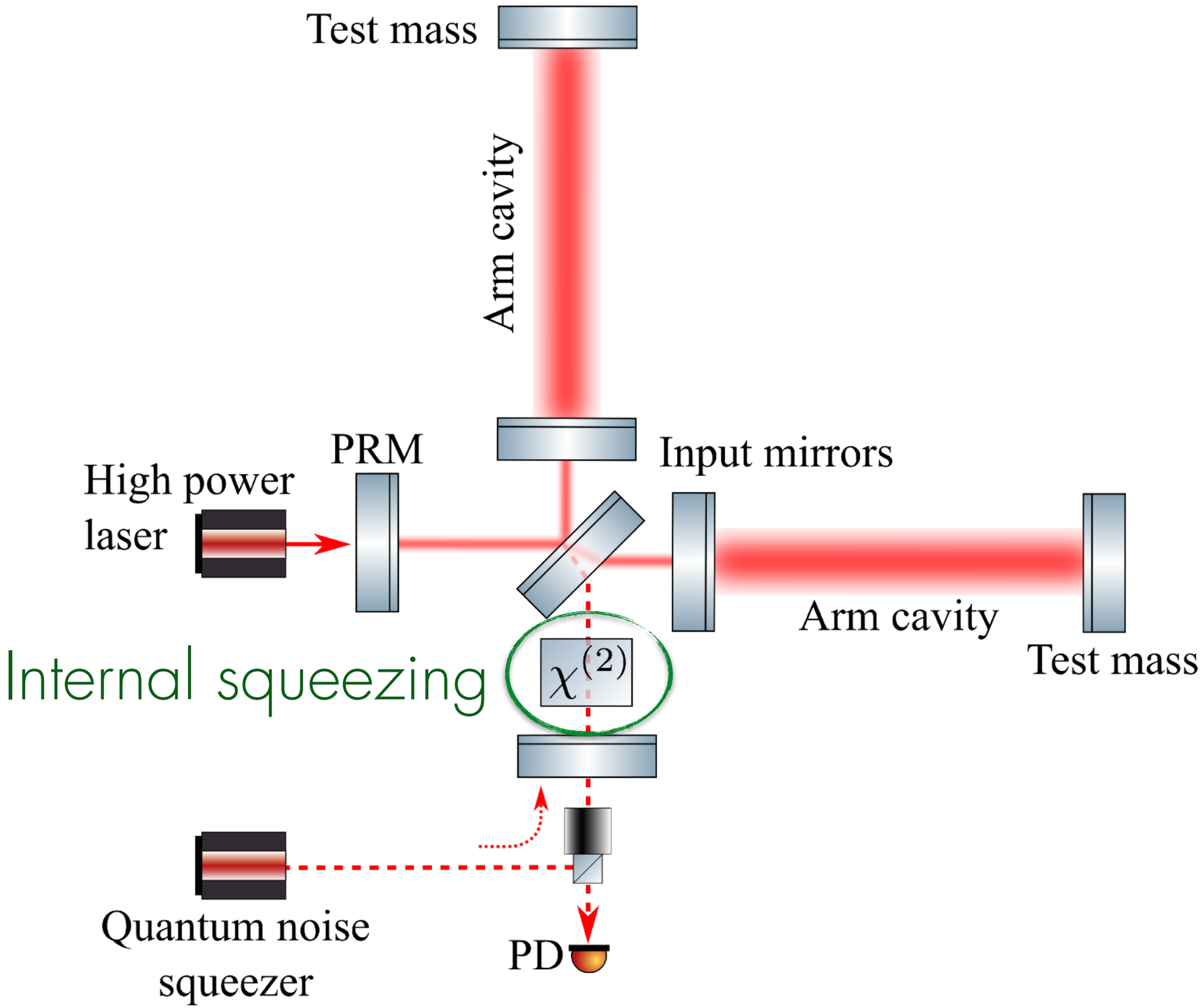
Introduction

Internal squeezing concept





arXiv: 2303.09983



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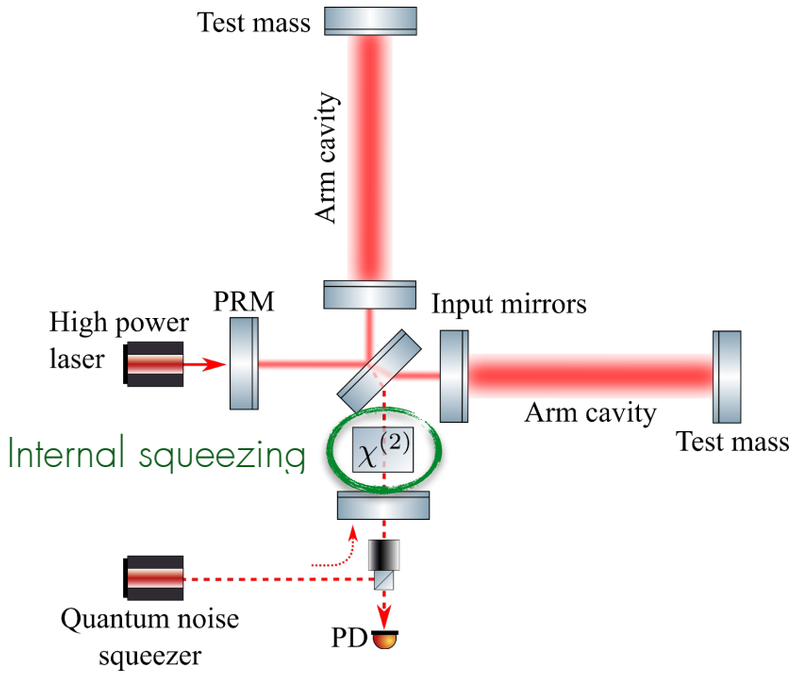
Introduction

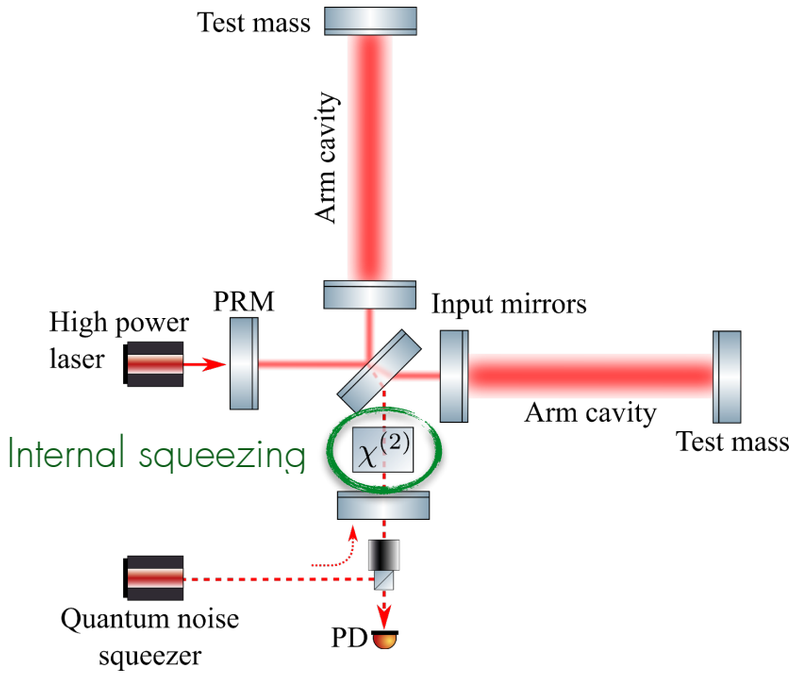


Internal squeezing concept

- Squeezed light is generated directly Inside the cavities
- Squeezed spectrum follows the coupled cavity spectral shape
- Can be flexibly tuned to enhance the detector

arXiv: 2303.09983

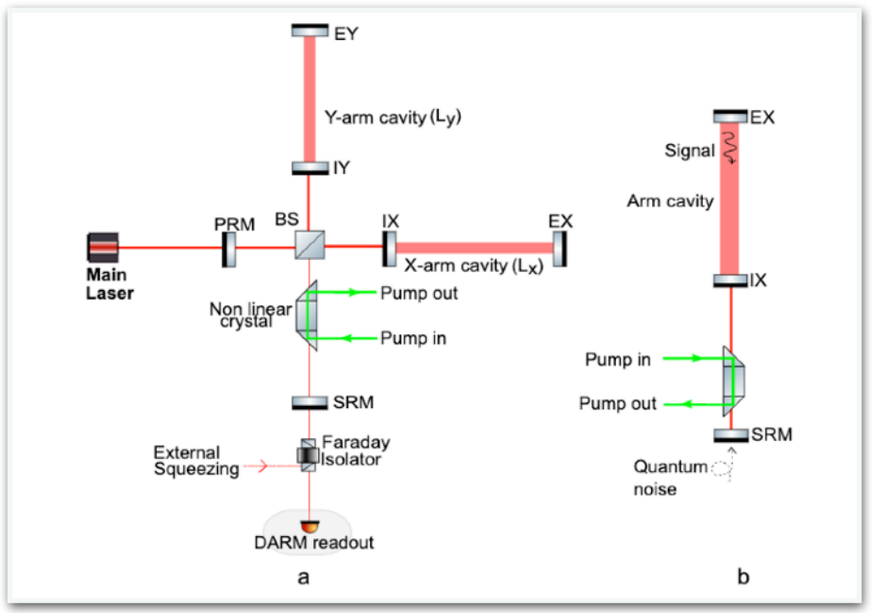
Introduction



Internal squeezing application

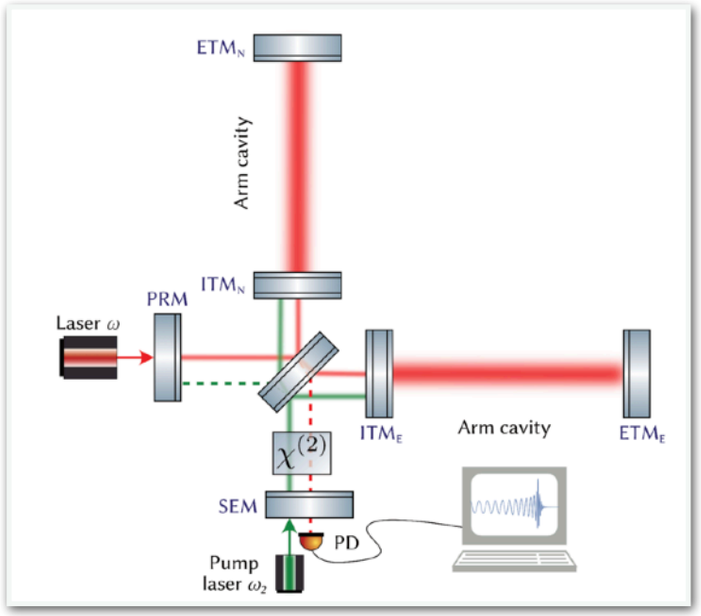
- Squeezed light is generated directly Inside the cavities
- Squeezed spectrum follows the coupled cavity spectral shape
- Can be flexibly tuned to enhance the detector

Quantum expander



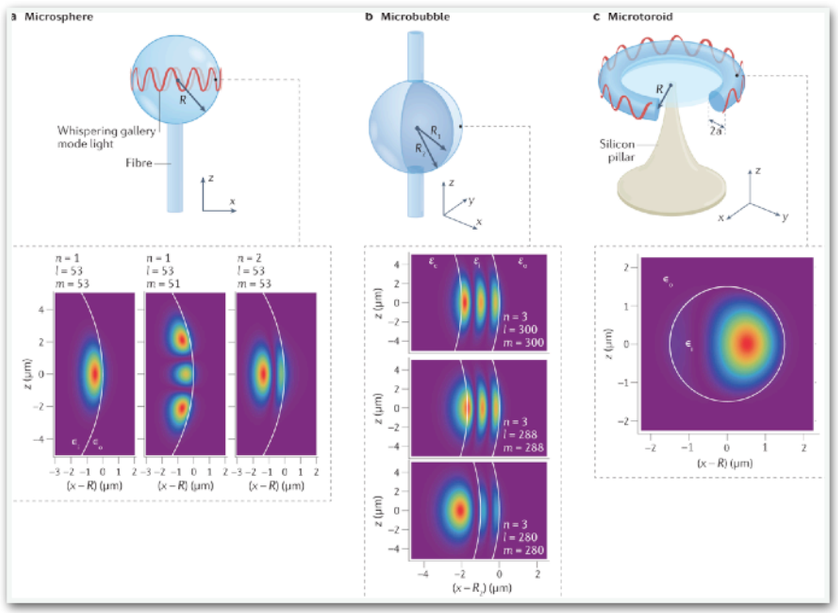
Korobko (2019), Adya (2020)

Optical spring



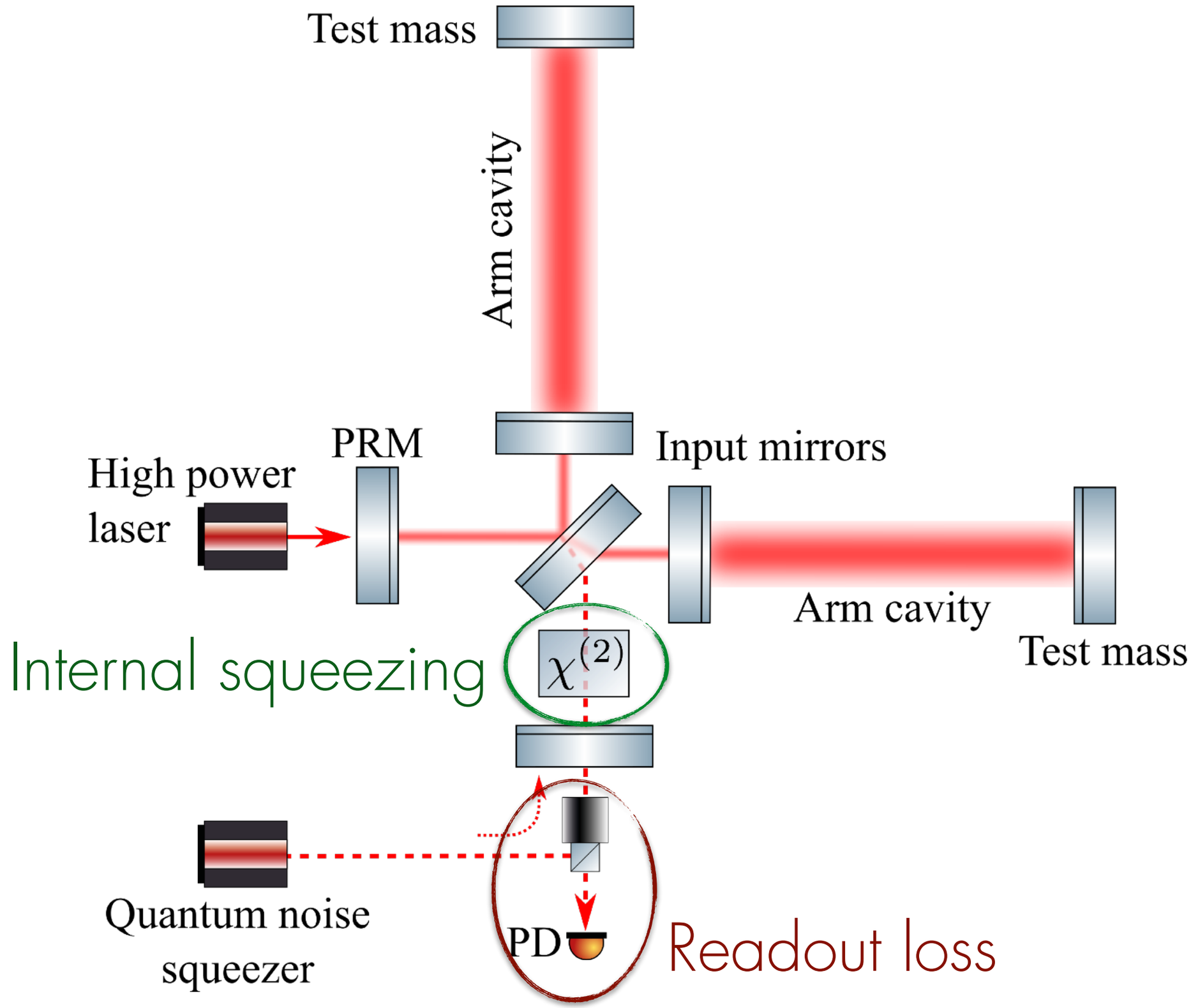
Somiya (2016), Korobko (2017)

Compact local sensors

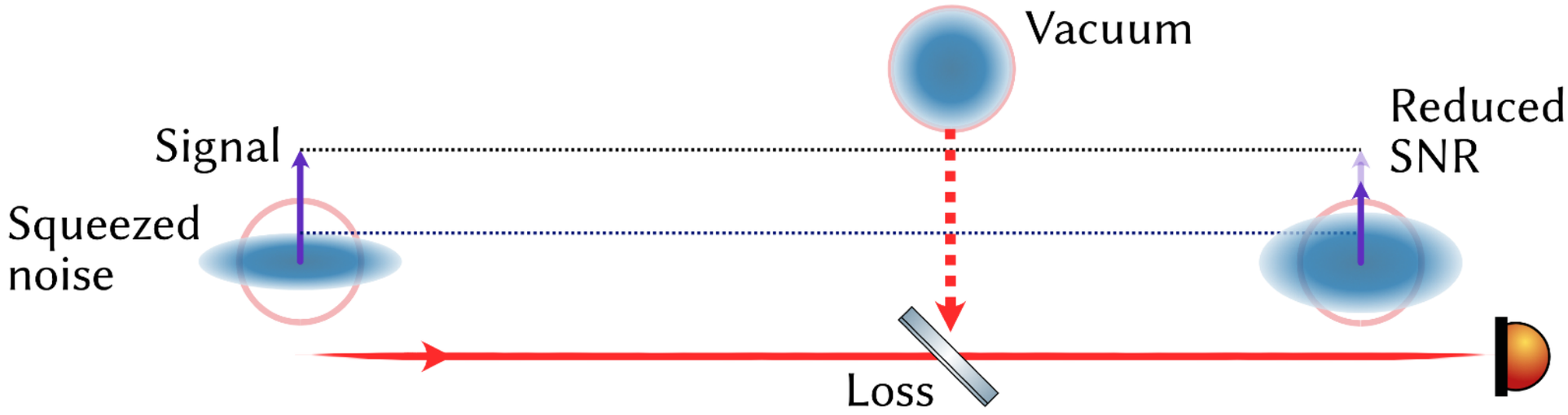


Yu et. al. (2021)

arXiv: 2303.09983


Test mass
Arm cavity
PRM
Input mirrors
High power laser
Arm cavity
Test mass
Internal squeezing
$\chi^{(2)}$
Quantum noise squeezer
PD
Readout loss

Optical loss

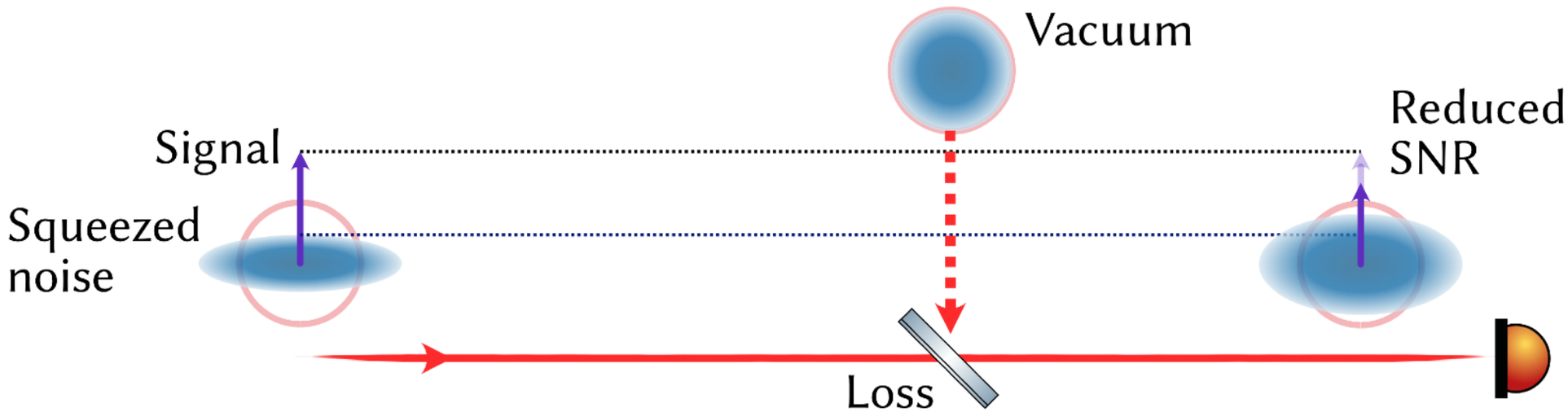


$$S = \eta(e^{-2r} + G^2) + 1 - \eta$$

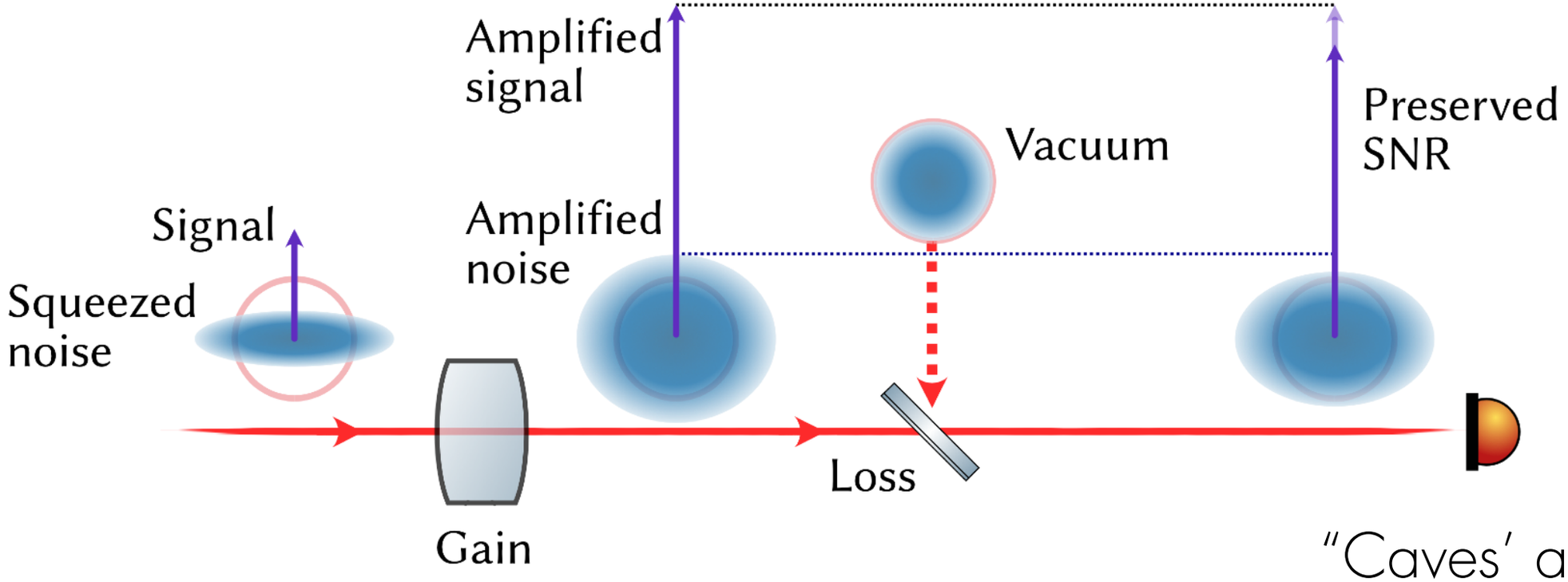
arXiv: 2303.09983

Introduction

Output amplification



$$S = \eta(e^{-2r} + G^2) + 1 - \eta$$



$$S_q = \eta(e^{-2r} + G^2)e^{2q} + 1 - \eta$$

$$\mathrm{SNR}_{q\to\infty} = e^{2r}$$

"Caves' amplifier" known from 80s

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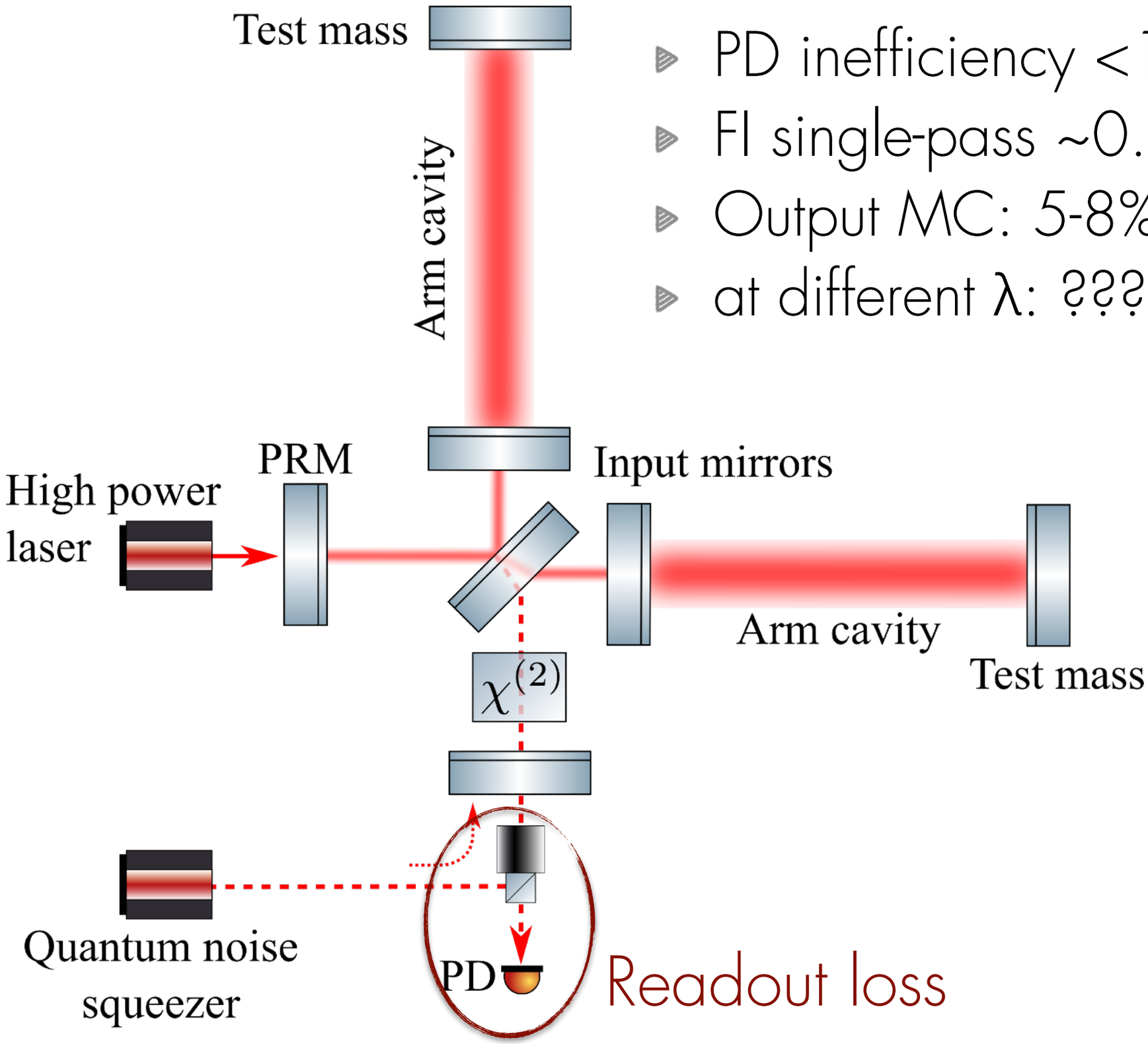
Readout loss composition

- PD inefficiency <1%
- FI single-pass ~0.5%
- Output MC: 5-8%
- at different λ: ???



arXiv: 2303.09983

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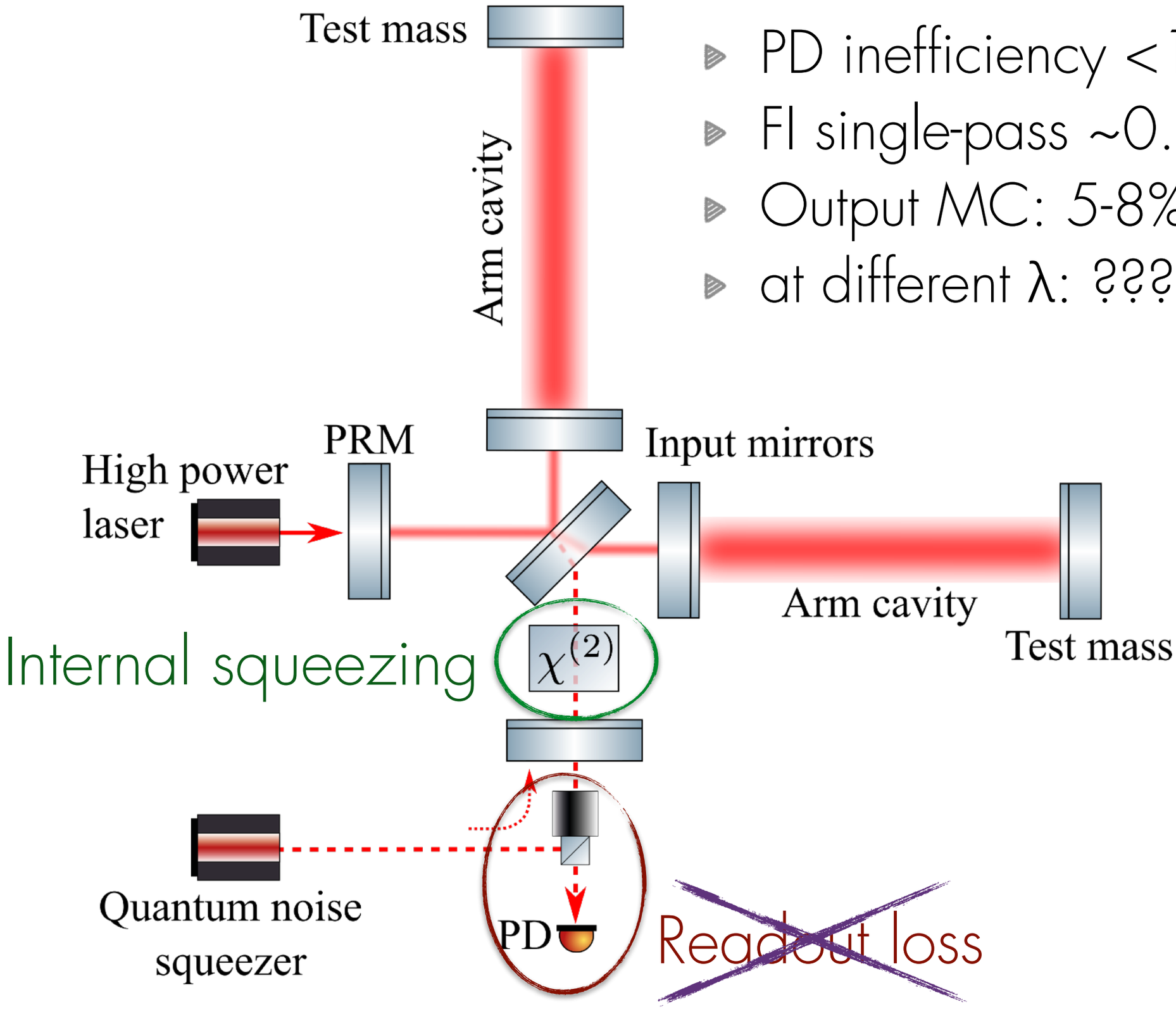
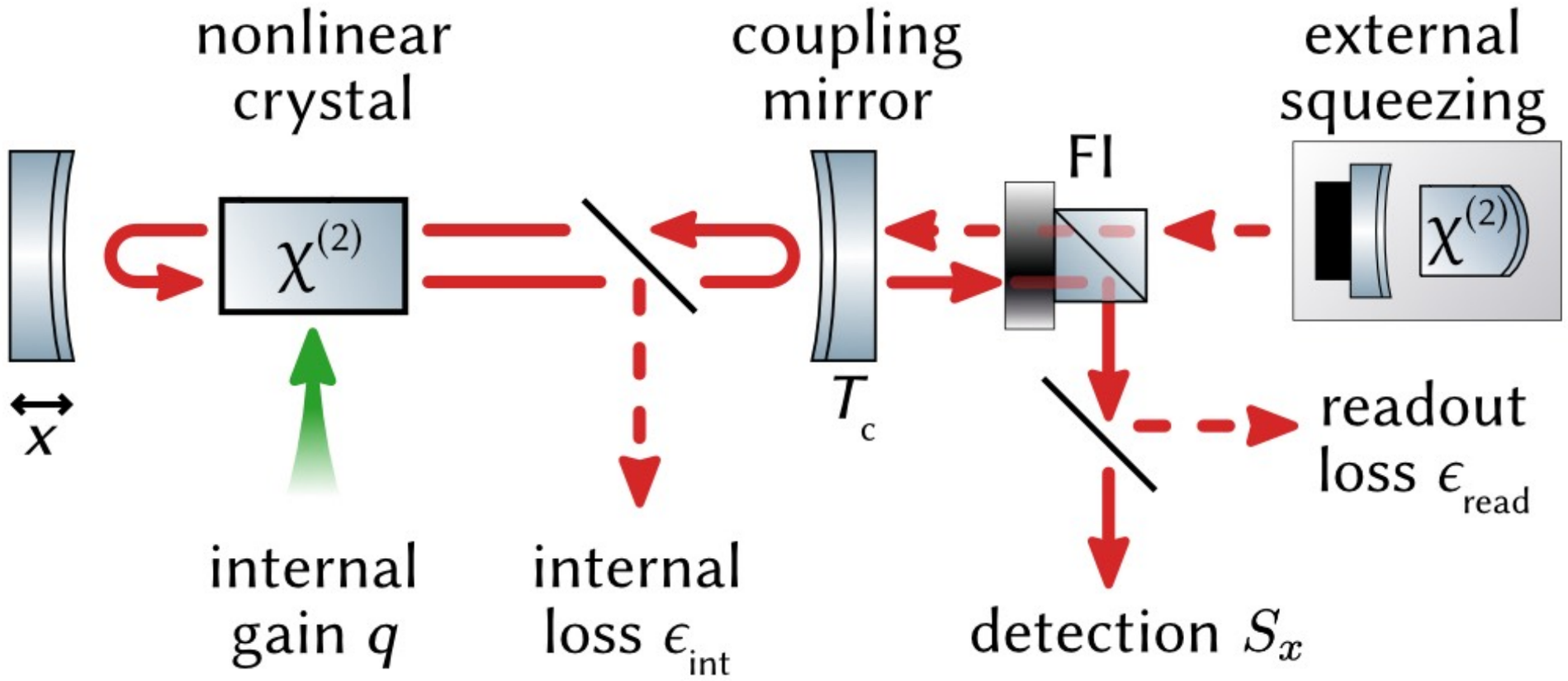


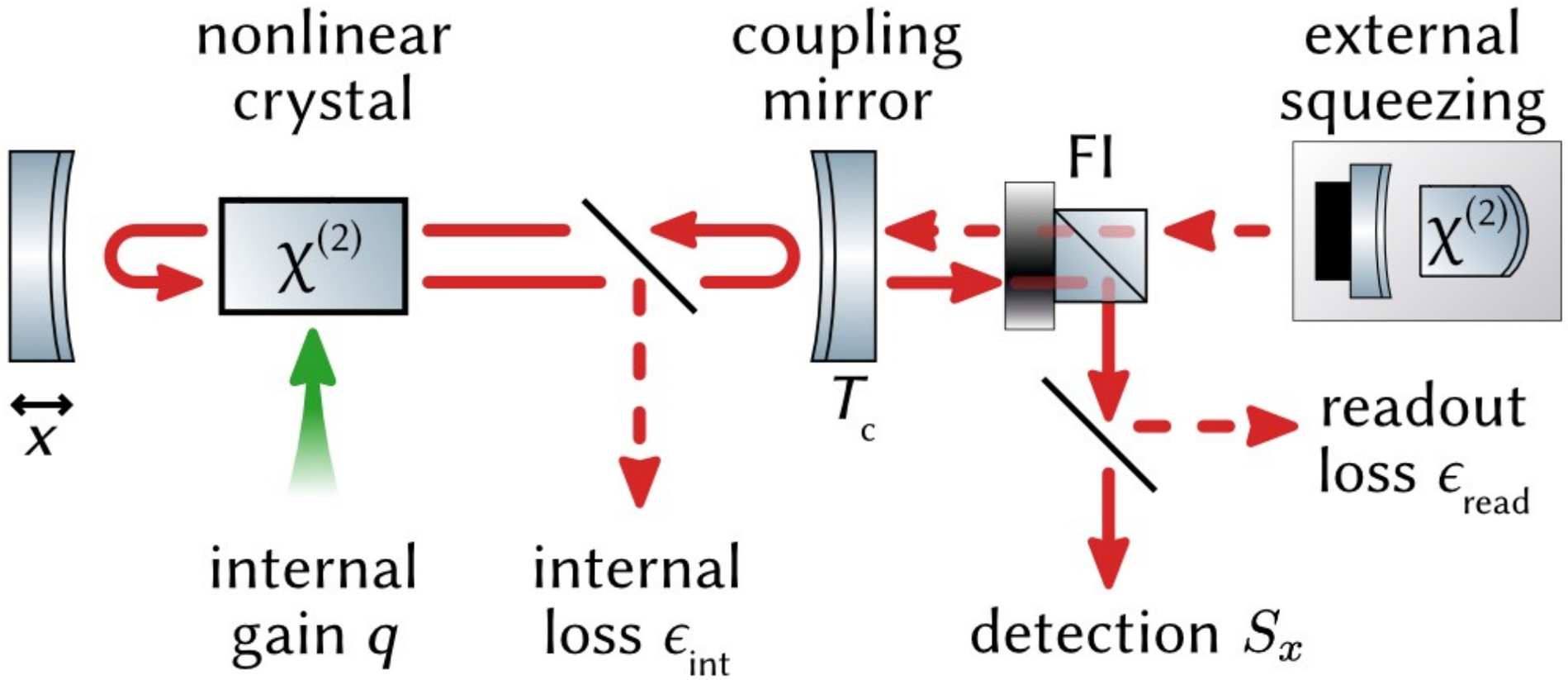
The experiment

Concept



- Signal is created by the moving end mirror (emulated)
- Internal gain creates squeezing & deamplifies the signal…
- Or amplifies the signal & the noise
- External squeezing is injected
- Readout and internal loss impact quantum state

arXiv: 2303.09983



- Signal is created by the moving end mirror (emulated)
- Internal gain creates squeezing & deamplifies the signal…
- Or amplifies the signal & the noise
- External squeezing is injected
- Readout and internal loss impact quantum state

Optimal choice depending on parameters

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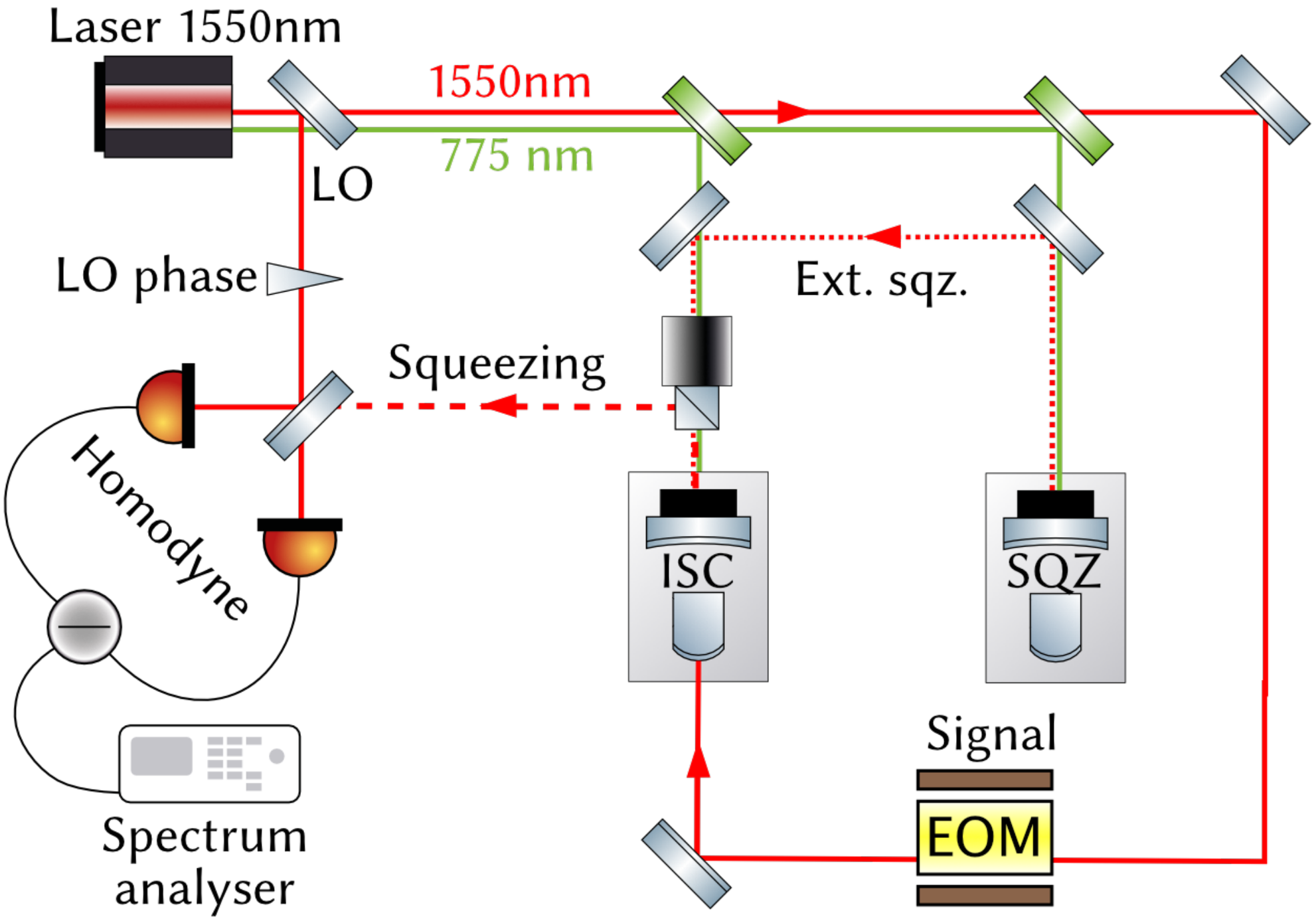
Experimental setup



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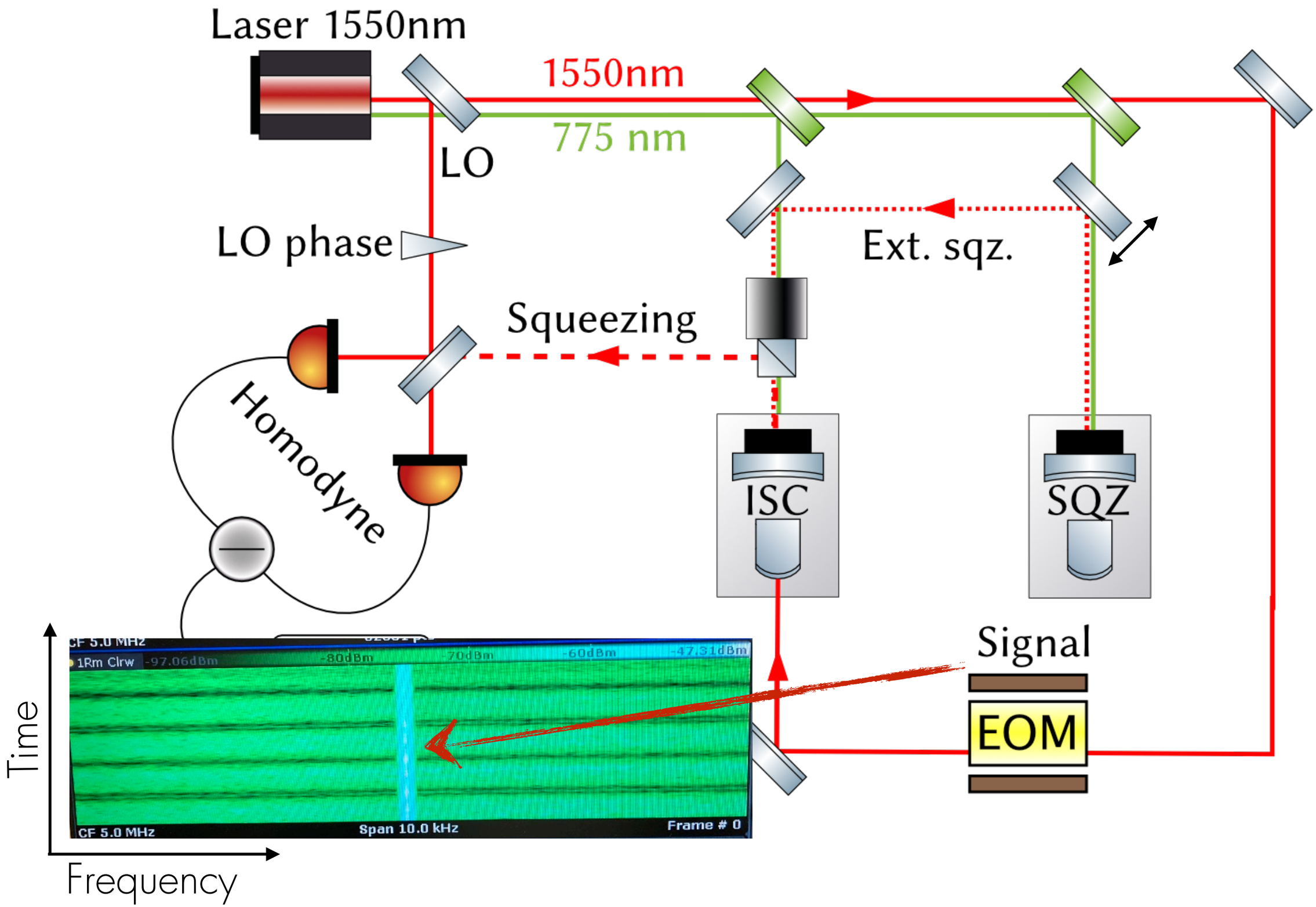
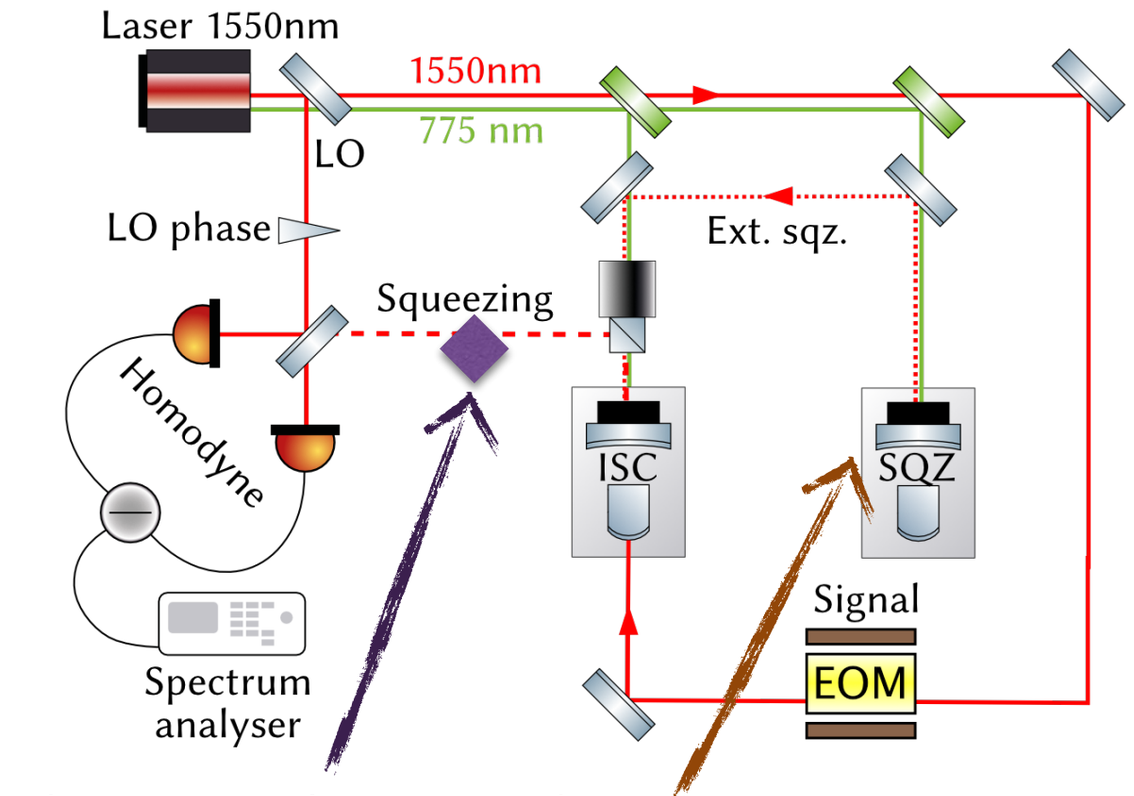
Experimental setup



arXiv: 2303.09983

Loss mitigation

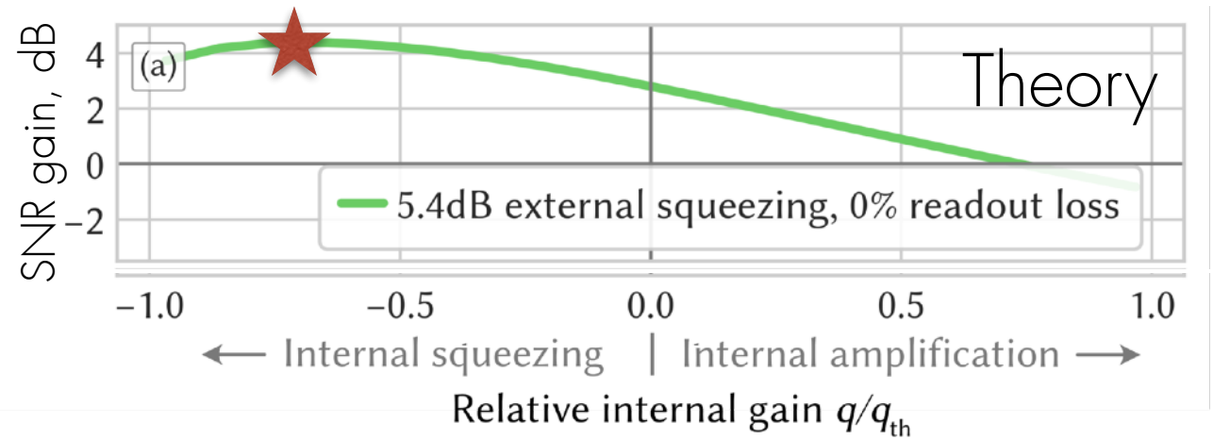
Experimental optimal gain



- up to 9 dB internal squeezing
- up to10.5 dB injected squeezing
- 8% injection loss
- 1.2% intra-cavity loss

arXiv: 2303.09983

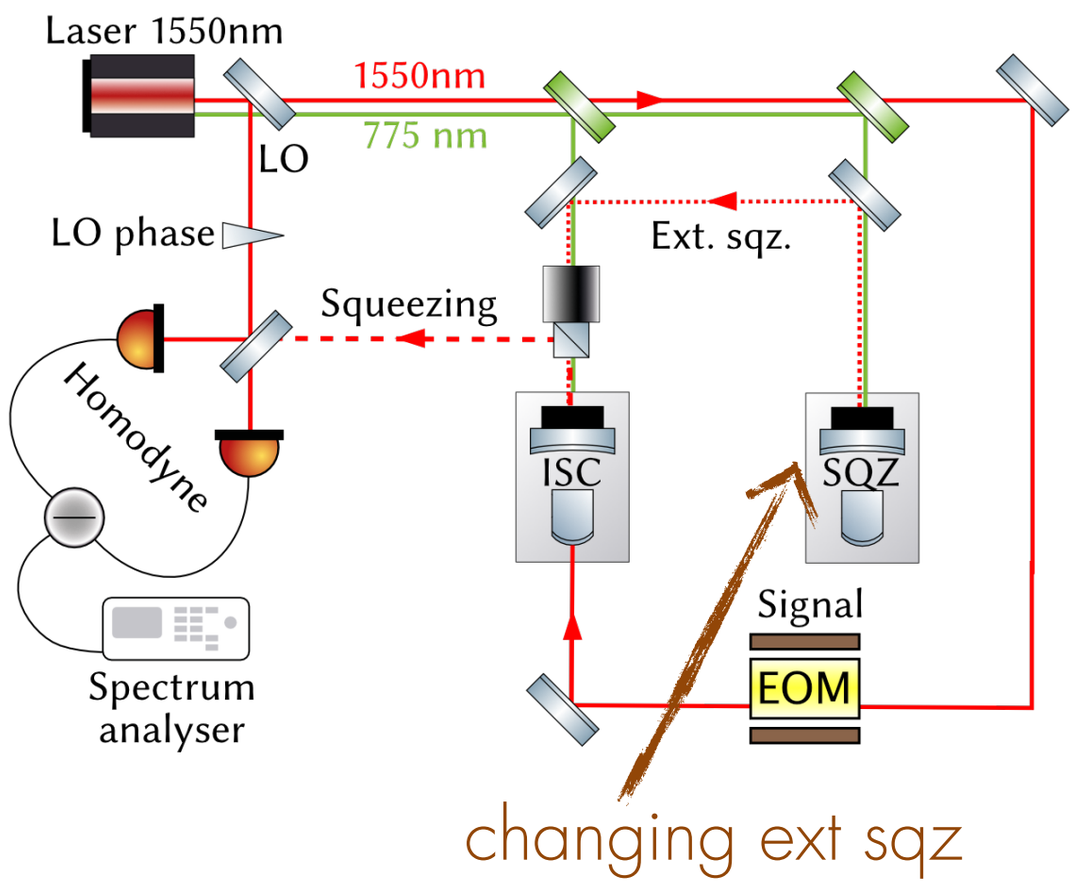
Loss mitigation



Low external sqz, no readout loss

- creating squeezing inside
- signal deamplification at high gain
- ~2.5dB w/o internal squeezing
- ~4.5dB with internal squeezing

Experimental optimal gain



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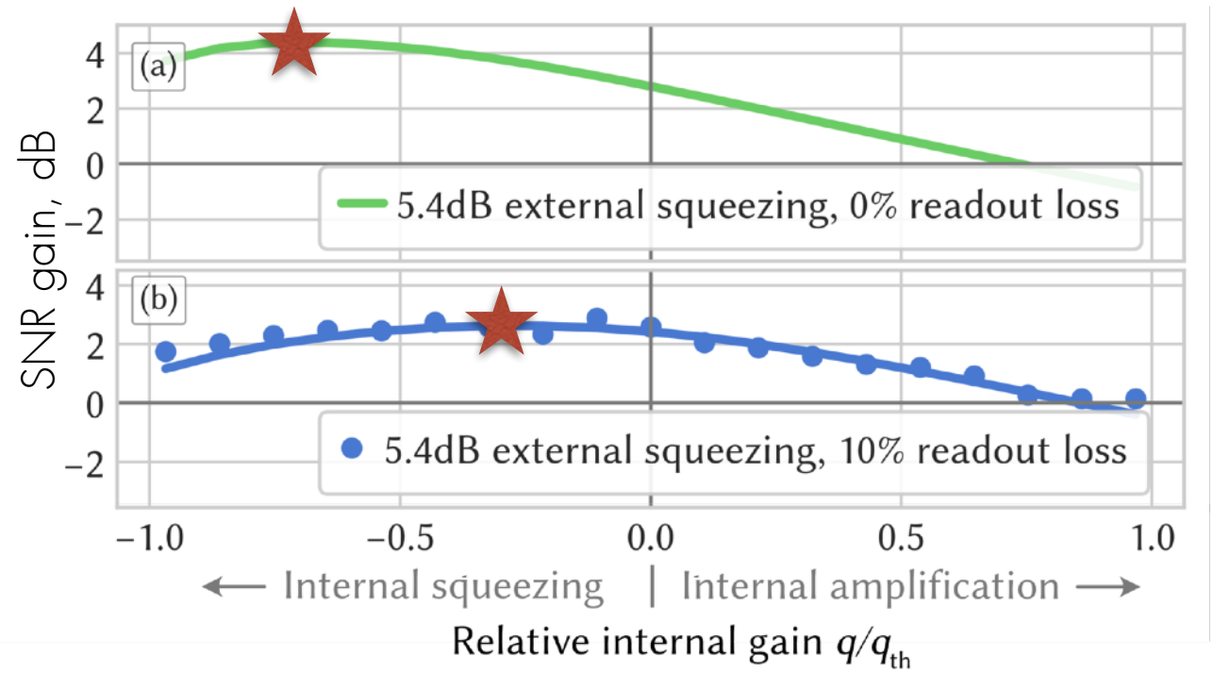
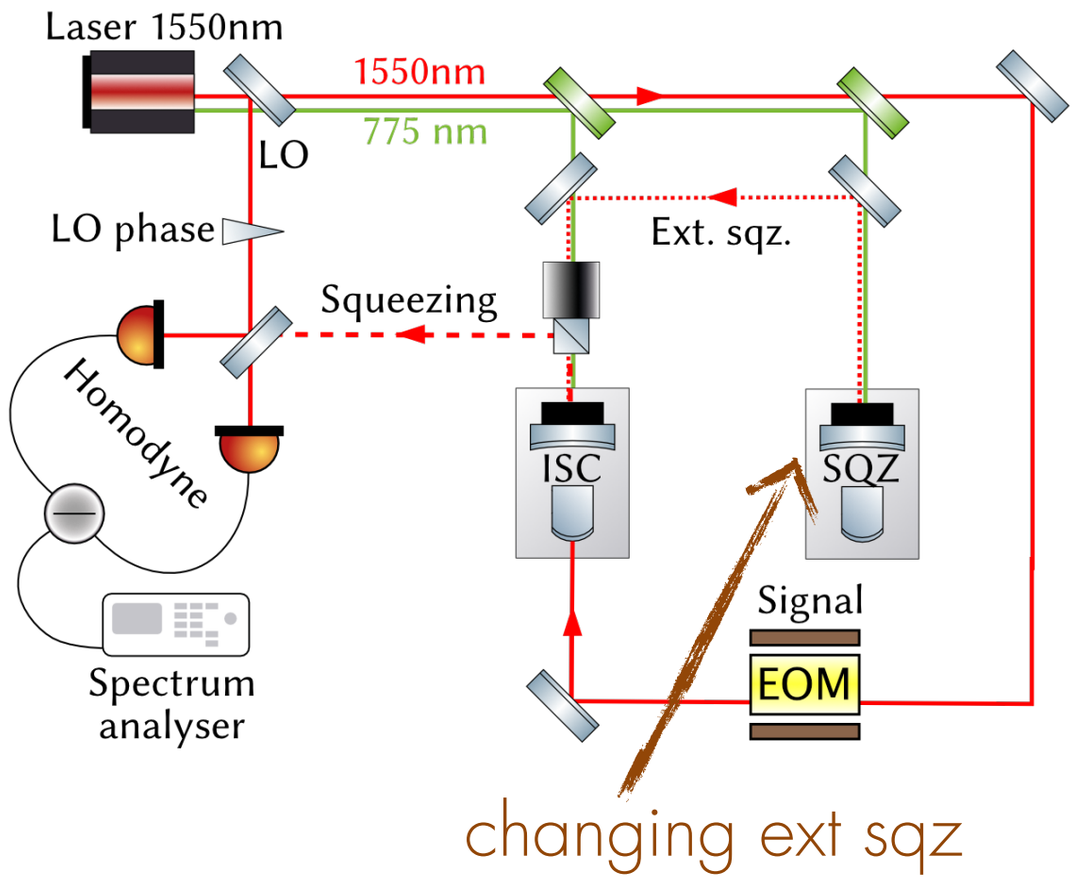
Loss mitigation



Low external sqz, 10% readout loss

- creating squeezing inside
- ~2.5dB w/o internal squeezing
- ~3.5dB with internal squeezing

Experimental optimal gain



- up to 9 dB internal squeezing
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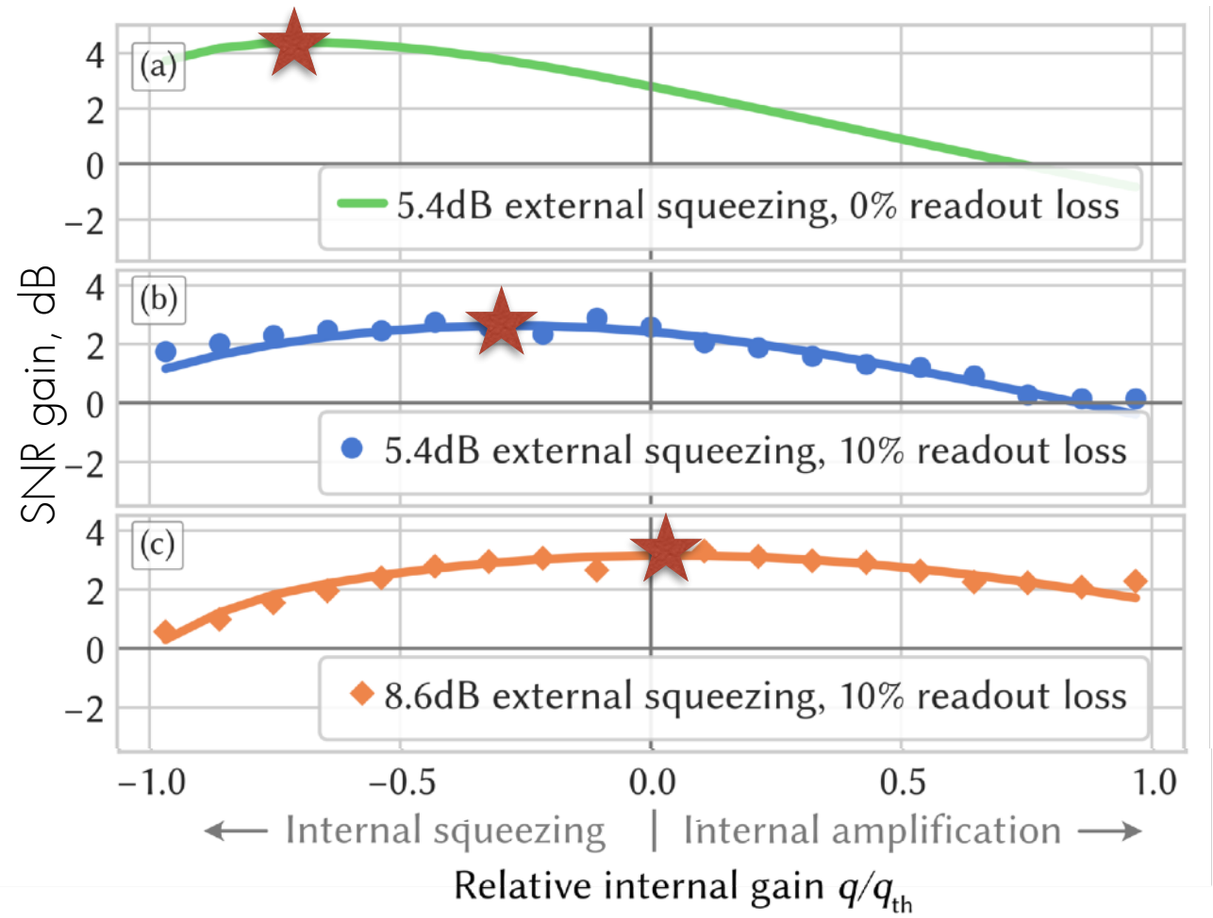
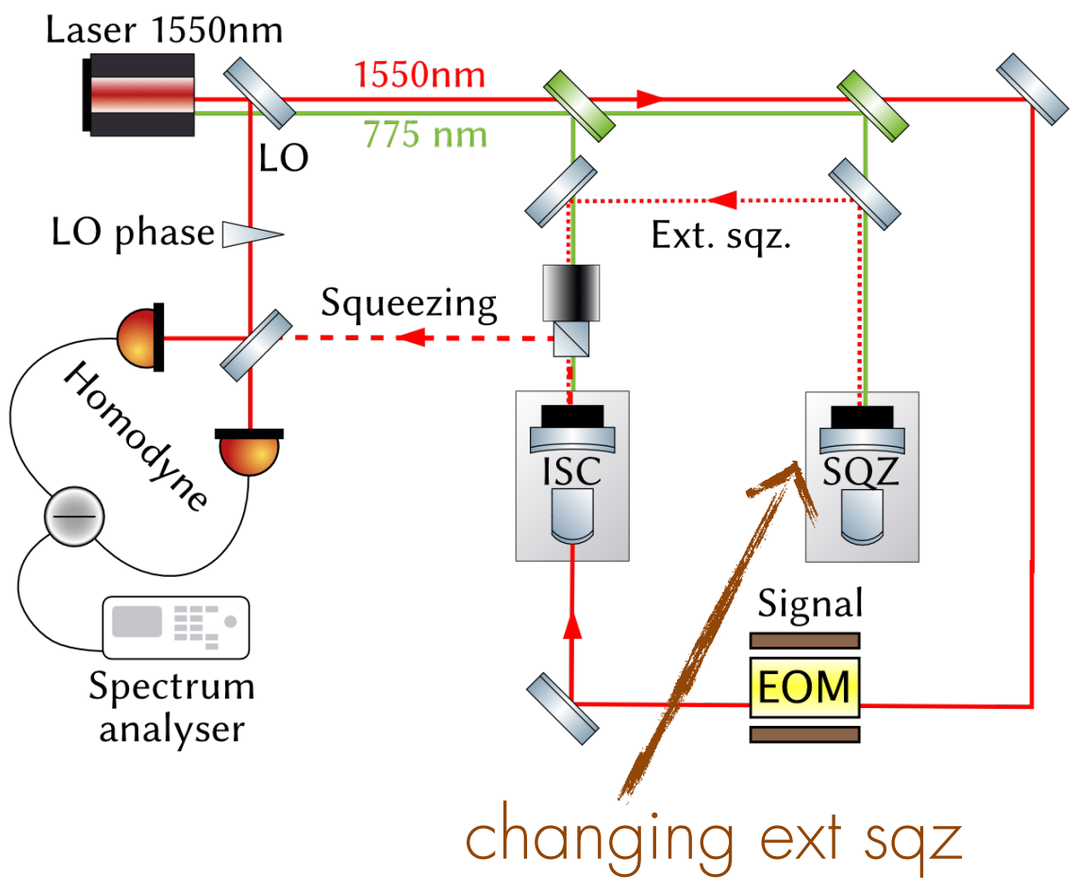
arXiv: 2303.09983

Loss mitigation



Experimental optimal gain



Increase external sqz ⟶ Change optimal gain

- up to 9 dB internal squeezing
- up to10.5 dB injected squeezing
- 8% injection loss
- 1.2% intra-cavity loss

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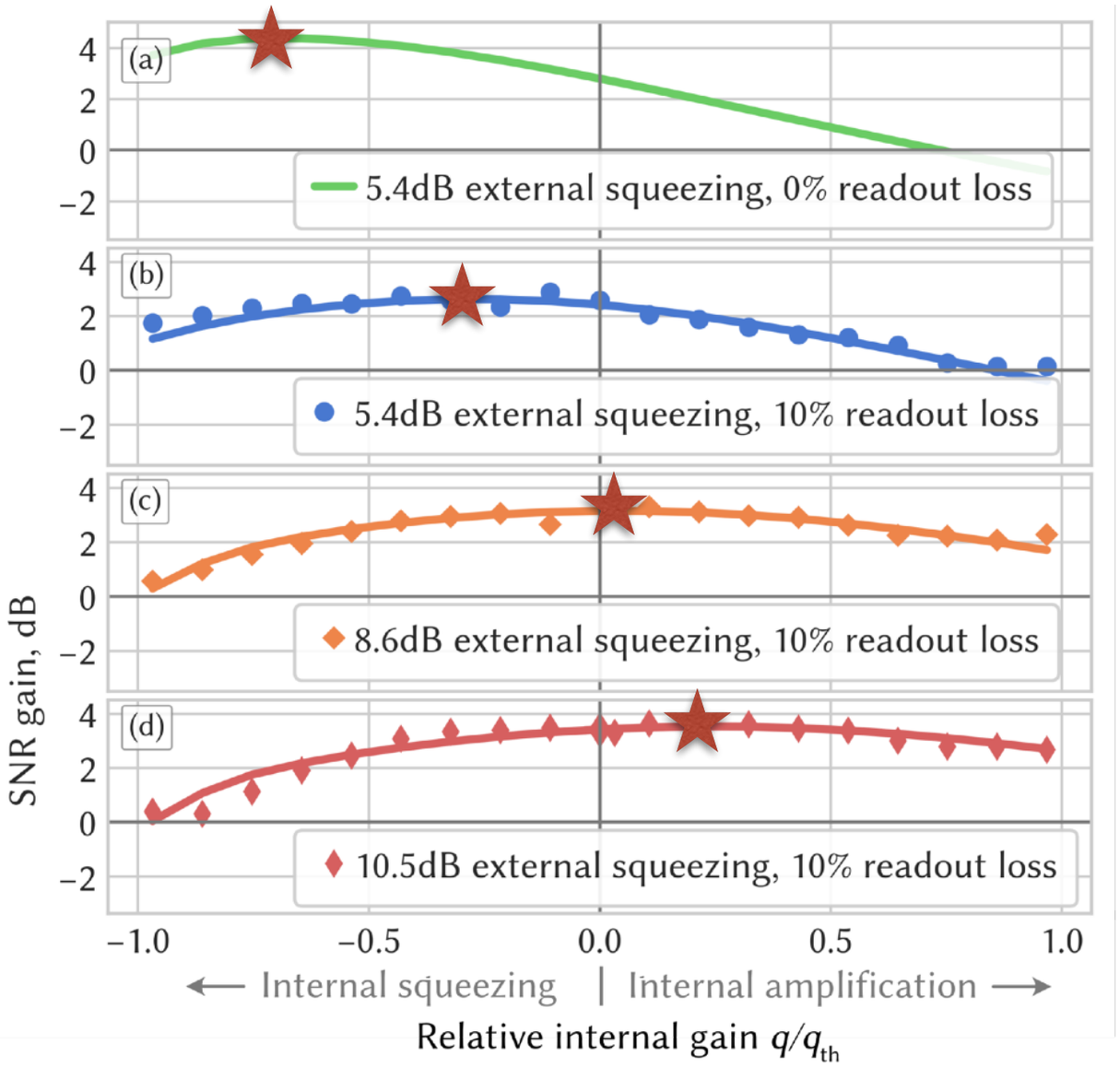
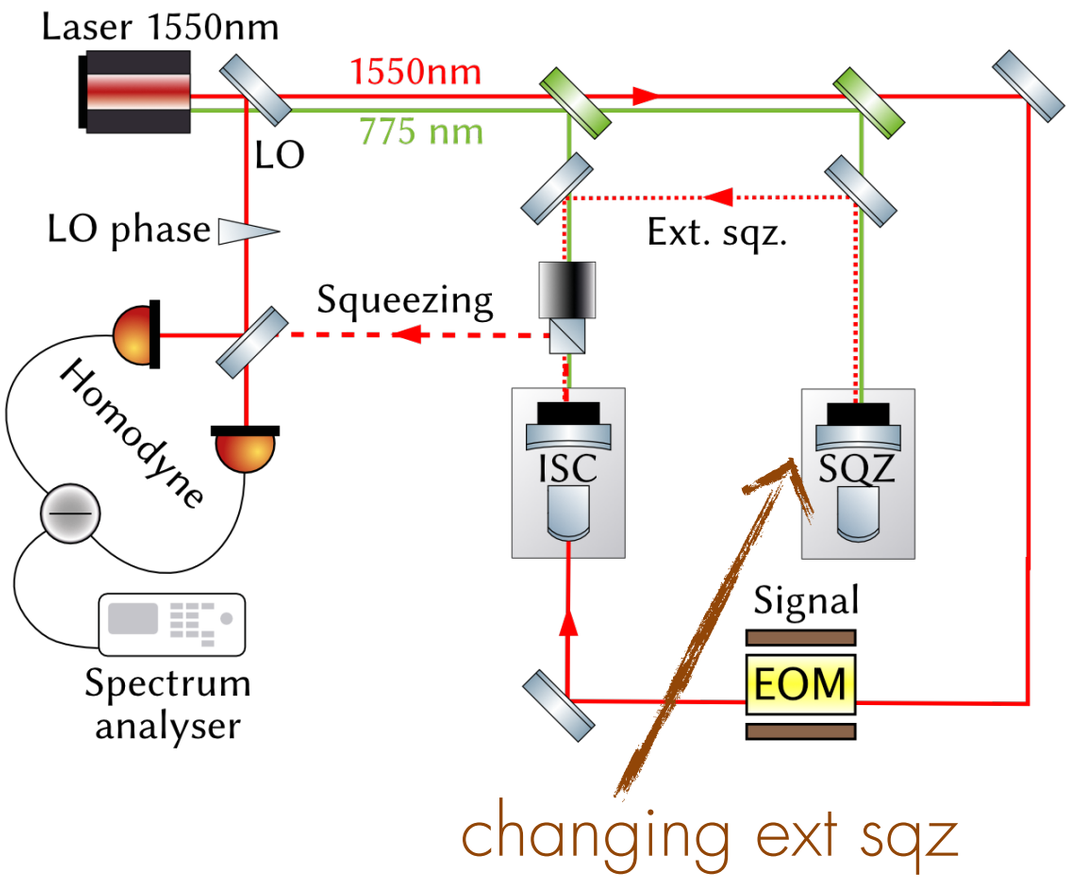
Loss mitigation



Experimental optimal gain



Increase external sqz ⟶ Optimal to amplify

- up to 9 dB internal squeezing
- up to10.5 dB injected squeezing
- 8% injection loss
- 1.2% intra-cavity loss

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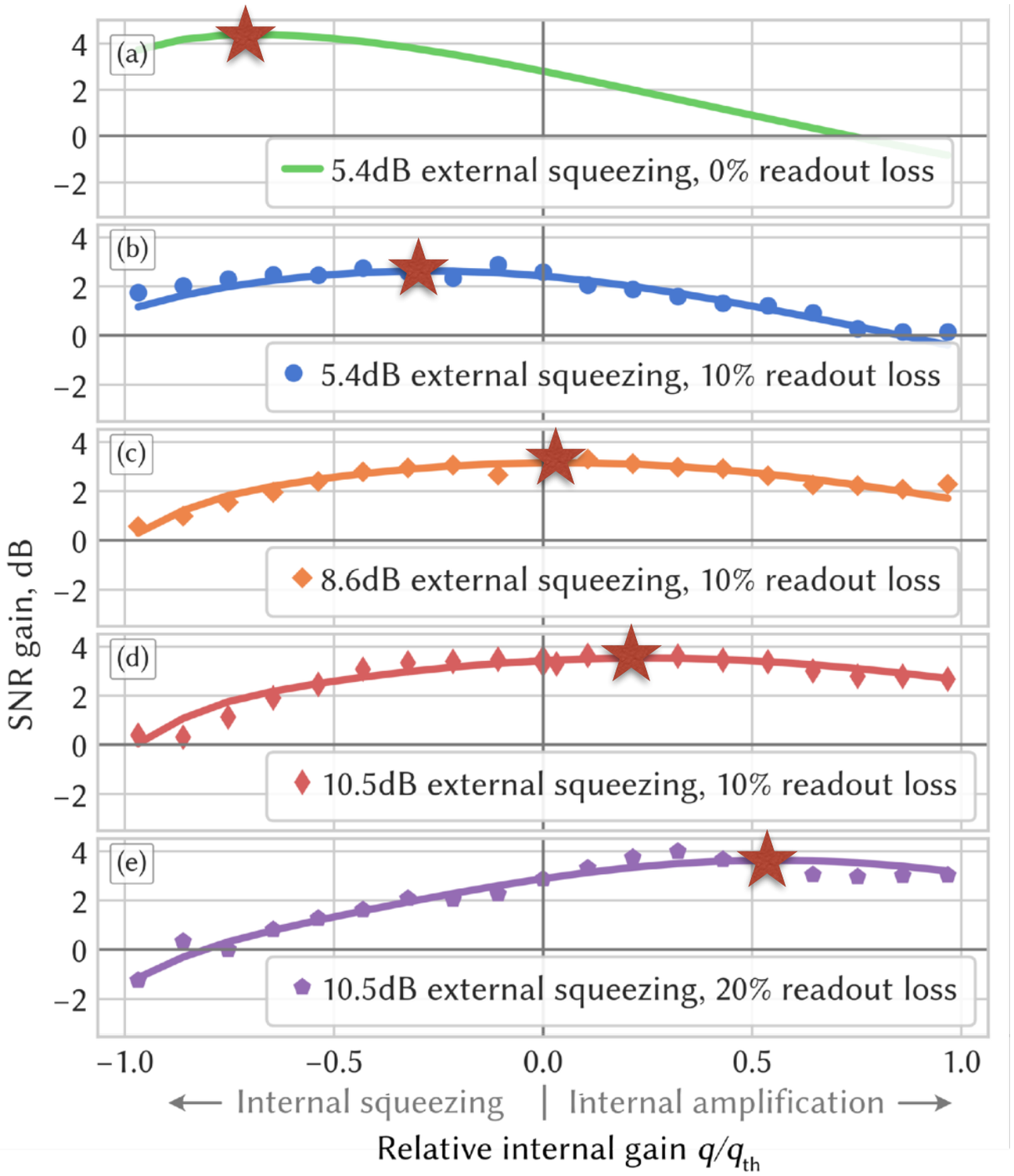
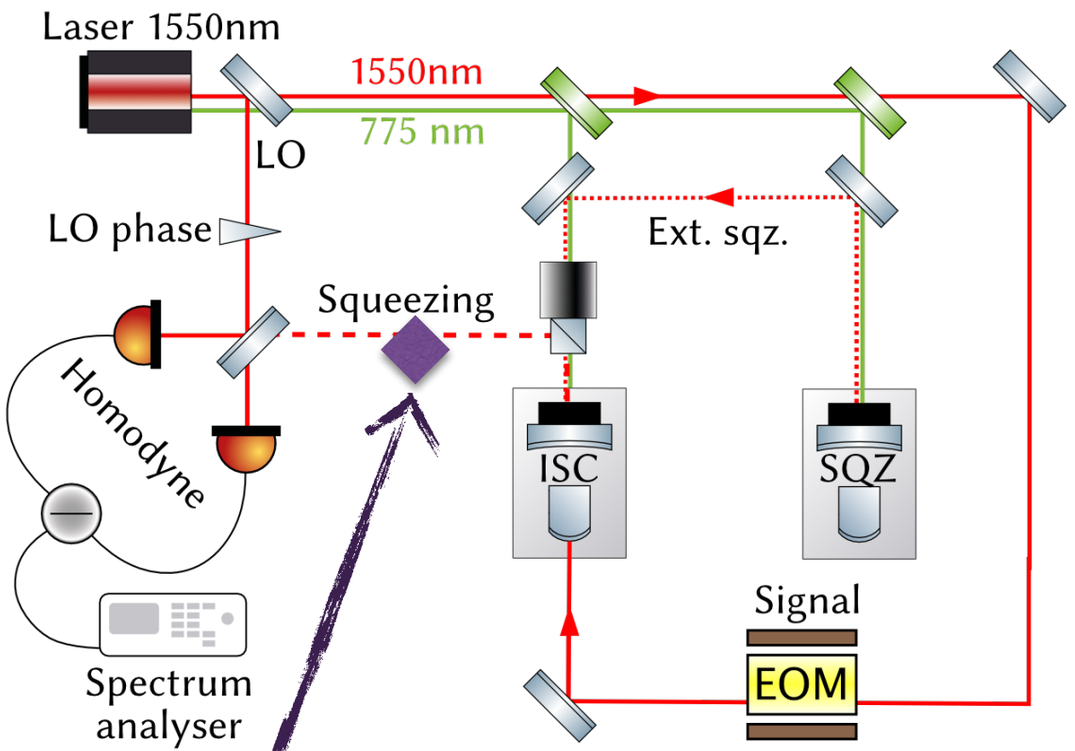
Loss mitigation



Experimental optimal gain



changing loss

- up to 9 dB internal squeezing
- up to10.5 dB injected squeezing
- 8% injection loss
- 1.2% intra-cavity loss

Increase readout loss ⟶ Optimal to amplify

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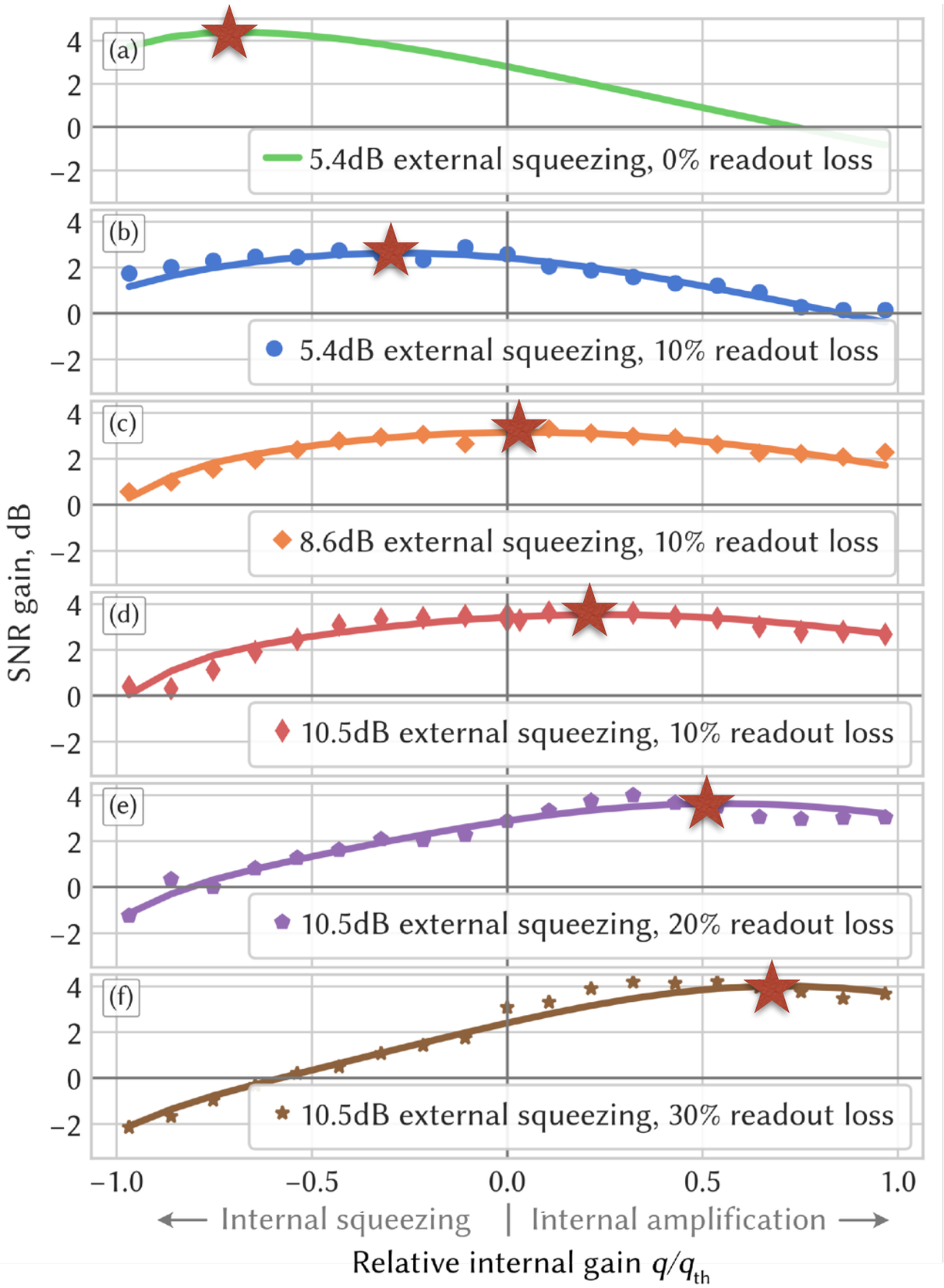
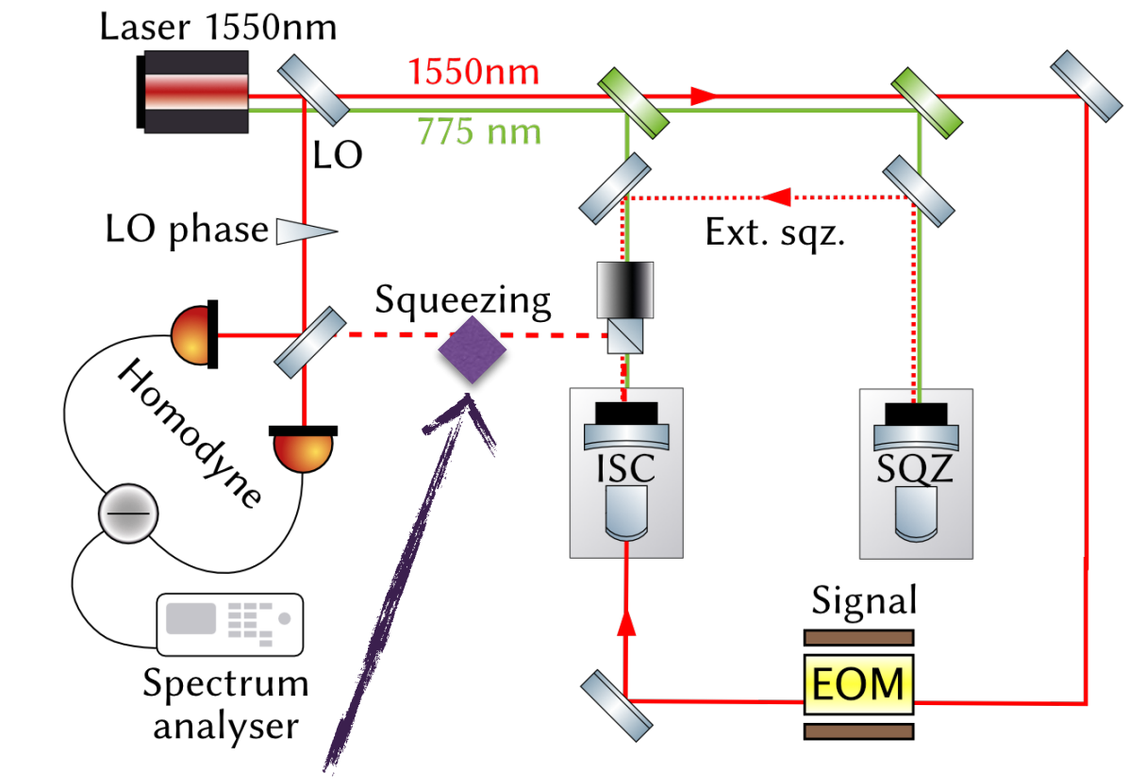
Loss mitigation



Experimental optimal gain



changing loss

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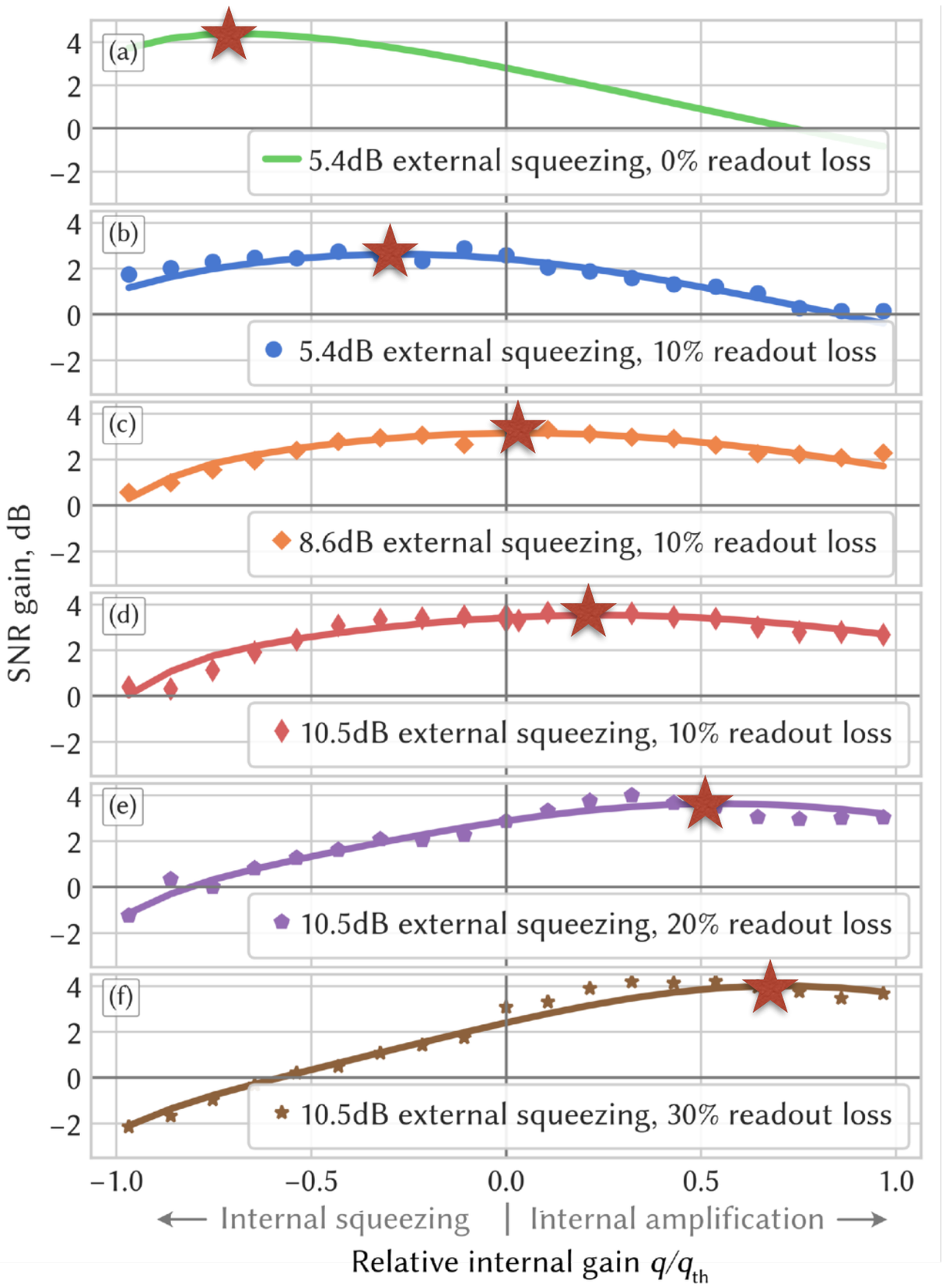
Loss mitigation



Experimental optimal gain

We observe ~4dB enhancement independent on readout loss from 10% → 30%

Optimal gain changes depending on:

- level of external squeezing
- readout loss

Solid curve (theory) is not a fit!
It's a prediction based on the measured parameters

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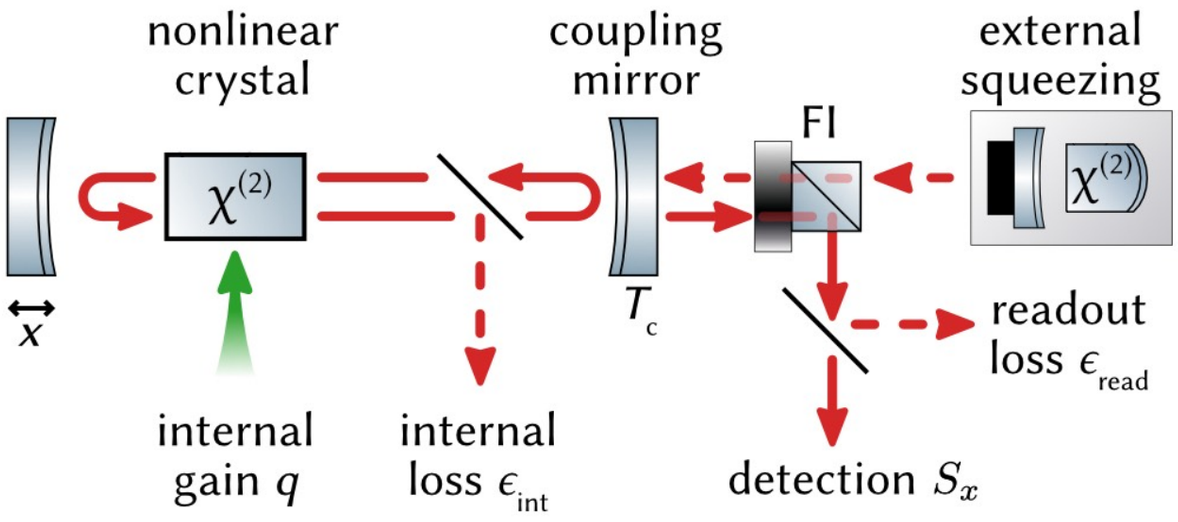
Fundamental quantum limit



Sources of loss

Different loss mechanisms

- injection loss limits the amount of sqz before interaction
- readout loss occurs after interaction and acts both on signal and noise
- internal loss happens during the measurement process

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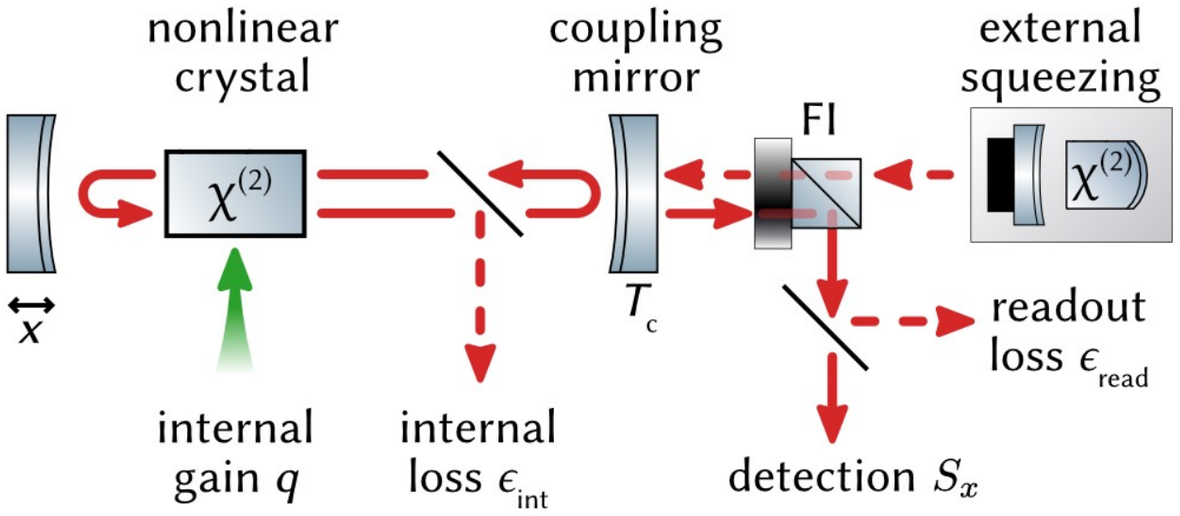
Fundamental quantum limit



Ultimate limit

Different loss mechanisms

- injection loss limits the amount of sqz before interaction
- readout loss occurs after interaction and acts both on signal and noise
- internal loss happens during the measurement process

Fundamental quantum limit

$$S^{\mathrm{lim}}(0) = 4\epsilon_{\mathrm{int}} \times \frac{\hbar\lambda c}{8\pi P_c}$$

External sqz → ∞

QCRB is defined by the interaction between the object and the meter. It's limited by the purity of the state.

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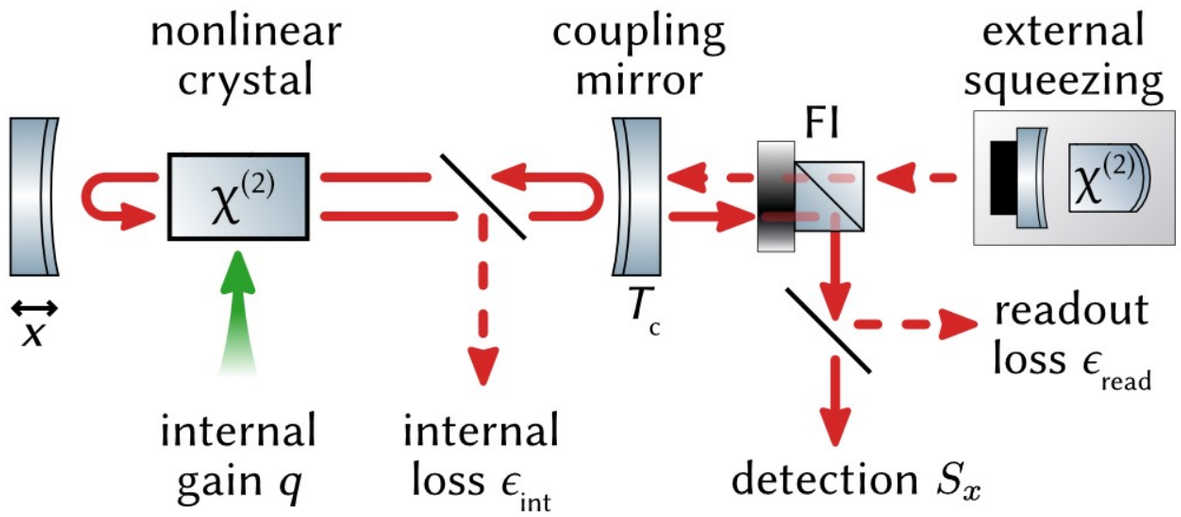
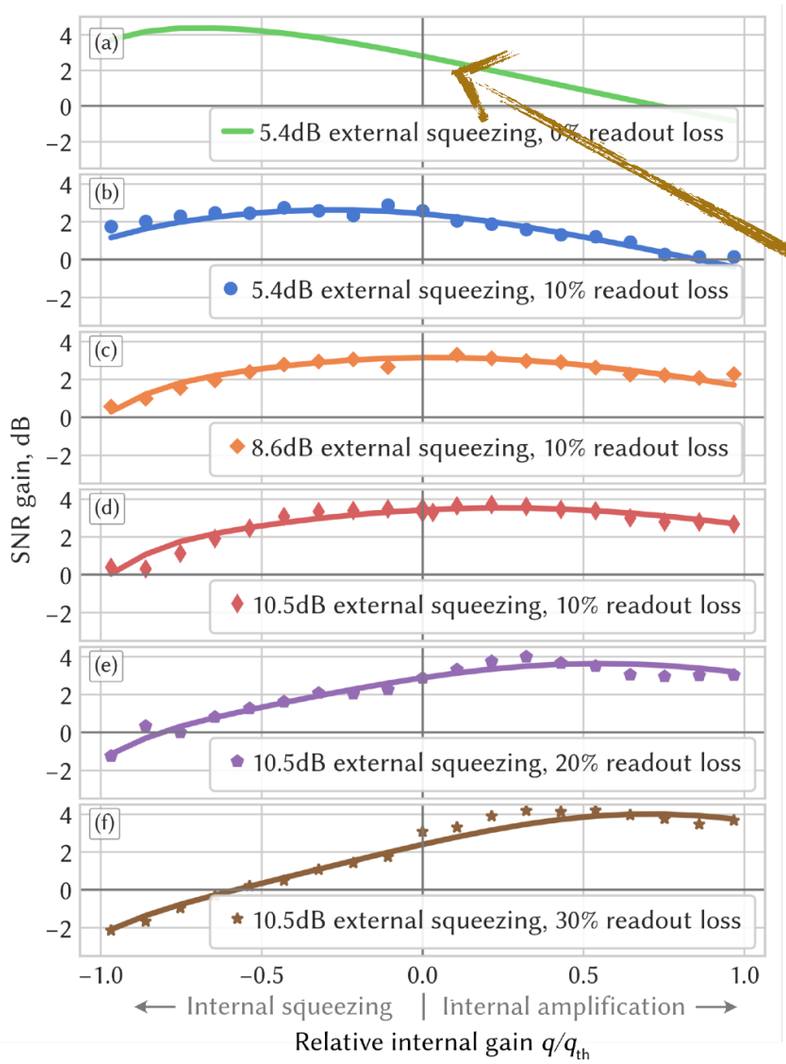
Fundamental quantum limit





General limit

Different loss mechanisms

- injection loss limits the amount of sqz before interaction
- readout loss occurs after interaction and acts both on signal and noise
- internal loss happens during the measurement process

For finite external sqz r, the fundamental limit:

$$S^{\text{opt}} \sim S^{\text{lim}} + 4\frac{T_c\epsilon_{\text{read}}}{\epsilon_{\text{read}}e^{2r} + (1-\epsilon_{\text{read}})}$$

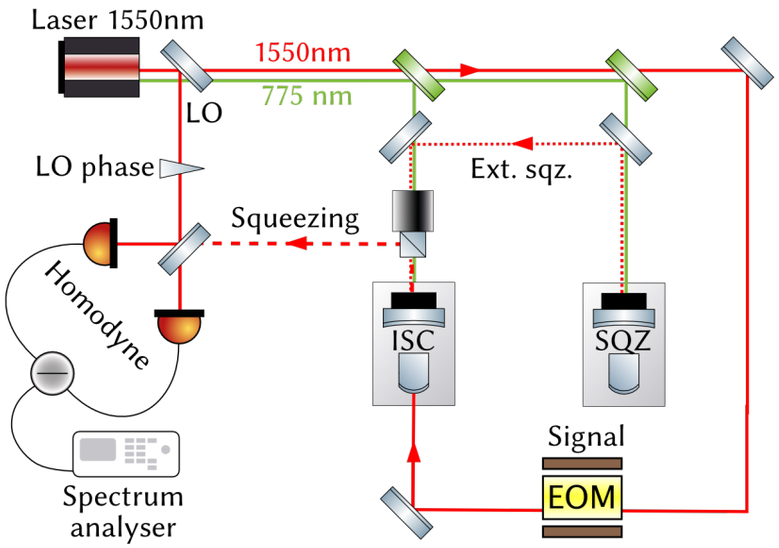
arXiv: 2303.09983

Conclusions

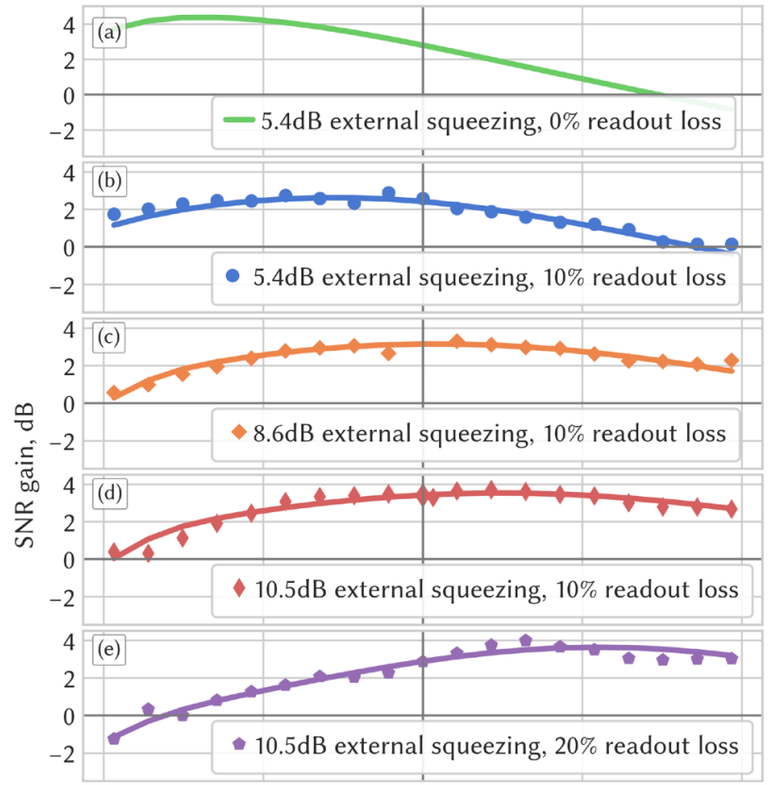
- First demonstration of combined internal+ external squeezing

- Optimal internal squeezing mitigates quantum decoherence

- The ultimate limit is given by internal loss



$$S^{\mathrm{lim}}(0) = 4\epsilon_{\mathrm{int}} \times \frac{\hbar\lambda c}{8\pi P_c}$$



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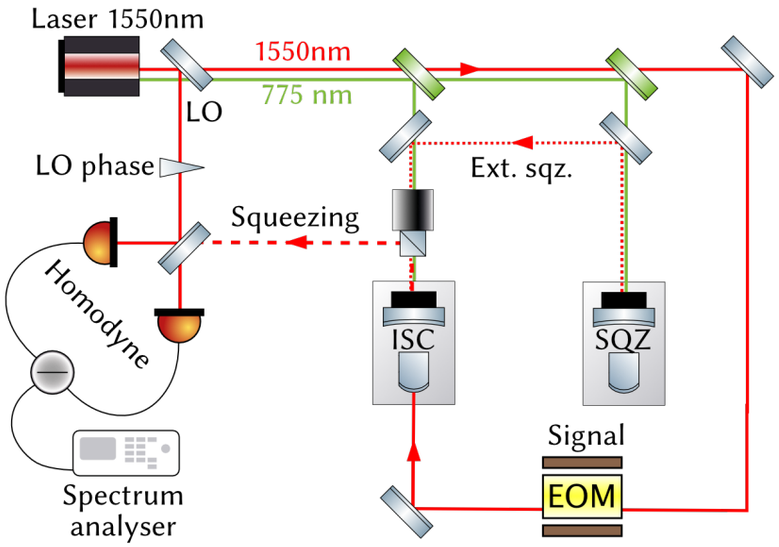

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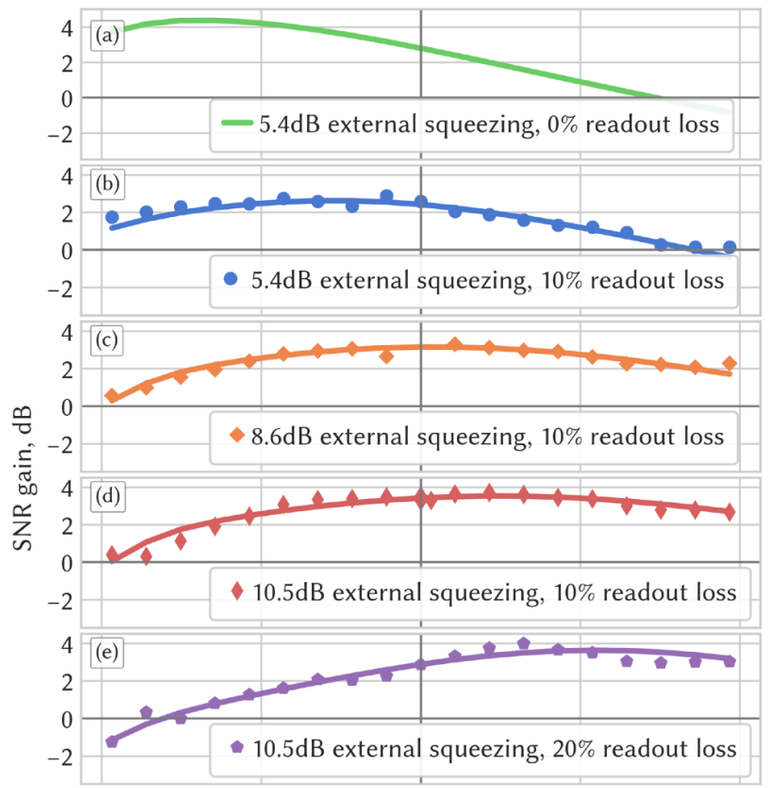


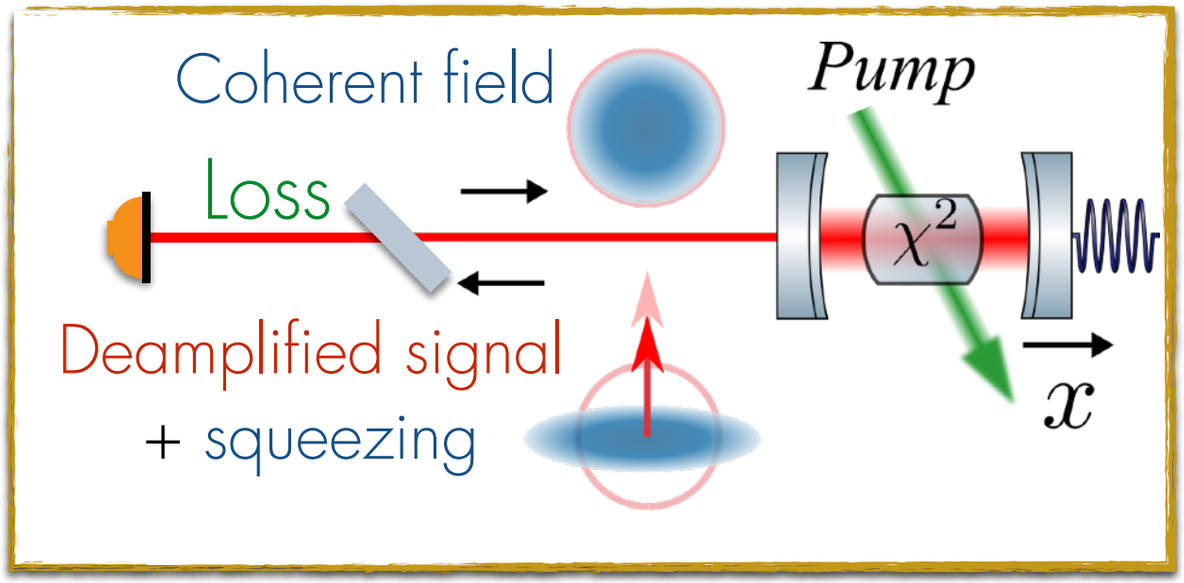
Thank you for your attention!

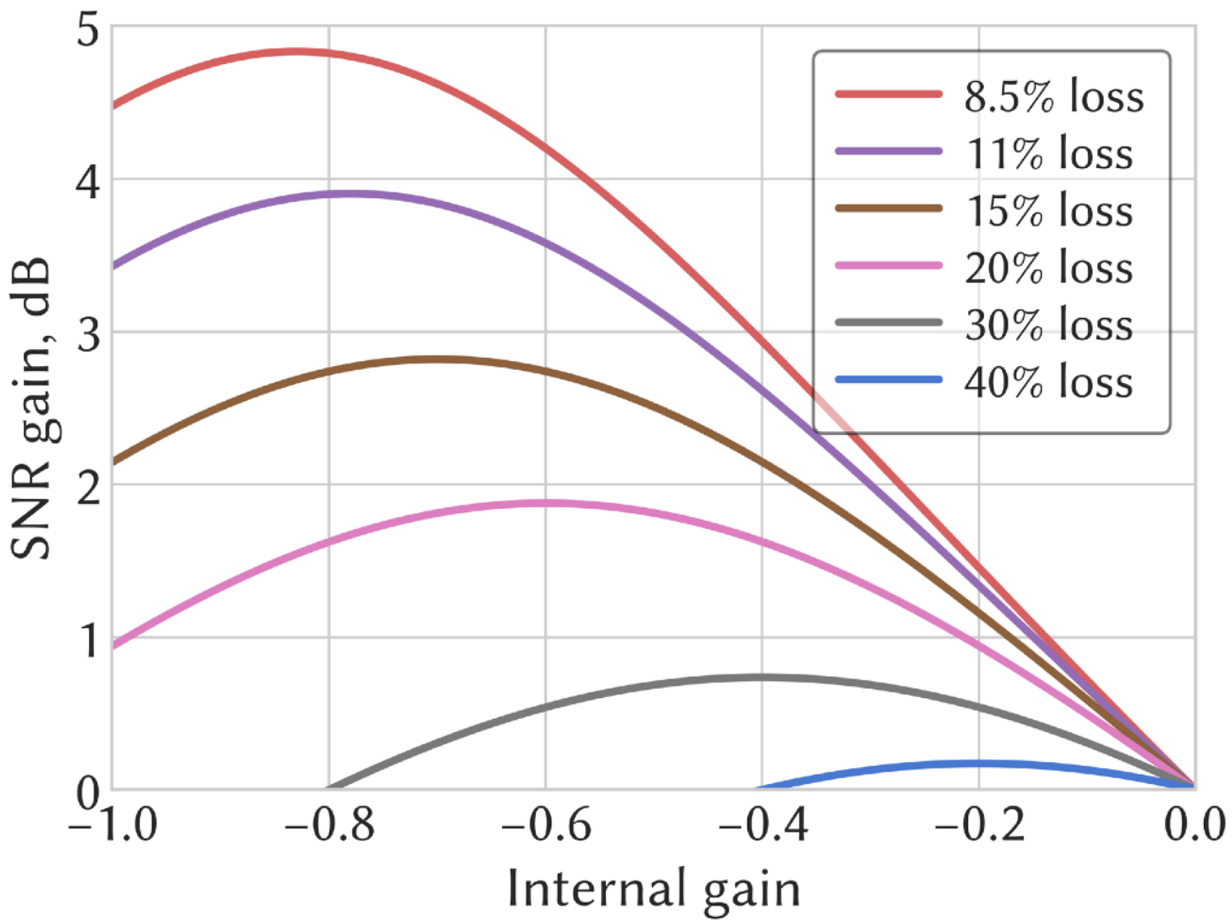
Details in preprint: 2303.09983

and theory in my thesis DCC P2000301

Extra

Internal squeezing concept





Optimal squeezing

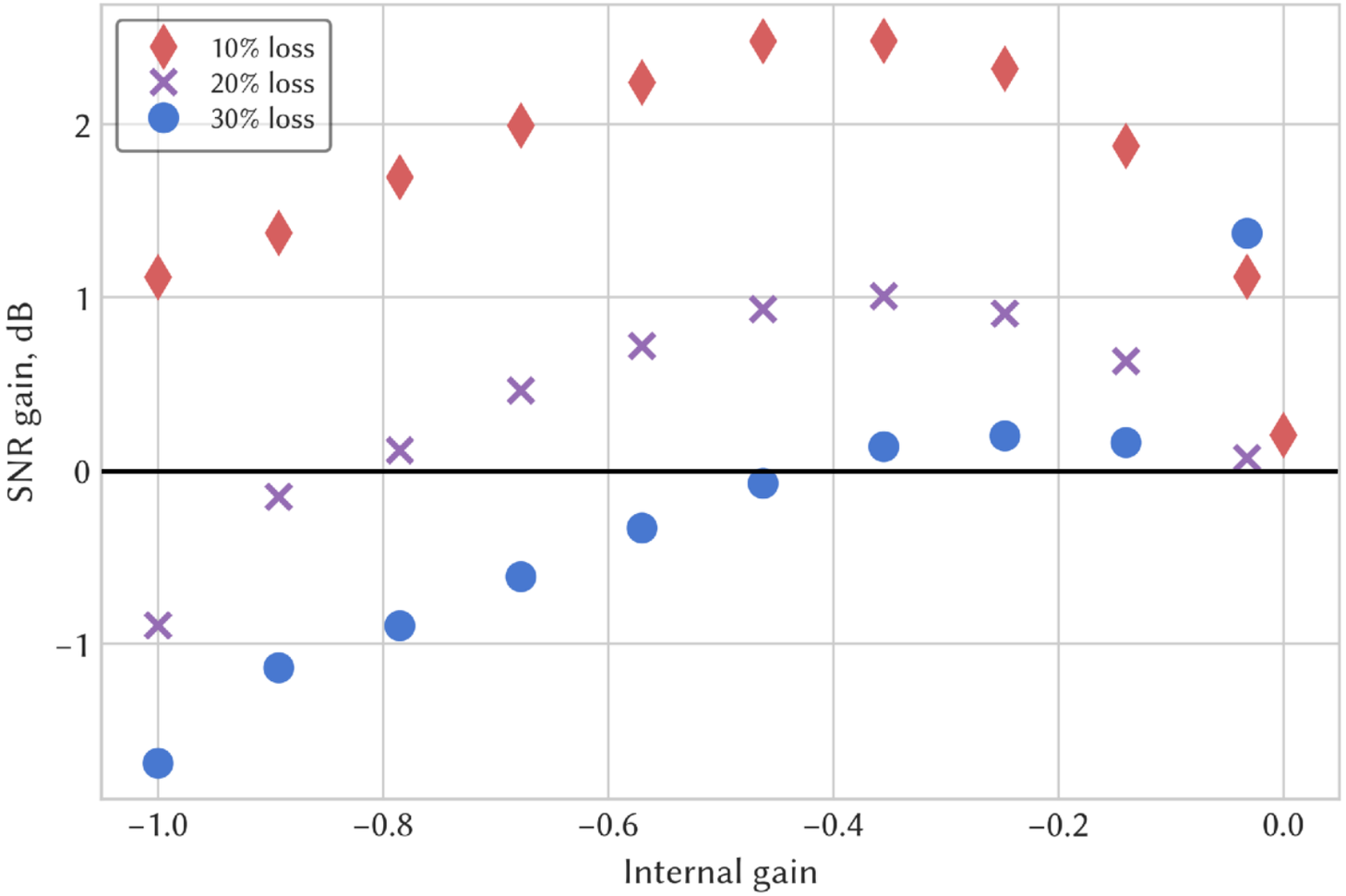
Maximal signal deamplification:
6dB at threshold

Maximal squeezing:
infinite

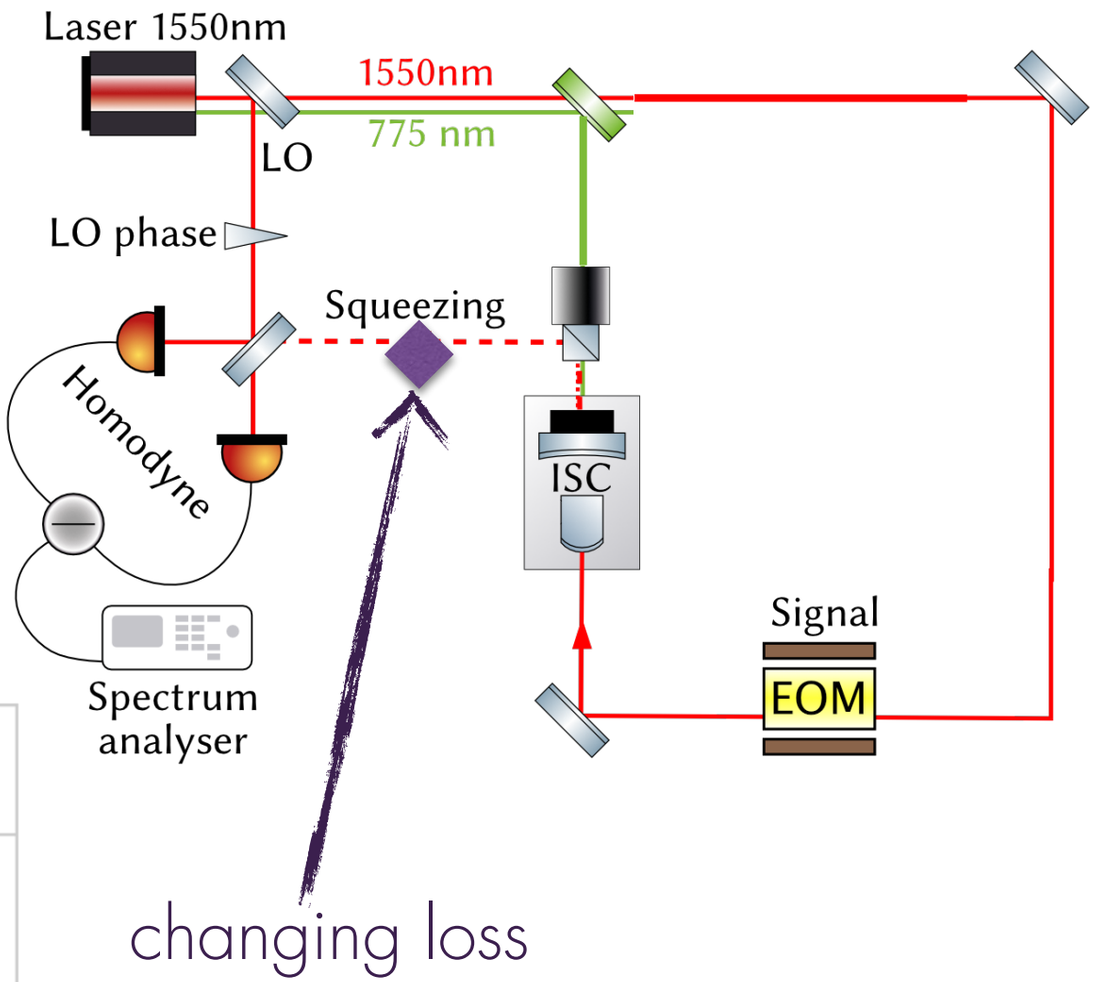
- There exists an optimum
- For different losses it's different

Internal squeezing concept

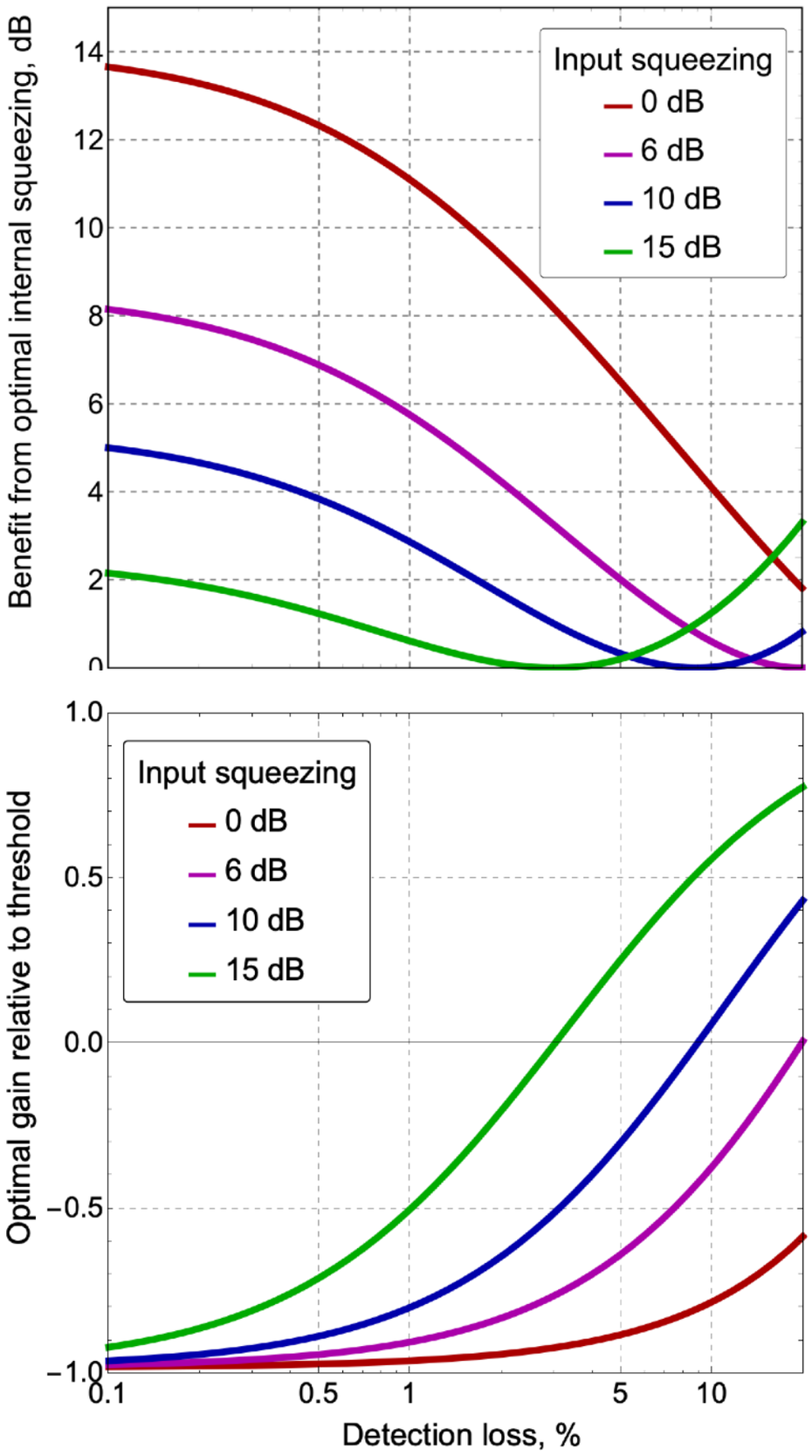
- There exists an optimum
- For different losses it's different



Experimental optimum



Internal + external sqz



Optimal gain

Benefit from optimal internal+external squeezing wrt to external squeezing

Internal squeezing balances two things

→ Creates squeezing for small loss

→ Amplifies signal for large loss

Limit with optimal internal squeezing

$$S^{\mathrm{lim}}(0) = 4\epsilon_{\mathrm{int}} \times \frac{\hbar\lambda c}{8\pi P_c}$$

internal loss