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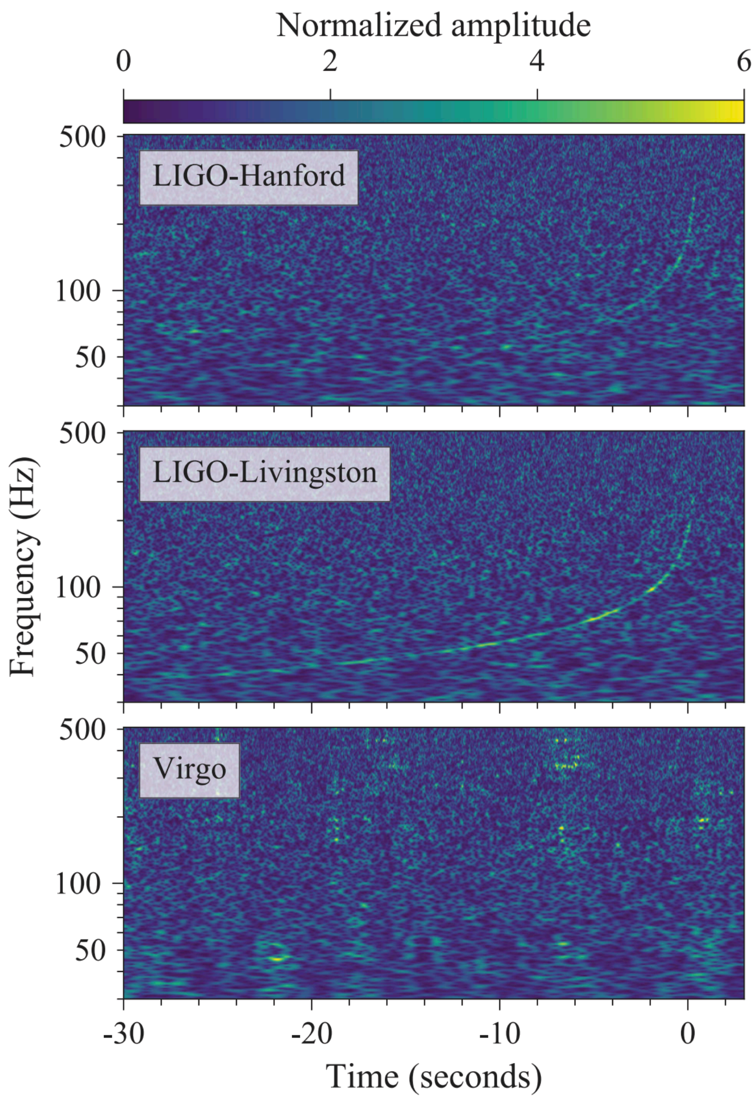
GEO 600 / ALBERT-EINSTEIN-INSTITUT HANNOVER
DISPUTATION, 15. JANUAR 2018

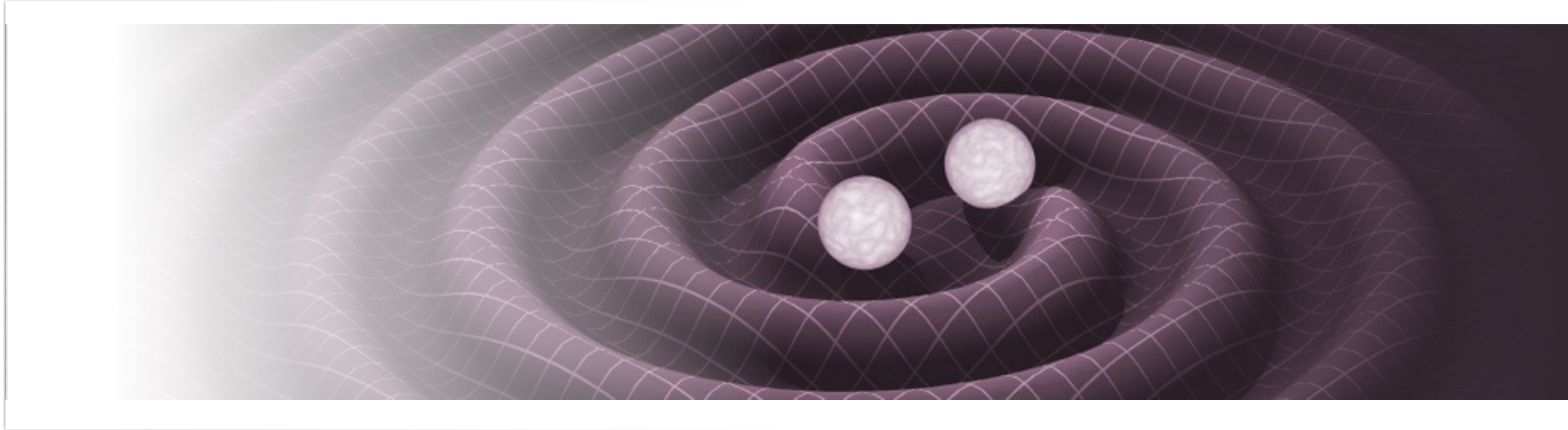
Gravitational-wave detection beyond the quantum shot-noise limit

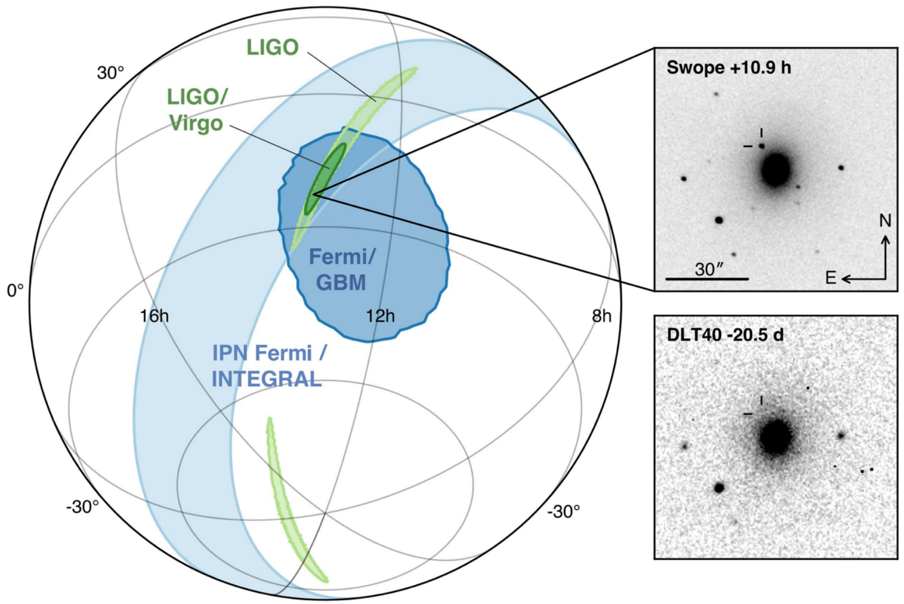
The integration of squeezed light in GEO600

Gravitational waves from a binary neutron star inspiral



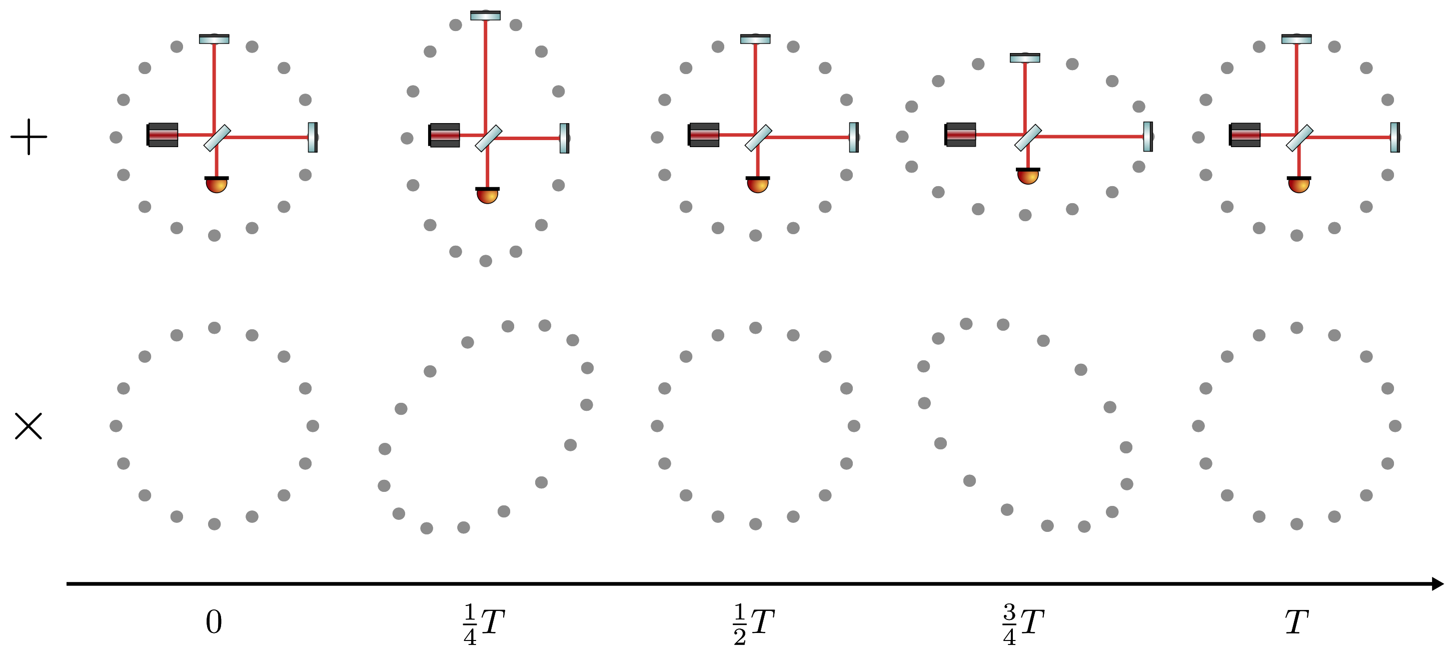
Abbott et al. (2017) PhysRevLet *119*(16), 161101.

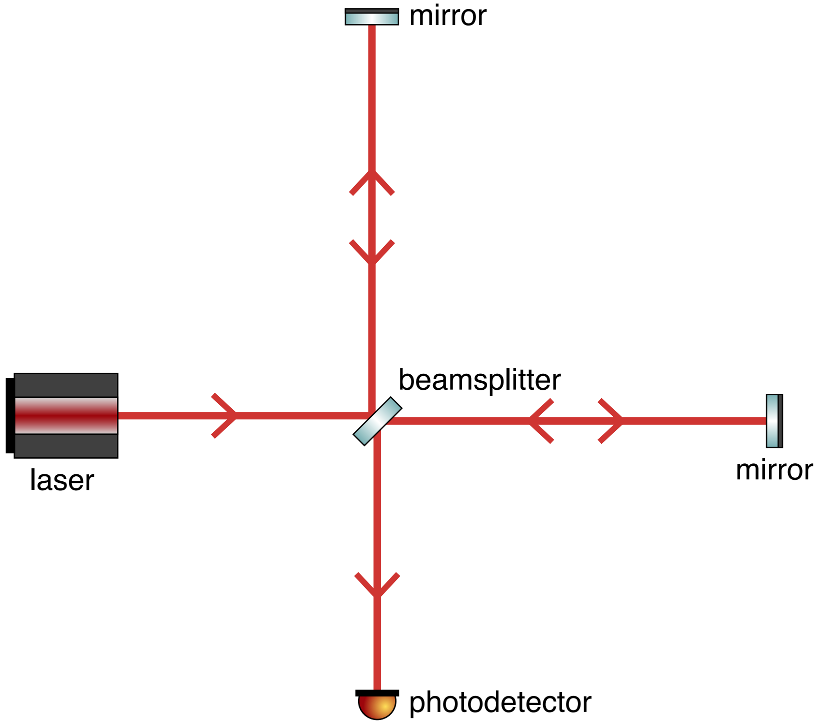




Abbott et al. (2017) APJL *848*(2), L12.

Gravitational waves in an interferometer

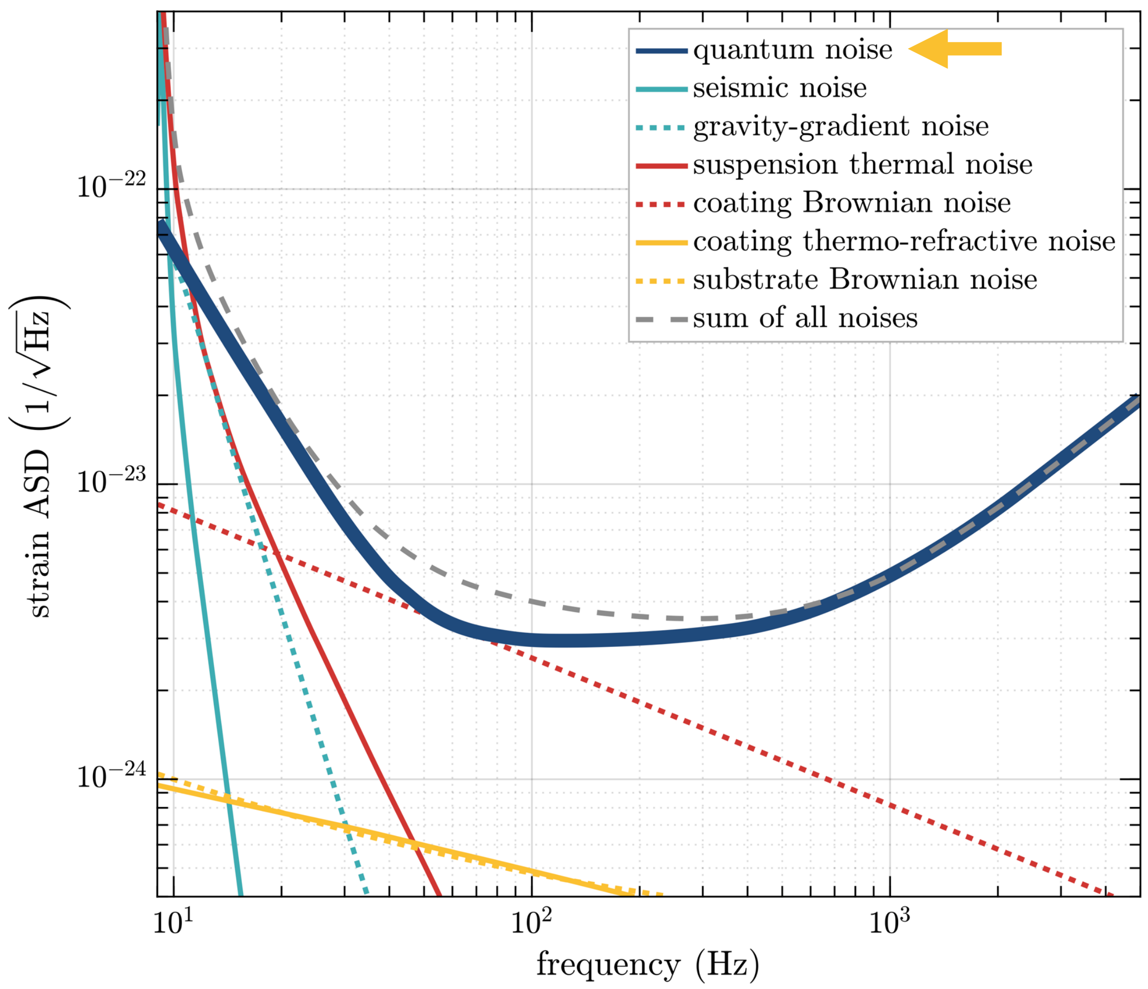




Michelson interferometer

Sensitivity of GW detectors

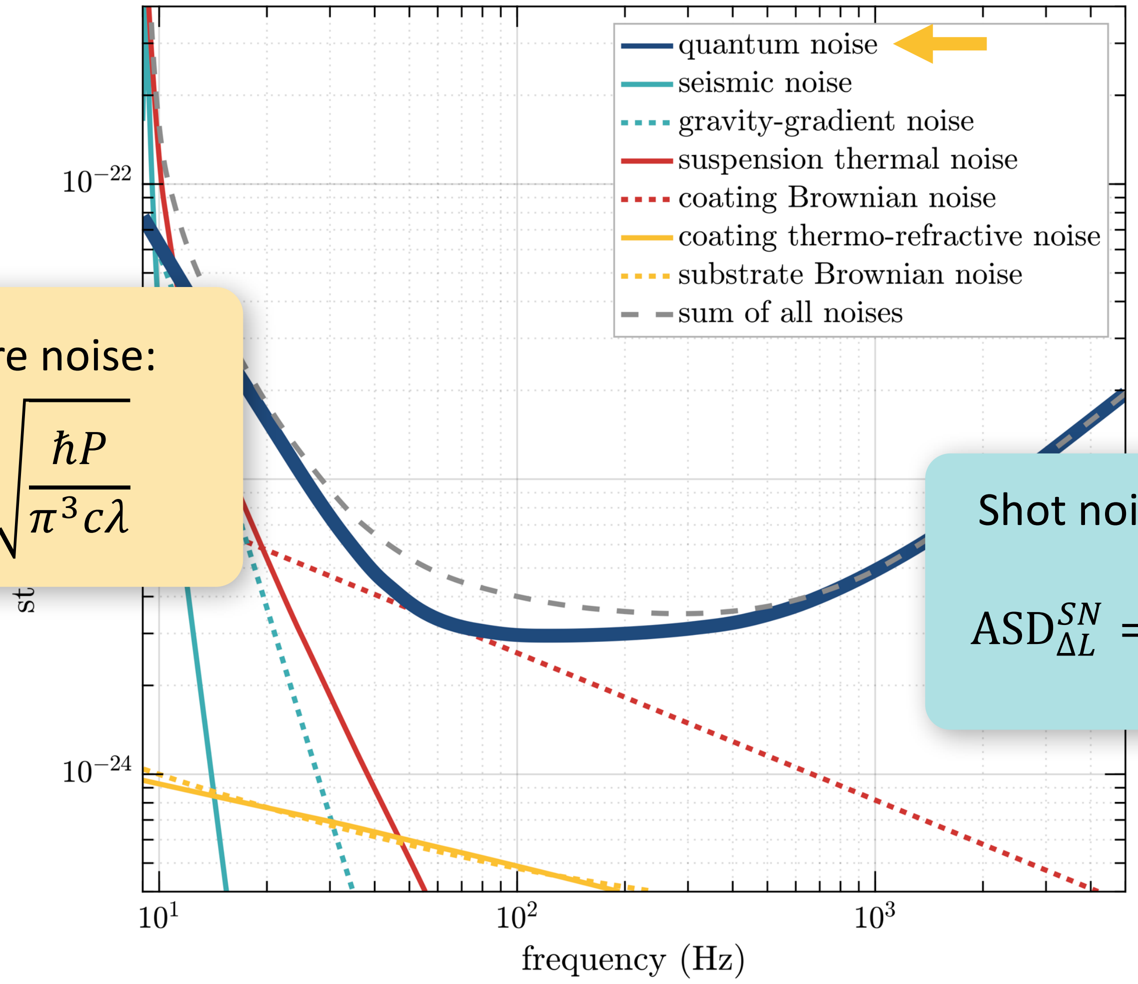
Advanced LIGO design noise budget:



Aasi et al. (2015) *CQG 32*(7), 74001.

Quantum noise

Advanced LIGO design noise budget:



Radiation pressure noise:

$$\mathrm{ASD}_{\Delta L}^{RPN} = \frac{1}{mf^2}\sqrt{\frac{\hbar P}{\pi^3 c\lambda}}$$

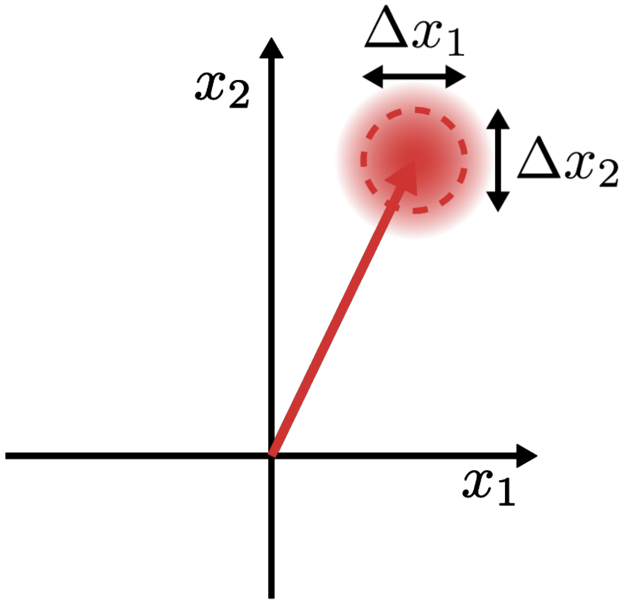
Shot noise:

$$\mathrm{ASD}_{\Delta L}^{SN} = \sqrt{\frac{\hbar c\lambda}{4\pi P}}$$

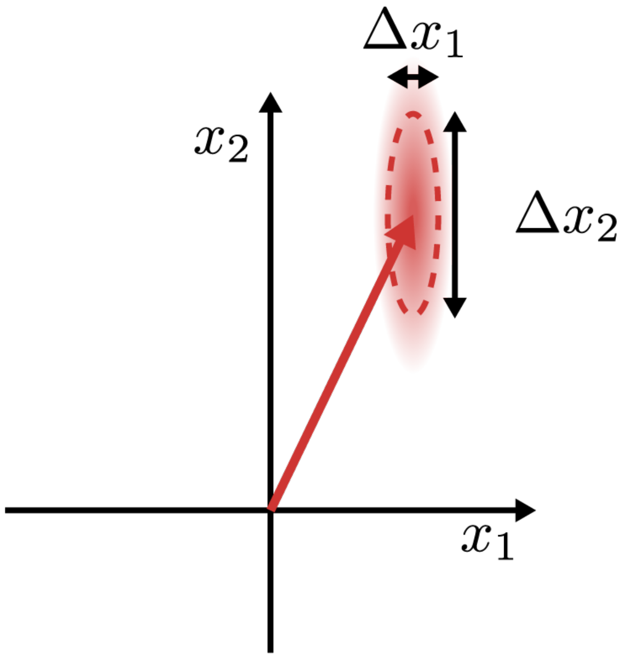
Aasi et al. (2015) *CQG 32*(7), 74001.

Quantum phasor diagram

coherent state:



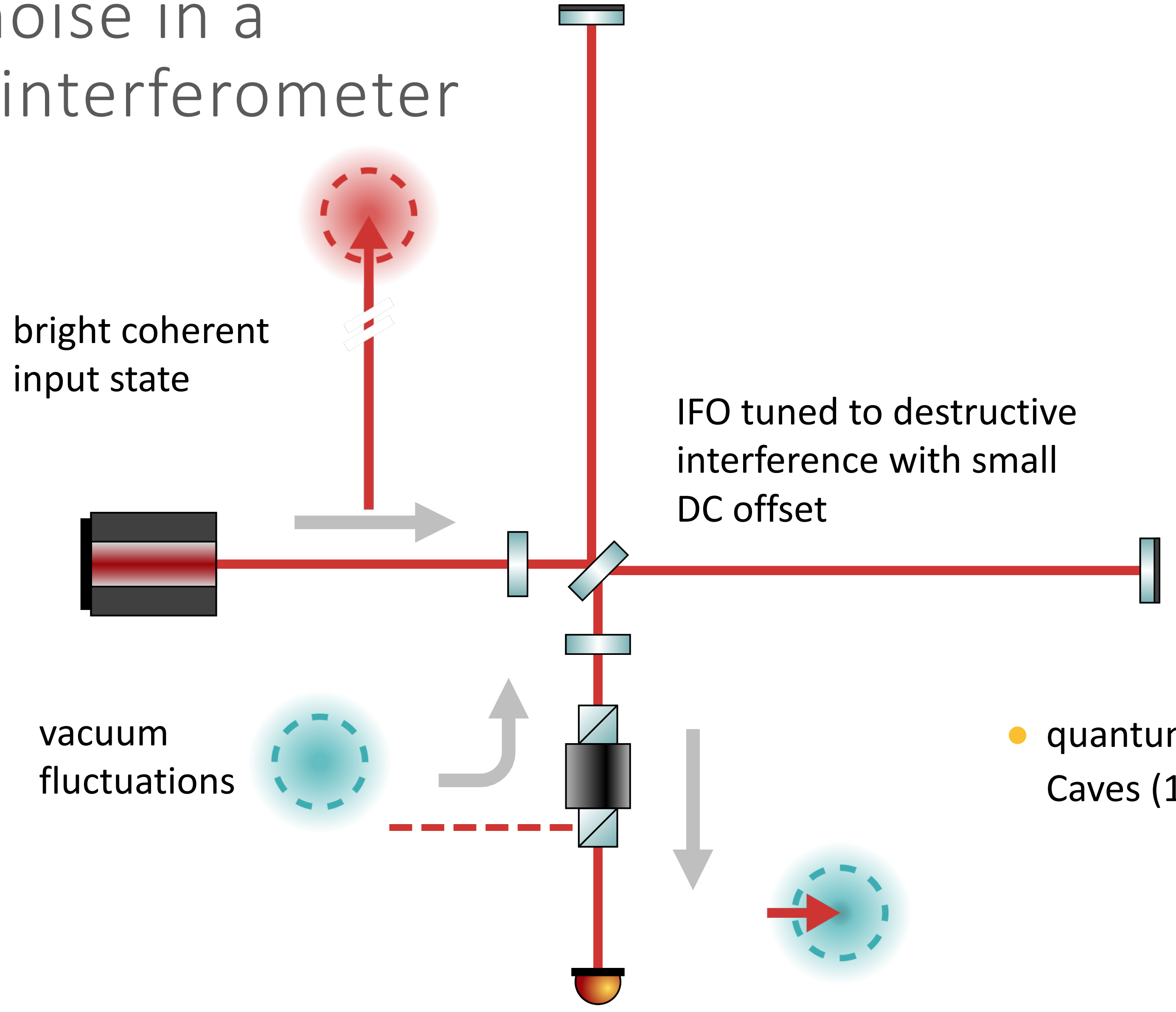
squeezed state:



Heisenberg uncertainty relation:

$$\Delta x_1 \Delta x_2 \geq \frac{1}{4}$$

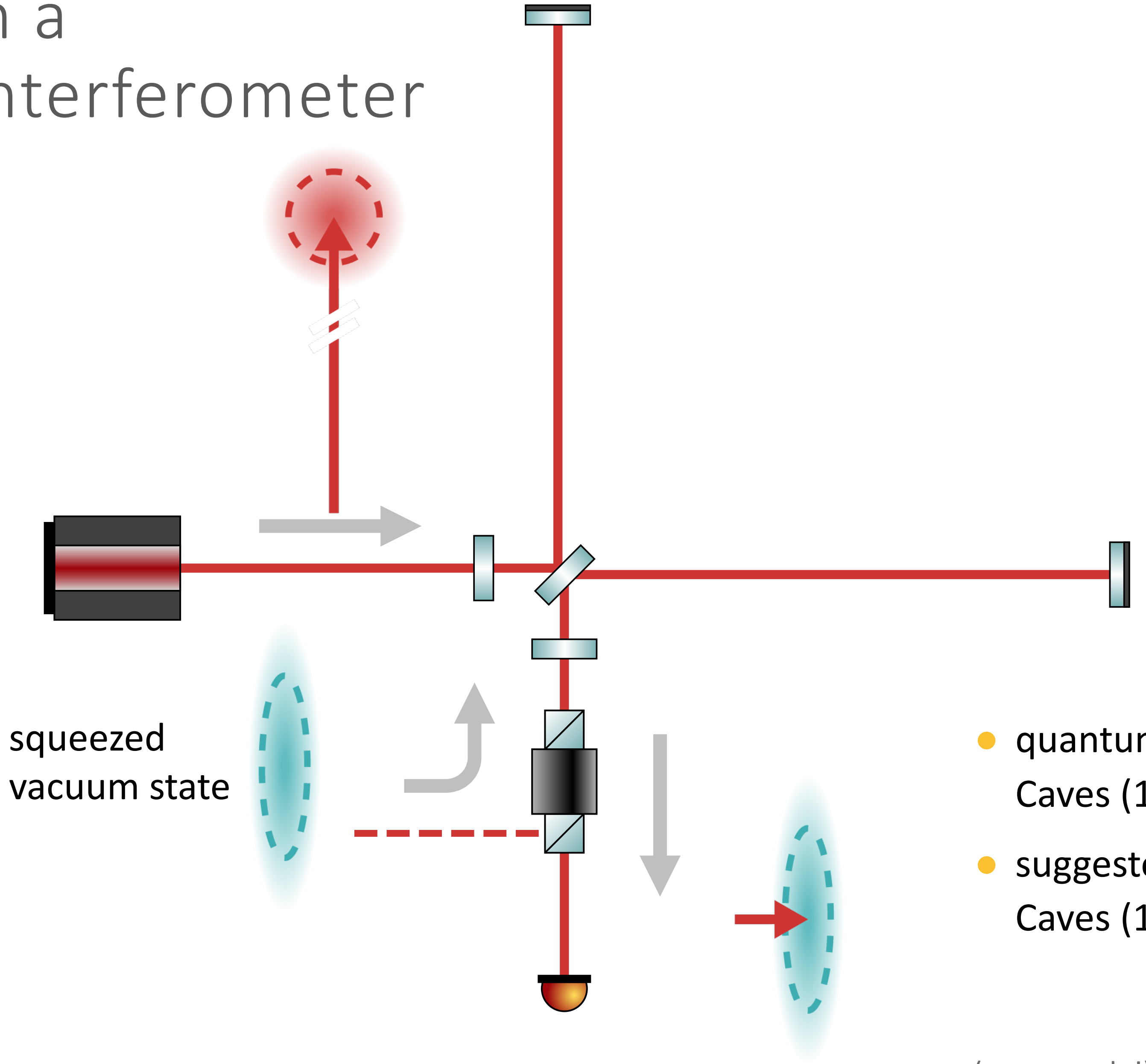
Quantum noise in a Michelson interferometer



- quantum noise in IFO explained: Caves (1980) *PRL 45*(2), 75–79.

(not to scale!)

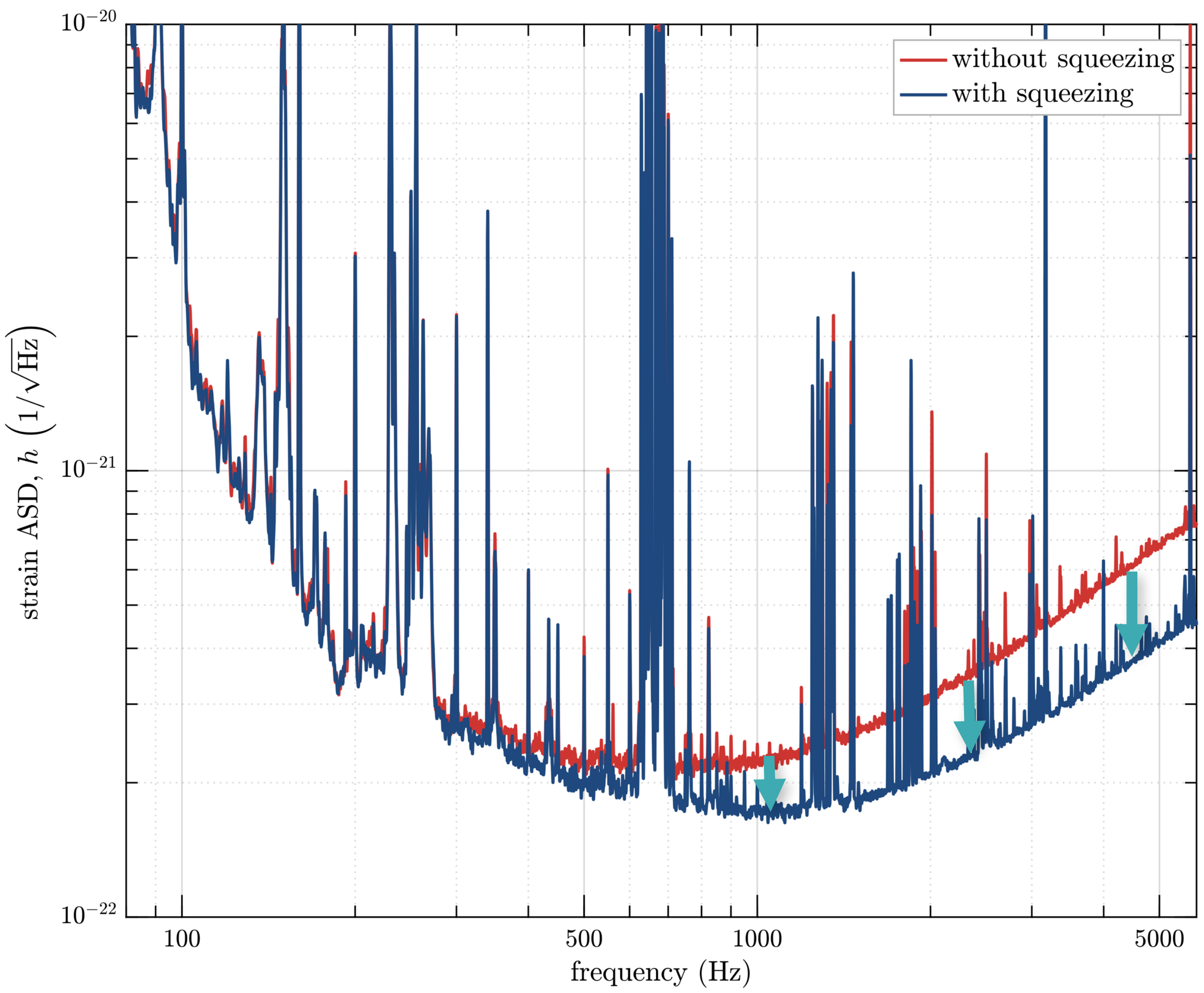
Squeezing in a Michelson interferometer



- quantum noise in IFO explained: Caves (1980) *PRL 45*(2), 75–79.
- suggested squeezing: Caves (1981) *PhysRev D 28*(8).

(not to scale!)

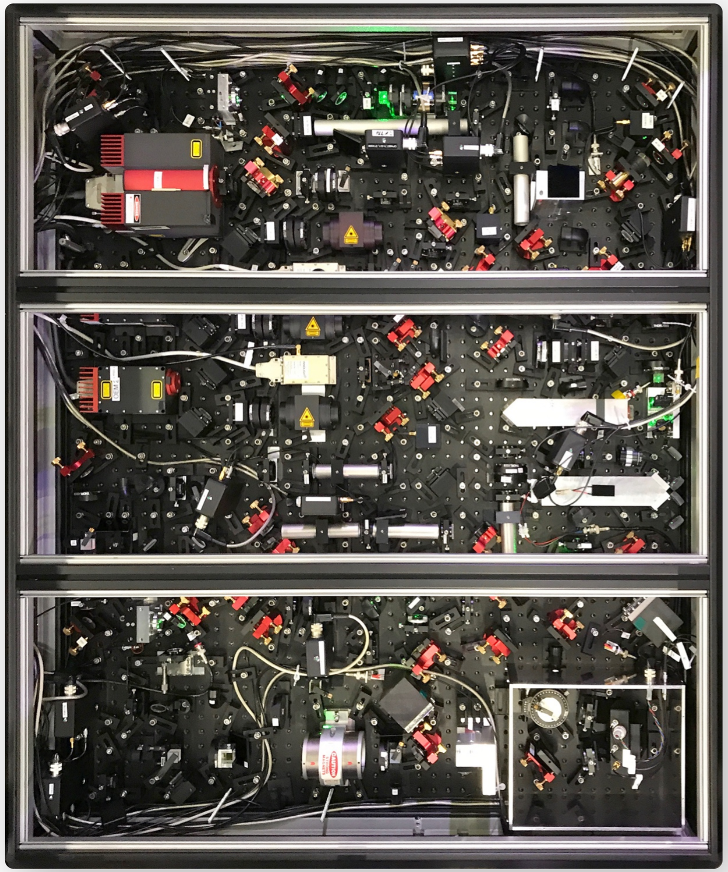
Squeezing in GEO 600



Outline

1. Long-term operation of the GEO 600 squeezed-light source
2. Influence of imperfections
3. Practical squeezing injection at GEO 600
   - phase control
   - alignment control
   - loss mitigation
   - dark noise
   - backscattering
   - a new Faraday design
4. Squeezing results
5. Outlook

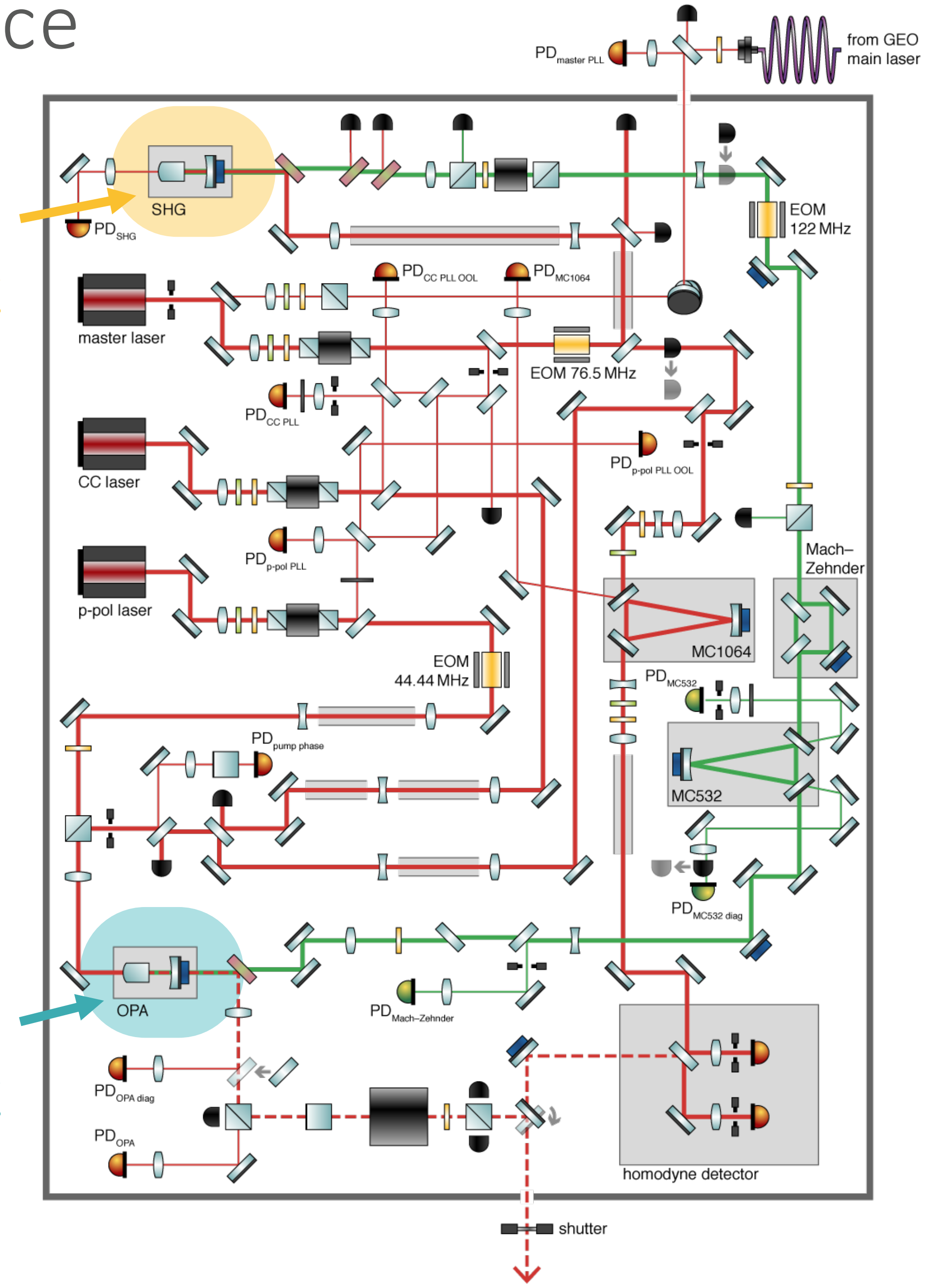
The GEO 600 squeezed-light source



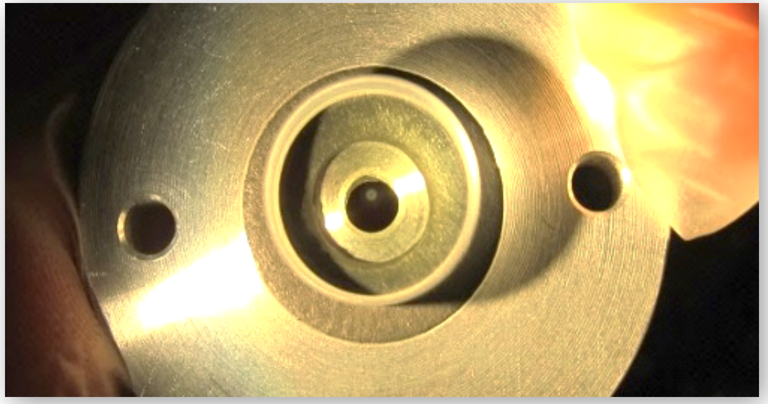
- build and characterized at the AEI
- installed at GEO 600 in 2010
  - → 7+ years of 24/7 operation

second harmonic generator

optical parametric amplifier

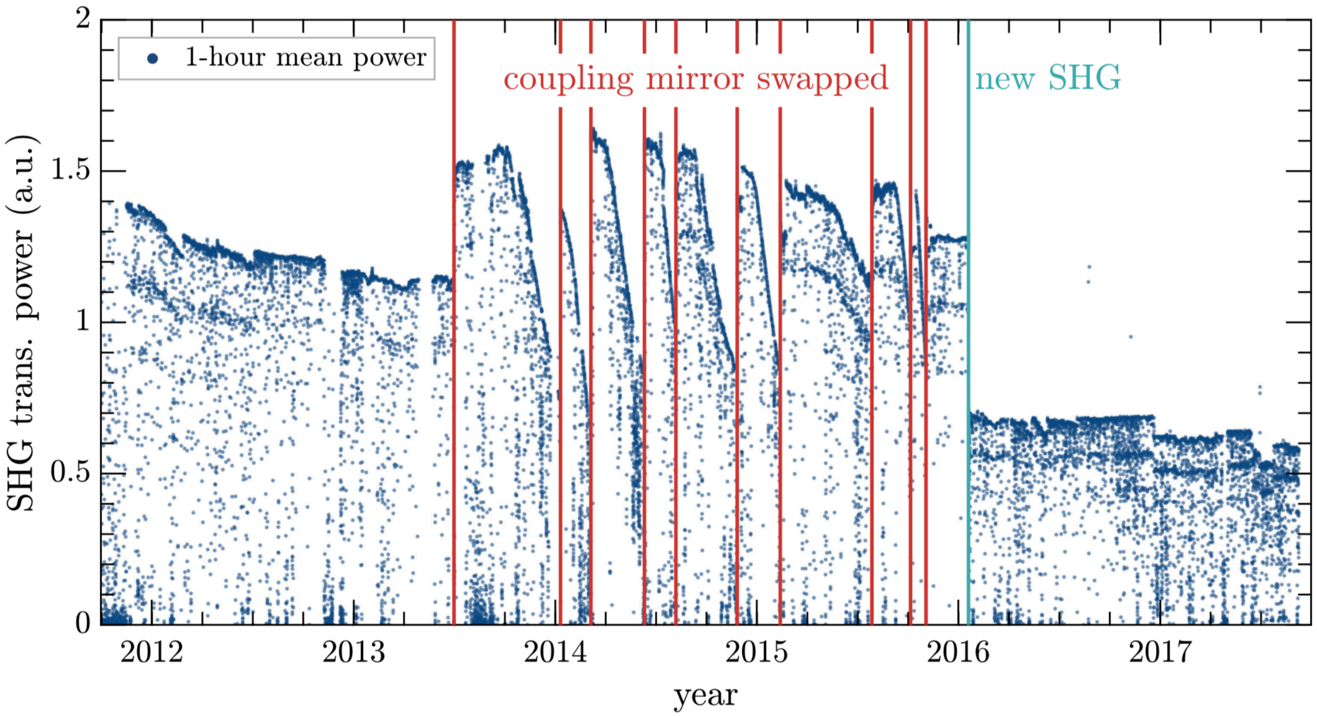


Long-term operation and degradation



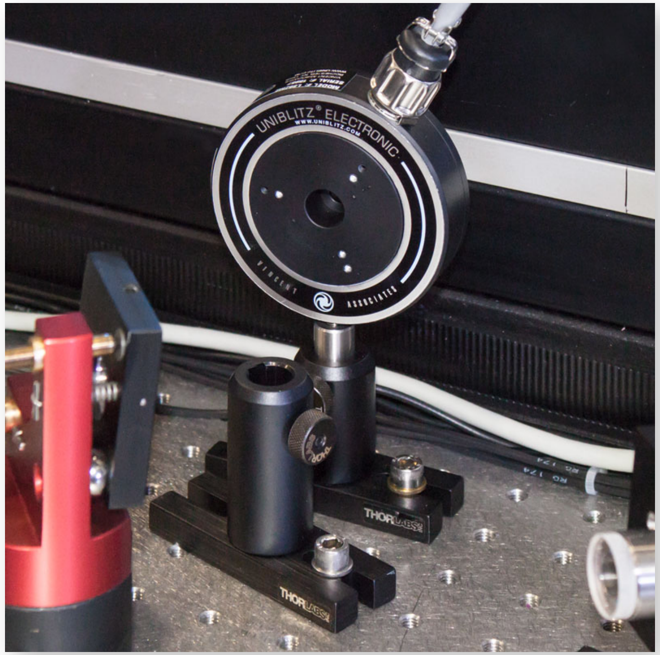
- routine maintenance:
  - temperature setpoint tuning
  - occasional alignment tuning

- observed power degradation in green path
- dirt accumulating on optics with high impinging green power
  - ➔ “laser-induced contamination”
- mitigated by using replacement parts avoiding all suspected contaminants (glue, thermal paste, vacuum grease)

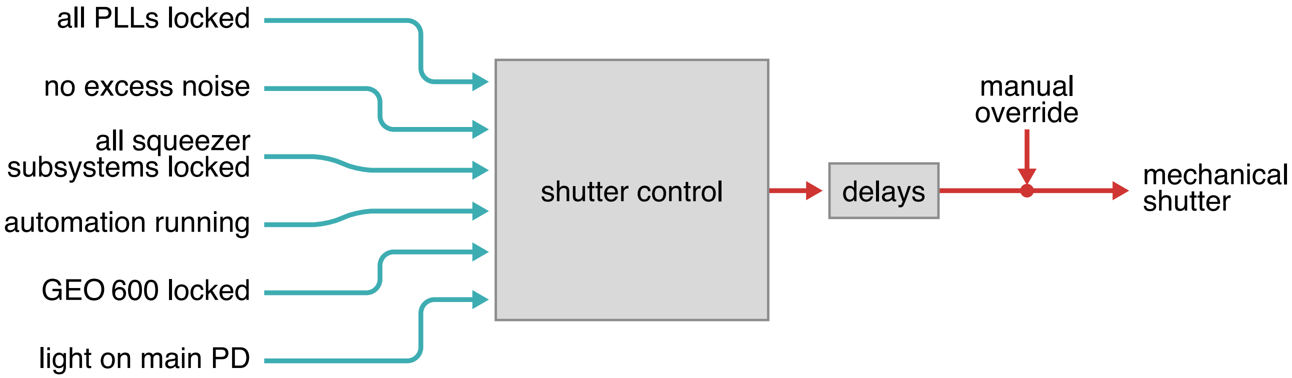


Automation

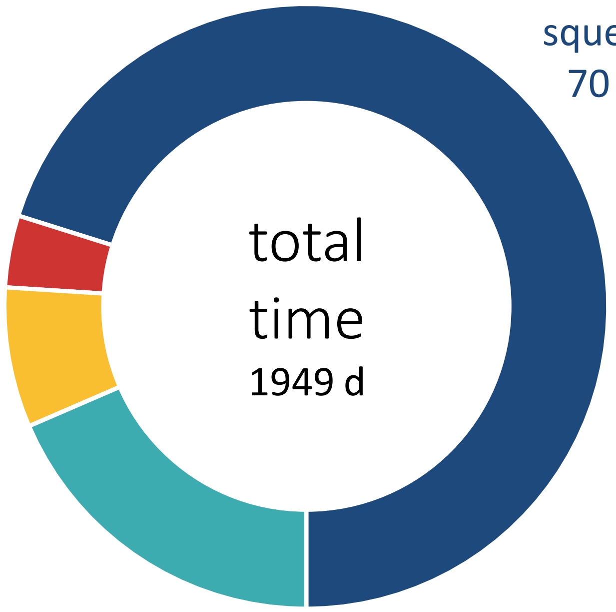
- fully automated locking of all squeezer subsystems
- implemented in digital real-time system (CDS)
- relock time optimized to < 3 s

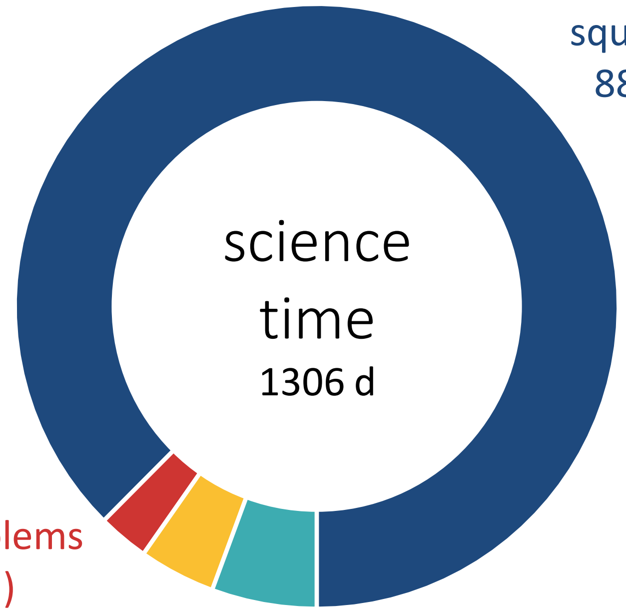


- mechanical shutter automatically disconnects squeezer from IFO in case of error
- reaction time < 50 ms



Duty cycle

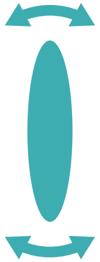




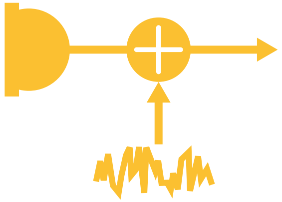
(full data recorded since 2012)

Four limiting factors

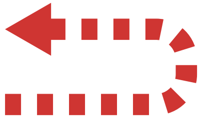
Optical losses



Phase noise

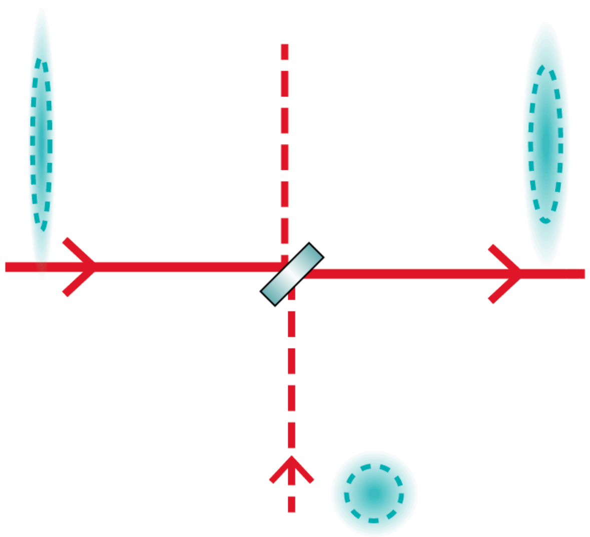


Dark noise



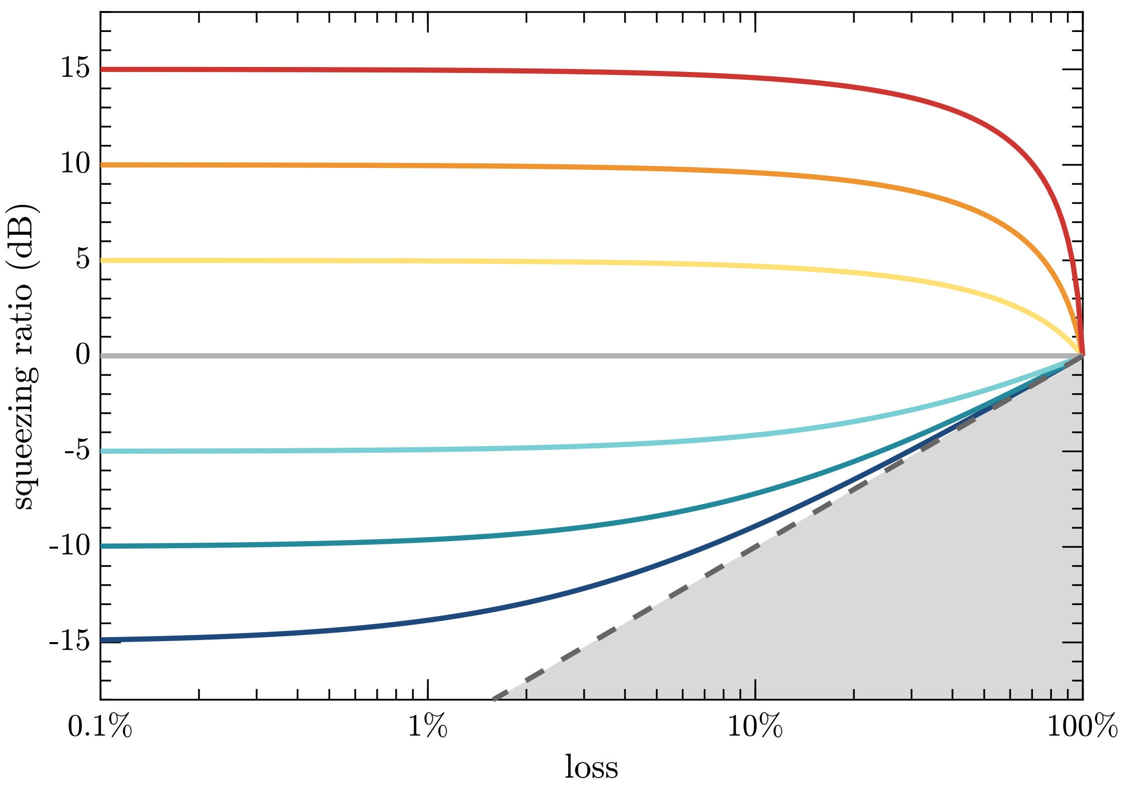
Backscattering

Optical losses

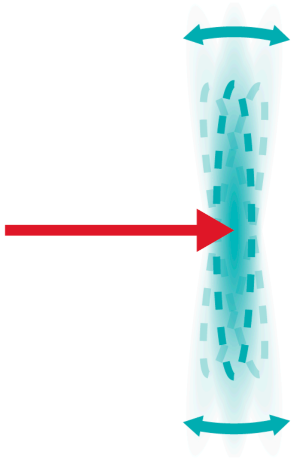


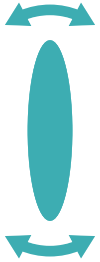
$$R_-^l = (1-l)\,R_- + l$$

- losses mix squeezed state with unsqueezed vacuum
- effective losses are caused by:
  - misalignment, mode mismatch, polarization mismatch
  - non-perfect escape efficiency of OPA
  - non-perfect quantum efficiency of detection PD

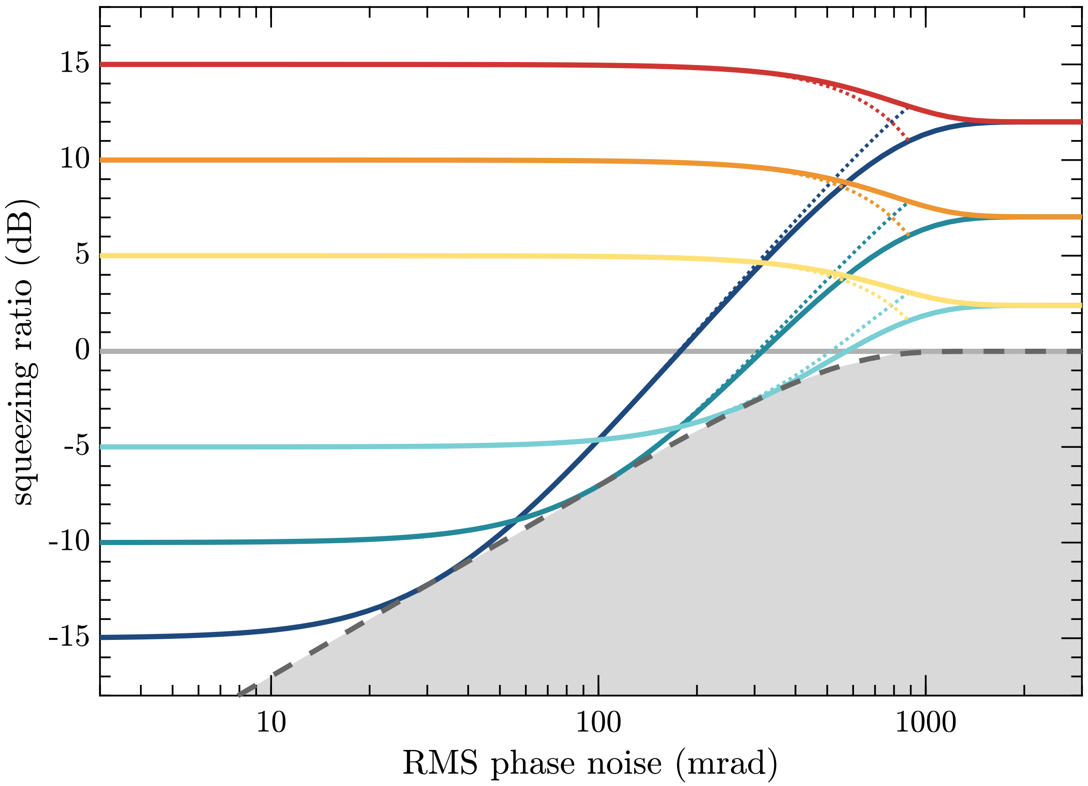


Phase noise



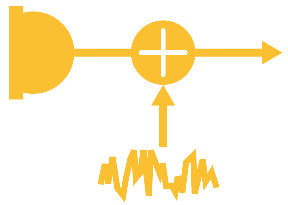


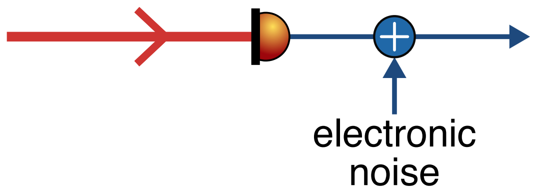
$$R_-^{\tilde{\theta}_{\mathrm{RMS}}} \approx R_- \cos^2 \tilde{\theta}_{\mathrm{RMS}} + R_+ \sin^2 \tilde{\theta}_{\mathrm{RMS}}$$



- phase noise couples noise from the antisqueezed quadrature to the squeezed quadrature
- limits the amount of usable nonlinear gain

Dark noise

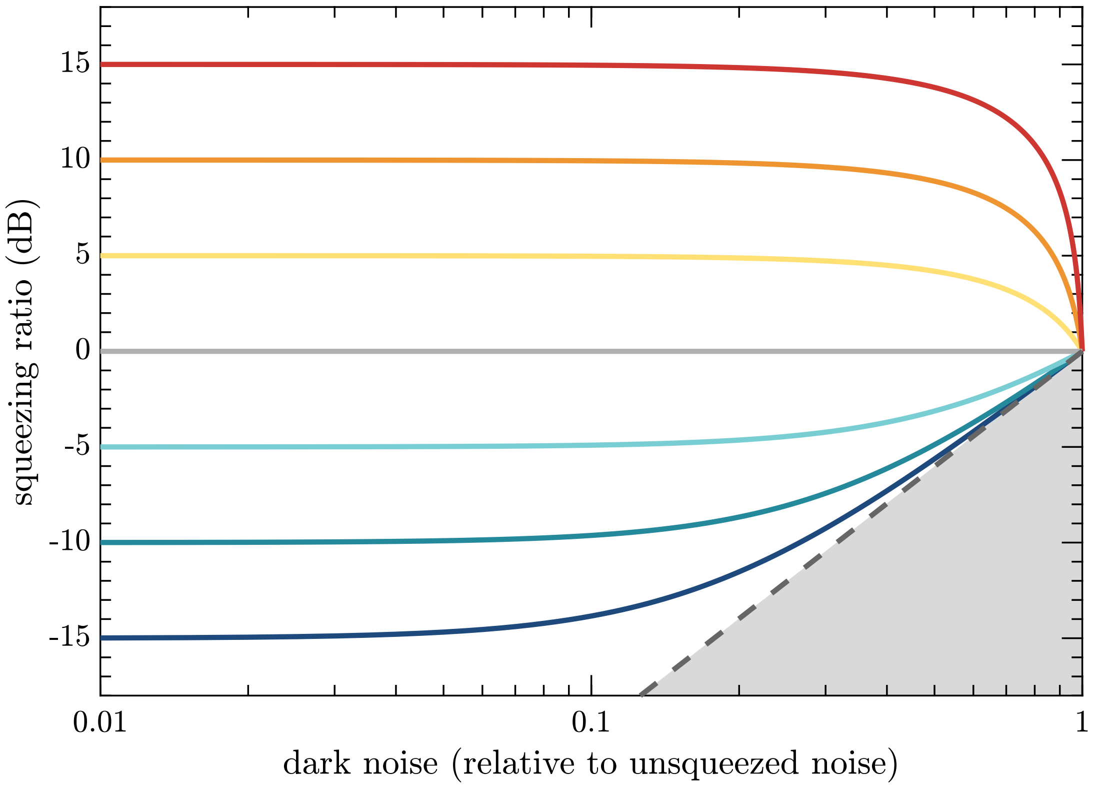




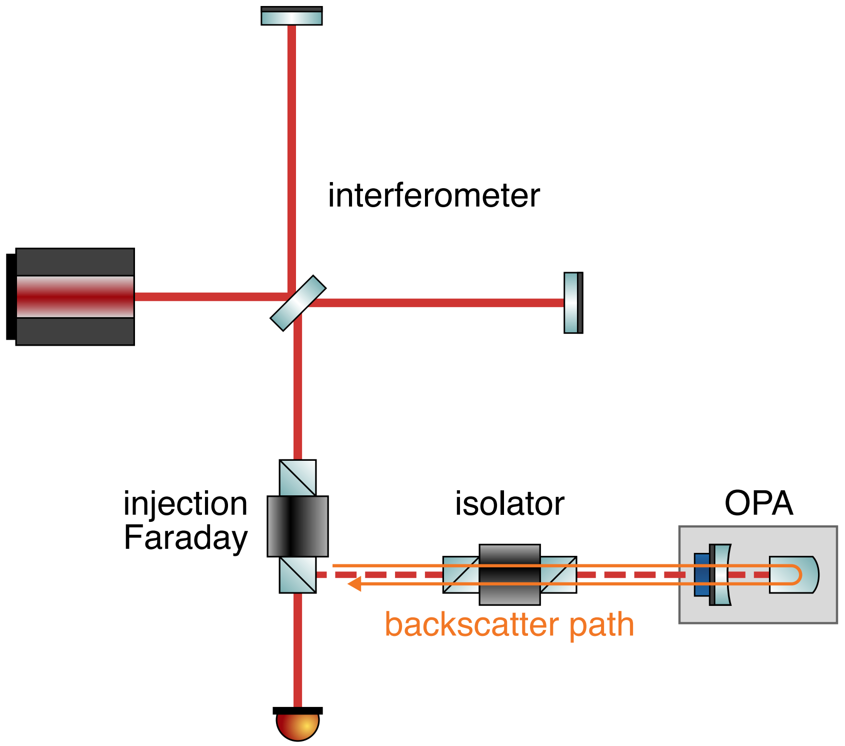
$$R_-^{\mathrm{obs}} = \left(1 - \frac{S_{\mathrm{dark}}}{S_{\mathrm{vac}}^{\mathrm{obs}}}\right) R_- + \frac{S_{\mathrm{dark}}}{S_{\mathrm{vac}}^{\mathrm{obs}}}$$

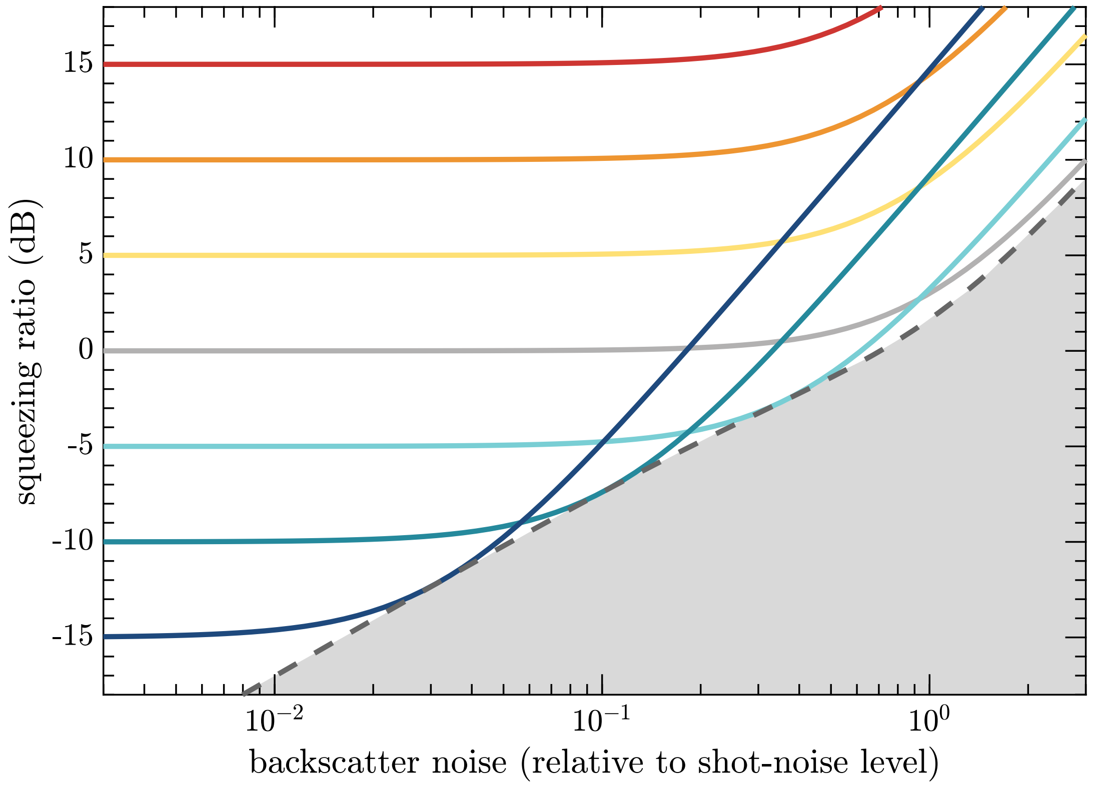
dark noise relative to
unsqueezed shot noise

- electronic dark noise is the second highest contribution at high frequencies after shot noise



Backscattering





decreases with squeezing parameter *r*

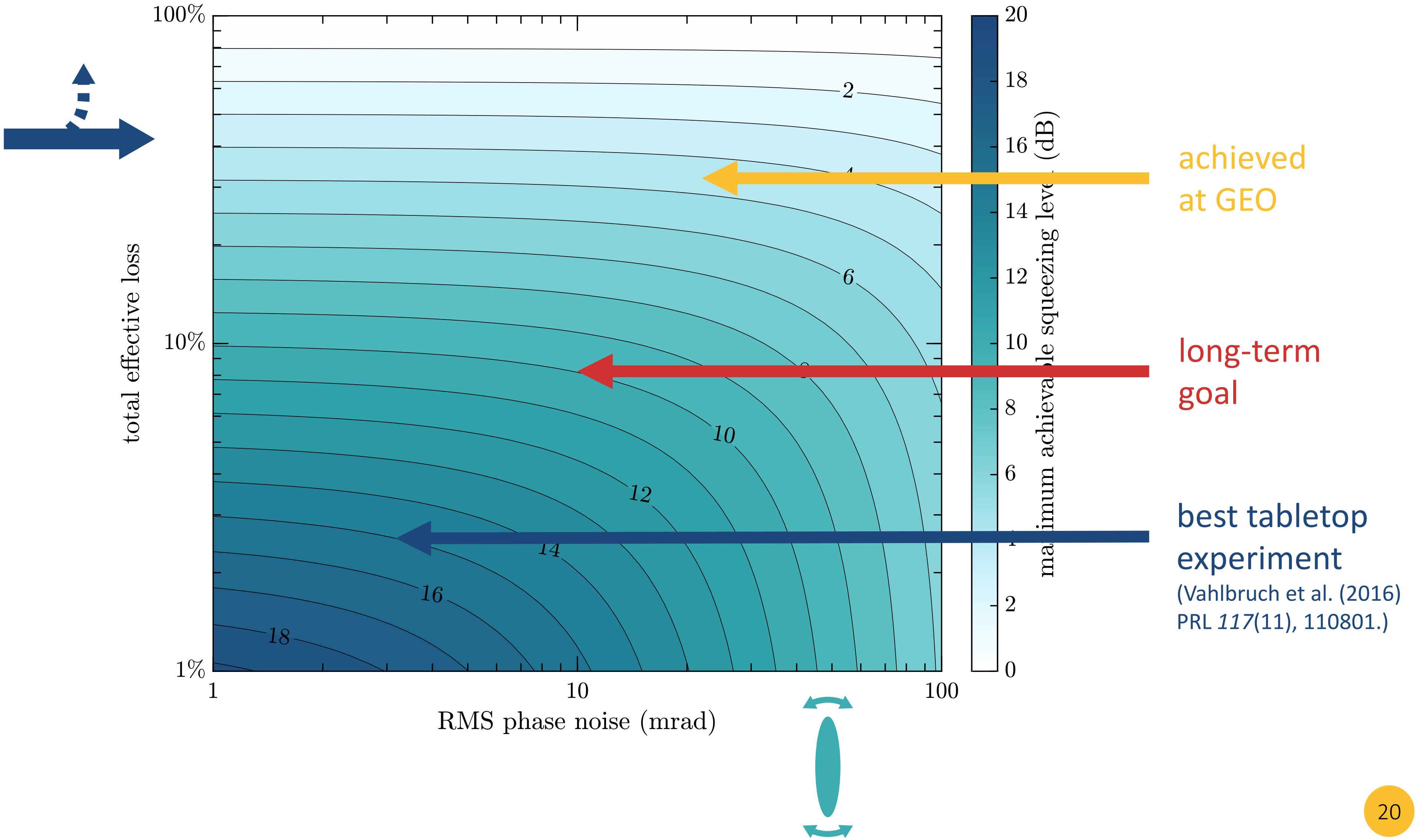
increases with squeezing parameter *r*

$$S_{\mathrm{RIN}}^{\mathrm{bsc}}(f) = \frac{\eta_{\mathrm{inj}} P_{\mathrm{stray}}}{P_{\mathrm{out}}} \left[\frac{1}{2} e^{-2r} S_{\delta\phi}(f) + 2\sinh^2(r) S_{\delta\theta}(f) \right]$$

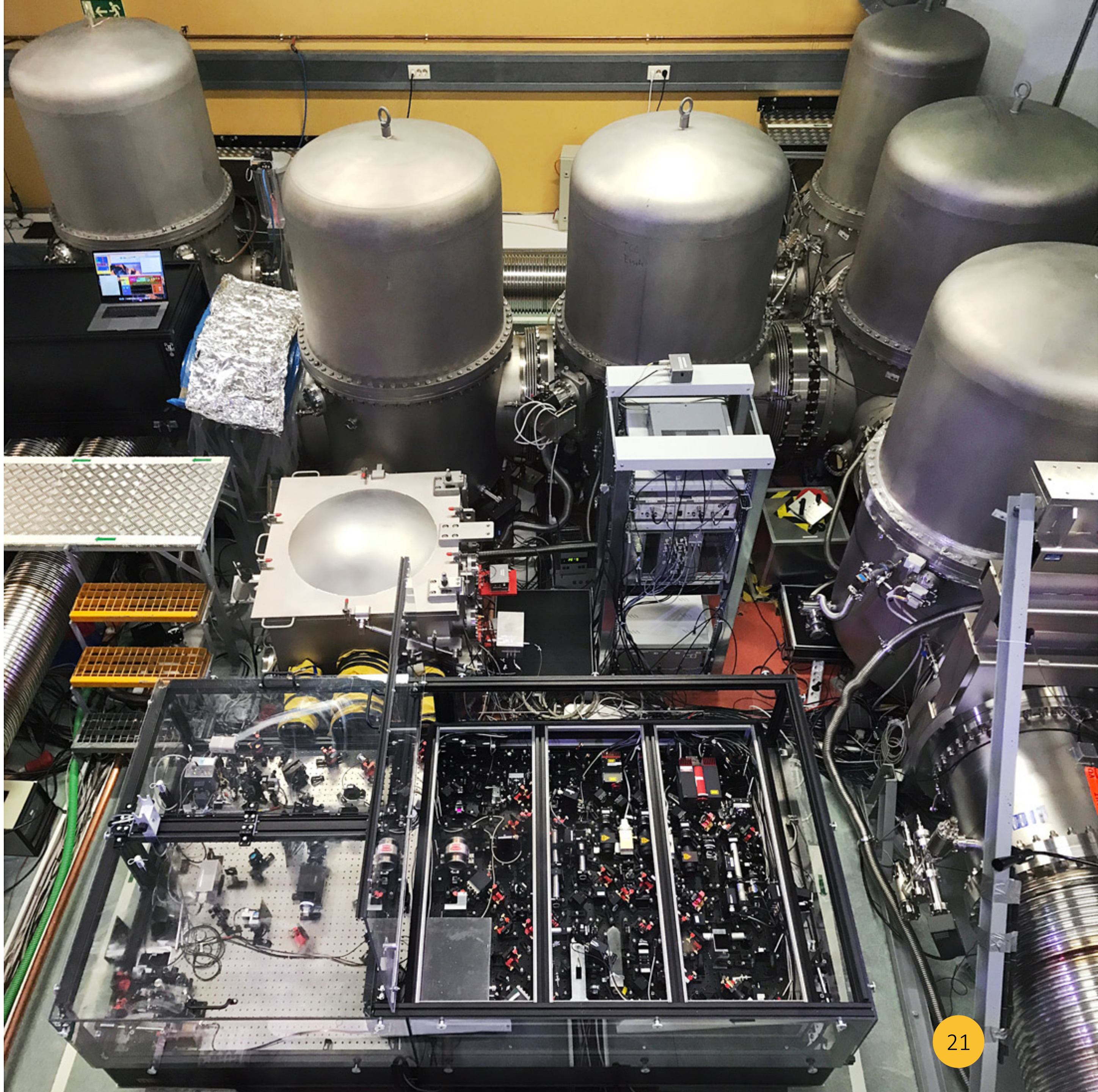
random phase fluctuations of stray light field

residual squeezing angle fluctuations

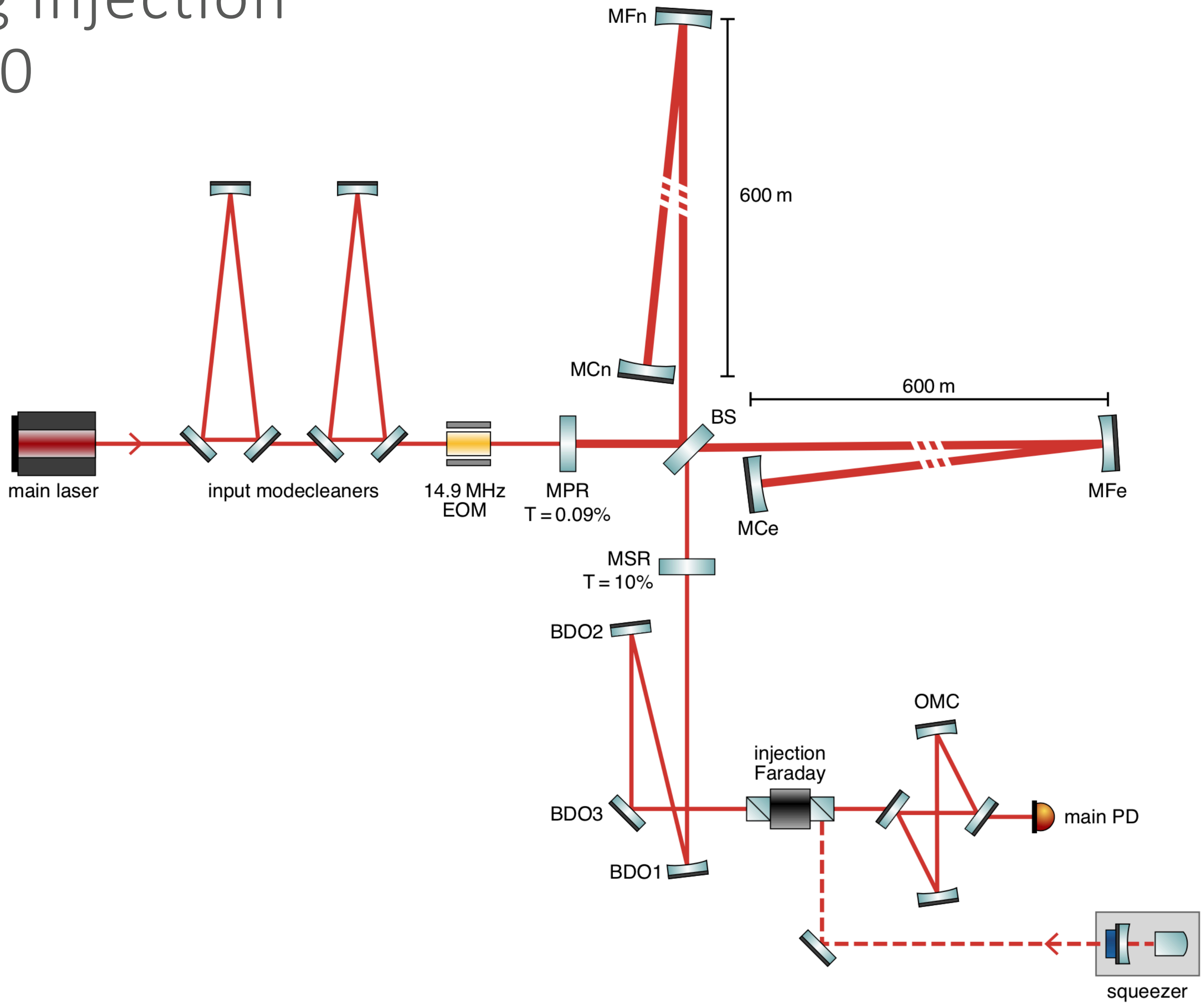
Maximum reachable squeezing



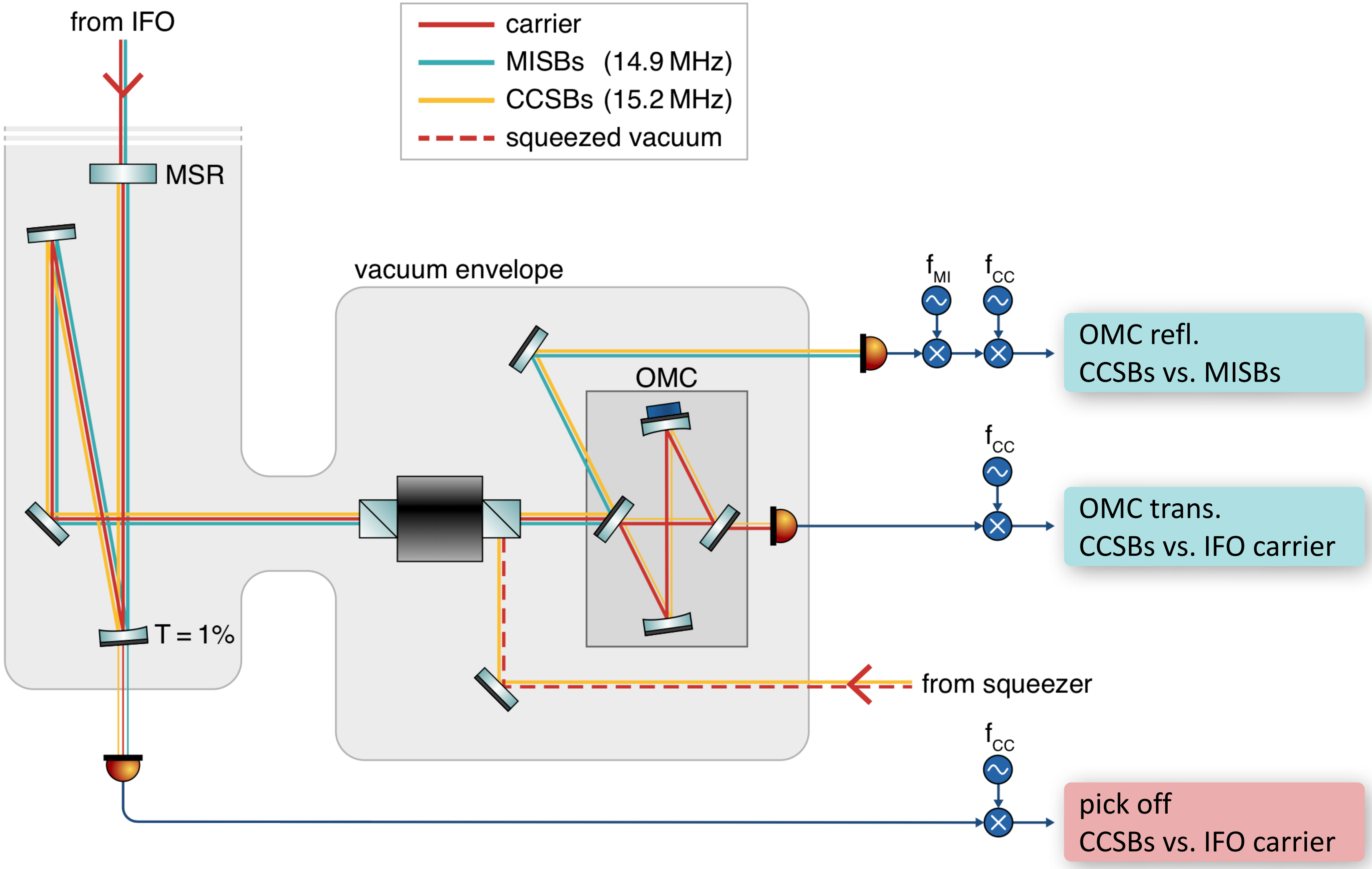
Squeezing injection at GEO 600



Squeezing injection at GEO 600



Phase control: Coherent control scheme

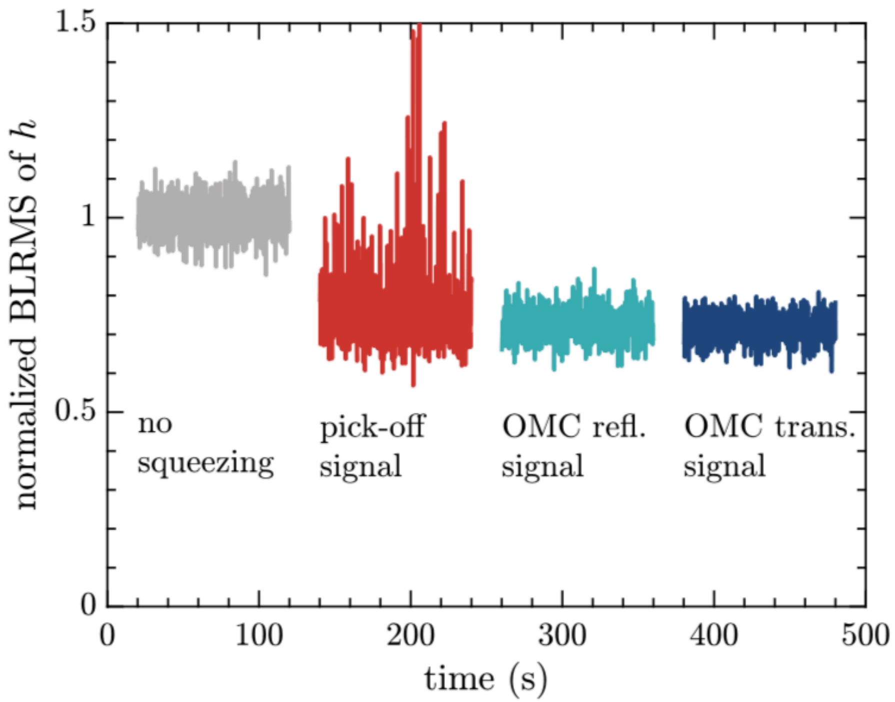


new

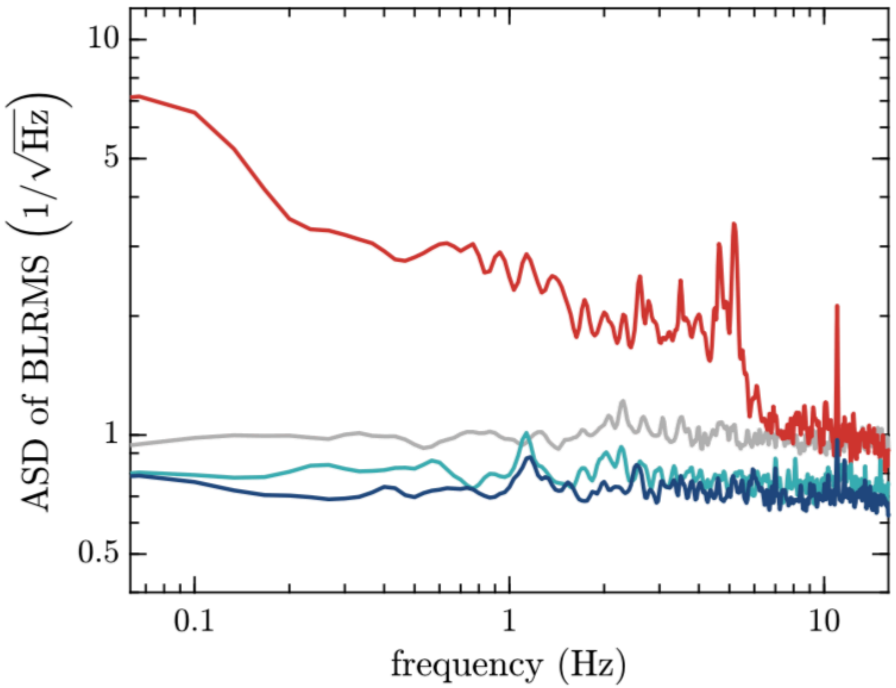
old

Phase control: Performance

time series of shot-noise level

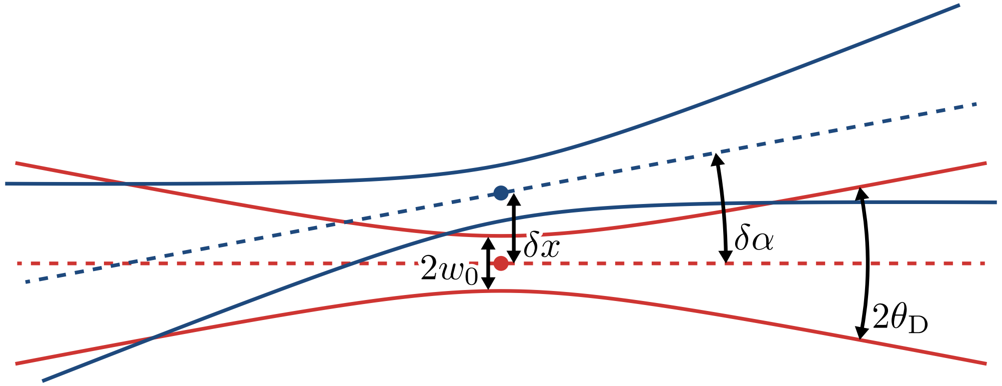


spectrum of shot noise level fluctuations

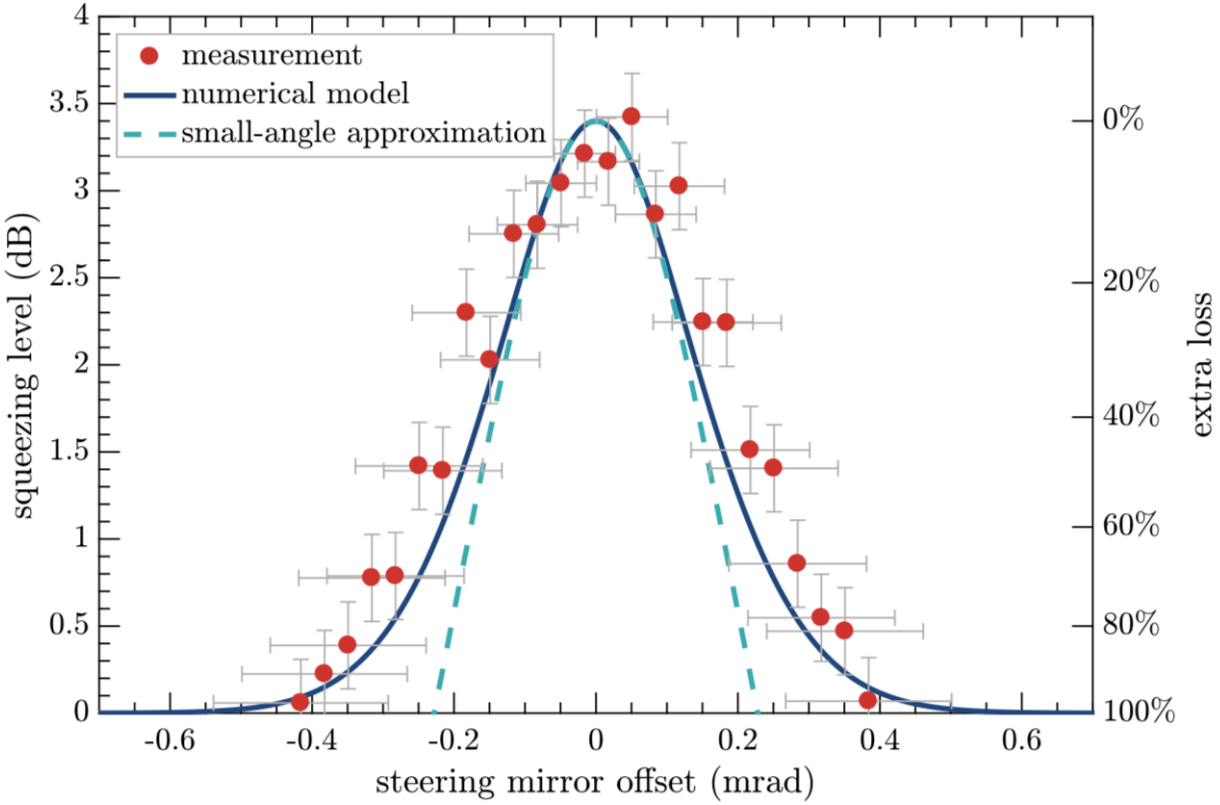


→ *published:*
K. Dooley, E. Schreiber, H. Vahlbruch et al. (2015)
"Phase control of squeezed vacuum states of light in gravitational wave detectors." *Optics Express*, *23*(7), 8235.

Misalignment

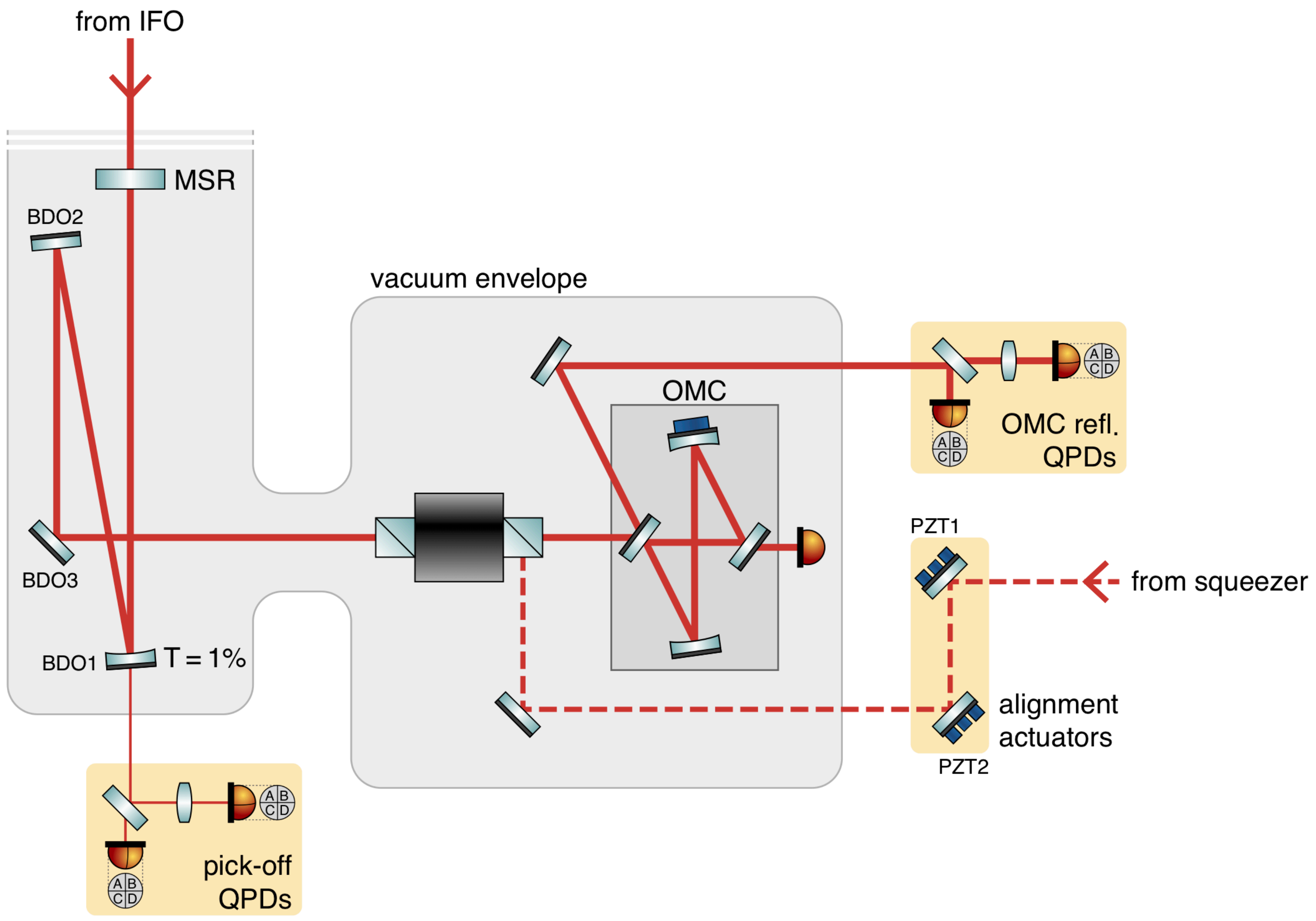


$$l_{\text{misalign}} \approx \frac{\delta x^2}{w_0^2} + \frac{\delta\alpha^2}{\theta_D^2}$$

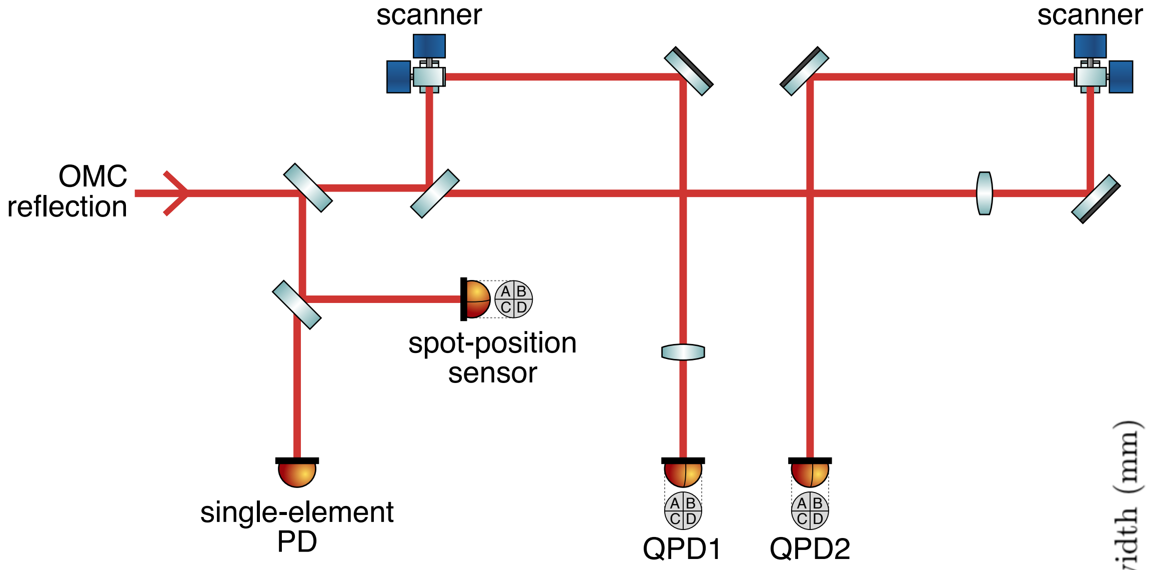


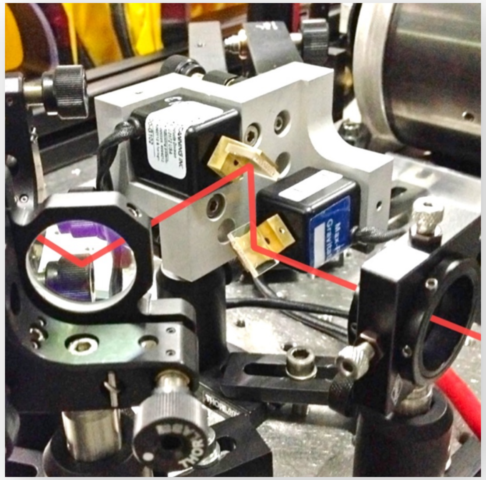
Alignment control with DWS*

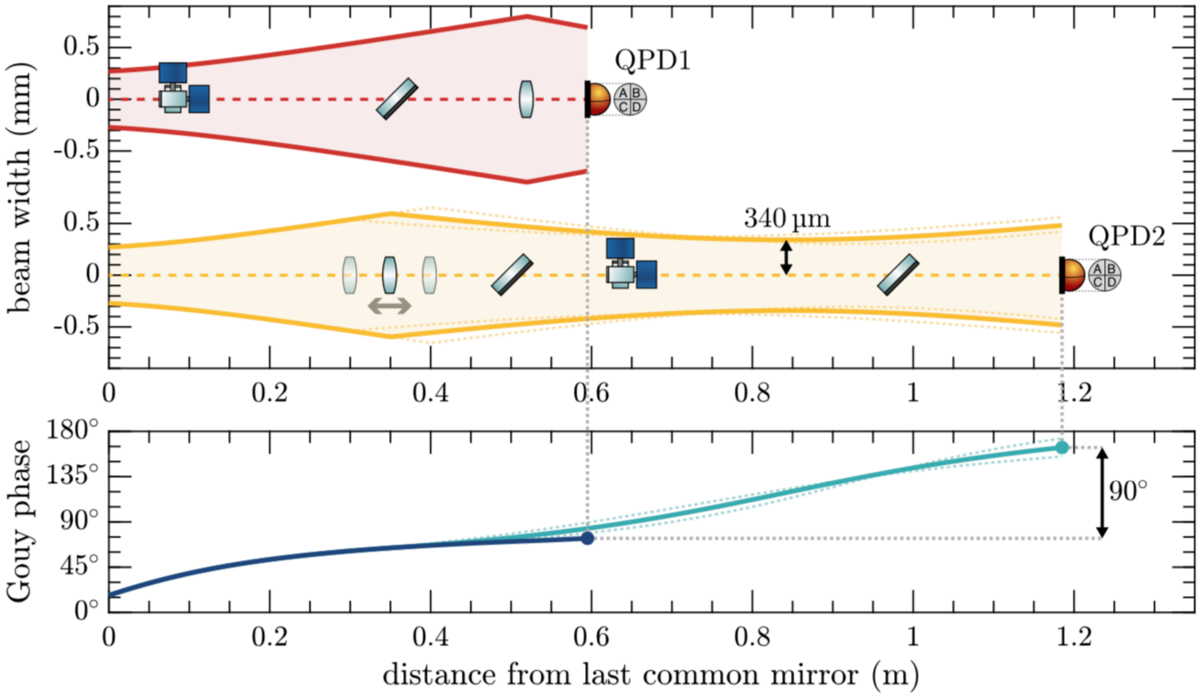
*differential wavefront sensing



Alignment sensing telescope







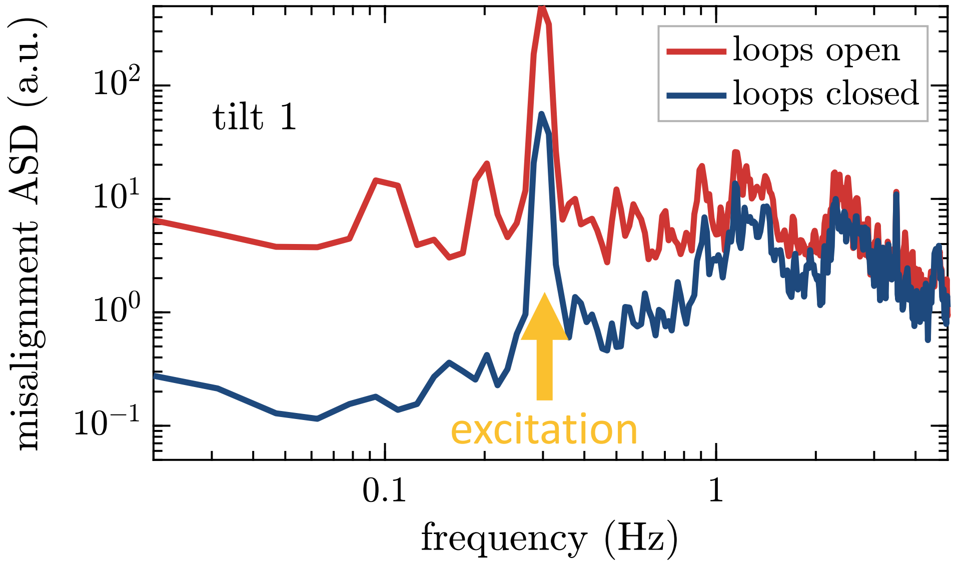
- 2 QPDs with 90° Gouy-phase offset
- mean spot position centred on QPD with scanners

Automatic alignment in action

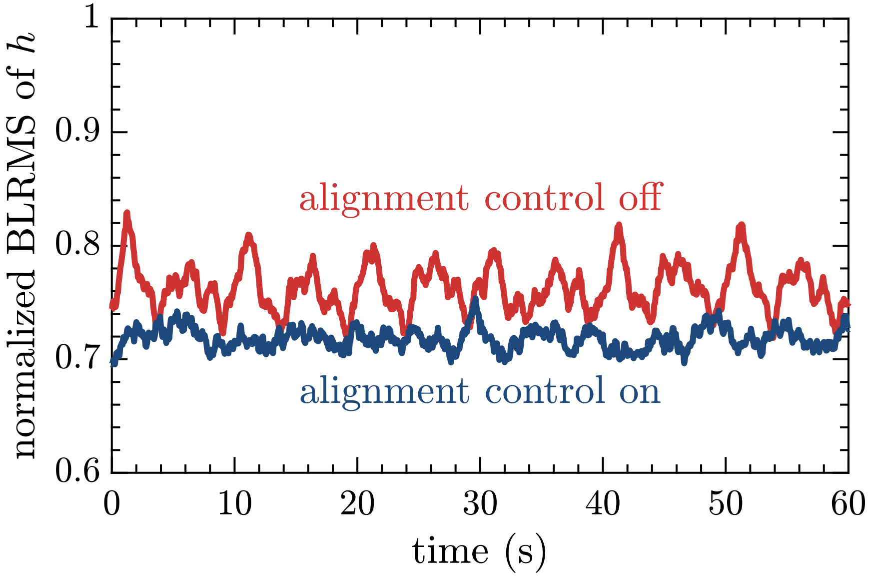
- squeezing not yet limited by fast alignment fluctuations
- will get more important with lower losses
- automatic alignment already helps a lot as drift control
- effectiveness can be demonstrated by artificial excitation:

→ *published:*
E. Schreiber, K. Dooley, H. Vahlbruch et al. (2016) “Alignment sensing and control for squeezed vacuum states of light.” *Optics Express*, *24*(1), 146.

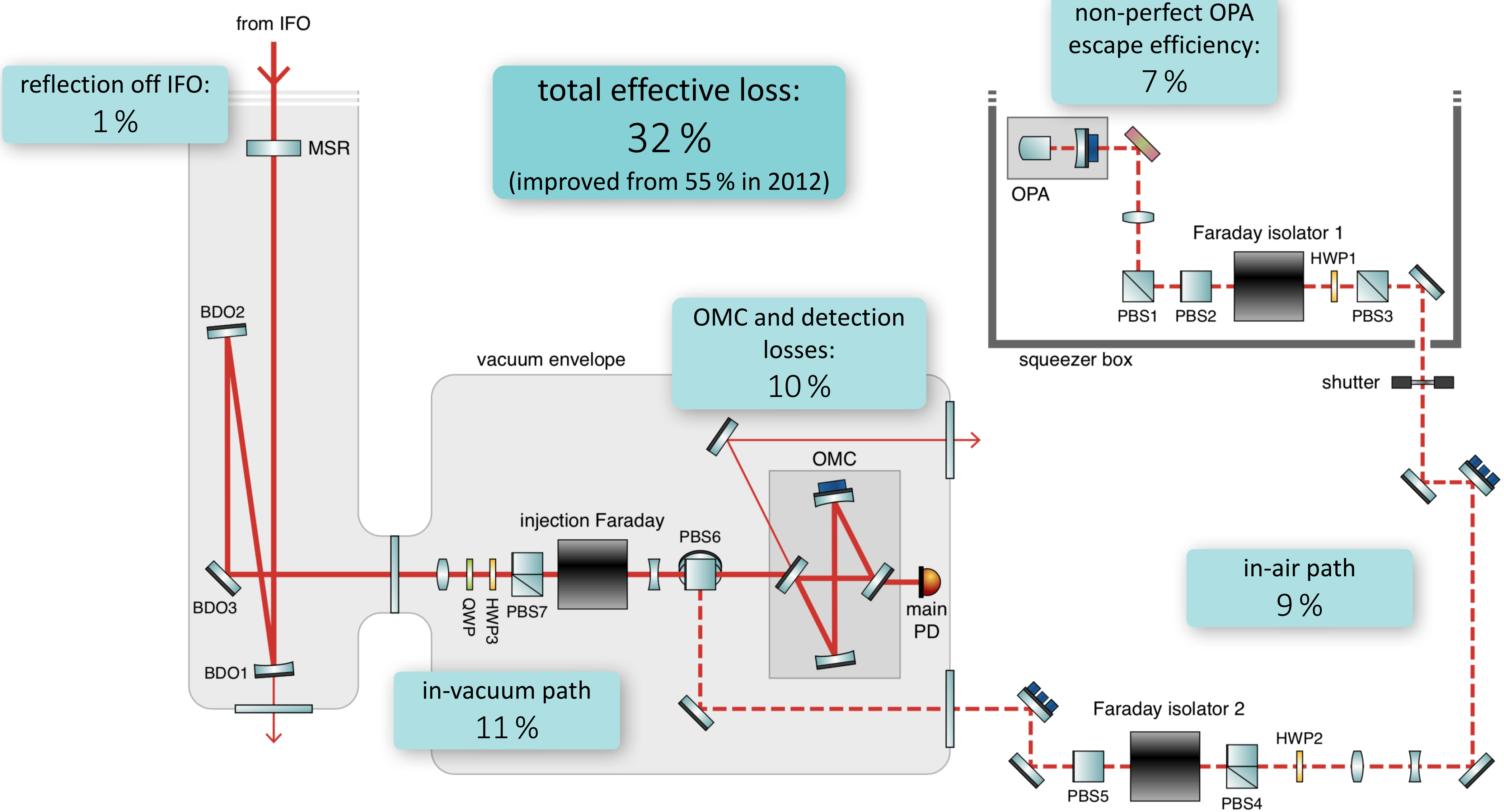
error-point spectra
(1 out of 4 DOFs shown)



time series of shot-noise level

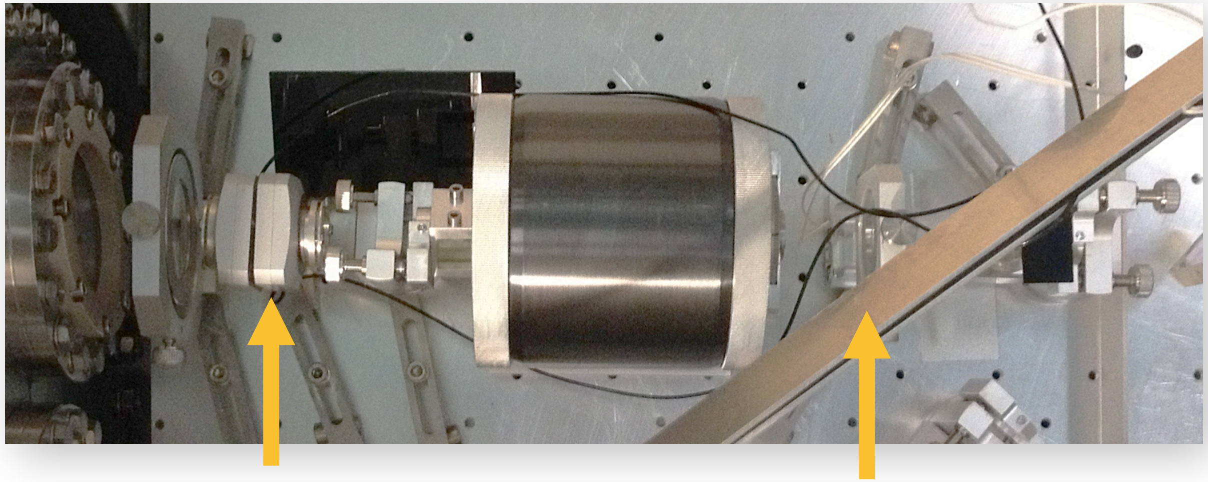


Injection path losses



Loss mitigation

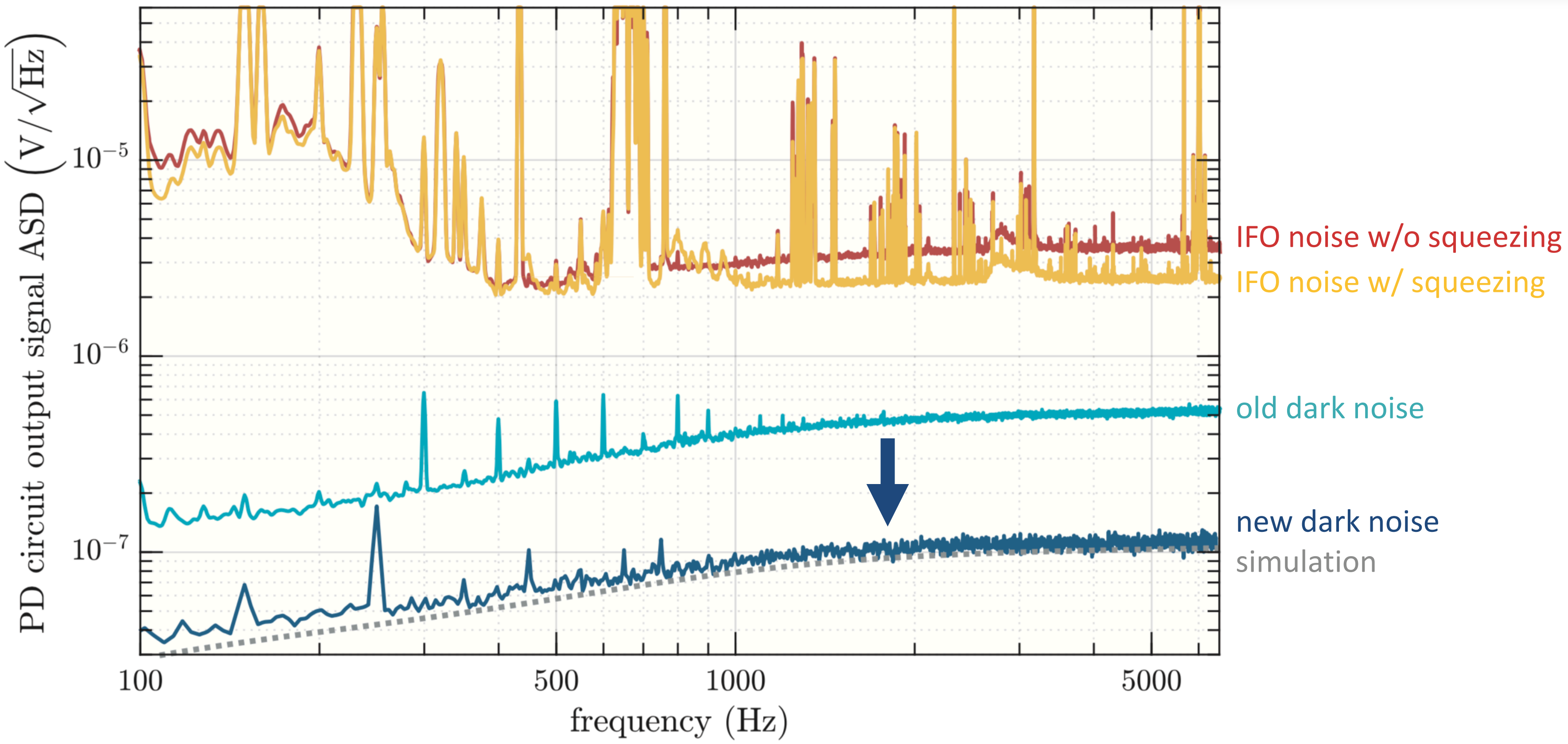
- simplified injection path to reduce number of optical components
- installed super-polished lenses and waveplates
- in-situ mode matching of IFO and squeezer to OMC
- polarization tuning with remote-controlled waveplates



Reducing dark noise

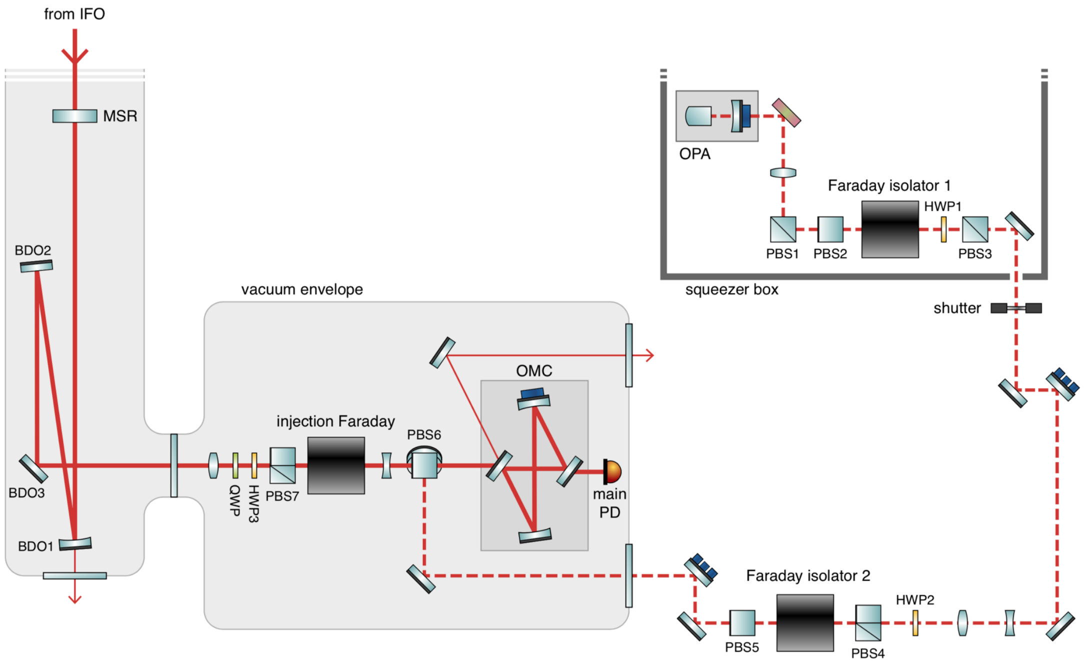
- new electronics with frequency-dependent transimpendance amplifier
- reduced high-frequency dark noise by more than a factor of four
- 0.2 dB more observed squeezing at the time

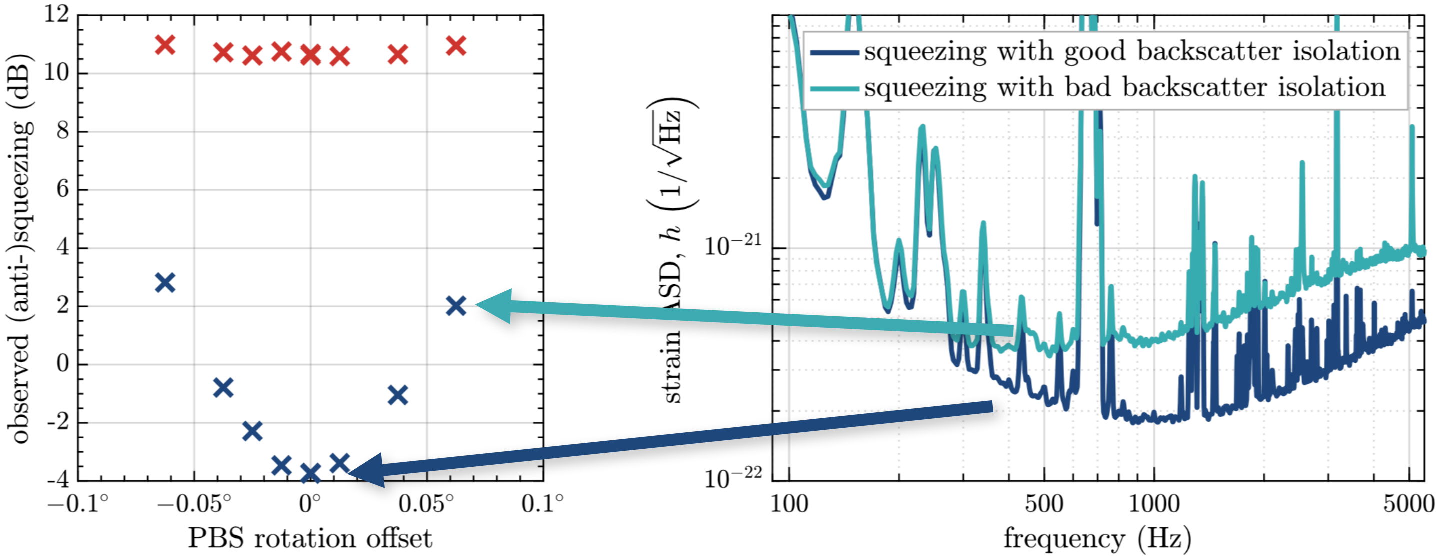
→ *published:*
H. Grote, M. Weinert et al. (2016).
"High power and ultra-low-noise photodetector for squeezed-light enhanced gravitational wave detectors."
Optics Express, *24*(18), 20107.



Backscattering

- noticed occasional excess noise that got worse when increasing the input squeezing
- explained by linear coupling of squeezer phase fluctuations in the presence of backscattering
- becomes limiting when phase noise is high or when isolation is compromised
- isolation is highly sensitive to polarizer rotation and angle of incidence



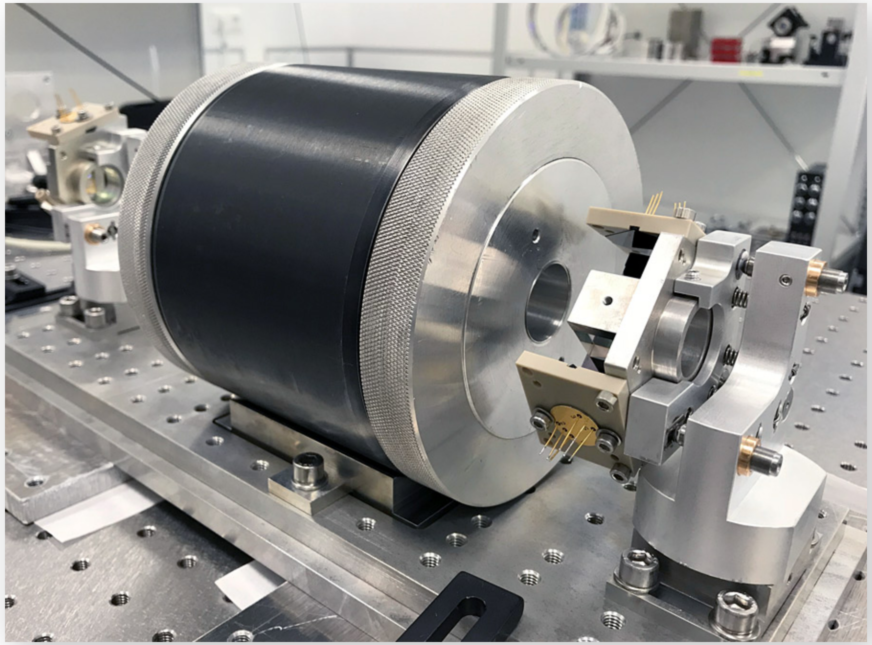


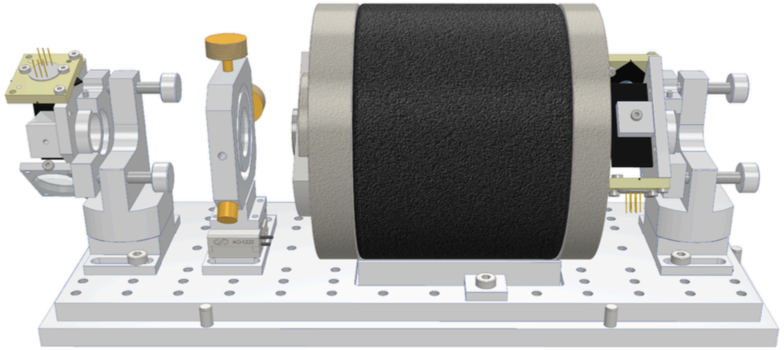
Improved Faraday setup

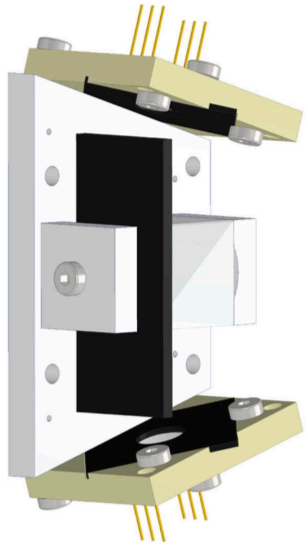
- assembly on breadboard to allow characterization in lab
- adjustable angle of incidence for PBS cubes
- QPDs at all rejection ports to help during alignment and polarization tuning

→ characterization in lab:

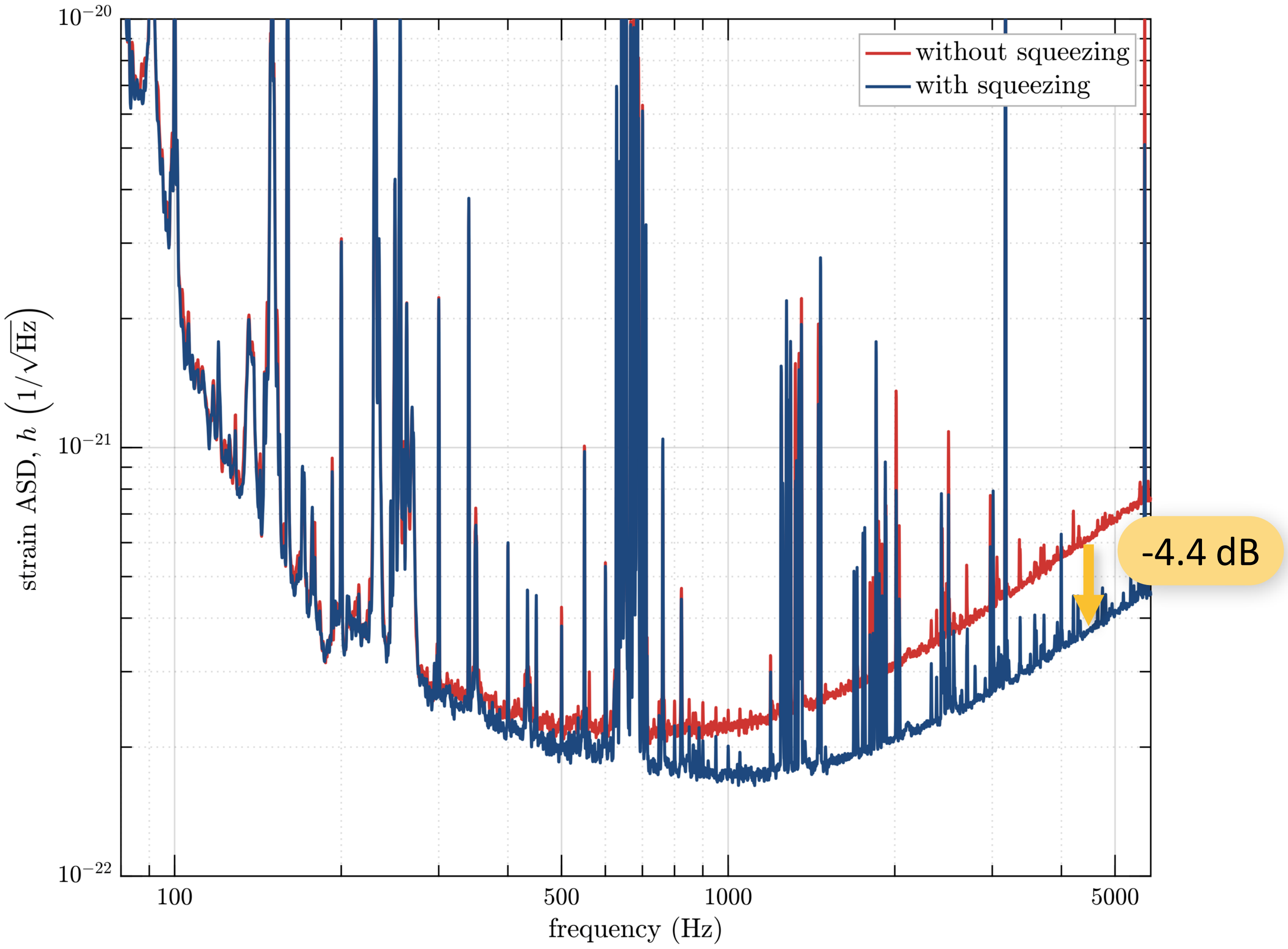
– **0.6 %** single-pass loss (from 3–5 %)
– **44 dB** isolation (from ~32 dB)



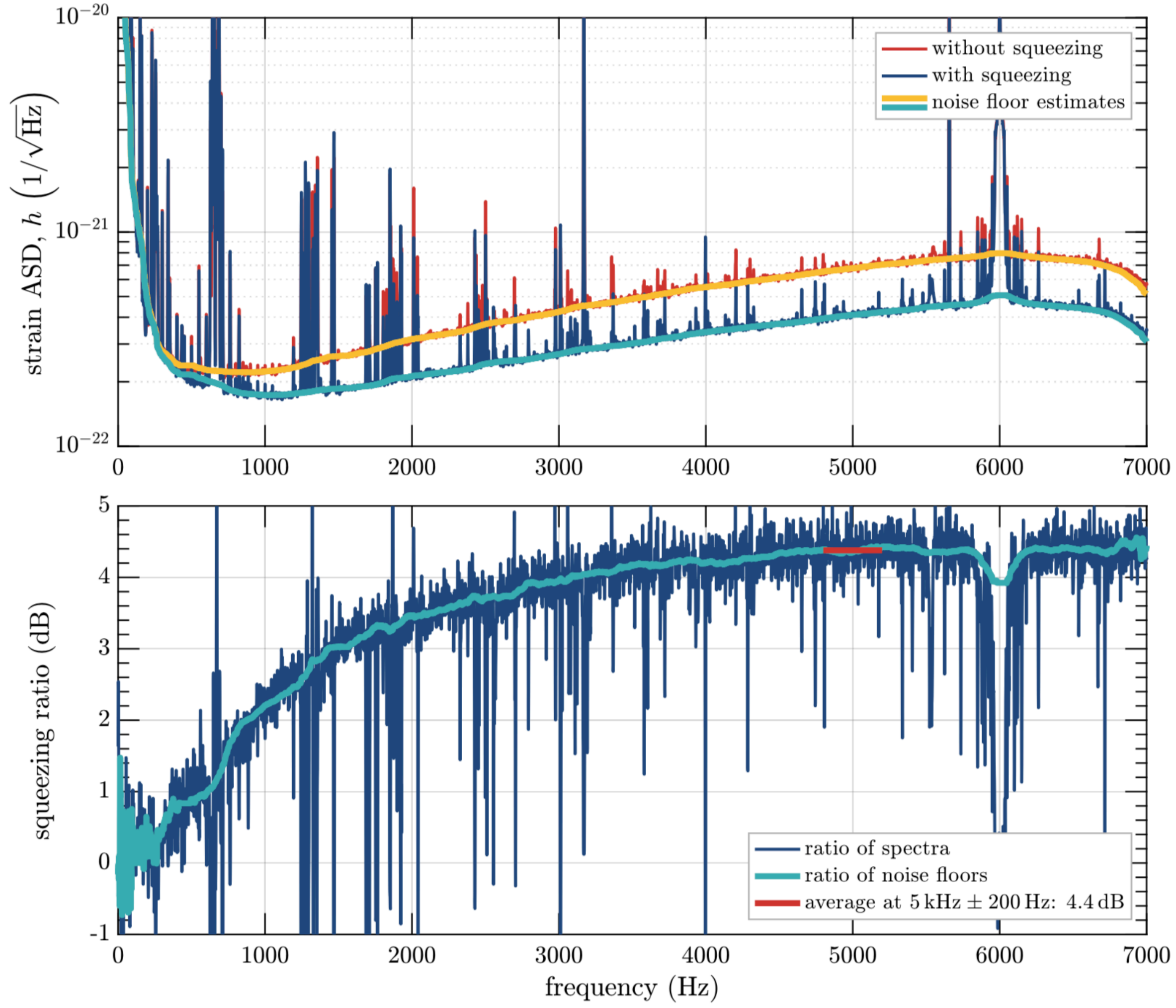




Squeezing results



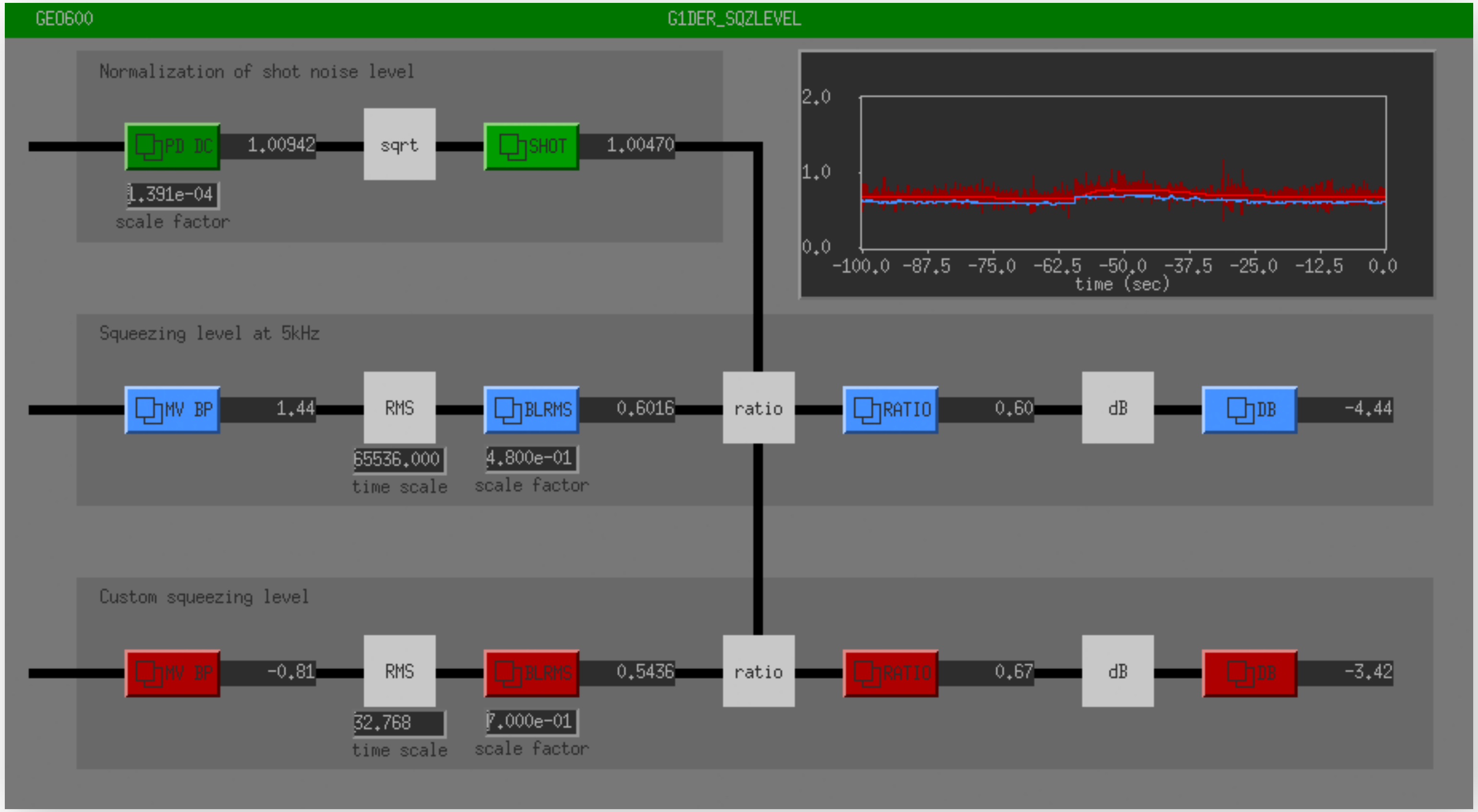
Calculating squeezing level from two reference times



- algorithm:
  1. get PSD of *h* for reference times
  2. estimate noise floor
  3. calculate spectral ratio of noise floors
  4. average over band of interest
  5. convert to decibel

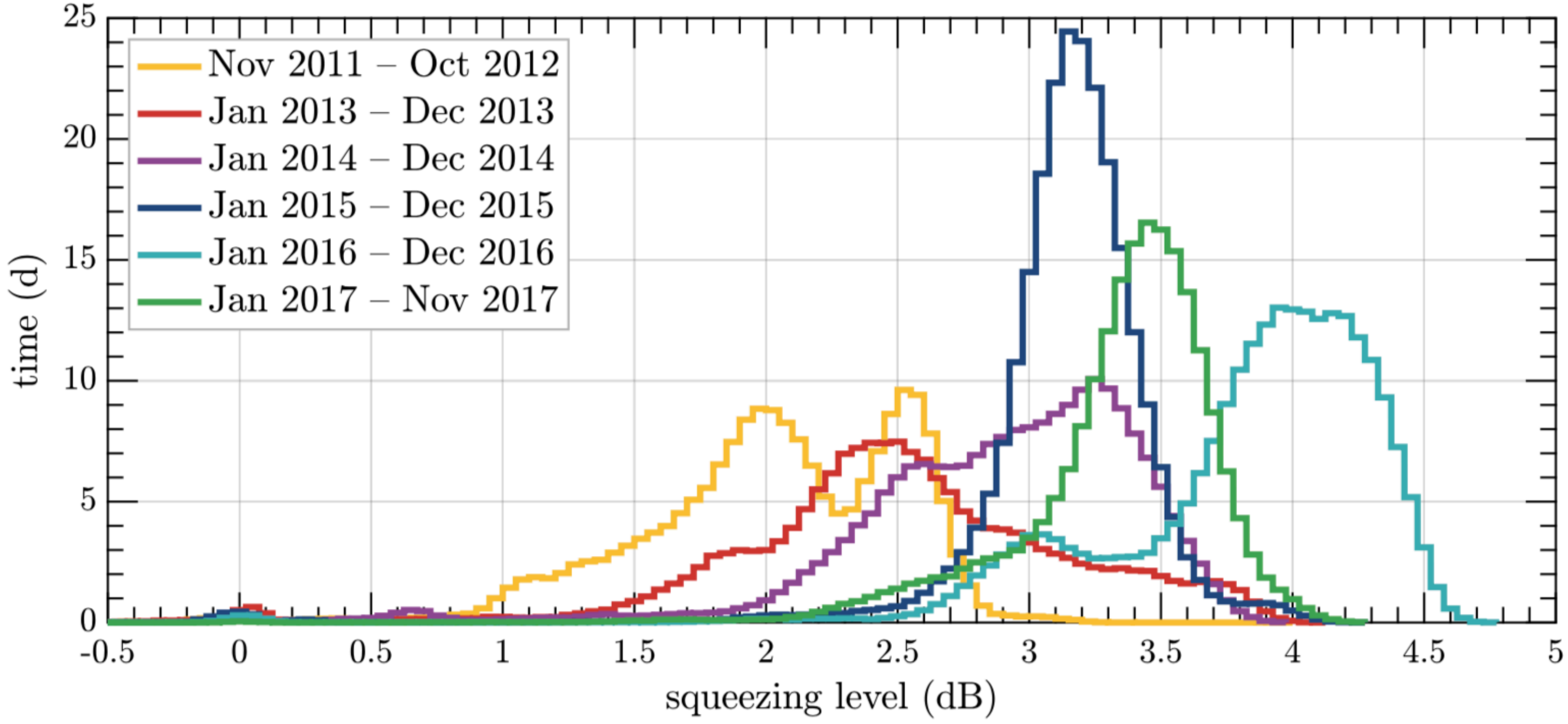
→ gives highly repeatable squeezing value for judging even small changes

Online estimation of squeezing level

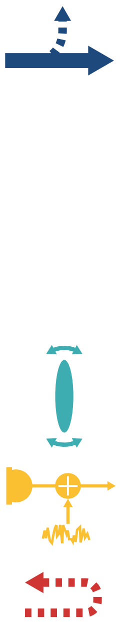


- real-time calculation of band-limited RMS of detector output
- normalized to account for changing DC power on PD
- can be calibrated automatically by forcing output to 0 dB with shutter closed

Squeezing over the years



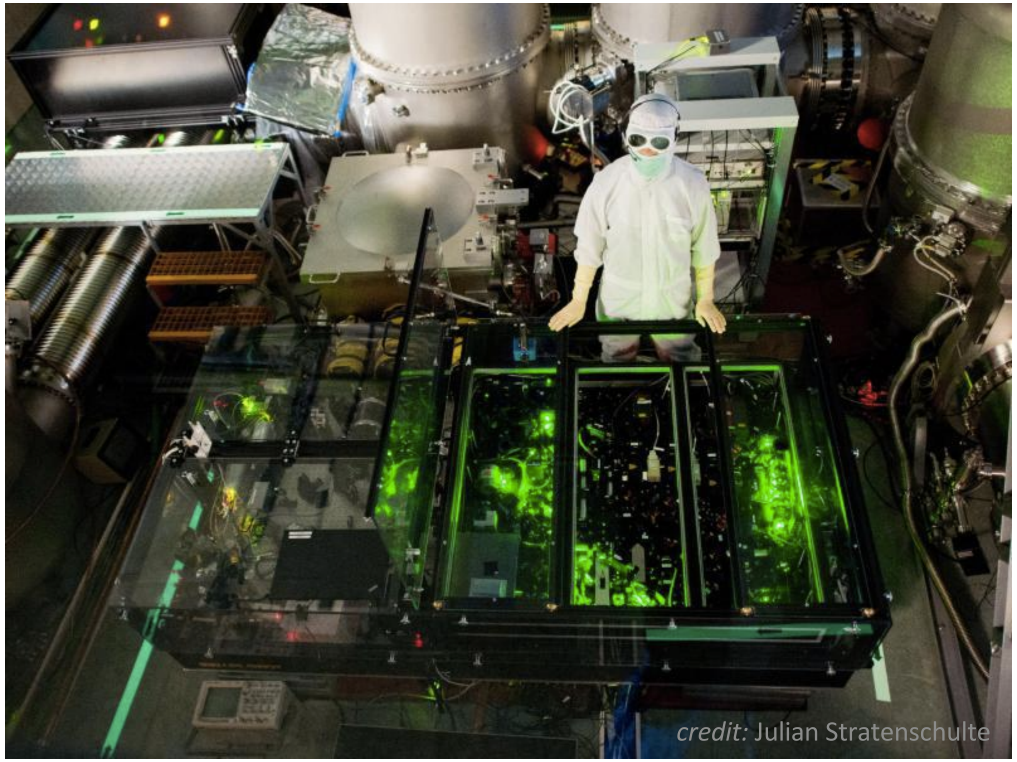
Where to go from here?



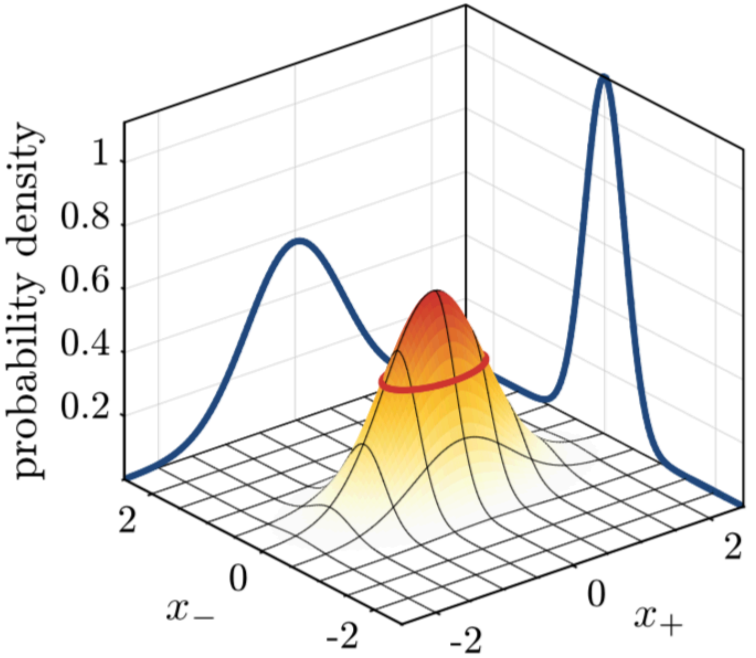
	best so far	in reach	long-term goal
loss mechanisms:			
finite OPA escape efficiency	7 %	7 %	→ 1 %
lenses, HR mirrors, etc.	3 %	→ 2 %	→ 0.5 %
in-air Faradays	$2 \times 3\,\%$	→ $2 \times 1\,\%$	→ $2 \times 0.6\,\%$
injection Faraday	$2 \times 4.5\,\%$	→ $2 \times 1\,\%$	→ $2 \times 0.6\,\%$
reflection off interferometer	1 %	1 %	→ 1 %
pick off	$2 \times 1\,\%$	$2 \times 1\,\%$	→ $2 \times 0.1\,\%$
OMC mismatch (all mode orders combined)	5 %	→ 3 %	→ 1 %
OMC loss	4 %	4 %	→ 1 %
finite PD quantum efficiency	1 %	1 %	→ 0.5 %
total losses	32 %	22 %	7.8 %
other imperfections:			
RMS phase noise	20 mrad	→ 15 mrad	→ 10 mrad
dark noise (rel. to unsqz. shot-noise)	0.03	0.03	≤ 0.03
backscattering (rel. to unsqz. shot-noise)	0.01	→ 0.005	→ ≤ 0.003
resulting observed squeezing	4.4 dB	6.2 dB	10.1 dB

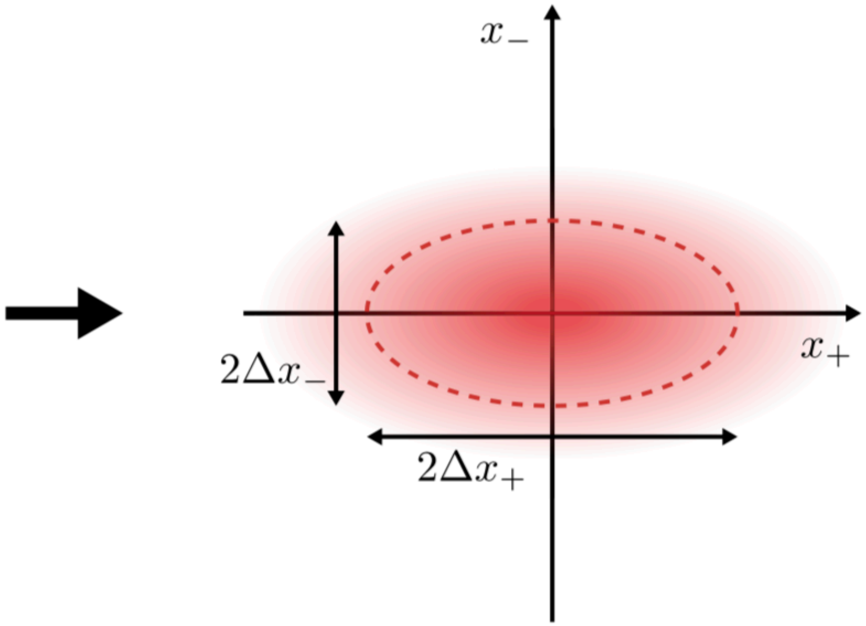
Thanks for listening!

Bonus slides



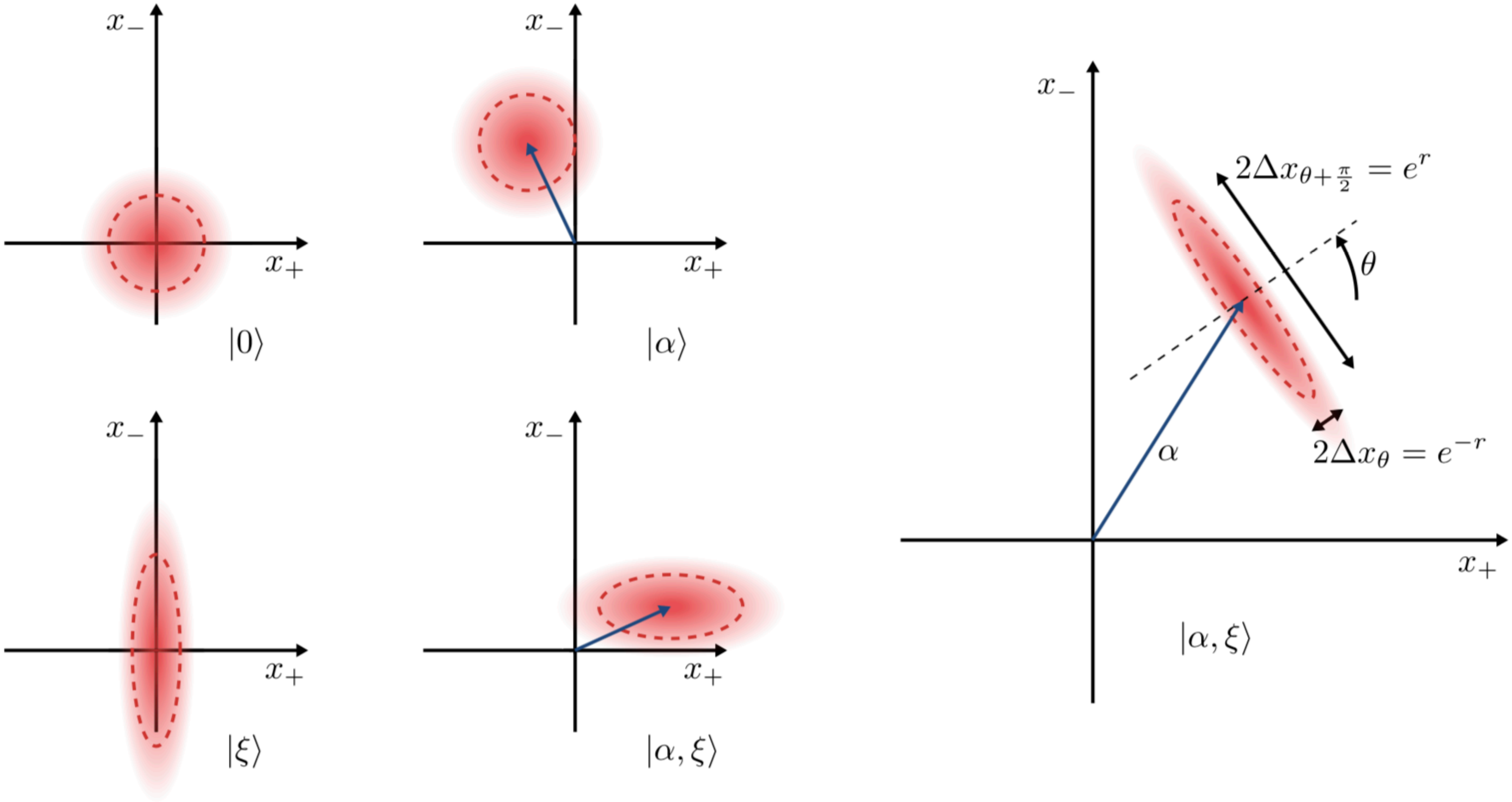
Wigner function of a squeezed state



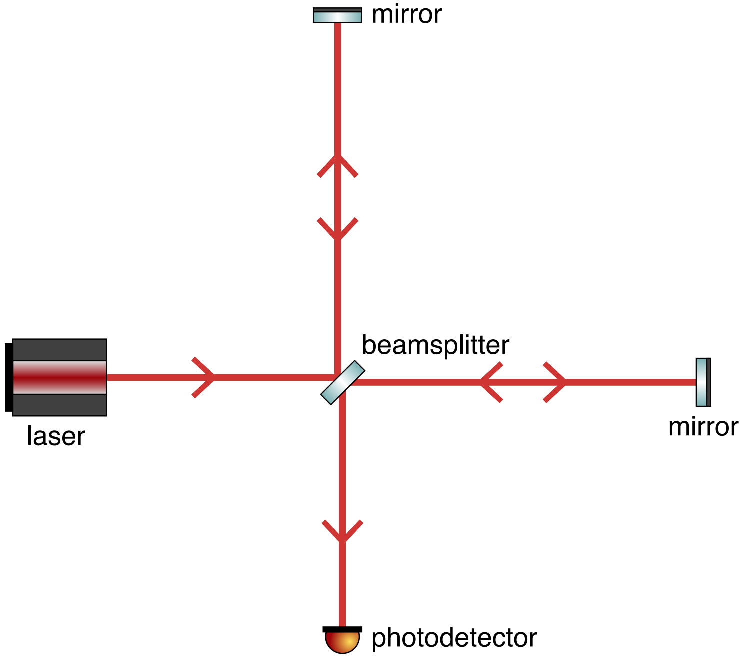


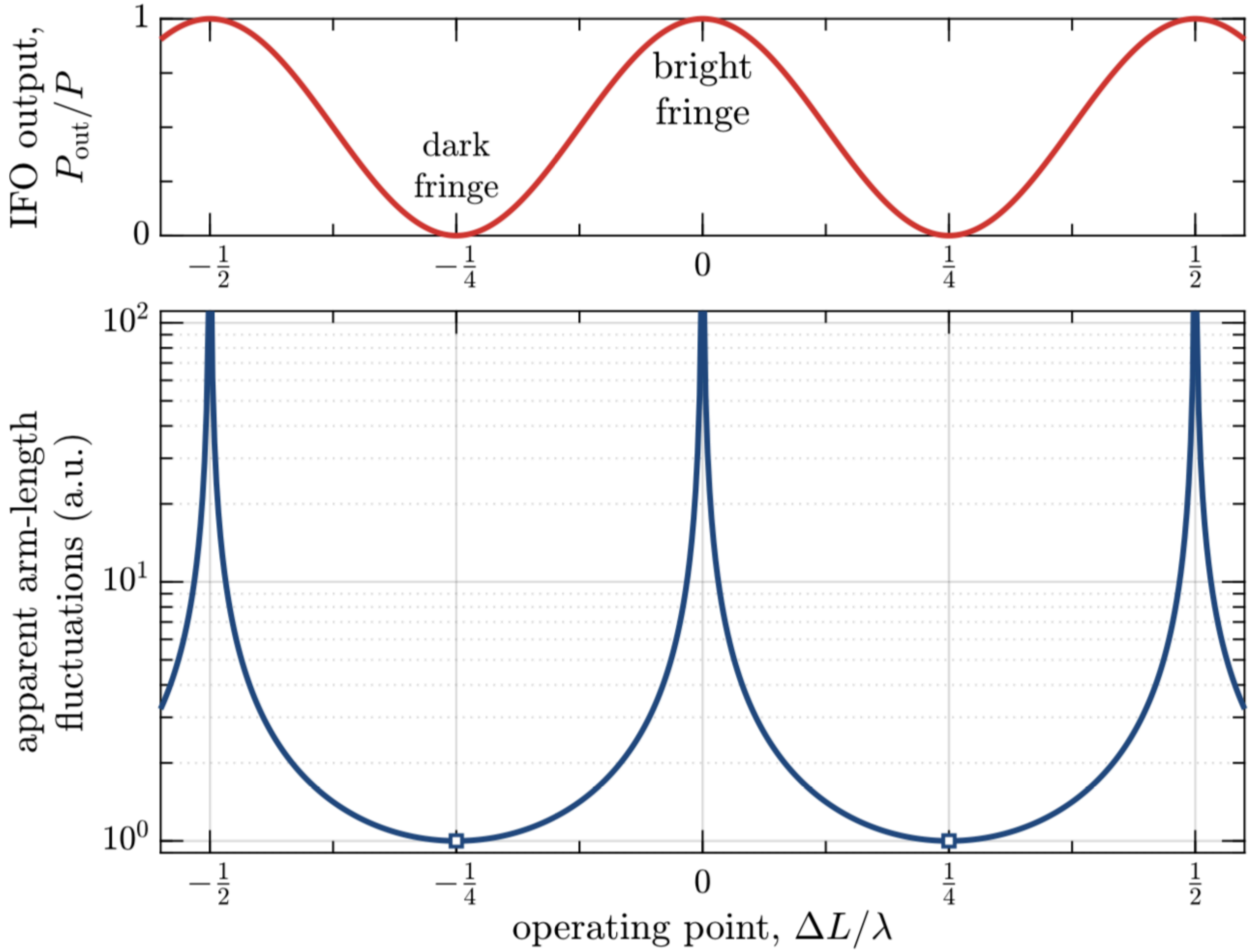
$$W(x_+, x_-) = \frac{2}{\pi} \exp\left[-2x_+^2 e^{2r} - 2x_-^2 e^{-2r}\right]$$

Phasor diagrams

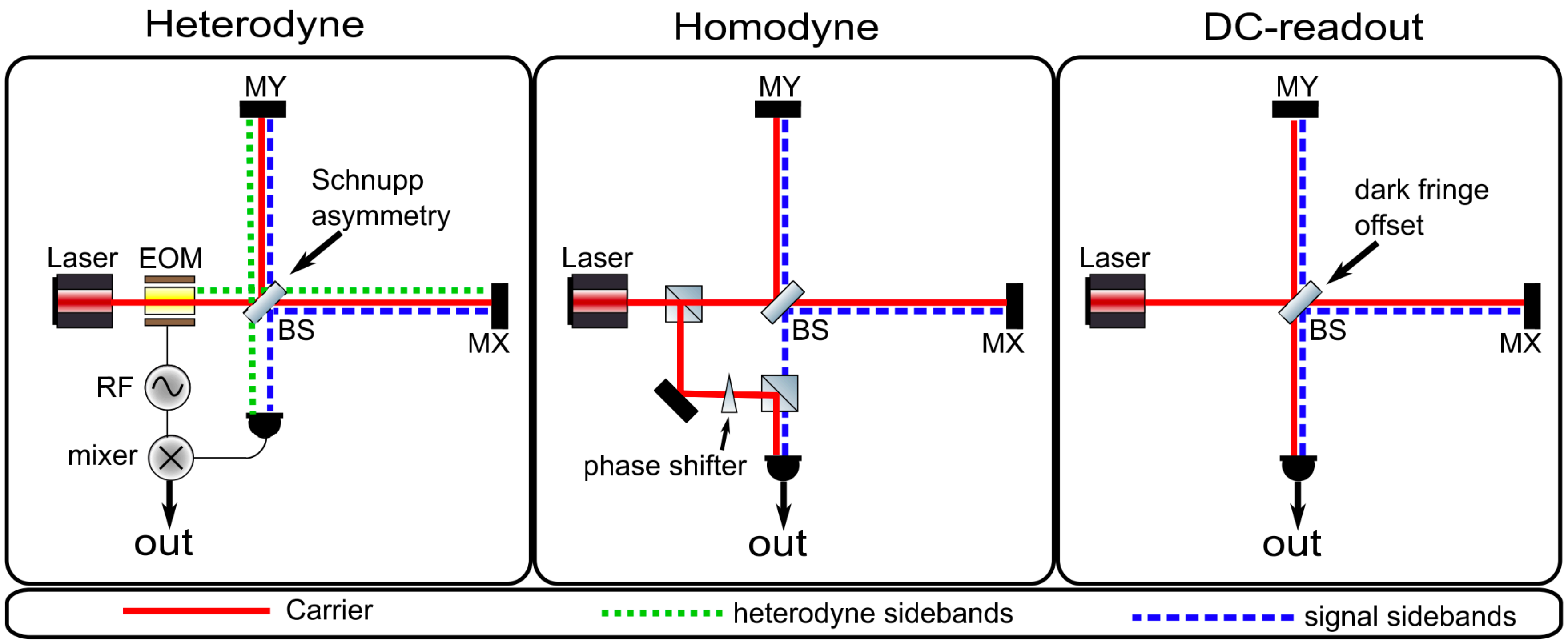


Shot noise in a Michelson interferometer



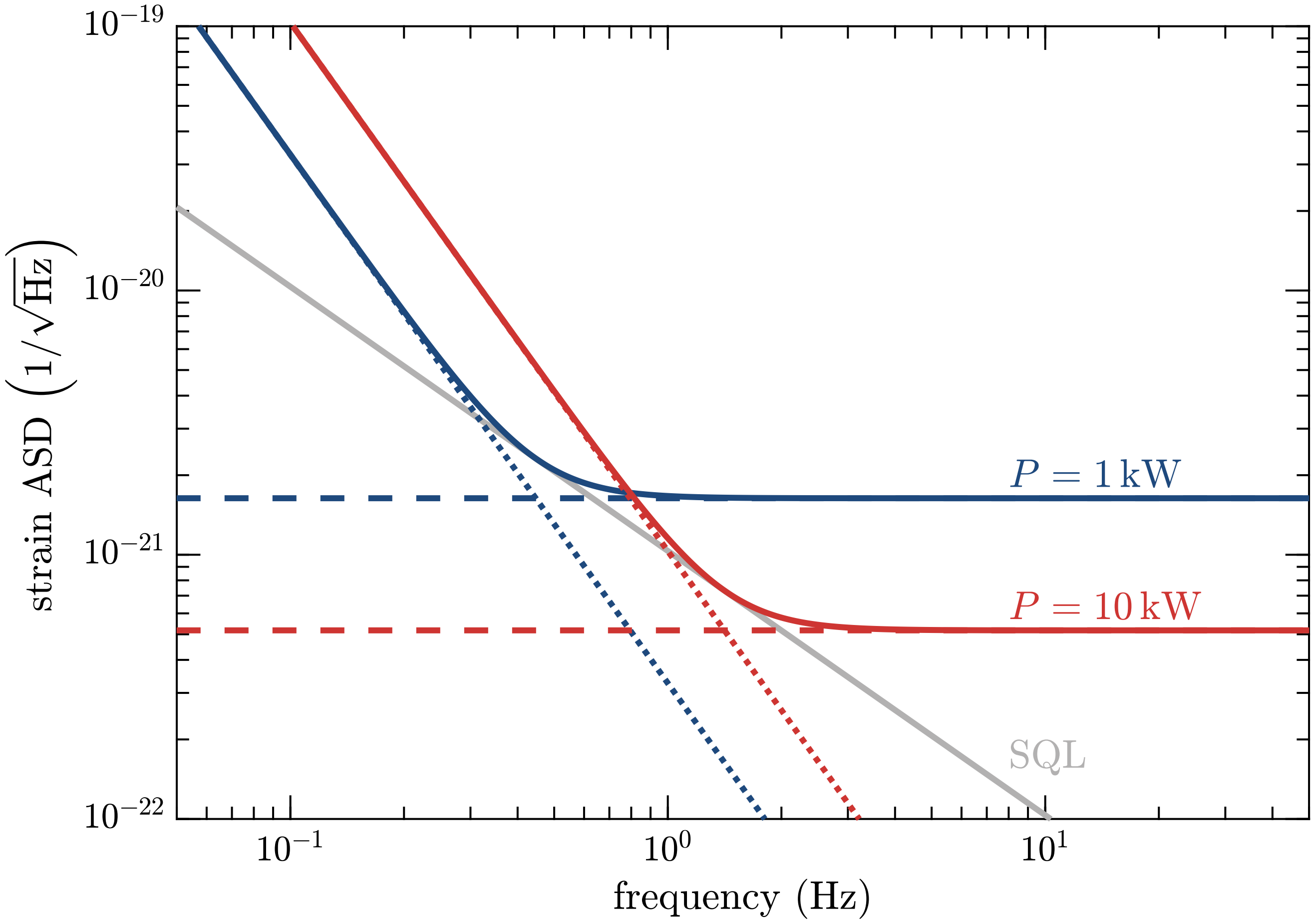


Readout schemes



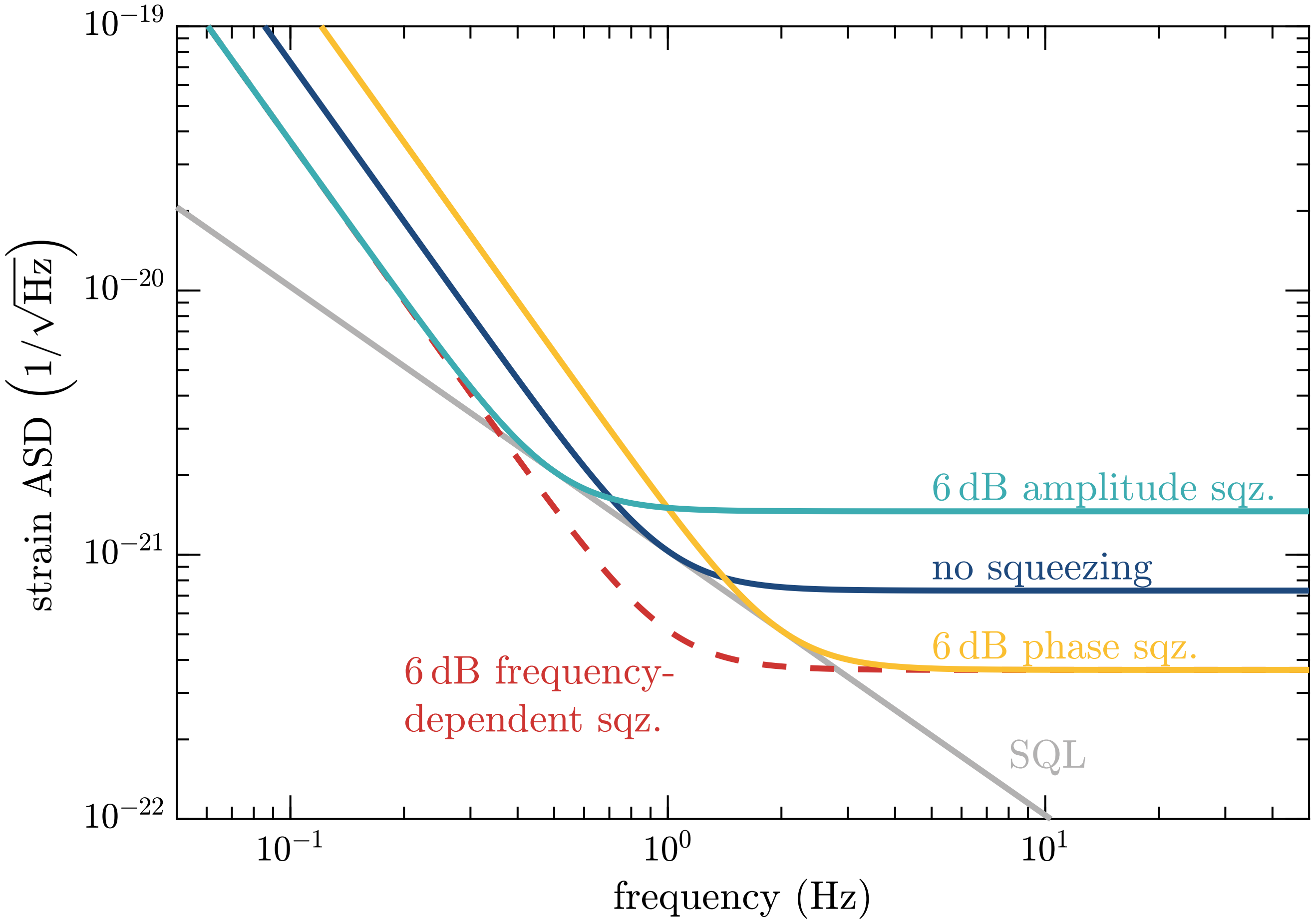
Hild et al. (2009). „DC-readout of a signal-recycled gravitational wave detector.“ *CQG 26*(5), 55012.

Standard quantum limit



$$\tilde{h}^{\text{SQL}}(f) := \min_P\left(\tilde{h}^{\text{qn}}(f)\right) = \frac{1}{\pi f L}\sqrt{\frac{\hbar}{m}}$$

Standard quantum limit with squeezing



Mizuno limit

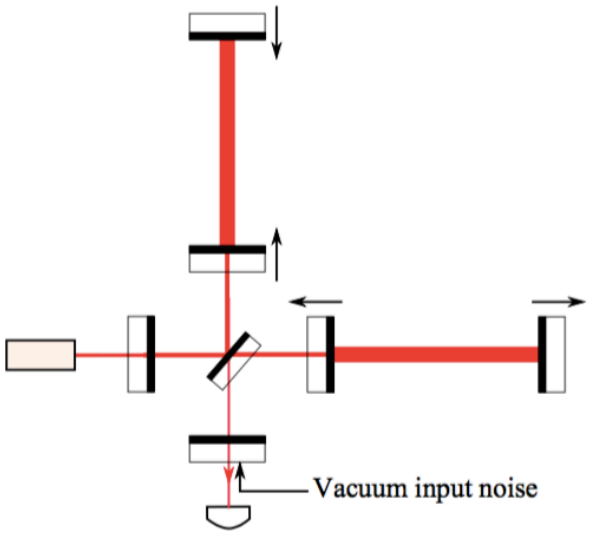
- in all simple dual-recycling configurations: limit on sensitivity-bandwidth product

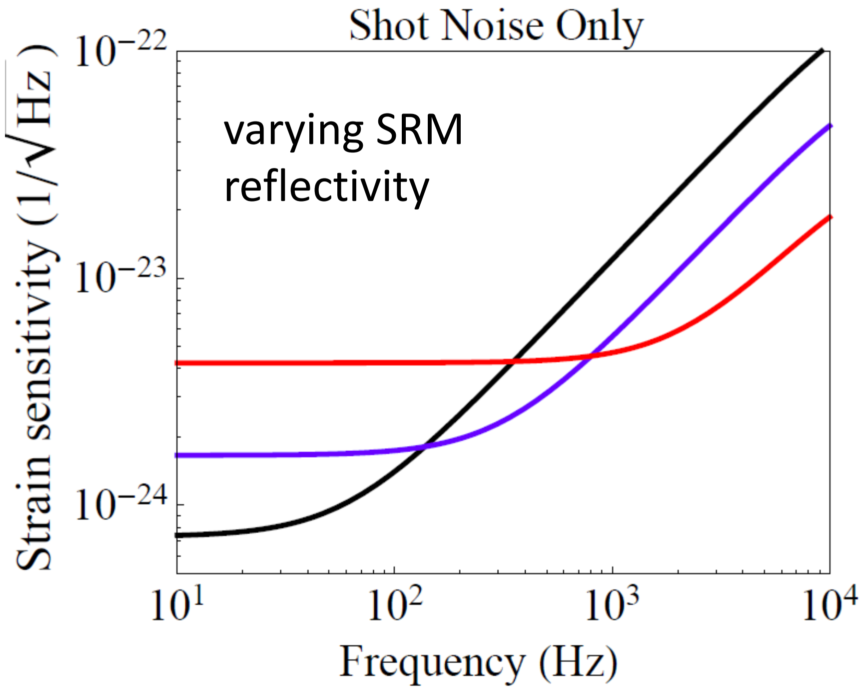
$$\Delta B / S_{hh}^{\text{shot}}|_{\text{peak}} \approx \text{constant}$$

- more precisely:

$$\int \frac{1}{S_{hh}^{\text{shot}}(\Omega)} \mathrm{d}\Omega \leq 2\pi\omega_0^2 \left(\frac{P_c L_{\text{arm}}}{\hbar \omega_0 c} \right)$$

(depends only on power in arms and arm length)





H. Miao, G1500730

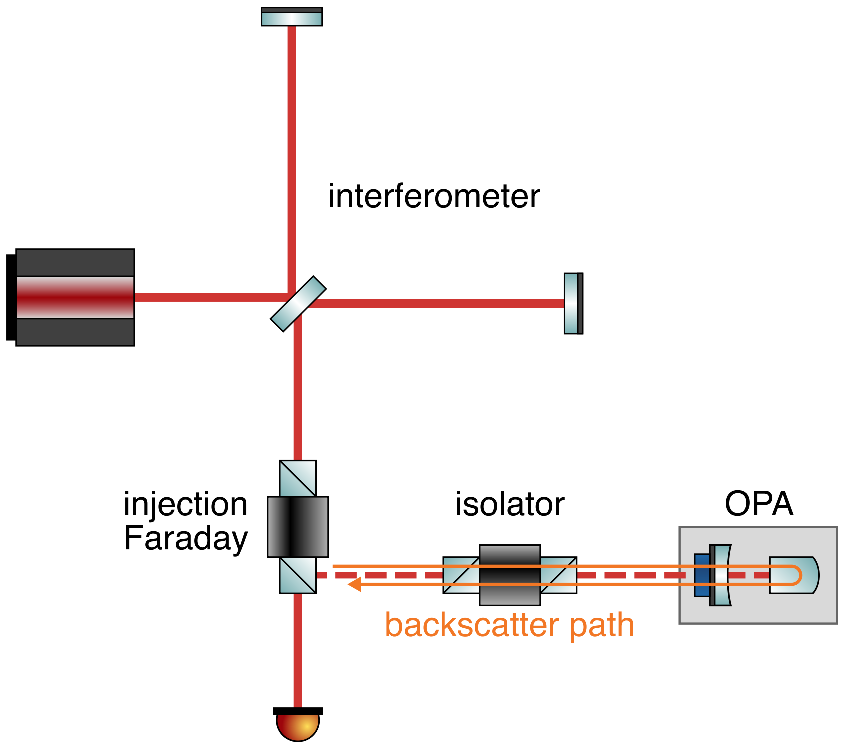
Backscatter noise

$$\beta_{\rm bsc} = b\left[e^{-r}\cos(\phi-\theta)e^{i\theta} + e^{r}\sin(\phi-\theta)e^{i(\theta+\frac{\pi}{2})}\right]$$

$$\phi(t) = \Phi(t) + \delta\phi(t)$$ stray light phase

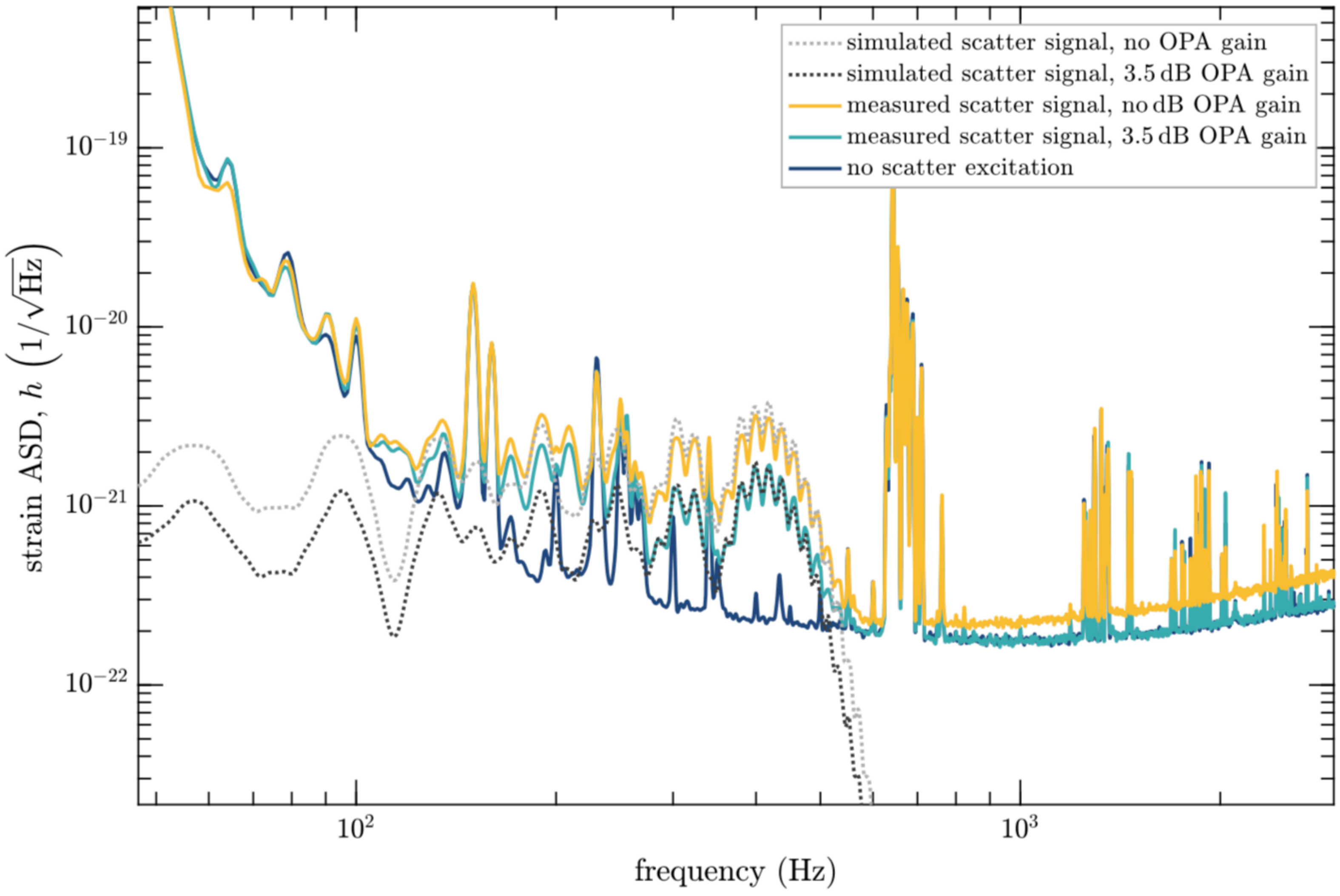
$$\theta(t) = \Theta(t) + \delta\theta(t)$$ squeezing phase

$$\begin{aligned} i_{\rm bsc}(t) &\propto \alpha b\left[e^{-r}\cos(\Phi+\delta\phi-\delta\theta)\cos(\delta\theta) + e^{r}\sin(\Phi+\delta\phi-\delta\theta)\sin(\delta\theta)\right] \\ &= \alpha b\left[e^{-r}\cos(\Phi)\cos(\delta\phi-\delta\theta)\cos(\delta\theta) - e^{-r}\sin(\Phi)\sin(\delta\phi-\delta\theta)\cos(\delta\theta)\right. \\ &\qquad \left. - e^{r}\sin(\Phi)\cos(\delta\phi-\delta\theta)\sin(\delta\theta) - e^{r}\cos(\Phi)\sin(\delta\phi-\delta\theta)\sin(\delta\theta)\right] \\ &\approx \alpha b\left[e^{-r}\cos(\Phi) - e^{-r}\sin(\Phi)\delta\phi - 2\sinh(r)\sin(\Phi)\delta\theta\right] \end{aligned}$$



Scattering "shoulder"

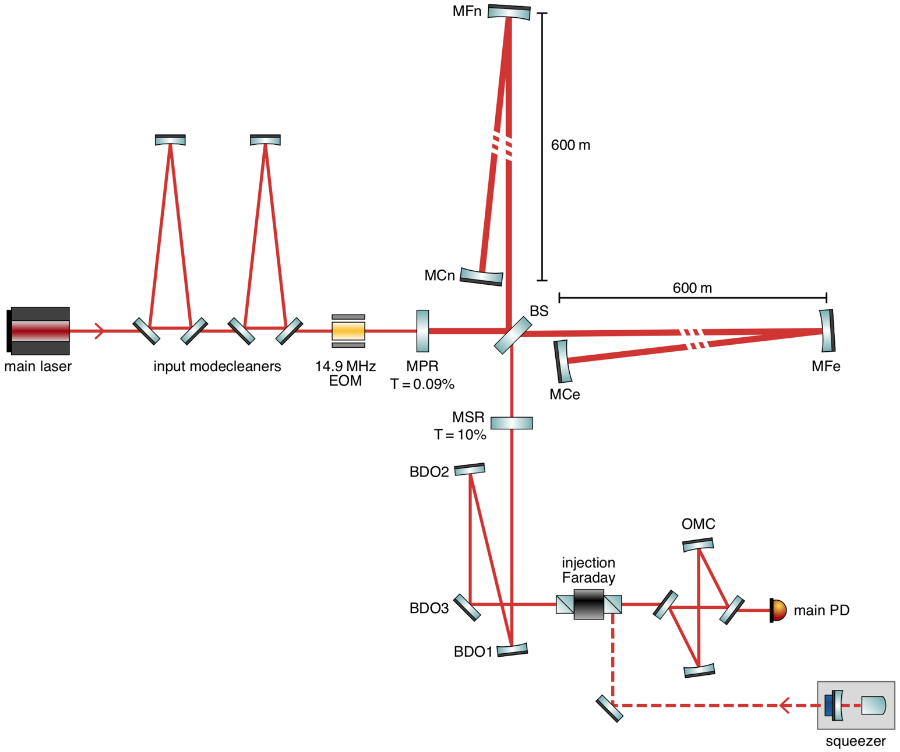
(upconversion of slow large-amplitude phase fluctuations)



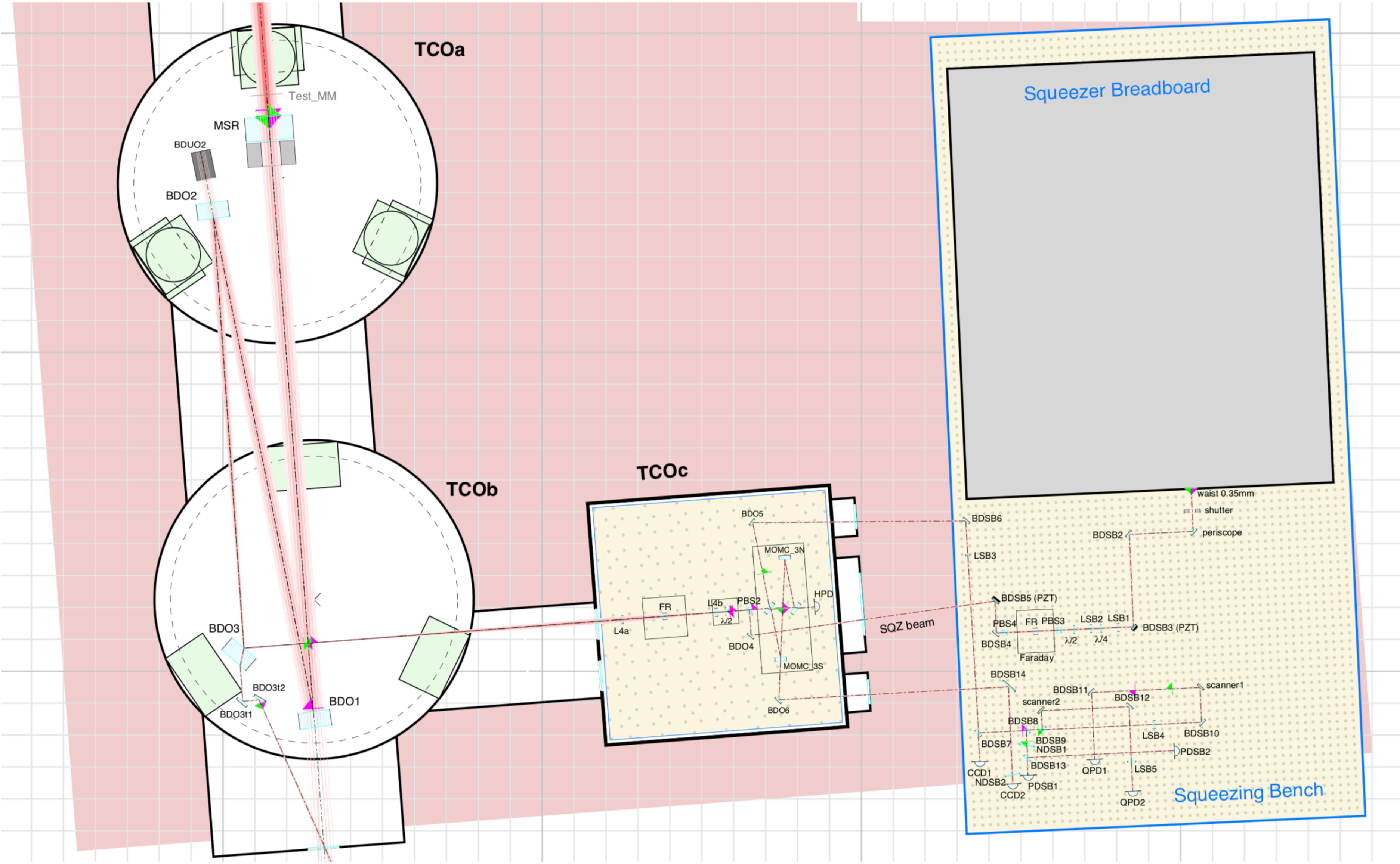
GEO 600

- British-German GW observatory
- 17 km south of Hannover
- part of the LIGO Scientific Collaboration

- the GEO on-site team consists of:
  - 3 operators, 1 technician
  - 5 postdocs
  - 2 PhD students

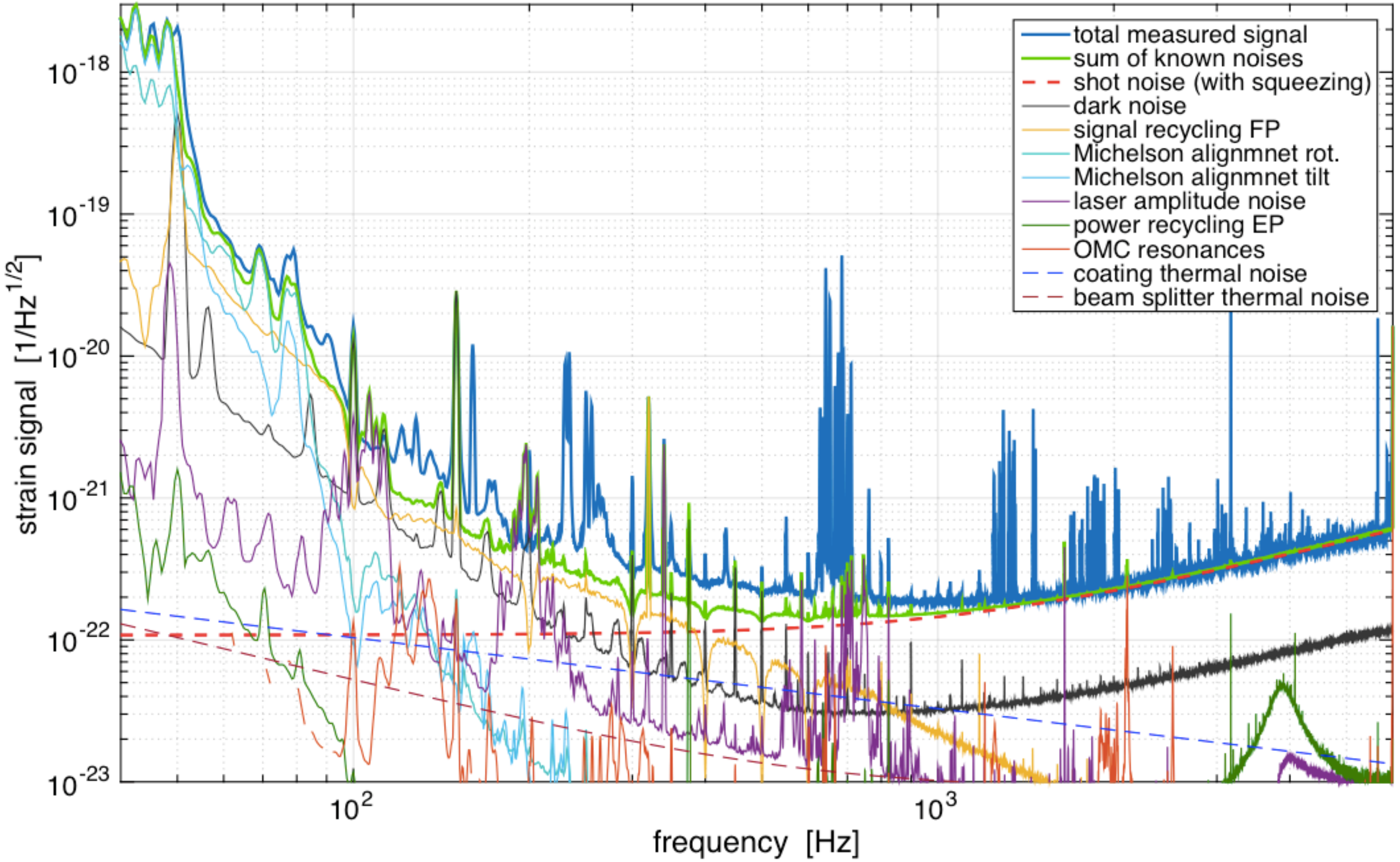


Optical layout

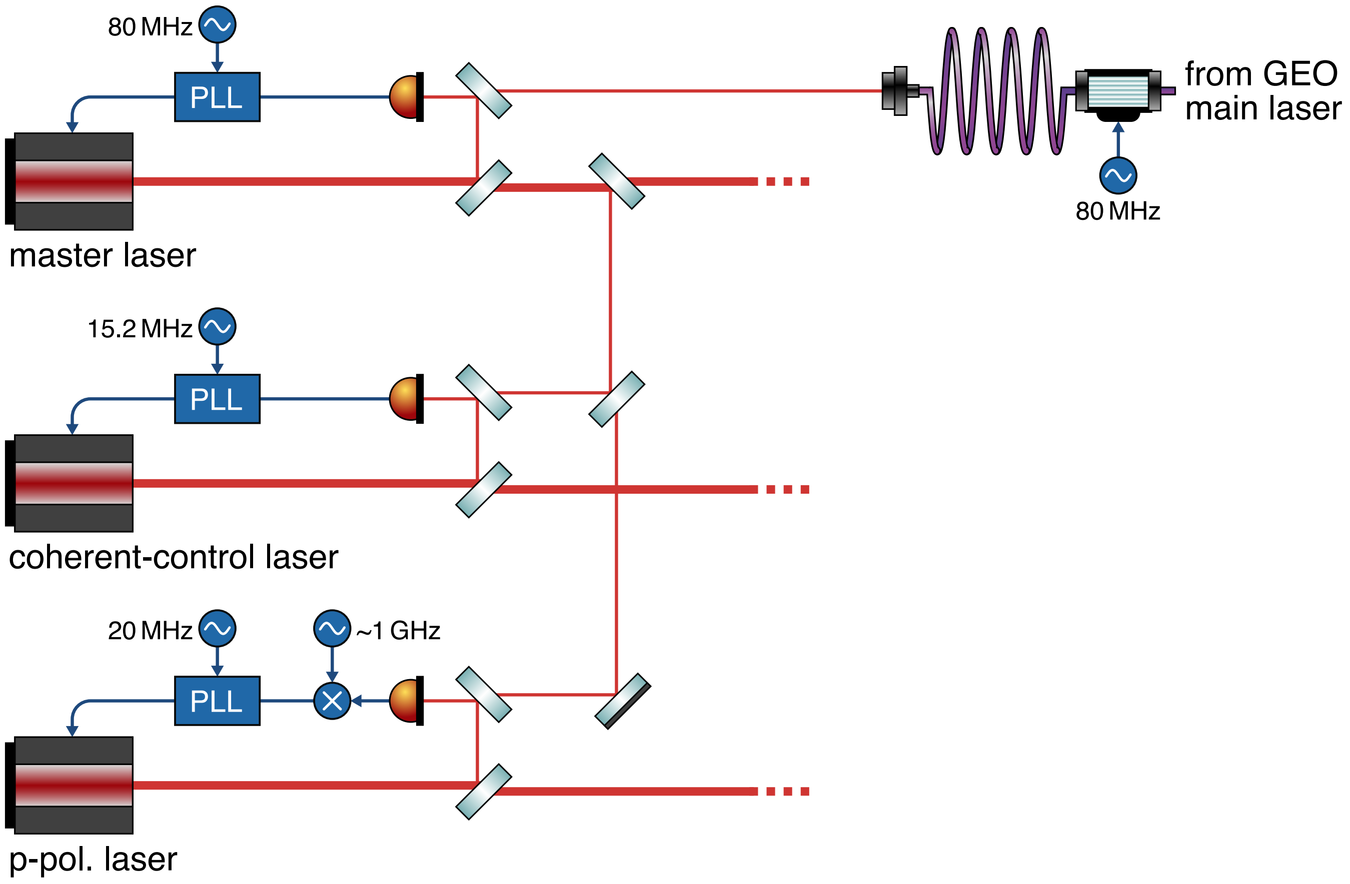


Credit: Roland Schilling

GEO noise budget

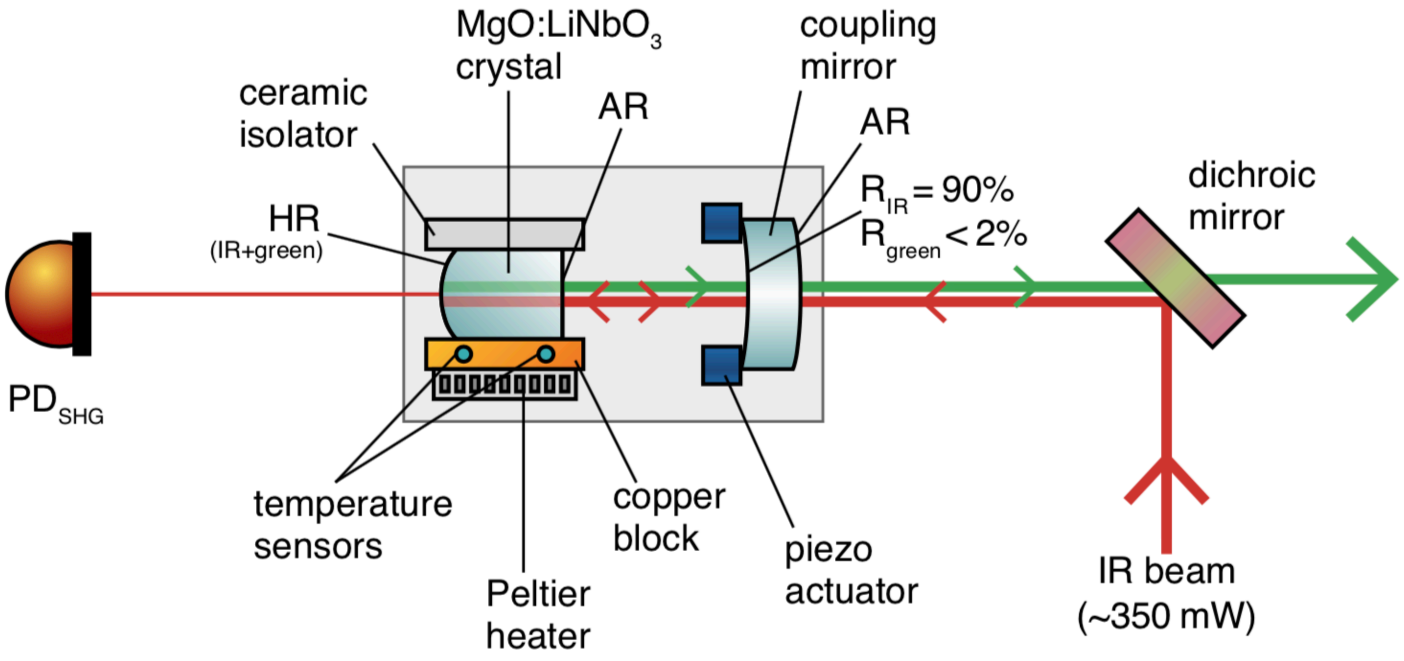


Auxiliary lasers

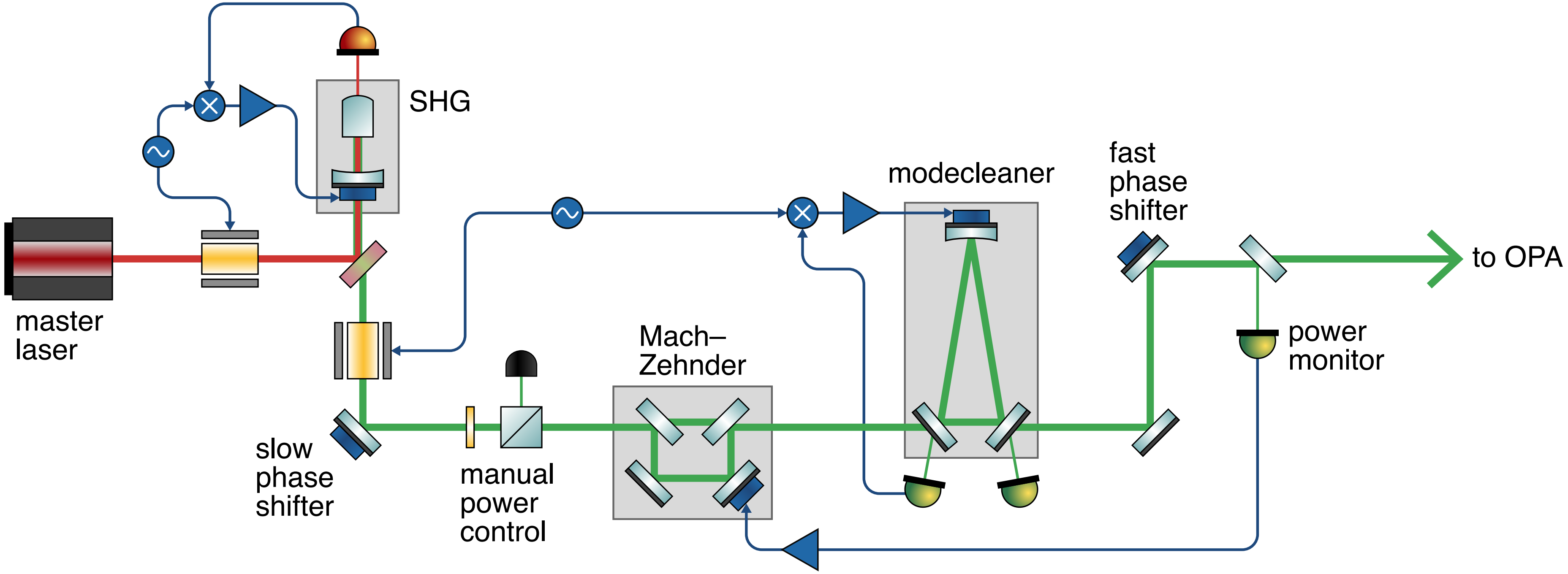


SHG*

*second harmonic generator

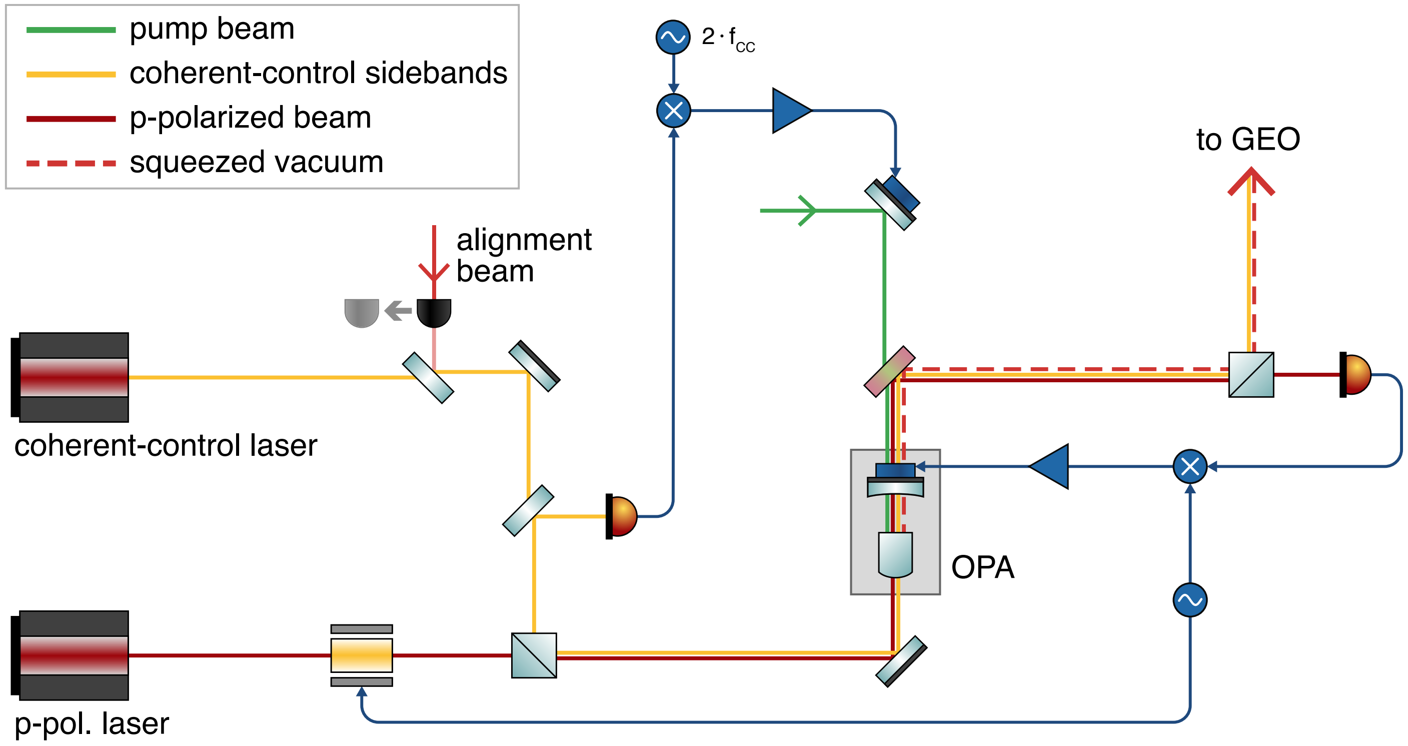


Green light path

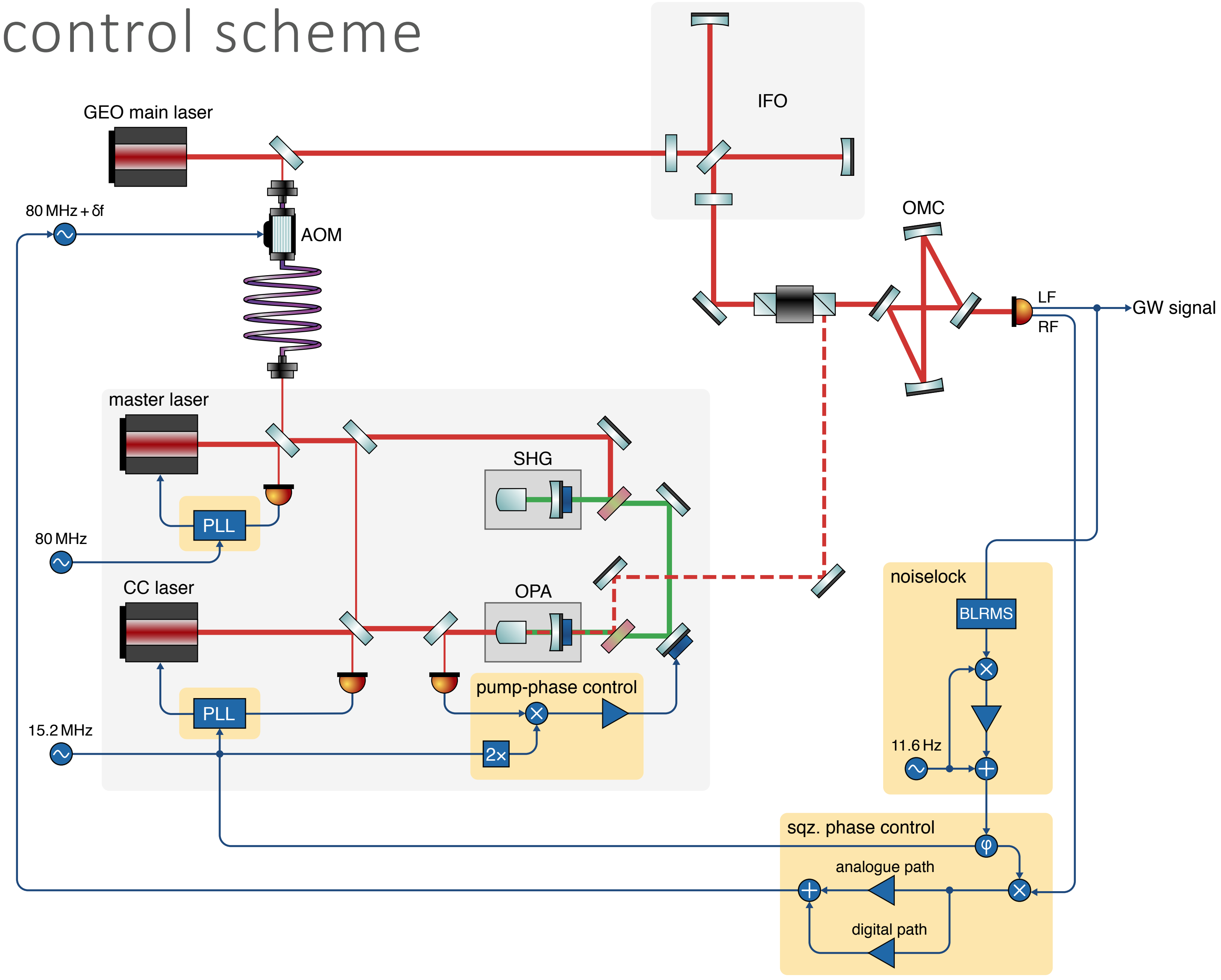


OPA*

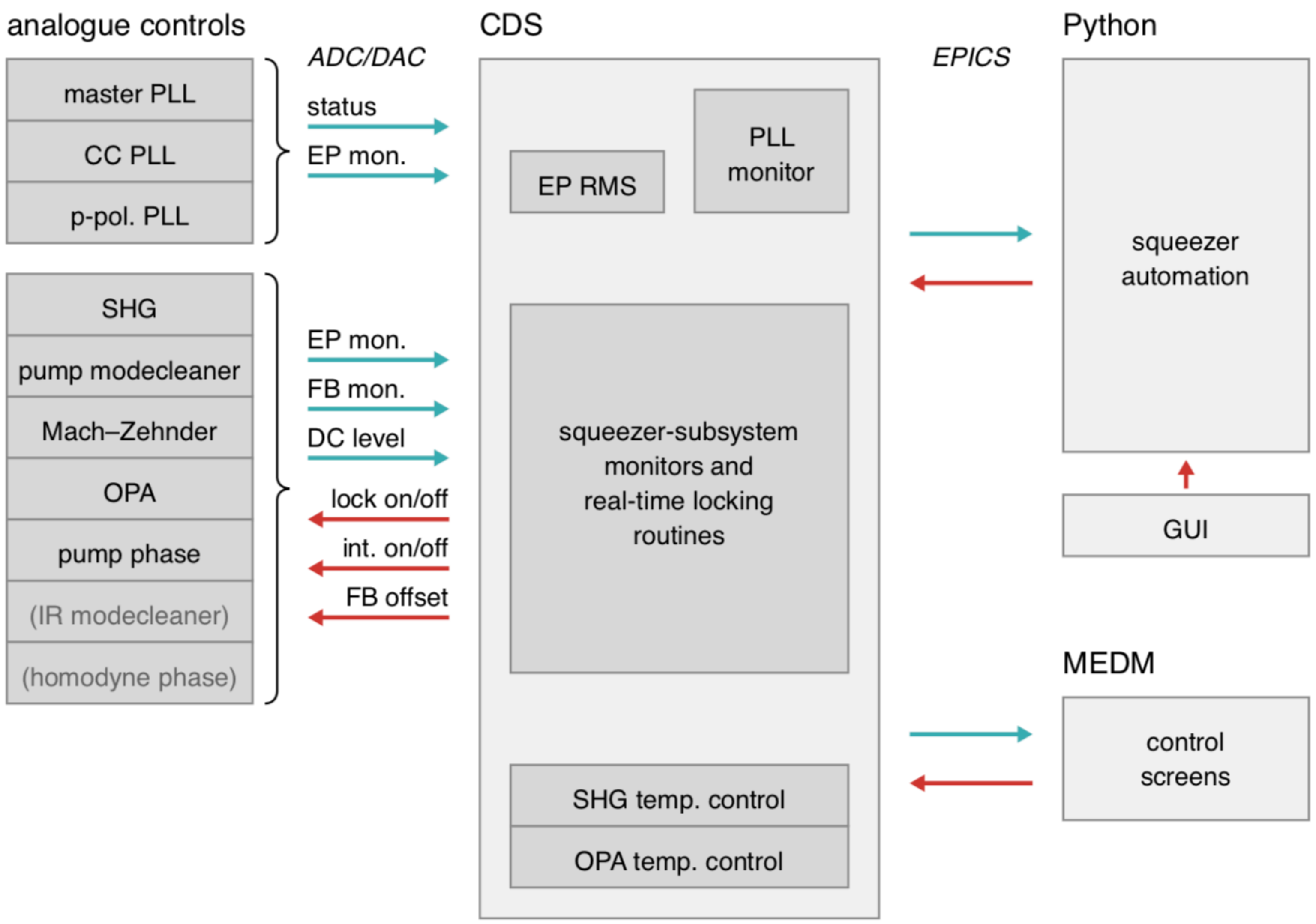
*optical parametric amplifier



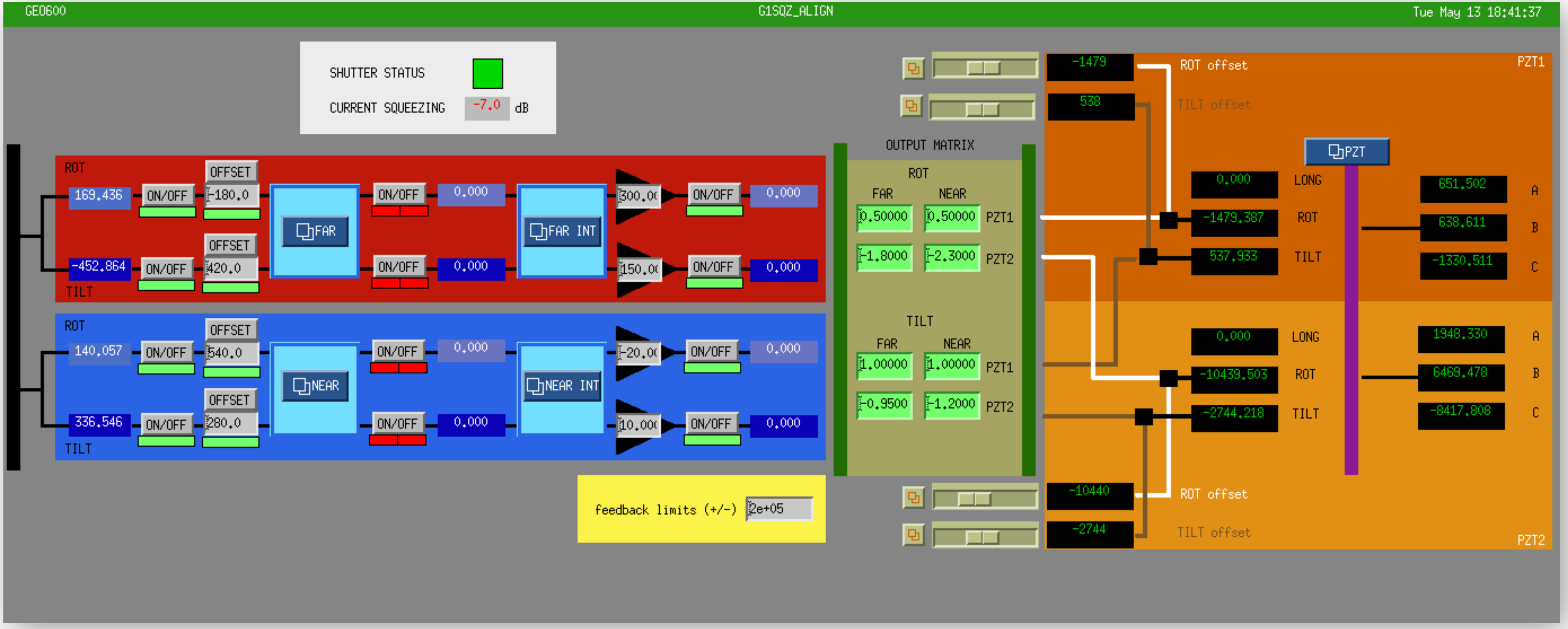
Full phase control scheme



Digital control of the squeezer subsystems

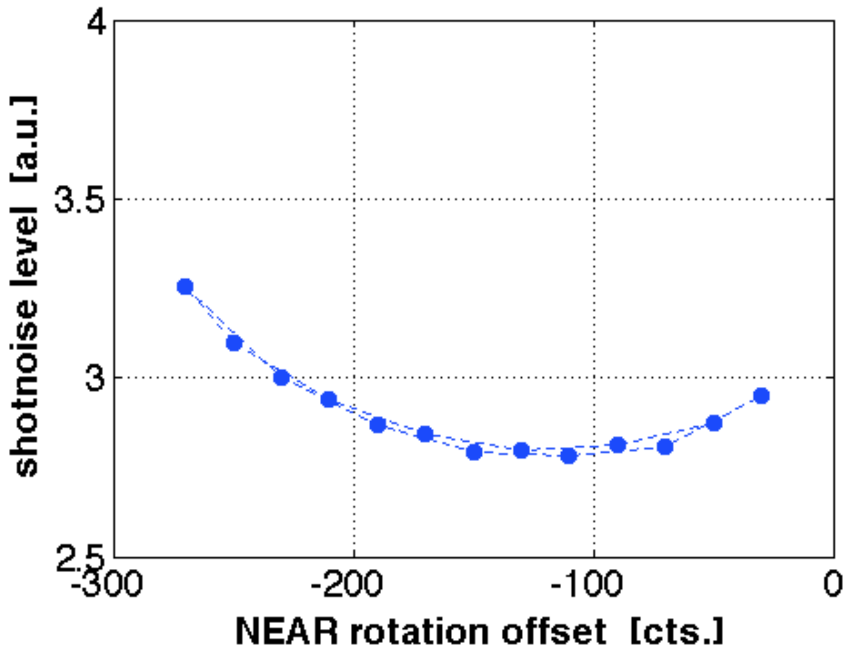


Digital alignment control (CDS)

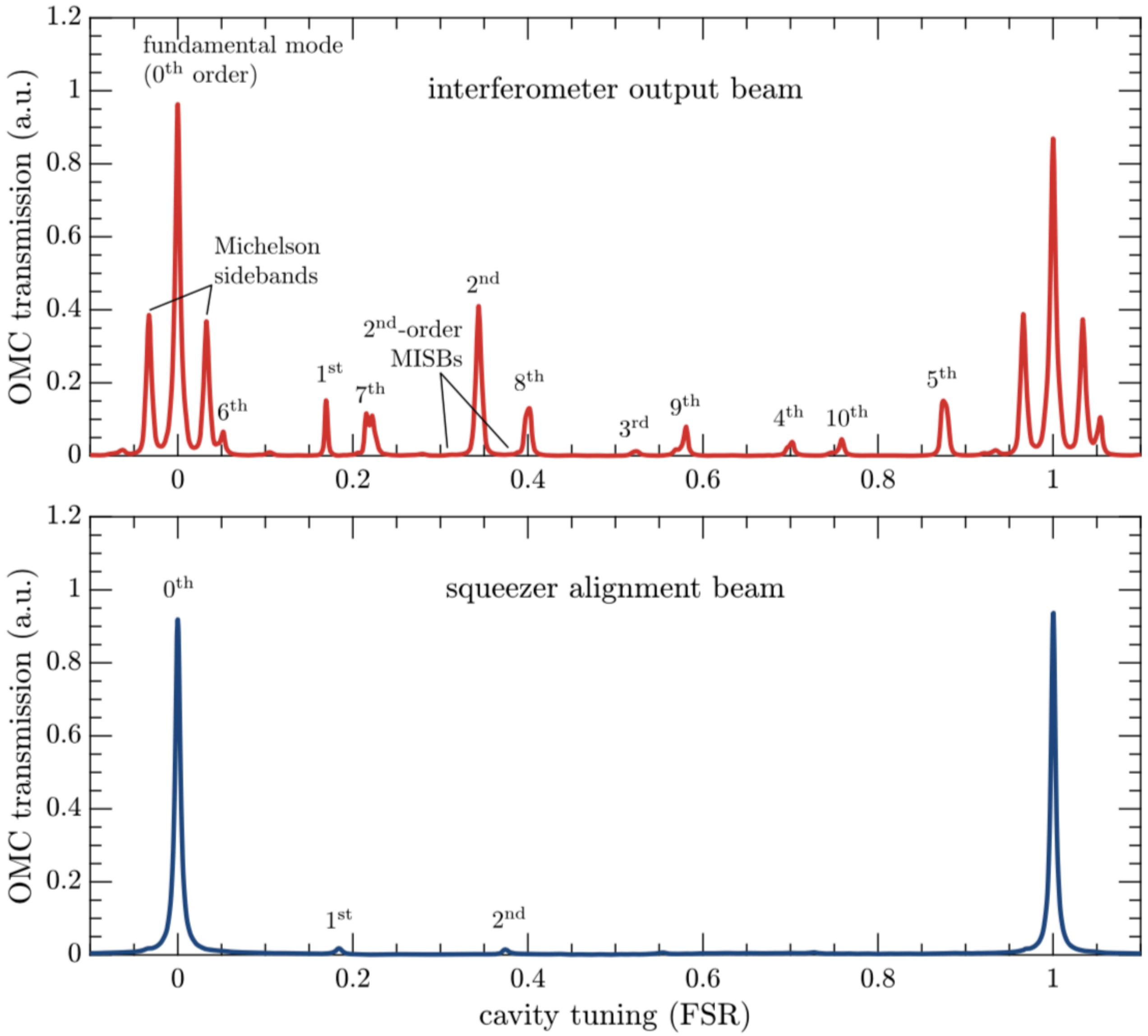


Tuning the alignment setpoints:

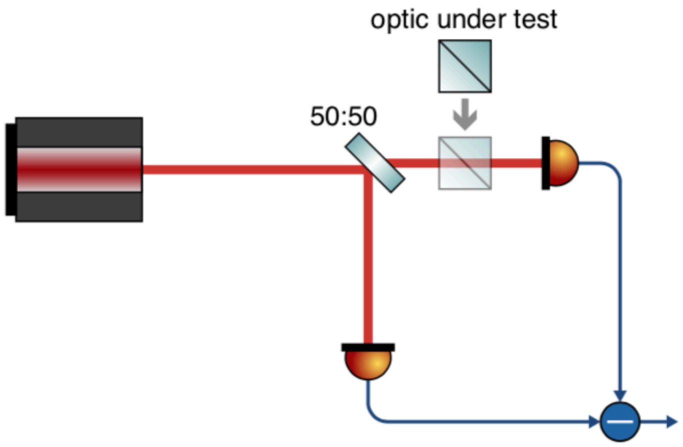
- error signals are not zero for optimal alignment
- optimal error-point offsets change slightly over periods of days
- possible culprits:
  - electronic offsets
  - first-order coupling of spot positions



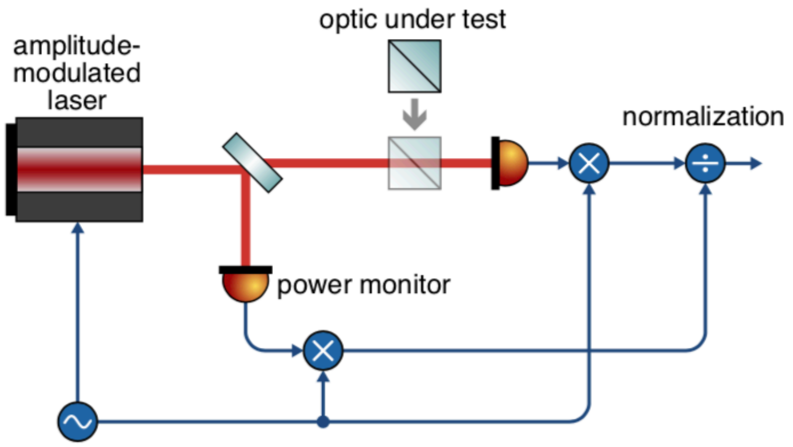
OMC modescan



Loss measurements

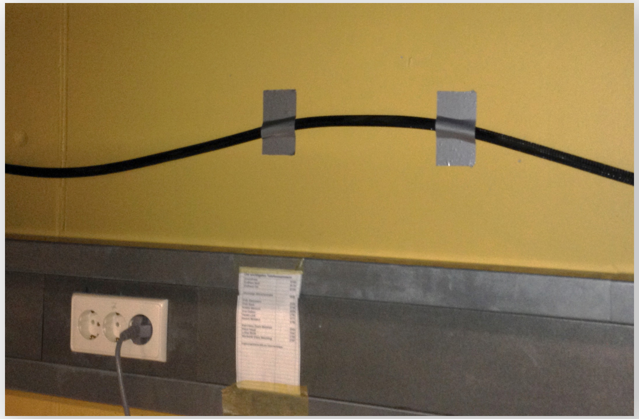


(a) Differential measurement

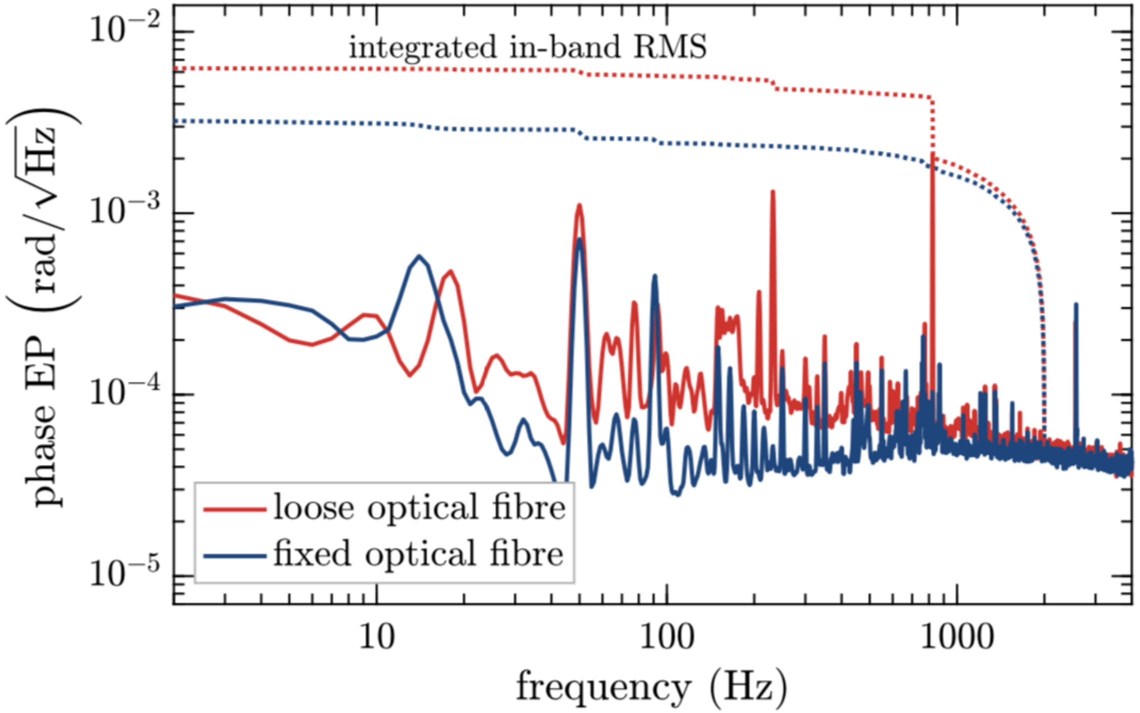


(b) Modulation measurement

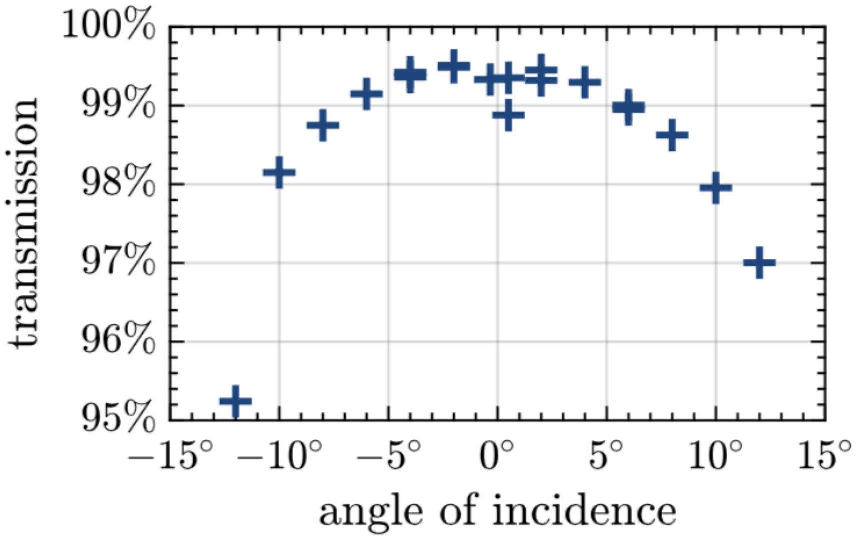
Improving residual phase noise



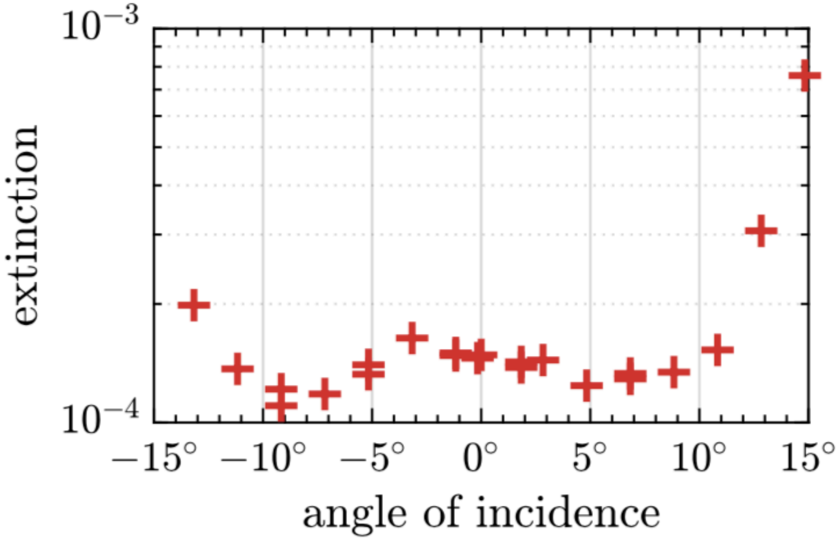
- fighting phase noise sources at the source
- important contributor is optical fibre for phase lock to GEO laser



PBS characterization



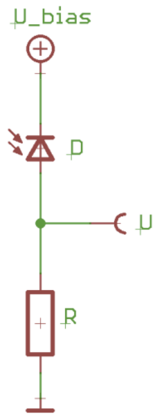
(a) Tuned for maximum transmission

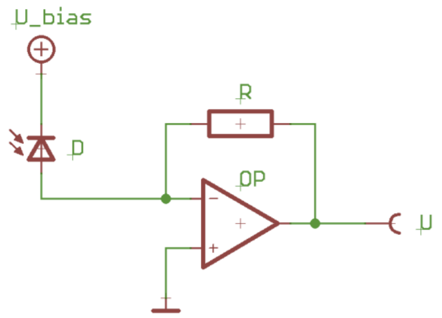


(b) Tuned for maximum extinction

Dark noise caused by thermal resistor noise

- shot noise of photo current (lower with squeezing): $$\tilde{I}_S = \sqrt{2eI}$$
- thermal noise (Johnson noise): $$\tilde{I}_T = \sqrt{\frac{4k_BT}{R}}$$
- we want shot noise to be dominating: $$SNR = \sqrt{\frac{eIR}{2k_BT}}$$
- possible solutions:
  - cryogenic electronics
  - high voltage
  - frequency dependent impedance



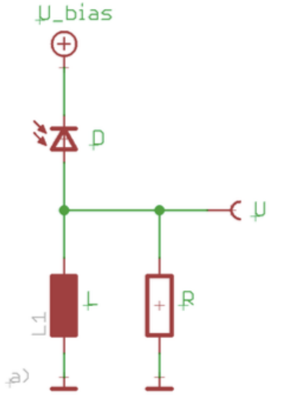


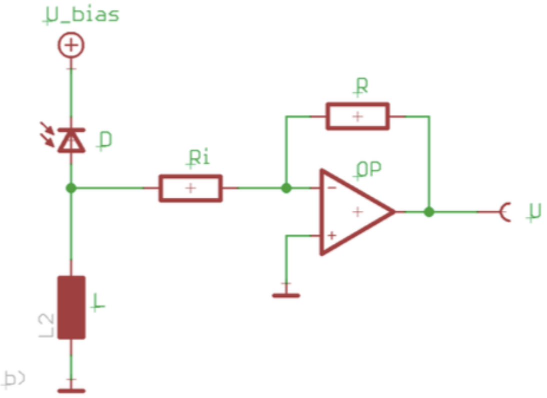
Grote et al., DCC P1500203

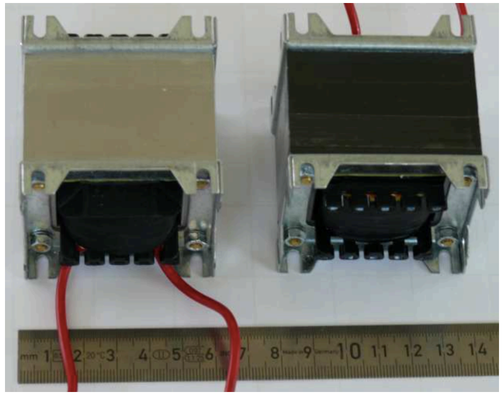
Inductor as frequency dependent impedance

- low frequencies see low impedance
  → DC current does not cause high DV voltage
- audio frequencies see high impedance
  → strong signal, well above dark noise

- needs very high impedance (~2 H)
  to achieve low corner frequency
- Barkhausen noise (flipping of magnetic domains in core material) was initially a problem,
- solved by high-quality inductor with stacked mu-metal core

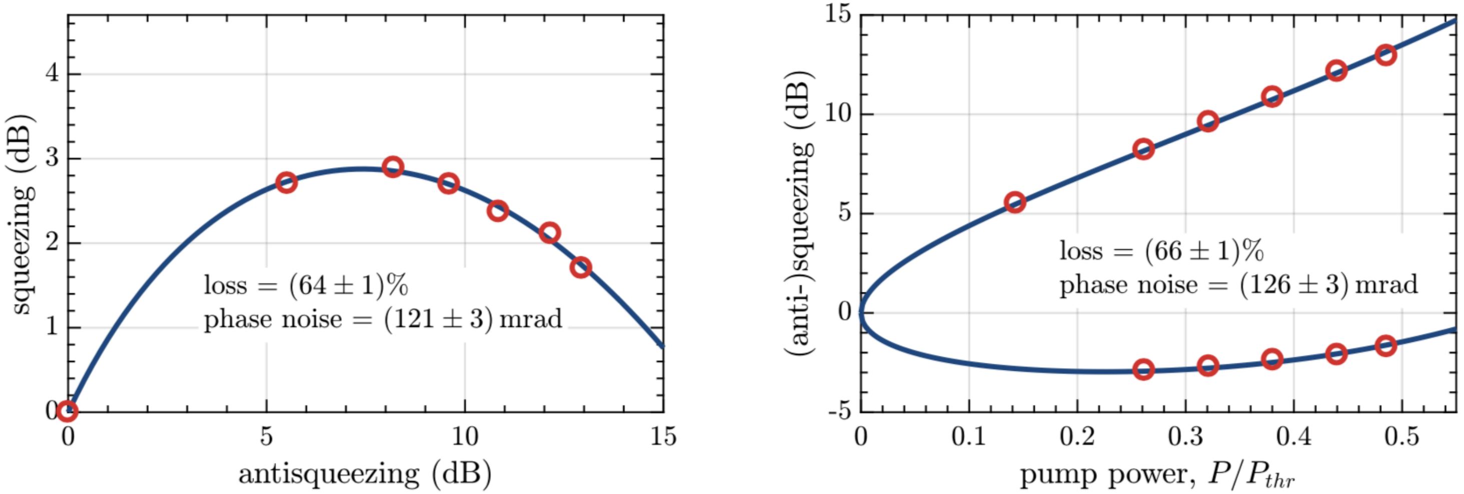




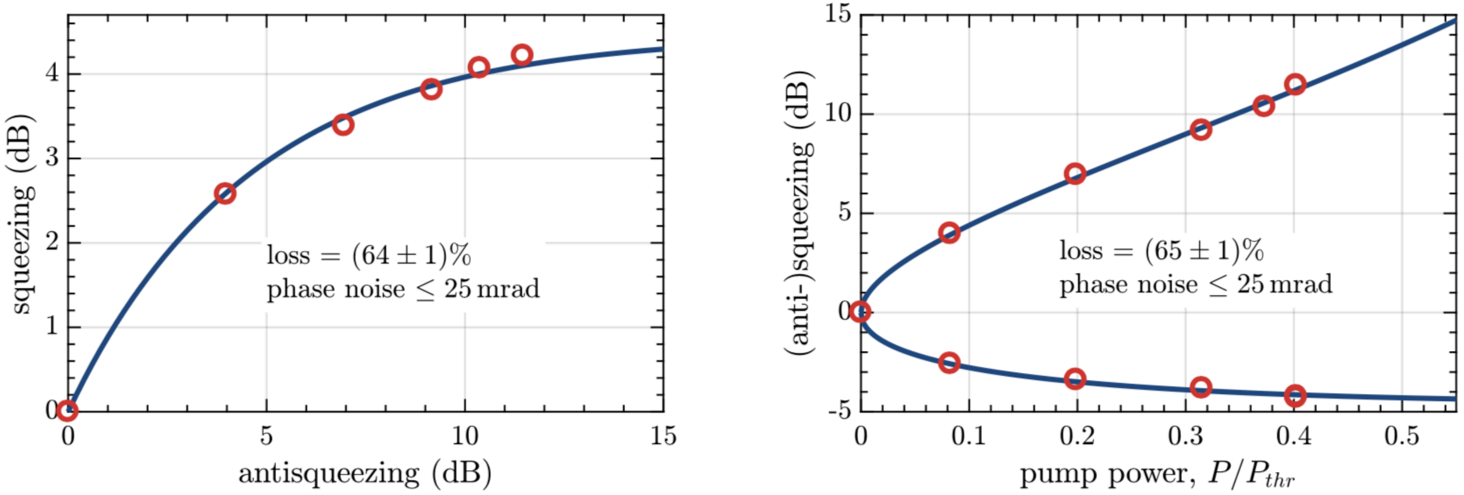


Grote et al., DCC P1500203

Squeezer characterization

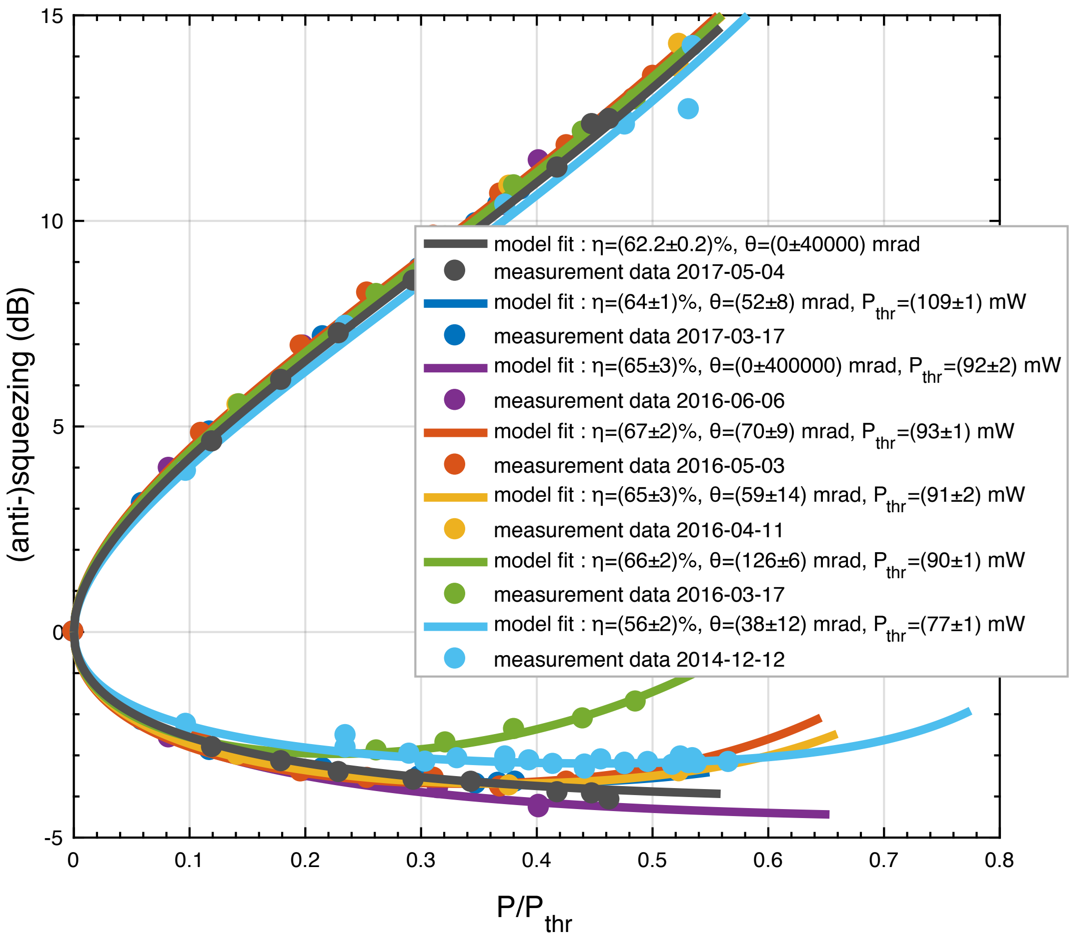


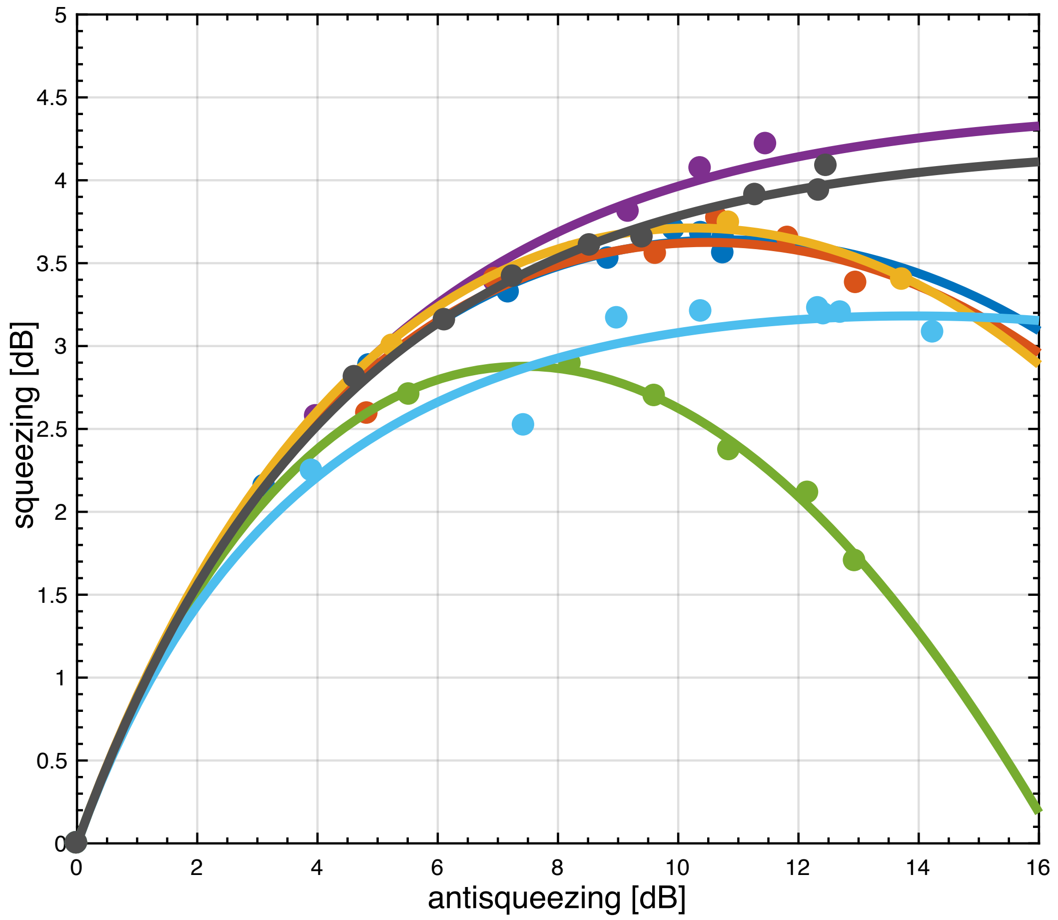
during backscatter problems



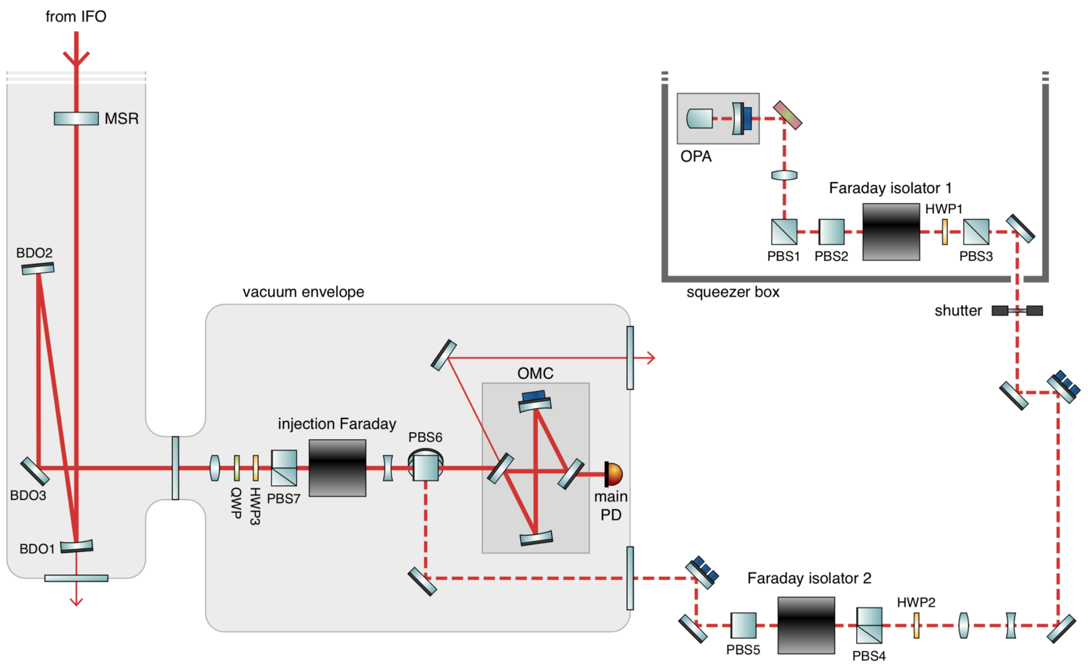
good performance

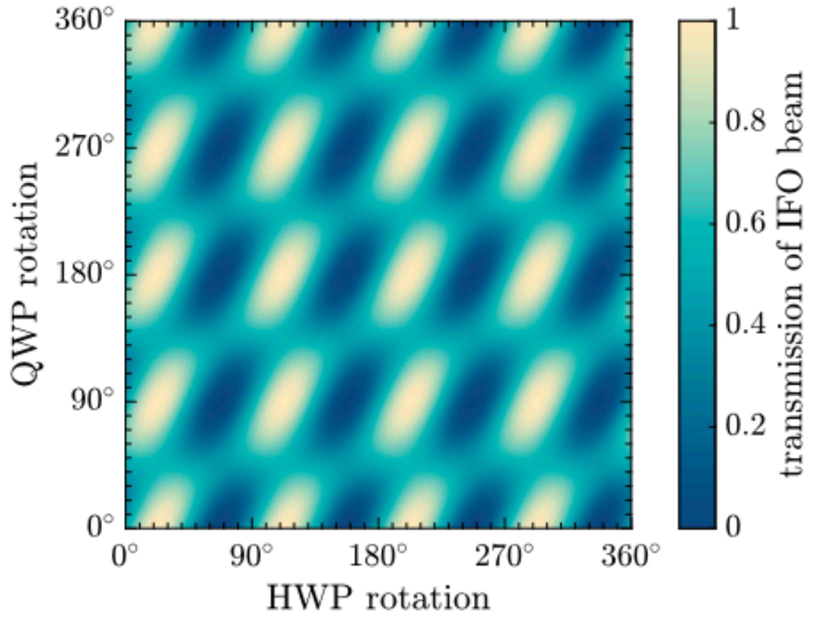
Varying pump power

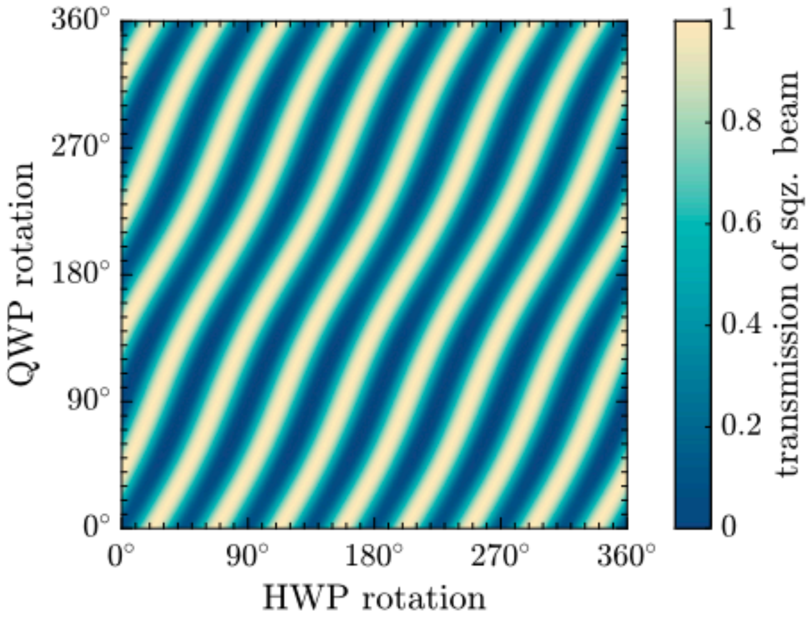




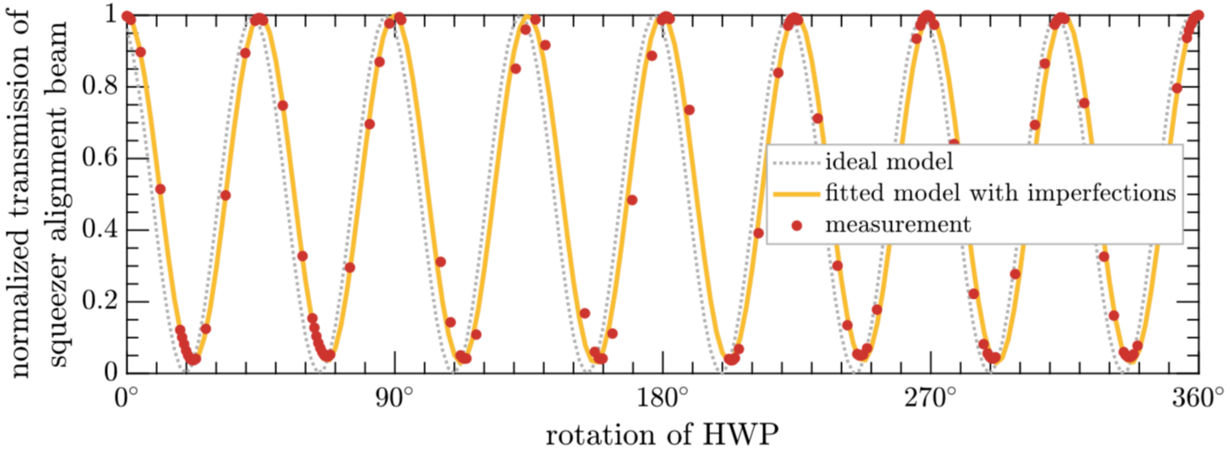
Polarization tuning 1



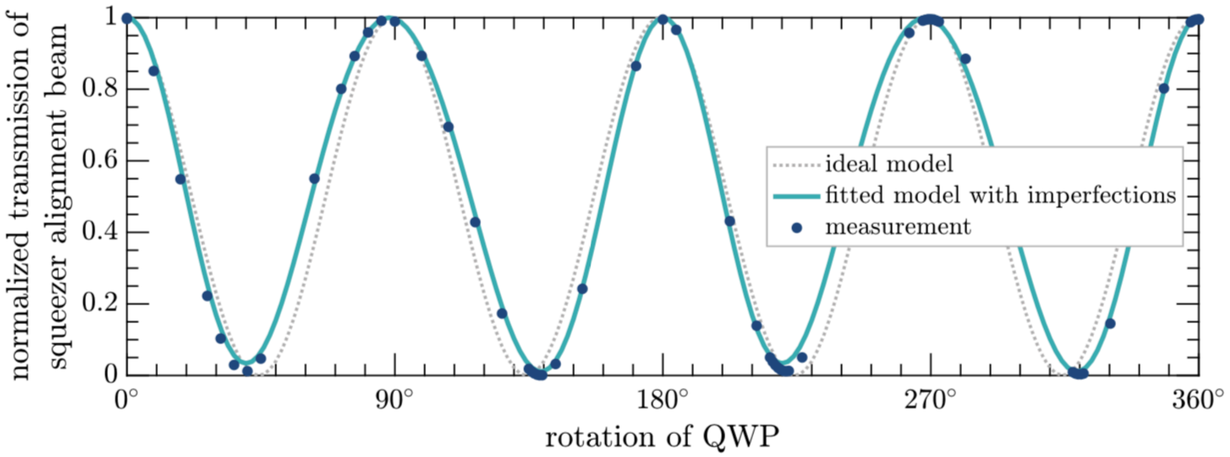




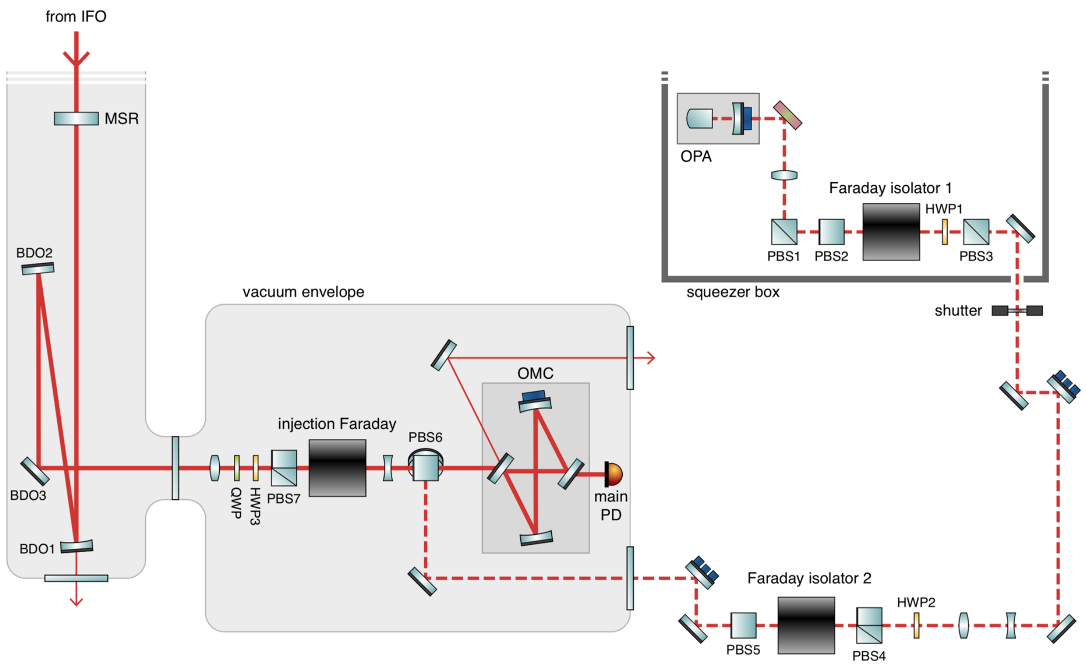
Polarization tuning 2



(a) Turning the half-wave plate

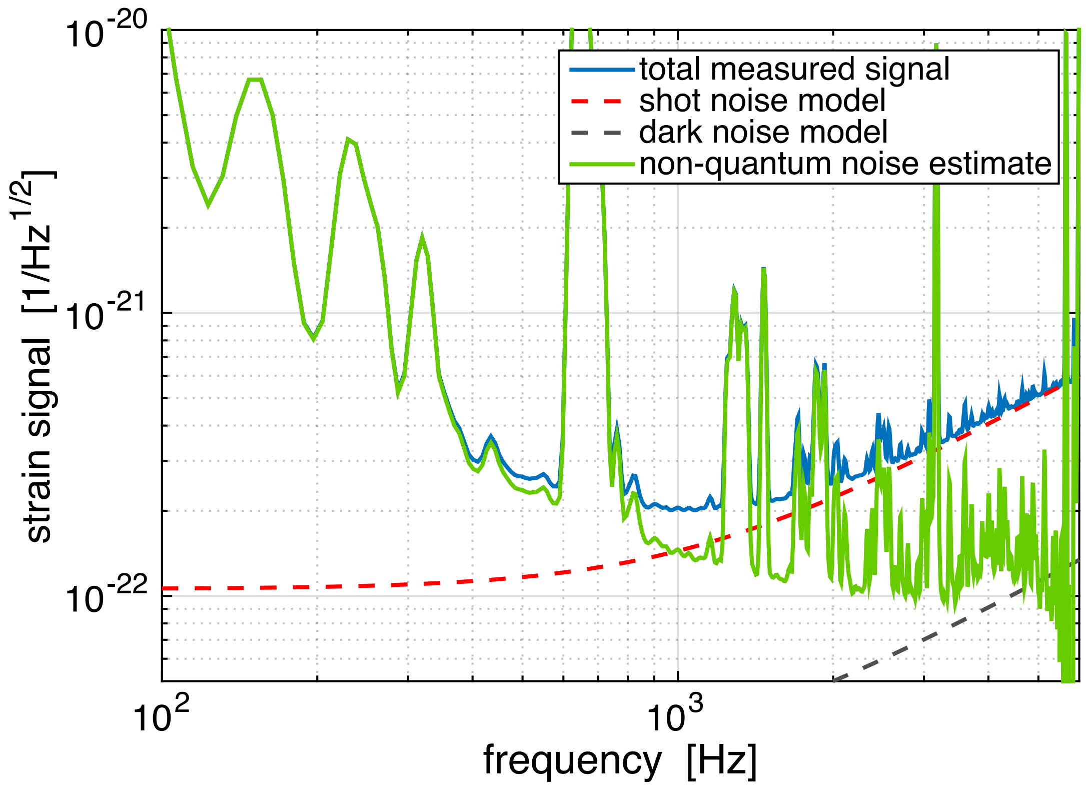


(b) Turning the quarter-wave plate



Noise subtraction

$$S_{rest} = \sqrt{S_{tot}^{2} - S_{shot}^{2} - \ldots}$$



pros:

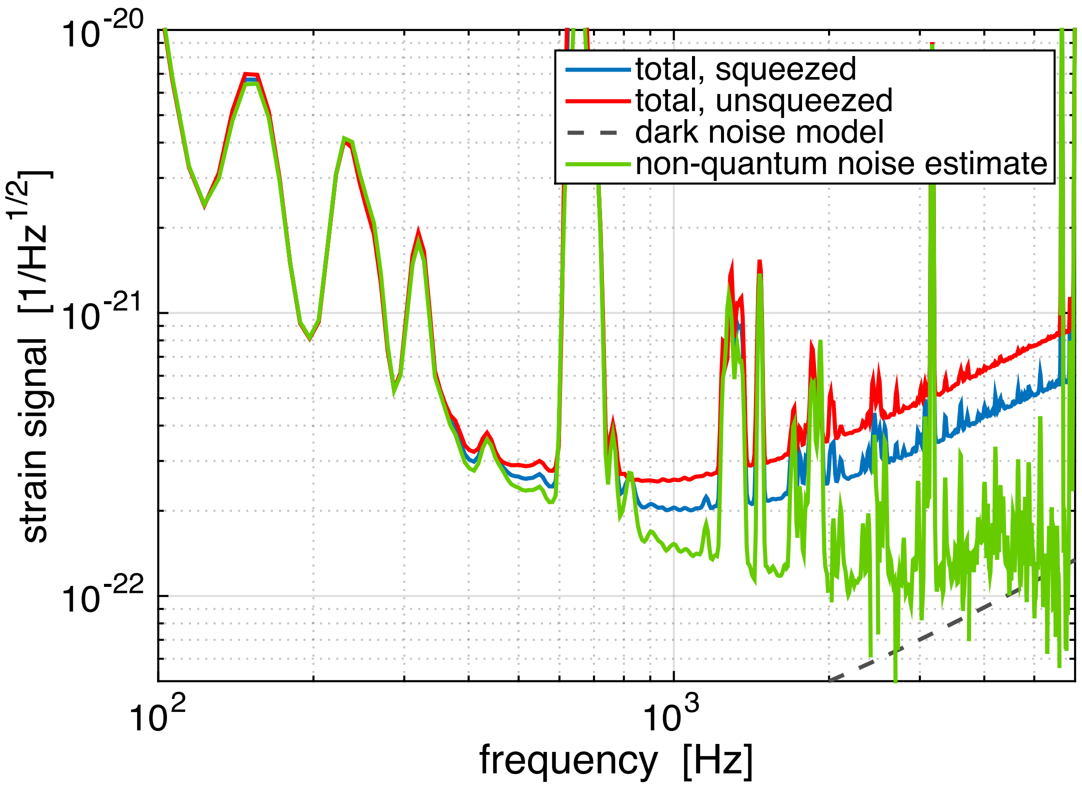
- very simple and can be done live
- all known noise terms can be included

cons:

- depends a lot on the correctness of the noise model
- many parameters need to be determined

Finding “unsqueezable” noise

$$S_{rest} = \sqrt{\frac{S_{sqz}^2 - r^2 \cdot S_{unsqz}^2}{1 - r^2}}$$



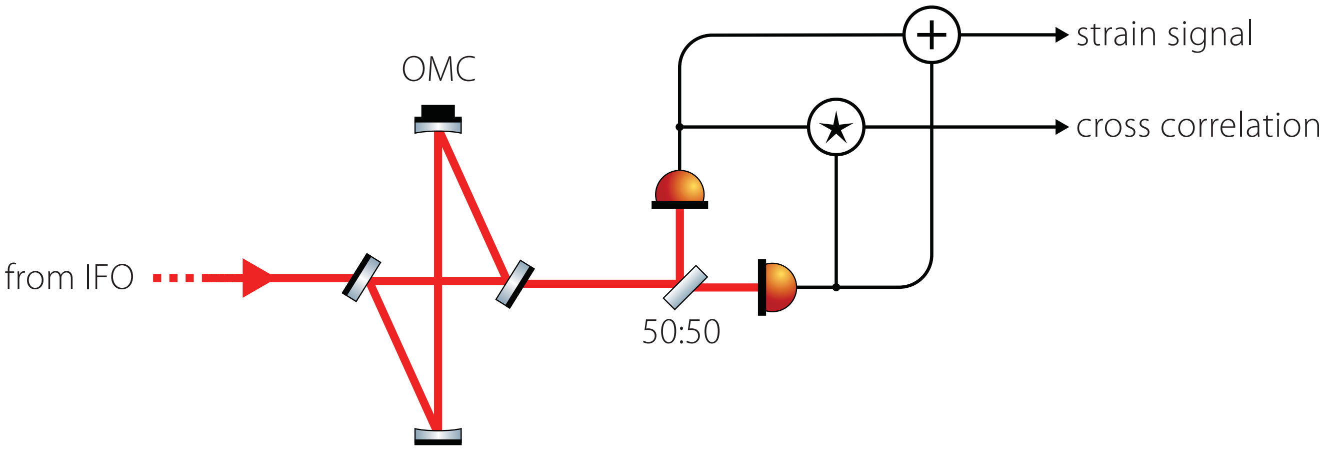
pros:

- needs no assumptions on shape and level of shot noise

cons:

- still needs squeezing factor as input parameter which is hard to measure independently with high accuracy

Cross correlation between two PDs



$$|S_{cross}|_T = \sqrt{S_{corr}^2 + 2\sqrt{\frac{\Delta T}{T}} S_{shot}^2}$$

pros:

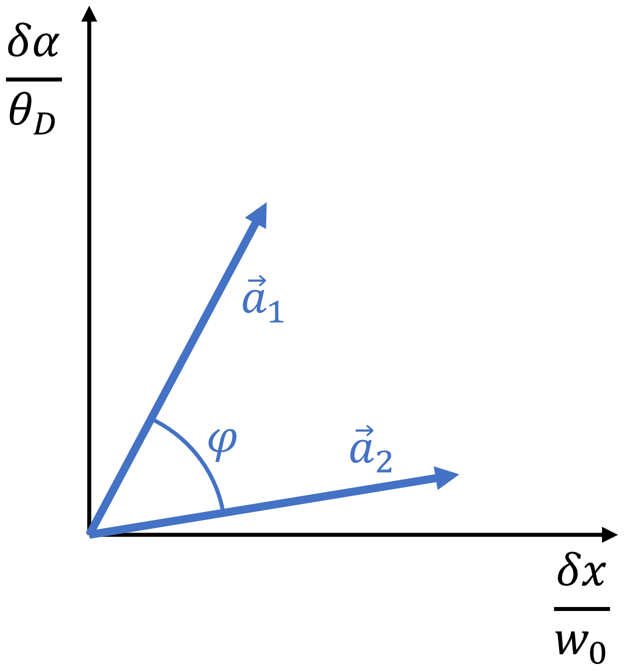
- cancels shot noise (and other uncorrelated noises) without any assumptions

cons:

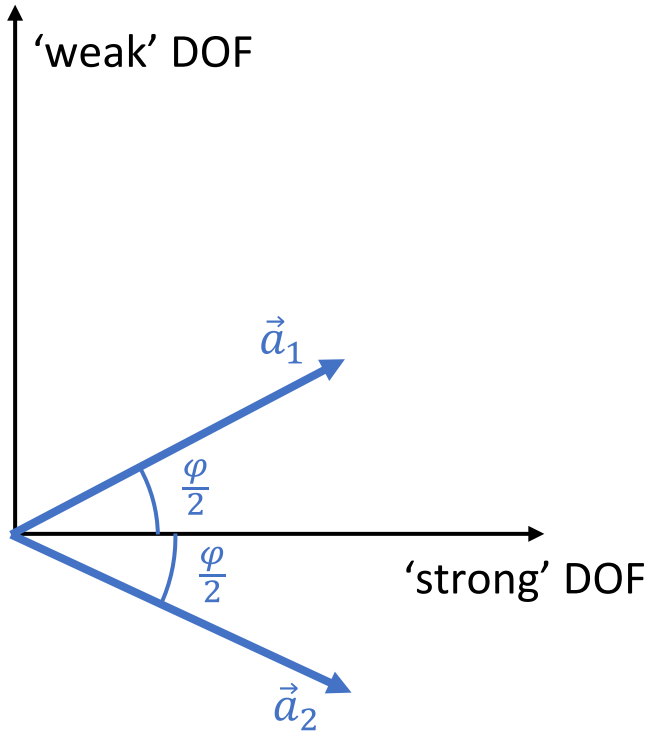
- currently not implemented (but we are thinking about changing that)

Separation of alignment actuators
Setup

- 'natural' basis:



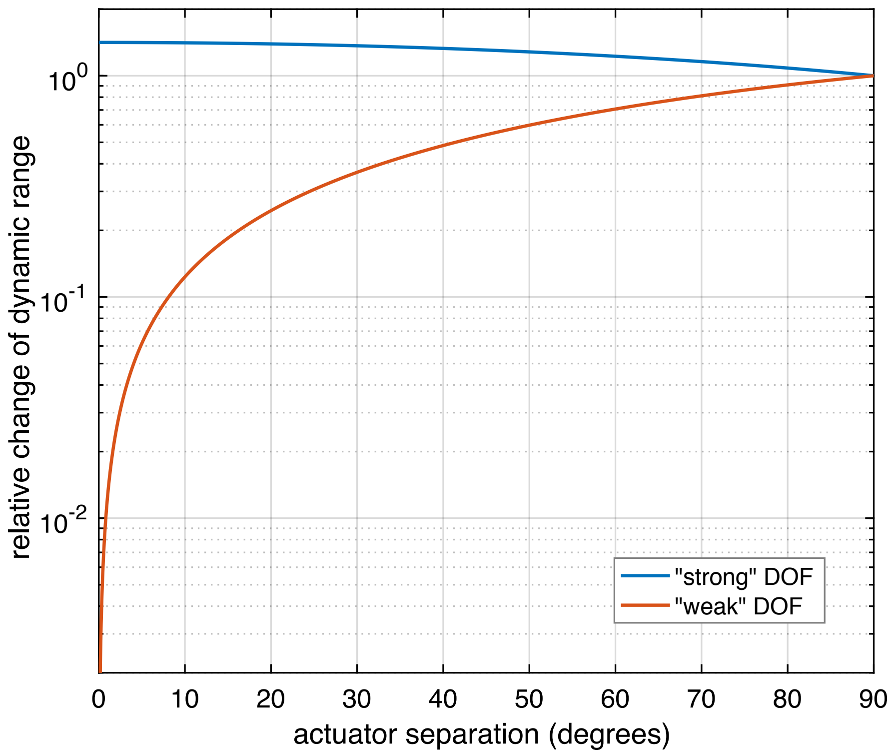
- rotated basis:

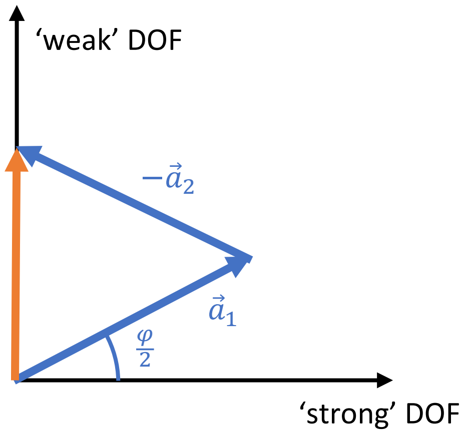


assume $0 \leq \varphi \leq 90°$ (otherwise flip sign of one actuator)

Separation of alignment actuators

Effect on dynamic range

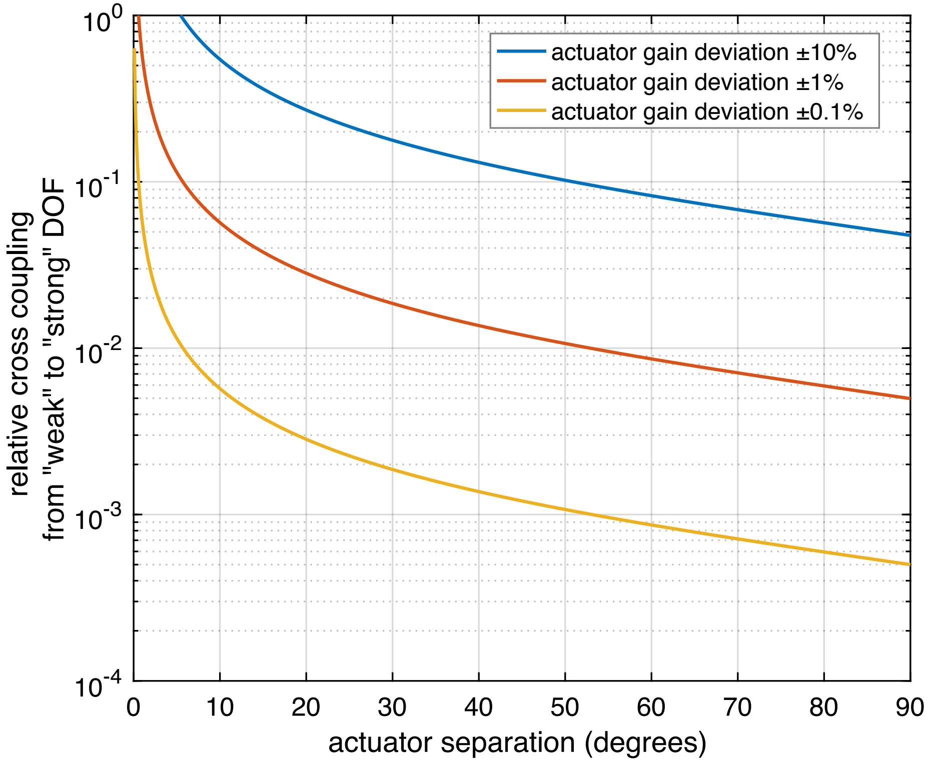


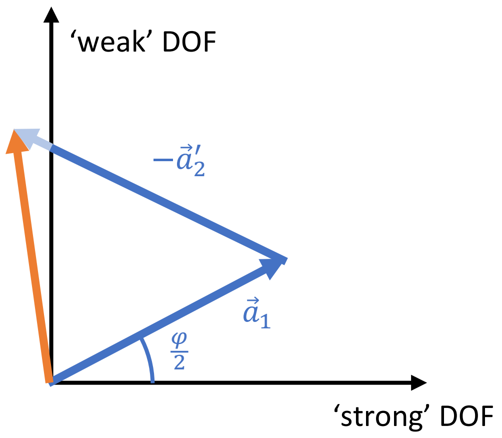


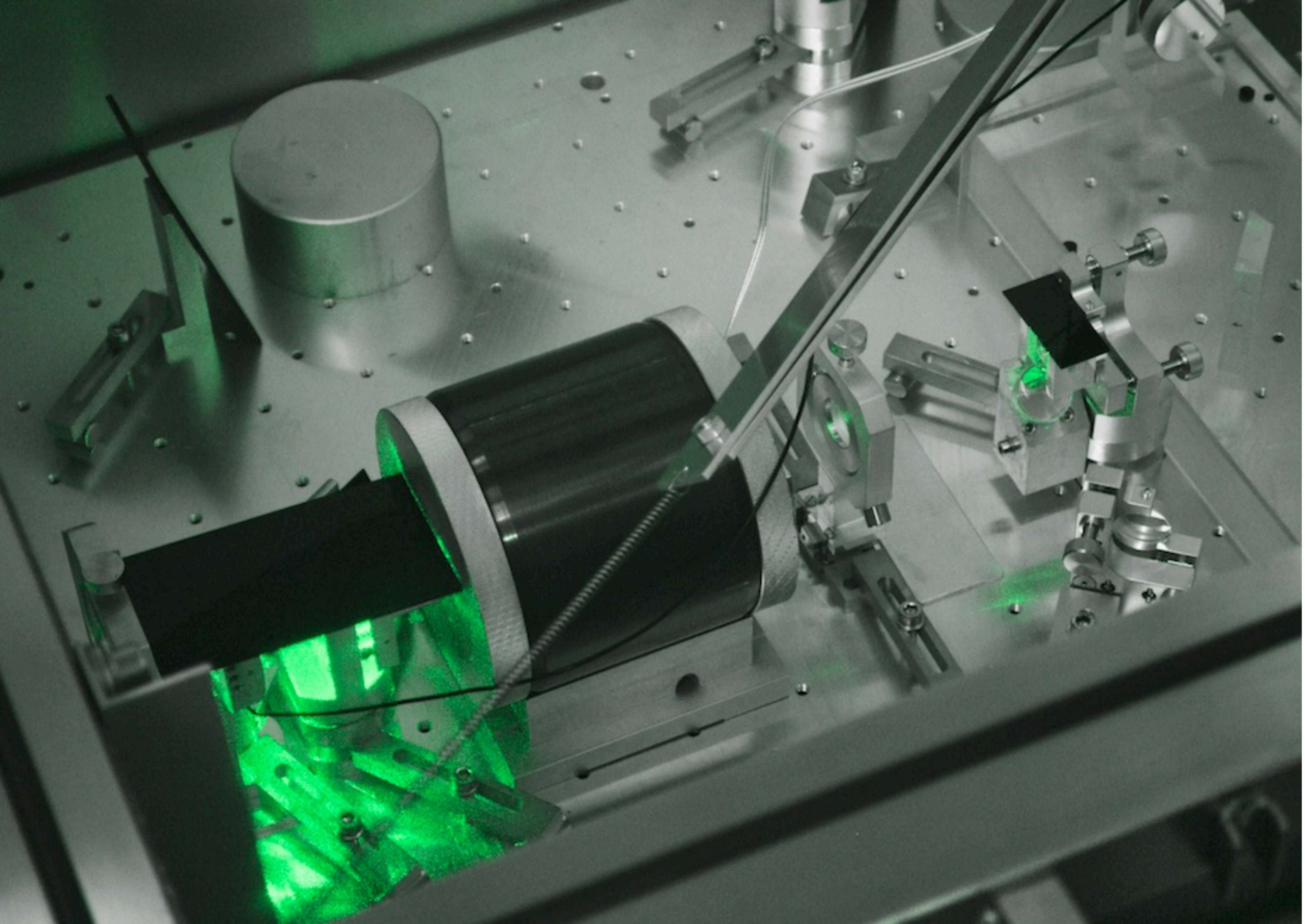
(This does not yet consider that the effect of the individual actuators also depends on their position along the beam.)

Separation of alignment actuators

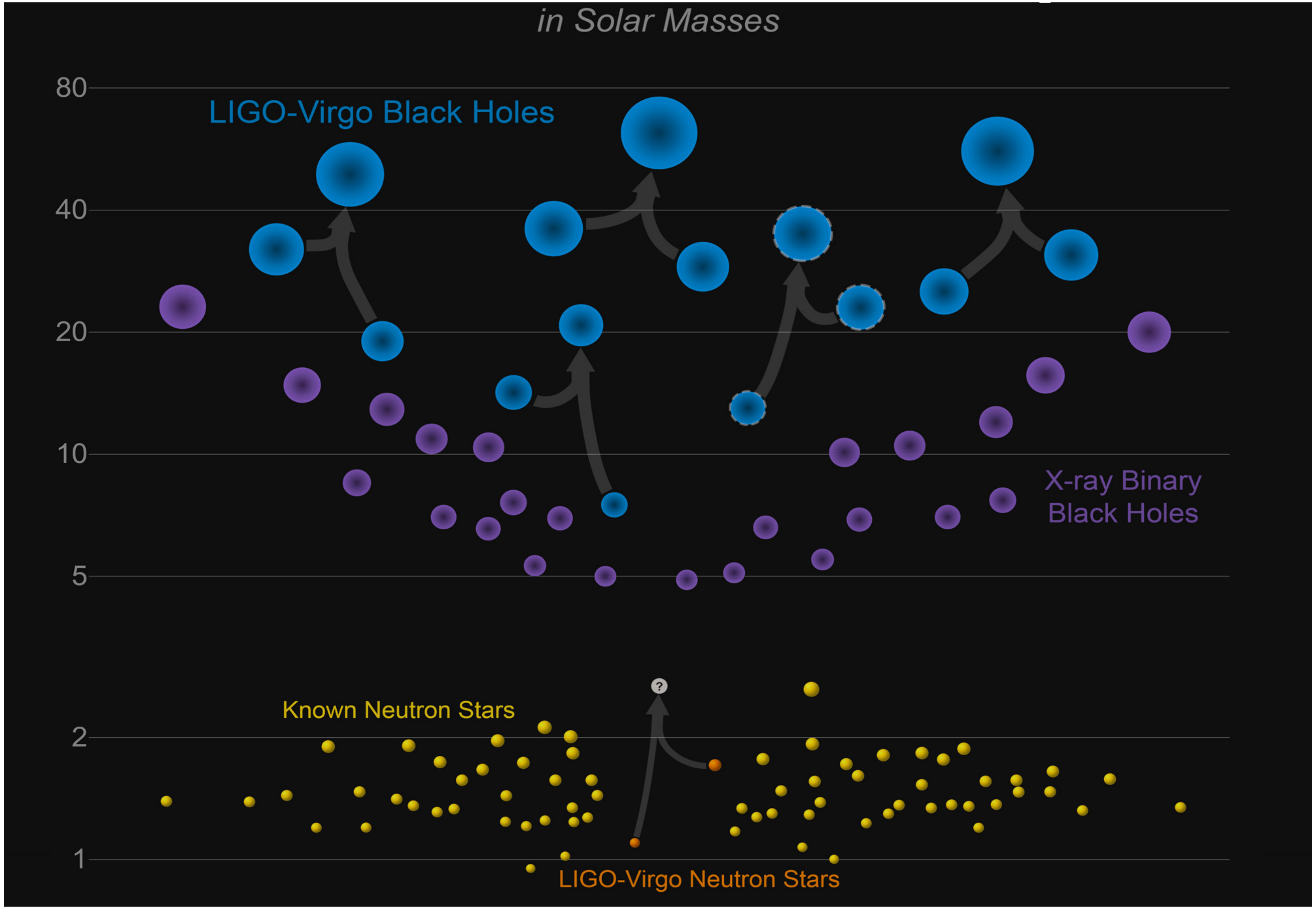
Effect on cross-coupling in the presence of parameter uncertainties





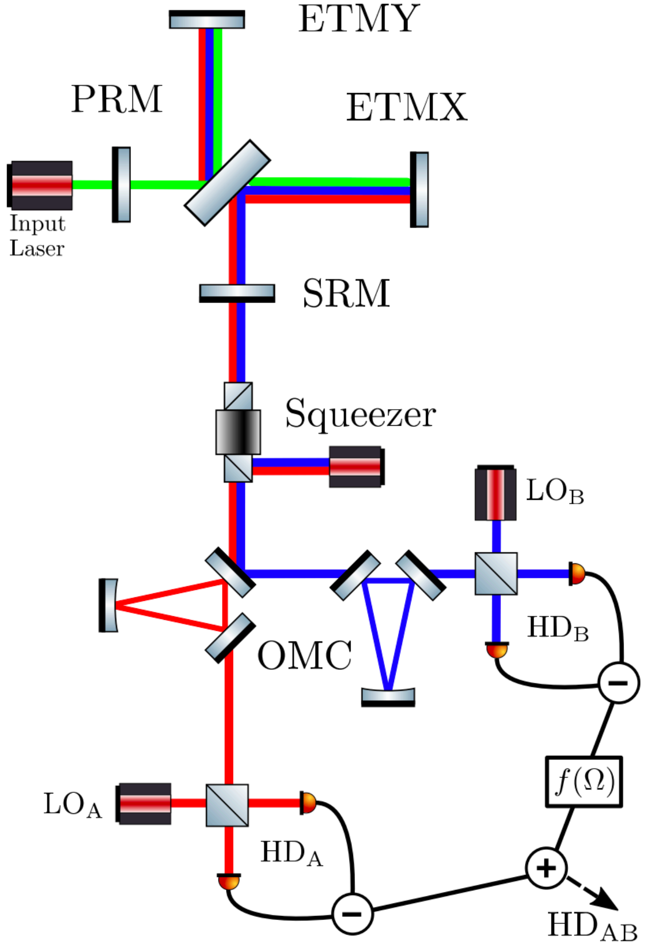


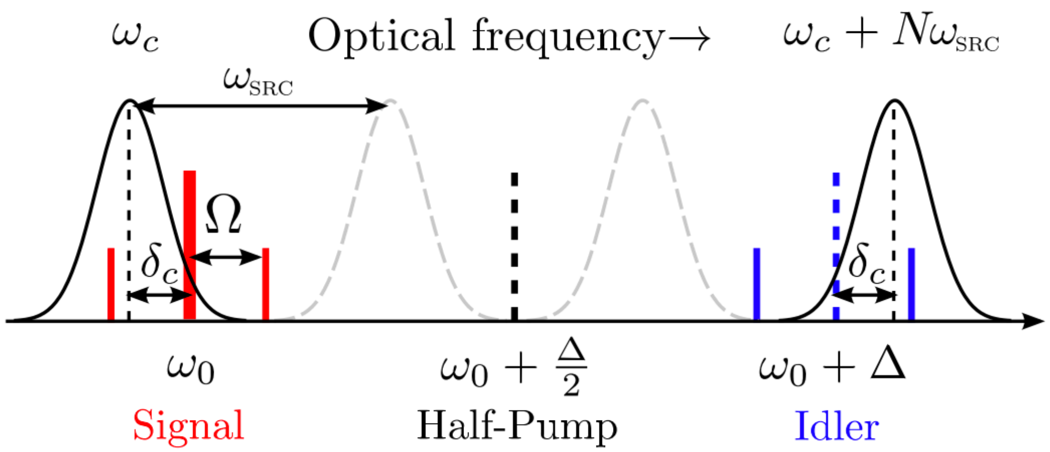
Masses of known neutron stars and black holes



Credit: LIGO-Virgo/Frank Elavsky/Northwestern University

Frequency-dependent squeezing with EPR entanglement





Brown et al. (2017) *PhysRev D*, *96*(6), 62003.