Squeezed light benches and optical alignment issues

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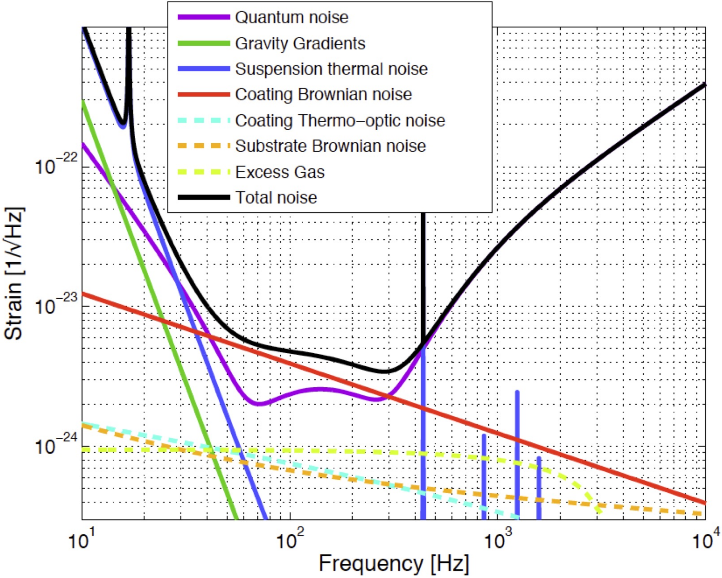
March 23, 2021

Overview

1. Quantum noise and squeezing
   - Nature of squeezed states
   - Generation of squeezed states
   - Squeezed light in interferometers
2. Experimental challenges
   - Losses
   - Phase noise
   - Technical noises
   - RPN and frequency-dependent squeezing
3. Status and perspectives
   - Implementation examples
   - Ongoing and future developments

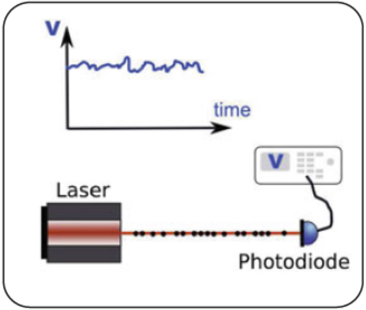
Quantum noise in GW detectors

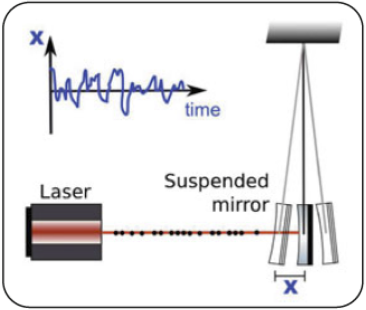


Quantum noise in GW detectors

- Photon Shot Noise
  $$h_{sn}(f) = \frac{1}{L}\sqrt{\frac{\hbar c \lambda}{2\pi P}}$$

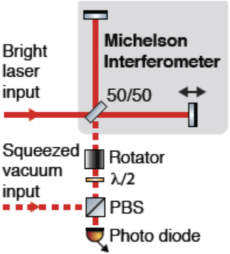
- Radiation Pressure Noise
  $$h_{rp}(f) = \frac{1}{mf^2 L}\sqrt{\frac{\hbar P}{2\pi^3 c \lambda}}$$

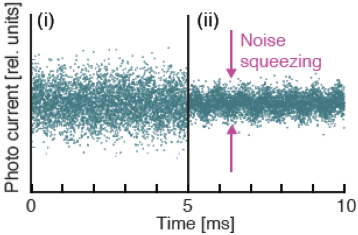




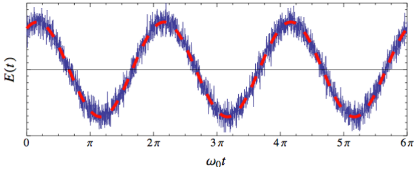
Squeezing the EM vacuum for quantum noise reduction

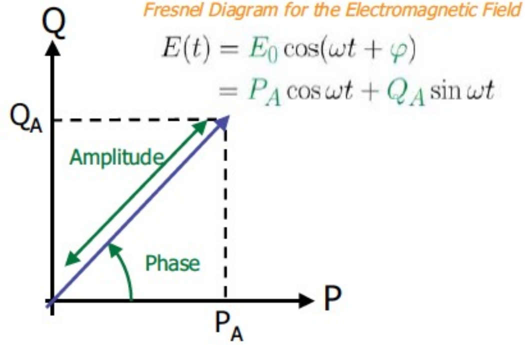
- Interferometric GW detectors operate at dark fringe
- Vacuum fluctuations enter the dark port of the ITF
  - *Carlton M. Caves. Quantum-mechanical noise in an interferometer. Physical Review D,* **23***(8):1693, 1981*
  - classical (coherent) states of light: no photon correlations
  - equal phase and amplitude fluctuations
- Quantum noise can be reduced by changing the statistical properties of vacuum optical field entering dark port
  - squeezed states of light: photon correlations
  - less phase fluctuations, more amplitude fluctuations (or vice versa)





- A given mode of the EM (a single mode laser) has two d.o.f.
- E.g. phase and amplitude, or any linear combination

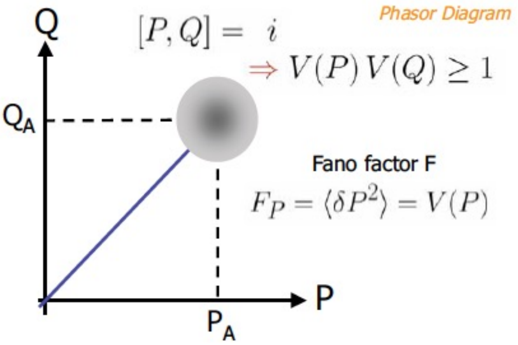




$$E(t) = E_0 \cos(\omega t + \varphi)$$
$$= P_A \cos \omega t + Q_A \sin \omega t$$

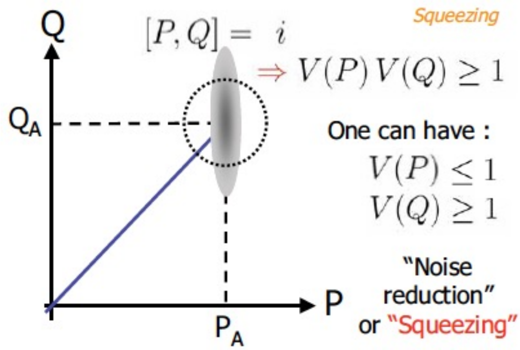
Quantum states of light - coherent states

- Representative of a classical laser field
- Equal fluctuations on both quadratures
- No correlations between photons - Poissonian statistics



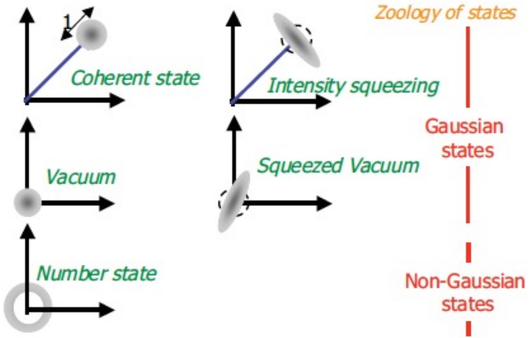
Quantum states of light - squeezed states

- Fluctuations are lower than in classical (coherent) states for a given quadrature (e.g. phase fluctuations)
- Fluctuations in the orthogonal quadrature must be higher than in classical states to obey uncertainty principle



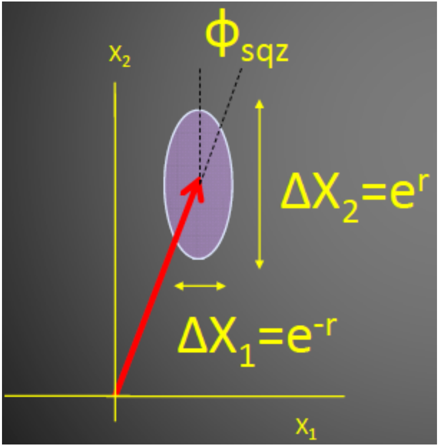
Quantum states of light - squeezed vacuum

- Mean values of quantum vacuum EM field quadratures are $= 0$, but fluctuations are $\neq 0 \rightarrow$ zero-point energy
- Quantum vacuum fluctuations can be isotropic (classical vacuum) or anisotropic (squeezed vacuum)



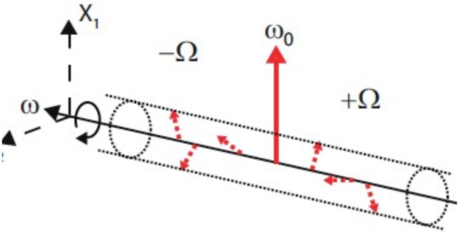
Quantum states of light - squeezing factor

- Squeezing factor r describes level of squeezing and anti-squeezing
- Squeezing angle ϕ_{sqz} describes which quadrature is squeezed



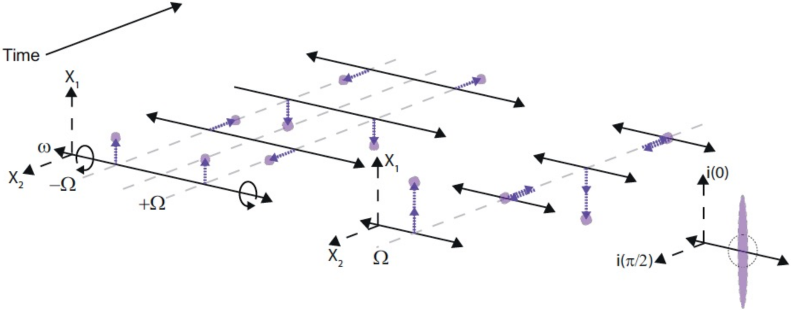
Quantum sideband picture

- For a more realistic picture add frequency axis
- Add noise sidebands around laser carrier
- Uncorrelated sidebands → coherent state



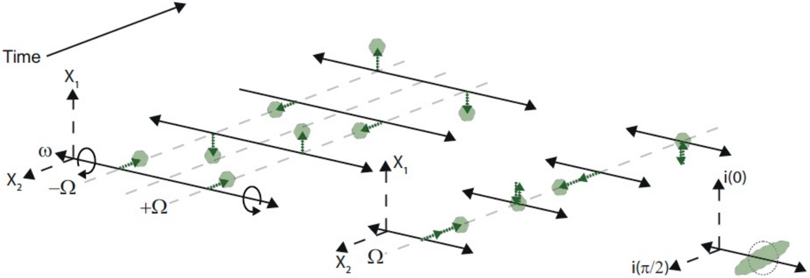
Squeezing in sideband picture

- Amplitude correlated sidebands → phase-squeezed state



Squeezing in sideband picture

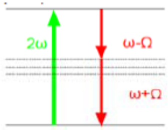
- Phase correlated sidebands → amplitude-squeezed state

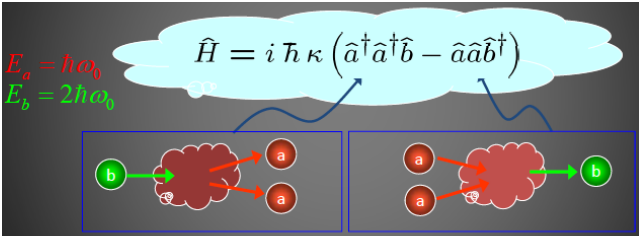


A recipe for squeezed light: difference frequency generation

- Correlations between IR photons from light-matter interaction
- e.g. DFG in a nonlinear material from a green pump field
- correlations between generated IR photons arise from energy/momentum conservation

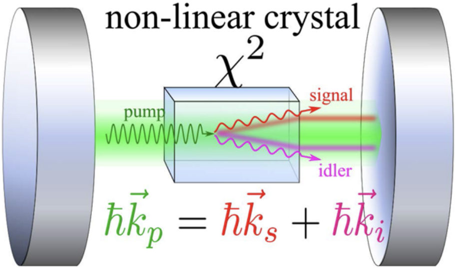
$$\vec{D} = \vec{E} + \chi^{(2)}\vec{E}^2$$





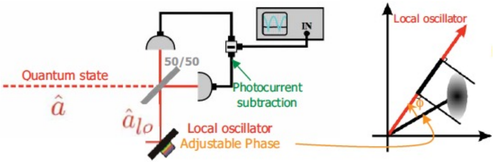
Optical Parametric Amplification

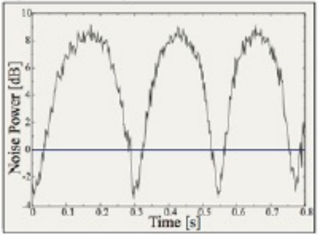
- embedding the nonlinear crystal in an optical resonator
- increase the efficiency of the nonlinear process against mixing with classical vacuum



Measuring quantum field fluctuations

- beating the quantum (vacuum) field against a (bright) classical local oscillator
- equivalent to project the vacuum field's fluctuations on the classical state
- squeezing angle is tuned by via the phase difference between quantum and classical field
- balanced homodyne detector to suppress correlated noise

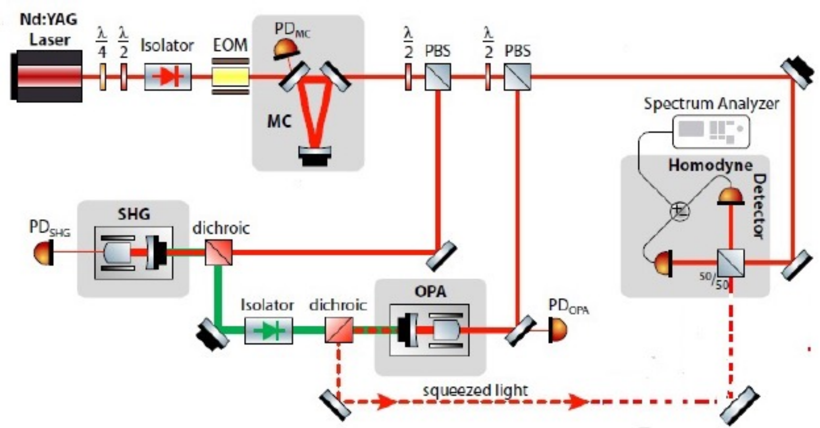




Variance

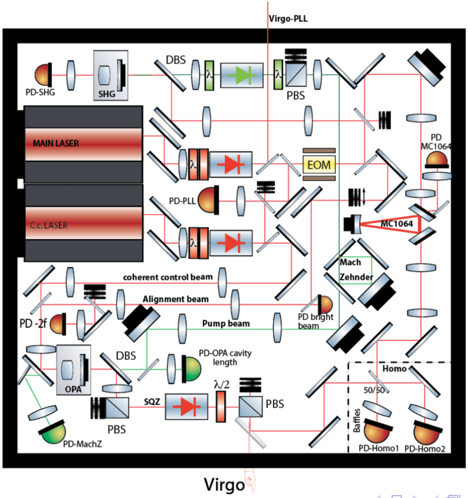
Basic squeezing experiment

- SHG optical resonator to generate pump beam
- MC optical resonator to suppress HOMs in homodyne detection
- OPA optical resonator
- homodyne detector for squeezing measurement



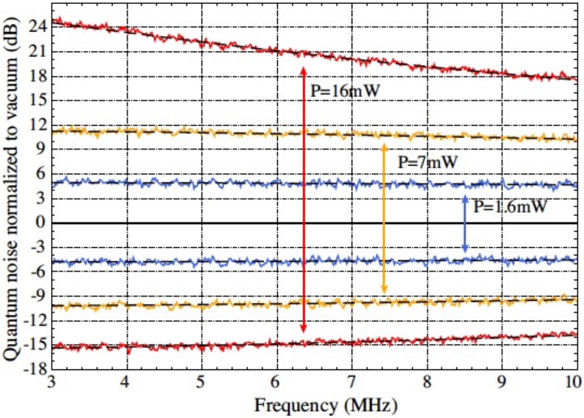
The AEI squeezer in Virgo

- Additional laser for the control of squeezing angle
- MZI to control optical pump power and stabilise squeezing level



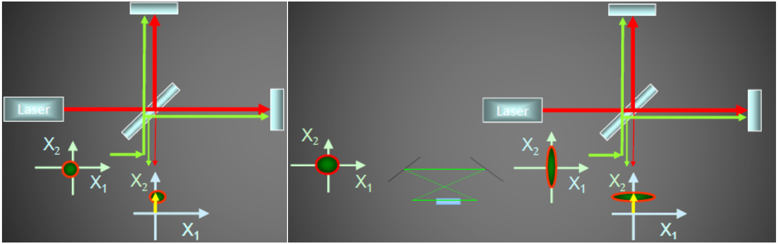
The AEI squeezer in Virgo

- State of the art: 15 dB squeezing
- H. Vahlbruch, M. Mehmet, K. Danzmann, and R. Schnabel, Phys. Rev. Lett. **117**, 110801

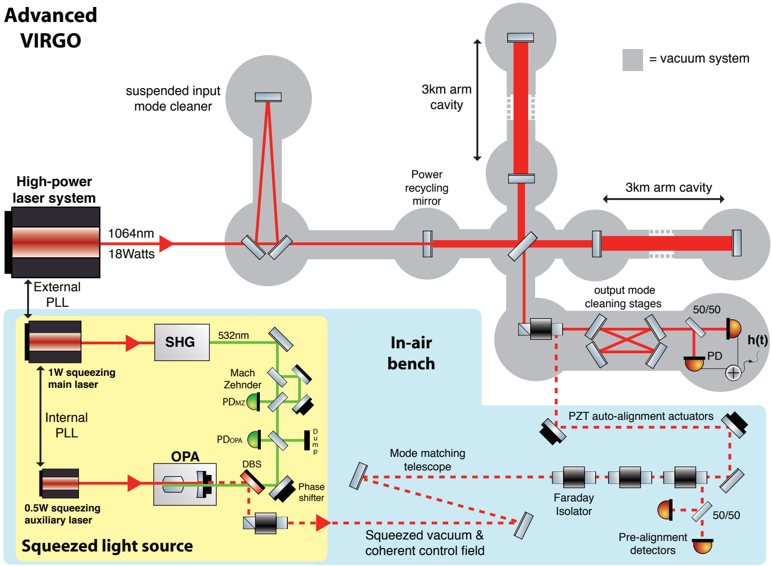


Squeezed light injection in ITF

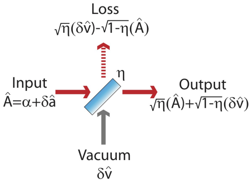
- quantum noise in the ITF can be seen as originating from vacuum fluctuations entering the dark port
- if a squeezed vacuum is injected from the dark port, quantum noise is modified accordingly

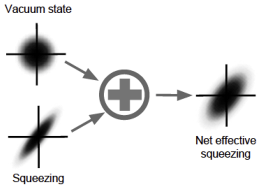


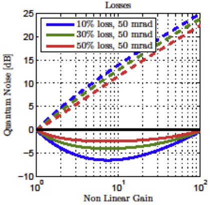
Frequency-independent squeezed light injection in ITF



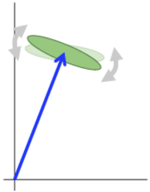
- Optical losses are equivalent to mixing with classical vacuum field

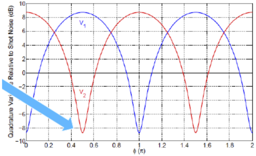


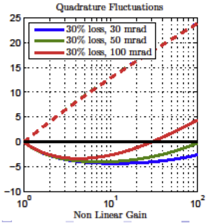




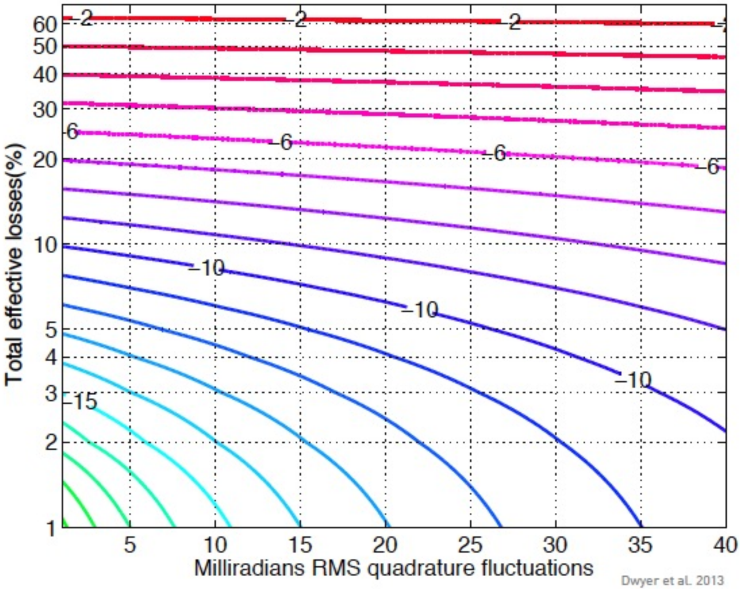
- Angle fluctuations of squeezed quadrature







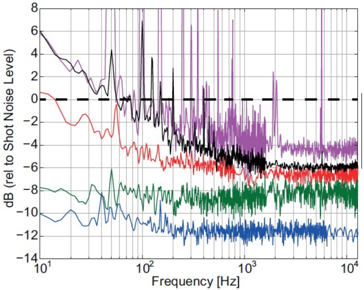
Losses and phase noise



Dwyer et al. 2013

Technical noises

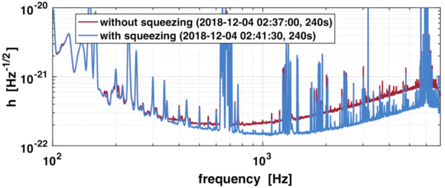
- technical noises mimic the effect of either losses or phase noise
- dark noise at detection photodiodes simply adds to shot noise
- scattered light from an external surface can recombine with the ITF carrier mode, producing a parasitic interference
- motion of the scattering surface yields optical path length changes of the scattered beam, and the effect on interference is equivalent to a phase angle jitter of the squeezing ellipse
- intensity modulations can impact low frequency noise measurement

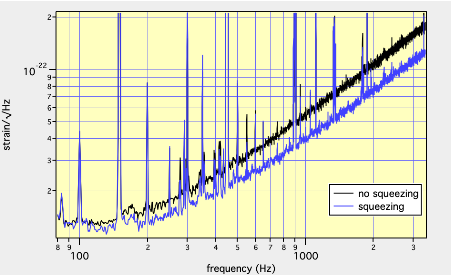


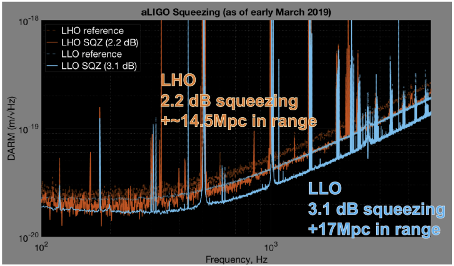
FIS in GW detectors: current performances

- GEO600: 6 dB $\longrightarrow$
- aLIGO: 3.1 dB
- AdV: 3.2 dB $\searrow$

$\downarrow$

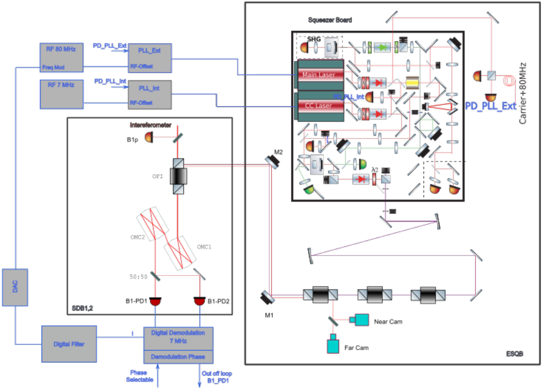






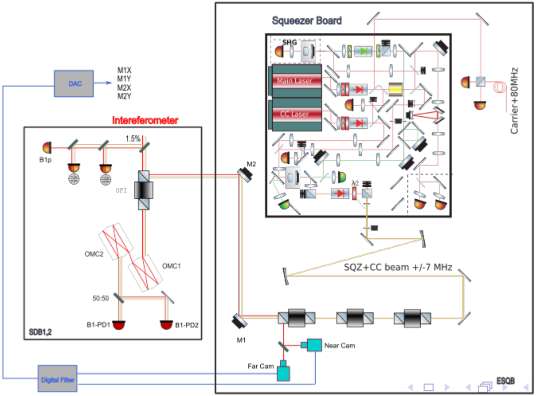
FIS controls in AdV: coherent control of squeezing angle

- RF sideband transmitted from OPA
- demodulated on B1 photodiode on detection bench
- error signal controls PLL frequency to lock main squeezer laser to main ITF laser



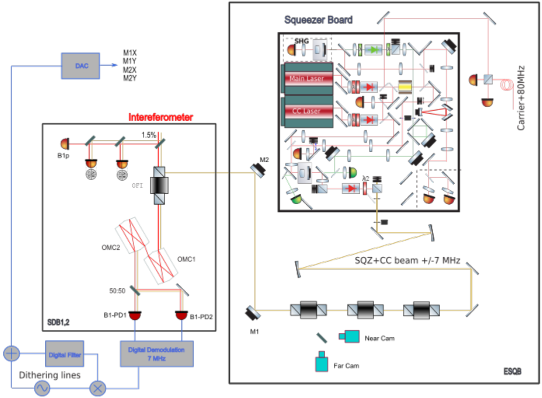
FIS controls in AdV: coarse automatic alignment

- need to minimise optical losses from misalignment and mode mismatch with ITF and OMC
- coarse AA using two cameras to stabilise the beam reflected off the FI on detection bench towards squeezer; works also when SQZ not injected



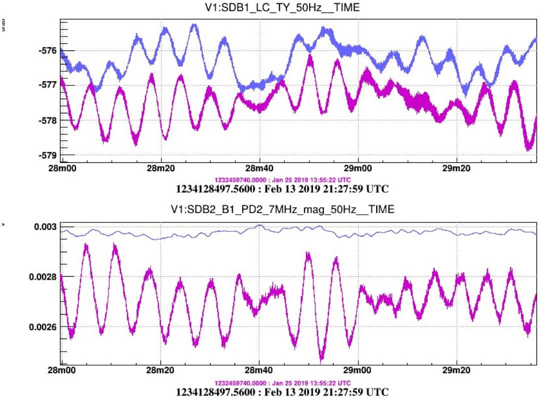
FIS controls in AdV: fine automatic alignment

- RF DWS badly affected by HOMs on ITF carrier
- use angular dither lines on SQZ path, demodulate the CC beat on B1 downstreams OMC)



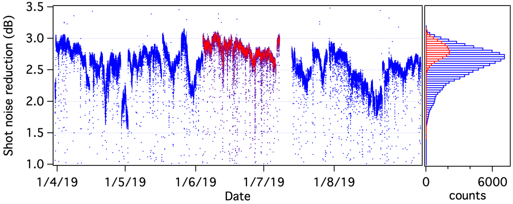
FIS controls in AdV: fine automatic alignment

- short term alignment noise dominated by angular jitter of detection bench
- AA too slow to correct for it
- but with AA loop engaged, angular noise contributes to less than 1% rms optical losses

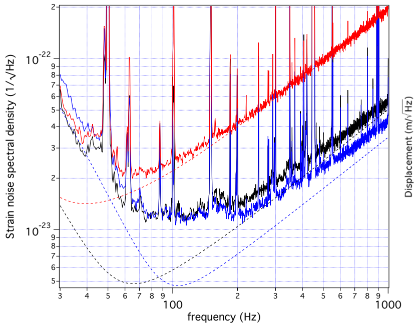


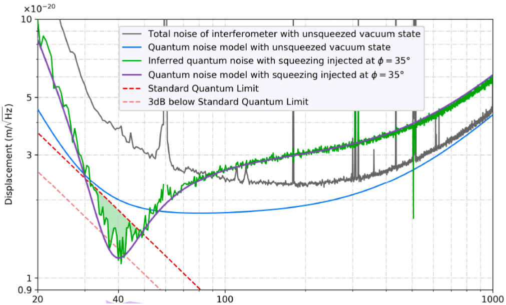
Quantum noise reduction in AdV during O3

- long-term drifts of produced squeezing
- mode matching changes
- slow rotations of squeezing ellipse
- stray light



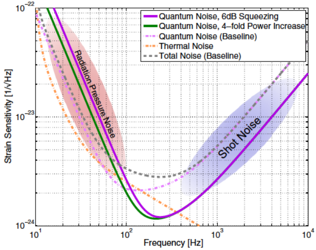
Evidence of RPN in AdV and aLIGO

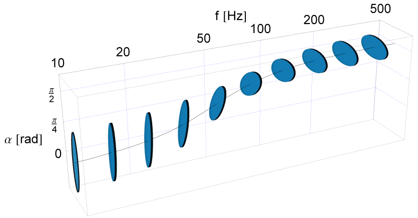




Limitations of frequency independent squeezing

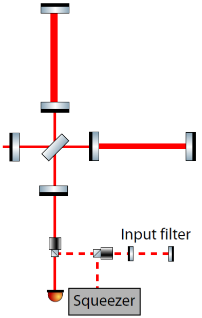
- In principle, injecting phase-squeezed vacuum improves the sensitivity at high frequency where ITF is dominated by shot noise
- At the same time, the corresponding amplitude anti-squeezing makes radiation pressure noise at low frequencies increase
- With increasing level of injected squeezing, this advantage is reduced by the increased low frequency noise
- A broadband sensitivity enhancement would require a frequency-dependent rotation of the squeezing ellipse

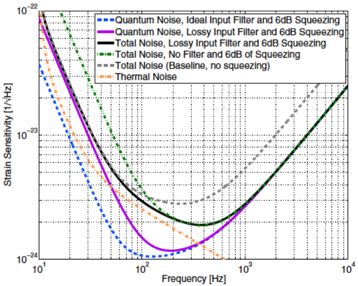




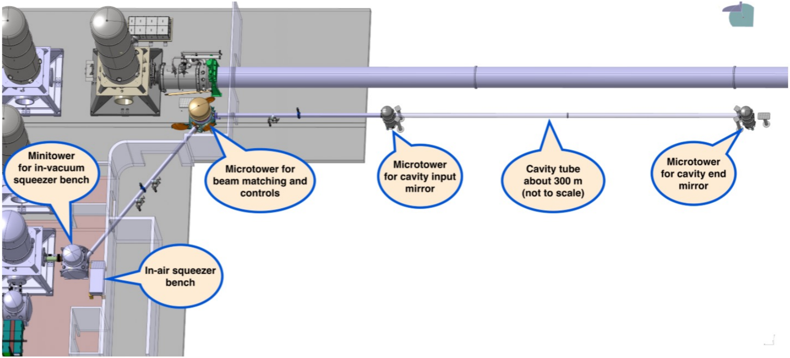
FDS and filter cavities

- Tune phase angle of squeezing ellipse vs signal frequency
- E.g. using a filter cavity with resonance width $\sim$ crossover frequency between radiation pressure and shot noise in ITF ($\sim 50 \div 200\,\mathrm{Hz}$)
- requirements on cavity parameters: finesse$\times$length product $> 10^6$
- management of losses is rather challenging
- can be tailored to a single configuration of SRC



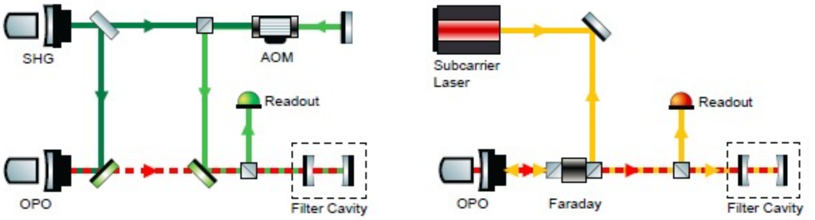


FDS implementation example: AdV+



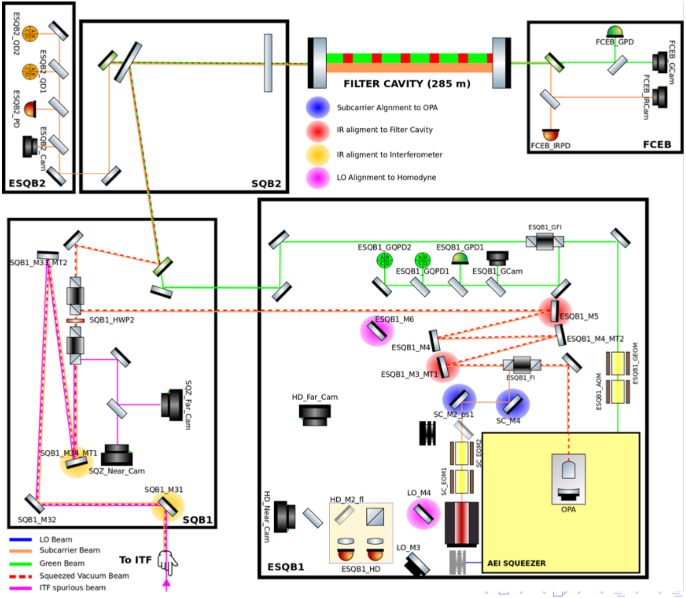
- 300m long filter cavity with suspended mirrors
- two in-air benches for AEI squeezer and FC control sensing
- two suspended optical benches for beam delivery to FC and to ITF
- target $> 6\,\mathrm{dB}$ shot noise reduction without RPN increase

FC control strategy



- green beam for lock acquisition, longitudinal and angular control of FC optical link between suspended benches
- IR sub-carrier field for high-precision longitudinal (and angular) control of FC

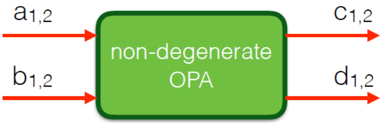
AdV+ FDS control strategy

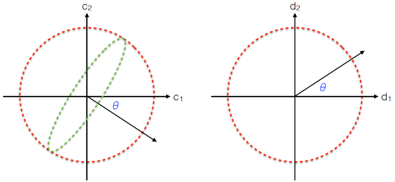


EPR entanglement

Non-degenerate OPA

Quantum noise in c and d enhanced, but measuring c, one can subtract from measurement of d and obtain (conditional) squeezing.

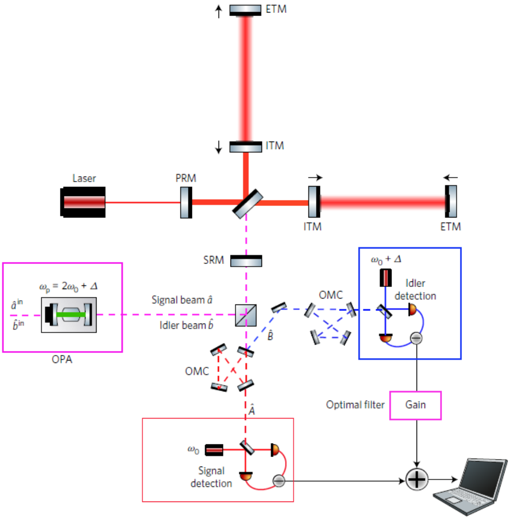




can predict $c_{-\theta} = c_1\cos\theta - c_2\sin\theta$
after subtraction: conditionally squeezed!

measuring $d_\theta = d_1\cos\theta + d_2\sin\theta$

FIS injection with EPR entanglement

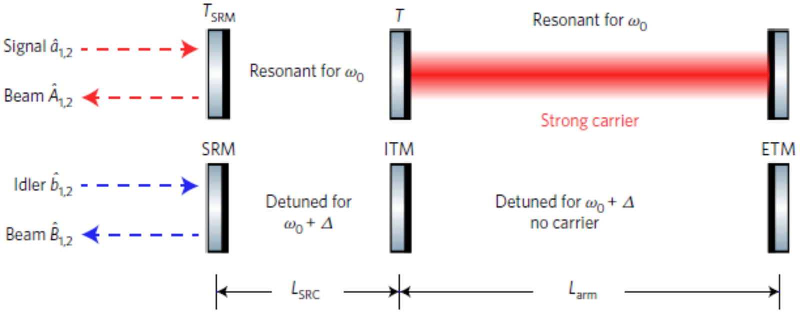


Y. Ma et al., Nature Physics 13, 776 (2017)

FIS injection with EPR entanglement

Auto-filtering

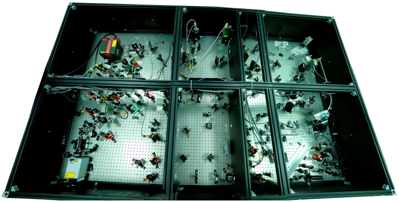
Given an OPA offset Δ, arm-cavity and SEC lengths can be fine-tuned to mimic filter cavity for idler

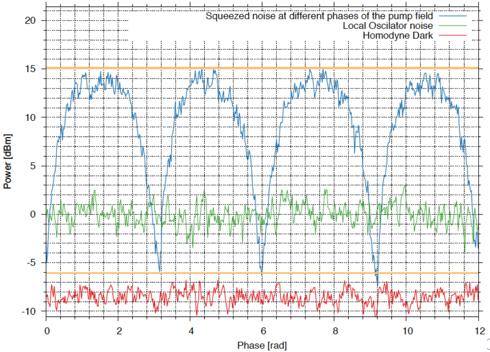


Test of finite state machine controls with the 1500W OPO squeezer at EGO

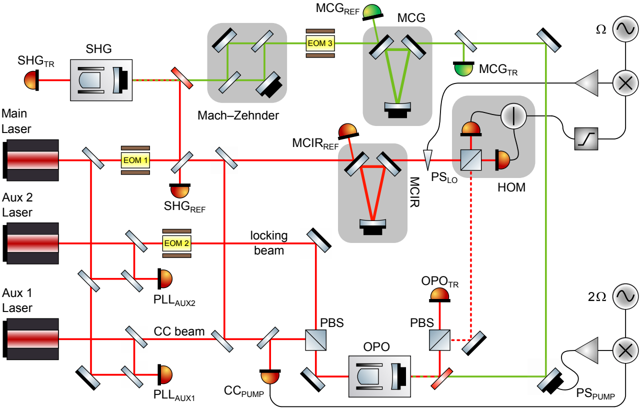
Motivation

Originally developed at EGO for FIS in AdV; 6 dB squeezing and 15 dB anti-squeezing demonstrated on April 2017. Currently being used for EPR demonstrator.



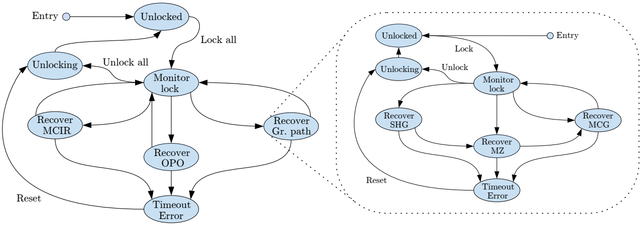


Test of finite state machine controls with the 1500W OPO squeezer at EGO

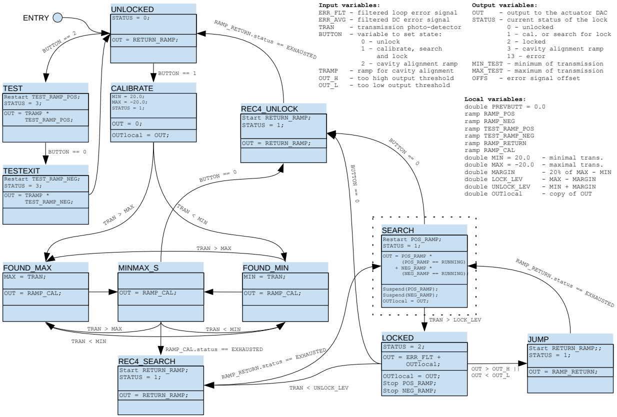


prod2.pdf

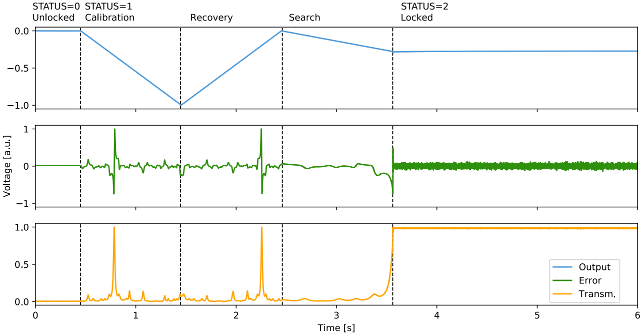
Bench lock software



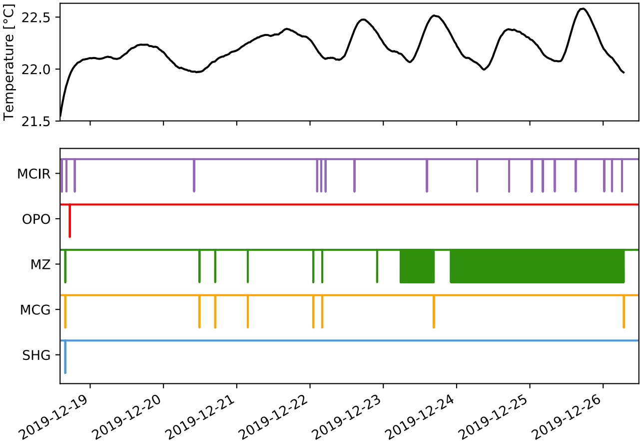
Single cavity lock detail



Example of cavity lock



Quality of service



Concluding remarks

- main challenges are to protect squeezed states from degradation inside ITF: losses, phase noise, technical noises (e.g. stray light)
- qualitatively similar to well known problems for ITF control and noise mitigation
- several methods discussed at this workshop would well apply
  - mitigation of losses from mode mismatch on ITF $\rightarrow$ Rob's talk
  - mitigation of phase noise from stray light couplings $\rightarrow$ Gabriele's talk
  - automation of complex control systems $\rightarrow$ Diego's talk
- challenges with FDS will substantially grow
  - largely increased complexity of optical setup and control system (filter cavity, suspended optics, SRC in Virgo)
  - exponential sensitivity of squeezing to degradation mechanisms
- quantum optics is an interesting playground for ML beyond the GW detectors (engineering of quantum states, quantum neural networks)
- For a theoretical review, see S. L. Danilishin et al., Advanced quantum techniques for future gravitational-wave detectors, Living Reviews in Relativity 22, 2 (2019) and references therein

The End