Squeezed light benches and optical alignment issues

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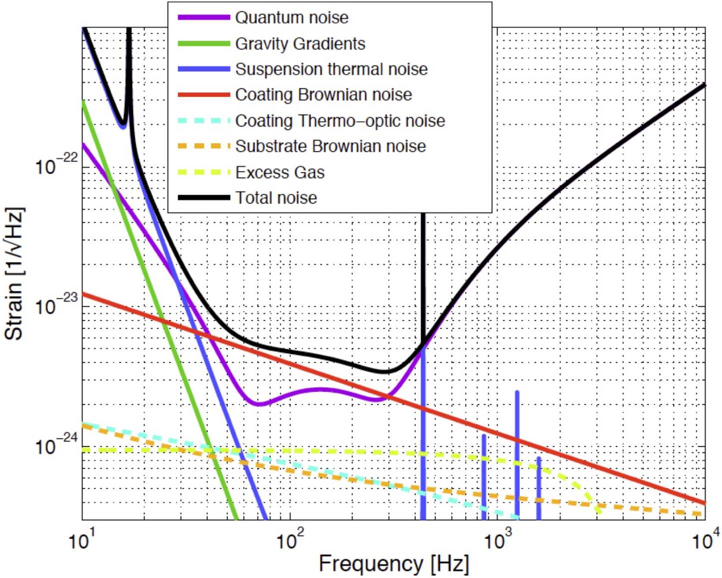
Overview

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

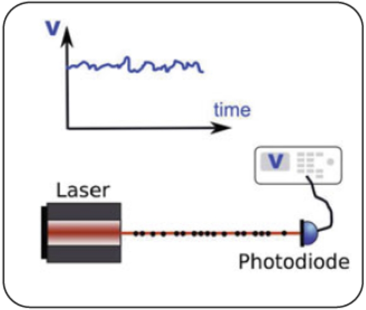
Quantum noise in GW detectors

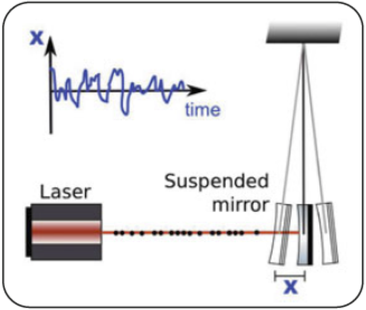


Quantum noise in GW detectors

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

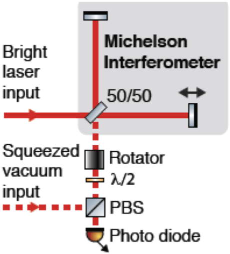
- Radiation Pressure Noise
  $h_{rp}(f) = \frac{1}{mf^2 L}\sqrt{\frac{\hbar P}{2\pi^3 c\lambda}}$

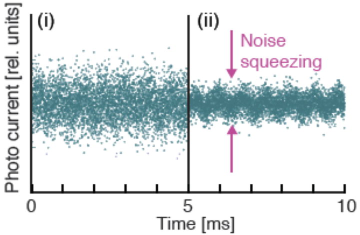




Squeezing the EM vacuum for quantum noise reduction

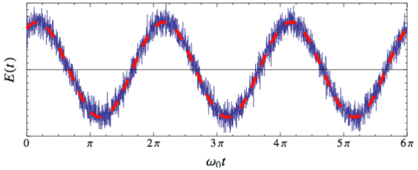
- Interferometric GW detectors operate at dark fringe
- Vacuum fluctuations enter the dark port of the ITF
  - *Carlton M. Caves. Quantum-mechanical noise in an interferometer. Physical Review D,* **23***(8):1693, 1981*
  - classical (coherent) states of light: no photon correlations
  - equal phase 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)

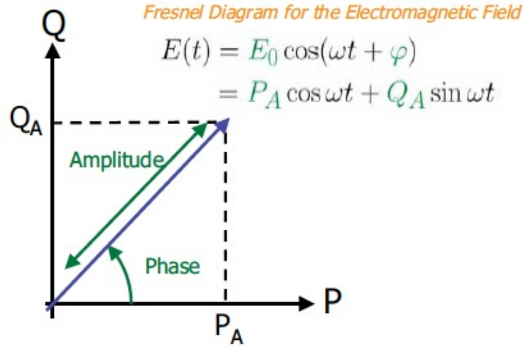




Quantum states of light - the quadrature picture

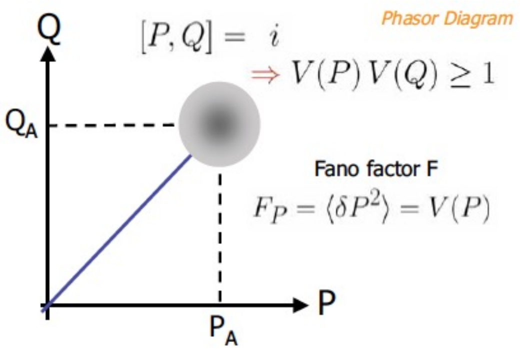
- A given mode of the EM (a single mode laser) has two d.o.f.
- E.g. phase and amplitude, or any linear combination





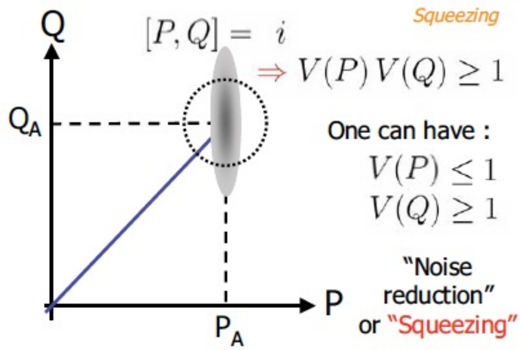
Quantum states of light - coherent states

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



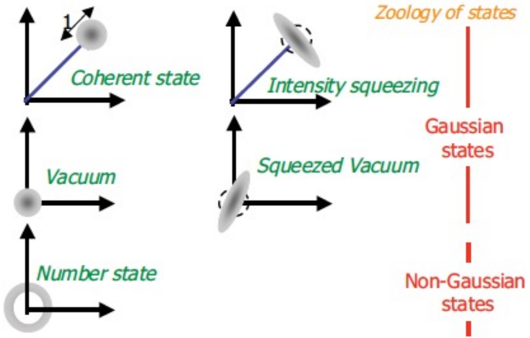
Quantum states of light - squeezed states

- 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



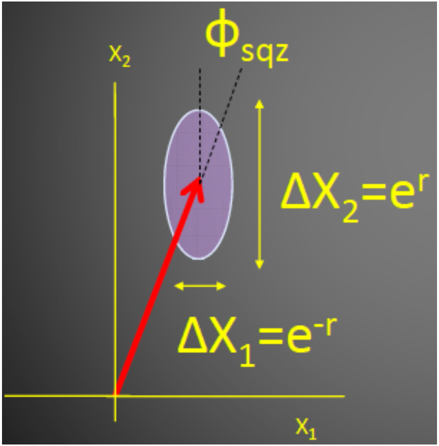
Quantum states of light - squeezed vacuum

- 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)



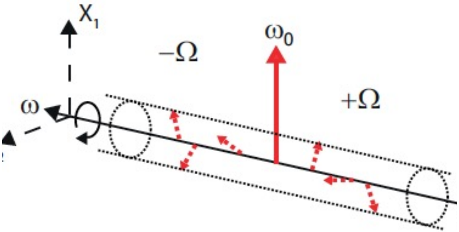
Quantum states of light - squeezing factor

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

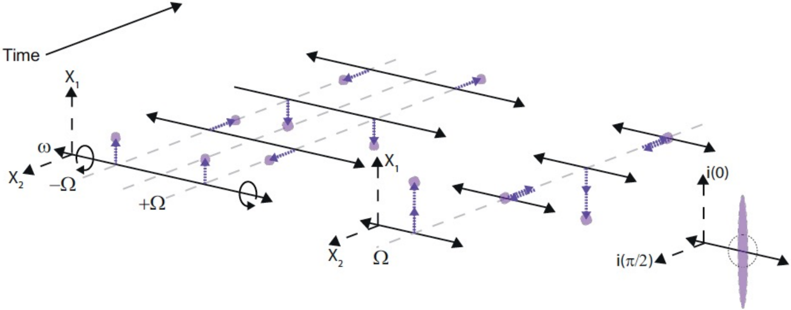


Quantum sideband picture

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

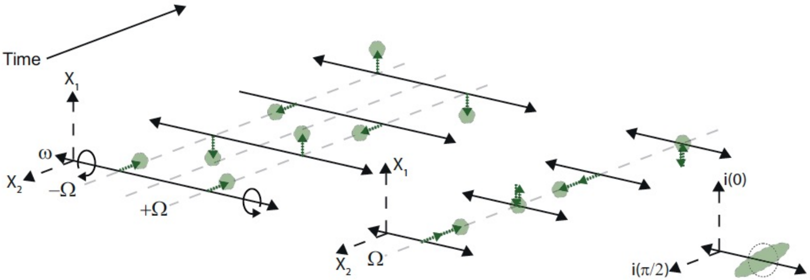


- Amplitude correlated sidebands → phase-squeezed state



Squeezing in sideband picture

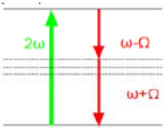
- Phase correlated sidebands $\rightarrow$ amplitude-squeezed state

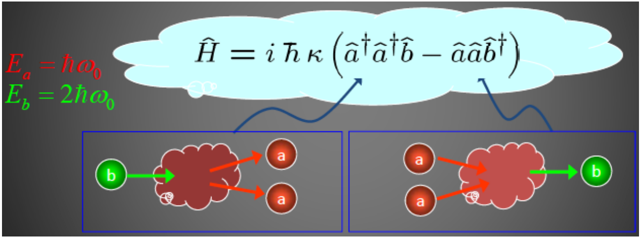


A recipe for squeezed light: difference frequency generation

- 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

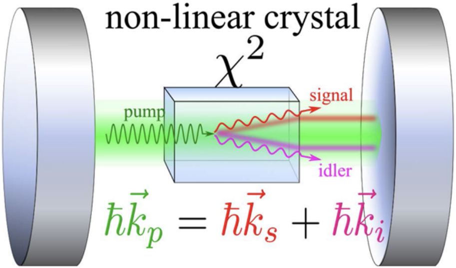
$$\vec{D} = \vec{E} + \chi^{(2)} \vec{E}^2$$





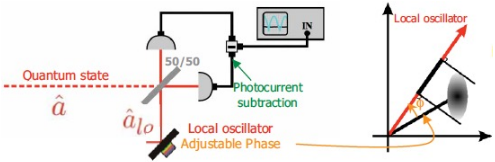
Optical Parametric Amplification

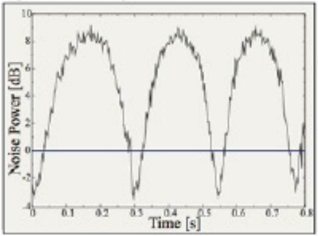
- embedding the nonlinear crystal in an optical resonator
- increase the efficiency of the nonlinear process against mixing with classical vacuum



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

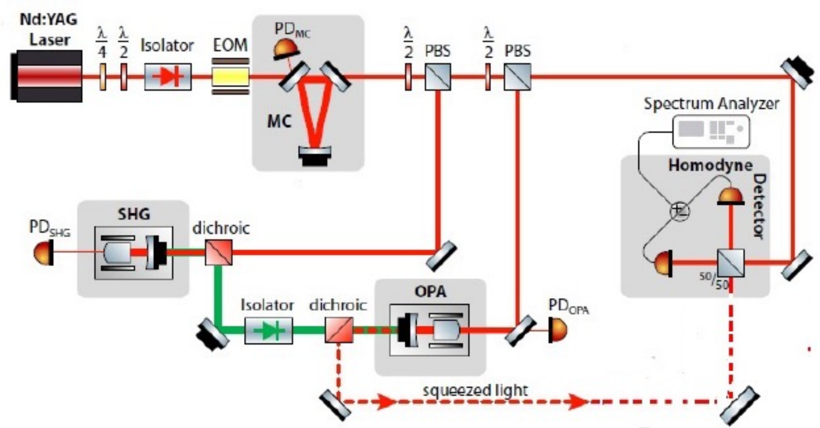




Variance

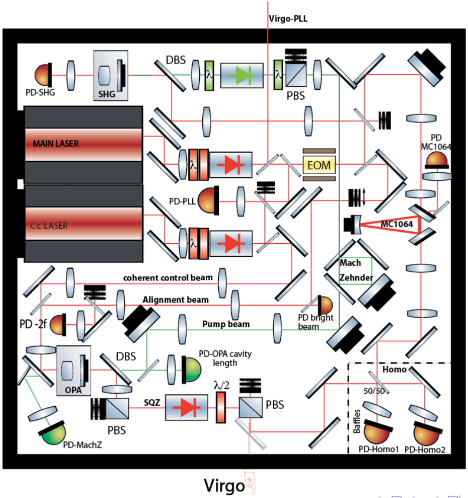
Basic squeezing experiment

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



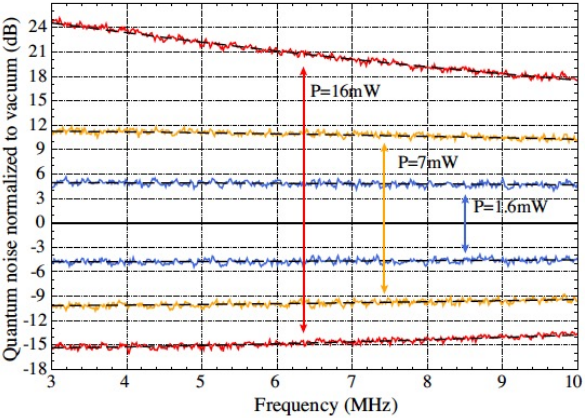
The AEI squeezer in Virgo

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



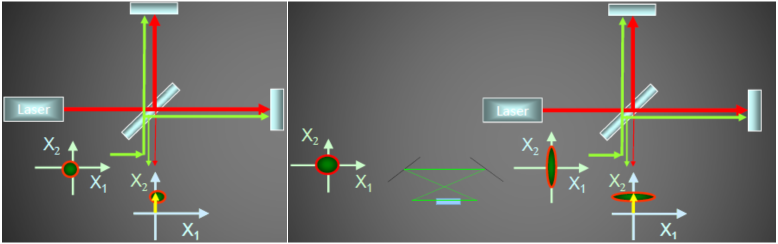
The AEI squeezer in Virgo

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

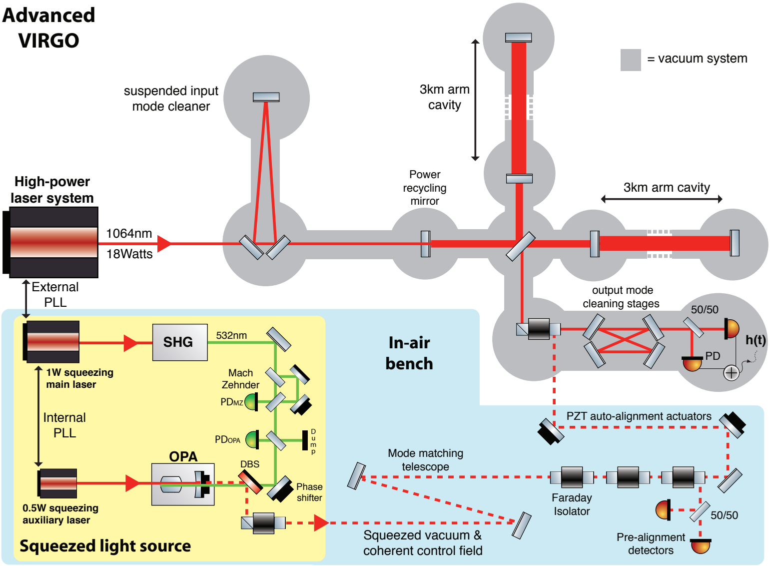


Squeezed light injection in ITF

- 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

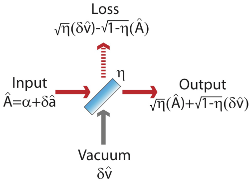


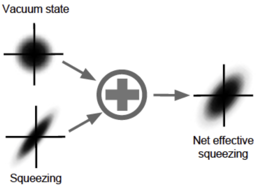
Frequency-independent squeezed light injection in ITF

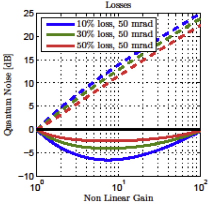


Limitations to QN reduction

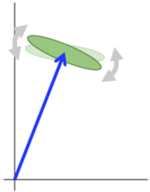
- Optical losses are equivalent to mixing with classical vacuum field

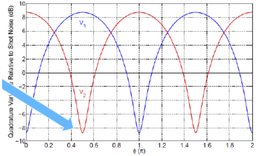


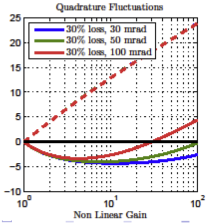




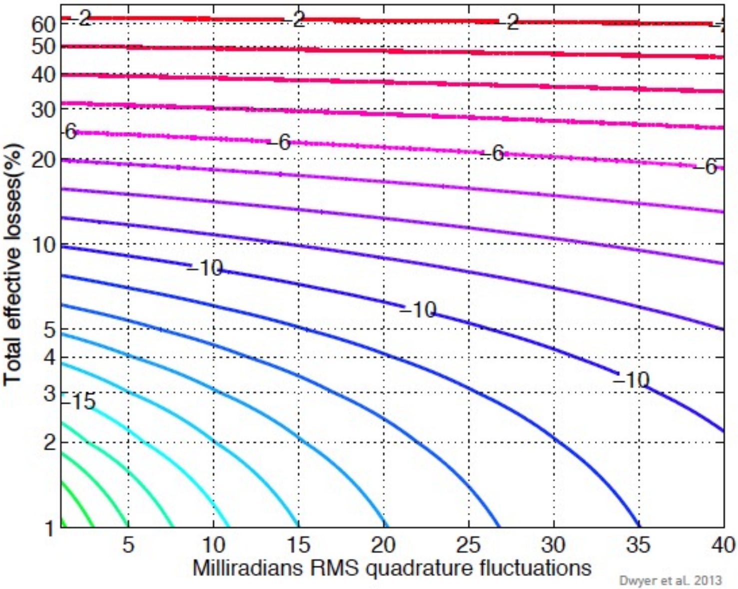
- Angle fluctuations of squeezed quadrature







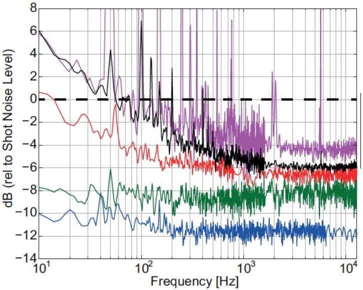
Losses and phase noise



Dwyer et al. 2013

Technical noises

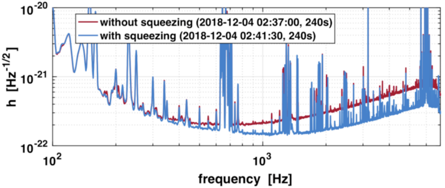
- technical noises mimic the effect of either losses or phase noise
- dark noise at detection photodiodes simply adds to shot noise
- scattered light from an external surface can recombine with the ITF carrier mode, producing a parasitic interference
- motion of the scattering surface yields optical 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

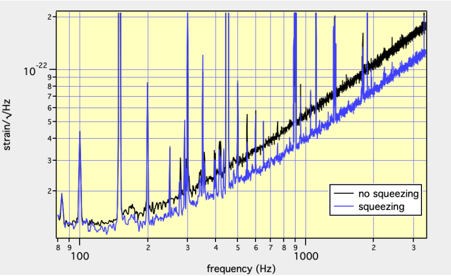


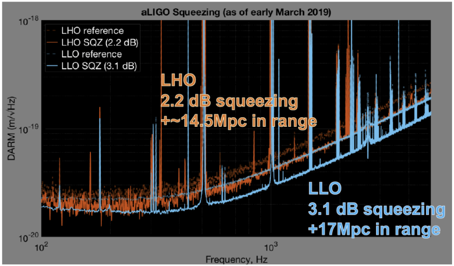
FIS in GW detectors: current performances

- GEO600: 6 dB ⟶
- aLIGO: 3.1 dB
- AdV: 3.2 dB ↘

↓

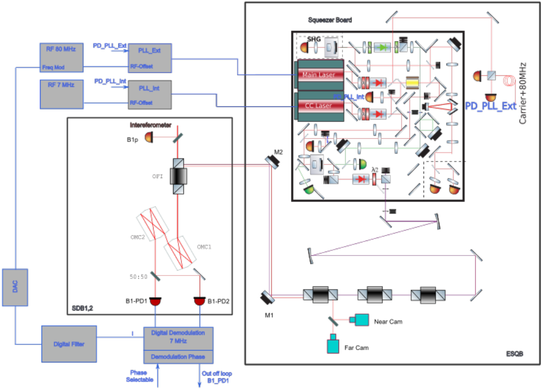






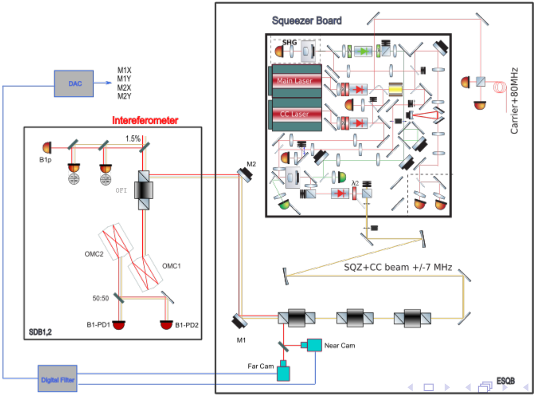
FIS controls in AdV: coherent control of squeezing angle

- 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



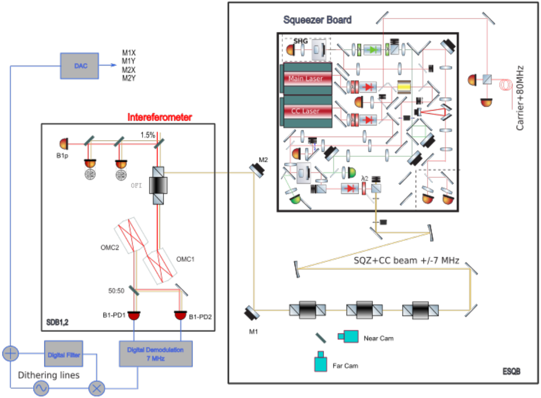
FIS controls in AdV: coarse automatic alignment

- 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



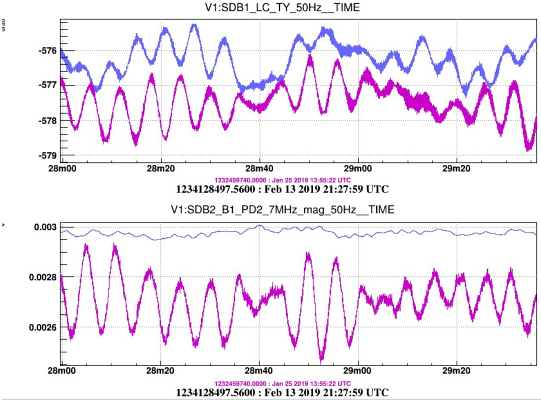
FIS controls in AdV: fine automatic alignment

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



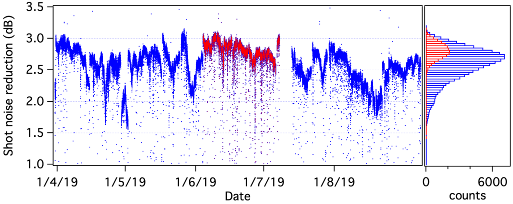
FIS controls in AdV: fine automatic alignment

- 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

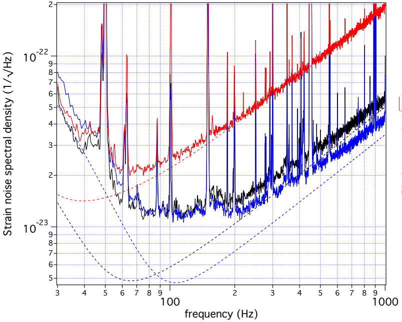


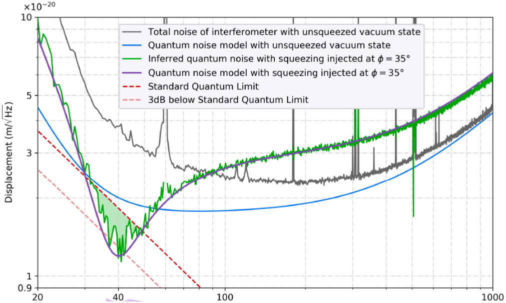
Quantum noise reduction in AdV during O3

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



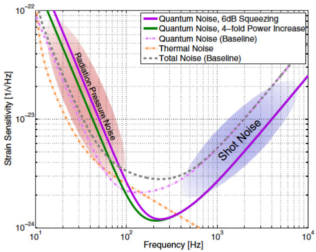
Evidence of RPN in AdV and aLIGO

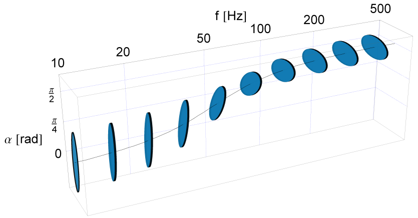




Limitations of frequency independent squeezing

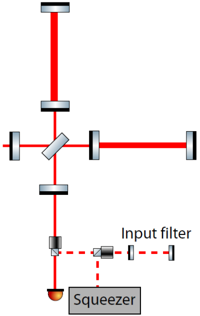
- In principle, injecting phase-squeezed vacuum improves the sensitivity at high frequency where ITF is dominated by shot noise
- At the same time, the corresponding amplitude anti-squeezing makes radiation pressure noise at low frequencies increase
- With increasing level of injected squeezing, this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

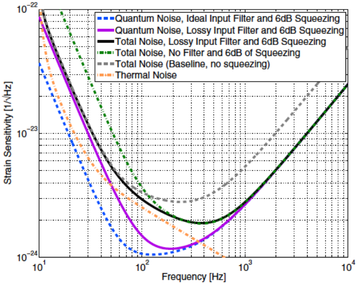




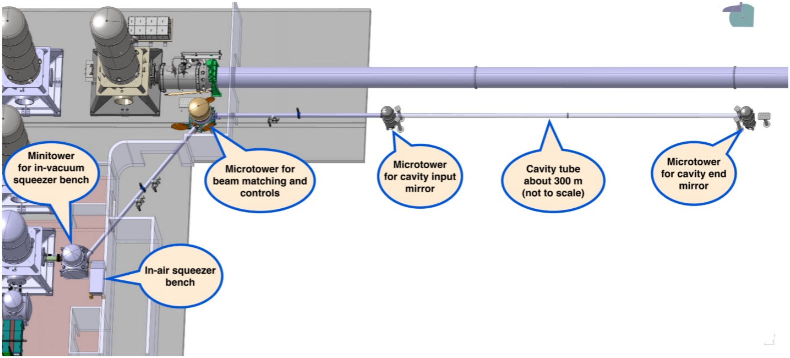
FDS and filter cavities

- 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



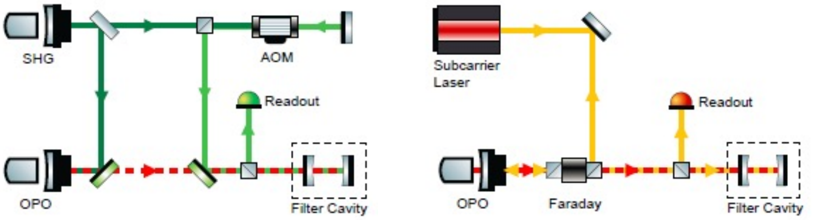


FDS implementation example: AdV+



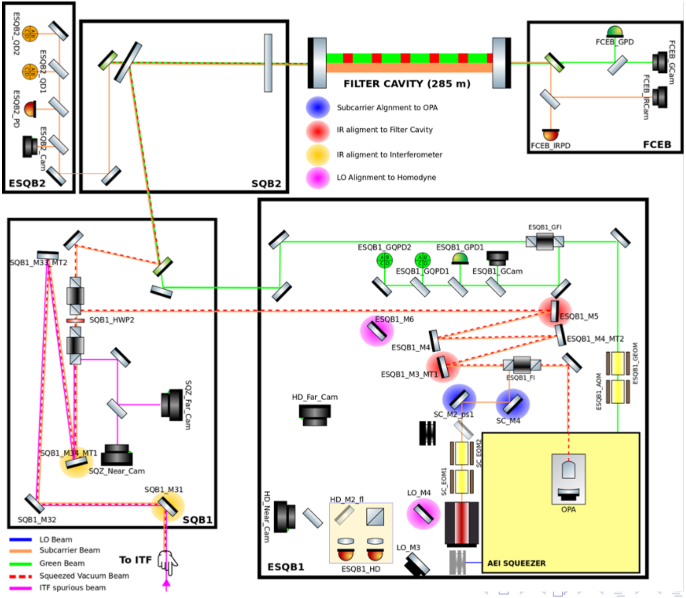
- 300m long filter cavity with suspended mirrors
- two in-air benches for AEI squeezer and FC control sensing
- two suspended optical benches for beam delivery to FC and to ITF
- target $> 6\,\mathrm{dB}$ shot noise reduction without RPN increase

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

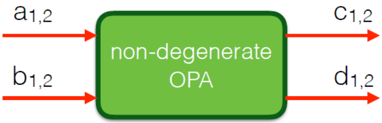
AdV+ FDS control strategy

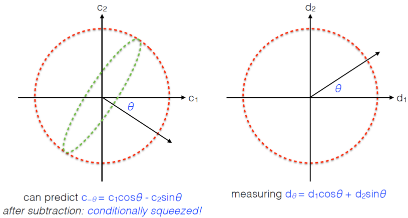


EPR entanglement

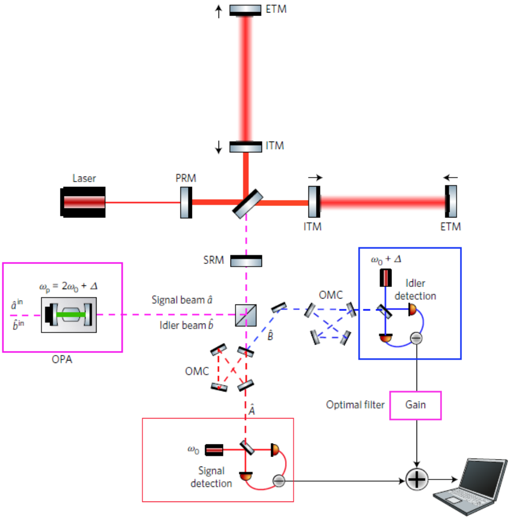
Non-degenerate OPA

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





FIS injection with EPR entanglement

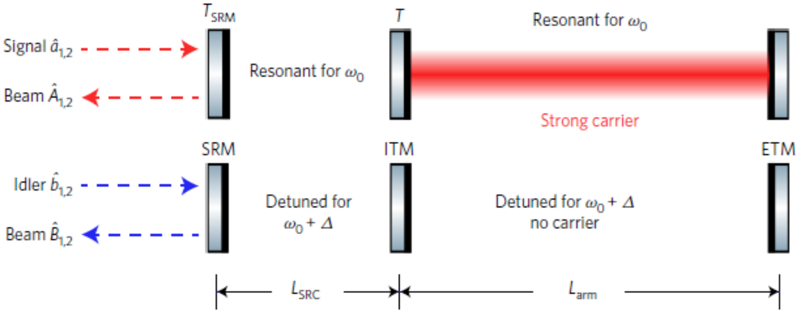


Y. Ma et al., Nature Physics 13, 776 (2017)

FIS injection with EPR entanglement

Auto-filtering

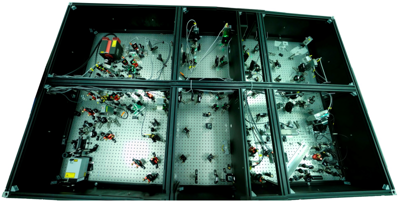
Given an OPA offset Δ, arm-cavity and SEC lengths can be fine-tuned to mimic filter cavity for idler

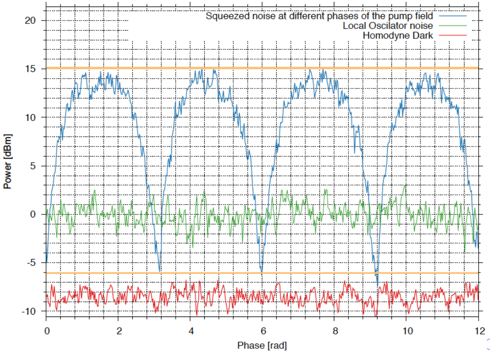


Test of finite state machine controls with the 1500W OPO squeezer at EGO

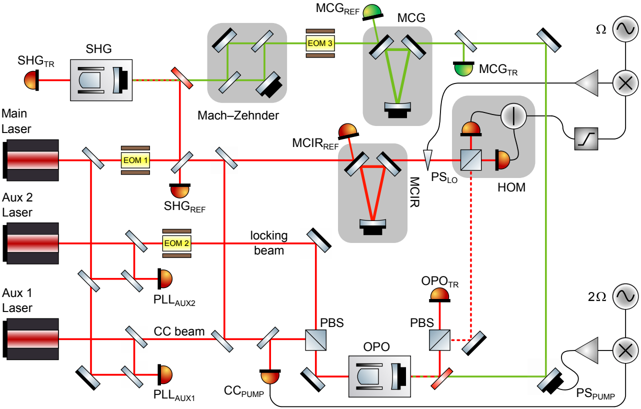
Motivation

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



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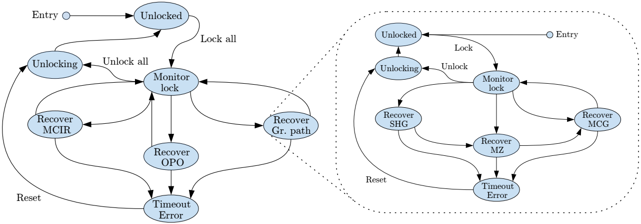
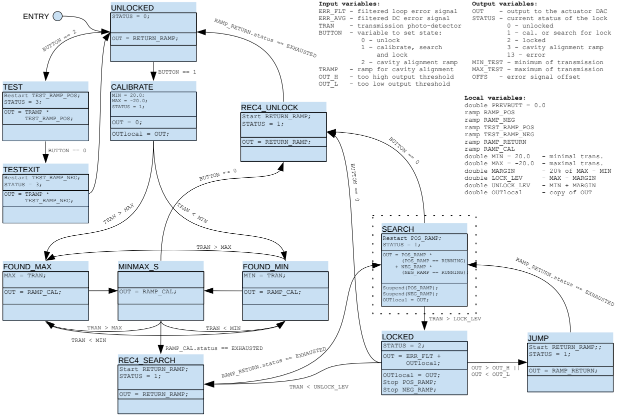
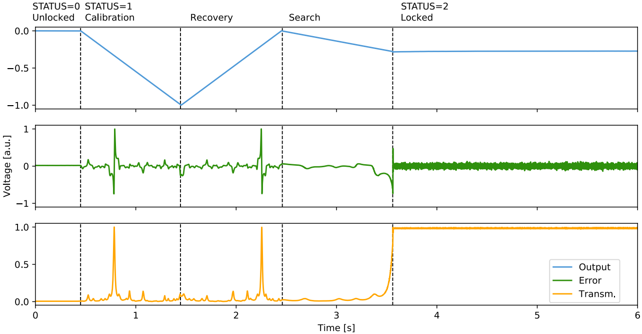
Bench lock software



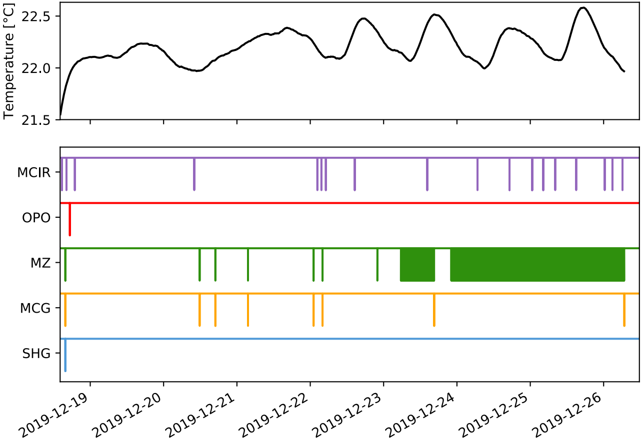
Single cavity lock detail



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 → Rob's talk
  - mitigation of phase noise from stray light couplings → Gabriele's talk
  - automation of complex control systems → 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)

The End