Noise sources-3

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In this third handout on noise sources, I summarize how squeezed light is used as a tool to beat the SQL (see figure 1).

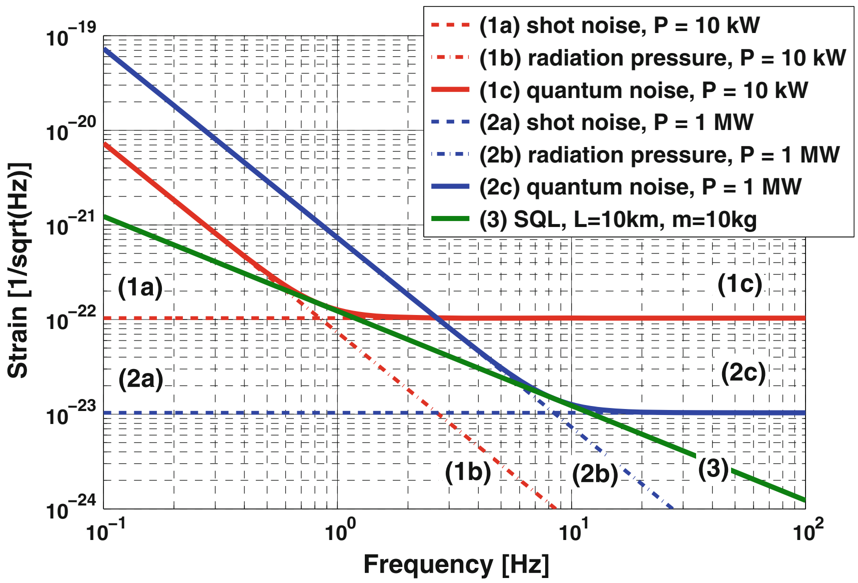

Figure 1: The SQL (trace 3) and the quantum noise contribution for a simple Michelson interferometer, featuring 10 km arm length and test masses of 10 kg weight, for low (traces 1a–1c) and high (traces 2a–2c) circulating power, from S. Hild, *A Basic Introduction to Quantum Noise and Quantum-Non-Demolition Techniques*, in M. Bassan (ed.) *Advanced Interferometers and the Search for Gravitational Waves, Lectures from the First VESF School on Advanced Detectors for Gravitational Waves*, Springer (2014).

- The basics of squeezed light are explained in this scientific paper: M. C. Teich and B. E. A. Saleh, *Squeezed states of light*, Quantum Opt., J. of the Eur. Opt. Soc. B 1 (1989) 153-19. Figure 2 provides further illustration of the concepts explained in that paper
- It is important to stress that one can squeeze a beam of unsqueezed light also by mixing it with another beam of strongly squeezed light.

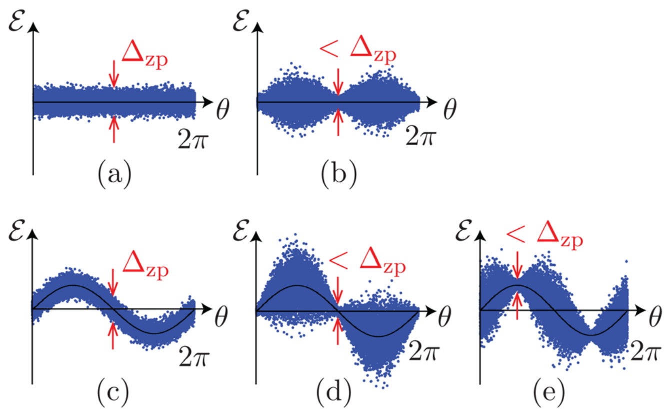

Figure 2: Statistics of electric field measurements for five different minimum-uncertainty states of the same optical mode. (a) Representation of the ground state and its zero-point (vacuum) fluctuation $Delta_{\rm zp}$. The uncertainty does not depend on the phase θ. (b) A squeezed vacuum state; such a state is produced by a phase-dependent (optical parametric) amplification of the zero-point fluctuation. (c) A coherent state, i.e., a displaced vacuum state. (d) A bright phase-squeezed state. (e) A bright amplitude-squeezed state. For all these states the uncertainty product of the electric fields at orthogonal phases meets the lower bound set by the Heisenberg uncertainty relation. Although these pictures are just illustrations, they can be experimentally reproduced by quantum state tomography using the beat signal with a homodyne local oscillator field of the same frequency. Figure from J. Bauchrowith, T. Westphal, and R. Schnabel, *A graphical description of optical parametric generation of squeezed states of light*, Am. J. Phys. **81** (2013) 767.

- How does squeezing help? We understand this as follows: both shot noise and radiation pressure noise produce amplitude fluctuations in the electric field impinging on the mirrors (radiation pressure noise produces phase noise as well, but we neglect it in the present picture as we concentrate on the low-frequency behavior that is dominated by radiation pressure). The amplitude fluctuations are converted to phase fluctuations by the response function of the interferometer (see figure 3). The net result is a large fluctuation in the phase coordinate, which overshadows the small electric field change due to GWs (see figure 4). Squeezed light can be used to mitigate noise at a given frequency by injecting a squeezed vacuum state (see below and figure 5). However, because of the interplay between radiation pressure noise and shot noise, any compensation in a given frequency range is offset by a loss in another frequency range. To obtain a better mitigation, it is necessary to introduce a *frequency dependent squeezing*, which we do not discuss here (see figure 6).

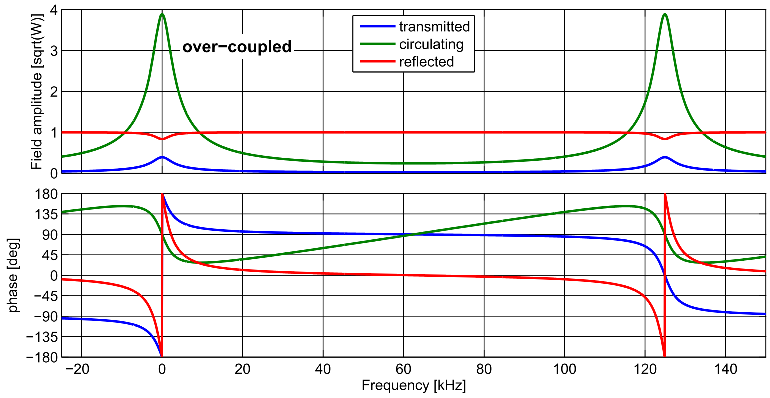

Figure 3: Amplitude and phase transfer functions for a Fabry-Perot cavity. Close to resonance the amplitude variations are exceedingly small for small frequency changes such as those induced by small phase changes like those due to the amplitude modulation from shot noise, on the contrary phase fluctuations are greatly amplified. Figure taken from Bond et al, *Interferometer techniques for gravitational-wave detection*, Living Rev. Relativ. **19** 2016) 3.

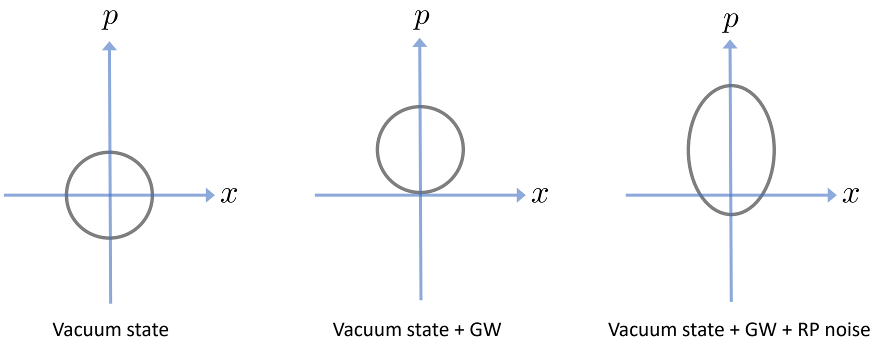

Figure 4: The left panel schematically represents a vacuum state. The middle panel shows a coherent state produced by the presence of a GW with its noise fluctuations: since the phase shift produced by the GW is small, the uncertainty ball is very close to that of the vacuum state. The third panel shows the effect of radiation pressure, that introduces a large phase uncertainty because of the coupling of amplitude and phase induced by the transfer function of the interferometer.

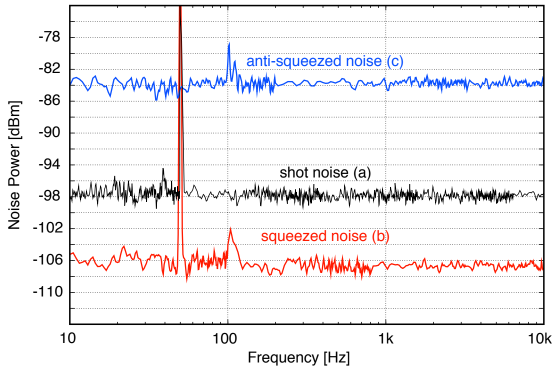

Figure 5: Squeezing of shot noise in the GEO600 IFO. Trace (a) constitutes the shot-noise (vacuum noise) reference of the BHD, measured with the squeezed light input blocked. Trace (b) shows the observed squeezed quantum noise from our source. A nonclassical noise suppression of up to 9 dB below shot-noise (a) was measured throughout the complete spectrum from 10 Hz up to 10 kHz. The corresponding anti-squeezing (c) was 14 dB above the shot-noise level. The electronic dark noise (not shown) was 17dB below the shot-noise and was not subtracted from the measured data. The peaks at 50 Hz and 100 Hz were due to the electric mains supply. Figure taken from H. Vahlbruch et al., *The GEO 600 squeezed light source*, Class. Quantum Grav. **27** (2010) 084003.

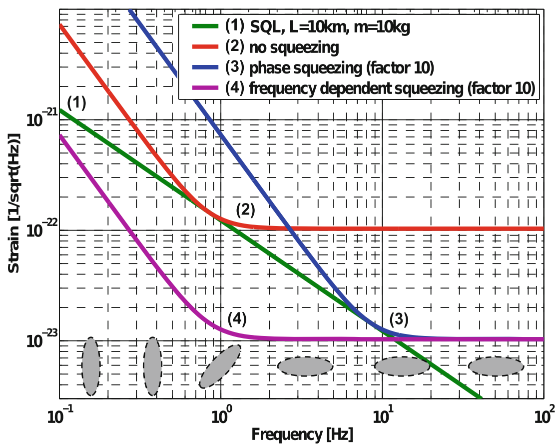

Figure 6: Quantum noise of a simple Michelson interferometer with pure phase squeezing as well as frequency-dependent squeezing. Figure taken from S. Hild, *A Basic Introduction to Quantum Noise and Quantum-Non-Demolition Techniques*, in M. Bassan (ed.) *Advanced Interferometers and the Search for Gravitational Waves, Lectures from the First VESF School on Advanced Detectors for Gravitational Waves*, Springer (2014).

- Crystal materials lacking inversion symmetry can exhibit a so-called $\chi^{(2)}$ nonlinearity. Apart from frequency doubling and sum and difference frequency generation, this allows for parametric amplification. Here, the signal beam propagates through the crystal together with a pump beam of shorter wavelength. Photons of the pump wave are then converted into (lower-energy) signal photons and the same number of so-called idler photons; the photon energy of the idler wave is the difference between the photon energies of pump and signal wave (see figure 7). Since the pump energy is fully converted into energy of signal and idler beams, the crystal material is not heated in this process.

  In the usual non-degenerate case, signal and idler waves constitute physically separate beams. However, there are degenerate parametric amplifiers where signal and idler wave are identical, i.e. have the same frequency and same polarization. The signal frequency then has to be exactly half the pump frequency, and the phase relationship between signal and pump determines the direction of energy flow, i.e., whether there is amplification or deamplification of the signal. This phase-sensitive amplification does not occur in a non-degenerate amplifier, where a signal with arbitrary phase can be amplified, and the phase of the generated idler will automatically adjust accordingly.

  For squeezed-light generation via degenerate OPA below threshold, a laser beam of moderate power is focused into the crystal serving as the pump field for the OPA process. Additional laser light inputs are not required, but zero-point fluctuations at all frequencies and all directions of propagation naturally enter the crystal as well. The pump field's intensity is high enough to produce an anharmonic oscillation of charges and thus a nonlinear dielectric polarization of the crystal. As a consequence, parts of the pump field spontaneously decay into pairs of signal and idler fields, whose frequency sum corresponds to the pump field frequency. For a below-threshold operation, the driving field intensity is still relatively low such that spontaneous emission dominates induced emission.

  "OPA below threshold" is also called "spontaneous parametric down-conversion" (SPDC), and it forms the basis not only for squeezed-light generation but also for the production of entangled photon pairs. For degenerate OPA, the signal and idler fields are indistinguishable, i.e., they have the same frequency, polarization, and direction of propagation. For many popular materials, this setting can be realized by stabilizing the crystal to a specific temperature, the so-called phase matching temperature for degenerate operation. Additionally, the nonlinear crystal is placed between two or more mirrors that have a high reflectivity for the signal/idler field. The mirrors form an optical resonator with the purpose that only a signal/idler field of a well-defined direction of propagation and transverse spatial mode constructively interferes with itself when reflected back and forth between the mirrors.

  To maximize the spontaneous down-conversion probability into this mode, the pump laser beam needs to be aligned such that its waist and direction of propagation are matched to the signal/idler field. Eventually, a single laser beam composed of the (nearly undepleted) pump field and the down-converted field leaves the crystal and its surrounding resonator. The two need to be separated from each other by a wavelength-selective mirror. The squeezing effect is observed on the degenerate signal/idler field. It initially enters the crystal being in the vacuum state and is converted inside the crystal into a squeezed vacuum state. If the initial state is a coherent state—if a coherent laser beam having half the frequency is co-propagating with the pump field—it is converted into a "bright" squeezed state of light. Note that the word bright need not be taken literally; a bright squeezed laser beam is usually much dimmer than the pump beam.

All gravitational-wave detectors currently implementing squeezing use a sub-threshold optical parametric amplifier (also called Optical Parametric Oscillator, OPO), to generate squeezed vacuum. The squeezer system starts with a laser which is phase locked to have the exact frequency as the main interferometer laser. The squeezer laser pumps a second harmonic generator (SHG) which frequency doubles the 1064 nm light to 532 nm, as shown in figure 8. The 532 nm light generated by the SHG is then used to pump the optical parametric oscillator. All of the squeezers in use for gravitational wave detectors use a potassium titanyl phosphate (PPKTP) crystal to create their nonlinear interaction.

(Text of this item adapted from `https://www.rp-photonics.com/optical_parametric_amplifiers.html`, from J. Bauchrowith, T. Westphal, and R. Schnabel, *A graphical description of optical parametric generation of squeezed states of light*, Am. J. Phys. **81** (2013) 767, and from S. E. Dwyer, G. L Mansell, and L. McCuller, *Squeezing in Gravitational Wave Detectors*, Galaxies **10** (2022) 10020046.).

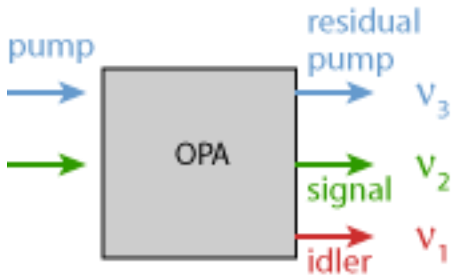

Figure 7: Basic diagram of OPA operation, from `https://www.rp-photonics.com/optical_parametric_amplifiers.html`.

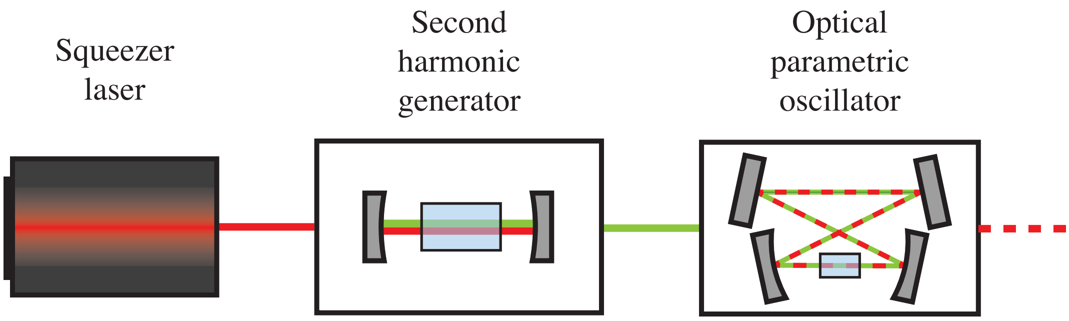

Figure 8: Schematics for the squeezed vacuum source in current IFOs (from S. E. Dwyer, G. L Mansell, and L. McCuller, *Squeezing in Gravitational Wave Detectors*, Galaxies **10** (2022) 10020046).

- The injection of vacuum states in the interferometers is carried out according to the scheme shown in figure 9. The scheme is implemented inside current interferometers as shown in figure 10. Finally, figure 11 shows a simplified version of the actual implementation in Advanced Virgo.

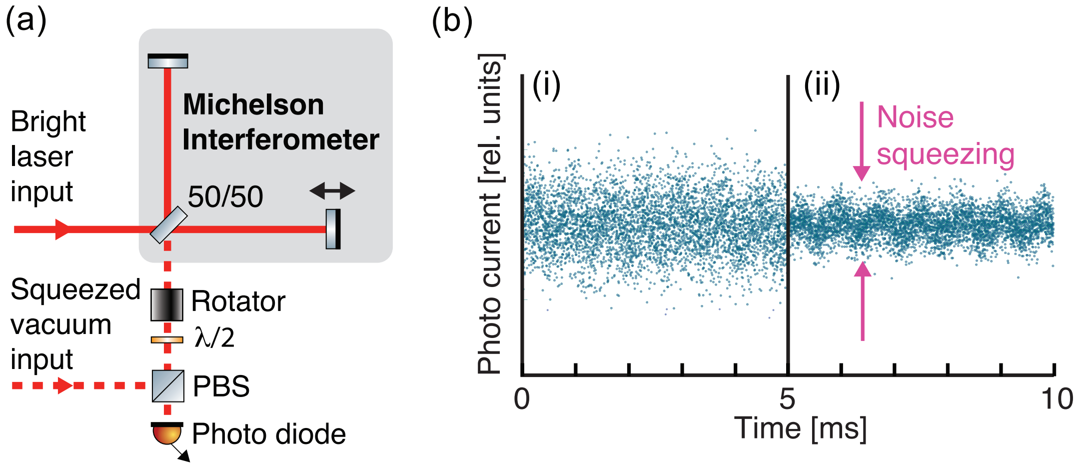

Figure 9: Squeezed-light enhanced gravitational-wave detection (a) Simplified scheme of a gravitational-wave (GW) detector with squeezed vacuum injection. A simplified Michelson interferometer is shown; in addition to the conventional bright coherent laser input, a broadband squeezed-vacuum field is injected into the dark signal port. Typically, a polarized beam splitter (PBS) is used as injection port for squeezing. The squeezed vacuum field beats agains a coherent beam (not shown) on the photo-diode. (b) Illustration of how the squeezed field reduces the output light's shot noise and improves the signal to shot-noise ratio in the photo- electron current. Without squeezing (i), the signal of the gravitational wave detector is not visible. With squeezing (ii), the shot noise is reduced and, here, a sinusoidal signal becomes visible (b, simulation by B. Hage, Albert Einstein Institute). Figure taken from L. Barsotti, J. Harms, R. Schnabel, *Squeezed vacuum states of light for gravitational wave detectors*, Rep. Prog. Phys. **82** (2018) 016905.

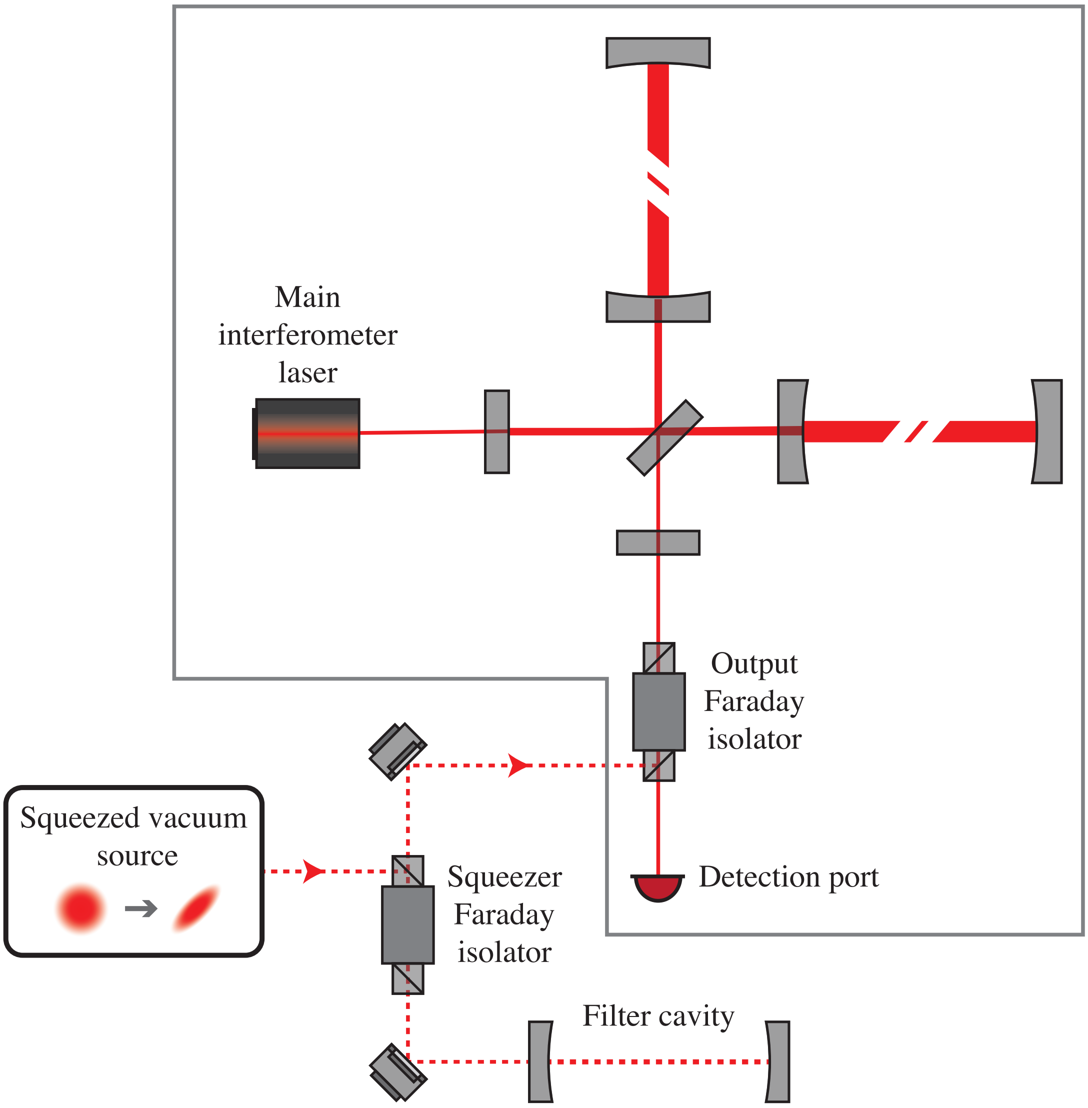

Figure 10: Simplified optical layout of a dual-recycled Fabry–Perot Michelson interferometer (grey box), with frequency-dependent squeezing injected at the output port, as is planned the aLIGO and AdVirgo detectors in Observing Run 4. The squeezed vacuum source generates frequency-independent squeezed light. The squeezed beam (dashed red line) is reflected off the filter cavity, passes back through one or more squeezer Faraday isolators, and is injected into the main interferometer through the output Faraday isolator. Figure taken from S. E. Dwyer, G. L Mansell, and L. McCuller, *Squeezing in Gravitational Wave Detectors*, Galaxies **10** (2022) 10020046.

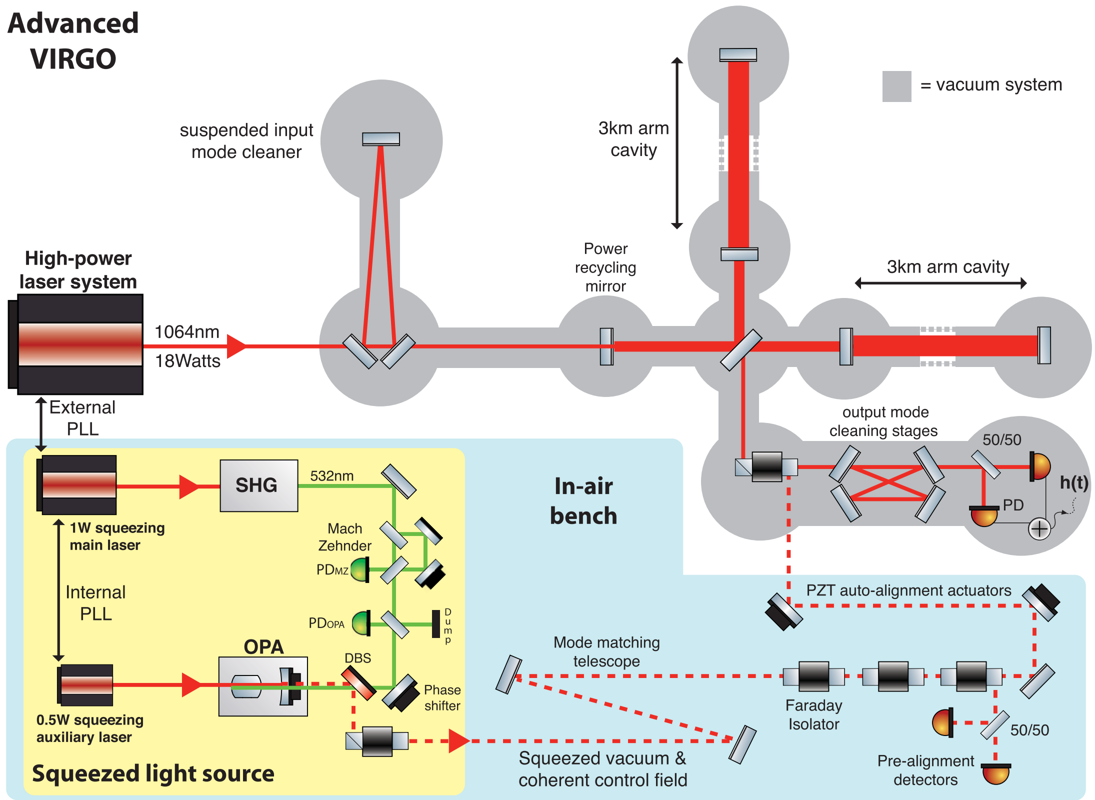

Figure 11: Simplified layout of the quantum enhanced Advanced Virgo gravitational-wave detector. The Advanced Virgo detector is a power recycled Michelson interferometer using 3 km long Fabry-Perot cavities in the arms. Before being injected into the interferometer, the high power (18 W) input laser beam passes through a 143 m long triangular mode cleaner cavity. After the recombination at the central beam splitter, a fraction of the carrier light copropagates with the signal field to be used for a dc readout scheme. This output field is spatially filtered by an output mode cleaning stage and divided into two beams before detection. The sum of the two photo detectors is used to derive the gravitational-wave signal $h(t)$. All the interferometer optics as well as the injection and the detection benches are suspended and operated in vacuum. Squeezed vacuum states of light are prepared externally on an optical bench (blue box). This in-air bench hosts the squeezed light source (yellow box), the reflective mode matching telescope, the Faraday isolators, and alignment steering mirrors. The bench is covered with an enclosure to protect the optics against acoustic noise and air turbulence and is passively suspended by means of elastomer attenuators. More sophisticated suspension stages are not required as below $\sim$ 30 Hz the squeezer backscattered light effect is dominated by the up-conversion of the low frequency ($\sim$ 0.15 Hz) microseismic peak. Finally, the squeezed beam is injected into the interferometer vacuum system through an antireflectively coated viewport. The path between the acoustic enclosure and this optical window is shielded by a tube from air turbulence. Figure taken from F. Acernese et al. (Virgo Collaboration), Phys. Rev. Lett. **123** (2019) 231108.