Frequency dependent squeezed vacuum for quantum noise reduction in gravitational-wave detectors

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Context and motivation

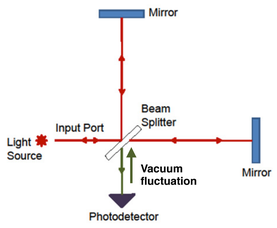
Gravitational-wave astronomy has begun in 2015 with **the first detection of a gravitational wave** (GW) from the merging of two black holes.

After that, few more signals (among which one from a binary neutron star merging) have been recorded by a network of detectors, composed by two LIGO and Virgo. The Japanese detector KAGRA is also expected to join the network soon.

The detectors are alternating periods of data taking and periods of commissioning. **The goal is to increase more and more the sensitivity** in order to have a higher rate of detections with louder signals. This will bring the gravitational-wave astronomy to a full maturity, with major scientific payoffs in general relativity, astrophysics and cosmology.

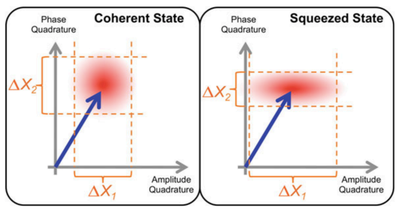
Our research focuses on the reduction of quantum noise, that is one of the main limitation of GW detectors sensitivity.

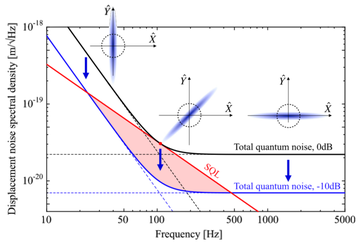
Quantum noise in gravitational wave detectors



- Amplitude and phase of coherent states of light have a minimum uncertainty on their product stemming from Heisenberg uncertainty principle
- Quantum noise in GW detectors is originated by quantum fluctuation of the coherent vacuum entering their asymmetric port

- **Squeezed states have a reduced uncertainty** in one quadrature at expenses of the other
- The injection of **squeezed vacuum can mitigate the quantum noise**



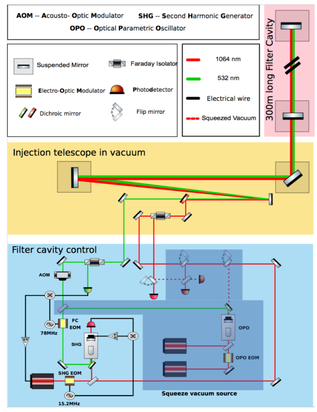


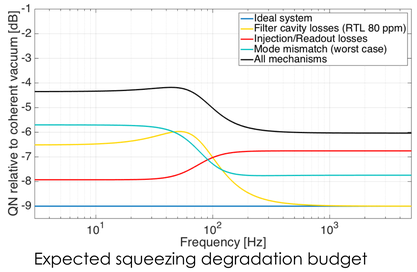
- A broadband noise reduction is obtained when the squeezing ellipse angle has a frequency dependence
- This is called **frequency dependent squeezing** and can be obtained by reflecting a squeezed state off a so-called **filter cavity**

Frequency dependent squeezing experiment at TAMA300 (NAOJ)

GOAL: developing a squeezed vacuum source and a full scale filter cavity prototype to test the production of frequency dependent squeezing with optimal squeezing angle rotation (~70 Hz)

- The filter cavity is installed in the arm of the former interferometer TAMA300 at National Astronomical Observatory of Japan (NAOJ)
- Cavity length: 300 m
- Storage time: 2.8 ms
- Suspended mirrors, 10 cm diameter
- Squeezed vacuum produced with an optical parametric oscillator
- Target squeezing level: 9dB

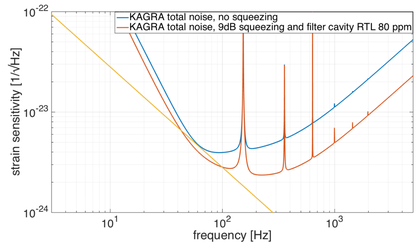




Expected squeezing degradation budget

- Squeezing Is easily degraded by optical losses (as those inside the filter cavity): cavity mirrors have been chosen to allow for a very low level of round trip losses (<80 ppm)[1]

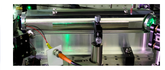
Expected improvement in KAGRA detector sensitivity



Expected sensitivity of the Japanese detector KAGRA with and without injecting frequency dependent squeezing (red and blue line, respectively)

Status of the experiment

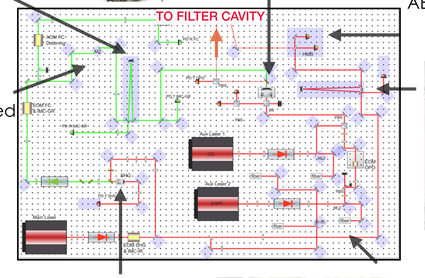
- Squeezed vacuum source



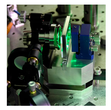
Green mode cleaner and **Mach-Zehnder interferometer** for power stabilization Installed and controlled

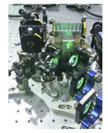
Optical parametric oscillator (OPO) installed and controlled

Homodyne detector in progress (in collaboration with AEI, Hannover)

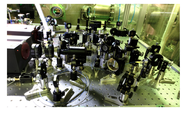


Infrared mode cleaner installed and controlled





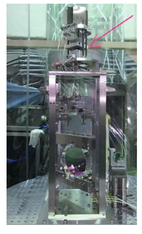
Second harmonic generator (SHG) assembled and operated



Phase locked loop (PLL) for auxiliary lasers installed and operated

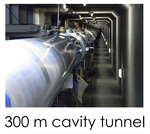
First squeezing measurement expected soon!

- 300 m filter cavity



Suspended mirror

- Suspensions, mirrors and injection optics installed
- Cavity has been controlled
- Cavity characterization performed: optical losses in agreement with the requirement [2]



300 m cavity tunnel

Beam resonating inside the cavity

Summary

- Frequency dependent squeezing is a promising technique to improve the sensitivity of gravitational-wave detectors
- We aim to demonstrate frequency dependent squeezing with optimal angle rotation using a 300 m filter cavity in TAMA300 (NAOJ)
- Status: the installation of the squeezing vacuum source has been completed and the filter cavity has been assembled, controlled and characterized
- Next steps: measure squeezing and inject it into the filter cavity

References

[1] E.Capocasa et al. "Losses estimation in a 300-m filter cavity and quantum noise reduction in the KAGRA gravitational-wave detector " Phys. Rev. D 93, 082204 (2016)

[2] E.Capocasa et al. "Measurement of optical losses in a high-finesse 300 m filter cavity for broadband quantum noise reduction in gravitational-wave detectors" Phys. Rev. D 98, 022010 (2018)