Displacement-Noise-Free Interferometry

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Outline

General issues

- Mechanism of displacement-noise-free GW detection
- "Displacement-noise-free theorem"

Complete displacement noise cancelation

Partial displacement noise cancelation

- Double-pumped Fabry-Perot cavity
- Two double-pumped Fabry-Perot cavities
- Resonant speed meter
- Double Michelson/Fabry-Perot interferometer

Displacement-noise-free GW detection. Basic idea

Displacement-noise-free GW detection is possible when an interferometer responds *differently* to the GW and displacement noise.

It is possible, in principle, because displacement noise is a *localized* effect (phase of the optical wave is affected at the instants of reflection), while the GW is a *distributed* effect (phase of the optical wave is affected along the path). The difference between two effects has the order of $O[h(L/\lambda_{GW})^2]$.

Displacement-noise-free interferometer cancels localized effects and the GW terms of the order of $O[h(L/\lambda_{GW})^0]$ and $O[h(L/\lambda_{GW})^1]$.

Advantages of displacement-noise-free interferometry:

- ✓ In principle, test masses are not needed to be isolated from the environment and cooled to low temperatures.
- ✓ Cancelation of displacement noise implies insusceptibility to radiation pressure noise and, therefore, to SQL – alternative to QND measurements.

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Seems to be ideal for ET...

“Displacement-noise-free theorem”

A system of *N* test masses exchanging optical signals with each other has *N(N-1)* channels of timing signals.

Each test can move in D spacial dimensions and has intrinsic timing noise – displacement noise is “4-dimensional”! DFI should cancel both displacement and timing noises. In laser interferometry timing noise is a laser noise.

Total number of noise channels in the system is *ND+N*.

It is possible, in principle, to construct *N(N-1) – N(D+1) = N(N-D-2)* displacement- and laser-noise-free signals. DFI is possible if *N>D+2*.

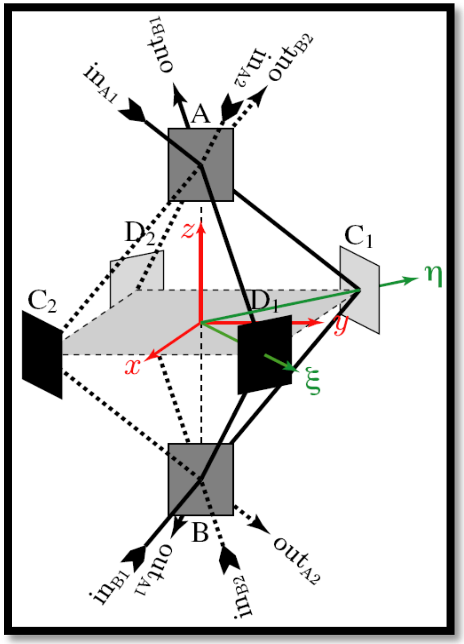
What about the GW response of DFI?

At D=1 (linear setup) DFI has a vanishing GW response.

At D=2 and 3 DFI GW response is a non-vanishing but is strongly suppressed (see next slide).

*Y. Chen and S. Kawamura, PRL **96**, 231102, 2006*

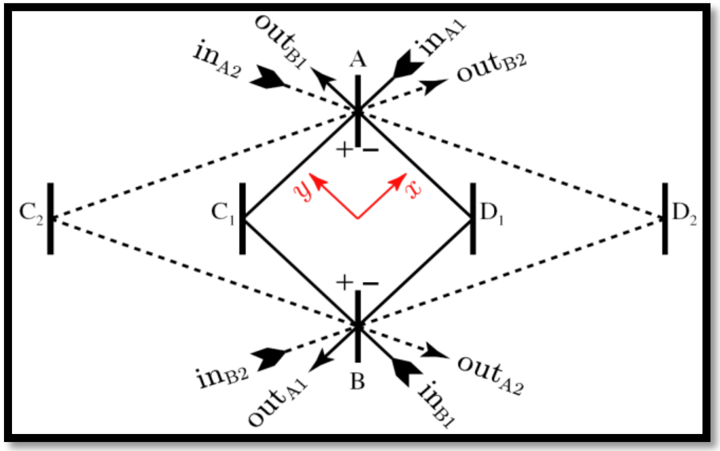
Displacement-noise-free interferometers



3D DFI (Octahedron) is composed of 4 Mach-Zehnder interferometers. The proper linear combination of their responses cancels displacement noises of all mirrors and beamsplitters. The GW response has the order of $h(L/\lambda_{GW})^2=10^{-5}h$ for L=10 km and f_{GW}=100 Hz.

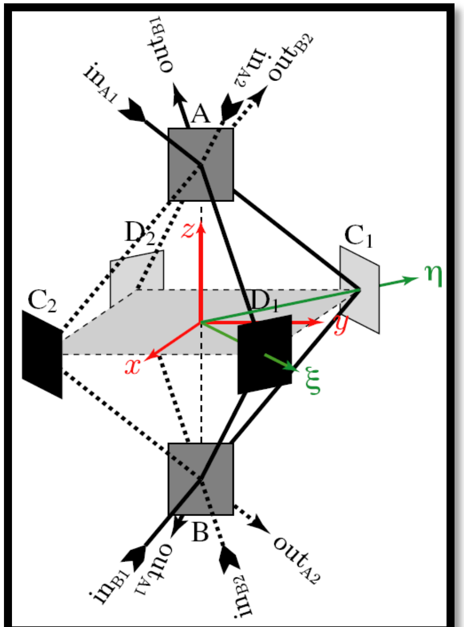
2D DFI has the GW response of the order of $h(L/\lambda_{GW})^3=10^{-7}h$ for L=10 km and f_{GW}=100 Hz.

Single-pass DFIs are sensitive around $f = c/L$ that are *very high* frequencies (tens of kHz) for the ground-based detectors.



*Y. Chen and S. Kawamura, PRL **97**, 151103, 2006*

Displacement-noise-free interferometers



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Use the cavities to increase the response

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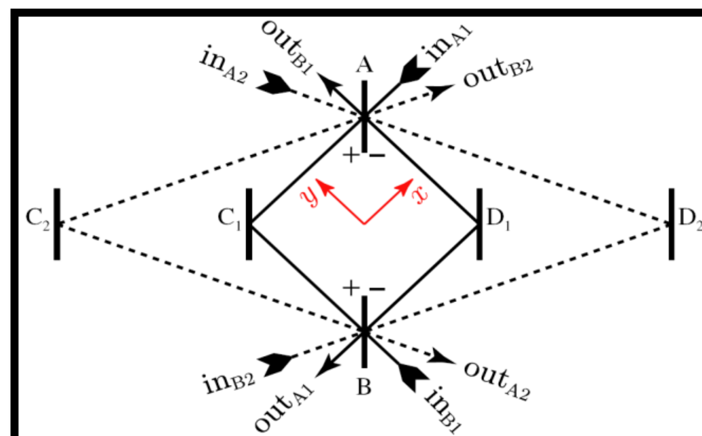

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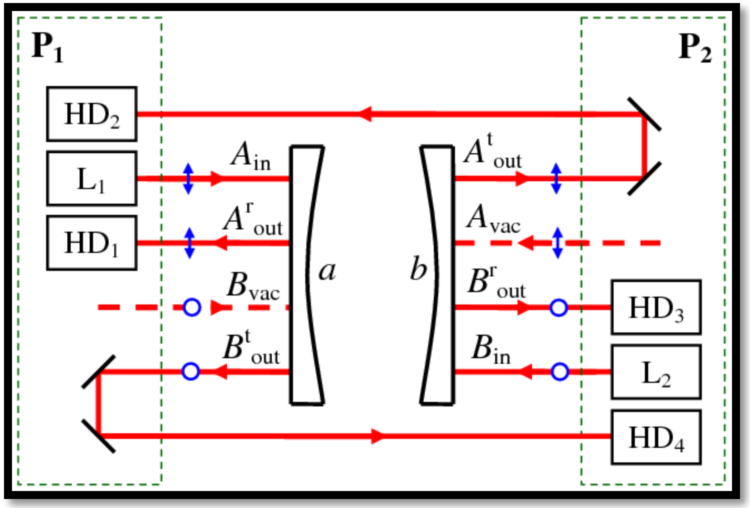
Double-pumped Fabry-Perot cavity



FP cavity is pumped from both sides. Experimentalist monitors 4 output signals: 2 reflected and 2 transmitted ones.

Reflected signal differs from the transmitted signal due to the prompt reflection effect.

It is possible to separate the GW signal from the displacement noise of the *cavity mirrors*.

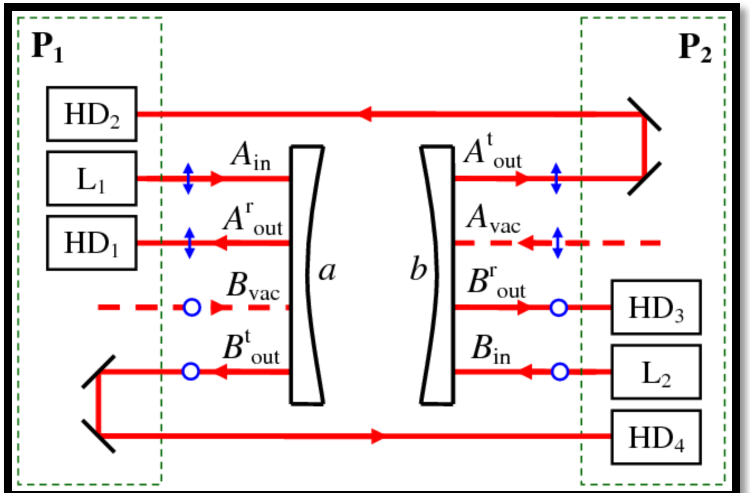
$$\text{response} \sim \text{laser noise} + \text{platforms disp. noise} + \frac{\omega_0}{c} L \left(\frac{L}{\lambda_{\rm GW}} \right)^0 h$$

Disadvantages of the double-pumped cavity model:

- ✓ Transfer of the noise issue from the mirrors to the platforms where lasers and photodetectors are mounted. Platforms noise should be suppressed "by hands".
- ✓ Uncanceled laser noise – requires balanced scheme.

*S.P. Tarabrin and S.P. Vyatchanin, PLA **372**, 6801, 2008*

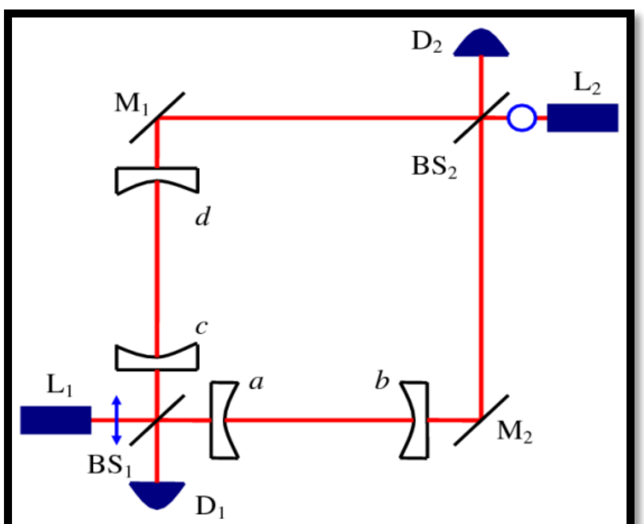
Double-pumped Fabry-Perot cavity

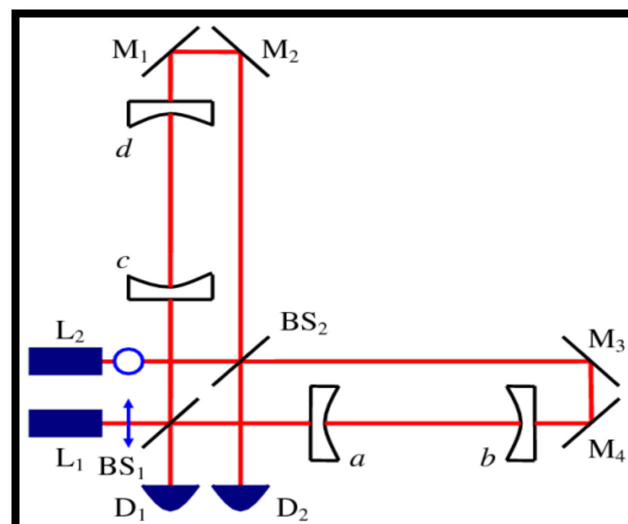


Balanced schemes.

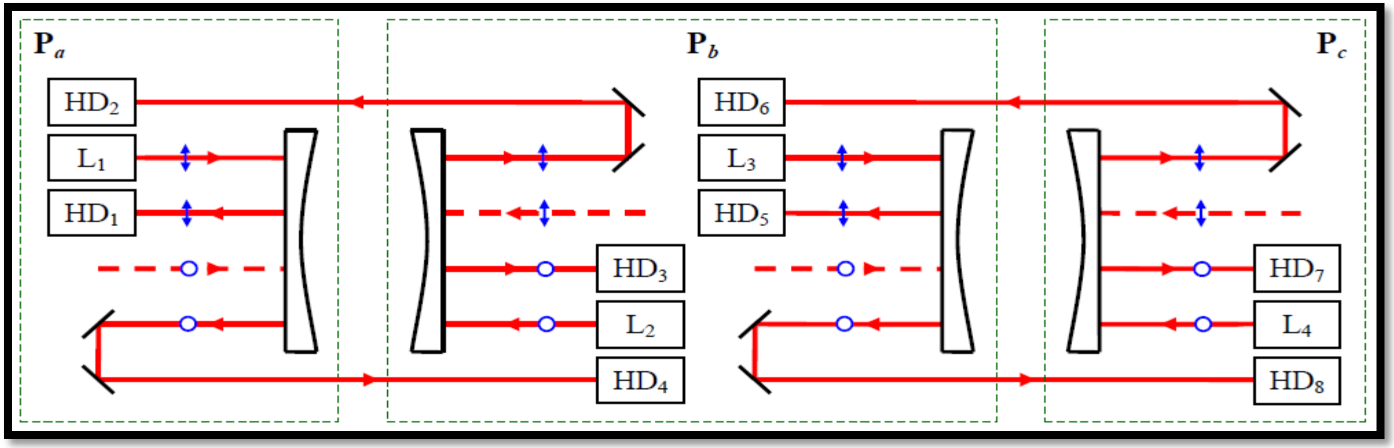
Mach-Zehnder/FP (two corner stations) or Michelson/FP (one corner station).

The net sensitivity is still limited by the residual displacement noise of the additional mirrors and beamsplitters.





Two double-pumped Fabry-Perot cavities



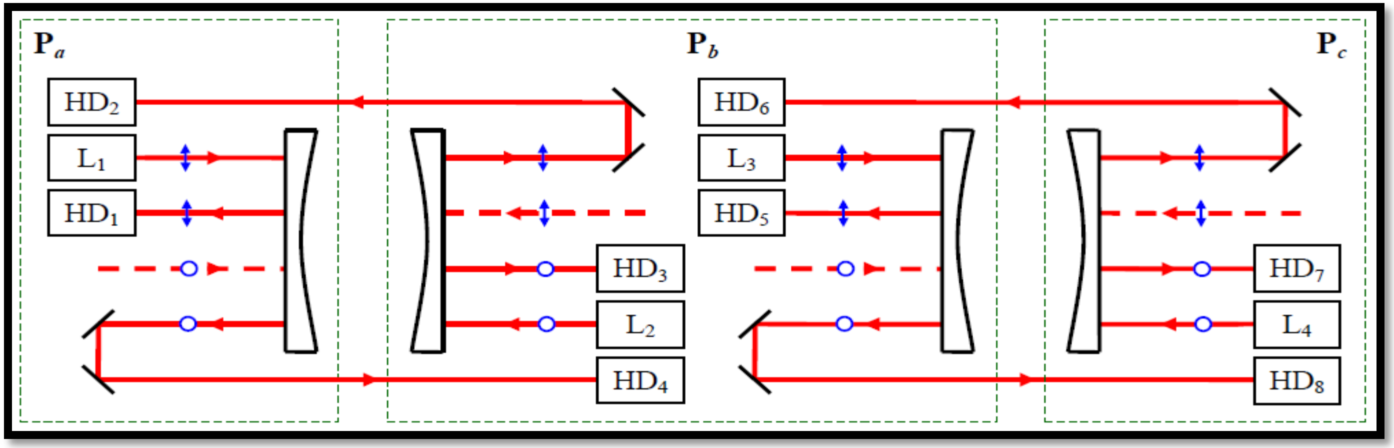
Three platforms with *rigidly mounted* lasers, photodetectors and cavities mirrors. Both cavities are pumped from both sides. An experimentalist monitors either reflected signals or transmitted ones.

Proper linear combination of the signals allows to cancel displacement noise of all three platforms with the response

$$\text{response} \sim \text{laser noise} + \frac{\omega_0}{c} L \left(\frac{L}{\lambda_{\text{GW}}} \right)^2 \frac{\tau_{\text{FP}}}{\tau} h$$

<u>*A.A. Rakhubovsky and S.P. Vyatchanin, PLA **373**, 13, 2008*</u>

Two double-pumped Fabry-Perot cavities



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$$\left(\frac{L}{\lambda_{\mathrm{GW}}}\right)^2 \frac{\tau_{\mathrm{FP}}}{\tau} h \approx h \times 10^{-3} \ \text{for}\ L = 10\ \text{km},\ f_{\mathrm{GW}} = \frac{1}{\tau_{\mathrm{FP}}} = 100\ \text{Hz}$$

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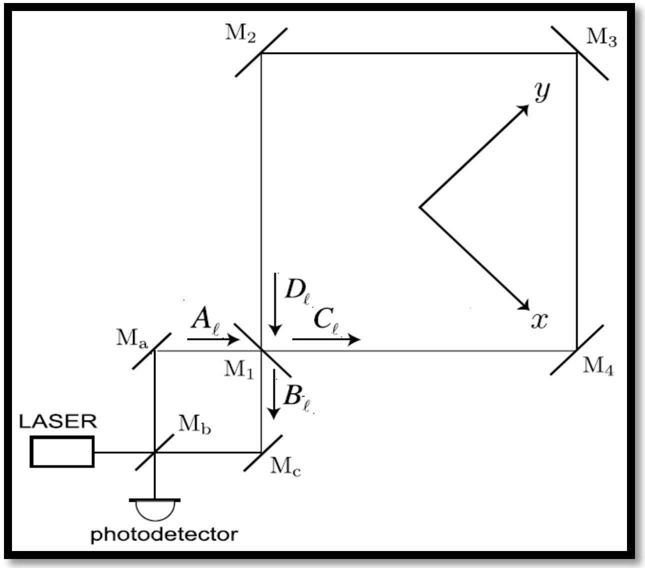
Resonant speed meter



Sagnac-type interferometer is not sensitive to the motions of the input and "end" mirrors at all frequencies, because clockwise and counterclockwise optical waves encounter them simultaneously.

In the vicinity of the FSR: complete DFI and GW resonantly amplified – narrow-band DFI.

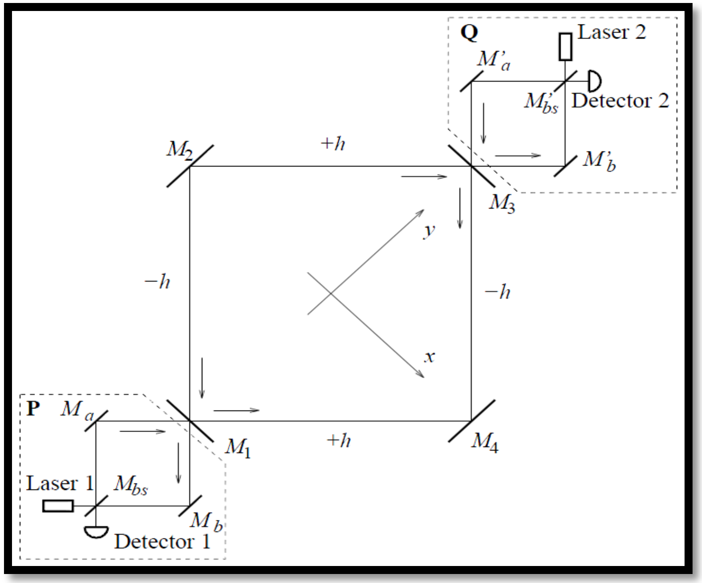
*Nishizawa, PRL **101**, 081101, 2008*

Adding the second pump allows broad-band DFI if we subtract the signal of the 1st detector from the signal of the 2nd.

$$\text{response} \sim \text{platforms noise} + \frac{\omega_0}{c} L \left(\frac{L}{\lambda_{GW}}\right)^1 \frac{\tau_{FP}}{\tau} h$$

Unfortunately, platforms displacement noise is comparable to GW signal.

S.P. Vyatchanin, arXiv:0808.3445



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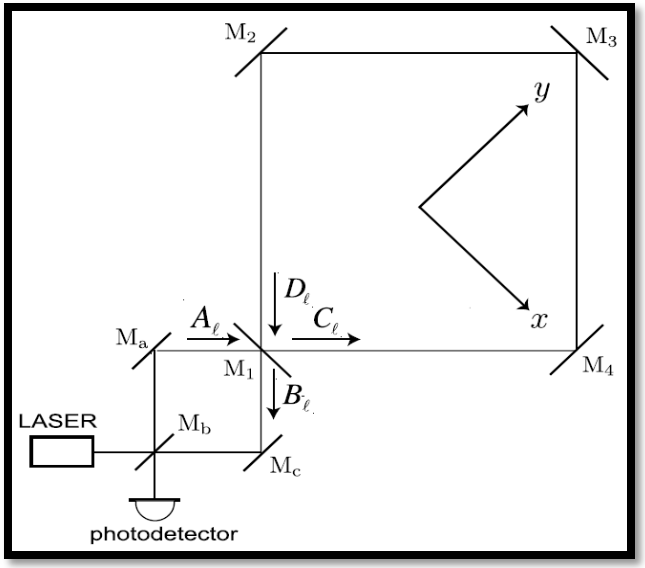

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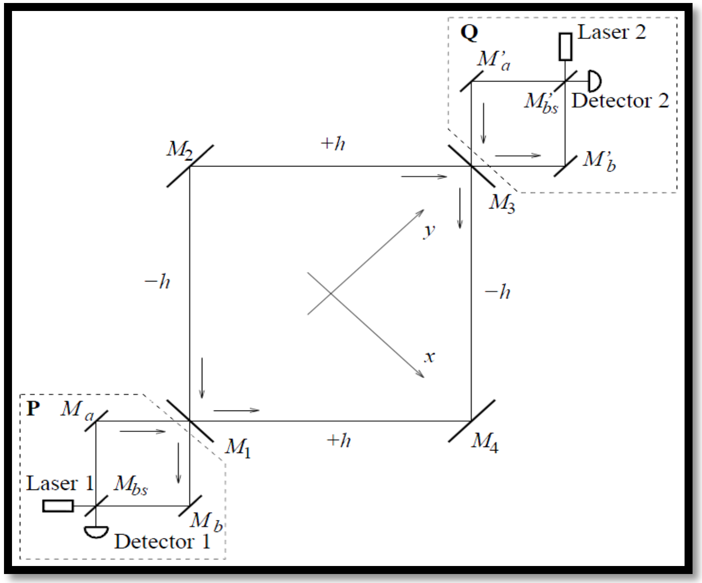
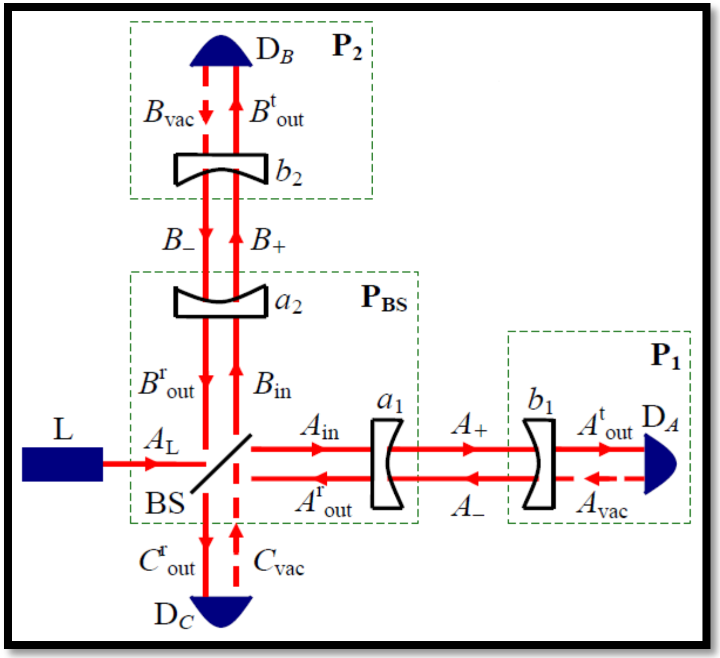


Double Michelson/FP interferometer



A single Michelson/FP interferometer with partially transmittable end-mirrors. Both reflected and transmitted waves are monitored. Transmitted waves are registered with the homodyne detectors.

Laser noise can be canceled from the transmitted waves by taking their difference.

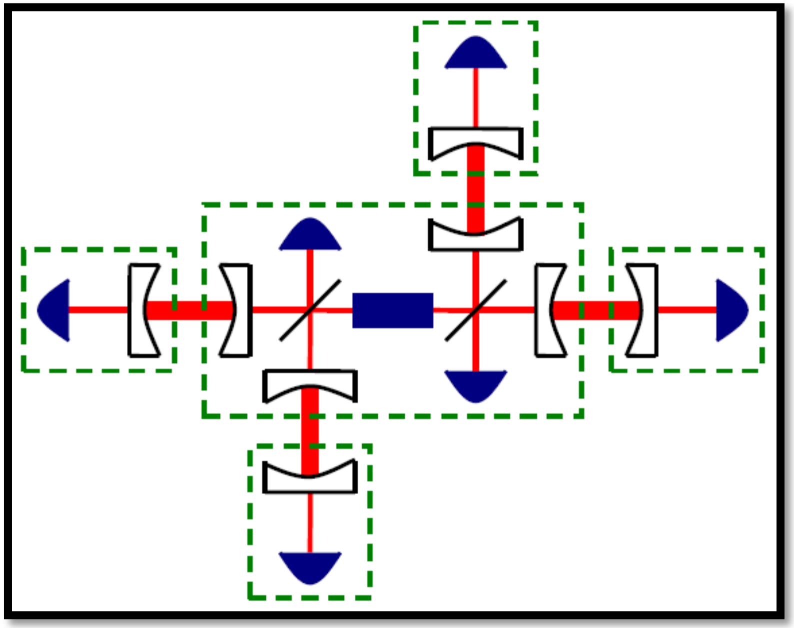
There are 4 fluctuative degrees of freedom: beamsplitter, input mirrors, end-mirrors, end-detectors. But there are only 2 signals (dark-port signal and differential bright-port signal)!

Two degrees of freedom should be suppressed "by hands":

- Input mirrors and the beamsplitter are rigidly mounted on the central platform.
- End-mirrors and end-detectors are rigidly mounted n the end-platforms.

Combination of 2 signals cancels the differential motion of the end-platforms.

Double Michelson/FP interferometer



To cancel the noise of the central platform the second interferometer is positioned symmetrically.

Central platform now contains both beamsplitters and all the input mirrors.

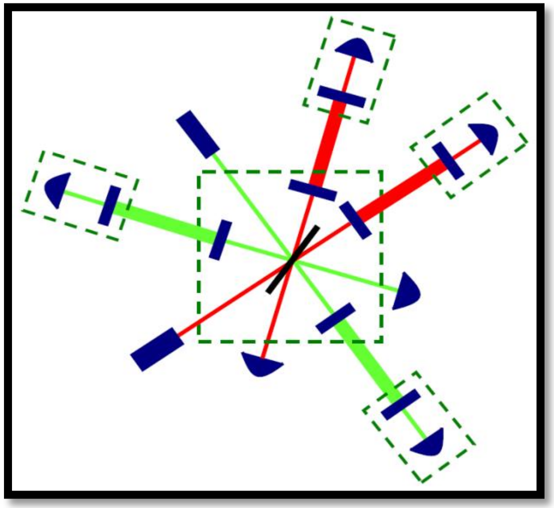
Proper combination of the signals of both interferometers allows DFI

$$\text{response} \sim \text{LOs noise} + \frac{\omega_0}{c} L \left(\frac{L}{\lambda_{GW}} \right)^1 h$$

The major limitation comes from the model of the rigid platform that is very impractical.

In principle, the setup with a single beamsplitter is possible.

Sensitivity is ultimately limited by the noise of local oscillators which are used for the detection of transmitted waves.



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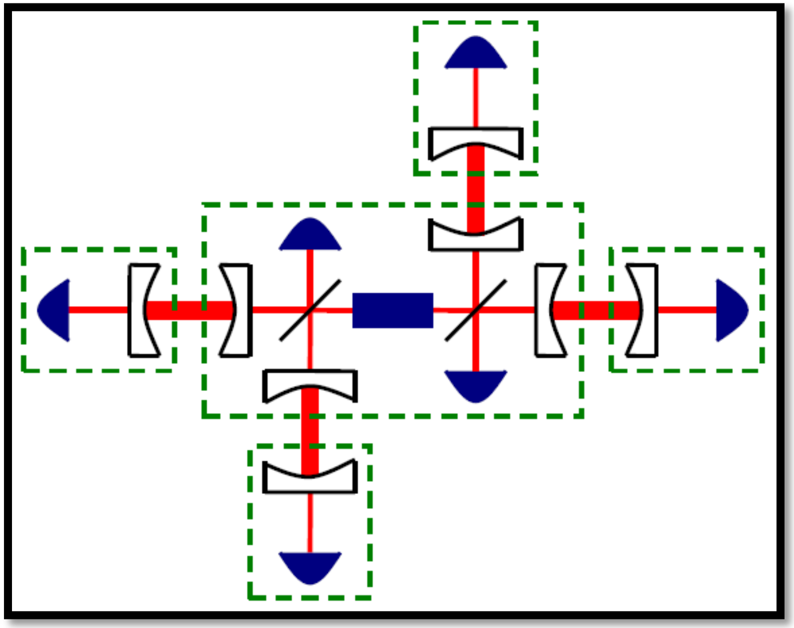

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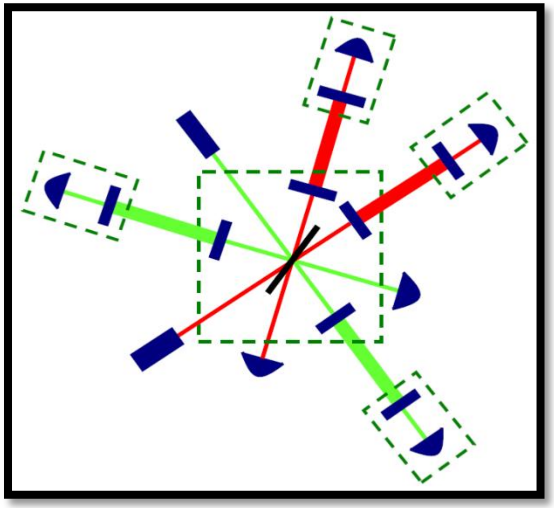

Conclusion

- Displacement-noise free interferometry (DFI) provides a way to deal with seismics, gravity-gradients, thermal noises and radiation pressure simultaneously.

- Unfortunately, the common feature of all DFIs, both complete and partial, is the significant decrease of the GW susceptibility. Given almost the same level of shot noise, the decrease of the sensitivity at astrophysically most interesting frequencies (1 – 1000 Hz) is dramatic (10^{-3} – 10^{-7}) for the arm lengths of the order of several kilometers.

- DFI schemes has almost no advantages over conventional interferometric (non-DFI) schemes for the means of *(under-)ground-based* GW detection.

- Still, DFI might be interesting for the space-based detectors (DECIGO, BBO).