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A Michelson Interferometer for the Demonstration of Gravitational Wave Detection

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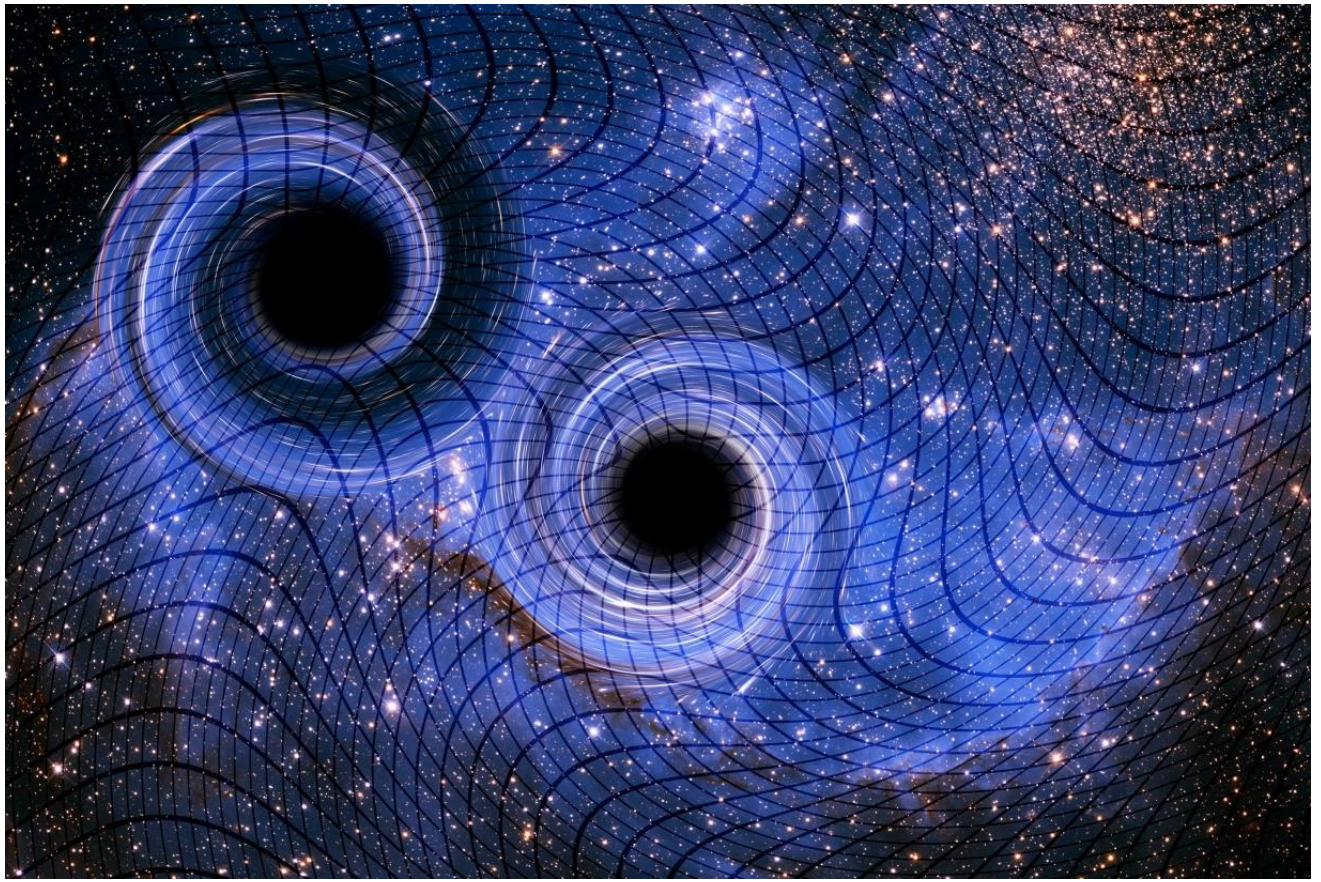
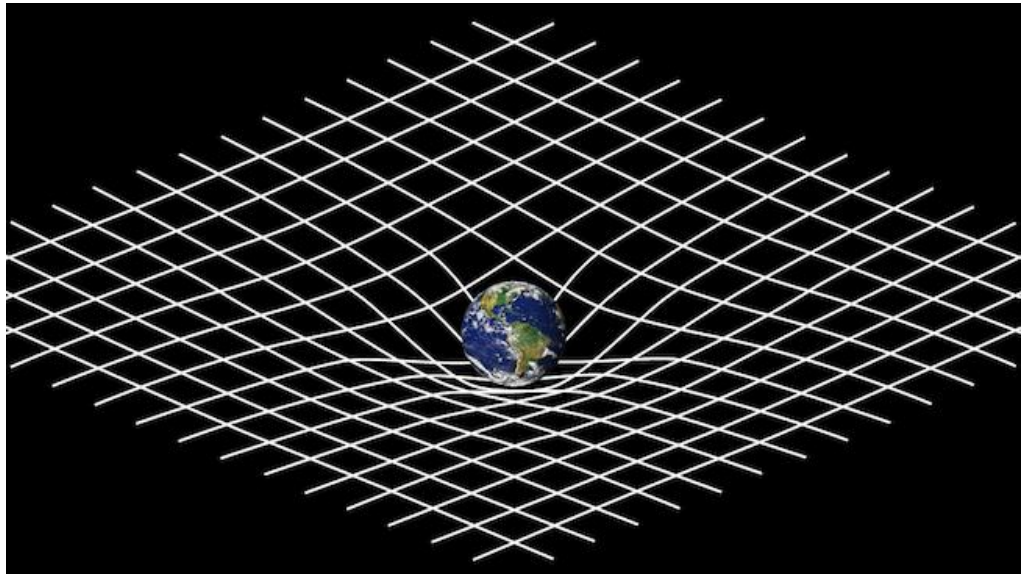


https://www.technologyreview.com/2019/12/14/131574/tidal-forces-carry-the-mathematical-signature-of-gravitational-waves/

Motivation of gravitational waves



https://imagine.gsfc.nasa.gov/science/toolbox/gwaves1.html

- GR: Gravitation ↔ curvature of spacetime
- Mathematical description by Einstein's field equations:

$$\underbrace{R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R}_{\text{curvature}} = \underbrace{\frac{8\pi G}{c^4} T_{\mu\nu}}_{\text{mass/energy}}$$

- Implication: Object moves → curvature changes
- Curvature changes propagate at c_0
- Gravitational waves = wave-like perturbation of the curvature/metric

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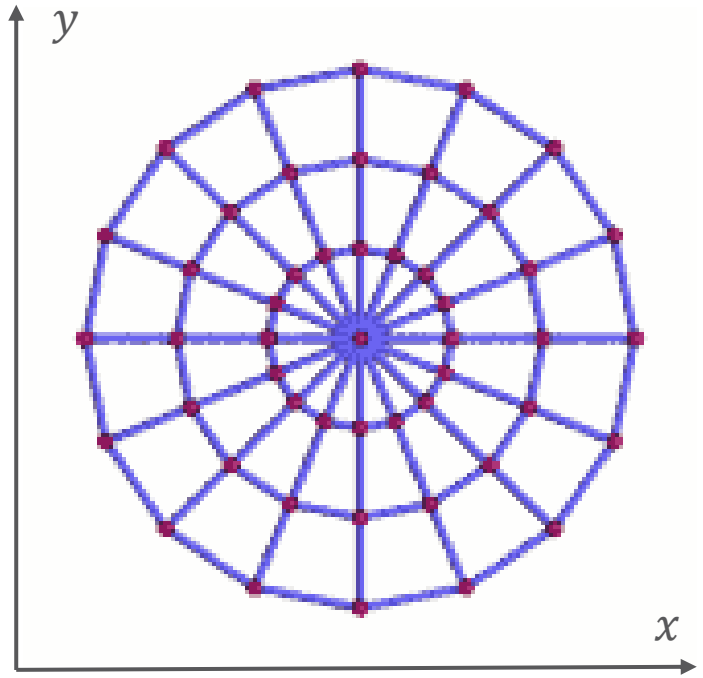

GW with “+”-polarization

https://www.einstein-online.info/en/spotlight/gw_waves/

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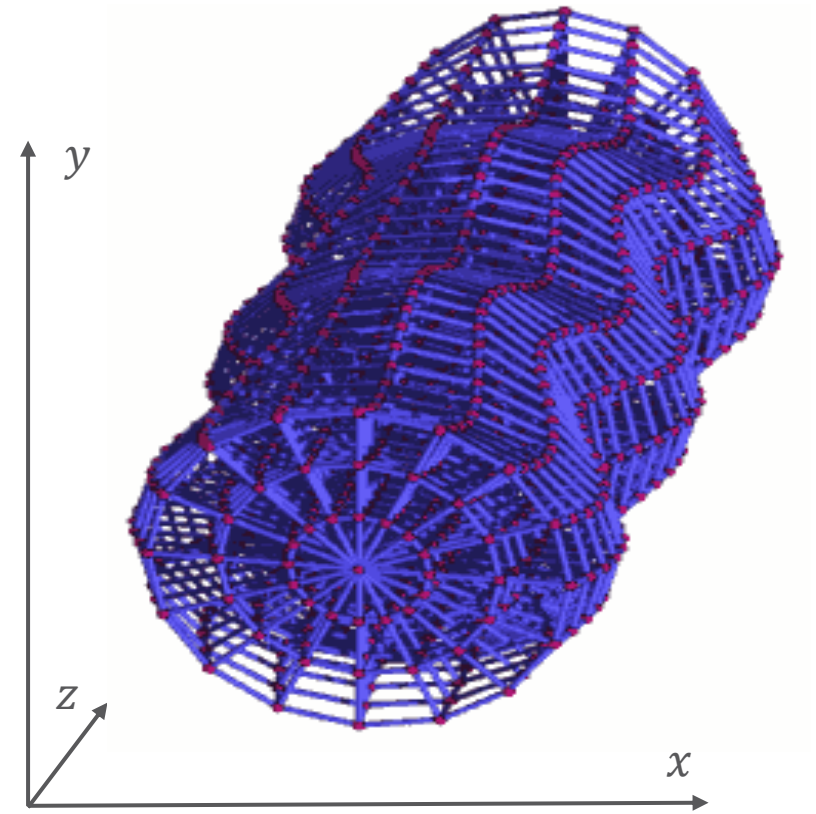

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Michelson Interferometers make great GW detectors!

- Phase difference $\Delta\phi = \frac{2\pi}{\lambda}\Delta x$

  → Interference

- Gravitational wave changes arm length

  → Light output changes

- L-shaped design perfectly suited for sensing a transverse traceless wave **(like a GW)**

- Multiple interferometers needed to make directional observations

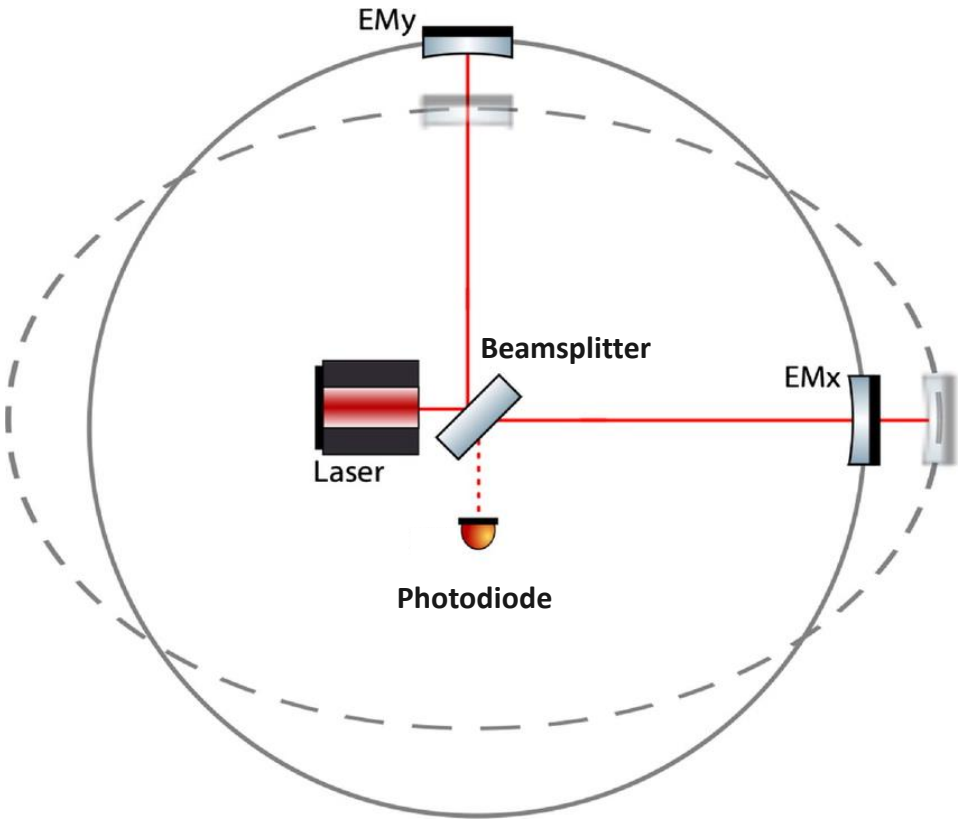
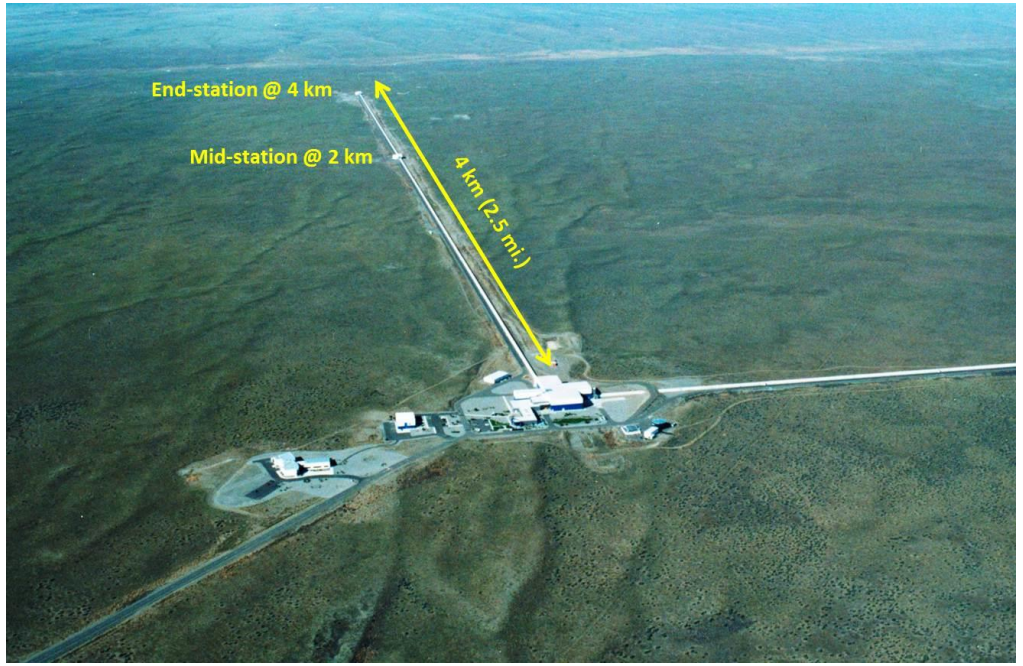


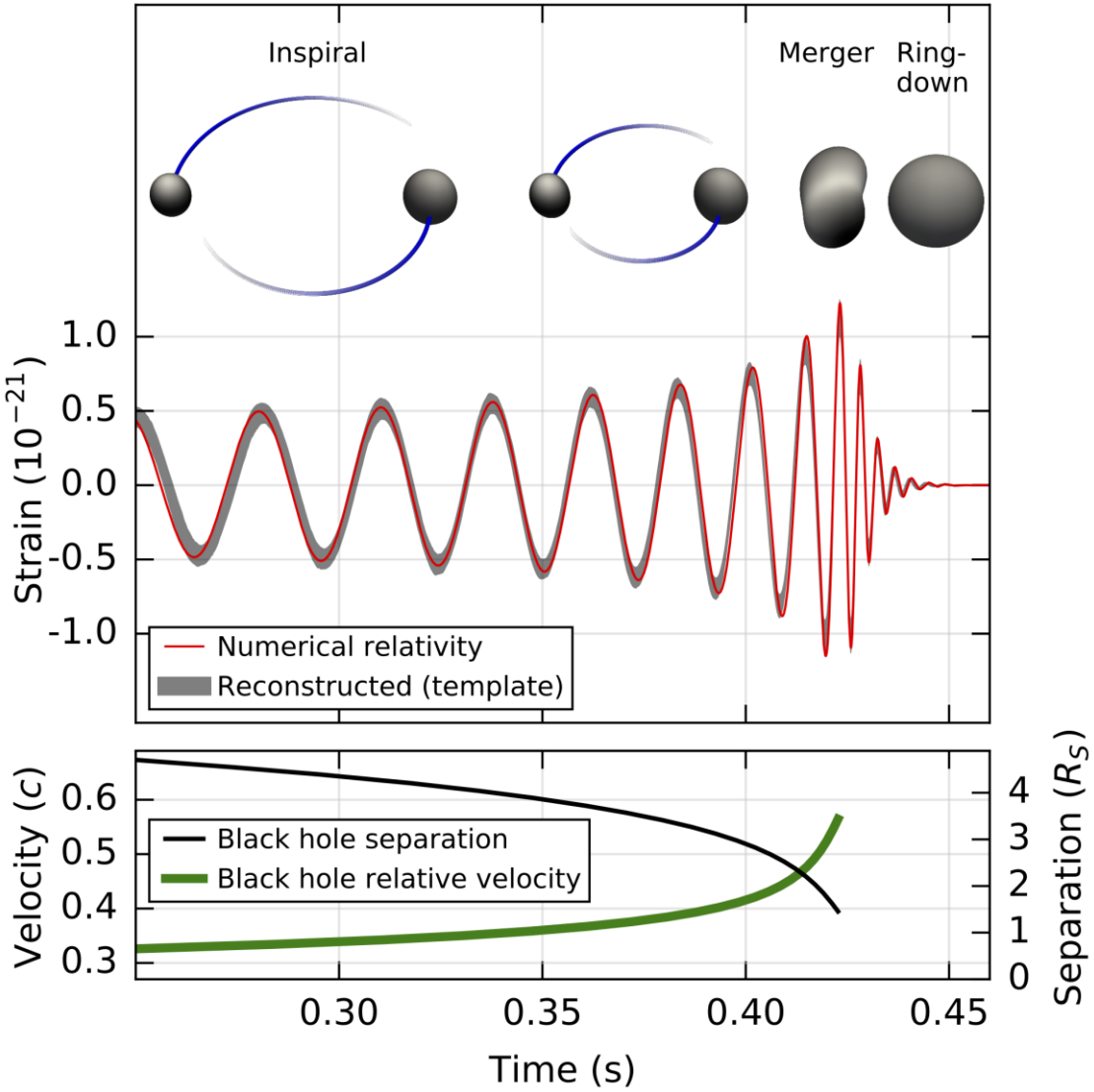
Image source: https://www.researchgate.net/figure/Simplified-schematic-of-Michelson-interferometer-acting-as-a-gravitational-wave-detector_fig11_260268927

Famous example: LIGO

- Two Michelson interferometers in Washington and Louisiana
- First direct detection of a gravitational wave in 2015

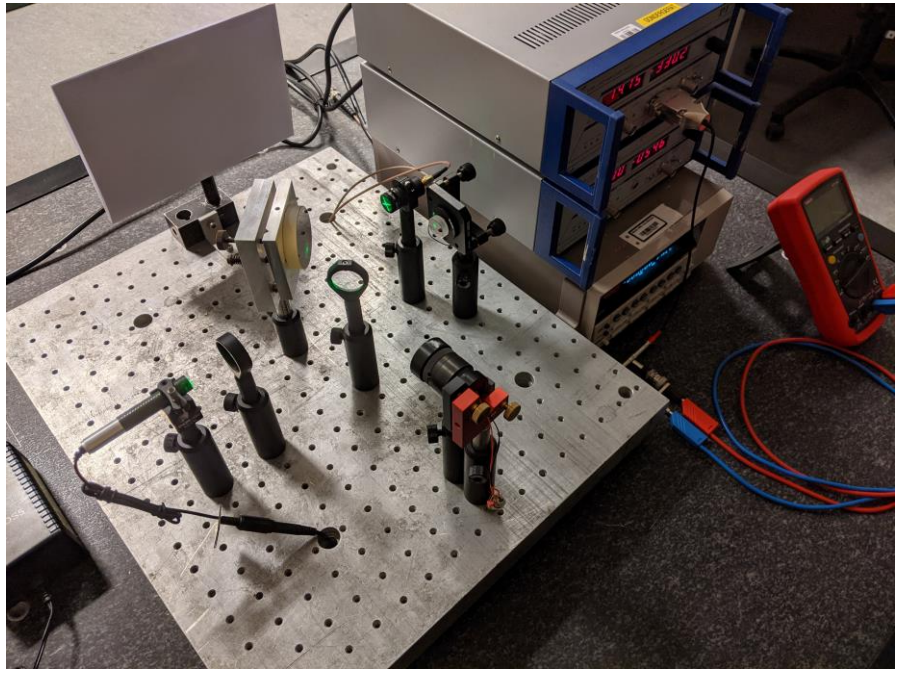


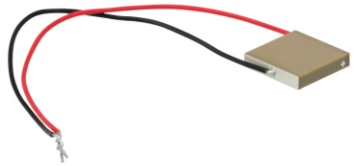
https://www.ligo.caltech.edu/page/ligo-detectors

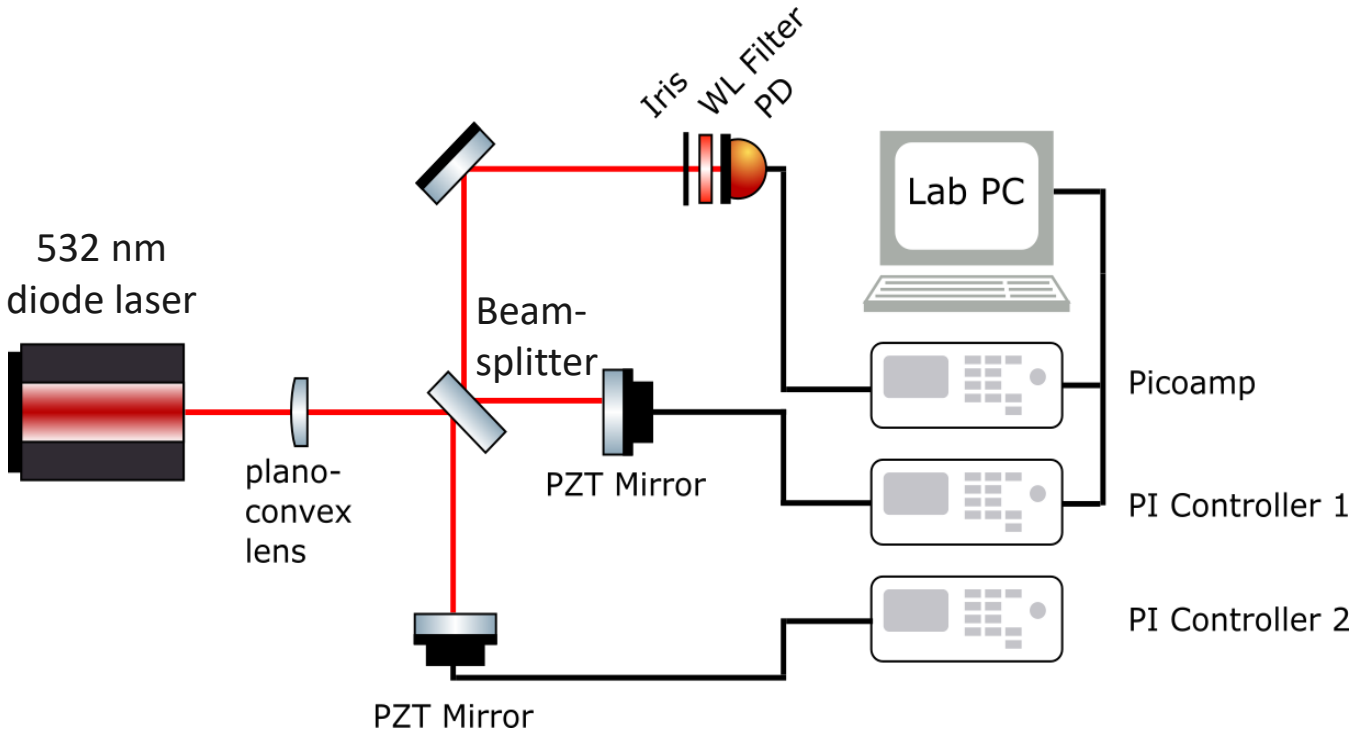


https://www.ligo.org/science/Publication-GW150914CBC/images/template.png

Idea: Small scale demonstration experiment

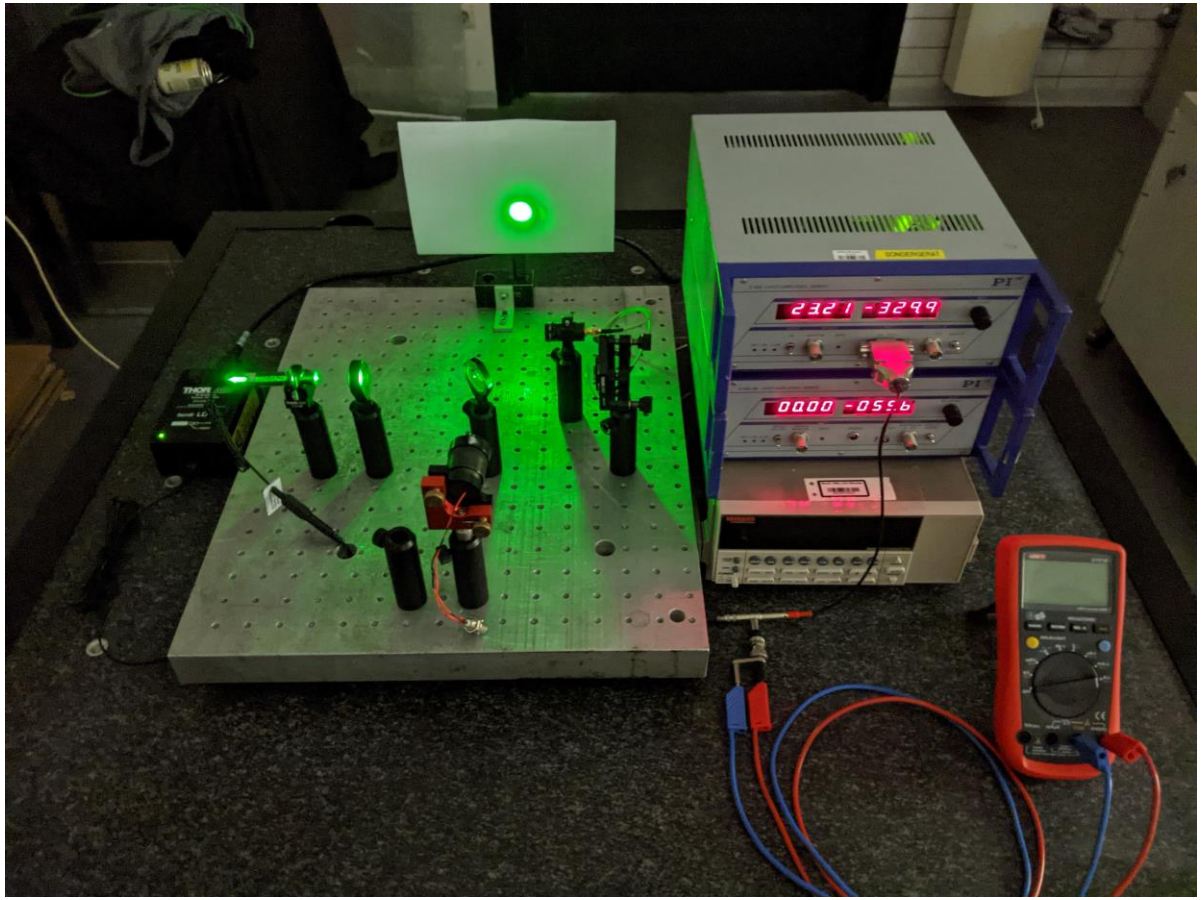


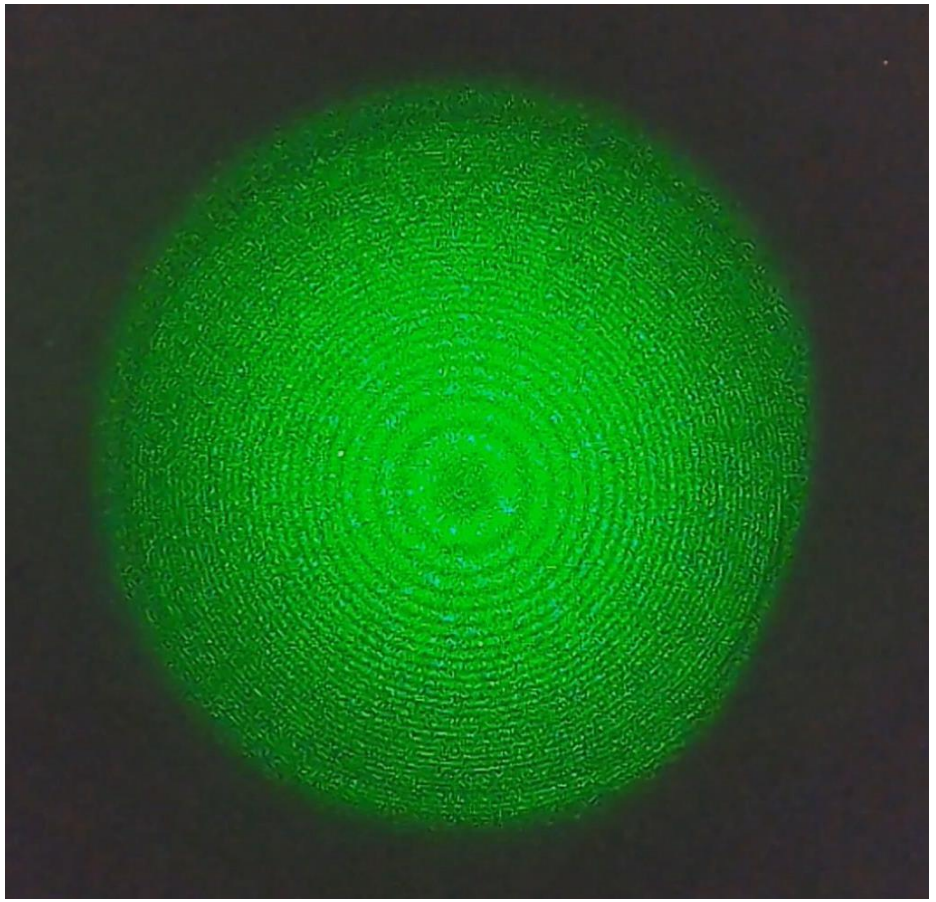




- Piezos (PZT) are used to adjust the mirrors
- Idea: Simulate gravitational waves by moving the mirrors

Projecting the fringe pattern on a screen

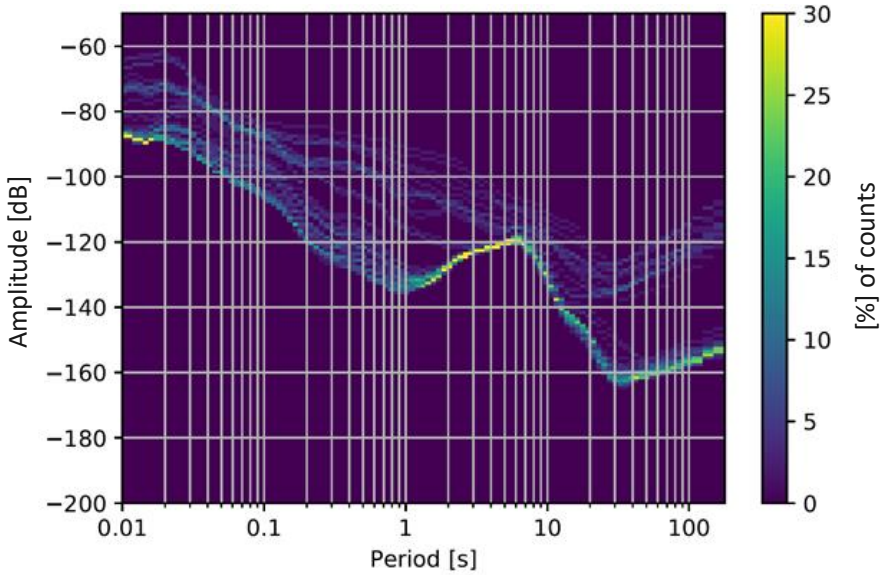


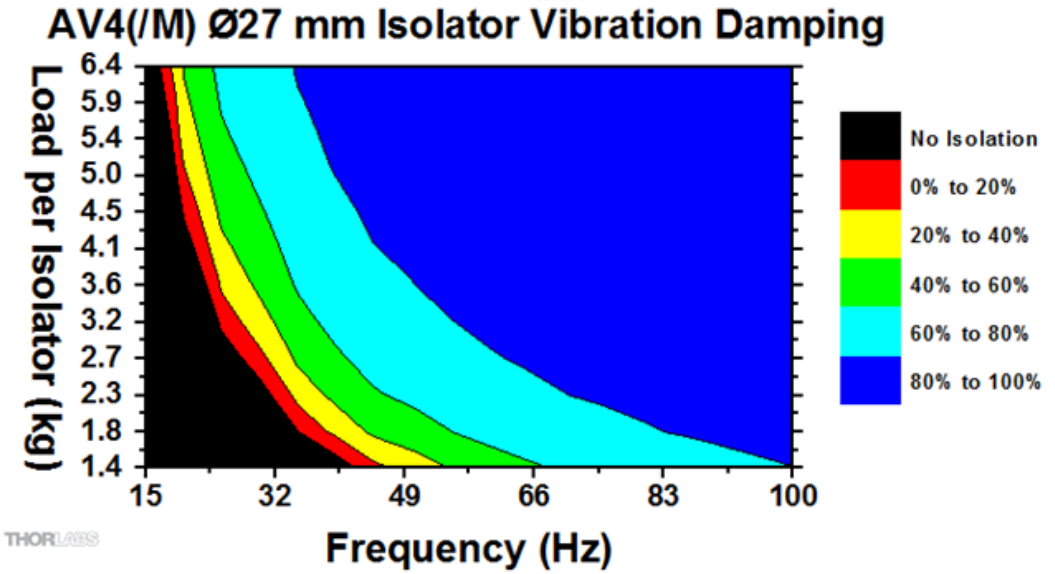


Seismic isolation measures

- Setup must be isolated against the lab's seismic background
- High amplitude found at high frequencies
- Installation of rubber feet
- Use of a ≈ 100 kg granite table

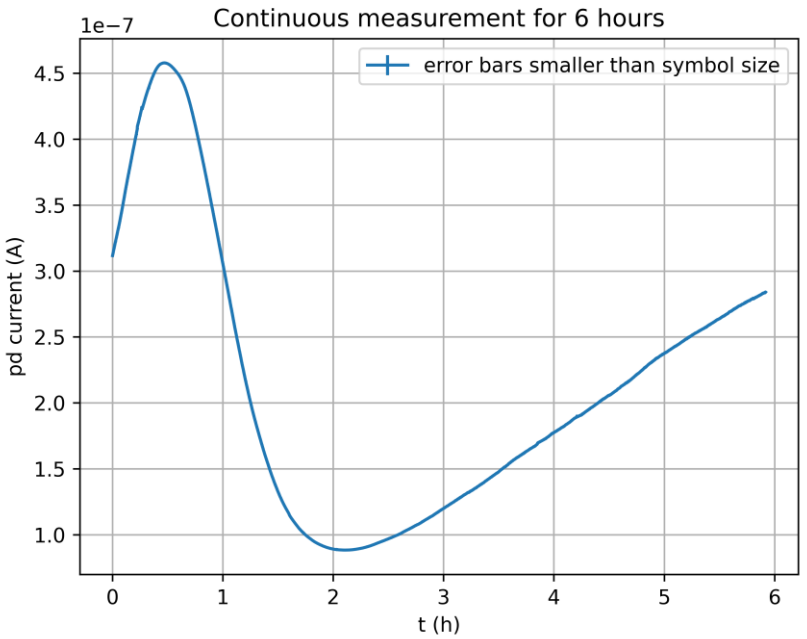
PPSD taken in the lab:

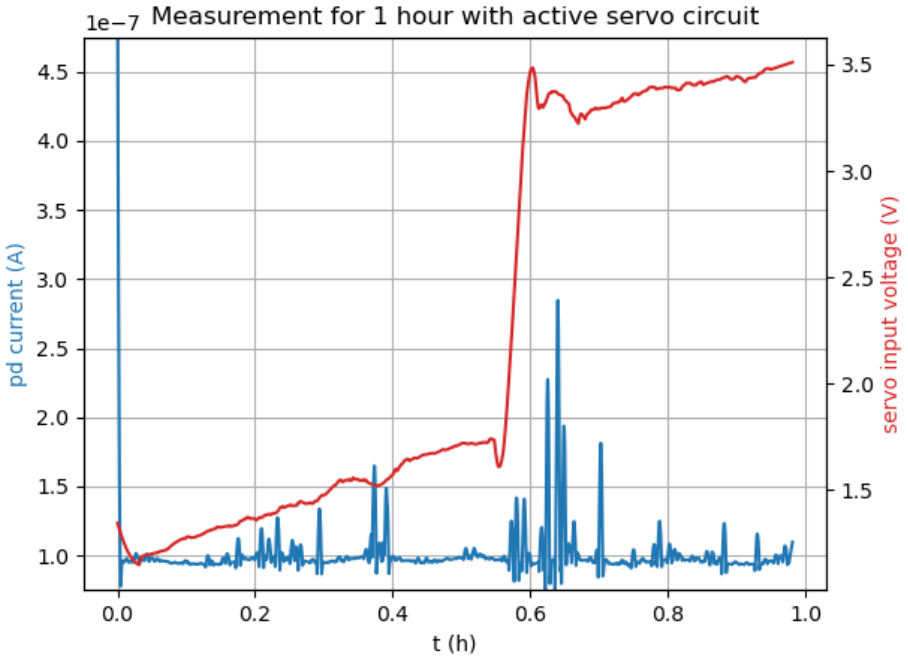


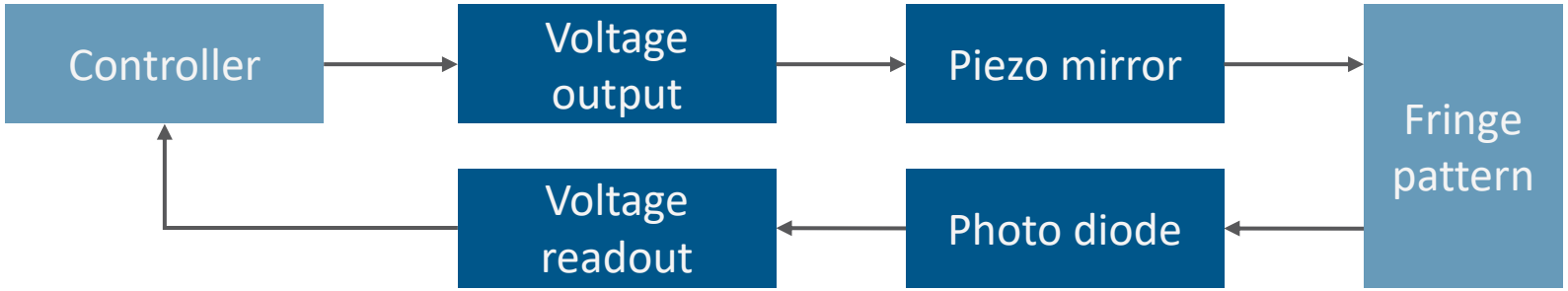


The drift problem

- Drift caused by thermal expansion of components
- Important to adjust interferometer to dark fringe before usage
  → **Servo circuit**
- Automatically adjusts to darkest output by gradient descent method







The drift problem

- Drift caused by thermal expansion of components
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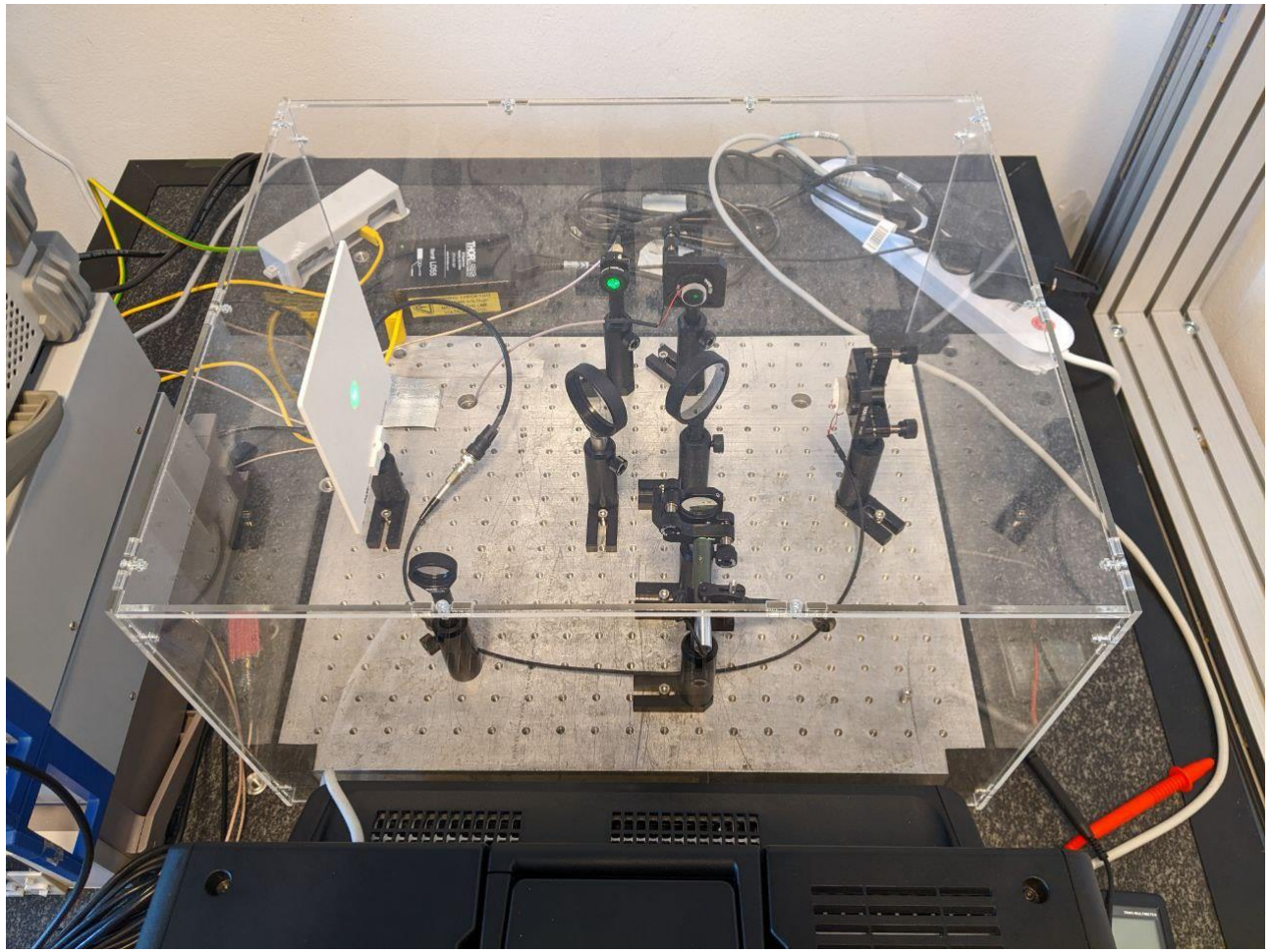
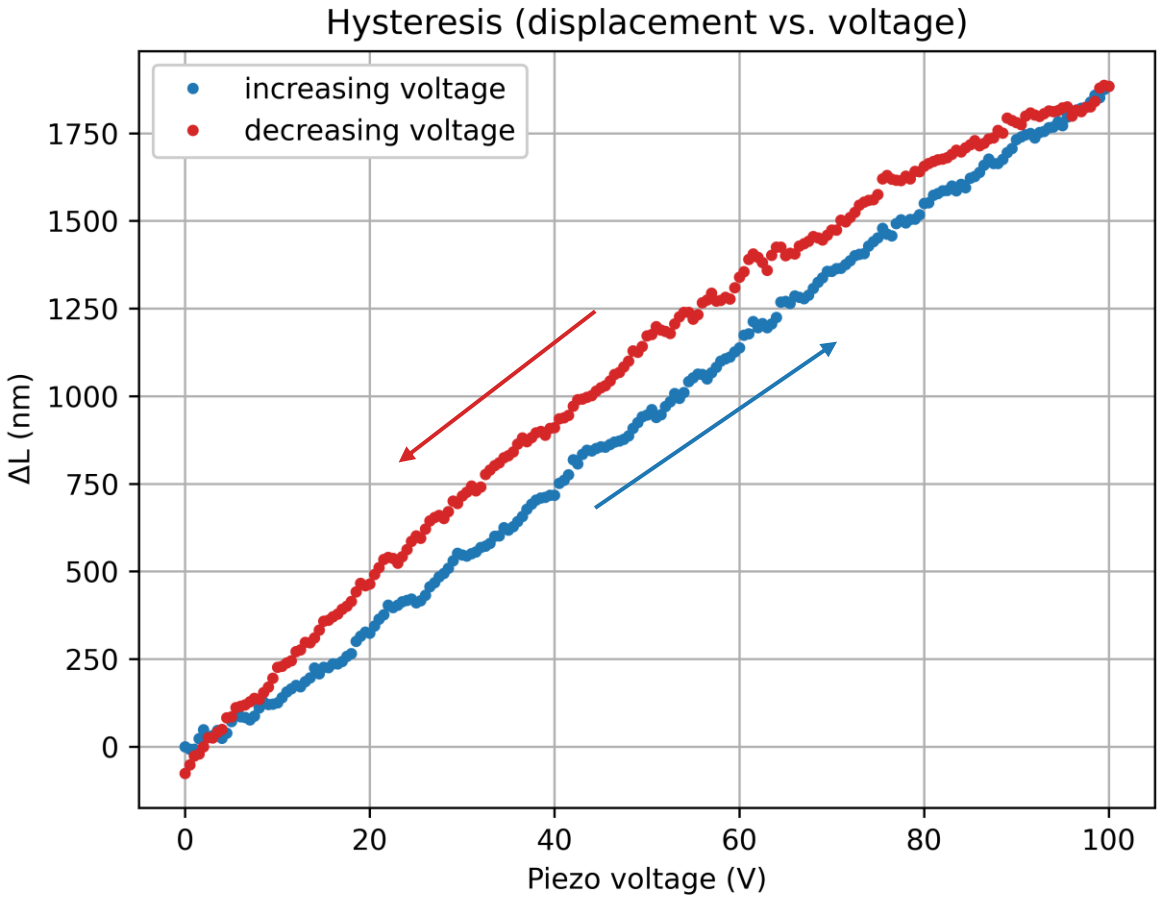
- Automatically adjusts to darkest output by gradient descent method
- Also effective: Plastic cover to reduce air turbulence



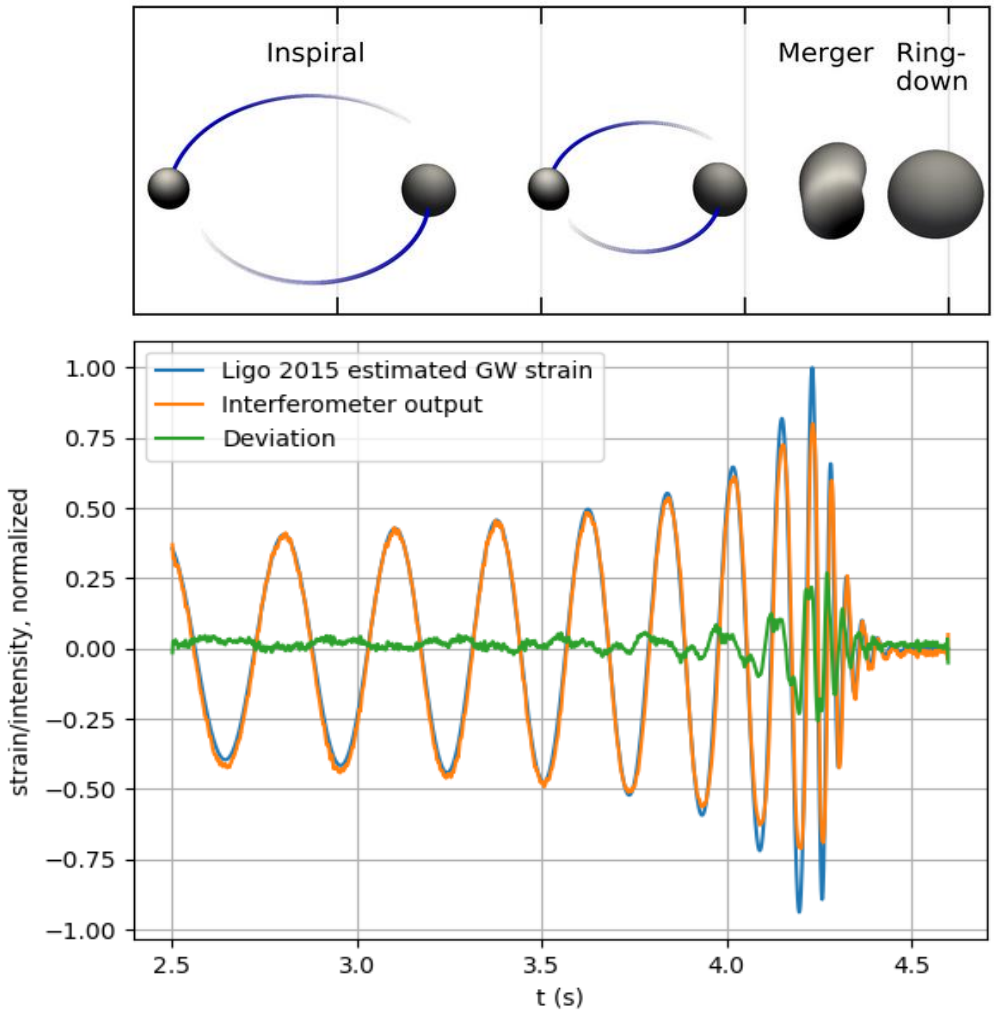
Compensation of piezo hysteresis

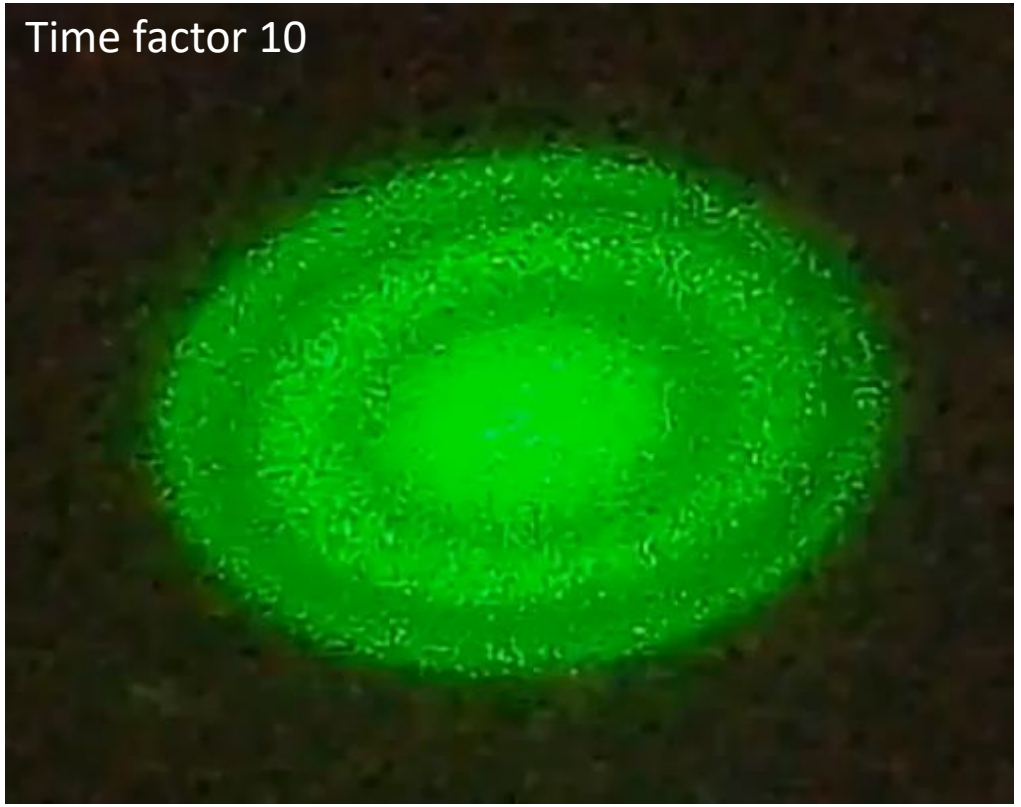
- Relation between the piezo's displacement and the applied voltage is not linear
- Exhibits hysteretic behavior
- If one assumes a linear relation, the signal gets distorted
  → A hysteresis model is needed
- **Preisach model** was used to model hysteresis and linearize piezo behavior



Displaying the 2015 LIGO event on the interferometer

https://www.ligo.org/science/Publication-GW150914CBC/images/template.png





- Hysteresis effects insignificant
- Deviation (lag) due to piezo response time

Conclusion

- Demonstration/Outreach experiment was successfully built and put into operation
- High quality result achieved through seismic/thermal stabilization and hysteresis correction