Study of Dielectric Mirror Coatings in Advanced LIGO and Virgo Gravitational Wave Detectors

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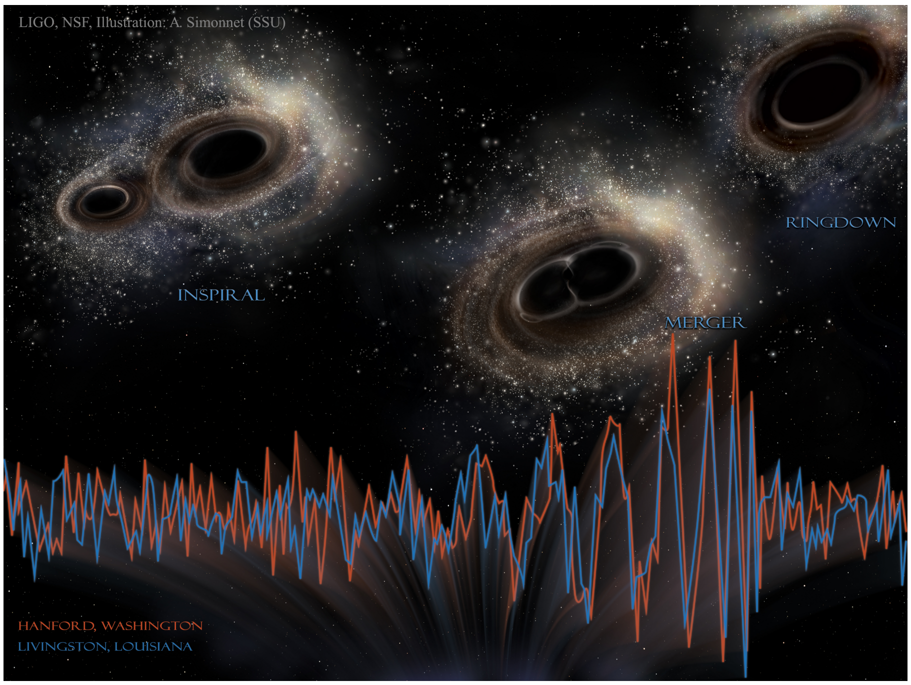

Waves Group

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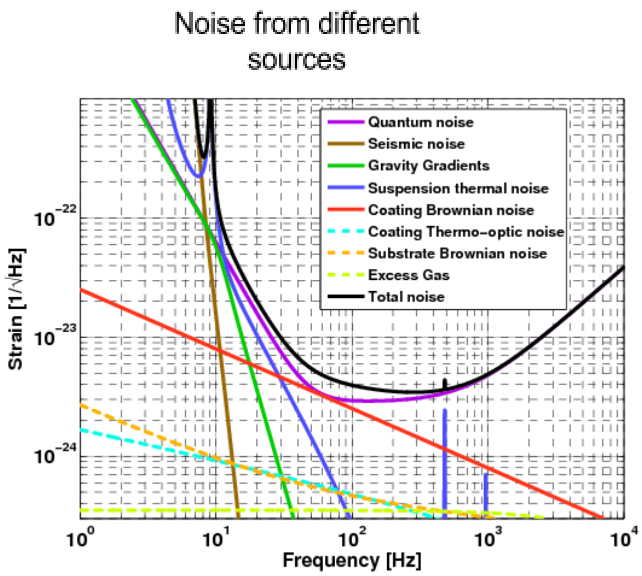
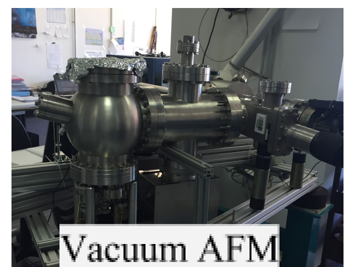
EXTERNSHIP at UNIVERSITÀ DEGLI STUDI DEL SANNIO – January 2018

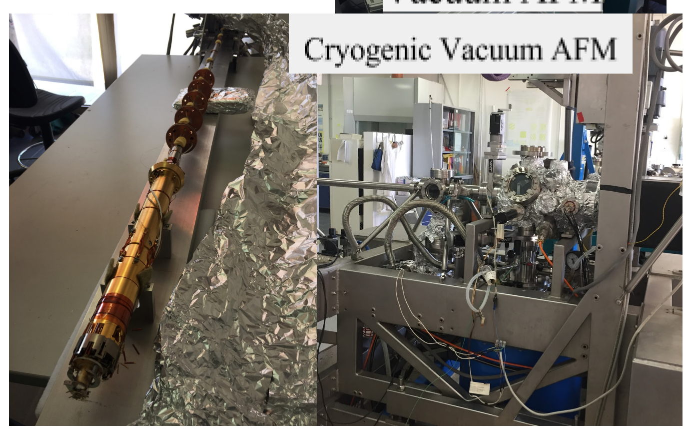


Summary:

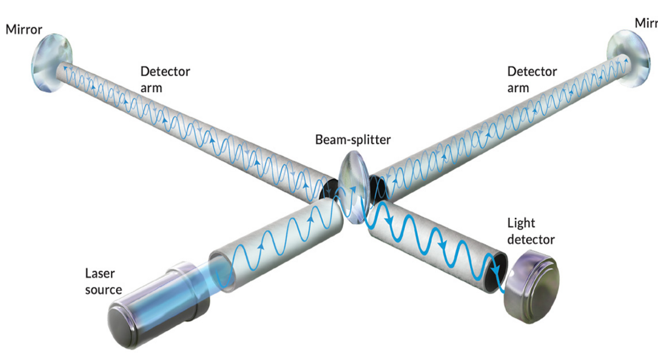
The detection of gravitational waves depends on the sensitivity of the advanced LIGO and Virgo interferometers. Many factors[1] contribute to detector sensitivity, including the arm length, temperature, mirror reflectivity, laser stability, and isolation from vibrations. Because the interferometers detect extremely small changes in spacetime, imperfection of these factors may produce 'noise,' or fake transient signals that obscure the signal produced by a gravitational wave.



With Professor Innocenzo Pinto at University of Sannio, I focused on learning about several factors which affect detector sensitivity, with an emphasis on minimization of Brownian thermal and thermo-optic noise. These types of noise are caused by molecular motion and small fluctuations of temperature within the mirror coatings, respectively. Though these are nanoscopic considerations, their effects multiply over the large distance that light must travel within the interferometer and when considering the minuscule nature of a gravitational wave signal.



In order to see how the coatings are tested and analyzed, I went to the University of Salerno and visited the facility where the atomic force microscopy (AFM), scanning-tunneling microscopy (STM), and x-ray diffraction (XRD) instruments are located. I learned how the machines work and can be used to analyze the coating morphology, crystallization, Young's moduli, and other properties. These instruments are extremely sensitive and capable of measuring properties on a nano scale, in vacuum conditions, and at cryogenic temperatures under 10K.



[1] Martynov, D. V., et al. "Sensitivity of the Advanced LIGO detectors at the beginning of gravitational wave astronomy." *Physical Review D* 93.11 (2016): 112004.

Next, I was lucky enough to visit the advanced Virgo detector itself, located in Cascina. Here, I attended the January 2018 Virgo Week, a periodic meeting between members of EGO, the European Gravitational Observatory. I was given a personal tour of the facility and was allowed to ask questions in order to understand in detail how the detector functions and about the many considerations necessary for the machine to run. I also listened to presentations on research updates regarding various aspects of the detector, as well as administrative planning issues about funding, outreach, and LIGO collaboration.

Lastly, I had the opportunity to visit the coating facility in Benevento, a unique lab which contains important instruments for the precise deposition of thin film optical coatings.

Unisannio Coating Machine

During my short time, I was also able to learn some coding in Mathematica and participate in the generation of results and graphs which will appear in a technical paper.

In all, the externship was an interesting and very valuable experience. I received a broad introduction to gravitational waves, detection technology, and current challenges in the field, and I feel prepared to enter a serious study of these topics.

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Extra details:

On the theoretical side, I read and learned in some depth about thermal noise in the advanced LIGO and Virgo mirror coatings. Thermal noise is the thermal movement of the suspended mirrors within the interferometer, and comes from mechanical losses[2] within the mirror coatings. In current interferometers, these mirror coatings are optimized for maximum reflectivity, which requires many layers of alternating high and low-index materials (silica and titanium doped tantala, presently). Though decreasing the

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[2] Principe, Maria, et al. "Material loss angles from direct measurements of broadband thermal noise." *Physical Review D* 91.2 (2015): 022005.

number of layers would decrease thermal noise, it would also decrease mirror reflectivity. Thus the current challenge is to minimize thermal noise without sacrificing mirror reflectivity[3].

Several ideas to solve this challenge have been proposed. Some options include changing the relative amount of silica and titanium-doped tantala in the coatings, changing the amount and thickness of the layers, reducing the temperature, and engineering a new coating material. One current project by Professor Pinto and his group seeks to decrease thermal noise by engineering a coating that can be heated to a higher temperature without crystallizing (the coatings must remain amorphous to have the correct optical properties). It is known that heating the coatings, a process called annealing, reduces thermal noise. Because the high index material in the coatings crystallizes at high temperatures, Professor Pinto's group is working to replace the high index layers with nano-layered composites[4], which they have modeled to withstand much higher temperatures before crystallization[5,6], and still exhibit favorable optical properties[7].

[3] Agresti, Juri, et al. "Optimized multilayer dielectric mirror coatings for gravitational wave interferometers." *Advances in Thin-Film Coatings for Optical Applications III*. Vol. 6286. International Society for Optics and Photonics, 2006.
[4] Cesarini, E., et al. "Measurement of Acoustic Loss in Nano-Layered Coating Developed for Thermal Noise Reduction." *Measurement* 1231 (2016): 45331.
[5] Principe, Maria. "Reflective coating optimization for interferometric detectors of gravitational waves." *Optics express* 23.9 (2015): 10938-10956.
[6] Pan, Huang-Wei, et al. "Thickness-dependent crystallization on thermal anneal for titania/silica nm-layer composites deposited by ion beam sputter method." *Optics Express* 22.24 (2014): 29847-29854.
[7] Magnozzi, M., et al. "Optical properties of amorphous SiO 2-TiO 2 multi-nanolayered coatings for 1064-nm mirror technology." *Optical Materials* 75 (2018): 94-101.