A NEW DARK MATTER SEARCH WITH THE SAPPHIRE MIRRORS OF THE KAGRA GRAVITATIONAL-WAVE DETECTOR

What is **dark matter**? Scientists have been asking themselves this question for nearly a century, but it remains a big mystery in the universe. Astrophysical observations have revealed that something invisible but heavy – dark matter – plays a critical role in forming galaxies and stars by pulling ordinary visible matter together with gravity. We now know that dark matter accounts for 85% of all the matter in our universe, but we still don't know what are its constituents. For example, dark matter could consist of primordial black holes, each weighing up to hundreds of solar masses, or it could be a new particle with a mass similar to our known heaviest elementary particles, or it could be an ultralight boson particle lighter than electrons by tens of orders of magnitude. So far, all the past experiments and observations have failed to make a convincing detection of any such dark matter candidates.

LIGO, **Virgo** and **KAGRA** are gravitational-wave detectors which measure tiny length changes caused by gravitational waves passing through their laser interferometers. Although they are designed primarily for gravitational-wave detection, they are also sensitive to certain types of dark matter which also cause length changes. One specific dark matter candidate is called **vector boson** dark matter. Just like charged masses in an electromagnetic field feel electromagnetic forces, masses in a vector field that have a different kind of "charge" beyond the standard model of particle physics feel non-standard forces. Ultralight vector dark matter creates oscillatory forces on any objects carrying such charges. These can be mirrors in a laser interferometer. The "charge" can be the baryon number, which simply counts the number of protons and neutrons in a mirror, or the **baryon minus lepton** number, or *B-L*, which equals the number of neutrons. Laser interferometers measure the oscillatory length changes between mirrors, caused by the forces from vector dark matter. In 2021, the LIGO–Virgo–KAGRA collaboration used the data from the third observing run (O3) of Advanced LIGO and Advanced Virgo and **placed the best upper limits** on the strength of such forces from vector dark matter.

In LIGO and Virgo, all the mirrors are made from fused silica glass, and all the mirrors move almost perfectly in common in the vector dark matter field because the charge-to-mass ratio is the same between all the mirrors. Laser interferometers are sensitive to the distance changes between mirrors, but not very sensitive when the mirrors move in common and the distance stays unchanged. In LIGO and Virgo's case, the sensitivity to vector dark matter is about five orders of magnitude less than when the mirrors move differentially. The KAGRA detector in Japan is unique in using sapphire for four main test mass mirrors and fused silica for other auxiliary mirrors. For dark matter coupled to the *B-L* number, sapphire mirrors move slightly more than fused silica mirrors because they are slightly more neutron-rich. Therefore, by measuring the distance between sapphire and fused silica mirrors, KAGRA can be more sensitive to vector dark matter than LIGO and Virgo, especially for lighter dark matter particles.

In this study, we used the data from KAGRA's first joint observing run together with the GEO600 detector in Germany (O3GK run). We have developed a new pipeline to search for oscillatory length changes. Since the mass of ultralight vector dark matter determines the frequency of the oscillatory length changes, we can search for dark matter particles at different masses by searching for length changes at different frequencies. Because of the statistics of ultralight dark matter particles, the strength of such length changes fluctuates at a timescale called *coherent time*. Therefore, we carefully accounted for the

FIGURES FROM THE PUBLICATION

For more information on these figures and how they were produced, read the freely available **preprint**.

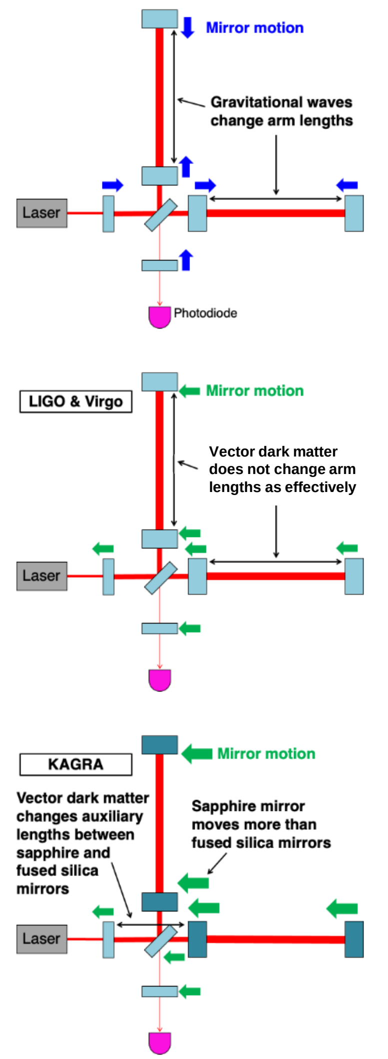

Figure 1: Infographics of the laser interferometer response to gravitational waves (top), to vector dark matter in LIGO and Virgo case (middle), and to vector dark matter in KAGRA's auxiliary lengths, which records the distance between sapphire and fused silica mirrors (bottom).

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stochastic nature of the signals from ultralight dark matter in our search. During O3GK, KAGRA took the data from auxiliary length channels which record the distance changes between sapphire test masses and fused silica auxiliary mirrors. By analyzing more than 100 hours of data, we found no evidence of dark matter signals and therefore set upper limits on how strong the forces from the *B-L* vector dark matter could be.

Since KAGRA had not yet reached its planned sensitivity at the time of the O3GK run, our limits are orders of magnitude less stringent than those from previous experiments. Still, our study has demonstrated the feasibility of using auxiliary length channels of gravitational-wave detectors like KAGRA for astrophysical observations. When the O3GK run was conducted in 2020, auxiliary length channels were not even considered useful for observational science. The main gravitational-wave channel records the distance changes between sapphire mirrors, and the auxiliary length channels are usually used only to keep this main channel sensitive to gravitational waves. With dedicated noise reductions in auxiliary length channels in future runs, KAGRA can give us insight into the question: what is dark matter?

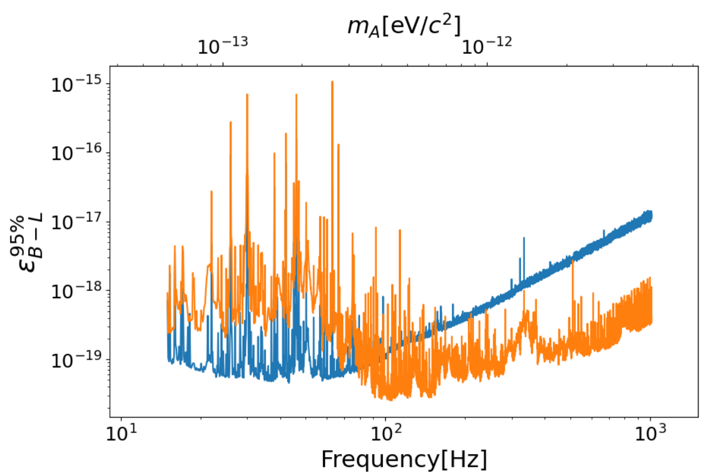

***Figure 3**: Upper limits on the strength of forces from B-L vector dark matter from KAGRA data. The two curves are from different auxiliary length channels. The strength is expressed in terms of a fraction of the electromagnetic force. For more information on this figure and how it was produced, read the freely available preprint.*

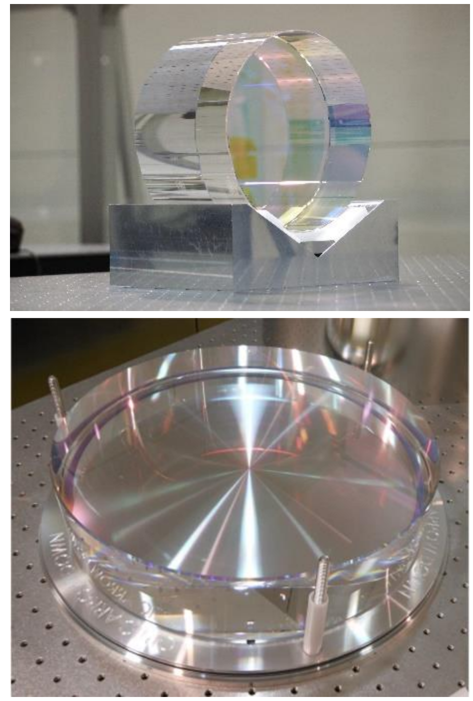

***Figure 2**: A sapphire mirror (top) and a fused silica mirror (bottom) were used for the KAGRA interferometer. Although they both look transparent and similar to our eyes, the sapphire mirror is slightly more neutron-rich, moving more than fused silica mirrors when interacting with B-L vector dark matter.*

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GLOSSARY

Baryon minus lepton number (*B-L*): Baryons and leptons are classes of particles. Baryon minus lepton number, or *B-L*, equals the number of baryons minus the number of leptons. Protons and neutrons are baryons, and electrons are leptons. Since the number of protons and electrons are the same for neutral atoms, *B-L* equals the number of neutrons. Just like electric charge is conserved, *B-L* is also conserved in the standard model of particle physics. So, baryon minus lepton number can be a new type of charge for a new force we don't know yet.

Dark matter: Invisible matter that accounts for 85% of the matter in the universe. We only know that it interacts gravitationally with the ordinary matter we know.

Fused silica: A common material for glass. An extremely pure fused silica, or silicon dioxide, is the material used for test mass mirrors in LIGO and Virgo, and for auxiliary mirrors in KAGRA.

GEO600: A gravitational-wave detector situated in Hannover, Germany. It is a laser interferometer with 600-m long arms. The laser beam travels through each arm twice, providing an optical arm length of 1.2 km.

KAGRA: An underground gravitational-wave detector situated at Kamioka in Gifu prefecture, Japan. It is a laser interferometer with 3 km long arms and cryogenically cooled sapphire test mass mirrors.

LIGO: The Laser Interferometric Gravitational-Wave Observatory (LIGO) is a US-based pair of gravitational-wave detectors. One is situated near Livingston, Louisiana, and the other near Hanford, Washington. Both detectors are laser interferometers with two perpendicular 4-km long arms.

Sapphire: KAGRA uses artificial sapphire for its test mass mirrors. Natural sapphires are blue due to impurities, but the artificial ones are pure aluminium oxide and are colorless. Sapphire mirrors have excellent optical and thermal properties at cryogenic temperatures.

Upper limit: A statement about the maximum value some quantity can have while still being consistent with the non-detection. Here, we use the concept to place constraints on the strength of the forces from baryon minus lepton vector dark matter at different masses or frequencies. We use a 95% degree-of-belief limit, i.e., given the data there is a 95% probability that the quantity is below this limit.

Vector boson: A class of particles that has a spin of 1. For example, a photon is a vector boson, and it carries electromagnetic force. Here we consider a vector boson and its force which are not included in the standard model of particle physics.

Virgo: A gravitational-wave detector situated near Pisa, Italy. It is a laser interferometer with 3-km long arms.