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RESEARCH ARTICLE

Investigation of the Effectiveness of Trees as Natural VHF RF Antennas for Cosmic Ray and Neutrino Detection

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ABSTRACT: This study aimed to investigate and evaluate the effectiveness of trees as radio frequency (RF) antennas in the VHF range. The hypothesis is that a tree's structure and physical properties allow it to be an analog of RF antennas in the VHF range for neutrino and atmospheric shower detection. This paper provides and discusses the results of field tests conducted to evaluate the performance of the trees. Observations and analyses of various physical factors on which signal reception depends have also been conducted. The paper has proposed two techniques, one for measuring signal strength and the other for measuring VSWR. Two types of connection of measuring devices to the tree, nail, and induction coil were compared. The research was conducted in two stages: the first was experimental, and the second was to analyze the collected data and identify the correlations of different factors. The work results showed that the measured trees have indices very close to the dipole antenna, indicating trees' possible application in detecting neutrino particles. The readings and measurements we have collected are proper in astronomy and may also be helpful in other fields of science. Trees can also reduce the financial cost of producing commercially available neutrino detection antennas. So far, very few papers have been written on using trees to detect atmospheric showers and neutrino particles, indicating the need for further research.

KEYWORDS: Astronomy and Cosmology, Astroparticle Physics, Cosmic Rays, Neutrino Physics, Radio-detection of Neutrino, Ultra-High Energy Neutrinos.

Introduction

With the development of multi-messenger astronomy, scientists make observations using four fundamental forces: gravitational, electromagnetic, weak, and strong nuclear interaction forces; neutrino astronomy is an example of observations of the weak nuclear interaction force.[1] Neutrinos are nearly massless, chargeless particles that interact only via the weak nuclear force, allowing them to traverse cosmic distances without being absorbed or deflected, as shown in Figure 1. This unique property enables scientists to study extreme astrophysical phenomena, such as supernovae, gamma-ray bursts, and active galactic nuclei, which might otherwise remain hidden due to the limitations of electromagnetic observations.

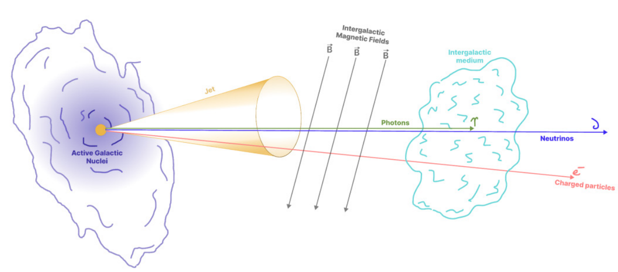

Figure 1: Cosmic ray flight from an astronomical object. Charged particles like electrons are deflected by intergalactic and planetary magnetic fields, photons are consumed by the intergalactic medium, making neutrinos a valuable astrophysical messenger.

Current neutrino detection techniques include the use of water and ice Cherenkov detectors, such as IceCube, Baikal GVD, and the Hyper-Kamiokande under construction, to detect the interaction of neutrinos with the medium (mainly ice).[2-4] Radiofrequency antennas such as ANITA, CODALEMA, TREND 50, and Tunka-Rex are also used to detect coherent radiation emitted from neutrino-atmosphere interactions.[5-8] Future projects such as GRAND and Hyper-Kamiokande are predicted to be the most significant area and volume detectors.[9] Thus, neutrino observations are becoming the most ambitious research and engineering projects.

The Ice-Cube Neutrino Observatory, located at the South Pole, utilizes more than 5,000 optical sensors embedded in a cubic kilometer of Antarctic ice to detect Cherenkov light produced through neutrino interaction with ice. Ice-Cube is known for being the first to identify a high-energy astrophysical flux, marking a major milestone in neutrino astronomy. In Russia, the Baikal-Gigaton Volume Detector (Baikal-GVD) operates in the depths of Lake Baikal and serves as one of the largest neutrino telescopes in the Northern Hemisphere. Similarly to the Ice-Cube, Baikal GVD uses strings of photomultiplier tubes to detect Cherenkov light, however, Baikal GVD aims to complement Ice-Cube by observing the opposite sky semisphere. Super-Kamiokande is a water Cherenkov detector in Japan located 1,000 meters underground, consisting of a 50,000-ton tank of ultra-pure water lined with over 11,000 photomultiplier tubes. Super-Kamiokande is highly sensitive to the lower-energy neutrinos. It has made precise measurements of solar neutrinos, helping to resolve the solar neutrino problem and confirming predictions of the Standard Solar

Model. Collectively, these detectors play a crucial role in the current development of multi-messenger astronomy and our understanding of neutrino oscillations and interactions. However, building such detectors involves using expensive hardware that occupies a large area, resulting in time-consuming and labor-intensive work and limitations due to financial concerns.

In this paper, we present and discuss the results of an experimental approach to evaluate the feasibility of using trees as radio frequency (RF) antennas in the very high-frequency range (VHF) as a replacement for commercially available RF antennas. This work was inspired by Stephen Prohira, who suggested in his paper that trees could be a good and effective analog of antenna arrays for neutrino detection since less hardware is required and more area can be covered.[10] One of the issues raised in Stephen Prohira's paper was the lack of data on tree performance in the VHF band (30-130 MHz). Our main goal was to measure the performance of trees in the VHF band and evaluate their performance, as well as to learn about possible factors that may affect the strength of signal reception.

Neutrino Radio Detection:

The principle of operation of neutrino radio detectors is to detect radio emission of cascades of charged particles arising due to two phenomena under study - the Askaryan effect and the geomagnetic effect.[11] The Askaryan effect occurs when a high-energy neutrino interacts with a dense medium, such as ice or lunar regolith, producing a cascade of charged particles that generates coherent radio emission due to the net negative charge excess in the cascade. The geomagnetic effect results from a deflection of charged particles by Earth's magnetic field, causing them to emit waves through the synchrotron-like radiation. The astrophysical neutrino, in the case of its interaction with the atmosphere, results in the appearance of an atmospheric rain of charged particles, which in turn emit radiation similar to that of the Cherenkov, only in the radio frequency range of 10-100 MHz. Often, as a radio neutrino detector, arrays of antennas are used to cover the largest possible area and then, using the method of signal angle of arrival (AoA), reconstruct the trajectory of the neutrino and relate it to a space object.

The Tree as an Antenna:

The first mention of the idea of using trees as antennas was proposed in a paper by Major General Squire in the 1900s; in this paper, several field tests were carried out, which showed that a nail hammered at a certain height into a tree could significantly increase the strength of the received signal.[12] Further subsequent works also carried out tests using various instruments at very low frequencies (hereafter VLF), ranging from 100 Hz to 100 kHz and at higher frequencies from 500 MHz to 1.5 GHz.[13-17] The results indicated that trees, when coupled with HEMAC toroidal induction coils, outperformed conventional ground-based dipole antennas by 10–18 dBV across both low and high-frequency ranges. Additionally, shrubs operating in the 500 MHz to 1.5 GHz range demonstrated strong efficiency as both radio wave transmitters and receivers.

Due to their physical and electrical properties, trees can work as antennas and interact with electromagnetic waves. Trees are electrically conductive due to the water content inside the trunk. The electrolytes that are dissolved in water make it a fairly efficient conductor. It is assumed that wood and the water it contains work as dielectrics, interacting with electromagnetic waves, causing polarization and changes in the path of wave propagation. Also, wood has resonant frequencies at which it interacts most effectively with electromagnetic waves; these depend on the height, structure, and moisture content of the wood. Given these properties, when an electromagnetic wave passes through a tree, the current generated by the wave can be converted into a signal.[16,17]

Methods

To assess the feasibility of using trees as natural antennas for receiving and analyzing VHF signals related to neutrino and cosmic ray detection, we adopted a quantitative approach in our studies. The methods described in previous works were used to create experimental setups. In total, two types of setups were created.[13-16]

The experimental setup illustrated in Figure 2 was assembled to measure the voltage response of the tree coupled with either a brass nail or a toroidal induction coil in comparison to the dipole antenna. A tree coupled with a brass nail or toroidal conduction coil was connected to the 200MHz bandwidth KEYSIGHT MSOX2024A oscilloscope via direct connection through the oscilloscope kit's probe. KEYSIGHT MSOX2024A has a 200 MHz bandwidth, which, in combination with a 200,000 waveforms/second update rate, was highly suitable for RF measurements in the VHF range. For grounding, a steel rod with a diameter of 16 mm was used, which was buried at a depth of 50 cm and connected to the oscilloscope through a crocodile clip. The radio waves emitted by Astana's local FM stations were received by a tree-antenna and dipole at the same location. The choice to measure RF signals from local radio stations is justified by the fact that their operational frequencies correlate with the peak of Askaryan coherent RF emission produced by cascades of charged particles. Therefore, the efficiency of trees in receiving RF signals from radio stations can be extrapolated to estimate their efficiency as neutrino detectors. The recorded signals were then analyzed to evaluate the performance of trees as antennas relative to conventional dipoles. Differences between the brass nail and the induction coil were compared in the "Results" section.

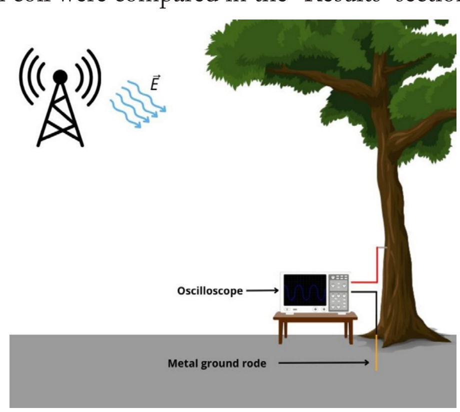

Figure 2: Experimental setup for signal amplitude measurement. FM signals transmitted by local FM stations are received by trees, and the signal strength is measured using an oscilloscope connected to a tree using either a brass nail or a toroidal induction coil.

The second setup was a similar system designed to measure the voltage standing wave coefficient (VSWR). An Amphenol coaxial cable was used for the measurements, and a Nano VNA was connected to a brass nail and ground. The Amphenol coaxial cable was calibrated using the calibration probes from the Nano VNA kit to minimize cable losses.

Before each test, measurements were taken with the meters (oscilloscope and Nano VNA) connected and disconnected from the tree to ensure that no excess signal was being received on the stylus or nail, which would distort the final results. Tests with nails and coils were conducted at different heights of the tree trunk relative to the ground to reveal a potential relationship between signal strength and nail/coil location. All measurements were carried out on different trees that differed from each other in terms of species, height, and trunk diameter (see below). To make sure that different temperatures, climates, and soil conditions do not affect our results, the tests were conducted at a specific location and under the same climatic conditions (temperature 27-32 degrees Celsius, humidity 57-59%).

The antenna designed as a reference was calculated using the dipole formula

$$L = \frac{468}{f} \times 0.3024 \quad (1)$$

Where ν is the frequency of the received signal, which in our case was 100 MHz

The number of turns for an induction coil was derived from the vector circulation theorem and Faraday's law.

$$N = \frac{R}{\mu_0 a\nu \cdot \ln\left(1 + \frac{b}{r_0}\right)} \quad (2)$$

Results

Measurement of FM signals:

Figure 3 presents a graph showing the voltage level (dBV) as a function of frequency (MHz). This graph illustrates the differences in signal amplitude recorded from a tree when an oscilloscope is connected to either a brass nail or an induction coil. The results indicate that the induction coil method provides a more effective means of capturing FM signals than the nail method. The voltage amplitude detected using the coil was approximately 2-3 dBV higher than that measured using the nail. This difference remained consistent across all tested trees, suggesting that the induction coil offers a more efficient coupling mechanism for detecting FM signals from trees.

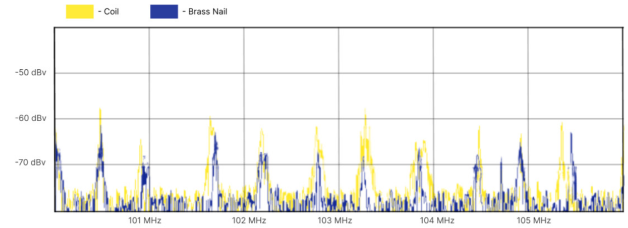

Figure 3: The graph shows a comparison of the voltage response between connection to wood using an induction coil and connection using a nail. The yellow graph represents voltage response values using a toroidal induction coil wrapped around the tree, while the blue graph represents the voltage response value using a brass nail. This graph demonstrates a significant difference between the nail and coil connection methods, indicating that the induction coil exhibits superior performance.

For comparative analysis, measurements were taken to evaluate the received signal strength from the nail and the induction coil relative to a self-designed dipole antenna, as shown in Figure 4. The dipole antenna was calibrated using a NanoVNA vector network analyzer to optimize reception in the FM radio broadcast band. According to the results, both the nail and the coil methods demonstrated acceptable performance when compared to the dipole antenna. However, Figures 4 and 5 indicate that while the induction coil approaches the signal reception capabilities of the dipole antenna, the nail connection is significantly less effective.

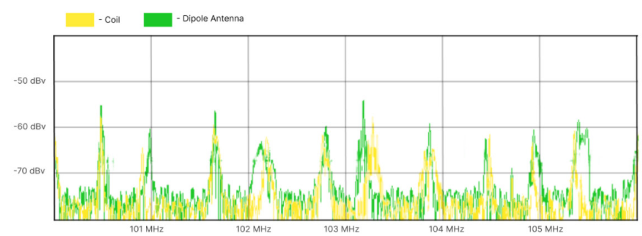

Figure 4: The graph shows a comparison of voltage response between connection to a tree using an induction coil and an antenna. The yellow graph represents voltage response values using a toroidal induction coil wrapped around the tree, while the green graph represents the voltage response value using a dipole antenna. This graph shows that the induction coil performs slightly worse than the antenna. However, the voltage response remains at a sufficient level, indicating that the induction coil can still be a viable alternative.

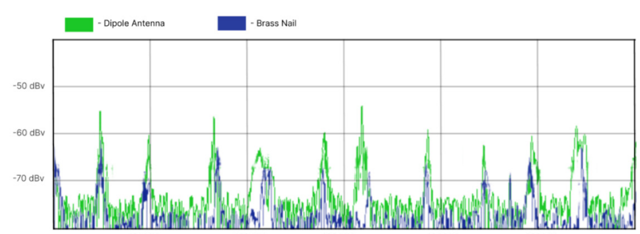

Figure 5: The graph shows a comparison of voltage response between connection to wood using a brass nail and antennas. The blue graph represents voltage response values using a brass nail as a conductor, while the green graph represents the voltage response values using a dipole antenna. This graph shows that the nail performs significantly worse than the antenna, as its voltage response is lower. This indicates that the nail cannot compete with the antenna.

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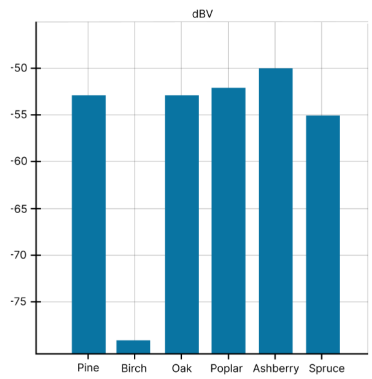

Figure 6: The bar chart represents the comparative average voltage response values among the various tree species. This chart indicates that tree species do not play a significant role, as all exhibit similar average performance. However, an anomaly is observed in birch trees, likely due to the age and humidity of most tested specimens.

In addition to measuring signal amplitude, the influence of tree species on signal reception was analyzed. Figure 6 presents a comparative bar chart of the average voltage response among different tree species. The results indicate that tree species generally do not have a significant impact on signal strength, except for birch trees, which exhibit lower amplitudes. This anomaly can be attributed to their relatively large trunk diameters. A larger trunk diameter increases the material through which the signal must propagate, leading to greater attenuation. Moreover, older trees typically have lower internal humidity, further reducing conductivity and signal transmission efficiency.

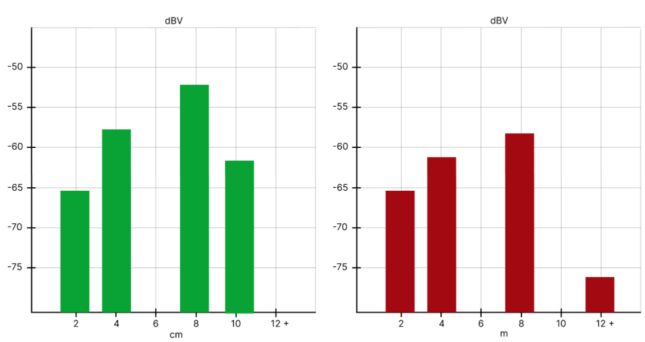

Figure 7: The green and the red bar charts are presented. Green bars represent the voltage response on trees with different radii. Red bars represent the voltage response of the trees with different heights. The graphs indicate that an optimal trunk radius is 8 cm, while the optimal trunk length is 8 meters.

Figure 7 investigates the effects of trunk radius and height on signal reception. The green bars represent voltage response as a function of trunk radius, while the red bars represent voltage response as a function of tree height. The optimal trunk radius for effective signal reception is approximately 8 cm, and the optimal tree height ranges between 3 and 9 meters. Beyond this range, either at heights below 2 meters or above 15 meters, the signal becomes significantly noisier and, in some cases, is completely lost. This suggests that tree dimensions play a critical role in determining the efficiency of signal coupling for both the nail and coil methods.

Measurement of VSWR:

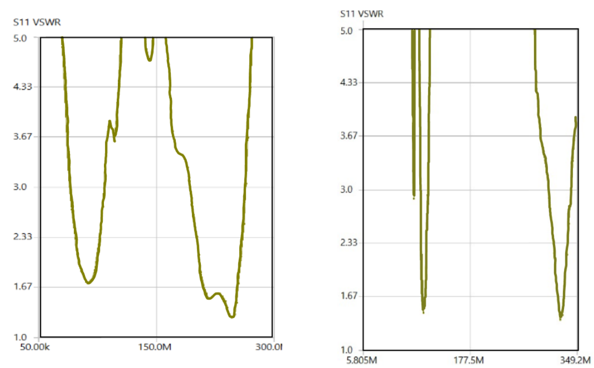

Figure 8: On the snapshot from Nano VNA, the left graph displays the tree's VSWR, and the right graph displays the antenna's VSWR. The graphs show that the tree's VSWR is higher than the antenna's, but it has a broader effective frequency range.

For a tree to function as a radio wave detector in the context of neutrino-induced radio emissions, it must exhibit a Voltage Standing Wave Ratio (VSWR) of less than 3 within the relevant frequency range. Most neutrino radio detection experiments operate within the frequency range of 1 MHz to 300 MHz.[5-8] Thus, the VSWR characteristics of the tree were analyzed over this range.

Figure 8 presents VSWR measurements for both the tree (left) and the dipole antenna (right) as recorded using the NanoVNA. The results indicate that while the tree's VSWR is higher than that of the dipole antenna, it maintains a broader effective frequency range. This suggests that, despite being slightly less efficient in terms of impedance matching, the tree may offer advantages in detecting broadband radio signals. This property could be particularly relevant in experiments aimed at detecting radio wave signatures from high-energy neutrino cascades, where broad frequency sensitivity is beneficial.

Overall, these findings support the hypothesis that trees can function as natural electromagnetic receptors, with their effectiveness being influenced by physical parameters such as trunk diameter, height, and species characteristics. Future research should focus on optimizing these natural detectors for improved performance in neutrino radio wave detection.

■ Discussion

The experimental analysis of tree-based antennas for RF signal detection highlights their potential as cost-effective, naturally occurring alternatives to conventional antennas in astroparticle physics, particularly for neutrino and ultra-high energy cosmic rays' detection. Although trees are subject to biological variability and environmental influences, the results suggest that, when properly selected and coupled, they can serve as effective electromagnetic receptors in the VHF range.

Measurements show that trees maintain acceptable performance in both signal amplitude and VSWR across a frequency range of approximately 20 MHz to 260 MHz. This range overlaps with the spectral window relevant to radio emissions produced by the Askaryan and geomagnetic effects. As seen in Figure 8, the tree's VSWR is higher than that of a dipole antenna, yet it maintains a broader frequency range. This indicates that while trees may be less efficient in terms of impedance matching, their ability to respond across a wide spectrum could be beneficial for detecting broadband impulsive radio signals generated by high-energy particle cascades. The coupling method was found to be one of the most important factors affecting performance. Trees connected using a toroidal induction coil consistently demonstrated higher voltage responses, by about 2–3 dBV, compared to those using a brass nail. This performance increase is likely due to improved impedance matching and reduced degradation at the contact point. While the dipole antenna still produced stronger absolute signals, the induction coil-tree system yielded a stable and sufficiently strong response that may be suitable for deployment in remote or resource-limited areas. In contrast, the brass nail configuration showed significantly weaker signals, likely due to inefficient coupling, oxidation, and capacitive leakage.

Tree dimensions were shown to be a critical factor. The highest signal amplitudes were recorded for trees with a trunk radius of approximately 8 cm and a height between 7 and 9 meters, as shown in Figure 7. Trees that were significantly smaller or larger performed worse, possibly due to impedance mismatches or excess signal attenuation through the biomass. While tree species had only a minor effect overall, birch trees showed lower signal strength, likely due to their thicker trunks and lower internal moisture content. Foliage density had no consistent effect on signal amplitude or VSWR, suggesting that, in the VHF band, leaves do not contribute significantly to signal attenuation or impedance changes. This simplifies the criteria for selecting trees in field deployments. Environmental conditions during testing were typical of a temperate continental climate, with temperatures ranging from 27°C to 32°C and relative humidity between 57% and 59%. Under these moderately dry conditions, the trees still performed well. However, studies such as that of Ikraf *et al*. [15] have shown improved performance in tropical climates, where higher internal moisture content leads to better dielectric properties and signal conductivity. This suggests that tropical and subtropical regions may provide more favorable conditions for the use of tree-based antennas.

Overall, these results support the idea that trees, under optimized conditions, can serve as viable components of RF detection networks. Future research should focus on standardizing coupling methods, investigating long-term seasonal effects, and developing calibration protocols for comparing performance across species and climates. It may also be valuable to test tree antennas during actual cosmic-ray or neutrino events and explore integration into hybrid detection systems alongside traditional RF infrastructure.

While tree antennas will not surpass engineered RF arrays for high-precision monitoring campaigns, they represent a promising, innovative complement for large-scale, low-cost deployment, especially for remote or underdeveloped areas. To increase the utility of this pioneering detection strategy, some research avenues are worthy of further development. Extension of the operational frequency range to cover the HF and UHF ranges might extend their use to other astrophysical events, for example, solar radio bursts and atmospheric transients. Merging the use of tree antennas within hybrid detection systems involving conventional dipoles, log-periodic antennas, or low-noise amplifiers might extend their sensitivity at a reasonable cost. Real-time deployment as a complement to particle detectors during cosmic-ray or neutrino events might confirm their potential under real observation scenarios. Long-term monitoring on a seasonal, environmental stability basis is important to assess their long-term feasibility.

Combining them with advanced signal processing algorithms—for example, matched filtering, noise reduction, and machine learning—might extend detection limits within noisy environments. Geo-informatics data capabilities, such as satellite imaging and LiDAR, may determine optimal deployment planning and network modeling. Modeling electromagnetic coupling biophysically, while considering the physiology of the trees and environmental variability, might advance their predictability and detailed design. It is likewise important to examine the ecology of using trees as scientific infrastructure to determine their sustainability, with minimal disruption to nature. Additionally, these antennas have the potential for use within education and even citizen science applications, especially in rural, underrepresented communities, to promote wider participation in science development. Along with autonomous, solar-powered data systems and low-bandwidth telemetry, these antennas might perform as autonomous, scalable units for passive long-term scanning over vast environments.

Conclusion

In this paper, the goal was to evaluate the performance and measure the performance of trees as antennas in the VHF band, as well as to determine what factors may affect the signal reception strength. The goal was achieved using the above-mentioned solution methods. In the "Analysis of Results" chapter, the data from the tree measurements were analyzed. The obtained data showed that the performance of trees in the VHF range, although inferior to the dipole antenna, is still at a sufficient level, and the tree may well be a cheaper substitute for the antenna, depending on what conditions and what equipment it is used with. It has also been shown that certain characteristics of the tree, such as species, trunk radius, and height of the tree, affect the strength of the signal reception. During the research work, the main obstacle was the weather, which caused some experiments to be postponed.

It must also be said that with more advanced and expensive measuring devices, more accurate measurements can be achieved, with less error and more parameters for additional measurements.

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Authors

Denis Kim and Kirill Ilin are students at the Canadian International School Astana with a deep passion for physics and engineering. Kirill's interests lie at the intersection of cosmology and high-energy physics, while Denis is dedicated to aerospace engineering. Their work has garnered significant attention from scientists at the Joint Institute for Nuclear Research, leading to an invitation to collaborate in person with researchers at the Dzhelepov Laboratory. In March, Denis and Kirill won the Republican Competition of Science Projects, qualifying their project for the International Science and Engineering Fair.

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