Edi Bon* and Ivan Bon**

RELICS OF THE FIRST SOUND WAVES IN THECOSMOS THROUGH SOUNDSCULPTURES

Abstract. Scientific concepts, especially in cosmology, can be complex and difficult to grasp for many. Art can serve as a bridge to help people understand these complex ideas. In our project, we introduce sound sculptures inspired by horn telescopes previously utilized to explore the early universe. These sculptures function as miniature radio telescopes, enabling audience to audibly experience the cosmic microwave background radiation (CMBR). This radiation, originating approximately 380,000 years after the Big Bang and now are the oldest radiation that we can detect, aged at about 13.7 billion years. A Nober Prize was awarded for its discovery. During this early period, the universe was filled with a primordial baryon-photon plasma, through which the first acoustic waves in the universe resonated, leaving behind density fluctuations embedded in the CMBR, now known as baryon acoustic oscillations (BAO). These shapes can be detected not only in the CMBR but also in the large-scale structure of the observable universe. These echoes of the first sound waves have proven that the expansion rate of the universe is accelerating, earning yet another Nobel Prize. These cosmic sound waves are of incredible importance for many aspects of cosmology. Therefore, simply being aware of their existence is profound, even though such concepts are very hard to understand. By employing sound as the medium of expression, we draw a parallel to the primordial plasma of the early universe, where the first acoustic waves originated. These sculptures encapsulate the core principles of cosmology, offering a unique avenue for understanding through sensory and interactive exploration. Simply making the audience aware of these ancient cosmic waves and CMBR is incredibly important, and these sculptures help us achieve that.

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*Astronomical Observatory, Belgrade, Serbia
ebon@aob.rs
ORCID: 0000-0002-0465-8112
**Faculty of Contemporary Arts, Belgrade, Serbia
ivanbon@gmail.com
ORCID: 0009-0004-6160-2301

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Contents

1. Introduction

The timeless interplay between science and art has given rise to a collaboration between two brothers, a sculptor and an astrophysicist. In this harmonious convergence, sound sculptures have emerged, transcending aesthetic appeal to serve as conduits for understandig of cosmology through listening to the relics of the first cosmic sound waves – the primordial echoes of the universe's first sound waves originated in the oldest radiation that we can receive from the sky.

The expanding universe, resonated with relic waves in its early times before it became transparent. Astrophysicists, armed with powerful instruments and theoretical frameworks, are constantly unveiling some secrets of the universe's early moments. Simultaneously, artists, inspired by the cosmic wonders above, have sought to capture the essence of cosmos through the language of art.

This work embarks on a journey through the intertwined realms of astrophysics and art, exploring the historical milestones that led to the discovery of the cosmic microwave background radiation (CMBR), a cosmic relic that carries the whispers of the universe's birth. We delve into the concept of Baryon Acoustic Oscillations (BAO), imprints of primordial sound waves frozen in the cosmic structure, and the physics behind resonators and standing waves. Our odyssey extends to the cosmic drum overture, the dance of temperature and density in the universe, and the futuristic exploration of cosmic sound sculptures that bridge the gap between scientific abstraction and artistic expression.

The resonant frequencies imprinted on the CMBR are received in sound sculptures as in miniature radio telescopes, where this oldest radiation is transformed into sound waves through radio receivers.

The concept of a resonating universe proposes an intriguing perspective on the fundamental nature of the cosmos, suggesting that resonances and standing waves play a crucial role in shaping the structure and dynamics of our universe with the universe's first acoustic waves. The resonating universe hypothesis posits that the cosmos is not a static entity but instead exhibits dynamic resonances and standing waves that contribute to its formation and evolution. This theory draws inspiration from various branches of physics, including astrophysics, cosmology and the physics of resonators. The universe, as we observe it, is a vast and interconnected web of galaxies, clusters, and cosmic structures.

Resonators, devices that exhibit the phenomenon of resonance, are integral to understanding the resonating universe, but also sound sculptures. The resonant frequencies of these cosmic imprint may give analogy to oscillating patterns in the resonator of these acoustic sculptures.

Standing waves, a fundamental concept in physics, are patterns of oscillation that appear to be stationary. In the resonating universe, standing waves may manifest on cosmic scales, influencing the distribution of matter, energy, and even the cosmic microwave background radiation.

Understanding the interplay between standing waves and resonances in cosmic structures could shed light on the formation of large-scale cosmic patterns and the distribution of matter in the universe.

The collaborative process between the art and science is characterized by a dynamic exchange of ideas, expertise, and methodologies. One such collaboration resulted with sculptures that serve as a medium for communicating scientific results about the expanding universe and cosmology. By creating sound sculptures inspired by old horn radio telescopes, the project allows the audience to experience science through their senses with the aim to better understand cosmology, such as the formation of the universe and the nature of cosmic phenomena This project is grounded in the often-overlooked fact that radio receivers have the capability to capture signals from space when tuned beyond the frequencies of Earth's radio broadcasts. In doing so, the receiver captures radio noise originating from epochs shortly after the Big Bang. It is the oldest radiation that we can receive. These sound sculptures serve as a medium for listening to the relic radiation of first acoustic waves in the universe, originating from the early epochs of the universe's birth.

This work explores the historical foundations of cosmology, delving into the discovery of cosmic microwave background, the concept of Baryon Acoustic Oscillations (BAO), and the physics behind resonators and standing waves in the early universe primordial plasma, and the construction of these sculptures. Additionally, we also explore the concepts of expanding universe, large-scale structures, temperature fluctuations, and the evolution of cosmos. These sculptures derive their inspiration from the remarkable ability to capture the relic radiation from the early universe, acting as miniature radio telescopes. By precisely tuning a radio receiver to a frequency unaffected by terrestrial radio emissions, we gain access to an auditory experience of listening to the sound of microwave background radiation (MBR) originating from epochs shortly after the Big Bang. While we may not directly perceive the first acoustic waves in the universe without the aid of satellites, what we can discern is the ambient noise of listening to the relic background radiation that preserves the picture of a resonance of these waves. This auditory phenomenon, although not a direct scientific measure, provides a captivating link to the cosmic acoustic symphony during its most primordial phase. We conclude by highlighting the importance of interdisciplinary collaboration which exemplifies the transformative potential of collaborative partnerships in pushing the boundaries of human creativity and understanding.

2. Sound sculptures

Art, a realm of boundless creativity, has constantly evolved through the ages, embracing various forms of expression. In this complex tapestry of artistic endeavors, the fusion of sculpture and sound emerges as a captivating intersection that transcends traditional boundaries. The journey of sound sculptures, intertwined with the annals of art history, traces a fascinating narrative of innovation and sensory exploration.

The exploration of sound as a sculptural element finds its roots in the avant-garde movements of the 20$^{\text{th}}$ century. Luigi Russolo, a leading figure in the Futurist movement, envisioned a world where noise itself became an artistic medium [2, 3]. His intonarumori, mechanical instruments designed to create a cacophony of industrial sounds, marked a groundbreaking moment in the convergence of sculpture and sound.

The development of sound sculptures has not occurred in isolation; it is part of a broader movement where various art forms converge. The collaboration between sculptors and musicians, the integration of sound into traditional sculptures, and the exploration of interactive experiences redefine the boundaries of artistic expression [4].

The exploration of sound in art has a rich history, with Luigi Russolo's "The Art of Noises" (1913) serving as a pioneering manifesto [1]. Russolo's avant-garde ideas embraced the sounds of modern life, challenging traditional notions of music. The parallels between Russolo's futurist concepts and the modern synthesis of art in sound sculptures echo the enduring spirit of experimentation and innovation across disciplines [3].

The intersection of art and science in sound sculptures finds echoes in the history of conceptual art and the exploration of "art of noises", a term popularized by Luigi Russolo in his seminal manifesto "The Art of Noises". Russolo's avant-garde ideas embraced the sounds of modern life, challenging traditional notions of music. The parallels between Russolo's futurist concepts and the modern synthesis of art and astrophysics in sound sculptures echo the enduring spirit of experimentation and innovation across disciplines.

This crucial turning point in the history of art is encapsulated by the avant-garde movement of the early 20$^{\text{th}}$ century. Luigi Russolo, an Italian futurist artist, composer, and the author of the groundbreaking manifesto "The Art of Noises", played a transformative role [5]. Russolo's manifesto advocated for the inclusion of everyday sounds, or "noises", into music, challenging conventional notions of harmony and melody. He envisioned a new musical language that embraced the cacophony of modern life — a departure from traditional classical compositions. Russolo's ideas, which emphasized the intrinsic musicality of noise, laid the groundwork for a broader exploration of sound as an artistic medium. His influence extended beyond the realm of music, inspiring artists to consider the sonic landscape as a canvas for creative expression.

The parallel with Russolo's concept of industrial noises emitted through his sculptures is now replaced with the ambient noise of the Cosmic Microwave Background Radiation (CMBR) emitted from these horn sound sculptures.

3. The cosmic score

The narrative begins in 1964 when Arno Penzias and Robert Wilson, using the Holmdel horn radio telescope in New Jersey (see figure 1), stumbled upon an enigmatic cosmic microwave background noise radiation (CMBR). Initially perplexed, the duo became pioneers in unraveling the cosmic microwave background radiation, revolutionizing our understanding of the universe's early moments [6].

It all started with Arno Penzias and Robert Wilson, researchers at Bell Labs in Holmdel, New Jersey. While conducting experiments using the Holmdel horn

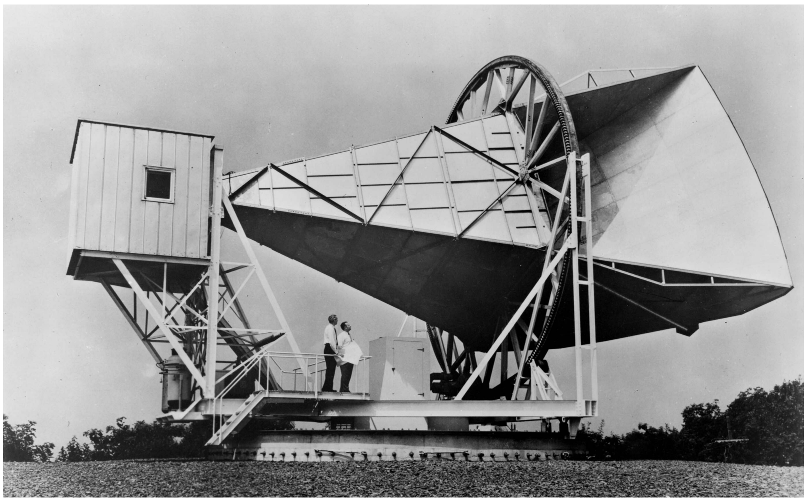

FIGURE 1. Holmdel Horn Telescope (Bell Telephone Laboratories, New Jersey): Crafted for satellite communication, this telescope was crucial in the discovery of cosmic microwave background radiation by radio astronomers Robert Wilson and Arno Penzias in 1964. Their groundbreaking work was acknowledged with the Nobel Prize in Physics in 1978. (Image Source: Flickr - NASA on The Commons)

radio telescope (see figure 1), Penzias and Wilson stumbled upon an unexpected and persistent source of noise. Initially dismissing it as unwanted interference, they soon realized that the signal was not terrestrial but permeated the entire sky, day and night [6].

Unknown to Penzias and Wilson, physicists Robert Dicke, Jim Peebles, P. J. E. Peebles, and David Wilkinson at Princeton University were contemporaneously formulating a theoretical framework foreseeing the presence of the cosmic microwave background. Their work, rooted in the Big Bang theory, proposed that the early universe, which was initially hot and dense, would have emitted radiation as it expanded and cooled to temperature under 3000 K [7]. Both groups published papers about this in the same volume of *Astrophysical journal* [6, 7].

Upon learning of Penzias and Wilson's accidental discovery, these Princeton physicists recognized it as the long-sought-after cosmic microwave background radiation, a key piece of evidence supporting the Big Bang model. This detected radiation, which adheres to the characteristics of black body radiation, originally existed at a temperature of 3000K during the epoch when the universe became transparent to electromagnetic radiation. This epoch is called the re-ionization [49]. However, with the ongoing expansion of the universe, this relic radiation has cooled significantly and currently stands at a temperature of 2.73 K, providing a unique cosmic fingerprint of the universe's evolution over time.

This groundbreaking revelation garnered widespread recognition and culminated in the Nobel Prize in Physics in 1978, awarded to Arno Penzias and Robert Wilson. Simultaneously, the Princeton team's theoretical contributions, especially those of Robert Dicke, were acknowledged, solidifying our understanding of the cosmic microwave background and affirming the Big Bang as the prevailing cosmological model [8].

The discovery of the CMB marks a turning point in astrophysics, providing a profound glimpse into the early moments of the universe. It stands as a testament to the power of interdisciplinary collaboration, where theoretical predictions and experimental observations converge to unlock the secrets of the cosmos.

Around 13.8 billion years ago, the universe erupted into existence with a cataclysmic event known as the Big Bang. In the initial moments, temperatures soared to inconceivable levels, and the cosmos seethed with a dense, hot plasma — an expanse filled with charged particles and radiation. As the universe expanded, this searing plasma embarked on a transformative journey, shaping the cosmic beat that we perceive today.

For the first 380,000 years, the universe existed in a state of opacity, akin to a cosmic curtain veiling the secrets of its early epochs. During this period, photons within the plasma encountered frequent collisions, preventing them from traveling significant distances. However, as the universe continued to expand, a crucial moment unfolded, marking the transition from a dense, opaque plasma to a transparent state.

The cosmic overture, played by the universe itself, reached its crescendo during this epoch of cosmic transparency. Approximately 380,000 years post-Big Bang, the relentless expansion cooled the cosmos to around 3000 K, a temperature crucial for the metamorphosis from a dense, opaque plasma to a transparent medium. This transformative cooling allowed photons to traverse space freely. At this moment, picture of universe is frozen in time in the form of small density fluctuations of first acoustic waves.

The radiation emitted during this epoch persists as the cosmic microwave background (CMB) radiation — a celestial beat frozen in time. The CMB, detected and studied with exquisite precision, encapsulates the symphony of the universe's evolution. Its fluctuations carry the imprints of temperature variations, density fluctuations, and the primordial conditions of the cosmos.

This cooling marked the cosmic drum overture, allowing photons to traverse freely through space. The radiation emitted during this epoch, now detectable as the cosmic microwave background noise, encapsulates the symphony of the universe's evolution — a harmonious blend of temperatures, densities, and frequencies.

4. Baryon acoustic oscillations (BAO)

The concept of Baryon Acoustic Oscillations (BAO) represents the imprints of first sound waves frozen in the large-scale structure of the universe. In early universe, before the era of transparency (the epoch of recombination, when the first atoms formed), pressure waves propagated through the baryon-photon plasma, creating regions of compression and rarefaction (see Figure 2). These primordial waves persist across cosmic epochs, shaping the cosmic web we observe today as the large scale structure [13].

The Figure 2 shows the CMBR observed by ESA's Planck satellite (upper right half) and by its predecessor, NASA's Wilkinson Microwave Anisotropy Probe (WMAP) CMBR (lower left half). The Planck data collection is based on the first 15.5 months of the mission, while the WMAP image is compiled from nine years of data.

As the universe expanded and cooled, these acoustic oscillations left a distinctive pattern in the distribution of matter. This cosmic fingerprint is discernible in the large-scale distribution of galaxies today (see, for eg. [24, 30, 31]). The resonant frequencies of these primordial waves, akin to the standing waves in resonators, have persisted across cosmic epochs, shaping the cosmic web we observe.

In the vast expanse of the cosmos, the cosmic microwave background radiation blankets the sky, presenting itself as a seemingly uniform backdrop to microwave telescopes. Missions, including NASA's COBE Planck and WMAP, scrutinized this celestial tapestry, uncovering a remarkable revelation: the temperature of the CMB hovers around 2.726 Kelvin (approximately –270 degrees Celsius) across much of the celestial sphere (see for eg. [17]). However, within this apparent uniformity lies a subtle yet profound secret. These observations uncovered tiny fluctuations in temperature, akin to whispers in the cosmic symphony, scattered across the celestial canvas. These delicate variations, mere small fractions of a degree in magnitude, hinting at the underlying structures that emerged in the primordial soup of the early Universe. Imagine them as the faint echoes of cosmic seeds, destined to sprout into the majestic galaxies we observe today. What truly sets Planck's instruments apart is their unparalleled sensitivity, capable of discerning temperature variations

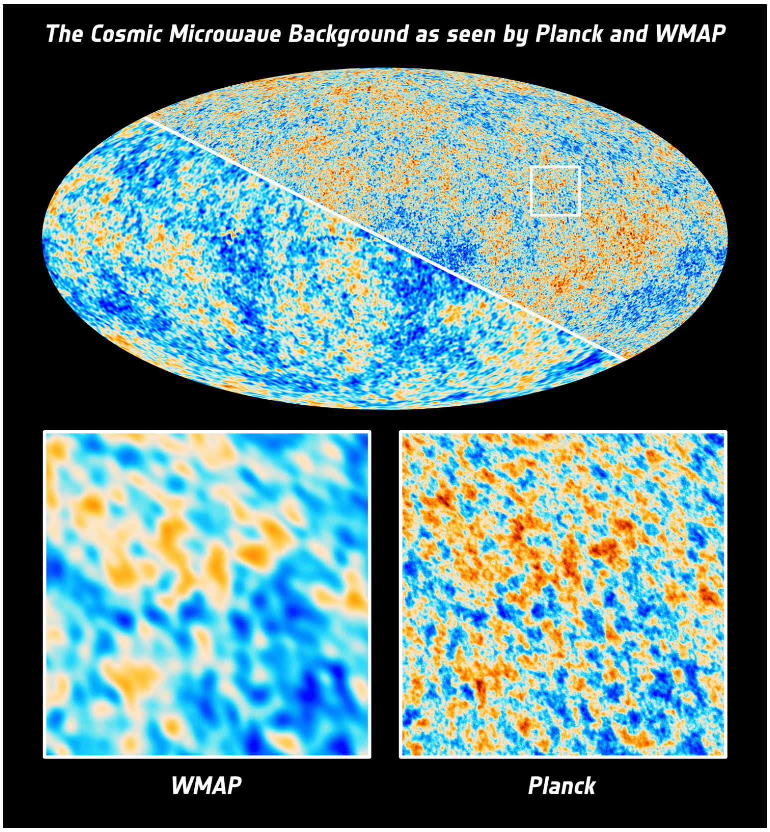

FIGURE 2. CMBR: Small fluctuations of temperature in the relic radiation of CMBR observed by ESA's Planck satellite (upper right half) and by its predecessor, NASA's Wilkinson Microwave Anisotropy Probe (lower left half). With greater resolution and sensitivity over nine frequency channels, Planck has delivered the most precise image so far of the Cosmic Microwave Background. Image credit: ESA and the Planck; NASA / WMAP Science Team Collaboration. Licence: ESA Standard Licence

as infinitesimal as a few millionths of a degree [11]. This extraordinary precision offers a tantalizing glimpse into the intricate tapestry of density fluctuations that adorned the cosmos in its infancy.

The interplay between dark matter, baryonic matter, and radiation during the epoch of BAO laid the foundations for the large-scale structures we observe today [24,25,30,31]. The cosmic web (a vast network of filaments and voids) is a testament to the enduring influence of these primordial acoustic oscillations. These structures, sculpted by the resonant echoes of the early universe, serve as cosmic mile markers, allowing astronomers to trace the vast cosmic landscape.

Baryon Acoustic Oscillations (BAO) serve as a critical tool in cosmology, providing a "standard ruler" for measuring the expansion rate of the universe. These oscillations, imprinted in the early universe, are observed in the distribution of galaxies and the cosmic microwave background (CMB). By analyzing BAO, cosmologists can trace the universe's expansion history, contributing significantly to our understanding of dark energy, along with studies that exploit so-called "standard candles" like Type Ia supernovae.

In 1998, two independent research teams studying Type Ia supernovae (SNIa) discovered that the expansion of the universe is accelerating, a groundbreaking finding that led to the 2011 Nobel Prize in Physics awarded to Saul Perlmutter, Brian P. Schmidt, and Adam G. Riess [19–21]. This acceleration implied the existence of a mysterious force termed dark energy, which constitutes approximately 68% of the total energy density of the universe.

5. Expansion of the universe and filament structures

BAO are fluctuations in the density of the visible baryonic matter of the universe caused by acoustic waves in the early universe. These waves, which traveled through the hot plasma of the early universe, were frozen in place when the universe cooled enough for protons and electrons to combine into neutral hydrogen atoms. This "freezing" left an imprint on the distribution of matter that we can observe today.

BAO appear as a distinct peak in the correlation function of galaxy distributions at a scale of about 150 Mpc (megaparsecs), providing a "standard ruler" for cosmological measurements [23, 34]. By measuring the apparent size of this ruler at different redshifts, astronomers can infer the rate at which the universe is expanding at various points in time.

The first clear detections of BAO at low redshifts came from the Two Degree Field Galaxy Redshift Survey (2dFGRS) and the Sloan Digital Sky Survey (SDSS) [24, 25]. These surveys provided precise measurements of the BAO scale, leading to robust estimates of the Hubble parameter, $H(z)$, which describes the expansion rate of the universe at different redshifts.

The Baryon Oscillation Spectroscopic Survey (BOSS), part of SDSS-III, significantly improved the precision of BAO measurements. BOSS aimed to measure the BAO scale with one-percent accuracy using a sample of 1.5 million luminous galaxies in the redshift range $0.2 < z < 0.7$ and make the first BAO measurement at $z > 2$ using the Lyα forest absorption observed in quasars [26]. BOSS data enabled precise determinations of both the Hubble parameter, $H(z)$, and the comoving angular diameter distance, $D_M(z)$, at various redshifts [27].

Recent analyses of BAO data have produced precise measurements of the Hubble parameter at different redshifts. For instance, the BOSS survey reported a 1.4% measurement of $D_M(z)$ and a 3.5% measurement of $H(z)$ at $z = 0.57$, alongside a 2.0% measurement of $D_V(z) \equiv [D_M^2(z) \times cz/H(z)]^{1/3}$ at $z = 0.32$ [28]. These measurements are crucial for constraining the properties of dark energy and testing cosmological models.

BAO measurements have significantly enhanced our understanding of the universe's expansion history. They provide an independent method to measure the expansion rate, complementing the results obtained from SnIa and the CMB. The combination of BAO data with CMB measurements from the Planck and WMAP satellites has yielded stringent constraints on the parameters of the ΛCDM model, which describes a universe dominated by cold dark matter and dark energy with a cosmological constant [29].

Moreover, the combination of BAO and SnIa data allows for a consistency check on the cosmic distance ladder, where the absolute calibration of the BAO scale is transferred to lower redshifts using SNIa. This "inverse distance ladder" approach has proven valuable in refining the Hubble constant, H_0, providing insights into potential discrepancies between local and early universe measurements.

The latest results from the Dark Energy Spectroscopic Instrument (DESI) project have further refined our understanding of BAO. DESI aims to measure the redshifts of over 30 million galaxies and quasars, providing unprecedented precision in BAO measurements. Preliminary results have already shown improvements in the accuracy of the BAO scale, enhancing our ability to trace the expansion history of the universe and constrain dark energy models [30, 31].

BAO have emerged as a powerful cosmological tool, offering precise measurements of the universe's expansion rate. These measurements complement other methods, such as SNIa and CMB, and contribute significantly to our understanding of dark energy. As surveys continue to improve, BAO data will remain important in testing cosmological models and exploring the fundamental properties of the universe.

BAO relics are now important from many aspects. One as being a standard rulers across the universe, allowing us to scale the universe, and to measure it's expansion rate [23, 31, 34].

The birth of the universe was accompanied by acoustic waves — pressure oscillations in the baryon-photon plasma. These waves, akin to ripples in a cosmic pond, propagated through space, freezing in the spatial pattern of the cosmic microwave background radiation. Detectors, positioned on satellites in Earth's orbit, have unveiled complex structures in the form of small temperature and density fluctuations in the early universe's plasma. These structures, born from the initial acoustic waves, echo through cosmic evolution.

The expansion of the universe, a fundamental aspect of cosmic evolution, has sculpted complex filament structures on the cosmic canvas. These filaments, colossal cosmic highways, are traces of Baryon Acoustic Oscillations frozen in the large-scale structure. As the universe expands, these filaments trace the imprints of primordial sound waves, shaping the cosmic web observed in the distribution of galaxies [16].

The temperature of the cosmic microwave background radiation, hovering at approximately 2.7K, is a testament to the expansive history of the universe. This temperature corresponds to the temperature of a blackbody radiating at the same intensity. The universe's fine structure, comprising a delicate balance of matter, radiation, and dark energy, shapes the blackbody spectral energy distribution of the observed background radiation [17].

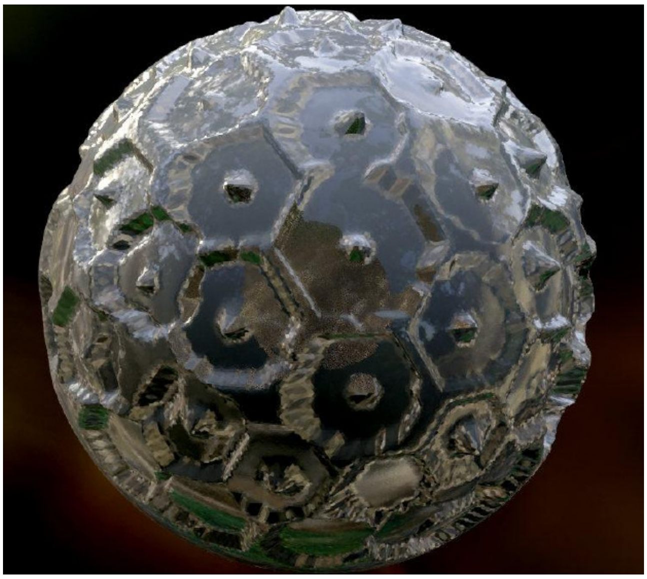

FIGURE 3. Cosmic Crescendo: An artist's vision (schematic representation) of primordial acoustic waves spreading over the curved surface of an early universe (BAO), depicting a spherical shell of curved spacetime expanding with the universe's early expansion. Resonant acoustic waves are artistically visualized in this cosmic panorama.

The cosmic symphony echoes through the universe in the form of the cosmic microwave background (CMB) radiation, a celestial relic that carries the thermal imprint of the universe's infancy. Understanding the temperature fluctuations of the CMB provides a crucial key to unraveling the cosmic narrative.

The discovery of the CMB marked a transformative moment in astrophysics, providing concrete evidence for the Big Bang theory. Theorists had predicted that as the universe expanded and cooled, the primordial plasma would eventually become transparent, releasing photons that we now observe as the CMB. The measured temperature of the CMB aligns with the predictions based on the blackbody radiation model [7].

The blackbody radiation assumption is fundamental to understanding the CMB temperature. According to this model, the CMB behaves like a perfect blackbody emitter, meaning it emits radiation across all wavelengths according to a specific temperature. The 2.7 Kelvin temperature of the CMB corresponds to the thermal equilibrium achieved as the universe transitioned from a dense, opaque plasma to its transparent state.

This transition, occurring approximately 380,000 years after the Big Bang, marks a crucial epoch known as recombination. Before recombination, the universe was a searing plasma, and photons were continuously scattered by charged particles, rendering the cosmos opaque. As the universe expanded and cooled, electrons and protons combined to form neutral hydrogen, allowing photons to travel freely for the first time.

The 2.7 Kelvin temperature of the CMB is a direct consequence of this recombination process and subsequent cosmic expansion. The blackbody spectrum of the CMB has been precisely measured by experiments such as the Cosmic Background Explorer (COBE) and the Planck satellite, confirming the remarkable agreement with the theoretical predictions [9, 11].

The CMB's temperature variations, on the order of microkelvins, reveal subtle imprints of the universe's early conditions. These fluctuations, studied in detail by high-precision instruments, contribute valuable insights into the distribution of matter, gravitational interactions, and the emergence of cosmic structures.

The fine structure of the universe, including galaxies and galaxy clusters, influences the CMB temperature in a phenomenon known as the Sunyaev-Zel'dovich effect [12]. As CMB photons traverse through regions with hot electron populations, they undergo energy exchange, leaving detectable imprints on the CMB spectrum.

The exquisite agreement between the predicted and observed temperature of the CMB stands as a testament to the precision of modern cosmology. The CMB's 2.7 Kelvin temperature serves as a cosmic benchmark, a lingering echo of the universe's formative stages. It encapsulates the transition from a hot, dense plasma to the expansive cosmos we observe today, providing a foundational element in our understanding of the grand cosmic symphony.

The cosmic microwave background (CMB) radiation permeates space as a uniform emission of thermal energy, akin to a black body, emanating from every corner of the celestial sphere. Despite its uniformity, the CMB exhibits subtle isotropic variations, amounting to only one part in 100,000. These variations, with a root mean square deviation of merely 18 μK, emerge once the dominant variation factor — the dipole anisotropy induced by the peculiar velocity of the Sun — is subtracted. This dipole anisotropy arises from the Sun's motion, moving at 369.82 ± 0.11 km/s towards the constellation Leo, with galactic coordinates of 264.021 ± 0.011 in longitude and 48.253 ± 0.005 in latitude. After accounting for this primary variation, measurements reveal the presence of additional dipole and aberrations at higher multipoles, consistent with the motion of our galaxy [18].

6. The connection between Baryon acoustic oscillations and formation of primordial supermassive black holes

Recent observations from the James Webb Space Telescope (JWST) have revealed the existence of supermassive black holes (SMBHs) at redshifts above 10, challenging the standard model of SMBH formation through accretion. This discovery suggests that SMBHs may have formed in the dense regions of BAO waves in the early universe. This theory provides a plausible explanation for the observed gap between stellar mass black holes (up to 100 solar masses) and SMBHs (above 10^6 solar masses).

The formation of supermassive black holes (SMBHs) in the early universe remains one of the most intriguing puzzles in cosmology. Traditional models suggest that SMBHs grow from stellar-mass black holes via accretion and mergers over billions of years. However, recent observations from the James Webb Space Telescope (JWST) have detected SMBHs at redshifts above 10 [33, 36], posing a significant challenge to these models due to the insufficient time available for such growth through standard processes.

Baryon Acoustic Oscillations (BAO) created regions of higher density that could have served as seeds for the formation of massive structures, including SMBHs. The dense regions in the BAO waves provided an ideal environment for the rapid collapse of matter, leading to the formation of primordial SMBHs [34].

The discovery of SMBHs at such high redshifts suggests that they formed much earlier than previously thought, necessitating a mechanism that can produce massive black holes quickly. Standard accretion processes cannot account for the rapid growth needed to form SMBHs by redshift 10 [35]. This has led to the hypothesis that primordial SMBHs could form directly from the collapse of dense regions in BAO waves.

The hypothesis that SMBHs formed in the dense regions of BAO waves provides a plausible explanation for the observed gap in black hole masses. Stellar mass black holes, formed from the collapse of massive stars, have masses up to 100 solar masses. In contrast, SMBHs with masses above 10^6 solar masses likely formed in the early universe's dense regions created by BAO waves. This formation mechanism bypasses the need for intermediate mass black holes, which are rarely observed.

The JWST has provided unprecedented insights into the early universe, including the detection of SMBHs at redshifts greater than 10. These observations have revealed that SMBHs existed less than a billion years after the Big Bang, suggesting that they must have formed through mechanisms other than gradual accretion [36]. The theory that dense regions of BAO waves facilitated the rapid formation of SMBHs aligns well with these discoveries, offering a compelling explanation for the early appearance of such massive objects, as seeds of formation of galaxies.

The connection between BAO and the formation of primordial SMBHs offers a new perspective on the early universe's structure formation. The dense regions created by BAO waves likely provided the necessary conditions for the rapid formation of SMBHs, explaining their presence at high redshifts and the mass gap between stellar and supermassive black holes. Ongoing and future observations by JWST and other instruments will continue to test this hypothesis and refine our understanding of black hole formation in the early universe.

Supermassive black holes (SMBHs) are typically found at the centers of galaxies, including our own Milky Way. These black holes can have masses ranging from millions to billions of times the mass of our Sun. Their immense gravitational pull influences the motion of stars and gas in their vicinity, creating distinctive signatures that astronomers can observe.

SMBHs are located at the hearts of galaxies, where they exert a dominant gravitational influence. In the case of our Milky Way, the SMBH is known as Sagittarius A star and is situated at the galactic center [48]. In distant galaxies, SMBHs are also central features, often surrounded by accretion disks of gas and dust spiraling into them due to their strong gravitational pull.

Detecting SMBHs at vast distances, particularly those in the early universe, relies on a combination of observational techniques. In our galactic center the motion of stars and gas around a SMBH can be measured to infer its presence and mass. By observing the high velocities of these objects, astronomers can deduce the existence of an unseen massive object — the SMBH. In case of distant galaxies, where stellar velocities cannot be resolved, astronomers use the signatures of matter falls into a SMBH, it forms an accretion disk that heats up and emits significant amounts of radiation (through their spectral energy distribution). SMBHs that are actively accreting large amounts of matter in centers of galaxies are seen as active galaxies and quasars (quasy stellar objects). They are some of the brightest objects in the universe (see more in [40]). Quasars can outshine their host galaxies and are detectable over billions of light-years. Their luminosity allows astronomers to study SMBHs from the early universe at high redshifts. The light from distant galaxies is redshifted due to the expansion of universe. By measuring the redshift, astronomers can determine the distance to these galaxies and, by extension, the SMBHs they contain. Instruments like the JWST and the Sloan Digital Sky Survey (SDSS) provide the necessary precision for these measurements.

Quasars, or quasi-stellar objects, are among the most luminous and energetic objects in the universe. Powered by supermassive black holes (SMBHs) at the centers of galaxies, quasars accrete matter at high rates, emitting intense radiation that can be observed across vast cosmic distances. This makes them invaluable tools in cosmology.

In cosmology, a "standard candle" is an astronomical object with a known intrinsic luminosity. By comparing the known luminosity to the observed brightness, astronomers can determine the distance to the object. Type Ia supernovae are the most well-known standard candles due to their consistent peak luminosity, but quasars are also being explored for this purpose.

Recent studies have shown promise in using quasars as standard candles. For instance, Risaliti and Lusso (2015) demonstrated a tight correlation between the X-ray and UV luminosity of quasars, suggesting that this could be used to measure cosmological distances with high precision [41]. Furthermore, the discovery of extremely accreting quasars provides an additional method for standardizing quasar luminosities, as these objects naturally reach a saturation point in their brightness [42].

The use of quasars as standard candles is still in its early stages compared to Type Ia supernovae, but it offers several advantages. Quasars are visible at much greater distances and earlier epochs in the universe, providing a complementary tool to supernovae for probing the expansion history and the nature of dark energy.

Quasars hold significant potential as standard candles for cosmological measurements. While there are challenges due to their variability, ongoing research is developing methods to standardize their luminosity. As these techniques improve, particularly with the inclusion of extremely accreting quasars [42–45], they could become a powerful tool for measuring cosmic distances and furthering our understanding of the universe's expansion.

Black holes, with their immense gravitational pull, are among the most enigmatic and significant objects in the universe. They come in various masses, ranging from stellar-mass black holes, formed from collapsing massive stars, to supermassive black holes (SMBHs), which reside at the centers of galaxies. Understanding the distribution of black hole masses across different epochs of the universe provides crucial insights into their formation and evolution.

Stellar-mass black holes, typically ranging from a few to about 100 solar masses, are the remnants of massive stars that have ended their life cycles in supernova explosions. These black holes are found throughout the Milky Way and other galaxies. Their masses are determined through observations of X-ray binaries, where a black hole accretes material from a companion star, and through gravitational wave detections of black hole mergers by observatories such as LIGO and Virgo [46]. Intermediate-mass black holes (IMBHs), with masses between 10^2 and 10^5 solar masses, remain somewhat mysterious, with missing evidence of their existence. Supermassive black holes, with masses ranging from 10^6 to over 10^{10} solar masses, reside at the centers of most large galaxies, including our Milky Way. The discovery of an SMBH at the heart of the Milky Way, known as Sagittarius A*, with a mass of about 4 million solar masses, has provided a cornerstone for understanding the nature of these colossal objects [48].

The formation and growth of SMBHs in the early universe, particularly at high redshifts ($z > 6$), pose significant challenges to current astrophysical models. The recent observations by the James Webb Space Telescope (JWST) have identified quasars powered by SMBHs at redshifts above 10, indicating that these black holes must have formed and grown to massive sizes within the first few hundred million years after the Big Bang [49]. These findings challenge the standard accretion model, suggesting that SMBHs might have formed in dense regions created by baryon acoustic oscillations (BAOs) in the early universe.

The observed gap between the masses of stellar-mass black holes and the smallest SMBHs suggests different formation pathways. Stellar-mass black holes form from the collapse of massive stars, while SMBHs could have formed from the direct collapse of massive gas clouds or through the mergers of smaller black holes in the dense regions of the early universe influenced by BAOs. The presence of SMBHs at high redshifts supports the theory that they might have grown rapidly in the dense environments shaped by these early-universe acoustic oscillations [50].

Detecting black holes across vast cosmic distances relies on various observational techniques. For stellar-mass black holes, X-ray observations and gravitational wave detection are very important. Gravitational waves, ripples in spacetime caused by the acceleration of massive objects, have opened a new window into the universe. Predicted by Einstein's General Theory of Relativity in 1915, they were directly detected a century later by the Laser Interferometer Gravitational-Wave Observatory (LIGO) [46]. Gravitational waves provide a unique means of probing the cosmos, complementing electromagnetic observations and offering new insights into astrophysical processes and the fundamental nature of gravity [51].

Gravitational waves have profound implications for cosmology. Gravitational waves can travel through the universe virtually unimpeded, providing information about epochs that are otherwise inaccessible. Primordial gravitational waves, if detected, could offer insights into the conditions of the universe moments after the Big Bang. These waves are predicted by inflationary models, which describe an exponential expansion of the universe in its first fractions of a second [19–21, 23, 31, 34]. Gravitational waves from binary neutron star mergers, accompanied by electromagnetic counterparts, can serve as "standard sirens" to measure cosmic distances. Gravitational wave observations offer a stringent test of General Relativity in the strong-field regime. By analyzing the waveform of gravitational waves from black hole mergers, researchers can test for deviations from the predictions of General Relativity, thus exploring possible extensions to our current understanding of gravity [55, 56]. Gravitational waves provide direct evidence of the existence of supermassive binary black hole systems [52–54] and their merger rates [51]. This information helps refine models of stellar evolution, binary interactions, and the formation channels of black holes throughout cosmic history [46, 51].

SMBHs are primarily identified through their association with active galactic nuclei (AGN) and quasars, where the intense radiation from accreting material can be observed across the electromagnetic spectrum. The redshift of these quasars provides a measure of their distance and, consequently, the epoch of the universe in which they are observed. JWST and other advanced telescopes continue to push the boundaries of these detections, revealing the presence and growth of black holes at ever greater distances and earlier times in the universe.

These techniques allow astronomers to not only detect SMBHs but also study their properties and growth over cosmic time. The recent discoveries by the JWST have pushed the boundaries of our understanding, revealing SMBHs in the early universe and suggesting rapid formation mechanisms linked to the dense regions created by Baryon Acoustic Oscillations (BAO).

7. Resonators and sound sculptures

Central to the functioning of sound sculptures are resonators, integral components that shape and amplify cosmic melodies. Resonators are carefully crafted forms where waves, by propagating, intensify through precise lengths, reinforcing their amplitude. In the context of these sculptures, the resonators enhance the acoustic signals derived from cosmic microwave background radiation, adding a distinctive color to the cosmic composition.

When sound waves encounter a resonator, they create standing waves within it. A resonator's dimensions dictate which frequencies can form standing waves. Frequencies that meet the condition for constructive interference, where reflected waves align with incoming waves, reinforce each other, leading to amplification. This amplification occurs because the resonator selectively enhances specific frequencies that align with its dimensions [14].

In the resonator, as waves bounce back and forth, only frequencies corresponding to resonant modes survive. Other frequencies interfere destructively, canceling each other out. The surviving resonant frequencies are like harmonics in music, representing fundamental tones resonating with the resonator's shape. This phenomenon mirrors the early universe's standing waves, where specific frequencies of acoustic oscillations survived due to the constructive interference of matter and radiation.

The formula for resonant frequencies in a resonator of length L is given by:

$$f_n = \frac{nv}{2L},$$

where f_n is the resonant frequency, n is the mode number, and v is the speed of sound [14].

The resonant frequencies imprinted on the cosmic microwave background radiation carry the signature of the universe's acoustic past—a cosmic symphony frozen in time. These frequencies, like cosmic echoes, provide a unique lens through which we can explore the conditions of the early universe and trace the cosmic journey from the inferno of the Big Bang to the vast cosmic chill.

Within the sculptures, resonant frequencies take charge of infusing color into the emitted sounds, while the horn-shaped design simultaneously acoustically amplifies the auditory experience.

Resonators give rise to standing waves, with certain frequencies persisting longer, while others dissipate.

8. Standing waves

Integral to this cosmic drumming are standing waves as a phenomenon where certain frequencies synchronize to create stationary patterns. In the early universe, these standing waves manifested as acoustic oscillations in the baryon-photon plasma. The interaction between radiation and matter led to the formation of regions of compression and rarefaction, imprinting the cosmic microwave background radiation with unique spatial variations.

This analogy between standing waves in resonators and those in the early universe adds a layer of depth to our understanding of the cosmic symphony. In resonators, standing waves arise from the constructive interference of incoming and reflected waves. Similarly, in the early universe, the standing waves of acoustic oscillations resulted from the interplay of radiation pressure and baryonic matter, creating patterns that persist in the cosmic background radiation.

9. Futuristic cosmic sound sculptures

The exploration of sound sculptures extends into futuristic concepts, where the creations of artists and astrophysicists engage with complex narratives. Equipped with technologies, these sculptures translate cosmic concepts into auditory experiences, promising a sensory odyssey into uncharted cosmic territories.

Artists collaborate with scientists, infusing sculptures with real-time cosmic data, creating dynamic installations evolving alongside the celestial landscape. By harnessing data visualization and sonification techniques, these sculptures captivate audiences, serving as educational tools offering a multi-sensory understanding of the cosmos.

The union of futuristic cosmic sound sculptures and the legacy of microwave background discovery represents an interstellar harmony, transcending traditional boundaries between art and science. This convergence invites us to contemplate the vastness of the cosmos not only through telescopic images and scientific data but also through the emotive power of artistic expression. The resonance of Baryon Acoustic Oscillations (BAO), frozen in the large-scale structure of the universe, finds its counterpart in the harmonies sculpted by artists.

The connection between science and art has often been an inspiration to both scientists and artists. Many famous scientists were also eminent artists. Today, in modern methods of data visualization in astrophysics, it is common to transform data into sound recordings, so that they can be analyzed more simply, but also better evoked and described. As a result of one such collaboration between sculptors and astrophysicists, sound sculptures were created to listen to the birth of the Cosmos. More precisely, 380,000 years after the Big Bang, the plasma of the early universe cooled to a temperature of about 3000K, which allowed the then universe to become transparent. The radiation that was emitted at that moment is detected today in the form of background noise, that is, microwave background radiation, which can be heard with a radio receiver when it is tuned to frequencies that are not occupied by the emission of human radio stations. Acoustic listening becomes even more interesting by placing the antenna and radio receiver in the sound sculptures, which in their shape resemble the old radio telescopes in the shape of a horn (the so-called horn or "horn" antenna), which were used to find background microwave radiation (for the detection of which Arno Penzias and Robert Wilson won the Nobel Prize in 1964). With the help of radio receivers located in the sculptures, these electromagnetic waves are converted into sound waves, which are then reproduced using a speaker located in the resonator part of the sculpture, which, with its characteristic horn shape, performs acoustic amplification and modulation of the emitted sound.

The conversion of these electromagnetic waves into sound, by means of a radio receiver, actually symbolizes the first acoustic waves of the early Universe, caused by radiation pressure on the airless, baryon-photon plasma. These acoustic waves propagated at extremely high speeds (about half the speed of light) and remained frozen in the background radiation image at the moment when the plasma of the early universe became transparent (see Fig. 3). With modern instruments, the structures of these waves can be detected in the form of small fluctuations in the spatial image of the background radiation. This radiation is actually not completely isotropic in space, as was previously thought, but structures of different densities are seen projected onto the celestial sphere at different epochs of the age of the universe. These acoustic waves of baryon-photon plasma are very significant, because they are used to determine the age of the universe, as the so-called. "standard rulers". The background radiation is actually the farthest distance in space that we can detect and is at a redshift of z=1100. Based on the reconstruction of the evolution of the expansion of the universe, these waves indicate an age of the universe of 13.7 billion years, which is consistent with estimates from other methods.

These waves are, in fact, the first acoustic waves in space, hence the inspiration to listen acoustically to the noise of the background radiation using sound sculptures. The sculptures themselves are designed to resemble the horn of the antenna that was used for the first detection of microwave radiation, and the determination of the temperature of today's universe, which corresponds to the temperature of a black body of about 2.7 K. "Big Bang", when the universe was of very small dimensions and extremely high temperatures. During the expansion, the temperature of the universe decreased, so that at the moment it became transparent (some 380,000 years after the Big Bang itself) the temperature dropped to values below 3,000 K, and at the present moment, after 13.1 billion years, that temperature is about 2.7 K.

At the time when microwave radiation was accidentally discovered by Arno Penzias and Robert Wilson in 1964, they did not know the nature and origin of this radiation. They made the detection while working on the then most modern directional horn-shaped radio telescope (the Holmdel horn radio telescope in New Jersey, built specifically for communication with satellites). CMBR was detected while they were trying to calibrate the telescope and put it into operation. However, they could not remove the noise that was constantly heard from the receiver, despite various attempts to eliminate it. This noise came from all directions, isotropic, regardless of the antenna's orientation. In their attempts to eliminate the noise, they even considered that it might originate from the droppings of pigeons that had remained inside the telescope. Even with constant and detailed cleaning of all parts of the structure, the noise could not be eliminated.

The same noise is emitted through these sound sculptures, reminding us of the process that led to the accidental discovery of CMBR.

At one of the discussions about this constant noise coming from their supersensitive equipment, a colleague suggested they contact Robert Dickey, a physicist at Princeton University, who with his group was searching for evidence of the Big Bang, but they had no means to make one. such a telescope with which they could investigate it. Penzias and Wilson learned in a telephone conversation with Dickey what they had actually detected. However, this discovery was published in a separate paper, without an explanation of what it was actually about, while in the same issue of the Astrophysical Journal Letters, together with this paper, a paper with a theoretical explanation was also published [6, 7]. In the end, only Penzias and Wilson received the Nobel Prize in 1978 for the detection of background radiation [8], despite the fact that they did not know what they detected, while the scientists who clarified the phenomenon remained in the shadows, which represents one of the biggest controversies related to the awarding of Nobel Prize. Therefore, these sculptures not only explain the scientific concepts behind the discoveries but also narrate the historical and sociological aspects associated with them.

Concept of BAO on CMBR is observed much later, when devices placed on specially designed satellites in Earth's orbit have detected a more precise picture of the background radiation, so we know about the fine fluctuations in the temperature and density of the plasma of the early universe. Also, these structures originating from these acoustic waves are visible in the structure of the filaments of the grouping of galaxies at different distances, which have the shape and characteristics of these acoustic waves, only their dimensions correspond to the sizes expected at those distances, due to the expansion of space. The importance of these first acoustic waves in the universe gave inspiration for the acoustic listening of the background radiation, in which the image of the last moment of oscillation of the first acoustic waves in the universe is hidden.

The similarity in form of these sound sculptures to horn-shaped radio telescopes actually serves a dual purpose to:

- collect and direct the signal of electromagnetic radiation from the direction in which the sculpture is directed (as well as on the horn-shaped telescopes themselves), so that the radio antenna in it actually receives the background radiation signal;
- make it possible to listen to the converted signal (using a radio receiver and speakers) in sound, amplifying this sound acoustically, with its shape.

Sound sculptures, as well as sound instruments, usually contain a resonator, which amplifies and colors the sound emitted through it. Resonators are forms in which waves are amplified by their propagation in such a way that in them, waves of precisely determined wavelengths manage to be amplified by passing through the resonator again, thus adding up their amplitudes. Since waves whose wavelength does not correspond to the characteristic length of $l = n(\lambda/2)$ dissipate very quickly, losing energy by propagating through the medium, only those frequencies that meet this condition "survive" longer in the resonator, amplifying the amplitude of the wave with each repeated passage. These frequencies are called harmonics and characterize each resonator, giving it a different "color" of sound (which allows us to recognize the color of different musical instruments).

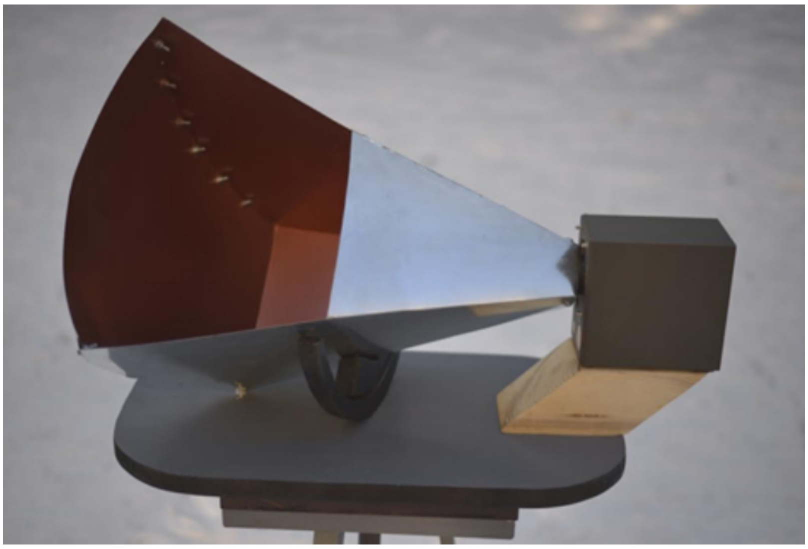

FIGURE 4. Horn sound sculpture for listening of the sound of cosmic microwave background radiation (CMBR) through the radio receiver named "Radio telescope No.1".

FIGURE 5. Noise Ensemble: Exhibition showcasing sculptures for attuning to the cosmic symphony [60].

As the forms of these directional horn antennas are reminiscent of acoustic sound amplifiers (horn-like shapes, like horns on old gramophones, or forms that combine tube and funnel, etc.), as in Luigi Russol's futuristic sound installations, these sculptures can be classified as conceptual similar sculptures, with the difference that in this case, instead of Luigi's noise of machines and industrial plants, these sound installations emit the noise obtained in a radio receiver, electromagnetic waves originating from the era close to the Big Bang (the birth of the universe itself).

In this particular case, through the sculpture, the speaker emits acoustic white noise obtained from a radio receiver, which has converted the electromagnetic signal of the background radiation into sound. This noise is amplified and modulated by the characteristic shape of the resonator (in the shape of a horn), as a reminder of the resonant frequencies of the harmonics of the first acoustic waves in the primeval universe. Hence the idea of listening to the beginning of the universe, which is somewhat reminiscent of listening to a signal imprinted with images of the first waves in space. These acoustic waves were also resonant waves of the early universe, like the waves in the resonator of sound sculptures.

In addition to this purpose, these sound sculptures were also used for musical performances in which the sounds received by radio telescopes from pulsars were simulated, as well as the expected sounds obtained by simulated data transformations of various celestial objects (for example, the sounds of pulsars, the orbit of binary black holes, etc.).

Also, these sound sculptures can work without power, using the received electromagnetic signal as a source of energy, while instead of an additional amplifier for the speaker, using a piezo-speaker, you can hear an acoustically amplified sound, where the amplification is done acoustically by the form of sculpture itself.

These sculptures were presented on many exhibitions [57–64]. The inaugural exhibition of these sculptures took place at the galery of Youth Center (Dom Omladine) in Belgrade in 2017 [60]. Presently, they adorn the permanent collection at the Museum of the Institute of Physics in Zemun [59]. One of these sculptures was awarded at prestigious Summer Sculpture Salon in Cvijeta Zuzorić Art Pavilion in Belgrade [61].

FIGURE 6. “Radio snail” sound sculpture for listening to cosmic microwave background radiation (CMBR) through a radio receiver.

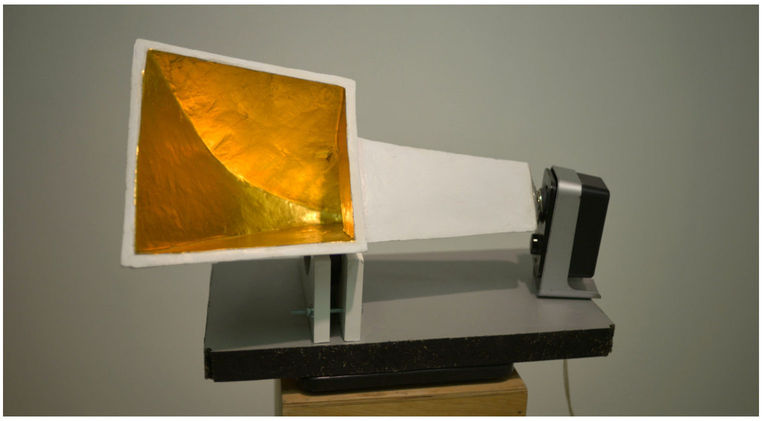

FIGURE 7. “Radio treverb” sound sculpture for listening of the sound of cosmic microwave background radiation (CMBR) through the radio receiver.

10. Conclusion

These sculptures aim to heighten awareness among the audience, emphasizing that through an acoustic listening experience of the cosmic microwave background noise, individuals are, in essence, tuning into the remnants of the universe's inaugural sound waves, known as Baryon Acoustic Oscillations (BAO).

Beyond their artistic allure, these sound sculptures serve as educational tools, illuminating the complex interplay between art and astrophysics. Their utilization extends to musical performances. They can also be used for emitting simulating sounds from celestial objects like pulsars and envisioning the echoes of cosmic events. In classrooms and galleries alike, these sculptures bridge the gap between the abstract realms of astrophysics and the tangible expressions of artistic creativity [15].

In the grand tapestry of the cosmos, the symphony of cosmic origins continues to unfold. Through the fusion of futuristic cosmic sound sculptures and the artistic expression inspired by the discovery of the cosmic microwave background, we embark on a journey that transcends the limits of imagination.

Standing at the intersection of art and astrophysics, we witness the birth of a new era – an era where the cosmic symphony is not merely observed but actively participated in. The resonance of the universe, captured in the complex melodies of these sculptures, invites us to explore, connect, and marvel at the profound beauty lying beyond the stars. In this cosmic dance, humanity takes its place as a harmonious note in the ever-expanding symphony of the cosmos.

As we listen to the cosmic symphony through these sculptures, we become witnesses to the universe's poetic evolution. From the fiery crescendo of the Big Bang to the delicate notes of acoustic oscillations, the sculptures encapsulate the grandeur of cosmic history. Through the harmonious collaboration of science and art, we not only perceive the echoes of the past but also glimpse the infinite possibilities that resonate in the cosmos. In this fusion of disciplines, the sculptures stand as testaments to the enduring quest to comprehend the cosmos' melodies and unlock the secrets of its primordial composition.

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