

How to Find the Lowest Temperature in the Universe: Scientific Methods for Exploring Cosmic Extremes

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ABSTRACT

Temperature is one of the most fundamental physical quantities describing the state of matter and energy in the universe. The search for the lowest temperature in the universe represents a profound scientific challenge that connects thermodynamics, quantum physics, astrophysics, and cosmology. According to the laws of physics, absolute zero (0 K, equivalent to -273.15°C) represents the theoretical limit at which all classical thermal motion ceases. However, reaching and measuring temperatures close to absolute zero requires highly sophisticated techniques because quantum fluctuations remain even at extremely low temperatures. This study reviews the methods used to identify the coldest environments in the universe, including astronomical observations of cosmic background radiation, interstellar molecular clouds, planetary environments, and laboratory-created ultracold matter. It discusses the principles of temperature measurement, observational challenges, and the role of advanced technologies such as radio astronomy, space telescopes, laser cooling, and quantum sensors. Understanding the lowest temperatures in the universe provides insights into the origins of cosmic structures, quantum states of matter, and the fundamental limits of physical reality.

Keywords: Absolute Cero; Quantum Fluctuations; Cosmic Background Radiation; Laboratory-Created Ultracold Matter; Origins of Cosmic Structures

INTRODUCTIONS

The search for the lowest temperature in the universe is one of the most fascinating questions in modern science. Temperature determines the behavior of matter, influencing everything from chemical reactions to the formation of stars and galaxies. While humans commonly experience temperatures ranging from hundreds of degrees Celsius, the universe contains regions that are either extremely hot or extraordinarily cold. The interior of stars reaches millions of degrees, whereas distant cosmic environments (Mondai et al., 2026) can approach temperatures only slightly above absolute zero. Finding the coldest place in the universe requires answering two fundamental questions: what is the lowest possible temperature allowed by physics, and how can scientists measure such extreme conditions? The theoretical lower limit is absolute zero, defined as 0 Kelvin (K) (Zhang et al., 2026). At this temperature, a system reaches its minimum possible thermal energy. However, according to quantum mechanics, particles cannot completely stop moving because of quantum fluctuations and the Heisenberg uncertainty principle (Lam et al., 2026). Scientists investigate the coldest

temperatures through two approaches. The first is astronomical observation, where researchers search for naturally occurring cold regions across the cosmos. The second is laboratory experimentation, where advanced technologies create artificial environments approaching absolute zero. Together, these approaches reveal how matter behaves under extreme conditions and improve our understanding of quantum phenomena (Angius et al., 2026) (Figure.1).

RESEARCH METHODOLOGY

This study adopts an interdisciplinary research methodology combining astrophysics, quantum physics, and experimental cryogenic science to investigate how the lowest temperatures in the universe can be identified and measured. Astrophysics is the branch of physics that applies the laws of physics to understand the origin, structure, evolution, and behavior of the universe and its celestial objects (Thomas et al., 2026). Quantum physics is the fundamental study of matter and energy at the most microscopic scales, typically at or below the level of atoms and subatomic particles (Harlow et al., 2026). While classical physics governs our visible, day-to-day world (like gravity and moving cars), the quantum world operates under an entirely different, highly mathematical, and often counterintuitive set of rules. First, a comprehensive literature review is conducted to examine theoretical foundations of absolute zero, thermodynamics, quantum mechanics, and modern temperature measurement techniques. Scientific observations from cosmic missions, including measurements of the cosmic microwave background (CMB) (Kim et al., 2026), are analyzed to determine large-scale universal temperatures and their evolution over time. Second, observational astronomy methods are evaluated, including radio astronomy and spectroscopy, to investigate naturally occurring ultracold environments such as interstellar molecular clouds and the Boomerang Nebula. Spectral line analysis of molecules provides indirect estimates of particle motion and thermal energy in extremely cold regions. Third, laboratory-based approaches are examined through analysis of laser cooling, magnetic evaporative cooling, and Bose–Einstein condensate (BEC) (Chavanis, 2025) experiments. These methods demonstrate how researchers experimentally approach temperatures within billionths of a Kelvin above absolute zero. Finally, this study compares natural and artificial ultracold environments using theoretical modeling and quantitative analysis of temperature limits, measurement uncertainty, and quantum effects. The methodology emphasizes that identifying the lowest temperature requires integrating astronomical observations with advanced quantum technologies, while recognizing the fundamental limitations imposed by thermodynamics and quantum mechanics. This framework provides a systematic approach for exploring the ultimate thermal boundaries of the universe.

The Concept of Absolute Zero and Temperature Measurement

Temperature is a measure of the average kinetic energy of particles within a system. In classical physics, lower temperature means slower particle motion. The Kelvin temperature scale begins at absolute zero: $0\text{K} = -273.15^\circ\text{C}$. At absolute zero, a system has the lowest possible internal energy. However, reaching exactly 0K is impossible according to the third law of thermodynamics. As a system approaches absolute zero, removing additional energy becomes increasingly difficult, requiring infinite effort in theory. At extremely low temperatures, classical concepts of temperature become insufficient. Quantum mechanics becomes dominant. Atoms and particles occupy discrete energy states, and even at the lowest energy state they retain

zero-point energy. Therefore, scientists define ultracold conditions not by complete absence of motion but by how close a system approaches its quantum ground state. Measuring extremely low temperatures requires specialized instruments. Traditional thermometers cannot function at temperatures near absolute zero because their materials lose conventional thermal properties. Instead, scientists use indirect measurement techniques, including spectroscopic measurements – analyzing radiation emitted or absorbed by atoms and molecules, Doppler broadening analysis, measuring particle velocities through changes in spectral lines, quantum thermometry, using atomic transitions and quantum states as temperature indicators and cosmic radiation measurements, determining temperatures from background electromagnetic radiation.

Searching for the Coldest Places in the Universe

The Cosmic Microwave Background: The Temperature of the Universe

The largest-scale search for the lowest cosmic temperature begins with the universe itself. The cosmic microwave background (CMB) is the residual radiation left from the Big Bang approximately 13.8 billion years ago. This radiation fills all space and provides a measurement of the average temperature of the universe. Observations from satellites such as the Planck spacecraft have measured the temperature of the CMB at approximately: 2.725K. This means that most of the universe is naturally colder than any environment found on Earth. As the universe expands, the wavelength of this radiation increases and its temperature gradually decreases. In the distant future, the universe may approach temperatures even closer to absolute zero. However, the CMB is not the coldest location. Local regions within the universe can become colder due to expansion, shielding from radiation, or special physical processes.

Interstellar Space and Molecular Clouds

Between stars exists the interstellar medium, consisting of gas, dust, and magnetic fields. Although space appears empty, it contains particles that can exchange energy with radiation. Dense molecular clouds, where stars are born, can reach temperatures of only about 10 K or slightly lower. These cold environments allow molecules such as carbon monoxide, ammonia, and hydrogen to form. Astronomers measure these temperatures using radio telescopes that detect molecular emission lines. Radio astronomy is particularly important because cold objects emit primarily at long wavelengths. Optical telescopes cannot easily detect very cold environments because they emit little visible light.

The Boomerang Nebula: A Natural Cosmic Refrigerator

One of the coldest known natural environments is the Boomerang Nebula. This object is produced by a dying star ejecting gas at extremely high velocity. The rapid expansion causes adiabatic cooling, similar to how compressed gas becomes cold when released. Measurements indicate that parts of the Boomerang Nebula reach temperatures of approximately: 1 K. This is colder than the cosmic microwave background. The Boomerang Nebula demonstrates that local physical processes can create temperatures below the average temperature of the universe.

Laboratory Methods for Creating the Coldest Temperatures

Although astronomical environments are extremely cold, laboratories on Earth have achieved even lower temperatures.

Laser Cooling

Laser cooling uses precisely tuned laser beams to slow atomic motion. When photons collide with atoms, they transfer momentum and reduce the atoms' kinetic energy. This technique allows scientists to cool atoms to microkelvin (millionths of a Kelvin) and even nanokelvin temperatures. Laser cooling has transformed physics by enabling detailed studies of quantum behavior, atomic clocks, and Bose–Einstein condensates.

Magnetic Evaporative Cooling

After laser cooling, scientists often use magnetic traps to remove the most energetic atoms. Similar to evaporation cooling in everyday life, the fastest atoms escape, leaving behind a colder population. This method has produced temperatures within billionths of a Kelvin above absolute zero.

Bose–Einstein Condensates

At extremely low temperatures, atoms can enter a unique quantum state called a Bose–Einstein condensate (BEC). In this state, thousands or millions of atoms behave as a single quantum object. BEC experiments allow researchers to study: (1) quantum superfluidity, (2) particle interactions, (3) quantum computing technologies and (4) fundamental properties of matter. The lowest temperatures ever achieved by humans have occurred in these carefully controlled laboratory systems.

Space-Based Experiments for Extreme Cooling

Space provides unique opportunities for studying ultracold physics because microgravity reduces disturbances caused by Earth's gravity. The International Space Station has hosted experiments involving ultracold atoms. Space-based cooling technologies allow researchers to maintain quantum states for longer periods and investigate physics that is difficult to observe on Earth. Future space missions may create even colder environments by combining: (1) passive radiative cooling, (2) cryogenic technology, (3) quantum sensors and (4) deep-space conditions. These technologies could approach temperatures closer to absolute zero than current terrestrial systems.

Challenges in Finding the Lowest Temperature

Determining the coldest temperature in the universe is challenging for several reasons.

First, temperature measurements require extremely sensitive instruments. At nanokelvin scales, even tiny environmental disturbances, such as electromagnetic radiation or mechanical vibrations, can significantly affect results. Second, the universe is constantly changing. Cosmic expansion continuously lowers the average temperature, meaning the coldest natural environments may exist in remote and unexplored regions. Third, temperature itself becomes complicated at quantum scales. Traditional concepts based on particle motion are replaced by quantum energy distributions, requiring new definitions and measurement approaches. Finally,

scientists must distinguish between the temperature of matter and the temperature of radiation. A region may contain extremely cold particles while still being exposed to warmer background radiation.

Future Directions

Future discoveries about the lowest temperatures in the universe will likely come from improvements in both astronomy and quantum technology. Advanced telescopes will search for colder cosmic environments by detecting faint infrared and microwave signals. Next-generation quantum laboratories will create more controlled ultracold systems approaching the fundamental limits of physics. Possible future research areas include: (1) Detecting naturally occurring environments below 1 K. (2) Studying quantum states of matter at extreme cold. (3) Developing quantum computers based on ultracold atoms. (4) Investigating dark matter through low-temperature detectors. (5) Understanding the thermal evolution of the universe. The search for the lowest temperature is not merely a measurement challenge; it is a pathway toward understanding the fundamental laws governing reality.

DISCUSSION

The search for the lowest temperature in the universe represents one of the most profound scientific efforts to understand the fundamental limits of matter, energy, and cosmic evolution. The discussion of extreme cold requires a transition from classical thermodynamics toward quantum physics, because temperature near absolute zero no longer behaves according to everyday intuition. Although absolute zero (0 K) represents the theoretical point at which a system reaches its minimum possible energy state, the third law of thermodynamics demonstrates that this condition cannot be achieved through any finite physical process. Therefore, the scientific goal is not to reach exactly zero Kelvin but to approach increasingly closer temperatures while exploring the quantum phenomena that emerge under such conditions. The identification of the coldest locations in the universe reveals an important distinction between average cosmic temperature and local extreme environments. The cosmic microwave background provides the most comprehensive measurement of the universe's thermal state, with a temperature of approximately 2.725 K. This value reflects the thermal history of the universe after the Big Bang and demonstrates how cosmic expansion has continuously reduced the energy density of radiation. However, the CMB temperature does not represent the absolute coldest environment. Local astrophysical processes, such as rapid gas expansion, molecular cloud formation, and radiation isolation, can produce regions with lower temperatures. The Boomerang Nebula is a significant example because its adiabatic expansion has created temperatures near 1 K, showing that natural mechanisms can generate colder conditions than the universal radiation background. The study of interstellar molecular clouds further demonstrates the complexity of measuring cosmic temperatures. These regions contain extremely cold gases where atoms and molecules interact weakly with their surroundings. Because such environments emit little visible radiation, traditional astronomical observations are insufficient. Instead, scientists rely on radio astronomy and molecular spectroscopy to determine temperature through the energy distribution of molecular transitions. These techniques illustrate that temperature in the universe is often inferred indirectly through physical indicators rather than measured by conventional thermometers. Laboratory experiments have achieved temperatures far below naturally occurring cosmic environments, demonstrating humanity's ability to engineer extreme physical conditions. Laser cooling, magnetic

evaporative cooling, and Bose–Einstein condensation have enabled researchers to cool atomic systems to nanokelvin levels above absolute zero. These achievements have expanded knowledge of quantum mechanics by allowing direct observation of quantum behaviors, including superfluidity, quantum coherence, and collective atomic states. Unlike astrophysical environments, laboratory ultracold systems provide controlled conditions where scientists can isolate specific quantum effects and investigate the fundamental properties of matter. Space-based ultracold experiments represent another important direction in this field. Microgravity environments reduce gravitational disturbances and allow quantum systems to remain stable for longer periods. Experiments conducted in space may provide opportunities to achieve colder temperatures and improve precision measurements beyond terrestrial limitations. The combination of cryogenic technology, quantum sensors, and passive cooling methods could significantly advance future exploration of extreme thermal states. Despite major achievements, defining the “lowest temperature in the universe” remains scientifically challenging. Temperature is not simply a property of location but depends on the physical system being measured, including particles, radiation, and quantum states. A region may contain extremely cold matter while still interacting with warmer background radiation. Furthermore, as cosmic expansion continues, future regions of the universe may naturally approach temperatures closer to absolute zero. However, observing such environments requires increasingly sensitive instruments capable of detecting extremely weak signals. Future research will likely integrate astronomical observation with quantum technology. Advanced microwave and infrared telescopes may discover colder natural environments, while next-generation quantum laboratories will continue approaching the fundamental cooling limits imposed by physics. These investigations may contribute to broader scientific questions, including the nature of dark matter, quantum information processing, and the long-term thermal evolution of the universe. Ultimately, the search for the lowest temperature is not only an attempt to find the coldest place but also a scientific journey toward understanding the relationship between energy, matter, and the origin and future of the cosmos.

CONCLUSION

The search for the lowest temperature in the universe represents one of the most profound scientific investigations into the limits of matter, energy, and the fundamental laws of physics. Although absolute zero (0 K) defines the theoretical minimum temperature, the third law of thermodynamics demonstrates that this state cannot be completely achieved because removing the final amount of thermal energy would require infinite effort. Instead, modern physics focuses on approaching the quantum ground state, where classical descriptions of motion are replaced by quantum phenomena such as zero-point energy, discrete energy levels, and collective quantum behavior. Scientific exploration of cosmic and laboratory cold environments has revealed that temperature is not a single universal condition but a property shaped by local physical processes. The cosmic microwave background provides the average temperature of the universe at approximately 2.725 K, representing the thermal legacy of the Big Bang. However, colder environments exist, including dense molecular clouds and the Boomerang Nebula, where expansion-driven cooling can reduce temperatures below the cosmic background. These discoveries demonstrate that the coldest regions of the universe are determined not only by cosmic expansion but also by specific astrophysical mechanisms. On Earth, advanced cooling technologies have surpassed natural cosmic temperatures. Laser cooling, magnetic evaporative cooling, and Bose–Einstein condensate experiments have allowed scientists to create environments within billionths of a

Kelvin above absolute zero. These achievements have provided essential insights into quantum mechanics, superfluidity, quantum computing, precision measurement, and the fundamental behavior of matter.

Furthermore, space-based ultracold experiments offer new opportunities to reduce environmental disturbances and explore quantum states under microgravity conditions. Future investigations combining advanced telescopes, quantum sensors, cryogenic technologies, and space-based laboratories will continue to push the boundaries of temperature measurement. The pursuit of the lowest temperature is not simply a search for the coldest location; it is an effort to understand the relationship between energy, matter, and the evolution of the universe itself. By exploring extreme cold, scientists gain access to previously unreachable physical regimes and develop technologies that may transform quantum science, astronomy, and our understanding of the fundamental structure of reality.

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Compliance with ethical statements consisting of conflicts of interest statements and informed consent

- All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.
- The author declares that there are no conflicts of interest.
- Informed consent was obtained from all individual participants involved in the study.
- This work does not include animals as subjects.

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FIGURE CAPTIONS

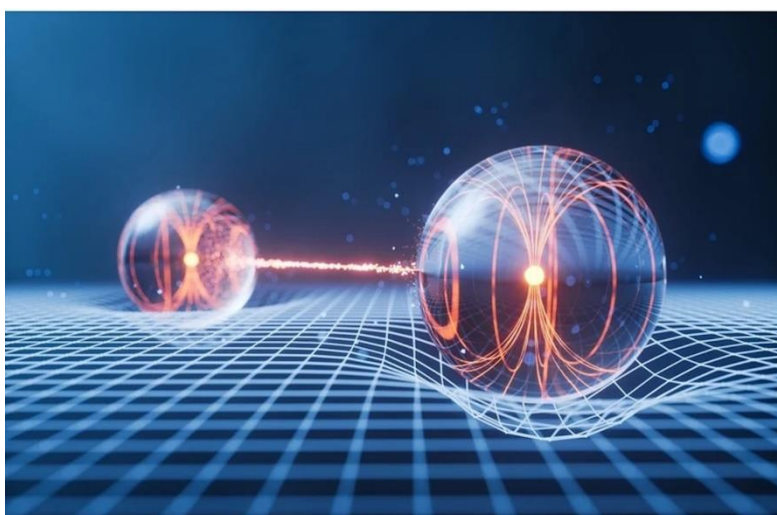


Figure.1 Quantum phenomena refer to the various behaviors and interactions of quantum systems, including principles such as superposition, interference and entanglement, which illustrate the unique characteristics and probabilistic nature of particles at the quantum level.