COLD

Cold, calculating, and extremely sensitive

ABSOLUTE
REST
ABSOLUTE
ZERO

COLD

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ABSOLUTE
ZERO

COLD

In the nineteenth century it was discovered that matter could not get colder than –273.15 degrees in the Celsius scale. A new temperature scale named Kelvin – after physicist William Thomson, Lord Kelvin – renumbered Celsius to assign zero to that newfound lower bound. Zero degrees Kelvin corresponds to the absolute zero of temperature, the absolute cold.

At the absolute zero all motion ceases to exist. The random movement of the microscopic constituents of matter ceases, and every degree of freedom remains frozen and under control. This is certainly not a pleasant place to be, but those are the idyllic conditions for errorless machine performance, in which computers, precision instruments, compasses, and diagnosis tools will work unaffected by the detrimental effects of thermal noise.

As appealing as it seems, the absolute zero is unreachable. Even in deep space, the background radiation filling the whole Universe since the Big Bang "keeps the vibe" at 3 K. If you were lucky enough to get to some interstellar objects made of expanding gases, like the Boomerang nebula, you could get cooler than that and drop to 1 K. Indeed, cooling by expansion of gases is the principle behind freezers and air conditioning, and it also explains why spray deodorants are so cold. The principle was discovered (again) by Lord Kelvin and had a central role in the development of thermodynamics, the physics of heat and cold. Learning to direct heat pushed steam trains forward while schemes to procure cold revolutionized the industry and commerce of food and products. At a more fundamental level, it propelled low-temperature labs worldwide into a hectic race to get closer and closer to the unreachable absolute zero. This race holds the key to understanding why we are now reaching temperatures of only millionths of billionths of a degree (and dropping).[1]

In 1908, the physicist Heike Kamerlingh Onnes got himself a prominent place in the competition, achieving a record temperature of 2.4 K with the liquefaction of helium. However, Onnes was not interested in the record itself, rather his motivation was confirming the existing theories about the behavior of metals at very low temperatures. He did not, however, find what he expected. Instead, he observed the first macroscopic manifestation of quantum mechanics. By then it was 1911, and the foundations of quantum mechanics were being laid. It took several years to understand that Onnes' surprising experiments produced an exotic state of matter in which electrical resistance vanishes: superconductivity.[2] Nowadays, superconductors support super-fast levitating trains and yield high-definition brain images.

At very low temperatures, quantum phenomena find a peaceful environment in which to emerge. Cold reduces almost all noise and uncontrolled mechanisms in atoms, revealing their quantum-mechanical behavior at large scales. If we could manipulate the quantum information stored in atoms, we could perform quantum computation, metrology, and sensing tasks that outperform their classical counterparts. This is why we want it cold. Light, through laser cooling, is the number one cooling agent, and through light–matter interactions it gives us direct access to and control of the quantum states of atoms.

[1] Yes, probably, the coldest points in the whole Universe are the low-temperature labs!
[2] The microscopic theory of superconductivity at low T was provided by Bardeen, Cooper and Schrieffer in 1957. We are still missing a fully satisfactory explanation of high-temperature superconductivity.

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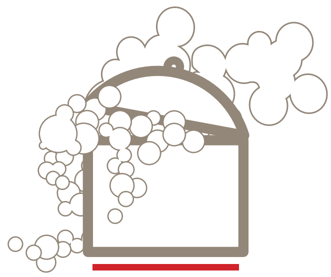
High temperature
means intense agitation and collisions.



At low temperatures,
particles are stiller, more calm and ordered.

At temperatures near the

absolute zero

atoms get **ultracold, calculating… and very, very sensitive.**

We could get extraordinary things from them, but they need to be treated with the lightest touch.

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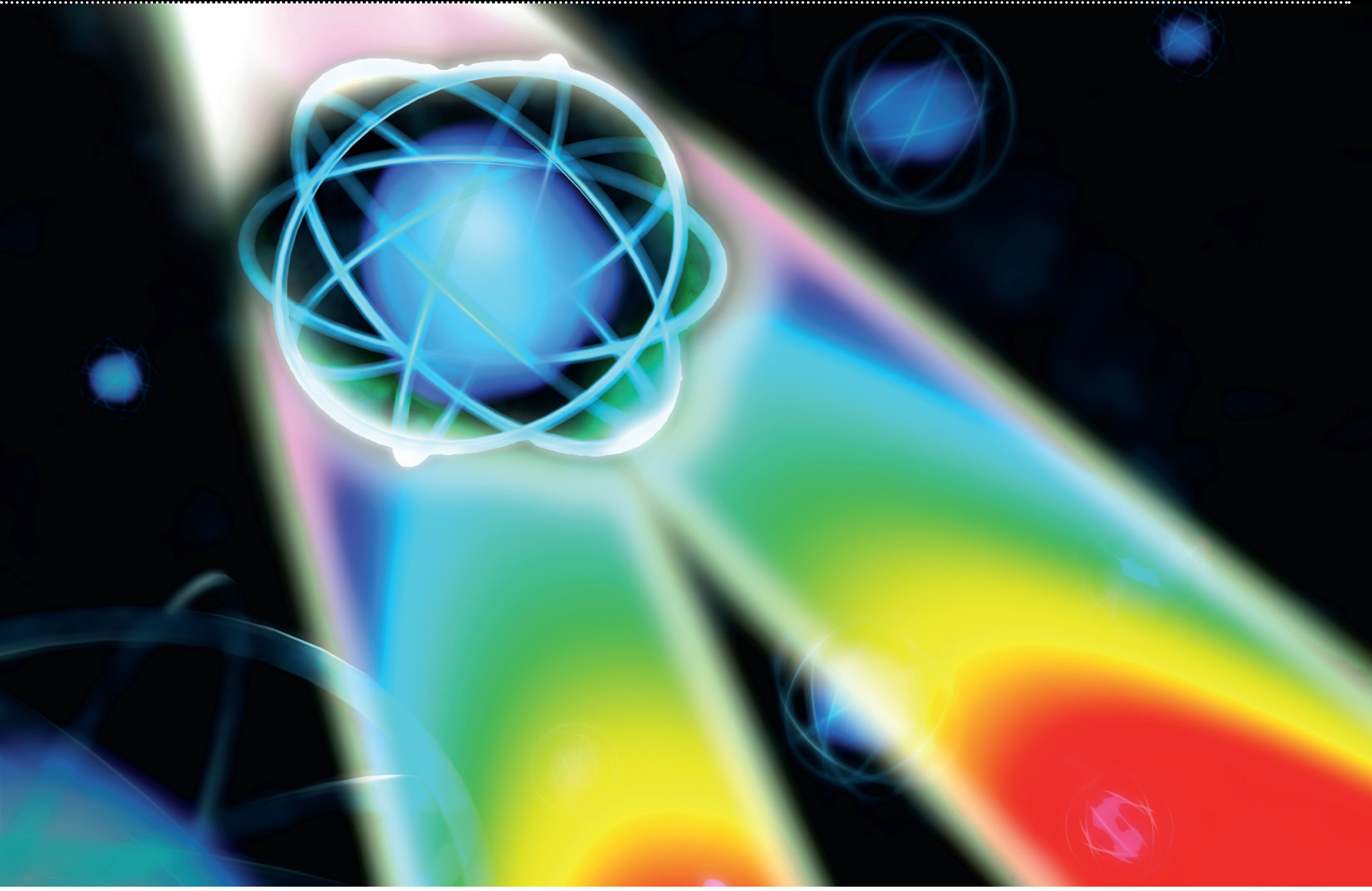
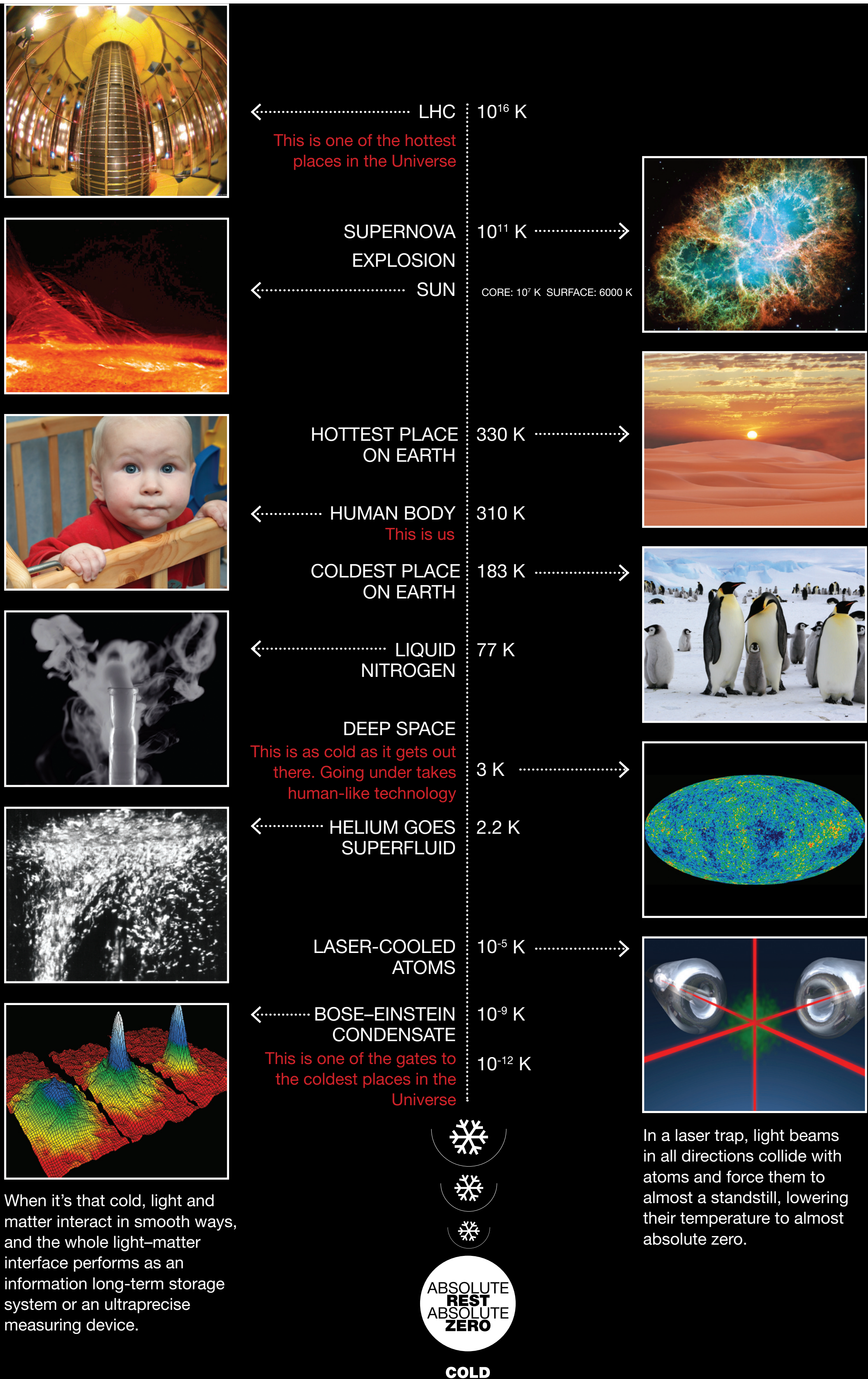
Laser cooling is a key step in the quest for **absolute zero**. It allows us to record microkelvin and subsequently nano- and picokelvin temperatures. At these regimes, quantum light–matter interactions find applications in quantum technologies as well as in the study of fundamental physics.

The mechanism behind laser cooling arises from the quantum features of quantum light–matter interaction. Photons are energy packages. Electrons, orbiting the atoms structured in **quantized** energy levels, can absorb or emit a photon when the energy it carries matches the energy difference between electronic transitions. Laser-cooling techniques enforce that when light is sent through an atomic ensemble, each atom is cooled by absorbing and re-emitting photons. When the photons leave the system, they take with them most of the heat and leave the atoms almost at rest – almost at absolute zero.

In a standard laser-cooling setting, a sample of alkali atoms (sodium, potassium, rubidium, cesium) is cooled to around 100 microkelvin with a combination of magnetic and optical forces. **Near-infrared** laser beams of a few milliwatts in all six directions slow down the atoms as a result of photon–atom **momentum** transfer, cooling the sample below 100 microkelvin in a few milliseconds. Evaporative cooling to a few nanokelvin is then achieved by confining the atoms in a **magnetic trap** and allowing the hottest atoms to escape. Further cooling to picokelvin is demonstrated by removing more energy from the atoms interacting with their **internal spin state**.





When it's that cold, light and matter interact in smooth ways, and the whole light–matter interface performs as an information long-term storage system or an ultraprecise measuring device.

In a laser trap, light beams in all directions collide with atoms and force them to almost a standstill, lowering their temperature to almost absolute zero.

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Glossary

ABSOLUTE ZERO The lowest possible temperature that is theoretically possible, at which the motion of particles that constitutes heat ceases completely. It corresponds to –273.15 °C on the Celsius temperature scale and to –459.67 °F on the Fahrenheit temperature scale.

INFRARED The portion of the electromagnetic spectrum extending from the red end of the visible region to the microwave range. The infrared range is usually divided into three regions: near-infrared, from 700 nm to 2 μm; medium-infrared, from 2 μm to 4 μm; and far-infrared, from 4 μm to 1 mm.

LASER Acronym for Light Amplification by Stimulated Emission of Radiation. A laser produces a highly coherent, highly directional, and nearly monochromatic beam of light, by stimulating atoms or molecules to emit light at particular wavelengths and amplifies that light, typically producing a very narrow beam of radiation.

MAGNETIC TRAP An apparatus which uses a magnetic field gradient to trap neutral particles with magnetic moments.

MOMENTUM The quantity of motion of a moving body.

QUANTIZED ENERGY LEVELS In an atom, they restrict the energy of electronic orbitals around the nucleus to assume only certain discrete magnitudes.

SPIN The intrinsic angular momentum of an atomic or subatomic particle.

Definitions adapted from
Oxford American English Dictionary
Encyclopaedia Britannica

Relevant reading

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GENTLE

Optical tweezers

GENTLE

GENTLE

Go – from the Japanese word igo, meaning "encircling game" – is a strategy board game that originated in China approximately 3500 years ago. The game starts with an empty grid set on a wooden board. Players then take turns to place black and white stones on the intersections of the crossing lines. The objective of each player is to capture the stones of the opponent. A stone – or chain of connected stones – is captured if all its four degrees of freedom (the four surrounding intersections) are occupied by an opponent's stones. Despite these simple rules, go is a game of extraordinary complexity and beauty. A player in any typical game among experts has an average of a few hundred choices per move, making strategies strongly tied to intuition, experience, and pattern recognition.[1] The players' skills strengthen by learning to identify a certain balance between the territory they give away and the force they exert on the opponent. It is a gentle-strategy game.

The lack of skillfulness typically results in pushing the opponent's beads instead of encircling them. Successful encircling calls for a delicate, wise balance between force and territory, limiting and yielding, pushing and letting go. A suitable way to go: attack from the corners. Continue along the sides. Move into the center. Trap. The goal is to constrain the freedom of the opponent applying the minimum amount of force.

In Nature, a similar balance sustains the glide of a seagull on a current of air. The form of the wings separates the flow of air molecules so that moving air molecules passing underneath exert a lifting force larger than the downward pressure of those passing above. The resulting force is just enough to compensate gravity and keep the bird in a comfortable flight.

In spirit, a similar balance is the principle behind optical trapping. Photons can exert tiny – but observable – forces by exchanging momentum with very small particles. Without a good strategy, though, photons can only push. If they are to "capture" a particle, photons need to "attack from the corners, continue along the sides, and then move into the center." The photon flow has to be shaped to create a balance of opposite forces on the particle. However, particles do not have wings, and therefore the flow needs to be shaped – focused – with the help of a lens.

This strategy allows the study of the composition, structure, and function of delicate microscopic objects like living cells, organelles, or DNA strands, exerting the right force to trap them under the microscope and leaving them unharmed.

[1] On a 19 x19 matrix, there are at least 10^{480} possible games of go. Shannon gave a number of 10^{120} possible games for chess. The visible Universe is estimated to have between 10^{79} and 10^{81} atoms.