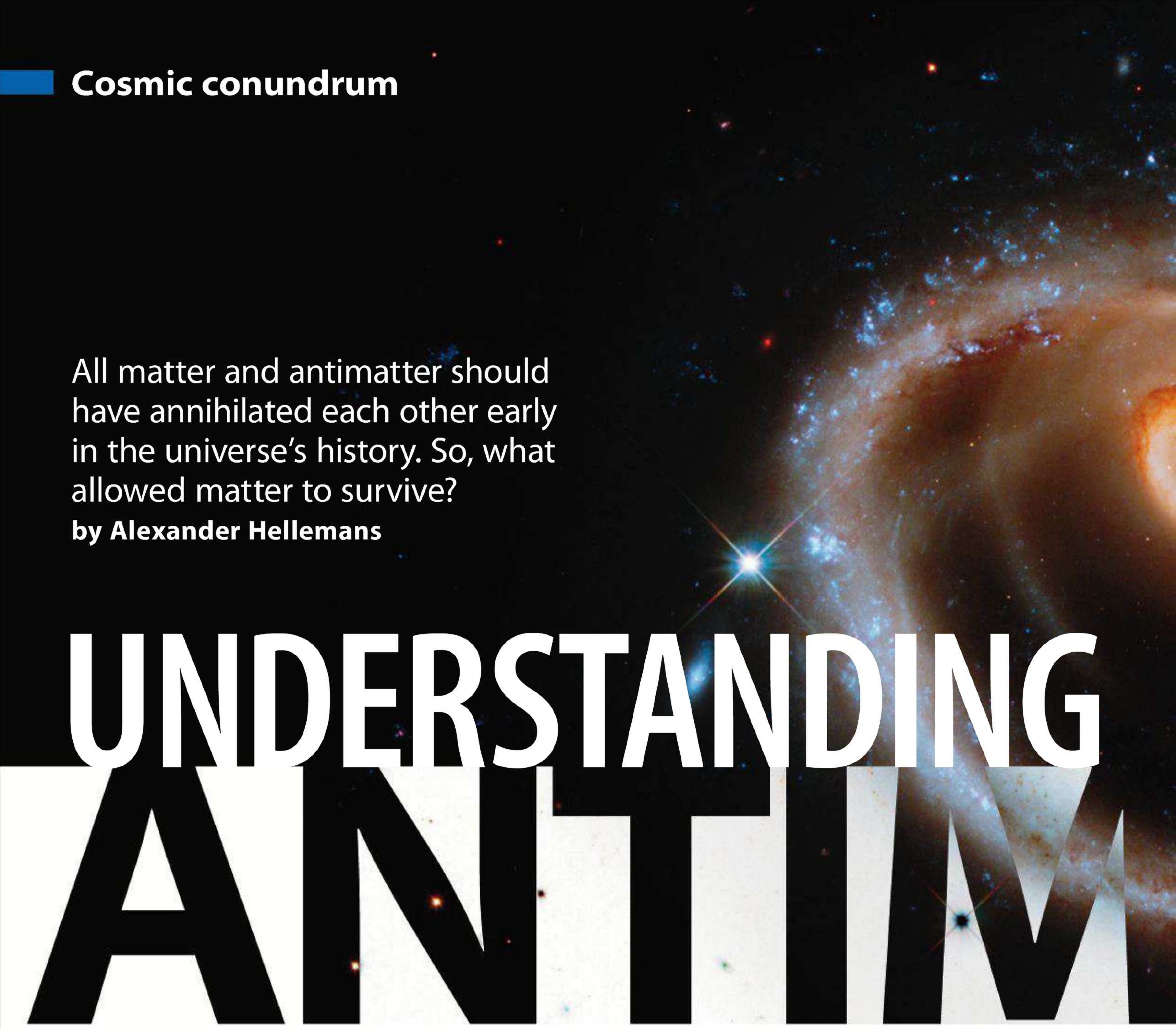


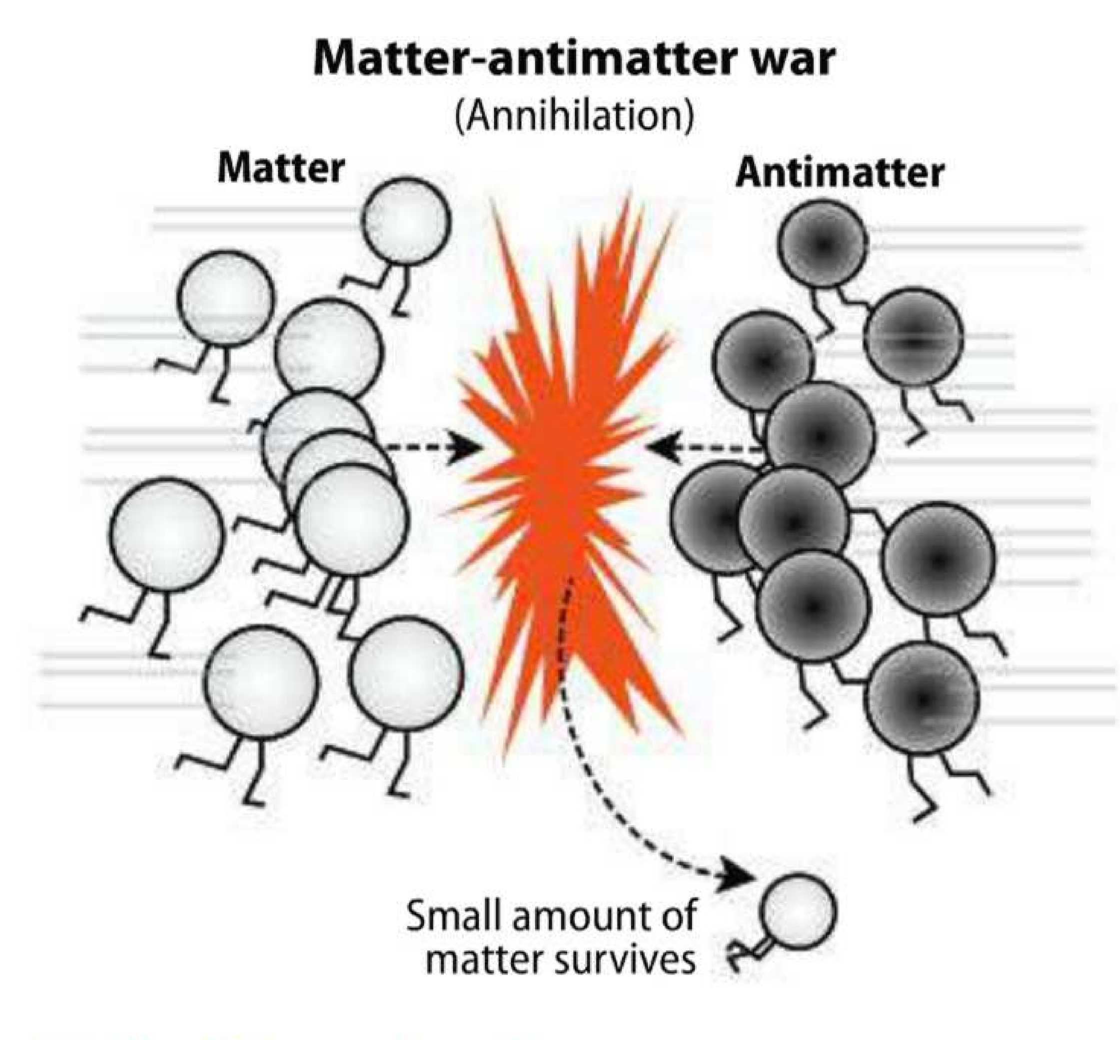
All matter and antimatter should have annihilated each other early in the universe's history. So, what allowed matter to survive?

by Alexander Hellemans

UNDERSTANDING ANTIM

Astrophysical theories say that equal amounts of matter and antimatter appeared in the universe shortly after its beginning. Matter and antimatter cannot coexist, so when they met, they would have immediately annihilated one another. All material would have converted into energy in the form of photons and an enormous flash of radiation.

While most of the universe converted into energy, a tiny amount of matter survived. This residue of the "matter-antimatter war" now forms the stars, planets, and all that we see in the universe. Why this matter survived is what intrigues astrophysicists. It contradicts the current physical theory about matter — the highly successful mathematical framework that scientists have



Antimatter and matter should have annihilated each other in a flash of radiation. Yet somehow, a small amount of matter survived this encounter. Why? All illustrations: *Astronomy*: Roen Kelly

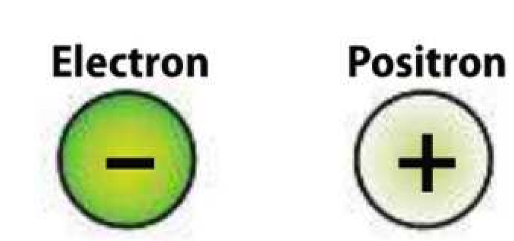
Galaxies of antimatter could exist elsewhere in our universe. Antimatter exhibits the same physical characteristics (such as mass and radiation signature) as normal matter, but it has an opposite charge. NASA/ESA/Hubble Heritage Team (STScI/AURA)

refined since the 1960s called the "standard model of particle physics."

So, what happened? Do we live in a part of the universe that consists entirely of matter, while distant antimatter parts just can't reach our part to cancel normal matter out? Or did something interfere in the annihilation of matter and antimatter after the Big Bang? Could matter and antimatter have slightly different properties, causing some of the former to survive the annihilation? Through the years, scientists have discovered hints, but they still haven't solved this cosmic conundrum. Here's where it stands right now.

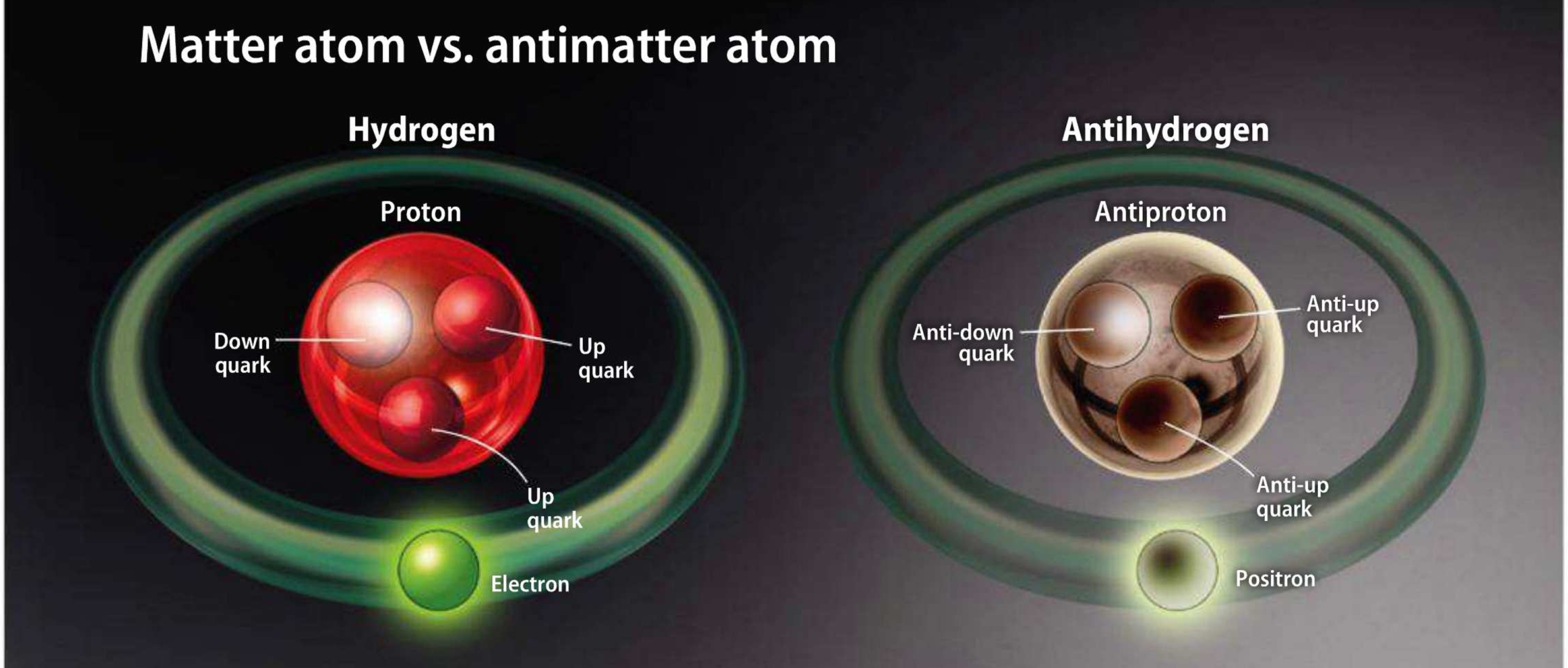
Antimatter worlds

In 1897, British physicist Joseph John Thomson discovered the electron — the elementary particle that carries a negative charge. As early as 1898, German-born British physicist Arthur Schuster suggested in two letters to the journal *Nature* that the electron might have a positive counterpart — now known as the positron — which could be part of what he called "antimatter." Schuster argued that solar systems made up of this antimatter might look just like ours — if they exist.



The positron, the electron's antiparticle, was the first type of antimatter discovered.

Schuster's views were considered science fiction until 30 years later, when British physicist Paul Dirac mathematically predicted the existence of the positron. By combining quantum theory with Albert Einstein's special theory of relativity, he devised an equation for the



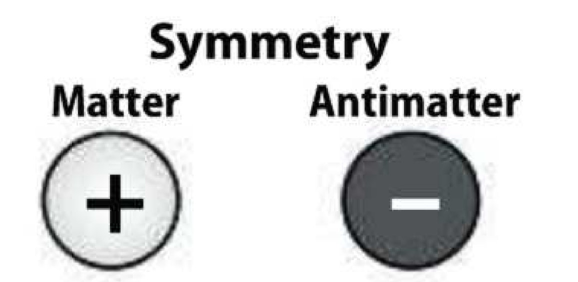
A hydrogen atom is made up of an electron and a proton (two "up quarks" and one "down quark"). An antihydrogen atom is exactly opposite — it holds a positron and an antiproton (two anti-up quarks and one anti-down quark). *Astronomy*: Roen Kelly

behavior of electrons that also required the existence of an electronlike particle with a positive charge. He predicted that for every matter particle, an antimatter partner would exist — one that is identical except for its charge. And just like Schuster, Dirac argued that parts of the universe could consist of antimatter.

In 1931, Carl Anderson, a physicist at the California Institute of Technology in Pasadena, discovered the first direct evidence of positrons. He was studying the composition of cosmic radiation using a cloud chamber — a device consisting of a transparent container filled with saturated water vapor or alcohol vapor and placed in a magnetic field. The magnetic field affects — and curves — elementary charged particles, leaving "ionization tracks" in the vapor. The electrons all followed paths deflected in one direction, but Anderson observed similar particles deflected in the opposite direction. This was proof that the latter particles had a positive charge.

Just like hydrogen, in which an electron binds with a proton, a positron can bind itself to an antiproton to form an antihydrogen atom.

Because positrons behave similarly to electrons — except for their behavior in magnetic or electric fields — scientists viewed matter and antimatter as being each other's "mirror image." It took more than 2 decades for scientists to discover other antiparticles. As time passed, they became convinced that for every subatomic particle, a matching antiparticle must exist. In 1955, Owen Chamberlain and Emilio Segré discovered the antimatter partner of the proton, the antiproton, in a particle accelerator. Just like hydrogen, in which an electron binds with a proton, a positron can bind itself to an antiproton to form an antihydrogen atom.

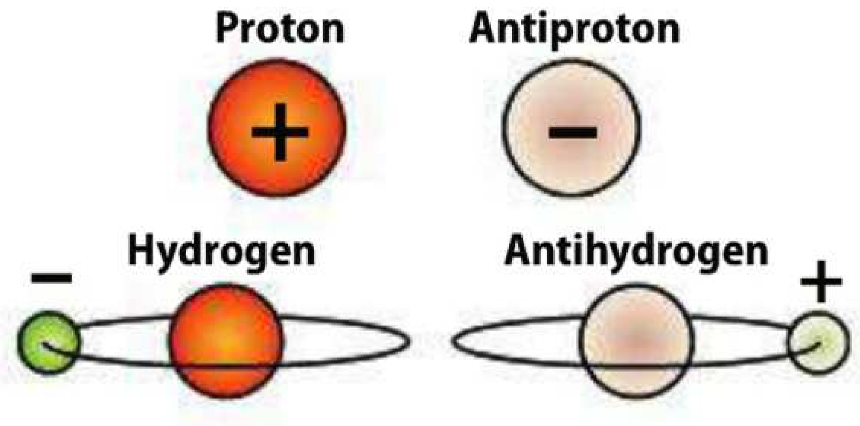


Matter and antimatter share all properties except charge.

According to this research, hydrogen and antihydrogen atoms should behave exactly the same way. This would be true for antimatter in general: Chemical reactions and other physical phenomena — such as the absorption or radiation of light — in an antimatter world would happen exactly the same way as in a matter world. For example, antimatter "water" would boil and freeze at exactly the same temperatures as normal water. Antimatter gas would display exactly the same absorption or emission spectrum as its matter counterpart. This property, in which matter and antimatter mirror each other by containing particles with opposite charges, is called symmetry. It's a fundamental law in physics, and it's the reason astrophysicists cannot distinguish atoms and anti-atoms in distant celestial objects — their spectra are identical.

Looking in space

Because an antimatter galaxy would be spectroscopically indistinguishable from a matter galaxy, scientists are looking for other smoking guns of antimatter. An antimatter galaxy would give itself away by the gamma-ray signature it produces. As particles



Both hydrogen and antihydrogen atoms have the same physical characteristics, like chemical reactions and spectra. So, scientists can't differentiate hydrogen from antihydrogen in distant objects.

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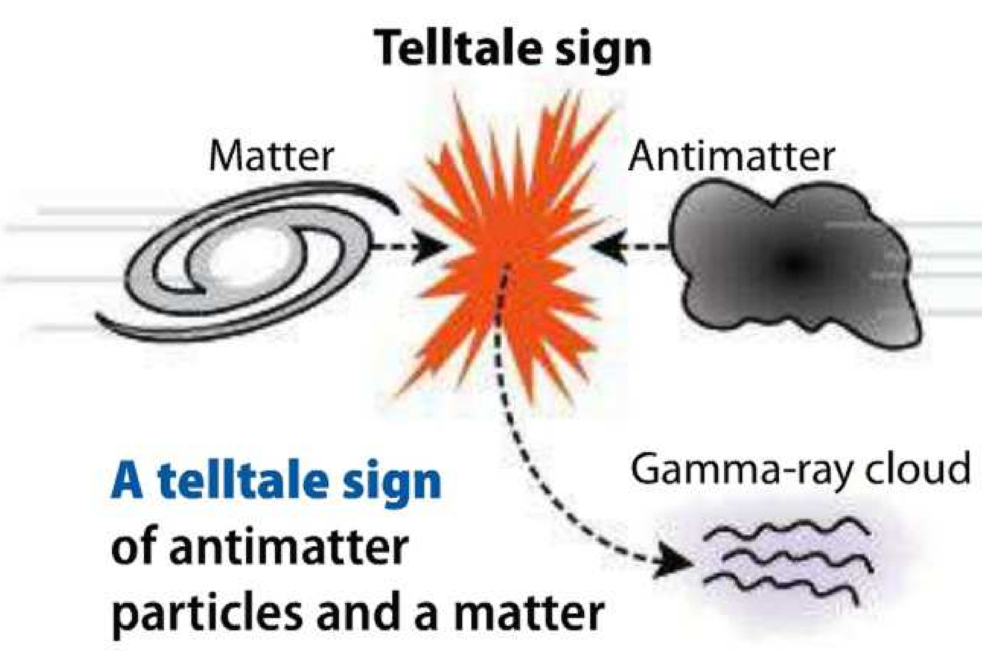
in a galaxy interact with intergalactic antimatter particles, they'd annihilate each other and produce a cloud of high-energy gamma rays. Scientists have not yet observed such halos, says Alexander Dolgov, a physicist at the Institute for Theoretical and Experimental Physics in Moscow, Russia, and the University of Ferrara in Italy. "Big amounts of antimatter gas are excluded, but if we have [specific objects, like] white dwarfs, neutron stars, or even normal stars of antimatter, it would be very difficult to observe them."

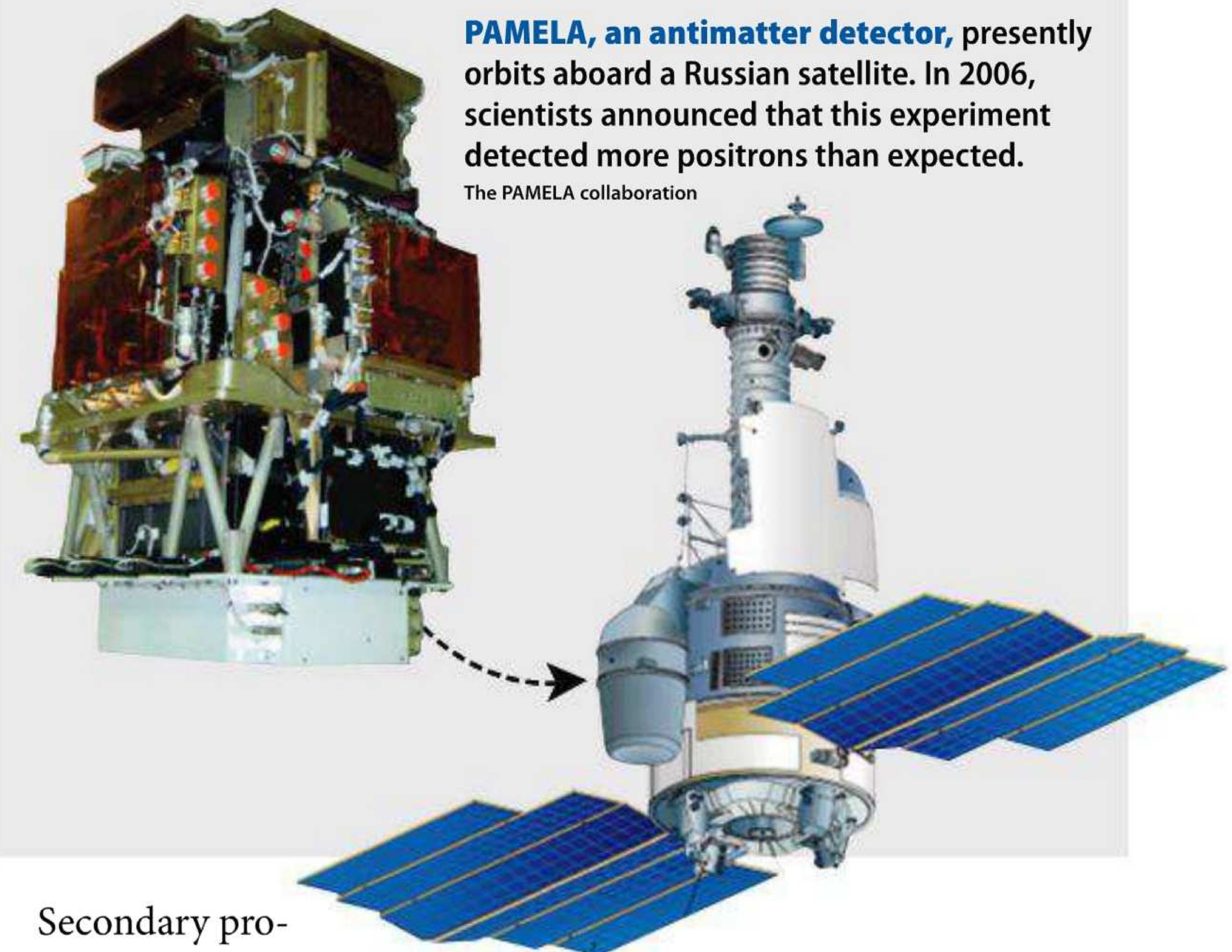


A telltale sign of antimatter particles and a matter galaxy interacting would be high-energy gamma rays.

Another approach is to look for antiparticles that might reach us, and here the results have been more encouraging. Because all antiparticles entering Earth's atmosphere would immediately annihilate with particles in the air, researchers look for antiparticles by using detectors above the atmosphere. The Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA), an Italian/Russian collaboration that launched in June 2006, discovered an intriguing excess of positrons. "This caused a lot of excitement among theorists," remembers Sacha Davidson, a theoretical physicist at the University of Lyon in France. "This excess of antimatter is there, but where does it come from?" she asks.

These particle tracks show an antihydrogen atom that converted into elementary particles. CERN

An antimatter detector



PAMELA, an antimatter detector, presently orbits aboard a Russian satellite. In 2006, scientists announced that this experiment detected more positrons than expected. The PAMELA collaboration

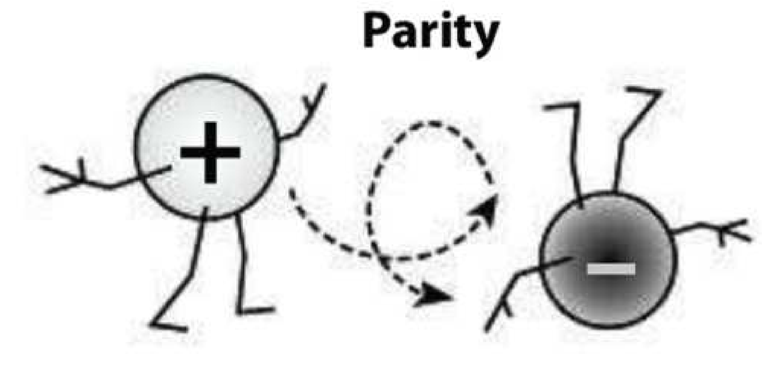
Secondary processes in pulsars and supernovae could create these positrons, argues Dolgov. "If you could find antihelium, or something [atomically heavier], it would be a real discovery because antihelium is not easily produced by secondary processes."

An international collaboration with the European Organization for Nuclear Research (CERN) in Geneva, Switzerland, devised an instrument capable of detecting heavier anti-nuclei. The Alpha Magnetic Spectrometer (AMS) first flew in 1998 aboard the space shuttle *Discovery* for 10 days. AMS-01 detected numerous helium nuclei, but none were antimatter. An updated version, AMS-02, consists of a particle tracker composed of silicon sensors placed inside a magnet to identify charged particles. AMS-02, equipped with a stronger superconducting magnet, headed to the International Space Station May 16, 2011, aboard the space shuttle *Endeavour*. Scientists expect the instrument will search for heavy anti-nuclei over 3 years.

Are matter and antimatter different?

Although there are hopes that scientists can find antimatter in space, many expect that perhaps only matter survived the annihilation after the Big Bang because there are slight differences between the two.

Russian physicist Andrei Sakharov first advanced this asymmetry in 1967. Up to then, physicists had assumed that matter and antimatter behaved exactly the same way, although they "mirrored" each other. One of the basic principles of physics states that a particle and its antiparticle should follow symmetry of characteristics called charge and parity. Charge takes opposite values in particles and antiparticles, while parity indicates

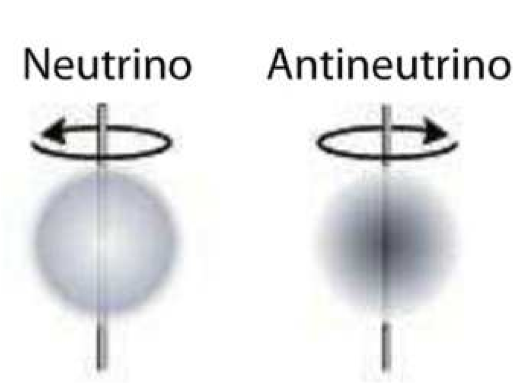


Parity is a property that says particles and antiparticles should be exact "mirrors" of each other in three dimensions.

The laws of physics say that matter and its antimatter counterpart must follow charge-parity (CP) symmetry. However, physicists have found this isn't always the case, which would account for why today's universe has more matter than antimatter. Parity symmetry means that an object and its mirror reflection that is then flipped 180 degrees obey the same laws of physics. This "parity-inverted" particle and its matter counterpart also have opposite charge. *Astronomy*: Roen Kelly

that the property of particles and antiparticles should be exact "mirrors" of each other in all three dimensions. Think of parity as the relationship between two car engines that are mirror images of each other; a car engine and its parity-reversed version should function in exactly the same way and obey the same laws of physics. The spatial configuration stays the same but they're mirrored and then flipped 180 degrees (see diagram above).

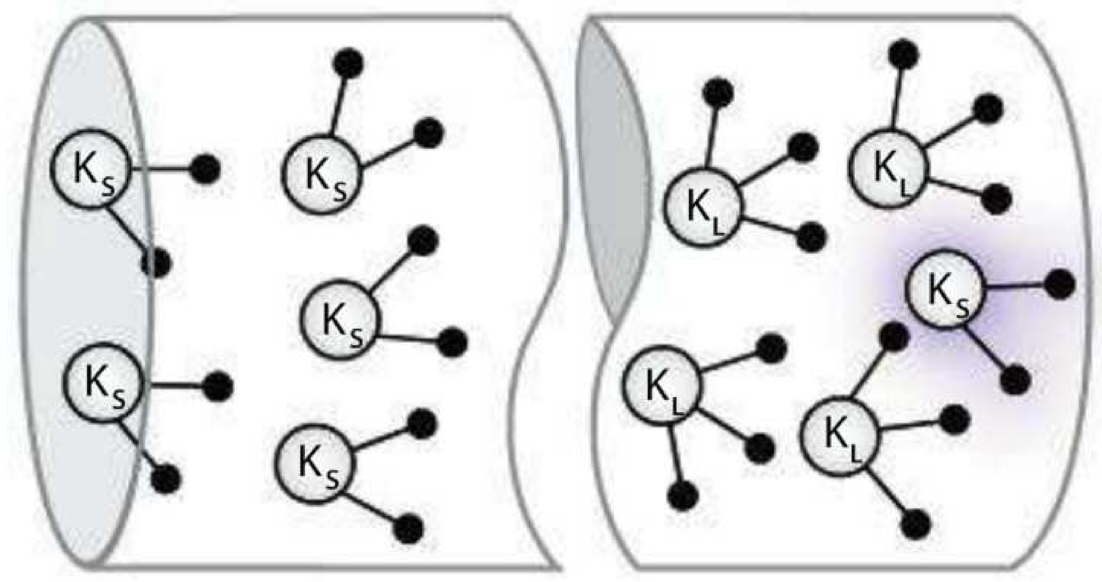
However, in 1957, physicists at Columbia University in New York City announced that this was not true for all particle-antiparticle pairs. Chien-Shiung Wu discovered that parity was not preserved in the force that controls radioactive decay — the so-called weak nuclear interactions. Neutrinos spin *only* left-handedly while antineutrinos spin *only* right-handedly, and "handedness" plays a role in weak interactions. Because neutrinos don't spin right-handedly, this violates the weak interaction. Wu's colleagues at Columbia, Chen-Ning Yang and Tsung-Dao Lee, predicted this property. While Wu's experiments showed that parity isn't preserved, the combination of charge and parity is.



Neutrinos spin only left-handedly while antineutrinos spin only right-handedly. This property violates parity symmetry.

A big surprise came in 1964 when physicists at Princeton University in Princeton, New Jersey, made one of the most important discoveries in physics. Val Fitch and James Cronin found that charge-parity (CP) symmetry was "broken" for the particle K-meson (also known as kaon) — a phenomenon called CP violation. Each meson contains one quark and one antiquark. Fitch and Cronin observed two different types of neutral K-mesons decay at slightly different rates. One type should decay quickly into two pions (these are the "short K-mesons"); the other type should decay slowly into three pions ("long K-mesons").

CP Violation



Two types of neutral K-mesons have different decay times. However, physicists observing particle decays in a long tube found that sometimes the short type violates CP symmetry.

However, Fitch and Cronin observed that a few out of 1,000 of the two-pion decays took too long — it was the first convincing observation that different physical laws govern matter and antimatter. For Sakharov, CP violation was a clear indication that matter and antimatter should not annihilate each other in equal proportions, and thus result in a preponderance of matter in the universe.

Collecting more data

Fast-forward nearly 4 decades. In 2001, researchers from the BaBar collaboration at the SLAC National Accelerator Laboratory in Menlo Park, California, and, independently, the Belle collaboration at the Japanese high-energy accelerator research organization found that B-mesons and their antiparticles also decay at different rates. This discovery of particle-antiparticle pairs that disintegrate at different rates reinforced the idea that matter and antimatter have different properties.

In May 2010, the DZero collaboration at Fermi National Accelerator Laboratory outside Chicago, Illinois, announced the discovery of CP violation in muons and antimuons of about 1 percent. While the discovery of CP violation in K-mesons and B-mesons does not directly contradict the standard model of particle physics, the 2010 discovery does. "The effect is about 50 times larger than what we would expect if this was just the standard model," says Stefan Söldner-Rembold, a particle physicist at the University of Manchester in the United Kingdom and a member of the DZero experiment.

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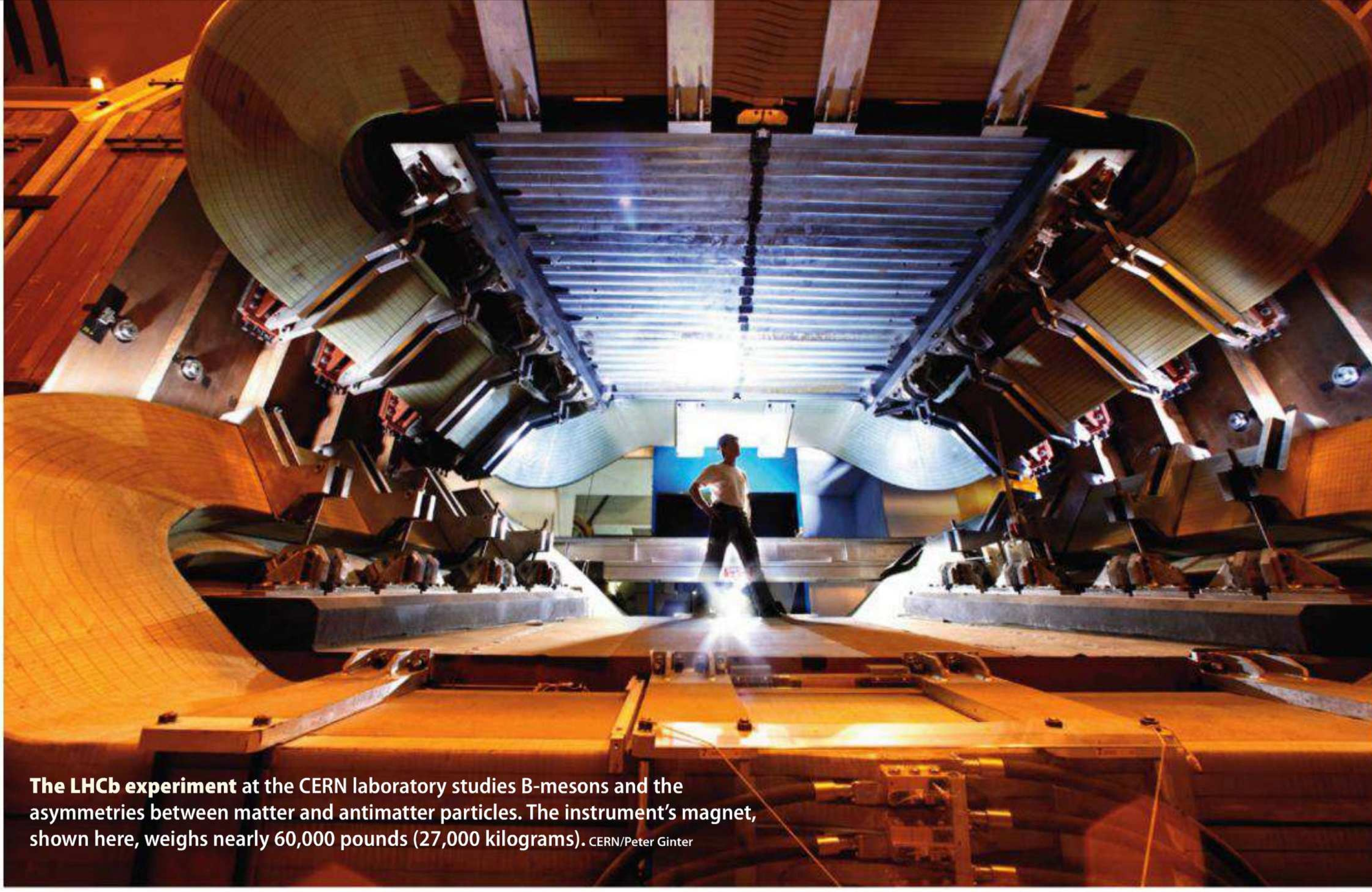
The DZero collaboration announced a confidence level of about 99.7 percent — scientists require 99.99994



The LHCb experiment at the CERN laboratory studies B-mesons and the asymmetries between matter and antimatter particles. The instrument's magnet, shown here, weighs nearly 60,000 pounds (27,000 kilograms). CERN/Peter Ginter

percent to claim a new discovery. The collaboration had hoped to run the experiment until 2014 and collect sufficient data to increase the confidence level; however, researchers will shut down Fermilab's Tevatron in September. Söldner-Rembold is confident the collaboration can still increase the confidence level by then. "Currently, we have recorded about 50 percent more data than what was used for the original measurement, and we hope to get at least another 10 to 20 percent more until September," he says.

In the meantime, scientists at the Large Hadron Collider (LHC) at CERN have also started collecting data for the LHCb experiment. The LHC uses proton-proton collisions while the Tevatron slams protons into their antiproton partners. "The nice thing with a proton-antiproton collision is the completely symmetric state of matter and antimatter in the detector, and it is very easy to interpret any asymmetry you have," says Söldner-Rembold.

However, the much more energetic particle flux of the LHC — some 7 times greater — will be an advantage. "If the Tevatron experiment cannot make it conclusive, the Large Hadron Collider will," says A. J. Stewart Smith, a physicist at Princeton University who took part in the BaBar experiment.

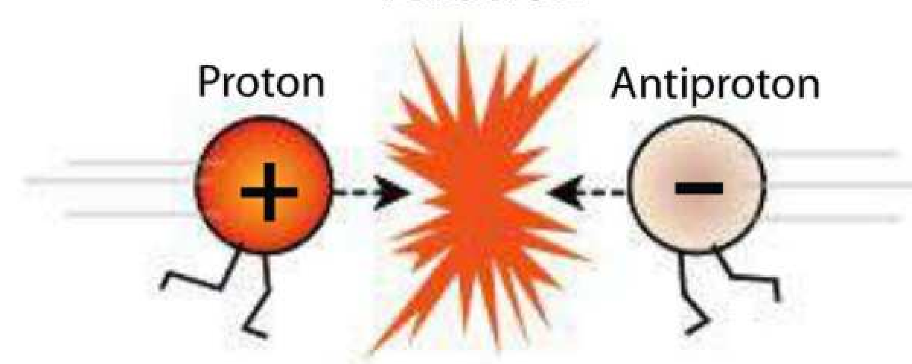
"If the [DZero muon-antimuon] observation is correct, this means that there is a new source of CP violation; something about the standard model is wrong and we have to figure out what this new source of CP violation is at these low energies, below cosmic scales," says Paul Steinhardt, a theoretical physicist at Princeton.

And theorists will have to return to the drawing board, says Smith: "We have to find out what this new process is and see what implication it has on the amount of asymmetry between matter and antimatter, and go back to our model of the beginning of the universe."

This is where the cosmologists may encounter a difficulty, according to Mark Wise, a theoretical physicist who investigates elementary particles and cosmology at Caltech. CP violation and matter-antimatter asymmetry in the universe will be within experimental reach if the asymmetry was generated at energies lower than those expected in the Big Bang; such lower energies are available at the LHC. "If it is generated at a higher-energy scale where we do not have direct connection with experiments, then it becomes difficult to know precisely how we are going to test the ideas developed by theorists," says Wise.

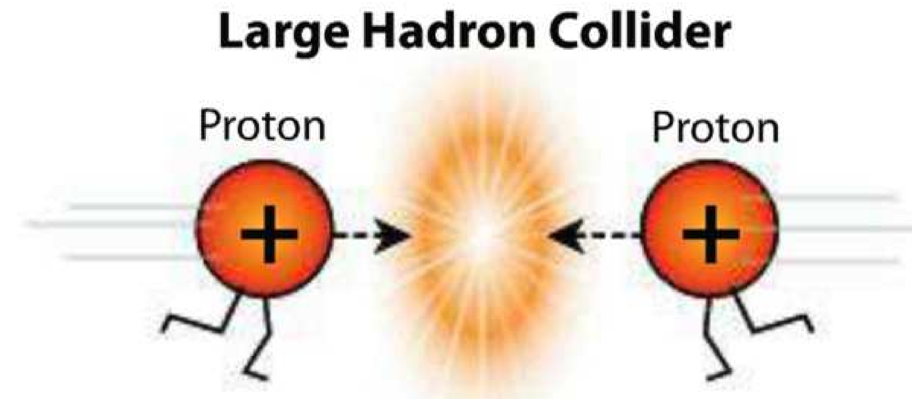
So it looks like the astrophysical community is not only waiting for the LHC to shed light on the nature of dark matter and the mystery of mass, but also why we live in a matter-dominated universe.

Tevatron



The Tevatron at Fermilab outside Chicago slams together protons and antiprotons, making it easy to pick out the asymmetry of the collision products.

Large Hadron Collider



The Large Hadron Collider at CERN in Europe collides protons with protons, making it harder to pick out the asymmetries. But it can reach higher energies than those used at the Tevatron.

CERN scientists have produced and captured antihydrogen atoms. Learn more about it at www.Astronomy.com/toc.