By Dan Falk
Photograph by Shauli Lendner

Cosmological Archaeology

Yann Gouttenoire looks deep into the past for hidden clues about the birth of our universe

For cosmologists like Yann Gouttenoire, knowing what happened in the first second after the birth of the universe could help address some very fundamental questions about dark matter, dark energy, gravity and other puzzles about the nature of our world

Cosmology is a relatively young field. It was only in the late 1920s, barely a century ago, that astronomers and physicists started developing what we now call the Big Bang model of cosmic origins. Observations of distant galaxies showed that the universe is expanding, and that expansion is thought to have begun about 13.8 billion years ago, when the universe emerged from an unimaginably hot and dense initial state.

But numerous puzzles remain. For starters, only about five per cent of the universe is made up of ordinary matter (from which stars, planets and galaxies are made). About a quarter is made up of "dark matter," whose nature remains a mystery. The rest is made of equally mysterious "dark energy," a peculiar force that acts against gravity, pushing galaxies away from one another. Then there's the puzzle of why there's so much more matter than antimatter in the universe today, when our most successful theory — the so-called Standard Model — predicts that they were equally abundant at the universe's birth. Another puzzle is why gravity is so much weaker than the three other known forces (electromagnetism and two short-range nuclear forces that operate within atomic nuclei).

It's precisely because of those puzzles that Yann Gouttenoire, a particle physics researcher at Tel Aviv University, is drawn to cosmology. "We need to ask the most fundamental questions we can possibly ask," says Gouttenoire, originally from France, who was recently awarded an Azrieli International Postdoctoral Fellowship. "We need to tackle these big puzzles — dark matter, dark energy, black holes, the problem of gravity," he says with youthful energy and enthusiasm evident even from thousands of kilometres away over Zoom.

Incredibly, physicists have a remarkably clear picture of the universe's evolution going all the way back to about the one-second mark. Before that, the picture becomes murkier. The infant universe was a hot soup of elementary particles, including quarks, gluons, Higgs bosons and dark matter. (Evidence for the Higgs boson was found by physicists at the Large Hadron Collider in 2012, a breakthrough recognized by a Nobel Prize the following year.) Eventually, quarks and gluons came together to form protons and neutrons, the building blocks of atomic nuclei. It was only hundreds of thousands of years later that the universe cooled enough for neutral atoms to form, with electrons whirling around the nuclei of hydrogen and helium atoms. There were photons of light as well, but at first the universe was so dense that it was opaque. It was only 370,000 years after its birth that the universe became transparent and photons could move freely.

But for cosmologists, it's that first second that's especially critical, and knowing what happened could help answer very fundamental questions. Could the four known forces (gravity, electromagnetism and the two short-range forces) be manifestations of some more basic single force? Where exactly did the dark matter come from? And what role did it play in cosmic evolution?

To tackle those questions, Gouttenoire uses sophisticated mathematical models to describe phenomena that took place in the very first moments of the universe's history. Those models can in turn be tested against data coming from various types of telescopes, particle colliders and gravitational wave interferometers. He sometimes calls his field "cosmological archaeology," the art of examining clues hiding in today's universe for insight into a much earlier era.

One of the theoretical models Gouttenoire has been investigating involves the effects of a "phase transition" in the early universe — roughly analogous to the phase transition that happens when water boils to become steam. In this case, what's boiling was the "Higgs field," a kind of fluid, associated with the Higgs boson, believed to fill the entire universe. When particles move, they encounter resistance from the Higgs field, similar to how a fish has to push through water to swim. This resistance is what gives particles their mass. This phase transition was a turning point in the universe's early history — suddenly, particles acquired mass — and, as Gouttenoire explains, it's also when the electromagnetic and weak nuclear forces separated from each other.

Important clues may come from studying gravitational waves: ripples in the fabric of space-time created whenever massive objects throw their weight around. Predicted by Einstein more than 100 years ago, gravitational waves were detected for the first time in 2015 (and recognized with a Nobel Prize in 2017). Those particular waves were emitted by pairs of orbiting black holes. But Gouttenoire is hoping we can snare a more elusive kind of gravitational wave: one that's of "primordial" origin, possibly created by the boiling Higgs field in the universe's earliest moments.

Traditional telescopes use light, which travels freely through empty space. But because the early universe was opaque, optical telescopes cannot reach so far back. Gravitational waves, on the other hand, could travel unimpeded. "Gravitational waves can propagate even when light can't," Gouttenoire says. "This makes them the ideal messenger for telling us about the early universe."

Gouttenoire is hoping that a European Space Agency–led space-based observatory known as LISA ("Laser Interferometer Space Antenna"), tentatively set to launch in 2037, will yield the necessary data, perhaps providing insights into a time when the universe was a mere trillionth of a second old. Other projects, including a planned underground detector known as the Einstein Telescope and a similar project called Cosmic Explorer, may also provide the crucial data that will tell Gouttenoire if he's on the right track.

Investigating the physics of the early universe is a project that, by its very nature, cuts across disciplines. Gouttenoire credits the Azrieli Fellows Program for allowing him to attend conferences around the world where he and other physicists have been able to share ideas. Gouttenoire's work requires "connecting together many kinds of knowledge, from highly conceptual theoretical physics to different types of observations in cosmology and particle physics," says Geraldine Servant, a theoretical physicist at the University of Hamburg who co-supervised his doctoral work. "What characterizes Yann is his infinite curiosity and his extraordinary energy and enthusiasm. The topics he is working on are exciting but also highly non-trivial."

Ultimately, Gouttenoire says he'd like to pin down "the principles that explain all the phenomena observed in the universe." That's a lofty goal, one that requires ambition and hard work and perhaps some luck as well. But one gets the impression that Gouttenoire is thrilled by the journey itself. ▲●■

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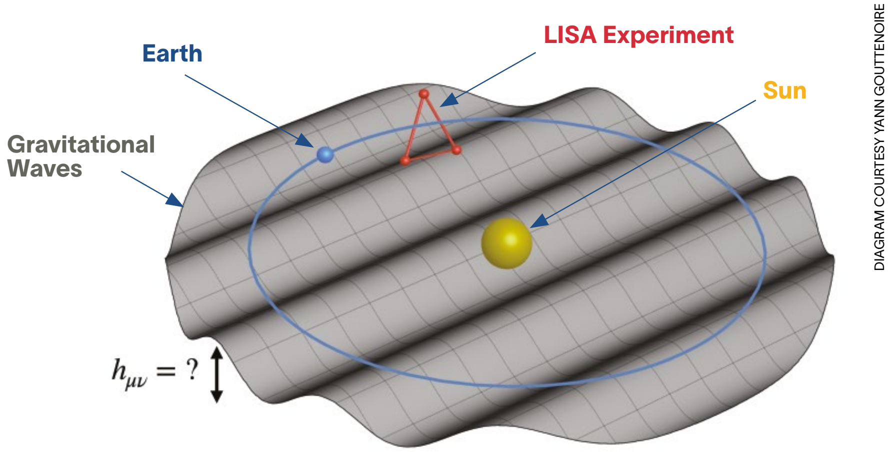

Because the early universe was opaque, optical telescopes that rely on light cannot reach so far back. Gravitational waves, however, could travel unimpeded. Gouttenoire uses sophisticated mathematical models to describe phenomena that took place in the very first moments of the universe's history. Those models can be tested against data coming from various types of telescopes, including gravitational wave interferometers such as LISA ("Laser Interferometer Space Antenna"). The European Space Agency–led space-based observatory — which Gouttenoire calls a "2.5-million-kilometre microphone for hearing spacetime vibrations" — is tentatively set to launch in the 2030s.