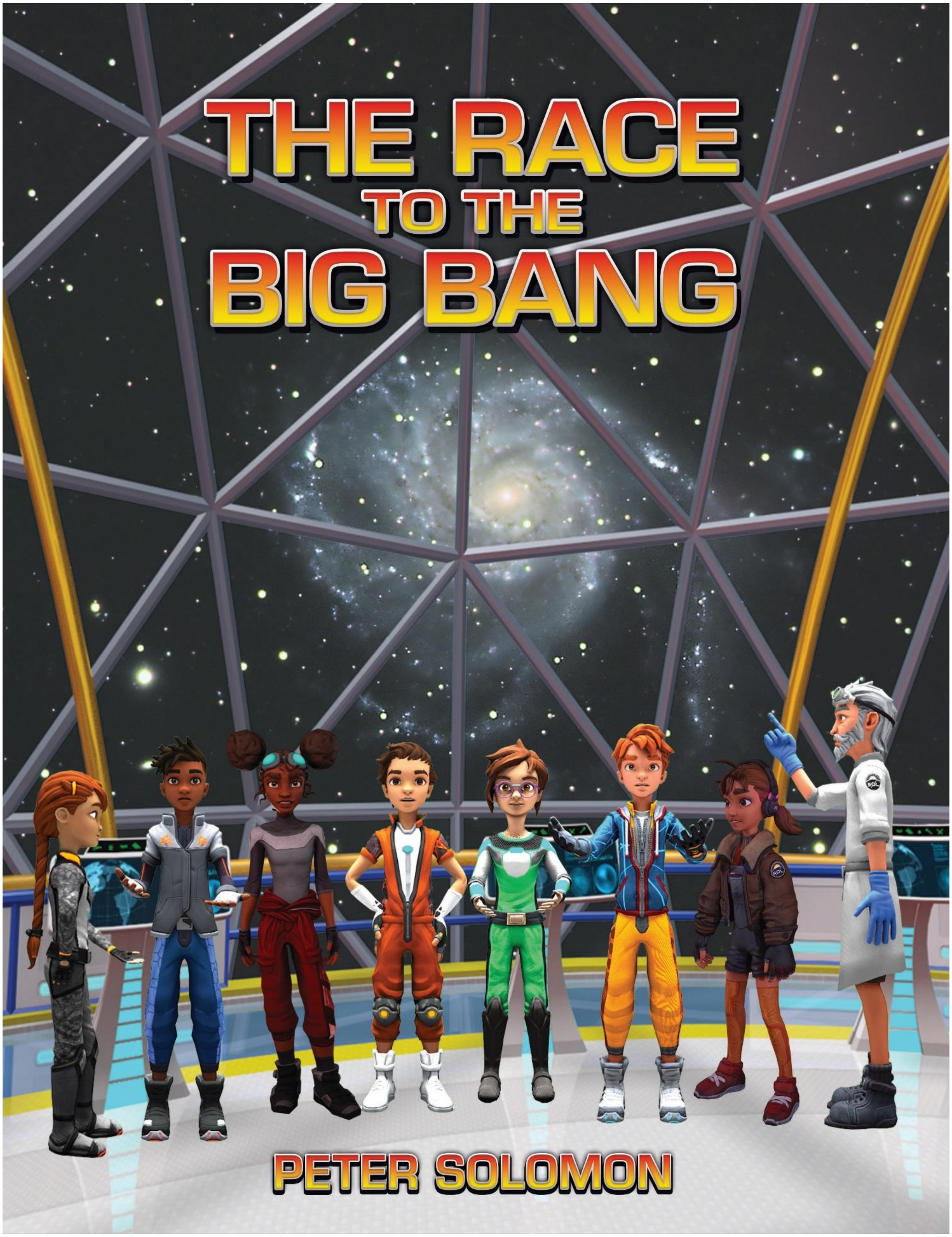

THE RACE
TO THE
BIG BANG
PETER SOLOMON

GRAVITATIONAL WAVES

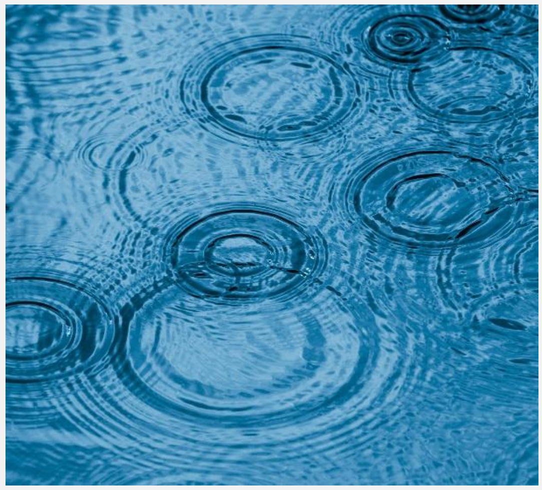
by

JOHARI, LIZZY, and VC (as Told by Johari)

"I guess it is not surprising that so many of the unusual things in the universe were predicted by Albert Einstein in the Special and General Theories of Relativity," I said. "The world he predicted, which has been proven correct, is *so* different from the world of our everyday experience. That world is definitely unusual."

That brings us to the number-four most unusual thing in the universe according to us *Cosmic Explorers*: *Gravitational waves*.

Think about the waves caused when raindrops hit the surface of a pond. The surface waves ripple out from the point of raindrop impact in circles that expand slowly. *Gravitational waves* expand as spheres, which are 3-D circles, traveling at the speed of light away from a major cosmic disturbance. The waves are in the dimensions of space. Space actually expands and contracts—like a rippling wave on a pond!



In one project, scientists, including our team member Tom, were trying to measure *Gravitational Waves*. They were trying even though Einstein predicted that they could never be measured because they were too small.

"VC," I said, "what is the smallest thing that you know of?"

"Atoms?" she responded. "I know from the *How Big Are My Atoms* video we made during the contest last year that carbon atoms are six million times smaller than sand grains."

"But we know some things that are smaller," I said, "like parts of atoms: protons, neutrons, and electrons. The size of a proton is a trillion times smaller than a sand grain—1,000,000,000,000 times smaller. Let's say there is a huge cosmic event trillions of miles away. Its gravitational wave seen on Earth is expected to stretch a piece of space four kilometers long by just one-thousandth of the diameter of a proton. The scientists who Tom worked with were confident that they could make the measurement no matter what Einstein said."

The detection of gravitational waves was going to be made by LIGO, the Laser Interferometer Gravitational wave Observatory.

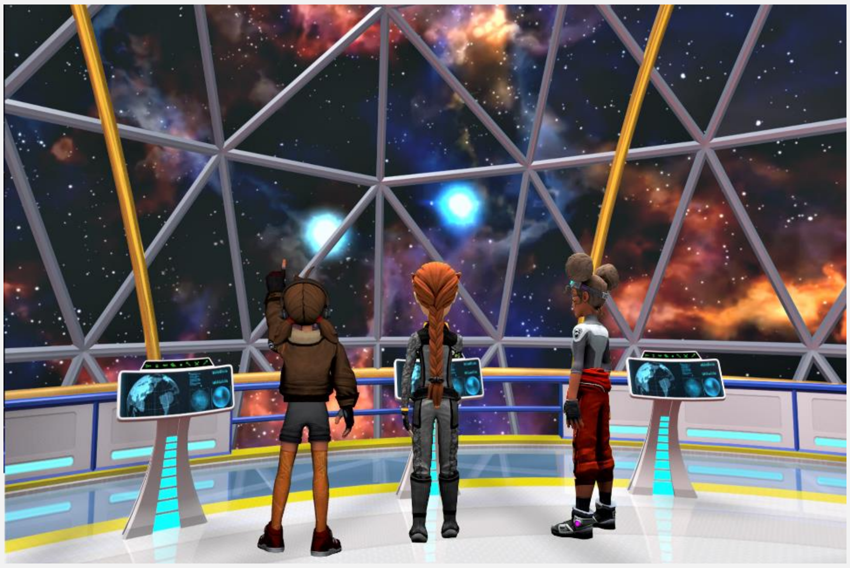
And they did it. (*Sorry, Albert!*) In 2015, they measured the *Gravitational Waves* produced by two black holes merging. The gravitational wave had been traveling at the speed of light for 1.3 billion years to reach Earth. In 2017, they detected two neutron stars merging. The event was much closer, so it only took 130 million years for the wave to arrive. What they saw on the detector from these explosive events was a tiny chirp that lasted about a minute.

"Hey," said Johari, "let's go in the *Cosmic Egg* to see the neutron star collission. It's only 130 million light years away. That's just around the corner with our *Hyper-Speed Booster*."

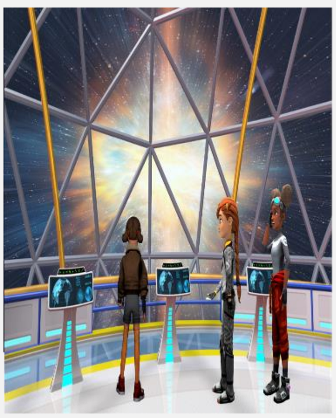
"I'm in," said VC and Lizzy at the same time.

We called Tom and got the location of the neutron star merger event. Then we logged into the *Virtual World*, went to the *Mystery Museum*, and teleported to the *Cosmic Egg*. VC was our *Navigator*. We time-traveled back 130 million years. Then she entered the coordinates that Tom gave us, selected the *Hyper-Speed Booster*, and off we went.

"There they are," said Lizzy. "Two tiny little stars circling each other."



We watched as the two neutron stars circled, getting closer with each rotation. Then they crashed into each other with a huge explosion. Instantly, our ship started shaking. Then the space stretching and contracting happened for about a minute. First, we were tall and thin and then short and fat. We were experiencing *Gravitational Waves* up close and personal.




"In 130 million years," observed Johari, "those waves will reach Earth and be detected by LIGO."

"Way cool," added Lizzy. "Let's head home."

GRANDPA'S GLOSSARY

Special Theory of Relativity: Albert Einstein's theory of special relativity was published in 1905. It explains how space and time are linked for objects that are moving at a consistent speed in a straight line. One prediction of the theory is that as an object approaches the speed of light, its observed mass approaches an infinite value. This is the basis for Einstein's prediction that objects cannot go faster than the speed of light. Another famous prediction is the relationship $E=mc^2$ between mass (m) and energy (E), where c is the speed of light.

General Theory of Relativity: General relativity is the geometrical theory of gravitation published by Albert Einstein in 1915. When Einstein became aware that feeling weightless in the absence of gravity, or in free fall acceleration because of it, were equivalent and something extremely fundamental, he called it the "happiest thought of my life." This observation guided him in the development of the theory in which gravity is a geometric property of space. In Einstein's theory, mass tells space how to curve, and the curvature of space tells mass how to move. The General Theory of relativity has important predictions. Georges Lemaître's solution of Einstein's equations for an expanding universe led to his Big Bang theory. The bending of light by gravity can lead to the phenomenon of gravitational lensing, in which multiple images of the same distant astronomical object are visible in the sky. The attraction of light by mass leads to the prediction of black holes, whose mass is so large that no light can escape. The theory predicts that cosmic events can produce gravitational wave distortions of space itself that travel at the speed of light. The first observation of gravitational waves was made by LIGO in 2015. The theory predicts the Twin Paradox described in chapter 18. The predictions of general relativity have been confirmed in all observations and experiments to date.

Gravitational Wave: Like black holes, gravitational waves are predicted by Einstein's General Theory of Relativity. They are disturbances in space itself (stretching and contracting) that travel at the speed of light away from the event that caused them.

LIGO: The National Science Foundation funded the development of the Laser Interferometer Gravitational-Wave Observatory (LIGO) to detect gravitational waves. Two of them were built far apart, and a disturbance must be seen simultaneously by both to be identified as a real event. The first event, detected in 2015, was believed to be produced by two black holes merging. In the summer of 2017, LIGO detected a gravitational wave produced by the merging of two neutron stars. Additional measurements from detectors of visible and other radiation wavelengths indicated that that event had produced a weight of gold equal to the weight of Planet Earth. Neutron star merging appears to be a very important event that produces our heavy atoms.

Atoms: Every solid, liquid, or gas in our world is made of atoms. Most things like water, people, trees, houses, and cars are made of combinations of different kinds of atoms. But some substances like silver, gold, oxygen, and carbon are made of only one kind of atom, and these are called chemical elements. The atom is the smallest unit that defines a chemical element. Anything made of atoms has mass, meaning that a force is necessary to make it go faster or slower, and it experiences a gravitational attraction to other masses. Atoms are very small. A single strand of human hair is almost 1 million carbon atoms wide. Atoms can be attached to one another in small units called molecules, in large crystals like diamond and salt, in mixtures of crystals, or in random arrangements in solids or liquids. You can see some of these arrangements in the animated science videos on the STARDUST MYSTERY YouTube channel. Milo, Lizzy, VC, Johari, and Neddy have starring roles in those videos. You can build atoms in the *Building the Universe* game available on Store.SteamPowered.com.

Some things in our world are not made of atoms. The most common is light, which consists of tiny particles called photons. Photons always move fast and have no mass. Some things are parts of atoms like a beam of electrons in an electron microscope or an old television tube. Then there are *dark energy* and *dark matter* that we think are out there in the universe but are not made of atoms. We are pretty sure they're there, but we don't yet know what they're made of.

Protons, Electrons, and Neutrons: All atoms are made of the same three particles: electrons, protons, and neutrons. Electrons are tiny particles that have very little mass and a negative electrical charge. Protons have almost 2,000 times the mass of an electron and are positively charged. Neutrons have almost the same mass as the proton but have no charge. In an atom, the protons and neutrons are tightly bound together in the nucleus, attracted by the nuclear force. The electrons circle around the nucleus and are bound to it because of the electrical force of attraction between the positive and negative charge of the particles. Different kinds of atoms have different numbers of electrons, protons and neutrons. Hydrogen, the lightest element, has only one electron and one proton. The heaviest natural element uranium has 92 electrons, 92 protons and between 141 and 146 neutrons. You can build protons and neutrons from their component quarks in the *Building the Universe* game available on Store.SteamPowered.com at https://store.steampowered.com/app/1237700/Building_the_Universe_The_Beginning_of_Time/

Black Holes: Black holes are super-dense masses that, thanks to their enormous gravitational pulls, suck everything into them like enormous monster vacuums. Their gravity is so strong that even light can't escape. That's why it's black. Black holes were predicted by Einstein's General Theory of Relativity. There is a supermassive black hole at the center of our Milky Way galaxy. The biggest black hole is believed to have a mass of over six billion times the mass of our sun.

Neutron Star Pair Merger: A neutron star is the collapsed core of a massive supergiant star, which had a total mass of between 10 and 25 solar masses. Except for black holes, and some hypothetical objects, neutron stars are the smallest and densest currently known class of stellar objects. It Is possible for a pair of such large stars (connected by the gravitational force) to form a pair of neutron stars. These neutron stars will circle each other, getting closer and closer together until, finally, they merge in a supernova explosion. Such a merger was observed by LIGO in 2017. Other radiation sensors observed the production of massive amounts of heavy elements. The weight of gold produced was estimated to be equal to the weight of Planet Earth. Neutron star pair mergers are now considered to be one of the major sources of heavy elements.

How Big Are My Atoms? Video: See https://www.youtube.com/watch?v=jw1-wMR7JRM, on the STARDUST MYSTERY YouTube Channel.

Light Years: The distances to other places in space are huge. For example, the distance from the Earth to the sun is 93 million miles; the distance to the closest star, Proxima Centauri, is 24 trillion miles; and the distance to the nearest galaxy, Andromeda, is 14 million trillion miles (14,000,000,000,000,000,000 miles). Astronomers decided that giving distances in such large numbers of miles or kilometers was not very easy for comparing different distances. So, they decided to invent a new unit of distance called the light year. The light-year is the distance that light travels in one year. Since the speed of light is 186,282 miles per second, it travels 5.79 trillion miles per year. Proxima Centauri is 4.22 light years away, and Andromeda is 2.5 million light years away.

When looking at an object in a telescope, the light year tells us something interesting besides distance. It is the time it took for the light we are now seeing to get here. So, we are really seeing how the object looked at some time in the past. When we see Andromeda in a telescope, we see how it looked 2.5 million years ago. When the Hubble telescope takes pictures of the furthest objects away from us, it is actually seeing what they looked like 13 billion years ago, not that long after the Big Bang. So, looking at objects that are further and further away lets us look at earlier and earlier times in the history of the universe.