The Surfer's Guide to Gravitational Waves

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In a nutshell: Gravitational waves are ripples in the fabric of space time produced by violent events, like merging together two black holes or the explosion of a massive star. Unlike light (electromagnetic waves) gravitational waves are not absorbed or altered by intervening material, so they are very clean proxies of the physical process that produced them. They are expected to travel at the speed of light and, if detected, they could give precious information about the cataclysmic processes that originated them and the very nature of gravity. That's why the direct detection of gravitational waves is such an important endeavor. Definitely worthy of a Nobel prize in physics.

General relativity is a theory of gravity, where gravity emerges as a particular geometrical property of space-time. This geometrical property is called curvature. Similarly to a large sheet that warps under the weight of an object, mass and energy bend space-time and create curvature. In the absence of mass and energy the space-time is flat, and objects move in straight lines. Around a large body like the Earth, objects move following the curvature produced by the mass of the planet. Which means if you throw a stone, it eventually curves and falls to the ground, and does not move in a straight line. **The elegant movements of celestial bodies in the cosmos are mostly orchestrated by mass and energy diligently following the (usually) gentle hills of space-time. Since moving mass and energy affect the curvature as well, the resulting dance is a complex, ever-changing choreography.** The laws of this dance can be written in a very elegant form, called the Einstein's Equation (1), maybe one of the most beautiful equations in physics.

$$G_{\mu\nu} + \Lambda T_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \tag{1}$$

Particularly energetic events like certain stellar explosions can accelerate mass and energy in ways that create ripples in the fabric of space-time. In a sense these events are like giant 'cosmic storms'. Every surfer knows that when he's enjoying a good swell, he's actually surfing waves produced by a very energetic event that occurred somewhere far away in the ocean. A smart surfer knows that looking at the direction and other properties of the waves he's on, he can in principle reconstruct important facts, like how intense the storm was and where it occurred. This is what astronomers hope to do by detecting the passage of gravitational waves on Earth. The big difference? The 'cosmic storms' that produce gravitational waves are usually so far, that by the time the gravitational waves reach the Earth, they are extremely tiny. How tiny? The displacement produced by the gravitational waves expected to be observed with the LIGO detectors are about 10^{21} times smaller than the displacement a surfer usually experiences when riding a wave. The LIGO detectors, with their 4km-long arms, can detect ripples in space-time that change the distance between two objects by 10^{-18}m, which is about 1000 smaller than the size of a proton. An incredibly tricky measurement, and quite a flat day for a surfer.

Why all this excitement? The existence of gravitational waves is the last big prediction of Einstein's theory of general relativity. General relativity is a theory of gravity that works amazingly well at the large scales of the universe, but has troubles blending with the other most successful physics theory of the 20th century, quantum mechanics, which instead explains amazingly well the realm of 'very small things'. Now, where is

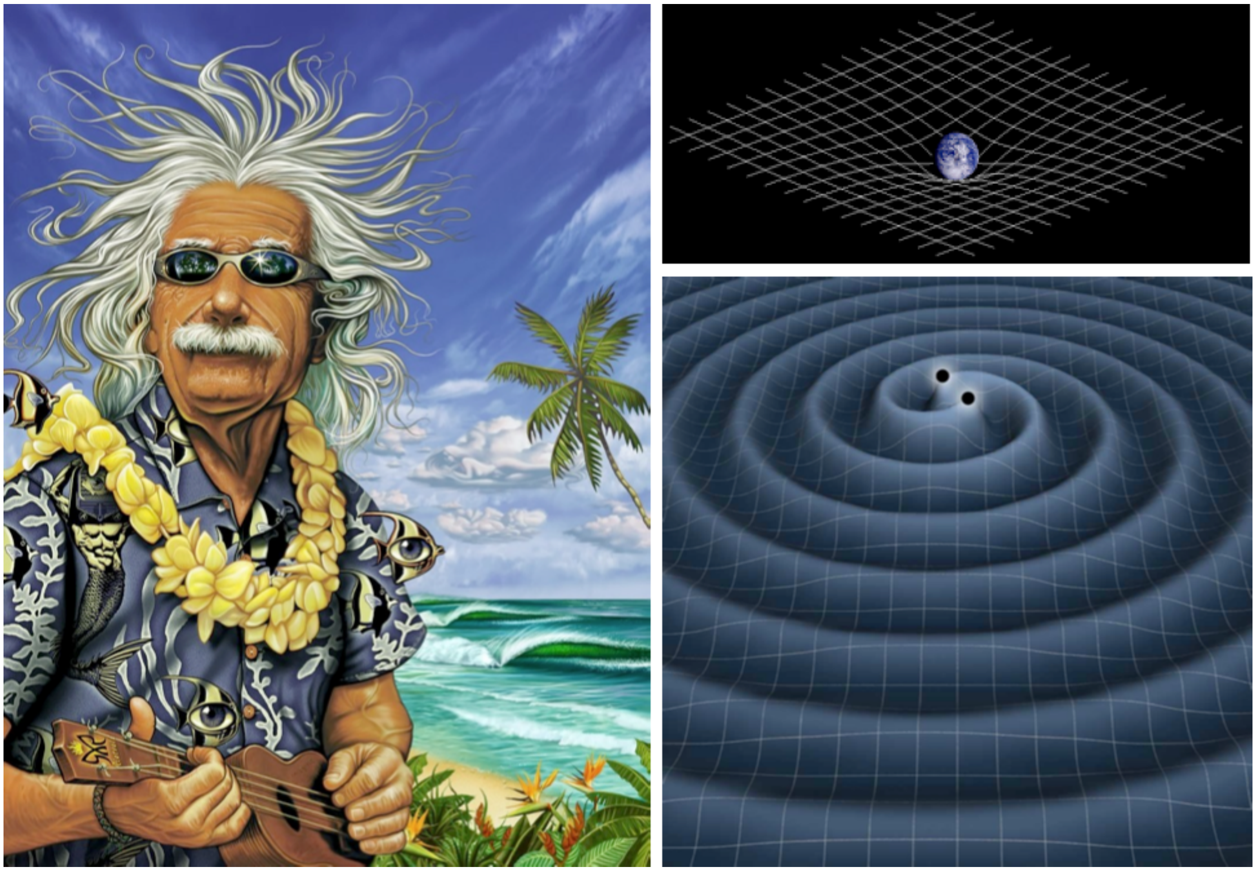

Figure 1: **Left:** 'AL' Einstein on vacation (Credits: Rick Rietveld) **Top Right:** The Earth's mass changes the curvature of space-time. **Bottom Right:** Gravitational waves generated by merging black holes (Credits: NASA/LIGO)

that general relativity and quantum mechanics don't get along? For example on the edges of black holes. And what can produce gravitational waves? Well, indeed the merger of two black holes. Interestingly, this is what the rumors say LIGO has detected [Update: They did it!]. In general, gravitational waves can open a new window for astronomers to observe distant, dramatic events like the coalescence of neutron stars and certain supernovae explosions. Some of these events, like the merger of two black holes, would be otherwise completely invisible. Very exciting times ahead!

Figure 2: When a gravitational wave passes by, the metric of space-time is affected. This is shown in the animation as a small change in distances between two red dots. Detecting this tiny change is a very difficult measurement, a challenge that instruments like LIGO have to face.