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Author
Gururangan, Kapil

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ACHILLES SPELIOTOPOULOS:

GENERAL RELATIVITY MEETS STATISTICAL MECHANICS

Kapil Gururangan, Elaine Owen

Achilles Speliotopoulos is a lecturer in the physics department and a theoretical physicist with a long history at UC Berkeley. After getting his B.S. in 1985 in engineering physics from Cal, he stayed to get his M.A. and Ph.D. in physics in 1987 and 1991, respectively. Though his doctoral thesis was on the theory of superfluidity in two dimensions, his work since has taken on a more cosmological scale. Happy accident has led Speliotopoulos to research in general relativity and quantum mechanics. While teaching here at Berkeley, his most recent work concerns adapting the geodesic equations of motion to a universe expanding under the influence of dark energy. Throughout his exploration of the mechanics of the physical world through mathematical models, Dr. Speliotopoulos has benefitted from instances of serendipity as, he says, these models and equations simplify to attractive and meaningful solutions to describe natural phenomena.

Figure 1. Speliotopolous sitting at his office desk in Le Conte Hall

DO YOU EVER HAVE ANY ACCIDENTS IN YOUR RESEARCH THAT LEAD TO UNEXPECTED DISCOVERIES?

Speliotopoulos: Oh, all the time! The reason why is because I'm a theorist, so what I do – you can't see it, you can't touch it, you can't do experiments on it – and the question is "how do you know what you're doing it right." There's a number of ways of doing it and they're all very time-consuming. One of the best ways is just to compare what the experiment says to the prediction for the experiment. That doesn't often happen, so another way to is make sure that it agrees with what's previously in the literature. That's tedious, but it's necessary. Another way, you know, as you're doing it there are these unexpected surprises you're talking about – a serendipitous "that works!" kind of thing. You think that "oh, it will work in this way for this part of the problem" when you're checking it and suddenly you find out that not only will it work for this, but it will also work for that part of it. It's almost like pieces of a puzzle start to fall in place and the system, the theory you're working on and the calculations you're doing, just work much, much better than you have any reason to expect. Things fall into place. That's what I would say about the serendipitous part of it, but if you actually think about – and I'm a physicist, not a mathematician – what we do is supposed to describe the universe around us. If it's supposed to be an accurate description of nature, then it has to be a part of nature in the sense that what you did has to fit into a bigger part of it. In that case, you're doing a small piece of a really big puzzle. So it's not surprising that certain unexpected things fall into place when you get it right. In fact, that's what occasionally happens when it's right.

CAN YOU EXPLAIN YOUR CURRENT RESEARCH?

Speliotopoulos: Sure. What I do currently – since I've had a number of research areas – is on the intersection of two very different subjects: one is general relativity, or gravitation; the other is statistical mechanics. Those are two very disjoint subjects; you wouldn't think that they have any overlap at all. The overall idea was "how do you start putting in statistical mechanical ideas and concepts in order to describe the behavior of a large number of particles?" in general relativity. That's the underlying idea and part of the reason why this happens, and this is why I'm interested in it, is because in the 1970s, Stephen Hawking and Jacob Bekenstein described black holes in terms of thermodynamics and entropy. There was a lot of work in the '70s that brought everything in terms of thermodynamics and thermodynamics is a very empirical description of the behavior of large objects – you know, they follow the zeroth law, the first law, the second law, the third law, and everything works. The question is where the laws come from: is there anything more fundamental? Like in most of research, you have an idea that you think that will work, and the idea here is that if I have laws of black hole thermodynamics here and this knowledge is to use this thermodynamics, statistical mechanics was used to describe a microscopic underpinning of thermodynamics. Hopefully, there would be a statistical mechanical version of formulas that would underpin black hole thermodynamics. Now, there has already been research on it – [Abhay] Ashtekar and company and others – and they calculated from first principles the black hole entropy, but the idea is to bring everything into an overall framework. This shows you clearly how you go from A to B and also you see clearly the underlying concepts you need to draw the system overall.

The most recent papers we've read of yours have been about dark energy and the geodesic equations of motion. As we understand it, those equations describe how things move on a spherical space or over a spherical surface, right?

Speliotopoulos: Actually, on any surface. It was meant to be a "what if?" question. If you look at the motion of a particle in general relativity, it was supposed to be described by these geodesic equations, which is a line that is the shortest proper time between two points in space. The equation is very, very straightforward and it's very geometrical. It is just the total length of the proper time from one point to another written in terms of a differential. The question is: is that the most general one you could have? As I say to my students, math is not physics. We're driven by and we use basic math, but we try to understand the universe and the universe tells us which math to use, not the other way around. The question is whether there is a more general equation you could write down for the motion of particles and it turns out that without dark energy, there isn't. The reason why there isn't is because there is no scale or fundamental size to the system and because of this, the only one you can really go with is the geodesic, but if you have dark energy, dark energy will give you a time scale and a length scale. When you have the length scale – which is something like 14,000 megaparsecs (Mpc), a really huge length scale – you can construct something that is more general. Fine, you construct it. In fact, it's an arbitrary one, but this goes back to the idea that you could propose this as a mathematical exercise to write these equations down and it will have these certain properties, but the question is whether it has any physical relevance whatsoever. We're physicists, not mathematicians. In order to have physical relevance, the first item is that if you're changing the equations of motion for how a particle moves, and that equation of motion is basically how the earth moves around the sun and so on, you'd better not have seen any of those effects already. They would have already been measured and this had already been done decades ago. That puts a limit on what's possible and what modifications should be made. You don't want it to have been seen already in terrestrial experience. That's one limit. It turns out the simplest modification I used was a parallel description and that exponent's lower bound was like, 1.5 based on a very simplistic view of what the experiment would be. Now that you have a lower bound on how effective it is, you say that, "if I can't see the universe around us, but it's not so small that I can never see it, then it won't be of any interest either, so I'd better see it on some scale." Well, the idea is that we don't have measurements over very large scales. So now you have this equation you've written down and apply it to the motion of stars and galaxies. This scale of 14,000 Mpc is much larger than a galactic scale, so you go back and start doing it again and then things start falling into place. In order to fit things for what you expect in the size of a galaxy, we know the approximate sizes of the galactic hub and approximate densities and we've also measured the distance from the center of the galaxy to where the density of the galaxy falls to 200 times the critical density of the universe, called the r200. You apply it there and you actually get hard numbers for your alpha [variable], fine, so what? All you did is to set what alpha was, you didn't check it, and this goes back to the process of checking your results to see what's going on. And lo and behold, you apply it to something else that's already been seen and you apply it to the universe as a whole using the WMAP [Wilkinson Microwave Anisotropy Probe, a measurement of the differences in temperature across the universe], which is already set. So you use two of the parameters that WMAP measured and pick your parameters and you predict the third, and lo and behold, the third matches what WMAP measured! So now you've shown that it matches at least what the experimental data shows; it's at least consistent with the experiment. There's no reason why it's wrong, but you haven't shown that it actually exists. So that's what I do, and things were falling into place. You didn't expect anything to happen at the galactic scale. The scale goes from the Earth, which is a few thousand kilometers, and what happened at Earth-scale jived very well with what happened at galactic scales, which is a few kiloparsecs, and what happened at galactic scales jived really well with what happened at cosmological scales, at the 10,000 Mpc scales! Everything started to fall in place. Things were working out more than it has any right whatsoever to work out. You didn't expect it – who would have expected that you could calculate

> *"I'm a theorist, so what I do – you can't see it, you can't touch it, you can't do experiments on it – and the question is 'how do you know what you're doing it right.'"*

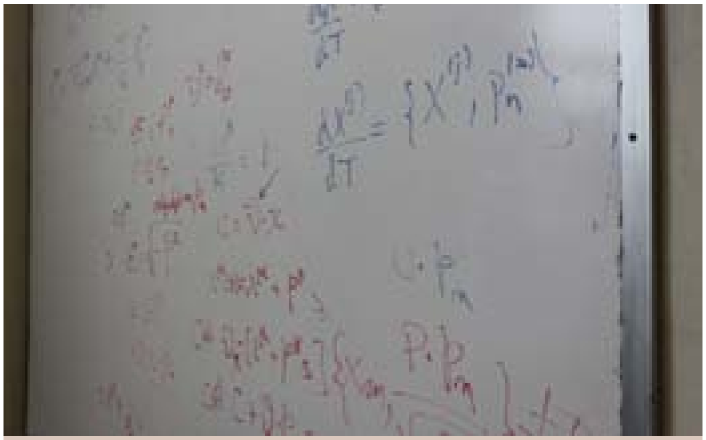

Figure 1. Calculations that run across the whiteboard located across from Speliotopolous' desk.

RMS fluctuations and have it check, within experimental error, with what is measured. You wouldn't expect it at all.

We saw a lot of other projects you've done before and one from 2004 was about merging quantum mechanics and general relativity, or perhaps simply finding a common interface – the MIGO?

Speliotopoulos: Oh yes, that was the research I was doing with Raymond Chiao, who was at this department at the time. He was an experimentalist and he was working a lot with laser interferometry. The idea was, could you use atom interferometry? Interferometry is basically looking at the interference between two waves, which in most cases is light. Because interferometry is extremely sensitive in measurement, you can measure very small deviations in a system and the size of the deviations depends on your length scale, which is this case is the wavelength of the light. I realize that at this point, it's more of a "will it ever work?" kind of idea. It turns out that atoms, because they have mass and behave like a wave as well as a particle, and you use their wave-nature and the fact that they're atoms, you'll find that you can interfere atoms. That was shown many years ago. The question is, because an atom has mass, the wavelength is extremely small, and it's easier to get much shorter wavelengths than you could with light because when light gets shorter in wavelength, it gets extremely energetic and it's harder to reflect with a mirror. Very energetic light tends to destroy what you're shining it on, so bad things happen with very energetic light, but now you're doing it with atoms – slow moving atoms – that hit objects. Atom interferometry is a very accurate measurement. Steven Chu, while he was at Stanford, measured the acceleration due to gravity to one part in a million! It was so sensitive that as you look at the atom as it drops down through a mineshaft, the variations in the local density would actually be big enough to cause fluctuations. It's very, very sensitive, so the question is: if it's that sensitive, would you be able to make an interferometry that would be able to detect gravitation waves and have it be much smaller than what laser interferometry is. Could you, because of very small wavelengths, make the interferometry this way? That was the question we were looking at. There are benefits and detriments to laser and atom interferometry. One of the detriments to atom interferometry is that how accurate your measurement, how precise it is and how much error there is, depends on how many atoms you throw at it. The larger the atom, the smaller the error – statistically 1/sqrt(n). It's actually relatively hard, and quite amazing, to get a very high-density beam of atoms or a lot of particles per unit area. It's just very hard to do so in part because atom interferometry has to work at very cold temperatures; by the time you get the gas down to cold temperatures, there's not enough. For practical purposes, it's very hard to get large numbers of particles. That's part of the problem. Light on the other hand – really easy to get large numbers of particles! A 1-watt laser has billions and billions of photons and the 1/sqrt(n) error gets very, very small. The issues with singleton noise came up and that was what that paper was on. We were not the first to look at interferometry with gravitation waves; it was done a couple of times before, but a few years afterwards, Mark Kasevich wrote a paper about using interferometers in space to look at gravitation waves. So it's slowly coming out.

Were those projects aimed at approaching quantum mechanics from the smallest gravitational scales?

Speliotopoulos: Not that small, no. It turns out the wavelength of atoms is the Bernoulli wave one, which is h/mv. You really want a nice slowly moving atoms which can interact with the gravitation wave as long as possible in order to get the biggest signal. These are fairly large. There is also some idea that the types of atoms used offer some variations. The wavelength goes along with the mass, and there are variations you can play with concerning the mass. You want slowly moving particles that are pretty much at a point that is quantum mechanical, but on a scale like ordinary and common physics.

> *"As I say to my students, math is not physics."*

What we also wanted to know was how you got interested in this branch of physics. Obviously, not everybody is in this specific field. How did you get involved with this?

Speliotopoulos: It's because when I was a student – I was an undergraduate here – I was interested in quantum mechanics. I really enjoyed the beauty inherent in quantum mechanics, but I was also interested in general relativity. You know, they're really disjoint fields, there's very little they have in common. And you ask me why am I going into this area, I think it's because it was a marriage between two fields of physics that I've always been interested in. Also, when I was doing a post-doc in Taiwan, I had collaborators who were also interested in the intersection between quantum mechanics and general relativity. In a certain sense, that intersection between quantum mechanics and general relativity is the last big thing that we're looking at. You really want to bring them back, even though they're so disjointed, you would like to have formula cover them all. So I had a number of collaborators in Taiwan when I was a post-doc who were looking at this intersection as well. Ray Chiao was looking at it in part because he's an experimentalist and he wants to see if there's actually something that's possible in order to measure it.