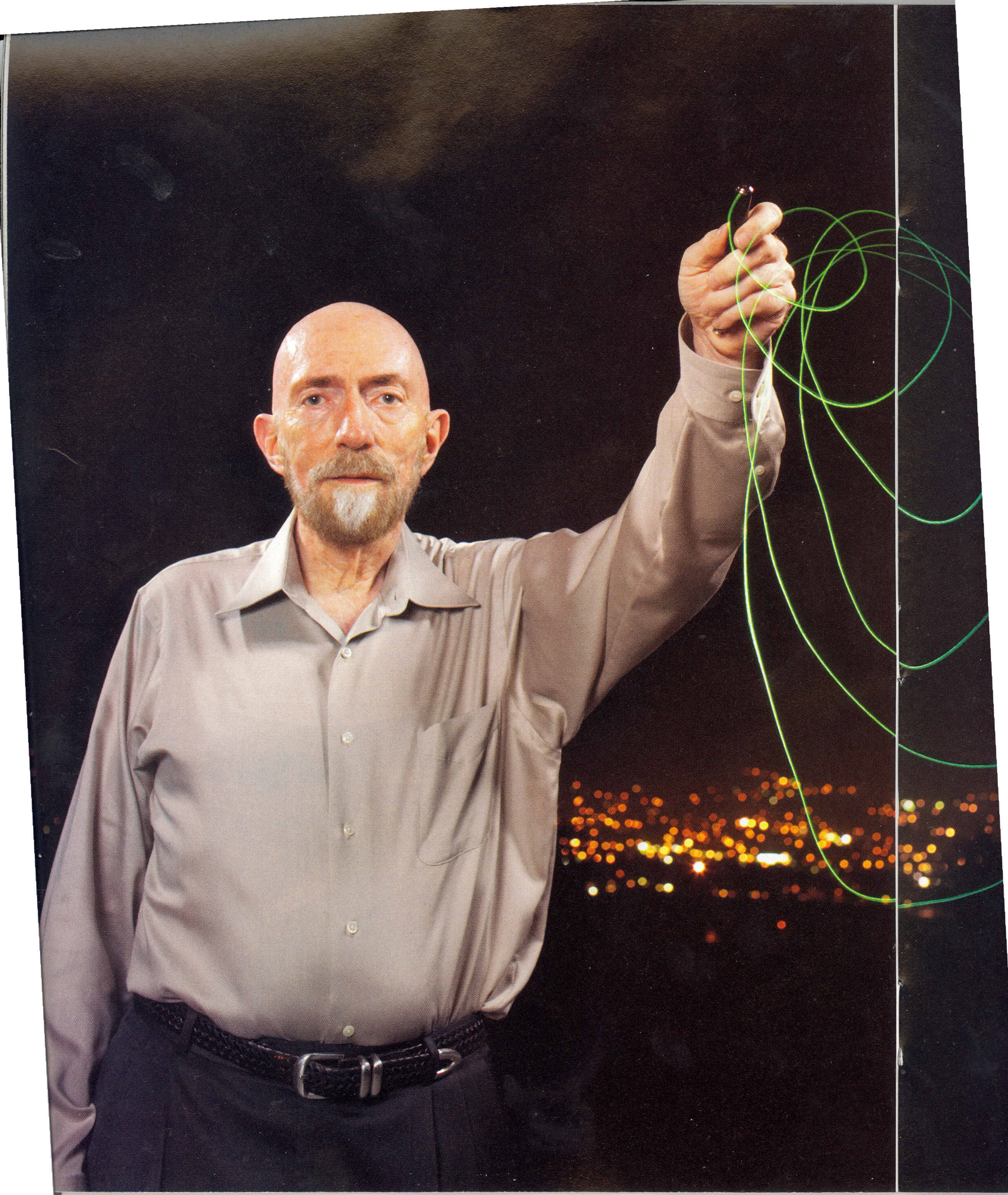


THE DISCOVER INTERVIEW
KIP THORNE

The legendary astrophysicist explains what black holes are made of, whether time travel is possible, and why Stephen Hawking never wins a bet.

BY **SUSAN KRUGLINSKI**
PHOTOGRAPH BY **BRAD SWONETZ**

Most people think of space as nothingness, the blank void between planets, stars, and galaxies. Kip Thorne, the Feynman Professor of Theoretical Physics at Caltech, has spent his life demonstrating otherwise. Space, from his perspective, is the oft-rumpled fabric of the universe. It bends, stretches, and squeezes as objects move through it and can even fold in on itself when faced with the extreme entities known as black holes. He calls this view the "warped side of the universe."

Strictly speaking, Thorne does not focus on space at all. He thinks instead of space-time, the blending of three spatial dimensions and the dimension of time described by Einstein's general relativity. Gravity distorts both aspects of space-time, and any dynamic event—the gentle spinning of a planet or the violent colliding of two black holes—sends out ripples of gravitational waves. Measuring the direction and force of these waves could teach us much about their origin, possibly even allowing us to study the explosive beginning of the universe itself. To that end, Thorne has spearheaded the construction of LIGO [Laser Interferometer Gravitational Wave Observatory], a $365 million gravitational-wave detector located at two sites: Louisiana and Washington State. LIGO's instruments are designed to detect passing gravitational waves by measuring minuscule expansions and contractions of space-time—warps as little as one-thousandth the diameter of a proton.

Despite the seriousness of his ideas, Thorne is also famous for placing playful bets with his longtime friend Stephen Hawking on questions about the nature of their favorite subject, black holes. Thorne spoke with DISCOVER about his lifetime pursuit of science, which sometimes borders on sci-fi, and offers a preview of an upcoming collaboration with director Steven Spielberg that will bring aspects of his warped world to the big screen.

What does a black hole actually look like?
A big misconception is that a black hole is made of matter that has just been compacted to a very small size. That's not true. A black hole is made from warped space and time. It may have been created by an imploding star [where the gravity becomes so concentrated that nothing, not even light, can escape]. But the star's matter is destroyed at the hole's center, where space-time is infinitely warped. There's nothing left anywhere but warped space-time. A black hole really is an object with very rich structure, just like Earth has a rich structure of mountains, valleys, oceans, and so forth. Its warped space whirls around the central singularity like air in a tornado. It has time slowing as you approach the hole's edge, the so-called horizon, and then inside the horizon, time flows toward and into the singularity [the central spot of infinite density and zero volume], dragging everything that's inside the horizon forward in time to its destruction. Looking at a black hole from the outside, it will bend light rays that pass near it, and in this way it will distort images of the sky. You will see a dark spot where nothing can come through because the light rays are going down the hole. And around it you will see a bright ring of highly distorted images of the star field or whatever is behind it.

If any civilization attempts to make a time machine, quantum effects will cause the machi

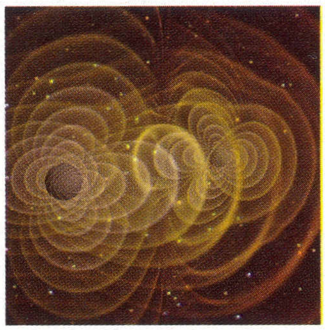
How sure are you about this model of a black hole? Could the picture be wrong?
It is a firm prediction from Einstein's general relativity laws. Gravitational waves will bring us exquisitely accurate maps of black holes—maps of their space-time. Those maps will make it crystal clear whether or not what we're dealing with are black holes as described by general relativity. It's extremely unlikely that they are anything else, but that's the exciting thing—we've been wrong before. We've had enormous surprises before.

Einstein thought of black holes as theoretical curiosities. Since no one has directly observed one, how do we know that black holes truly exist?
We see very strong evidence right at the center of our own galaxy. Astronomers have seen massive stars fall toward some central object and whip around it, like a comet around the sun, and fly back out. They have weighed that central object by measuring how strongly it whips stars around it. It turns out to have the same gravitational pull as approximately 3 million suns, and it is very dark—astronomers see only weak radio waves there. It almost certainly is a black hole. And when quasars [extremely bright, compact objects at the centers of some galaxies] were discovered in the early 1960s, it was obvious that the source of power had to be gravitational because even nuclear power, which powers the stars, is too inefficient. The idea that quasars are powered by the accretion of matter onto black holes was proposed within months after the discovery of quasars. This was a huge change of people's views of the universe, and it came very quickly. There followed a period of rapid research, and by the mid-1970s we came to understand that black holes are dynamic objects with a rich set of properties. They spin, and they can vibrate.

What are the latest discoveries about black holes?
The most exciting things to me are the first supercomputer simulations of two black holes that spiral together and then collide, triggering wild vibrations of their warped space and time. There's a fascinating recent simulation by a group led by Manuela Campanelli and Carlos Lousto, who are now at the Rochester Institute of Technology, in which the two holes are spinning with their axes pointed in opposite directions in the plane of their orbit. As they come together, the whirling space around each hole grabs hold of the other hole and throws it upward, just before they collide. The merged hole flies upward from where the collision occurred, vibrating wildly, and fires a burst of gravitational waves in the opposite direction in order to conserve total momentum. It's similar to how a smoke ring propels itself forward through air.

How soon might we see hard evidence of gravitational waves from violent events like colliding black holes?
LIGO is a several-stage project. We upgrade the detectors to better and better sensitivity. We are now operating our first detectors, completing the first long search. It's possible, but not probable, that we already have gravitational waves in the can, that we will see them as we complete the data analysis. In Advanced LIGO, which will begin its searches early in the coming decade, we expect to see a rich plethora of different types of waves, with signals coming in every day or week.

From the 1960s through the 1980s, you collaborated quite a bit with Russian physicists. What was it like to work with them during the cold war?
I managed to do this in large part because a Russian astrophysicist named Yakov Zel'dovich took me under his wing. He and Andrei Sakharov had been the principal designers of the hydrogen bomb in Russia. John Wheeler, one of the designers of the American hydrogen bomb, was my Ph.D. thesis adviser, so I was personally close to the designers of both the Russian and U.S. hydrogen bombs. I moved freely back and forth between Russia and the United States as an intellectual gadfly, carrying astrophysics and relativity ideas back and forth and helping the two sets of scientists communicate with each other.



Were you watched and questioned by government agents?
I was pretty sure that the CIA or FBI was bugging my telephone occasionally here in the United States, but they never came to me directly. After I would leave the U.S.S.R., my Russian colleagues were typically debriefed by the KGB about what had happened during my visit. The monitoring was much more intense on the Soviet side. The KGB often tried to use Russian scientists as spies, and this was a painful issue that some of my Russian colleagues had to struggle with. The CIA never, ever tried to use me as a spy.

Science fiction fans love you because in the 1980s you suggested that time travel might be possible by passing through a thing called a wormhole. How would that work?
A wormhole is a hypothetical warp of space that can serve as a shortcut between two different regions of the universe. It's sort of like if a worm drilled a hole through an apple from one side to the other. If you were an ant and you lived on the surface of the apple, there could be two routes to get from one side of the apple to the other. One is around the outside, on the surface, which we can think of as being like our universe's gently warped space; the other is down the wormhole. In the case of our universe, the wormhole might be quite short and still reach from, say, our solar system to the center of our galaxy. General relativity says wormholes could exist. When we combine general relativity with quantum theory, we find moderately strong evidence that wormholes cannot exist after all—but we just don't know for sure yet.

How did wormholes lead to your interest in time travel?
In Carl Sagan's original version of his novel *Contact,* he had his heroine traveling through a black hole to a distant part of the universe, and he asked me for advice. I immediately told him, "You can't do that. Black holes can't be used in that way," and I suggested he use a wormhole instead. That got me interested in the issue of whether or not there really could be wormholes that

OPPOSITE PAGE: HENZE/NASA, THIS PAGE: DANA BERRY/NASA.

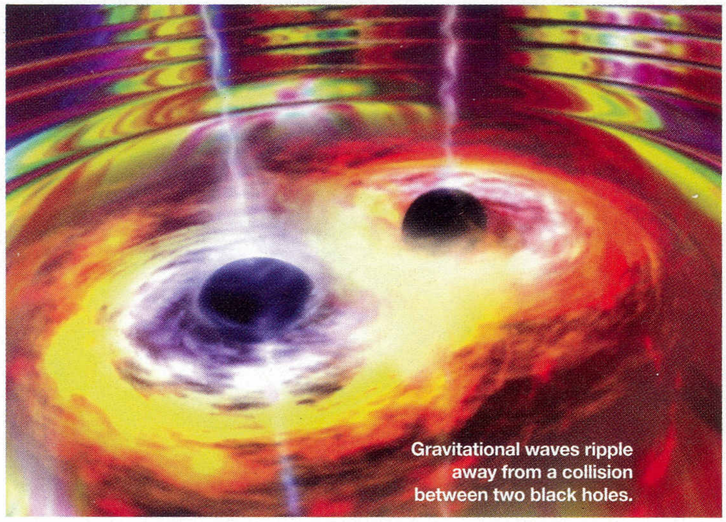
achine to begin to self-destruct.

you could travel through, and quite quickly I came to realize that if they did exist, it would not be hard for a very advanced civilization to use a traversable wormhole to make a time machine. That forced me to face the issue of self-inconsistent histories: Could you go back and kill your father before you were conceived? And that question led me to realize that these kinds of thought experiments can be a very powerful way to probe the laws of physics. I had friends who worried about whether I'd gone off the deep end when they first heard about this, but most became enthusiastic after they learned the details.

Could it really be possible to travel backward in time?
It's quite unlikely that one can go backward in time—although it is certainly not ruled out—and it may be that nature has mechanisms to prevent backward time travel. When I was studying this, I came away convinced that the laws of physics can be readily adapted to backward time travel without any serious loss of ability to predict and without self-inconsistencies. I think more interesting was the discovery I made with a postdoc, Sung-Won Kim from Korea, that there is a universal mechanism that always occurs: If any highly advanced civilization attempts to make a time machine for backward time travel, quantum effects will cause the time machine to begin to self-destruct explosively at the moment you activate it. We don't know whether the explosion is strong enough to always destroy the time machine. We will have to have in our hands the full quantum theory of gravity [a combination of general relativity and quantum mechanics, yet to be understood] to find out the answer.

There is a rumor that you are working on a sci-fi project with Steven Spielberg. True?
I'm working on a science fiction film with Steven that's based on a treatment I coauthored with the producer Lynda Obst. I will be an executive producer on the film, basically focused on bringing good science into it. I expect that nothing in the film will violate fundamental physical law, and all the wild speculations in the film will spring from science. The working title is *Interstellar,* but it's unlikely that will be the final title. It is a story in which the warped side of the universe plays a major role.

Can you describe some of the bets you've had with Stephen Hawking—and who won?
Our first bet was about Cygnus X-1, the first strong candidate for a black hole that anyone had found. Is it really a black hole? Hawking characterized that bet as his insurance policy because he had so much invested in it turning out to be a black hole, so he bet against his hopes. He figured if it turned out not to be a black hole, he at least would get something out of the disappointment. The bet was very nonpolitically correct: He gave me a subscription to *Penthouse* magazine when I won. We also had another bet: John Preskill and I on one side—Preskill's a physicist at Caltech—and Hawking on the other. The bet was over whether the laws of nature permit an implosion to produce a naked singularity—a singularity that is not inside a black hole. We bet that it could, and Hawking bet it couldn't. He had to concede when a naked singularity was actually created in a finely tuned implosion, simulated on



Gravitational waves ripple away from a collision between two black holes.

a computer. Now we have a new bet over whether a naked singularity could occur naturally in the universe.

What did you win on that second bet?
The loser had to give the winner an item of clothing to hide the winner's nakedness. Hawking conceded in a public lecture at Caltech, and he had his assistant present to us T-shirts that had a picture of a woman hiding her nakedness with a towel. On the towel was written "Nature Abhors Naked Singularities."

You also placed a wager on one of the strangest ideas about black holes: Not only do they swallow matter and light, they even obliterate any clues or information about the event. What was the argument in this case?
If you have something that implodes to make a black hole, which then completely evaporates due to what's called Hawking radiation [a kind of radiation that can escape right along the horizon of the hole], does all the information that went into the black hole come back out? The fundamental principles of quantum theory say yes, and Preskill took their side. General relativity seems to say no, and that's the side that Stephen and I took. About three years ago, Stephen found a new way to analyze the evaporation process, a way that convinced him that Preskill was right and that the information could be recovered, in principle. Hawking conceded in a big ceremony at an international meeting in Dublin where I was the chair. But I haven't conceded yet.

It sounds like Hawking hasn't done very well in his bets.
He hasn't won any of these bets yet. I think that characterizes the fact that he's ready to go out on a limb and challenge people, as a way of trying to foster the forward movement of science.

Are you still in contact professionally with Hawking?
He and I have never written a paper together. His current focus is the birth of the universe. Mine is probing its warped side. I will be going to Cambridge soon and spend a day with him, and we'll be talking about physics and about life. He's just finished writing a book for children called *George's Secret Key to the Universe.* I'm eager to read it. It should contain gems of wisdom, not just for children but for adults and probably also for physicists like me. ■

For an extended version of this interview, with Thorne speaking about miniature black holes, his friendship with Carl Sagan, and how a human-size object can behave in a quantum way, go to www.discovermagazine.com.