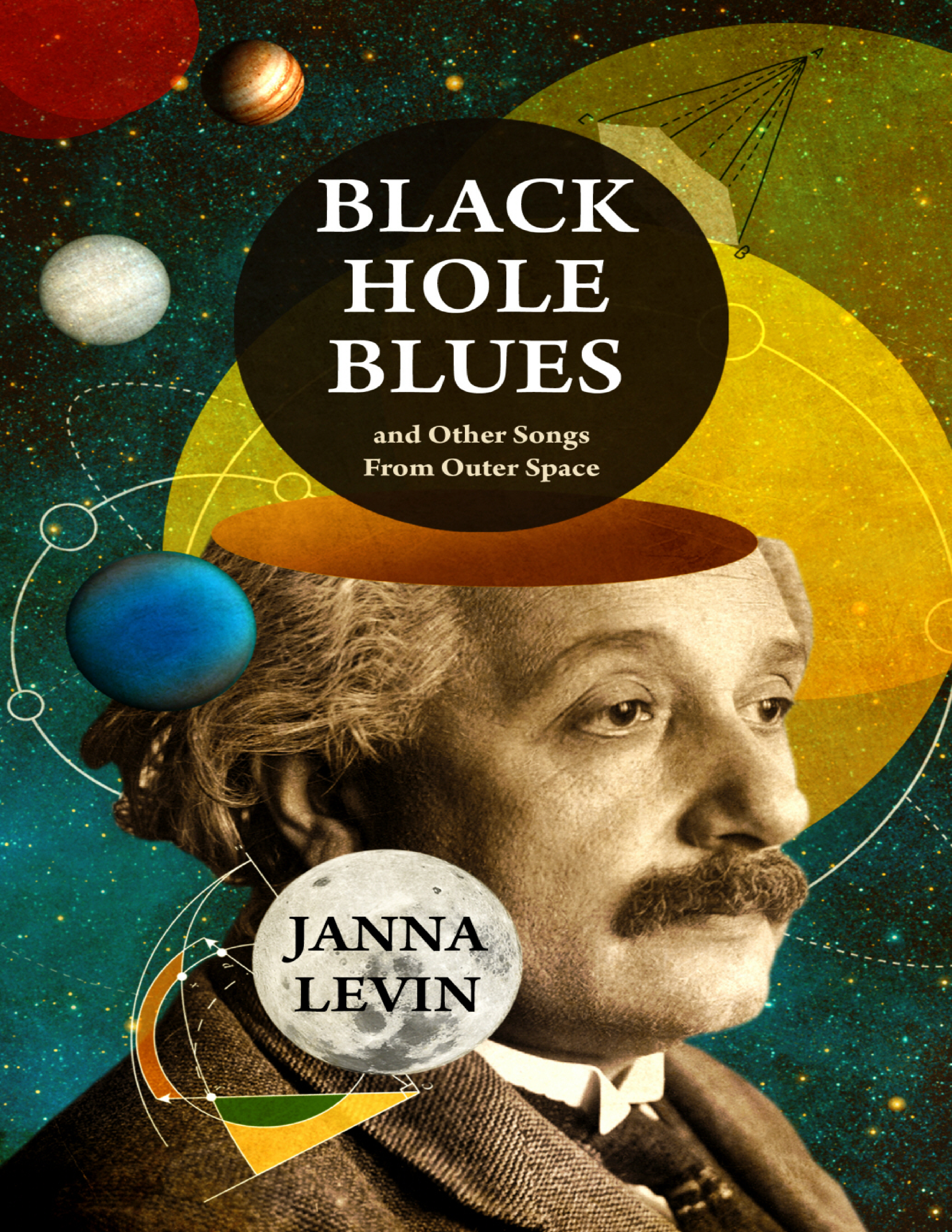
BLACK
HOLE
BLUES
and Other Songs
From Outer Space
JANNA
LEVIN

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About the Book

The full inside story of the detection of gravitational waves at LIGO, one of the most ambitious feats in scientific history.

Travel around the world 100 billion times. A strong gravitational wave will briefly change that distance by less than the thickness of a human hair. We have perhaps less than a few tenths of a second to perform this measurement. And we don't know if this infinitesimal event will come next month, next year or perhaps in thirty years.

In 1916 Einstein predicted the existence of gravitational waves: miniscule ripples in the very fabric of spacetime generated by unfathomably powerful events. If such vibrations could somehow be recorded, we could observe our universe for the first time through sound: the hissing of the Big Bang, the whale-like tunes of collapsing stars, the low tones of merging galaxies, the drumbeat of two black holes collapsing into one. For decades, astrophysicists have searched for a way of doing so…

In 2016 a team of hundreds of scientists at work on a billion-dollar experiment made history when they announced the first ever detection of a gravitational wave, confirming Einstein's prediction. This is their story, and the story of the most sensitive scientific instrument ever made: LIGO.

Based on complete access to LIGO and the scientists who created it, *Black Hole Blues* provides a firsthand account of this astonishing achievement: a compelling, intimate portrait of cutting-edge science at its most awe-inspiring and ambitious.

About the Author

Janna Levin is a Professor of Physics and Astronomy at Barnard College of Columbia University and Director of Sciences at Pioneer Works, a centre for art and innovation in Brooklyn. She has contributed to the understanding of black holes, the cosmology of extra dimensions and gravitational waves. She was the first scientist-in-residence at the Ruskin School of Fine Art and Drawing at Oxford University with an award from NESTA, and was recently named a Guggenheim fellow. Her previous books are *How the Universe Got Its Spots* and a novel, *A Madman Dreams of Turing Machines*, which won the PEN/Bingham prize. She has also appeared at TED and contributes to numerous radio and television programmes.

Also by Janna Levin

A Madman Dreams of Turing Machines

How the Universe Got Its Spots

To Warren, Gibson, and Stella

BLACK HOLE BLUES

and Other Songs from Outer Space

JANNA LEVIN

THE BODLEY HEAD
LONDON

There is nothing more difficult to take in hand, more perilous to conduct, or more uncertain in its success, than to take the lead in the introduction of a new order of things.

—MACHIAVELLI, *The Prince* (1513)

1

When Black Holes Collide

Somewhere in the universe two black holes collide—as heavy as stars, as small as cities, literally black (the complete absence of light) holes (empty hollows). Tethered by gravity, in their final seconds together the black holes course through thousands of revolutions about their eventual point of contact, churning up space and time until they crash and merge into one bigger black hole, an event more powerful than any since the origin of the universe, outputting more than a trillion times the power of a billion Suns. The black holes collide in complete darkness. None of the energy exploding from the collision comes out as light. No telescope will ever see the event.

That profusion of energy emanates from the coalescing holes in a purely gravitational form, as waves in the shape of spacetime, as gravitational waves. An astronaut floating nearby would see nothing. But the space she occupied would ring, deforming her, squeezing then stretching. If close enough, her auditory mechanism could vibrate in response. She would *hear* the wave. In empty darkness, she could hear spacetime ring. (Barring death by black hole.) Gravitational waves are like sounds without a material medium. When black holes collide, they make a sound.

No human has ever heard the sound of a gravitational wave. No instrument has indisputably recorded one. Traveling from the impact as fast as light to the Earth could take a billion years, and by the time the gravitational wave gets from the black hole collision to this planet, the din of the crash is imperceptibly faint. Fainter than that. Quieter than can be described with conventional superlatives. By the time the gravitational wave gets here, the ringing of space will involve relative changes in distance the width of an atomic nucleus over a stretch comparable to the span of three Earths.

A campaign to record the skies began a half century ago. The Laser Interferometer Gravitational-Wave Observatory (LIGO) is to date the most expensive undertaking ever funded by the National Science Foundation (NSF), an independent federal agency that supports fundamental scientific research. There are two LIGO observatories, one in Hanford, Washington, and the other in Livingston, Louisiana. Each machine frames 4 square kilometers. With integrated costs exceeding a billion dollars and an international collaboration of hundreds of scientists and engineers, LIGO is the culmination of entire careers and decades of technological innovation.

The machines were taken offline over the past few years for an upgrade to their advanced detection capabilities. Everything was replaced but the nothing—the vacuum—one of the experimentalists told me. In the meantime, calculations and computations are under way in groups across the world to leverage predictions of the universe at its noisiest. Theorists take the intervening years to design data algorithms, to build data banks, to devise methods to extract the most from the instruments. Many scientists have invested their lives in the experimental goal to measure "a change in distance comparable to less than a human hair relative to 100 billion times the circumference of the world."

In the hopefully plentiful years that follow a first detection, the aspiration is for Earth-based observatories to record the sounds of cataclysmic astronomical events from many directions and from varied distances. Dead stars collide and old stars explode and the big bang happened. All kinds of high-impact mayhem can ring spacetime. Over the lifetime of the observatories, scientists will reconstruct a clanging discordant score to accompany the silent movie humanity has compiled of the history of the universe from still images of the sky, a series of frozen snapshots captured over the past four hundred years since Galileo first pointed a crude telescope at the Sun.

I follow this monumental experimental attempt to measure subtle shifts in the shape of spacetime in part as a scientist hoping to make a contribution to a monolithic field, in part as a neophyte hoping to understand an unfamiliar machine, in part as a writer hoping to document the first human-procured records of bare black holes. As the global network of gravity observatories nears the final stretch of this race, it gets harder to turn attention away from the promise of discovery, although there are still those who vehemently doubt the prospects for success.

Under the gloom of a controversial beginning and the opposition of powerful scientists, grievous internal battles, and arduous technological dilemmas, LIGO recovered and grew, hitting projections and escalating in capability. Five decades after the experimental ambition began, we are on the eve of the crash of a colossal machine into a wisp of a sound. An idea sparked in the 1960s, a thought experiment, an amusing haiku, is now a thing of metal and glass. Advanced LIGO began to record the skies in the fall 2015, a century after Einstein published his mathematical description of gravitational waves. The instruments should reach optimum sensitivity within a year or two, maybe three. The early generation of machines proved the concept, but still success is never guaranteed. Nature doesn’t always comply. The advanced machines will lock on and tolerate adjustments and corrections and calibrations and wait for something extraordinary to happen, while the scientists push aside their doubts and press toward the finish.

As much as this book is a chronicle of gravitational waves—a sonic record of the history of the universe, a soundtrack to match the silent movie—it is a tribute to a quixotic, epic, harrowing experimental endeavor, a tribute to a fool’s ambition.

2

High Fidelity

At 6:00 PM the building is quiet for an MIT headquarters. I have to wait outside until a graduate student rolls up and pops off a bicycle to let me in the locked doors, carrying the bike with her up the stairs. “Rai’s office is straight down.” She points to the hall behind her and wheels away, one foot jumped into the stirrup of the pedal, the other hanging on the same side. She hops off again and is inhaled by a pale office door. Rai’s door looks exactly the same and I have the sense it would be easy to mistake offices, like mistaking hotel rooms.

Rainer Weiss waves me in. We skip conventional social openers and speak with familiarity, although this is our first meeting, as though we’ve known each other for as long as imaginable, the shared experience of our scientific community outweighing a shared hometown or even generation. We lean back in mismatched chairs, our feet propped up on a single stool.

“I started life with one ambition. I wanted to make music easier to hear. As a kid I was in the revolution of high fidelity. Because, look, I was a kid in around 1947. I built hi-fis of the first kind. The immigrants that came to New York, most of them were very eager to listen to classical music.

“See that loudspeaker there? That came from a movie theater in Brooklyn. Behind the screen you had a matrix of those things. I had twenty of them. I lugged them all on the subway. They had a huge fire at the Brooklyn Paramount, and they were getting rid of them. So I had what were movie-studio quality loudspeakers and I had this fantastic circuit that I was building and I had FM radio. And I would invite friends over to listen to the New York Philharmonic and it was unbelievable. You felt like you were in the theater. An unbelievable sound came out of those things."

Rai gestures to the conical metal guts of a circa 1935 speaker. The raw frame has an exaggerated heft that design advances have banished but otherwise looks surprisingly technologically recent, more 1970s indulgence than 1930s necessity. The object fits in visually with the other metal frames from various apparatuses that are stashed around the hive of scientists attending to a gravitational instrument that first imposed itself as a compelling thought experiment in the 1960s. Although he would later find out he wasn't the first, Rai dreamed up a device to record the sound of spacetime ringing. A paragon of scientific ambition, the experiment is now too colossal for this building or even for Cambridge, Massachusetts. An R&D laboratory to develop some of the machines' components is housed in the basement of the building next door, while the fully integrated instruments are constructed on remote sites.

In 2005, Rai molted the venerable role of professor of physics at MIT so he could walk 4 kilometer cement tunnels, affix oscilloscopes to laser beam tubes, appraise 18,000 cubic meters of hard vacuum for leaks, and measure seismic vibrations in dank wasp-infested enclosures. Rai seceded essentially for the privilege to reemerge as a student again but with the elevation of the august title offered the most admired retired—but active—faculty: professor emeritus.

Rai talks with the emphatic rhythms of a generation of New Yorkers, with the quintessentially American phonetics that emerged from an amalgam of European accents. Any

German cadence that he contributed to that mix blended away, the familiar timbre reminding me as much of an era as of a region. He was born in Berlin in 1932 to a rebellious father, Frederick Weiss, a communist from a wealthy Jewish family. (Rai's paternal grandmother was from the prominent Rathenau family. "Very German, slightly Jewish" is Rai's characterization.) Rai's mother, Gertrude Lösner, he describes also as a rebel, not Jewish, and an actress. "Somehow they hitched up," Rai says as though there are some things we should never try to understand. "I was the product of that meeting; they were not married yet," he clarifies.

Like every other immigrant listening to the Philharmonic in Rai's living room, he has a narrative for how he got there, a bit of setup to land the tone, but it's not the real action of his life story, which starts soon after the exchange of papers on Ellis Island. Rai's prelude begins in a communist workers' hospital in Berlin where his father was a neurologist. The Nazis infiltrated the infirmary and the district, as they had other neighborhoods. A Nazi plant botched an operation at the hospital, killing the patient and impelling his politicized father to report the incident to the diminished authorities. Like a marauding gang, the Nazis nabbed him off the street in retribution and interned him in a cellar; the family narrative fails to specify where exactly. There he might have rotted—Frederick's own family had disowned him on account of his zealous communism—if he hadn't conceived Rai on New Year's Eve. Rai's pregnant mother and her father, a local bureaucrat in the Weimar Republic, managed his release. Although free to leave, Rai's father was no longer free to stay.

Frederick was pushed over the border into Czechoslovakia. His new family followed him soon after. Rai cannot figure how his parents stopped fighting long enough to conceive his sister Sybille Weiss in 1937. (They used to blame Hitler for their troubled marriage.) As a reprieve from the marital acrimony, the family of four took their first vacation together in the Tatra Mountains on the Polish border. In the hotel lobby, an old wooden Gothic radio with glowing tubes mesmerized Rai during a broadcast of Chamberlain's appeasement foreign policy that would ultimately deliver parts of Czechoslovakia for German annexation. They adjusted the radio dials to lock onto Chamberlain's voice, to register the message without distortion. Rai describes a spooked flock of expatriate Germans, many of them Jews, taking off, trying to get the hell out of the mountains, to get to Prague and then out of Czechoslovakia before this agreement was consummated. "We got out. We were very lucky that way. My father being a doctor is what got him out, because a lot of people didn't."

In New York, his mother supported the family for several years with odd jobs until his father began his own practice as a psychoanalyst. "I went to a school in New York called Columbia Grammar School, which Murray Gell-Mann [Nobel laureate in physics] had gone to. He was several years ahead of me. I was always being compared with him. You know: 'That guy really knew something. You're just a bum.' That kind of thing."

People had frequency modulation radio for the first time, and Rai knew enough electronics to build an amplifier and augment the quality of the sound. He had a little business going. The first person who bought his system was not an aunt by genetics but by affinity, a woman he called "Aunt Ruth." He doesn't remember what he earned—not that I ask—but he remembers he only charged for the cost of parts. He had become an entrepreneur with a following: the community of immigrants with an appetite for high fidelity. Once they heard the music clarified through Rai's system, the demand grew by word of mouth.

"There were things called shellac records, which were the original records. They had a background hiss. Vinyl records don't have that. They might make a pop. This was a real background hiss. *Shshshshsh.* You see, the stylus was always being driven by the roughness of the surface, and I was trying to think of ways to get rid of that goddamn hiss.

"During the quiet passage of a Beethoven sonata or something like that, when it's slow you always hear the *hish.* And how do you get rid of it? When you have lots of sound it doesn't matter anymore. It gets masked. And I tried to make a circuit that would change the bandwidth of the device as a function of the amplitude of the sound. And I knew that I didn't know enough to do that on my own, and so I knew I wanted to go to college to learn about that.

"I went to MIT for college—I wanted to learn how to do audio engineering well, because that was all I knew. But I very rapidly realized that I didn't want to become an engineer. I switched to physics, and I don't know why. . . . No, I'll tell you; it was really stupid. The Physics Department had fewer requirements than the others, and I was totally undisciplined—I didn't want any requirements."

. . .

Rai assures me everyone on the MIT team is still working. I can see a few shoulders through the open doors. More people are in the laboratory next door. We check into the R&D lab. Experimenters sit on the floor to sift through a bundle of cables or hunch over optics tables, or ratchet some tool or lift their goggles to focus on a bizarrely antiquated oscilloscope used for diagnostics. I swear I see a floppy disk. I promise that the caliber of the technology is mostly impressive, so I kind of gawk at the floppy disk. The physical labor and the meticulous details layer and integrate and feedback and are compounded until a machine is ultimately built. The power structure of the operation is horizontal at some strata. Everybody seems to understand the job, so the collective operates like an elaborate ant colony in constant but not necessarily rapid motion. Without pause, one thing is done and then another. The target of any one scientist's concentration seems incredibly compressed, microscopic given the scale of the thing they're working toward. Everyone is skilled and physically equipped for the awkward pressures on the body and the long hours. A graduate student gingerly shifts a delicate piece on an optics table. Each person contributes to the fabrication of a hypersensitive device that will be ready to record the sounds from space one hundred years—maybe plus a few—after Einstein surmised that spacetime was mutable.

They're constructing a recording device, not a telescope. The instrument—scientific and musical—will, if it succeeds, record Lilliputian modulations in the shape of space. Only the most aggressive motion of great astrophysical masses can ring spacetime enough to register at the detectors. Colliding black holes slosh waves in spacetime, as can colliding neutron stars, pulsars, exploding stars, and as yet unimagined astrophysical spacetime cataracts. The contractions and expansions of spatial distances and of the tempo of clocks move through the universe—through the shape of spacetime—like waves on an ocean. Gravitational waves are not sound waves. But they can be converted to sound through sheer analog technology, much like a wave on the string of an electric guitar can be converted to sound with a conventional amplifier. In a less than perfect analogy, astrophysical calamities are the finger pickers, spacetime is the set of strings, and the experimental apparatus is like the body of the guitar. Or, moving up a few dimensions, astrophysical calamities are the mallets, spacetime is the skin of a three-dimensional drum, and the apparatus records the modulations in the shape of the drum to play the silent score back to us as sound. Scientists in the control room listen to the detector amplified through store-bought speakers, although they have only ever heard background noise. The *"hish." Shshshshsh.*

The MIT facility is invaluable but puny in the larger scheme of the operation. LIGO headquarters is at Caltech, as is another prototype also humbled by the two full-scale instruments at remote sites. Rai asks, “You haven’t been to the sites yet? When are you going? Oh, wait till you see it.” He leans back in revived amazement. The full-scale instruments are roughly two and a half thousand times longer than Rai’s first prototype. I lean back too and consider the proportions. “We don’t get so many visitors to the sites.”

From the time he started college, his scientific life has been in this mesh of streets in Cambridge, although the moment he stepped out of the subway in Kendall Square he vowed to go back to New York. On that dank morning in September, the industrial corner of the city stank—an unholy mixture of soap made from the renderings of dead animals and their fat mixed in with mayonnaise and pickles. The chocolaty finish was just too much. He didn’t go back to New York but toughed his way past the humid fumes on an elongated trajectory that would veer away from Cambridge only for brief but essential intervals. Though no intransigence was suggested during his first few months enrolled at MIT.

“Well, the next thing that happened was that I fell in love with somebody. This was at the height of the Korean War. Like an idiot, I decided that I was just going to take off, and I flunked out. I chased this woman to Chicago. She was a pianist. But she changed my life, by the way. I had never thought of a lot of that stuff, and that’s why I started the piano at twenty—or [older], I guess. It was because of her.

“Many years later when I began to think of gravitational waves, I immediately thought, ‘Look, LIGO covers the same frequency range as the piano.’

“Anyway, I was totally gaga, crazy in love. I didn’t think of what the consequences of that would be. Of course, the girl went off with somebody else. You can never fall in love— I