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### The Golden Era of Particle Cosmology, or How I Joined the Chicago Mafia

It was in a hospital bed in Tokyo that I realized I had to become a physicist. I was 22 years old. Although I had earned an undergraduate degree in physics from Princeton University 2 years before, I still felt unsure about what I wanted to do with my life. I had rushed to college at age 16, spent the first 2 years dating boys and the next 2 studying way too hard. After applying to graduate school, I was surprised when 12 of the 14 doctoral programs I'd contacted accepted me. But I needed a break. So I decided to travel the world.

Tokyo was the first stop. To earn money for the rest of the trip, I taught English for a while, then served drinks in a bar. It was as hostess in the bar that I learned to deflect men's advances and demand to be treated professionally—skills that later proved invaluable in the male-dominated physics world. Tokyo was my first experience of a big city, and I loved it. I stayed there for nearly 2 years.

As a side trip I took a boat to South Korea for sightseeing. There I found myself doubled over with stomach pain throughout most of the voyage. When I returned to Tokyo 2 weeks later, the pain suddenly became excruciating. I took myself to the first emergency room listed in my guidebook, at a hospital run by English nuns. I needed an emergency appendectomy. A surgeon operated immediately and discovered that my appendix had started to rupture. Afterward I lay in the hospital bed in agony, drifting in and out of consciousness. It was a semi-private hospital room, but for several days I didn't even realize I had a roommate. Once I started to feel better, I quickly became bored. The patient in the neighboring bed couldn't speak English, so I asked the nuns for a textbook to learn to speak Japanese. They looked at me as though they thought I was crazy. So instead I began reading the only physics book I had brought with me: *Spacetime Physics*<sup>1</sup> by Edwin Taylor and John Wheeler.

What an amazing subject and an amazing book. *Spacetime Physics* is all about Albert Einstein's theory of Special Relativity. It's built on two simple postulates: one, the speed of light is always constant, and two, the laws of physics don't depend on your state of motion—they're the same whether you're on a moving train or standing still on the platform. These two postulates immediately lead to bizarre phenomena. One is the twin paradox: if one of two identical twins speeds into outer space and then back to Earth, she will return younger than the twin she left behind. So in a way, relativity allows time travel to the future.

Reading *Spacetime Physics* was exhilarating. I spent the remainder of my week in the hospital reading the entire book and solving every problem at the end of each chapter. The book inspired me to want to learn more. I felt that if one elementary text could substantially alter my perceptions of the Universe, then I had to go back to school for a deeper understanding. If physics from the early 1900s could be so fascinating, what would the next millennium bring? After my release from the hospital, I hightailed it back to the United States, reactivated my acceptance from Columbia University, and headed to graduate school.

### **New York City**

I started graduate school at Columbia University intending to become an experimental high-energy physicist. During my first semester, I was a little side-tracked by many nights at Studio 54, the most famous nightclub in the world. It was exciting to dance alongside celebrities like Andy Warhol, Mariel Hemingway, Robert Duvall, and Diana Ross. I lived on 112th Street and ate daily at Tom's Diner next door, now well known from the *Seinfeld* television show. I even harbored thoughts of becoming an actor, like my two cousins. But the pull of physics was stronger. Despite all my partying, I passed my classes (barely). After a year and a half, I moved to Fermilab, the particle accelerator laboratory that at the time was the preeminent high-energy physics facility in the world.

### **Fermilab: The Atom Smasher in the Prairie**

Fermilab is built on a large farm in the middle of the prairie an hour west of Chicago. Buffalo graze on site, and visiting scientists are housed in transplanted farmhouses. The contrast with the urban environment of New York City was a jolt. The winter was extreme. The wind chill temperature dipped down to

minus 80 degrees F. Any part of your body exposed for even 10 minutes would be frostbitten. Every night my car battery died, and the Fermilab crew had to come start it up again. When I tried to walk up the stairs into the High Rise, the central 15-story building where I worked, I couldn't make it against the wind. A few of us went to a theater in a nearby town to watch the movie *Reds*, which is set partly in Siberia. Halfway through the movie the theater owner had to refund our money, because he couldn't keep the theater warm enough. Outside the scenery looked exactly like the Russian steppes we had been watching in the movie. Siberia isn't impressive if you're in the middle of a good Fermilab winter. Then one day in April the temperature miraculously changed from minus 20 to plus 80. Spring lasted about 5 minutes during lunchtime.

I was one of only a handful of women at Fermilab. When I walked into the cafeteria, I felt the attention of the hundreds of male physicists. I was somewhat uncomfortable, but my heart soared at the prospect of working on such an impressive piece of machinery and discovering something new about the fundamental constituents of nature.

When I arrived at Fermilab, I joined a team working on an experiment to discover neutrino mass. Neutrinos are subatomic particles produced in radioactive decays and in nuclear reactions in the Sun. A member of our group, the head of the Fermilab theory division, promised to strangle one of the buffalo on site by hand if the experiment resulted in a discovery. Fortunately for the buffalo, we did not succeed. Instead the experiment placed limits on neutrino properties. The discovery of neutrino mass had to wait almost two more decades.

Fermilab's particle detectors were enormous; a student could gain familiarity with only a small part of the experiment. My first task was to check 1,000 phototubes to see whether they were working properly. This meant removing any input to them and then making sure they were recording zero signal, as they should. The test is known as measuring the dark current. I had to manually remove cables from the phototubes, check the signal, and then replace the cables. When I was done, my hands were bleeding from the effort. Today I joke that I switched from working on dark current to working on dark matter and dark energy.

Soon I realized that participating in a team of hundreds did not suit me. I enjoy having command of the entire project—from the initial idea, to the calculations, and finally to a publication—all on a quick turnaround time. I am a theorist by temperament, working with ideas, pen, paper, and computers. I prefer to work on my own schedule. When a senior experimentalist taking a night shift said to me, "You will learn to live on little sleep," I decided this field was not for me.

## Chicago: A New Zeitgeist in Cosmology

In the interest of getting into Chicago a few times a week, I wanted to take a class in the city. It was the beginning of October. I looked into acting classes at the theaters, but they had already started a month earlier. I am incredibly lucky that, of all the universities in America, the University of Chicago is one of the few where the fall semester begins in October. I signed up for a cosmology class twice a week in the early morning taught by Professor David Schramm.

Little did I know that I was putting my future in the hands of one of the giants in all of science, both literally and figuratively. He was a huge man, a wrestling champ as well as a leader of the field of modern cosmology. He was a pioneer in the emerging field known as particle astrophysics. In 1968 he had been a finalist in the Olympic trials for Greco-Roman wrestling. We nicknamed him Schrambo. Dave pushed the limits both in his work as an astrophysicist and in his daily life. He was an expert skier, though not particularly graceful. With his enormous leg strength, he powered his way down double black diamond runs.<sup>2</sup> He seemed to simply shove the moguls out of the way.<sup>3</sup>

Twice a week I drove the hour from Fermilab to Schramm's early morning class at the university. I loved the course and found myself skipping my work at the experiment to stay behind (in the farmhouse where I lived) to read cosmology. Here the book with the greatest impact on me was Steven Weinberg's *Gravitation and Cosmology*.<sup>4</sup> Though I was merely auditing, I went ahead and took the exams in the class. The day before the midterm, I saw the exam sitting on the secretary's desk. Despite the temptation, I didn't look at the problems. I aced the test nonetheless, and as a consequence, Dave asked me if I would like to work on a project with him. Had I cheated, I would never have known whether his confidence in me was misplaced. I considered his proposal of a collaboration and then asked him if I could switch to become his graduate student. He immediately agreed, and that is how my career in cosmology began (Figure 1.1). I was lucky to get into the new field of particle astrophysics in its infancy, at a time when even simple ideas could have a big impact.

One of the benefits of becoming a theoretical physicist was the opportunity to visit the Aspen Center for Physics in Colorado. George Stranahan, physicist and heir to the Champion Spark Plug fortune, founded the center in 1962. There physicists spend long blocks of uninterrupted time thinking and brainstorming together. Important ideas have emerged from discussions among experts in different specialties who would never have met outside the center. I've participated in many of the summer and winter workshops. I enjoy the sports activities, including biking up the Rockies and skiing down them.

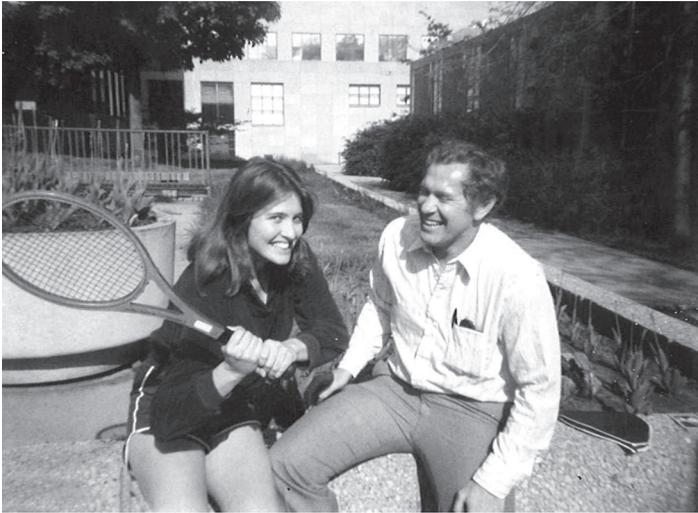


FIGURE 1.1 A picture with my PhD advisor David Schramm behind the Astronomy and Astrophysics Center at the University of Chicago in 1983.

Ever since a bee stung my leg while I was traveling downhill on my bicycle at 50 miles an hour, I ride the bike up the mountain and take the bus back down. Dave tried to get me to go mountain climbing with him, but I declined because of stories I'd heard from his previous student. They were roped together, when the student saw Dave lose control above him and come hurtling down. They were both barely hanging on when a helicopter rescued them. As they were being airlifted, Dave started haggling with the pilot about the bill.

Unfortunately, Dave Schramm's risk-taking style eventually cost him his life. He flew his own plane, which he named Big Bang Aviation. On the way to Aspen the engine failed, and Dave was forced to land next to the highway. Apparently the wing snagged a tree, the plane flipped over, and sadly, Dave died. Another close friend of mine (and former fiancé), Josh Frieman, had originally intended to be a passenger on the flight. Fortunately, he overslept, or I would have lost another important person in my life. My last image of Dave Schramm is on the final ski run of the day down Aspen Mountain. He had found a patch of remaining powder under a ski lift already shut down for the night. He yelped with excitement as he carved his way down the mountain, and that is the same approach he took to doing science.

Chicago felt like the center of the world for particle astrophysics. Dave Schramm led the Center for Astronomy and Astrophysics at the University and also created the Center for Particle Astrophysics at Fermilab. He hired

Michael Turner, who quickly rose to become another of the leaders in cosmology. Michael, then an assistant professor, was the other important person in my early career. He taught his students to do back-of-the-envelope estimates that are so crucial to determining whether an idea is worth pursuing. After we had done the calculations, he showed us the mechanics of putting a paper together quickly. Michael had long hair, wore humorous T-shirts, and often treated students to lunch. When I was in between offices, Michael let me use his.

The University of Chicago became a cutting-edge center for students in particle astrophysics. Those of us who were trained there came to be known as the Chicago Mafia.

### **Dunkle Materie: The Dark Enigma**

After obtaining my PhD, I went to Harvard as a postdoctoral fellow, and it was there that I started working on unraveling the dark matter problem. This mystery began in the 1930s and remains one of the grandest unsolved problems in all of science. The rapid motions of stars and gas in galaxies and clusters of galaxies imply the existence of a new massive component exerting a powerful gravitational pull. This dark matter is now known to dominate the mass of galaxies and clusters, as we'll see in Chapter 2. We call it "dark" because it does not give off light and cannot be seen in telescopes. Its nature is mysterious, but its existence is certain. Using the recent technology of gravitational lensing, scientists have mapped out the dark matter inside typical galaxies and shown that it extends out to hundreds of thousands of light-years.

Most people believe the predominant constituent of our surroundings to be the ordinary atomic matter of our daily experience: the chairs we sit on, the walls of our rooms, the air that we breathe, the planets and stars. Yet over the past few decades it has become clear that all these objects add up to only 5% of the content of the Universe. All atomic matter, which is made of neutrons and protons (or at a more fundamental level, quarks) and electrons, only constitutes a small portion of the matter and energy in the Universe.

A greater part of creation is dark matter, which makes up most of the mass of the Universe. Scientists believe the dark matter is made of a new type of fundamental particle—not neutrons, protons, or quarks, but something altogether different. Billions of these particles may be passing through our bodies every second, yet typically they go right through us without hitting any of our nuclei. Because they interact weakly with matter, they are very difficult to identify in detectors. And so the nature of this material has remained a deep mystery.

In the 1980s, the scientific community was divided into two camps debating the identity of dark matter. Many of the more traditional astronomers believed it consisted of faint stars or substellar objects. Although bright stars couldn't solve the problem, it was certainly possible that huge numbers of faint stars could exist, just beyond the limits of detection in telescopes. However, even at that time there was a new *Zeitgeist* in cosmology. Scientists originally working on particle physics were beginning to have a major impact on astronomy. This second camp of astroparticle physicists was proposing the idea of new fundamental particles as the likely origin for most of the mass in the Universe. This disagreement became the battle between the MACHOs and the WIMPs. Here MACHO stands for Massive Compact Halo Object (that is, some type of stellar object), and WIMP stands for Weakly Interacting Massive Particle, the most likely particle candidate for dark matter. I played a role in both sides of this debate.

### **WIMPs at Harvard**

In the mid-1980s I was fortunate to be in the right place and the right time to make early contributions that started the hunt for dark matter particles. My collaborators and I sat around a table at the Harvard / Smithsonian Center for Astrophysics and made proposals for ways to search for WIMPs. In the quarter of a century since we wrote down our ideas, the experimental race for dark matter detection has been on.

At the Large Hadron Collider at the European Organization for Nuclear Research (known by its French acronym, CERN)<sup>5</sup> in Geneva, for instance, physicists accelerate two proton beams in opposing directions around a 27-kilometer (17-mile) long ring and smash them together at tremendously high energies. A major goal of this enterprise is the hunt for dark matter. Laboratory "direct detection" experiments are designed to detect traces of dark matter particles from the Galaxy striking nuclei in the detectors. These experiments are recording data deep underground, in abandoned mines and Alpine tunnels. "Indirect detection" experiments aboard balloons, at the South Pole, or mounted on satellites in space are searching for signs of dark matter annihilation products. Now even dark matter detectors made of DNA have been proposed.

Some of these experiments are reporting anomalous signals and even claims of discovery. Theorists are feverishly trying to explain all the results. The current situation is both exciting and perplexing.

The field of modern dark matter cosmology was created by a surprisingly small number of individuals. The experimental groups are modest in size,

typically consisting of a dozen people. Perhaps it is for this reason that a disproportionate number of women have gone into dark matter studies. An individual can make a mark without jostling with the crowd and without fighting preconceptions about what the leader of a large group should look like.

The personalities of the leaders of these experiments are strong and can create intense conflicts. Yet at the same time the dark matter community is full of vibrant friendships. I am close to many of these people, and in the following pages I tell their stories as they intersect with mine. The tendency is to depersonalize scientific discoveries and to attribute them in the end to one person. But in reality, it is the collaboration of many people with sympathetic scientific views and outlooks that solves problems—and the hunt for dark matter is no exception. Through this community effort, I believe that the unraveling of the dark matter problem is at hand.