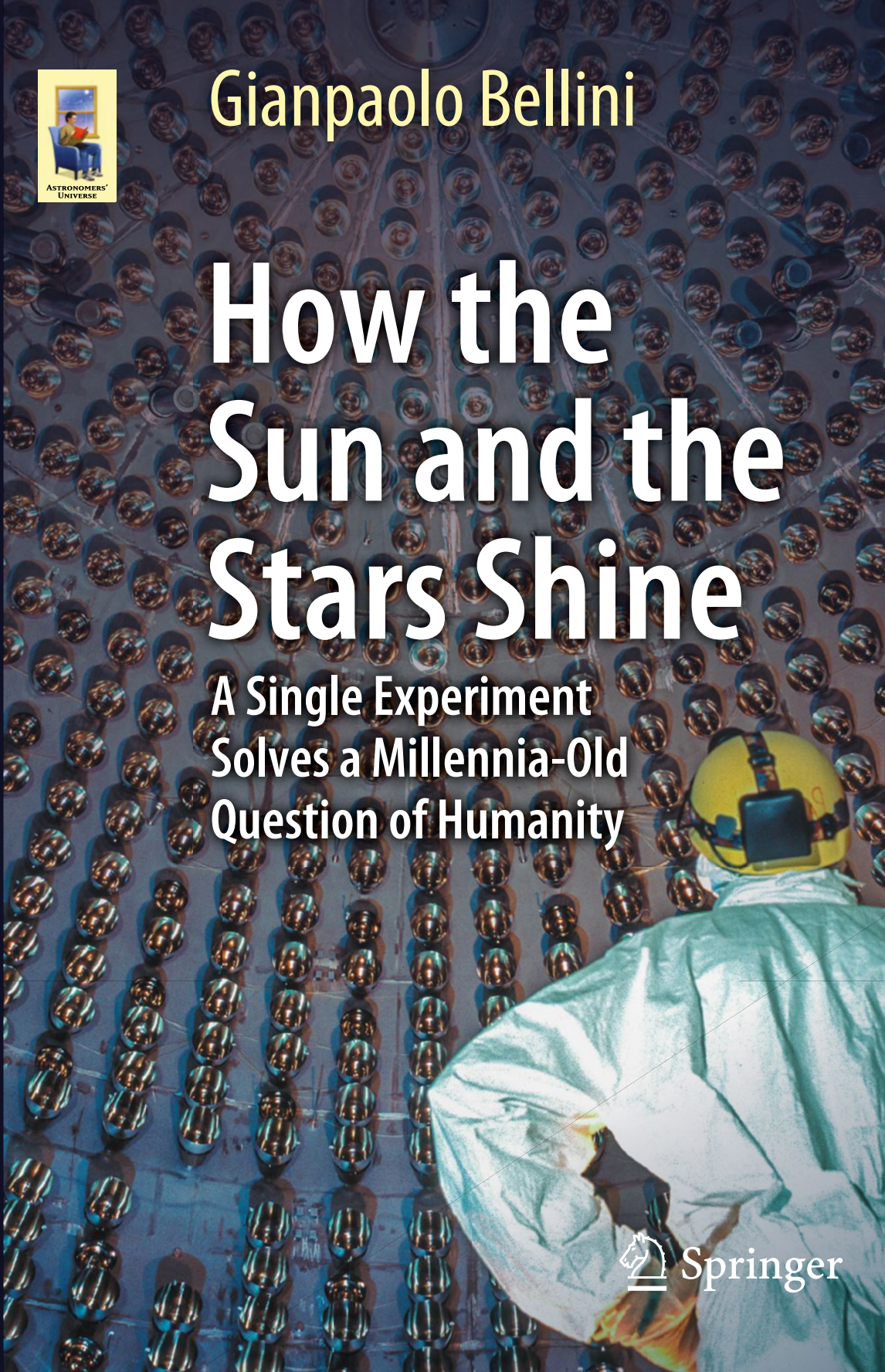
Astronomers' Universe
Gianpaolo Bellini
How the Sun and the Stars Shine
A Single Experiment Solves a Millennia-Old Question of Humanity
Springer

Astronomers' Universe

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To Nice, my invaluable wife

Foreword

How the Sun shines is a very important question for us living on the Earth. We live on Earth thanks to the light radiated from the Sun. It has long been known that observing neutrinos from the Sun can reveal how the Sun shines. However, this is experimentally very difficult, because the neutrinos pass through everything easily.

Gianpaolo Bellini is a distinguished physicist who led a solar neutrino experiment, called Borexino, for more than 30 years, and showed how the Sun shines. As you will see reading this book, this was a remarkable achievement made possible by the collaboration of many scientists who contributed to this success through their diverse expertise and wisdom.

I hope that, through this book, many people will learn how great scientific achievements are made.

Nobel Laureate, 2015

Takaaki Kajita
Special University Professor at the University of Tokyo

Humanity's age-old question about the nature and workings of the Sun and stars has finally been answered in recent years through a groundbreaking experiment featuring a one-of-a-kind detector.

Competing Interests The author has no competing interests to declare that are relevant to the content of this manuscript.

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About the Author

Gianpaolo Bellini, emeritus professor of the University of Milan, emeritus scientist of the National Institute for Nuclear Physics, and experimental physicist in the fields of elementary particles and astroparticles, has performed and directed various experiments in the most important laboratories in the world such as CERN (Geneva, CH), IHEP (Protvino, Russia), Fermi National Laboratory (Batavia, USA), and Gran Sasso laboratories (Assergi, Italy). His discoveries concern resonances, coherent interactions on nuclei, and lifetime of particles with the charm quark, the mechanisms that make the Sun and stars shine. He has been rewarded with the prestigious international Bruno Pontecorvo Prize, the Enrico Fermi Prize, and the Wanda and Giuseppe Cocconi Prize of the European Physical Society addressed to the Borexino Collaboration. The Borexino experiment conceived and directed by him at the Gran Sasso laboratories produced results that have been nominated among the world's ten best breakthroughs in 2014 and 2020, while a celebratory stamp has been dedicated by the Italian post office. He is the author of about 210 papers in international journals and editor of 10 books on elementary particle physics and 4 books on popular science.

1

Introduction and Guidance for Readers

1.1 Introduction

The Sun and the stars have accompanied the lives of all human beings since the dawn of humanity. There is no human who has not been warmed by the Sun's rays or, perhaps, gazed at the starry sky at night. But I wonder how many have thought about how long the Sun will last in its current state—one of the countless conditions that make life on Earth possible—and how our star has so much energy to spread light and heat throughout the solar system. Perhaps, few people know that the light reaching us today was actually produced on the average 100,000 years ago, around the time when Neanderthals occupied much of Europe and western Asia, and Homo sapiens began their first migrations out of Africa. Similarly, some might have wondered how the stars of the Milky Way, so beautifully visible at night, may have enough energy to emit light that travels from tens to hundreds of thousands of years before reaching our Earth, an infinitesimal point in the vastness of the universe.

Astronomy and astrophysics have uncovered many things about how the universe around us was formed and how it works. However, when it came to understanding how the Sun and stars were capable of producing so much energy and therefore so much light, hypotheses were made, but there was no direct evidence of what actually happens inside these celestial bodies.

To understand the mechanisms that power the Sun and the stars, it is crucial to explore their interiors, as energy production occurs in the core of them. Given that the temperature inside them reaches millions of degrees, it is evident that no man-made object could function as a probe. However, there exist

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extraordinary natural probes capable of fulfilling this role: one of the fundamental building blocks of matter, known as *neutrino,* which can travel completely undisturbed through the matter that makes up the Sun and the stars.

In recent decades, an experiment installed in the Apennine mountain range in Italy, under 1400 m of rock, has been able to study the Sun's interior with the help of these natural probes and identify the mechanisms that make the Sun and stars shine. This experiment lasted 31 years and was both a great scientific and human adventure, as such an endeavor would not have been possible without a profound passion for science—no one would dedicate half a lifetime to conducting such an experiment otherwise.

I was one of the principal architects and responsible of this experiment, and I decided to publish this book to share the story of this adventure, which is not only scientific but also human. My aim is to help even readers who may not have a particular interest in, or connection to, scientific activities understand what it means to do science, how science progresses, and the countless small steps required to try to comprehend how the world around us works. Certainly, the results of this experiment represent a small step, a tiny piece in the vast puzzle of human knowledge. However, everything we know today is the result of the collective assembly of such pieces, particularly over the past century and a half. There is still so much to understand, and with each new discovery, we uncover more of what we have yet to grasp; however, I think it is fascinating for everyone to understand how all of this works and to better understand the world in which we are so deeply immersed.

I have tried to describe this experiment in the simplest way possible, so it can be understood by anyone, and I also wanted to present it as a human adventure that involves the lives of some people, and in any case, the work of many people.

I hope that the readers of this book, regardless of their background, will be able to understand the work carried out and the results achieved, and that, in the end, he will have gained something by learning a little more about the sky above us. I would like to recall the words of the great scientist Albert Einstein, who said that the universe around us is already a miracle, but an even greater miracle is that it is intelligible to humankind.

1.2 Guidance for the Reader

When discussing a scientific experiment, one cannot avoid describing and explaining scientific and technical aspects, all within the context of a human endeavor. In this book, I have used language that is as simple as possible for a

general reader, and I have omitted some descriptions and figures typical of the scientific language regarding the experiment, which lies at the intersection of particle physics and astrophysics—what is currently referred to as astro-particle physics. I hope, therefore, that it will be understandable to everyone. However, I have included annexes, which are in-depth information for those with some scientific knowledge who are eager to delve deeper and understand more of what is explained in the text. These annexes are placed at the end of each chapter.

2

The Context

2.1 A Scientific Experiment: What Is It?

The central focus of this book is a scientific experiment that uncovered how the Sun and stars generate their light and energy. Before delving into the details of this subject, it may be helpful to address some fundamental questions about scientific experimentation: What is a scientific experiment? Why is it undertaken? Why choose one experiment over another? How does the idea for an experiment arises? What resources and preparations are needed to carry it out?

Scientists undertake experiments for various reasons. For example, a prior experiment might not have sufficiently explained the phenomena under investigation, necessitating further experiments to clarify unresolved aspects. Alternatively, a scientist may be driven by fascination with a topic, motivating deeper exploration. In my case, I pursued the experiment discussed here because I believed that understanding why and how the Sun and stars shine has been a profound and timeless question for humanity. I also felt it was essential to provide a definitive answer to this mystery.

Often, a scientist's curiosity is sparked by theoretical hypotheses or models that need experimental validation—the only way to determine if these ideas accurately reflect reality. Every hypothesis, model, or scientific theory must be tested experimentally. Without experimental confirmation, a hypothesis or theory cannot be considered truly scientific; it remains a mathematical model, a philosophical idea, or something similar. Take, for example, Galileo Galilei's hypothesis in the early seventeenth century: he proposed that all objects fall

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