Dieter Frekers · Peter Biermann

Universe, Neutrinos, Stars and Life

Intriguing Insights from Astrophysical Research

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For the Reader

The authors of this book have tried to convey physical relationships as intuitively as possible and in an easy-to-read form. In doing so, they have largely dispensed with mathematical equations. Should mathematical formulas nevertheless occur in some places, these are specially marked in color (i.e., highlighted in yellow) and can be skipped without great disadvantage to understanding. The authors have also attempted to write the individual chapters in such a way that they can be read selectively and do not refer to contents of previous ones.

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Chapter 1

Foreword

1.1 This is how it all began

The "Münster Astro-Seminar" is an event that has been held annually for more than 20 years, always at the end of September/beginning of October from Friday to Saturday and at the Physics Department of the University. The target group is an interested audience from all walks of life — and of course, the admission is free. During these two days, the current research and the latest results on specific topics from the fields of space research, astrophysics, astro-particle physics and cosmology are being presented in lectures and discussions by a few selected experts and scientists from these fields, and this always in a scientifically comprehensible and even in an enjoyable and entertaining way.

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The fact which makes this event even more special and unique is that it is organized down to the last detail by PhD students from the Institute for Experimental Nuclear and Particle Physics. They alone define the topic and arrange the program over the two days. They invite as speakers internationally renowned scientists from the different research areas, apply for necessary financial resources, organize the publicity campaigns, provide the premises and the necessary technical equipment, arrange for refreshments and small snacks during the breaks, and they usually also participate by giving short talks about their own work on a particular and matching topic. There is no interference of any kind on the part of the university lecturers and professors. The "Münster Astro-Seminar", which is by now firmly established in Münster, is in this way unique in all of Germany and a real success story, as over the years the event has attracted an ever increasing audience from an ever larger periphery of Münster.

In 2000, the Astro-Seminar started quite modestly with a lecture on an astrophysical topic by one of the authors of this book, Prof. Dr. Dr. h.c. Peter L. Biermann, member of the Max Planck Institute for Radio Astronomy and of the University of Bonn. The occasion was an event in Münster organized for scholarship holders of the German Academic Scholarship Foundation ("Studienstiftung") [1]. Afterwards, the host from the Institute of Planetology at Münster University, Prof. Dr. Elmar K. Jessberger, invited the attendees to his home, where a small remaining group of a handful of students from different departments discussed with the two colleagues further subjects of astrophysics and cosmology until late that night. The students were deeply impressed, and they proposed to repeat the event the following year in the same form and with an even broader range of topics.

Thanks to a young medical student from this small circle, this suggestion was indeed not forgotten, and the following year the group took the initiative and put together a program of topics and speakers to which the authors of

[1] The mandate of the non-profit foundation "Studienstiftung" (German Academic Scholarship Foundation): The German Academic Scholarship Foundation promotes students whose talent and personality give rise to expectations of special achievements in the service of the general public (translated text passage: https://www.studienstiftung.de/studienfoerderung/). In this context, events such as the one described here are promoted in particular.

this book were invited for a series of lectures on a freely chosen astrophysical topic. The number of interested students increased, although in the first few years the participants continued to be limited to the members of the above mentioned Scholarship Foundation. A subsequent survey among the participants showed that there was great interest in continuing this form of event in the years to come and also in making the event more public by expanding the circle of participants. Further annual events followed, which were again initially organized by the fellows of the Scholarship Foundation. Specially designed advertising posters were placed in the university buildings in order to draw the attention of students from all disciplines to this event. This quickly caused an increase of the number of participants to about 20 – 30. Appropriate rooms had to be booked, which was not easy because this "Astro-event" was still more or less private. However, the organizers were quite imaginative; there was always someone who knew this or that professor or caretaker who could be asked to make the premises (and the keys) available from Friday afternoon to Saturday evening. In the beginning, they met in a small lecture hall of the Anatomy Department, later e.g., in the seminar room of the "Pfarrzentrum Heilig-Kreuz" ("Parish Center of the Holy Cross") in Münster.

The awareness of the Astro-Seminar started to grow and the event got a new format with new faces in the course of time. In 2005, the event was held for the first time at the Institute of Nuclear Physics. Meanwhile, the organizers were students from this institute who, with great ambition and personal commitment, succeeded in reaching an audience even outside the university and attracting scientists from the international community to this event. The number of visitors unexpectedly skyrocketed and the seminar room in the Institute of Nuclear Physics holding about 35 seats soon proved to be much too small. In the following years the large lecture hall of the Physics Department together with the support from the technical staff could be obtained, and this also thanks to the special and unhesitant support of the Dean of the Department, who was able to even provide some extra financial support.

Surprisingly, the attractiveness of the event has not faded over the years, which was of course due to the evermore exciting new topics, but also because each time special highlights were built into the program, e.g.,

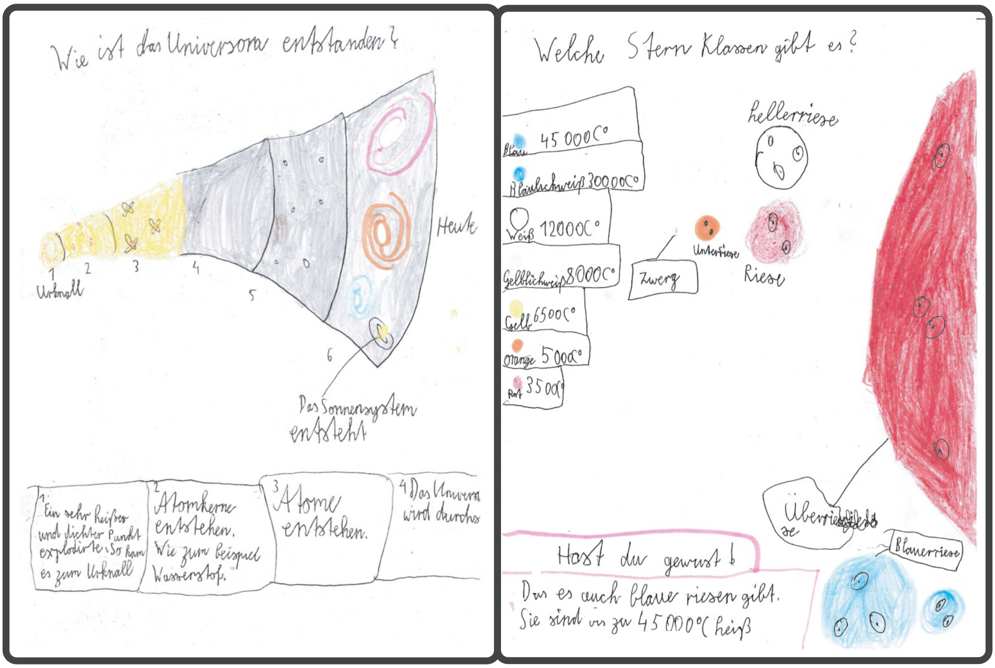

Fig. 1.1: The World in the eyes of an 8-year old.

a lecture on "Life in space" by ESA[2] astronaut Dr. Gerhard Thiele, a theatrical interlude about Victor Franz Hess, the discoverer of cosmic rays, or a particularly amusing lecture on "fact-vs-fiction" physics from the television series Star Trek. Small prizes for particularly good and sharp questions were regularly awarded after each lecture, laboratory tours were part of the program, or one was simply a point of contact for students who were considering studying Natural Sciences.

The student Andreas M. at the age of 8 was probably the youngest participant of the Astro-Seminar. Some lectures had impressed him so much that he independently designed a small series of pictures and passed them on to the authors of this book. Two of his drawings are included in this book (Fig. 1.1) to show that physics is an extraordinarily inspiring and exciting field, and this for all age groups.

Currently, the Astro-Seminar can count on 300 – 500 visitors every year

[2] ESA = European Space Agency

(see Fig. 1.2). Congratulations to all the students who contributed to this tremendous achievement!

This book is an attempt to review the topics that have been touched upon in the years since the Astro-Seminar came into existence. However, it is not possible in hindsight to summarize or comment on the many lectures individually. The selection of topics in this book is therefore based on the subjective and very limited point of view of the authors.

The book begins (after clarifying what physics "is", and what it "is not") with an outline about Cosmic Inflation and pursues the question of how compelling such an amazing phase of development is that began immediately after the "Big Bang" and was already completed within an inconceivably short time of $\approx 10^{-30}$ seconds. After that it dives into the phase of the Early Universe and Early Element Synthesis, which started about some microseconds after the "Big Bang" and lasted approximately 10 minutes. The book will then illuminate how cosmic microwave radiation came into existence, and what it may tell us today; it further explains how elements are formed in supernova explosions, and how such explosions, which can outshine an entire galaxy for a few days, can be used to calibrate the expansion velocity of the Universe, thereby providing us with an extremely surprising (and ultimately Nobel Prize-winning) result. Chapters and sections about relativity, neutron stars, Black Holes, dark matter and neutrinos will follow, whereby also the questions will be put forward: «*how could Life arise*», and «*do neutrinos, which are at the 'edge of existence'*» have anything to do with it? Finally, we turn to cosmic rays. Cosmic rays are messengers of the past, but what do they tell us and how can one decode their messages?

Since man hasn't been witness to any of these long gone epochs of the Universe or to any of the processes that occurred at these infinite distances[3], the legitimate question arises: «*how does one know if no one has ever been there?*» Fortunately, these past and distant events have left a multitude of unmistakable fingerprints containing information which just needs to be decoded. From all of this, a consistent overall picture slowly comes to light, much like putting together a big puzzle with a still growing number of

[3] The term "infinite" is not to be understood here in the mathematical sense.

pieces. Interestingly, these studies also allow making short- and long-term predictions, e.g., for the solar system, for the galaxies, or even for events which lie in the far distant future of the Universe.

However, in order to understand that “Physics” is not a collection of intellectual fantasies born in the minds of scientists, the authors of this book think it is important to first provide some clarity about “what physics is and what physics is not”.

Fig. 1.2: Photo-reminiscences of the Astro-Seminar in the large lecture hall of physics

Chapter 2

Physics and Cognizance

2.1 Physics is — what ... ?

Yes — what is it...? There is a seemingly endless number of more or less profound and deeply rooted philosophical, theological or other meaningful discourses, which attempt to subsume the essence of natural sciences and the insights arising from it in some suitably matching scheme of thought. It will not be the objective of this book to take stock of this. Instead, the authors will try to draw a simple and common sense picture, freed from

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theological and philosophical burdens. This is in keeping with the daily work of natural scientists, who merely deal with the simple question of how things are put together and how they interact with each other. By following this line one quickly comes to realize that Nature is knitted up in an utterly simple, transparent and rational manner, whilst at the same time maintaining clear and strict laws. And with a little intelligence, these can be combined and utilized in an immensely beneficial way [1)].

During the Middle Ages and even up to Modern Times, trying to understand and to explore Nature became exactly a bone of contention, at least in the Christian-European cultural sphere: the study of the laws of Nature and exploring the essence of Nature was classified as heretical and by no means in conformity with divine teachings [2)]. However, Nature reveals itself voluntarily to us human beings, all by itself and without any of our doing. Under no circumstances does a human peer into the cards of an "Intelligent Being", let alone in an improper or forbidden way.

Furthermore, we will even see that processes that took place far in the past (e.g., shortly after the "Big Bang", 13.8 billion years ago) had and still have an enduring effect on the evolution and the composition of our present world, and are also of continuing relevance for the world's future development. This makes it possible to trace back processes from bygone epochs in all detail by means of the laws laid down by Nature. The basis for this is the creation of robust and resilient description models laid out in a consistent mathematical language. These models must be inferred solely by observing recurring patterns and must be fundamentally falsifiable from the design stage, i.e., be verifiable through experimental tests (which is equivalent to "observing"). This includes, foremost, that models are capable of making verifiable predictions using mathematical inference and deduction. Models which do not provide predictions or which describe or hypothesize things that do not exist, are not falsifiable and therefore useless. An example: A model that describes the era before the "Big Bang" is of no relevance if it does not at the same time specify in mathematical language

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[1)] A trivial example: Force creates a change in motion (the law), which allows one to move unerringly from A to B (the benefit).

[2)] The reader may want to consult the biography of the last Staufer emperor and king Frederic II. (1194 – 1250) and his astoundingly modern view of how to uncover the laws of Nature by making observations and carrying out experiments.

the measurable properties of this era. The scenarios captured in this book about the evolution of our Universe, though some sound truly spectacular, are therefore very pragmatically and unemotionally based on known laws of physics and well established models and are not figments of scientists' imaginations.

Fig. 2.1 summarizes in a simple way how to establish physical models that describe the laws of Nature. In words:

1 start with observations,
2 find regulatory patterns and create a model for their description in a mathematical language,
3 make predictions on the basis of the developed models,
4 test the predictions and check the validity of the model,
5 improve (e.g., by further observation and with better techniques) the model and start again with point 2.

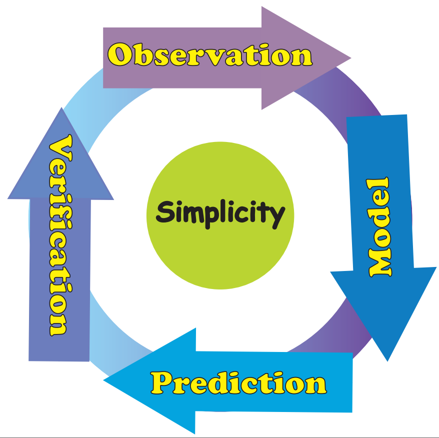

Fig. 2.1: The essence of physics

A central feature is the simplicity of a model, i.e., its restriction to a minimum number of relevant parameters. It may be instructive to remind oneself of the large number of the naturally occurring chemical elements together with their stable isotopes (approx. 250), which are ultimately composed of only 3 different building blocks, the proton, the neutron and the electron.

Furthermore, the power of a descriptive model is given by its ability to make correct and verifiable predictions. In this way, for example, Quantum Mechanics or the Standard Model of elementary particles have established themselves by having been able to withstand all experimental tests with an astounding accuracy (at times up to the 15^{th} decimal place).

2.2 Answer: Physics is — this!

In oder to better understand what the very essence of physics is, we will in the following section turn the argument around and examine what physics is NOT and what physics does NOT achieve under any circumstances. These explanations are important for the understanding of this book, in order to keep a critical view of the processes that happened in the past or synonymously at great distances. The individual and essential arguments are:

1. Physics merely describes and does NOT explain
2. Physics does NOT claim ultimate Truth
3. Physics does NOT provide Proof of Truth
4. Physics is NEVER exact
5. Physics does NOT describe things that never appear (i.e., things that do NOT exist)

In the perception of natural sciences, and of physics in particular, the general public frequently seems to be unaware of these important features, an unawareness that at times leads to completely absurd chains of arguments. Yet, some self-criticism may be in order, because the reason this happens is also due to the at times imprecise and lax language of physicists and scientists, when they talk about «*proof*» but mean «*verification*» or talk about «*exact and true*» but mean «*accurate within the scope of the measurement accuracy*». In particular, the term «*within the scope of the measurement accuracy*» ought to be noted! We will come back to this later.

This may all sound a bit subtle and philosophical, so at this point a little more explanation of the individual statements is in order.

▶ 1: Physics merely describes and does NOT explain

The laws of Nature, which manifest themselves foremost in the area of physics, are the basis for any being, especially for any intelligent being, to create a plan, which allows it to find its way around in Nature. Even a toddler will make such a plan in order to understand and coordinate motion. He/she does this effortlessly and without mathematics, just by experimenting, observing and communicating. Mathematics comes into play later, and with the help of it physical processes can be described through models. Mathematics is therefore only a tool, or, if one wishes, the language in which models/laws are being communicated or logically linked with one another (e.g., distance covered = speed multiplied with time passed). Physics does not claim to explain anything, it merely describes those things in life, which are relevant for being able to make verifiable and reliable predictions. An explanation of why things are the way they are and not otherwise is not important to the plan. What is important, though, is that a model fits into a self-contained, uniform and simple overall model of Nature. One may put it in different way, for physics Nature appears simple and regular, and it is utterly nonphysical to construct separate models for each rainbow in the sky or for each shooting star appearing at night. Those types of particulate models are useless for predictions and planning. «*Miracles may happen*» they say, but they are not within the domain of predictable physics laws, though they are not negated by physics either. There is no mandate for that. Physics is not in conflict with Religion and Belief.

▶ 2: Physics does NOT claim ultimate Truth

It is also not of importance that a description model is ultimately correct and true. The only thing that matters is that it can make reasonable predictions within the context of an accuracy which is relevant for enabling progress and moving ahead, and/or making a meaningful planning possible. This stays true up to the point when weaknesses of the model become apparent, which then require improvements or extensions. As a simple example, one may take the repeatedly used legend of the apple, which allegedly fell on Isaac Newton's head in 1666. From this apple anecdote (no! — it was the "Philosophiae Naturalis Principia Mathematica") the theoretical model of Newtonian (or classical) mechanics unfolded, which became the basis of all motion processes on Earth (and beyond). It describes these processes with a remarkable precision, verified by an almost infinite number of experimental tests. And if, for instance, Bernoulli's fluid mechanics is added to Newton's law, then even airplanes can be made to fly.

In this way, Newtonian mechanics seems to represent the ultimate truth — unfortunately badly wrong! With the development of techniques allowing for a continuous increase of experimental precision over the last 50 – 100 years, more and more discrepancies between measured quantities and classical predictions emerged. A remedy for these was finally provided by the mathematically quite demanding theory of General Relativity, which is most closely associated with the name Albert Einstein. It was developed solely to account for the experimentally observed constancy of the speed of light. In fact, General Relativity elegantly reduces to Newtonian mechanics in the limiting case of a so-called «*small laboratory*», which also means, it is not a particulate model. A «*small laboratory*» is realized whenever the curvature of space-time in this «*small laboratory*» environment has a negligible effect on the relevant measurement results or on the conception of strategies. This is indeed the case for practically all motion processes on Earth. If highest precision is required, e.g., for the Global Positioning System (GPS), for the determination of a time standard (important for digital radio communication, i.e., for mobile phones), or for satellite navigation, then the curvature of space-time caused by the presence of masses and their different distributions is significant and must be taken into account.

The constancy of the speed of light is not intuitive in the simple human way of thinking, but it is undeniably observed as such. The accuracy with which the theory of General Relativity stands up to experimental scrutiny is impressive. To date, there is no indication at which precision or after which decimal point this theory ought to be replaced by an even more extensive or even more general theory. The question arises: is this theory now after all the true and correct theory, or the other way round, at which decimal point does Truth begin? The answer is superfluous because the theory of General Relativity has at least one unresolved and inherent and most worrisome shortcoming. It is divergent near a Black Hole, i.e., infinities occur at the boundary to the Black Hole. The same happens at the time of the "Big Bang". Infinities, however, are simply and utterly nonphysical. At the (fictitious) transition from a finiteness into an infiniteness and vice versa, causality is violated, i.e., time sequences are thrown into disarray, or more pointedly, they are completely dissolved. Everything is and remains infinite forever with no beginning and with no end.

Of course, there are other disciplines in physics, such as electrodynamics (keywords: electricity, television), thermodynamics (keywords: temperature, life), hydrodynamics (keywords: weather, airplane), and especially the theory of quantum mechanics (keywords: atom, computer). They all intertwine in an elegant and consistent way and describe natural processes in close interaction with each other, and they do this with astonishing precision. Based on this interplay, even more distant fields such as chemistry, biology or medicine were able to manifest themselves as independent disciplines over the course of time. They all have in common that they merely describe natural processes, at times not even deterministically but only on the basis of probabilities. In physics this probabilistic situation is most notably evident in the field of thermodynamics and even more so in quantum mechanics. Truth, however, cannot be subject to probability. The fact that quantum mechanics does not describe physical phenomena deterministically must simply be accepted. Of course one may ask, does Nature on the smallest scales gamble with its own laws, or is it perhaps because on these scales the usual definitions of time and space no longer apply? So far, there is no answer to this question. Regardless of this, quantum mechanics passes all tests; it thus establishes itself as an extremely useful descriptive model.

► 3: Physics NEVER provides Proof of Truth

This is perhaps the most important point about what physics is NOT, seeing that this is frequently ignored and disregarded in numerous pertinent discussions and likewise in numerous philosophical treatises.

Physics can NEVER lead to proofs of truth, this is simply impossible. Physics, or synonymously the knowledge and the progress that develops from it, are always and without exception connected with measurements. However, every outcome of a measurement is subject to an error margin. A measurement without an error is inconceivable. Conversely, providing a result from a measurement without an estimate of the measurement error is also useless. Every technical drawing requires tolerances be specified. Without this information, no technician or engineer will ever begin to manufacture a workpiece. In daily life, though, not every trivial piece of information like e.g., the temperature of the day, the size of an area, the speed of a car, the energy used in private households, the indications on food containers or whatever else one may imagine, ought to be provided with an error statement — that would be highly nonsensical in daily life, yet in the technical and the scientific fields this information is essential.

One can formulate the above statement 3 even more pointedly by means of an example. In the ideal world of mathematics we learn (mostly in school) that parallels intersect at infinity. One may ask if there is any teacher who has experimentally verified parallelism even over a length of only 10 meters? Obviously, this seems to make so much intuitive sense that one would not even have to bother checking it. Carl Friedrich Gauss (1777 – 1855), to whom we will come back later, had already doubted this dogma for the real world, but unfortunately his measuring accuracy was not sufficient to detect deviations.

Furthermore, in the ideal world of mathematics we learn that the circumference of a unit circle is 2π. In the real world, because of the infinite series of the number π, this result is not at all provable by any measurement and certainly not correct either. The mere presence of a mass inevitably results in a curvature of space, which on Earth already leads to a discrepancy in the 10^{th} digit after the decimal point — a giant effect, if one considers how many digits still follow, but completely negligible for most things in our «*small laboratory*» Earth. And now, one may imagine how many physics formulae contain such transcendental numbers such as the number π or Euler's number e, or for instance those irrational numbers expressed by simple square roots.

▶ 4: Physics is NEVER exact

This is almost synonymous with the above statement 3. Physics always takes place in a real world. And mathematics is the language, in which physics (within the framework of theories and models) is communicated and quantified in a uniform and generally understandable way, although mathematics always and with no exception describes physics in an idealized environment. Yet, progress in the real world of physics is inconceivable without the language of mathematics, and in fact, physics is even a driving force behind the steady advancement of mathematics. Mathematics sees itself as an exact science, and if one leaves epistemic subtleties aside, this is a reasonable assertion. The logic of mathematics is always based on certain presuppositions, and these are always and without exception prefixed in mathematical conclusions (i.e., proofs). The presupposition made in the present case that the circumference of a unit circle is 2π is Euclidean geometry or the «*flatness*» of space. Of course, the circumference of a circle can be mathematically calculated in any curved geometry, but it does not change the fundamental inability to quantitatively prepare or single out a very specific mathematical presupposition and then claim this to be the ultimate truth by means of an inherently error-prone measurement.

▶ 5: Physics does NOT describe things that do NOT exist

This is in itself an amusing assessment and, of course, self-evident. How should one describe things that don't exist? What knowledge could be gained, and above all, which models could be created from this? Which verifiable predictions are these supposed to make? Which technological progress could be derived from describing things that don't exist in any way whatever? Nevertheless, there are always scurrilous arguments that attempt to discredit scientific research as allegedly incapable and lacking knowledge. Of course, physics can never prove that there is NOT an invisible[3)] teapot orbiting the Earth. To cite this as an argument for its existence, is scurrilous and absurd. Of course, science can never prove that the protective effect against measles or chickenpox does NOT exist if lying down on a meadow at midnight under a full moon. Conversely, to predict such a protective effect simply because one hasn't yet contracted chickenpox, or one is convinced of it, is also absurd and unrealistic. There are many variants of this line of arguments. They represent a turning away from the firm laws of Nature and take us into abstruseness and back into long gone times of mysticism and superstition[4)].

There is no question that so-called "zero"-experiments are a part of physics, however, these ought not be contrived as an attempt to prove something does NOT exist. Perhaps the best known experiment of this type is that of Michelson and Morley (1881 and 1887), which is being repeated even to this day with increasingly refined techniques. The aim was, and still is, to determine the motion of Earth relative to a hypothetical ether that acts as the carrier of light-waves. The light-speeds in and against the direction of Earth's motion should be different in the presence of such a carrier. All

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3) In the sense of "not at all interacting".

4) Here we are not talking about placebo effects; they are scientifically quite well-founded.

experiments measured a "0"-value, but be aware about: "within the error margin of the measurement !" Today, these experiments are considered a test of the so-called Lorentz invariance, i.e., a test of the constancy of the speed of light in a uniformly moving system. At present, relative deviations in the speed of light $\Delta c/c$ in the order of 10^{-17} can be ruled out experimentally, still in agreement with the theory of relativity, which predicts the value "0" for this [5),6)].

[5)] Ch. Eisele, et al., *Laboratory Test of the Isotropy of Light Propagation at the* 10^{-17} *level*, Physical Review Letters 103, 090401 (2009).

[6)] S. Herrmann, et al., *Rotating optical cavity experiment testing Lorentz invariance at the* 10^{-17} *level*, Physical Review D 80, 105011 (2009).

Chapter 3

Measured Values $\longleftrightarrow$ Magnitudes

In this book we will frequently talk about measurements and the various dimensional units given to the outcome of these, i.e., their results. Dimensional units are fundamental if physics processes are to be quantified and compared with each other. Moreover, in astrophysics and cosmology the scales or the range of magnitudes play a decisive role, and frequently comprehension seems to fade when trying to map cosmological quantities onto our small personal domain of life. This remains a perpetual challenge even for scientists, who deal with these issues professionally on a daily basis.

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3.1 Distances

These are usually expressed in units of meters (m) or kilometers (km). For cosmological distances, these units are generally regarded as not particularly useful, and one regularly resorts to light-years (ly) or parallax-seconds (pc), which are the standard dimensional units in that case.

Meter and kilometer are perceivable units in everyday life. Dealing with a light-year, which is the distance light travels within a year, the connection to personal life dwindles, especially if one were to express this distance in kilometers. Here a simple conversion of a light-year to kilometers:

> 1 year $\simeq \pi \times 10^7$ s
> speed of light $\simeq 300,000$ km/s
> therefore: 1 light-year $\simeq \pi \times 10^7 \times 300,000 \simeq 9.42 \times 10^{12}$ km $\simeq 10^{13}$ km

Surely, a year does not exactly translate to $\pi \times 10^7$ seconds, because a year really doesn't have anything to do with π. Nonetheless it's a relatively easy number to remember. The correct number is $3.155\,760 \times 10^7$ seconds, but note that this value makes exactly 365.25 days to a year. This definition of a year was set by the International Astronomical Unit (IAU) to avoid making small annual adjustments resulting from changes in the Earth's orbital period. Similarly, the speed of light is not exactly 300,000 km/s either, but rather 299,792.458 km/s [1]. In this way, the exact value of a light-year is $9.460\,730\,472\,580\,800 \times 10^{12}$ km, which is an awkward number to remember if one ever wishes to make quick estimates. The difference between this value and the easier to remember number of $(\pi \times 10^7) \cdot (3 \times 10^5) = 9.42 \times 10^{12}$ km, is just 1.5 light-days, which is about the size of our solar system. Present day precision measurements of distances smaller than about 1000 ly do much better than this, whereas at larger distances (above about 10,000 ly) this small difference as well as the 5% discrepancy between a light-year and the even more generously estimated value of 10^{13} km gets to be less and less

[1] For practical reasons the year is fixed by the International Astronomical Unit (IAU) to 365.25 days. Further, the quoted value for the speed of light comes by definition and carries no experimental error — the reason one chose this unwieldy number rather than the much easier to remember 300,000 km/s, is a different story, as this would have required a significant adjustment to the length scale of a meter.

significant.

The parallax-second (pc) originates from astronomical observations and is obtained by simple trigonometry. It is defined as the distance at which the Earth's orbital radius around the Sun, which is 149.598 million kilometers or one astronomical unit, subtends an angle of one arcsecond (i.e., $1''$ is 1/3600 of an angular degree). Conversely, a fixed star at this distance, when observed from Earth, seems to move by an arc-size of $1''$ over the course of half a year. The conversion to light-years gives:

$1\,\text{pc} \simeq 3.2616\,\text{ly} \simeq 30.9 \times 10^{12}\,\text{km}$
with: $1000\,\text{pc}=1\,\text{kpc}$, $1000\,\text{kpc} = 1\,\text{Mpc}$, $1000\,\text{Mpc} = 1\,\text{Gpc}$

This angle can also be mapped to a more easily imaginable reference size, which is the diameter of a human hair at a distance of approximately 20 meter. Today's astronomical instruments (e.g., the Gaia space probe) have an angular resolution corresponding to the diameter of a human hair at a distance of approx. 2 km or $0.01''$. Distances of stars up to about 100 pc ($\simeq 300$ ly) can be determined by simple triangulation, and with a few tricks and for selected objects even up to 5000 pc. The closest star Proxima Centauri has a parallax of only $0.772''$ (corresponding to a distance of 4.225 ly or 1.295 pc), which at this point already shows that the area of 300 ly around our solar system is only a tiny fraction of the entire Milky Way Galaxy. In the visible spectrum the Milky Way has a diameter of about 200,000 ly ($\simeq 60,000$ pc), in the outer part a height of about 3000 ly ($\simeq 900$ pc) and in the inner part a height of about 20,000 ly ($\simeq 6000$ pc). Some 200 billion stars cavort in this volume. In its center ($\simeq 27,000$ ly away from the solar system) resides a Black Hole (Sagittarius A*) with a mass

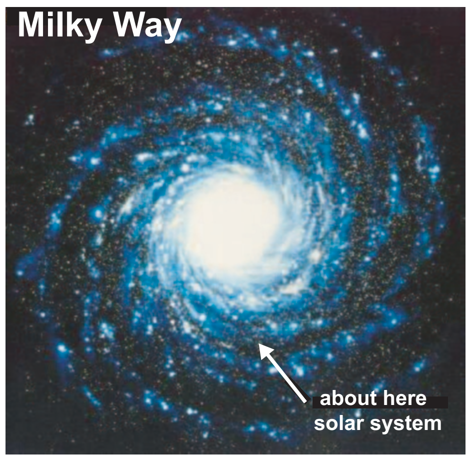

Fig. 3.1: An artist perception of the Milky Way Galaxy