Why do we Still Believe in Newton’s Law?
Facts, Myths and Methods in Gravitational Physics

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Abstract
An overview of the experimental and observational status in gravitational physics is given, both for the known tests of general relativity and Newtonian gravity, but also for the increasing number of results where these theories run into problems, such as for dark matter, dark energy, and the Pioneer and flyby anomalies. It is argued that (1) scientific theories should be tested (2) current theories of gravity are poorly tested in the weak-acceleration regime (3) the measurements suggest that the anomalous phenomena have a common origin (4) it is useful to consider the present situation under a historical perspective and (5) it could well be that we still do not understand gravity. Proposals for improving the current use of scientific methods are given.

'We do not know anything - this is the first. Therefore, we should be very modest - this is the second. Not to claim that we do know when we do not- this is the third. That's the kind of attitude I'd like to popularize. There is little hope for success.' (Karl Popper)

1 Introduction

For by far the longest part of history gravity was just the qualitative observation that earth attracts objects, and for about 1500 years, this was a strong argument backing the geocentric model of Ptolemy. Its accurate, but complicated epicycles with excentrics, equants and deferents had hidden the better and simpler ideas thought already by the Greek astronomer Aristarchus. King Alfonso X of Spain, who learned the Ptolemaic system from Arab libraries in his country [1], commented the system of epicycles: ‘If the Lord Almighty had consulted me before embarking upon Creation, I should have recommended something simpler.’ Though this seems common sense, the Copernican revolution, backed by the excellent observations of Tycho Brahe, by Kepler’s ingenious descriptive laws and by Galilei’s famous first use of the telescope, was a difficult process until it terminated with the general acceptance of Newton’s law of gravitation. What lasted that long for the human perception was a blink of an eye with respect to the age of the universe, of which we now can take the Hubble time \( H_0^{-1} \approx 14 \text{ billion years} \) as a measure.

Astronomy became modern Astrophysics and Cosmology, and for the last two decades mankind collected data of unique precision. Satellite-based telescopes covering all frequencies and digital image processing were not a minor revolution than the application of the telescope itself in 1608. Theoretically, this enormous amount of surprising data is described by a model of standard cosmology. This, in the light of the history of gravitation, fast digestion of data is accompanied by an increasing number of parameters \( H_0, \Omega, \Omega_b, \Omega_{DM}, q_0, \Lambda, A_s, n_s \)\(^1\). While the numerical values become more and more precise, little advance

\(^1\)Hubble constant, density parameter, baryonic density, density of dark matter, deceleration parameter, cosmological constant, optical depth scalar fluctuation amplitude, scalar spectral index. See also, e.g.
http://en.wikipedia.org/wiki/Lambda–CDM_model.
has been achieved in the question as to what the related quantities ‘dark matter’ and ‘dark energy’ do really mean. A soulmate of King Alfonso, the astronomer Aguirre [2] commented: ‘these new discoveries... have been achieved at the expense of simplicity’. The question why nature comes up with a bunch of numbers like 0.73 must be allowed or at least not forgotten. Though standard cosmology has various free parameters now, it had started from a profound but simple physical concept, the equivalence principle. Based on that, in 1915 Einstein revealed a deep relation of gravity to the geometry of spacetime, which was enthusiastically accepted after the verification of light deflection in 1919 and the explanation of the anomalous advance of the perihelion of mercury known since 1859. From the 1960s until today, general relativity (GR) has undergone an impressive series of confirmations I will briefly review below. However, the following comment in a textbook of galactic astronomy ([3], p. 635), is remarkable:

‘It is worth remembering that all of the discussion so far has been based on the premise that Newtonian gravity and general relativity are correct on large scales. In fact, there is little or no direct evidence that conventional theories of gravity are correct on scales much larger than a parsec or so. Newtonian gravity works extremely well on scales of ∼ 10^{14} cm (the solar system).

(...) It is principally the elegance of general relativity and its success in solar system tests that lead us to the bold extrapolation that the gravitational interaction has the form \( \frac{GM}{r^2} \) on the scales \( 10^{21} - 10^{26} \text{ cm} \).‘

While the tests of GR mostly regard strong fields, the phenomena which actually are not explained yet like galaxy rotation curves (dark matter), the Pioneer anomaly etc. seem to occur in weak fields where GR does not distinguish from the Newtonian limit. The above cited bold extrapolation seems to have encountered observational problems even in the solar system [4] now.

The experimental situation motivates to try an overview on all possible and available tests of gravity.\(^2\) Due to the amount of material, I must refer to other review articles where appropriate. The experimental and observational evidence is presented at various distances, masses, and accelerations. This last ordering is particulary adopted to put into evidence the big gaps where our knowledge is not really tested.

The major part of researchers will be happy to fine-tune the standard model with better data. This article instead is addressed to those who think we have gone to the limits in introducing new parameters [6] in gravitational physics, and instead of the excentrics and deferents adjusting the epicycles, it may be time to think about alternatives.

While presenting alternatives is not the task of this article, we shall touch some historically interesting attempts briefly. On the other hand, speculations on extensions or modifications of gravity have to match a huge amount of high-quality data. Since it is not easy to collect results from very different research areas, the overview given below can be a first guide to facts that must be taken into consideration.

\section*{2 Observational and experimental tests}

‘Theories crumble, but good observations never fade’ - Howard Shapley

\textbf{Newton’s law of gravitation}

\[ F = G \frac{Mm}{r^2}, \]

in which I shall call \( M \) field mass and \( m \) test mass, must be tested under several aspects. The dependence on \( m \), in particular the material independence of the acceleration \( \frac{GM}{r^2} \) is usually called (weak) equivalence principle. Many tests refer to the so-called inverse-square law in distance, but we will also discuss observations that test the dependence on \( M \). Since mass estimates of the whole universe depend on it, determining the absolute value of \( G \) is very important, and fortunately, a lot of research has been done in

\(^2\)The growing interest is also reflected by the announced review [5].
the past years here. There are however independent tests of the spatial and temporal dependence of \( G \), which can be seen as tests of Newton’s law as well.

**Einstein’s theory of general relativity,** at the time of its development, had only a few observational confirmations. This changed in the 1960s [7], and a lot of spectacular measurements were in perfect agreement with GR. Since the recent focus of interest are tests in the low-acceleration-scale where GR is Newtonian, I shall briefly mention GR tests and refer the reader to specific reviews [8, 9, 10, 11].

### 2.1 Tests ordered by distance

The tests described in the following involve measurements of \( G \), its possible variation, tests of the \( 1/r^2 \)-dependence and of the equivalence principle. The absolute \( G \) measurements are unique in the sense that the mass determination of the whole universe rely on them; all other measurements yield mass ratios.

**Atomic scale.** Though it is common folklore to calculate the ratio of electric and gravitational forces (\( m_p, m_e \) proton and electron mass) as

\[
\frac{F_e}{F_g} = \frac{e^2}{4\pi\varepsilon_0 G m_e m_p} = 2.27 \times 10^{39},
\]

this number has never been measured, since elementary particles are too light for being used as field masses. With the earth as field mass instead, \( G \) measurements with atom interferometry have reached a remarkable accuracy [12, 13].

**Sub-millimeter-scale.** A violation of the inverse-square-law was suggested by fifth force and string theories. The E¨ot-Wash group [14, 15, 16], using a sophisticated version of the torsion balance, obtained good evidence for the validity of the inverse square law for masses separated on the above scale and obtained tight constraints on the violation parameters \( \alpha \) and \( \lambda \). These are difficult experiments, since electrostatic effects and the Casimir effect [17, 18] have to be eliminated carefully. The claim of a sub-mm-test is however a little misleading, since the barycentric distance of the masses was much greater.

#### 2.1.1 Laboratory scale.

**Torsion balance.** The most famous, important, and precise measurement of the gravitational force uses the 200 year old Cavendish torsion balance, to which only minor modifications were applied until recently. The distance is usually \( 10 - 20 \) cm. Long [19] claimed to have observed deviations of the inverse-square law at laboratory distances. It seems however that these experiments have not received independent confirmation. About 20 years ago, the determination of \( G = 6.6726 \times 10^{-11} m^3s^{-2}kg^{-1} \) by [20] was considered to have an uncertainty of 0.013 \%. In 1995, the PTB [21] published a much higher, probably wrong value for \( G \), but this paper encouraged many groups to perform new measurements of \( G \). In the following, astonishing discrepancies arose and led to an increase of the uncertainty in the CODATA value of \( G \) to 0.15 \%. The 1982 measurement [20] was shown to bear systematic errors [22], which were corrected much later [23] to \( G = 6.6740 \pm 0.0007 \). A different setup with a rotating torsion balance was used by recent precision measurements [24] and [25]. Though their values \( G = 6.674215 \pm 0.000092 \) and \( G = 6.67559 \pm 0.00027 \) are still more discrepant than the respective error bars, the controversy seems to be settled.

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\(^3\)For simplicity, the unit \( 10^{-11} m^3s^{-2}kg^{-1} \) will be dropped in the following
Gravitational redshift. With the recoil-free emission of X-ray photons from crystals (Mössbauer effect), frequencies could be measured with an accuracy unknown so far. Pound and Rebka [26, 27] used this to demonstrate the gravitational redshift of a photon leaving the field of the earth. This is the only test of GR at the laboratory scale.

2.1.2 Movable field masses - intermediate scale (1 – 100 m)

There are few other laboratory methods. [28] measured the effect of a moving mass of 280 kg on a superconducting gravimeter and obtained \( G = 6.675 \pm 0.007 \). A similar setup, though with a ‘free fall’ method was used by [29] with the result \( G = 6.6873 \pm 0.0094 \) and a field mass of 500 kg. [30] used a beam balance with 13521 kg of mercury as field masses. Their measurement \( G = 6.67407(22) \) at a distance of 1 m agreed with other recent values (see the references in there). The above superconducting gravimeter was used by [31] to determine \( G \) from the water level variation of a little storage lake, with the result \( G = 6.688 \pm 0.011 \). [32] obtained \( G = 6.678 \pm 0.007 \) and \( G = 6.669 \pm 0.005 \) with a lake experiment using a precision balance instead of a gravimeter. The effective distances were 88 m and 112 m, respectively, and this much more accurate than the value \( G = 6.689 \pm 0.057 \) obtained in an early lake experiment with effective distance of 22 m [33]. A review on early intermediate scale measurements is [34], whereas a review on the discrepant values in the 1990s is [35].

To summarize, the very discrepant measurements of \( G \) in the 1990s seem to converge to a commonly accepted value of \( G = 6.674 \). This accuracy still cannot compete with other constants of nature that reach a relative precision of \( 10^{-12} \). New ideas for space-based experiments were reviewed in [36]. On a meta-level, a result of the past decade is however that precision measurements of \( G \) are of enormous difficulty and therefore many groups tended to overestimate the accuracy of their results. Going into the details, in many papers one can find considerable variation in the single measurements which is believed to be of statistical nature. This holds also for [24] and [30]. On the other hand, no convincing mechanism for a variation of \( G \) could be backed by the experiments.

2.1.3 Geophysical scale

A couple of interesting measurements with gravimeters have been conducted by measuring the gradient of \( g \), which can be calculated if the density of the surrounding material is known. While the measurements on towers [37, 38] were disputed and not confirmed [39], a discrepancy from Newton’s law was found for a mine hole [40, 41]. Interestingly, a discrepancy in the same direction was found independently for a hole in the Greenland ice cap [42], where good estimates for the ice density were available. Despite the anomalous gravity gradient, they concluded, however, ‘we cannot unambiguously attribute it to a breakdown of Newtonian gravity because it might be due to unexpected geological features in the rock below the ice.’ This is a general problem of all experiments with moving gravimeters - the uncertainty of the density distribution of the earth crust usually limits accuracy. In a similar submarine experiment, \( G = 6.677 \pm 0.013 \) was obtained [43], in agreement with laboratory values.

Spatial variation of \( G \). The GGP (global geodynamics project) network of superconducting gravimeters allows a high-precision measurement \( (10^{-12} \frac{\text{m}}{\text{s}^2}) \) of local gravity \( g \). Though no absolute values can be obtained due to a drift (which is clearly instrumental, but of unknown origin yet), variations due to tides, air pressure and a variety of geophysical effects can be monitored and modelled. In principle, the slightly elliptic earth orbit allows also to test a possible spatial dependence of \( G \) [44].

Eötvös experiments, equivalence principle. In 1907, the Hungarian baron showed the material-independence of the gravitational acceleration \( g \) with an extraordinary precision. Though unknown to Einstein, this experiment confirmed the theoretical basis of GR, the equivalence principle (EP). The
accuracy was greatly improved by experiments in the 1970s [45, 46]. An even greater accuracy could be achieved by satellite experiments in projection [47]. See also [9, 10] for an overview.

**The Hafele-Keating clock experiment.** In 1972, two atomic clocks were transported in airplanes orbiting the earth eastwards and westwards [48]. Besides the SR effect of moving clocks that could be eliminated by the two flight directions, the results showed confirmation of the first-order general relativistic time delay, whose accuracy was improved later [49].

### 2.1.4 Satellite scale.

**Lunar Laser Ranging (LLR).** There are no other experiments determining $G$ directly on larger scales. The product $GM_E$ however can be measured by orbital data of the moon and artificial satellites. LLR, which became possible after the Apollo missions where reflectors were left, has reached an extraordinary accuracy of some cm, and in the near future it will go even below (see [50] for a review, and [51, 52]). It is therefore suited to put constraints on parameterized post-Newtonian (PPN) parameters and $\dot{G}$. The problem however is that a change in $G$ which results in a distance variation earth-moon, is masked by a well-known distance increase due to the tidal friction. Earth rotation is slowed down by energy dissipation, and the earth-moon system has to conserve its angular momentum. Since the dissipation process is very hard to quantify, an independent measurement of the earths rotation slowdown is sought. Recent investigations with ancient solar and lunar eclipses [53] showed a discrepancy of so far unknown origin. A similar claim is stated by [54]. A possible time dilation is claimed by [55].

**LAGEOS.** The LAGEOS satellites orbit earth at a height of 5900 km and, so to speak, consist of mirrors only. This ‘cannonball’ type of satellite was designed with a minimum of disturbing components thus allowing various precision measurements by analyzing its orbital data. For instance, the general relativistic perigee shift could be verified [56]. Combining the earth gravity field data of the CHAMP and GRACE satellites, an even better accuracy is expected. Moreover, the launch of an improved satellite LARES is planned [57]. Recently, LAGEOS data were used to test the Lense-Thirring effect and geodetic precession [58], which should independently be tested in the near future by the gravity probe B mission launched in 2004.

**APSI** is an artificial planetary system in space designed to test gravity under unprecedented conditions [59].

**LATOR.** The Laser Astrometric Test Of Relativity is a satellite-based Michelson-Morley-type experiment that will use optical interferometry by interplanetary laser ranging. The accuracy of the GR parameters measured so far will be greatly improved and further parameters will be determined which were never measured before. The LATOR results will be able to distinguish various extensions and modifications of GR [60].

**The flyby anomaly.** The swing-by technique for satellites is used to change the direction and heliocentric velocity of spacecraft [61]. In various occasions, after a swing-by process at the earth, satellites showed an unexplained velocity increase $\Delta v$, to which for years little attention was given. Until now, it has been observed three times independently (Galileo, NEAR, Rosetta, see [61]), though under very different conditions and with a great variation in the amount of $\Delta v$. Recently, a possible dependence on the eccentricity and the perigee distance was suspected [4]. While the existence of the effect is quite accepted, further data is needed for a systematic description of this puzzling behavior. The hyperbolic trajectory of all occurrences seems to be the main difference to many other well-tested satellite orbits. With respect to the extensive data on bound orbits, the observational basis of escape orbits is very poor [62].
2.1.5 Inner solar system scale.

Planetary orbits allow to test the inverse-square-dependence or the constancy of Kepler’s constant \( GM_{\text{sun}} = \frac{4\pi^2}{T^2} \), where \( a \) is the semimajor axis and \( T \) the time of revolution. The precision of planetary orbits is partly obtained by astronomical observations, such as transits of mercury and Venus. Distance measurements are obtained from the reflection of radar signals at Venus, and in particular from the Viking lander missions on Mars 1979-1982 [63]. No deviations from Kepler’s law but constraints on \( \dot{G}/G \) were found\(^4\). The precise data allow even to constrain dark matter [65] and dark energy [66, 67].

Classical tests of GR. Three of the four classical tests of GR take place at these distances. The deflection of light passing near the sun, measured for the first time in 1919, has now been measured to be within the predicted value by 0.1% [7]. The perihelion advance of mercury, known since 1859, has shown less progress in precision [68, 69]. The Shapiro time delay [70] of radar signals passing nearby the sun has been measured in the 1960s for the first time. The best agreement with GR is currently obtained by the Cassini spacecraft data [71].

Helioseismology, the analysis of acoustic waves of the sun, has become an interesting area of research. Relevant for gravitation are the constraints on a possible variation of \( G \) which reach \( G/G < 10^{-12}\text{yr}^{-1} \) [64, 72].

2.1.6 Outer solar system scale.

Data from the outer Planets were collected by the numerous satellite missions Pioneer 10 and 11, Galileo, Ulysses, Voyager and Cassini. Among other important scientific results which are not addressed here, radio tracking techniques improved the orbital data accuracy [73]. While planetary data showed no hint for a violation of Newton’s law\(^5\), a surprising anomalies were observed regarding the motion of the spacecraft itself.

The Pioneer anomaly. Though Pioneer 10 and 11 were launched in 1972 and 1973 already, the first detailed investigation of predicted and observed motion was published in 1998 [75]. This had mainly three reasons: (1) nobody had expected a deviation, (2) the effect is small and difficult to separate from other influences, (3) it seemed to have occurred after the last maneuvers and planetary flybys in 1974/79. The anomaly consists of an unmodelled acceleration \( a_p = 8.74 \pm 1.33 \times 10^{-10}\text{m} / \text{s}^2 \) directed towards the sun, or equivalently, an anomalous blue shift drift \( (2.92 \pm 0.44) \times 10^{-18} \text{s} / \text{s} \) of the radio tracking signal [76, 77, 78]. In the meantime, an enormous effort has been conducted to model whatever physical effect that could influence the spacecraft motion. Two possible explanations favored by group members were: (1) some effect related to the heat produced by the spacecrafts energy source (2) gas leaks that lead to an acceleration. Both hypotheses became more and more unlikely, because (1) the decreasing heat production should have translated into a decreased force that has not been observed (2) gas leaks would require an astonishing constancy and the unlikely coincidence to be aligned with motion for all spacecrafts.

However, this remarkable observation would never have attracted so much attention if it hadn’t contained a challenge for theoreticians: the numerical coincidence of \( a_p \) with \( cH_0 \), the product of speed of light and the Hubble constant. A review of theoretical speculations explaining the Pioneer anomaly is given in [76]. Probably most of these proposals are going to be ruled out by orbital data of the outer planets, which have shown to be incompatible with an extra acceleration of the amount \( a_p \) [73, 79, 80]. Considerations on comets and minor planets [81, 82] give hope that in the near future it can be tested if \( a_p \) influences highly elliptic orbits. While new missions are proposed to test the anomaly [83, 84], the analysis of newly

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\(^4\)See [64] for a review on \( G/G \) constraints.\(^5\)with the recent exception [74]
recovered data [85] will be extremely interesting. Since the anomaly of Pioneer 11 seems to have started with the last flyby (Saturn), the old data, containing the Pioneer 10 Jupiter flyby, will reveal if there is a link to the flyby anomaly [61]. Besides the constant acceleration, there are anomalous daily and annual signals, too. Since there are more possibilities for systematic errors [76], less importance has been given to those.

2.1.7 Extrasolar scale.

Very little gravity tests are possible in the range just above the solar system. This has changed a little with the discovery of planets. Though the effective distance is of the same order as the solar system (0.01-5 AU), Iorio [86] deduced limits on the spatial variation of $G$ using orbital data from www.exoplanet.eu.

2.1.8 Globular cluster scale.

The first test of Newtonian gravity in the scale of $20-50 \, pc^6$ relies on very recent observations. Globular clusters, dominated by radial motion of stars, cannot be accessed by observing rotation curves like galaxies (see below). Following the suggestion of [87], [88, 89, 90] investigated velocity dispersion curves for $\omega Cen$, $M\, 15$, $NGC\, 6171$, $NGC\, 6341$ and $NGC\, 7099$. Instead of an expected Keplerian falloff, the curves show a flattening of the velocity profile, at the same acceleration $a_0$ that has been observed at galactic rotation curves (see sec. 2.3.2). Remarkably, this phenomenon has been confirmed at the low-concentration cluster $NGC\, 288$ which has an entirely flat dispersion profile [91].

2.1.9 Galactic scale.

**Galactic rotation curves** of about 1000 Galaxies [92] have provided the by far strongest evidence for the disagreement of ‘dynamical’ and visible mass. Assuming that all mass of a spiral galaxy is contained within its optical radius, one expects due to

$$v^2 = \frac{GM}{r}$$

a radial dependency $v \sim r^{-\frac{1}{2}}$ in the velocity profile of clouds that can be measured by Doppler shifts. Interestingly, up to multiples of the optical radius practically all galaxies show rather constant (‘flat’) velocities than the expected Keplerian behaviour. Usually, an explanation with ‘dark matter’ is given, though this requires a particular distribution. While the deviation is already visible within the optical radius, in the outer regions ratios of dark and luminous matter up to 1000 are required [93]. The form of the galactic rotation curves seem to depend just on the size of the galaxy [93, 94], a fact which is hard to explain by the properties of any dark matter candidate. Many precision profiles are conflict with the standard model [95], among these the most extended velocity profile of NGC 3741 [96]. While many questions are still open [97, 98] the anomaly itself is beyond any experimental doubt (see overviews [2, 99, 100]). There are clear hints that the morphology of galaxies is dominated by systematics we do not understand yet [101, 102].

**Low surface brightness dwarf galaxies** (LSBD) show the same behavior, but require an even higher relative amount of dark matter; this is in contradiction to cosmological DM models [103, 104], as it is adressed in detail in [105]. The same holds for tidal dwarf galaxies [106, 107].

$^61 \ pc = 3.262$ light years.
**Globular cluster distribution.** Rotation curves could be explained with dark matter located in the disc, but there is clear evidence that the gravitational potential obeys radial symmetry. The spatial distribution and velocities of globular clusters makes a dark matter concentration in the disk extremely unlikely, besides other evidences like the magellanic stream [2].

**LMC and SMC.** Recently, the HST provided 3-D velocity measurements of these objects known as satellite galaxies [108, 109]. The abnormal high value suggests either that we are witnessing a coincidental fly by of the Magellanic Clouds at the milky way, or a conflict with the mass estimates hitherto existing. Thought the effective distance is at the planetary scale, recently extracted data on eclipsing binary systems in the LMC could be useful for gravity tests [110].

**Local group, M31.** The Milky Way and Andromeda (M31), the biggest galaxies in the local group, are approaching each other much faster than can be explained by gravitational attraction of the visible mass. The extra (dark) matter required exceeds the visible one by a factor of about 70 [111]. In this context, the recent discovery of very distant halo stars in Andromeda [112] is surprising, too. Velocity dispersions of the local group are analyzed in [113].

### 2.1.10 Galaxy cluster scale

**The peculiar velocities** of galaxies in galaxy clusters were the first hint that observed and expected (from luminosity and Newton’s law) velocities did not match. This was discovered as early as 1933 by Zwicky [114] and called the ‘missing mass problem’. Recent measurements are [115].

**Gravitational lensing** confirms this result, since the observed light deflection is much greater that the amount that could be explained by visible matter. There is however a discrepancy in mass determinations for scales smaller than 300 kpc ([111], p. 264).

**Hot gas** in galaxy clusters is a further, independent confirmation of the ‘dark matter’ phenomenon. X-ray emission allows to determine the temperature of intergalactic gas. Assuming that hot gas being bound to the galaxy cluster (otherwise it should have left the cluster), much more mass than the visible amount is needed to explain the gravitational force that keeps it. A discrepancy with ΛCDM predictions was claimed by [116].

**Galaxy distribution** is an interesting testbed for gravity theories. Excellent data are now provided by the Sloan Digital Sky Survey (SDSS) and the 2dF redshift survey. Both contain positions and redshifts of galaxies, thus yielding information on the 3-D structure. It is known for more than 20 years that the distribution of galaxies is not really homogeneous. Rather there seems to be a hierarchy of galaxy groups, clusters and superclusters that concentrate on twodimensional structures, while there are large voids in between (‘sponge structure’) [117, 118]. Only for scales larger than 100 Mpc, the universe appears homogeneous (but see also [119]). In particular the presence of large voids has been puzzling to cosmologists [120] since they appear hard to explain by the ΛCDM model [121]. There is an ongoing discussion whether the large scale structure becomes homogeneous or possesses a fractal structure [122].

It is remarkable that the relation dark to visible matter is even higher for galaxy clusters than for spiral galaxies. It seems that the larger the structures, the more dark matter is needed to explain their stability.

### 2.1.11 Cosmological scale

**High-redshift supernovae.** The determination of today’s value of the Hubble constant $H_0$ is a long story. In the 1990’s, there was still a large discrepancy between groups favoring a value of
80 – 100 $kms^{-1} Mpc^{-1}$ based on several methods and the value of about 50 $kms^{-1} Mpc^{-1}$ which arose from quite accurate measurements of the luminosity of supernovae of type Ia (the actual accepted value is 73 ± 8 $kms^{-1} Mpc^{-1}$ [123, 124]). Then [127, 128, 129] and [130] independently announced that the relatively too faint high-redshift supernovae should be interpreted as an accelerated expansion of the universe. This is commonly explained by postulating a new form of matter called ‘dark energy’ (DE) that acts repulsively. It should be kept in mind that considerable data reduction has taken place. There are hints that the chemical distribution of elements causes brightness differences in SN explosions that would affect systematically the SN Ia data; simulations are currently carried out [131]. While the data clearly exclude a universe of ordinary matter, the question as to what ‘dark energy’ consists of is completely open. Laboratory tests could not give evidence for it yet [16] and there are still discrepant observations from X-ray data [132, 133]. A detailed look at the data [134] however shows that some surprising interpretation is not yet excluded; the data is even compatible with an ‘empty’ $\Omega = 0$ universe.

Weak gravitational lensing [136] is a powerful tool to estimate mass distributions on cosmological scales. These data indeed can constrain the long-range properties of gravity. The additional claim [137] that alternative theories are ruled out by the data refers however to a special class of models which show different radial dependencies. Alternative approaches in general, not even the concrete MOND proposal, cannot be tested, see [137], sec. 3. It seems that those results attack models with fixed-$r$ crossovers, something which is already dead [2].

Big Bang Nucleosynthesis (BBN). The big bang scenario with a hot, fast expanding universe allows to make testable predictions regarding the abundances of light elements that must have formed in the first minutes, in particular helium and deuterium. Though doing calculations in this extreme state of matter requires considerable extrapolation of physical laws, the observed abundances in primordial clouds justify this interplay of thermodynamics and nuclear physics. Since gravitation should slow down the expansion, a tiny effect on element abundances could be predicted due to gravity, too. [138] have used this to constrain the value of $G$, and by assuming some temporal dependency, also to put limits on $\dot{G}/G$ and on scalar-tensor theories of gravity [139]. To evaluate the significance of such a test for gravitational physics, some remarks must be given. There is no doubt that the amount of He$_4$ found in primordial clouds backs the big bang model in general. For further predictions, deuterium abundances from QSO spectra are measured which are less accurate. It is then assumed that the amount of D did not change since primordial times. Moreover, a lot of recent knowledge of particle physics, such as neutrino oscillations enter the calculations. Reading [140] is useful to get an impression of the complexity of what experts call the simplest case. All assumptions entering seem plausible at the moment, but there are many of them. Additionally, to interpret the missing baryon density, dark matter is needed. Most importantly perhaps, the application of GR to this very early, radiation-dominated phase of the universe, requires the strong equivalence principle, which is not really tested elsewhere.

Cosmic microwave Background (CMB). The COBE and WMAP missions provided unique data on the blackbody character [141], on the fluctuations and on the polarization of the CMB. Its very existence is a very strong evidence for the hot big bang scenario. From its power spectrum, a couple of physical parameters can be estimated, such as the baryon-to-photon ratio used in the BBN calculations [142], and imprints of modified gravity could be found there [143]. A critical point of view is outlined by [6]. The most important result is that at the largest scales, the universe appears to be flat, or, in old-fashioned terms, kinetic and potential energy are perfectly balanced. An interesting aspect is that CMB - for the

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7It is a fact that ‘generally accepted’ may change quickly in cosmology. [125] reports 62 ± 1.3 $kms^{-1} Mpc^{-1}$, see the review [126]. John Huchra maintains a list of $H_0$ determinations: http://cfa-www.harvard.edu/ huchra/hubble.plot.dat.

8See [135] for recent constraints.
first time in the history of physics- introduced a physically meaningful a preferred system. Of course, there is no conflict with Lorentz invariance.

The density fluctuations of the CMB are by far insufficient to explain galaxy formation. Large amounts of ‘dark matter’ and additional assumptions on its fluctuations are needed to match the observed galaxy distribution.

2.2 Tests ordered by mass

I will refer sometimes to the previous section, but it is useful to have a look on gravity tests under different aspects. If Newton's law with its symmetry is not assumed \( a \text{ priori} \), one first has to distinguish test and field masses. The independence of test masses is called the (weak) equivalence principle (EP), but it usually refers to a material independence. It is hard to imagine a scale dependence without being in conflict with logic, but a strict test is possible only if the mass of the test particle is precisely known.

2.2.1 General remarks and small scales.

**Linearity and superposition.** More interesting seems to wonder about a dependency of the law of gravitation on the amount of the field mass. Of course, in the case \( m = M \) the law should become symmetric again, but a deviation for large masses would not necessarily violate the EP, at least within its experimental constraints which mostly apply to test masses. It is not that common to wonder about such a dependence because it is completely out of our theoretical expectations. For instance, mass distributions with spherical symmetry could not automatically be replaced by point masses any more. Moreover, the method of mass integration as such bears a linearity that would be put into question by a mass dependence. We are used to the nonlinearities arising in GR, and automatically infer that gravity must be linear in the Newtonian limit, that is, the superposition principle holds. The claim that any physical theory must be linear in the weak-field-limit reflects some of our experience but cannot be rigorously proven. Strictly speaking, we perform an extrapolation of our simple mathematical methods which must be tested. While observations regarding distance test the exponent 2 in (1), it turns out that the exponent 1 on \( M \) is much more difficult to prove.

**Light.** Gravity obviously acts on particles without rest mass, too. Inserting the photon energy \( E = h f \) and \( m = E/c^2 \) however would yield only the wrong (half) value of a deflection due to gravity, thus light deflection needs to be understood relativistically. An effect of photons as field masses would be postulated by the strong EP. There is no test available.

**Atomic scale.** Though there is hope to measure gravity for neutrons as test particles by interferometry \([144]\), the effect of an elementary particle or atom as field mass seems unconquerable small.

2.2.2 Laboratory scale.

**Torsion balance experiments.** One has to skip 25 orders of magnitude in both field and test masses to get the first measurable effect of gravity. Torsion balance experiments usually work with equal masses in the range of 10 kg. Modern versions \([24, 25]\) provide the most accurate measurements of \( G \). The accuracy for determining \( G \) however usually decreases while using heavier field masses.
2.2.3 Geophysical scale

The measurements with moving gravimeters considered above must be seen as tests with an effective mass of a part of the upper crust surrounding the gravimeter. A crude estimate of the volume corresponding to the Greenland ice experiment [43] with a depth of 1673 m would be some km$^3$, reaching a mass scale of about $10^{12}$ kg. Though there were claims for deviations from Newton’s law in this regime, the experiments remain difficult to interpret. Usually, the gravitational mass determination enters all geophysical models of the core and mantle composition. It is however interesting to try a purely geophysical mass estimate by the earth’s volume and the suspected chemical distribution [145]. Important information about that can be obtained from seismic waves. According to the common model, there is a density jump from 6–10 g cm$^{-3}$ at the core-mantle boundary ([146], p. 30).

2.2.4 Solar System scale

There is quite a big gap between the previous tests and those arising from orbital data of celestial bodies. Strictly speaking, a possible field mass dependence of Newton’s law (i.e. an exponent $M^\alpha$ with $\alpha \neq 1$ in eqn. 1) can hardly be detected by satellite trajectories, since the same data are used to measure the mass. Independent assumptions on the densities of the sun and its planets usually lead to crude estimates only. While the Keplerian constants from different satellites (planets) are very accurate tests of the inverse-square-law in distance, they cannot reveal an $\alpha$ slightly different from 1. Thus, as far as field masses are concerned, in the range from $10^{23}$ kg (moon) to $10^{30}$ kg (sun) no test with significant accuracy exists.

2.2.5 Galactic scale

As a matter of principle, the same problem of an independent mass estimate holds for galaxies, too. The difference is that even very crude estimates like the assumption of a solar mass-to-light ratio by far do not match the dynamically determined mass which is in the range of $10^{50} – 10^{44}$ kg. This phenomenon could be explained either by forms of matter which interact gravitationally only (‘dark matter’) or by failure of Newton’s law. Contrarily to opposite claims, a mass dependence $M^\alpha$ with $\alpha < 1$ does not imply a violation of the equivalence principle, since the latter holds for test particles. From galactic rotation curves, a dependence $M^\frac{1}{2}$ has been suspected [147].

Radial and tangential velocities. The data of solar system observations consist of precise orbital data in three dimensions. The situation is very different on larger scales. While radial velocity measurements can easily performed by Doppler methods on galactic and cosmological distances, measuring velocities perpendicular to the line of sight was almost impossible for a long time. This changed very recently for the galactic scale when VLBI and HST detected secular shifts of galactic objects on the microarcsecond level. Many of these results, however, were surprising in the sense that they did not match the predictions of Keplerian ellipses [108, 109, 148]. The problem at the galaxy and galaxy cluster scale is that our knowledge comes from a snapshot of tens of years and we do not really know about the secular dynamics. The common picture of stable and virialized systems is an extrapolation of accepted theories of gravity. Observations on possible radial flows in galaxies are discussed in [149].

2.2.6 Cosmological scale

For a long time, mass (or equivalently, density) estimates were used to decide the question whether the universe will stop its expansion due to gravitational attraction and recontract (closed universe, $\Omega > 1$) or expand forever (open, $\Omega < 1$). Interestingly, many measurements suggested a state just in between ($\Omega = 1$). The recent WMAP data also indicate the puzzling case $\Omega = 1$. The problem is that this nice picture is completely screwed up by the SNIa data that show an accelerated expansion of the universe (while before the debate was going on how much it was decelerated). Though since Newton attraction
is quite a characteristic property of matter, many physicists do not have problems to assume a repulsive interaction to DE, while others admit that ‘dark energy’ might be just a name for something we do not understand.

2.3 Tests ordered by acceleration

This seems uncommon but it may be useful to consider the different orders of magnitude in which the respective tests are performed. We should be aware of an inadequate extrapolation of physical theories.

2.3.1 Strong and intermediate scale

**Black holes.** Though GR predicts the existence of black holes (BHs), the current, mostly indirect observational evidence for BHs is not a quantitative test of GR. Spectacular measurements of stellar orbits around the center of the milky way [30] allowed to deduce a mass concentration that indicates a supermassive black hole (SMBH). This is however not a quantitative measurement of the Schwarzschild radius \( r_s = \frac{2GM}{c^2} \), independent from the validity of GR, since \( r_s \) in this case would be still smaller than the perigee distance by a factor of about 1500. This factor may be decreased by VLBI observations [150]. The transition from neutron stars to BH’s is discussed in [151]. A review of strong field tests is [152].

**Neutron stars.** At the surface of neutron stars, accelerations up to \( 10^{12} \text{m/s}^2 \) can be reached. Compared to the acceleration of an electron a the Bohr radius, \( 10^{23} \text{m/s}^2 \), this is not really high, but of course, no gravity test can be performed. The highest possible (orbital) accelerations in binary star systems like the famous PSR 1913+16 are in the order of \( 50 - 350 \text{m/s}^2 \), the double Pulsar PSR J0737−3039 [153] reaches \( 100 \text{m/s}^2 \). Indeed, the periastron advance of PSR 1913 + 16 is a qualitative proof that the well-known Mercury perihelion advance exists in the strong acceleration regime, too. Assumed that GR is correct, this allows a unique mass determination of the binary system. Moreover, the decrease of the rotation of the system is in excellent agreement with the energy loss predicted by the radiation of gravitational waves. Reviews on testing gravity with binary and millisecond pulsars are [154, 155].

**Planetary surfaces.** While typical accelerations are in the order of \( 10 \text{m/s}^2 \), local gravity measures on earth with superconducting gravimeters have reached an accuracy of \( 10^{-12} \text{m/s}^2 \). Due to a variety of geophysical effects, it is difficult to perform gravity tests. All absolute \( G \) measurements have been conducted under these ‘background’ conditions. However, the experiments [24, 25] and [30] measured the gravitational accelerations in perpendicular directions.

**Satellite orbits.** Satellites like LAGEOS act at an orbital acceleration of about \( 2.5 \text{m/s}^2 \), therefore this regime is tested extremely well. The flyby anomaly, however, occurs at similar experimental situations, though on hyperbolic orbits. The amount of the corresponding anomalous acceleration is not measured very well yet.

**Solar system scale.** The orbital accelerations of the planets range from \( 3.9 \times 10^{-2} \) to \( 6.6 \times 10^{-6}\text{m/s}^2 \) (Neptune). Newtonian gravity is tested extremely well in this regime, and, as far as planetary orbits are concerned, no deviations are found above \( 10^{-10}\text{m/s}^2 \) [79]. This is important since the Pioneer anomalous acceleration \( a_p = 8.74 \times 10^{-10}\text{m/s}^2 \) was measured for a comparatively light spacecraft on a hyperbolic orbit.

2.3.2 Weak (galactic) scale

**Galaxy rotation curves and MOND.** This scale is the most interesting one and the reason for analyzing gravity under the aspect of acceleration strength. The most recent observational overviews are
A detailed look however shows that many observational facts can hardly be explained by any ‘dark matter’ theory\cite{158}. Further overviews focussing on that problems are\cite{159,160}. As an alternative, galactic rotation curves gave rise to speculations on a modification of Newton’s law. However, all proposals that tried to modify it with respect to distance, ran into a tremendous mismatch with the data, which is outlined in detail by\cite{2}. The very unusual proposal of Modified Newtonian Dynamics (MOND)\cite{161,162}, received with scepticism, was based on the remarkable observation that the assumed failure of Newton’s law occurred at a fixed dynamical scale in the order of $10^{-10}\text{ms}^{-2}$. The concrete proposal of an effective acceleration

$$g = \sqrt{\frac{a_0GM}{r^2}}$$

with the fitted parameter $a_0 \approx 1.1 \times 10^{-10}\text{ms}^{-2}$ indeed matches most of the galactic rotation curves with a reasonable accuracy\cite{161,162}. As in the case of the Pioneer anomaly, the approximate coincidence of $a_0$ with $cH_0$ (you may divide by $2\pi$) attracted attention. There are even phenomenological models encompassing both effects\cite{163}. Laboratory\cite{164} and solar system\cite{165} tests for MOND have been proposed, while artificial planetary systems in space may reach this small acceleration scale\cite{59}. Of course, MOND is unusual and it is quite boring to itemize the fundamental principles of theoretical physics it contradicts\cite{166}, and there are observations where MOND has problems, too\cite{167}. So what? I don’t know if anybody thinks that MOND is the last word in gravitational physics. Its indisputable merit however is to have attracted attention to the fact that Newton’s law is poorly tested for accelerations below $10^{-10}\text{ms}^{-2}$. The approximate agreement of $a_0$ with $cH_0$ is either a coincidence invented by nature to fool astronomers or a proof that we do not understand gravity yet.

**Globular clusters.** Globular clusters, though orders of magnitude smaller than spiral galaxies, have comparable accelerations at their boundaries. The recent observations\cite{89,91} that flat velocity dispersion profiles occur in globulars, too, have a great impact. It is not important whether this is properly described by MOND (though $a_0$ is the same), but if the results are confirmed, they will bring the dark matter model into serious trouble.

**Galaxy clusters.** Obviously the accelerations in galaxy clusters are usually even weaker than the centripetal ones of rotation curves. Again, the gravitational accelerations necessary to keep clusters together would be much greater than those suggested by visible matter. The data do not allow to distinguish between the dark matter hypothesis and a failure of Newtonian gravity (with instructive comments,\cite{158,168}).

**2.3.3 Cosmological scale.**

Though there is no direct measurement of the large-scale accelerations occurring during cosmic evolution, the predictions of Friedmann-Lemaitre cosmology can be tested. As outlined above, there are some contradicting results with no satisfactory solution at hand yet. To get an order of magnitude, one may assume the masses to be accelerated to the Hubble velocity during $H_0^{-1} = 13.4\text{ Gyr}$, ending up with $cH_0 \approx 7 \times 10^{-10}\text{ms}^{-2}$, again in the weak-acceleration regime. If Newtonian gravity turns out to be wrong here, one should search for a different explanation of the observational puzzles of cosmic evolution, too.

**2.4 Collection of funny coincidences, problems and results under debate**

‘Everybody believes the experimenter - besides the experimenter himself’.

**The Tully-Fischer (TF) relation** is an empiric law\cite{169} that relates the total luminosity $L$ of a galaxy to the maximal rotational velocity observed by Doppler shifts

$$L \sim v^\beta,$$  \hspace{1cm} (5)
whereby $\beta$ ranges from 3.5 to 4.5. The TF relation is quite accurate, thus it has been used to determine the Hubble constant, too. A theoretical reason for its origin does not exist in standard cosmology. A similar relation has recently been observed for the radial velocity [170].

**Further relations.** The $L_{bulge} - \sigma$ or Faber-Jackson-relation [171] relates the luminosity in the central region to the velocity dispersion $\sigma$ of the respective stars. Even more surprisingly, there is a correlation of the central black hole mass $M_{BH}$ of a galaxy and the velocity dispersion, the $M_{BH}-\sigma$ relation [172, 173]. While the details of these dependences are under discussion, the pure existence of relations between these three quantities are an unexpected regularity which miss a theoretical explanation.

**Density waves.** It has long been noted that the visible spirals of galaxies cannot rotate rigidly, because differential rotation would swipe them out soon, i.e. after a few hundred million years. The phenomenon is commonly explained by acoustic waves that in the compressed regions form bright, short-living stars that lead to a greater visibility of the spiral arms. A direct proof of this theory has not been given yet (cfr.[174]), and one may ask how the galaxies maintain their ability to supply the star forming regions after dozens of density wave passings. The formation of jets is not fully understood as well [175].

**Barred Galaxies** show a couple of results that are poorly understood yet. These discrepancies and others are discussed in [159]. An extensive review on barred galaxies is given in [176].

**Numerical simulations** of galactic structure formation predict thousands of dwarf galaxies in the vicinity of large spirals like the milky way. There are only 35 objects of that type observed currently.

**The quadrupole-anomaly** has been detected in the COBE and WMAP data of the CMB [177, 4]. It means that the fluctuation amplitude is much lower than expected, and moreover, the anomalous small quadrupole and octupole component are aligned to the ecliptic. The alignment to the ecliptic, rather than to the galactic plane, makes it unlikely that an artefact appeared due to the need of removing foreground signals from the data.

**An increase of the astronomic unit** of about 10m per century has been reported recently [178, 179, 180, 4]. If this result which is still under debate is confirmed, it will be quite hard to find a conventional mechanism that explains it.

**The third-parameter problem** means the impossibility to account for the observed variability in HRD diagrams of globular clusters by means of two parameters. ‘Either there is some fundamental failing in our understanding of stellar evolution, or there must be some other factor beside the metallicity and age which dictates the properties of globular clusters’ ([181], p. 352).

**Absorption lines of quasars** have been used to estimate the fine structure constant $\alpha$ in the early universe. Webb [182, 183] deduced a different value for $\alpha$, but a corresponding rate of change would be to large for being undetected by actual precision measurements [184], see also [185]. The debate is going on, in particular which other constants of nature can be affected by a change, if any [64].

**Quasar statistics** reveal that they appear more frequently near the sight line of foreground galaxies, at least this is claimed by Arp, a highly skilled cosmologist [186, 187]. The cosmological model favored by him seems too exotic to be credible, but in his nevertheless recommendable book [188] he soberly observes lots of facts that do not fit into the commonly accepted picture.
The astrometry satellite HIPPARCOS provided data of unique precision\(^9\), and the parallax method of determining distances is considered the most direct and best for small distances. However, the parallactic distances were considerably smaller than those measured by other methods. Recently, [189] presented a distance measurement using spectroscopically gained orbital data of a binary star system, which can be considered similarly direct (‘geometric’) than parallaxes. The discrepancy with the HIPPARCOS distance awaits for an explanation. Problems with HIPPARCOS distances are also discussed in [190], see also [191].

Galaxy surfaces. The ‘surface’ of the Milky way can be approximated by \(2r_g^2\pi\) with \(r_g = 10000 \text{ pc}\). Assuming as a crude estimate \(10^{11}\) Galaxies of this kind in the universe leads to a total ‘surface’ in the range of \(10^{52} - 10^{53} \text{ m}\) which coincides with the surface of a sphere with \(r = cH_0^{-1}\). Given that galaxies are assumed to be unchanged in shape (‘virialized’) for a long time, this is an astonishing property of the present epoch.

The ‘direct detection’ of dark matter was a recent claim [192]. These interesting observations however do rather raise new questions than resolve the DM riddle [193, 116].

Gravitational waves have not been detected yet, notwithstanding enormous efforts, see [194] for a review. The evidence provided by the slowdown of the pulsar \(PSR\ 1913 + 16\) for this prediction of GR thus remains indirect (cfr. [154, 155]).

Cryogenic sapphire oscillators show drift rates linear and in the same direction for many years [195]. Since the order of magnitude is \(10^{-13}\) to \(10^{-14}\) per day, one could speculate on a possible connection to the Hubble time (see also [196]).

Gravity shielding. There are quite suspicious reports on gravity shielding over superconducting coils [197, 198]. This seems extremely unlikely; one the other hand there is no reason why one should not try to repeat a quite simple experiment.

2.5 Overview

‘It is the stars, the stars above us, govern our conditions’ (King Lear, Act IV, Scene 3)

The gaps. Fig. 1 gives an overview of the orders of magnitude involved by tests of gravity. Roughly, there are three groups: left (below), middle and (upper) right. The left group involves tests on small scales, and only here absolute \(G\) measurements are possible. Then a considerable gap follows, and one should not forget that as far as masses are concerned, anything else is extrapolation. The middle group is the well-tested regime of celestial mechanics, on which our belief in Newtonian gravity and GR relies, but strictly speaking it tests Kepler’s law rather than Newton’s. The Pioneer and flyby results are not explained yet, however. The upper right group represents gravity tests from the galactic to the cosmologic scale. None of them yields undoubtable evidence for the validity of Newton’s law, i.e. i must be backed by additional assumptions like DM or DE. In summary,

1. Tests of the field mass dependence are entirely determined by only 1-2 independent types of experiments on small scales. Given the relatively poor accuracy, the extrapolation to the following is courageous.
2. The data in the middle group is well-tested, but keeping in mind the logarithmic diagram, further extrapolation is not backed by the observations, not even for Kepler’s law.

\(^9\)This precision will still be increased by the GAIA mission.
Figure 1: Overview on data domains, length is upwards, masses to the right. BBN is shown at the then-horizon and the corresponding density. For the SMBH, \(10^6 M_{\text{Sun}}\) is assumed, but there is no test. The logarithmic units may yield to an underestimation of the degree of extrapolation. Actually there are two big gaps. In the right upper region, no gravity tests at all are available. The dotted line corresponds to the acceleration \(cH_0 \approx 7 \times 10^{-10} m^2 s^{-1}\). Below that regime (above the line) there are no significant tests of gravity.

A general failure of gravity at low accelerations?

*The fault, dear Brutus, is not in our stars, but in ourselves* (Julius Caesar, Act I, Scene 2)

In the last section a variety of anomalies was discussed. The most puzzling fact is that accelerations of the order \(10^{-10} m s^{-2}\) occur in several completely different circumstances. If we try to give an order of strength of evidence, this involves (1) Galactic rotation curves, (2) The Pioneer anomaly, (3) Globular cluster data. Moreover, all the other unexpected phenomena consistently occur below that acceleration regime. The enigmatic coincidence with \(cH_0\) is an additional strong hint that the discrepancies have a common origin and may lead to a general failure of Newton’s law in the weak-acceleration regime.

3 The agreement with theory

*‘The great tragedy of Science—the slaying of a beautiful hypothesis by an ugly fact.’ - Thomas H. Huxley*

This is an ironic version of Popper’s criterion of falsifiability, indeed a good attribute for testing whether a theory is scientific or not. For the development of science however it tells only how things *should* work. In practice, established theories which frequently are considered ‘beautiful’, do not die suddenly when confronted with ugly facts, they rather affiliate them by becoming extended ‘models’. This process was described by the philosopher Kuhn [199] as ‘normal science’, which tries to understand the observations
within an accepted framework. When the anomalies pile up to an obviously too complicated scheme, a paradigm shift takes place that may lead to a ‘scientific revolution’. What is ‘obvious’ and whether the crisis has begun or not is not easy to decide. The last occurrence in history, the Copernican paradigm shift, tells us in retrospect only that scientists may be blind for a long time.

3.1 Standard cosmology, $\Lambda$CDM

‘Cosmologists are often in error, but never in doubt’ - Lev D. Landau.

Friedmann-Lemaitre cosmology and ‘dark energy’. After having discovered the relation between gravity and geometry, Einstein wasn’t aware that his field equations did not permit the static solutions he desired. This was shown by Friedmann, and Lemaitre started to develop the model which is nowadays called big-bang-cosmology. To justify his favored steady-state-model, Einstein introduced the cosmological constant $\Lambda$, but after having realized that Hubble’s data supported an expansion of the universe, he later called $\Lambda$ the ‘biggest blunder’ of his life. The high-redshift supernovae, indicating an accelerated expansion, led to a renaissance of $\Lambda$, now called ‘dark energy’. To claim Einstein was right and praise his ingenuity however is in this case misleading - apart from the fact that a couple of his interesting ideas still are considered blunders by modern-minded people. Einstein was ready to introduce a mathematical complication in order to save a physically simple model, because of his deep-rooted conviction that laws of nature must be simple in a physical sense. Today’s dark energy instead is just an additional free parameter used to adjust a more and more complicated observational situation [200, 201]. I think that Einstein had preferred to admit a blunder rather than being a chief witness for $\Lambda$.

Dark matter.

‘There is certainly not a lack of chutzpa in extragalactic astronomy’ - Margret Geller

There is overwhelming evidence that the ‘dark matter’ phenomenon exists on various scales. While the DM hypothesis explains galactic rotation curves at a first glance, maintaining it in the light of more recent results seems to rely on the absence of detailed knowledge. Moreover, the absence of any decline suggests that the dark halos continue to regions not accessible by current technology. Cosmologists should be prepared that the ‘fraction of DM’ turns out to be just a measure of telescope resolution. Then, it is strange enough that the relative amount of dark matter seems to increase with the size of the structures (galaxy clusters contain much more than galaxies), but dark matter can clearly not explain the recent anomaly found in globular clusters or even the Pioneer anomaly. I am curious to future priority claims for introducing the terms ‘dark molasse’ and ‘dark substance’, which, with an appropriately chosen distribution, could describe both phenomena satisfactory. Details of what has been proposed as candidates for DM cannot be addressed here. Massive compact halo objects (MACHOS), such as brown dwarfs, would have been detected by microlensing if they existed in the required amount. While the question of hot (fast, relativistic particles) or cold dark matter seems to be answered in favor of the latter, no reasonable candidate particle has been found in the laboratories yet. To some people, postulating neutralinos (or elsewhere, photinos and axinos) still gives hope for a possible explanation, since Italian language will hardly run out of diminutives. Following this road, poorly understood new results [202, 203] can be readily interpreted as evidence for various dark matter particles. On the other hand, this development reminds strongly from Ptolemaic epicycles [204].

Dark matter however remains at least an urgent need in the codes of programs simulating cosmic structure formation. The fluctuations in the CMB are by far insufficient to explain the clumping that corresponds to the concentration of galaxies. Dark matter instead, numerically much cheaper than ordinary matter, clumps so easily as long as we do know about its properties. Isn’t that a nice proof of its existence? Or should we admit that we do not understand structure formation?
It is time to put into question the obvious idea of explaining deviations from Newton's law with gravitationally interacting matter not yet detected. From the point of view of scientific methodology, the last success of a dark matter theory was the discovery of Neptune.

‘Once the error is based like a foundation stone in the ground, everything is built thereupon, nevermore it returns to light.’ - Rudolf Clausius

The Flatness problem. Measurements of the density parameter \( \Omega \), in particular from the recent WMAP data, yield a value very close to 1. However, evolution models of the universe would predict a strong drift of this value, once there is a minute deviation from 1. Therefore, at early times, \( \Omega \) must have been as close as \( 10^{-60} \) to 1, and the question arises how this fine-tuning of a measuring value occurred, or if there is a theoretical reason beyond.

The Horizon problem. The finite speed of light implies that we are not able to see parts of the universe further away than the distance light could travel since the big bang. This implies that, at the time being emitted, CMB photons at different positions (separated by more than 1 deg) in the sky could not ‘know from each other’, i.e. there was no causal contact. The question arises how a common mechanism suggested by the highly uniform temperature, could occur.

‘Inflation is a fashion the high-energy physicists have visited on the cosmologists; even aardvarks think that their offspring are beautiful.’ - Roger Penrose

Inflation is called that the hypothesis that the universe expanded by a factor \( 10^{40} \) at the period around \( 10^{-34} \)s after the big bang. Indeed, it provides an explanation for the horizon and flatness problem. Looking at the uniformity of structures, such arguments appear superficial ([205], ch. 28.5):

‘whatever this generic singular structure is, it is not something we can expect to become ironed out simply because of a physics that allows inflationary processes.’

While inflation becomes more and more a component of the standard model, many physicists feel uncomfortable with it. The problem is not - as it may seem - that there is no physical mechanism for such a superluminal process, actually there are many of them - but no one will ever be tested. How to observe \( 10^{-34} \)s after\(^{10}\) the big bang, which is still 380000 years before the last scattering surface of the CMB.\(^{11}\) Inflation does not have a problem with explaining phenomena, it has the problem that it explains almost everything. The question which observation would be incompatible with inflation, was raised by [207]:

‘This elasticity has diminished the faith of the general astronomical community in inflation, and even led some researchers to question whether inflationary cosmology is a branch of science at all’.

It is frequently claimed that inflation ‘predicted’ a flat universe. However, before the BOOMERANG and WMAP data ultimately measured the curvature \( K \approx 0 \), numerous versions of inflation predicting \( K \neq 0 \) were circulating. But most importantly, we cannot act as if \( K = 0 \) were a measuring value like other numbers. The observed flatness seems to be a very deep, cogent feature of the universe, for which an inherent theoretical reason should exist, not just an ad-hoc, qualitative mechanism. Of course, there could be some exotic topology in the WMAP data (still to be detected) that would bring inflation into trouble, but it is hard to imagine that people were unable to fix that by some modified or extended version... To conclude, the theory of inflation, if not the origin of a never ending universe, is at least a starting point for an inflation of theories never tested.

\(^{10}\)The only reasonable measurement of time that can be performed in physics is based on the frequencies of atomic or nuclear transitions. Since this could be at best in the range of \( 10^{-13} \)s, such theories will never come down to earth.

\(^{11}\)See [206] on the vague possibilities of testing inflation with the CMB.
**Not really an alternative theory but...** the flatness and the horizon problem arises, because we believe in Friedmann-Lemaître (Newtonian) cosmology. At a constant expansion rate, more distant objects have a greater relative ‘velocity’ (Hubble’s law). The distance that corresponds to $c$ is called horizon. If the expansion is slowed down by gravity, new objects drop into the horizon. If there was no gravity acting, there is no slowdown, no horizon increase and no problem. Instead of believing in a theory relying on the constancy of $c$, then running into problems, and resolving these problems by postulating an expansion $v \gg c$, isn’t it just more honest to say that standard cosmology is incompatible with observation and we do not understand yet cosmic evolution?

**The coincidence problem** is best explained in a visual manner (see fig. 2).

![Figure 2: The coincidence problem](image)

While conventional models of matter (closed, $\Omega = 1$, and open) seem to be excluded by the SNIa data (dots), the dark energy term predicts an evolution of the universe corresponding to the above line $\Lambda > 0$. But isn’t it strange that the ‘actual’ tangent (Hubble’s constant, corresponding to $\Omega = 0$) hits the curved line ($\Lambda > 0$) at the origin (big bang)? Or in other words: we seem to live in a very preferred period\(^\text{12}\), since the inverse current expansion rate coincides with the time past since the big bang. Let $p$ be the probability that the evolution of intelligent life takes place in such a period, and $q$ the probability that our actual understanding of cosmic evolution is quite complete, it’s up to the reader to decide whether $pq > (1 - p)(1 - q)$ holds.

**The PPN formalism.** While the standard model fits free parameters to data otherwise unexplainable, there are many ideas of suggested violations of current theories which have not been observed yet. A systematic method to embrace these constraints is the PPN formalism [209, 210, 10], which defines several parameters that could indicate certain kinds of violations. This is a very useful tool for maintaining an overview on precision tests. To take the values of the parameters in agreement with the standard model as support for its validity, is however a circular argument. Besides the fact that such a list of parameters can hardly be complete (e.g. [211]), a nonzero violation parameter may easily turn into a new

\(^{12}[208]\) outlined this from a funny point of view.
free parameter of an extended standard model. PPN, keeping the tradition of fitting parameters is thus rather a seduction for future model makers than a helpful indication that a fundamental new theory may be needed. Sometimes one can hear that the PPN parameter space volume left by precision tests does not leave space for extensions of gravity [212, 213]. It is well-known that the Ptolemaic model gave an accurate description of planetary orbits, that means the ‘post-Ptolemaic-parameters’ were close to zero. But it is also well-known that the Copernican revolution did not take place in a small ‘volume’ of such a parameter space - actually Newtonian gravity was something fundamentally deeper, not an extension of an existing model. Taking the PPN formalism too serious could make us blind for such a possibility. Further general comments on the standard model are given in [201, 214, 215].

3.2 Alternatives

‘Nobody believes the theorist - besides the theorist himself’.

This is going to be the most subjective and incomplete section, but it seems obvious to me that there is more need for a review of observations than of theories. GR was an extremely successful extension of Newtonian gravity, but science requires the agreement with observation, since ‘the danger of judging a theory on the basis of elegance, simplicity or perfection is obvious’ (R. Dicke [216], p. 363). If a Copernican revolution is needed, it could well be that some Aristarchus had already appeared, thus it might be smart to study some of the old ideas. Publications on physical theories are inevitably influenced by fashion like other creations of mankind; the extremely high quality of the present observational data justifies indeed to neglect some older data. This led however to an overestimation of current theoretical approaches with respect to genius thinkers of the 19th and 20th century, a kind of arrogance of the presence.

At the same time, the standards what is to be considered a good physical theory [217] seem to be in erosion. Einstein built a theory on the equivalence principle. Nowadays we don’t worry about deep principles, rarely there are theoretical results, and many conferences entitled ‘Trends on ...’ take place.

Science and the Planck scale. It is common folklore that gravity needs to be unified with quantum mechanics, and everybody, independent of loop or string preference, claims this must occur at the Planck level \( l_p = \sqrt{\frac{Gh}{c^3}} \approx 10^{-35} m \), which protects comfortably from being falsified by experiment \(^ {13}\). The problem is that \( l_p \) is deduced from \( G \) and therefore significance of the argument relies on the correctness of conventional theories of gravity. A theory that puts into practice Mach’s principle, could construct a relation of \( G \) to the mass distribution of the universe and therefore reveal the Planck level as an artifact. Many theories would lose then even a hypothetical contact to experiment. For instance, another way to look at the flatness problem is that potential energy equals kinetic energy, or, simplified,

\[
\sum G \frac{m_i m_j}{r_{ij}} \approx \sum m_i v_i^2.
\]

Indeed,

\(^ {14}\)Ernst Mach suggested that the gravitational interaction had its origin in the distribution of matter in the universe.\(^ {14}\) One possible idea to put Mach’s principle into practice is to modify (6) and express \( G \) as a function of the positions and velocities of all masses in the universe. [220, 221] and [222] are intelligent approaches in this direction.

\(^ {13}\)It seems that in quantum gravity approaches this is slightly different. As Smolin [218] points out, sophisticated proposals have been made how to approach the Planck level, while string theories seem not to care any more about falsifiability.

\(^ {14}\)See [219] for an overview on Mach.
A variable speed of light was another interesting ‘blunder’ of Einstein. Those who think that such ideas contradict relativity or even worse, pure logic, should remember that Einstein in 1907 wrote:

The constancy of the velocity of light can be maintained only insofar as one restricts ... to ... regions with constant gravitational potential...

and in 1911,

‘From the proposition which has just been proved, that the velocity of light in the gravitational field is a function of the place, we may easily infer, by means of Huyghens’s principle, that light-rays propagated across a gravitational field undergo deflexion’.

Recently, Ranada [223] has reconsidered Einstein’s ideas in the context of the Pioneer anomaly and collected several citations of Einstein that put into evidence that the principle of constancy (over space-time) of the speed of light is not a necessary consequence of the principle of relativity. Furthermore, the notion of VSL is implicitly present in GR (see [224], ref. 70, citing numerous examples of GR textbooks). Despite this, there are physicists who consider a variable c to be in contradiction with pure logic, since the value of c is defined by the unit system. If however time and length scales which are defined by atomic transitions change accordingly, the change in c is hidden at first glance. A drift of fundamental constants seems to provoke similar reactions like a motion of the earth some hundreds of years ago:

‘If earth is moving around the sun, why isn’t there a strong wind blowing due to that motion ?’ was an argument of the adherents of Ptolemy. Galilei responded:

‘Close yourself with a friend in a possibly large room below deck in a big ship. [...] ...of all appearances you will not be able to deduce a minute deviation...’ [1]

Sometimes it’s useful to read Galilei, and sometimes it’s useful to read Einstein.

Dirac’s large number hypothesis, like Mach’s principle, is another example of profound thoughts standing quite isolated in the current fashion of theories. Dirac [225] observed that all measured dimensionless quantities in physics are either in the order of unity, or in the order of $10^{40}$ or $10^{80}$. Suggesting that this can hardly be coincidence, he was speculating if the number of protons in the universe is related to the square of the ratio of electric and gravitational forces. Another example is that the Hubble time $13.4 \text{ Gyr}$ is about $10^{40}$ times the time light needs to pass the proton radius. Though Dirac postulated a time-dependence of the gravitational constant $G/G$ which is above the current observational constraints [64], these deep ideas should not be discarded completely [226].

The wonderful ‘conceptual’ agreement of the quantum vacuum density and the cosmological $\Lambda$, failing by just 120 orders of magnitude, is at least another interesting number fitting into Dirac’s considerations. Astonishingly, field theorists usually do not appreciate Dirac’s ideas.

Robert Dicke is famous for his contribution to the CMB discovery and for creating an alternative theory of gravity. This so-called Brans-Dicke or scalar-tensor theory is in the meantime ruled out or at least reduced meaningless by the $\omega > 500$ constraints [63]. Dicke’s initial thoughts [216] which have been anticipated by Sciama [220], however were much more general than the final form in collaboration with Brans [227]. Scalar-tensor theory sounds like an additional feature of GR, i.e. a potentially unnecessary complication. Dicke’s original idea was similar to a pure scalar theory with a variable speed of light. Here, ‘scalar’ does not mean a scalar theory coupled to matter to which later Einstein had expressed caveats in general.15

15[228] has given clarifying comments on that topic. It is pointed out that there is no shortcut as a matter of principle, rather at the moment no convincing example of such a theory that matches the data.
**Anything else?** In the outlooks or conclusions of modern textbooks one usually can find the statement that after all, the standard model is the most likely option, after having mentioned MOND and its problems. But apart from being the most likely, is it likely at all that our understanding is quite complete? Why are people so sure about this? In his excellent book on the worrying situation of theoretical physics [218], Lee Smolin gives an example of the mechanism that leads to such a narrowing of our view: 'The [...] possibility - that we are wrong about Newton’s laws, and by extension general relativity - is too scary to contemplate.' (p.15).

### 3.3 Basic problems

Rather than postulating new quantities without meaning, advance in theoretical physics has often been achieved by a better understanding of quantities one was already familiar with. There are still some points left where our knowledge must be scrutinized. Research has shifted too much towards the technical issues, leaving behind the fundamental questions.

**Time.** Barbour [229] has presented a very deep reflection on the nature of time. Analogously to the concept of space which does not make sense without matter, he claimed that the concept of a time as an invisible river that runs without relation to matter is senseless. If instead the evolution of the universe and the periodic processes in there define time, profound consequences for the laws of nature must be expected.

**Energy.** The concepts of potential and kinetic energy were born when physicists described Galileo’s free fall experiments with the time-independent quantity

\[ mgh + \frac{1}{2}mv^2 = \text{const.} \]  

(7)

Newton’s potential \( GM/r \) and all the other forms of energy found in the following were based on the same idea of finding time-independent laws of nature. In quantum mechanics, this is reflected by the fact that only stationary states of the wave function have a well-defined energy. While the concept of energy conservation is extremely successful in describing local effects, its application to cosmology remains questionable. The observations of the evolution of the universe, for instance the CMB, the galaxy distribution and star formation processes tell us that the wave function of the universe is anything but stationary. Though standard cosmology (Friedmann-Lemaître) is based on it, the notions of kinetic and potential energy may be inadequate.\(^\text{16}\) Is there a reason why energy should exist in two disparate and independent forms? Their separate existence is the reason why pure inertial motion is allowed in Newtonian mechanics [222], something which is not really tested for small accelerations. The considerations of Anderson [61] are interesting in this context.

**Mass.** is another poorly understood concept in physics. Barbour [222] has tried a definition by means of inverse accelerations, but what is behind that? Einstein’s famous \( E = mc^2 \), applied to gravitational energy \( \frac{GMm}{r} \), tells us that mass can be proportional to a product of masses. This remains a very strange fact, or could indicate that \( G \) is an artefact that can be calculated from parameters of the universe.

**The equivalence principle,** the fact that a kinematic property measured by accelerations, mass, at the same time should be a ‘charge’ for a certain interaction, is very deep and puzzling. ‘I was ultimately astonished by its validity’, Einstein said [230]. The (weak) EP is probably the most important constraint for developing alternative theories, and its validity guarantees a special role for gravity among the fundamental interactions.

\(^\text{16}\)The commonly used Euler-Lagrange formalism is just a general mathematical tool on top.
4 Methods

A hierarchy of theory quality.

‘correct theories of physics are perfect things, and a replacement theory must be a new perfect thing, not an imperfection added onto an old perfect thing. This is the essence of "revolution", the replacement of the old with a new, not the adding of more crap onto the old.’ - Richard Feynman

The history of science shows many examples were knowledge has not increased in a direct and steady way. Really fundamental theories like electrodynamics and quantum mechanics yield revolutionary new insight by reducing the number of the constants of nature, i.e. by the relation $\varepsilon_0 \mu_0 = 1/c^2$ or by expressing Rydberg’s constant as a function of $h, e, \varepsilon_0$ and $m_e$. The next class consists of theories like QED or GR which make testable predictions of extraordinary accuracy, such as for the Lamb shift and the anomalous magnetic moment of the electron, and the classical tests of GR. They ‘fail’ however to derive quantities like $G$ and $m_e$, which is not excluded as a matter of principle - in the case of $m_e$ this was considered by Feynman\textsuperscript{17}, while Mach suggested that $G$ could be calculated from the mass distribution of the universe. The modern developments in theoretical physics are much less ambitious, which is reflected by the term ‘model’ rather than ‘theory’. The predictions merely regard the existence of particles or concepts, while quantitative predictions are abandoned by introducing free parameters. String and superstring ‘theories’ have gone down further and predict nothing - though in a self-confident manner [218, 231]. Cosmology should be kept away from such a development.

Theories on top of theories.

‘They defend the old theories by complicating things to the point of incomprehensibility.’ - Fred Hoyle

Theoretical, as well as observational insight has hierarchical structure. The research on reaction rates of complex molecules would be on sandy grounds if there was any doubt on Mendelejew’s order of chemical elements. Thus one has to be careful when acquiring new knowledge on the basis of older one. This holds in particular for astrophysics and cosmology, where no direct experiments are possible. For instance, a different population of cepheid stars, as initially used by Hubble, led to wrong estimates of the age of the universe. Even every accepted theory may be wrong with a small probability, and thus one has to take care of the cumulating effect when building theories on top of others.

It is dangerous in particular when observational results are interpreted with respect to a wrong theory. Almost five years of research in nuclear physics were lost with a wrong theory of transuranic elements, and the discovery of nuclear fission, compared to the discovery of the cosmos, was an easy task. In astrophysics, research has shifted its focus to galactic and extragalactic observations, the regime in which the underlying theory is least tested. While parameter measuring becomes more accurate, the interest as to the nature of DM seems to decrease (while theoretical proposals for the recently discovered DE have reached their peak). There is danger of brushing aside such conceptional questions and of getting used to sandy grounds.

High-energy and particle physics.

‘If you can’t talk about something you have to hush.’ - Ludwig Wittgenstein

The closer cosmology approaches the big bang, the more increases the need to introduce knowledge from the smallest scales. Though particle physics is not commented here\textsuperscript{18}, one can say that cosmology did not

\textsuperscript{17} See his Nobel lecture at http://nobelprize.org/.
\textsuperscript{18} The interested reader is referred to Smolin’s remarkable book [218].
develop the first standard model with an inflation of free parameters and starry-eyed extrapolations of partly successful theories have already occurred in physics. Sometimes one can hear that inflationary and particle models have so similar concepts that there must be a deep relation. There is a relation indeed: the closer we go to the big bang, the more we can say that ignorance meets ignorance.

Separate data from interpretation.

‘No theory should fit all data, because some data are surely wrong’.

One possibility to do clean science is to separate observations from theoretical interpretation, even if this might seem complicated. Good science titles ‘Excess antenna temperature observed at 4080 $Mc/s$’ and not ‘God plays accordion’. A tiny progress is ‘cosmological redshift’ instead of ‘Hubble expansion’, and ‘faint high-redshift SNIa’ tells more than ‘dark energy measurement’. Even if there is little doubt on a certain theoretical model, new results must remain readable for those who think about alternatives.

Looking at alternative proposals, it is suspicious when a surprising observational result immediately backs a new theory at hand. Even for true and honest scientists it makes sense to maintain a distance between their theories and the experiments supporting them. A famous example are the erroneous results of Dicke and Goldenberg on the quadrupole moment of the sun that should give evidence to a scalar-tensor theory of gravity. Extraordinary claims need extraordinary evidence.

Science is quantitative. There are lots of results that cannot be understood with conventional physics. With ‘conventional physics’ I mean here baryonic matter of known particles. It is not really scientific to postulate unknown forms of matter if these forms for a long time fail to show up in laboratory experiments. Moreover, is has become a habit just to state that something does not work without dark matter. But how much? There are ratios for dark and visible matter for spiral and elliptic galaxies, for clusters, superclusters, and there are estimates for DM needed to explain structure formation, WMAP data, big bang nucleosynthesis, and so on. Does all this really fit together in a quantitative way? It seems that every field of research fixes its problems with DM, but hardly an encompassing calculation is done [232]. To be concrete, the current parameter ratio $\Omega_b, \Omega_{DM}, \Omega_{DE}$ is 0.02 : 0.24 : 0.74. How does this fit to ratios dark to visible matter in the range of 100, for which we have evidence on the galactic scale? Where has all the DM gone since the discovery of DE?

The use of numerical models, though useful for certain problems, is questionable whenever free parameters are introduced. Regarding the simulations of structure formation, ‘Don’t-the-pictures-look-alike?’ -results do not tell whether the underlying equations are correct.

Repeatability and source code.

‘What is the chance that a person who notices an important discrepancy in a scientific announcement has the opportunity to check it out at the level of the primary data?’ - Halton Arp

Repeatability of results is a basic element of science. An increasing number of results require extensive data reduction and numerical calculations. It is obviously unsatisfactory if just one group in the world can obtain a particular result (think about to who it concerns), and oligarchy is only a partly solution. A satisfactory solution would be if important results can be verified by an unlimited number of scientists who have access to a concise source code written in a widespread language or a computer algebra system. As far as possible, access to the raw data should be possible. An important step in this direction is the worldwide availability of satellite data, the SDSS, or NASA’s ephemeris site HORIZONS, though the latter has a kind of monopole.

19Original title of the CMB discovery.
**Unexpected is better than sought.** Regarding our recent paradigm that includes ‘dark energy’, it should not be forgotten that without that interpretation, $H_0$ measurements were in conflict with the age of the universe. The revolutions in physics however did not start with looked-for results but with completely unexpected ones: Michelson-Morley, Perihelion advance, spectral lines of atoms, blackbody spectrum, cosmic microwave background.\(^{20}\) The Pioneer anomaly could fit into this line.

**Generic and special** are terms of mathematical logic. To say that two planes in threedimensional space do intersect and form a straight line, is generically correct though there is the special case of parallelism.\(^{21}\) In astrophysics and cosmology, a lot of observations seem to describe special cases (flatness, coincidence, the ‘empty universe’ at SNIa data etc.) while the theory allows the general case. From a scientific point of view, this is highly unsatisfactory, and ‘explaining’ an apparent parallelism of planes with a mechanism that decreases the intersecting angle, as inflation does, is painting over rust.

**Heisenberg, not Dirac.** In Heisenberg’s autobiography [233] he reports on a discussion with Dirac on the best method to attack physical problems. Using the metaphor how to climb a steep mountain, Dirac’s opinion was to proceed step-by-step, since looking at the whole task would be discouraging. Heisenberg instead favored planning the route strategically, since otherwise the risk of getting into a dead end after following a promising track was too high. To decide which way to take is not a scientific question, but to get lost in details seems to be an obvious danger for modern theories, too. If Newtonian gravity turns out to be wrong, it will be not an easy task to replace it. Such attempts should not try to describe isolated phenomena but should at least have the potential to encompass a wide range of anomalies. Given that it took Einstein about eight years to develop general relativity [234], and a substantial modification of it is not supposed to be easier, the number of alternatives published every month is remarkable. People work fast today.

**Publish or perish.**

*‘Do you know that the journal ... is going to be published with superluminal velocity?’ - ‘well, it does not contain information.’*

There is a tendency for publishing sensational discoveries, but a lack of sustained systematic and methodic research projects.

*‘... in the scientific magazines you can find lots of articles on brilliant discoveries of galaxies, black holes or similar, but you’ll never find anything on those unsung heros who for five years were trying to improve our knowledge of opacity in a dissertation without which we would never understand the internal processes in stars.’*

(James Kaler, retranslation [235]).

Many scientists mention the difficulty to publish non-mainstream results (e.g. [188, 218, 236]). It seems that there is more danger in suppressing new unconventional ideas than in distracting scientists by exposing them to speculative and potentially wrong papers. Reasons in the organization of science cannot be discussed here, but some unsparing comments are given in [204].

**Einstein and de Haas** measured the effect named after them in 1915, expecting a result of 1 for the gyromagnetic relation. Experimentally they obtained 1.02 and 1.45, and discarded the latter value because they thought it contained a systematic error [234]. The published 1.02 was in ‘excellent agreement’ with theory until the correct theory predicted 2 which was measured by others who repeated the experiment.

\(^{20}\) Though this was predicted earlier.

\(^{21}\) Generically correct can be defined as correct besides on a null set.
This little story tells us not to underestimate psychology, in particular because (1) compared to current astrophysical observations, the Einstein-de Haas experiment was a quite simple one (2) Einstein was an open-minded, true researcher (3) he did not need to become famous any more.

5 Outlook

‘The frog at the bottom of a well measures the extension of the sky with respect to the border of the well.’ (Chinese proverb)

The theory of gravitation began with Galileo’s $F = mg$, describing effects on earth precisely. Newton’s generalization of this formula and the description of the solar system celestial mechanics was an ingenious big leap for science which at that time required an amount of mathematical abstraction and new physical concepts we hardly can imagine today. This holds even more for the refinement revealed by the general theory of relativity. Since those theoretical developments our knowledge of the universe has increased drastically, in a relatively short span of time: the discovery of galaxies, the Hubble redshift, the cosmic microwave background. Due to satellite technique, improved telescopes and the computer-induced revolution in image processing we are collecting data of fantastic quality which allow to do quantitative cosmology for the first time.

I fear however that the hierarchy of structures earth - solar system - galaxy - cosmos does not stop at laws found for the solar system but requires a corresponding hierarchy of theories which may be similarly hard to imagine like Newton’s theory in 1600. Introducing new parameters, data fitting and numerical simulations will not do the job; rather this seems to be a modern version of the deferents, excentrics and equants of the epicycles of Ptolemy. It is not only the complication of our current theories that merits a warning from history, but also the amount of extrapolation we perform. Though the range of the universe we know about has increased dramatically, we extrapolate conventional theories of gravity to those scales. The extrapolation of classical mechanics over 10 orders of magnitude to the atomic level was a quite childish attempt, driven by the haughty attitude of the end of the 19th century that the basic laws of physics were found and only ‘corrections on the 6th decimal place’ (Michelson) were needed. Actually, this was the age of the first ‘standard model’ of physics. There were just two clouds on the horizon of 19th century physics: the outcome of the Michelson experiment and the blackbody radiation. Two thunderstorms came up, relativity and quantum mechanics. The amount of research in cosmology which is done nowadays on the base of an untested extrapolation over 14 orders of magnitude is a quite remarkable phenomenon. It could be a good idea to pay attention to the clouds. The wonderful observational data of the present should not lead us to neglect the theoretical efforts of scientists in the past. Sometimes one can learn more from the ‘blunders’ of deep thinkers like Einstein, Lord Kelvin, Mach or Sciama than from the latest theories in fashion.

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