**Wolfgang Priester: from the big bounce to the Λ-dominated universe**

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**In memoriam Wolfgang Priester, 22 April 1924 – 9 July 2005**

**Abstract** Wolfgang Priester was one of Germany’s most versatile and quixotic astrophysicists, re-inventing himself successively as a radio astronomer, space physicist and cosmologist, and making a lasting impact on each field. We focus in this personal account on his contributions to cosmology, where he will be most remembered for his association with quasars, his promotion of the idea of a nonsingular “big bounce” at the beginning of the current expansionary phase, and his recognition of the importance of dark energy (Einstein’s cosmological constant Λ) well before this became the standard paradigm in cosmology.

**Key words** cosmology: big bang – dark energy – cosmological parameters – quasars: absorption lines

1 Early Career(s)

Born in Detmold in 1924, Wolfgang Priester began his university studies in astronomy, mathematics and physics at Göttingen in 1946. One of his teachers was Theodor Kaluza, the father of modern higher-dimensional unified field theory, whom Wolf remembered as “not very demanding.” He obtained his doctorate in 1953 with a thesis on photometry with the sodium D line [1-3]. His subsequent scientific career can be divided into four distinct phases. The first of these, devoted to radio astronomy and astrophysics, began immediately with two years under Albrecht Unsöld in Kiel [4-8] and continued in Bonn, where Wolf helped in the construction of the 25 m Stockert radio telescope and completed a major survey of the radio sky at 200 MHz with Franz Dröge in 1956 [9]. This period saw the publication of his first article in *Naturwissenschaften* (on radio emission from comets [10]), as well as an influential 1958 study of the statistics of extragalactic radio sources (based on his Habilitation thesis under Friedrich Becker and cosmologist Otto Heckmann [11]) which played a role in the then-raging conflict between big-bang and steady-state theories [10]. There were other papers during this period [12-14], but Wolf’s greatest legacy as a radio astronomer was probably a practical one: as founding director of the Institute for Astrophysics and Space Research at the University of Bonn (1964-89), he initiated (together with Friedrich Becker and Otto Hachenberg) the construction of the world’s largest fully steerable radio telescope at Effelsberg. The performance of this 100 m instrument, which was inaugurated in 1971, remained unsurpassed for thirty years.

Wolfgang Priester’s second scientific career, that as a space physicist, began when he used radio transmissions from the newly launched Sputnik satellite to compute its orbit in 1958 [15,16], a feat which resulted in his invitation to join NASA’s Goddard Institute for Space Studies in New York City between 1961 and 1964. He was among the first to use such signals to derive physical models of the Earth’s atmosphere, particularly as it is affected by solar activity. This work that led to a second article in *Naturwissenschaften* [17] as well as many other papers [18-37], including four in *Nature*. Of these publications, and Wolf’s guiding roles in bodies such as COSPAR (the Committee for Space Research) during these years, probably no contribution has proved more influential than a detailed model of the upper atmosphere that he developed together with Isadore Harris during his years in the U.S.A. [38-47]. The Harris-Priester model remains in use by NASA and is still taught in graduate schools after more than forty years.

The third subject that exerted a lifelong fascination on Wolfgang Priester can also be traced back to his time in the U.S.A. Wolf was present at the epochal First Texas Symposium on Relativistic Astrophysics in Dallas in December of 1963, where the problem of the immense energy output of the objects then known as “quasi-stellar
radio sources” was first confronted in earnest. This was the meeting at which Thomas Gold famously speculated “that the relativists with their sophisticated work were not only magnificent cultural ornaments but might actually be useful to science” [111].

Less well known is how these enigmatic objects eventually became known as “quasars.” The full story has been told by Nigel Calder, who notes ironically that it took native German and Chinese speakers to come up with a decent acronym during meetings at the Goddard Institute in New York City [112]. Wolf Priester’s initial suggestion of “quastar” was rejected by his colleague Hong-Yee Chiu on the grounds that it sounded too much like the name of the telescope maker “Questar.” Chiu shortened Wolf’s proposal to “quasar” [113], the new term was picked up by the New York Times beginning in April 1964 (and reluctantly accepted by the Astrophysical Journal in 1970 [114]), and that is how the most luminous objects in the Universe got their name. Quasars remained a source of never-ending wonder for Wolf, who co-authored a major review of their properties with Johan Rosenberg in 1965 [48], later expanded in 1968 [49]. He returned to the subject in publications throughout his tenure as director of the Institute of Astrophysics and Space Research in Bonn [50-59], and hosted guests such as Thomas Gold, Bob Jastrow and Maurice Shapiro over the years. It is likely that these relativistic engines at the edge of the universe also drew him back to his first and last love: cosmology.

2 Cosmology and the vacuum

Wolfgang Priester’s fourth career, that as a cosmologist, occupied most of his last two decades and accounted for almost half of his more than 100 publications. The beginning of his relationship with this field can however already be seen in his second paper on radio sources and the value of Hubble’s constant in 1954 [4], and in his 1958 treatment of the statistics of extragalactic radio sources in relativistic cosmology [11]. His return to the field dates from a 1982 survey [60] and two 1983 publications titled “From the big bang to black holes” [61] and “Where is the antimatter?” [62]. These were followed by a 1984 address on cosmic evolution [63] and a series of review articles with Hans-Joachim Blome in Naturwissenschaften covering almost all aspects of what is now called physical cosmology [64-66]. When these articles appeared, this field was still in its infancy; the definitive text (by James Peebles) had only been circulating for a few years and the particle-cosmology revolution heralded by such authors as Rocky Kolb and Michael Turner was five years away. For many, the word “cosmology” still conjured up something close to metaphysics. Wolf Priester was in the vanguard as it grew into a fully fledged empirical science.

At the heart of these articles and later ones with Blome and Josef Hoell was Wolf’s insistence on confronting the physical reality of vacuum energy (represented in Einstein’s theory of general relativity by the symbol \( \Lambda \), and now more popularly known as “dark energy”). This insistence made him something of a prophet in the wilderness. Most cosmologists at the time preferred to ignore the \( \Lambda \)-term on the grounds that no value satisfying observational bounds could be understood theoretically, while no reasonable theoretical expectations for this quantity made sense observationally (i.e., the cosmological constant problem, which persists today). Wolf was fond of emphasizing that Einstein himself had recognized the importance of this issue, referring to vacuum energy in 1920 as the “new ether of general relativity” [66]. His characteristically playful 1984 sketch captured the perplexity of the astronomer in the face of this “new ether” (Fig. 1).

3 The big bounce

From the physical reality of dark energy, together with the fact that upper limits on its energy density are many orders of magnitude smaller than one expects based on quantum field theory, Blome and Priester were led in
1984 to the possibility of vacuum decay and its corollary, a time-dependent cosmological “constant” based, for example, on the vacuum expectation value of a scalar field [60, 67]. Largely taboo at the time, these subjects have since grown into an industry under the name of “quintessence” [145] although the underlying idea is now often attributed to Christoph Wetterich and others in 1988 [118, 119]. We would argue that it goes back at least to work carried out by Ernst Streeruwitz in 1975 [120] and cited in Refs. [66, 67].

After several more projects [68-71], including an elegant de-mystification of cosmological recession velocities in Naturwissenschaften [72], Wolfgang Priester returned to the Λ term in 1987. This time he set his sights on the vacuum’s potential for addressing the problem of the initial singularity — an issue which was never far from his mind, and in which we can probably discern the early influence of Otto Heckmann. Wolf and his colleagues were among the first to take seriously the possibility that a phase transition might separate the early universe from a primordial de Sitter-like era, so that the contents of the present universe might literally have sprung from the pure vacuum energy of that earlier epoch. A de Sitter phase further opened up the possibility that the expanding universe began in a nonsingular “big bounce” rather than a big bang singularity [73-75]. Wolf raised an early question as to whether vacuum energy or relativistic particles would dominate in a pre-inflationary universe, a debate that continues today.

It proved possible to be quite specific about the properties that such a bounce must have, if it is to satisfy natural initial conditions and also join smoothly to standard radiation-dominated cosmology at later times. Fig. [2] illustrates the range of allowed models for pre-inflationary scenarios dominated by vacuum energy. The energy density ρ_v of the primordial quantum vacuum lies in the range 10^{-18}ρ_{Pl} ≤ ρ_v ≤ ρ_{Pl}, where ρ_{Pl} is the Planck density, and the curvature radius R_{min} at the bounce can be shown to satisfy

\[ \ell_{Pl} \leq R_{min} = \sqrt{3c^2 / (8\pi G \rho_v)} \leq 2 \times 10^8 \ell_{Pl}, \]

where \( \ell_{Pl} \) is the Planck length.

Qualitatively, of course, bounce models have a venerable history and were endorsed on largely philosophical grounds by such thinkers as Willem de Sitter, Carl Friedrich von Weizsäcker, George McVittie and George Gamow (who however stressed that “from the physical point of view we must forget entirely about the pre-collapse period”) [122]. The advent of inflation in the 1980s gave them a new impetus [123], and they remain in vogue today among inflationary model-builders [124].

Caldwell et al were not the first contemporary scientists to revive this venerable term, as is often supposed: it was formally introduced into geology and cosmochemistry during NASA’s Apollo program [110, 112]. We thank an anonymous referee for pointing this out.

string theorists [125] and quantum cosmologists [126]. With all this attention, it is worth recording that the term “big bounce” appears to have been introduced to cosmology by Wolfgang Priester in 1987.2

4 The Λ-dominated universe

By 1988, Wolf had concluded that “the a priori restriction to models with Λ = 0 is not justified” in physical cosmology [76, 77], a view he urged on readers with another of his wonderful drawings (Fig. [3]). The basis for this conclusion was both observational and theoretical. A universe with Λ = 0 could not have lasted as long as the oldest stars unless it were now expanding very slowly, in contradiction with most observational data. This “age problem” became particularly acute in the newly popular inflationary paradigm, which implied the existence of large amounts of gravitating dark matter, thereby decelerating the Universe even more quickly. If, instead of weighing down the Universe with more matter, one filled it with self-repelling dark energy, deceleration would be counteracted and the problem solved. Thus, after intervening work on baryon asymmetry and other topics, [78, 79, 80, 81, 82, 83, 84], Wolf wrote with Josef Hoell in 1991 that “if the Hubble constant is greater than 50 km s^{-1} Mpc^{-1} ... the cosmological constant must be greater than zero ... The apparently missing fraction of 90% or more

2 It was re-introduced the following year in Iosif Rozental’s Big Bang, Big Bounce, a revised translation of a Russian book (by a different title). The phrase apparently first appeared as the title of a 1969 novel by Elmore Leonard.
of cosmic matter is entirely compensated for by the cosmological constant" \cite{28}. He was among the very first to draw this conclusion \cite{27}, and did so four years before some of the more celebrated names that have become attached to it since \cite{28,29}.

Wolf also recognized a more aesthetic motivation for a nonzero \( \Lambda \) term, based primarily on its role as a fundamental length scale in a (closed) universe via the de Sitter radius \( R_\Lambda = 1/\sqrt{\Lambda} \) \cite{28}. Those who had the pleasure of discussing cosmology with him for any length of time were likely to become familiar with the late-time limit of the Friedmann-Lemaitre equation:

\[
\Lambda c^2 = 3H_\infty^2 .
\]

The deceptive simplicity of this relationship between a dynamical quantity (the expansion rate \( H \)) and an apparently fundamental constant of nature (\( \Lambda \)) was a source of endless fascination to Wolf, so much so that he joked that he would like to have it engraved on his tombstone. In this he would have found a fellow believer in Arthur Eddington, who wrote that there must be a tombstone. In this he would have found a fellow believer

5 The Bonn-Potsdam model

For Wolfgang Priester, final confirmation of the existence of dark energy appeared courtesy of his old friends, the quasars. Spectra taken in the direction of these distant objects show characteristic absorption lines making up what is known as the Lyman-\( \alpha \) (\( \text{Ly} \alpha \)) forest. These lines arise when the light from the quasars passes through intervening concentrations of gas which are thought to be distributed around emptier regions known as voids (Fig. 4). With Josef Hoell, he realized in 1991 that these lines could be used as tracers of cosmic expansion, if intrinsic evolution in the absorber population could be neglected in comparison with the Hubble expansion rate \( \Omega_0 \). Together with Dierck-Ekkehard Liebscher, Priester and Hoell applied this method to a set of high-resolution spectra from 21 quasars between 1992 and 1994 and found that the spacings of the absorption lines varied with redshift in a way that, if attributed entirely to cosmic expansion, implied a spatially closed, \( \Lambda \)-dominated world model whose expansion was accelerating, not decelerating as was almost universally believed at the time. Their best-fit model, which came to be known as the “Bonn-Potsdam” or BN-P model, was characterized by a dark-energy density of \( \Omega_{\Lambda,0} \approx 1.08 \) and a total matter density of \( \Omega_{M,0} \approx 0.014 \), as measured in units of the critical density \( \Omega_0 \).

The BN-P model attracted little attention, its large value of \( \Omega_{\Lambda,0} \) in particular “falling outside the range of theories considered polite in the mid-1990s,” as Wolf later commented \cite{31}. He was fond of recounting a story from the 1994 Erice school on high-energy astrophysics, where one well-known cosmologist told him, “Your \( \Lambda \) is outrageous! It does not exist — it is zero!” Four years later, the cosmological tide turned with the announcement by two teams of supernova observers in the U.S.A. that \( \Omega_{\Lambda,0} \) was in fact greater than zero, and probably greater than \( \Omega_{M,0} \), implying that we live in an accelerating universe — developments that were hailed by \textit{Science} magazine as the Breakthrough of the Year in 1998 \cite{32}. The same cosmologist wrote to Wolf on his birthday that year: “Well, there are still new things to learn.” “Saulus became Paulus,” Wolf always concluded with satisfaction in his talks.

His early measurement of \( \Omega_{\Lambda,0} \) using quasar absorption lines is recognized as follows in the \textit{Oxford Guide to Modern Science}: “Historians of science may note that Wolfgang Priester of Bonn and Dierck-Ekkehard Liebscher of Potsdam reported the cosmic acceleration in 1994. That was more than three years before other astronomers, with great fanfare, announced the acceleration seen by observing exploding stars” \cite{31}. From a historical perspective, however, it is probably too soon to assess the extent to which anyone can truly be said to have anticipated the detection of dark energy by the supernova teams in 1998. There are similarities here to the detection of cosmic microwave background (CMB) in
In 1965, perhaps the only event of comparable significance in cosmology since the discovery of cosmic expansion itself, whose “pre-discovery” by numerous people is still a subject of historical controversy after forty years [132].

In the case of dark energy, astronomers had been led to closed, BN-P-like models with high ratios of $\Omega_{\Lambda,0}$ to $\Omega_{M,0}$ on at least three previous occasions. These models were never conclusively ruled out; rather, interest in them simply faded when the observational phenomena which seemed to call for them became less compelling.

The common feature that unites models of this kind is the existence of a quasi-static “loitering period” that occurs as a result of the struggle between the self-gravity of ordinary matter and the gravitational self-repulsion of vacuum energy. (Acceleration is inevitable in such models because the energy density of ordinary matter drops with expansion, whereas that of vacuum energy remains constant and eventually dominates.) Georges Lemaître first invoked such a loitering phase in the 1930s in response to an early variant of the age problem: measurements of Hubble’s constant at that time wrongly suggested that the age of the universe would otherwise be less than the age of the Earth [133]. (He also pointed out that the quasi-static phase would be ideal for the growth of large-scale structure, an observation that remains valid today.) Loitering models reappeared in the late 1960s as a way to explain the puzzling concentration of quasar redshifts near $z \sim 2$ [135-137]. Most cosmologists have since preferred to attribute this phenomenon to evolutionary and/or astrophysical factors, though a definitive explanation is still lacking. Again, it was pointed out in the early 1990s that the rapid growth of structure during a loitering phase could reconcile data on galaxy clustering with the lack of anisotropy then seen in the CMB [138,139]. Interest in this proposal waned when the hoped-for anisotropies were finally detected by COBE. Irrespective of whether it is eventually seen as something more, the BN-P model certainly holds a place in this respectable tradition.

The main objection that was raised against loitering models during their later historical revivals goes back to Robert Dicke in the 1960s and has been argued most forcefully by Peebles [130]. The Dicke “coincidence argument,” as it is known, is essentially the observation that any quasi-static phase long enough to be interesting (relative to the Hubble timescale) requires a degree of fine-tuning in the cosmological parameters $\Omega_{\Lambda,0}$ and $\Omega_{M,0}$. As we have seen, however, by 1998 such arguments were no longer persuasive enough to overcome the overpowering observational case for a large $\Lambda$ term. Indeed, cosmologists have now been obliged to accept values for $\Omega_{\Lambda,0}$ and $\Omega_{M,0}$ that are widely regarded as “preposterous” by virtue of their nearness to each other [141]. This “coincidence problem” itself pales into insignificance beside the grand-daddy of all conundrums, the cosmological-constant problem, which implies that all contributions to the vacuum-energy density cancel each other out to a precision of some 120 decimal places — while agreeing with observation at the 121st and 122nd. Until such an absurdity is better understood, questions of fine-tuning to order of magnitude are, to a certain extent, like worries about whether or not one is whistling off-key in the middle of a hurricane.

For the time being, cosmological models are best judged on their empirical merits alone. The measurements of Wolfgang Priester and his colleagues in 1992 using quasar spectra yielded significantly larger values of $\Omega_{\Lambda,0}$ (and smaller values of $\Omega_{M,0}$) than those reported six years later using supernovae. The BN-P universe is not only dominated by dark energy; it contains almost nothing else, putting it perilously close to upper limits on $\Omega_{\Lambda,0}$ based on other phenomena such as the statistical frequency and maximum observed redshift of gravitational lenses. Its low matter density leaves little or no room for cold dark matter, which (although it has not been detected directly) is thought by many to have been necessary as a sort of “cosmological midwife” during the birth of large-scale structure at early times. Also, its lengthy loitering phase implies a universe considerably older than anything yet seen in it, unless the Hubble parameter lies at the upper end of experimental limits — a “reverse age problem” which, while not necessarily fatal, does raise the question of why we should find ourselves in an unusually young corner of the cosmos. On the other hand, the model’s long gestation period eases problems with conventional structure formation theory, and some support for the high ratio of $\Omega_{\Lambda,0}$ to $\Omega_{M,0}$ appears in the unexpectedly low amplitude of the second peak in the CMB power spectrum.

The study of these issues occupied most of the last ten years of Wolf’s career, including two more review articles in Naturwissenschaften, a chapter in the authoritative Bergmann-Schaefer Lehrbuch der Experimentalphysik and many more publications [94-109]. We will not
go over this material in detail here; recent reviews may be found in [107] and [102]. Instead, we will approach the phenomenon of quasar absorption lines in a different way and focus on what is probably the “Achilles heel” of the BN-P approach: its assumption that intrinsic evolution in the absorber population can be neglected relative to the Hubble expansion rate. A similar assumption underlies measurements based on supernovae, of course, but in that case there is a wider consensus that systematic evolutionary effects are unlikely to be important. In the case of Lyα absorbers, no such consensus has emerged, and we will argue that a generalization of the BN-P method that allowed for intrinsic evolution might have yielded a more widely accepted detection of dark energy and cosmic acceleration.

6 Evolution and the Lyman-α forest

A general expression for absorption-line number density follows directly from the space density of absorbers, which may be expressed in a standard isotropic and homogeneous universe as

\[ n(z) \propto (1 + z)^{3 + \eta} . \] (3)

Here \( \eta \) parametrizes intrinsic evolution in the absorber population. If \( \eta = 0 \), then comoving number density is constant and density goes as \( (1 + z)^3 \), as appropriate for a pressureless fluid of conserved particles. The line-number density per redshift increment is the derivative of Eq. (3) with regard to \( z \):

\[ \frac{dn}{dz} \propto n(z) \frac{R}{\sqrt{1 - k r^2}} \frac{dr}{dz} \propto n(z) \frac{dt}{dz} . \] (4)

Since \( dt/dz = -[(1 + z)H(z)]^{-1} \) where Hubble’s parameter \( H(z) = H_0[\Omega_{M,0}(1 + z)^3 + \Omega_{\Lambda,0} - (\Omega_{T,0} - 1)(1 + z)^2]^{1/2} \) and \( H_0 \) is Hubble’s constant, Eq. (4) can be expressed in terms of the total matter density \( \Omega_{M,0} \) and the dark-energy density \( \Omega_{\Lambda,0} \) as

\[ \frac{dn}{dz} = \frac{\zeta(1 + z)^{2 + \eta}}{\sqrt{\Omega_{M,0}(1 + z)^3 + \Omega_{\Lambda,0} - (\Omega_{T,0} - 1)(1 + z)^2}} . \] (5)

Here \( \Omega_{T,0} = \Omega_{M,0} + \Omega_{\Lambda,0} \) and \( \zeta \) is a constant.

If the cosmological constant \( \Lambda \) is zero, as was once widely thought, then we can follow standard texts [143] and rewrite Eq. (5) in the form

\[ \frac{dn}{dz} \propto (1 + z)^{1 + \eta} \sqrt{1 + \Omega_{M,0} z} . \] (6)

Thus for example in the Einstein-de Sitter (EdS) model with \( \Omega_{\Lambda,0} = 0 \) and \( \Omega_{M,0} = 1 \):

\[ \frac{dn}{dz} \propto (1 + z)^{\eta + 1/2} \] (EdS). (7)

To compare this with observation, a recent analysis of eight high-resolution, high signal-to-noise quasar spectra using VLT/UVES leads to the following best-fit expression over \( 1.5 \leq z \leq 4 \) [145]:

\[ \frac{dn}{dz} = 6.1(1 + z)^{2.47 \pm 0.18} . \] (8)

Eqs. (7) and (8) together imply that in an EdS universe, the number density and/or absorption cross-section of Lyα absorbers must climb very steeply with redshift, \( \eta \approx 2.5 \). This is the basis for the traditional argument that intrinsic evolution is likely to frustrate any attempt to extract useful limits on \( \Omega_{M,0} \) and \( \Omega_{\Lambda,0} \) from observations of the Lyα forest [140].

In light of the fact that dark energy is now known to exist, however, this argument must be re-examined. Is strong intrinsic evolution still required to fit the data in a \( \Lambda \)-dominated universe?

The problem can be posed mathematically as follows: for any given model in the wider cosmological phase space defined by \( (\Omega_{M,0}, \Omega_{\Lambda,0}) \), what values of \( \eta \) best fit the theoretical prediction of Eq. (5) to the observational data in Eq. (8)? And in particular, is any part of this phase space compatible with \( \eta \approx 0 \)? We rewrite Eqs. (5) and (8) for convenience as

\[ f_{\text{th}}(x) = \frac{\zeta x^{2 + \eta}}{\sqrt{\Omega_{M,0} x^3 + \Omega_{\Lambda,0} - (\Omega_{M,0} + \Omega_{\Lambda,0} - 1) x^2}} . \] (9)

\[ f_{\text{obs}}(x) = \alpha x^\beta , \] (10)

where \( x \equiv (1 + z) \). We are interested in the slopes of \( f_{\text{th}}(x) \) and \( f_{\text{obs}}(x) \); hence the relevant dimensionless functions are:

\[ \tilde{f}_{\text{th}}(x) \equiv \frac{f_{\text{th}}'(x)}{f_{\text{th}}(x)} = \frac{2 + \eta}{x} - \frac{3\Omega_{M,0} x^2 - 2(\Omega_{T,0} - 1)x^2}{2(\Omega_{M,0} x^3 + \Omega_{\Lambda,0} - (\Omega_{T,0} - 1)x^2)} \] (11)

\[ \tilde{f}_{\text{obs}}(x) \equiv \frac{f_{\text{obs}}'(x)}{f_{\text{obs}}(x)} = \beta \] . (12)

We seek the value of \( \eta \) that minimizes the square of the difference between \( \tilde{f}_{\text{th}}(x) \) and \( \tilde{f}_{\text{obs}}(x) \), averaged over \( 2.5 \leq x \leq 5 \). In other words,

\[ \frac{d}{d\eta} \left\{ \int_{x_1}^{x_2} \left[ \tilde{f}_{\text{th}}(x) - \tilde{f}_{\text{obs}}(x) \right]^2 dx \right\} = 0 . \] (13)

The required best-fit value of \( \eta \) is given by

\[ \eta = \beta - 2 + \left( \frac{x_1 x_2}{x_2 - x_1} \right) \sqrt{\frac{\int_{x_1}^{x_2} \left[ 3\Omega_{M,0} x^2 - 2(\Omega_{T,0} - 1) \right] dx}{\frac{\Omega_{M,0} x^3 + \Omega_{\Lambda,0} - (\Omega_{T,0} - 1)x^2}}} . \] (14)

Eq. (14) is plotted in Fig. 5 in the form of “iso-evolution” contours \( \eta(\Omega_{M,0}, \Omega_{\Lambda,0}) = \text{const.} \) for \( x_1 = 2.5 \), \( x_2 = 5 \) and \( \beta = 2.47 \) as suggested by Eq. (8).

Fig. 5(a) confirms that strong evolution is required across most of the phase space defined by \( \Omega_{M,0} \) and \( \Omega_{\Lambda,0} \).
including the EdS model ($\eta \approx 2$), the $\Lambda$CDM model with $\Omega_{M,0} = 0.3$ and $\Omega_{\Lambda,0} = 0.7$ ($\eta \approx 1.9$) and the open cold dark matter or OCDM model with $\Omega_{M,0} = 0.3$ and $\Omega_{\Lambda,0} = 0$ ($\eta \approx 1.8$). Also shown for comparison is a $\Lambda$+baryonic dark matter or ABDM model with $\Omega_{M,0} = 0.03$ (a lower limit on the matter density, corresponding to current estimates for the baryonic matter density $\Omega_{\text{bary}}$) and $\Omega_{\Lambda,0} = 1$ (a typical upper limit from, e.g., gravitational lensing statistics). This model still requires moderate evolution with $\eta = 5/4$.

Fig. 5(b) is a close-up of the rectangle at the upper left-hand corner of Fig. 5(a). Of special interest is the shaded region bounded by thin solid lines. Within this region, Eq. 8 provides a best fit to Eq. 5 with no evolution at all; i.e. $\eta = 0 \pm 0.18$. The BN-P model lies almost precisely in the center of this “no-evolution” region, thus confirming the conclusion of Wolfgang Priester and his colleagues that closed and heavily vacuum-dominated models are singled out by the data on quasar absorption lines over this redshift range — provided that $\eta = 0$. The level of agreement is actually striking, because we have used newer experimental data and a different method of analysis. While unsophisticated, the approach followed here has the merit of showing very quickly and unambiguously that the BN-P results stand or fall on the validity of the underlying assumption that intrinsic evolution in the Ly$\alpha$ forest can be neglected. It also suggests that a modification of the BN-P approach to take evolution into account might lead to values of $\Omega_{M,0}$ and $\Omega_{\Lambda,0}$ in better agreement with those obtained six years later using Type Ia supernovae.

As a check on the above results, Fig. 6 compares the predictions of Eq. 5 to the data in Eq. 8 using best-fit values of $\zeta$ for each model over $1.5 \leq z \leq 4$. (The EdS, OCDM and ABDM curves have been omitted for clarity; they are close to $\Lambda$CDM.) Fig. 6 confirms that the data on $n(z)$ can be fit either by a $\Lambda$CDM model with strong evolution ($\eta \approx 2$), or by the BN-P model with no evolution at all ($\eta = 0$).

There are several possible reasons why the comoving number density of absorbers might evolve with redshift. Numerical simulations suggest — under the assumption of large quantities of cold dark matter — that the intergalactic medium (IGM) which is responsible for Ly$\alpha$ absorption lines passes through several distinct “topological” stages [15], as depicted schematically in Fig. 4. At the highest redshifts, this material is distributed in the form of two-dimensional bubble walls around overdense regions. Later on (at intermediate redshifts) the IGM condenses to form one-dimensional fil-

![Fig. 5](image)

**Fig. 5** (a) Top: best-fit values of the parameter $\eta$ governing the evolution of the Ly$\alpha$ forest according to Eq. 8 in the phase space defined by $\Omega_{M,0}$ and $\Omega_{\Lambda,0}$. World models above the solid curve marked “Einstein limit” are of the “big bounce” rather than “big bang” type; their scale size drops to a nonzero minimum and then begins to climb again in the past direction. (b) Bottom: enlargement of the rectangular region at the upper left corner of Fig. 5(a). Inside the shaded region, the observational data on $dn/dz$ are satisfied with no evolution in the Ly$\alpha$ forest; i.e., $\beta = 2.47 \pm 0.18$ and $\eta = 0$. The labelled points correspond to models discussed in the main text: EdS ($\Omega_{M,0} = 1, \Omega_{\Lambda,0} = 0$), OCDM (0.3,0), $\Lambda$CDM (0.3,0.7), ABDM (0.03,1) and BN-P (0.014,1.08).

![Fig. 6](image)

**Fig. 6** Least-squares fits of Eq. 5 to the data on Ly$\alpha$ line number density, Eq. 8, for the $\Lambda$CDM and BN-P models assuming either no evolution ($\eta = 0$) or strong evolution ($\eta = 2$) in the Ly$\alpha$ forest. The $\Lambda$CDM model requires strong evolution, while the BN-P model is consistent with none.
aments which roughly trace the boundaries of the overdense regions. And at the lowest redshifts, these filaments in turn collapse to zero-dimensional knots. In such a picture, the slope of the absorption-line number density should bend upward at intermediate and high redshifts since lines of sight to distant quasars will “miss” much of the absorbing material in knots at low redshifts, while intercepting most of it in bubble walls at high redshifts. But while this picture is qualitatively easy to grasp, the quantitative implications for $dn/dz$ are not well established. Kim et al. (2002) find evidence for one such sharp upturn at lower redshifts, $z \sim 1$.

Evolution of the Lyα forest will also be driven by changes in the mean ionization of the IGM. It has been suggested that neutral hydrogen column densities in the IGM should decrease with time relative to the ionizing flux from distant quasars, which remains roughly constant as the Universe expands [148]. This would also lead to an increase in Lyα absorption-line number density with redshift.

Whether these effects are enough to produce the steep evolution that is required in the context of models such as $\Lambda$CDM remains an open question. A generalization of the BN-P approach designed to take gravitational clustering and changes in ionization into account would be of interest as an independent probe of the cosmological parameters $\Omega_{M,0}$ and $\Omega_{\Lambda,0}$. If Wolfgang Priester was right, then part of what has been taken as evidence for rapid evolution may instead be pointing to a closed universe that is even more strongly vacuum-dominated than has usually been thought.

7 Wolf and his legacy

The breadth of Wolf’s interests is reflected by the range of contributions to a special issue of Naturwissenschaften that was dedicated to him on the occasion of his sixty-fifth birthday in 1989 by many of those he had gathered around him in Bonn: Wolfgang Kundt, Peter Blum, Max Römer, Gerd Prölls, Jörg Pfeiderer, Hans Volland, Hans-Joachim Blome, Hans-Jörg Fahr and Thomas Schmutzler [149]. Wolf remained extraordinarily active after his official retirement that year, delivering his last lectures at the Winter School on Cosmic Evolution in Bad Honnef in January 2005. He was indefatigable as a scientist and charming as a host. He was stubborn in defending his convictions, but always did so with a twinkle in his eye. Sooner or later, those who worked with him always heard the motto, “If you believe in something, stick your neck out!” Wolf was well aware of the evidence both for and against his positions, and kept eager track of the latest experimental data on, for example, Hubble’s constant, the value of which became the subject of a long-running wager with other members of his Institute. He carried with him the culture and erudition of a vanishing age, and delighted in embellishing his talks and articles with Latin, Greek and even Hebrew flourishes, as well as the clear and intricate diagrams that were so characteristic of the way he thought. Once, when urged by him to assume a value of $H_0$ that seemed unjustified by observation, one of us went to see him in his office and, without missing a beat, Wolf responded at once with the line that follows: “Das Wunder ist des Glaubens liebstes Kind!” (“The miraculous is faith’s dearest child!”)

As a cosmologist, Wolf would have wanted to be remembered for the three key tenets of his preferred world model: a closed universe ($k = +1$) dominated by vacuum energy without “exotic” cold dark matter ($\Omega_{\Lambda,0} \gtrsim 1$, $\Omega_{M,0} \sim \Omega_{\text{bar}}$) and with a high value for Hubble’s constant ($H_0 \gtrsim 80$ km s$^{-1}$ Mpc$^{-1}$). Of these, the jury is still out on the first, while the second and third appear increasingly at odds with cosmological consensus. However, Wolfgang Priester’s real legacy does not lie in the details of the model he espoused, but in the way he inspired those who were fortunate enough to know him. In bidding farewell to a teacher, colleague and dear friend, we can do no better than borrow from Albert Einstein, who wrote in 1918: “The supreme task of the physicist is to arrive at those universal elementary laws from which the cosmos can be built up by pure deduction. There is no logical path to these laws; only intuition, resting on sympathetic understanding, can lead to them ... The state of mind that enables a man to do work of this kind is akin to that of the religious worshipper or the lover; the daily effort comes from no deliberate intention or program, but straight from the heart.”

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