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Empirical scenarios of galaxy evolution

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Contents

Abstract. **Our present understanding of the evolution of the Universe is not fully comprehensive. While the conventional LCDM cosmological model provides an explanation for the large-scale structure and evolution of the Universe, problems are encountered at the level of individual galaxies. For this reason, attention is now focused on empirical scenarios of the formation and evolution of galaxies, which are based on precision observations of high-redshift galaxies. During the last 10–15 years, several such scenarios have been proposed and subjected to verification. For example, the discovery in 2007–2009 of the unexpectedly rapid growth of giant elliptical galaxies enabled rejecting a major merger as the primary mechanism by which such objects are formed. A so-called two-stage scenario is now common in which a compact stellar 'seed' is formed at an early stage, after which an elliptic galaxy rapidly 'swells' due to multiple dissipationless minor mergers. The discovery of a population of quasars at $z > 6$, whose central black holes have masses of the order of a billion solar masses or more, prompted the development of scenarios in which the black hole independently grows at an early stage, to be later 'coated' with galaxies. In the same vein, the recent massive acquisition of integral-field spectroscopic data using large telescopes has enabled 'pinning down' the critical moment in the evolution of spiral galaxy dynamics at $z = 1$, which was previously overlooked by cosmological models of the evolution of the Universe.**

Keywords: galaxy evolution, galaxy formation, structure of galaxies, star formation, chemical evolution

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1. Introduction

1.1 Approaches to the study of the evolution of galaxies

The study of the evolution of galaxies, which includes the study of changes over time in their main characteristics — mass, structure, stellar composition, gas content, and star formation rates in galaxies — in the last 20 years has finally become a predominantly observational task in astronomy. Commissioning a whole bunch of large telescopes, with mirror diameters of 8 m or more, made very distant galaxies available for direct observations. The further away a galaxy is from us, the longer light travels from this galaxy. Due to the finite speed of light, we are currently observing distant galaxies at their much earlier stages of development than objects close to us. If we have a cosmological model that describes the geometry of the Universe at various stages of its expansion, we can unambiguously relate the 'moment,' or age of the Universe after the Big Bang, to the value of the redshift of the object under observation. At redshift z, the estimated cosmological age of the Universe, which is the time elapsed since the Big Bang, is calculated in the general case by the formula

$$t(z) = \frac{1}{H_0} \int_z^{\infty} \frac{\mathrm{d}z}{(1+z)\,E(z)}\,,$$

where

$$E(z) = \sqrt{\Omega_\Lambda + (1-\Omega_0)(1+z)^2 + \Omega_m(1+z)^3 + \Omega_r(1+z)^4}\,.$$

In some special cases (which, as we now believe, are realized in our Universe), for example, in a geometrically flat universe, where $\Omega_\Lambda + \Omega_m = 1$, the integral is taken analytically:

$$t(z) = \frac{2}{3H_0\sqrt{\Omega_\Lambda}} \ln\left(\frac{\sqrt{\Omega_\Lambda(1+z)^{-3}} + \sqrt{\Omega_\Lambda(1+z)^{-3} + \Omega_m}}{\sqrt{\Omega_m}}\right).$$

If the redshift $z \gg 1$, then in all models

$$t(z) \approx \frac{2}{3H_0}\,\Omega_m^{-1/2}\,(1+z)^{-3/2}\,.$$

In the modern 'standard' cosmological model, $\Omega_\Lambda \approx 0.7$ and $\Omega_m \approx 0.3$, and, at a redshift value of 0.5, we observe galaxies in their state 5 billion years ago, those at the redshift value $z = 1$, 8 billion years ago, and those at the redshift value $z = 2$, 10 billion years ago. The distance record currently belongs to the galaxy GN-z11, for which a redshift value of almost 11 is spectroscopically confirmed [1, 2]. We caught this galaxy at a moment in its life when the Universe was only 0.4 billion years old. This implies that we observe 'at a glance' almost the entire history of the expansion of the Universe, from the age of 0.4 billion years to the present age of 13.7 billion years. For redshifts of 7–8, when the Universe was only 0.7 billion years old, there are already well-studied *samples* of galaxies, numbering dozens of objects. In principle, by establishing associations between well-studied galaxies at different stages of their development and observed at different redshifts, a real evolutionary sequence can be built and the ways certain properties of galaxies developed and changed can be traced. However, the impression that we are directly observing the evolution of galaxies in this way is, of course, an illusion. At different redshifts, different galaxies are observed, and not the same one; to link them into a single evolutionary chain, a model approach is required that offers physical mechanisms for the formation and transformation of the structure and contents of galaxies. Nevertheless, the wealth of observational material regarding the properties of galaxies at different redshifts significantly limits the freedom of theorists in choosing key factors and the main paths for models of the evolution of the contents of the Universe.

1.2 Theoretical models of the evolution of galaxies

The history of the development of galaxy formation *models* is almost as long as that of their observational research. The first models, classical ones which are now commonly referred to as 'monolithic collapse' models, were described and then used for calculations in the second half of the 1960s and the first half of the 1970s. In 1967, Partridge and Peebles, combining the expansion of the Universe filled with matter and the gravitational instability of this same matter according to Jeans, estimated that the protogalaxy — the future Milky Way — with a mass of 10^{11} solar masses and a radius of 20 kpc would separate from the Hubble expansion and begin to collapse under the effect of its own gravity at a redshift value of about 10–30 [3]. Next, it was necessary to simply calculate using a computer how exactly a large gas cloud with a mass commensurate with that of the future galaxy, under the effects of Newtonian gravity and Jeans instability, will collapse, fragment, and form stars. The calculations based on the most popular series of such models were made by the then very young Richard Larson [4–6]; in fact, it was the content of his PhD thesis. However, as early as the end of the 1970s, along with the explosive development of cosmology, it became clear that the evolution of individual galaxies should be 'embedded' into the evolution of the entire Universe. The classic work, in which the formation of galaxies as baryon structures already followed the evolution of the large-scale structure of the Universe controlled by the gravity of dark matter, was the study by Simon White and Martin Rees [7]. They asserted that the main successive stages in the formation of galaxies were the collapse of the dark halo (which is noteworthy, under the action of the same Newtonian gravity and Jeans instability), the virialization of gas inside this halo, and its further radiative cooling inside the halo and settling into the disk. The radius — the distance from the center of the halo in the plane of the disk — at which a specific portion of the cooled gas was located was determined by the angular momentum inherited from dark matter. Entire star formation already occurred in the disk: stars were formed from cold fragmenting gas. This simple scheme created a basis of all models of galaxy formation for the 30 years that passed after the classic work of Simon White and Martin Rees [7].

Models that were developed in the 1990–2000s can be classified as so-called 'physical and 'semi-analytical.' Models of both types are based on the numerical calculation of the gravitational clumping of dark matter and the collapse (separation from the general background of the expanding Universe) of self-gravitating dark halos. Due to the hierarchical nature of the gravitational clumping of dark matter, which was initially uniformly distributed throughout the volume of the expanding Universe, the mass distribution of dark halos shifts over time towards larger masses. The mass distribution of dark halos at all stages of evolution is tilted towards low-mass halos and, after several cycles of mergers, no longer depends on the initial spectrum of density fluctuations [8]. In the early stages of the evolution of the Universe, in the era of the birth of the first stars, the most massive dark halos do not exceed 10^6 solar masses [9], and by now the estimated upper limit of self-gravitating dark halos is 10^{15} solar masses and is identified with galaxy clusters [10]. Consequently, early models of galaxy formation based on cosmology assumed that dwarf galaxies were the first to be formed in the Universe (for example, the dwarf galaxies of the Local Group were even given the title 'bricks,' from which more massive galaxies like the Milky Way were gradually built). In fact, observations have already shown that the most massive elliptical galaxies have the oldest stellar population in the modern Universe. Over time, observers succeeded in convincing theoreticians that the so-called anti-hierarchy (downsizing) is typical in the real Universe, i.e., the main evolutionary events first result in the formation of the largest galaxies, and with time they also develop in dwarfs. To reconcile these two opposing trends — the hierarchical nature of the formation of dark halos and the anti-hierarchy among observed galaxies — it was necessary to explore in detail the physics of baryons inside dark halos. It is precisely the accepted baryon physics that is still very 'individual' in various families of physical and semi-analytical models of galaxy formation.

1.2.1 Physical cosmological models of the evolution of galaxies. Physical models include a numerical calculation of the complete physical picture for both the dark and baryon components of matter. A good overview of the results of physical models of galaxy formation in the complete cosmological LCDM-Universe is presented by Somerville and Davi [11]. An elaborate description of technical details and features of the specific approaches for modern cosmological numerical models can be found in the technical review by Vogelsberger et al. [12]. At present, there are several well-known sets of such complete physical models of the evolution of the Universe. Among the most popular are Illustris [13], EAGLE [14], Magneticum Pathfinder [15], Horizon-AGN [16], MassiveBlack-II [17], FIRE [18], MUFASA [19], BAHAMAS [20], and Simba [21]; there are also other models which are no less worthy. The gravitational basis for all models is approximately the same, but the gas dynamics required to trace the evolution of the baryon component differs significantly, and not only with regard to spatial resolution. Due to this circumstance, the results of models on small scales, which are of importance for the formation of individual galaxies, sometimes differ even visually. This is perfectly demonstrated by Fig. 2 in review [22], which presents face-on views of model disk galaxies calculated using the gas-dynamic codes GASOLINE, AREPO, GIZMO, GADGET, and RAMSES. The list of differences among the interpretations of gas dynamics contains points that critically affect the very nature of the formation of galaxies. Perhaps the most pronounced difference of this kind is evidenced by the discussion of the importance of cold gas streams flowing onto individual dark halos along cosmological filaments — details of the large-scale structure of the Universe. Do the focused cold gas flows reach the galaxies themselves [23] or are they otherwise dissolved in the hot virialized gas that fills the dark halos of galaxies [24]? The whole picture of the evolution, for example, of the angular momentum of the galactic disk essentially depends on the choice between these two options. Theorists still disagree on this issue.

1.2.2 Semi-analytical cosmological models of the evolution of galaxies. Semi-analytical galaxy formation models (SAMs) were developed in parallel with physical ones — in fact, the first detailed models were semi-analytical [25] — and they were especially attractive due to the significant savings in computer resources they provided. This economy was achieved due to the fact that computers were only used to calculate the evolution of dark matter and the associated dynamic and structural evolution of the galaxy, while all baryon physics was handled analytically, using the phenomenological parametric relationships known from observations between the main characteristics of galaxies, whether integral or local. For example, the rate of cooling of a hot (virialized) halo gas is related to its density, temperature, and metallicity in a known way; the rate of star formation is proportional to the density of the already *cold* disk gas to some small degree, the Kennicut–Schmidt law; the generation of new heavy elements is associated with the rate of star formation, and their ejection into the hot gas of the halo is associated with the energy of massive stars, the number of which is also proportional to the star formation rate. The luminosity of a galaxy is calculated by the method of evolutionary synthesis based on the history of star formation and the evolution of metallicity. Thus, the evolution of the main parameters of a galaxy, i.e., luminosity, stellar mass, star formation rates, the proportion of gas in the baryon mass, and chemical composition, is completely described by a small number of power relations and can be easily calculated.

The entire problem consists in the parametrization of these analytical relations and in the selection of the 'principal' relation. Some arbitrariness and creative freedom in choosing parametric relations between the main characteristics of stellar-gas systems were aggravated by the need to find a mechanism for 'suppressing' star formation in massive galaxies at a fairly early stage of their development; otherwise, anti-hierarchy and the observed correlation between the age of stellar systems and their mass cannot be reproduced. The rich choice of mechanisms for stopping star formation has prompted over the past decade many semi-analytical models of the formation and evolution of galaxies which focus on explaining individual specific observational manifestations and infrequently make an attempt to cover the entire available set of such manifestations. Examples of such models are the approach in [26], where cold gas accretion is suppressed for a halo with a mass below a certain threshold; the approach in [27], where the key agent for suppressing star formation at large redshifts is not the dark halo mass but the reduced metallicity of the gas; the approach in [28], where the entire evolution is driven by the ratio of the characteristic times of gas influx and its exhaustion for star formation; and many other various approaches. The last of the mentioned semi-analytical models, [28], can be classified as a subspecies of 'regulatory' models. These models, in which the entire evolution of the baryonic, including stellar, content of a galaxy is regulated by the balance between the influx of gas from outside and its escape as a result of the 'injection' of energy associated with star formation, have now become especially popular. According to review [29], the most popular of them is the Simon Lilly model [30]. We briefly describe below, as an example, the features of his approach.

The model of Simon Lilly et al. [30] is based on the direct relationship, assumed by the authors, between the accretion of dark matter onto the 'seed' of a galaxy and its star formation rate (SFR), which is obviously related to the amount of gas in the galaxy (and to the rate of its inflow from outside if the galaxy forms stars in a quasi-stationary regime). The authors themselves insistently call their model a 'very simple physical model,' and, indeed, assuming that some key 'regulators' are constant in time, this model can even be presented in an analytical form. The idea to link the accretion rate of dark matter (theoretical) and the accretion rate of an external gas, which determines the star formation rate (observable), was prompted by two facts. If calculated per unit mass, both quantities are extremely weakly dependent on the total mass of the galaxy (its halo), but steeply, with an

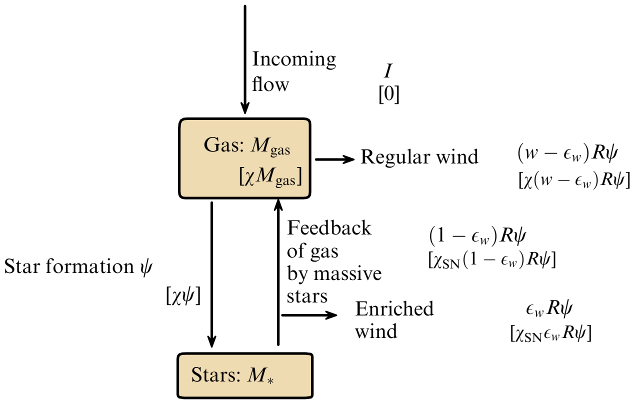

Figure 1. Layout of the 'gas regulator' of the evolution of main sequence galaxies. (Adapted from [33].)

exponent of 2–3, increase with increasing redshift:

$$\frac{dM_{\rm DM}/dt}{M_{\rm DM}} \propto (1+z)^{2.2} \quad [31]\,,$$

$$\frac{\rm SFR}{M_*} \propto (1+z)^{2.8} \quad [32]\,.$$

Although the powers of redshift in these two — the theoretical (the former) and the empirical (the latter) — relations are, strictly speaking, not equal, their certain similarity prompts an assumption to be made in the models that gas flows into the galaxy from the outside at the same rate, or at least proportional to that of dark matter; and the rate of dark matter inflow at each stage of the evolution of the Universe is known from numerical models. It is precisely the fluxes of gas flowing into and out of the galaxy that 'regulate' the evolution of the galaxy; in turn, the amount of gas inside the galaxy at each current moment regulates the star formation rate. A layout of these processes, shown in Fig. 1, however, is not taken from [30], but from study [33], which is devoted exclusively to the local chemical evolution of galaxy disks; however, this setup has already become a standard. The figure shows the mechanisms that regulate the content of cold gas in the galaxy: the influx of gas from outside, I, the consumption of gas already inside the galaxy for star formation, ψ or SFR, and the loss of gas after and as a result of star formation. Lilly et al. [30] consider these flows to be a single galactic wind, while, in more advanced models [33], the wind is divided into an enriched one, originating directly from star-forming regions and supernova remnants and carrying away freshly synthesized heavy elements, and a regular one, outflowing over the entire disk with a metallicity value equal to the average metallicity of the gas in the galaxy at the moment. An important feature of the model, which allows its analytical description, is the proportionality of the gas outflow to the star formation rate, based on the physical assumption that the energy that enables the gas to leave the galaxy is injected by young massive stars (stellar wind) and exploding supernovae (kinetic energy of shells and radiation pressure of flares). This coefficient of proportionality between the wind and star formation, if assumed to be constant in time, makes it possible to derive the balance equations for the mass of gas (and metals) in the galaxy and solve them analytically. The second parameter is the coefficient of proportionality between the SFR and the gas mass, a value inversely proportional to the gas exhaustion time. The wind parameter in model [30] is assumed to be constant in time, but fairly strongly dependent on the stellar mass of the galaxy. The time of exhaustion of gas for star formation, in turn, does not depend on the mass of the galaxy (more precisely, all the physical dependences involved there compensate each other), but depends on time, and in a global way, being proportional to $H(z)^{-1}$ [29]. Comparing the model's predictions with the scaling relations of the nearby Universe, at $z = 0$, makes it possible to determine all these parameters.

1.3 Empirical (astronomical) models of the evolution of galaxies

Regulatory models that skillfully explain the construction of so-called scaling relations (see Section 3 below) in the standard LCDM model and even sometimes describe their evolution over time regularly fail when new observational data become available. Therefore, in recent years, so-called empirical scenarios of the evolution of galaxies based on statistics of the observed physical properties of galaxies at various redshifts have appeared and quickly gained popularity. The difference between the empirical models and physical and semi-analytical models is that they are not initially linked to numerical cosmological models of the evolution of dark matter in the Universe: the key stages in the evolution of galaxies of various types are taken directly from observations. An overview of some of these scenarios and the observations on which they are based is the subject of this publication.

The two pillars on which successful models of the formation and evolution of galaxies rest are a change in the structure of galaxies with a redshift observed by astronomical methods and a change with a redshift of the so-called scaling relations that connect the main integral characteristics of galaxies: the mass of the stellar component, the rotation velocity, sizes, luminosities, the proportion of gas in the total baryon mass, star formation rates, and the chemical compositions of gas and stars that also evolve and whose evolution is measured in observations. The next two sections provide a brief overview of our current knowledge of these two issues.

2. Morphology and observed features of distant galaxies

One of the main difficulties that hinders the description of galaxies observed at different redshifts as a single evolutionary sequence is that they look completely different. The first deep Hubble fields, which, due to the record spatial resolution of images in the optical range, $\sim 0.1''$, already made it possible to discern the details of the structure of distant galaxies [34], demonstrated that, while up to a redshift of $z \sim 1$, the morphology of galaxies can be mostly described within the Hubble classification scheme [35] (Fig. 2), for $z > 1.5$ the dominant morphological type in the nearby Universe — spiral galaxies — disappears altogether, and irregularly shaped galaxies appear instead [36, 37]. Initially, these irregular galaxies at redshifts of the order of two, which look like chains or bunches of bright compact 'clumps' (Fig. 3), were interpreted as an observational manifestation of a hierarchical 'assemblage' of large galaxies from small ones through multiple mergers — this is exactly the mechanism predicted by the first versions of cosmological scenarios for the evolution of the Universe. In the cosmological models, the evolution of the Universe as a whole is the formation of a complex inhomogeneous large-scale structure under the effect

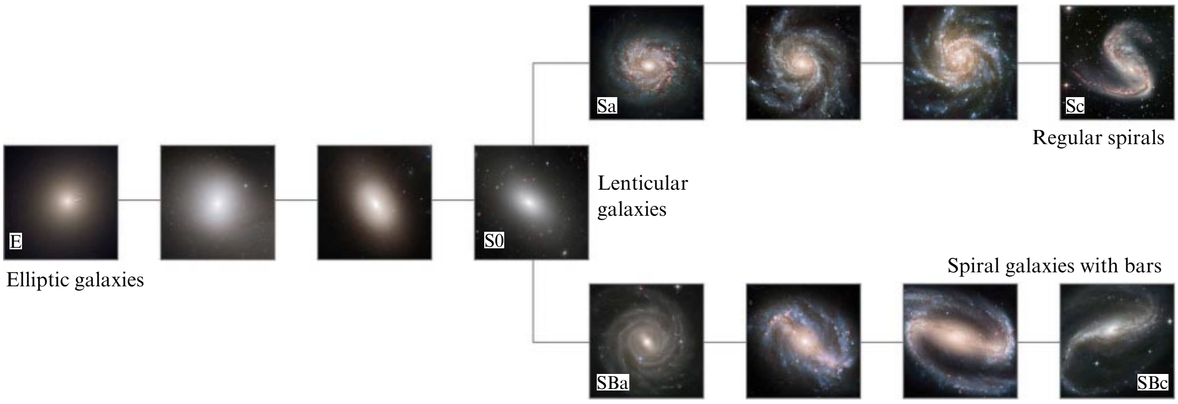

Figure 2. Standard Hubble system for the morphological classification of galaxies. (Picture designed by A V Kasparova.)

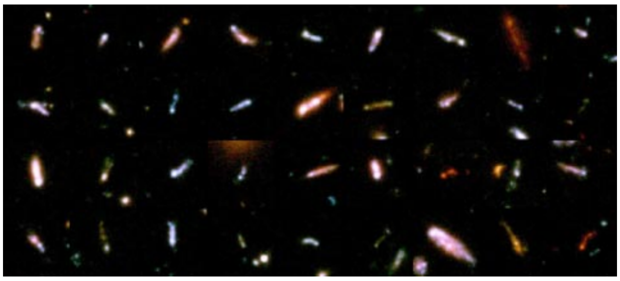

Figure 3. Irregular morphology of galaxies at large redshifts: examples of 'tadpoles' at redshifts greater than 1.5 from Hubble Space Telescope surveys. (Illustration courtesy of NASA Image Galleries, public collection.)

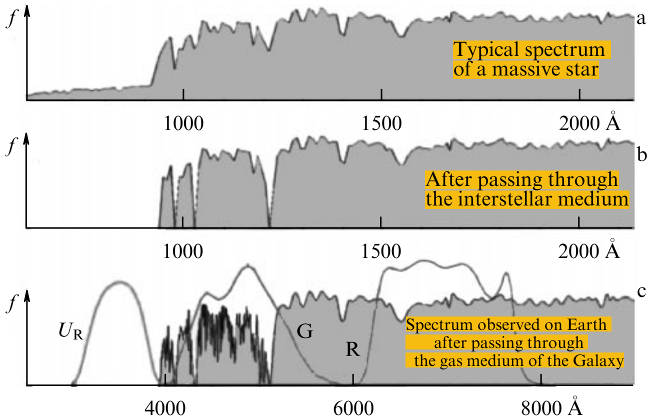

Figure 4. Physical scheme for the search for Ly-break galaxies: (a) spectrum of the young stellar population, (b) absorption of radiation in the Lyman continuum by the 'hydrogen coat' of the galaxy, (c) spectrum measured in ground-based observations in wide photometric bands.

of the gravitational clumping of dark matter (and baryons, being a small fraction of the total density, must follow the dark matter in its global clumping under the action of gravity). However, it gradually became clear that in fact these kiloparsec-long clumps of visible matter are not separate dwarf galaxies in the process of merging, but giant star-forming regions inside large dynamically united galactic disks [38]. However, these disks do not look similar to the thin stellar disks of today's spiral galaxies: first of all, they are much thicker [39], with a vertical scale of up to 1.0–1.5 kpc, and, in terms of structure, they rather resemble the thick old disk of the Milky Way. In such a thick disk, a spiral structure cannot develop, and a bar cannot appear: this disk is dynamically hot and therefore is stable with respect to global nonaxisymmetric perturbations. However, due to the high content of gas, which constitutes up to half of the entire baryonic component, such a disk is gravitationally unstable precisely in its gaseous collisional component: the gas clusters into large clumps, and very efficient star formation takes place in these clusters, due to which these structures feature high surface brightness [40, 41].

2.1 Ly-break galaxies

In compiling observational samples of galaxies at redshifts in the 1–3 range, both objects which are passive, with an old stellar population, and those with active star formation are selected in photometric surveys based on color, more often two-color, criteria [42–44] calculated by modeling the photometric evolution of the stellar population. This approach makes it possible to sample galaxies at large redshifts in almost the entire range of their properties. However, at redshifts greater than three, the selection criterion becomes more specific, which narrows the space of parameters inherent in the selected objects. The most popular and 'working' approach is the search for Ly-break galaxies. The concept of this approach is illustrated in Fig. 4. If the galaxy is at an early stage of formation and has recently begun to form stars, it should contain much of its original gas, hydrogen. If star formation began in the central region, and the gas, not yet involved in star formation, is concentrated in the outer regions of the galaxy, the light from the young, newly formed stellar population passes through the 'coat' of neutral hydrogen. In this case, in neutral hydrogen, the galaxy 'coat,' all radiation at wavelengths shorter than the Lyman limit, Ly-break, should be absorbed to zero, which in the laboratory system of wavelengths corresponds to 912 Å. If the 'coat' is inhomogeneous and contains clouds and diffuse gas, it absorbs even in the Lyα line, which corresponds to a laboratory wavelength of 1216 Å. If the gas envelope of the galaxy expands and there is a 'galactic wind,' the absorption in the Lyα line is shifted due to the Doppler effect to the blue side of the emission (and this phenomenon is indeed observed [45]). Immediately beyond Lyα, to the red side of the line, the spectrum should be observed as bright and blue, because the young stellar population corresponding to current star formation should be bright and blue. Charles Steidel calculated that, for galaxies with redshift $z \geqslant 3$, Ly-break should relocate to the violet region of the spectrum: $912 \times 4 \approx 3650$ Å, which corresponds to the Johnson broad-

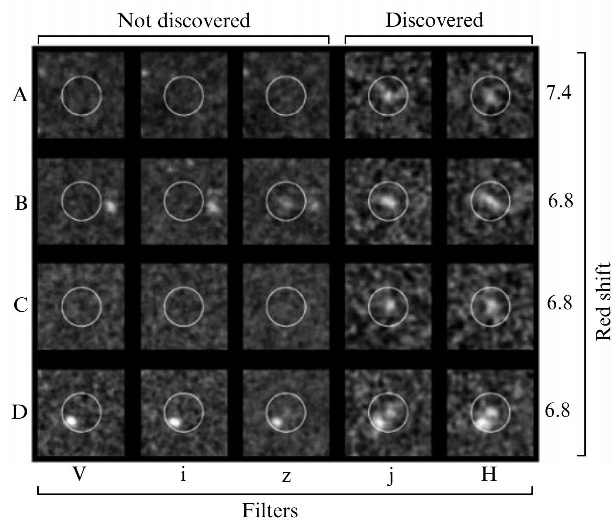

Figure 5. Examples of Ly-break galaxies at a redshift value of 7: they are not visible up to a wavelength of 1 μm and only emerge in the near infrared range. (Illustration courtesy of NASA Image Galleries, public collection.)

band filter U. Therefore, young galaxies at $z \geqslant 3$ should not be visible in the U filter, should be bright in the B filter, and should be increasingly faint in redder filters [46]. This method can be easily extended to the search for galaxies at larger redshifts. If a galaxy is not seen in the U and B filters, while in the V filter it immediately appears bright, this is a B-dropout, a candidate for a galaxy at redshift 4. If a galaxy is not seen in the U, B, or V filters, while in the R filter it immediately appears bright (V-dropout), this is a candidate for a galaxy at redshift 5. And so on: the further the Lyman continuum moves to the red region, the larger the redshifts it corresponds to (Fig. 5). If we search for distant Ly-break galaxies with a specific set of broadband filters with a focus on a specific redshift, vast areas of the sky can be explored and deep images obtained with large telescopes, and then the desired distant objects can be 'pinned down' on these images by simply blinking neighboring photometric bands. Now, at redshifts from 3 to 8, thousands, and at the largest z values, dozens of Ly-break galaxies are already known, which makes it possible to make conclusions about their typical properties and distributions in terms of parameters (luminosities, masses, star formation rates, stellar population ages).

Typical parameters of Ly-break galaxies lie in a rather narrow range: the mass of the stellar component is about 10^{10} solar masses; the star formation rate is several ten solar masses per year; and the amount of dust is fairly small, on average, $E(B-V) = 0.15$ [47]. The outer hydrogen shell of Ly-break galaxies is optically thick in lines; as a rule, it expands as a result of the influx of energy from the central burst of star formation, forming a galactic wind, and in this wind not only are quanta of the Lyman continuum absorbed, but absorption lines of hydrogen and heavy elements are also formed. Thus, an analysis of their spectra already shows the essentially nonzero metallicity of the gas that has not yet undergone the process of star formation in this particular galaxy. Even at redshifts of 7–10, less than a billion years after the Big Bang, these are still not the primordial galaxies that should form stars from gas with zero metallicity. The very first galaxies should form even earlier, at $z > 11$. A surprising property of Ly-break galaxies is the apparent absence of evolution: at $z = 3$, $z = 4$, $z = 5$, and at $z = 6$, their stellar mass is, on average, the same [48], although at star formation rates of several ten solar masses per year, for two billion years, between $z = 6$ and $z = 3$, they should have increased their masses by almost an order of magnitude. It may be concluded that Ly-break galaxies are a rather short star-forming phase in the life of early galaxies. Between these states, the galaxies should somehow look different, but what specifically should be the difference(s) is not yet clear from observations. Arguably, most galaxies at redshifts $z > 3$ have not yet been observed at all.

2.2 Lyα-emission galaxy (LAE)

The discovery of Ly-break galaxies by Charles Steidel was preceded by a long and dramatic history of searching for primordial galaxies using strong Lyα emission at large redshifts. The classical work of Partridge and Peebles [3] forecast, on the basis of a simple model of a monolithic collapse of a protogalactic cloud with a mass of 10^{11} solar masses, that the galaxy at the time of its first star formation burst would emit at least 2×10^{45} erg s^{-1} in the Lyα emission line. Such a bright object in a narrow line could be observed by ground-based telescopes in the early 1990s. However, all the efforts undertaken by scanning the sky in narrow bands, which focused on the Lyα emission line shifted due to a redshift of 3–5 units into the optical region of the spectrum, failed to give any results at that time. The decade of fruitless searches was summarized in an article by Thompson and Djorgovski [49]: scanning of the accompanying 110,000 Mpc^3 carried out at the 5-meter Palomar telescope with a scanning Fabry–Perot interferometer to a lower limit of 2×10^{43} erg s^{-1} (star formation threshold of 100 solar masses per year) failed to yield even a single candidate for distant galaxies in a redshift range of 2.78–4.89. It is only after the 10-meter Keck telescope joined the search that Lyα-emission galaxies (LAE) were detected [50, 51] at a redshift of about 4.5. As it turned out, they mainly had a luminosity on a line less than 6×10^{42} erg s^{-1} (the star formation rate is less than several solar masses per year) [52].

Now, the search for LAE is successfully carried out using the SUBARU wide-field camera, an 8-meter Japanese telescope; the samples of such galaxies are compiled up to redshift $z = 6$; at larger distances the opacity of the Universe, in which reionization has not yet occurred, interferes. A review of the results of these searches and statistics on the properties of LAE galaxies at large redshifts are reported in [53]. They are dwarf galaxies with a typical mass of the stellar component of $10^8 - 10^9$ solar masses and star formation rates of 1–10 solar masses per year. These galaxies, similar to Ly-break galaxies, are surrounded by a hydrogen coat that expands at a speed of about 100 km s^{-1}. However, the gas density in this shell is much lower than in Ly-break galaxies, $N(\mathrm{HI}) < 10^{20}$ cm^{-2}, which leads to different equivalent widths of the Lyα emission in these two types of galaxies (in Ly-break galaxies the emission is weak or absent). The gas metallicity in LAE, 0.1–0.3 times the solar metallicity, corresponds to their small mass: these galaxies cannot be considered primordial either; they form their stars from a gas already enriched with heavy elements.

2.3 Submillimeter galaxies

The most massive galaxies observed at redshifts from 2 to 5 are submillimeter galaxies [54, 55]. These galaxies look very different from Ly-break objects or LAEs. More precisely, in the optical range of the spectrum, they are almost invisible:

though their bolometric luminosity is high, they have emissions primarily in the submillimeter range. They are massive galaxies with a stellar component mass of about $10^{11}\ M_{\odot}$, with a star formation rate of hundreds of solar masses per year [56]. Such regions of extreme star formation at large redshifts, as in the nearby Universe, are always immersed in a dense dust cocoon; it is only the black-body spectrum of dust heated by young massive stars that comes out. In the nearby Universe, the maximum of the energy distribution in the spectrum of such galaxies is located at 100 μm; consequently, at $z > 3$, this maximum shifts to wavelengths of 400 μm or more. Submillimeter galaxies were discovered in the 1990s using the James Clerk Maxwell Telescope (JCMT) in Hawaii in the SCUBA project, a sky survey of Earth's atmosphere in two transparency windows, at 450 and 850 μm [57]. Extensive lists of objects bright at submillimeter wavelengths have been compiled. However, at first, it turned out to be difficult to prove that it is these galaxies that are located at large redshifts. To determine the redshift, it was necessary to obtain the spectrum of the galaxy, or better yet, to determine it along with emission lines. To obtain spectra with emission lines, it was necessary to identify these galaxies in the optical range; and with a spatial resolution of JCMT observations of 15 arc seconds, there were dozens of contenders in the box of coordinate errors if this area was viewed with the Hubble Space Telescope. Finally, the problem was solved: emission lines were searched for in the radio range, not in the optical range, at millimeter wavelengths, where molecular gas has emissions on the CO line. The resolution of millimeter-wave interferometers, which was by that time 2–4 arc seconds, made it possible to unambiguously identify submillimeter galaxies in other spectral ranges. Indeed, these turned out to be massive galaxies with a burst of star formation in the redshift interval of 2–4 [58].

The detection and study of submillimeter galaxies (SMGs) is now a routine procedure. In addition to the SCUBA-2 project at JCMT [59], the list of candidates for SMGs has been extended using radio telescopes in the Atacama Desert in Chile (LABOCA, ALESS project) [60] and a specialized submillimeter telescope in Antarctica, SPT (South Pole Telescope), where the atmosphere is very dry and transmits submillimeter radiation well [61]. The identification and detailed study of galaxies on these lists are carried out using the ALMA interferometer, a multi-wave instrument that can thus be used to make maps both in the continuum (hot dust) and in lines (atomic and molecular gas) with a resolution better than an arcsecond. This ground-based interferometer located in the Atacama Desert rivals the Hubble Space Telescope in spatial resolution! Consequently, in recent years, we have learned a great number of new and unexpected things about submillimeter galaxies. Initially, the general opinion was that such powerful bursts of star formation as in SMGs can only be the result of a major merging (merger of galaxies of similar masses), by analogy with the nature of ultra-luminous infrared galaxies (ULIRGs) in the nearby Universe. However, the analogies drawn between the near and far Universe once again turned out to be not quite adequate. Some part of SMGs actually exhibits multiple morphology (although, if we recollect the clumpy galaxies at $z = 2$, multiple morphology does not guarantee that galaxy mergers are observed). However, among SMGs, there are also many single unresolved objects [62, 63]. A burst of star formation with a rate of 1000 solar masses per year occurs in a volume with a radius of 1 kpc!

Literally in recent months, completely unexpected results have appeared regarding the nature of distant submillimeter galaxies at $z = 4-5$. A comparison of images in a continuum (hot dust) and in the emission lines of molecular (CO) and atomic ([CII]λ158 μm) gas has shown that the gas distribution is much more extended. This implies that what is observed is a powerful burst of star formation in the center of a 'quiescent' gaseous disk with a radius of many kiloparsecs. However, the most surprising thing is that the gaseous disks of these galaxies, observed on the ([CII]λ158 μm) line, are thin, with low velocity dispersion [64–66]! They turn out to be less turbulent than the gaseous disks of galaxies at $z = 2$. The nonmonotonic evolution of the characteristic dispersion of gas cloud velocities in large-scale disks of massive galaxies is a completely unexpected and so far inexplicable observational phenomenon [66]. An attempt by cosmologists led by Avishai Dekel to search for an analog of such objects in physical cosmological models using high-resolution, 55 pc, dark matter simulations and the RAMSES gas-dynamic code [67] resulted in the discovery of only one such model galaxy. It has successfully maintained a thin gas disk at $z \approx 4$ for five revolutions due to a long episode, several hundred million years long, of laminar coplanar accretion of cold gas from the cosmological filament, after which the disk was destroyed by merging and a replacement of the feeding filament. The conclusion from this approach to explain the new observed class of galaxies made by theoreticians was first, that this is a transient phase, i.e., there should be very few such galaxies; and second, that the dynamic 'coldness' $v_{\rm rot}/\sigma > 7$ is only reached when observing a molecular gas, which is 'colder' from the dynamic point of view than a neutral or ionized gas. However, to date, it has been assumed that the ionization of carbon and the emission of the [CII]λ158 μm line occur mostly in the regions of the atomic gas. Nevertheless, the explanation is tentatively accepted — hundreds of such objects among submillimeter galaxies at large redshifts $z > 4$ have not yet been discovered.

3. Scaling relations of galaxy parameters

Linking individual galaxies at different redshifts, or even individual types of galaxies, into a single evolutionary chain is an almost unsolvable task for ordinary logic, since galaxies can change their structure, mass, and stellar and gas content in an unpredictable way. However, an approach has already been invented that makes attempts to make the evolutionary paths of galaxies much more meaningful. This approach is the study of changes over time in the scaling relations between the parameters of galaxies. As it turns out, after the accumulation of statistically significant sets of data on galaxies with measured parameters, these parameters — luminosity, size, chemical composition, rotation speed, dynamic mass, baryon mass — are connected in various combinations by strong correlation relations, the physics of which are sometimes clear and sometimes obscure. It is these strong correlations and their change over time (redshift value) that make it possible to consider not the evolution of individual galaxies in all the variety of their characteristics but the evolution of global parameters of galaxies: mass, size, rotational momentum, metallicity of gas and stars, and star formation rate. In turn, after having distinguished the typical stages of specific changes in the characteristics of galaxies, physically reasonable assumptions can be made regarding the events in the life of the galaxy that led to precisely such changes in parameters.

3.1 'Virial' relations: Tully–Fisher relation for spiral galaxies and Faber–Jackson relation for elliptical galaxies

In the era of the first flourishing of the observational study of galaxies, in the 1970s, dynamic dependences were discovered almost immediately: the optical luminosity (and hence the mass of the stellar population) of spiral galaxies correlated with the rotation speed of their gaseous disks in logarithmic units, i.e., was described by a power law [68], and the optical luminosity (and hence the mass of the stellar population) of elliptical galaxies correlated with the stellar velocity dispersion in logarithmic units, i.e., also showed some power dependence [69]. While it was immediately determined that the power exponential in the latter dependence is four, in the former relation, the Tully–Fisher relation, at first, when taking into account luminosity in the blue range of the spectrum, a value of approximately 2.7 was obtained. However, photometric studies gradually reached the near-infrared range, and, in comparing the luminosity of spiral galaxies in the K filter, at a wavelength of 2 μm, with the speed of their rotation, a power of four began emerging. Tully concluded that the slope of the ratio in the blue range of the spectrum is distorted by the strong dust effect for massive spiral galaxies: "The strong dependence of the (absorption) corrections on luminosity acts to steepen the luminosity–linewidth (21 cm) correlation" [70]. The inclusion of a new morphological type, irregular dwarf galaxies, in this relation first resulted in a downward bend in the dependence at low rotation velocities. Taking into account the high content of neutral hydrogen in these galaxies and the transition from relating the stellar mass rather than the total baryonic mass to the rotation speed led to the disappearance of the inflection of the dependence and the persistence of a single power law in the entire range of rotation velocities from 40 to 300 km s^{-1} in a range of baryon masses of galaxies from 10^8 to 10^{11} solar masses, and to a decrease in the scatter of points around the relation curve [71–73]. So now the relation is referred to as the 'baryon Tully–Fisher relation.' If the luminosity in the K filter (wavelength 2.2 μm) is carefully expressed in terms of stellar mass, taking into account the stellar population age and metallicity, the gas mass in the baryon mass is taken into account, and the rotation velocity is measured precisely in the outermost regions of the disk, where the rotation curve plateaus, the Tully–Fisher dependence exhibits a power-law behavior with exponent 4 over the entire range of rotation velocities, and the scatter of these galaxies around the power-law dependence decreases to characteristic observational errors, i.e., there is no *physical* spread of objects around this power dependence, and it is fundamental [74, 75].

The fundamental nature of the Tully–Fisher relation becomes increasingly more visible in comprehending new observational data. As we move to large redshifts, where the gaseous disks of galaxies are more turbulent than in the nearby Universe, it was proposed that a combined kinematic 'estimator,' which includes both the velocity of ordered rotation and the dispersion of chaotic velocities of gas clouds, be used: $S_{0.5} \equiv (0.5V_{\rm rot}^2 + \sigma_{\rm g}^2)^{1/2}$. This resulted in a significant decrease in the scatter of points around the power-law dependence with slope 4 [76]. Moreover, both the slope and the zero point of the modified Tully–Fisher law coincided with those of the Faber-Jackson law for elliptical galaxies, which involves the velocity dispersion of stars, rather than gas [77]. The lap has been closed, and we have arrived to a relationship common to all galaxies.

As a result of the physical comprehension of the parameters included in the dependences and the nature of their relationships, it has now become completely clear that the Tully–Fisher dependence for spiral galaxies and the Faber-Jackson relation for elliptical galaxies have the same nature: both of them are virial. The point is that the gaseous disks of spiral galaxies are dynamically relatively cold, and for them the virial estimate of the gravitating mass is based on the velocity of ordered circular rotation of the gas at large distances from the center. In elliptical galaxies, the dominant motion of stars (gas is found less often there) usually consists of random chaotic movements in arbitrary directions, and, consequently, their dynamic mass is estimated based on the dispersion of stellar velocities. So, the nature of both relations is virial. Initially, when it was believed that the main gravitating mass of galaxies is provided by their stars, the Tully–Fisher relations for spiral galaxies and the Faber–Jackson relation for elliptical galaxies could look like a trivial consequence of the virial theorem. When it became clear that the main contribution to the dynamic mass is made by dark matter, and luminosity only refers to the stellar component of galaxies, the connection between these quantities ceased to look trivial. It is now generally accepted that these relationships, which link the baryonic and nonbaryonic contents of galaxies, determine the physics of galaxy formation; all global cosmological models first and foremost make an attempt to reproduce for their model galaxies a Tully–Fisher dependence similar to the observed one. It should be stressed that the desired similarity was not gained immediately; it took about 15 years of trial and error and the insertion to the model by hand of powerful feedback from star formation [78].

As for the evolution of this relation, it has now been traced to $z \sim 2.3$ [79]. While the slope of the Tully–Fisher baryon relation persists, the zero-point evolves in a strange nomonotonic way, which requires the concurrent inclusion of several factors in the qualitative model of the evolution of disk galaxies with star formation. The main one of these factors, apparently, is the decrease with time in the fraction of gas in the baryonic mass and an increase in the contribution of dark matter to the dynamic mass of the central part of the galaxy [79].

3.2 Fall's dependence: angular momentum, how it is acquired, and where it disappears to

Such a common property of galaxies as rotation was also independently parameterized: the angular momentum of the disks of galaxies turned out to be closely related to their mass. This strong correlation was first pointed out by Fall in his report at the famous 100th Symposium of the International Astronomical Union (IAU) [80]: the specific angular momentum of the disks of spiral galaxies, expressed as $j_{\rm exp} = 2R_{\rm d}V_{\rm flat}$ for exponential stellar disks with surface density distribution scale $R_{\rm d}$ and flat rotation curves that plateau at the $V_{\rm flat}$ level, turned out to be proportional to the stellar mass of the galaxy disk to a power of $2/3$. Modern data statistics make it possible to trace this power-law dependence in the stellar mass range of galactic disks of $10^7 - 10^{11}$ solar masses with a very small scatter of the order of 0.15 dex (decimal exponent) [81], which also indicates the fundamental nature of this relation. Elliptical galaxies also follow a similar dependence of specific angular momentum on stellar mass; however, it lies much lower, reproducing the shape of dependence for spiral galaxies. Fall's empirical dependence turned out to be very similar to that predicted by cosmologists for the origin of the dark halo momentum. Peebles [82] proposed a mechanism for 'spinning up' dark matter halos at the moment of their gravitational collapse by the tidal effect from neighboring similar dark halos flying past, and that model also yielded a power-law dependence of the specific momentum on mass with an exponent of $2/3$. The similarity of the power-law mass dependences of the specific momenta of dark halos (in theory) and stellar systems (in observations) enabled an assertion that baryons inherit their momentum from dark halos. However, since then, theorists have not yet overcome the disagreements: is the momentum inherited entirely or maybe partially, and if partially, then in what proportion? And what physical effect determines this proportion?

Recent progress in kinematic observations of elliptical galaxies using panoramic spectroscopy observations, including those that extended to large radiuses, with inclusion in estimating the rotation velocities of galaxies at extremely large distances from the center of their system of globular clusters and planetary nebulae (for example, the SLUGGS [83–85] and ePN.S [86] projects), provided a correct estimation of the radial profile of specific momentum and its integral value for spheroidal galaxies as well. Analysis on a new observational base, performed by Romanowsky and Fall [87], showed that spiral galaxies inherit from their dark halos about 6 times more of the initial rotational momentum than do elliptical ones: 60% versus 10%. From the perspective of scenarios for the evolution of galaxies of various types, it is tempting to associate this difference with different paths of dynamic evolution of galaxies of different morphological types — for example, to recognize the large role (and frequency) of multiple minor mergers in the life of elliptical galaxies.

Regarding the observed evolution of the Fall relation, the currently available amount of observational data from panoramic spectroscopy (gas velocity fields) of disk galaxies with star formation is sufficient to study this relation. Using the results of the KMOS/KROSS (K-band Multi-Object Spectrograph Redshift One Spectroscopic Survey) survey with the VLT telescope of the European Southern Observatory, spectral properties of 586 disk galaxies with star formation in the stellar mass interval of $10^9 - 10^{11}\ M_{\odot}$ [88] were measured at a redshift value close to 0.9, i.e., in the epoch 7 billion years ago (which is half the age of the expansion of the Universe). It turns out that for these galaxies the Fall dependence can also be traced, with an exponent of 0.6 ± 0.2. However, the observed normalization of this dependence indicates that 7 billion years ago the specific (normalized) angular momentum of disk galaxies was approximately half of that of galaxies in the local Universe with the same stellar mass. This implies that the increase in the rotational momentum of disk galaxies over the past 7 billion years has been very noticeable, and this circumstance is now a decisive factor in constructing empirical scenarios for the evolution of disk galaxies (see Section 6 below).

3.3 Size–mass correlation and the fundamental plane

The size of the galaxy and its stellar mass are also closely related in local Universe objects: the greater the mass (luminosity) of the galaxy, the more extended is its radial distribution of brightness. This strong correlation in elliptical galaxies was first pointed out by John Kormendy in his early papers [89]. Later, it turned out that a strong correlation between luminosity and size exists not only for elliptical galaxies but also for disk galaxies and for individual structural components of galaxies, large-scale disks and bulges. Bulges, as it should be for spheroids, follow elliptical galaxies in this dependence, while disks form a separate dependence that coincides at low luminosities with that for dwarf *spheroidal* galaxies [90]. For the same luminosity, disks are usually more extended than spheroids. After the first mass survey of galaxies in the local Universe, the SDSS (Sloan Digital Sky Survey), collected sufficient statistics on the photometric parameters of galaxy images, the forms of the radius–mass dependence for various types of galaxies were studied [91]. Making a rough division into early-type galaxies (ETGs) and late-type galaxies (LTGs), which is based on the general steepness of the radial brightness profiles (the so-called Sérsic index), power-law dependences were constructed: for ETGs, $R_e \propto M_*^{0.56}$, for massive LTGs, $R_e \propto M_*^{0.39}$, and for low-mass LTGs, $R_e \propto M_*^{0.14}$. Here, R_e is the so-called effective radius, which includes half of the entire luminosity of the galaxy. Since the dependence for LTGs is flatter than for ETGs and it is located higher, the dependences for early and late types of galaxies 'meet' at large masses; this occurs at stellar masses slightly greater than 10^{11} solar masses. It should be noted that the formal division into early-type galaxies and late-type galaxies according to the Sérsic index is not adequate for the division into elliptical and disk galaxies: early-type galaxies include both some lenticular and all Sa-type spiral galaxies, in which the contribution of the bulge (central spheroid) plays an important role in the structure. In this sense, it is better to rely on the approach of Kormendy and Bender [90], since different large-scale components of the galaxy — disks and bulges — apparently follow evolution paths that differ in terms of both dynamic mechanisms and time scales of stellar population formation.

Observations of galaxies at large redshifts make it possible to estimate the size evolution rate. It turns out that, earlier, all galaxies were more compact, i.e., smaller in size with the same stellar mass, and the evolutionary increase in size developed much faster for spheroidal galaxies than for disks [92]. It is on this observation that one of the most successful empirical scenarios for the evolution of elliptical galaxies is based, which will be discussed in the next section.

It was for elliptical galaxies that fairly early the dynamic luminosity-dispersion of stellar velocities correlation (the Faber–Jackson relation) and the structural luminosity–size correlation (the Kormendy relation) were successfully combined into a single 'fundamental' plane. The report on the fundamental plane appeared simultaneously and independently in the articles published by two groups of researchers in the same issue of the *Astrophysical Journal* [93, 94]. It was discovered that, in the space of three parameters — size, dispersion of stellar velocities, and surface brightness (luminosity) — elliptical galaxies were concentrated on a single two-dimensional surface. In principle, such a relation between parameters is expected from the theory if it is hypothesized that a homogeneous stellar spheroid is in a state of virial equilibrium, i.e., dynamically relaxed. However, virial equilibrium predicts the relation between parameters with an integer power exponential: $L \propto \sigma^2 R_e$ or $R_e \propto \sigma^2 I_e^{-1}$. In reality, the exponents of the velocity dispersion differ from two fairly strongly, and that of the surface brightness I_e, from minus one fairly significantly. When the fundamental plane was built on the basis of a large sample of about 8000 elliptical galaxies in the observed SDSS survey, it exhibited the dependence $R_e \propto \sigma^{1.5} I_e^{-0.8}$ [95]. Subsequently, based on the results of the surveys, using this time panoramic spectroscopy methods, which also make it possible to relate the measurements of the stellar velocity dispersion to the effective radius, in contrast to aperture spectroscopy that concentrates at the center of galaxies, the following 'slopes' were obtained with high accuracy for the formula $L \propto \sigma^a R_e^b$: $a = 1.249 \pm 0.044$ and $b = 0.964 \pm 0.03$ according to the results of the ATLAS-3D survey [96] and $a = 1.294 \pm 0.039$ and $b = 0.912 \pm 0.025$ according to the results of the SAMI survey [97]. In analyzing the reasons for the disagreement between the real powers in the fundamental plane formula and the predictions of the virial equilibrium theory, astronomers have proposed two qualitative explanations. First, the heterogeneity of the properties of the stellar population inside an elliptical galaxy is apparent: gradients of metallicity and the age of stars exist along the radius, which leads to a more complex relationship between surface brightness (luminosity) and density (mass). Second, galaxies can be non-homologous, i.e., inside the spheroid, for example, a compact stellar disk can be embedded. The multicomponent nature of the stellar system will change the conditions of dynamic equilibrium. It is not yet completely clear which of these explanations plays a decisive role. However, an attempt to proceed from luminosity to stellar mass by means of evolutionary modeling of the integral spectrum of galaxies, which was undertaken recently by a team of specialists on stellar dynamics from the ATLAS-3D survey in studying elliptical galaxies in the Coma cluster (thus ensuring the same distance to all galaxies and, with some probability, the same age of the stellar population), indeed brought the slope of the fundamental plane (renamed by the authors the Mass Plane) closer to the value predicted by the virial theorem, yielding $a = 1.87 \pm 0.04$ [98].

In any case, the strong concentration of elliptical galaxies near the fundamental plane, the shape of which is well measured using data on the nearby Universe, makes it possible to study the evolution of this type of galaxy at large redshifts.

3.4 Main sequence of galaxies (star formation rates)

Current rates of star formation in galaxies are also incorporated into a whole system of scaling relations. The most logical (and discovered earlier than these relations) was the dependence of the star formation rate on the mass of gas in the galaxy (more precisely, the local star formation rate depends on the local gas density). Indeed, if stars are formed from gas, it is logical to expect that, the more gas there is, the younger the stars are. This dependence was searched for by Maarten Schmidt in 1959 from the very first observations of neutral hydrogen in the 21-cm line in the vicinity of the Sun to find that the star formation rate is proportional to the gas mass (more precisely, volume density) squared [99]. The dependence was called Schmidt's law. Later, Robert Kennicutt put a lot of effort and years of work into refining Schmidt's law using observations of spiral galaxies other than the Milky Way. All of them are visible in the projection onto the sky plane, so Kennicutt connected the star formation rate with the surface rather than the volume density of the gas. He determined the star formation rate from the integral (or local) luminosity of the galaxy on the $H\alpha$ emission line. This approach involves many assumptions; first of all, the assumption that the entire $H\alpha$ emission is associated with the Strömgren zones around massive stars (in fact, usually, very different components of the interstellar medium with very different excitation sources contribute to the emission of ionized gas). Nevertheless, Kennicut obtained a correlation between the star formation rate and the surface gas density, and the power exponent of this dependence (slope) was determined to have a value of 1.44, which is far from an integer [100]. The result of [100] was welcomed by the astronomical community, but some dissatisfaction still remained: the unphysical power exponent of the gas density was intriguing along with the threshold values of the gas density found by Kennicut, below which star formation could not begin in principle: these threshold values turned out to be different for different galaxies. Examination of the Schmidt law, which after 1998 became known as the Kennicut–Schmidt law, continued, and shortly afterward logic guided explorers to a very simple modification of the law: stars are formed inside *molecular* gas clouds; therefore, the star formation rate should be compared not with the entire mass of the gas but with the mass of the molecular gas. Usually, galaxies contain much less molecular gas: the typical value of $M(H_2)/M(HI)$ for spiral galaxies of the nearby Universe ranges between 0.2 [101] and 0.3 [102]. As a result, the slope of the dependence changed; it became linear, and the gas density thresholds for igniting star formation vanished [103]. So the Kennicut–Schmidt law was reduced to a very simple physical formulation, which, however, entailed significant changes in the concept of the evolution of galaxies. The existence of a simple linear relationship between the star formation rate and the amount of molecular gas in a galaxy meant that, if the latter quantity is divided by the former one to estimate the time of gas of exhaustion in a galaxy, the same number should be obtained for all spiral galaxies in the nearby Universe. This exhaustion time turned out to be rather short, about 0.5–2 billion years [103, 104], and independent of the galaxy mass or size. If the goal is to determine the time of neutral hydrogen exhaustion, it is also universal for galaxies of the nearby Universe and equal to approximately 3 billion years [104]. Such a short time scale of gas exhaustion immediately shows that galaxies could not regularly form young stars for the last 8 billion years (namely, this is the age of the thin stellar disk of our Galaxy) if cold gas is not continuously pumped into them from outside. Thus, the concept of the evolution of spiral galaxies in the regime of constant stationary accretion of external cold gas has finally been established.

Compliance with the Kennicut–Schmidt law was tested at large redshifts, when first the IRAM millimeter interferometer and later ALMA provided the richest observational material on the content of molecular gas in individual distant galaxies (it is of interest that the content of neutral hydrogen in these galaxies is known with lower accuracy). The relationship between the star formation rate and the content of molecular gas in distant disk galaxies also turned out to be close to linear, but the gas exhaustion time at large redshifts is less than that in the local Universe: at $z = 2$, it is only 0.7 billion years [105] instead of the local scale of 2 billion years, and at redshifts up to $z \sim 3$, it decreases on average as $(1 + z)^{-0.3}$, while depending only very weakly on the galaxy mass [106]. This implies that the efficiency of converting gas into stars at large redshifts was higher.

As a result of the emergence of many thousands of statistics on various characteristics of galaxies in the nearby Universe, the SDSS survey revealed another quasi-linear relationship: star formation rates in the vast majority of galaxies is proportional to their stellar masses [107], and, as

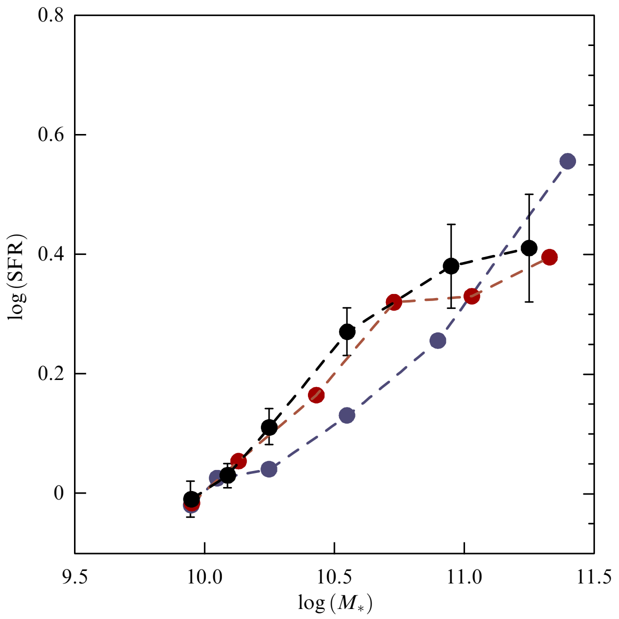

Figure 6. Main sequence for galaxies in the nearby Universe according to data from [108]. Dots of different colors correspond to different ways of calculating the star formation rate: based on Hα emission (black), infrared flux (red), and spectral energy distribution in the spectrum (blue).

a result, galaxies are located along a very narrow sequence on the SFR (M_*) dependence (Fig. 6 based on data from [108]). This sequence was called the 'main sequence' of galaxies [109], assigning it an evolutionary meaning by analogy with the main sequence of stars. For galaxies in the main sequence, the time they need to build their entire stellar mass at a given star formation rate is commensurate with the Hubble time (the Universe expansion age). A qualitative conclusion follows this observation: staying on the main sequence is a quiescent, uniform regime of star formation, and it is in this mode that galaxies spend most of their lives. The main sequence of star formation is contrasted with outbursts of star formation, which are characterized by a rate enhanced compared to the value averaged over the galaxy life and which therefore must be very short. Surprisingly, most star-forming galaxies lie on the main sequence not only in the nearby Universe, at $z = 0$, but also at $z = 1$ [110], $z = 2$ [111], and $z = 4-6$ [32] .... It turns out that mergers of galaxies, which are always accompanied by outbursts of star formation, do not play a significant role in the life of galaxies at any redshifts up to the very early stages of the evolution of the Universe. This observation, generally speaking, disagrees with early conclusions that follow from the classical paradigm of cosmologists about the continuous hierarchical growth of galaxies through mergers of small objects into large ones, i.e., mergers that are especially frequent at the early stages of the Universe expansion when galaxies have not yet dispersed far from each other. It also disagrees with early interpretations of the high cosmic star formation rate at redshifts $z = 1-2$ as supposedly due to the almost 100% major merging of massive galaxies in that epoch [112].

The accumulation of observational data on distant galaxies in photometric surveys with large telescopes makes it possible now to trace the evolution of the main sequence of star formation rates up to $z = 6$ in samples that contain many thousands of objects. Evolution manifests itself in two directions. First, while maintaining a close relationship between the mass of a galaxy and its star formation rate (the spread around the main sequence, 0.2 dex, does not change with the redshift value), with increasing distance from us (and with decreasing comoving age of the Universe), the star formation rates are growing in galaxies of all masses. However, the slope of the main sequence also increases [32], which is a manifestation of so-called down-sizing: galaxies of large masses form their stellar population earlier, and the process of conversion of gas into stars is more efficient in these galaxies. Over time, the center of events — the main star formation in the Universe — shifts to galaxies of lower masses. An increase in the star formation rate with a change in redshifts shows a kink on a logarithmic scale near $z \approx 2$ [113]: from $z = 5$ (the age of the Universe is 1 billion years) to $z = 2$ (the age of the Universe is 3 billion years), the star formation rate in a typical massive galaxy decreases on average by 1.7 times, and between $z = 2$ (the age of the Universe is 3 billion years) and $z = 0.4$ (the age of the Universe is 10 billion years), already by a factor of 13. This evolution echoes the general sharp decrease in the volumetric cosmic rates of star formation in the last 8–9 billion years [114]. Second, this is the flattening of the main sequence at large masses for near-Universe galaxies, $M_* \geqslant 10^{11}$ $M_\odot$. In the local Universe, massive galaxies usually barely form stars; however, this bend of the main sequence vanishes at large redshifts [115], although there are still disagreements in observations: in some surveys, this bend is no longer visible at $z \approx 2$ [116], while in other surveys it is traced up to $z = 3.5$ [113].

3.5 Puzzles of chemical evolution: mass–metallicity relationship for galaxies

The efficiency of the chemical evolution of a galaxy is also related to its mass: a mass–metallicity dependence is observed. In elliptical galaxies, this relation manifests itself in the simplest form easily measured in mass surveys as a correlation between the color and the luminosity of the galaxy. Such a correlation was discovered at the very dawn of photometric studies of galaxies (see, for example, [117]). The identification of this correlation was facilitated by the fact that many elliptical galaxies are located in clusters of galaxies, for example, in Virgo, which is closest to us, and all of them are located approximately at the same distance from us; therefore, a color–magnitude correlation is observed [118], which is naturally interpreted as a color–luminosity correlation. When Sandra Faber discovered that the equivalent widths of metal lines in low-resolution spectra increase in absolutely the same way with the luminosity of elliptical galaxies [119], she interpreted the long-known color–luminosity relation for elliptical galaxies as a metallicity–luminosity relation. However, the 'age–metallicity' degeneracy effect for the integrated spectra of stellar systems had not yet been known at that time: both a decrease in metallicity and a decrease in age equally lead to a blueing of the stellar system and a decrease in the depth of absorption lines of metals in its spectrum [120]. However, over time, researchers learned to cope with the 'age–metallicity' degeneracy in modeling the integral spectra of stellar systems [121, 122], and after that it was confirmed that, for elliptical galaxies, there really is a correlation between the metallicity of the stellar population and their mass: the more massive the galaxy, the richer in metals its stellar population [123–125].

For late-type galaxies — spiral and irregular — a 'metallicity–luminosity' dependence also exists; however, for these galaxies, this dependence was first established using emission spectra. Consequently, in the case of these galaxies, it refers to the metallicity of gas, most often associated with the abundance of oxygen in the hot ionized gas. The tools for handling the emission spectra of an ionized gas were developed quite early [126], and, consequently, correlations were also directly discovered fairly early. For irregular galaxies, a quality sample of data was collected and a low-dispersion and steep dependence of the abundance of oxygen in a gas on the luminosity of galaxies was discovered as early as the 1990s [127], while for spiral galaxies, a highly professional analysis with an extension of the dependence towards higher luminosities was presented in [128]. After the appearance of an immense array of spectral data provided by the SDSS survey, the corresponding scaling relation for the relationship between the metallicity of gas and the luminosity (and stellar mass) of galaxies that demonstrated ongoing star formation was updated [129, 130], and since then it is only this relation that is quoted in publications. As for the metallicity of the stellar component, it was paid less attention in studies of spiral galaxies; however, in the 1980s–1990s, in the 'golden age' of extragalactic astronomy of the nearby Universe, there were valuable advancements in this area as well. For example, Gregory Bothun et al. [131] noted that the extension of broadband photometry to the near-infrared range makes it possible to remove the age–metallicity degeneracy, since the $J-H$ infrared color characterizes primarily the old component of the stellar population, while the $J-H$ color correlation with the stellar mass of spiral galaxies should be interpreted specifically as a mass–metallicity correlation. On the other hand, the young population emits more light in the blue range of the spectrum, and the $B-H$ color is thus a characteristic of the average age of the stellar population [132].

In recent years, evidence has emerged that the 'mass–metallicity' scaling relation can and should be combined with the main sequence of galaxies into a 'fundamental metallicity relation' (FMR) that links three global characteristics of a galaxy: mass, metallicity, and current star formation rates are a single evolutionary relationship [133, 134]. The point is that initially spiral galaxies showed a certain scatter around the 'mass–metallicity of gas' dependence, and in [135] it was found for the first time that the deviation of a galaxy from the mean trend on this dependence anti-correlates with the star formation rate. The inclusion of the third parameter in the FMR reduces the average scatter of points around the 'mass–metallicity' dependence to 0.05 dex [134], and, presumably, it is the FMR that is the main physical dependence between the global parameters of the evolution of spiral galaxies. However, not all researchers and not all reviews show the significance of the anti-correlation of the deviation of the galaxy from the mean trend on the 'mass–metallicity' dependence with the star formation rate [136,137]: this issue is still a matter of discussion.

Qualitative mechanisms proposed to explain the physical FMR dependence include the parametrization of the inflow of cold external gas and the outflow of internal hot gas with the mass of the galaxy [138]. The issue of the need for constant accretion of external gas onto the disks of spiral galaxies has constantly emerged in the discussion of their evolution since the 1980s and the first models of the chemical evolution of the solar neighborhood. The so-called G-dwarf paradox — the invariable chemical composition of stars in the thin disk of the Milky Way over the past 8 billion years — required as its solution a constant influx of external gas with zero metallicity. In the 1990s, this mechanism was supported by cosmologists: there should be a lot of gas (baryons) in the Universe that did not undergo the star stage and retained the primordial chemical composition with zero metallicity, and this gas should flow under the effect of gravity into the nodes of the large-scale structure of the Universe, where galaxies reside. According to the Kennicut–Schmidt law, the more gas (has flown in) at a given moment, the higher the star formation rate. Gas flows more actively into deep potential wells. Thus, the greater the galaxy mass, the more gas available and the more intense the star formation. The anti-correlation with metallicity is a consequence of the recent influx of primordial gas with zero metallicity into the galaxy disk, which stimulated the intense star formation discussed above. However, the global 'mass–metallicity' trend *per se* is controlled not by the inflow of gas but by its outflow. During active star formation, the gas is locally heated by the radiation of young stars and obtains kinetic energy from stellar winds and supernova explosions (so-called feedback). A galactic wind can form: the gas heated and accelerated to high speeds by young stars can leave the galaxy. The smaller the potential well depth, the easier it is for the gas freshly enriched with metals from supernovae to 'escape' from this well. This is the very 'enriched wind,' which is shown in Fig. 1 and was included in the model of chemical evolution of local regions of the galaxy in [33]. It is this involved interplay between the inflow and outflow of gas depending on the mass of the galaxy that forms the FMR scaling dependence. According to surveys of distant galaxies, it persists unchanged at least up to $z = 2.5$ [133], i.e., for the last 10–11 billion years.

3.6 Supermassive black holes at the centers of galaxies

The centers of most galaxies host supermassive black holes. Sometimes (in a few percent of cases) gas flows into them in a favorable geometric configuration and in the required amount, and, should this be the case, the supermassive black hole manifests itself as an active galactic nucleus, shining with an intensity comparable to or even stronger than that of the parent galaxy. However, most often such favorable conditions do not occur, and the supermassive black hole in the center of the galaxy is 'silent'; its presence can only be felt by colossal gravity in its vicinity, in the very center of the galaxy. John Kormendy was the first to decisively ascertain the presence of 'quiescent' supermassive black holes in the centers of nearby galaxies in the 1980s. He carried out spectral observations with a long slit using the CFHT (Canadian-French-Hawaiian Telescope) in Hawaii; at that time, there were the best astroclimatic conditions combined with availability of a fairly large telescope and spectrographs with advanced design. The typical spatial resolution of spectroscopic observations he carried out was about 0.4–0.5 arc seconds. Such a unique spatial resolution of ground-based observations allowed him to detect in the centers of nearby large galaxies M 31 [139], NGC 4594 [140], and NGC 3115 [141] a sharp increase in the stellar velocity dispersion and a burst in the rotational speed of the stellar component near the nuclei, which, in these cases were not accompanied by the presence of a sufficiently bright stellar nucleus capable of providing such gravity. Kormendy immediately asserted that these were super-massive black holes. However, his statement was received with distrust, because, even in the Andromeda

Nebula, a spatial resolution of 0.5 arc seconds (about 2 pc) is not sufficient to rule out less exotic explanations, including clusters of dim objects (neutron stars, brown dwarfs etc.), or even to rule out a nonaxisymmetric distribution of stellar mass, which in some projections can imitate increased gravity. Nevertheless, based on his small sample, John Kormendy, in collaboration with Douglas Richstone, reported a correlation between the mass of the central black hole and the mass of the galaxy bulge [142].

After the Hubble Space Telescope, which was initially misaligned, was repaired in 1994, the key program for the dynamic search for central black holes in galaxies immediately started, since the spatial resolution of observations with the Hubble Space Telescope was by that time 5 times better than the resolution available to Kormendy at CFHT. First of all, the presence of black holes was confirmed in the centers of NGC 3115 [143], NGC 4594 [144], and the Andromeda Nebula [145], and then the measurement of the masses of central black holes based on their dynamic manifestation acquired an industrial character: dozens of objects have already been discovered. The strong correlation between the masses of central black holes and the luminosity of the entire galaxy, if the galaxy is elliptical, and the luminosity of the bulge, if the galaxy is a disk, has been confirmed in a large sample of objects [146]. The extension to the infrared spectral range even bettered this correlation [147] to finally make it clear that it is the stellar mass of the bulge, the spheroidal component of the structure of galaxies, that is related to the mass of the central black hole (Fig. 7). Eventually, the ratio of the masses of the central black hole and the spheroidal stellar component for galaxies of the nearby Universe converged to a value of 0.002–0.003 [148]. However, the strongest correlation was obtained with the stellar velocity dispersion in the bulge, which for dynamically hot systems is a measure of the *dynamic* (*gravitating*) mass of the bulge [149]. Such a strong relation between the mass of the central black hole and the dynamic mass of the galaxy spheroid persists in the mass range of black holes from slightly less than a million to several billion solar masses [150].

The advancement to dynamic estimates has prompted the introduction of the total gravitating mass of the galaxy, i.e., its dark halo. The concept of a synchronous growth of a stellar spheroid and a central black hole, so-called co-evolution [151], which was enthusiastically welcomed by cosmologists, immediately arose, since the synchronous growth of a stellar spheroid and a central black hole perfectly fits into the hierarchical model of constant mergers of galaxies, in which, at the same time, both the masses of merging galaxies and the masses of their central black holes are summed up. Structurally, the body of the galaxy emerging after a large merger should be exactly a dynamically hot spheroid [152]. It only remained to check the evolution of this scaling relation on a long time scale: if the co-evolution mechanism is operative, this ratio should not show any changes. However, these expectations were not met.

Everything failed, as always, due to the development of observational tools. Deep spectral observations of distant quasars with the 8- and 10-meter VLT and Keck telescopes made it possible to collect statistics on the masses of black holes in these active nuclei: it was sufficient to straightforwardly estimate the lower limit of their masses under the assumption of the Eddington luminosity of the quasar. It turned out that at $z > 6$ the typical masses of black holes in quasars are on the order of a billion solar masses, i.e., are in

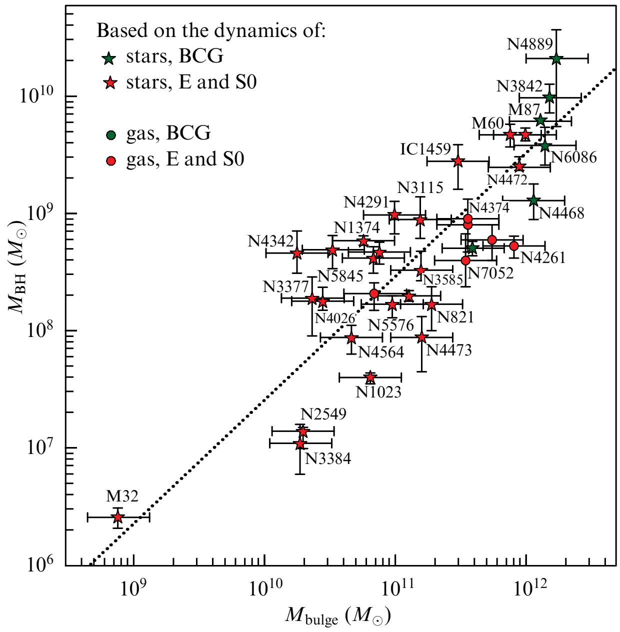

Figure 7. Correlation between the mass of the central black hole determined from the dynamics of stars or gas in the center of the galaxy and the mass of the spheroidal stellar component for early-type galaxies according to [148]. Each point is labeled with a galaxy name (M=Messier, N=NGC, ...).

no way inferior to the most massive black holes of the nearby Universe. However, the masses of the host galaxies, estimated from the dynamics of their large gaseous disks using the ALMA interferometer, turned out to be much more modest, as was expected within the hierarchical concept. As a result, for 27 quasars at $z > 6$, the ratios $M_{\mathrm{BH}}/M_{\mathrm{dyn}}$ ranging from 0.004 to 0.05 were obtained in [153], making, on average, one percent, i.e., 5 times larger than in the nearby Universe.

4. Empirical scenario for the formation of giant elliptical galaxies

Elliptical galaxies have a number of macroscopic properties, the 'squeezing' of which into a single formation scenario is a fairly challenging problem. The initial main property, which was considered necessary to explain, was the dynamically 'hot' status of their stellar component: at a relatively low rotational momentum, almost the entire kinetic energy of stars is contained in their chaotic motions throughout the volume of the galaxy. Actually, it is the shape of the ellipsoid of stellar velocity dispersion inside the galaxy that determines its geometric shape: if velocity dispersion is isotropic, a ball is obtained, while strong anisotropy yields a triaxial ellipsoid. In addition, the stellar mass–metallicity correlation was known as early as the 1970s. In 1979, Beatrice Tinsley and Richard Larson proposed the formation of giant elliptical galaxies by the merger of two spiral galaxies of similar masses, so-called major merging [154]. Indeed, dynamic modeling in the spirit of the Toomre brothers [155] revealed the dominant role of violent relaxation during the merger of two disk galaxies of similar masses, as a result of which the momentum escaped from the merger product, and the product acquired a spheroidal shape. The inevitable presence of gas in merging disk galaxies led to a concentration of gas in the center of the merger product [156] and an accompanying burst of star formation, which enhanced the metallicity of the stellar population in each merger event and thus led to the mass–metallicity correlation [154]. This scenario was especially hailed by cosmologists: in their early picture of hierarchical mergers of galaxies during the evolution of the Universe, large mergers were a central event [157]. However, the problem is that the burst of star formation not only increases the metallicity of the stellar population but also lowers its average age. Astronomers have known for a long time that the stellar population of elliptical galaxies is old. By the 2000s, they also learned that, for giant elliptical galaxies, there is a mass–age correlation: the more massive the galaxy, the earlier the formation of its stellar population was completed [124, 125]; however, these observations apparently disagreed with the hierarchical concept, in which massive galaxies should have been formed last. Nevertheless, oddly enough, it was not this knowledge that ultimately undid the scenario of major merging for giant elliptical galaxies. Purely psychologically, the astronomical community was persuaded by the results of a direct observational study of the evolution of the sizes of elliptical galaxies in the course of large-format photometric surveys of galaxies at large redshifts. Still, before narrating this victorious story, it would be relevant to mention our timely contribution to the revolution in scenarios of the formation of elliptical galaxies.

4.1 Premises for revolution: metallicity gradient in elliptical galaxies

Another feature of elliptical galaxies, apparently related to the mechanism of their formation, is the radial gradient of metallicity: towards the periphery, the metallicity of the stellar population in elliptical galaxies decreases. This feature was initially discovered in observations, again using the results of broadband photometry: the blueing towards the edge in elliptical galaxies was associated with metallicity for the same reasons that the decrease in color indices with decreasing luminosity was also associated with it. The first models of the formation of elliptical galaxies in which this qualitative effect was reproduced were the 'monolithic collapse' models developed in the 1980s by Raymond Carlberg [158]. The mechanism for the emergence of radial metallicity gradients in these models was similar to that for establishing a metallicity–mass correlation: it is feedback, the impact on gas from a powerful burst of star formation that forms the entire galaxy at once. The smaller the depth of the potential well, the easier it is for the gas heated by young stars to leave the galaxy or a specific place in the galaxy (the fact that scaling relations also work on local scales has been excellently demonstrated in Sebastian Sanchez's review [137]). If feedback with star formation is included in the model, star formation at the periphery of the galaxy stops earlier than at the center due to the earlier escape of gas, so chemical evolution there does not have time to advance to supersolar values of metallicity. However, in the center of a massive elliptical galaxy, the time for this advancement is sufficient. Carlberg's models [158] yielded numerical predictions regarding the metallicity gradient: it is, on average, -0.5 dex per dex, i.e., metallicity decreases threefold over a radial interval of an order of magnitude, for example, from $r = 5''$ to $r = 50''$. Early observational estimates of the metallicity gradient in elliptical galaxies generally gave a similar estimate: on average, -0.3 dex per dex. However, since the accuracy of the observations was not high, the specific functional form of the metallicity gradient was not analyzed, and a single linear dependence in logarithmic coordinates was incorporated into the measurements. Using the 6-meter telescope of the Special Astrophysical Observatory, we started studying the deep spectroscopy of giant elliptical galaxies with round isophotes in the early 2000s based on the program of Maarten Baes, a specialist in stellar dynamics from Ghent University (Belgium). Baes intended to determine the radial profile of the stellar velocity dispersion, but we calculated in addition the parameters of the stellar population. It turns out that in all five studied galaxies the radial metallicity profile exhibits a kink at about half the effective radius. This implies that, in the center, the metallicity gradient is steep, -0.5 dex per dex or steeper, while in the outer regions it plateaus. It is here that the cosmological simulations of metallicity gradients in elliptical galaxies made by Chioka Kobayashi, a postgraduate student at the University of Munich, proved to be very timely and helpful [159]. She found that, with a major merging, metallicity gradients do not survive, and this occurs due to the same violent relaxation due to which the rotational momentum vanishes. Kobayashi's calculations also revealed a quantitative criterion: if an elliptical galaxy has undergone a large merger in the last 10 billion years (the typical modern age of the stellar population in early-type galaxies), then its metallicity gradient cannot be steeper than -0.3 dex per dex. However, in the central regions of the galaxies that we studied, it turns out, and with good accuracy, to be steeper everywhere, since the spectra for the central regions are obtained with a good signal-to-noise ratio. In 2007, we published an article [160], in which we proposed a 'two-stage' scenario for the formation of giant elliptical galaxies: first, the inner regions of the galaxies are formed by a monolithic collapse, and then satellites can fall on them, and in this way the outer, strongly mixed regions with a low metallicity gradient can grow. It was this scenario that was independently proposed by western colleagues a couple of years after the publication of our article to explain a completely different observational fact — a sharp increase in the characteristic sizes of massive elliptical galaxies between $z = 2$ and $z = 0$, i.e., in the last 10 billion years.

4.2 Premises for revolution: size evolution in elliptical galaxies

The study of the evolution of the scaling mass–size ratio became possible in the late 2000s, when several deep multicolor photometric surveys of fairly extended selected sky areas were simultaneously carried out with large ground-based telescopes: DEEP2 [161], GOODS [162], CANDELS [163], and COSMOS [164]. Two-color criteria, such as BzK or UVJ, made it possible, based on the results of these surveys, to compose samples of hundreds of galaxies at large redshifts, up to $z = 2-3$, classifying them, in addition, into star-forming galaxies and 'passive' galaxies. This was followed by observations of these distant galaxies using the Hubble Space Telescope (HST) and a morphological analysis of their images; the spatial resolution of the HST, 0.1 arc seconds, enabled resolution of the radial distributions of brightness and, by applying the Sersic law to them, to separate elliptical galaxies from disk galaxies. In 2007, Trujillo et al. [92] published a resounding result based on data from the DEEP2 survey: massive elliptical galaxies at $z = 2$, in the mass range $M_* > 10^{11} M_{\odot}$, turn out to be 5 times more compact than at $z = 0$. In the case of later types of disk galaxies, the evolution of sizes turns out to be much more modest. These results were confirmed in 2008 by the results of the GOODS survey [165] obtained this time on a time base of up to $z = 3$: the sizes of massive elliptical galaxies 10 billion years ago turn out to be smaller by a factor of 4.3, and 11 billion years ago, by a factor of 7. The results of the CANDELS survey provided hints of a power law in the evolution of the sizes of galaxies at a fixed stellar mass: $r_e \propto (1+z)^{-1.48}$ for galaxies without star formation (presumably elliptical) and $r_e \propto (1+z)^{-0.75}$ for galaxies with star formation [166]. A question arose about the mechanisms of dynamic evolution, which can provide such a rapid growth in the size of purely stellar — i.e., dynamically collisionless — systems without the addition of young stars with a moderate increase in mass. Three candidates were suggested: major merging, which was previously the most popular scenario for the formation of giant elliptical galaxies; swelling of a galaxy by injection of kinetic energy from an active nucleus (a quasar at the center of the galaxy) [167]; and multiple minor merging, which proved to be the winner in this contest among the scenarios. In [168], all three mechanisms are considered in detail, and two of them are recognized as nonworking. In the case of a major merging, the radius grows in proportion to the mass. If elliptical galaxies at $z = 2$ with a mass $M > 10^{11} M_\odot$ had increased their size by a factor of 5 in 10 billion years due to major merging, there would now be a massive population of elliptical galaxies with a stellar mass of $10^{12} M_\odot$ or more, which is not observed in the nearby Universe. The active nucleus mechanism is only operative in combination with a burst of star formation (which does not exist at all in the considered distant galaxies at the moment $z = 2$) and, due to this, generates an anti-correlation between the size and age of the stellar population at a fixed mass, which is not observed in the nearby Universe either [169, 170]. Thus, the winner was multiple small 'dry' merging, which leads to an increase in the size of the stellar system in proportion to the mass squared [168]. Estimates show that, for an elliptical galaxy to grow by a factor of 5, eight satellites should fall on it in 10 billion years, each with a mass of 10% of the host galaxy. Specific dynamic modeling showed that such an effective increase in radius as a result of minor merging occurs due to the fact that satellites that have come close to a large galaxy are first disintegrated by a tidal gravitational effect, so it is not a gravitationally bound stellar system that is absorbed, but its fragments [171]. 'Stripping' rather than 'violent relaxation' (which is considered the dominant stage of a major merging) leads to an increase in the size of the galaxy in proportion to the mass squared compared to a linear growth with major merging. Moreover, a careful numerical consideration and comparison of the dynamical events of a major merging with a mass ratio of 1:1 and multiple minor merging with a mass ratio of 1:10 showed that the second option can be even more efficient, given that the stellar body of the galaxy is immersed in an extended dark halo. Should this be the case, the power dependence $r_e \propto M_*^\alpha$, which is incorporated into the calculated evolution of the galaxy model, is restricted in the first scenario of major merging by the inequality $\alpha < 1$, while, in the second scenario, the minor merging scenario, $\alpha = 2.4$ [172]. In general, all arguments indicate multiple minor merging as the only mechanism of significance for the evolution of massive elliptical galaxies in the last 10 billion years, and the astronomical community, including both observers and theorists, agreed unexpectedly quickly with this scenario. For theorists, perhaps, a convincing argument was that the same rapid growth in size is exhibited in cosmological models by dark halos merging in a hierarchical sequence, i.e., mostly absorbing small subhalos; consequently, it is only necessary to assume that the increase in the effective radius of the stellar system occurs synchronously with the increase in the radius of the dark halo [173].

4.3 Modern evolutionary scenario for elliptical galaxies

Figure 8 shows this scenario in the popular presentation of the NASA Public Gallery of Astronomical Pictures. We now review images in this picture, which represent the stages proposed for the evolution of giant elliptical galaxies. Shortly after the Big Bang (more precisely, after recombination), in the first billion years of the life of the Universe, 'merging' occurred, as a result of which compact stellar systems of mass $M_* = 10^{11} M_\odot$ were immediately formed. It is already at this step that the term 'merging' should not be trusted. Indeed, mergers occurred, but merging occurred with numerous gas fragments with masses corresponding to the Jeans mass at that time, implying that this is a classic monolithic collapse — à la Larson [4, 6]. As a result of this 'merging,' gas fragments collide inelastically, lose energy and momentum, build up at the gravitational potential center, and there, as a result of extremely efficient and intense star formation, form a compact stellar system. Such compact massive galaxies with a star formation rate of about 1000 solar masses per year are actually observed at redshifts $z > 3$ among submillimeter galaxies. The next proposed stage is labelled the '2 billion years' epoch (after the Big Bang). At this stage again, due to the flow of gas to the center, a central supermassive black hole, a quasar is activated in the galaxy center, and it is its activity that halts star formation in the surrounding galaxy through feedback, i.e., by injection of kinetic and thermal energy into the surrounding gas (Fig. 9). This moment is of utmost importance for the entire scenario. Indeed, between redshift $z = 4$ and redshift $z = 2.5$, a mass emergence of actively emitting quasars is observed in the Universe [174]. In the scenario of the evolution of elliptical galaxies, the impact from them is necessary to stop early star formation in the most massive galaxies, i.e., to ensure that by now they all exhibit an old stellar population. Moreover, the correlation of the mass of the central black hole with the mass of the galaxy, which is observed in the nearby Universe, yields the qualitatively correct effect: the more massive the galaxy, the more massive its black hole, the brighter (and earlier [174]) its quasar ignites, the more energy it releases, and the faster it halts star formation. We obtain the correct slopes of the mass–stellar population age and mass–star formation duration correlations, which are also observed for elliptical galaxies of the nearby Universe [125]. After the star formation stops at redshift $z = 2-2.5$, elliptical galaxies enter the longest evolutionary phase, passive aging of the stellar population and a steep increase in size due to multiple fallout of gas-free satellites onto the galaxy. And, if a satellite with gas falls, students ask me. If the amount of gas is noticeable, this galaxy will cease to be elliptical and will grow a disk around itself. No wonder there are so few elliptical galaxies in the nearby Universe, only 3%–5% of all galaxies, since they need a rare, gas-free evolutionary trajectory for the last 10 billion years.

The described scenario, arguably the most successful and widely accepted by the community of researchers of galaxies, contains, however, an unconfirmed point: this is feedback, the impact of quasars, which should suppress star formation. For the successful integration of the empirical scenario of the

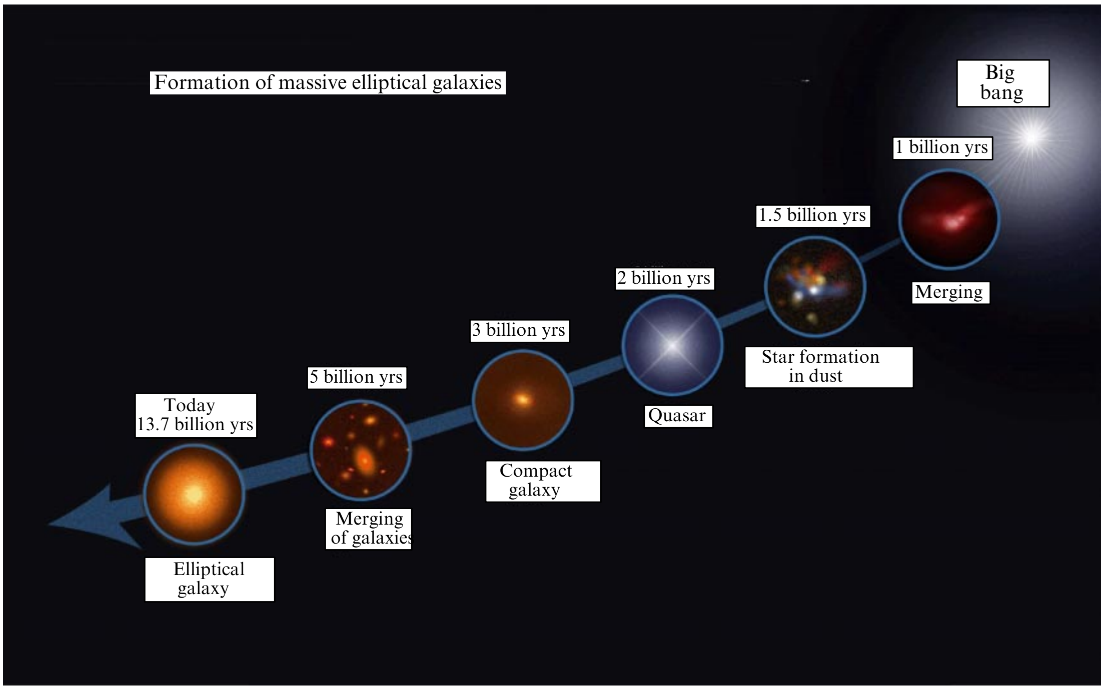

Figure 8. Modern concept of the formation and evolution of giant elliptical galaxies. (Illustration courtesy of NASA Image Galleries, public collection.)

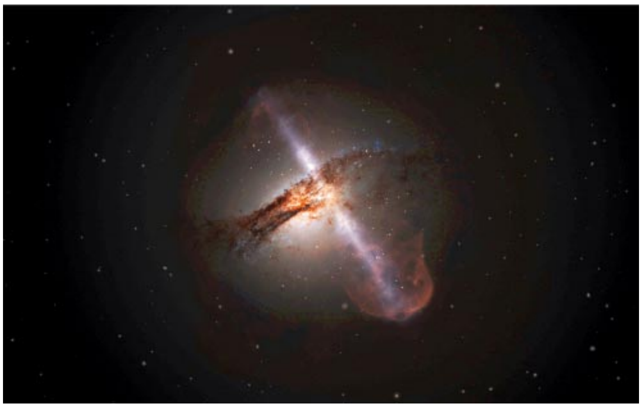

Figure 9. Artist's rendering of the impact of the active galaxy nucleus on the interstellar medium surrounding it by means of a collimated high-energy spout, a jet. (Illustration courtesy of NASA Image Galleries, public collection.)

formation of elliptical galaxies into the cosmological context, it is absolutely necessary to reconcile the theoretical hierarchical concept of the growth of dark halos with the observed anti-hierarchy in the evolution of galaxies, i.e., to relocate all evolutionary processes from massive galaxies in the young Universe to low–mass galaxies in the modern era. However, it has not yet been possible to obtain observational evidence that active nuclei — supermassive black holes in the stage of noticeable energy release — suppress star formation in galaxies. A special task was assigned to the Herschel infrared space telescope, which conducted a survey of sites already explored earlier by X-ray telescopes, in particular Chandra: to find the anti-correlation of the star formation rate with the X-ray flux from the active nucleus. No such anti-correlation has been found. Moreover, it is in the host galaxies of active nuclei that the most frequent and strongest bursts of star formation are observed at redshifts of up to $z \sim 4$ [175]. A recent survey of distant galaxies, $1 < z < 3$, at submillimeter wavelengths in the SCUBA-2 project found no relationship between star formation rates and X-ray emission from active nuclei [176]. Some hope was aroused by the detection with the ALMA interferometer of powerful outflows of gas from active nuclei, because, if the active nucleus ejects gas from its surroundings, star formation should stop due to the lack of material for the formation of new stars. However, panoramic spectroscopy of these host galaxies, which host quasars at a redshift of 2.4, showed that star formation proceeds at an accelerated rate around the cavities cleared by outflows, and there are no reasons to introduce suppression of star formation on a galaxy-wide scale [177]. The issue of negative feedback between quasars and star formation remains unresolved.

5. Which came first, the chicken or the egg, or an empirical view of the formation of central black holes in galaxies

The discovery of a correlation between the mass of the central black hole and the mass of the spheroidal host galaxy has given rise to many models of their co-growth. Fitting perfectly into the general cosmological context, they hypothesized two main mechanisms for synchronizing the growth of the mass of the central black hole and the galaxy. The major merging, as the main dynamic event that forms an elliptical galaxy, assumed a concurrent proportional increase in mass (doubling) for both the black hole and the galaxy [178]. The same event should have caused the concentration of all the gas of merging disk galaxies in the center of the merger product, followed by a simultaneous burst of star formation and the ignition of the active nucleus. In turn, the active nucleus stopped star formation in galaxy models through feedback, and again a correlation was obtained between the increase in the mass of the black hole due to gas accretion and the increase in the mass of the galaxy bulge due to central star formation [179]. This harmonious scenario was supported by the great similarity of the cosmic history of star formation and the evolution of the total X-ray luminosity of quasars per unit volume in the Universe [114] (both histories feature a maximum around $z \sim 2$), and therefore was very popular in the 2000s. However, in parallel, there was another, less popular, scenario, which nonetheless was suggested by very authoritative theorists [180], according to which it was black holes with a million solar masses each that were the first to appear in the Universe and were formed even before galaxies due to the same classical monolithic collapse of a large gas cloud. This scenario eventually turned out to be timely.

5.1 Premises for revolution: supermassive black holes at large redshifts

Again in the 2000s, observational material on the masses of black holes in the most distant quasars at redshifts of more than six was actively collected. As a result of SDSS, DES, DECaLS, PanSTARRS, SHELLQs, and HSC-SSP mass photometric surveys of the sky, many dozens of objects have been discovered. More precisely, about 200 quasars at $z \geqslant 6$ are now known [181]. Half of the distant quasars studied in detail (and even most of them at $z > 6.5$) have turned out to be the hosts of very massive black holes, each with a mass of a billion solar masses or more [182–187]! There is apparently also a selection effect: bright quasars are detected first. Nevertheless, it is only normalization rather than the shape of the luminosity function of quasars that evolves between $z = 6$ and $z = 4$ [188], which implies that the average mass of a black hole in quasars remains about the same, a billion solar masses in the brightest of them. For a black hole to gain such a mass in less than one billion years after the Big Bang, very specific conditions were required. In any case, due to the unhurried growth in the model of galaxy mergers in the hierarchical concept, central black holes did not have time to gain a mass of $10^9 M_\odot$ at $z = 6-7$. If an assumption is made that the black holes of quasars gained their mass exponentially through the accretion of gas on them, this accretion should have occurred at a near-Eddington rate and started at redshifts $z = 30-40$ from seed black holes with a mass of 100 solar masses or more [181]. Growth scenarios are considered in [189] for five fairly modest quasars found with the SUBARU telescope (SHELLQs survey) in the redshift range $6.1 < z < 6.7$, with masses from $6 \times 10^8 M_\odot$ to $2 \times 10^9 M_\odot$. It turns out that, accreting at the Eddington limit, these quasars can grow from 'seeds' that had a mass of $10^2 - 10^3 M_\odot$ at a redshift of 30. Such seeds can emerge as remnants of the evolution of stars of so-called population III, i.e., stars of the very first generation, each of which was formed in its personal dark halo with a mass of $10^5 - 10^6 M_\odot$ from a gas with zero metallicity. These objects, due to the specifics of cooling of zero-metallicity gas, should have significantly larger masses than modern stars [190]. However, many theorists are skeptical about the possibility of long-term subsequent accretion of gas onto such seeds at the Eddington limit, since the gravitational potential of the parent halo of an individual population-III star is very shallow, and powerful feedback from the active nucleus (release of kinetic energy into the environment) will prevent accretion of gas to a black hole. Therefore, more massive 'seeds,' $10^4 - 10^6 M_\odot$, are also considered; proposed for them are various scenarios of 'direct collapse' of either a purely gaseous cloud or a dense primordial cluster of stars with the ejection of some members of the cluster.

5.2 Independent emergence of supermassive black holes

The formation of 'seed' black holes with a mass of up to $10^5 M_\odot$ is often referred to as the 'direct monolithic collapse' of a gas cloud, but this term is not entirely accurate. Let us discuss the formation of a supermassive star in the center of a dark halo, up to $10^5 - 10^6 M_\odot$, which evolves very quickly and collapses into a black hole of approximately the same mass [191]. The formation of such a massive super(proto) star requires flows of hot gas with a temperature of about 10^4 K, since it is only due to constant heating of the gas, which may not contain metals or dust, that it is possible to avoid fragmentation of the accretion flow and the disk into many smaller protostars. Many mechanisms for such heating have now been proposed. If the halo with the emerging superstar is in a dense environment, there may be a nearby protogalaxy with intense star formation, which, via the ultraviolet radiation of its young stars, will destroy the H_2 molecules in the neighboring halo. Molecular hydrogen is the only effective coolant for zero-metallicity gas, so destroying it will stop gas cooling and prevent fragmentation. All the gas will flow down into the central object in a diffuse flow [192]. There are other options for heating a collapsing gas cloud, for example, by a violent collision or merger of smaller clouds (dark halos) [193] or by a rate of baryon inflow increased in comparison to the dark matter [194]. It is also important that gas accretion onto the central object proceed at a high rate, at least $\sim 0.1 M_\odot$per year. In this case, the central object swells, the temperature drops, thermonuclear reactions fail to start, and the feedback from the energy release of the star does not slow down accretion [195]. If cooling nevertheless occurs and the cloud has fragmented, even then it is still possible to obtain 'seed' black holes with a mass of $10^3 - 10^4 M_\odot$. Star clusters with a mass of $10^5 - 10^6 M_\odot$ formed from a gas with the primordial chemical composition have a high density. The times of collision of stars inside the clusters are less than the time of evolution of stars. Therefore, cluster stars are expected to clump even at the protostar stage, especially if the protostars are immersed in dense gas and gas accretion continues; due to this, protostars increase their radius, i.e., the collision cross section [196]. Under such conditions, the cluster rapidly collapses into a single black hole like intermediate-mass black holes, $10^3 - 10^4 M_\odot$.

Finally, there is always the scenario of primordial black holes formed approximately 1 s after the Big Bang, at the stage when weak interactions are separated. The typical limiting mass of such primordial black holes is also about $10^5 M_\odot$ [197, 198], and they can later gather stellar systems around themselves [199].

Further, from these seeds, in 700–900 million years, a black hole can grow with a mass of a billion solar masses, especially if supercritical accretion is possible for at least a short time, which can be realized in some regimes [200]. In this case, black holes will apparently be formed in the full range of masses, but the most massive of them will reach the very observational limit that is now so impressive to theorists. Interestingly, in most scenarios, the formation and initial growth of a black hole in the center of a dark halo are only possible if star formation in its vicinity is suppressed; thus, the central black hole is first formed, and only much later, after hundreds of millions of years, does the galaxy start growing around the black hole. However, observations indicate that, already at $z = 7$, star formation in the center of the quasar's host galaxy is under way, at a rate of up to a thousand solar masses per year [201]. How then does the central black hole grow further, and why is such a strong proportional relationship between the mass of the black hole and the mass of the spheroidal component of the galaxy finally established?

5.3 Evolution of supermassive black holes

As noted in Section 4.3, the statistics on star formation rates and radiation manifestations of the central black hole in galaxies do not directly show a correlation at any redshifts whatsoever, up to $z \sim 4$ [202, 203]. However, according to physics logic in its entirety, such an (anti)correlation should exist: not a single cosmological model of the evolution of the Universe is being developed now without the suppression of star formation in massive galaxies due to the activity of the nucleus. Theorists invented an explanation for this apparent contradiction: the so-called 'activity cycle' of an active nucleus, i.e., the fraction of time that a supermassive black hole spends in a state of activity is significantly less than unity, and the characteristic on/off time of accretion onto it is significantly less than 100 million years. Since star formation on a galaxy scale is more inertial, it is not possible now to see an active nucleus in a galaxy in which this very nucleus was active only twenty million years ago and succeeded in suppressing star formation during this time. The difference between the time scale of star formation and that of nucleus activity obscures any correlation. This is probably true in reality, since the distributions of the accretion rates of active nuclei (measured from the X-ray flux) are very broad, even for galaxies of the same mass at the same redshift [204]. Actually, having available these distributions built on the basis of a high-quality sample of several hundred active nuclei and assuming that in individual galaxies we notice (or do not notice) a short episode of gas accretion onto a central black hole, both the 'activity cycle' of the active nucleus and the average accretion rate integrated over time can be estimated. Since the opinion has now prevailed that central black holes increase their mass almost exclusively due to accretion, a large number of statistics on active nuclei can be used to trace the relationship between the rate of mass gain by a central black hole and the global characteristics of the galaxy, for example, the star formation rate. This system has recently been implemented using a sample of more than 120,000 galaxies in the CANDELS survey, among which 364 active nuclei have been identified by X-rays [204]. Extremely interesting results were obtained, which need to be analyzed. For example, for galaxies belonging to the main sequence, the higher the rate of accretion onto the central black hole, the higher the star formation rate, and this correlation is observed at all redshifts. When large redshifts, $z > 2$, are reached, the average accretion rate increases, but the normalization of the main sequence increases as well. According to modern concepts of the evolution of disk galaxies (see below), this result is understandable: both star formation and nucleus activity are maintained by the same cold gas that entered the disk of a galaxy from outside. Due to problems related to hindered acquisition of momentum, the nucleus obtains 1000–2000 times smaller amount of this gas that a large-scale stellar disk does. It is here that the puzzle appears. The galaxies below the main sequence, in which, according to the general belief, star formation is quenched (while actually it is only suppressed by one or two orders of magnitude), also exhibit a correlation between the rates of accretion onto a black hole and the star formation rate; however, the accretion rates in this dependence are one and a half to two orders of magnitude larger than those in the dependence for disk galaxies extrapolated to low star formation rates [205]. Massive passive galaxies apparently have a different and more efficient main source of 'fuel' for the nucleus activity. No reasonable hypothesis regarding this mechanism has been proposed so far [205].

5.4 Forecasts of the scenario for supermassive black holes...

Models that describe the co-evolution of galaxies and their central black holes have primarily been classified as cosmological physical and cosmological semi-analytical. It is worth mentioning a very popular series of papers by Philip Hopkins et al. [206, 207], where the emphasis was placed on reproducing luminosity functions at various redshifts and on mergers as the main mechanisms for the growth of the mass of black holes and elliptical galaxies. However, these articles were published in 2008, even before the scenario for the evolution of elliptical galaxies radically changed. It was believed at that time that major merging plays a decisive role in the life of massive elliptical galaxies, which also inspired the development of the corresponding scenario for the growth of black holes. Next, a whole set of semi-analytical models appeared, which explained the anti-hierarchy (downsizing) of active nuclei already in the new paradigm; see, for example, [208–210]. Similar to other semi-analytical models, they included very diverse, ad hoc assumptions and failed to explain the complete set of observational dependences. Since the breakthrough with data on quasars at large redshifts occurred quite recently and literally in the last five years the results of several deep mass photometric surveys of distant galaxies have appeared, an empirical model of the evolution of central black holes in conjunction with the properties of host galaxies in the full range of redshifts is being created right now and its development can be observed. The first approach to this problem proposed recently has appeared.

Many of the authors of the observational papers cited above are involved in the model called TRINITY. To date, only the first part of the work that describes the basic principles of the model has been published [211]. In the near future, six more articles about TRINITY are scheduled, in which various aspects of the model will be detailed. The model is really very complex. It is sufficient to say that in parameterizing various links between scaling relations, the authors sequentially introduce 48 free parameters — 28 for galaxies and 20 for their central black holes — and all of them are then determined by minimizing the deviations between the predicted scaling relations and those observed. This empirical model, however, starts from an absolutely purely cosmological theory: the history of the merger of dark halos in simulations of the evolution of the large-scale structure of the Universe by the N-body method. Associated with the dark halo mass is the rate of star formation in the galaxy. This step, of course, involves some arbitrariness, since observations only provide the relationship between the star formation rate and the mass of the stellar component of the galaxy rather than its dynamic mass. However, this arbitrariness makes it possible to immediately launch simulations of the history of the formation of the stellar component in galaxies on the scale of the entire Universe, since simulations unambiguously reconstruct the history of the 'assembly' of dark halos of different masses. Generally speaking, because of such a calculation basis, the TRINITY model cannot be considered completely empirical, although the authors reveal this shortcoming in the first lines of the abstract of their article. Like the previously mentioned model of the gas regulator proposed by Lilly et al. [30], the TRINITY model is close to the class of semi-analytical ones. Nevertheless, the number of observed scaling relations included in the model is really impressive and prompts the conclusion that this model contains more astronomical observations than does the cosmological theory. The cosmological piece of TRINITY itself was already formulated earlier in a semi-analytical model for the evolution of galaxies [212], and now TRINITY has been complemented with the evolution of central black holes. So, the mass distribution of dark halos evolves, parametrized star formation occurs in them, and the stellar mass of galaxies is formed. The empirical connection of the stellar mass of a galaxy with the mass of its bulge, found earlier for various redshifts, is used to make a transition to the masses of the bulges, and from them to the masses of the central black holes via the corresponding scaling relation. For black holes of various masses, the 'activity cycle' is known from observational statistics, along with the distribution of accretion rates, which yields the observed energy release of active nuclei. At all stages of building the model, compliance with the observations of the following scaling relations is checked, including the stellar mass function of galaxies at various redshifts, the complete history of star formation in the Universe, the main sequence of star formation rates at various redshifts, the luminosity function of quasars at various redshifts, and the mass distribution of black holes in active nuclei at various redshifts. Eventually, the authors find the model that is optimal in all 48 parameters and check its prediction regarding the growth of black holes. Even though the model allows black holes to merge, since dark halos do merge anyway, mass gain from mergers typically contributes less than a percent to a black hole's mass growth. The main mechanism for the growth of a central black hole in a galaxy is gas accretion (which manifests itself in observations as the activity of the galaxy nucleus). In addition, since dark halos grow hierarchically, galaxies are also allowed to grow on average. However, the bulge mass black–hole mass relation at large redshifts should have been much steeper than now, which makes it possible to obtain in the model black holes weighing a billion solar masses at $z = 6-7$, even in relatively small galaxies. In galaxies with star formation, the manifestation of nucleus activity and global star formation itself are synchronized, but no attempt is made to separate them in the model. This star formation causes the removal of momentum from the gas and feeding of the central black hole, otherwise both processes are fed on an equal basis by the influx of gas into the galaxy from the outside. Finally, the ratio of the rate of gas accretion onto a black hole (the energy release of the active nucleus) to the star formation rate has been growing over the past billion years in the most massive galaxies, because star formation is fading in them, while the nucleus activity changes much more slowly. This implies that 'passive' galaxies have some source of cold gas for the central black hole which is not associated with star formation and does not feed this process. There are no hypotheses yet as to the nature of this source. It should be admitted that it is a little surprising that the model does not contain any scaling relation linking the mass of cold gas in the galaxy to its total mass; such scaling relations have already been built on the basis of observations for at least up to $z \sim 2$. In general, the TRINITY model seems to have linked, albeit with some effort, almost all scaling relations known for galaxies; however, many physical mechanisms that underlie these relationships remain unclear and, possibly, unknown.

6. Empirical scenario for the formation of disk galaxies

Finally, we proceed to the most global issue, the empirical scenario of the evolution of disk galaxies with star formation. As mentioned in Section 3, the largest number of scaling relations are known for this type of galaxy, and linking them all together into a single evolutionary scenario is a big challenge. However, astronomers are responding to this challenge increasingly more passionately, so now every self-respecting researcher of galaxies has an original and preferable approach of his/her own to the search for the key physical factors of their formation and evolution.

6.1 Key factors in the evolution of disk galaxies

For example, the organization of star formation, which is one of the key processes in the evolution of galaxies, at various scales can be described based on various assumptions about the nature of cold/cooling gas turbulence in disks. Bruce Elmegreen and his colleagues traditionally prefer to build the gas turbulence spectrum in galaxy disks on the basis of its gravitational instability (see, for example, [213]). However, Mark Krumholz et al. [214, 215] are proponents of the key role of feedback from star formation, since both the energy of young stars and the momentum of their ejected shells also make it possible to construct a self-consistent picture of the development of turbulence in a gas at various scales. Both approaches offer observational arguments, not to mention physical ones. Here, it would be appropriate to note that observational mapping of the kinematic properties of ionized gas in dwarf galaxies carried out in Russia supports the picture with the key role of feedback [216].

The determining factor in the evolution of disk galaxies is probably the constant influx of cold gas from outside into their disks. The discussion of cold gas accretion onto the disk, first of the Milky Way, and then of all spiral galaxies, started as early as the 1970s, triggered by a note by Richard Larson, a father of extragalactic astronomy [5]. Larson noted already then that the rate of accretion onto the Milky Way seems to roughly correspond to the star formation rate and, therefore, all the gas observed in the disk of the Galaxy was acquired by it quite recently as a result of accretion from outside. The observed evolution of the chemical composition of stars in the Milky Way disk also required such accretion: the constant chemical composition of the stars forming over 8 billion years and the absence of an age-metallicity correlation in the thin disk of the Milky Way [217] could be explained, given continuously ongoing nucleosynthesis in stars, only by the influx from outside of a gas with low-metallicity that does not exceed 10% of the solar one [218]. Another argument in favor of the mandatory feeding of the current star formation with gas from the outside appeared after it was discovered that the time of exhaustion of the current gas reservoirs of galaxies is short and is the same for all nearby spiral galaxies [103, 219]. The directly estimated and evolutionarily substantiated rate of gas influx from the outside in the case of, for example, the Milky Way turns out to be comparable to (albeit slightly lower than) the star formation rate in a thin disk over the past 10 billion years [220].

What could be the source of the constant influx of cold gas from the outside into the disks of galaxies? There are also several well-founded and popular answers to this question. The currently popular mechanism of minor merging can also operate successfully for spiral galaxies, just as it works for

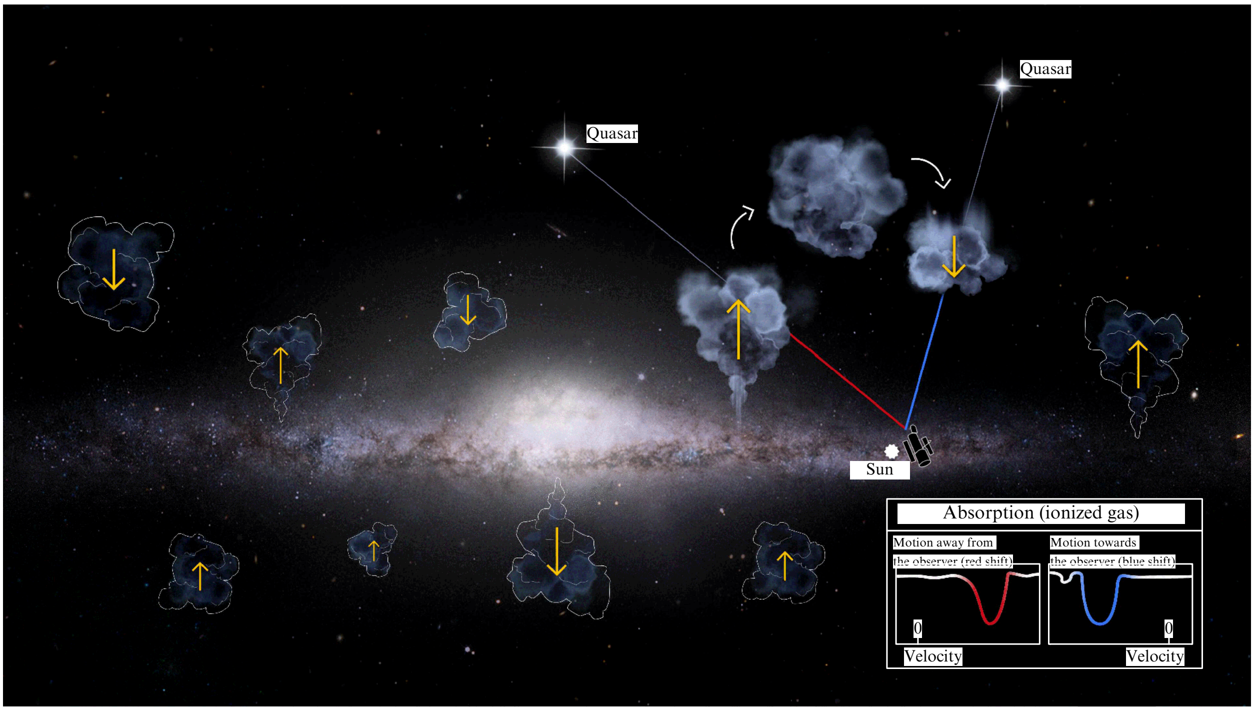

Figure 10. Artist's rendering of cold clouds of gas flying in the Milky Way halo observed in the absorption lines in the spectra of quasars, the beam of which passes through the cloud before reaching a telescope. Redshift value of these absorption lines is naturally close to zero. (Illustration courtesy of NASA Image Galleries, public collection.)

elliptical galaxies: if the evolution of elliptical galaxies requires multiple consummation of purely stellar dwarf systems, regularly repeated consumation of dwarf satellites with gas can provide feeding fuel for star formation. However, estimates reported, for example, by Sancisi et al. [221] presumably show that, given the average number of dwarf galaxies in the modern Universe, it is not possible to ensure the total volume of the necessary accretion of cold gas from the outside onto all modern spiral galaxies by means of the consumation of satellites alone. Cosmologists also contributed to the solution to the problem of sources of accretion. At $z = 0$, the distribution of gravitating matter in the Universe, according to modern model calculations, consists of numerous filaments between nodes that contain galaxies and clusters of galaxies. The formation of such an inhomogeneous large-scale structure of the Universe and the concept of a hierarchical assembly of dark halos make it possible to relate the influx of baryons from the outside into the galaxy with the arrival of dark matter through flows in filaments. Generally speaking, cosmologists propose two types of accretion: cold and hot. The difference is that, in the case of cold accretion, gas with a temperature not exceeding 10^4 K reaches the edge of the galaxy disk in a narrow stream [222]. In hot accretion, the gas first virializes inside the dark halo to X-ray temperatures and only subsequently, by cooling through radiation, undergoes accretion onto the galaxy disk over its entire expanse (see, for example, Refs [223, 224]). In both cases, accretion of primordial gas, with a metallicity close to zero, is considered. However, scenarios are available in the paradigm of accretion of hot virialized gas that provide accretion of a mixture of primordial gas and gas that passed through the stellar stage. For example, in recent years, Filippo Fraternali and co-authors have been actively developing such a scenario. To reduce the cooling time of the gas in the halo, in this scenario, a galactic fountain 'spouts' from the star-forming region in the disk; enriched gas from this region ascends into the halo and cools there. Moving through the hot primordial gas of the halo, the cooled clump from the fountain entrains some amount of hot primordial gas into its wake and falls back onto the disk with it [225]. The galaxy disk obtains in this way additional gas and additional momentum, since the place where gas returns to the disk is different from the place of its start. Such halo-flying clumps of cold gas near the Milky Way are identified with the so-called high-velocity clouds observed in the 21-cm neutral hydrogen line, and in absorption, in the background quasar spectra (Fig. 10).

6.2 Is everything determined by evolution of momentum?

Since the main kinetic energy of stars and gas in disk galaxies is the energy of regular rotation, and since the very structure (shape) of a large-scale disk of galaxies is determined by its angular momentum, the evolution of the disk galaxy momentum is also a key point in constructing an empirical model for the formation and evolution of disk galaxies. The point is that accreting baryons bring momentum with them, which is their orbital momentum [226]. The values of the momentum can strongly differ, depending both on the nature of accretion — the laminar flow of primordial gas along cosmological filaments brings more momentum than minor merging or hot accretion — and the direction from which the gas comes. This natural diversity currently greatly complicates our understanding of the dynamic evolution of disk galaxies. The accretion of external gas, as it is comprehended by cosmologists, is to a large extent a stochastic process, implying that the accretion geometry can and even must change in time. However, the dispersion in the Fall dependence is very small, and it is not clear how to 'squeeze' all these

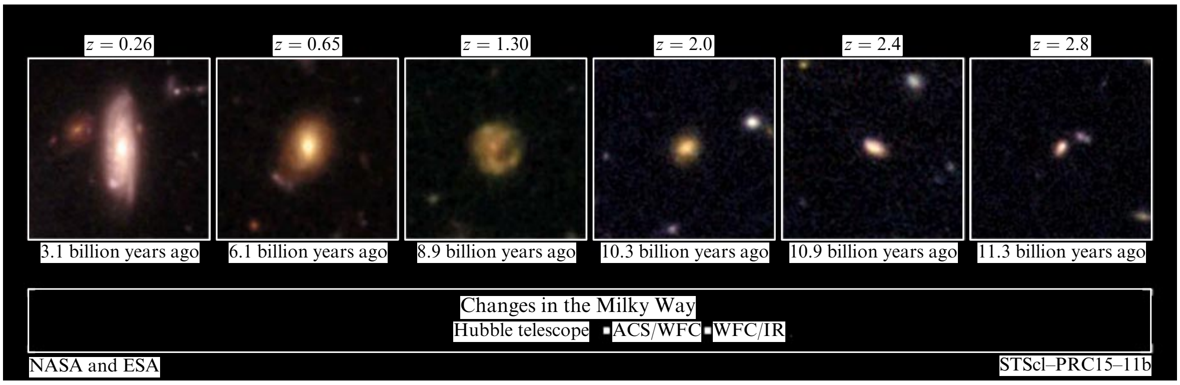

Figure 11. Modern scheme of the formation and evolution of giant spiral galaxies. (Illustration courtesy of NASA Image Galleries, public collection.)

stochastic features into such a small spread of galaxies around the dependence of the final angular momentum of the disk on its stellar mass. The very process of hierarchical growth of structures and dark halos in the cosmological models of the Universe is monotonic, while the observed evolutionary dependences exhibit some hints of the existence of 'watershed' redshifts, after which the dominant mechanisms of evolution probably alter. Such qualitative changes inevitably result in observed breaks in the evolutionary sequences of galaxy parameters. The evolution of galactic disk momentum just refers to 'inhomogeneous' evolutionary sequences. At a redshift of two, 10 billion years ago, gaseous galactic disks were thick and turbulent, and from them, in the course of very efficient star formation, with gas exhaustion times of the order of half a billion years, thick stellar disks were formed. Our Galaxy contains a thick stellar disk with a vertical scale of about 1.5 kpc, the stars are 10–11 billion years old, and the formation time (estimated based on the ratio of the abundances of alpha elements to iron) is less than 1 billion years. This seems to be the same relic disk, the formation of whose counterparts is observed at $z = 2$. Disks at $z = 2$ are supported by rotation, but they are significantly hotter in dynamic terms than disks of contemporary spiral galaxies: $V_{\rm rot}/\sigma_{\rm g} \approx 1$ then [227] versus $V_{\rm rot}/\sigma_{\rm g} \approx 7$ now. This evolution occurs mainly due to a decrease in the velocity dispersion of gas clouds over time, but the rotation rate also increases with time: for galaxies with mass $10^{10} M_{\odot}$ it has increased by a factor of 1.5 over the past 10 billion years [228]. Alvio Renzini estimated in his recent notes [229, 230] the rate of evolution of the angular momentum of disk galaxies with star formation (belonging to the main sequence) based on the most recent data on the rates of evolution of key parameters of galaxies. Since the momentum is $J \propto M_* V_{\rm rot} R_{\rm d}$, he multiplied an 8-fold increase in mass (the evolution of the galaxy along the main sequence) by a 1.5-fold increase in the rotational velocity and a 3-fold increase in radius over the last 10 billion years to conclude, taking into account all the dispersions and uncertainties, that the momentum of galactic disks has increased during the same time by a factor of 20 to 50. This value significantly exceeds the growth rate of the momentum of the parent dark halos of the same galaxies. The main growth of the momentum occurred in the epoch $z < 1$ [231], i.e., the last 8 billion years (Fig. 11). Indeed, the thin stellar disk of the Milky Way began to form exactly 8 billion years ago.

Where does the momentum to the disks of galaxies come from? The only natural answer is that it is delivered by accreting baryons. However, for the momentum to increase by a factor of 20–50 in 10 billion years, it is of importance to strictly constrain the geometry of baryon arrival: throughout this period, the external gas must arrive strictly in the plane of the galactic disk, and the direction of its orbital momentum must coincide with that of the momentum of the galactic disk rotation [229]. It is only under such conditions that modern spiral galaxies can be the main population of the galaxies of the nearby Universe. Observations of the kinematics of gas absorption lines 'eaten away' by extended gaseous disks of nearby, $z \sim 0$, giant spiral galaxies in the spectra of background quasars that are projected onto them seem to confirm such a dominant geometry of external gas accretion, i.e., occurring strictly in a plane and rotating with the inner region of the galaxy [232]. However, can such an accretion regime have persisted around every spiral galaxy during the last 8–10 billion years? Cosmologists are not yet ready to give a decisive answer. The only sign of hope offered by specialists in numerical modeling of the cosmological evolution of the Universe is a qualitative estimate of the momentum of accreting baryons. In all modern models (and analyzed in [233] were the results of the five currently most popular cosmological physical models), it turns out that a filamentary flow of cold gas approaching the boundary of an individual dark halo carries an orbital momentum which is, on average, 4 times larger than that of the concurrently accreting dark matter. This is due to the accretion geometry: the average spin of the inflowing cold gas at $z < 1.5$ reaches the value $\lambda_{\rm cold} \approx 0.12$ [233] compared to a general Universe-averaged value of 0.03. Another aspect of this mechanism is that, after this cold gas enters the dark halo, it is subject to very diverse interactions with its own hot halo gas, and the momentum may decrease, but these, as is commonly said, are nothing but details of implemented physics, and they can be changed if necessary ....

6.3 ...Or nevertheless is it the accretion regime that drives star formation? Evolution of lenticular galaxies

Finally, the now lively discussed issue of the evolution of disk galaxies, which in the present era do not have star formation: lenticular galaxies. All 'gas regulator' models refer to main-sequence galaxies. If galaxies below the main sequence are addressed, most researchers say the magic word 'quenching' and stop discussions. However, there is no agreement among theorists and interpreters regarding the nature of the mechanism of this very halting of star formation, which, according to most researchers, should result in the transformation of a spiral galaxy into a lenticular one, and the characteristic times of this process are unknown. It is surprising that this same expression, "the transformation of spiral galaxies into lenticular ones," is still in use by the broad masses of researchers, not paying attention to the fact that 25 years ago it was proven that spiral galaxies appeared as a morphological species only 8 billion years ago, when thin disks of galaxies began to form. As early as 10 years ago, it was found that the age of the disks of modern lenticular galaxies is more than 10 billion years [234, 235].

However, the now triumphant paradigm asserting that the evolution of disk galaxies is driven by the accretion of external gas on them, must offer a solution to the problem of the evolution of lenticular galaxies. The thick stellar disks of galaxies are formed at $z \sim 2$ from thick gaseous disks, while the gas exhaustion time at $z \sim 2$ on the main sequence is about 700 million years. This implies that, between $z \sim 2$ and $z \sim 1$, a whole population of disk galaxies is expected to appear, in which star formation quickly occurred and halted, since the internal gas reserves were completely exhausted. Later, at $z < 1$, everything depends on whether accretion of external cold gas on this disk galaxy continues. First, a disk galaxy can get into an environment where accretion is not possible. This environment may consist of clusters of galaxies, which begin to 'assemble' *en masse* just after $z = 1$. Inside the cluster radius, $\sim 2-3$ Mpc, everything is filled with hot intergalactic medium, and cold gas flows coming from outside should simply evaporate and dissolve before reaching the galaxies, members of the cluster. It is for this reason that most disk galaxies in modern clusters are lenticular, free of gas and star formation [236]. These lenticular galaxies have never been spiral; they are failed, incomplete galactic disks due to the absence of an influx of cold gas from the outside for the last 8 billion years [237]. As for field lenticular galaxies, which are much more numerous in the modern Universe than cluster lenticular galaxies, in most cases they contain cold gas, which apparently came from the outside [238]. However, only half of gas-rich lenticular galaxies exhibit signs of star formation, most often arranged into ring-shaped structures [239]. Based on studies of massive gaseous disks in nearby lenticular galaxies, we believe that it is related to the accretion geometry: if gas arrives not in the galaxy disk plane but at an angle, and sometimes even in the polar plane, it heats up when hitting the potential well of the galaxy disk and, having become hot, can no longer form stars [240]. However, Alvio Renzini, who was advancing in approximately the same direction, hypothesized that it may be related to the momentum of incoming gas: if this momentum is too large, the incoming gas must remain at the periphery of the galaxy, at large radii, where, however, there are few triggers for the start of star formation, and the gas density turns out to be insufficient for the development of gravitational instability [230]. Both mechanisms can prevent star formation in the available gas and the formation of a thin stellar disk necessary for the development of a spiral structure, despite the fact that accretion of external cold gas in lenticular galaxies of the field takes place.

7. Conclusion

The breathtaking development of observational technology in the last 20 years, purposefully focused on the study of galaxies at large redshifts in a wide range of wavelengths, has led to the accumulation of data that enabled direct tracing of the evolution of various characteristics of galaxies — structural, dynamic, and chemical — almost throughout the existence of the Universe. As a result, it is now possible to construct purely empirical scenarios for the formation and evolution of galaxies. Some of them were later smoothly integrated into the standard cosmological model, as, for example, the scenario of the origin and growth of central black holes. On the other hand, some of the scenarios, especially those related to the evolution of disk galaxies, still have a rather complicated relationship with the hierarchical paradigm, and these problems are gradually being solved by cosmologists by means of 'fine tuning' of the model of physical processes in the Universe. However, it should be admitted that at this stage it is the observational data, which are extended and updated every year, that are the engine of progress in streamlining our understanding of the evolution of galaxies.

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