detailed chemical analysis provided by WFMOS, we will, for the first time, be able to reunite the long-dispersed stars from ancient accretion events, completely dissecting the Milky Way and laying bare its history. We will then be able to directly determine to what extent the Galaxy was built from dwarf galaxies that fell in through the local cosmic web.

What are the future challenges in understanding our local cosmology? Clearly, we are entering the age where near-field archaeologists will be awash with observational data, and we will be faced with the kinematics of a billion stars and detailed chemistry of several million stars not only in the Milky Way but also within our nearest neighbors. The resulting data challenges are substantial, and novel data-mining techniques will be required to cross-match the kinematic and chemical fingerprints to uncover stellar siblings. But how are the results of this to be interpreted? Again, astronomers will have to rely on the power of numerical simulations to examine in detail the growth of the Milky Way through the continual accretion of dwarf galaxies. However, it is important to remember that a galaxy like our own Milky Way contains roughly 200 billion individual stars, embedded within a much more massive dark matter halo, and as of yet no computer can track the complex gravitational interplay between these many bodies. Hence, our current simulations, where a single particle will represent roughly 10 to 100 thousand stars, present us with an exceedingly crude, sledgehammer view of the subtleties of galaxy formation, and we will need a revolution in computer power before we truly understand the origins of the Milky Way galaxy and its relation to the cosmic web.

References

1. G. Smoot *et al.*, *Astrophys. J.* **396**, L1 (1992).
2. D. Spergel *et al.*, *Astrophys. J.* **170** (suppl.), 377 (2007).
3. V. Springel *et al.*, *Nature* **435**, 629 (2005).
4. J. Navarro, C. Frenk, S. White, *Astrophys. J.* **490**, 493 (1997).
5. A. Klypin, S. Shandarin, *Mon. Not. R. Astron. Soc.* **204**, 891 (1983).
6. B. Moore *et al.*, *Phys. Rev. D* **64**, 063508 (2001).
7. J. Diemand, B. Moore, J. Stadel, *Nature* **433**, 389 (2005).
8. S. Chapman *et al.*, *Astrophys. J.* **662**, L79 (2007).
9. S. Majewski *et al.*, *Astrophys. J.* **670**, L9 (2007).
10. R. Braun, D. Thilker, *Astron. Astrophys.* **417**, 421 (2004).
11. R. Ibata, G. Lewis, M. Irwin, E. Totten, T. Quinn, *Astrophys. J.* **551**, 294 (2001).
12. B. Yanny *et al.*, *Astrophys. J.* **540**, 825 (2000).
13. R. Ibata, M. Irwin, G. Lewis, A. Ferguson, N. Tanvir, *Nature* **412**, 49 (2001).
14. V. Belokurov *et al.*, *Astrophys. J.* **654**, 897 (2007).
15. B. Willman *et al.*, *Astrophys. J.* **626**, 85 (2005).
16. N. Martin *et al.*, *Mon. Not. R. Astron. Soc.* **371**, 1983 (2006).
17. A. Klypin, A. Kravtsov, O. Valenzuela, F. Prada, *Astrophys. J.* **522**, 82 (1999).
18. J. Bullock, A. Kravtsov, D. Weinberg, *Astrophys. J.* **539**, 517 (2000).
19. K. Venn *et al.*, *Astron. J.* **128**, 1177 (2004).
20. L. Sales, J. Navarro, M. Abadi, M. Steinmetz, *Mon. Not. R. Astron. Soc.* **379**, 1464 (2007).
21. K. Johnston, L. Hernquist, M. Bolte, *Astrophys. J.* **465**, 278 (1996).
22. K. Freeman, J. Bland-Hawthorn, *Annu. Rev. Astron. Astrophys.* **40**, 487 (2002).

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PERSPECTIVE

Numerical Simulations Unravel the Cosmic Web

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The universe is permeated by a network of filaments, sheets, and knots collectively forming a "cosmic web." The discovery of the cosmic web, especially through its signature of absorption of light from distant sources by neutral hydrogen in the intervening intergalactic medium, exemplifies the interplay between theory and experiment that drives science and is one of the great examples in which numerical simulations have played a key and decisive role. We recount the milestones in our understanding of cosmic structure; summarize its impact on astronomy, cosmology, and physics; and look ahead by outlining the challenges faced as we prepare to probe the cosmic web at new wavelengths.

Cosmologists envision a universe made up of filaments, knots, and sheets reminiscent of pancakes (*1*), dubbed the "cosmic web" by Bond and collaborators (*2*). This picture of the cosmos—now well entrenched even in popular culture—is, however, much more than mere fantasy. Indeed, it is one of the best-established results of cosmological research and underpins much of our contemporary understanding of large-scale structure and galaxy formation.

After Schmidt's spectroscopic observations of a distant quasar (a fantastically bright point source located at a cosmological distance, later understood to be powered by a supermassive black hole accreting from its host galaxy) in 1965 (*3*), Gunn and Peterson (*4*) and (independently) Scheuer (*5*) and Shklovski (*6*) pointed out that the spectra of distant quasars should show absorption by neutral hydrogen along the line of sight blueward of their Lyman-α (Lyα) emission line. Refining this calculation, Bahcall and Salpeter (*7*) argued that the clumpy intergalactic gas should give rise to a collection of discrete absorption lines, termed the "Lyα forest." The following year, observers, particularly Lynds and co-workers (*8*), indeed saw those lines.

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Their exact nature, however, gave rise to a more extended and heated debate. Were the lines—then poorly resolved—really of cosmological origin, or were they instead associated with the quasars themselves? The extreme conditions needed for quasar ejecta to produce the Lyα forest (*9*), the random redshift distribution of the absorption lines (*10*), as well as the association of metal-rich systems with intervening galaxies (*11*), eventually left no doubt that most of the Lyα clouds are in fact cosmological.

Inspired by research on the interstellar medium, the Lyα absorbers were originally envisioned as dense, cool clouds confined by pressure within a hotter, tenuous intercloud background (*12*, *13*). However, this model raised questions of its own, namely, how did the clouds form in the first place? Ultimately, the model simply failed to account for the observed distribution of neutral hydrogen column densities, and other confinement mechanisms involving gravity were also found unsatisfactory.

The key breakthrough in elucidating the nature of the Lyα forest came as astrophysicists tried to understand the formation of structure in the universe. In our current model of structure formation, tiny fluctuations in the primordial plasma grew through the gravitational instability, eventually forming a cosmic network of knots, filaments, and sheets. Because gravity is a purely attractive force, regions of slightly higher density in the early universe accrete matter from their surroundings and grow more overdense with time. As the universe evolves, the cosmic web sharpens: Underdense regions, known as voids, empty material onto the filaments, and this material subsequently flows into overdense knots (Fig. 1). On large scales, where gas pressure can be neglected, intergalactic neutral hydrogen should trace this web.

What if, then, the Lyα forest were simply a representation of the cosmic density field? This was a far-reaching question transcending intergalactic clouds, for its answer not only would provide a powerful test of structure formation models but also would potentially leave us with a new and exquisitely detailed astrophysical and cosmological probe.

After promising analytical calculations, particularly by Rees (*14*), suggested that absorption by gas confined in dark matter "mini-halos" could account for the basic properties of the Lyα forest, two major developments in the 1990s allowed astrophysicists to tackle the question with unprecedented precision: the advent of high-resolution spectrographs and numerical cosmological simulations. The new High Resolution Echelle Spectrometer (HIRES) spectrograph installed at the Keck Observatories on Mauna Kea, Hawaii, provided quasar spectra with fully resolved Lyα forests. At about the same time, the Cosmic Background Explorer (COBE) satellite had recently detected small anisotropies, subsequently mapped in sharp detail by the Wilkinson Microwave Anisotropy Probe (*15*), imprinted on the cosmic microwave background when the universe was only 400,000 years old (*16*). The COBE observations fueled efforts to model the growth of structure in the universe. Did the minuscule fluctuations in the very early universe observed by COBE actually evolve into the rich structure observed by astronomers? After advances in computer algorithms and technology, first-principles simulations traced the hydrodynamic evolution of cosmic structures from initial conditions motivated by the cosmic microwave background down to the current epoch [see discussion and references in (*17*)]. Zel'dovich did anticipate the cosmic network of filaments, knots, and sheets seen in the simulations. However, the detailed simulations turned the model into a quantitative one, with predictions worthy of comparison against the exacting data now available. Assuming that the Lyα forest originated from absorption by intervening neutral hydrogen, it was then straightforward to produce mock spectra, which could be tested directly against the actual observations (Fig. 2).

The results of these analyses showed that the simulations were exactly right. In particular, the calculations of (*18*, *19*) demonstrated correspondence between observations and theory over nearly eight orders of magnitude in the strength of the absorbing structures, at the time an unprecedented achievement in numerical cosmology. The level of agreement has only improved over the past decade as simulations and observations have been refined and as our knowledge of the underlying cosmological model has become firmer. The conclusion appears inescapable: The primordial fluctuations seen in the cosmic microwave background did grow by five orders of magnitude over billions of years, precisely as calculated, to form the observed cosmic web.

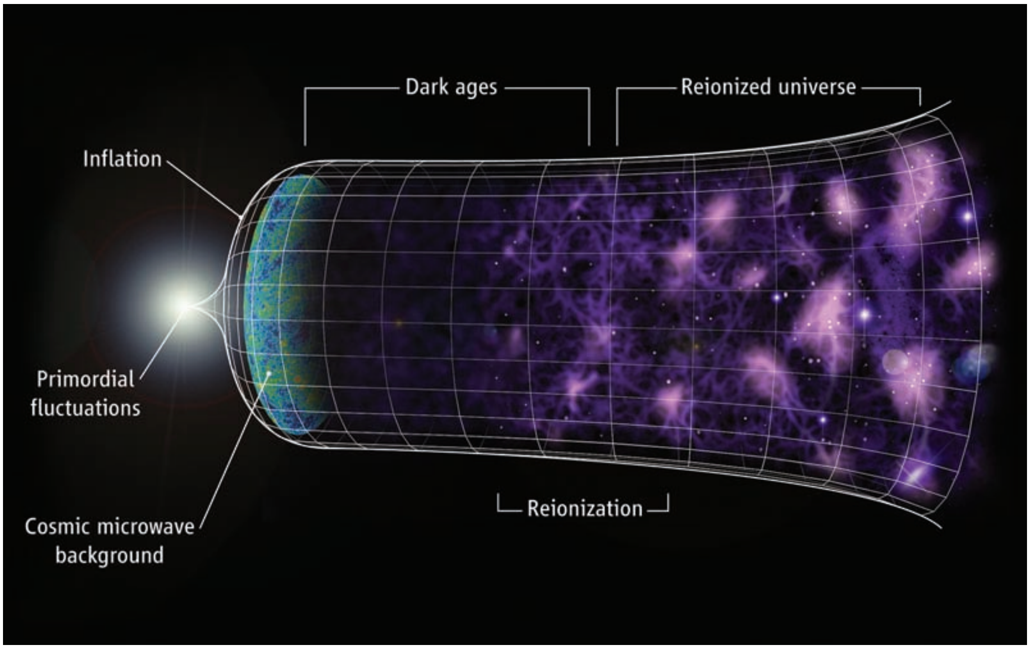

Fig. 1. View of the expanding universe illustrating the evolving cosmic web. Primordial fluctuations of quantum mechanical origin are stretched by an early superluminal phase of expansion known as "inflation." Four hundred thousand years after the Big Bang, these fluctuations imprint tiny anisotropies in the cosmic microwave background as electrons and protons combine to form neutral hydrogen. As the universe continues to expand, these fluctuations grow through the gravitational instability, eventually giving rise to the first stars and galaxies, whose radiation reionizes the intergalactic medium, thereby ending the cosmological "dark ages." The cosmic web sharpens as the universe becomes more mature and becomes visible in the Lyα forest and in the spatial distribution of galaxies.

The discovery of the cosmic web in the Lyα forest has had a broad and profound impact beyond confirming the gravitational instability paradigm for structure formation and explaining the basic properties of the intergalactic medium in a cosmological context. In current hierarchical models of structure formation, condensed objects such as galaxies are thought to form in the denser clumps of the cosmic web. The same numerical simulations that were so successful in explaining quasar absorption systems can thus be used to theoretically calculate the spatial distribution of galaxies, another prediction that can be put to stringent test by observations, and indeed has been vindicated by galaxy surveys. The intergalactic medium probed by current observations is almost fully ionized, owing to the ultraviolet radiation field from star-forming galaxies and the super-massive black holes powering quasars. The imprint of the cosmic web in the Lyα forest, arising from the small residual fraction of neutral gas, thus also traces the cosmic radiation content, providing a unique record of the cosmic history of star formation and black hole growth (*20*).

Observations of the cosmic web have reached beyond astrophysics and into fundamental physics as well. In the paradigm of structure formation that the Lyα forest has been instrumental in establishing, the cosmic web is nothing but an evolved snapshot of the tiny primordial fluctuations produced at the very beginning, in an epoch of "inflation" during which the universe expanded by more than 25 orders of magnitude in size. By measuring the detailed properties of the cosmic web, we can constrain the properties of inflation itself and the physical mechanisms driving it (*21*, *22*). In addition, an overwhelming number of lines of evidence, including galactic rotation curves, the velocity dispersions of galaxy clusters, and gravitational lensing, indicate that the cosmic matter budget is dominated by invisible "dark matter."

Owing to its lack of nongravitational interactions with the rest of the universe, however, the nature of dark matter remains largely a mystery. The leading dark matter candidate is an exotic particle, never yet observed in Earth-bound laboratories, generically referred to as a "weakly interacting massive particle," or WIMP. Observations of large-scale structure through galaxy surveys first ruled out the neutrino as a candidate for "hot" dark matter (*23*), leading to the present cold dark matter paradigm, and are now putting severe upper limits on the neutrino's mass (*24*). The Lyα forest, being more sensitive to smaller scales on

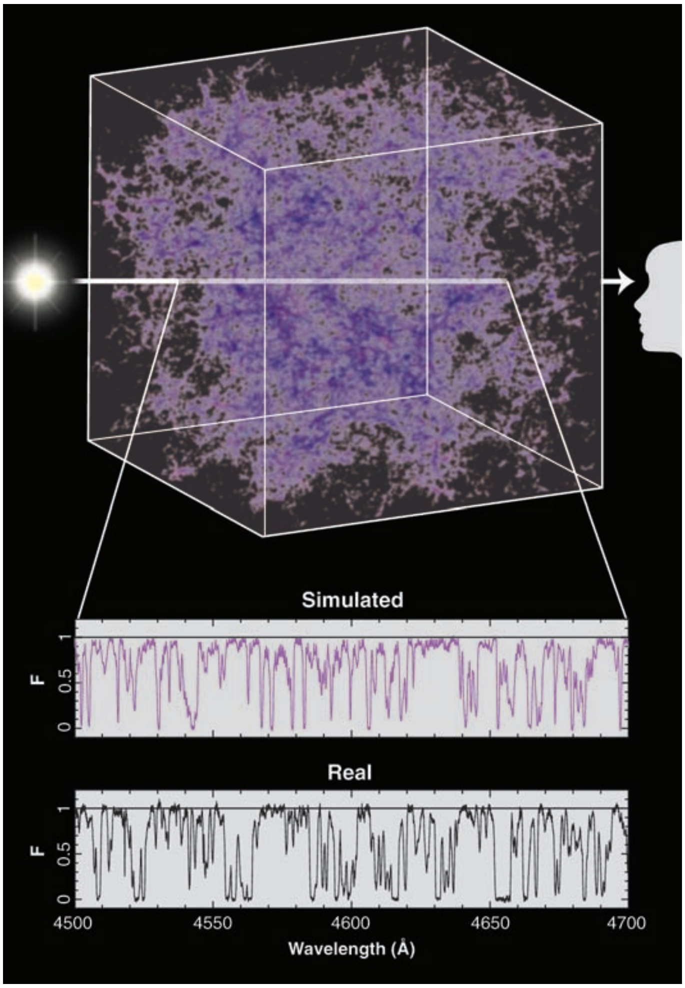

Fig. 2. Illustration of the Lyα forest. An observer looks at a distant quasar. Neutral hydrogen tracing the cosmic web produces absorption features, collectively known as the Lyα forest, in the quasar spectrum. The figure shows a line of sight through a cosmological simulation, with the resulting mock Lyα forest compared to the spectrum of an actual quasar, known as Q1422, and located at redshift $z = 3.6$ (spectrum courtesy of M. Rauch, Observatories of the Carnegie Institution of Washington, Pasadena, CA, and W. Sargent, California Institute of Technology, Pasadena, CA). The similarity between the mock and actual spectra is remarkable, unambiguously elucidating the nature of the Lyα forest as the imprint of cosmological fluctuations. Each spectrum has been normalized by its continuum level.

the order of 1 megaparsec, currently provides the most rigorous constraints on intermediate models of "warm," more massive, dark matter (*25*, *26*).

The bulk of research on cosmic structure, in particular from the Lyα forest and galaxy surveys, has thus far focused on observations in the optical part of the electromagnetic spectrum. Astronomy, however, is an increasingly multiwavelength endeavor, and the study of the cosmic web is poised to follow this trend as new frontiers are explored. Accordingly, new opportunities for novel theoretical calculations and observational discoveries abound.

One of the most exciting frontiers of contemporary cosmology is the early universe, when the first stars and galaxies formed and illuminated their surroundings. During this epoch of "reionization," electrons were unbound from hydrogen atoms (which had combined to become neutral at the time the anisotropies were imprinted in the cosmic microwave background) by ultraviolet radiation, which had begun filling intergalactic space. Neutral hydrogen before and during reionization can potentially be observed through its emission of 21-cm radio radiation. Several low-frequency observatories—such as the Murchison Widefield Array (MWA) in Western Australia, the Low Frequency Array (LOFAR) in the Netherlands and, ultimately, the Square Kilometer Array (SKA)—are being planned, constructed, or entering service to detect this redshifted emission. Simultaneously, ever more powerful infrared telescopes are attempting to discover the first sources of light directly. This is in fact a primary scientific goal of the James Webb Space Telescope, the Hubble Space Telescope's successor scheduled for launch in 2013, as well as of very large ground-based observatories.

New windows are also now opening on the lower-redshift universe. A new ultraviolet spectrograph, the Cosmic Origins Spectrograph (COS), will be installed aboard Hubble during its 2008 servicing mission and will provide a direct and detailed probe of the cosmic distribution of helium at intermediate redshifts. Because more energetic photons are required to doubly ionize helium, it is thought to have been fully ionized later than hydrogen, near the peak of quasar activity. The study of helium reionization thus promises to become a powerful probe of quasar activity and its feedback on the intergalactic medium in the very near future.

At still lower redshifts, the nonlinear growth of cosmic structure shocks the intergalactic medium, heating it to temperatures up to 10^7 K (*27*, *28*). The high temperatures in the local "warm-hot intergalactic medium," or WHIM, imply that yet heavier elements are ionized and hence that higher-energy wavelengths, including x-rays, are the probes of choice for this physical regime.

Each of these observations is, however, accompanied by theoretical challenges. The epochs of hydrogen and helium reionization involve nonequilibrium radiative transfer phenomena, which are only beginning to be included in cosmological simulations. Simulations must evolve large regions of the universe to overcome cosmic variance and capture the large scales of reionization, yet high resolution is needed to resolve the sources and sinks of radiation, as well as the clumpiness of the gas. At the present time, approximations are used to treat the problem with available computational resources and explore the important effects without resorting to prohibitive, fully self-consistent radiation hydrodynamics (*29*, *30*). Feedback processes such as galactic winds and metal enrichment are only crudely, if at all, included and may be particularly important to understand the low-redshift high-energy absorption. Moreover, star and galaxy formation and quasar activity are often modeled using prescriptions, which, albeit physically motivated, do not offer the satisfaction of ab initio calculations.

As the rich array of new and diverse observations promises a wealth of surprises, will the theoreticians be clever enough to provide results with true predictive power for the multiwavelength cosmic web?

References and Notes

1. Y. B. Zel'Dovich, *Astron. Astrophys.* **5**, 84 (1970).
2. J. R. Bond, L. Kofman, D. Pogosyan, *Nature* **380**, 603 (1996).
3. M. Schmidt, *Astrophys. J.* **141**, 1295 (1965).
4. J. E. Gunn, B. A. Peterson, *Astrophys. J.* **142**, 1633 (1965).
5. P. A. G. Scheuer, *Nature* **207**, 963 (1965).
6. I. S. Shklovskii, *Sov. Astron.* **8**, 638 (1965).
7. J. N. Bahcall, E. E. Salpeter, *Astrophys. J.* **142**, 1677 (1965).
8. E. M. Burbidge, C. R. Lynds, G. R. Burbidge, *Astrophys. J.* **144**, 447 (1966).
9. P. Goldreich, W. Sargent, *Comments Astrophys.* **6**, 133 (1976).
10. J. N. Bahcall, P. J. E. Peebles, *Astrophys. J.* **156**, L7 (1969).
11. J. Bergeron, *Astron. Astrophys.* **155**, L8 (1986).
12. W. L. W. Sargent, P. J. Young, A. Boksenberg, D. Tytler, *Astrophys. J. Suppl.* **42**, 41 (1980).
13. J. P. Ostriker, S. Ikeuchi, *Astrophys. J.* **268**, L63 (1983).
14. M. J. Rees, *Mon. Not. R. Astron. Soc.* **218**, 25P (1986).
15. D. N. Spergel *et al.*, *Astrophys. J. Suppl.* **148**, 175 (2003).
16. G. F. Smoot *et al.*, *Astrophys. J.* **396**, L1 (1992).
17. M. Rauch, *Annu. Rev. Astron. Astrophys.* **36**, 267 (1998).
18. L. Hernquist, N. Katz, D. H. Weinberg, J. Miralda-Escude, *Astrophys. J.* **457**, L51 (1996).
19. N. Katz, D. H. Weinberg, L. Hernquist, J. Miralda-Escude, *Astrophys. J.* **457**, L57 (1996).

20. M. Rauch et al., Astrophys. J. 489, 7 (1997).
21. R. A. C. Croft, D. H. Weinberg, N. Katz, L. Hernquist, Astrophys. J. 495, 44 (1998).
22. P. McDonald et al., Astrophys. J. 635, 761 (2005).
23. S. D. M. White, C. S. Frenk, M. Davis, Astrophys. J. 274, L1 (1983).
24. U. Seljak, A. Slosar, P. McDonald, J. Cosmol. Astropart. Phys. 10, 14 (2006).
25. M. Viel, J. Lesgourgues, M. G. Haehnelt, S. Matarrese, A. Riotto, Phys. Rev. Lett. 97, 071301 (2006).
26. U. Seljak, A. Makarov, P. McDonald, H. Trac, Phys. Rev. Lett. 97, 191303 (2006).
27. R. Cen, J. P. Ostriker, Astrophys. J. 514, 1 (1999).
28. R. Davé et al., Astrophys. J. 552, 473 (2001).
29. M. McQuinn et al., Mon. Not. R. Astron. Soc. 377, 1043 (2007).
30. O. Zahn et al., Astrophys. J. 654, 12 (2007).

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PERSPECTIVE

Missing Baryons and the Warm-Hot Intergalactic Medium

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Stars and gas in galaxies, hot intracluster medium, and intergalactic photo-ionized gas make up at most half of the baryons that are expected to be present in the universe. The majority of baryons are still missing and are expected to be hidden in a web of warm-hot intergalactic medium. This matter was shock-heated during the collapse of density perturbations that led to the formation of the relaxed structures that we see today. Finding the missing baryons and thereby producing a complete inventory of possibly the only detectable component of the energy-mass budget of the universe is crucial to validate or invalidate our standard cosmological model.

Despite recent progress in cosmology in assaying the energy and mass budget of the universe, very little is still known about the nature and origin of most of its constituents. Within the framework of our standard cosmological model (SCM) (*1*, *2*), most (95%) of the universe (or Ω, the mass density of the universe divided by the critical density required to close the universe) is composed primarily of "dark" energy (70%) and "dark" matter (25%), both dubbed "dark" as a reflection of our inability to directly detect and identify them. Less well known is that the situation is only marginally better for the universe's remaining 5% of detectable matter.

As baryons—the protons and atomic nuclei that constitute the ordinary matter of which stars, planets, and ourselves are made—this remaining matter should, in principle, be in a form that we can detect and measure in its physical state. We know from absorption line spectroscopy of distant quasars that clouds of baryons were present in the early universe about 10 billion years ago (redshift $z \cong 2$) (*3*, *4*)), in the form of photo-ionized diffuse intergalactic gas, accounting for at least three-quarters of the total baryon mass in the universe as inferred by both cosmic microwave background anisotropies (*1*, *2*) and "big-bang nucleosynthesis" predictions when combined with observed light-element ratios at $z > 2$ (*5*) ($\Omega_b > 3.5\%$, i.e., >73% of the estimated baryon mass in the universe). However, these clouds of photo-ionized intergalactic gas became more and more sparse as time moved toward the present and structures (galaxies, galaxy groups, and clusters) started to be assembled. Only a small fraction of the baryons that were present in the intergalactic medium at $z > 2$ are now found in stars, cold or warm interstellar matter, hot intracluster gas, and residual photo-ionized intergalactic medium. Today we can account for less than 50% of the baryon mass predicted by the SCM, implying that at least 50% of the baryons are now "missing" (*6*, *7*) (Fig. 1).

The leading theory of cosmological structure formation (known as Λ-CDM; or, cold dark matter models including dark energy, designated by the cosmological constant Λ) predicts that, as the universe evolves toward the present and density perturbation grows to form structures, baryons in the diffuse intergalactic medium accelerate toward the sites of structure formation under the growing influence of gravity and go through shocks that heat them to temperatures of millions of kelvin. These "missing baryons" may have become difficult to detect by being concentrated in a filamentary web of tenuous (baryon density

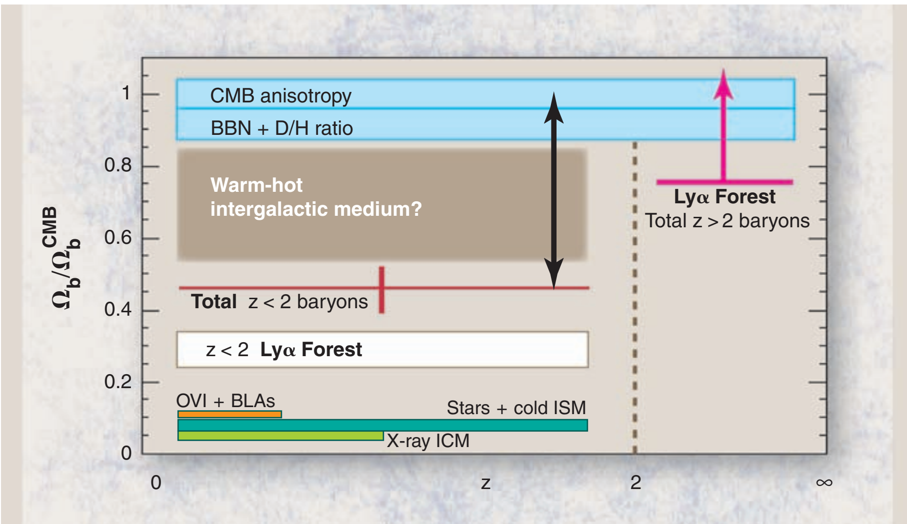

Fig. 1. Baryon density in the universe, at all redshifts, normalized to the cosmological mass density of baryons derived from cosmic microwave background (CMB) anisotropy measurements. Two completely independent measures, based on anisotropies of the CMB, on one hand, and on observations of the deuterium-to-hydrogen (D/H) ratio combined with big bang nucleosynthesis (BBN) models, on the other, nicely converge toward a total cosmological mass density of baryons in the universe of ~4.5% (cyan shaded rectangle). At redshifts $z > 2$, nearly all the expected baryons are found in the Lyα forest (magenta lower limit; the measure is a lower limit due to uncertainties in the ionization correction). At $z \leq 2$, however, adding up the baryons observed in stars and cold interstellar medium (ISM) in galaxies, residual low-z Lyα forest, OVI and BLA absorbers, and x-ray hot gas in clusters of galaxies accounts for less than half of the expected cosmological mass density of baryons in the universe (red point). The rest of the baryons still elude detection, and hence are "missing baryons." A theoretical solution to this problem has been relatively recently offered by hydrodynamical simulations for the formation of structures in the universe.

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