18. DARK MATTER

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18.1. Theory

The total mass-energy of the Universe is composed of several constituents, each of which may be characterized by its energy density $\rho_i \equiv \Omega_i \rho_c$ and its pressure $p_i \equiv w_i \rho_i$. Here $\rho_c \equiv 3H_0^2/8\pi G_N$ is the critical density, and H_0 is the present value of the Hubble parameter. We will take $H_0 = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ when a numerical value is needed; then $\rho_c = 5.2 \times 10^{-6}\,\mathrm{GeV/cm^3}$. We can express the total density as $\rho_0 = \Omega_0 \rho_c$, where $\Omega_0 = \sum_i \Omega_i$. The deceleration parameter $q_0 \equiv (-\ddot{R}/R)_0/H_0^2$, where $R(t)$ is the scale factor and the subscript 0 denotes the present value, is then given by $q_0 = \frac{1}{2}\Omega_0 + \frac{3}{2}\sum_i \Omega_i w_i$.

In general, relativistic particles have an equation of state specified by $w = +\frac{1}{3}$, nonrelativistic particles have $w = 0$, and the cosmological constant (here treated as another form of matter) has $w = -1$. Spatially uniform scalar fields which are oscillating rapidly in time (that is, with a frequency much greater than the Hubble parameter H_0) also have $w = 0$. Spatially uniform scalar fields which are changing slowly in time have $-1 < w < 0$. Certain contributions to the mass density are well determined. The photons of the cosmic microwave background radiation (CMB) have $\rho_\gamma = \frac{\pi^2}{15} T_0^4$, where $T_0 = 2.73\,\mathrm{K} = 2.35 \times 10^{-4}\,\mathrm{eV}$ is the present temperature of the CMB; this yields $\Omega_\gamma = 5.1 \times 10^{-5}$. Results from Big-Bang nucleosynthesis indicate that the total baryon density is $\Omega_B = 0.039 \pm 0.004$; roughly 10% of this is accounted for by stars. A single species of neutrino with a Majorana mass m_ν would have $\Omega_\nu = 0.56\, G_N T_0^3 H_0^{-2} m_\nu = m_\nu/(45\,\mathrm{eV})$ and $w_\nu = 0$ if $m_\nu \gg T_0$. In the other limit $\Omega_\nu = 0.23\,\Omega_\gamma$ and $w_\nu = \frac{1}{3}$ if $m_\nu \ll T_0$.

There is strong evidence from a variety of different observations for a large amount of dark matter in the Universe [1]. The phrase "dark matter" signifies matter whose existence has been inferred only through its gravitational effects. Two categories should be distinguished: baryonic dark matter, composed of baryons which are not seen (including black holes formed by stellar collapse), and nonbaryonic dark matter, composed either of massive neutrinos, or of elementary particles or fields which are as yet undiscovered (including primordial black holes). The particles or fields which comprise nonbaryonic dark matter must have survived from the Big Bang, and therefore must either be stable or have lifetimes in excess of the current age of the Universe.

There are a number of different observations which indicate the presence of dark matter (baryonic or nonbaryonic). These include rotation curves of spiral galaxies [2]; in these measurements, the circular velocity $v_{\rm c}$ of matter surrounding the galaxy is measured (via Doppler shift of spectral lines) as a function of radius r. If there were no dark matter, at large r we would find $v_{\rm c}^2 \simeq G_{\rm N} M_{\rm vis}/r$, since the visible mass $M_{\rm vis}$ of a spiral galaxy is concentrated at its center. However, observations of many spiral galaxies instead find a velocity $v_{\rm c}$ which is independent of r at large r, with a typical value $v_{\rm c} \sim 200\,{\rm km/sec}$. Such a "flat rotation curve" implies that the total mass within radius r grows linearly with r, $M_{\rm tot}(r) \simeq G_{\rm N}^{-1} v_{\rm c}^2 r$, and hence a density profile that falls off like $1/r^2$ at large r, indicating a "halo" of dark matter. A self-gravitating ball of ideal gas at a uniform temperature of $kT = \frac{1}{2} m_{\rm dm} v_{\rm c}^2$ would have this mass profile; here $m_{\rm dm}$ is the mass of one dark matter particle. An important question is what happens at radii both much smaller (since the local density cannot be infinite) and much larger (since the total mass cannot be infinite). Numerical simulations of halo formation indicate a density profile that has a cusp at small radius, $\rho_{\rm halo}(r) \sim r^{-\alpha}$ with $\alpha = 1$ [3] or $\alpha = 1.5$ [4], and falls off like $1/r^3$ at large radius. Present observational data appears inconsistent with these cuspy halos (see *e.g.*, Ref. 5 for a summary). In our Galaxy, estimates of the local density of dark matter typically give $\rho_{\rm dm} \simeq 0.3\,{\rm GeV/cm^3}$. but this result depends on the details of the halo profile.

An estimate of the total pressureless matter density Ω_M (that is, of all components, baryonic and nonbaryonic, with $w_i = 0$) can be made in several ways (for more details see "Global Cosmological Parameters" in Sec. 17 of this *Review*), with the result $\Omega_M = 0.3 \pm 0.1$. For example, the baryonic mass of a rich cluster of galaxies can be inferred from x-ray emissions, and the total mass from galactic velocities (via the virial theorem) or gas dynamics. Assuming that the ratio of these masses is typical of the Universe as a whole, we obtain the value of Ω_M/Ω_B. Using the nucleosynthesis value of Ω_B then yields $\Omega_M = 0.3 \pm 0.1$. This is consistent with a number of other estimates of Ω_M, such as from mass-to-light ratios for clusters and from large-scale velocity fields. This value of Ω_M would imply that 70% of the pressureless matter in the Universe is nonbaryonic.

An estimate of the total density Ω_0 can be made from fluctuations in the CMB (see "Big-Bang Cosmology" in Sec. 15 of this *Review*), The first acoustic peak in the power spectrum of these fluctuations is predicted to occur at a multipole $\ell \sim 220\,\Omega_0^{-1/2}$; current data yields $\Omega_0 = 1.02 \pm 0.05$. This is consistent with the generic prediction $\Omega_0 = 1$ of inflationary models.

Type Ia supernovae can be used as standard candles to get information on the relationship between redshift and distance [6]. If we assume that the dominant contributions to Ω_0 are from pressureless matter and an unknown component X, then the results require $w_X < -0.6$ (at the 95% CL, ignoring any systematic errors). Assuming $w_X = -1$ (a cosmological constant), the results constrain the combination $0.8\,\Omega_M - 0.6\,\Omega_X$ to be -0.2 ± 0.1.

None of these observations give us any direct indication of the nature of the dark matter. The halos of galaxies could have significant fractions of baryonic dark matter in the form of remnants (white dwarfs, neutron stars, black holes) of an early generation of massive stars, or smaller objects which never initiated nuclear burning (and would therefore have masses less than about $0.1\,M_\odot$). These massive compact halo objects are collectively called MACHOs. Results from searches via gravitational lensing effects [7] show that MACHOs with masses from $10^{-6}\,M_\odot$ to $0.1\,M_\odot$ each are not a significant component of our Galaxy's halo. However, the results also indicate that MACHOs with masses of approximately $0.4\,M_\odot$ comprise roughly 20% of the total mass of the halo. This situation is difficult to reconcile with models of star formation.

For purposes of galaxy formation models [8], nonbaryonic dark matter is classified as "hot" or "cold," depending on whether the dark matter particles were relativistic or nonrelativistic at the time when the horizon of the Universe enclosed enough matter to form a galaxy. If the dark matter particles are in thermal equilibrium with the baryons and radiation, then only the mass of a dark matter particle is relevant to knowing whether the dark matter is hot or cold, with the dividing line being $m_{\rm dm} \sim 1\,{\rm keV}$. In addition, specifying a model requires giving the power spectrum of initial density fluctuations. Inflationary models generically predict a power spectrum which is nearly scale invariant. With these inputs, galaxy formation models require primarily cold dark matter, with significantly less hot dark matter. However, either a negative-pressure component or some hot dark matter is needed in addition to cold dark matter. For example, a model with $\Omega_{\rm cdm} = 0.3$, $\Omega_{\rm hdm} = 0$, $\Omega_X = 0.7$ and $w_X = -0.6$ gives a good fit to all current data [9].

There is a constraint on neutrinos (or any light fermions) if they are to comprise the halos of dwarf galaxies: the Fermi–Dirac distribution in phase space restricts the number of neutrinos that can be put into a halo [10], and this implies a lower limit on the neutrino mass of roughly $m_\nu > 80\,{\rm eV}$.

There are no presently known particles which could be cold dark matter. However, many proposed extensions of the Standard Model predict a stable (or sufficiently long lived) particle. The key question then becomes the predicted value of $\Omega_{\rm cdm}$.

If the particle is its own antiparticle (or there are particles and antiparticles present in equal numbers), and these particles were in thermal equilibrium with radiation at least until they became nonrelativistic, then their relic abundance is determined by their annihilation cross section $\sigma_{\rm ann}$: $\Omega_{\rm cdm} \sim G_{\rm N}^{3/2} T_0^3 H_0^{-2} \langle \sigma_{\rm ann} v_{\rm rel} \rangle^{-1}$ (see Ref. 11 for a review). Here $v_{\rm rel}$ is the relative velocity of the two incoming dark matter particles, and the angle brackets denote an averaging over a thermal distribution of velocities for each at the freeze-out temperature $T_{\rm fr}$ when the dark matter particles go out of thermal equilibrium with radiation; typically $T_{\rm fr} \simeq \frac{1}{20} m_{\rm dm}$. One then finds (putting in appropriate numerical factors) that $\Omega_{\rm cdm} \simeq 7 \times 10^{-27}\,{\rm cm^3\,s^{-1}} / \langle \sigma_{\rm ann} v_{\rm rel} \rangle$. The value of $\langle \sigma_{\rm ann} v_{\rm rel} \rangle$ needed for $\Omega_{\rm cdm} \simeq 1$ is remarkably close to what one would expect for a weakly interacting massive particle (WIMP) with a mass of $m_{\rm dm} = 100\,{\rm GeV}$: $\langle \sigma_{\rm ann} v_{\rm rel} \rangle \sim \alpha^2 / 8\pi m_{\rm dm}^2 \sim 3 \times 10^{-27}\,{\rm cm^3\,s^{-1}}$.

If the dark matter particle is not its own antiparticle, and the number of particles minus antiparticles is conserved, then an initial asymmetry in the abundances of particles and antiparticles will be preserved, and can give relic abundances much larger than those predicted above.

If the dark matter particles were never in thermal equilibrium with radiation, then their abundance today must be calculated in some other way, and will in general depend on the precise initial conditions which are assumed.

The two best known and most studied cold dark matter candidates are the lightest supersymmetric particle (LSP) and the axion. The Minimal Supersymmetric extension of the Standard Model, or MSSM (see "Supersymmetry" in the Search Listings of the *Review of Particle Physics*) predicts (among many other as yet undiscovered particles) four neutral, massive Majorana fermions; these mass eigenstates are linear combinations of the superpartners of the photon, the Z^0 boson, and two neutral Higgs bosons. In the MSSM, interactions conserve the number of new particles modulo two (this is called R-parity conservation), and so the lightest new particle (the LSP) is stable. If it is a neutralino, it qualifies as a WIMP, with a theoretically expected mass in the range of tens to hundreds of GeV. Because of the complexity of the parameter space of the MSSM, it is difficult to state general results on the relic density of LSPs; in minimal supergravity models (which have a greatly reduced parameter space), it is possible to have parameters consistent with all experimental constraints and $\Omega_{\rm LSP} \sim 0.3$ for $m_{\rm LSP}$ in a range from ~ 100 to $\sim 600\,\mathrm{GeV}$ [12].

The axion is predicted by extensions of the Standard Model which resolve the strong CP problem (see "Axions and other Very Light Bosons" in the Boson Listings of the *Review of Particle Physics*). Axions can occur in the early universe in the form of a Bose condensate which never comes into thermal equilibrium. The axions in this condensate are always nonrelativistic, and can be a significant component of the dark matter if the axion mass is approximately $10^{-5}\,\mathrm{eV}$. Axions can also arise from the decay of a network of axion strings and domain walls.

Both the LSP and the axion would behave as collisionless particles for the purposes of structure formation, and hence would be expected to form cuspy halos. Because of the observational problems with cuspy halos, forms of cold dark matter with significant self-interactions have recently been proposed [13], and this is currently a subject of active research.

18.2. Experiment

18.2.1. *Status of WIMP Direct Searches*:

WIMPs interact with normal matter by elastic scattering from nuclei. The energy deposited by the resulting recoil nuclei or atoms has a characteristic exponential spectrum. This is determined mainly by the kinematics of the interaction, the WIMP mass relative to that of the recoiling nuclei and the velocity of the WIMP, determined by the velocity of the Earth through the Galactic halo [14]. The favored range of WIMP masses, velocities and likely cross sections (for instance for MSSM) lead to recoil spectra expected to have energy ranging from a few keV up to a few hundred keV with rate $< 1\ \mathrm{kg}^{-1}\mathrm{day}^{-1}$. The latter rate is typically 10^6 times lower than the ambient rate from background electron recoils due to gammas from surrounding natural radioactivity.

These characteristics determine basic requirements of direct detection technology, the need for low energy threshold, and some means of identifying genuine recoils from the much higher rate of background electron recoils. The latter is feasible in principle because the rate of energy loss with distance (dE/dx) for electrons is typically $\times 10$ lower than for nuclear recoils [15]. However, any neutrons present, such as those produced by cosmic ray muons, can produce background nuclear recoils indistinguishable from those expected from WIMP interactions. Therefore, it is essential also that direct WIMP searches be performed in deep underground sites, typically > 1000 meters water equivalent (m.w.e.), where this flux is negligible or can be sufficiently reduced using neutron shielding.

Several technologies hold out prospects for achieving the requirements above but the most favored at present are ionization, scintillation, and low-temperature bolometric devices. Germanium ionization detectors, used initially for double beta decay searches, set the first limits. Of recent note have been the Heidelberg-Moscow detector and the HDMS prototype Ge detectors [16] operating at Gran Sasso. These have produced currently competitive limits. However, detectors using ionization alone have no means of actively distinguishing nuclear recoils from electron background. Hence only limits can be set, based on the measured continuum background. The recent development of Ge detectors have thus tended to concentrate on material purification, in an effort to reduce intrinsic radioactivity. However, development towards larger mass Ge (10–100 kg), exemplified by the GENIUS proposal [17] and others [18], may allow observation of the expected annual modulation of the dark matter event rate arising from the earth's varying speed through the Galaxy.

Scintillation and low temperature detectors provide a route to the required additional information for recoil identification. In the former, in crystal scintillators or liquid noble gases, the high dE/dx for nuclear recoils results in pulse decay times 30–50% shorter than for electrons. Statistical analysis can then be used to identify a population of faster events. First limits using this idea were set in 1994–95 with NaI detectors. Recently the Rome group (DAMA), operating 100 kg of NaI at Gran Sasso, has reported an annual fluctuation in the total count rate over 4 years. They interpret this as consistent with the annual fluctuation predicted for WIMPs [19,20]. This is not yet widely accepted because the technique does not separate nuclear recoils from the much larger low-energy background which, in principle, could be subject to other modulating systematics [21].

Several experiments based on counting contained events in low temperature bolometers are underway and have set limits, notably by CRESST and the Milan group [22–24]. Of greater significance are schemes in which nuclear recoil identification is achieved in bolometric detectors by combining with simultaneous observation of ionization or scintillation. The former is used by the CDMS-I and Edelweiss experiments, the latter is being developed by CRESST [25,26]. The CDMS experiment, although not yet located deep underground and hence needing neutron background subtraction, has obtained data that appear to exclude the Rome result [27]. They reach a spin-independent WIMP-nucleon limit around 2×10^{-6} pb in the mass range 20–100 GeV. Edelweiss have also released results that significantly cut into the Rome allowed region but with the advantage that no neutron subtraction is needed as they already operate deep underground, at the Modane site [28].

New generations of experiment are being developed now aimed at sensitivity improvements by factors of 10–1000 over 2–5 years. Notable also is the growing interest in liquid Xe. For instance, a 1000 kg liquid Xe detector is being designed by the UKDM team to set limits below 10^{-9} pb [29]. Other novel techniques, in particular using superheated droplet detectors, may also eventually prove very sensitive but ultimately the most convincing demonstration of the existence of WIMPs would be correlation of the direction of nuclear recoils with our motion through the Galaxy. The most promising technique to achieve this is by means of a low pressure Time Projection Chamber in which recoil tracks of a few mm length can be imaged. A UK/US collaboration is now running such a device with a 1 m^3 volume called DRIFT-I [30,31]. Such a directional dark matter detector offers the prospect of a dark matter "telescope" able to distinguish possible different velocity components of the dark matter, a suggested possibility [32].

18.2.2. *Status of WIMP Indirect Searches*:

If WIMPs are Majorana neutralinos then pair annihilations can occur. It may be possible to detect the resulting neutrinos, gamma rays, positrons or antiprotons. Such indirect detection of WIMPs is quite complementary to direct observation though much more model dependent, affected for instance by possible non-Maxwellian velocity components in the halo. Indirect searches can be more sensitive to high mass WIMPs, while neutralino models which produce low direct detection rates can sometimes produce substantial annihilation rates, for example through the gamma-gamma channel [33]. The most likely scenario is a search for high energy neutrino signals from the Sun, Earth, or Galactic center, where the WIMP density may be sufficiently enhanced by gravitational capture. The halo may provide a further source if the dark matter is clumpy [34]. Neutrinos, like annihilation gammas, have the advantage of maintaining their original direction.

The ν-$\overline{\nu}$ channel is probably the most easily detected. Observation of muon neutrinos provide the best hope for observing the neutrino channel, since the resulting upgoing muons produced in the Earth have long range in present Čerenkov neutrino detectors such as AMANDA [35] (and larger detectors planned for the future), and can be distinguished from background down-going atmospheric muons. The Sun is a particularly favorable source, and since it is predominantly hydrogen the predicted muon rates are relatively easy to calculate. However, calculations have been made for both Sun and Earth [38].

Present neutrino experiments have already provided limits on the solar and terrestrial neutrino-induced muon flux that are sufficient to constrain MSSM models [39,40]. Limits in the range 10^3–10^4 muons km^{-2}yr^{-1} are found for the Sun above 10^2 GeV and down to 10^3 muons km^{-2}yr^{-1} above 10^3 GeV for the Earth [41]. The latter limit is sufficient to indicate a possible contradiction with the DAMA direct search signal. A recent analysis by the SuperK collaboration to produce a WIMP-nucleon cross section limit using combined Sun, Earth and Galactic center data also appears to exclude parts of the DAMA-allowed region [42].

Searches for antiprotons, positrons, and gamma rays from annihilation in the halo are also underway. The former two channels are hindered by uncertainty in galactic propagation models and the featureless nature of predicted spectra. Nevertheless balloon-borne experiments to search for neutralino annihilation antiprotons at the top of the atmosphere have been performed, for instance Bess and Caprice [43–45], to provide comparison with predictions of secondary antiproton background [46]. Despite large possible systematic effects, such as from cosmic-ray induced antiprotons, interesting limits can be placed for the highest annihilation rates [33]. Balloon observations of the positron continuum have also been performed [47–49].

Although very sensitive to the local neutralino halo density, annihilation gamma-ray lines from the halo can be observed in principle by existing or planned air Čerenkov detectors (ATCs). This technique may be the only one available to probe for heavy (TeV) stable neutralinos. The ATCs have acceptance angles suitable for searches of possible Galactic center signals. The high energy resolution of GLAST makes it suitable for high precision line searches [50,51].

18.2.3. *Axion Searches*:

Axion in the mass range 10^{-5} eV $\lesssim m \lesssim 10^{-2}$ eV are viable dark matter candidates. The mass constraints come mainly from cosmological and stellar arguments, including the dynamics of The axion couples so weakly to matter that direct interactions in conventional detectors cannot be used to identify a signal. However, it does couple to two photons via intermediate quark states. This leads to the possibility of resonant conversion between an axion and a photon in the presence of a strong magnetic field [52]. A detector can thus be devised comprising a volume of high magnetic field containing microwave cavities that can be tuned to scan through the likely axion mass range. First stage experiments where run in the 1990's using this technique [53,54] but where unable to reach the predicted coupling strength for the two principal theoretical models, KSVZ and the lower-strength DFSZ [55]. However, two new experiments are reaching the required sensitivity for parts of the mass range, or can do so with further upgrades. Notable is the large-scale US halo axion detector. This initially excluded the KSVZ axion mass range 2.9 μeV–3.3 μeV at the 90% CL [56]. Imminent further data should extend this limit down to around 2.2 μeV and then exclude the full KSVZ up to about 8 μeV. The use of SQUID amplifiers opens the possibility of someday excluding the lower DFSZ model [57].

An alternative technique has been developed by the Kyoto group, where Rydberg atoms are used to detect the axion-converted photons [58]. The Kyoto CARRACK I detector has performed an axion search around 10 μeV, and it is planned that CARRACK II will expand the mass window to 2μeV–50μeV. The DFSZ limit throughout the mass range might be reached in a few years [59].

Similarly, a radio-telescope search for axions has recently ruled out the mass range 298–363 μeV at the 96% CL with an axion-to-two photon coupling of $g_{\alpha\gamma\gamma} > 1.0 \times 10^{-9}$ GeV^{-1} [60].

18.2.4. *Neutrinos with Mass*:

Neutrinos could be a significant component of dark matter if their masses where in the approximate range 1–50 eV. $m_\nu \gtrsim 20$ eV would mean that neutrinos are dominant. This scenario is disfavored on cosmological grounds because neutrinos behave like hot dark matter [61], implying that structure forms from the top down, in contrast to observation.

Mass limits based on decay kinematics provide upper limits in the MeV range for neutrinos produced in association with tau or muon decay, while tritium decay sets an effective mass limit of 2.8 eV for whatever mass eigenstate combination is produced in the decay.

The disappearence of atmospheric neutrinos passing through the earth can be interpreted as the result of mass eigenstate mixing with a squared mass difference in the range of 10^{-3} eV^2 [64,65]. Recent results from SNO strongly indicate that solar neutrinos produced in association with electrons can interact as τ or μ neutrinos, in this case indicating a mass difference of $< 10^{-3}$ eV^2 [66]. This difference, together with the tritium decay result, limits the sum of the mass eigenvalues of active neutrinos to be between 0.05 and 8.4 eV, so that $0.001 \lesssim \Omega_\nu \lesssim 0.18$ for the neutrino contribution to the critical density of the universe.

18.2.5. *Baryonic Searches*:

The success of Big Bang nucleosynthesis in predicting the light element abundances only works if the baryon density parameter $\Omega_B h^2$ lies in the range 0.007–0.022, where h is the Hubble parameter in units of 100 km s^{-1}Mpc^{-1} (see section BIGBANGNUC). This range is well below unity, even if relaxed by models of inhomogeneous nucleosynthesis [67]. It is also greater than the density of luminous (baryonic) matter, implying the existence of non-baryonic dark matter. In clusters these dark baryons almost certainly exist as hot, x-ray emitting intracluster gas [69,70]. Within galaxies, including our own, the dark baryons may be in diffuse gas dark stars. The latter, in the form of white dwarfs, neutron stars, black holes or other objects with mass too low to produce hydrogen burning, correspond to the class know as Massive Compact Halo Objects or MACHOs.

Extensive searches for MACHOs have been undertaken using gravitational lensing near the Galaxy by several large teams, MACHO [71], EROS [72], and OGLE [73]. Millions of stars in the LMC and SMC are monitored for the characteristic intensity magnification when a massive object passes directly in the line of sight between observer and star. The detection of MACHO events depends critically on the selection criteria used. There is also degeneracy in the parameters extracted, so that for a given event one cannot determine both the lens distance and the lens mass. Statistical methods are thus required to estimate a MACHO halo fraction and typical MACHO mass [74]. All three MACHO search collaborations have detected events. The results now indicate that a 100% MACHO halo is ruled out at 95% CL, though there could be a 20% contribution in the halo [74,75].

The most likely MACHO mass inferred from the lensing results is 0.15 M$_\odot$ to 0.9 M$_\odot$ [74]. There is thus a mystery because such objects should be luminous. A recently claim for a population of white dwarfs has been made [76], but there are problems with this scenario. For instance, the star formation rate required to produce them is much higher than normally measured, and anyway an alternative interpretation of the MACHO events is an as-yet undetected component in the LMC [75]. Thus there are many uncertainties and the possibility remains that the baryonic component of our galaxy, which is clearly not 100% MACHOs, may be gas, as in clusters but cooler ($T \sim 10^5$K) and hence difficult to detect. This is consistent with numerical simulations suggesting that most baryons should still be in gaseous form [77].

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