From Little Bangs to the Big Bang

John Ellis
Theory Division, Physics Department, CERN, CH-1211 Geneva 23, Switzerland
E-mail: john.ellis@cern.ch CERN-PH-TH/2005-070 astro-ph/0504501

Abstract.

The ‘Little Bangs’ made in particle collider experiments reproduce the conditions in the Big Bang when the age of the Universe was a fraction of a second. It is thought that matter was generated, the structures in the Universe were formed and cold dark matter froze out during this very early epoch when the equation of state of the Universe was dominated by the quark-gluon plasma (QGP). Future Little Bangs may reveal the mechanism of matter generation and the nature of cold dark matter. Knowledge of the QGP will be an essential ingredient in quantitative understanding of the very early Universe.

1. The Universe is Expanding

The expansion of the Universe was first established by Hubble’s discovery that distant galaxies are receding from us, with redshifts proportional to their relative distances from us. Extrapolating the present expansion backwards, there is good evidence that the Universe was once 3000 times smaller and hotter than today, provided by the cosmic microwave background (CMB) radiation. This has a thermal distribution and is very isotropic, and is thought to have been released when electrons combined with ions from the primordial electromagnetic plasma to form atoms. The observed small dipole anisotropy is due to the Earth’s motion relative to this cosmic microwave background, and the very small anisotropies found by the COBE satellite are thought to have led to the formation of structures in the Universe, as discussed later [1].

Extrapolating further back in time, there is good evidence that the Universe was once a billion times smaller and hotter than today, provided by the abundances of light elements cooked in the Big Bang [2]. The Universe contains about 24% by mass of $^4$He, and somewhat less Deuterium, $^3$He and $^7$Li. These could only have been cooked by nuclear reactions in the very early Universe, when it was a billion times smaller and hotter than today. The detailed light-element abundances depend on the amount of matter in the Universe, and comparison between observations and calculations suggests that there is not enough matter to stop the present expansion, or even to explain the amount of matter in the galaxies and their clusters. The calculations of the light-element abundances also depend on the number of particle types, and in particular on the number of different neutrino types. This is now known from particle collider experiments to be three [3], with a corresponding number of charged leptons and quark pairs.

2. The Very Early Universe and the Quark-Gluon Plasma

When the Universe was very young: $t \rightarrow 0$, also the scale factor $a$ characterizing its size would have been very small: $a \rightarrow 0$, and the temperature $T$ would have been very large, with
characteristic relativistic particle energies $E \sim T$. In normal adiabatic expansion, $T \sim 1/a$, and, while the energy density of the Universe was dominated by relativistic matter, $t \sim 1/T^2$. The following are some rough orders of magnitude: when the Universe had an age $t \sim 1$ second, the temperature was $T \sim 10,000,000,000$ degrees, and characteristic thermal energies were $E \sim 1$ MeV, comparable with the mass of the electron. It is clear that one needs particle physics to describe the earlier history of the Universe [1].

The very early Universe was presumably filled with primordial quark-gluon plasma (QGP). When the Universe was a few microseconds old, it is thought to have exited from this QGP phase, with the available quarks and gluons combining to make mesons and baryons. The primordial QGP would have had a very low baryon chemical potential $\mu$. Experiments with RHIC reproduce cosmological conditions more closely than did previous SPS experiments, as seen in Fig. 1 and the LHC will provide [4] an even closer approximation to the primordial QGP. I shall not discuss here the prospects for discovering quark matter inside dense astrophysical objects such as neutron stars, which would have a much larger baryon chemical potential.

![Phase Diagram](image)

**Figure 1.** The phase diagram of hot and dense QCD for different values of the baryon chemical potential $\mu$ and temperature $T$ [5], illustrating the physics reaches of SPS, RHIC and the ALICE experiment at the LHC [4].

To what extent can information about the early Universe cast light on the quark-hadron phase transition? The latest lattice simulations of QCD with two light flavours $u, d$ and one moderately heavy flavour $s$ suggest that there was no strong first-order transition. Instead, there was probably a cross-over between the quark and hadron phases, see, for example, Fig. 2 [5], during which the smooth expansion of the Universe is unlikely to have been modified substantially. Specifically, it is not thought that this transition would have induced inhomogeneities large enough to have detectable consequences today.

### 3. Open Cosmological Questions
The Standard Model of cosmology leaves many important questions unanswered. **Why is the Universe so big and old?** Measurements by the WMAP satellite, in particular, indicate that its age is about 14,000,000,000 years [6]. **Why is its geometry nearly Euclidean?** Recent data indicate that it is almost flat, close to the borderline for eternal expansion. **Where did the matter come from?** The cosmological nucleosynthesis scenario indicates that there is approximately one proton in the Universe today for every $1,000,000,000$ photons, and no detectable amount
Figure 2. The growth of the QCD pressure with temperature, for different values of the baryon chemical potential $\mu$ \textsuperscript{[5]}. The rise is quite smooth, indication that there is not a strong first-order phase transition, and probably no dramatic consequences in the early Universe.

of antimatter. How did cosmological structures form? If they did indeed form from the ripples observed in the CMB, how did these originate? What is the nature of the invisible dark matter thought to fill the Universe? Its presence is thought to have been essential for the amplification of the primordial perturbations in the CMB.

It is clear that one needs particle physics to answer these questions, and that their solutions would have operated in a Universe filled with QGP.

4. A Strange Recipe for a Universe
According to the ‘Concordance Model’ suggested by a multitude of astrophysical and cosmological observations, the total density of the Universe is very close to the critical value: $\Omega_{\text{Tot}} = 1.02 \pm 0.02$, as illustrated in Fig. 3 \textsuperscript{[6]}. The theory of cosmological inflation suggests that the density should be indistinguishable from the critical value, and this is supported by measurements of the CMB. On the other hand, the baryon density is small, as inferred not only from Big-Bang nucleosynthesis but also and independently from the CMB: $\Omega_{\text{Baryons}} \sim \text{few\%}$.

The CMB information on these two quantities comes from observations of peaks in the fluctuation spectrum in specific partial waves corresponding to certain angular scales: the position of the first peak is sensitive to $\Omega_{\text{Tot}}$, and the relative heights of subsequent peaks are sensitive to $\Omega_{\text{Baryons}}$. The fraction $\Omega_m$ of the critical density provided by all forms of matter is not very well constrained by the CMB data alone, but is quite tightly constrained by combining them with observations of high-redshift supernovae \textsuperscript{[7]} and/or large-scale structures \textsuperscript{[8]}, each of which favours $\Omega_{\text{Matter}} \sim 0.3$, as also seen in Fig. 3.

As seen in Fig. 4 there is good agreement between BBN calculations and astrophysical observations for the Deuterium and $^4$He abundances \textsuperscript{[2]}. The agreement for $^7$Li is less striking, though not disastrously bad \textsuperscript{1}. The good agreement between the corresponding

\textsuperscript{1} It seems unlikely that the low abundance of $^7$Li observed could have been modified significantly by the decays.
determinations of $\Omega_{\text{Baryons}}$ obtained from CMB and Big-Bang nucleosynthesis calculations in conventional homogeneous cosmology imposes important constraints on inhomogeneous models of nucleosynthesis. In particular, they exclude the possibility that $\Omega_{\text{Baryons}}$ might constitute a large fraction of $\Omega_{\text{Tot}}$. Significant inhomogeneities might have been generated at the quark-hadron phase transition, if it was strongly first-order [10]. Although, as already discussed, lattice calculations suggest that this is rather unlikely, heavy-ion collision experiments must be the final arbiter on the nature of the quark-hadron phase transition.

5. Generating the Matter in the Universe
As was pointed out by Sakharov [11], there are three essential requirements for generating the matter in the Universe via microphysics. First, one needs a difference between matter and antimatter interactions, as has been observed in the laboratory in the forms of violations of C and CP in the weak interactions. Secondly, one needs interactions that violate the baryon and lepton numbers, which are present as non-perturbative electroweak interactions and in grand unified theories, but have not yet been seen. Finally, one needs a breakdown of thermal equilibrium, which is possible during a cosmological phase transition, for example at the GUT or electroweak scale, or in the decays of heavy particles, such as a heavy singlet neutrino $\nu_R$ [12]. The issue of heavy particles [9]: it would be valuable to refine the astrophysical determinations.

Figure 3. The density of matter $\Omega_m$ and dark energy $\Omega_\Lambda$ inferred from WMAP and other CMB data (WMAPext), and from combining them with supernova and Hubble Space Telescope data [7].
then is whether we will be able to calculate the resulting matter density in terms of laboratory measurements. Unfortunately, the Standard Model C and CP violation measured in the quark sector seem unsuitable for baryogenesis, and the electroweak phase transition in the Standard Model would have been second order. However, additional CP violation and a first-order phase transition in an extended electroweak Higgs sector might have been able to generate the matter density [13], and could be testable at the LHC and/or ILC. An alternative is CP violation in the lepton sector, which could be probed in neutrino oscillation experiments, albeit indirectly, or possibly in the charged-lepton sector, which might be related more directly to the matter density [14].

In any case, detailed knowledge of the QGP equation of state would be necessary if one were ever to hope to be able to calculate the baryon-to-entropy ratio with an accuracy of a few percent.

6. The Formation of Structures in the Universe

The structures seen in the Universe - clusters, galaxies, stars and eventually ourselves - are all thought to have developed from primordial fluctuations in the CMB. This idea is supported visually by observations of galaxies, which look smooth at the largest scales at high redshifts, but cluster at smaller scales at low redshifts [15]. This scenario requires amplification of the small fluctuations observed in the CMB, which is possible with massive non-relativistic weakly-interacting particles. On the other hand, relativistic light neutrinos would have escaped from smaller structures, and so are disfavoured as amplifiers. Non-relativistic 'cold dark matter' is preferred, as seen in a comparison of the available data on structures in the Universe with the cosmological Concordance Model [8].

The hot news in the observational tests of this scenario has been the recent detection of baryonic ripples from the Big Bang [16], as seen in Fig. 5. These are caused by sound waves spreading out from irregularities in the CMB, which show up in the correlation function between structures in the (near-)contemporary Universe as features with a characteristic size. In addition to supporting the scenario of structure formation by amplification of CMB fluctuations, these observations provide measurements of the expansion history and equation of state of the Universe.
Do Neutrinos Matter?
Oscillation experiments tell us that neutrinos have very small but non-zero masses \([17, 18]\), and so must make up at least some of the dark matter. As already mentioned, since such light neutrinos move relativistically during the epoch of structure formation, they would have escaped from galaxies and not contributed to their formation, whereas they could have contributed to the formation of clusters. Conversely, the success of the cosmological Concordance Model enables one to set a cosmological upper limit on the sum of light neutrino masses, as seen in Fig. 6:
\[ \Sigma m_\nu < 0.7 \text{ eV} \]  \([6]\), which is considerably more sensitive than direct laboratory searches. In the future, this cosmological sensitivity might attain the range indicated by atmospheric neutrino data \([17]\).

However, even if no dark matter effect of non-zero light neutrino masses is observed, this does not mean that neutrinos have no cosmological role, since unstable heavier neutrinos might have generated matter via the Sakharov mechanism \([11]\).

Particle Dark Matter Candidates
Candidates for the non-relativistic cold dark matter required to amplify CMB fluctuations include the axion \([19]\), TeV-scale weakly-interacting massive particles (WIMPs) produced thermally in the early Universe, such as the lightest supersymmetric partner of a Standard Model particle (probably the lightest neutralino \(\chi\)), the gravitino (which is likely mainly to have been produced in the very early Universe, possibly thermally), and superheavy relic particles that might have been produced non-thermally in the very early Universe \([20]\) (such as the ‘cryptons’ predicted in some string models \([21]\)).

Supersymmetric Dark Matter
Supersymmetry is a very powerful symmetry relating fermionic ‘matter’ particles to bosonic ‘force’ particles \([22]\). Historically, the original motivations for supersymmetry were purely theoretical: its intrinsic beauty, its ability to tame infinities in perturbation theory, etc. The first phenomenological motivation for supersymmetry at some accessible energy was that it
Figure 6. The likelihood function for the total neutrino density $\Omega_\nu h^2$ derived by WMAP [6]. The upper limit $m_\nu < 0.23$ eV applies if there are three degenerate neutrinos.

might also help explain the electroweak mass scale, by stabilizing the hierarchy of mass scales in physics [23]. It was later realized also that the lightest supersymmetric particle (LSP) would be stable in many models [24]. Moreover, it should weigh below about 1000 GeV, in order to stabilize the mass hierarchy, in which case its relic density would be similar to that required for cold dark matter [25]. As described below, considerable effort is now put into direct laboratory searches for supersymmetry, as well as both direct and indirect astrophysical searches.

Here I concentrate on the minimal supersymmetric extension of the Standard Model (MSSM), in which the Standard Model particles acquire superpartners and there are two doublets of Higgs fields. The interactions in the MSSM are completely determined by supersymmetry, but one must postulate a number of soft supersymmetry-breaking parameters, in order to accommodate the mass differences between conventional particles and their superpartners. These parameters include scalar masses $m_0$, gaugino masses $m_{1/2}$, and trilinear soft couplings $A_0$. It is often assumed that these parameters are universal, so that there is a single $m_0$, a single $m_{1/2}$, and a single $A_0$ parameter at the input GUT scale, a scenario called the constrained MSSM (CMSSM). However, there is no deep theoretical justification for this universality assumption, except in minimal supergravity models. These models also make a prediction for the gravitino mass: $m_{3/2} = m_0$, which is not necessarily the case in the general CMSSM.

As already mentioned, the lightest supersymmetric particle is stable in many models, this because of the multiplicative conservation of $R$ parity, which is a combination of spin $S$, lepton number $L$ and baryon number $B$: $R = (-1)^{2S - L + 3B}$. It is easy to check that conventional particles have $R = +1$ and sparticles have $R = -1$. As a result, sparticles are always produced in pairs, heavier sparticles decay into lighter ones, and the lightest supersymmetric particle (LSP) is stable.

The LSP cannot have strong or electromagnetic interactions, because these would bind it to conventional matter, creating bound states that would be detectable as anomalous heavy nuclei.
Among the possible weakly-interacting candidates for the LSP, one finds the sneutrino, which has been excluded by a combination of LEP and direct searches for astrophysical dark matter, the lightest neutralino $\chi$, and the gravitino. There are good prospects for detecting the neutralino or gravitino in collider experiments, and neutralino dark matter may also be detectable either directly or indirectly, but gravitino dark matter would be a nightmare for detection.

10. Constraints on Supersymmetry

Important constraints on supersymmetry are imposed by the absences of sparticles at LEP and the Tevatron collider, implying that sleptons and charginos should weigh $> 100$ GeV \(^{26}\), and that squarks and gluinos should weigh $> 250$ GeV, respectively. Important indirect constraints are imposed by the LEP lower limit on the mass of the lightest Higgs boson, 114 GeV \(^{27}\), and the experimental measurement of $b \rightarrow s\gamma$ decay \(^{28}\), which agrees with the Standard Model. The measurement of the anomalous magnetic moment of the muon, $g_\mu - 2$, also has the potential to constrain supersymmetry, but the significance of this constraint is uncertain, in the absence of agreement between the $e^+e^-$ annihilation and $\tau$ decay data used to estimate the Standard Model contribution to $g_\mu - 2$ \(^{29}\). Finally, one of the strongest constraints on the supersymmetric parameter space is that imposed by the density of dark matter inferred from astrophysical and cosmological observations. If this is composed of the lightest neutralino $\chi$, one has $0.094 < \Omega_\chi h^2 < 0.129$ \(^{6}\), and it cannot in any case be higher than this. For generic domains of the supersymmetric parameter space, this range constrains $m_0$ with an accuracy of a few per cent as a function of $m_{1/2}$, as seen in Fig. 7 \(^{30}\).

Figure 7. The $(m_{1/2}, m_0)$ planes for (a) $\tan \beta = 10$ and $\tan \beta = 50$ with $\mu > 0$ and $A_0 = 0$, assuming $m_t = 175$ GeV and $m_b(m_b)_{\overline{MS}} = 4.25$ GeV. The near-vertical (red) dotted-dashed lines are the contours $m_h = 114$ GeV, and the near-vertical (black) dashed line is the contour $m_{\chi^\pm} = 104$ GeV. Also shown by the dot-dashed curve in the lower left is the corner excluded by the LEP bound of $m_{\tilde{\tau}} > 99$ GeV. The medium (dark green) shaded region is excluded by $b \rightarrow s\gamma$, and the light (turquoise) shaded area is the cosmologically preferred regions with $0.094 \leq \Omega_\chi h^2 \leq 0.129$. In the dark (brick red) shaded region, the LSP is the charged $\tilde{\tau}_1$. The region allowed by the E821 measurement of $a_\mu$ at the 2-$\sigma$ level, is shaded (pink) and bounded by solid black lines, with dashed lines indicating the 1-$\sigma$ ranges \(^{30}\).
11. The Relic Density and the Quark-Gluon Plasma

The accurate calculation of the relic density depends not only on the supersymmetric model parameters, but also on the effective Hubble expansion rate as the relic particles annihilate and freeze out of thermal equilibrium [25]:

\[ \dot{n} + 3Hn = -\langle \sigma_{\text{ann}}v \rangle (n^2 - n_{eq}^2). \]

This is, in turn, sensitive to the effective number of particle species:

\[ Y_0 \simeq \left( \frac{45}{\pi} \right)^{\frac{1}{2}} \frac{1}{m_{\chi} <\sigma_{\text{ann}}v>_{T_f} g_{*}^{1/2}(T_f)} \]

where

\[ g_{*}^{1/2}(T) = \frac{H_{\text{eff}}}{g_{\text{eff}}} \left( 1 + \frac{T}{3} \frac{d\ln h_{\text{eff}}}{dT} \right). \]

To calculate this at the per-cent level, one needs to understand with comparable accuracy the equation of state of hot QCD around the freeze-out temperature [31], which is typically \( m_{\chi}/20 \sim \) a few GeV. Fig. 8 the comparison between the predictions of different equations of state for \( h_{\text{eff}} \): it would be good to reach consensus on at the per-cent level.

12. Supersymmetry Searches at the LHC

A ‘typical’ CMSSM event should be relatively ‘easy’ to see at the LHC, as it should have a lot of ‘missing’ transverse energy carried away by invisible neutralinos, accompanied by several jets and/or leptons. Many studies have shown that the LHC should be able to cover most of the region of parameter space allowed by cosmology [32], as seen in Fig. 9 [33]. Moreover, the LHC should be able to see several species of supersymmetric particles, which might make possible the a priori calculation of the relic density with an uncertainty comparable to that provided by astrophysical and cosmological data [34]. Minimal supergravity models might be even easier to discover, since in generic domains of parameter space the next-to-lightest supersymmetric particle would live a long time before it decayed into the gravitino [35], liberating a large amount of energy that could be measured in a dedicated detector [36].
13. Strategies for Detecting Supersymmetric Dark Matter

These include searches for the annihilations of relic particles in the galactic halo: $\chi \chi \to \text{antiprotons or positrons}$, annihilations in the galactic centre: $\chi \chi \to \gamma + \ldots$, annihilations in the core of the Sun or the Earth: $\chi \chi \to \nu + \ldots \to \mu + \ldots$, and scattering on nuclei in the laboratory: $\chi A \to \chi_i A$.

After some initial excitement, recent observations of cosmic-ray antiprotons are consistent with production by primary matter cosmic rays. Moreover, the spectra of annihilation positrons calculated in a number of CMSSM benchmark models [32] seem to fall considerably below the cosmic-ray background [37]. Some of the spectra of photons from annihilations in Galactic Centre, as calculated in the same set of CMSSM benchmark scenarios, may rise above the expected cosmic-ray background, albeit with considerable uncertainties due to the unknown enhancement of the cold dark matter density. In particular, the GLAST experiment may have the best chance of detecting energetic annihilation photons [37], as seen in the left panel of Fig. 10. Annihilations in the Solar System also offer detection prospects in some of the benchmark scenarios, particularly annihilations inside the Sun, which might be detectable in experiments such as AMANDA, NESTOR, ANTARES and particularly IceCUBE, as seen in the right panel of Fig. 10 [37].

The rates for elastic dark matter scattering cross sections calculated in the CMSSM are typically considerably below the present upper limit imposed by the CDMS II experiment, in both the benchmark scenarios and the global fit to CMSSM parameters based on present data [38]. However, if the next generation of direct searches for elastic scattering can reach a sensitivity of $10^{-10}$ pb, they should be able to detect supersymmetric dark matter in many supersymmetric scenarios. Fig. 11 compares the cross sections calculated under a relatively optimistic assumption for the relevant hadronic matrix element $\sigma_{\pi N} = 64$ MeV, for choices of CMSSM parameters favoured at the 68% (90%) confidence level in a recent analysis using the

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**Figure 9.** Scatter plot of the masses of the lightest visible supersymmetric particle (LVSP) and the next-to-lightest visible supersymmetric particle (NLVSP) in the CMSSM. The darker (blue) triangles satisfy all the laboratory, astrophysical and cosmological constraints. For comparison, the dark (red) squares and medium-shaded (green) crosses respect the laboratory constraints, but not those imposed by astrophysics and cosmology. In addition, the (green) crosses represent models which are expected to be visible at the LHC. The very light (yellow) points are those for which direct detection of supersymmetric dark matter might be possible [33].
Figure 10. Left panel: Spectra of photons from the annihilations of dark matter particles in the core of our galaxy, in different benchmark supersymmetric models [37]. Right panel: Signals for muons produced by energetic neutrinos originating from annihilations of dark matter particles in the core of the Sun, in the same benchmark supersymmetric models [37].

Figure 11. Scatter plots of the spin-independent elastic-scattering cross section predicted in the CMSSM for (a) $\tan\beta = 10, \mu > 0$ and (b) $\tan\beta = 50, \mu > 0$, each with $\sigma_{\pi N} = 64$ MeV [38]. The predictions for models allowed at the 68% (90%) confidence levels [39] are shown by blue $\times$ signs (green + signs).

observables $m_W, \sin^2\theta_W, b \to s\gamma$ and $g_\mu - 2$ [38].

14. Connections between the Big Bang and Little Bangs
Astrophysical and cosmological observations during the past few years have established a Concordance Model of cosmology, whose matter content is quite accurately determined. Most of the present energy density of the Universe is in the form of dark vacuum energy, with about 25% in the form of dark matter, and only a few% in the form of conventional baryonic matter.
Two of the most basic questions raised by this Concordance Model are the nature of the dark matter and the origin of matter.

Only experiments at particle colliders are likely to be able to answer these and other fundamental questions about the early Universe. In particular, experiments at the LHC will recreate quark-gluon plasma conditions similar to those when the Universe was less than a microsecond old \[4\], and will offer the best prospects for discovering whether the dark matter is composed of supersymmetric particles \[40, 41\]. LHC experiments will also cast new light on the cosmological matter-antimatter asymmetry \[42\]. Moreover, discovery of the Higgs boson will take us closer to the possibilities for inflation and dark energy.

There are many connections between the Big Bang and the little bangs we create with particle colliders. These connections enable us both to learn particle physics from the Universe, and to use particle physics to understand the Universe.

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