A Quark-Matter Dominated Universe

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Abstract
We present a new scenario for the development of the Universe after the Big Bang, built on the conjecture that a vast majority of the primordial quark matter did not undergo a phase transition to normal nuclear matter, but rather split up into massive quark objects that remained stable. Hence, such primordial quark matter would make up the so-called dark matter. We discuss, mostly in qualitative terms, the consequences for galaxy formation, the origin of normal matter, the occurrence of massive black-holes in galactic centres and the cosmic gamma-ray bursts.
1 Introduction

One of the most fascinating mysteries in modern astrophysics and cosmology is the nature and origin of the so-called dark matter in the cosmos. It is (by definition) non-luminous, and reveals itself only through its gravitational interaction with the luminous galactic matter or with light. Its main signature is that most studied galaxies rotate in a “non-Keplerian” way, as estimated from their luminous matter [1]. It appears as if the galaxies contain some extra, non-luminous matter, with a total mass believed to be about an order of magnitude higher than that of the luminous matter. There are weaker indications that also galaxy clusters behave strangely, and therefore would contain some extra matter inbetween the galaxies. There are also theoretical, cosmological arguments favouring an overall density much higher than the one estimated from direct observations of luminous matter.

Detailed studies of galaxy rotations seem to indicate that dark matter has a more extended density profile than the luminous matter, stretching out to several times the conventional galactic radii. However, there is no general agreement as to the geometrical shape of the dark-matter halo of a typical spiral galaxy, and suggestions of spherical as well as slightly flattened mass distributions can be found in the literature. Neither is there a generally accepted functional dependence of the density $\rho(r)$ as a function of the distance $r$ to the galactic centre, even for fits to spherical distributions. One often assumes a form that at least asymptotically falls off as $r^{-\alpha}$. In most analyses an $\alpha < 2$ is used, so that one has to introduce a cut-off in $r$ in order to avoid an infinite galactic mass; i.e., an *ad hoc* galactic radius. Normally, one assumes that the total mass of a galaxy is around ten times that of the luminous matter, while the radius can vary widely, depending on the exact choice of density distribution. Some recent discussions of best-fit analytical forms can be found in [2]. The widely varying forms originate from different analytic methods (except for the trivial reason that they are sometimes used for different galaxies). Different groups aim at fitting different parts of the dark-matter distribution, which sometimes refers to all galactic dark matter, and sometimes only to the part being more peripheral than our solar system. There is also a distinction between analyses that are founded on model-dependent simulations of galaxy formation, including conjectured values of cosmological parameters, and those built on observations of the Milky Way and other galaxies.
During the last few years an extensive study of stars in the Large Magellanic Cloud (LMC) has also found a few cases of gravitational lenses, so-called machos (Massive Compact Halo Objects), which magnify the light from those stars, and seem to move in the outskirts of our galaxy. The masses of the discovered objects lie below the solar mass \( M_\odot \), maybe in the range \((0.01 - 0.8)M_\odot\) \cite{3}. It is an open question if the machos can make up for all dark matter in the Milky Way. The MACHO collaboration itself gives some support to an average value for the macho mass of \( 0.5M_\odot \), and a 50 per cent macho fraction in the Milky Way halo (assuming a spherical shape).

There is no lack of imaginative models for the dark matter, a majority of which rely on ideas that have never been confirmed, or even supported, by independent experiments or measurements on earth or in space \cite{1}. The least speculative ones are those built on astrophysical ideas about dark, compact objects of normal matter, \textit{e.g.}, bodies created like normal stars, but with too small masses to ignite fusion processes and become luminous. So-called jupiters and brown dwarfs fall into this category. One can also think of planets or comets that have escaped solar systems in large numbers.

Most explanations built on particle physics are much more speculative. Sometimes they even rely on new fundamental ideas that were invented \textit{just} to explain dark matter. Examples of interesting, but entirely hypothetical, particles assumed to contribute to the dark matter, are “neutralinos” and “axions” \cite{1}.

There are only two particle-physics motivated dark-matter models that are based on relatively well-known, or theoretically well-studied phenomena. The simplest one is the “heavy-neutrino” model, \textit{i.e.}, the suggestion that at least one neutrino species has a rest mass high enough to make up for the galactic dark matter. Such neutrinos cannot, of course, explain the discovered gravitational lenses in the Milky Way, neither can they easily be reconciled with the fact that dark matter seems more peripheral than normal matter. There are also more general problems with galaxy formation, and it is believed that heavy neutrinos can account for only a small fraction of the dark matter \cite{4}.

The other model of this kind identifies dark matter with objects consisting of a so-called quark-gluon plasma (QGP), \textit{i.e.}, a form of matter with only quarks, and no structuring into protons and neutrons. Such objects are expected from, or at least not forbidden by, basic quark theory; quantum chromodynamics (QCD). There is no reason to believe that systems of just a
few quarks (two or three) would be the only ones of physical or astrophysical interest. There is indeed an intense current research about QGPs. One example is the extensive experimental programmes at several high-energy laboratories, which aim at creating a QGP in heavy-ion collisions. The idea is to compress nuclear matter into such a dense state that individual nucleons can no longer be distinguished. Then the QGP might perhaps survive long enough to send out some clear signals, before converting (“hadronising”) into normal matter again. A few hints of QGP creation have indeed been found (“strangeness enhancement” and “$J/\Psi$ suppression”), above all at the CERN laboratory in Geneva, but these have also been disputed, and claimed to be consequences of more conventional physical phenomena.

The extension of QGP ideas into astrophysics is straightforward, since the bulk of matter must have been in the form of such a plasma just after the Big Bang, when densities were still far above those inside atomic nuclei, and of the order of those inside protons and neutrons. There are also many current astrophysical situations where one can think of extremely high densities, such as inside a neutron star, or a collapsing would-be supernova.

Normal hadronic matter is believed to have been created spontaneously as soon as the Universe expanded into an average density of the order of normal nuclear densities, although there is no agreement as for the details of this universal hadronisation. One can think of an explosive and very fast phase transition, going from the cooler periphery of the Universe and inwards, or a slower growth of bubbles of normal matter inside local density fluctuations, until finally the QGP disappeared, as shrinking bubbles inside the normal hadronic matter.

It seems a very natural line of thinking to speculate that something went wrong within this scenario, so that a vast majority of the primordial matter stayed in the QGP phase, and now constitutes the dark matter. From a minimalistic point of view it is more natural to build on the fact that the Universe has already been in a specific “dark-matter” state, than to speculate about completely unknown forms of matter.

However, this requires the QGP to be the absolute ground state of matter, at least in some cosmically interesting mass region. Ideas along such lines began to flourish in the early 1970s, with a pioneering work by Bodmer [5], and subsequent analyses in 1979 by Chin and Kerman [6], and Bjorken and McLerran [7]. In 1984 De Rújula and Glashow [8], Fahri and Jaffe [9], and Witten [10] presented more refined analyses, which strengthened the
conclusion that quark-matter “nuggets” or “bags” are indeed the ground state of matter, and hence contribute to dark matter.

This idea cannot be rigorously underbuilt by basic principles, i.e., from QCD. Rather, the rule of the game is to rely on “QCD-inspired” phenomenological models, and the one most frequently used for analysing existing and hypothetical multi-quark objects is the so-called MIT bag model \(^{[12]}\). It is built on the assumption that quarks are confined to hadronic “bags” due to an external “vacuum” pressure, quantified by the so-called bag constant \(B\), which takes a universal value, normally given as \(B^{1/4} \approx 150\) MeV. The \(B\) value is fitted to known properties of normal hadrons, in a variational procedure, where the total energy (mass) of a hadron, primarily the proton, is minimised with the help of the bag radius. The known values of the proton mass and radius are then used to fit the model parameters, \(B\) being the most crucial one. Many versions of the MIT bag model have been developed, containing various corrections, one of which is for interactions among the quarks, which were assumed to be free inside the bag in the original version.

When analysing bags with more than three quarks, it appears as if already those with six quarks have a chance of being stable against decays via strong interactions. The case of such “H dibaryons” \(^{[13]}\) is still debated in the literature, but no experimental evidence has so far been found. There is a clear trend within the model toward a higher stability for heavier objects with even more quarks. Such a stability appears in the analysis as a lower total energy per quark than inside a single nucleon. However, this conclusion requires that heavy quark objects, and already the \(H\) dibaryon, contain an equal (or almost equal) number of the three lightest quarks, the \(u\), the \(d\) and the \(s\) quarks. In this respect, the quark objects predicted by the MIT bag model differ from the structure of a hypothetical, strongly compressed atomic nucleus. The reason that the \(s\) quarks are so crucial, in spite of their assumed higher mass, is that the Pauli principle does not forbid them to occupy the low-energy states of the \(u\) and \(d\) quarks. Once the \(s\) quarks are captured in low-lying energy levels they cannot decay through weak interaction, much in the same way as neutrons in atomic nuclei can be stable.

Still, some authors present results for a QGP of just \(u\) and \(d\) quarks, but this is mainly motivated with simplicity arguments in order to avoid computational difficulties.

Hence, the macroscopic quark objects predicted to be of astrophysical value are often referred to as strangelets, strange stars, etc. There are
several obvious, but interesting, consequences of this peculiar composition. One is that a quark object can be electrically neutral, due to the charges $(+2e/3, -e/3, -e/3)$ of the $(u, d, s)$ quarks. Hence a “strangelet” qualifies as dark matter, since it cannot attract an electron cloud, and therefore not send out light through “atomic” processes. It can still emit temperature radiation would it have a hot surface, but if it represents the ground state of matter, it will do so even at temperature $T = 0$.

Another observation is that a strangelet cannot easily be produced by a contraction of atomic nuclei in high-energy heavy-ion reactions at accelerators. It would require weak-interaction conversions to $s$ quarks of many of the original $u$ and $d$ quarks in the very short time available before the nuclear matter flies apart again. At the best, one can hope for a “baryon-free” plasma, consisting of newly created quarks and antiquarks. If so, one might detect an enhanced production of hadrons containing $s$ and $\bar{s}$ quarks, as the result of a limited QGP creation. The experimental evidence for enhanced strangeness due to such processes is under an intense study [11].

However, an almost exact balance between the three quark species is expected inside the cosmological plasma created after the Big Bang. In fact, “any” set of equally fundamental particles were in balance as long as the temperature (given in conventional mass units) was still much higher than the particle masses. Therefore, it suffices that the temperature obeyed $T \leq 150$ MeV at the time of the $s$ quarks being captured inside their final quark objects. More massive quarks ($c$, $b$ and $t$) are not believed to exist in significant numbers inside absolutely stable quark matter, although they certainly contributed to the processes in the very early Universe.

In the early work on such primordial quark nuggets in the cosmos, the authors did not commit themselves to a certain size (mass) of the objects, nor to an estimate of their absolute importance as dark matter. This probably has to do with the fact that numerical results from the MIT bag model, for objects containing more than a handful of quarks, are unreliable. The original results for protons and other low-mass hadrons were achieved through exact solutions of the Dirac equation inside a spherical bag. Various approximations must be applied for systems with dozens of quarks, not to mention the $10^{30}$ quarks, or more, inside astrophysical objects. Many of these are built on computational methods from nuclear physics, or from relativistic statistical mechanics.

One typical MIT bag model analysis of this kind, presented in [11], shows
that a QGP with less than about 20 quarks has a higher total energy than a corresponding nucleus, or set of free nucleons. This result assures that light nuclei do not decay to a QGP. However, heavier objects have lower total energies per quark, and are hence stable according to this model. This has been analysed up to a few hundred quarks, where the limit is set by practical computer capacities. We will assume that these MIT bag model results apply all the way up to quite heavy objects. For extremely heavy (astrophysical) objects also gravity is assumed to play an important role, and the MIT bag model must be complemented with general relativity. We will discuss this problem later.

Strangely enough, this simple and logical dark-matter model does not seem to have reached a popularity in line with those built on much more exotic and controversial ideas. The modern literature on a quark-object dominated Universe is scarce, and, in fact, non-existent (would it not be for a persistent interest in its very early stage, and the presumed phase-transition from quark-matter to hadrons).

This neglect cannot have been caused by published counter-arguments, because these are scarce too. A much quoted one is an analysis by Madsen [4]. He studied the effect of quark nuggets in space hitting a neutron star, and found that an impact of a very small amount of strange QGP into the dense interior of a normal neutron star would catalyse a phase transition of its full core. Hence, even a tiny lump of quark matter would turn a neutron star into a “quark star” (or “hybrid star”), with a QGP-dominated interior. Such an extremely compact core would prevent the neutron star from experiencing a so-called pulsar glitch, i.e., a sudden change of rotational frequency, which is believed to be caused by a “starquake” coupled to an immediate change of the moment of inertia around the rotational axis. Since the probability of a pulsar glitch occurring in a neutron star can be estimated from observations, these arguments lead to an upper limit for the density of quark-matter nuggets in space, which, according to Madsen, excludes them as the dominant dark matter.

However, Madsen’s conclusion has been disputed, and there are even claims that pulsar glitches require the presence of a quark-matter core, or are caused by the very phase transition when the core turns from neutron to quark matter. Hence, there is by now a rich literature built on the idea that some, or all, neutron stars have quark-matter cores. In fact, the main interest in cosmic quark matter in the modern literature now focuses on such
conventional compact stars. Here, the quark matter is assumed to appear as the result of a gravitational contraction of normal matter, or of a rapid collapse after a supernova explosion. A review of the current literature can be found in Glendenning’s book *Compact Stars* [15].

The true reason for quark matter to be out of fashion as a dark-matter candidate therefore seems to be sociological, namely that other ideas are more in line with the current development in theoretical and experimental high-energy physics. Here, the trends are toward “smaller length-scales” and higher mass-scales, parallel to the construction of new accelerators at CERN and elsewhere. This has led to a strongly increased interest in concepts like supersymmetry, leptoquarks, massive neutrinos and Higgs bosons, including a full spectrum of interesting astrophysical and cosmological implications. An important reason is probably also that some of these ideas, *e.g.*, on massive neutrinos and on supersymmetric partners of quarks and leptons, can be tested with the impressive astrophysical Cherenkov detectors now in use around the globe. Dark-matter quark objects would be more elusive in this sense, primarily because they would be orders of magnitude less frequent than the exotic single-particle candidates, due to their much higher masses. Also, the atmosphere (or the water, ice or rock surrounding the Cherenkov detectors) would presumably erase their traces. Such traces are not even well-defined, and can therefore probably not be discriminated from an impact of normal atomic nuclei in, *e.g.*, a space-born detector.

Nevertheless, we argue that the original ideas of quark objects as dark matter are worthy of a revival, as they have not been convincingly counter-proved, and since they are built on a very simple principle, *i.e.*, the one about the absolute stability of massive multi-quark states. We will assume that practically all dark matter is in this form, and try to limit the model parameters with the help of astrophysical data. For natural reasons, the discussion will be mainly qualitative since really conclusive data are indeed scarce. Also, the particle-physics foundations are not too well known, and in particular not the proper way of using the MIT bag model for very massive objects.

\section{Quark objects in the early Universe}
2.1 General considerations

We take it for granted that a quark-gluon plasma (even at $T = 0$) represents the absolute ground state of matter, at least beyond some minimal number of quarks, as indicated by the MIT bag model results. This limit can be of the order of a few dozen quarks, without being in conflict with the stability of normal matter, since a spontaneous decay of a heavy nucleus into a QGP would be exceedingly improbable. The most natural way for matter to stabilise after the most violent expansion phase following the Big Bang would then be to remain as massive quark objects. Hence, the global plasma simply split up into smaller objects in a more or less random way due to the expansion after the quarks had been created, and after the matter-antimatter annihilation period had ended.

Such a split-up is probably impossible to analyse in quantitative terms, regarding all uncertainties in the standard Big Bang scenario. The consequence crucial for the further development is naturally the distribution of quark-object masses and radii after the split-up phase. A separation of two regions of quark matter could be a consequence of the strong quark-confining forces and to some extent gravitation, both counteracting the general expansion. One can also think of an earlier cause of this phenomenon, e.g., through very early quantum-mechanical fluctuations or a split-up before (hypothetical) subquarks joined to form the quarks. The split-up would follow fractures of weakened QCD (or subquark) forces, and continue until all objects were small enough to screen their own internal expansion. This would give the early Universe a fractal structure, as for the mass distribution of the “final” quark objects. This is quite a different scenario compared to the normal quark-nugget idea, because the quark objects are formed directly from the global plasma, and not as “survivors” inside a high-pressure hadron gas.

It is tempting to guess that this fractal process led to the creation of more or less separated regions containing a total mass of typically galactic proportions (or maybe those of galaxy-clusters). That would explain why proto-galaxies were formed so quickly after the Big Bang, a fact that is hard to reproduce in simulations of a purely gravitational development inside a homogenous Universe of normal atomic matter.

The smallest quark objects in such a fractal distribution are obviously free nucleons, while the most massive ones are harder to define. One can think of a limitation given either by stability criteria against a gravitational collapse,
or by relativistic horizon arguments. Horizon arguments cannot be strict
since we do not know when the first global split-up occurred. This problem
was discussed recently by Cottingham et al. [16] within the context of a field-
theoretic model by Lee and Wick [17]. The conclusion is that supercooling of
the global plasma promoted a wider horizon than commonly believed, which,
in turn, would allow for quark objects within a very wide mass range. The
maximal mass depends strongly on the chosen values of model parameters,
and the authors give an example where half the plasma hadronised, while
the other half remained as quark objects of up to around one solar mass.
This application of the Lee-Wick model has been criticised recently [18],
and the horizon argument is far from clear. We will therefore leave this question
open and discuss three different scenarios, based on different mass scales for
the heaviest quark objects.

The most “conventional”, and therefore also least interesting, such sce-
nario would be that the primordial matter was split up, immediately or in
successive steps, into rather small objects, where some fraction quickly hadro-
nised, while the rest remained as stable quark objects. The crucial size would
be the few dozen quarks hinted at by the MIT bag model, and the hadronic
fraction would be the 10 per cent or so given by indirect observations of
the dark-matter content of galaxies. However, this simple-minded scenario
cannot explain why the dark-matter quark objects would have a more pe-
ripheral, and maybe spherical, distribution in galaxies, while the luminous
matter is mostly in a central disc. Neither would it be credible that a high
fraction would be in the form of massive machos of up to a solar mass, while
a substantial minority would be smaller than a few dozen quarks. This would
hardly be reconcilable with a fractal structure, where one expects the number
of objects heavier than a mass \( M \) to drop like \( M^{-\gamma} \), with some power \( \gamma \) of
the order unity.

We therefore suggest that all of the pregalactic matter was in the form of
rather massive quark objects, i.e. that only an insignificant fraction hadro-
nised immediately. The nuclear matter in the present-day Universe must
then be the result of an enforced phase transition of the primordial quark
matter, taking place only after the first structuring into proto-galaxies. Still,
this hadronisation must have started early enough for more well-known pro-
cesses to occur in due time, e.g., the forming of atoms, and the decoupling
of the cosmic microwave radiation. Hence, also the latter process took place
inside proto-galaxies, explaining why there is still a certain lumpiness in this
(mostly) thermalised radiation.

An enforced hadronisation can be a consequence of an external or internal disturbance, leading to an expansion (or split-up) of the object to a density (or mass) well below that for hadronisation. A simple cooling of the object due to Planck radiation will not cause a hadronisation, once we assume that quark matter remains the ground state also at $T = 0$.

There are now two interesting cases as for the choice of an upper quark-object mass. One is that the maximal mass was all from the start near the upper limit for stability against gravitational contraction (or collapse). The other is that the very early quark objects indeed reached galactic masses during a very brief epoch. We will discuss these options separately.

### 2.2 Stability criteria

The most obvious criterion for the stability of a massive (non-rotating) object is that its radius must not fall below the Schwarzschild radius given by

$$ r_s = \frac{2M_{qm}G}{c^2}, $$(1)

where $M_{qm}$ is the mass. For a quark-matter object this leads to a critical (upper) radius for stability against a gravitational collapse, $R_{\text{crit}}$, given by

$$ R_{\text{crit}} = \sqrt{\frac{3c^2}{8\pi\rho_{qm}G}}, $$

where $\rho_{qm}$ is the density. Assuming that it is, on the average, equal to the density of a proton of radius 0.8 fm, this gives $\rho_{qm} = 3m_p/(4\pi r_p^3) \approx 10^{15}$ g/cm$^3$, $R_{\text{crit}} \approx 14$ km and $M_{\text{crit}} \approx 5M_\odot$.

However, a more refined analysis of a quark object under internal gravitation shows that also smaller systems would be unstable, since they would slowly contract beyond the Schwarzschild radius, and ultimately collapse into black holes. The formalism for analysing such situations comprises the so-called Tolman-Oppenheimer-Volkoff (TOV) equations [19], which are built on general relativity, as well as on the equation of state of a static, spherical, ideal-liquid system, and on the assumption that stability is equivalent to a zero-pressure at the surface of the object. They are derived in many
textbooks in general relativity, e.g., in [20], and contain the following set of equations:

\[
\frac{dp}{dr} = \frac{[\epsilon(r) + p(r)][m(r) + 4\pi r^3 p(r)]}{r[r - 2m(r)]}, \tag{3}
\]

\[
\frac{dm(r)}{dr} = 4\pi r^2 \epsilon(r), \quad m(r) = 4\pi \int_0^r \epsilon(r')r'^2 dr', \tag{4}
\]

\[
p(r = 0) = p_c, \tag{5}
\]

\[
p(r = R) = 0. \tag{6}
\]

Here the TOV equations are expressed in gravitational and natural units, \(c = \hbar = G = 1\). \(p\) is the total pressure, supposed to be built up by a normal kinetic pressure, the external vacuum pressure, the gravitational pressure and an internal “degeneration pressure”, which is a phenomenological way of preventing the quarks from violating the Pauli principle. \(\epsilon\) is the energy density and \(m(r)\) is the mass inside the radial coordinate \(r\).

Many such analyses of various stellar systems can be found in the literature. They are based on different equations of state, and other detailed assumptions. Some recent computations by one of us [21] give results that are typical for analyses in the spirit of the MIT bag model. A QCD-based equation of state for a system of (equally many) \(u\), \(d\) and \(s\) quarks was used. Some of the results are illustrated in Fig. 1.

For \(B^{1/4} = 150\) MeV the stable quark objects have masses below around \(\sim 1.8M_\odot\) and radii below \(\sim 11\) km. Similar results can be found in many analyses of the stability of neutron stars, in particular those with a sizeable quark-matter core [15]. This applies also to rather different assumptions about the internal structure and forces of such quark or hybrid stars.

One example, which is of some interest for our subsequent discussion, is a quark object built up by diquarks, i.e., tight pairs of two quarks, generally prescribed to have total spin 0. Early suggestions of such systems were presented by two of us in the late 1980s, including discussions of their astrophysical relevance [22, 23]. A general review of the diquark concept can be found in [24], and a topical review of their astrophysical relevance is given in [25]. The interesting property of a “diquark star” is that the diquarks absorb
Figure 1: The stability relations (full lines) between the mass and the radius of an MIT bag for different values of the bag parameter $B$, namely $B^{1/4} = 180$ MeV (curve 1.), 150 MeV (2.), 120 MeV (3.), 100 MeV (4.), 75 MeV (5.) and 50 MeV (6.). For clarity, only the most relevant segments of the full lines are shown. The hatched line shows the criterion for collapse into a black hole, as given by the Schwarzschild radius. Other parameter values can be found in [21].
almost all attractive two-quark (QCD) forces in the system, so that the net forces inbetween diquarks are believed to be either negligible, leading to a possible Bose condensation [23], or repulsive.

The latter situation was first analysed by Donoghue and Sateesh [24], and later applied to neutron-star cores by Kastor and Traschen [27]. An interesting result is that a diquark star is expected to be less dense than a “conventional” quark object. And with a choice of somewhat extreme (but not excluded) parameter values it might even less dense than normal atomic nuclei. Horvath et al. [28] refined this model, and concluded that diquark stars might exist even without a gravitational pressure. They also stressed that the normal way of treating quark objects within the MIT bag model must be revised if there are diquarks in the plasma. All parameters must, e.g., be re-fitted to baryon properties with diquark effects included, in particular the bag parameter $B$. As can be seen in Fig. 1 the mass-radius relation, and hence the density, is quite sensitive to the $B$ value.

This particular example therefore shows that although the maximal quark-object mass is in the range of $1−5$ solar masses in almost all detailed analyses, there is no general agreement about such important details as the average density of the objects. It should also be stressed that the TOV equations with the external pressure of the MIT bag model, and the equation of state from QCD, does not exactly reproduce the MIT bag model results for small systems mentioned earlier. Hence, one cannot trust the trend found in the TOV mechanism that objects smaller than around one solar mass would have a too low density for being quark objects. This trend simply does not match the MIT bag model result that objects with more than a few dozen quarks are stable against hadronisation.

In most quark-matter analyses of neutron stars it is nevertheless assumed that a density below $2−3$ times the normal nuclear density is too low to allow for a pure quark phase [15]. Since the density in the surface layers falls below these values even for the most massive objects, it is often assumed that a neutron star at most has a quark core, surrounded by a crust of nuclear matter, while smaller objects has no quark matter at all. Even if this interpretation is correct, the primordial quark objects suggested by us need not turn into systems identical to neutron stars. The reason is that these two classes of dense objects were created in completely different ways. Neutron stars are the result of a compression of normal atomic nuclei inside stars, while our quark objects were created from the original quark-gluon plasma
soon after the Big Bang.

Neither is there any basic theoretical evidence that quark matter must hadronise once its density falls below some $2 - 3$ times that of nuclear matter. These densities are the ones believed to be needed for a phase transition when nuclear matter is compressed at high temperatures in heavy-ion collisions, and need not have much relation to the conditions needed for the reversed hadronisation of a quark-gluon plasma with $T = 0$. It seems more realistic to assume that a quark object remains in a pure quark phase until a nuclear density is reached as a consequence of an enforced expansion.

We therefore conclude that there are no basic theoretical arguments in contradiction to our main assumption that the bulk of the dark matter is identical to stable quark-matter objects of a few solar masses and down. One reservation must be made though, namely for the fate of quark objects that exceeded the mass limit of around $5M_\odot$ given by the Schwarzschild relation, or of the $(1 - 5)M_\odot$ given by the TOV equations, as discussed above. Such objects must have turned into black holes, which could hence make up a considerable fraction of the dark matter. The literature on black holes is very rich \cite{29}, and we will not go into details on the issue of black holes as dark-matter candidates.

### 2.3 Highly unstable quark-matter proto-galaxies

It is tempting to speculate what would happen if quark objects of up to galactic masses were formed as an intermediate step in the very early (fractal) split-up of the global quark-gluon plasma. This would certainly avoid all problems with the standard assumption of a gravitational accretion into galaxies, and imply that galaxies are instead shaped by explosions. The latter idea was presented by Ambartsumian \cite{30} already in 1958 and cannot easily be dismissed \cite{31}. It turns out that galaxies are “too often” in binary systems, which do not seem to be gravitationally bound, but rather expanding. Also, there are other more detailed paradoxes that might be resolved within an explosive scenario.

We cannot prove that a fractal split-up after the Big Bang ever gave rise to typical galactic masses, but we can discuss some possible consequences. Taking the Milky Way as an example, a typical mass at this first stage was $M_{qm} \approx 10^{12}M_\odot = 2 \times 10^{45}$ g, assuming that the luminous matter now is around 100 billion solar masses, and that the total mass, including dark
matter, is an order of magnitude higher.

We also assume that this embryonic galaxy had a density given by the MIT bag model, \textit{i.e.}, in which it is almost independent of the mass, and hence equal to that of the proton. Therefore any quark-matter object is assumed to have a density \( \rho_{qm} \approx 10^{15} \text{ g/cm}^3 \). If the early quark-dominated Milky Way was spherical, its radius was hence given by \( R_{qm} \approx 78,000 \text{ km} \), \textit{i.e.}, around a quarter of a light-second.

Such an object would, naturally, be utterly unstable, and it seems as if a quark-dominated proto-galaxy would immediately fall into a black hole. However, the situation is obviously not that simple, because then the whole the Universe would have done so at an earlier stage. The situation is complicated by the fact that the first formation of proto-galaxies took place in a highly unstable and dynamically rapid sequence of events.

Two circumstances could have prevented the galaxy from “disappearing” instantly, namely its internal expansion and its rotation, both presumably being extremely rapid (\textit{i.e.}, relativistic). Such phenomena are difficult to analyse within general relativity, and we therefore limit ourselves, in this first qualitative analysis to present some qualitatively motivated conjectures about the very early phase of the galaxy, including the creation of the first normal hadronic matter.

It is likely that the expansion of the galaxy was slowed down first of all in its central parts, when the overall expansion of the Universe, \textit{i.e.}, of the “coordinates”, was screened, or balanced, by the internal gravitational and quantum chromodynamic forces. Hence, the matter in the central part would be the first to “discover” that the Schwarzschild condition for collapse was fulfilled. This information travelled at the speed of light, once the proto-galaxy was formed, so that some fraction of the central quark object must have collapsed in a fraction of a second, and “long” before the whole galaxy had a chance to follow. It is well known that many galaxies have central black holes, with masses of \((10^6 - 10^{10}) M_\odot\) \cite{32}, which, in our model, could be from this very early phase.

The central matter that collapsed into such a black hole, “emptied” a sphere in the galaxy, with a radius of around 4,000 km, assuming a typical mass of \(10^8 M_\odot\) (note that the central black hole in the Milky Way is probably much smaller; of the order of \(10^6 M_\odot\)). The original “MIT bag” therefore turned into a hollow sphere, and this disruption might well have caused an internal explosion that ripped the proto-galaxy apart into the smaller
quark objects discussed in the previous section. Some details of this will be discussed in the next chapter, since it might be connected to a central phase transition into normal matter.

The idea that a central explosion broke up the whole proto-galaxy before it had the chance to know that it was smaller than its own Schwarzschild radius does not need to be a paradox. The expansion and rotation would possibly have given the same results by themselves, and galaxies could therefore lack a central black hole.

Assuming that the rotation of a typical spiral galaxy is primordial, one can estimate the original angular momentum inside the quark object. Strangely enough, it seems as if the galactic halo has a negligible net angular momentum, since there is no correlated motion among halo stars. The disc, however, has an angular momentum of the order of \(10^{72}\) erg s, which hints at a relativistic rotation in the inner part of the quark-dominated proto-galaxy. This perhaps indicates that the disc-form is closely connected to the Kerr metric of a rotating central black hole, while the more spherical halo is related to the more symmetric primordial expansion and early explosion.

Apart from the central black hole and possible phase transition caused by it, the explosion broke up the outer part of the quark-gluon plasma into smaller objects, which either continued to break up, fell into small black holes, or stabilised in the sense discussed in the previous section. This means that the subsequent history of the early galaxy would be much the same in the two scenarios, differing only as for the structure of the galactic centre.

### 3 Hadronisation and gamma-ray bursts

Here we suggest that the normal nuclear matter was created “violently” in the proto-galaxy, and mostly in its centre. Such events gave rise also to bursts of gamma radiation, some of which can still be observed from far-away galaxies in the form of the much-discussed gamma-ray bursts.

We start by discussing some general aspects of such bursts, and then turn to the two different sources of bursts that are connected to the two scenarios in the previous chapter. A preliminary discussion was presented in [33].
3.1 Gamma-ray bursts and distance scales

The bursts of intense gamma rays (GRB), first observed in the 1960s by the Vela military satellites and disclosed to the civilian research community in 1973 [34], have confounded physicists and astronomers ever since. Although the outbursts must be very energetic, the actual value of the total energy depends on their distance from the earth. The time-span of the bursts is typically $0.01 - 1000 \, \text{s}$, and no characteristic features, such as spectral lines, have been detected, with two interesting exceptions. The burst named GRB970508 has been related to an object that appeared as an optical transient shortly after the burst, revealing clear spectral absorption lines. The absorbing body, which can be either a host-galaxy of the GRB, or an intervening foreground body, has been shown to have a redshift parameter $z \approx 0.835$. Hence the GRB source itself has $z \geq 0.835$. There is also some indirect evidence for an upper limit, $z \leq 2.3$ [35]. Similar values have been suggested for the more recent GRB971214 [36], namely $1.89 \leq z \leq 2.5$.

There are still no clues to whether these GRBs are “average” in any sense. Future optical GRB transients with spectral lines is certainly needed before a distance-scale can be confirmed. Only after such a scale has been determined, will it be possible to discriminate between the several dozen published theoretical models of the origin of bursts. It should be noted that all other efforts by authors of GRB publications to pinpoint an absolute distance to a particular GRB, or a well-chosen class of GRBs, are model-dependent, and therefore less reliable. Such estimates seem to cluster around $z$ values of $1 - 2$.

In the 1980s, the consensus among researchers was that the bursts originate within our own galaxy [37]. When the Burst and Transient Source Experiment (BATSE) [38], aboard the Compton Gamma Ray Observatory (CGRO), began to produce much more data it became evident that the gamma-ray bursts are distributed isotropically in the sky, not following the visible outlines of the Milky Way (nor of the Andromeda). The opinion among astrophysicists then swayed to models assuming a cosmological origin. A few thousand gamma-ray bursts have been detected to date (and there have been roughly as many different publications on the subject).

The most popular GRB model seems to be that they originate from the binary collapse of two very compact star remnants; neutron stars, black holes, or a combination thereof. Such models take it for granted that these
events occur at random in all normal galaxies, typically $1 - 100$ per a million years per galaxy. The rarity of such mergers would explain why none of the detected bursts has yet occurred close to a visible galaxy, and why there has been no repetition of events from the same locations. The low frequency is also in line with estimates of the number of neutron stars in galaxies, and even the energy release seems to fit what would be expected if two neutron stars merge. If the GRBs are evenly distributed among galaxies, the bursts seem to release $10^{51} - 10^{53}$ erg of gamma rays, which is one or two orders of magnitude less than the expected gain in gravitational energy due to a merger. A weak point of all such models is, however, that it is hard to understand how this gravitational energy converts into gamma rays. A chain of processes has been suggested, where the primary energy turns into a shock-wave of neutrinos, which annihilate into $e^+e^-$ pairs, and ultimately into gammas when the charged leptons hit the thin interstellar medium.

In our model GRBs are a consequence of the phase transition of quark matter into hadrons in the early proto-galaxies, and hence we assume that they are not at all evenly distributed in space, with a universal frequency per galaxy, but instead strongly biased toward large distances, i.e., the early Universe and high redshifts. Since such a phase transition would give a wealth of almost directly produced gammas, there will at least not be any problems with understanding the very high gamma intensities.

Lacking an absolute distance-scale, it is, in fact, almost trivial to fit a distribution of GRB distances, with any chosen average distance, to the observations of gamma-ray fluxes. We will demonstrate how this works, with a simple choice of such distributions.

As is customary, we restrict ourselves to an Einstein-de Sitter universe with vanishing cosmological constant and global curvature. This choice seems, by comparison to observational data, to be a reasonably good approximation of the Universe. We also assume that the individual bursts can be treated as “standard candles”, i.e., that the characteristics of a typical (“average”) burst stays the same during the full burst epoch and in all galaxies. This condition need not be true and can easily be relaxed, but that would not give any deeper insight into the relevant processes.

Each burst is assumed to emit the radiation uniformly in all directions (i.e., not in beams). Relaxing this condition would, of course, require more bursts, and a lower energy release per burst. As will be argued later there are indeed reasons to believe that there is some beaming in phase transitions
caused by the merging of two quark objects.

There seems to be no consensus regarding possible time-dilation effects in GRB spectra, nor regarding an intrinsic duration-luminosity correlation (incompatible with the standard-candle assumption), with strong bursts having shorter duration and vice versa. We simply ignore such (presumably weak) effects in the following analysis, and concentrate on the number/peak-flux relation.

Taking one or more of these complications into account would not change our general observation that a wide range of GRB space distributions can be fitted to the flux data.

The flux of a particular gamma-ray burst can, if the conditions mentioned above are satisfied, be given as a function of its redshift parameter, \( z \),

\[
P(z) = \frac{L(z)}{4\pi r(z)^2(1+z)^2}, \tag{7}
\]

where \( L(z) \) is the luminosity of the burst. Note that the “redshift” is normally defined as “1 + \( z \)”. The present distance to the source, \( r(z) \), depends on the cosmological model. In our case (flat Einstein-de Sitter space), this relation reads

\[
r(z) = \frac{2c}{H_0} \left(1 - \frac{1}{\sqrt{1 + z}}\right), \tag{8}
\]

where \( H_0 \) is the Hubble constant (taken as 75 km/s/Mpc).

The source luminosity detectable by an instrument near the earth, with an effective energy detection window between \( E_{\text{min}} \) and \( E_{\text{max}} \), is given by

\[
L(z) = \int_{E_{\text{min}}(1+z)}^{E_{\text{max}}(1+z)} \phi(E) dE, \tag{9}
\]

where

\[
\phi(E) = A_0 \frac{e^{-E/kT}}{E} \tag{10}
\]

is the spectral form (thermal bremsstrahlung) conventionally chosen for modelling the burst [40]. \( kT \) is a characteristic energy for a typical burst, chosen to be 350 keV. For BATSE, \( E_{\text{min}} = 50 \text{ keV} \) and \( E_{\text{max}} = 300 \text{ keV} \).
For simplicity, we assume that the number density, $\rho(r)$, of the bursts is a gaussian,

$$\rho = C \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(r-r_0)^2}{2\sigma^2}},$$  \hspace{1cm} (11)

centred around $r_0 = r(z_0)$, and with variance $\sigma$. The normalising constant $C$ is fitted to the data. A homogeneous distribution in Euclidean (fairly nearby) space, within a spherical shell with nothing outside, is also compatible with the BATSE data within observational errors, although such an abrupt cut-off seems unphysical. A smoothed-out version of such a distribution, or some completely different distribution altogether, could equally well be fitted to the data. For brevity, we only consider a gaussian distribution here.

Finally, in a given concentric spherical shell, there will be a differential number of bursts given by

$$n = \frac{dN}{dr} = 4\pi \rho r^2,$$  \hspace{1cm} (12)

where $N$ is the total number of GRBs within a sphere of radius $r$, i.e., the total number with observed fluxes below some value (because of our standard-candle assumption).

It is, in principle, possible to fit the BATSE data on the $n$ distribution reasonably well with any choice of $z_0$, while $\sigma$ would be derived by the fit (being smaller for higher $z_0$ value). A typical form of $n$ as a function of $z$ is shown in Fig. 2. The gamma-ray energy emitted by a “standard-candle” source, which is needed to fit the typical energy flow into the detector (i.e. around $10^{-5}$ erg/cm$^2$) is shown as a function of $z$ in Fig. 3.

We conclude this section with the observation that there is no real limitation on the average distance to the bulk of gamma-ray sources, except for hints from two events (GRB970228 and GRB971214) with redshift $z$ values estimated to be $0.835 - 2.3$ and $1.89 - 2.5$, where the upper bounds are motivated mainly by “non-observations” (of redshifted Lyman absorption lines in hydrogen).

### 3.2 A central galactic explosion

If indeed a supermassive black hole was created in the centre of the very early and unstable quark-matter proto-galaxy, there should have been an
Figure 2: An example of the differential number \((n)\) of gamma-ray bursts as a function of redshift parameter \((z)\) in flat Einstein-de Sitter space for a gaussian distribution with the quoted values of \(z_0\) and \(\sigma\). The form is chosen as to fit the BATSE data on the differential number distribution as a function of apparent intensity.

Figure 3: The total gamma-ray energy emitted by the source, given a flat Einstein-de Sitter space, and a typical detected energy flow of \(10^{-5}\) erg/cm\(^2\). The Hubble constant, \(H_0\), is taken as 75 km/s/Mpc.
immediate implosion of the plasma into the “vacuum” dug out at the centre.

This is a type of enforced expansion of the quark matter that could have catalysed a phase transition into normal hadronic matter. It would not be equivalent to a condensation outwards on the periphery of the bag, because the physical situation on the inner and outer surfaces are entirely different. On the outer surface there is still gravity and confinement (vacuum pressure), while on the inner surface neither of these would prevent the plasma from an implosion. Hence the galaxy would undergo a phase transition from inside out, which explains why normal matter, unlike dark matter, is in the central parts of a galaxy (and, of course, also why there are black holes in so many galactic centres).

A black hole of mass $10^8 M_\odot$ would need to swallow quark matter within an original radius of roughly 3,000 km. If this was subsequently filled with hadronising matter, it could sustain a mass of around $3 \times 10^7 M_\odot$ without exceeding normal nuclear densities. For simplicity, we ignore that some of that matter would also fall into the black hole, and so on. If we now assume that this enforced phase transition released some $10 - 100$ MeV of energy for each produced nucleon, the total energy radiating from the centre of the proto-galaxy would be of the order of $10^{60} - 10^{61}$ erg. If, for some reason, all the current luminous matter was created in this implosion, the corresponding energy (for the Milky Way) would be roughly $10^{64}$ erg.

Such energies are far in excess of the gravitational binding energy of a quark object of $10^{12}$ solar masses, and would hence suffice to tear the galaxy apart and provide a sizeable outflow of energetic hadrons and gammas. The effect would naturally be even stronger if the proto-galaxy was already highly unstable, and even diluted (supercooled) at the centre, due to the overall expansion of the Universe and an internal rotation.

It is interesting to note that the emitted gamma energy of a typical gamma-ray burst would correspond to around $10^{61}$ erg, would the source be at a redshift with $z_0 = 10000$. Such $z$ values are typical for the epoch of the global quark-hadron phase transition in the conventional Big Bang scenario.

Hence we have sketched a mechanism for creating, at a very early stage, a massive black hole and a sizeable amount of normal matter in the centre of the galaxy, while pushing the dark matter to the periphery in an explosive event. All this would be marked with an enormously energetic gamma-ray burst. The fact that normal matter is in disc-form might be a consequence
of an original rotation of the galactic centre, while the sphericity of the dark-matter halo might mirror the large-scale isotropy of the burst (the gammas would radiate at random, in spite of the rotation).

It is tempting to speculate that these gamma-ray bursts are still visible, since it would certainly be thrilling if we can still see the creation of whole galaxies. This idea would probably not be in contradiction with such well-known GRB features as their overall time-scale and “spiky” time development. It would, however, be hard to understand how they can still appear as pointlike events, regarding the fact that the proto-galaxies must have been formed during an epoch when they were closely packed in space. The gammas should then have been efficiently scattered and absorbed by nearby matter, and hence thermalised quickly.

Also, it is unlikely that all atomic matter in a galaxy was created through an inflow of quarks in the limited space created by the black hole. We therefore assume that the bulk of normal matter was created somewhat later, from the remaining, smaller quark objects in the galaxy.

### 3.3 Binary quark-object mergers

Here we assume that the very early proto-galaxy was a collection of quark objects of all sizes allowed by the stability criteria discussed above. We do not discriminate between the two possible prehistories, i.e., whether this epoch was preceded by a central galactic explosion as described above, or a more peaceful gathering of these objects into galactic regions.

The most credible way of enforcing a phase transition into normal matter in the galactic centre would then be through mergers in quark-object binaries. Again, we suggest that such transitions would also produce gamma-ray bursts and that these constitute the bulk of the observed GRBs.

It is worth noting that this idea is similar, but still orthogonal, to the popular conjecture that gamma-ray bursts originate from neutron-star mergers [11]. A majority of such models rely on some either unspecified, or very complicated, mechanism for converting the energy-gain into gammas. However, there are also models were the gamma-ray bursts originate from a hadron-quark phase transition inside a neutron star, or in connection to a merger [12]. These transitions are from a hadron phase to a quark phase, and hence opposite to our scenario.

A typical sequence of events inside a single neutron star (pulsar) is that
its rapid rotation is gradually slowed down by gravitational radiation (and maybe also “frame dragging”). This leads to a weakening of the internal centrifugal forces, and hence an increase of the central density, until (possibly) a phase transition occurs, creating a quark-matter core.

In our model, a quark-object binary would, on the contrary, spiral into a closer and closer orbit, with an increasing rotational frequency, until the two objects would trigger a mutual phase transition into hadronic matter. This could take place as a consequence of two different physical phenomena. One would be that there would form a bridge of matter between the two objects once they are close enough, i.e., when the confinement in one object would be counterbalanced by the gravitational pull from the other. Such matter flows occur in many cosmic situations, e.g., between galaxies, between normal stars in a binary system, and from an accretion disc into a black hole. There are rather well-established formalisms for analysing such situations \[43\]. Another catalyst could be that the tidal effects, and the centrifugal forces, in the last stage of the merging, would pull one or both objects into such a low density that they would hadronise separately.

Suppose that such mergers would lead to the hadronisation of half the matter in the two quark objects. Then the energy release from them would be maximally $10^{53} - 10^{54}$ erg, assuming that a maximal mass of $5M_\odot$ would be involved, and that the microscopic energy release is $10 - 100$ MeV per produced nucleon. If a sizeable fraction of this energy goes directly into gammas, we would get a gamma-ray burst typical for source redshifts with $z = 5 - 10$, i.e., before the epoch of star formation in galaxies.

One might ask whether such a scenario would be in jeopardy with some obvious observational restrictions. Although this new model for gamma-ray bursts has many macroscopic and microscopic features in common with GRB models with neutron-star mergers, there are two important differences. Firstly, we do have any problems to understand why so many gammas can result from a binary merger, since they come directly from the source, and not from the interstellar medium. Secondly, our mergers must have been much more frequent in the past than those of neutron stars, since they involve the bulk of galactic (dark) matter, and are the source of the normal (luminous) matter.

Neutron-star mergers are estimated to happen at a frequency of roughly $10^{-4} - 10^{-6}$ y$^{-1}$ during the life of a galaxy. Quark-object mergers must, however, have occurred at least around $2 \times 10^{10}$ times in the Milky Way, as-
suming that all the luminous matter of mass $10^{11} M_\odot$ was created in mergers where up to $5 M_\odot$ hadronised at a time. This gives an average frequency of more than one GRB per year per typical galaxy. An overwhelming majority of these must originate in the galactic centre, where the fraction of binaries must have been much higher than in the halo, since the tendency to form binaries depends strongly on the overall density. This explains why the normal matter is concentrated in the galactic centre.

Such a high frequency is naturally excluded by the clear lack of GRB repeaters from correlated regions in space. In our model this “paradox” can be explained by several simple facts, of which three will be discussed below.

Firstly, a majority of the mergers must have happened in the very early, quark-matter dominated galaxy. We know that the bulk of atomic matter was created shortly (maybe only a hundred thousand years) after the Big Bang. The galaxy was then very compact (according to our model), and the radiation pressure from all the early mergers can have helped the galactic halo to an early expansion. In this dense environment, the bursts could probably not be seen from outside the galaxy. Rather, the bursts contributed to the general, thermalised radiation background, which was later decoupled from the atoms and still exists as the microwave background. Such an early self-destruction of quark objects led to a lack of binaries in the current dark matter in low-redshift galaxies, including our own. There is, for instance, a “disturbing” deficit of binary events among the observed machos, since only one macho has been observed to have a double-spiked structure. Contrary to the situation for neutron stars there is no production of new quark bodies, and new binaries can come about only through random gravitational captures.

Secondly, only the most violent mergers of quark objects would give gamma energies in the range of $10^{53}$ erg. The bulk of the events might be orders of magnitude less energetic, and maybe even unobservable if they occur mainly in galactic centres. The ultimate test of this idea would of course be to observe one such event in our own galaxy, with clear indications of a quark-hadron phase transition.

Thirdly, a gamma-ray burst from a hadronising bridge of matter between two nearby objects can be strongly “beamed”, and hence less energetic than what is expected for an isotropic emitter. In fact, the radiation should be more or less compressed into a disc-like region perpendicular to the symmetry line between the centres of the two objects. This is so, because the phase transition should start only when the two quark objects come very close to
each other (say, within a few km). Then they would simply shadow the
gammas in directions away from such a central disc. The whole system is
also rotating very rapidly at this stage, maybe with a period of a fraction of
a second, so that the disc-like radiation zone would sweep the sky rapidly.

The latter mechanism, i.e. a disc-like radiation zone, rotating rapidly
around an axis in its own plane (and maybe even wobbling), could be the
true cause of the very spiky nature of many gamma-ray bursts. Another
explanation of these spikes is that the matter does not flow smoothly into
the hadronising region, but as several jets, or in the form of chunks of quark-
gluon plasma.

The very irregular time structure of a GRB can also be caused by a range
of other complications; one being the reheating of the original quark matter
by the radiation from the first stage of the phase transition, and perhaps
also an instant radiation pressure on the objects, which pushes them into a
wider orbit for a short time, until they come closer again, and the transition
continues.

As for the total time-scale of 0.1 – 1000 s for a GRB, it does not seem
unlikely that this would be typical for a partial or complete phase transition
of quark objects of up to a few solar masses. The same conclusion can be
drawn for neutron-star mergers, and the time-scale is probably set by the
size of the objects and the time it takes for the excess energy to leave the
region.

The energy distribution of the gammas is known to be non-thermal, and
with a broad and smooth distribution around a few hundred keV. This is
expected for gammas created inside the source, and with a partial thermalisa-
tion in a dense “nuclear” environment. The thermalisation cannot possibly
be complete, because the region is only a few km thick, and it should also
blow apart due to the internal radiation.

Much of the current work on GRBs focuses on the observed X-ray after-
glows from six of them, three of which have been correlated also to optical
afterglows, the most recent one being the GRB971214 [44, 45]. In our model,
the hadronised matter most certainly emits radiation of gradually decreasing
frequencies, as a consequence of the further development of the created
nuclear and atomic matter. The first phenomenon would be the weak decays
of the $s$ quarks into $u$ and $d$ quarks (in roughly $10^{-10}$ s), and the following
beta decays of the neutrons in a few thousand seconds, leading to a shower
of neutrinos and electrons (roughly $10^{57}$ from a solar-mass object).
The electrons would then slow down, either inside the cloud or when hitting the interstellar medium, and give off X rays. An optical afterglow can be a consequence of electrons being captured by the protons from neutron decay, and hence mark the creation of hydrogen atoms.

All these processes would be a rapid mini-version of the standard Big Bang scenario, where the much shorter time-scale is determined by the size of the object. The kilometre-sized region of hadronised matter simply cools off very rapidly after the re-heating caused by the phase transition.

We therefore conclude this discussion of gamma-ray bursts by pointing out that there are no observational data that contradict the idea that GRBs come from phase transitions of massive quark objects. On the contrary, this model avoids some of the problems of models built on neutron-star mergers.

4 Conclusions

The model presented here is, to the best of our knowledge, the first one that relates gamma-ray bursts to the dark-matter problem, and to the creation of normal atomic matter in the galactic centres.

These ideas limit the model in the sense that they require a completely different sequence of events immediately after the Big Bang, as compared to the standard scenario. The most original “details” here are that the global quark-gluon plasma must have gathered into proto-galaxies before the quark-hadron phase transition, and that the final structure of the galaxy can be a result of an explosive development, following the creation of a massive, central black hole, or a fireworks of early mergers of quark-object binaries.

Such a fantastic scenario does not seem to violate qualitative astrophysical facts, but certainly most of the more conventional models, including the later phases of the so-called standard Big Bang scenario. It remains to analyse if it is also in line with the wealth of more detailed data from the cosmos. In the longer perspective it will also be interesting to wait for some clear-cut signatures of the more than 1000 billion massive quark objects that we expect to orbit our own galaxy e.g., in the form of a much better statistics in the studies of gravitational micro-lenses.

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