DO WE NEED COSMOLOGICAL DEBRIS FROM THE QUARK–HADRON TRANSITION?

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Abstract

It is shown that new observations of large scale structure in the Universe (voids, foam, and large-scale velocity fields) may require either strings or percolated explosions to be understood. If the answer is percolated explosions, then seeds for the explosions are required. Perhaps the best seed candidates are debris left from the quark–hadron transition. The type of debris includes planetary mass black holes are strange matter nuggets of the type proposed by Witten. Current theoretical arguments make it difficult but not impossible to form either. If percolated explosions are indeed required, we may be forced to produce such debris after all.

The quark–hadron transition is potentially very important to cosmology (Ref. 1 and references therein). This is the transition where the Universe turns from a soup of free quarks to an ensemble of confined hadrons. It has also been noted that the chiral symmetry breaking transition occurs at this same point and that the combined transition appears to be a first order phase transition in the latest QCD latice gauge modeling. However, it is also clear that this transition cannot inflate or yield major entropy generation since it involves no baryon non-conserving interaction, thus all the entropy can do is dilute the baryon/photon ratio that previously existed and we can't allow too much such dilution. Without inflation, it is also clear that this transition cannot generate fluctuations larger than the horizon at the time of the transition thus this transition cannot directly affect scales larger than $\sim 1M_{\odot}$, with excess baryon mass confined to planetary scale. However, within that scale two possible cosmologically significant objects are conceivable. One is a planetary mass black hole[2], and the other is the so-called "Witten nugget"[3]. A planetary mass black hole can be formed if a QCD fluctuation can produce an overdensity that exceeds the critical valve so that the assemblage of quarks finds itself within its own Schwarzschild radius. Since the critical density is lower for larger scales, it might be easier to make such black holes near horizon scale. Crawford and Schramm[2] found in their simulations that such fluctuations could actually occur but they were somewhat rare (down by factors of $\sim 10^8$) over what would be needed to close the Universe with such objects.

A "Witten nugget" is a lump of strange matter, that is, an assemblage of quarks with the number of strange quarks comparable to the number of up and down quarks. Such a configuration has less difficulties with Pauli exclusion even without invoking color, so it could have a significantly higher binding energy per quark than normal up–down matter. The difficulty is how to construct such a nugget and how long it would survive. At the quark–hadron transition the Universe has an equal number of quarks and anti-quarks to ~ 1 part in 10^{10}. Thus, to make a strange matter nugget requires an annihilation of all but 10^{-10} of the material without disrupting the configuration. Applegate and Hogan[4] showed that it would be very difficult to cool rapidly enough to form a strange nugget. However, it has been argued[5] that if the enhanced binding energy of the strange matter is high enough, then the formation might go via detonation rather than the deflagration assumed by Applegate and Hogan, so the formation might be able to occur.

Such a large binding energy excess is unlikely but not impossible. However, to make matters more difficult, Alcock and Farhi[6] showed that even if a strange nugget could form, it would evaporate prior to recombination. They argued that isolated cosmologically produced chunks of strange matter are unstable to evaporation and such matter would only survive in large ($\gtrsim 1M_{\odot}$) gravitationally bound "quark star" configurations. Bonnometto[7] and his collaborators have found a loophole in their argument if again the excess binding energy of the strange matter is larger than normally assumed.

Thus current theoretical arguments do not favor the existence of large amounts of either planetary mass black holes or strange nuggets; however, they cannot be categorically ruled out.

The astrophysical evidence is thus worth examining to see whether there is a need for them. From an astrophysical viewpoint, strange nuggets and planetary mass black holes are equivalent. Both make excellent cold dark matter in that they cluster on small scales and are not limited by big bang nucleosynthesis baryon density constraints. Freese, Price, and Schramm[8] showed that such objects cold cluster and be seeds that baryons would first fall onto at recombination. They went on to show that these seeds would then grow to $\sim 1000 M_{\odot}$ stars. Such stars would probably evolve and explode on rapid timescale. (It is interesting to note that no realistic stellar evolution calculations have been done for $1000 M_{\odot}$ stars with black hole, or nugget cores. The nucleosynthesis as well as the evolution might be worth exploring in more detail.) These stars might be the seeds for the Ostriker–Cowie[9] explosion scenario of galaxy formation. The only other plausible seed formation mechanism would be some other form of cold dark matter. However, current large-scale structure arguments[10] using observed voids, foam, and velocity fields now seem to favor at least some hot matter which would damp out the growth of most cold matter seeds but possibly not stop these more massive pieces of debris from having an effect. If so, the only way the explosion picture could survive is with quark–hadron debris. Following reference 10, let us review the large-scale structure situation to see if we need explosions and hot matter.

Hot matter ($\sim 10 eV$ mass neutrinos) was once quite popular as a candidate for solving the cosmological dark matter problem, since this was the least exotic of the non-baryonic options, and neutrinos naturally clustered only on large scales where the dark matter was needed, rather than on the small scales where the contribution of dark matter was known to be minimal (ref. 11 and references therein). Neutrinos received a major boost with the preliminary reports of measured mass (ref. 12 and references therein) for ν_e (although probably only the most massive ν is cosmologically important, and that might well be ν_τ which could still have a $\sim 10 eV$ mass, even if $m_{\nu_e} \ll 1 eV$). Also, they gained strength when it was shown[3] that the neutrino Jean's mass was

$$M_J \sim \frac{3 \times 10^{18} M_{\odot}}{m_\nu^2(eV)} \text{ or } \lambda_J \sim \frac{1300 Mpc}{m_\nu(eV)}$$

which for $m_\nu \sim 30 eV$ yielded $M \sim 3 \times 10^{15} M_{\odot}$, and $\lambda \sim 40 Mpc$, the mass and scale of superclusters.

Unfortunately, massive neutrinos fell into disrepute as dark matter when it was emphasized[14] that in the standard adiabatic model of galaxy formation with a random phase, Zel'dovich fluctuation spectrum of the type expected by inflation, and with $\delta T/T$ constrained by microwave observations, galaxies did not form until redshift $z \lesssim 1$. This occurred because the initially formed pancakes with mass M_J took a while to fragment down to galaxy size. This contradicted the observations which showed that quasars existed back to $z \sim 3.5$. In addition, if baryons stay in gas form in the potential wells of the large ν pancakes, they light up in the x-rays beyond what is observed[15].

While some[16] have appealed to statistical tails, etc., to escape these conclusions, most cosmologists began abandoning neutrinos and adopting cold dark matter[17], which could enable rapid galaxy formation[18,19].

Cold matter also had its problems[20]. In the standard model, it would all cluster on small scales, and thus be measured by the dynamics of clusters, such as the Virgo infall. Since such measurements implied that $\Omega \sim 0.2 \pm 0.1$ on cluster scales, this meant that $\Omega_{cold} \lesssim 0.3$, and not unity. Remember that $\Omega_{baryon} \sim 0.1$, so observationally, non-baryonic dark matter is not required unless one wants an Ω of unity, so cold matter wasn't naturally solving one problem for which it was postulated. This constraint on cold matter could be escaped if it were *also* assumed that galaxy formation was biased[19,21] and did not occur everywhere. Thus, there could be many clumps of cold matter and baryons that did not shine for some ad hoc reason. Biasing ran into problems when it could not explain the observation[22] of a very large cluster–cluster correlation function, ξ_{cc}, relative to the galaxy–galaxy correlation function[20,21], ξ_{gg}. With biasing $\xi_{cc} \propto \xi_{gg}$ but in all models $\xi_{gg} < 0$ for a few 10's of Mpc, whereas ξ_{cc} was observed to be positive out to scales $\gtrsim 50 Mpc$.

Hardcore cold matter lovers had to argue that the ξ_{cc} data might be wrong, although no one has been able to disprove it. A way out of the ξ_{cc} problem was proposed in Reference 23. There we noted that the correlation functions appear to be scale free, thus implying that large-scale structure is dominated by something other than random noise and gravity, say either percolated explosions or strings. In fact, the scale-free structure is characterized by a fractal of dimension $D \sim 1.2$, not too different from the $D \sim 1$ that naive string theory might yield. String calculations[24] of galaxy formation indeed found support for such a fractal process with the appropriate dimension being valid from galaxy to supercluster scales.

Thus, there were already strong hints that something was wrong with the previous, in vogue, picture of biasing and cold matter with random noise initial fluctuations. To this we now add the new observations of many large voids[25,26] of diameter $50 h_{1/2} Mpc$ ($h_{1/2} \equiv H_0/50 km/sec/Mpc$), with most galaxies distributed on the walls of the voids, and the observation[27] that our local 40 Mpc region of space is moving with a coherent velocity field of $\sim 600 km/sec$ toward Hydra-Centaurus. While at least one large void (in Böotes) had been observed before[28], using a pencil beam approach, until the Harvard redshift[25] survey work, it was not known how ubiquitous voids were. In fact, the Harvard data shows that almost all galaxies are distributed along the "walls" of voids; galaxies and clusters are not randomly distributed, but fit onto a well-ordered pattern.

While the Harvard work only goes out to $\sim 100 Mpc$, there is substantial evidence that this sort of pattern persists to redshifts $z \sim 1$ from the Koo and Kron survey[26], as well as the earlier work of Tifft and others on distributions of quasar redshifts which showed "quantization". A simple explanation for the peaks and valleys in the distribution of galaxies and quasars with redshift is that one is looking through filaments or shells with voids in between, once again demonstrating that galaxies and clusters are not laid out randomly on the sky, but follow a pattern.

While statistical fluctuations with cold matter might yield a few large voids as well as many small voids[15,19], it is difficult to get all of space filled with large voids and have galaxies appear only at the boundaries unless some special form of "biasing" is used. However, the real killing blow for the cold matter plus biasing scheme comes from the velocity field work. Even if the biasing could be selected so as to give ubiquitous large voids, the velocities of a $40Mpc$ region of galaxies would be relatively small and random, rather than large and coherent[29,30]. Thus, it appears that the large-scale structure is telling us that we need something that gives us $\sim 40Mpc$ coherent patterns, and cold matter doesn't appear the way to go.

Since neutrinos naturally gave us patterns on this scale, maybe they should be reexamined. In addition, since the voids look rather spherical, and since explosions tend to produce spherical holes after a few expansion times even if the initial explosion is asymmetric, perhaps an explosive mechanism should be considered also. Since the Ostriker–Cowie[9] explosion mechanism by itself cannot yield such large voids, the only way it could work is via a high density network of explosions which percolated[20,31]. However, to get $\Omega = 1$ with an exploding scenario would still require non-baryonic matter that did not cluster with the light emitting stuff. In principal, this could be either neutrinos or cold matter but at least with neutrinos an $\sim 40Mpc$ scale might still be naturally imposed.

Of course, in order for neutrinos to work as the dominant matter, some mechanism to rapidly form galaxies must be imposed both to enable galaxies to exist at $z \sim 5$, and to condense out the gas before it falls into the forming deep potential wells, and emits x-rays. Two ways that might achieve this rapid formation are either via the aforementioned explosion scheme within the collapsing ν-pancakes, or via cosmic strings[32] which would act as nucleation sites for galaxy formation. Since strings are not free-streamed away by the relativistic neutrinos[33], the galaxy scale fluctuations remain within the ν-pancakes. Notice that since neutrinos are not used by themselves simple arguments based on relating their primordial fluctuation spectrum to observed galaxy velocity and distribution features are not necessarily valid and must be reexamined in the more complete scenario.

To summarize, the above possibilities leaves us with two viable options: 1. Neutrinos and strings; or 2. Neutrinos and percolated explosions. A third option of cold matter and percolated explosions cannot be completely dismissed, but does not naturally give us the $\sim 40Mpc$ scale; however, the explosions could be a way of clearing the baryons out of the cold matter clumps in the voids and leave a critical density of matter not associated with the light emitting regions. In such a scenario, the voids would then be filled with clumps of cold matter.

It is interesting that the two most viable options involve the same two options that the scale-free cluster–cluster correlation function arguments point towards. Let us look at each of these scenarios in a little more detail and see if there might be ways of resolving whether either of them might actually be correct. Also, let us see what each requires for the physics of the early Universe.

Both of these scenarios have hot matter, presumably neutrinos as the dominant matter of the Universe. If $\Omega = 1$, as is necessary to avoid our living at a special epoch, and as agrees with the recent large-scale galaxy count arguments of Loh and Spillar[34] and the dynamics on 200 Mpc scales of Rowan–Robinson[35] (but disagrees with the direct dynamical arguments on scales of clusters and smaller, and with the baryonic measurements from nucleosynthesis), then $m_\nu \lesssim 35eV$. It is curious that the requirement that we want the neutrinos to give us the large-scale structure, $\lambda_J \sim 40Mpc$, or $M_J \sim 10^{16} M_\odot$, also gives us $m_\nu \sim 30eV$, a mass about what is necessary to get $\Omega \sim 1$. Also, we have a lower bound from the nucleosynthesis argument[36] that the number of neutrino species with $m_\nu \lesssim 10MeV$ is three or at most four. Since the sum of all neutrino masses cannot exceed the $35eV$ limit mentioned above, and since the lowest mass for the most massive one occurs when they are all equal, then if $N_\nu \leq 4$,

$$m_\nu \gtrsim 9eV.$$

The first scale to be able to condense and thus have their density grow will be the horizon scale when the neutrinos become non-relativistic, which is M_J. However, in the string option, loops of string will exist down to scales of galaxy size (scales smaller than galaxy size gravitationally radiate away[32]). So as the neutrinos become non-relativistic they can be trapped on smaller scales. The baryons will not be able to begin clustering until after recombination. However, the slow-moving baryons will rapidly fall on to the pre-existing loops of string plus neutrinos. Thus, galaxies will be able to form shortly after recombination, and well before $z \sim 1$.

The correlation functions of galaxies through superclusters will be characterized by the string picture[24] and will naturally yield a fractal near $D \sim 1$. The collapsing ν-pancakes on $\lambda_J \sim 40Mpc$ scales will create large voids on that scale, and leave galaxies in planes. Although actual detailed evolutionary calculations of ν-pancakes plus string-induced galaxy formation remain to be completed[37].

While this string plus neutrino scenario naturally yields $D \sim 1$, it does not so naturally give $D = 1.2$. Fine tuning[38] of string parameters may enable such variation on the scale of the galaxy–galaxy correlation function, or some modification of the criteria for the formation of light-emitting regions around the strings may be necessary.

In this regard it should be remembered that because of possible systematic errors, not everyone agrees that 1.2 is significantly different from 1.0, even for the galaxy–galaxy correlation function[39], which is the best determined[40]. The uncertainties in the exponent of the cluster–cluster correlation functions are *far* larger, thus problems in trying to explain variations from $D = 1$ fractals are not serious at the present time. With strings there is the additional problem of tuning the primordial phase transition so as to inflate first, and then produce strings[41]. While not impossible, this is constraining.

The second way to get neutrinos to work involves explosive galaxy formation. Here we need initial seeds to lead to condensations which produce massive baryonic objects which explode. Under the third option, where the explosions are used with cold matter, the baryons might naturally collect around the growing small-scale (globular cluster mass) cold matter clumps. However, as mentioned before, such a model does not naturally give us $40Mpc$ structure. If we use neutrinos then the seeds must be in a form which does not get free-streamed away by the relativistic neutrinos. Strings don't work well here because the string scales that might lead to rapidly evolving baryonic objects are radiated away gravitationally. Thus, the seeds must come in some other isothermal-like form. Perhaps the best option would be the above mentioned condensates from the quark–hadron transition.

The scale affected by explosions of single galaxy size[36] is at most a few Mpc; however, it has been shown[31] that at sufficiently high densities and high trigger rates, the explosions can percolate at least out to scales of a few 10's of Mpc. The fractal dimension of such percolated ensembles is quite sensitive to parameter assumptions and usually varies with scale, thus showing that it is not a true scale-free fractal. If it is made to fit the small scale (few Mpc) with $D \sim 1$ it is usually larger ($D \sim 2$) on scales of $\gtrsim 10Mpc$. Since, as mentioned above, the exponent of the cluster–cluster correlation function is not, at present, well determined, such models cannot be ruled out. With such explosions percolating within ν-pancakes, we might naturally have their pattern superimposed on the $\sim 40Mpc$ neutrino scale. In addition, although percolated explosions will initially be highly non-spherical, their shape will evolve towards sphericity with the smaller axes catching up in length to the largest one. In order for large-scale percolation to occur, several generations[21] of explosions must occur; however, cooling arguments and time to initial explosions, plus the need for condensed objects by $z \sim 4$ and the need to hide from present observers, the radiation produced by the explosions, severely restrict the possibility of such percolation and thus quite a bit of fine tuning is required to escape the constraints.

Thus, while we cannot explicitly rule out this latter case, unless some new physics can be developed to show how the fine-tuned parameters are natural for other reasons, we must lean towards the string option as the present frontrunner. Strings, of course, would have other observational consequences (see ref. 32 and references therein) like gravitational double lensing of distant objects and shifts in the 3° background across such a line of lenses, and a background of gravitational radiation from the evaporation of small-scale strings which might affect the millisecond pulsar. Thus, observations should eventually be able to confirm or deny this frontrunner.

If they rule it out then we may be forced to explosions whether we like them or not; and with explosions goes the need for seeds which may force us to produce debris during the quark–hadron transition.

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