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PHASE TRANSITIONS AND DARK MATTER PROBLEMS

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The possible relationships between phase transitions in the early universe and dark matter problems are discussed. It is shown that there are at least 3 distinct cosmological dark matter problems 1) halos; 2) galaxy formation and clustering; and 3) $\Omega = 1$, each emphasizing different attributes for the dark matter. At least some of the dark matter must be baryonic but if problems 2 and 3 are real they seem to also require non-baryonic material. However, if seeds are generated at the quark-hadron-chiral symmetry transition then alternatives to the standard scenarios may occur. At present no simple simultaneous solution (neither "hot", "warm", nor "cold") exists for all 3 problems, but non-standard solutions with strings, decaying particles or light not tracing to mass may work. An alternative interpretation of the relationship of the cluster-cluster and galaxy-galaxy correlation functions using renormalized scaling is mentioned. In this interpretation galaxies are more strongly correlated and the cluster-cluster function is not expected to go negative until $\gtrsim$ 200 Mpc. Possible phase transition origins for the cluster-cluster renormalized scale are presented as ways to obtain a dimension 1.2 fractal.

1. INTRODUCTION

In this paper the various cosmological dark matter problems will be examined with a particular emphasis on the possible roles that phase transitions in the early universe may play. To do this, the 3 different cosmological dark matter problems: 1) halos, 2) galaxy formation and clustering, and 3) $\Omega = 1$; will be discussed. It will be shown that problems 2 and 3 are in part a consequence of our believing in the existence of phase transitions in the early universe. With regard to clustering, the relationship of the cluster-cluster and galaxy-galaxy correlation functions will be discussed from the alternative view of a renormalized length scale. Possible solutions to the dark matter problems will then be discussed. It will be emphasized that at least some of the dark matter must be baryonic, and in fact all of the halo material could, in principal, be baryonic. However if problems 2 and 3 are real then we are forced to require additional non-baryonic material. Simple one particle dark matter hypotheses where "hot" or "cold" or "warm" are shown to not simultaneously solve all 3 problems and even hybrids of two kinds of stable non-baryonic matter fail. ["Hot" particles are those which are relativistic, like 10 eV ν's, until shortly before recombination, "cold" particles are ones which are slow moving well before decoupling like 10 GeV gravitinos or axions and warm ones are in between.] More complex "ugly" solutions can be made to work but at present need more fine tuning than one would like. Solutions with strings, seeds from the quark-hadron-chiral symmetry transition, decaying particles and light not being an unbiased tracer of mass are all presented.

2. HALOS

The classical dark matter problem is the, now well established observational fact that galaxies have dark halos. This problem is nicely described and documented in numerous reviews[1,2] so it won't be gone into detail here. A simple summary of the results will suffice. Basically galactic masses, M, are measured using simple dynamics.

$$M \sim v^2 r/G \qquad (1)$$

where v is the orbital velocity, r the separation distance and G, Newton's constant. When this is applied to the visible regions of spiral galaxies, the typical mass obtained is $\sim 10^{11}\ M_{\odot}$ with a mass-to-luminosity ratio $M/L \sim 10h_o$ in solar units where h_o is the Hubble constant in units of 100 km/sec/Mpc. As an aside it is interesting to note that this value for galactic disks may actually be about a factor of two higher than what can be accounted for with stars, gas, dust, etc. seen in the disk. This discrepancy is well documented in the solar neighborhood[2,3] and can be referred to as a fourth dark matter problem although its solution is probably not cosmological.

When equation (1) is applied to binaries and small groups, it is found that the implied masses increase by a factor of ~ 10 while the light/galaxy is not increased at all, thus M/L approaches $\sim 100h_o$. This is known as the dark halo problem. The mass must be there so it is not the mass which is missing but the light, thus Steigman and DNS[4] refered to it as the "missing light problem". The need for dark halos has also been discussed on theoretical grounds[5] as necessary for disk stability. As well described in the reviews it is also supported by measurements of distant material such as stars and gas as well as other galaxies. While mentioning dark halos it is important to note that dark halos may even surround small dwarf spheroidal galaxies[6] as well as spirals and ellipticals. If true this has important implications on what material could form these halos since phase-space arguments[7] would not allow neutrinos to work on these small scales.

As we go to the still larger scales of large clusters and superclusters the apparent mass per galaxy and thus the best estimate for M/L continues to rise, however the uncertainties and scatter in the data also increase. The range for M/L's implied from these large scale measurements using the virial theorem (where averages for $\langle v^2\rangle$ and $\langle r\rangle$ are used in eq. 1) and from looking at the deviations in the Hubble flow caused by infall into the Virgo cluster[8] is from $\sim 100h_o$ to $\sim 500h_o$. Nothing gives a significantly larger M/L. It should also be noted that whether M/L keeps rising beyond $\sim 100h_o$ or not at large scales is still not unambiguous.

The M/L's can be made cosmologically relevant by multiplying by $\mathcal{L} \approx 2 \times 10^8 h_o L_\odot/\mathrm{Mpc}^3$, the average luminosity density (care needs to be taken to use the same filter-bands for $\mathcal{L}$ and the L's in the M/L's, different M/L's than I have listed are frequently quoted but they correspond to a different thus maintaining the resultant product.) This product $\rho = M/L \cdot \mathcal{L}$ is the implied matter density if that M/L applies to the average light in the universe. The density parameter $\Omega \equiv \rho/\rho_{crit}$ thus obtained is independent of h_o since $\rho_{crit} \propto h_o^2$ and $M/L \cdot \mathcal{L} \propto h_o^2$. The results are summarized in Table I. Note that since most galaxies are not in the largest clusters, their M/L may not be associated with $\mathcal{L}$ but perhaps is only related to some special process involved in forming these things. Thus while we can say with some confidence that $\Omega \gtrsim 0.07$, we are not forced to make it significantly larger on the grounds

of unambiguous observational evidence. Note also that while the M/L and the implied Ω do tend to rise with scale, no observation yields an implied Ω of unity or larger. The only way to achieve an $\Omega \gtrsim 0.4$ would be to have significant amounts of material that does not cluster within the bounds of the largest clusters.

3. BARYONS

Before looking at the other dark matter problems, it is useful to see what ordinary baryonic matter can and cannot do for us. In particular a detailed comparison of the state-of-the-art Big Bang Nucleosynthesis calculations and the current observed abundances yields[10] an extreme upper bound on the baryonic density, Ω_b, of 0.19 with a reasonable bound put at 0.14. Yang, et. al. also point out the existence of an extreme lower bound on Ω_b of ~ 0.01. This lower bound can be tightened[11] to $\Omega_b > 0.03$ using limits on the age of the universe from nucleochronology and globular clusters. This range on Ω_b is intriguing. On the one hand it tells us that the halos even in the large clusters can in principle be completely baryonic. On the other, it tells us that at least <u>some of the baryons are not shining.</u> We know that some of these non-optically shining baryons are shining in x-rays as evidenced by the x-ray gas associated with large clusters.[12] If all galaxies have as many non-optical baryons associated with them as do the ones in large clusters then we know the answer to the dark halo problem[4] - baryons. However Hegyi and Olive[13] argue that it would take a very peculiar baryonic object to work. Jupiters or low mass stars work but only if produced in large excess of any extrapolation of observed stellar initial mass functions. Similarly stellar mass black holes work only if they are not produced with accompanying heavy element producing supernovae. (Stellar mass black holes count as baryons since they would have been in the form of baryons during Big Bang Nucleosynthesis.) Although these are reasonable arguments, they do have loopholes since no fundamental physics is being violated, therefore the halo problems can in principle be completely solved with dark baryons. In fact, the old solution[14] of $\Omega \sim 0.1$ is still valid and cannot be ruled out if the universe is baryonic. However, we will see that other arguments lean towards a dominant admixture of non-baryonic stuff.

4. GALAXY FORMATION

To form a galaxy requires a density fluctuation, δn_b in the baryon density, n_b. Such a fluctuation can come from a primordial fluctuation or it can be created by shocks coming from explosions of pre-existing seeds,[15] with the origin of the seeds still requiring some primordial occurrence. Classically,[16,17] two kinds of primordial fluctuations were discussed;

1) isothermal where n_γ = const

2) adiabatic where n_b/n_γ = const

where n_γ is the photon density.

We now know that baryons can be produced by Grand Unified (GUTs) interactions in the early universe[18] and we have no other convincing way to produce the observed excess of baryons over antibaryons. Turner, Schramm and Press[19] noted that such production is only easy to make compatable with primordial adiabatic fluctuations since in such schemes n_b is a unique function of temperature T, thus δn_b must be accompanied by a δT yielding a δn_γ. Once primordial adiabatic fluctuations are accepted then there is a direct connection between $\delta n_b/n_b$ and the hoped-to-be observed variations in the 3K background. Recent limits on the 3K anisotropy[20] tell us that

$$\delta T/T \lesssim 2 \times 10^{-5}$$

at the decoupling of the radiation from the matter which occurs at $T \sim 3000$ K. We know that density perturbations grow linearly with $1/T$ in an expanding universe once the universe is matter dominated. (Growth will cease in an open universe at redshift $z \sim 1/\Omega$). Since baryons are coupled to the radiation, their perturbations must be small at $T \sim 3000$ K. (Naively $\delta\rho/\rho \sim 3\delta T/T$ but

detailed calculations[21,22] through the decoupling epoch taking into account the averaging techniques in the measurements show that the proportionality is a little different from 3.)

We know that at the present epoch of $T \sim 3$K, that density variations $\delta\rho/\rho \sim 1$ exist on scales up to at least the large clusters of galaxies. Linear growth tells us that this requires $\delta\rho/\rho \gtrsim 10^{-3}$ at $T \sim 3000$K. But, $\delta n_b/n_b \sim 3\delta T/T \lesssim 2 \times 10^{-5}$ thus $\delta\rho/\rho \gg \delta n_b/n_b$ at $T \sim 3000$ K. That is, we are forced to non-baryonic matter <u>if</u> we assume adiabatic perturbations and linear growth. Detailed calculations[21,22] even with non-baryonic matter, noting the growth cut off at $\sim 1/\Omega$ find that $\Omega \sim 1$ (at least $\Omega > 0.2$) is required to get $\delta\rho/\rho \sim 1$ today. [Remember once $\delta\rho/\rho \gtrsim 1$ non-linear growth can occur so the existence of some objects with $\delta\rho/\rho \gg 1$ is not a problem unless the scale is so large that $\delta\rho/\rho$ could not have reached unity.]

5. GALAXY CLUSTERING

An important constraint on the dark matter involved with galaxy formation is how galaxies are clustered and how clusters are clustered. There are two important considerations here. The first is the galaxy and cluster correlation functions. The second is the existence of large scale filaments and voids. Let us begin with the latter.

Although there is still no unambiguous, unbiased statistical study of the problem, there is definitely a growing trend among observers to note large scale holes in space and to note the lining up of the largest clusters along filamentary lines.[23] The scales of such ordering corresponds to mass scales $\delta M > 10^{16} M_\odot$. Such structure requires density fluctuations $\delta\rho/\rho$ exceeding unity on extremely large scales. It has been estimated[24] that with random fluctuations the probability of such large scales having $\delta\rho/\rho \gtrsim 1$ so that non-linear growth can set-in is about equivalent to a 4σ event.

The existence of these very large scales has been used by some to argue for neutrinos[4,11,25] (or other "hot" matter) as the dark matter candidates or to favor non-random phases.[26,27] However it may also be possible through statistical fluctuations to obtain a few rare such cases in "cold matter" scenarios.[28] The test will be whether larger surveys reveal these very large structures to be rare or common.

The use of 2, 3, and even 4 point correlation functions has been developed by Peebles[17] and his co-workers to a fine art that has now become a cornerstone of modern cosmology. In particular the 2-point galaxy-galaxy correlation function $\xi(r)$ which is defined as the excess probability over random for a galaxy to be at a distance r from another galaxy is found to be proportional to $r^{-1.8}$ which is equivalent to a fractal of dimension 1.2. That is, galaxies do not fill all space and are correlated. The correlation deviates from this power law at large scales and may even go negative[23] for $r \gtrsim 40$ Mpc. It is also interesting that the 3-point function is what one would expect for a hierarchical clustering scenario where large scale builds up from small. This used to be a strong argument in favor of primordial isothermal fluctuations before grand unified theories, since a pure baryonic isothermal model produced hierarchical clustering whereas a pure baryonic adiabatic model produced large scales first and required fragmentation. However, we now know that hierarchical clustering can be achieved with cold (or warm) particles in adiabatic scenarios. In addition Fry[29] has shown that scenarios which produce large scale filaments will also yield a 3-point function which fits the data.

An exciting new result by Bahcall and Soniera[30] and Klypin and Khlopov[31] following earlier explorations by Peebles[17] is the recognition that the correlation function between clusters also has the $r^{-1.8}$ power law dependence but is ~ 20 times stronger than the galaxy-galaxy function on the same scale and is definitely non-zero on scales up to at least 100Mpc. This seemed somewhat perplexing, and was not a simple quantitative consequence of pure baryonic nor "cold" nor "hot" models.[32] One possible explanation was that clusters are 3σ effects[33] and the correlation of such effects would be significantly enhanced over the rest of the fluctuations. Such an

interpretation would mean a proportional amplication, thus if the galaxy-galaxy function goes negative at 40 Mpc so should the cluster-cluster function. This seems to contradict the observations, however both the negativity at 40 Mpc in the galaxy-galaxy function and the strength of the cluster-cluster function at scales $\gtrsim 50$ Mpc are not yet beyond question. More observational work is clearly required.

An alternative way to look at the cluster-cluster versus galaxy-galaxy functions is use a renormalization approach as is done in condensed matter studies with correlation functions. In particular, instead of using the same units for r for both galaxies and clusters one "renormalizes" and uses a unit of the average separation distance of the object being studied. In these renormalized units for the Bahcall and Soneira samples the cluster-cluster function is actually weaker than the galaxy-galaxy function by a factor of about 3. But as one goes to higher richness clusters with longer renormalized length scales the renormalized amplitude stays roughly constant (in absolute units higher richness classes yield stronger correlations). Such a renormalized approach also means that negative correlations in the galaxy-galaxy function at ~ 40Mpc would not manifest themselves onto the cluster-cluster function until ~ 200Mpc since the renormalized length units for clusters are ~ 5 times those for the galaxy sample. Thus there is a clear test for comparing the renormalized approach with the 3σ approach with current data leaning towards renormalization. If the renormalized approach has any physical merit it must mean that there is some other physical process at play on large scales with a different correlation scale than that at play on small scales. Presumably the small scale process is gravitational attraction which in the renormalized view is giving additional correlation strength over the large scale function. Since the $r^{-1.8}$ or 1.2 fractal character holds in both limits this would imply that the process giving the large scale is the 1.2 fractal producing process. Possible physical processes which yield large scale structure include neutrino "pancakes"[25] or strings[27,34]. Szalay and DNS are preparing a more detailed examination of this renormalized approach.

6. INFLATION

Let us now look at the third cosmological dark matter problem, namely the fact that inflation[35] seems to require Ω=1 [barring a finely tuned minimal inflation which is almost as unattractive as having no-inflation at all, other than making the flatness problem one of logarithmic rather than linear fine tuning.] While philosophical arguments about an open versus closed universe have existed for years, inflation has now provided us with a physical reason to favor a model just at the critical density, a flat, open universe, which with a cosmological constant of Λ=0, implies Ω=1. It is well known that the original inflation had problems which were cured by Linde[36] and Albrecht and Steinhardt[37] using a "smooth" phase transition which in effect could put the whole universe in a single bubble of a multiple bubble universe. Since this bubble inflated away all the primordial fluctuations to solve the horizon, flatness, and monopole problems, it was necessary to look at the self generated quantum fluctuations in the bubble itself to see if any fluctuations were generated. Numerous[35] workers did this and found that fluctuations were generated with the Harrison-Zeldovich[16] spectrum of fluctuations which put equal power on all scales which fits observations well; however all the standard Grand Unified models ended up with primordial $\delta\rho/\rho \gtrsim 10$ as opposed to $\lesssim 10^{-4}$ required by the 3K anisotropy limits. Such large fluctuations would rapidly collapse to black holes not galaxies. Solutions which yielded proper sized fluctuations have been proposed[38,39,40,41] involving supersymmetry (SUSY), Supergravity (SUGR), or extra Higgs sectors but each has necessitated some ad hoc assumptions whose only motivation is to solve this particular problem. Therefore, no solution yet proposed is as yet convincing. At this point, one might ask "why then is inflation viewed with so much certainty?" The answer is that even though the detailed physics of the phase transition and the possible role of the Higgs sector and GUTs, SUGR, or SUSY is still highly

questionable, it does seem clear that the only way to set the initial conditions of the universe so as to solve the horizon and flatness problems is to go through a deSitter phase. This point was made earlier by Gliner,[42] Kazanas,[43] and Gott[44] regarding the horizon problem and connected to the flatness and monopole problems by Guth[45] who ingeneously coupled the deSitter phase to the GUT phase transition and coined the term inflation. Only through GUTs and reheating could the new post-inflation universe produce baryons and not be empty. In addition, it has been noted[46] that if the inflation energy scale, E_I, is $\gtrsim 10^{17}$GeV, the inflation will occur too near the planck scale, $M_p \sim 10^{19}$ GeV and gravitons will produce fluctuations in the microwave background corresponding to $\delta\rho/\rho \sim (E_I/M_p)^2$ which exceed the observational limits. This argues that quantum gravity or even those SUSY models with $E_I \sim M_p$ cannot cause the deSitter phase to occur. This leaves us with the need for some generic inflation whose microscopic details remain to be resolved.

In any case, the result inevitably seems to require a flat universe. Of course a flat universe at the present can be achieved by having Λ and Ω effects cancel, but such a cancellation is epoch dependent since the density term varies in a different functional manner with the expansion than does the Λ term. Barring our living at a special epoch leaves only the option that Ω=1. From nucleosynthesis we know that this implies that $\gtrsim$85% of the universe must be non-baryonic. In other words, <u>we don't [illegible] made of the "right stuff!"</u>

7. CANDIDATES

Single particle non-baryonic candidates have been divided into "hot", "cold", and "warm" following Bond.[47] The key to this division comes from the effective Jeans mass

$$(M_J)_i = \frac{3\times10^{18}M_\odot}{m_i^2(eV)} \qquad (2)$$

This is the smallest scale which can initially collapse when particle i first dominates the mass density of the universe. At times earlier when the temperature KT of the universe exceeds $m_i c^2$ then species i would be relativistic and damp out all adiabatic fluctuations out to the horizon. M_J is related to the horizon mass at $KT \approx m_i c^2$. For light-hot particles M_J is large and large cluster scales form first and eventually fragment to make galaxies, for heavy-cold particles, M_J is small so small scales form first and large scales get hierarchically built. [Axions have a small mass but were never in thermal equilibrium so they have a low velocity and thus a small M_J.] Table II lists various proposed particles and their classification.

Massive neutrinos are the least exotic of the proposals since they are known particles and although their massiveness is not required it is also not forbidden. Since neutrino interactions and spins are well known, it is easy to calculate the exact density of them produced in the big bang (cf. ref. 4 and references therein). In particular it can be shown that they decouple at ~ 1MeV so their present temperature will be ~ 2°K compared to a photon temperature of 3K, due to subsequent e^+e^- annihilation heating the photons relative to the neutrinos. The net result including spin factors is that the number density of a neutrino species $\nu_i + \bar{\nu}_i$ is ~ 150/cm^3 as compared to ~ 450 for photons. Other more weakly interacting species like gravitinos decouple sooner allowing more annihilations to heat up ν's and γ's. Therefore the temperature and number densities of these ultra weak species will be still lower,[48] thereby allowing larger single particle masses without exceeding cosmological density limits.

Planetary mass black holes behave just like any elementary cold particle but their production requires a first order phase transition to occur when the cosmological horizon exceeds 10^{15}g, so the black holes don't disintegrate via the Hawking process, and yet they must form before nucleosynthesis if the light element abundances are not to constrain their total density. The two transitions that fall into this range are the electro-weak (T ~ 100GeV) and the quark-hadron-chiral symmetry transitions at T ~ 1GeV the possible production of planetary black holes in the latter was discussed by Crawford and Schramm[49,50]

and in the former by Crawford[51] and Novikov.[52] At present it appears that the quark-hadron-chiral transition might be first order and thus may have some chance, however; see other papers in this volume for a more detailed discussion. The electro-weak does not appear capable of significant planetary mass black hole production.[51]

It has been noted[11,28,53,54] that neither a single cold nor a single hot nor even a single warm particle can simultaneously solve all three cosmological dark matter problems in the simple model with non-interacting free particles undergoing gravitational clustering.

Hot particles have $M_J \sim 10^{16} M_\odot$ so they give the large scale structure and their large clustering scale can put the bulk of them outside of the largest clusters thus enabling Ω=1 without conflicting with the observation that $\Omega_{cluster} \sim 0.2$ of within a factor of 2. However such models need to have galaxies form late[55] ($z \lesssim 1$) which conflicts with observations of quasars at $z \gtrsim 3.5$. Thus they don't make galaxies well. In addition phase space arguments prevent them from being the dark halo matter of dwarf spheroidals, but that is not critical since we know some dark baryons must exist somewhere. While cold matter has received much praise recently[28,53] due to its being able to solve the galaxy formation problem and fit galaxy-galaxy correlations as well as serve as halos even on the small scales of dwarf galaxies, it does have the serious flaw[11,56] of putting all of its matter on scales that should be measured by cluster dynamics *if* light traces mass in some unbiased way. Thus if $\Omega_{cold} \sim 1$, then $\Omega_{cluster} \sim 1$ in conflict with observations. No warm particle mass has been found which doesn't fall into either the cold or hot difficulty. Thus there is no simple solution. Hybrid two particle models have also been tried using a hot and a cold particle. These also fail because the hot particles will damp out the growth of the cold density fluctuations until the hot particles become non-relativistic.[57,11] Such damping occurs unless $\Omega_{cold} \gg \Omega_{hot}$ but from observations $\Omega_{cluster} < 0.4$, thus $\Omega_{cold} < \Omega_{hot}$ if $\Omega \sim 1$.

This dilemma is now forcing various groups to look at more complex models, all of which seem somewhat contrived at this time.

8. "UGLY" SOLUTIONS

Table III lists "ugly" solutions which have been proposed and can, with enough tweaking of the parameters, be made to simultaneously solve the 3 dark matter problems. The "ugliness" differs from case to case as is listed in the Table. While none are compelling at the present time, they at least have the advantage of making different specific predictions which might eventually be checked. In particular the "light-not-a-tracer" and the "decay" scenarios make statements about large scale structure and cluster-cluster correlations which future large sky surveys should be able to resolve. They will also tell us whether the large superclusters and voids are rare or common. If common, this would argue for non-random phases and perhaps for the GUT phase transition going via strings.

A very nice way to begin to resolve the dark matter problem would be to find some of the stuff in the lab. If neutrinos are found to have a mass or if a 10GeV photino is found this would immediately collapse the degrees of freedom in the proposals.

9. SUMMARY

This paper has discussed the 3 cosmological dark matter problems of 1) the halos, 2) galaxy formation and clustering, and 3) the inflationary Ω=1. The halo problem comes directly from observational astronomy and could be solved with dark baryons, the 2nd and 3rd require non-baryonic matter (however they also only occur because of natural theoretical biases rather than direct observation). We have seen that no simple model of baryons plus one cold or hot particle species simultaneously solves all three problems and even hybrid solutions of a hot plus a cold species fail. Complex solutions can be made to work but at present each has some ugliness which can only be removed if other

physics also forces us in those directions or if observation or experiment force us in those directions. It is interesting how so many aspects of the dark matter problem are intertwined with phase transitions. These interrelationships include GUTs and the need for adiabatic fluctuations which relates to the galaxy formation problem; inflation; strings; and the generation of dark matter candidates including possible planetary mass black holes of the quark-hadron-chiral symmetry transition.

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TABLE I

Scale	r	M/L*	Implied Ω
Stars	<1 pc	~1 to 2	$\lesssim 10^{-3}$
visible regions of galaxies	$\sim 10^4$ pc	$\sim 10 h_o$	~0.007
binaries and small groups	$\sim 10^6$ pc	$\sim 100 h_o$	~0.07
large clusters	$\sim 3 \times 10^7$ pc	$\sim 100 h_o$ to $500 h_o$	~0.07–~0.4

*Uses bandwidth consistent with $\mathcal{L} = 2 \times 10^8\ L_\odot/\mathrm{Mpc}^3$

TABLE II

Popular Candidates

Name	Mass	Classification
Neutrinos	$5 \lesssim m_\nu \lesssim 50$ eV	hot
Neutral heavy leptons	$\gtrsim 3$ GeV	cold
"Inos" [gravitinos, photinos, sneutrinos, axinos, ...]	$\gg \gtrsim 10$ GeV (favored by experimental limits)	cold
	few 10^2 eV $\lesssim m \lesssim$ few keV	warm
	$m \lesssim 10^2$ eV	hot
dimensions and other topological beasts	$m \sim 10^{17}$ GeV	cold
axions	$\ll 1$ eV	cold
planetary black holes	10^{15} g $\lesssim M \lesssim 10^{33}$ g	cold

TABLE III

Ugly Solutions

Solution	Ugliness	References
Light is not an unbiased tracer of mass	In the extreme this means observational astronomy is a waste of time	
version 1-cold matter	requires semi-ad hoc assumption that only 3σ density fluctuations lead to light emitting galaxies	28
version2-hot matter	requires "special" hydrodynamics or magnetohydrodynamics to prevent large dark pancakes from becoming observable x-ray sources. Also requires assumptions about fragmentation of some pancakes into galaxies. (May be aided by shock induced galaxy formation.)	58 59 25
A cold or warm particle decays to a hot one after galaxies form ($\nu_{heavy} \to \nu_{light} + X$ or gravitino→axino+axion or ?)	Requires a finely tuned particle model with no other current reason for the tuning than the solution to these problems	57, 60, 61 62, 63
Non-random phases (strings?)	Opens up a tremendous range in multiparameter space once the assumption that the fluctuations are random is thrown out. Different physical models, like strings, do provide some constraints but their model parameters have no strong motivation other than this class of problems	26,27
Shock enhanced galaxy formation	Requires initial seeds which either come from cold or hot models with their problems or from baryons falling onto clusters of planetary mass black holes whose production is dependent on the physics of poorly understood phase transitions.	15 64
Non-zero cosmological constant	Always invoked to solve cosmological problems, requires that we live at a special epoch	61

REFERENCES

1) S. Faber and J. Gallagher, Ann. Rev. Astron. and Astrophys. 17 (1979) 135.

2) P.J.E. Peebles, in: Physical Cosmology, eds. J. Audouze, R. Balian and D. Schramm (Reidel, Amsterdam, 1980).

3) J. Bahcall, in: Proc. Inner Space/Outer Space, eds. E. Kolb and M. Turner (U. of Chicago Press, Chicago, 1984).

4) D. Schramm and G. Steigman, Ap. J. 243 (1981) 1.

5) J. Ostriker and P.J.E. Peebles, Ap. J. 186 (1973) 467.

6) S. Faber, in: Proc. CERN Meeting on Particle Physics and Cosmology (CERN, Geneva, 1984) and references therein.

7) S. Triemaine and J. Gunn, Phys. Rev. Lett. 42 (1979) 407.

8) M. Davis and P.J.E. Peebles, Ann. Rev. Astron. and Astrophys. 21 (1983) 109, and references therein.

9) R. Kirshner, G. Oemler and D. Schecter, Ap. J. 84 (1979) 951.

10) J. Yang, M. Turner, G. Steigman, D. N. Schramm, and K. Olive, Ap. J. 281 (1984) 493.

11) K. Freese and D. N. Schramm, Nucl. Physics B233 (1984) 167.

12) S. Lea, J. Silk, E. Kellogg and S. Murray, Ap. J. 184 (1973) L105.

13) D. Hegyi and K. Olive, Phys. Lett. 126B (1983) 28.

14) J. Gott, J. Gunn, D. Schramm, and B. Tinsley, Ap. J. 194 (1974) 543.

15) J. Ostriker and L. Cowie, Ap. J. 243 (1980) L127.

16) Y. Zeldovich and I. Novikov, in: Relativistic Astrophysics, Vol. II (U. of Chicago Press, Chicago, 1983).

17) P.J.E. Peebles, in: Large Scale Structure of the Universe (Princeton University Press, 1981).

18) E. Kolb and M. Turner, Ann. Rev. Nucl. & Part. Sci. 33 (1983) 645, and references therein.

19) M. Turner and D. N. Schramm, Nature 279 (1978) 303; also W. Press, Physica Scripta 21 (1980) 702.

20) J. Uson and D. Wilkinson, in: Proc. Inner Space/Outer Space Conf., eds. E. Kolb and M. Turner (U. of Chicago Press, 1984).

21) N. Vittorio and J. Silk, in: Proc. Inner Space/Outer Space Conf., loc. cit.

22) J.R. Bond and G. Efstathiou, in: Proc. Inner Space/Outer Space Conf., loc. cit.

23) M. Davis, in: Proc. Inner Space/Outer Space Conf., loc. cit., and references therein.

24) M. Davis and N. Kaiser, private communication (1984).

25) R. Bond and A. Szalay, Ap. J. 274 (1983) 443, and references therein.

26) P.J.E. Peebles, Ap. J. 277 (1984) 470.

27) N. Turok and D.N. Schramm, Nature (submitted, 1984).

28) M. Davis, G. Efstathiou, C. Frenk and S. White, Ap. J. (Suppl.) (in press, 1984).

29) J. Fry, Ap. J. 270 (1983) L31.

30) N. Bahcall and R. Soniera, Ap. J. 270 (1983) 20.

31) A. Klypin and N. Khlopov, in: Proc. COSPAR Mtg. (Bulgaria, 1983) communicated by R. Sunyaev.

32) G. Efstathiou, in: Proc. COSPAR Mtg. (Bulgaria, 1983).

33) N. Kaiser, in: Proc. Inner Space/Outer Space, loc. cit.

34) A. Vilenkin, Physics Reports (in press, 1984).

35) A. Guth, in: Inner Space/Outer Space Conf., loc. cit., and references therein.

36) A. Linde, Phys. Lett. 108B (1982) 384.

37) A. Albrecht and P. Steinhardt, Phys. Rev. Lett. 48 (1982) 1220.

38) J. Ellis, D. Nanopoulis, K. Olive, and K. Tamvakis, Phys. Lett. 118B (1983) 335, and references therein.

39) S.Y. Pi, this volume (1984).

40) A. Vilenkin, Tufts Univ. Preprint (1984).

41) P. Steinhardt, in: Inner Space/Outer Space, loc. cit.

42) E. Gliner, JETP 49 (1965) 542; also E. Gliner and T.G. Dymikova, Sov. Astro. Lett. 1 (1965) 93.

43) D. Kazanas, Ap. J. 241 (1980) L54.

44) J.R. Gott, Nature 295 (1982) 304.

45) A. Guth, Phys. Rev. D 23 (1981) 347.

46) K. Fabbri and M. Pollack, Phys. Lett. 125B (1983) 445; V. Rubakov, M. Sazhin, A. Varyashin, Phys. Lett. 115B (1982).

47) R. Bond, in: Proc. Recontre de Moriond (1983).

48) K. Olive, D. Schramm and G. Steigman, Nucl. Phys. B180 (1981) 497.

49) M. Crawford and D.N. Schramm, Nature 298 (1982) 538.

50) D.N. Schramm and K. Olive, in: Proc. Brookhaven Conf. on Quark Matter (1984).

51) M. Crawford, Ph.D. Thesis (U. of Chicago, 1984).

52) I. Novikov, in: Proc. IAU Mtg. (Patras, Greece, 1982).

53) G.R. Blumenthal, S. Faber, J. Primack and M. Rees, Nature (in press, 1984).

54) A. Dekel and M. West, Ap. J. (in press, 1984).

55) C. Frenk, S. White and M. Davis, Ap. J. 271 (1983) 417.

56) J. Gunn, B. Lee, I. Lerche, D. Schramm, and G. Steigman, Ap. J. 223 (1978) 1015.

57) M. Davis, M. LeCar, C. Pryor and E. Witten, Ap. J. 250 (1981) 423.

58) A. Szalay and N. Kaiser, in preparation (1984).

59) S. White, M. Davis and C. Frenk, M.N.R.A.S. 209 (1984) 27p.

60) K. Olive, D.Seckel and E. Vishniac, Fermilab Preprint (1984).

61) M. Turner, G. Steigman, and L. Krauss, Phys. Rev. Lett. 52 (1984) 2090.

62) G. Gelmini, D.N. Schramm, J.W.F. Vollee, Phys. Lett. (in press, 1984).

63) K. Olive, D. Schramm, and M. Srednicki, Fermilab Preprint (1984).

64) K. Freese, R. Price, and D. Schramm, Ap. J. 275 (1983) 405.