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# THICK STRINGS, THE LIQUID CRYSTAL BLUE PHASE AND COSMOLOGICAL LARGE SCALE STRUCTURE *

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## ABSTRACT

A phenomenological model based on the liquid crystal blue phase is proposed as a model for a late-time cosmological phase transition. Topological defects, in particular thick strings and/or domain walls, are presented as seeds for structure formation. It is shown that the observed large scale structure, including quasi-periodic wall structure, can be well fitted in the model without violating the microwave background isotropy bound nor the limits from induced gravitational waves and the millesecond pulsar timing. Furthermore, such late-time transitions can produce objects such as quasars at high redshifts($z \gtrsim 5$). The model appears to work with either cold or hot dark matter.

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# (I) Introduction

Every cosmological structure formation scenario has to face the potentially conflicting constraint of the microwave background isotropy $\Delta T/T$, and the existence of quasars and galaxies at large redshifts ($z \gtrsim 4$) as well as the existence of large structures (the great wall (Geller and Huchra 1989), the great attractor (Burstein 1987), and the possible existence of quasi-periodic walls (Broadhurst 1990) stretching over scales $\sim 100/h \ Mpc$ (where $h = H_0/100km/sec/Mpc$). One proposal (Hill, Schramm, and Fry 1989) around such problems has been to generate the cosmological seeds at a late-time phase transition following the decoupling of the microwave background. Such a vacuum transition can generate topological defects and/or vacuum fluctuations (Press, Ryden, and Spergel 1990; Wasserman, 1986) which can serve as cosmological seeds while providing the minimum $\Delta T/T$ for the production of a given size object (Schramm 1990; Turner, Watkins, and Widrow 1990; Nambu 1990; Goetz 1990). In this paper, we will use the analogy of the "blue phase" that has been well studied in liquid crystals to develop a phenomenological model for a cosmological transition that appears to have many promising features. The liquid crystal blue phase is particularly interesting since it yields structure on relatively large scale ($\sim 5000\AA$) from micro-physics processes with relatively small ($\sim 10\AA$) correlation length. (The structure on $5000\AA$ is why it is called the "blue phase.") This might be somewhat analogous to a late-time phase transition with a Compton wavelength of the fundamental physical interaction being $\sim 1 \ Kpc$ to $\sim 1 \ Mpc$ (Hill, Schramm, and Fry 1989) producing structure on scales of $\gtrsim 100 \ Mpc$.

The density fluctuations in this scenario are associated with the formation of topological defects. The best studied defect for a late-time phase transition has been the domain wall originating from a scalar field. The numerical work of Press *et al.* (1989) on the $Z_n$ wall network demonstrates that in most cases it is hard to form interesting structure from walls due to the one wall dominating the horizon volume (see also Stebbins and Turner 1989). One way out is to consider the sine-Gordon potential (Hill, Schramm, and Widrow

1990) which yields multiple "balls of wall" that serve as point-like seeds, but the relationship of such seeds to large wall-like structures is model-dependent and remains to be demonstrated. Other options to escape the one wall domination problem, such as slowing the wall via friction (Massarotti 1991) or decaying walls (Kawano 1990) to delay evolution, has been explored. We note here that a network of walls with wall-induced growth (baryons clumping in the repulsive gravitational field of the wall) modeled after the blue phase can fit the observed structure well. We also try to note that this model can utilize some of the results of the well explored cosmic string (Albrecht and Turok 1989) scenario. Although at late times, strings can be thick ($\sim 1\ Kpc$ to $5\ Mpc$), some aspects of cosmic string evolution can be preserved even if the strings form at late times provided that the mean separation of the string is much larger than the thickness of the string. In this paper, we note that strings can bound walls and be quite rigid and join together to vortices (Vilenkin 1984). The resulting network is quite rigid and only expands conformally with the expansion of the universe (see Figure 1). Such a rigid wall network can avoid the single wall domination problem raised by Press *et al.* and Stebbins and Turner (1989).

Similair hybrid defects applied to the very early universe were studied several years ago (Vilenkin 1985; Kibble 1985), but were found to be not interesting because they vanished rapidly through gravitational radiation. We will show that this disappearance doesn't hold for the thick string-wall system produced at late times. The simplest way to generate this wall/string network is to assume a vacuum phase transition analogous to the cholesteric liquid crystal blue phase.

To understand what is meant by cholesterics, let us first note that nematics is the basic object of liquid crystals. A nematics liquid crystal is a fluid made of rod-like molecules which possesses a long range orientational order (rod-like) but no long range position order (liquid). Usually the local preferred orientation of the rod $n$ is taken as the order parameter to characterize the nematics. This orientation is a headless vector or director because $n$ and $-n$ are the same thing. Cholesterics is simply chrial nematics. In the plane normal to an axis, the molecules have the same preferred orientation $n$. As one goes along the axis, the director $n$ twists about an axis perpendicular to the director with a spatial period $L$, usually called the pinch size. For the blue phase, the pinch size is $\sim 5000\AA$. In other words, as noted earlier, rod-like molecules with a scale of $\sim 10\AA$ show regular structure on the scales of $5000\AA$.

One nice thing about the cholesteric liquid crystal is that the phase transition from isotropic to cholesteric phase passes through several intermediate stable blue phases. Each of these displays a mosaic of bright color which is produced by the selective Bragg reflection of visible light. This indicates that they have periodic structure of size $\sim 5000\AA$. Let us note that while the coherence length of the liquid is only of order $10\AA$, the blue phase is the large scale structure in the liquid. The research on blue phase is well documented in the review article of Wright and Mermin (1989). Blue phase is interpreted as the periodic arrangement of the line defects–disclination lines in the liquid. These facts have a remarkable similarity to the relative scale related to cosmic structure formation by assuming that late-time topological defects serve as seeds for structure formation. This analogy of blue phase and large scale structure is the motivation of this paper. Such a "blue phase" can serve as the cosmological model which might be probed in the laboratory (Chuang 1991).

The arangement of this paper is the following: in Part II we describe the model, and in part III we present the cosmological implications and constraints. In the conclusion we comment on the possible future directions for the approach presented. In the appendices we present the topological consideration of the problem and show direct construction of plausible defects.

## II) The Model

By analogy to the cholesteric liquid crystal (Wright and Mermin 1989), we use a $3\times3$ traceless symmetric tensor $Q_{ij}$ as an order parameter to write the Ginzberg-Landau phenomenlogical free energy density of the universe as:

$$f = f_{bulk} + f_{gradient}$$

$$= a'trQ^2 + b'trQ^3 + c'trQ^4 + K[(\nabla_i Q_{jk})(\nabla_i Q_{jk}) + 2qtr(Q\nabla \times Q) + trQ^2] \qquad (1)$$

In the so called Low-chirality limit (Wright and Mermin 1989) in which we are interested, the tensor field field can be decomposed as

$$Q_{ij} = \frac{1}{\sqrt{6}}\phi(r)(3n_i n_j - \delta_{ij}). \qquad (2)$$

The free energy, then, can be written as

$$f = a'\phi^2 + \frac{b'}{\sqrt{6}}\phi^3 + \frac{c'}{2}\varphi^4 + K[(\nabla\phi)^2 - \frac{\phi^2}{2} + 3\phi^2(\nabla_i n_j + q\epsilon_{ijk}n_k)^2]. \qquad (3)$$

Let us rescale $\phi \rightarrow \sqrt{K}\phi$ and redifine $\frac{a'}{2K} \rightarrow a$, $\frac{b'}{\sqrt{6}K^{1.5}} \rightarrow b$, $\frac{c'}{2K^2} \rightarrow c$, then

$$f = a\phi(r)^2 + b\phi(r)^3 + c\phi(r)^4 + [(\nabla\phi(r))^2 - \frac{\phi(r)^2}{2} + 3\phi(r)^2(\nabla_i n_j + q\epsilon_{ijk}n_k)^2]. \qquad (4)$$

In principle, we can relate the phenomenological constants $a$ and $c$ to the the Neutrino-Schizon model (Hill,Schramm, and Fry 1989), as an expansion from $V(\phi) = m_\nu{}^4(\cos\frac{2\phi}{f} - 1)$, $a = m_\phi{}^2 = 4m_\nu{}^4/f^2$, $c = 4m_\phi{}^2/f^2 = 16m_\nu{}^4/f^4$, where $m_\phi$ is the mass of the pseudo-Nambu-Goldstone boson, which has Compton wavelength $1/m_\phi$ of order 1 $Kpc$ to 1 $Mpc$, and $q = 2\pi/L$, where $L$ is chosen to be 130 $Mpc$ to fit the pencil beam redshift survey (Broadhurst 1990).

The minimization of the free energy requires that

$$\nabla_i n_j + q\epsilon_{ijk}n_k = 0, \qquad (5)$$

but since $\nabla_s\nabla_i n_j - \nabla_i\nabla_s n_j = q^2(\delta_{js}n_i - \delta_{ji}n_s) \neq 0$ violates the intergrability condition, there will be no unit director field $n(r)$ which could satisfy (5) without generating a singularity. This singularity is the disclination line. As shown in Appendix 2, four line defects emerge from the center of the unit cell of size $L = 2\pi/q$. We call these defects thick strings because they have large core radii. The core radius $R$ can be estimated following the method of Meiboom *et al.* (1981) by rewriting gradient free energy in the one constant approximation:

$$f = f1 + f2$$
$$= K[(\nabla \cdot \vec{n})^2 + q(\vec{n} \cdot \nabla \times \vec{n})^2 + (\nabla \times \nabla \times \vec{n})^2] + K\nabla \cdot [(\vec{n} \cdot \nabla)\vec{n} - \vec{n} \cdot (\nabla \cdot \vec{n})] \qquad (6)$$

Near the transition temperature $T_c$, neglecting the surface tension of the string, the total free energy along the string per unit length is

$$F = \alpha\pi R^2 - \pi K + \frac{\pi K}{4} ln \frac{R_{max}}{R}. \qquad (7)$$

$\frac{\partial F}{\partial R}$=0 at $R = \sqrt{\frac{K}{8\alpha(T_c - T)}}$, insert back into (7), F=0 at

$$\frac{R_{max}}{R} = 3.5, or \frac{R_{max}}{R} \approx 30. \qquad (8)$$

$R_{max}$ is taken to be the pinch size L in the comoving frame of the expanding universe, $L = L_0/(1+z)$, where $L_0$ is the pinch size today. We choose $L_0$ to be 130 $Mpc$ according to the deep pencil beam survey. $z$ is the redshift at the time of phase transition. Choose $z = 30$, then the core radius $R = 130Mpc/30(1+z) \sim 100$ $Kpc$ which is the same order of magnitude as the Compton wavelength of the pseudo-Goldstone boson in the Neutrino-schizon model.

It is shown in Appendix 2 that four strings can join together to form a vortex. As soon as a vortex is formed, the motion of the strings becomes localized and finally reaches equilbrium. The role of the connected thick string network is to provide a rigid skeleton for the universe which is stretched conformally only by the expansion of the universe. Since $f_{bulk}/f_{gradient} \approx (m_\phi L)^2 \approx 10^4$ outside the core of the string, the dominate term of the free energy is:

$$f = a\phi(r)^2 + b\phi(r)^3 + c\phi(r)^4. \qquad (9)$$

$f$ is minimized by two nonzero vaccum expectation values $\phi_1$ and $\phi_2$ (if $b = 0$, we have two degenrate vacuum: if $b \neq 0$ then one is a false vacuum and the phase transition is first order). In different regions of space, field $\phi$ may end up with a different vacuum expectation value (VEV). The boundary between the different vaccum states is a domain wall.

Domain walls from this scalar field may be attached to the thick string skeleton in two ways:

(I) strings bounded by walls (see figure 2A)

(II) walls bounded by strings (see figure 2B).

Each option has its own cosmological implications and constraints, which we will explore in next section.

## III) Cosmological implications and Constraints

An obvious object of the model is to explain the results of the pencil-beam survey. (The statistical significance of the pencil-beam result, of course, remains to be determined with future observations.) Let us now look at the two options from the previous section.

(I) Strings bounded by walls

The baryons outside the thick string are compressed due to the replusive (Goetz 1990; Kolb and Turner 1990) gravitational field of the wall-like surface. We have approximately one-to-one correspondence between the thick string and the "Great Wall" hit by the pencil beam (see figure 3A). The volume fraction of the thick string is about $(R/L)^2 \approx 0.1\%$ which is rather small. If this picture is true, then, when the pencil-beam direction shifts by $\Delta\theta \approx 2R/L \approx 3°$, the quasi-period will change significantly.

(II) Walls bounded by thick-strings

In this case, we would expect to have quasi-periodicity in every direction. However, because of the orientation of walls relative to each other, we also expect the quasi-period will change as the direction of the pencil beam changes (see figure 3B).

The microwave background anisotropy bounded $\delta T/T \lesssim 10^{-5}$ can be met in the late time transition model provided that the surface density of wall $\sigma \leq 10Mev^3$. Recently, many authors have made detailed calculations of the anisotropy for the late time domain wall system. Thus, we don't intend to repeat the calculation here. For our model, $\sigma \leq 10Mev^3$ is not a restrictive bound in either case. Collapse of domain walls is important in the first version where a pattern of spots will appear on the microwave sky (Turner, Watkins, and Widrow 1990). The wall-driven gravitational motion is important in the second version (Nambu 1990; Rees and Sciama 1968), where the calculation shows that $\delta T/T \sim 10^{-5}$, which is marginally consitent with the current observational bounds.

Gravitational radiation is important in such a hybrid wall-string system (Vilenkin 1985). The characteristic gravitational radiation frequency of a wall of size $R$ is $1/R$, the mass of the wall is $\sigma R^2$, the quadrople moment is $\sim MR^2$, so energy loss rate is

$$\frac{d\epsilon}{dt} \approx G(\sigma R^4)^2\omega^6 \approx G\sigma M, \tag{10}$$

which yields a life time

$$\tau \approx \frac{M}{(d\epsilon/dt)} \approx \frac{1}{G\sigma} \approx 3\times 10^5(\frac{Mev^3}{\sigma})\frac{1}{H_0} \tag{11}$$

where $H_0$ is the Hubble constant.

For hybrid defects wall-string networks produced in the very early universe, $\sigma \geq 10^9 Mev^3$. Thus, they vanish rapidly via gravitational radiation. But for the very light walls generated in the late time, $\sigma \leq 10Mev^3$, so that $\tau$ is much large than the age of the universe.

The total energy stored in the gravitational waves is

$$\epsilon_g = \int \frac{d\epsilon}{dt}dt \sim G\sigma M\frac{z}{1+z}\frac{1}{H_0}. \tag{12}$$

This yields

$$\Omega_g \sim G\sigma\Omega_{wall}z/(1+z)(\frac{1}{H_0}) \approx 3\times 10^{-6}\Omega_{wall}(\frac{\sigma}{Mev^3}). \tag{13}$$

The present upper bound on the energy density of the gravitational wave coming from the millisecond pulsar (Lyne, Anderson, and Taylor 1985) is $\Omega < 10^{-5}$. In our first version, there is no problem, but for the second option, where the wall-strings may dominate the present energy density of the universe, $\Omega_{wall} \approx 1$, the gravitational radiation constraints the surface tension to be $\sigma \leq 3 Mev^3$.

## IV) Comments and Conclusion

The phenomenological model proposed seems to provide a plausible picture of the very large scale structure of the universe. We hope that this blue phase analogy for a late time phase transition can provide useful initial conditions for more detailed numerical modeling of the structure evolution. We also hope that these phenomenlogical models might stimulate the development of a more realistic particle physics model that has the properties desired. For example, Hill (1991) has noted that the pion field from the dynamical breakdown of chrial $SU(2)_L \times SU(2)_R$ symmetry at the late time ($\sim 1ev$) can give rise to the free energy we need. We will explore this in a future paper. We also note that the laboratory experiment of Chuang *et al.* (1991) provides an interesting way to create analogous models of the universe if the phenomenlogical connection decribed here turns out to be relevant.

## Acknowledgments

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# Appendix 1 Topological Consideration

The mathmatical tool to deal with the defects is the homotopy group theory. Given a topological space $X$, the 0th homotopy group $\pi_0(X)$ is the disconnected piece of $X$. The $n$th homotopy group $\pi_n(x)$ is defined as the equivalent class of maps of unit sphere $S^n$ in $n$ dimensions into $X$. Two maps are equivalent, or homotopic, if they are continuously deformable into one another. The connection between homotopy group and topological defects is well illustrated by the work of t'Hooft and Polyakov (1974) in their monopole theory and by Toulouse and Kelmin (1976) in condensed matter. In the language of field theory, spontaneously breaking of a larger symmetry group G to a smaller one H is achieved by a vacuum phase transition. The topological space X is the vacuum manifold M, which is equal to the quotient group G/H. In condensed matter physics it is called "the ordered parameter space." In the following, 'vacuum' and 'ordered parameter space' will be used interchangeably. The existence of defects is classified by homotopy group as:

$$\pi_0(M) \neq I \longrightarrow stable\ wall$$

$$\pi_1(M) \neq I \longrightarrow stable\ string$$

$$\pi_2(M) \neq I \longrightarrow stable\ point\ defect(monopole)$$

$$\pi_3(M) \neq I \longrightarrow texture$$

and so on, where $I$ is the identity matrix

We require only the 0th and the first homotopy for our problem because of the appearance of walls and strings. Fortunately, calculation of 0th and 1st homotopy group is straight-forward. For any given vacuum manifold $M$, to find $\pi_0(M)$, simply count how many disconnected pieces $M$ there are. Each piece is an element of the homotopy group. Coventionally, the discrete group of $n$ elements is labeled by $Z_n$, so if a vacuum manifold has $n$ disconnected pieces, $\pi_0(M)$ will be $Z_n$ . The simplest example is the Ising model for the ferromagnet. In this case the spin can point two directions, 'up' and 'down', with the same energy. We do know that in a magnet there are domains. The vacuum manifold has two disconnected pieces, one for spin up, another for spin down. The 0th homotopy group is $Z_2$ which is different from the identity $I$. They conclude that there exist domain walls in the system which is correct.

The calculation of the 1st homotopy group goes in two steps. First, check if there is an unshrinkable closed path in $M$ or not, then $\pi_1(M)$ can be found by counting the number of different paths in $M$ which cannot shrink to a point in $M$ continuously. We know that all circles on the surface of a ball can shrink to a point, but if there is a hole on the surface, all circles around this hole can never shrink to a point continuously. In order to find the homotopy group, we have to classify the path by its 'winding number': how many times does the path goes around the hole? This number can have any integer value, so $\pi_1(M))$ to $Z$, the integer group.

Rod-like molecules are invariant under space inversion and rotation with respect to rod axis, so the ordered parameter space is $\frac{SO(3))}{U(1)\times Z_2} = S^2/Z_2$. It is a hemisphere (see figure A1).

For figure A1, a type I path can shrink to a point. A type II path is also a closed path because P, Q are considered to be the same point, but it is clear that this path cannot shrink to a point. There is no other type closed path, so $\pi_1(M) = Z_2$. By the rules we list above, there are string defects in the system.

If we want strings to join together to form a vortex, the requirement is that in the vortex region, the field should be non-singular. Thus, the defects are removed in that region. For a $Z_n$ string (1st homotopy group is $Z_n$), since $Z_n$ is a $n$-cyclic group, any element $a$ of the group, $a^n$ =I . This means that all paths in the $n$-vortex region are shrinkable, so $Z_n$ strings can form $n$-vortices. Also, since $a^{2n} = a^{3n} = \cdots = I$, $Z_n$ strings can also form $2n$-vortices, $3n$-vortices, etc. In our case, we have $Z_2$ strings, 4 strings joined to form a 4-vortices. In Appendix 2, we adapt some material from Wright and Mermin

(1989) to show this via direct construction.

## Appendix 2

As shown in Part II, the minimization of the free energy requires

$$\nabla_i n_j + q\epsilon_{ijk} n_k = 0. \qquad (A-1)$$

We know that no non-singular unit vector field can satisfy the condition throughout all the space. However, one can satisfy (A-1) along lines, and by continuity the local bulk free energy density will be lower than that of the cholesteric phase in the neighbourhood of these lines as well.

One choice is the double twist cylinder, given by Meiboom *et al.* (1981). The director $n$ twists along a pair of othogonal directions,

$$\hat{n} = \hat{z}cos(qr) - \hat{\phi}sin(qr). \qquad (A-2)$$

One can check that

$$(\nabla_i n_j + q\epsilon_{ijk} n_k)^2 = (\frac{sinqr}{r})^2 - q\frac{sin2qr}{r} + q^2 \qquad (A-3)$$

which show that $\nabla_i n_j + q\epsilon_{ijk} n_k$ does indeed vanish on the axis of the cylinder (r=0).

Note that the double twist cylinder order parameter is not the thick string we present. Strings arise from the packing of the order parameter.

Periodic arrangements of the cylinders form the base of the blue phase. Since the local free energy in a double cylinder still compares favorably with that of the cholesteric phase, even when the director has turned as much as 45-60 degrees from the cylinder axis, the diameters of the constituent cylinder can be of the order of the pinch L, which is the scale of the characteristic blue phase lattice constant.

The first such arrangement of the cylinder was proposed by Meiboom *et al.* (1981). Consider three families of cylinder double twists to an angle of 45 degrees with the axis. Such cylinders can be woven into a periodic array with simple cubic translational symmetry.

One feature of the arrangement is that in the vicinity of four of the eight body diagonals emerging from the center of the cubic cell, there is no way to interpolate unixial material without resulting in a singularity in the director field. This is easily verified by attaching "arrowhead" to the director, keeping track of their orientation as one encircles such a line, and noticing that when one returns to the starting point, the direction of the arrowing is reversed. Figure A2 and A3 show the topological signature of the stable $\pi$ - disclination line.

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# Figure Captions

Figure 1: skeleton of the universe

Connected string network stretched conformally with the expansion of the universe.

Figure 2A: String bounded by wall, cross section veiw.

The cylinderic domain wall attached to the surface of a thick string, the thickness of string will shrink due the surface tension of wall.

Figure 2B: A wall bounded by string, cross section view.

Figure 3A: Pencil-beam survey for the first case - string bounded by wall.

Figure 3B: Pencil-beam survey for the second case - wall bounded by string, strings are at the edges of walls.

Figure A1: Two types of closed loop on the hemisphere.

Figure A2: The arrangement of double twist cylinders.

Figure A3:

(a) The cubic unit cell of a simple cubic structure in a distorted view, the parts of the double twist cylinders contained in the cell are shown.

(b) Shows the four disclination lines for the cube diagnols.

(Both A2 and A3 are from Wright & Mermin)

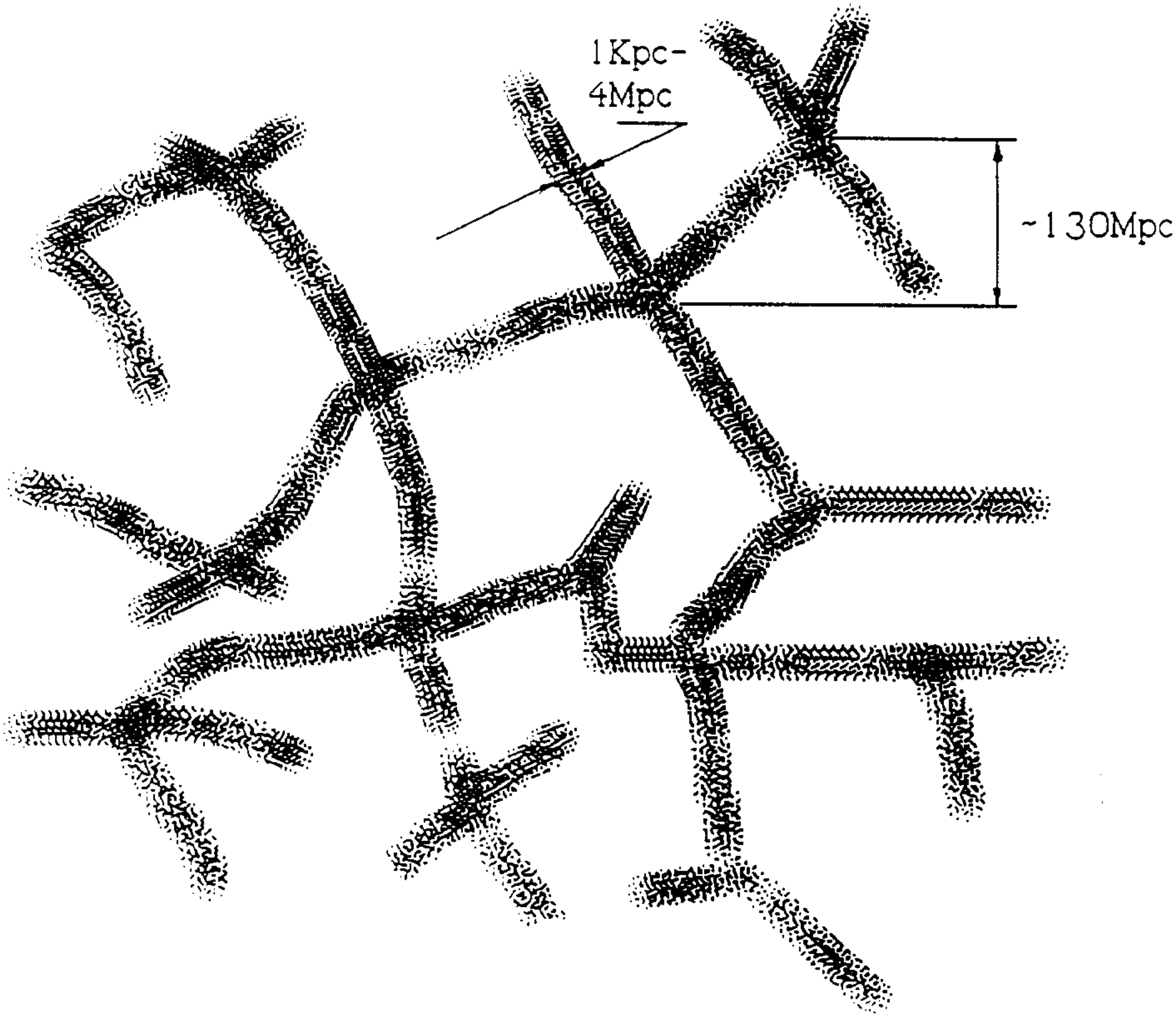



Figure 1

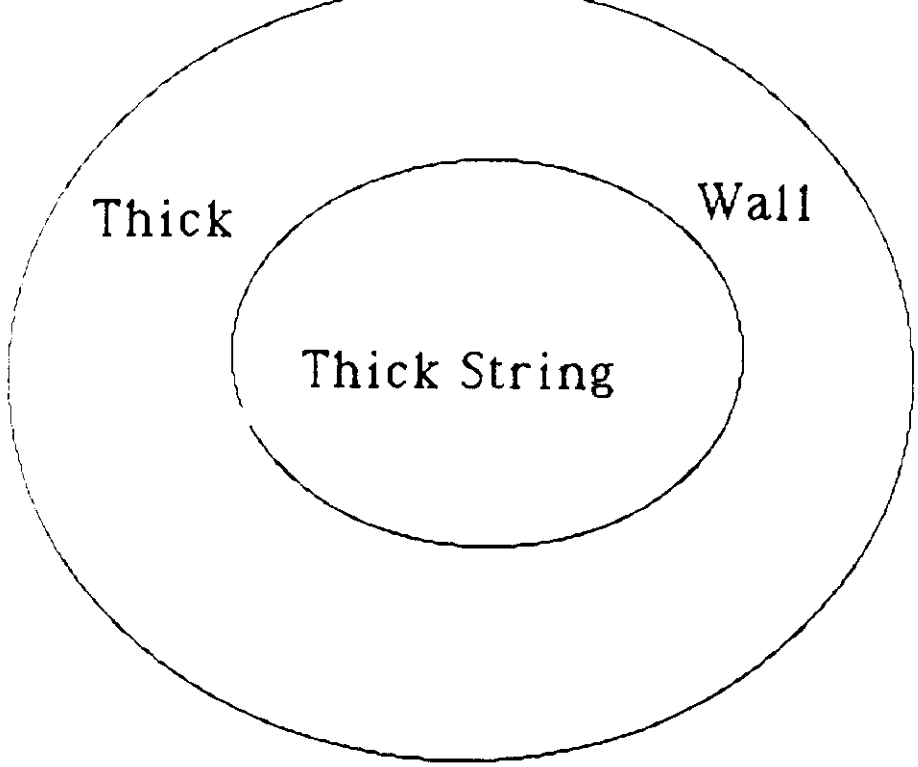



Figure 2A

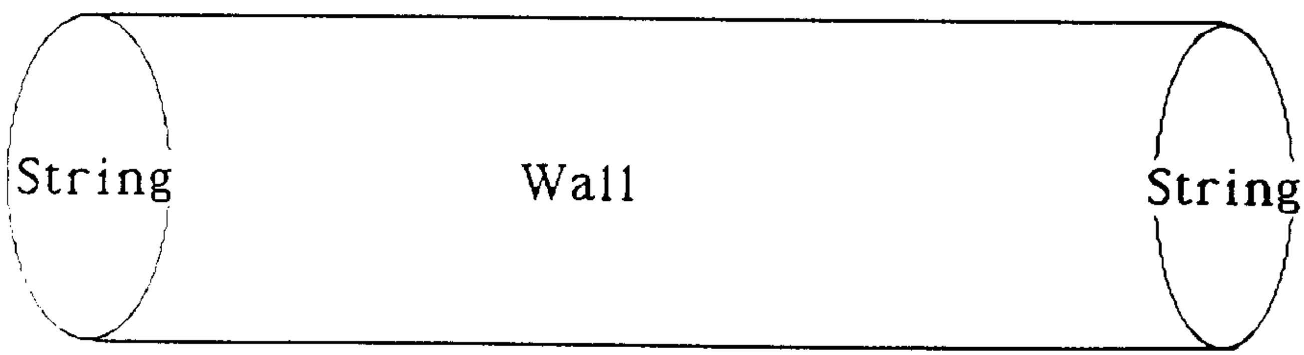



Figure 2B

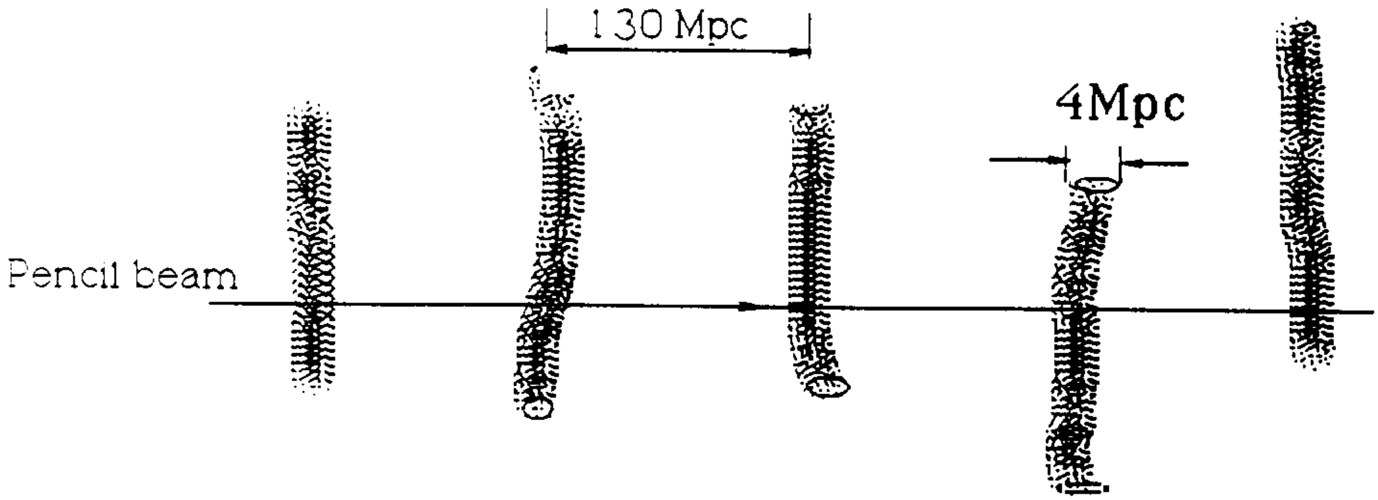



Figure 3A

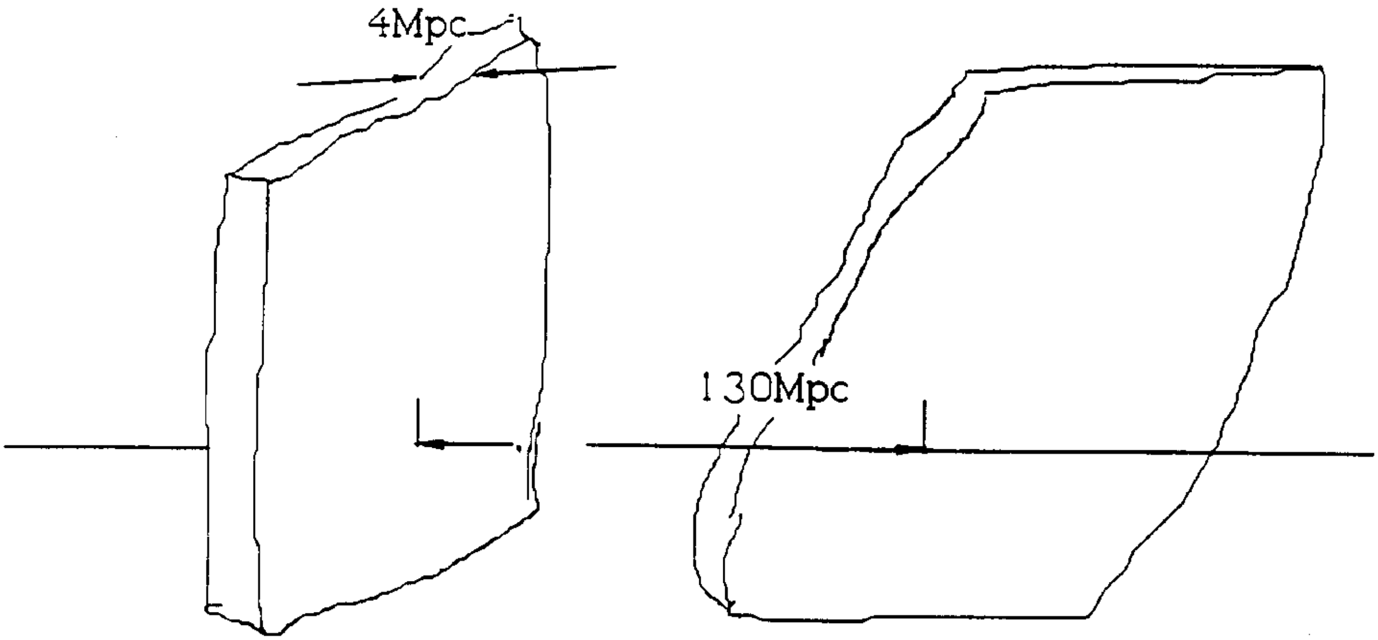



Figure 3B

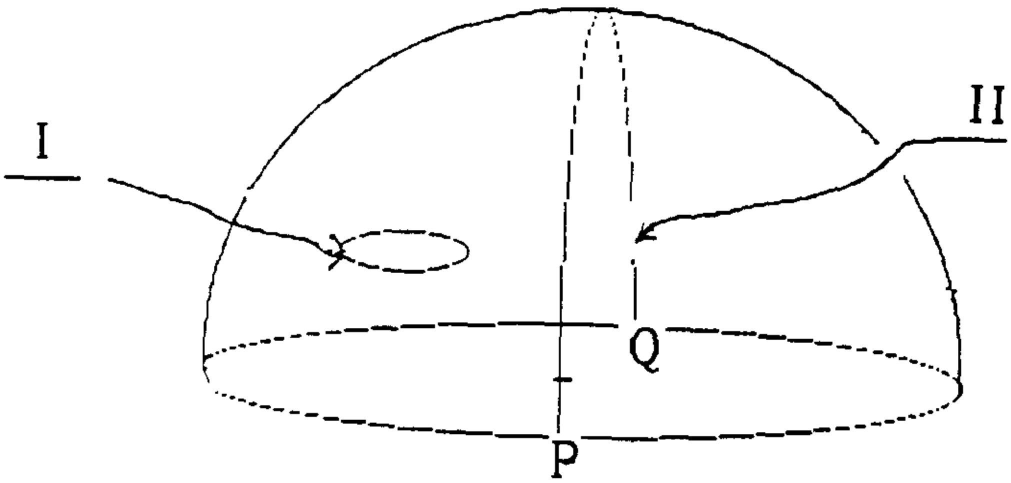



Figure A1

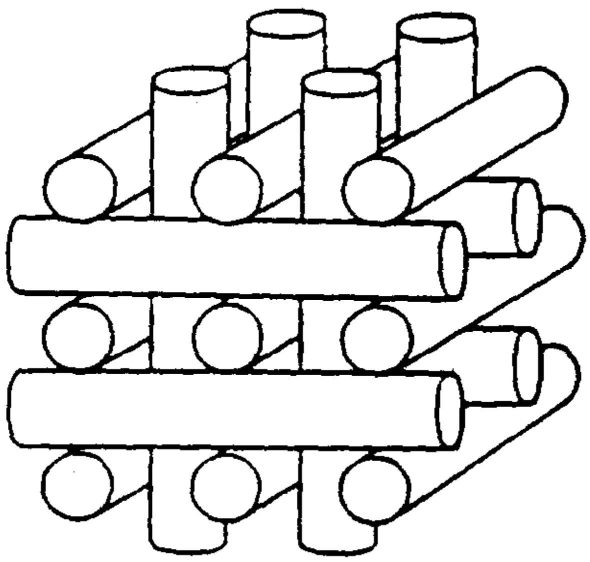
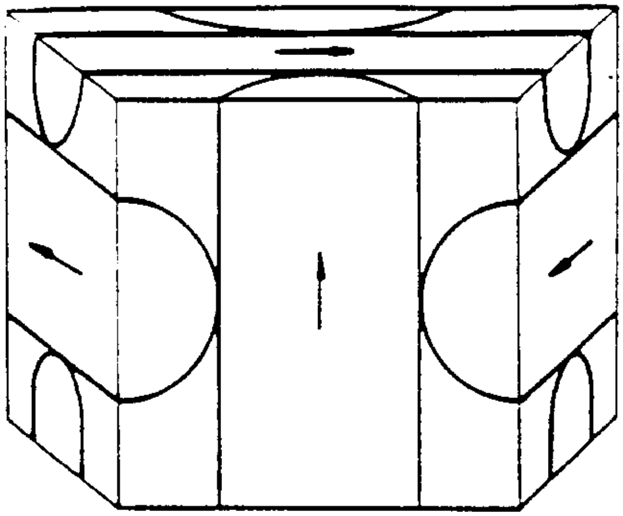
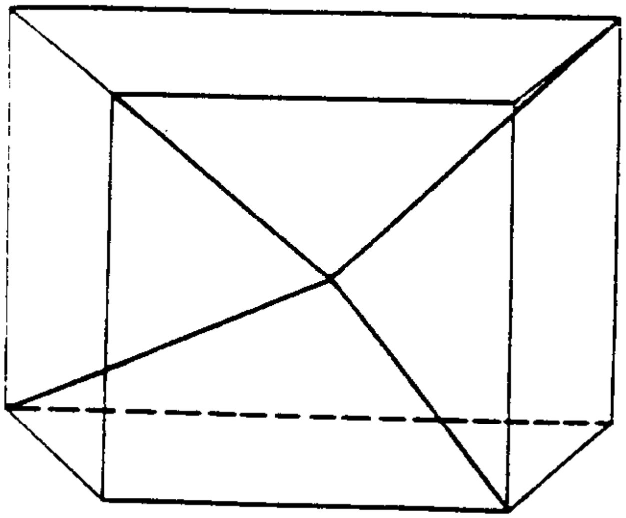


Figure A2



(a)



(b)

Figure A3

Fermi National Accelerator Laboratory

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# THICK STRINGS, THE LIQUID CRYSTAL BLUE PHASE AND COSMOLOGICAL LARGE SCALE STRUCTURE *

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ABSTRACT

A phenomenological model based on the liquid crystal blue phase is proposed as a model for a late-time cosmological phase transition. Topological defects, in particular thick strings and/or domain walls, are presented as seeds for structure formation. It is shown that the observed large scale structure, including quasi-periodic wall structure, can be well fitted in the model without violating the microwave background isotropy bound nor the limits from induced gravitational waves and the millesecond pulsar timing. Furthermore, such late-time transitions can produce objects such as quasars at high redshifts($z \gtrsim 5$). The model appears to work with either cold or hot dark matter.

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