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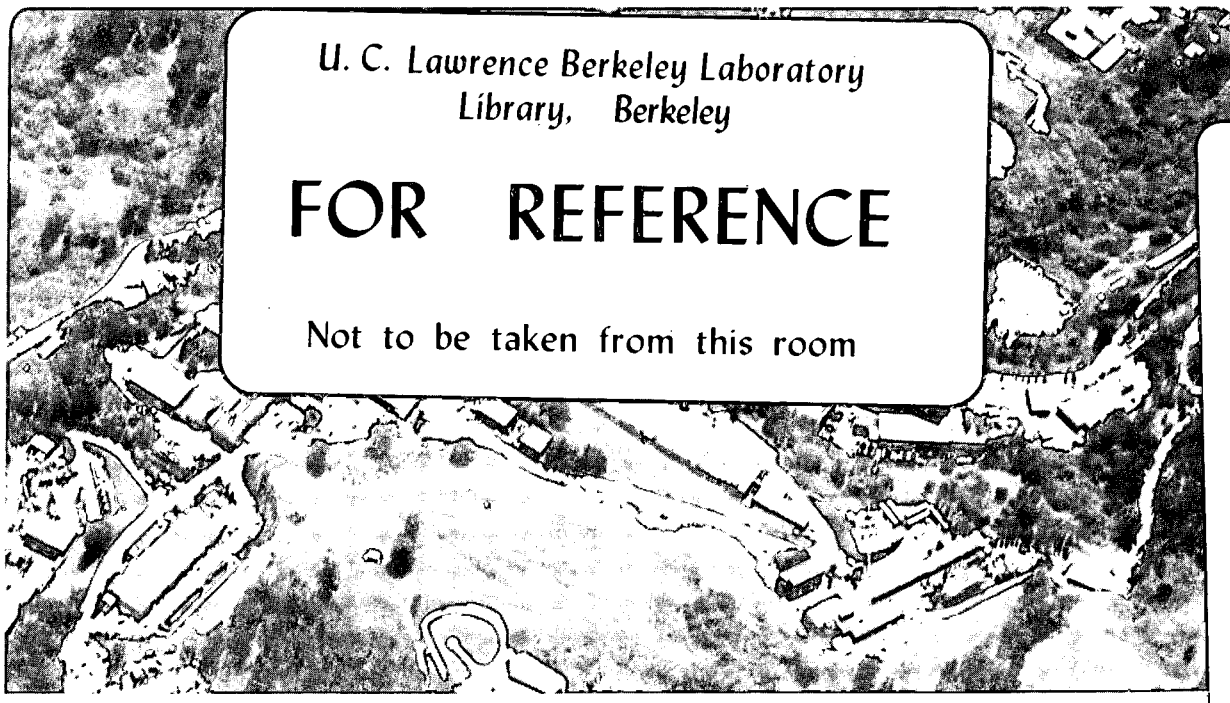

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PARTICLE PHYSICS AND COSMOLOGY*†

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Abstract

I give a brief review of the cosmological implications for new particle physics, the search for dark matter and the general nature of dark matter.

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(I) Does Cosmology Imply New Particle Physics?

The hot big bang model of the early universe provides the simplest framework for understanding cosmological observations. Does it imply new particle physics beyond the standard model?

Probably the most significant aspect of the hot big bang model is this: given a theory of particle interactions the contents of the universe can be calculated.[1] For elementary particles with perturbative couplings calculating the present abundance is straightforward. For extended objects, such as monopoles[2] or black holes,[3] the tools have not been developed to make a real calculation, but estimates are still very important. For non-perturbatively coupled particles, calculations again cannot be made, although in this case the abundances can be bounded by unitarity constraints[4,5].

For photons the relic abundance calculation is especially simple. At temperatures above a GeV the light quarks and leptons and gluons are all in thermal equilibrium with the photons in the primordial plasma. As the temperature cools the plasma dilutes and reaction cross-sections decrease. One by one the particles lose thermal contact with the plasma, until finally the plasma contains just the photons which are not even able to interact among themselves but which maintain a thermal spectrum with a constantly redshifting temperature $T(t)$, where t is the age of the universe. Probably the most convincing evidence in favor of the big bang is that estimating the age of the universe t_0 to be 10^{10} years (for example from old star populations, or from the inverse of the Hubble parameter: H_0^{-1}), the model predicts $T(t_0)$ to be the observed value of 3^0K. I do not believe there is any other such coherent understanding of this number.

The only other stable particles of the standard model are the neutrinos, the electron and the proton. The neutrinos of the minimal standard model are massless and they have a redshifted number density and energy close to that of the massless photons. Hence their energy density today, relative to the critical energy density ρ_c, is $\Omega_\nu = \rho_\nu/\rho_c \simeq 10^{-4}$. There is no known way to observe this thermal background of neutrinos since their typical energies are meV. The electron and proton number densities are equal because the total electric charge of the universe must vanish. Hence in the standard model there is only one non trivial relic abundance to be calculated: that of the spatially averaged baryon

density n_B. From the viewpoint of particle physics, perhaps the most important cosmological observation is n_B: it is too large to be explained by the standard model. The large observed value of n_B is the only truly convincing cosmological argument for new physics beyond the standard model. The sceptic might reply that the cosmological baryon asymmetry is simply an initial condition to the universe, and that no new dynamics is required. I reject that viewpoint; I believe that all measured quantities are to be explained.

In fact nobody has actually calculated what n_B is in the standard model. A few years ago I would have said that it was zero: the interaction vertices of the standard model conserve baryon number and hence should lead to a universe with zero cosmological baryon asymmetry. At temperatures beneath a GeV $p\bar{p}$ annihilation would reduce $n_B = n_{\bar{B}}$ to an extremely low level. Further gravitational clumping of the non-relativistic baryons would reduce n_B even further. This picture of the baryon density in the standard model may be too simplistic. The point is that the standard model does have all three ingredients necessary for producing a cosmological baryon asymmetry[6], including B violation, when the temperature is somewhere in the region of 100 GeV. Baryon number is violated by weak interactions, because the baryon current has an electroweak anomaly.[7] A departure from thermal equilibrium probably occurs at the electroweak phase transition, and finally, weak interactions do violate CP. At this point I should stress the word "probably" in the previous sentence. We now know that the Higgs boson is heavier than 51 GeV[8], and studies have shown[9] that, providing the Higgs is not too heavy, a first order phase transition occurs very soon after the symmetric phase becomes metastable. However there are two crucial caveats. Nobody knows how the phase transition proceeds if the Higgs boson is heavy. This is not only because eventually the theory becomes non-perturbative; even in the the perturbative domain it is not clear what the correct high temperature effective potential for the Higgs field actually is. This is especially true in view of the infrared divergences which appear near the temperature at which the Higgs mass in the asymmetric phase vanishes.[10]

In view of our ignorance about the electroweak phase transition in the standard model, how can we be certain that the standard model does not generate an acceptable n_B? The answer is that the magnitude of the CP violation of the standard model is simply too small.[11] The dimensionless parameter that

we seek to explain, $n_B/n_\gamma \simeq 10^{-9}$, is larger than the dimensionless parameters that measure CP violation in the standard model. This assertion is not obvious, but I believe that it is valid. One may counter that the standard model *does* explain the much larger observed CP violating parameter $\epsilon \simeq 10^{-3}$, and in B meson decays the standard model can lead to CP asymmetries sin $2\alpha, sin2\beta$ and $sin2\gamma$ which are 0(1).[12] In these cases the observed CP violating parameters are large partly because they are actually defined as ratios of (CP violating quantity)/(highly suppressed CP conserving quantity). It is the small denominators which make quantities like ϵ and $sin2\beta$ so large. However, in calculating the baryon asymmetry per unit comoving volume $f_B \simeq n_B/n_\gamma$ one simply calculates the rate for a CP violating process. There is no small denominator to divide by. Hence n_B/n_γ cannot be bigger than the true dimensionless measure of CP violation. In the standard model this weak CP parameter can be written as IJ,[13] where J is a function of the Kobayashi-Maskawa matrix elements which is known to be $\lesssim 10^{-4}$, and I is a function of quark mass differences and is known to be very much less than 10^{-5}. Is it possible that the relevant CP violating parameter is the QCD $\bar{\theta}$ parameter? Although we know experimentally that today $\bar{\theta} < 10^{-9}$, in axion models it could be much larger when the temperature of the universe was larger than 1 GeV. Even if $\bar{\theta}$ was order unity then, the CP violation is still too small, because we know strong CP violation must vanish when any quark mass vanishes. Hence the relevant CP violating parameter would be $\bar{\theta}I'$ where I' is basically a product of the quark Yukawa couplings and is very much less than 10^{-9}.

I conclude that the cosmological observation of the average mass density in the universe composed of shining baryonic material can only be understood if there is CP violation beyond that of the standard model. I find this exciting for many reasons:

1) The cosmological observation is completely solid. Since standard model CP violation is very far from obtaining n_B/n_γ of 10^{-9} there is no need for a precise observational determination of n_B.

2) Additional CP violation which could generate a sufficient n_B implies a considerable extension of the standard model.

3) If the B violation responsible for n_B is indeed coming from the electroweak anomaly in the baryon current, then the new CP violation must occur

beneath the TeV scale. This suggests that measurements of $sin2\alpha, sin2\beta$ and $sin2\gamma$ from CP asymmetries in neutral B meson decay could uncover departures from the standard model.[14] Observing $\alpha + \beta + \gamma \neq \pi$ would be a strong hint that baryogenesis occurs at the electroweak phase transition. Although this may be the most interesting possibility for baryogenesis, it cannot be excluded that baryogenesis occurs at some inaccessible, high scale by producing a $B - L$ asymmetry.

The second most convincing evidence from cosmology that there is particle physics beyond the standard model comes considering the origins of the irregularities in the mass density of the universe. Where did galaxies come from? To explain the distribution of mass clustering seen in the universe, one must understand how the density inhomogenities rose from an initially homogeneous state. All proposed mechanisms for this involve phase transitions, which in the particle theory will be manifest as symmetry breakings. In the standard model there are two phase transitions: the electroweak symmetry breaking and the QCD phase transition (the latter might actually involve more than one phase transition) at scales $v = 250$ GeV and $\Lambda = 250$ MeV respectively. The horizon masses at these eras are so small: $M_H(v) \simeq 10^{-6} M_{SUN}$ and $M_H(\Lambda) \simeq M_{SUN}$ that causal processes cannot produce density inhomegeneities on anywhere near galactic scales. Subsequent statistical fluctuations on larger scales are also insufficient. The *only* hope for producing larger scale structure in the standard model is that significant inflation occurs at one of these phase transitions; this could increase the length scale of the density fluctuation. In the pictures put forward for these phase transitions, there is no significant inflation. However, in the non-perturbative cases there is no proof that inflation does not occur. Suppose such inflation did occur and that somehow baryogenesis could be implemented after inflation, the resulting universe would have $\Omega = \rho/\rho_c = 1$. This conflicts with the standard model. We have seen that $\Omega_{\nu+\bar{\nu}+\gamma} \simeq 10^{-4}$ so that there must be critical energy density in baryons + vacuum energy. $\Omega_B = 1$ conflicts with nucleosynthesis;[15] for example by many orders of magnitude in the deuterium abundance. A cosmological contact $\Lambda \simeq (3.10^{-3} eV)^4$ appears to conflict with the standard model because it contains a scale, 0(meV), which does not appear in the standard model.

I conclude that generation of density perturbations requires physics beyond

the standard model. Of course, it is very unclear what that physics is. However it does seem clear that for the density perturbations to be on a large enough length scale, either one must have inflation, or the perturbations must be produced at a late ($T <$ eV) phase transition[16], or the density perturbations must evolve to always give horizon sized perturbations as the universe expands, as in the case of textures.[17]

A third cosmological argument for particle physics beyond the standard model is the argument for inflation.[18] Inflation solves the cosmological monopole, horizon and flatness problems. It is also useful for large scale structure formation: the cosmological phase transition can both produce density perturbations, and put them on a large length scale.[19] Inflation implies two types of physics beyond the standard model: one to produce inflation, and one to give exotic dark matter necessary to yield $\Omega = 1$.

It is crucial to separate the above motivation for exotic dark matter from the observational evidence for dark matter. Observations of the gravitational dynamics of our galaxy and its disk and of our local group tell us that in our vicinity of the universe there is a lot of dark matter.[20] Similar amounts of dark matter are seen in more distant galaxies, suggesting a contribution to Ω from dark matter clumped on galactic scales of $\Omega_{DM} \simeq 0.1$. This dark matter is the crucial motivation for the dark matter searches, both direct and indirect, that I mention in the next section. It could be that this dark matter is baryonic since such a value of Ω_B is not in contradiction with big bang nucleosynthesis,[15] and hence this dark matter is not evidence for particle physics beyond the standard model. Searching for this dark matter is very important and is completely unrelated to whether inflation occurred. Indeed if inflation is correct, then the additional dark matter cannot be clumped into galaxies.

(II) The Search For Dark Matter

Reasonable dark matter candidates have been proposed with masses (M) which vary over a range of 70 orders of magnitude, and with viral velocity cross sections on a nucleon (σ) which vary over at least thirty orders of magnitude. Even with a wide range of detection techniques, the full M/σ plane cannot be probed. Nevertheless important regions have been excluded and will be probed in the future. For masses of the dark matter particle $M < 10^{19}$ GeV, several

excluded regions are sketched in Figure 1. For precise exclusion regions please refer to the original works. Region A is excluded by the direct detection method: searching in the laboratory for the recoil energy of a nucleus struck by a dark matter particle.[21] Two other groups have also presented limits by searching for nuclear recoil energy.[22] Region B is not excluded: it is the primary focus of future experimental direct detection searches.[23] The lowest values of σ which will be obtained depends on how well background γ events can be removed. In this regard measuring both phonon and ionization energies will be crucial. It is important to consider whether any well-motivated dark matter candidates lie in this region.

Region C is a region which can be excluded by searching for high energy neutrinos from the sun in the Kamiokande detector;[24] limits have also been obtained from IMB.[25] This provides a stringent limit only on particles with mass between about 3 and 100 GeV, and only if $\sigma > 0(10^{-40} cm^2)$, since only in this case does the sun trap a significant number of the particles. For a particular candidate, whether this shaded region is actually excluded depends on how many neutrinos are produced in the annihilation of two dark matter particles in the sun, and on the energy of the neutrinos. However, for candidates with M and σ in region C the limits are quite powerful. The differential flux of ν_i of energy E at the earth is predicted to be about $10 cm^{-2} s^{-1} (100 \text{ GeV}/M)\ \overline{N}(E)$, where $\overline{N}(E)$ is the average number of ν_i of energy E per annihilation in the sun. This should be compared with the limits shown in figure 17 of ref. 24. For example the integrated flux at the earth for $\nu_\mu + \overline{\nu}_\mu$ with energy above (3, 10, 30) GeV is $(.5, 3.10^{-3}, 10^{-4}) cm^{-2} s^{-1}$.

The possibility of strongly interacting dark matter was a much neglected topic, but has received recent attention by Starkman et al.[26] They have used a variety of observations to exclude the region D. Some of the regions they were unable to exclude were subsequently excluded by the direct detection search, as shown by region A.

From Figure 1 it is clear that heavier particles are less well constrained observationally. This is because the number density of local dark matter particles is proportional to $1/M$. The frustrating inability to probe much of the heavy mass region of Figure 1 is partially offset by the fact that it is harder to motivate such heavy, elementary, dark matter candidates. The contribution of a stable

dark matter candidate to Ω is proportional to $1/\sigma_A$ where σ_A is its annihilation cross section in the big bang at a temperature an order of magnitude or more beneath its mass. Even strongly interacting particles cannot annihilate with $\sigma_A v$ much greater than $1/M^2$ so this simple argument implies that stable particles with $M > 10^6$ GeV will "overclose" the universe.[4] A more careful analysis of this unitarity condition lowers this mass limit by a factor of 3[5] and is shown on Figure 1. This bound is not a rigorous one, one can invent many exotic ideas to circumvent it, but nevertheless I think it is a strong motivation that exotic dark matter particles will have a mass less than 300 TeV. Furthermore, for 300 TeV the dark matter particles are non-perturbatively coupled; particles with only perturbative couplings will be lighter. It should now be clear why attention of the field is now focussed on region B.

As there is no definitive theoretical argument for local exotic dark matter, it is important to note that two groups[27] are currently planning to search for massive compact halo objects by microlensing of stars in the LMC, as proposed by Paczynski in 1986.[28] The massive lensing object might be Jupiter-like and composed of baryons, or it might be a black hole, presumably from stellar collapse or a late phase transition, or it may be bound extended clumps of exotic material. When such an object passes in front of a field star there is a brightening of the field star, since the double image cannot be resolved. The time scale of this brightening event will yield the mass of the halo object: $\tau \simeq 10^7 sec\sqrt{\frac{M}{M_{SUN}}}$. Watching a million stars in LMC every night for a year will probe M from 10^{-1} to $10^{-7} M_{SUN}$.

(III) Comments on Dark Matter Candidates

In this short review I have purposely not discussed a list of dark matter candidates. This is mainly because excellent reviews already exist, see for example ref. [29, 30, 31]. It is also because, even though many candidates can be motivated by particle physics concerns, I do not find the motivation for any to be particular convincing. Consider, for example, the case of the lightest superpartner in supersymmetric extensions of the standard model. Its status as a favored candidate rests on its stability. However, it is stable not for any fundamental reason that has to do with supersymmetry or its motivation, but rather stability was forced on the theory by imposing an R parity symmetry. This is

not very impressive: it is always possible to get stable particles by enforcing symmetries. As another example consider the axion. This dark matter candidate is motivated by the elegant original Peccei-Quinn solution to the strong CP problem of why $\bar{\theta} < 10^{-9}$. However, over the years the improvements on the limits on the axion have made this solution less elegant. It now requires a new physics scale at around 10^{12} GeV, which is not going to be very much easier to understand than a small $\bar{\theta}$.

There is certainly one set of candidates which should be considered seriously: those which exist in the standard model. Could the dark matter be baryons or neutrinos? In the case of baryons I have already mentioned the result: galactic dark matter could be baryonic, but $\Omega_B = 1$ is forbidden by nucleosynthesis, unless some new exotic physics is introduced [32, 33]. The three known neutrinos give $\Omega_\nu = 0(10^{-4})$ if they are massless, hence they are only an interesting dark matter candidate when the minimal standard model is extended in some way to give neutrino masses. A mass of 30eV would give $\Omega_\nu = 1$, but such a hot dark matter scenario does not give a good representation of large scale structure,[34] and furthermore such light neutrinos cannot be the dark matter in dwarf galaxies.[35] A ν_μ or ν_τ with mass larger than 0(30 eV) could be the dark matter only if it is both stable and its relic number density is significantly depleted below that of photons. I know of only two acceptable schemes. One uses a large τ neutrino magnetic moment to remove ν_τ via: $\nu_\tau \bar{\nu}_\tau \to \gamma^* \to e^+e^-$ [36]. This requires $m_{\nu\tau}$ greater than $2m_e$. Another possibility is to have ν_μ or ν_τ in the mass range of keV to 30 MeV, with cosmological depletion occurring via annihilation to Majorons.[37]

Since much of this workshop has been concerned with dynamical electroweak symmetry breaking, it is worth mentioning just one beyond-the-standard-model candidate: that of technibaryons.[38,39] There are several features of this candidate which make it especially interesting.

- The lightest technibaryon is likely to be stable. Our experience with ordinary baryons leads us to guess a lifetime $\tau \simeq M_{GUT}^4/M_{TB}^5 \simeq 10^{17} yrs$. This means that technibaryons in the halo have a significant probability of decaying and giving a high energy neutrino signal[40].

- The requirement that the lightest technibaryons be stable provides non-

trivial constraints on the technicolor theory[39].

- Suppose there is no technibaryon asymmetry. We can estimate the relic densities of technibaryons and antibaryons by scaling the QCD baryon annihilation X-section for $\bar{p}p \to \pi \ldots$, to find $\Omega_{TB} \simeq 10^{-3}$.

This is a lower limit since a technibaryon asymmetry will only increase this number. Hence if the lightest technibaryon is neutral and long lived and couples to the Z, it will show up in the next round of direct detection experiments in region B of figure 1, with a mass of several TeV. If $\Omega_{TB} \simeq 10^{-1}$ the present experiments are on the edge of seeing/excluding it and this provides a real motivation for even a modest improvement.[4]

Finally it is worth mentioning that although a host of dark matter candidates have been proposed, there is a simple particle physics classification scheme which has just five categories[47]. These are

- plasma relics, which were relativistic at decoupling ($\gamma, \nu_i, \ldots$)
- freezeout relics, which were non-relativistic at decoupling and which can either have particle-antiparticle symmetry ($\tilde{\gamma}, \ldots$) or asymmetry (p, ...)
- secondary relics, which are decay products of unstable freezeout relics. They could be relativistic and unclumped today.
- coherent scalar field oscillations (axions, ...)
- "solitons" a very broad category which includes all localized but extended forms of energy density (monopoles, domain walls, strings, non-topological solitons, black holes ...)

Summary

In this short review[42] I have argued that there are three aspects of the hot big bang and cosmological observation which imply new particles physics. In the order which I find most convincing, these are

- the observed baryon density implies non-standard CP violation.

- the large length scale of observed density irregularities implies new physics beyond the standard model. However, it is not possible to identify what this new physics is, except that it must involve new symmetry breaking.
- various arguments suggest an era of inflation, which predicts $\Omega = 1$. There are exotic scenarios where $\Omega_B = 1$ can be reconciled with nuclosynthesis, but most people have preferred the option where the dark matter is exotic.

I briefly mentioned searches for galactic dark matter and a few theoretical points about such dark matter.

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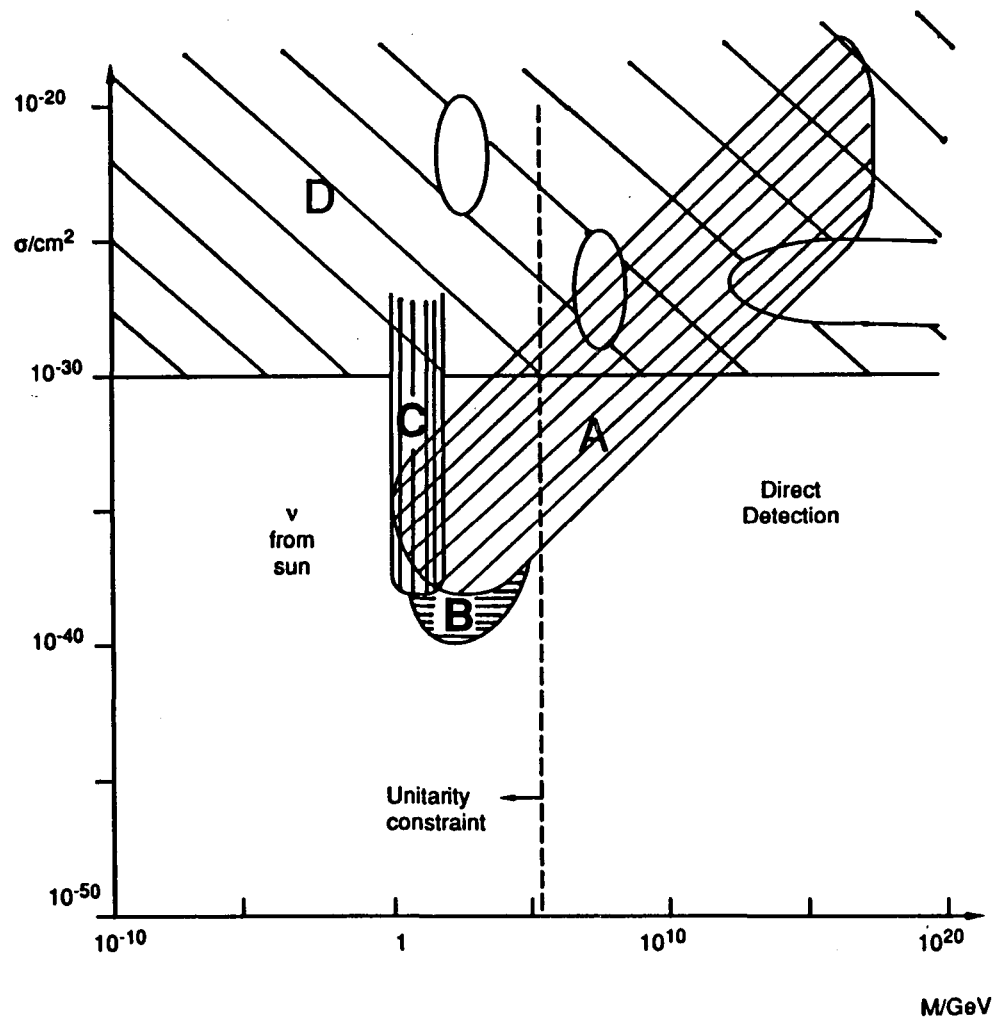

FIGURE 1 Limits and searches: galactic dark Matter

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