POSSIBLE CONSTITUENTS OF HALOS

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ABSTRACT. There still seem to be three serious contenders for the dark matter in galactic halos and groups of galaxies: (i) very low mass stars, (ii) black hole remnants of very massive stars or (iii) some species of particle (e.g. axions, photinos, etc.) surviving from the big bang. There are genuine prospects of detecting individual objects in all three of these categories, and thereby narrowing down the present range of options. If the Universe has the critical density ($\Omega = 1$), rather than the lower value ($\Omega = 0.1 - 0.2$) inferred from dynamical evidence, then the galaxies must be more clustered than the overall distribution even on scales 10 - 20 Mpc. "Biased" galaxy formation could account for this.

1. INTRODUCTION

At this conference, we have heard evidence for dark matter on various scales, which may implicate objects of different kinds. The local mass discrepancy within our Galactic disc probably involves low mass stars or white dwarfs, and I shall have little to say about it in this talk. On the scale of galactic halos and clusters, the evidence now points insistently towards the view that Ω (defined as the ratio of the actual mean density to the cosmological critical density $\rho_{crit} = (8/3\pi\, Gt^2)^{-1}$ is in the range 0.1 - 0.2, but that only 10 percent of this (Ω = 0.01 - 0.02) is definitely baryonic. However, there is no dynamical evidence for $\Omega = 1$: there are no bound systems with $M/L = 1000\, h_{50}$ solar units, which would be the universal value if $\Omega = 1$ (h_{50} denotes Hubble's constant H_0 in units of 50 km $s^{-1}Mpc^{-1}$).

The factor $\sim$ 10 discrepancy between the amount of "luminous" mass and the amount inferred from the dynamics of groups and clusters is the prime evidence for dark matter. This will be my main topic; in a concluding section I shall, however, comment on the theoretically-important issue of whether the Universe could have the critical density ($\Omega = 1$).

The extensive menu of possible candidates could be shortened in several ways. For instance, progress in particle physics may give us

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firmer views on what particles should survive from the big bang, and their expected contribution to Ω. The predictions of cosmogonic models, particularly regarding clustering scales, halo density profiles, etc., can tell us whether or not the dark matter has undergone dissipative processes. There is a clear distinction between so-called 'hot' and 'cold' non-baryonic matter. The former, typified by 10 ev neutrinos, would have had sufficiently high thermal velocities in the early universe for phase mixing to have smeared out fluctuations on scales up to that of a galaxy cluster. In contrast, cold matter, such as axions or GeV super-symmetric particles, would be sufficiently slow-moving that primordial fluctuations would survive on all interesting scales, leading to a hierarchical picture for the buildup of gravitationally-bound cosmic structures.

The most clear-cut way to settle the nature of the hidden mass would of course be to detect the objects that make it up. It is on this aspect that I will concentrate in the present paper. Baryonic systems - stars or their remnants - are already severely constrained by the fact that the dark mass is so inconspicuous. More remarkably, there are genuine prospects that elementary particles of the kind that could dominate the halo hidden mass may be individually detectable by terrestrial experiments.

2. BARYONIC DARK MATTER: FAINT STARS, MASSIVE STELLAR REMNANTS, ETC.

The constraints from primordial nucleosynthesis are reviewed by Audouze (these proceedings). The baryonic contribution to Ω in a "standard" model is constrained to lie in the range

$$0.04 \lesssim \Omega_b \, h_{50}^2 \lesssim 0.15 \qquad (1)$$

This restriction comes primarily from the measured D and ^{3}He abundance; values outside these limits cannot be excluded, but require modification of the standard homogeneous hot big bang, or some alternative (non-cosmological) mechanism for producing light elements such as deuterium. The inequalities (1) imply that for a low Hubble constant, some dark mass must be baryonic, and everything that is dynamically inferred could be. Contrariwise, a standard hot big bang with a high Hubble constant requires non-baryonic matter even to account for galactic halos and the virial equilibrium of clusters.

If $H_0 = 50$ km s^{-1} Mpc^{-1}, all the dynamically-inferred dark matter could be baryonic. The astronomical constraints on this option have been recently discussed in detail by Carr, Bond and Arnett (1984) and are summarized by Carr (these proceedings). The import of these studies is that stars or their remnants cannot contribute $\Omega \gtrsim 0.1$ unless they are either predominantly "Jupiters" (stars of below $0.1\ M_\odot$) or else black holes which are the remnants of very massive objects ("VMOs") with masses between a few hundred solar masses and $10^6\ M_\odot$.

Low mass stars

The main present constraint on low mass stars in galactic halos comes from limits to the observed optical and infrared emission. A very faint optical halo in M87 has been traced out to 300 kpc (Arp and Bertola 1969). In the edge-on spiral NGC 4565, there are limits on the near infrared emission, corresponding to 76 solar units in the I-band (Hegyi and Gerber, 1977), and 38 solar units in the K-band (Boughn, Saulson and Seldner 1981). The constraints thereby imposed on the slope of the initial mass function (IMF) have been discussed by Peebles (1985), and by Hegyi and Olive (1985). If the entire halo mass were contributed by stars with an IMF of the form

$$\frac{dn}{dm} \propto m^{-(1+x)} \qquad (2)$$

down to some minimum mass M_{min}, then if M_{min} exceeds 0.007, $x \gtrsim 1.9$. (Salpeter's classic (1955) study derived x = 1.35 for our galactic disc.) In fact the infrared colours are not specially helpful in pinning down x, since for any $x < 2$, they are dominated by red giants. Note that the power-law example (2) is only illustrative; the same amounts of mass could equally be concealed by a population with a log gaussian distribution peaking below 0.1 $M_\odot$.

One thing is clear: one cannot invoke a smooth extension of the IMF that is observed below 1 $M_\odot$, which actually seems to flatten off below $\sim$ 0.3 $M_\odot$. The objects constituting the dark matter must in some sense by a "special creation". However, this is perhaps not a cogent objection to the idea. After all, the IMF derived by Miller and Scalo (1979) and Scalo (1985) for the solar neighbourhood does not look like a single power-law, but rather resembles two superposed log gaussian distributions. In an interesting recent discussion, Larson (1985) suggests that these represent the products of two distinct modes of star formation, and that the relative importance of these two modes may have varied over galactic history. Conceivably the star formation process relevant to the halo involved a third mode with a different characteristic mass. If the halo objects formed at an early pregalactic epoch, and subsequently clustered non-dissipatively into galaxies and clusters, then there would be even less reason to suspect that their IMF should resemble that of stars forming here and now. Indeed, we should remain open-minded even about the IMF of stars forming within galaxies. Cooling flows in clusters of galaxies (Fabian, Canizares and Nulsen 1984, Fabian, Arnaud and Thomas 1986), where the gas pressure is $\sim$ 100 times higher than in our Galactic Disc, have been interpreted as implying star formation with a very steep IMF. When stars in the halo formed, conditions maybe resembled those in cooling flows more than they resembled those in our Galaxy now. Perhaps the Salpeter-Miller-Scalo function pertains only in environments of atypically low pressure.

Improved infrared limits to the brightness of halos (e.g in NGC 4565) can in principle constrain the properties of these hypothetical "Jupiters", as of course can IRAS-type searches for high-proper-motion objects in our own Galaxy. However, because the luminosity is such a steep function of mass below 0.1 $M_{\odot}$, even a substantial improvement of such tests only tightens the IMF constraints slightly.

VMO remnants

Heavy elements are expelled from massive stars in their terminal phases unless they are so massive that they end their lives by collapsing to black holes after the pair-production instability (Truran and Cameron 1971; Woosley and Weaver 1982; Carr, Bond and Arnett 1984 and references cited therein). Collapse rather than explosion is thought to occur for core masses above $\sim$ 200 $M_{\odot}$. If the hidden mass were in VMOs, then the requirement that heavy elements be not overproduced therefore requires a very flat IMF. If this were actually a power law, the value of x (in equation (2)) would actually have to be negative. Moreover, there must be a cutoff above $\sim 10^6 M_{\odot}$, at least for objects within individual halos, because dynamical friction would have increased the velocity dispersion of disc stars to an excessive degree (Carr 1978; Lacey 1984). Within the context of VMO theories, we have little evidence on whether the preferred mass is closer to 10^3 or to $10^6 M_{\odot}$. The upper mass limit could be pushed downward if we had a firmer understanding of what luminosity would result from accretion onto black holes passing through the Galactic Disc (Ipser and Price, 1977, 1982; McDowell 1985; Lacey and Ostriker 1985).

VMO remnants, black holes in the mass range 10^3 to $10^6 M_{\odot}$, could reveal their presence by accretion of surrounding gas. The accretion rate for supersonic motion at speed V through gas of density n is proportional to $nV^{-3}M^2$. The luminosity depends on the accretion rate, and also on the efficiency ε. The latter is the least sure thing. For spherical accretion, where the efficiency is low because the radiative cooling time is long compared to the free-fall time, ε should scale with $\dot{M}$, making the luminosity proportional to $\dot{M}^2$. For disc-like accretion, ε may be as much as 0.1, independent of $\dot{M}$. The spectrum of the emergent radiation is also uncertain. The case of spherical inflow has been considered by Ipser and Price (1977), who argue that the radiation emerges mainly in cyclotron harmonics. These would typically peak in the infrared. Disc-type accretion could yield a high luminosity, predominantly thermal radiation in the ultraviolet.

The most conspicuous holes would be those which were passing through dense gas clouds, and which had V much less than the mean velocity. Although the number of these scales with V^3, the resultant higher $\dot{M}$ ($\propto V^{-3}$) makes them more readily detectable, despite the fact that the nearest one would be more distant from us (distance $\underset{\sim}{\propto} V^{-3/2}$).

The detectability of massive holes in our galaxy has been discusssed by McDowell (1985). He shows, following the assumptions of Ipser and Price, that if the typical mass is $10^5 M_{\odot}$ or more, the nearest objects passing through a dense interstellar cloud would be at 1 kpc distance, and would contribute 400 Jy flux at 100 microns, well above the IRAS detection limit; the same object would have an optical magnitude V = 10 (plus some correction for absorption). Lacey and

Ostriker (1985), assuming disc-mode accretion, predict even higher luminosities, but suggest that this would be UV radiation giving rise to an HII region. The Ipser/Price estimates of luminosity are indeed rather conservative even on the basis of their assumed spherical infall, since a possible non-thermal tail of electrons is neglected. Unfortunately, the distinctive signature of an accreting black hole is hard to estimate, and so one cannot at the moment place firm limits on the number or mass of putative halo objects of this kind. Nevertheless, it already seems unlikely that the bulk of the mass could be in objects that are individually as heavy as $10^6 M_\odot$.

Gravitational "minilensing"

At the moment, it is conceivable that halos are made up of compact objects whose masses range from $10^6 M_\odot$, down to Jupiters, about 10^8 times smaller. One way of discriminating between these options is by searching for manifestations of gravitational lensing. The probability of seeing lensing due to an object in our own halo is only of order 10^{-6}. However, it is, ironically, much easier to detect objects in the halos of galaxies half way out to the Hubble radius. As was first clearly realized by Refsdal (1970), the probability that a compact source at a redshift $z > 1$ is significantly lensed by objects along its line of sight is of order $\Omega_{\rm lens}$, independent of the individual lens masses involved. However, the angular separation θ of the lens images is a diagnostic of the masses. For a path length of order the Hubble radius

$$\theta \cong 10^{-6} \left(\frac{M_{\rm lens}}{M_\odot}\right)^{\frac{1}{2}} \text{ arc sec.} \qquad (3)$$

For $M_{\rm lens} > 10^5 M_\odot$, very long baseline radio interferometers provide adequate resolution. For $M_{\rm lens} < 0.1\ M_\odot$ ("Jupiters") the angular scale is $< 10^{-6}$ arc sec. This cannot be directly resolved by any technique, until optical interferometers are deployed in space. There is nevertheless a genuine prospect of detecting lensing of this kind because of the variability that would ensue if the lens were to move transversely (Gott 1981, Young 1981). It takes only a few years for an object at the Hubble radius moving at $\sim 10^3$ km per sec to traverse an angle 10^{-6} arc seconds. Another possibility, emphasised by Canizares (1982) is that "minilensing" might be detectable because it would affect the optical continuum of quasars but not the spectral lines, since the latter come from a more extended region. If there were a firm observational limit to the scatter in the equivalent widths of the lines from quasar to quasar (i.e. in the line/continuum ratio) this would constrain the value of Ω contributed by small compact objects.

To detect very small compact objects via lensing requires bright background sources whose intrinsic angular size is well below the value of $\theta(\propto M_\ell^{\frac{1}{2}})$ given by (3). The optical continuum of quasars probably comes from a region small enough to be lensed by Jupiters ($\sim 10^{-2} M_\odot$); its typical size, is, however, uncertain, and could be anywhere in the range 10^{14} - 10^{16} cm. Although no conventional astrophysical process could predominantly produce macroscopic discrete masses $\ll 10^{2} M_{\odot}$, such objects could be the outcome of, for instance, phase transitions at early epochs. Is there any class of source, detectable out to large z, that could be even more compact than quasars, and thereby able to lens such masses? One such candidate would be supernovae, whose effective radius at peak light is a few times 10^{14} cm. A significant contribution to Ω in $\sim 10^{-6} M_{\odot}$ objects would prevent supernovae from behaving as standard candles; the light curve of an individual supernova would also be distorted because the magification (along a typical line of sight) would change as its surface area expands.

3. EXOTIC PARTICLES

Provided we know the mass and annihilation cross-section of an elementary particle, we can in principle calculate how many of them survive from the big bang, and the resultant contribution to Ω. Progress in experimental particle physics may therefore reveal a particle which must contribute significantly to Ω, unless we abandon the hot big bang theory entirely. No such definite candidate is known at present; the masses of known particles such as neutrinos are not well enough determined experimentally; and there are many possible species whose existence is still conjectural. The idea of non-baryonic dark matter is nonetheless attractive, especially because the clustering properties of such matter could mimic the inferred mass distributions in galaxies and clusters in a gratifying way (Blumenthal et al. 1984 and references cited therein; Frenk et al. 1985).

Many ways have been recently proposed for detecting, or at least constraining, candidate particles. If the "inos" were unstable, and photons were among the decay products, there may be observational traces even for a decay timescale as long as 10^{24} seconds. This is because limits to the hard radiation background amount to only 10^{-8} of the critical density. Antiprotons observed in the cosmic radiation may even be decay products of "inos" (Silk and Srednicki 1984).

There has recently been a spate of interesting suggestions about how "inos" might reveal their presence relatively close at hand. Weakly interacting massive (GeV) particles would have cross sections σ of order 10^{-36} cms^{-2} for interactions with nucleons. The "optical depth" of the Sun is of order $(\sigma/10^{-36}\mathrm{cm}^{-2})$. Such a particle, scattering elastically off a nucleon in the Sun would lose energy via the recoil, and could thereby become trapped (Steigman et al. 1978, Press and Spergel 1985). Over the lifetime of the Sun, an accumulated isothermal core of "inos" could build up a mass of $10^{-12} M_{\odot}$ if annihilations did not occur. However, annihilations would restrict this buildup, unless one adopts a rather artificial model in which the cross section for annihilation is far below that for scattering (Krauss et al. 1985a). However, even though annihilations may prevent a dense enough core building up to effect the standard solar neutrino problem, high energy neutrinos from these annihilations may reveal their presence in the underwater detectors developed to search for proton decay. Already, scalar or Dirac neutrinos with mass exceeding

6 GeV can be excluded. Analogous limits come from considering annihilations in the Earth rather than the Sun, as discussed by Silk, Olive, and Srednicki (1985) and Krauss, Srednicki, and Wilczek (1985).

Goodman and Witten (1985) and Drukier, Freese and Spergel (1985) have discussed _direct detection_ of "inos" in the laboratory, using a so-called "super CD" - an array of superconducting grains maintained just below the transition temperature. The heat deposited by a single "ino" could raise the temperature of one of these grains above the critical value, thereby allowing magnetic flux to penetrate in a manner that could be detected. If the "inos" were, for instance, scalar neutrinos of mass > 5 GeV, the halo density would yield up to 10^4 counts per day per kilogram of detector. (For photinos, the expected rates are $\sim 10^3$ lower). The thermal noise in the system could perhaps be lowered sufficiently to detect particles with masses down to 2 Gev. The count rate is proportional to the 7th power of the velocity. By adjusting the threshold, one could thereby, if such effects were detected, determine the velocity distribution of the halo particles, and see if the halo were rotating. (Alternative schemes are discussed by Moody (these proceedings) and by Krauss _et al_. (1985b)).

Witten (1984) conjectured that grains or nuggets of "strange matter", containing up, down, and strange quarks, may survive stably from the quark hadron transition at $t = 10^{-4}$ seconds. Such objects, in some sense intermediate between elementary particles and lumps of astrophysical size, would count as non-baryonic matter in the context of nucleosynthesis. Recent work (Applegate and Hogan 1985, Alcock and Farhi 1985) suggests that neutrino heating would destroy nuggets unless they had a mass of planetary order, and it is unclear that any larger than this would even form, since this would involve coordination over a scale larger than the particle horizon at the relevant epoch. I find the "demise" of Witten's nuggets disappointing for two reasons. First, they might, as De Rujula and Glashow (1984) have suggested, have been detectable: interesting constraints could be set from the results of monopole searches, proton decay experiments, from the number of meteor showers, and from limits on the frequency of small-scale seismic events. A second appealing feature of the nugget concept is that it leads naturally to a universe where the respective contributions of ordinary and dark matter to Ω do not differ by more than an order of magnitude. If the dark matter were in, for instance, axions, some "fine tuning" must be invoked to prevent these contributions from differing by many powers of 10.

So there are at least three serious candidates for the dark matter in galactic halos and clusters: low mass stars; black hole remnants of very massive objects; or non-baryonic matter, in the form of supersymetric particles or axions. I would myself lay even odds between these three options at the moment. However, it is gratifying that we can expect the odds to change quite rapidly, owing either to (i) improved observational and experimental searches for candidate objects, (ii) progress in particle physics, or (iii) clearer evidence on how the dark matter is distributed (is it really present, for instance, in dwarf galaxies?).

4. A FLAT UNIVERSE?

At an IAU Symposium held in Poland in 1973, the mean density of the universe was a topic of discussion. In the concluding session the Chairman, Profesor Wheeler, conducted a poll among the audience to seek the favoured value of Ω. A gratifying feature of this poll was that a majority of participants accepted that Ω was unknown. Many, however, shared Professor Wheeler's aesthetic preference for a closed universe (or even an ensemble of closed universes) with Ω well in excess of unity. A similar poll taken today would doubtless reveal a "reasoned prejudice" in favour of $\Omega = 1$, this being the value favoured by inflationary cosmology. Maybe it is worth spelling out the basis for this attitude.

For all the present observable universe to have evolved from a region that was in causal contact at the earliest times, inflation by a factor of at least $\sim 10^{30}$ is required. In most versions of inflation, the exponential growth, once started, readily continues for many expansion timescales: it is likely to overshoot, stretching any small part of an initial chaotic hypersurface so that it becomes essentially flat over our present horizon scale. This would yield $\Omega = 1$, with a precision of order 1 part in 10^{5} (the expected fluctuation amplitude). For inflation to yield the dynamically preferred value $\Omega = 0.1$, the inflation factor would have to be "just" $\sim 10^{30}$, making the present Robertson-Walker curvature radius of order the Hubble radius. This would demand some coincidence. Moreover, there is an additional requirement: our present universe would have to arise from a segment of the initial hypersurface with the special property that its curvature was uniform to one part in 10^{5} - otherwise the curvature fluctuations that would produce quadrupole effects in the microwave background would not be 10^{5} times smaller than the overall Robertson-Walker curvature. Our universe could thus not have inflated from a typical element of an initial chaotic hypersurface: the required region would have to be special, rather as the surface of a sphere would be special if the perturbations amounted to 10^{-5} of the mean curvature. (The alternative formulation of inflation due to Gott (1982) actually fulfils this latter requirement quite naturally, though it still requires fine turning of the amount of inflation.)

If the universe were indeed flat, what could make it so? Recall that most of the dynamical evidence suggests that Ω is only 0.1 - 0.2. Moreover, our infall towards Virgo (relative to the Hubble flow) is only ~ 250 km s^{-1}. This tells us, essentially, the amount of excess mass within a sphere centred on the Virgo cluster and whose surface lies near the local Group. The galaxies within this sphere are ~ 3 times more close-packed than in a typical volume of space, and the relatively low infall velocity is then inconsistent with $\Omega = 1$, unless for some reason the galaxy distribution is more clumped than the mass in general.

There are two ways of reconciling the observations with a flat universe, both of which require that the dominant hidden mass must be more smoothly distributed on larger scales than are the galaxies, or at least the conspicuous galaxies included in surveys. (Note that, if the conventional hot big bang model is correct, the nucleosynthesis constraint (3) favours a non-baryonic form for the dynamically dominant constituent of an $\Omega = 1$ universe):

(i) The Universe may be dynamically dominated by ultrahot weakly interacting particles which do not cluster. One difficulty here is that if such particles had always been present they would have inhibited gravitational clustering altogether, as well as yielding an unaceptably fast expansion timescale at the era of nucleosynthesis. This problem is eased if the hot particles represent decay products of massive particles with a lifetime $\sim 10^9$ years. A non-zero cosmological constant (Λ-term) is an alternative hypothesis whose consequences are similar (but to postulate a value of Λ such that it is dynamically competitive with matter at the present epoch introduces the kind of unappealing fine tuning that inflationary cosmology seeks to avoid).

(ii) Some kind of biasing in the galactic distribution might render galaxies more clumped than the overall mass distribution even on scales as large as 20 Mpc. Were this so, voids would not be as empty as they look, and the local "Virgo Supercluster" would not be a threefold enhancement in the total density. It is unlikely, especially in the otherwise attractive dark matter cosmology discussed in section 3, that material (even baryonic material alone) could be pushed over distances exceeding 20 Mpc. So could the efficiency with which baryons transform into luminous galaxies be patchy? If so, the ratio of baryons to cold dark matter could be constant on all scales larger than one or two megaparsecs (up to which we expect some segregation due to cooling flows, etc.).

The latter possibility involve a simple consistency requirement. If clusters such as Coma embody a fair sample of the contents of the Universe - i.e. if their ratio of baryonic to total mass equals Ω_b/Ω_{total} - then the fraction of baryons in clusters cannot exceed the value of Ω naively estimated from Coma-like systems, i.e. 0.1 or 0.2. So if

$$(M/L)_{Universe} \cong 1000\, h_{50}\, \Omega_{total} \tag{4}$$

then $\Omega_{total} = 1$ and $\Omega_b = 0.1$ are compatible with $(M/L)_{cluster} = 100$ provided that M/L for galaxies is less than 10; these illustrative "round numbers" do indeed seem marginally consistent. This idea suggests that up to 90 per cent of baryons may remain as diffuse gas in voids, or else in faint or low surface brightness galaxies; the mean (M/L) for baryonic matter would then be ~ 100. In this connection, one wonders whether there might, in some voids, be dark halos with no luminous galaxies in them. Such objects might account for double quasars with no sign of a galaxy to act as a gravitational lens.

Physical mechanisms for bringing about this biasing have been discussed by Rees (1985), Silk (1985) and others. A feature common to several such mechanisms is that the first galaxies to form would exert negative feedback on the formation of later ones. This has the advantage that the resulting galaxies would then automatically display enhanced clustering, for reasons decribed in detail by Kaiser (1984). No mechanism has yet been worked out in convincing detail. However, the idea of biasing is not just an *ad hoc* contrivance, introduced to shore up the philosophically attractive $\Omega = 1$ model against apparently conflicting evidence. It would be astonishing if no such mechanism were important — if *no* large scale environmental effects influenced galaxy formation, and if light did indeed trace mass on all scales $>$ 1 Mpc. Any convincing determination of Ω must await much further data on galactic morphology and evolution, on the content of voids, and on the nature of the hidden mass. In the meantime, the virial evidence does not seem a severe embarassment for advocates of $\Omega = 1$.

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DISCUSSION

SHAPIRO: In your table in which you considered the feasibility of different candidates for dark matter, you excluded hot dark matter as a possible explanation for galactic halos. I am not aware of any argument that excludes hot dark matter except for the the still-uncertain inferences from the observed stellar velocities in dwarf elliptical galaxies. Were you using these results? If not, I do not think that either the phase-space density arguments or the numerical simulations yet exclude massive neutrinos, for example, as constituents of ordinary galactic halos.

REES: The table I showed (which comes from Bernard Carr's poster paper at this conference) should really be depicted in shades of gray rather than in black and white! The dwarf galaxy data, as we've heard from Kormendy and Aaronson, are still tentative. Even if there is dark matter in dwarfs (which we know couldn't be low-mass neutrinos), this still doesn't necessarily exclude neutrinos as the main contributors on larger scales. My personal view is that the main problem for neutrino-dominated cosmogony (with adiabatic fluctuations) is to understand how bound systems can form early enough to account for high-z quasars.

CARR: My constraints diagram excludes hot ino's from comprising the closure or cluster dark matter on the basis of the numerical simulations reported by White at this conference. However, the associated regions are only shaded lightly in view of the uncertainty in this conclusion. Hot ino's are excluded from comprising galactic halos on the basis of the Tremaine-Gunn argument. In fact, numerical simulations indicate that this conclusion need not apply in some circumstances, so that region should also be shaded lightly.

MELOTT: Since a number of independent numerical studies of the collapse of pancakes in hot particle models have shown that at least 10% of the particles wind up with a low velocity and high phase-space density, I would maintain that such particles as 30 eV neutrinos could comprise the material of halos around normal galaxies, even in the context of adiabatic perturbations. The formation of individual galaxies can be driven by thermal instabilities inside the pancakes where the neutrino condensate exists.

REES: The simulations that you and your collaborators have done certainly show that the phase-space dilution is less catastrophic than naive arguments suggest, especially when the collapse is essentially one-dimensional rather than quasi-spherical. Until we understand the gas-dynamical aspects of galaxy formation, I agree that we must be cautious in our claims that neutrino-dominated models run into problems when confronted with the clustering data. Your comment also highlights the important question of whether all galaxies have similar dark halos, or whether some might have formed from squeezed clouds of baryons whose location isn't necessarily correlated with potential wells dominated by non-baryonic matter.

J. JONES: One of the problems with putting the dark matter in abnormal-mass stars is that there are quite strong constraints on the proportion of such objects that can be accommodated in the disk. What mechanism could be responsible for causing the majority of the mass to go into such stars in the halo but not in the disk?

REES: Several authors have conjectured how the IMF might change from place to place, with different conclusions. I'm not sure we know enough about star formation even to decide whether a very different IMF for Population III is likely or unlikely.

SILK: You have presented with more-or-less equal emphasis three different possibilities for the nature of dark matter. Two, namely Jupiters and supermassive black holes, involve extreme and ad hoc extrapolations beyond any directly measured aspects of star formation. The third, exotic particles, may involve similar extrapolations by the particle physicist. Would you care to indicate your ranking of these options in terms of plausibility? (laughter)

REES: I gave them equal emphasis because I am genuinely agnostic. In particular, I am very unconvinced by theoretical arguments that claim to prove that the first stars "must" or "cannot" have such-and-such a mass. To be specific, I would assess the three options as having 25% probability each, leaving the last 25% for things that we haven't thought of yet. But what is most encouraging is the prospect of observational and/or experimental discrimination between the options over the next few years. We won't stay "in the dark" forever.

FABER: Suppose it were to be shown that dark matter really exists in a galaxy like Ursa Minor. What additional constraints might you have on massive objects from dynamical friction in such a system?

REES: Naively, there is a dynamical friction problem for any mass above $\sim 200\ M_{\odot}$, as you yourself have pointed out. Now, I think there is an escape clause, which Lacey and Ostriker have pointed out. Unless we really know the density profile, can we really rule out the presence of, say, one $10^6\ M_{\odot}$ black hole in the middle of such a system, or a few in orbit around it? It is certainly the case that if you have massive black holes, then dynamical friction is important; it will for these systems tend to make the black hole go outward and the ordinary stars go inward, contrary to the way things usually happen. But that might still leave you with one or two in the center and a few around the outside. Before you can shoot down the massive black hole model using this line of argument, you need to know not merely the overall velocity dispersion but something about its distribution with radius.

PACZYNSKI: It might be easier to detect Jupiters, if there are any, in the halo of our Galaxy rather than in halos at cosmological distances. If you put a Jupiter at a cosmological distance, you have to wait an unreasonably long time before any lensing variation is observable. Besides, the events are not frequent. But if you calculate the optical depth to gravitational lensing in galactic halo objects, it is about one part in 10^6. This is small but not hopeless. So if you put in the background a large number of point sources, like in the Magellanic Clouds, one out of 10^6 would be a minilens at any given time, if the objects in our halo had the right mass. There is a lower mass limit of $\sim 10^{-8}\ M_\odot$, at which the splitting is comparable to the size of a dwarf star in the Magellanic Clouds, and the event would last for a fraction of an hour. The upper end of the suitable mass range is $\sim 10^3\ M_\odot$, where the variation time is ~ 10 years and we run into the limit set by our own lifetimes.

REES: I agree. The situation for cosmologically distant objects may not be quite as bad as you think, because the velocity you should use is not the transverse velocity of a typical star in the halo but the velocity of the galaxy as a whole. That could be large.

E. TURNER: Alcock and Anderson have pointed out that the dispersion in time-delay H_0 determinations for different gravitational lens systems is related to the fluctuations in the total mass along various lines of sight out to cosmological distances. In principle, this could be compared to the observed galaxy clustering amplitude and thus directly test the hypothesis that the total mass is more uniformly distributed than the luminous matter.

REES: Yes, this is a good test. Gravitational lensing is also a possible probe for "failed galaxies" in voids, i.e., halos of dark matter without luminous cores. It also offers a way of testing the "pre-Newtonian" theories of Milgrom and others, unless these theories predict exactly the same relationship between the bending angle for light rays and the gravitational acceleration of ordinaty matter as does standard physics.

PEEBLES: Martin, I might remind you that astrophysically biased galaxy formation could go either way - it could depress Ω as well as raise it. When I look at the data, it suggests, if anything, that Ω has been pushed down. The Coma Cluster has surely been accreting material. If Ω were unity, that material would have to have a high mass-to-light ratio. But when you look at the data you find, if anything, that the mass-to-light ratio decreases with increasing radius.

REES: I'm reluctant to dissent from any of that. Let me just say that we do not have any quantitative picture for biasing, we just have lots of rather poor and vague ideas. The best idea is in fact your own, which is that we do another unattractive thing and abandon Gaussian random phases. Then you could imagine that the Universe is inherently more perturbed in some places than in others. This could prevent galaxy formation. But there is no lack of ideas, and I think that all one can say is that on general grounds we cannot rule out a model where in 90% of the Universe we have uncondensed baryons while in the other 10% we have baryons turned into galaxies.

NOLTHENIUS: Simon White and Marc Davis pointed out that both their Ω = 0.2 unbiased and Ω = 1 biased simulations provide reasonable fits to the two- and three-point correlation functions and overall sky appearance. However, my latest results from looking at their simulations favor the biased scenario: the detailed properties of the biased-simulation groups - M/L ratios, percentage of galaxies in groups, many other measures, and their trends with selection cutoffs - are all in agreement with the CfA data, while the Ω = 0.2 unbiased simulations are not. The unbiased catalogs give too few galaxies in groups, M/L's that are too high, and trends with cutoff that differ from the observations.