Astro/Physics 224 Winter 2008

Origin and Evolution of the Universe

Week 1

A Brief History of Dark Matter

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A Brief History of Dark Matter

1930s - Discovery that cluster $\sigma_V \sim 1000$ km/s

1970s - Discovery of flat galaxy rotation curves

1980 - Most astronomers are convinced that dark matter exists around galaxies and clusters

1980-84 - short life of Hot Dark Matter theory

1984 - Cold Dark Matter theory proposed

1992 - COBE discovers CMB fluctuations as predicted by CDM; CHDM and LCDM are favored CDM variants

1998 - SN *I*a and other evidence of Dark Energy

2000 - ΛCDM is the Standard Cosmological Model

2003 - WMAP and LSS data confirm ΛCDM predictions

~2010 - Discovery of dark matter particles??

Early History of Dark Matter

1922 - Kapteyn: "dark matter" in Milky Way disk[1]
1933 - Zwicky: "dunkle (kalte) materie" in Coma cluster
1937 - Smith: "great mass of internebular material" in Virgo cluster
1937 - Holmberg: galaxy mass 5×10^{11} M_{sun} from handful of pairs[1]
1939 - Babcock observes rising rotation curve for M31[1]

1940s - large cluster σ_V confirmed by many observers

1957 - van de Hulst: high HI rotation curve for M31
1959 - Kahn & Woltjer: MWy-M31 infall $\Rightarrow$ $M_{LocalGroup} = 1.8 \times 10^{12}$ M_{sun}
1970 - Rubin & Ford: M31 flat optical rotation curve
1973 - Ostriker & Peebles: halos stabilize galactic disks
1974 - Einasto, Kaasik, & Saar; Ostriker, Peebles, Yahil: summarize evidence that galaxy M/L increases with radius
1975, 78 - Roberts; Bosma: extended flat HI rotation curves
1979 - Faber & Gallagher: convincing evidence for dark matter[2]

1980 - Most astronomers are convinced that dark matter exists around galaxies and clusters

[1] Virginia Trimble, in D. Cline, ed., *Sources of Dark Matter in the Universe* (World Scientific, 1994).
[2] S. M. Faber and J. S. Gallagher 1979, ARAA 17, 135

Fritz Zwicky

1937 ApJ 86, 217

ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

F. ZWICKY

The Coma cluster contains about one thousand nebulae. The average mass of one of these nebulae is therefore

$$\overline{M} > 9 \times 10^{43} \text{ gr} = 4.5 \times 10^{10} M_{\odot} . \tag{36}$$

Inasmuch as we have introduced at every step of our argument inequalities which tend to depress the final value of the mass $\mathscr{M}$, the foregoing value (36) should be considered as the lowest estimate for the average mass of nebulae in the Coma cluster. This result is somewhat unexpected, in view of the fact that the luminosity of an average nebula is equal to that of about 8.5×10^7 suns. According to (36), the conversion factor γ from luminosity to mass for nebulae in the Coma cluster would be of the order

$$\gamma = 500 , \tag{37}$$

as compared with about $\gamma' = 3$ for the local Kapteyn stellar system.

This article also proposed measuring the masses of galaxies by gravitational lensing.

INTERGALACTIC MATTER AND THE GALAXY

1959 ApJ 130, 705

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The fact that the motion is one of approach is significant. For if the Local Group is a physical unit, the Galaxy and M31 are not likely to have been formed very far from each other, certainly not at a much greater distance than their present separation. This indicates that they must have performed the larger part of at least one orbit around their center of gravity during a time of about 10^{10} years. Consequently, their orbital period must be less than 15 billion years. From this we obtain the total mass of the system as follows. According to Kepler's third law, we have

$$P^2 = \frac{4\pi^2}{GM^*}\, a^3 \leq 2 \times 10^{35}\ \mathrm{sec}^2 , \tag{1}$$

where M^* represents the effective mass at the center of gravity. To obtain a minimum estimate for M^*, we assume that the system has no angular momentum. Then conservation of energy gives, for our Galaxy,

$$\frac{GM^*}{2a} = \frac{GM^*}{D} - E_k , \tag{2}$$

where D denotes the present distance of the Galaxy to the center of gravity (480 kpc) and E_t is its present kinetic energy per unit mass. From these equations we obtain

$$M^* \geq 1.8 \times 10^{12} m_{\odot} , \tag{3}$$

which is six times larger than the reduced mass of M31 and the Galaxy.

The discrepancy seems to be well outside the observational errors.

See Rubin's "Reference Frame" in Dec 2006 Physics Today and her article, "A Brief History of Dark Matter," in *The dark universe: matter, energy and gravity*, Proc. STScI Symposium 2001, ed. Mario Livio.

1970 ApJ 159, 379

ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*

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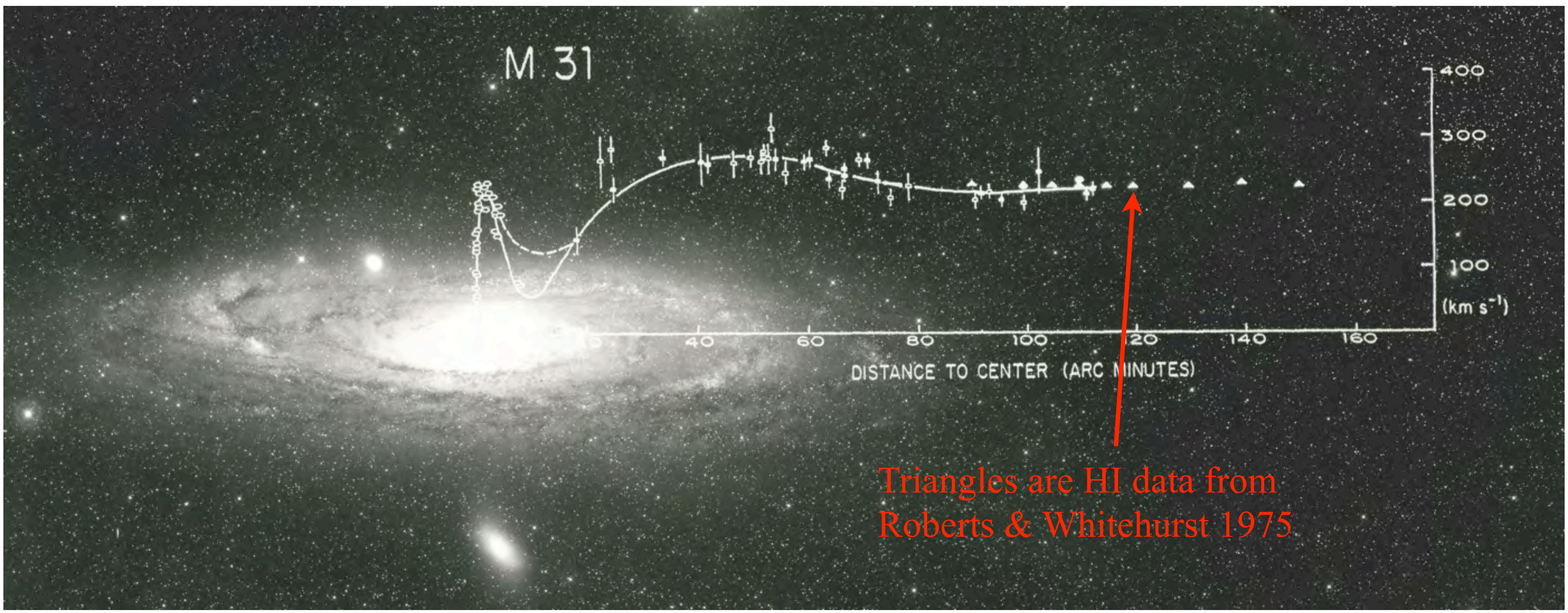

Triangles are HI data from Roberts & Whitehurst 1975

A NUMERICAL STUDY OF THE STABILITY OF FLATTENED GALAXIES: OR, CAN COLD GALAXIES SURVIVE?*

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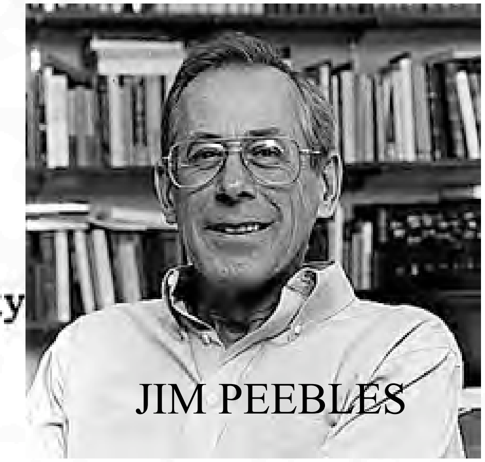
Received 1973 May 29



ABSTRACT

To study the stability of flattened galaxies, we have followed the evolution of simulated galaxies containing 150 to 500 mass points. Models which begin with characteristics similar to the disk of our Galaxy (except for increased velocity dispersion and thickness to assure local stability) were found to be rapidly and grossly unstable to barlike modes. These modes cause an increase in random kinetic energy, with approximate stability being reached when the ratio of kinetic energy of rotation to total gravitational energy, designated t, is reduced to the value of 0.14 ± 0.02. Parameter studies indicate that the result probably is not due to inadequacies of the numerical N-body simulation method. A survey of the literature shows that a critical value for limiting stability $t \simeq 0.14$ has been found by a variety of methods.

Models with added spherical (halo) component are more stable. It appears that halo-to-disk mass ratios of 1 to $2\frac{1}{2}$, and an initial value of $t \simeq 0.14 \pm 0.03$, are required for stability. If our Galaxy (and other spirals) do not have a substantial unobserved mass in a hot disk component, then apparently the halo (spherical) mass *interior* to the disk must be comparable to the disk mass. Thus normalized, the halo masses of our Galaxy and of other spiral galaxies *exterior* to the observed disks may be extremely large.

Nature 250, 309 - 310 (26 July 1974)

Dynamic evidence on massive coronas of galaxies

JAAN EINASTO, ANTS KAASIK & ENN SAAR

A LONGSTANDING unresolved problem in galactic astronomy is the mass discrepancy observed in clusters of galaxies. The virial mass of the cluster per galaxy and the mass–luminosity ratio are considerably larger than the corresponding quantities for individual galaxies. This discrepancy cannot be a result of expansion or be because of the recent origin of clusters: these ideas contradict our present knowledge of the physical evolution and ages of galaxies1. Therefore it is necessary to adopt an alternative hypothesis: that the clusters of galaxies are stabilised by hidden matter.

According to new estimates the total mass density of matter in galaxies is 20% of the critical cosmological density.

Both papers: $\Omega_m \approx 0.2$

THE SIZE AND MASS OF GALAXIES, AND THE MASS OF THE UNIVERSE

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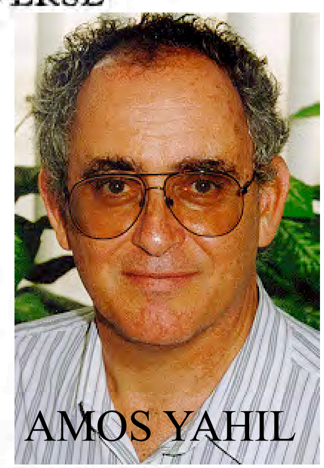
1974 ApJ 194, L1



ABSTRACT

Currently available observations strongly indicate that the mass of spiral galaxies increases almost linearly with radius to nearly 1 Mpc. This means that the total mass per giant spiral is of the order of 10^{12} $M_\odot$, and that the ratio of this mass to the photographic light within the Holberg radius, f, is ~ 200 $(M/L)_\odot$. Using this value of f and the luminosity function of surveyed galaxies, we determine a local mean cosmological mass density $\approx 2 \times 10^{-30}$ g cm^{-3} corresponding to $\Omega \equiv \rho/\rho_{crit} \approx 0.2$. The uncertainty in this result is not less than a factor of 3.

THE ENORMOUS MASS OF THE ELLIPTICAL GALAXY M87: A MODEL FOR THE EXTENDED X-RAY SOURCE*

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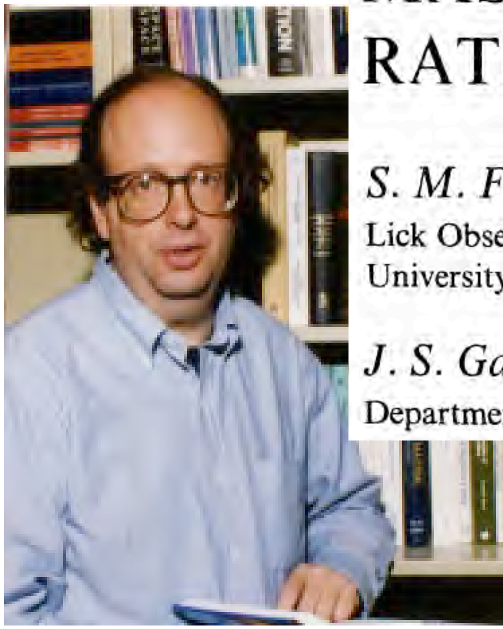
ABSTRACT

An analysis of the X-ray data from the Virgo cluster indicates that the mass of the giant elliptical galaxy M87 exceeds $10^{13}\,\mathfrak{M}_\odot$ and may be $\sim 10^{14}\,\mathfrak{M}_\odot$ or greater. This large mass is required in order to confine the extended thermal X-ray source to its observed projected size—provided the gas which radiates X-rays is essentially isothermal ($T = 3 \times 10^7$ K) and in hydrostatic equilibrium. Isothermality follows from the efficiency of heat conduction and the suggested origin of the gas. If these reasonable assumptions are correct, the bulk of the mass in M87 must be distributed in a low-density, low-luminosity component quite unlike the distribution of luminous matter. The mass of this component, which is uncertain by a factor of about 2, could account for the "missing mass" in the Virgo cluster.

1978 ApJ 219, 413



MASSES AND MASS-TO-LIGHT RATIOS OF GALAXIES[1]

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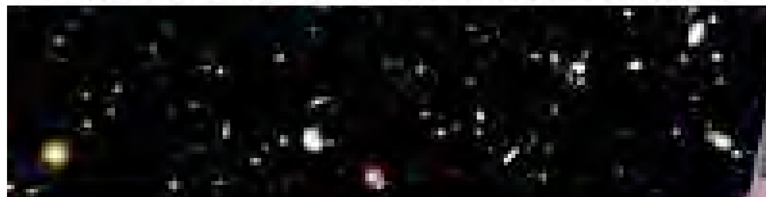

After reviewing all the evidence, it is our opinion that the case for invisible mass in the Universe is very strong and getting stronger. Particularly encouraging is the fact that the mass-to-light ratio for binaries agrees so well with that for small groups. Furthermore, our detailed knowledge of the mass distribution of the Milky Way and Local Group is reassuringly consistent with the mean properties of galaxies and groups elsewhere. In sum, although such questions as observational errors and membership probabilities are not yet completely resolved, we think it likely that the discovery of invisible matter will endure as one of the major conclusions of modern astronomy.

1980 - Most astronomers are convinced that dark matter exists around galaxies and clusters - but is it Hot or Cold?

It was known that BBN ⇒ $\Omega_b \approx 0.03$. Theorists usually assumed $\Omega_m=1$, but observers typically found $\Omega_m \approx 0.2$.

The Hot-Warm-Cold DM terminology was first used by Dick Bond and me in our talks at the 1983 Moriond Conference.

1973 - Marx & Szalay, Cowsik & McClelland: $m_\nu < 100\ h^2$ eV
1980 - Zel'dovich group develops Hot Dark Matter theory[1]
1983 - White, Frenk, Davis: 1st simulation rules out HDM

In ~1980, when purely baryonic adiabatic fluctuations were ruled out by the improving upper limits on CMB anisotropies, theorists led by Zel'dovich turned to what we now call the HDM scenario, with light neutrinos making up most of the dark matter. However, in this scheme the fluctuations on small scales are damped by relativistic motion ("free streaming") of the neutrinos until $T<m_\nu$,
which occurs when the mass entering the horizon is about $10^{15}\ M_{sun}$, the supercluster mass scale. Thus superclusters would form first, and galaxies later form by fragmentation. This predicted a galaxy distribution much more inhomogeneous than observed.

[1] E.g., Doroshkevich, Khlopov, Sunyaev, Szalay, & Zel'dovich 1981, NYASA 375, 32; Zel'dovich, Einasto, Shandarin 1982, Nature 300, 407; Bond & Szalay 1982, ApJ 274, 443.

Some steps toward understanding galaxies

Many people thought the early universe was complex (e.g. mixmaster universe Misner, explosions Ostriker, …).

But Zel'dovich assumed that it is fundamentally simple, with just a scale-free spectrum of adiabatic fluctuations of

(a) baryons

and when that failed [$(\Delta T/T)_{CMB} < 10^{-4}$] and Moscow physicists thought they had discovered neutrino mass

(b) hot dark matter.

Blumenthal and I thought simplicity a good approach, but we tried other simple candidates for the dark matter, first

(c) warm dark matter, and then, with Faber and Rees,

(d) cold dark matter, which moved sluggishly in the early universe.

Weakly Interacting Particles as Dark Matter

THE ASTROPHYSICAL JOURNAL, 180: 7–10, 1973 February 15

GRAVITY OF NEUTRINOS OF NONZERO MASS IN ASTROPHYSICS

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Received 1972 July 24

ABSTRACT

If neutrinos have a rest mass of a few eV/c^2, then they would dominate the gravitational dynamics of the large clusters of galaxies and of the Universe. A simple model to understand the virial mass discrepancy in the Coma cluster on this basis is outlined.
Subject headings: cosmology — galaxies, clusters of — neutrinos

The possibility of a finite rest mass for the neutrinos has fascinated astrophysicists (Kuchowicz 1969). A recent discussion of such a possibility has been in the context of the solar-neutrino experiments (Bahcall, Cabibbo, and Yahil 1972). Here we wish to point out some interesting consequences of the gravitational interactions of such neutrinos. These considerations become particularly relevant in the framework of big-bang cosmologies which we assume to be valid in our discussion here.

In the early phase of such a Universe when the temperature was ~1 MeV, several processes of neutrino production (Ruderman 1969) would have led to copious production of neutrinos and antineutrinos (Steigman 1972; Cowsik and McClelland 1972). Conditions of thermal equilibrium allow an easy estimate of their number densities (Landau and Lifshitz 1969):

$$n_{\nu i} = \frac{1}{\pi^2 \hbar^3} \int_0^\infty \frac{p^2 dp}{\exp [E/kT(z_{eq})] + 1} . \qquad (1)$$

Here $n_{\nu i}$ = number density of neutrinos of the *i*th kind (notice that in writing this expression we have assumed that both the helicity states are allowed for the neutrinos because of finite rest mass); $E = c(p^2 + m^2c^2)^{1/2}$; k = Boltzmann's constant; $T(z_{eq}) = T_r(z_{eq}) = T_\nu(z_{eq}) = T_e(z_{eq}) \cdots$ = the common temperature of radiation, neutrinos, electrons, etc., at the latest epoch characterized by redshift z_{eq} when they may be assumed to have been in thermal equilibrium; $kT(z_{eq}) \simeq 1$ MeV.

Since the masses of the neutrinos are expected to be small, $kT(z_{eq}) \gg m_{\nu i}c^2$, in the extreme-relativistic limit equation (1) reduces to

$$n_{\nu i}(z_{eq}) \simeq 0.183[T(z_{eq})/hc]^3 . \qquad (2)$$

As the Universe expands, only the neutrinos (in contrast to all other known particles) survive annihilation because of extremely low cross-sections (deGraff and Tolhock 1966), and their number density decreases with increasing volume of the Universe, simply as $\sim V(z_{eq})/V(z) = [(1 + z)/(1 + z_{eq})]^3$. Noting that $(1 + z_{eq})/(1 + z) = T_r(z_{eq})/T_r(z)$, the number density at the present epoch ($z = 0$) is given by

$$n_{\nu i}(0) = n_{\nu i}(z_{eq})/(1 + z_{eq})^3 \simeq 0.183[T_r(0)/hc]^3 \simeq 300 \text{ cm}^{-3} , \qquad (3)$$

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More than 30 years ago, beginnings of the idea of weakly interacting particles (neutrinos) as dark matter

Massive neutrinos are no longer a good candidate (hot dark matter)

However, the idea of weakly interacting massive particles as dark matter is now standard

Giant voids in the Universe

1982 Nature
300, 407

Ya. B. Zeldovich*, J. Einasto†‡ & S. F. Shandarin*

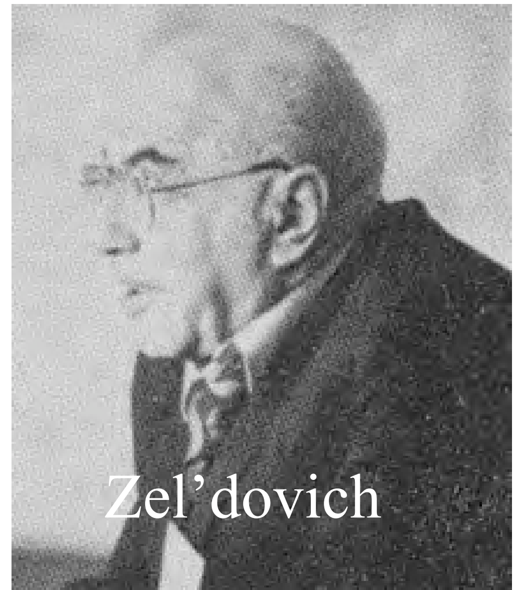
Neutrino dominated Universe

Perhaps the weakest point in the adiabatic scenario is its need for too large an amplitude of density perturbations at the decoupling era: $\delta\rho/\rho \approx 10^{-3}$ if $\Omega = 1$ and $\delta\rho/\rho \approx 10^{-1}$ if $\Omega = 0.02$ (ref. 40). As noted already by Silk[23], density fluctuations at the epoch of decoupling correspond to similar angular fluctuations of the temperature of the microwave background. $\delta T/T \sim 1/3\delta\rho/\rho$. On the other hand, observations give an upper limit of temperature fluctuations of the order 10^{-4} (refs 22, 23).

This controversy would be solved if the Universe were neutrino dominated with the neutrino mass $m \approx 10$ eV. Neutrino gas does not interact with radiation, thus perturbations in the neutrino gas could develop much earlier than in the baryon dominated Universe and could have the necessary amplitude. Baryon gas is bound to radiation and has smaller density fluctuations, after decoupling it simply flows to gravitational wells formed in the neutrino gas.

Thus in the neutrino dominated Universe one has low baryon density $\Omega_b \approx 0.01$–0.1 while the total density is close to the closure once $\Omega_t \approx \Omega_\nu \approx 1$.

The formation of the structure in a neutrino dominated Universe is, essentially, an adiabatic scenario[44–51]. The initial ratio of baryons to neutrinos is the same everywhere (the entropy is constant), small-scale fluctuations are damped, the characteristic mass of objects to form first is $10^{15} M_\odot$ as in the conventional adiabatic scenario.



CLUSTERING IN A NEUTRINO-DOMINATED UNIVERSE

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Received 1983 June 17; accepted 1983 July 1

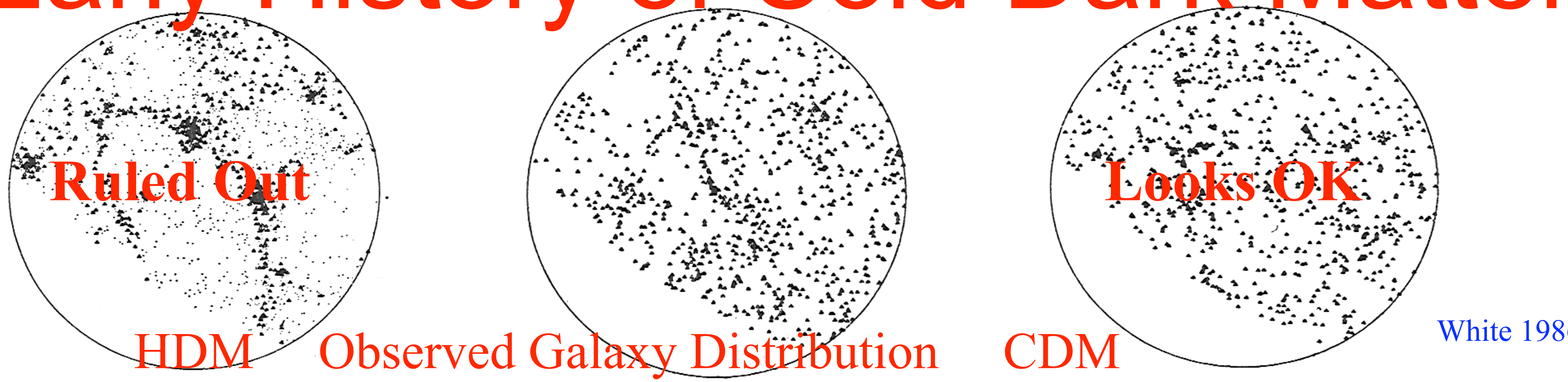
1983 ApJ 274, L1

ABSTRACT

We have simulated the nonlinear growth of structure in a universe dominated by massive neutrinos using initial conditions derived from detailed linear calculations of earlier evolution. Codes based on a direct *N*-body integrator and on a fast Fourier transform Poisson solver produce very similar results. The coherence length of the neutrino distribution at early times is directly related to the mass of the neutrino and thence to the present density of the universe. We find this length to be too large to be consistent with the observed clustering scale of galaxies if other cosmological parameters are to remain within their accepted ranges. The conventional neutrino-dominated picture appears to be ruled out.

Early History of Cold Dark Matter



1967 - Lynden-Bell: violent relaxation (also Shu 1978)
1976 - Binney, Rees & Ostriker, Silk: Cooling curves
1977 - White & Rees: galaxy formation in massive halos
1980 - Fall & Efstathiou: galactic disk formation in massive halos
1982 - Guth & Pi; Hawking; Starobinski: Cosmic Inflation $P(k) = k^1$
1982 - Pagels & Primack: lightest SUSY particle stable by R-parity: gravitino
1982 - Blumenthal, Pagels, & Primack; Bond, Szalay, & Turner: WDM
1982 - Peebles: CDM P(k) - simplified treatment (no light neutrinos)
1983 - Goldberg: photino as SUSY CDM particle
1983 - Preskill, Wise, & Wilczek; Abbott & Sikivie; Dine & Fischler: Axion CDM
1983 - Blumenthal & Primack; Bond & Szalay: CDM P(k)
1984 - Blumenthal, Faber, Primack, & Rees: CDM compared to CfA data
1984 - Peebles; Turner, Steigman, Krauss: effects of Λ
1984 - Ellis, Hagelin, Nanopoulos, Olive, & Srednicki: neutralino CDM
1985 - Davis, Efstathiou, Frenk, & White: 1st CDM, ΛCDM simulations

Core condensation in heavy halos: a two-stage theory for galaxy formation and clustering

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Summary. We suggest that most of the material in the Universe condensed at an early epoch into small 'dark' objects. Irrespective of their nature, these objects must subsequently have undergone hierarchical clustering, whose present scale we infer from the large-scale distribution of galaxies. As each stage of the hierarchy forms and collapses, relaxation effects wipe out its substructure, leading to a self-similar distribution of bound masses of the type discussed by Press & Schechter. The entire luminous content of galaxies, however, results from the cooling and fragmentation of residual gas within the transient potential wells provided by the dark matter. Every galaxy thus forms as a concentrated luminous core embedded in an extensive dark halo. The observed sizes of galaxies and their survival through later stages of the hierarchy seem inexplicable without invoking substantial dissipation; this dissipation allows the galaxies to become sufficiently concentrated to survive the disruption of their halos in groups and clusters of galaxies. We propose a specific model in which $\Omega \simeq 0.2$, the dark matter makes up 80 per cent of the total mass, and half the residual gas has been converted into luminous galaxies by the present time. This model is consistent with the inferred proportions of dark matter, luminous matter and gas in rich clusters, with the observed luminosity density of the Universe and with the observed radii of galaxies; further, it predicts the characteristic luminosities of bright galaxies and can give a luminosity function of the observed shape.

1982 PRL 48, 224

Supersymmetry, Cosmology, and New Physics at Teraelectronvolt Energies

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(Received 17 August 1981)

If one assumes a spontaneously broken local supersymmetry, big-bang cosmology implies that the universe is filled with a gravitino ($g_{3/2}$) gas—possibly its dominant constituent. From the observational bound on the cosmological mass density it follows that $m_{g_{3/2}} \lesssim 1$ keV. Correspondingly, the supersymmetry breaking parameter F satisfies $\sqrt{F} \lesssim 2\times 10^3$ TeV, requiring new supersymmetric physics in the teraelectronvolt energy region. An exact sum rule is derived and used to estimate the threshold and cross section for the production of the new states.

Galaxy formation by dissipationless particles heavier than neutrinos

1982 Nature 299, 37

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In a baryon dominated universe, there is no scale length corresponding to the masses of galaxies. If neutrinos with mass <50 eV dominate the present mass density of the universe, then their Jeans mass $M_{J\nu} \sim 10^{16} M_{\odot}$, which resembles supercluster rather than galactic masses. Neutral particles that interact much more weakly than neutrinos would decouple much earlier, have a smaller number density today, and consequently could have a mass >50 eV without exceeding the observational mass density limit. A candidate particle is the gravitino, the spin 3/2 supersymmetric partner of the graviton, which has been shown[1] to have a mass ≤ 1 keV if stable[2]. The Jeans mass for a 1-keV noninteracting particle is $\sim 10^{12} M_{\odot}$, about the mass of a typical spiral galaxy including the nonluminous halo. We suggest here that the gravitino dominated universe can produce galaxies by gravitational instability while avoiding several observational difficulties associated with the neutrino dominated universe.

LARGE-SCALE BACKGROUND TEMPERATURE AND MASS FLUCTUATIONS DUE TO SCALE-INVARIANT PRIMEVAL PERTURBATIONS

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Received 1982 July 2; accepted 1982 August 13

ABSTRACT

The large-scale anisotropy of the microwave background and the large-scale fluctuations in the mass distribution are discussed under the assumptions that the universe is dominated by very massive, weakly interacting particles and that the primeval density fluctuations were adiabatic with the scale-invariant spectrum $P \propto$ wavenumber. This model yields a characteristic mass comparable to that of a large galaxy independent of the particle mass, m_x, if $m_x \gtrsim 1$ keV. The expected background temperature fluctuations are well below present observational limits.

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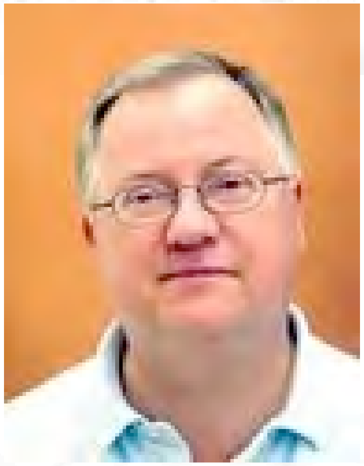
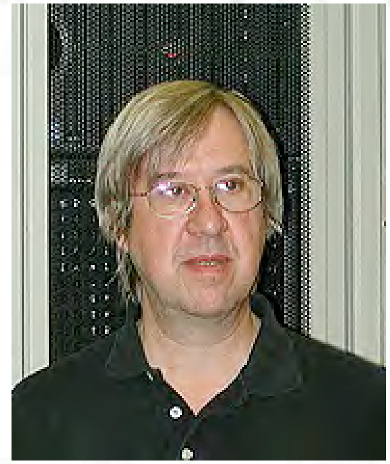
THE COLLISIONLESS DAMPING OF DENSITY FLUCTUATIONS IN AN EXPANDING UNIVERSE



1983 ApJ 274, 443

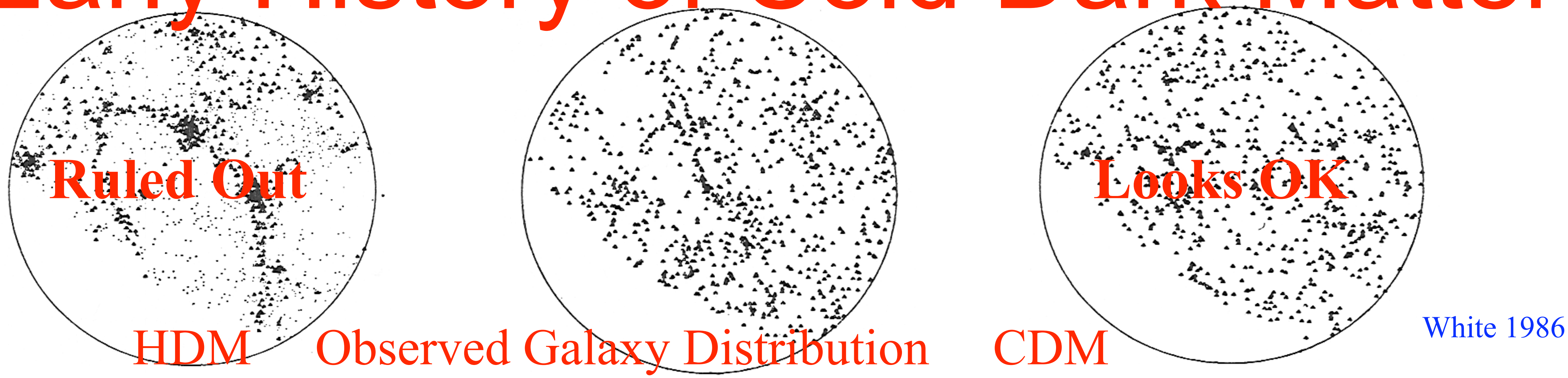


J. R. BOND AND A. S. SZALAY

ABSTRACT

The best candidate for the dark matter is a massive collisionless non-baryonic relic of the early universe. The most natural type of initial density fluctuations expected are of the adiabatic rather than of the isothermal type. We calculate the temporal evolution of the (initially adiabatic) fluctuation spectrum by numerical integration of the coupled Einstein-Boltzmann equations for scalar perturbations in the metric and in the density of photons, neutrinos, and collisionless relics. Our output linear perturbation spectrum, which is itself input to the nonlinear problem of large scale structure formation, is shown to be characterized by two scales: the damping mass and the horizon mass when the energy density in relativistic particles equals that in nonrelativistic ones, M_{Heq}. Collisionless relics which decouple when relativistic may be of two basic types if they are to dominate the mass of the universe: massive neutrinos of 10–100 eV, or massive gravitinos (or other weakly interacting particles) of mass about 1 keV. For massive neutrinos, both scales are of supercluster size; and the Zel'dovich pancake picture, in which a large scale is the first to collapse, is expected, regardless of initial spectrum. For massive gravitinos, the damping mass is of galactic scale. Depending upon the initial spectrum, one can get either hierarchical clustering from the damping scale upward or fragmentation of the large M_{Heq} scale. Collisionless relics which decouple when nonrelativistic have negligible damping masses; again, hierarchical clustering from very small scales or large scale fragmentation is possible in this adiabatic picture.

Early History of Cold Dark Matter

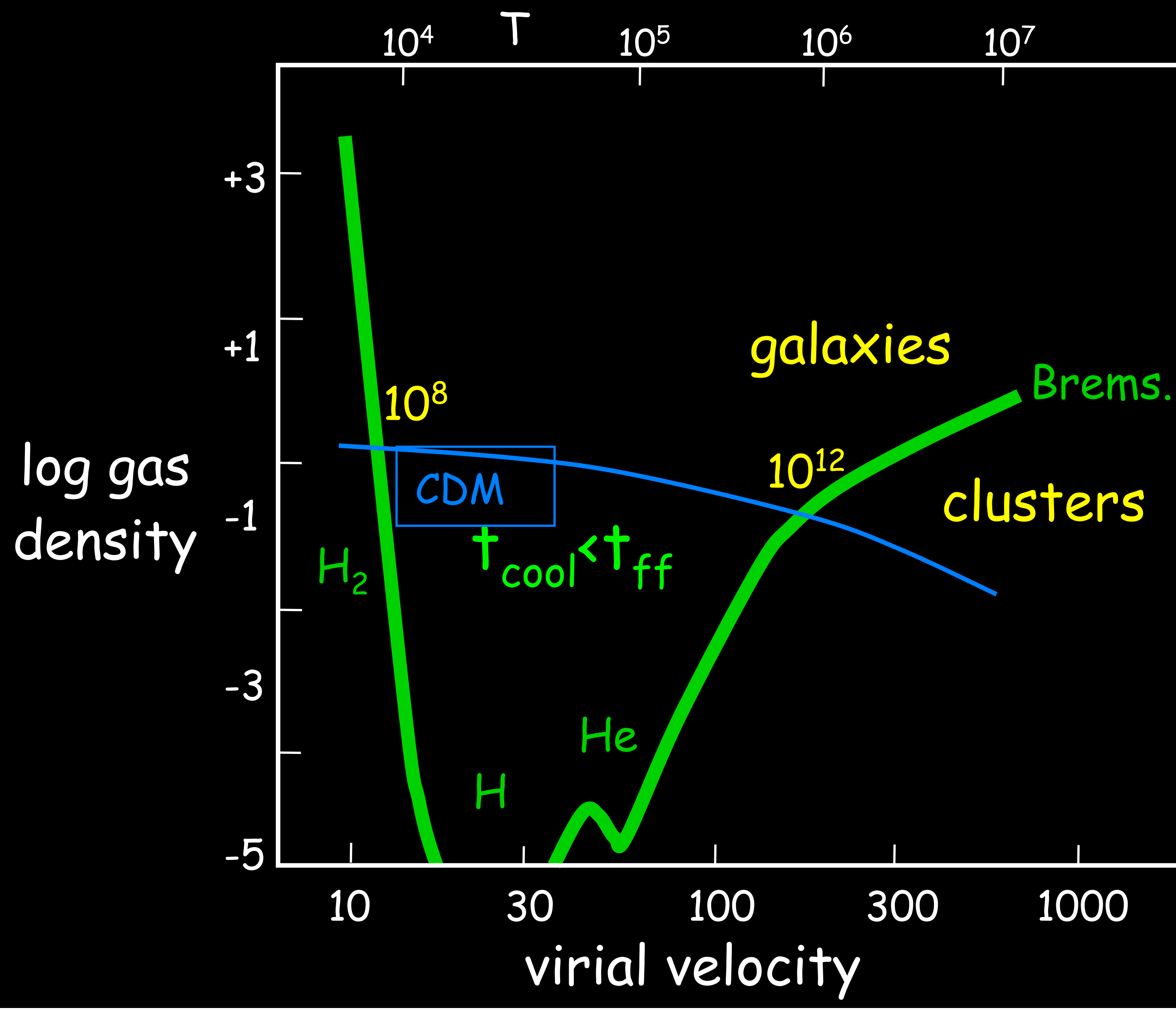


1967 - Lynden-Bell: violent relaxation (also Shu 1978)
1976 - Binney, Rees & Ostriker, Silk: Cooling curves
1977 - White & Rees: galaxy formation in massive halos
1980 - Fall & Efstathiou: galactic disk formation in massive halos
1982 - Guth & Pi; Hawking; Starobinski: Cosmic Inflation $P(k) = k^1$
1982 - Pagels & Primack: lightest SUSY particle stable by R-parity: gravitino
1982 - Blumenthal, Pagels, & Primack; Bond, Szalay, & Turner: WDM
1982 - Peebles: CDM P(k) - simplified treatment (no light neutrinos)
1983 - Goldberg: photino as SUSY CDM particle
1983 - Preskill, Wise, & Wilczek; Abbott & Sikivie; Dine & Fischler: Axion CDM
1983 - Blumenthal & Primack; Bond & Szalay: CDM P(k)
1984 - Blumenthal, Faber, Primack, & Rees: CDM cp. to CfA data
1984 - Peebles; Turner, Steigman, Krauss: effects of Λ

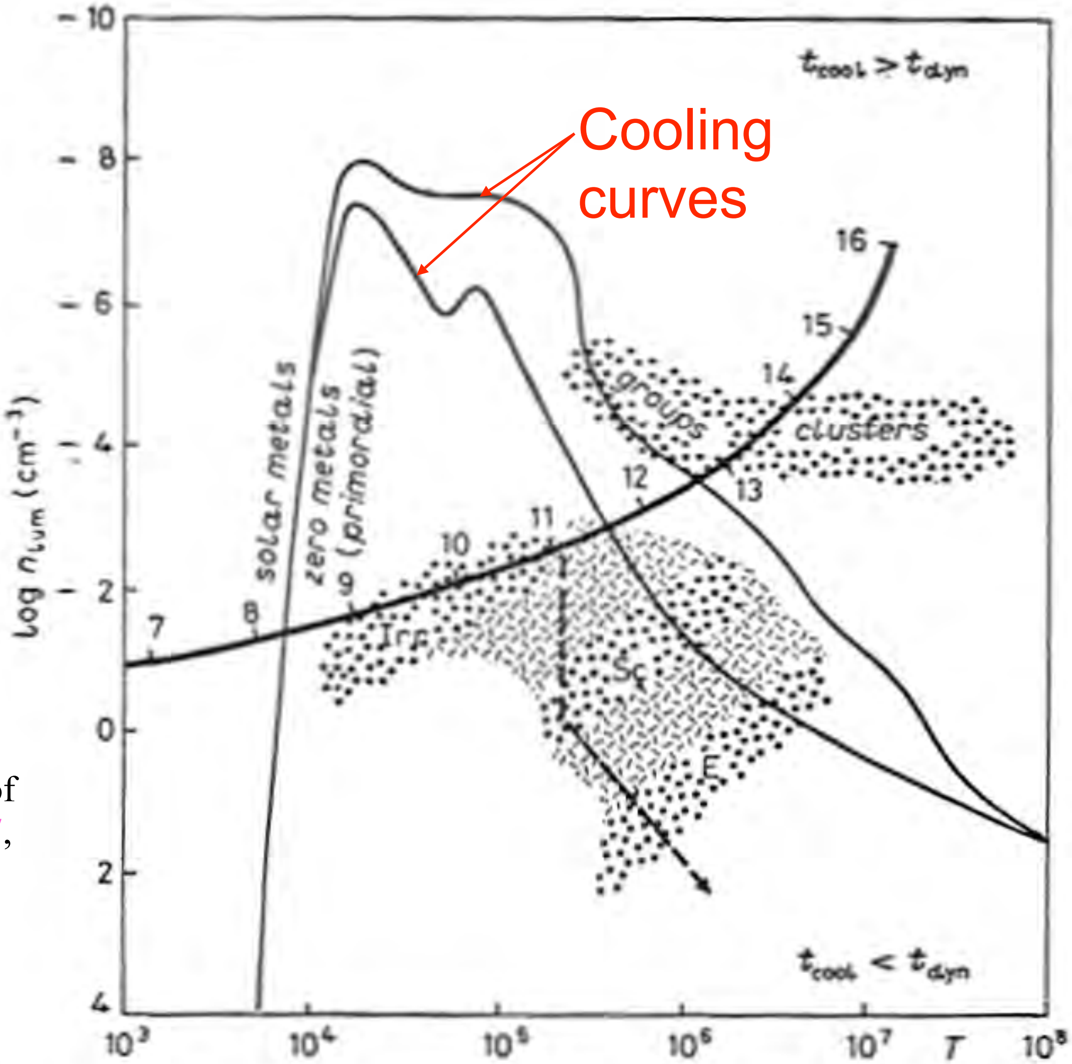
1984 - Ellis, Hagelin, Nanopoulos, Olive, & Srednicki: neutralino CDM 1985 - Davis, Efstathiou, Frenk, & White: 1^{st} CDM, ΛCDM simulations

CDM Correctly Predicted the Masses of Galaxies

Rees & Ostriker 77, Silk 77, Binney 77, White & Rees 1978
CDM: Blumenthal, Faber, Primack, & Rees 1984



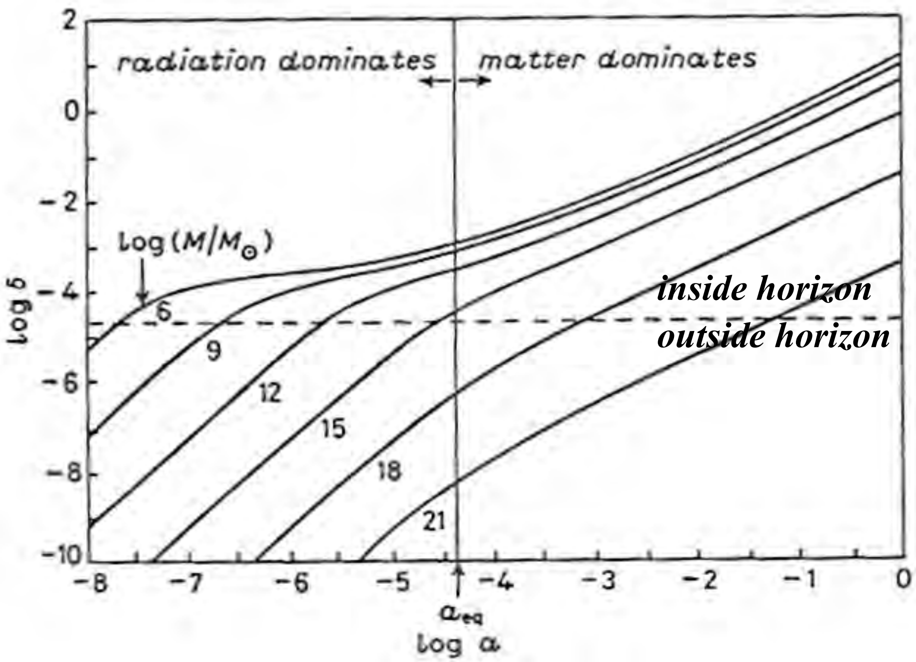
CDM Spherical Collapse Model



The baryonic density *vs.* temperature as root-mean-square perturbations having total mass M become nonlinear and virialize. The numbers on the tick marks are the logarithm of M in units of $M_\odot$. This curve assumes $n = 1$, $\Omega = h = 1$ and a baryonic to total mass ratio of 0.07. The region where baryons can cool within a dynamical time lies below the cooling curves. Also shown are the positions of observed galaxies, groups and clusters of galaxies. The dashed line represents a possible evolutionary path for dissipating baryons.

Primack & Blumenthal 1983 based on CDM, cooling theory of Rees & Ostriker 1977, Silk 1977, Binney 1977 and baryonic dissipation within dark halos White & Rees 1978

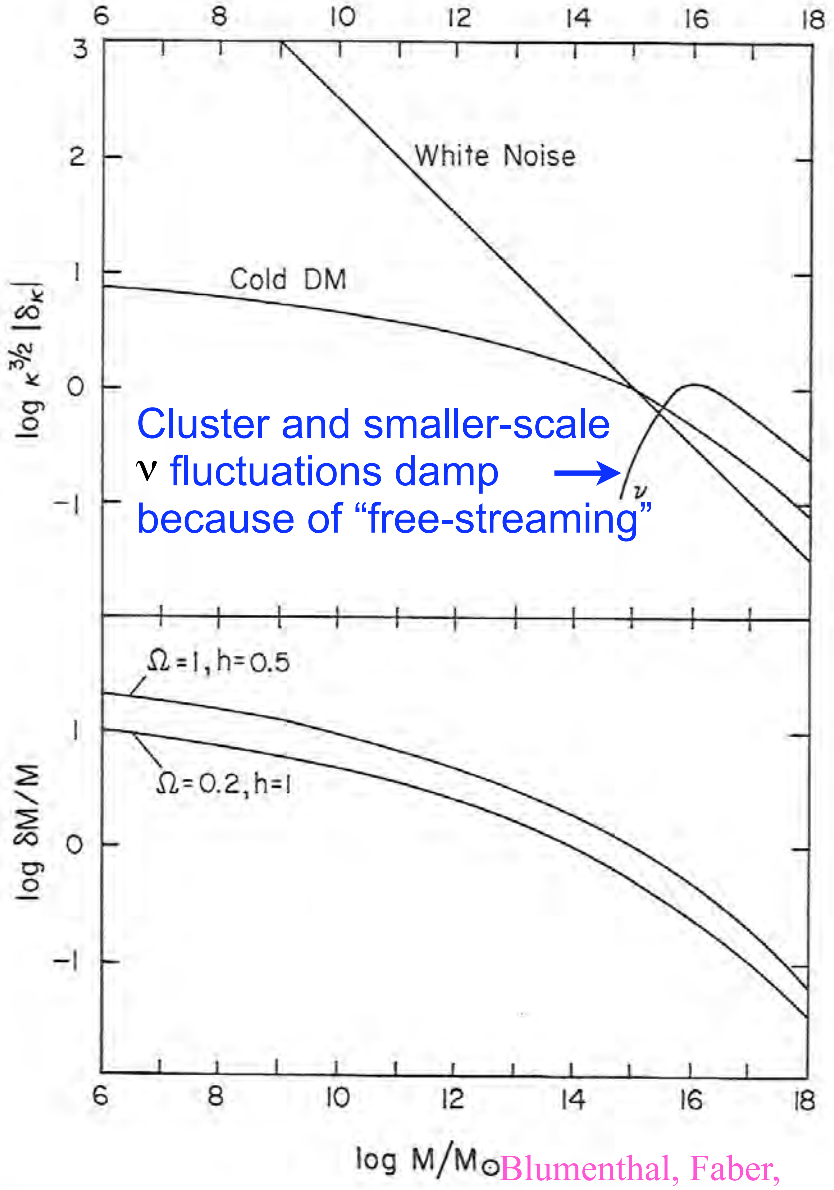
CDM Structure Formation: Linear Theory



Primack & Blumenthal 1983

Matter fluctuations that enter the horizon during the radiation dominated era, with masses less than about 10^{15} , grow only ∝ log ***a***, $M_\odot$ause they are not in the gravitationally dominant component. But matter fluctuations that enter the horizon in the matter-dominated era grow ∝ ***a***. This explains the characteristic shape of the CDM fluctuation spectrum, with

$\delta(k) \propto k^{-n/2-2} \log k$



Blumenthal, Faber, Primack, & Rees 1984

Formation of galaxies and large-scale structure with cold dark matter

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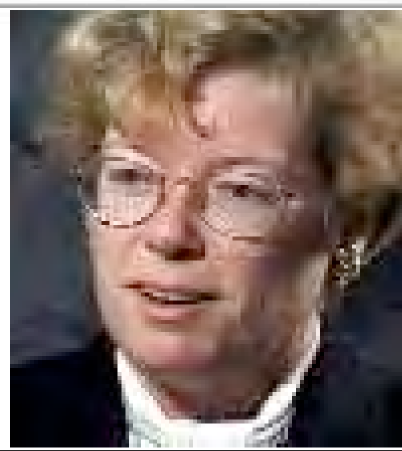
The dark matter that appears to be gravitationally dominant on all scales larger than galactic cores may consist of axions, stable photinos, or other collisionless particles whose velocity dispersion in the early Universe is so small that fluctuations of galactic size or larger are not damped by free streaming. An attractive feature of this cold dark matter hypothesis is its considerable predictive power: the post-recombination fluctuation spectrum is calculable, and it in turn governs the formation of galaxies and clusters. Good agreement with the data is obtained for a Zeldovich ($|\delta_k|^2 \propto k$) spectrum of primordial fluctuations.



Formation of galaxies and large-scale structure with cold dark matter

… We conclude that a straightforward interpretation of the evidence summarized above favours $\Omega \approx 0.2$ in the cold DM picture, but that $\Omega = 1$ is not implausible. …

Conclusions

We have shown that a Universe with ~10 times as much cold dark matter as baryonic matter provides a remarkably good fit to the observed Universe. This model predicts roughly the observed mass range of galaxies, the dissipational nature of galaxy collapse, and the observed Faber–Jackson and Tully–Fisher relations. It also gives dissipationless galactic haloes and clusters. In addition, it may also provide natural explanations for galaxy-environment correlations and for the differences in angular momenta between ellipticals and spiral galaxies. Finally, the cold DM picture seems reasonably consistent with the observed large-scale clustering, including superclusters and voids. In short, it seems to be the best model available and merits close scrutiny and testing.



Flatness of the Universe: Reconciling Theoretical Prejudices with Observational Data

1984 PRL 52, 2090

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Theoretical prejudices argue strongly for a flat Universe; however, observations do not support this view. We point out that this apparent conflict could be resolved if the mass density of the Universe today were dominated by (i) relativistic particles produced by the recent decay of a massive, relic particle species, or by (ii) a relic cosmological constant. Scenario (i) has several advantages in the context of galaxy formation, but must confront the problem of a young Universe.

1985 ApJ 292, 371

THE EVOLUTION OF LARGE-SCALE STRUCTURE IN A UNIVERSE DOMINATED BY COLD DARK MATTER

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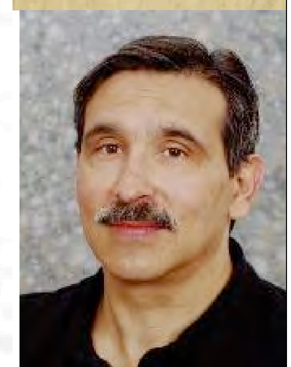
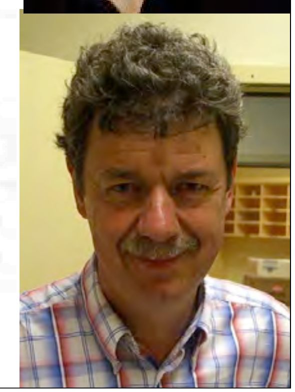
ABSTRACT

We present the results of numerical simulations of nonlinear gravitational clustering in universes dominated by weakly interacting, "cold" dark matter (e.g., axions or photinos). These studies employ a high resolution N-body code with periodic boundary conditions and 32,768 particles; they can accurately represent the theoretical initial conditions over a factor of 16 in length scale. We have followed the evolution of ensembles of models with $\Omega = 1$ and $\Omega < 1$ from the initial conditions predicted for a "constant curvature" primordial fluctuation spectrum. We also ran one model of a flat universe with a positive cosmological constant. Large filamentary structures, superclusters of clumps, and large low-density regions appear at certain times in all our simulations; however, we do not find large regions as extreme as the apparent void in Boötes. The evolution of the two-point correlation function, $\xi(r)$, is not self-similar; its effective power-law index becomes more negative with time. Models with $\Omega = 1$ are inconsistent with observation if galaxies are assumed to be unbiased tracers of the underlying mass distribution. The peculiar velocities of galaxies are predicted to be much too large. In addition, at times when the shape of $\xi(r)$ matches that observed, the amplitude of clustering is inferred to be too small for any acceptable value of the Hubble constant. Better agreement is obtained for $\Omega = 0.2$, but in both cases the rms relative peculiar velocity of particle pairs decreases markedly with pair separation, whereas the corresponding quantity for galaxies is observed to increase slowly. In all models the three-point correlation function ζ is found to fit the observed form, $\zeta \propto Q\xi^2$, but with Q depending weakly on scale. On small scales Q substantially exceeds its observed value. Consistent with this, the mass distribution of clusters is very broad, showing the presence of clumps with a very wide range in mass at any given time. The model with a positive cosmological constant closely resembles an open model with the same value of Ω. If galaxies are a random sampling of the mass distribution, none of our models is fully consistent with observation. An alternative hypothesis is that galaxies formed only at high peaks of the initial density field. The clustering properties of such "galaxies" are biased; they appear preferentially in high-density regions and so are more correlated than the overall mass distribution. Their two- and three-point correlation functions and their relative peculiar velocity distribution may be consistent with observation even in a universe with $\Omega = 1$. If this is an appropriate model for galaxy formation, it may be possible to reconcile a flat universe with most aspects of the observed galaxy distribution.



Some Later Highlights of CDM

1983 - Milgrom: modified Newtonian dynamics (MOND) as alternative to dark matter to explain flat galactic rotation curves

1986 - Blumenthal, Faber, Flores, & Primack: baryonic halo contraction

1986 - Large scale galaxy flows of ~600 km/s favor no bias

1989 - Holtzman: CMB and LSS predictions for 96 CDM variants

1992 - COBE: CMB fluctuations confirm CDM prediction $\Delta T/T \approx 10^{-5}$, favored variants are CHDM and ΛCDM

1996 - Seljak & Zaldarriaga: CMBfast code for P(k), CMB fluctuations

1997 - Nararro, Frenk, & White: universal radial structure of DM halos

1997 - Hipparchos distance scale, SN Ia dark energy ⇒ $t_0 \approx 14$ Gyr

2001 - Bullock et al.: concentration-mass-z relation for DM halos; universal angular momentum structure of DM halos

2002 - Wechsler et al.: halo concentration from mass assembly history

2003 - WMAP and Large Scale Structure surveys confirm ΛCDM predictions with high precision

WHAT IS THE DARK MATTER?

Lensing limits on MACHOs are getting stronger - skewness of high-z vs. low-z Type Ia SN disfavors $10^{-2} < M_{MACHO}/M_{SUN} < 10^8$ (Metcalf & Silk).

Prospects for DIRECT and INDIRECT detection of WIMPs are improving -- but what kind of WIMP? SUSY LSP, NLSP->LSP, KK? Or is the DM AXIONs?

WHAT IS THE DARK ENERGY??

We can use existing instruments to measure $w = P/\rho$ and see whether it changed in the past. But better telescopes (e.g. LSST, SNAP) will probably be required both on the ground and in space, according to the Dark Energy Task Force (Albrecht+). See the NAS Beyond Einstein report Sept 2007.

SUMMARY

- We now know the cosmic recipe. Most of the universe is invisible stuff called “nonbaryonic dark matter” (25%) and “dark energy” (70%). Everything that we can see makes up only about 1/2% of the cosmic density, and invisible atoms about 4%. The earth and its inhabitants are made of the rarest stuff of all: heavy elements (0.01%).
- The ΛCDM Cold Dark Matter Double Dark theory based on this appears to be able to account for all the large scale features of the observable universe, including the details of the heat radiation of the Big Bang and the large scale distribution of galaxies.
- Constantly improving data are repeatedly testing this theory. The main ingredients have been checked several different ways. There exist no convincing disagreements, as far as I can see. Possible problems on subgalactic scales may be due to the poorly understood physics of gas, stars, and massive black holes.
- But we still don’t know what the dark matter and dark energy are, nor really understand how galaxies form and evolve. There’s lots more work for us to do, much of which will be discussed in this course.