Insights from simulations into the Dark Matter problem

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Dynamic evidence on massive coronas of galaxies

A longstanding unresolved problem in galactic astronomy is the mass discrepancy observed in clusters of galaxies. The

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

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Received 1974 May 28; revised 1974 July 15

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
Currently, available observations strongly indicate that the radius to nearly 1 Mpc. This means that the total mass in galactic astronomy and clusters of galaxies. The P.J.E. Joseph Henry Laboratory Princeton University Observatory, Princeton, New Jersey

LOG $M_12$ (Rmpc)

LOG (Rmpc)

Timing

Virial

Binary

Tidal

Rotation

Ants Kaasik

Estonia, USSR

ENN SAAR
FORMATION OF GALAXIES AND CLUSTERS OF GALAXIES BY SELF-SIMILAR GRAVITATIONAL CONDENSATION*

WILLIAM H. PRESS AND PAUL SCHECHTER
California Institute of Technology

Received 1973 August 1

ABSTRACT

We consider an expanding Friedmann cosmology containing a "gas" of self-gravitating masses. The masses condense into aggregates which (when sufficiently bound) we identify as single particles of a larger mass. We propose that after this process has proceeded through several scales, the mass spectrum of condensations becomes "self-similar" and independent of the spectrum initially assumed. Some details of the self-similar distribution, and its evolution in time, can be calculated with the linear perturbation theory. Unlike other authors, we make no ad hoc assumptions about the spectrum of long-wavelength initial perturbations: the nonlinear $N$-body interactions of the mass points randomize their positions and generate a perturbation to all larger scales; this should fix the self-similar distribution almost uniquely. The results of numerical experiments on 1000 bodies are presented; these appear to show new nonlinear effects: condensations can "bootstrap" their way up in size faster than the linear theory predicts. Our self-similar model predicts relations between the masses and radii of galaxies and clusters of galaxies, as well as their mass spectra. We compare the predictions with available data, and find some rather striking agreements. If the model is to explain galaxies, then isothermal "seed" masses of $\sim 3 \times 10^7 M_\odot$ must have existed at recombination. To explain clusters of galaxies, the only necessary seeds are the galaxies themselves. The size of clusters determines, in principle, the deceleration parameter $q_0$; presently available data give only very broad limits, unfortunately.
FORMATION OF GALAXIES AND CLUSTERS OF GALAXIES BY SELF-SIMILAR GRAVITATIONAL CONDENSATION

WILLIAM H. PRESS AND PAUL SCHECHTER
California Institute of Technology

We consider the mass spectrum of a larger system assumed to be composed of single particles. The mass spectrum initially can be calculated in terms of expressions about the interactions of the particles; this should be done from the components of the mass spectra. We compare model predictions with observed data. The mass spectrum of a larger system is obtained from the spectra of its components.
cluster simulation 1977

N = 700
cluster simulation 1977

N = 700
ON THE FRAGMENTATION OF COSMIC GAS CLOUDS. I. THE FORMATION OF GALAXIES AND THE FIRST GENERATION OF STARS

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Cooling, dynamics and fragmentation of massive gas clouds: clues to the masses and radii of galaxies and clusters

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THE PHYSICS OF DISSIPATIONAL GALAXY FORMATION

JAMES BINNEY
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Received 1976 July 8; revised 1976 December 6
ON THE FRAGMENTATION OF COSMIC GAS CLOUDS. I. THE FORMATION OF GALAXIES AND THE FIRST GENERATION OF STARS

JAMES BINNEY
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Received 1976 July 8; revised 1976 December 6
Core condensation in heavy halos: a two-stage theory for galaxy formation and clustering

S. D. M. White and M. J. Rees Institute of Astronomy, Madingley Road, Cambridge

Received 1977 September 26

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

S. D. M. White and M. J. Rees Institute of Astronomy,
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Efstathiou & Eastwood 1981
AN ESTIMATE OF THE $v_e$ MASS FROM THE $\beta$-SPECTRUM OF TRITIUM IN THE VALINE MOLECULE

V.A. LUBIMOV, E.G. NOVIKOV, V.Z. NOZIK, E.F. TRETYAKOV and V.S. KOSIK

Institute of Theoretical and Experimental Physics, Moscow, USSR

Received 4 June 1980

The high energy part of the $\beta$-spectrum of tritium in the valine molecule ($C_5H_{11}NO_2$) was measured with a high precision by a toroidal $\beta$-spectrometer. The results give evidence for a non-zero electron antineutrino mass.

$$14 \leq M_\nu \leq 46 \text{ eV} \quad (99\% \text{ C.L.}) .$$

We consider this as an indication that the electron antineutrino has a non-zero mass. For the time being we do not see any effects which could have shifted essentially the above-mentioned limits. We continue the experimental study of the $\beta$-spectrum of tritium.

The authors would like to thank Yu. Galaktionov, S. Gerstein, Ya. Zeldovich, I. Kaplan, L. Okun, B. Pontecorvo, K. Ter-Martirosian and V. Shevchenko for useful discussions.
Klypin & Shandarin 1983

30 Mpc/h
PRIMEVAL ADIABATIC PERTURBATIONS: EFFECT OF MASSIVE NEUTRINOS

P. J. E. Peebles
Joseph Henry Laboratories, Physics Department, Princeton University
Received 1981 October 19; accepted 1982 February 2

ABSTRACT

The autocorrelation function of the mass distribution prior to galaxy formation is computed under the assumptions that the universe is dominated now by neutrinos with mass some tens of eV and that the primeval density fluctuations are adiabatic and linear, $\delta \rho / \rho < 1$. The computation includes the massive neutrinos, zero-mass weakly interacting particles, ordinary matter, and radiation. The distribution of massive neutrinos is computed as a function of the magnitude and direction of the momentum. Matter and radiation are treated as a single ideal fluid. The coherence length $\lambda_\gamma$ of the mass distribution prior to galaxy formation may be compared to the present clustering length of galaxies. In the conventional scenario the coherence length is uncomfortably large unless the universe is quite dense, $\Omega h \sim 1$ ($\Omega =$ density parameter, $H = 100h$ km s$^{-1}$ Mpc$^{-1}$), and the initial spectrum of density fluctuations is steep, $|\delta_k|^2 \propto k^n$, $n \geq 2$.

THE COLLISIONLESS DAMPING OF DENSITY FLUCTUATIONS IN AN EXPANDING UNIVERSE

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AND
A. S. Szalay
Astronomy Department, University of California, Berkeley; and Astronomy and Astrophysics Center, The University of Chicago
Received 1982 July 26; accepted 1983 February 10

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.
PRIMEVAL ADIABATIC PERTURBATIONS: EFFECT OF MASSIVE NEUTRINOS

P. J. E. Peebles
Joseph Henry Laboratories, Physics Department, Princeton University

The addition of massive particles to the primordial density perturbations is quite significant. The rate of perturbation growth is strongly dependent on the energy density of the massless neutrinos and the early composition of the universe. (Adapted from Bond & Szalay 1983)

The universe is seen to be described by a series of scale-invariant scalar perturbations in the metric and in the density of photons, neutrinos, and baryons. The normalizations for the early adiabatic fluctuations are constrained by super-horizon behavior, fluctuations at recombination, and the cosmological principle. The density contrast at recombination is measured through the fluctuations in the angular distribution of the cosmic microwave background.}

The energy density of the neutrinos increases with growing mass and temperature, slowing the rate of gravitational collapse of the early universe. The energy density of the neutrinos is much less than that of the baryons and photons, with the neutrinos comprising 15% of the mass density.

The energy density of the massive neutrinos is determined by their mass and temperature, with the neutrinos having the largest energy density. The adiabatic perturbations are strongly dependent on the energy density of the neutrinos, with the dark matter component comprising less than 90% of the energy density.
PRIMEVAL ADIABATIC PERTURBATIONS: EFFECT OF MASSIVE NEUTRINOS

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CLUSTERING IN A NEUTRINO-DOMINATED UNIVERSE

SIMON D. M. WHITE,1, 2 CARLOS S. FRENK,1 AND MARC DAVIS1, 3
University of California, Berkeley
Received 1983 June 17; accepted 1983 July 1

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.

The evolution of the universe beyond the last scattering surface is also determined by the early adiabatic perturbations in the metric and in the density of photons, neutrinos, and cosmic relic plasma.
Excluding massive neutrinos as the Dark Matter

CDM1  v1  CfA

CDM2  v2  v3
THE EVOLUTION OF LARGE-SCALE STRUCTURE IN A UNIVERSE DOMINATED BY COLD DARK MATTER

MARC DAVIS,1,2 GEORGE Efstathiou,1,3 CARLOS S. FRENK,1,4 AND SIMON D. M. WHITE1,5

Received 1984 August 20; accepted 1984 November 30

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.

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.

| TABLE 1 |

**MODEL PARAMETERS**

<table>
<thead>
<tr>
<th>Model</th>
<th>( L ) (l)</th>
<th>( \eta ) (l)</th>
<th>( M_T ) (m)</th>
<th>( m_p ) (10^{-4}m)</th>
<th>( \Omega_i )</th>
<th>( \Omega_m )</th>
<th>( \Omega_\Lambda )</th>
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</thead>
<tbody>
<tr>
<td>EdS1–EdS5</td>
<td>32.5</td>
<td>0.15</td>
<td>9.4</td>
<td>2.9</td>
<td>1</td>
<td>1</td>
<td>0</td>
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<tr>
<td>EdS6–EdS8</td>
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<td>0.30</td>
<td>75</td>
<td>23</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>L1</td>
<td>32.5</td>
<td>0.15</td>
<td>9.4</td>
<td>2.9</td>
<td>0.796</td>
<td>0.2</td>
<td>0.8</td>
</tr>
<tr>
<td>O1–O4</td>
<td>32.5</td>
<td>0.15</td>
<td>9.4</td>
<td>2.9</td>
<td>0.446</td>
<td>0.2</td>
<td>0</td>
</tr>
</tbody>
</table>
Davis et al 1985
Low density universes
\( \Omega = 0.2 \)
$z = 0$  
Dark Matter
$z = 0$ Galaxy Light
The average dark matter density of a dark halo depends on distance from halo centre in a very similar way in halos of all masses at all times in all cosmologies -- a universal profile shape --

\[
\rho(r)/\rho_{\text{crit}} \approx \delta \frac{\rho_s}{r(1 + r/r_s)^2}
\]

More massive halos and halos that form earlier have higher densities (bigger \( \delta \))

\[
N_{200} \sim 7 \times 10^3
\]
Density profiles of dark matter halos

The average dark matter density of a dark halo depends on distance from halo centre in a very similar way in halos of all masses at all times in all cosmologies -- a universal profile shape --

\[ \rho(r)/\rho_{\text{crit}} \propto \left(1 + r/r_s\right)^{-2} \]

More massive halos and halos that form earlier have higher densities (bigger \( \delta \))

Navarro, Frenk & White 1996
A high-resolution Milky Way halo

Navarro et al 2006

\[ N_{200} \sim 3 \times 10^7 \]
Comparison of lensing strength measured around real galaxy clusters to that predicted by simulations of structure formation

Okabe et al 2009
Dark Matter around the Milky Way?
The significance of halo substructure

WHERE ARE THE MISSING GALACTIC SATELLITES?
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DARK MATTER SUBSTRUCTURE WITHIN GALACTIC HALOS
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Dark Matter as seen by Fermi?
Cold Dark Matter (axion?)  Warm Dark Matter (sterile $\nu$?)

Milky Way halos?

Lovell et al 2012
...are the fundamental nonlinear units of cosmic structure
50% of all mass is in halos with $M_h > 10^{10} M_\odot$
60% of all mass is in halos with $M_h > 10^{8} M_\odot$

...are triaxial systems with near-universal density structure
\[ \frac{\rho(r)}{\rho_{\text{crit}}} \approx \delta \frac{r_s}{r} \left(1 + \frac{r}{r_s}\right)^2 \]

...have many subhalos containing $\sim 10\%$ of their mass and
\[ dN/dM \sim M^{-1.9} \]

...are the sites where galaxies form through the dissipative condensation of baryonic gas

Their properties (abundance, structure, evolution, clustering) have been predicted entirely by numerical simulation
Near-future simulation input to DM studies

Small-scale structure

Nature of the DM
--- warm vs cold
--- self-interacting vs non-interacting
--- interaction with DE?

Very small-scale structure

Annihilation signal?
Direct detection signal

“Precision” large-scale structure

Input to lensing studies of cosmology
Effects of interaction with baryonic structure growth
Moore's Law for Cosmological N-body Simulations

Computers double their speed every 18 months

A naive N-body force calculation needs $N^2$ op's

Simulations double their size every 16.5 months

Progress has been roughly equally due to hardware and to improved algorithms
Moore's Law for Cosmological N-body Simulations

Computers double their speed every 18 months

A naive N-body force calculation needs $N^2$ op's

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Numerical Simulation in Astrophysics/Cosmology

Computing power is the fastest growing aspect of astrophysics.

Simulations are now the primary tool for confronting observed objects with theoretical ideas about their nature and origin.

Studies of cosmic structure formation are simplified by the fact that the initial conditions are observed to be simple, precise, robust and testable predictions for nonlinear structures when the underlying physics is also simple (e.g. halo structure for comparison with lensing data).

High quality simulations complement new observations in most proposed tests of the current cosmological paradigm.

For many problems, we are currently limited by (astro)physical understanding, not by computer power.