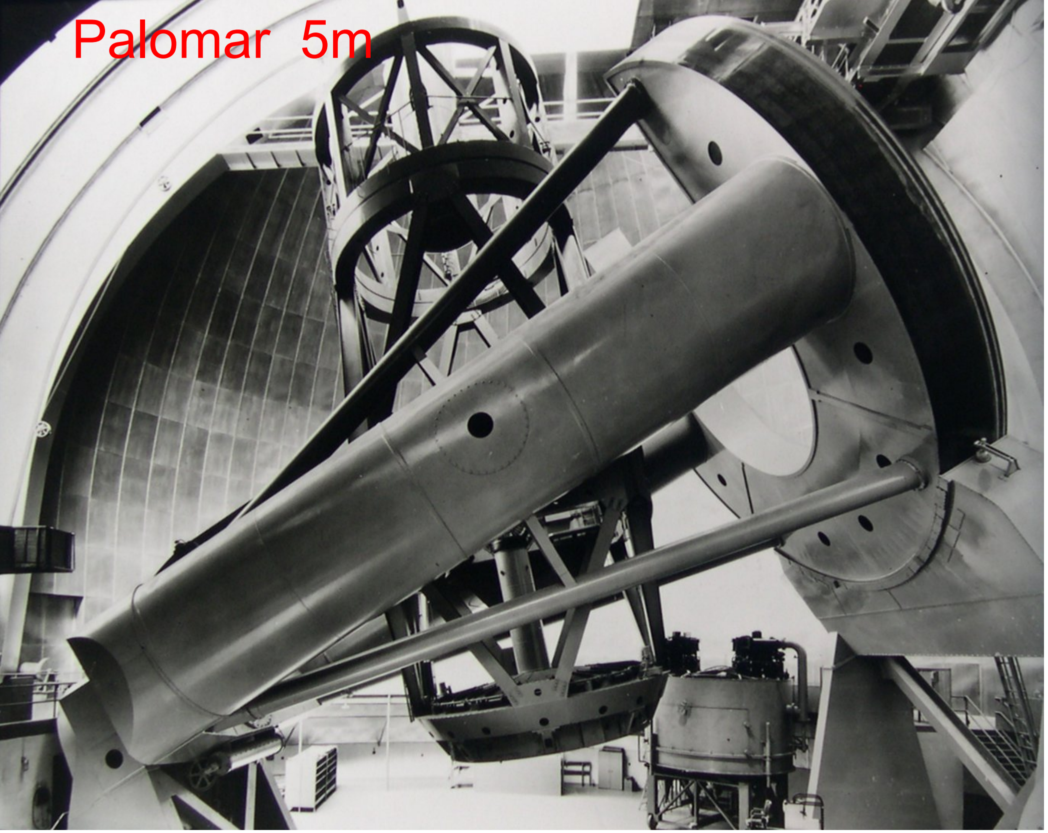
Insights from simulations into the Dark Matter problem

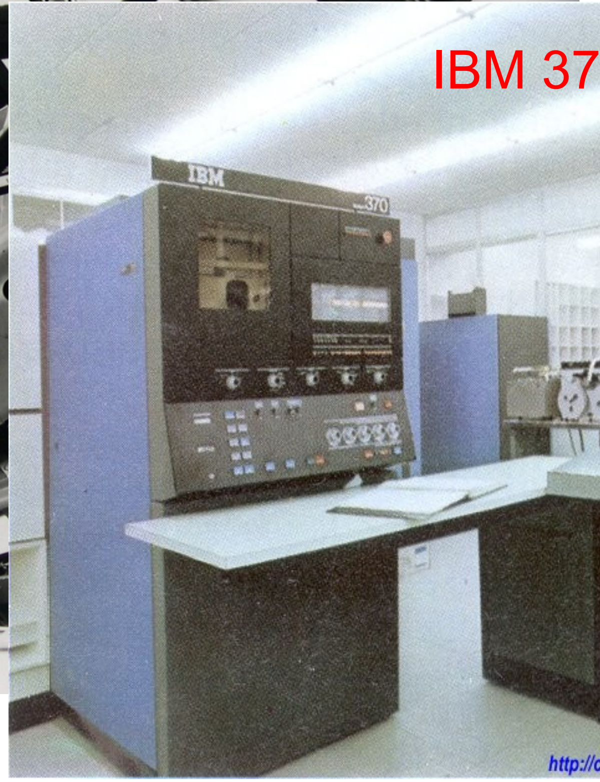
Simon White
Max Planck Institute for Astrophysics


Palomar 5m


Palomar 5m


IBM 370
IBM
370
http://compuclasico.homelinux.net


Palomar 5m


IBM 370


Palomar 5m
IBM 370
IBM
370
HYDROSTATICS (METRIC)
INPUT CREDIBILITY (METRIC)
BONJEANS
STATICAL STABILITY

The Coma Galaxy Cluster

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

W. Struve Astrophysical Observatory, 202444 Tôravere, Estonia, USSR

Received April 10, 1974.

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

J. P. OSTRIKER
Princeton University Observatory

P. J. E. PEEBLES
Joseph Henry Laboratories, Princeton University

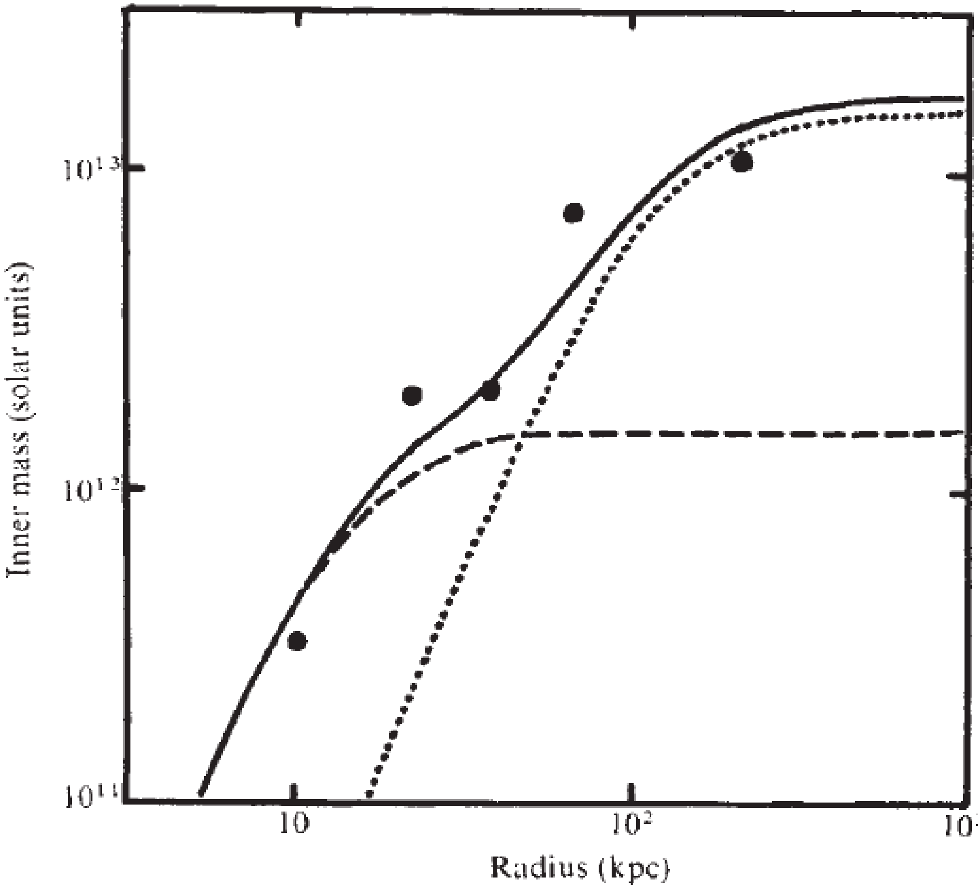
AND

A. YAHIL
Princeton University Observatory; and Department of Physics, Tel-Aviv University

Received 1974 May 28; revised 1974 July 15

ABSTRACT

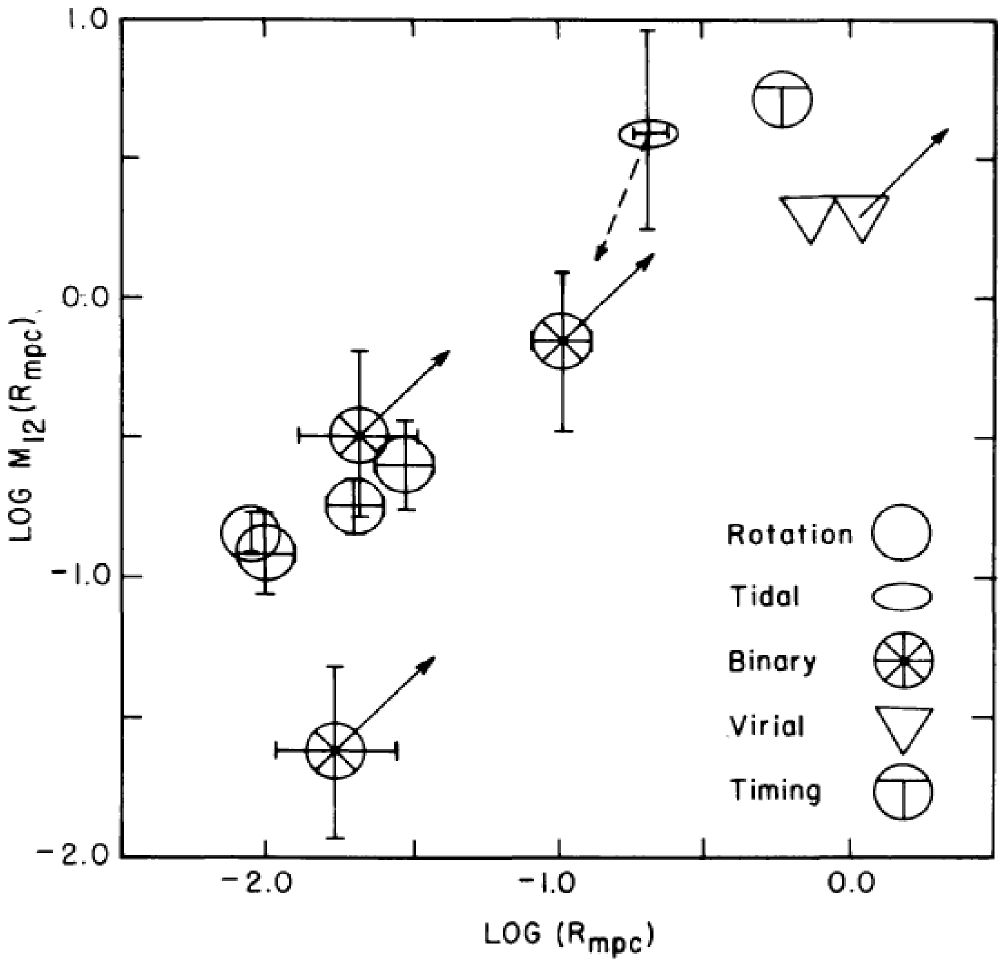
Currently available observations strongly indicate that the mass of spiral galaxies increases almost linearly with radius to nearly 1 Mpc. This means that the total mass per giant spiral is of the order of $10^{12}\ M_\odot$, and that the ratio



Jaan Einasto
Ants Kaasik
Enn Saar

in galactic astronomy
usters of galaxies. The

ysical Observatory,
Estonia, USSR



Princeton Unive

P. J. E.
Joseph Henry Laborato
A
A. Y
Princeton University Observatory; and D
Received 1974 May 2

ABST

Currently available observations strongly indicate tha
radius to nearly 1 Mpc. This means that the total mass p

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

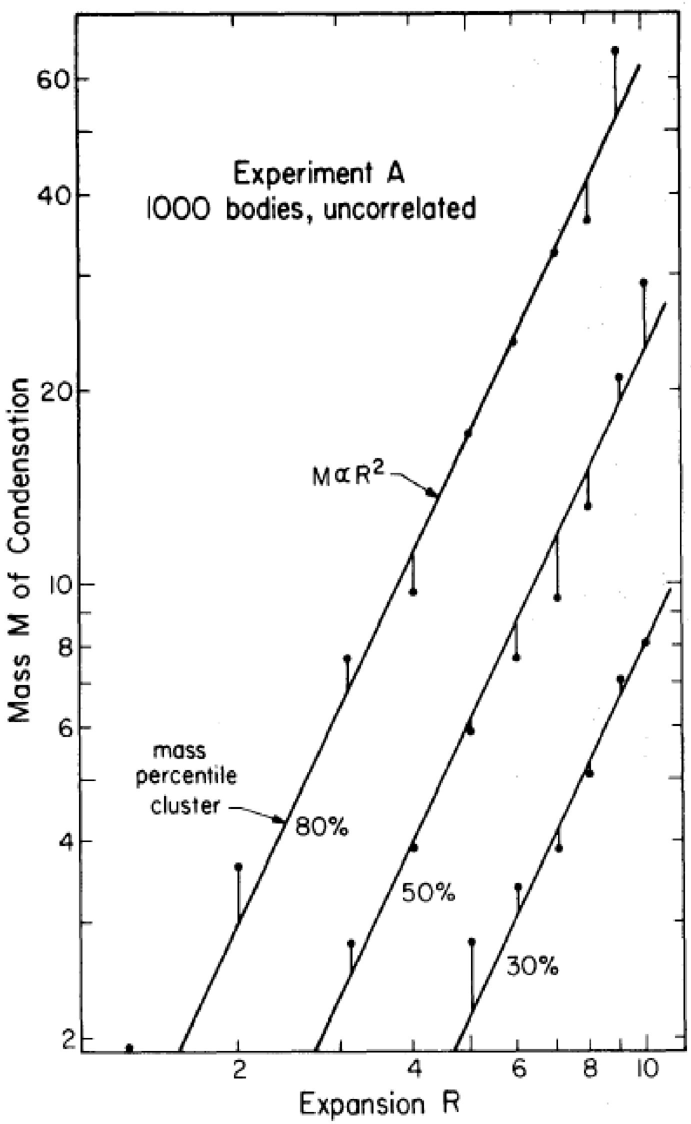
William H. Press and Paul Schechter
California Institute of Technology
Received 1973 August 1

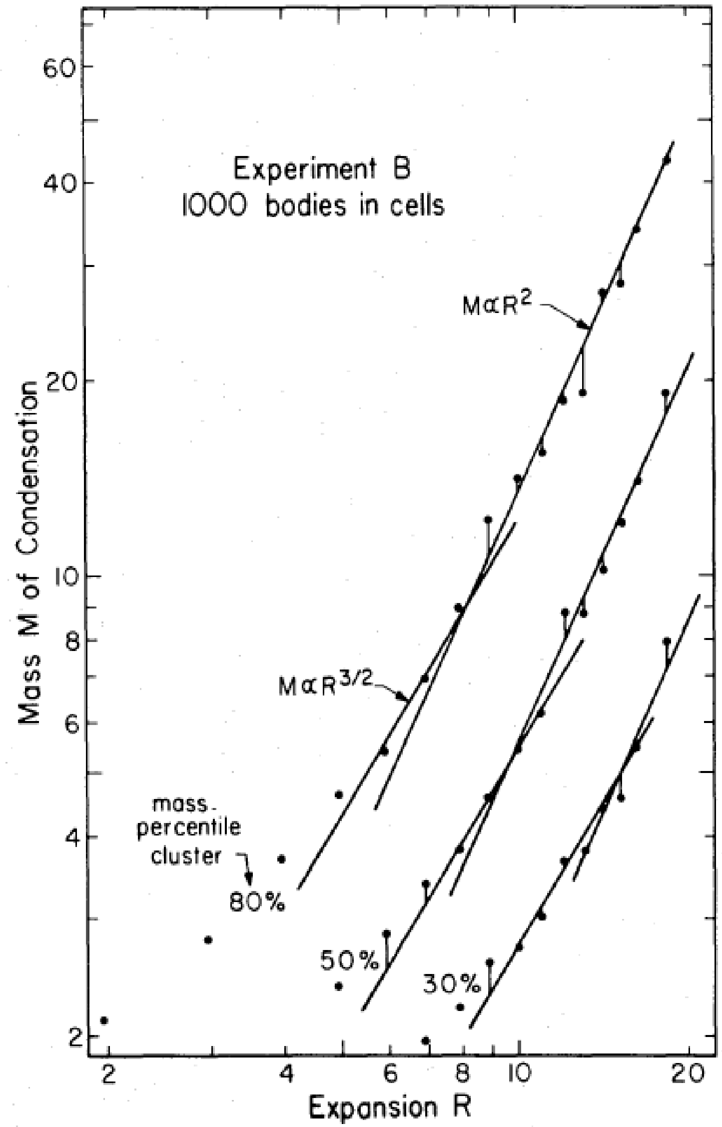
ABSTRACT

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.

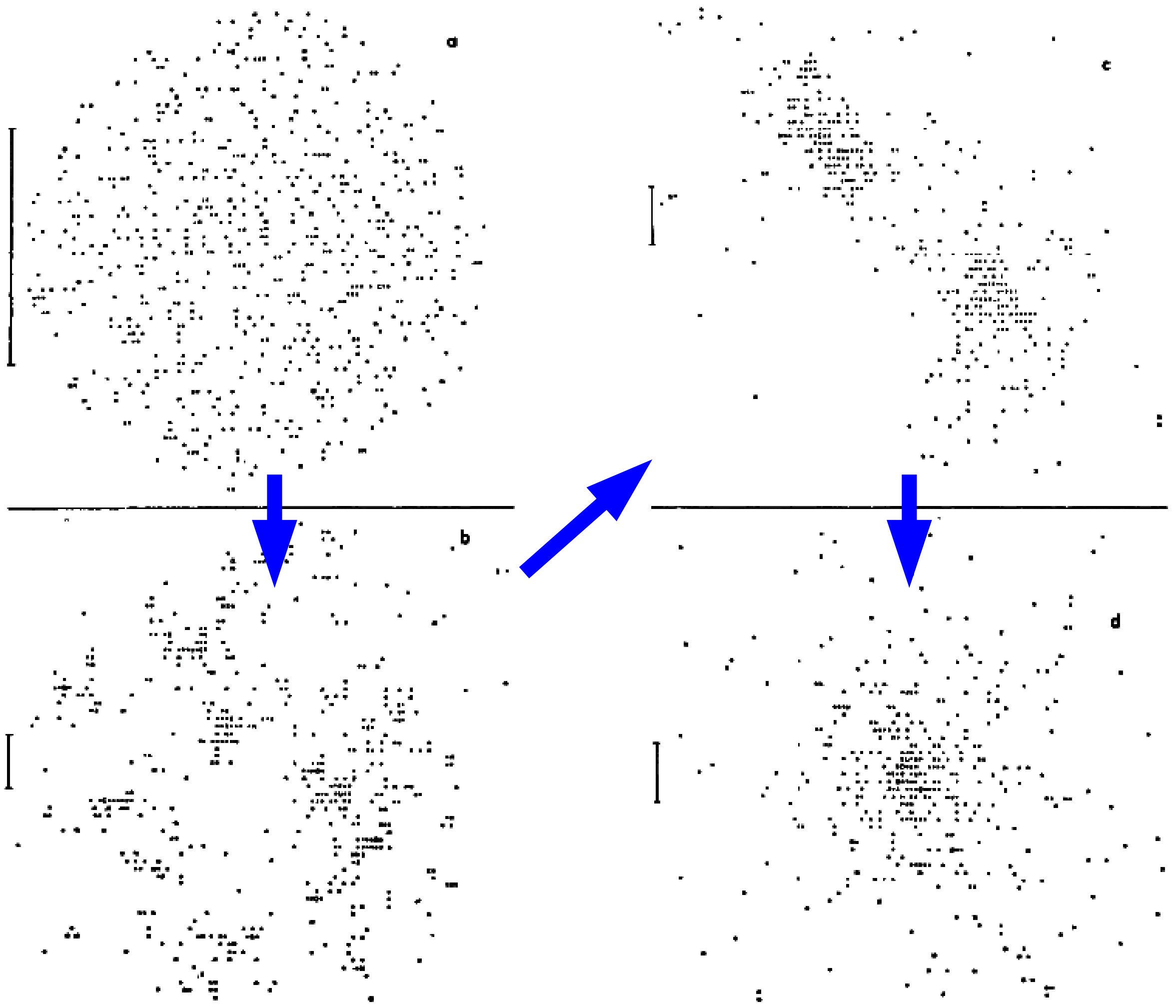
FORMATION OF GALAXIES AND CLUSTERS OF GALAXIES BY SELF-SIMILAR GRAVITATIONAL CONDENSATION*

WILLIAM H. PRESS AND PAUL SCHECHTER
California Institute of Technology



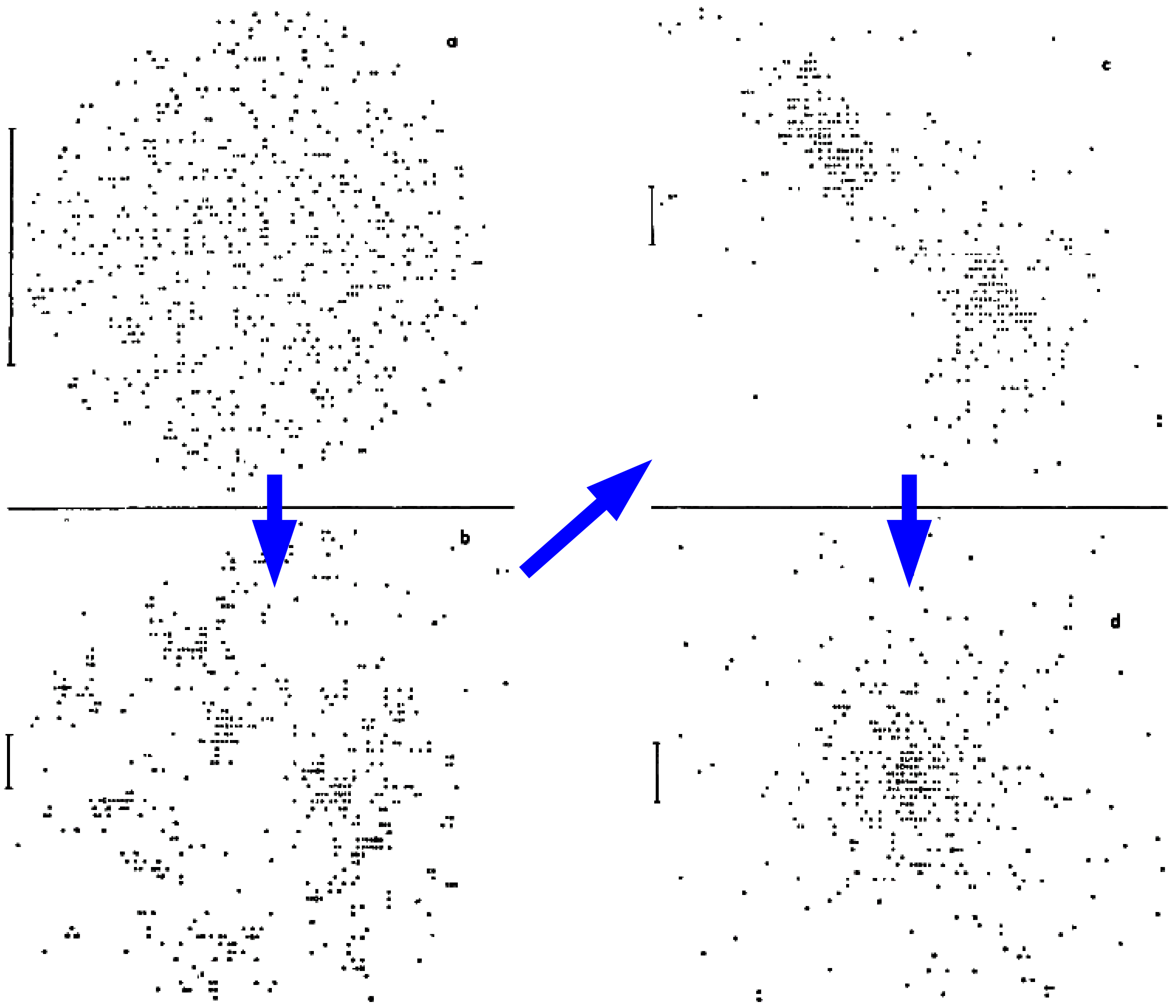


We con vitating masses.
The masse single particles
of a large scales, the mass
spectrum ctrum initially
assumed. n be calculated
with the l mptions about
the spectr ractions of the
mass poin les; this should
fix the se ments on 1000
bodies are n “bootstrap”
their way redicts relations
between t ass spectra. We
compare eements. If the
model is st have existed
at recomb galaxies them-
selves. Th sently available
data give



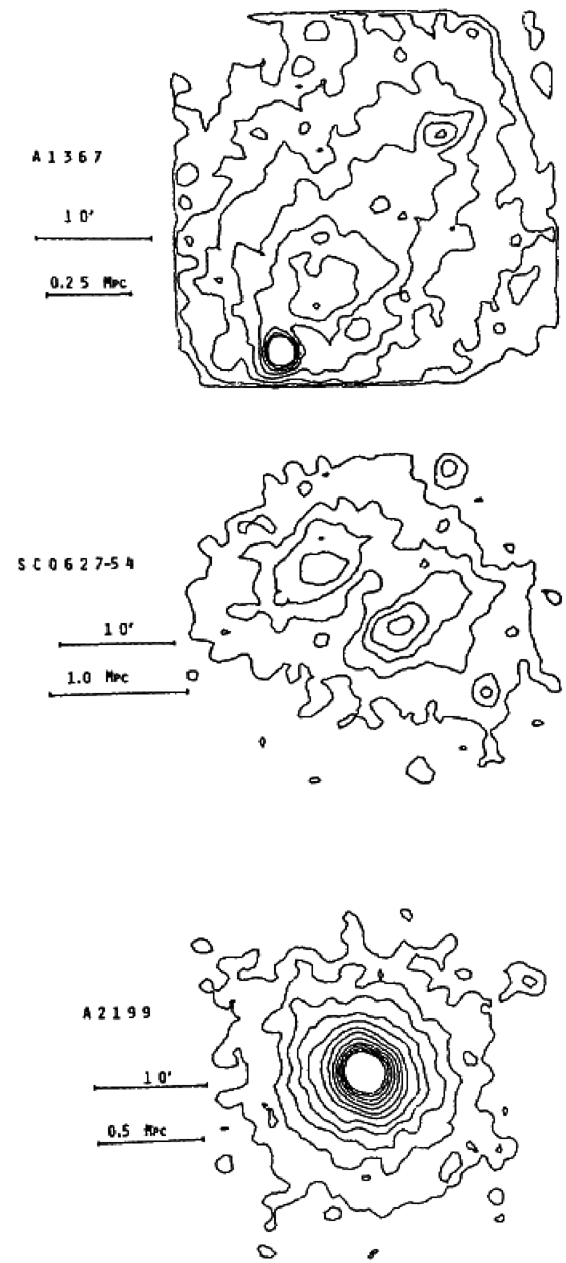
cluster simulation 1977

N = 700



cluster simulation 1977

N = 700



cluster images 1980

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

JOSEPH SILK *
Institute for Advanced Study, Princeton, New Jersey 08540
Received 1976 April 5; revised 1976 June 22

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

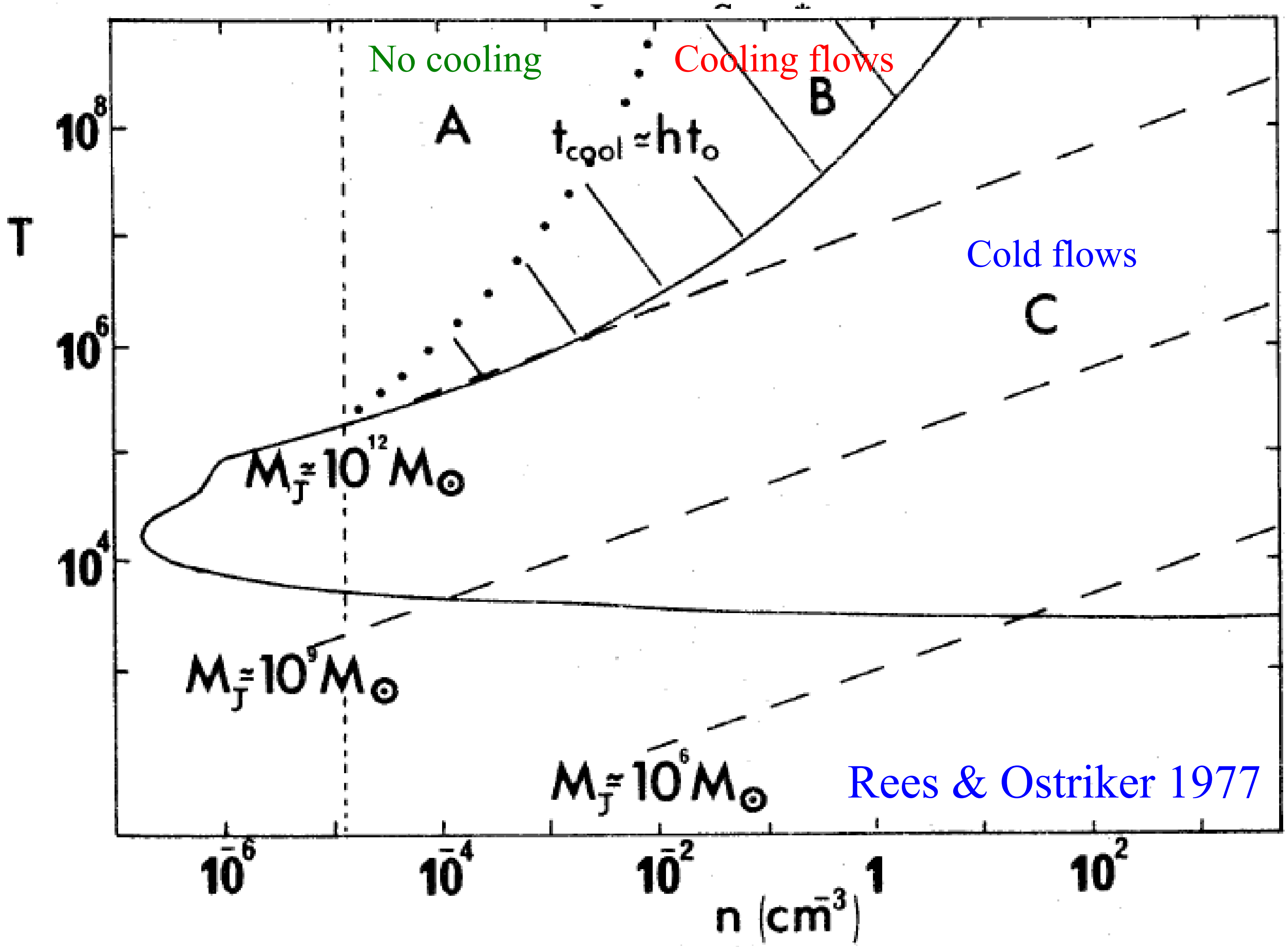
M. J. Rees *Institute of Astronomy, Madingley Road, Cambridge CB3 0HA*
J. P. Ostriker *Department of Astronomy, Princeton University, Princeton, New Jersey 08540, USA*

Received 1976 November 5; in original form 1976 July 7

THE PHYSICS OF DISSIPATIONAL GALAXY FORMATION

JAMES BINNEY
Princeton University Observatory
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
Princeton University Observatory

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

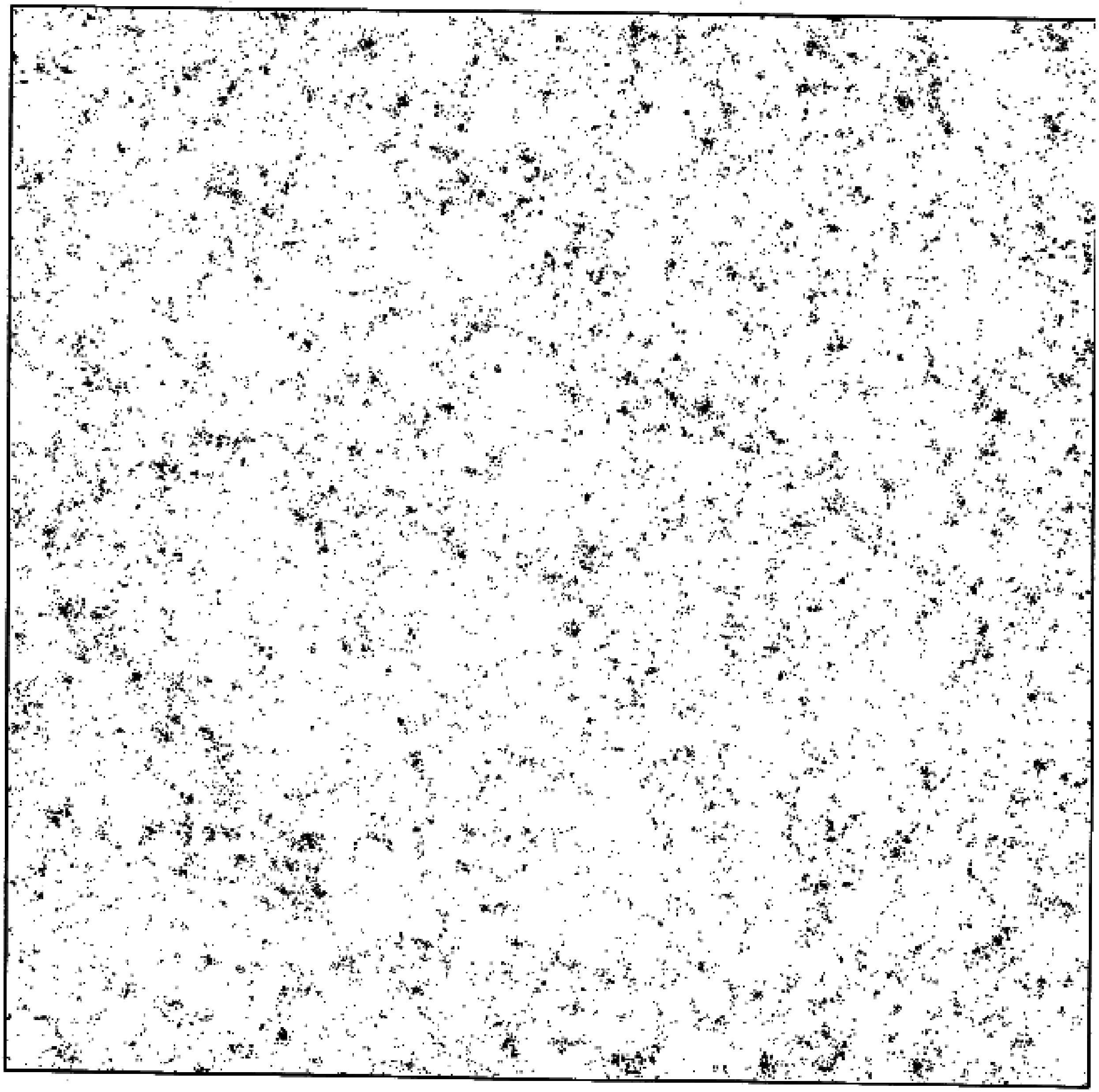
Summary. We suggest that most of the material in the Universe condensed at an early epoch into small 'dark' objects. Irrespective of their nature, these objects must subsequently have undergone hierarchical clustering, whose present scale we infer from the large-scale distribution of galaxies. As each 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.

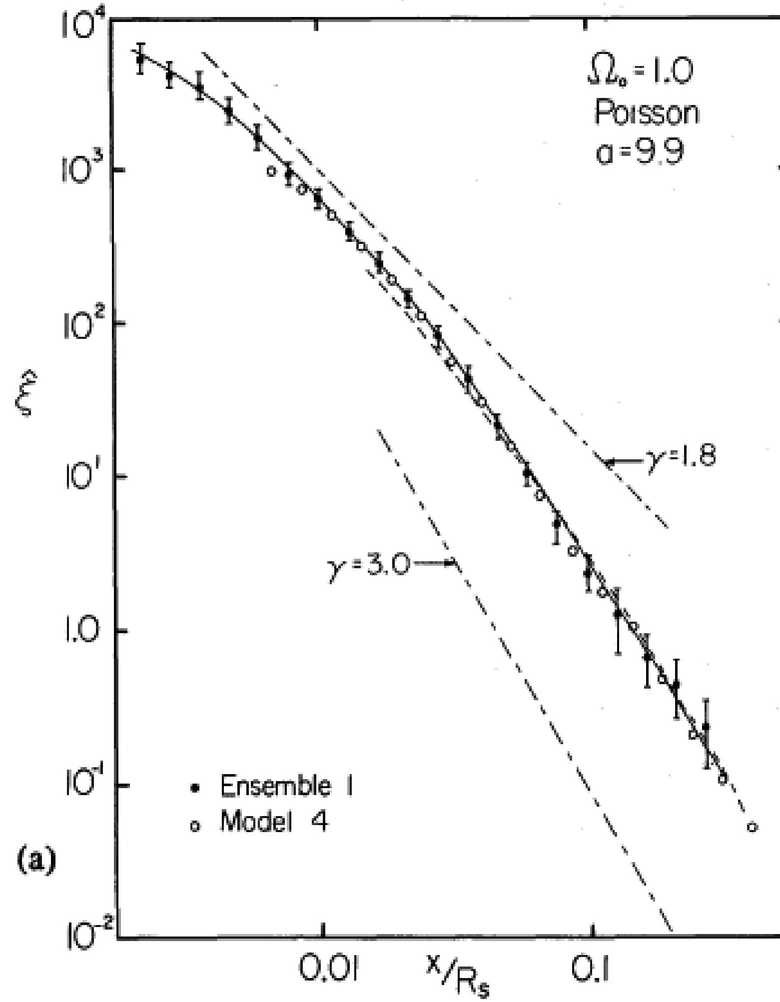
Core condensation in heavy halos: a two-stage theory for galaxy formation and clustering

S. D. M. White and M. J. Rees *Institute of Astronomy, 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.





Efstathiou & Eastwood 1981

AN ESTIMATE OF THE ν_e MASS FROM THE β-SPECTRUM OF TRITIUM IN THE VALINE MOLECULE

V.A. LUBIMOV, E.G. NOVIKOV, V.Z. NOZIK, E.F. TRETYAKOV and V.S. KOSIK [1]
Institute of Theoretical and Experimental Physics, Moscow, USSR

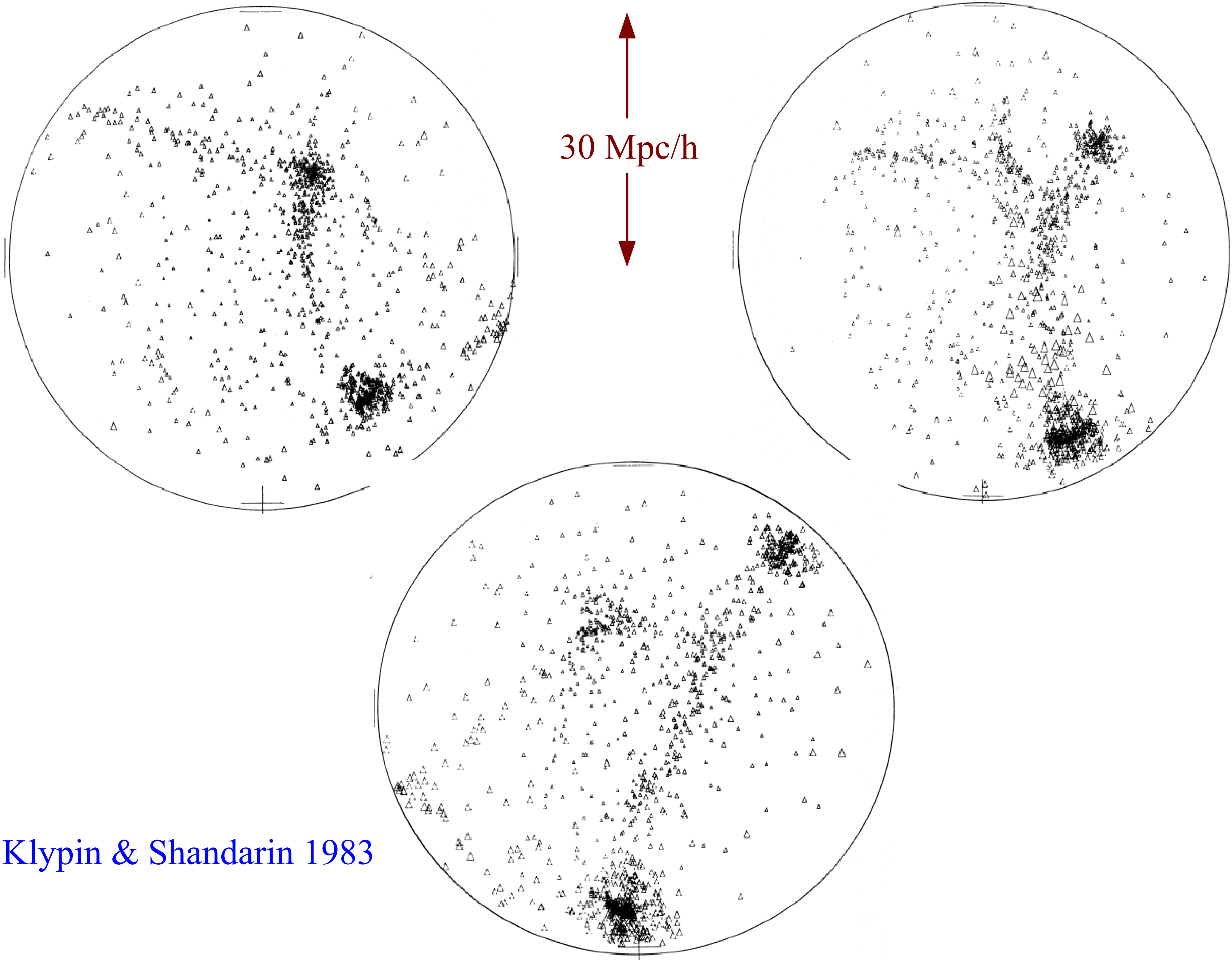
Received 4 June 1980

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

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

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 β-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

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 λ_J 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, $|\delta_k|^2 \propto k^n$, $n \gtrsim 2$.

THE COLLISIONLESS DAMPING OF DENSITY FLUCTUATIONS IN AN EXPANDING UNIVERSE

J. R. BOND
Institute of Theoretical Physics, Department of Physics, Stanford University

AND

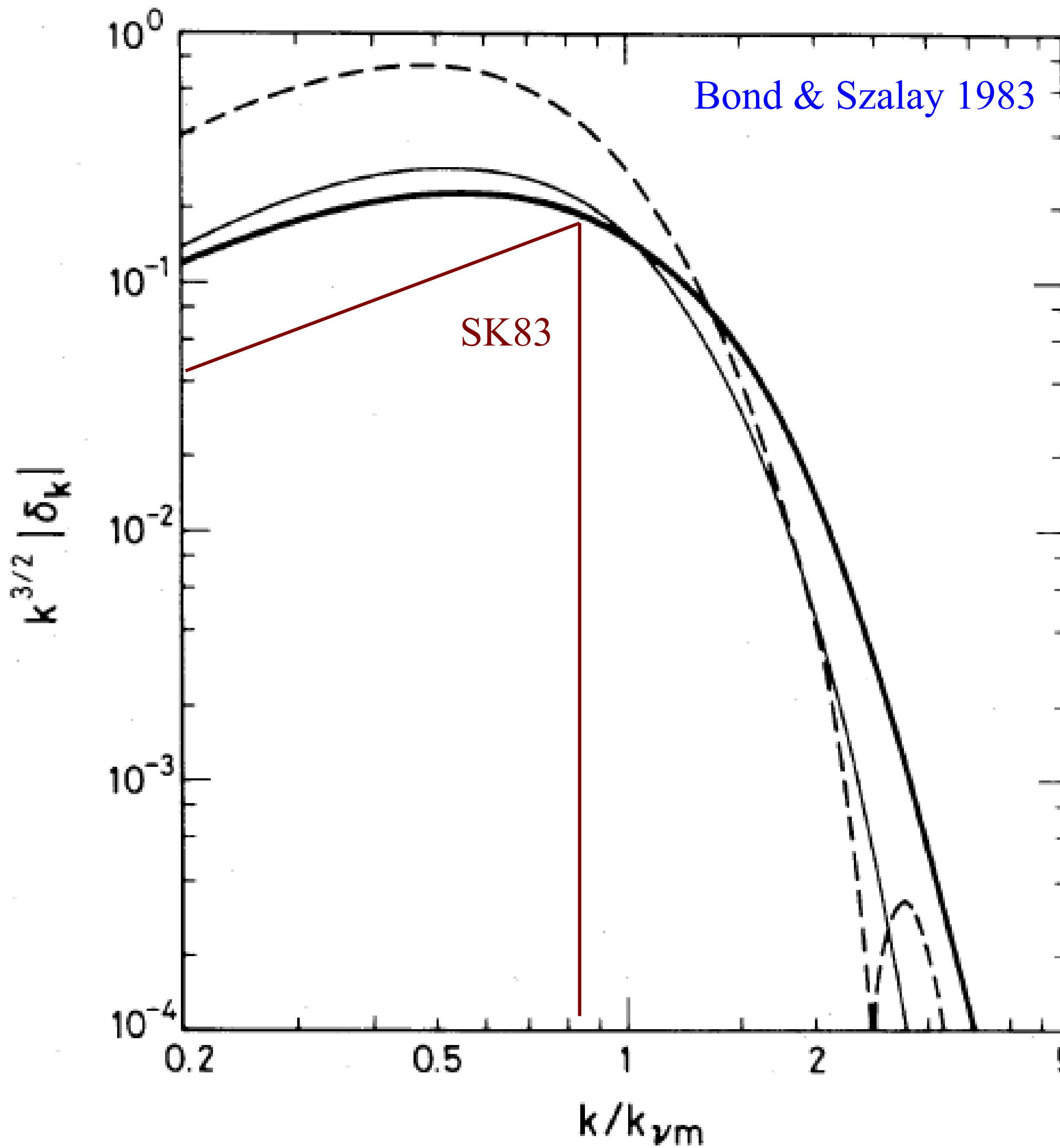
A. S. SZALAY
Astronomy Department, University of California, Berkeley; and Astronomy and Astrophysics Center, The University of Chicago
Received 1982 July 26; accepted 1983 February 10

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 a … ted under
the assu … and that
the prir … cludes the
massive … tion. The
distribu … on of the
momen … λ_J of the
mass di … length of
galaxies … universe
is quite … ectrum of
density …

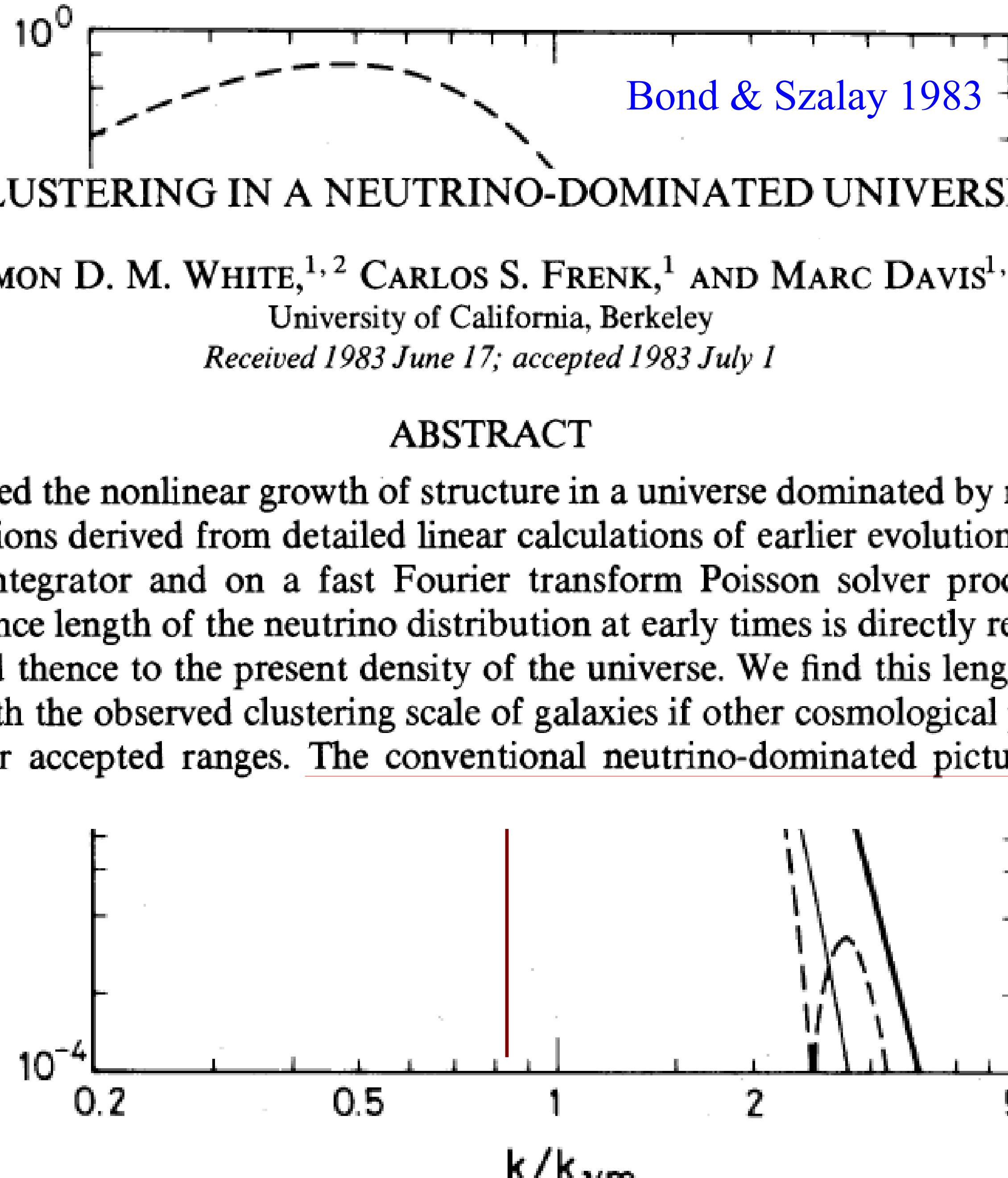
… er,

The t … the early
universe … tic rather
than of … adiabatic)
fluctuat … ations for
scalar p… less relics.

PRIMEVAL ADIABATIC PERTURBATIONS: EFFECT OF MASSIVE NEUTRINOS

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

The a … ted under



CLUSTERING IN A NEUTRINO-DOMINATED UNIVERSE

Simon D. M. White,[1,2] Carlos S. Frenk,[1] and Marc Davis[1,3]
University of California, Berkeley
Received 1983 June 17; accepted 1983 July 1

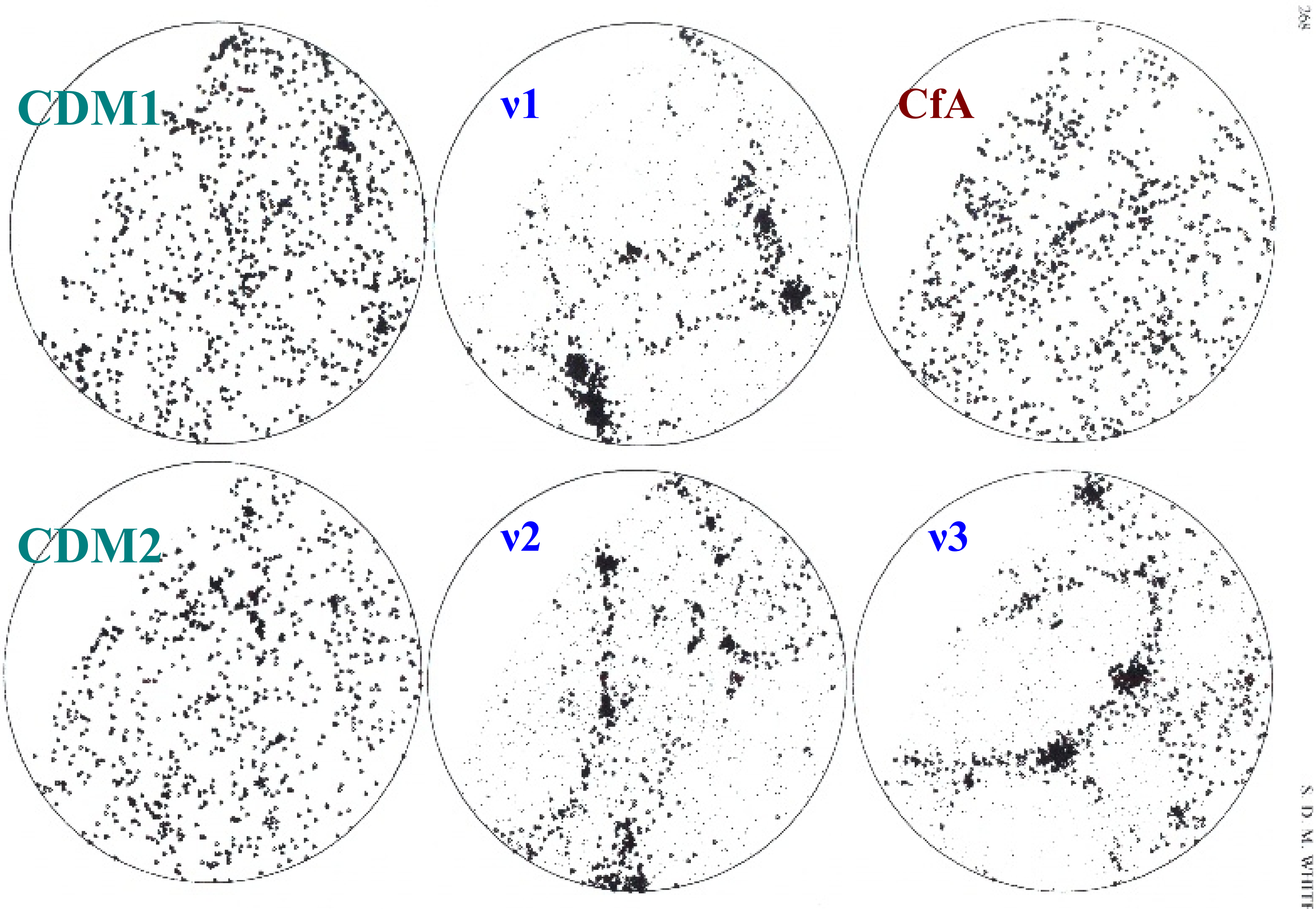
ABSTRACT

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.

…er,

The b … the early universe … atic rather than of … adiabatic) fluctuat… ations for scalar perturbations in the metric and in the density of photons, neutrinos, and collisionless relics.

Excluding massive neutrinos as the Dark Matter



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. WHITE[1,5]

Received 1984 August 20; accepted 1984 November 30

ABSTRACT

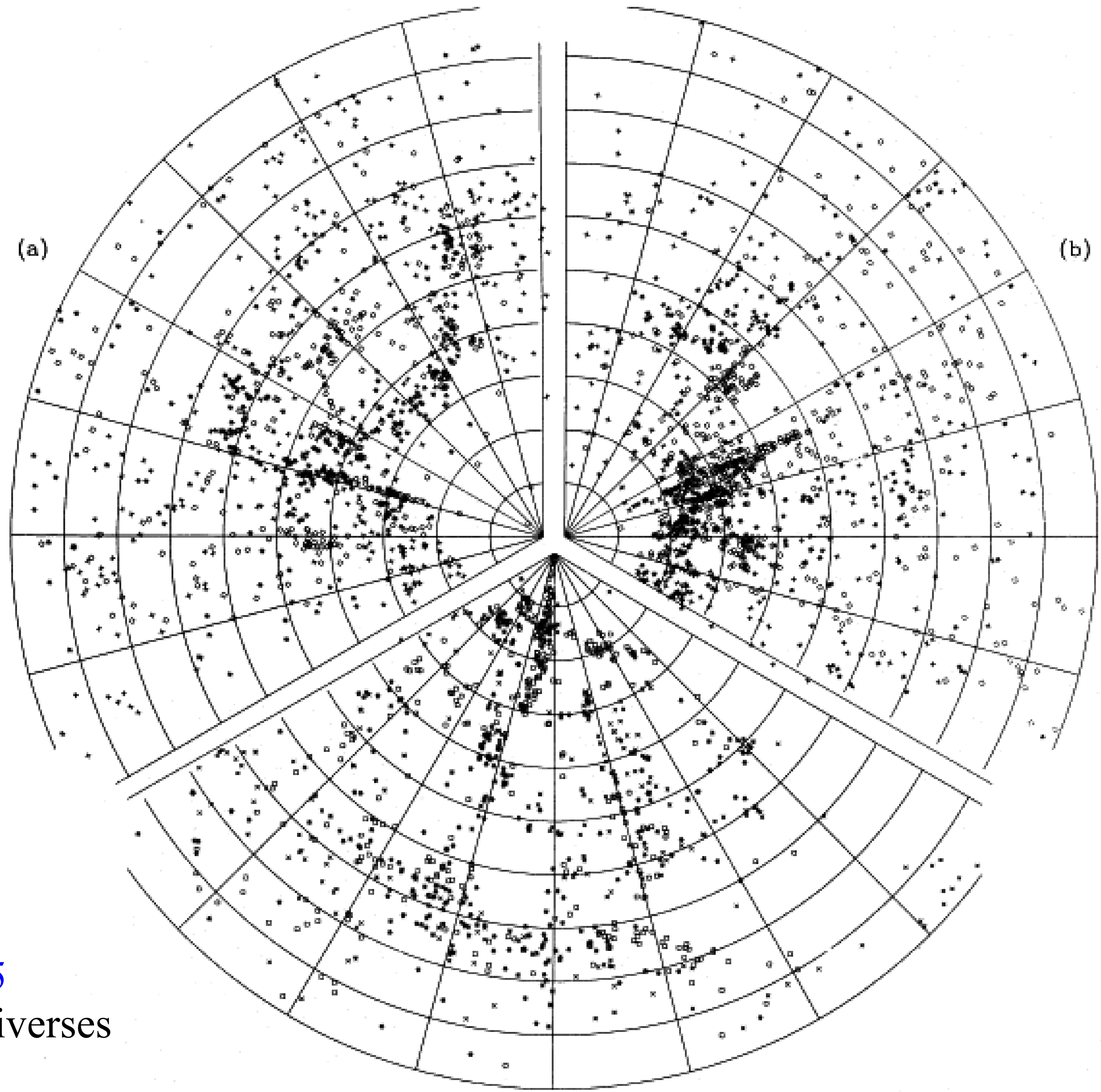
We present the results of numerical simulations of nonlinear gravitational clustering in universes dominated by weakly interacting, "cold" dark matter (e.g., axions or photinos). These studies employ a high resolution N-body code with periodic boundary conditions and 32,768 particles; they can accurately 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.

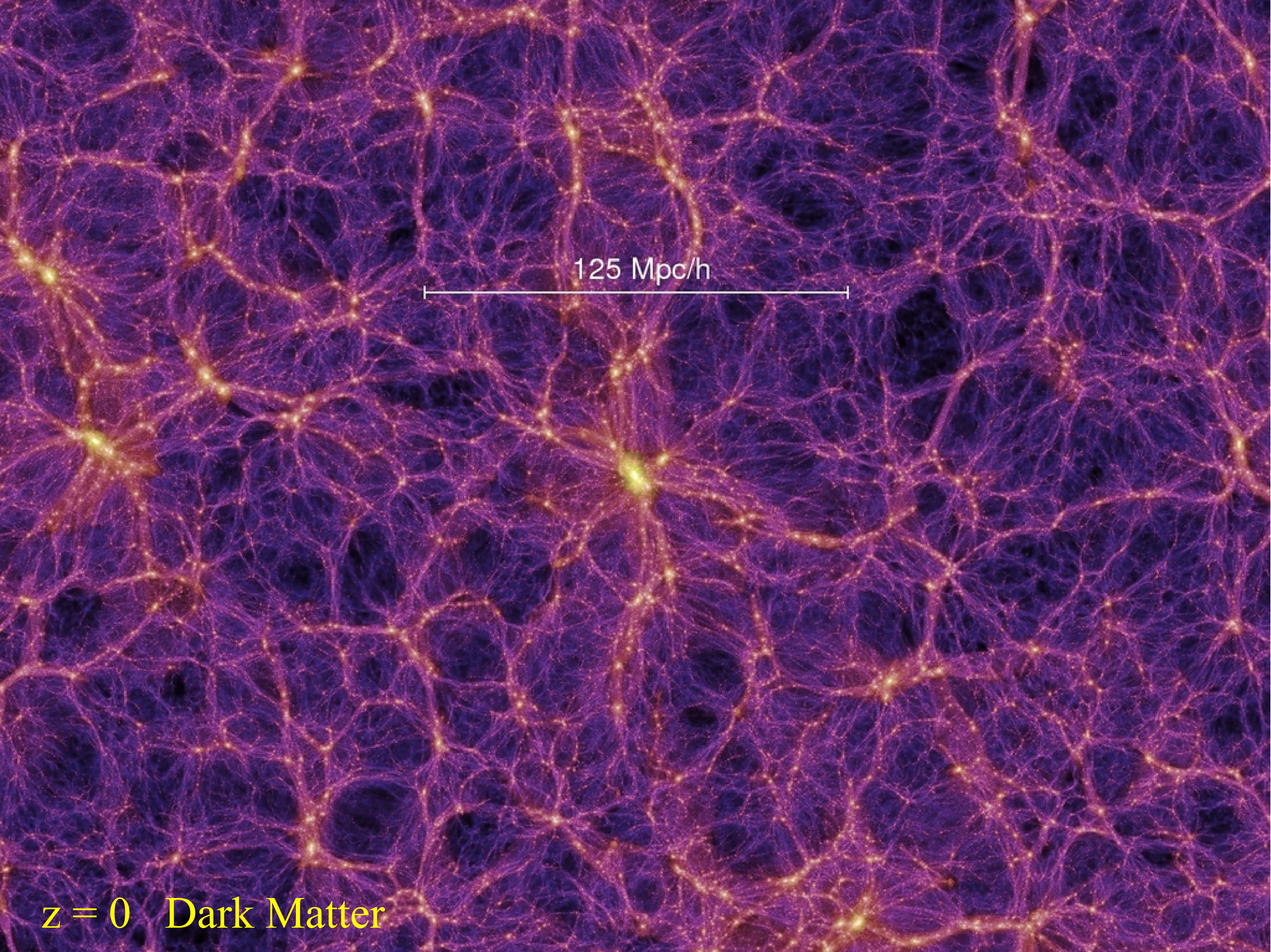
TABLE 1

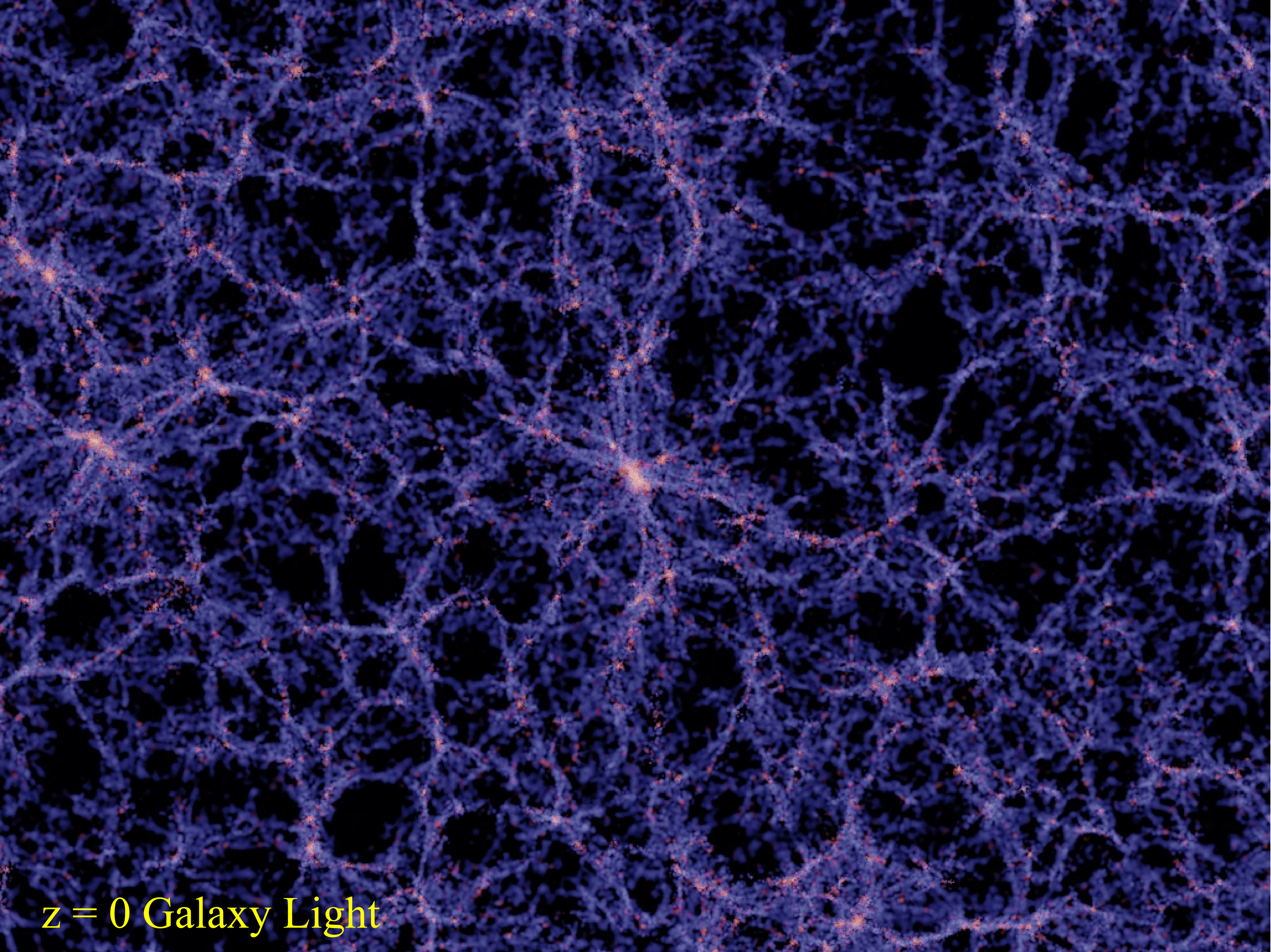
MODEL PARAMETERS

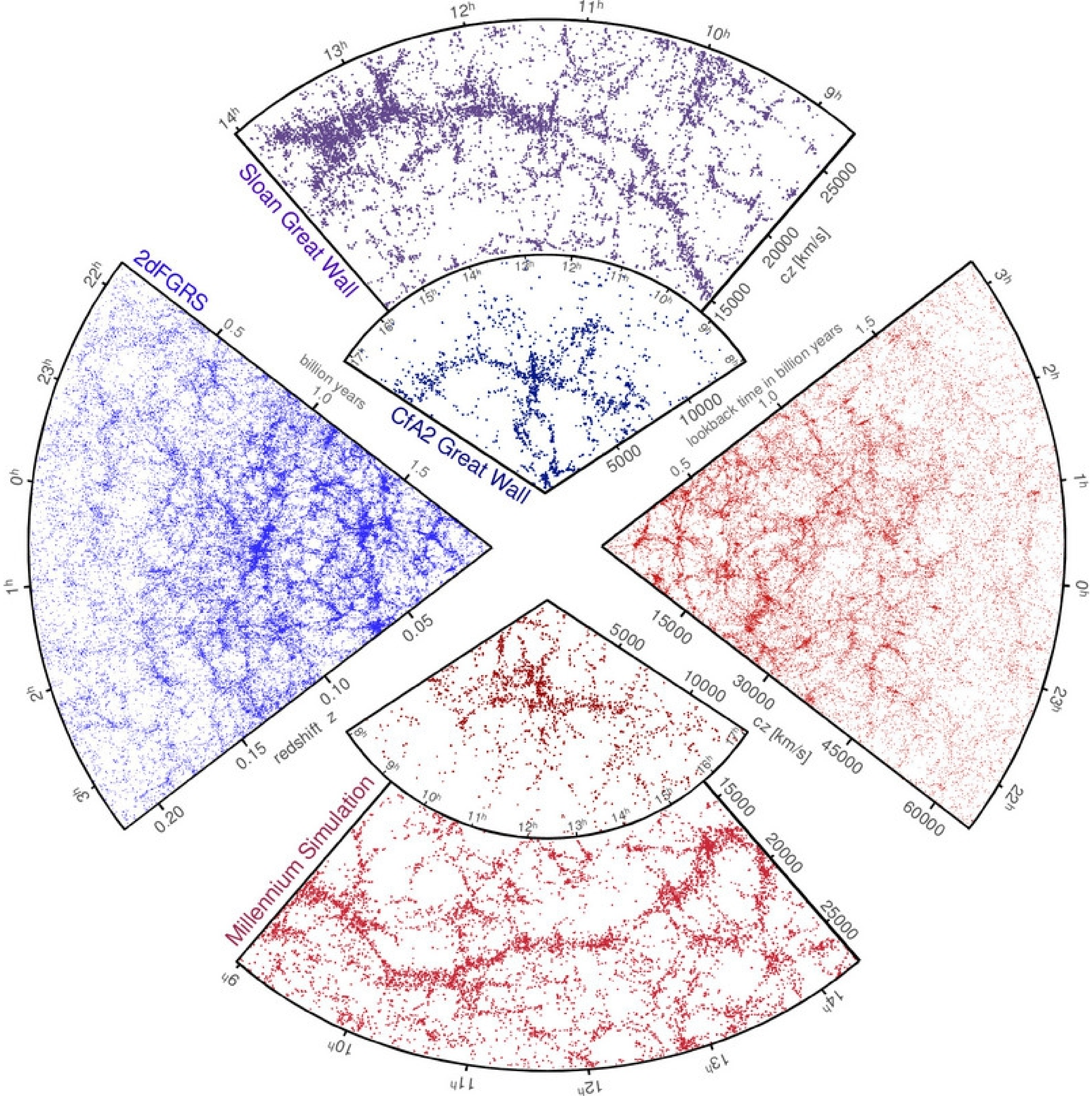
Model	L (l)	η (l)	M_T (m)	m_p $(10^{-4}m)$	Ω_i	Ω_m	Ω_Λ
EdS1–EdS5	32.5	0.15	9.4	2.9	1	1	0
EdS6–EdS8	65.0	0.30	75	23	1	1	0
L1	32.5	0.15	9.4	2.9	0.796	0.2	0.8
O1–O4	32.5	0.15	9.4	2.9	0.446	0.2	0



Davis et al 1985
Low density universes
$\Omega = 0.2$


125 Mpc/h
z = 0 Dark Matter

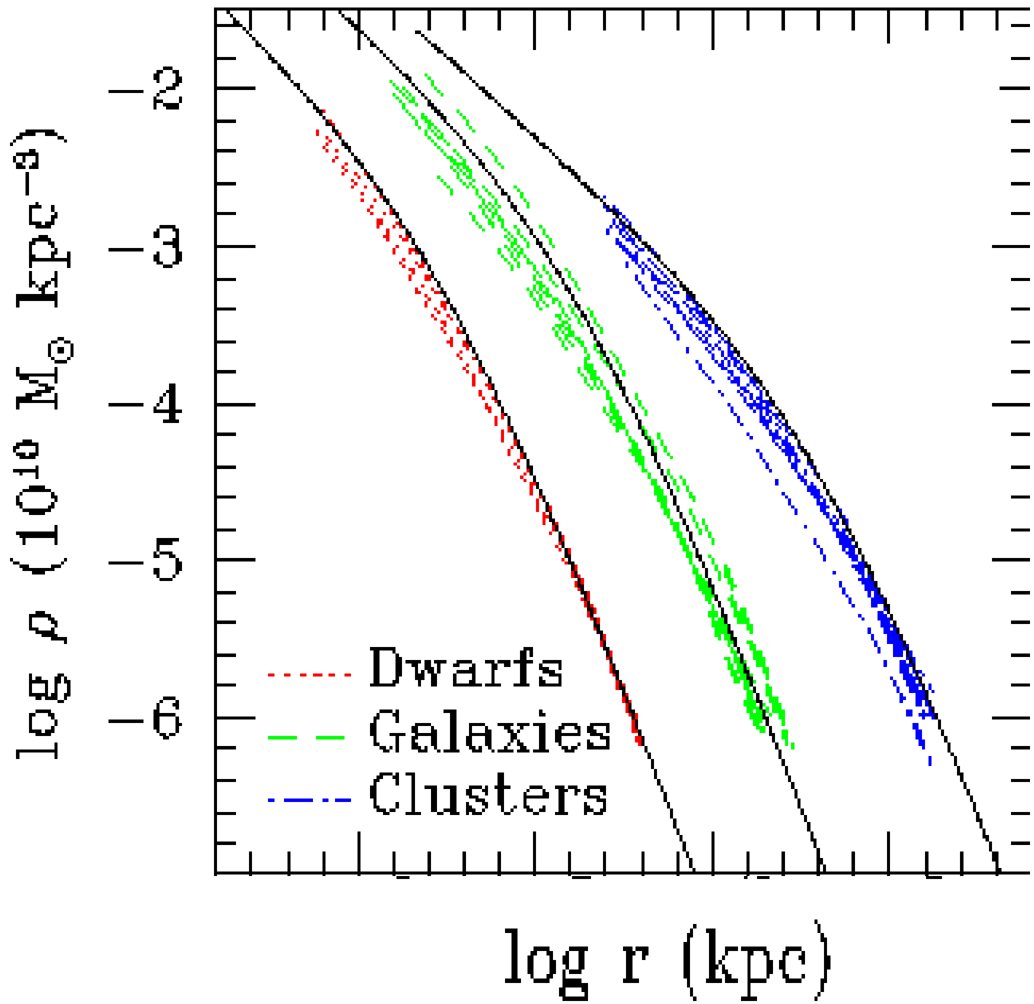

z = 0 Galaxy Light



Sloan Great Wall
2dFGRS
CfA2 Great Wall
Millennium Simulation
cz [km/s]
billion years
lookback time in billion years
redshift z

Density profiles of dark matter halos

Navarro, Frenk & White 1996



$N_{200} \sim 7 \times 10^3$

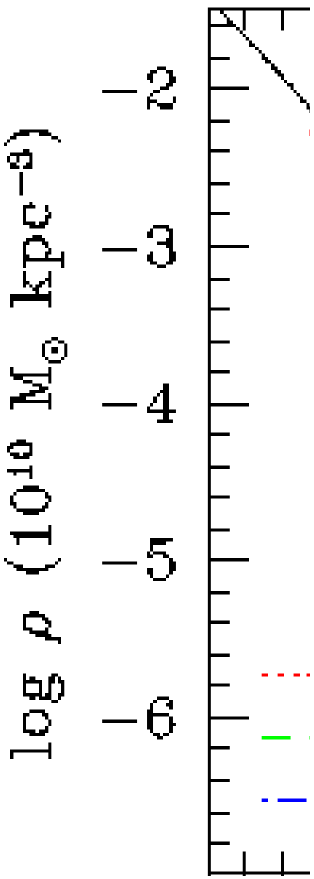
The average dark matter density of a dark halo depends on distance from halo centre in a very similar way in halos of all masses at all times in all cosmologies

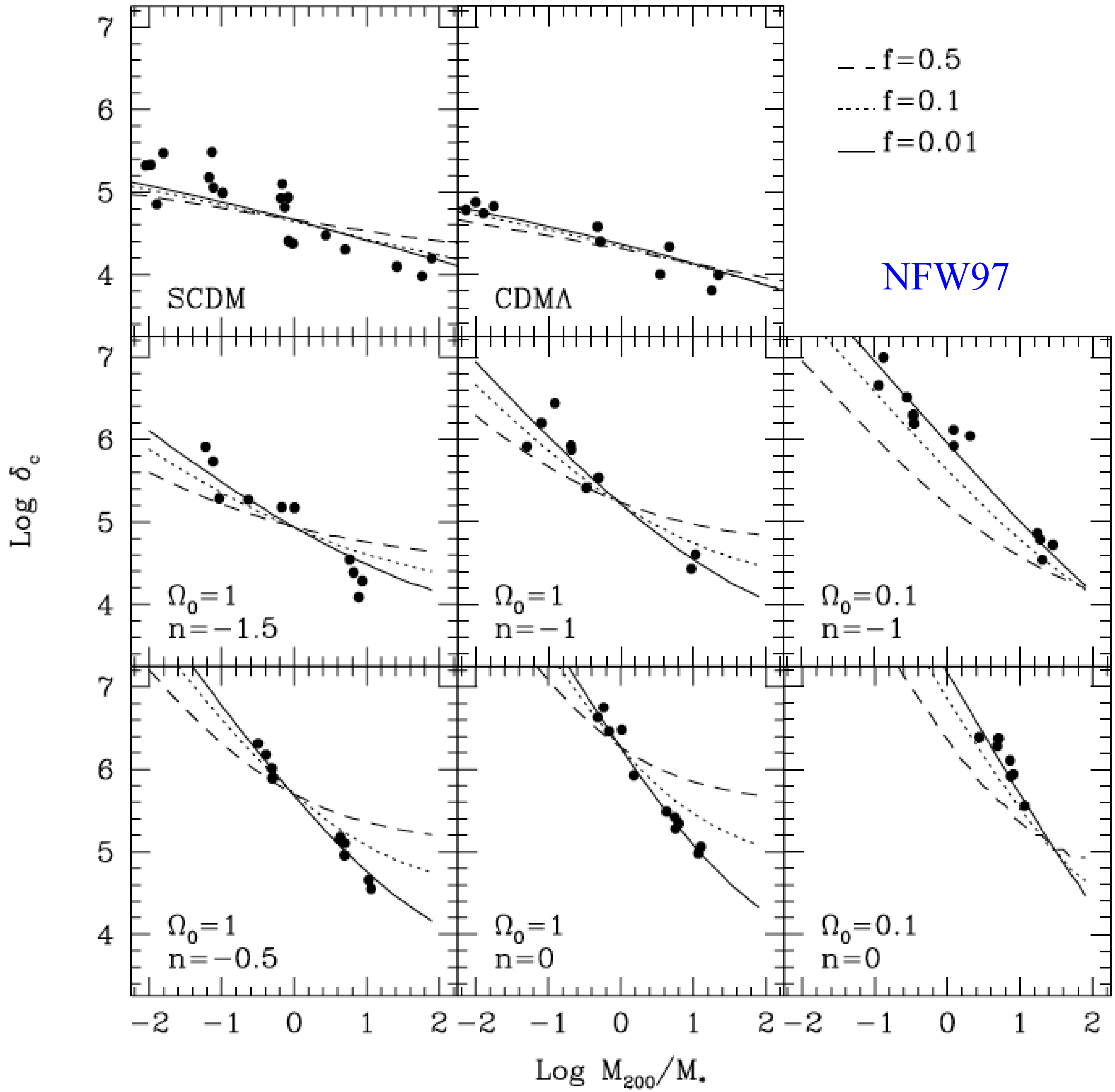
-- a universal profile shape --

$$\rho(r)/\rho_{crit} \approx \delta \; r_s / r(1 + r/r_s)^2$$

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

Density profiles of dark matter halos





atter
o depends
o centre in
halos of
s in all

e shape --

$+ r/r_s)^2$

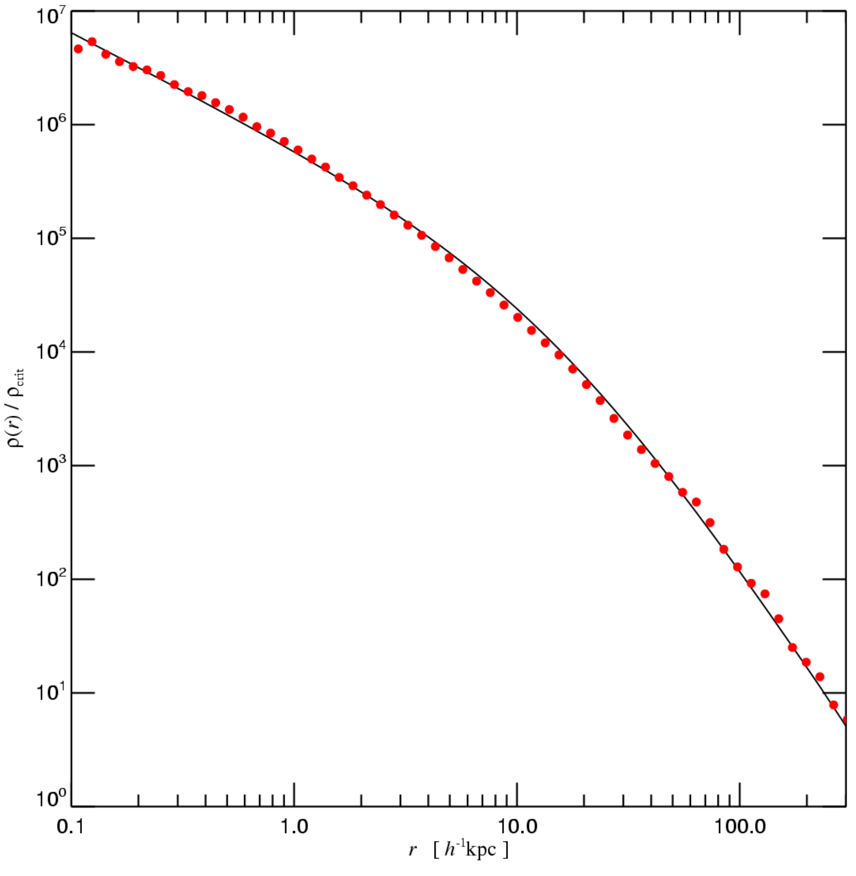
and halos
e
ger δ)

A high-resolution Milky Way halo

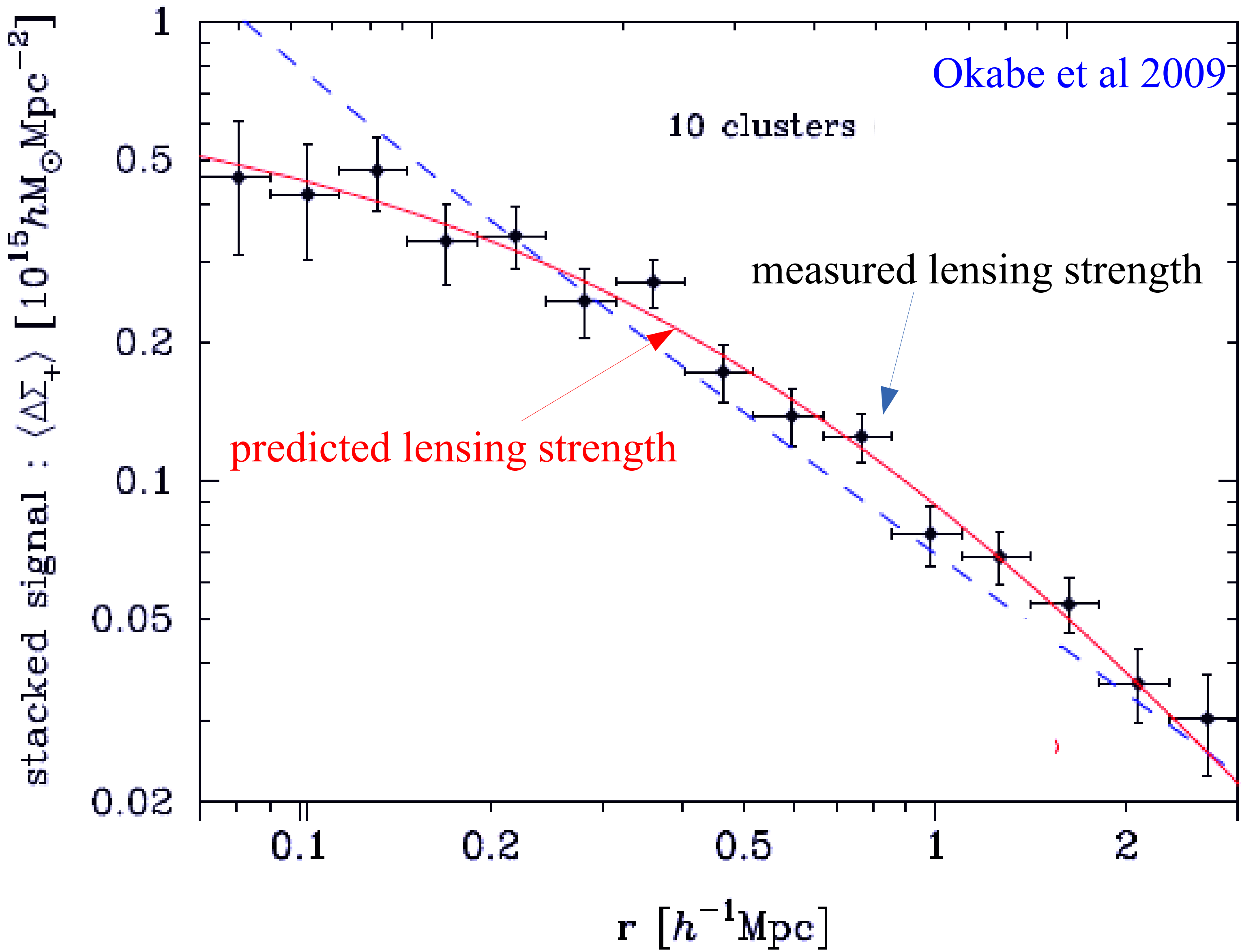
Navarro et al 2006

$$N_{200} \sim 3 \times 10^7$$

600 kpc



Comparison of lensing strength measured around real galaxy clusters to that predicted by simulations of structure formation



Dark Matter around the Milky Way?

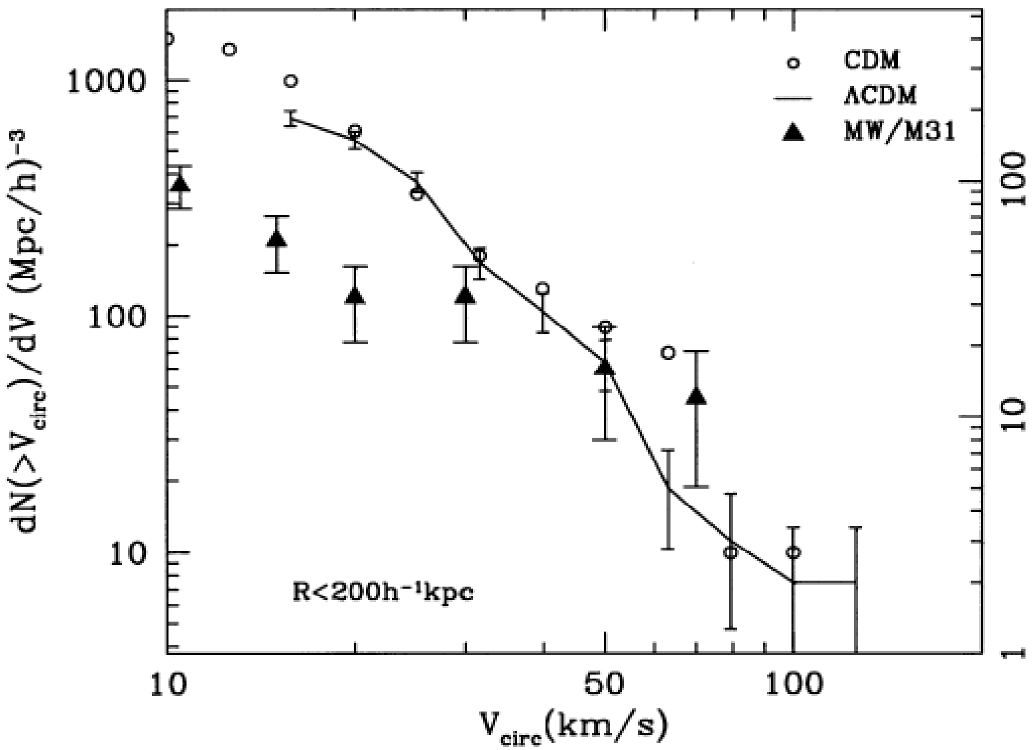
The significance of halo substructure

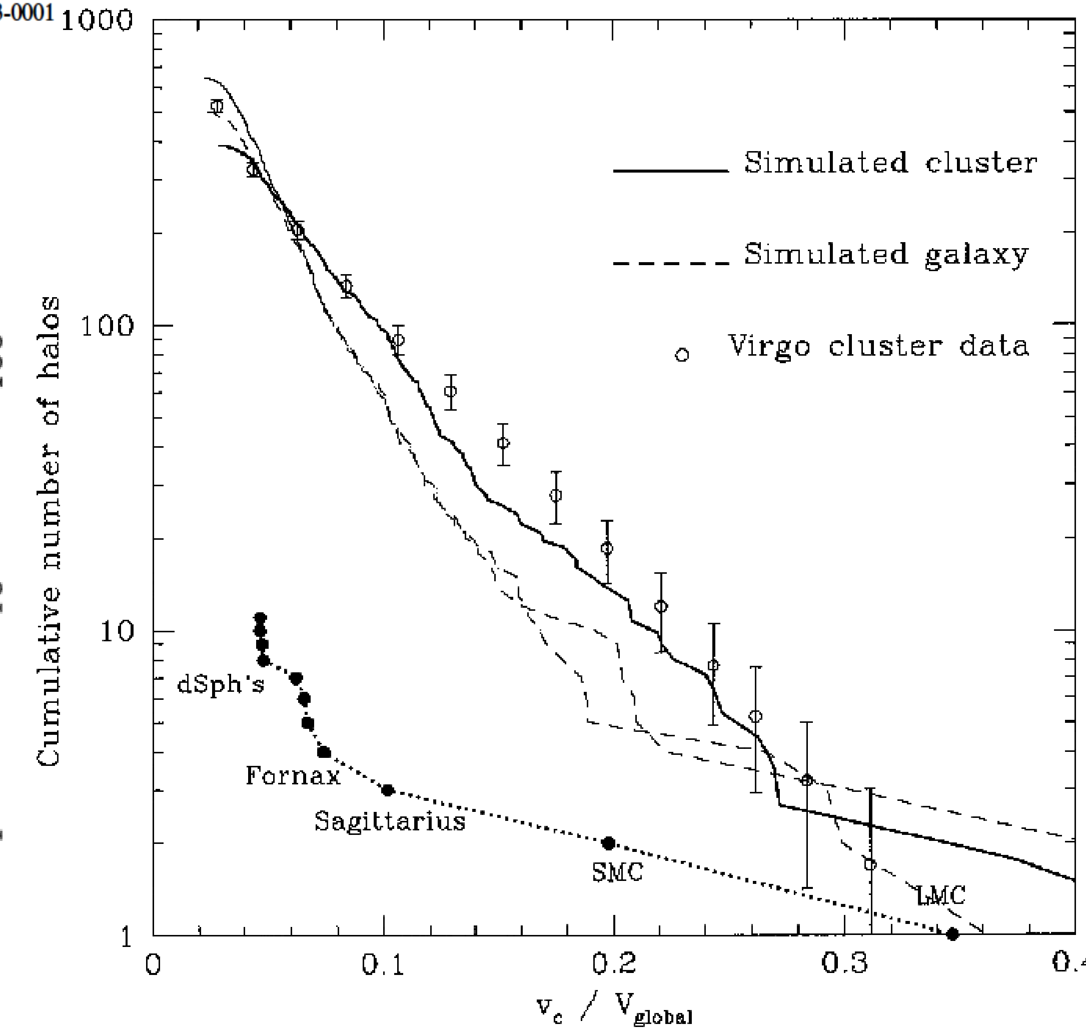
DARK MATTER SUBSTRUCTURE WITHIN GALACTIC HALOS

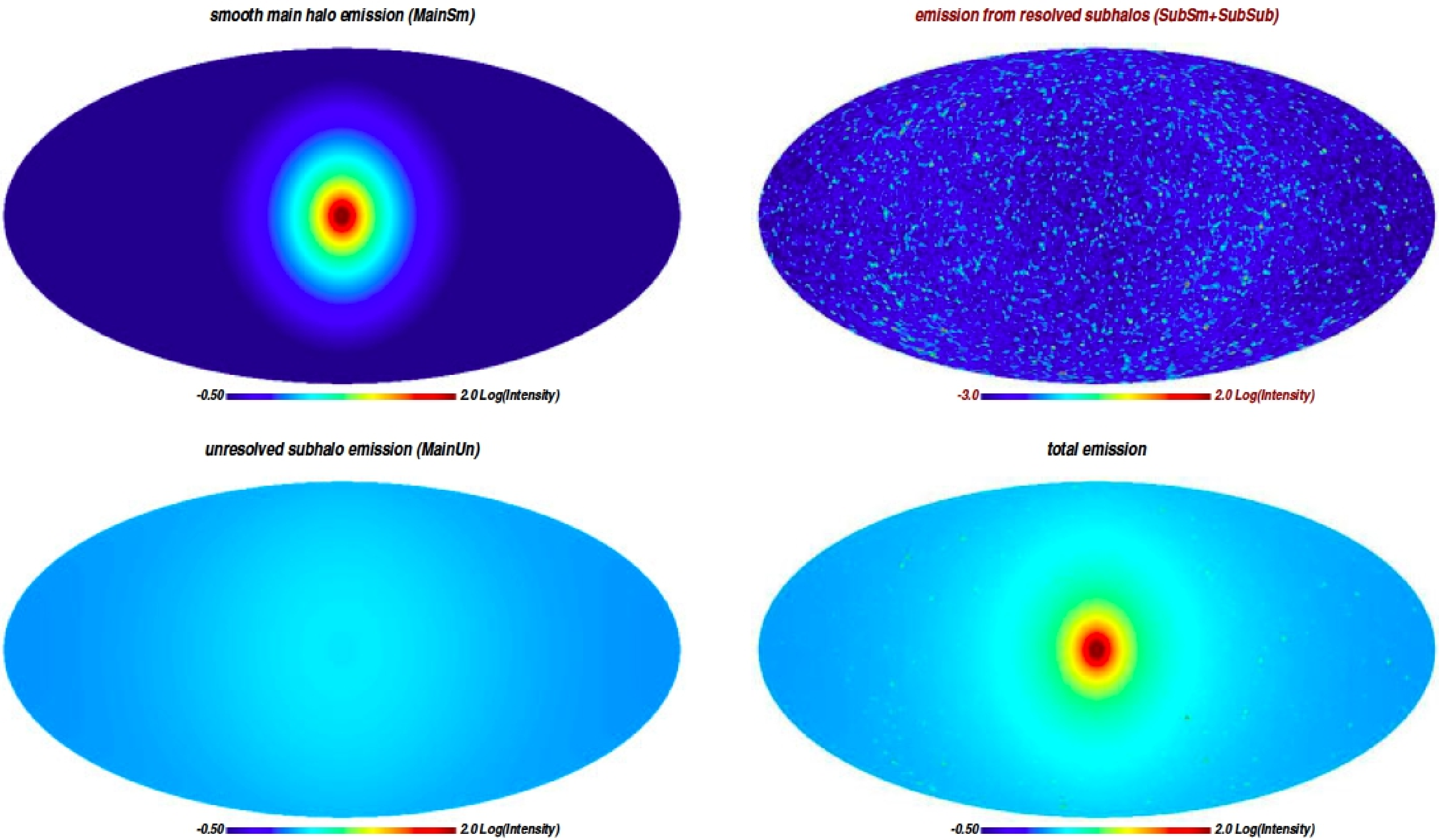
Ben Moore, Sebastiano Ghigna, and Fabio Governato
Department of Physics, Science Laboratories, South Road, University of Durham, Durham, England, DH1 3LE, UK; ben.moore@durham.ac.uk, ssg@durham.ac.uk, fabio@antares.merate.mi.astro.it
George Lake, Thomas Quinn, and Joachim Stadel
Department of Astronomy, Box 351580, University of Washington, Seattle, WA 98195-1580; lake@hermes.astro.washington.edu, trq@hermes.astro.washington.edu, stadel@hermes.astro.washington.edu
and
Paolo Tozzi
Osservatorio Astronomico di Roma, Via Frascati, 33, Monteporzio Catone, Rome, I-00040, Italy; paolo@pha.jhu.edu
Received 1999 April 16; accepted 1999 August 2; published 1999 September 13

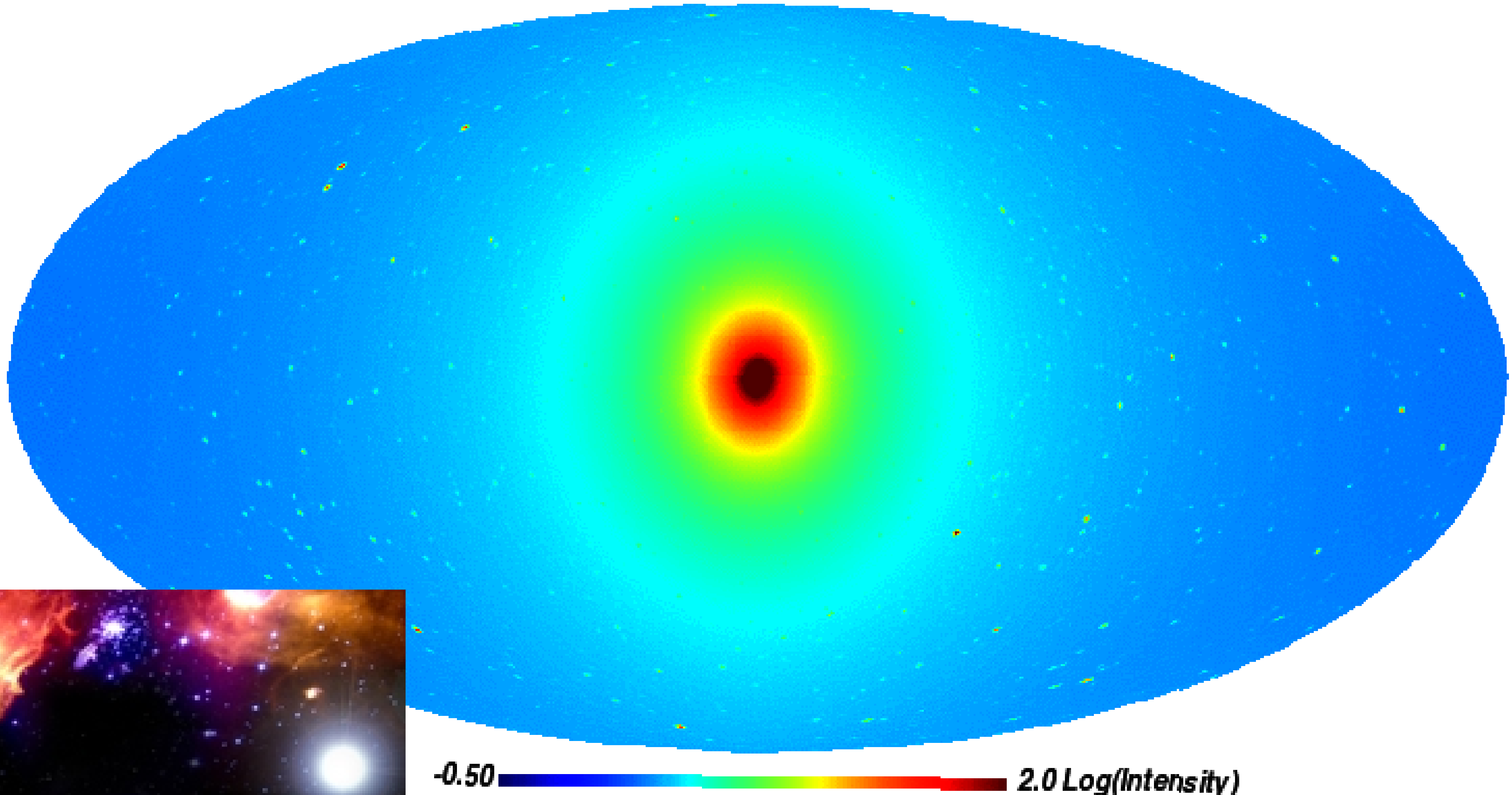
WHERE ARE THE MISSING GALACTIC SATELLITES?

Anatoly Klypin, Andrey V. Kravtsov, and Octavio Valenzuela
Astronomy Department, New Mexico State University, Box 30001, Department 4500, Las Cruces, NM 88003-0001
and
Francisco Prada
Instituto de Astronomia, Apartado Postal 877, 22900 Ensenada, Mexico
Received 1999 January 18; accepted 1999 April 15



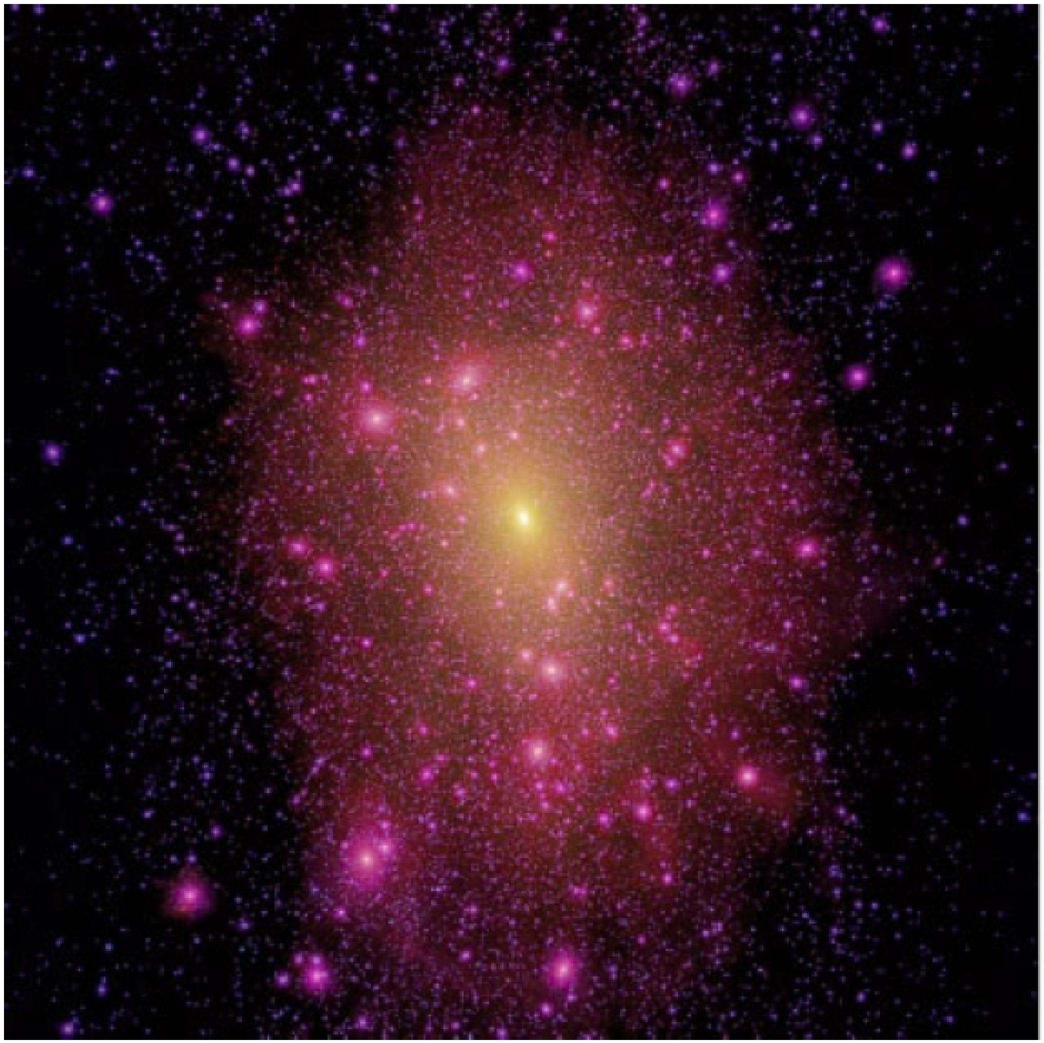



smooth main halo emission (MainSm)
-0.50
2.0 Log(Intensity)
emission from resolved subhalos (SubSm+SubSub)
-3.0
2.0 Log(Intensity)
unresolved subhalo emission (MainUn)
-0.50
2.0 Log(Intensity)
total emission
-0.50
2.0 Log(Intensity)

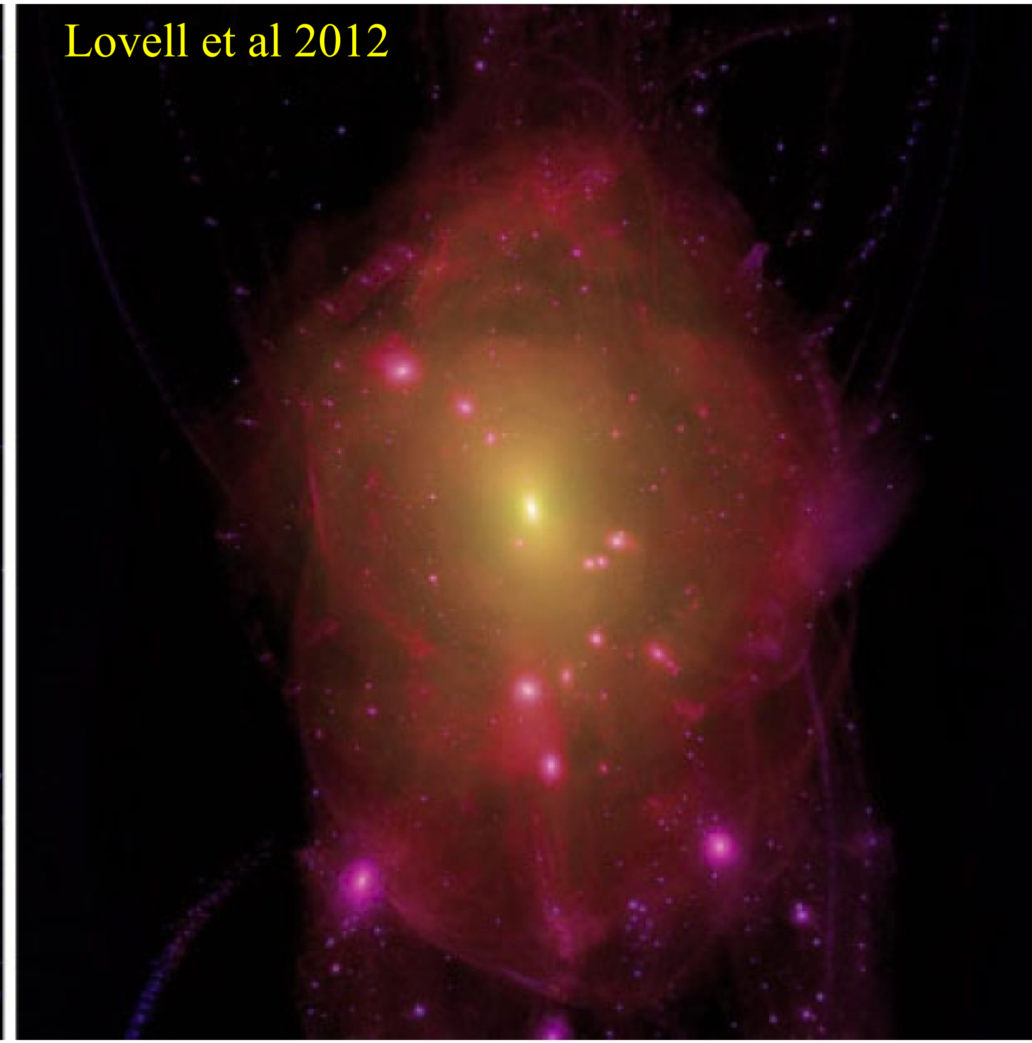


Dark Matter as seen by Fermi?

Milky Way halos?



Cold Dark Matter (axion?)



Warm Dark Matter (sterile υ?)

Dark Matter Halos

...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

$$\rho(r) / \rho_{crit} \approx \delta\, r_s / r\,(1 + r/r_s)^2$$

...have many subhalos containing ~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 <u>entirely</u> 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

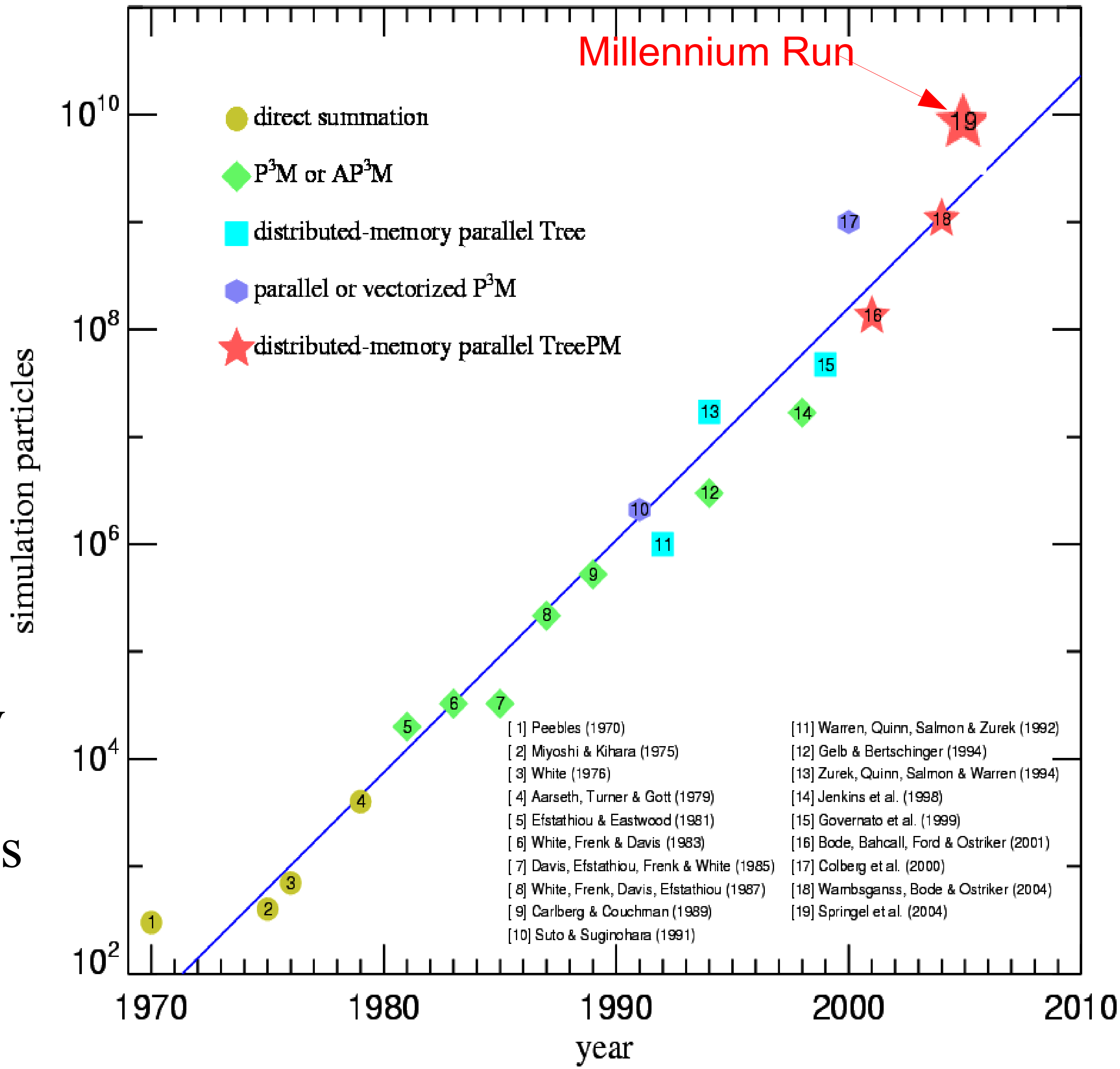
Moore's Law for Cosmological N-body Simulations

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



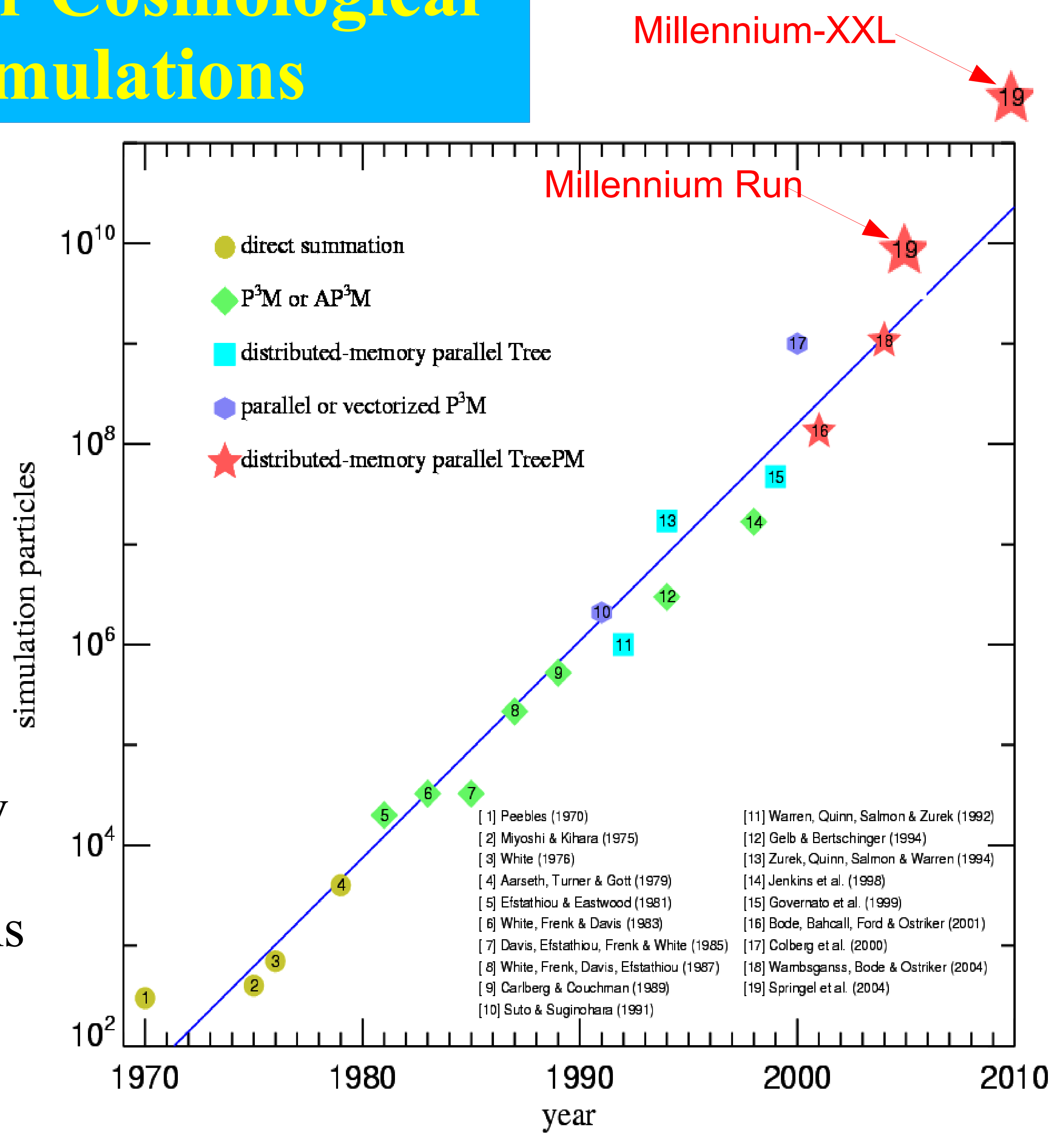
Moore's Law for Cosmological N-body Simulations

Computers double their speed every 18 months

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

Simulations double their size every 16.5 months

Progress has been roughly equally due to hardware and to improved algorithms



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 <u>observed</u> 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