VICTOR ROTHSCHILD MEMORIAL SYMPOSIA
THE HEBREW UNIVERSITY OF JERUSALEM

Israel Institute for Advanced Studies
The 30th Jerusalem Winter School in Theoretical Physics
with the support of the European Science Foundation

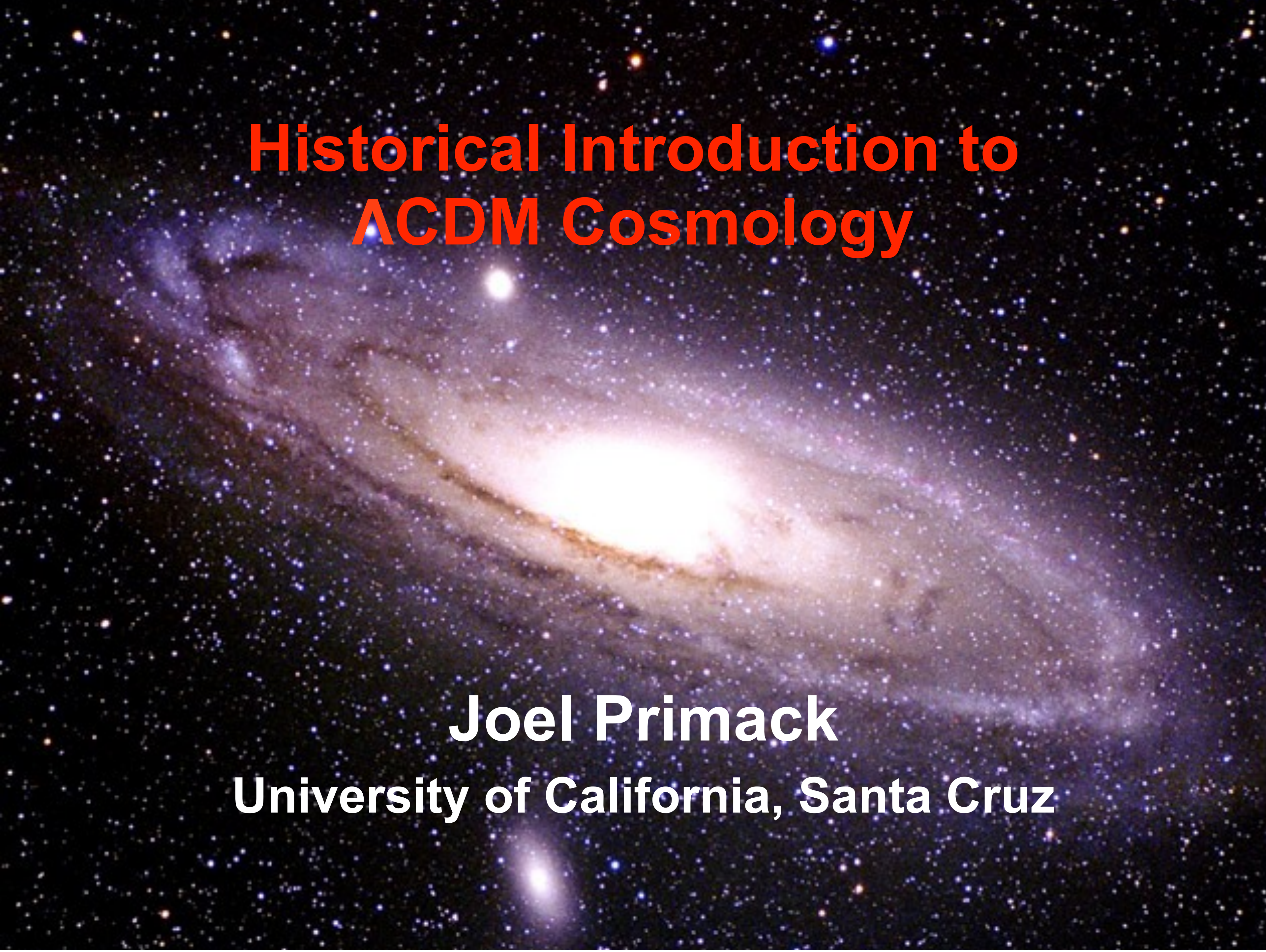
EARLY GALAXY FORMATION IN LCDM

December 31, 2012 – January 10, 2013

General Director: David Gross (KITP and UCSB)
Directors: Avishai Dekel (HUJI) & **Reinhard Genzel** (MPE)

Monday, December 31

09:00-09:30	Registration at IAS lobby
09:30-11:00	**Joel Primack** (UC Santa Cruz) *1. Introduction to LCDM Cosmology*



Historical Introduction to ΛCDM Cosmology

Joel Primack

University of California, Santa Cruz

Historical Introduction to ΛCDM Comology

Joel Primack, UCSC

Although the first evidence for dark matter was discovered in the 1930s, it was not until about 1980 that astronomers became convinced that most of the mass holding galaxies and clusters of galaxies together is invisible. For two decades, alternative theories were proposed and challenged. By the beginning of the 21st century the ΛCDM "Double Dark" standard cosmological model was accepted: cold dark matter -- non-atomic matter different from that which makes up the planets, stars, and us -- plus dark energy together make up 95% of the cosmic density. ΛCDM correctly predicts the cosmic background radiation and the large-scale distribution of galaxies. The challenge now is to understand the underlying physics of the dark matter and the dark energy. The lecture concludes with David Weinberg's "Dark Matter Rap."

A Brief History of Dark Matter

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

1970s - Discovery of flat galaxy rotation curves

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

1980-84 - short life of Hot Dark Matter theory

1983-84 - Cold Dark Matter (CDM) theory proposed

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

1998 - SN Ia and other evidence of Dark Energy

2000 - ΛCDM is the Standard Cosmological Model

2003-12 - WMAP and LSS data confirm ΛCDM predictions

~2013 - Discovery of dark matter particles??

Early History of Dark Matter

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

1940s - Zwicky's large cluster σ_V confirmed by many observers

1957 - van de Hulst: high HI rotation curve for M31
1959 - Kahn & Woltjer: MWy-M31 infall $\Rightarrow$ $M_{LocalGroup} = 1.8\text{x}10^{12}$ 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
1978 - Mathews: X-rays reveal enormous mass of Virgo cluster
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

Early History of Dark Matter

SLIDES

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

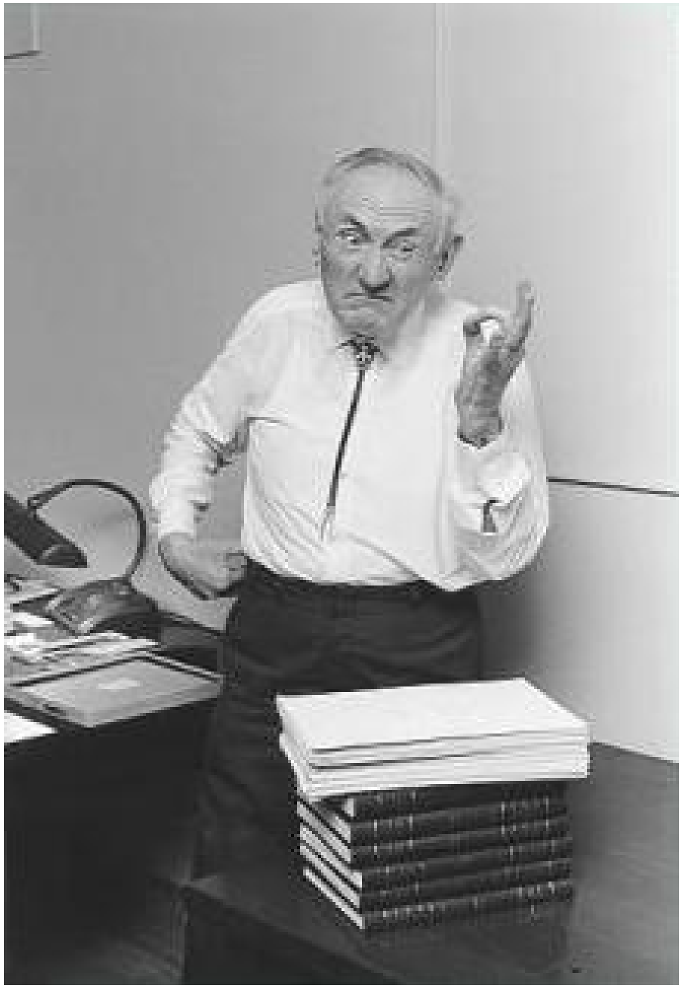
1940s - Zwicky's large cluster σ_V confirmed by many observers

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
1978 - Mathews: X-rays reveal enormous mass of Virgo cluster
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

1937 ApJ 86, 217



Fritz Zwicky

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

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

Inasmuch as we have introduced at every step of our argument inequalities which tend to depress the final value of the mass $\mathcal{M}$, 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

$$\text{Mass/Light} = \quad \gamma = 500 , \quad (37)$$

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

F. D. KAHN* AND L. WOLTJER†

1959 ApJ 130, 705

Princeton University Observatory and the Institute for Advanced Study, Princeton, New Jersey

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

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

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,

$$\frac{GM^*}{2a} = \frac{GM^*}{D} - E_k , \quad (2)$$

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

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

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

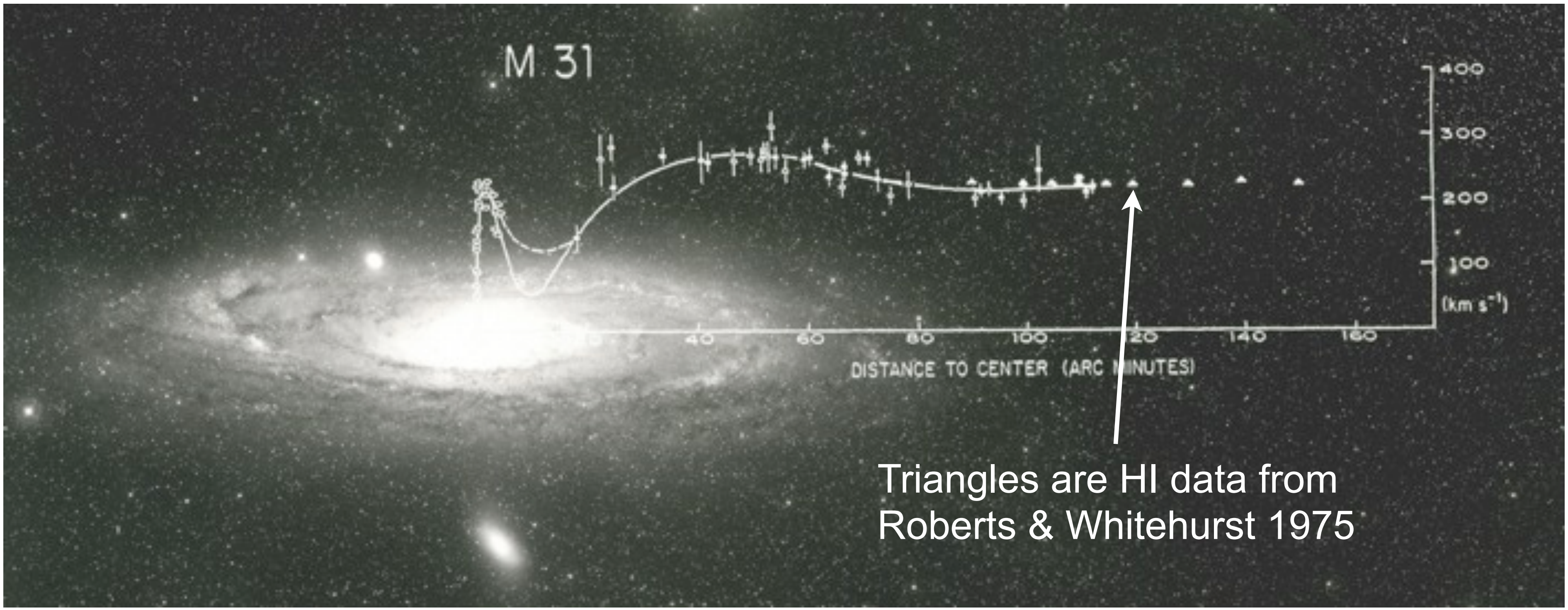
The discrepancy seems to be well outside the observational errors.

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

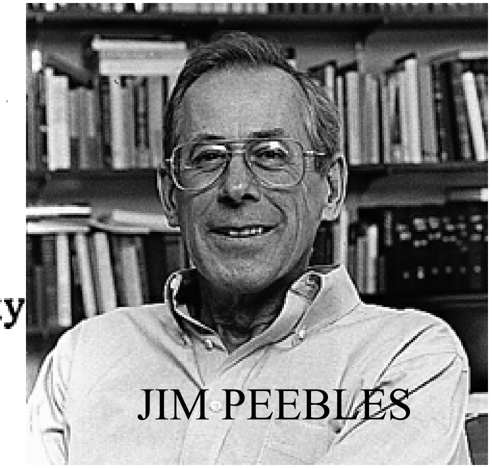
ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*

VERA C. RUBIN† AND W. KENT FORD, JR.†
Department of Terrestrial Magnetism, Carnegie Institution of Washington and Lowell Observatory, and Kitt Peak National Observatory‡



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

J. P. OSTRIKER
Princeton University Observatory
AND
P. J. E. PEEBLES
ph Henry Laboratories, Princeton University



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.

Monday, December 31, 12

Nature 250, 309 - 310 (26 July 1974)

Dynamic evidence on massive coronas of galaxies

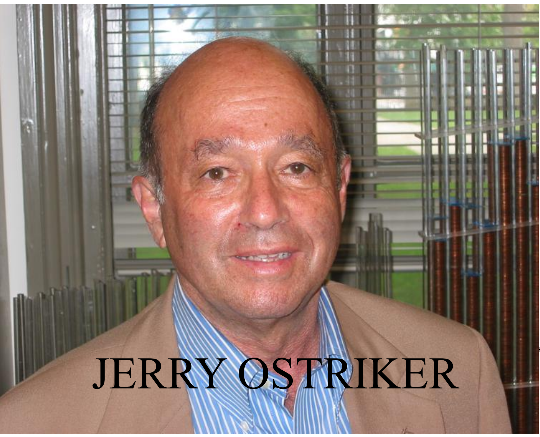
JAAN EINASTO, ANTS KAASIK & ENN SAAR

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 galaxies. 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



J. P. OSTRIKER
Princeton University Observatory

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

AND

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

Received 1974 May 28; revised 1974 July 15

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 $\sim 200\ (M/L)_\odot$. 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.

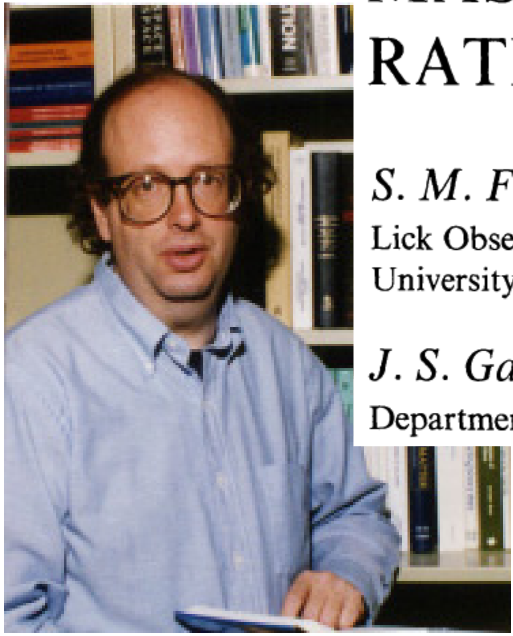
THE ENORMOUS MASS OF THE ELLIPTICAL GALAXY M87: A MODEL FOR THE EXTENDED X-RAY SOURCE*

WILLIAM G. MATHEWS
Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz
Received 1977 March 28; accepted 1977 July 20

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

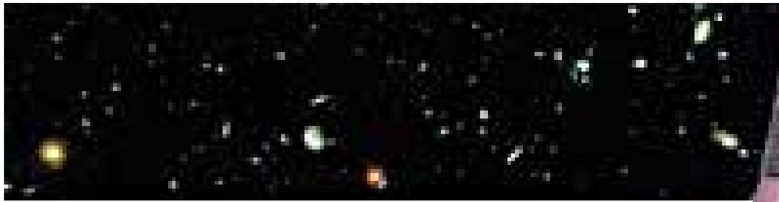


MASSES AND MASS-TO-LIGHT RATIOS OF GALAXIES

ARAA 1979

S. M. Faber
Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz, California 95064

J. S. Gallagher
Department of Astronomy, University of Illinois, Urbana, Illinois 61801



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? Theorists usually assumed Ω_m=1, but observers typically found $\Omega_m \approx 0.2$.

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

1973 - Marx & Szalay, Cowsik & McClelland: $m_\nu < 100$ eV
1980 - Zel'dovich group develops Hot Dark Matter (HDM) theory[1]
1983 - White, Frenk, Davis: 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 cosmic structure formation

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.

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

GRAVITY OF NEUTRINOS OF NONZERO MASS IN ASTROPHYSICS

R. COWSIK* AND J. MCCLELLAND
Department of Physics, University of California, Berkeley
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 ith 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; $T(z_{eq}) = T_\gamma(z_{eq}) = T_\nu(z_{eq}) = T_e(z_{eq}) \cdots$ = 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

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

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 $(1 + z_{eq})/(1 + z) = T_\gamma(z_{eq})/T_\gamma(z)$, the number density at the present epoch ($z = 0$) is given by

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

* On leave from the Tata Institute of Fundamental Research, Bombay, India.

Weakly Interacting Massive Particles (WIMPs) as Dark Matter

Neutrinos with masses of 10s of eV (hot dark matter) are no longer a good candidate.

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*

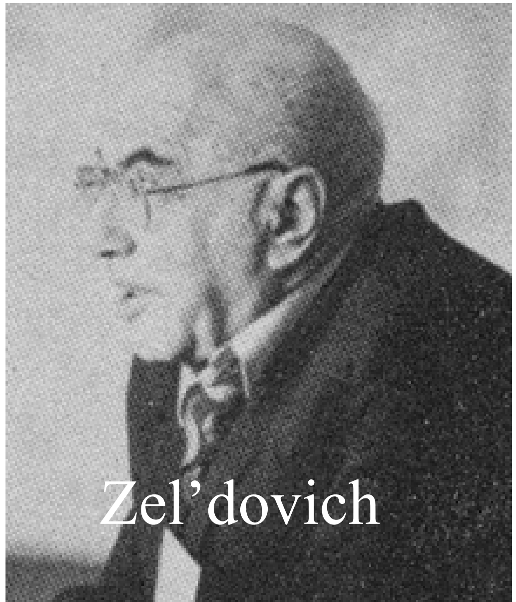
Neutrino dominated Universe

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.



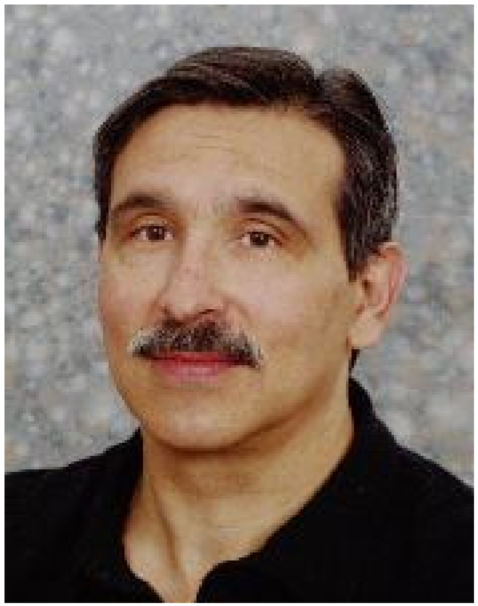
CLUSTERING IN A NEUTRINO-DOMINATED UNIVERSE

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

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)
1977 - Binney, Rees & Ostriker, Silk: Cooling curves
1978 - 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 survey
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

Core condensation in heavy halos: a two-stage theory for galaxy formation and clustering 1978

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

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

Heinz Pagels
The Rockefeller University, New York, New York 10021

and

Joel R. Primack
Physics Department, University of California, Santa Cruz, California 95064

(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

George R. Blumenthal*, Heinz Pagels† & Joel R. Primack‡

* Lick Observatory, Board of Studies in Astronomy and Astrophysics, ‡ Board of Studies in Physics, University of California, Santa Cruz, California 95064, USA
† The Rockefeller University, New York, New York 10021, USA

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.

Monday, December 31, 12

1982 ApJ 263, L1

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

P. J. E. PEEBLES
Joseph Henry Laboratories, Physics Department, Princeton University
Received 1982 July 2; accepted 1982 August 13

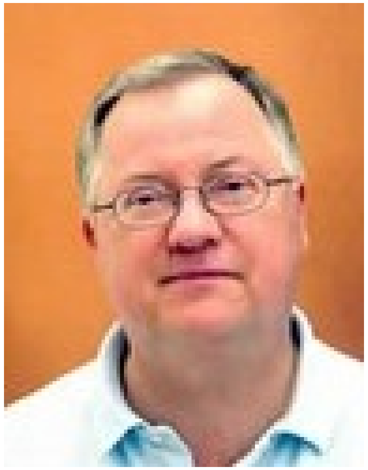
ABSTRACT

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.

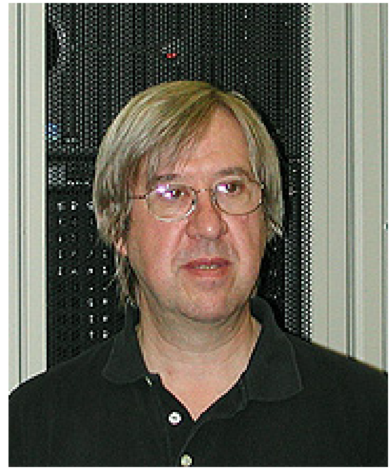
REFERENCES

Bahcall, N. A., and Soneira, R. M. 1982, preprint.
→ Blumenthal, G. R., Pagels, H., and Primack, J. R. 1982, *Nature*, in press.
Bond, J. R., Szalay, A. S., and Turner, M. S. 1982, *Phys. Rev. Letters*, **48**, 1636.
Boughn, S. P., Cheng, E. S., and Wilkinson, D. T. 1981, *Ap. J.* (*Letters*), **243**, L113.
Davis, M., Lecar, M., Pryor, C., and Witten, E. 1981, *Ap. J.*, **250**, 423.
Davis, M., and Peebles, P. J. E. 1983, *Ap. J.*, submitted.
Doroshkevich, A. G., Khlopov, M. Yu., Sunyaev, R. A., Szalay, A. S., and Zel'dovich, Ya. B. 1981, in *Proceedings of the Tenth Texas Symposium*, *Ann. NY Acad. Sci.*, **375**, 32.
Fixsen, D. J. 1982, Ph.D. thesis, Princeton University.
Harrison, E. R. 1970, *Phys. Rev.*, **D1**, 2726.
Hauser, M. G., and Peebles, P. J. E. 1973, *Ap. J.*, **185**, 757.
Hawking, S. W. 1982, preprint.
Hogan, C. J. 1982, *Ap. J.* (*Letters*), **256**, L33.
Lubin, P. M. 1982, paper presented at the 86th course of the International School of Physics, Varenna.
Melchiorri, F., Melchiorri, B. O., Ceccarelli, C., and Pietranera, L. 1981, *Ap. J.* (*Letters*), **250**, L1.
Ostriker, J. P., and Cowie, L. L. 1981, *Ap. J.* (*Letters*), **243**, L127.
Peebles, P. J. E. 1980, *The Large-Scale Structure of the Universe* (Princeton: Princeton University Press) (LSS).
———. 1981*a*, *Ap. J.*, **248**, 885.
———. 1981*b*, *Ap. J.* (*Letters*), **243**, L119.
———. 1982*a*, *Ap. J.*, **258**, 415.
———. 1982*b*, *Ap. J.*, **259**, 442.
Peebles, P. J. E., and Groth, E. J. 1976, *Astr. Ap.*, **53**, 131.
Peebles, P. J. E., and Yu, J. T. 1970, *Ap. J.*, **162**, 815.
Press, W. H., and Vishniac, E. T. 1980, *Ap. J.*, **236**, 323.
Silk, J., and Wilson, M. L. 1981, *Ap. J.* (*Letters*), **244**, L37.
Wasserman, I. 1981, *Ap. J.*, **248**, 1.
Zel'dovich, Ya. B. 1972, *M.N.R.A.S.*, **160**, 1P.

THE COLLISIONLESS DAMPING OF DENSITY FLUCTUATIONS IN AN EXPANDING UNIVERSE



1983 ApJ 274, 443

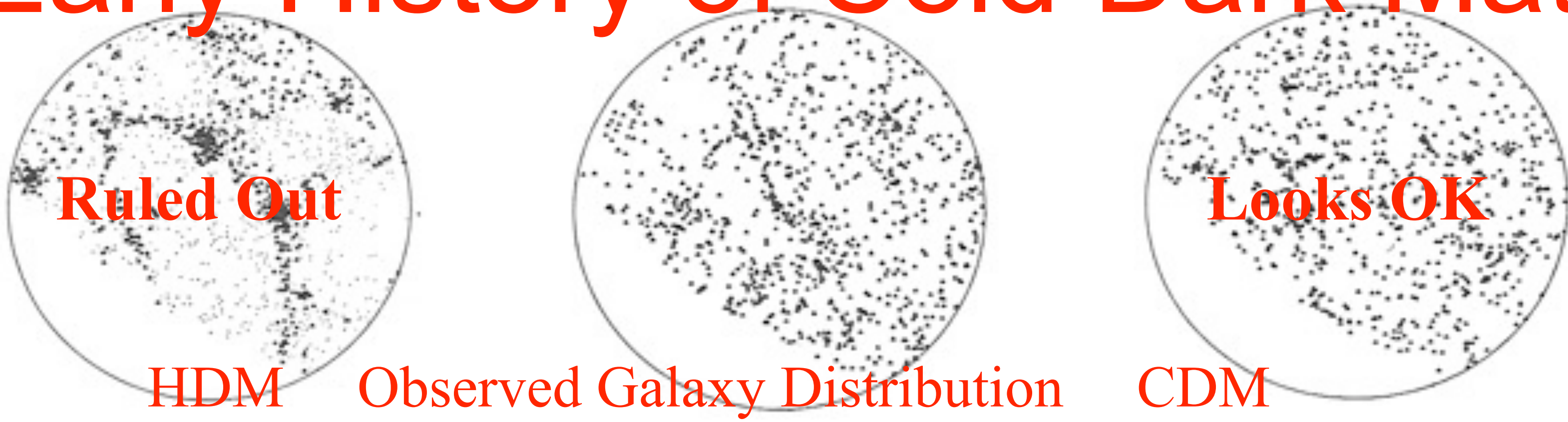


J. R. BOND AND A. S. SZALAY

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



HDM   Observed Galaxy Distribution   CDM

White 1986

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, WDM P(k)

1984 - Blumenthal, Faber, Primack, & Rees: CDM compared to CfA1 redshift survey
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

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

George R. Blumenthal* & S. M. Faber*

* Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz, California 95064, USA

Joel R. Primack†§ & Martin J. Rees‡§

† Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, USA
‡ Institute of Theoretical Physics, University of California, Santa Barbara, California 93106, USA

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

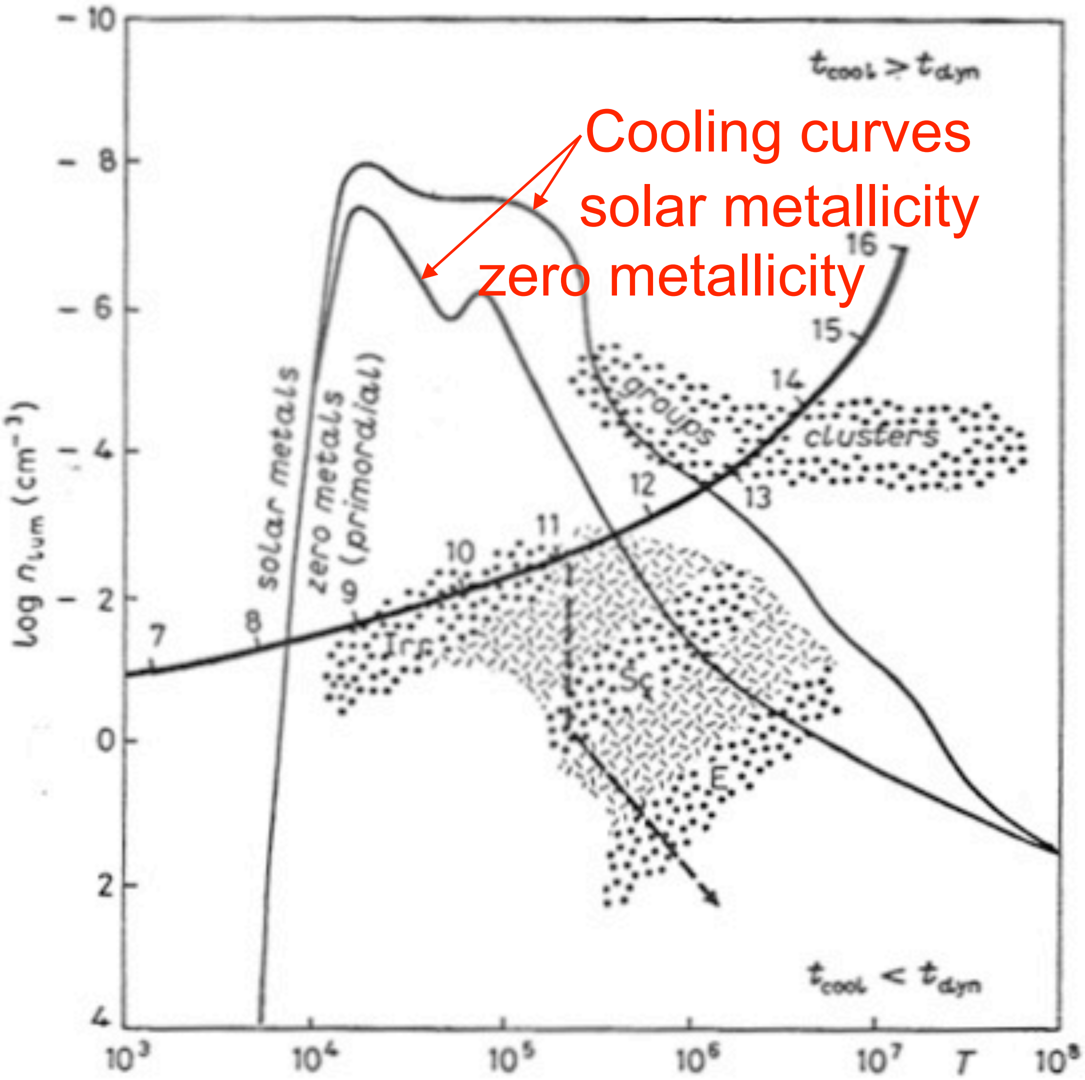
… We conclude that a straightforward interpretation of the evidence summarized above favours $\Omega \approx 0.2$ in the cold DM picture, but that $\Omega = 1$ is not implausible. …

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.

Blumenthal, Faber, Primack, & Rees 1984

CDM Spherical Collapse Model



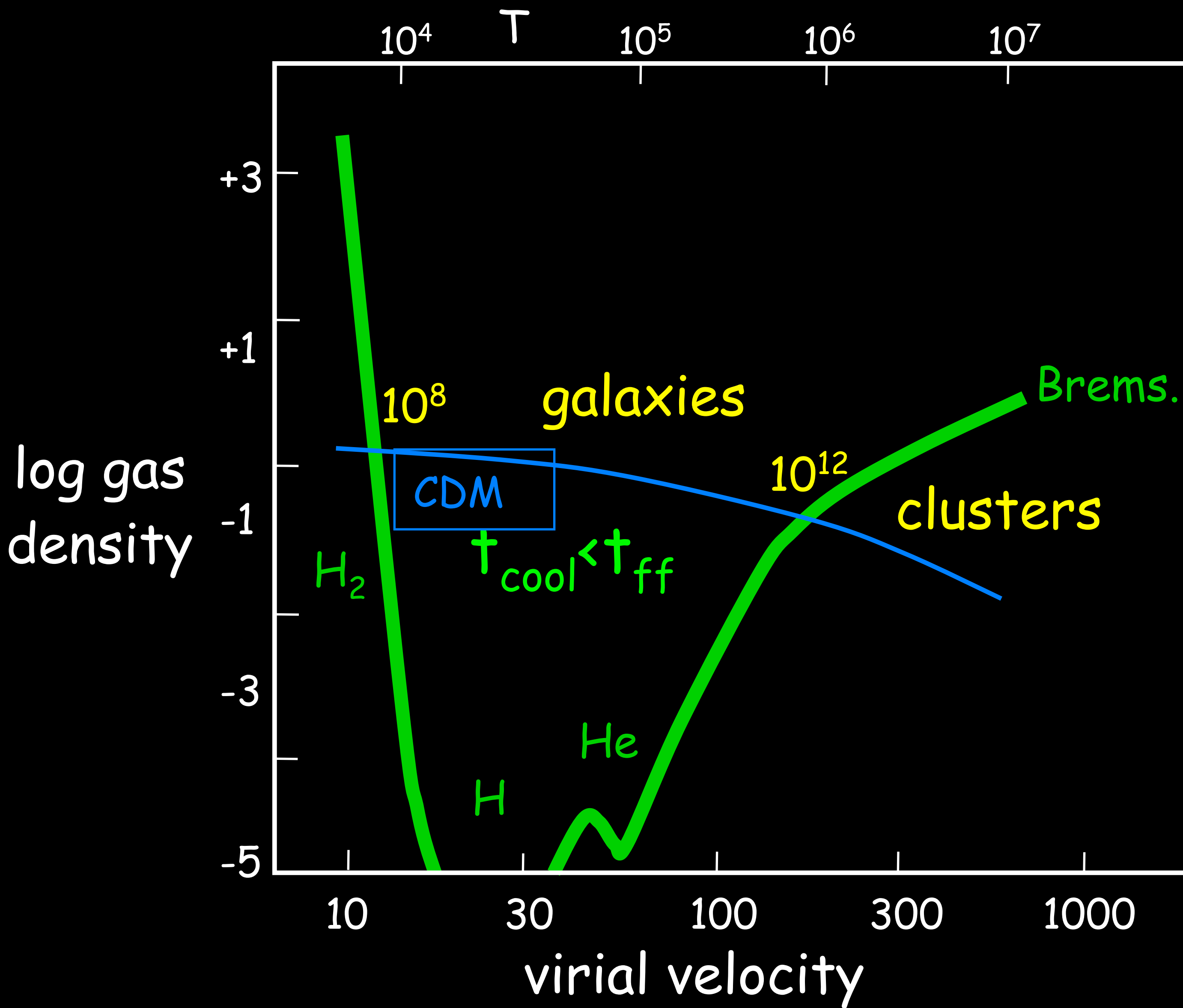
Primack & Blumenthal 1983 based on CDM, cooling theory of Rees & Ostriker 1977, Silk 1977, Binney 1977 and baryonic dissipation within dark halos White & Rees 1978

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.

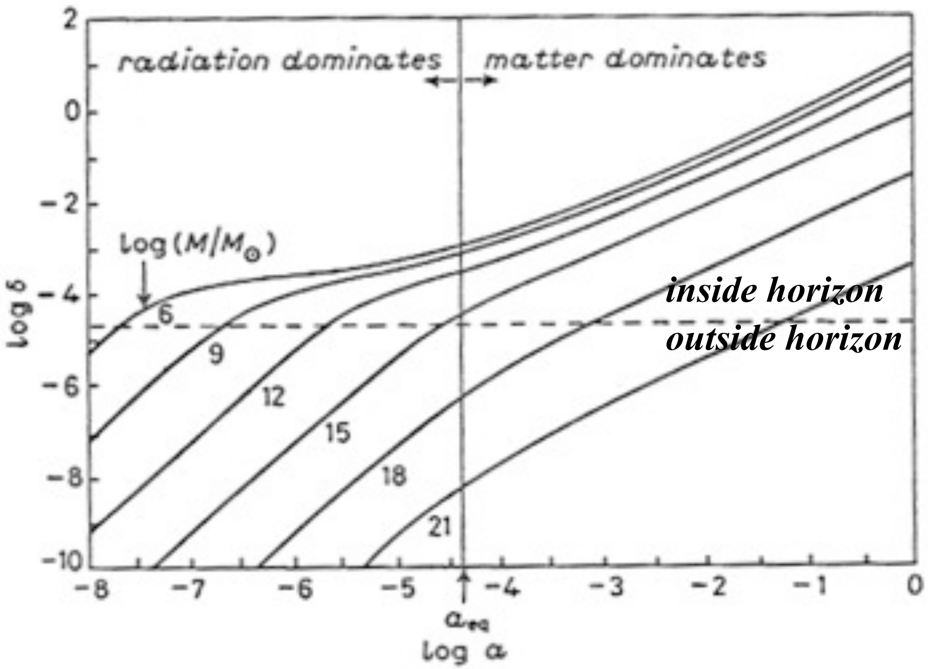
CDM Correctly Predicted the Masses of Galaxies

Rees & Ostriker 77, Silk 77, Binney 77, White & Rees 1978

CDM: Blumenthal, Faber, Primack, & Rees 1984

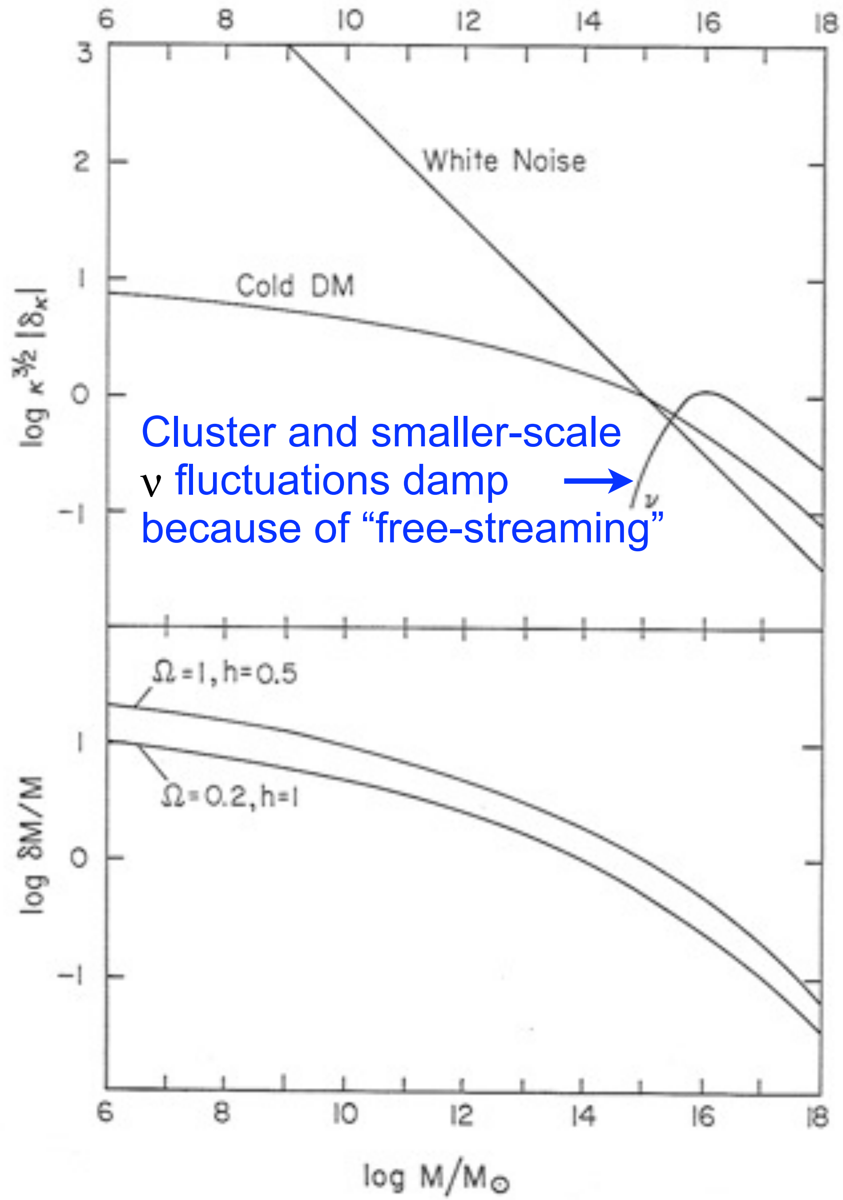


CDM Structure Formation: Linear Theory

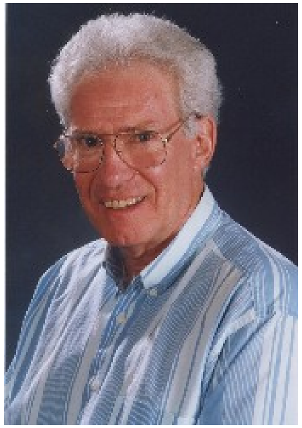


CDM fluctuations that enter the horizon during the radiation dominated era, with masses less than about $10^{15} M_{\odot}$, grow only $\propto$ log $\boldsymbol{a}$, because they are not in the gravitationally dominant component. But matter fluctuations that enter the horizon in the matter-dominated era grow $\propto \boldsymbol{a}$. This explains the characteristic shape of the CDM fluctuation spectrum, with $\delta(k) \propto k^{-n/2-2} \log k$

Primack & Blumenthal 1983,
Primack Varenna Lectures 1984



Blumenthal, Faber, Primack, & Rees 1984

Flatness of the Universe: Reconciling Theoretical Prejudices with Observational Data

1984 PRL 52, 2090

Michael S. Turner
Theoretical Astrophysics, Fermi National Accelerator Laboratory, Batavia, Illinois 60510, and The University of Chicago, Chicago, Illinois 60637

and

Gary Steigman
Bartol Research Foundation, University of Delaware, Newark, Delaware 19716

and

Lawrence M. Krauss
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 2 March 1984)

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

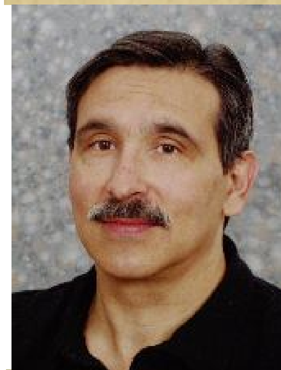
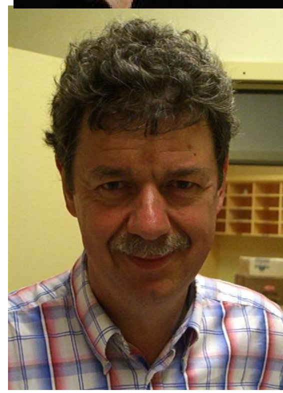
MARC DAVIS,[1,2] GEORGE EFSTATHIOU,[1,3] CARLOS S. FRENK,[1,4] AND SIMON D. M. WHITE[1,5]

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. 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

1983 - Davis & Peebles CfA redshift survey galaxy correlation function $\xi_{gg}(r) = (r/r_0)^{-1.8}$

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

1986 - Seven Samurai: 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

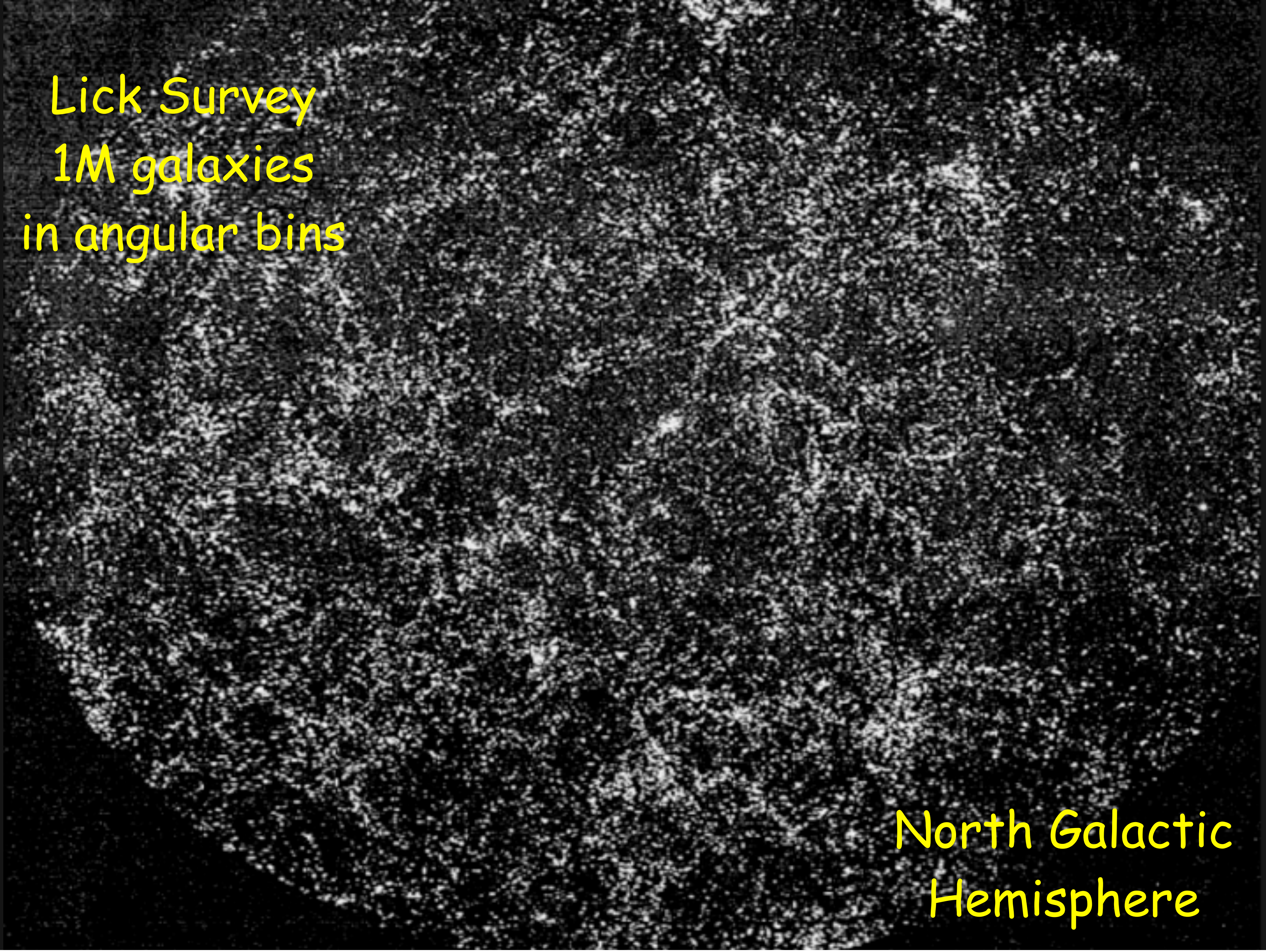
1997 - Nararro, Frenk, & White: DM halo structure $\rho_{NFW}(r) = 4\, \rho_s\, (r/r_s)^{-1}(1+r/r_s)^{-2}$

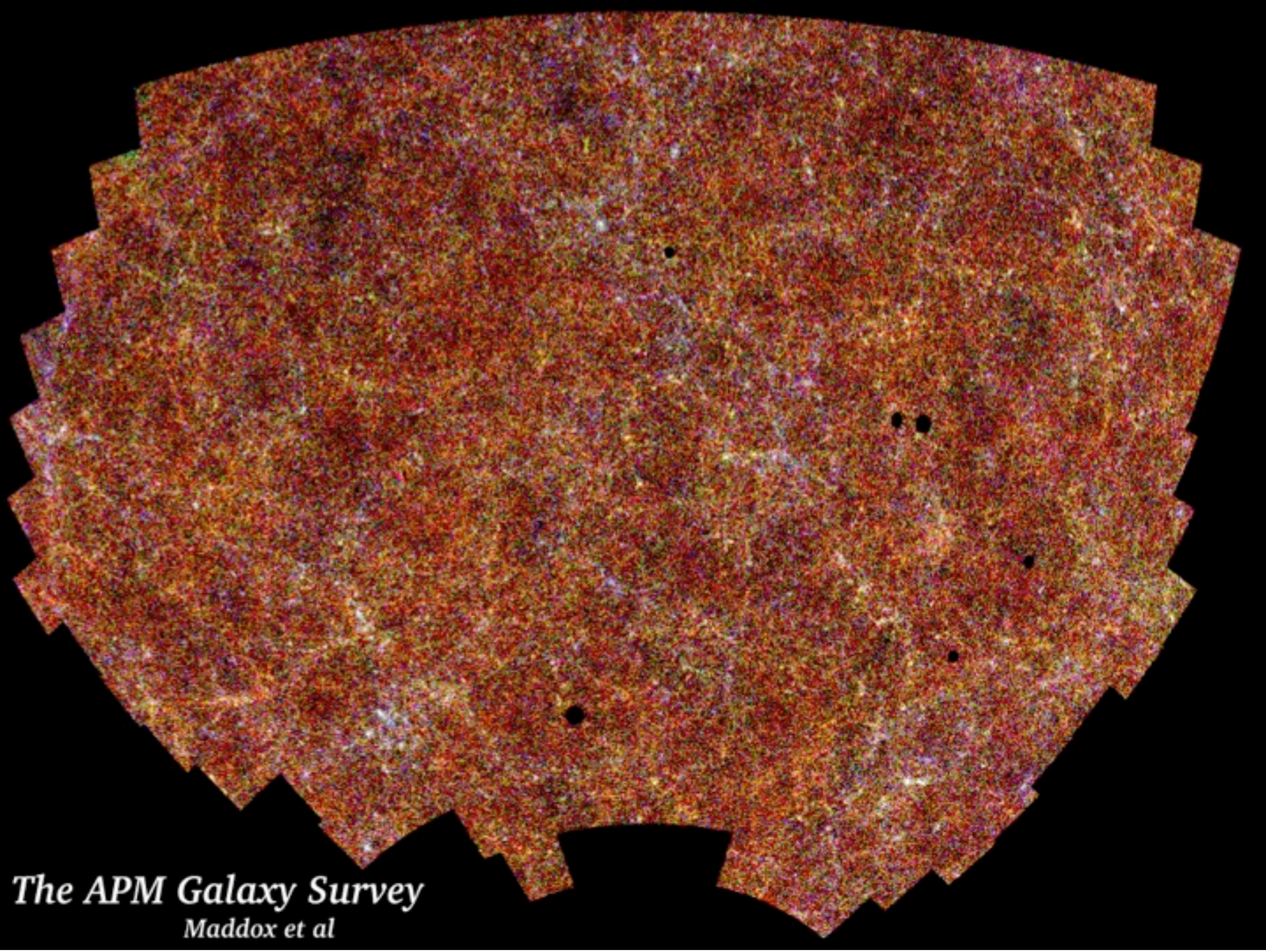
1997 - Hipparchos distance scale, SN Ia dark energy ⇒ $t_0 \approx 14$ Gyr, ΛCDM

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

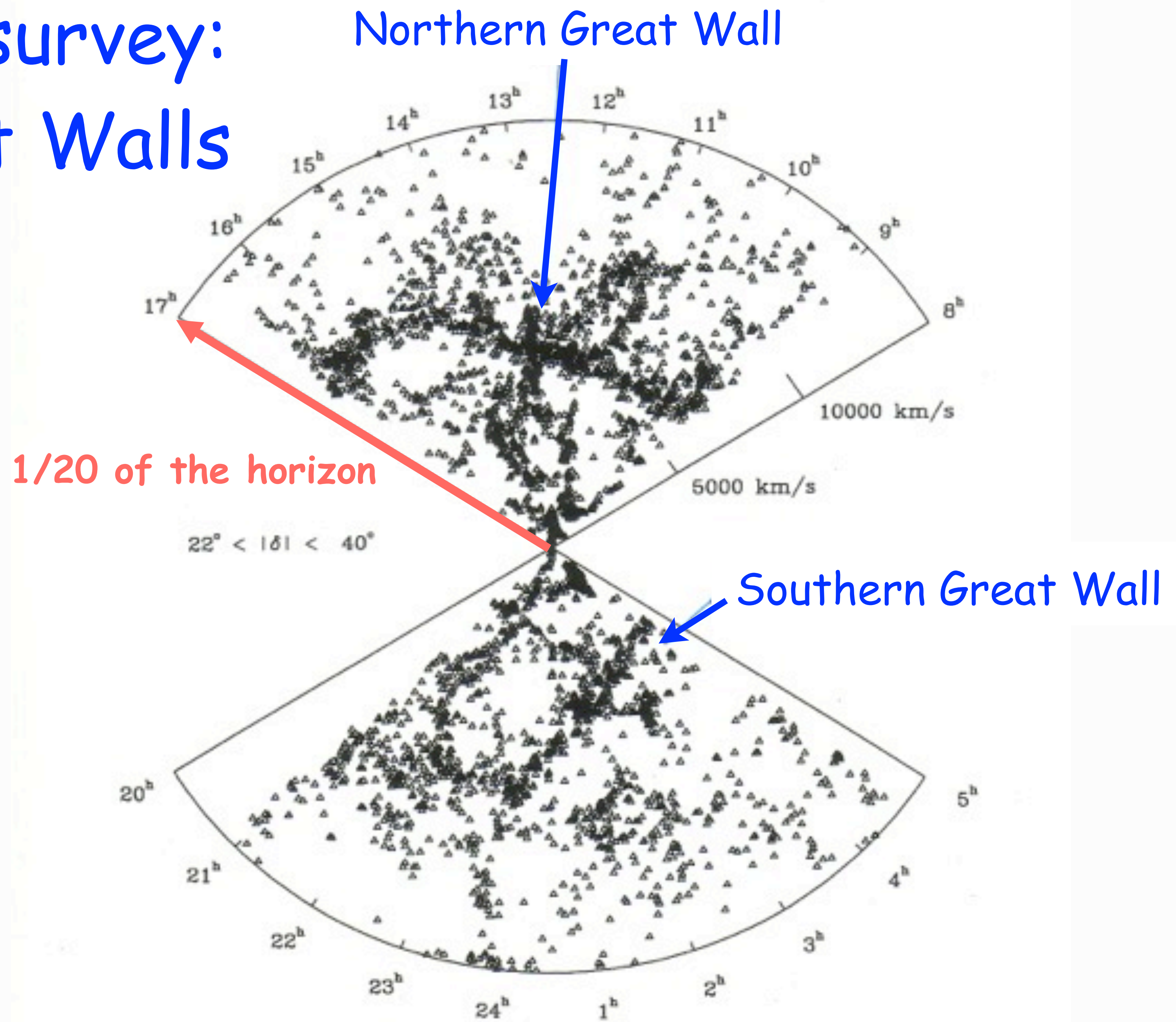
2002 - Wechsler et al.: halo concentration from mass assembly history

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

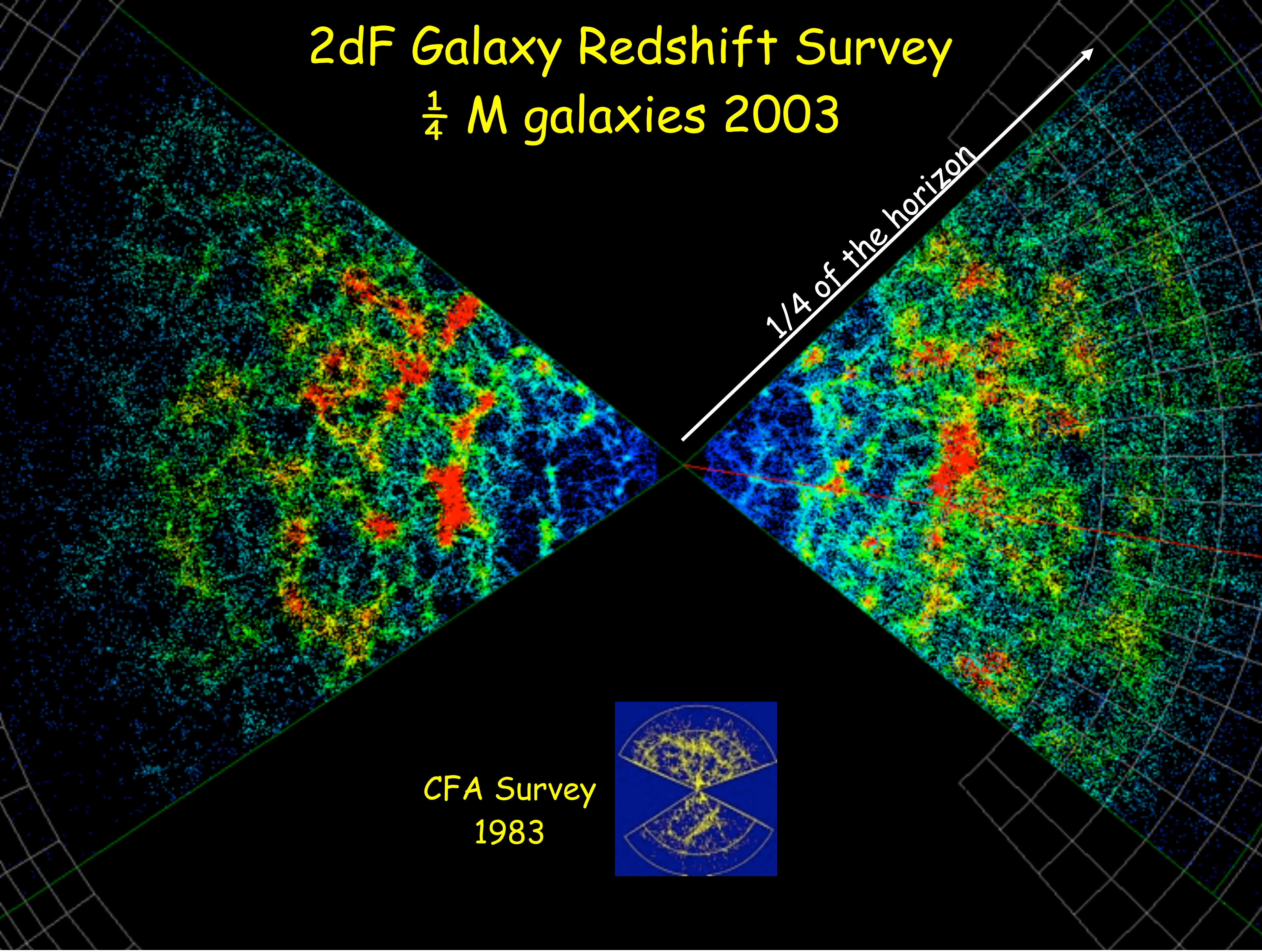

Lick Survey
1M galaxies
in angular bins
North Galactic
Hemisphere


The APM Galaxy Survey
Maddox et al

CfA survey: Great Walls

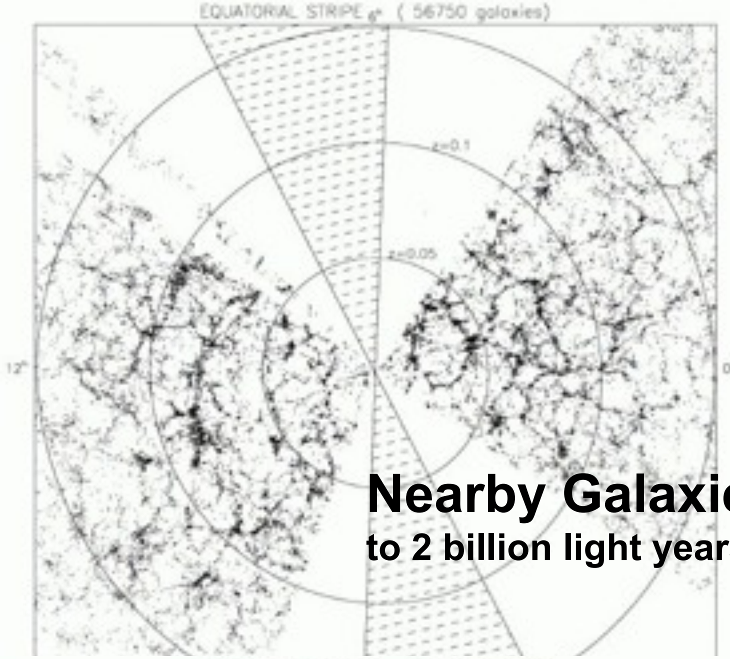


2dF Galaxy Redshift Survey
¼ M galaxies 2003

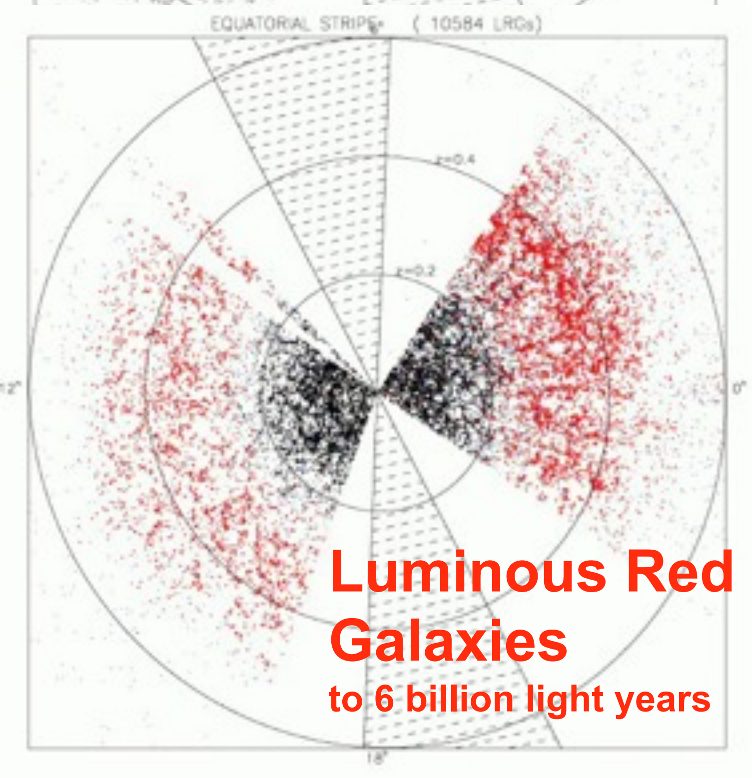


CFA Survey
1983

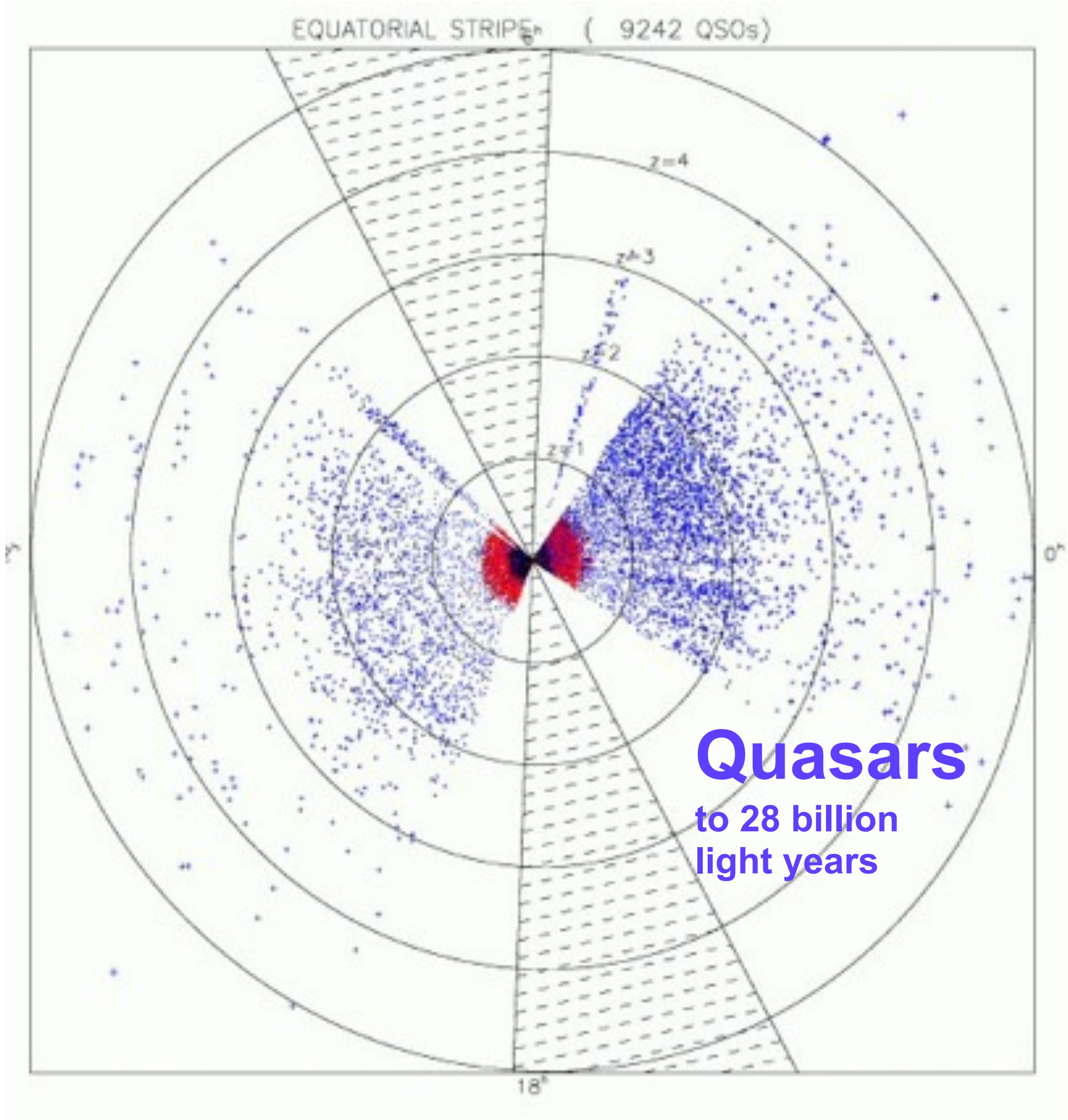
Mapping the Galaxies
Sloan Digital Sky Survey



Nearby Galaxies
to 2 billion light years

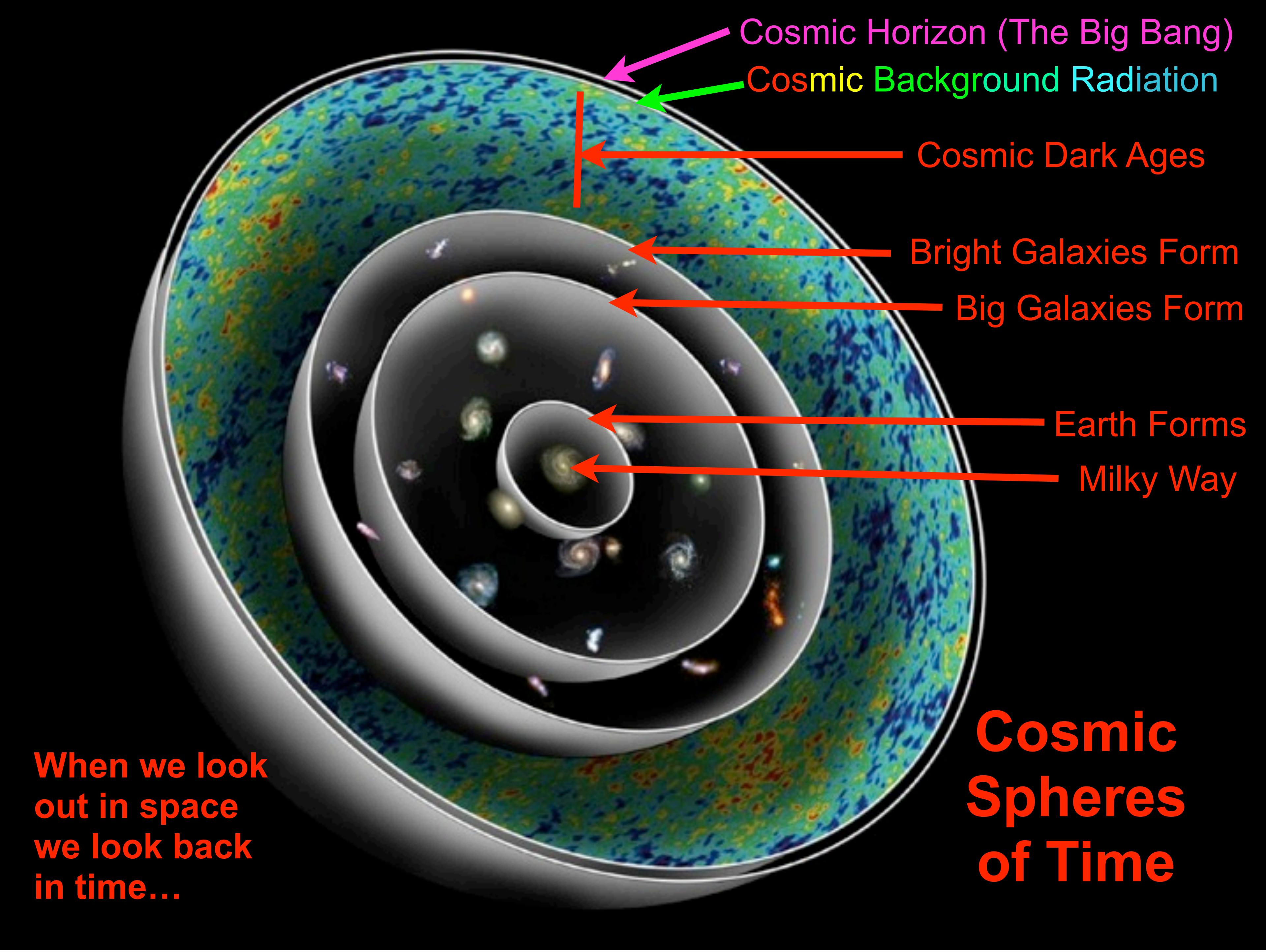


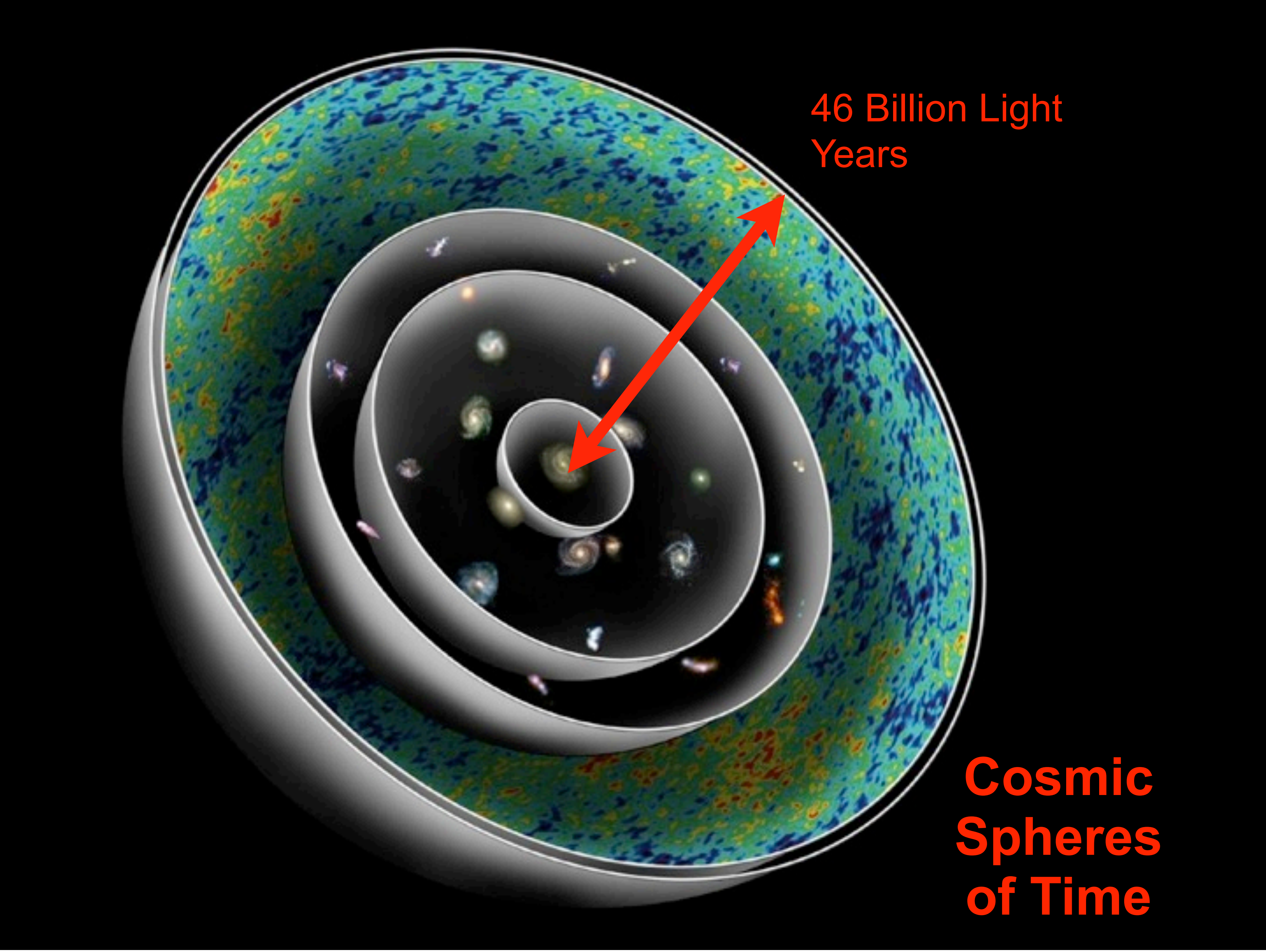
Luminous Red Galaxies
to 6 billion light years



Quasars
to 28 billion light years

GALAXIES MAPPED BY THE SLOAN SURVEY


Cosmic Horizon (The Big Bang)
Cosmic Background Radiation
Cosmic Dark Ages
Bright Galaxies Form
Big Galaxies Form
Earth Forms
Milky Way
When we look out in space we look back in time…
Cosmic Spheres of Time

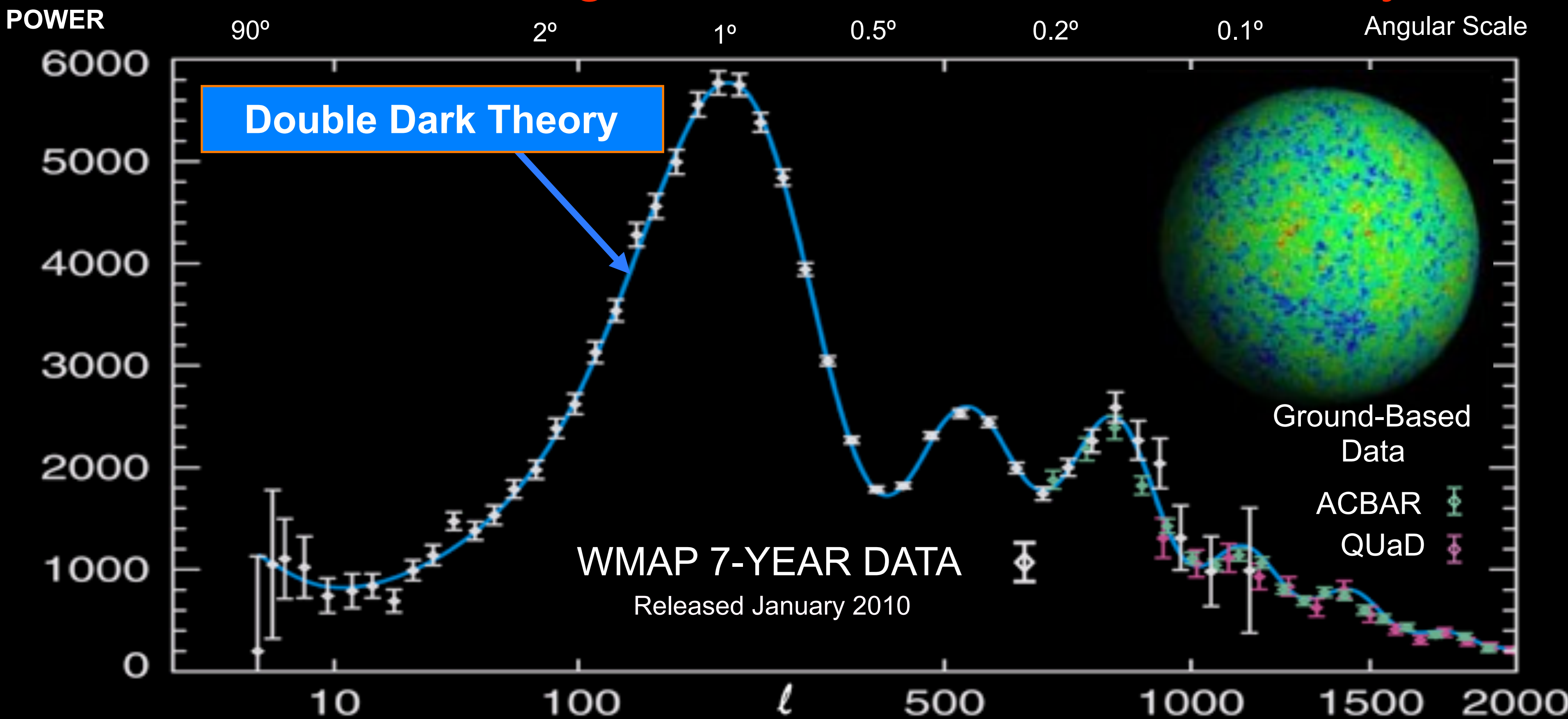

46 Billion Light Years
Cosmic Spheres of Time

DARK MATTER + DARK ENERGY = DOUBLE DARK THEORY

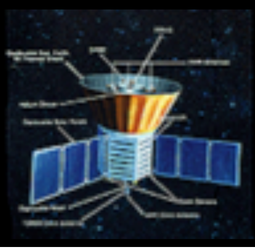
Technical Name:

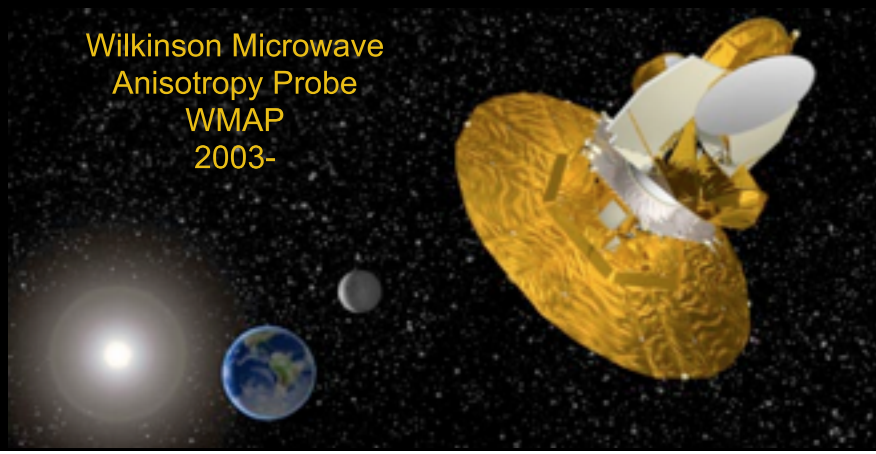
Lambda Cold Dark Matter (ΛCDM)

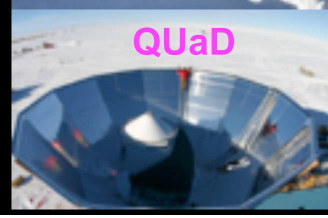
Big Bang Data Agrees with Double Dark Theory!

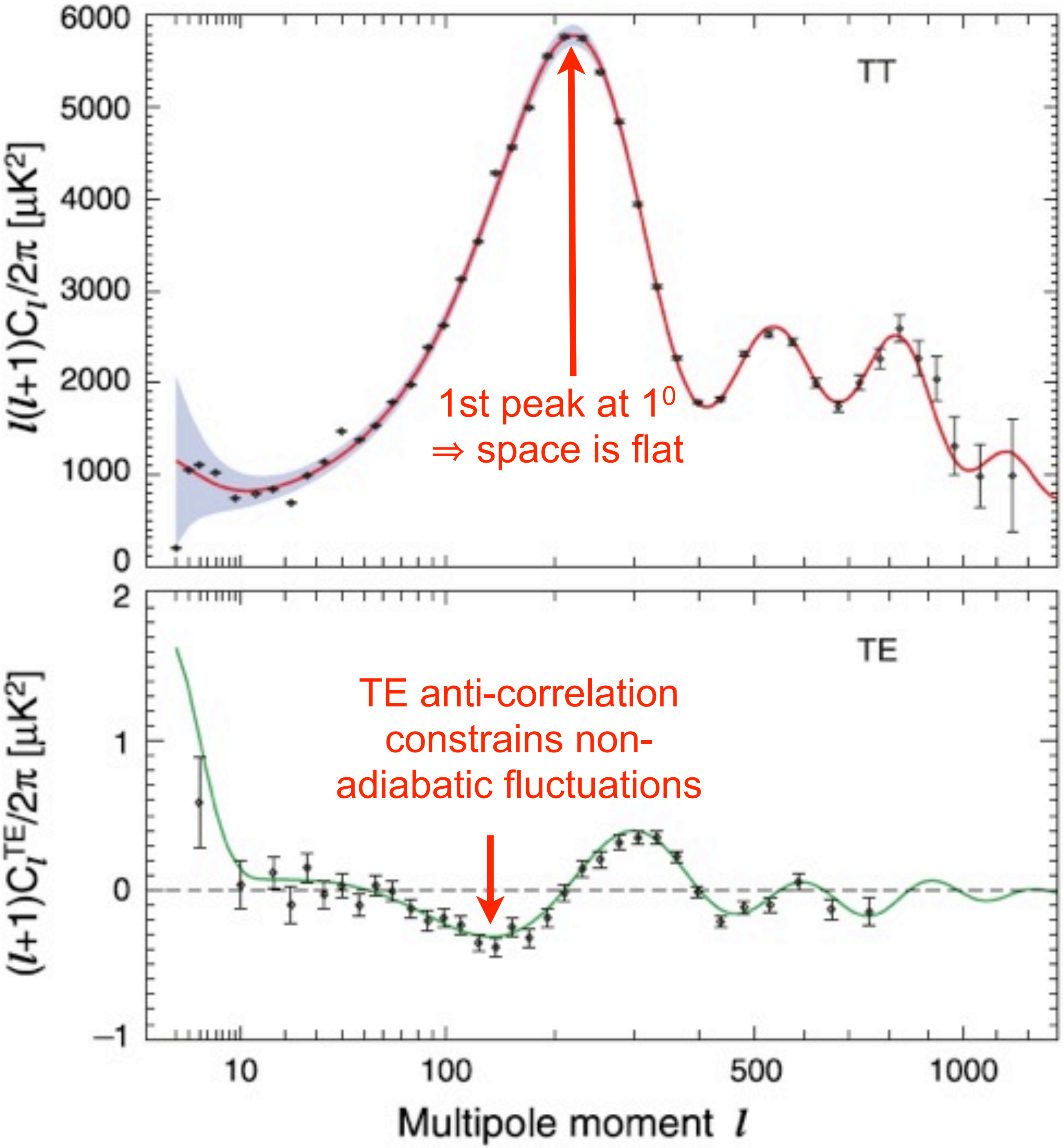


Cosmic
Background
Explorer
COBE
1992





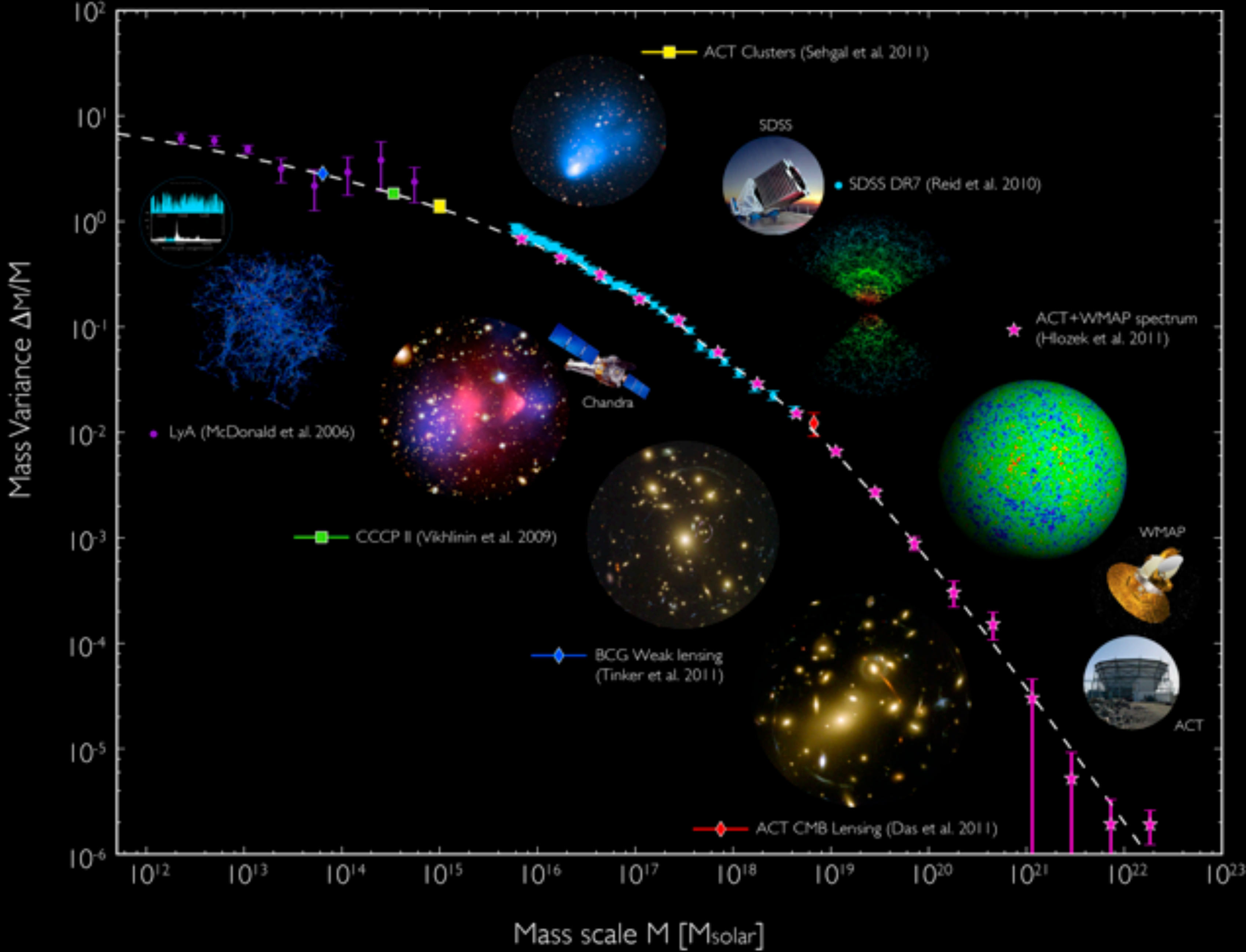




WMAP7

Fig. 9.— The temperature (TT) and temperature-polarization (TE) power spectra for the seven-year WMAP data set. The solid lines show the predicted spectrum for the best-fit flat ΛCDM model. The error bars on the data points represent measurement errors while the shaded region indicates the uncertainty in the model spectrum arising from cosmic variance.

Matter Distribution Agrees with Double Dark Theory!



SEVEN-YEAR WILKINSON MICROWAVE ANISOTROPY PROBE (WMAP) OBSERVATIONS: COSMOLOGICAL INTERPRETATION - E. Komatsu, et al. - January 2010

The combination of 7-year data from *WMAP* and improved astrophysical data rigorously tests the standard cosmological model and places new constraints on its basic parameters and extensions. By combining the *WMAP* data with the latest distance measurements from the Baryon Acoustic Oscillations (BAO) in the distribution of galaxies (Percival et al. 2009) and the Hubble constant (H_0) measurement (Riess et al. 2009), we determine the parameters of the simplest 6-parameter ΛCDM model. The power-law index of the primordial power spectrum is $n_s = 0.963 \pm 0.012$ (68% CL) for this data combination, a measurement that excludes the Harrison-Zel'dovich-Peebles spectrum by more than 3σ. The other parameters, including those beyond the minimal set, are also consistent with, and improved from, the 5-year results. We find no convincing deviations from the minimal model. The 7-year temperature power spectrum gives a better determination of the third acoustic peak, which results in a better determination of the redshift of the matter-radiation equality epoch. Notable examples of improved parameters are the total mass of neutrinos, $\sum m_\nu < 0.58$ eV (95% CL), and the effective number of neutrino species, $N_{\rm eff} = 4.34^{+0.86}_{-0.88}$ (68% CL), which benefit from better determinations of the third peak and H_0. The limit on a constant dark energy equation of state parameter from *WMAP*+BAO+H_0, without high-redshift Type Ia supernovae, is $w = -1.10 \pm 0.14$ (68% CL). We detect the effect of primordial helium on the temperature power spectrum and provide a new test of big bang nucleosynthesis by measuring $Y_p = 0.326 \pm 0.075$ (68% CL). We detect, and show on the map for the first time, the tangential and radial polarization patterns around hot and cold spots of temperature fluctuations, an important test of physical processes at $z = 1090$ and the dominance of adiabatic scalar fluctuations. The 7-year polarization data have significantly improved: we now detect the temperature-E-mode polarization cross power spectrum at 21σ, compared to 13σ from the 5-year data. With the 7-year temperature-B-mode cross power spectrum, the limit on a rotation of the polarization plane due to potential parity-violating effects has improved by 38% to $\Delta\alpha = -1.1^\circ \pm 1.3^\circ$ (statistical) $\pm 1.5^\circ$ (systematic) (68% CL). We report a significant (8σ) detection of the Sunyaev-Zel'dovich (SZ) effect at the locations of known clusters of galaxies, and show that the measured SZ signal is a factor of 0.5 to 0.7 times the predictions from analytical models, hydrodynamical simulations, and X-ray observations. This lower amplitude is consistent with the lower-than-expected SZ power spectrum recently measured by the South Pole Telescope collaboration.

Nine-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Final Maps and Results

arXiv:1212.5226 (WMAP9)

C. L. Bennett, D. Larson, J. L. Weiland, N. Jarosik, G. Hinshaw, N. Odegard, K. M. Smith, R. S. Hill, B. Gold, M. Halpern, E. Komatsu, M. R. Nolta, L. Page, D. N. Spergel, E. Wollack, J. Dunkley, A. Kogut, M. Limon, S. S. Meyer, G. S. Tucker, E. L. Wright

(Submitted on 20 Dec 2012)

We present the final nine-year maps and basic results from the WMAP mission. We provide new nine-year full sky temperature maps that were processed to reduce the asymmetry of the effective beams. Temperature and polarization sky maps are examined to separate CMB anisotropy from foreground emission, and both types of signals are analyzed in detail. The WMAP mission has resulted in a highly constrained LCDM cosmological model with precise and accurate parameters in agreement with a host of other cosmological measurements. When WMAP data are combined with finer scale CMB, baryon acoustic oscillation, and Hubble constant measurements, we find that Big Bang nucleosynthesis is well supported and there is no compelling evidence for a non-standard number of neutrino species (3.26+/-0.35). The model fit also implies that the age of the universe is 13.772+/-0.059 Gyr, and the fit Hubble constant is H0 = 69.32+/-0.80 km/s/Mpc. Inflation is also supported: the fluctuations are adiabatic, with Gaussian random phases; the detection of a deviation of the scalar spectral index from unity reported earlier by WMAP now has high statistical significance (n_s = 0.9608+/-0.0080); and the universe is close to flat/Euclidean, Omega_k = -0.0027 (+0.0039/-0.0038). Overall, the WMAP mission has resulted in a reduction of the cosmological parameter volume by a factor of 68,000 for the standard six-parameter LCDM model, based on CMB data alone. For a model including tensors, the allowed seven-parameter volume has been reduced by a factor 117,000. Other cosmological observations are in accord with the CMB predictions, and the combined data reduces the cosmological parameter volume even further. With no significant anomalies and an adequate goodness-of-fit, the inflationary flat LCDM model and its precise and accurate parameters rooted in WMAP data stands as the standard model of cosmology.

N. Jarosik et al. - January 2010

Table 8. WMAP Seven-year Cosmological Parameter Summary

Description	Symbol	*WMAP*-only	*WMAP*+BAO+H_0
Parameters for Standard ΛCDM Model [a]			
Age of universe	t_0	13.75 ± 0.13 Gyr	13.75 ± 0.11 Gyr
Hubble constant	H_0	71.0 ± 2.5 km/s/Mpc	$70.4^{+1.3}_{-1.4}$ km/s/Mpc
Baryon density	Ω_b	0.0449 ± 0.0028	0.0456 ± 0.0016
Physical baryon density	$\Omega_b h^2$	$0.02258^{+0.00057}_{-0.00056}$	0.02260 ± 0.00053
Dark matter density	Ω_c	0.222 ± 0.026	0.227 ± 0.014
Physical dark matter density	$\Omega_c h^2$	0.1109 ± 0.0056	0.1123 ± 0.0035
Dark energy density	Ω_Λ	0.734 ± 0.029	$0.728^{+0.015}_{-0.016}$
Curvature fluctuation amplitude, $k_0 = 0.002$ Mpc^{-1} [b]	$\Delta^2_{\mathcal{R}}$	$(2.43 \pm 0.11) \times 10^{-9}$	$(2.441^{+0.088}_{-0.092}) \times 10^{-9}$
Fluctuation amplitude at $8h^{-1}$ Mpc	σ_8	0.801 ± 0.030	0.809 ± 0.024
Scalar spectral index	n_s	0.963 ± 0.014	0.963 ± 0.012
Redshift of matter-radiation equality	z_{eq}	3196^{+134}_{-133}	3232 ± 87
Angular diameter distance to matter-radiation eq. [c]	$d_A(z_{eq})$	14281^{+158}_{-161} Mpc	14238^{+128}_{-129} Mpc
Redshift of decoupling	z_*	$1090.79^{+0.94}_{-0.92}$	$1090.89^{+0.68}_{-0.69}$
Age at decoupling	t_*	379164^{+5187}_{-5243} yr	377730^{+3205}_{-3200} yr
Angular diameter distance to decoupling [c,d]	$d_A(z_*)$	14116^{+160}_{-163} Mpc	14073^{+129}_{-130} Mpc
Sound horizon at decoupling [d]	$r_s(z_*)$	$146.6^{+1.5}_{-1.6}$ Mpc	146.2 ± 1.1 Mpc
Acoustic scale at decoupling [d]	$l_A(z_*)$	302.44 ± 0.80	302.40 ± 0.73
Reionization optical depth	τ	0.088 ± 0.015	0.087 ± 0.014
Redshift of reionization	z_{reion}	10.5 ± 1.2	10.4 ± 1.2
Parameters for Extended Models [e]			
Total density [f]	Ω_{tot}	$1.080^{+0.093}_{-0.071}$	$1.0023^{+0.0056}_{-0.0054}$
Equation of state [g]	w	$-1.12^{+0.42}_{-0.43}$	-0.980 ± 0.053
Tensor to scalar ratio, $k_0 = 0.002$ Mpc^{-1} [b,h]	r	< 0.36 (95% CL)	< 0.24 (95% CL)
Running of spectral index, $k_0 = 0.002$ Mpc^{-1} [b,i]	$dn_s/d\ln k$	-0.034 ± 0.026	-0.022 ± 0.020
Neutrino density [j]	$\Omega_\nu h^2$	< 0.014 (95% CL)	< 0.0062 (95% CL)
Neutrino mass [j]	$\sum m_\nu$	< 1.3 eV (95% CL)	< 0.58 eV (95% CL)
Number of light neutrino families [k]	N_{eff}	> 2.7 (95% CL)	$4.34^{+0.86}_{-0.88}$

The parameters reported in the first section assume the 6 parameter flat CDM model, first using WMAP data only (Larson et al. 2010), **then using WMAP+BAO+H_0 data** (Komatsu et al. 2010). The H_0 data consists of a Gaussian prior on the present-day value of the Hubble constant, $H_0 = 74.2 \pm 3.6$ km s^{-1} Mpc^{-1} (Riess et al. 2009), while the BAO priors on the distance ratio $r_s(z_d)/D_V(z)$ at $z = 0.2, 0.3$ are obtained from the Sloan Digital Sky Survey Data Release 7 (Percival et al. 2009). **Uncertainties are 68% CL unless otherwise noted.**

WMAP Cosmological Parameters

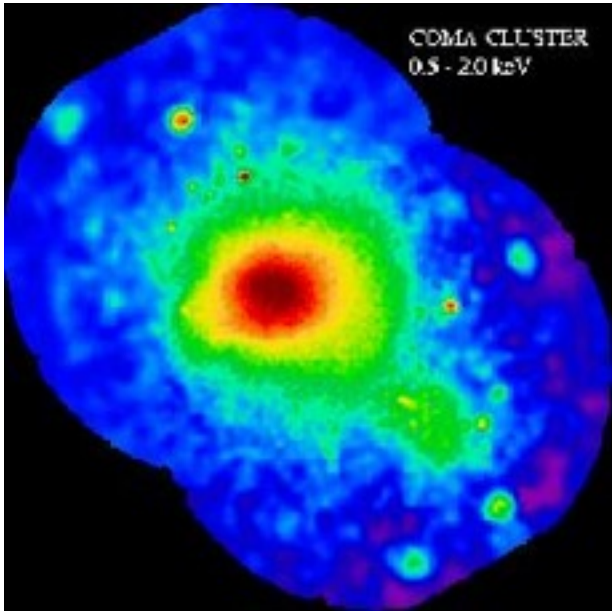
Model: lcdm

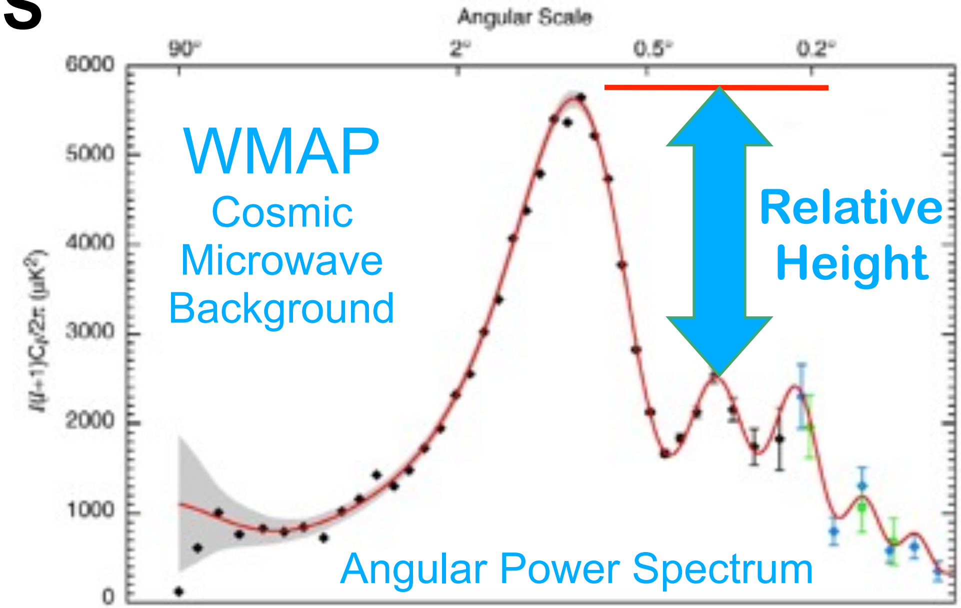
Data: wmap9+spt+act+snls3

$10^9\Delta^2_{\mathcal{R}}$	$2.407^{+0.081}_{-0.082}$	H_0	71.2 ± 1.5 km/s/Mpc
$A_{\rm clustered}$	< 10 (95% CL)	$A^{\rm ACT}_{\rm Poisson}$	14.8 ± 2.3
$A^{\rm SPT}_{\rm Poisson}$	> 17 (95% CL)	$\ell(\ell+1)C_{220}/(2\pi)$	5752^{+32}_{-33} μK^2
$d_A(z_{\rm eq})$	14263^{+83}_{-84} Mpc	$d_A(z_*)$	14099 ± 84 Mpc
$D_v(z=0.57)/r_s(z_d)$	13.07 ± 0.22	η	$(6.12 \pm 0.10) \times 10^{-10}$
$k_{\rm eq}$	0.00975 ± 0.00023	$\ell_{\rm eq}$	$137.4^{+2.4}_{-2.5}$
ℓ_*	$301.98^{+0.42}_{-0.41}$	n_b	$(2.513 \pm 0.041) \times 10^{-7}$ cm^{-3}
n_s	$0.9674^{+0.0096}_{-0.0095}$	n_s	$0.95 < n_s < 0.99$ (95% CL)
Ω_b	0.0441 ± 0.0016	$\Omega_b h^2$	0.02237 ± 0.00037
Ω_c	0.220 ± 0.015	$\Omega_c h^2$	0.1112 ± 0.0032
Ω_Λ	0.736 ± 0.017	Ω_m	0.264 ± 0.017
$\Omega_m h^2$	0.1335 ± 0.0031	$r_s(z_d)$	153.32 ± 0.92 Mpc
$r_s(z_d)/D_v(z=0.106)$	$0.3539^{+0.0085}_{-0.0084}$	$r_s(z_d)/D_v(z=0.2)$	0.1929 ± 0.0043
$r_s(z_d)/D_v(z=0.35)$	0.1156 ± 0.0023	$r_s(z_d)/D_v(z=0.44)$	0.0948 ± 0.0017
$r_s(z_d)/D_v(z=0.54)$	$0.0800^{+0.0014}_{-0.0013}$	$r_s(z_d)/D_v(z=0.57)$	0.0765 ± 0.0013
$r_s(z_d)/D_v(z=0.6)$	0.0735 ± 0.0012	$r_s(z_d)/D_v(z=0.73)$	$0.06323^{+0.00092}_{-0.00091}$
$r_s(z_*)$	146.67 ± 0.84	R	1.718 ± 0.011
σ_8	0.805 ± 0.017	$\sigma_8\Omega_m^{0.5}$	0.413 ± 0.020
$\sigma_8\Omega_m^{0.6}$	0.362 ± 0.019	$\alpha_{\rm SNLS}$	1.43 ± 0.11
$\beta_{\rm SNLS}$	3.26 ± 0.11	$A_{\rm SZ}$	< 1.1 (95% CL)
t_0	$13.719^{+0.075}_{-0.074}$ Gyr	τ	0.086 ± 0.013
θ_*	0.010403 ± 0.000014	θ_*	0.59607 ± 0.00082 °
$\tau_{\rm rec}$	285.4 ± 1.7	$t_{\rm reion}$	469 ± 65 Myr
t_*	378789^{+2952}_{-2945} yr	z_d	$1019.85^{+0.82}_{-0.83}$
$z_{\rm eq}$	3196 ± 74	$z_{\rm rec}$	$1088.24^{+0.66}_{-0.65}$
$z_{\rm reion}$	10.4 ± 1.1	z_*	$1091.08^{+0.63}_{-0.62}$

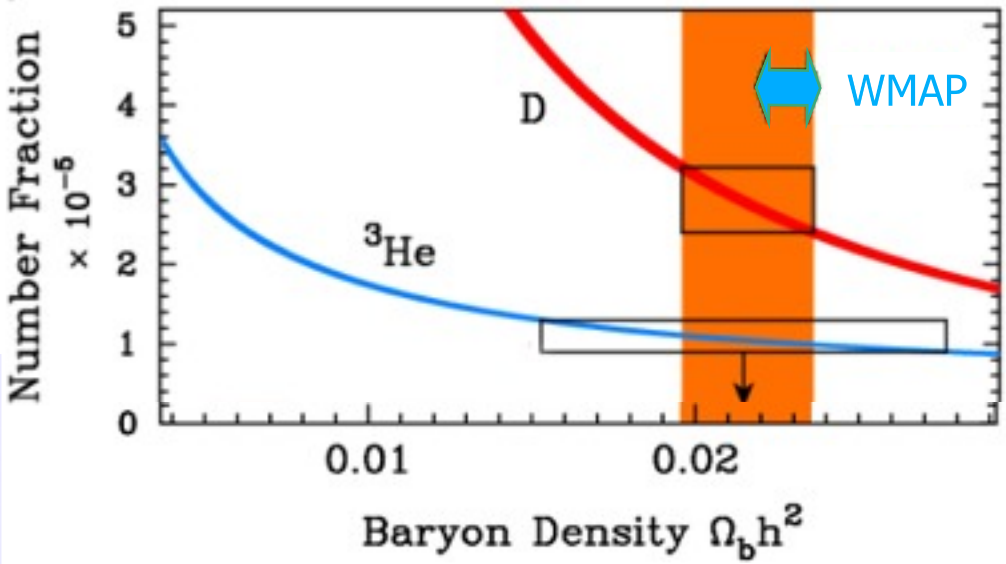
5 INDEPENDENT MEASURES AGREE: ATOMS ARE ONLY ~4% OF COSMIC DENSITY

Galaxy Cluster in X-rays

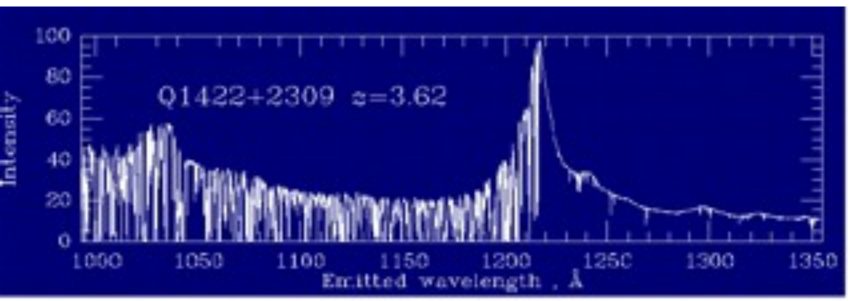




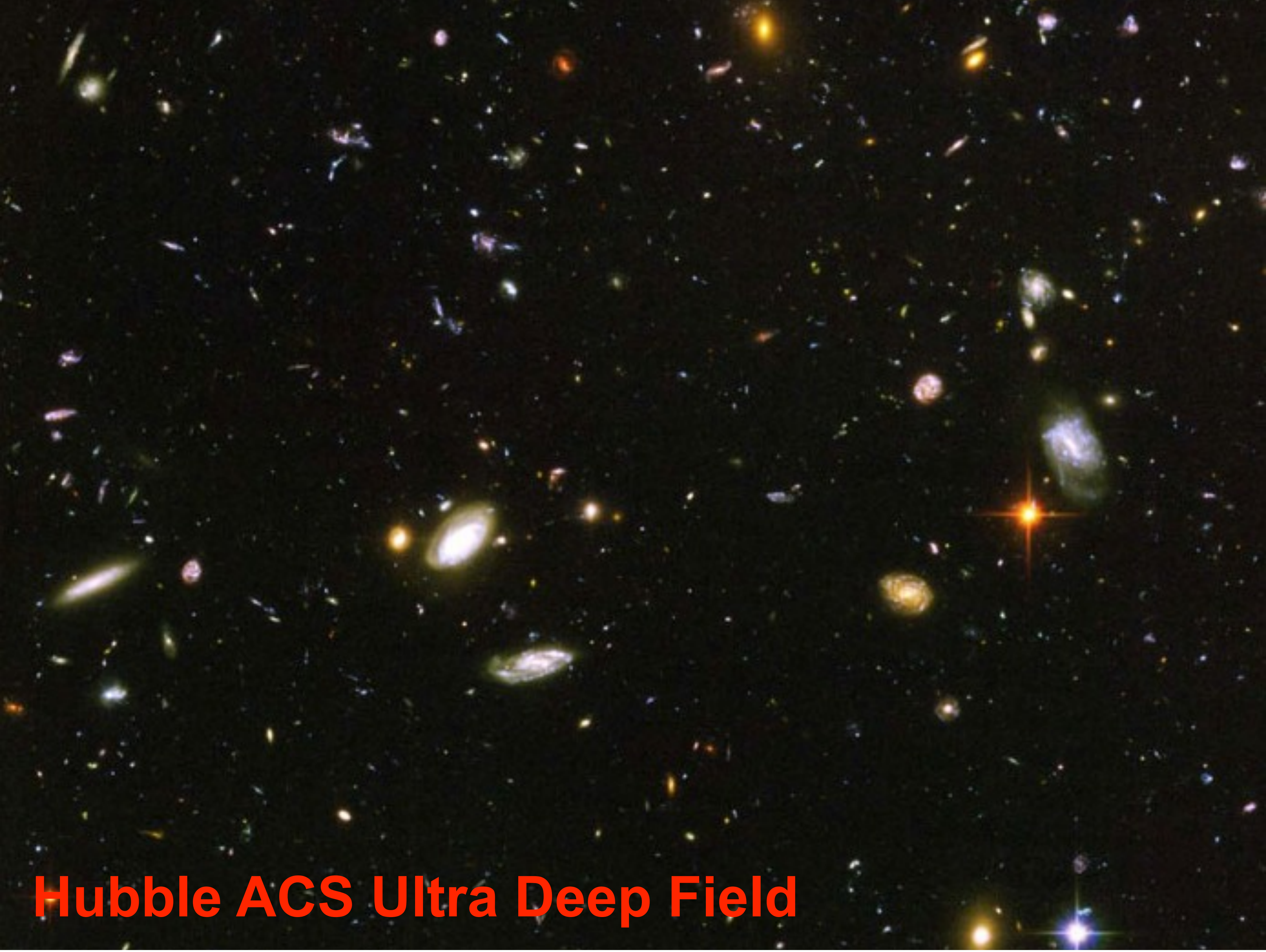
Deuterium Abundance + Big Bang Nucleosynthesis



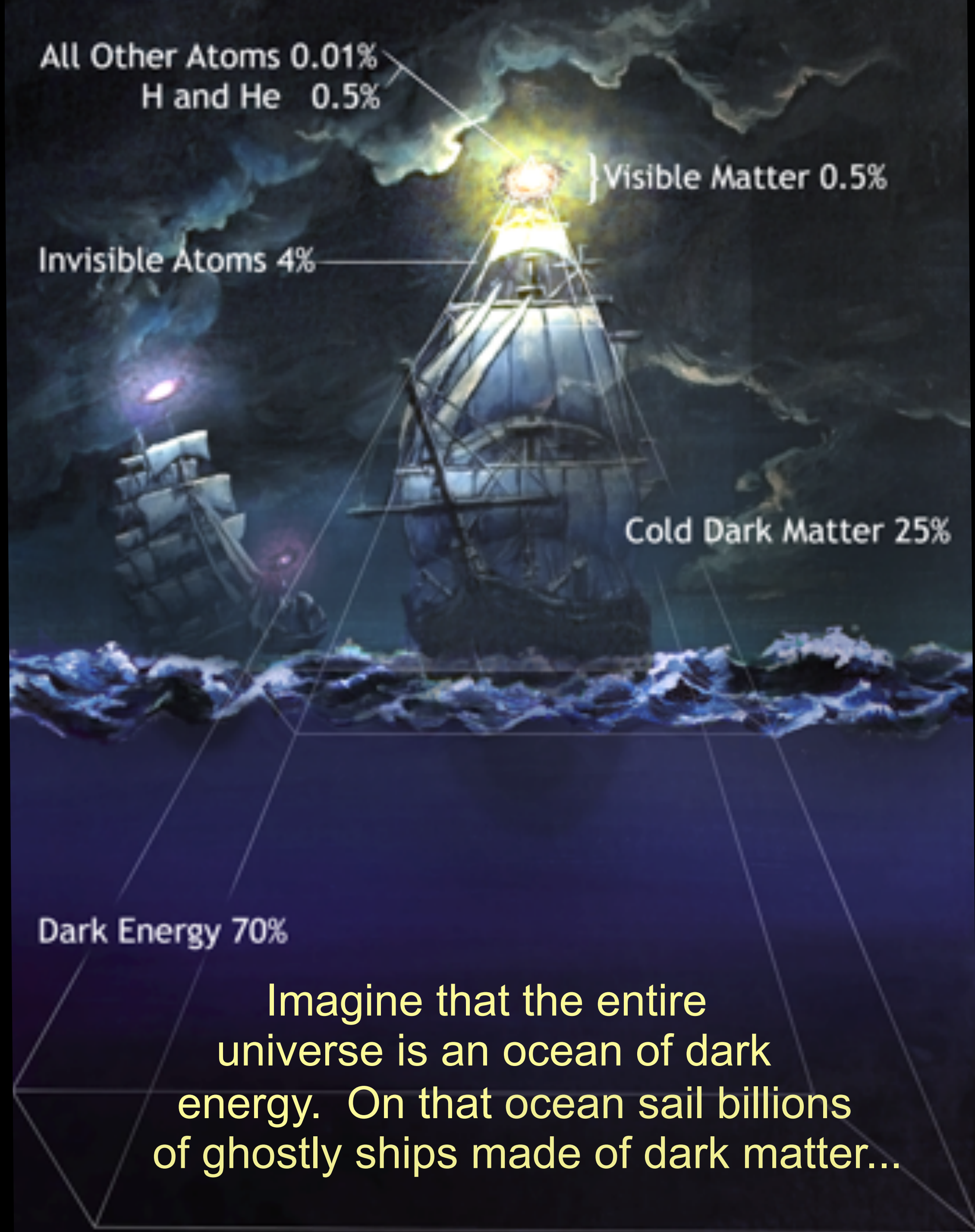
Absorption of Quasar Light



& BAO WIGGLES IN GALAXY P(k)


Hubble ACS Ultra Deep Field

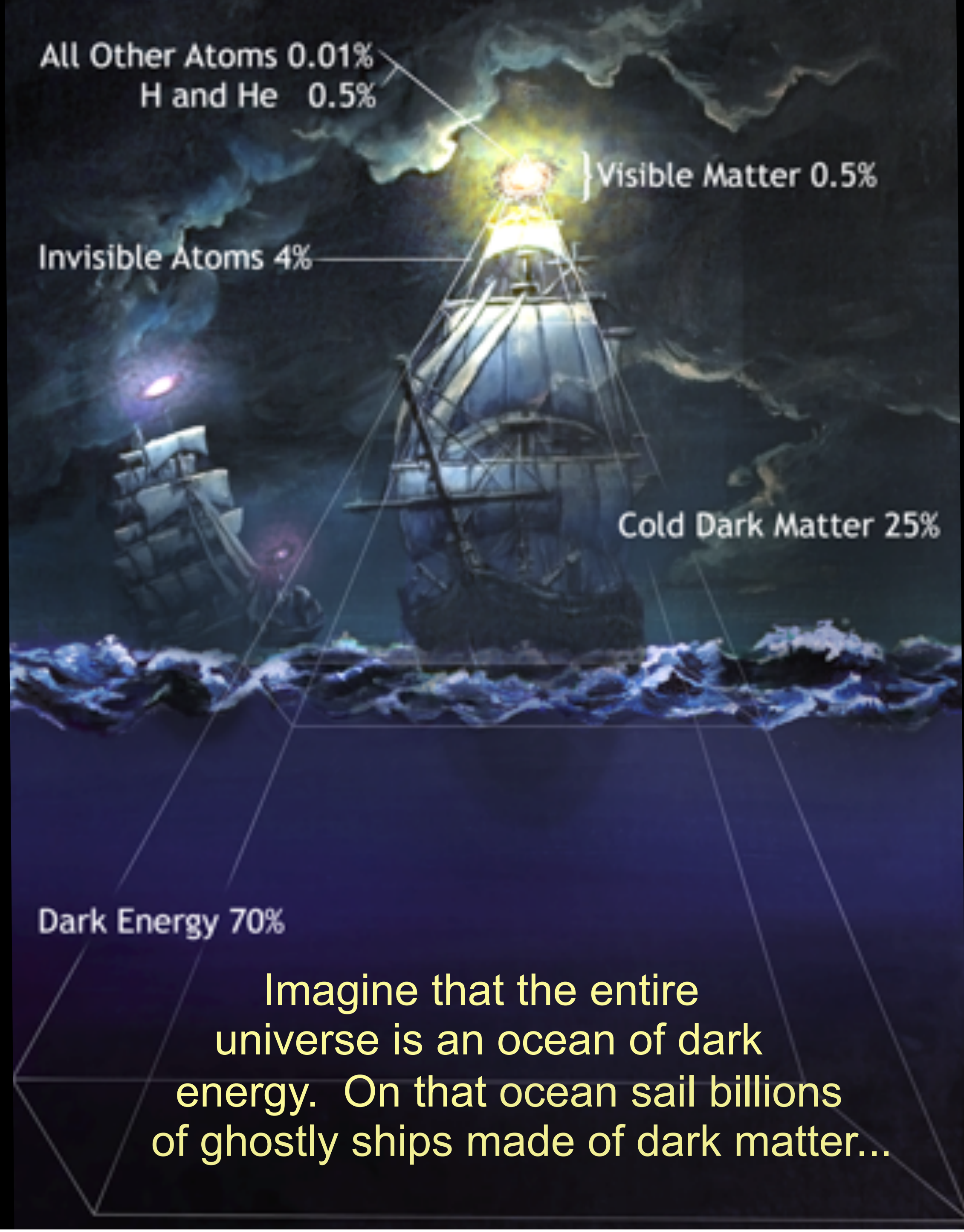
Matter and Energy Content of the Universe



Dark Matter Ships

on a

Dark Energy Ocean



Matter and Energy Content of the Universe

ΛCDM

Double Dark Theory

Cosmological Simulations

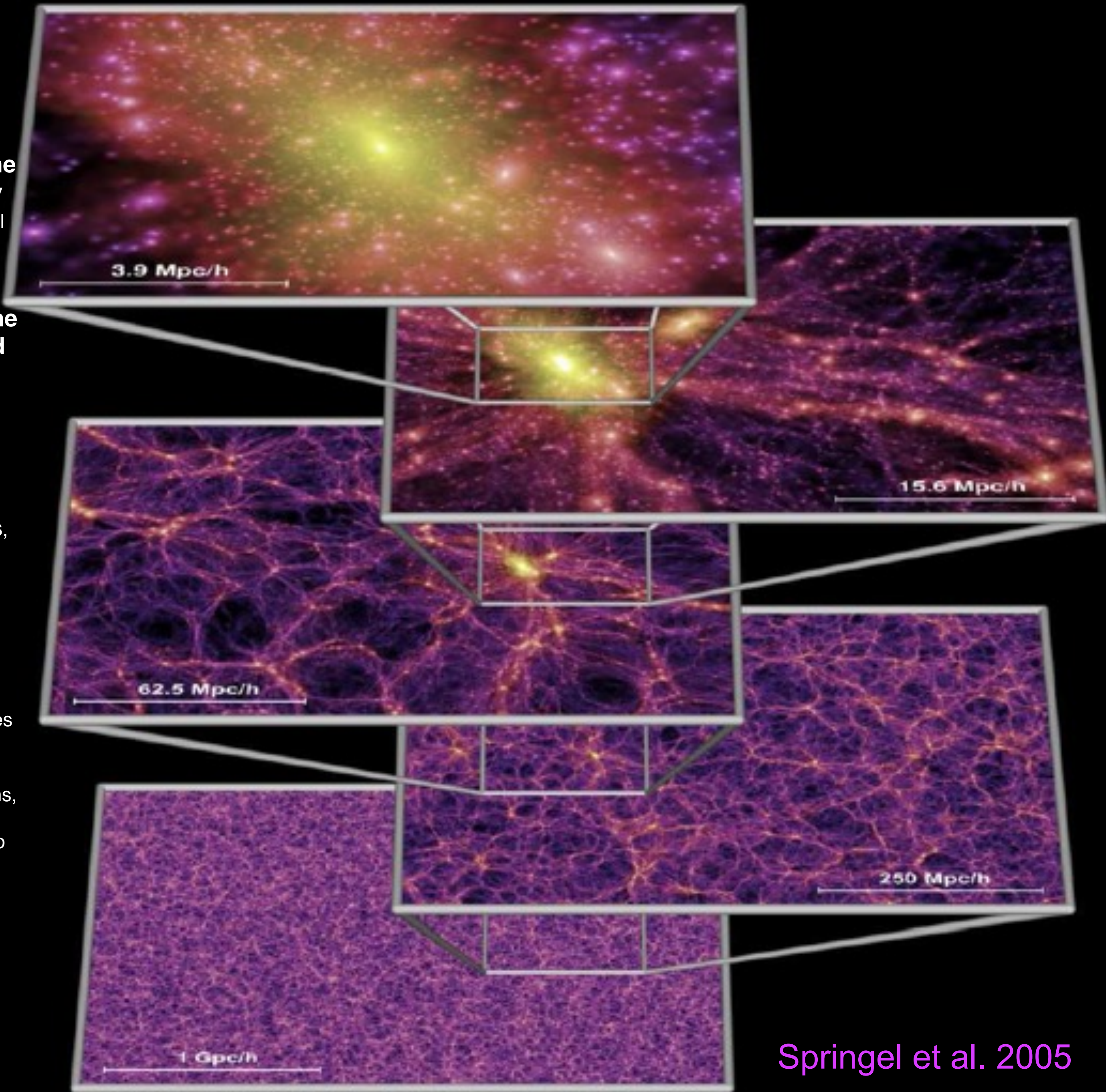
Astronomical observations represent snapshots of moments in time. It is the role of astrophysical theory to produce movies -- both metaphorical and actual -- that link these snapshots together into a coherent physical theory.

Cosmological dark matter simulations show large scale structure, growth of structure, and dark matter halo properties

Hydrodynamic galaxy formation simulations: evolution of galaxies, formation of galactic spheroids via mergers, galaxy images in all wavebands including stellar evolution and dust

The Millennium Run

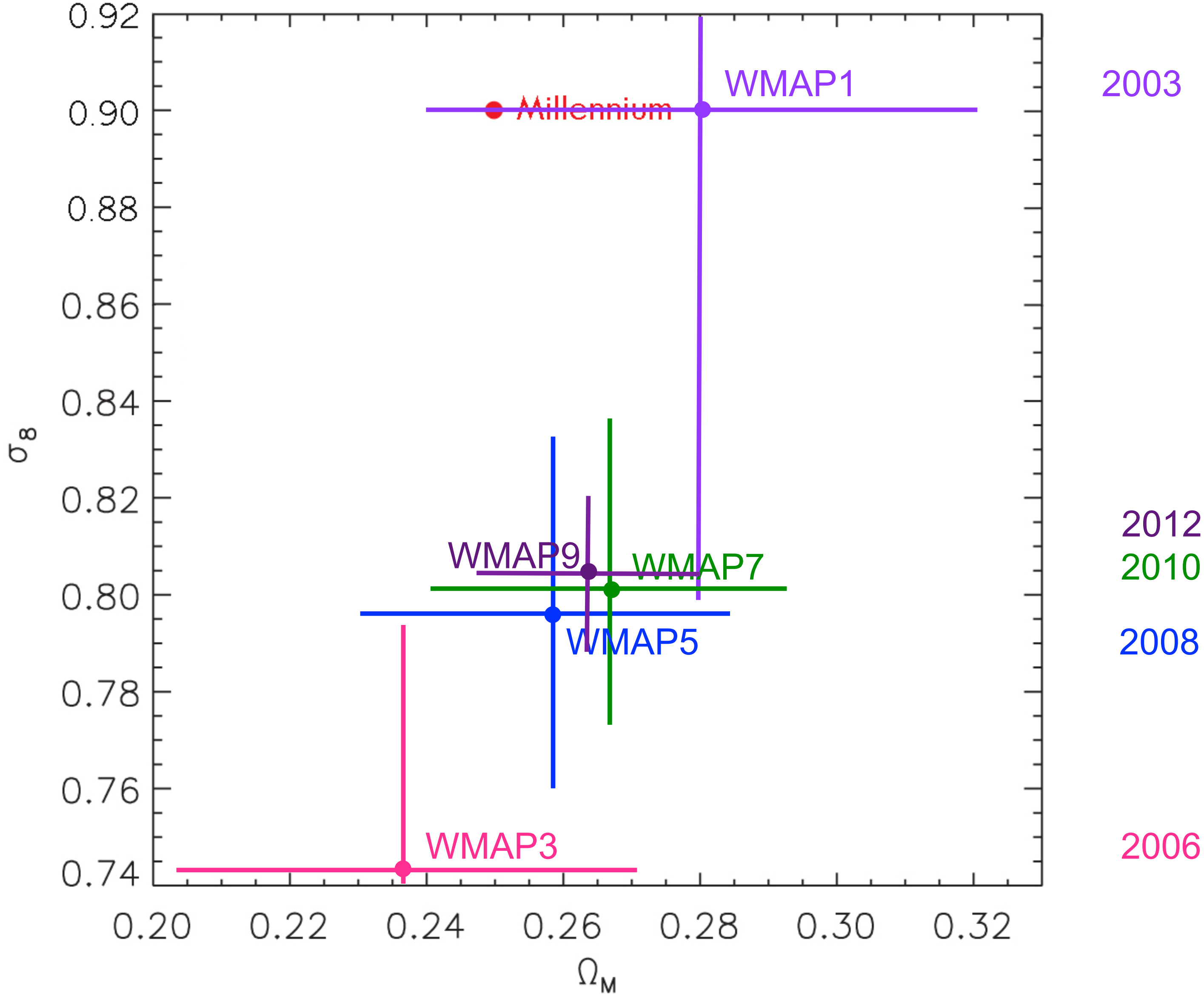
• **properties of halos** (radial profile, concentration, shapes)
• **evolution of the number density of halos**, essential for normalization of Press-Schechter-type models
• **evolution of the distribution and clustering of halos** in real and redshift space, for comparison with observations
• **accretion history of halos**, assembly bias (variation of large-scale clustering with as- sembly history), and correlation with halo properties including angular momenta and shapes
• **halo statistics** including the mass and velocity functions, angular momentum and shapes, subhalo numbers and distribution, and correlation with environment



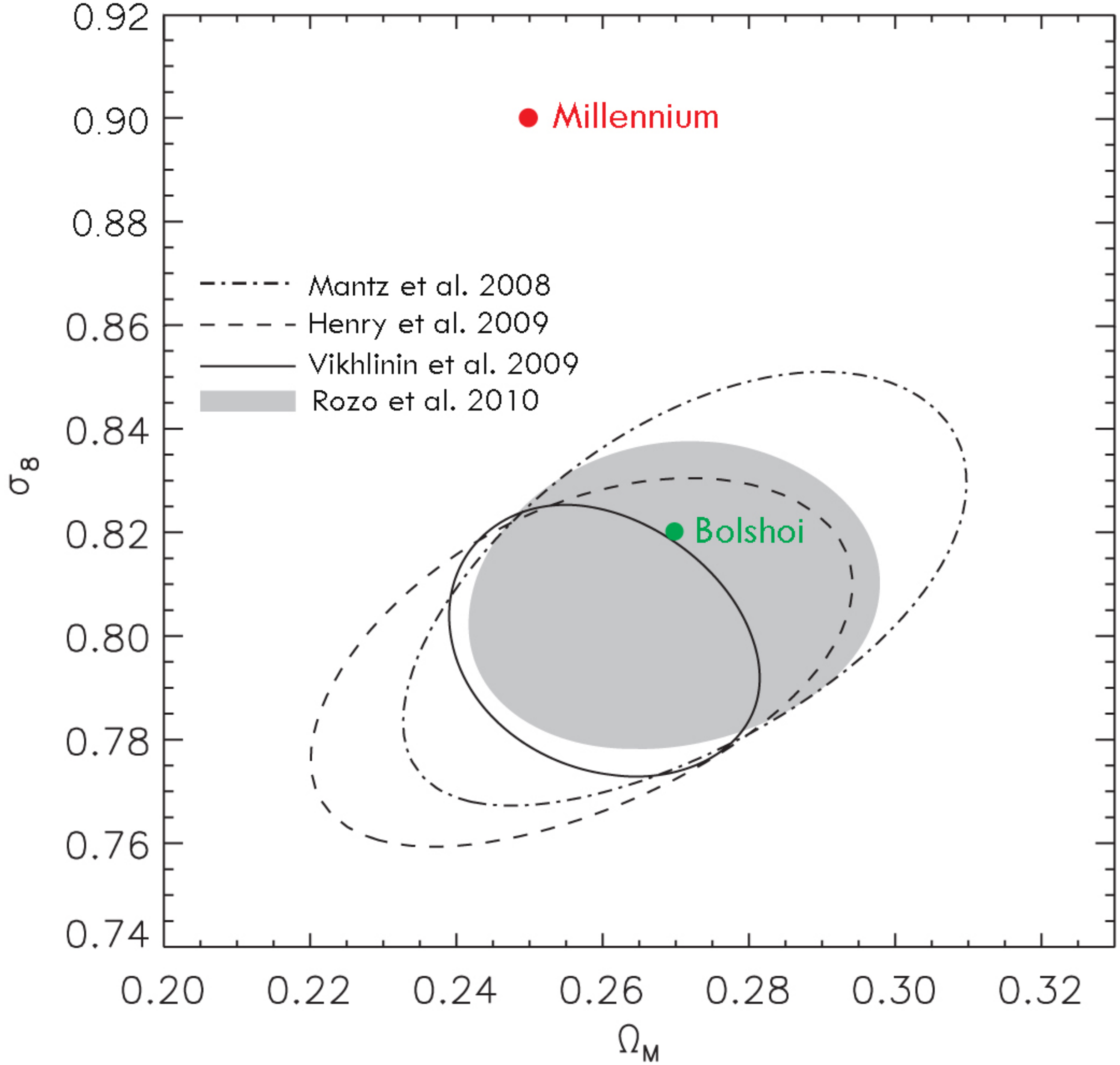
• **void statistics**, including sizes and shapes and their evolution, and the orientation of halo spins around voids
• quantitative descriptions of the evolving **cosmic web**, including applications to weak gravitational lensing
• preparation of **mock catalogs**, essential for analyzing SDSS and other survey data, and for preparing for new large surveys for dark energy etc.
• **merger trees**, essential for **semi-analytic modeling** of the evolving galaxy population, including models for the galaxy merger rate, the history of star formation and galaxy colors and morphology, the evolving AGN luminosity function, stellar and AGN feedback, recycling of gas and metals, etc.

Springel et al. 2005

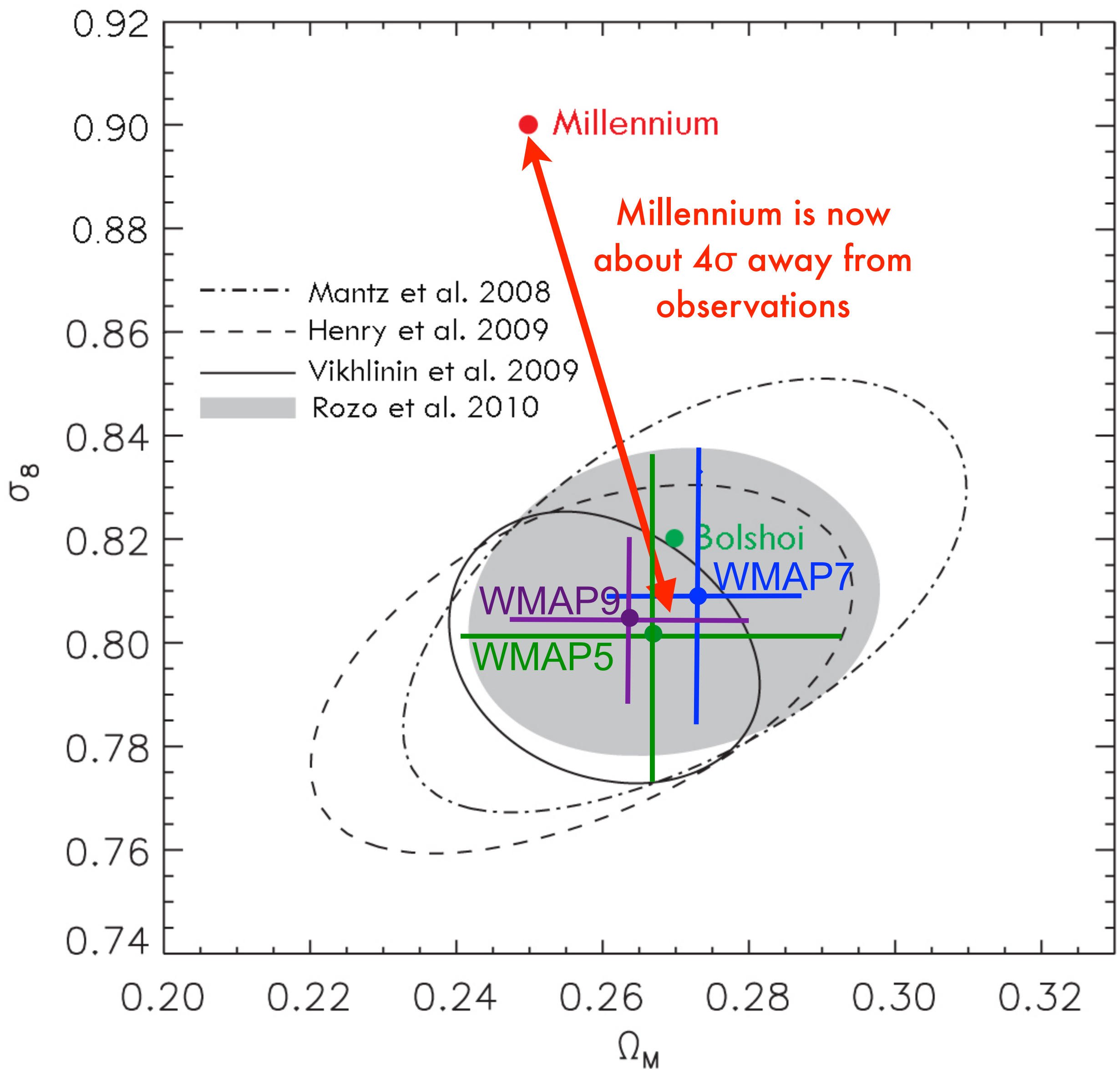
WMAP-only Determination of σ_8 and Ω_M



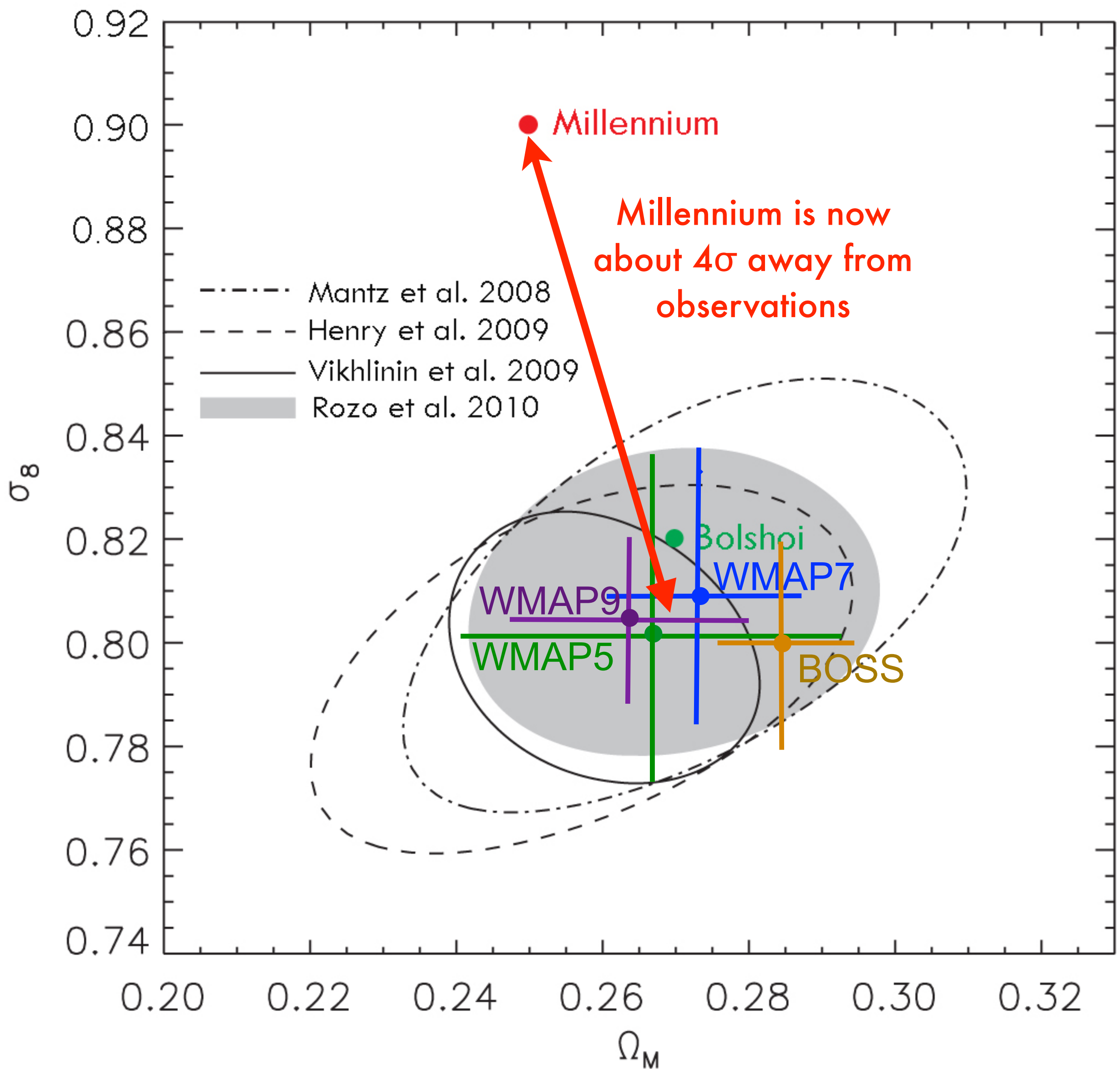
WMAP+SN+Clusters Determination of σ_8 and Ω_M

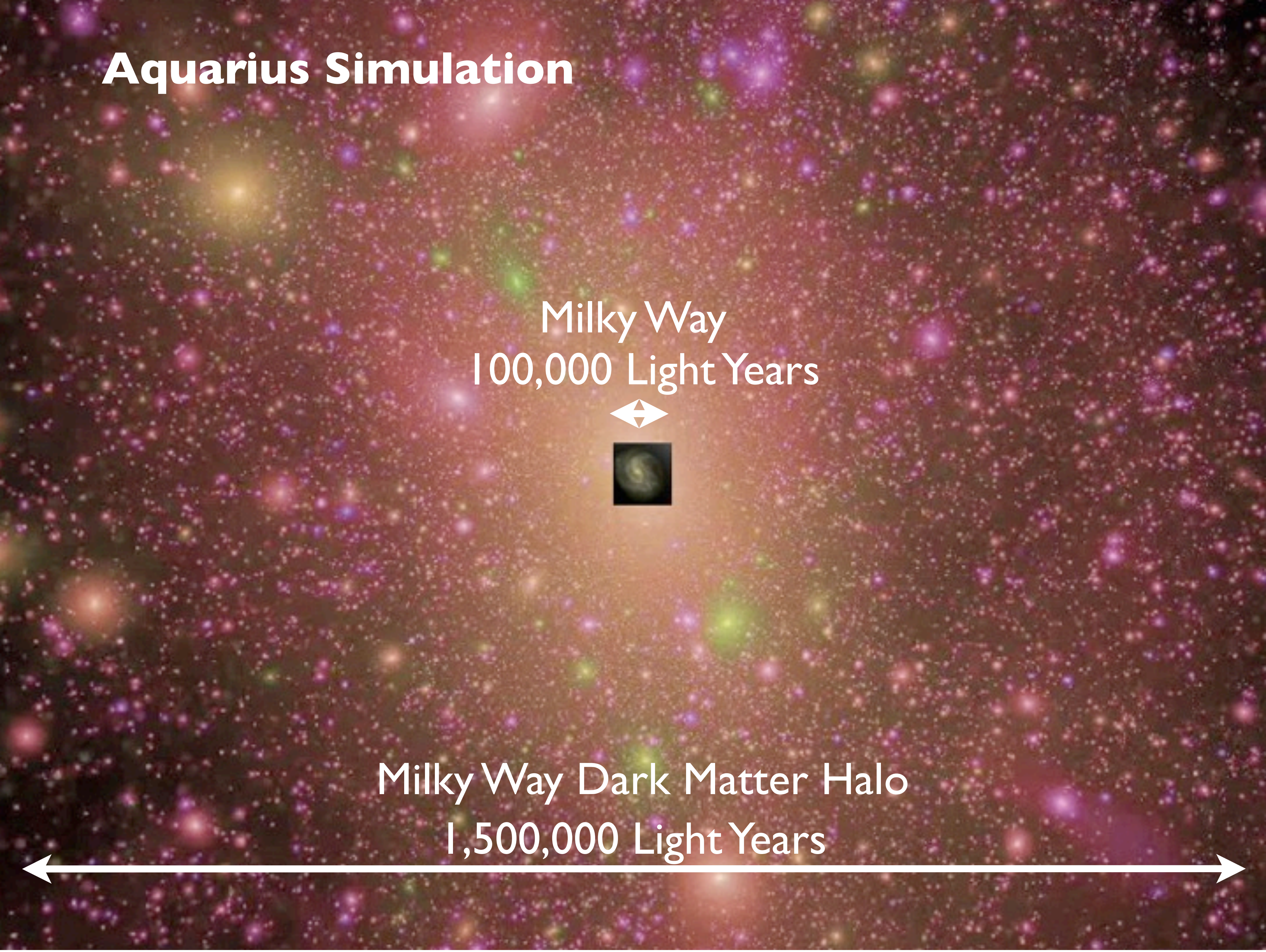


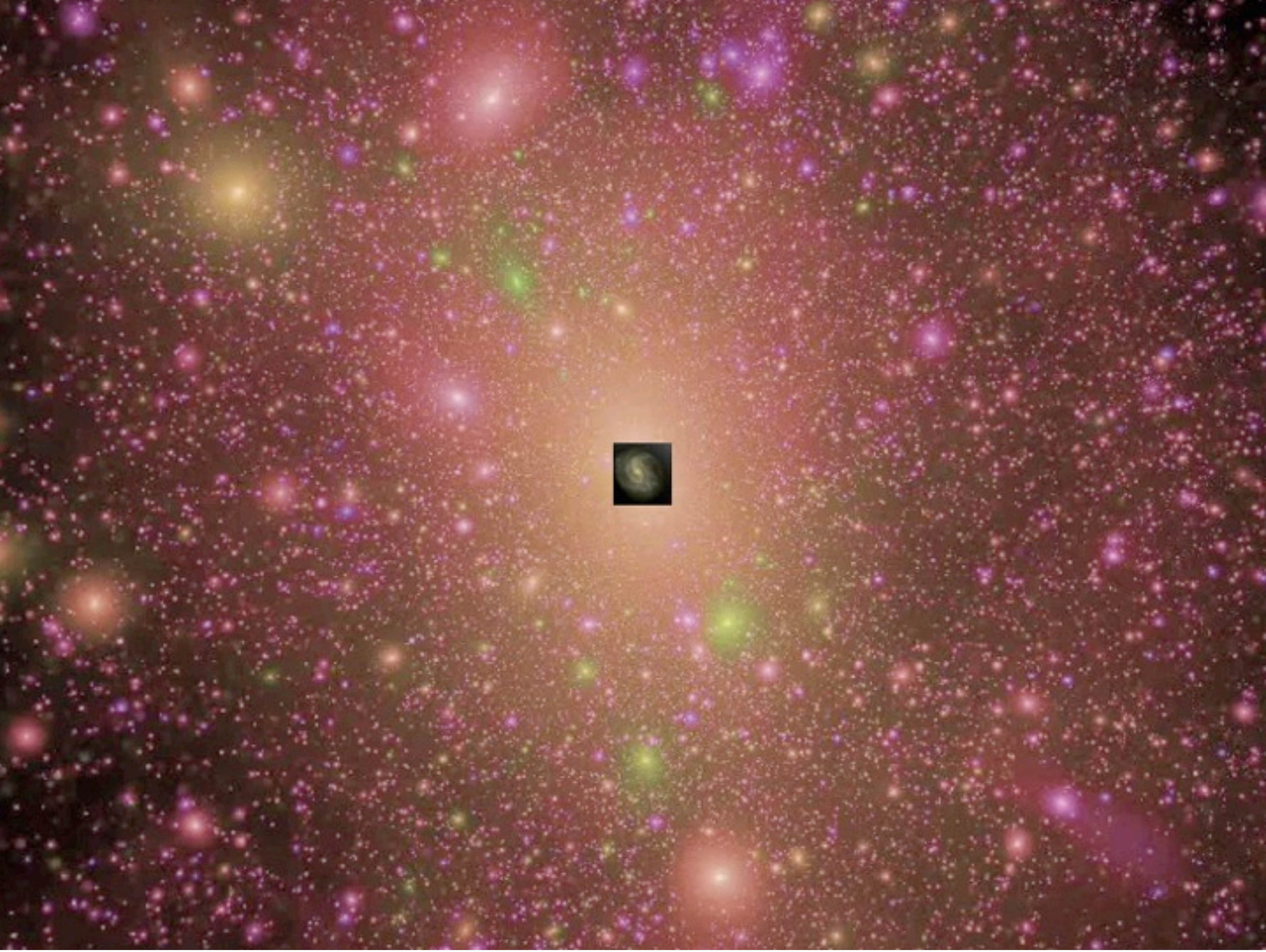
WMAP+SN+Clusters Determination of σ_8 and Ω_M



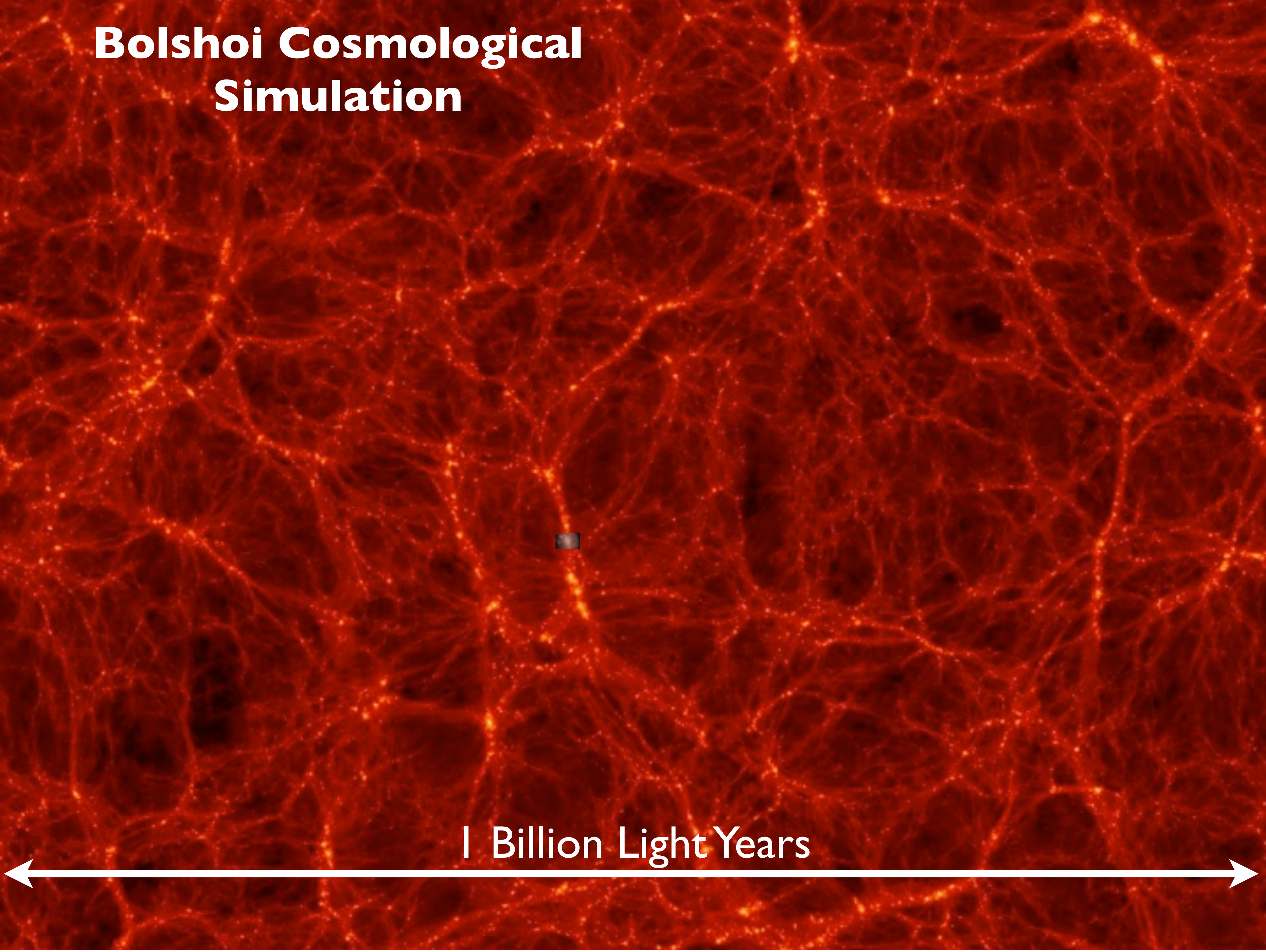
WMAP+SN+Clusters Determination of σ_8 and Ω_M




Aquarius Simulation
Milky Way
100,000 Light Years
Milky Way Dark Matter Halo
1,500,000 Light Years



Bolshoi Cosmological Simulation



The Bolshoi simulation

ART code

250Mpc/h Box
LCDM

σ_8 = 0.82
h = 0.70

8G particles
1kpc/h force resolution
1e8 Msun/h mass res

dynamical range 262,000
time-steps = 400,000

NASA AMES
supercomputing center
Pleiades computer
13824 cores
12TB RAM
75TB disk storage
6M cpu hrs
18 days wall-clock time

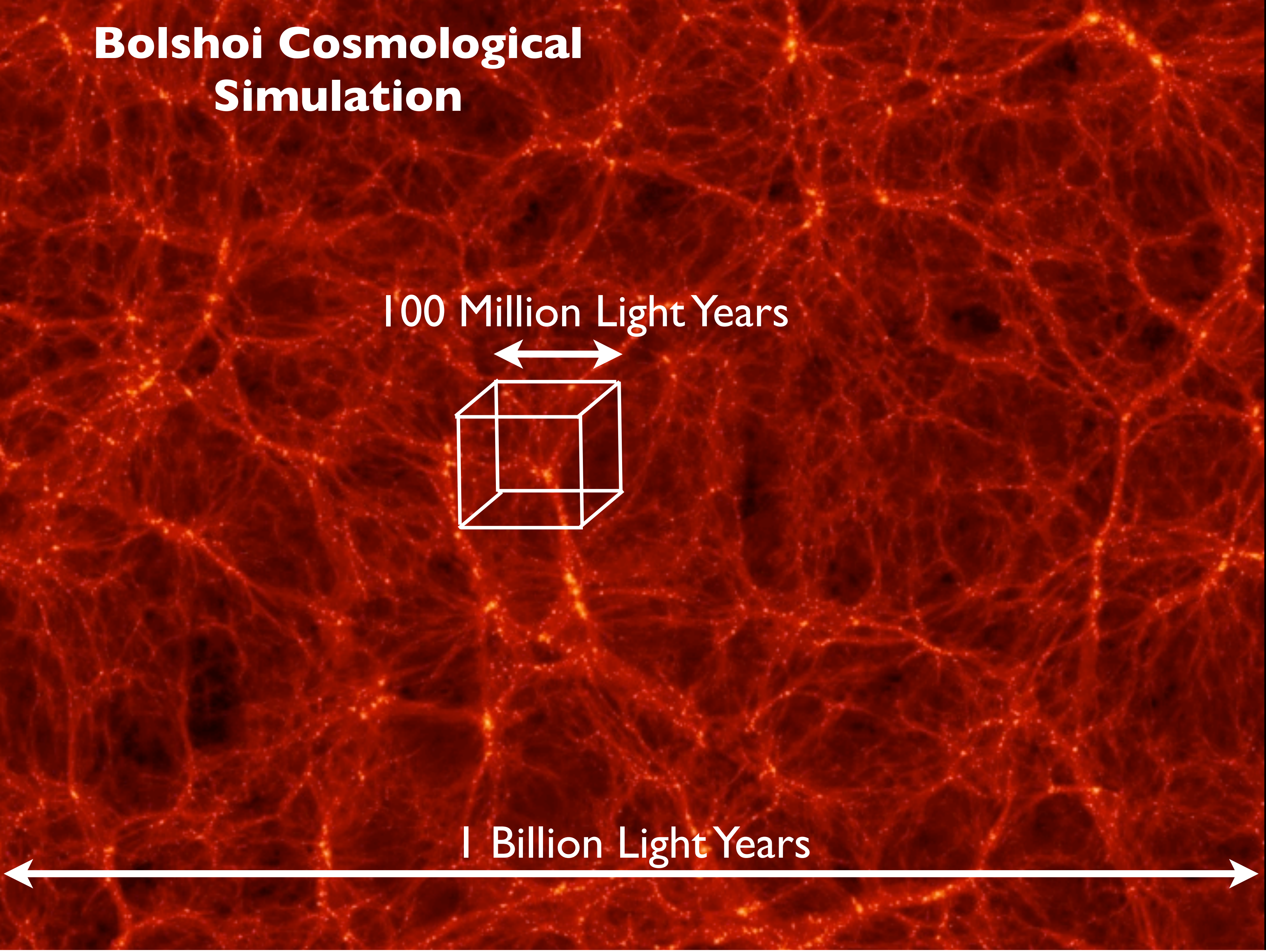
Cosmological parameters are consistent with the latest observations

Force and Mass Resolution are nearly an order of magnitude better than Millennium-I

Force resolution is the same as Millennium-II, in a volume 16x larger

Halo finding is complete to V_{circ} > 50 km/s, using both BDM and ROCKSTAR halo finders

Bolshoi and MultiDark halo catalogs were released in September 2011 at Astro Inst Potsdam; Merger Trees available July 2012

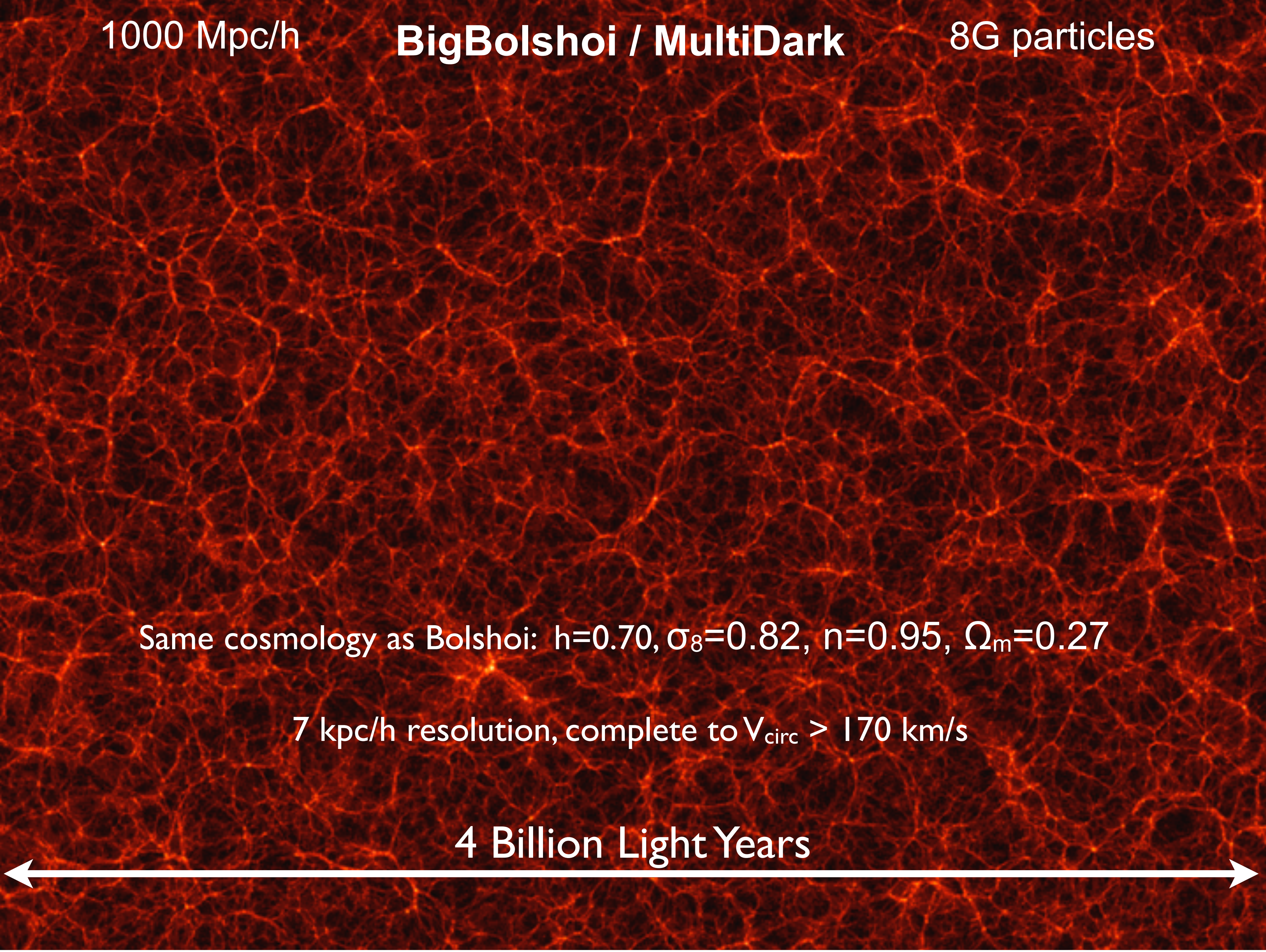

Bolshoi Cosmological Simulation
100 Million Light Years
1 Billion Light Years

BOLSHOI SIMULATION FLY-THROUGH

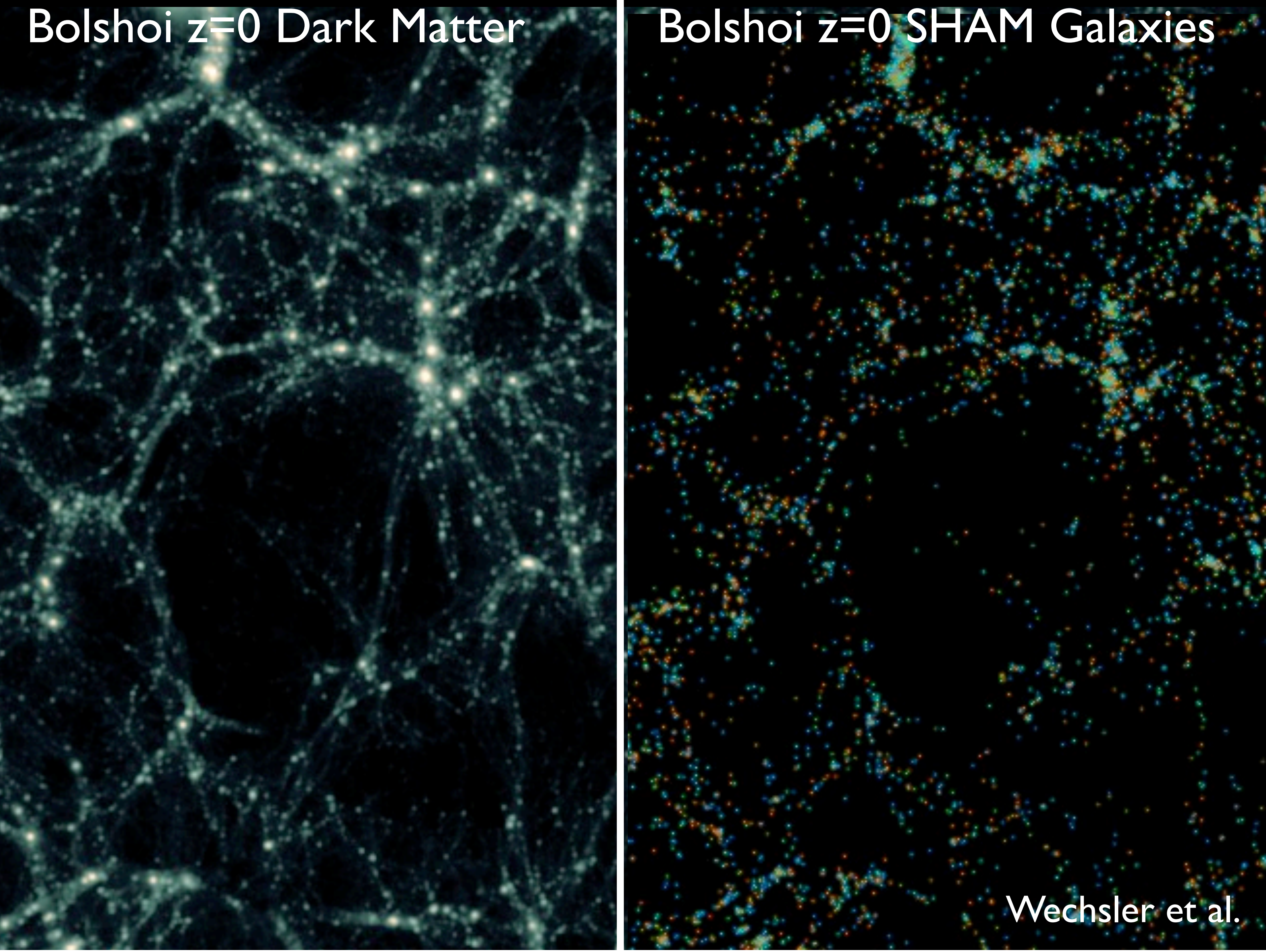
$<10^{-3}$
of the
Bolshoi
Simulation
Volume

Bolshoi Merger Tree for the Formation of a Big Cluster Halo

Peter Behroozi



Monday, December 31, 12

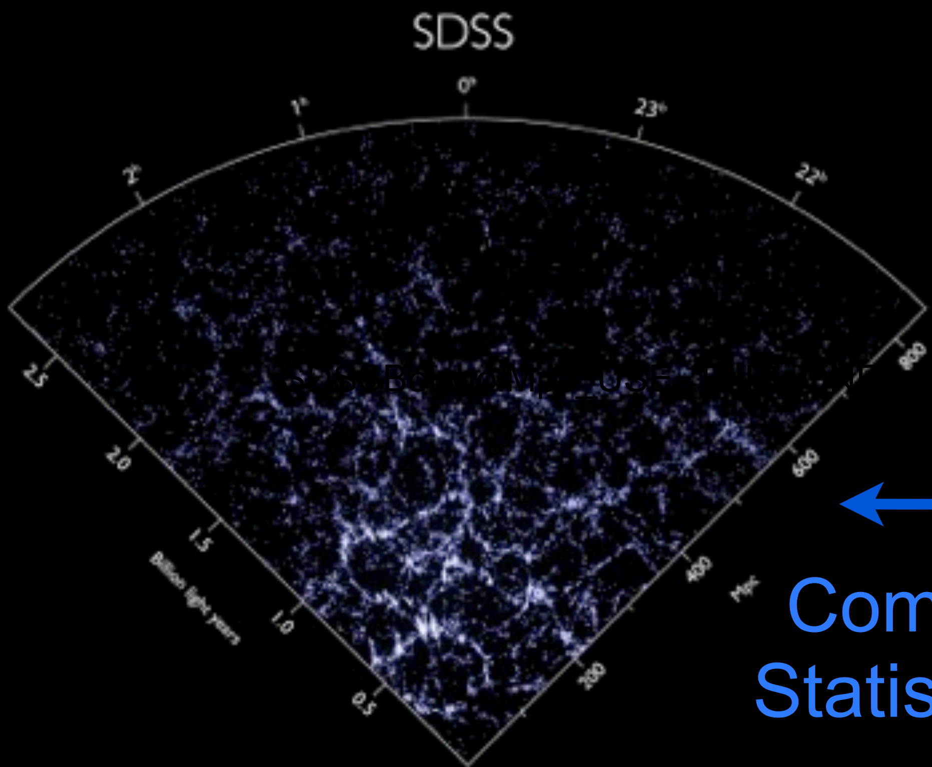

Bolshoi z=0 Dark Matter
Bolshoi z=0 SHAM Galaxies
Wechsler et al.

Observational Data

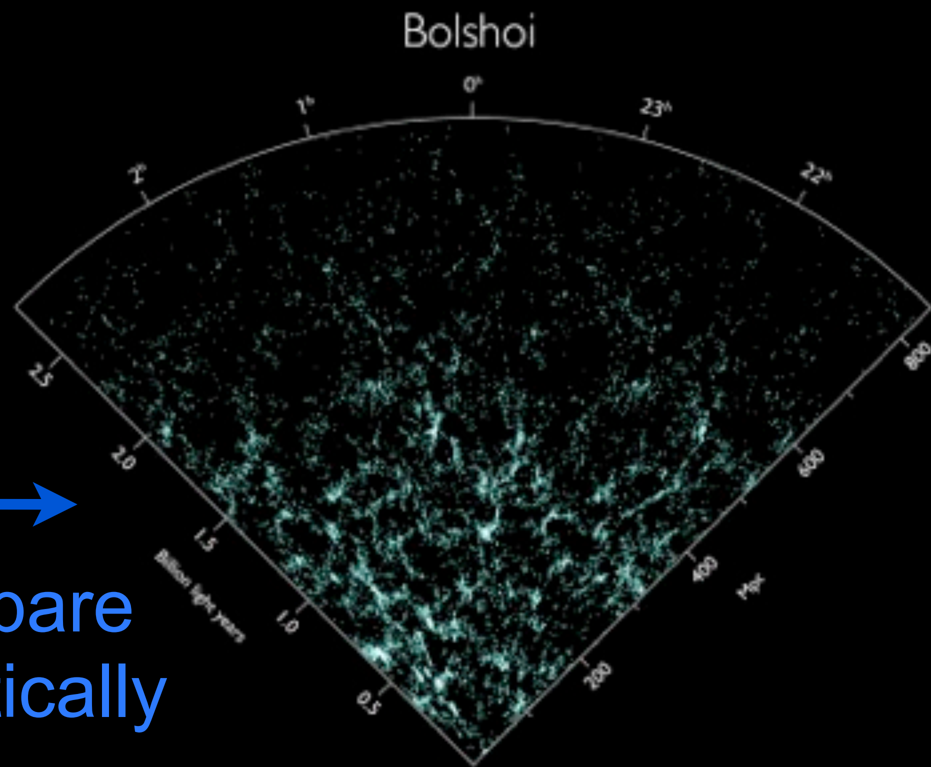
Sloan Digital Sky Survey

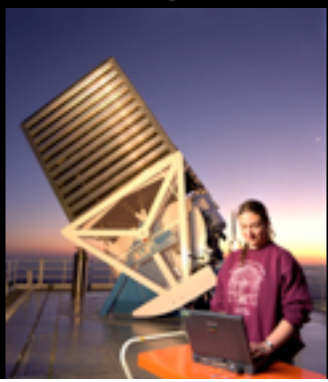
Cosmological Simulation

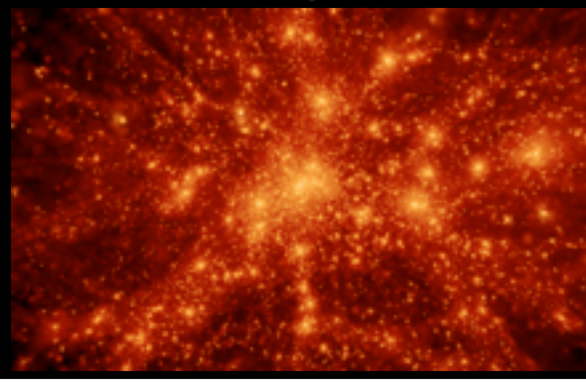
Risa Wechsler, Ralf Kahler, Nina McCurdy



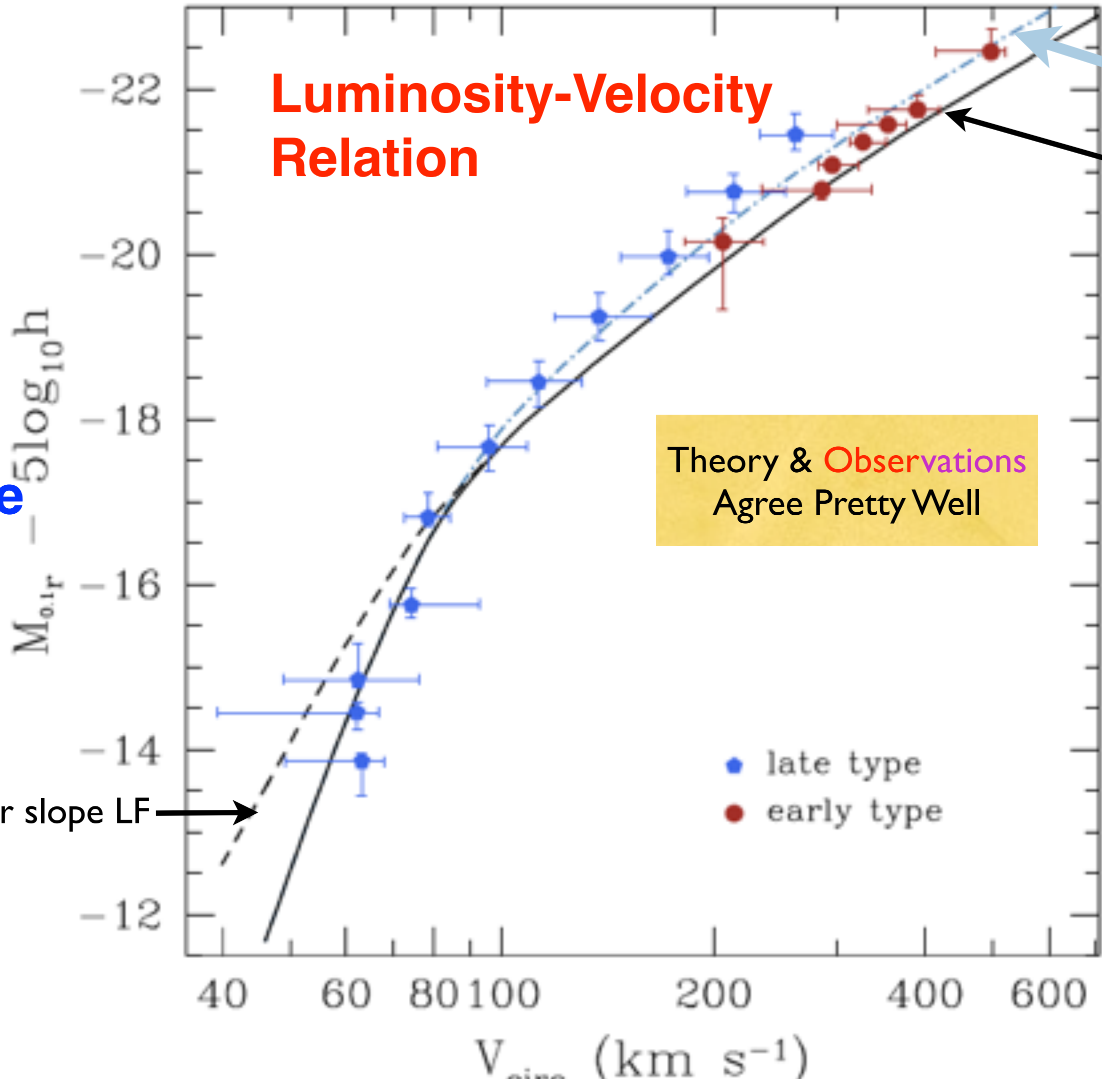
Compare Statistically







Bolshoi Sub-Halo Abundance Matching



median Vcirc without AC

median Vcirc with AC

"AC" = Adiabatic Contraction of dark matter halos when baryons cool & condense to halo centers, following Blumenthal, Faber, Flores, & Primack 1986

steeper slope LF

Trujillo-Gomez, Klypin, Primack, & Romanowsky 2011 ApJ

Fig. 4.— Comparison of the observed Luminosity Velocity relation with the predictions of the ΛCDM model. The solid curve shows the median values of $^{0.1}r$-band luminosity vs. circular velocity for the model galaxy sample. The circular velocity for each model galaxy is based on the peak circular velocity of its host halo over its entire history, measured at a distance of 10 kpc from the center including the cold baryonic mass and the standard correction due to adiabatic halo contraction. The dashed curve show results for a steeper ($\alpha = -1.34$) slope of the LF. The dot-dashed curve shows predictions after adding the baryon mass but without adiabatic contraction. Points show representative observational samples.

Bolshoi Sub-Halo Abundance Matching

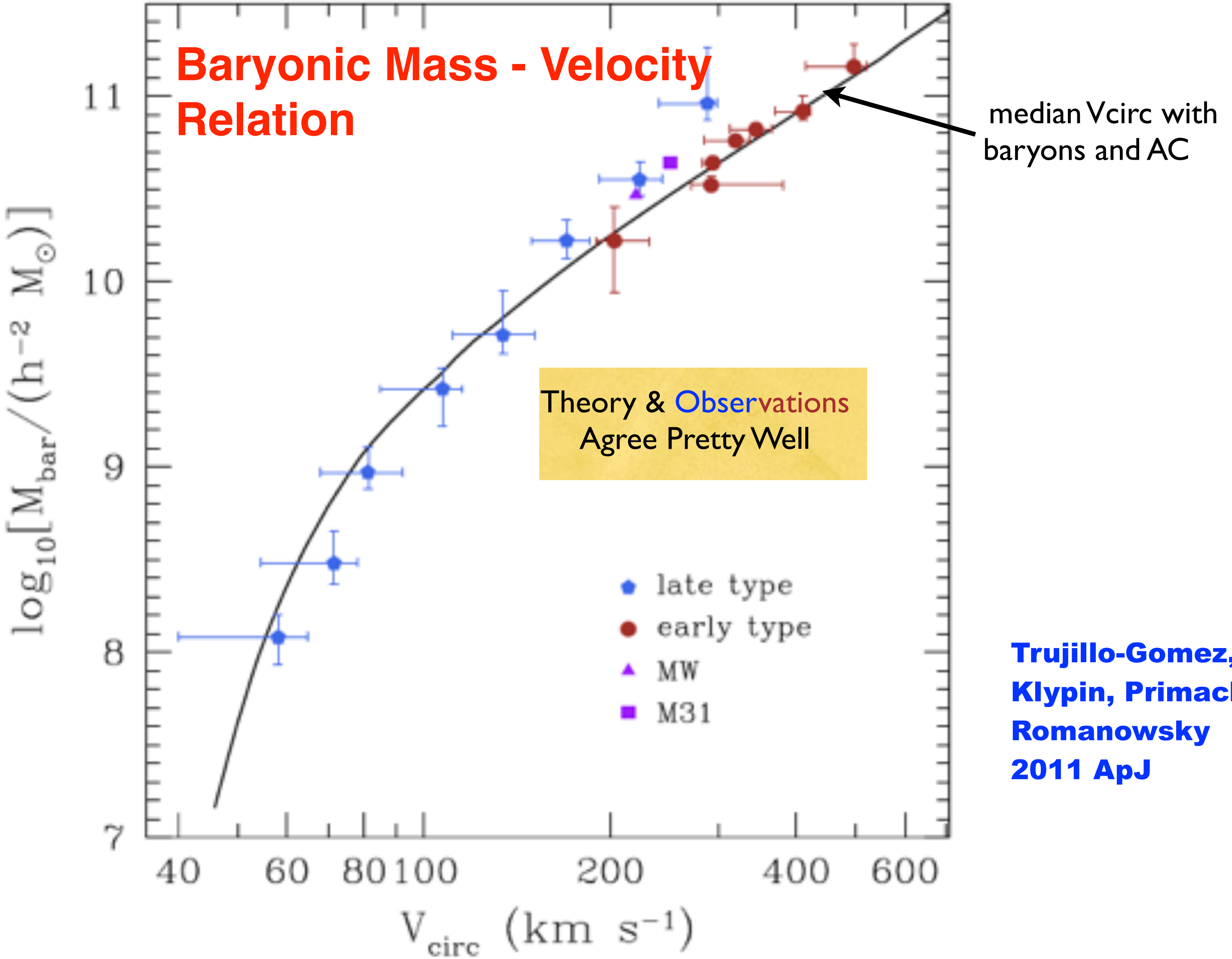
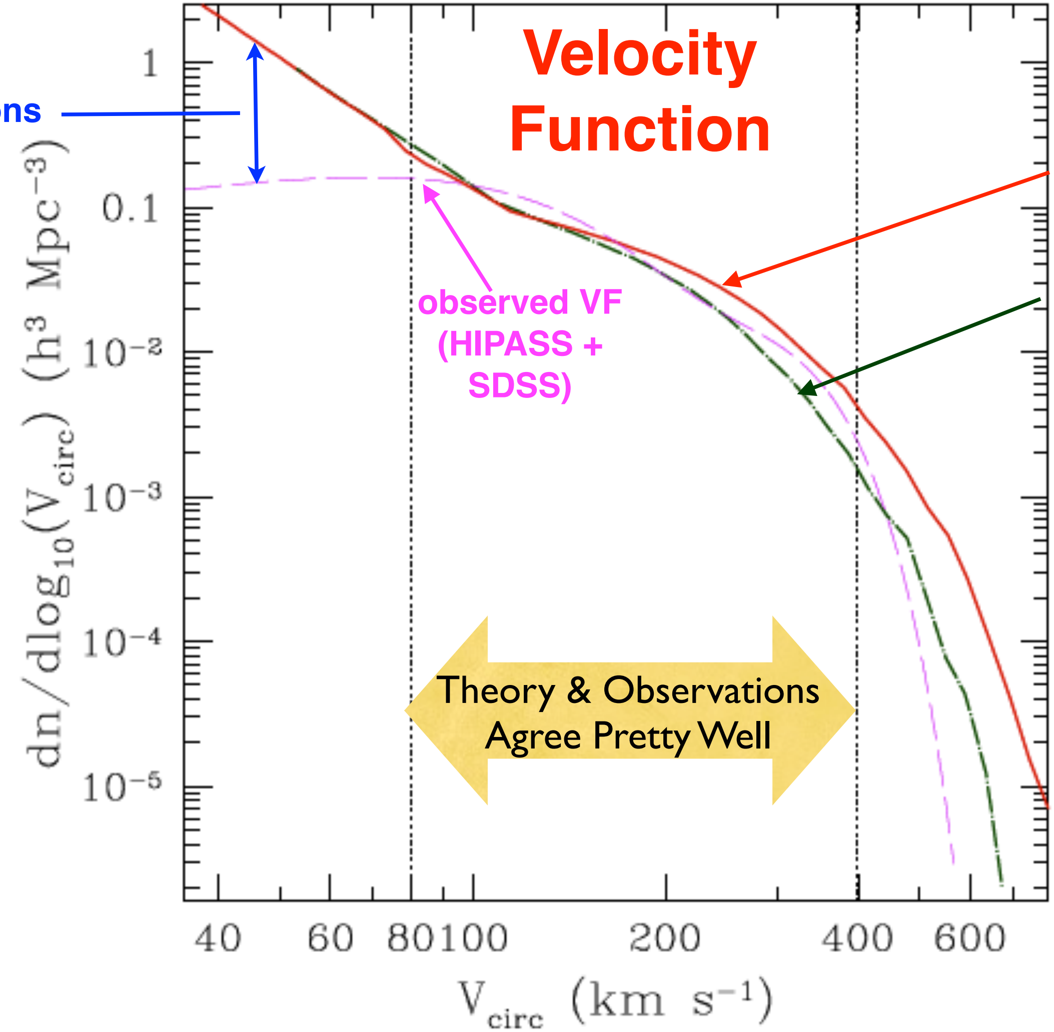


Fig. 10.— Mass in cold baryons as a function of circular velocity. The solid curve shows the median values for the ΛCDM model using halo abundance matching. The cold baryonic mass includes stars and cold gas and the circular velocity is measured at 10 kpc from the center while including the effect of adiabatic contraction. For comparison we show the individual galaxies of several galaxy samples. Intermediate mass galaxies such as the Milky Way and M31 lie very close to our model results.

Trujillo-Gomez, Klypin, Primack, & Romanowsky 2011 ApJ

Discrepancy due to incomplete observations or ΛCDM failure?

Bolshoi Sub-Halo Abundance Matching



theoretical VF with AC

theoretical VF without AC

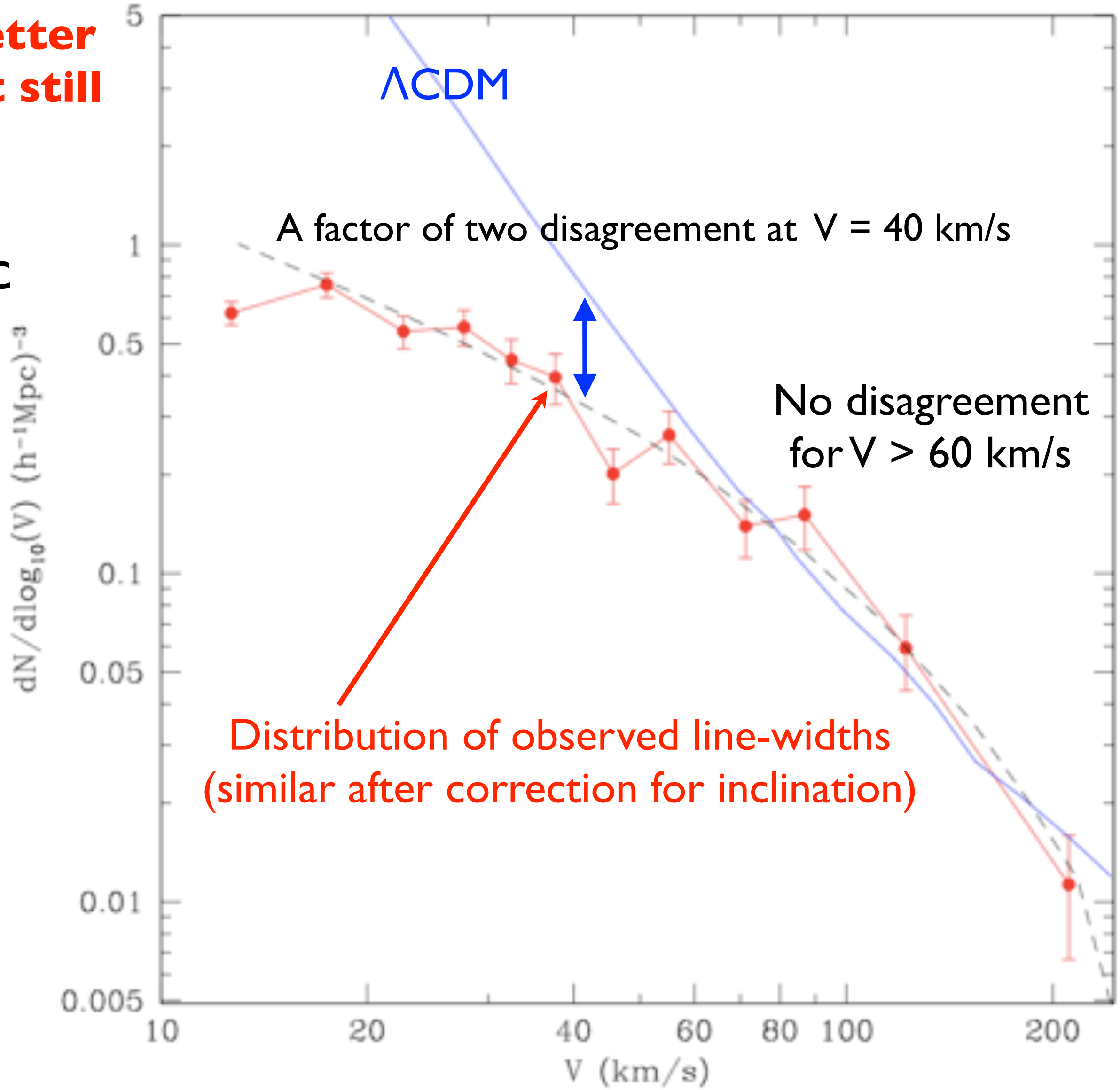
Trujillo-Gomez, Klypin, Primack, & Romanowsky ApJ 2011

Fig. 11.— Comparison of theoretical (dot-dashed and thick solid curves) and observational (dashed curve) circular velocity functions. The dot-dashed line shows the effect of adding the baryons (stellar and cold gas components) to the central region of each DM halo and measuring the circular velocity at 10 kpc. The thick solid line is the distribution obtained when the adiabatic contraction of the DM halos is considered. Because of uncertainties in the AC models, realistic theoretical predictions should lie between the dot-dashed and solid curves. Both the theory and observations are highly uncertain for rare galaxies with $V_{circ} > 400$ km s^{-1}. Two vertical dotted lines divide the VF into three domains: $V_{circ} > 400$ km s^{-1} with large observational and theoretical uncertainties; < 80 km s^{-1} $< V_{circ} < 400$ km s^{-1} with a reasonable agreement, and $V_{circ} < 80$ km s^{-1}, where the theory significantly overpredicts the number of dwarfs.

Klypin, Karachentsev, Nasonova 2012

Deeper Local Survey -- better agreement with ΛCDM but still more halos than galaxies below 50 km/s

Local Volume: D <10Mpc



Total sample: 813 galaxies

Within 10Mpc: 686

M_B<-13 N=304

M_B<-10 N=611

80-90% are spirals or dIrr (T>0)

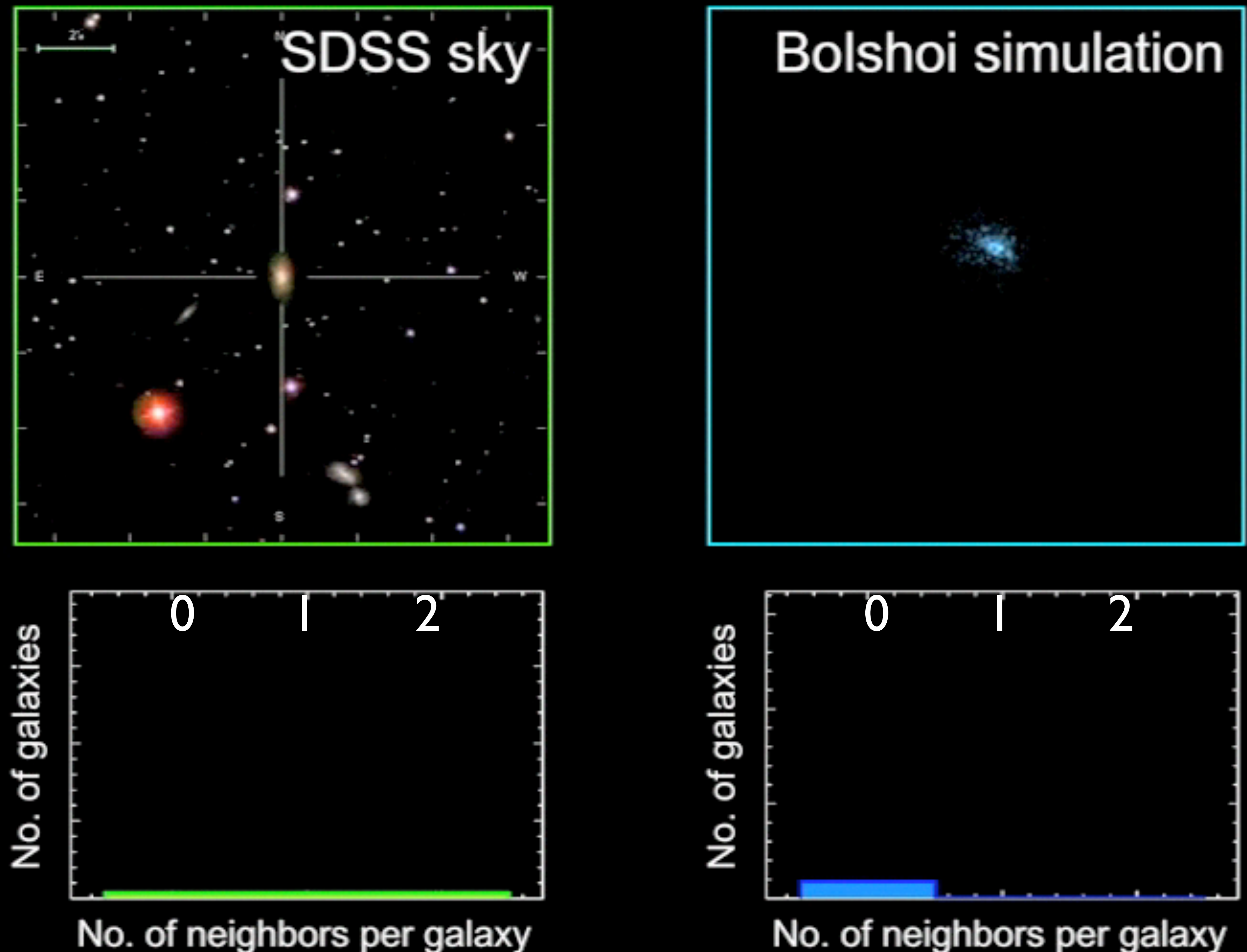
Accuracy of distances are 8-10%

80% with D<10Mpc have HI linewidth

Vrot = 150x10^(-(20.5+M_B)/8.5)km/s

The Milky Way has two large satellite galaxies, the small and large Magellanic Clouds

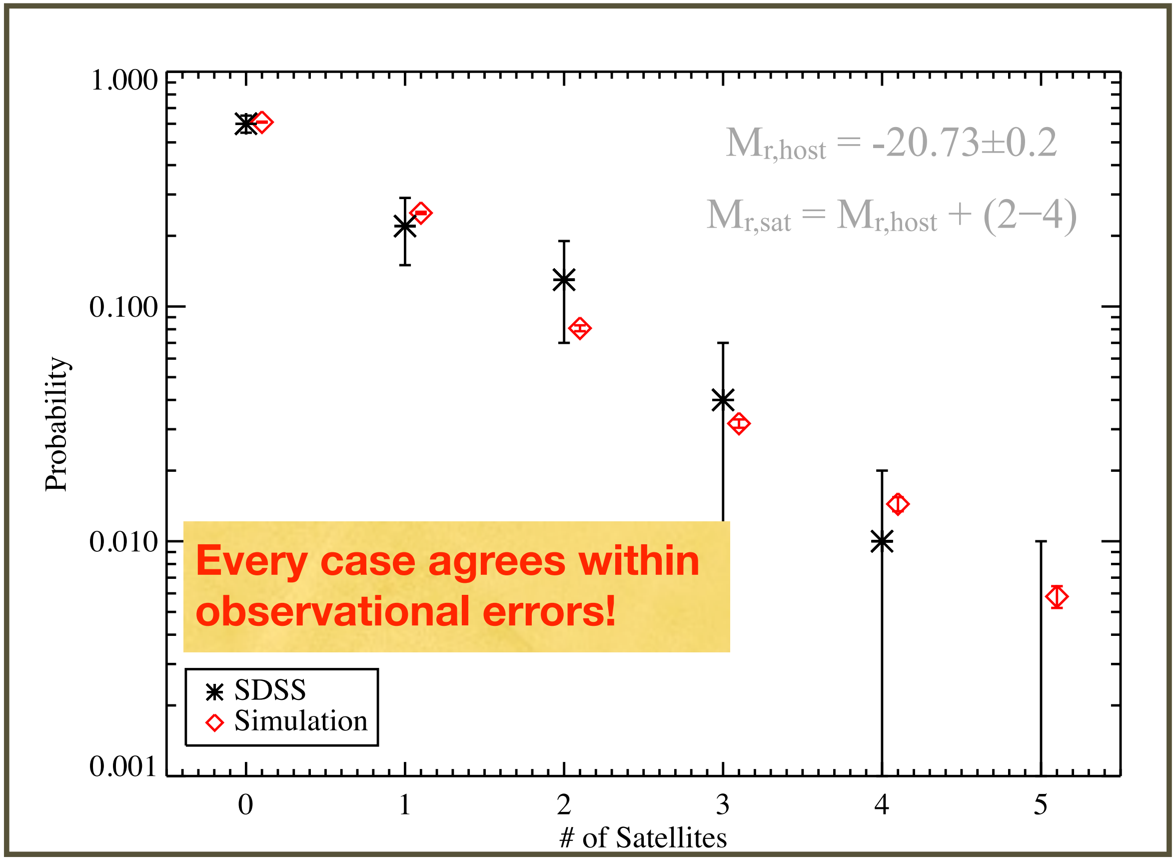
The Bolshoi simulation + halo abundance matching predicts the likelihood of this


SDSS sky
Bolshoi simulation
0 1 2
No. of galaxies
No. of neighbors per galaxy
0 1 2
No. of galaxies
No. of neighbors per galaxy

- Apply the same absolute magnitude and isolation cuts to Bolshoi+SHAM galaxies as to SDSS:
  - Identify all objects with absolute $^{0.1}M_r = -20.73 \pm 0.2$ and observed $m_r < 17.6$
  - Probe out to z = 0.15, a volume of roughly 500 $(Mpc/h)^3$
  - leaves us with 3,200 objects.
- Comparison of Bolshoi with SDSS observations is in close agreement, well within observed statistical error bars.

# of Subs	Prob (obs)	Prob (sim)
0	60%	61%
1	22%	25%
2	13%	8.1%
3	4%	3.2%
4	1%	1.4%
5	0%	0.58%

Statistics of MW bright satellites: SDSS data vs. Bolshoi simulation



Busha et al 2011; Liu, Gerke, Wechsler 2011

Similarly good agreement with SDSS for brighter satellites with spectroscopic redshifts compared with Millennium-II using abundance matching -- Tolorud, Boylan-Kolchin, et al.

Galaxy Formation - Introduction

ΛCDM vs. Downsizing

ΛCDM:

hierarchical formation
(small things form first)

"Downsizing":

massive galaxies are old, star
formation moves to smaller galaxies

ΛCDM		Downsizing
small structures	early	large galaxies
↓		↓
large structures	late	small galaxies

Galaxy Formation - Introduction

ΛCDM vs. Downsizing

ΛCDM:

hierarchical formation
(small things form first)

"Downsizing":

massive galaxies are old, star formation moves to smaller galaxies

mass assembly

DM simulations

↓

present-day structure

How are these processes related?

star formation history

semi-analytic models

↓

current stellar population

Galaxy Formation - Introduction

An old criticism of ΛCDM has been that the order of cosmogony is wrong: halos grow from small to large by accretion in a hierarchical formation theory like ΛCDM, but the oldest stellar populations are found in the most massive galaxies -- suggesting that these massive galaxies form earliest, a phenomenon known as "downsizing." The key to explaining the downsizing phenomenon is the realization that **star formation is most efficient in dark matter halos with masses in the band between about 10^{10} and 10^{12} $M_\odot$**. This goes back at least as far as the original Cold Dark Matter paper (BFPR84), from which the following figure is reproduced.

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

Blumenthal, Faber, Primack, & Rees -- Nature 311, 517 (1984)

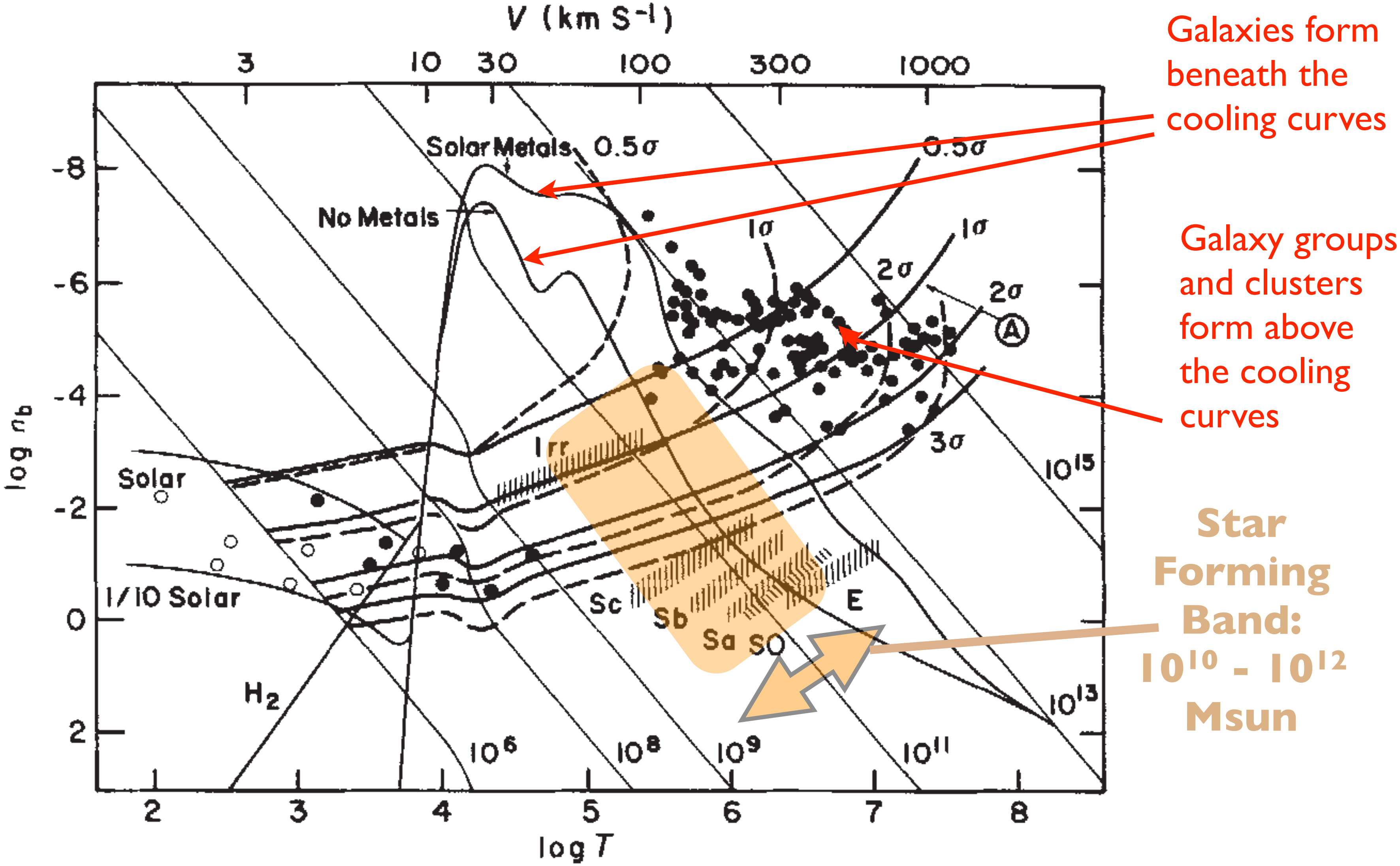
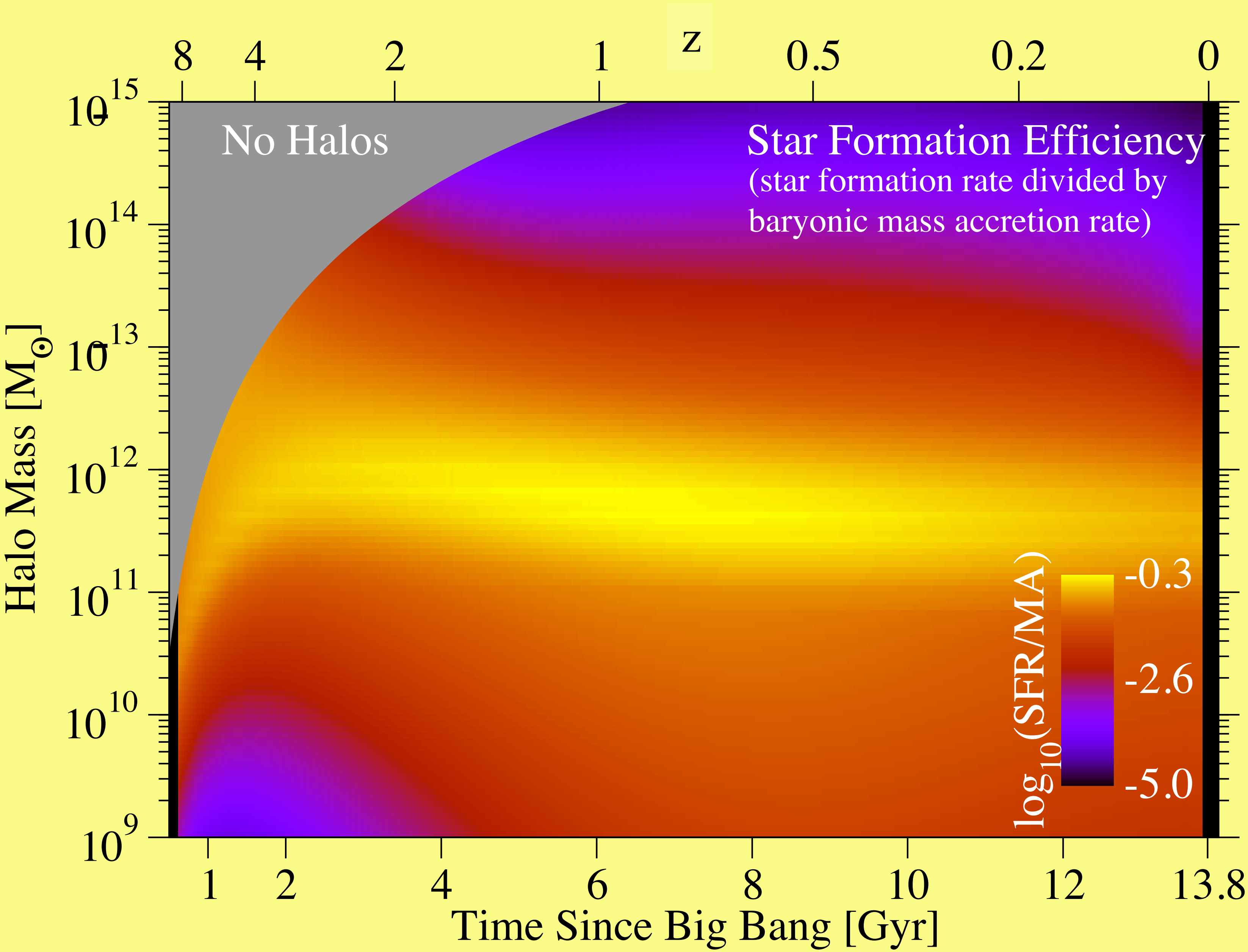
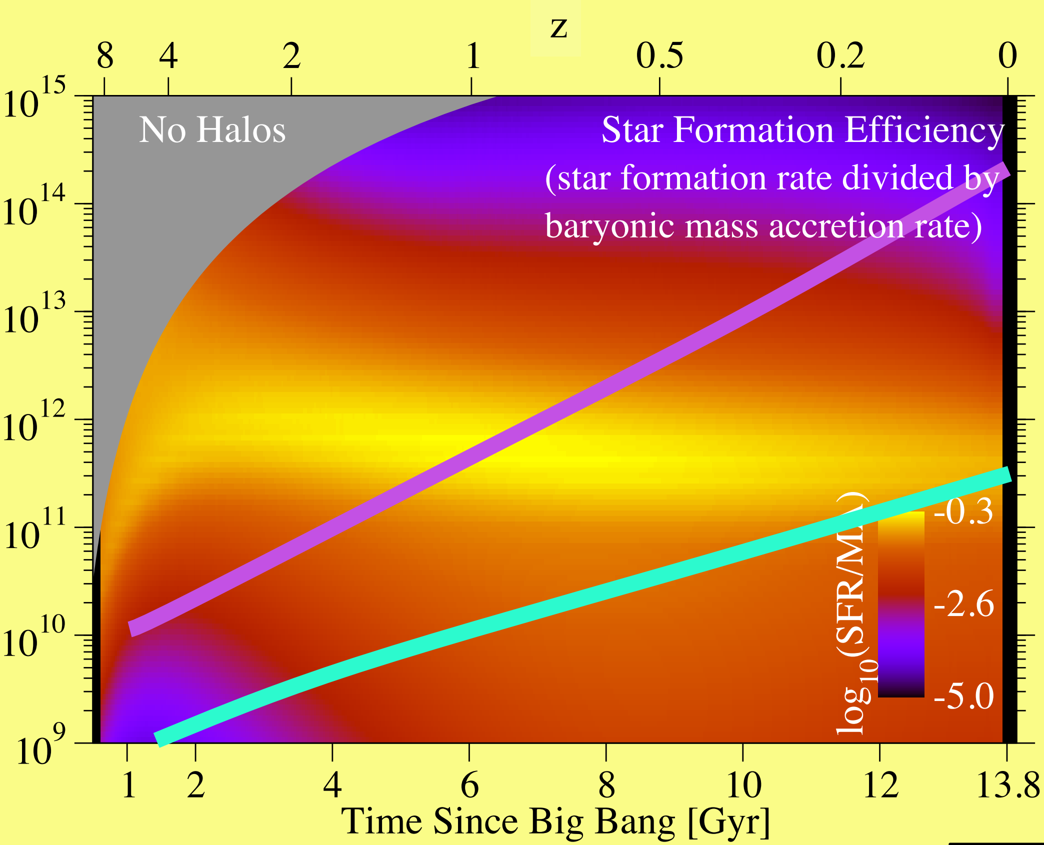


Fig. 3 Baryon density n_b versus three-dimensional, r.m.s. velocity dispersion V and virial temperature T for structures of various size in the Universe. The quantity T is $\mu V^2/3k$, where μ is mean molecular weight ($\approx$0.6 for ionized, primordial H+He) and k is Boltzmann's constant.



From Figure 1 of Behroozi, Wechsler, Conroy ApJL, 762, L31 (2013)

Implications of the Star-Forming Band Model



Massive galaxies:

- Started forming stars early.
- Shut down early.
- Are red today.
- Populate dark halos that are much more massive than their stellar mass.

Small galaxies:

- Started forming stars late.
- Are still making stars today.
- Are blue today.
- Populate dark halos that match their stellar mass.

"Downsizing"

Star formation is a wave that started in the largest galaxies and swept down to smaller masses later (Cowie et al. 1996).

From Figure 1 of Behroozi, Wechsler, Conroy ApJL, 762, L31 (2013)

small scale issues

Angular momentum

ΛCDM simulations are increasingly able to form realistic spiral galaxies, as resolution improves and feedback becomes more realistic.

Cusps

The observed velocity structure of LSB and dSpiral galaxies may be consistent with cuspy ΛCDM halos. Baryonic physics may soften the central cusp.

Satellites

The discovery of many faint Local Group dwarf galaxies is consistent with ΛCDM predictions. Reionization, lensing, satellites, and Lyα forest data imply that WDM must be Tepid or Cooler. But the "too big to fail" problem may be serious.

WHAT IS THE DARK MATTER?

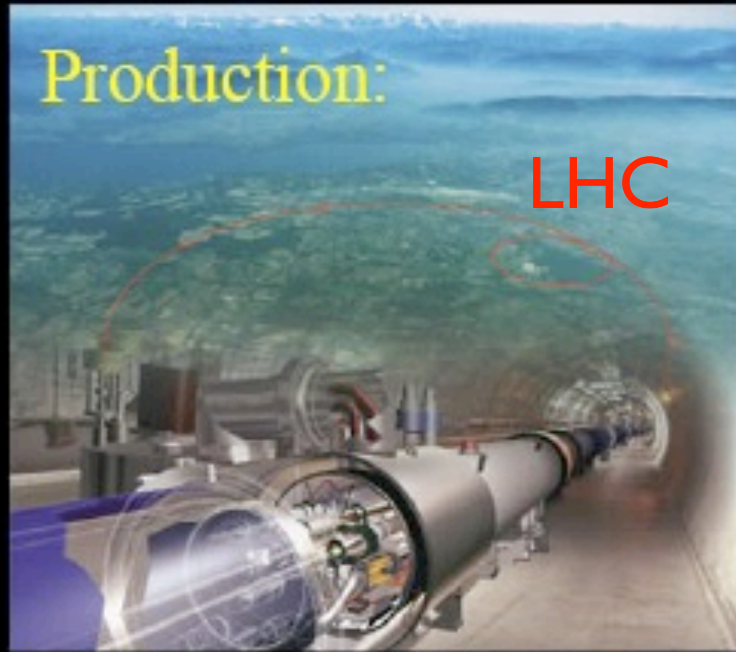
Prospects for DIRECT and INDIRECT detection of WIMPs are improving.

With many upcoming experiments

- Large Hadron Collider
- Planck and other new satellites
- Fermi GRST and larger ACTs
- Direct Detection
  - Spin Independent - CDMS-II, XENON100, LUX
  - Spin Dependent - COUPP, PICASSO

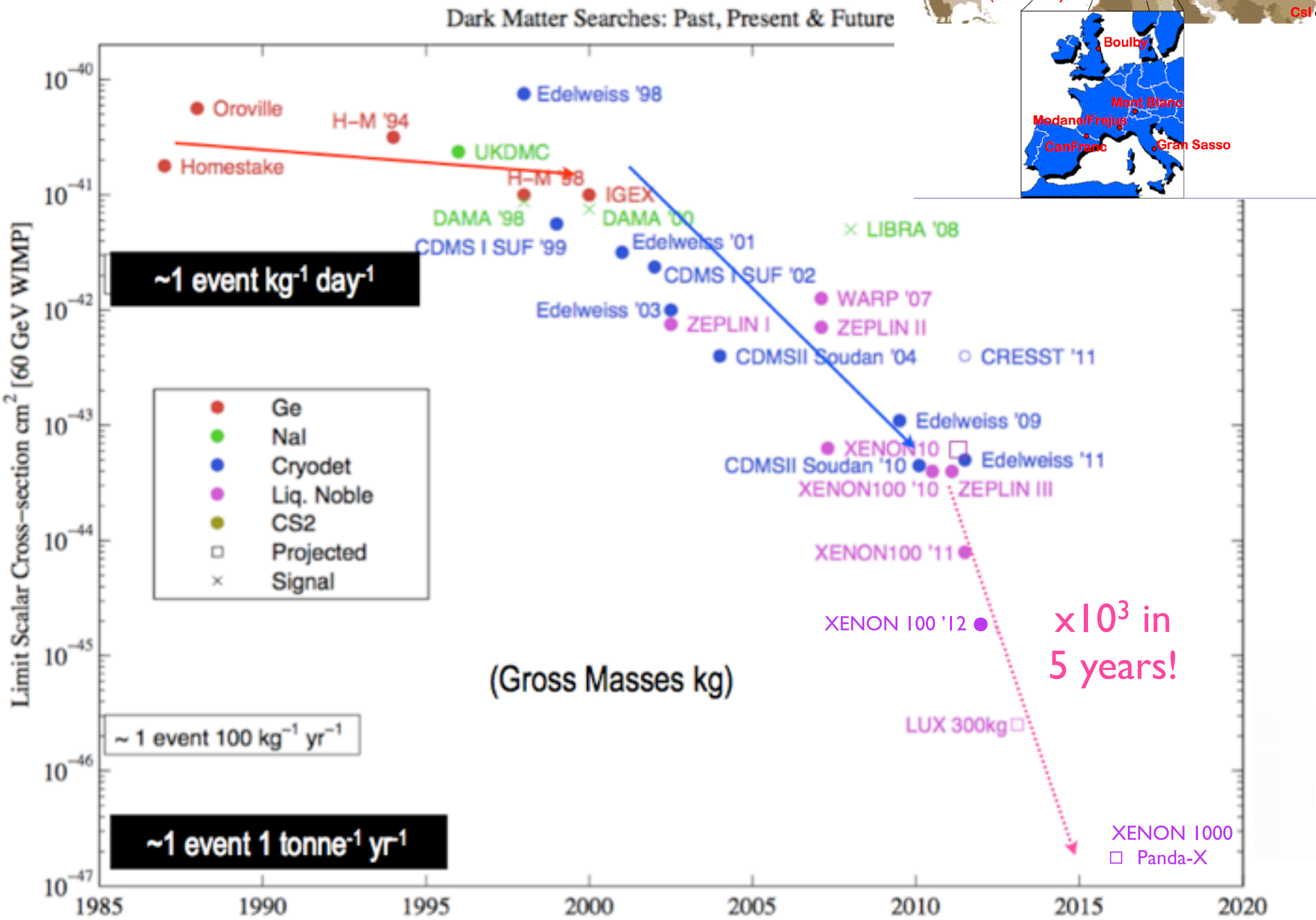
-- there could well be a big discovery in the next year or two!

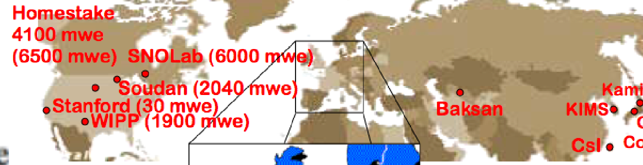
Four roads to dark matter: *catch it, infer it, make it, weigh it*



With all these upcoming experiments, the next few years will be very exciting!

DM Direct Search Progress Over Time (2012)

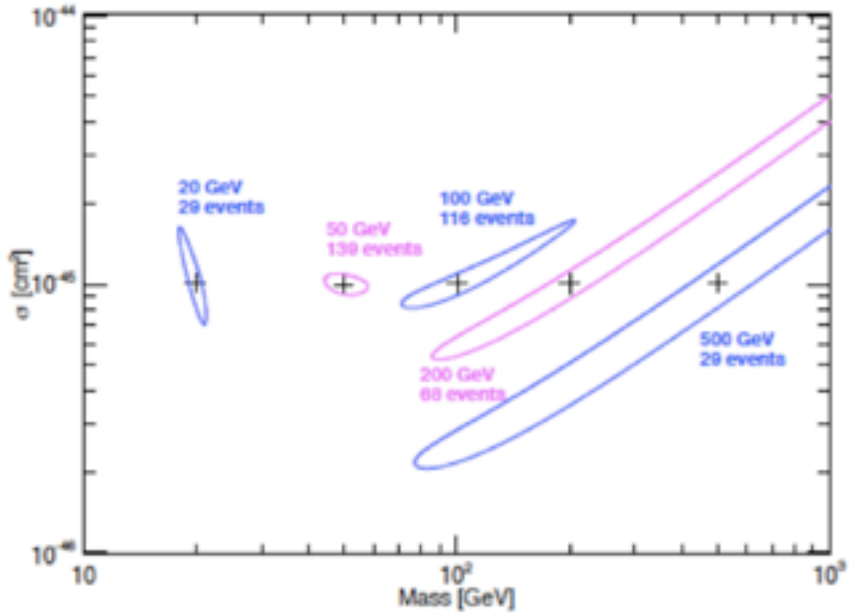


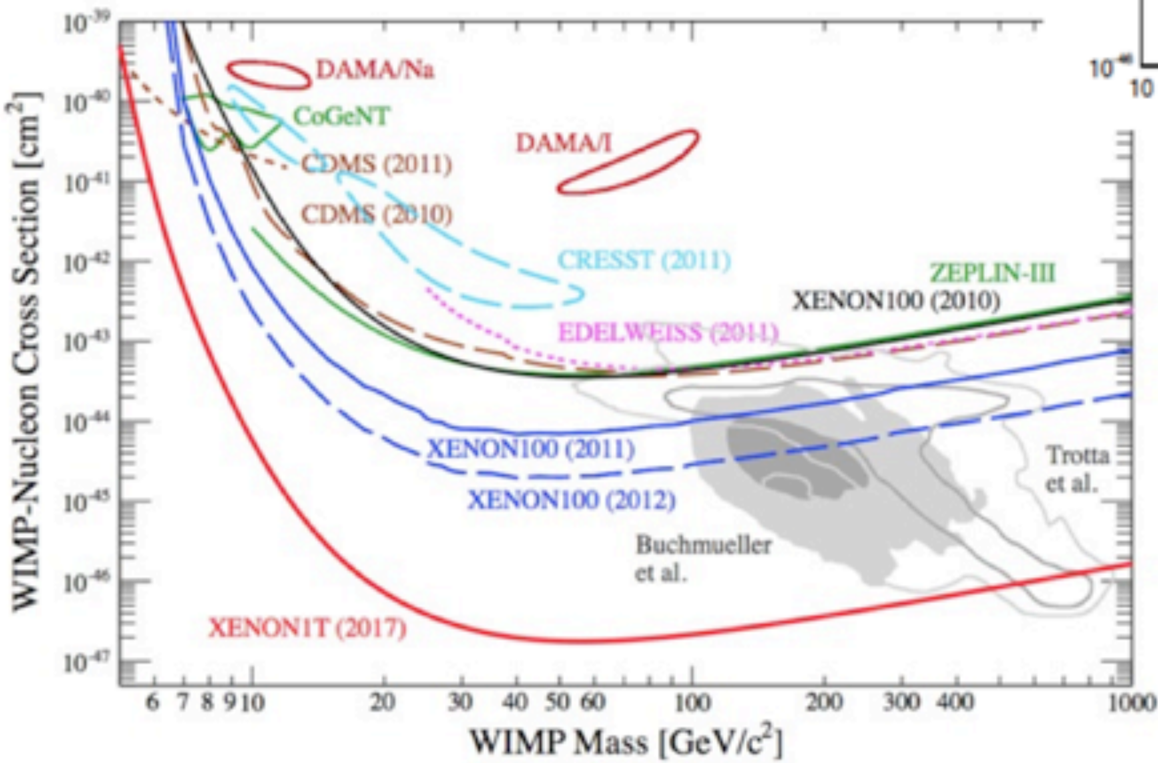


The XENON1T Science Case

a statistically significant WIMP signal after 2.2 ton-years of data

~100 events if cross section at 10^{-45} cm^2





two orders of magnitude improvement in SI cross-section sensitivity w/r to XENON100

LNGS Underground Laboratory – Hall B

LNGS Underground Laboratory – Hall B

WHAT IS THE DARK ENERGY??

We can use existing telescopes to measure $w = P/\rho$ and see whether it changed in the past. But to get order-of-magnitude better constraints than presently available, and a possible detection of non-cosmological-constant dark energy, better instruments (e.g. LSST, JDEM) will probably be required both on the ground and in space, according to the Dark Energy Task Force (2006).

The National Academy Beyond Einstein report (2007) recommended JDEM as the first Beyond Einstein mission, with the dual goal of measuring dark energy by at least two different methods and also collecting valuable data on galaxy evolution. The National Academy Astronomy Decadal Study (2010) chose the similar WFIRST mission as its highest priority large mission. NASA says it can't afford WFIRST in the present decade, but in October 2011 the ESA chose the less ambitious Euclid mission for launch in 2019. Donation of an unused U.S. spy satellite might allow restart of WFIRST.

The Dark Matter Rap: Cosmological History for the MTV Generation by David Weinberg*

My name is Fritz Zwicky,
I can be kind of prickly,
This song had better start
by giving me priority.
Whatever anybody says,
I said in 1933.
Observe the Coma cluster,
the redshifts of the galaxies
imply some big velocities.
They're moving so fast,
there must be missing mass!
Dark matter.

Dark matter: Do we need it? What is it? Where is it? How much?
Do we need it? Do we need it? Do we need it? Do we need it?

* www.astronomy.ohio-state/~dhw/Silliness/silliness.html (1992)

The Dark Matter Rap: Cosmological History for the MTV Generation by David Weinberg

My name is Fritz Zwicky,
I can be kind of prickly,
This song had better start
by giving me priority.
Whatever anybody says,
I said in 1933.
Observe the Coma cluster,
the redshifts of the galaxies
imply some big velocities.
They're moving so fast,
there must be missing mass!
Dark matter.

Dark matter: Do we need it? What is it? Where is it? How much?
Do we need it? Do we need it? Do we need it? Do we need it?

SUMMARY

- We now know the cosmic recipe. Most of the universe is invisible stuff called "nonbaryonic dark matter" (23%) and "dark energy" (72%). 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. Or maybe not...
- 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!