LAMAT

Seminar
25 June 2016

Dark Matter: History & Cosmology

Joel R. Primack
Distinguished Professor of Physics, UCSC


Hubble Space Telescope Ultra Deep Field - ACS
This picture is beautiful but misleading, since it only shows about 0.5% of the cosmic density.
The other 99.5% of the universe is invisible.

Dark Matter: History and Cosmology

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 stars, planets, 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, and how they result in the universe of galaxies that we observe.

A Brief History of Dark Matter

1930s - Discovery that cluster velocity dispersion $\sigma_V \sim 1000$ 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 satellite 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

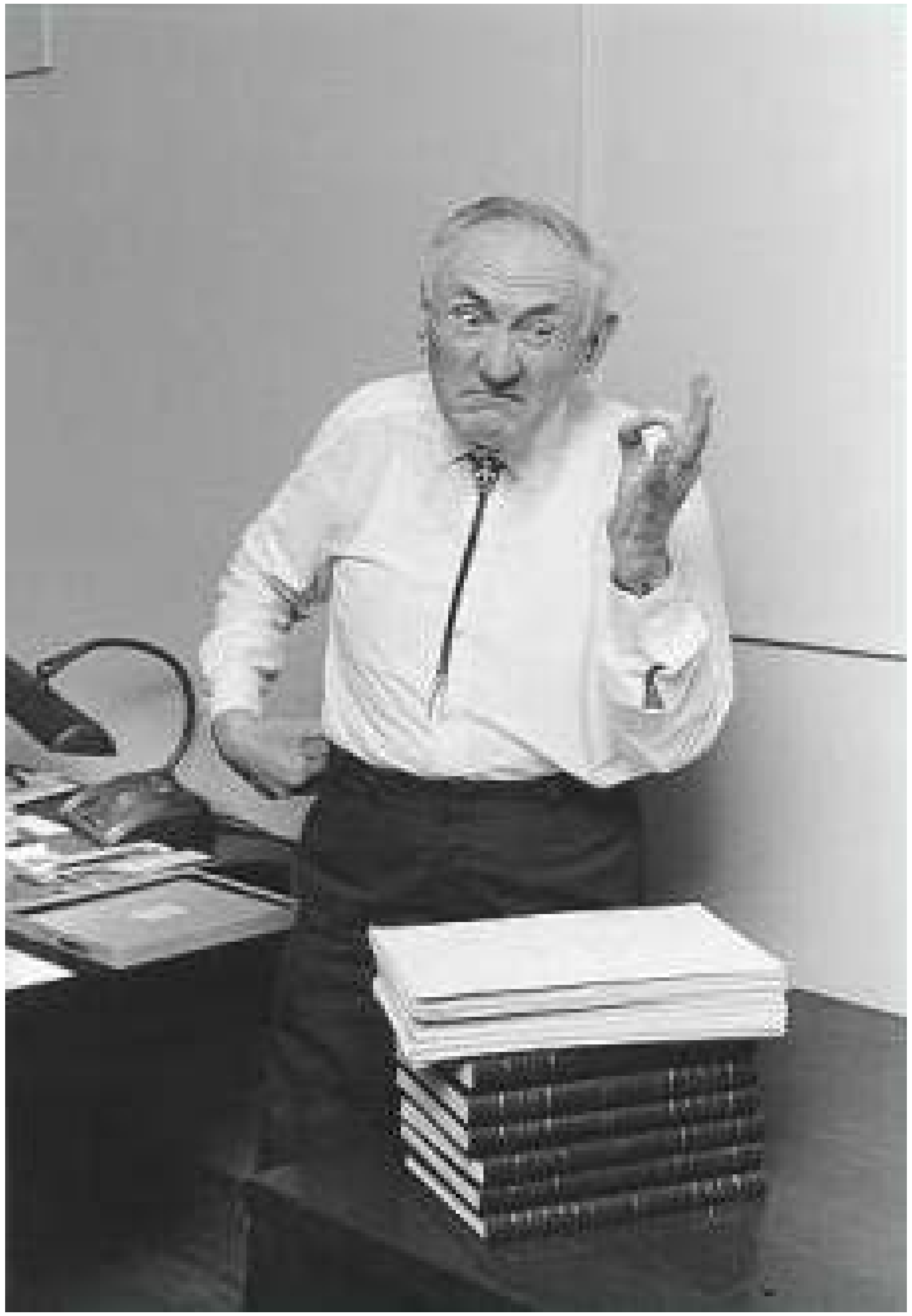
2003-16 - WMAP, Planck, and LSS confirm ΛCDM predictions

~2016 - Discovery of dark matter particles??

1937 ApJ 86, 217

ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

F. ZWICKY



Fritz Zwicky

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

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

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

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

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

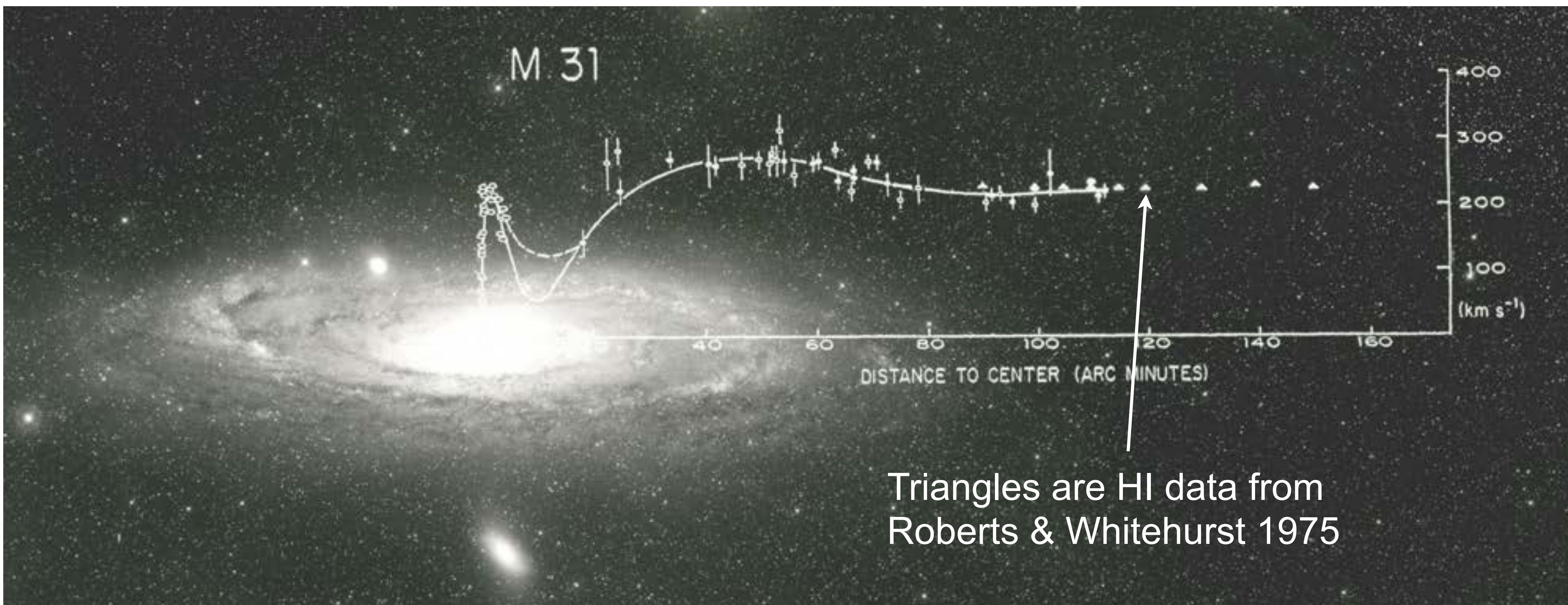
This article also proposed measuring the masses of galaxies by gravitational lensing.

See Rubin's "Reference Frame" in Dec 2006 Physics Today and her article, "A Brief History of Dark Matter," in T*he 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‡



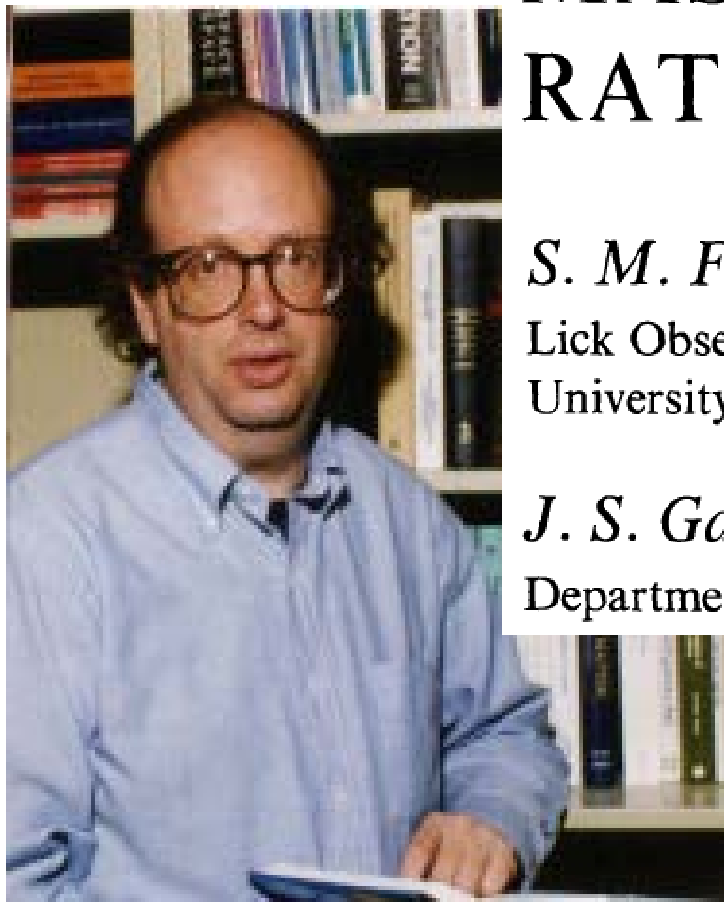
THE ENORMOUS MASS OF THE ELLIPTICAL GALAXY M87: A MODEL FOR THE EXTENDED X-RAY SOURCE*

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

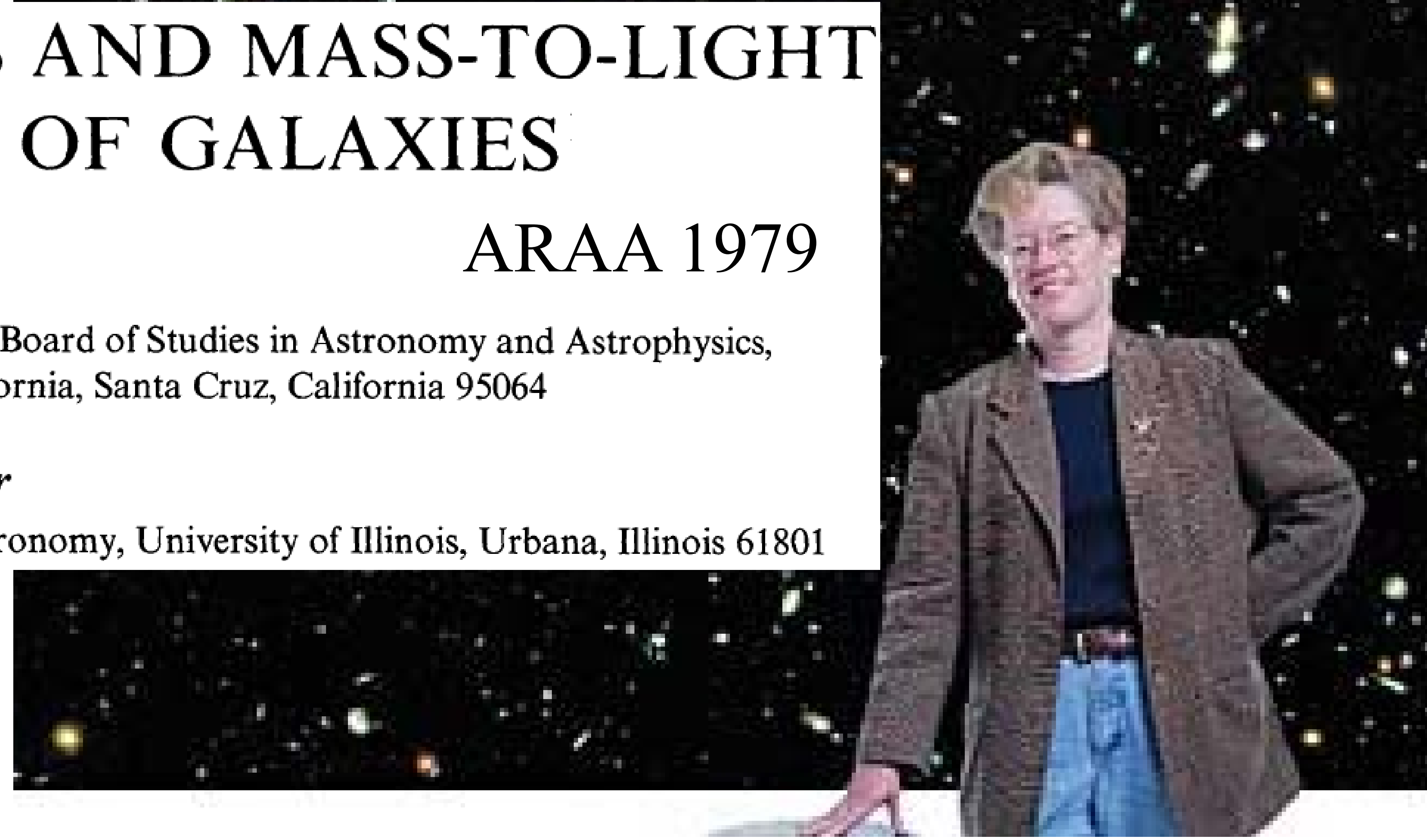


MASSES AND MASS-TO-LIGHT RATIOS OF GALAXIES

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.

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.

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.

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.

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.

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

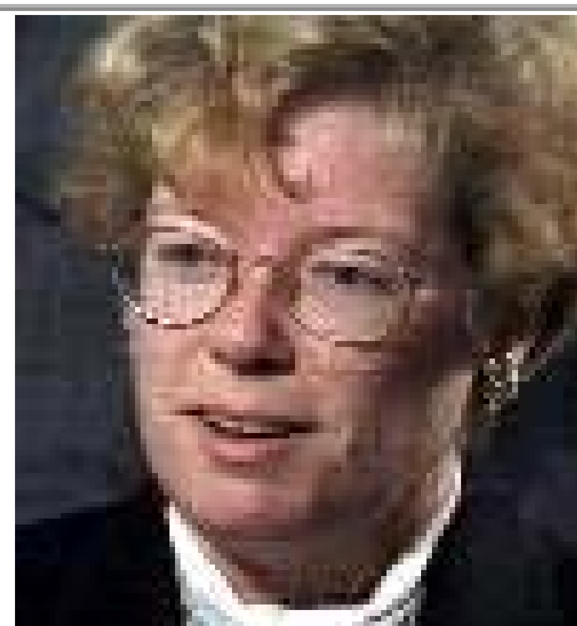
George R. Blumenthal* & S. M. Faber*

* 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

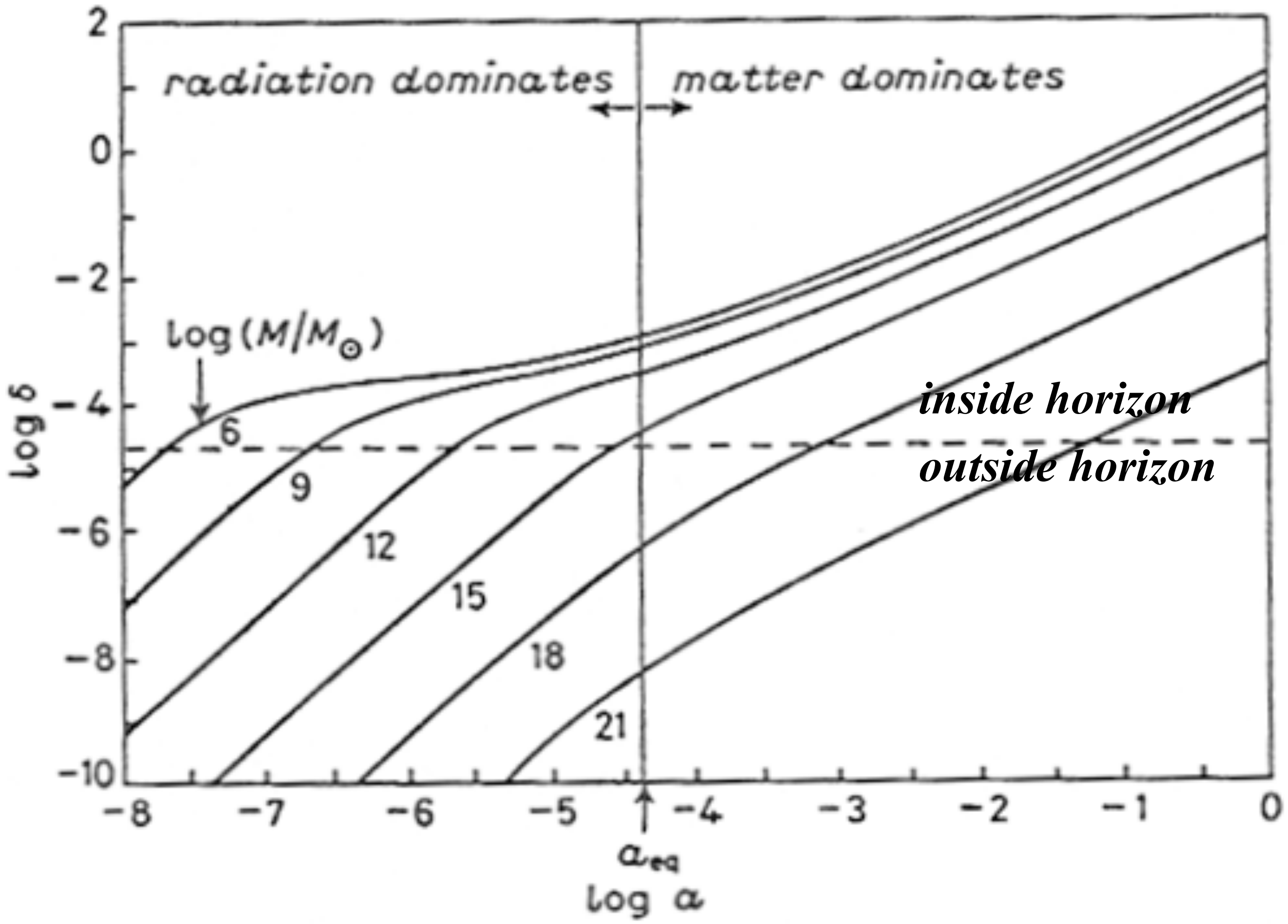
… We conclude that a straightforward interpretation of the evidence summarized above favours $\Omega \approx 0.2$ in the cold DM picture, but that $\Omega = 1$ is not implausible. …

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.

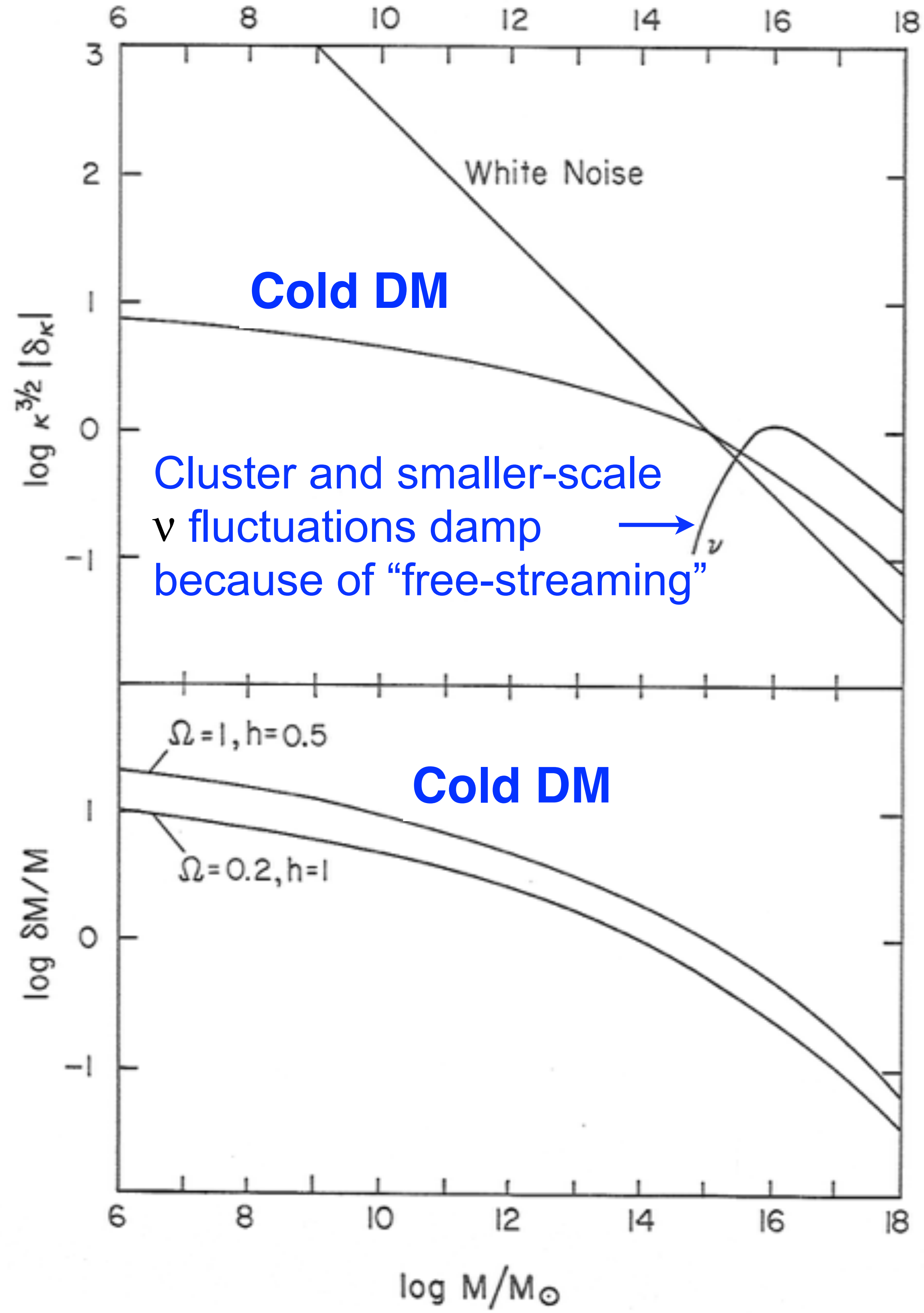
Blumenthal, Faber, Primack, & Rees 1984

CDM 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

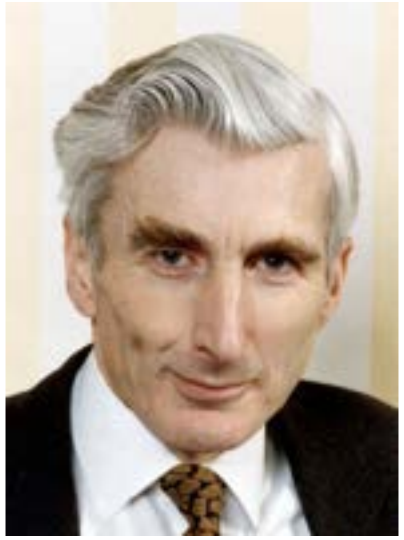


Blumenthal, Faber, Primack, & Rees 1984

Mon. Not. R. astr. Soc. (1991) **251**, 128–136

Dynamical effects of the cosmological constant

Ofer Lahav, Per B. Lilje, Joel R. Primack, and Martin J. Rees



SUMMARY

The possibility of measuring the density parameter Ω_0 and the cosmological constant $\lambda_0 \equiv \Lambda/(3H_0^2)$ using dynamical tests is explored in linear and non-linear theory. In linear theory we find that the rate of growth of the perturbations at the present epoch is approximated by $f(z=0) \approx \Omega_0^{0.6} + \frac{1}{70}\lambda_0(1+\frac{1}{2}\Omega_0)$. Therefore, dynamical tests such as infall around clusters and dipoles at the present epoch do not distinguish well between universes with and without a cosmological constant. At higher redshifts, the perturbations also depend mainly on the matter density at a particular epoch, $f(z) \approx \Omega^{0.6}(z)$, which has a strong dependence on λ_0 at $z \approx 0.5$–2.0. Therefore, information on both parameters can be obtained by looking at clustering at different redshifts. In practice, however, the other observables also depend on the cosmology, and in some cases conspire to give a weak dependence on λ_0. By using the non-linear spherical infall model for a family of Cold Dark Matter (CDM) power-spectra we also find that dynamics at $z=0$ does not tell much about λ_0. At higher redshifts there is unfortunately another conspiracy between conventional observables, which hides information about λ_0. The final radius of a virialized cluster (relative to the turn-around radius) is approximated by $R_f/R_{ta} \approx (1-\eta/2)/(2-\eta/2)$, where η is the ratio of Λ to the density at turn-around. Therefore a repulsive Λ gives a smaller final radius than a vanishing Λ.

Matter and Energy Content of the Universe

Imagine that the entire universe is an ocean of dark energy. On that ocean sail billions of ghostly ships made of dark matter...

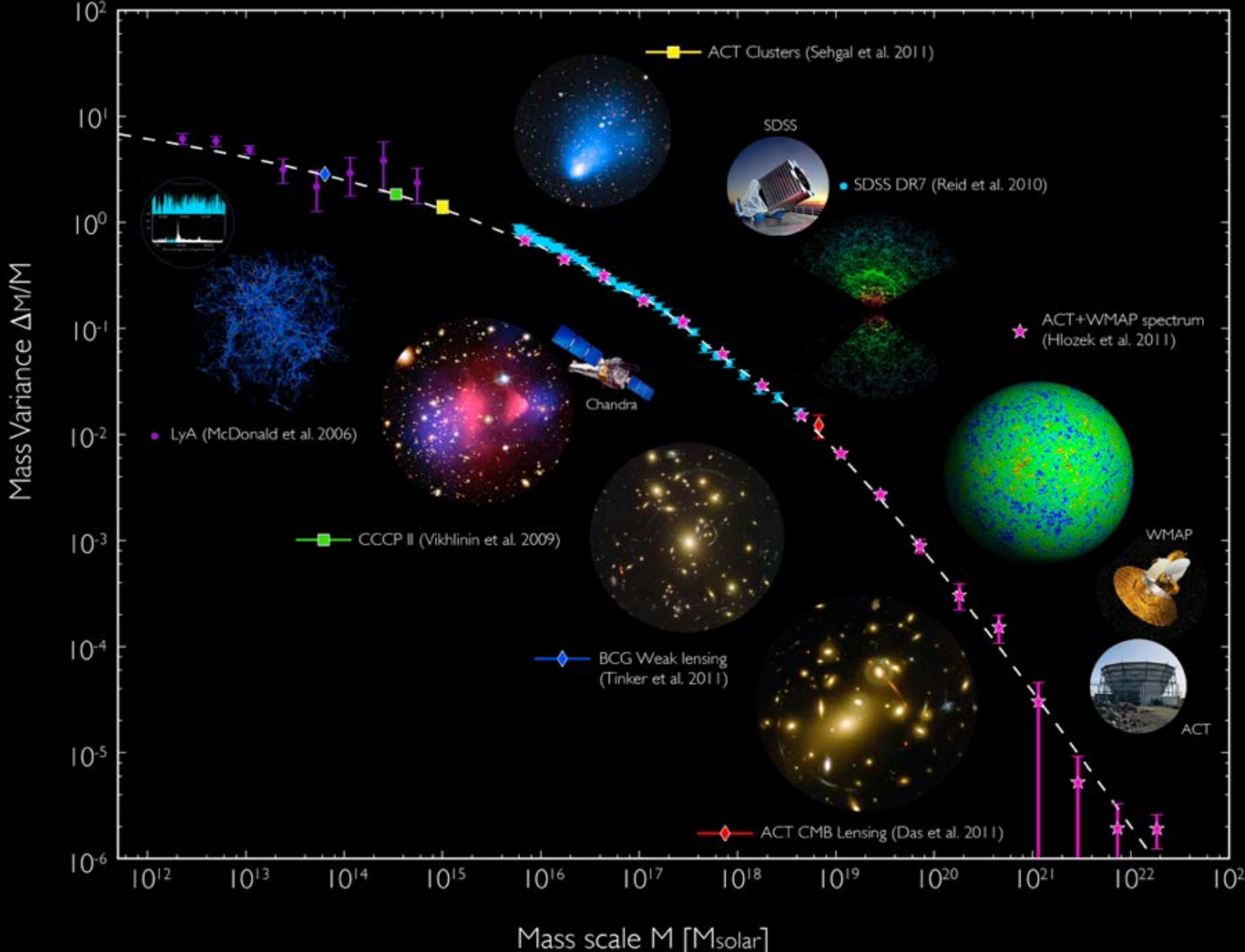
Dark Matter Ships on a Dark Energy Ocean

Matter and Energy Content of the Universe

ΛCDM

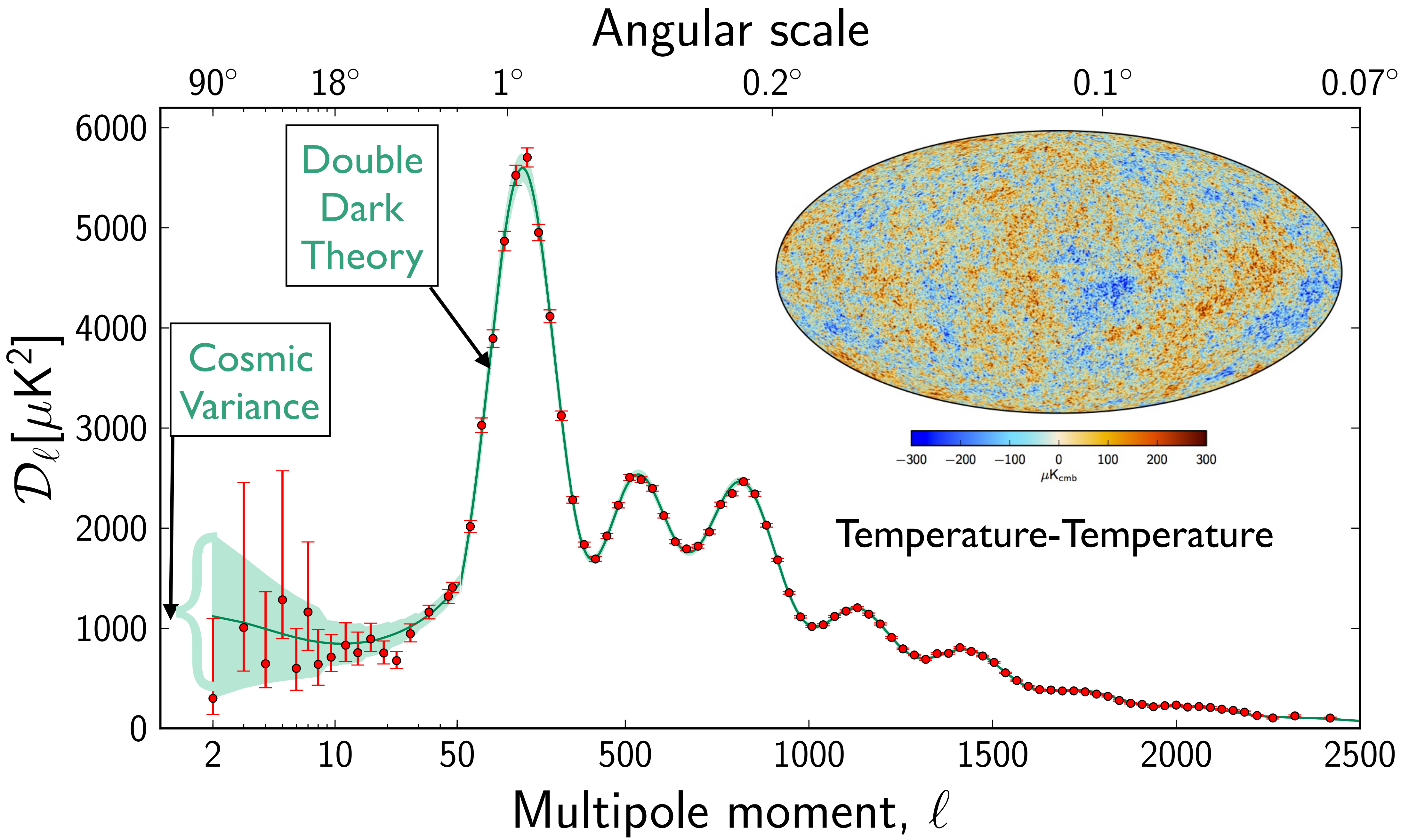
Double Dark Theory

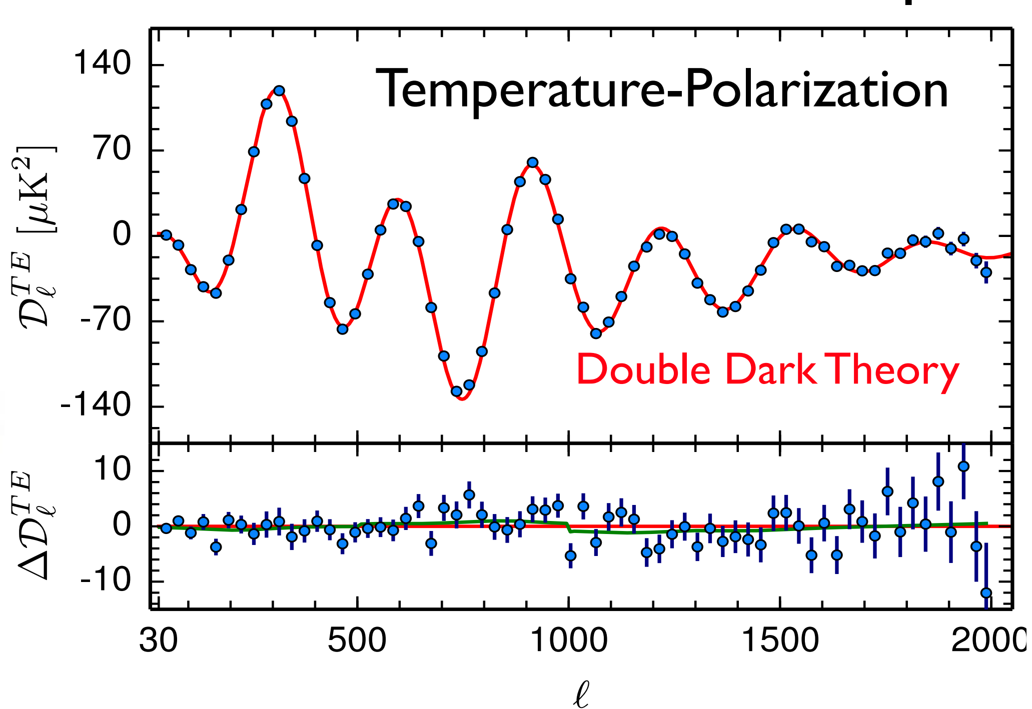
Matter Distribution Agrees with Double Dark Theory!

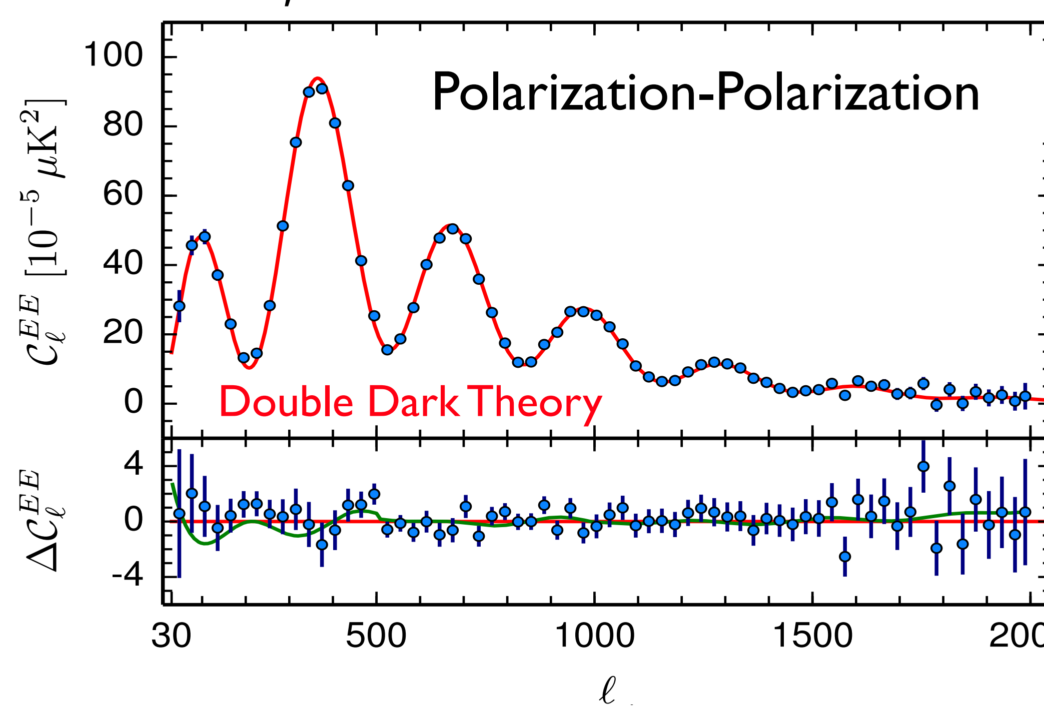


European Space Agency PLANCK Satellite Data

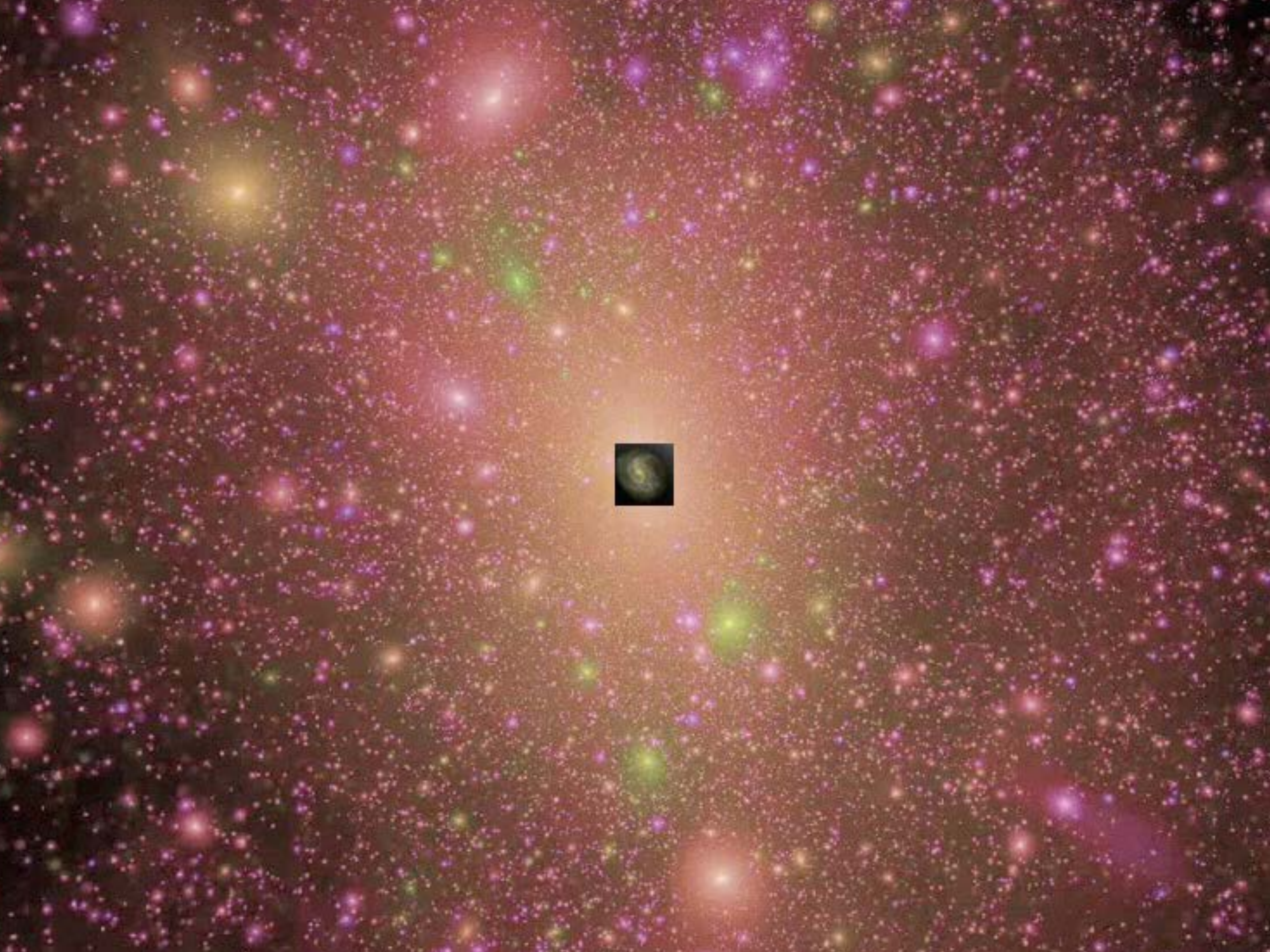
Released February 9, 2015

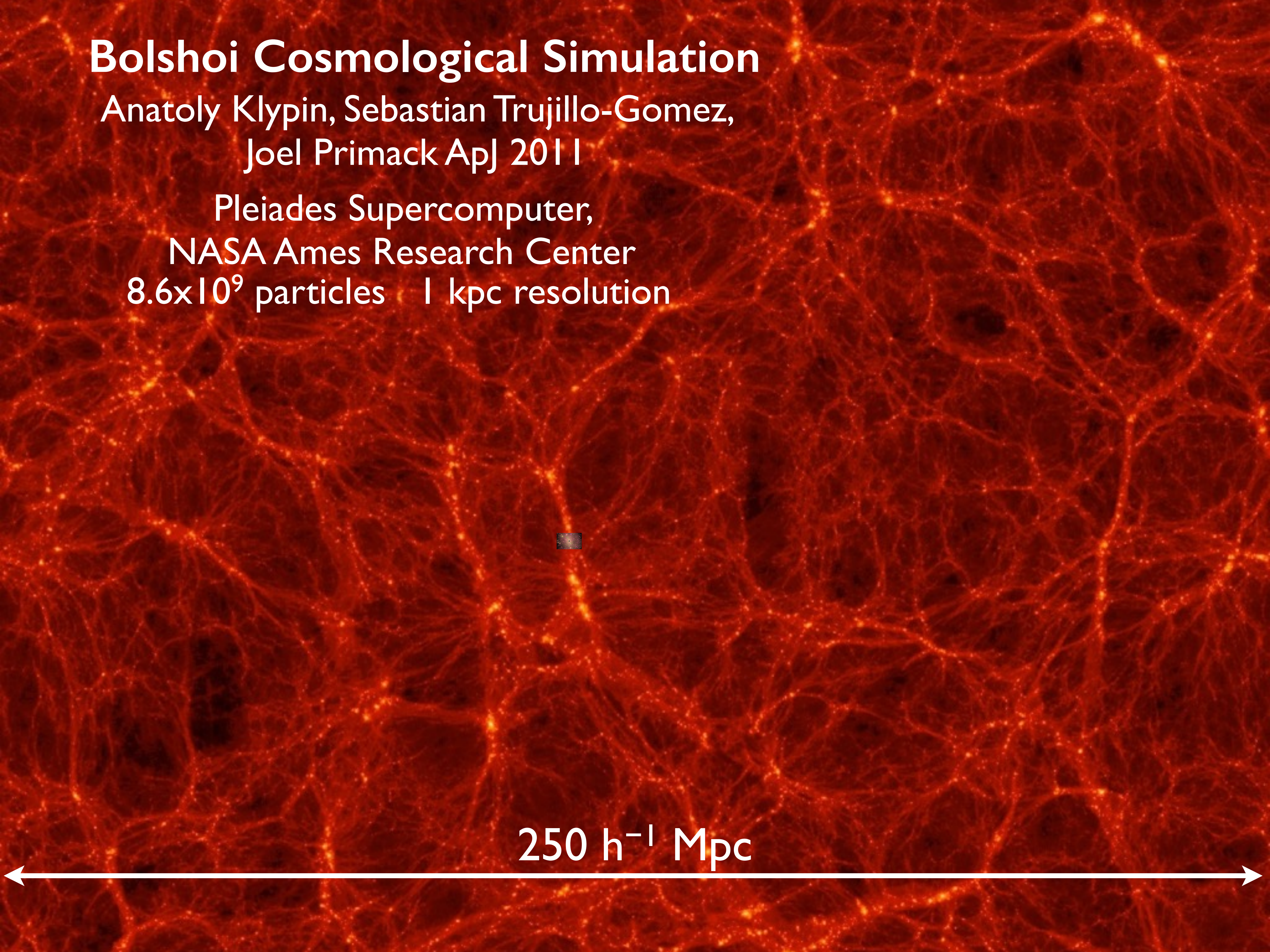


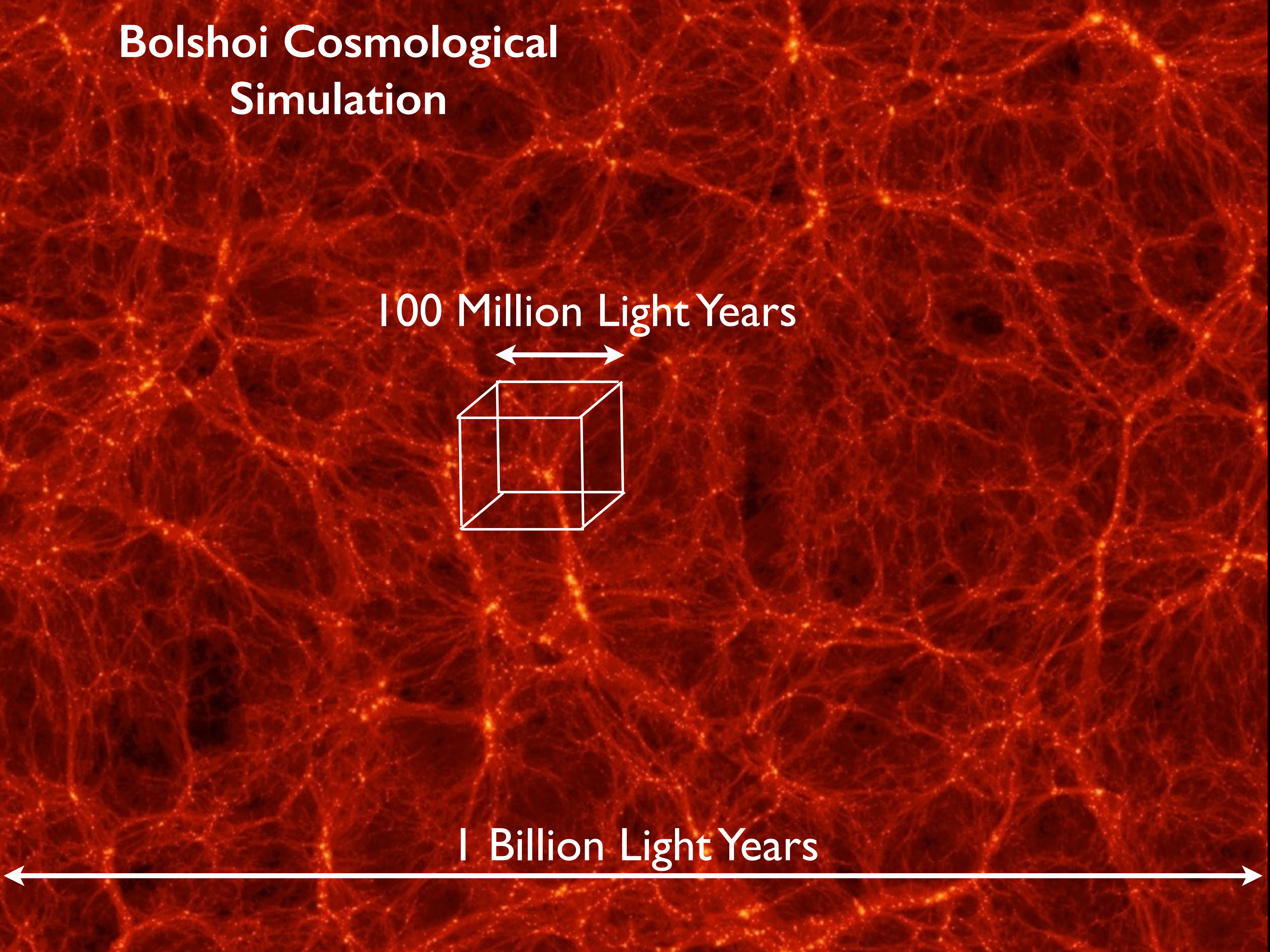





Aquarius Simulation
Volker Springel
Milky Way
30 kpc
Milky Way Dark Matter Halo
500 kpc




Bolshoi Cosmological Simulation
Anatoly Klypin, Sebastian Trujillo-Gomez,
Joel Primack ApJ 2011
Pleiades Supercomputer,
NASA Ames Research Center
8.6x10^9 particles   1 kpc resolution
250 h^{-1} Mpc


Bolshoi Cosmological Simulation
100 Million Light Years
1 Billion Light Years

How the Halo of the Big Cluster Formed

100 Million Light Years

Bolshoi-Planck Cosmological Simulation

Merger Tree of a Large Halo

Structure Formation Methodology

- Starting from the Big Bang, we simulate the evolution of a representative part of the universe according to the Double Dark theory to see if the end result matches what astronomers actually observe.

Structure Formation Methodology

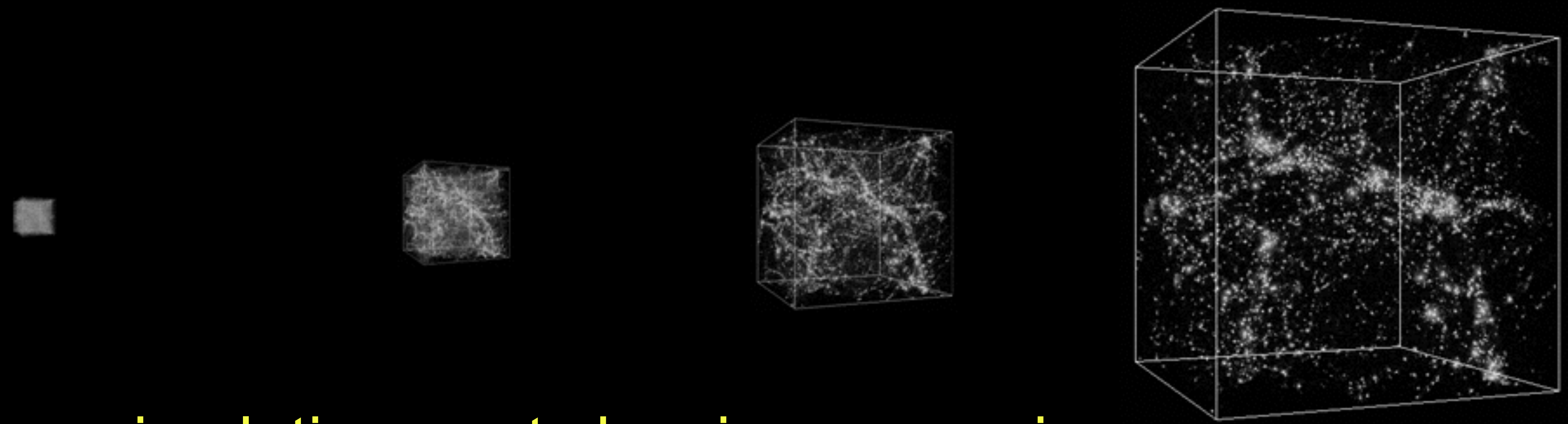
- Starting from the Big Bang, we simulate the evolution of a representative part of the universe according to the Double Dark theory to see if the end result matches what astronomers actually observe.
- On the large scale the simulations produce a universe just like the one we live in. We're always looking for new phenomena to predict — every one of which tests the whole theory!

Structure Formation Methodology

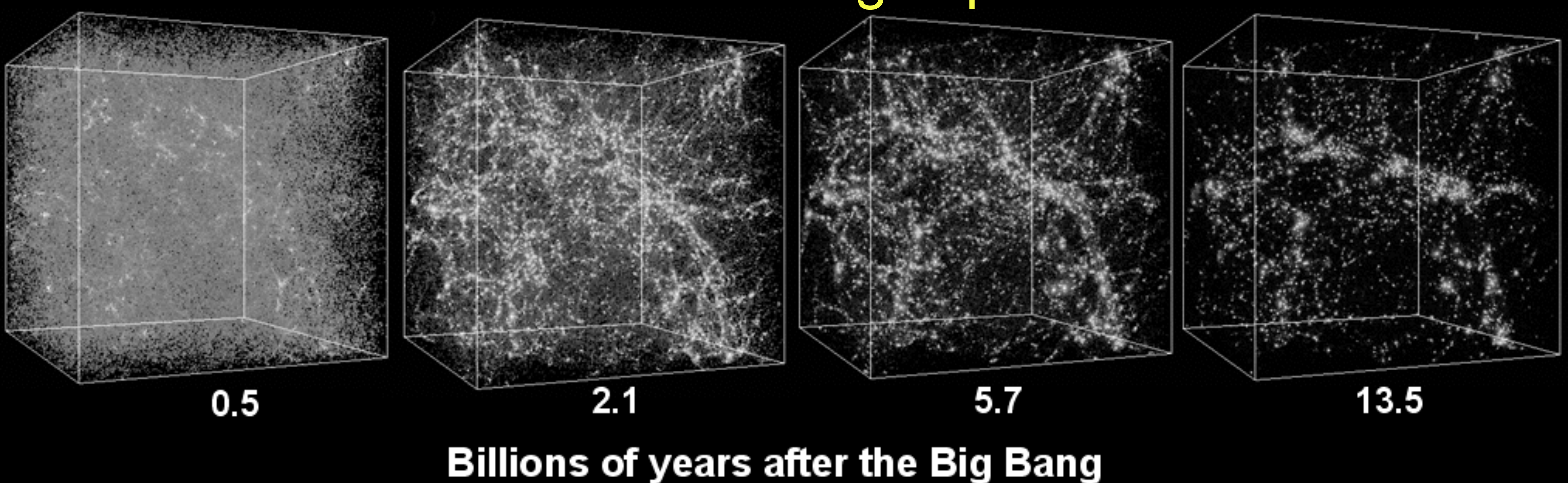
- Starting from the Big Bang, we simulate the evolution of a representative part of the universe according to the Double Dark theory to see if the end result matches what astronomers actually observe.
- On the large scale the simulations produce a universe just like the one we live in. We're always looking for new phenomena to predict — every one of which tests the theory!
- But the way individual galaxies form is only partly understood because it depends on the interactions of the ordinary atomic matter as well as the dark matter and dark energy to form stars and black holes. We need help from observations.

"QUARKS. NEUTRINOS. MESONS. ALL THOSE DAMN PARTICLES YOU CAN'T SEE. THAT'S WHAT DROVE ME TO DRINK. BUT NOW I CAN SEE THEM!"

dark matter simulation - expanding with the universe



same simulation - not showing expansion



Andrey Kravtsov

CONSTRAINED LOCAL UNIVERSE SIMULATION

Stefan Gottloeber, Anatoly Klypin, Joel Primack

Visualization: Chris Henze (NASA Ames)

WHAT IS THE DARK MATTER?

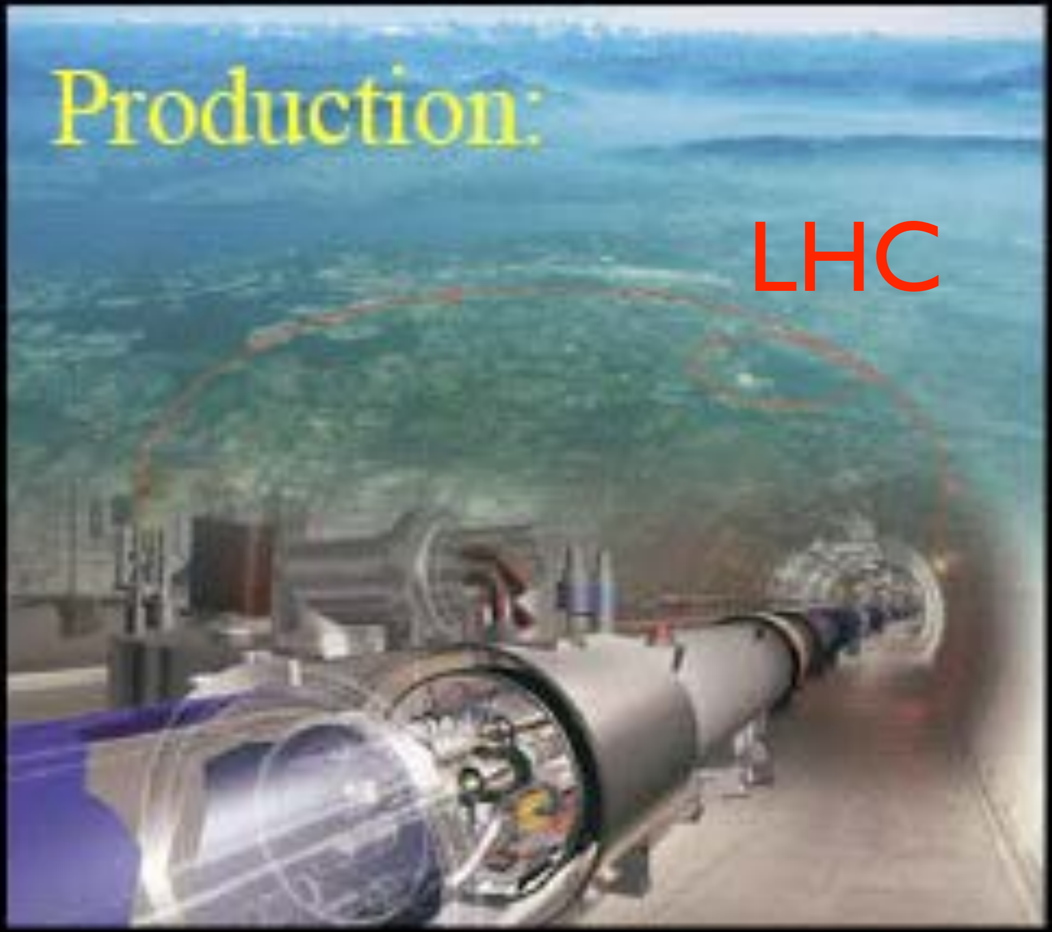
Prospects for DIRECT and INDIRECT detection of WIMPs are improving.

With many upcoming experiments

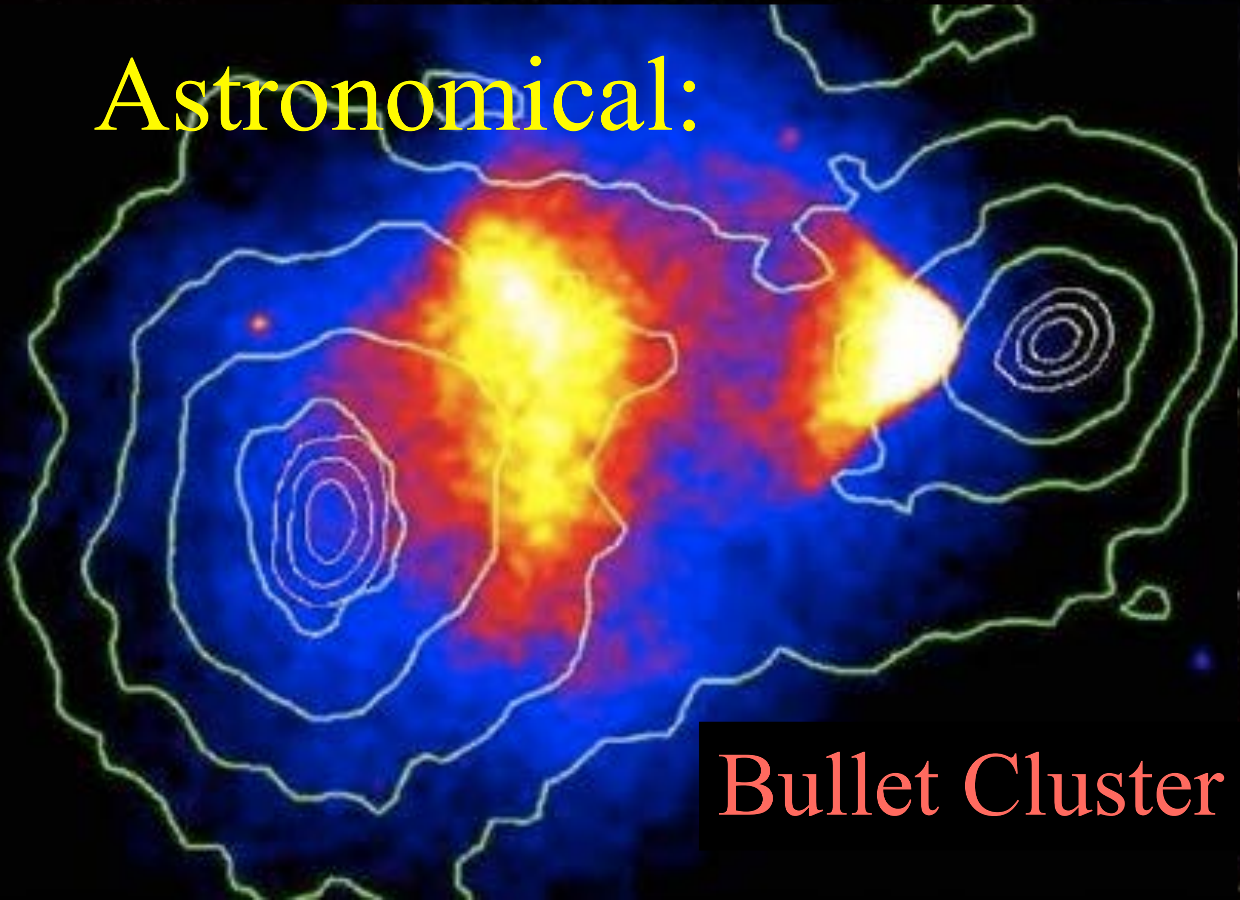
- Large Hadron Collider
- Planck and other new satellites
- Fermi GRST and larger ACTs
- Direct Detection
  - Spin Independent - CDMS-II, LUX, XENON1000, LZ
  - Spin Dependent - COUPP, PICASSO

-- 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 improving experiments, the next few years will be very exciting!



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 Study (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 said 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 has allowed restart of WFIRST, now expected to launch in 2024.

Big Challenges of AstroComputing

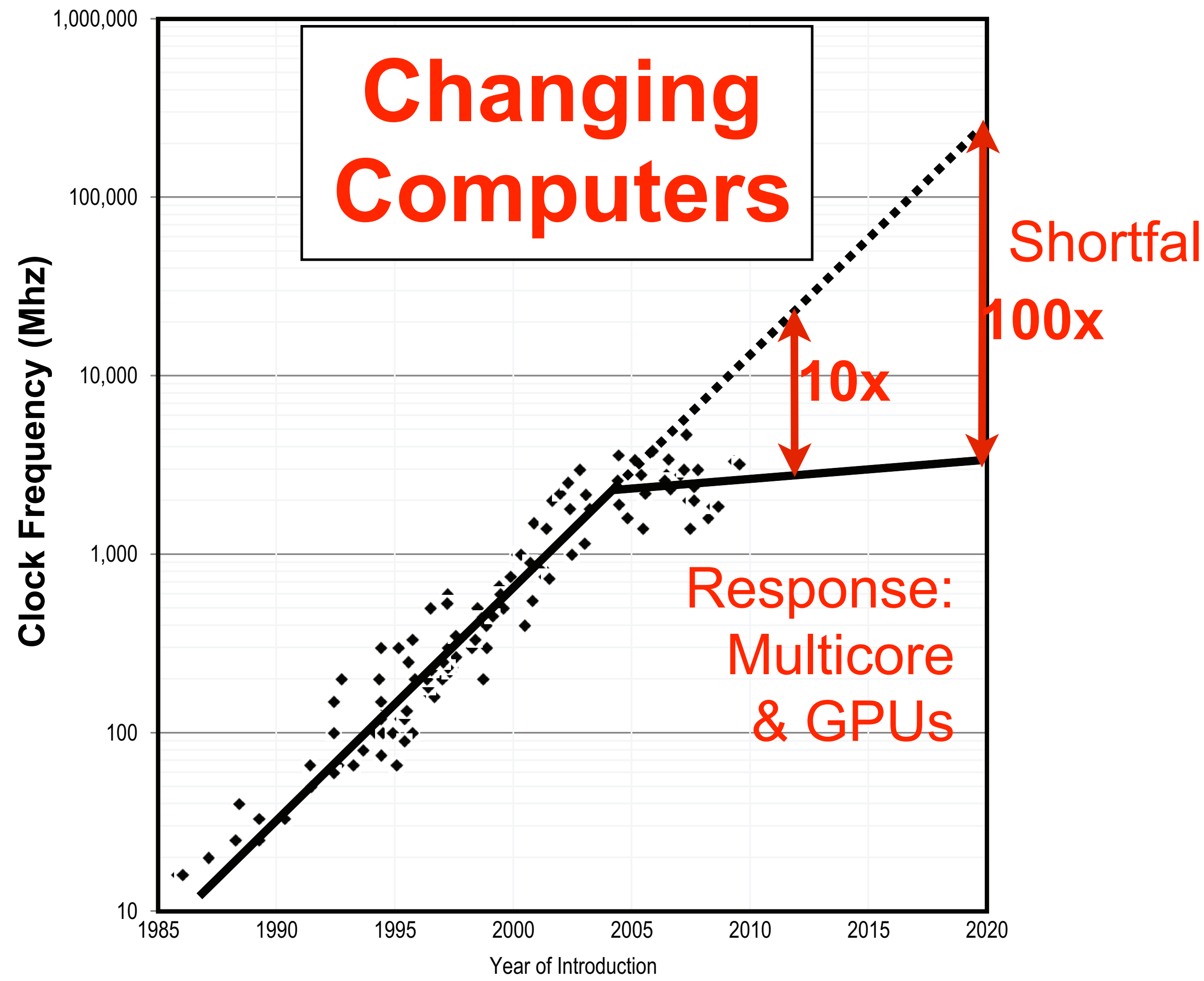
Big Data

Sloan Digital Sky Survey (SDSS) 2008
- 2.5 Terapixels of images
- 40 TB raw data ➠120 TB processed
- 35 TB catalogs

Mikulski Archive for Space Telescopes (MAST) 2013
- 185 TB of images
- 25 TB/year ingest rate
- >100 TB/year retrieval rate

Large Synoptic Survey Telescope (LSST) ~2020
- 15 TB per night for 10 years
- 100 PB image archive
- 20 PB final database catalog

Square Kilometer Array (SKA) ~2024
- 1 EB per day (~ internet traffic today)
- 100 PFlop/s processing power
- ~1 EB processed data/year



Increasingly inhomogeneous computers are harder to program! We need computational scientists and engineers, automatic load balancing and fault tolerance, and data scientists to help compare simulations and observations.

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 within dark matter halos. There's lots more work for us to do!

THANKS!


George
Blumenthal
Avishai Dekel
Joel
Primack
Sandy
Faber


T. J. Cox
James Bullock
Rachel Somerville
Risa Wechsler
Brandon Allgood
Joel Primack
Nancy Abrams
Ricardo Flores
Kim Griest