Why Galaxies Start Pickle-Shaped

An Historical Introduction to Dark Matter and Galaxy Formation

Joel Primack (UCSC)

Abstract: According to modern cosmology, invisible dark matter and dark energy drive the evolution of the universe – and astrophysicists are still working out the implications. Newton's laws explained why planetary orbits are elliptical, but not why the planetary orbits in the solar system are nearly circular, in the same plane, and in the same direction as the sun rotates. Laplace explained this as a consequence of angular momentum conservation as the sun and planets formed in a cooling and contracting protoplanetary gas cloud. For similar reasons, many astronomers once thought that galaxies would start as disks. But Hubble Space Telescope images of forming galaxies instead show that most of them are prolate – that is, pickle-shaped. This turns out to be a consequence of most galaxies forming in prolate dark matter halos oriented along massive dark matter filaments. This colloquium will include background on the 2019 Nobel Prize in Physics to Jim Peebles *"for theoretical discoveries in physical cosmology"* [1] and the 2020 Lilienfeld Prize of the American Physical Society to Joel Primack *"for seminal contributions to our understanding of the formation of structure in the universe, and for communicating to the public the extraordinary progress in our understanding of cosmology"* [2].

[1] https://www.nobelprize.org/prizes/physics/2019/prize-announcement/, nobelprize.org/uploads/2019/10/advanced-physicsprize2019.pdf.

[2] https://www.eurekalert.org/pub_releases/2019-08/aps-aa2082719.php, https://news.ucsc.edu/2019/09/primack-lilienfeld-prize.html. (See also Primack's popular article https://www.americanscientist.org/article/why-do-galaxies-start-out-as-cosmic-pickles.)

UCSC PHYSICS COLLOQUIUM
17 October 2019

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An Historical Introduction to Dark Matter and Galaxy Formation

Joel Primack

Distinguished Professor of Physics Emeritus, UCSC

Nearby large galaxies are mostly disks and spheroids — but they start out looking more like pickles.

Outline

Evidence for Modern Cosmology: the Double Dark Theory

Observational Evidence that Galaxies Start Pickle-Shaped

Historical Introduction to Dark Matter and Cosmology

Introduction to Galaxy Formation

Why Galaxies Start Pickle-Shaped and How They Evolve

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DISCOVERING THE INVISIBLE UNIVERSE

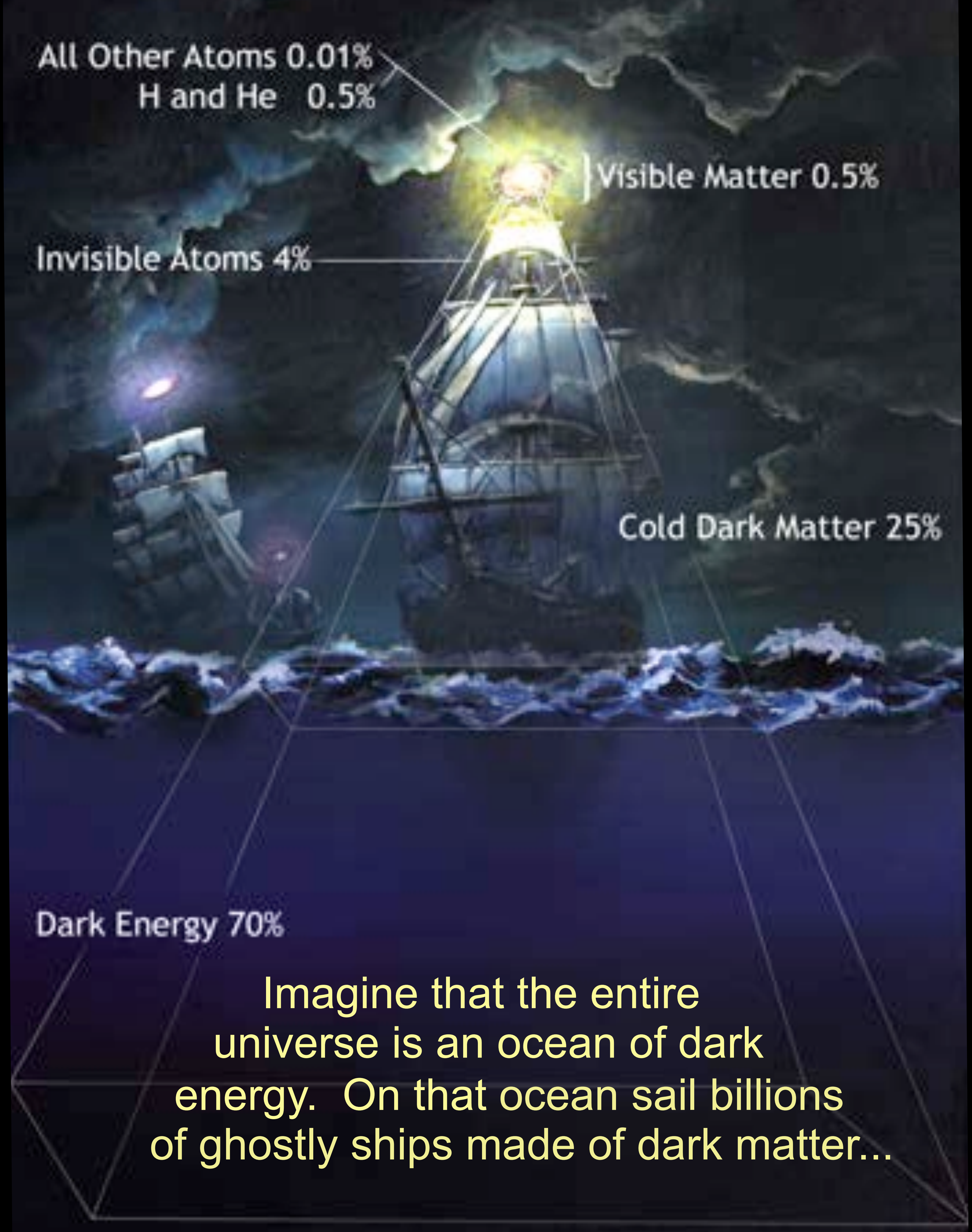
Although the first evidence for dark matter was discovered in the 1930s, it was not until about 1980 that astronomers became convinced that most of the mass holding galaxies and clusters of galaxies together is invisible. For two decades, alternative theories were proposed and challenged. By the beginning of the 21st century the ΛCDM "Double Dark" standard cosmological model was accepted: dark energy Λ plus Cold Dark Matter − non-atomic matter different from that which makes up the stars, planets, and us − 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.

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.

Matter and Energy Content of the Universe



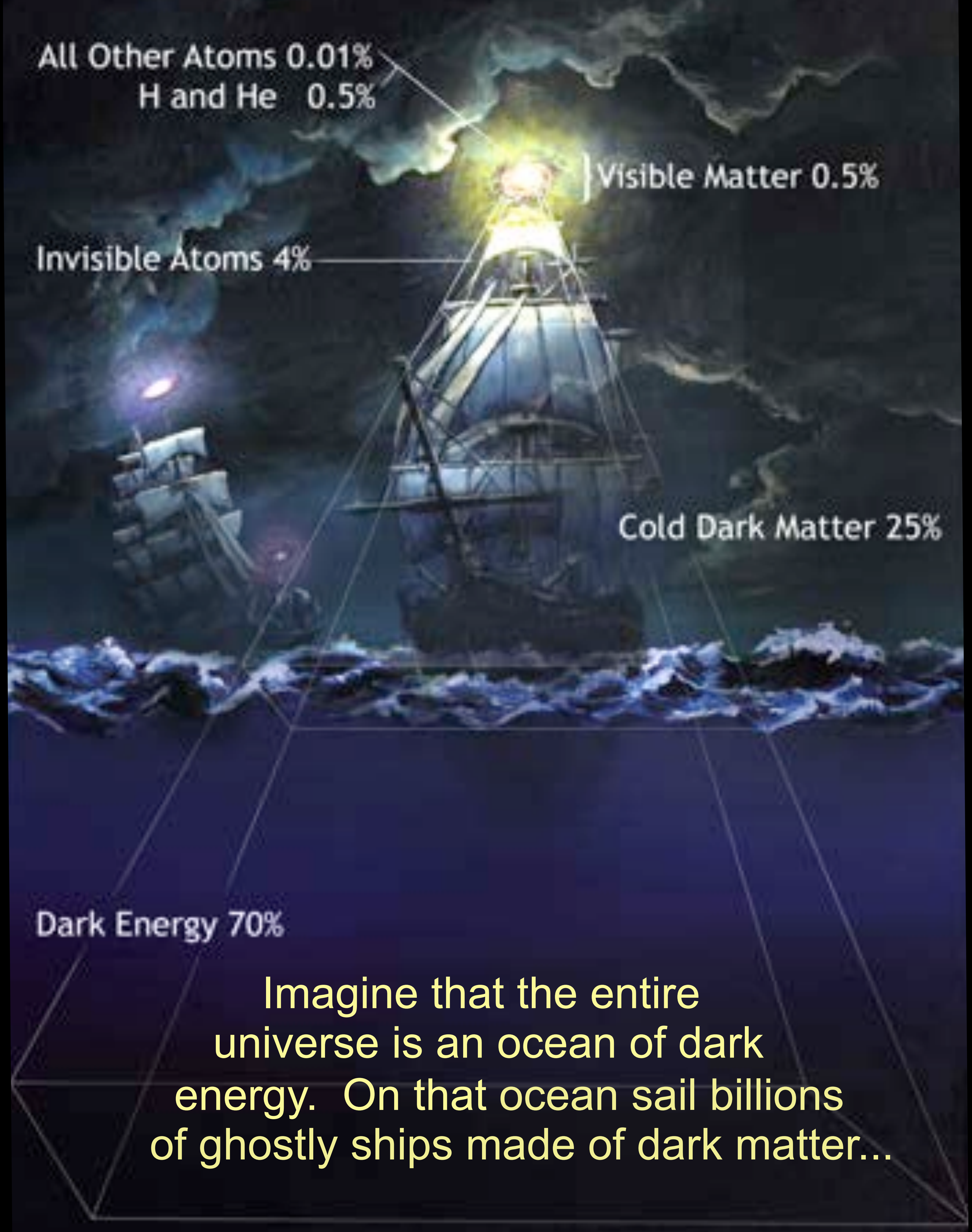
Imagine that the entire universe is an ocean of dark energy. On that ocean sail billions of ghostly ships made of dark matter...

Matter and Energy Content of the Universe

Dark Matter Ships

on a

Dark Energy Ocean



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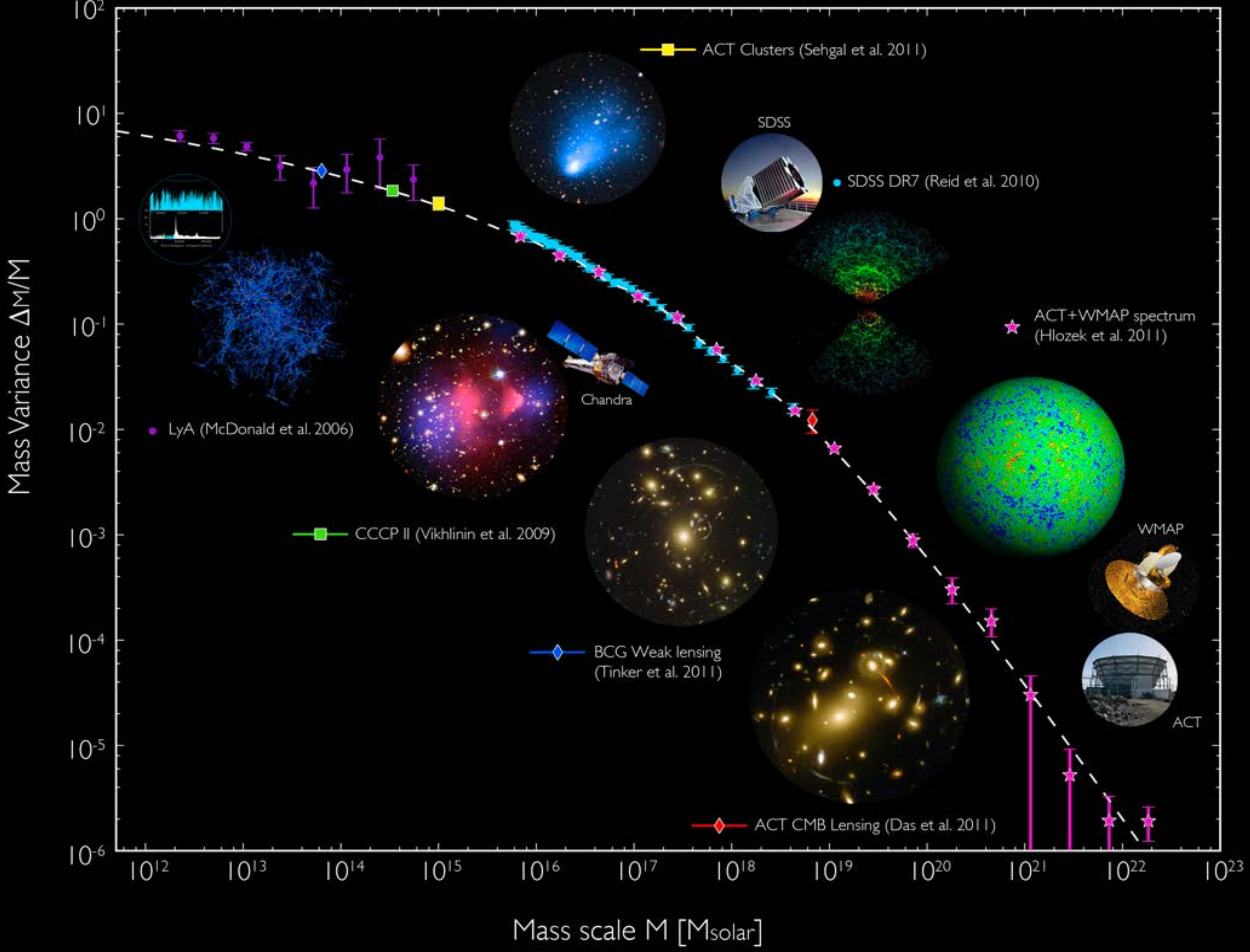
ΛCDM

Double Dark Theory

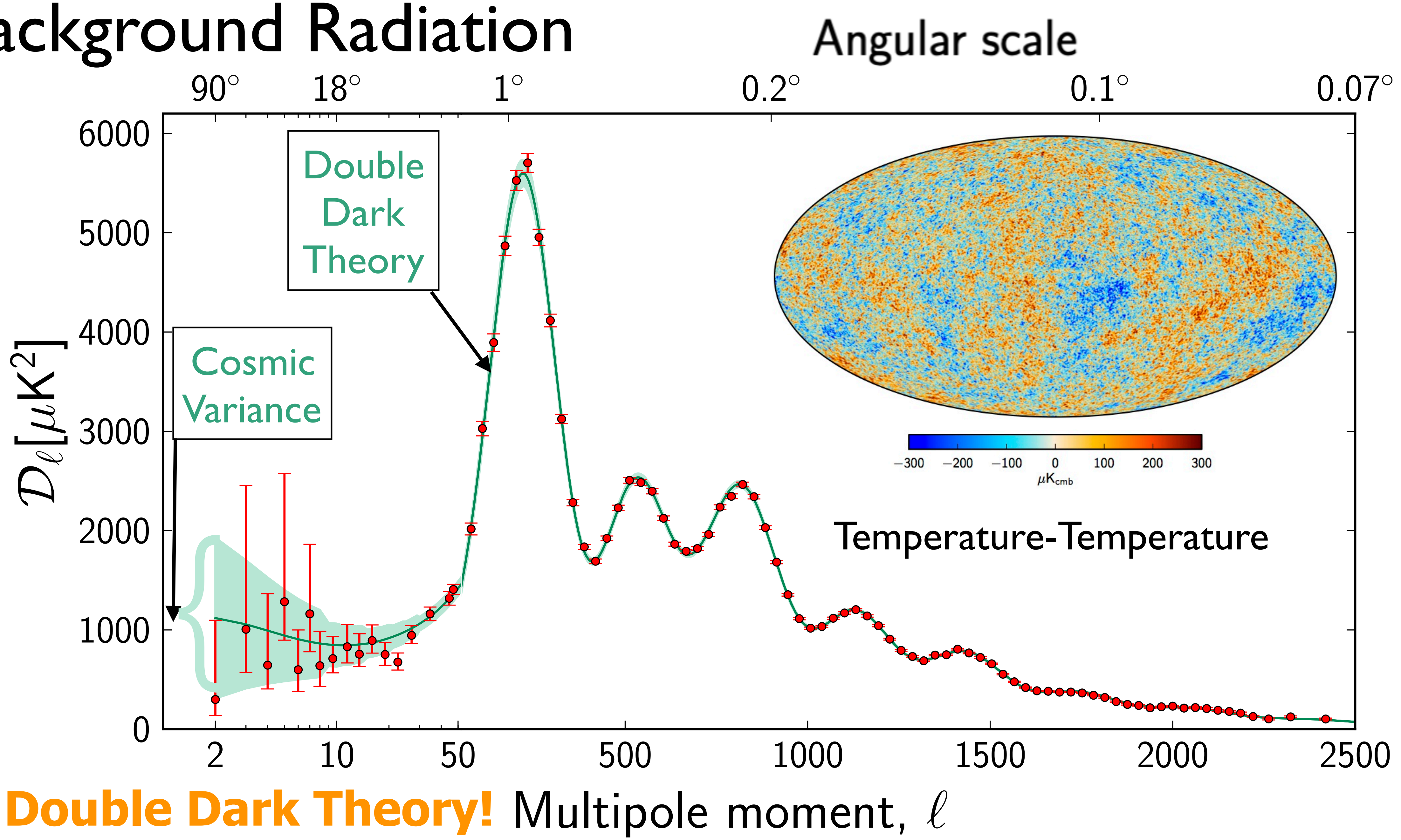
Matter Distribution Agrees with Double Dark Theory!



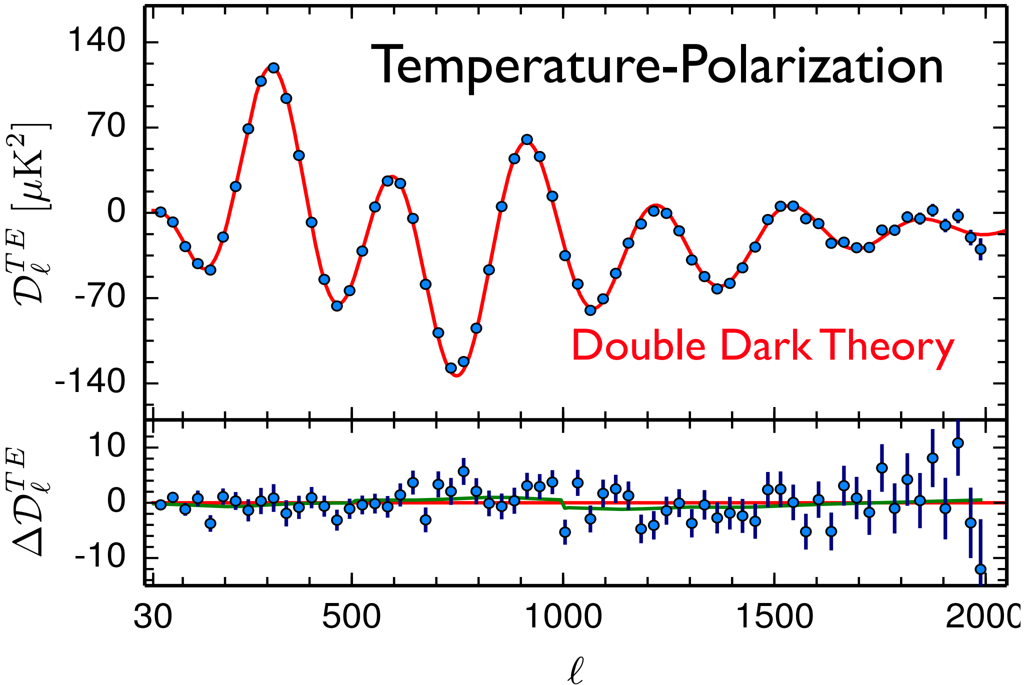
Cosmic Background Radiation

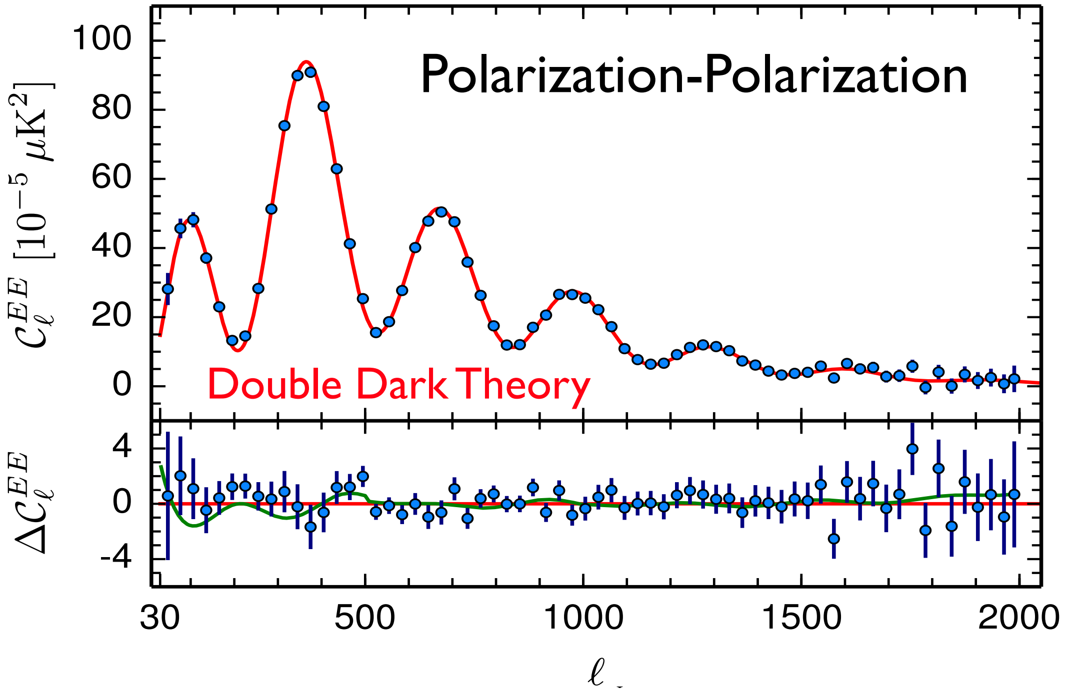
European
Space
Agency
PLANCK
Satellite
Data

Released
February 9,
2015



Agrees with Double Dark Theory!





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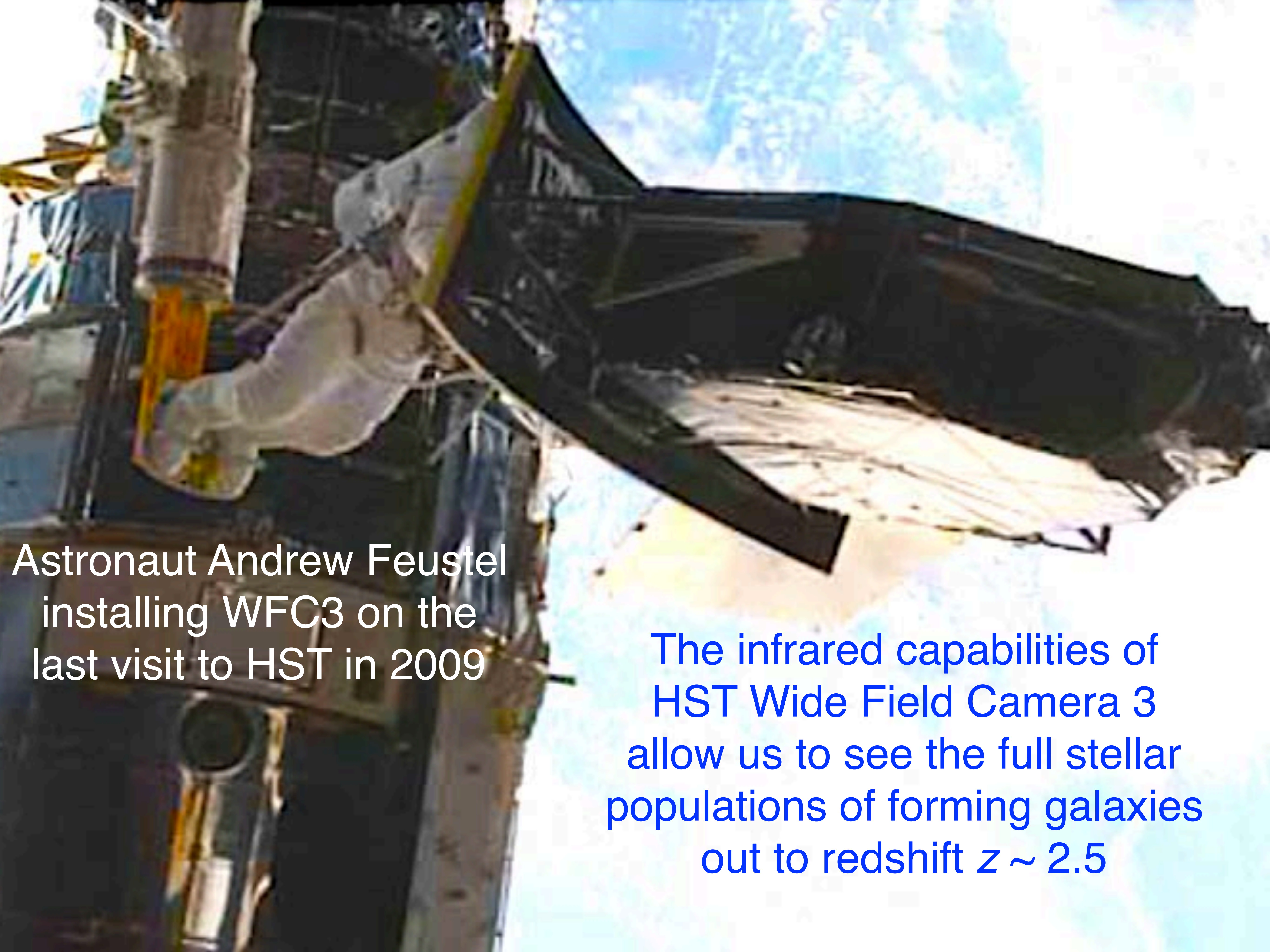
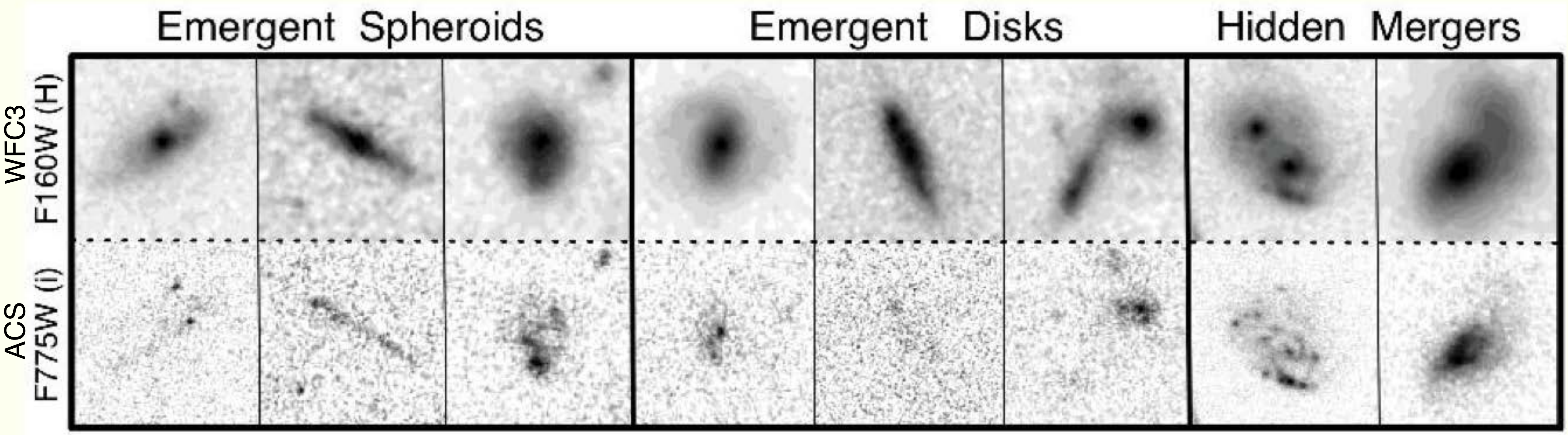


Astronaut Andrew Feustel
installing WFC3 on the
last visit to HST in 2009

The infrared capabilities of
HST Wide Field Camera 3
allow us to see the full stellar
populations of forming galaxies
out to redshift $z \sim 2.5$

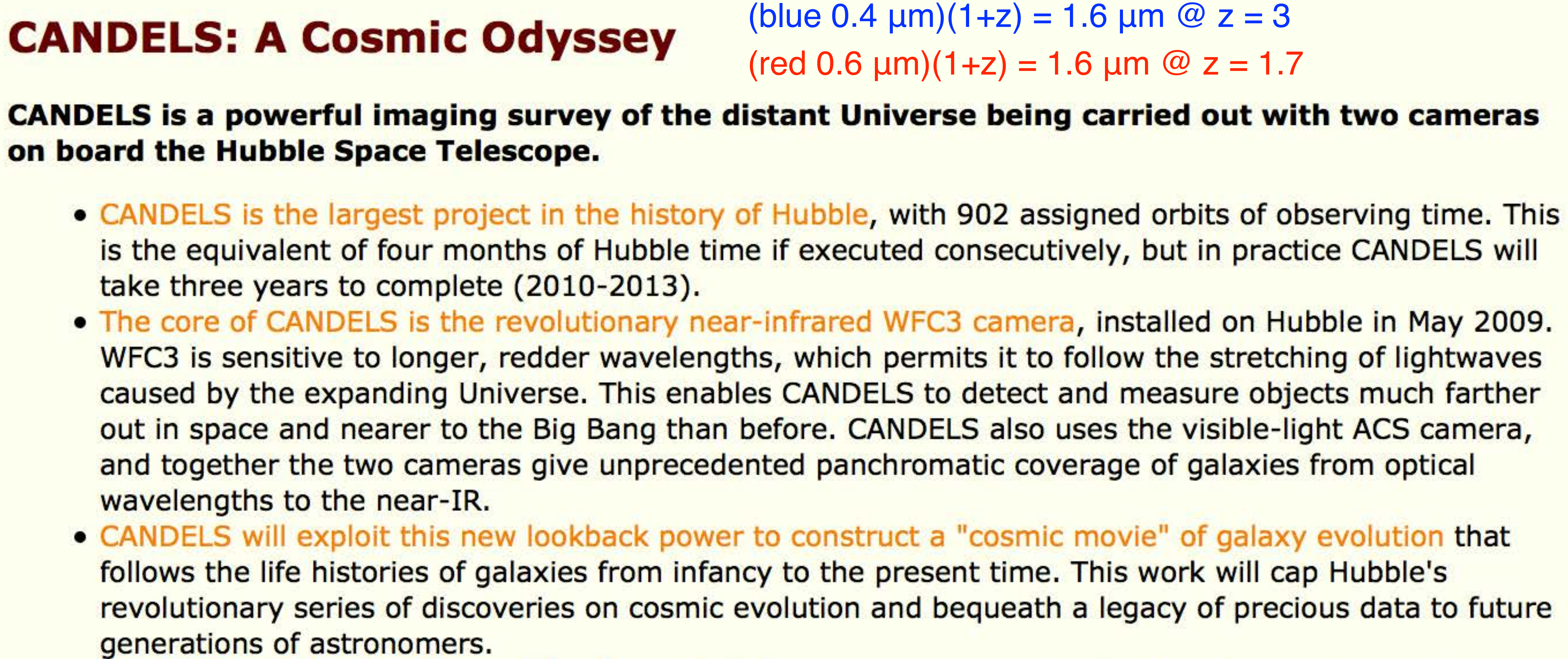
The CANDELS Survey shows shapes of $z \lesssim 2.5$ galaxies

candels.ucolick.org



(blue 0.4 µm)(1+z) = 1.6 µm @ z = 3

(red 0.6 µm)(1+z) = 1.6 µm @ z = 1.7

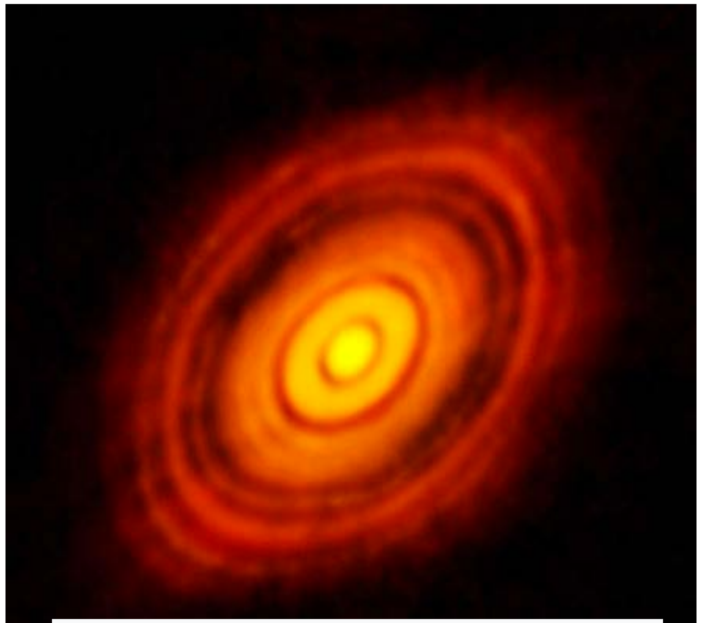


CANDELS: A Cosmic Odyssey

CANDELS is a powerful imaging survey of the distant Universe being carried out with two cameras on board the Hubble Space Telescope.

- CANDELS is the largest project in the history of Hubble, with 902 assigned orbits of observing time. This is the equivalent of four months of Hubble time if executed consecutively, but in practice CANDELS will take three years to complete (2010-2013).
- The core of CANDELS is the revolutionary near-infrared WFC3 camera, installed on Hubble in May 2009. WFC3 is sensitive to longer, redder wavelengths, which permits it to follow the stretching of lightwaves caused by the expanding Universe. This enables CANDELS to detect and measure objects much farther out in space and nearer to the Big Bang than before. CANDELS also uses the visible-light ACS camera, and together the two cameras give unprecedented panchromatic coverage of galaxies from optical wavelengths to the near-IR.
- CANDELS will exploit this new lookback power to construct a "cosmic movie" of galaxy evolution that follows the life histories of galaxies from infancy to the present time. This work will cap Hubble's revolutionary series of discoveries on cosmic evolution and bequeath a legacy of precious data to future generations of astronomers.

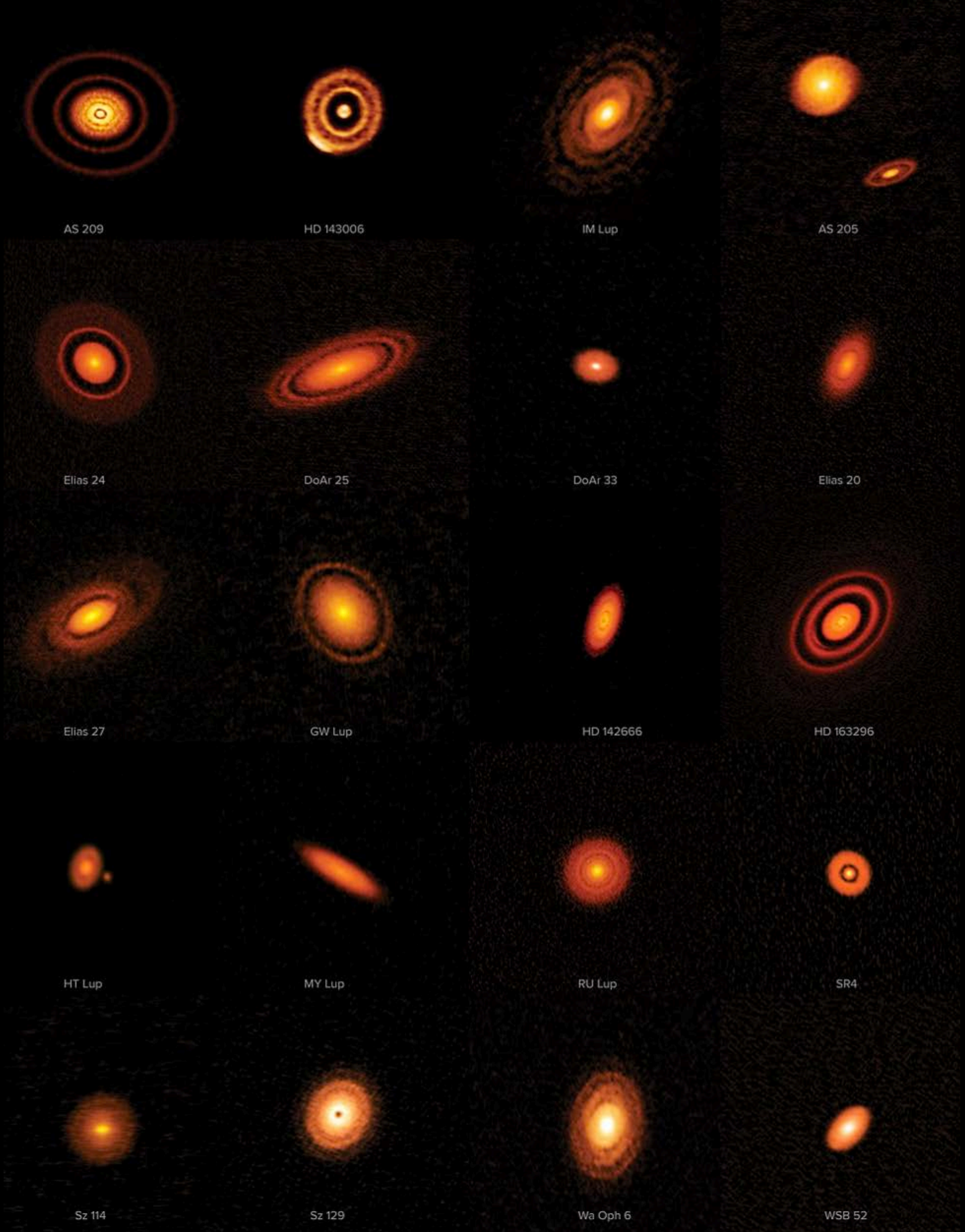
Newton's laws explained why planetary orbits are elliptical, but not why the planetary orbits in the solar system are nearly circular, in the same plane, and in the same direction as the sun rotates. Laplace explained this as a consequence of angular momentum conservation as the sun and planets formed in a cooling and contracting protoplanetary gas cloud — like this one:



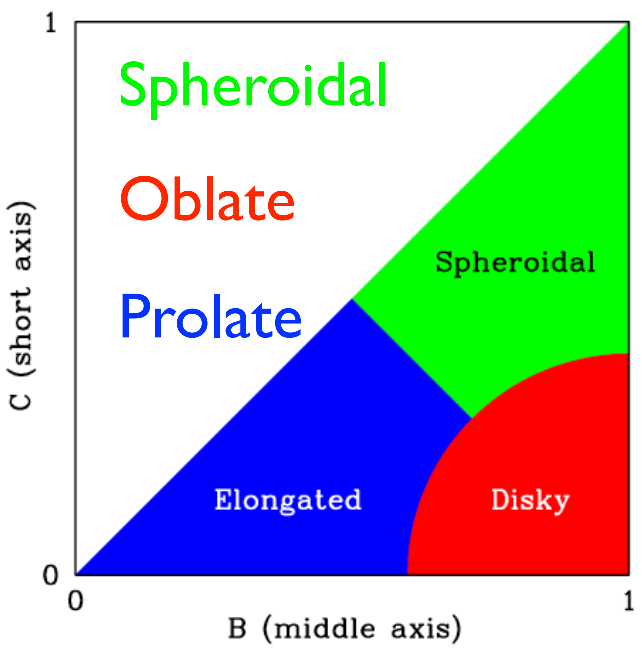
ALMA image of HL Tauri

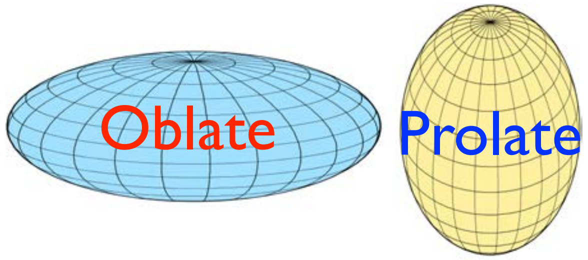
For similar reasons, many astronomers once thought that galaxies would start as disks. But Hubble Space Telescope images of forming galaxies instead show that most of them are prolate – that is, pickle-shaped. As we will see, this is a consequence of most galaxies forming in prolate dark matter halos oriented along massive dark matter filaments.

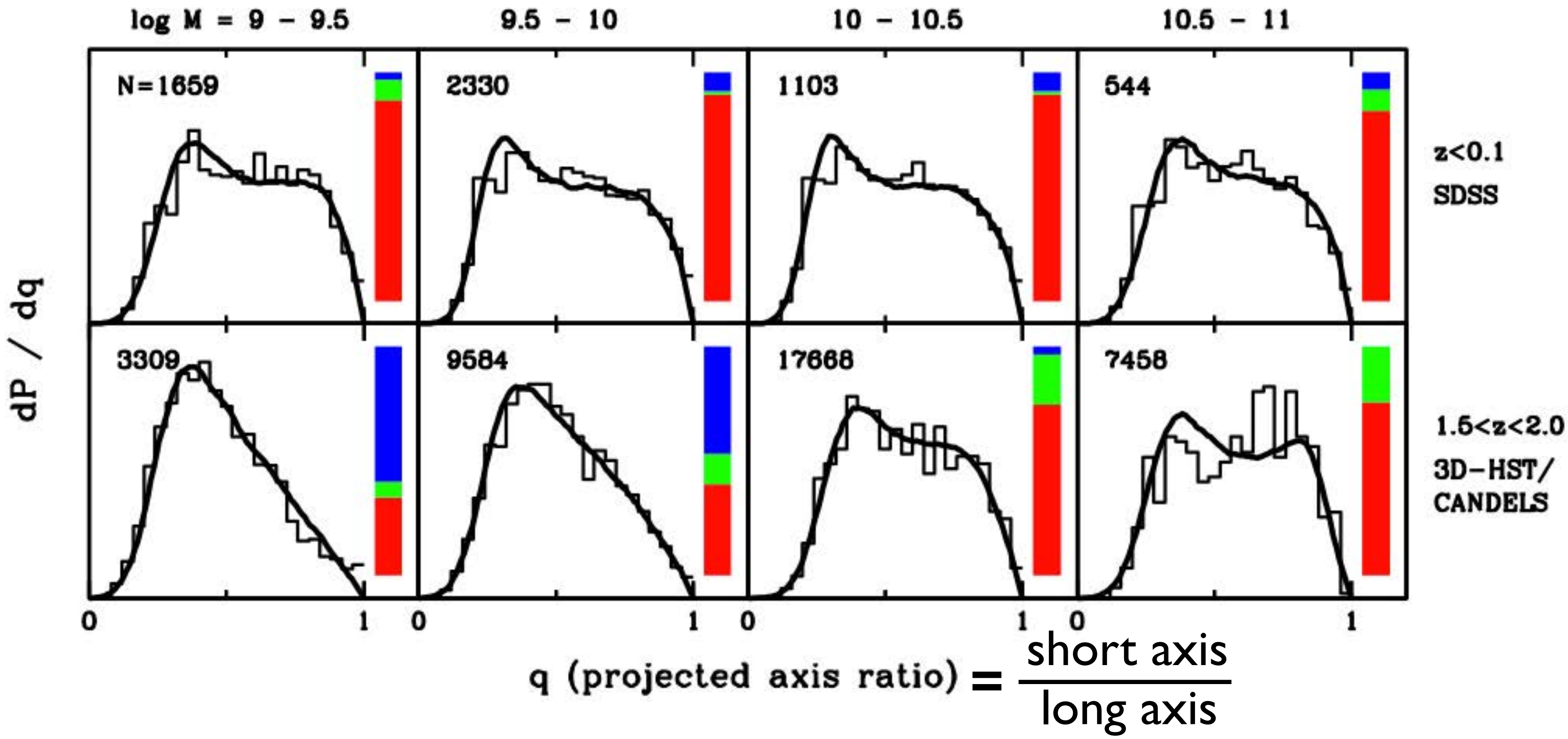
20 Protoplanetary Disks from ALMA's High Angular Resolution Project DSHARP (2019)

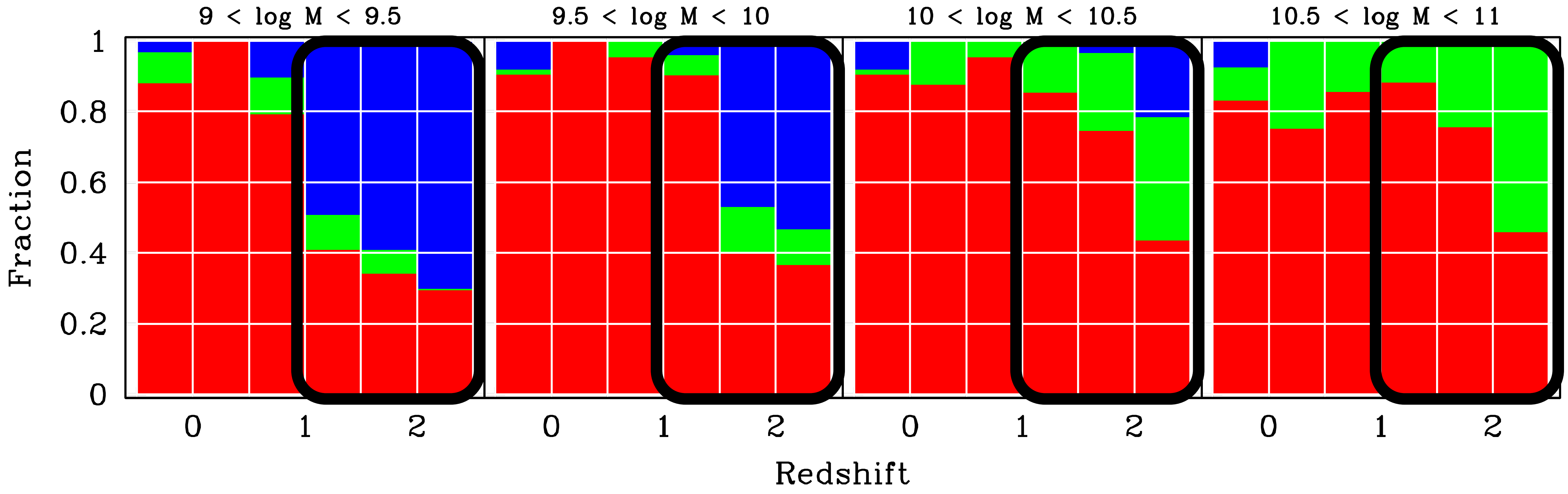


Prolate Galaxies Dominate at High Redshifts & Low Masses









See also Morphological Survey of Galaxies z=1.5-3.6 Law, Steidel+ ApJ 2012

When Did Round Disk Galaxies Form? T. M. Takeuchi+ ApJ 2015

CANDELS

van der Wel+2014

The Evolution of Galaxy Shapes in CANDELS: from Prolate to Oblate

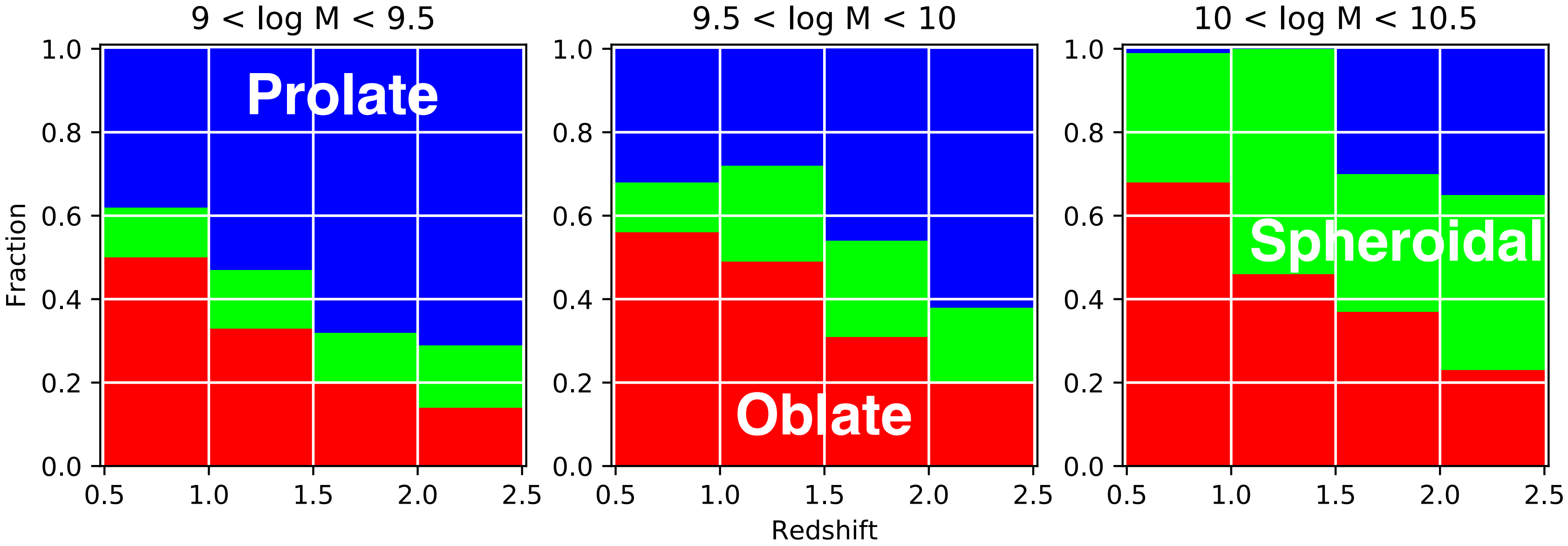
Haowen Zhang, Joel R. Primack, S. M. Faber, David C. Koo, Avishai Dekel, Zhu Chen, Daniel Ceverino, Yu-Yen Chang, Jerome J. Fang, Yicheng Guo, Lin Lin, and Arjen van der Wel

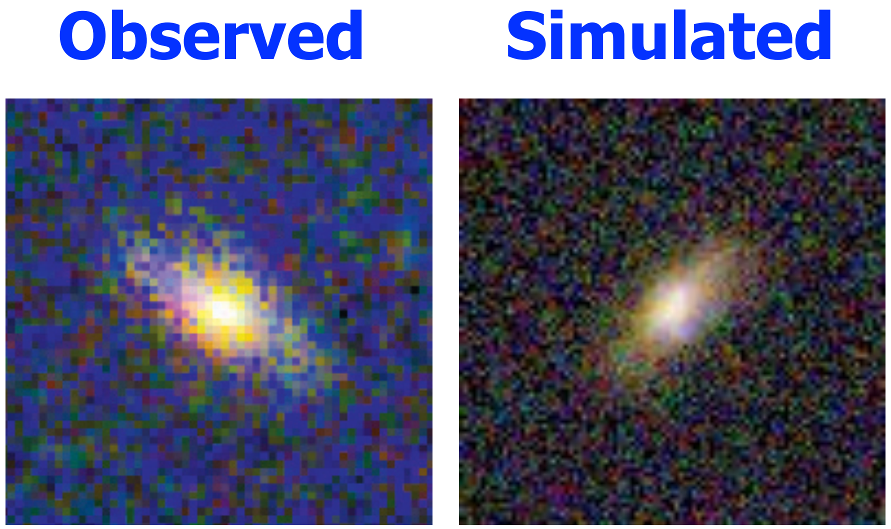
MNRAS 484, 5170 (2019)

arXiv:1805.12331

ABSTRACT

We model the projected $b/a - \log a$ distributions of CANDELS main sequence star-forming galaxies, where a (b) is the semi-major (semi-minor) axis of the galaxy images. We find that smaller-a galaxies are rounder at all stellar masses M_* and redshifts, so we include a when analyzing b/a distributions. Approximating intrinsic shapes of the galaxies as triaxial ellipsoids and assuming a multivariate normal distribution of galaxy size and two shape parameters, we construct their intrinsic shape and size distributions to obtain the fractions of prolate, oblate, and spheroidal galaxies in each redshift and mass bin. We find that galaxies tend to be prolate at low M_* and high redshifts, and oblate at high M_* and low redshifts, qualitatively consistent with van der Wel et al. (2014), implying that galaxies tend to evolve from prolate to oblate. These results are consistent with the predictions from simulations (Ceverino et al. 2015, Tomassetti et al. 2016) that the transition from prolate to oblate is caused by a compaction event at a characteristic mass range, making the galaxy center baryon dominated. We give probabilities of a galaxy's being prolate, oblate, or spheroidal as a function of its M_*, redshift, and projected b/a and a, which can facilitate target selections of galaxies with specific shapes at high redshifts. We also give predicted optical depths of galaxies, which are qualitatively consistent with the expected correlation that A_V should be higher for edge-on disk galaxies in each $\log a$ slice at low redshift and high mass bins.



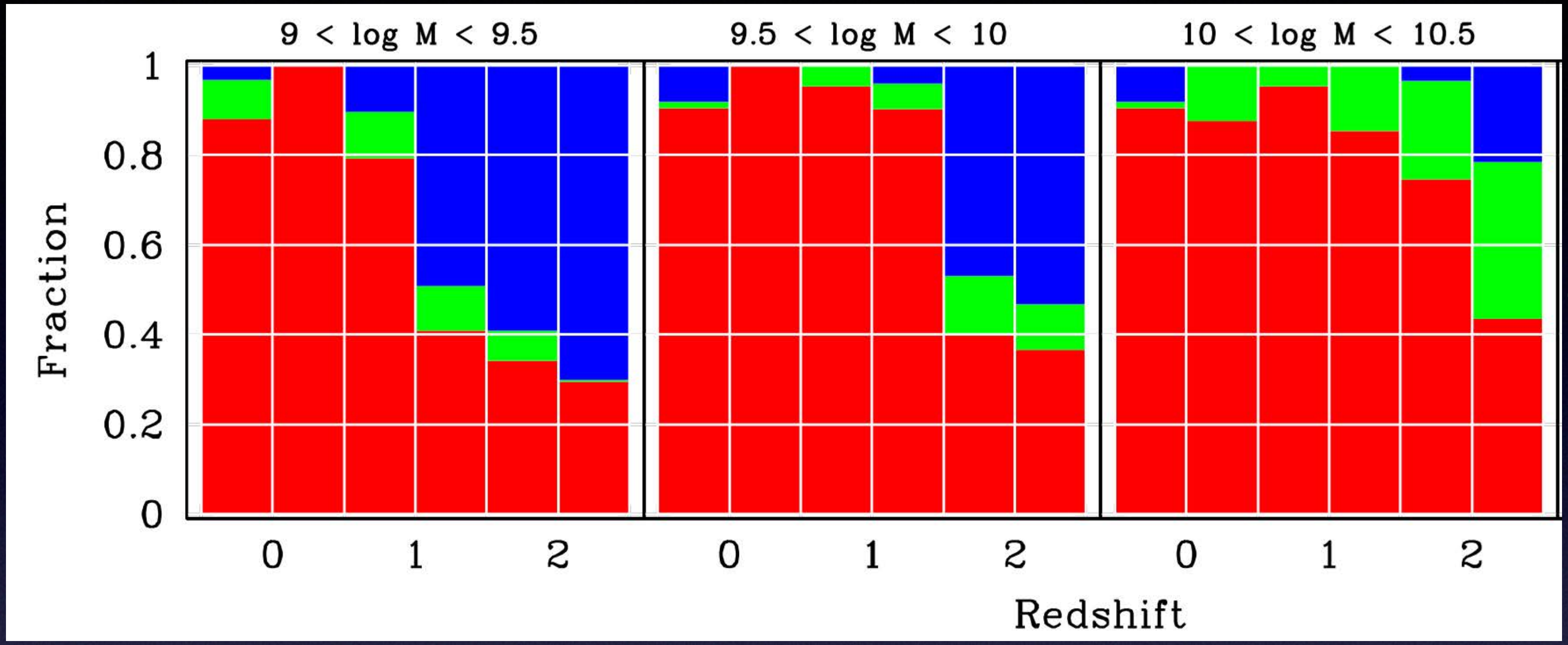


(a) CANDELS galaxy

(b) VELA galaxy

CANDELS: galaxies start out elongated

Arjen van der Wel+14

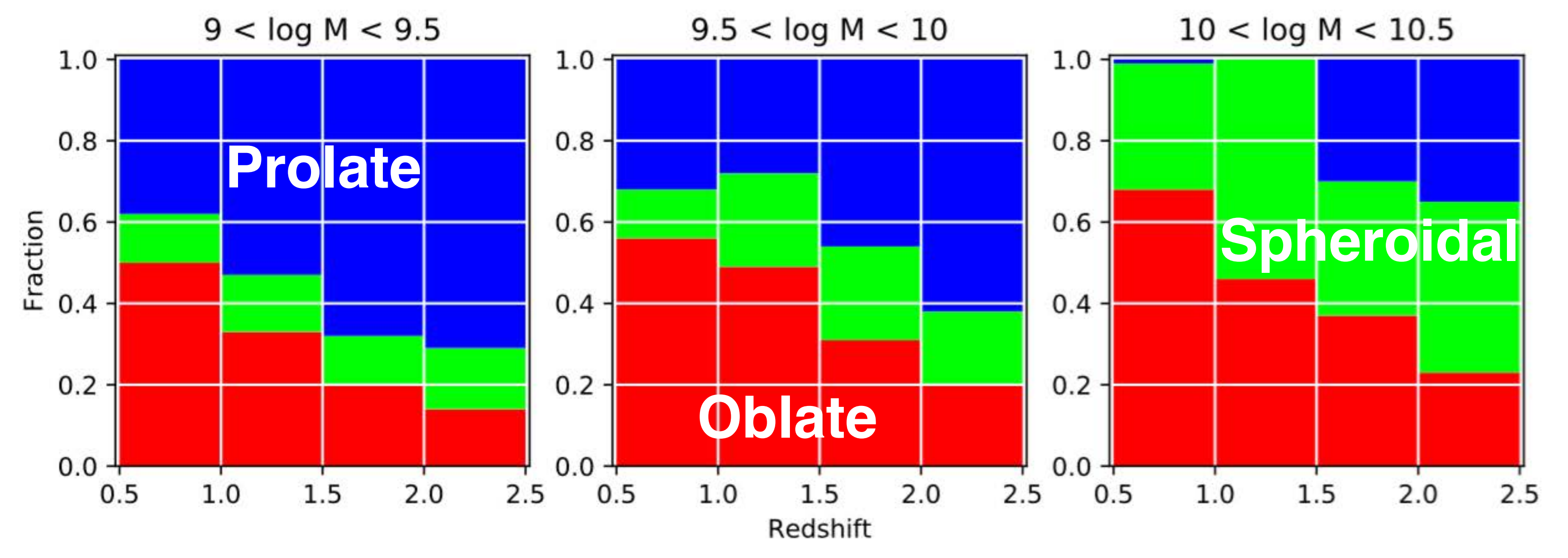


Blue = elongated

Green = Spheroidal

Red = disky

Haowen Zhang+18



Four stellar mass—redshift bins with >50% prolate fraction:

$1.0 < z < 1.5, 9.0 < \log M_* < 9.5$

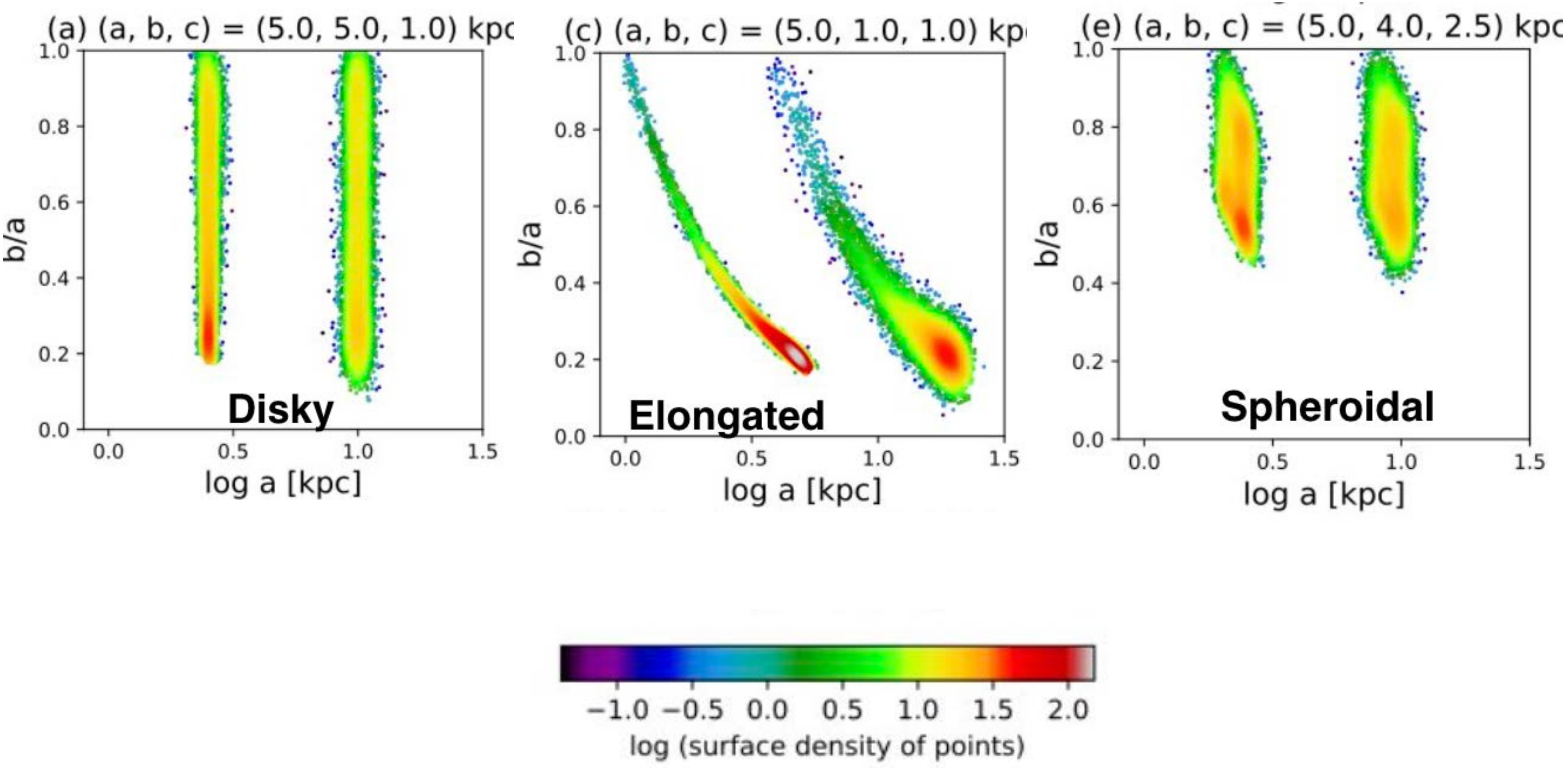
$2.0 < z < 2.5, 9.0 < \log M_* < 9.5$

$1.5 < z < 2.0, 9.0 < \log M_* < 9.5$

$2.0 < z < 2.5, 9.5 < \log M_* < 10.0$

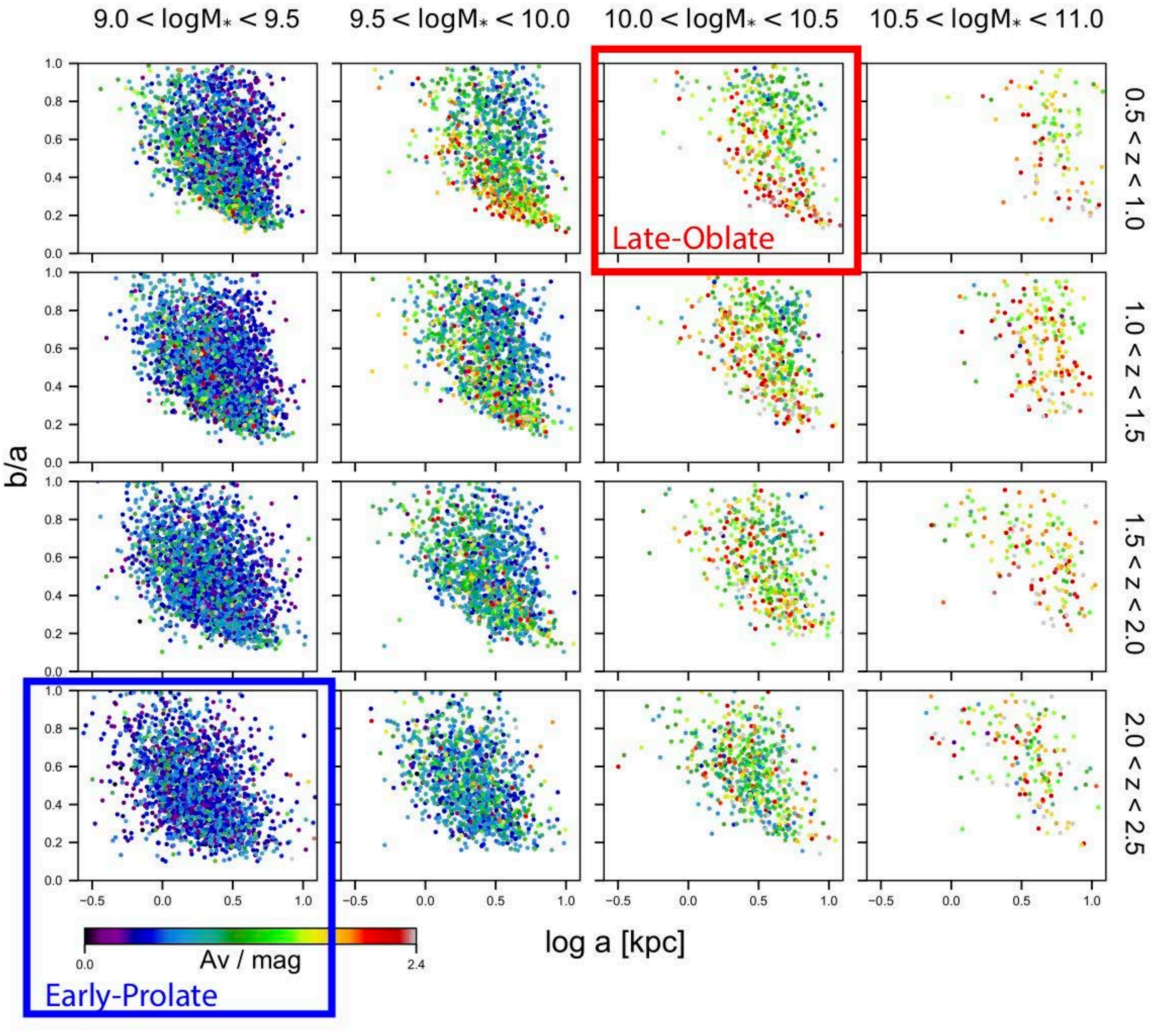
The Evolution of Galaxy Shapes in CANDELS: from Prolate to Oblate

b/a - log a distribution modeling to determine the shape distribution statistics



The Evolution of Galaxy Shapes in CANDELS: from Prolate to Oblate

Projected b/a - log a distributions of CANDELS galaxies in redshift-mass bins

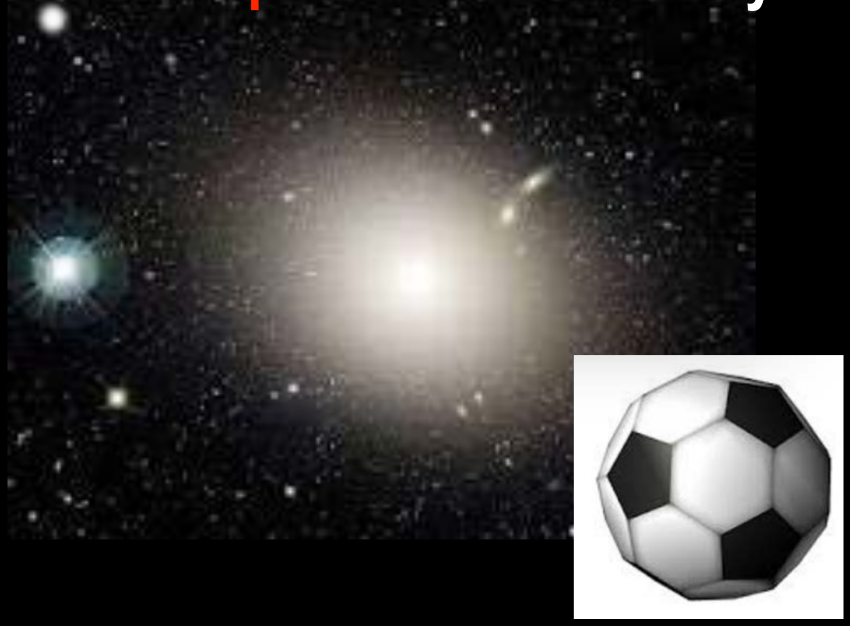


mass increasing

redshift increasing

galaxy evolution

Nearby large galaxies are mostly disks and spheroids — but they start out looking more like pickles.



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A Brief History of Dark Matter

1930s - Cluster velocity dispersion $\sigma_V \sim$ 1000 km/s => Dark Matter

1970s - Flat galaxy rotation curves => Dark Matter

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

1980-84 - Short life of Hot Dark Matter theory

1982-84 - Cold Dark Matter (CDM) theory proposed

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

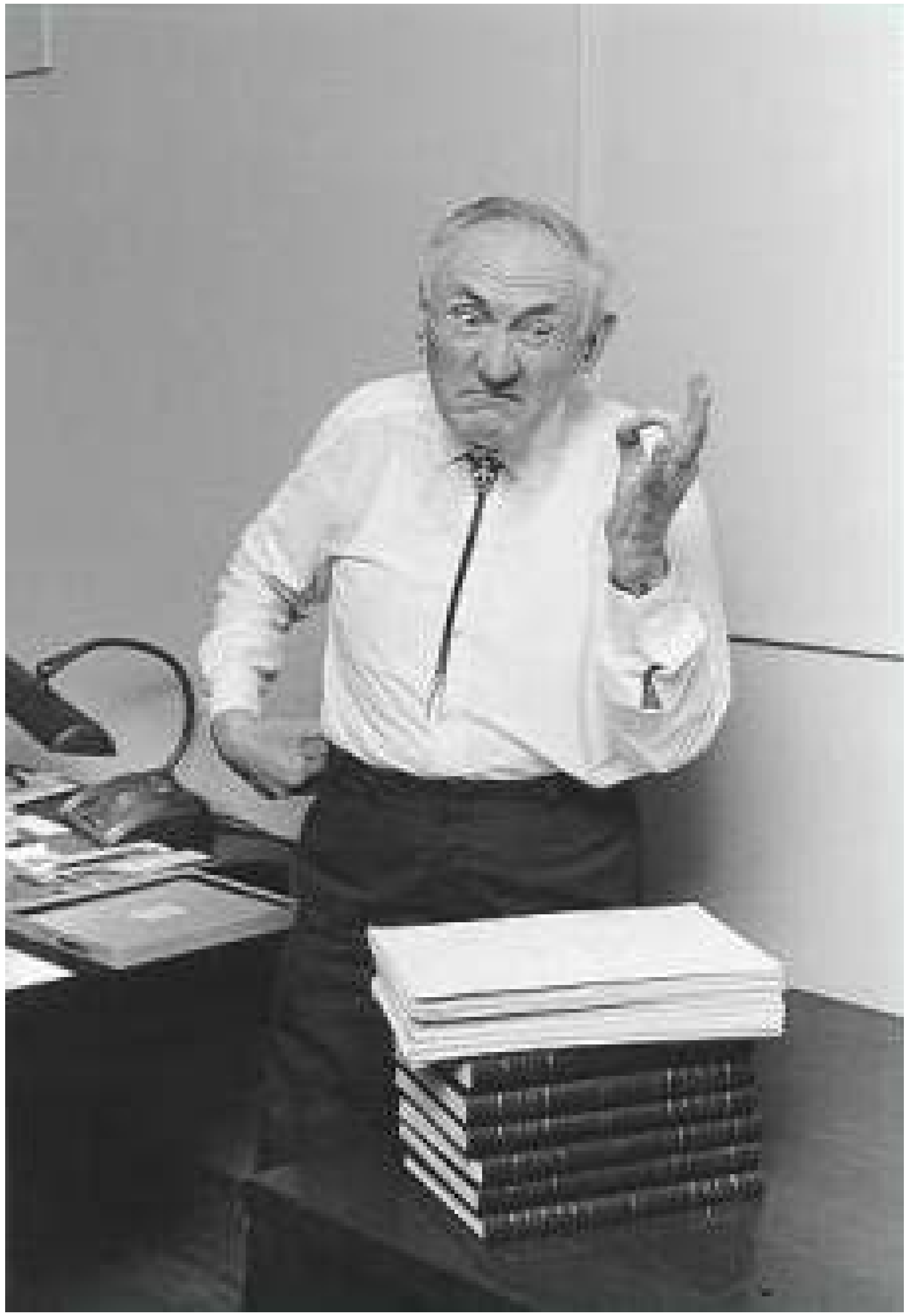
1998 - Discovery of Accelerated Expansion => Dark Energy

2000 - ΛCDM is the Standard Cosmological Model

2003-2019 - CMB and LSS confirm ΛCDM predictions

~2020 - Discovery of dark matter particles??

Galaxy Clusters Are Mostly Dark Matter



Fritz Zwicky

ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

F. ZWICKY   1937 ApJ 86, 217

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

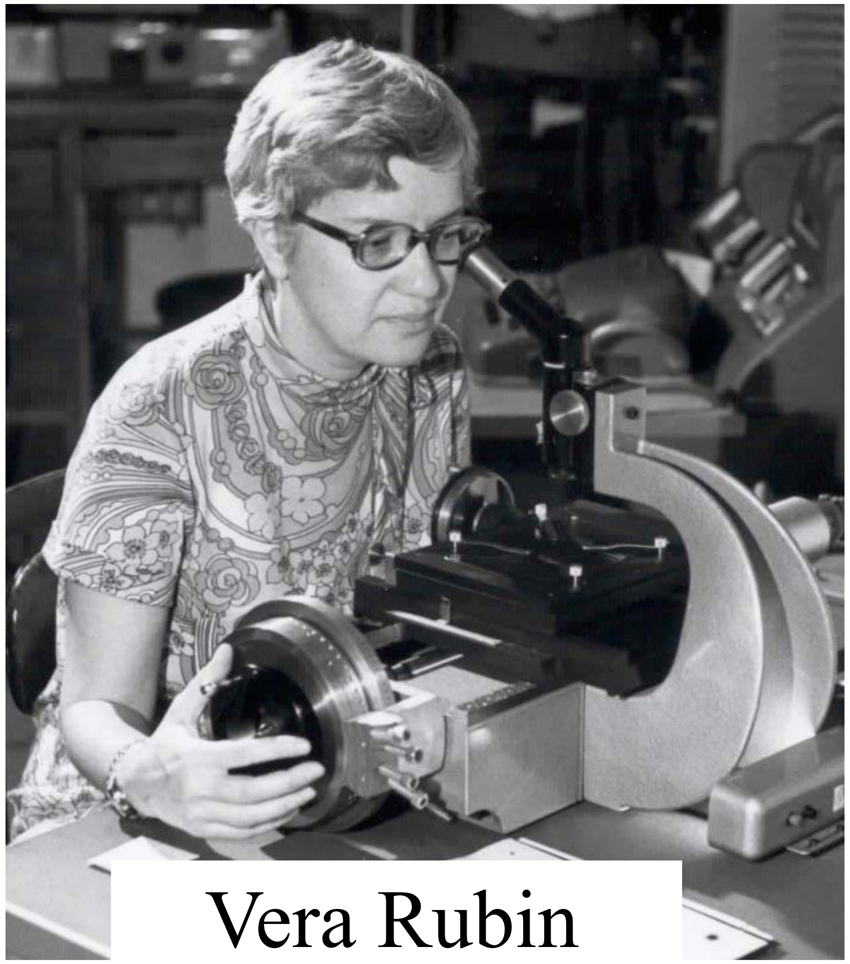
$$\overline{M} > 9 \times 10^{43}\ \mathrm{gr} = 4.5 \times 10^{10}\ M_{\odot} . \tag{36}$$

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

$$\text{Mass/Light} = \gamma = 500 , \tag{37}$$

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

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

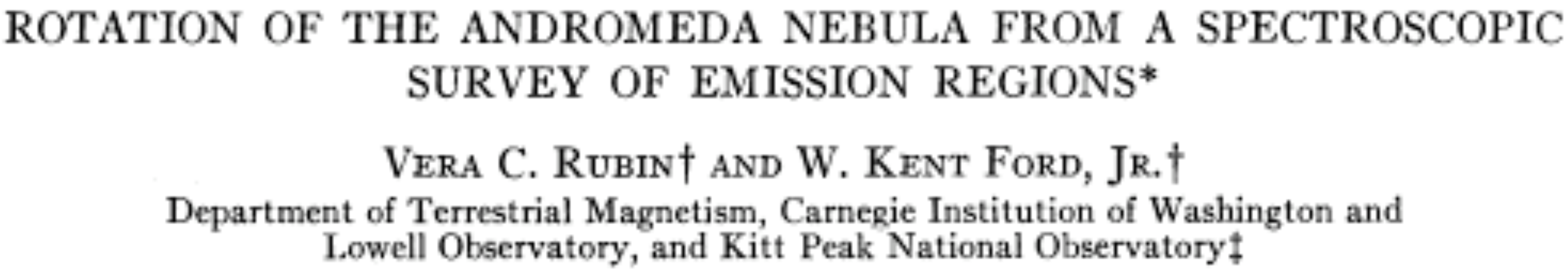


Vera Rubin

Flat Rotation Curves imply that

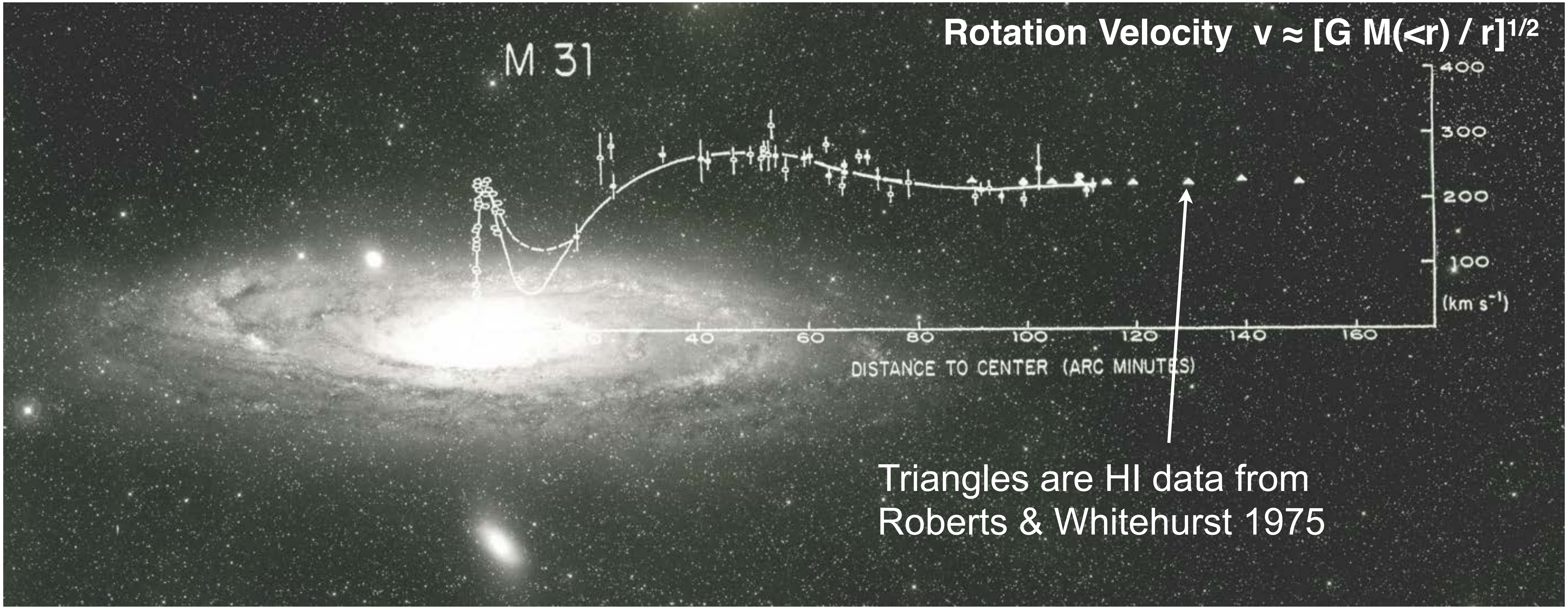
Galaxies Are Mostly Dark Matter

1970 ApJ 159, 379



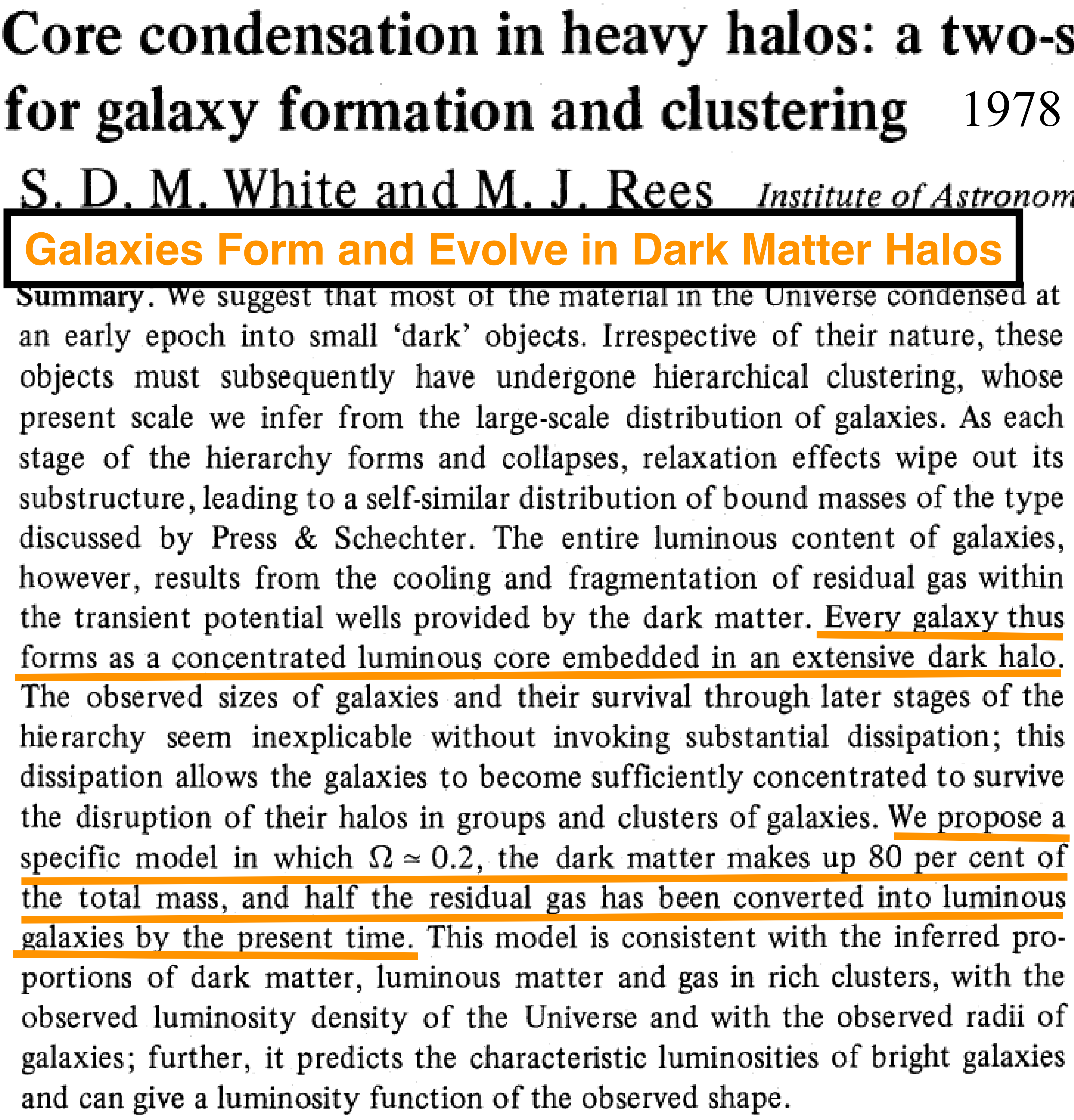
ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*

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



Rotation Velocity $v \approx [G\,M(<r) / r]^{1/2}$

Triangles are HI data from Roberts & Whitehurst 1975



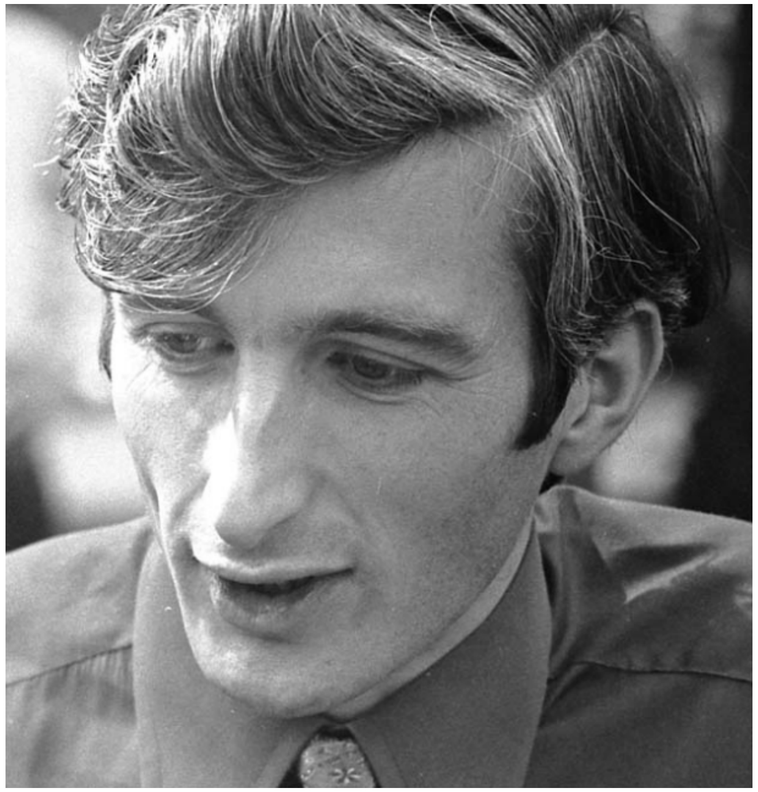
Core condensation in heavy halos: a two-stage theory for galaxy formation and clustering

1978

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

Galaxies Form and Evolve in Dark Matter Halos

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.

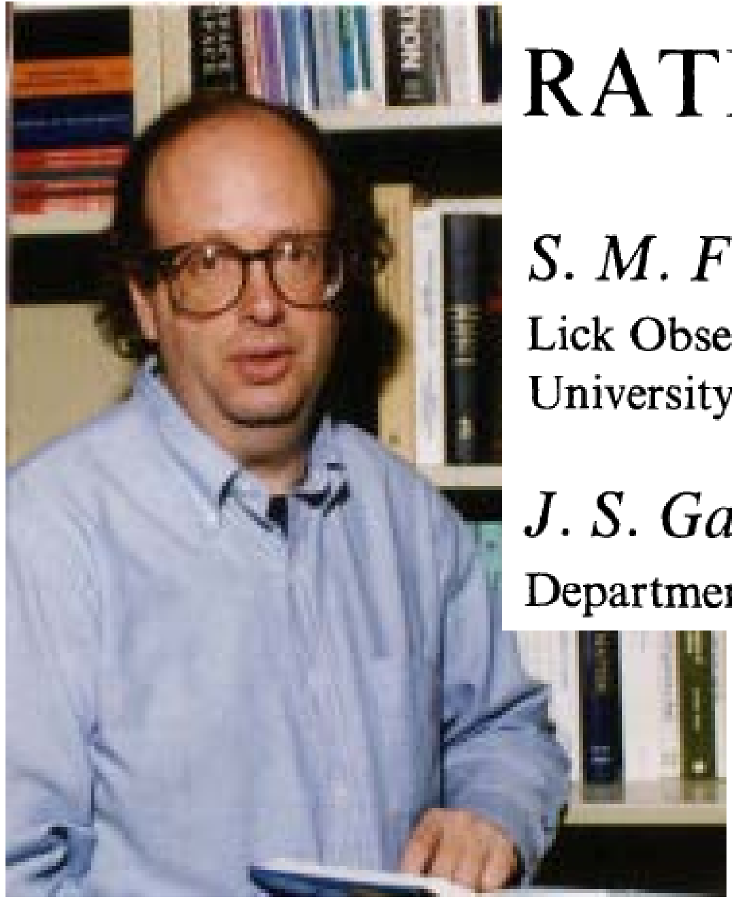


MASSES AND MASS-TO-LIGHT RATIOS OF GALAXIES

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



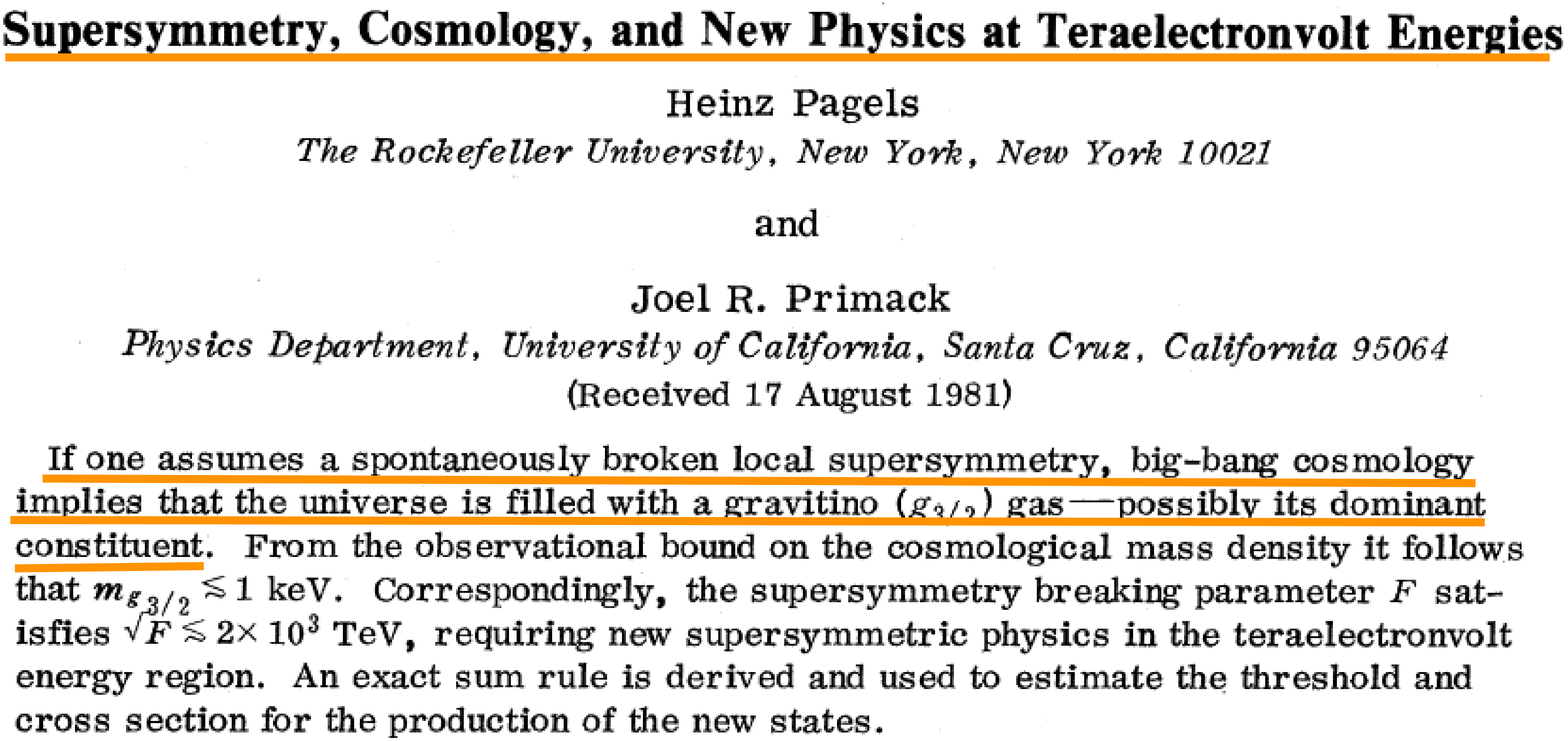
Sandy Faber

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.

Weakly Interacting Massive Particles

WIMP Dark Matter

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.

Some steps toward cosmic structure formation

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

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

(a) baryons (i.e., ordinary matter)

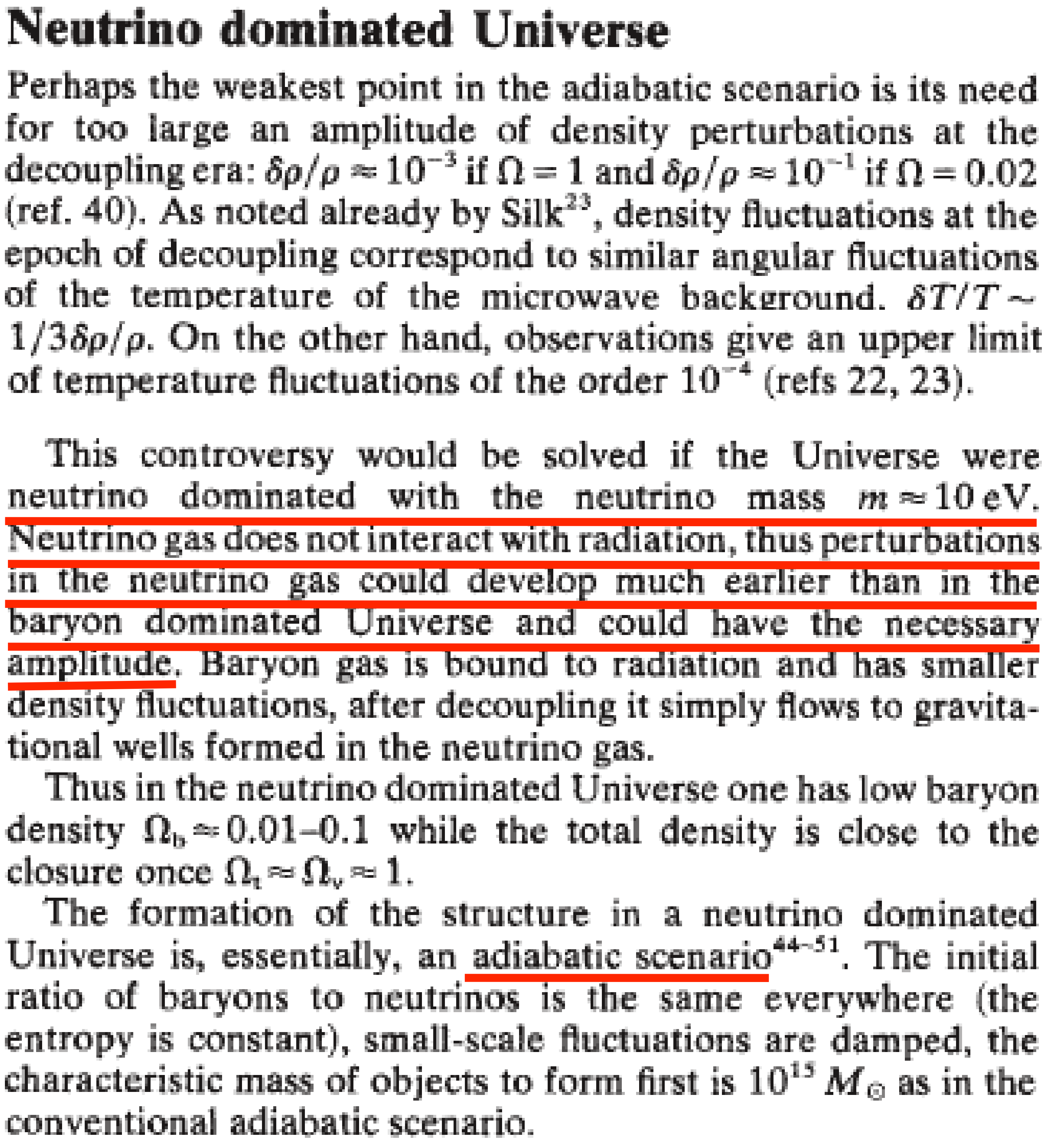
and when that failed $[(\Delta T/T)_{CMB} < 10^{-4}]$ and Moscow physicists thought they had discovered neutrino mass

(b) hot dark matter (i.e., neutrinos).

Giant voids in the Universe

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

1982 Nature
300, 407



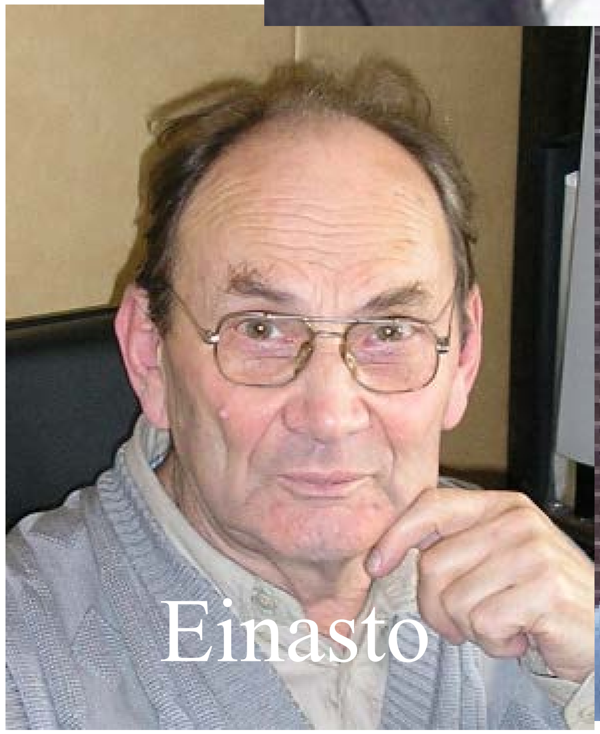
Neutrino dominated Universe

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.


Einasto


Shandarin

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(b) hot dark matter (i.e., neutrinos).

George 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.

shout-out to the UCSC mascot!

Galaxy formation by dissipationless particles heavier than neutrinos

1982 Nature 299, 37

George R. Blumenthal*, Heinz Pagels†
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Warm Dark Matter

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 $\lesssim 1$ 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.

Peebles: Cold Dark Matter and CMB

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

The Large-Scale Structure of the Universe

by

P.J.E. Peebles

Princeton Series in Physics

P. J. E. Peebles

1982 ApJ 263, L1

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.

The case $m_x \sim 1$ keV is discussed by Bond, Szalay, and Turner (1982) and Blumenthal, Pagels, and Primack (1982). I discuss here a particularly simple and perhaps important limiting case, $m_x \gtrsim 1$ keV. The main results are the spectrum of mass fluctuations, which seems quite reasonable for the production of galaxies and clusters of galaxies, the statistical character of the background temperature fluctuations, and the expected size of the mass density anticorrelation at large separations.

II. CALCULATION

I assume zero cosmological constant and $\Omega = 1$, the mass being mainly in weakly interacting particles, mass m_x. Following Davis *et al.* (1981), I take the particle

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Davis, M., Lecar, M., Pryor, C., and Witten, E. 1981, *Ap. J.*, **250**, 423.
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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.
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NATURE VOL. 311 11 OCTOBER 1984 REVIEW ARTICLE 517

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

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

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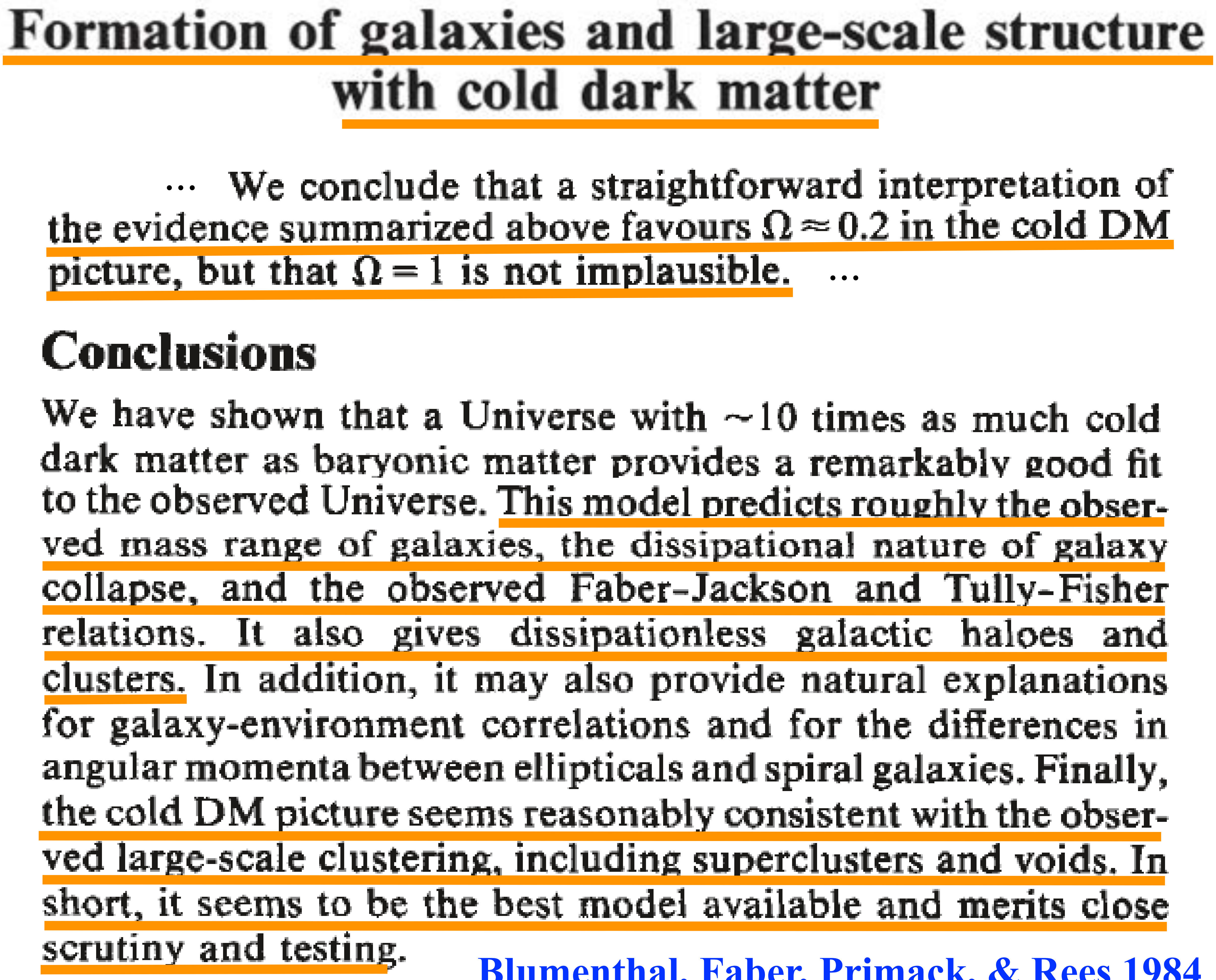
The dark matter that appears to be gravitationally dominant on all scales larger than galactic cores may consist of axions, stable photinos, or other collisionless particles whose velocity dispersion in the early Universe is so small that fluctuations of galactic size or larger are not damped by free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



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

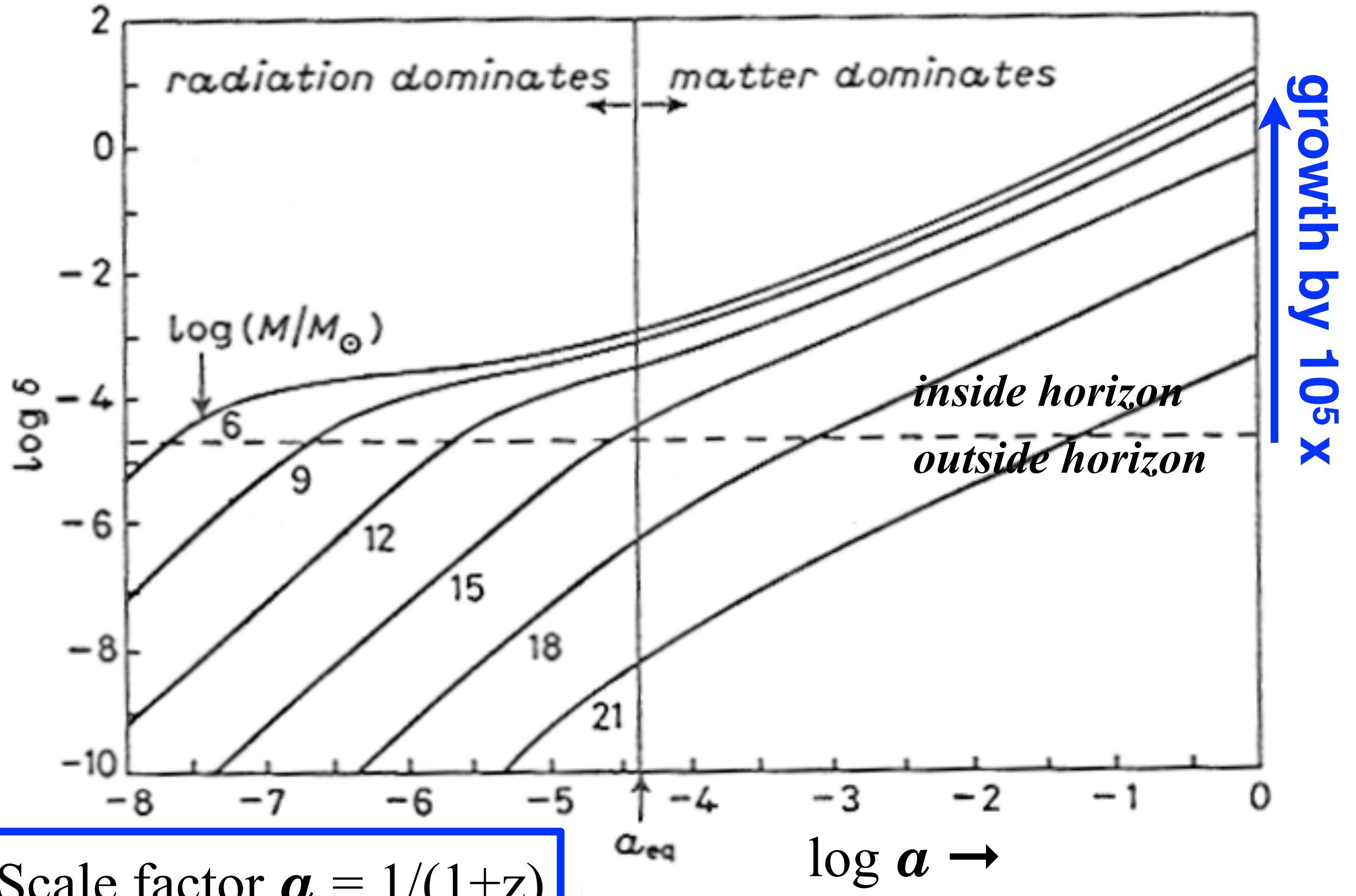
… We conclude that a straightforward interpretation of the evidence summarized above favours $\Omega \approx 0.2$ in the cold DM picture, but that $\Omega = 1$ is not implausible. …

Conclusions

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

Blumenthal, Faber, Primack, & Rees 1984

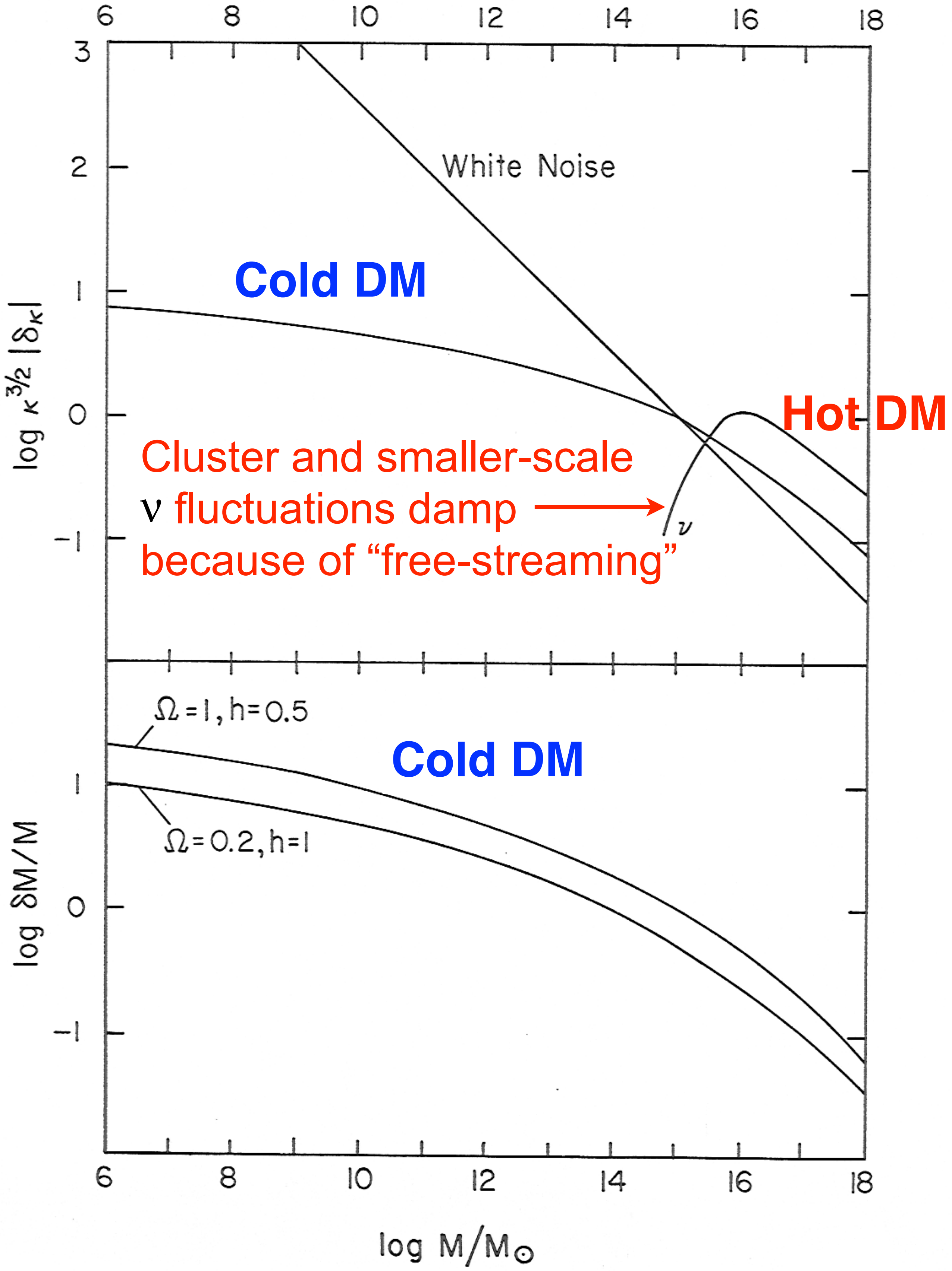
CDM Structure Formation: Linear Theory



Scale factor $a = 1/(1+z)$

CDM fluctuations that enter the horizon during the radiation dominated era, with masses less than about 10^{15} M$_\odot$, grow only $\propto$ log a, because they are not in the gravitationally dominant component. But matter fluctuations that enter the horizon in the matter-dominated era grow $\propto a$. 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

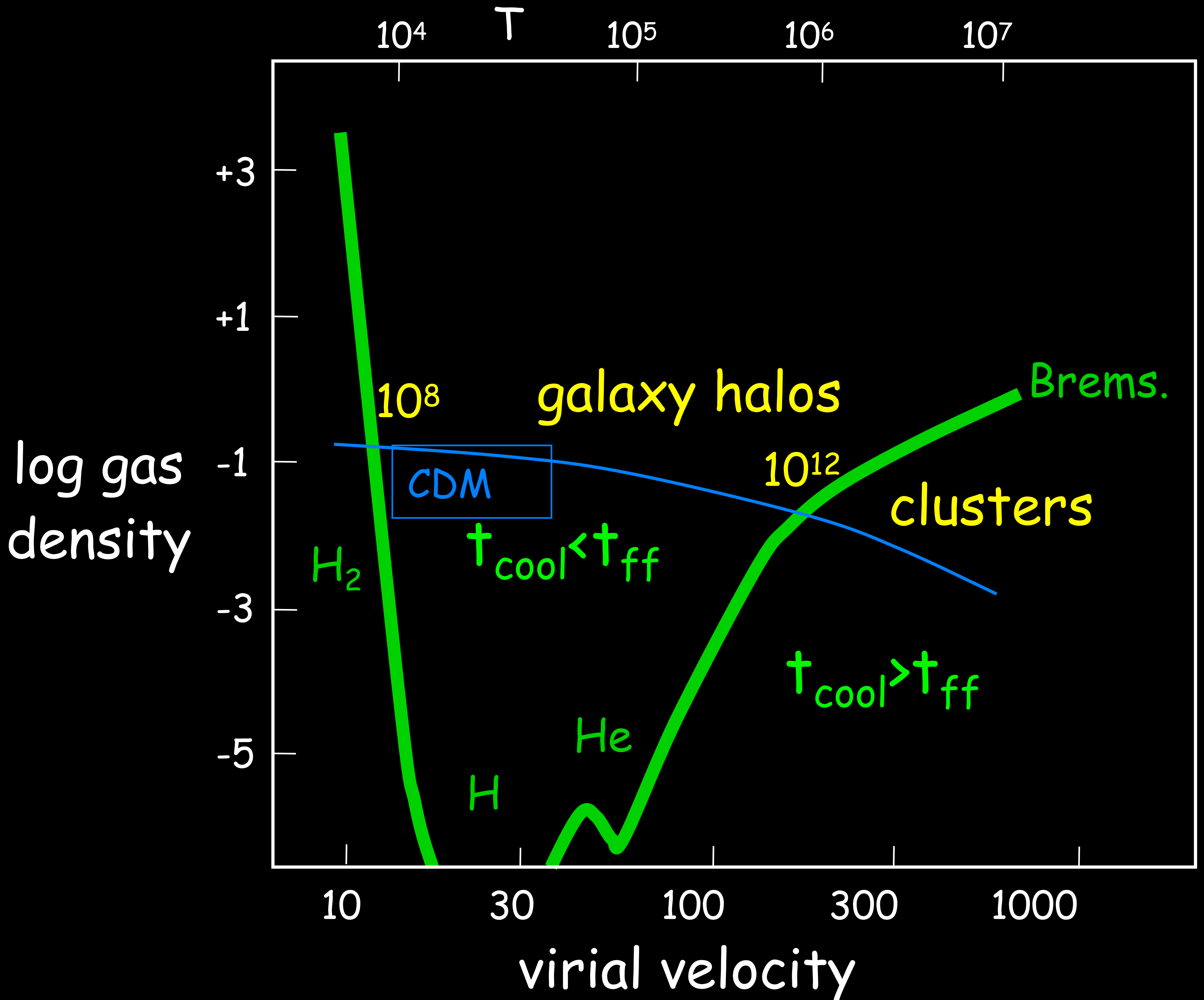


Blumenthal, Faber, Primack, & Rees 1984

CDM Correctly Predicted the Masses of Galaxies

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

CDM: Blumenthal, Faber, Primack, & Rees 1984



Ann. Rev. Nucl. Part. Sci. 1988. 38: 751–807

DETECTION OF COSMIC DARK MATTER

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Santa Cruz Institute for Particle Physics, University of California,
Santa Cruz, California 95064

Bernard Sadoulet

Physics Department, University of California, Berkeley, California 94720

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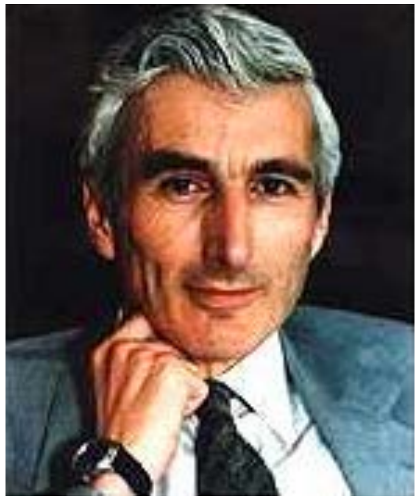
Mon. Not. R. astr. Soc. (1991) **251,** 128–136

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.

Accelerating Expansion Discovered in 1998

Nearby large galaxies are mostly disks and spheroids — but they start out looking more like pickles.

Outline

Evidence for Modern Cosmology: the Double Dark Theory

Observational Evidence that Galaxies Start Pickle-Shaped

Historical Introduction to Dark Matter and Cosmology

Introduction to Galaxy Formation

Why Galaxies Start Pickle-Shaped and How They Evolve

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 and dark matter halo properties, basis for semi-analytic models

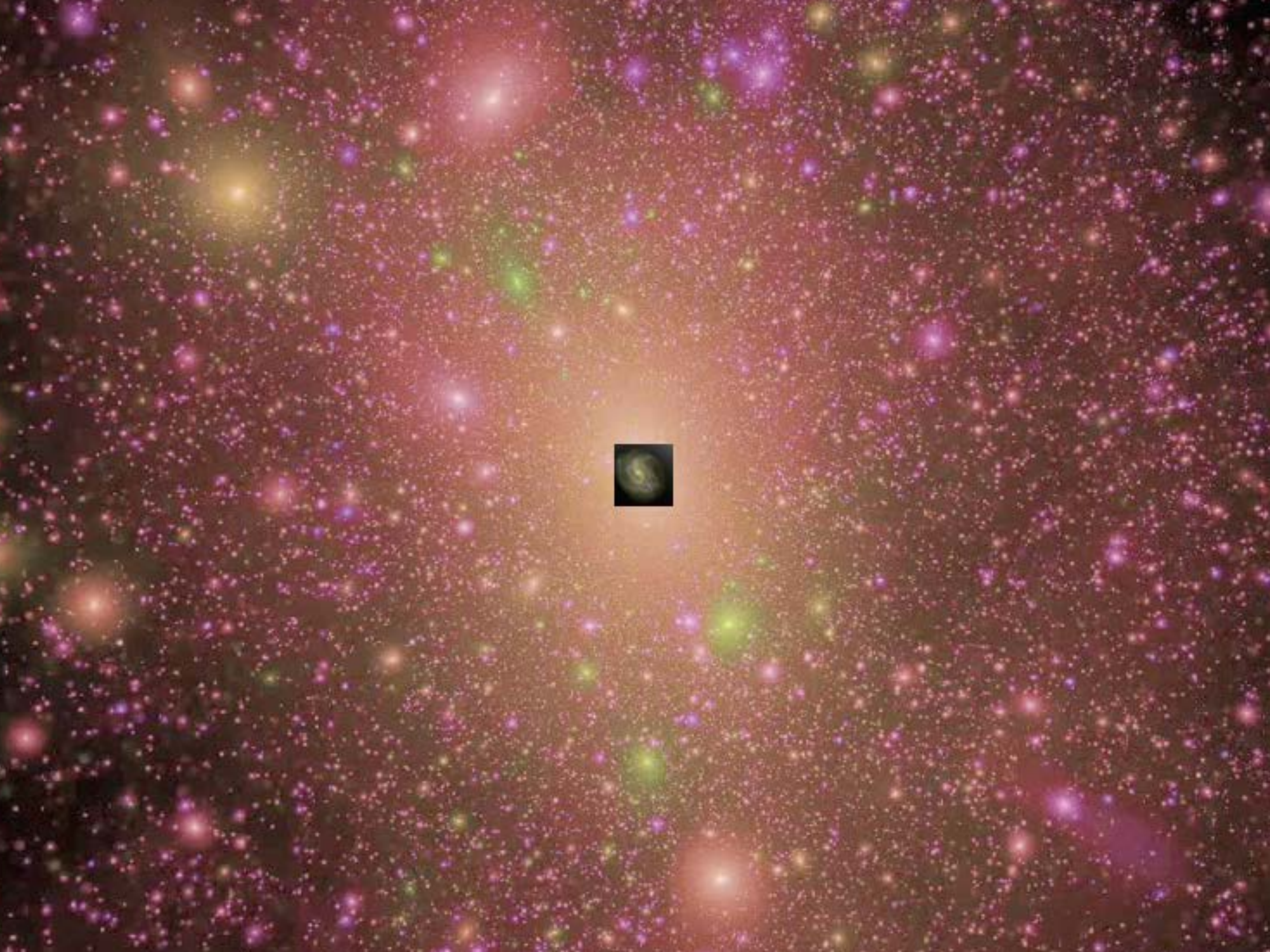
Hydrodynamic galaxy formation simulations: evolution of galaxies, formation of galactic spheroids, mock galaxy images and spectra including stellar evolution and dust effects

Aquarius Simulation

Volker Springel

Milky Way
100,000 light years

Milky Way Dark Matter Halo
1.5 million light years

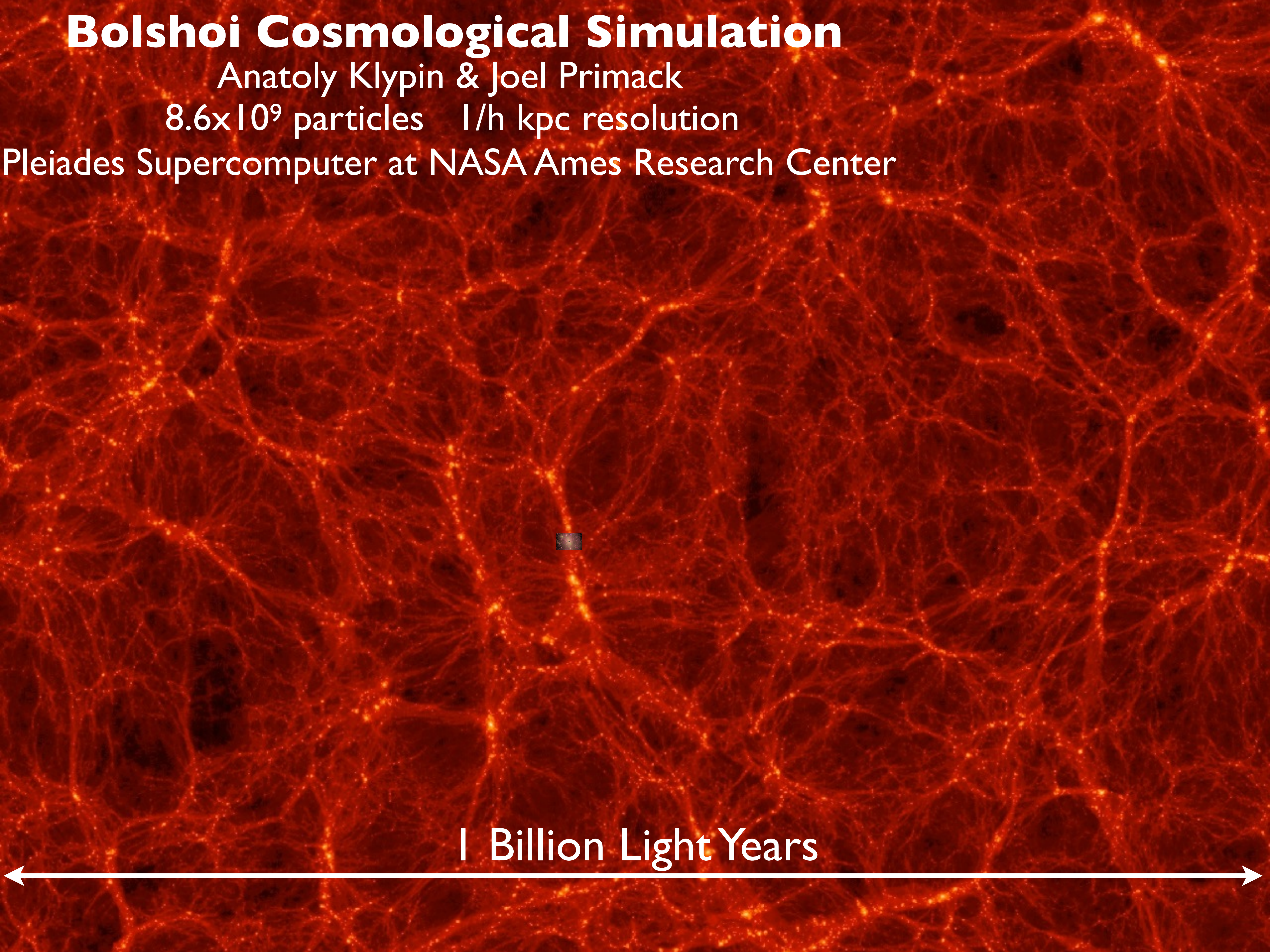


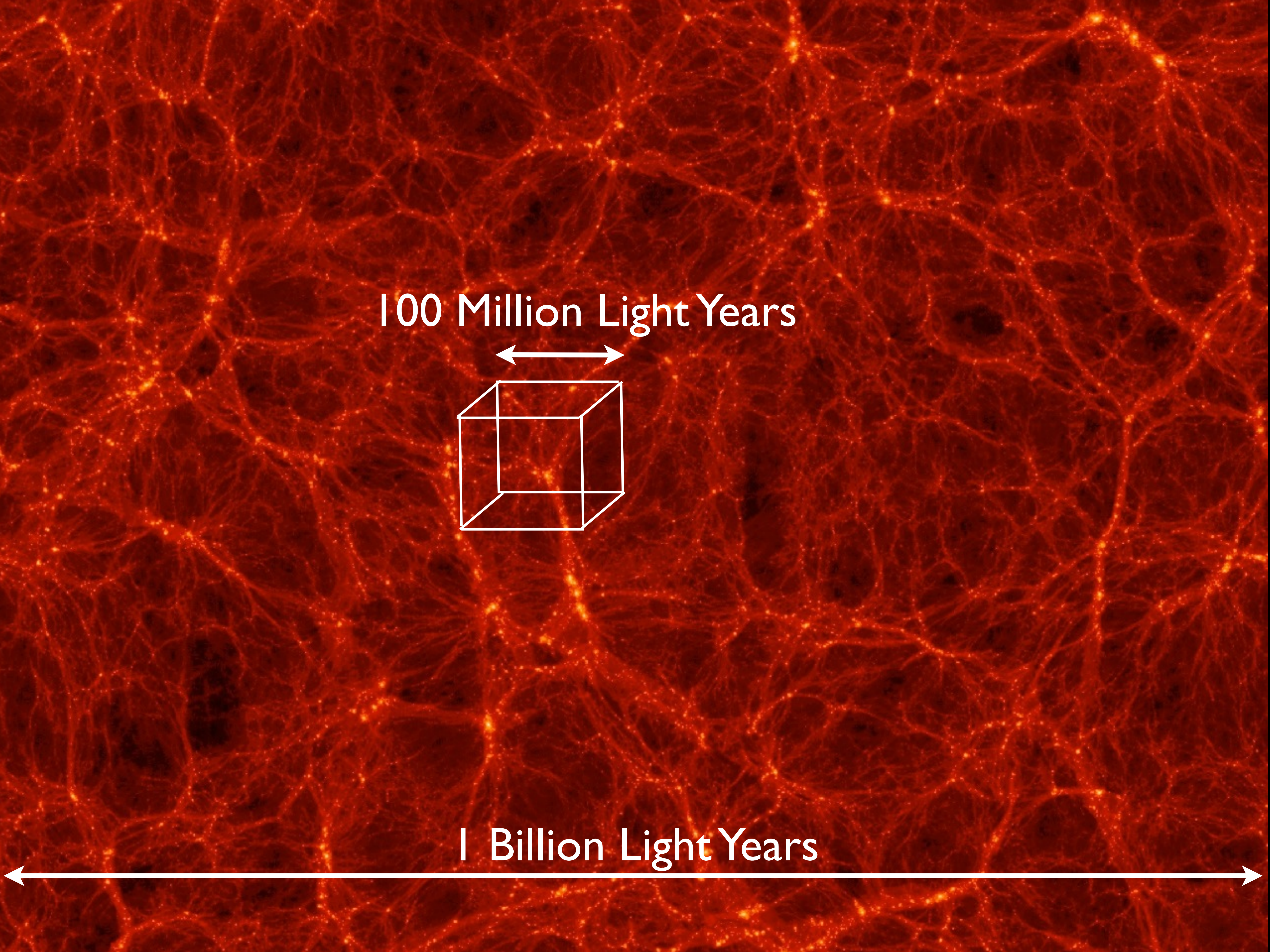
Bolshoi Cosmological Simulation

Anatoly Klypin & Joel Primack

8.6×10^9 particles   1/h kpc resolution

Pleiades Supercomputer at NASA Ames Research Center




100 Million Light Years
1 Billion Light Years

How the Halo of the Big Cluster Formed

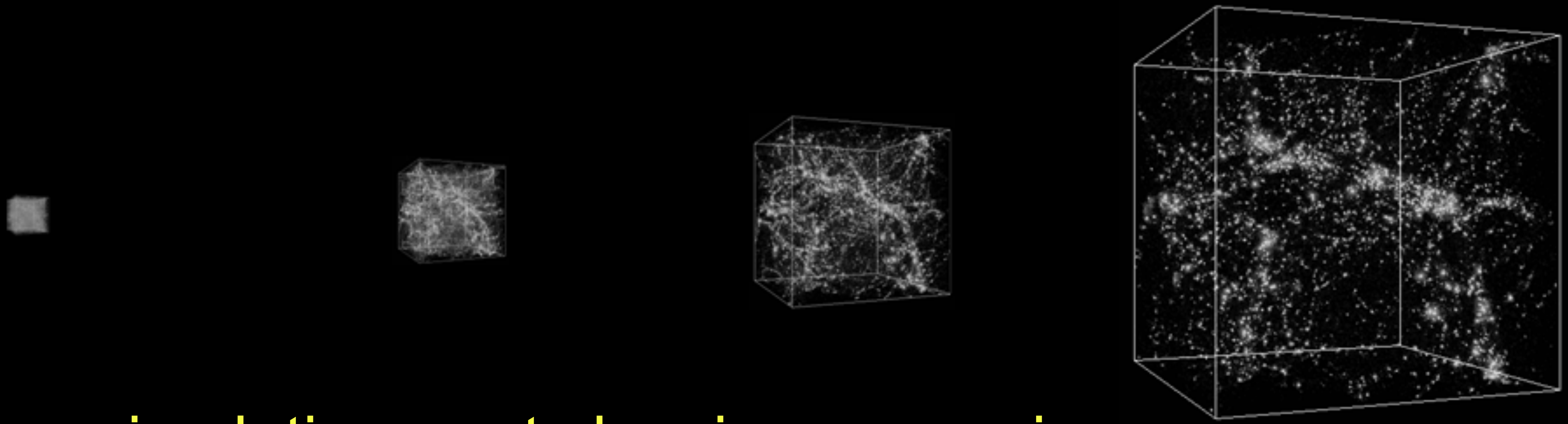
100 Million Light Years

Bolshoi-Planck Cosmological Simulation

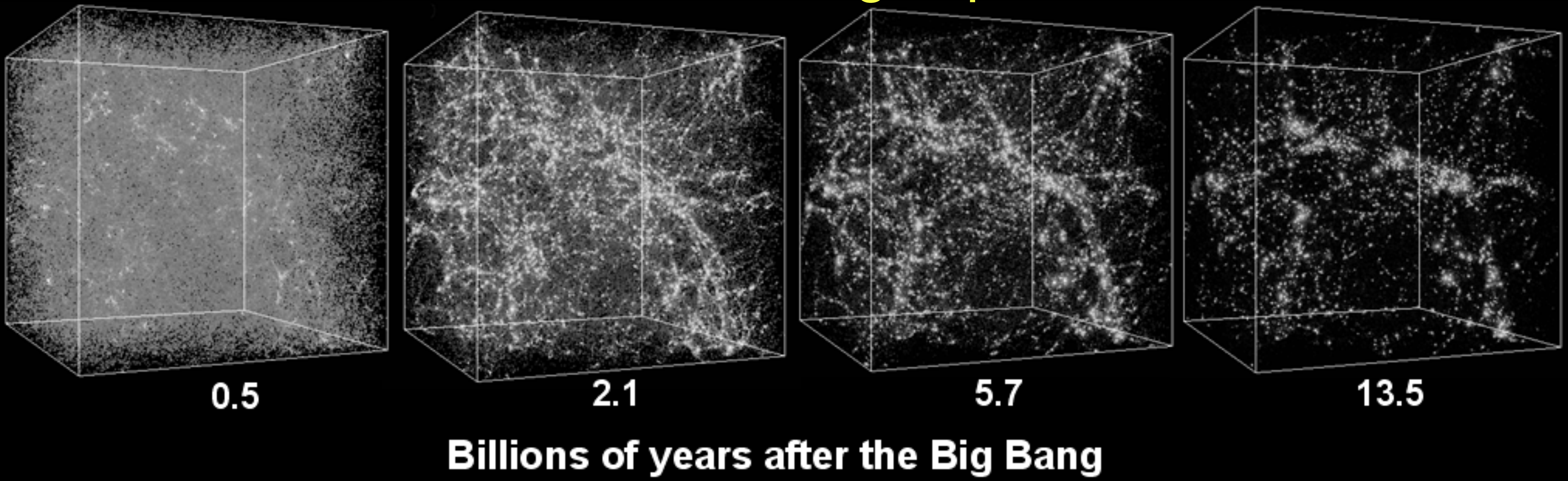
Merger Tree of a Large Halo

Peter Behroozi & Christoph Lee

dark matter simulation - expanding with the universe



same simulation - not showing expansion



Andrey Kravtsov

CONSTRAINED LOCAL UNIVERSE SIMULATION

Stefan Gottloeber, Anatoly Klypin, Joel Primack

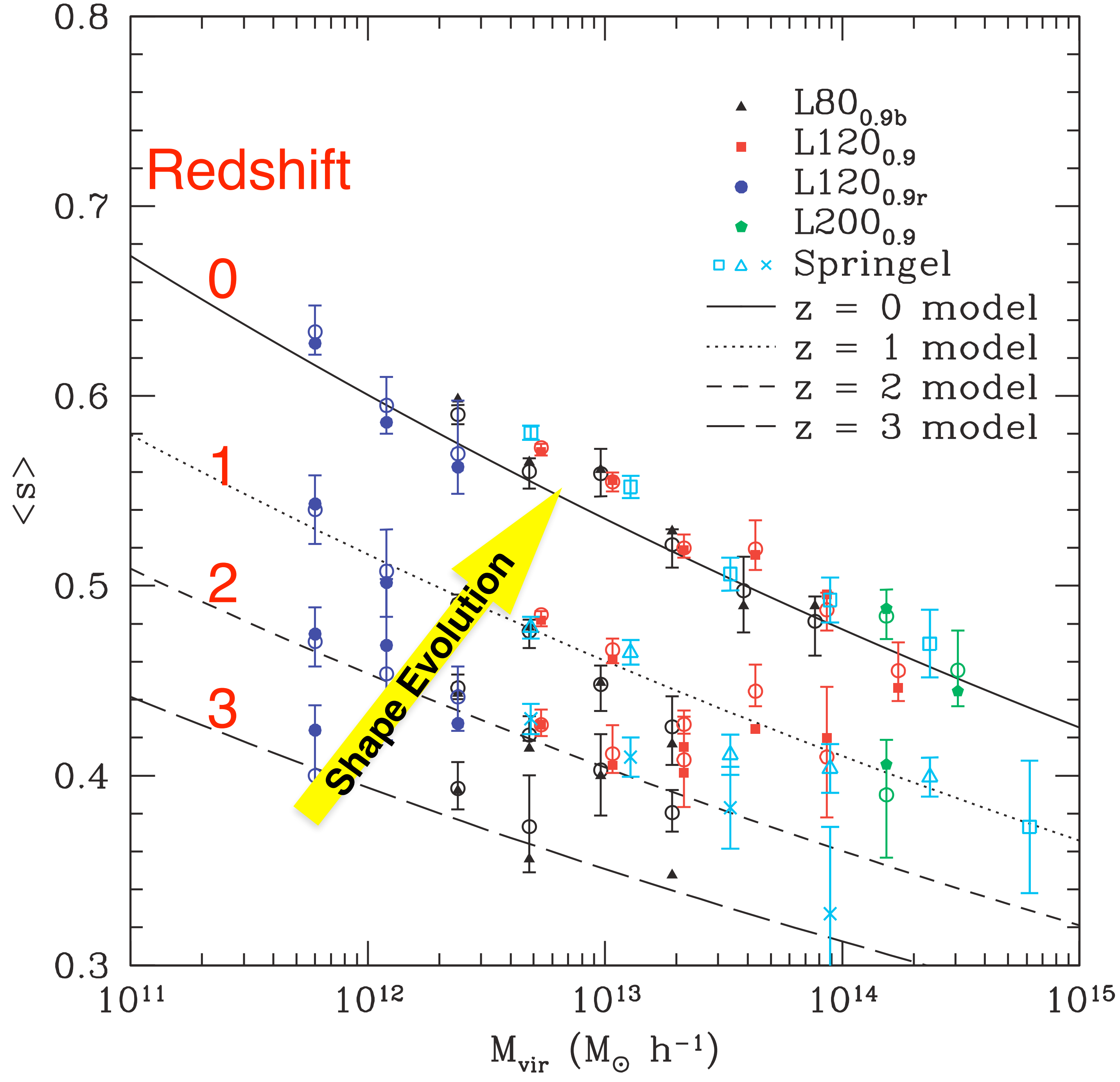
Visualization: Chris Henze (NASA Ames)

MNRAS 367, 1781–1796 (2006)

The shape of dark matter haloes: dependence on mass, redshift, radius and formation

Brandon Allgood, Ricardo Flores, Joel R. Primack, Andrey V. Kravtsov, Risa Wechsler, Andreas Faltenbacher and James S. Bullock

s = c/a = short axis / long axis

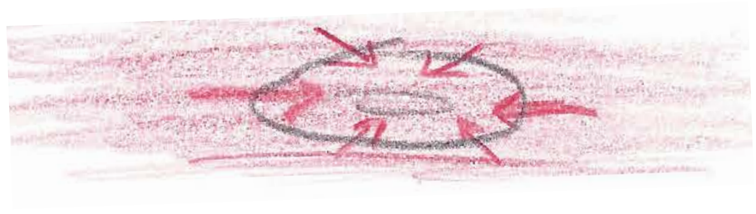


Halos are approximately triaxial ellipsoids

$$\frac{x^2}{a^2}+\frac{y^2}{b^2}+\frac{z^2}{c^2}=1$$

Halos start prolate, especially at low radius, and later become more spherical.

Low-redshift halo, accreting more spherically



High-redshift halo, accreting mainly along filament

supported by anisotropic velocity dispersion, larger along principal axis

Nearby large galaxies are mostly disks and spheroids — but they start out looking more like pickles.

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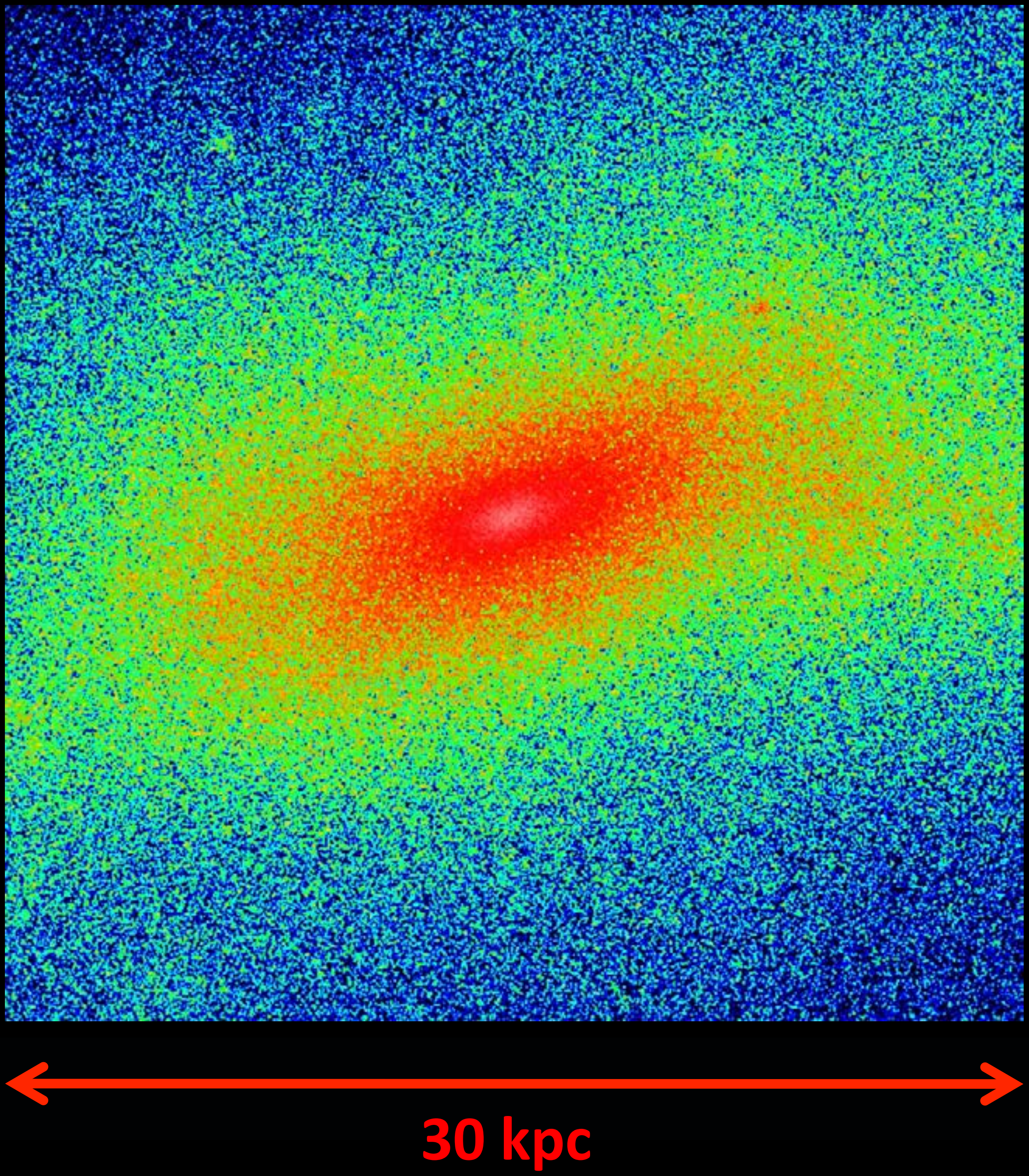
Our cosmological zoom-in simulations often produce elongated galaxies like observed ones. The elongated distribution of stars follows the elongated inner dark matter halo.

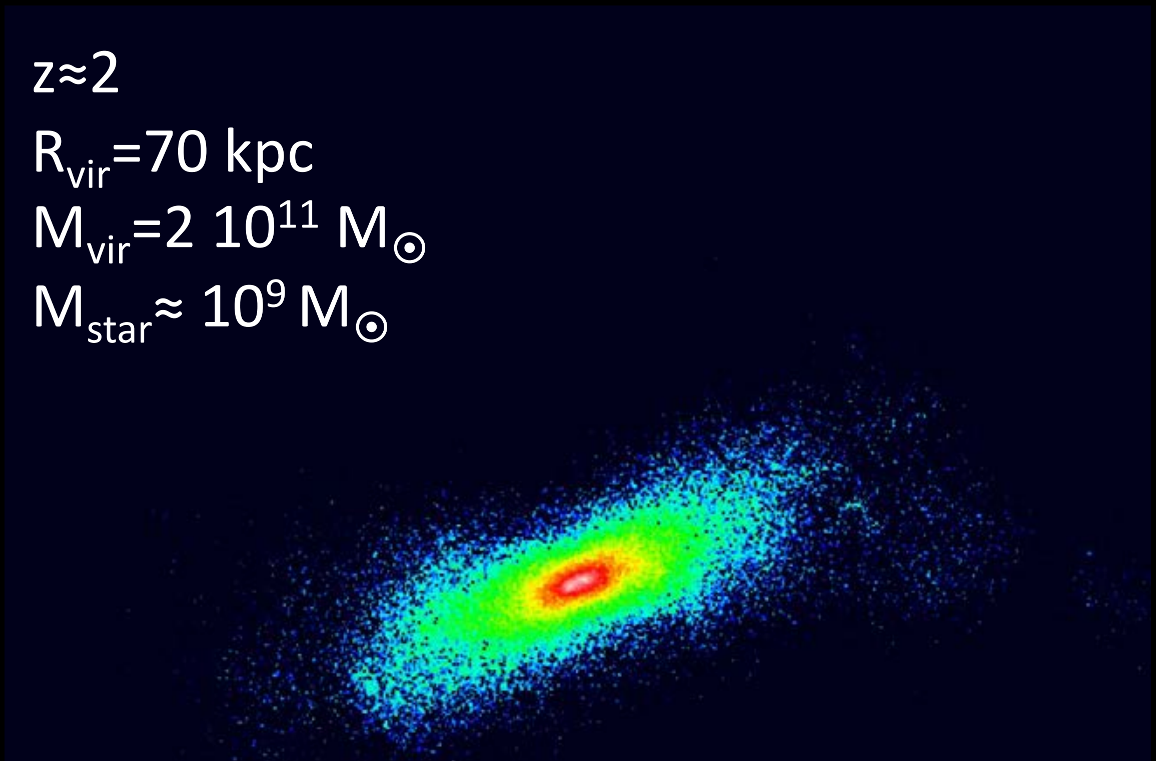
Prolate DM halo → elongated galaxy

DM



VELA28RP

stars



z≈2

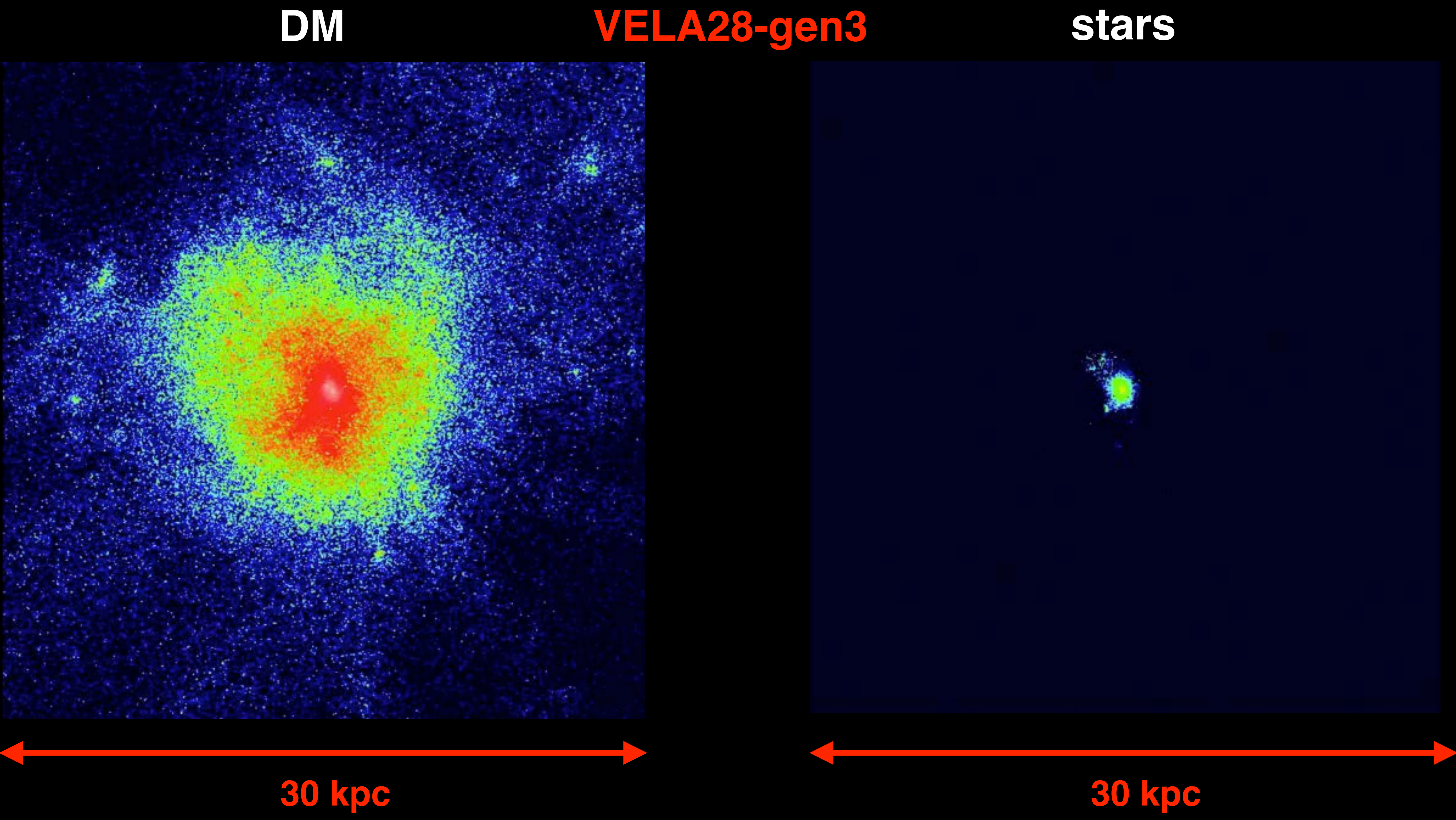
R_{vir}=70 kpc

M_{vir}=2 10^{11} $M_\odot$

M_{star}≈ 10^9 $M_\odot$

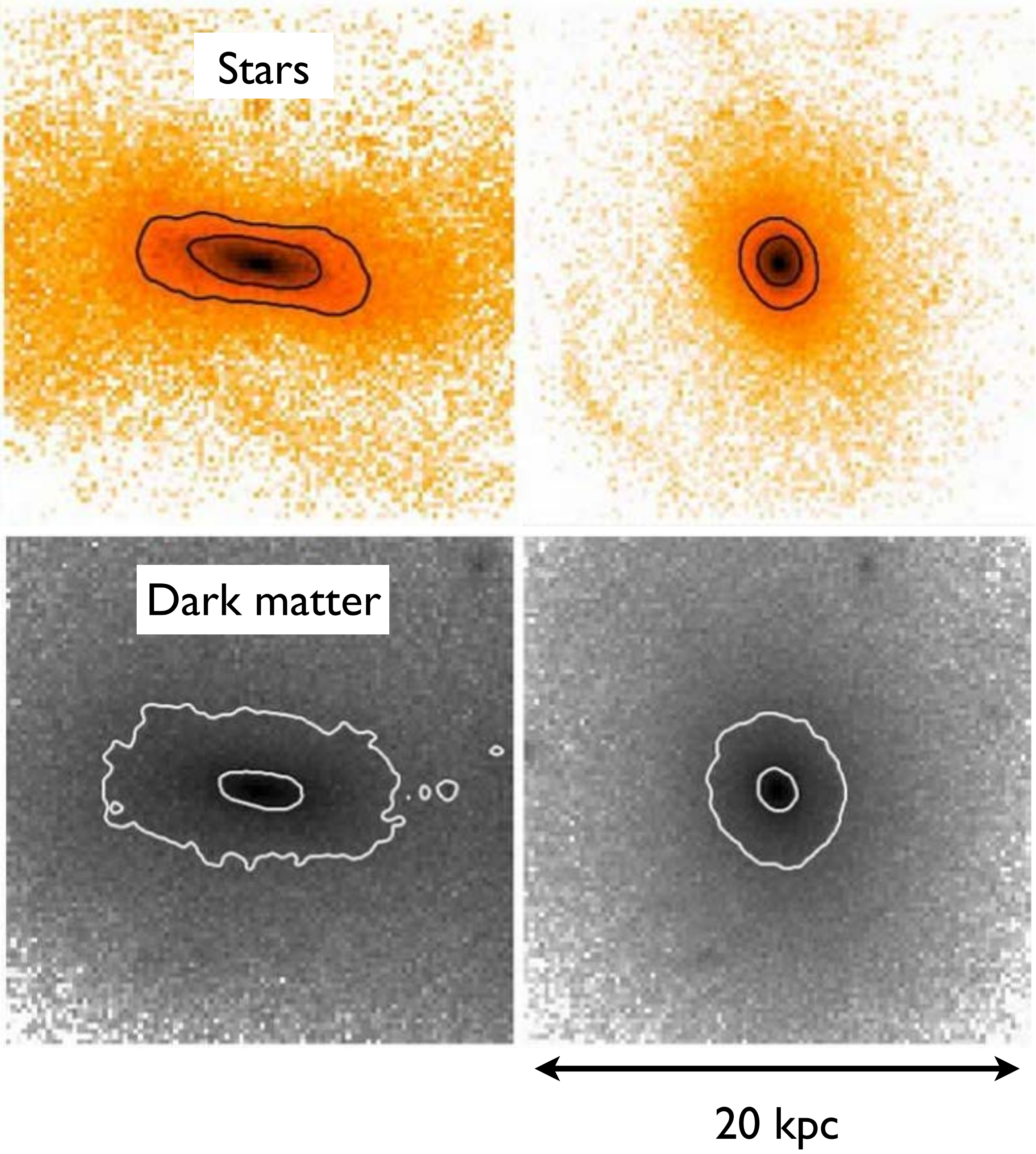
Dark matter halos are elongated, especially near their centers. Initially stars follow the gravitationally dominant dark matter, as shown. But later as the ordinary matter central density grows and it becomes gravitationally dominant, the star and dark matter distributions both become disky — as observed by Hubble Space Telescope (van der Wel+ ApJL Sept 2014).

Our cosmological zoom-in simulations often produce elongated galaxies like observed ones. The elongated distribution of stars follows the elongated inner dark matter halo. Here we show the evolution of the dark matter and stellar mass distributions in our zoom-in galaxy simulation VELA28, viewed from the same fixed vantage point.

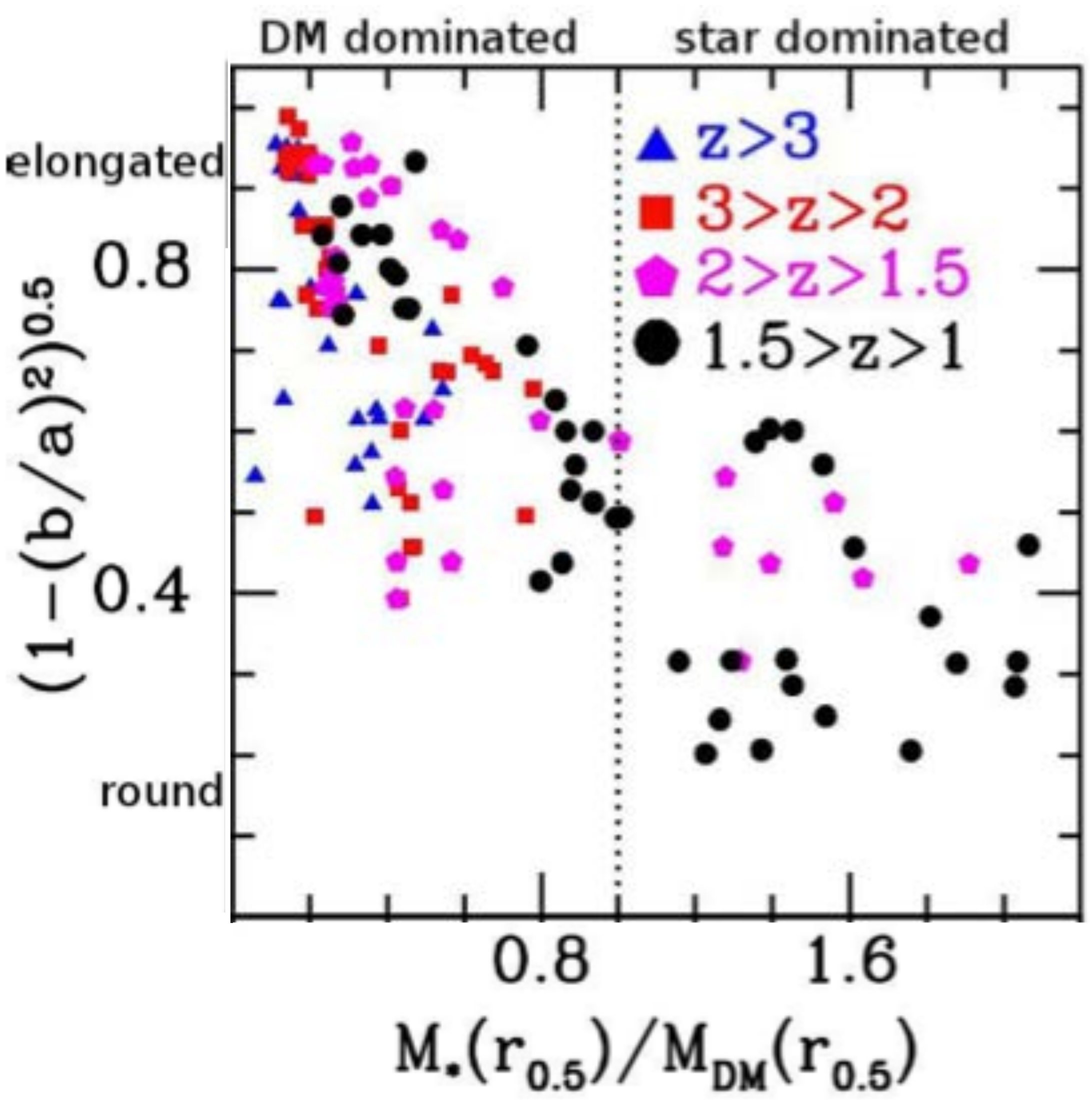


Formation of elongated galaxies with low masses at high redshift

Daniel Ceverino, Joel Primack and Avishai Dekel **MNRAS 2015**



$M_* < 10^{10} M_\odot$ at z=2



Tomassetti et al. 2016 MNRAS

Simulated elongated galaxies are aligned with cosmic web filaments, become round after compaction (gas inflow fueling central starburst)

Pandya, Primack, et al. 2019 Alignments of prolate galaxies trace cosmic web?

Face Recognition for Galaxies

Huertas-Company, Primack, et al. 2018

Pre-BN **BN** **Post-BN**

VELA High-Res Sunrise Images

VELA HST-Res Sunrise Images

CANDELS HST Images

Some Concluding Thoughts

Without Dark Matter We Wouldn’t Exist

With only the ordinary matter, the universe would be a low-density featureless soup

Dark matter started to form structures very early

Galaxies formed within bound “halos” of dark matter

Stars formed within galaxies, and stars made elements beyond hydrogen and helium: carbon, oxygen, …

Rocky planets formed from these heavier elements

Life began and evolved on one such planet

Dark matter is our ancestor and our friend!

Science Is Much Stranger Than Fiction

Before the discovery that most of the mass of the universe is invisible, no one imagined this

What else remains to be discovered?

THANKS!