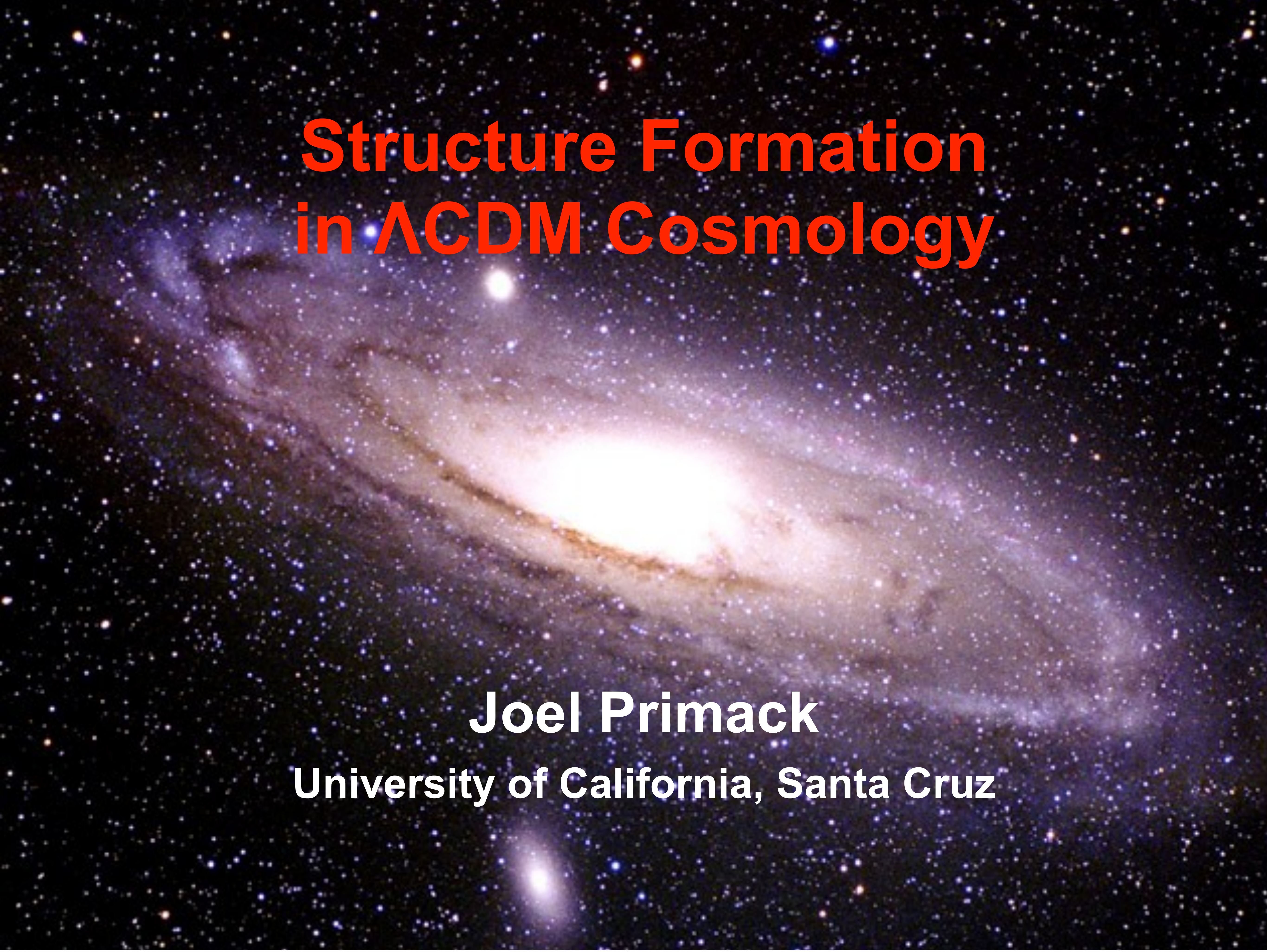


Structure Formation in ΛCDM Cosmology

Joel Primack

University of California, Santa Cruz

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: $V_{rot} \approx$ constant

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

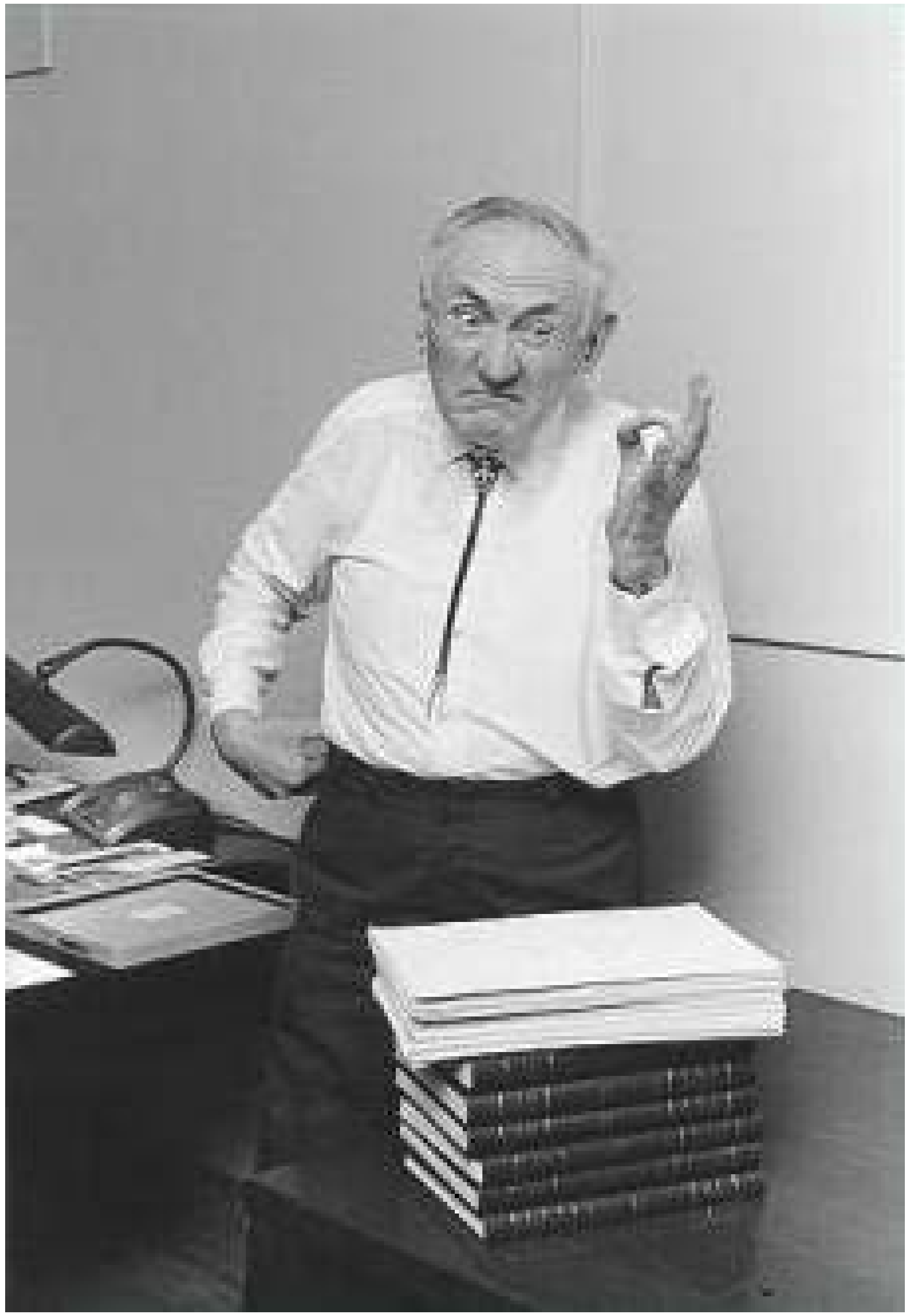
1998 - SN Ia and other evidence of Dark Energy

2000 - ΛCDM is the Standard Cosmological Model

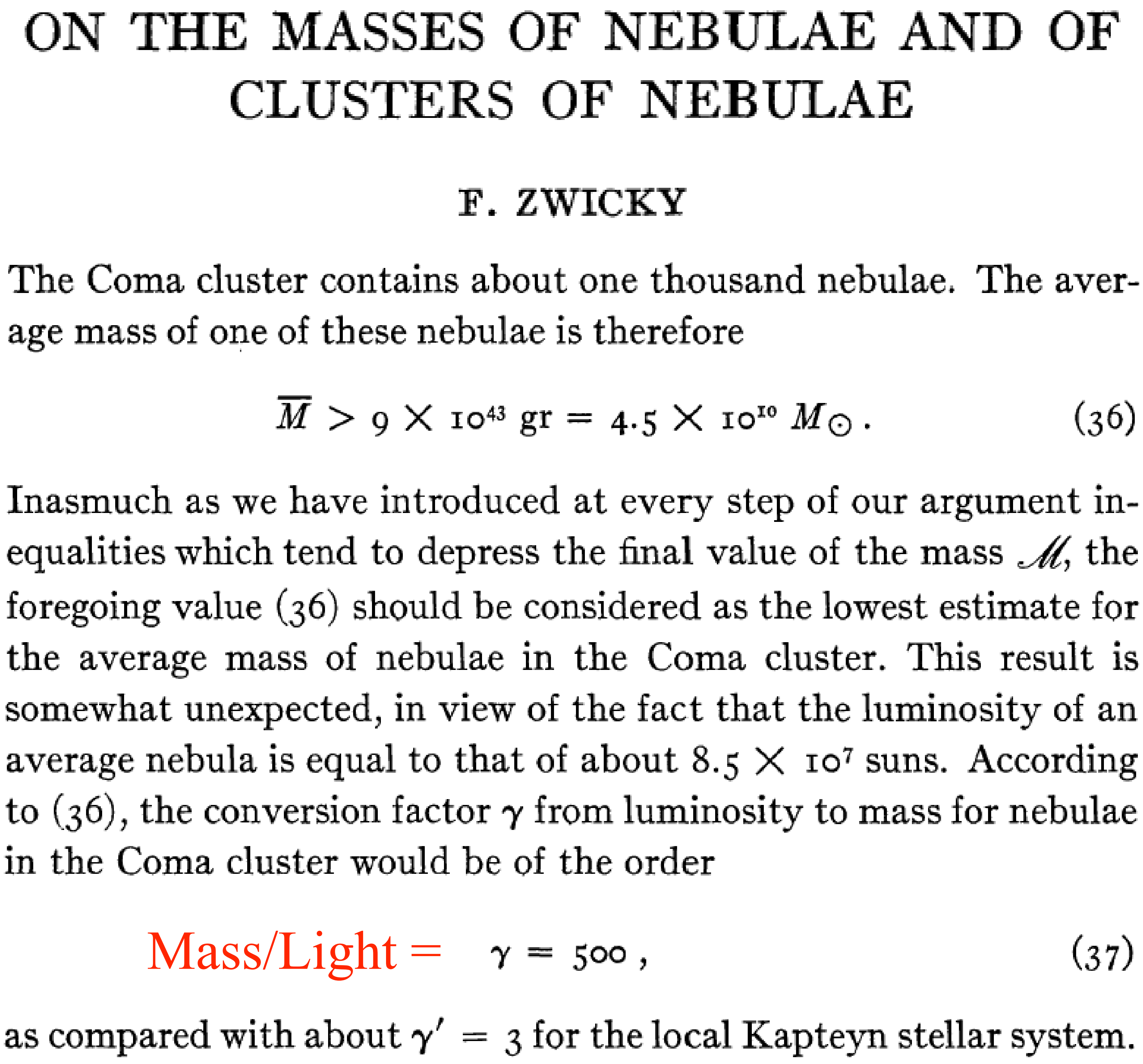
2003-12 - WMAP, Planck, and LSS confirm ΛCDM predictions

~2013 - Discovery of dark matter particles??

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

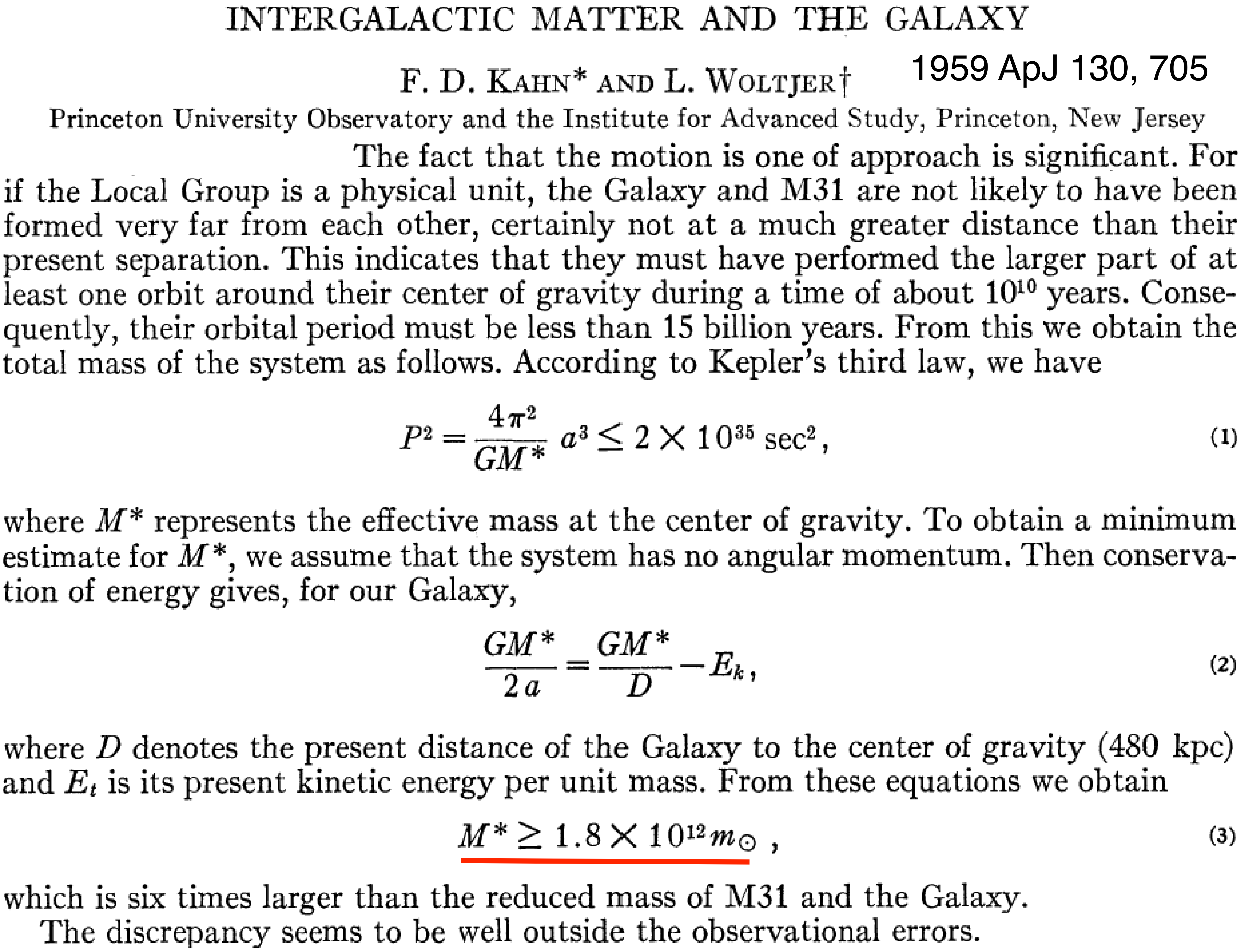
$$\overline{M} > 9 \times 10^{43}\ \text{gr} = 4.5 \times 10^{10}\ M_{\odot}\ . \tag{36}$$

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

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

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

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



INTERGALACTIC MATTER AND THE GALAXY

1959 ApJ 130, 705

F. D. KAHN* AND L. WOLTJER†
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

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

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,

$$\frac{GM^*}{2a} = \frac{GM^*}{D} - E_k , \tag{2}$$

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

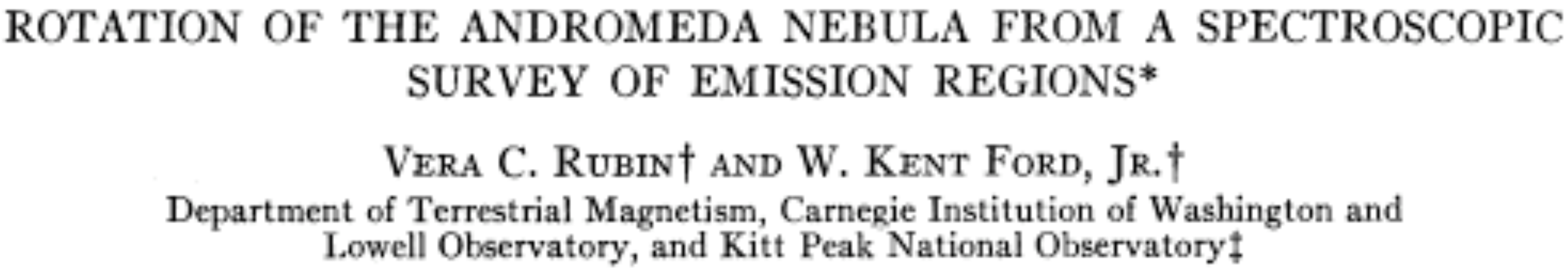
$$\underline{M^* \geq 1.8 \times 10^{12} m_\odot} , \tag{3}$$

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

The discrepancy seems to be well outside the observational errors.

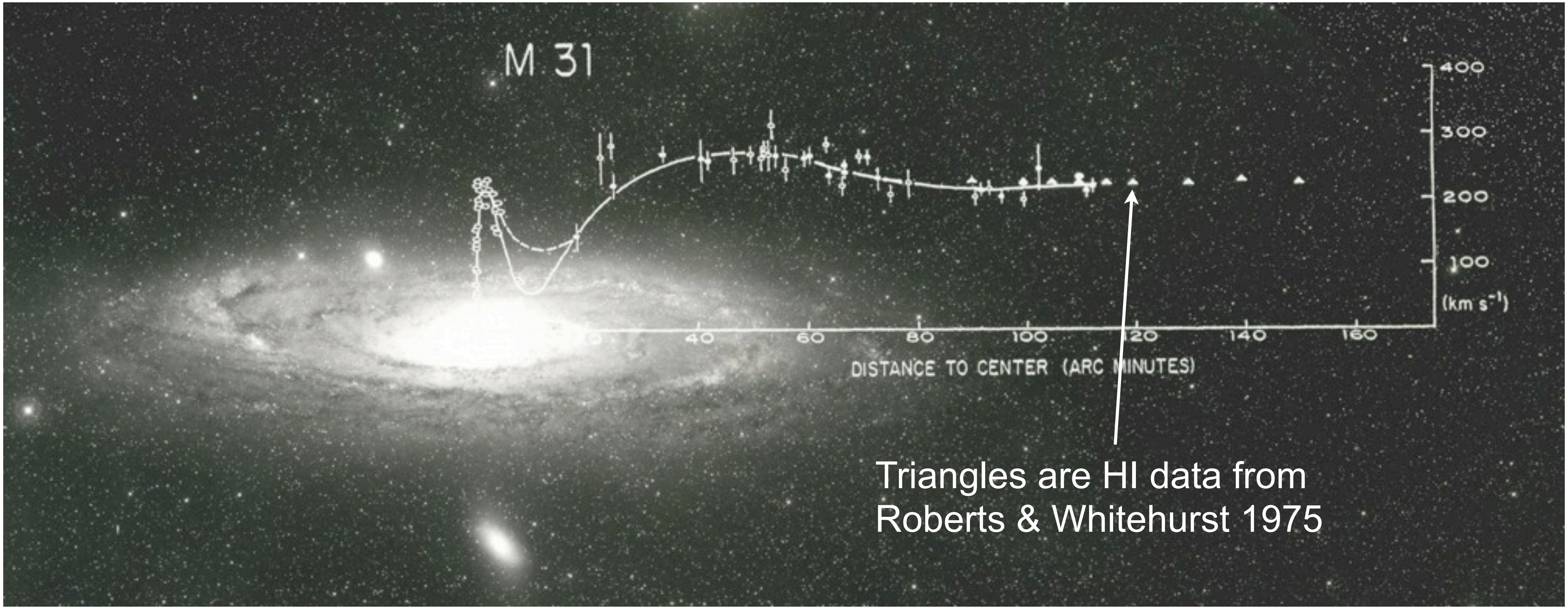
See Rubin's "Reference Frame" in Dec 2006 Physics Today and her article, "A Brief History of Dark Matter," in T*he dark universe: matter, energy and gravity*, Proc. STScI Symposium 2001, ed. Mario Livio.

1970 ApJ 159, 379

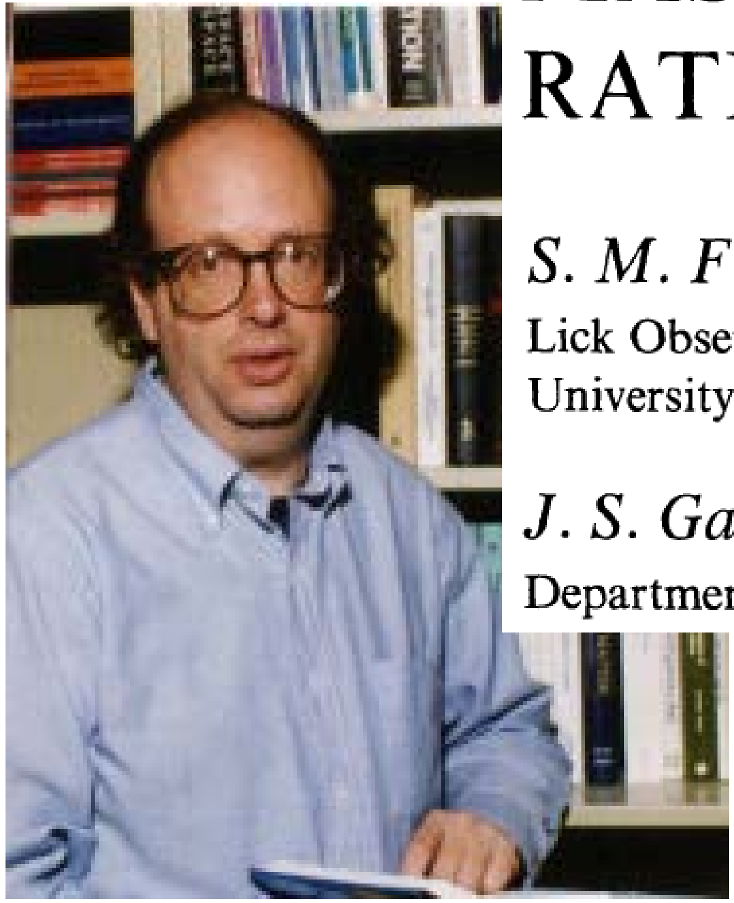


ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*

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



Triangles are HI data from Roberts & Whitehurst 1975

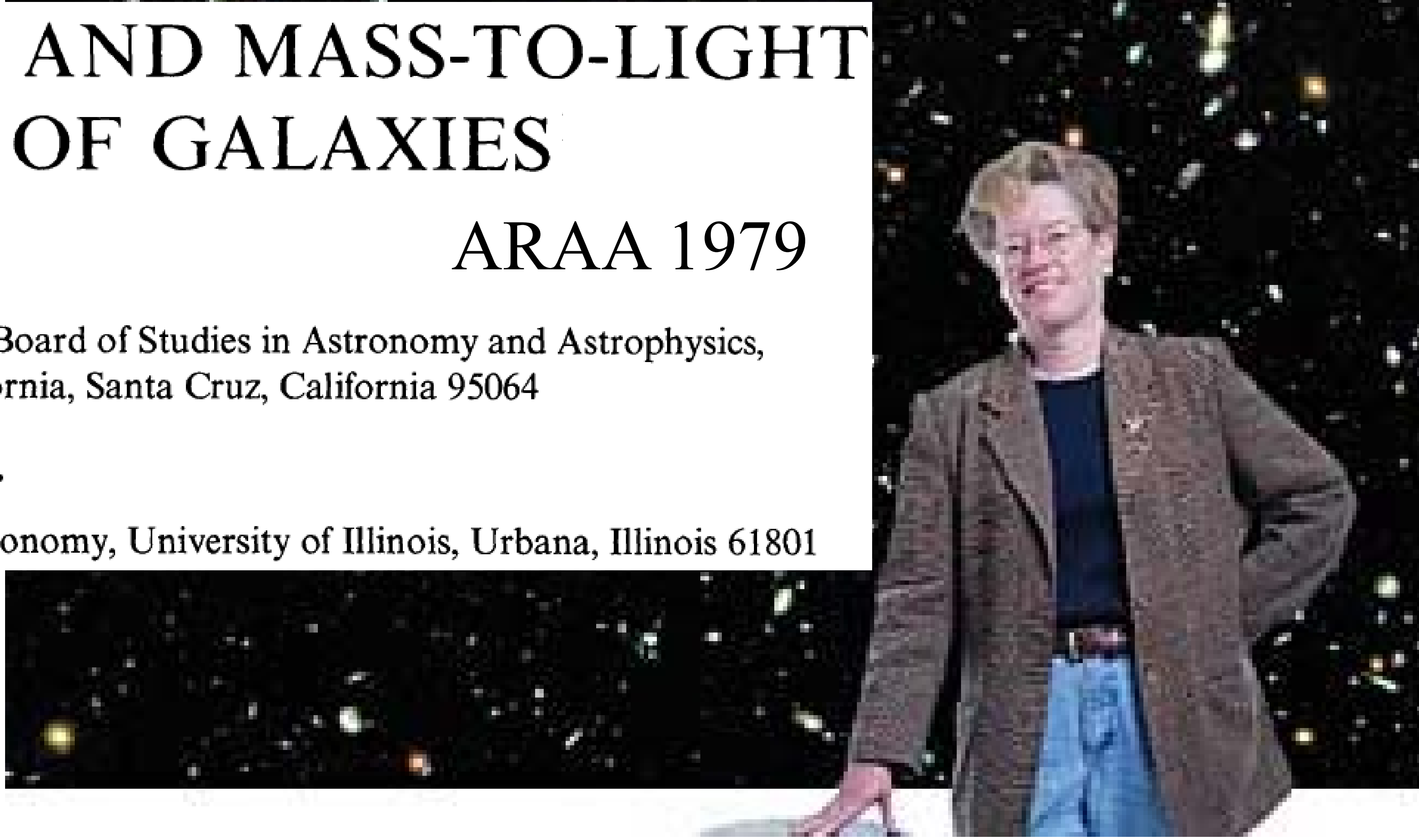


MASSES AND MASS-TO-LIGHT RATIOS OF GALAXIES

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

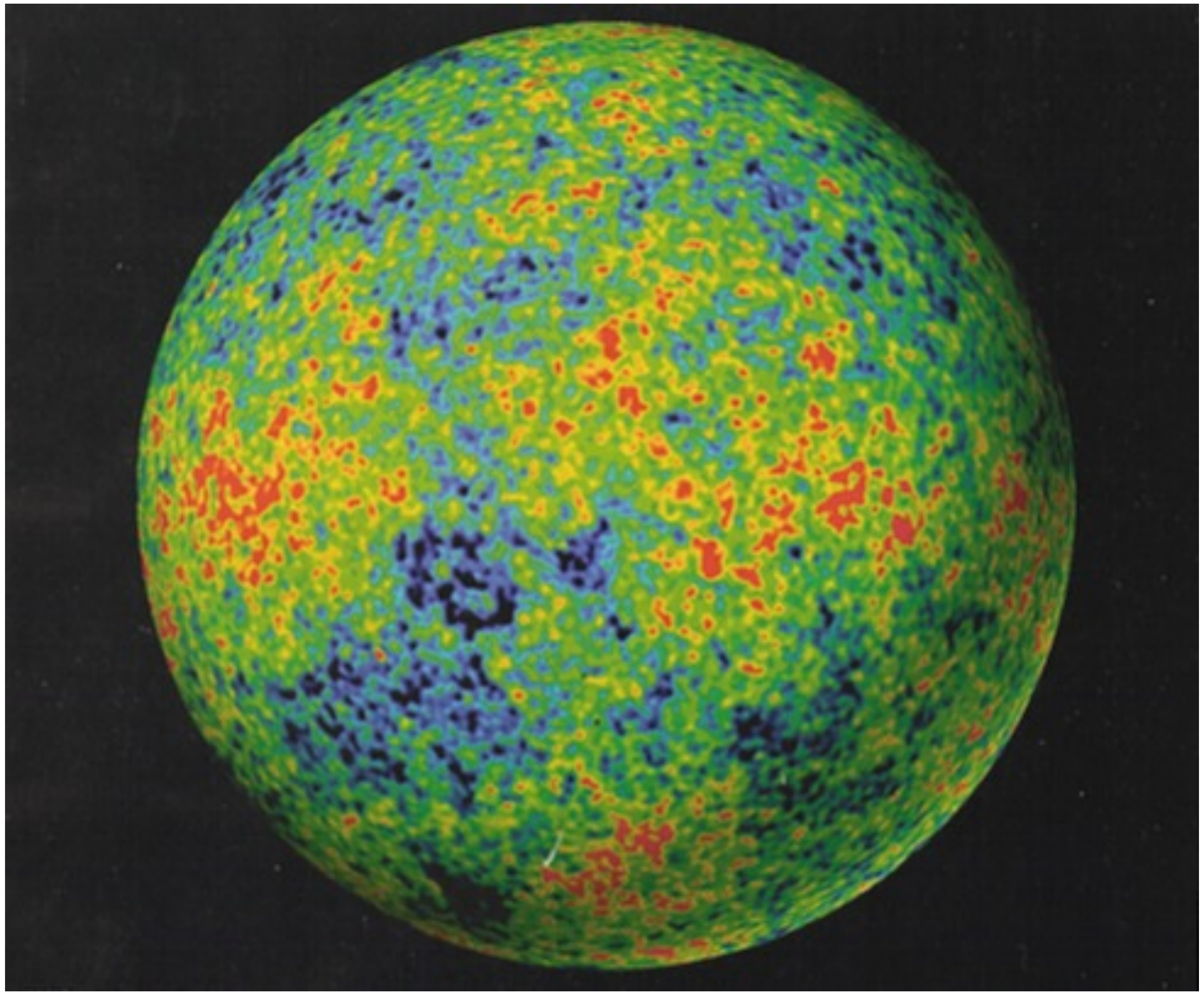
1978

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.

GRAVITY – The Ultimate Scrooge Principle

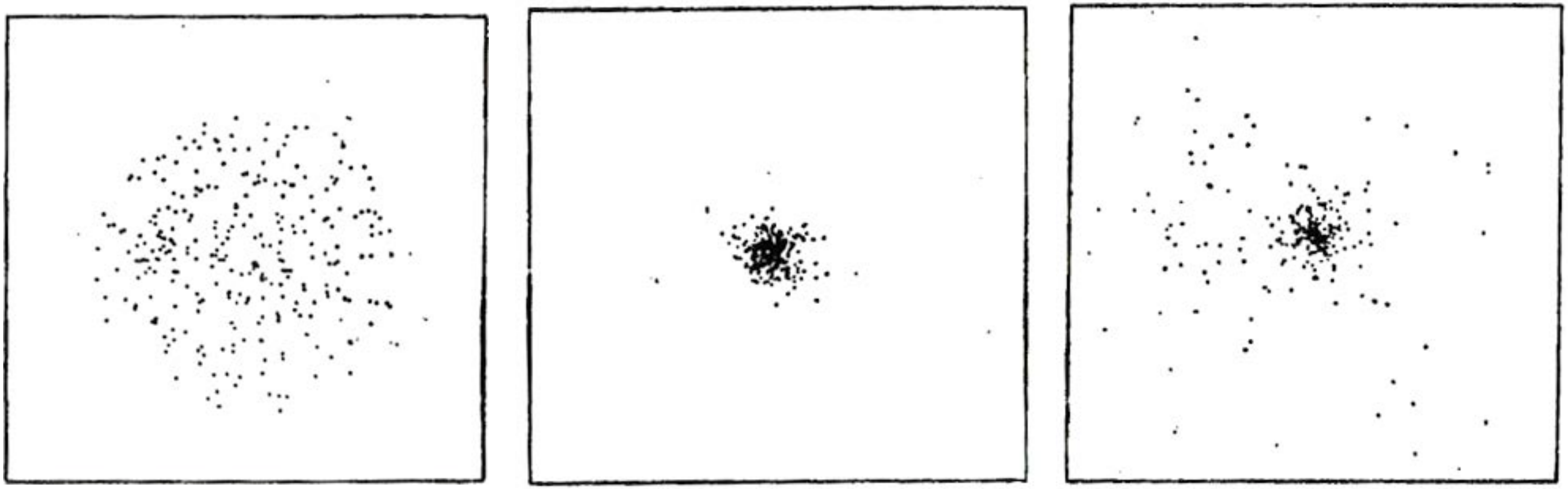
How does structure form in the universe? Astronomers say that a region of the universe with more matter is "richer." Gravity magnifies differences—if one region is slightly denser than average, it will expand slightly more slowly and grow relatively denser than its surroundings, while regions with less than average density will become increasingly less dense. The rich always get richer, and the poor poorer.



Temperature map at 380,000 years after the Big Bang. **Blue** (cooler) regions are slightly denser. From NASA's **WMAP** satellite, 2003.

The early universe expands ***almost*** perfectly uniformly. But there are small differences in density from place to place (about 30 parts per million). Because of gravity, denser regions expand more slowly, less dense regions more rapidly. Thus gravity amplifies the contrast between them, until…

Structure Formation by Gravitational Collapse



When any region becomes about twice as dense as typical regions its size, it reaches a maximum radius, ***stops expanding***,

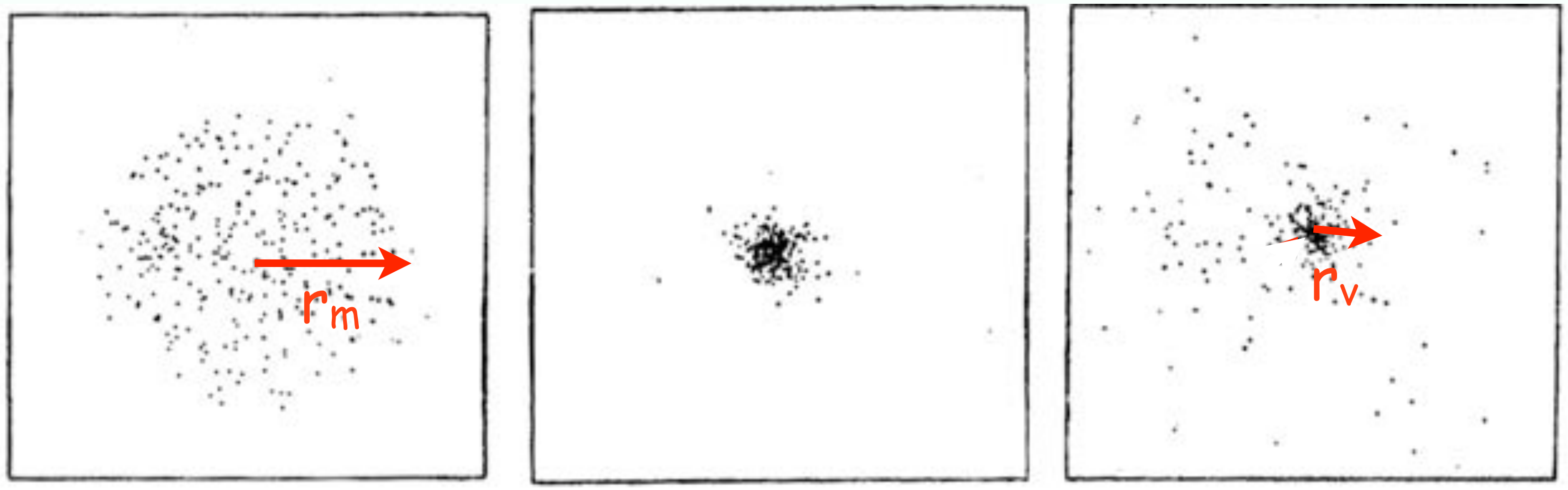
and starts falling together. The forces between the subregions generate velocities which ***prevent*** the material from ***all falling toward the center***.

Through Violent Relaxation the dark matter quickly reaches a ***stable configuration*** that's about half the maximum radius but denser in the center.

Simulation of top-hat collapse: P.J.E. Peebles 1970, ApJ, 75, 13.

Used in my 1984 summer school lectures "Dark matter, Galaxies, and Large Scale Structure," http://tinyurl.com/3bjknb3

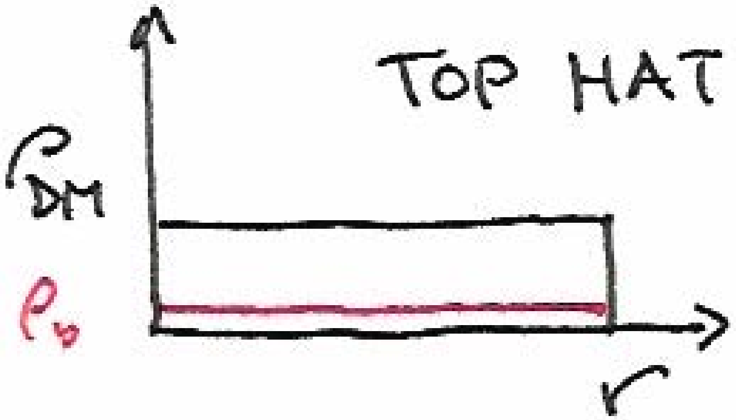
Structure Formation by Gravitational Collapse



TOP HAT
Max Expansion

VIOLENT RELAXATION

VIRIALIZED



Virial Theorem: $\langle K \rangle = -\frac{1}{2}\langle W \rangle$

$-W_m = \frac{C}{r_m}$, so after virialization

$$-\frac{C}{r_m} = E = W + K = \frac{1}{2}\langle W \rangle = -\frac{C}{2 r_v}$$

$$\Rightarrow r_v = \frac{1}{2} r_m, \quad \rho_v = 8 \rho_m \approx 50 \bar{\rho}(t_m)$$

$$\langle v^2 \rangle \approx \frac{GM}{r_v}$$

VIOLENT RELAXATION: Lynden-Bell 1967, Shu 1978

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

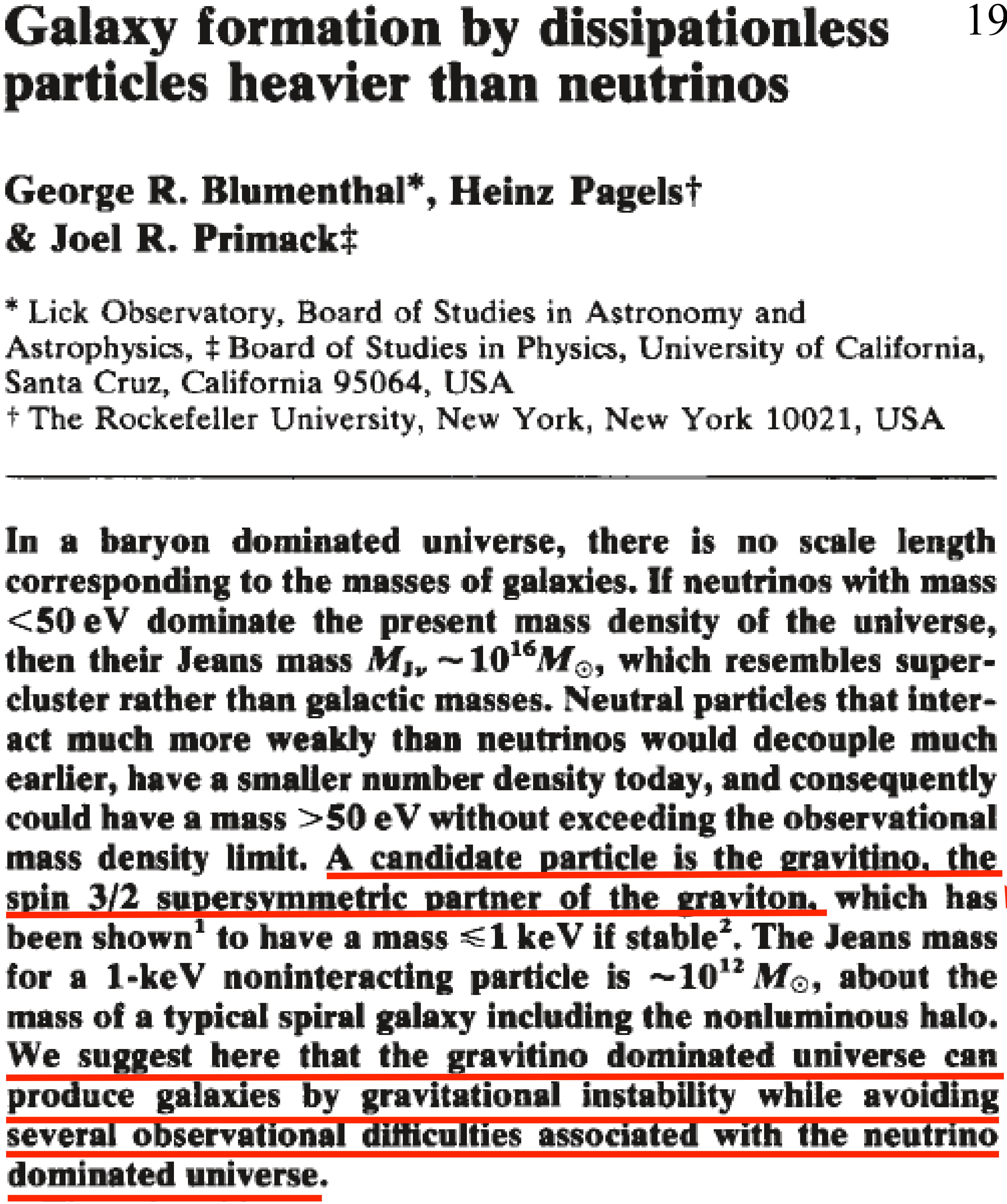
(b) hot dark matter.

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 Nature 299, 37



Galaxy formation by dissipationless particles heavier than neutrinos

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.

Pagels & Primack 1982

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.

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 $P(k) \approx k^1$
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

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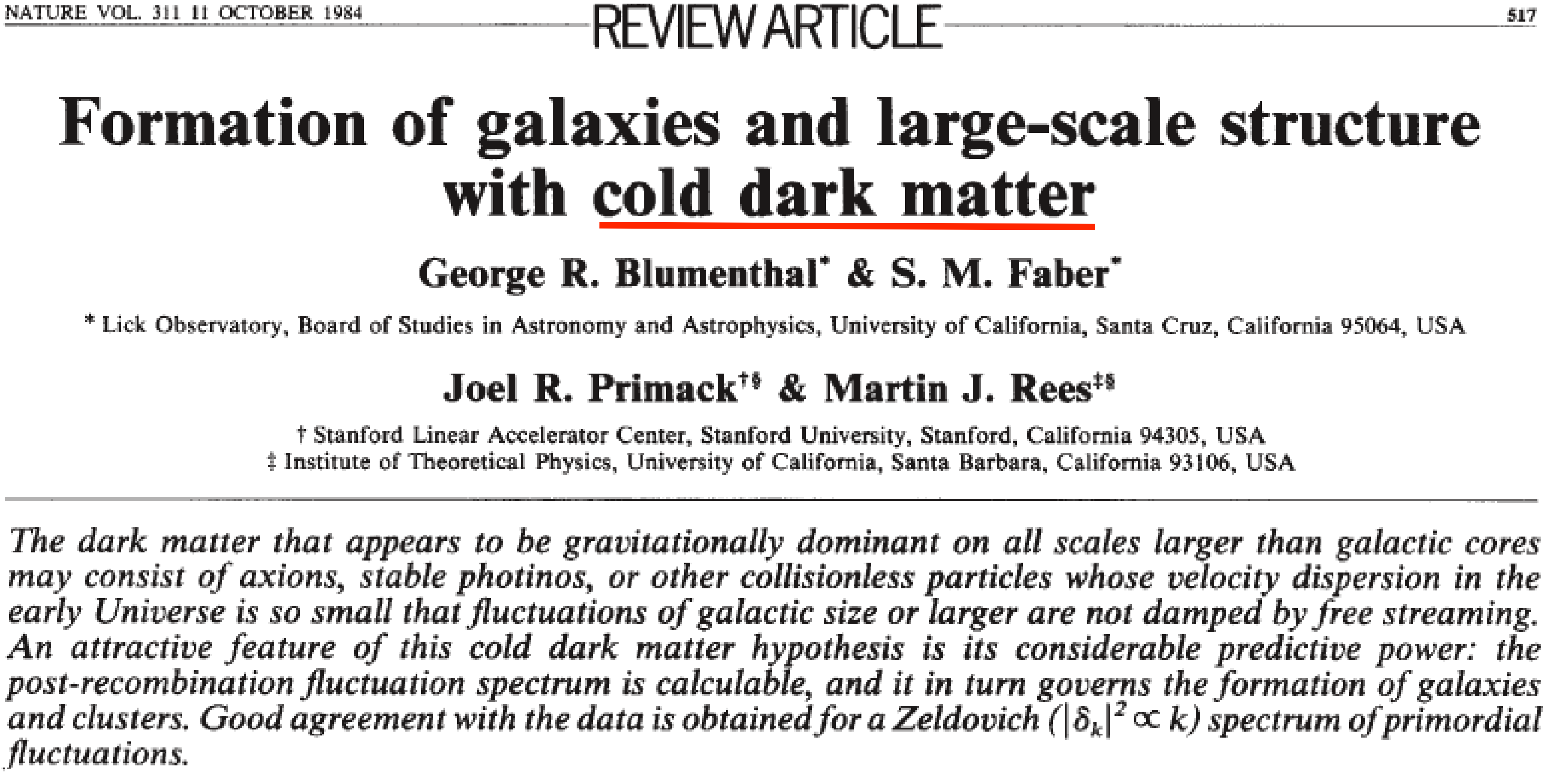
1984 - Peebles; Turner, Steigman, Krauss: effects of Λ
1984 - Ellis, Hagelin, Nanopoulos, Olive, & Srednicki: neutralino CDM
1985 - Davis, Efstathiou, Frenk, & White: 1st CDM, ΛCDM simulations



NATURE VOL. 311 11 OCTOBER 1984

REVIEW ARTICLE

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

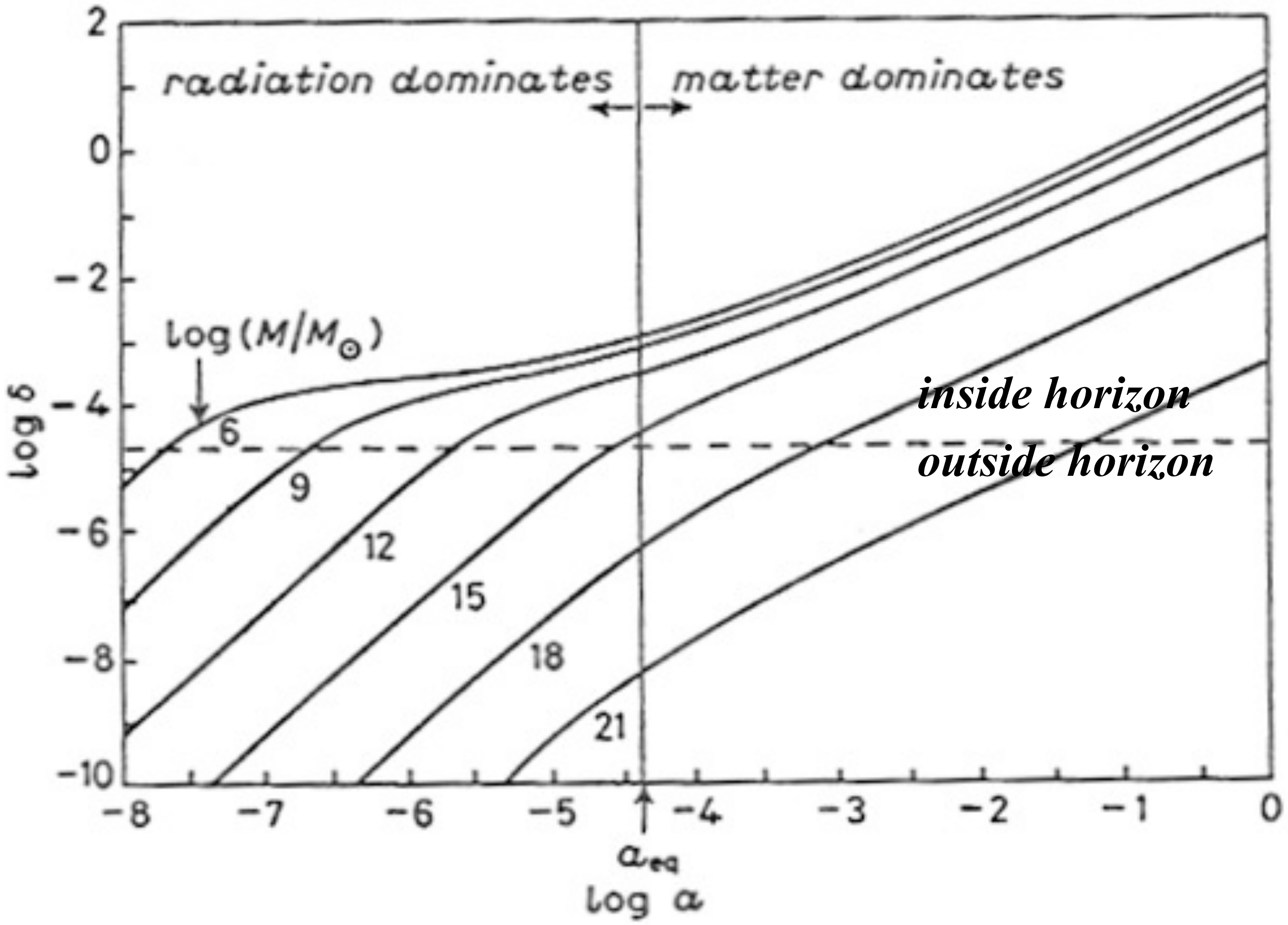
… We conclude that a straightforward interpretation of the evidence summarized above favours $\Omega \approx 0.2$ in the cold DM picture, but that $\Omega = 1$ is not implausible. …

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.

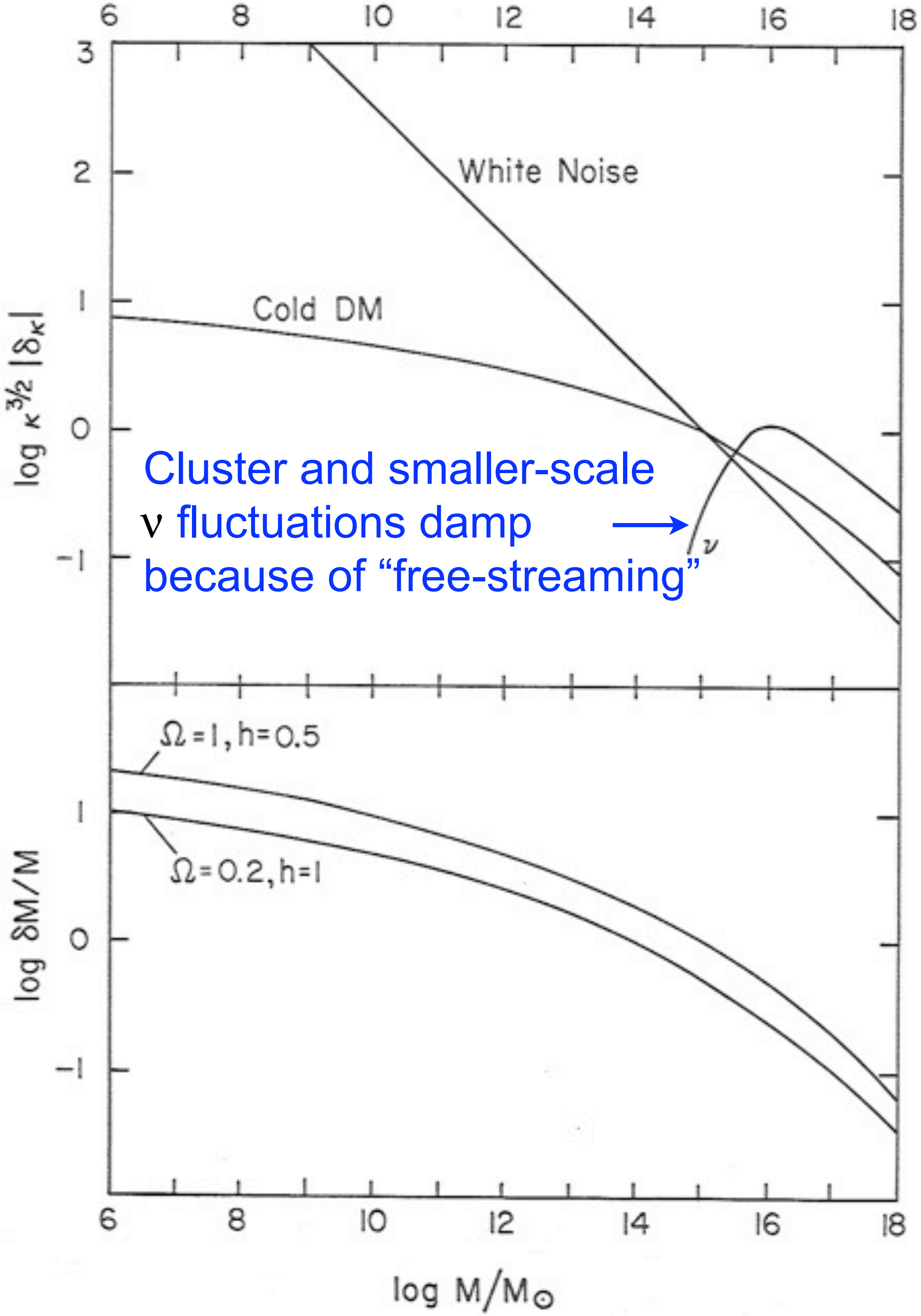
Blumenthal, Faber, Primack, & Rees 1984

CDM Structure Formation: Linear Theory



inside horizon

outside horizon



Cluster and smaller-scale ν fluctuations damp ⟶ because of “free-streaming”

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

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

1996 - Navarro, Frenk, & White: DM halo structure $\rho_{NFW}(r) = 4\,\rho_s\,(r/r_s)^{-1}(1+r/r_s)^{-2}$

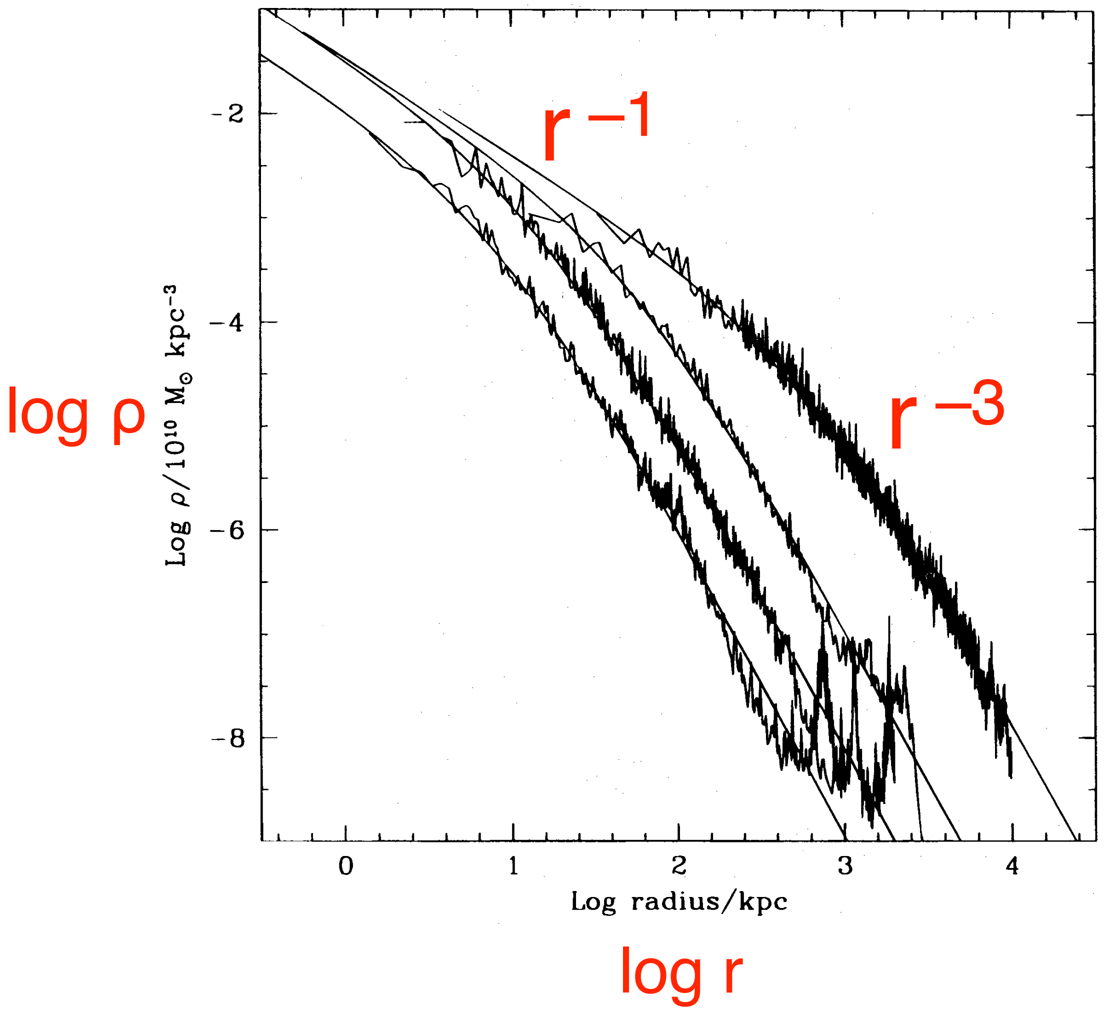
1997 - Hipparchos distance scale, SN Ia dark energy $\Rightarrow t_0 \approx 14$ Gyr, ΛCDM

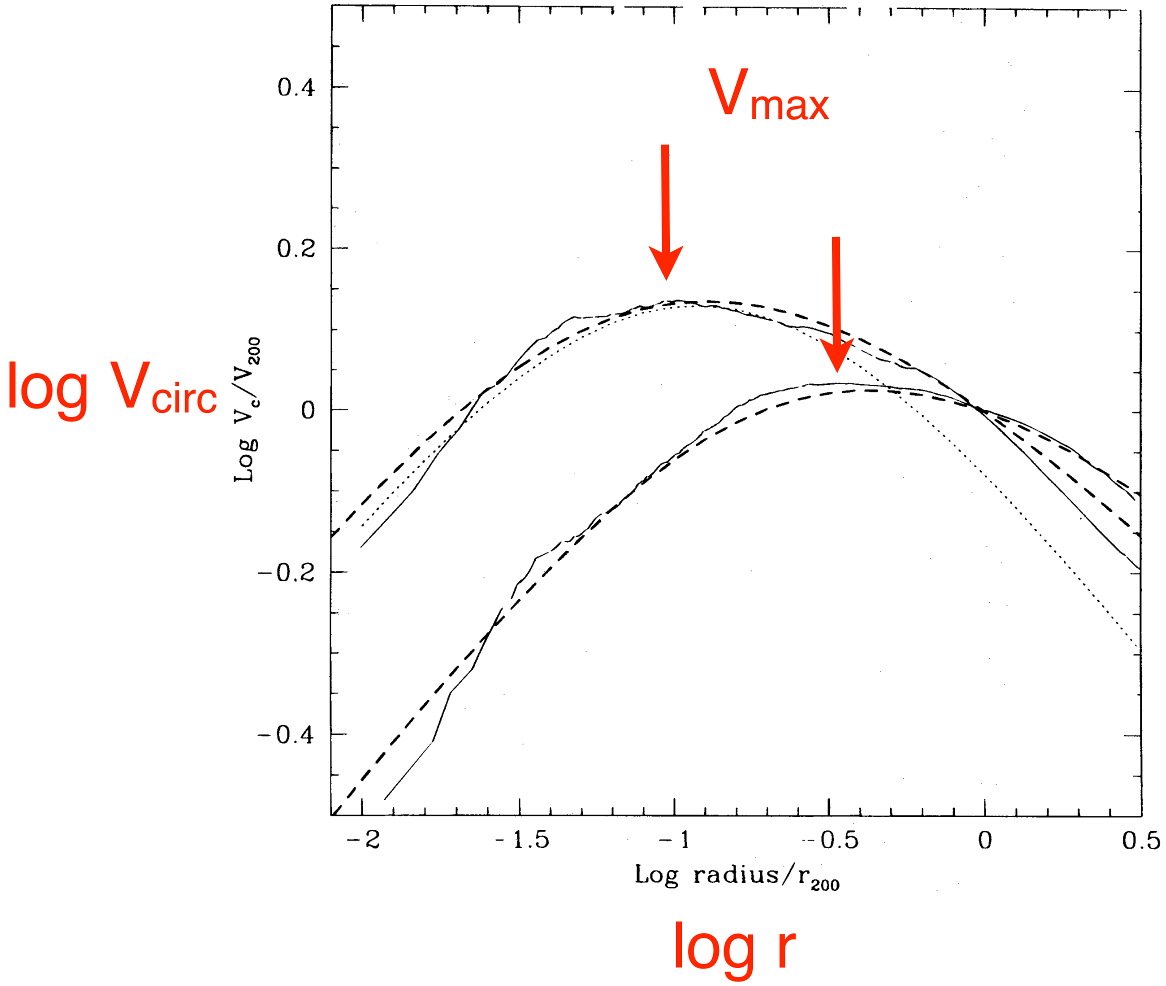
2001 - Bullock et al.: concentration-mass-z relation for DM halos; universal angular momentum structure of DM halos

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

2003-present - Large Scale Structure surveys, WMAP and Planck CMB observations confirm ΛCDM predictions with increasing precision

Dark Matter Halo Structure





1996 - Navarro, Frenk, & White: DM halo structure $\rho_{NFW}(r) = 4\ \rho_s\ (r/r_s)^{-1}(1+r/r_s)^{-2}$

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 $M(z) = M_0\ e^{-\alpha z}$

2003-present - Large Scale Structure surveys, WMAP and Planck CMB observations confirm ΛCDM predictions with increasing precision

ΛCDM PREDICTS EVOLUTION IN THE GALAXY CORRELATION FUNCTION

$\xi_{gg}(r)$

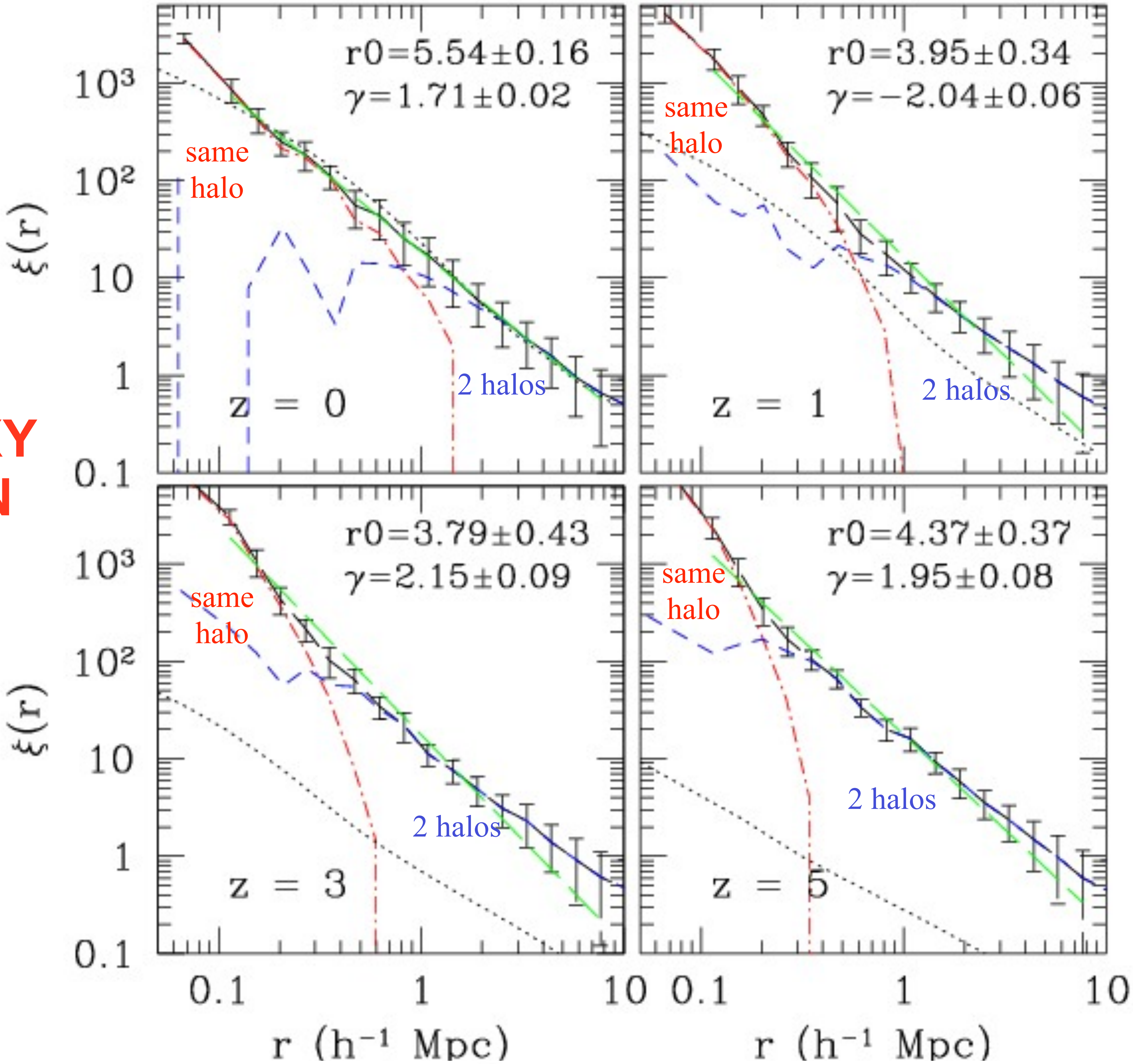


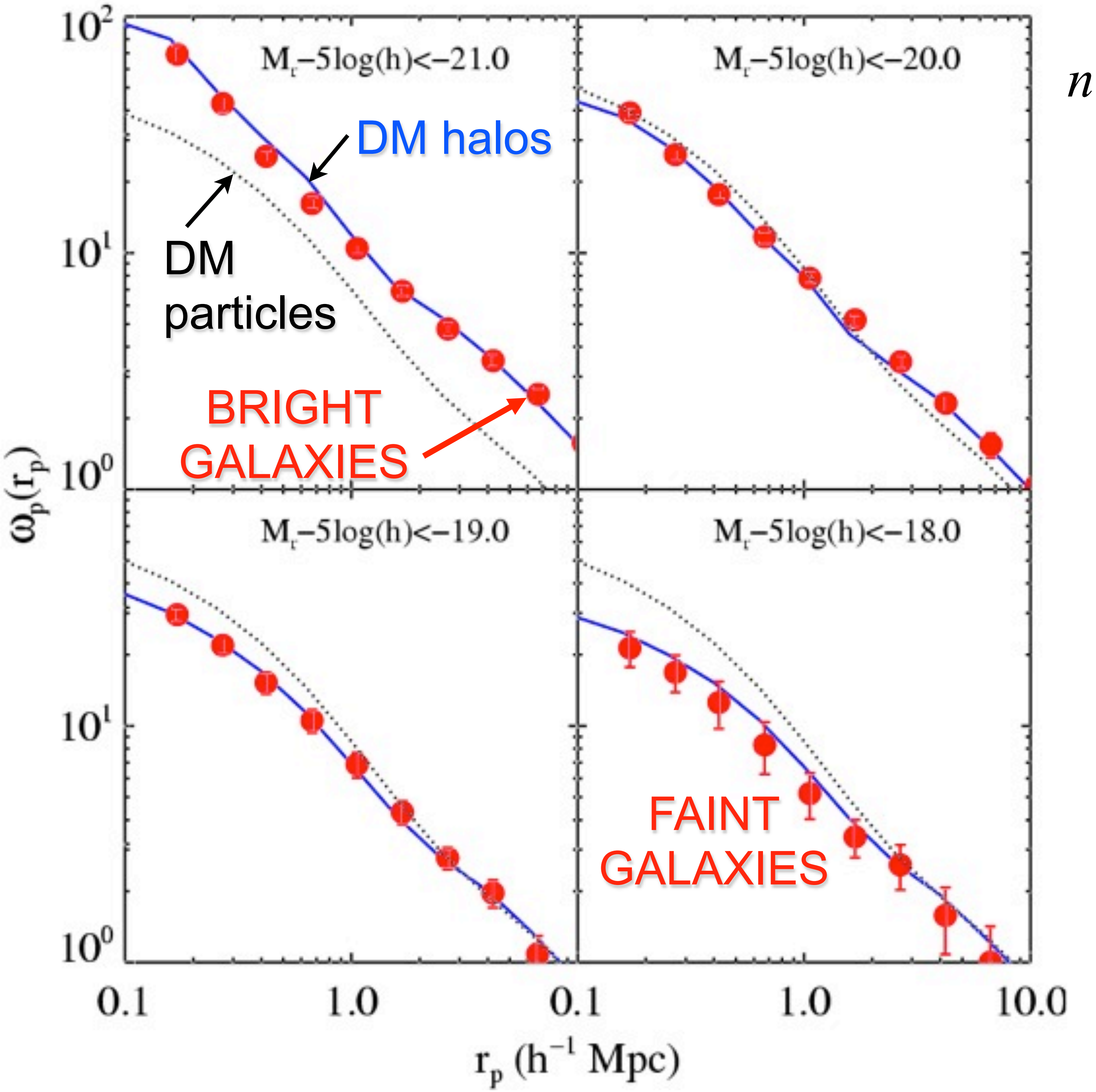
FIG. 8.— Evolution of the two-point correlation function in the 80h^{-1} Mpc simulation. The solid line with error bars shows the clustering of halos of the fixed number density $n = 5.89 \times 10^{-3} h^3$ Mpc^{-3} at each epoch. The error-bars indicate the "jack-knife" one sigma errors and are larger than the Poisson error at all scales. The dot-dashed and dashed lines show the corresponding one- and two-halo term contributions. The long-dashed lines show the power-law fit to the correlation functions in the range of $r = [0.1 - 8h^{-1}$ Mpc$]$. Although the correlation functions can be well fit by the power law at $r \gtrsim 0.3h^{-1}$ Mpc in each epoch, at $z > 0$ the correlation function steepens significantly at smaller scales due to the one-halo term.

Kravtsov, Berlind, Wechsler, Klypin, Gottloeber, Allgood, & Primack 2004

Galaxy clustering in SDSS at z~0 agrees with ΛCDM simulations

$n(>V_{\mathrm{max,acc}})=n(>L)$

projected
2-point
correlation
function

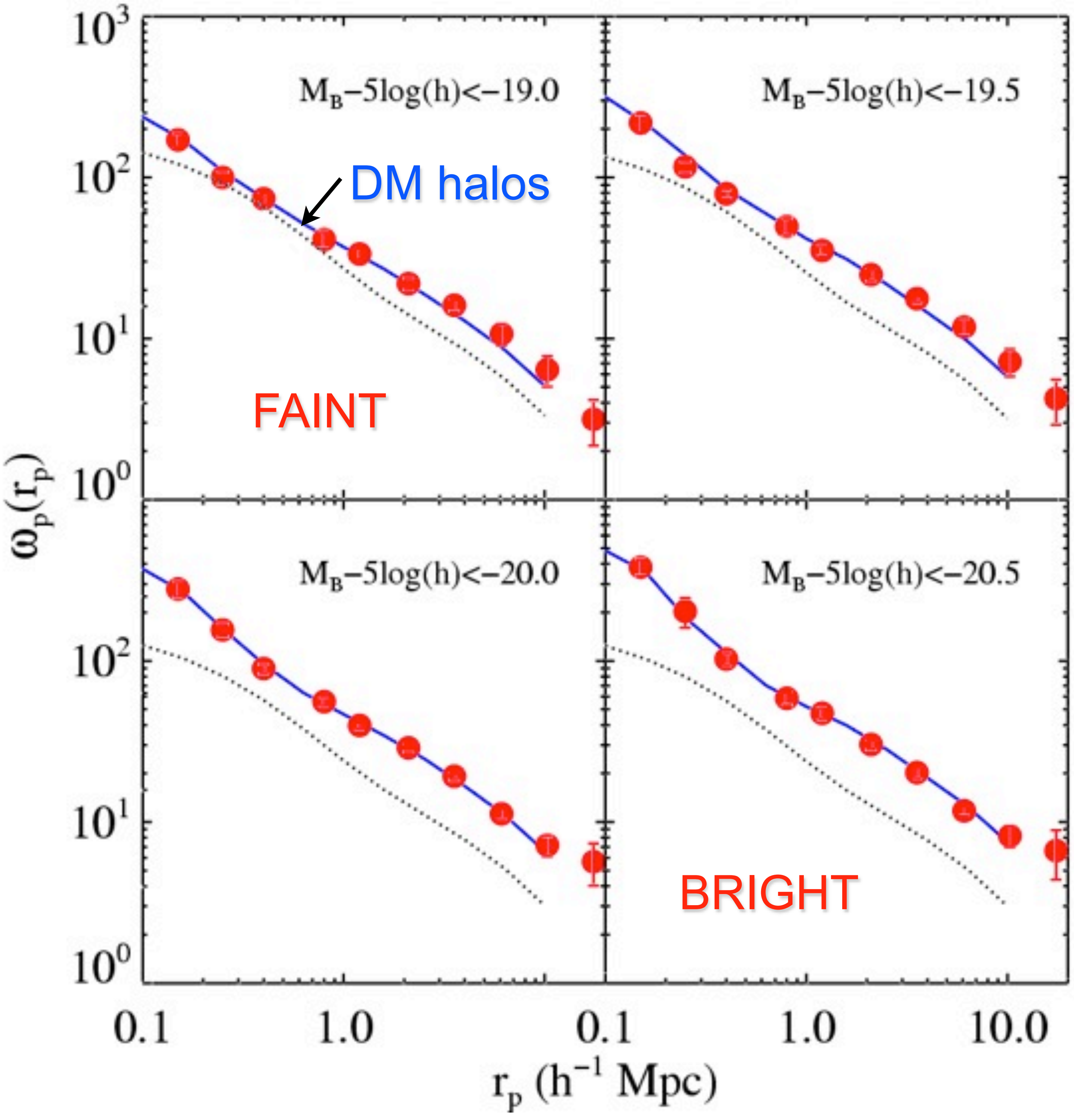


projected separation

Conroy,
Wechsler &
Kravtsov
2006, ApJ 647, 201

and at redshift z~1 (DEEP2)

projected
2-point
correlation
function



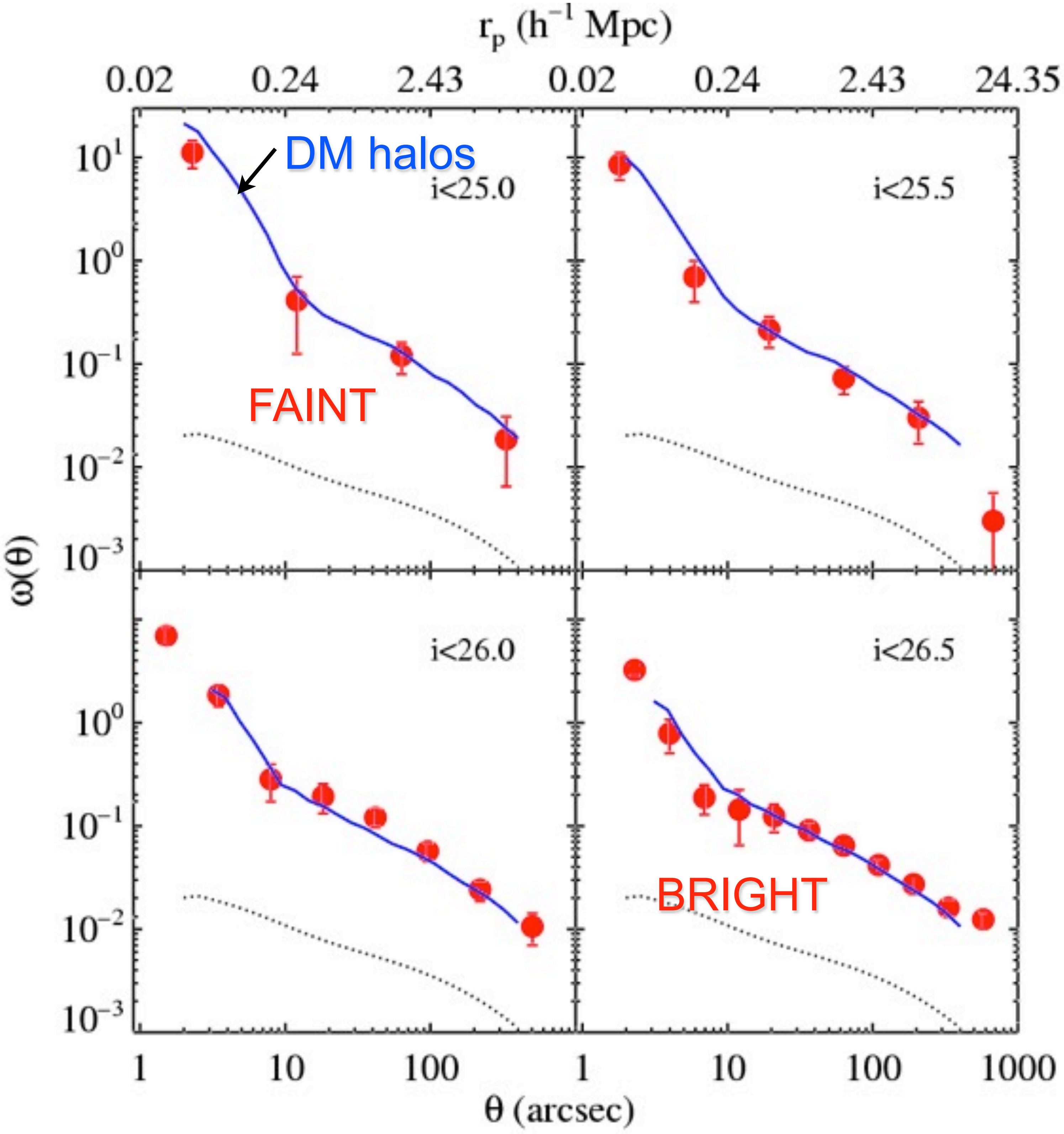
$n(>V_{\mathrm{max,acc}})=n(>L)$

Conroy,
Wechsler &
Kravtsov 06

projected separation

and at z~4-5 (LBGs, Subaru)!

angular 2-point correlation function



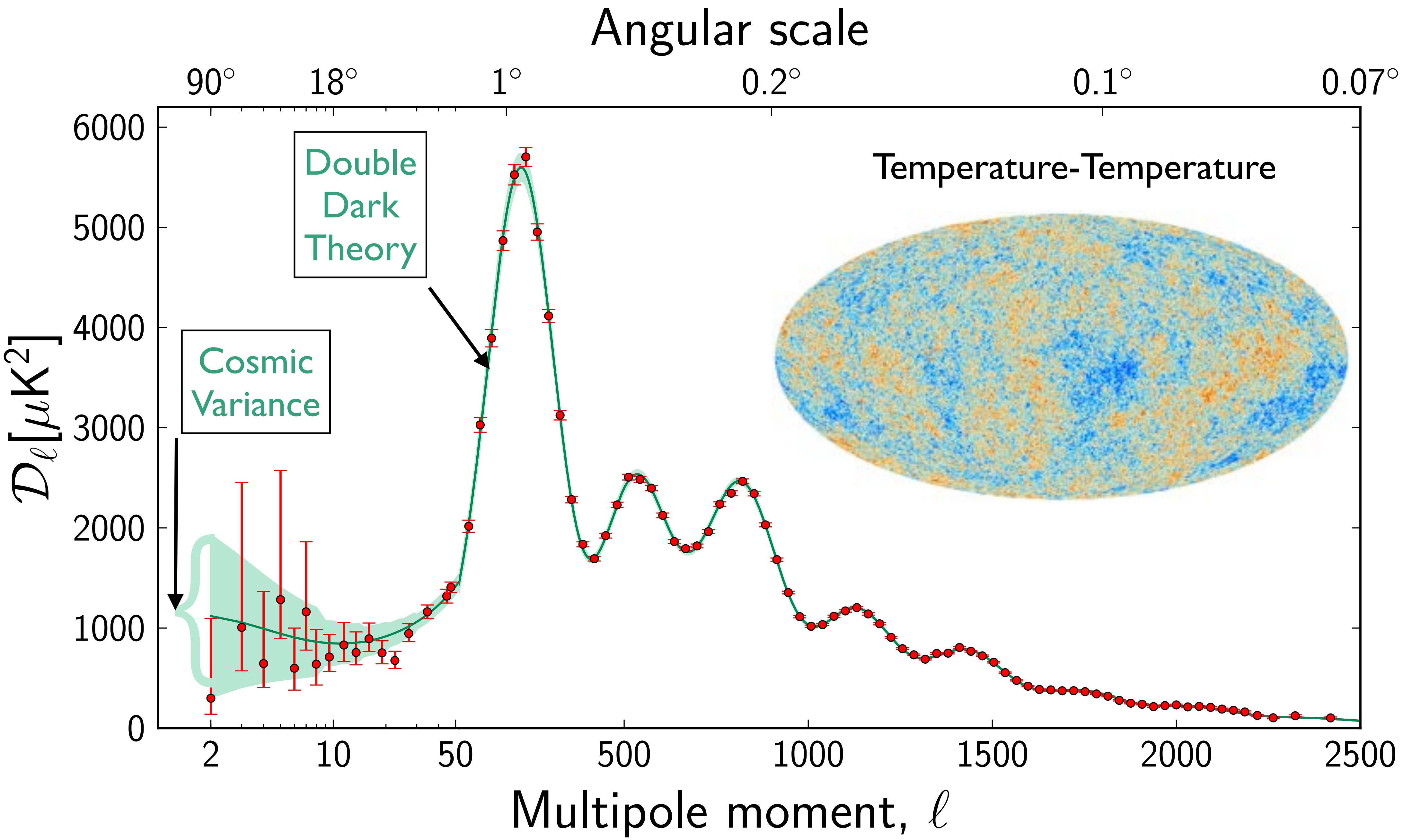
$n(>V_{\mathrm{max,acc}})=n(>L)$

projected separation

Conroy, Wechsler & Kravtsov 06

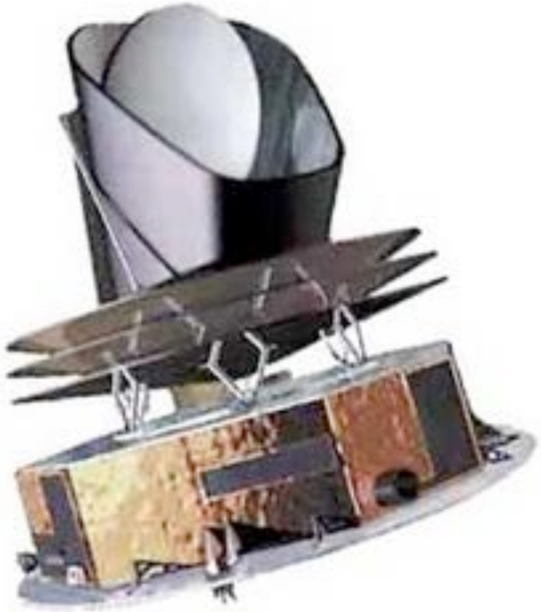
European Space Agency PLANCK Satellite Data

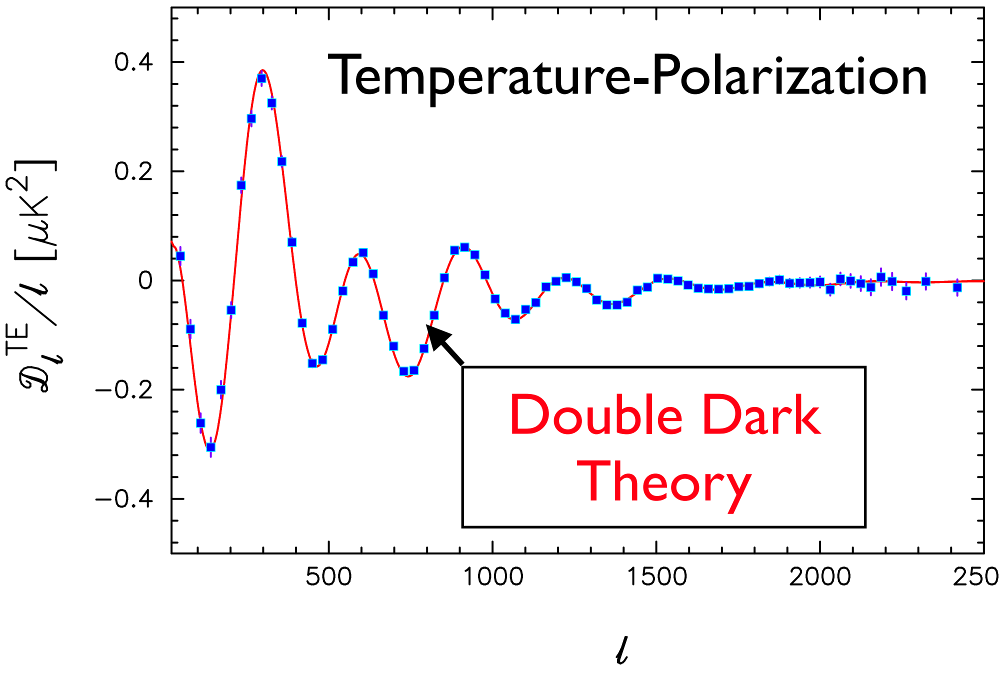
Released March 21, 2013



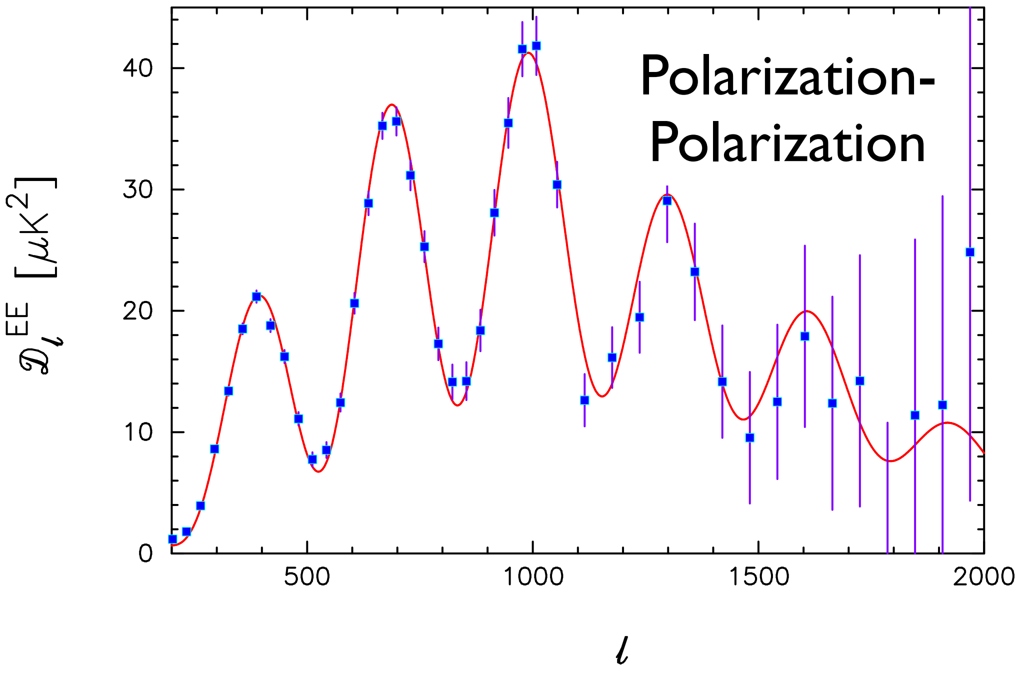
Double Dark Theory

Cosmic Variance



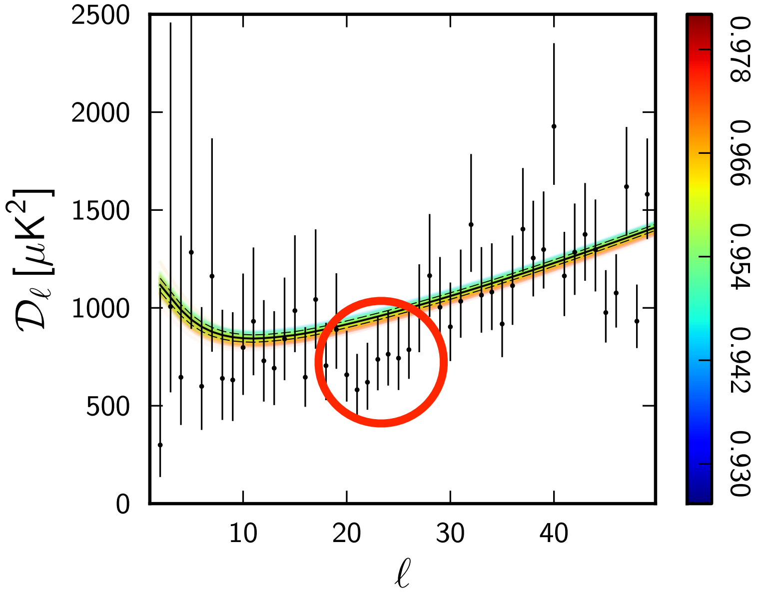


Double Dark Theory



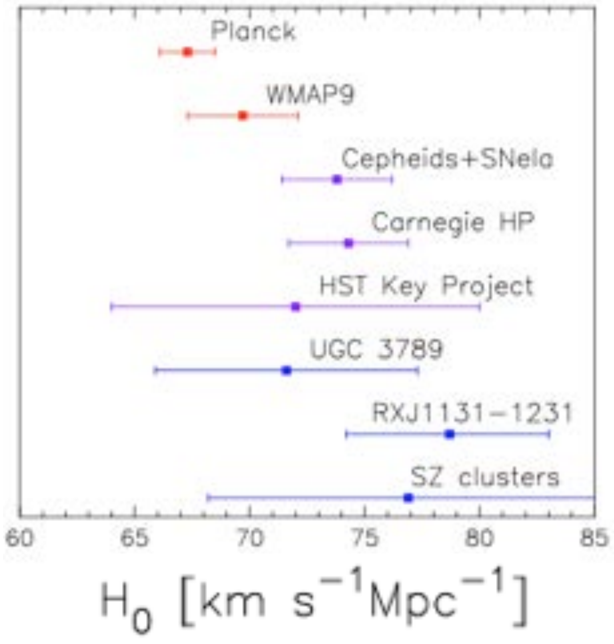
Planck 2013 results. XVI. Cosmological parameters

Abstract: This paper presents the first cosmological results based on *Planck* measurements of the cosmic microwave background (CMB) temperature and lensing-potential power spectra. We find that the *Planck* spectra at high multipoles ($\ell \gtrsim 40$) are extremely well described by the standard spatially-flat six-parameter ΛCDM cosmology with a power-law spectrum of adiabatic scalar perturbations. Within the context of this cosmology, the *Planck* data determine the cosmological parameters to high precision: the angular size of the sound horizon at recombination, the physical densities of baryons and cold dark matter, and the scalar spectral index are estimated to be $\theta_* = (1.04147 \pm 0.00062) \times 10^{-2}$, $\Omega_b h^2 = 0.02205 \pm 0.00028$, $\Omega_c h^2 = 0.1199 \pm 0.0027$, and $n_s = 0.9603 \pm 0.0073$, respectively (68% errors). For this cosmology, we find a low value of the Hubble constant, $H_0 = 67.3 \pm 1.2\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, and a high value of the matter density parameter, $\Omega_m = 0.315 \pm 0.017$. These values are in tension with recent direct measurements of H_0 and the magnitude-redshift relation for Type Ia supernovae, but are in excellent agreement with geometrical constraints from baryon acoustic oscillation (BAO) surveys. Including curvature, we find that the Universe is consistent with spatial flatness to percent level precision using *Planck* CMB data alone. We use high-resolution CMB data together with *Planck* to provide greater control on extragalactic foreground components in an investigation of extensions to the six-parameter ΛCDM model. We present selected results from a large grid of cosmological models, using a range of additional astrophysical data sets in addition to *Planck* and high-resolution CMB data. None of these models are favoured over the standard six-parameter ΛCDM cosmology. The deviation of the scalar spectral index from unity is insensitive to the addition of tensor modes and to changes in the matter content of the Universe. We find a 95% upper limit of $r_{0.002} < 0.11$ on the tensor-to-scalar ratio. There is no evidence for additional neutrino-like relativistic particles beyond the three families of neutrinos in the standard model. Using BAO and CMB data, we find $N_{\mathrm{eff}} = 3.30 \pm 0.27$ for the effective number of relativistic degrees of freedom, and an upper limit of 0.23 eV for the sum of neutrino masses. Our results are in excellent agreement with big bang nucleosynthesis and the standard value of $N_{\mathrm{eff}} = 3.046$. We find no evidence for dynamical dark energy; using BAO and CMB data, the dark energy equation of state parameter is constrained to be $w = -1.13^{+0.13}_{-0.10}$. We also use the *Planck* data to set limits on a possible variation of the fine-structure constant, dark matter annihilation and primordial magnetic fields. Despite the success of the six-parameter ΛCDM model in describing the *Planck* data at high multipoles, we note that this cosmology does not provide a good fit to the temperature power spectrum at low multipoles. The unusual shape of the spectrum in the multipole range $20 \lesssim \ell \lesssim 40$ was seen previously in the *WMAP* data and is a real feature of the primordial CMB anisotropies. The poor fit to the spectrum at low multipoles is not of decisive significance, but is an "anomaly" in an otherwise self-consistent analysis of the *Planck* temperature data.



The main Planck anomaly is the low amplitudes at $\ell \approx 21\text{-}27$

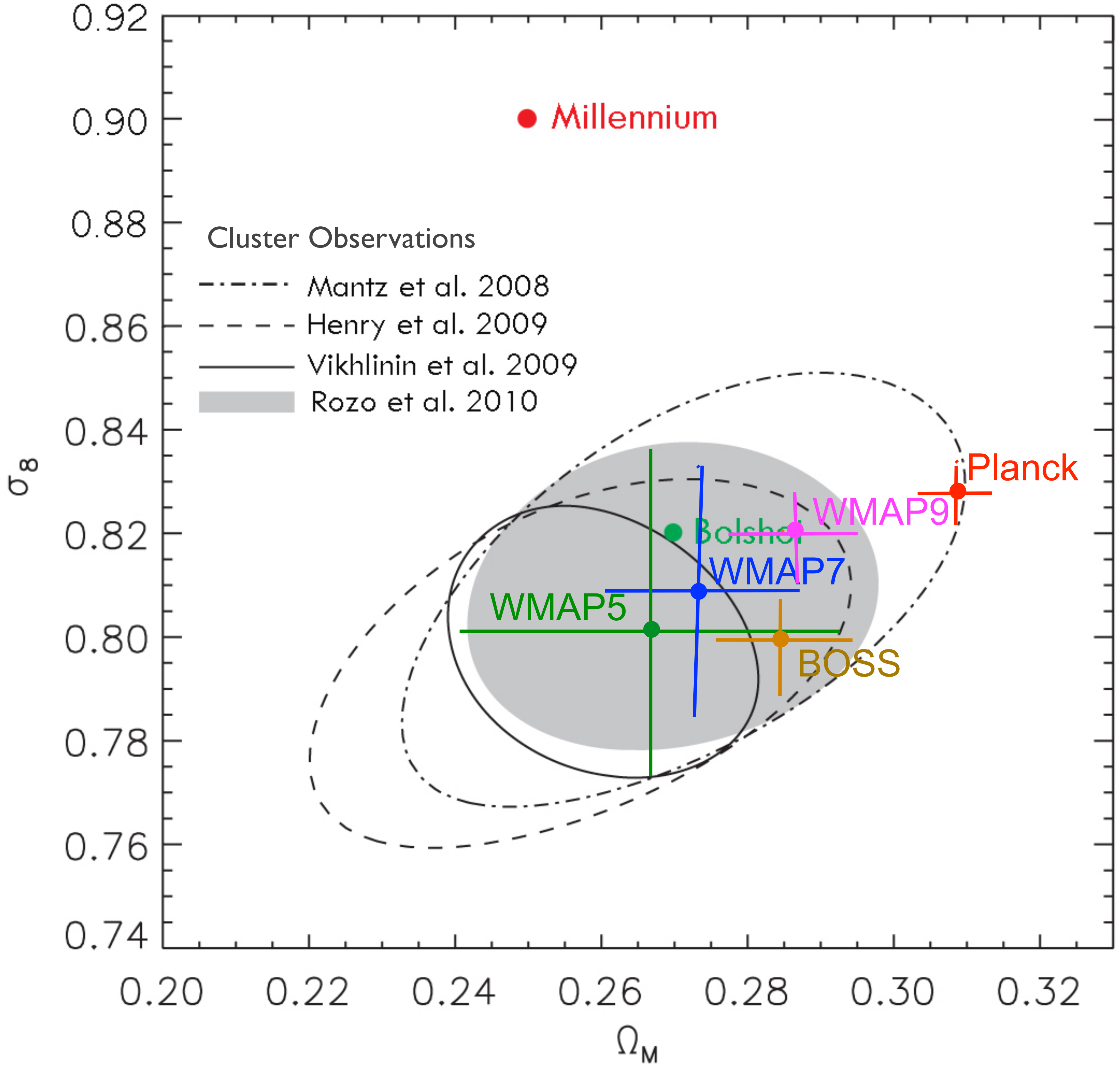
Planck errors are small and Planck's values for H_0 and Ω_m are rather different from WMAP's



Determination of σ_8 and Ω_M from CMB+

WMAP+SN+Clusters Planck+WP+HighL+BAO

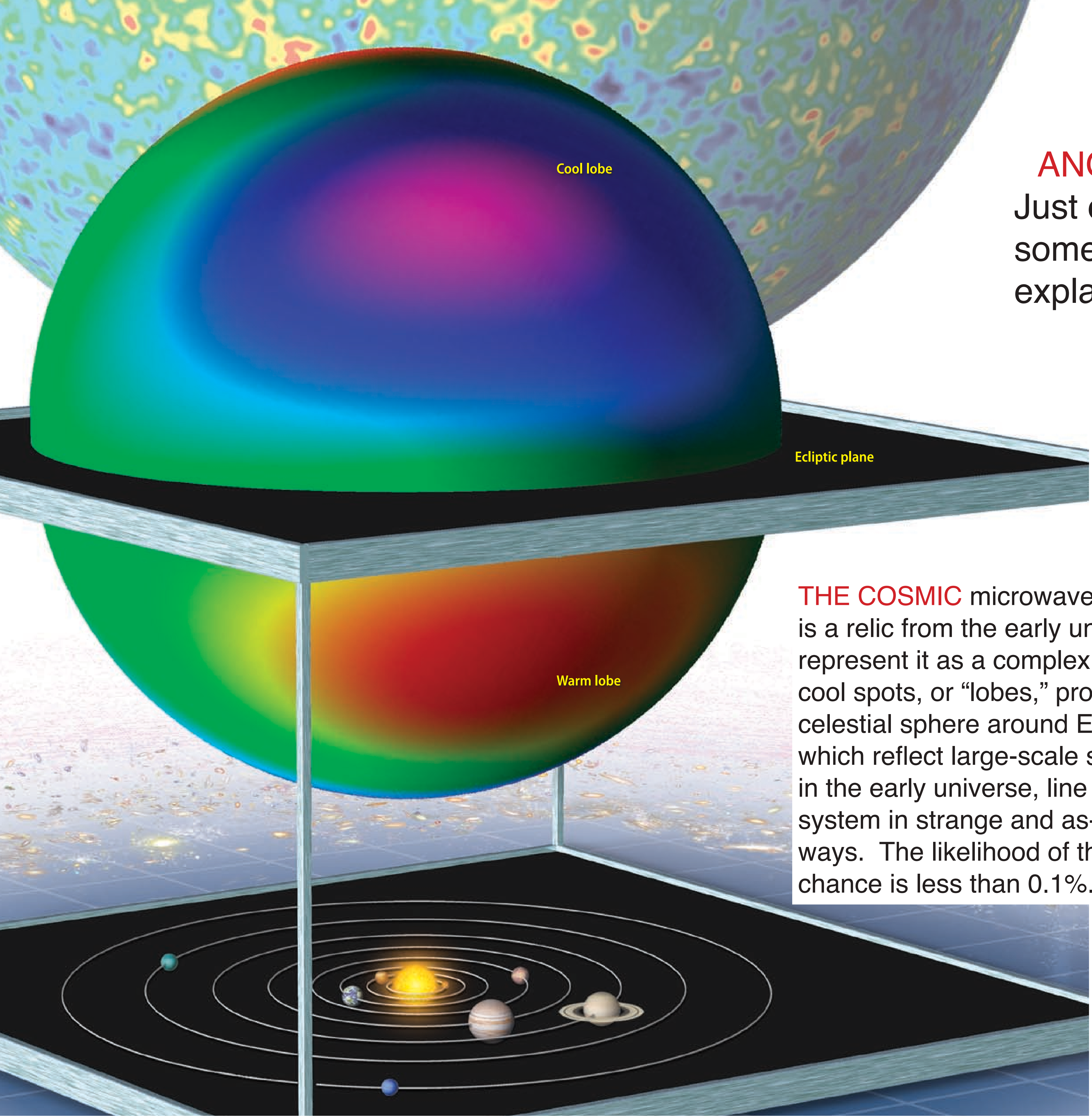
Power
Spectrum
Amplitude



Cosmic Dark Matter Fraction

ANOMALIES

Just chance, or something to be explained?



THE COSMIC microwave background (CMB) is a relic from the early universe. Scientists represent it as a complex pattern of warm and cool spots, or “lobes,” projected onto the celestial sphere around Earth. The patterns, which reflect large-scale structures pres- ent in the early universe, line up with the solar system in strange and as-yet-unexplained ways. The likelihood of this occurring by chance is less than 0.1%.

D. Huterer
Astronomy
Dec 2007

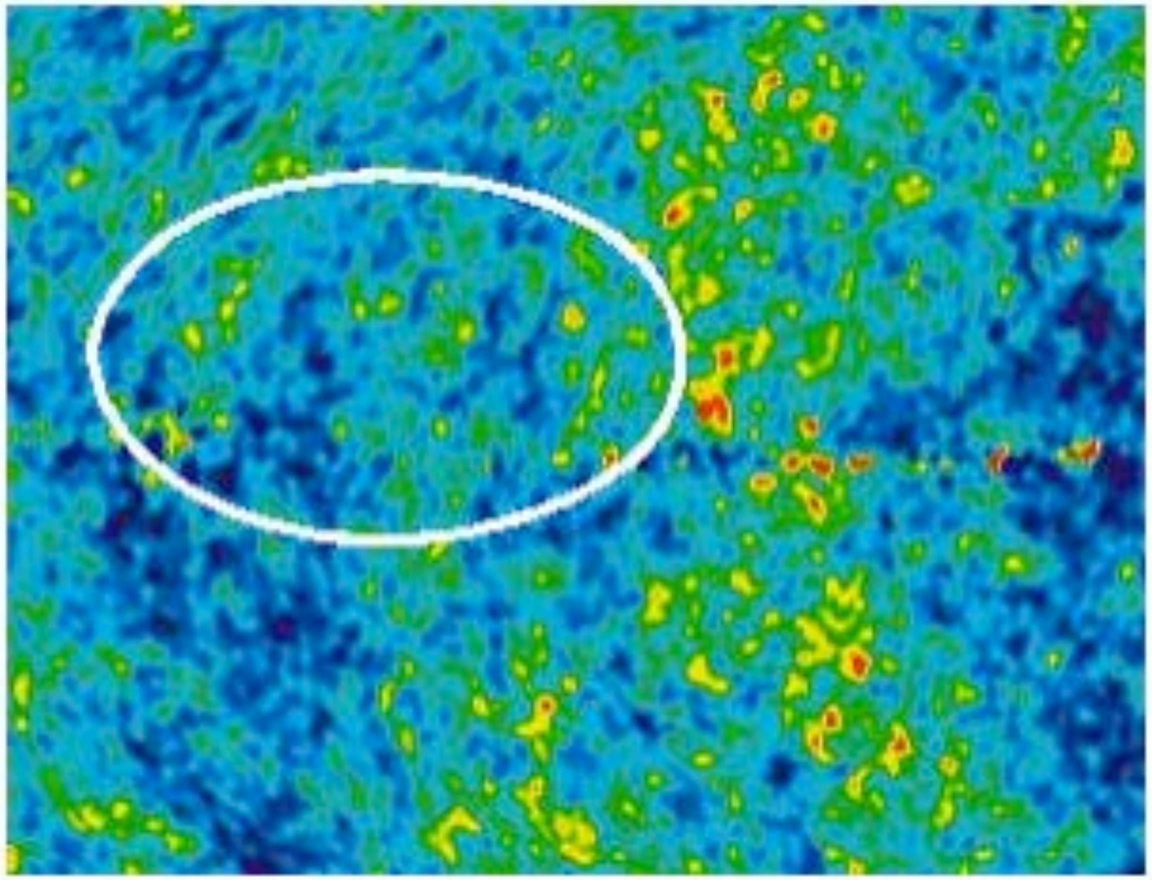
ANOMALIES

Just chance, or something to be explained?

NASA's Wilkinson Microwave Anisotropy Probe team used Hawking's initials to draw attention to a serious point. With each new round of WMAP data, apparent anomalies called "anisotropies" in the CMB have puzzled physicists. Such patterns have also been used to justify various exotic theories.

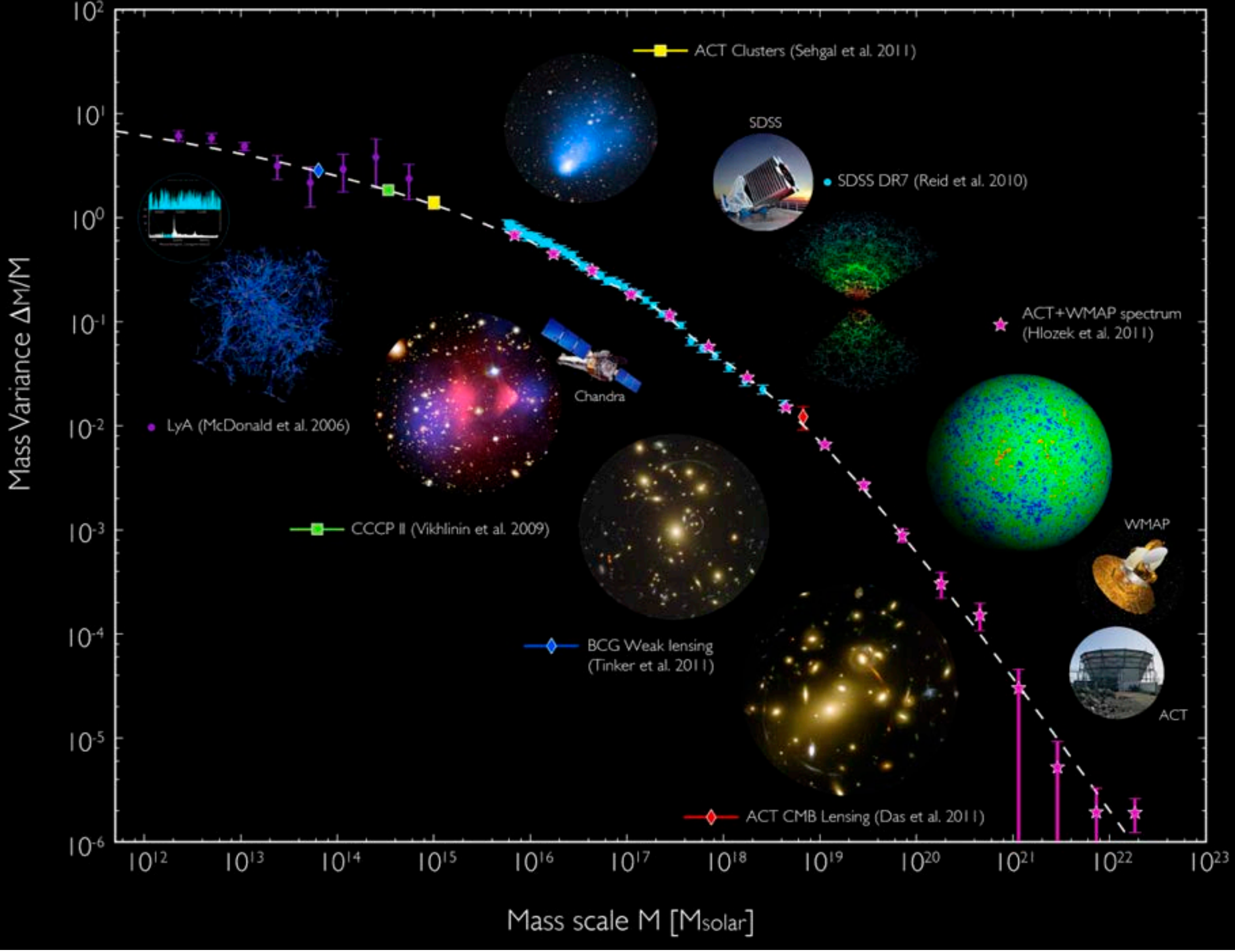
One notorious anomaly is the "axis of evil", an apparent alignment in the hot and cold regions where there should be randomness. Another is the "cold spot", a particularly large void in the CMB, which some have proposed is evidence of another universe nestling next to our own.

The WMAP team point out that if something as apparently unlikely as Hawking's initials can be found in the CMB data, then the chances of finding other apparently improbable patterns may also be quite high.



Stephen Hawkings leaves his mark (Image: NASA/WMAP Science Team)

Matter Distribution Agrees with Double Dark Theory!



Cosmological Simulations

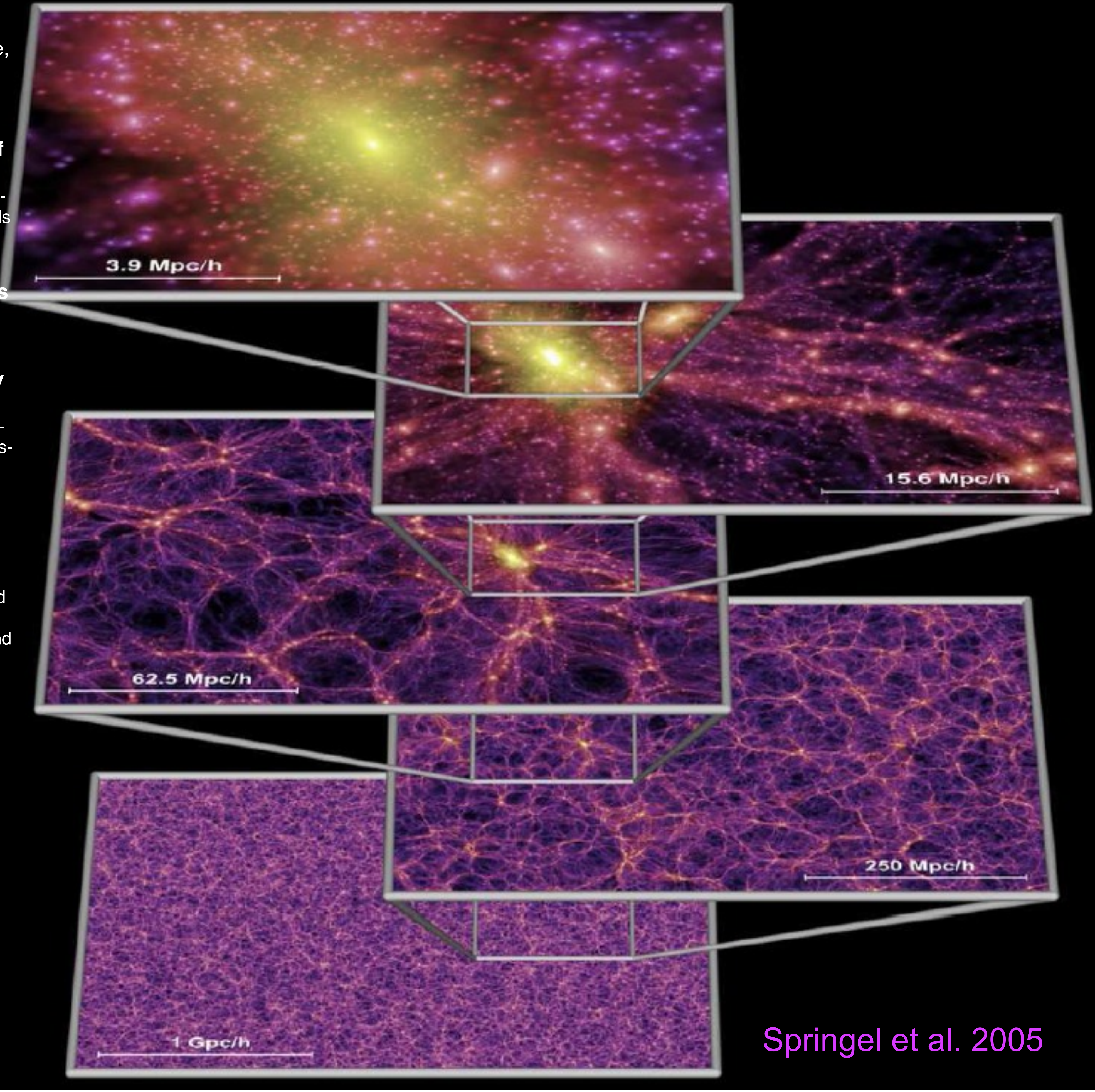
Astronomical observations represent snapshots of moments in time. It is the role of astrophysical theory to produce movies -- both metaphorical and actual -- that link these snapshots together into a coherent physical theory.

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

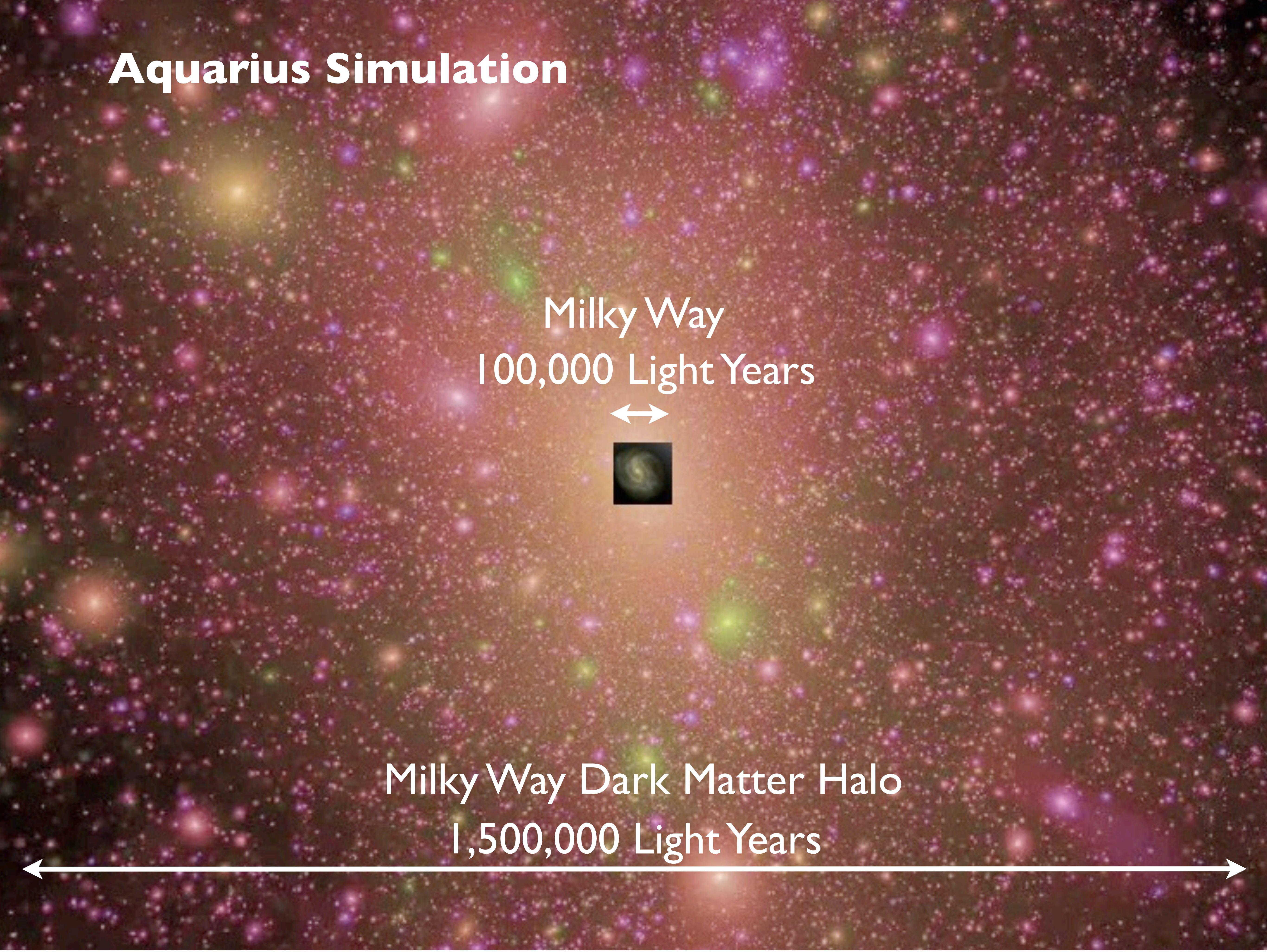
- **properties of halos** (radial profile, concentration, shapes)
- **evolution of the number density of halos**, essential for normalization of Press-Schechter- type models
- **evolution of the distribution and clustering of halos** in real and redshift space, for comparison with observations
- **accretion history of halos**, assembly bias (variation of large-scale clustering with assembly 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.

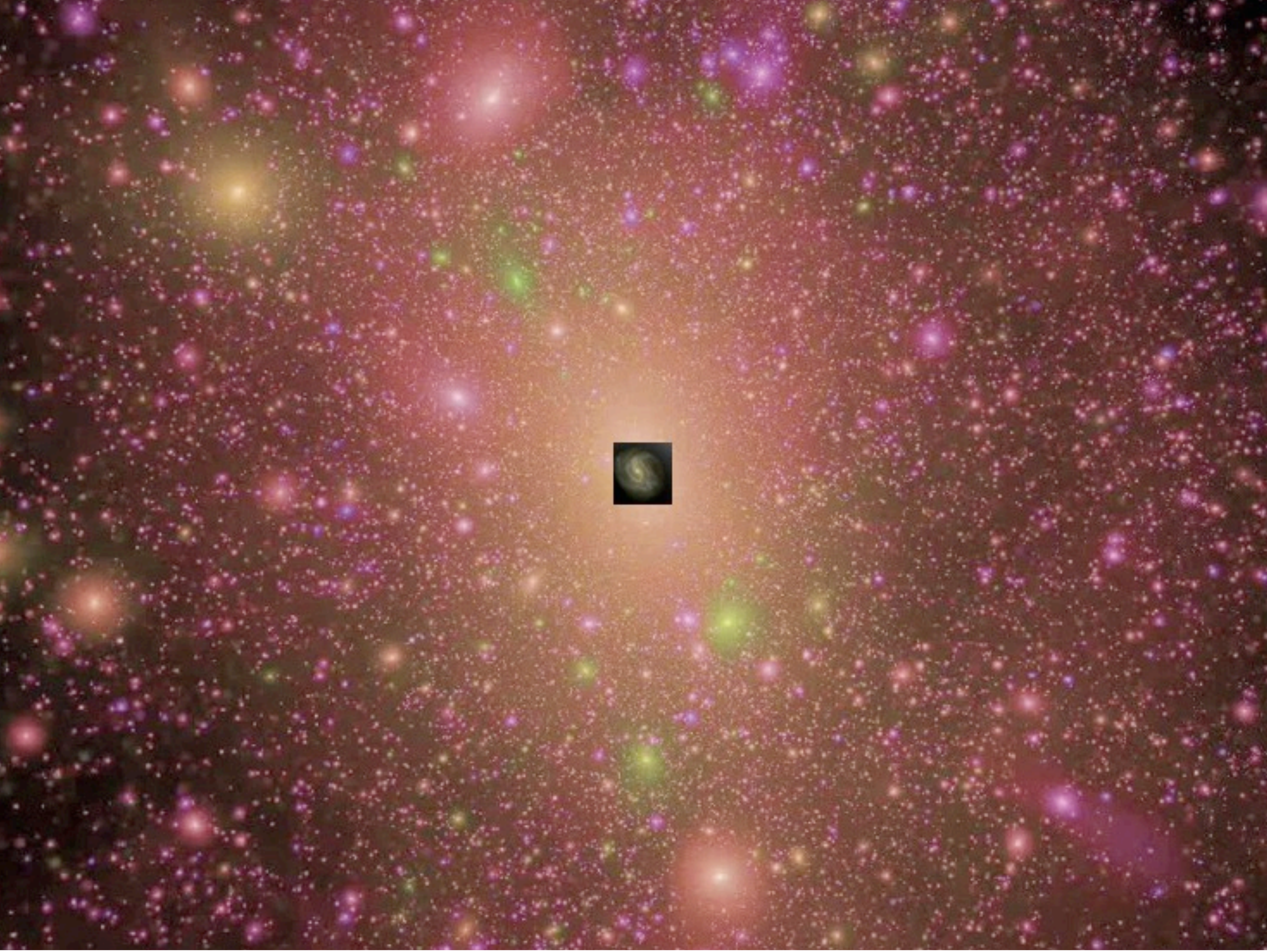
Springel et al. 2005

Aquarius Simulation

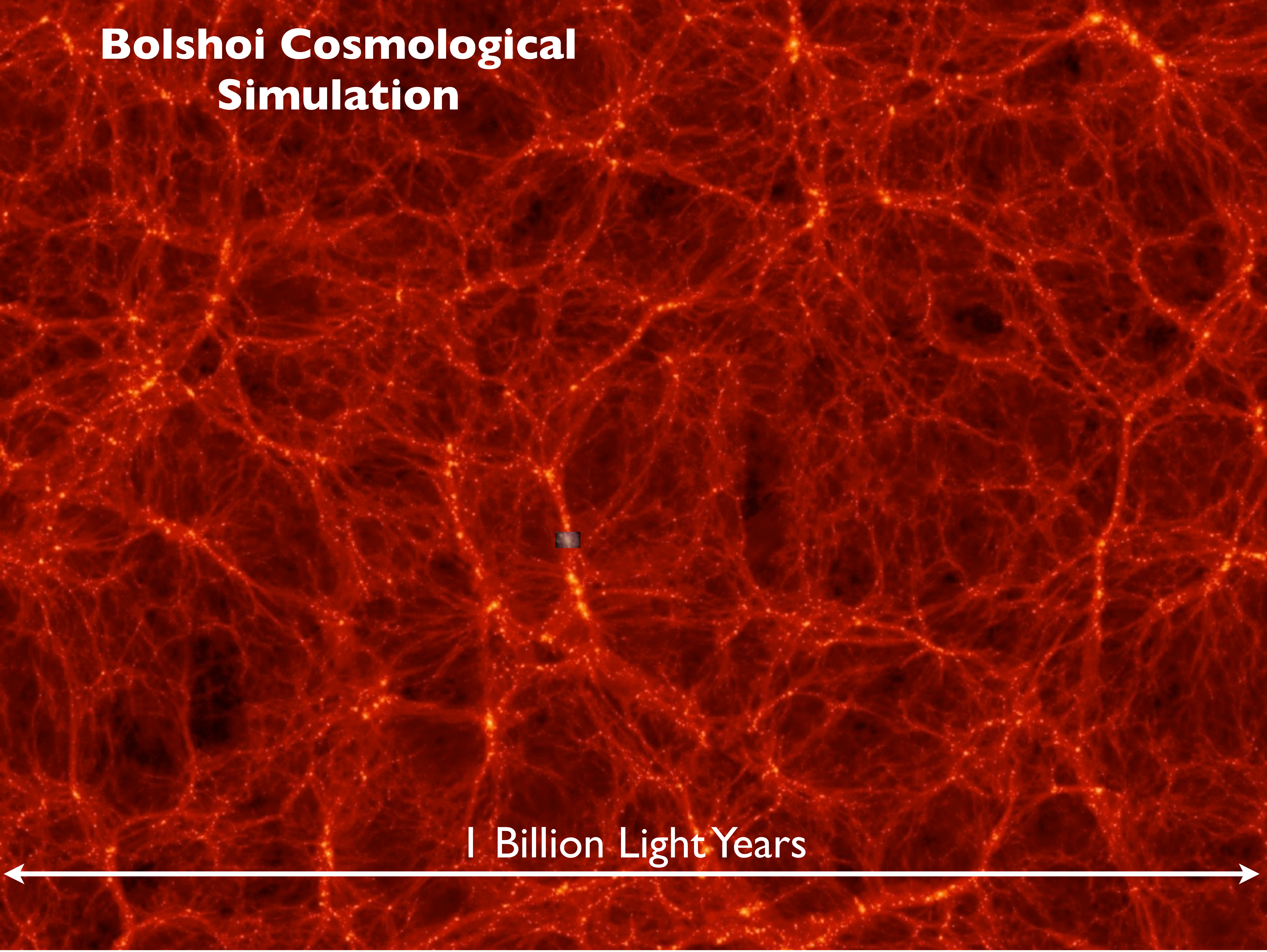


Milky Way
100,000 Light Years

Milky Way Dark Matter Halo
1,500,000 Light Years



Bolshoi Cosmological Simulation



The Bolshoi simulation

ART code

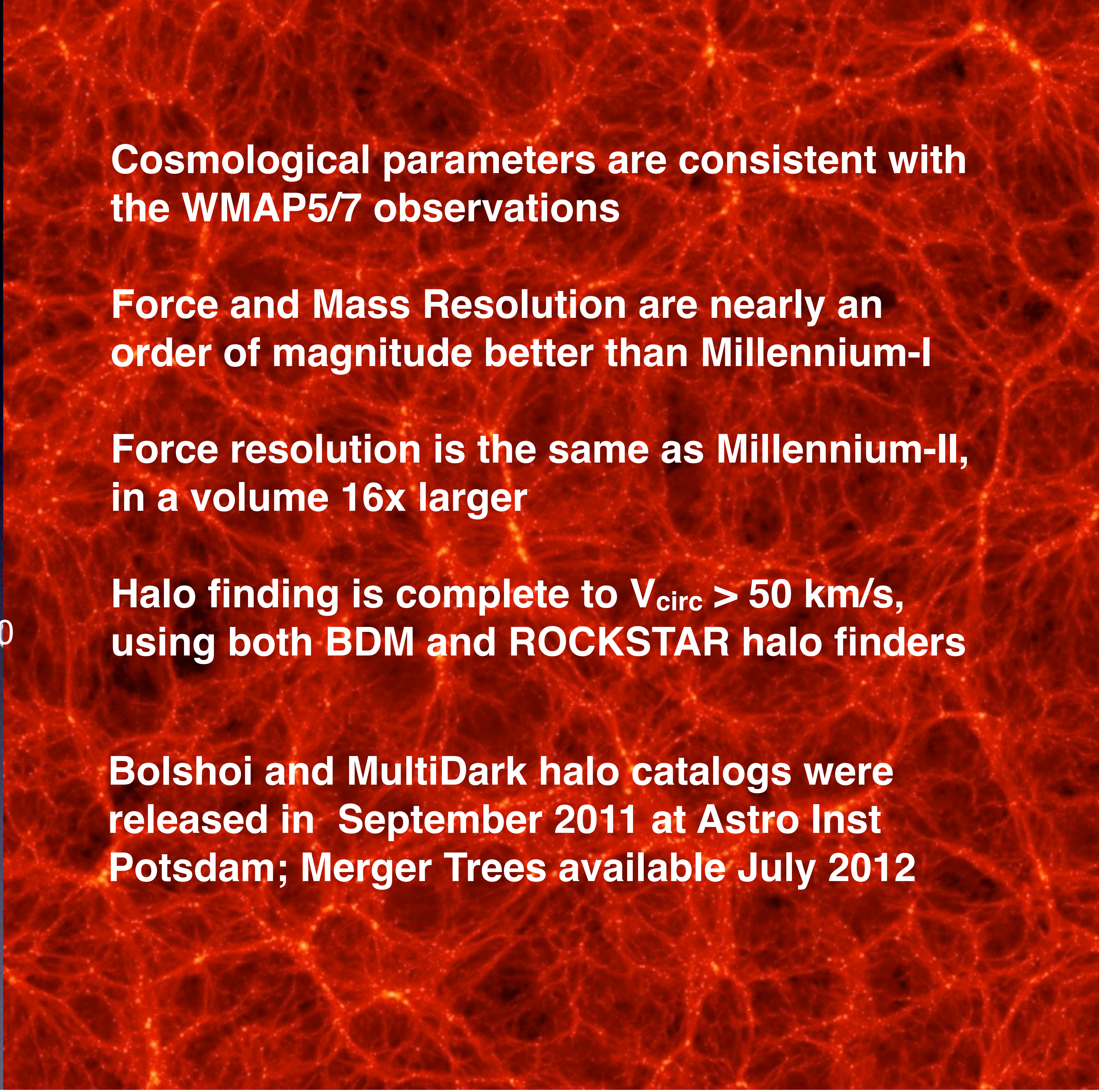
250Mpc/h Box
LCDM

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 WMAP5/7 observations

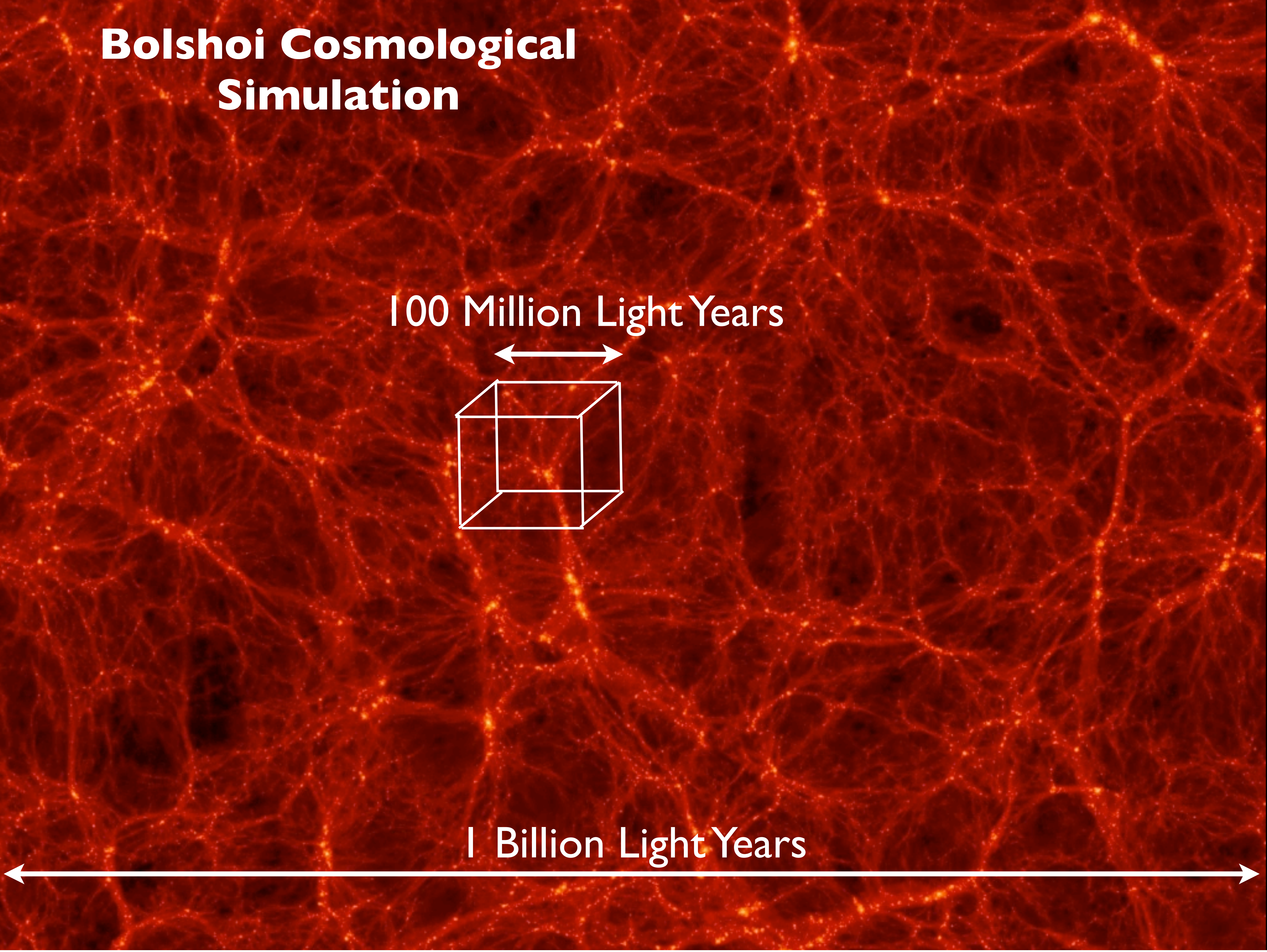
Force and Mass Resolution are nearly an order of magnitude better than Millennium-I

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



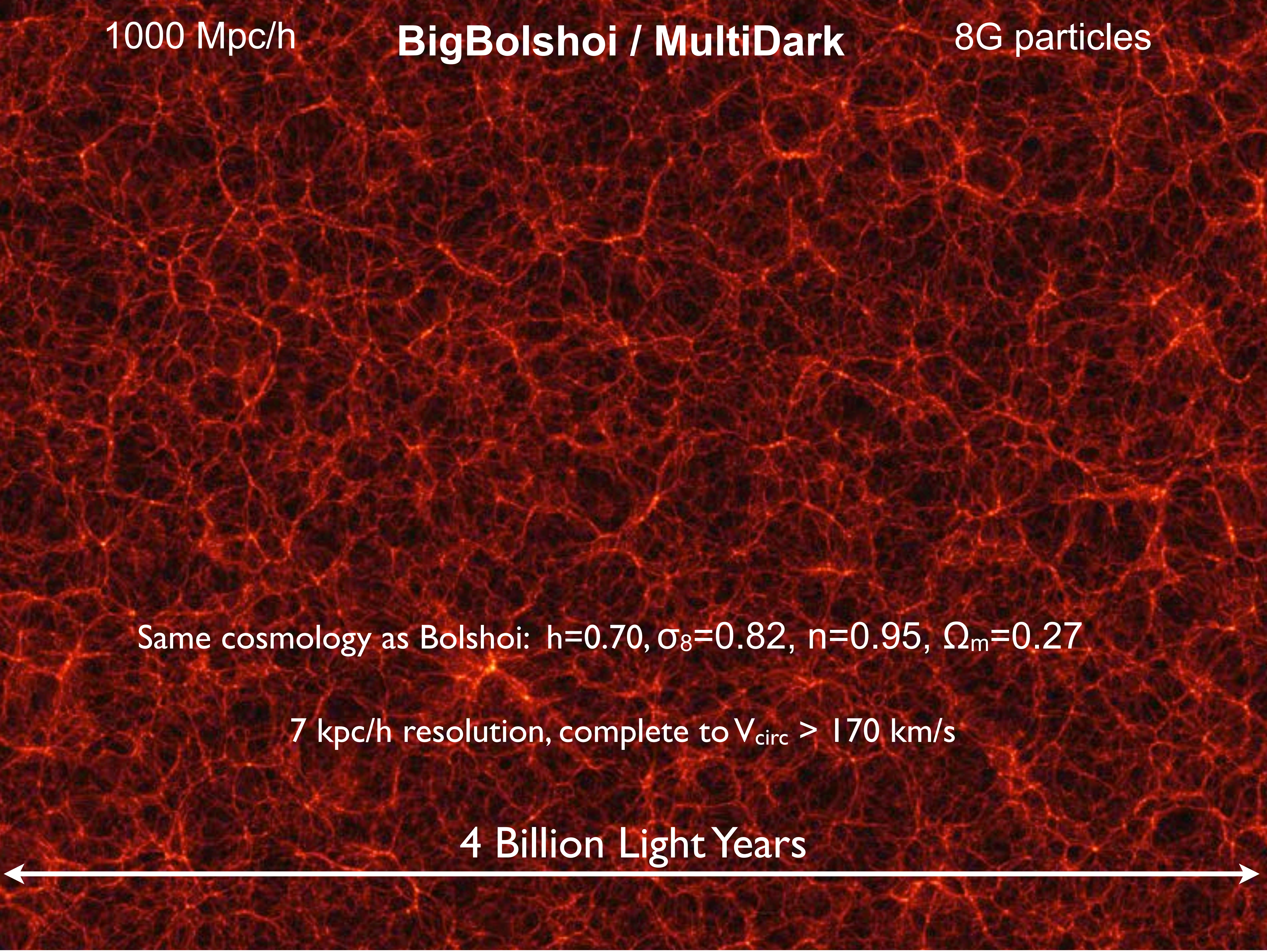
BOLSHOI SIMULATION FLY-THROUGH

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

Bolshoi Merger Tree for the Formation of a Big Cluster Halo

```
Time: 13664 Myr Ago
Timestep Redshift: 14.083
Radius Mode: Rvir
Focus Distance: 6.1
Aperture: 40.0
World Rotation: (216.7, 0.06, -0.94, -0.34)
Trackball Rotation: (0.0, 0.00, 0.00, 0.00)
Camera Position: (0.0, 0.0, -6.1)
```

Peter Behroozi



1000 Mpc/h

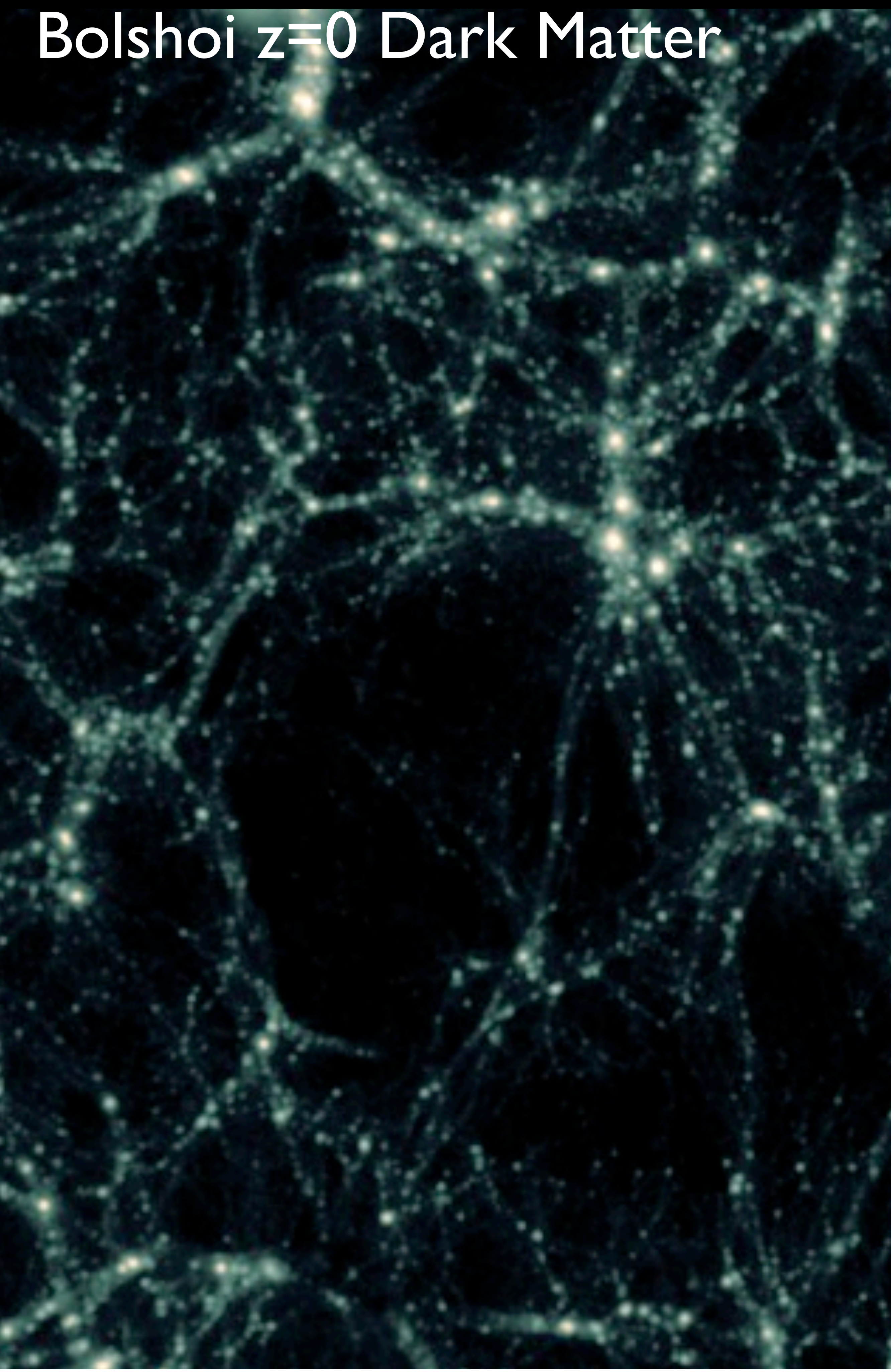
BigBolshoi / MultiDark

8G particles

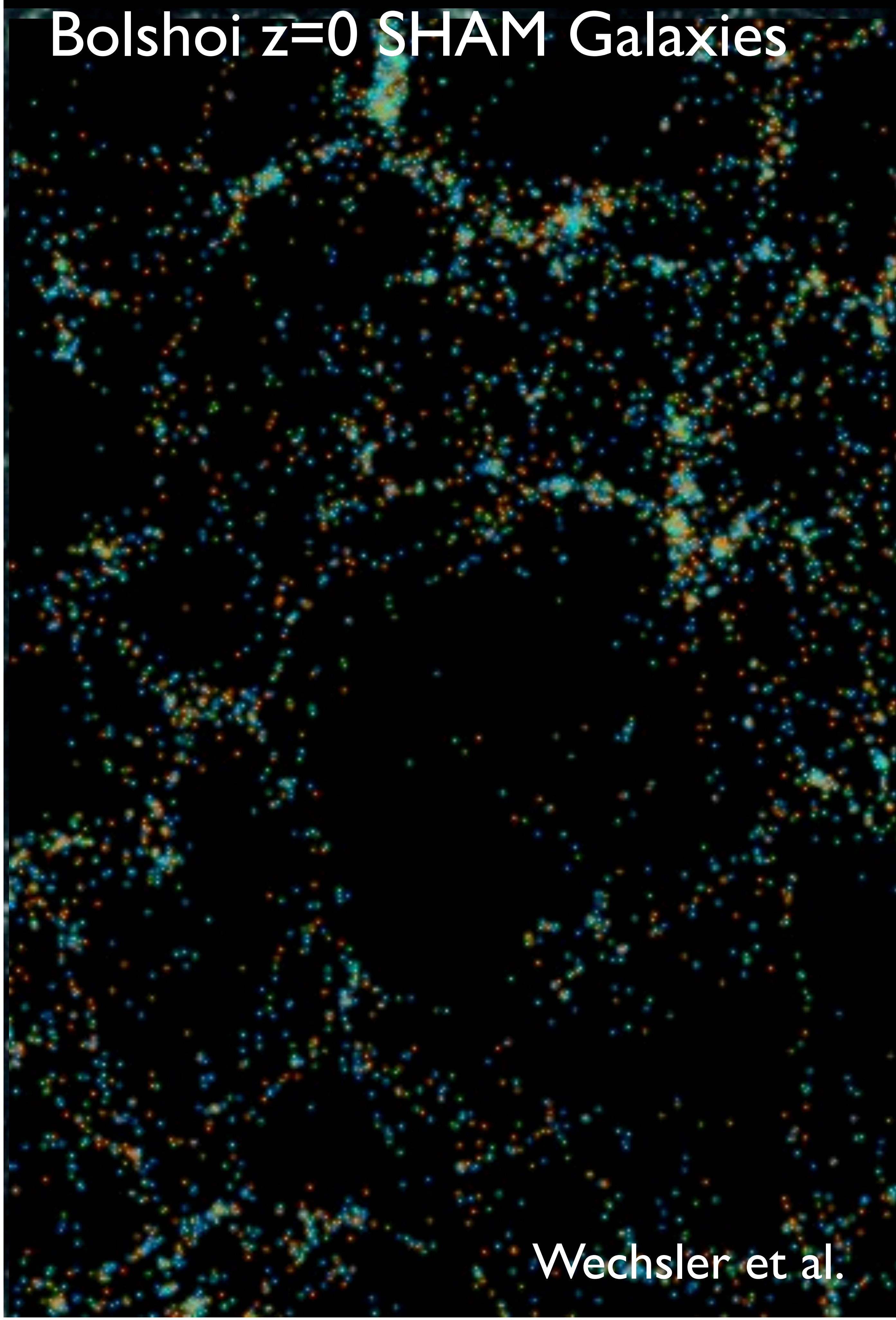
Same cosmology as Bolshoi: $h=0.70$, $\sigma_8=0.82$, $n=0.95$, $\Omega_m=0.27$

7 kpc/h resolution, complete to $V_{circ} > 170$ km/s

4 Billion Light Years



Bolshoi z=0 Dark Matter



Bolshoi z=0 SHAM Galaxies

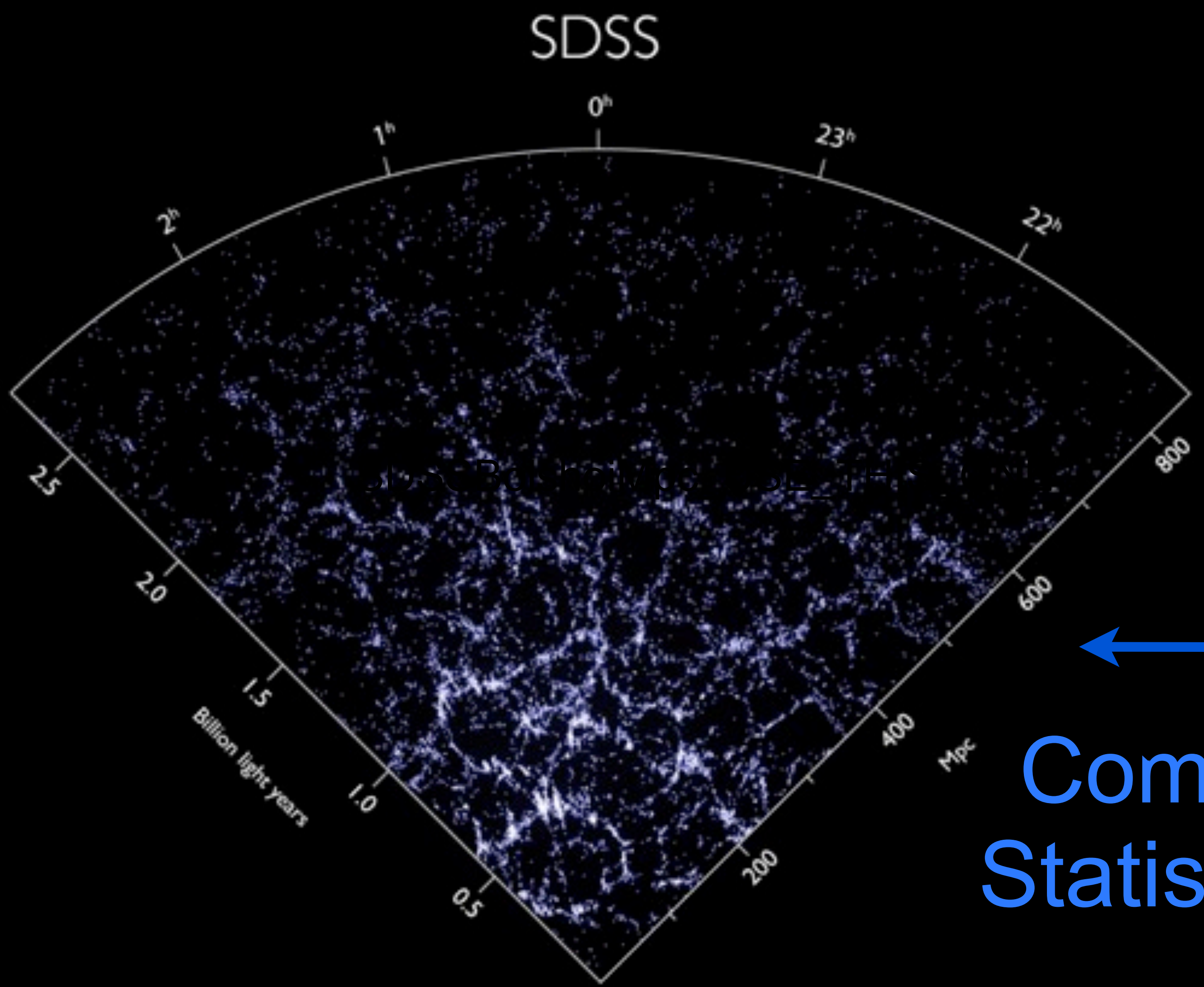
Wechsler et al.

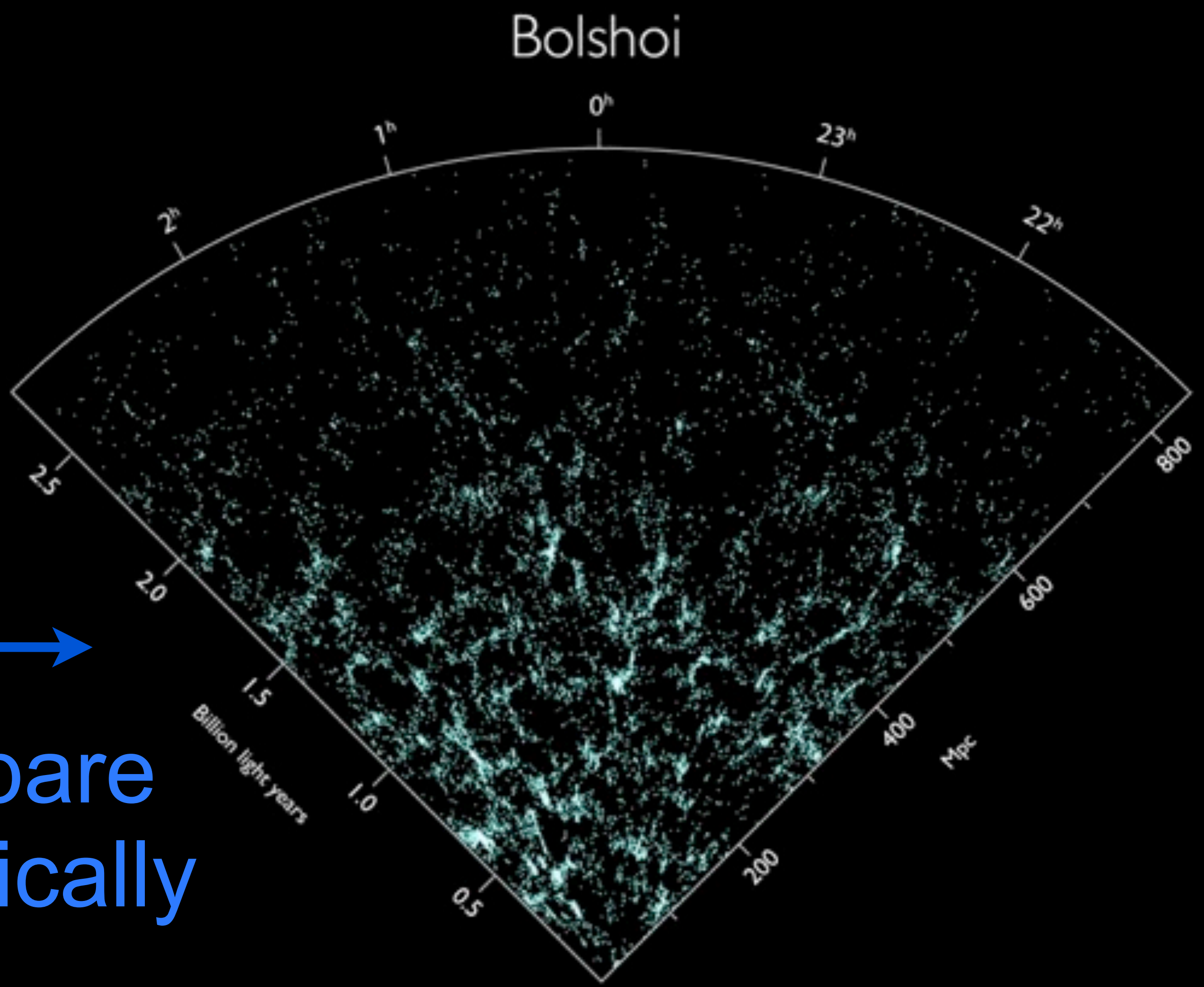
Observational Data

Sloan Digital Sky Survey

Cosmological Simulation

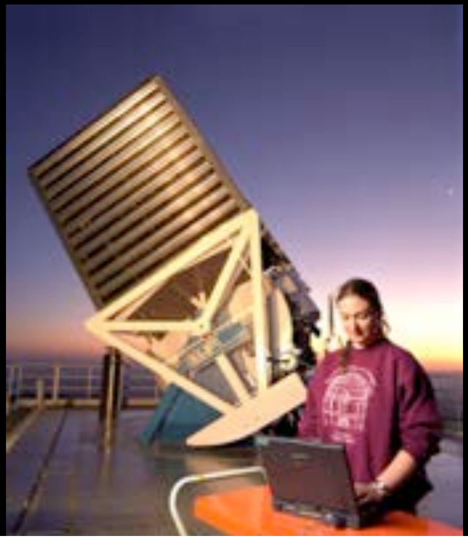
Risa Wechsler, Ralf Kahler, Nina McCurdy

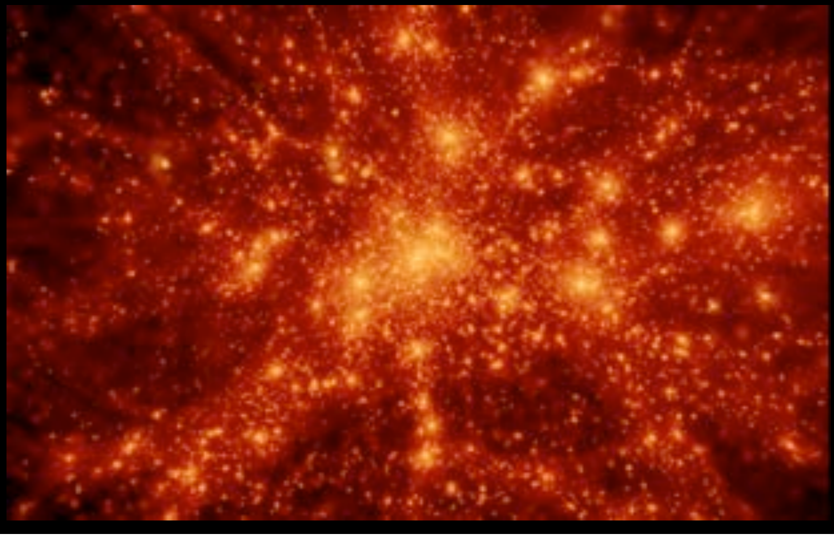




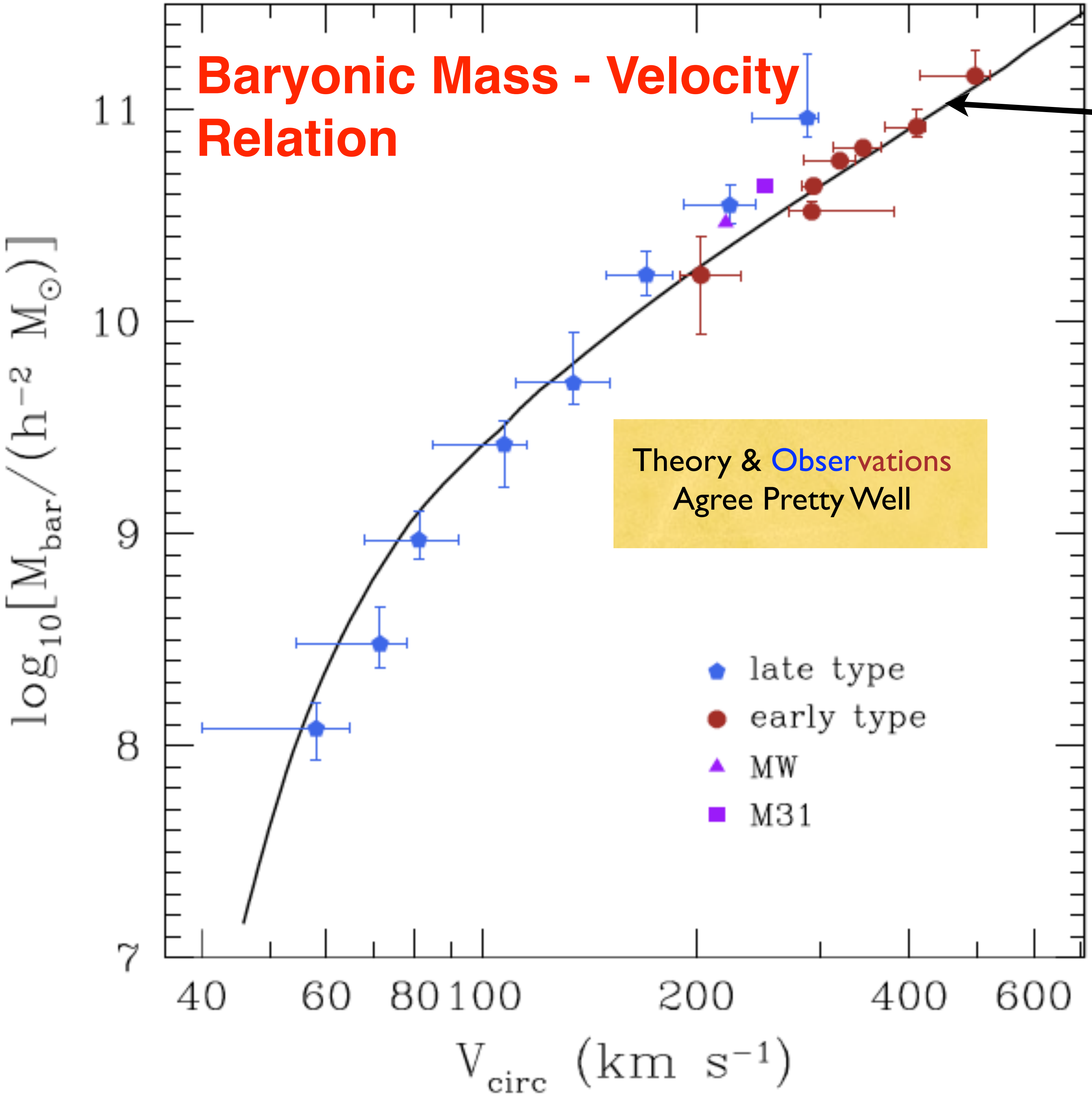
↔

Compare Statistically





Bolshoi Sub-Halo Abundance Matching



Theory & Observations Agree Pretty Well

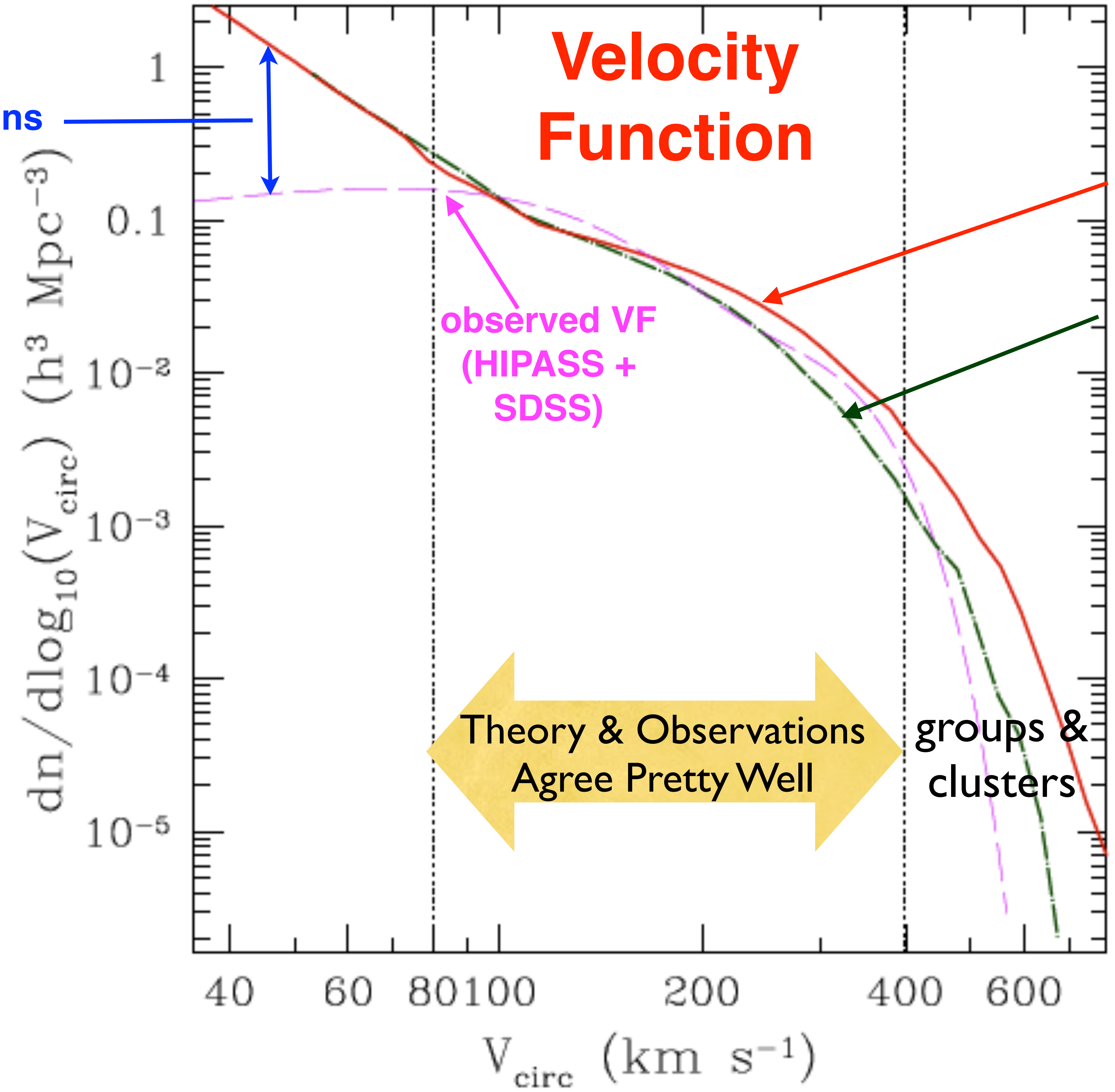
median Vcirc with baryons and AC (halo Adiabatic Contraction)

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

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.

Bolshoi Sub-Halo Abundance Matching

Velocity Function



Discrepancy due to incomplete observations or ΛCDM failure?

observed VF (HIPASS + SDSS)

theoretical VF with AC

theoretical VF without AC

Theory & Observations Agree Pretty Well

groups & clusters

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.

Presented at KITP Conf "First Light and Faintest Dwarfs" Feb 2012 and UCSC Galaxy Workshop Aug 2012

Klypin, Karachentsev, Nasonova 2012

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

Local Volume: D <10 Mpc

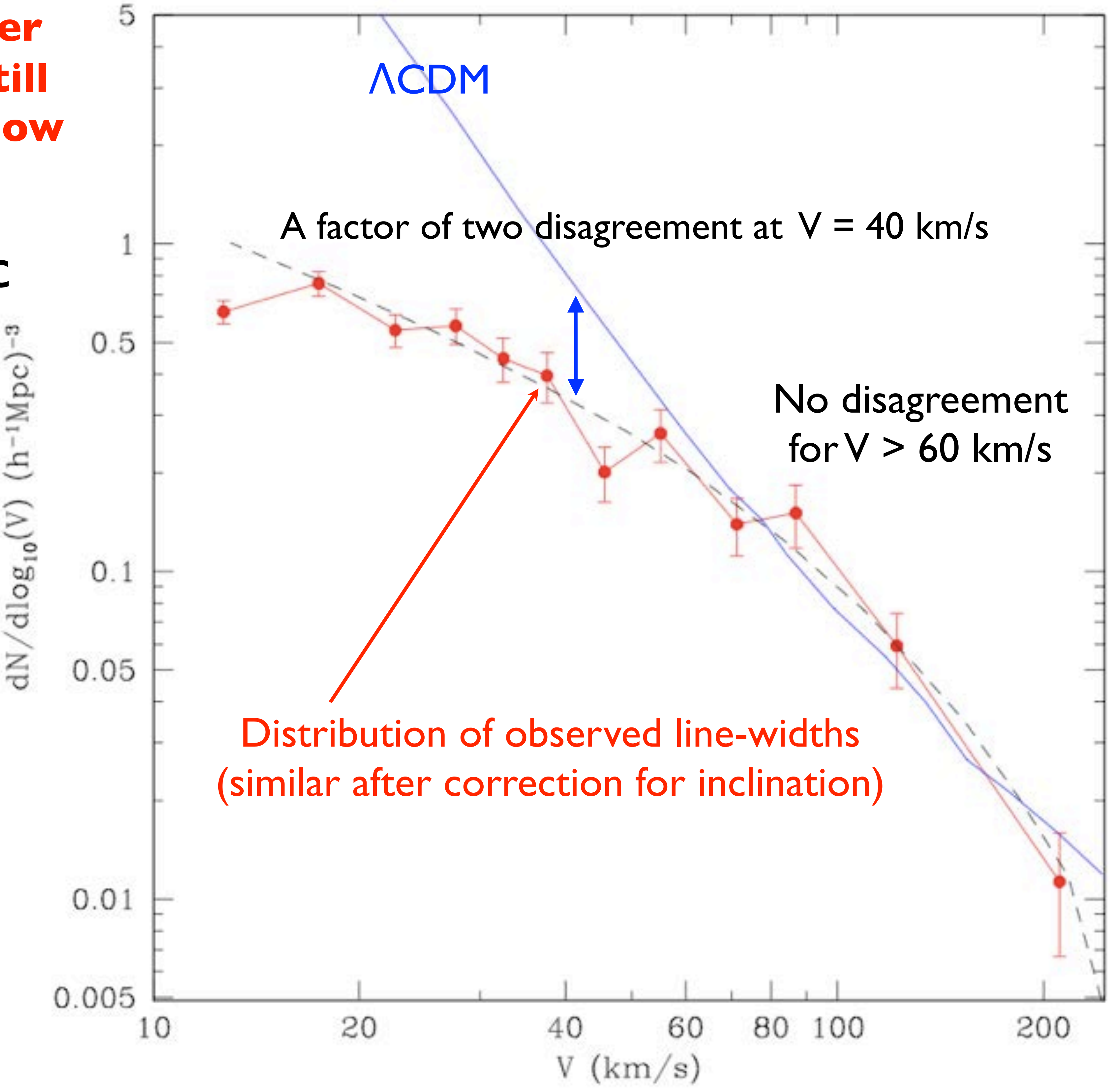
Total sample: 813 galaxies
Within 10 Mpc: 686
M_B<-13 N=304
M_B<-10 N=611

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



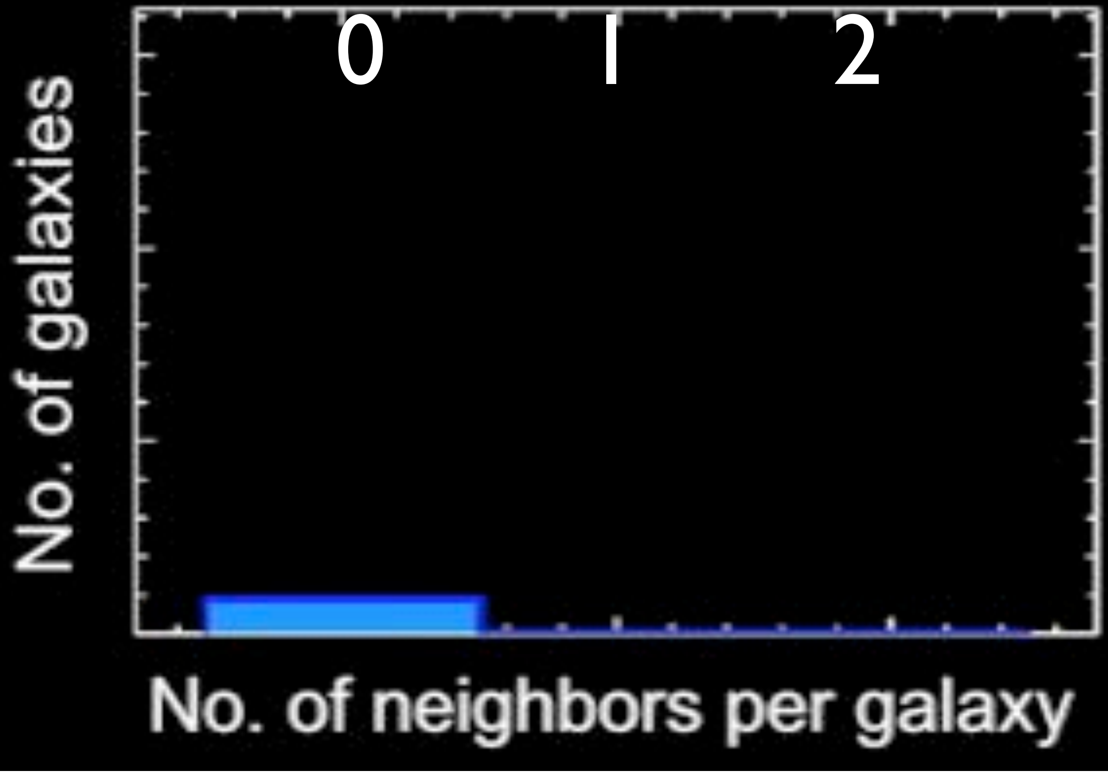
The Milky Way has two large satellite galaxies, the small and large Magellanic Clouds

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


SDSS sky
E
W
S


Bolshoi simulation

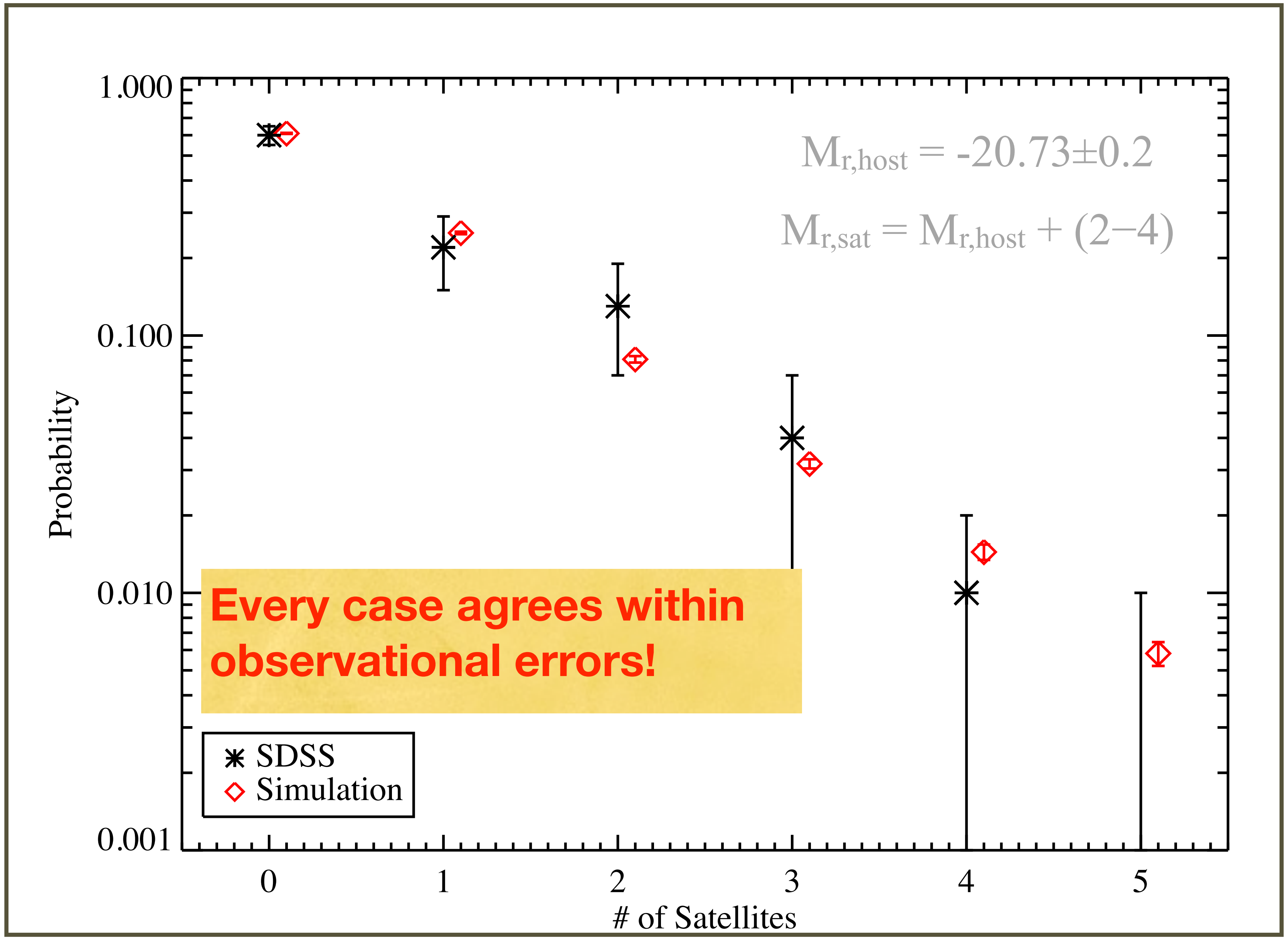

0
1
2
No. of galaxies
No. of neighbors per galaxy


0
1
2
No. of galaxies
No. of neighbors per galaxy

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

- Apply the same absolute magnitude and isolation cuts to Bolshoi+SHAM galaxies as to SDSS:
  - Identify all objects with absolute $^{0.1}M_r = -20.73\pm0.2$ and observed $m_r < 17.6$
  - Probe out to $z = 0.15$, a volume of roughly 500 $(\mathrm{Mpc}/h)^3$
  - 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%



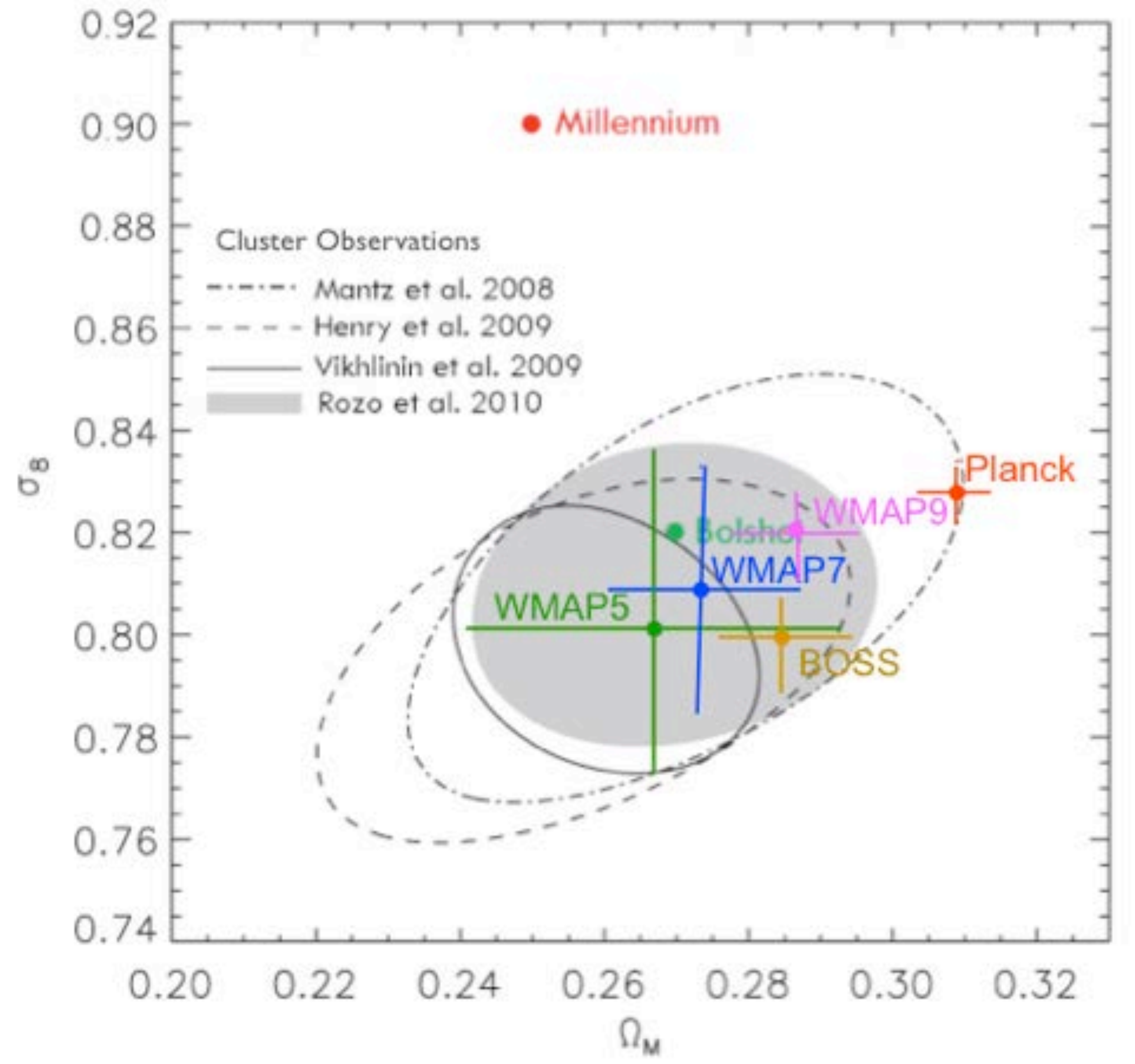
Every case agrees within observational errors!

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.

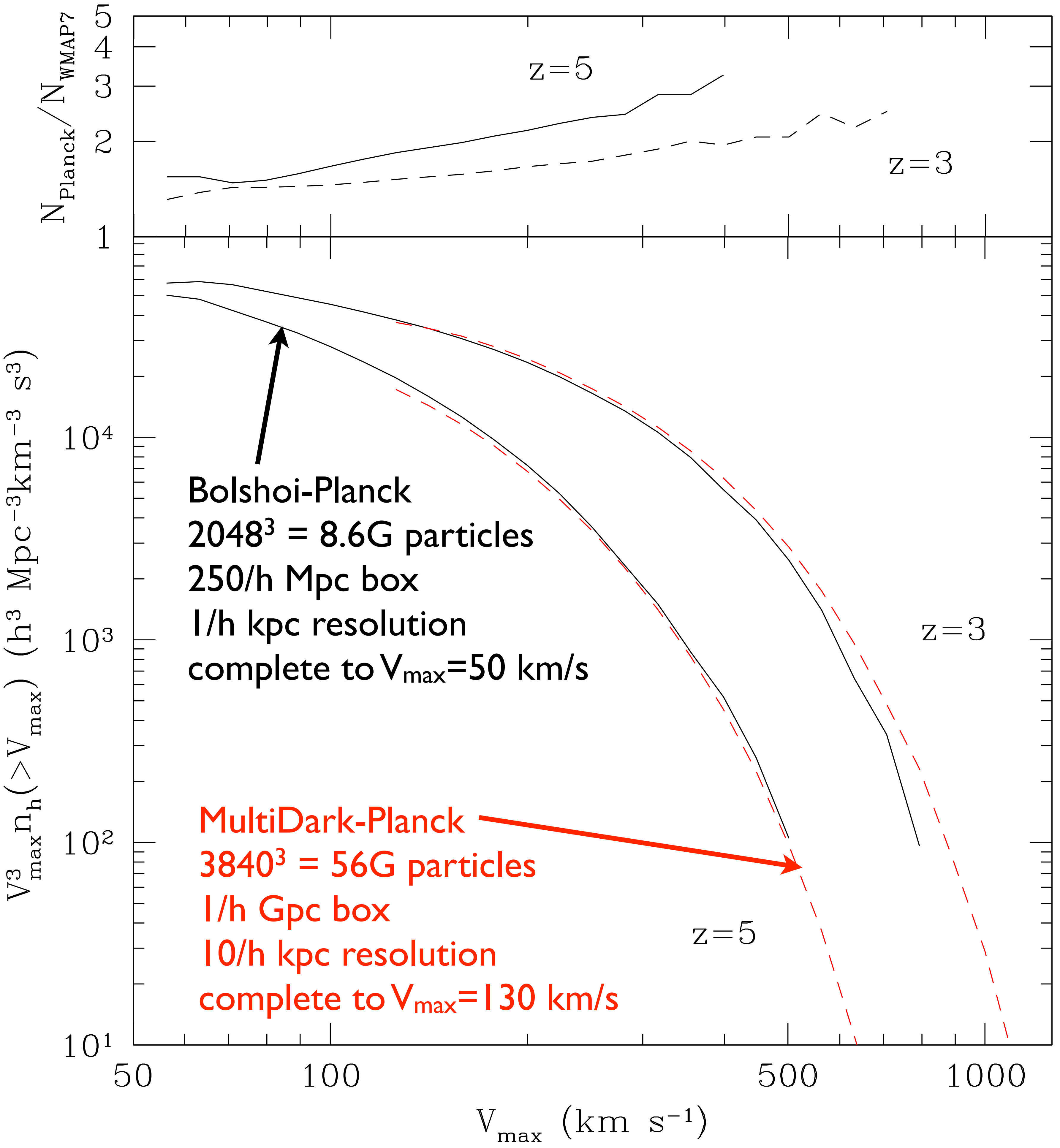
Bolshoi-Planck Cosmological Simulation

Anatoly Klypin & Joel Primack
Finished 8/6/13 on Pleiades computer
at NASA Ames Research Center
$8.6\text{x}10^9$ particles   1/h kpc resolution
analysis by Peter Behroozi



1 Billion Light Years

Bolshoi-Planck has a lot more massive halos at high redshifts than Bolshoi!



Bolshoi-Planck
2048^3 = 8.6G particles
250/h Mpc box
1/h kpc resolution
complete to $V_{\rm max}$=50 km/s

MultiDark-Planck
3840^3 = 56G particles
1/h Gpc box
10/h kpc resolution
complete to $V_{\rm max}$=130 km/s

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

↓

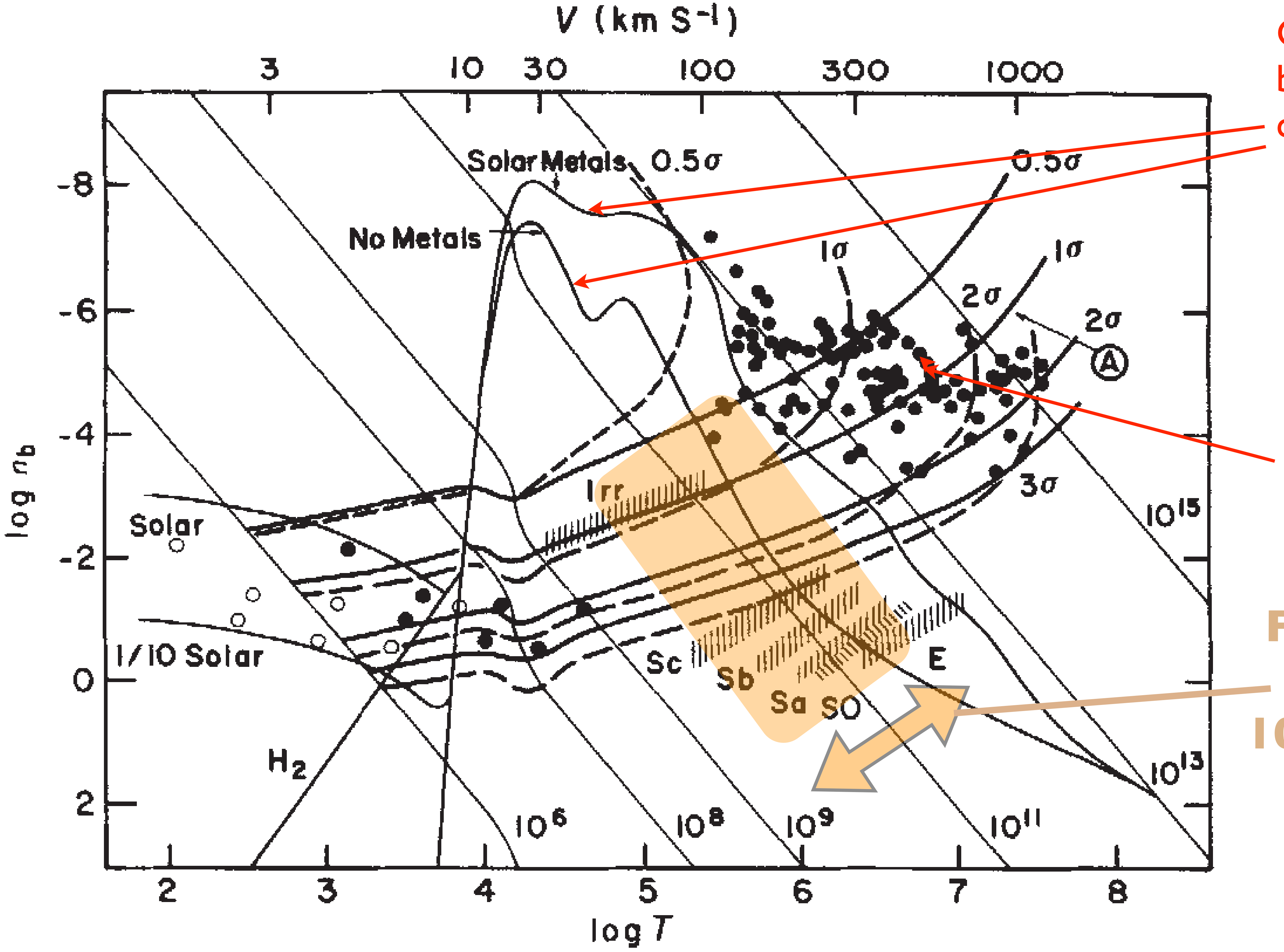
current stellar population

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 about 10^{11} - $10^{12.5}$ $M_\odot$**. 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)

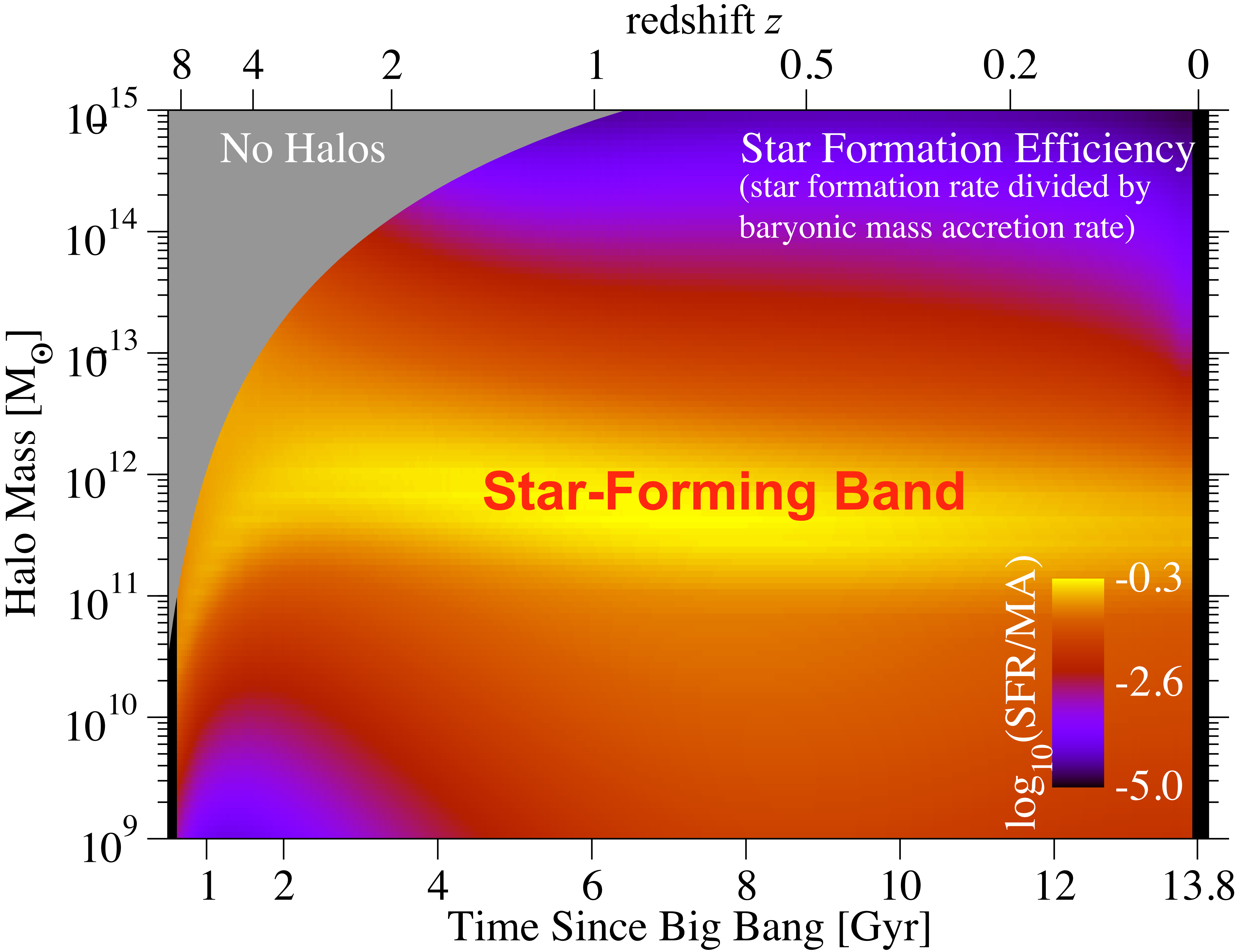


Galaxies form beneath the cooling curves

Galaxy groups and clusters form above the cooling curves

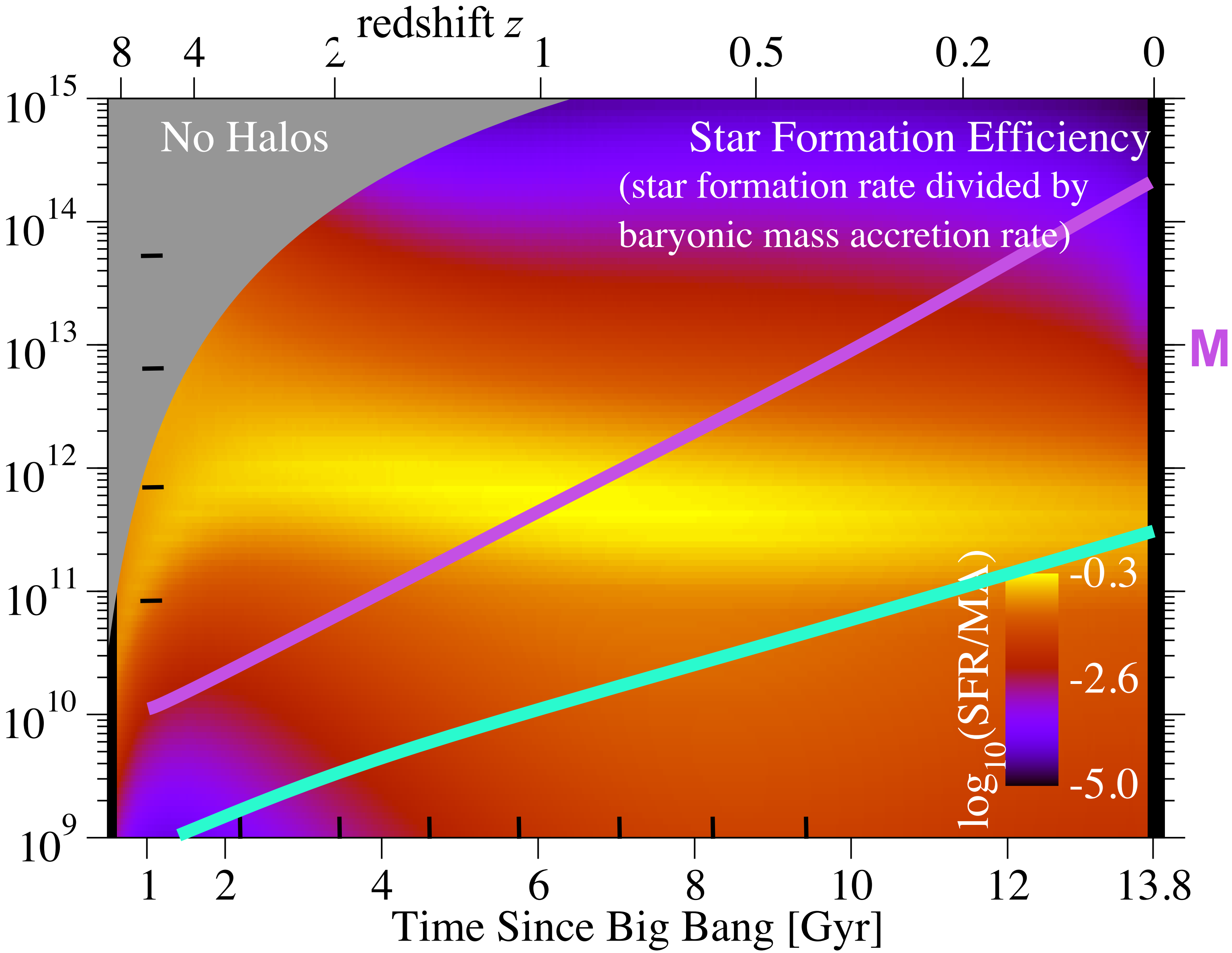
Star Forming Band: 10^{10} - 10^{12} Msun

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:

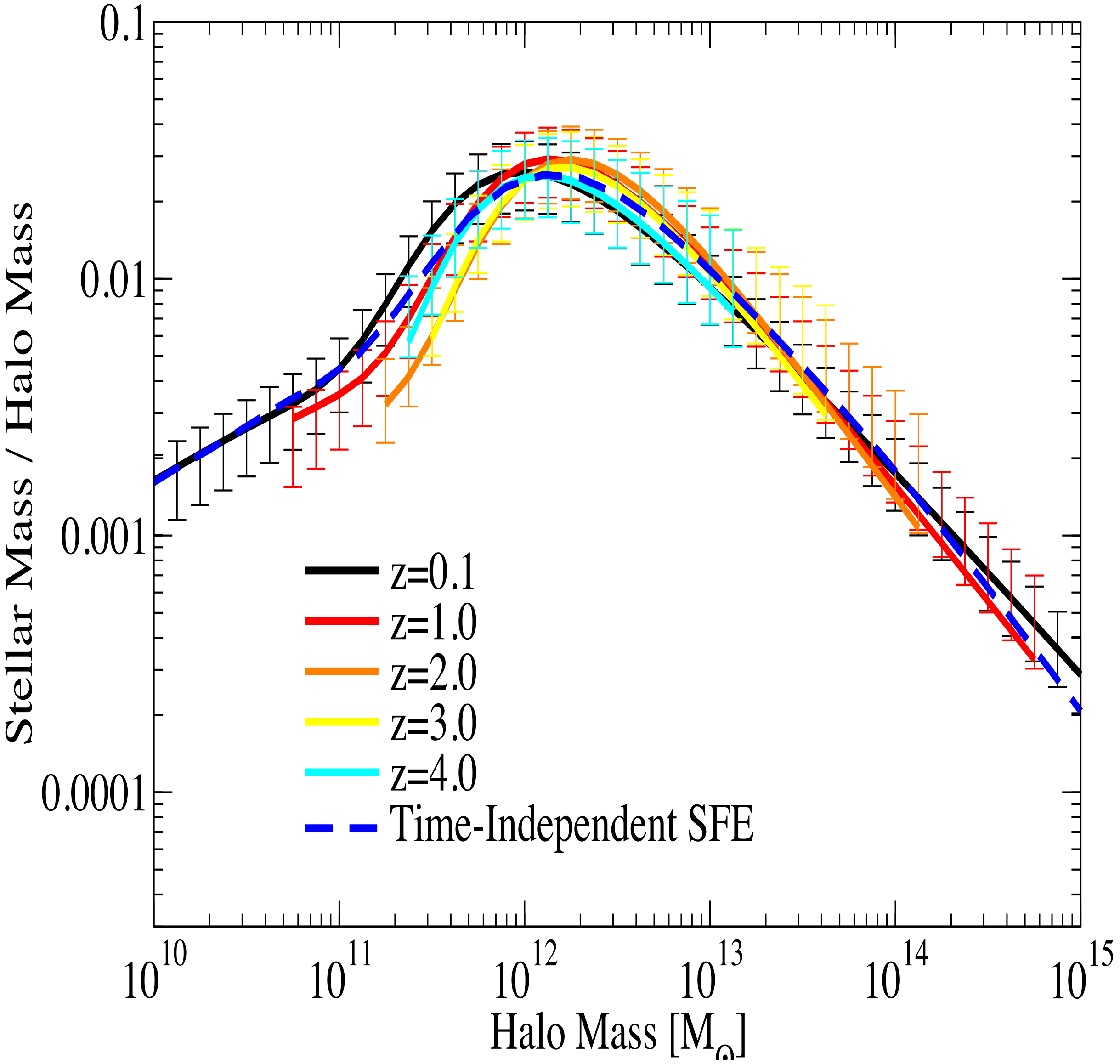
- Started forming stars late.
- Are still making stars today.
- Are blue today.
- Populate dark halos that scale with their stellar mass.

"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)

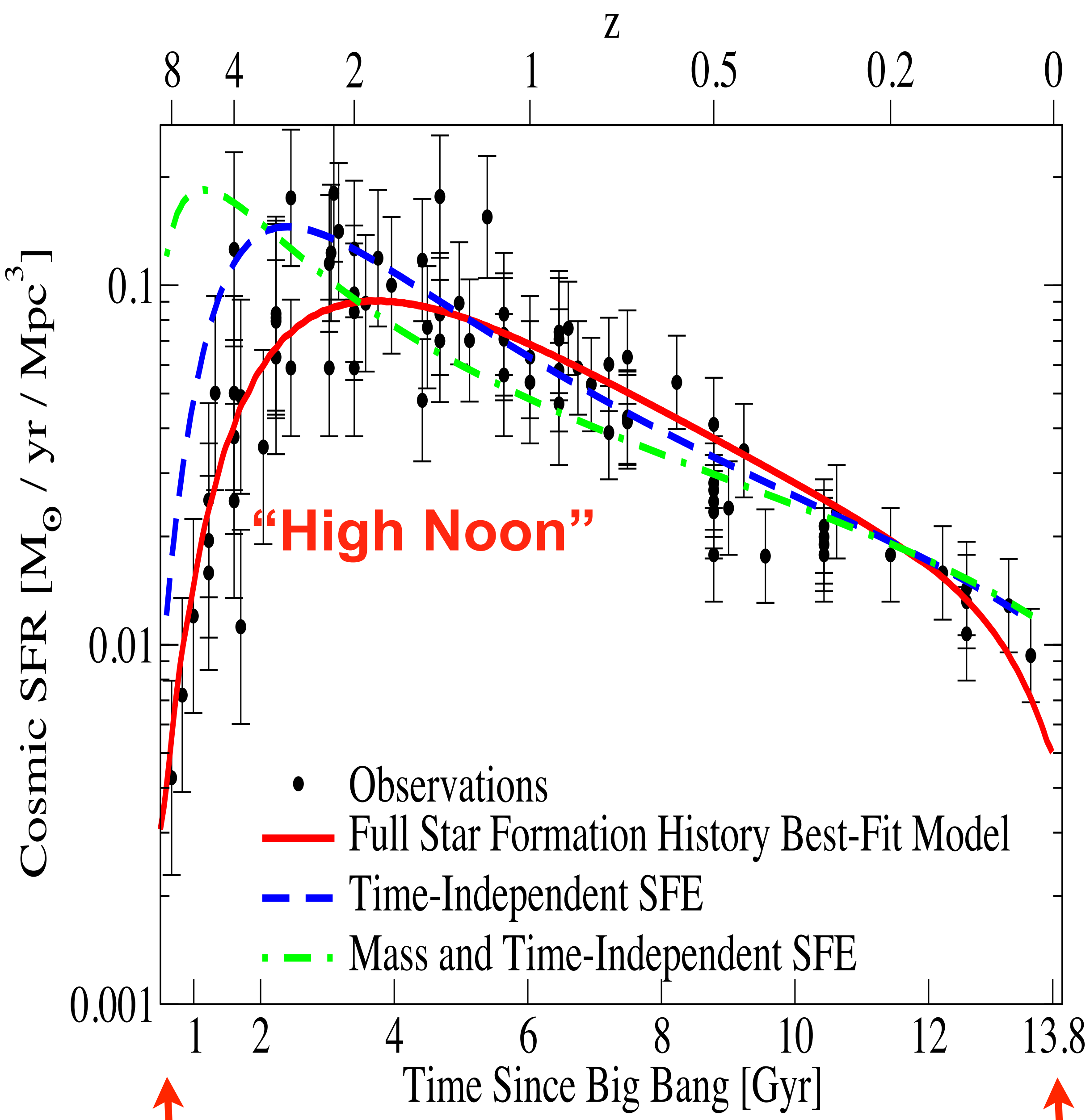
Inefficient Star-Formation



Highest stellar mass fraction (~3%) for Milky Way mass halos, for which stars are ~ 20% of baryons.

Cosmic baryon fraction = 0.045/0.31 = 14%
Milky Way M^*/M_{halo} = 0.2 x 14% = 3%

Star-Formation History



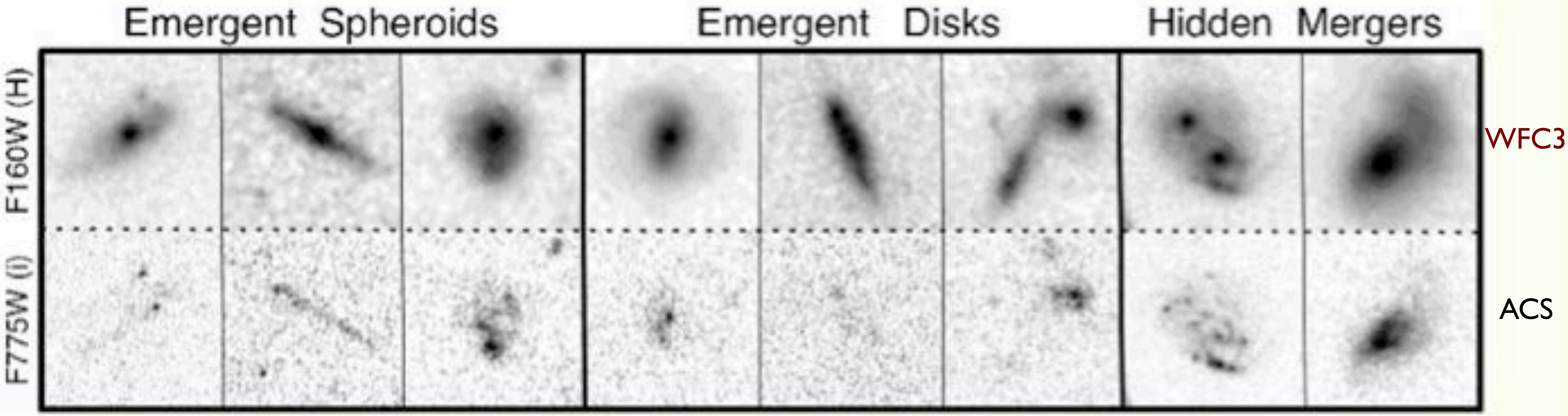
"Cosmic Dawn"

Today

Behroozi, Wechsler, Conroy ApJL, 762, L31 (2013)

The CANDELS Survey with new near-ir camera WFC3

GALAXIES ~10 BILLION YEARS AGO



CANDELS makes use of the near-infrared WFC3 camera (top row) and the visible-light ACS camera (bottom row). Using these two cameras, CANDELS will reveal new details of the distant Universe and test the reality of cosmic dark energy.

Hubble
Space
Telescope

http://candels.ucolick.org

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.

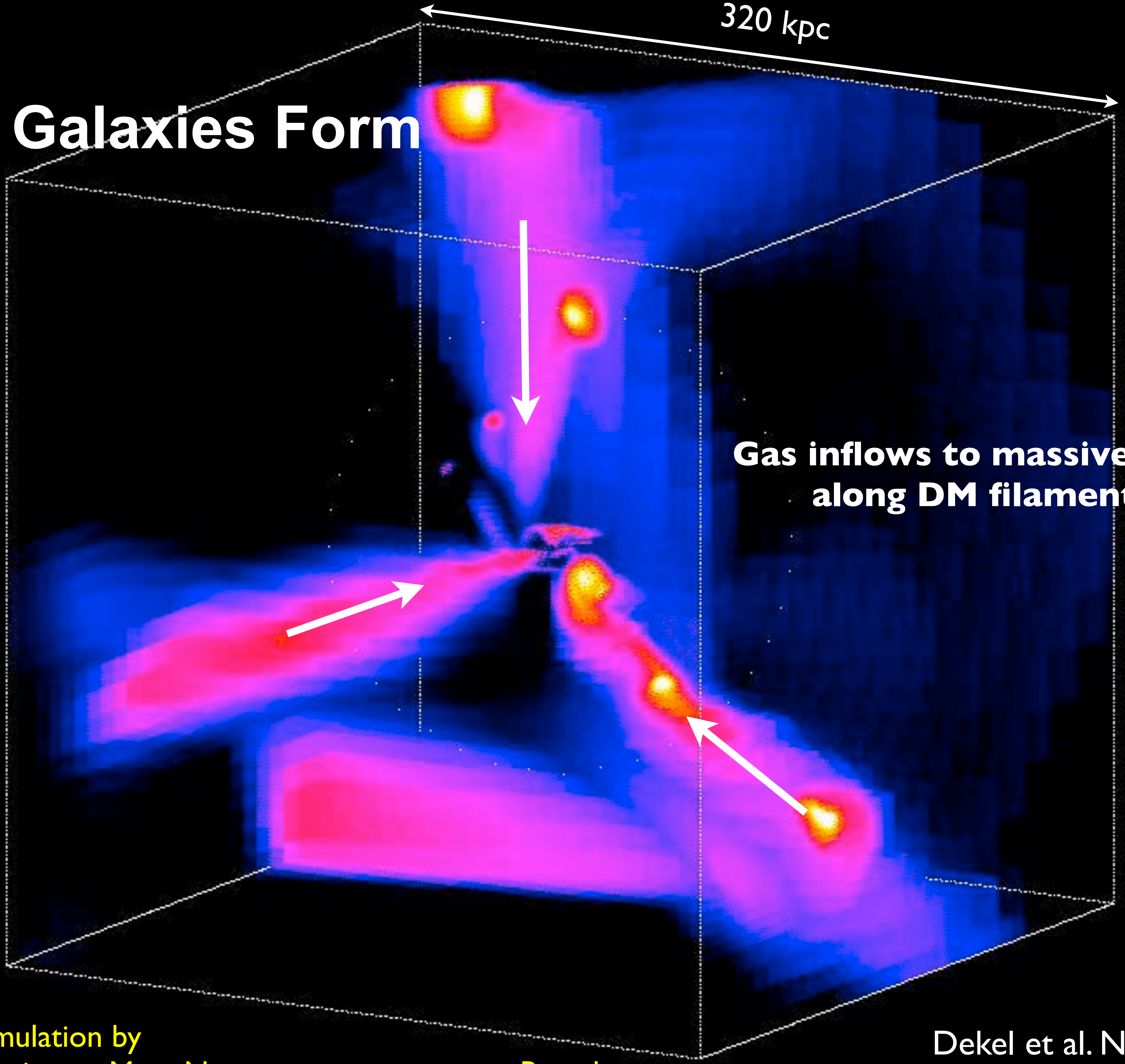
Cosmological Simulations

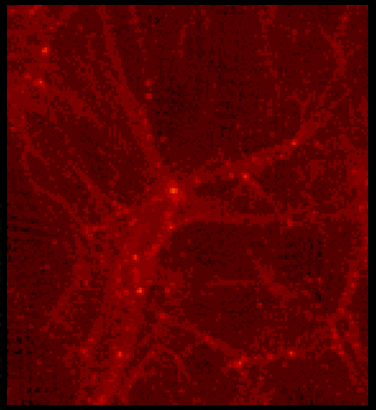
Astronomical observations represent snapshots of moments in time. It is the role of astrophysical theory to produce movies -- both metaphorical and actual -- that link these snapshots together into a coherent physical theory.

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

How Galaxies Form



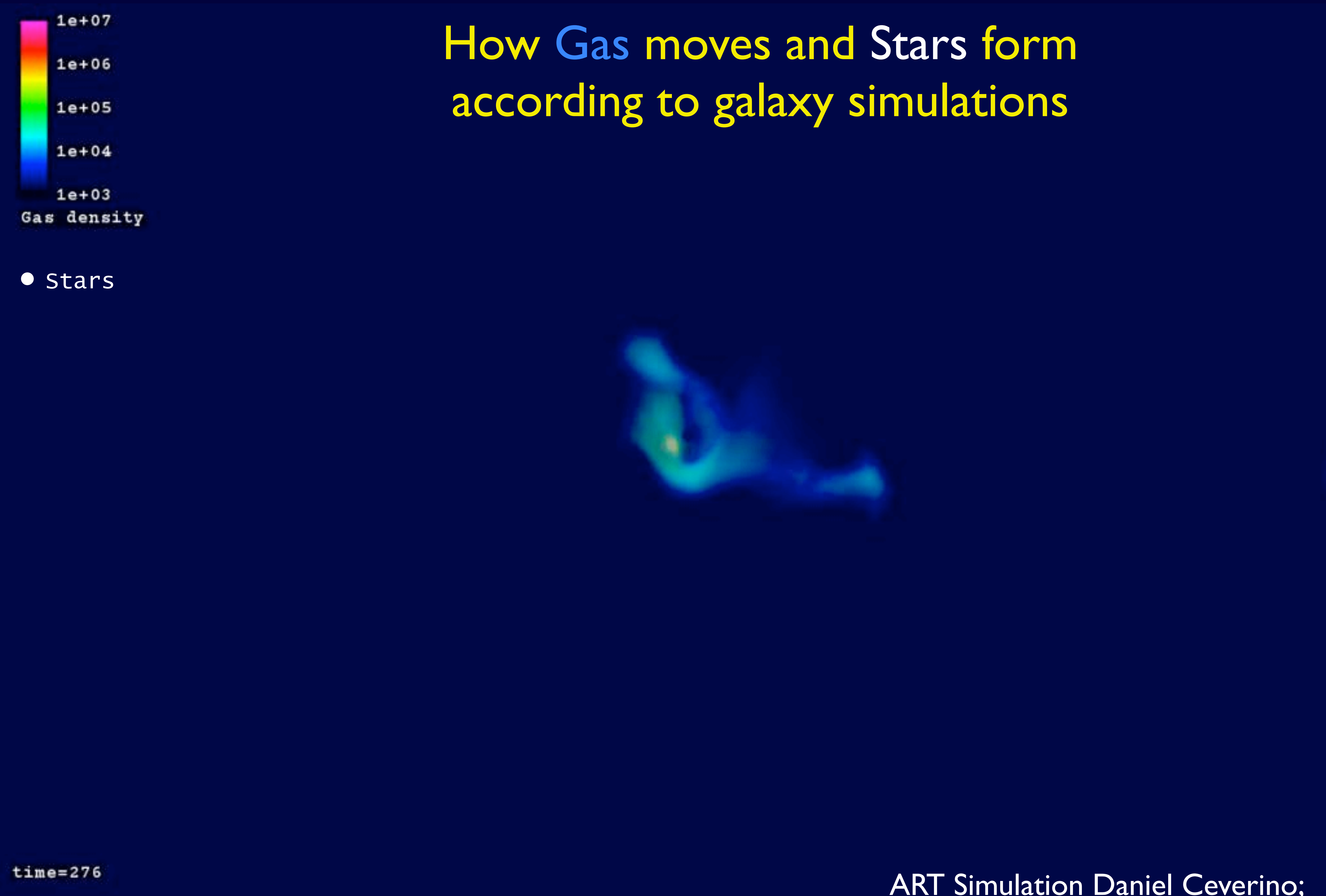


Gas inflows to massive halos along DM filaments

RAMSES simulation by
Romain Teyssier on Mare Nostrum supercomputer, Barcelona

Dekel et al. Nature 2009

How Gas moves and Stars form according to galaxy simulations

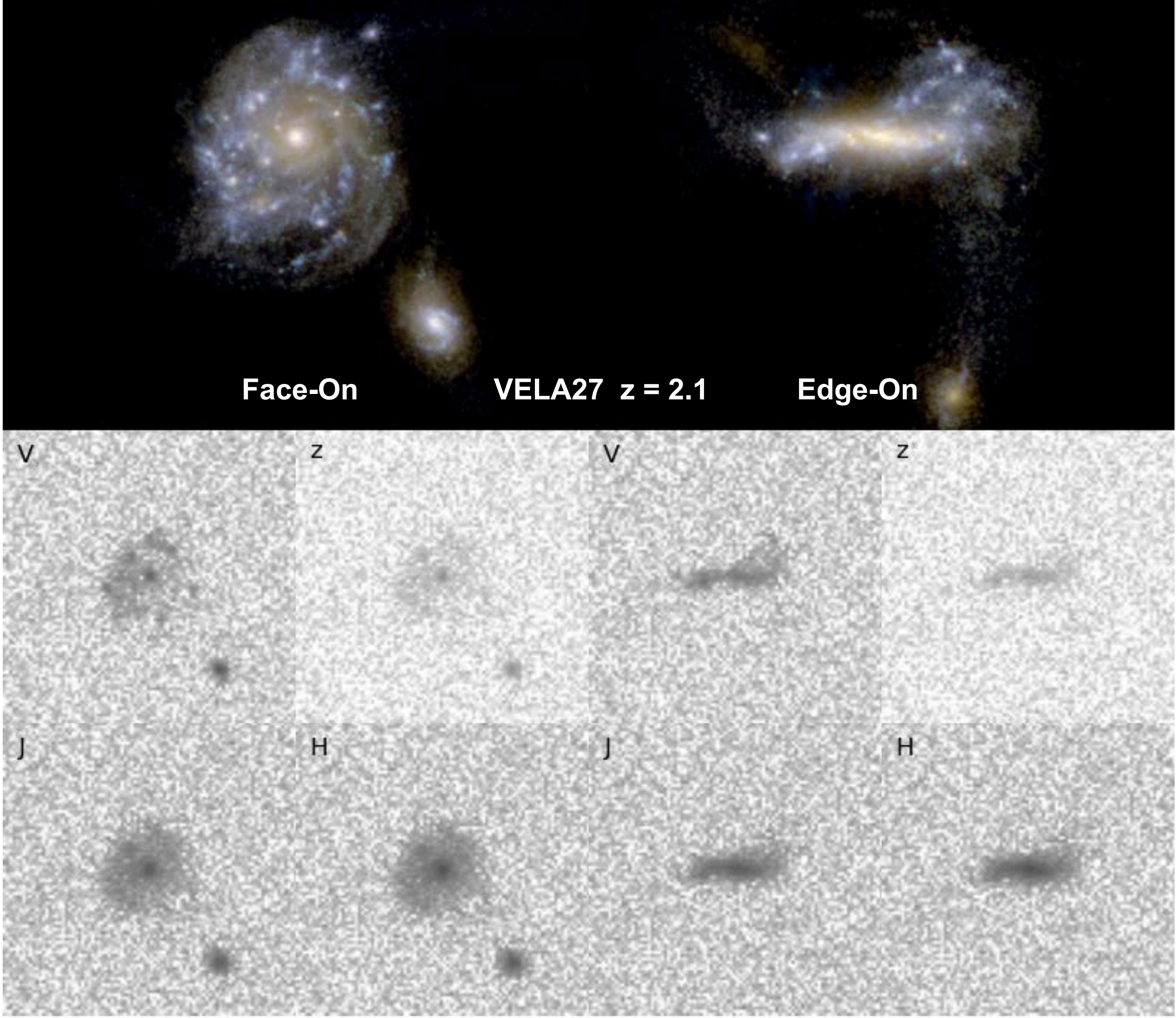


ART Simulation Daniel Ceverino;
Visualization: David Ellsworth

Simulated Galaxy 10 billion years ago (z ~ 2) as it would appear nearby to our eyes

as it would appear to Hubble's ACS visual camera

as it would appear to Hubble's WFC3 infrared camera



small scale issues

Angular momentum

The Eris simulation shows that ΛCDM simulations are increasingly able to form realistic spiral galaxies, as resolution improves and feedback becomes more realistic.

Cusps

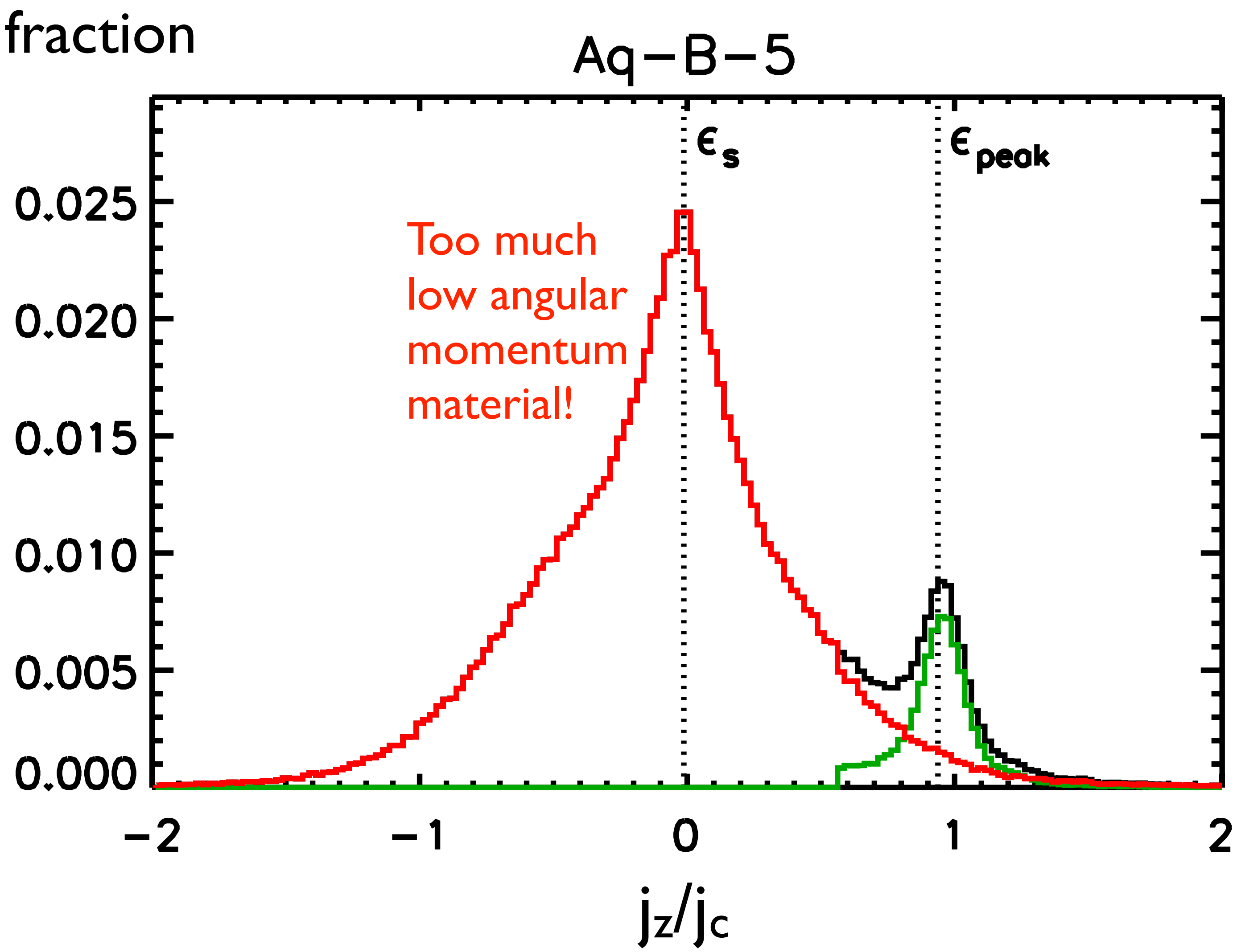
WDM doesn’t resolve cusp issues. New observations and simulations suggest that velocity structure of LSB, dSp, and dSph galaxies may be consistent with cuspy ΛCDM halos.

Satellites and Subhalos

The discovery of many faint Local Group dwarf galaxies is consistent with ΛCDM predictions. Lensing flux anomalies gaps in stellar streams require the substructure predicted by CDM. But the “too big to fail” problem needs resolution.

The Angular Momentum Catastrophe

In practice it is not trivial to form galaxies with massive, extended disks and small spheroids. The angular momentum content of the disk determines its final structure.



Too much low angular momentum material!

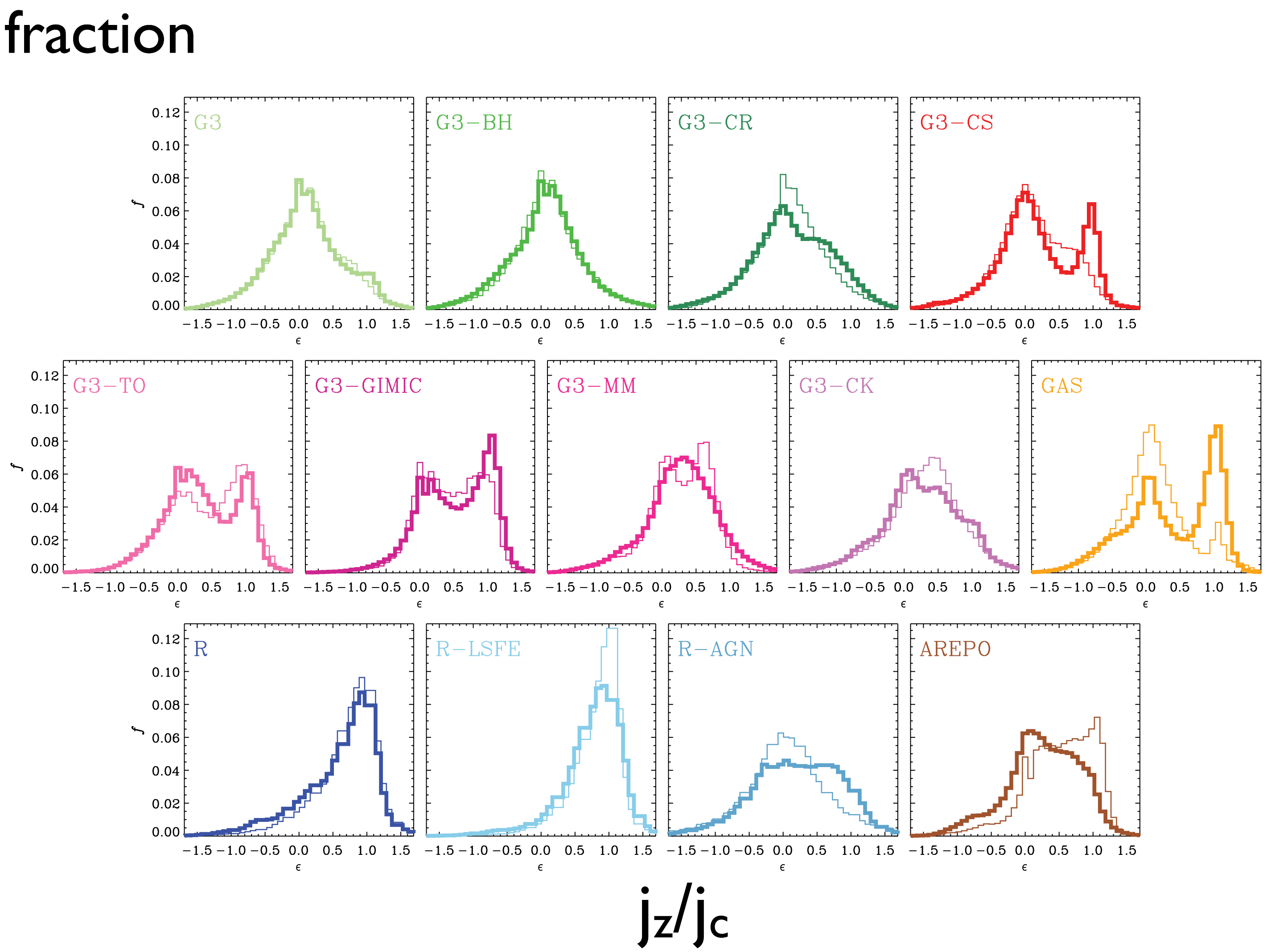
≠

Scannapieco et al. 2009

angular momentum / ang mom needed for rotational support

The Angular Momentum Catastrophe

In practice it is not trivial to form galaxies with massive, extended disks and small spheroids. The angular momentum content of the disk determines its final structure. None of the 2012 Aquila low-resolution galaxy simulations had realistic disks.



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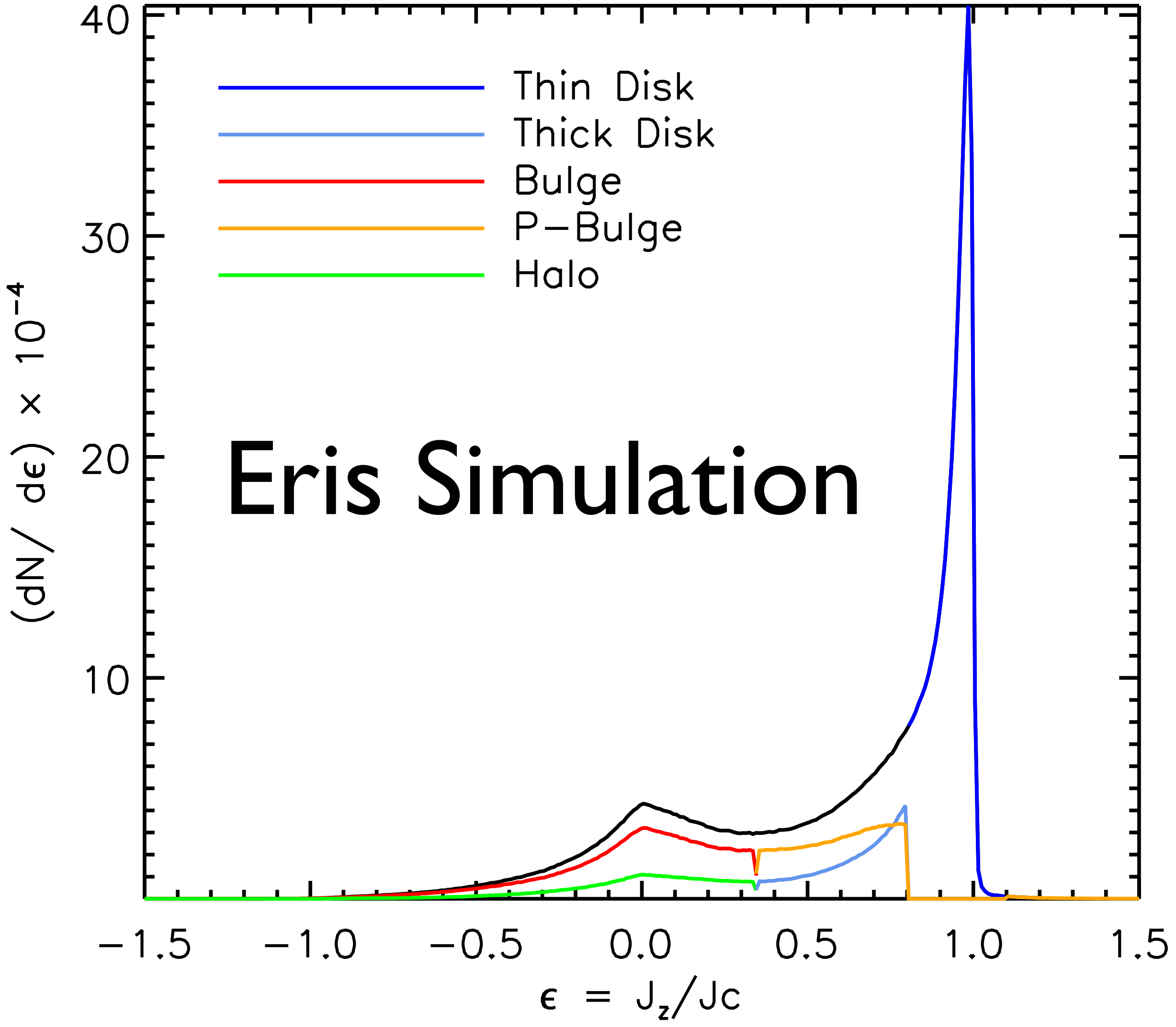
Scannapieco et al., Aquila Galaxy Simulation Comparison, 2012

The Angular Momentum ~~Catastrophe~~

Eris, the first high-resolution simulation of a ~10^{12} $M_\odot$ halo, produced a realistic spiral galaxy. Adequate resolution and physically realistic feedback appear to be sufficient.



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Guedes, Callegari, Madau, Mayer 2011 ApJ

Mon. Not. R. Astron. Soc. **424,** 1105–1112 (2012)

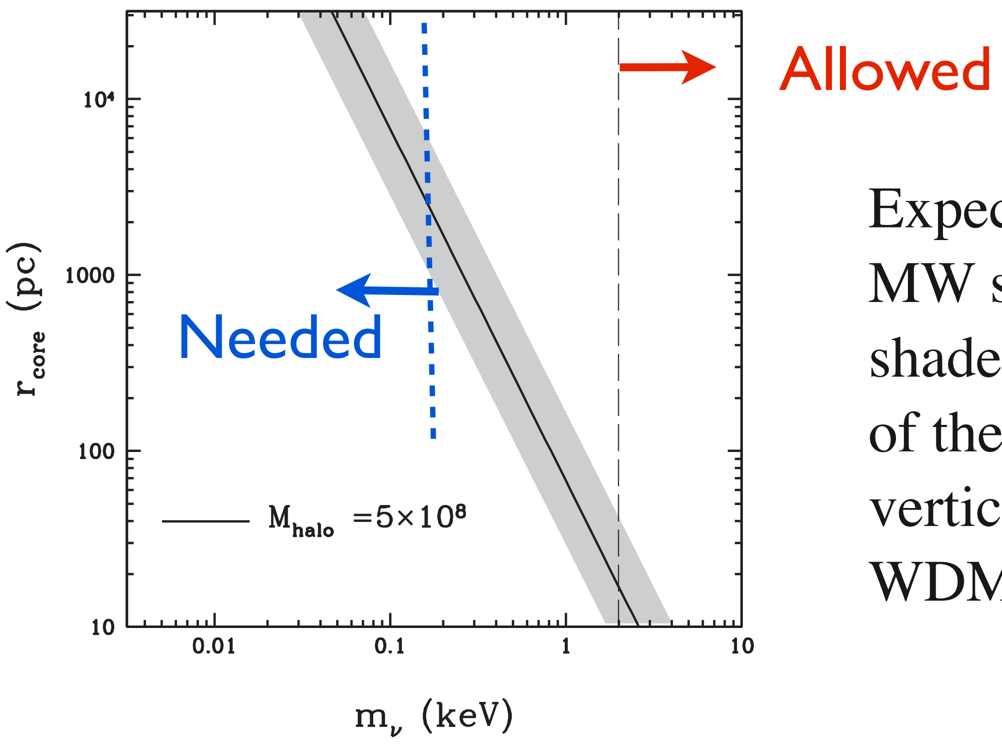
Cores in warm dark matter haloes: a Catch 22 problem

Andrea V. Maccio, Sinziana Paduroiu, Donnino Anderhalden, Aurel Schneider and Ben Moore

ABSTRACT

The free streaming of warm dark matter particles dampens the fluctuation spectrum, flattens the mass function of haloes and sets a fine-grained phase density limit for dark matter structures. The phase-space density limit is expected to imprint a constant-density core at the halo centre in contrast to what happens for cold dark matter. We explore these effects using high-resolution simulations of structure formation in different warm dark matter scenarios. We find that the size of the core we obtain in simulated haloes is in good agreement with theoretical expectations based on Liouville's theorem. However, our simulations show that in order to create a significant core ($r_c \sim 1$ kpc) in a dwarf galaxy ($M \sim 10^{10}\,M_\odot$), a thermal candidate with mass as low as 0.1 keV is required. This would fully prevent the formation of the dwarf galaxy in the first place. For candidates satisfying large-scale structure constraints (m_ν larger than ≈1–2 keV), the expected size of the core is of the order of 10 (20) pc for a dark matter halo with a mass of 10^{10} (10^8) $M_\odot$. We conclude that 'standard' warm dark matter is not a viable solution for explaining the presence of cored density profiles in low-mass galaxies.

WDM doesn't resolve cusp issues

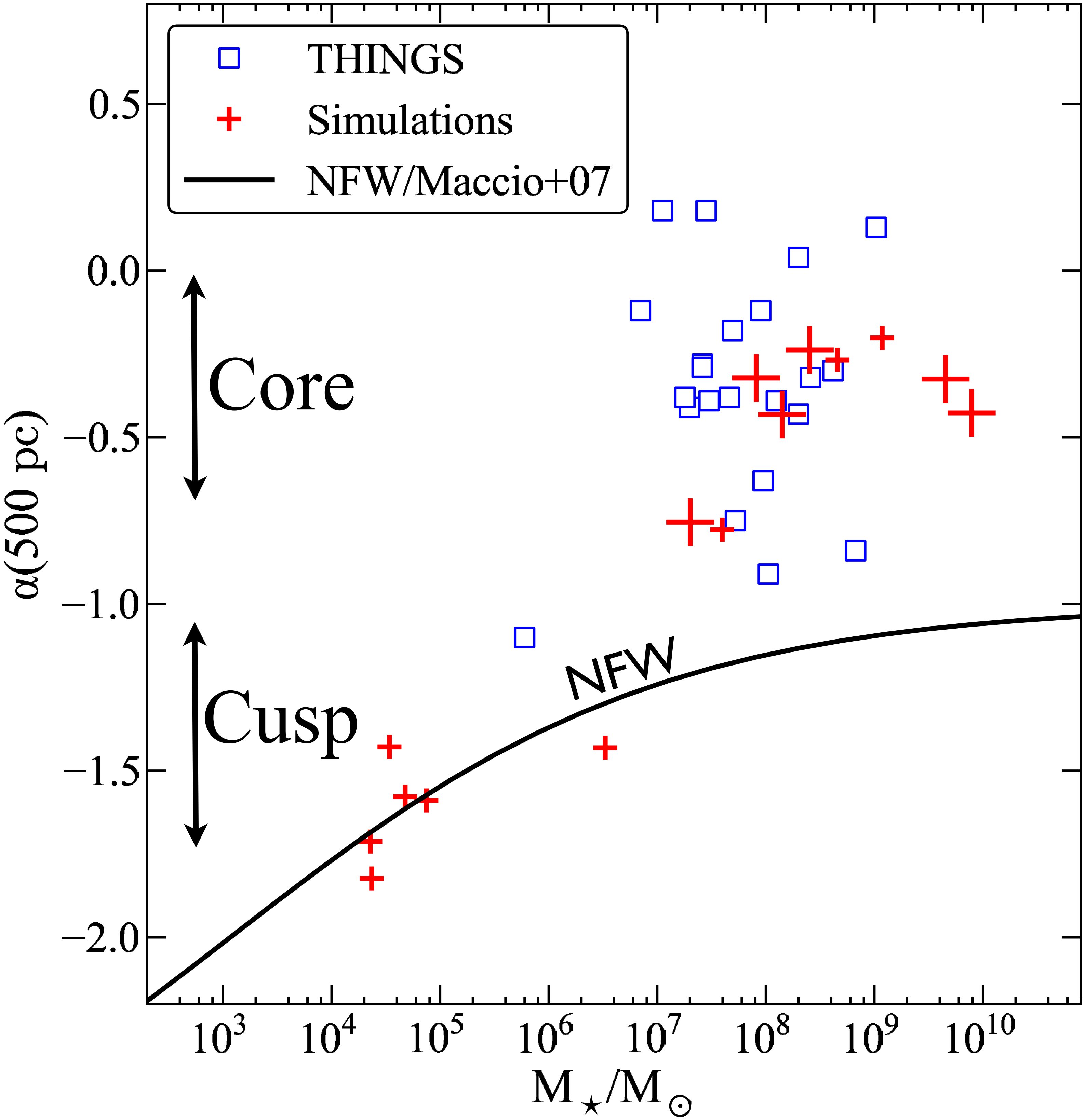


Expected core size for the typical dark matter mass of MW satellites as a function of the WDM mass m_ν. The shaded area takes into account possible different values of the local density parameter $0.15 < \Omega_m < 0.6$. The vertical dashed line shows the current limits on the WDM mass from large-scale structure observations

Cuspy No More: How Outflows Affect the Central Dark Matter and Baryon Distribution in ΛCDM Galaxies.

MNRAS
2012

F.Governato[1⋆] A.Zolotov[2], A.Pontzen[3], C.Christensen[4], S.H.Oh[5,6], A. M.Brooks[7], T.Quinn[1], S.Shen[8], J.Wadsley[9]



Slope of the central dark matter density $\rho \sim r^\alpha$ vs. stellar mass in ΛCDM simulations compared with The HI Nearby Galaxy Survey (THINGS) observations. Repeated episodes of baryons cooling into the center and then ejected by feedback produce cores in simulated low-mass galaxies that are observed to have cores.

Satellites and Subhalos

The discovery of many faint Local Group dwarf galaxies is consistent with ΛCDM predictions. Satellites, reionization, lensing flux anomalies, stellar streams, and Lyα forest data imply that WDM must be Tepid or Cooler.

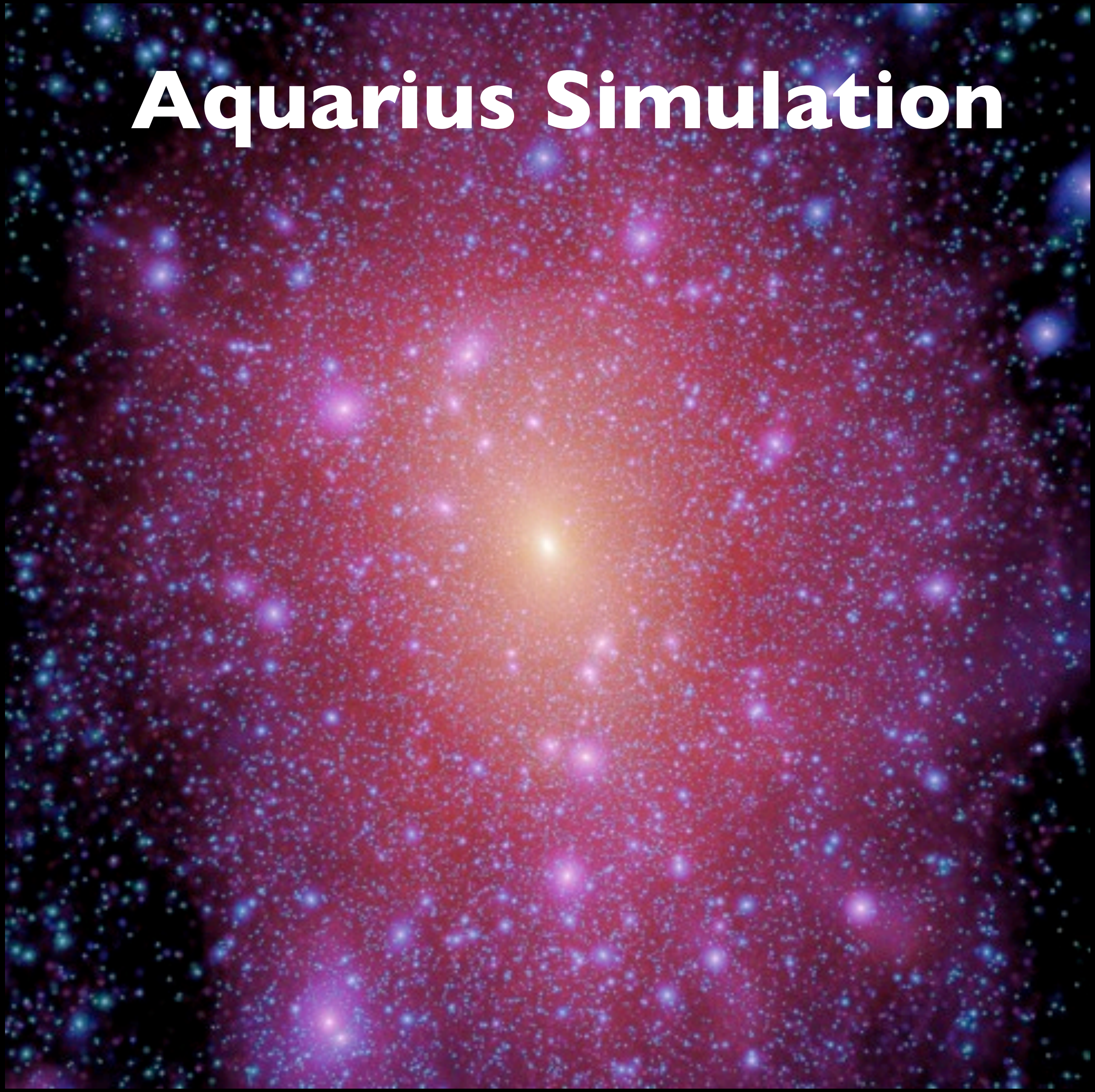
New Developments

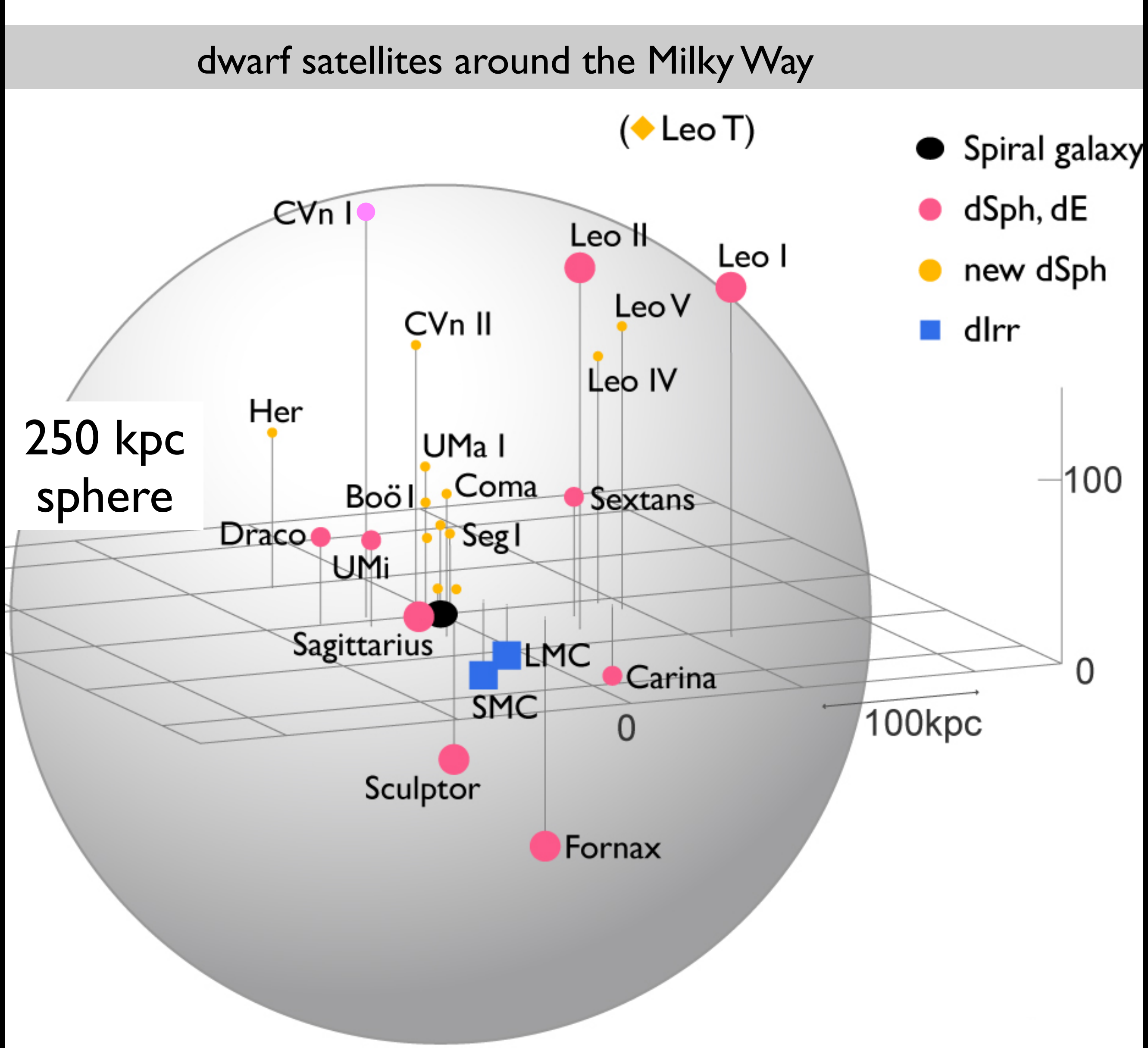
- The "too big to fail" problem appears to be the most serious current challenge for ΛCDM, and may indicate the need for a more complex theory of dark matter.
- High resolution ΛCDM simulation substructure is consistent with quad-lens radio quasar flux and galaxy-galaxy lensing anomalies and indications of substructure by stellar stream gaps.
- ΛCDM predicts that there is a population of low-luminosity stealth galaxies around the Milky Way. Will new surveys with bigger telescopes find them?

The “too big to fail” problem

ΛCDM subhalos vs. Milky Way satellites

“Missing satellites”: Klypin et al. 1999, Moore et al. 1999





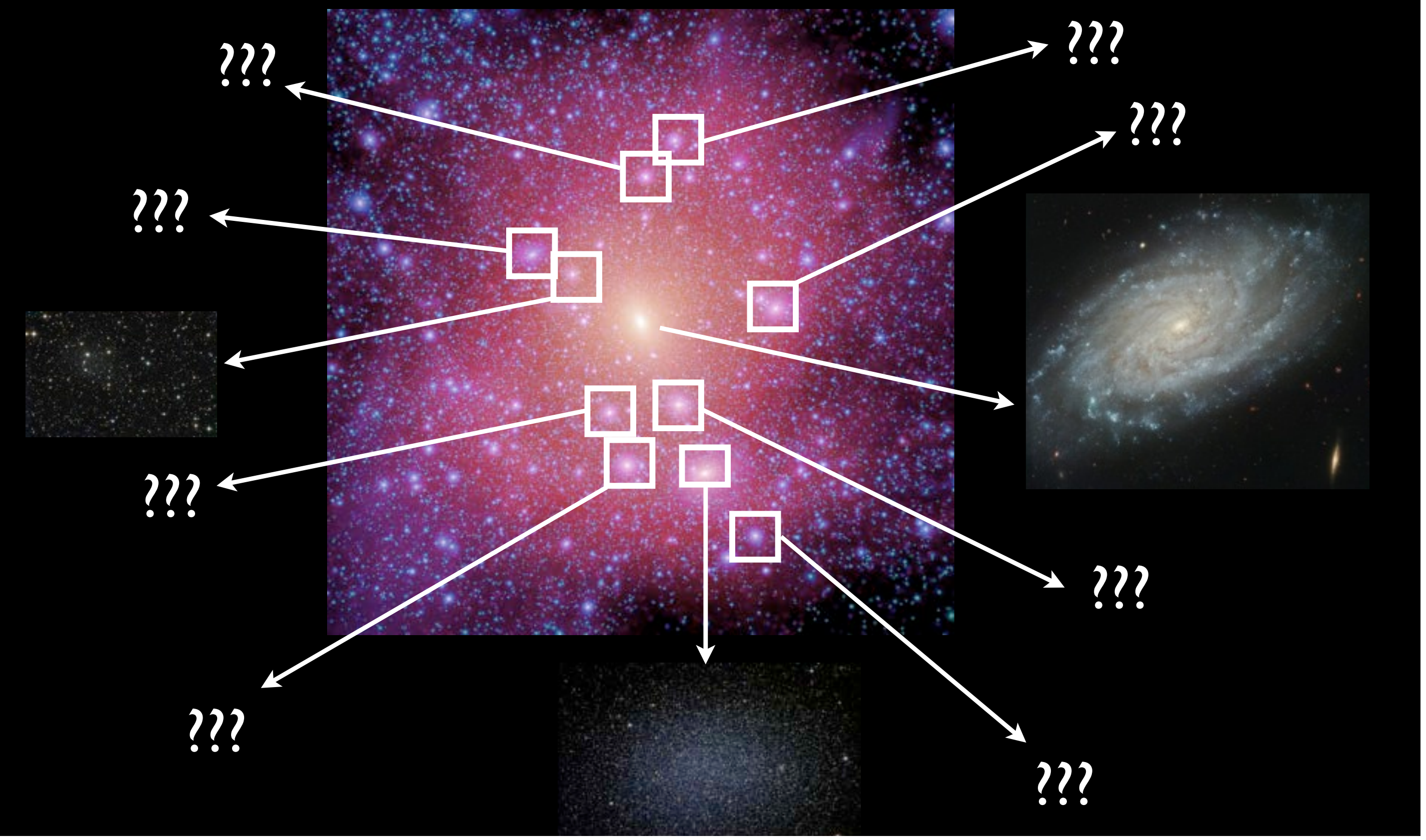
>10^5 identified subhalos

12 bright satellites $(L_V > 10^5 L_\odot)$

V. Springel / Virgo Consortium

S. Okamoto

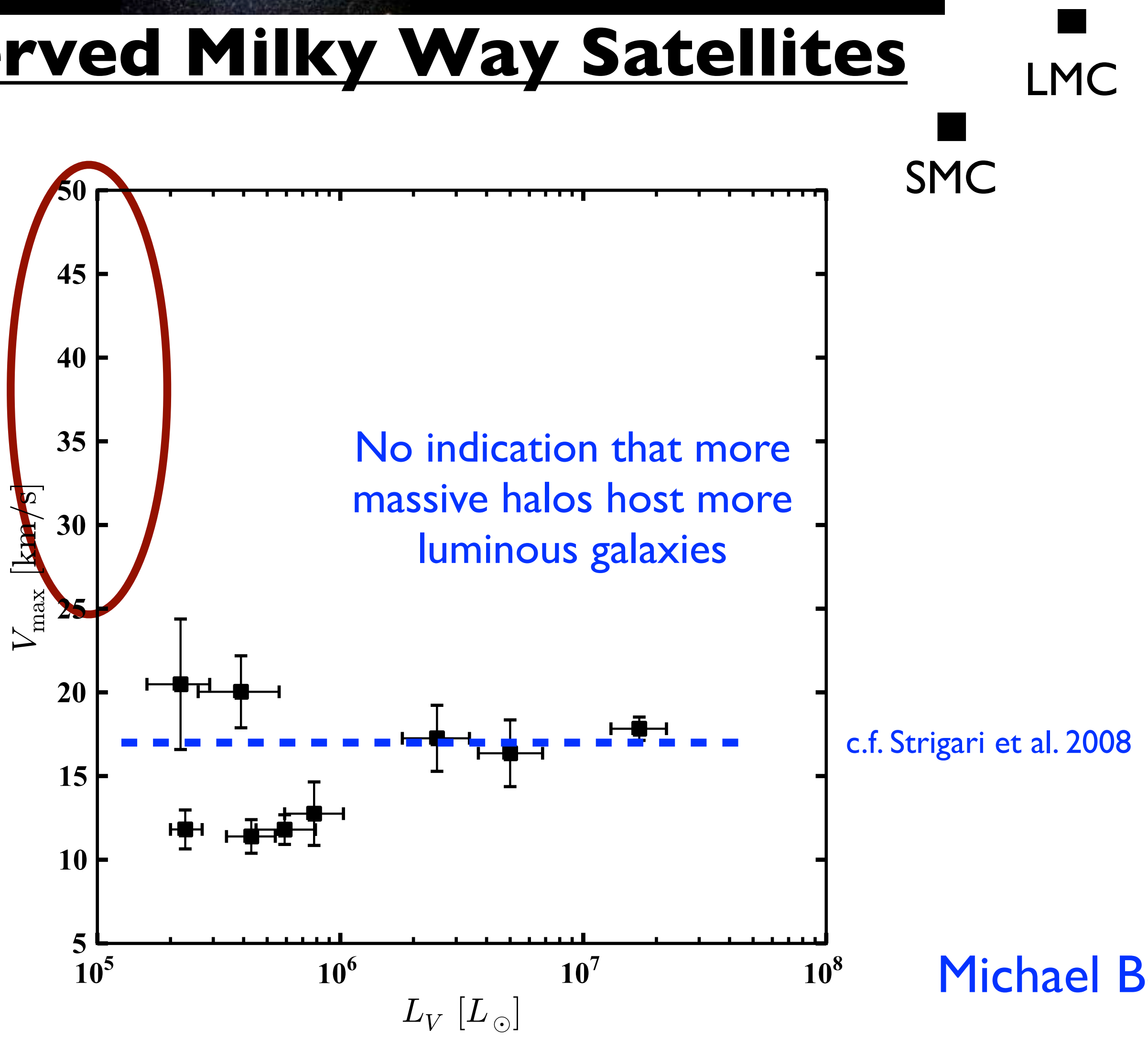
Of the ~10 biggest subhalos, ~8 cannot host *any* known bright MW satellite



Observed Milky Way Satellites

“massive failures”: highest resolution LCDM simulations predict ~10 subhalos in this range in the MW, but we don’t see ***any*** such galaxies [except Sagittarius (?)]

All of the bright MW dSphs are consistent with $V_{\rm max} \lesssim 25\,{\rm km/s}$
(see also Strigari, Frenk, & White 2010)



No indication that more massive halos host more luminous galaxies

c.f. Strigari et al. 2008

Possible Solutions to “too big to fail”

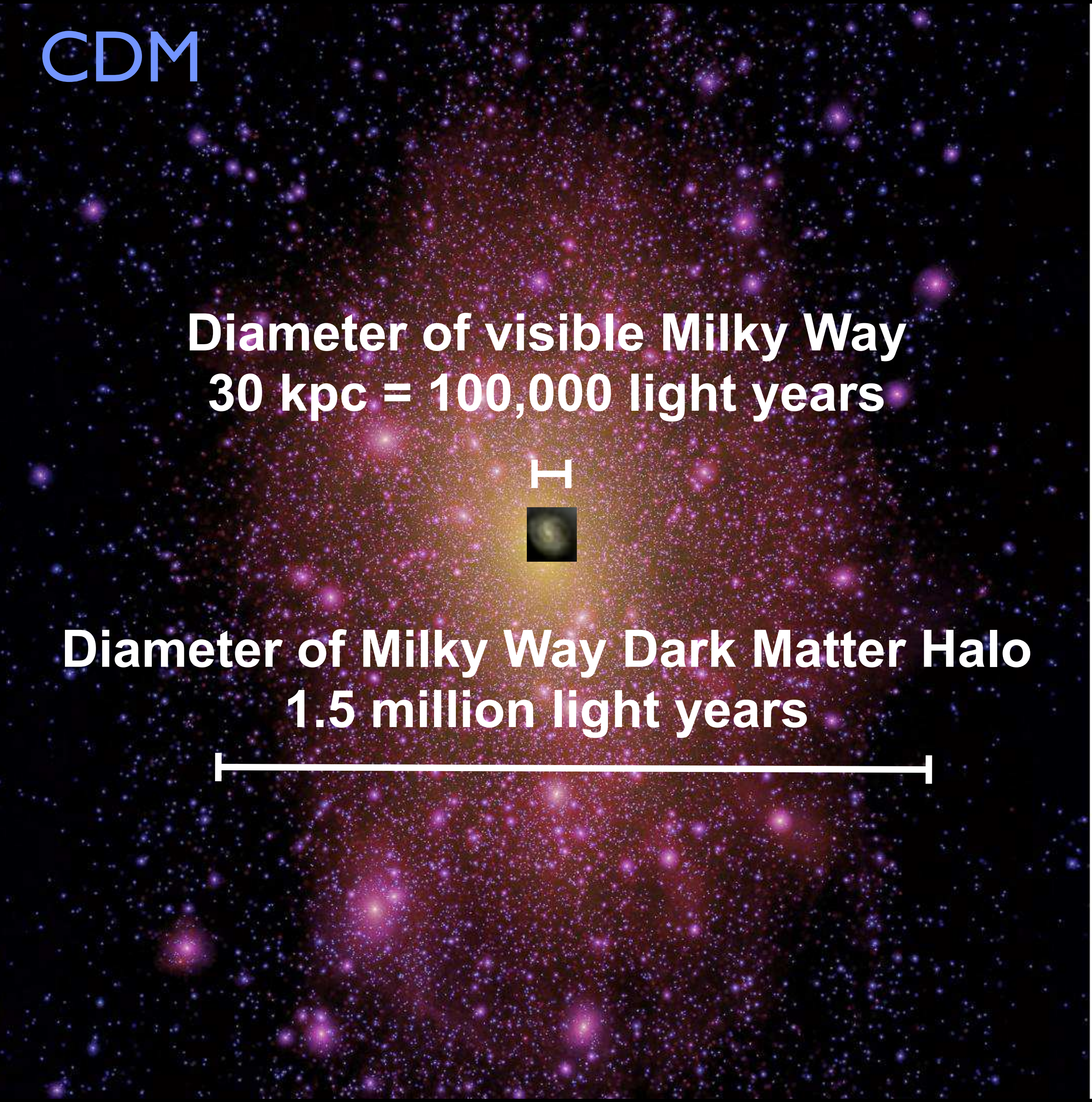
The Milky Way is anomalous?

The Milky Way has a low mass dark matter halo?

Galaxy formation is stochastic at low masses?

Dark matter is not just CDM -- maybe WDM or even self-interacting?

Michael Boylan-Kolchin, Bullock, Kaplinghat 2011, 2012

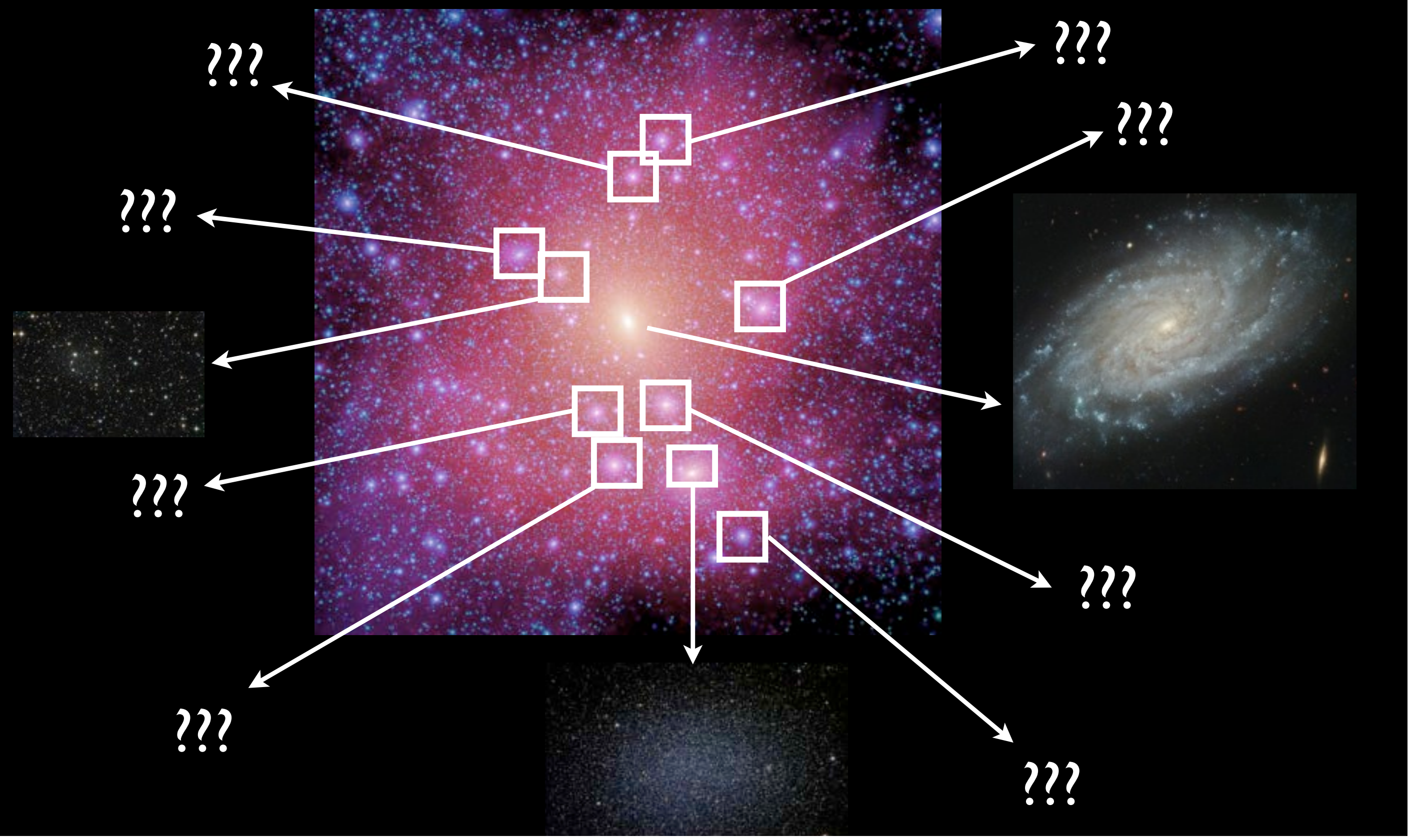


Aquarius simulation. Springel et al. 2008

Lovell, Eke, Frenk, et al. 2011

WDM simulation at right has no "too big to fail" subhalos, but it doesn't lead to the right systematics to fit dwarf galaxy properties. It also won't have the subhalos needed to explain radio flux anomalies and gaps in stellar streams, as we are about to explain.

Of the ~10 biggest subhalos, ~8 cannot host *any* known bright MW satellite



Observed Milky Way Satellites

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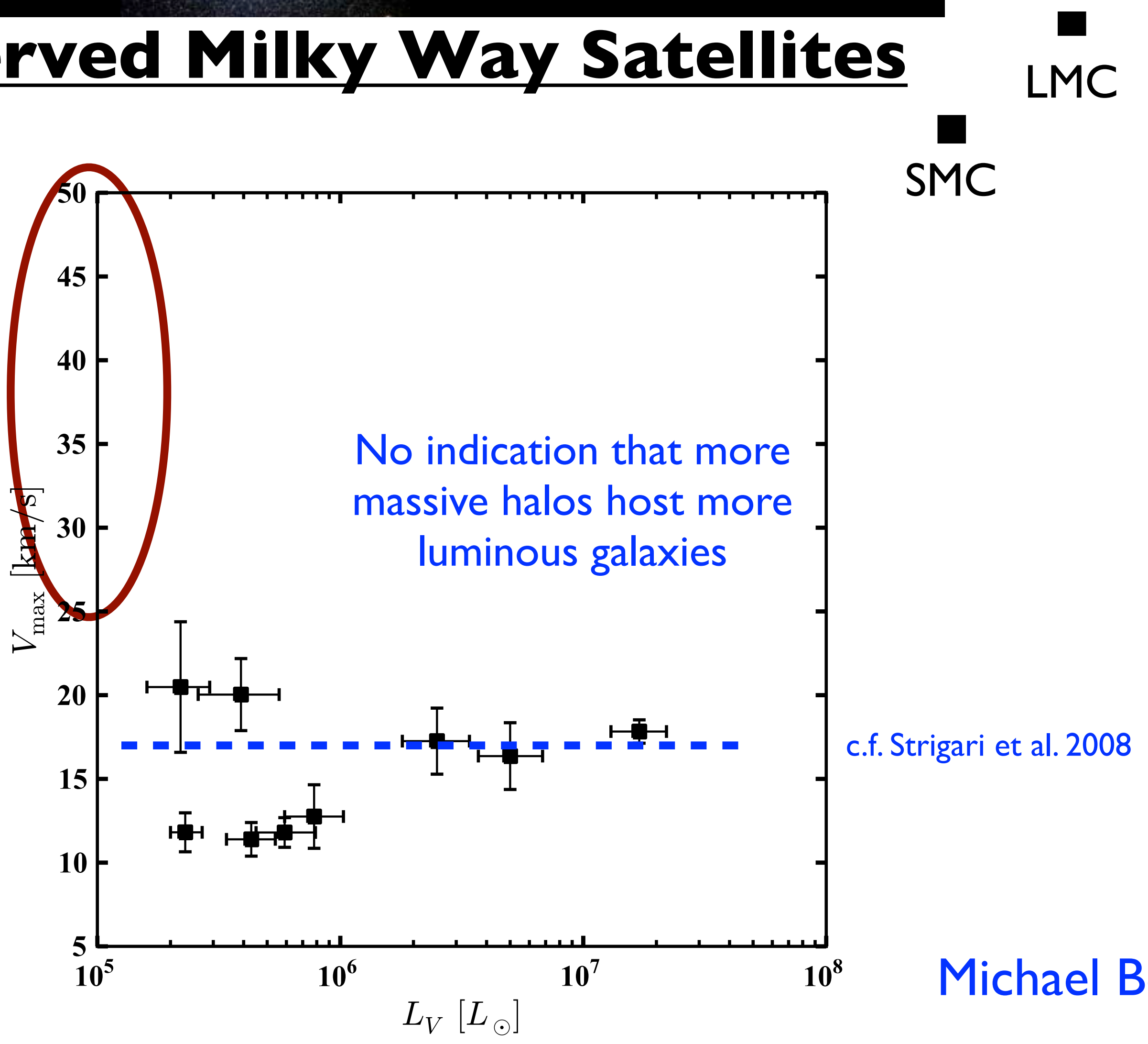

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Possible Solutions to “too big to fail”

The Milky Way is anomalous?

The Milky Way has a low mass dark matter halo?

Galaxy formation is stochastic at low masses?

Dark matter is not just CDM -- maybe WDM or even self-interacting?

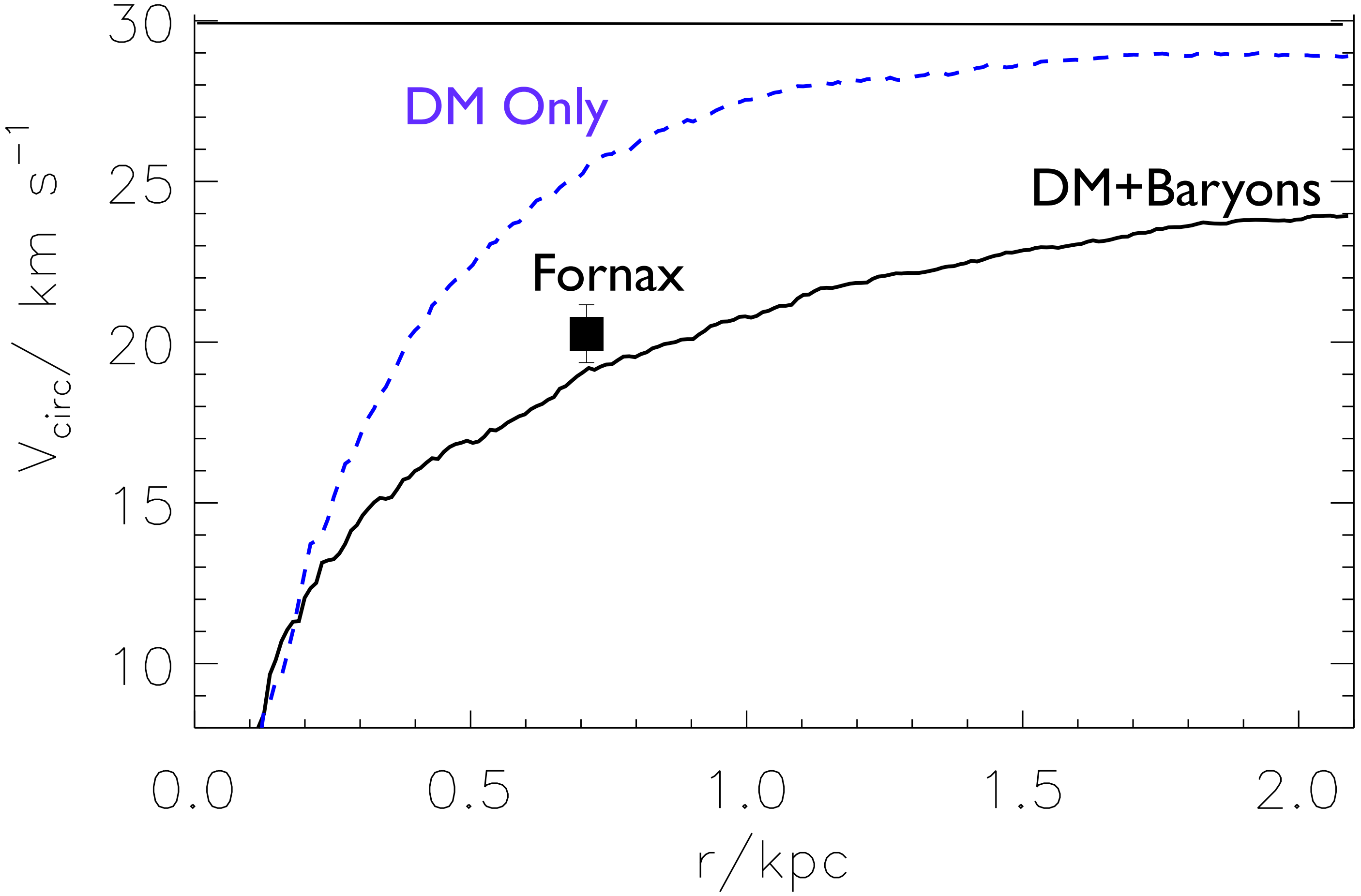
Or maybe high-resolution CDM-only simulations are being misinterpreted? Maybe baryons strongly modify the structure of subhalos?

Michael Boylan-Kolchin, Bullock, Kaplinghat 2011, 2012

WHY BARYONS MATTER: THE KINEMATICS OF DWARF SPHEROIDAL SATELLITES

Alyson M. Brooks & Adi Zolotov - Submitted to ApJ Letters

We use some of the highest resolution cosmological simulations ever produced of Milky Way-mass galaxies that include both baryons and dark matter to show that baryonic physics (energetic feedback from supernovae and subsequent tidal stripping) significantly reduces the dark matter mass in the central regions of luminous satellite galaxies. The reduced central masses of the simulated satellites reproduce the observed internal dynamics of Milky Way and M31 satellites as a function of luminosity. Including baryonic physics in Cold Dark Matter models naturally explains the observed low dark matter densities in the Milky Way's dwarf spheroidal population. Our simulations therefore resolve the tension between kinematics predicted in Cold Dark Mater theory and observations of satellites, without invoking alternative forms of dark matter.



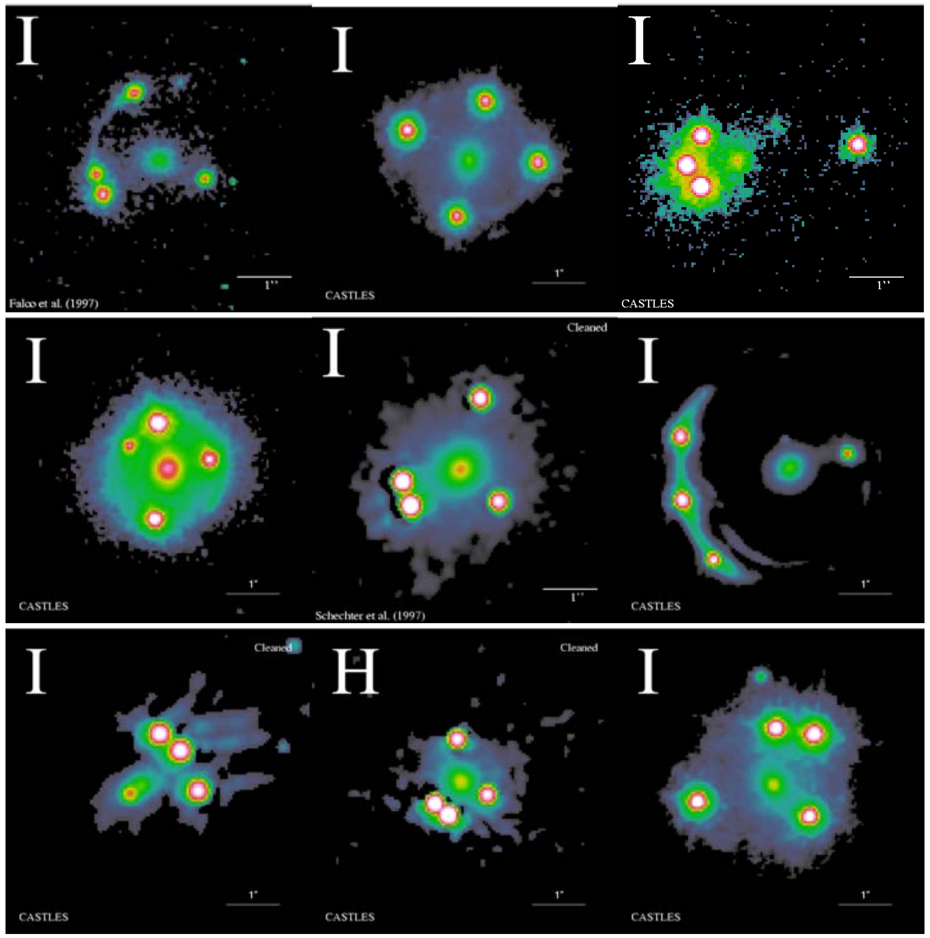
The z = 0 rotation curves of a simulated satellite and its DM-only counterpart. The V_{circ} for Fornax is over-plotted, based on the data in Walker et al. (2009). The combination of SN feedback (before infall) and tidal stripping (after infall) substantially lower the V_{circ} of the SPH satellite by z = 0, and is in good agreement with the observed V_{circ} of Fornax.

Based on simulations in Zolotov +2012 with force softening 174 pc, $M_{DM} = 1.3\times10^5\ M_\odot$, and $M_{baryon} = 2.7\times10^4\ M_\odot$. This is at best barely adequate resolution.

See also Brooks et al. ApJ 2013, Arraki et al. 2012 preprint

Radio flux-ratio anomalies

Quasar lenses



(CASTLES project, http://www.cfa.harvard.edu/castles)

Radio flux-ratio anomalies ⇒

Strong evidence for dark matter clumps with M ~ 10^6 - 10^8 Msun as expected in ΛCDM

Flux ratio anomalies are generic

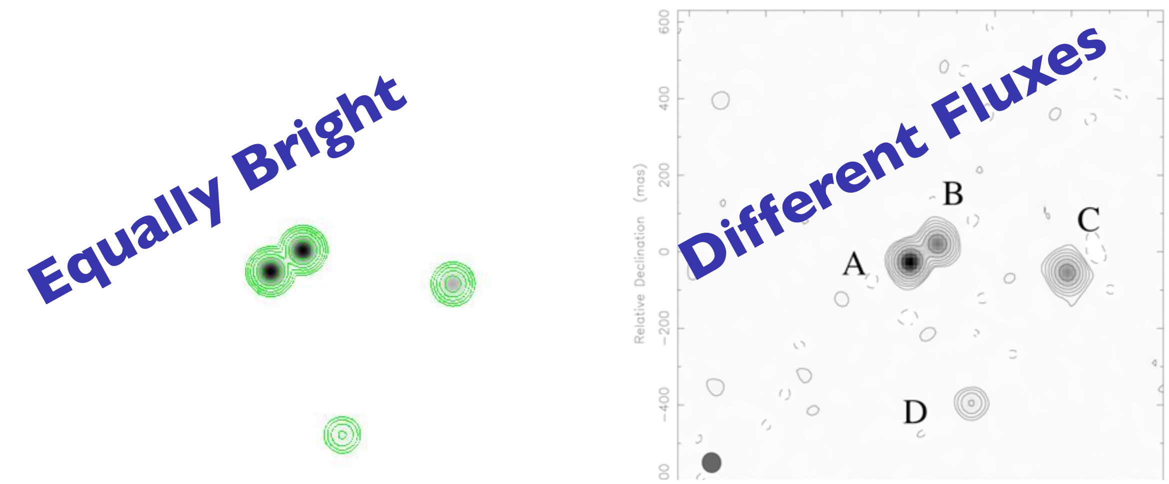
"Easy" to explain image positions (even to ∼0.1% precision)

- ellipsoidal galaxy
- tidal forces from environment

But hard to explain flux ratios!

expected

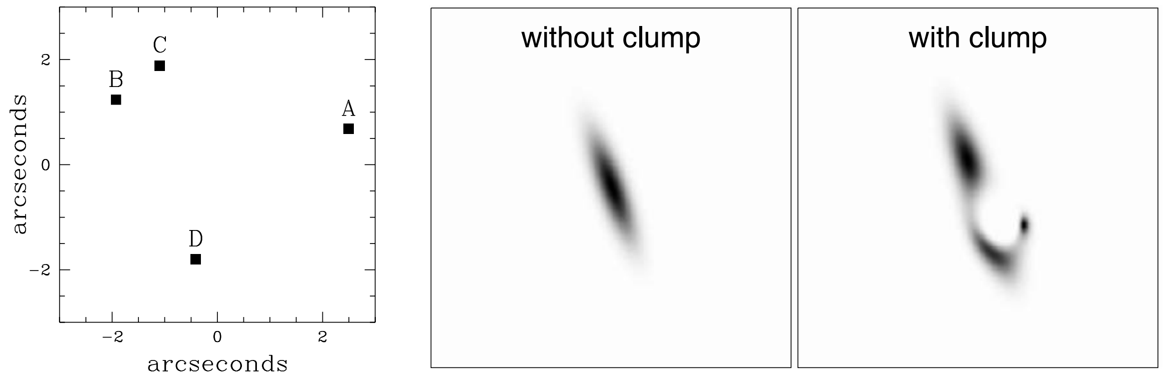
observed *(Marlow et al. 1999)*



Substructure and lensing

Q) What happens if lens galaxies contain mass clumps?

A) The clumps distort the images on small scales.



(cf. Mao & Schneider 1998; Metcalf & Madau 2001; Chiba 2002)

Chuck Keeton

The Aquarius simulations have not quite enough substructure to explain quad-lens radio quasar flux anomalies -- but perhaps including baryons in simulations will help.

Effects of dark matter substructures on gravitational lensing: results from the Aquarius simulations

D. D. Xu, Shude Mao, Jie Wang, V. Springel, Liang Gao, S. D. M. White, Carlos S. Frenk, Adrian Jenkins, Guoliang Li and Julio F. Navarro

MNRAS **398,** 1235–1253 (2009)

We conclude that line-of-sight structures can be as important as intrinsic substructures in causing flux-ratio anomalies. ... This alleviates the discrepancy between models and current data, but a larger observational sample is required for a stronger test of the theory.

Effects of Line-of-Sight Structures on Lensing Flux-ratio Anomalies in a ΛCDM Universe

D. D. Xu, Shude Mao, Andrew Cooper, Liang Gao, Carlos S. Frenk, Raul Angulo, John Helly

MNRAS (2012)

We investigate the statistics of flux anomalies in gravitationally lensed QSOs as a function of dark matter halo properties such as substructure content and halo ellipticity. ... The constraints that we are able to measure here with current data are roughly consistent with ΛCDM N-body simulations.

Constraints on Small-Scale Structures of Dark Matter from Flux Anomalies in Quasar Gravitational Lenses

R. Benton Metcalf, Adam Amara

MNRAS 419, 3414 (2012)

CLUMPY STREAMS FROM CLUMPY HALOS: DETECTING MISSING SATELLITES WITH COLD STELLAR STRUCTURES

Joo Heon Yoon[1]⋆, Kathryn V. Johnston[1], and David W. Hogg[2]

2011 ApJ 731, 58

ABSTRACT

Dynamically cold stellar streams are ideal probes of the gravitational field of the Milky Way. This paper re-examines the question of how such streams might be used to test for the presence of "missing satellites" — the many thousands of dark-matter subhalos with masses $10^5 - 10^7 M_\odot$ which are seen to orbit within Galactic-scale dark-matter halos in simulations of structure formation in ΛCDM cosmologies. Analytical estimates of the frequency and energy scales of stream encounters indicate that these missing satellites should have a negligible effect on hot debris structures, such as the tails from the Sagittarius dwarf galaxy. However, long cold streams, such as the structure known as GD-1 or those from the globular cluster Palomar 5 (Pal 5) are expected to suffer many tens of direct impacts from missing satellites during their lifetimes. Numerical experiments confirm that these impacts create gaps in the debris' orbital energy distribution, which will evolve into degree- and sub-degree-scale fluctuations in surface density over the age of the debris. Maps of Pal 5's own stream contain surface density fluctuations on these scales. The presence and frequency of these inhomogeneities suggests the existence of a population of missing satellites in numbers predicted in the standard ΛCDM cosmologies.

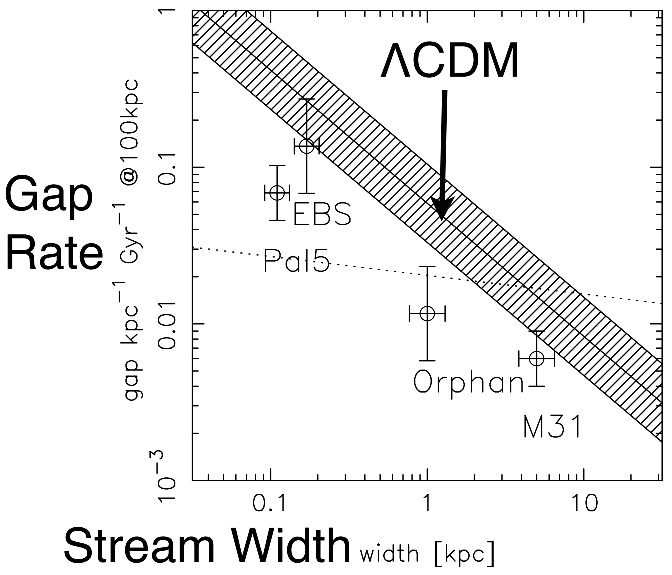


FIG. 11.— The estimated gap rate vs stream width relation for M31 NW, Pal 5, the EBS and the CDM halo prediction. All data have been normalized to 100 kpc. The width of the theoretical relation is evaluated from the dispersion in the length-height relation of Fig. 8. Predictions for an arbitrary alternative mass functions, $N(M) \propto M^{-1.6}$ normalized to have 33 halos above $10^9\,M_\odot$ is shown with a dotted line.

DARK MATTER SUB-HALO COUNTS VIA STAR STREAM CROSSINGS

R. G. Carlberg[1] 2012 ApJ 748, 20

Comparison of the CDM based prediction of the gap rate-width relation with published data for four streams shows generally good agreement within the fairly large measurement errors. **The result is a statistical argument that the vast predicted population of sub-halos is indeed present in the halos of galaxies like M31 and the Milky Way.** The data do tend to be somewhat below the prediction at most points. This could be the result of many factors, such as the total population of sub-halos is expected to vary significantly from galaxy to galaxy, allowing for the stream age would lower the predicted number of gaps for the Orphan stream and possibly others as well, and most importantly these are idealized stream models.

THE PAL 5 STAR STREAM GAPS

R. G. CARLBERG[1], C. J. GRILLMAIR[2], AND NATHAN HETHERINGTON[1]

2012 ApJ 760, 75

ABSTRACT

Pal 5 is a low-mass, low-velocity-dispersion, globular cluster with spectacular tidal tails. We use the Sloan Digital Sky Survey Data Release 8 data to extend the density measurements of the trailing star stream to 23 deg distance from the cluster, at which point the stream runs off the edge of the available sky coverage. The size and the number of gaps in the stream are measured using a filter which approximates the structure of the gaps found in stream simulations. We find 5 gaps that are at least 99% confidence detections with about a dozen gaps at 90% confidence. The statistical significance of a gap is estimated using bootstrap resampling of the control regions on either side of the stream. The density minimum closest to the cluster is likely the result of the epicyclic orbits of the tidal outflow and has been discounted. To create the number of 99% confidence gaps per unit length at the mean age of the stream requires a halo population of nearly a thousand dark matter sub-halos with peak circular velocities above 1 km s^{-1} within 30 kpc of the galactic center. These numbers are a factor of about three below cold stream simulation at this sub-halo mass or velocity but, given the uncertainties in both measurement and more realistic warm stream modeling, are in substantial agreement with the LCDM prediction.

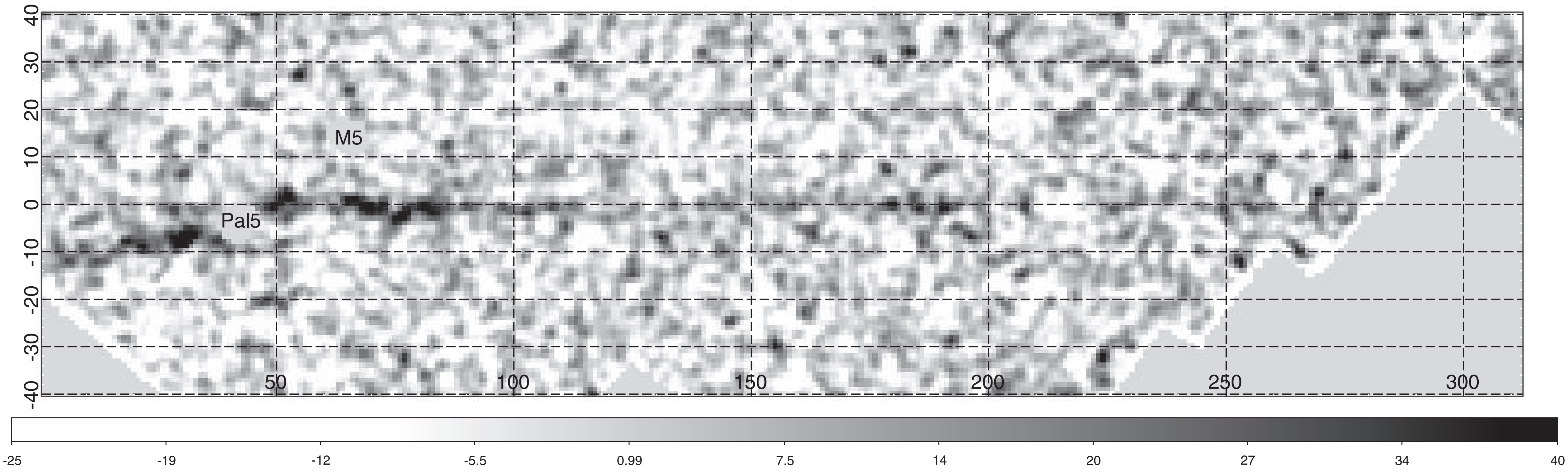
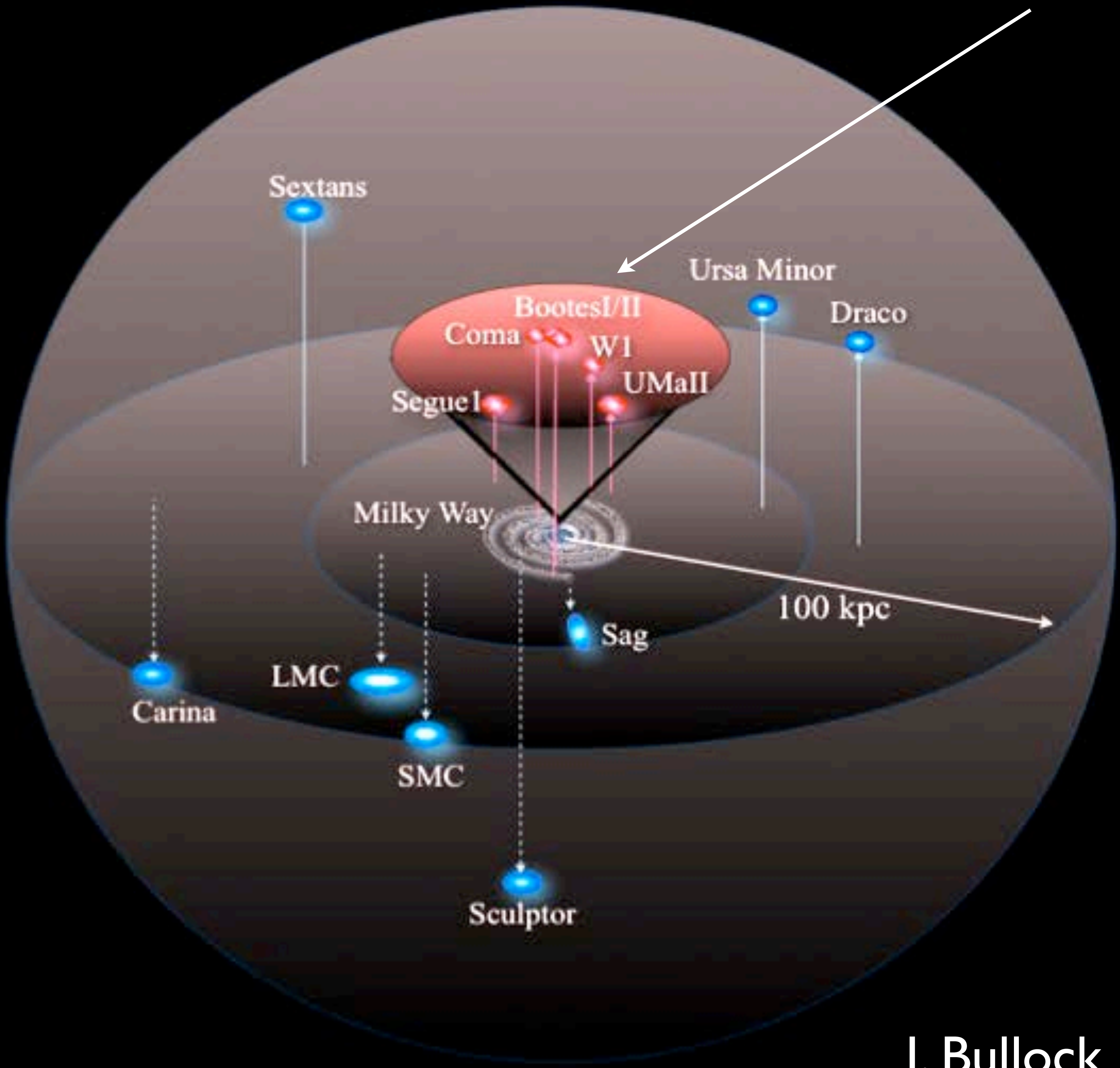


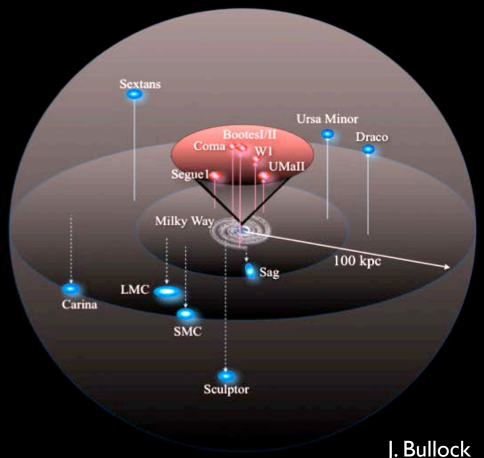
Figure 2. Matched filtered star map of the Pal 5 field, with Pal 5 and the foreground M5 cluster masked out. To remove the varying background, the masked image ha
been smoothed over 4° subtracted from the original image, and then smoothed with a 2 pixel, or, 0°.2 Gaussian. The analysis is conducted on the original uncorrelate
pixels. We have made no attempt to straighten the southern part of the stream, left of the cluster in this image.

SDSS satellite search

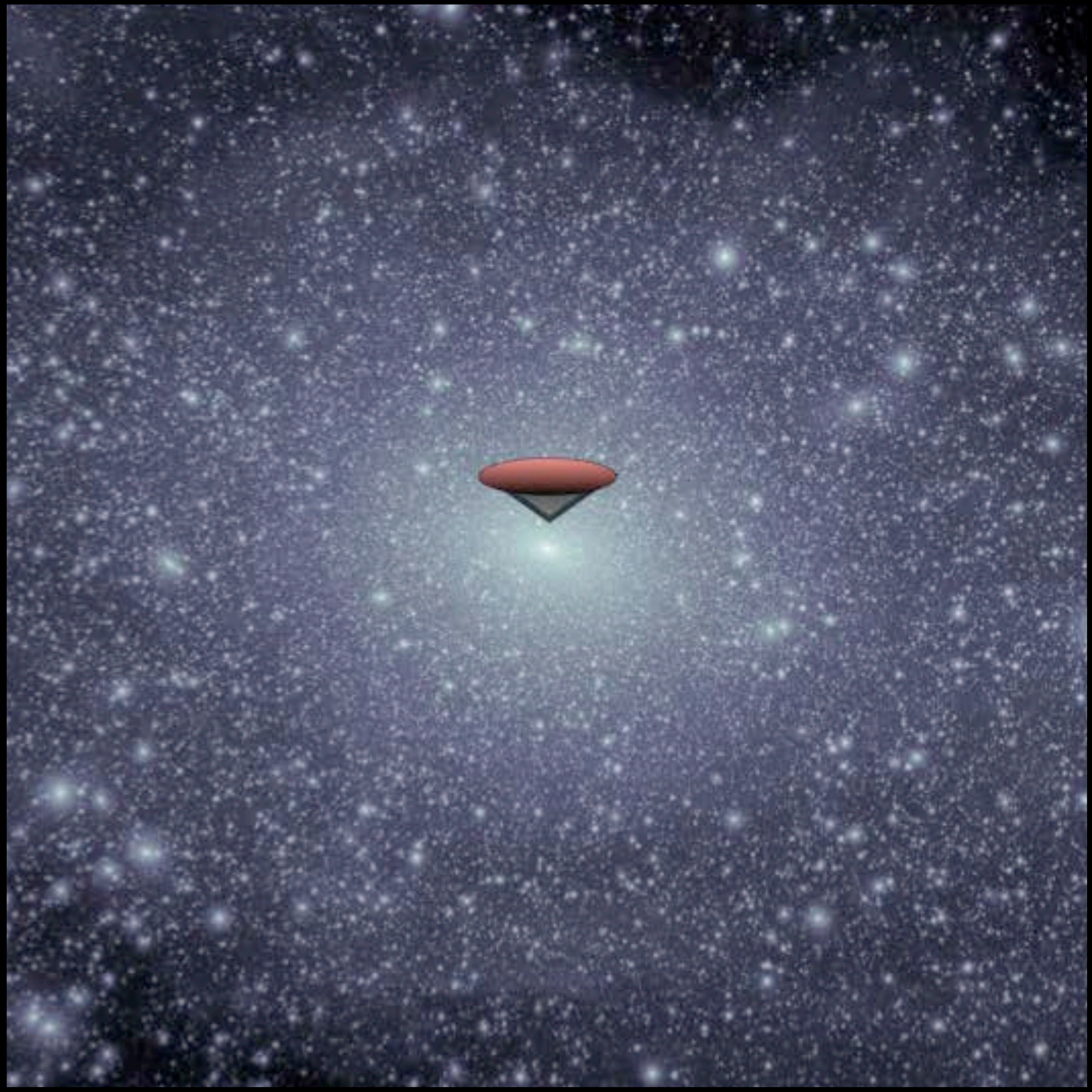


J. Bullock

The search for faint Milky Way satellites has just begun



J. Bullock



The Dark Energy Survey will cover a larger region of the Southern Sky, and LSST will go much deeper yet

Conclusions

- CMB and large-scale structure predictions of ΛCDM with modern cosmological parameters are in agreement with observations. There are no known discrepancies.
- On galaxy and smaller scales, many of the supposed former challenges to ΛCDM are now at least partially resolved. The "angular momentum catastrophe" in galaxy formation appears to be resolved with better resolution and more realistic feedback. Cusps can be removed by starbursts blowing out central gas.
- Lensing flux anomalies and gaps in cold stellar streams appear to require the sort of substructure seen in ΛCDM simulations. However, the biggest subhalos in ΛCDM MWy-type dark matter halos do not host observed satellites. This "too big to fail" problem may indicate the need for a more complex theory of dark matter -- but it now seems increasingly likely to just require better understanding of the effects of baryonic physics.