SLAC NATIONAL ACCELERATOR LABORATORY

Sid Drell Symposium

Friday January 12, 2018
Panofsky Auditorium

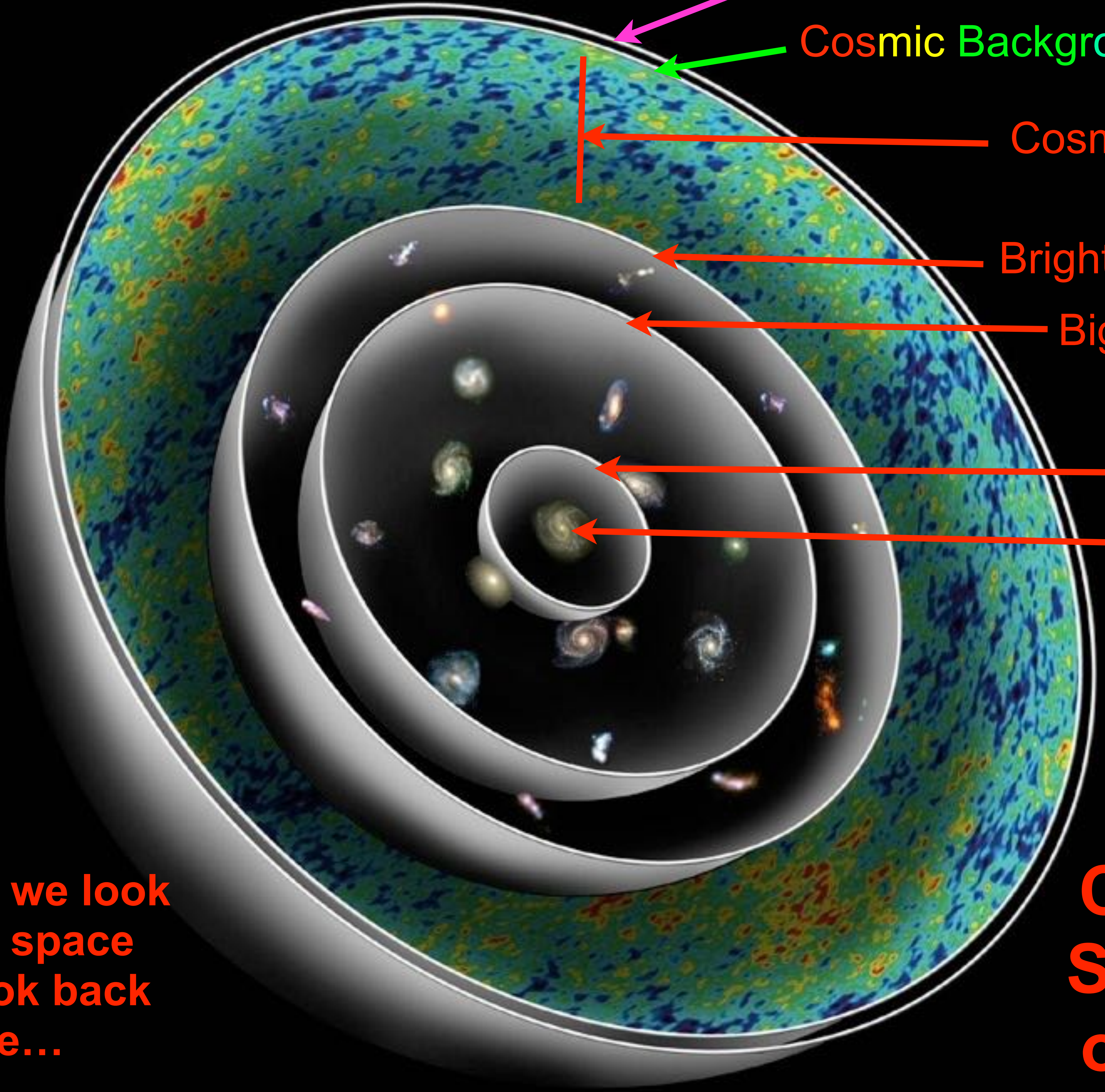
The Structure of the Universe

Joel Primack, UCSC

ΛCDM - the Double Dark Theory of Cosmology
Large Scale Structure of the Universe
The Galaxy - Halo Connection
How Galaxies Form - Hubble Space Telescope + Simulations

Science and Technology Policy

Cosmic Spheres of Time



Cosmic Horizon (The Big Bang)

Cosmic Background Radiation

Cosmic Dark Ages

Bright Galaxies Form

Big Galaxies Form

Earth Forms

Today

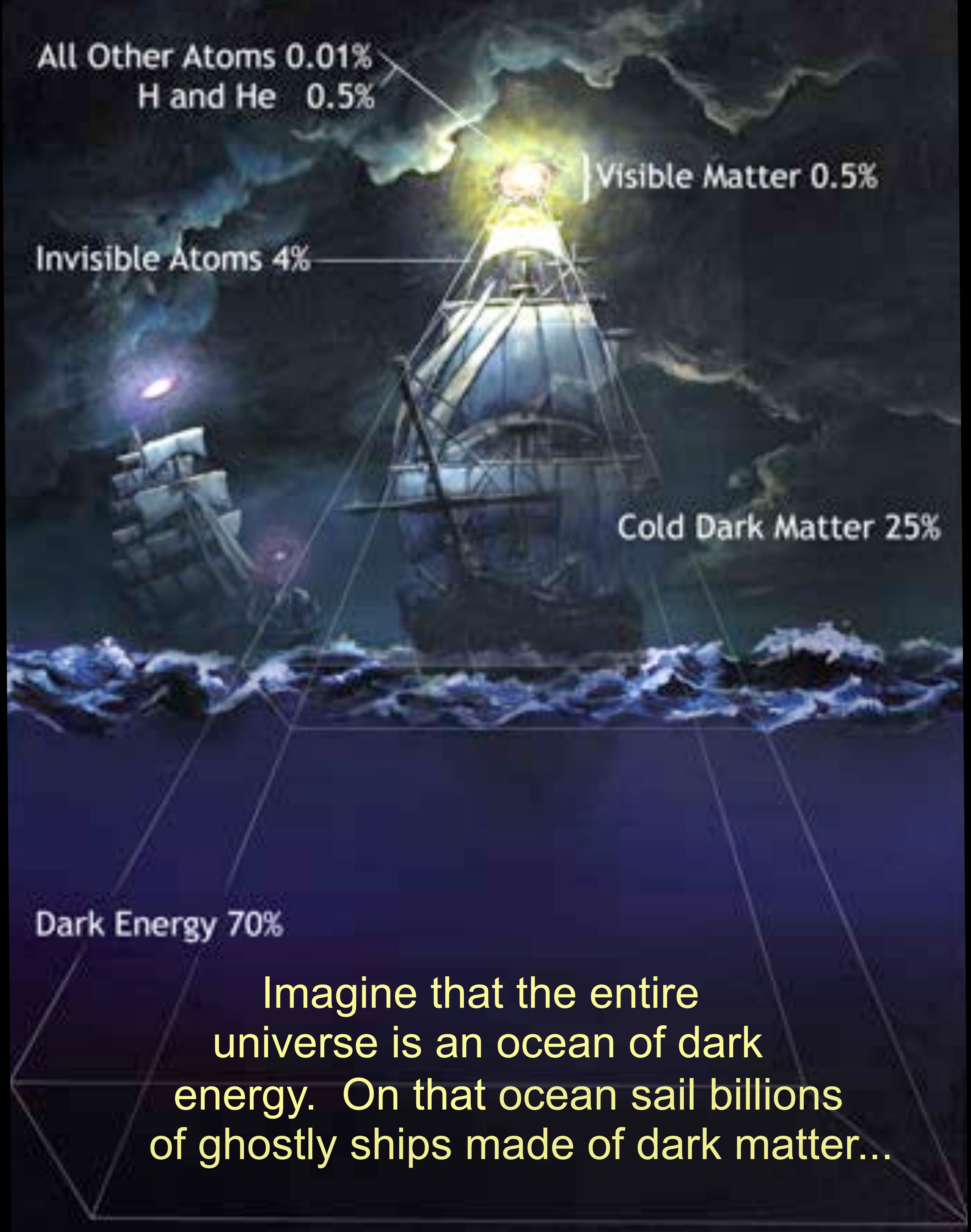
When we look out in space we look back in time…

Matter and Energy Content of the Universe

Dark Matter Ships

on a

Dark Energy Ocean



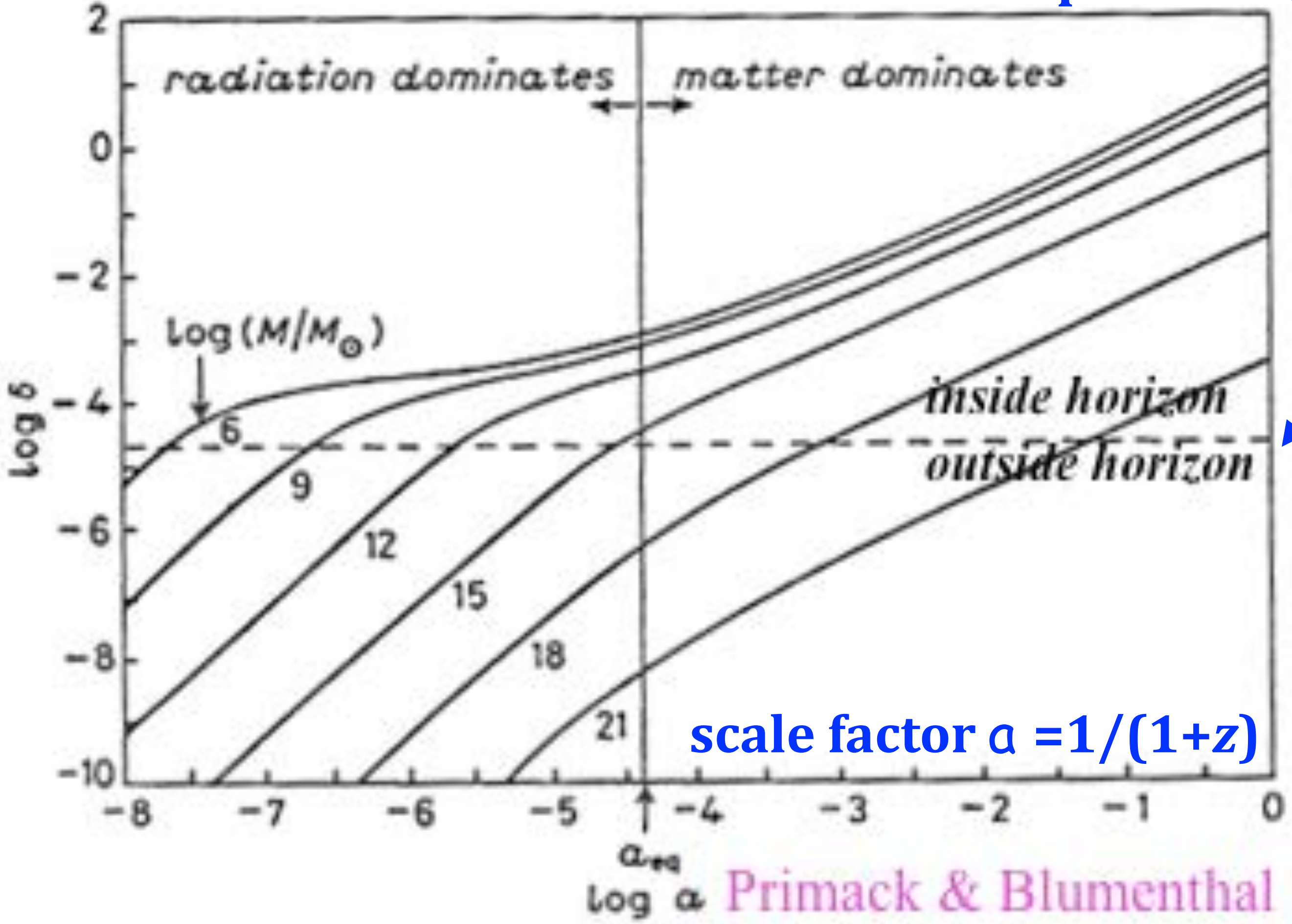
Imagine that the entire universe is an ocean of dark energy. On that ocean sail billions of ghostly ships made of dark matter...

ΛCDM

Double Dark Theory

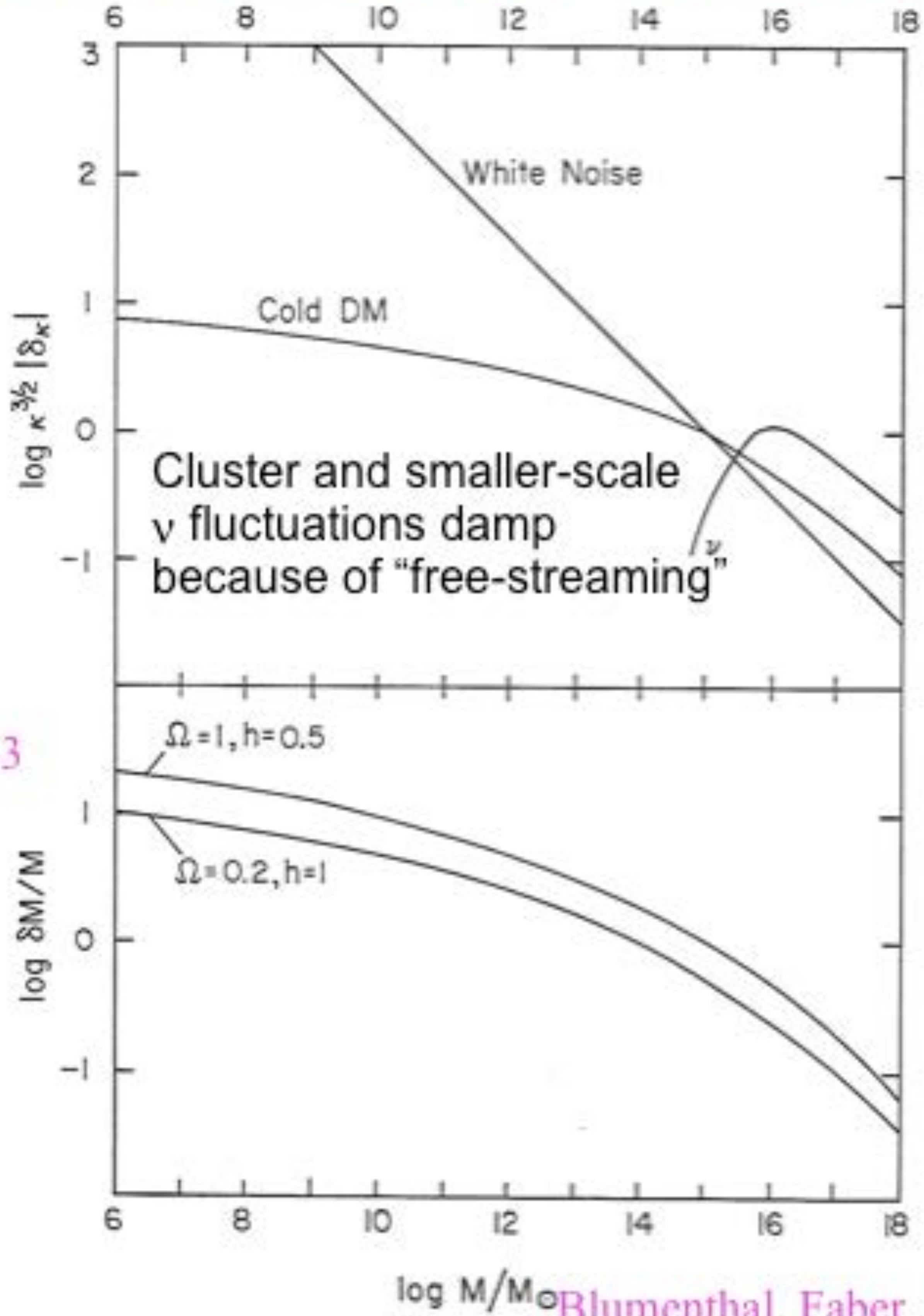
CDM Structure Formation: Linear Theory

Cosmic Inflation: matter fluctuations enter the horizon with about the same amplitude



scale factor a =1/(1+z)

Primack & Blumenthal 1983

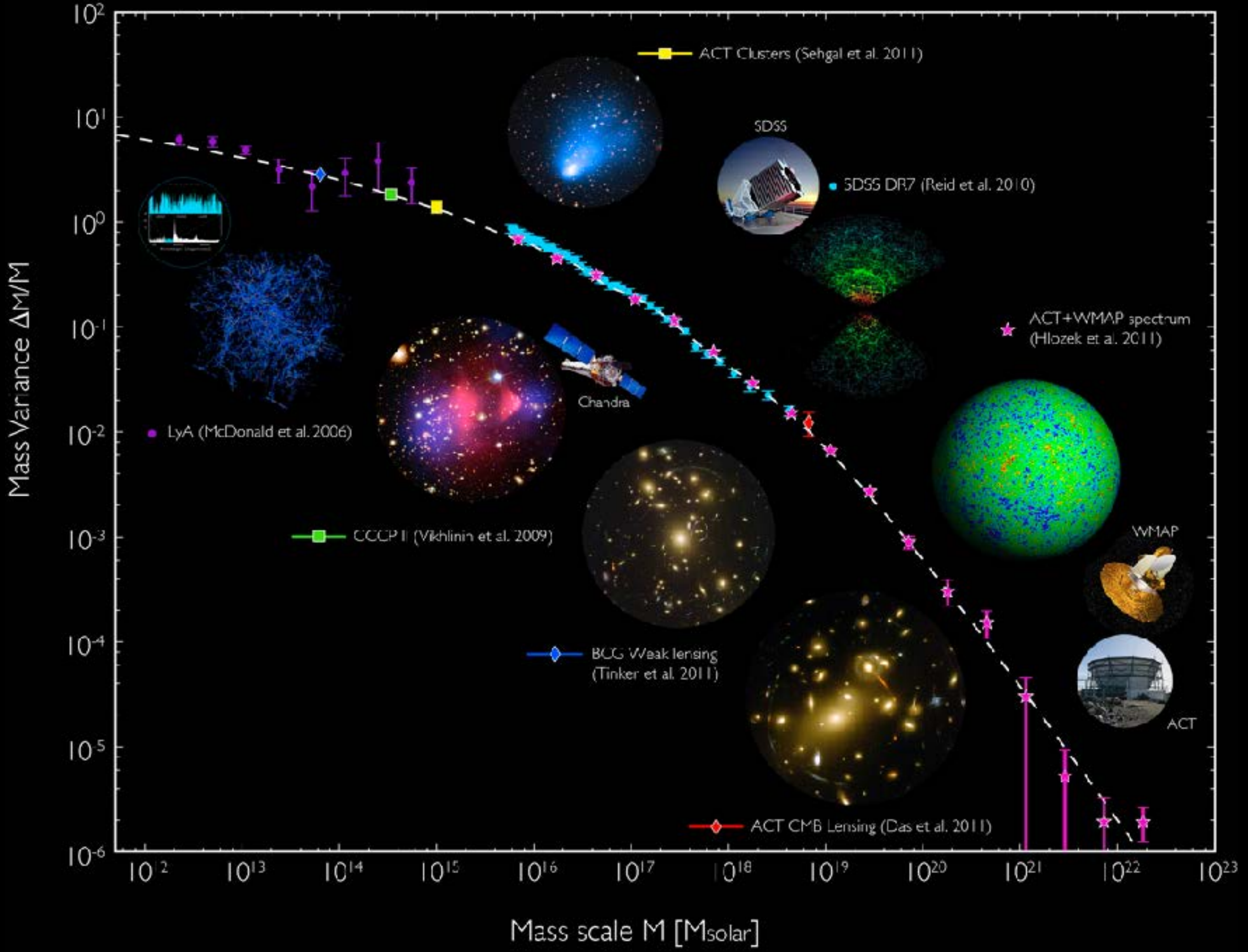


Cluster and smaller-scale ν fluctuations damp because of "free-streaming"

Blumenthal, Faber, Primack, & Rees 1984

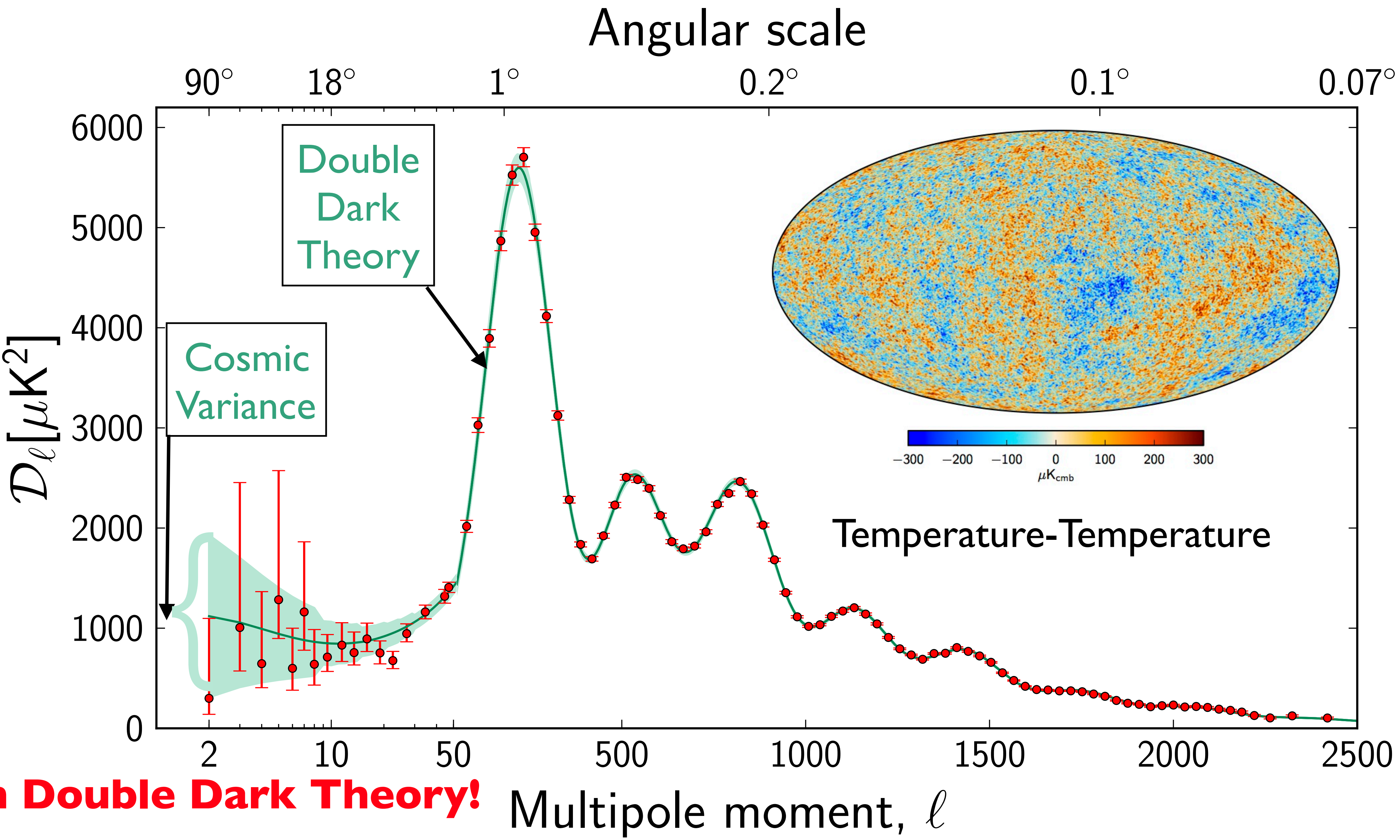
Matter fluctuations that enter the horizon during the radiation dominated era, with masses less than about 10^{15} $M_\odot$, grow only $\propto \log a$, because they are not in the gravitationally dominant component. But matter fluctuations that enter the horizon in the matter-dominated era grow $\propto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

Matter Distribution Agrees with Double Dark Theory!

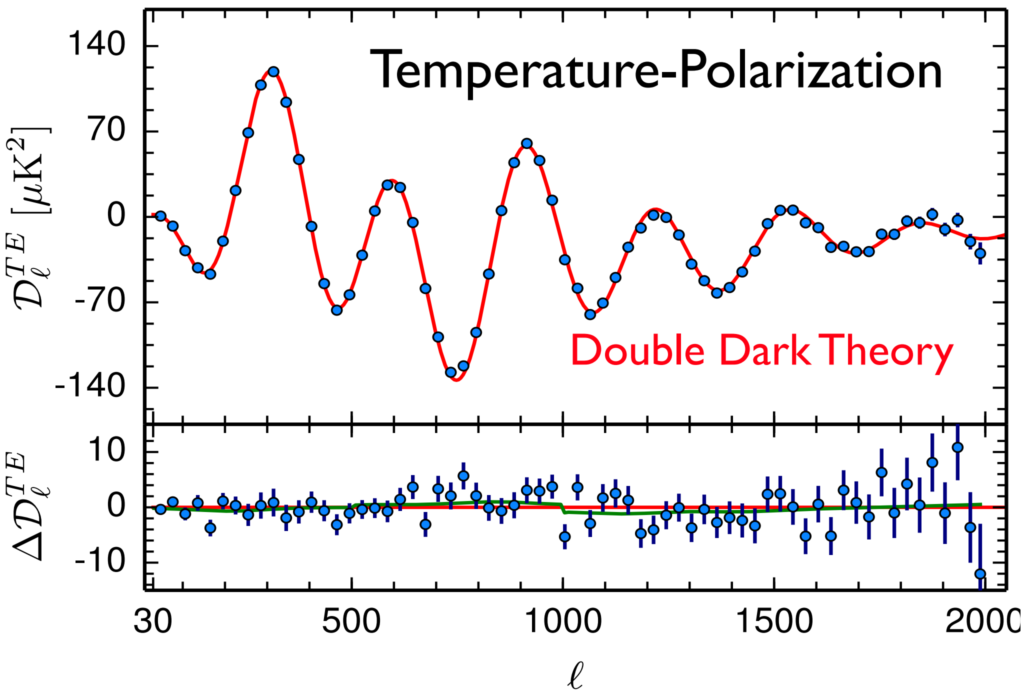


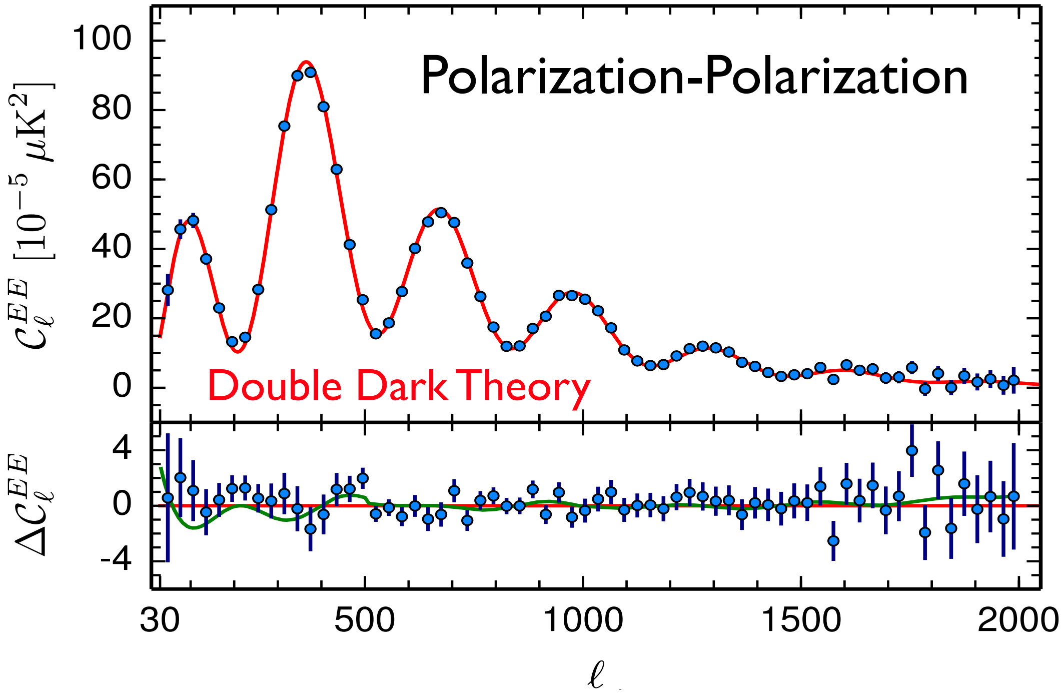
European Space Agency PLANCK Satellite Data

Released February 9, 2015



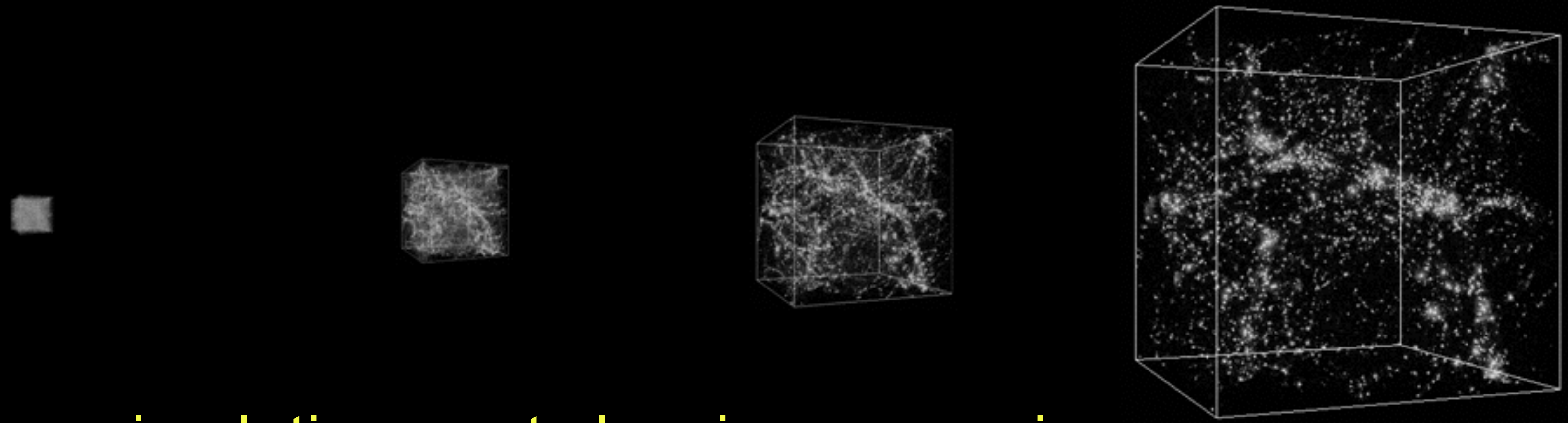
Agrees with Double Dark Theory!



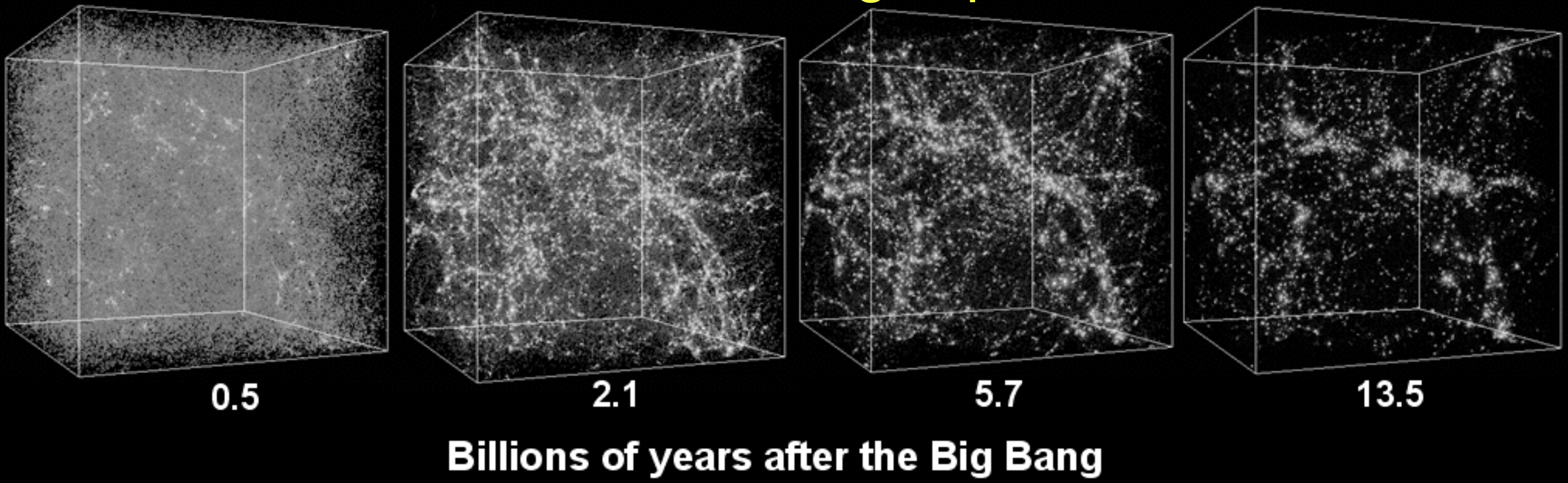


"QUARKS. NEUTRINOS. MESONS. ALL THOSE DAMN PARTICLES YOU CAN'T SEE. THAT'S WHAT DROVE ME TO DRINK. BUT NOW I CAN SEE THEM!"

dark matter simulation - expanding with the universe



same simulation - not showing expansion



Andrey Kravtsov

CONSTRAINED LOCAL UNIVERSE SIMULATION

Stefan Gottloeber, Anatoly Klypin, Joel Primack

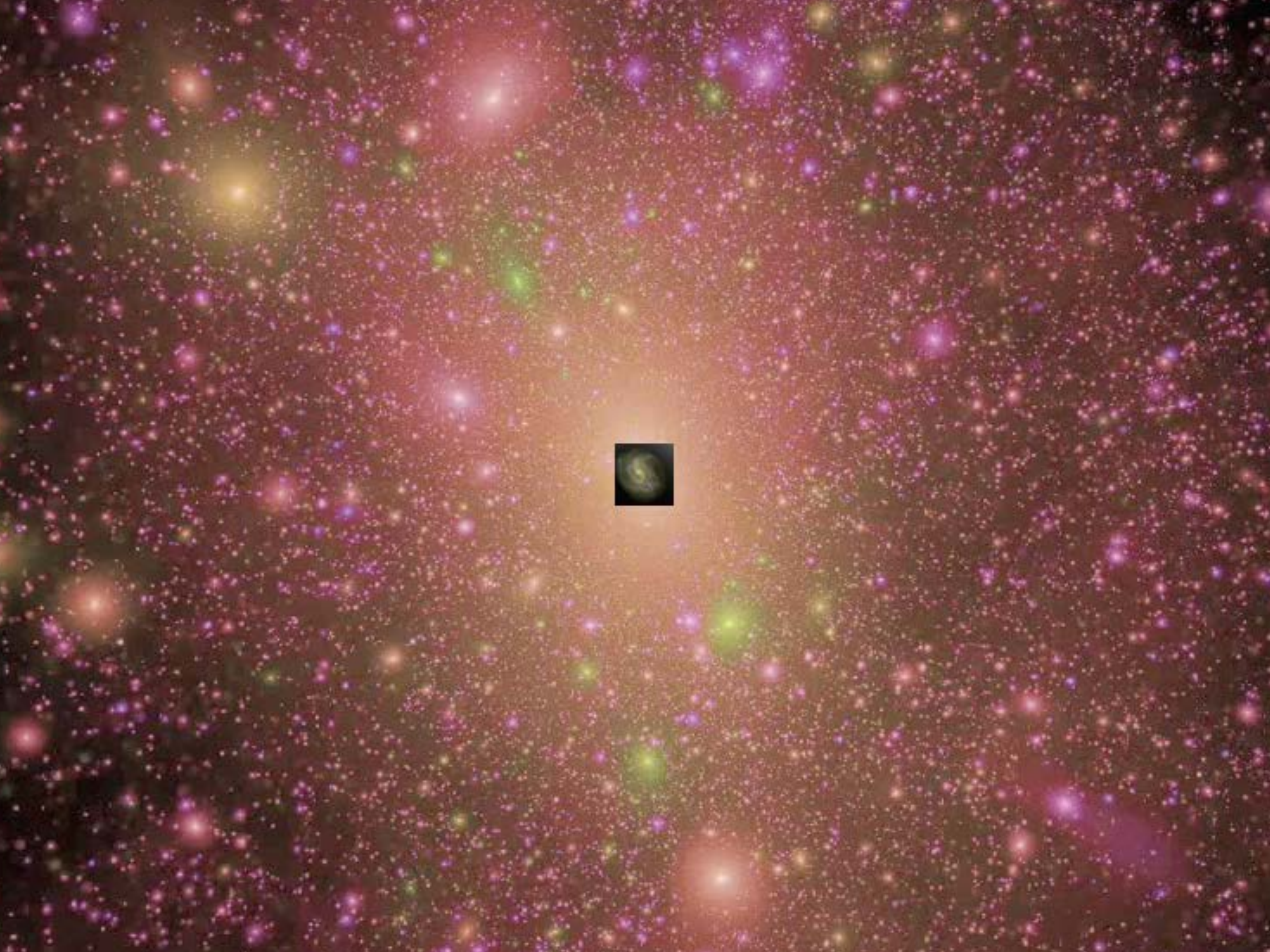
Visualization: Chris Henze (NASA Ames)

Aquarius Simulation

Volker Springel

Milky Way
100,000 light years

Milky Way Dark Matter Halo
1.5 million light years

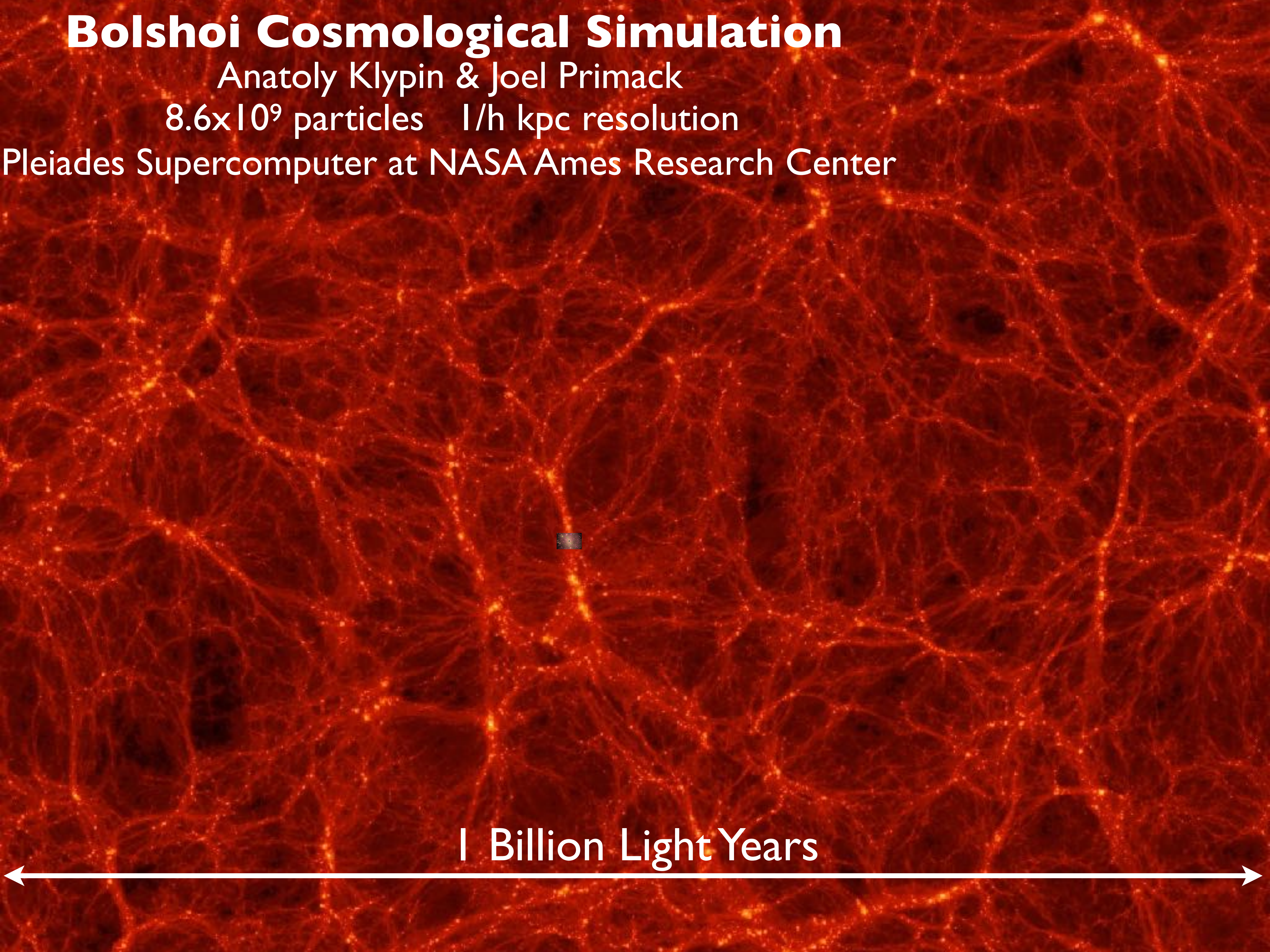


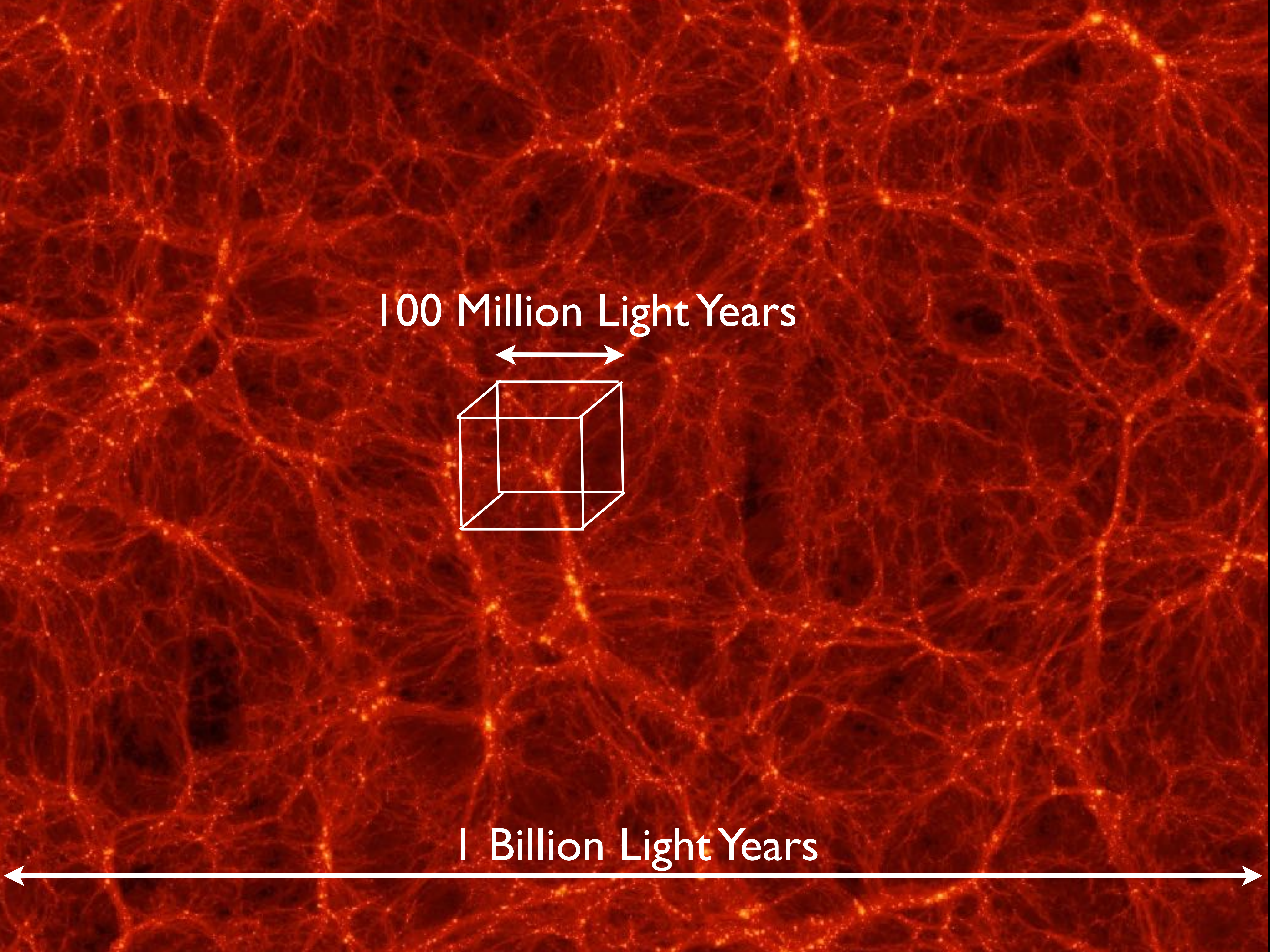
Bolshoi Cosmological Simulation

Anatoly Klypin & Joel Primack

$8.6x10^9$ 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

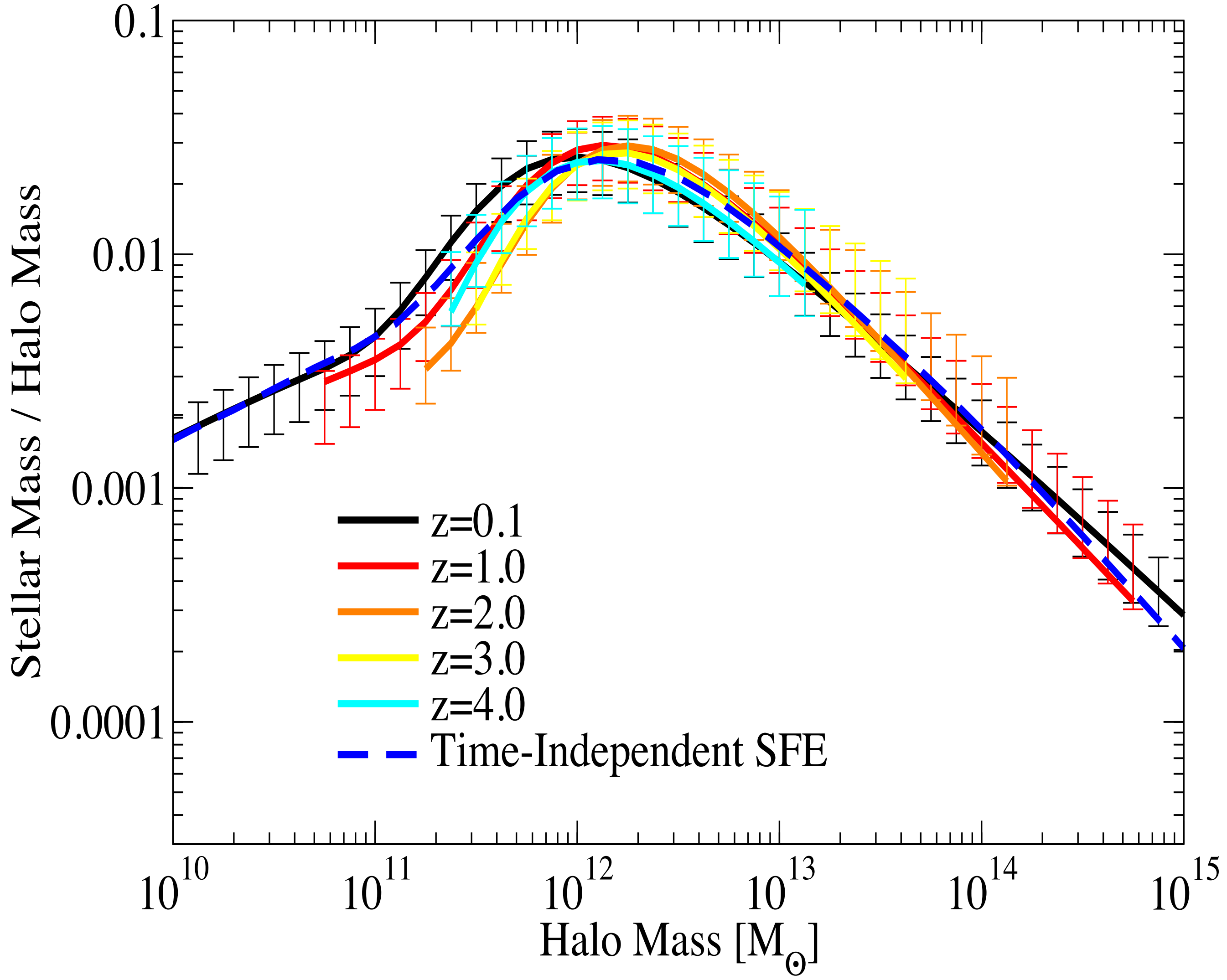
Peter Behroozi & Christoph Lee

Structure Formation Methodology

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

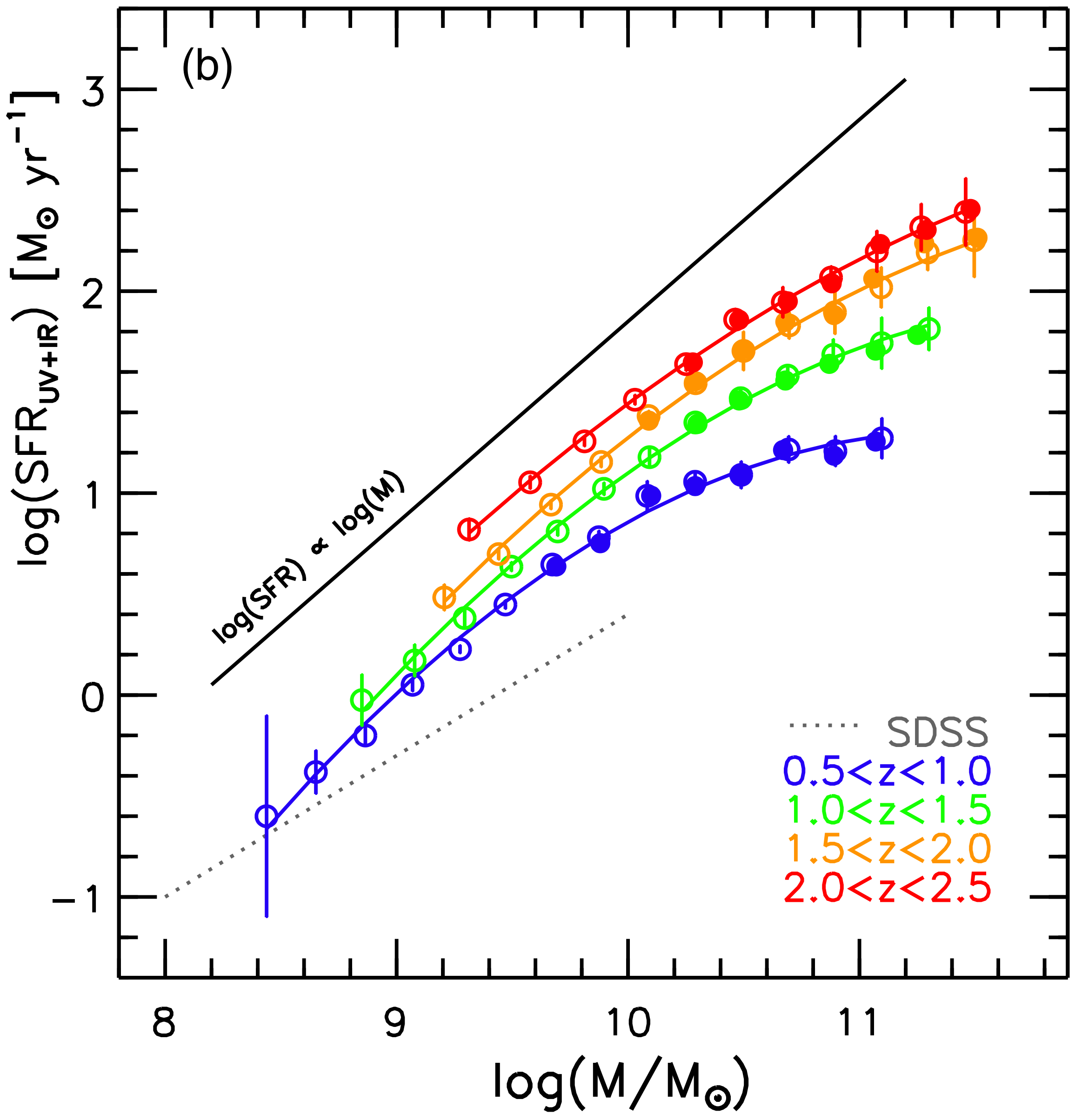
Two Key Discoveries About Galaxies

Relationship Between Galaxy Stellar Mass and Halo Mass



The stellar mass to halo mass ratio at multiple redshifts as derived from observations compared to the Bolshoi cosmological simulation. Error bars show 1σ uncertainties. A time-independent Star Formation Efficiency predicts a roughly **time-independent stellar mass to halo mass relationship**. (Behroozi, Wechsler, Conroy, ApJL 2013)

Star-forming Galaxies Lie on a "Main Sequence"

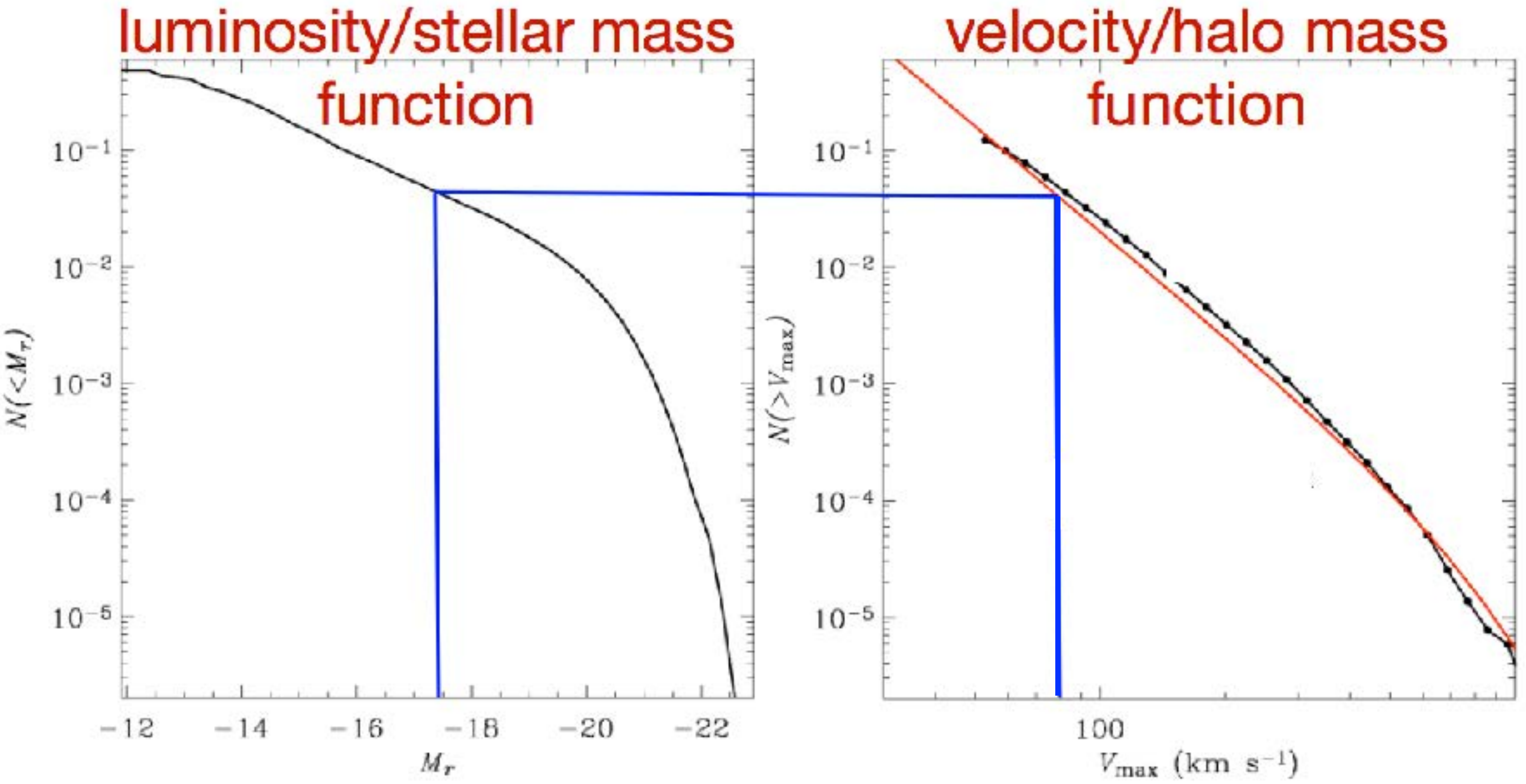


Just as the properties of hydrogen-burning stars are controlled by their mass, **the galaxy star formation rate (SFR) is approximately proportional to the stellar mass**, with the proportionality constant increasing with redshift up to about $z = 2.5$. (Whitaker et al. ApJ 2014)

Constraining the Galaxy Halo Connection: Star Formation Histories, Galaxy Mergers, and Structural Properties

by Aldo Rodriguez-Puebla, Joel Primack, Vladimir Avila-Reese, and Sandra Faber **MNRAS 470, 651 (2017)**

We use results from the Bolshoi-Planck simulation (Aldo Rodriguez-Puebla, Peter Behroozi, Joel Primack, Anatoly Klypin, Christoph Lee, Doug Hellinger 2016, MNRAS 462, 893), including halo and subhalo abundance as a function of redshift and median halo mass growth for halos of given M_{vir} at $z = 0$. Our semi-empirical approach uses **SubHalo Abundance Matching (SHAM)**, which matches the cumulative galaxy stellar mass function (GSMF) to the cumulative stellar mass function to correlate galaxy stellar mass with (sub)halo mass.

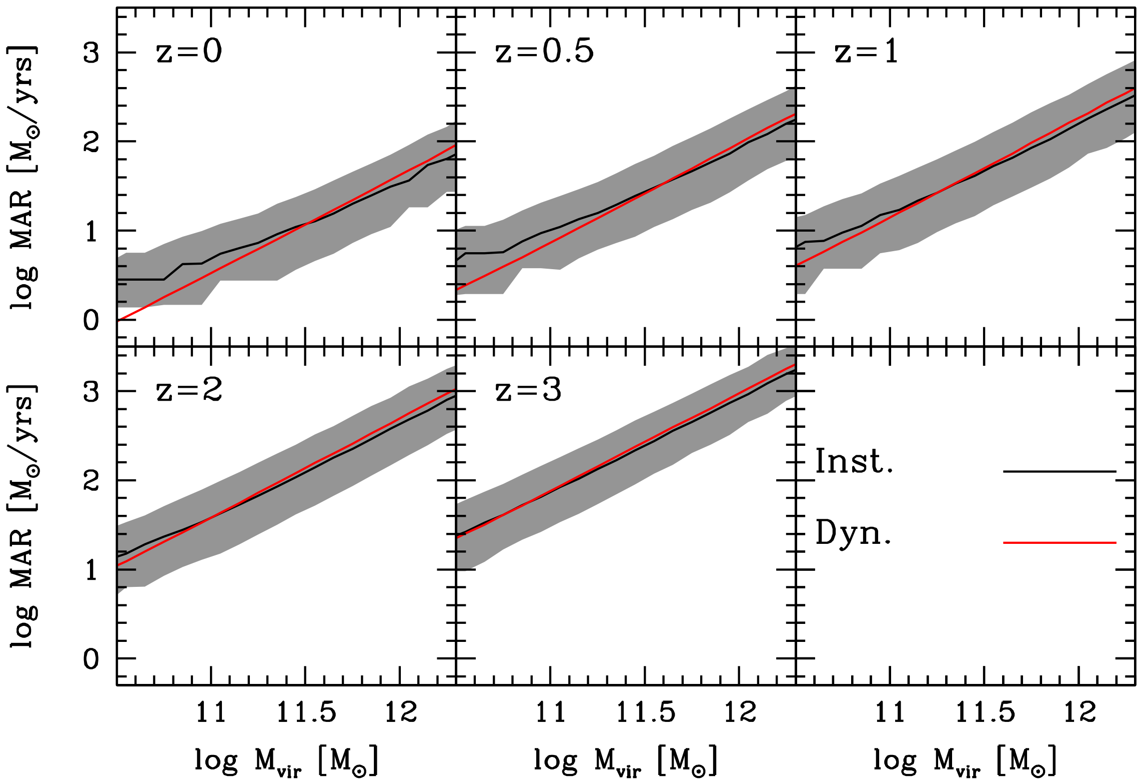


Assumptions: every halo hosts a galaxy, mass growth of galaxies is associated with that of halos

Is Main Sequence SFR Controlled by Halo Mass Accretion?

by Aldo Rodríguez-Puebla, Joel Primack, Peter Behroozi, Sandra Faber **MNRAS 2016**

Halo mass accretion rates z=0 to 3



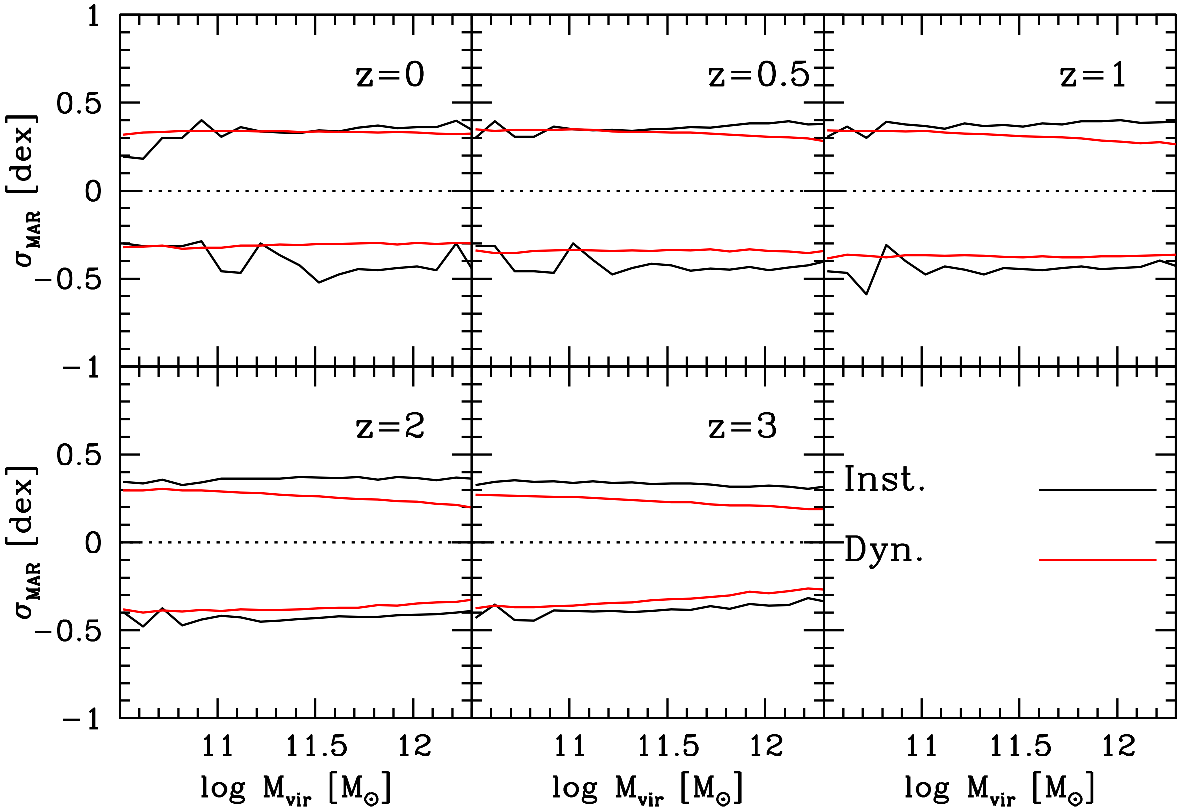
$$\frac{dM_*}{dt} = \frac{\partial M_*(M_{\rm vir}(t), z)}{\partial M_{\rm vir}} \frac{dM_{\rm vir}}{dt} + \frac{\partial M_*(M_{\rm vir}(t), z)}{\partial z} \frac{dz}{dt}$$

but if the M_*–$M_{\rm vir}$ relation is independent of redshift then the stellar mass of a central galaxy formed in a halo of mass $M_{\rm vir}(t)$ is $M_* = M_*(M_{\rm vir}(t))$ and the second term vanishes. From this relation star formation rates are given simply by

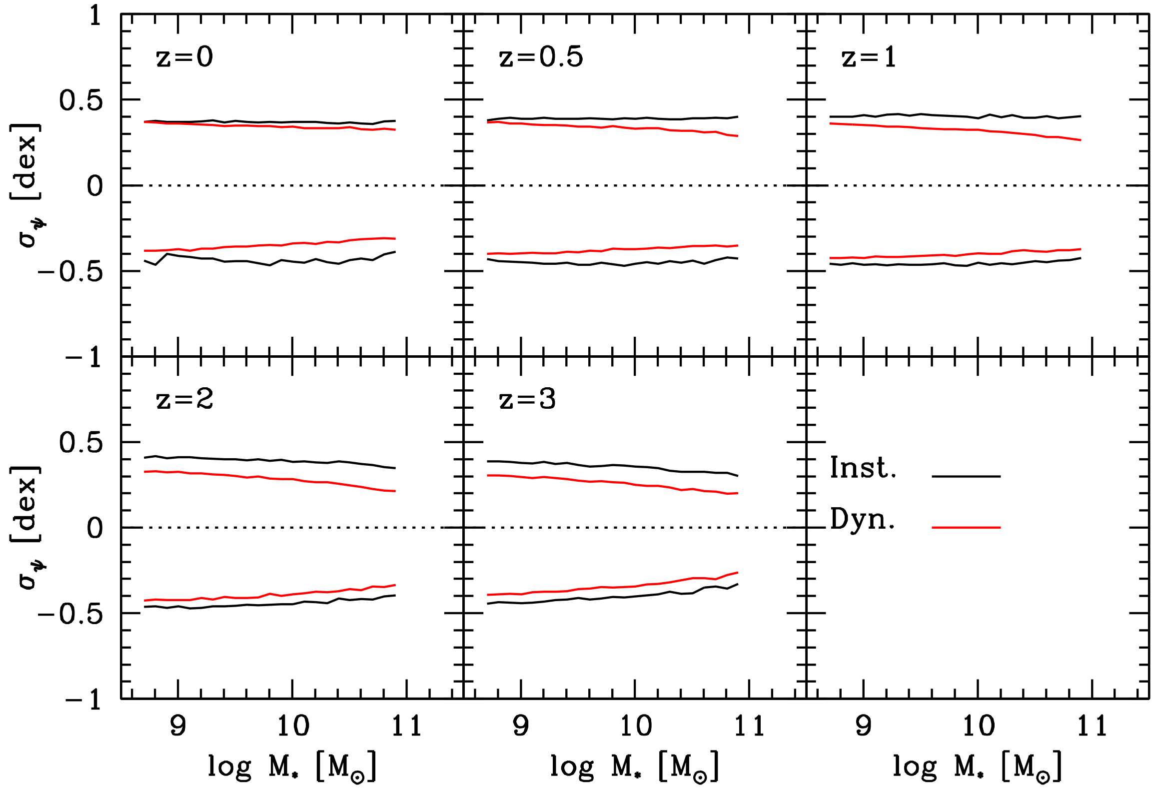
$$\frac{dM_*}{dt} = \frac{\partial M_*(M_{\rm vir}(t), z)}{\partial M_{\rm vir}} \frac{dM_{\rm vir}}{dt} = f_* \frac{d\log M_*}{d\log M_{\rm vir}} \frac{dM_{\rm vir}}{dt},$$

where $f_* = M_*/M_{\rm vir}$. We call this **Stellar-Halo Accretion Rate Coevolution (SHARC)** if true halo-by-halo for star-forming galaxies.

Scatter of halo mass accretion rates



Implied scatter of star formation rates

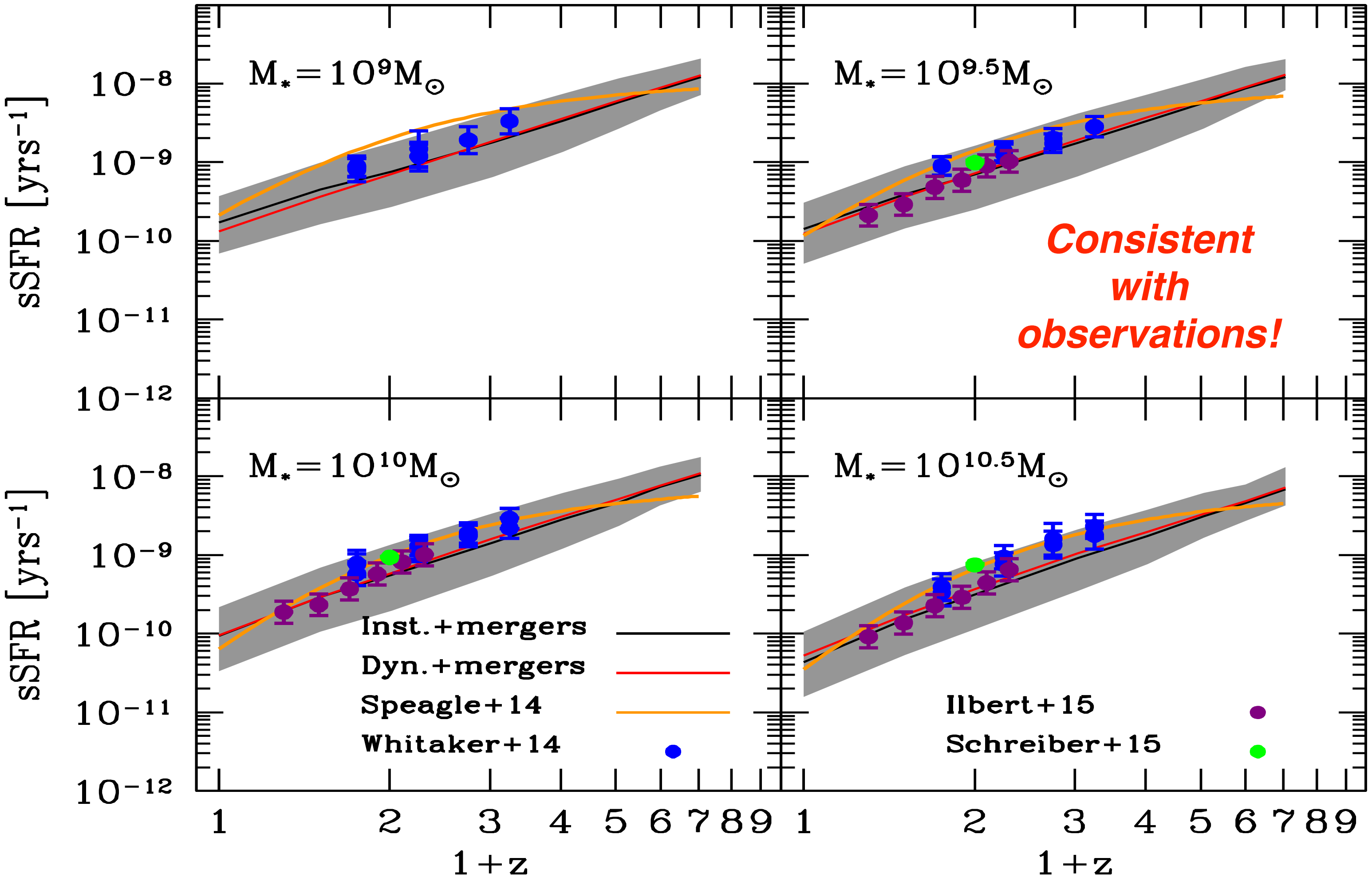


Consistent with observations!

Is Main Sequence SFR Controlled by Halo Mass Accretion?

by Aldo Rodríguez-Puebla, Joel Primack, Peter Behroozi, Sandra Faber **MNRAS 2016**

SHARC correctly predicts star formation rates to z ~ 4



Consistent with observations!

SHARC predicts "Age Matching" (blue galaxies in accreting halos) & "Galaxy SFR Conformity" at low z

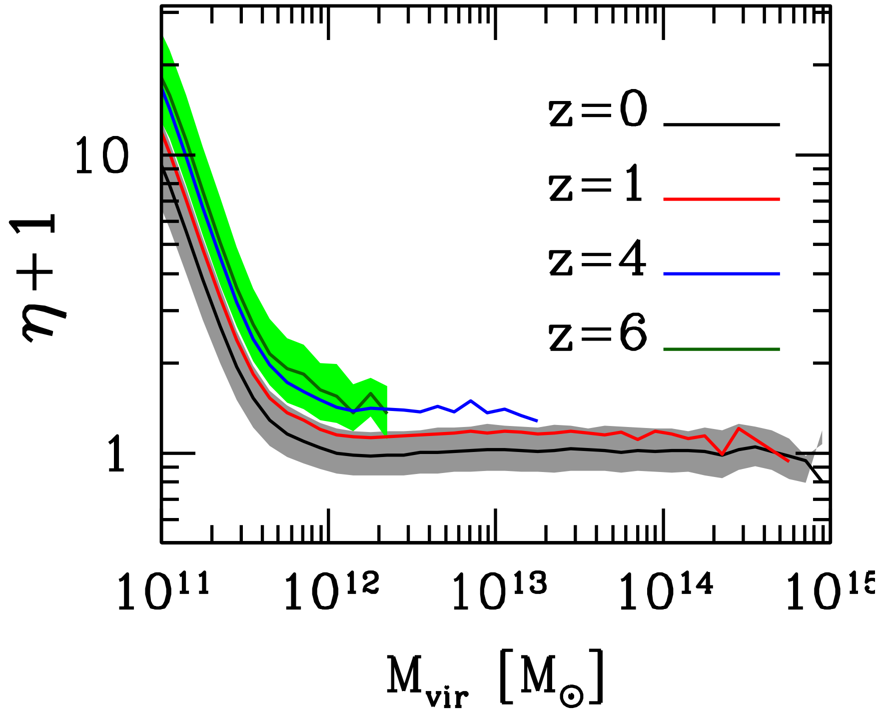
Open Questions:

Extend SHARC to higher-mass galaxies

Also take quenching into account

Does SHARC correctly predict the growth rate of central galaxy stellar mass from the accretion rate of their halos? Test this in simulations!

We put **SHARC** in "bathtub" equilibrium models of galaxy formation & predict mass loading and metallicity evolution



Net mass loading factor η from an equilibrium bathtub model (E+SHARC)

Does the Galaxy-Halo Connection Vary with Environment?

Radu Dragomir, Aldo Rodriguez-Puebla, Joel Primack, Christoph Lee

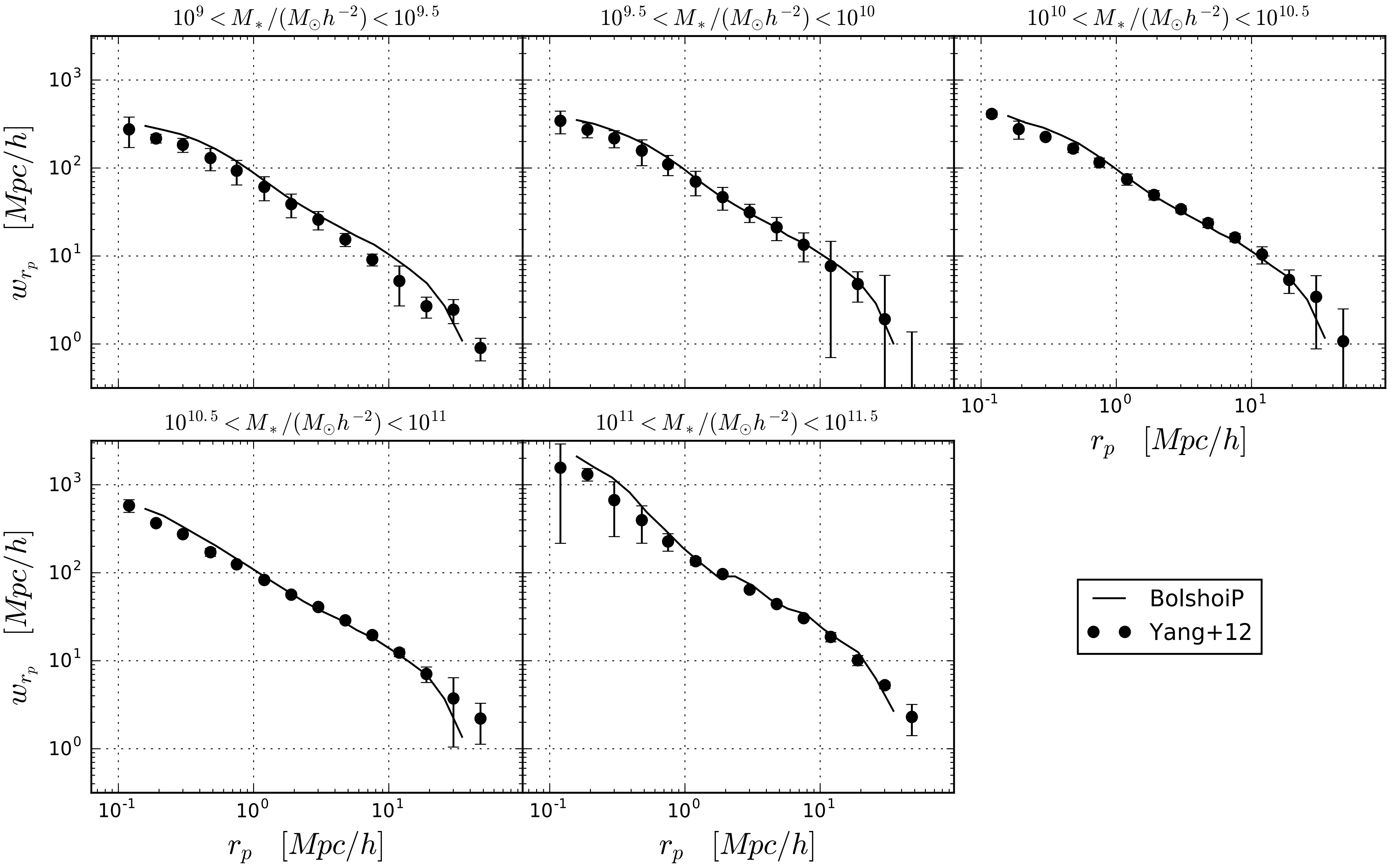


Figure 5. Two-point correlation function in five stellar mass bins. The solid lines show the predicted two-point correlation based on our stellar mass-to-$V_{\max}$ relation from SHAM, while the circles with error bars show the same but for SDSS DR7 (Yang et al. 2012).

Does the Galaxy-Halo Connection Vary with Environment?

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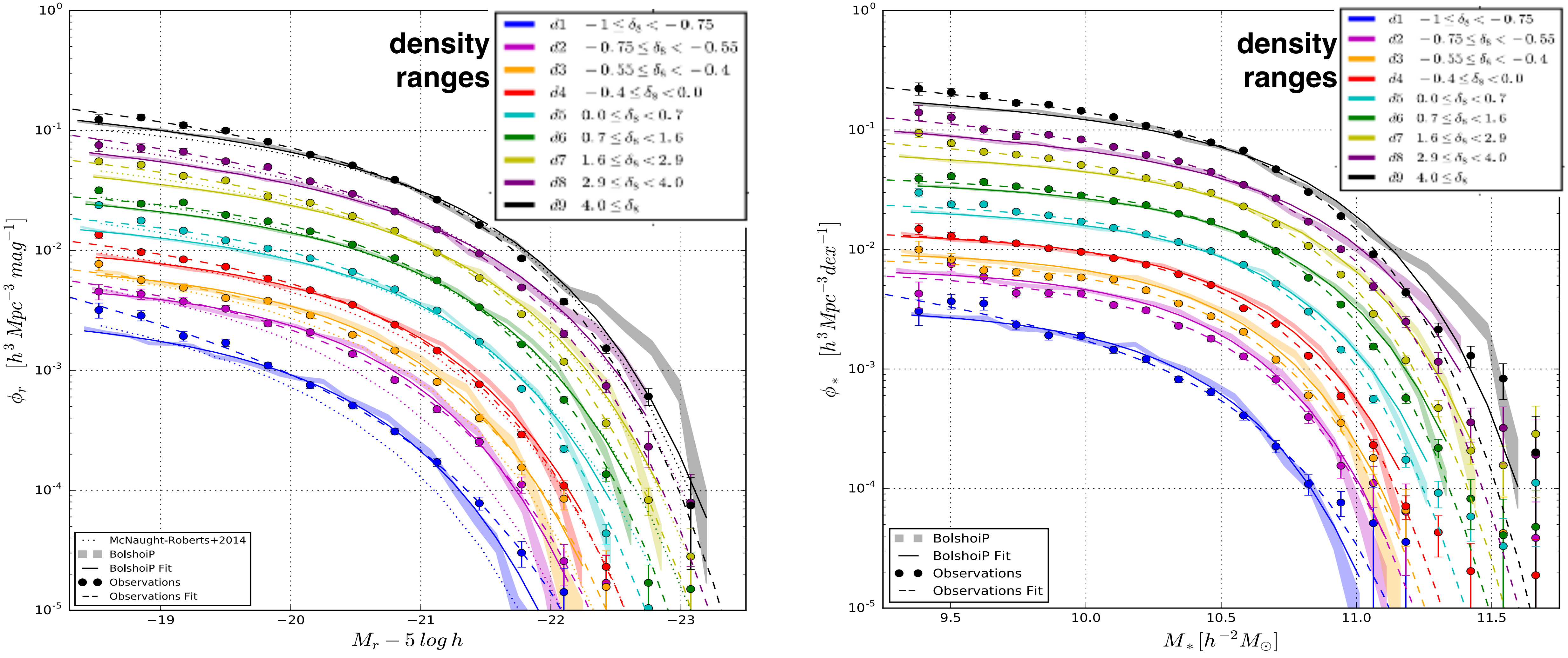
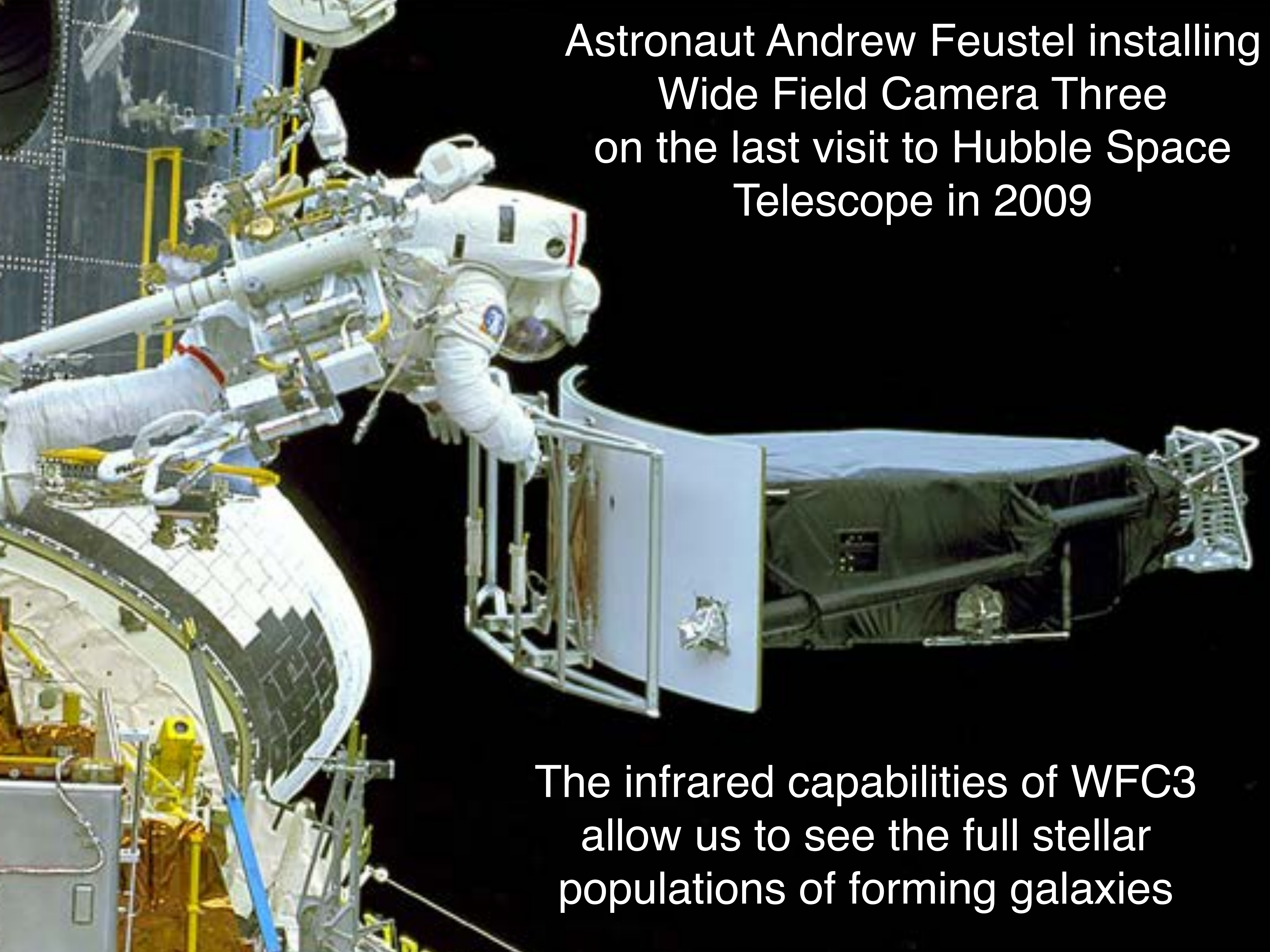


r-Band Luminosity Function

Stellar Mass Function

Figure 7. Left Panel: Comparison between the observed $r-$band GLF with environmental density in spheres of 8 h^{-1}Mpc, filled circles with error bars, and the ones predicted based on the BolshoiP simulation from SHAM, shaded regions. The dashed lines show the best fitting Schechter functions to the r-band GLFs from the GAMA survey (McNaught-Roberts et al. 2014). **Right Panel:** Similar to the left panel but for the GSMF with environmental density. Here again the dashed lines are the best fitting Schechter functions.

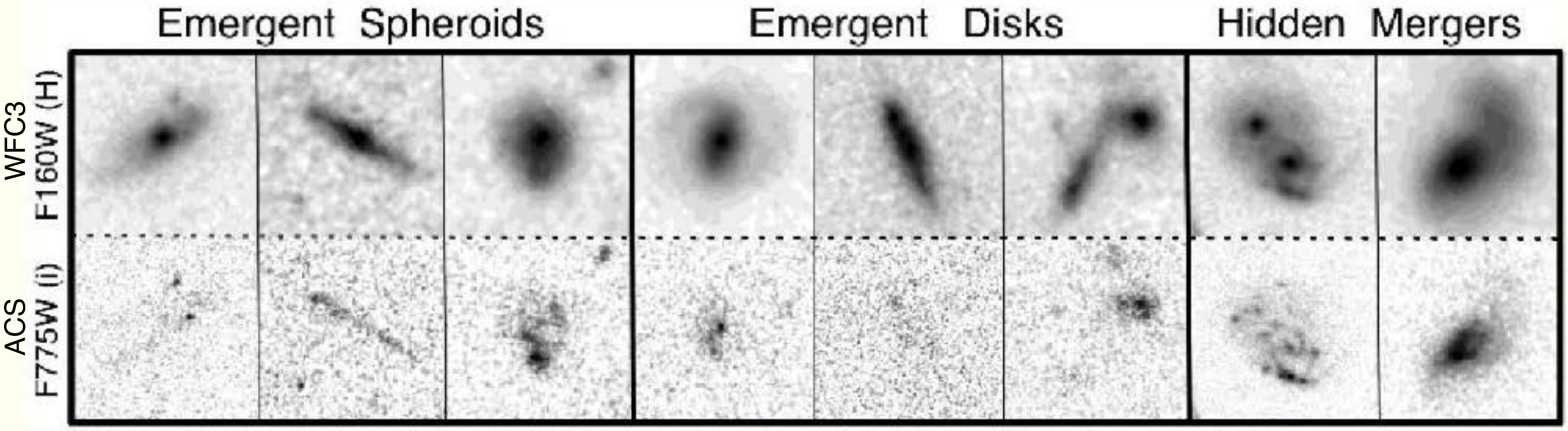


Astronaut Andrew Feustel installing
Wide Field Camera Three
on the last visit to Hubble Space
Telescope in 2009

The infrared capabilities of WFC3
allow us to see the full stellar
populations of forming galaxies

The CANDELS Survey

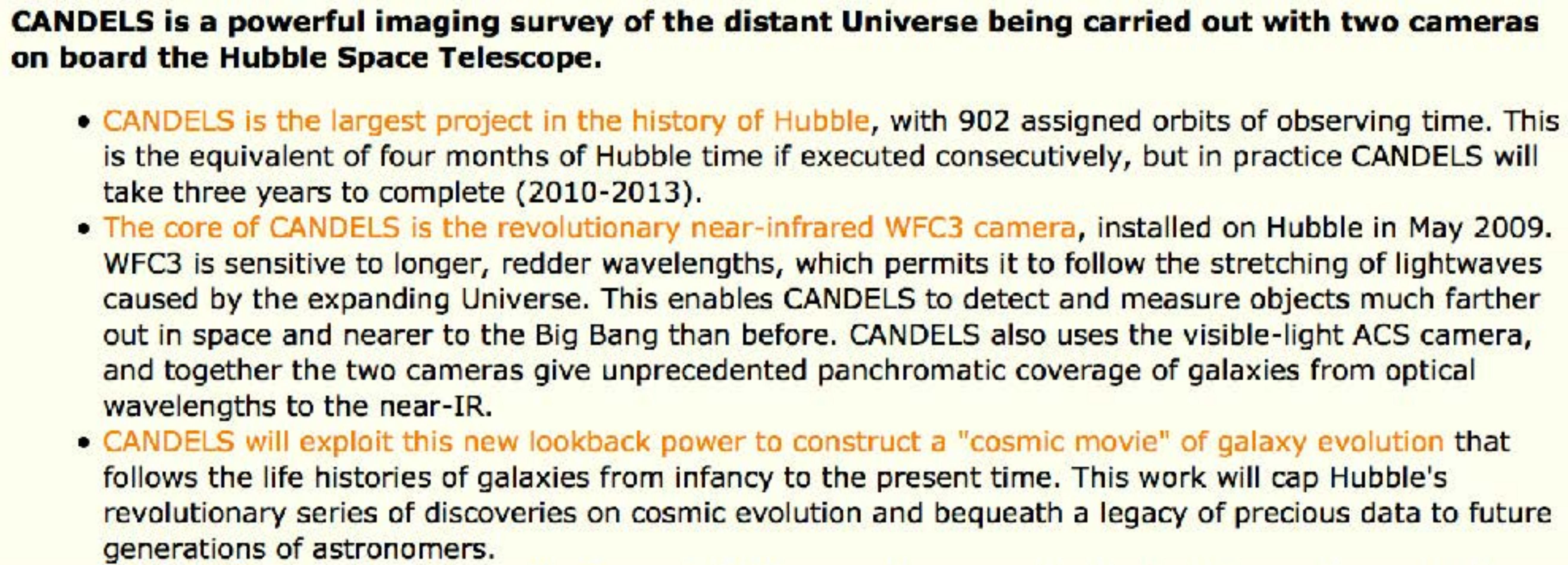
candels.ucolick.org



CANDELS: A Cosmic Odyssey

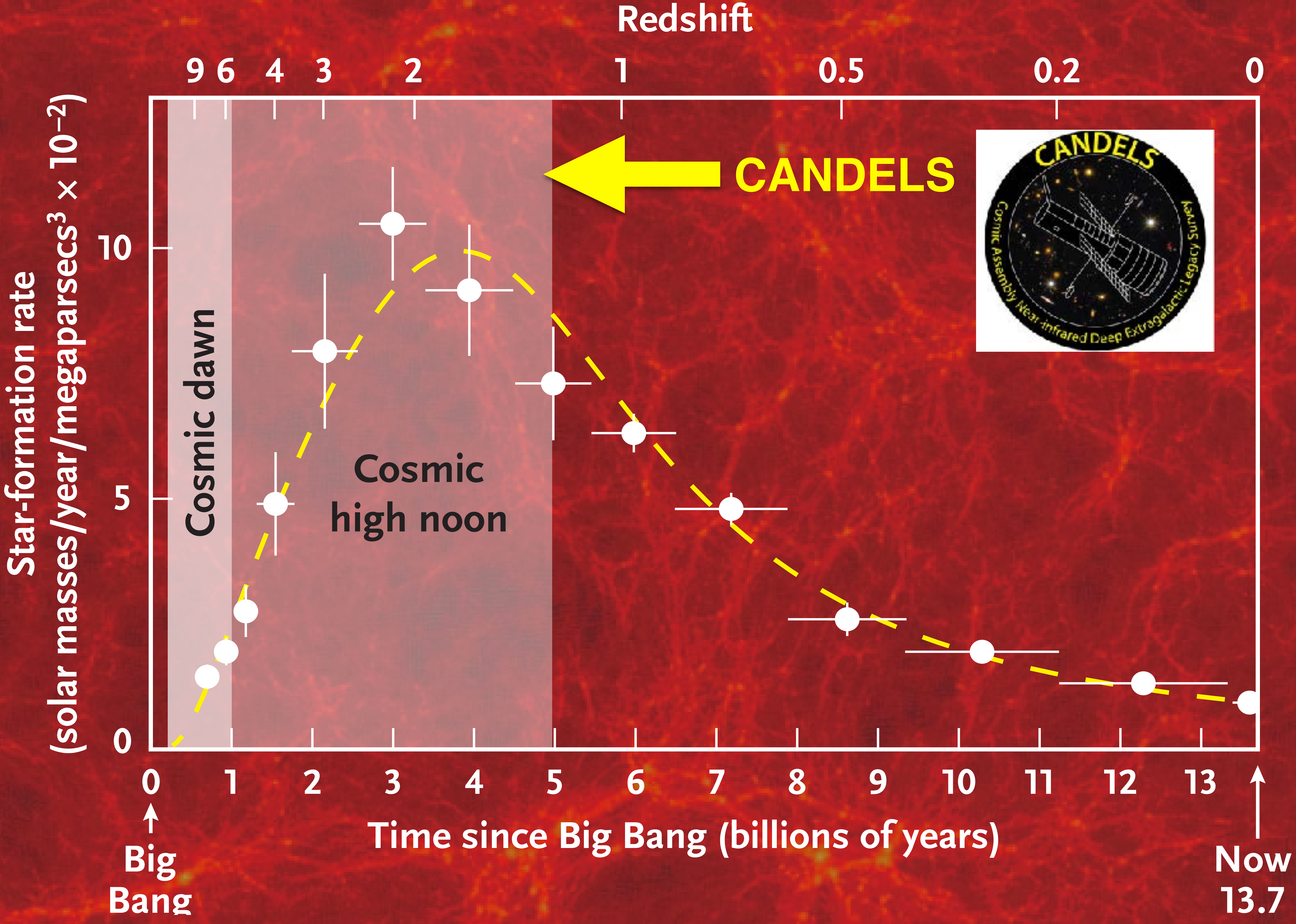
$(\text{blue } 0.4\ \mu\text{m})(1+z) = 1.6\ \mu\text{m}$ @ $z = 3$

$(\text{red } 0.7\ \mu\text{m})(1+z) = 1.6\ \mu\text{m}$ @ $z = 2.3$



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.



CANDELS

CANDELS

Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey

Most astronomers used to think

(1) that galaxies form as disks,

(2) that forming galaxies are pretty smooth, and

(3) that galaxies generally grow in radius as they grow in mass.

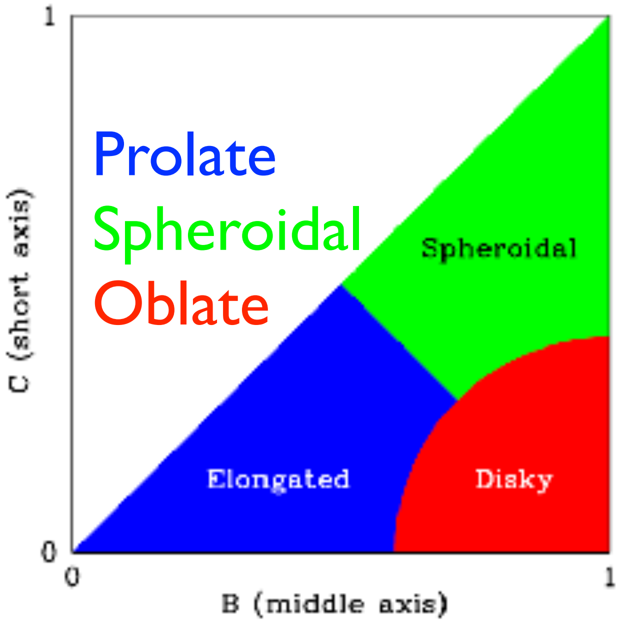
But CANDELS and other HST observations show that all these statements are questionable!

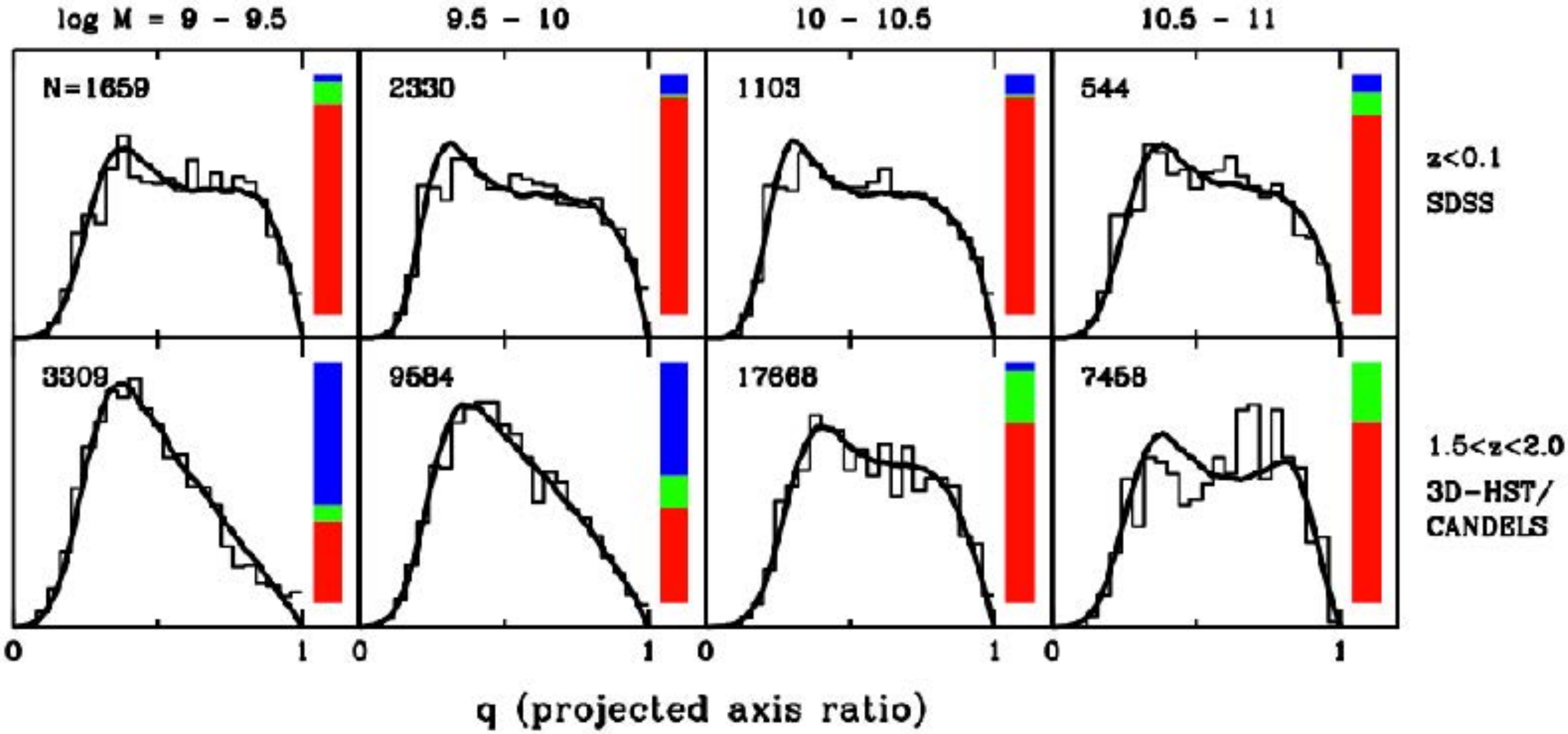
(1) The majority of star-forming galaxies at $z > 1$ apparently have mostly elongated (prolate) stellar distributions rather than disks or spheroids, and our simulations may explain why.

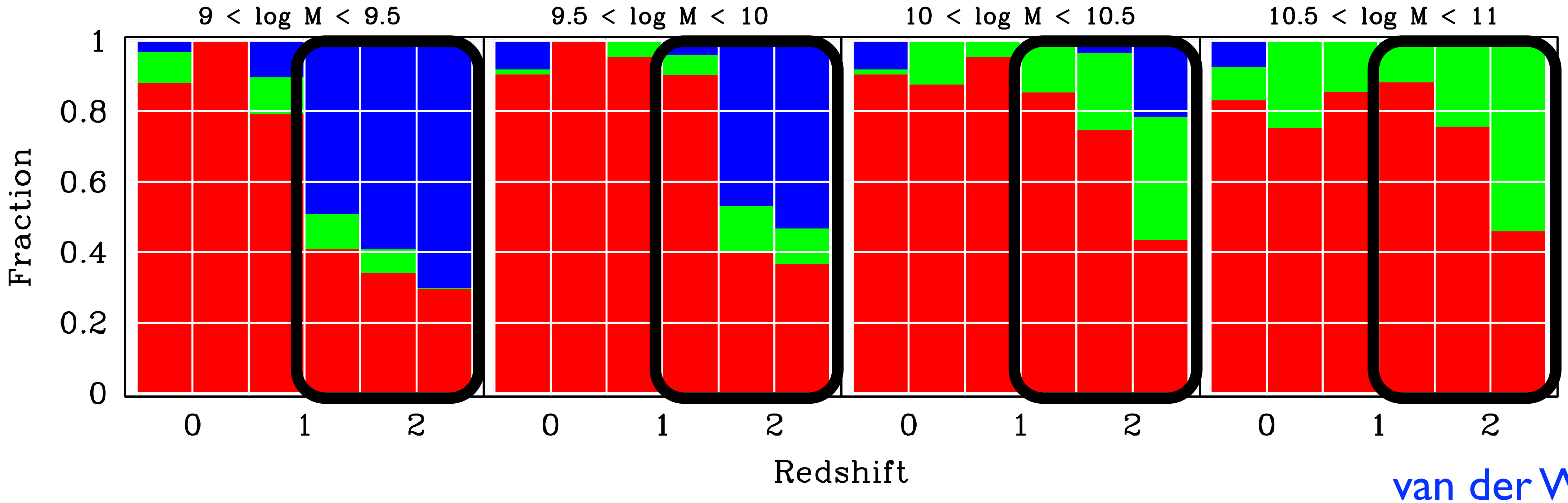
(2) A large fraction of star-forming galaxies at redshifts $1 < z < 3$ are found to have massive stellar clumps; these originate from phenomena including mergers and disk instabilities in our simulations.

(3) These phenomena also help to create compact stellar spheroidal galaxies ("nuggets") through galaxy compaction (rapid inflow of gas to galaxy centers, where it forms stars).

Prolate Galaxies Dominate at High Redshifts & Low Masses







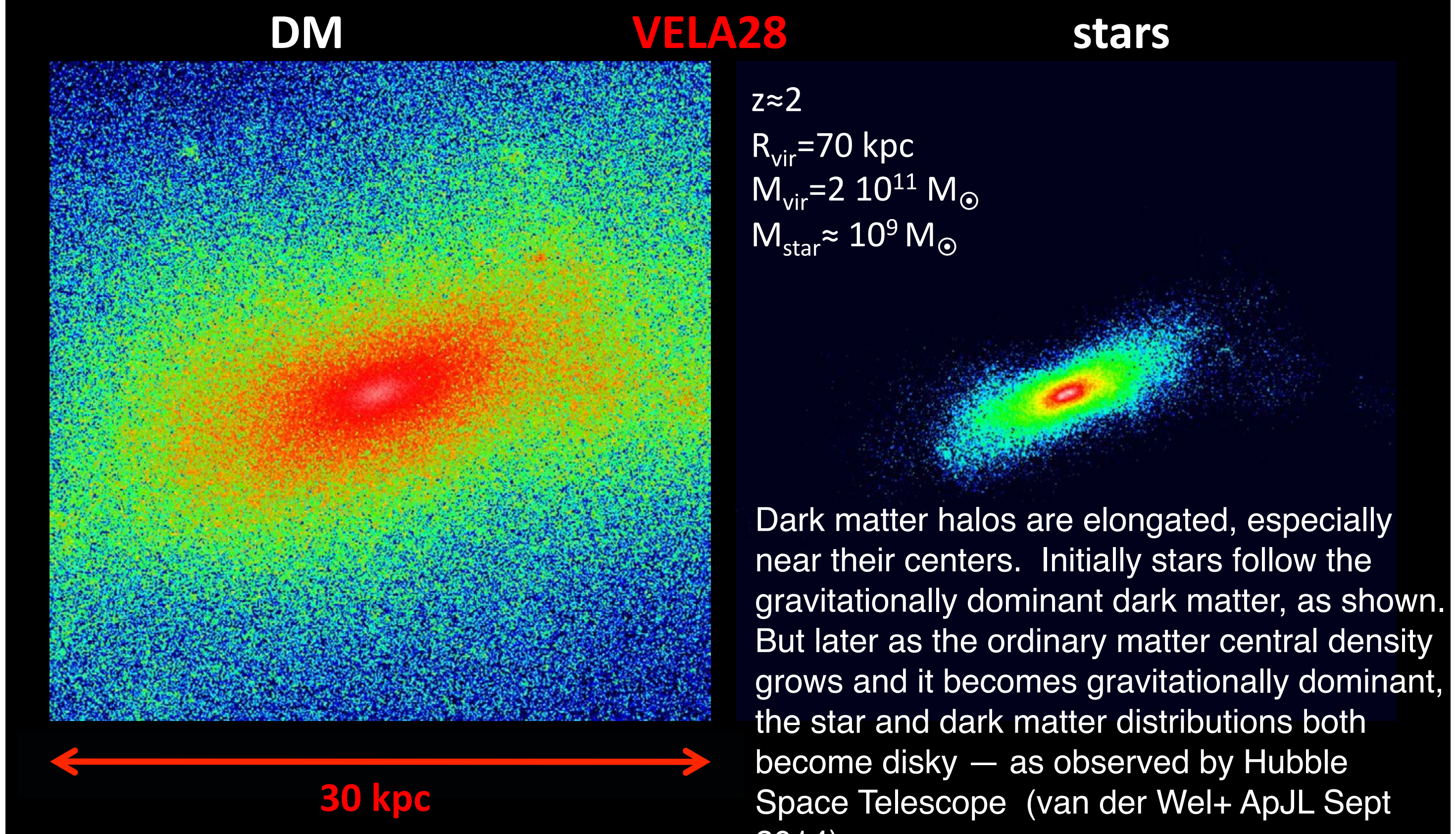
van der Wel+2014

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

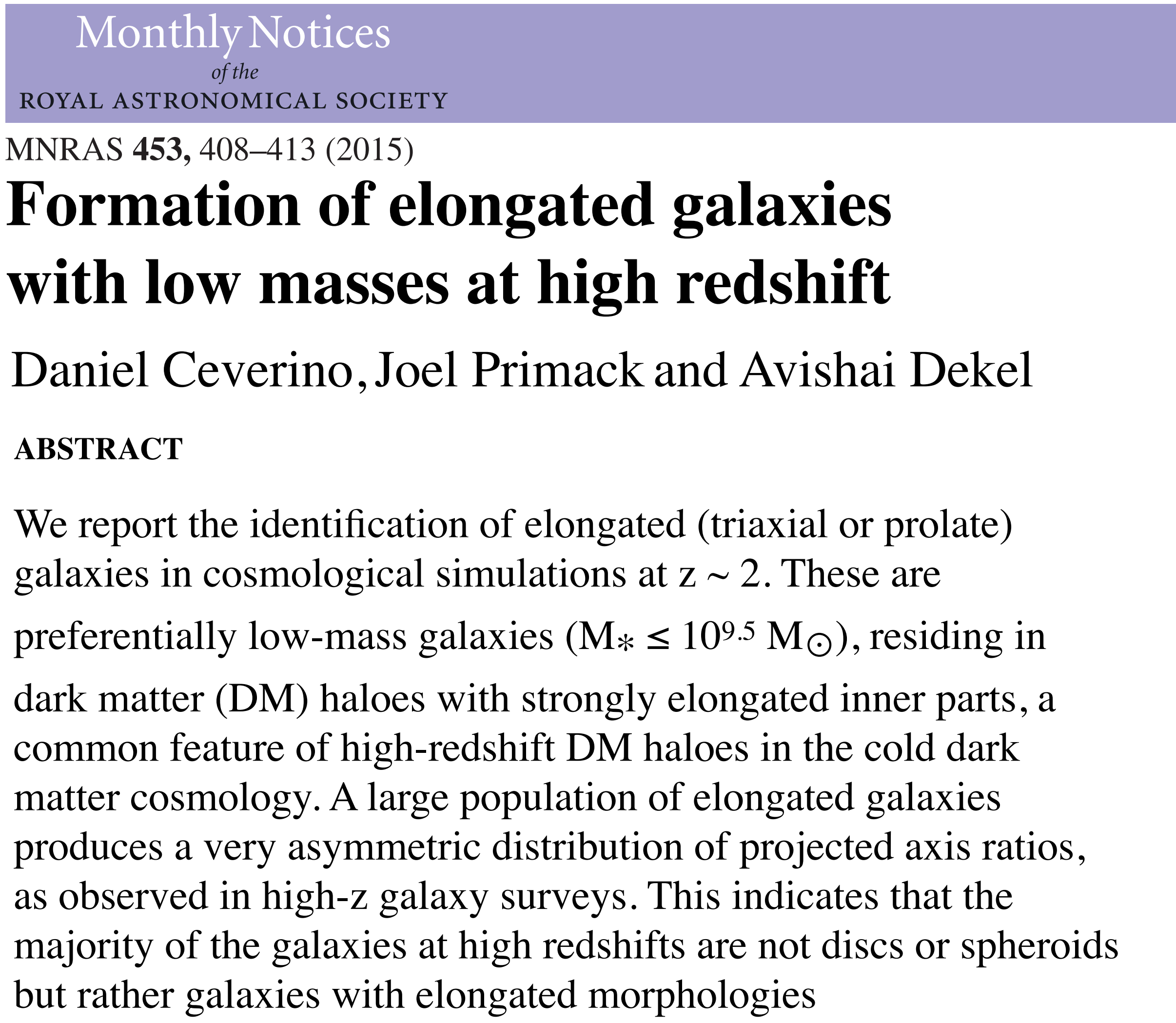
Our cosmological zoom-in simulations often produce elongated galaxies like observed ones. The elongated stellar distribution follows the elongated inner dark matter halo.

Prolate DM halo → elongated galaxy



z≈2
R_{vir}=70 kpc
M_{vir}=2 10^{11} $M_\odot$
$M_{star}\approx 10^9 M_\odot$

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).



Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

MNRAS **453,** 408–413 (2015)

Formation of elongated galaxies with low masses at high redshift

Daniel Ceverino, Joel Primack and Avishai Dekel

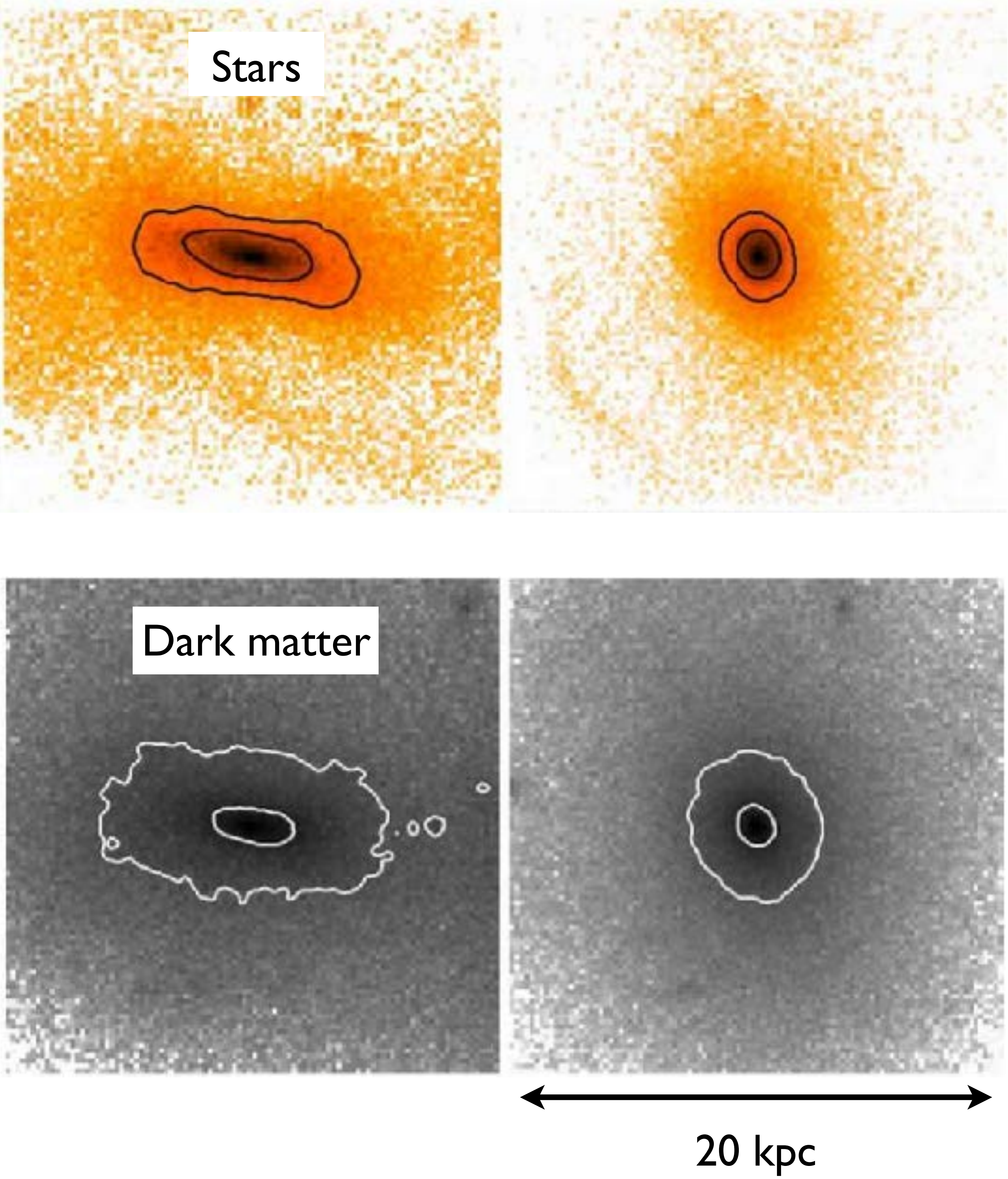
ABSTRACT

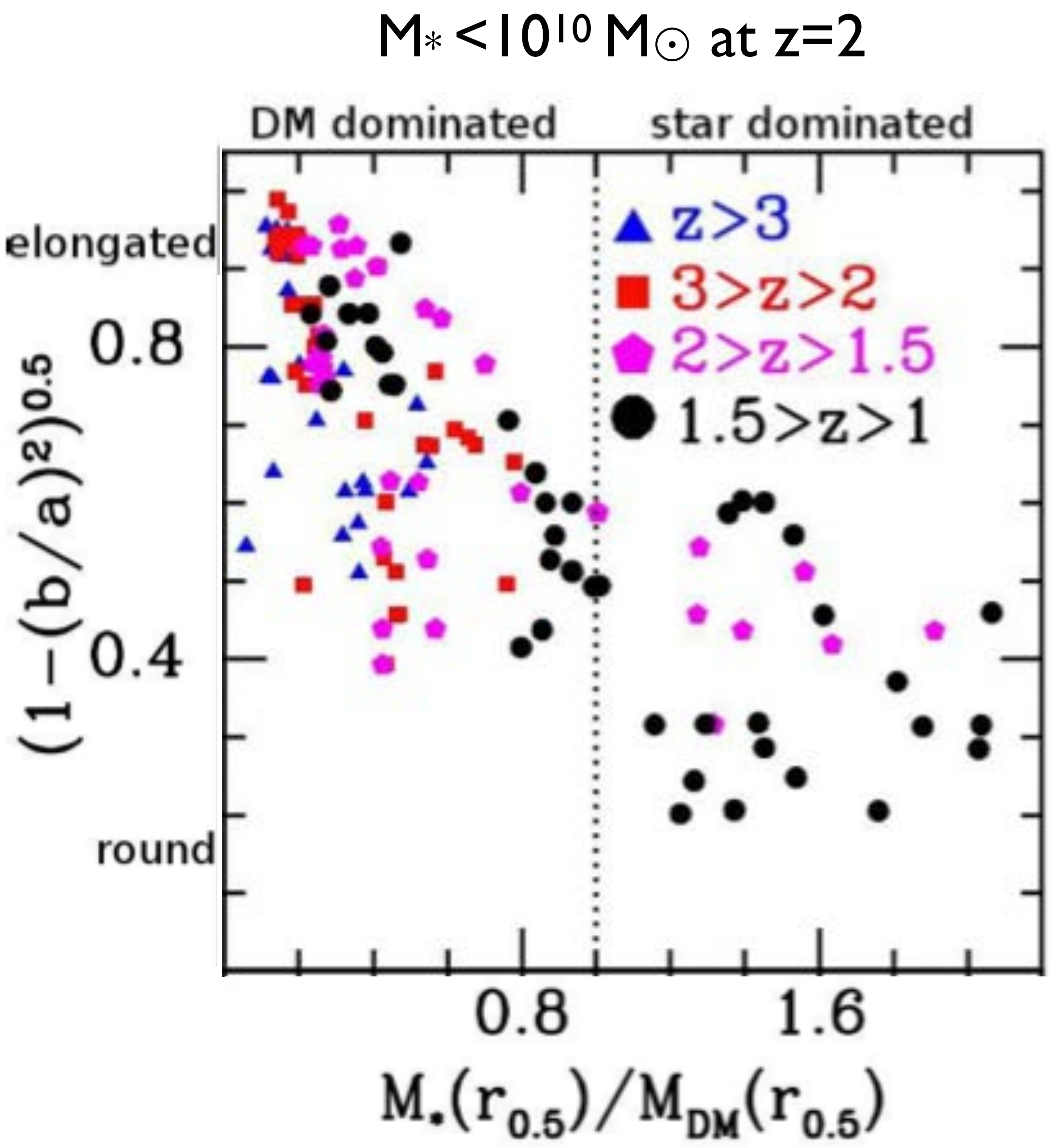
We report the identification of elongated (triaxial or prolate) galaxies in cosmological simulations at z ~ 2. These are preferentially low-mass galaxies ($M_* \leq 10^{9.5}$ $M_\odot$), residing in dark matter (DM) haloes with strongly elongated inner parts, a common feature of high-redshift DM haloes in the cold dark matter cosmology. A large population of elongated galaxies produces a very asymmetric distribution of projected axis ratios, as observed in high-z galaxy surveys. This indicates that the majority of the galaxies at high redshifts are not discs or spheroids but rather galaxies with elongated morphologies

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

Formation of elongated galaxies with low masses at high redshift

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





Also Tomassetti et al. 2016 MNRAS

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

Science and Technology Policy

Partly inspired by Sid’s devotion to science and technology policy,

I started Stanford Workshops on Political and Social Issues (SWOPSI) with Joyce Kobayashi and Bob Jaffe in 1969, and I helped to start the following spherically sensible programs

the APS Forum on Physics and Society (FPS) 1972

the program of APS Studies on Public Policy Issues 1973

the Congressional Science and Technology Fellowship program 1973

the AAAS Program on Science and Human Rights 1976

the NSF Science for Citizens Program 1977

Later on I led the Federation of American Scientists project that helped convince the USSR to end its RORSAT program of nuclear reactor powered radar satellites 1987-90. I chaired the AAAS Committee on Science, Ethics, and Religion 2000-2002, led a POPA study in 2004, chaired FPS in 2005, …

Science and Technology Policy

After I received the APS Leo Szilard Lectureship Award in 2016, I was asked to run for two leadership positions, and I'm now Vice Chair of FPS again and President-Elect of Sigma Xi, the scientific research honor society, which publishes ***American Scientist*** magazine. In these new roles, I have been thinking of ways that we scientists can improve the public appreciation of scientific research, and the importance of taking scientific information into account in decision making. I want to share one of these ideas with you, and challenge you to think of additional ones.

We can't depend on just a few public spokespeople like Bill Nye and Neil deGrasse Tyson to explain and defend science. Sigma Xi could expand its Distinguished Lectureship program to include **younger and more diverse scientists who are chosen for being especially effective at reaching a broad pubic audience**. Going further, Sigma Xi could work with other scientific societies to create a speakers bureau to help find audiences and media opportunities for these science speakers, we could also curate best science videos for a broad audience.