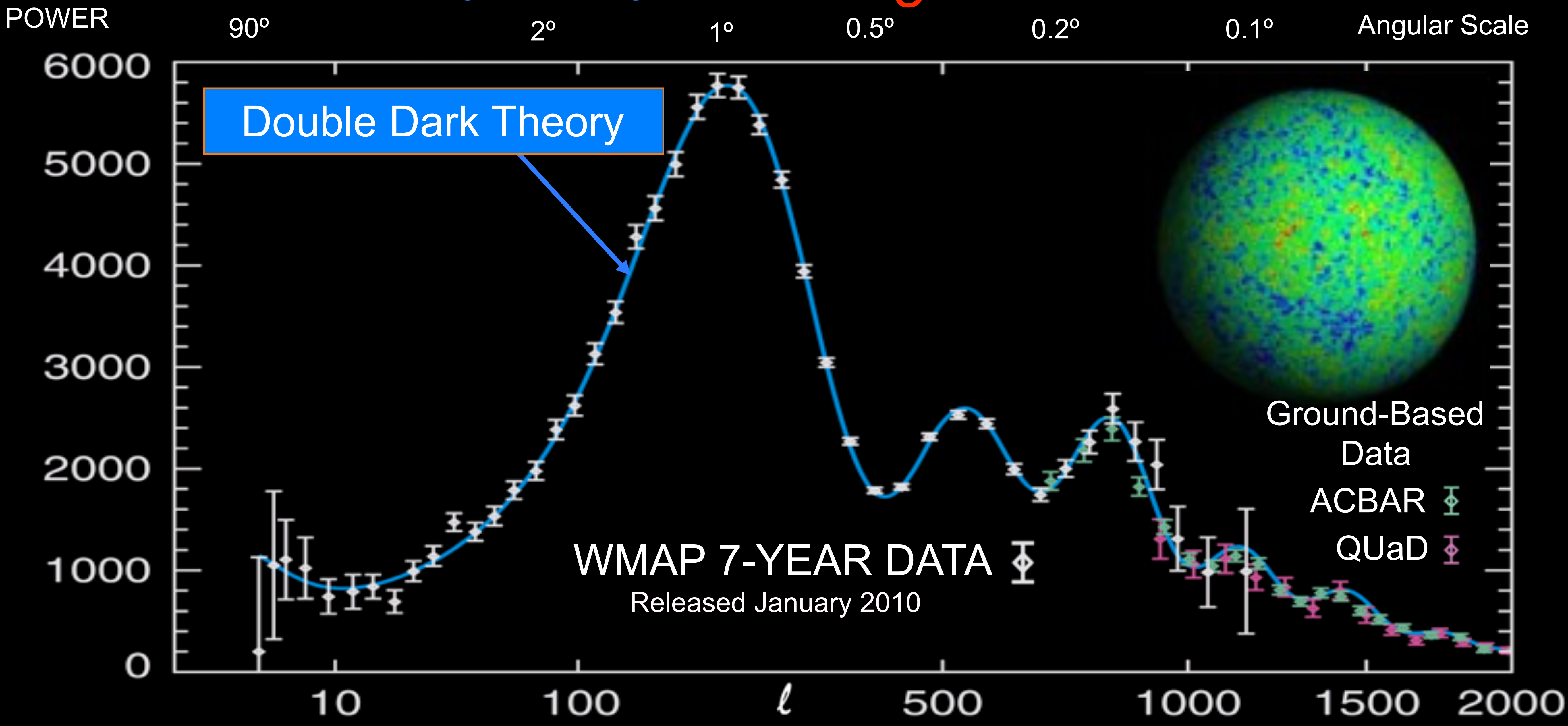
UC Irvine special astro seminar 15 June 2010

SIMULATING AND VISUALIZING THE UNIVERSE

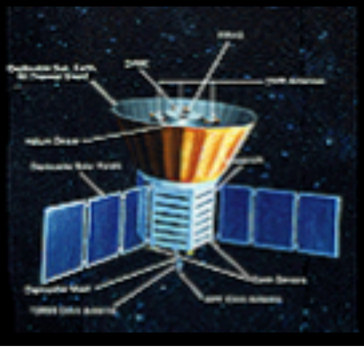
JOEL PRIMACK, UCSC

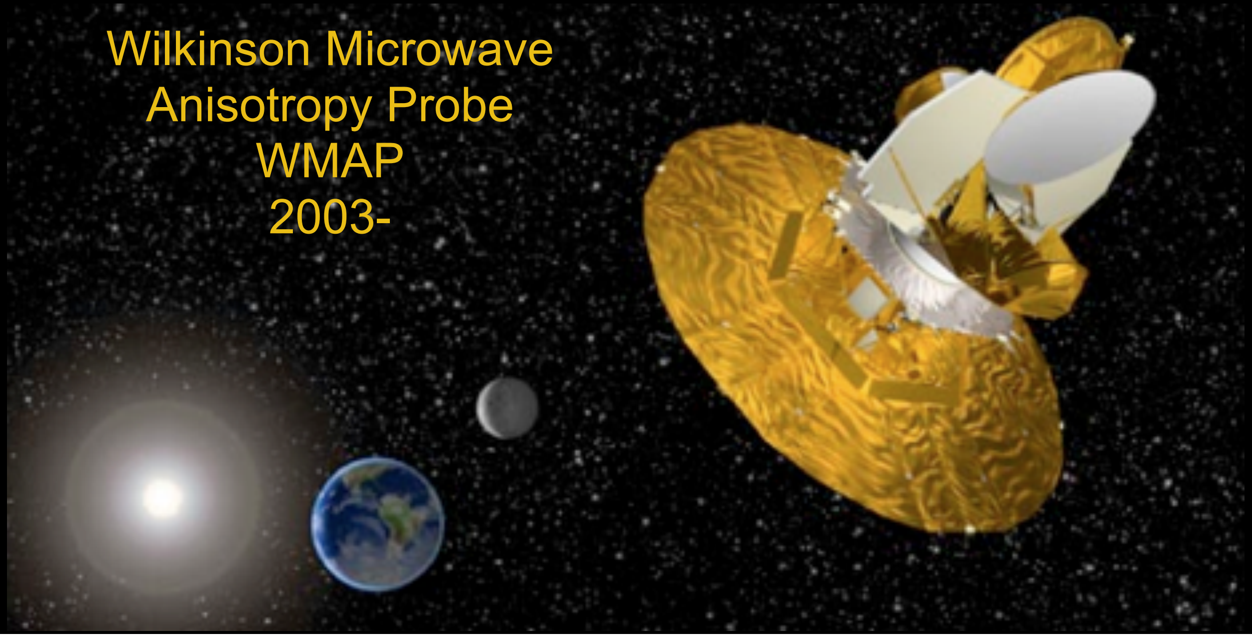
ΛCDM "Double Dark" theory agrees with observations
Bolshoi Cosmological Simulations
Halo Abundance Matching (HAM) vs. Observations
Halo Merger Trees are the basis for Semi-Analytic Models
High-Resolution Galaxy Simulations, to compare with
AEGIS multiwavelength and CANDELS HST surveys
High-Performance AstroComputing Center (UC-HIPACC)
Education and Public Outreach with Planetariums

Big Bang Data Agrees with ΛCDM



Cosmic
Background
Explorer
COBE
1992

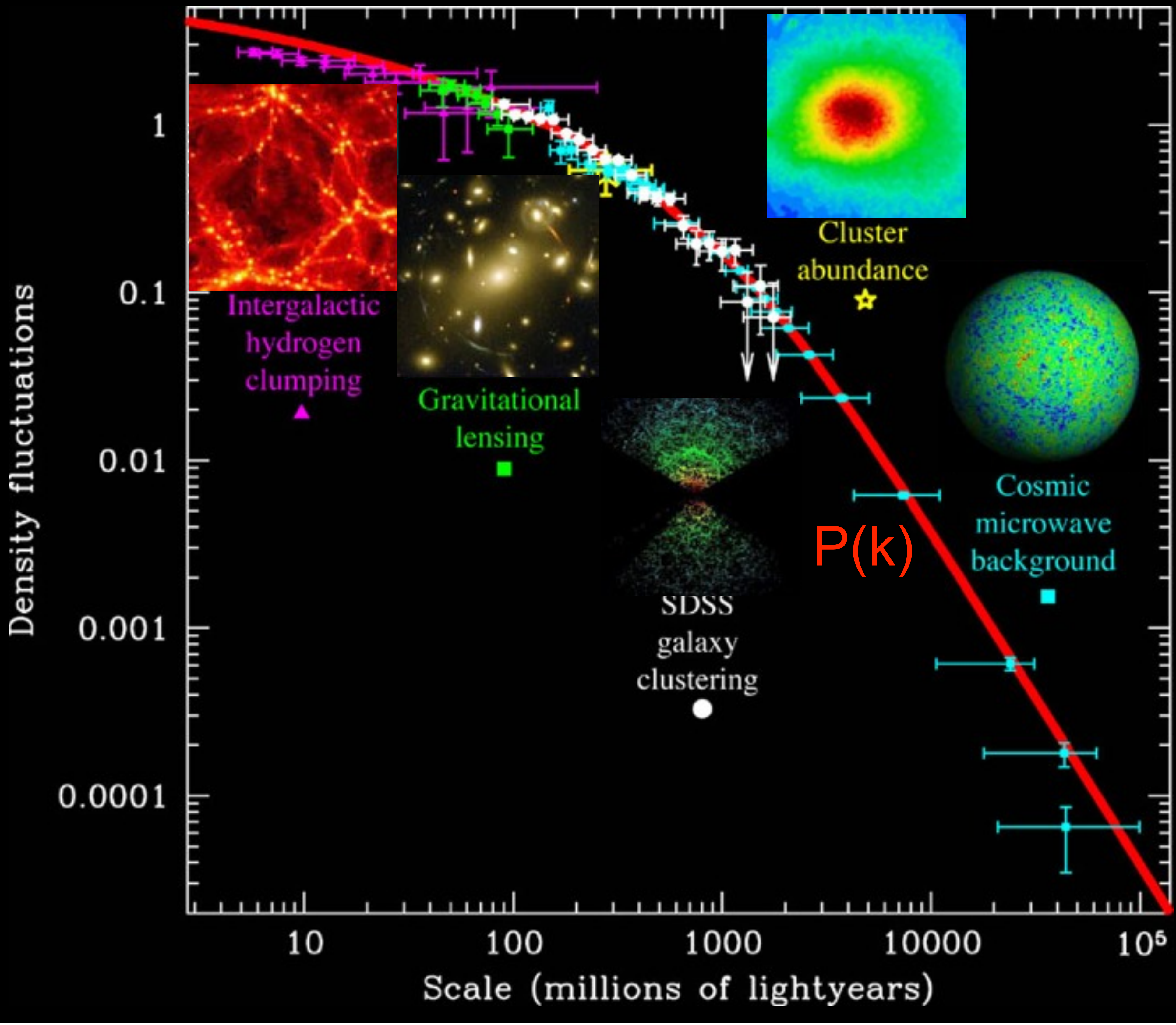




Wilkinson Microwave
Anisotropy Probe
WMAP
2003-

Distribution of Matter

Agrees with ΛCDM



Max Tegmark

Periodic Table
of Metals

Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn		- -		- -		- -
		Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu		
		Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr		

Light blue - Big Bang

Pink - Small Stars

Purple - Supernovae

Green - Cosmic Rays

Blue - Large Stars

Dull gray - Made in Lab

stardust

stars

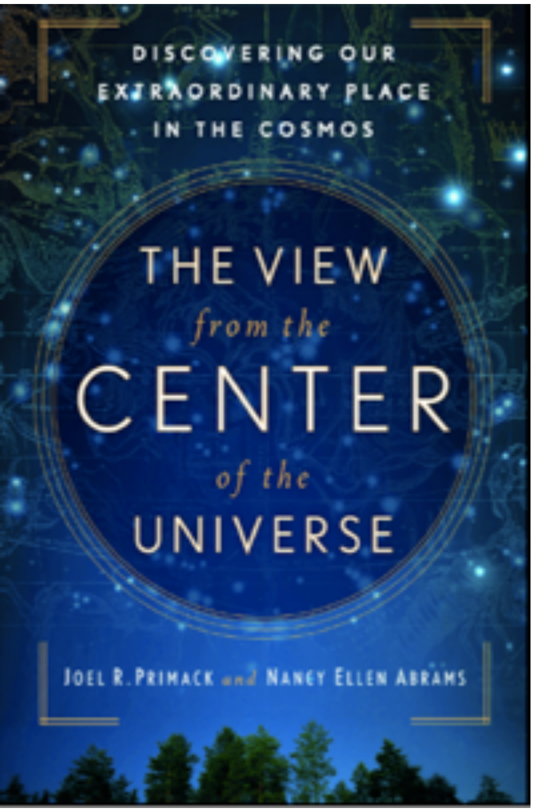
stardust

stars

COSMIC DENSITY PYRAMID

http://viewfromthecenter.com/

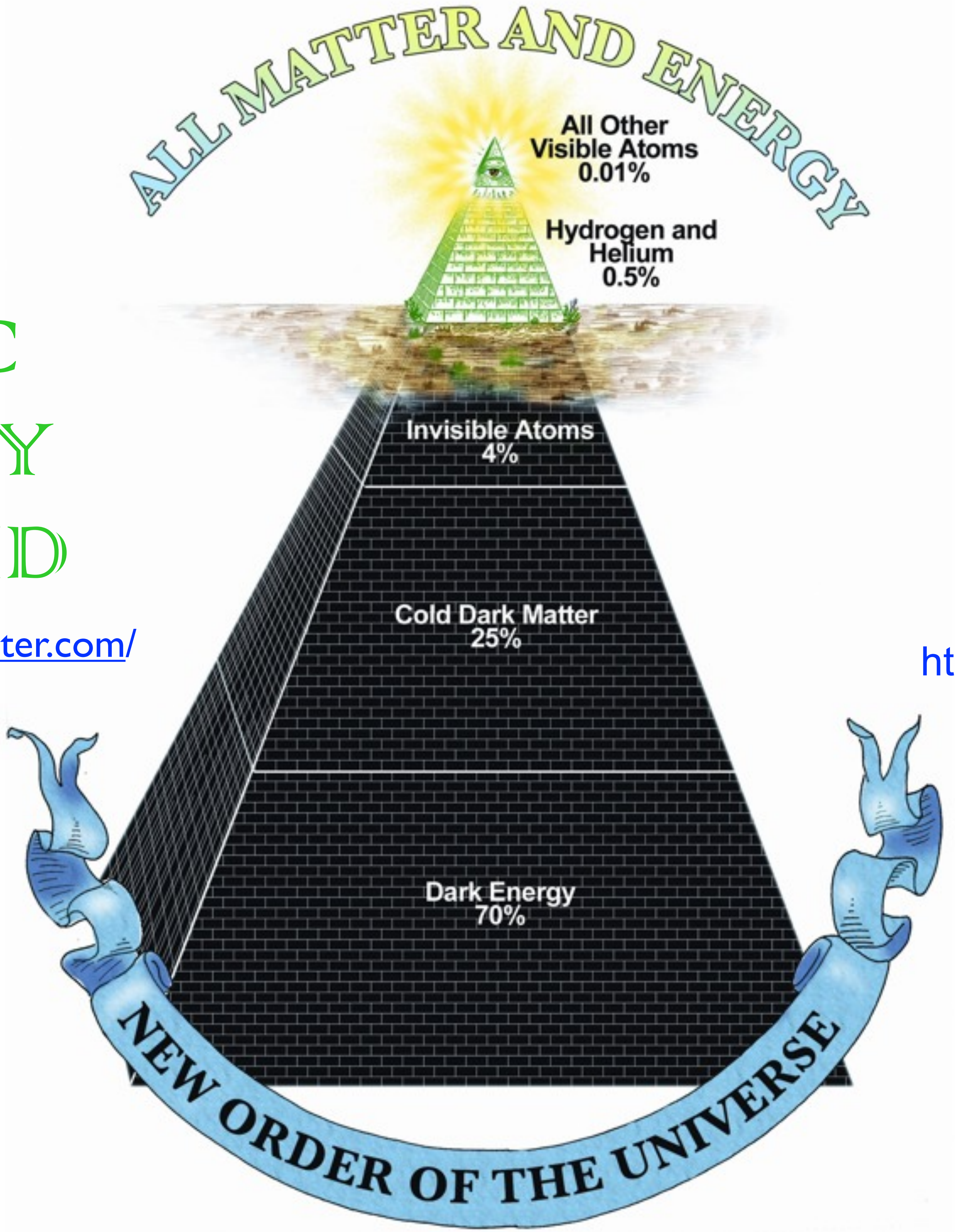
Published 2006



DISCOVERING OUR EXTRAORDINARY PLACE IN THE COSMOS

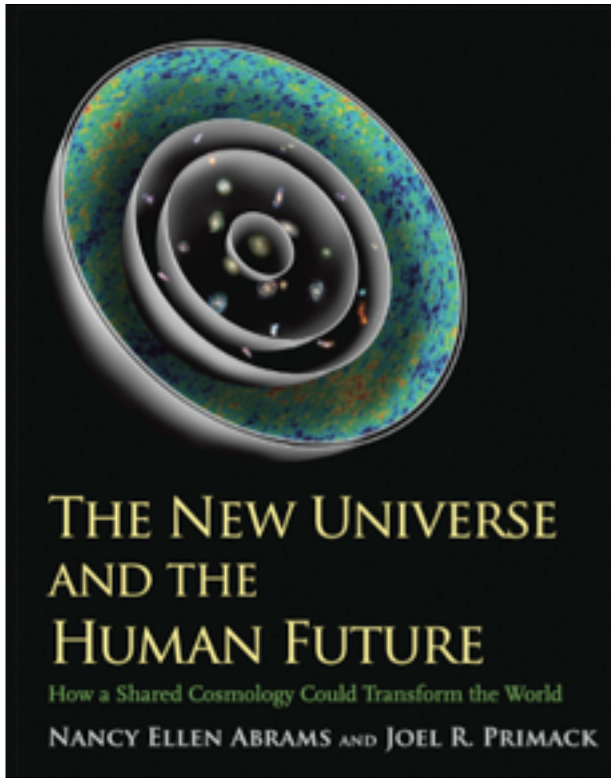
THE VIEW *from the* CENTER *of the* UNIVERSE

JOEL R. PRIMACK *and* NANCY ELLEN ABRAMS



http://new-universe.org

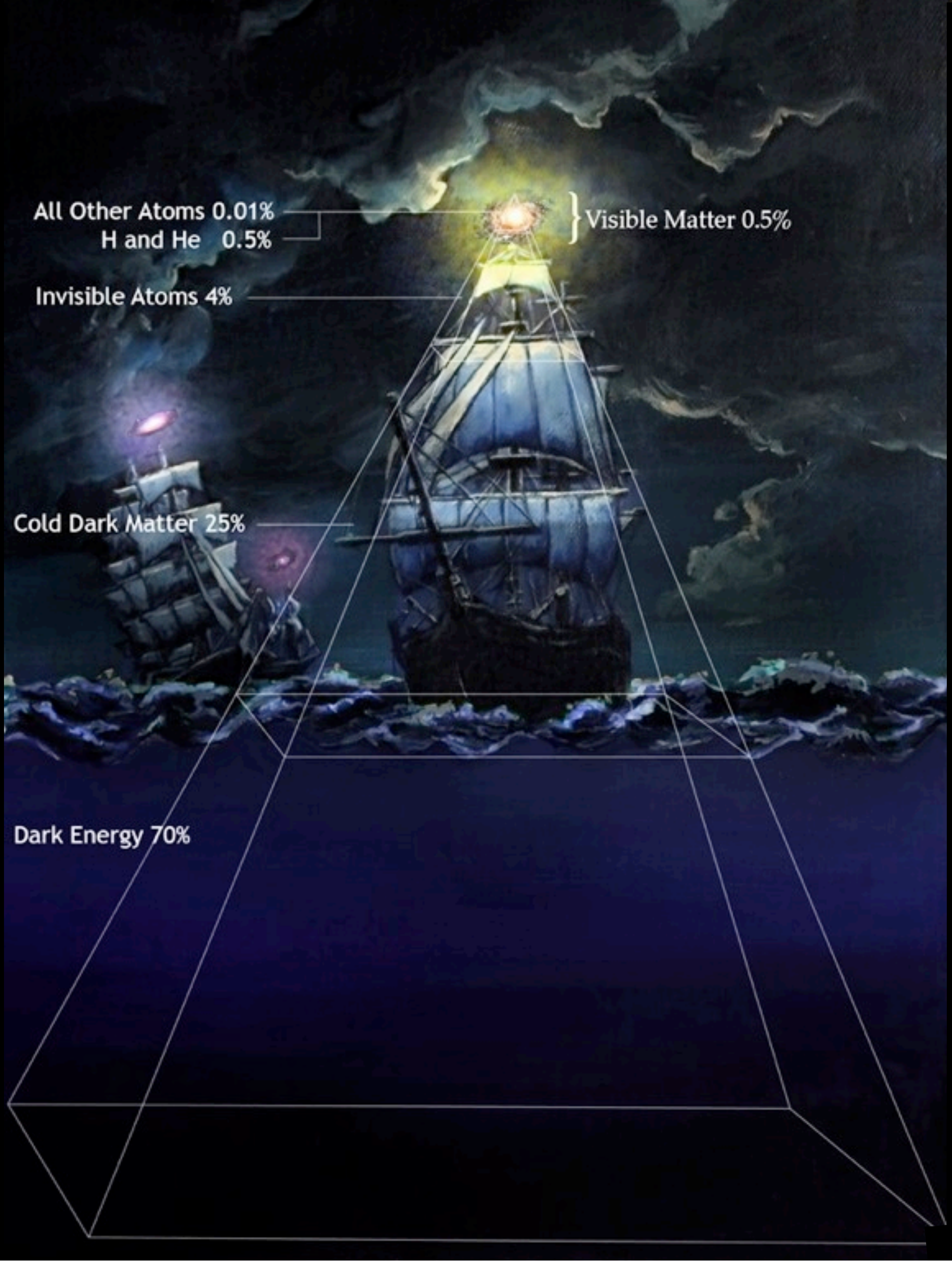
Just Published



THE NEW UNIVERSE AND THE HUMAN FUTURE

How a Shared Cosmology Could Transform the World

NANCY ELLEN ABRAMS AND JOEL R. PRIMACK



Imagine that the entire universe is an ocean of dark energy, On that ocean sail billions of ghostly ships made of dark matter. We don’t see the ocean or the ships -- just the lights at the tops of the tallest masts of the largest ships ... the galaxies.

ΛCDM PREDICTS EVOLUTION IN THE GALAXY CORRELATION FUNCTION

$\xi_{gg}(r)$

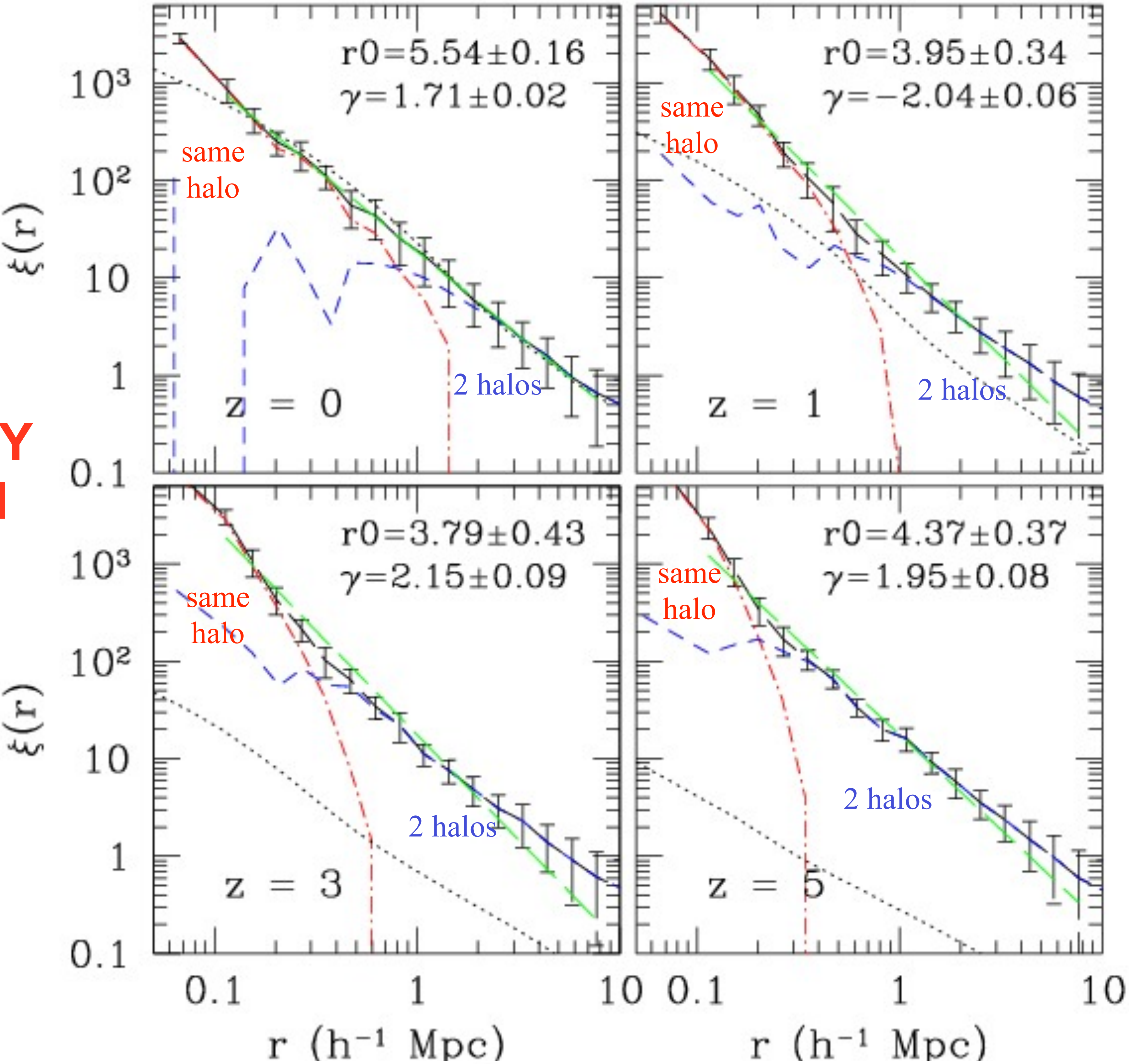
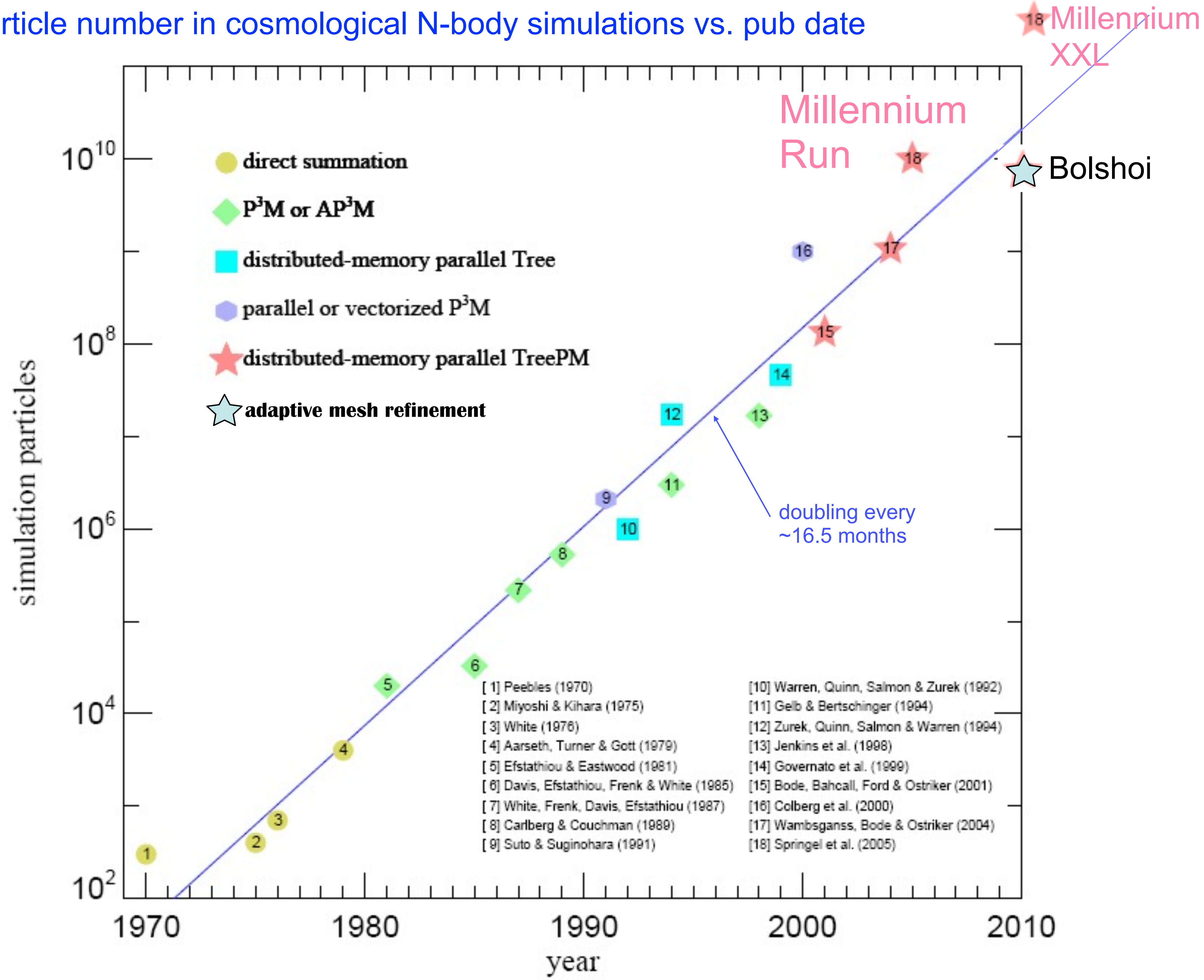


FIG. 8.— Evolution of the two-point correlation function in the $80h^{-1}$ Mpc simulation. The solid line with error bars shows the clustering of halos of the fixed number density $n = 5.89 \times 10^{-3} h^3$ Mpc^{-3} at each epoch. The error-bars indicate the "jack-knife" one sigma errors and are larger 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.

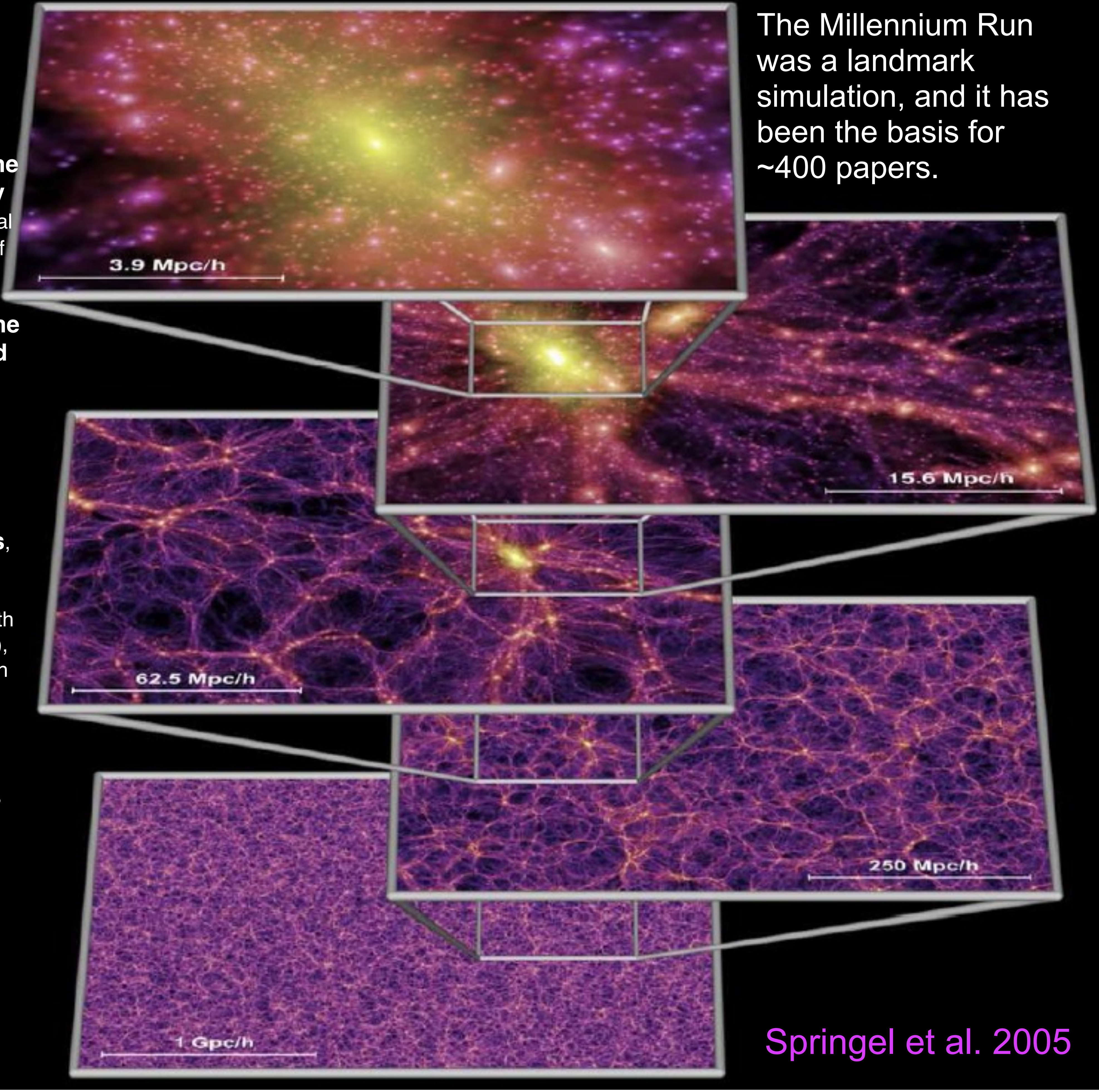
Kravtsov, Berlind, Wechsler, Klypin, Gottloeber, Allgood, & Primack 2004

Particle number in cosmological N-body simulations vs. pub date



The Millennium Run

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

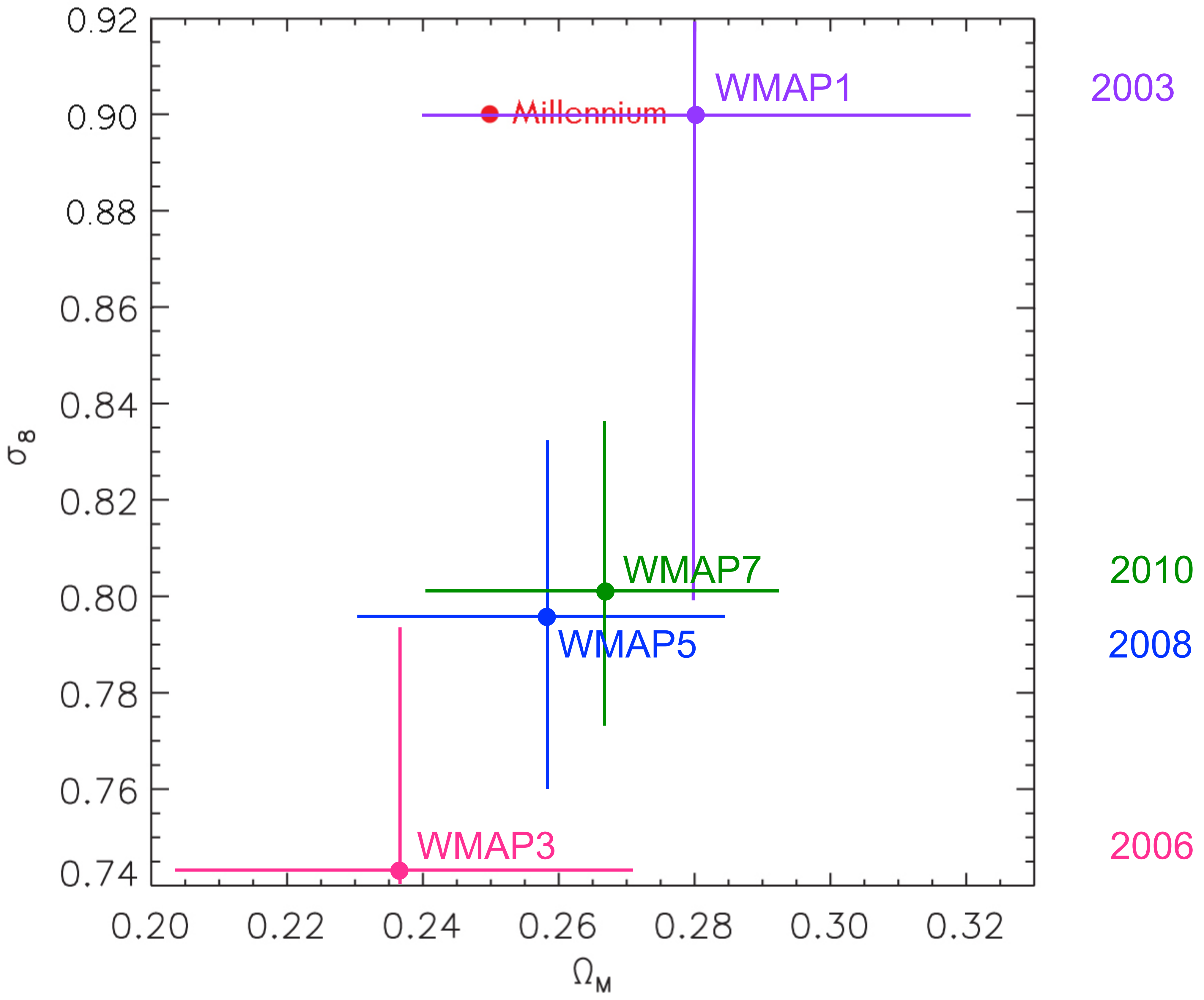


The Millennium Run was a landmark simulation, and it has been the basis for ~400 papers.

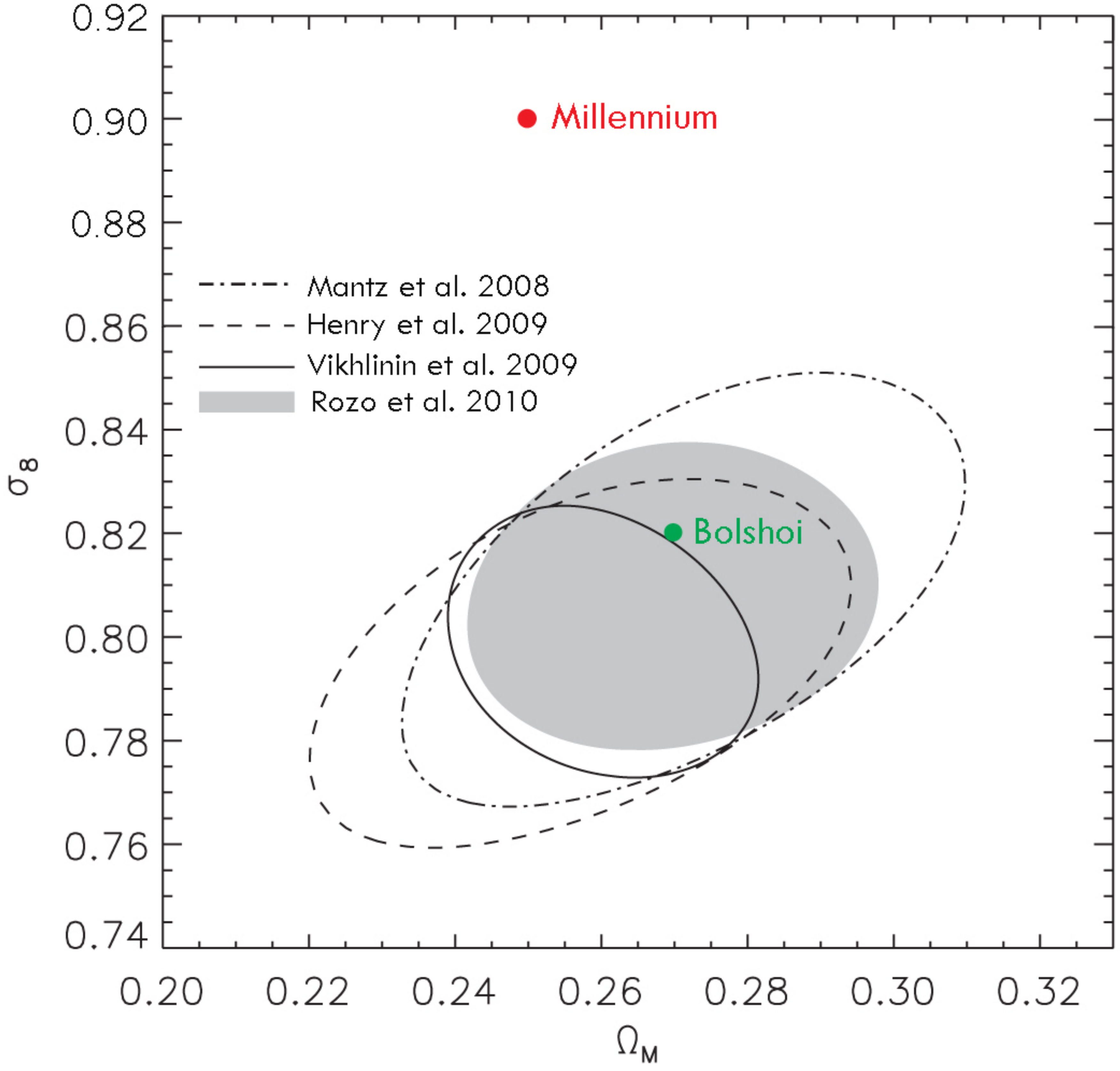
Springel et al. 2005

- **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.

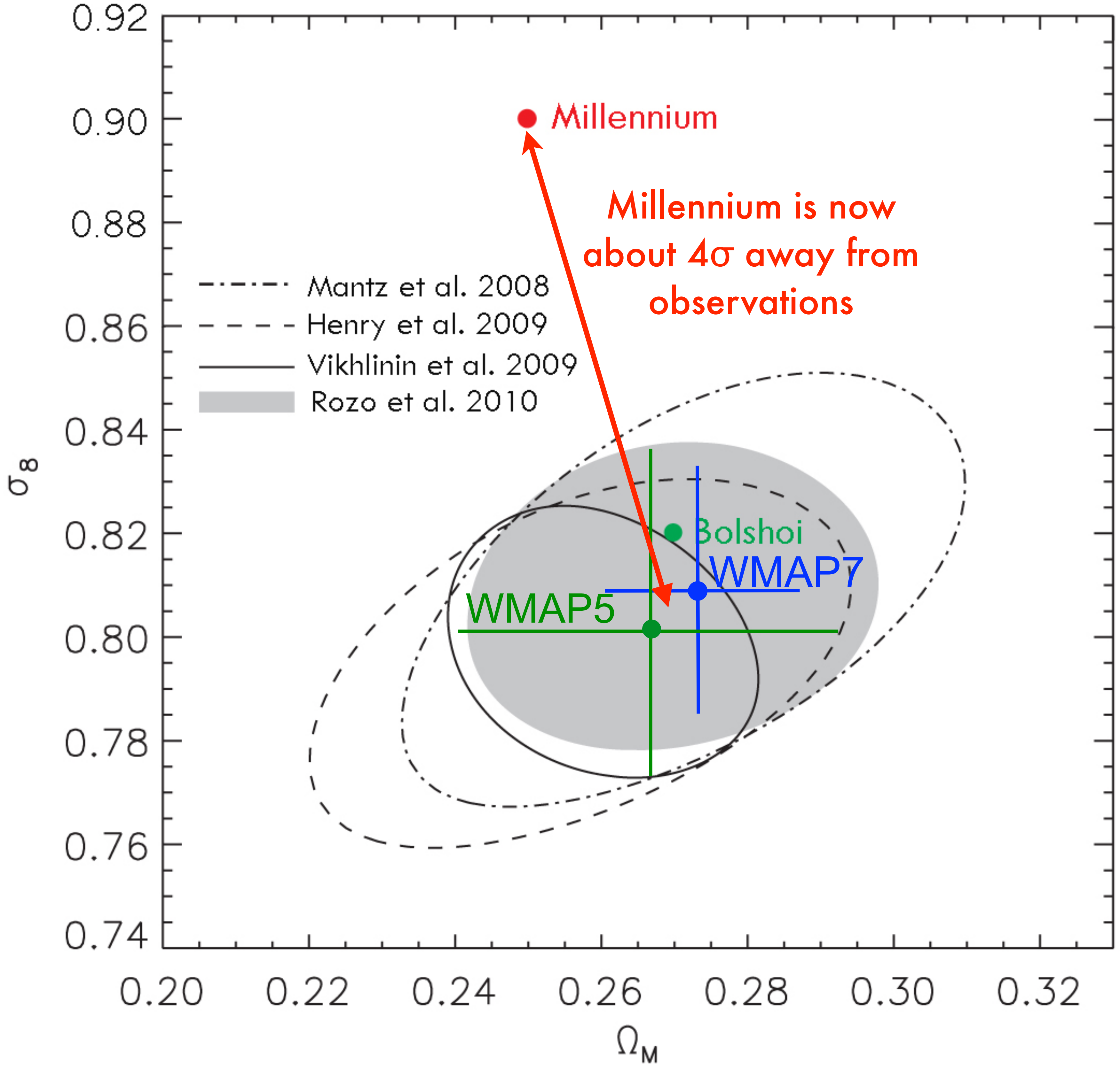
WMAP-only Determination of σ_8 and Ω_M



WMAP+SN+Clusters Determination of σ_8 and Ω_M



WMAP+SN+Clusters Determination of σ_8 and Ω_M



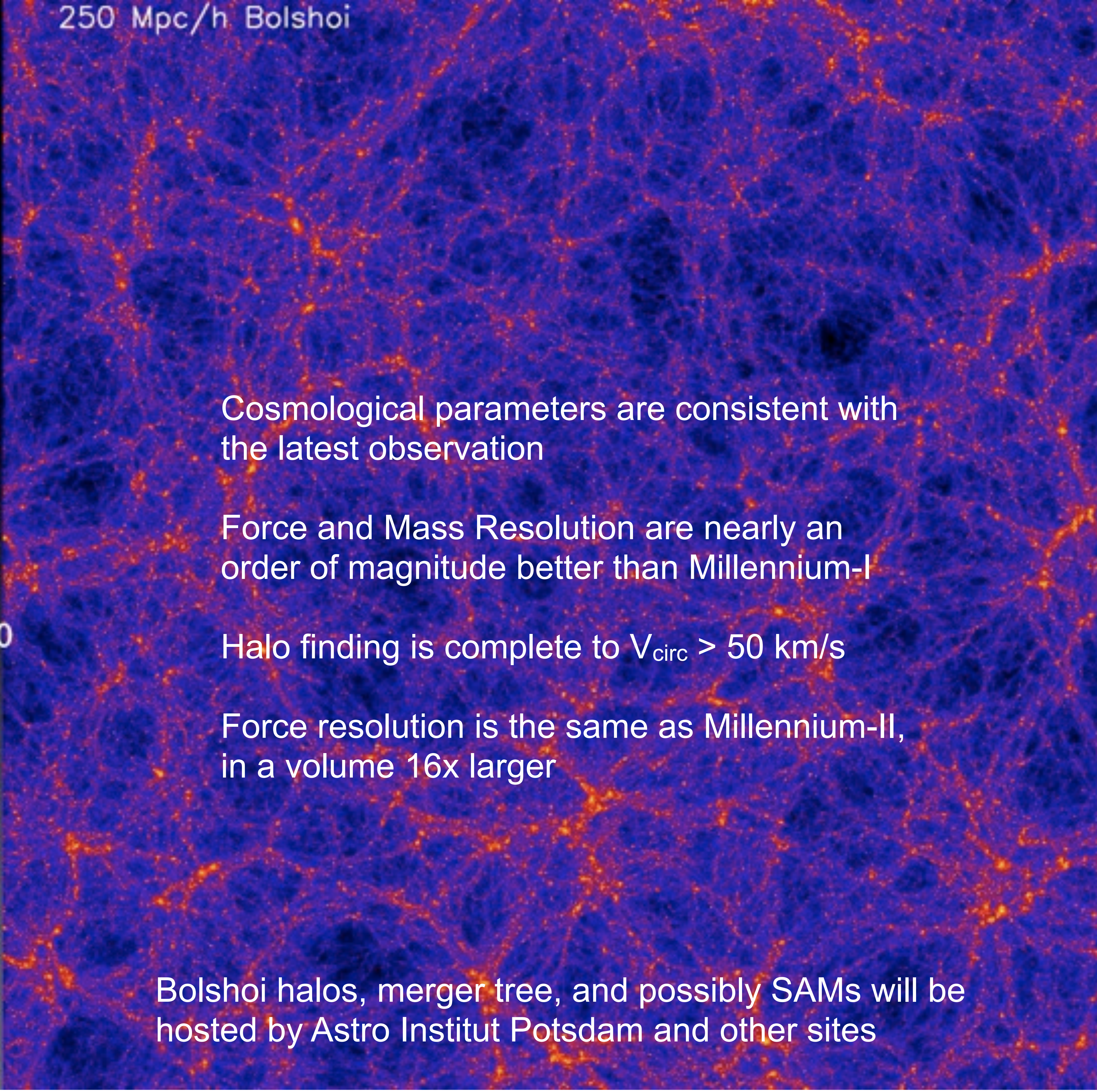
The Bolshoi simulation

ART code

250Mpc/h Box
LCDM
σ_8 = 0.82
h = 0.73
8G particles
1kpc/h force resolution
1e8 Msun/h mass res

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

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



Cosmological parameters are consistent with the latest observation

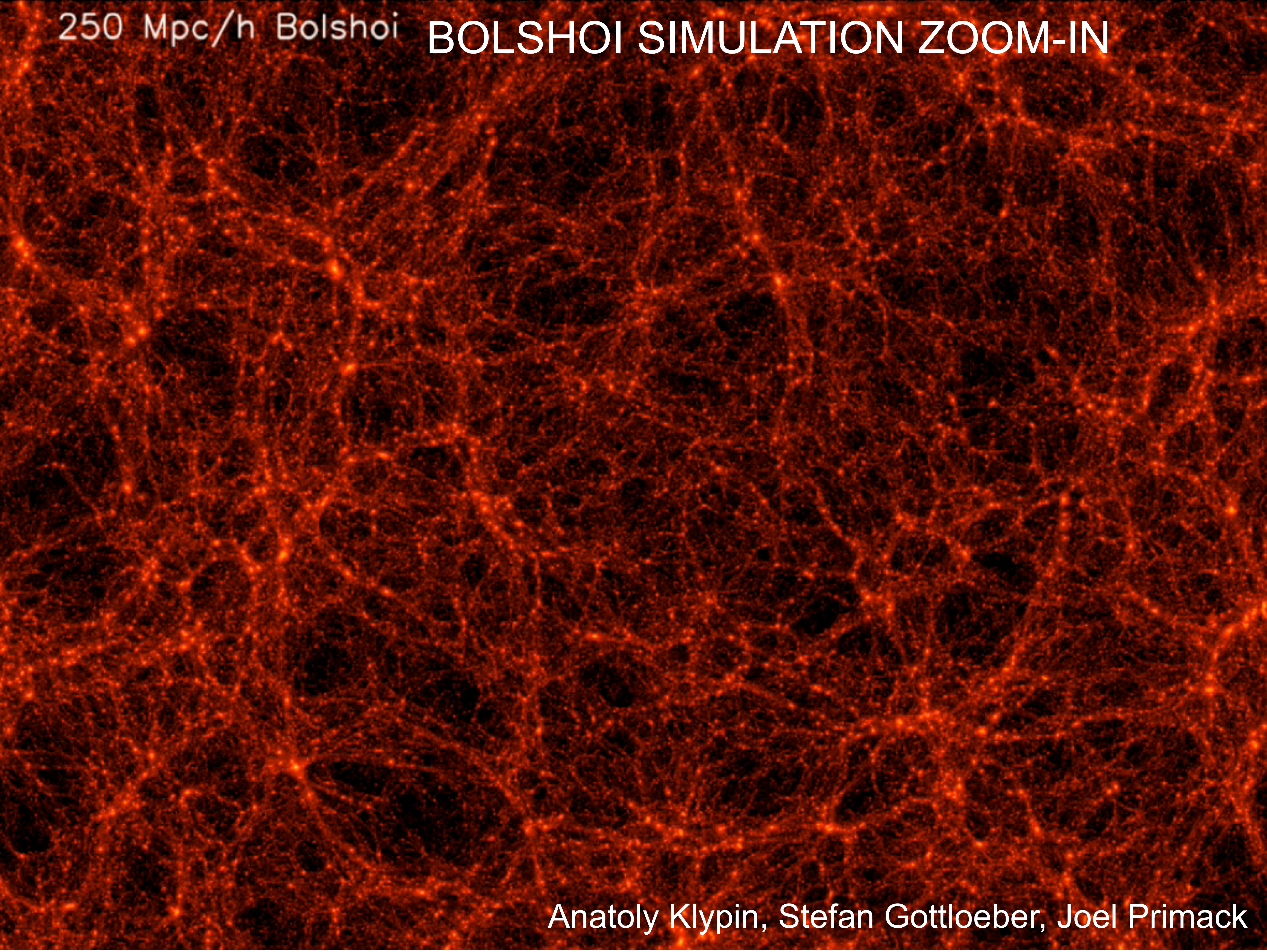
Force and Mass Resolution are nearly an order of magnitude better than Millennium-I

Halo finding is complete to V_{circ} > 50 km/s

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

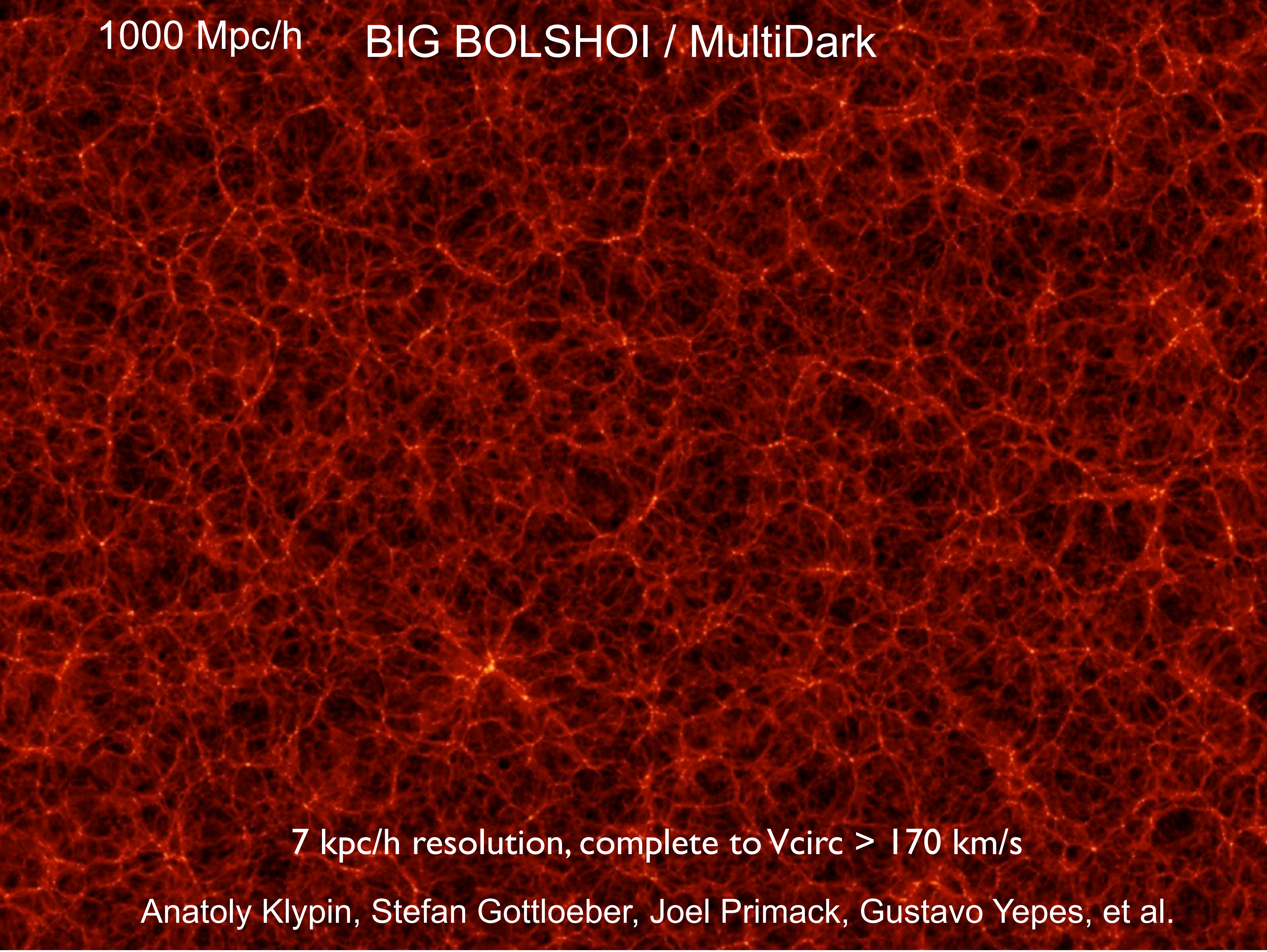
Bolshoi halos, merger tree, and possibly SAMs will be hosted by Astro Institut Potsdam and other sites

BOLSHOI SIMULATION ZOOM-IN



Anatoly Klypin, Stefan Gottloeber, Joel Primack

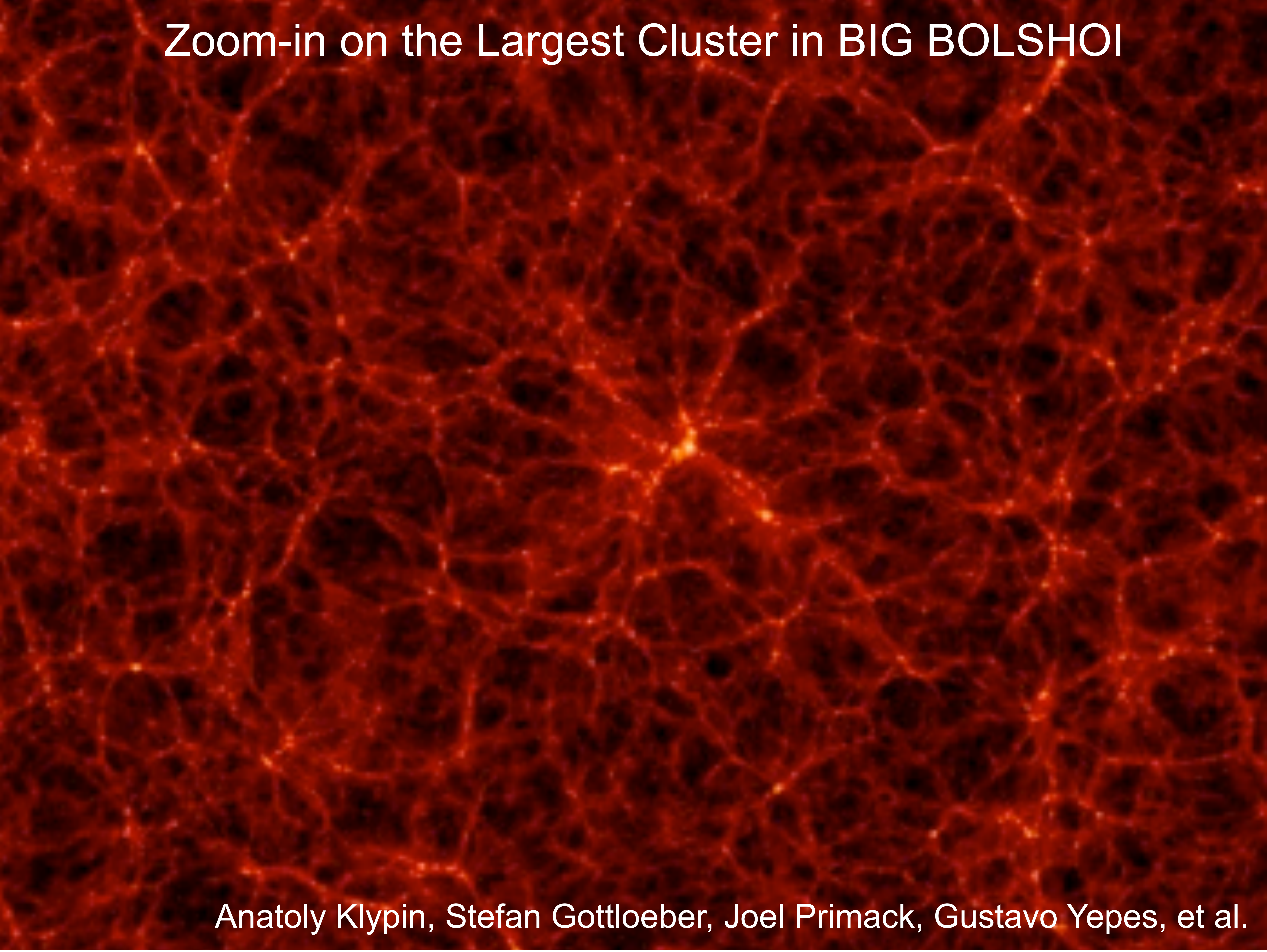
BIG BOLSHOI / MultiDark



7 kpc/h resolution, complete to Vcirc > 170 km/s

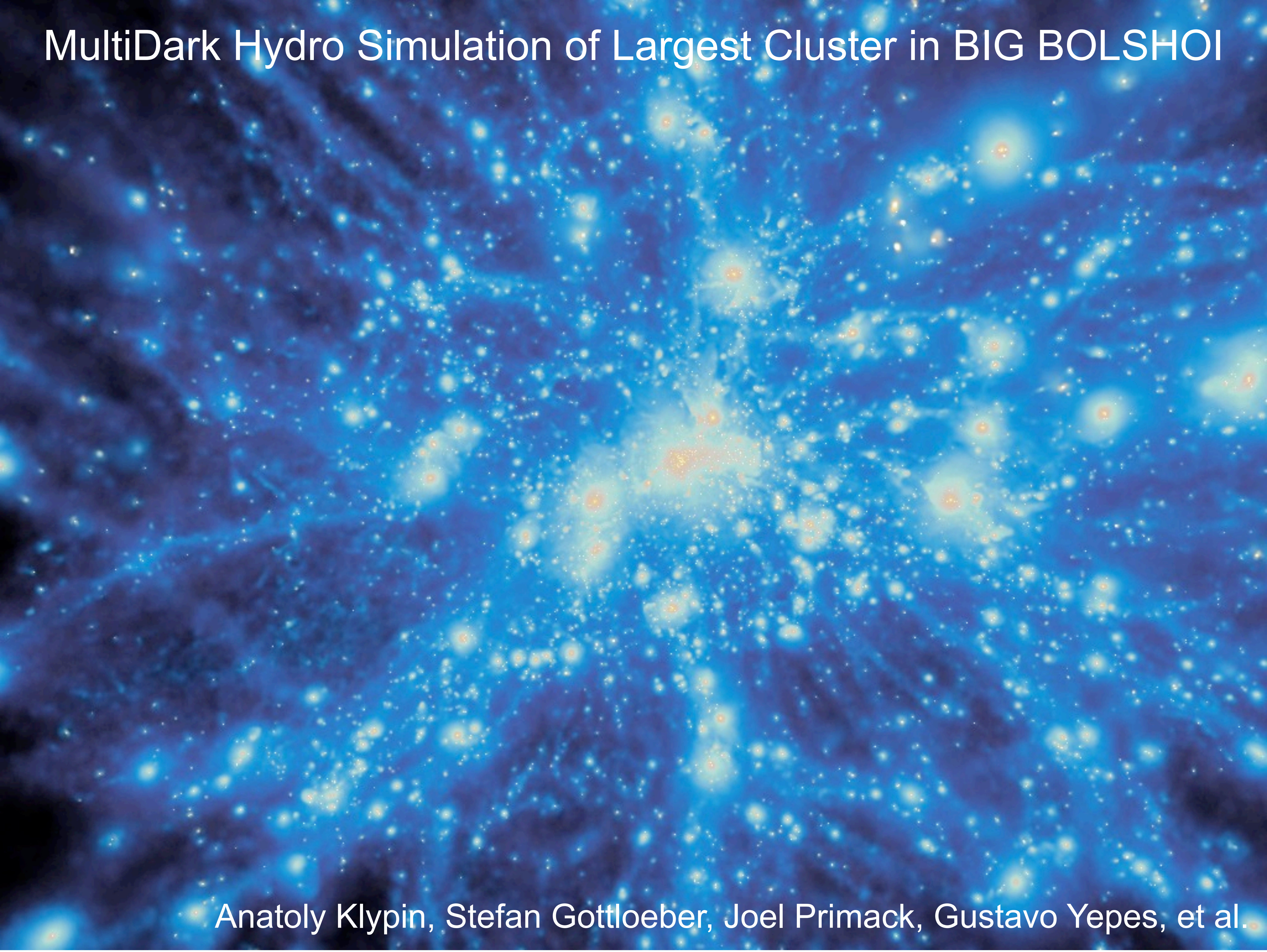
Anatoly Klypin, Stefan Gottloeber, Joel Primack, Gustavo Yepes, et al.

Zoom-in on the Largest Cluster in BIG BOLSHOI



Anatoly Klypin, Stefan Gottloeber, Joel Primack, Gustavo Yepes, et al.

MultiDark Hydro Simulation of Largest Cluster in BIG BOLSHOI



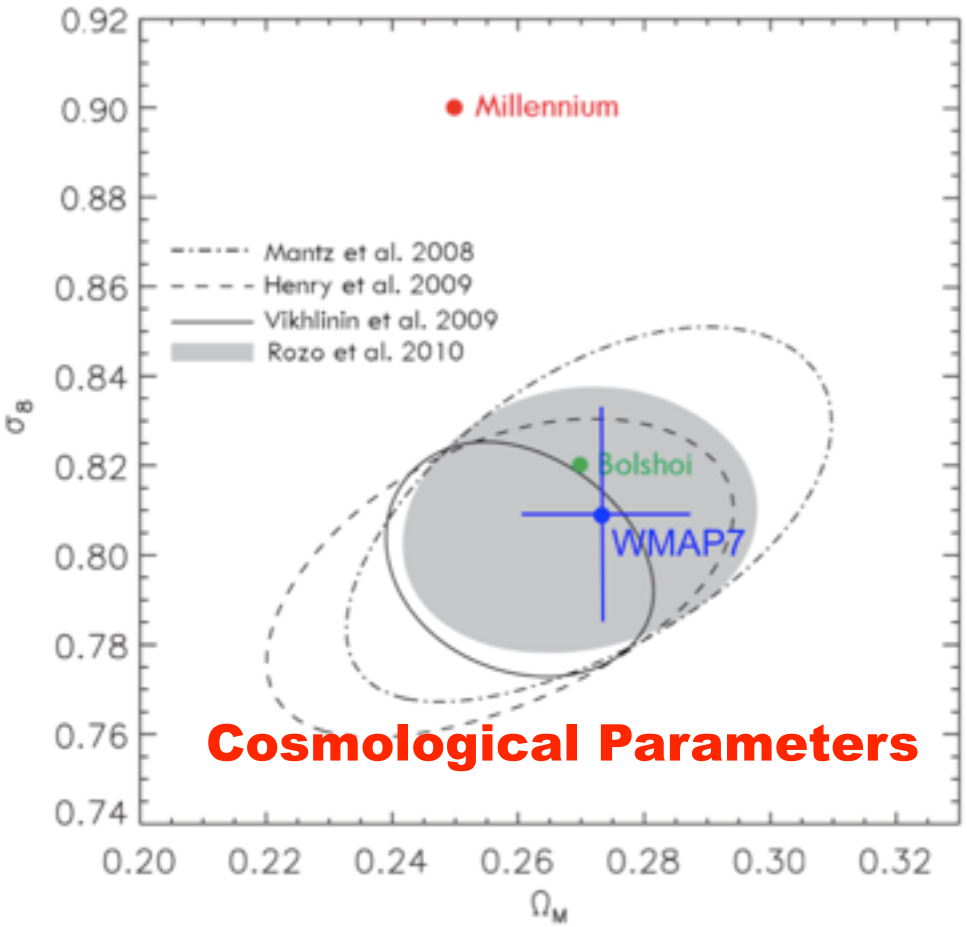
Anatoly Klypin, Stefan Gottloeber, Joel Primack, Gustavo Yepes, et al.

BOLSHOI SIMULATION FLY-THROUGH

less than
1/1000
of the
Bolshoi
Simulation
Volume

100 million light years

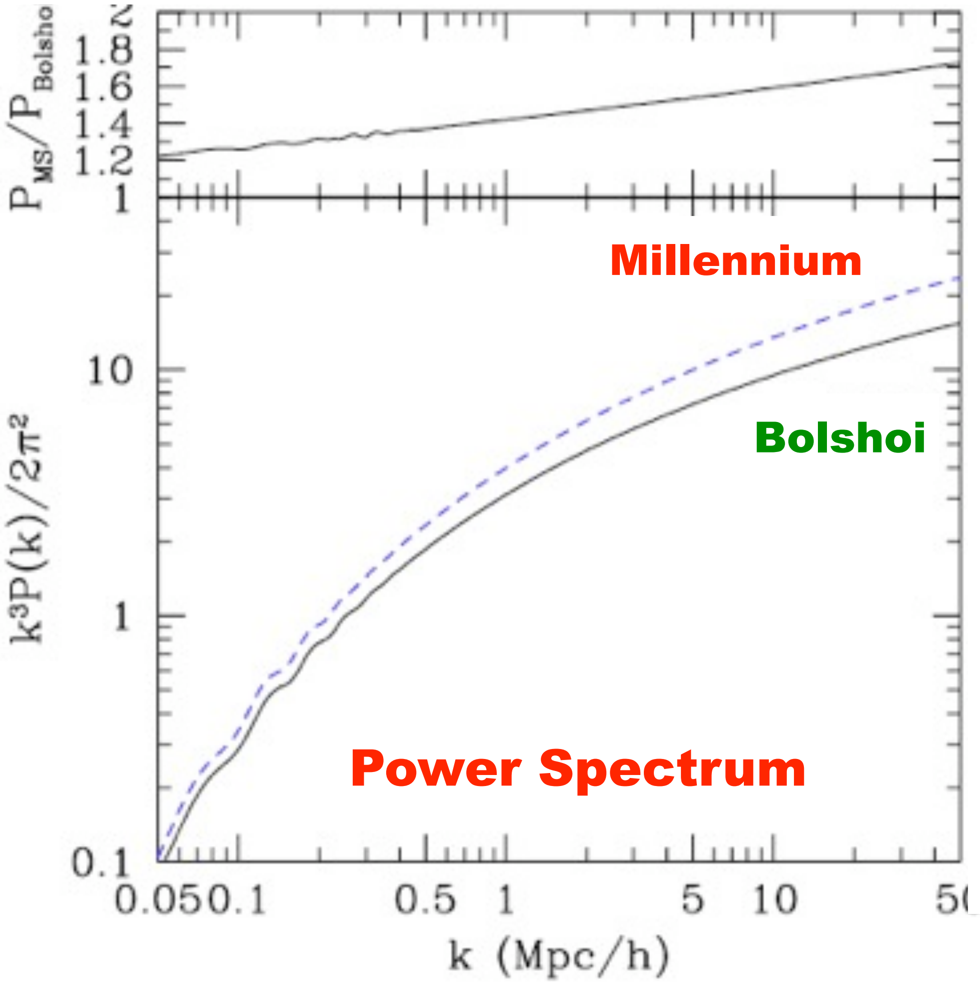
Halos and galaxies: results from the **Bolshoi** simulation



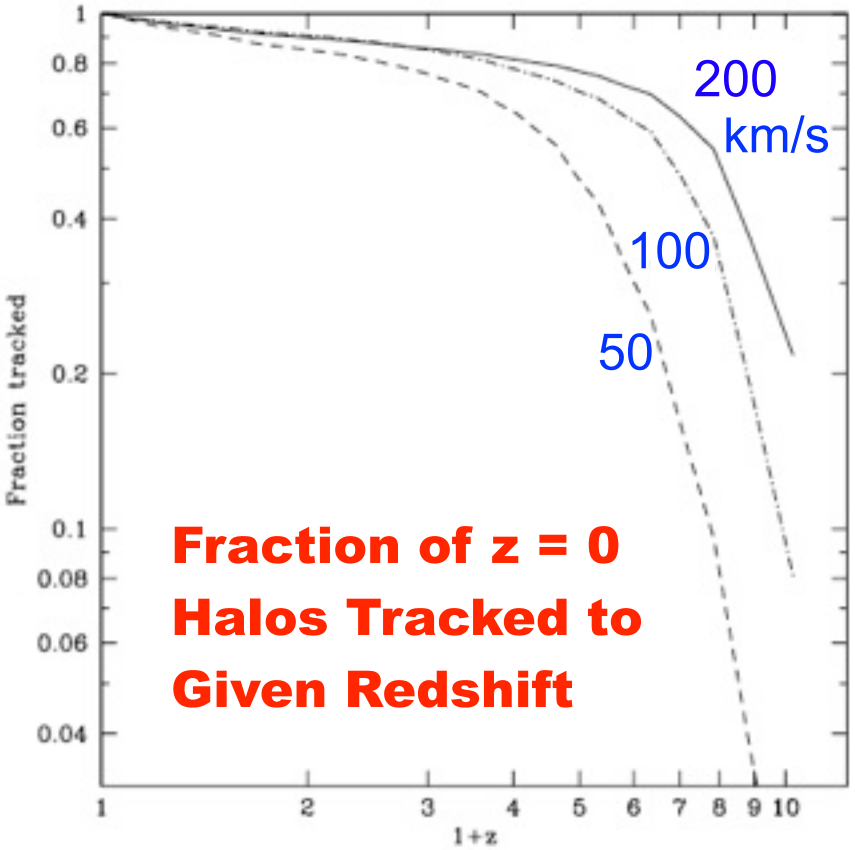
Cosmological Parameters

The Millennium Run (Springel+05) was a landmark simulation, and it has been the basis for ~400 papers. However, it and the new Millennium-II simulations were run using WMAP1 (2003) parameters, and the Millennium-I resolution was inadequate to see many subhalos. The new **Bolshoi** simulation (Klypin, Trujillo & Primack 2010) used the WMAP5 parameters (consistent with WMAP7) and has nearly an order of magnitude better mass and force resolution than Millennium-I. We have now found halos in all 180 stored timesteps, and we have complete merger trees based on Bolshoi.

Klypin, Trujillo-Gomez, & Primack, arXiv:1002.3660 ApJ in press

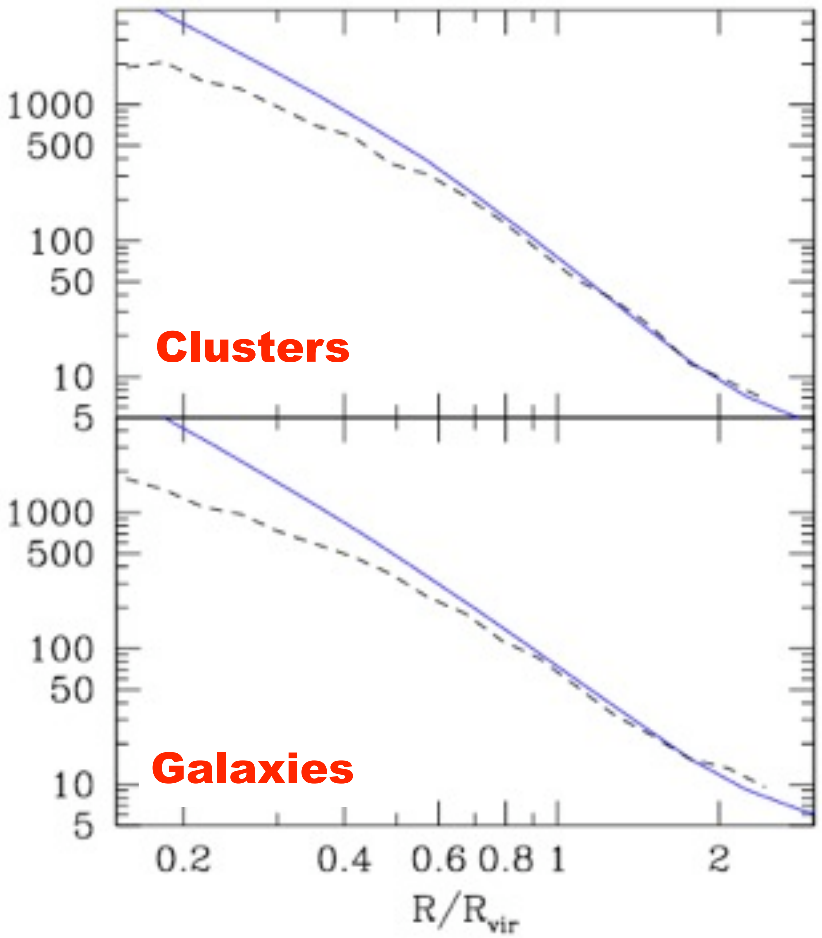


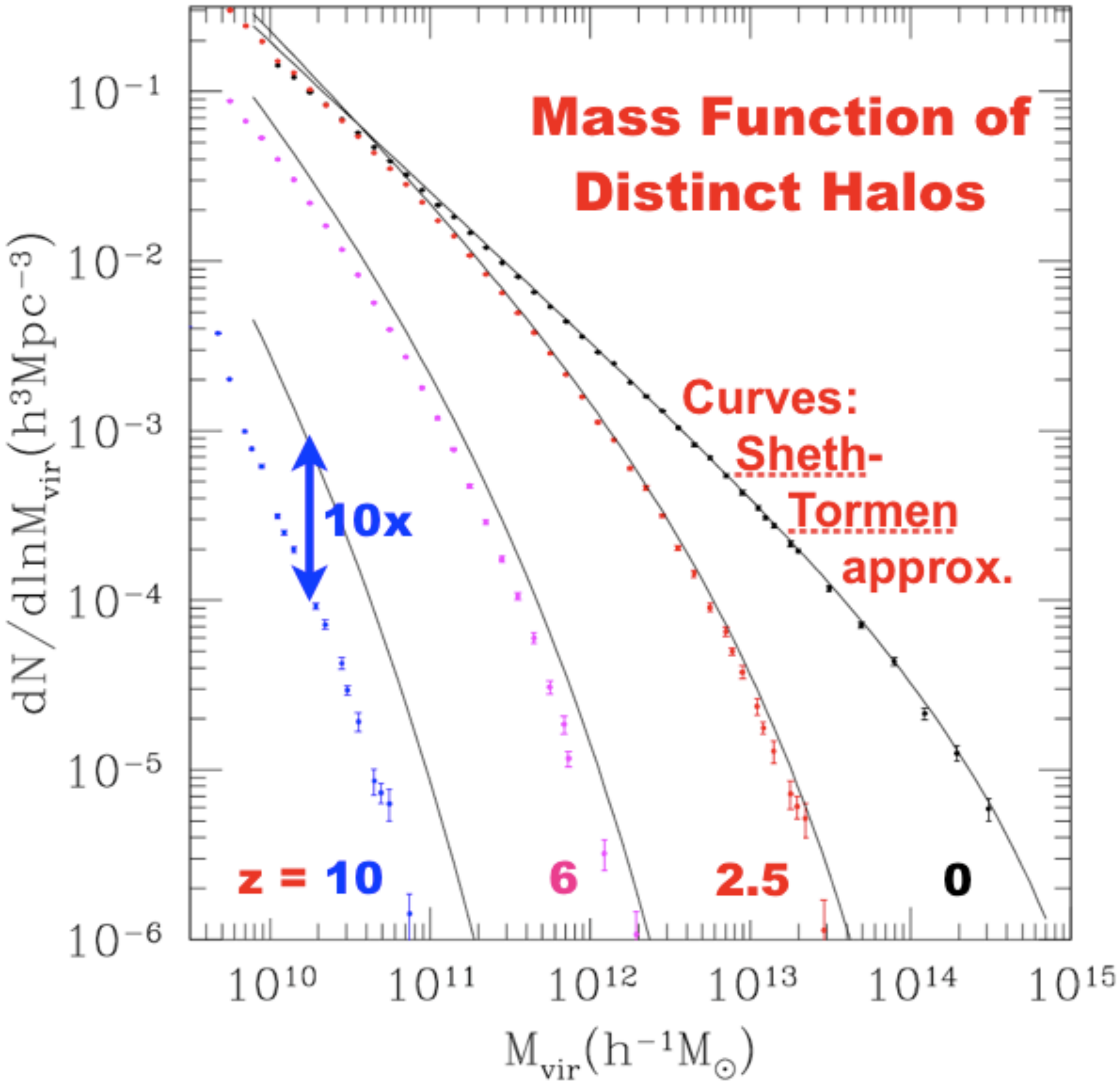
Power Spectrum



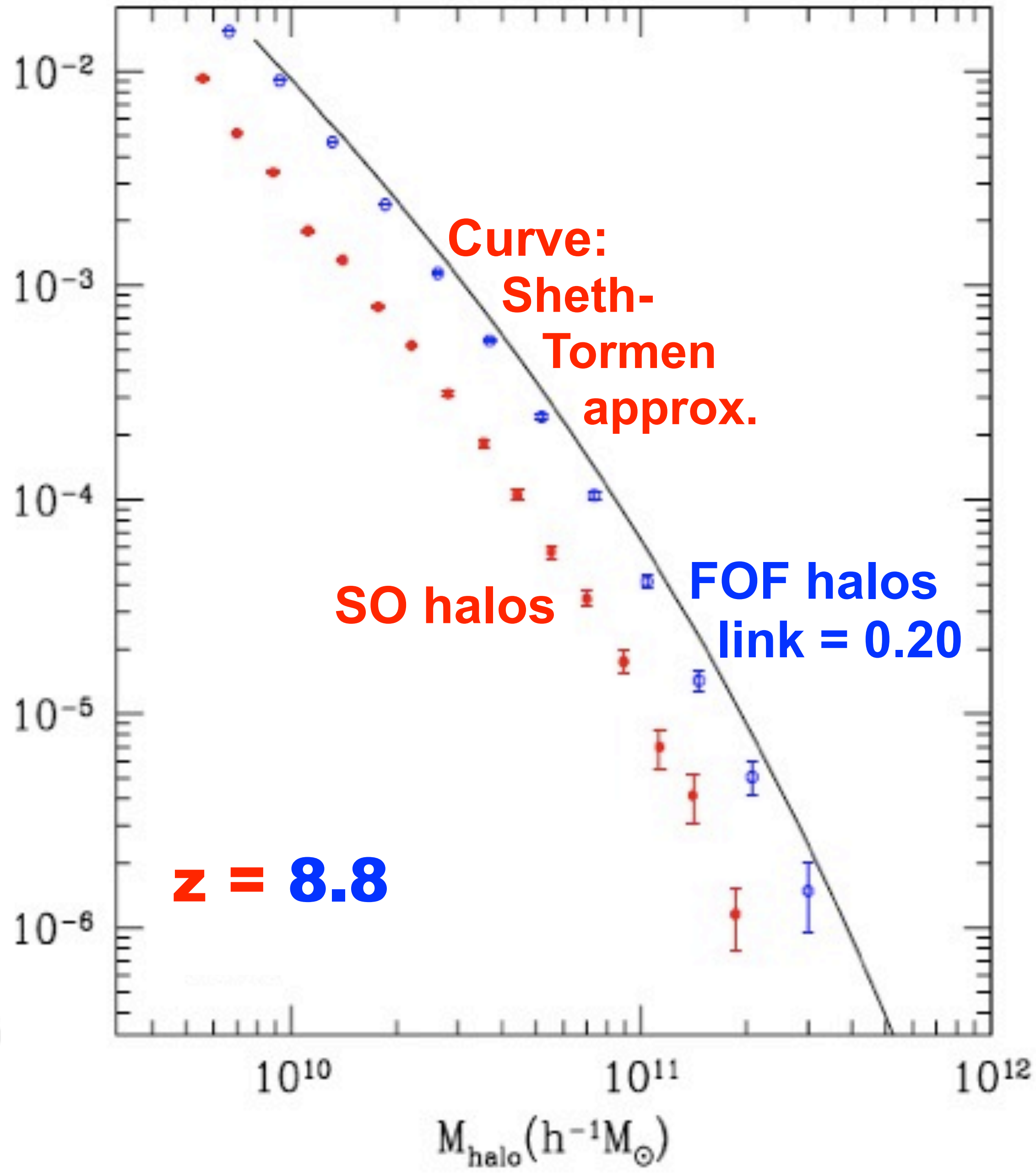
Fraction of z = 0 Halos Tracked to Given Redshift

Subhalos follow the dark matter distribution



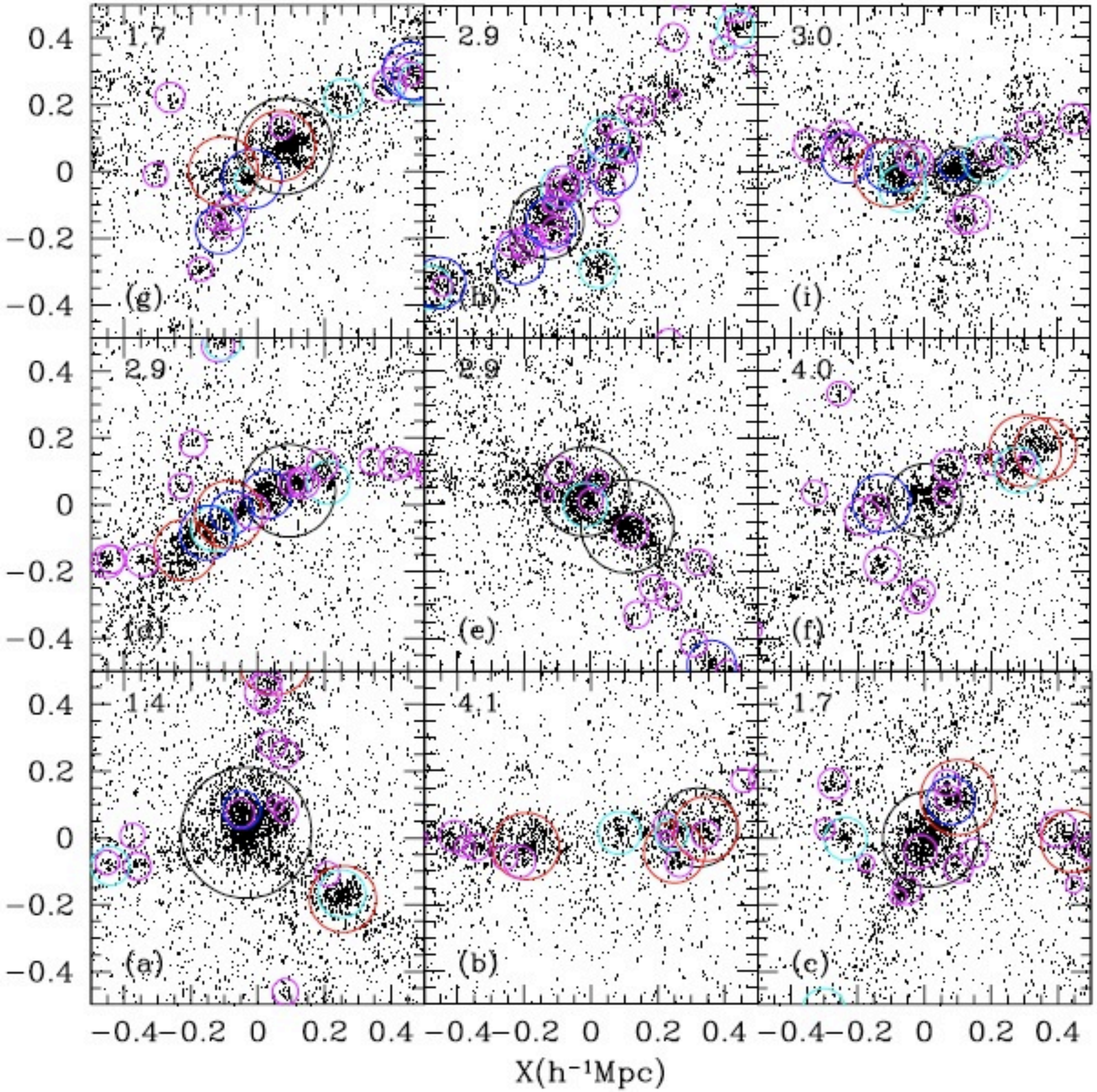


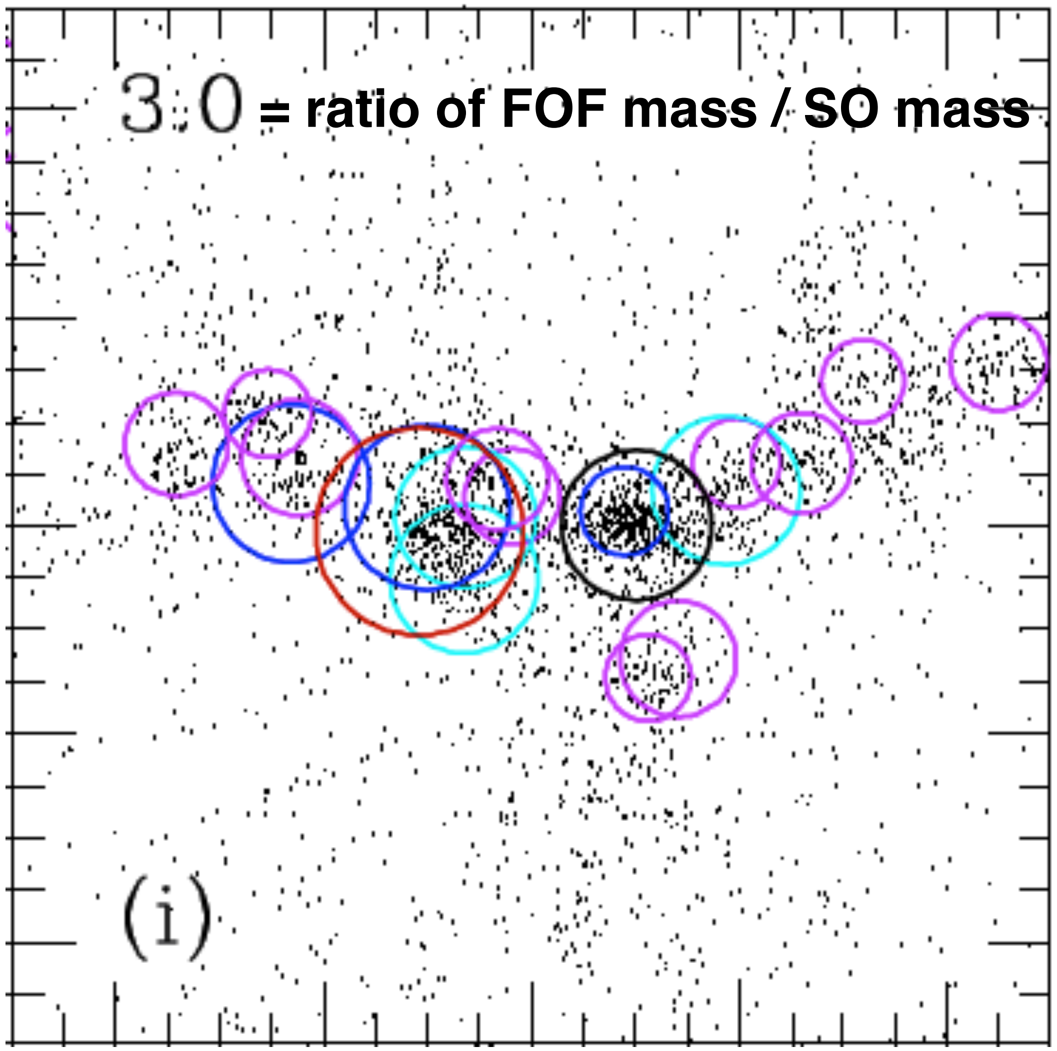
Sheth-Tormen Fails at High Redshifts



The Sheth-Tormen approximation with the same WMAP5 parameters used for the Bolshoi simulation very accurately agrees with abundance of halos at low redshifts, but increasingly overpredicts bound spherical overdensity halo abundance at higher redshifts. ST agrees well with FOF halo abundances, but FOF halos have unrealistically large masses at high *z*.

Klypin, Trujillo-Gomez, & Primack, arXiv: 1002.3660 ApJ in press





3.0 = ratio of FOF mass / SO mass

FOF linked together a chain of halos that formed in long and dense filaments (also in panels b, d, f, h; e = major merger)

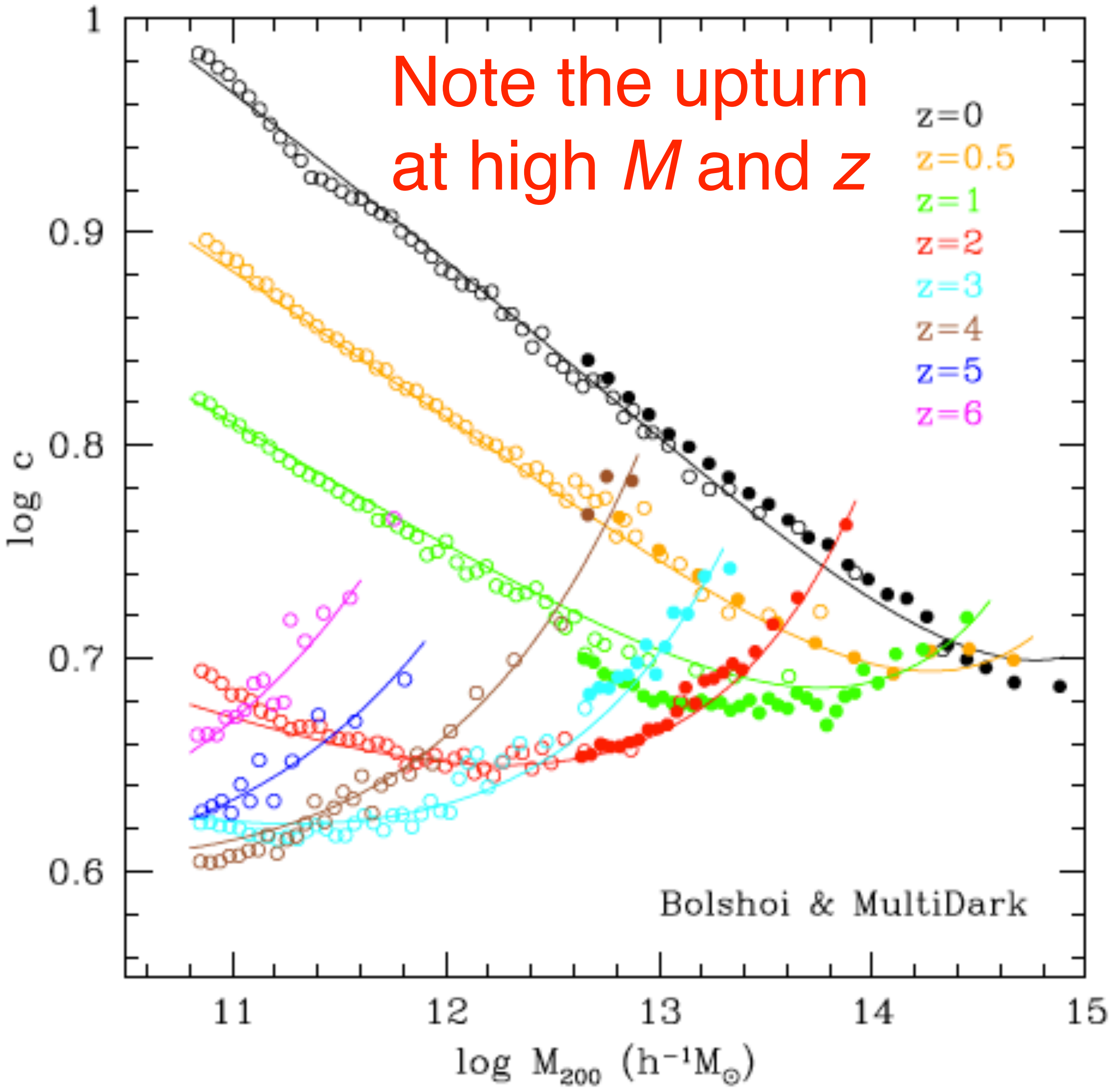
Each panel shows 1/2 of the dark matter particles in cubes of 1*h*$^{-1}$ Mpc size. The center of each cube is the exact position of the center of mass of the corresponding FOF halo. The effective radius of each FOF halo in the plots is 150 – 200 *h*$^{-1}$ kpc. Circles indicate virial radii of distinct halos and subhalos identified by the spherical overdensity algorithm BDM.

Klypin, Trujillo-Gomez, & Primack, arXiv: 1002.3660 ApJ in press

Halo concentrations in the standard CDM cosmology

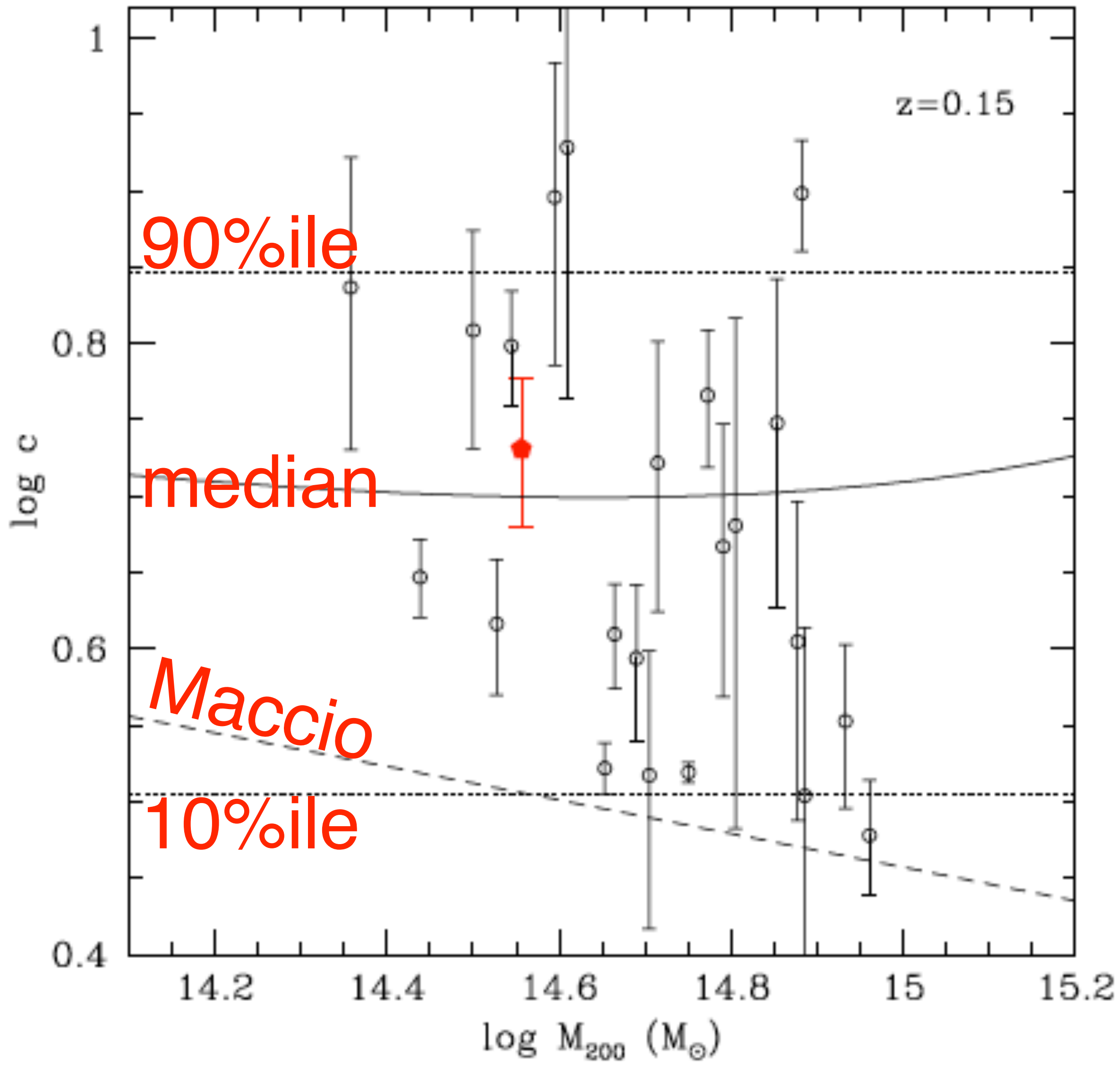
Francisco Prada, Anatoly A. Klypin, Antonio J. Cuesta, Juan E. Betancort-Rijo, and Joel Primack

arXiv:1104.5130



Note the upturn at high *M* and *z*

Halo mass–concentration relation of distinct halos at different redshifts in the Bolshoi (open symbols) and MultiDark (filled symbols) simulations is compared with an analytical approximation.



90%ile

median

Maccio

10%ile

Comparison of observed cluster concentrations (data points with error bars) with the prediction of our model for median halo concentration of cluster-size halos (full curve). Dotted lines show 10% and 90% percentiles. Open circles show results for X-ray luminous galaxy clusters observed with XMMNewton in the redshift range 0.1-0.3 (Ettori et al. 2010). The pentagon presents galaxy kinematic estimate for relaxed clusters by Wojtak & Lokas (2010). The dashed curve shows prediction by Macci`o, Dutton, & van den Bosch (2008), which significantly underestimates the concentrations of clusters.

Halo concentrations in the standard CDM cosmology

Francisco Prada, Anatoly A. Klypin, Antonio J. Cuesta, Juan E. Betancort-Rijo, and Joel Primack

V_{max}/V_{200} for Millennium-1,II and Bolshoi/MultiDark

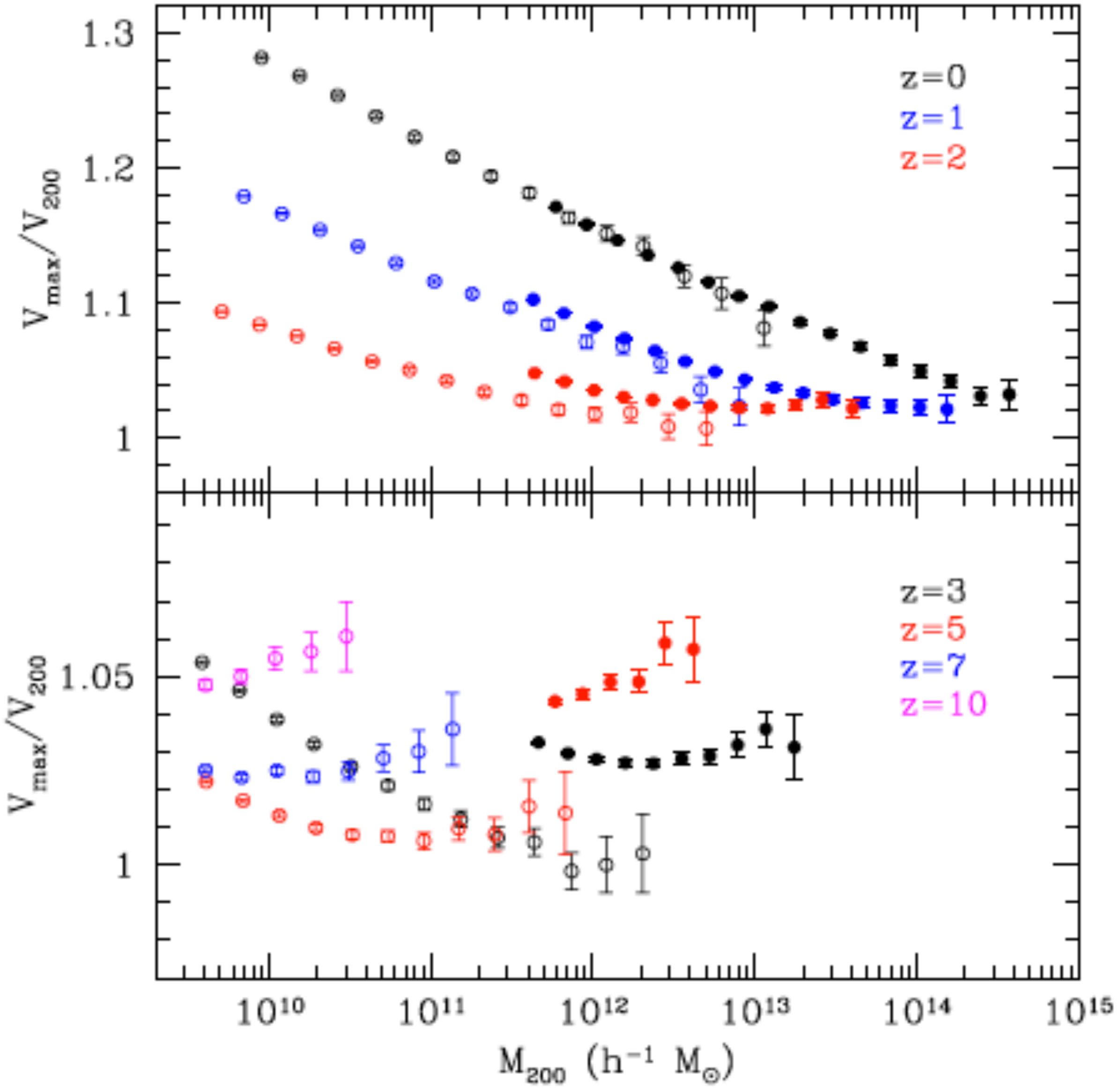


Figure 5. The ratio $V_{\max}/V_{200}$ of the maximum circular velocity to the virial velocity as a function of mass M_{200} for distinct halos at different redshifts for MS-I (filled symbols) and MS-II (open symbols) simulations. Error bars are statistical uncertainties. The MS-I and MS-II simulations agree quite well at $z = 0$. At higher redshifts there are noticeable differences between MS-I and MS-II.

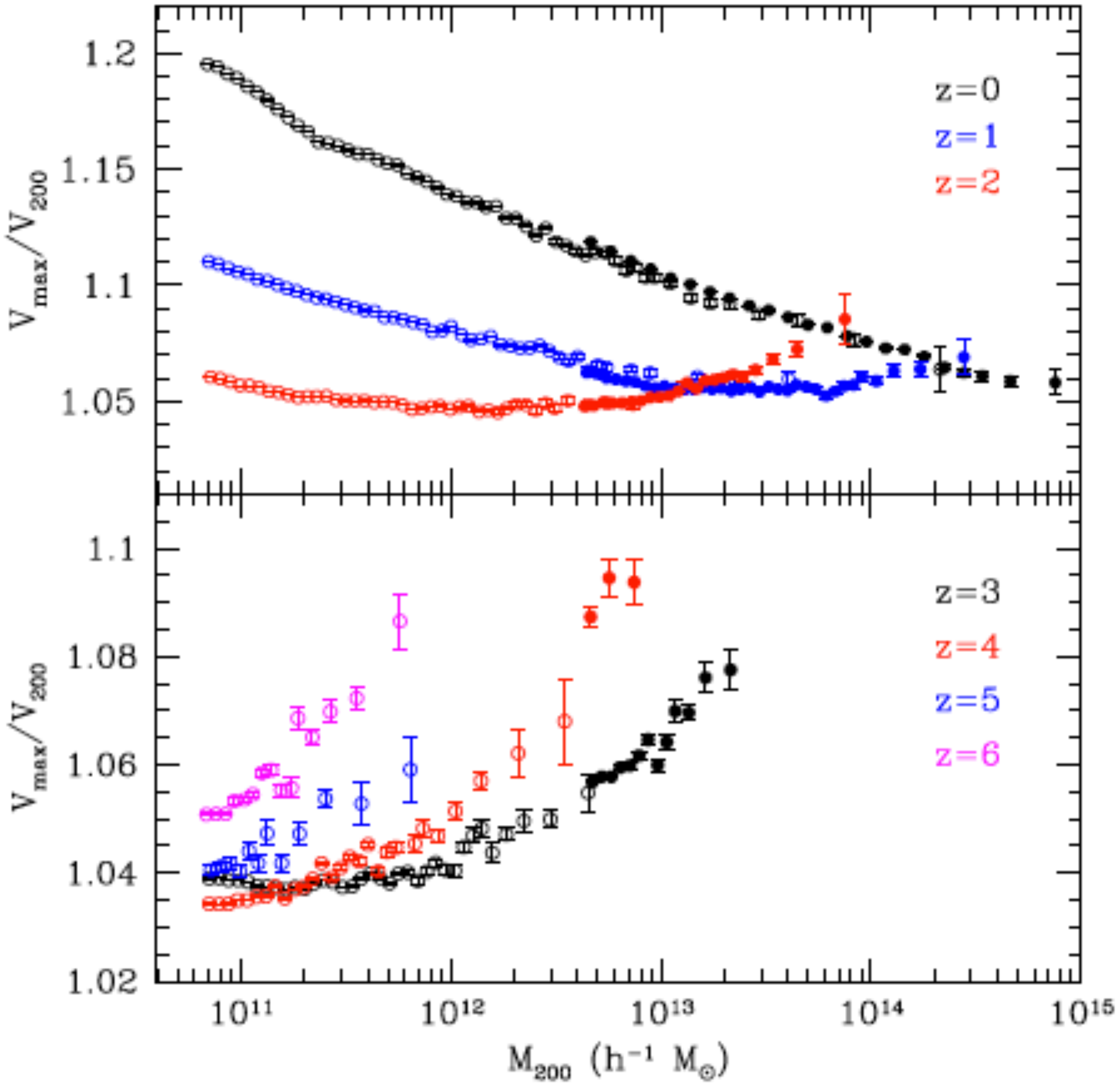


Figure 6. The same as Figure 5 but for Bolshoi (open symbols) and MultiDark (filled symbols) simulations. Both simulations show remarkable agreement at all masses and redshifts.

GRAVITATIONALLY CONSISTENT HALO CATALOGS AND MERGER TREES FOR PRECISION COSMOLOGY

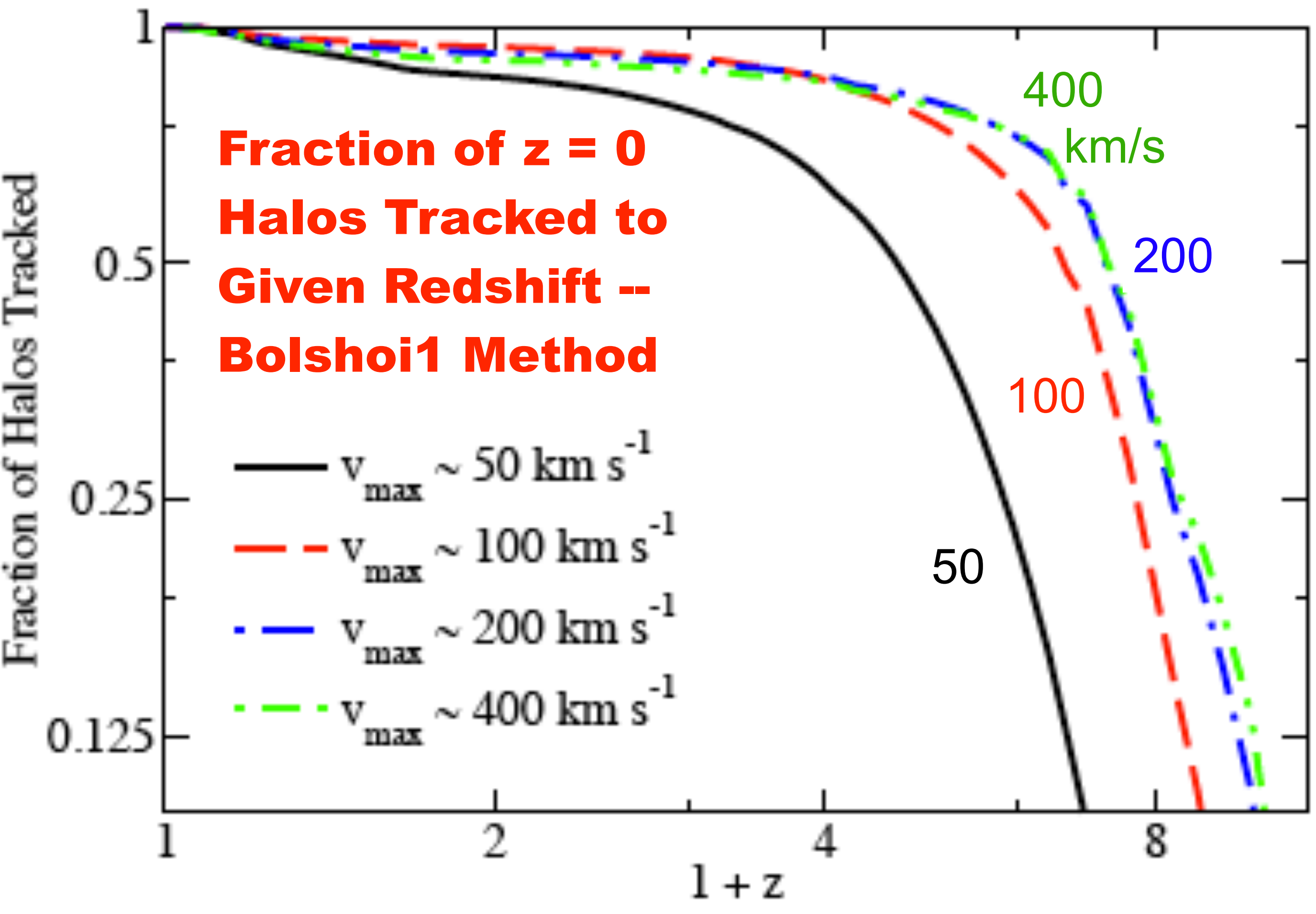
PETER S. BEHROOZI, MICHAEL T. BUSHA, RISA H. WECHSLER, HAO-YI WU
Physics Department, Stanford University; Department of Particle and Particle Astrophyiscs, SLAC National Accelerator Laboratory; Kavli Institute for Particle Astrophysics and Cosmology Stanford, CA 94305

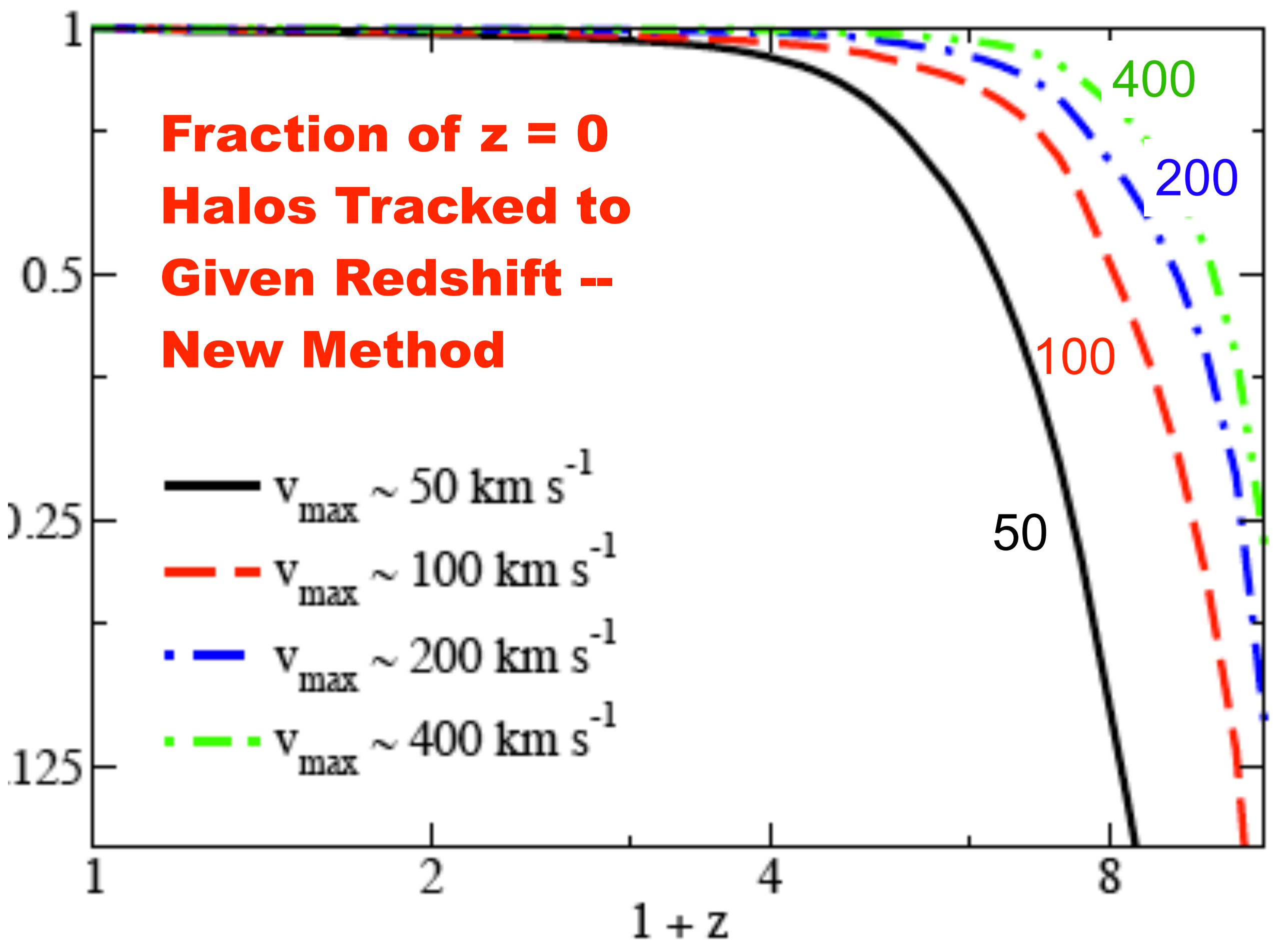
ANATOLY KLYPIN
Astronomy Department, New Mexico State University, Las Cruces, NM, 88003

JOEL PRIMACK
Department of Physics, University of California at Santa Cruz, Santa Cruz, CA 95064

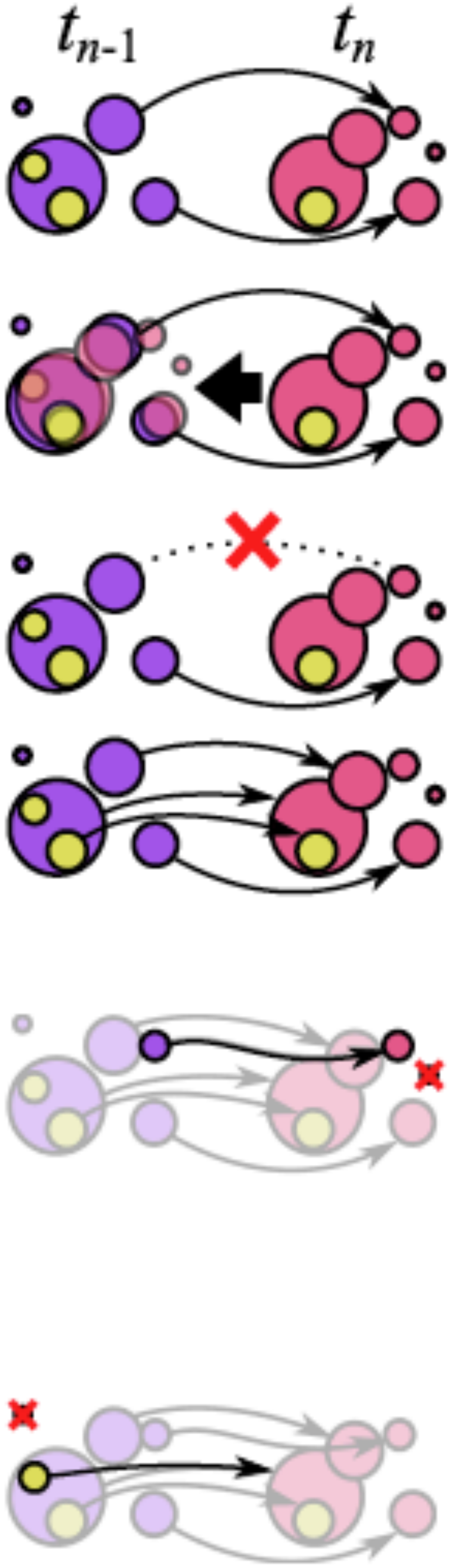
Preliminary

We present a new algorithm for generating merger trees and halo catalogs which explicitly ensures consistency of halo properties (mass, position, velocity, radius) across timesteps. Our algorithm has demonstrated the ability to increase both the completeness (through inserting otherwise missing halos) and purity (through removing spurious objects) of both merger trees and halo catalogs. In addition, our method is able to robustly measure the self-consistency of halo finders; it is the first to directly measure the uncertainties in halo positions, halo velocities, and the halo mass function for a given halo finder based on actual cosmological simulations. We use this algorithm to generate merger trees for two large simulations (Bolshoi and Consuelo) and evaluate two halo finders (BDM and ROCKSTAR). We find that the ROCKSTAR halo finder self-consistently recovers the halo mass function at the 1-2% uncertainty level, whereas BDM recovers it at the 5-10% uncertainty level. Our code is publicly available at http://code.google.com/p/consistent-trees ; our trees and catalogs are available on request, and they will be posted on a public website once the referee process is complete.


Fraction of z = 0 Halos Tracked to Given Redshift -- Bolshoi1 Method


Fraction of z = 0 Halos Tracked to Given Redshift -- New Method

HALO MERGER TREE ALGORITHM



1. Identify halo descendants using a traditional particle algorithm.

2. Gravitationally evolve the positions and velocities of all halos at the current timestep back in time to identify their most likely positions at the previous timestep.

3. Based on predicted progenitor halos in step (2), cut ties to spurious descendants.

4. Create links for halos with likely progenitors at the previous timestep for cases in which step (2) has identified a good match.

5. For halos in the current timestep without likely progenitors, create a new halo at the previous timestep with position and velocity given by the evolution in step (2). Remove any such halos generated from previous rounds if they have had no real progenitors for several timesteps.

6. For halos in the previous timesteps which have no descendants, assume that a merger occurred into the halo exerting the strongest tidal field across it at the previous timestep. If a halo with no descendant is too far removed from other halos to experience a significant tidal field, assume that it is a statistical fluctuation and remove it from the tree and catalogs.

Consistent Merger Trees

Requirements for accurate identification
of halo progenitors:

Do the haloes identified by the halo finder move consistently with the laws of physics?

Are halo properties (mass, radius, vmax) stable across timesteps? Especially subhalos?

We can build explicit modeling of the gravitational evolution of halos into the merger tree code:

Gravitational Acceleration

$$F = \frac{GM_1M_2}{r^2 + r_{vir}^2}$$

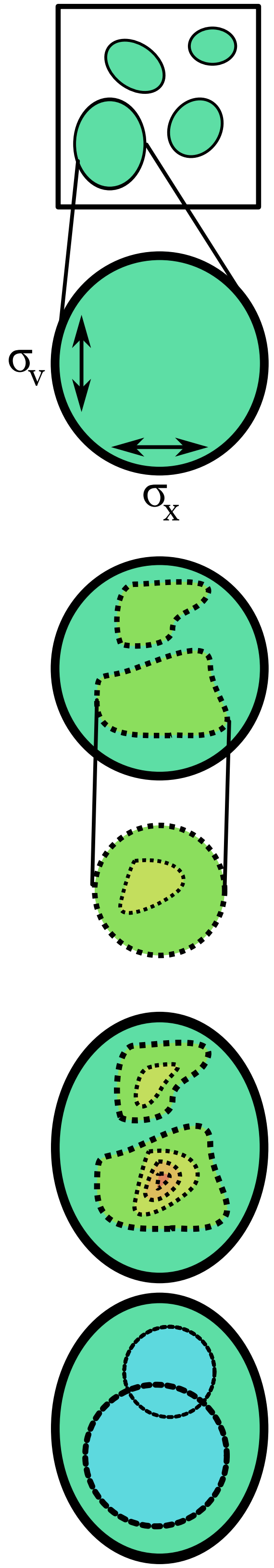
Tidal Merger Criterion

$$\frac{dF}{dr} = \frac{2GM_1M_2}{r^3} > T_{min}$$

```
Time: 13293 Myr Ago
Timestep Redshift: 8.775
Radius Mode: Rvir
Focus Distance: 10.3
Aperture: 40.0
World Rotation: (209.9, 0.08, -0.94, -0.34)
Trackball Rotation: (0.0, 0.00, 0.00, 0.00)
Camera Position: (0.0, 0.0, -10.3)
```

BOLSHOI
Merger Tree
Peter Behroozi, et al.

The Rockstar Halo Finder



The simulation volume is divided into 3D Friends-of-Friends groups for easy parallelization.

For each group, particle positions and velocities are divided (normalized) by the group position and velocity dispersions, giving a natural phase-space metric.

A phase-space linking length is adaptively chosen such that 70% of the group's particles are linked together in subgroups.

The process repeats for each subgroup: renormalization, a new linking-length, and a new level of substructure calculated.

Once all levels of substructure are found, seed halos are placed at the lowest substructure levels and particles are assigned hierarchically to the closest seed halo center in phase space. (see Knebe et al. 2011 for specific details).

Once particles have been assigned to halos, unbound particles are removed and halo properties (positions, velocities, spherical masses, radii, spins, etc.) are calculated.

Behroozi et al. in prep.

The Rockstar Halo Finder

In practice, how does it *work*?
That is, how well does it recover halo properties?

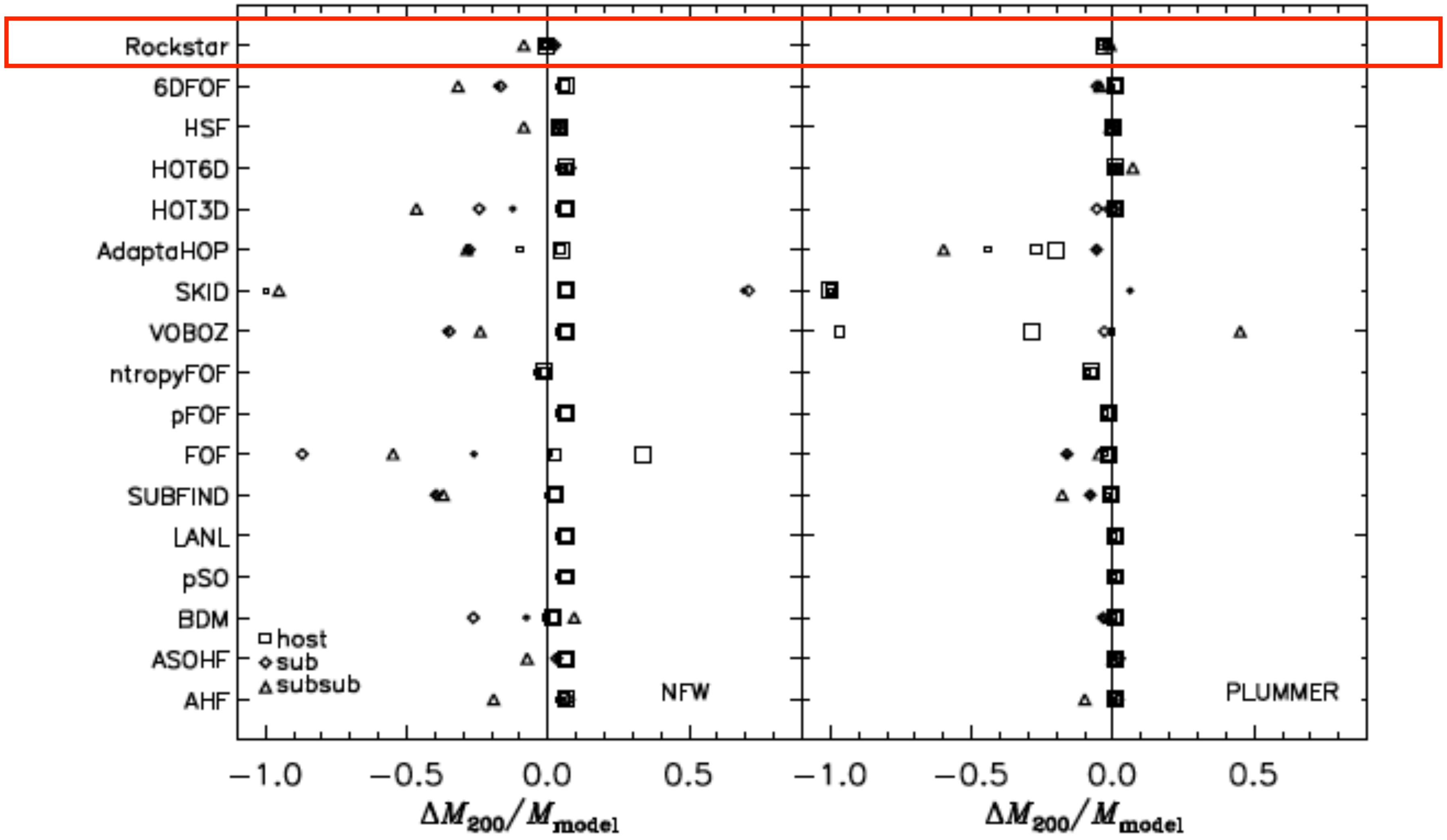
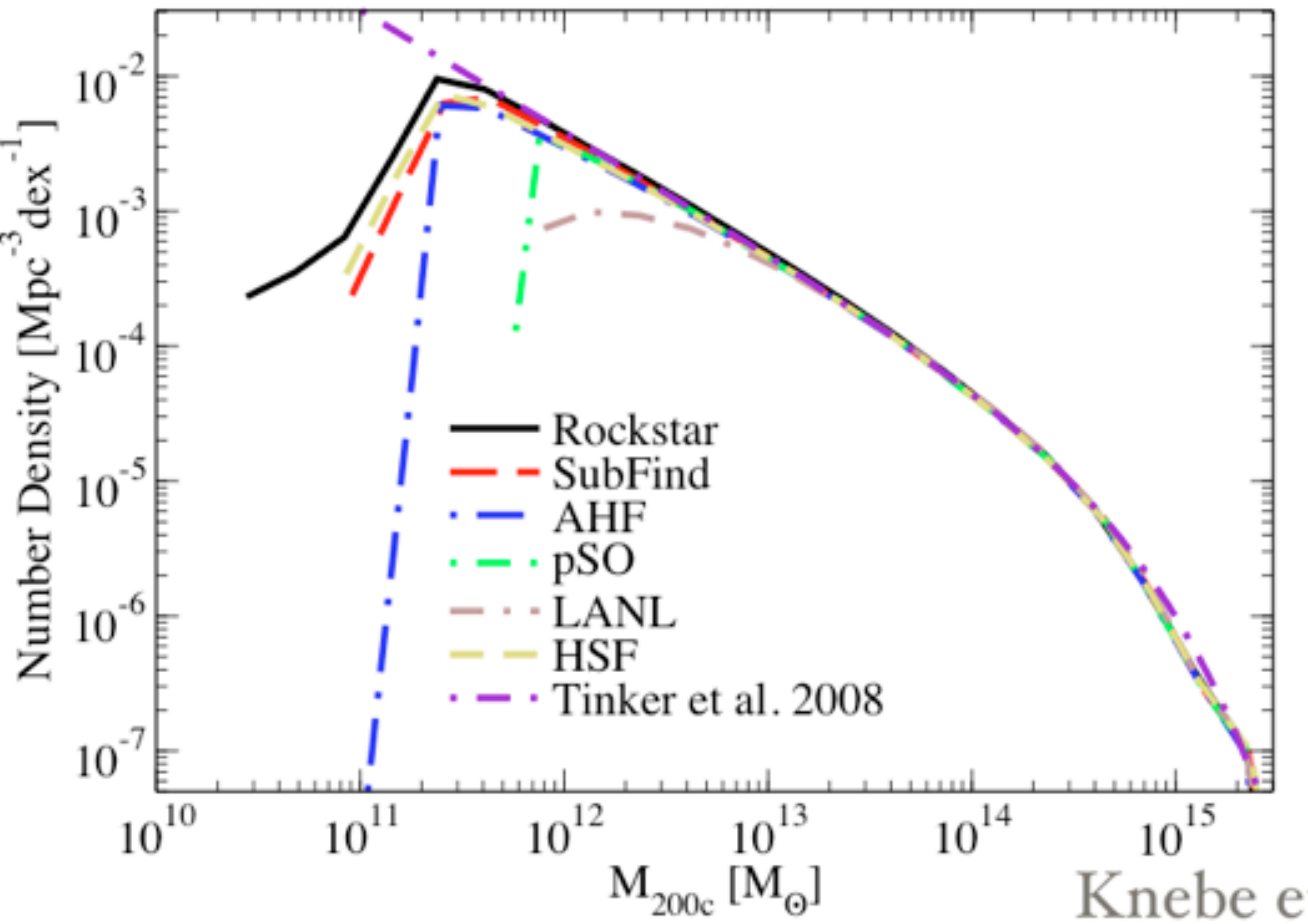


Figure 5. M_{200} mass (as determined from the supplied particle lists) measured according to the mean enclosed density being $200 \times \rho_{\rm crit}$ criterion for the NFW (left) and Plummer (right) density mock haloes extracted from each finder's list of gravitationally bound particles. The symbols have the same meaning as in Fig. 2

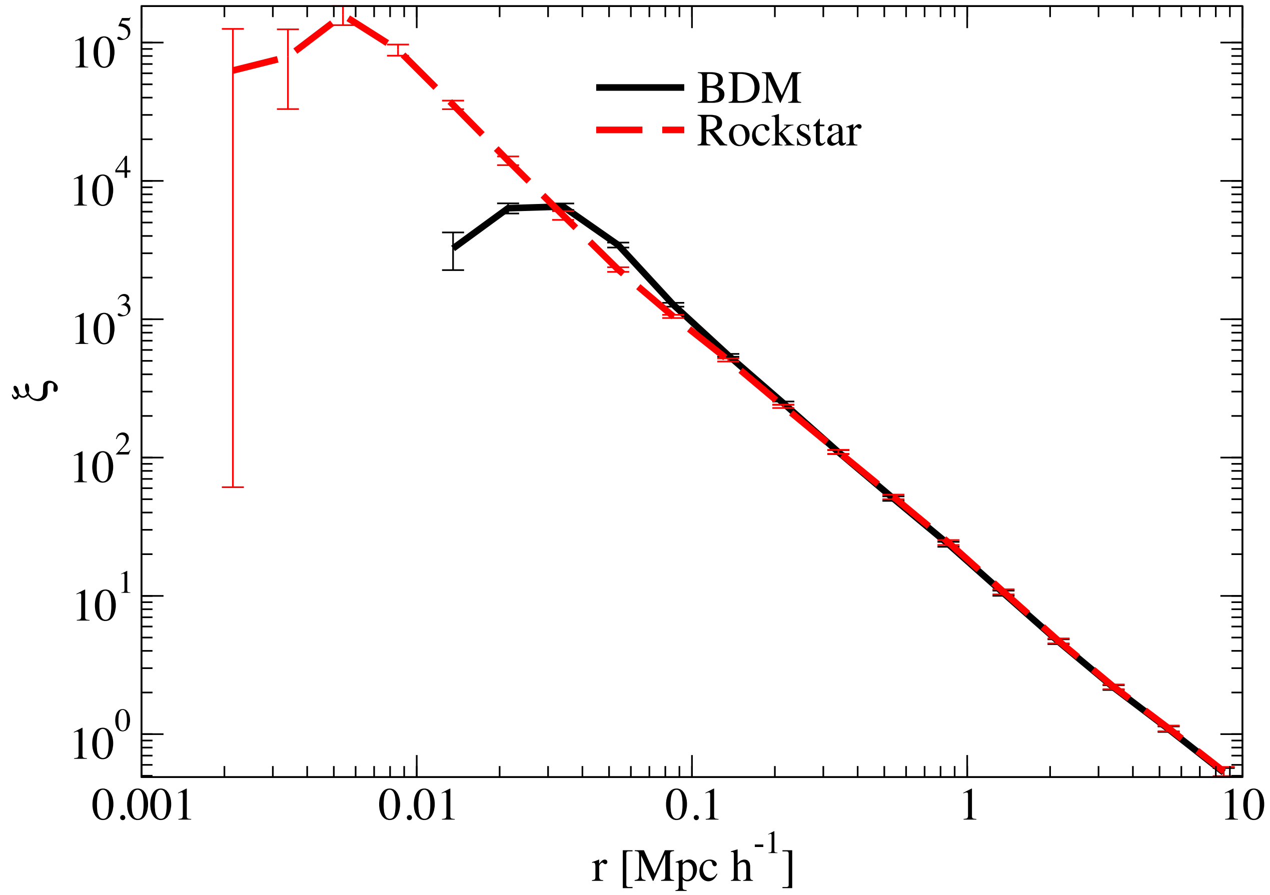
Knebe et al. 2011

Successes of Behroozi et al. ROCKSTAR halo finder

Halo Number Density

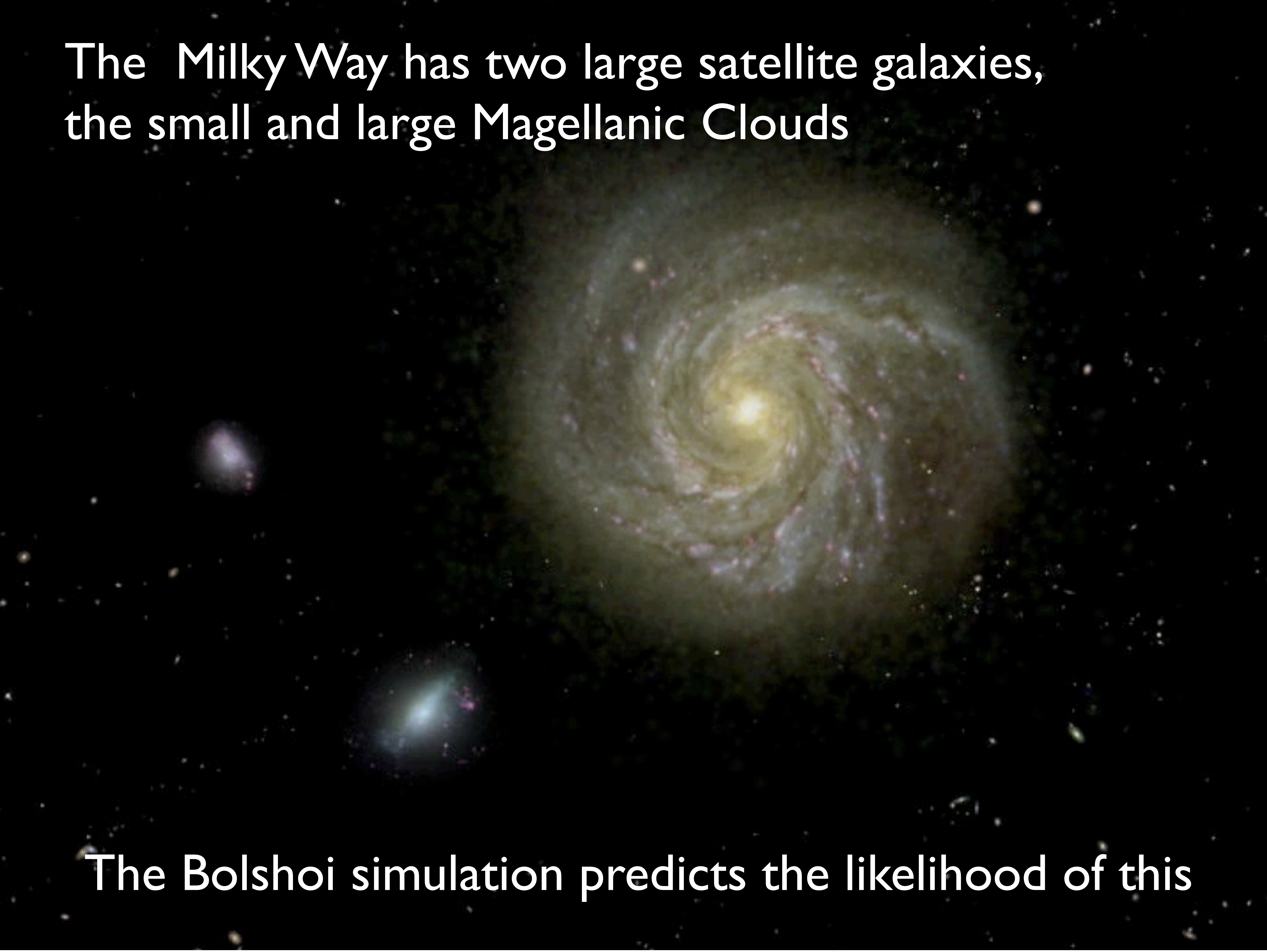


Halo Autocorrelations



Knebe et al. 2011

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



The Bolshoi simulation predicts the likelihood of this

Statistics of MW-satellite analogs

Liu, Gerke & Wechsler

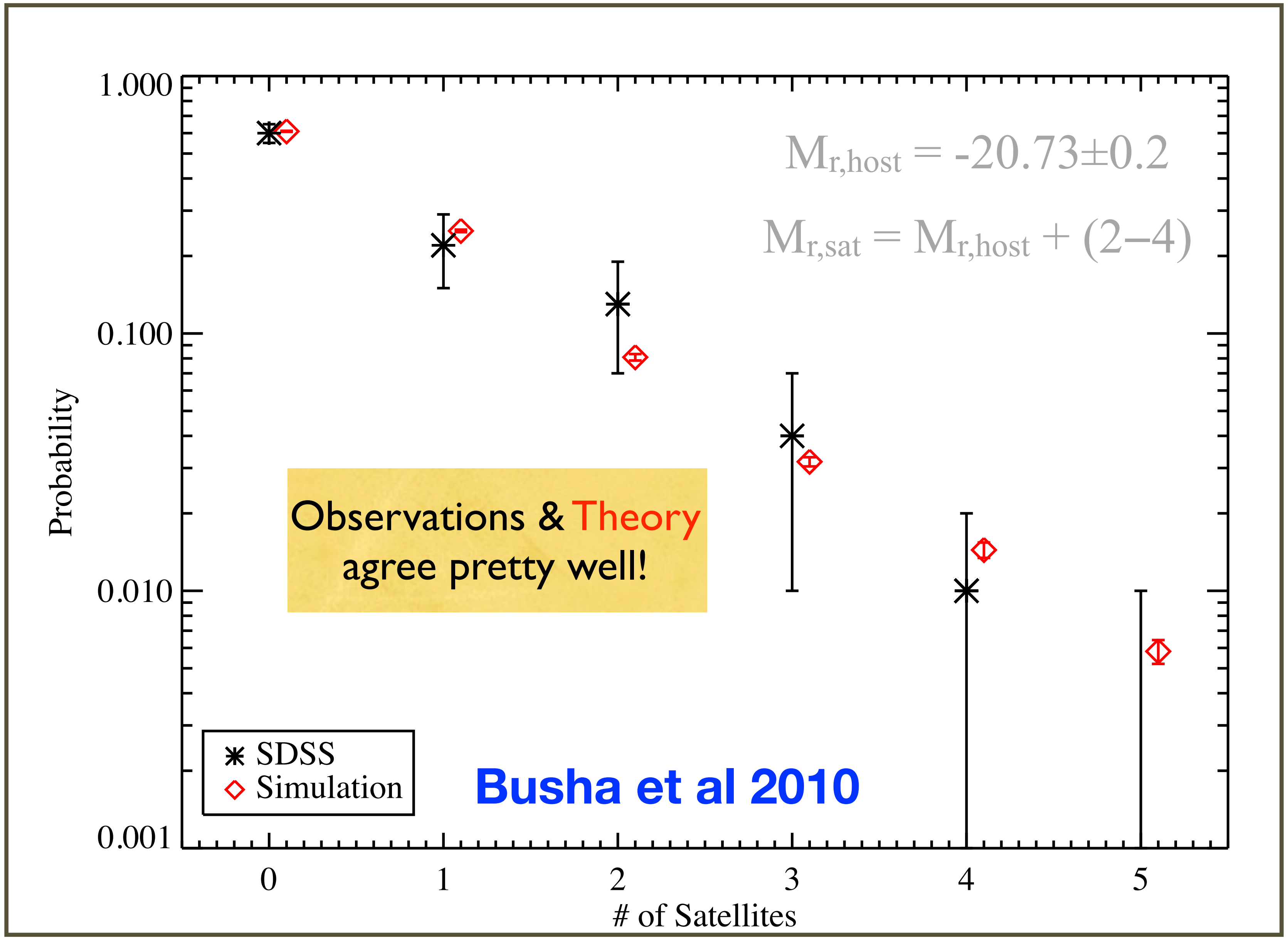
- Search SDSS DR7 Co-Add data to look for analogues of the LMC/SMC in extragalactic hosts
- SDSS Co-Add Data:
  - Stripe-82 in the SDSS was observed ~370 times, complete to observed magnitude limit $M_r = 23.6$ over ~270 sq. deg; main sample spectroscopy (mostly) complete down to $M_r = 17.77$
  - Photometric redshifts calculated for the remaining objects using a template method.
    - Training/validation set taken from CNOC2, SDSS main, and DEEP2 samples.
    - Measured scatter: $\Delta z = 0.02$
  - 23,000 spectroscopic galaxy (non-QSO) candidates in Stripe 82 with $m_r < 17.77$
- Magnitude Cuts:
  - Identify all objects with absolute ${}^{0.1}M_r = -20.73 \pm 0.2$ and observed $m_r < 17.6$
  - Lets us probe out to $z = 0.15$, a volume of roughly 500 $(\mathrm{Mpc}/h)^3$
  - leaves us with 3,200 objects.
- Isolation Criteria: exclude objects in clusters, since those are likely biased -- exclude candidates with neighbors brighter than itself within a cylinder defined by:
  - radial distance 1000 km/s -- the velocity dispersion of a typical cluster and $\Delta z \approx 0.01$ at our relevant redshifts.
  - projected angular distance $R_{iso} = 0.7$ Mpc
  - leaves us with 1,332 hosts.

Risa Wechsler

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 (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%

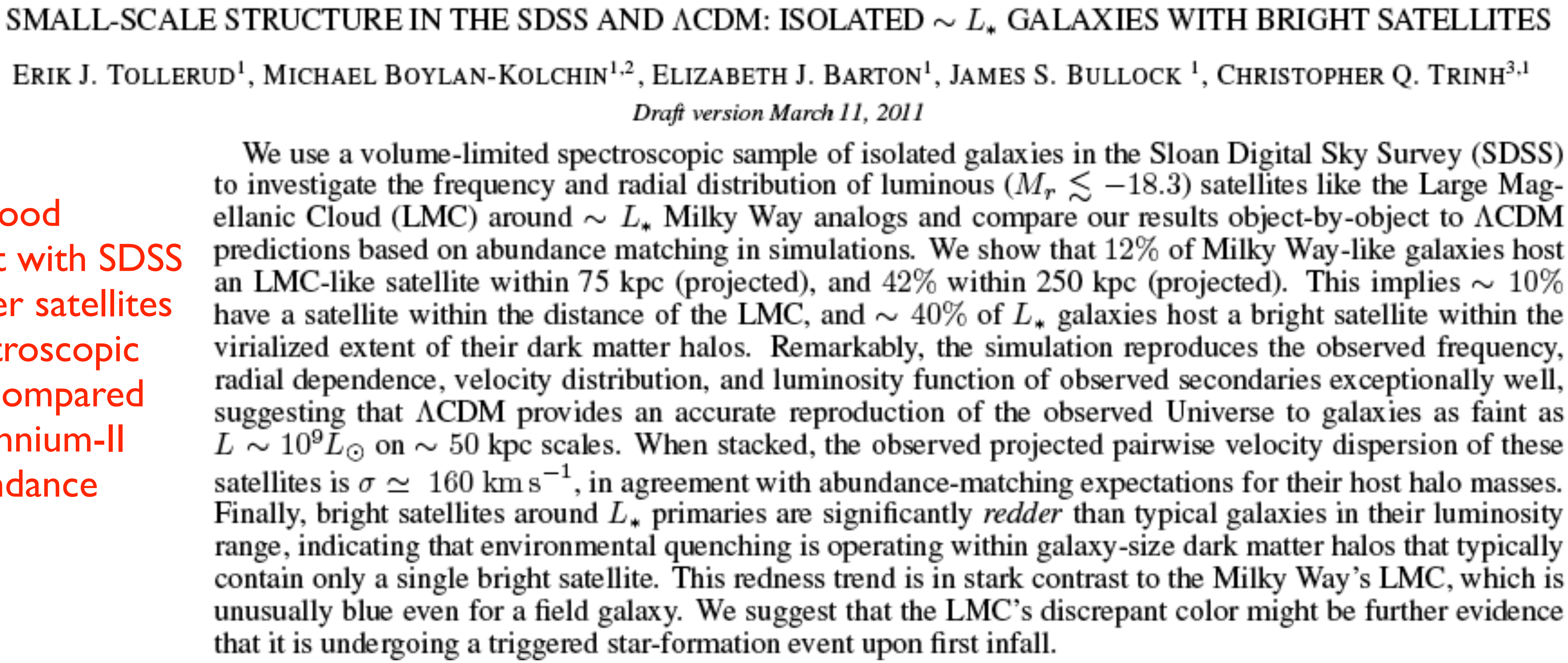


Observations & Theory agree pretty well!

Busha et al 2010

Every case agrees within observational errors!

Risa Wechsler



SMALL-SCALE STRUCTURE IN THE SDSS AND ΛCDM: ISOLATED $\sim L_*$ GALAXIES WITH BRIGHT SATELLITES

Erik J. Tollerud[1], Michael Boylan-Kolchin[1,2], Elizabeth J. Barton[1], James S. Bullock [1], Christopher Q. Trinh[3,1]

Draft version March 11, 2011

Similarly good agreement with SDSS for brighter satellites with spectroscopic redshifts compared with Millennium-II using abundance matching.

We use a volume-limited spectroscopic sample of isolated galaxies in the Sloan Digital Sky Survey (SDSS) to investigate the frequency and radial distribution of luminous ($M_r \lesssim -18.3$) satellites like the Large Magellanic Cloud (LMC) around $\sim L_*$ Milky Way analogs and compare our results object-by-object to ΛCDM predictions based on abundance matching in simulations. We show that 12% of Milky Way-like galaxies host an LMC-like satellite within 75 kpc (projected), and 42% within 250 kpc (projected). This implies $\sim$ 10% have a satellite within the distance of the LMC, and $\sim$ 40% of L_* galaxies host a bright satellite within the virialized extent of their dark matter halos. Remarkably, the simulation reproduces the observed frequency, radial dependence, velocity distribution, and luminosity function of observed secondaries exceptionally well, suggesting that ΛCDM provides an accurate reproduction of the observed Universe to galaxies as faint as $L \sim 10^9 L_\odot$ on $\sim$ 50 kpc scales. When stacked, the observed projected pairwise velocity dispersion of these satellites is $\sigma \simeq 160\ \mathrm{km\,s^{-1}}$, in agreement with abundance-matching expectations for their host halo masses. Finally, bright satellites around L_* primaries are significantly *redder* than typical galaxies in their luminosity range, indicating that environmental quenching is operating within galaxy-size dark matter halos that typically contain only a single bright satellite. This redness trend is in stark contrast to the Milky Way's LMC, which is unusually blue even for a field galaxy. We suggest that the LMC's discrepant color might be further evidence that it is undergoing a triggered star-formation event upon first infall.

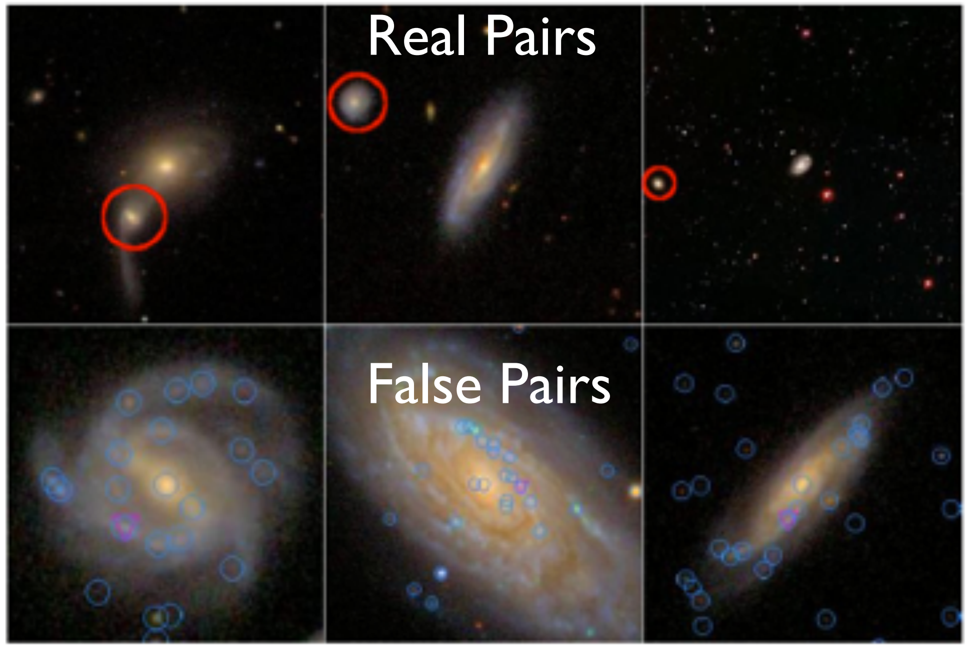


FIG. 1.— Examples of SDSS primary/secondary pairs in the clean sample (upper) and false pairs (lower). Secondaries identified by our criteria (see text) are marked with red circles (upper panels) or magenta triangles (lower panels). The upper three are all in the clean sample (have redshifts close to the primary) and span a range of projected separations. For the lower three images, blue circles are SDSS pipeline photometric objects, clearly showing the identification of HII regions as photometric objects. For these same lower three, the secondaries are clearly HII regions in the primary (or satellites that are indistinguishable from HII regions). We visually identify and remove all pairs of this kind from our sample.

Good agreement between simulated and observed pairwise velocities

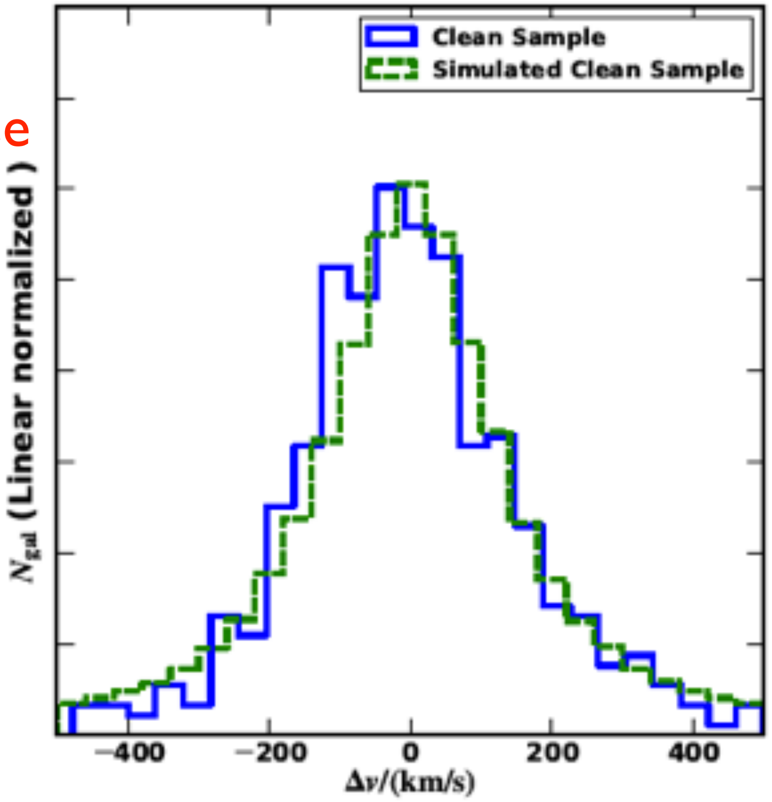
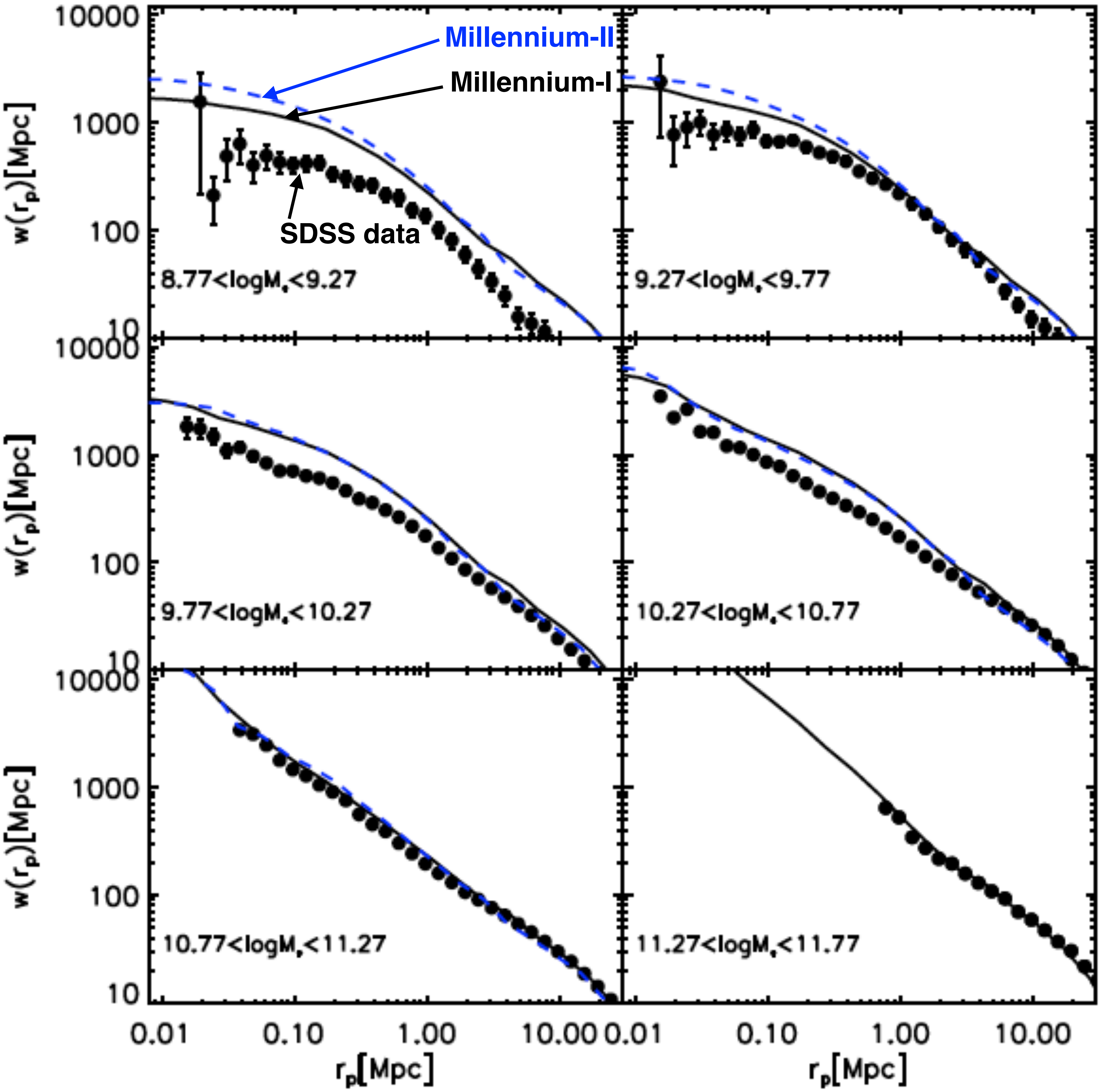


FIG. 6.— Distribution of $\Delta v \equiv c(z_{\rm pri} - z_{\rm sec})$ for the clean sample (solid blue histogram), the clean-like sample from MS-II (dashed green). The KS test yields $p_{\rm KS} = 33\%$. The pairwise velocity dispersion in the observed sample is $\sigma = 161\ \mathrm{km\,s^{-1}}$.

Projected Galaxy Correlation Functions



Projected correlation functions for galaxies in different stellar mass ranges, in SAM based on Millennium I and II. Black solid and blue dashed curves give results for preferred model applied to the MS and the MS-II, respectively. Symbols with error bars are results for SDSS/DR7 calculated using the same techniques as in Li et al. (2006). The two simulations give convergent results for $M_* > 6\times10^9\ M_{sun}$. At lower mass the MS underestimates the correlations on small scales.The model agrees quite well with the SDSS at all separations for $M_* > 6\times10^{10}\ M_{sun}$. But **at smaller masses the correlations are overestimated substantially, particularly at small separations. The authors attribute this to the too-high $\sigma_8 = 0.90$ used in MS-I & II.**

Guo, White, et al. MNRAS in press.

To investigate the statistics of galaxies and their relation to host DM halos as predicted by the LCDM model, we predicted the properties of our model galaxies using the following procedure:

1. Using the merger tree of each DM halo and subhalo, obtain V_{acc} = the peak value of the circular velocity over the history of the halo (this is typically the maximum circular velocity of the halo when the halo is first accreted). Perform abundance matching of the velocity function of the halos to the LF of galaxies to obtain the luminosity of each model galaxy.

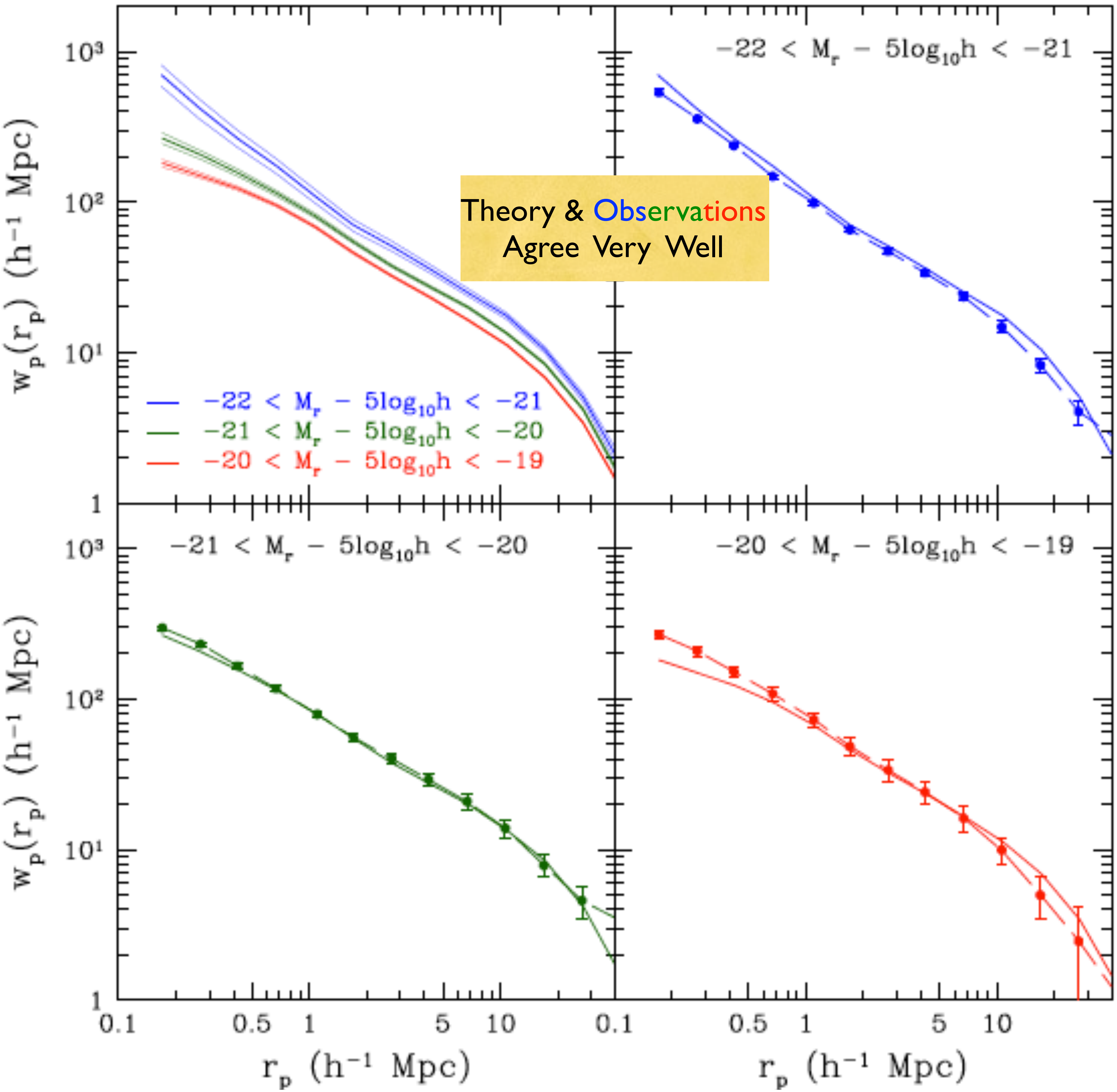
2. Perform abundance matching of the velocity function to the stellar mass function of galaxies to obtain the stellar mass of each model galaxy.

3. Use the observed gas-to-stellar mass ratio as a function of stellar mass to assign cold gas masses to our model galaxies. The stellar mass added to the cold gas mass becomes the total baryonic mass.

4. Using the density profiles of the DM halos, obtain the circular velocity at 10 kpc (V_{10}) from the center of each halo. Multiply the DM mass, as it comes from simulations, by the factor $(1 - f_{bar})$, where f_{bar} is the cosmological fraction of baryons. This is the dark-matter-only contribution. Add the contribution to V_{10} of the baryon mass from step 3 assuming it is enclosed within a radius of 10 kpc.

5. Optionally implement the BFFP86 correction to V_{10} due to the adiabatic contraction of the DM halos from the infall of the baryon component to the center.

Projected Galaxy Correlation Functions



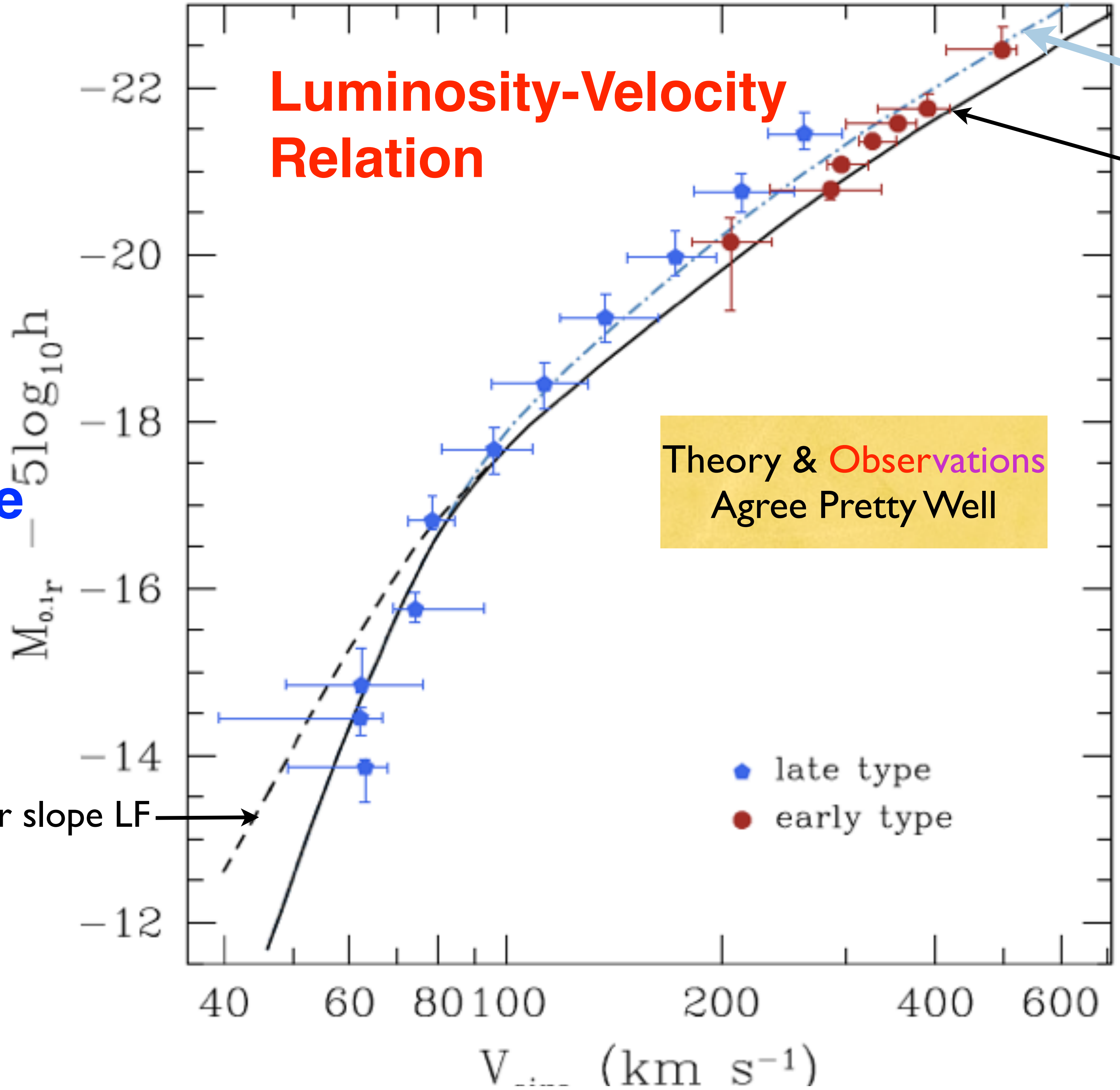
Theory & Observations Agree Very Well

The correlation function of SDSS galaxies vs. Bolshoi galaxies using halo abundance matching, with scatter using our stochastic abundance matching method. This results in a better than 20% agreement with SDSS. *Top left:* correlation functinon in three magnitude bins, showing Poisson uncertainties as thin lines. *Remaining panels:* correlation function in each luminosity bin compared with SDSS galaxies (points with error bars: Zehavi et al. 2010).

Trujillo-Gomez, Klypin, Primack, & Romanowsky arXiv: 1005.1289

Luminosity-Velocity Relation

Bolshoi Sub-Halo Abundance Matching



median Vcirc without AC

median Vcirc with AC

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

Theory & Observations
Agree Pretty Well

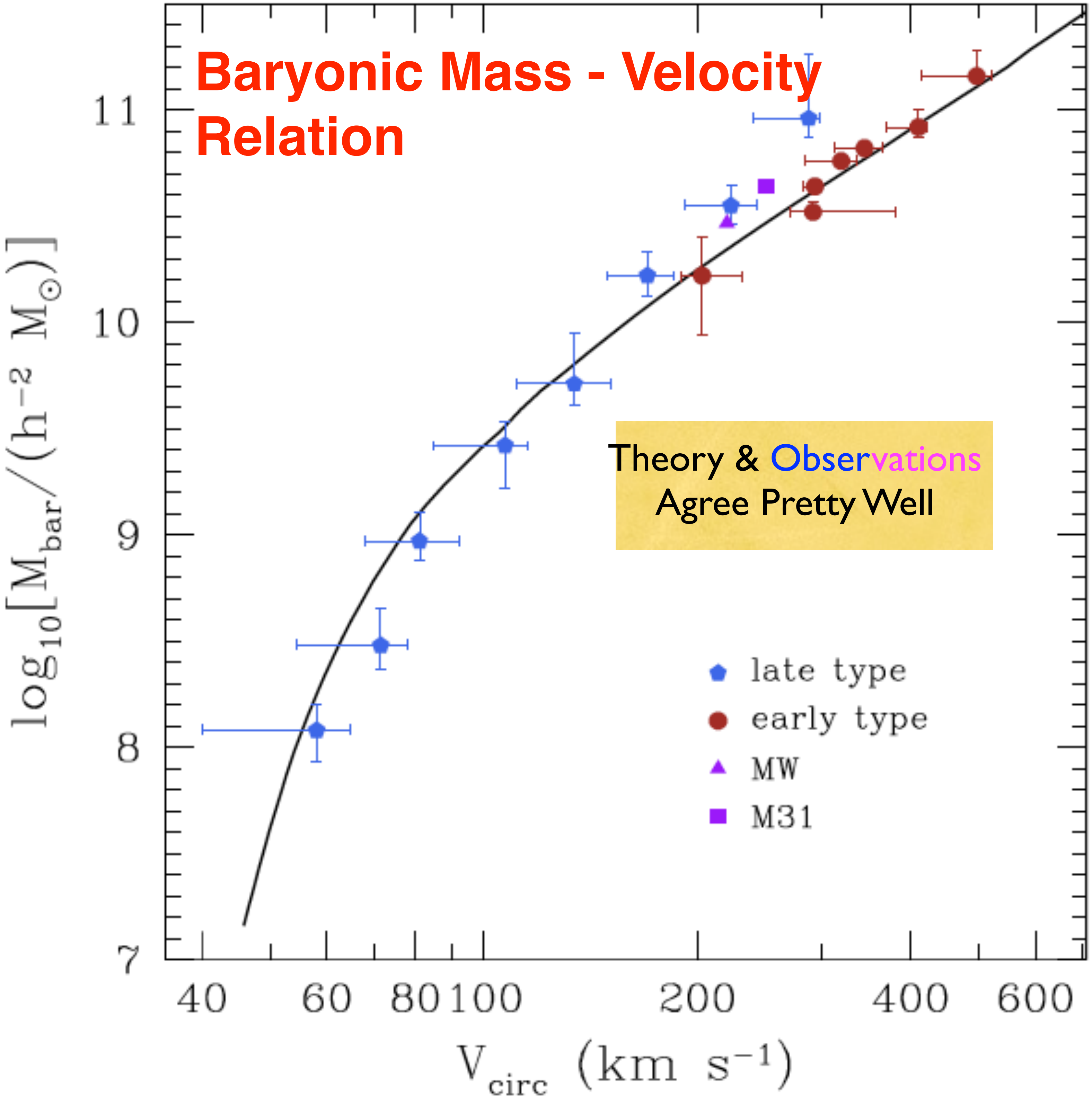
steeper slope LF

Trujillo-Gomez, Klypin, Primack, & Romanowsky
arXiv: 1005.1289
ApJ in press

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

Baryonic Mass - Velocity Relation

Bolshoi Sub-Halo Abundance Matching



Theory & Observations
Agree Pretty Well

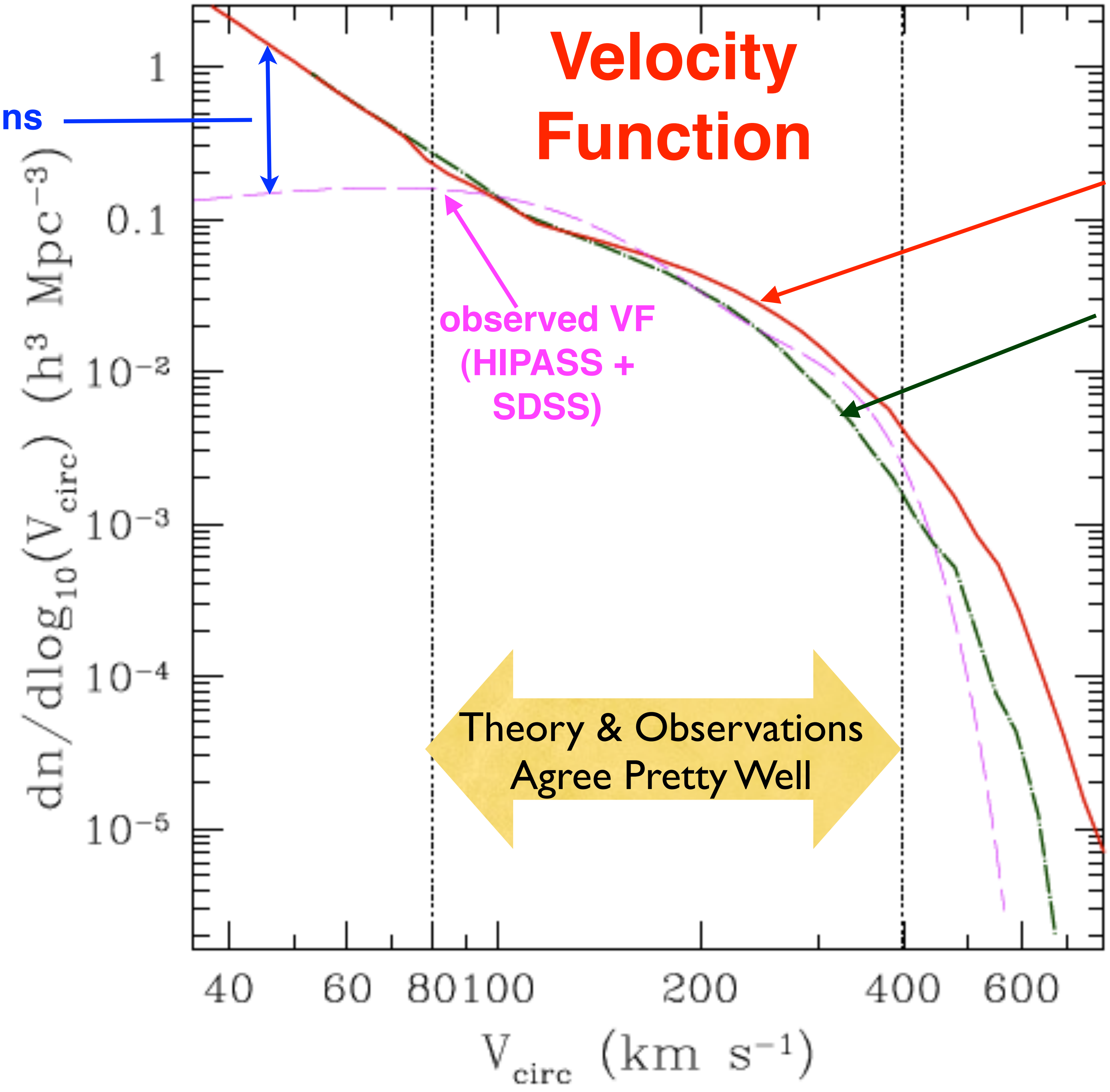
Trujillo-Gomez, Klypin, Primack, & Romanowsky
arXiv: 1005.1289
ApJ in press

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.

Velocity Function

Discrepancy due to incomplete observations or ΛCDM failure?

Bolshoi Sub-Halo Abundance Matching



theoretical VF with AC

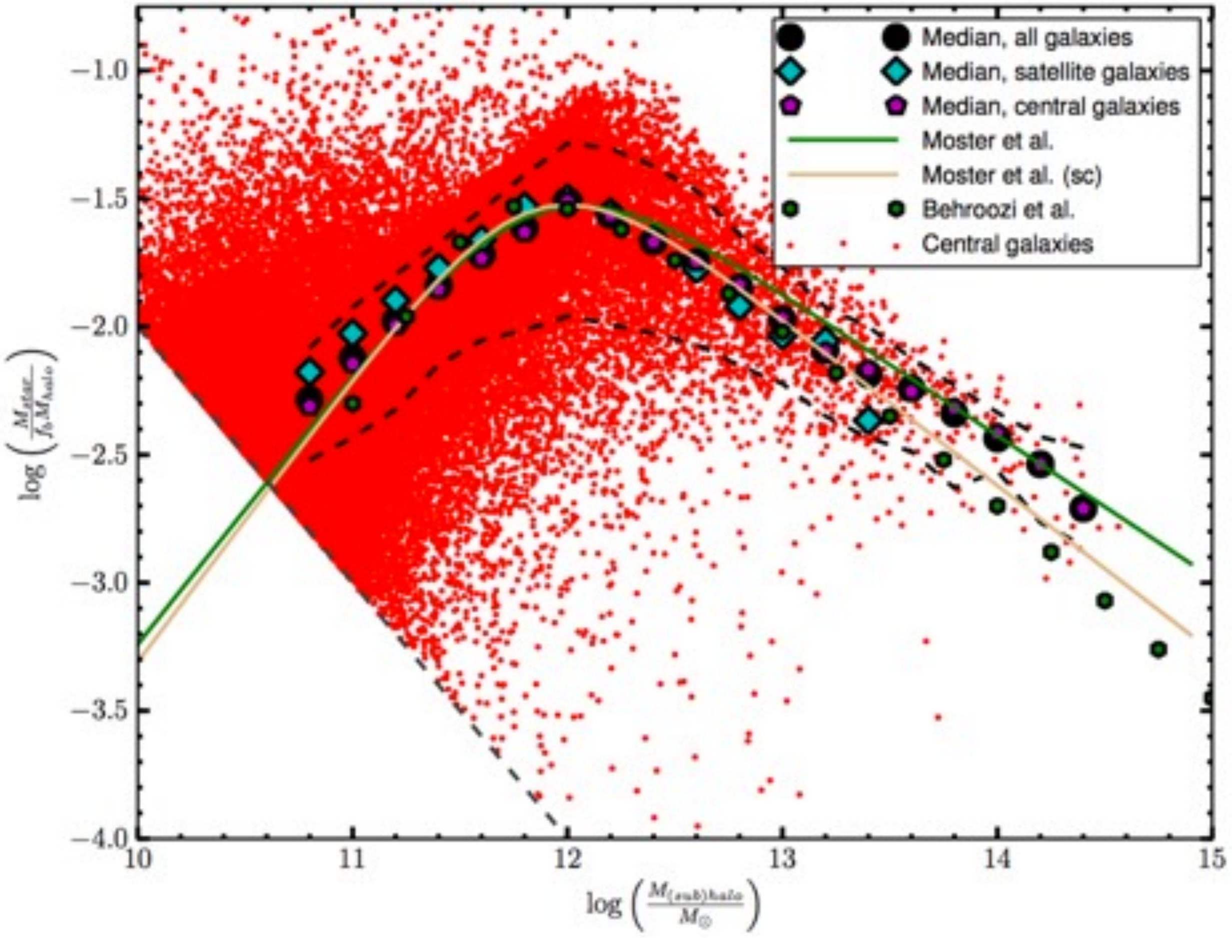
theoretical VF without AC

Trujillo-Gomez, Klypin, Primack, & Romanowsky arXiv: 1005.1289

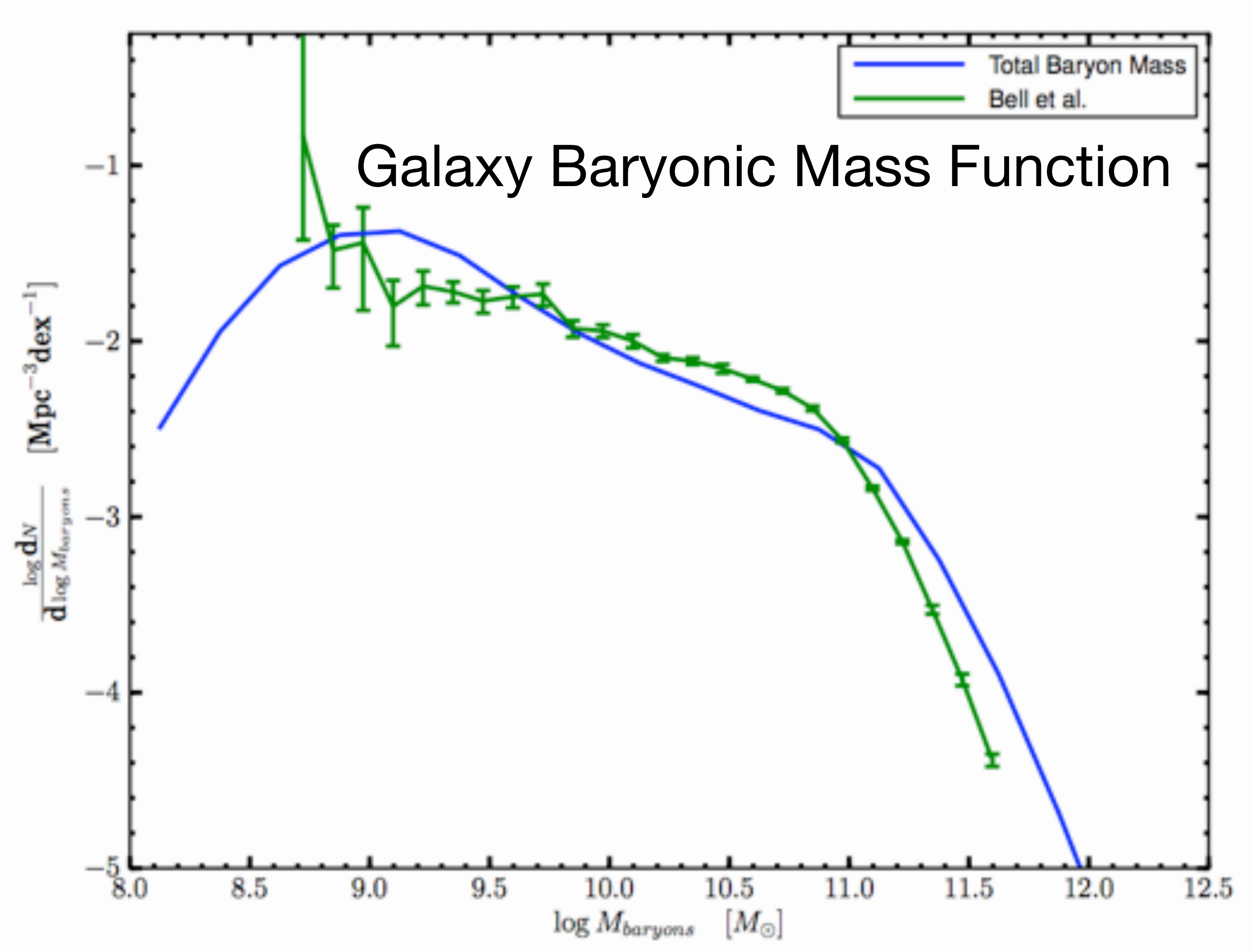
Fig. 11.— Comparison of theoretical (dot-dashed and thick solid curves) and observational (dashed curve) circular velocity functions. The dot-dashed line shows the effect of adding the baryons (stellar and cold gas components) to the central region of each DM halo and measuring the circular velocity 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.

First SAM galaxy results with Bolshoi - Rachel Somerville

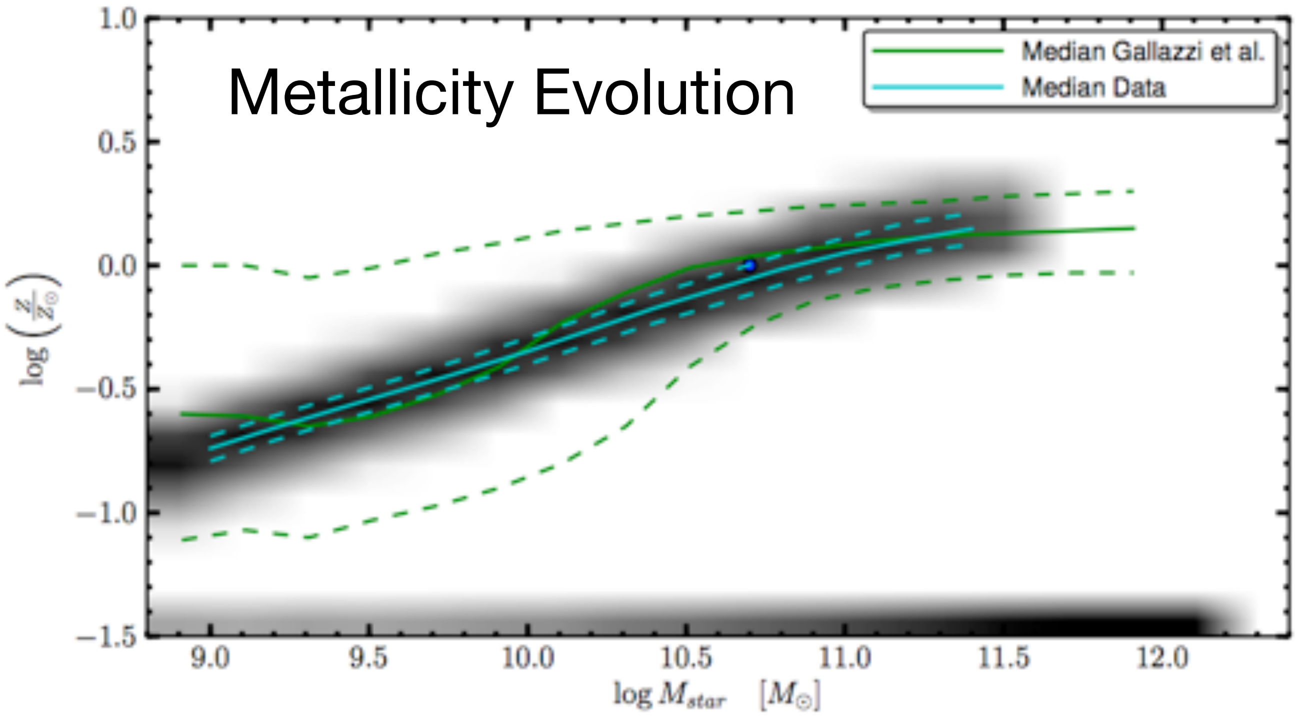
Star Formation Efficiency



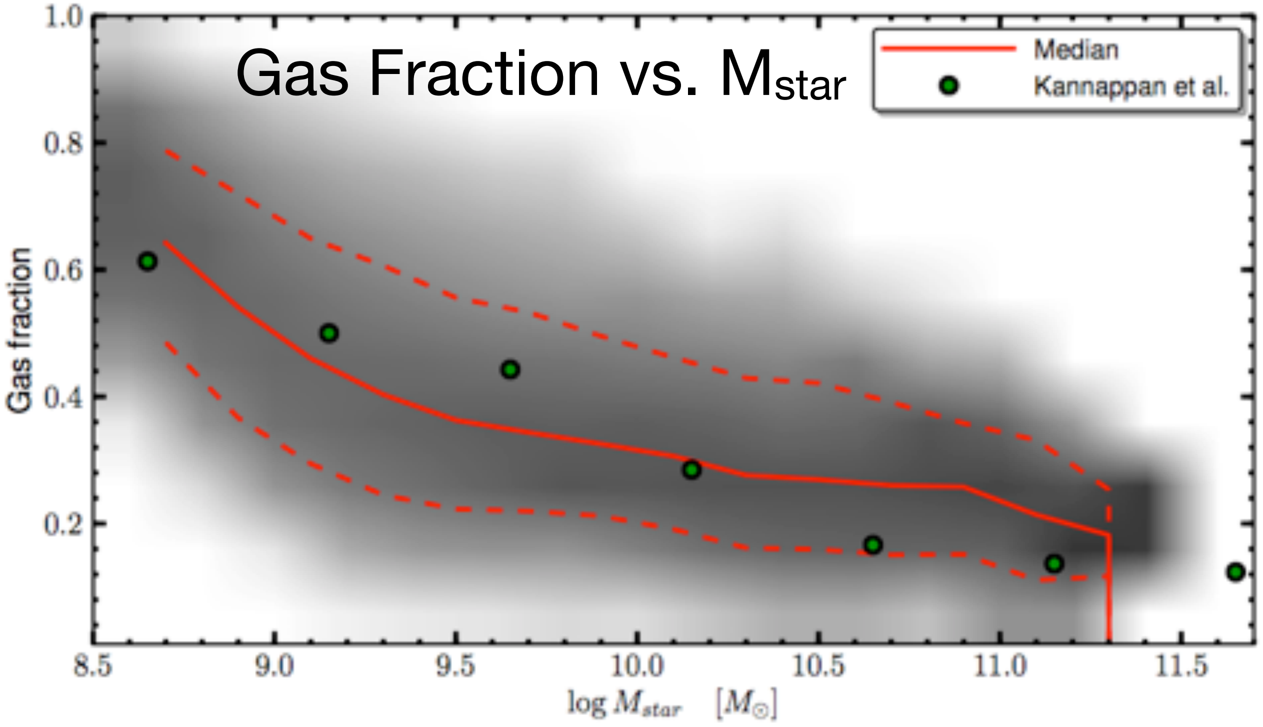
Galaxy Baryonic Mass Function

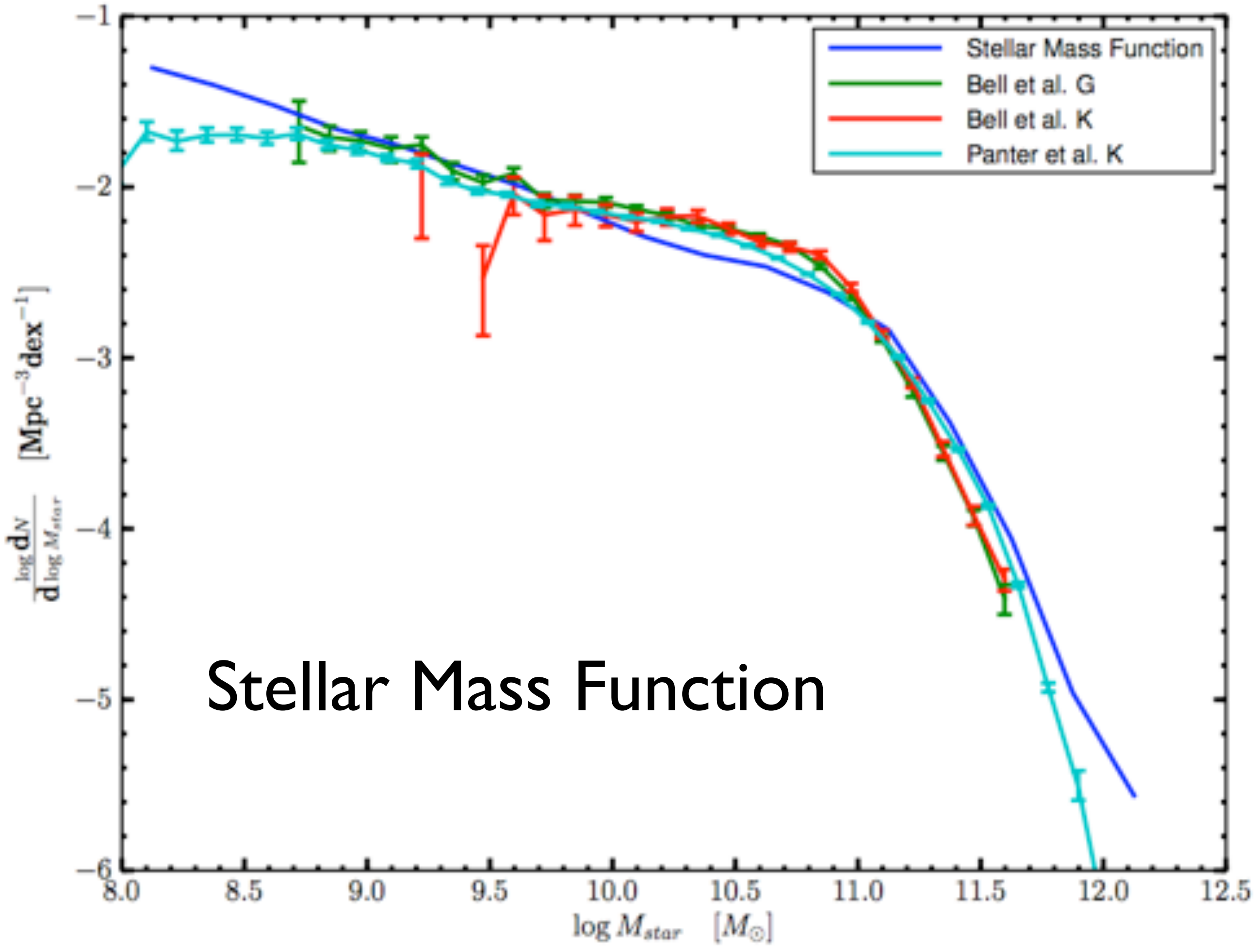


Metallicity Evolution

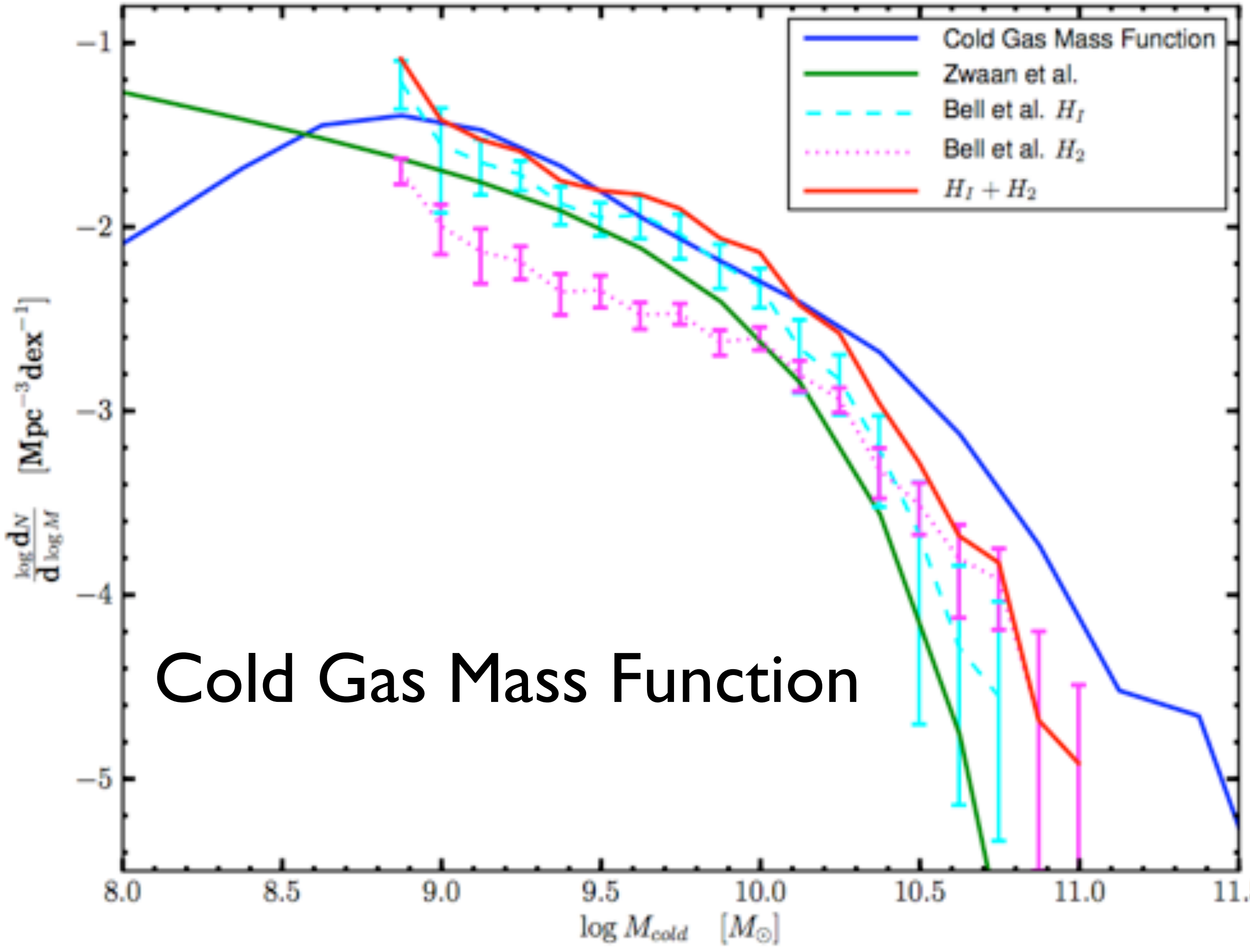


Gas Fraction vs. M_{star}



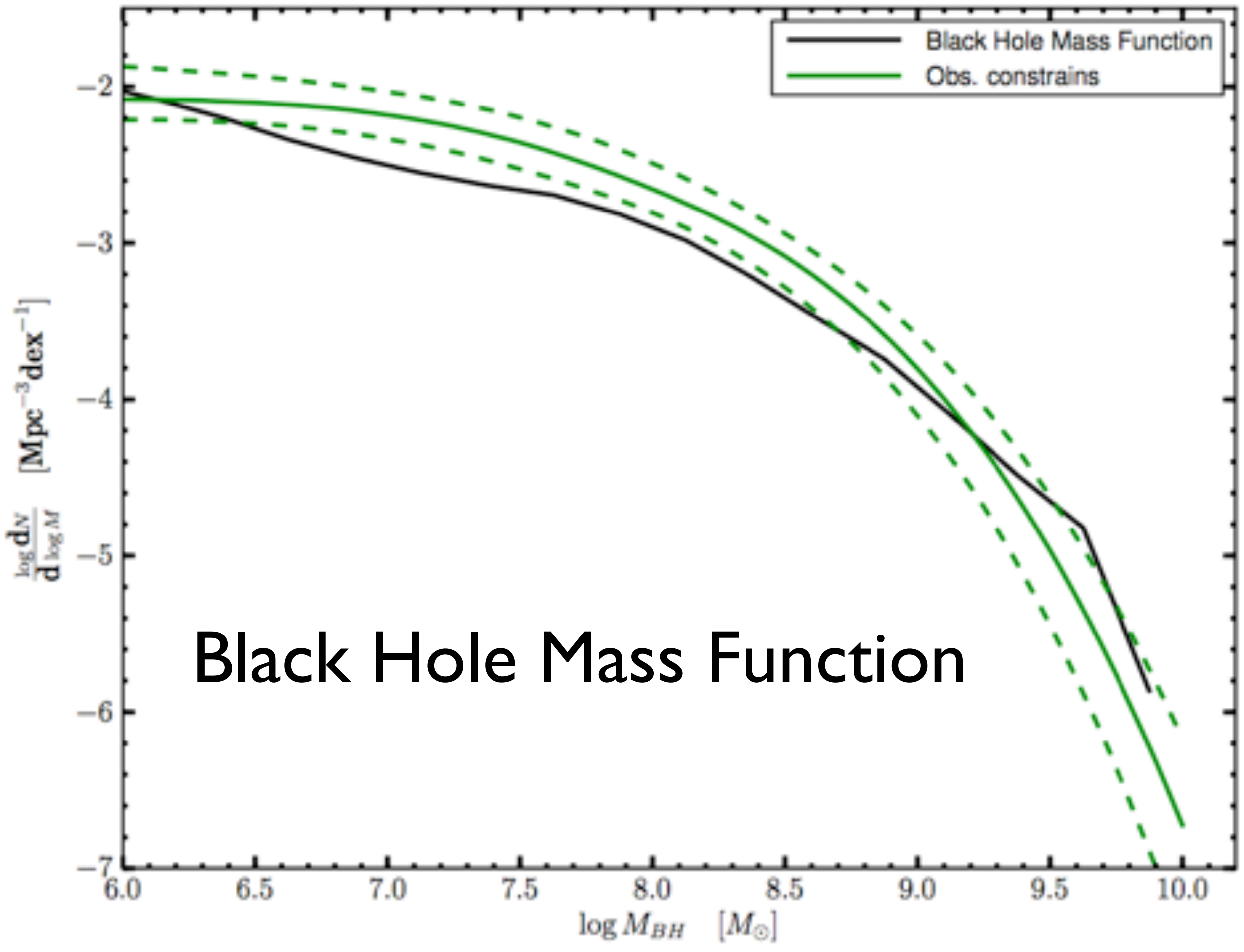


Stellar Mass Function

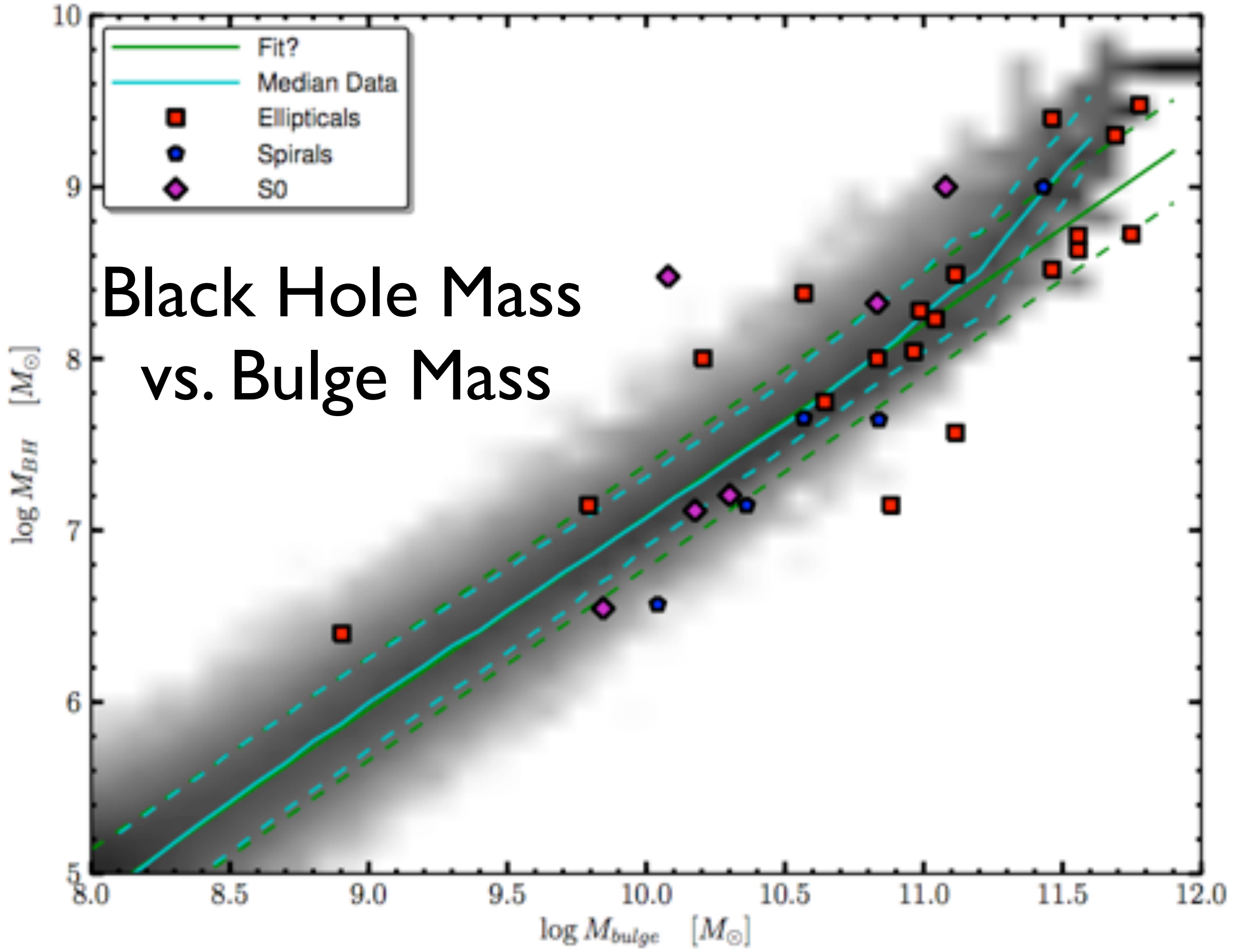


Cold Gas Mass Function

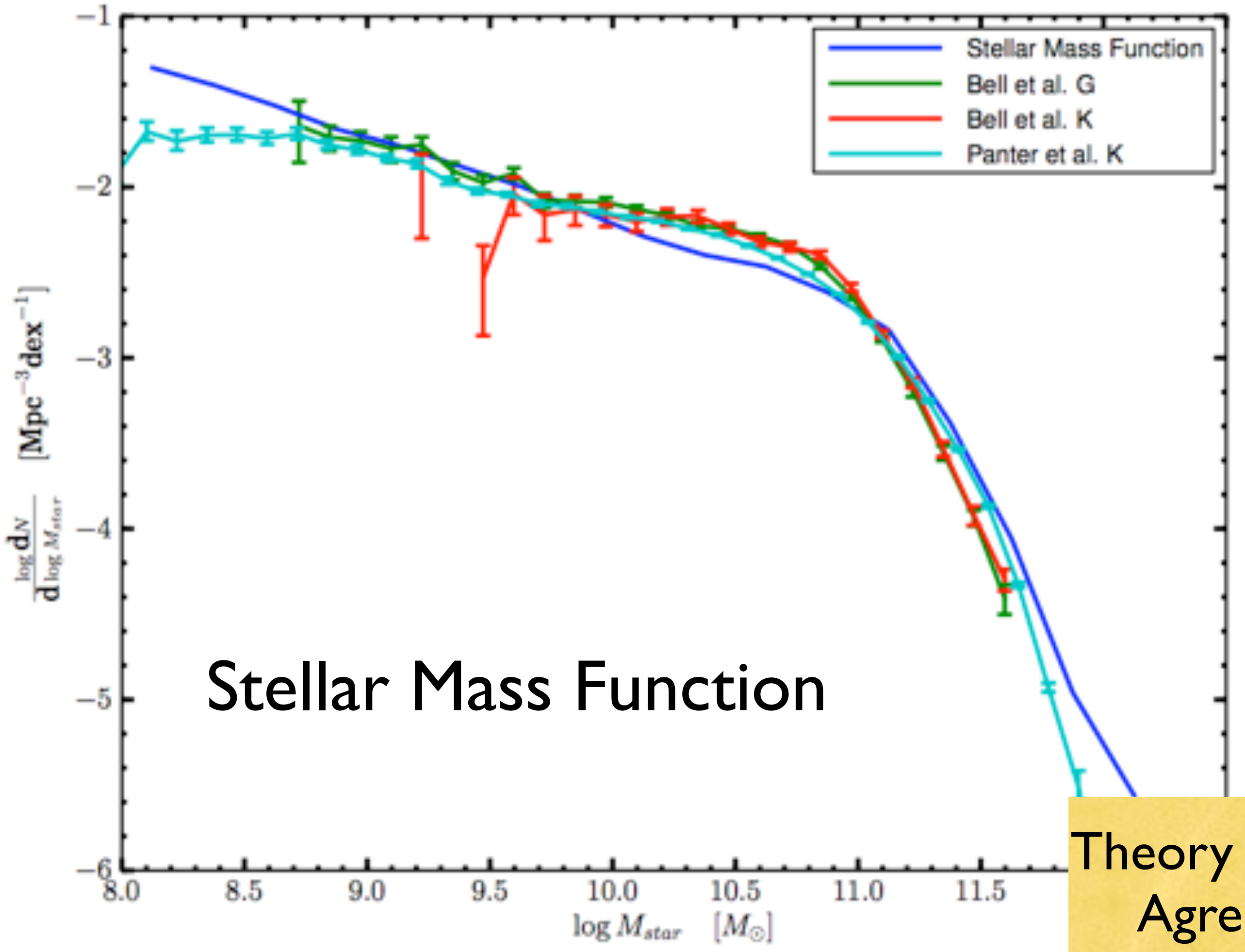
S



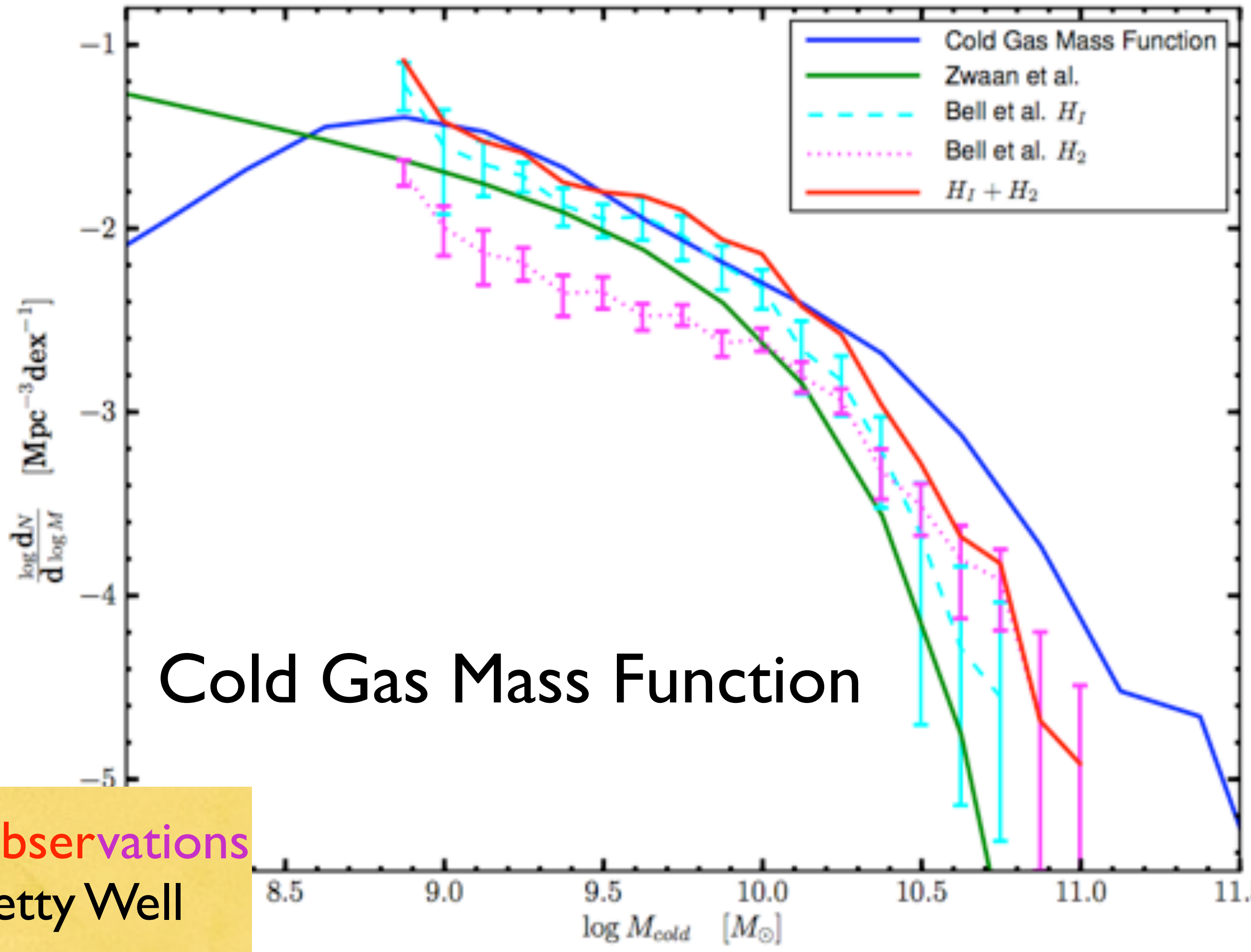
Black Hole Mass Function



Black Hole Mass
vs. Bulge Mass

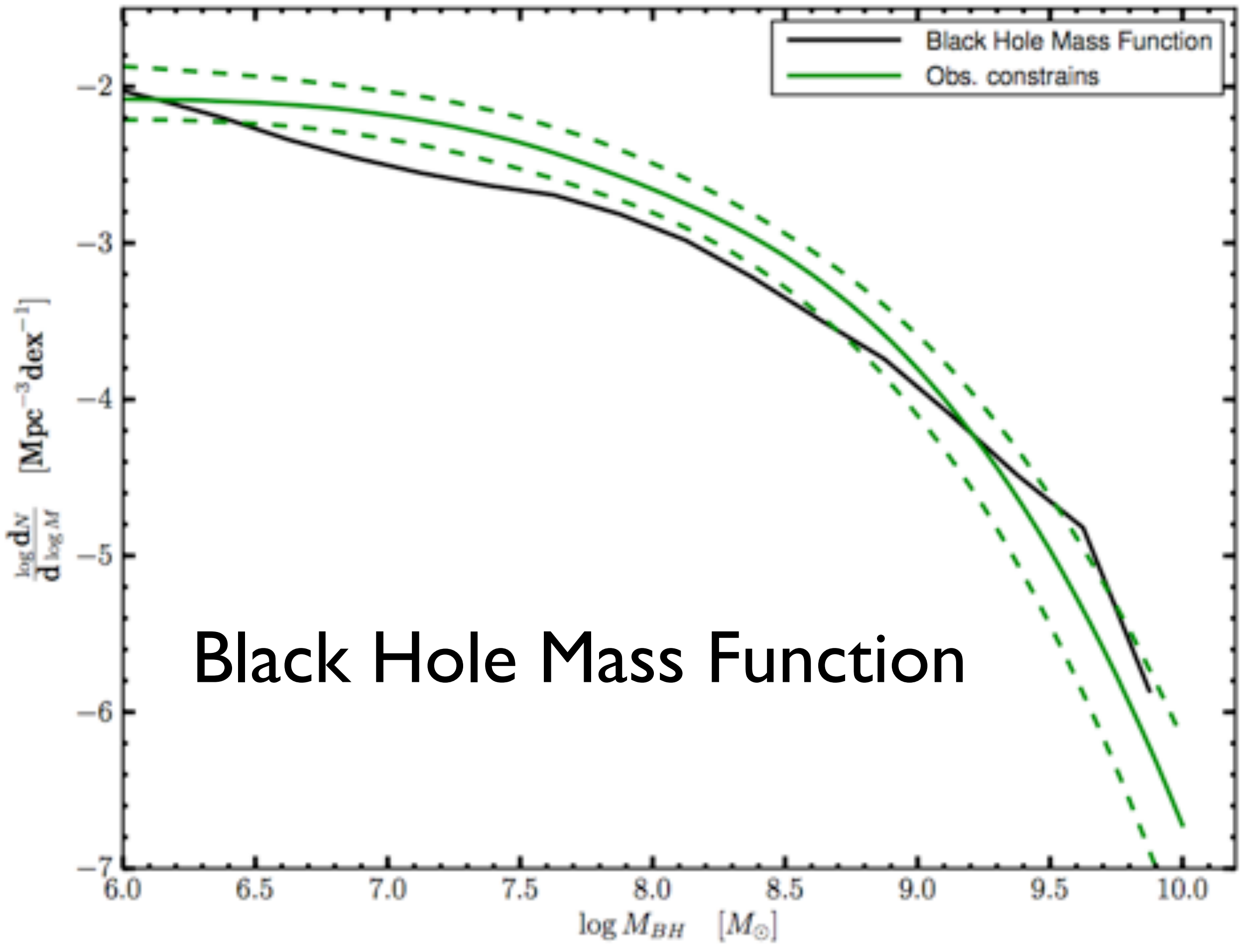


Stellar Mass Function

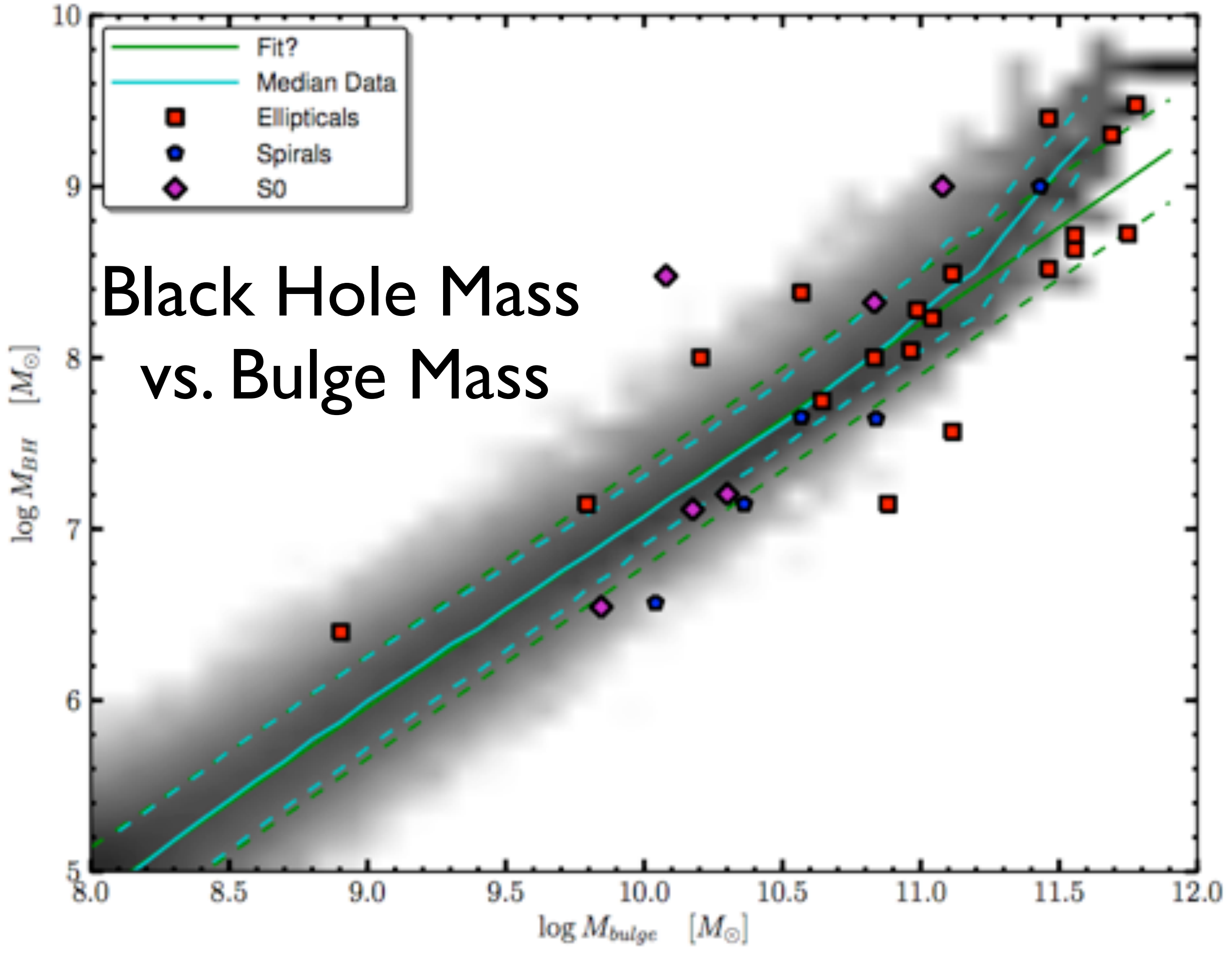


Cold Gas Mass Function

Theory & Observations
Agree Pretty Well



Black Hole Mass Function



Black Hole Mass
vs. Bulge Mass

Bolshoi simulations - recent progress

- Anatoly Klypin has improved his BDM halofinder. It now finds the spin parameter, concentration, and shape and orientation of all halos. It also produces catalogs for both "virial" and overdensity-200 halo definitions. Results on all 180 stored timesteps of the **Bolshoi** simulation will be finished in a week or so. Peter Behroozi has written a new phase-space halofinder that finds subhalos better in the central regions of larger halos.
- All catalogs are finished for **BigBolshoi** (MultiDark), which has the same cosmology as Bolshoi in a volume 64x larger. It has 7 kpc/h resolution, and is complete to Vcirc > 170 km/s (so all MWy-size halos are found). BigBolshoi simulations can now be run and analyzed in one week; two more are planned to get statistics for BOSS. Merger trees are coming soon.
- A new **miniBolshoi** simulation is running now. It will have a force resolution of about 100 pc and a mass resolution of about 10^6 M_{sun} and it will be complete to 15 km/s or better. We will have complete merger histories and substructure for hundreds of MWy-size halos.
- All catalogs will be available soon at Astrophysicalishes Institut Potsdam: http://www.multidark.org/MultiDark/ (You have to get an account there.) We hope to have them up soon also on the VAO and at SLAC.

The University of California
High-Performance AstroComputing Center

A consortium of nine UC campuses and three DOE laboratories

Website maintained by Nina McCurdy
nmccurdy@ucsc.edu

UC-HIPACC
337 Natural Sciences 2 Building (NS2)
Santa Cruz, CA 95064
Phone: (831)459-1531
email: hipacc@ucsc.edu

Deep field image of the Andromeda Galaxy created by co-adding 423 images.

Collaborators: Peter Nugent (LBNL).

At the National Energy Research Scientific Computing Center (NERSC), Peter Nugent (LBNL) and his colleagues combine Astrocomputing with observation to study dark energy in the Universe.

News /Announcements

Welcome to the new UC High-Performance AstroComputing Center (HIPACC) website!

- Announcing the 2011 International Astro-Computing Summer School on Computational Explosive Astrophysics. Now accepting applications! [more]
- View UC HIPACC's Annual Report for 2010 here.

Quick Links

- The 2010 International Summer School on AstroComputing focused on Galaxy Formation [more]
- The Future of AstroComputing conference was held on Dec 16 & 17 at the San Diego Supercomputer Center. View the conference website [here]

place the cursor over the image to pause the slideshow

http://hipacc.ucsc.edu/

The University of California
High-Performance AstroComputing Center

A consortium of nine UC campuses and three DOE laboratories

As computing and observational power continue to increase rapidly, the most difficult problems in astrophysics are now coming within reach of simulations based on solid physics, including the formation and evolution of stars and supermassive black holes, and their interactions with their galactic environments.

The purpose of HIPACC is to realize the full potential of the University of California's worldleading computational astrophysicists, including those at the affiliated national laboratories. HIPACC will do this by fostering their interaction with each other and with the rapidly increasing observational data, and by empowering them to utilize efficiently the new supercomputers with hundreds of thousands of processors both to understand astrophysical processes through simulation and to analyze the petabytes and soon exabytes of data that will flow from the new telescopes and supercomputers. This multidisciplinary effort links theoretical and observational astrophysicists, physicists, earth and planetary scientists, applied mathematicians, and computer scientists on all nine UC academic campuses and three national labs, and exploits California's leadership in computers and related fields.

HIPACC's outreach activities will include developing educational materials, publicity, and websites, and distribution of simulation outputs including visualizations that are beautiful as well as educational.

The University of California
High–Performance AstroComputing Center

A consortium of nine UC campuses and three DOE laboratories

UC-HIPACC Leadership

Executive Committee

Director: Joel Primack (UCSC) <joel@ucsc.edu>
Coordinator from Northern California: Peter Nugent (LBNL)
Coordinator from Southern California: Michael Norman (UCSD)

Council

UC Berkeley: Christopher McKee
UC Davis: TBA
UC Irvine: James Bullock
UC Los Angeles: Steve Furlanetto
UC Merced: TBA
UC Riverside: Gillian Wilson
UC San Diego: Michael Norman
UC Santa Barbara: S. Peng Oh
UC Santa Cruz: Sandra Faber
Los Alamos National Lab: TBA
Lawrence Berkeley National Lab: Peter Nugent
Lawrence Livermore National Lab: Peter Anninos

UC-HIPACC Staff

UC-HIPACC Office Manager: Coral Conner <hipacc@ucsc.edu>
Webmaster and Outreach Specialist: Nina McCurdy <nmccurdy@ucsc.edu>
Publicity and Proposal Writing: Trudy E. Bell <tebell@ucsc.edu>

The University of California
High-Performance AstroComputing Center
A consortium of nine UC campuses and three DOE laboratories

Annual Conferences in Northern and Southern California

HIPACC will sponsor two large meetings each year especially (but not exclusively) for scientists working on computational astrophysics and related topics at the UC campuses and labs. Unlike the more specialized meetings of working groups, we expect that these larger meetings will be broad, with the purpose of bringing theoretical astrophysicists together with computer science specialists, computer hardware experts, and observational astronomers. One meeting will be in northern California and the other in southern California to promote maximum participation. In addition to sharing new information, these meetings will highlight problems needing attention to advance the state-of-the-art and introduce participants to potential colleagues and begin collaborations.

Annual International AstroComputing Summer Schools

HIPACC will support an annual school aimed at graduate students and postdocs who are currently working in, or actively interested in doing research in, AstroComputing. Topics and locations of the annual school will rotate, and Caltech and Stanford are also welcome to participate.

The 2010 school was at UCSC, on the topic of Hydrodynamic Galaxy Simulations. Lectures were presented by experts on the leading codes (AMR codes ART, Enzo, and RAMSES, and SPH codes Arepo, GADGET, and Gasoline) and the Sunrise code for making realistic visualizations including stellar SED evolution and dust reprocessing. There were 60 students, including 20 from outside the USA. Lecture slides and videos, codes, inputs and outputs are on the UC-HIPACC website http://hipacc.ucsc.edu. Funding from NSF helped to support non-UC participant expenses.

The 2011 school will be July 11-23 at UC Berkeley/LBNL/NERSC, on the topic of Computational Explosive Astrophysics: novae, SNe, GRB, and binary mergers. The scientific organizers are Daniel Kasen (LBNL/UCB) and Peter Nugent (LBNL). The 2012 school will be on Astroinformatics at UCSD.

The University of California
High-Performance AstroComputing Center

A consortium of nine UC campuses and three DOE laboratories

The 2010 school was at UCSC, on the topic of Hydrodynamic Galaxy Simulations

COMPUTATIONAL EXPLOSIVE ASTROPHYSICS

UC HIPACC's 2011 International Summer School on AstroComputing

Dates: July 18 – July 29, 2011

Location: University of California Berkeley/ Lawrence Berkeley National Lab/ National Energy Research Scientific Computing Center

Description: This year's summer school will focus on computational explosive astrophysics, including the modeling of core collapse and thermonuclear supernovae, gamma-ray bursts, compact object mergers, and other energetic transients. Lectures will include instruction in the physics and numerics of multi-dimensional hydrodynamics, general relativity, radiation transport, nuclear reaction networks, neutrino physics, and equations of state. Workshops will guide students in running and visualizing simulations on supercomputers using codes such as FLASH, CASTRO, GR1D and modules for equations of state, nuclear burning, and radiation transport.

Scientific Organizers: Daniel Kasen and Peter Nugent (UCB & LBNL)

Lecturers and main workshops will include:

Ann Almgren (LBNL) - CASTRO
Alan Calder (Stony Brook) - FLASH
Hank Childs (NERSC) - VisIt
Christian Ott (Caltech) and Erik Schnetter (LSU) - GR1D/Cactus
Frank Timmes (Arizona State) - Equation of state, reaction network modules

Additional lecturers and topics will include:

Katie Antypas (NERSC) - Using NERSC
George Fuller (UC San Diego) - neutrino physics
Daniel Kasen (UC Berkeley) - radiation transport
Andrew MacFadyen (NYU) - MHD, gamma-ray bursts
Eliot Quataert (UC Berkeley) - compact object mergers
Enrico Ramirez-Ruiz (UC Santa Cruz) - tidal disruptions, collisions
Stan Woosley (UC Santa Cruz) - thermonuclear supernovae
Jim Lattimer (Stony Brook) - nuclear equation of state

Other Details:

Housing: Students will be staying at Stern Hall on the UC berkeley campus ($64/night).

Registration for the summer school will be $250. Payment will be required at the time of acceptance. **Aid:** UC HIPACC will cover lodging and travel expenses for UC students, and some financial assistance may be available for other students.

For more information and to apply, visit us on the web: http//hipacc.ucsc.edu/ISSAC2011.html

The Univeristy of California High-Performance AstroComputing Center | http://hipacc.ucsc.edu | hipacc@ucsc.edu | (831)459-1531

Announcing the 2011 UC-HIPACC International AstroComputing Summer School on Computational Explosive Astrophysics

Topics Include: supernovae, gamma-ray bursts, compact object mergers, energetic transients

Location: University of California, Berkeley/ Lawrence Berkeley National Lab/ National Energy Research Scientific Computing Center

Dates: July 18 – July 29, 2011

Organizers: Daniel Kasen & Peter Nugent (UCB/LBNL)

Description: The University of California High-Performance Astro-Computing Center (UC-HIPACC) is pleased to announce the continuation of its international summer school, to be held this year by UC Berkeley and LBNL from July 18-29, 2011. This year's summer school will focus on computational explosive astrophysics, including the modeling of core collapse and thermonuclear supernovae, gamma-ray bursts, neutron star mergers, and other energetic transients. Lectures will include instruction in the physics and numerical modeling of multi-dimensional hydrodynamics, general relativity, radiation transport, nuclear reaction networks, neutrino physics, and equations of state. Afternoon workshops will guide students in running and visualizing simulations on supercomputers using codes such as FLASH, CASTRO, GR1D and modules for nuclear burning and radiation transport. All students will be given accounts and computing time at NERSC and have access to the codes and test problems in order to gain hands on experience running simulations at a leading supercomputing facility.

http://hipacc.ucsc.edu/

The University of California
High–Performance AstroComputing Center

A consortium of nine UC campuses and three DOE laboratories

Funding Opportunities

Calls for proposals scheduled twice annually for Fall/Winter & Spring/Summer funding Cycles.

UC-HIPACC will support focused working groups of UC scientists from multiple campuses to pursue joint projects in computational astrophysics and related areas by providing funds for travel and lodging. At the heart of UC-HIPACC are working groups. These groups will typically consist of collaborations of two to a dozen people, in practice mostly graduate students and post-doctoral fellows, from two or more UC campuses or DOE labs. Periods will typically range from a few days to a few months.

1. Small travel grants enable scientists, graduate students, and post-doctoral students to travel easily and spontaneously between Center nodes. UC-HIPACC will fund travel grant proposals submitted by faculty members, senior scientists, postdocs or graduate students up to $1000 on a first-come-first-served basis with a simple application describing the plan and purpose of the travel.

2. Grants ranging between $1000 - $5,000 to support larger working groups or participation in scientific meetings.

3. Mini Conference grants of up to $5,000 to support collaborations of multiple UC campuses and DOE labs.

4. Innovative initiative proposals for other purposes that are consistent with the goals of UC-HIPACC. Such purposes could include meetings or workshops, software development, matching funds for astrocomputing hardware, or education and outreach.

The University of California High-Performance AstroComputing Center

UC HIPACC

SDSC

Presents...

The Future of AstroComputing

December 16 & 17, 2010
San Diego Supercomputer Center
San Diego, CA

hipacc.ucsc.edu/FOA2010.html

The goal of this conference is to clarify the big issues for the next ~5 years in astrophysical computation and data, and to bring leaders in the field and at the main funding agencies and industrial organizations to meet with key computational astrophysicists, especially from the University of California and its affiliated DOE laboratories (LANL, LBNL, LLNL) and other West Coast institutions including Stanford, Caltech, and the University of Washington.

Principal organizers: Mike Norman (SDSC), Joel Primack (UCSC), Alex Szalay(JHU)

If you want a copy, ask
joel@ucsc.edu

TRT 01:31:19
Aired: 9:00 PM on October 24th, 2010

NATIONAL GEOGRAPHIC CHANNEL

INSIDE THE MILKY WAY

Including interviews with Astronomers Tom Abel, James Bullock,
Richard Ellis, Alex Filippenko, Andrea Ghez, Robert Kirshner,
Avi Loeb, Geoff Marcy, Joel Primack, and Seth Shostak
Director/Producer: Duncan Copp, DOX Productions Ltd.

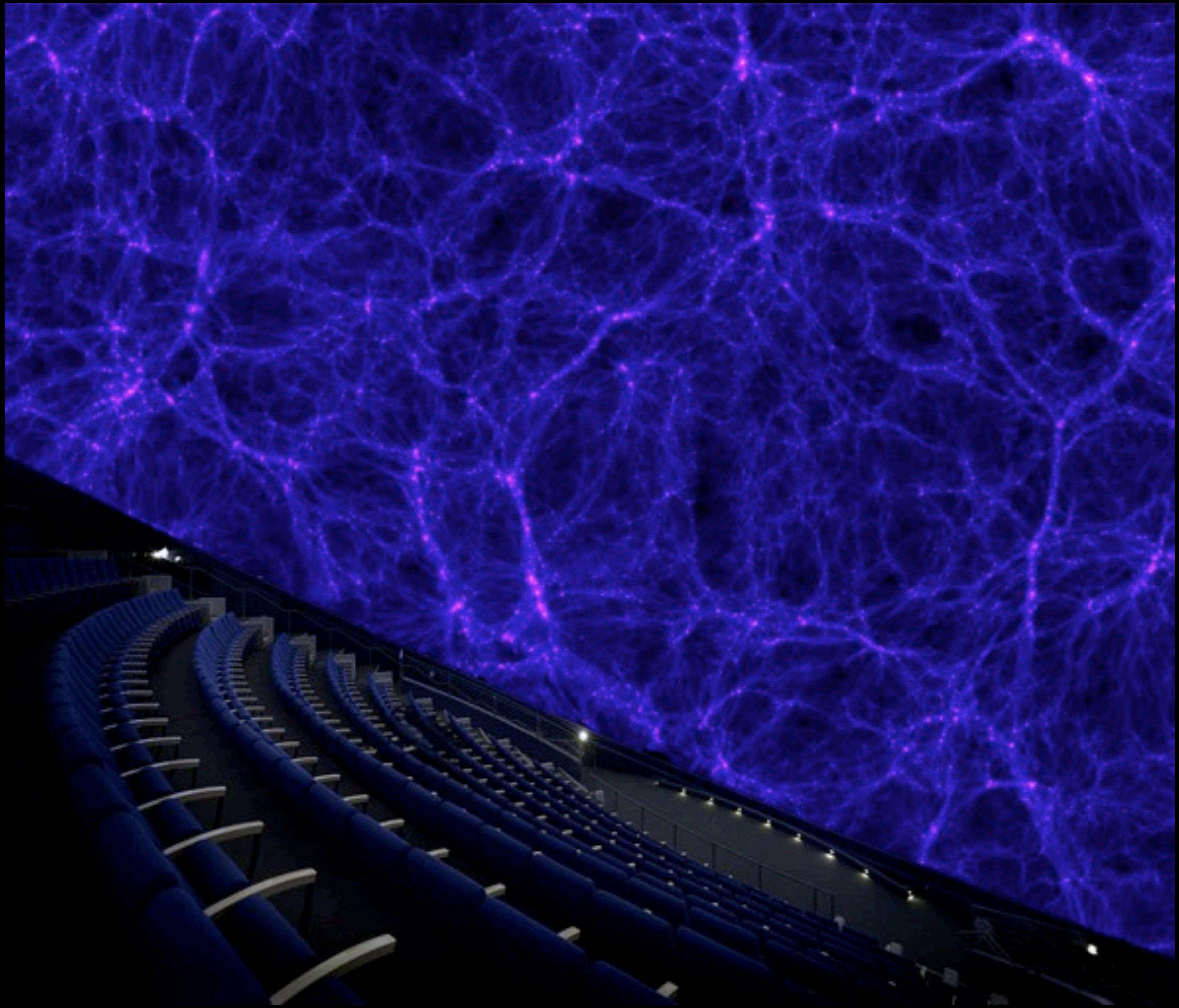
Astro-Computation Visualization and Outreach

Project lead: Prof. Joel Primack, Director, UC High-Performance AstroComputing Center
UC-HIPACC Visualization and Outreach Specialist: Nina McCurdy


Pleiades Supercomputer
NASA Ames


California
Academy of Sciences


Adler Planetarium
Chicago


HIPACC is working with the Morrison Planetarium at the California Academy of Sciences (pictured here) to show how dark matter shapes the universe. We are helping prepare their planetarium show opening fall 2010, and also working on a major planetarium show to premiere at the Adler Planetarium in spring 2011.

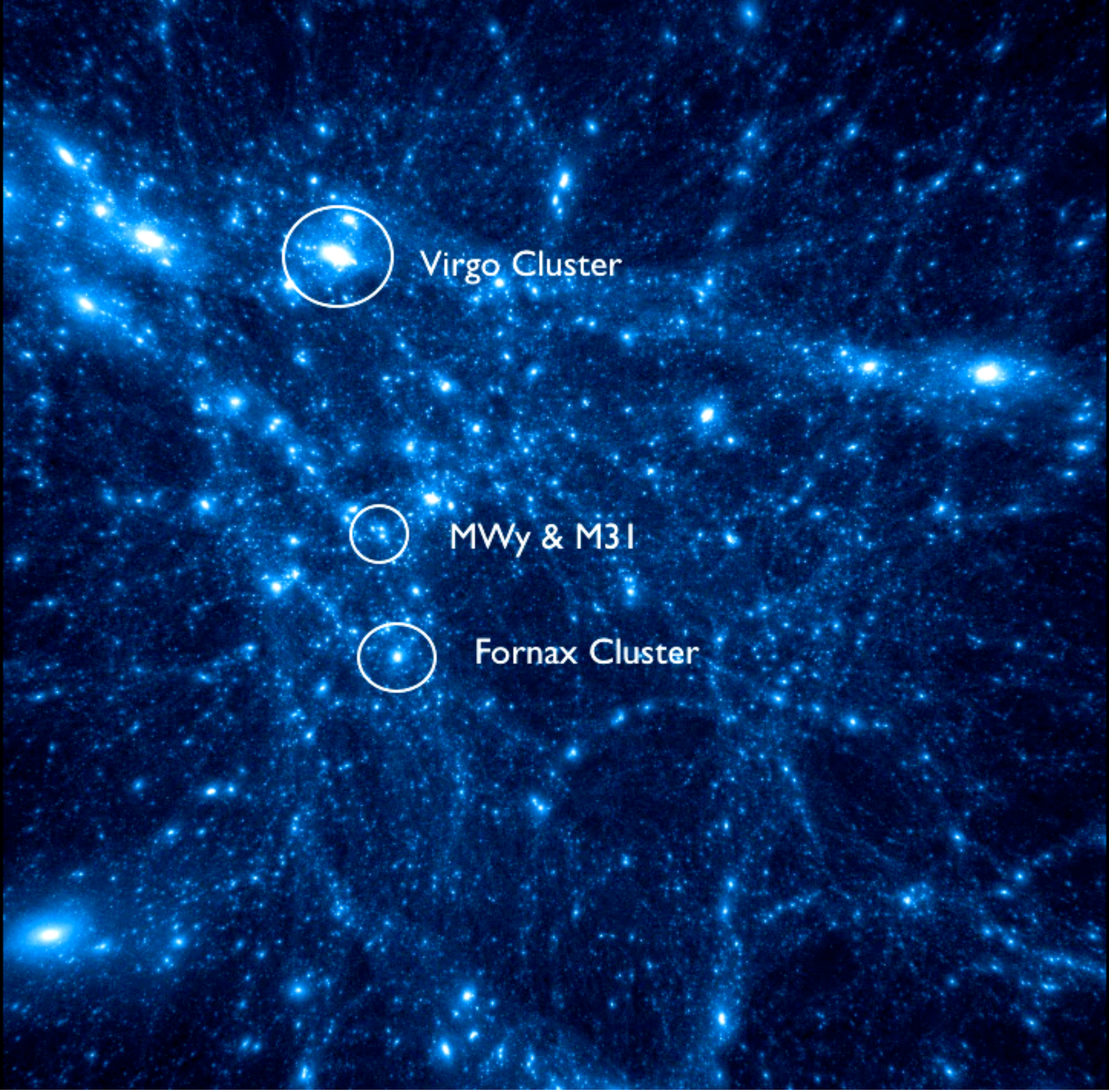
Galaxy Merger Simulation

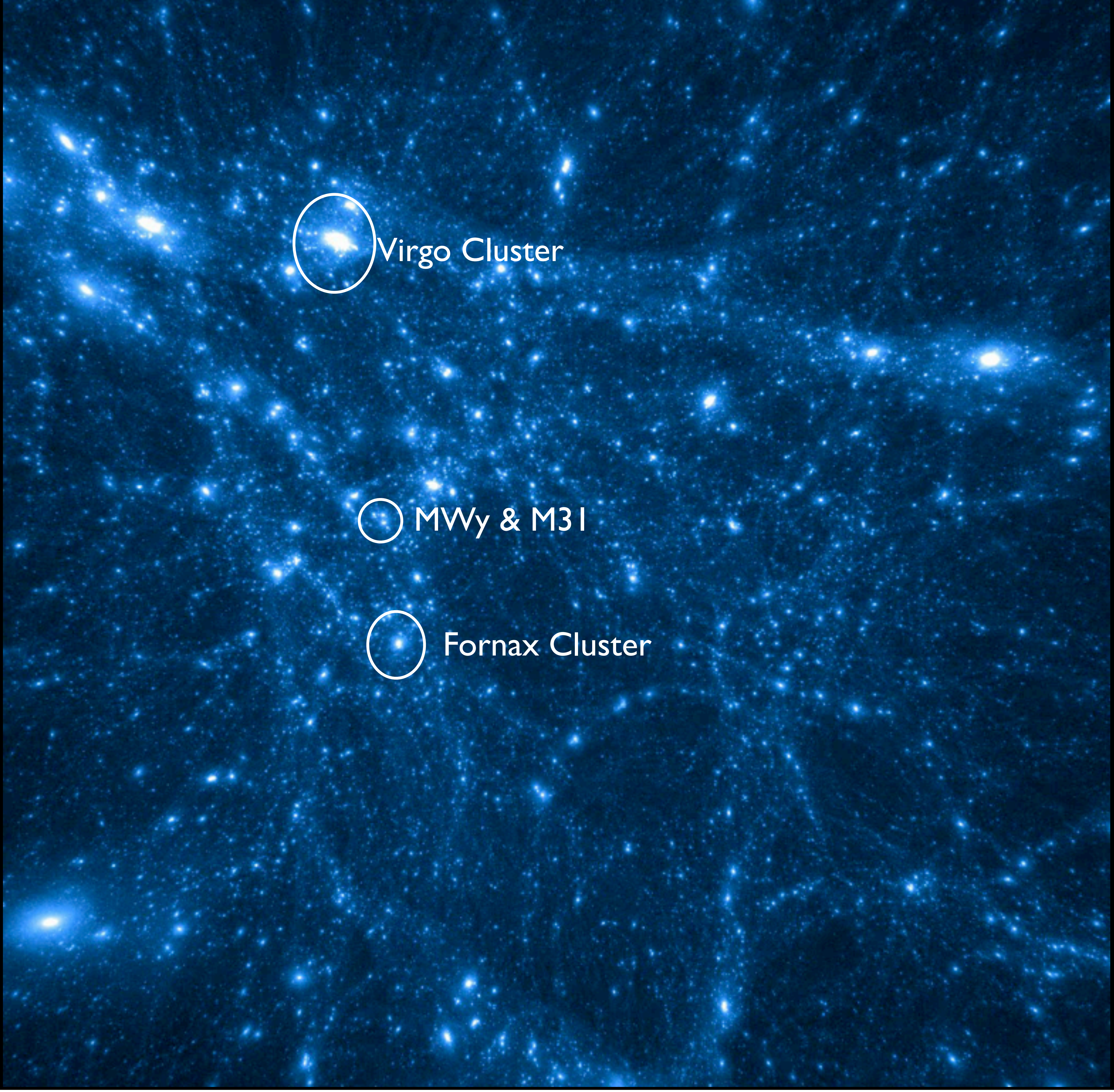
Run on Columbia **Supercomputer at NASA Ames Research Center.**
Dust simulated using the Sunrise code (Patrik Jonsson, UCSC/Harvard).

Astronomical **observations** represent snapshots of particular moments in time; it is effectively the role of astrophysical simulations to produce movies that link these snapshots together into a coherent physical theory.

Showing Galaxy Merger simulations in 3D will provide a deeper, more complete picture to the **public** and scientists alike.

CONSTRAINED LOCAL UNIVERSE SIMULATION


Virgo Cluster
MWy & M31
Fornax Cluster


Virgo Cluster
MWy & M31
Fornax Cluster