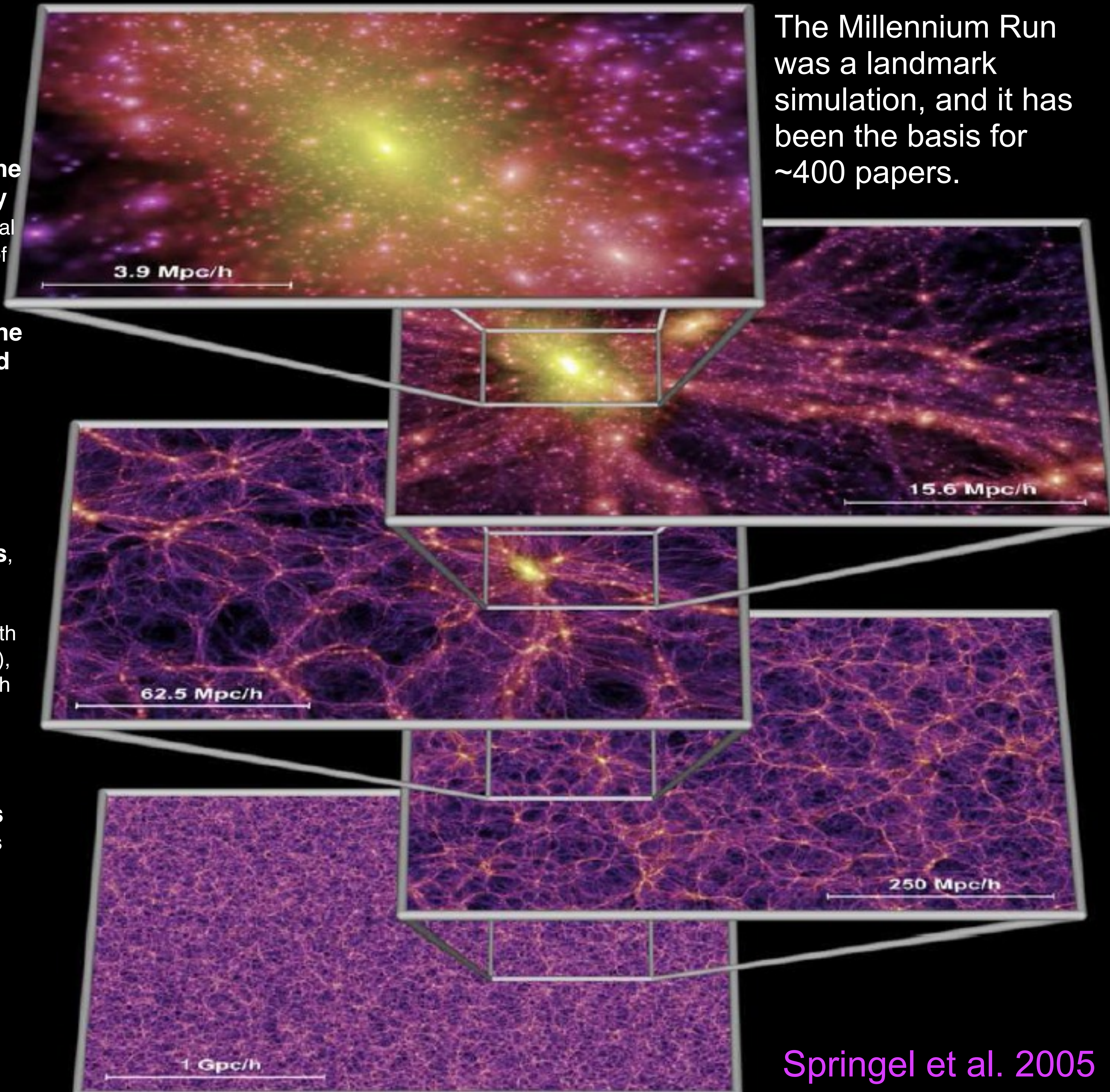
THE BOLSHOI COSMOLOGICAL SIMULATIONS AND THEIR IMPLICATIONS

JOEL PRIMACK, UCSC

- ΛCDM Cosmological Parameters for **Bolshoi** and **BigBolshoi**
- Halo Mass Function is 10x Below Sheth-Tormen at z=10
- Cluster Concentrations Agree with ΛCDM Predictions
- Improved Halo Finding and Merger Trees
- Predicted LMC/SMC Likelihood Agrees with Observations
- HAM Galaxy Correlations Agree with Observations
- HAM Galaxy Luminosity-Velocity Relations OK
- Galaxy Velocity Function OK for $V_{circ} > 80$ km/s
- First **Bolshoi** and **BigBolshoi** data release in September 2011

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

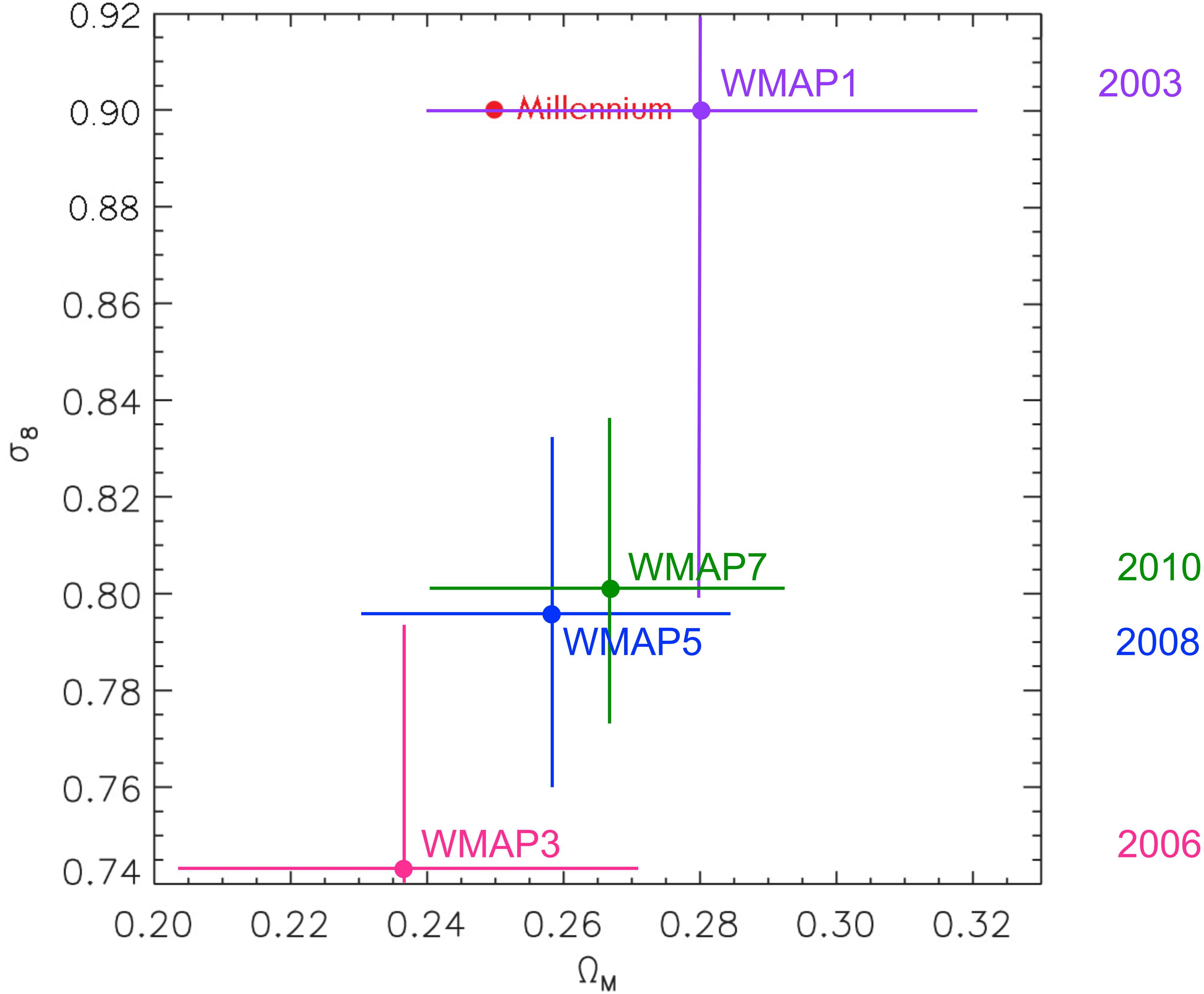


The Millennium Run was a landmark simulation, and it has been the basis for ~400 papers.

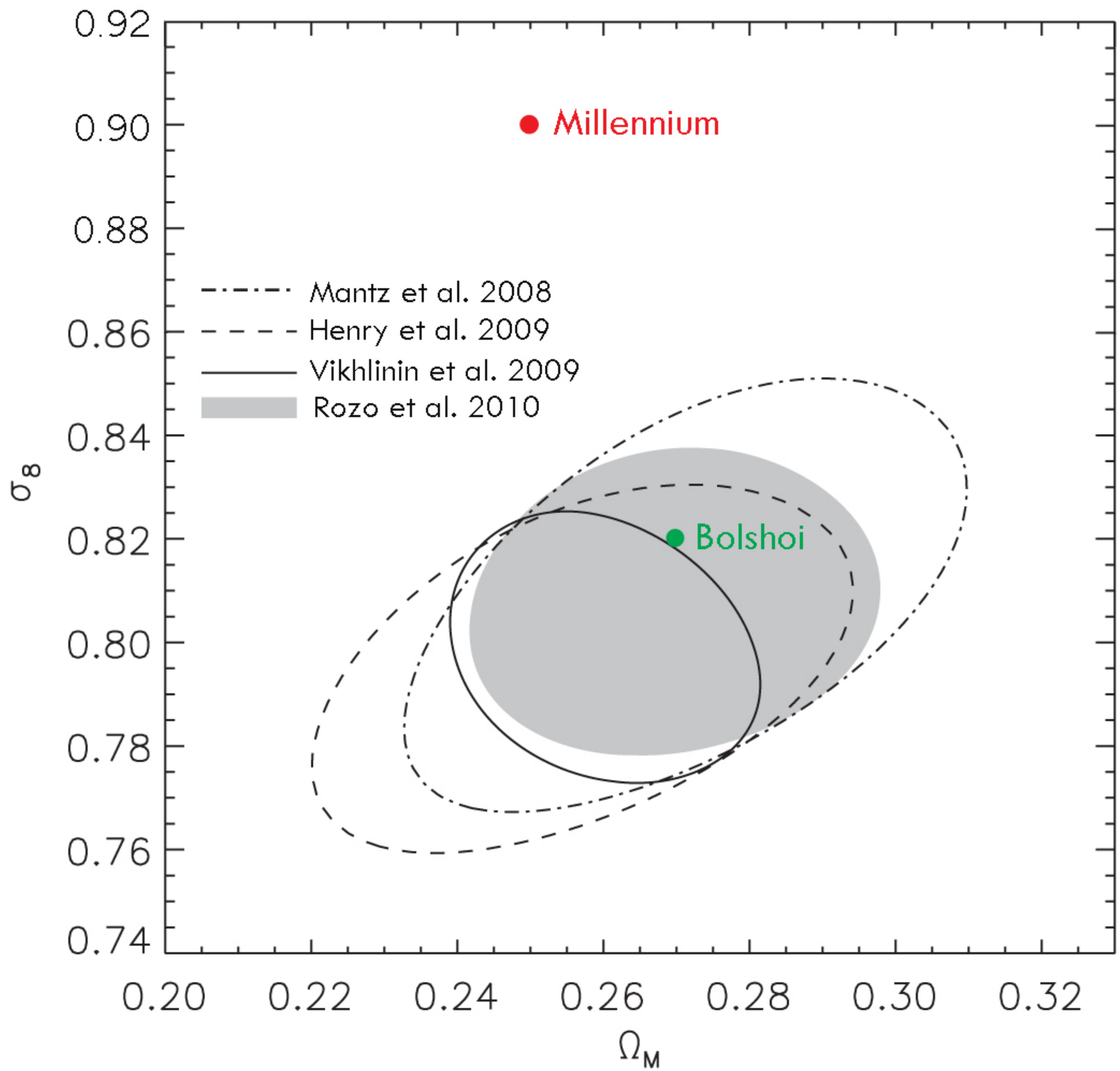
Springel et al. 2005

- **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.

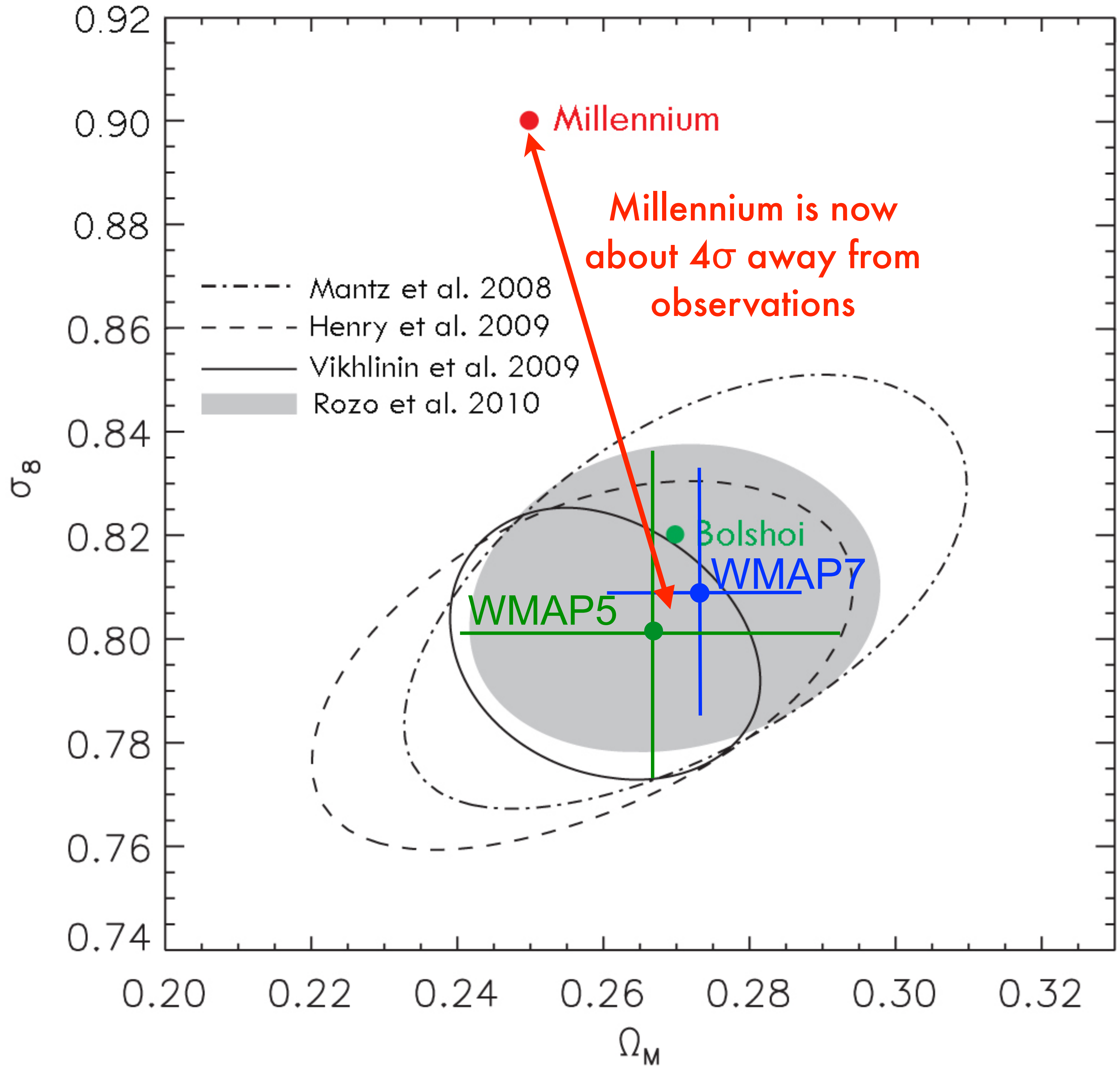
WMAP-only Determination of σ_8 and Ω_M



WMAP+SN+Clusters Determination of σ_8 and Ω_M



WMAP+SN+Clusters Determination of σ_8 and Ω_M



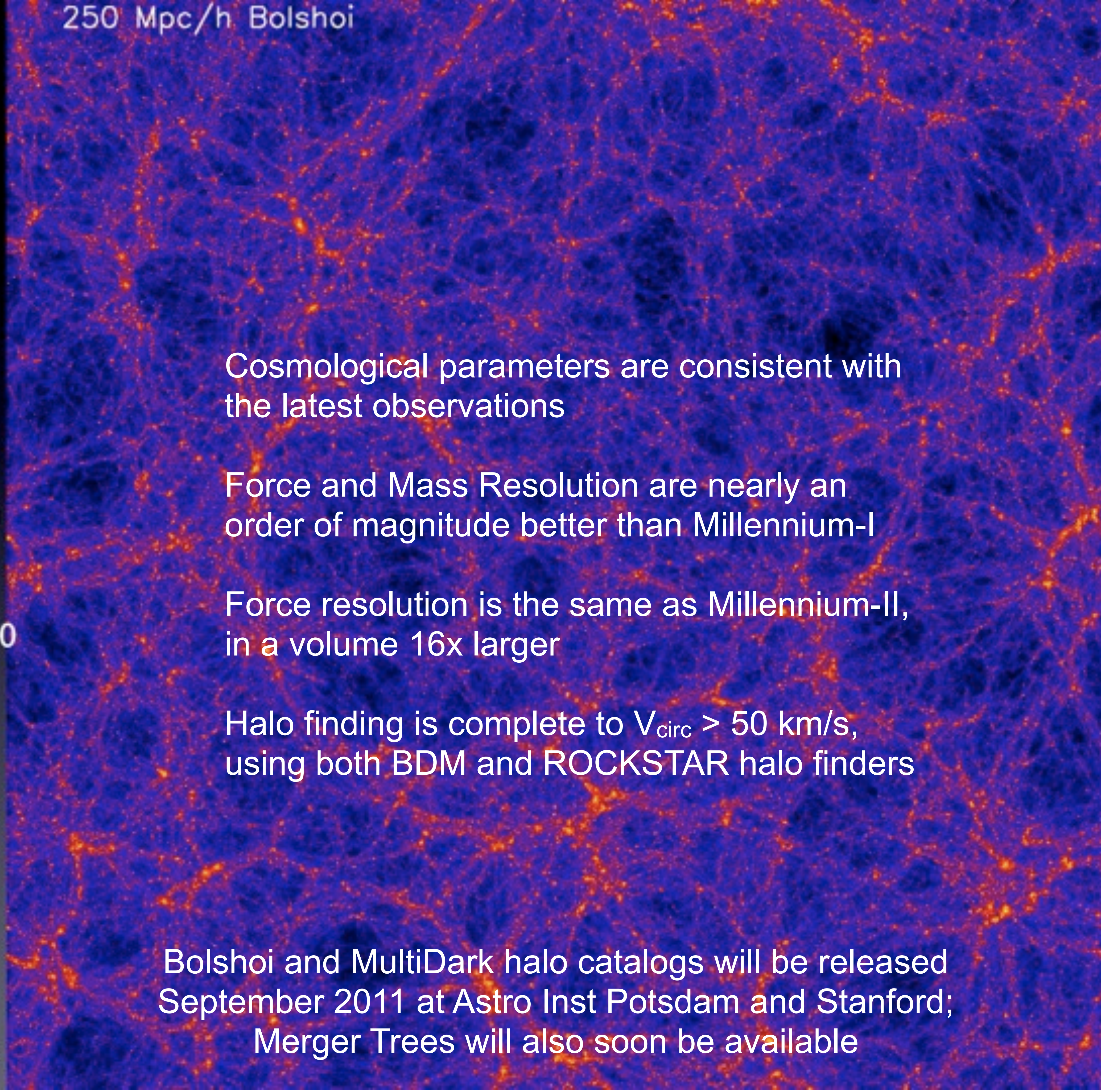
The Bolshoi simulation

ART code

250Mpc/h Box
LCDM
$\sigma_8 = 0.82$
$h = 0.70$
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



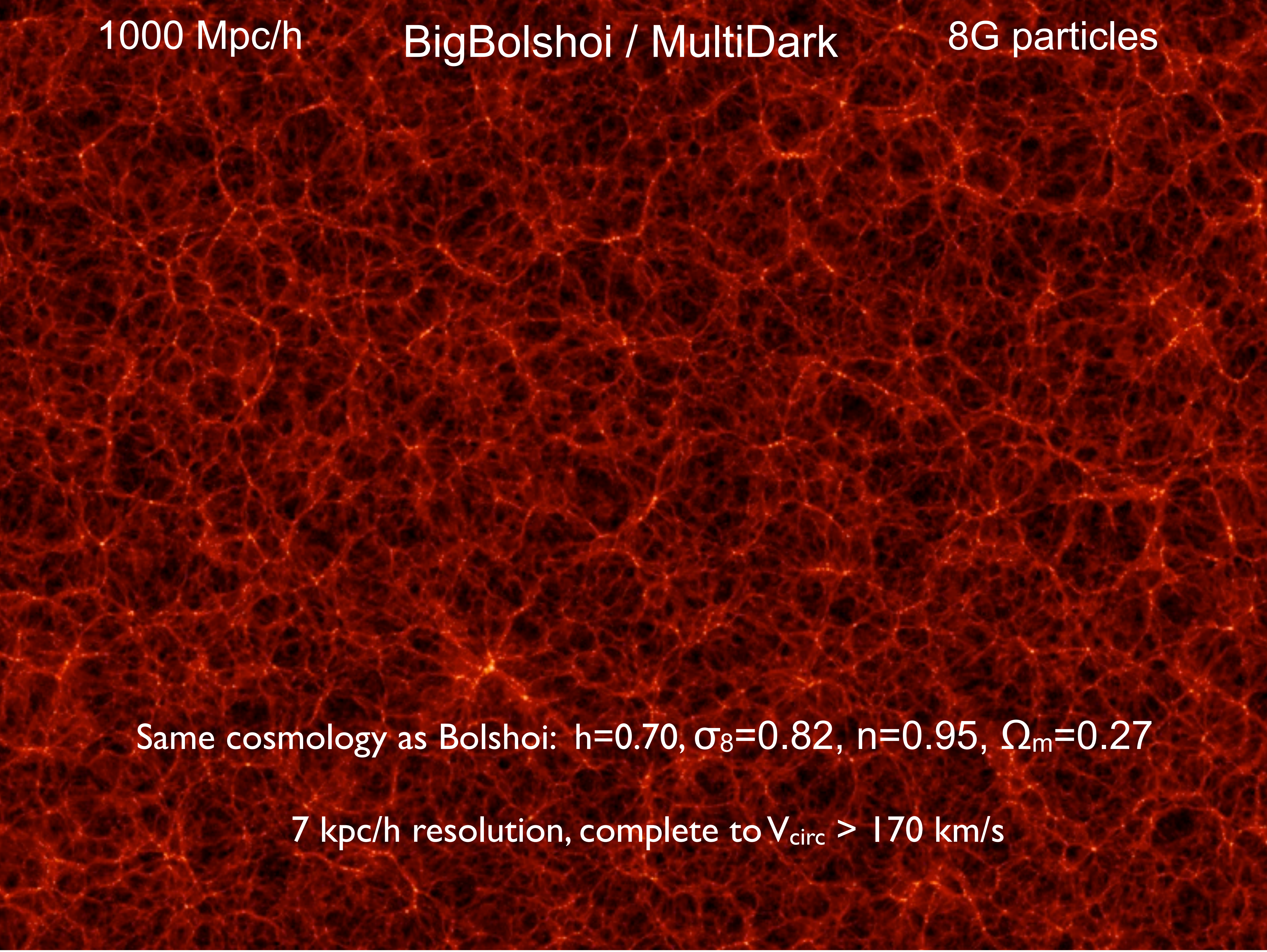
Cosmological parameters are consistent with the latest observations

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

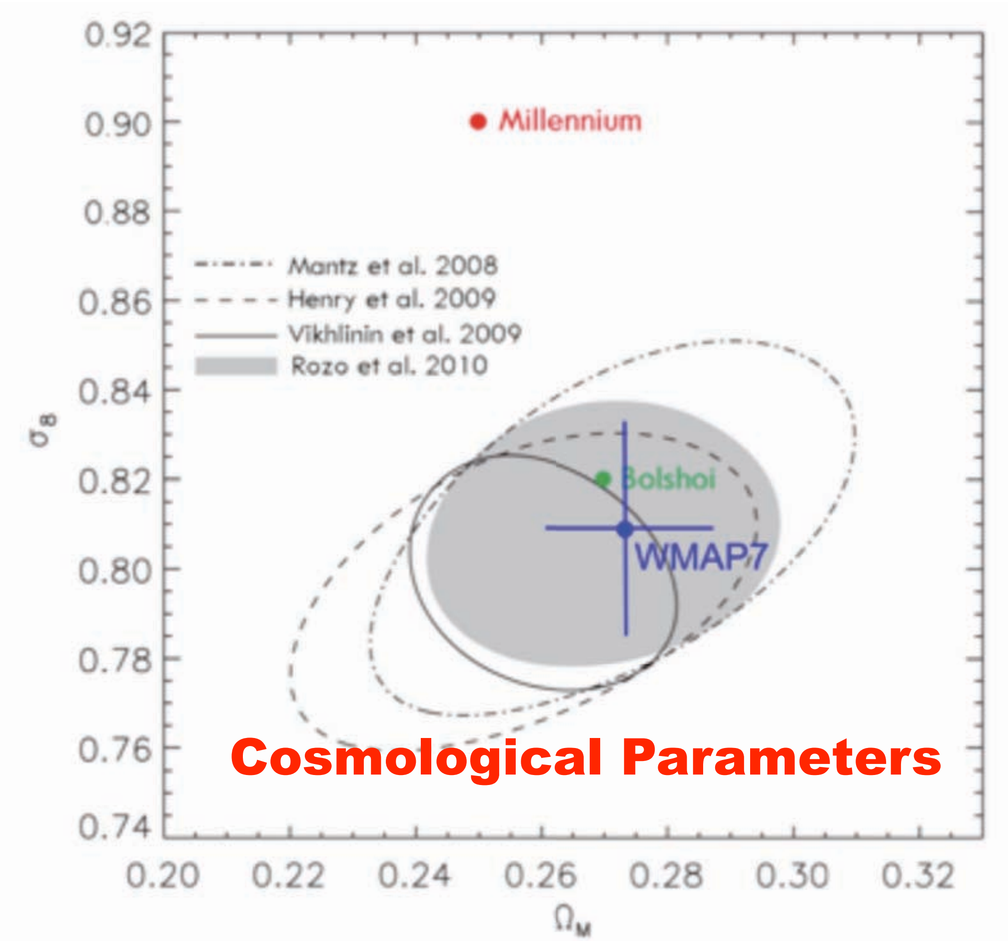
Force resolution is the same as Millennium-II, in a volume 16x larger

Halo finding is complete to $V_{circ} > 50$ km/s, using both BDM and ROCKSTAR halo finders

Bolshoi and MultiDark halo catalogs will be released September 2011 at Astro Inst Potsdam and Stanford; Merger Trees will also soon be available

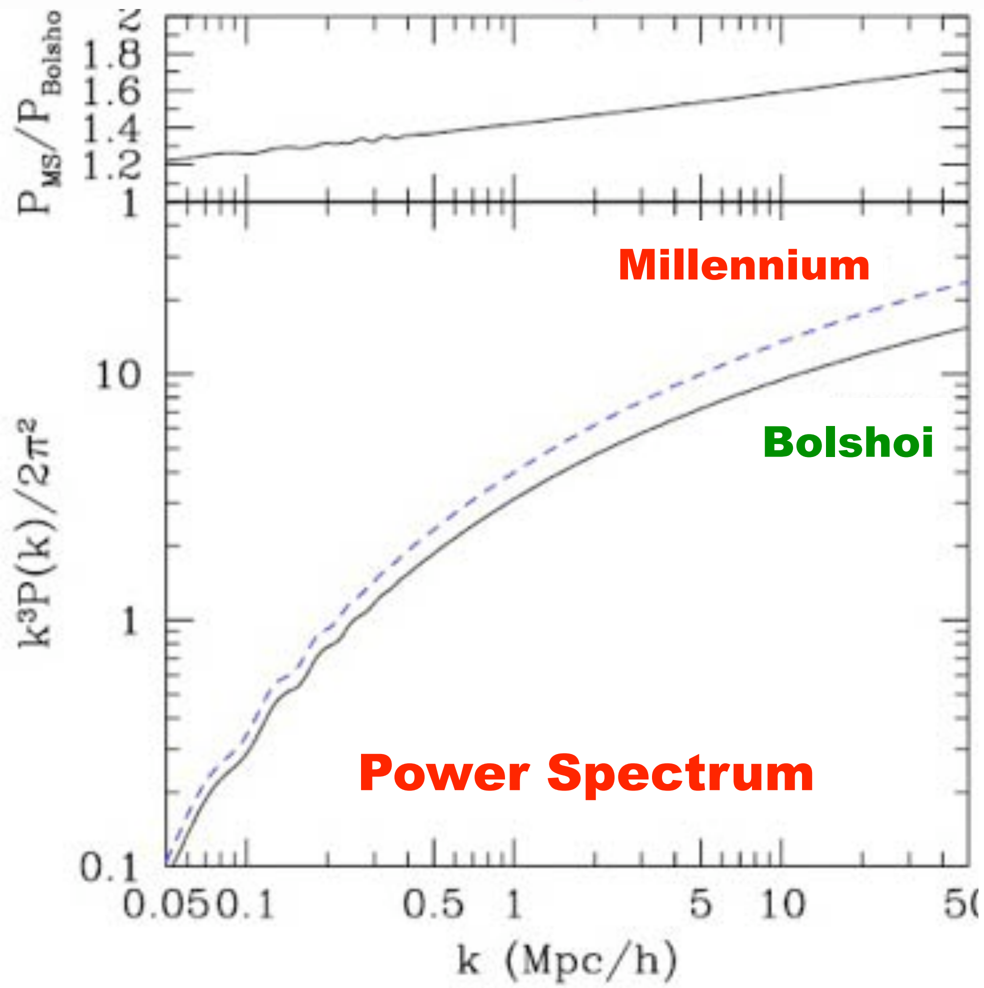

1000 Mpc/h
BigBolshoi / MultiDark
8G particles
Same cosmology as Bolshoi: h=0.70, σ8=0.82, n=0.95, Ωm=0.27
7 kpc/h resolution, complete to Vcirc > 170 km/s

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

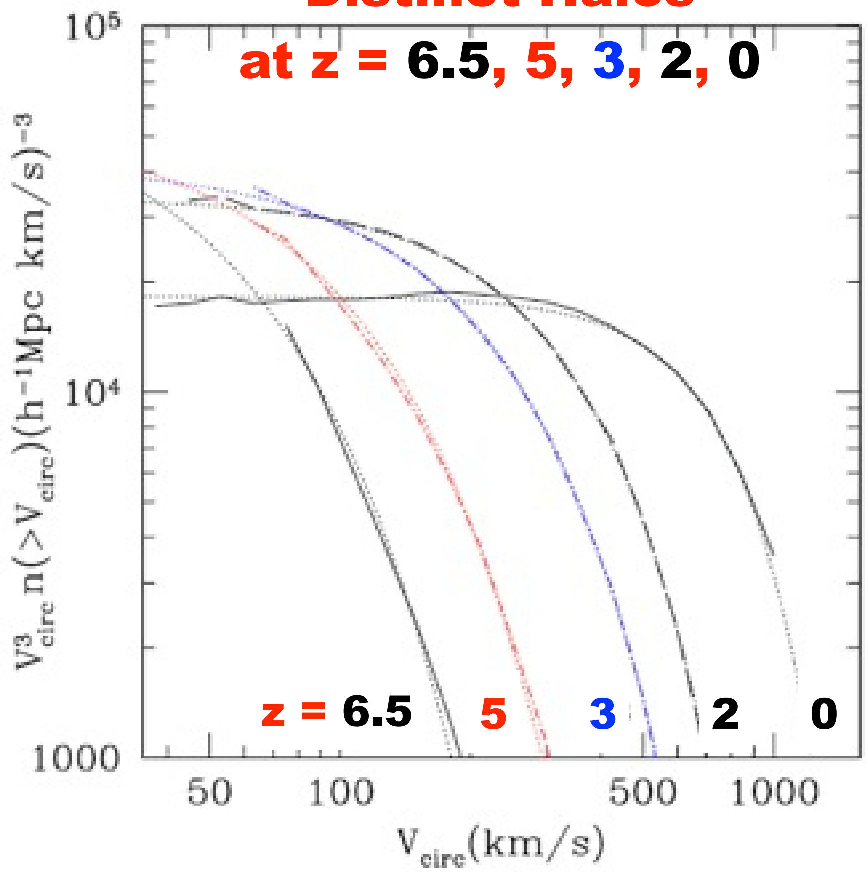


The Millennium Run (Springel+05) was a landmark simulation, and it has been the basis for ~400 papers. However, it and the new Millennium-II and XXL were run using WMAP1 (2003) parameters, and the Millennium-I resolution was inadequate to see many subhalos. The new **Bolshoi** simulation (Klypin, Trujillo & Primack 2011) 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.

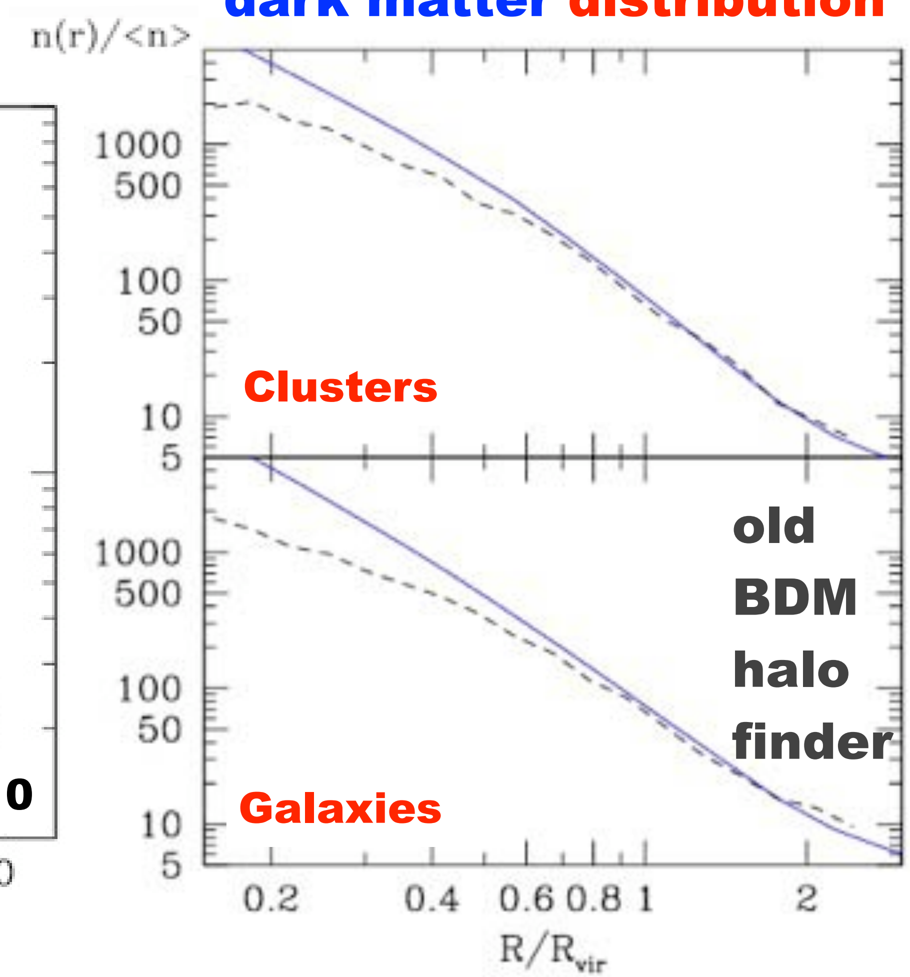
Klypin, Trujillo-Gomez, & Primack, arXiv:1002.3660 ApJ in press

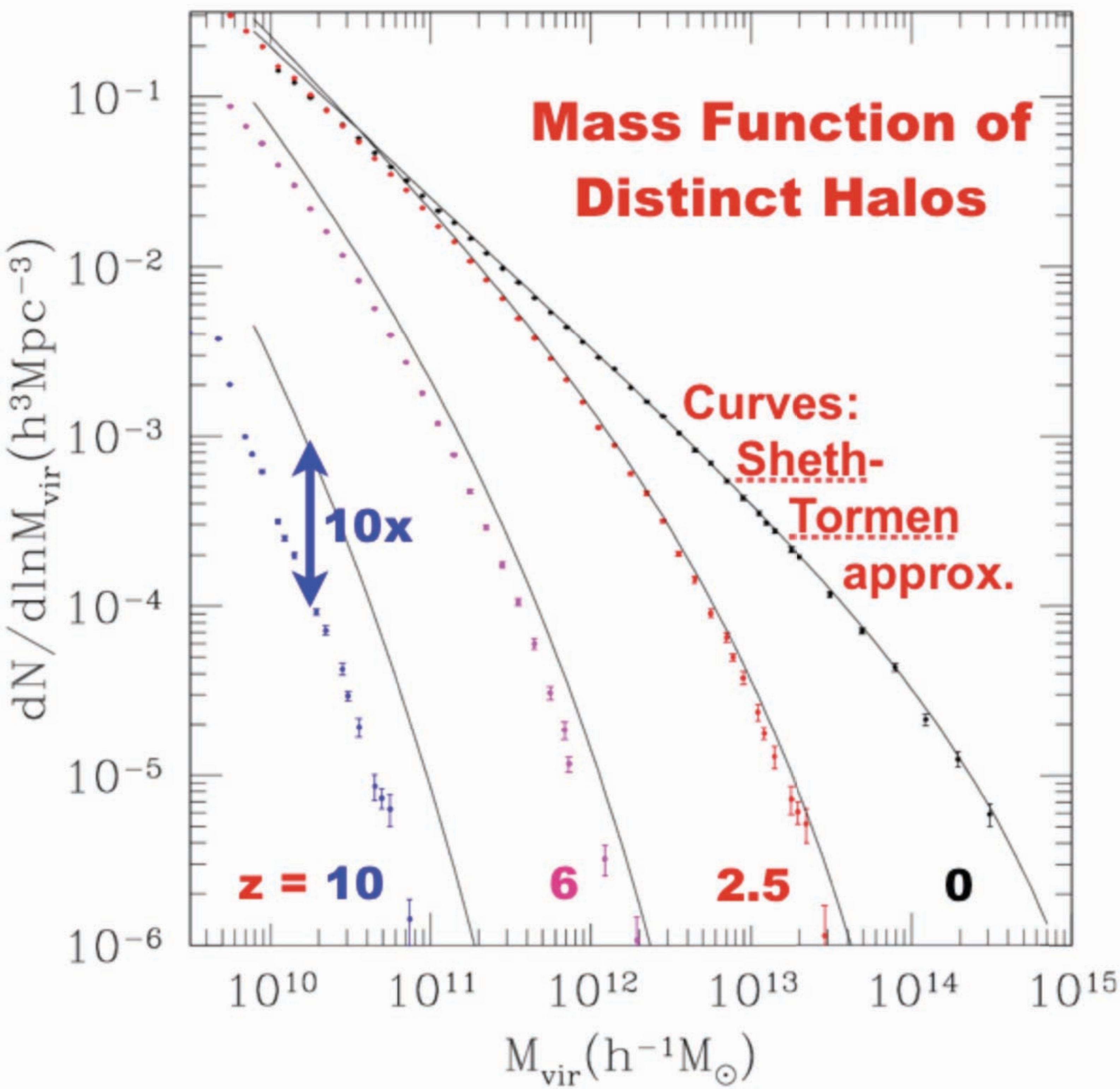


Velocity Function of Distinct Halos

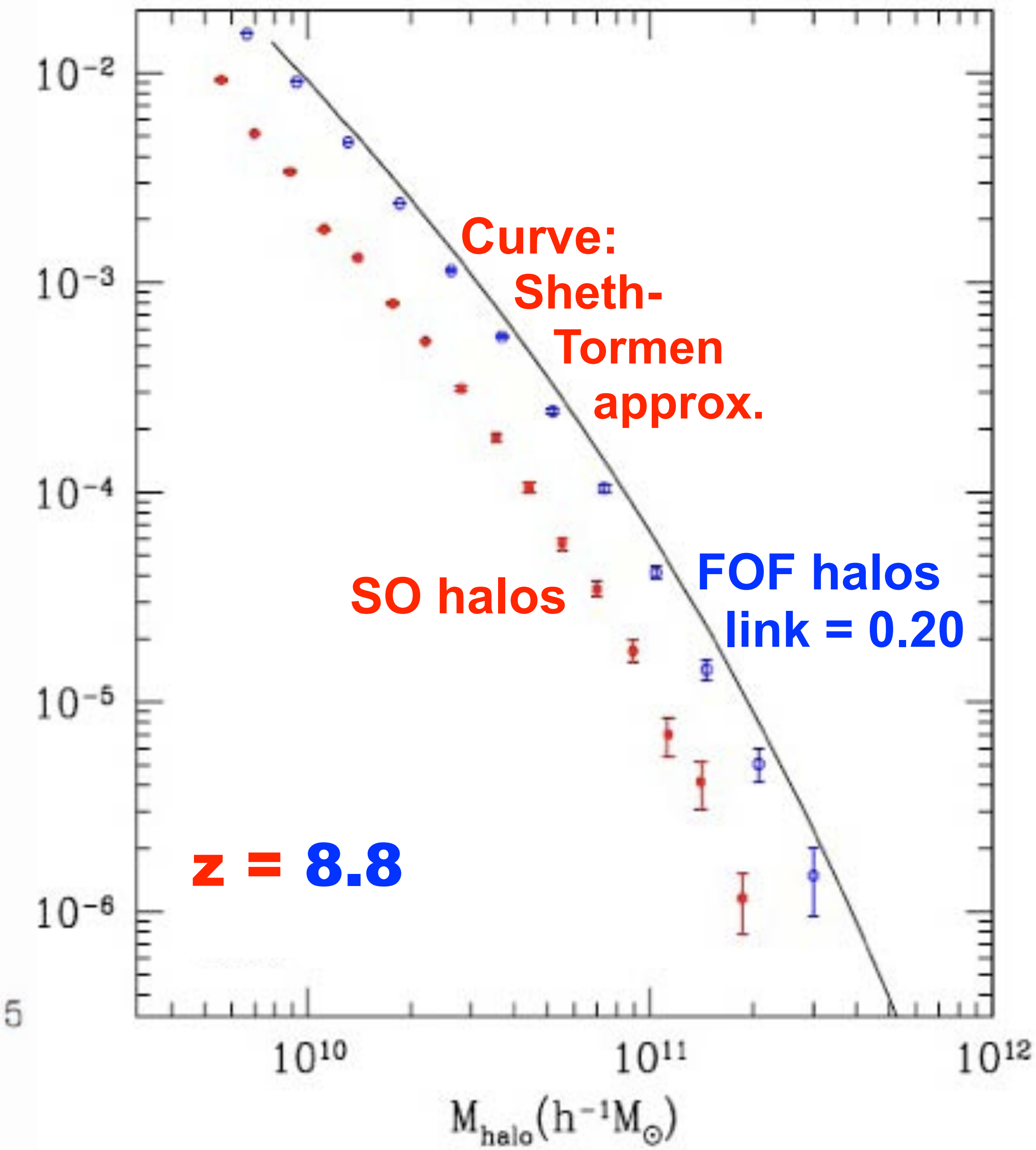


Subhalos follow the dark matter distribution



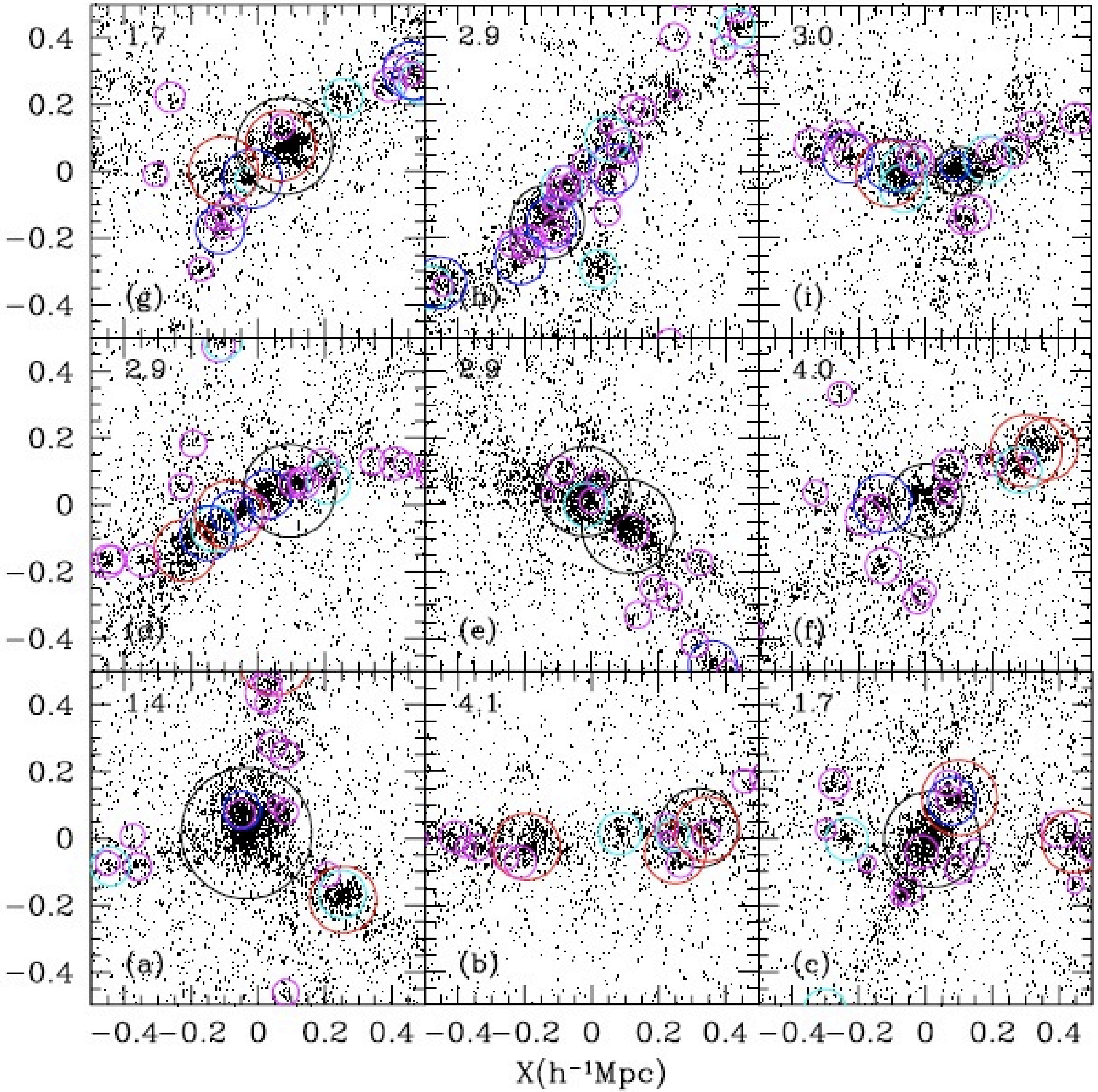


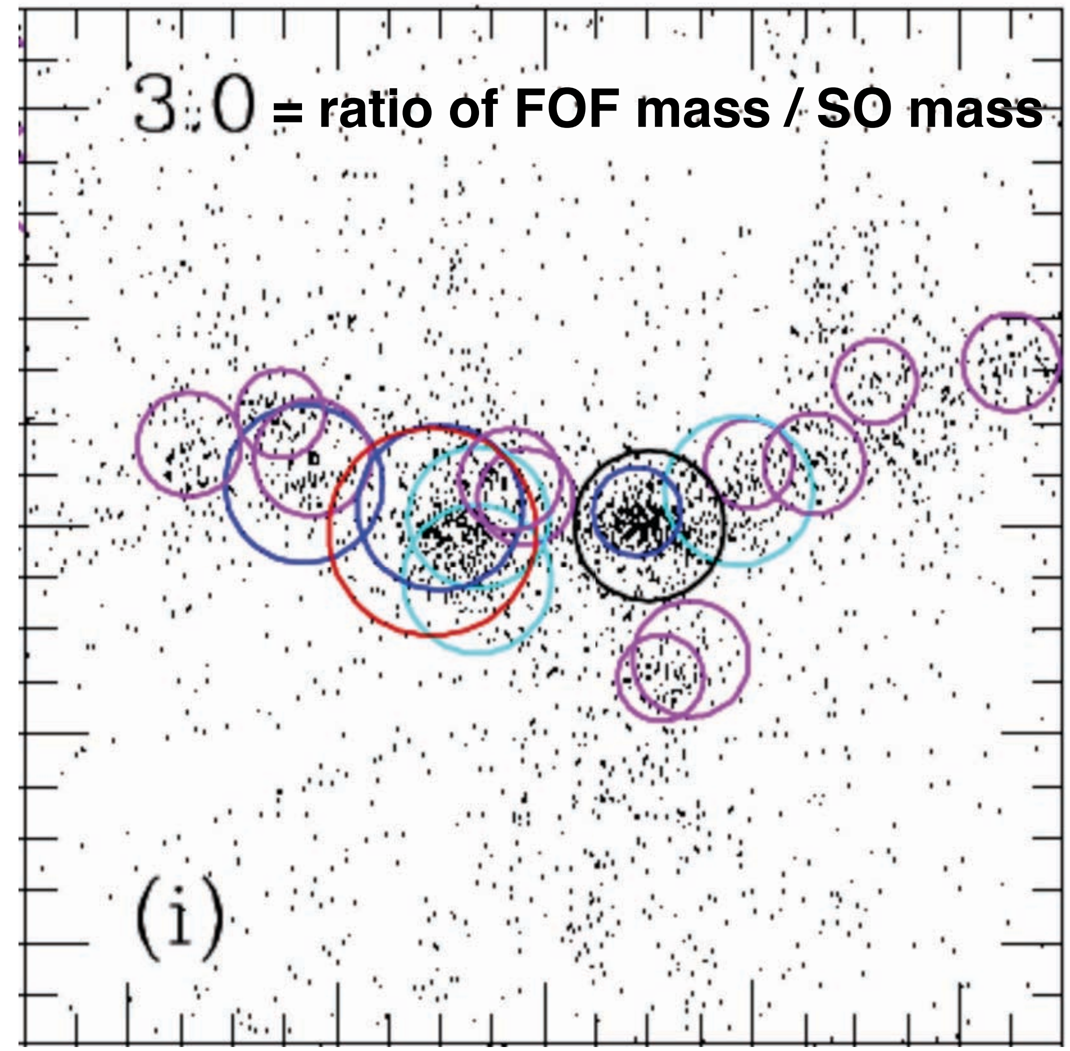
Sheth-Tormen Fails at High Redshifts



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



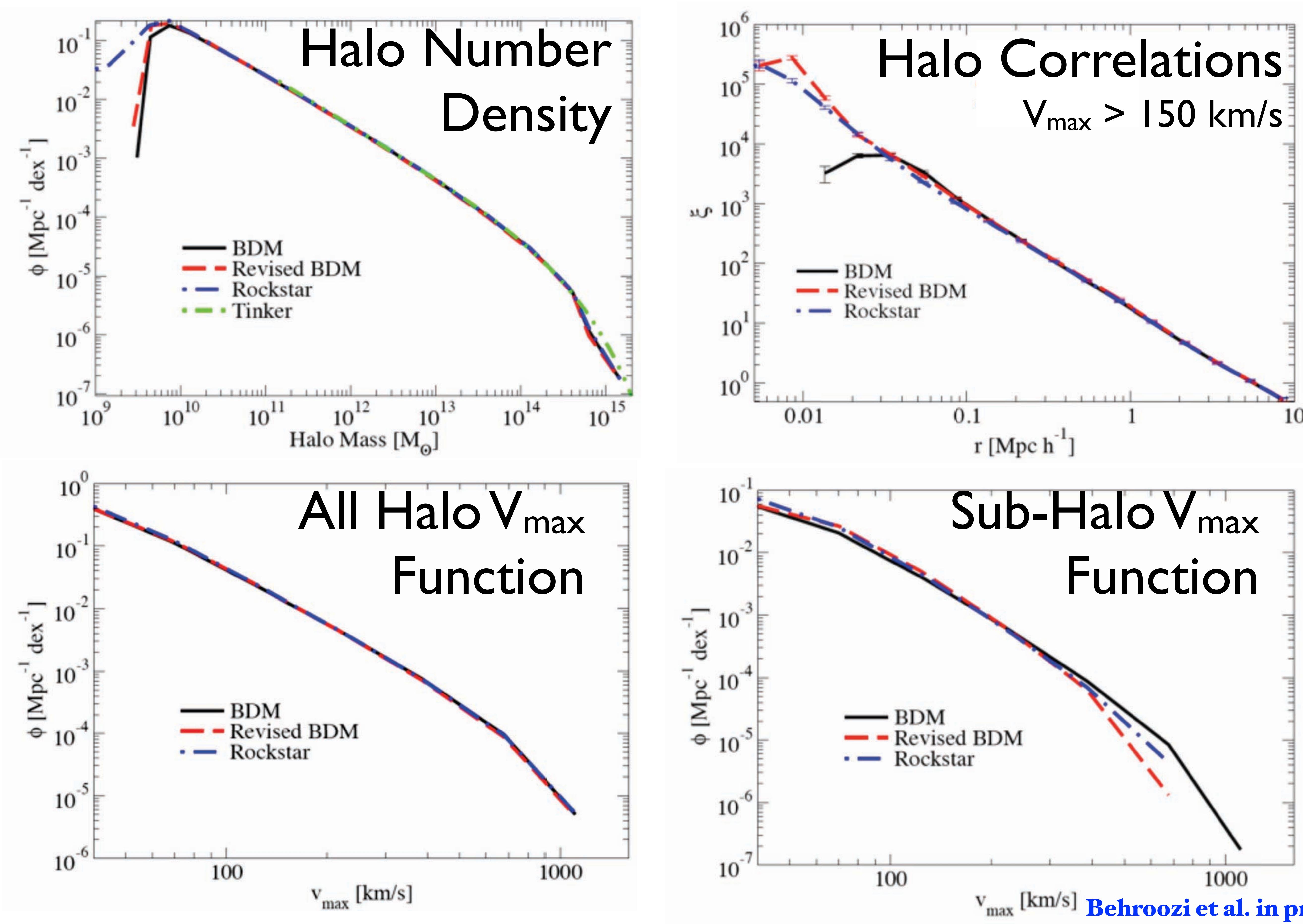


FOF linked together a chain of halos that formed in long and dense filaments (also in panels b, d, f, h; e = major merger)

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

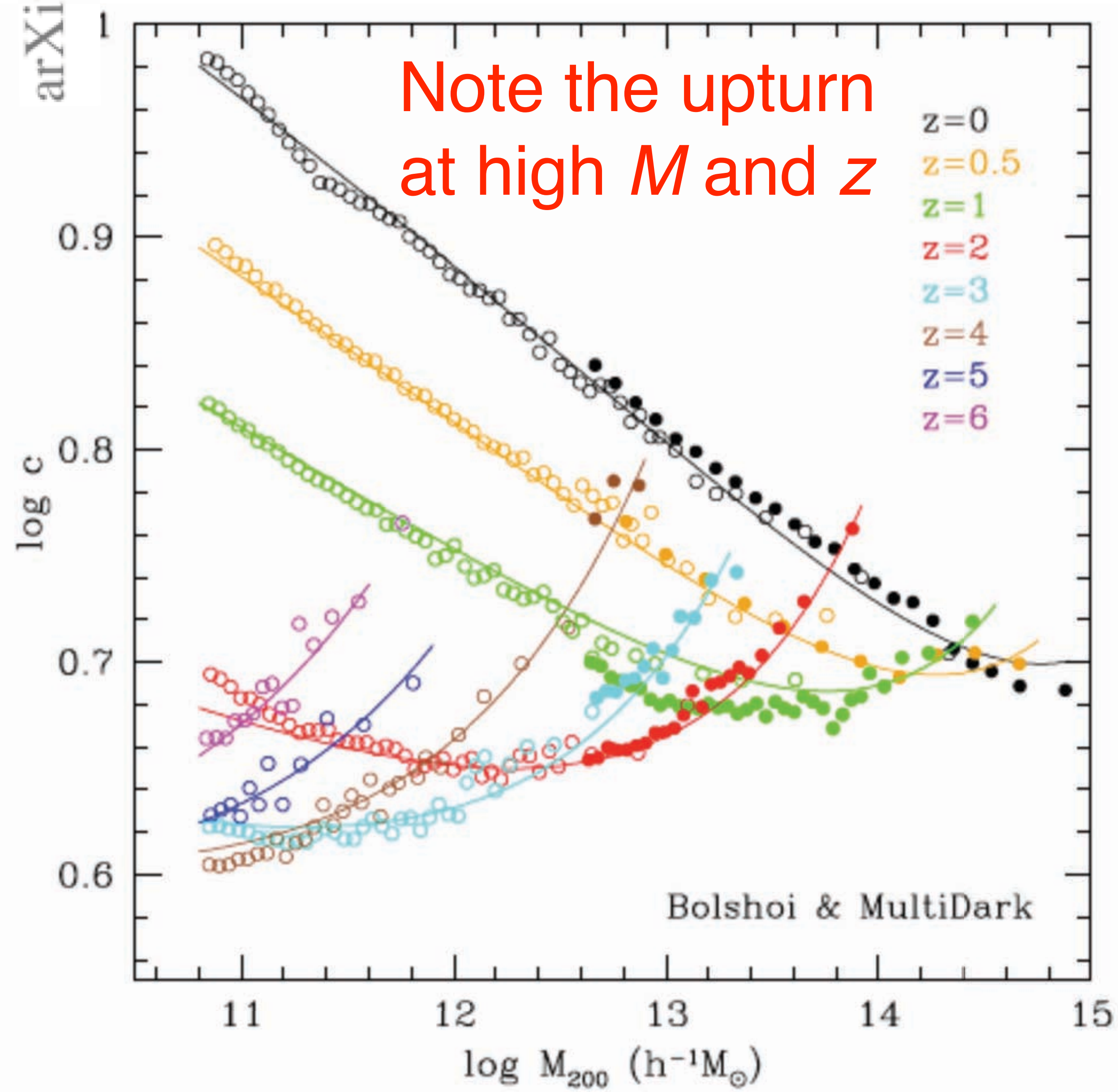
Bolshoi Simulation Analyzed by Various Halo Finders



Behroozi et al. in prep.

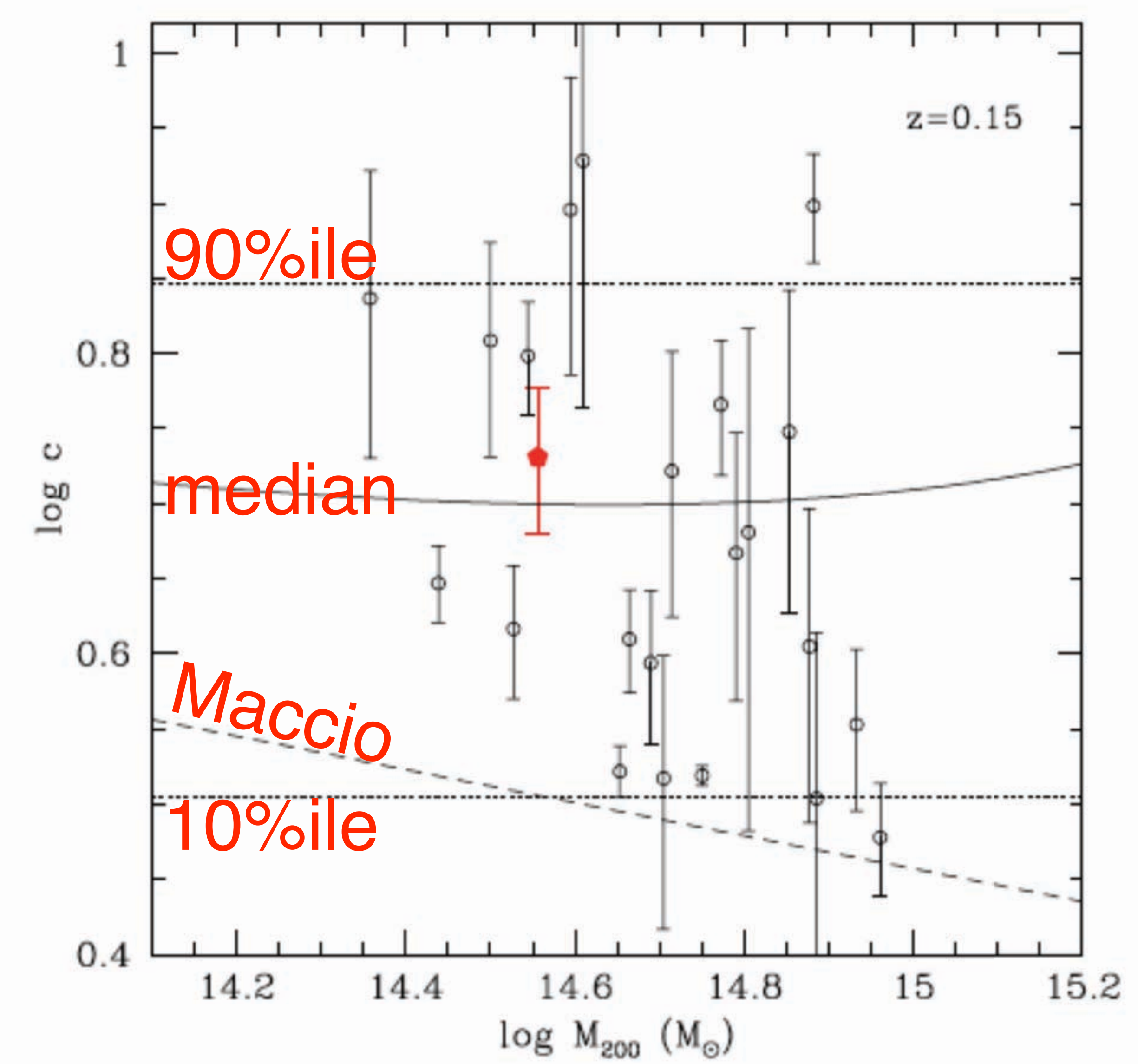
Halo concentrations in the standard CDM cosmology

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



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.

Cluster Concentrations



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-I,II and Bolshoi/MultiDark

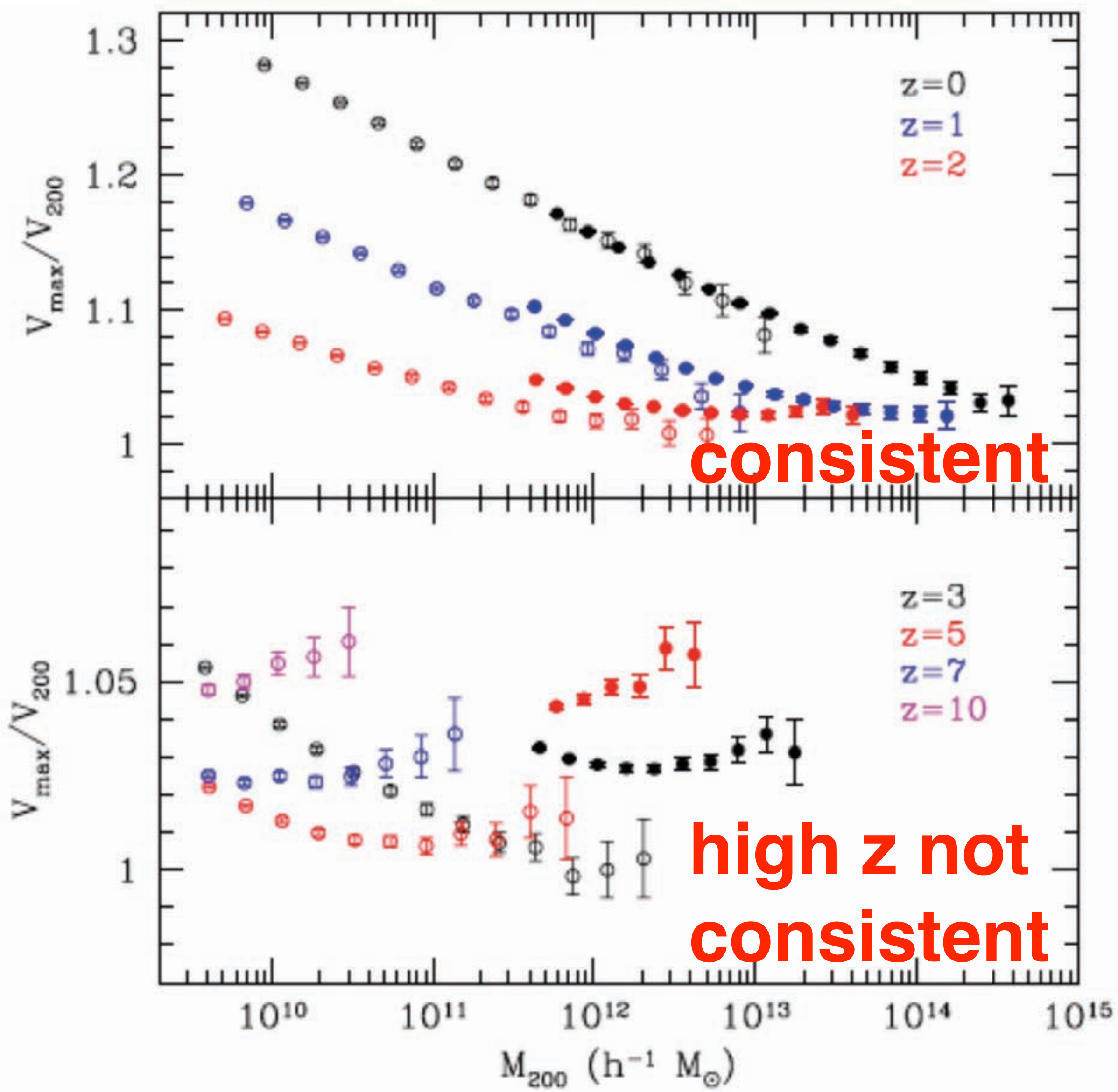


Figure 5. The ratio V_{max}/V_{200} of the maximum circular velocity to the virial velocity as a function of mass M_{200} for distinct halos at different redshifts for MS-I (filled symbols) and MS-II (open symbols) simulations. Error bars are statistical uncertainties. The MS-I and MS-II simulations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

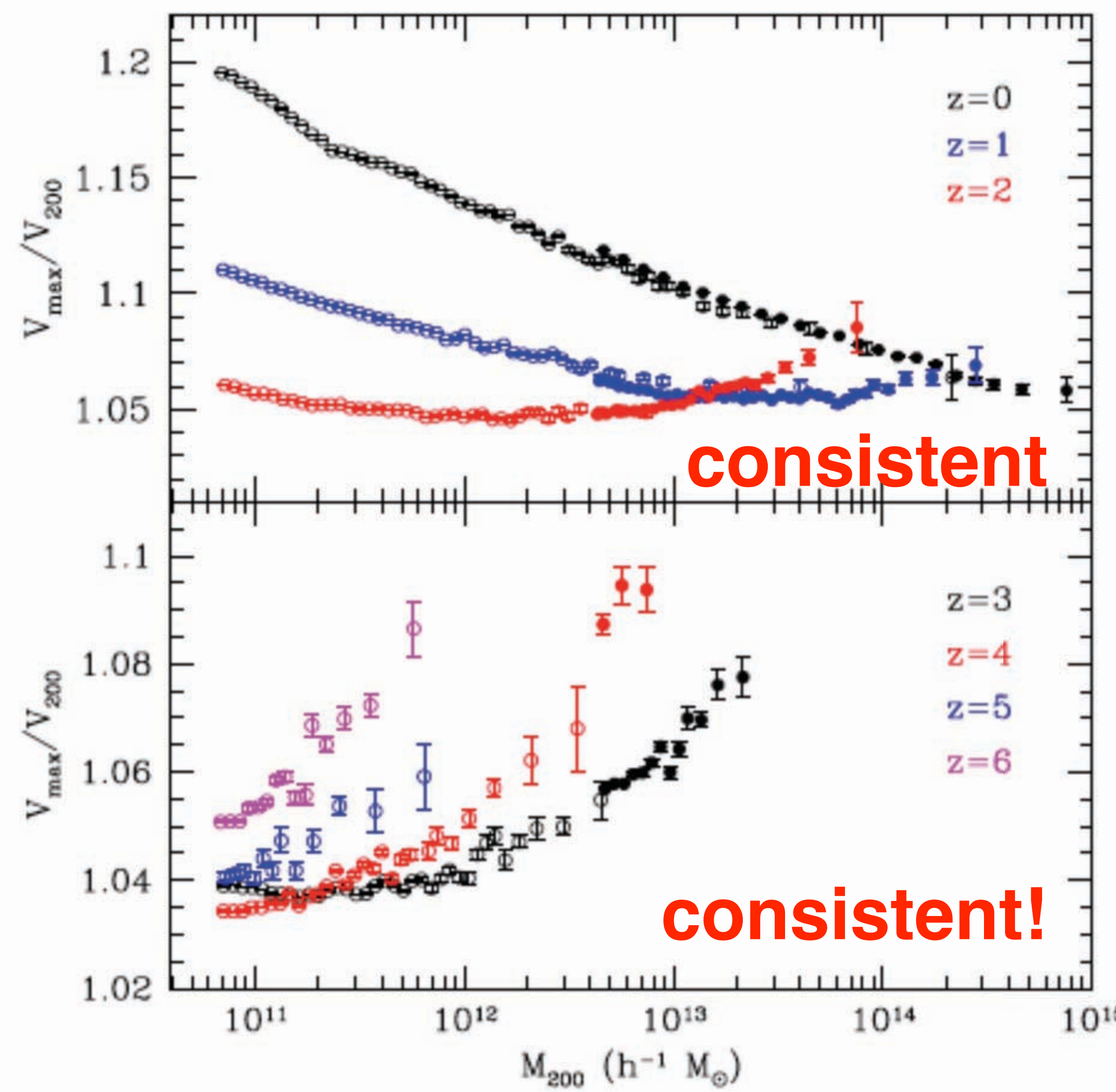


Figure 6. The same as Figure 5 but for Bolshoi (open symbols) and MultiDark (filled symbols) simulations. Both simulations show remarkable agreement at all masses and redshifts.

GRAVITATIONALLY CONSISTENT HALO CATALOGS AND MERGER TREES FOR PRECISION COSMOLOGY

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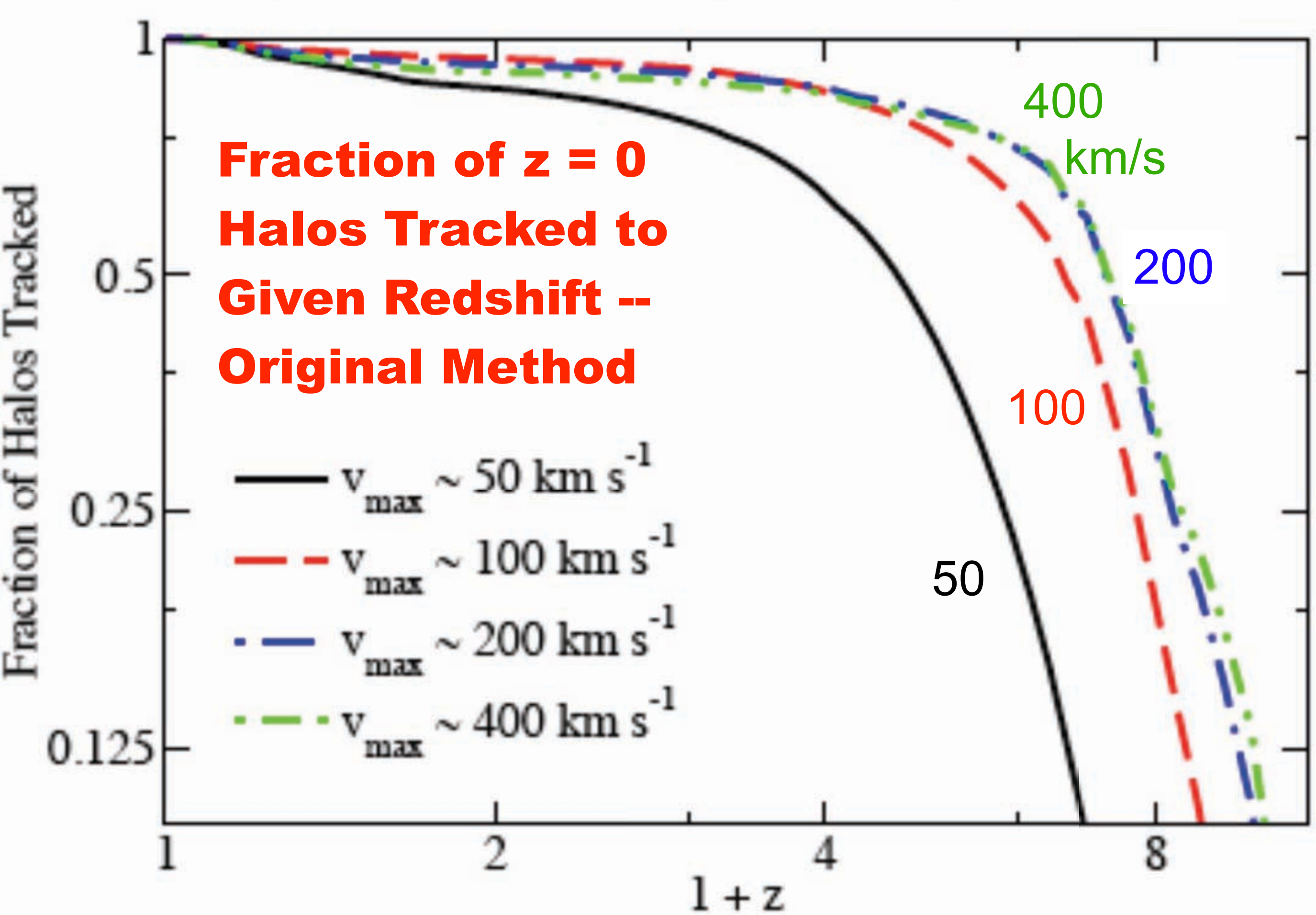
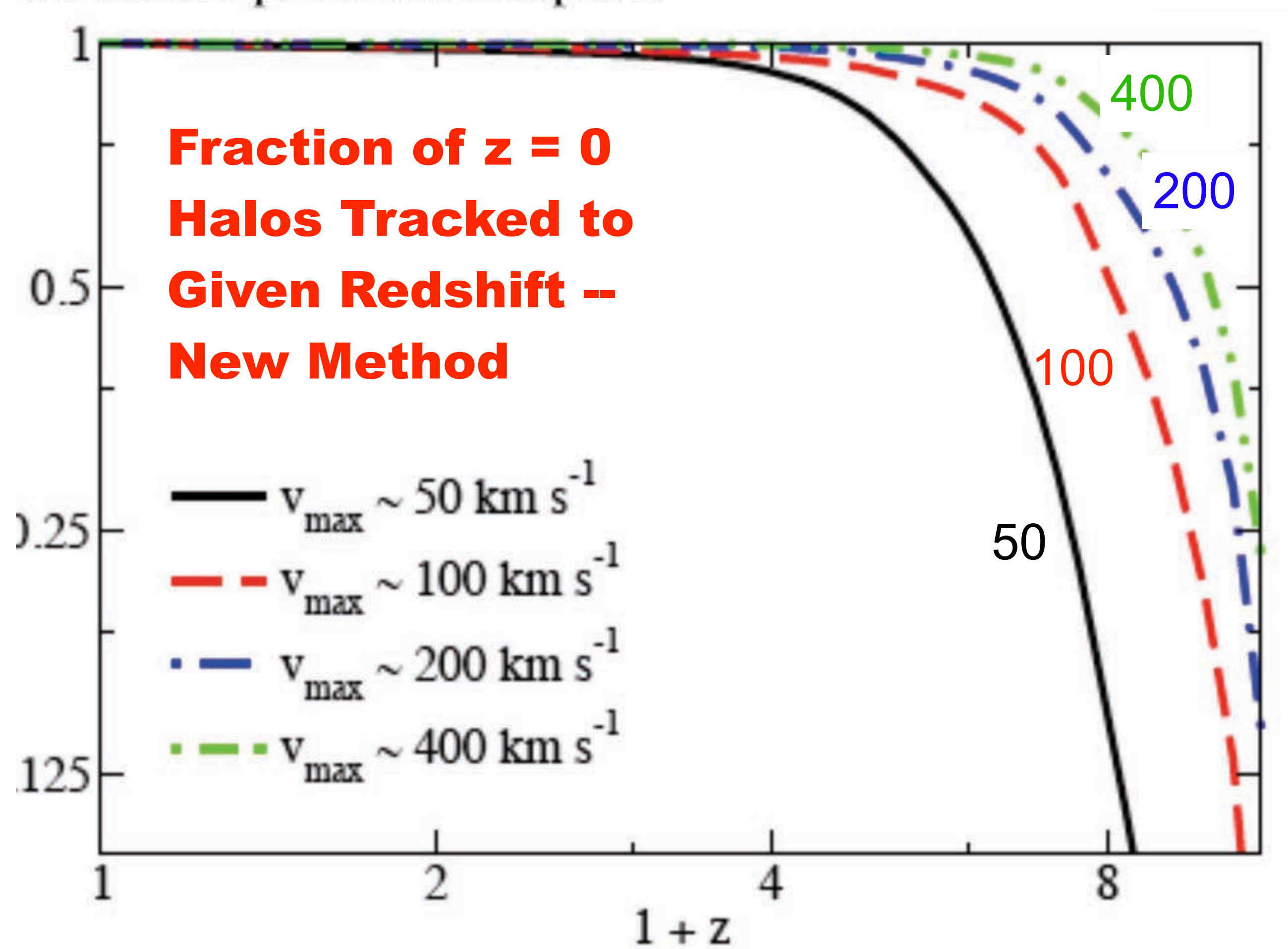
Preliminary

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.





Halo Merger Tree Algorithm

1. Identify halo descendants using a traditional particle algorithm.

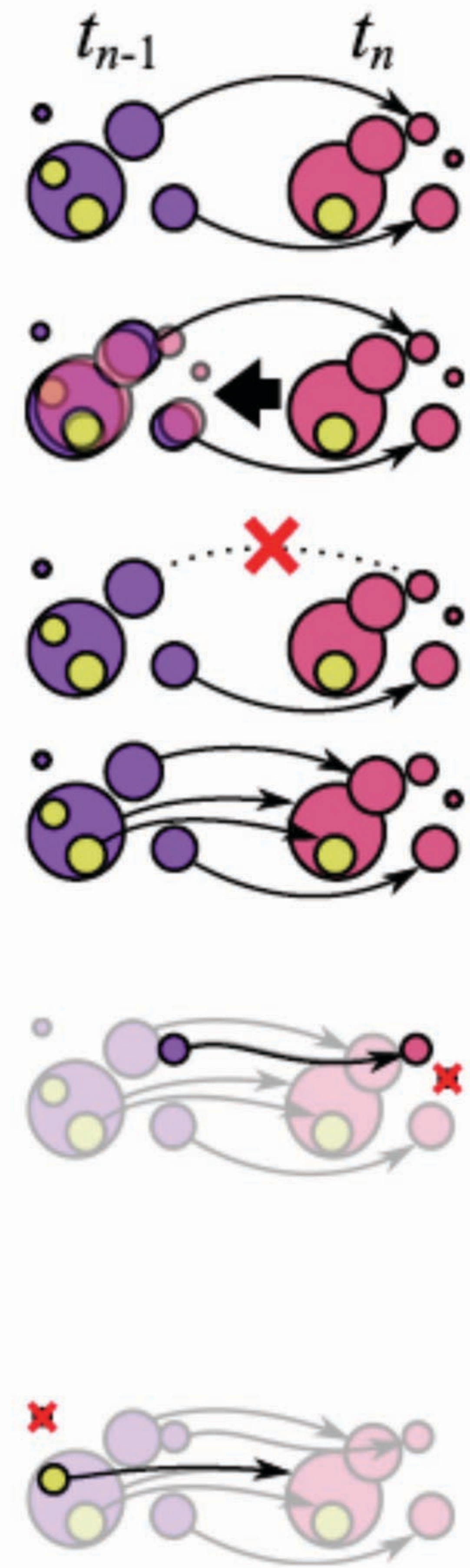
2. Gravitationally evolve the positions and velocities of all halos at the current timestep back in time to identify their most likely positions at the previous timestep.

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.

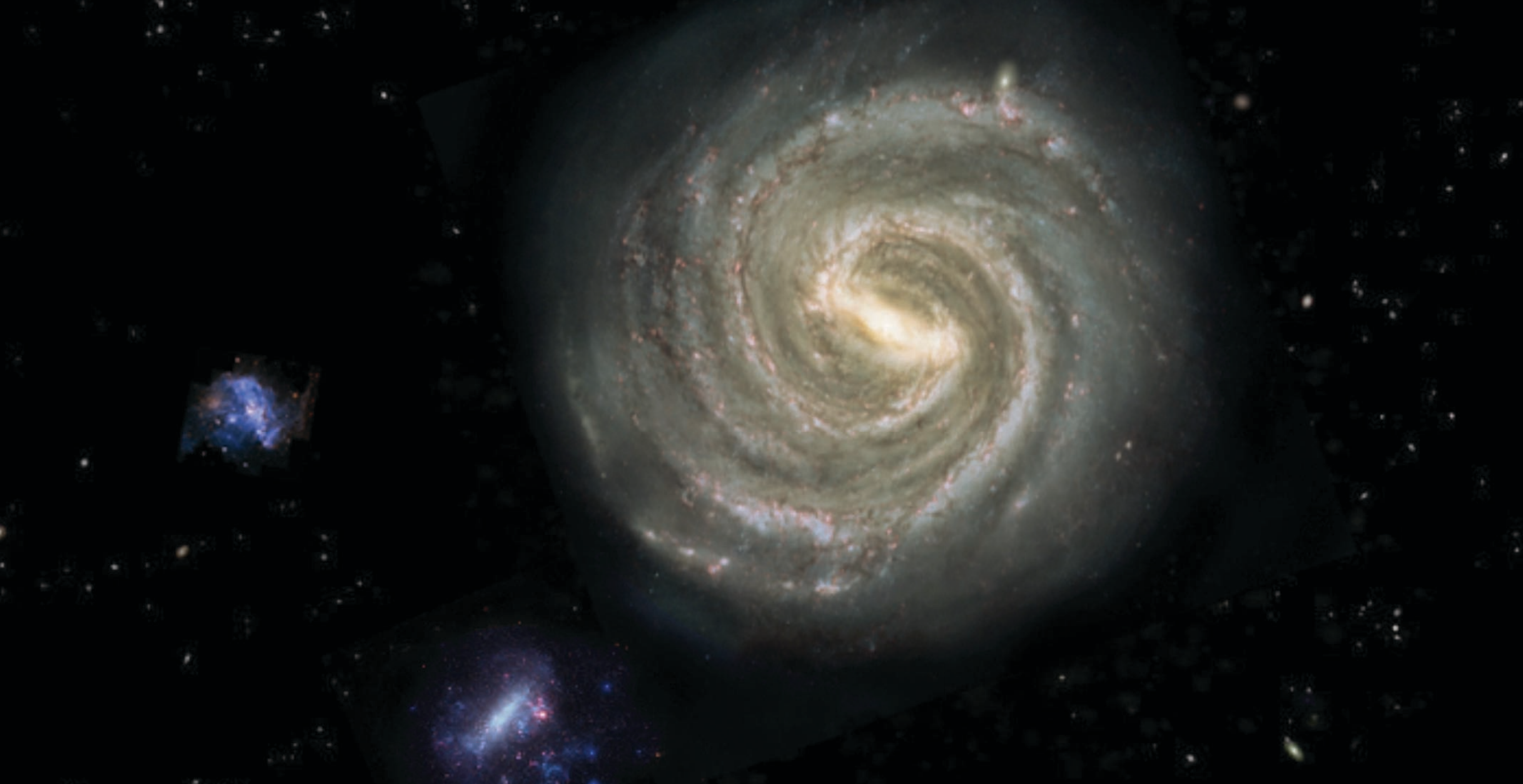
6. For halos in the previous timesteps which have no descendants, assume that a merger occurred into the halo exerting the strongest tidal field across it at the previous timestep. If a halo with no descendant is too far removed from other halos to experience a significant tidal field, assume that it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



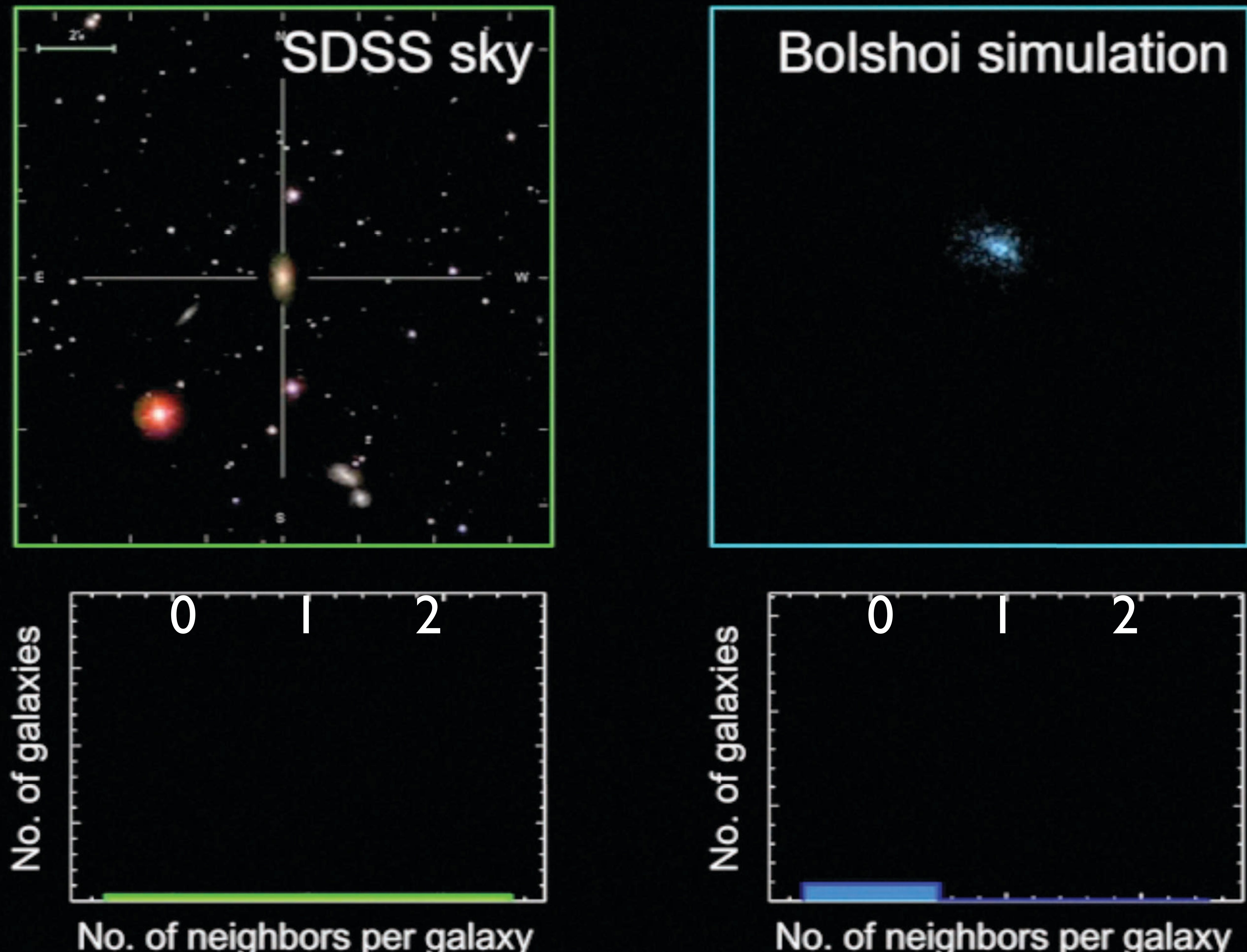
Behroozi et al. in prep.


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



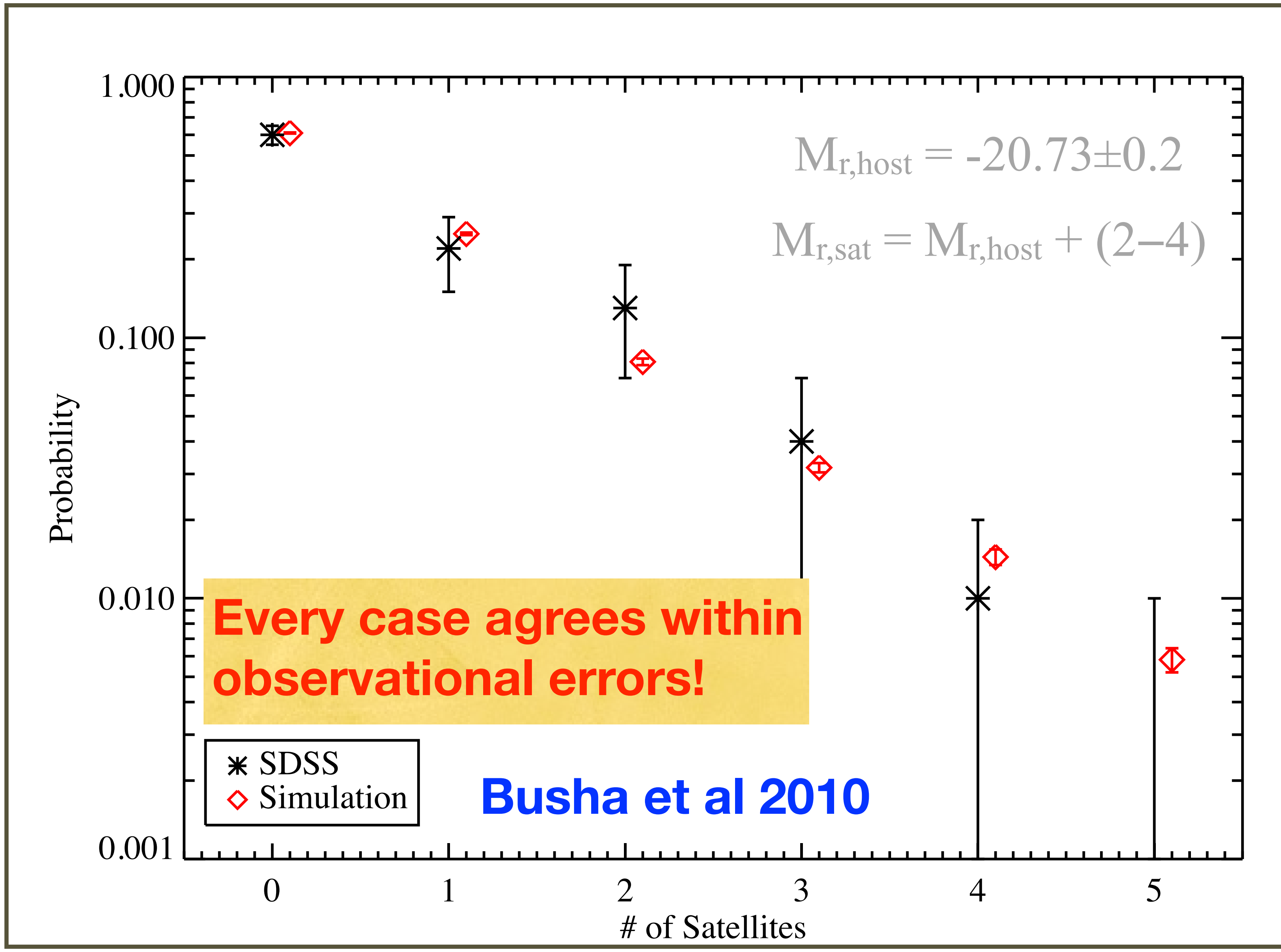
The Bolshoi simulation + halo abundance matching predicts the likelihood of this


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

- 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%

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



Risa Wechsler

Similarly good agreement with SDSS for brighter satellites with spectroscopic redshifts compared with Millennium-II using abundance matching -- Tolorud, Boylan-Kolchin, et al.

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

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Draft version March 11, 2011

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.

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

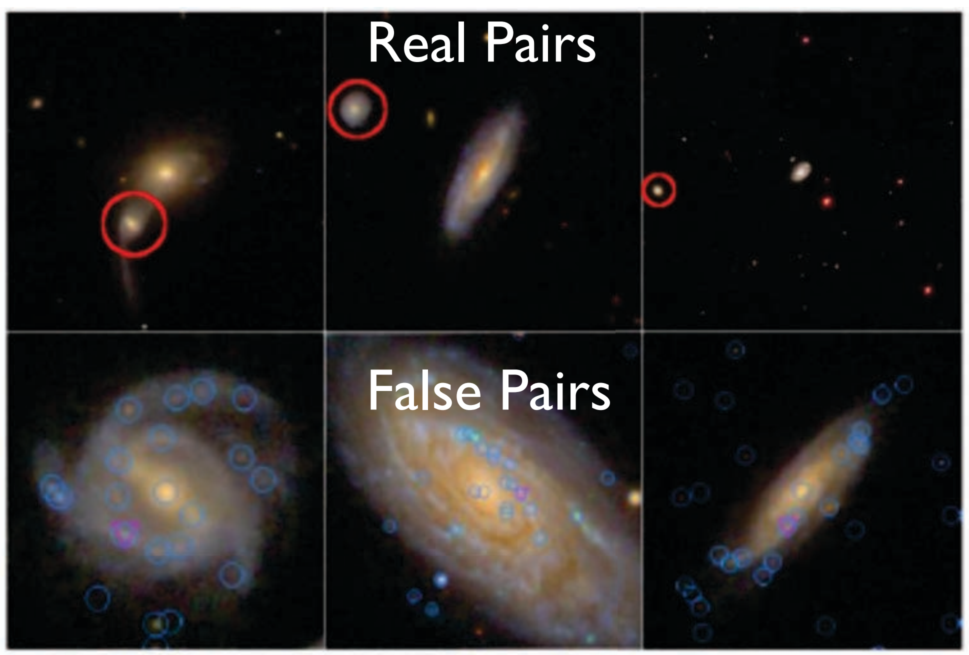


FIG. 1.— Examples of SDSS primary/secondary pairs in the clean sample (upper) and false pairs (lower). Secondaries identified by our criteria (see text) are marked with red circles (upper panels) or magenta triangles (lower panels). The upper three are all in the clean sample (have redshifts close to 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: see James Bullock's talk

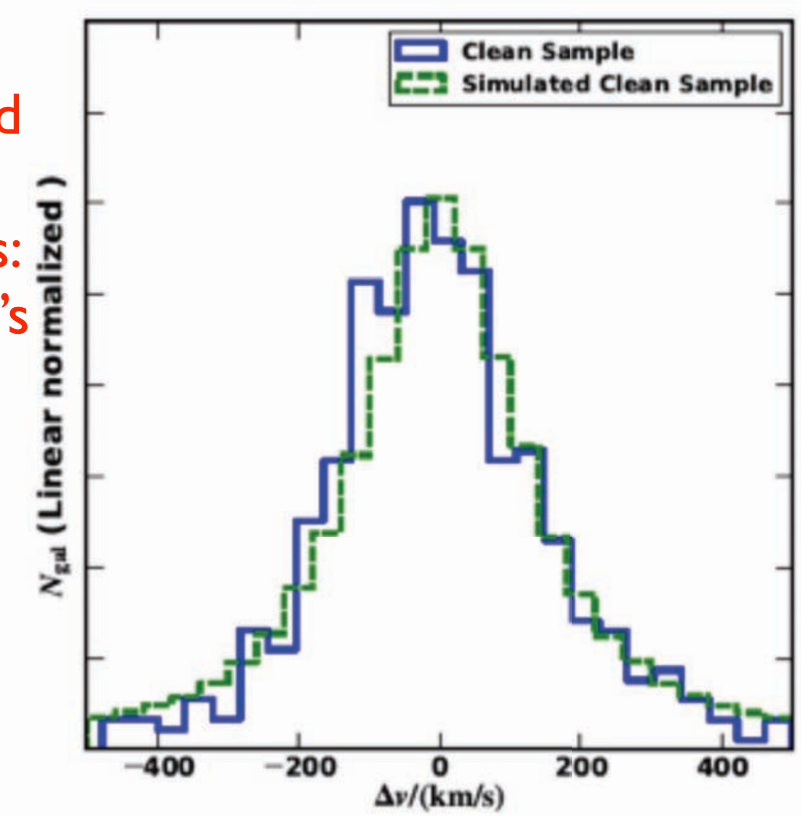
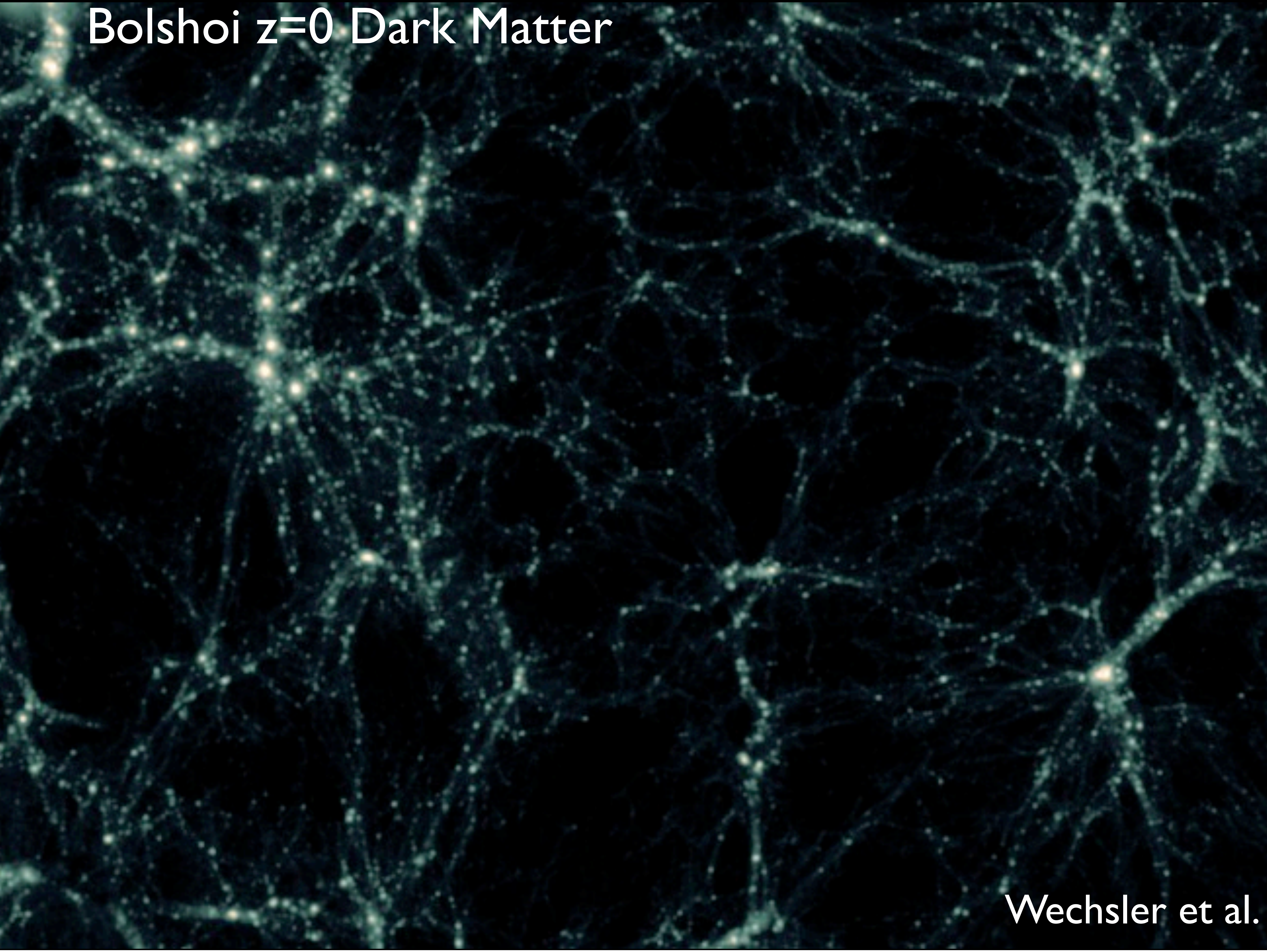
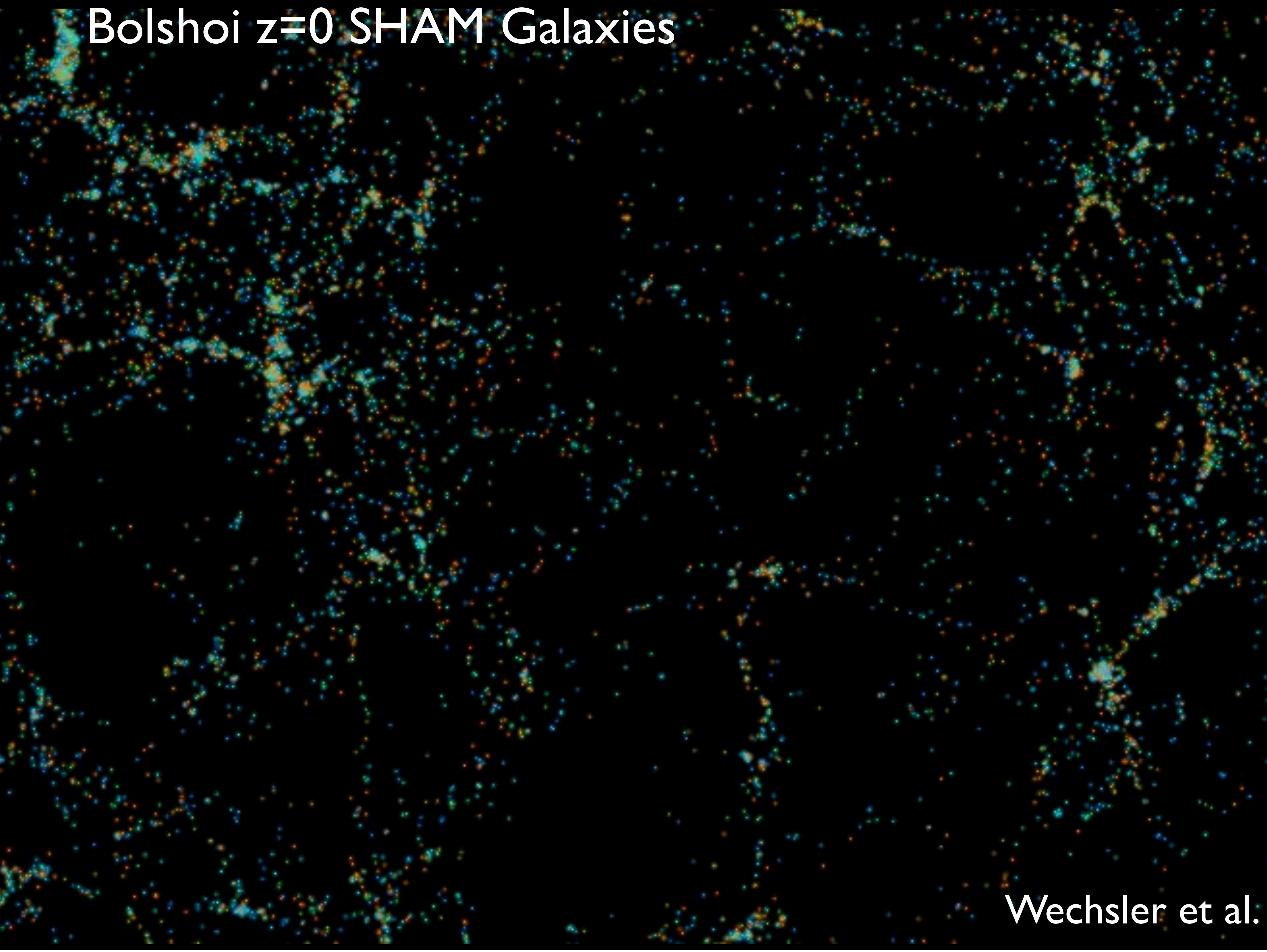
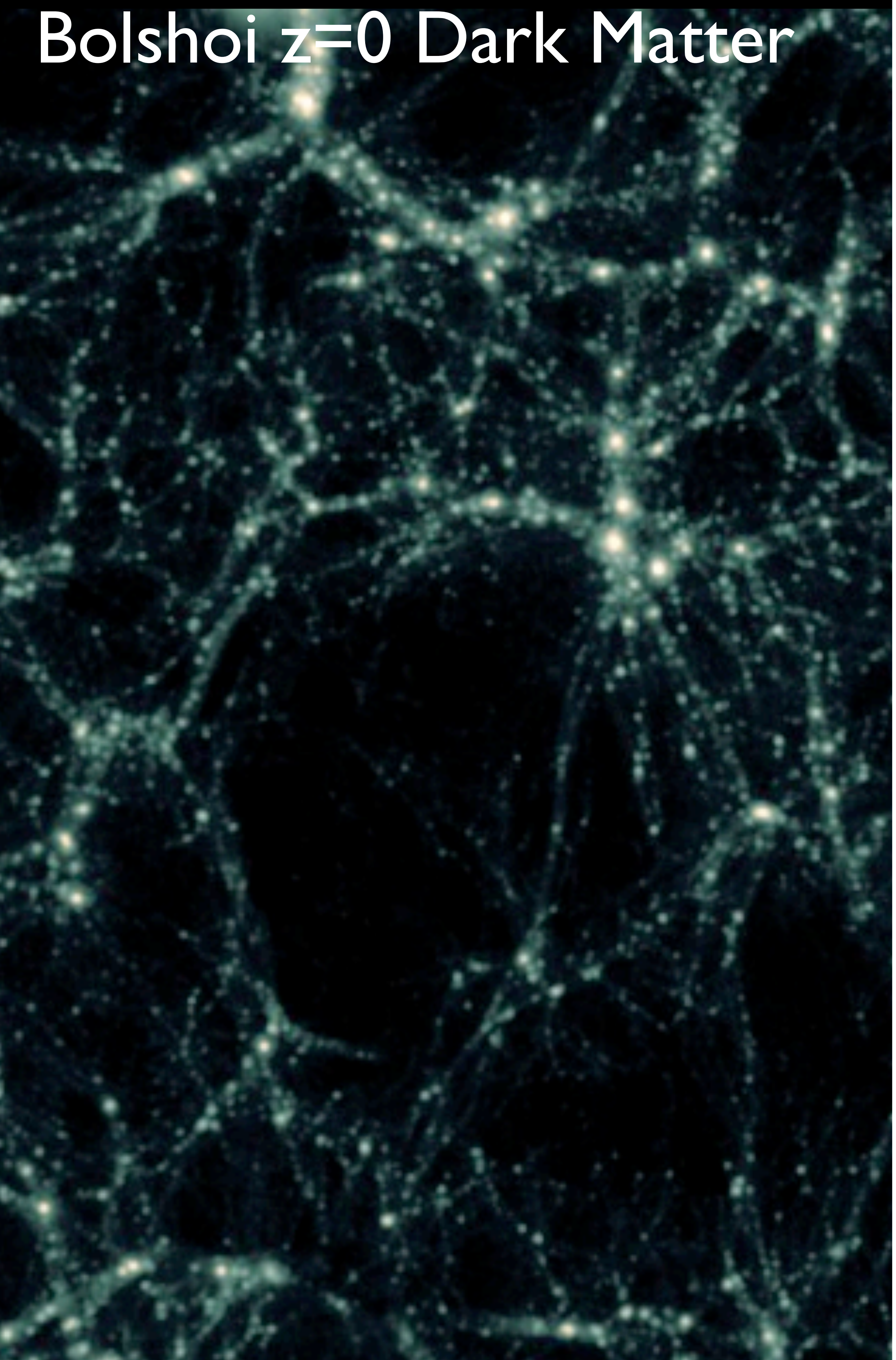
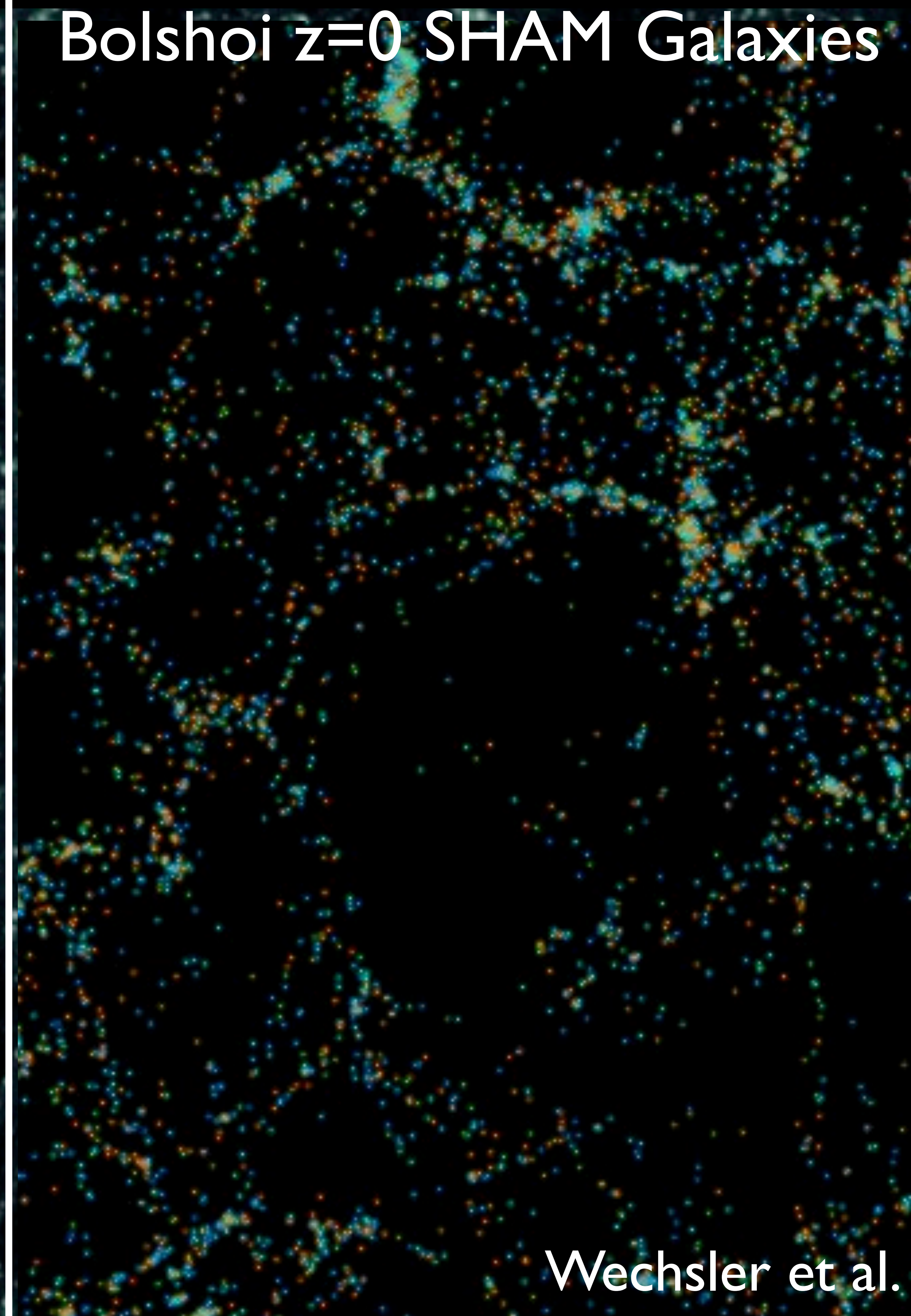


FIG. 6.— Distribution of $\Delta v \equiv c(z_{\rm pri} - z_{\rm sec})$ for the clean sample (solid blue histogram), the clean-like sample from MS-II (dashed green). The KS test yields $p_{\rm KS} = 33\%$. The pairwise velocity dispersion in the observed sample is $\sigma = 161\ \mathrm{km\,s^{-1}}$.

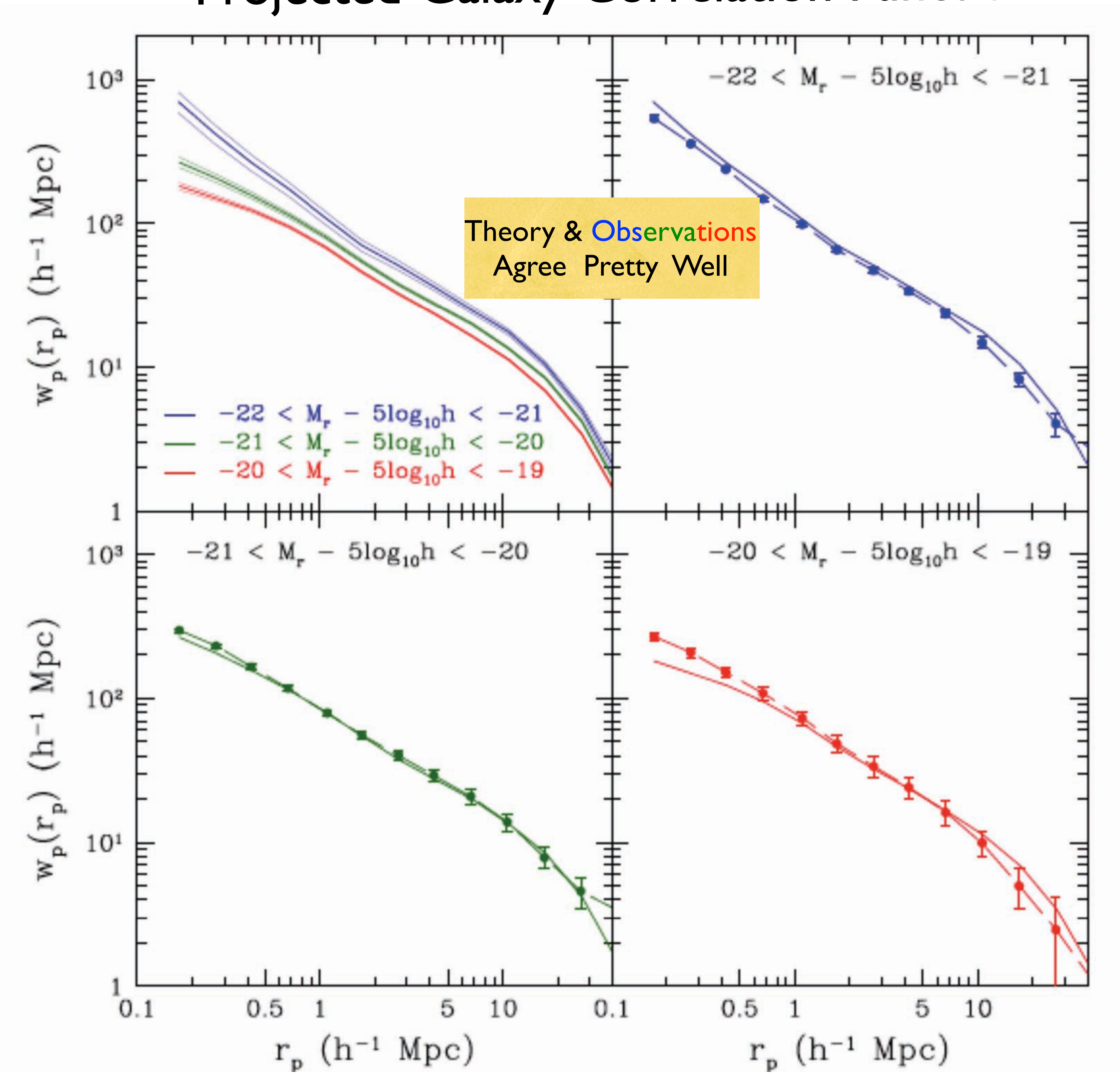

Bolshoi z=0 Dark Matter
Wechsler et al.


Bolshoi z=0 SHAM Galaxies
Wechsler et al.


Bolshoi z=0 Dark Matter


Bolshoi z=0 SHAM Galaxies
Wechsler et al.

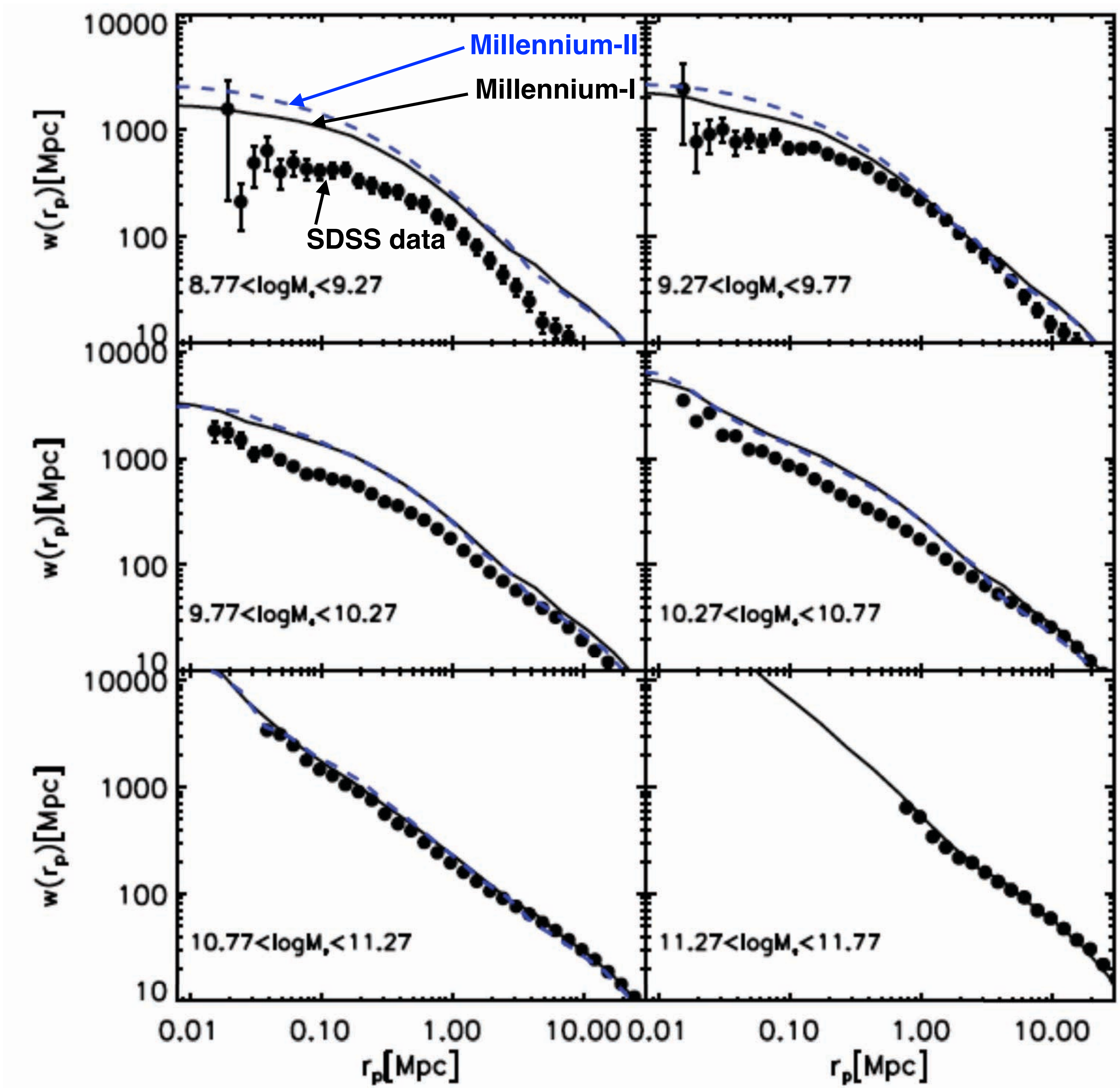
Projected Galaxy Correlation Functions



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 (ApJ soon)

Projected Galaxy Correlation Functions

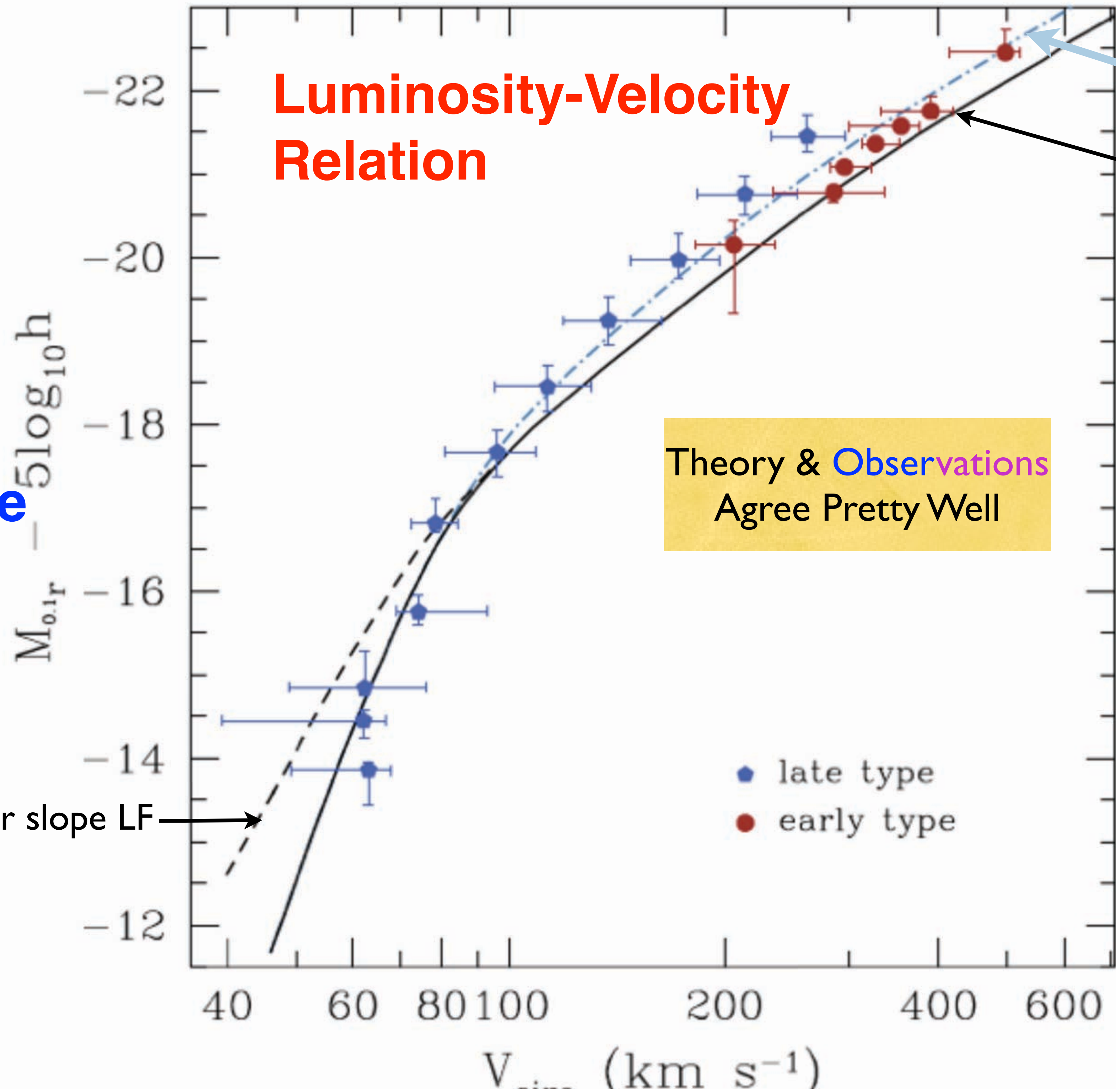


Projected correlation functions for galaxies in different stellar mass ranges, in SAM based on Millennium I and II. Black solid and blue dashed curves give results for preferred model applied to the MS and the MS-II, respectively. Symbols with error bars are results for SDSS/DR7 calculated using the same techniques as in Li et al. (2006). The two simulations give convergent results for $M_* > 6X10^9 M_{sun}$. At lower mass the MS underestimates the correlations on small scales.The model agrees quite well with the SDSS at all separations for $M_* > 6X10^{10} M_{sun}$. 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. 2011 MNRAS

Luminosity-Velocity Relation

Bolshoi Sub-Halo Abundance Matching

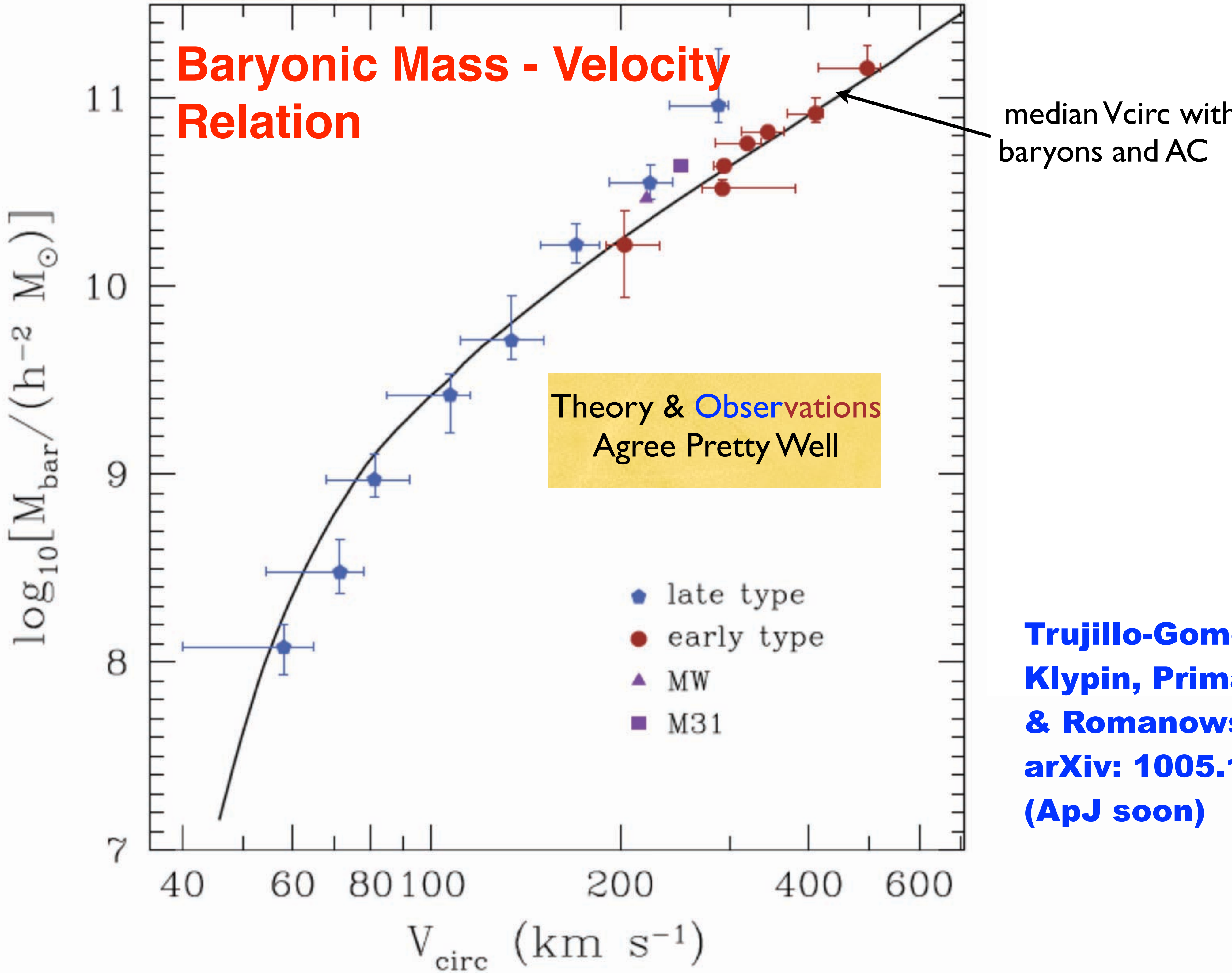


"AC" = Adiabatic Contraction of dark matter halos when baryons cool & condense to halo centers, following Blumenthal, Faber, Flores, & Primack 1986

Trujillo-Gomez, Klypin, Primack, & Romanowsky arXiv: 1005.1289 (ApJ soon)

Fig. 4.— Comparison of the observed LuminosityVelocity 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.

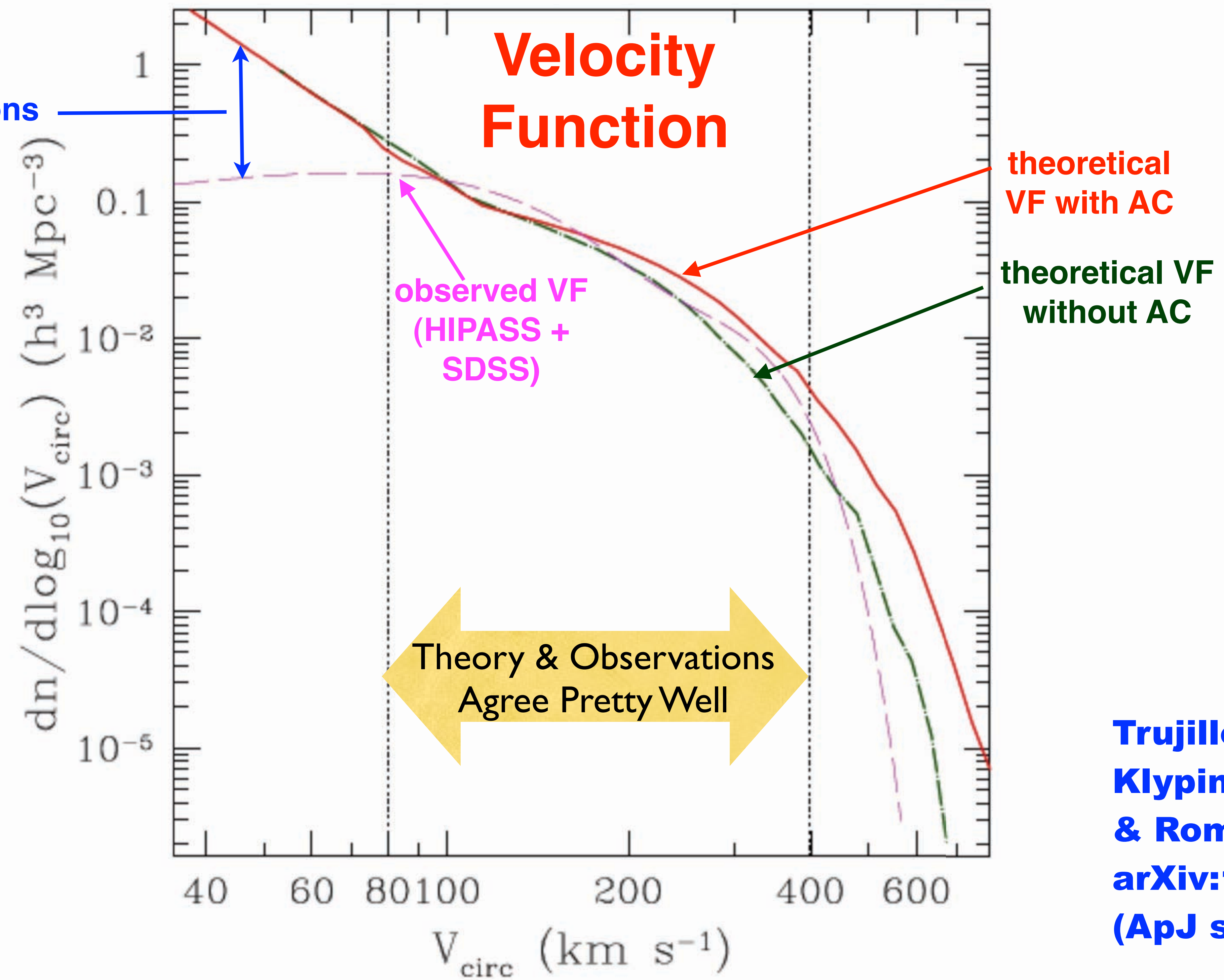
Bolshoi Sub-Halo Abundance Matching



Trujillo-Gomez, Klypin, Primack, & Romanowsky arXiv: 1005.1289 (ApJ soon)

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

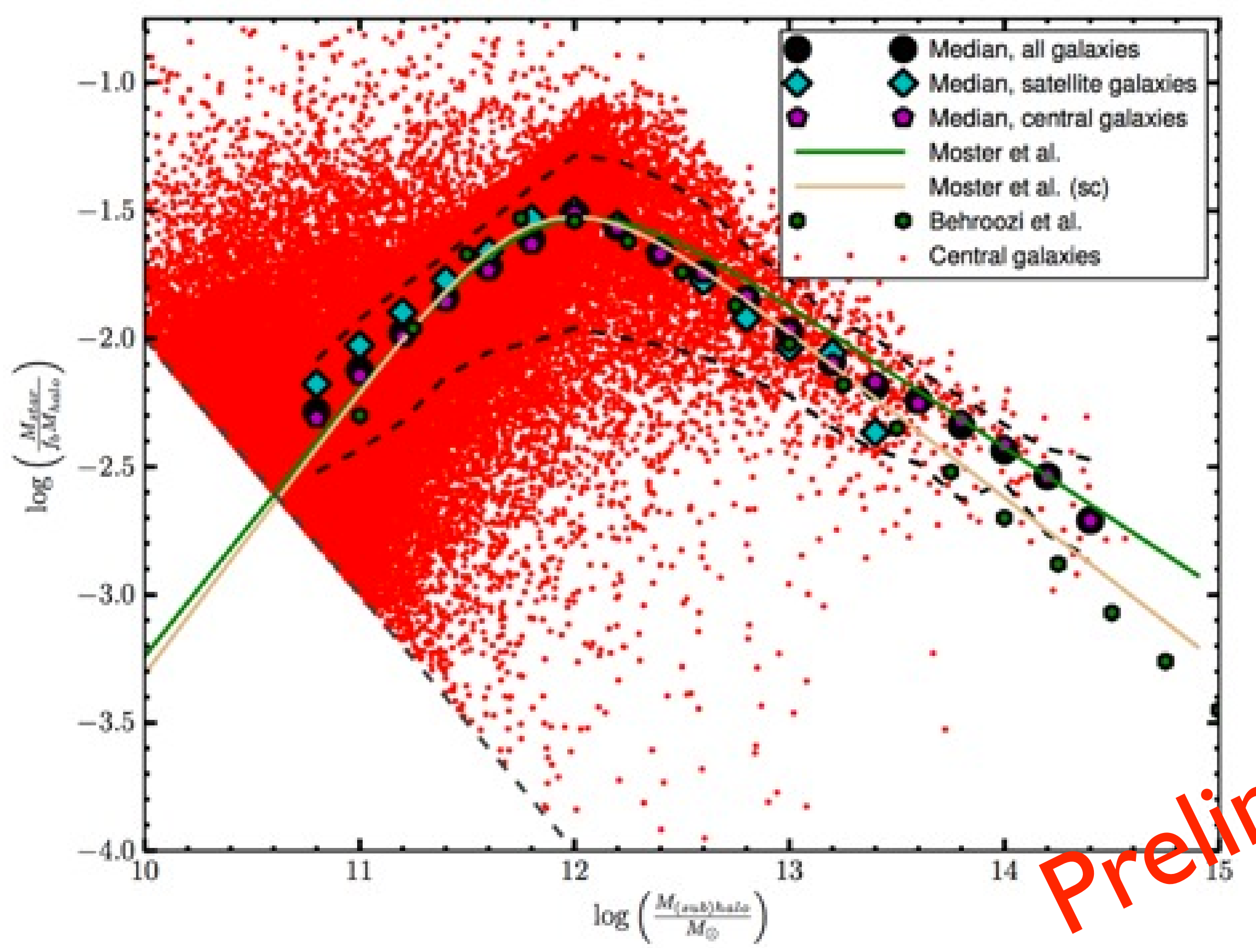


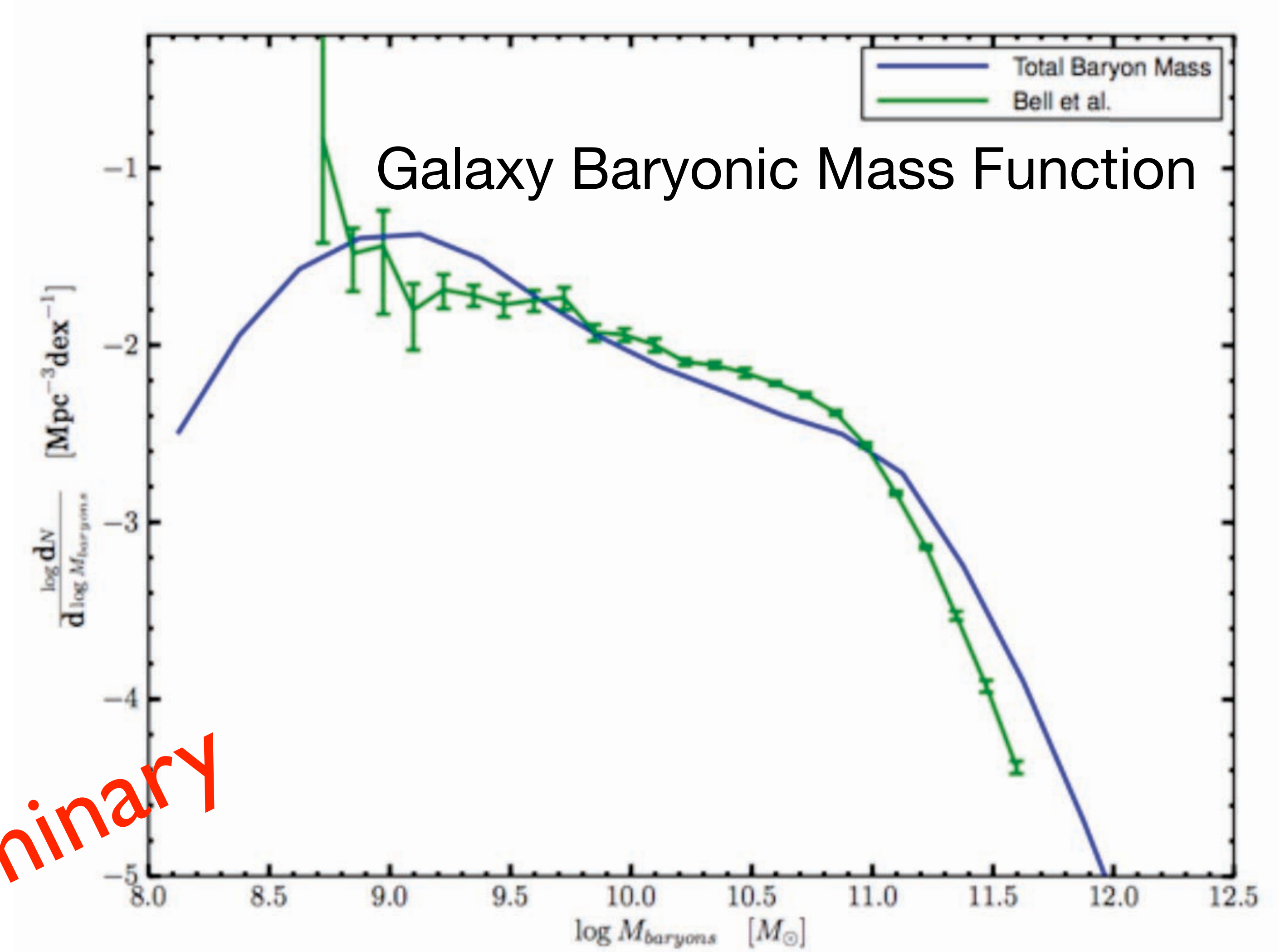
Trujillo-Gomez, Klypin, Primack, & Romanowsky arXiv:1005.1289 (ApJ soon)

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





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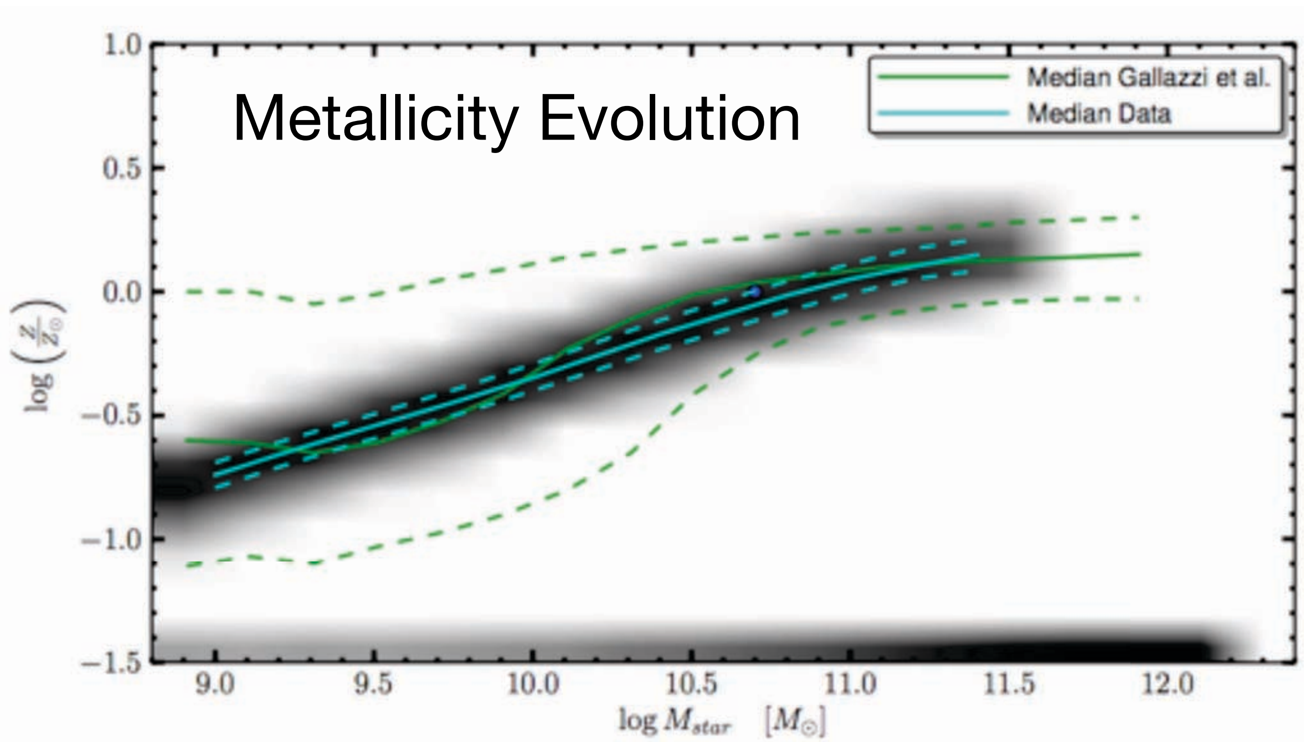

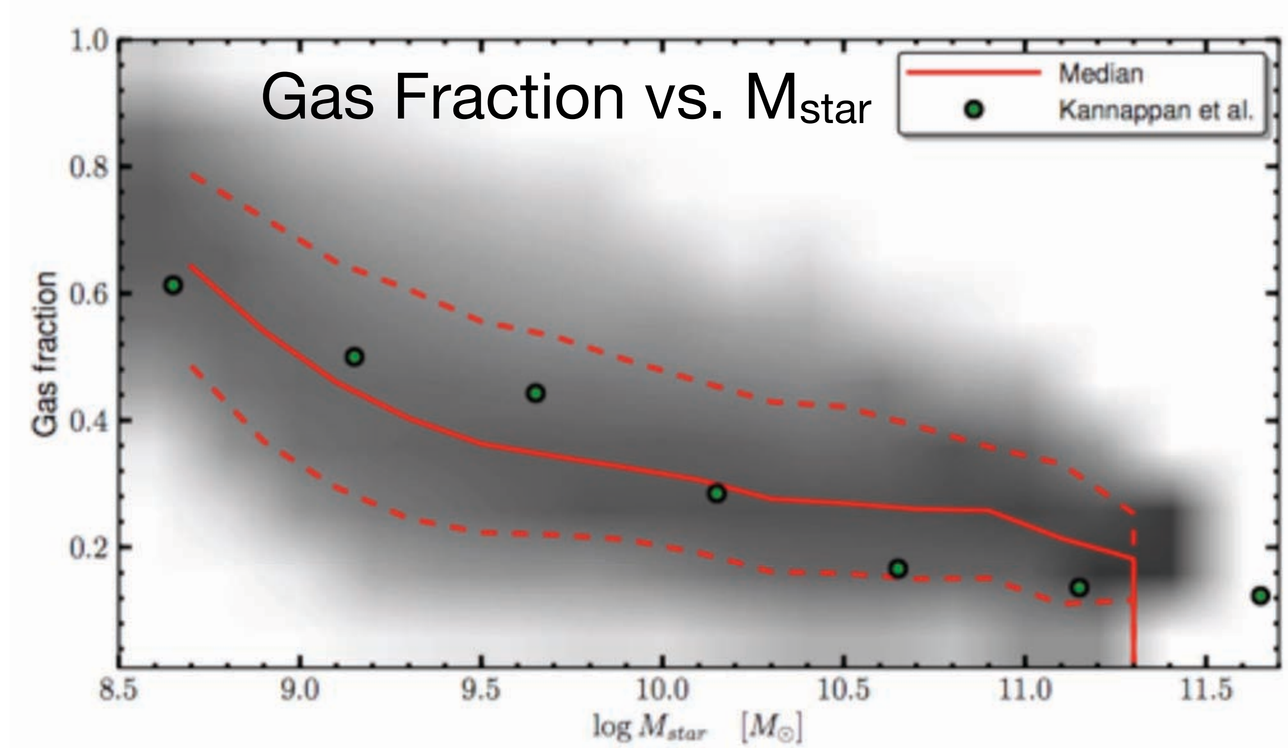

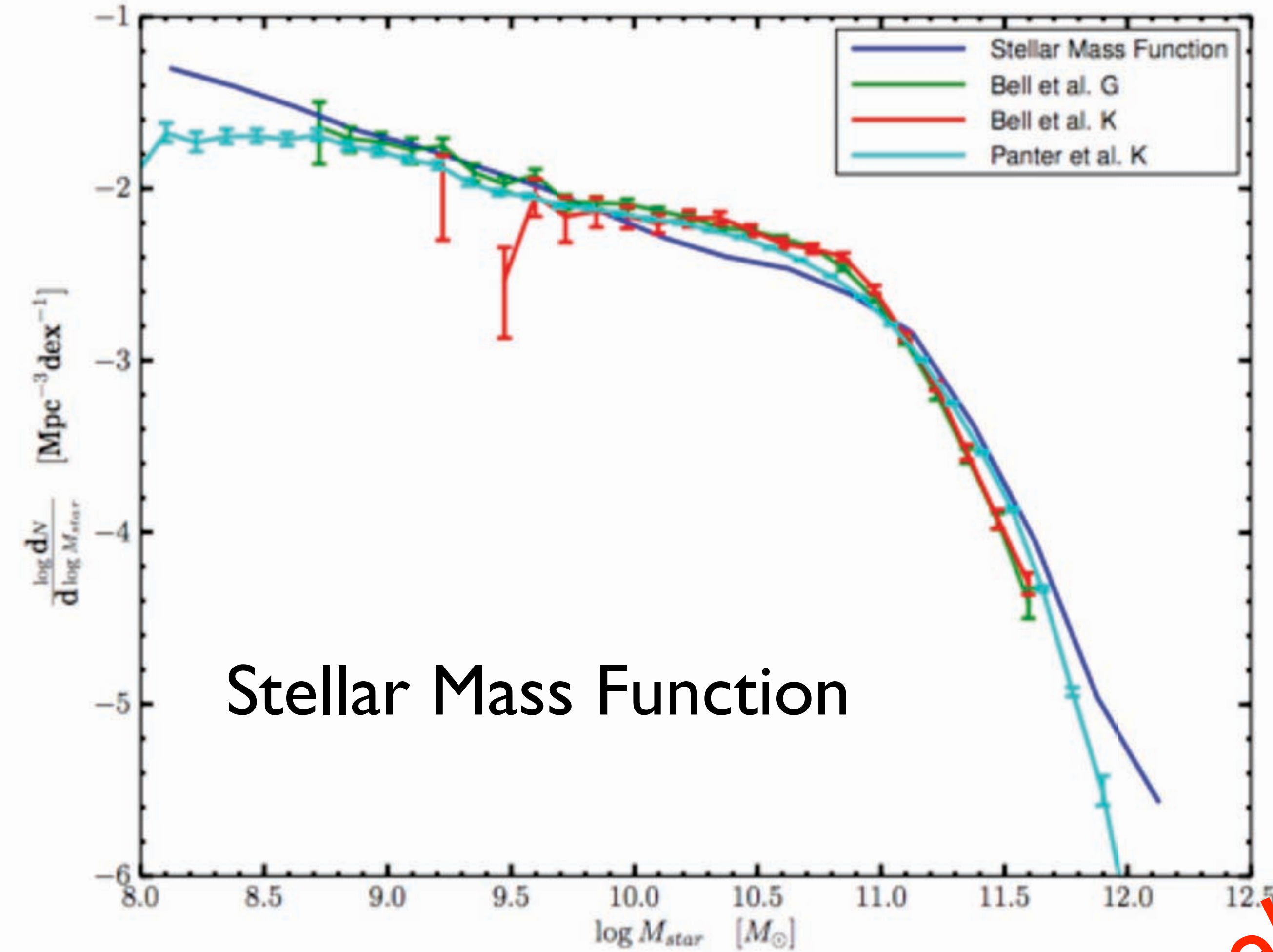

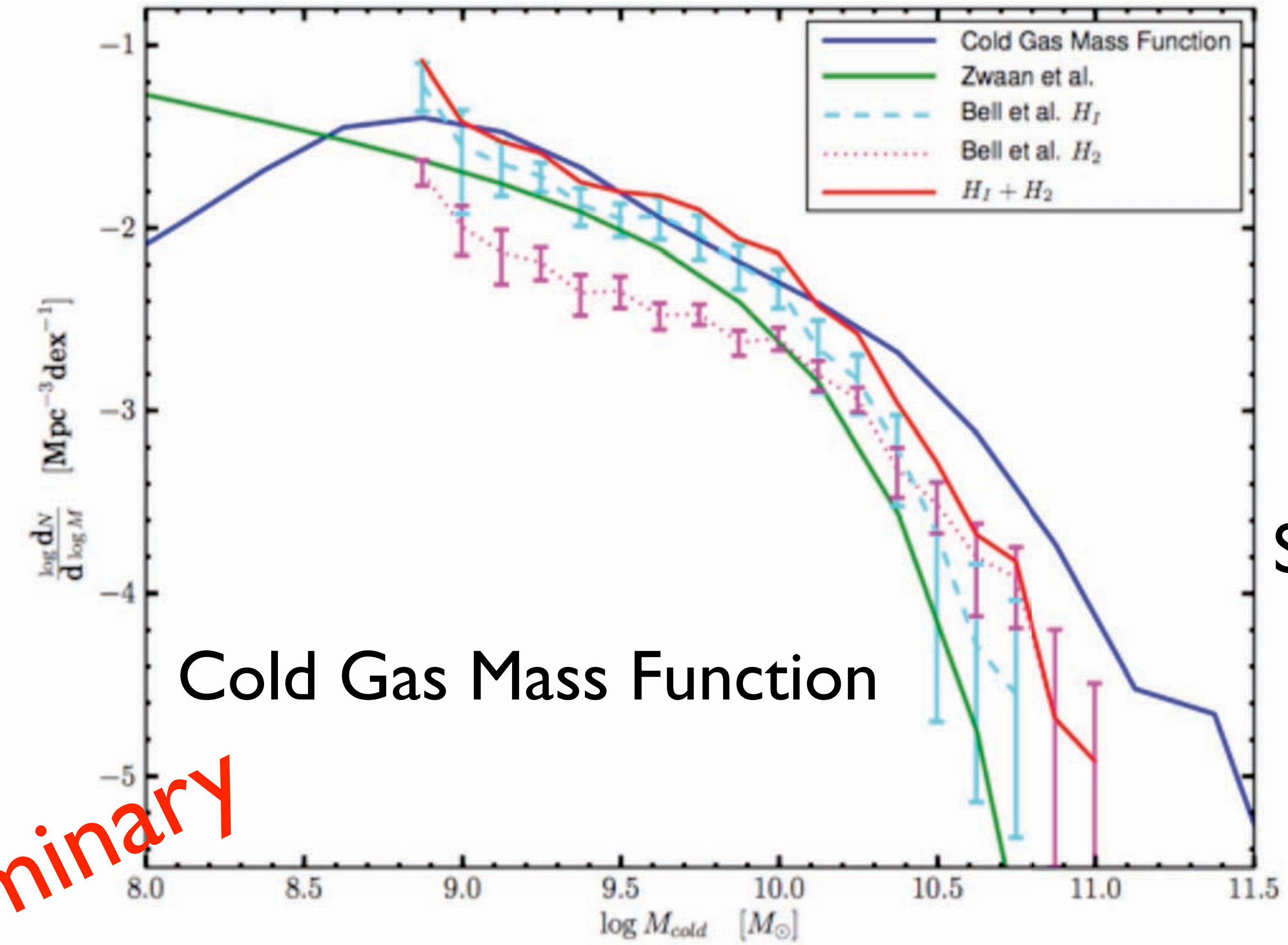

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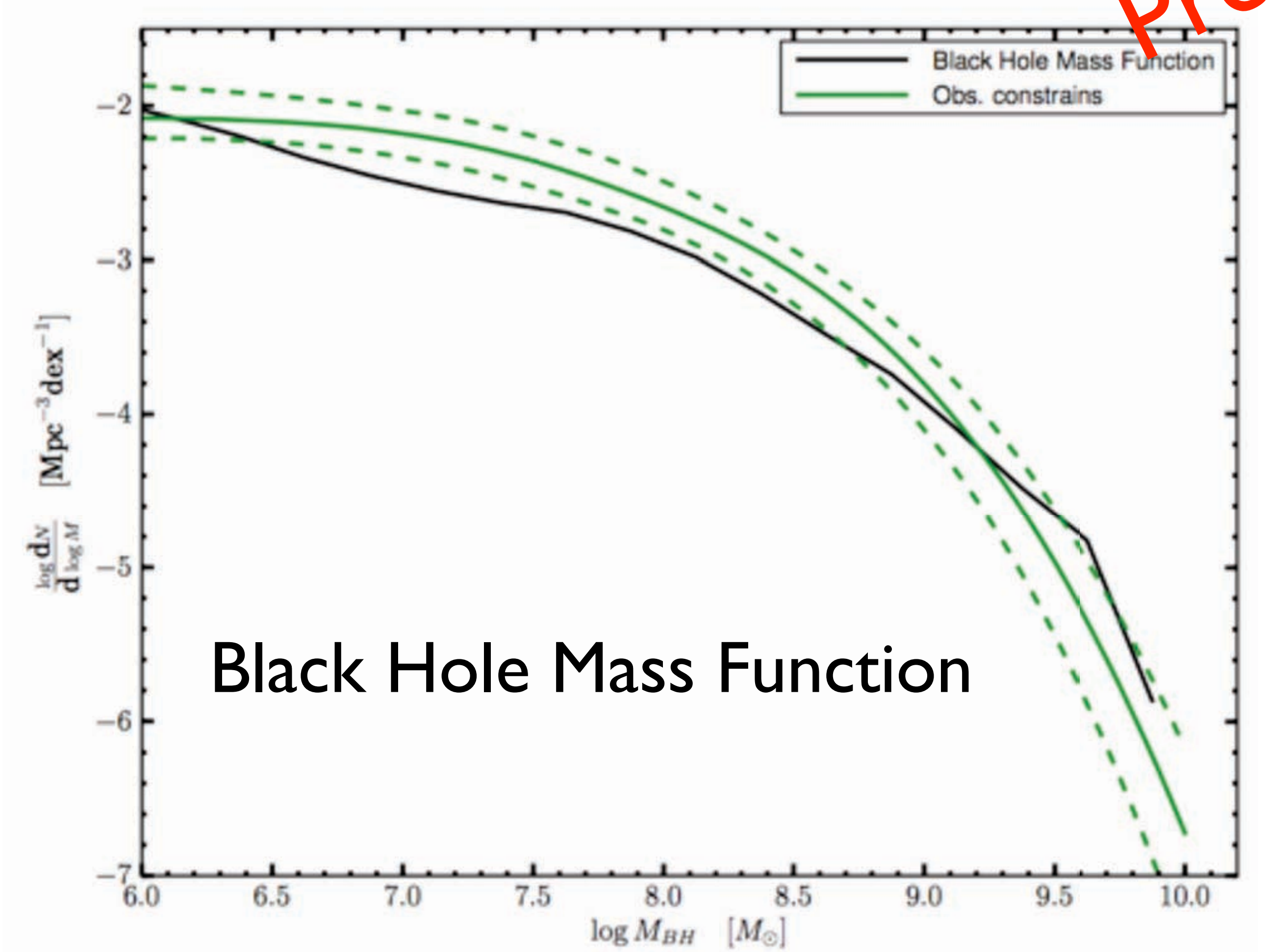

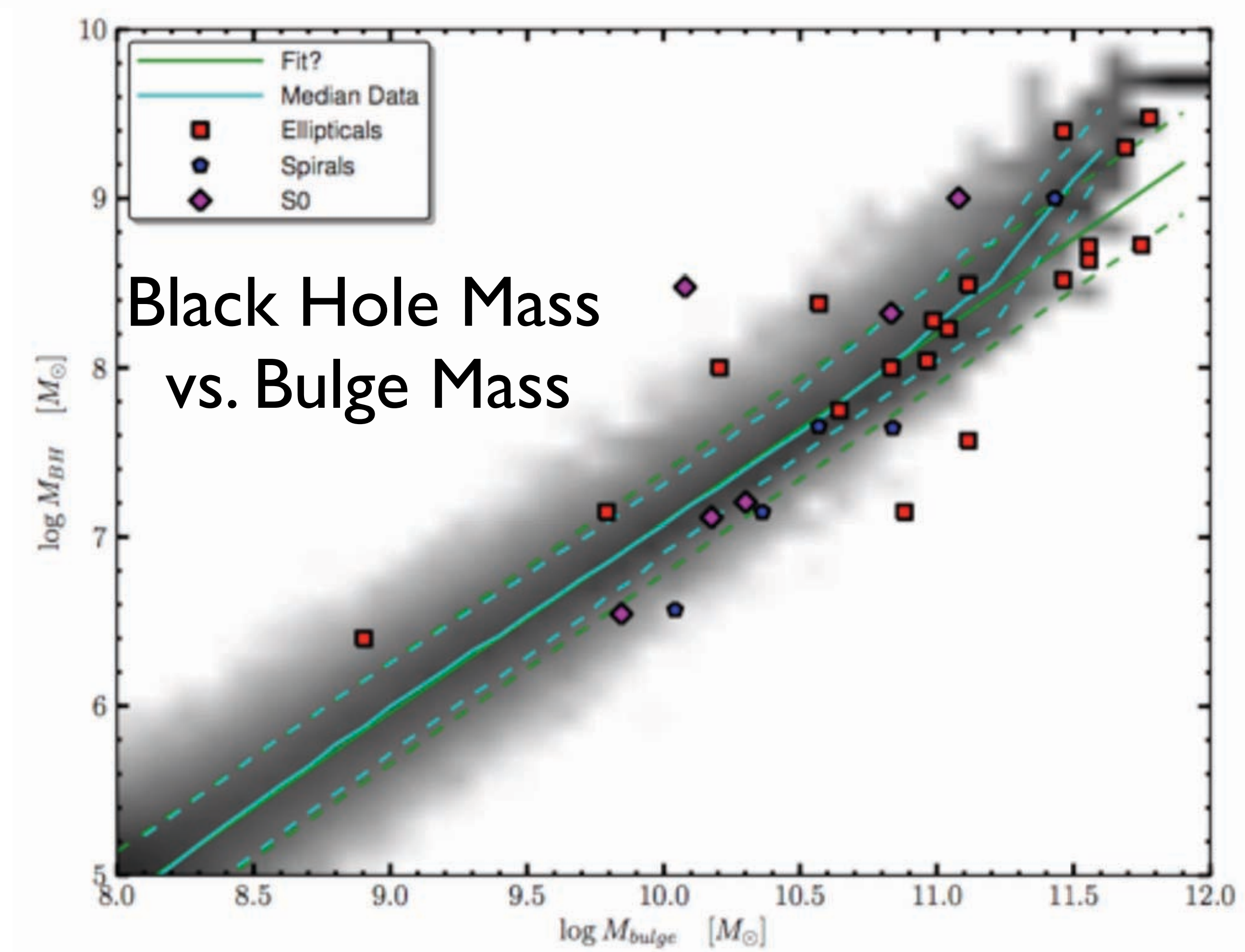

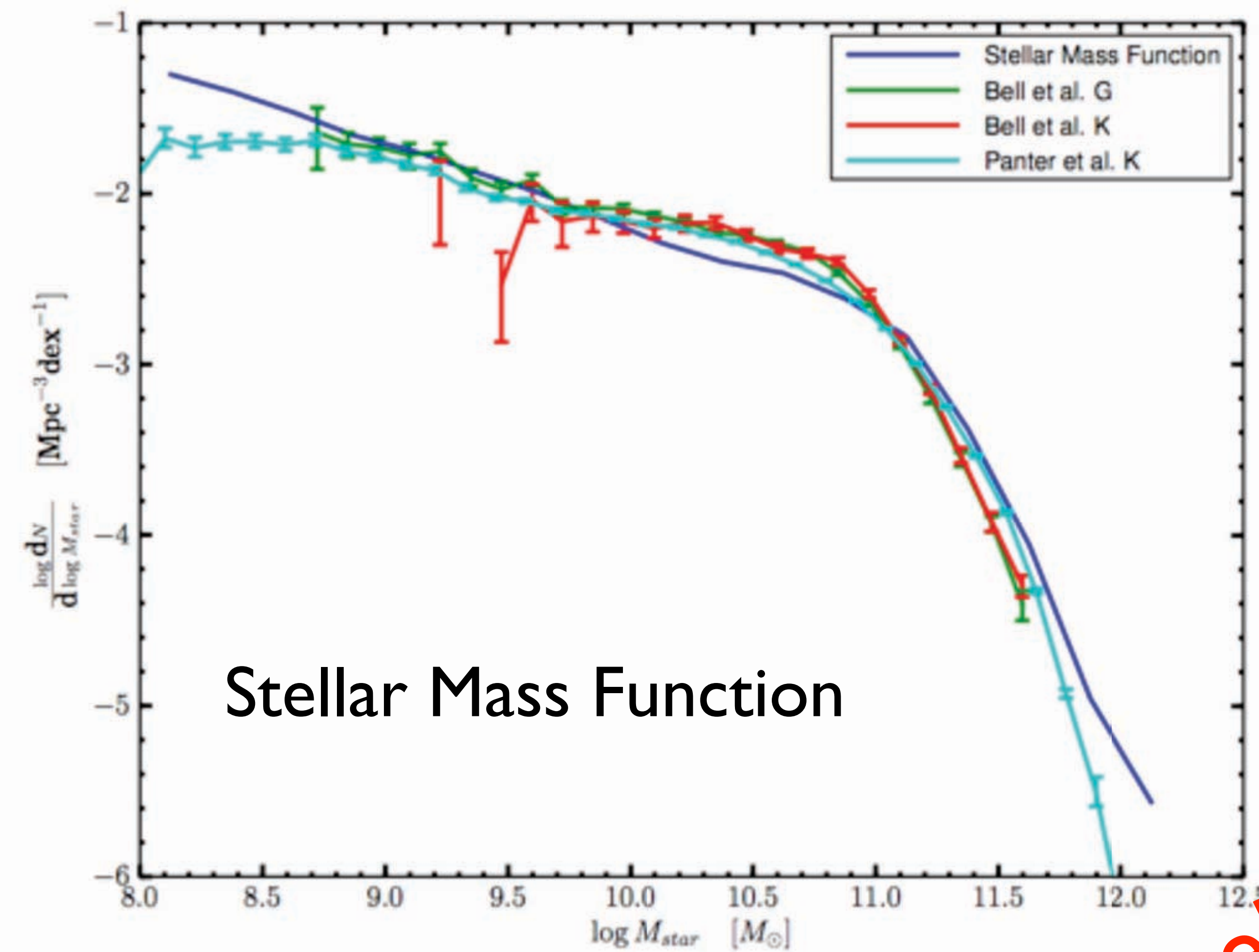

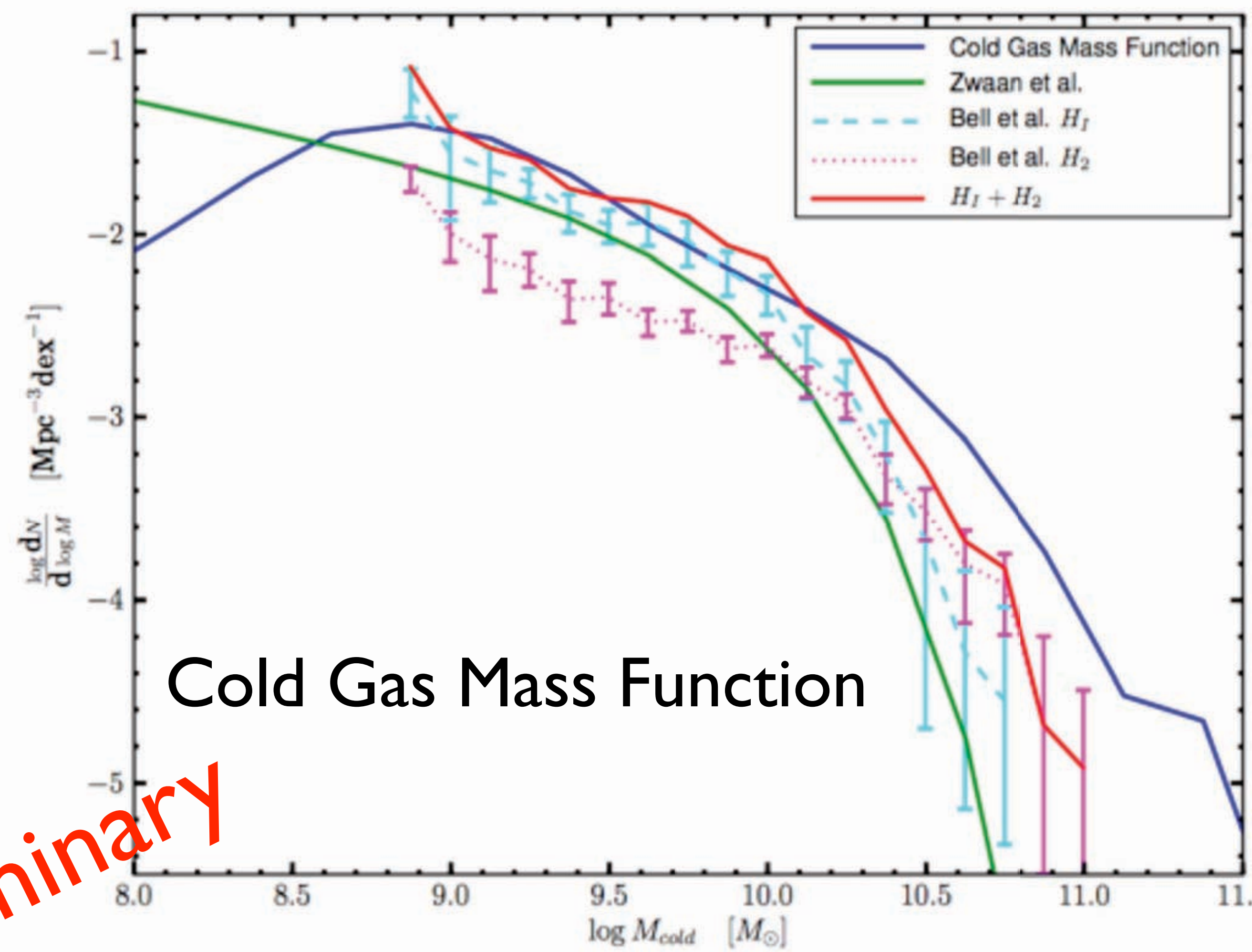

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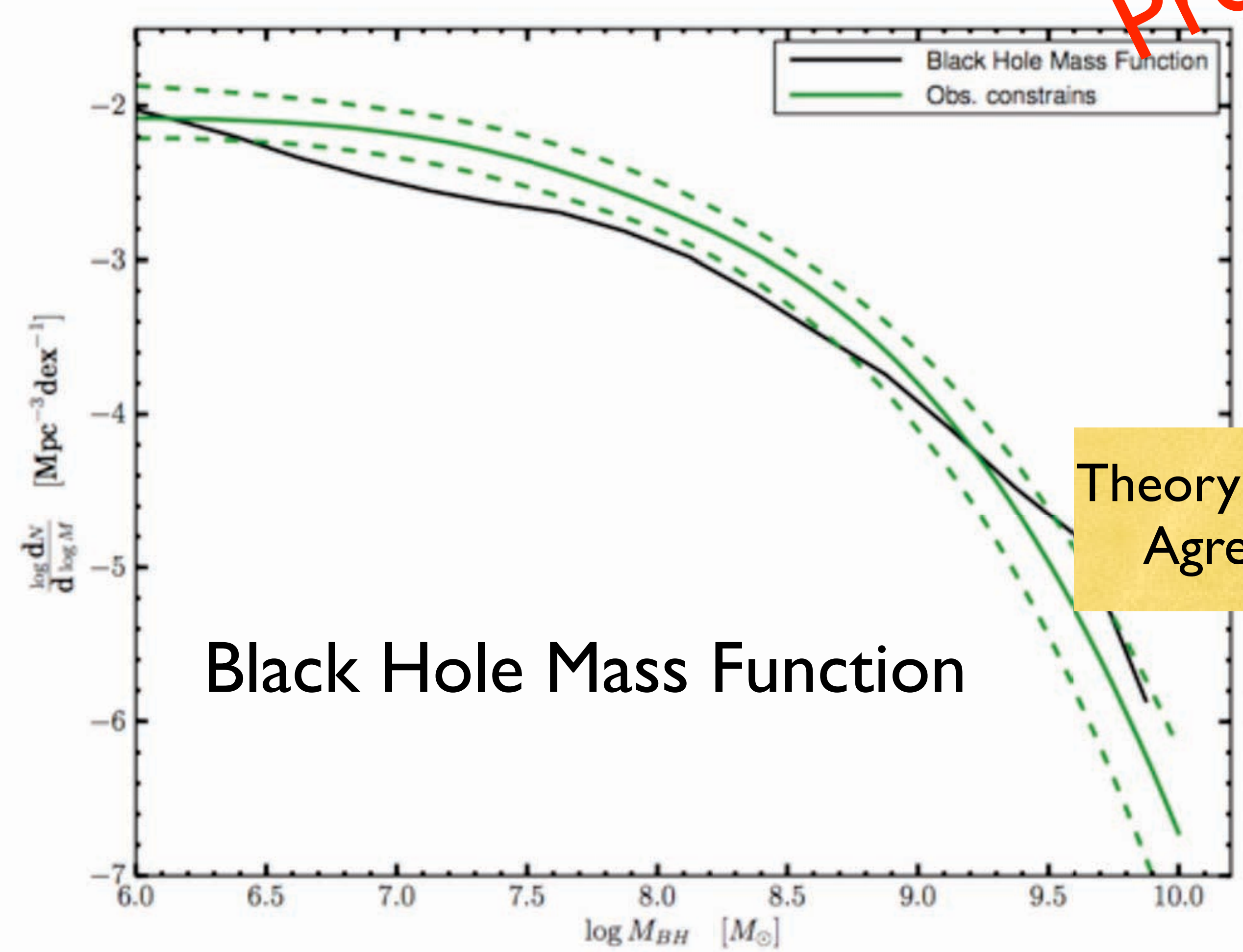
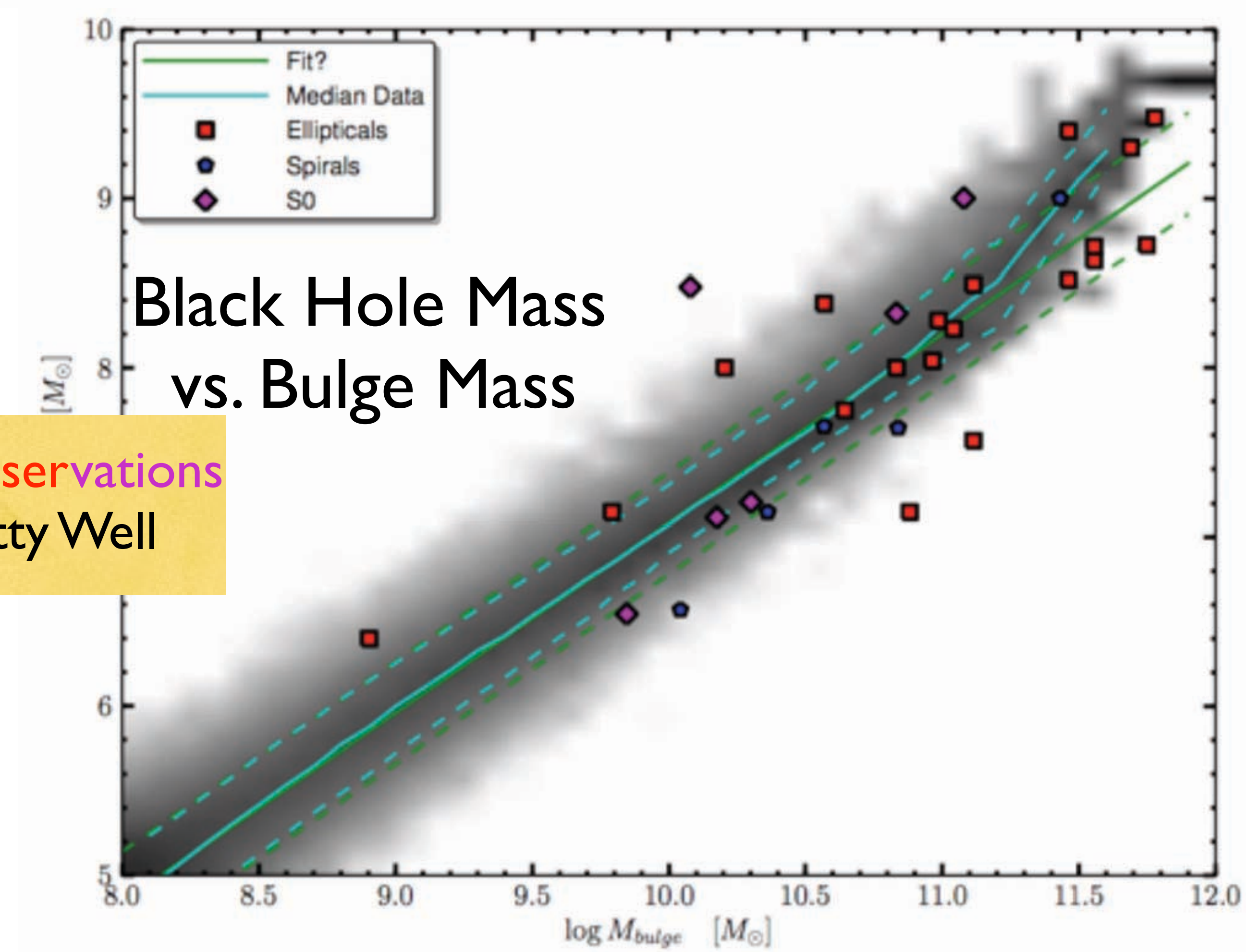


Theory & Observations
Agree Pretty Well



Bolshoi simulations - recent progress

- Anatoly Klypin has improved his BDM halofinder. It now finds the spin parameter, concentration, 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** and 50 timesteps of the **BigBolshoi/MultiDark** simulation will be available using both BDM and Peter Behroozi new phase-space halo finder ROCKSTAR.
- 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 2×10^6 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.
- Halo catalogs and particle data for z=0 etc. will be available in Sept 2011 at http://www.multidark.org/MultiDark/ (You have to get an account there.) We hope also to have complete merger trees available soon at Stanford.

Santa Cruz Galaxy Workshop 2011

University of California, Santa Cruz

August 8 - 12, 2011

THE BOLSHOI COSMOLOGICAL SIMULATIONS AND THEIR IMPLICATIONS

JOEL PRIMACK, UCSC

ΛCDM Cosmological Parameters for **Bolshoi** and **BigBolshoi**

Halo Mass Function is 10x Below Sheth-Tormen at z=10

Cluster Concentrations Agree with ΛCDM Predictions

Improved Halo Finding and Merger Trees

Predicted LMC/SMC Likelihood Agrees with Observations

HAM Galaxy Correlations Agree with Observations

HAM Galaxy Luminosity-Velocity Relations OK

Galaxy Velocity Function OK for $V_{circ} > 80$ km/s

First **Bolshoi** and **BigBolshoi** data release in September 2011