UC-HIPACC
& Astrophysics with the Bolshoi Simulation

JOEL PRIMACK
UCSC

Monday, June 28, 2010
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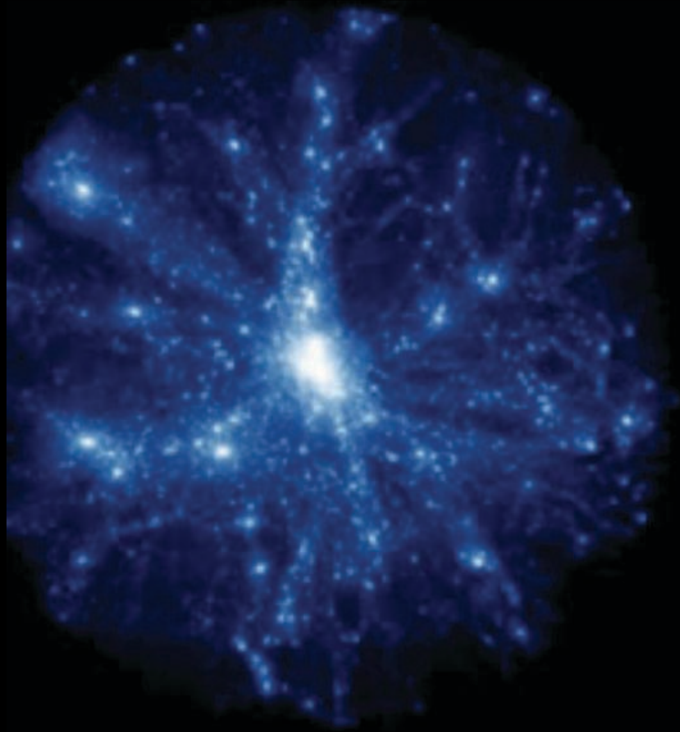

UC-HIPACC

The University of California
High-Performance AstroComputing Center

A consortium of nine UC campuses and three DOE laboratories

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- HIPACC community

Website maintained by
Nina McCurdy
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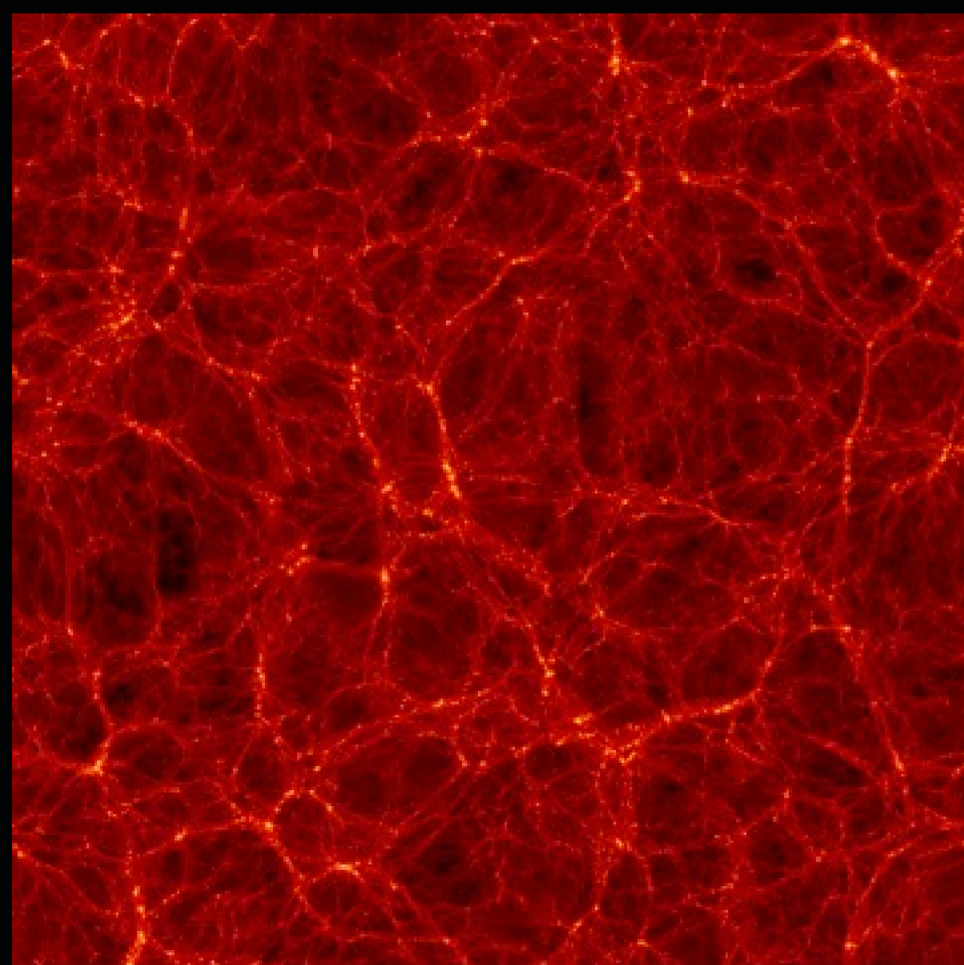

Z=0 snapshot from 8G particle"Bolshoi Simulation"
made with the Adaptive Refinement Tree (ART) code.
Refinement (AMR), grid-based hybrid code
Collaborators: A.Kravtsov (U.Chicago), A.Klypin (NMSU), J. Primack (UCSC), and S.Gottl√ber (AIP,Germany)

News/Announcements

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

The application period for the 2010 International AstroComputing summer school is now closed. For more information about the school, click here.

place the cursor over the image to pause the slideshow

http://hipacc.ucsc.edu/

UC-HIPACC

Summer School

- Home
- About the Center
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  - 2010 Summer School
  - -Program & Information
  - -Projects & Computing
  - -Posters & Flyers
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The application period for this year's summer school is now closed.

2010 Program

The 2010 school will run July 26 - August 13, and hosting it at UCSC will allow synergy with ISIMA, first International Summer Institute for Modeling in Astrophysics July 5 - Aug 13 on Transport Processes in Astrophysics (see the ISIMA website for more information).

Our 2010 summer school will include lectures on all the main codes currently used in high resolution simulations of galaxy formation and evolution: the adaptive mesh refinement codes ART, Enzo, and Ramses; the smooth particle hydro codes GADGET, Arepo and Gasoline/PKDGRAV; and also the Sunrise code for creating images of simulated galaxies in all wavebands including scattering, absorption, and reemission by dust.

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UC-HIPACC

Monday, July 26, 2010
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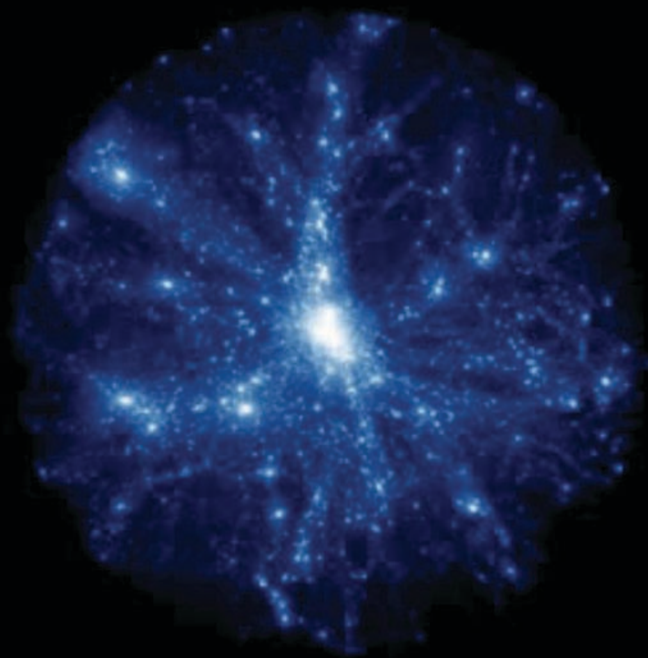

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UC-HIPACC Contact Information: Phone: (831)459-1531

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!

UC-HIPACC Community: Accepting applications for small grants for travel and collaboration.
Application Deadline: July 30, 2010 5 pm PDT. Click here for more information.

place the cursor over the image to pause the slideshow

Next summer's AstroComputing school will probably be on supernovae and high energy astrophysics at LBNL, led by Peter Nugent. Peter is Group Lead, Computational Cosmology Center, and Team Lead, NERSC Analytics. NERSC is the National Energy Research Scientific Computing Center at LBNL.

http://hipacc.ucsc.edu/

Astrophysics with the Bolshoi Simulation

Huge amounts of new galaxy data
from surveys like AEGIS and CANDELS
challenge theorists to understand
galaxy formation and evolution.

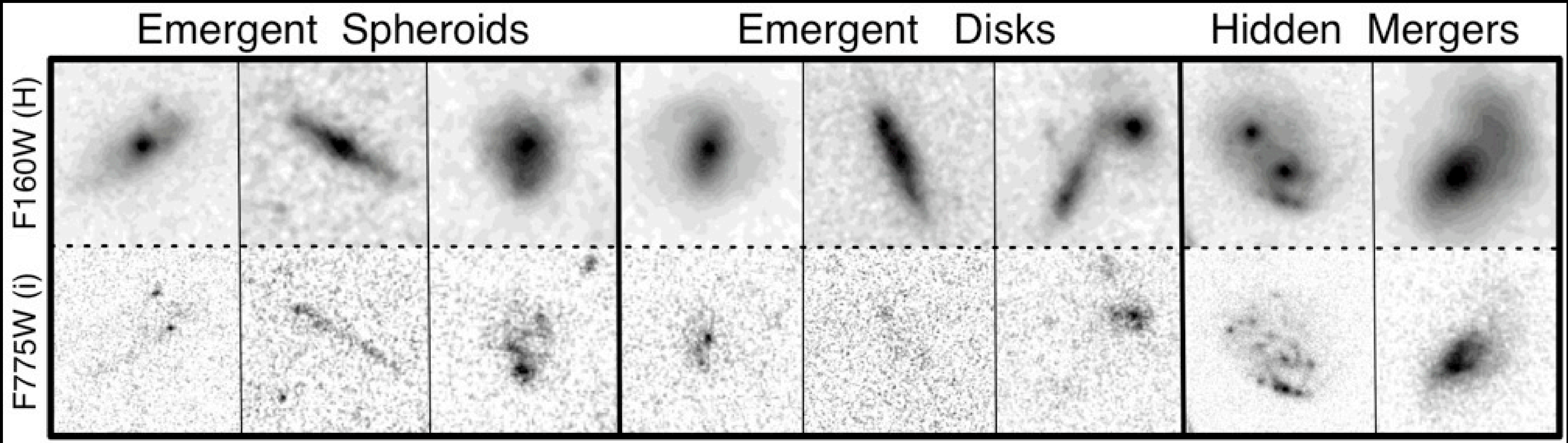
http://aegis.ucolick.org/

Monday, August 16, 2010

CANDELS

Field Centers	RA	Dec	PA on sky
Wide field COSMOS	10 00 31	+02 24 00	180
Wide field EGS	14 18 36	+52 39 00	41
Wide field UDS	02 17 49	-05 12 02	270
Deep GOODS-S	03 32 30	-27 47 19	160
Deep GOODS-N	12 36 55	+62 14 18	45

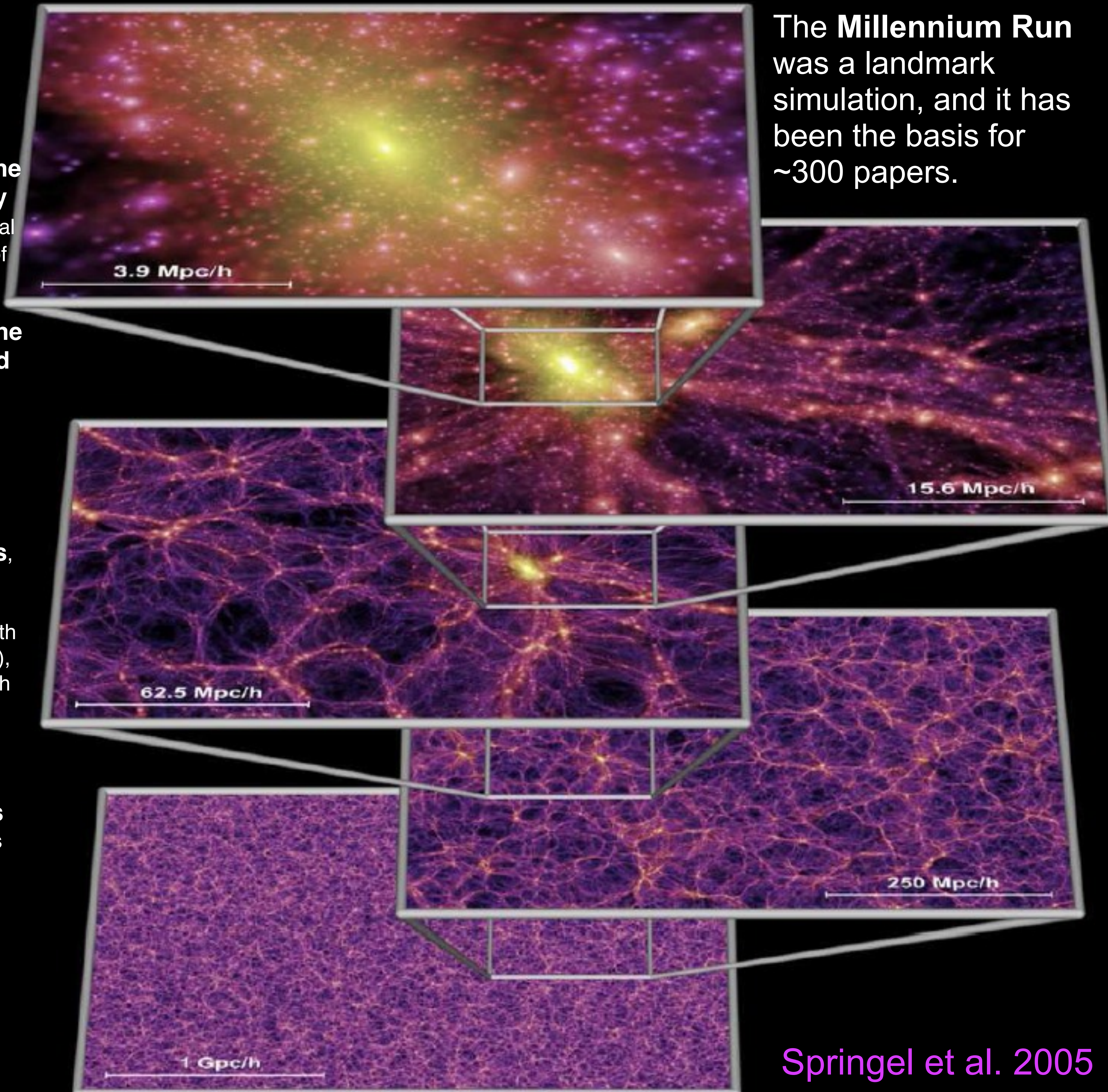
Leaders - PI: Sandra Faber (UCSC)
Assoc. PI: Harry Ferguson (STScI)



The Cosmic Assembly Near-IR Deep Extragalactic Legacy Survey (CANDELS, http://csmct.ucolick.org/) is a Hubble Space Telescope Multi-Cycle Treasury project awarded 902 orbits with WFC3 and ACS during 2010-2013. CANDELS will obtain data on 250,000 galaxies to complete Hubble's legacy in the area of deep lookback observations of galaxy evolution. A time-domain search will discover Type Ia supernovae at z>1.5 to determine their progenitors and possible evolution. The Deep survey covers ~0.04 deg^2 in the GOODS fields to a 5-sigma AB depth of H=28, including UV data in GOODS-N. The Wide survey covers ~0.2 deg^2 to H=27 in the same fields plus COSMOS, EGS, and UDS and is tuned to study rarer objects such as massive galaxies and AGN.

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 ~300 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.

The Millennium Simulation-II

Resolving Cosmic Structure Formation with the Millennium-II Simulation

2009 MNRAS 398, 1150

Michael Boylan-Kolchin[1⋆], Volker Springel[1], Simon D. M. White[1], Adrian Jenkins[2], and Gerard Lemson[3,4]

We present the Millennium-II Simulation (MS-II), a very large N-body simulation of dark matter evolution in the concordance ΛCDM cosmology. The MS-II assumes the same cosmological parameters and uses the same particle number and output data structure as the original Millennium Simulation (MS), but was carried out in a periodic cube one-fifth the size ($100\,h^{-1}$ Mpc) with 5 times better spatial resolution (a Plummer equivalent softening of $1.0\,h^{-1}$ kpc) and with 125 times better mass resolution (a particle mass of $6.9 \times 10^6\,h^{-1}\,M_\odot$). By comparing results at MS and MS-II resolution, we demonstrate excellent convergence in dark matter statistics such as the halo mass

The Millennium Simulations I & II are the basis for a semi-analytic model with unprecedented mass and force resolution

From dwarf spheroidals to cDs: Simulating the galaxy population in a ΛCDM cosmology

Qi Guo[1,2 ⋆], Simon White[1], Michael Boylan-Kolchin[1], Gabriella De Lucia[3], Guinevere Kauffmann[1], Gerard Lemson[1], Cheng Li[1], Volker Springel[1,4], Simone Weinmann[1]

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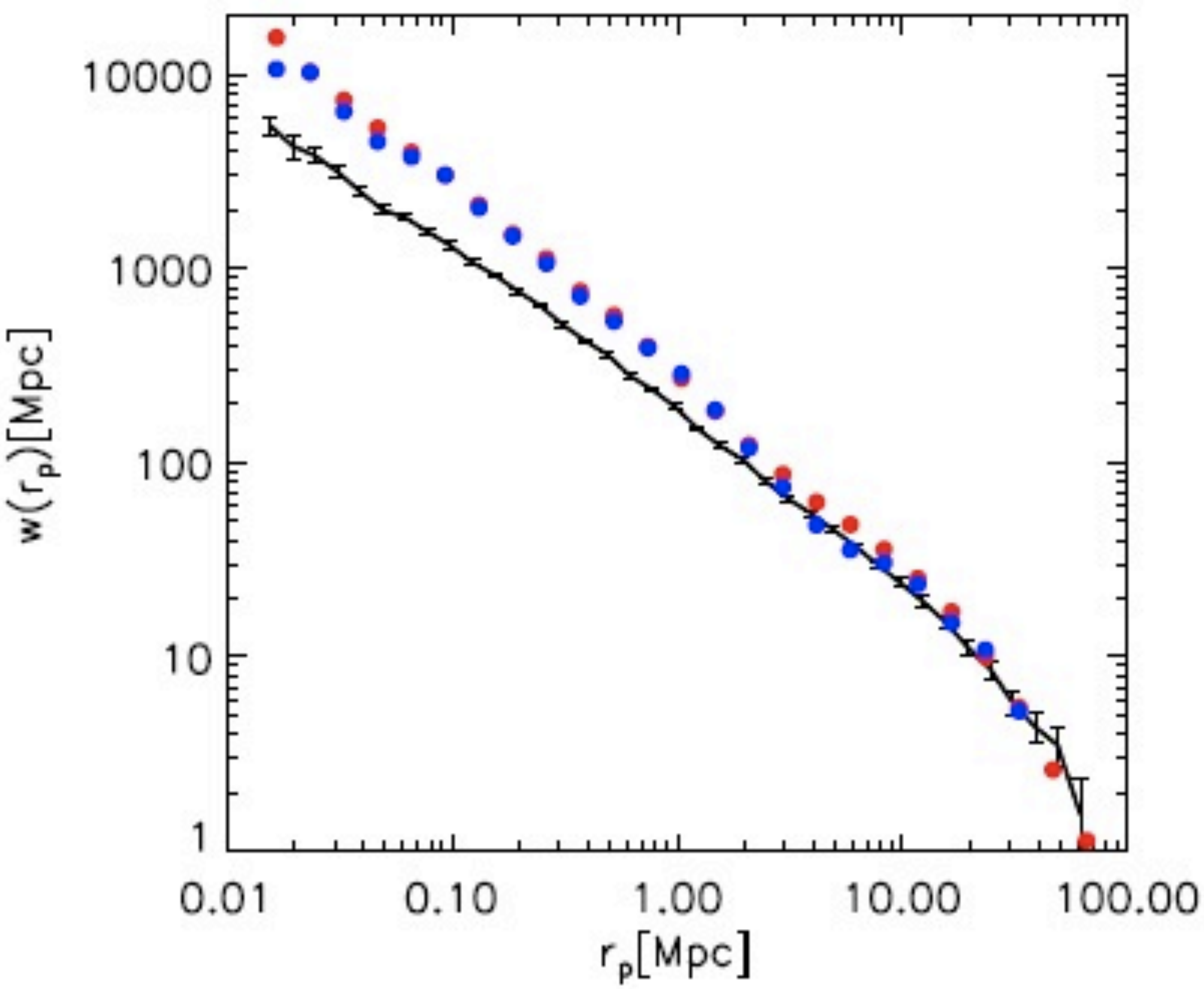


Figure 19. The projected autocorrelation function of stellar mass. Blue and red circles show results from our preferred model applied to the MS-II and to the MS respectively. Numerical convergence is excellent, even on scales below 100 kpc. An estimate from the final release of the SDSS is shown by a black solid line joining points with error bars which include both counting noise and cosmic variance (Li & White 2009). On large scales our model overestimates the observed amplitude of clustering by 10 to 20%. On small scales the discrepancy rises to a factor of two.

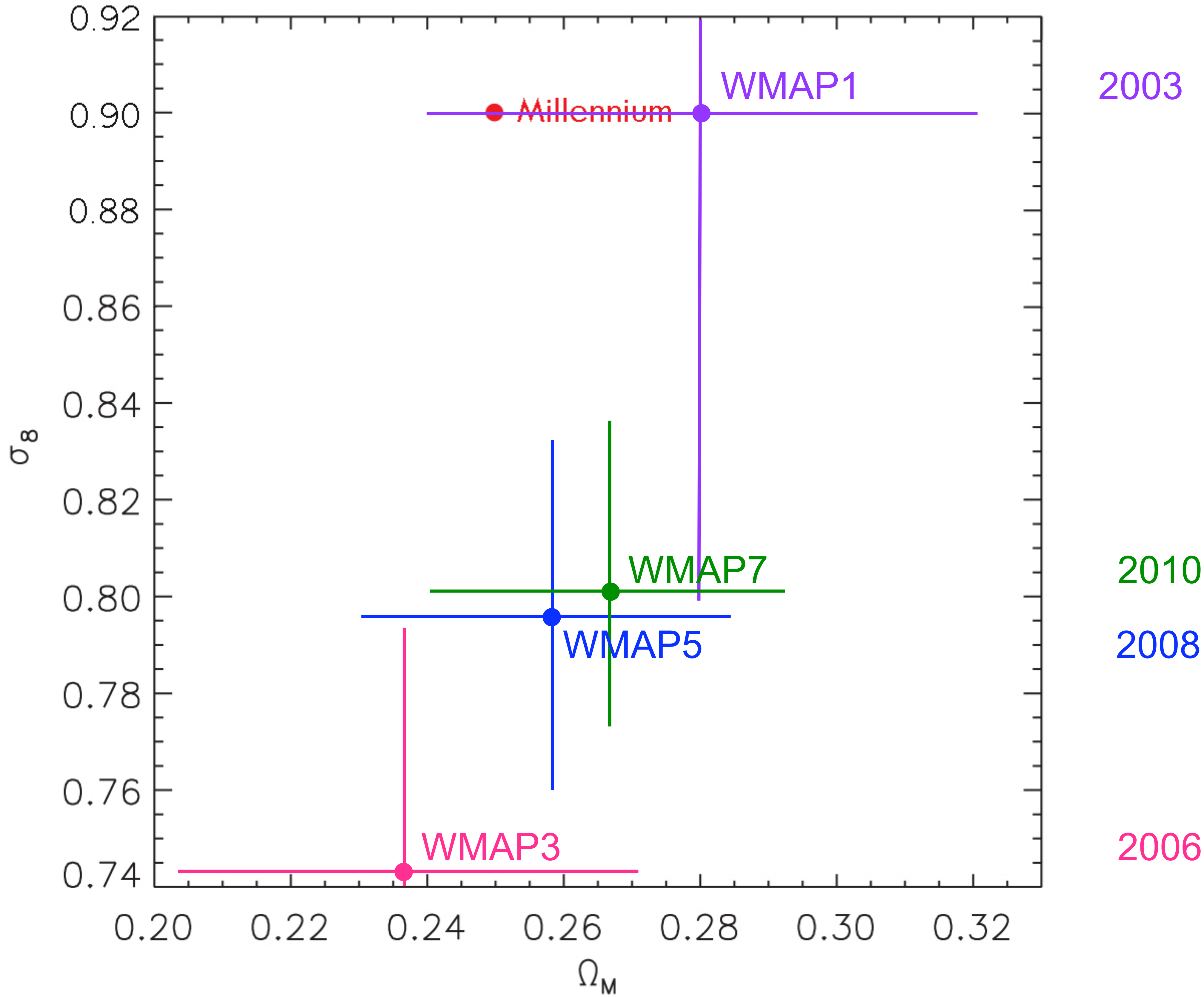
Discussion of Fig. 19

For $r_p > 2$ Mpc, where the correlations are produced by galaxies inhabiting different halos (thus typically both type 0 galaxies), the model auto-correlation function is 10 to 20% higher than that observed. On smaller scales where the correlations are dominated by galaxy pairs inhabiting the same halo (thus typically type 0 – type 1, or type 0 – type 2 pairs) the discrepancy grows, reaching a factor of 2 at $r_p < 100$ kpc. This suggests an over-dominance of 1-halo relative to 2-halo pairs in comparison to the observations, arguing, perhaps, for a lower value of σ_8 than used in the MS cosmology (see Li & White 2009).

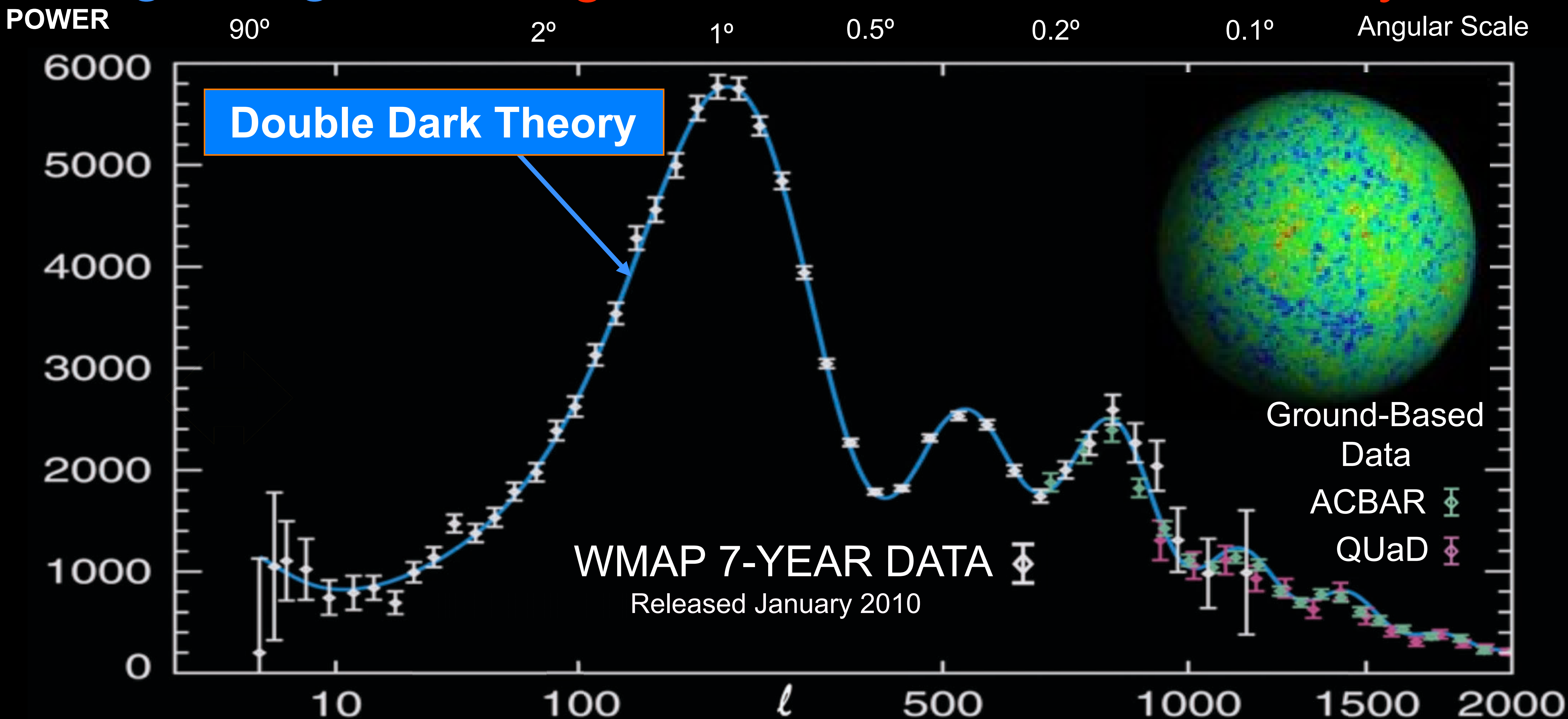
From the Conclusions

Given that our model matches both the stellar mass function and the mass-dependent large-scale clustering data from SDSS, this excessive small-scale clustering implies that too large a fraction of our galaxies are satellites at each stellar mass. Since individual groups and clusters in our model have galaxy occupation numbers and radial distributions in quite good agreement with observation, the discrepant small-scale correlations suggest that massive halos are overabundant in our simulations, i.e. that $\sigma_8 = 0.9$ is too large (c.f. van den Bosch et al. 2007).

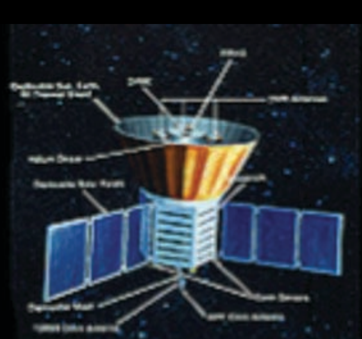
WMAP-only Determination of σ_8 and Ω_M

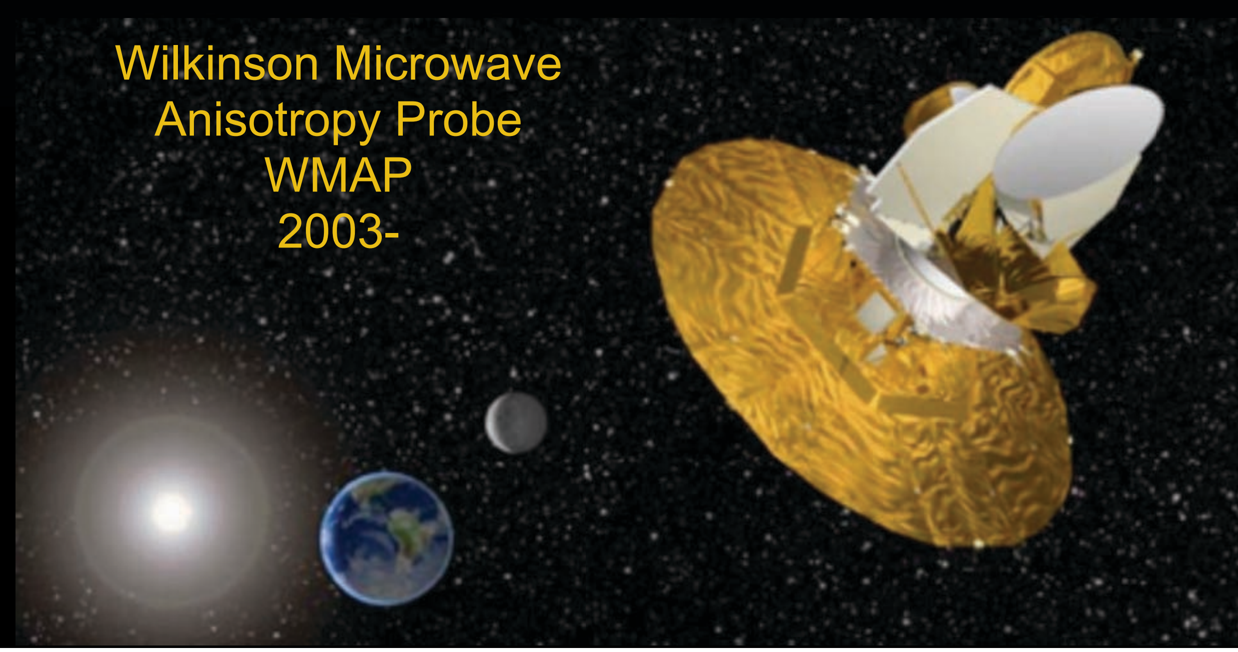


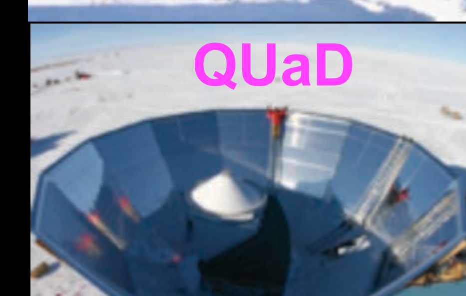
Big Bang Data Agrees with Double Dark Theory!



Cosmic Background Explorer COBE 1992







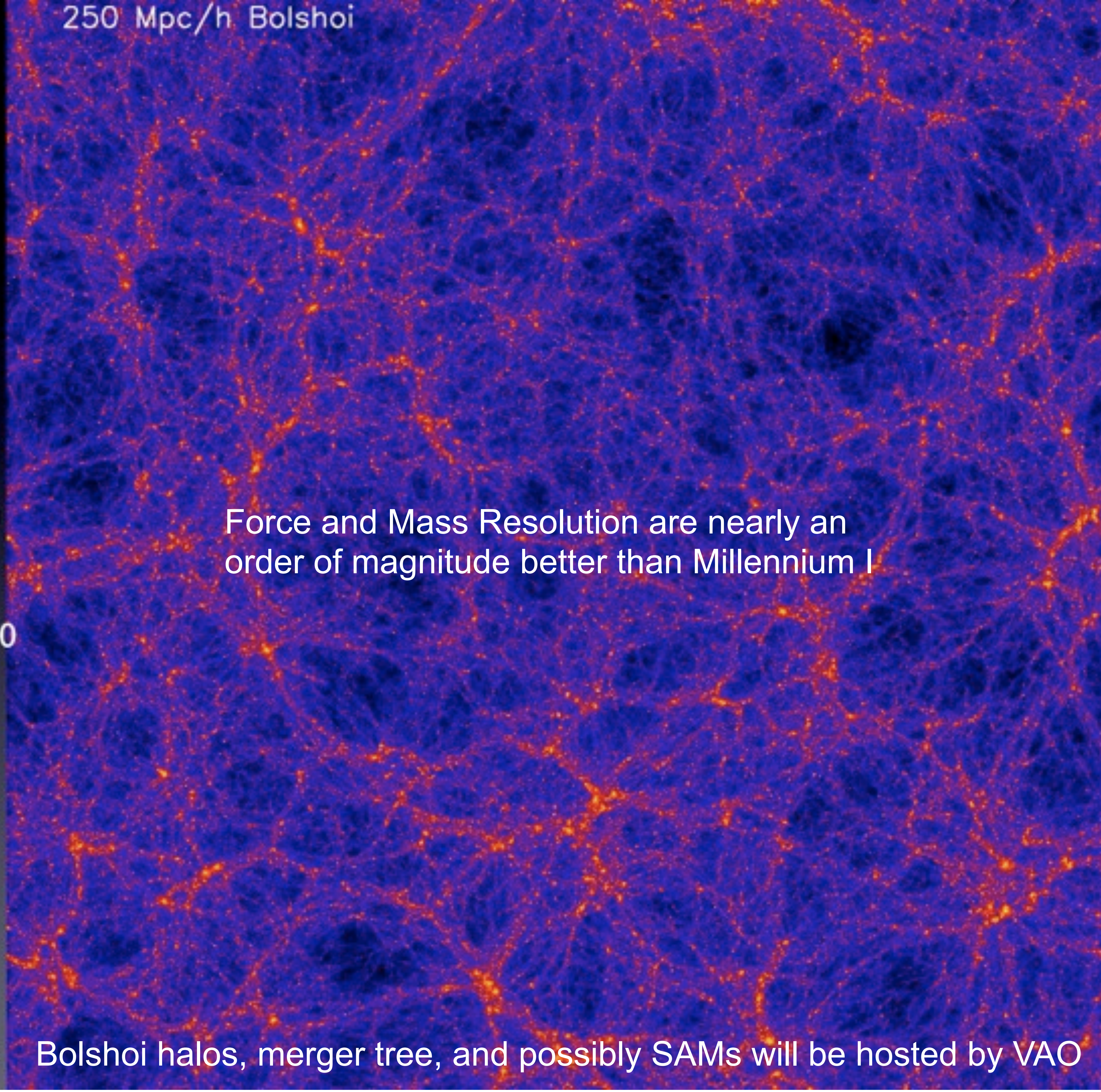
The Bolshoi simulation

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

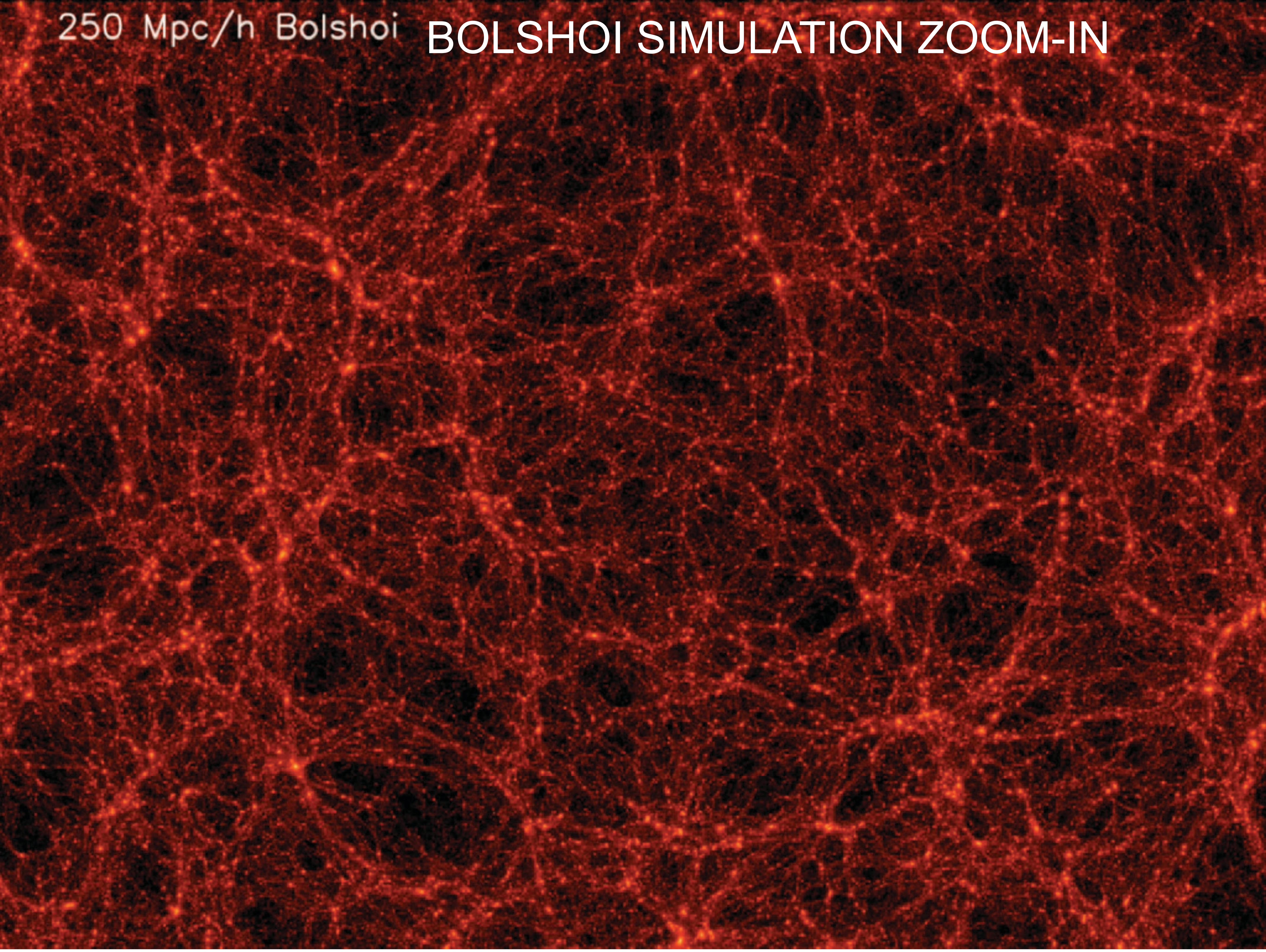
NASA AMES
supercomputing center
Pleiades computer
13824 cores
12TB RAM
75TB disk storage
6M cpu hrs
18 days wall-clock time



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

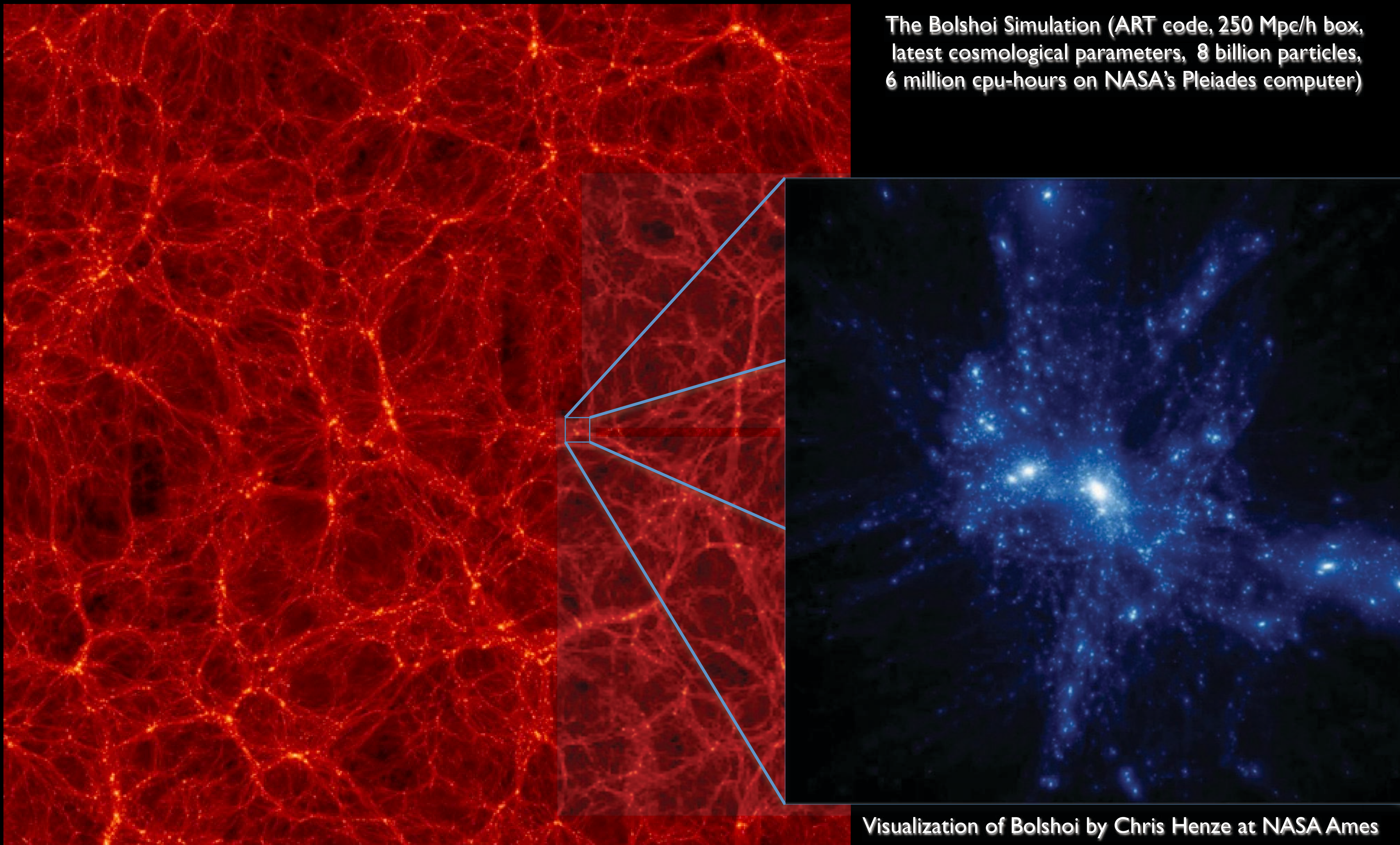
Bolshoi halos, merger tree, and possibly SAMs will be hosted by VAO

BOLSHOI SIMULATION ZOOM-IN



Cosmological Simulation of the Large Scale Structure of the Universe

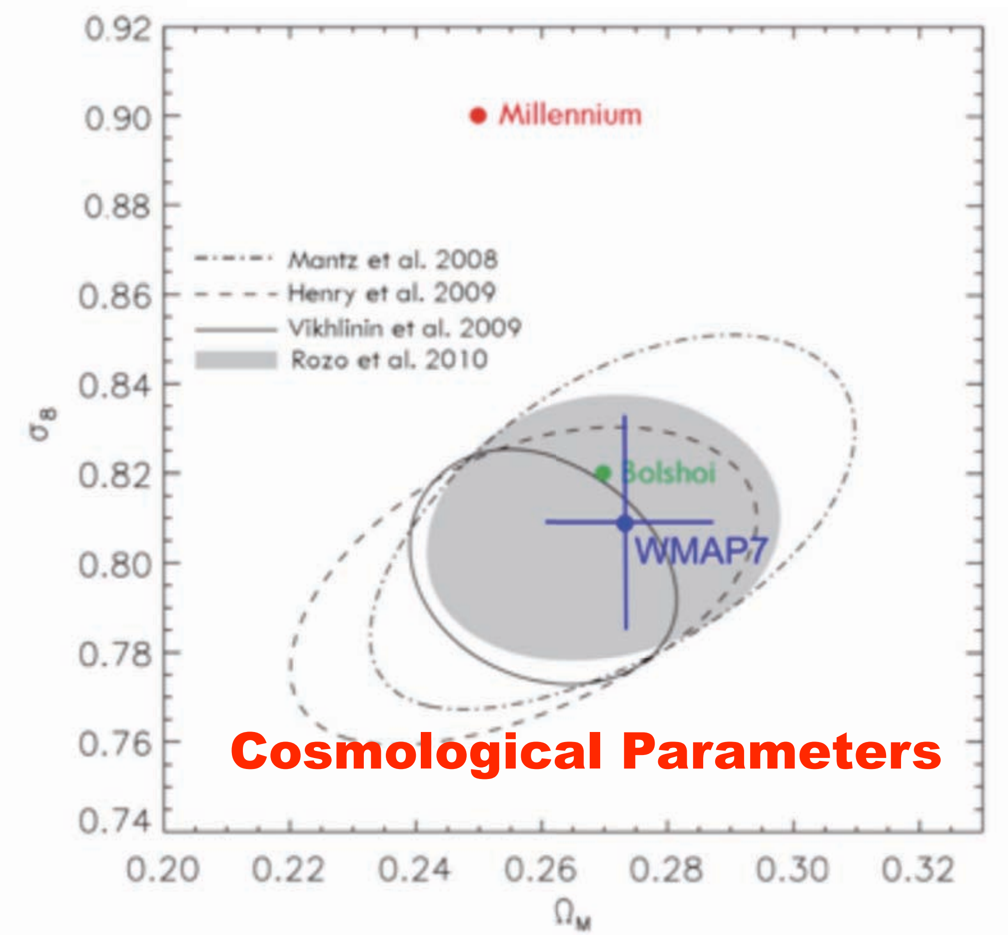
The Bolshoi Simulation (ART code, 250 Mpc/h box, latest cosmological parameters, 8 billion particles, 6 million cpu-hours on NASA's Pleiades computer)



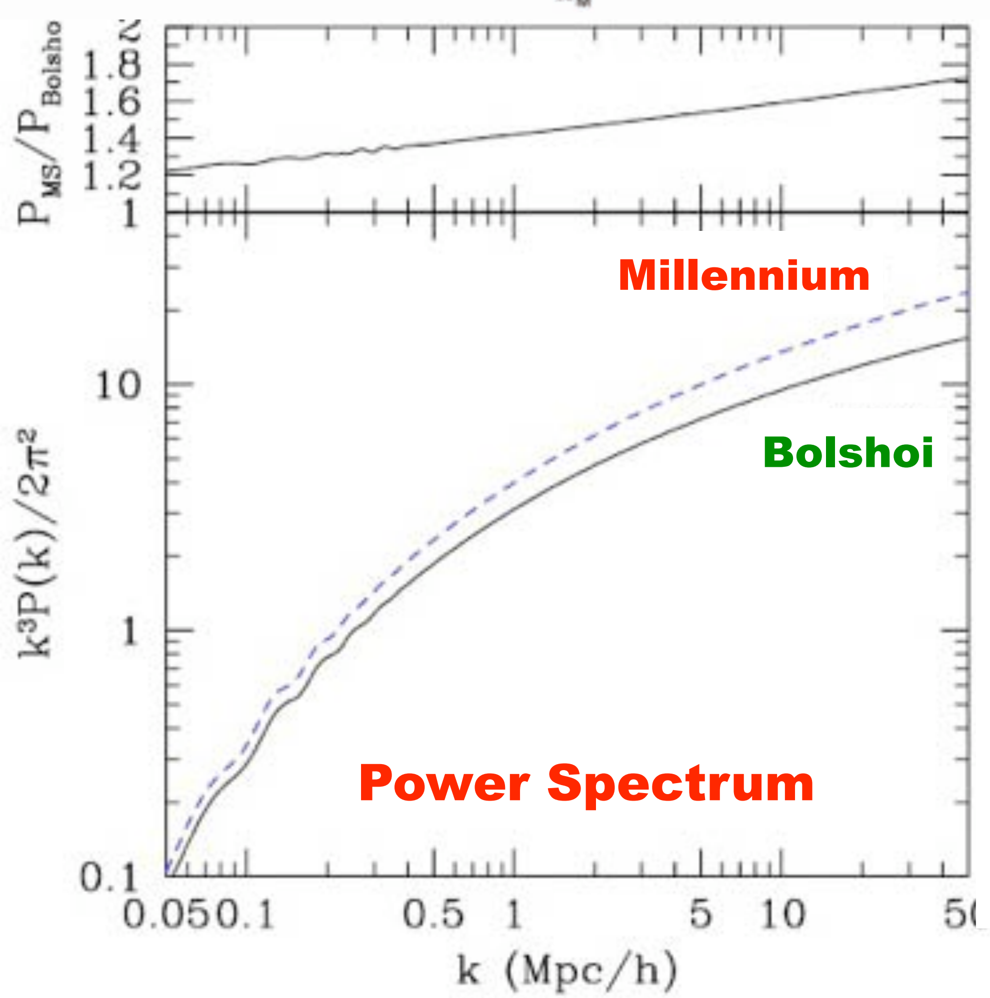
Visualization of Bolshoi by Chris Henze at NASA Ames

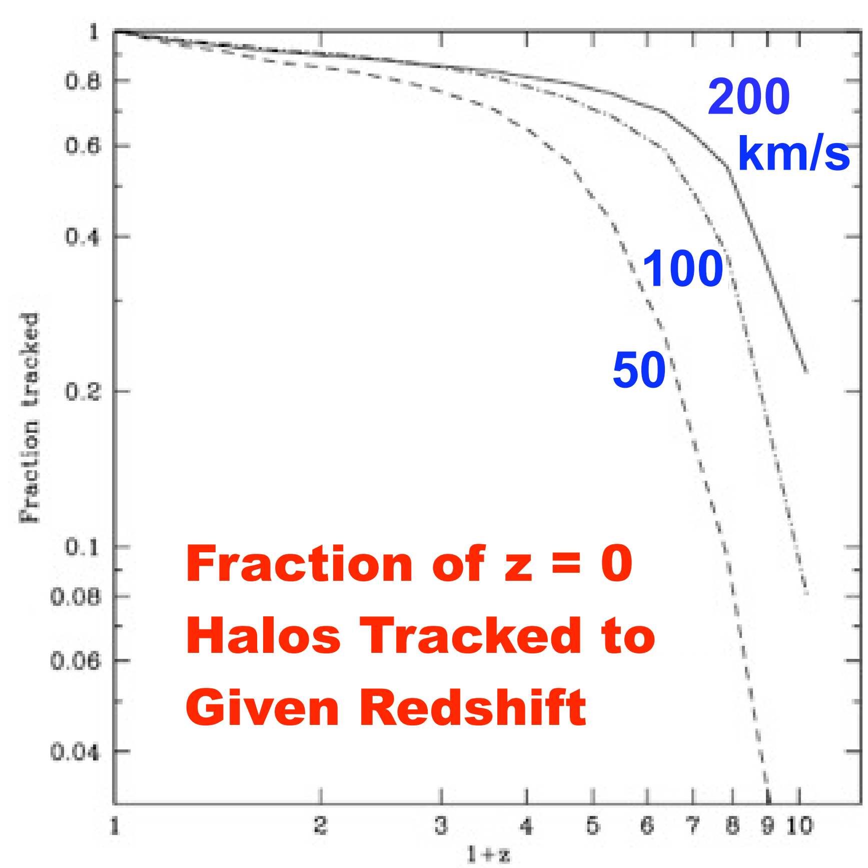
The visible material in the universe – stars, gas, dust, planets, etc. – accounts for only about 0.5% of the cosmic density. The remaining 99.5% of the universe is invisible. Most of it is non-atomic dark matter (~23%) and dark energy (~72%), with non-luminous atomic matter making up ~4%. In order to describe the evolution and structure of the universe, it is essential to show the distribution of dark matter and the relationship of dark matter to visible structures.

Halos and galaxies: results from the Bolshoi simulation

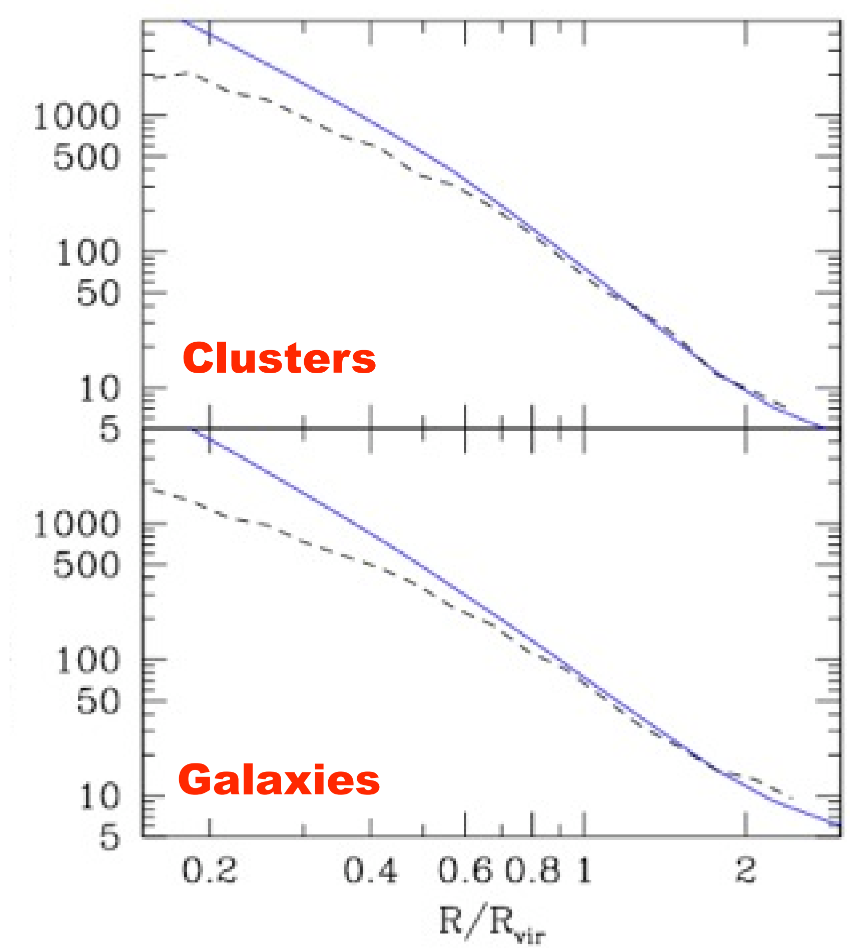


The Millennium Run (Springel+05) was a landmark simulation, and it has been the basis for ~300 papers. However, it and the new Millennium-II simulations were run using WMAP1 (2003) parameters, and the Millennium-I resolution was inadequate to see many subhalos. The new Bolshoi simulation (Klypin, Trujillo & 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. on based on Bolshoi.

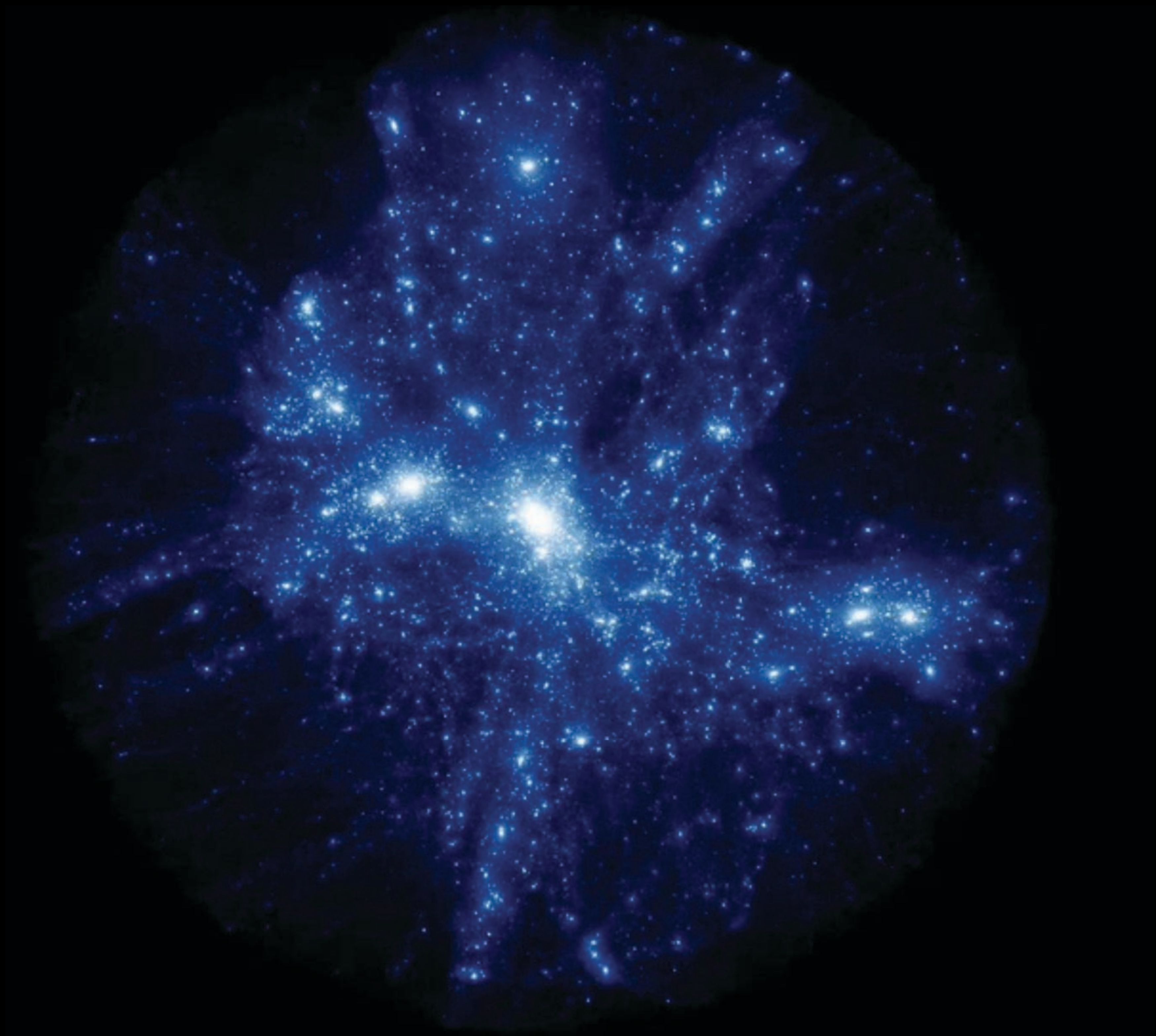




Subhalos follow the dark matter distribution

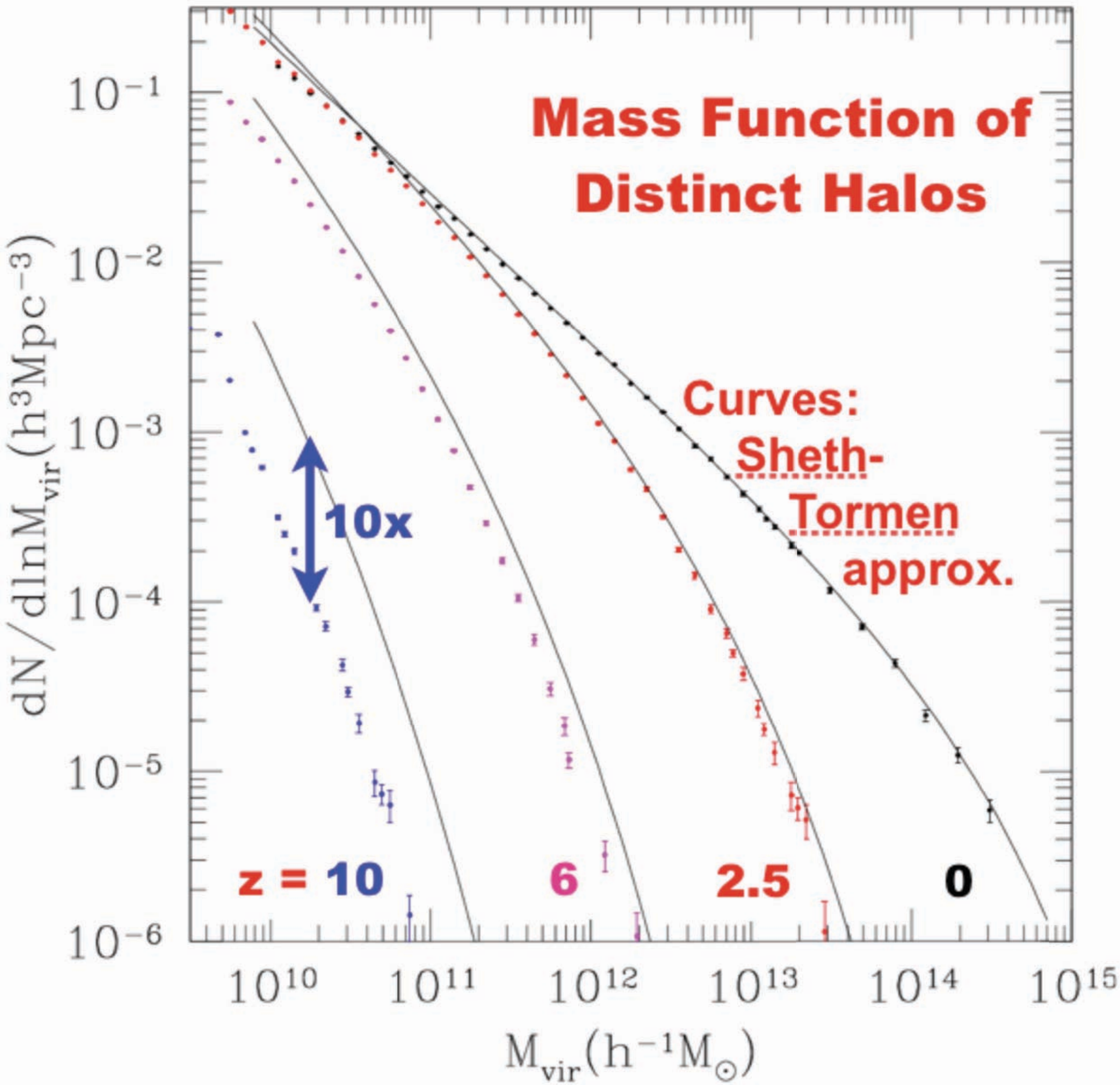


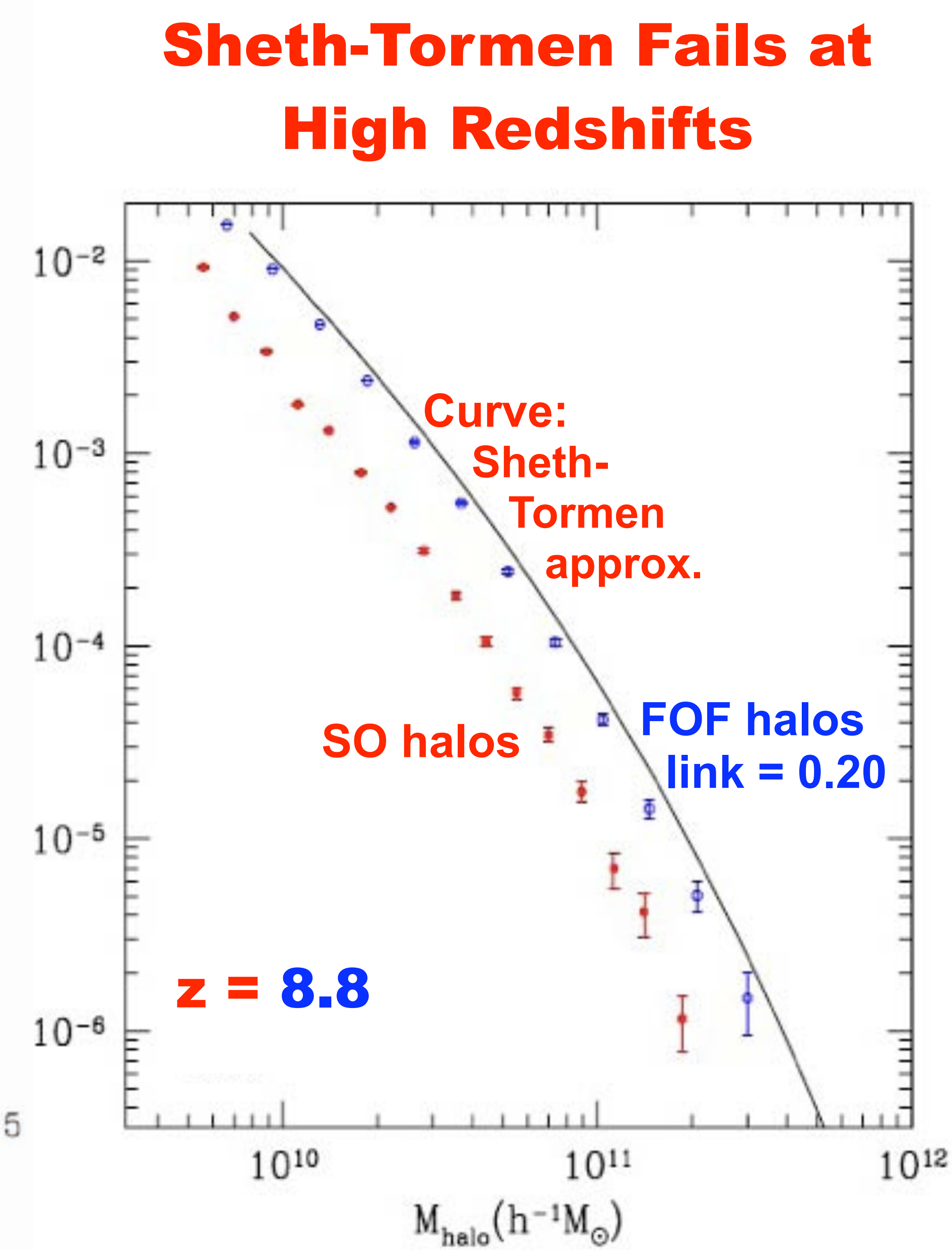
BOLSHOI SIMULATION FLY-THROUGH



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

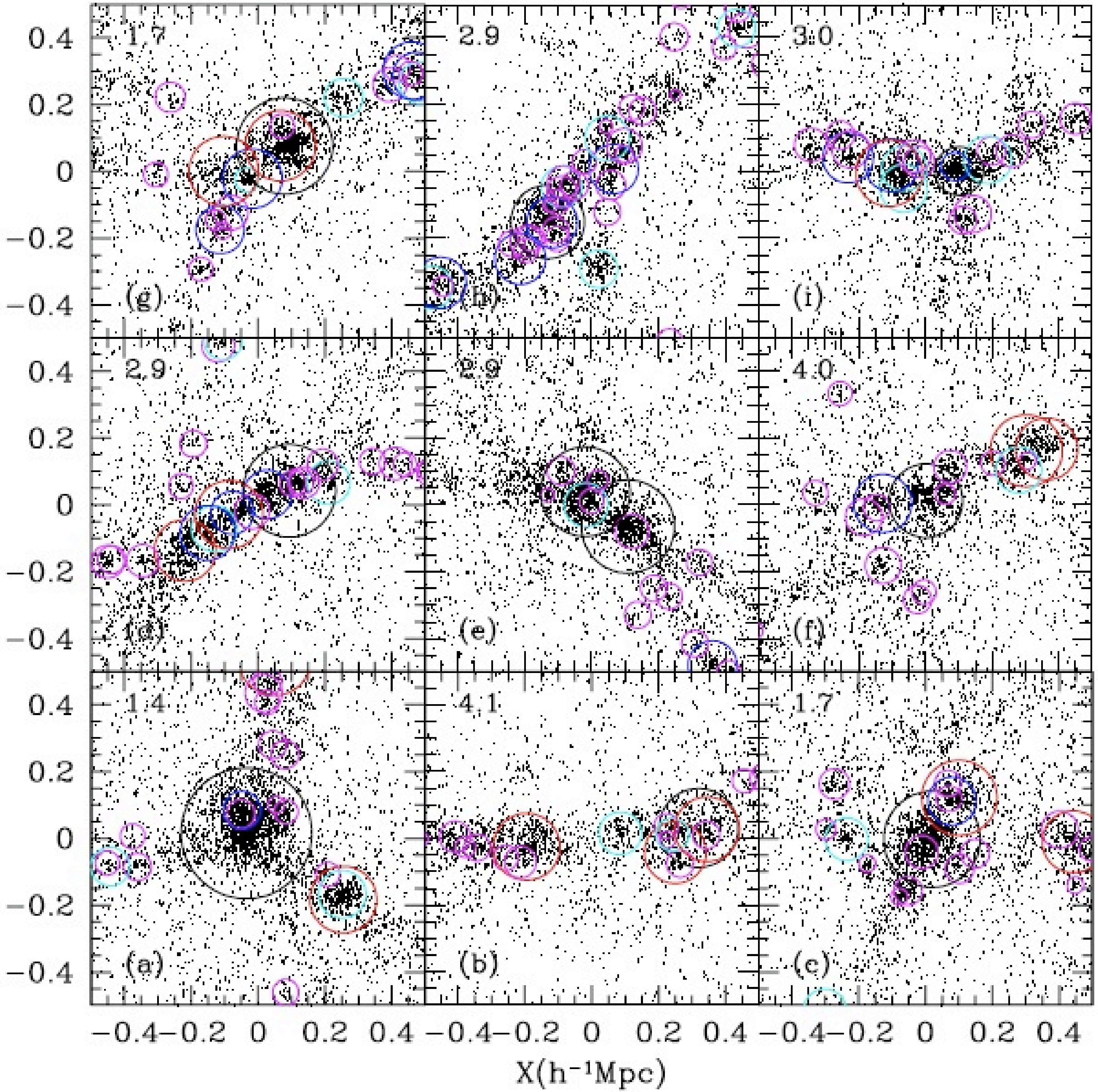

Time: 13293 Myr Ago
Timestep Redshift: 8.775
Radius Mode: Rvir
Focus Distance: 10.3
Aperture: 40.0
World Rotation: (209.9, 0.08, -0.94, -0.34)
Trackball Rotation: (0.0, 0.00, 0.00, 0.00)
Camera Position: (0.0, 0.0, -10.3)
BOLSHOI
Merger Tree
Peter Behroozi,
Risa Wechsler, &
Mike Busha

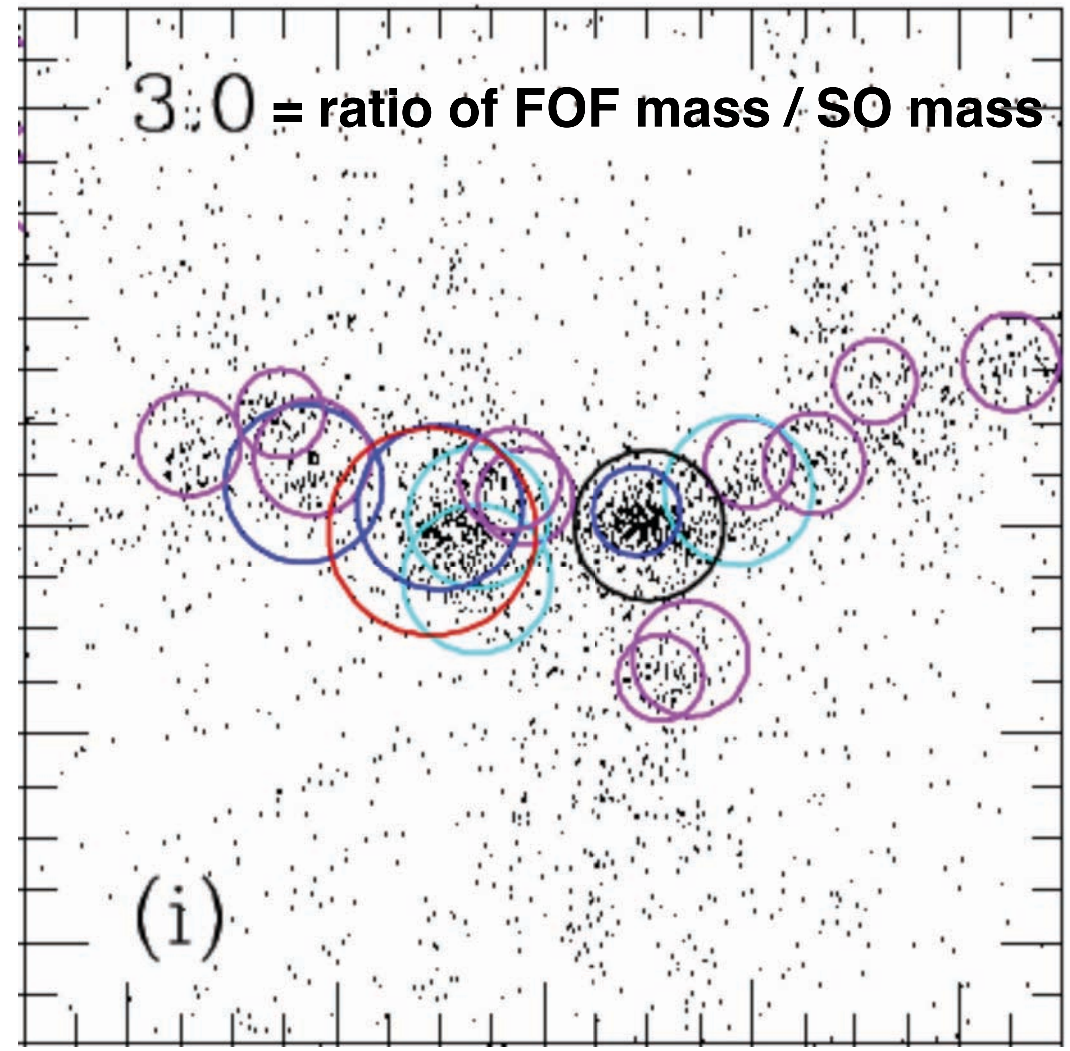




The Sheth-Tormen approximation with the same WMAP5 parameters used for the Bolshoi simulation very accurately agrees with abundance of halos at low redshifts, but increasingly overpredicts bound spherical overdensity halo abundance at higher redshifts. ST agrees well with FOF halo abundances, but FOF 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 1h^{-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

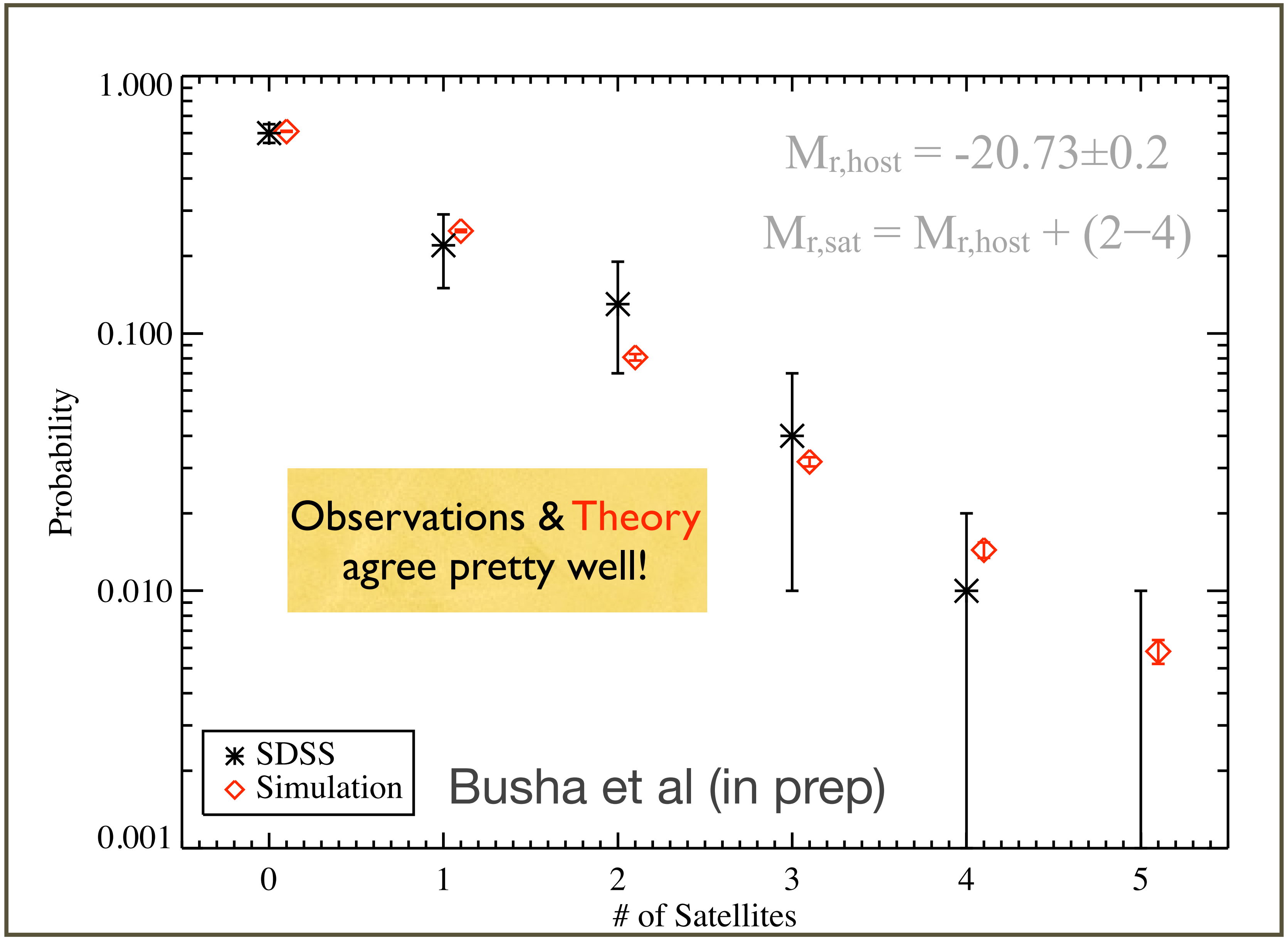
The Milky Way has two large satellite galaxies, the small and large Magellanic Clouds

The Bolshoi simulation predicts the likelihood of this

- 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±0.2 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

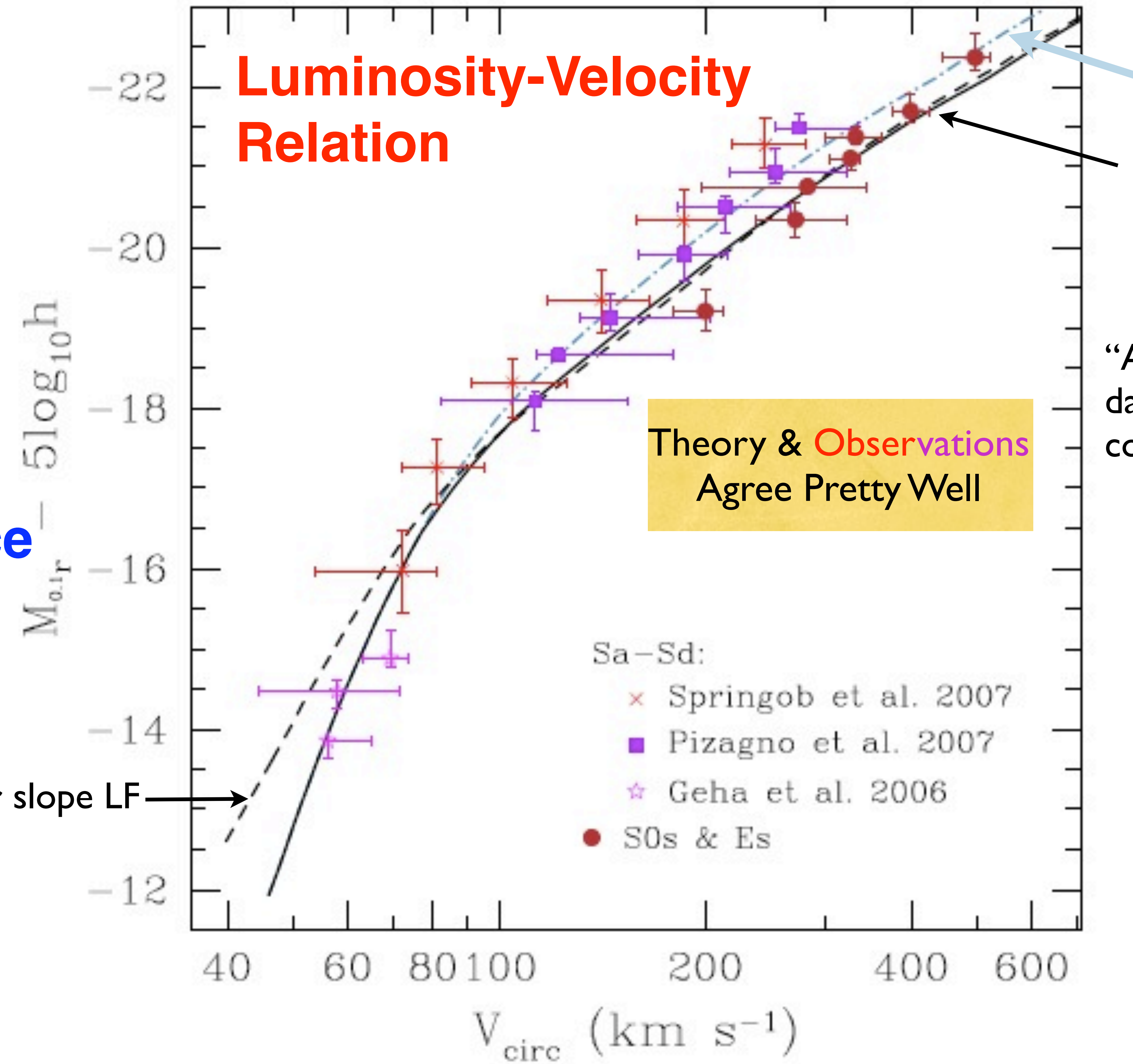


Every case agrees within observational errors!

Risa Wechsler

Luminosity-Velocity Relation

Bolshoi Sub-Halo Abundance Matching

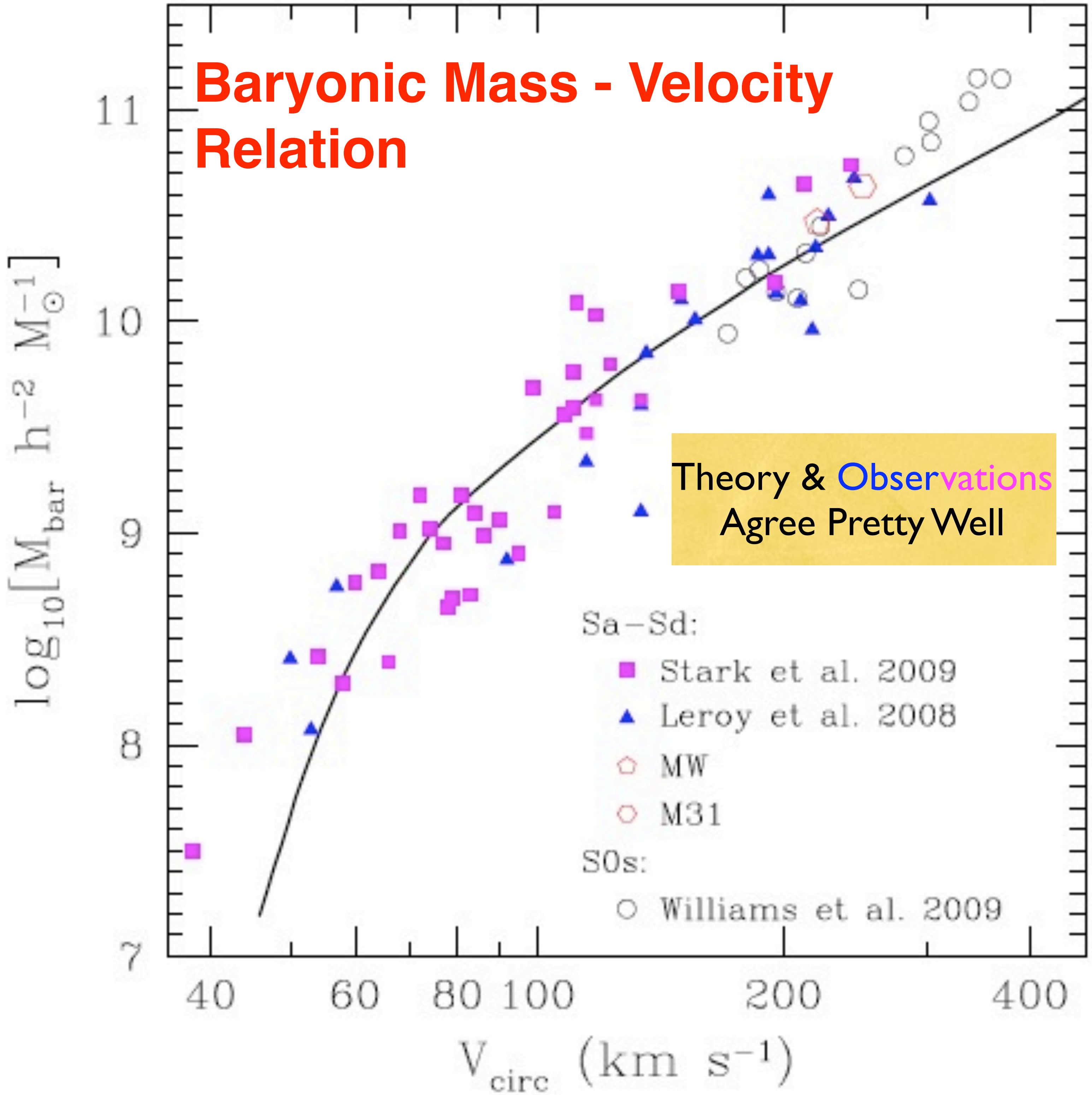


"AC" = Adiabatic Contraction of dark matter halos when baryons cool & condense to halo centers, following Blumenthal, Faber, Flores, & Primack 1986

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

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.

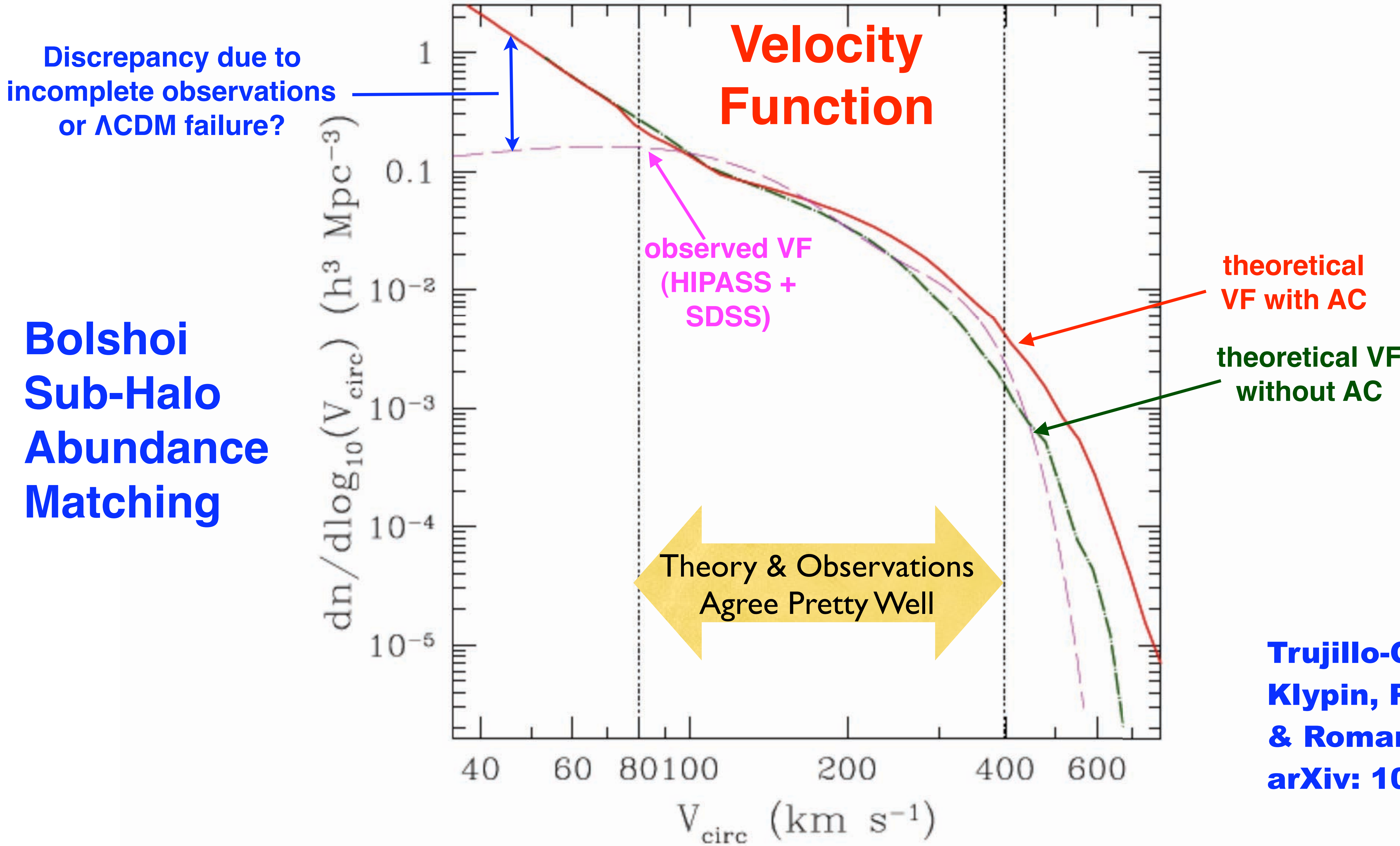
Bolshoi Sub-Halo Abundance Matching



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

Fig. 10.— Mass of baryons as a function of circular velocity. The solid curve shows median values for the ΛCDM model. The total 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.

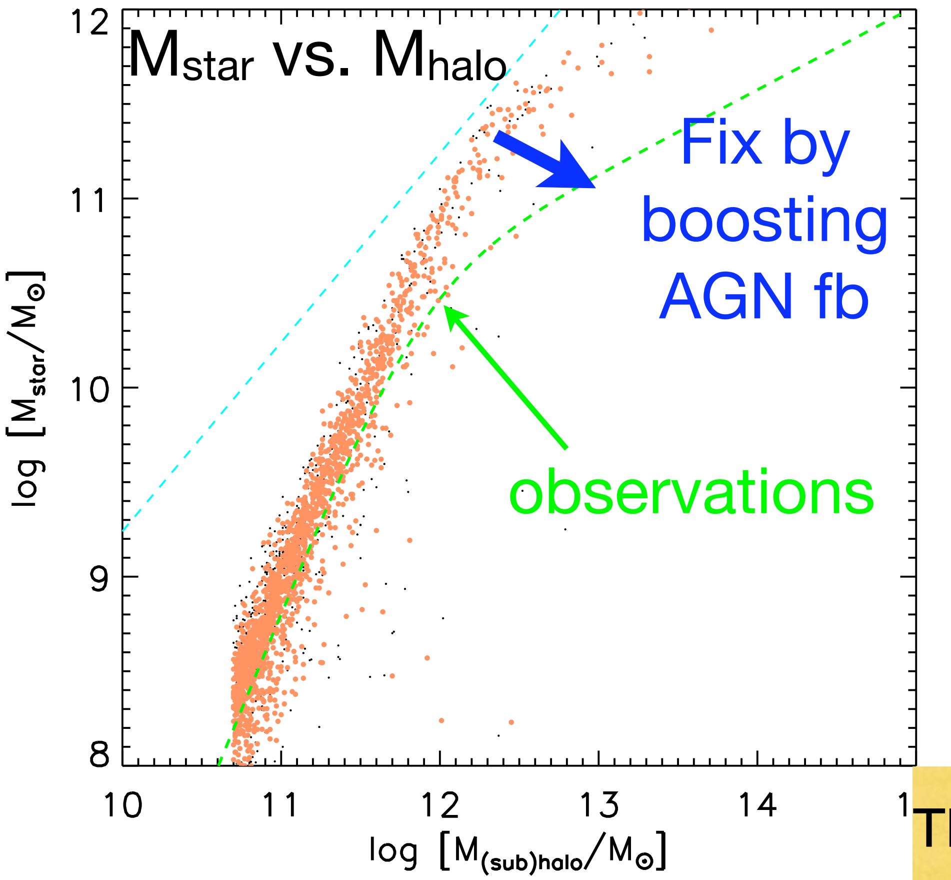
Bolshoi Sub-Halo Abundance Matching

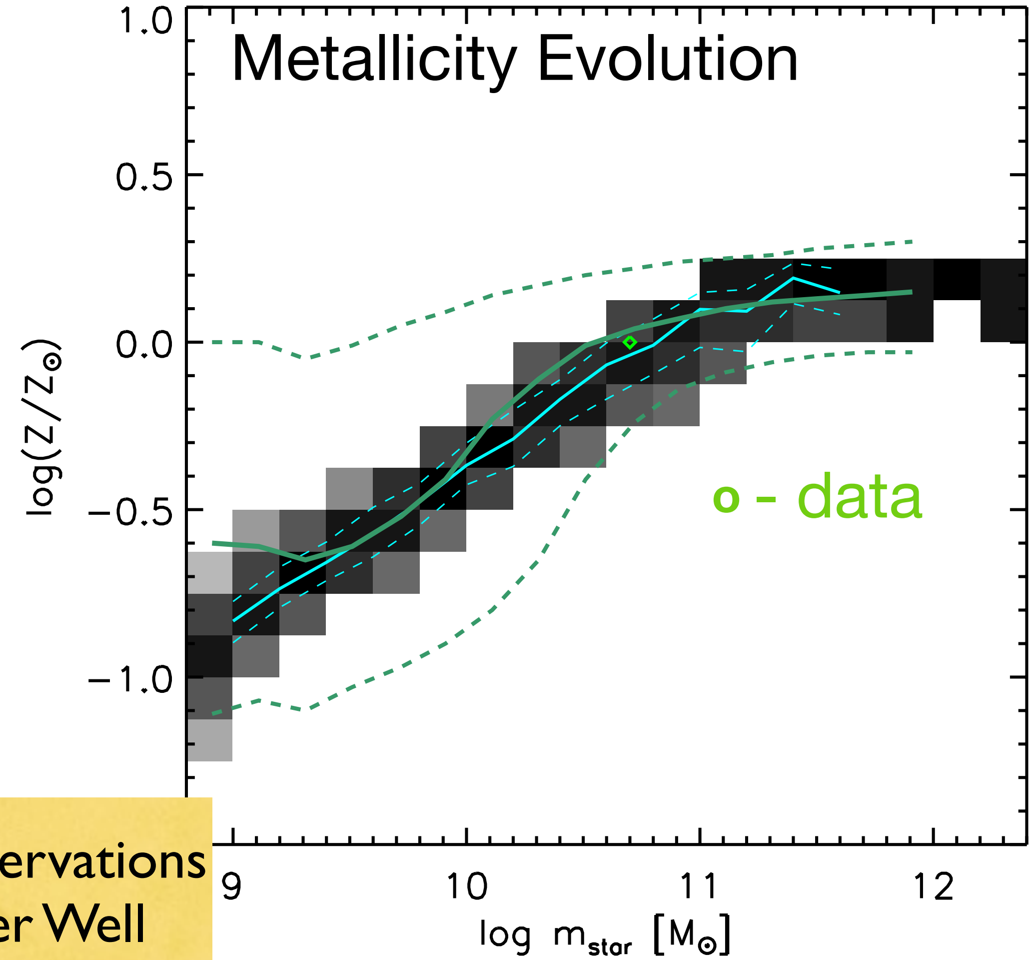


Trujillo-Gomez, Klypin, Primack, & Romanowsky arXiv: 100.1289

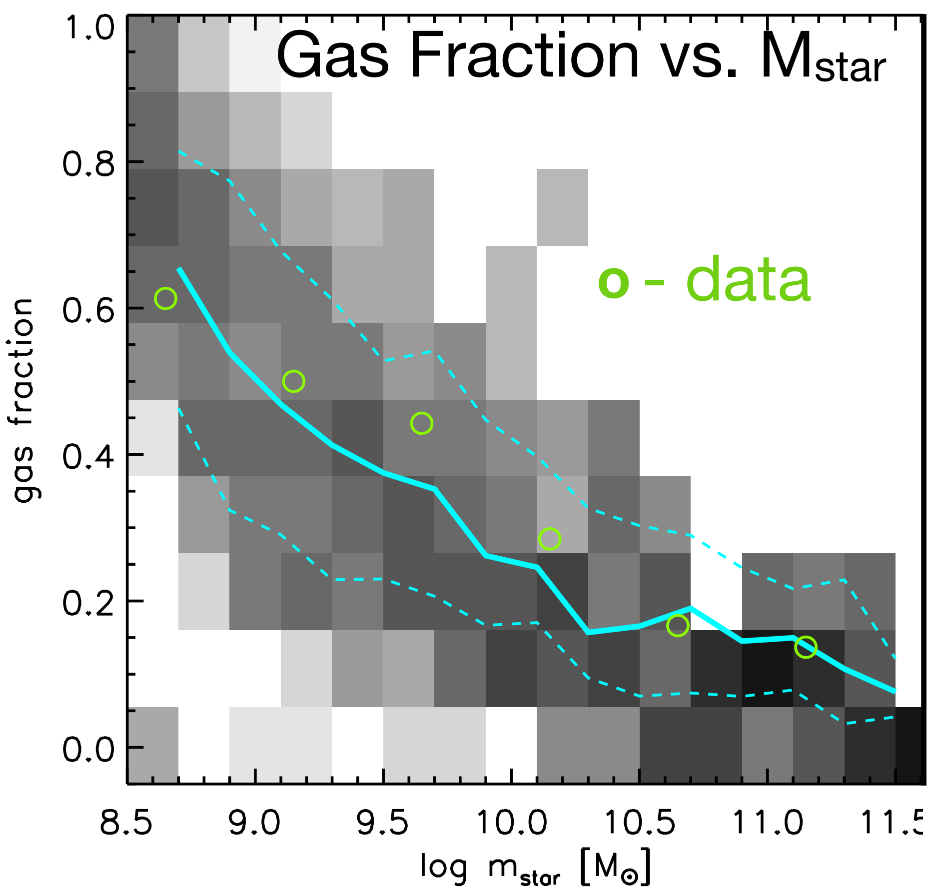
Fig. 11.— Comparison of theoretical (dot-dashed and thick solid curves) and observational (dashed curve) circular velocity functions. The dot-dashed line shows the effect of adding the baryons (stellar and cold gas components) to the central region of each DM halo and measuring the circular velocity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

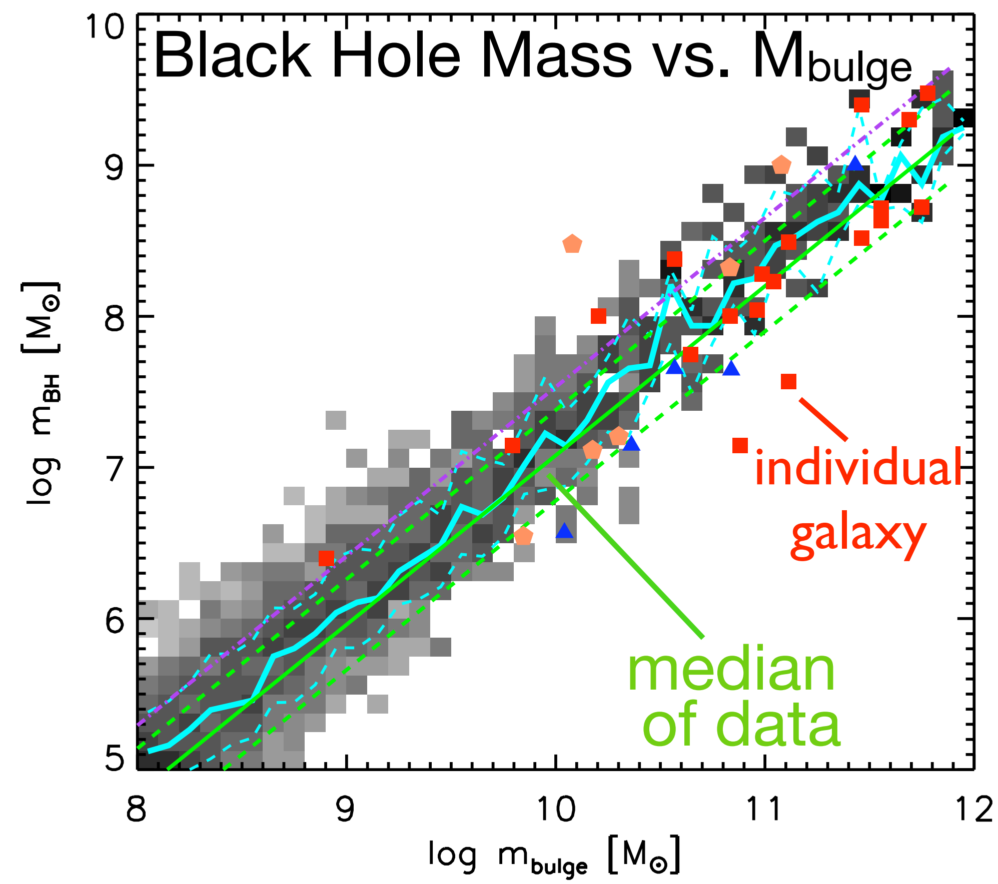
First SAM galaxy results with Bolshoi - Rachel Somerville





Theory & Observations Agree Rather Well





Theoretical Work in Progress (partial list)

Filling Bolshoi DM halos with galaxies

using more elaborate sub-halo abundance matching (SHAM)

Risa Wechsler, Brian Gerke, Darren Croton: mock catalogs

using improved semi-analytic models (SAMs) including $r_{half\text{-}light}$, σ

Darren Croton; Avishai Dekel: GalICS;

Rachel Somerville and Lauren Porter: synthetic spectra

Lauren Porter and Andrew Benson: GALFORM

Understanding dynamics better

better study of adiabatic contraction in early and late type galaxies

New Bolshoi-size DM simulations with higher-resolution subregions

focus on early-forming dark matter halos **(in progress on Pleiades)**

focus on regions hosting Milky-Way-type galaxies

Constrained simulation of local universe vs. observations

galaxy properties vs. locations in cosmic web by Zel'dovich analysis

High-resolution hydrodynamic galaxy formation simulations

Ceverino, Dekel, Klypin, Trujillo: ~35 pc, with stellar & SMBH feedback

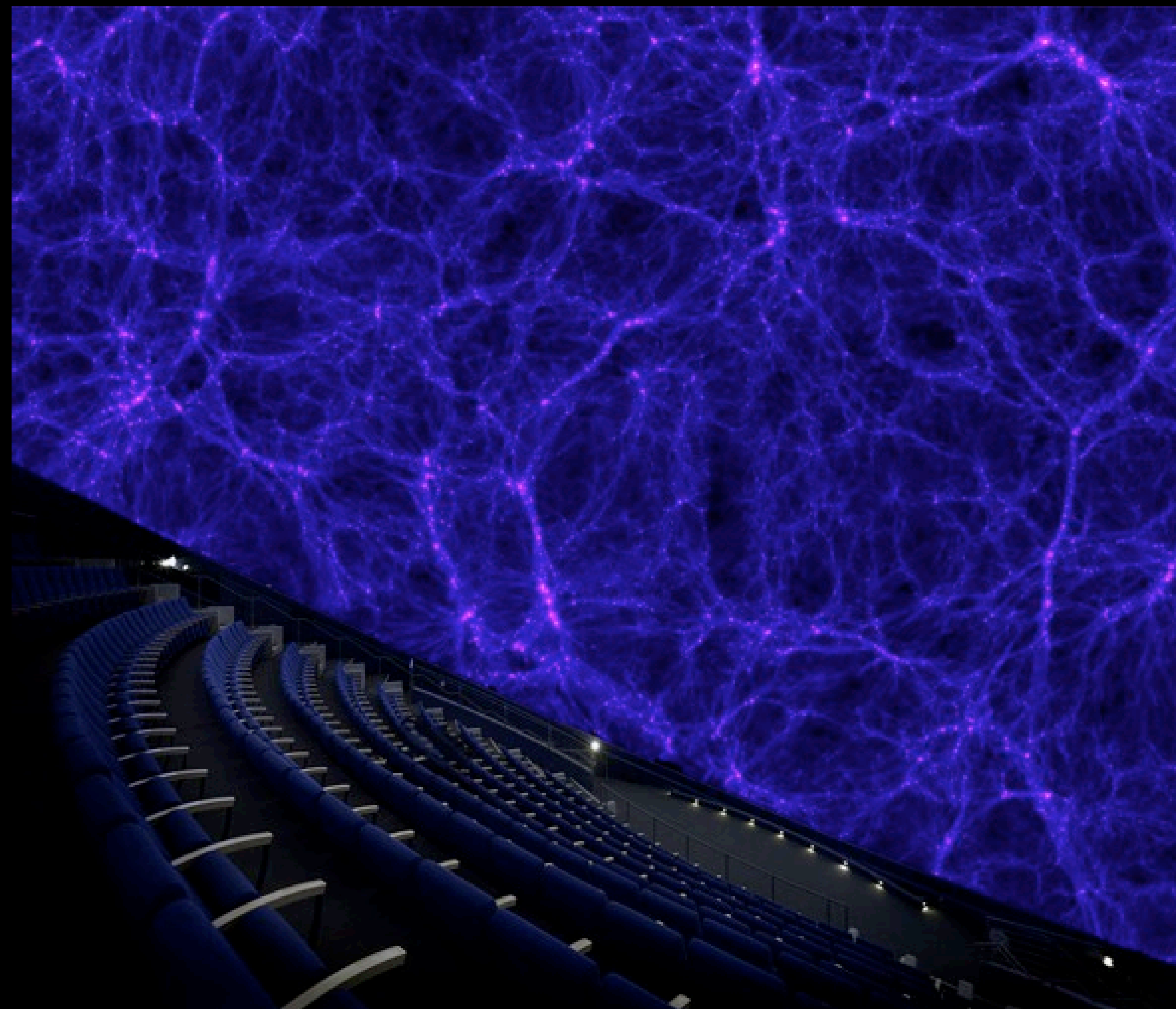
Visualizations of Simulations for Education and Public Outreach

in collaboration with Adler Planetarium and Morrison Planetarium

(in progress with Chris Henze's group at Ames and UC-HIPACC)

Astro-Computation Visualization and Outreach

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



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.

COSMOLOGY: Ripe Questions Now
Lots of great projects to be done!

Nature of Dark Matter - ΛCDM $n_{halos}(V_{max}, z)$, clustering vs. observations

Nature of Dark Energy - using SN1a

How Galaxies Form and Evolve

- Early galaxies and reionization: pop III?, escape fraction, upsizing
- Mechanisms of early SF and AGN: gas-rich mergers *vs.* cold inflows
- What quenches SF: AGN, shock heating for $M_{halo} > 10^{12} M_{sun}$, morphology
- Evolution of galaxy morphology: need new morphology measures
- Evolution of galaxy kinematics and metallicity (need spectra)
- Extragalactic Background Light (EBL): measure, constrain with γ-rays

Theoretical Approaches

- Simulations: dissipationless, hydrodynamic
- Mock catalogs, Sub-Halo Abundance Matching ("SHAM")
- Semi-Analytic Models (SAMs) constrained by simulations & observations
- Toy Models to clarify key astrophysical processes