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
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
Galaxy Hydrodynamic Simulations
SUNRISE Radiative Transfer Code - Stellar Evolution, Dust
Comparision with Hubble CANDELS Images

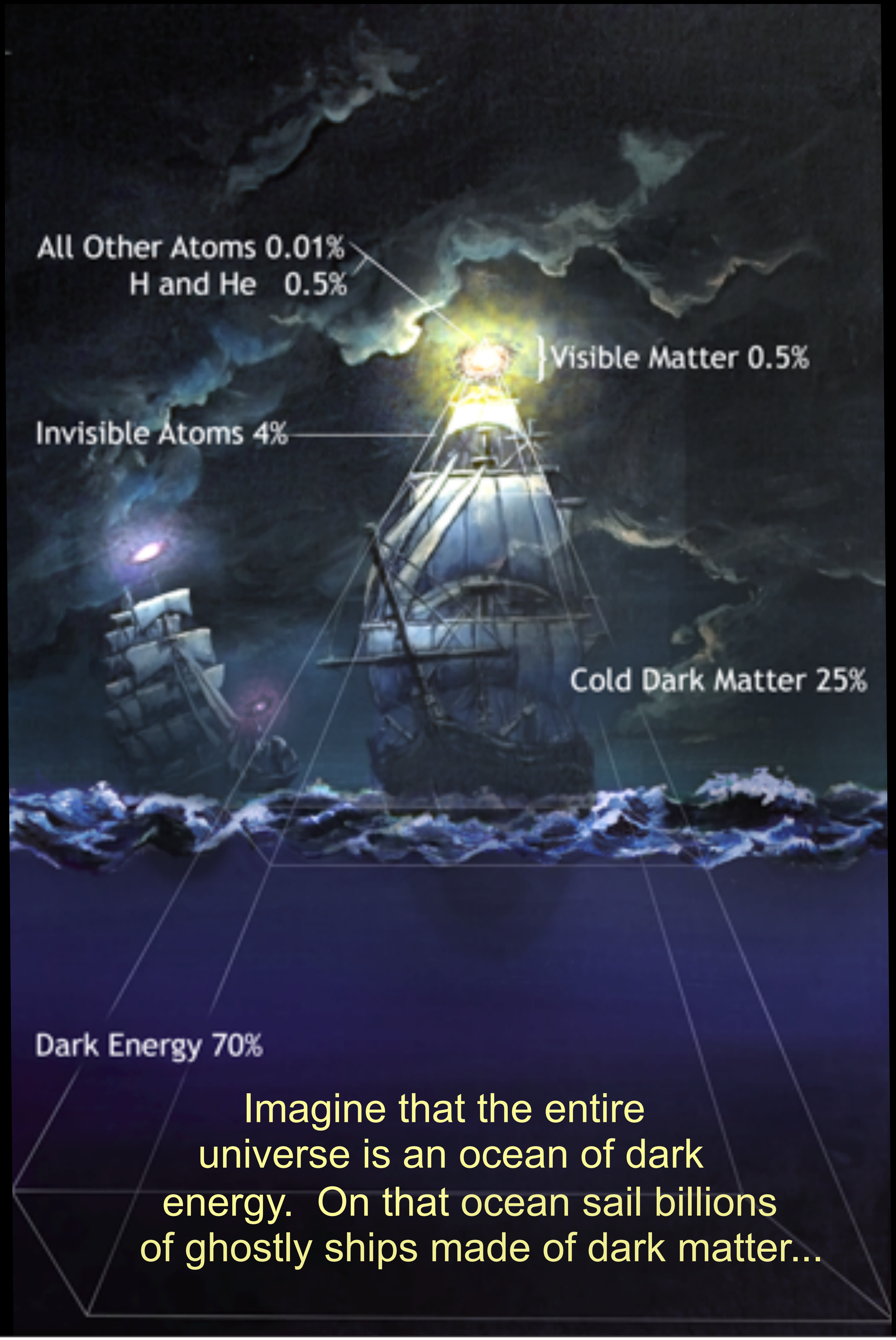
Opportunities for Grad Student Projects

Analysis of Bolshoi cosmological simulations
- halo shapes, orientation, and cosmic web
- formation of MWy-type galaxies

Semi-Analytic Models of Galaxy Population Evolution
- filling dark matter halos with galaxies
- evolution of galaxy properties vs. observations

Hydrodynamic Galaxy Simulations
- comparing simulated galaxies with observed ones

Matter and Energy Content of the Universe

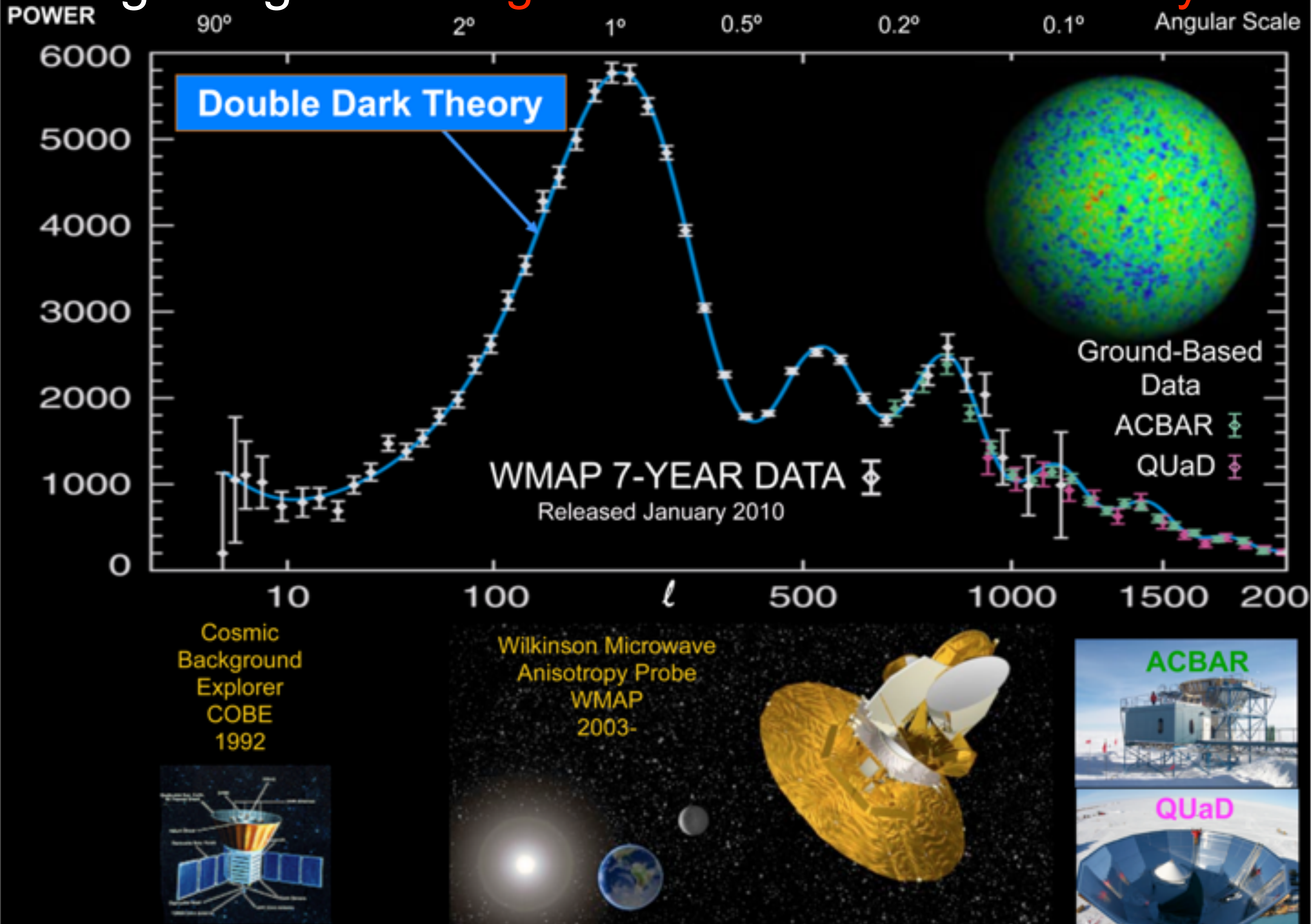


DARK MATTER + DARK ENERGY = DOUBLE DARK THEORY

Technical Name:

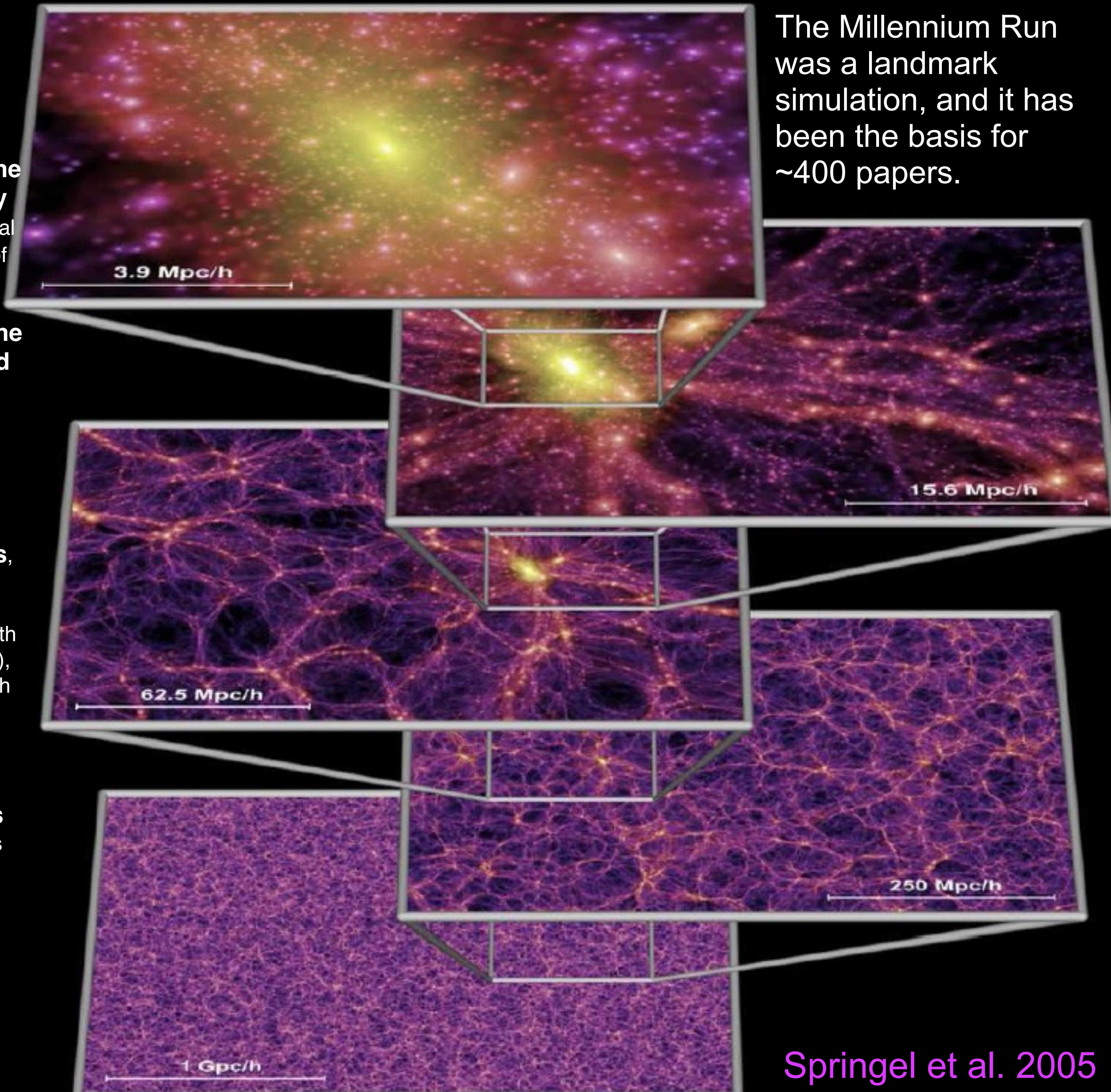
Lambda Cold Dark Matter (ΛCDM)

Big Bang Data Agrees with Double Dark Theory!



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

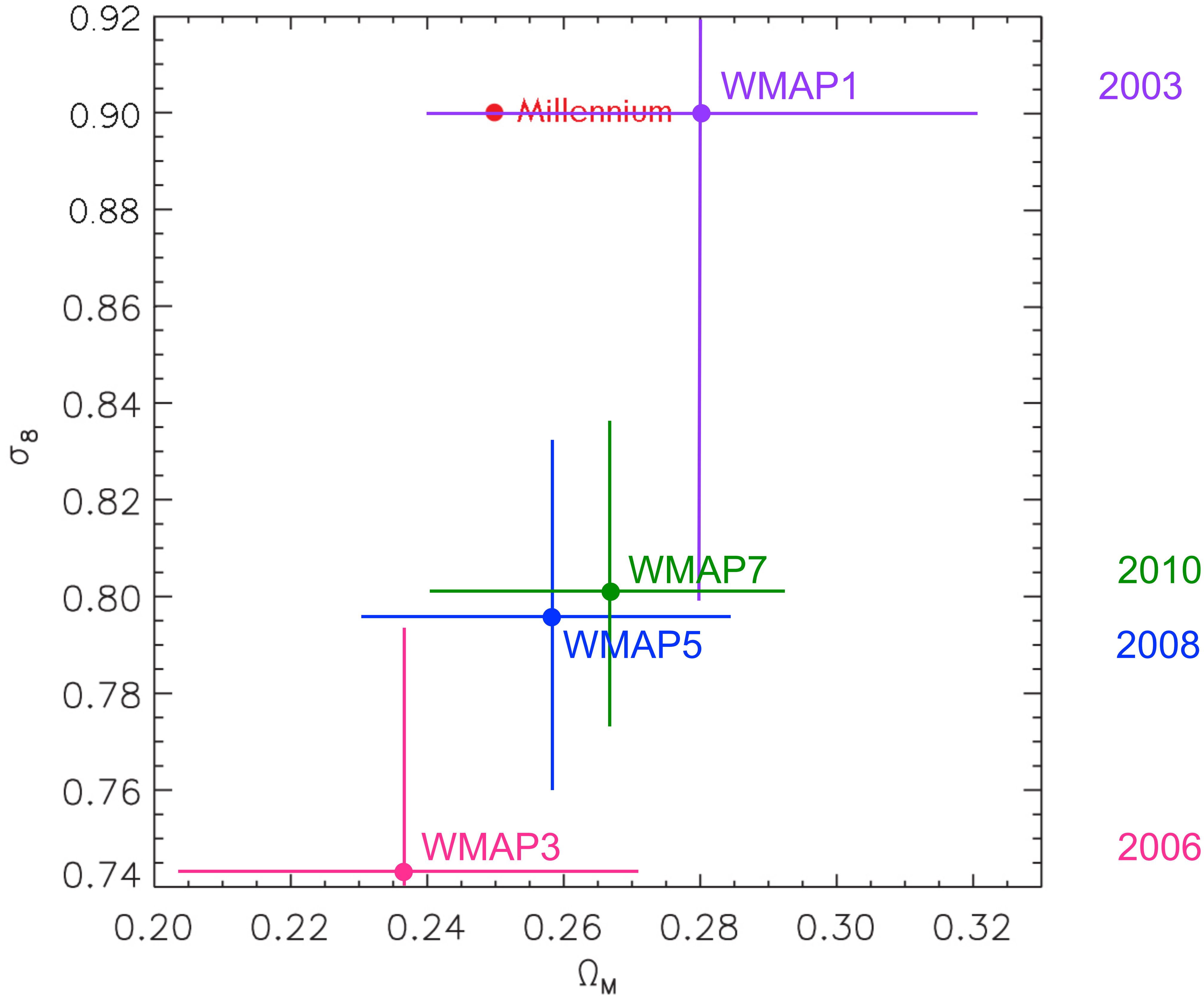


The Millennium Run was a landmark simulation, and it has been the basis for ~400 papers.

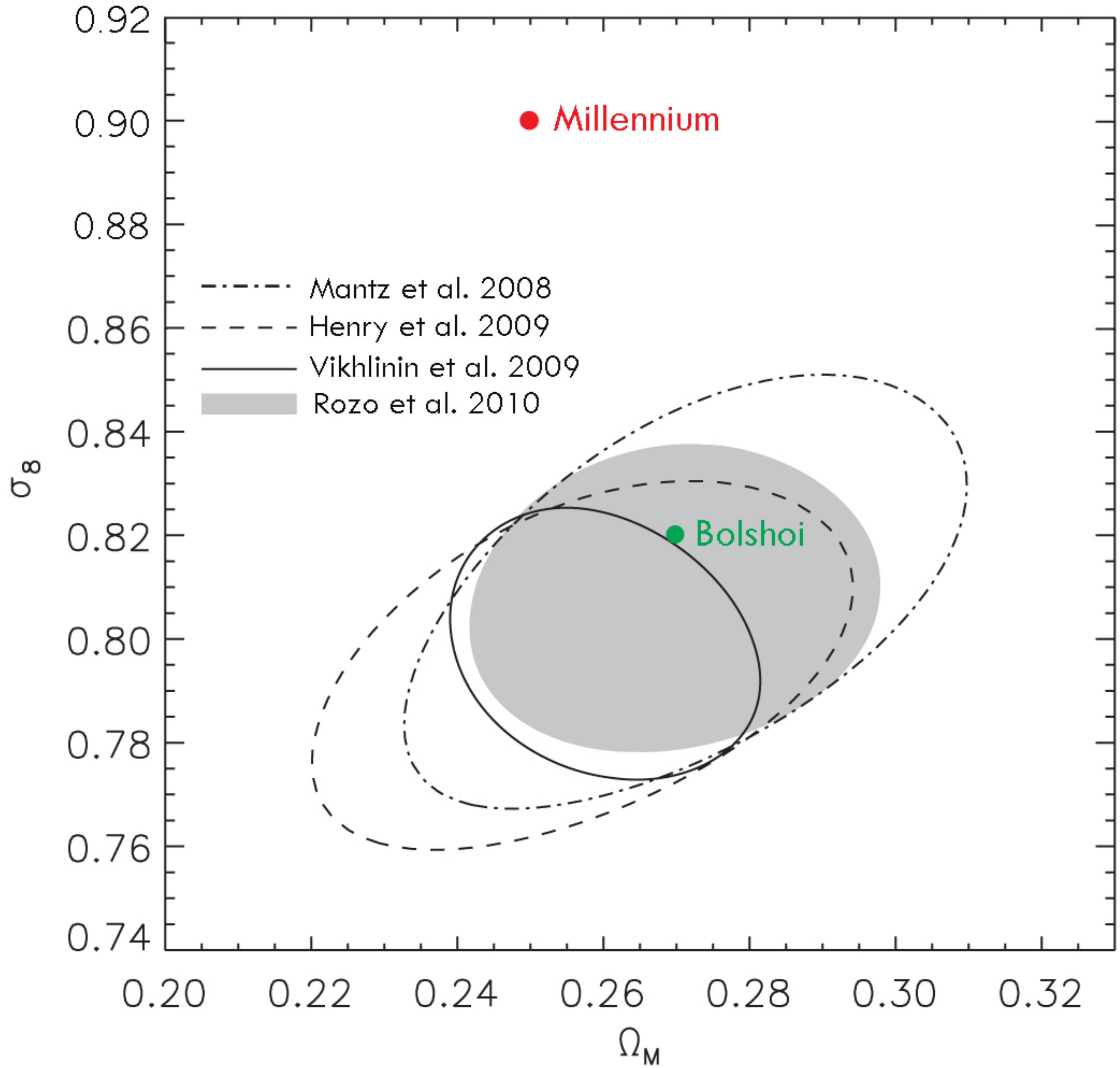
- **void statistics**, including sizes and shapes and their evolution, and the orientation of halo spins around voids
- quantitative descriptions of the evolving **cosmic web**, including applications to weak gravitational lensing
- preparation of **mock catalogs**, essential for analyzing SDSS and other survey data, and for preparing for new large surveys for dark energy etc.
- **merger trees**, essential for **semi-analytic modeling** of the evolving galaxy population, including models for the galaxy merger rate, the history of star formation and galaxy colors and morphology, the evolving AGN luminosity function, stellar and AGN feedback, recycling of gas and metals, etc.

Springel et al. 2005

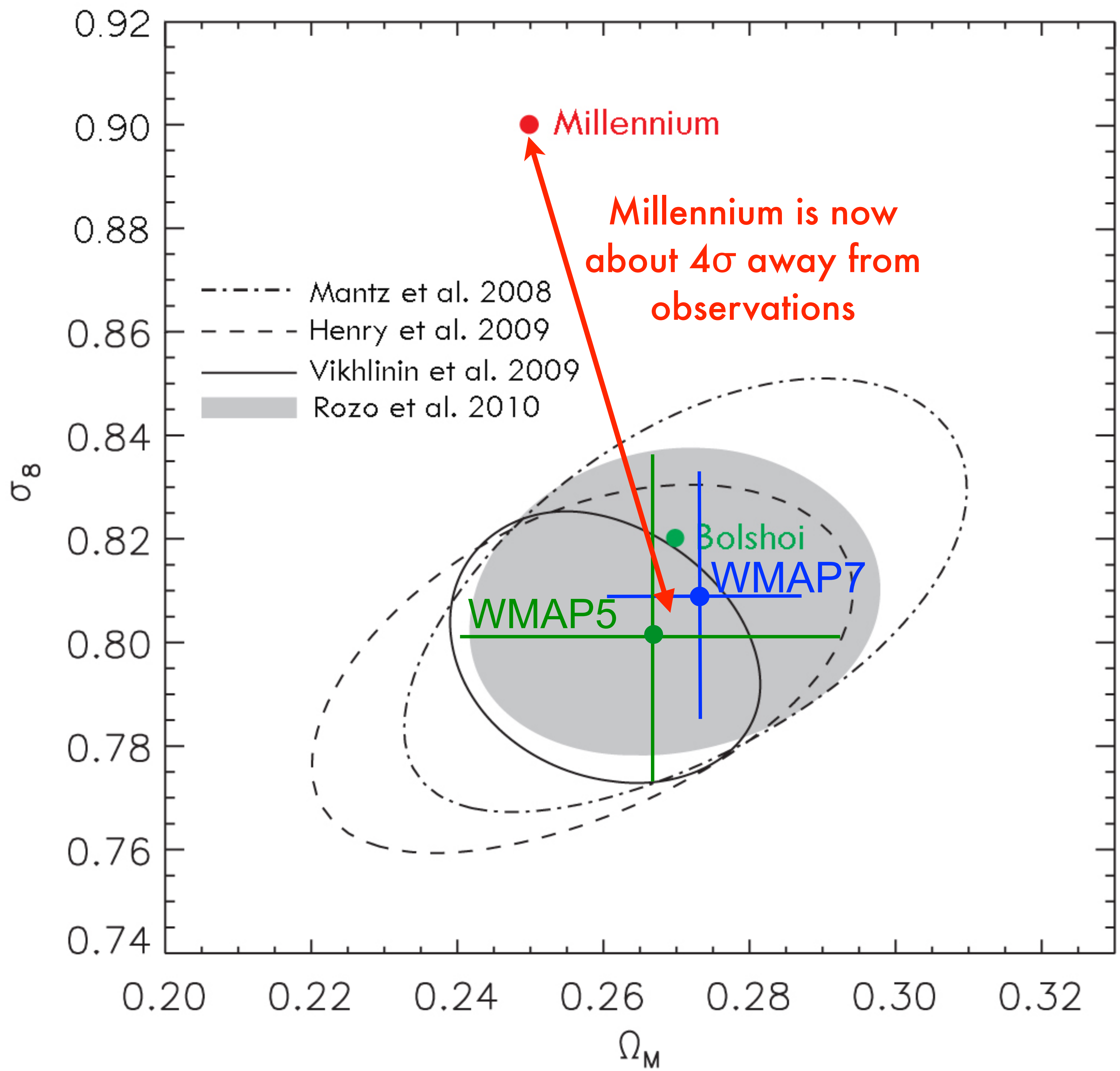
WMAP-only Determination of σ_8 and Ω_M



WMAP+SN+Clusters Determination of σ_8 and Ω_M



WMAP+SN+Clusters Determination of σ_8 and Ω_M



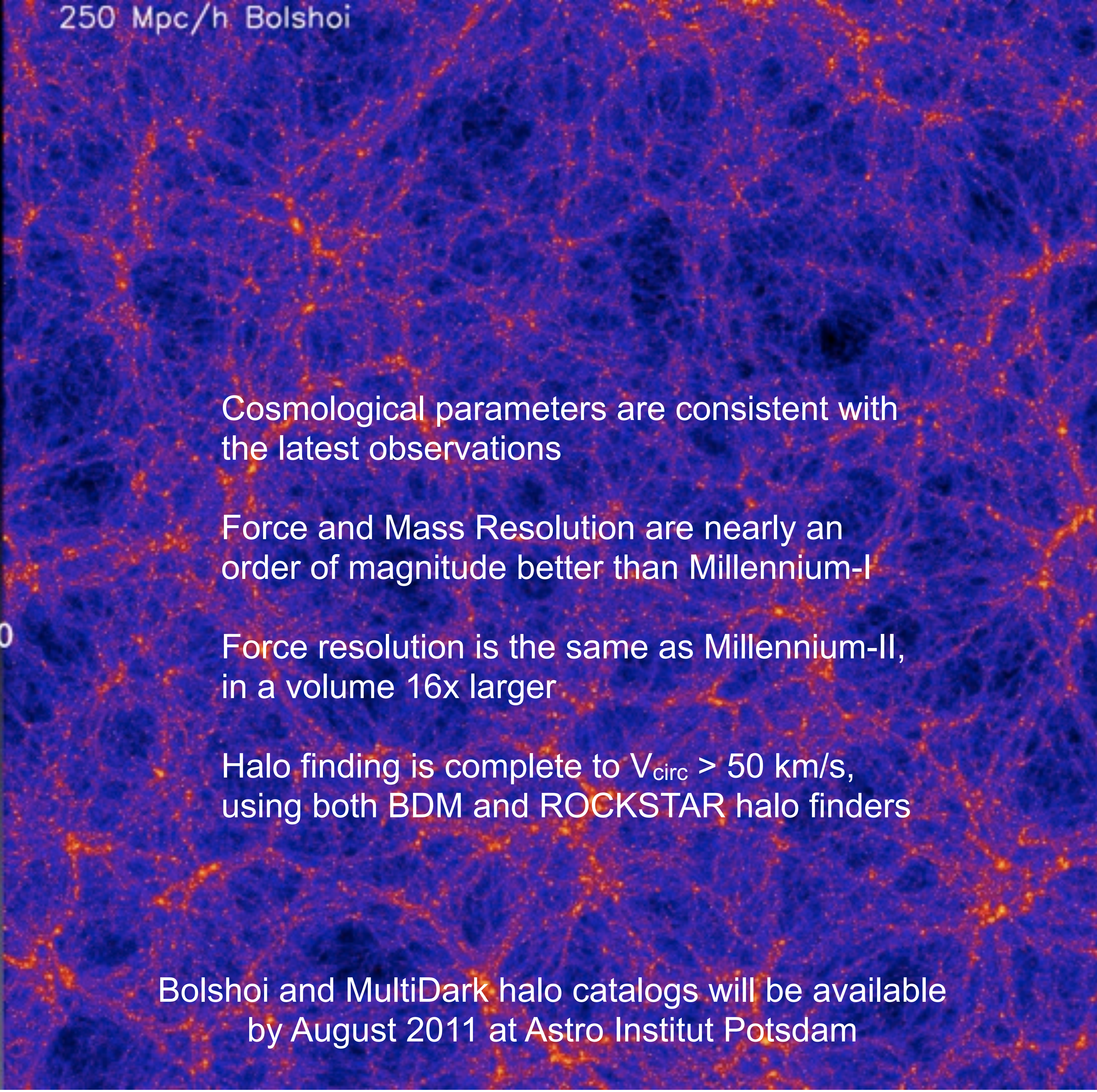
The Bolshoi simulation

ART code

250Mpc/h Box
LCDM
σ_8 = 0.82
h = 0.70
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



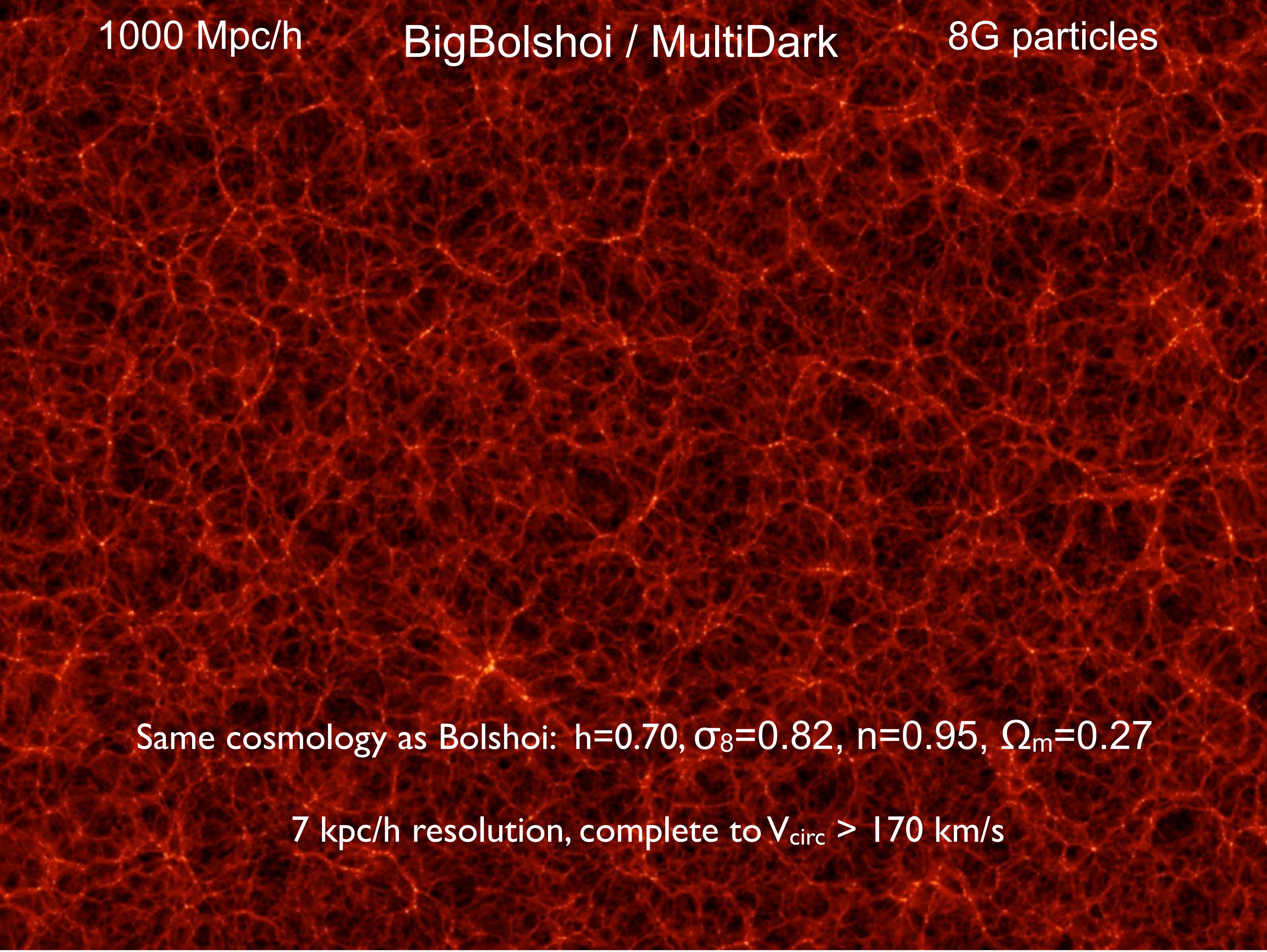
Cosmological parameters are consistent with the latest observations

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 available by August 2011 at Astro Institut Potsdam



1000 Mpc/h

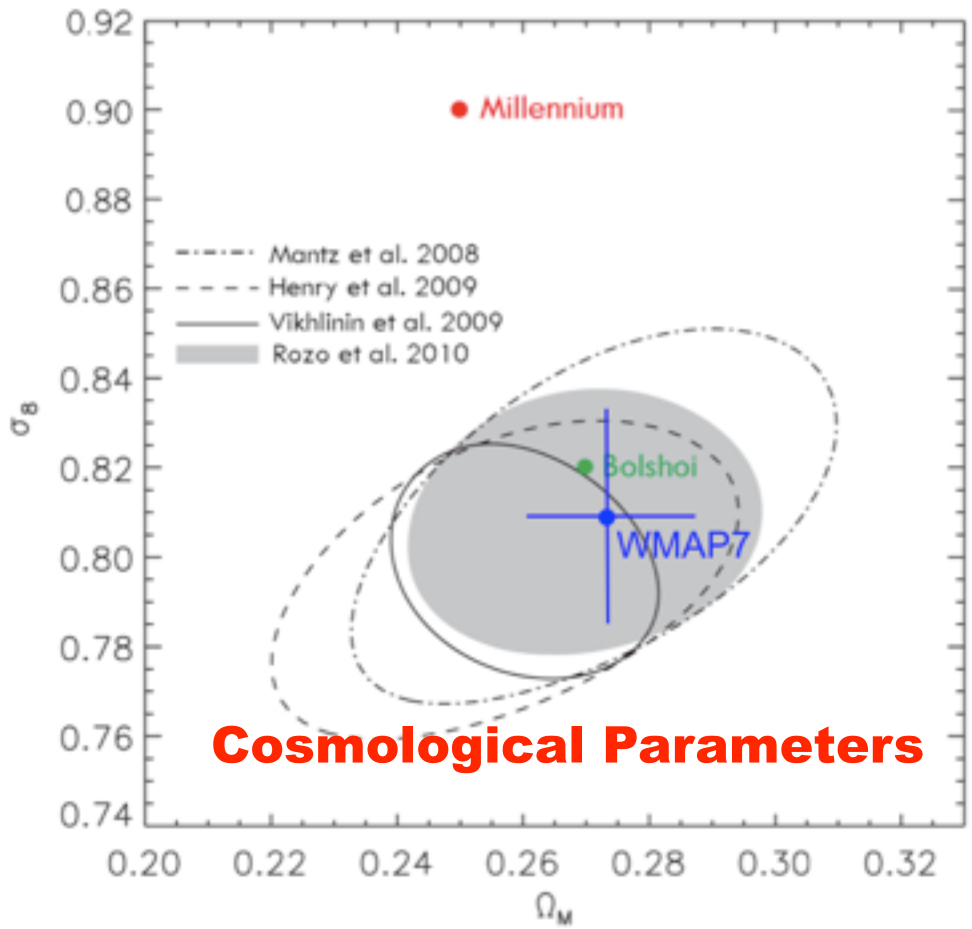
BigBolshoi / MultiDark

8G particles

Same cosmology as Bolshoi: h=0.70, σ_8=0.82, n=0.95, Ω_m=0.27

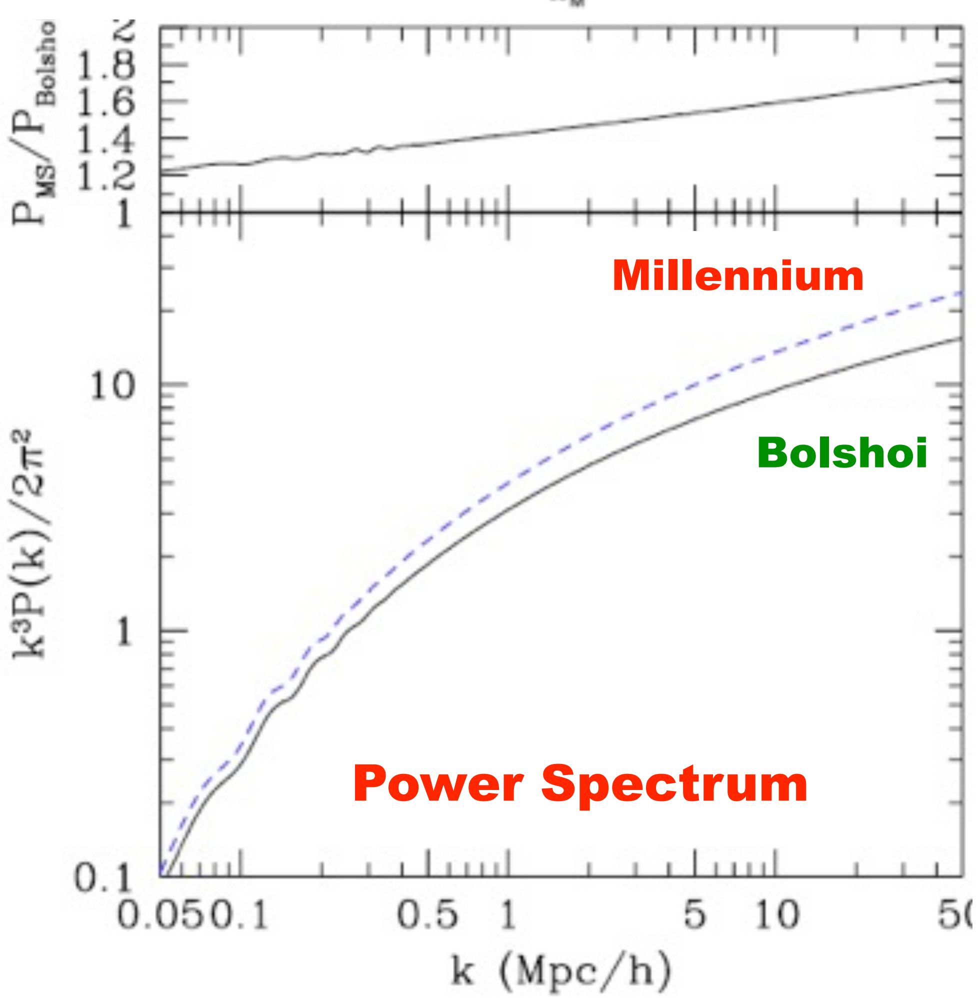
7 kpc/h resolution, complete to V_{circ} > 170 km/s

Halos and galaxies: results from the Bolshoi simulation

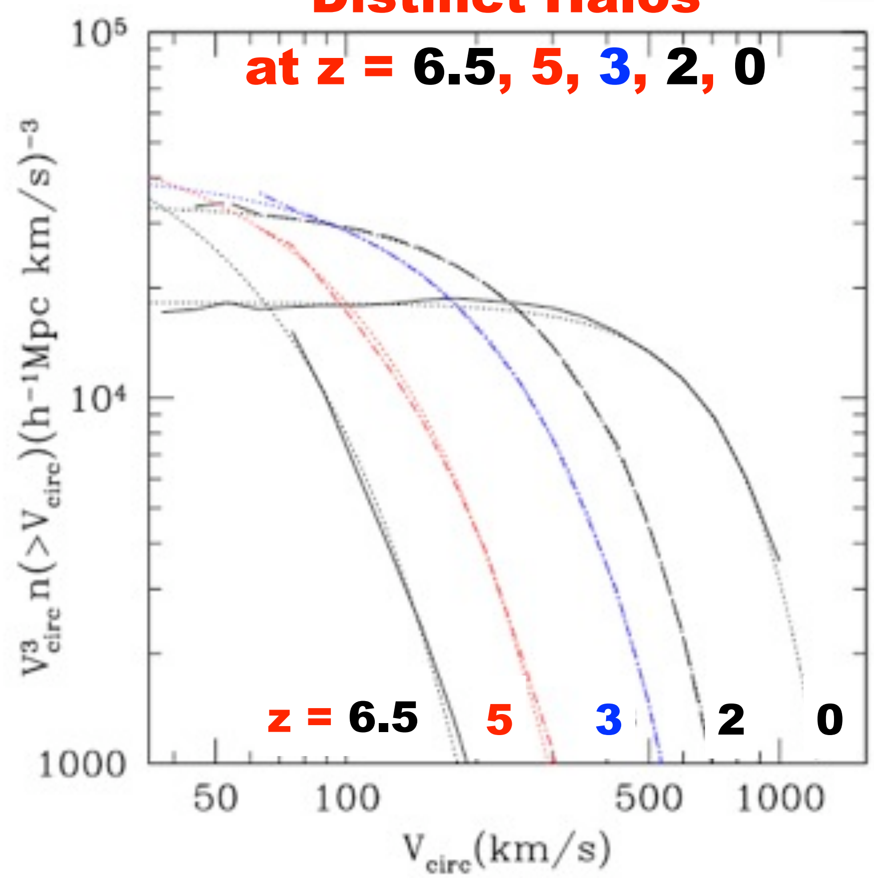


The Millennium Run (Springel+05) was a landmark simulation, and it has been the basis for ~400 papers. However, it and the new Millennium-II and XXL were run using WMAP1 (2003) parameters, and the Millennium-I resolution was inadequate to see many subhalos. The new **Bolshoi** simulation (Klypin, Trujillo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

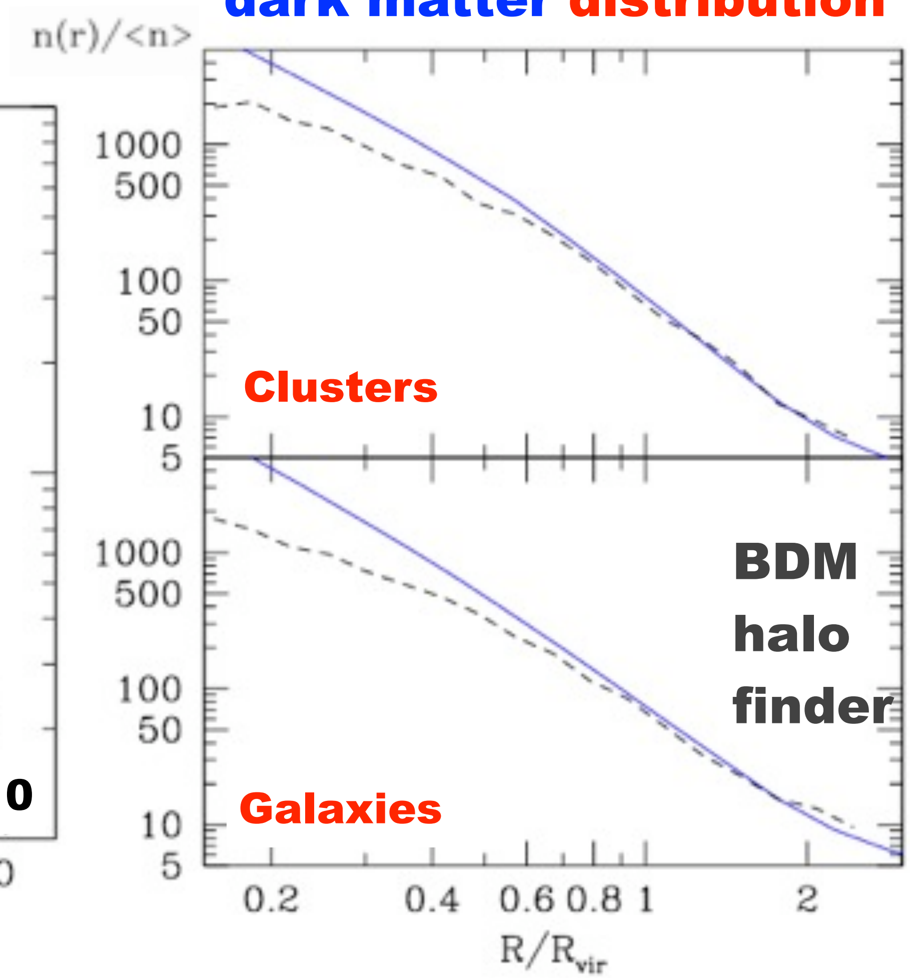
Klypin, Trujillo-Gomez, & Primack, 2011 ApJ



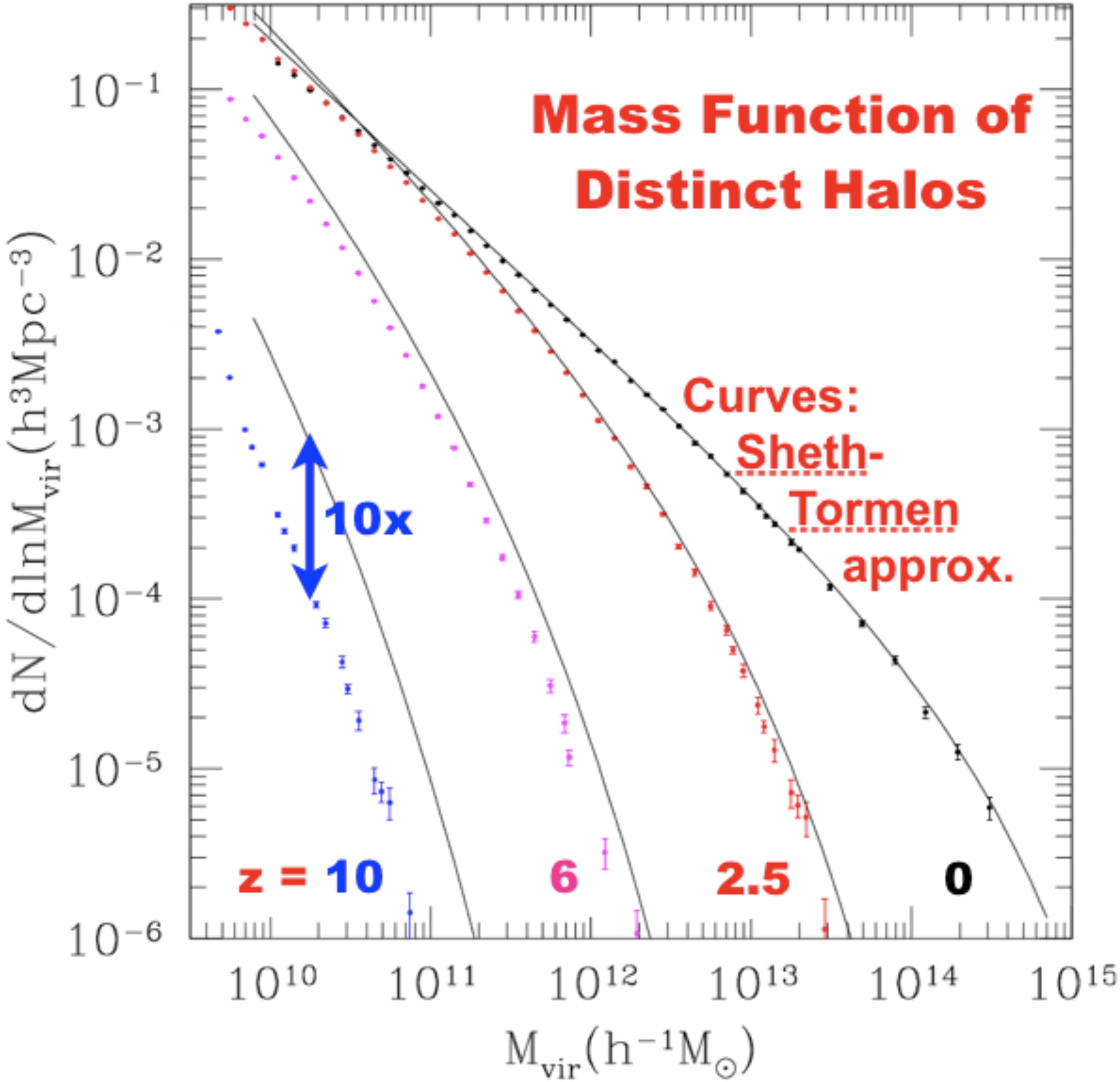
Velocity Function of Distinct Halos

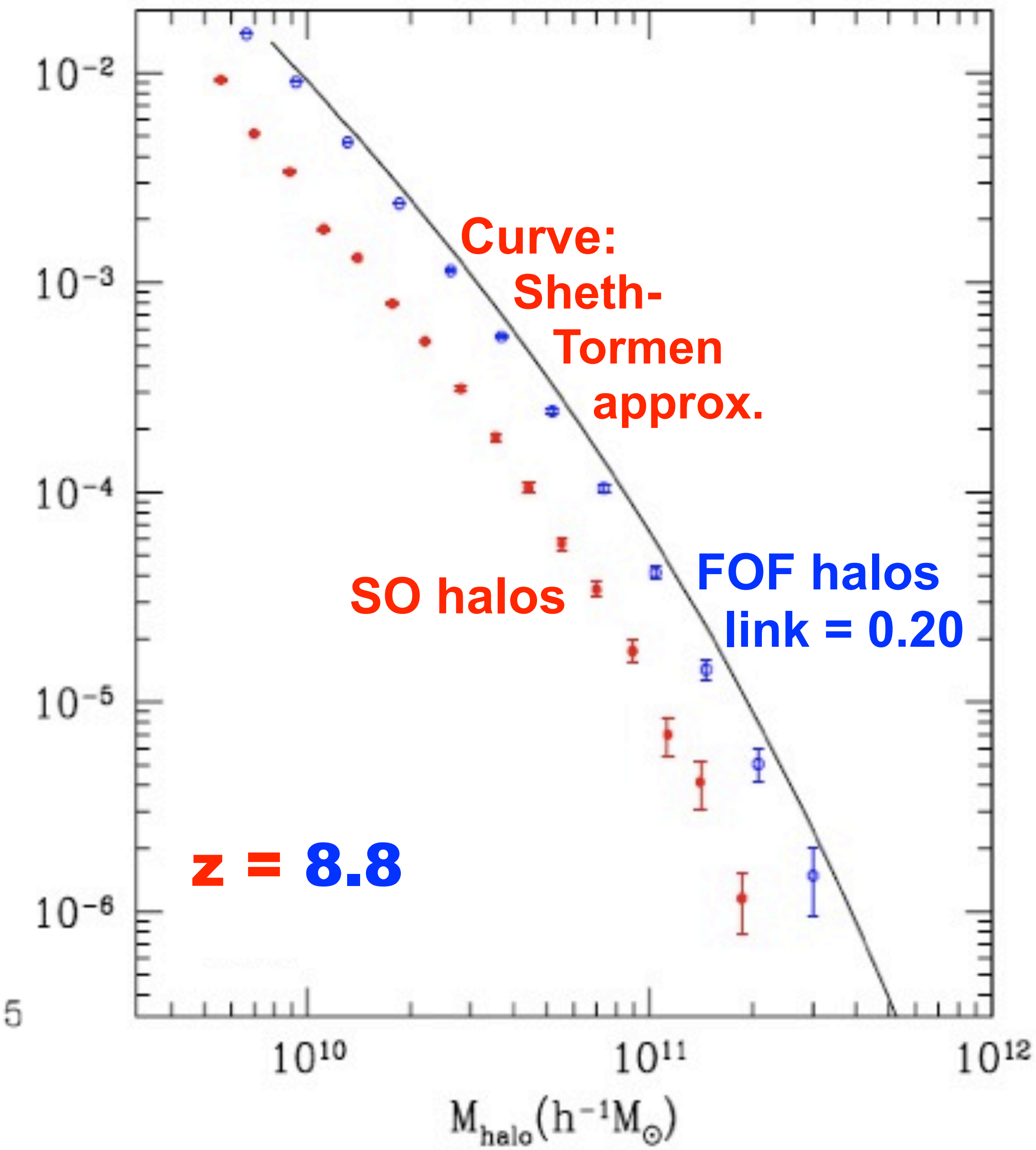


Subhalos follow the dark matter distribution



Sheth-Tormen Fails at High Redshifts





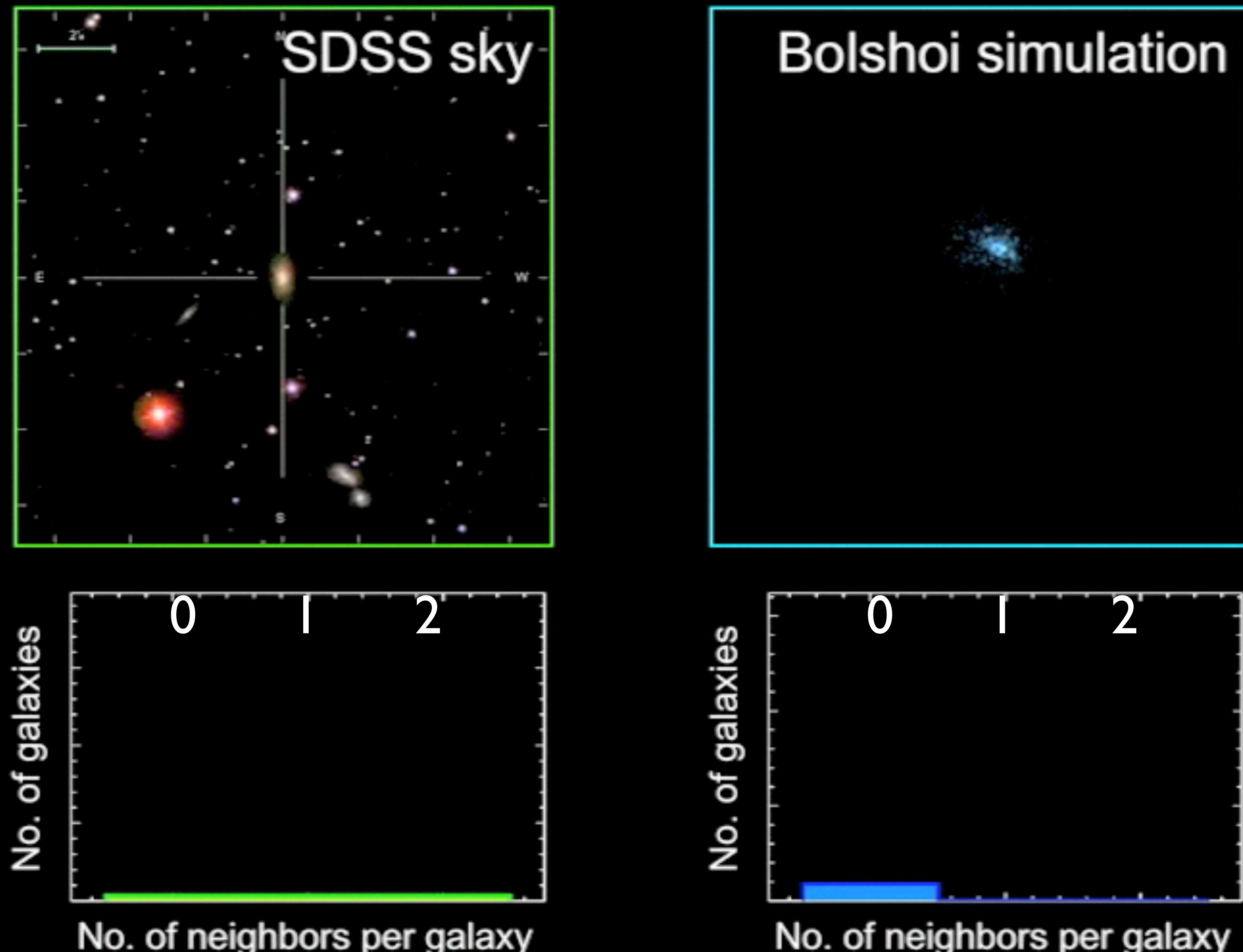
The Sheth-Tormen approximation with the same WMAP5 parameters used for the Bolshoi simulation very accurately agrees with abundance of halos at low redshifts, but increasingly overpredicts bound spherical overdensity halo abundance at higher redshifts. ST agrees well with FOF halo abundances, but FOF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

Klypin, Trujillo-Gomez, & Primack, 2011 ApJ


BOLSHOI
Merger Tree
Peter Behroozi, et al.
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)

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

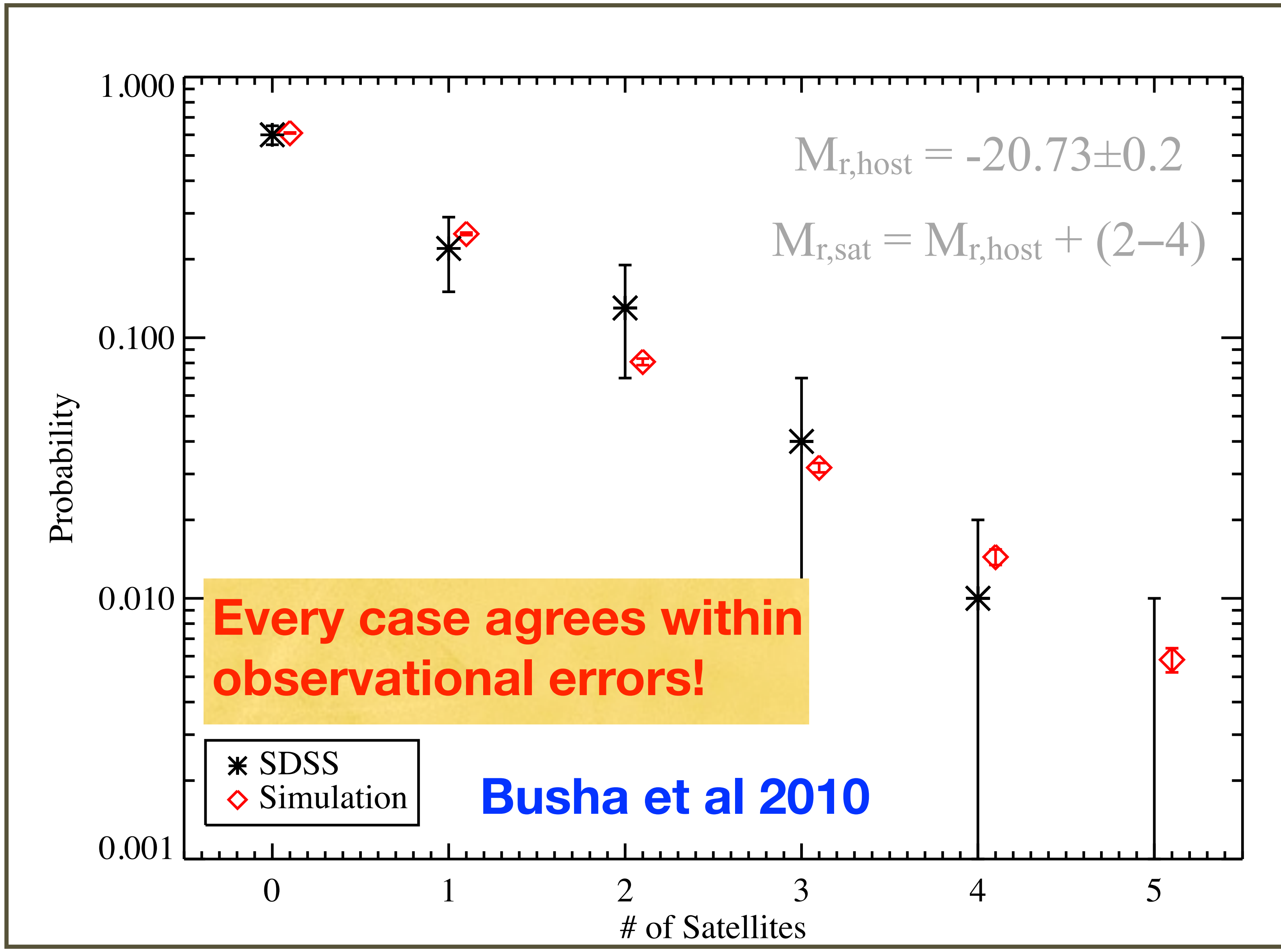
The Bolshoi simulation + halo abundance matching predicts the likelihood of this


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 ${}^{0.1}M_r = -20.73 \pm 0.2$ 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%

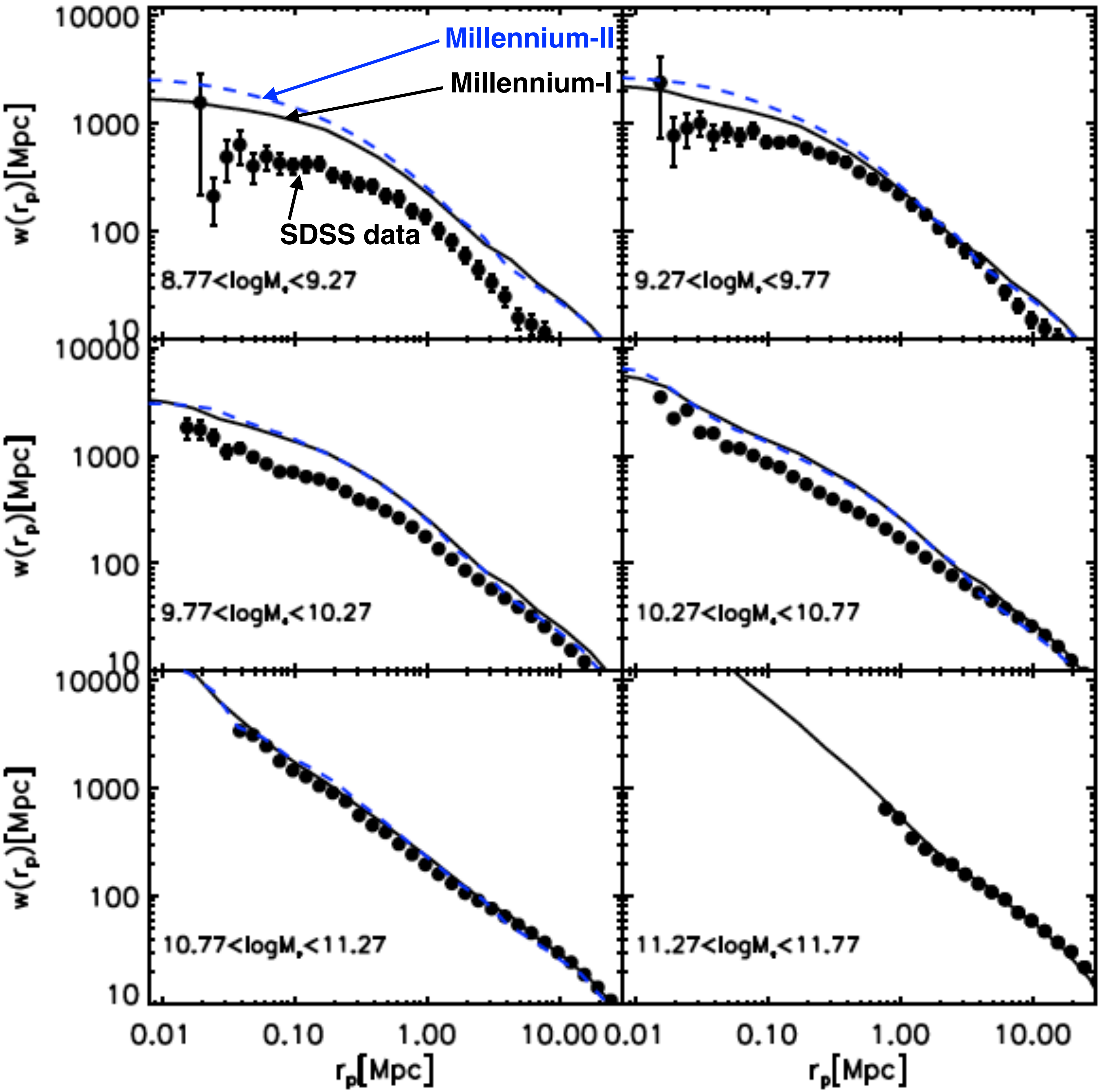
Statistics of MW bright satellites: SDSS data vs. Bolshoi simulation



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.

Projected Galaxy Correlation Functions

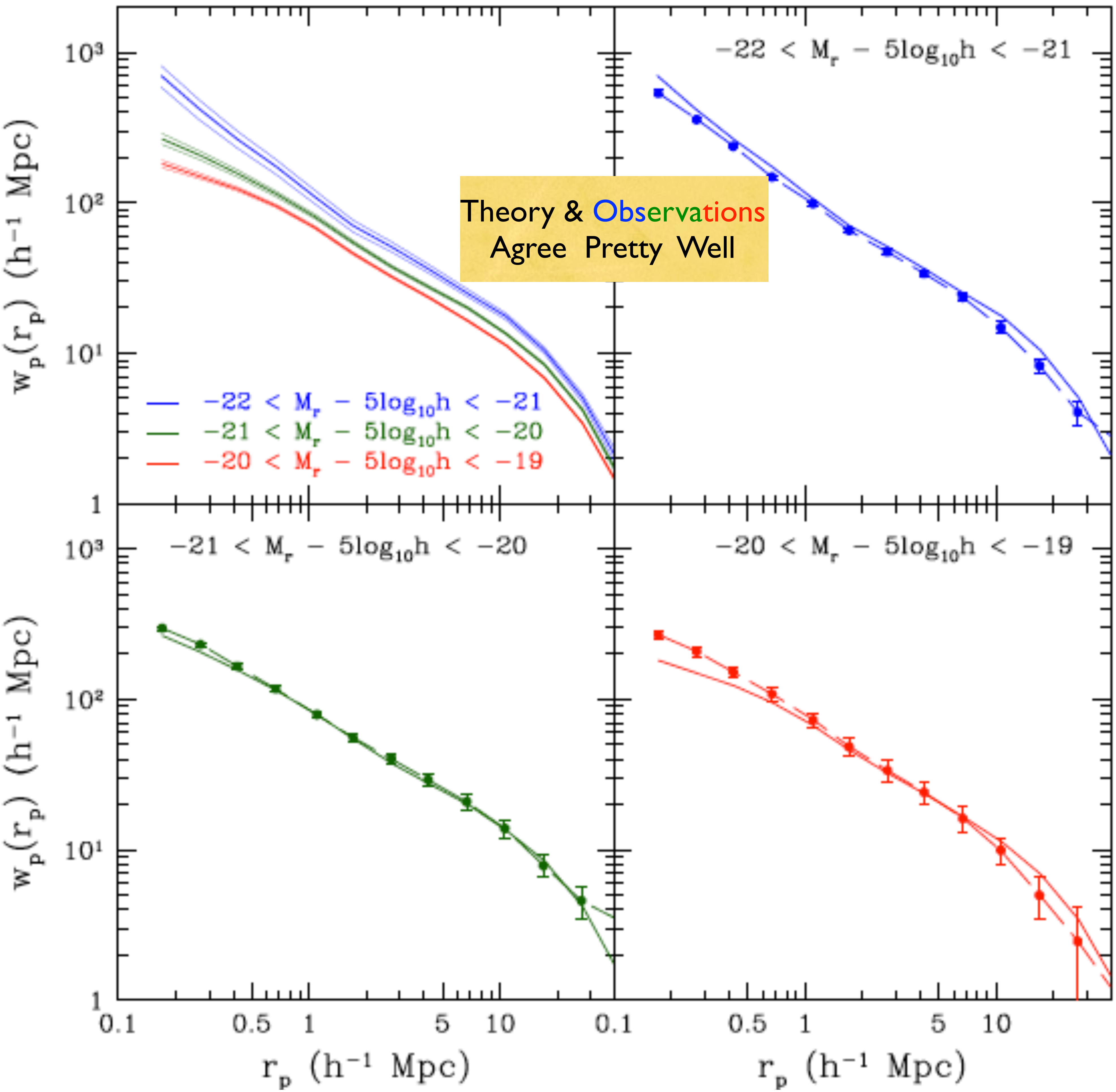


Projected correlation functions for galaxies in different stellar mass ranges, in SAM based on Millennium I and II. Black solid and blue dashed curves give results for preferred model applied to the MS and the MS-II, respectively. Symbols with error bars are results for SDSS/DR7 calculated using the 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 σ_8 = 0.90 used in MS-I & II.**

Guo, White, et al. MNRAS in press.

Monday, February 13, 2012

Projected Galaxy Correlation Functions

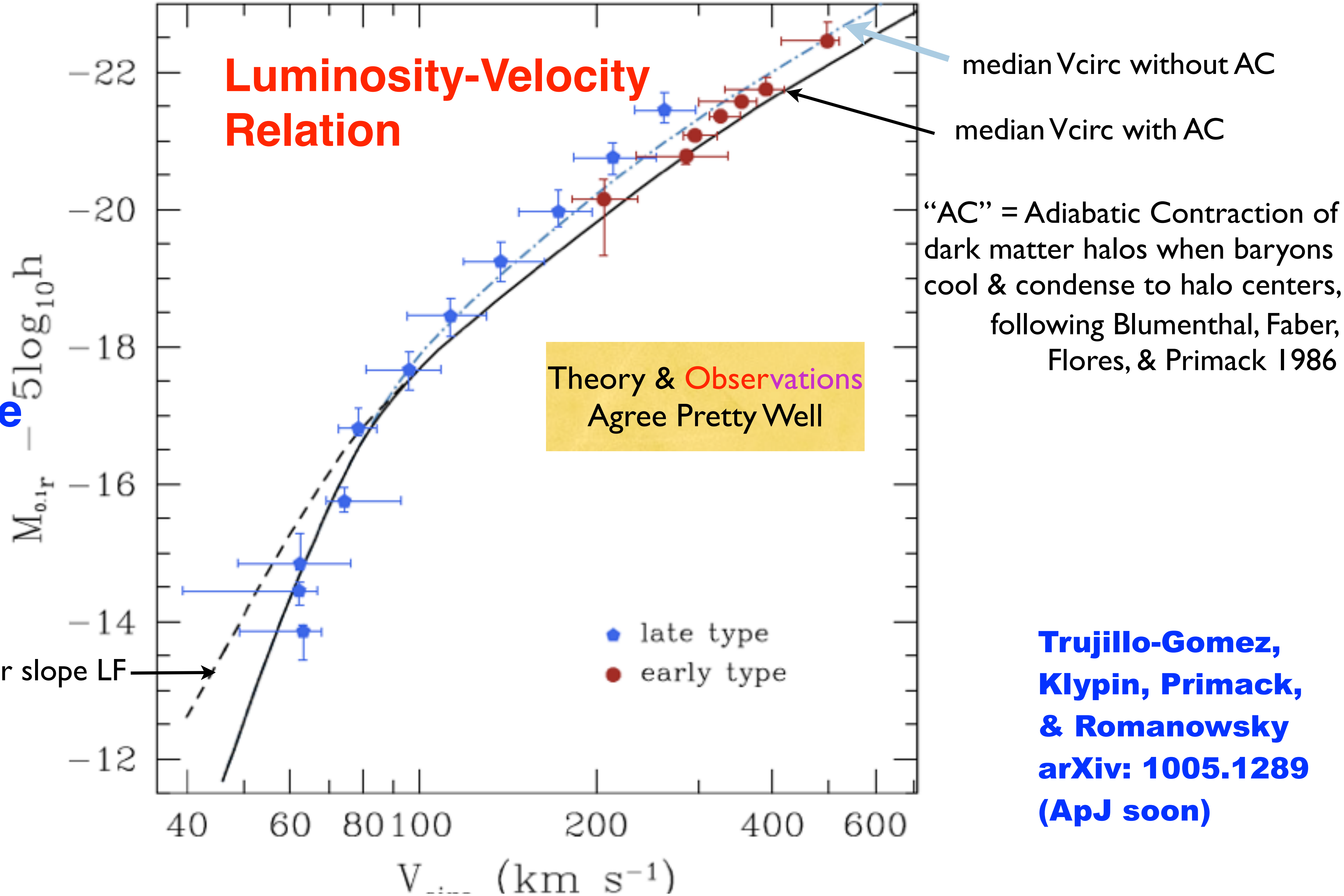


The correlation function of SDSS galaxies vs. Bolshoi galaxies using halo abundance matching, with scatter using our stochastic abundance matching method. This results in a better than 20% agreement with SDSS. *Top left:* correlation functinon in three magnitude bins, showing Poisson uncertainties as 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)

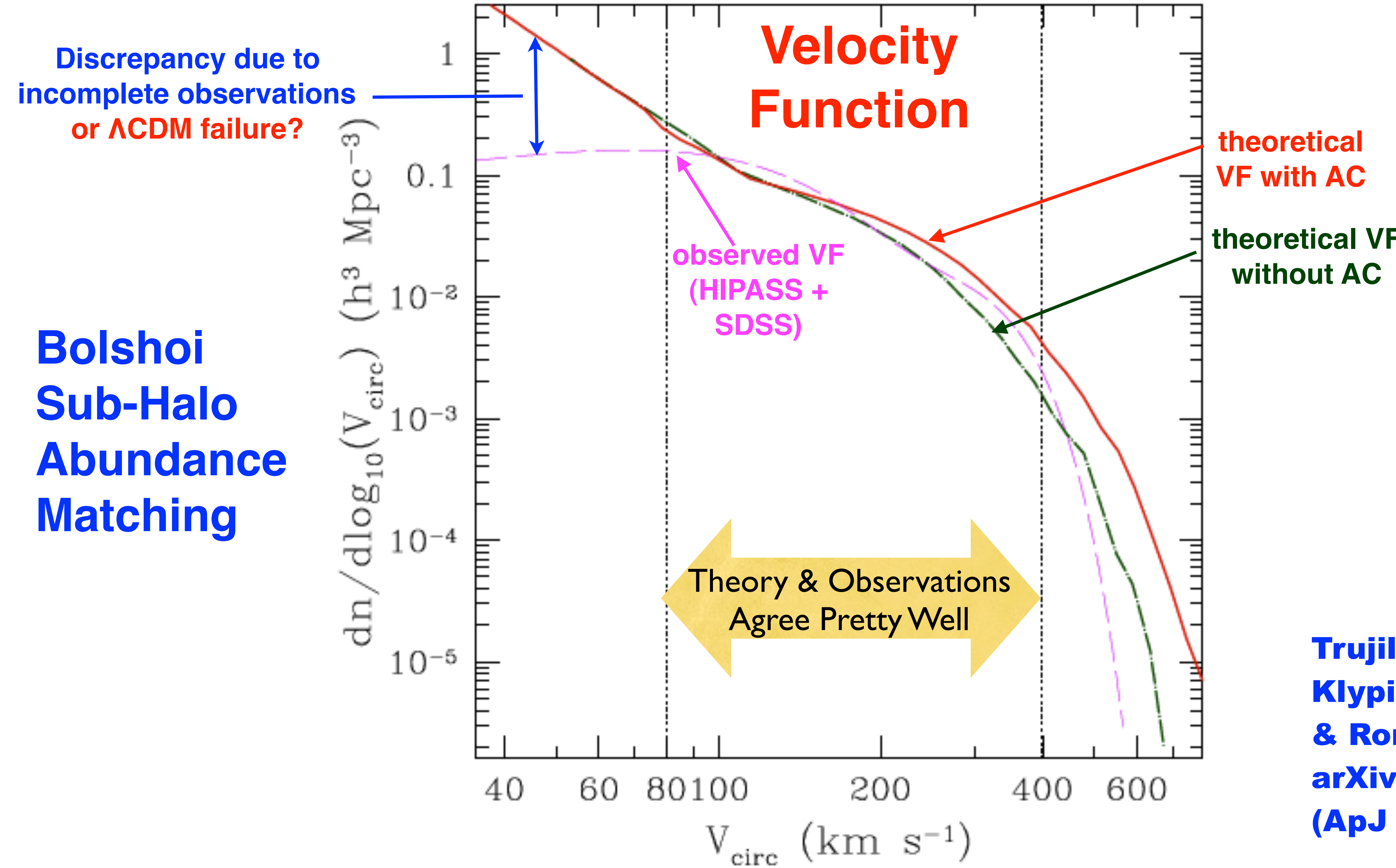
Luminosity-Velocity Relation

Bolshoi Sub-Halo Abundance Matching



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

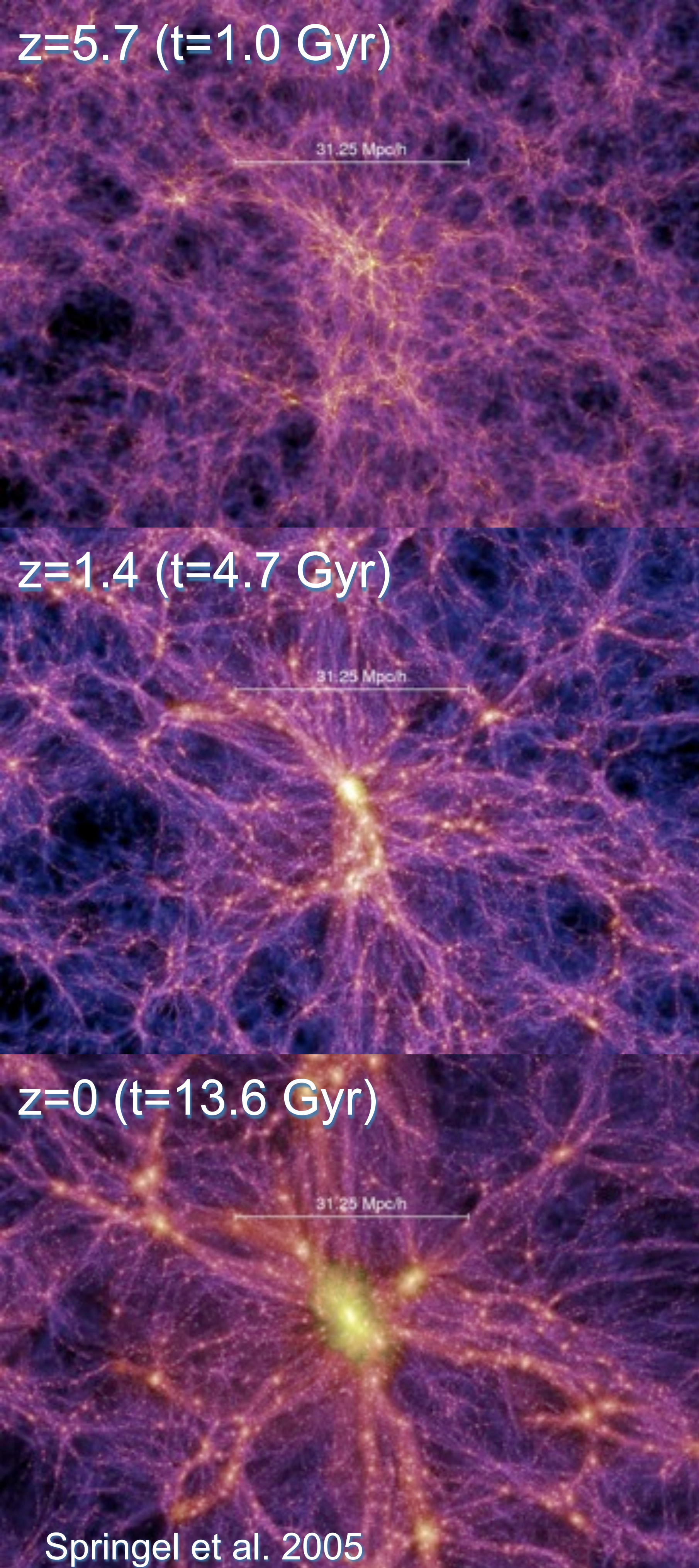
Fig. 4.— Comparison of the observed LuminosityVelocity relation with the predictions of the ΛCDM model. The solid curve shows the median values of $^{0.1}r$-band luminosity vs. circular velocity for the model galaxy sample. The circular velocity for each model galaxy is based on the peak circular velocity 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.



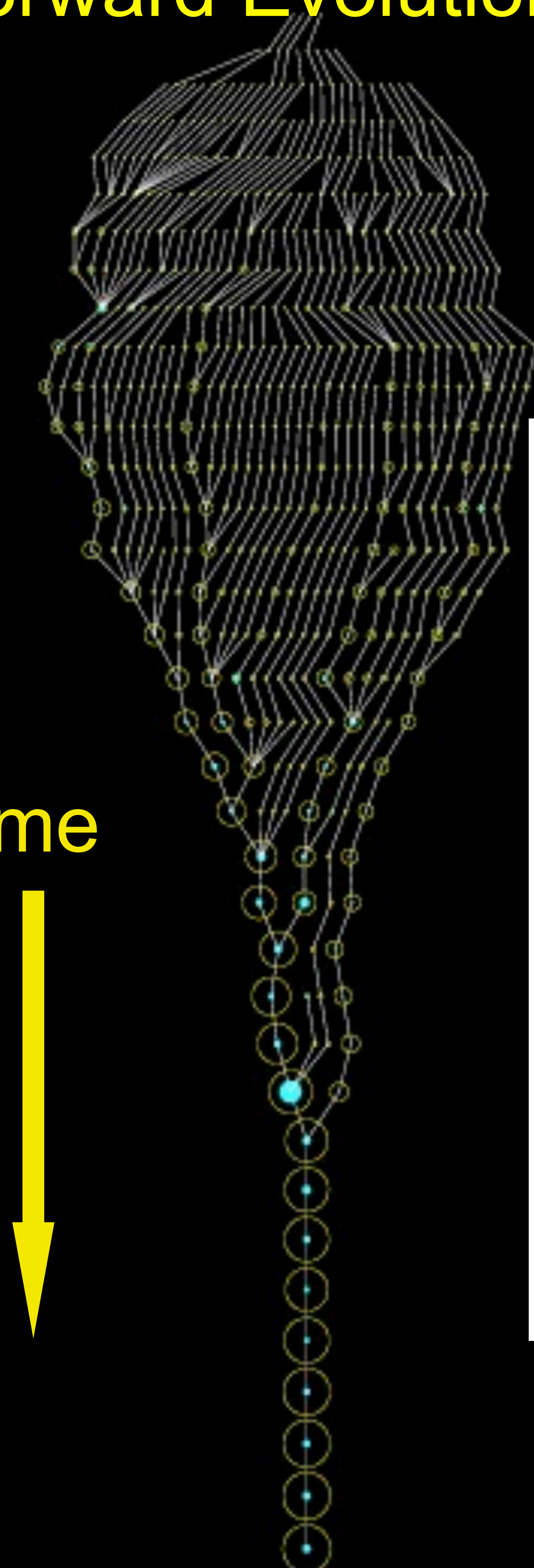
Bolshoi Sub-Halo Abundance Matching

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

Fig. 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 $V_{\rm circ} > 400$ km s^{-1}. Two vertical dotted lines divide the VF into three domains: $V_{\rm circ} > 400$ km s^{-1} with large observational and theoretical uncertainties; < 80 km s^{-1} $< V_{\rm circ} <$ 400 km s^{-1} with a reasonable agreement, and $V_{\rm circ} < 80$ km s^{-1}, where the theory significantly overpredicts the number of dwarfs.



Forward Evolution

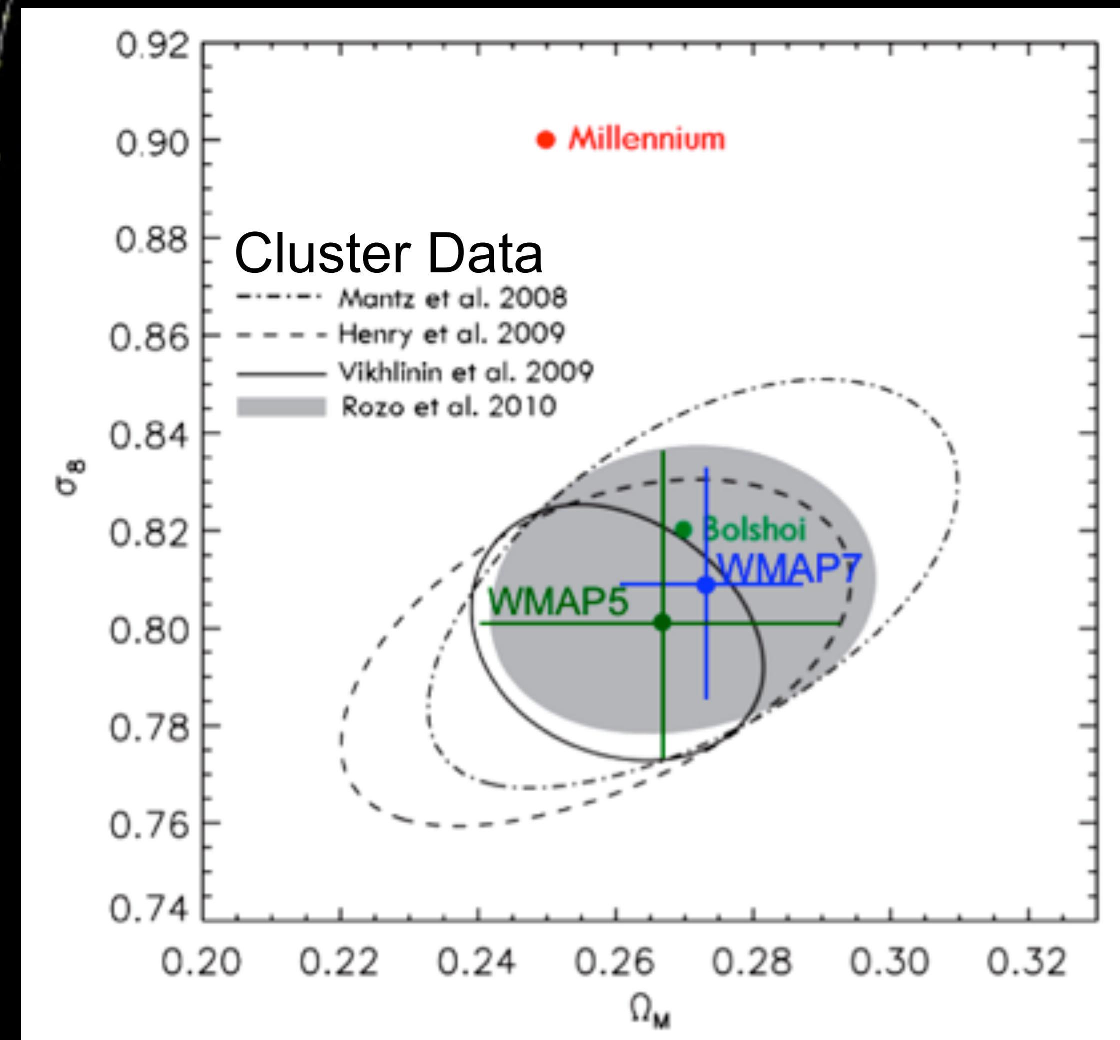


time

Wechsler et al. 2002

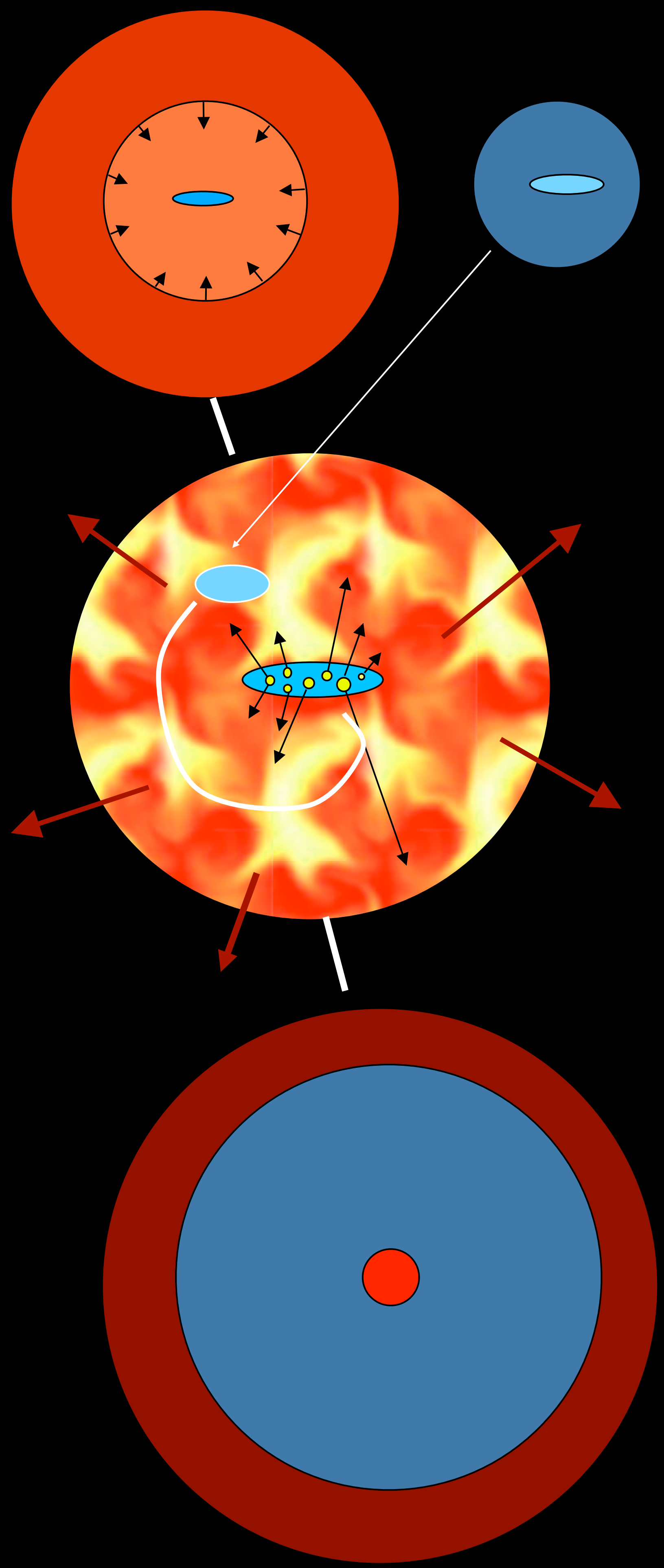
Present status of ΛCDM "Double Dark" theory:

- cosmological parameters are now well constrained by observations



- mass accretion history of dark matter halos is represented by 'merger trees' like the one at left

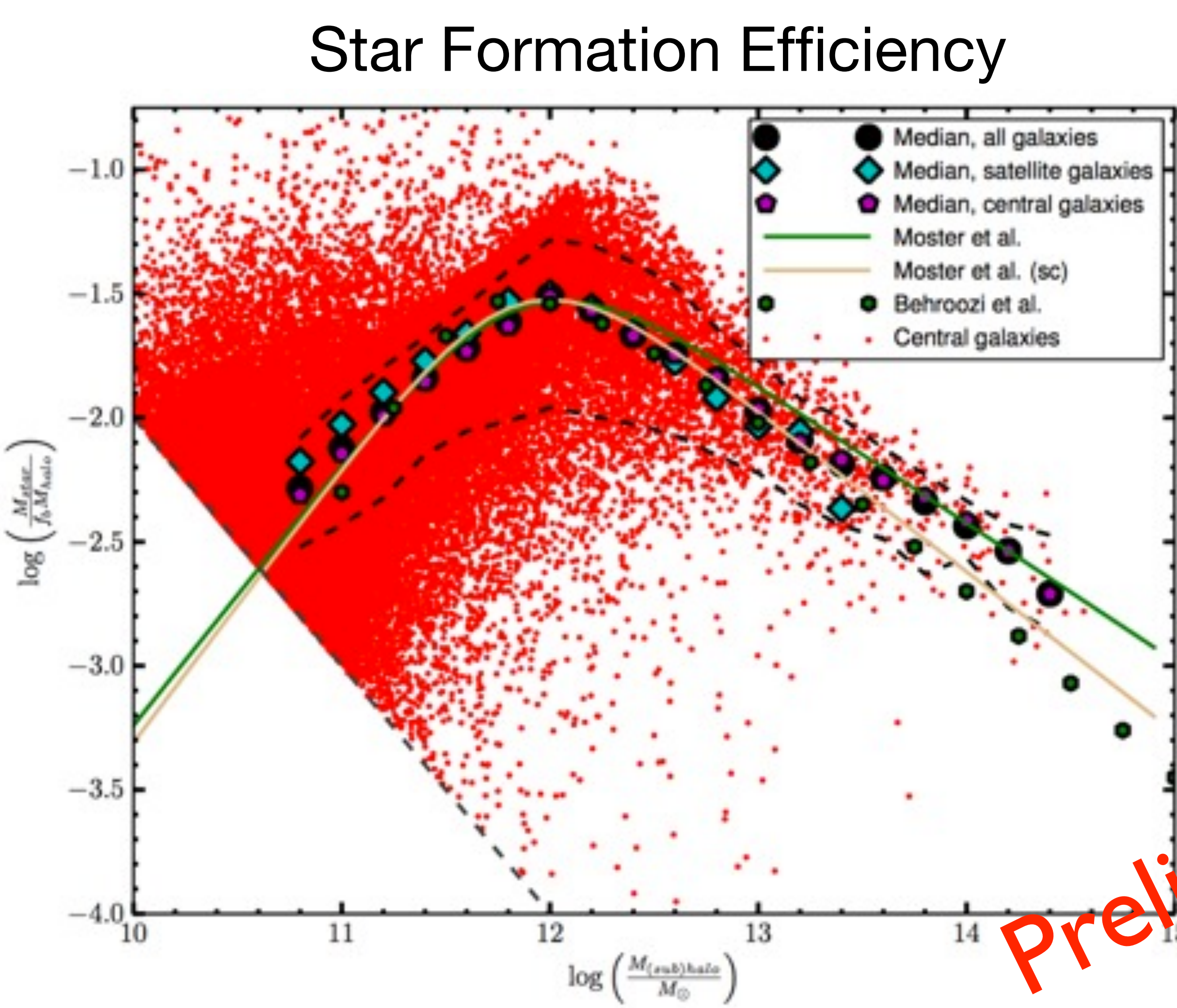
Galaxy Formation in ΛCDM

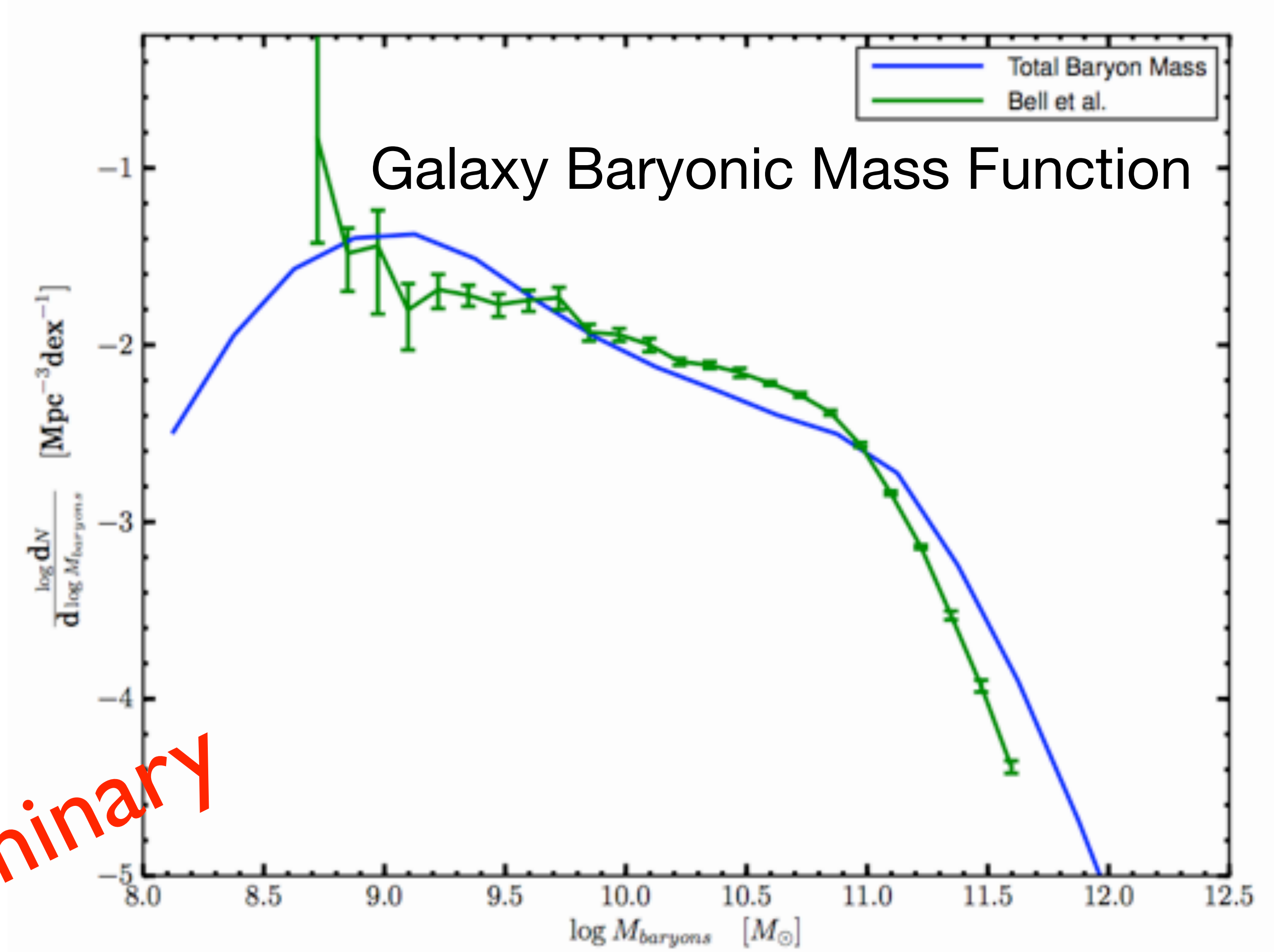


- gas is collisionally heated when perturbations ‘turn around’ and collapse to form gravitationally bound structures
- gas in halos cools via atomic line transitions (depends on density, temperature, and metallicity)
- cooled gas collapses to form a rotationally supported disk
- cold gas forms stars, with efficiency a function of gas density (e.g. Schmidt-Kennicutt Law)
- massive stars and SNae reheat (and in small halos expel) cold gas and some metals
- galaxy mergers trigger bursts of star formation; ‘major’ mergers transform disks into spheroids and fuel AGN
- AGN feedback cuts off star formation

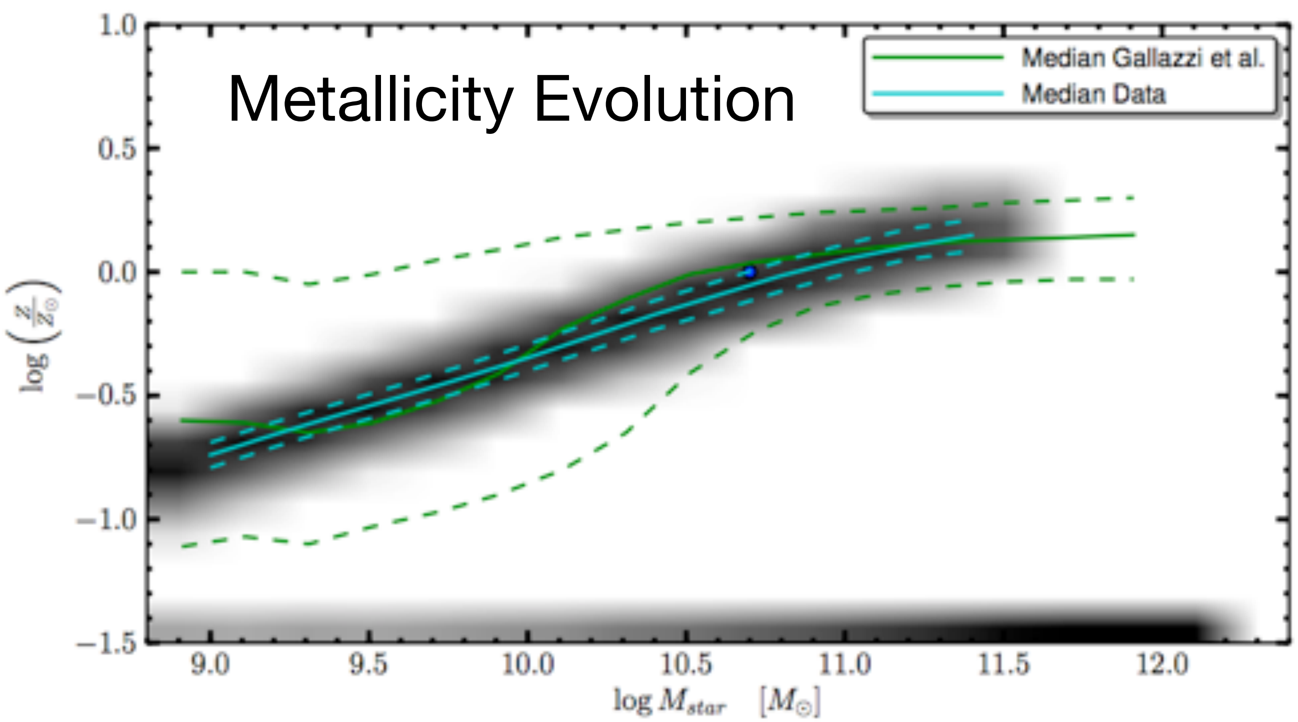
White & Frenk 91; Kauffmann+93; Cole+94; Somerville & Primack 99; Cole+00; Somerville, Primack, & Faber 01; Croton et al. 2006; Somerville +08; Fanidakis+09; Guo, White, et al. 2011; Somerville, Gilmore, Primack, & Dominguez 12 (reported here)

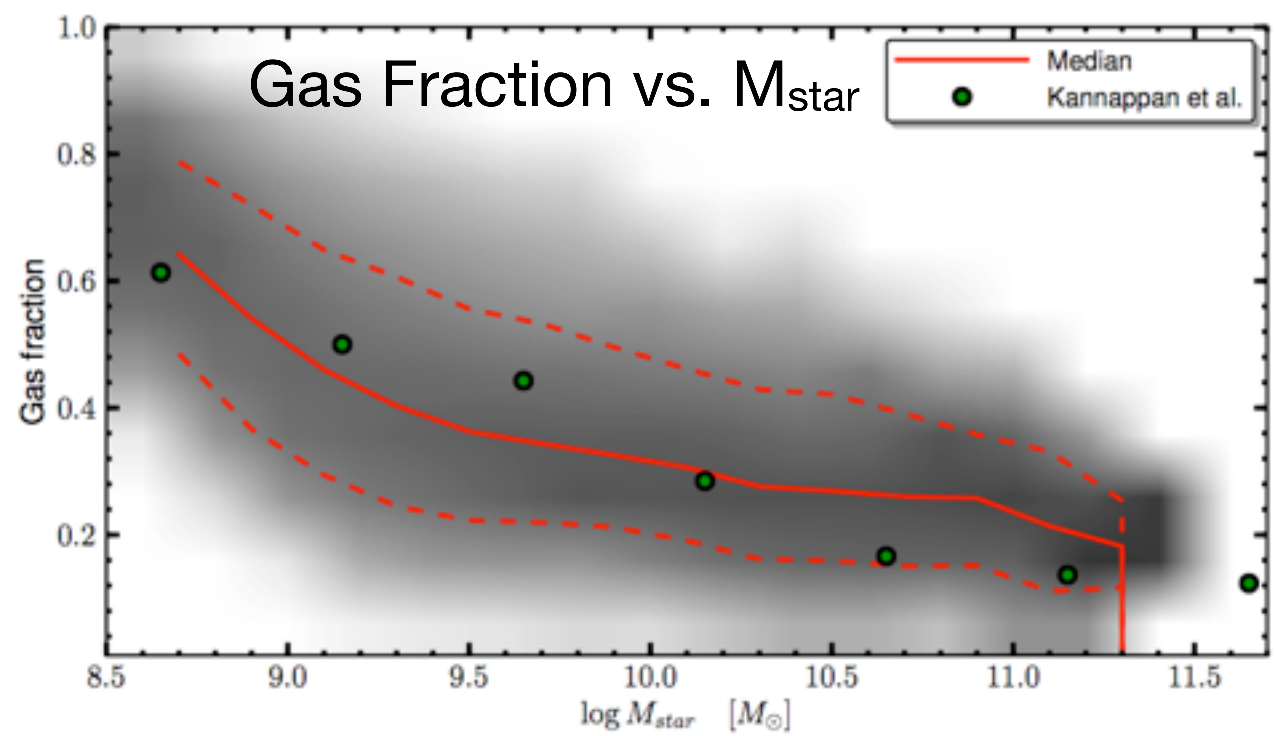
First SAM galaxy results with Bolshoi - Rachel Somerville

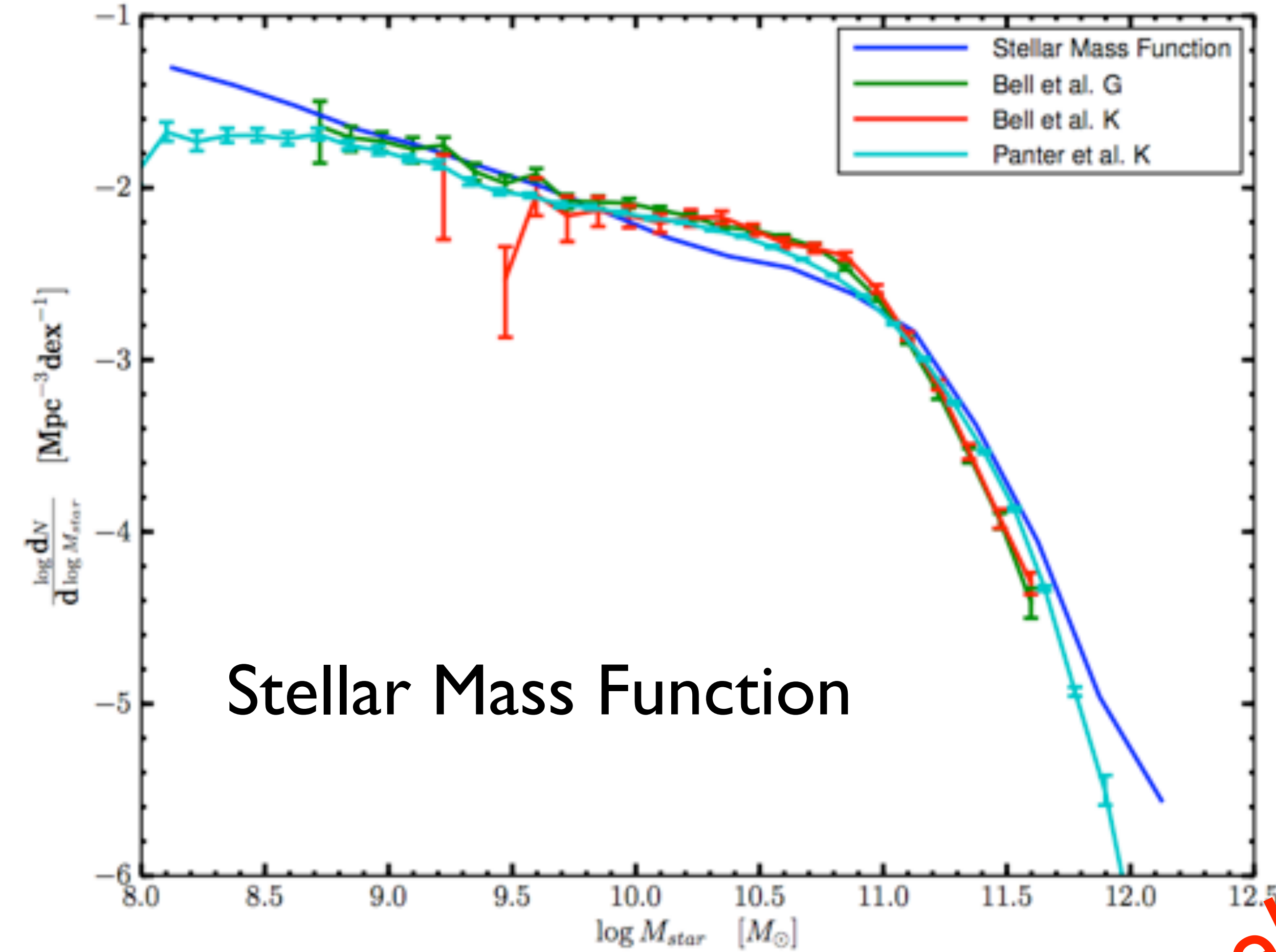


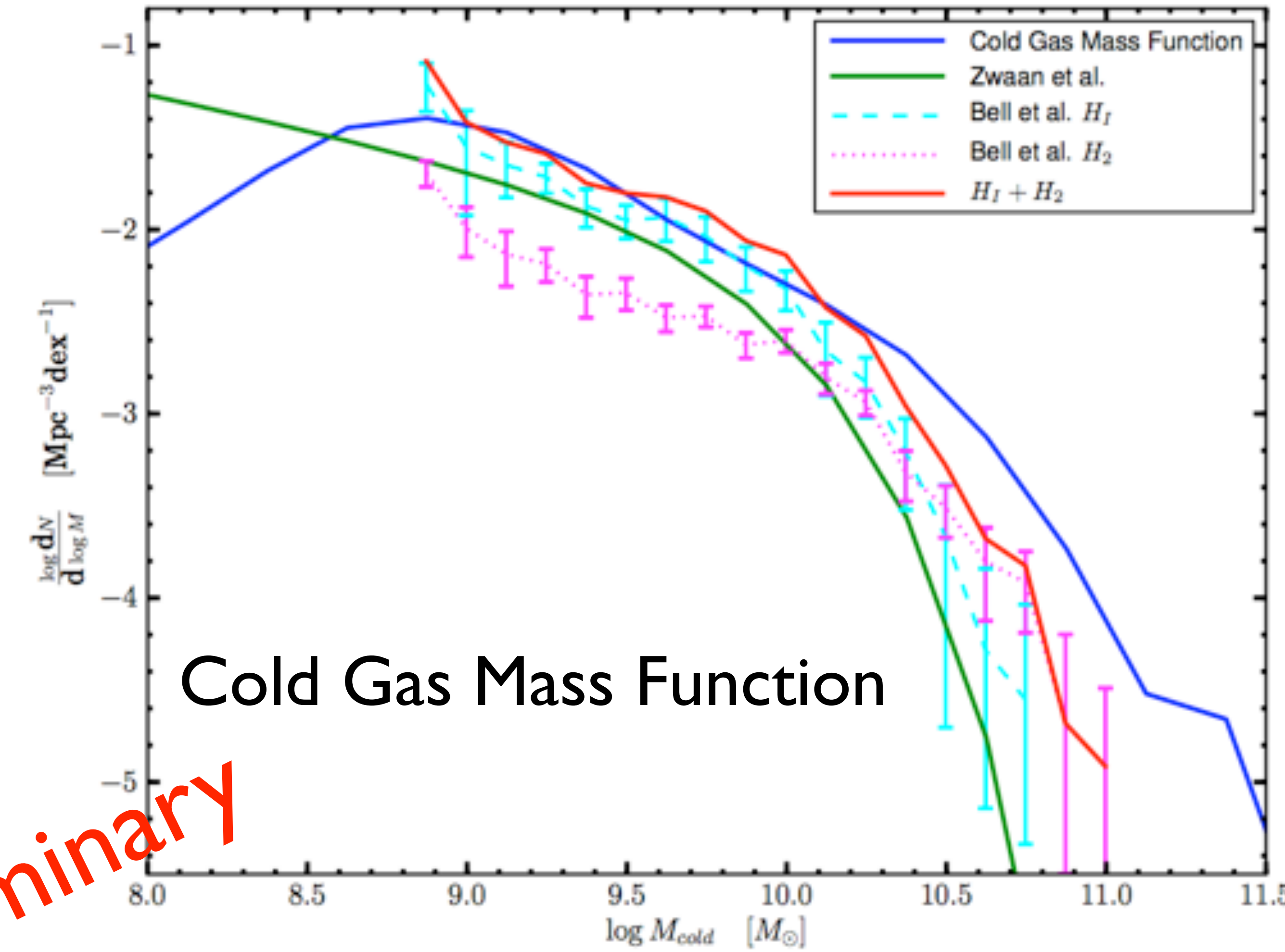


Preliminary









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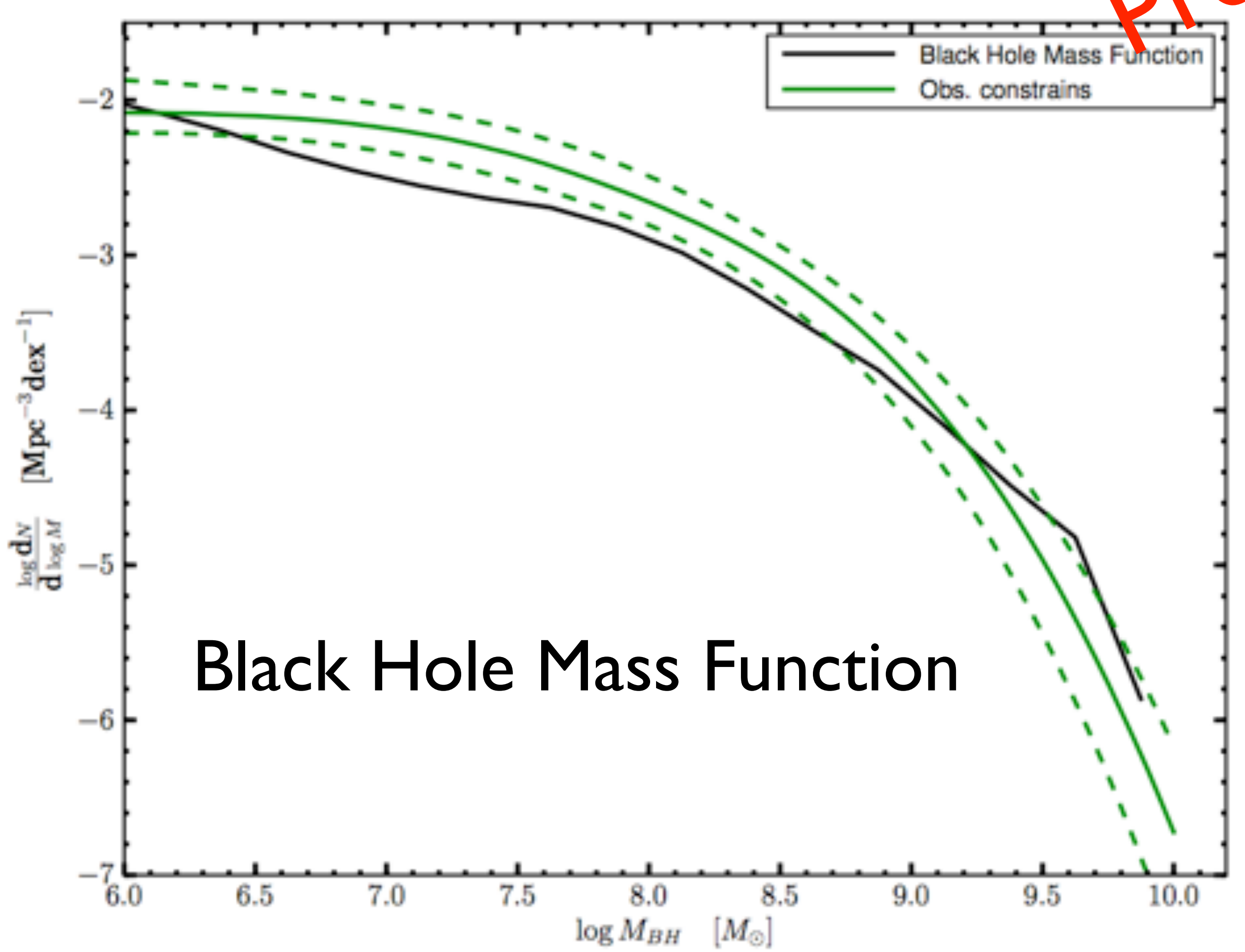

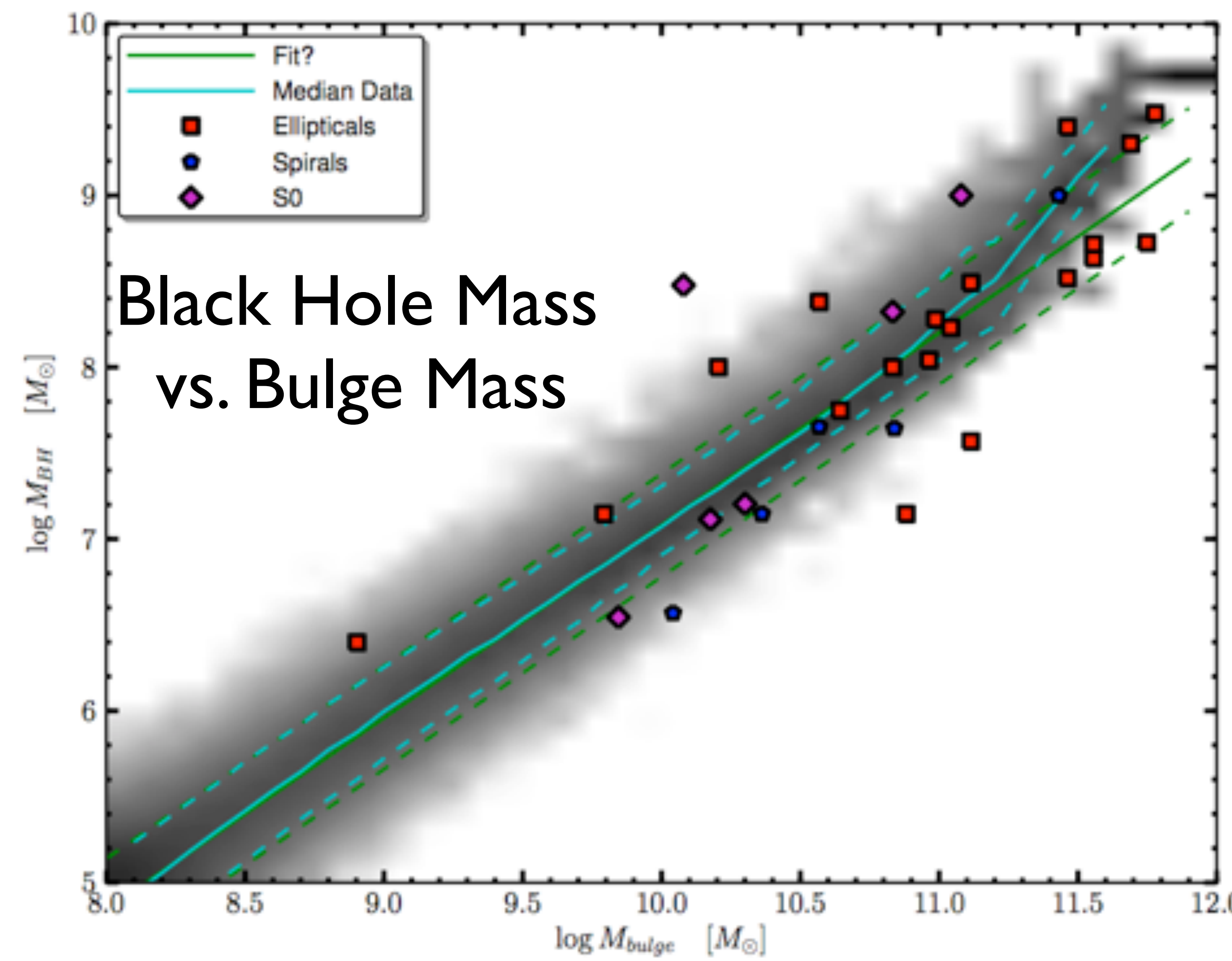

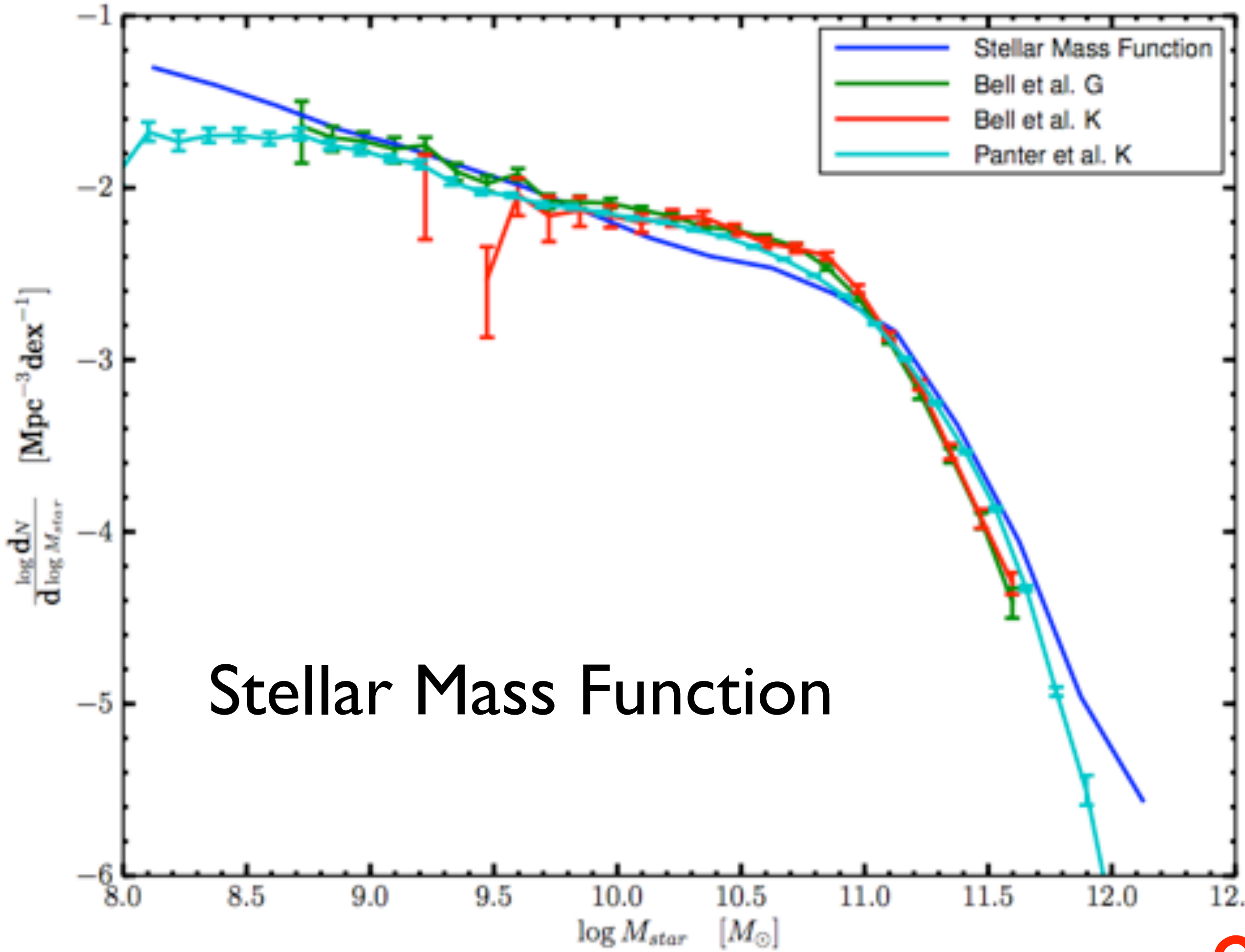

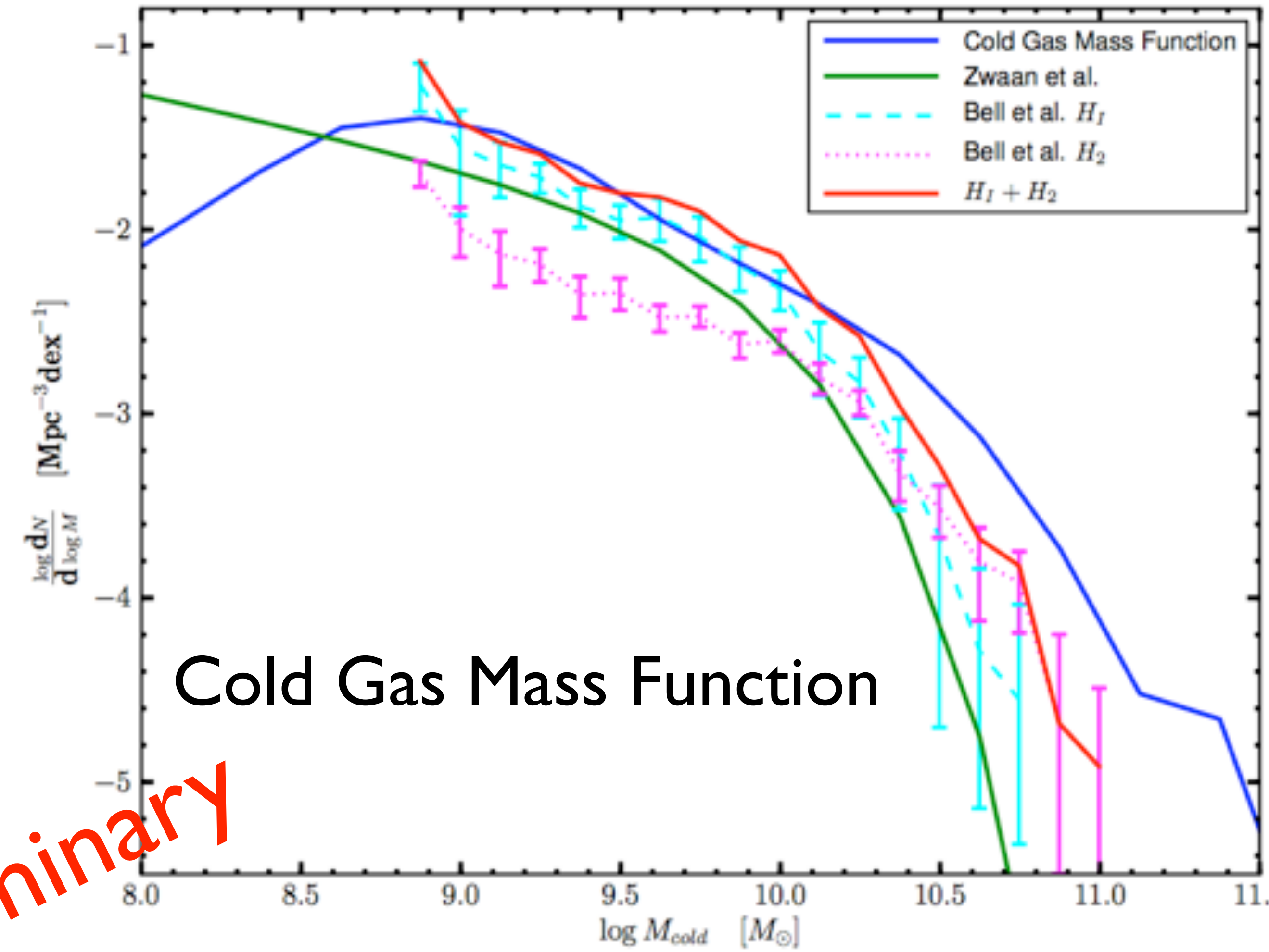

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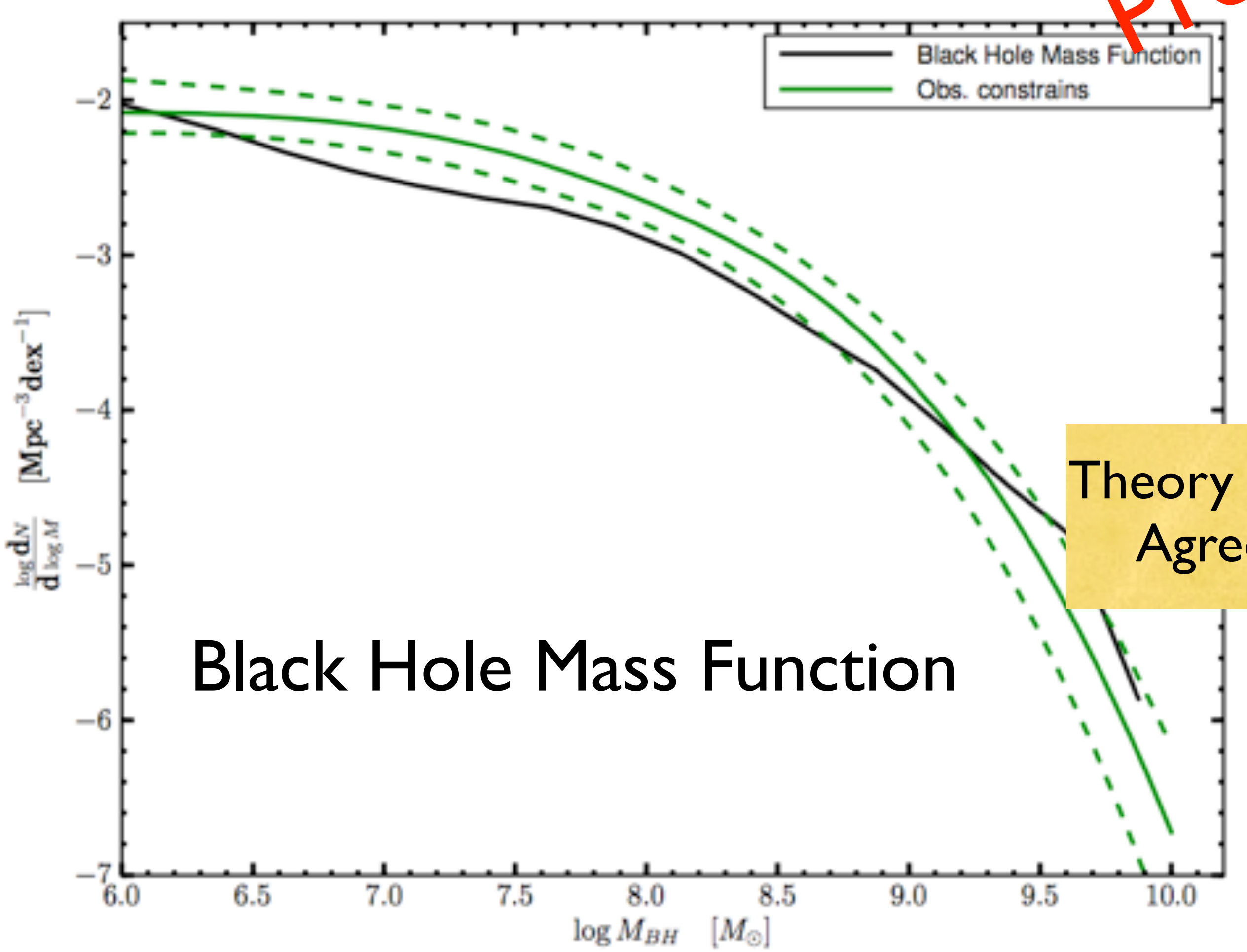

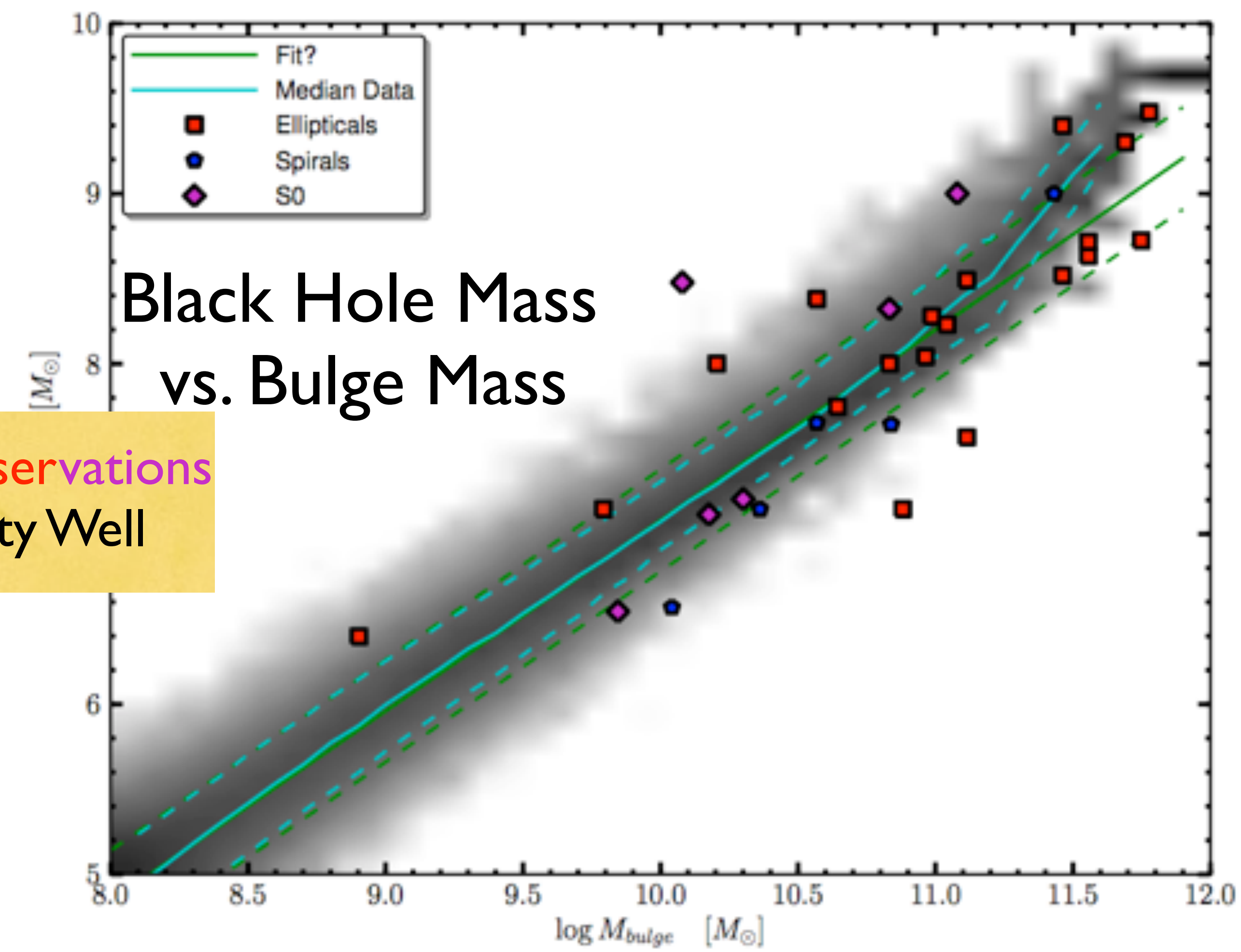

Theory & Observations
Agree Pretty Well

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** simulation will be available. Peter Behroozi new phase-space halo finder ROCKSTAR 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 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 were made available in September 2011at Astro Inst Potsdam: http://www.multidark.org/MultiDark/ (You have to get an account there.) Next: Merger Trees. We hope to have them up soon also at other sites.

The University of California
High-Performance AstroComputing Center

A consortium of nine UC campuses and three DOE laboratories

Simulation Visualizations

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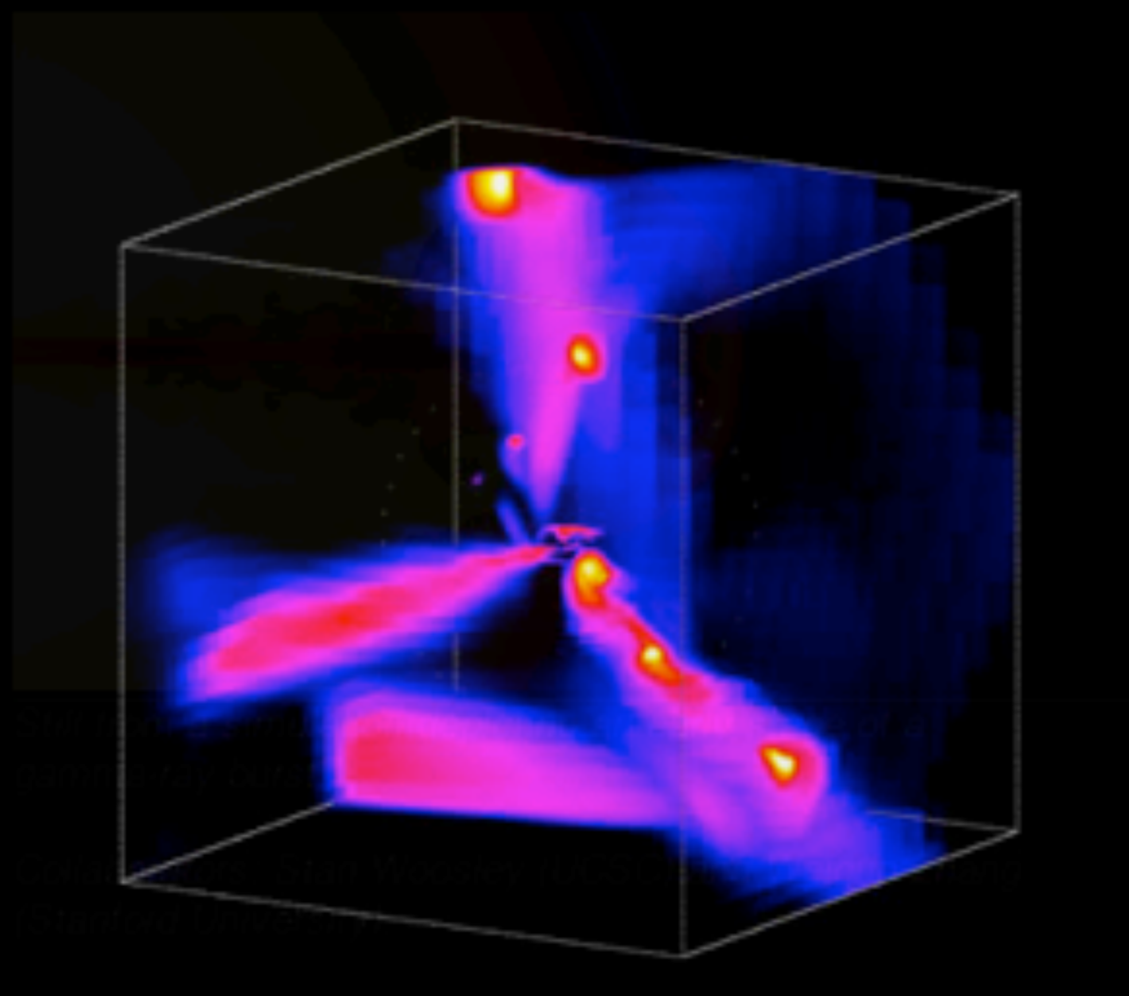


COLD STREAMS feeding a massive galaxy at high redshift: Mare Nostrum cosmological simulation

Image Credit: Avashai Dekel (Hebrew University of Jerusalem)

News /Announcements

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

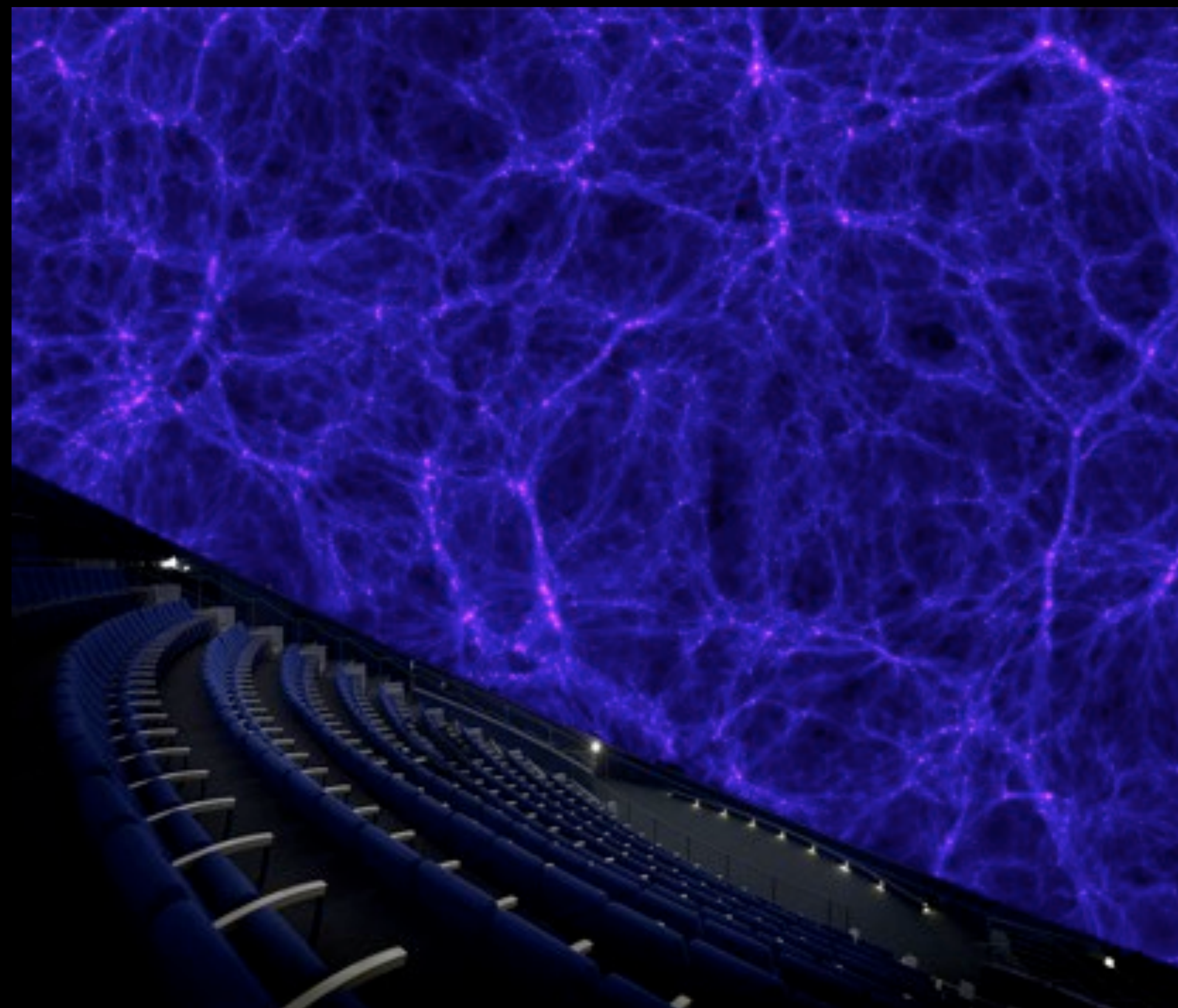
- **Published in September 15, 2011 issue of Nature Magazine:** A dwarf galaxy that has collided twice with our own Milky Way galaxy may well have triggered the formation of the Milky Way's beautiful spiral arms...[read more]
- Three "Bolshoi" Supercomputer Simulations of the Evolution of the Universe Announced by Authors from University of California, New Mexico State University...[more]
- **Visit the new Bolshoi website** [here]
- Now accepting proposals for the Fall 2011 Small Grants Program. Deadline: Nov. 4, 2011 [more]

Quick Links

- The 2011 International Astro-Computing Summer School on Computational

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 helped prepare their show *LIFE: a Cosmic Story* that opened in fall 2010, and also a major planetarium show that opened the new Adler Planetarium Grainger Sky Theater July 8, 2011.

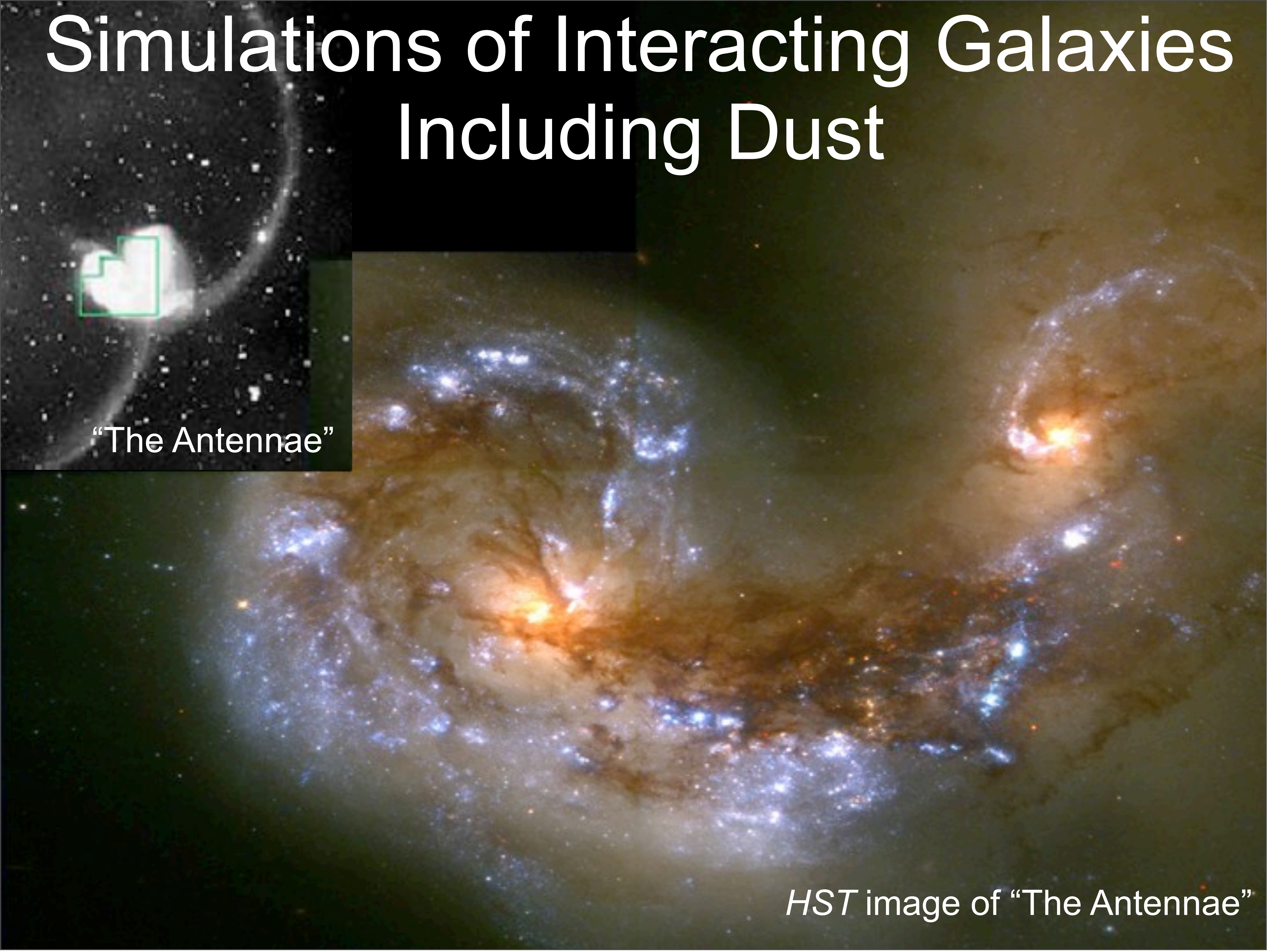
Galaxy Merger Simulation

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.

Simulations of Interacting Galaxies Including Dust

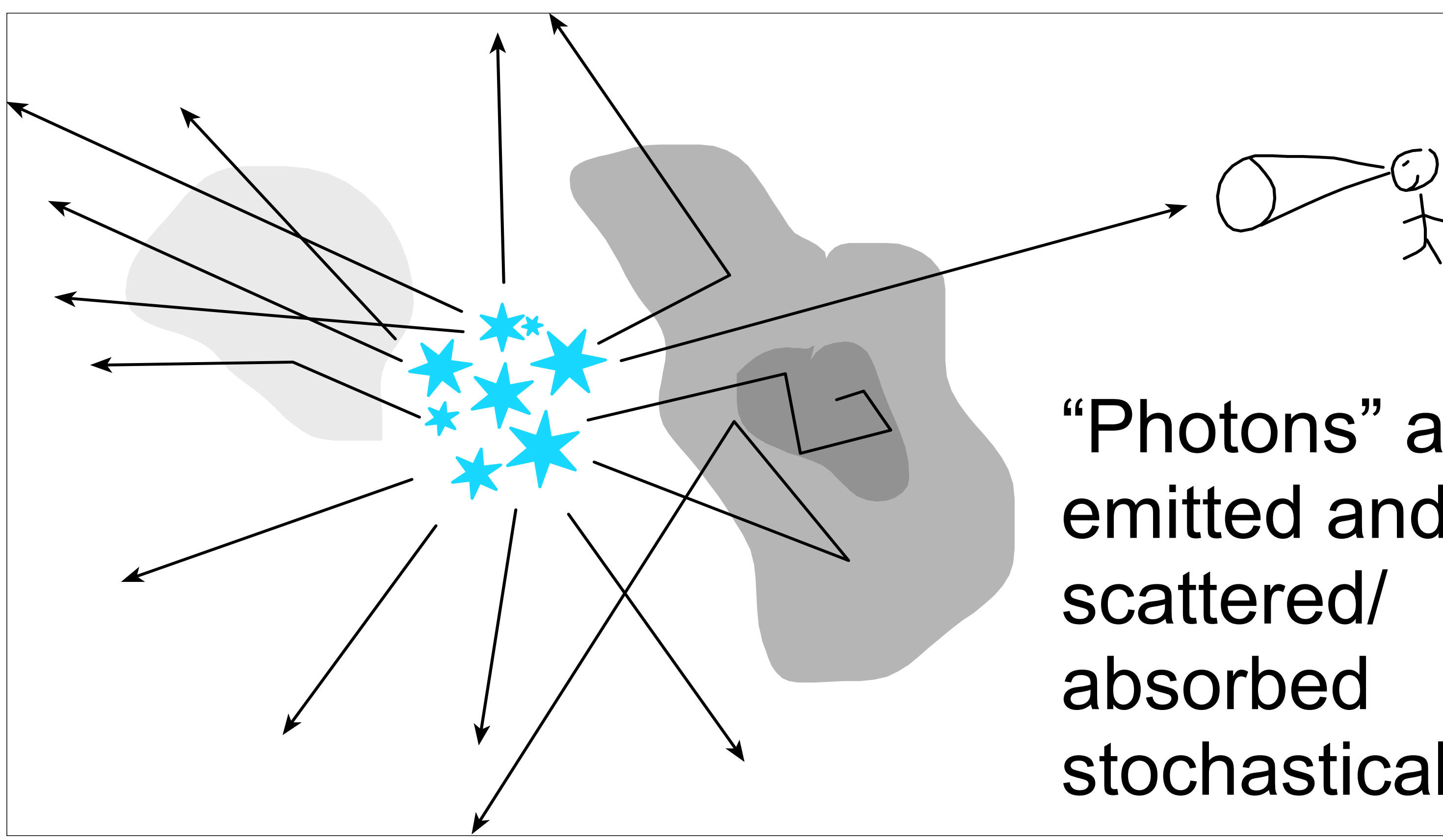


HST image of “The Antennae”

Sunrise Radiative Transfer Code

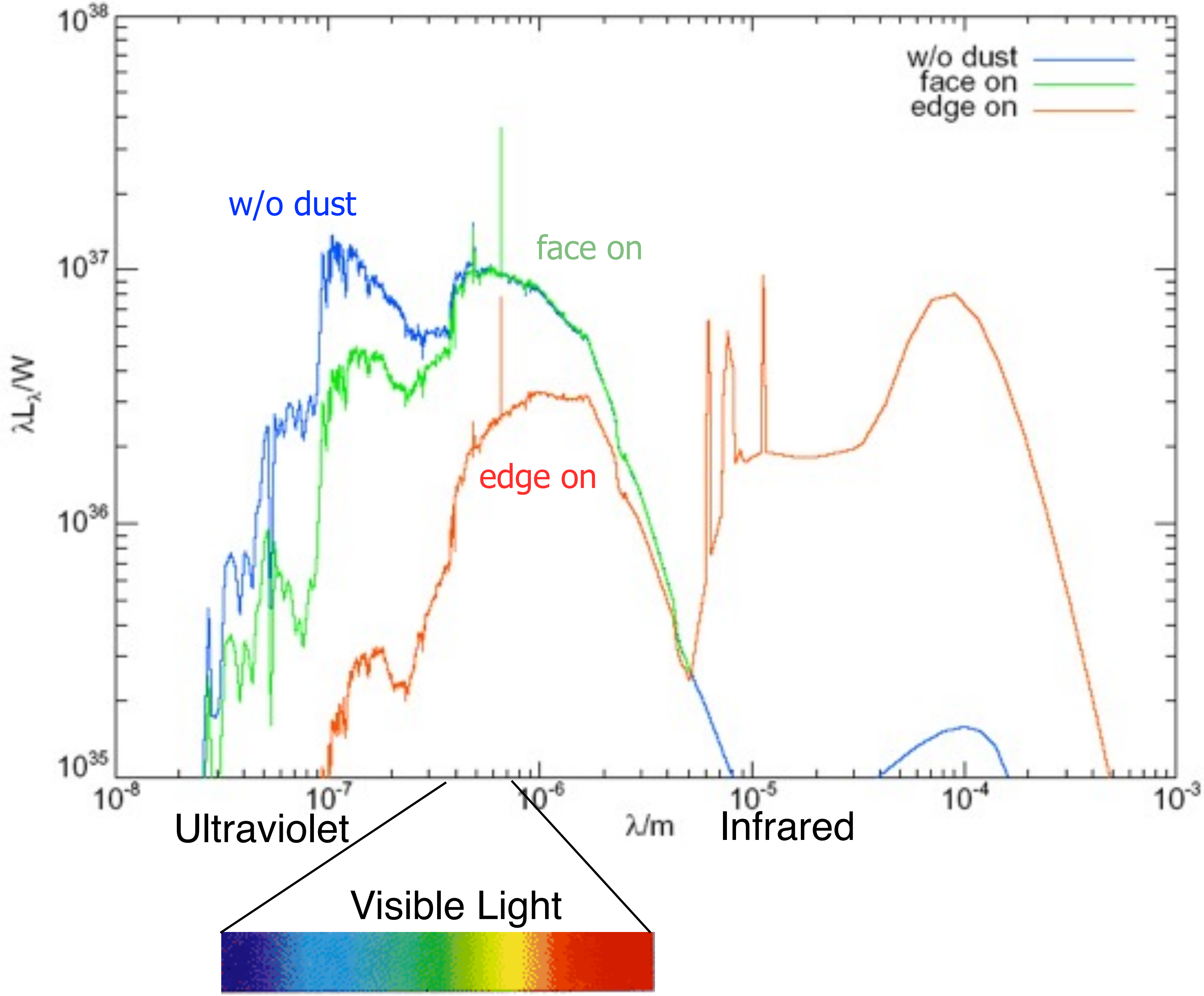
For every simulation snapshot:

- SED calculation
- Adaptive grid construction
- Monte Carlo radiative transfer
- “Polychromatic” rays save CPU time



Patrik Jonsson

Spectral Energy Distribution



Patrik Jonsson

Sunrise Visualizations

UCSC grad student Chris Moody (working with Primack, Matt Turk, and Patrik Jonsson) has created a pipeline to process ART simulation outputs efficiently to create multiwavelength *Sunrise* images. UCSC grad student Mark Mozena (working with Faber, Dekel, Koo, Lotz, and Primack) has perfected methods to convolve with appropriate PSFs and add noise to these *Sunrise* images, so that they can be compared directly with observations. We know that *Sunrise* with standard dust assumptions matches SEDs of nearby galaxies. We are runnning a number of dust models on hydro simulations of z ~2 to 3 galaxies to see what dust models will best agree with observed SEDs for similar galaxies. We plan to generate simulated images in ~5 wavebands of ~10 orientations of ~10 timesteps of the ~20 simulated galaxies that we have now (leading to about 10^4 images).

We plan to expand this by an order of magnitude over the next year or so (producing ~10^5 images). We are also looking into machine classification of real and simulated galaxy images, initially as a senior thesis project with UCSC astrophysics major Andrew Breslin. We would like to collaborate with experts on Computer Vision and Feature Extraction.

Galaxy Hydrodynamic Simulations

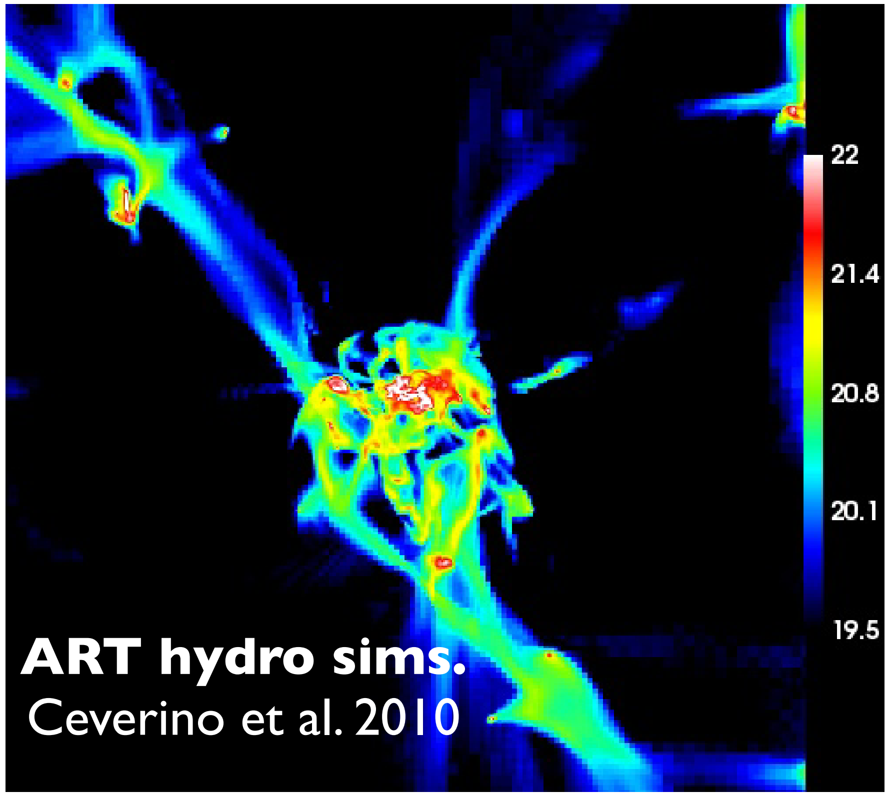
Physical phenomena included in ART simulations analyzed thus far:

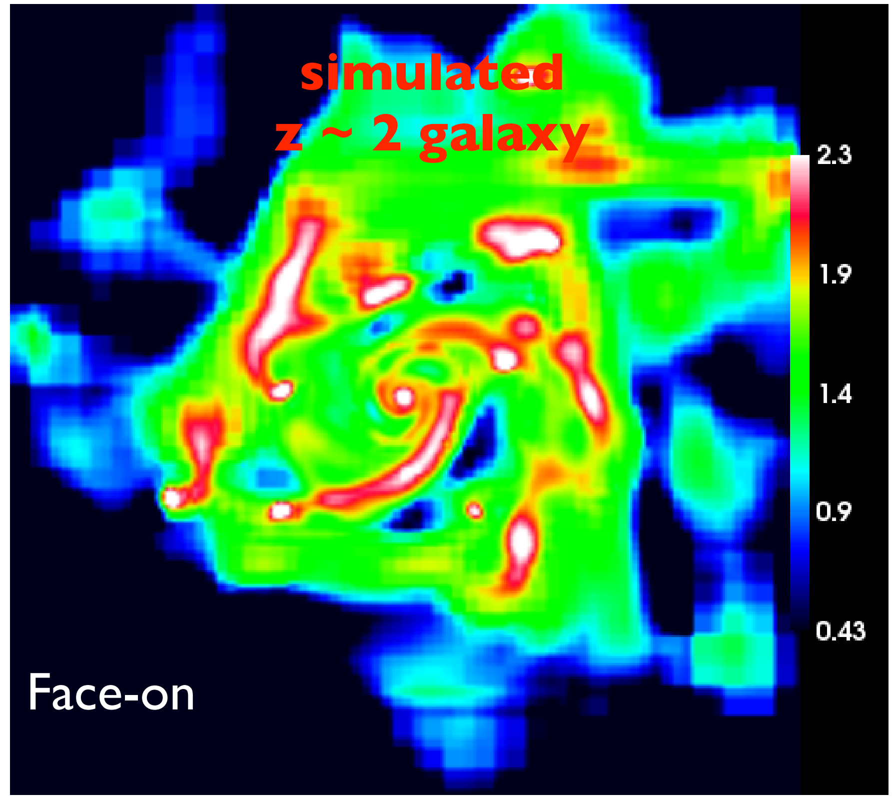
Dark matter and baryons, metal and molecular hydrogen cooling to ~100K, UV background with self-shielding, star formation, energy input from stellar winds and supernovae, advection of metals.

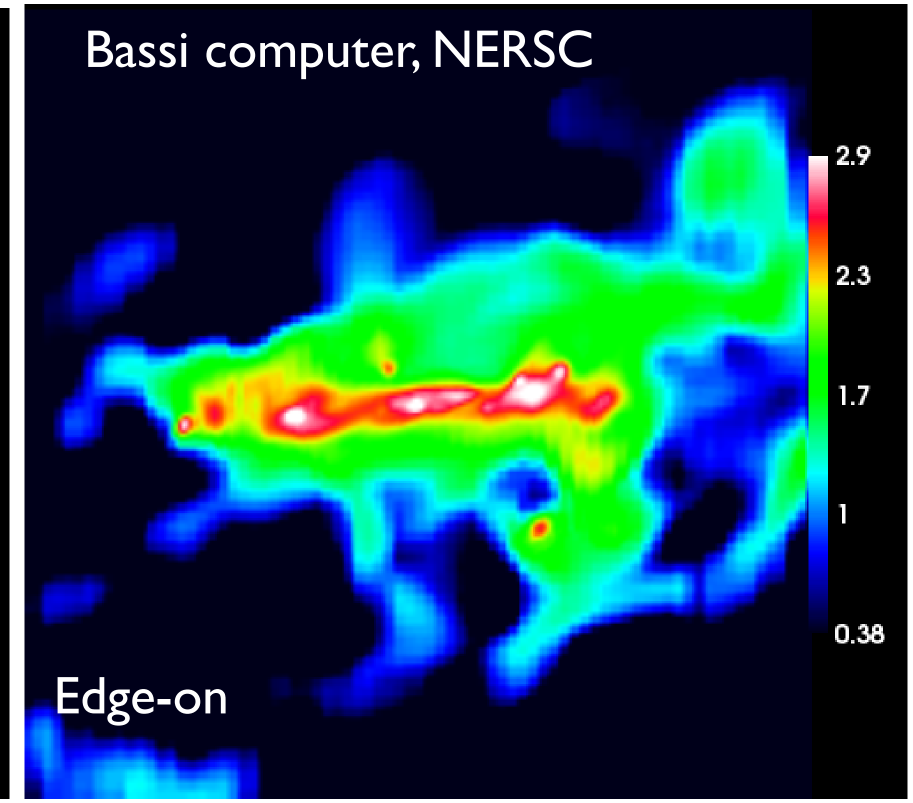
See Ceverino & Klypin 2009; Dekel, Sari, & Ceverino 2009; Ceverino, Dekel, & Bournaud 2010; Goerdt, Dekel, Sternberg, Ceverino, Teyssier, & Primack 2010; Fumagalli, Prochaska, Kasen, Dekel, Ceverino, & Primack 2011; Ceverino, Dekel, Mandelker, Bournaud, Burkert, Genzel, & Primack 2011; Kasen et al. 2011 and other papers in preparation.

Additional phenomena included in ART simulations currently running:

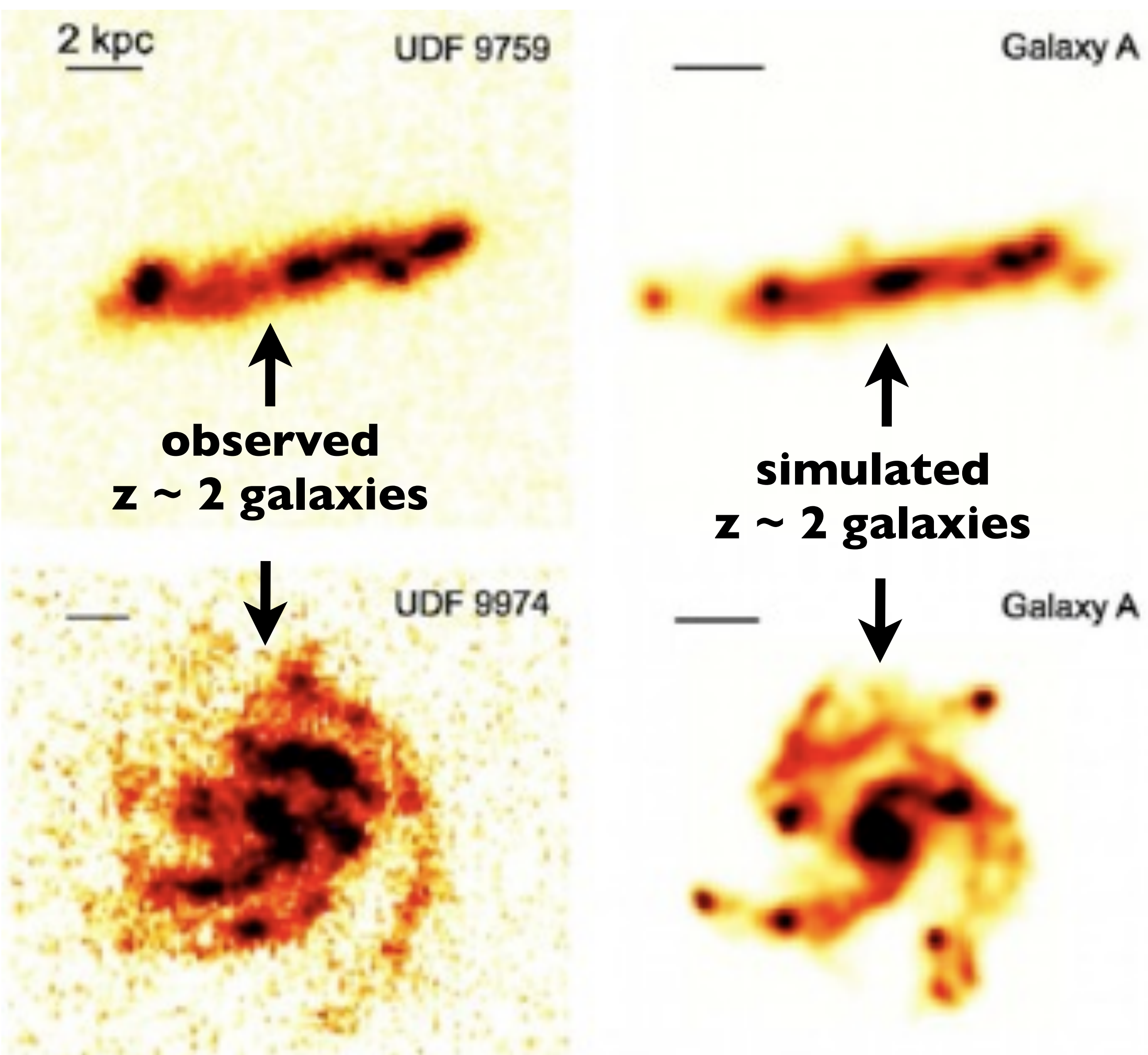
Radiative feedback from luminous stars and from AGN.



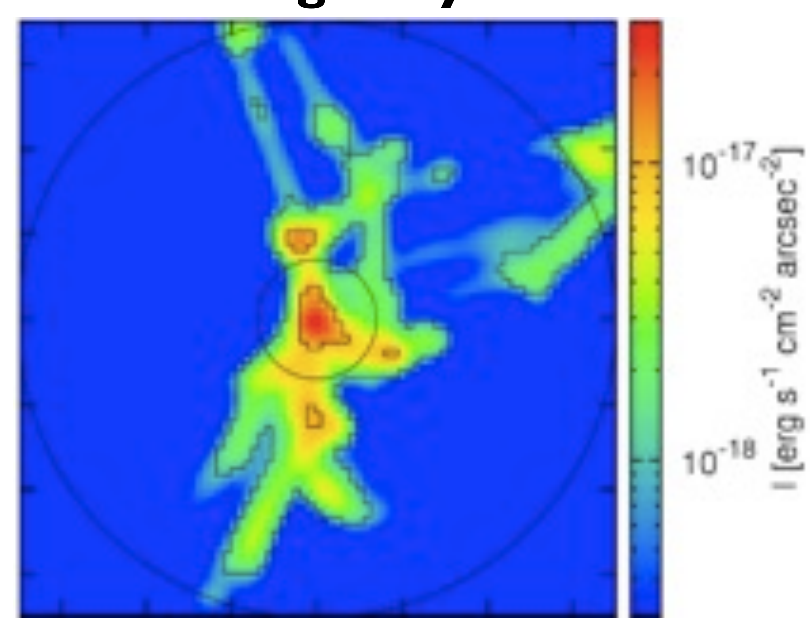




now running on NAS
Schirra computer

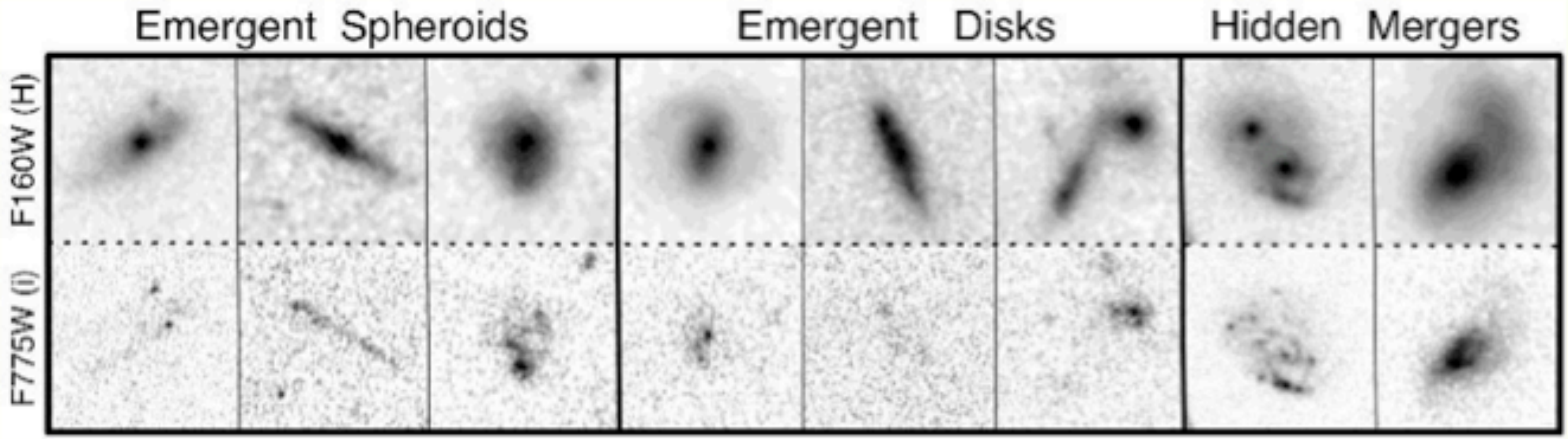


simulated
z ~ 2 galaxy



Ly alpha blobs
from same simulation
Goerdt et al. 2010

The CANDELS Survey

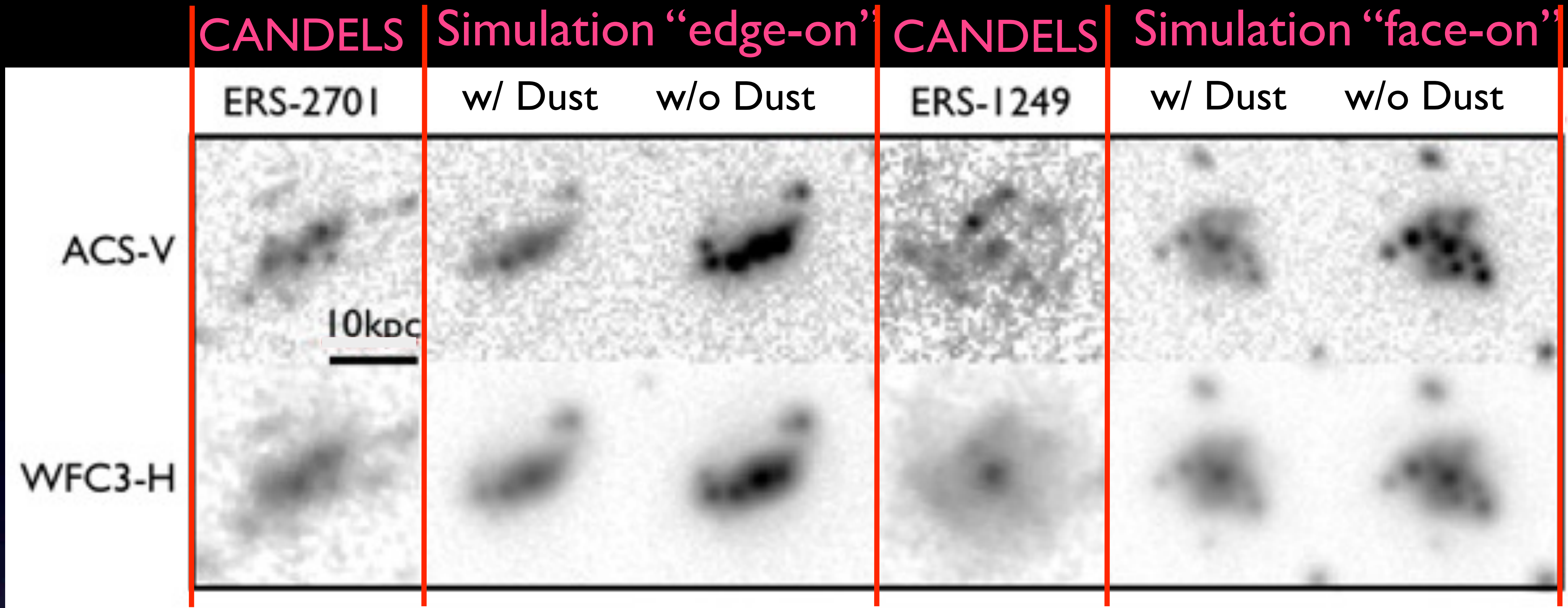


CANDELS makes use of the near-infrared WFC3 camera (top row) and the visible-light ACS camera (bottom row). Using these two cameras, CANDELS will reveal new details of the distant Universe and test the reality of cosmic dark energy.

CANDELS: A Cosmic Odyssey

CANDELS is a powerful imaging survey of the distant Universe being carried out with two cameras on board the Hubble Space Telescope.

- CANDELS is the largest project in the history of Hubble, with 902 assigned orbits of observing time. This is the equivalent of four months of Hubble time if executed consecutively, but in practice CANDELS will take three years to complete (2010-2013).
- The core of CANDELS is the revolutionary near-infrared WFC3 camera, installed on Hubble in May 2009. WFC3 is sensitive to longer, redder wavelengths, which permits it to follow the stretching of lightwaves caused by the expanding Universe. This enables CANDELS to detect and measure objects much farther out in space and nearer to the Big Bang than before. CANDELS also uses the visible-light ACS camera, and together the two cameras give unprecedented panchromatic coverage of galaxies from optical



Simulation shown is MW3 at z=2.33 'imaged' to match the CANDELS observations in ACS-Vband and WFC3-Hband
- 0.06" Pixel scale
- convolved with simulated psfs
- noise and background derived from ERS observations (same field as examples shown)

MW3 was imaged at 'face-on' and 'edge-on' viewing angles both with and without including dust models

Mark Mozena

Websites related to this talk:

- http://hipacc.ucsc.edu University of California High-Performance AstroComputing Center (UC-HiPACC)
- http://hipacc.ucsc.edu/Bolshoi Bolshoi simulations
- http://candels.ucolick.org CANDELS Hubble survey
- http://code.google.com/p/sunrise/ Sunrise dust code
- http://new-universe.org Many beautiful visualizations

Opportunities for Grad Student Projects

Analysis of Bolshoi cosmological simulations
- halo shapes, orientation, and cosmic web
- formation of MWy-type galaxies

Semi-Analytic Models of Galaxy Population Evolution
- filling dark matter halos with galaxies
- evolution of galaxy properties vs. observations

Hydrodynamic Galaxy Simulations
- comparing simulated galaxies with observed ones