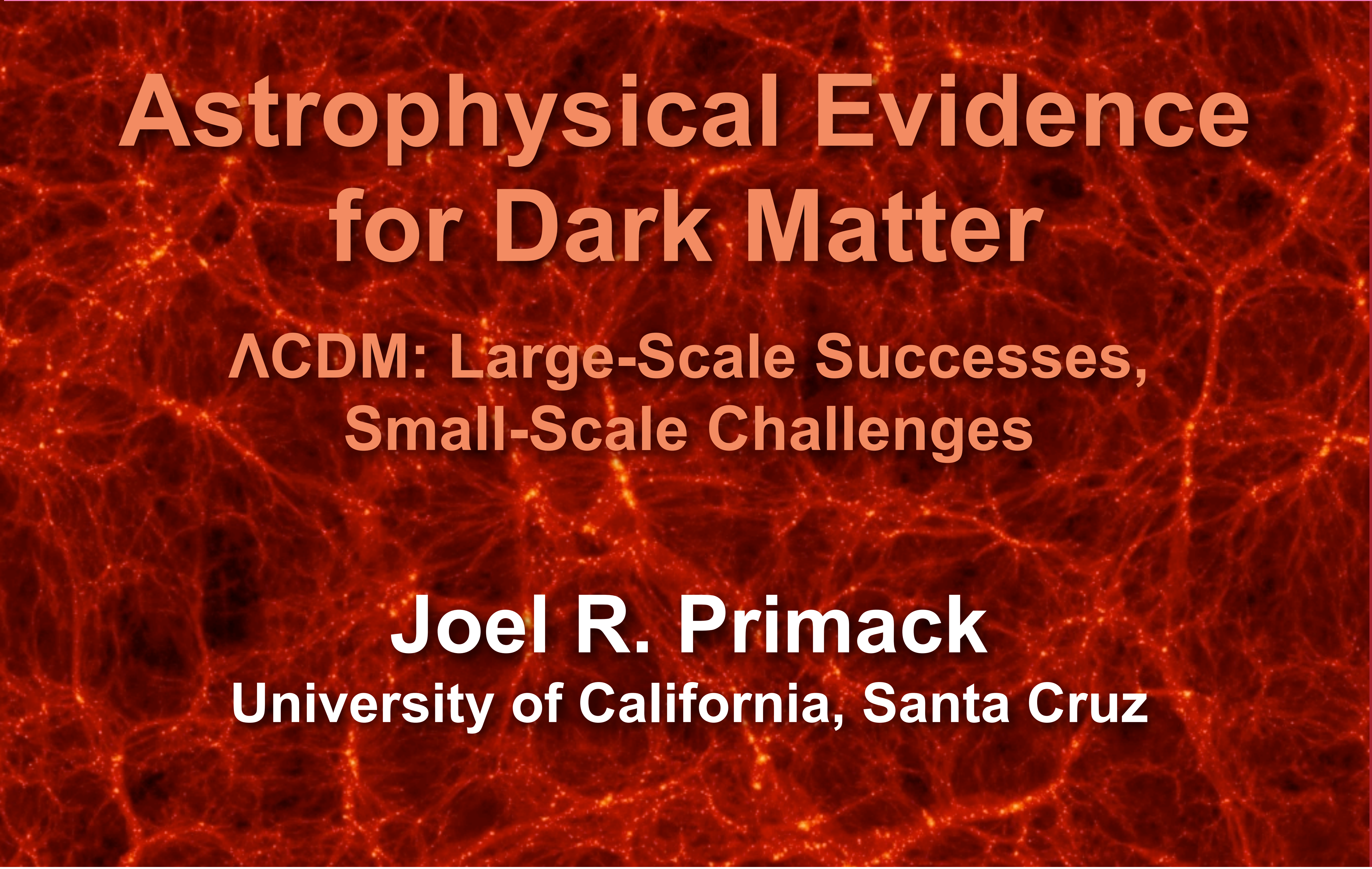
COSMO 2012
September 10-14, 2012
Beijing, China



Astrophysical Evidence for Dark Matter

ΛCDM: Large-Scale Successes, Small-Scale Challenges

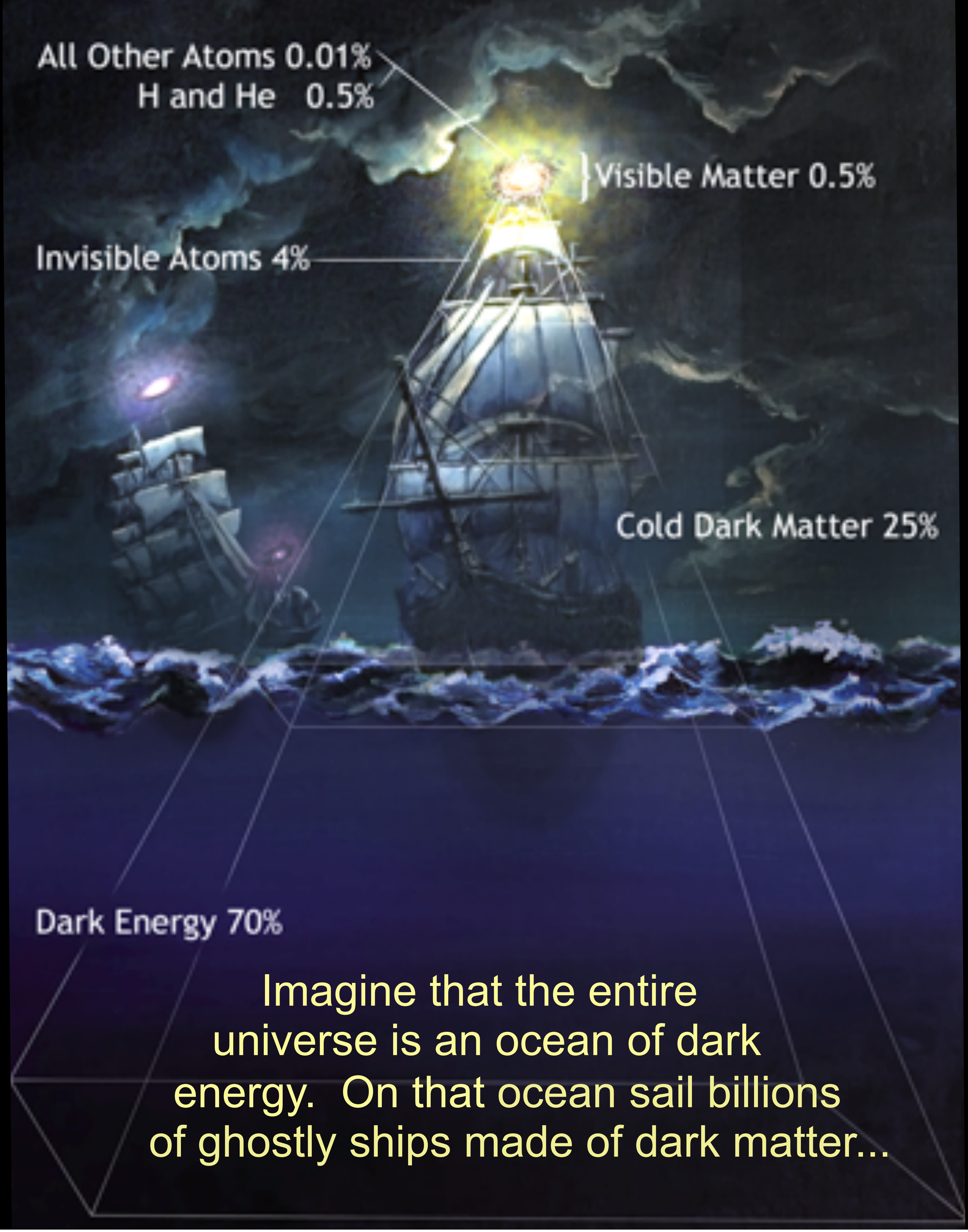
Joel R. Primack
University of California, Santa Cruz

Matter and Energy Content of the Universe

Dark Matter Ships

on a

Dark Energy Ocean

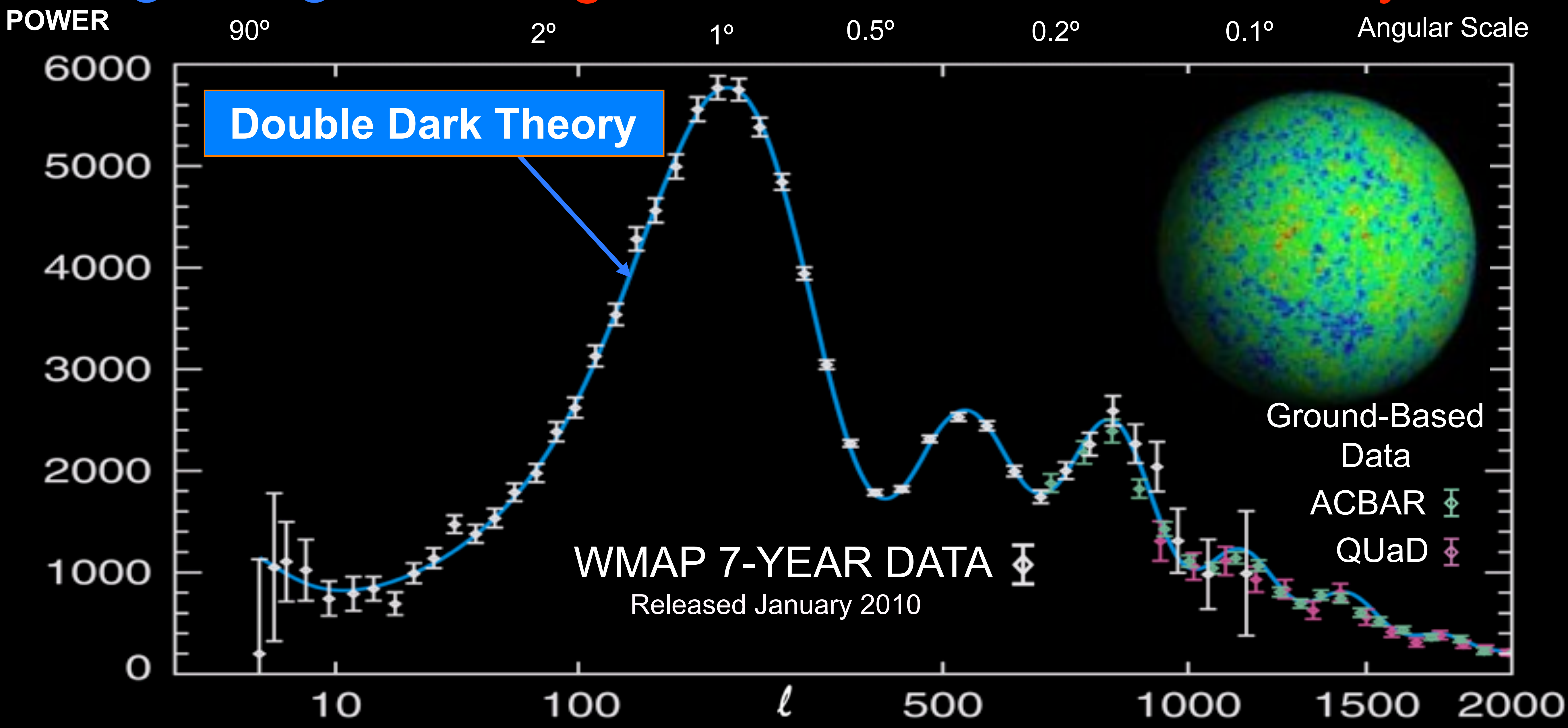


Imagine that the entire universe is an ocean of dark energy. On that ocean sail billions of ghostly ships made of dark matter...

ΛCDM

Double Dark Theory

Big Bang Data Agrees with Double Dark Theory!

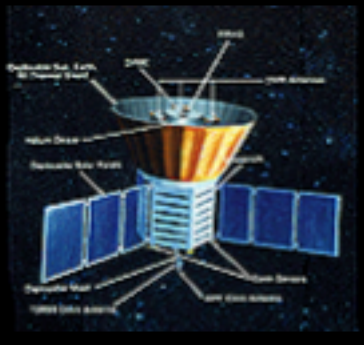


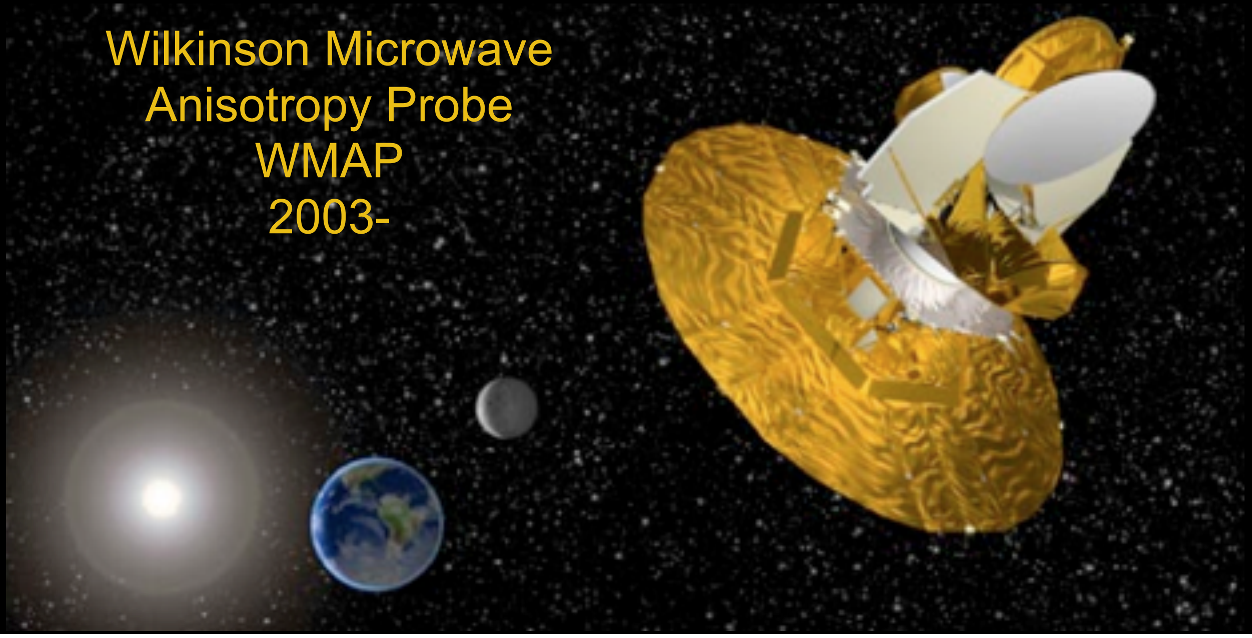
Double Dark Theory

WMAP 7-YEAR DATA

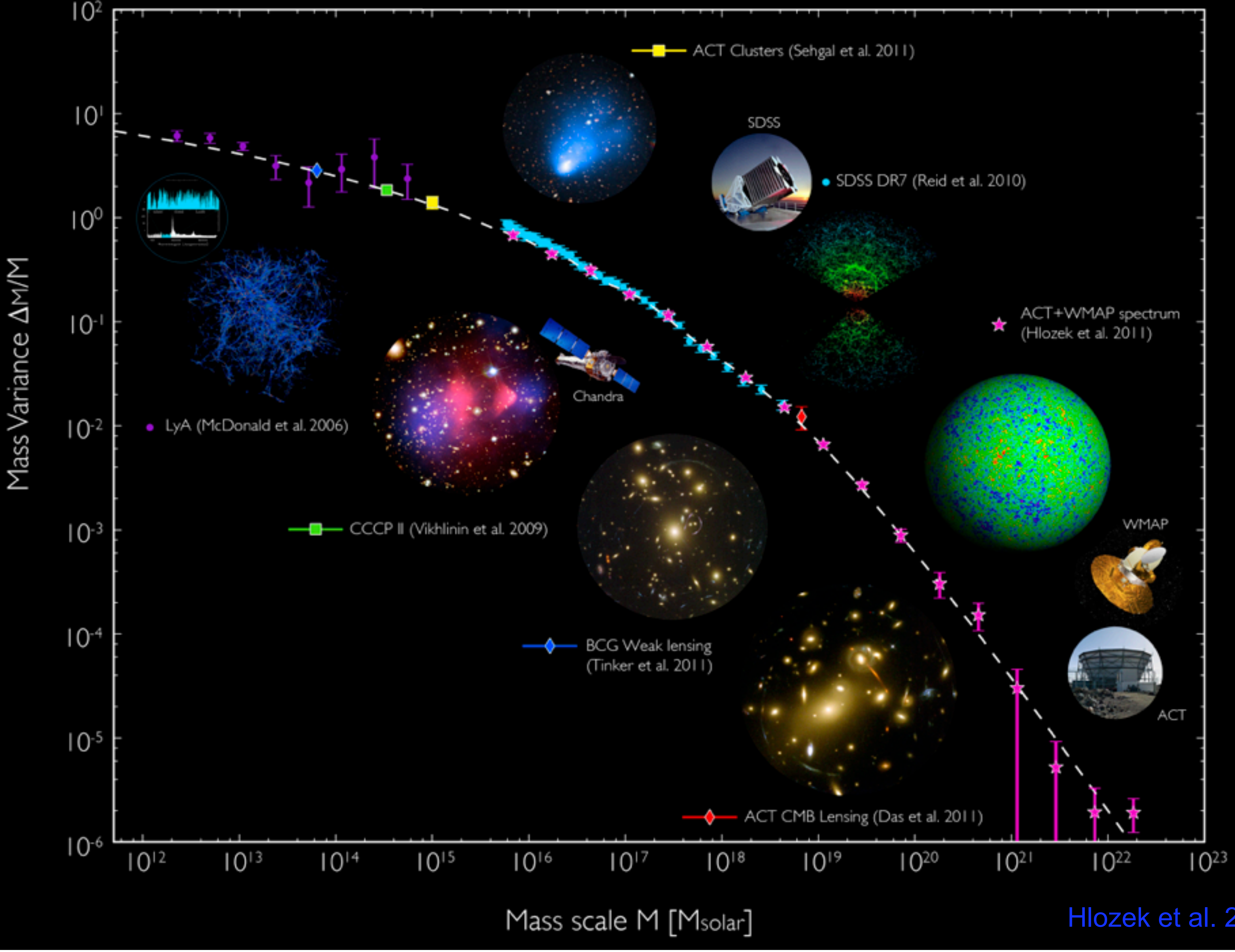
Released January 2010

Cosmic Background Explorer COBE 1992




Wilkinson Microwave Anisotropy Probe WMAP 2003-

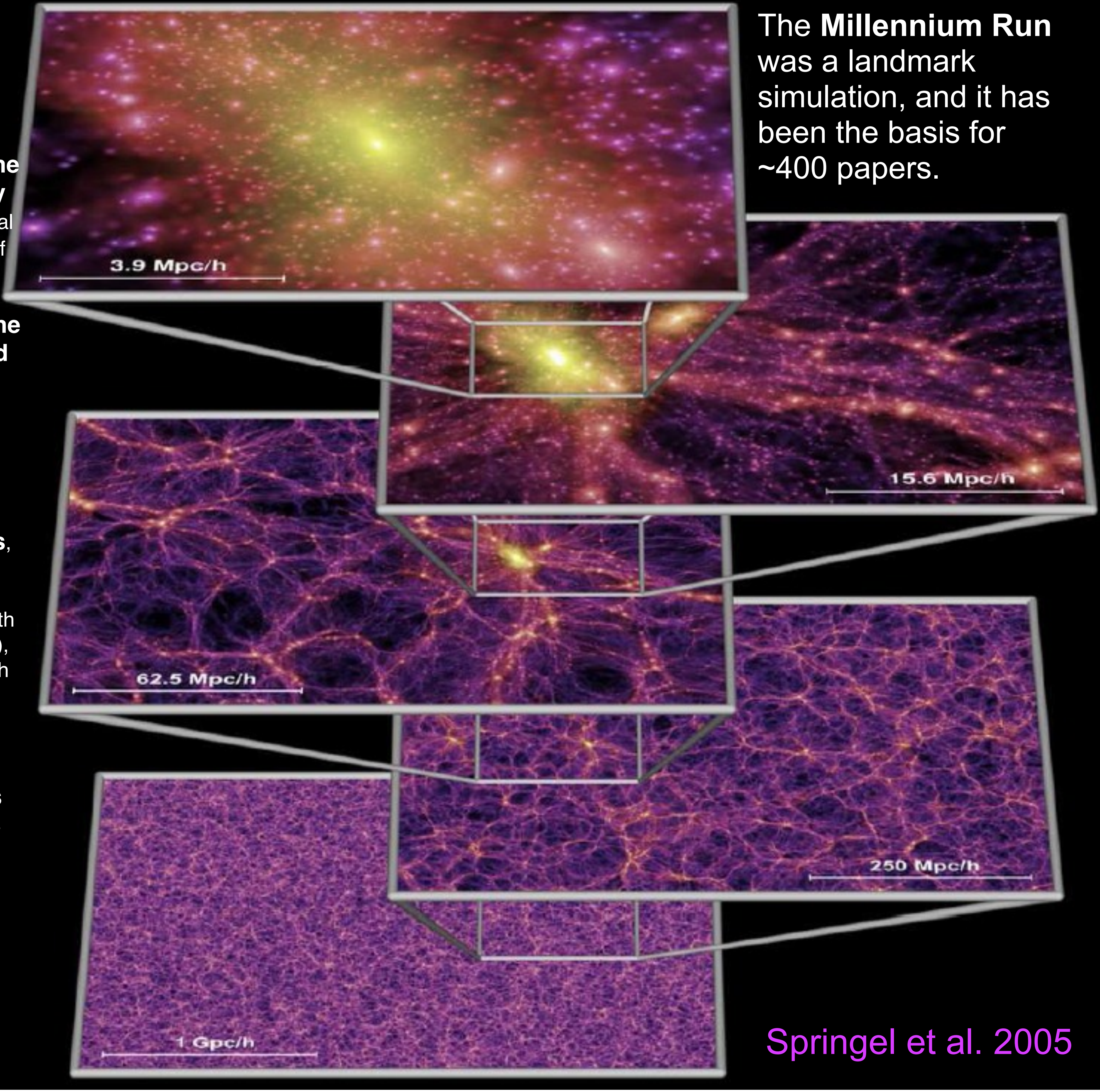
Matter Distribution Agrees with Double Dark Theory!



Hlozek et al. 2012

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

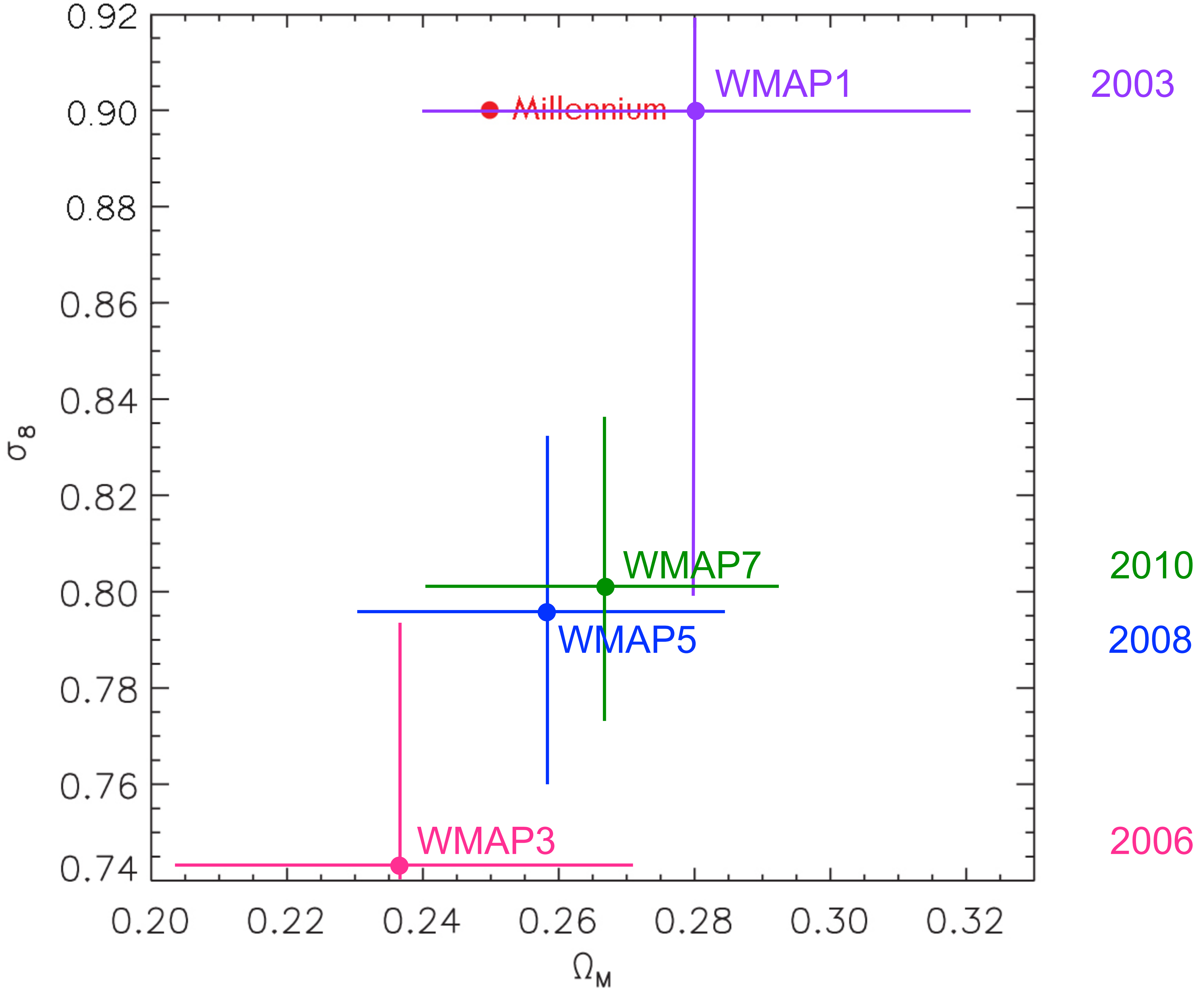


The **Millennium Run** was a landmark simulation, and it has been the basis for ~400 papers.

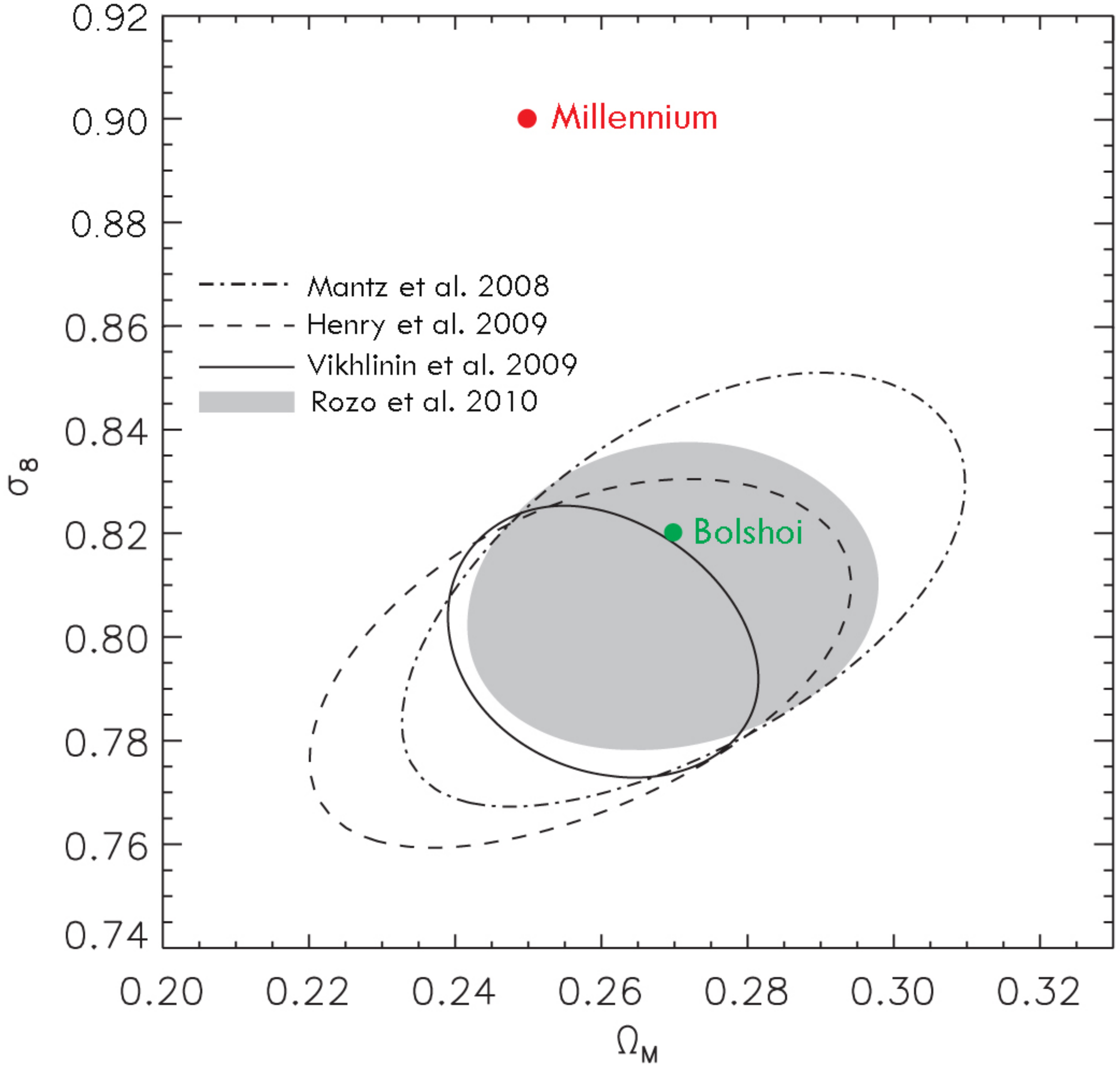
Springel et al. 2005

- **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.

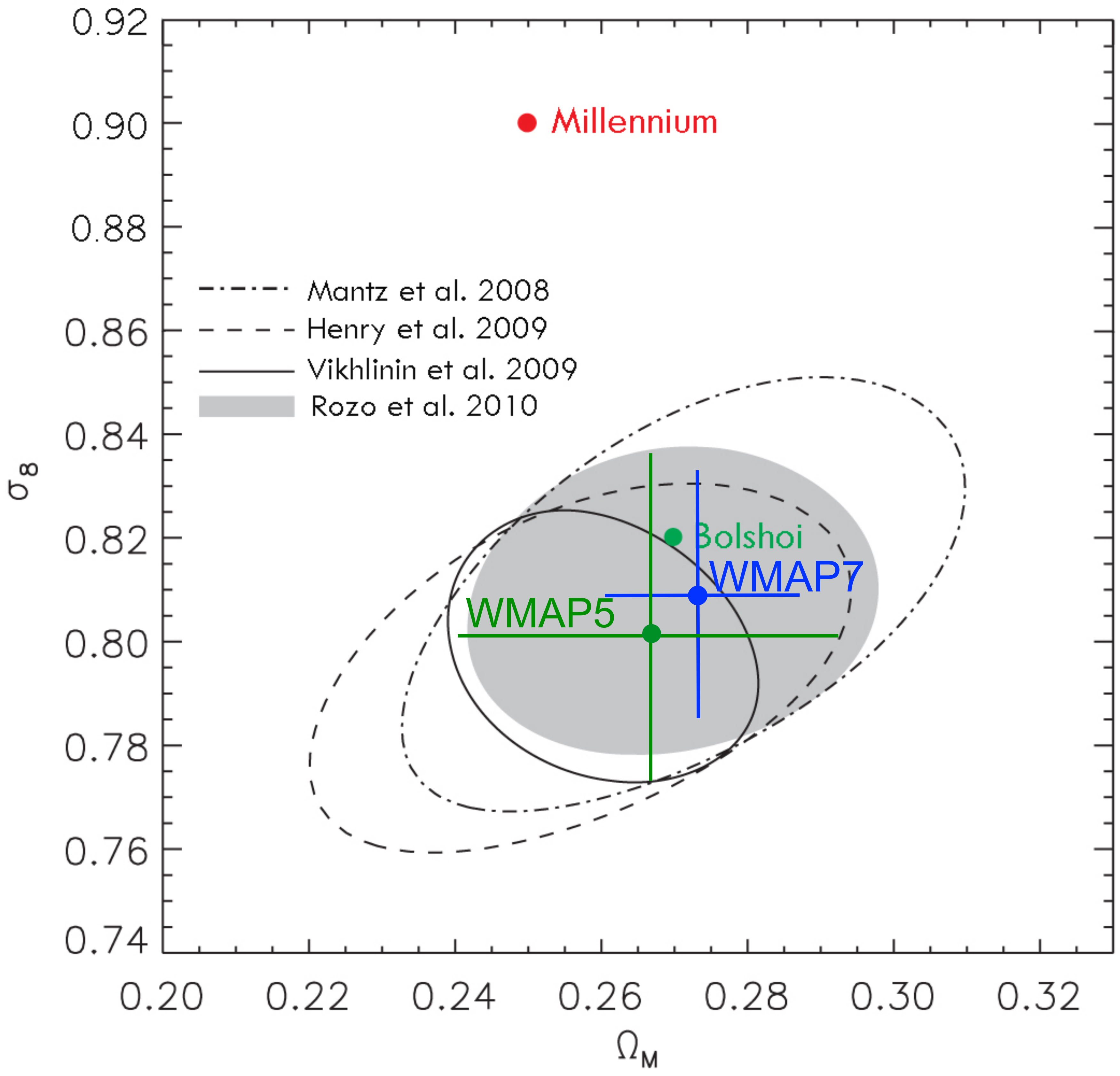
WMAP-only Determination of σ_8 and Ω_M



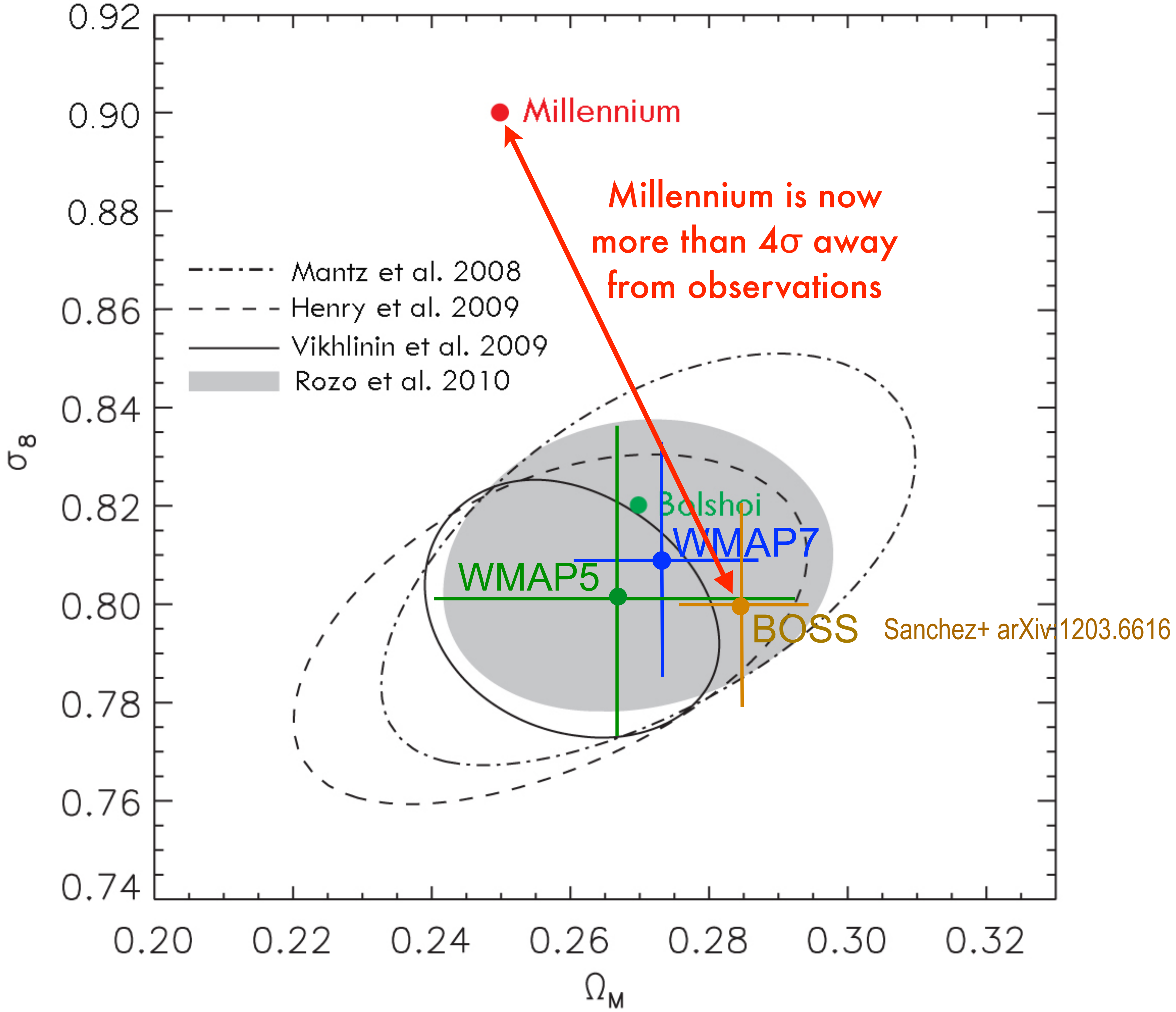
WMAP+SN+Clusters Determination of σ_8 and Ω_M



WMAP+SN+Clusters Determination of σ_8 and Ω_M



WMAP+SN+Clusters Determination of σ_8 and Ω_M



Millennium is now more than 4σ away from observations

Sanchez+ arXiv:1203.6616

The clustering of galaxies in the SDSS-III Baryon Oscillation Spectroscopic Survey: cosmological implications of the large-scale two-point correlation function

Sanchez et al. arXiv:1203.6616v3 MN in press

We combined the two-point correlation function ξ(s) measured from the BOSS-DR9 CMASS sample with additional cosmological probes, including CMB, SN, and BAO measurements from other data sets, to derive constraints on cosmological parameters. Conclusions:

Our results show that the simple ΛCDM model is able to describe all the datasets that we have included in our analysis. The basic parameters of this model are constrained to an accuracy better than 5%. Our results show no significant evidence of deviations from the ΛCDM picture, which can still be considered as our best cosmological model.

We obtain the curvature constraint $\Omega_k = -0.0043 \pm 0.0049$.

When massive neutrinos are considered in the analysis, we find a limit of $\sum m_\nu < 0.61$ eV on the sum of the three neutrino species. This limit is improved to $\sum m_\nu < 0.51$ when SN and BAO data are added to the analysis.

Our results are in excellent agreement with those of Anderson et al. (2012) and Reid et al. (2012), who explored the cosmological implications of the BAO and redshift-space distortions measurements in the CMASS sample. This highlights the consistency between the different analysis techniques implemented in each of these studies, and provides a reassuring demonstration of the robustness of our results.

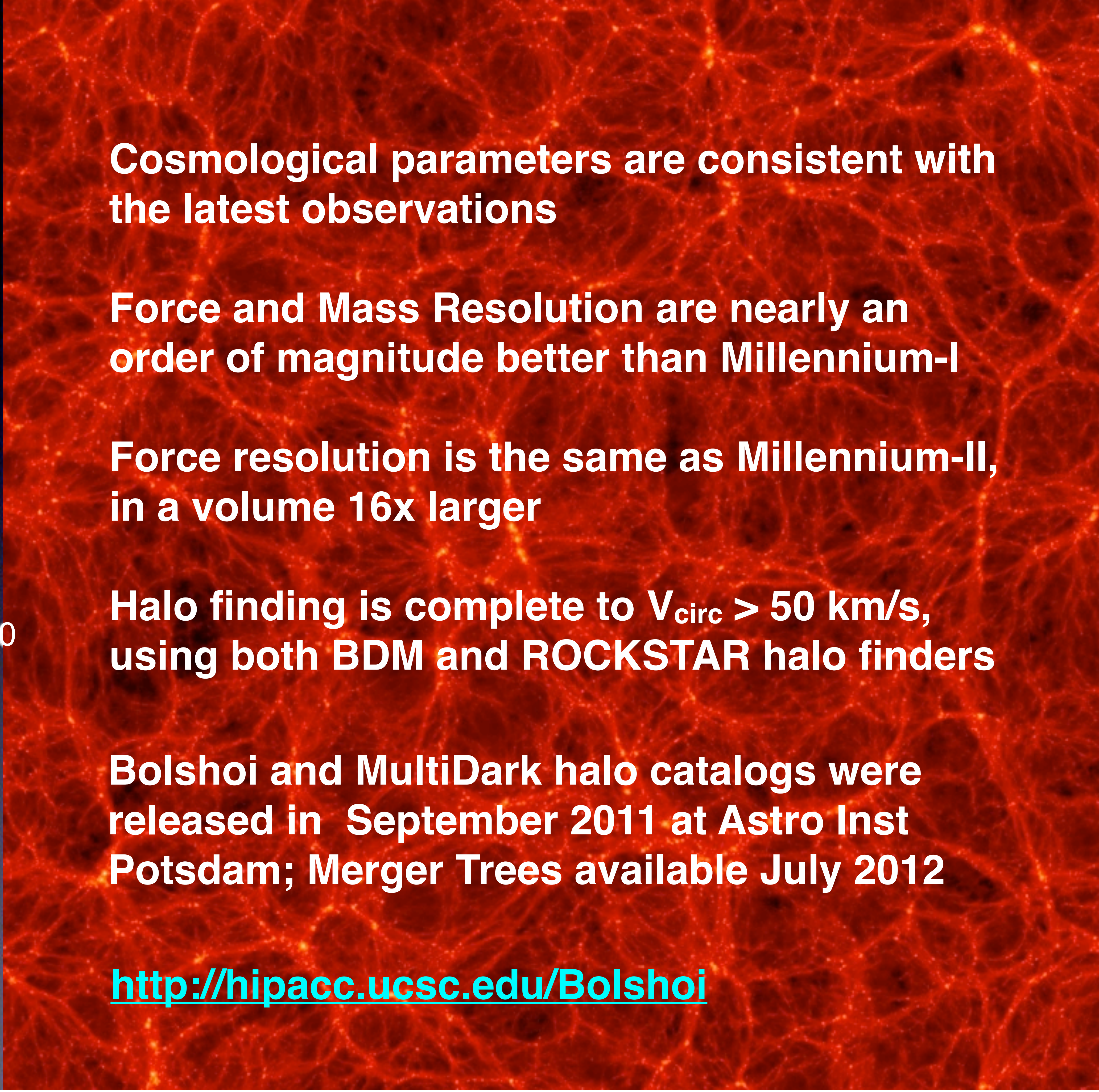
The Bolshoi simulation

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

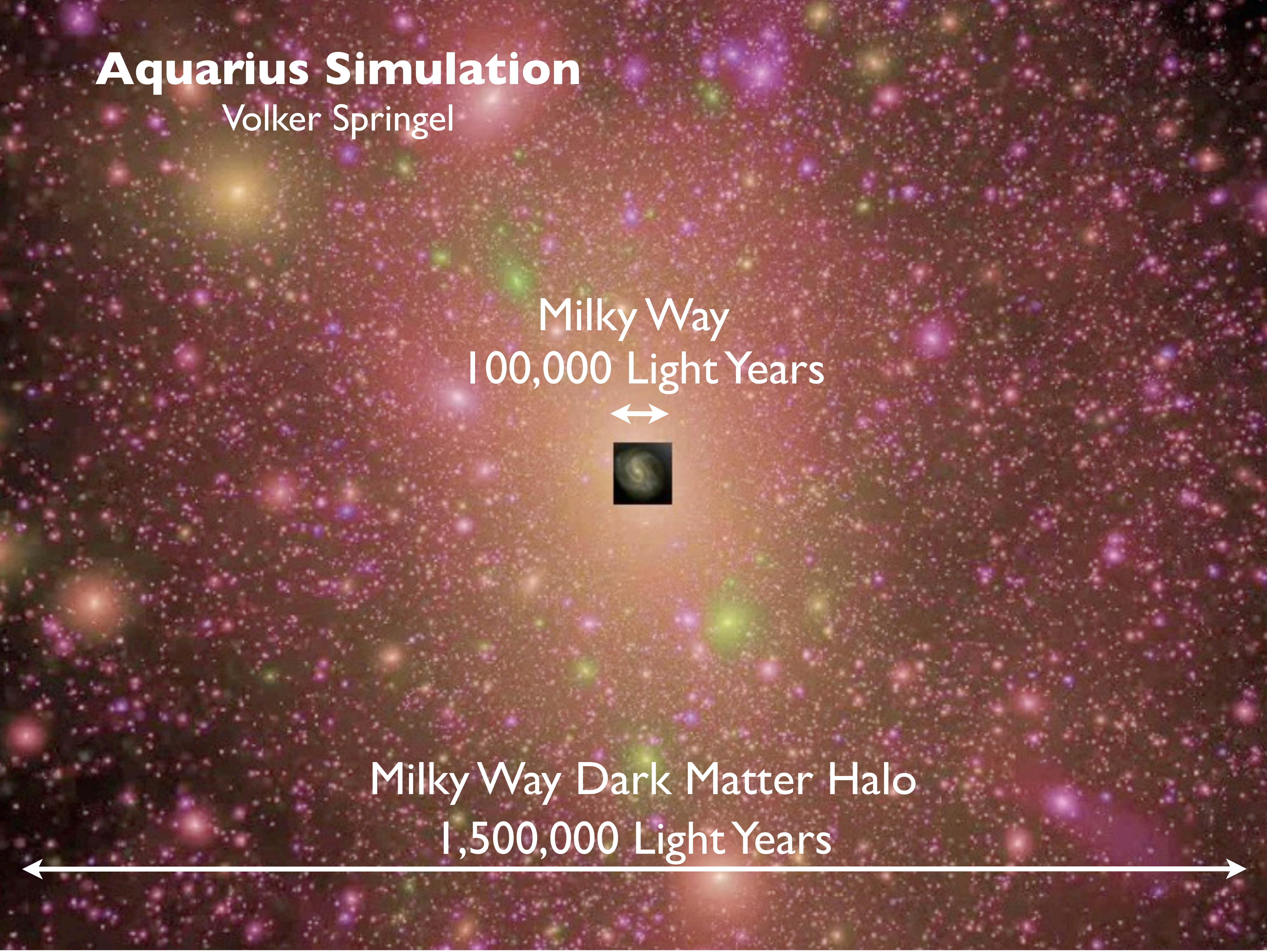
Halo finding is complete to V_{circ} > 50 km/s, using both BDM and ROCKSTAR halo finders

Bolshoi and MultiDark halo catalogs were released in September 2011 at Astro Inst Potsdam; Merger Trees available July 2012

http://hipacc.ucsc.edu/Bolshoi

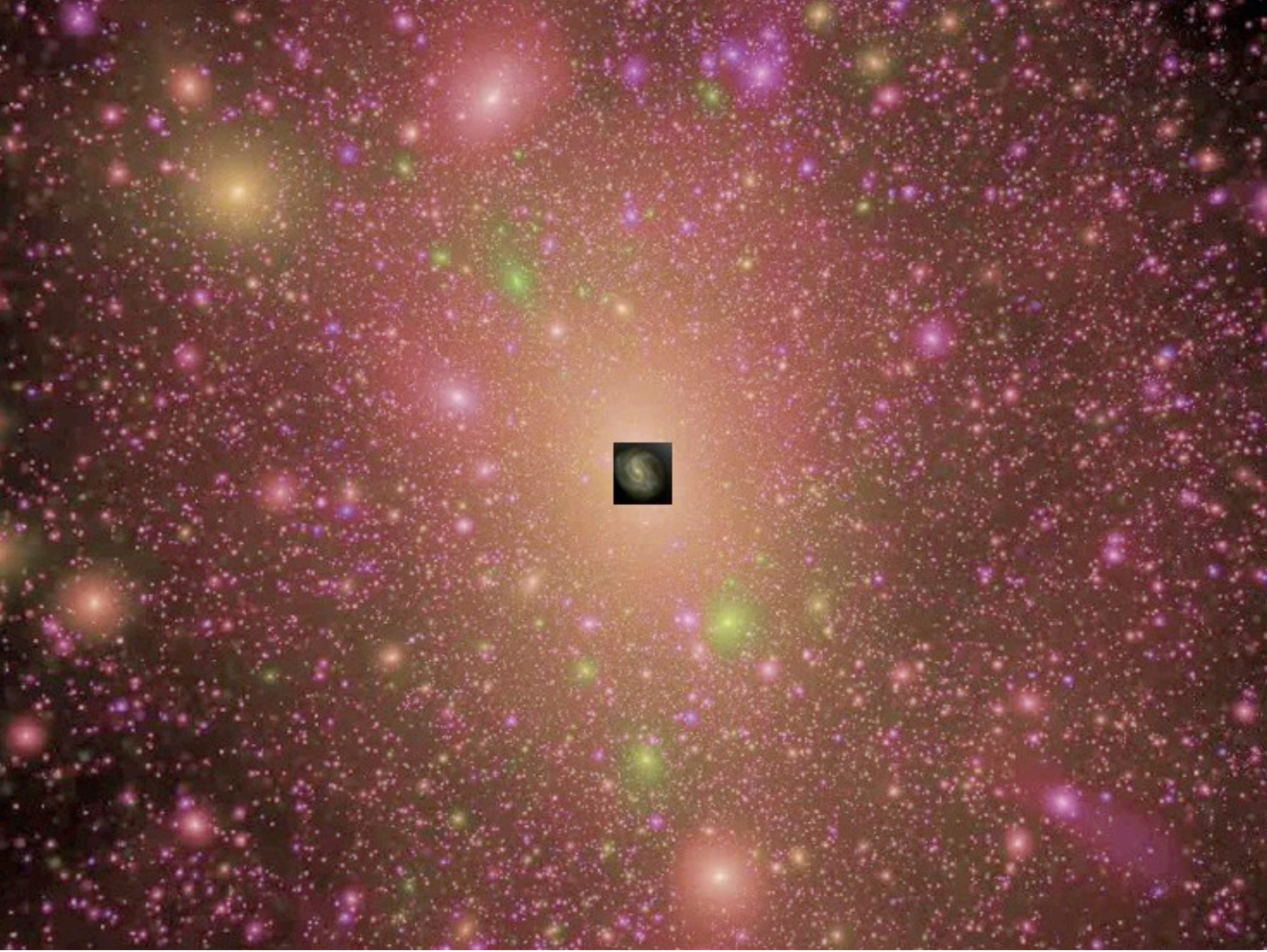
Aquarius Simulation

Volker Springel

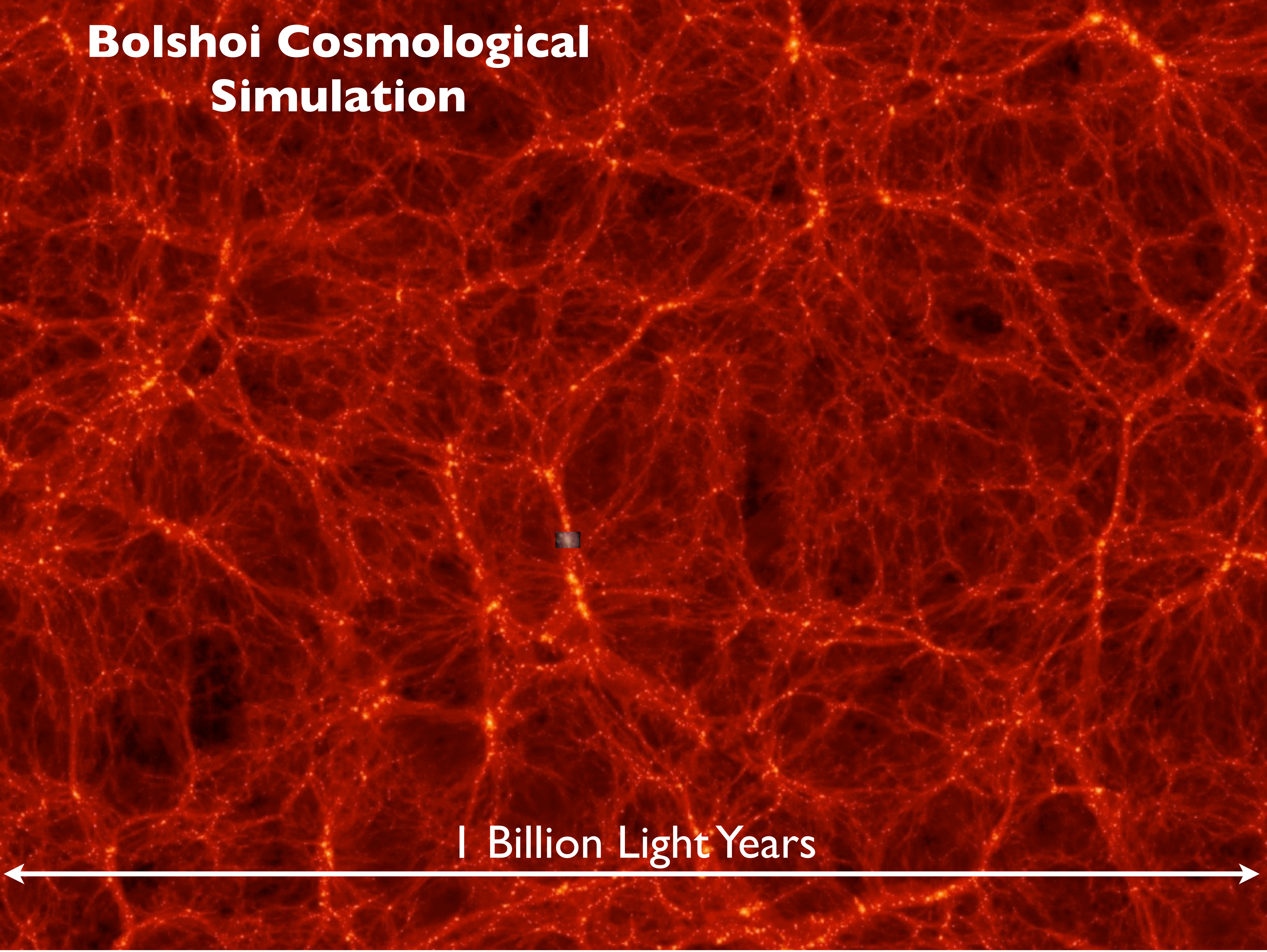


Milky Way
100,000 Light Years

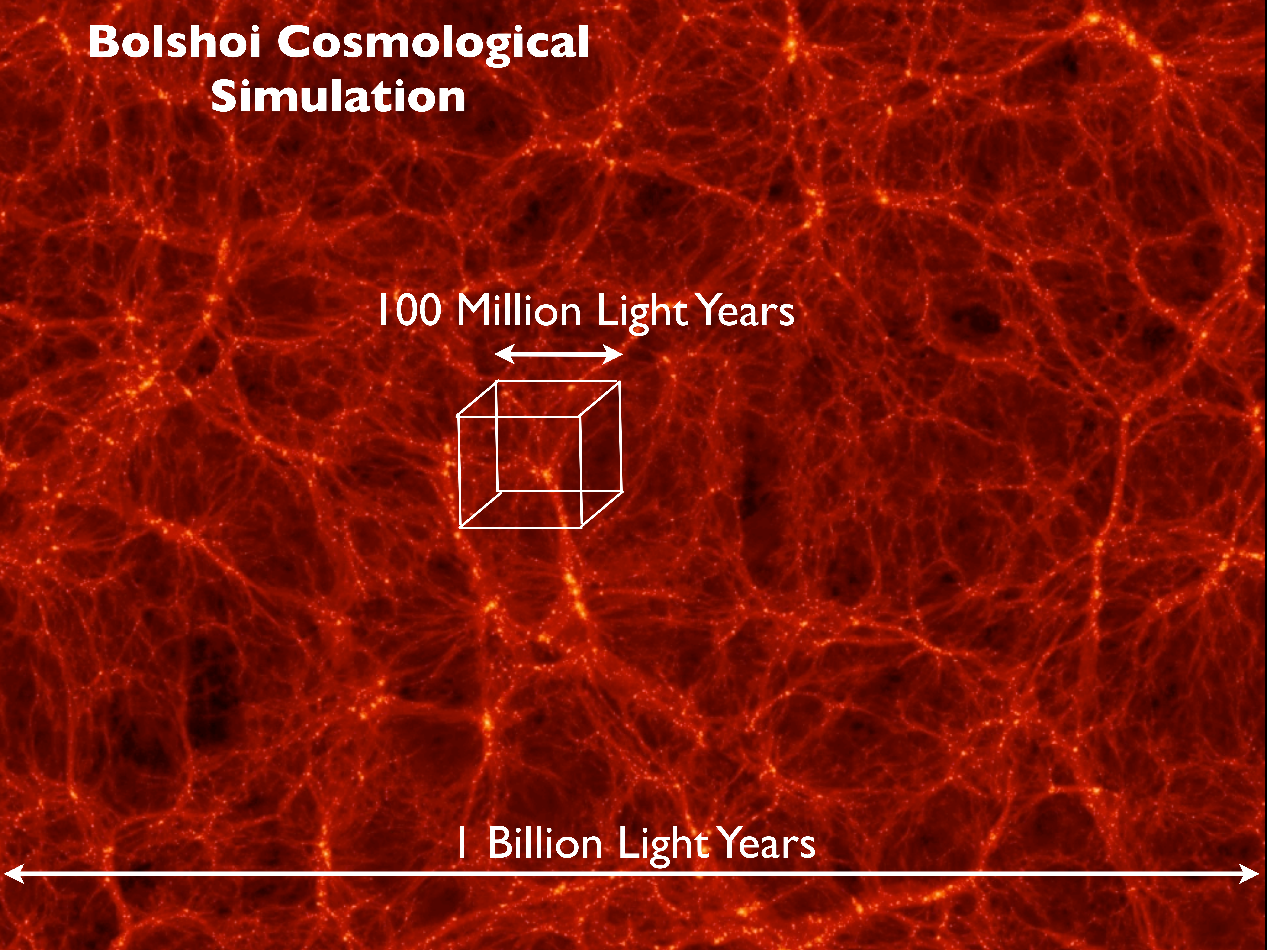
Milky Way Dark Matter Halo
1,500,000 Light Years



Bolshoi Cosmological Simulation



Bolshoi Cosmological Simulation



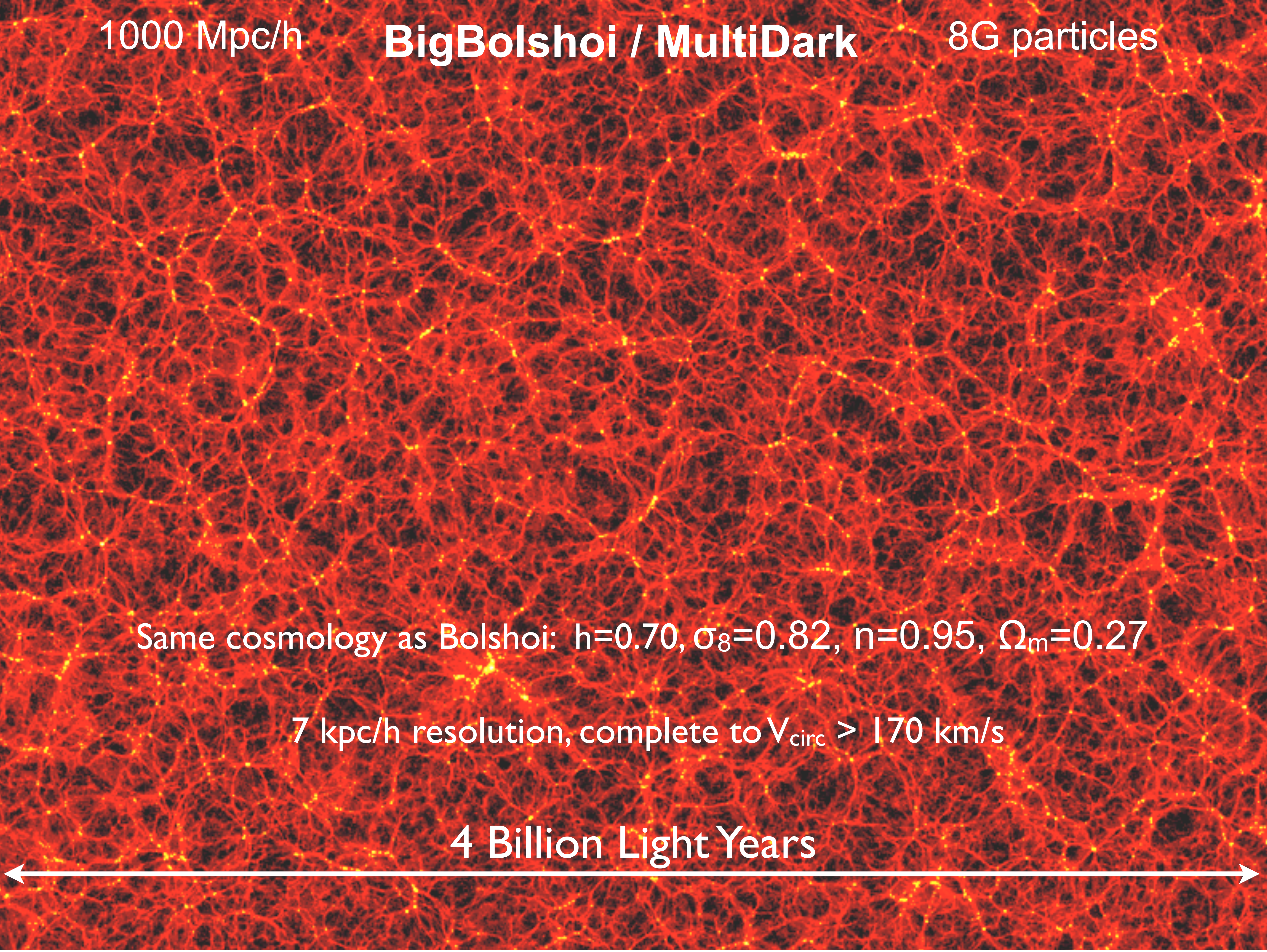
Bolshoi Cosmological Simulation

100 Million Light Years

Bolshoi Merger Tree for the Formation of a Big Cluster Halo

Time: 13664 Myr Ago
Timestep Redshift: 14.083
Radius Mode: Rvir
Focus Distance: 6.1
Aperture: 40.0
World Rotation: (216.7, 0.06, −0.94, −0.34)
Trackball Rotation: (0.0, 0.00, 0.00, 0.00)
Camera Position: (0.0, 0.0, −6.1)

Peter Behroozi



1000 Mpc/h

BigBolshoi / MultiDark

8G particles

Same cosmology as Bolshoi: $h=0.70$, $\sigma_8=0.82$, $n=0.95$, $\Omega_m=0.27$

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

4 Billion Light Years

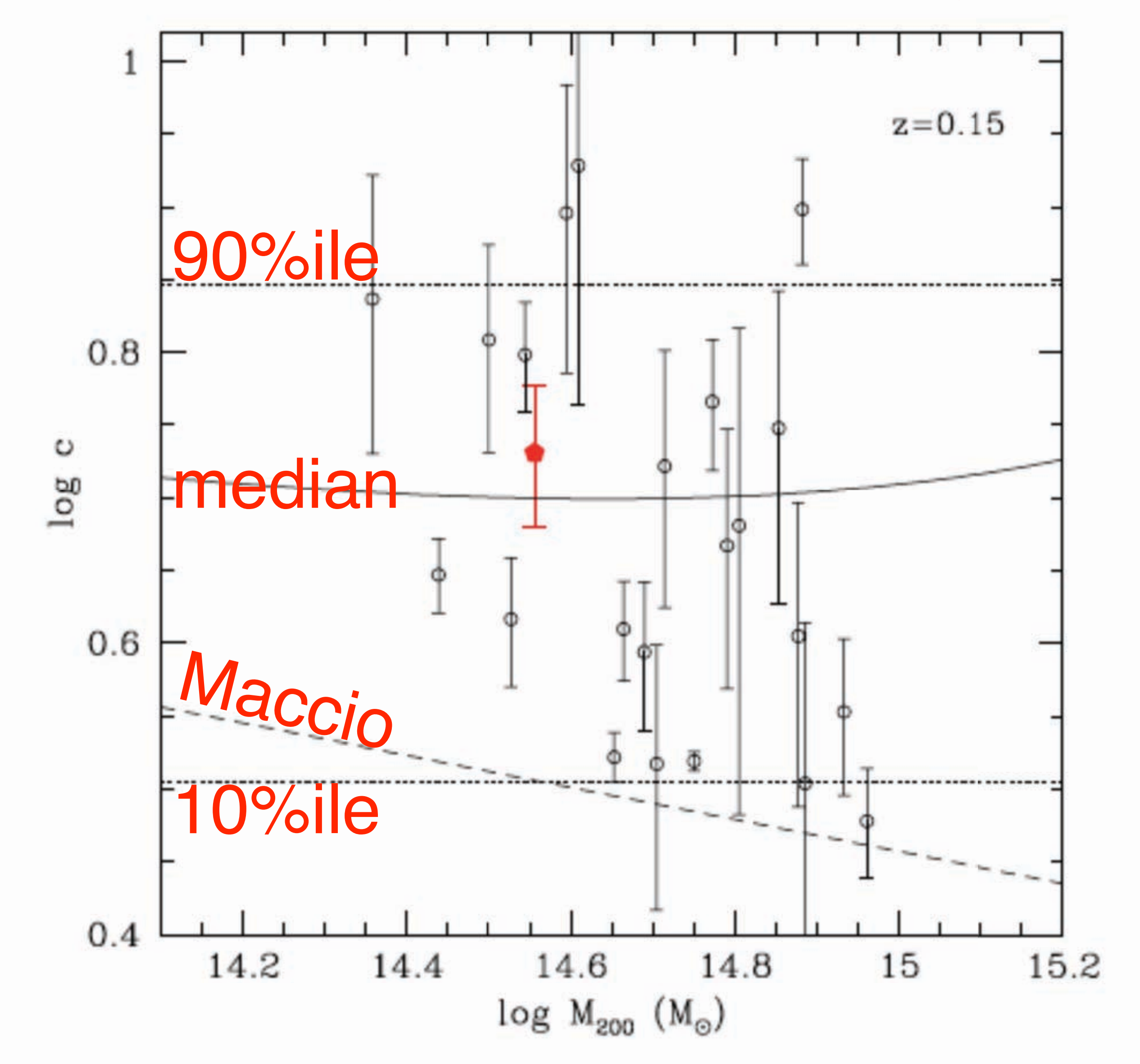
Halo concentrations in the standard CDM cosmology

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

ABSTRACT

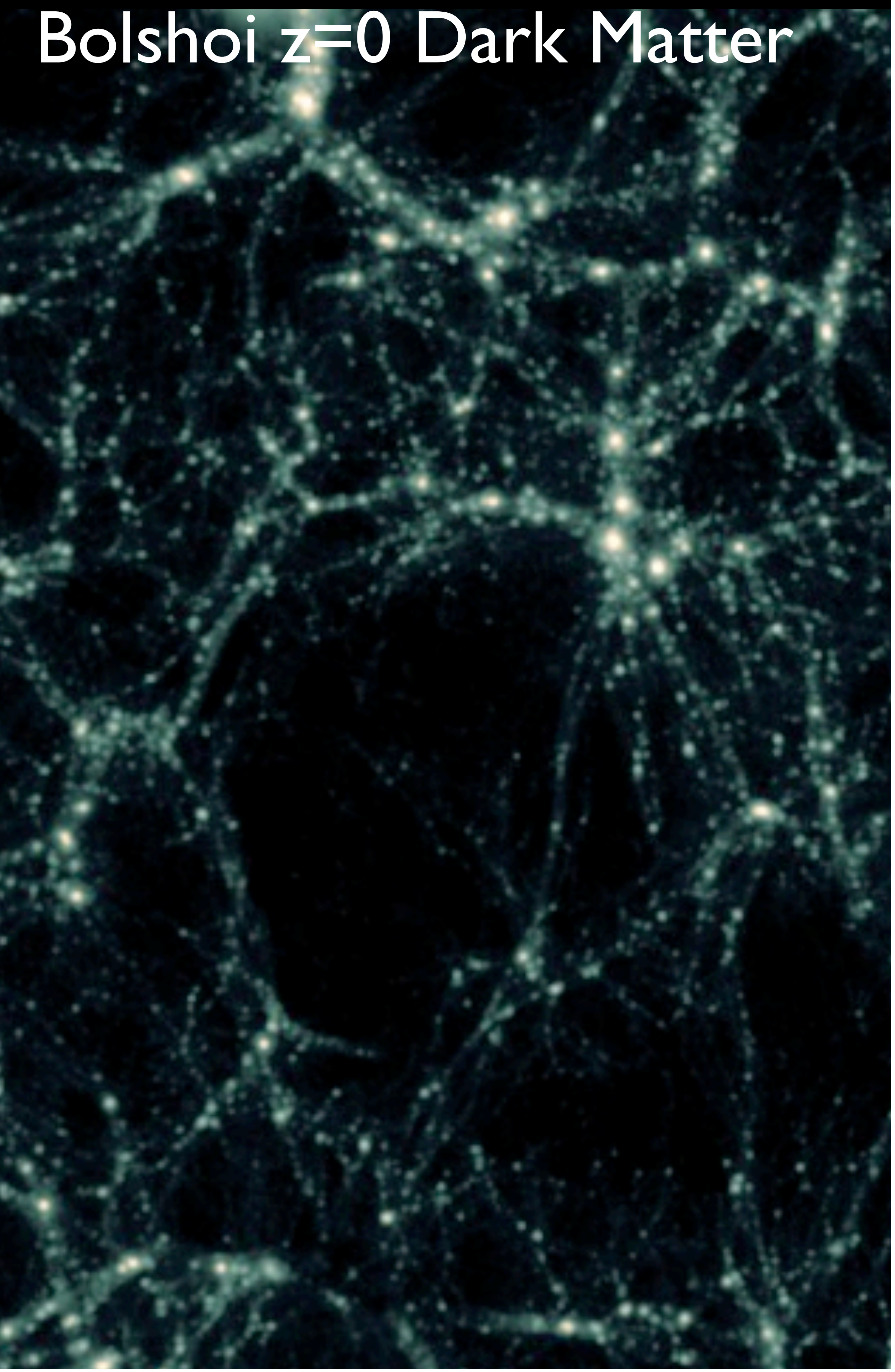
We study the concentration of dark matter halos and its evolution in N-body simulations of the standard ΛCDM cosmology. The results presented in this paper are based on 4 large N-body simulations with ~ 10 billion particles each: the Millennium-I and II, Bolshoi, and MultiDark simulations. The MultiDark (or BigBolshoi) simulation is introduced in this paper. This suite of simulations with high mass resolution over a large volume allows us to compute with unprecedented accuracy the concentration over a large range of scales (about six orders of magnitude in mass), which constitutes the state-of-the-art of our current knowledge on this basic property of dark matter halos in the ΛCDM cosmology. We find that there is consistency among the different simulation data sets, despite the different codes, numerical algorithms, and halo/subhalo finders used in our analysis. We confirm a novel feature for halo concentrations at high redshifts: a flattening and upturn with increasing mass. The concentration c(M, z) as a function of mass and the redshift and for different cosmological parameters shows a remarkably complex pattern. However, when expressed in terms of the linear rms fluctuation of the density field σ(M, z), the halo concentration c(σ) shows a nearly-universal simple U-shaped behaviour with a minimum at a well defined scale at σ ~ 0.71. Yet, some small dependences with redshift and cosmology still remain. At the high-mass end (σ < 1) the median halo kinematic profiles show large signatures of infall and highly radial orbits. This c–σ(M,z) relation can be accurately parametrized and provides an analytical model for the dependence of concentration on halo mass. When applied to galaxy clusters, our estimates of concentrations are substantially larger – by a factor up to 1.5 – than previous results from smaller simulations, and are in much better agreement with results of observations.

Cluster Concentrations

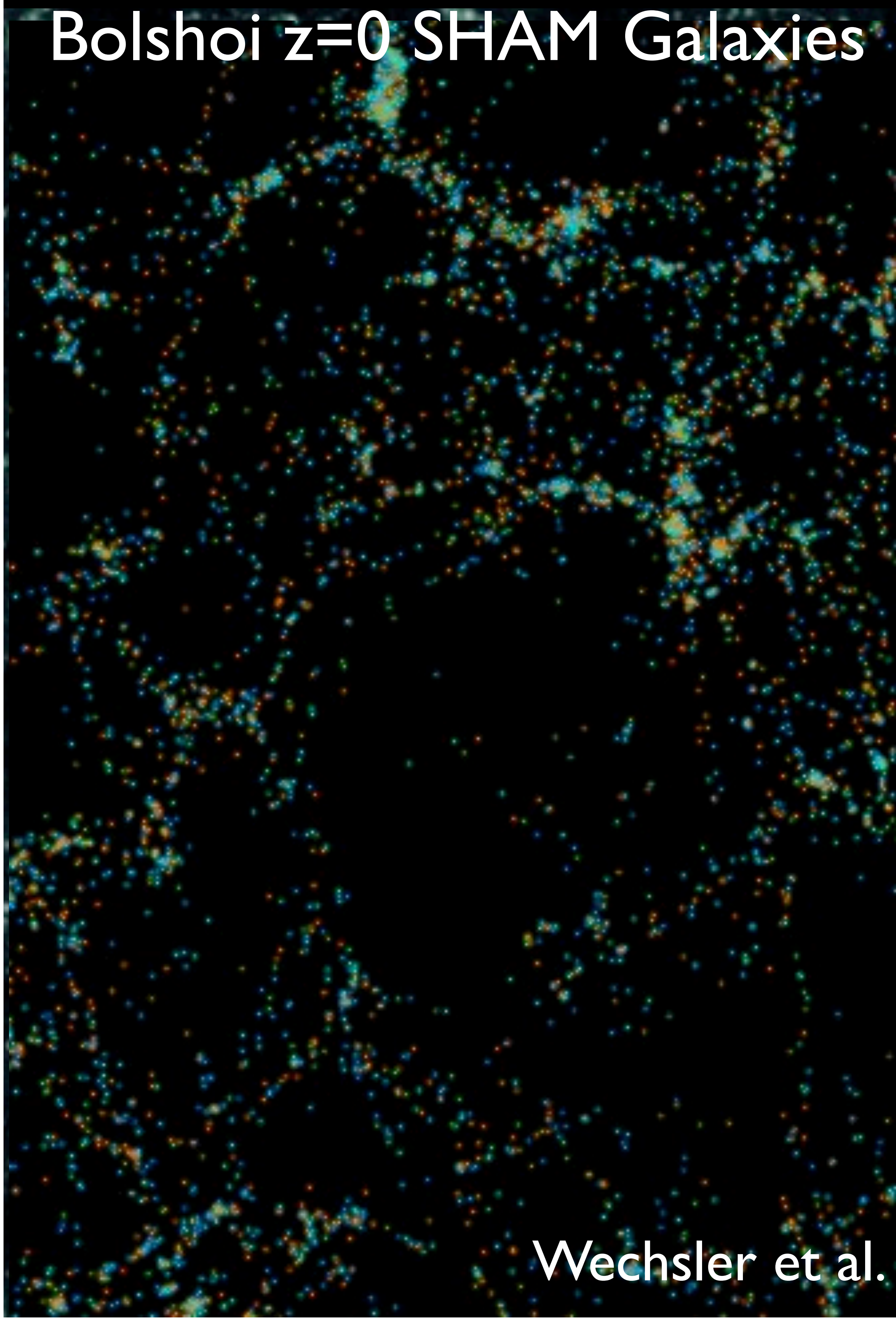


Comparison of observed cluster concentrations (data points with error bars) with the prediction of our model for median halo concentration of cluster-size halos (full curve). Dotted lines show 10% and 90% percentiles. Open circles show results for X-ray luminous galaxy clusters observed with XMMNewton 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.

2012 MNRAS



Bolshoi z=0 Dark Matter



Bolshoi z=0 SHAM Galaxies

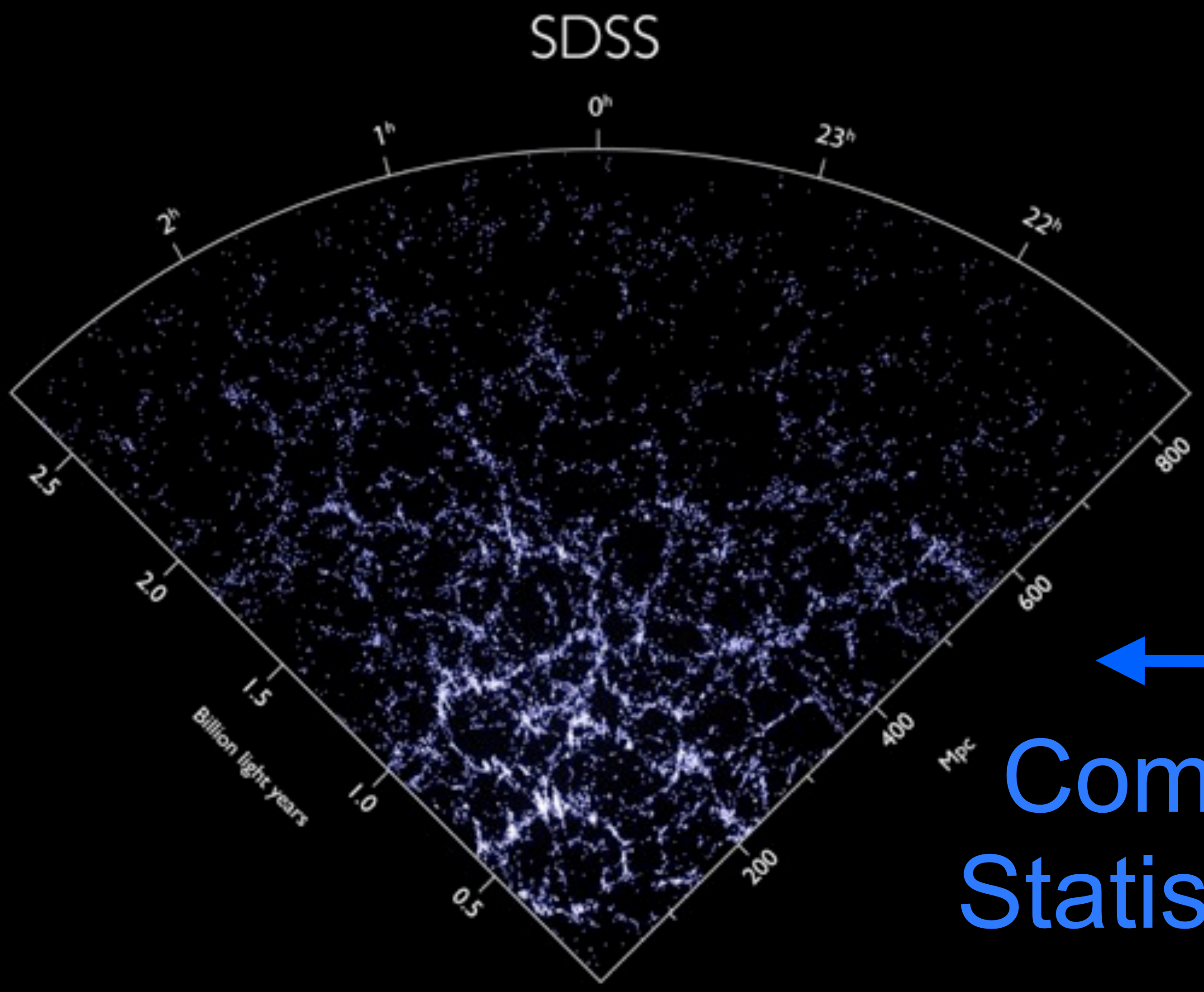
Wechsler et al.

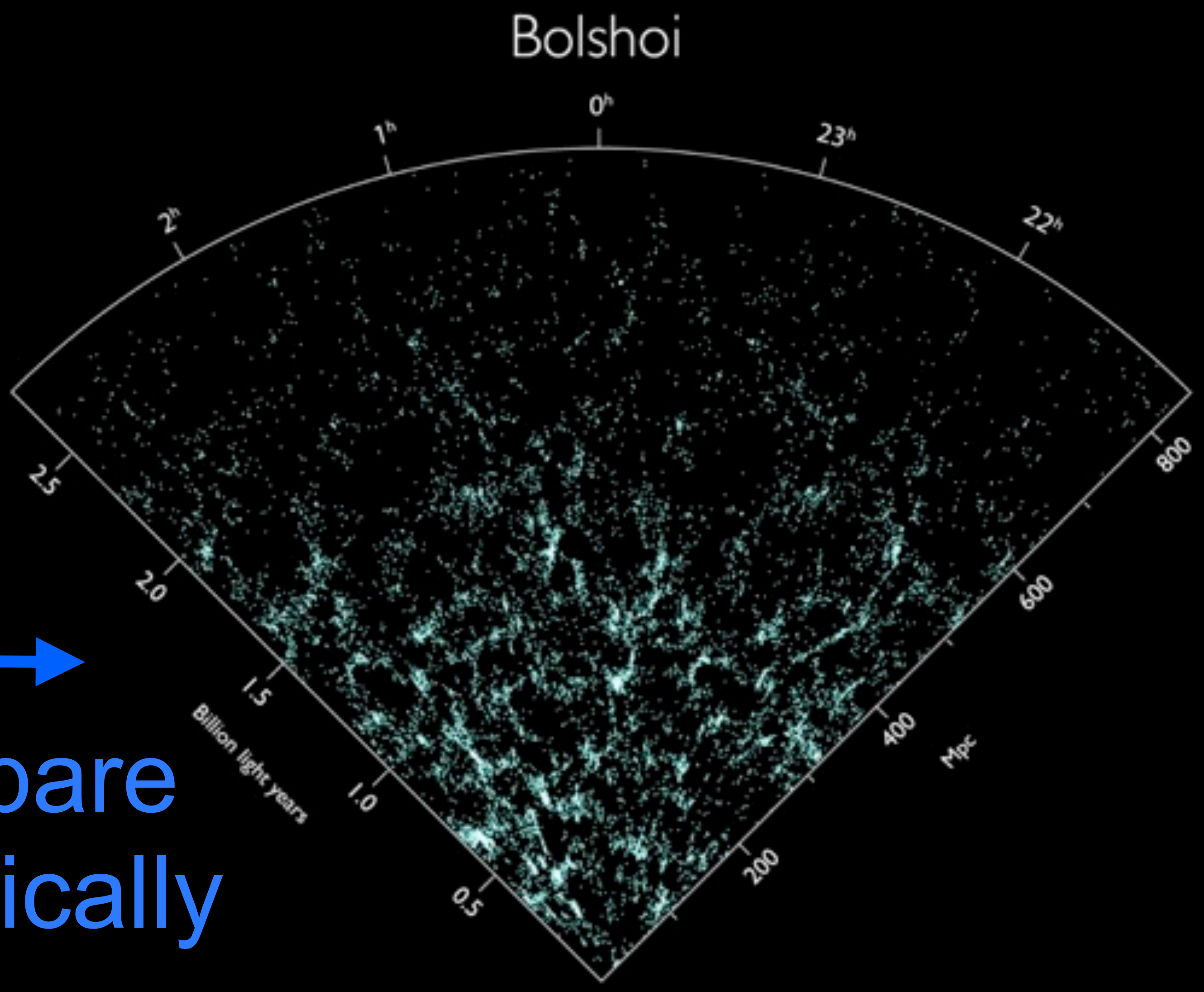
Observational Data

Sloan Digital Sky Survey

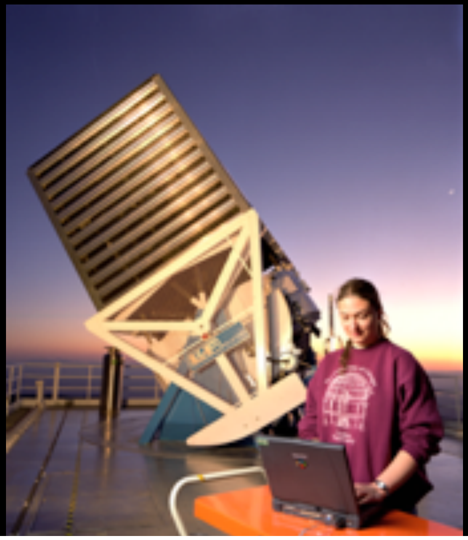
Cosmological Simulation

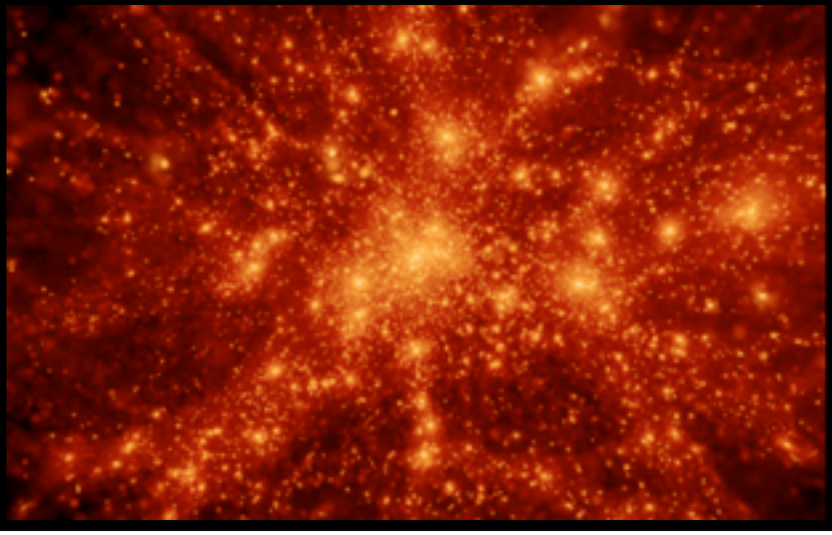
Risa Wechsler, Ralf Kahler, Nina McCurdy



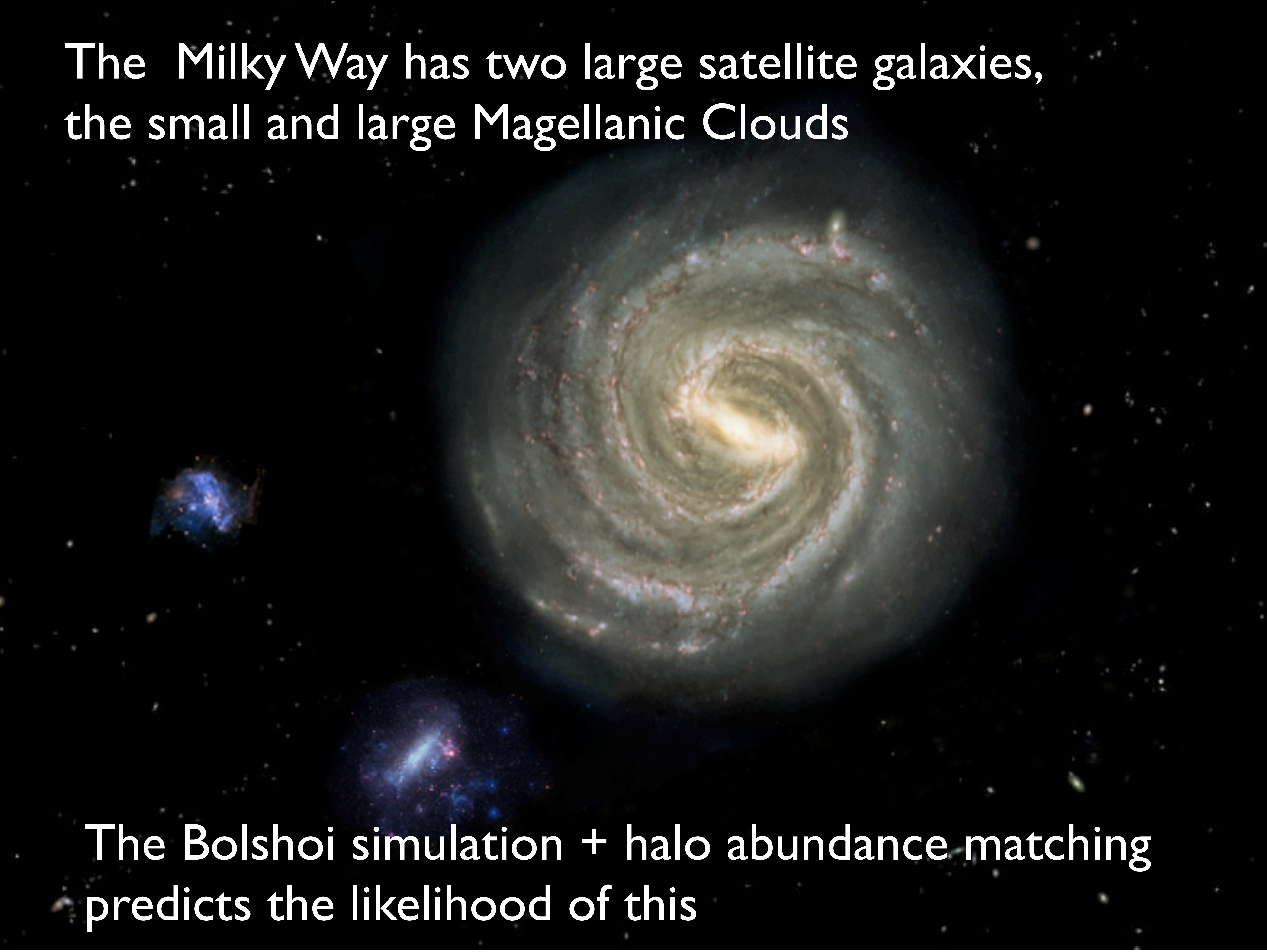


Compare Statistically

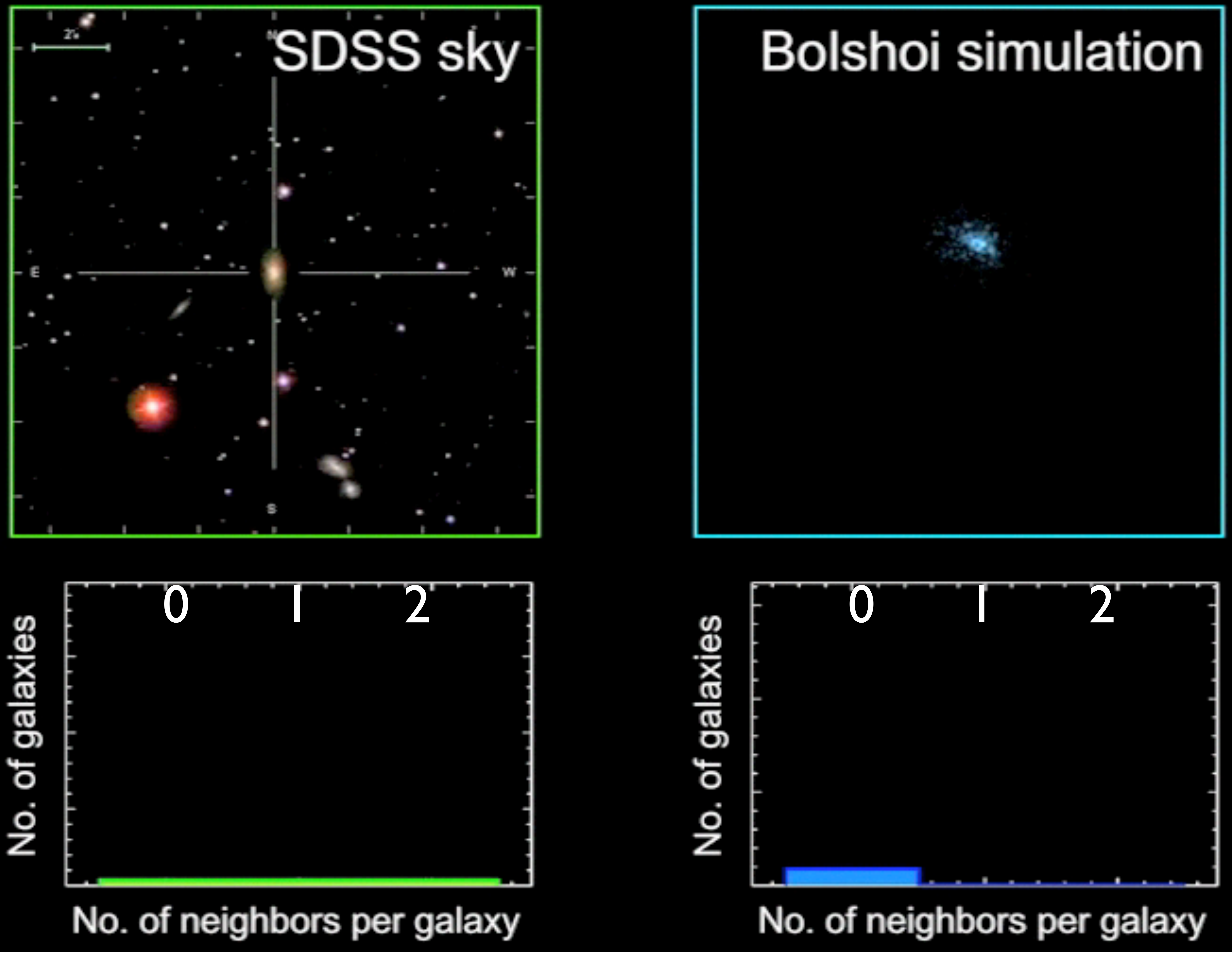




The Milky Way has two large satellite galaxies, the small and large Magellanic Clouds



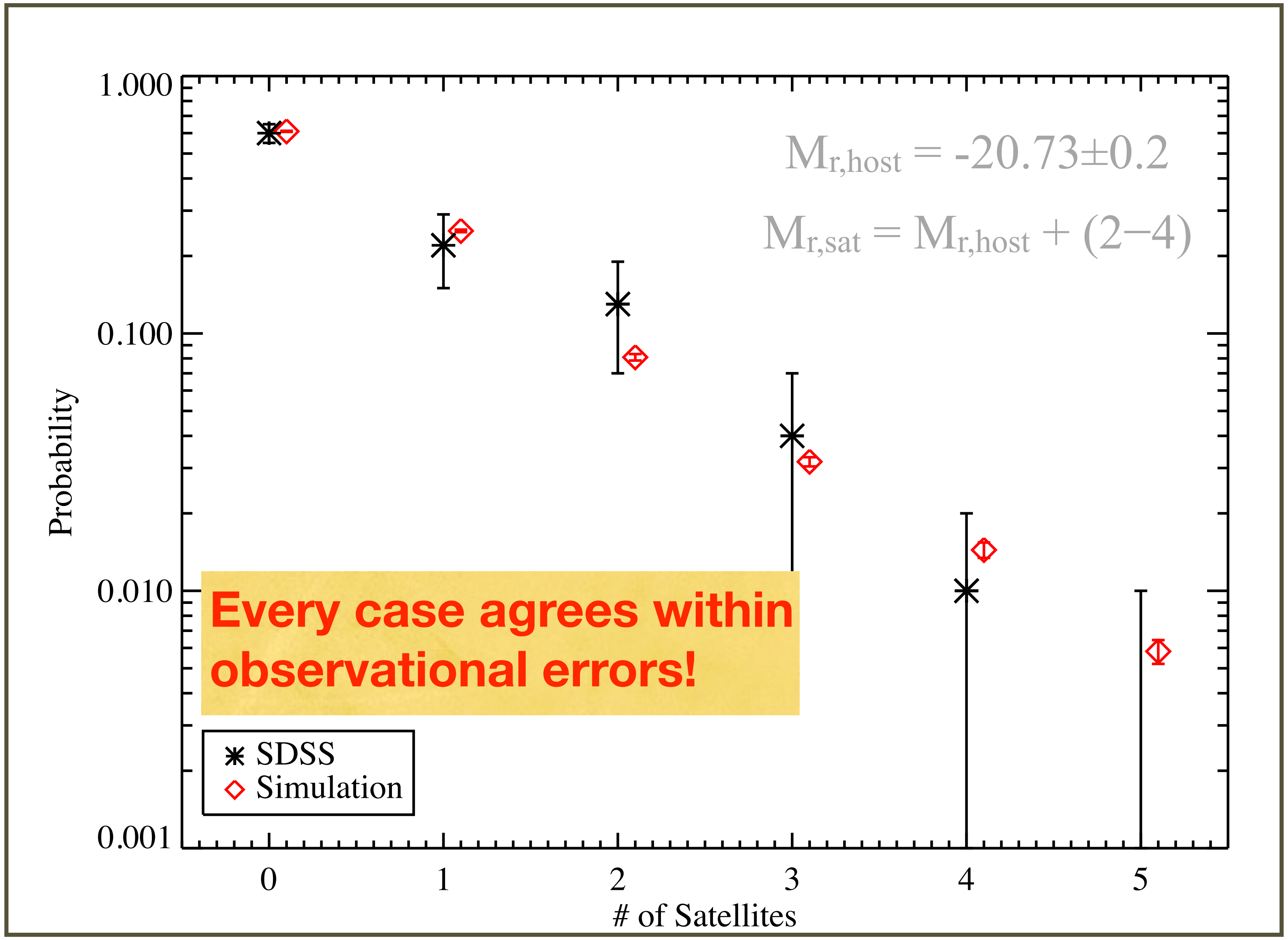
The Bolshoi simulation + halo abundance matching predicts the likelihood of this


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

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



Every case agrees within observational errors!

Busha et al 2011; Liu, Gerke, Wechsler 2011

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

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 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.

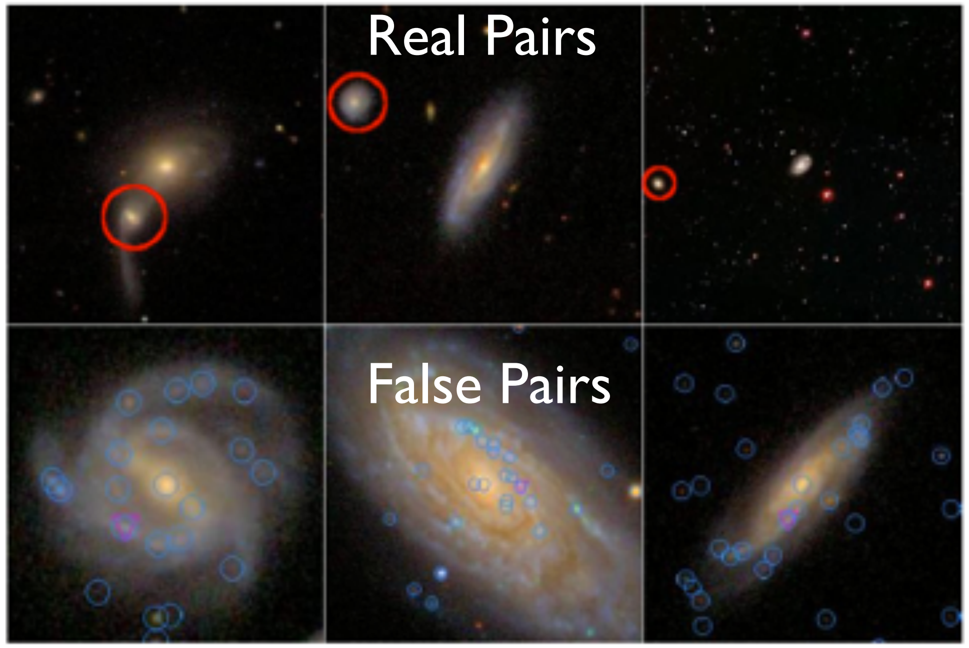


FIG. 1.— Examples of SDSS primary/secondary pairs in the clean sample (upper) and false pairs (lower). Secondaries identified by our criteria (see text) are marked with red circles (upper panels) or magenta triangles (lower panels). The upper three are all in the clean sample (have redshifts close to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

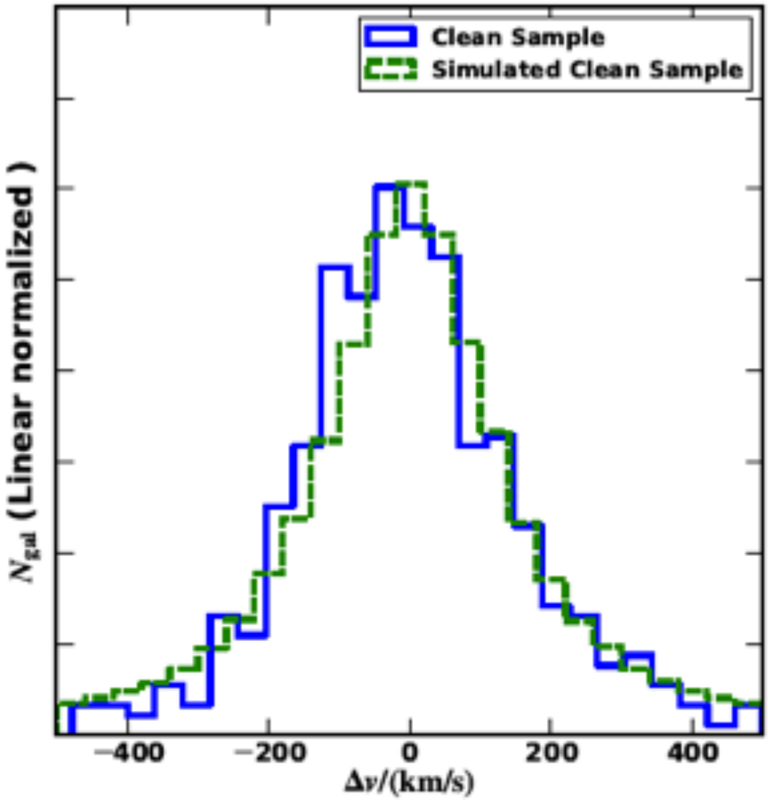
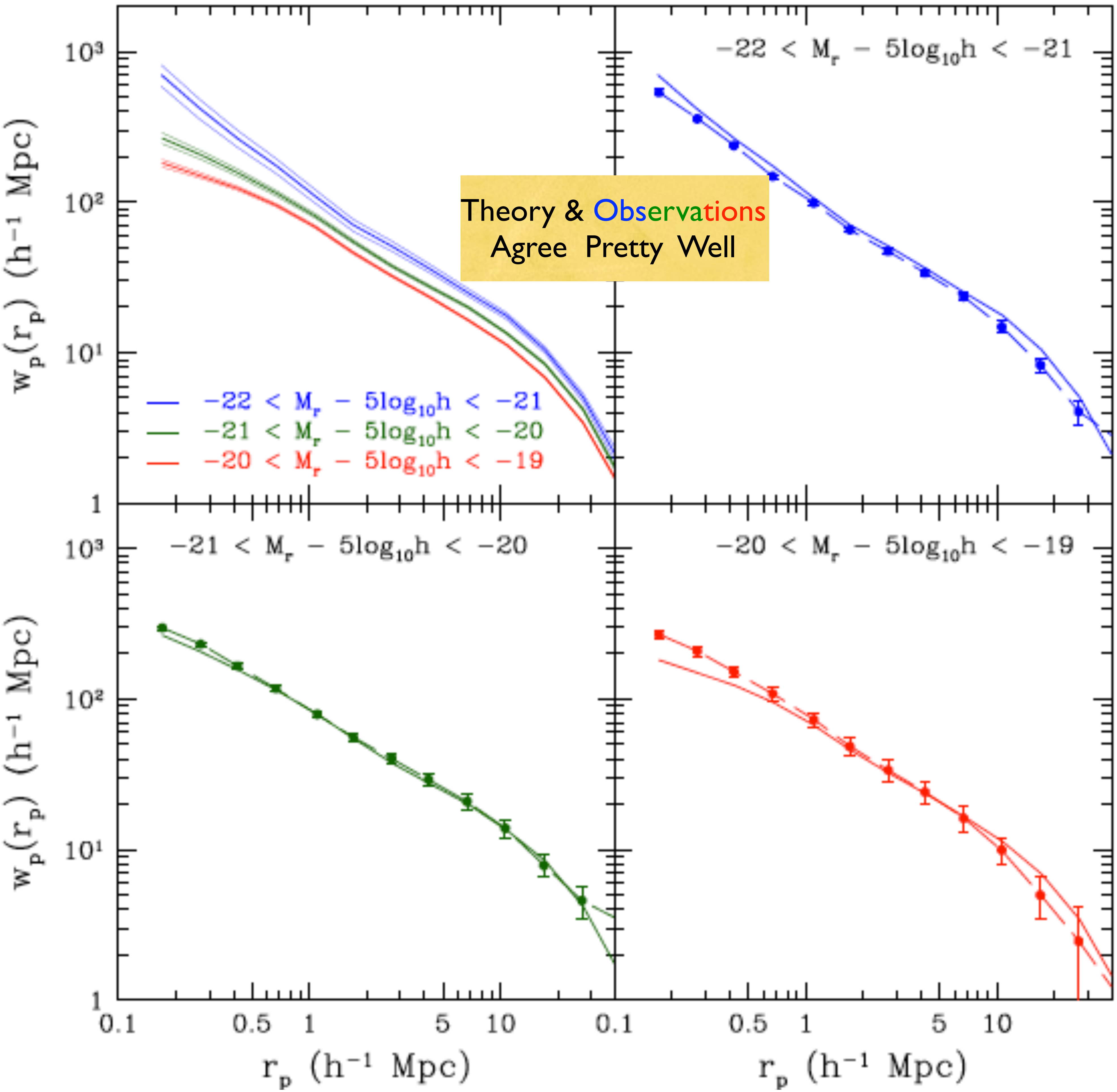


FIG. 6.— Distribution of $\Delta v \equiv c(z_{\rm pri} - z_{\rm sec})$ for the clean sample (solid blue histogram), the clean-like sample from MS-II (dashed green). The KS test yields $p_{\rm KS}$ = 33%. The pairwise velocity dispersion in the observed sample is $\sigma = 161$ km s^{-1}.

Projected Galaxy Correlation Functions



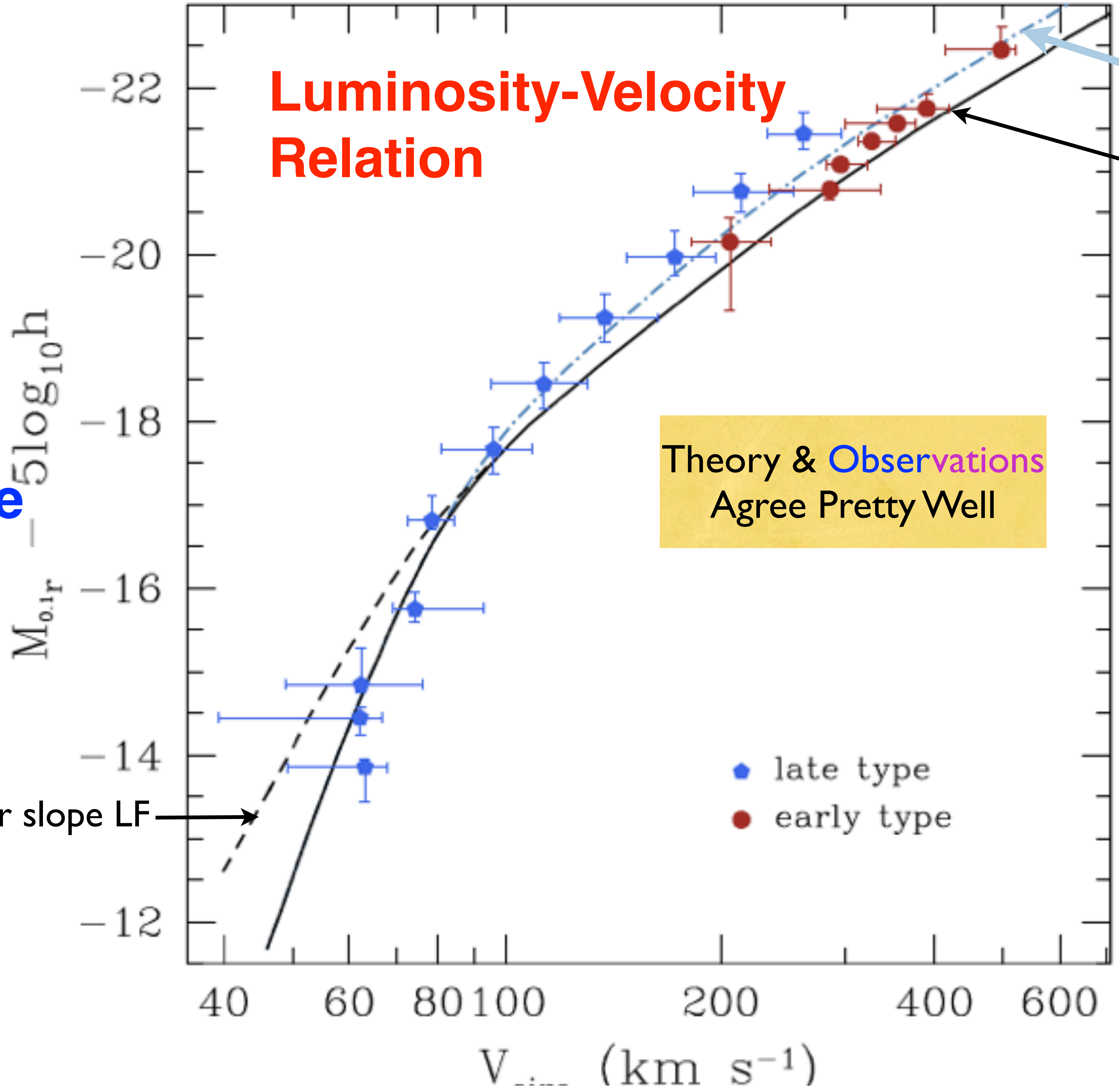
Theory & Observations
Agree Pretty Well

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 ApJ 2011

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

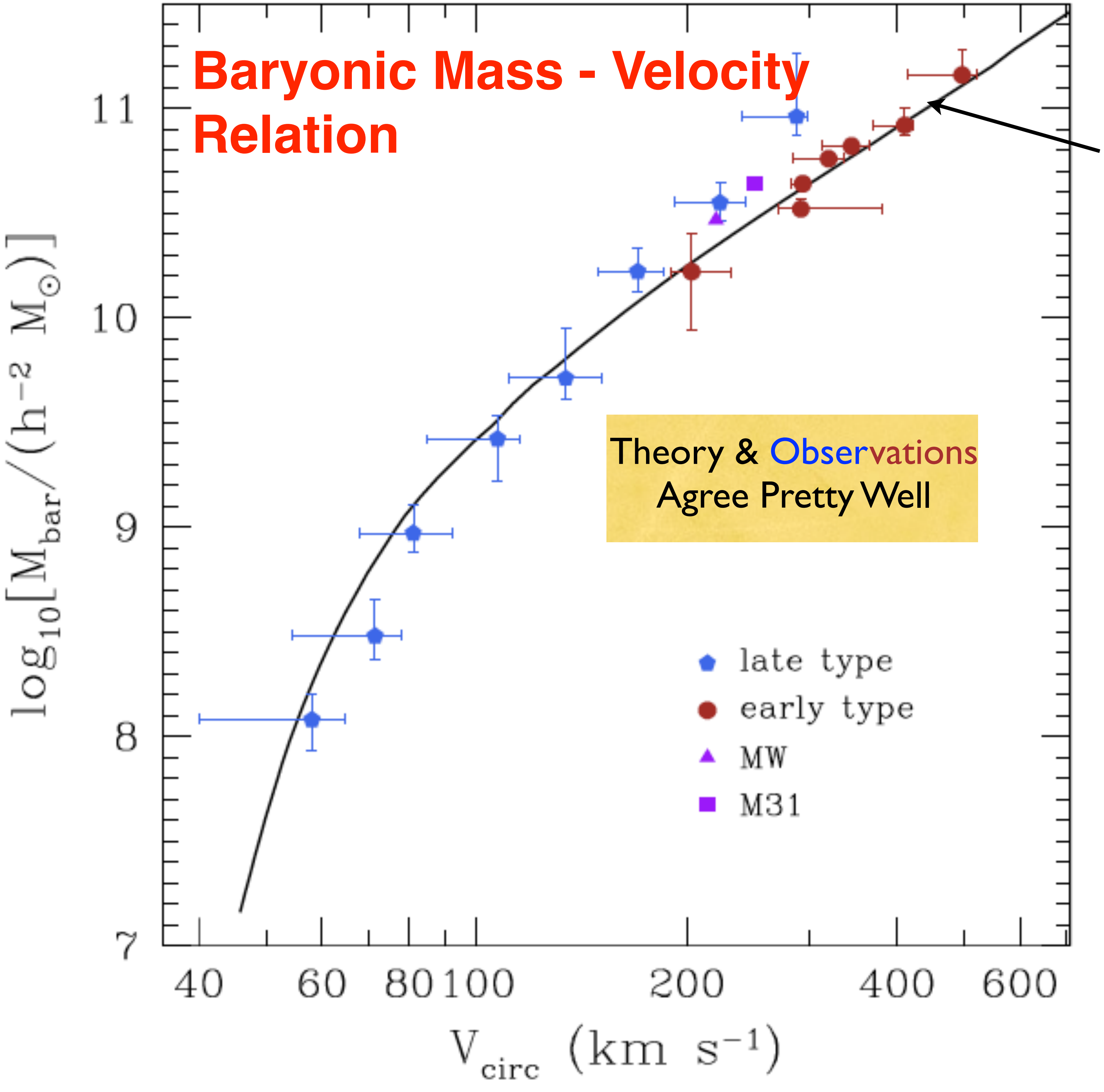
steeper slope LF

Trujillo-Gomez, Klypin, Primack, & Romanowsky ApJ 2011

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



median Vcirc with baryons and AC

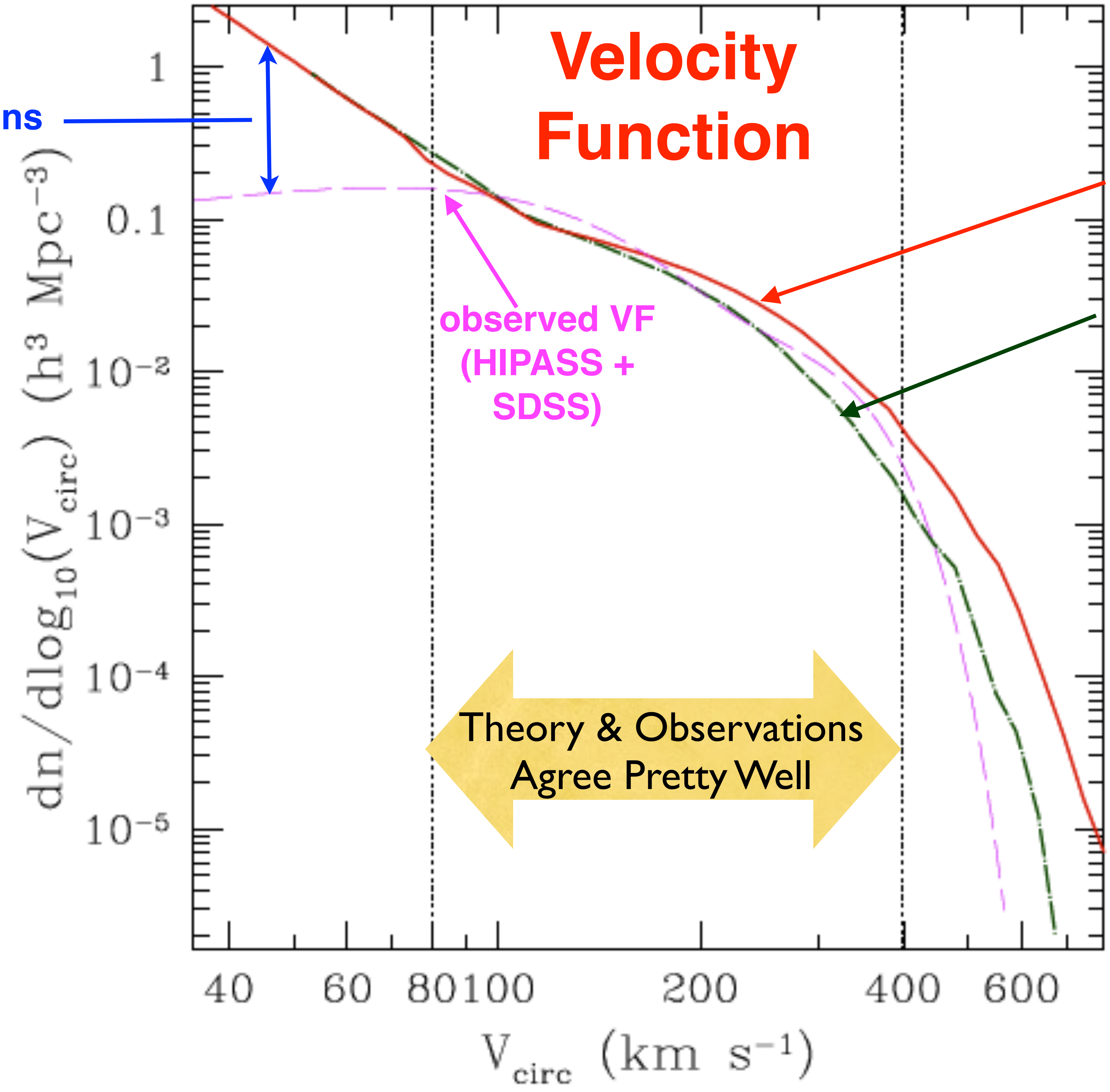
Theory & Observations Agree Pretty Well

Trujillo-Gomez, Klypin, Primack, & Romanowsky ApJ 2011

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

Bolshoi Sub-Halo Abundance Matching



Discrepancy due to incomplete observations or ΛCDM failure?

observed VF (HIPASS + SDSS)

theoretical VF with AC

theoretical VF without AC

Theory & Observations Agree Pretty Well

Trujillo-Gomez, Klypin, Primack, & Romanowsky ApJ 2011

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.

Presented at KITP Conference "First Light and Faintest Dwarfs" Feb 2012 and Santa Cruz Galaxy Workshop 15 Aug 2012 Klypin, Karachentsev, Nasonova 2012

Deeper Local Survey -- better agreement with ΛCDM but still more halos than galaxies at Vmax ≲ 50 km/s

Local Volume: D <10Mpc

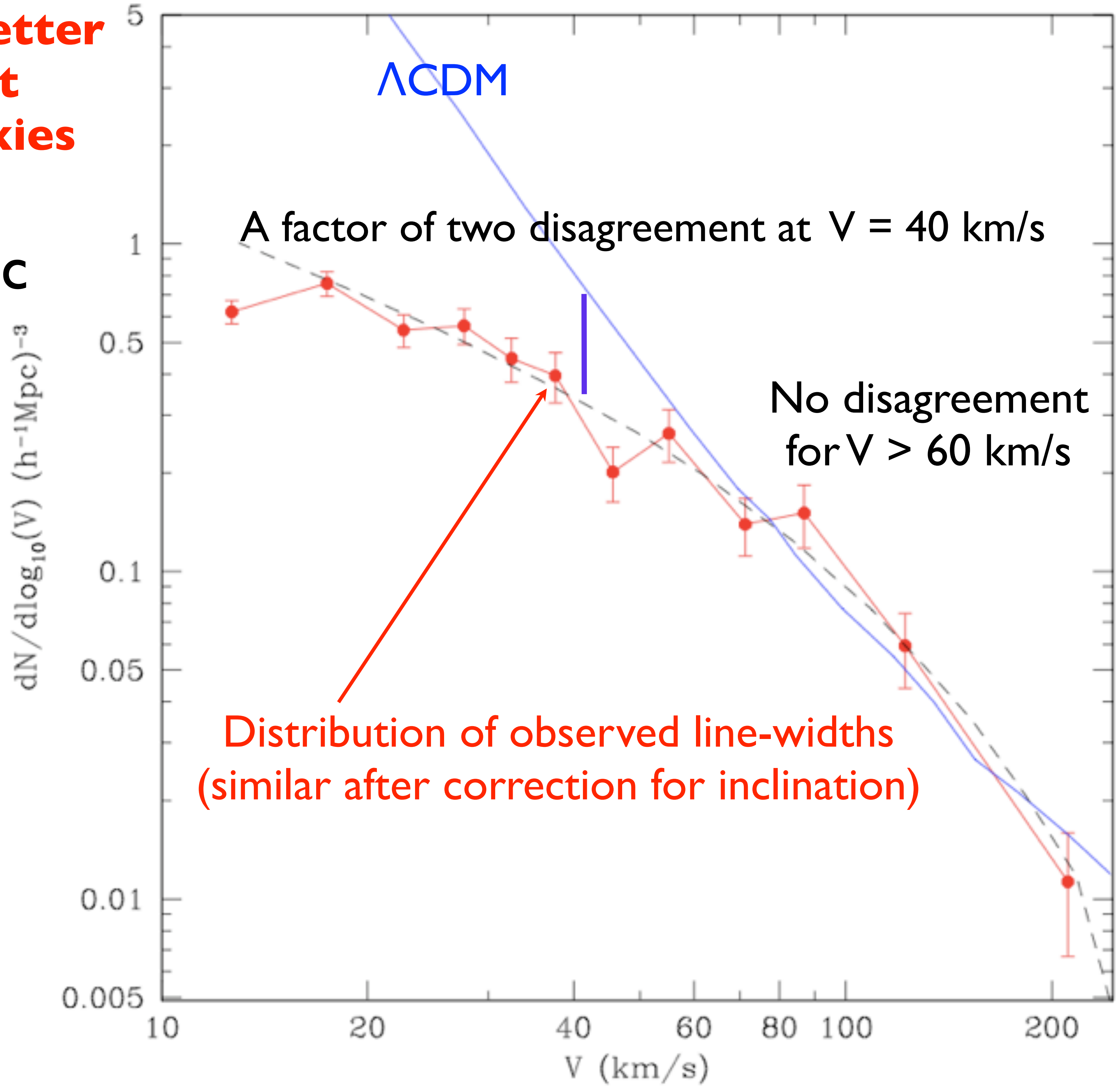
Total sample: 813 galaxies
Within 10 Mpc: 686
M_B<-13 N=304
M_B<-10 N=611

80-90% are spirals or dIrr (T>0)

Accuracy of distances are 8-10%

80% with D<10 Mpc have HI linewidth

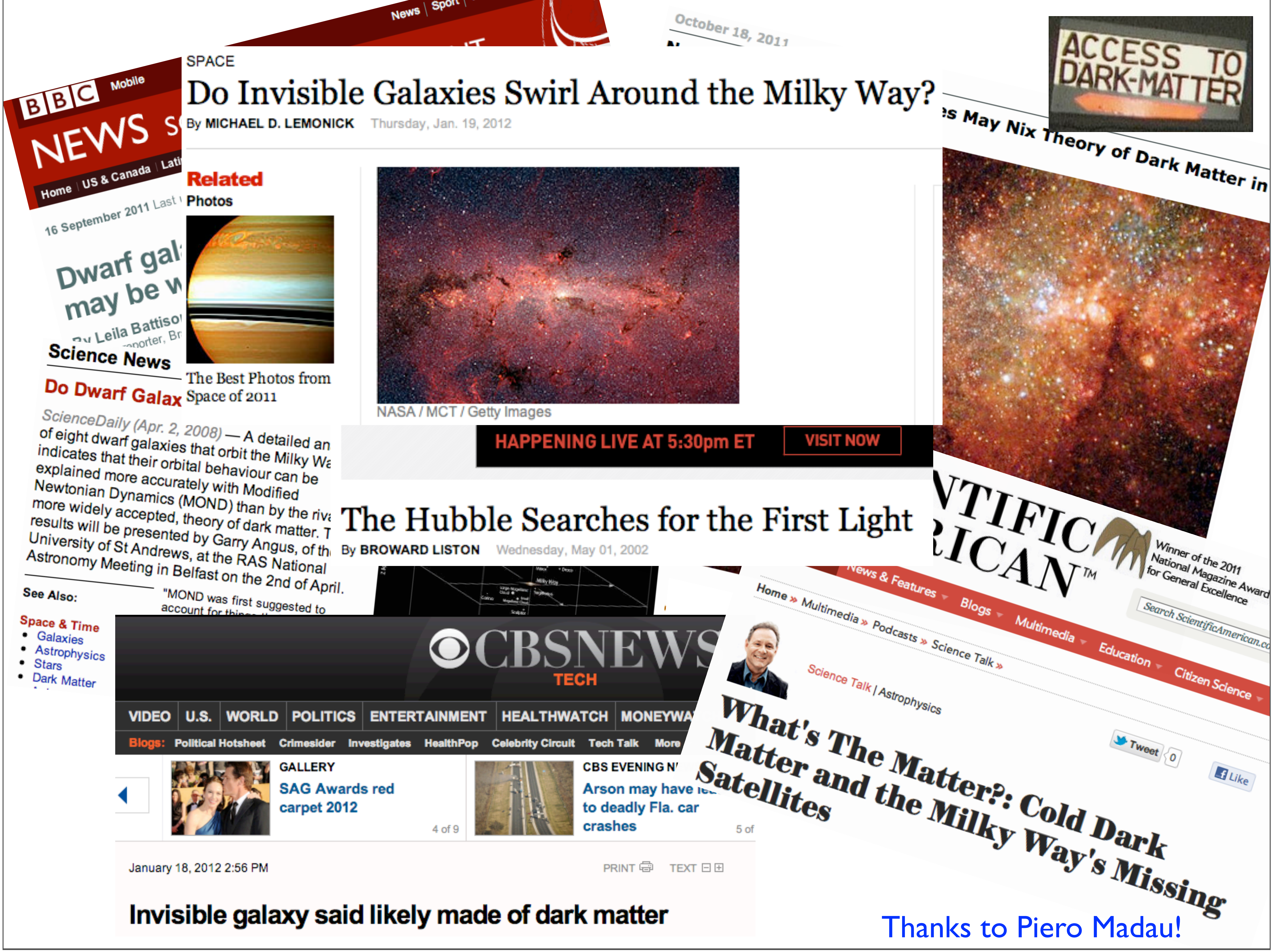
Vrot = 150x10^(-(20.5+M_B)/8.5)km/s



16 September 2011 Last updated at 13:47 ET

Dwarf galaxies suggest dark matter theory may be wrong

By Leila Battison
Science reporter, Bradford



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October 18, 2011

ACCESS TO DARK-MATTER

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16 September 2011 Last

Dwarf gal may be w

By Leila Battiso

Science News

Do Dwarf Galax

ScienceDaily (Apr. 2, 2008) — A detailed an of eight dwarf galaxies that orbit the Milky Wa indicates that their orbital behaviour can be explained more accurately with Modified Newtonian Dynamics (MOND) than by the riva more widely accepted, theory of dark matter. T results will be presented by Garry Angus, of th University of St Andrews, at the RAS National Astronomy Meeting in Belfast on the 2nd of April.

"MOND was first suggested to account for thin

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SPACE

Do Invisible Galaxies Swirl Around the Milky Way?

By **MICHAEL D. LEMONICK** Thursday, Jan. 19, 2012

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By **BROWARD LISTON** Wednesday, May 01, 2002

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What's The Matter?: Cold Dark Matter and the Milky Way's Missing Satellites

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January 18, 2012 2:56 PM PRINT TEXT

Invisible galaxy said likely made of dark matter

Thanks to Piero Madau!

small scale issues

Angular momentum

The Eris simulation shows that ΛCDM simulations are increasingly able to form realistic spiral galaxies, as resolution improves and feedback becomes more realistic.

Cusps

WDM doesn't resolve cusp issues. New observations and simulations suggest that observed velocity structure of LSB, dSpiral, dSph galaxies may be consistent with cuspy ΛCDM halos. But the "too big to fail" problem needs solution.

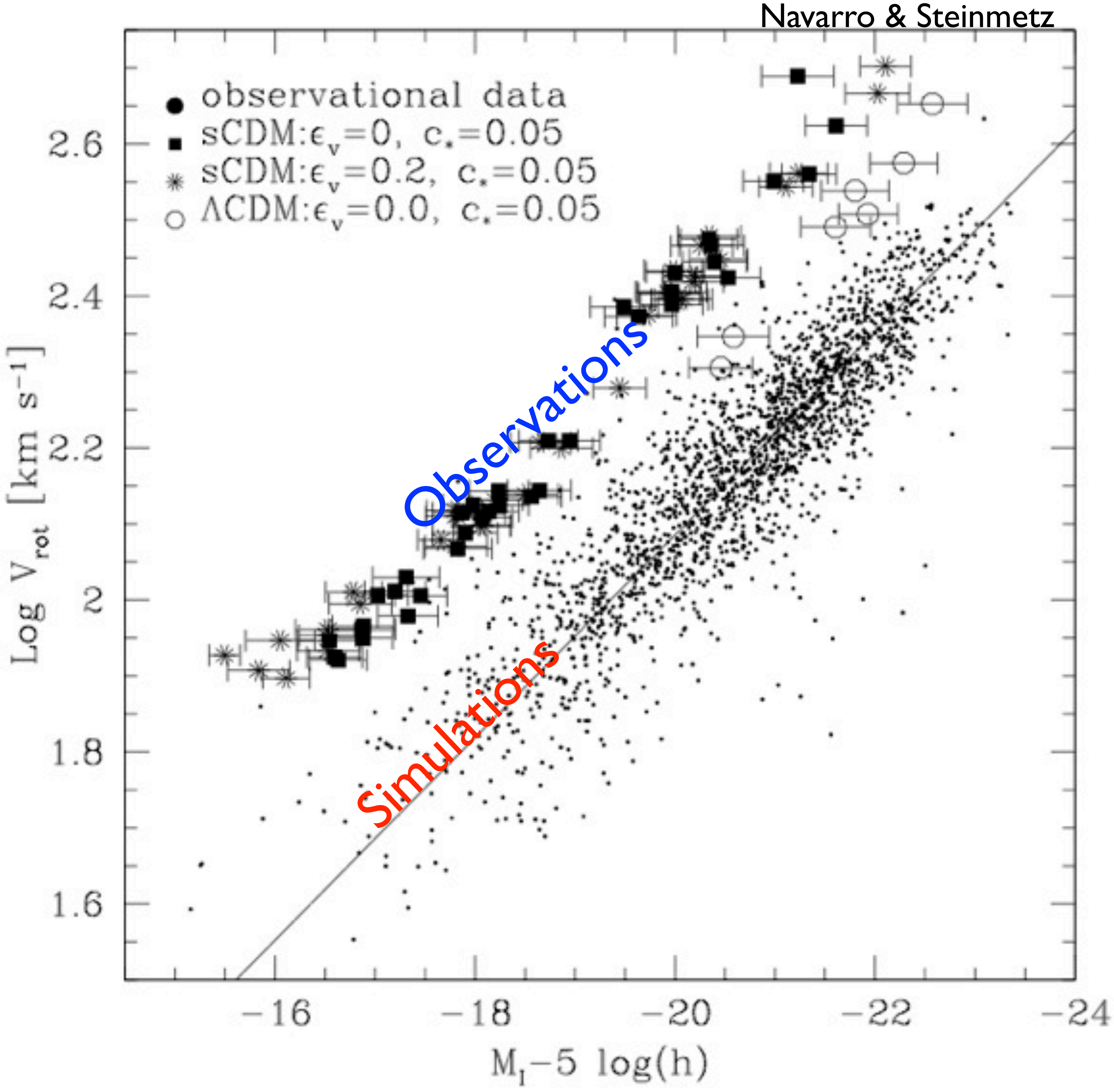
Satellites and Subhalos

The discovery of many faint Local Group dwarf galaxies is consistent with ΛCDM predictions. Satellites, reionization, lensing flux anomalies, gaps in stellar streams, and Lyα forest data imply that WDM must be Tepid or Cooler.

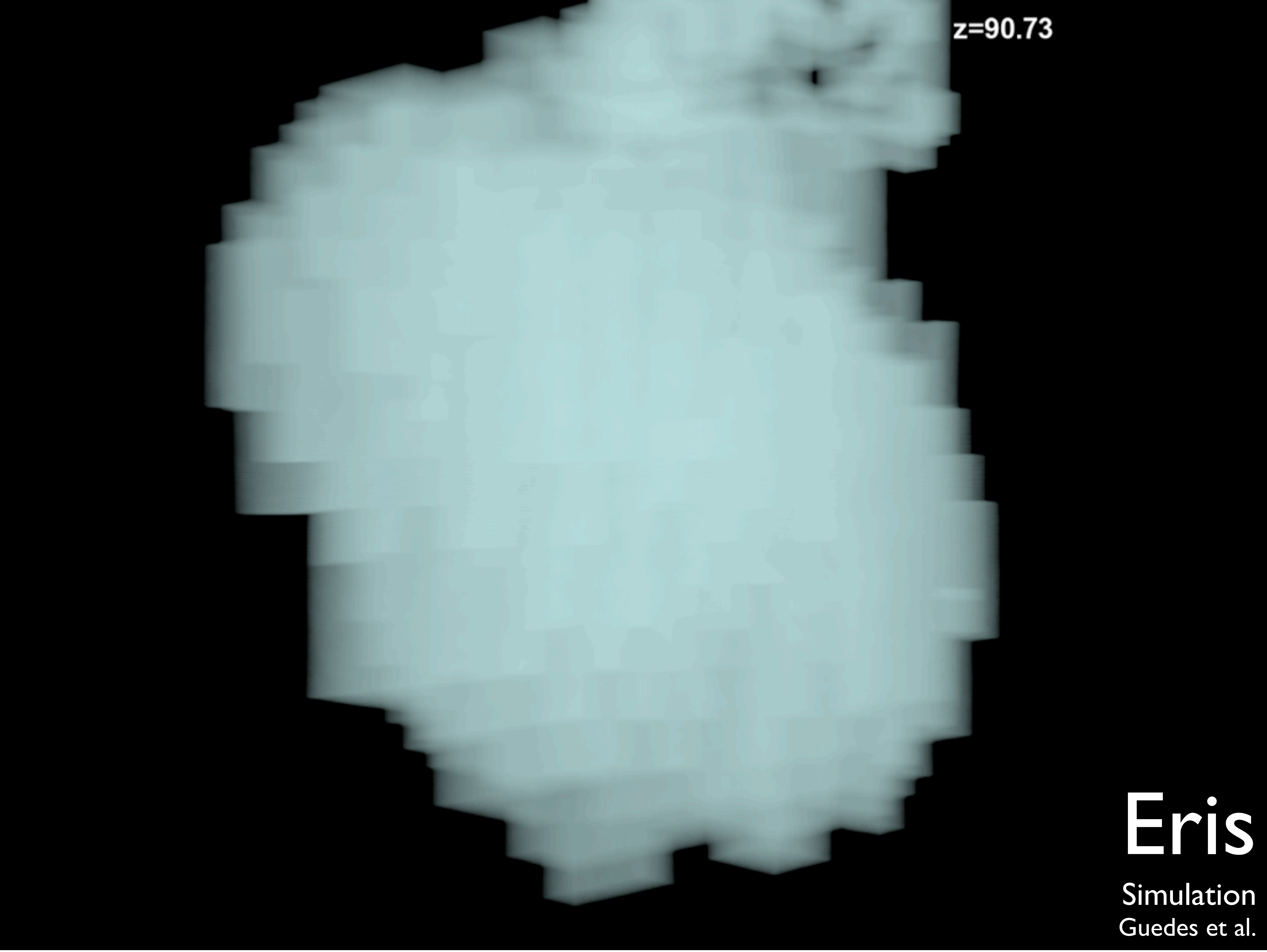
Can ΛCDM Simulations Form Realistic Galaxies?

The Angular Momentum Problem

Cooling was too effective particularly in low-mass halos at early times.



> “Agreement between model and observations appears to demand substantial <u>revision to the CDM scenario or to the manner in which baryons are thought to assemble</u> and evolve into galaxies in hierarchical universes.”
>
> Navarro & Steinmetz 2000 ApJ

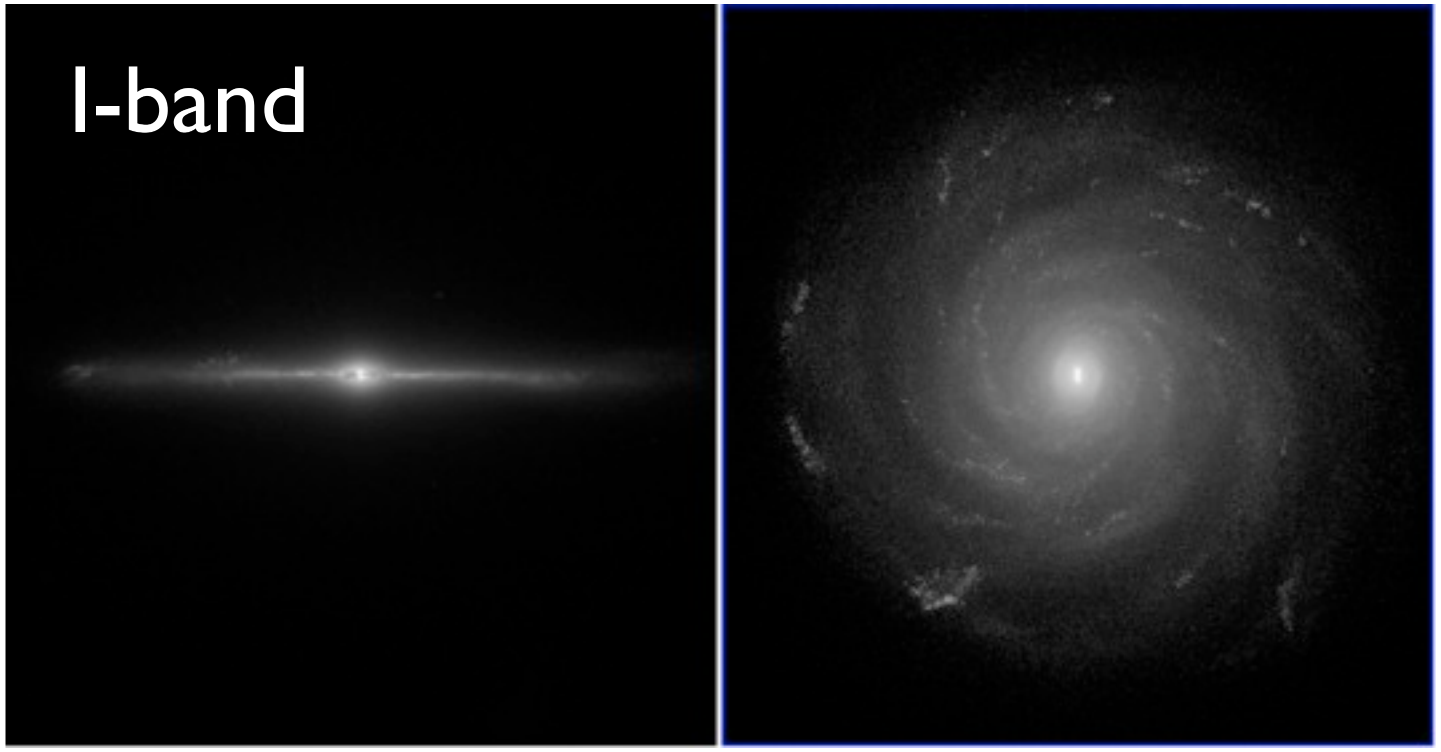


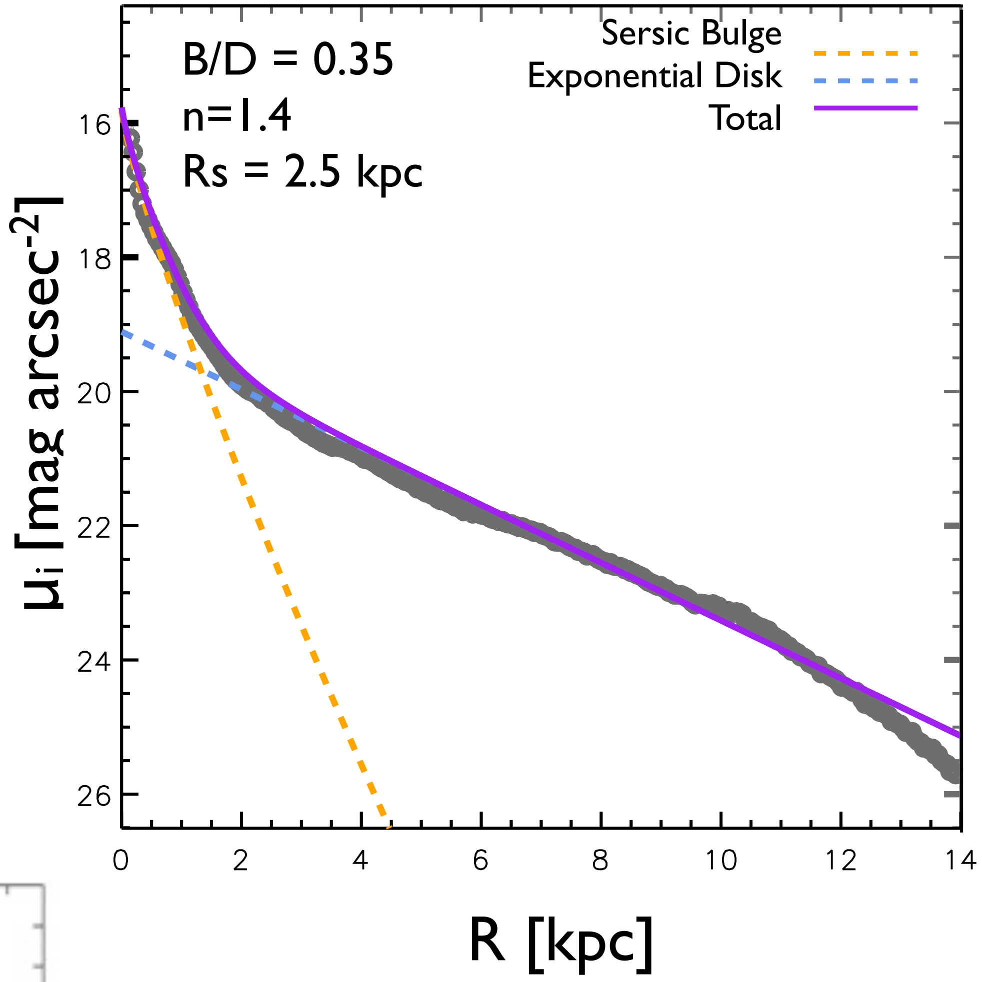
Eris

Simulation

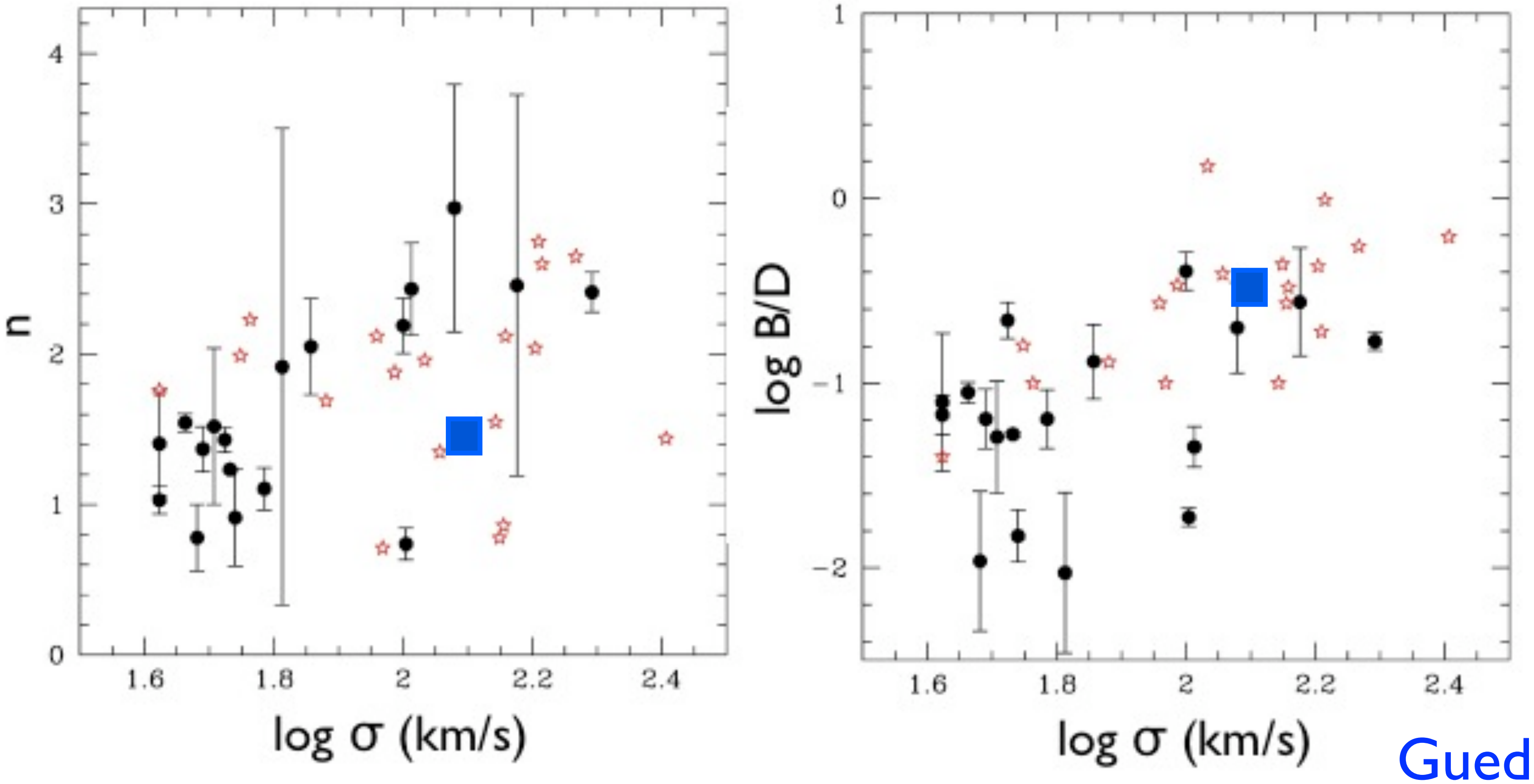
Guedes et al.

Structural Properties: Eris Bulge-to-Disk Ratio





Ganda et al. 2006, 2009



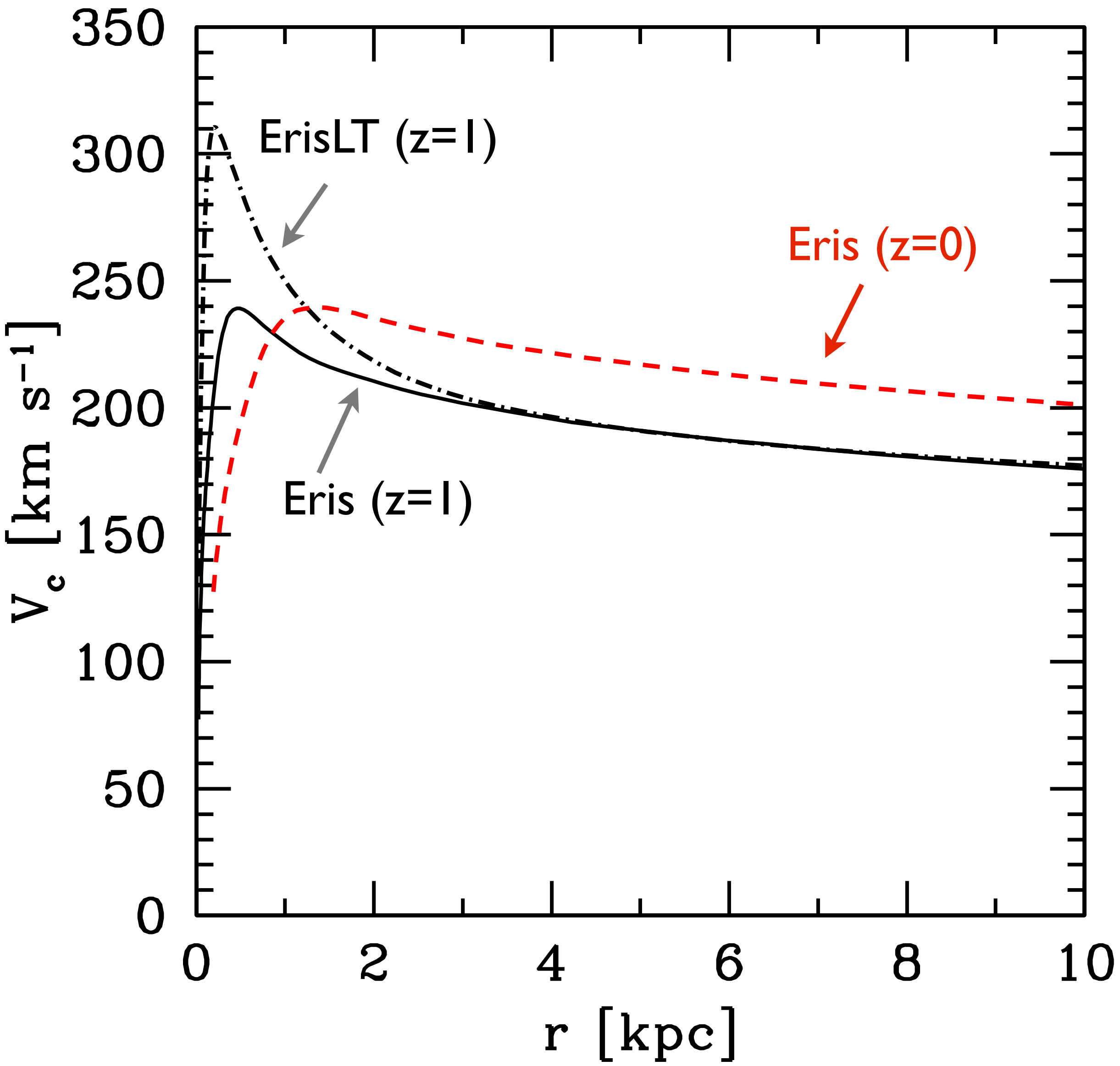
Photometric decomposition in i-band using Galfit (Peng et al. 2002)

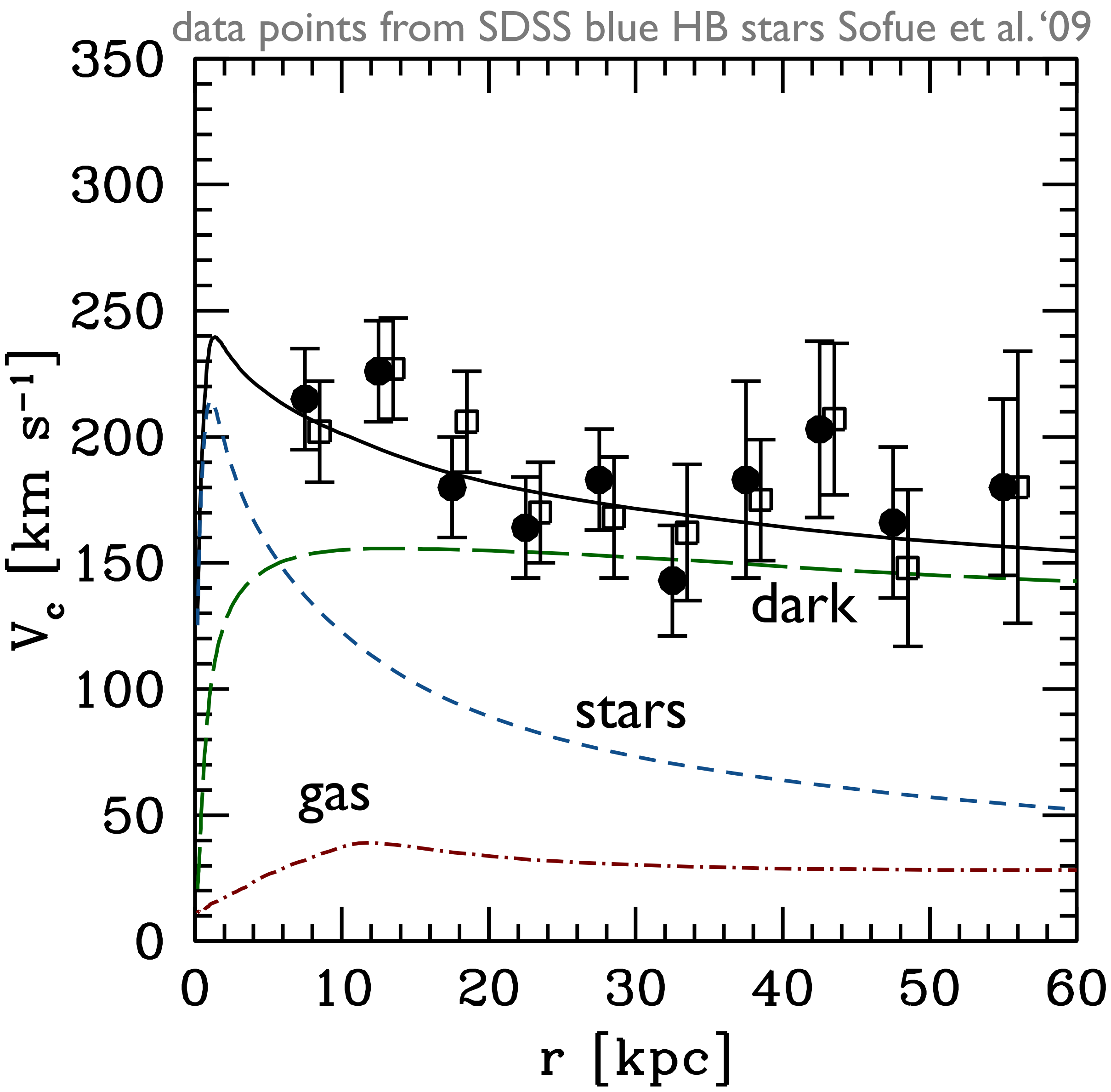
- ● Late-type spirals
- ☆ Early-type spirals
- 🟦 Eris

Guedes, Callegari, Madau, Mayer 2011 ApJ

Eris Rotation Curve

The z=0 is not highly peaked at the center, and falls slowly at large radii, in agreement with observations.





Javiera Guedes, et al. 2011 ApJ

Cusps

WDM doesn't resolve cusp issues. New observations and simulations suggest that observed velocity structure of LSB and dSpiral galaxies may be consistent with cuspy ΛCDM halos. But the "too big to fail" problem needs solution.

New Developments

- New observations undermine some previous evidence for dark matter cores in dwarf galaxies
- The properties of density cores of dwarf spiral galaxies are inconsistent with expectations from WDM
- New simulations show that gas blowout during evolution of dwarf spiral galaxies can remove cusps
- But the biggest subhalos in MWy size dark matter simulations may be too dense to host the observed satellites

Beware of darkness: A cuspy dark matter halo from stellar kinematics where gas shows a core

NGC 2976 presented in ApJ, Vol. 745, 92, 2012; 10 more galaxies coming in future papers

Joshua J. Adams[1], Joshua D. Simon[1], Karl Gebhardt[2], Guillermo A. Blanc[1], Maximilian H. Fabricius[3], Gary J. Hill[4], Jeremy D. Murphy[2], Remco C.E. van den Bosch[5], Glenn van de Ven[5]

We here present measurements and anisotropic Jeans models for late-type dwarfs obtained from stellar kinematics. Until recently, DM mass profiles in such systems have been obtained exclusively from atomic or ionized gas. The nearby member of the M81 group, NGC 2976 (SAc), has been measured in ionized gas to have a DM core with a strong constraint on the DM power law index of $0.01<\alpha<0.17$ (Simon et al. 2003), where $\alpha=1$ corresponds to the center of an NFW profile. **In our first work on NGC 2976, we confirm that the simplest models from gas kinematics reveal a cored DM halo but find that the stellar kinematic are most consistent with an NFW profile. We advocate the stellar kinematics as more robust due to the tracer's collisionless nature while the gas is subject to more uncertainties from radial motion, warped disks, and pressure support.** We are making an ongoing study by which the type, strength, and conditions of feedback can be constrained from new measurements and comparison to simulations.

Joshua Adams poster at KITP Conference "First Light and Faintest Dwarfs" February 2012

A METHOD FOR MEASURING (SLOPES OF) THE MASS PROFILES OF DWARF SPHEROIDAL GALAXIES

MATTHEW G. WALKER[1,2,3] & JORGE PEÑARRUBIA[2]   2011 ApJ

Using separately higher metal stars at lower radiu plus lower metal stars farther out gives dm radial slope inconsistent with NFW at high confidence for Sculptor and Fornax dwarf spheroidal MWy satellites.

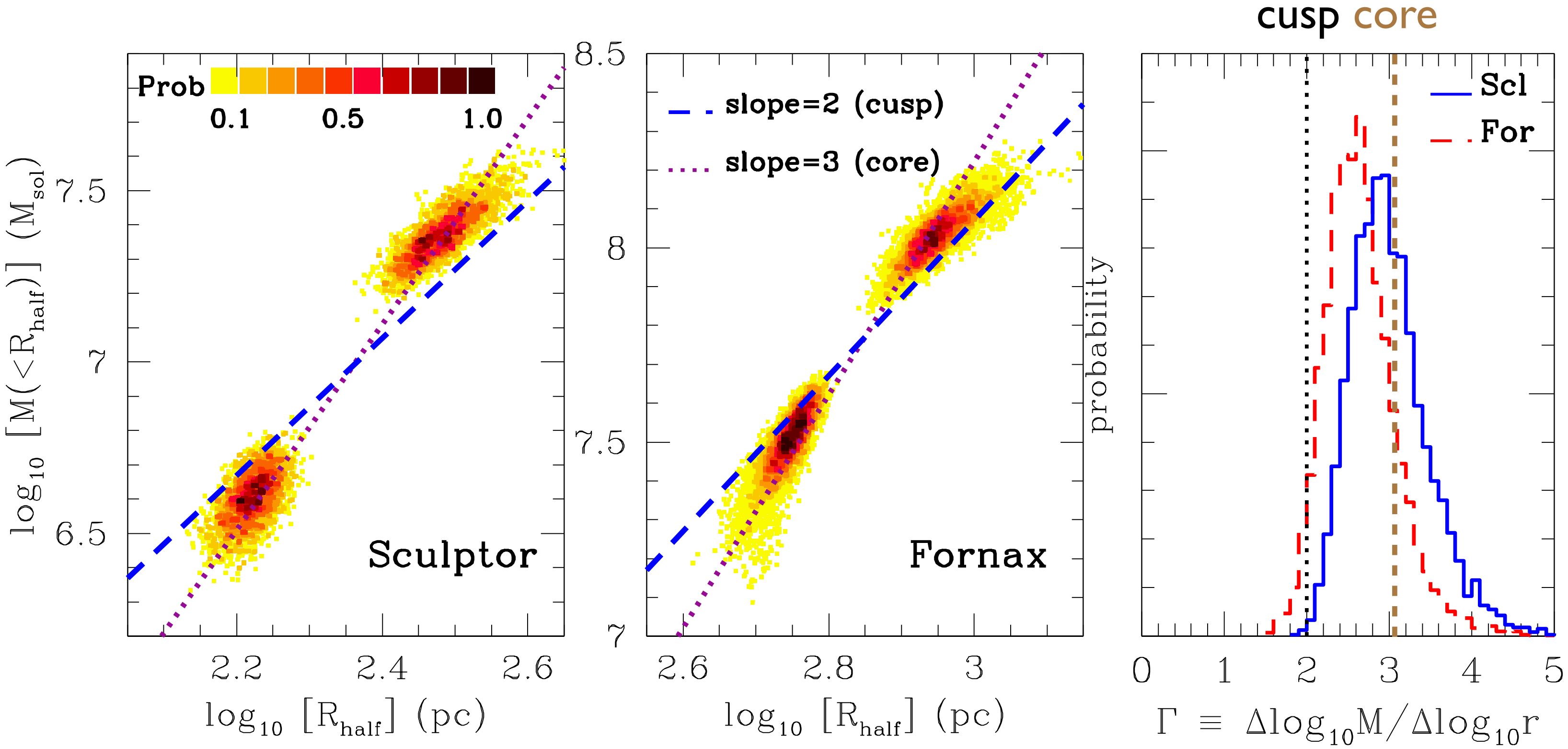


FIG. 10.— *Left, center:* Constraints on halflight radii and masses enclosed therein, for two independent stellar subcomponents in the Fornax and Sculptor dSphs. Plotted points come directly from our final MCMC chains, and color indicates relative likelihood (normalized by the maximum-likelihood value). Overplotted are straight lines indicating the central (and therefore maximum) slopes of cored ($\lim r \to 0\ d\log M/d\log r] = 3$) and cusped ($\lim r \to 0\ d\log M/d\log r] = 2$) dark matter halos. *Right:* Posterior PDFs for the slope Γ obtained for Fornax and Sculptor. The vertical dotted line marks the maximum (i.e., central) value of an NFW profile (i.e., cusp with $\gamma_{DM} = 1$, $\lim r \to 0\ [d\log M/d\log r] = 2$). These measurements rule out NFW and/or steeper cusps ($\gamma DM \geq 1$) with significance $s \geq 96\%$ (Fornax) and $s \geq 99\%$ (Sculptor).

Similar results for Sculptor in Amorisco & Evans 2012 MNRAS. Jardel & Gebhardt present a Schwarzschild model fit to the Fornax dwarf, again favoring core rather than cusp.

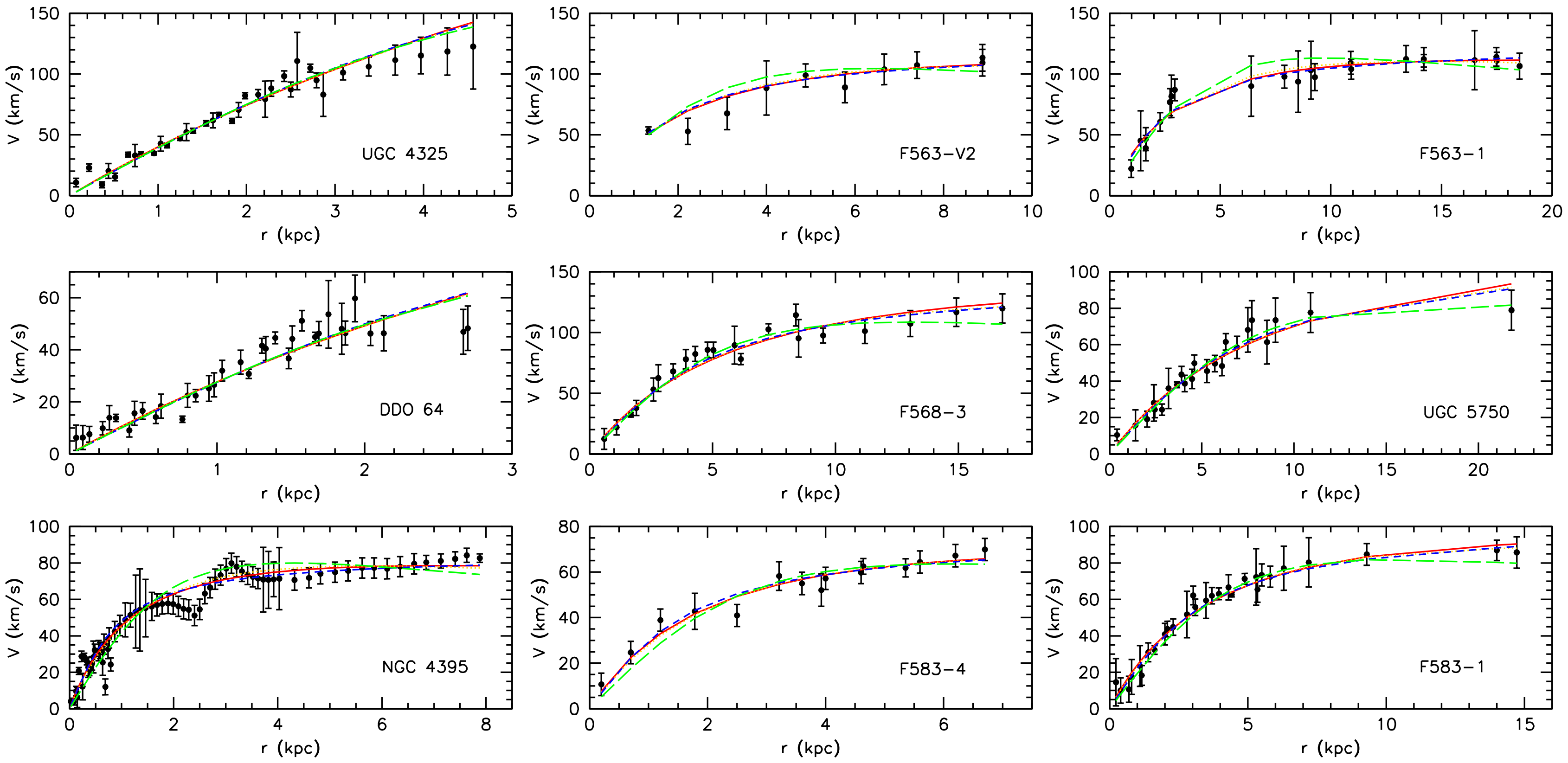
The Case Against Warm or Self-Interacting Dark Matter as Explanations for Cores in Low Surface Brightness Galaxies

2010, ApJ, 710L, 161

Rachel Kuzio de Naray, Gregory D. Martinez, James S. Bullock, Manoj Kaplinghat

Warm dark matter (WDM) and self-interacting dark matter (SIDM) are often motivated by the inferred cores in the dark matter halos of low surface brightness (LSB) galaxies. We test thermal WDM, non-thermal WDM, and SIDM using high-resolution rotation curves of nine LSB galaxies. If the core size is set by WDM particle properties, then **even the smallest cores we infer would require primordial phase space density values that are orders of magnitude smaller than lower limits obtained from the Lyman alpha forest power spectra.** We also find that the dark matter halo core densities vary by a factor of about 30 while showing no systematic trend with the maximum rotation velocity of the galaxy. This strongly argues against the core size being directly set by large self-interactions (scattering or annihilation) of dark matter. **We therefore conclude that the inferred cores do not provide motivation to prefer WDM or SIDM over other dark matter models.**

We fit these dark matter models to the data and determine the halo core radii and central densities. While the minimum core size in WDM models is predicted to **decrease** with halo mass, we find that the inferred core radii **increase** with halo mass and also cannot be explained with a single value of the primordial phase space density.

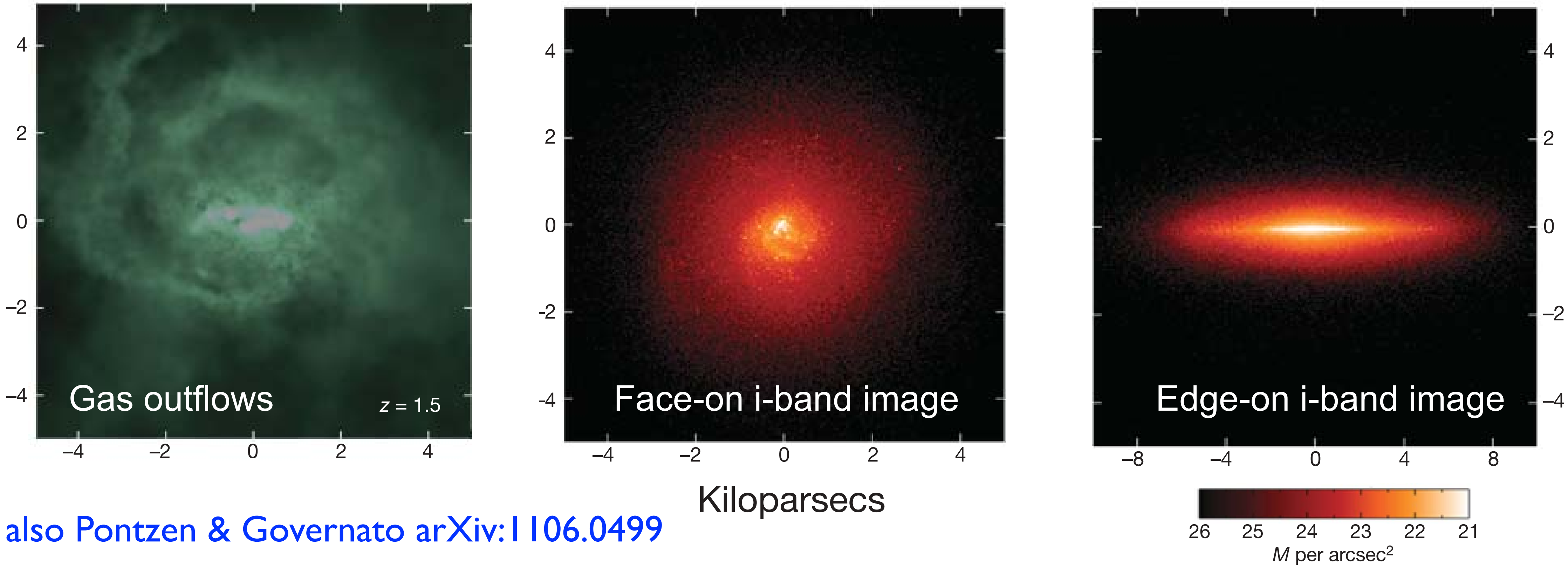


New simulations show that several episodes of gas blowout during evolution of dwarf spiral galaxies can remove cusps

Bulgeless dwarf galaxies and dark matter cores from supernova-driven outflows

F. Governato, C. Brook, L. Mayer, A. Brooks, G. Rhee, J. Wadsley, P. Jonsson, B. Willman, G. Stinson, T. Quinn & P. Madau **Nature** 463, 203 (Jan 2010)

Most observed dwarf galaxies consist of a rotating stellar disk embedded in a massive dark-matter halo with a near-constant-density core. Models based on CDM, however, invariably form galaxies with dense spheroidal stellar bulges and steep central dark-matter profiles, because low-angular-momentum baryons and dark matter sink to the centers of galaxies through accretion and repeated mergers. Here we report hydrodynamical simulations in which the inhomogeneous interstellar medium is resolved. **Strong outflows from supernovae remove low-angular-momentum gas, which inhibits the formation of bulges and decreases the dark-matter density to less than half of what it would otherwise be within the central kiloparsec. The analogues of dwarf galaxies—bulgeless and with shallow central dark-matter profiles—arise naturally in these simulations.** Simulations using the same implementation of star formation and feedback reproduce some global scaling properties of observed galaxies across a range of masses and redshifts.



See also Pontzen & Governato arXiv:1106.0499

Cuspy No More: How Outflows Affect the Central Dark Matter and Baryon Distribution in ΛCDM Galaxies.

F.Governato[1⋆] A.Zolotov[2], A.Pontzen[3], C.Christensen[4], S.H.Oh[5,6], A. M.Brooks[7],
T.Quinn[1], S.Shen[8], J.Wadsley[9]

MNRAS in press 2012

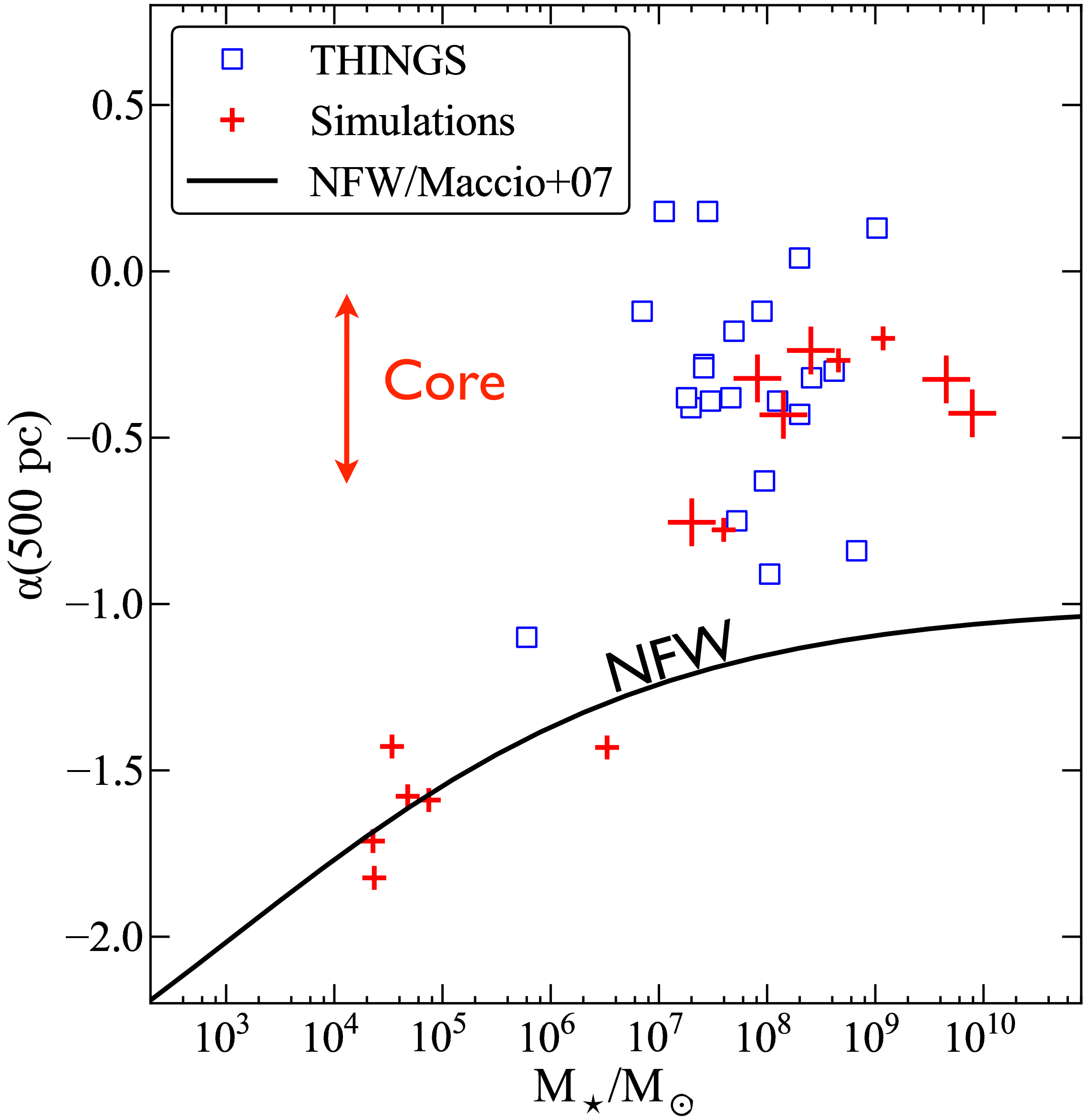
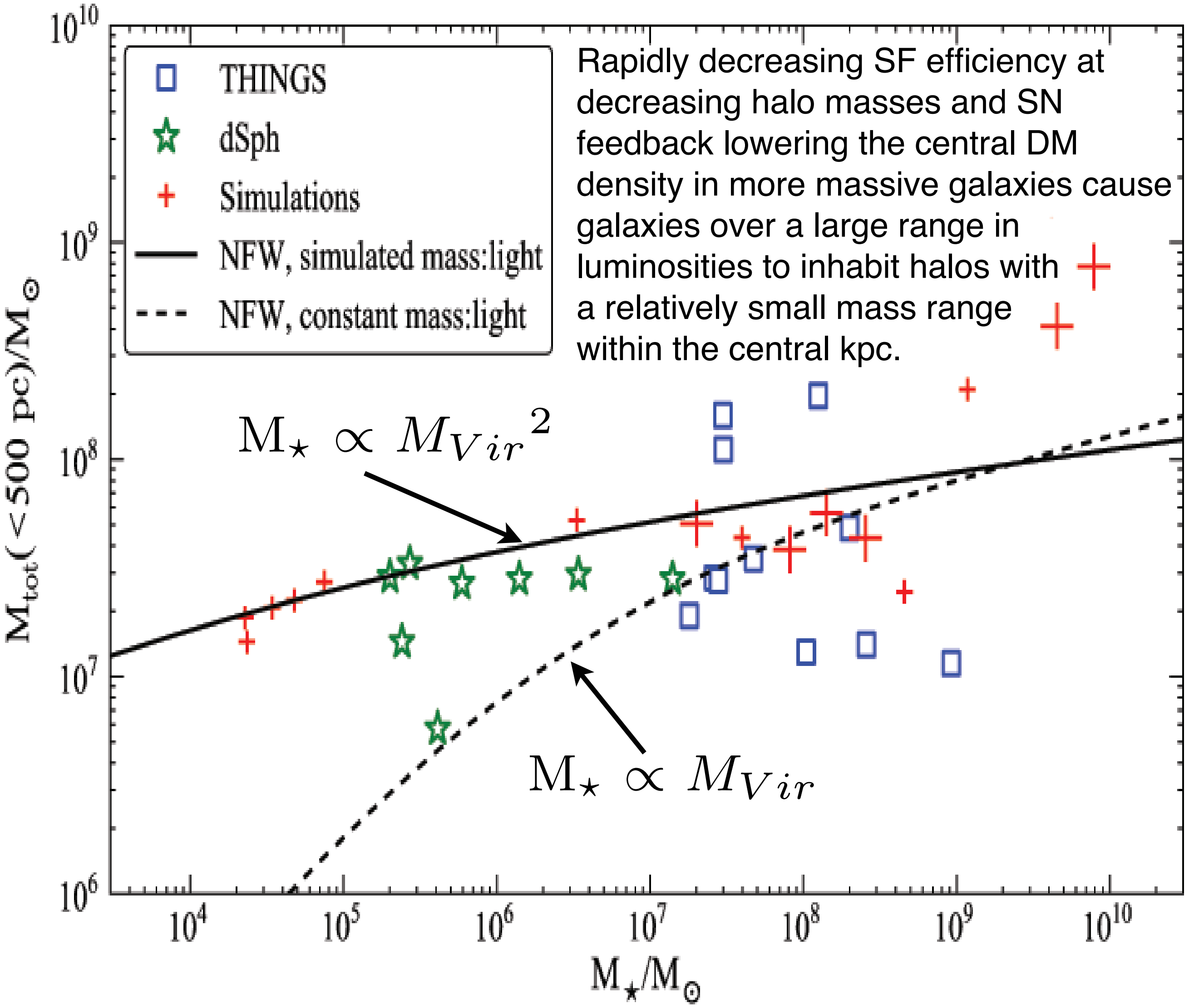


Figure 1. *The slope of the dark matter density profile* α vs stellar mass measured at 500 pc and z=0 for all the resolved halos in our sample. The Solid 'DM-only' line is the slope predicted for the same CDM cosmological model assuming i) the NFW concentration parameter trend given by Macció et al (2007) and ii) the same stellar mass vs halo mass relation as measured in our simulations to convert from halo masses. Large Crosses: haloes resolved with more than 0.5×10^6DM particles within R_{vir}. Small crosses: more than 5×10^4 DM particles. The small squares represent 22 observational data points measured from galaxies from the THINGS and LITTLE THINGS surveys.



Rapidly decreasing SF efficiency at decreasing halo masses and SN feedback lowering the central DM density in more massive galaxies cause galaxies over a large range in luminosities to inhabit halos with a relatively small mass range within the central kpc.

Figure 4. The total mass (baryons and DM) within the central 500 pc as a function of stellar mass: Large and small crosses: simulations. Open squares: galaxies from THINGS (Oh et al. in prep). Stars: dSph from Walker (priv. comm.). Theoretical predictions reproduce the observed flat trend from 10^5 to 10^9 M⊙. This is largely due to the large drop in SF efficiency at small halo masses, that stretches the range of galaxy luminosities over a relatively smaller halo mass range. The solid and dashed lines assume different stellar mass - total halo mass relations. A close fit to the simulations as $M^* \sim M_{Vir}^2$ (solid) and one showing $M^* \sim M_{Vir}$ (dashed). Only when the star formation efficiency is a steep function of halo mass it is possible to reproduce the observed trend, as discussed in §4. More massive galaxies above the solid line have a small bulge component.

Satellites and Subhalos

The discovery of many faint Local Group dwarf galaxies is consistent with ΛCDM predictions. Satellites, reionization, lensing flux anomalies, stellar streams, and Lyα forest data imply that WDM must be Tepid or Cooler.

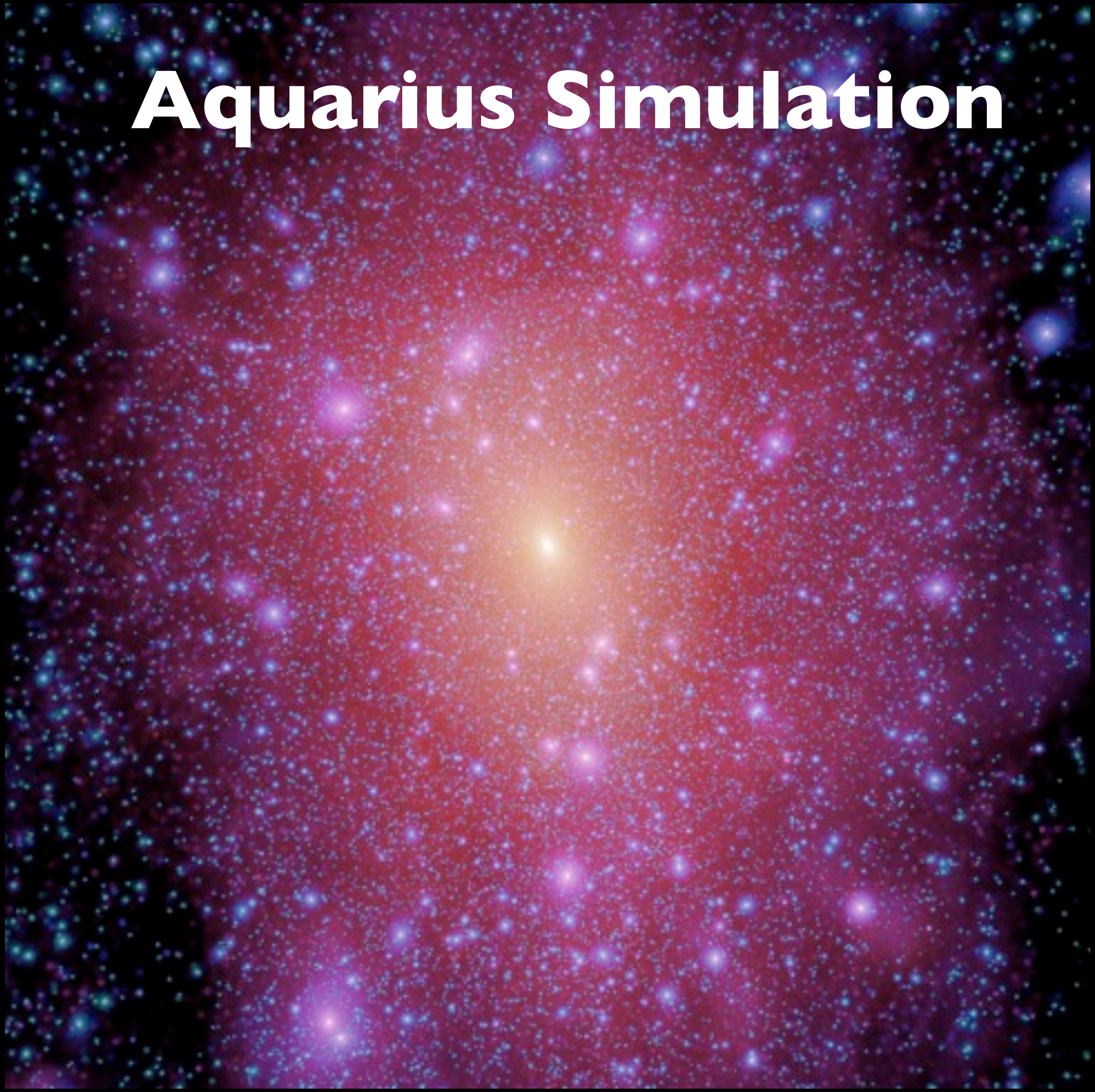
New Developments

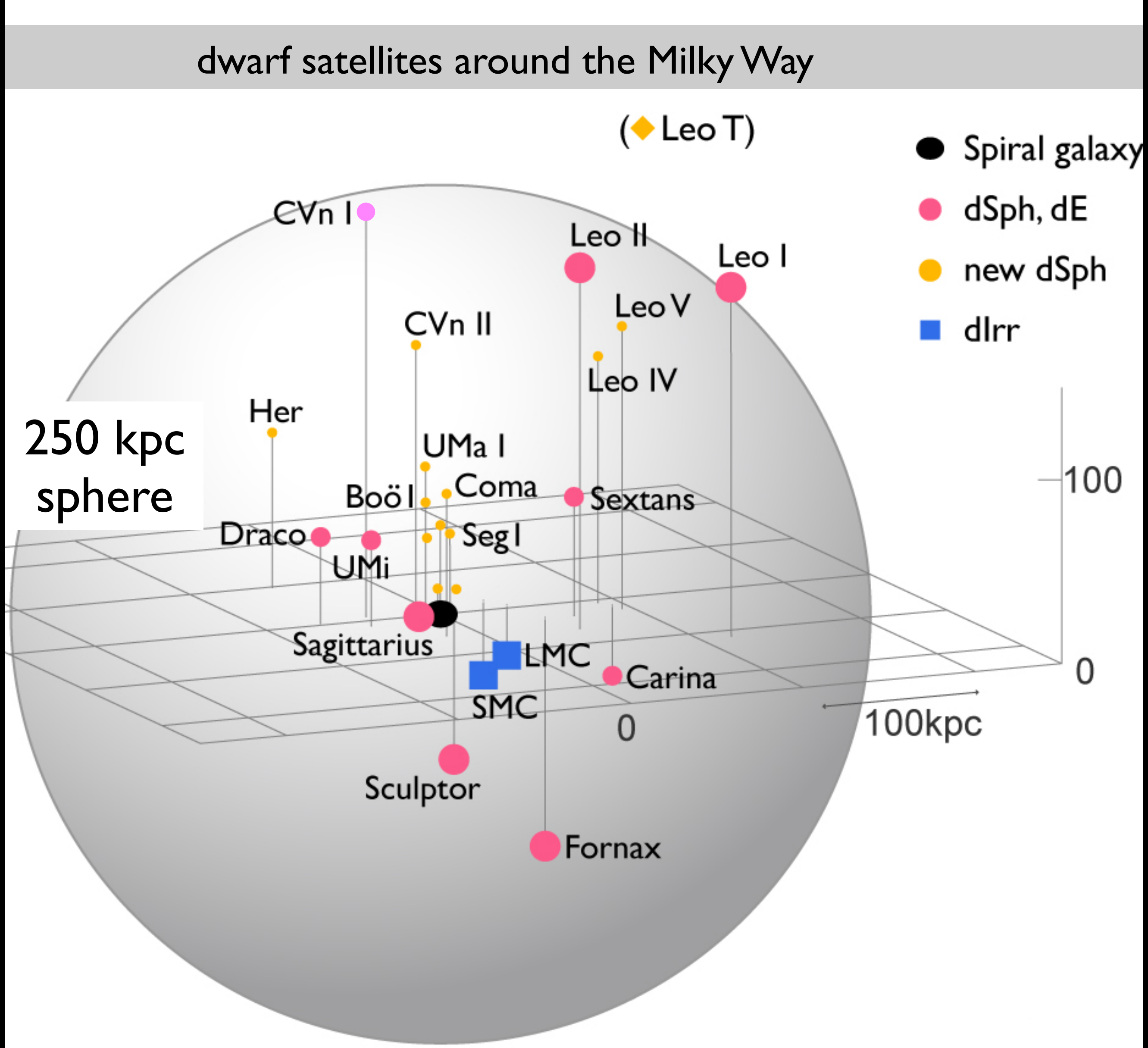
- The "too big to fail" problem appears to be the most serious current challenge for ΛCDM, and may indicate the need for a more complex theory of dark matter.
- High resolution ΛCDM simulation substructure is consistent with quad-lens radio quasar flux and galaxy-galaxy lensing anomalies and indications of substructure by stellar stream gaps.
- ΛCDM predicts that there is a population of low-luminosity stealth galaxies around the Milky Way. Will new surveys with bigger telescopes find them?

The "too big to fail" problem

ΛCDM subhalos vs. Milky Way satellites

"Missing satellites": Klypin et al. 1999, Moore et al. 1999





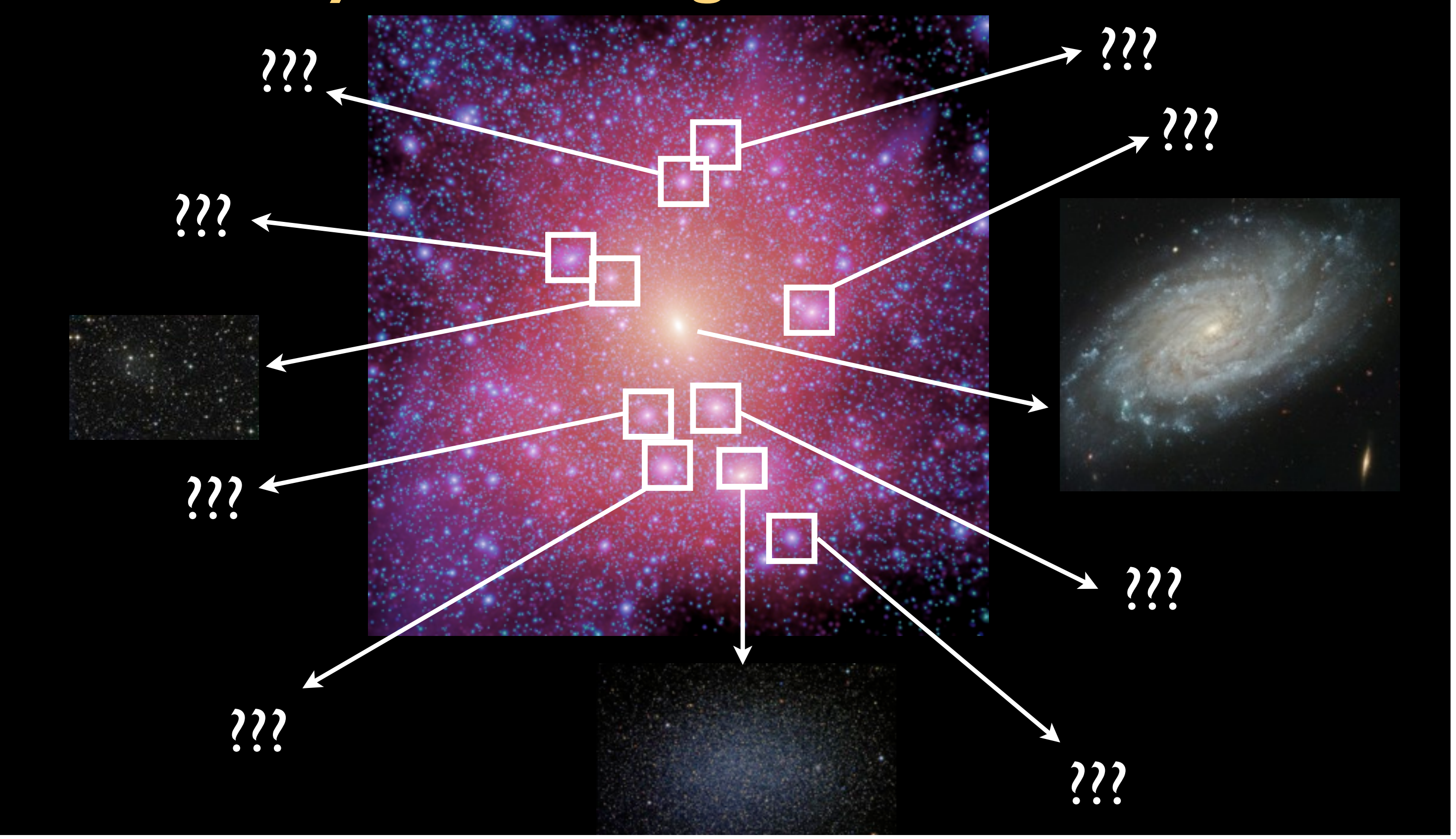
>10^5 identified subhalos

12 bright satellites $(L_V > 10^5 L_\odot)$

V. Springel / Virgo Consortium

S. Okamoto

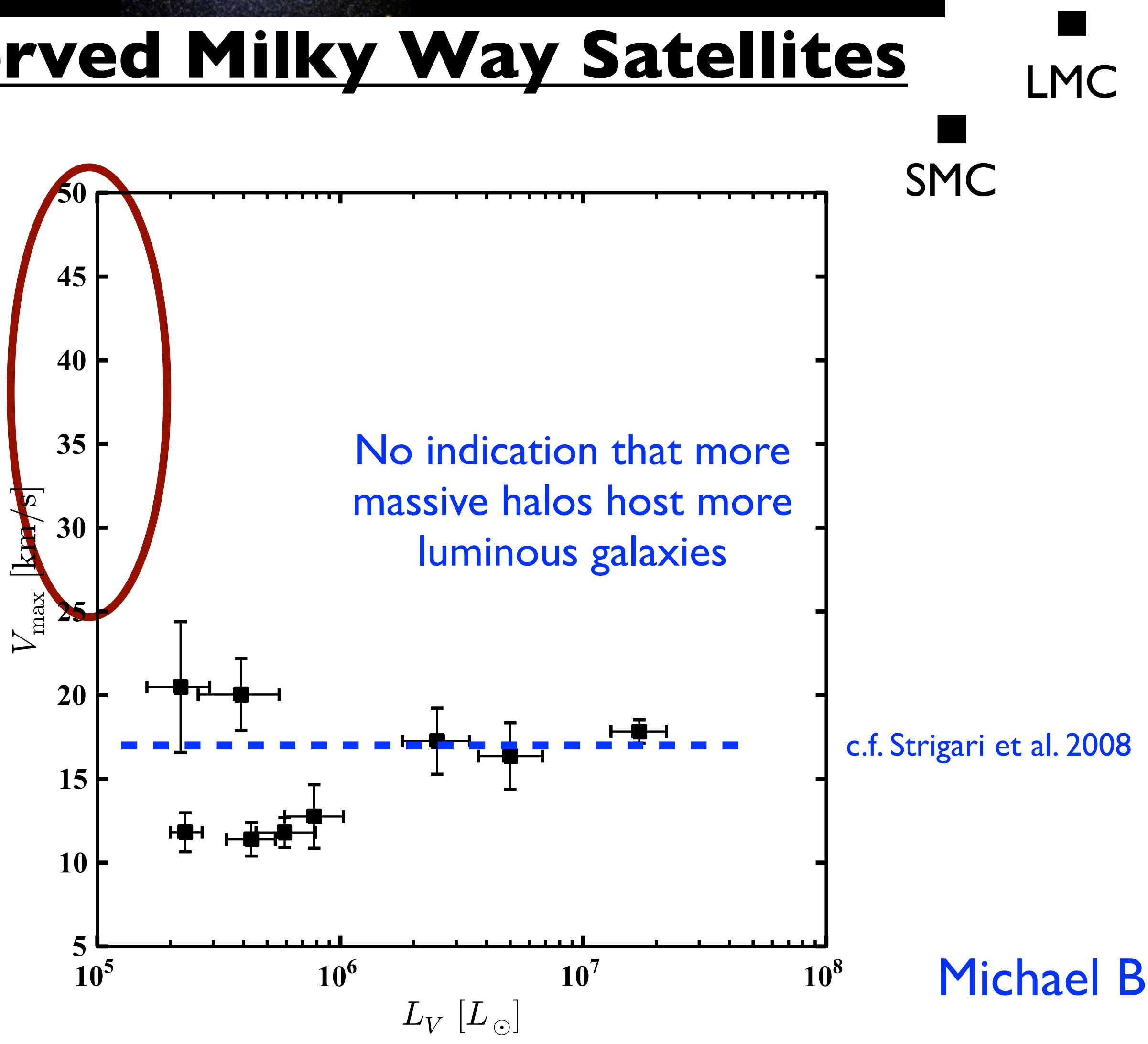
Of the ~10 biggest subhalos, ~8 cannot host *any* known bright MW satellite



Observed Milky Way Satellites

“massive failures”: highest resolution LCDM simulations predict ~10 subhalos in this range in the MW, but we don’t see ***any*** such galaxies [except Sagittarius (?)]

All of the bright MW dSphs are consistent with $V_{\max} \lesssim 25\,\mathrm{km/s}$
(see also Strigari, Frenk, & White 2010)



No indication that more massive halos host more luminous galaxies

c.f. Strigari et al. 2008

Possible Solutions to “too big to fail”

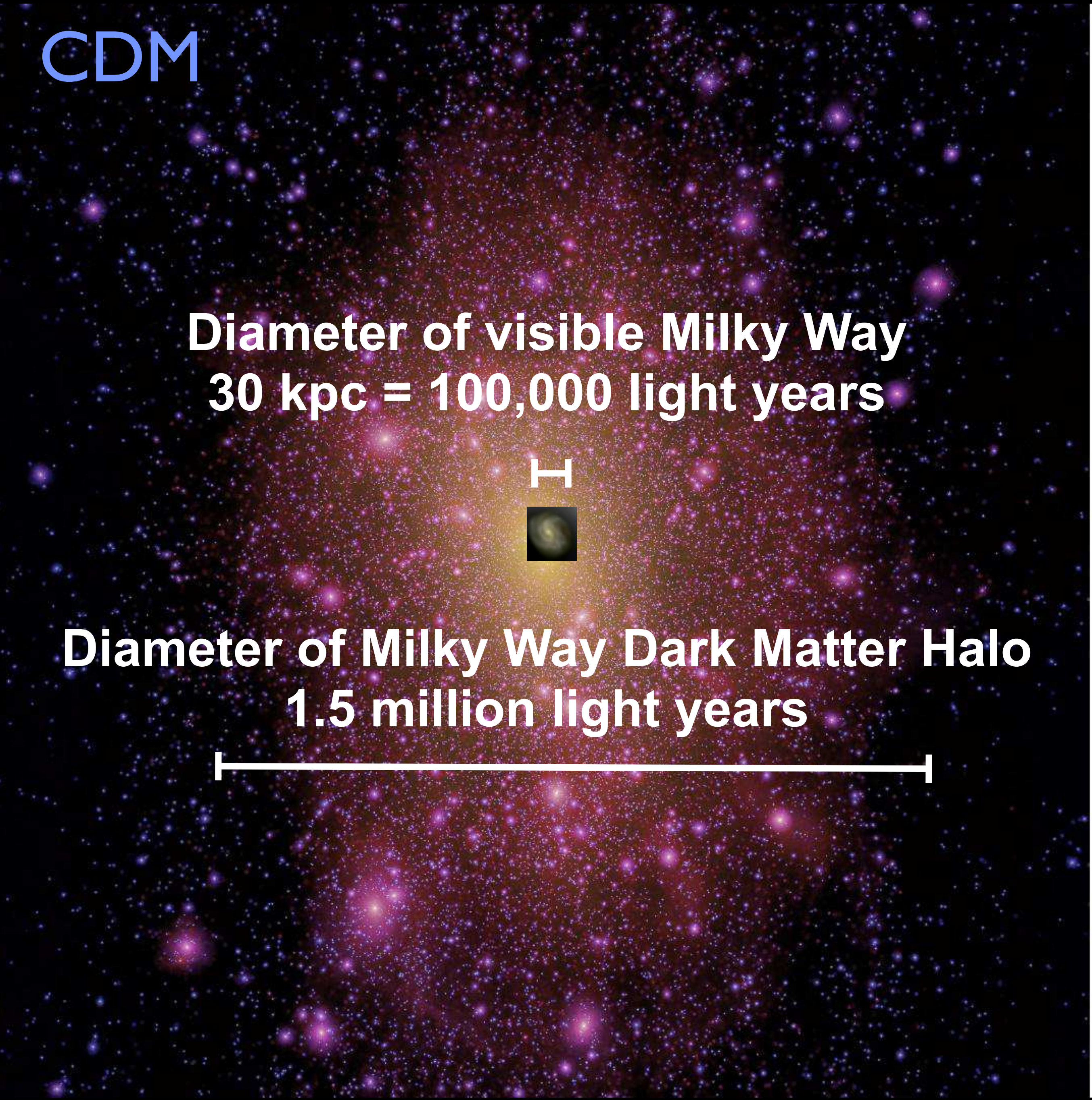
The Milky Way is anomalous?

The Milky Way has a low mass dark matter halo?

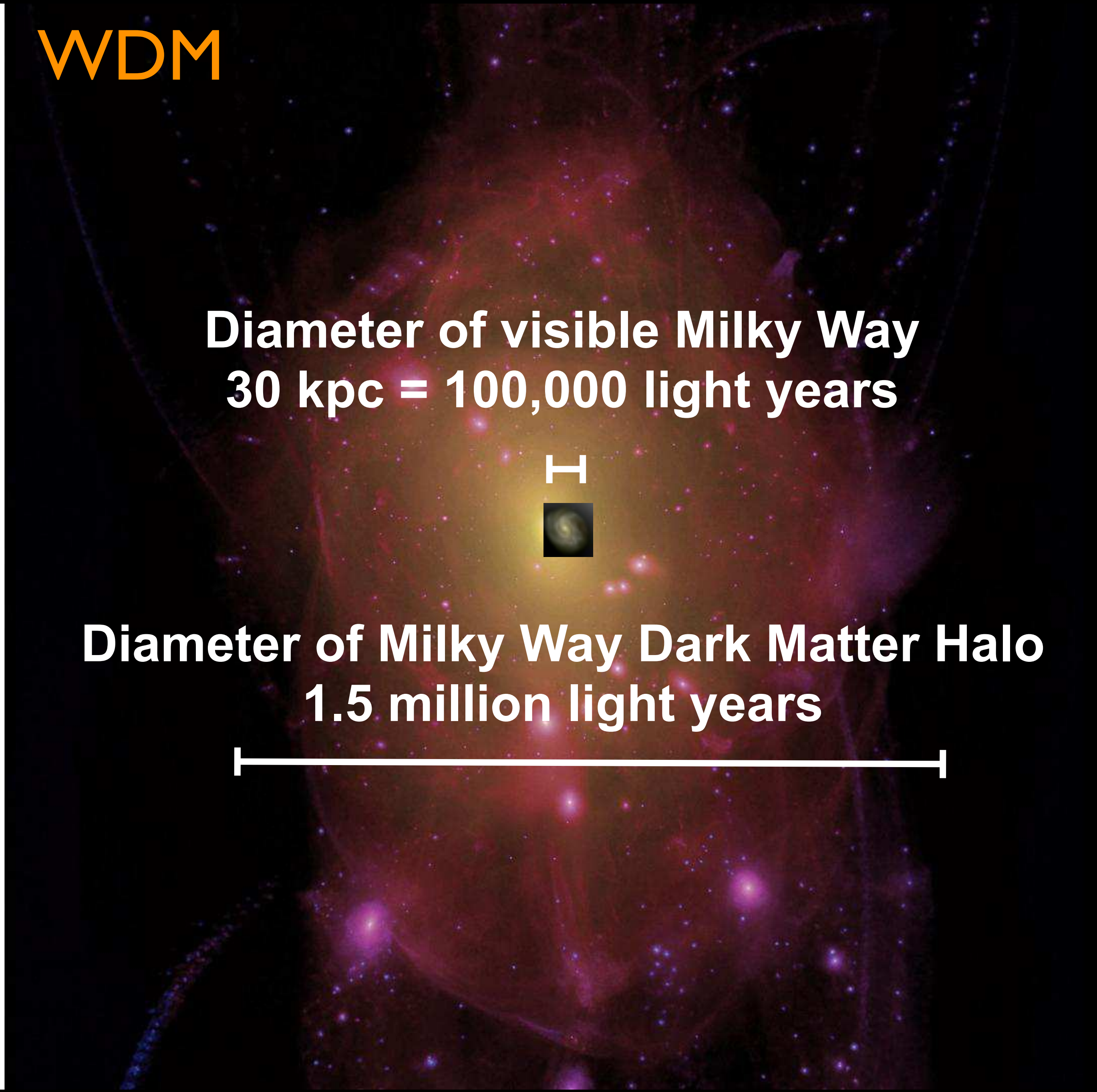
Galaxy formation is stochastic at low masses?

Dark matter is not just CDM -- maybe WDM or even self-interacting?

Michael Boylan-Kolchin, Bullock, Kaplinghat 2011, 2012



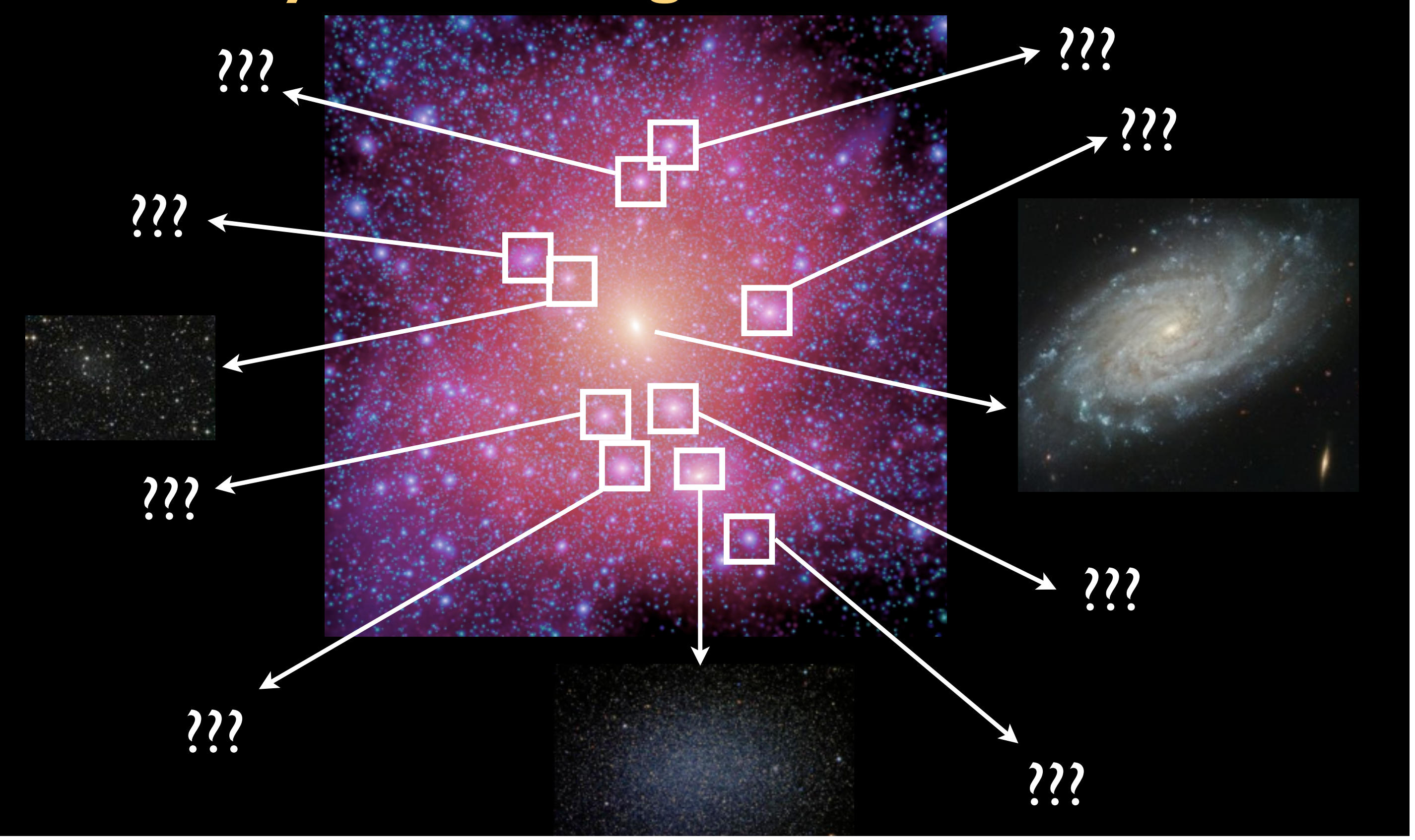
Aquarius simulation. Springel et al. 2008



Lovell, Eke, Frenk, et al. 2011

WDM simulation at right has no "too big to fail" subhalos, but it doesn't lead to the right systematics to fit dwarf galaxy properties as Kuzio de Naray et al. showed. It also won't have the subhalos needed to explain radio flux anomalies and gaps in stellar streams.

Of the ~10 biggest subhalos, ~8 cannot host *any* known bright MW satellite



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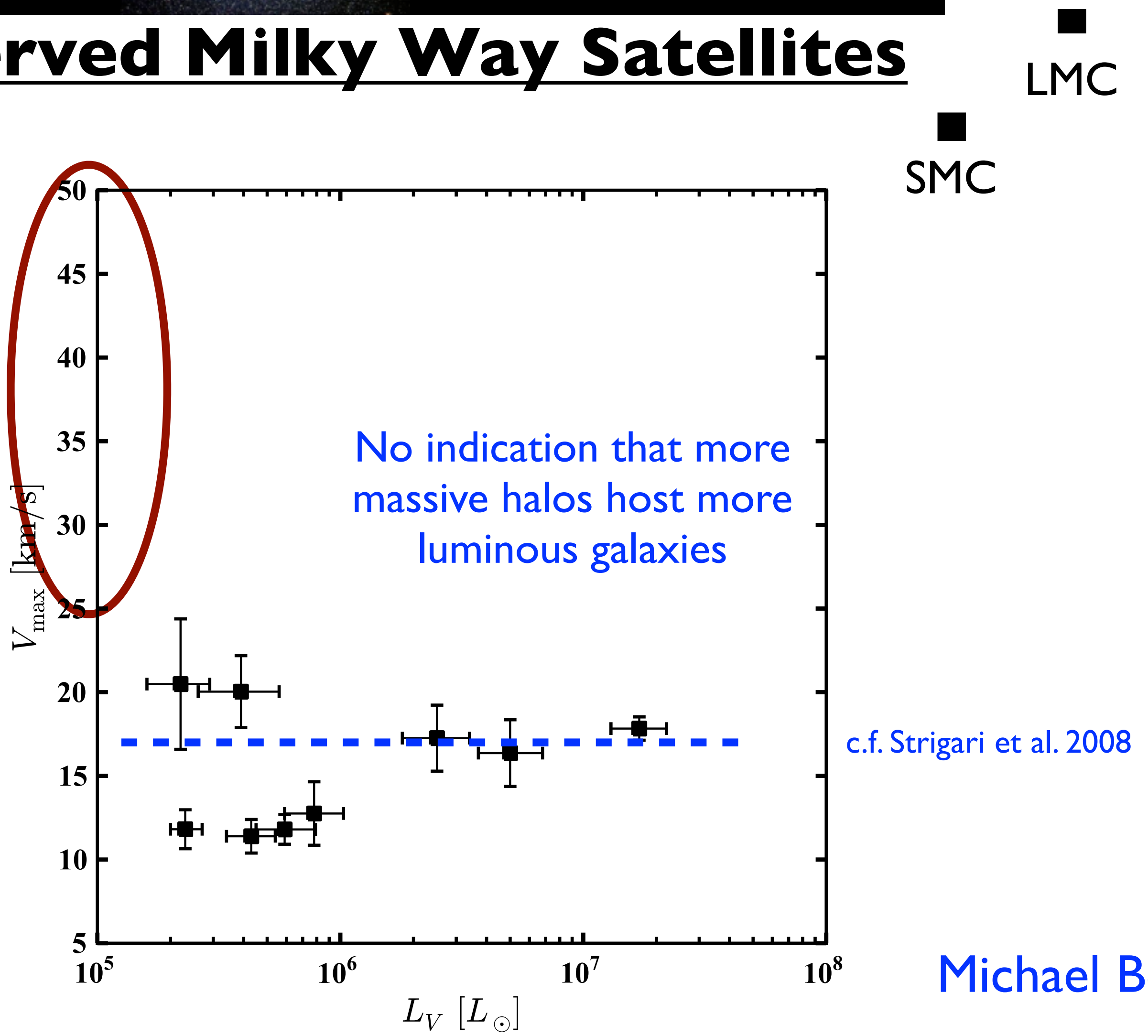

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Possible Solutions to “too big to fail”

The Milky Way is anomalous?

The Milky Way has a low mass dark matter halo?

Galaxy formation is stochastic at low masses?

Dark matter is not just CDM -- maybe WDM or even self-interacting?

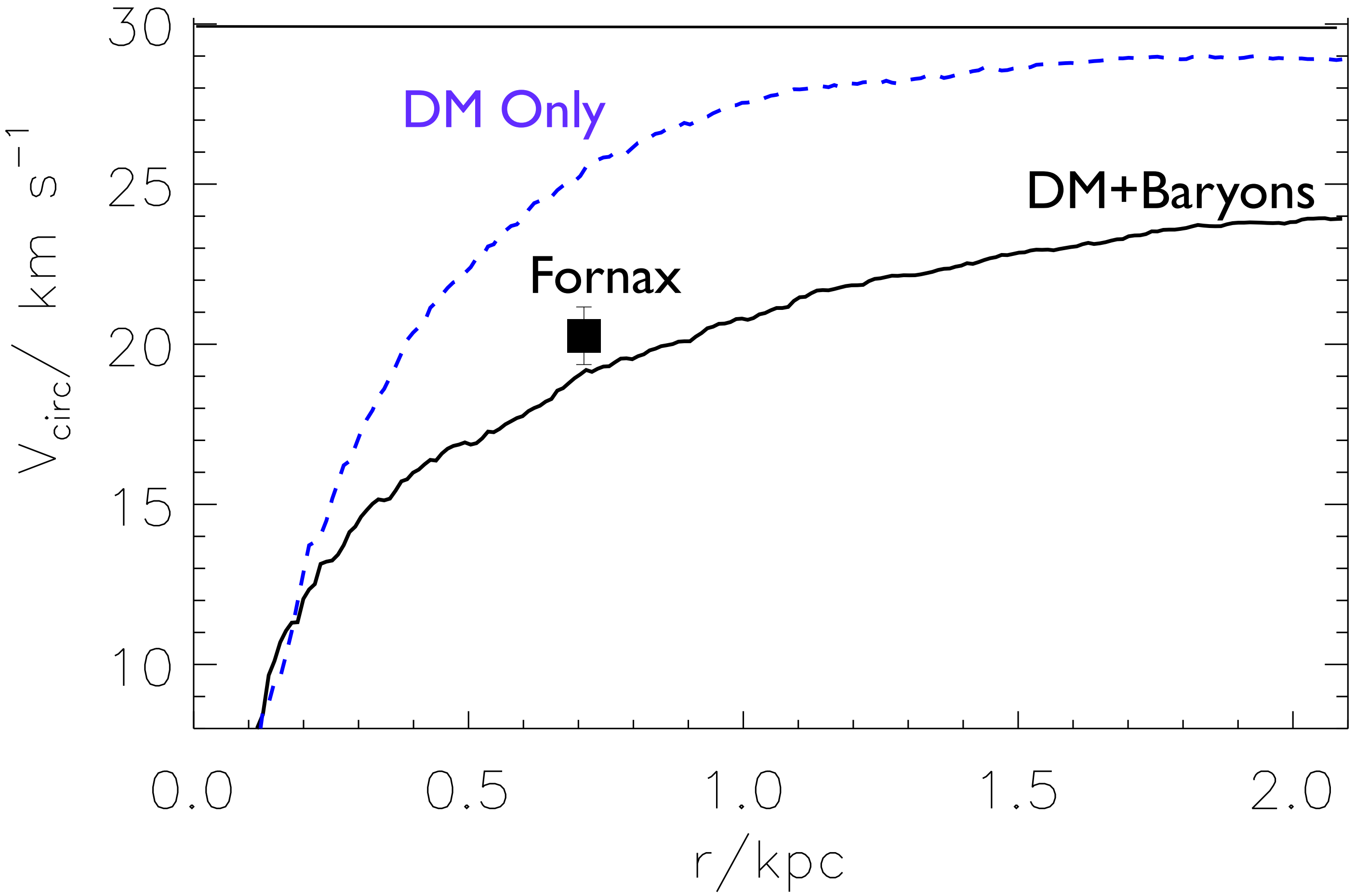
Or maybe high-resolution CDM simulations are being misinterpreted? Maybe baryons strongly modify the structure of subhalos?

Michael Boylan-Kolchin, Bullock, Kaplinghat 2011, 2012

WHY BARYONS MATTER: THE KINEMATICS OF DWARF SPHEROIDAL SATELLITES

Alyson M. Brooks & Adi Zolotov - Submitted to ApJ Letters

We use some of the highest resolution cosmological simulations ever produced of Milky Way-mass galaxies that include both baryons and dark matter to show that baryonic physics (energetic feedback from supernovae and subsequent tidal stripping) significantly reduces the dark matter mass in the central regions of luminous satellite galaxies. The reduced central masses of the simulated satellites reproduce the observed internal dynamics of Milky Way and M31 satellites as a function of luminosity. Including baryonic physics in Cold Dark Matter models naturally explains the observed low dark matter densities in the Milky Way's dwarf spheroidal population. Our simulations therefore resolve the tension between kinematics predicted in Cold Dark Mater theory and observations of satellites, without invoking alternative forms of dark matter.



The z = 0 rotation curves of a simulated satellite and its DM-only counterpart. The V_{circ} for Fornax is over-plotted, based on the data in Walker et al. (2009). The combination of SN feedback (before infall) and tidal stripping (after infall) substantially lower the v_c of the SPH satellite by z = 0, and is in good agreement with the observed v_c of Fornax.

For almost all of our satellites, the DM-only runs produce satellites with 2-4 times more mass in the central 1 kpc than their SPH counterparts.

If a satellite fainter than $M_V \sim -12$ underwent substantial stripping (~90% of its total mass, Peñarrubia et al. 2008), it could have started off as a more luminous dSph with a DM core.

The presence of cored density profiles at radii under ~ 500 pc in satellites fainter than MV ~ –12 is not ruled out by our simulations, as we do not resolve this region.

Regardless of the density profile, the tidal effects of the disk can dramatically lower the central DM mass of any satellite, depending on infall time and orbital eccentricity.

Based on simulations in Zolotov+2012 with force softening 174 pc, $M_{DM} = 1.3\times10^5\ M_\odot$, and $M_{baryon} = 2.7\times10^4\ M_\odot$. This is at best barely adequate resolution.

Effects of baryons on the circular velocities of dwarf satellites

Anatoly Klypin, Kenza Arraki (NMSU), Shurud More (U. Chicago)

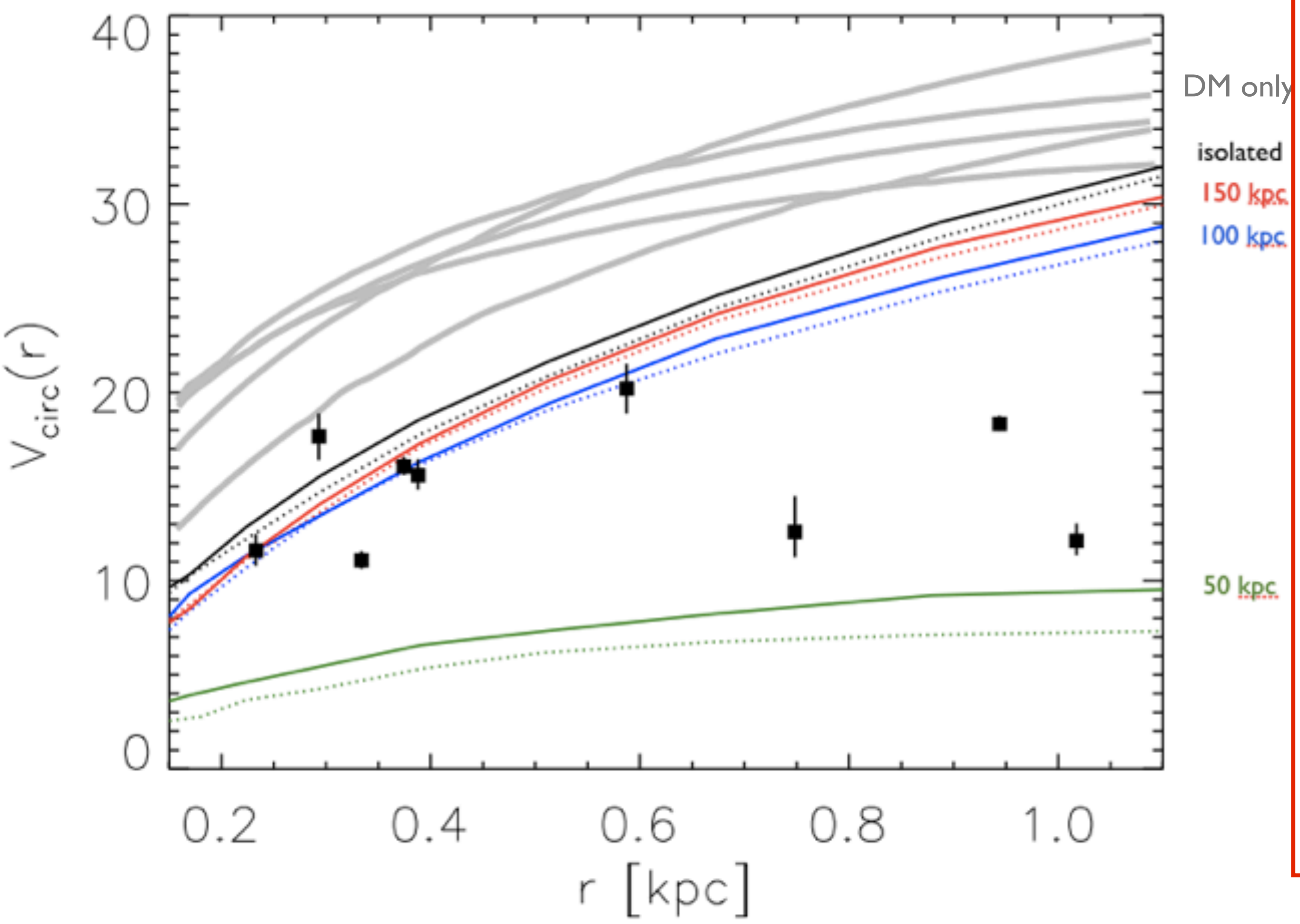
15 Aug 2012 Santa Cruz Galaxy Workshop

High resolution N-body simulations: 20 pc, $m_1 = 10^3$ Msun

Satellites: r_s=4 kpc v_{max}=63 km/s m_0=3.20x10^{10}

MW halo: r_s=25 kpc v_{max}=180 km/s m_0=1.4x10^{12}

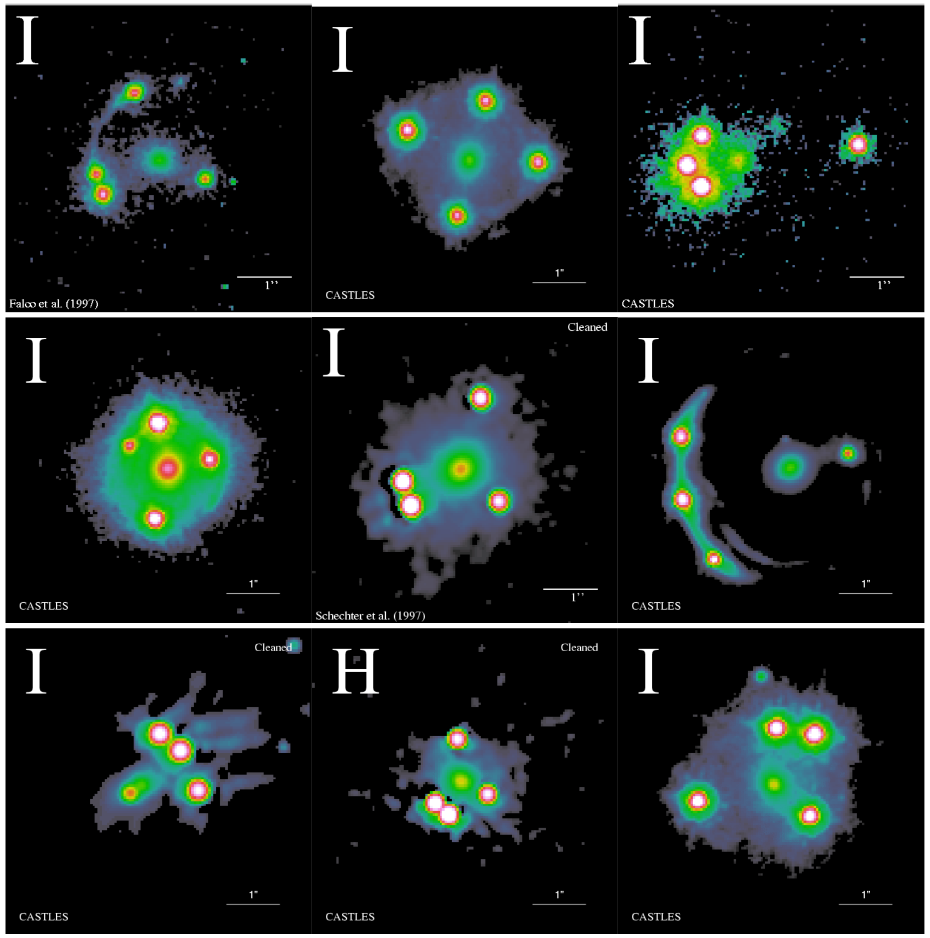
MW disk: r_0=3.0 kpc m_0=6x10^{10}



- Effects of baryons on dSph is unexpectedly strong
- Removal of a large fraction of baryons from the central region results in adiabatic expansion of the dwarf
- Fast or slow removal produce the same results
- Estimates of annihilation signal may be compromised if they use a large boost factor from substructure

Radio flux-ratio anomalies

Quasar lenses



(CASTLES project, http://www.cfa.harvard.edu/castles)

Radio flux-ratio anomalies ⇒

Strong evidence for dark matter clumps ~ 10^6 - 10^8 Msun as expected in ΛCDM

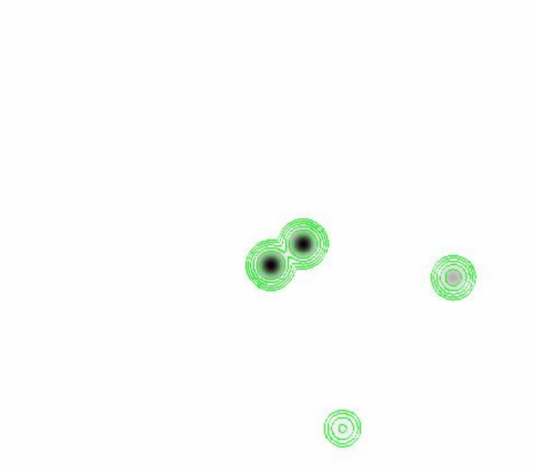
Flux ratio anomalies are generic

"Easy" to explain image positions (even to ~0.1% precision)

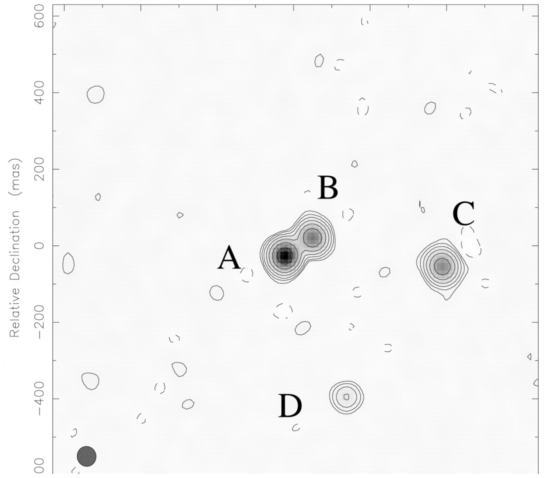
- ellipsoidal galaxy
- tidal forces from environment

But hard to explain flux ratios!

expected



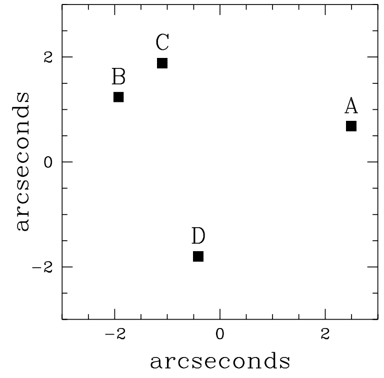
observed *(Marlow et al. 1999)*

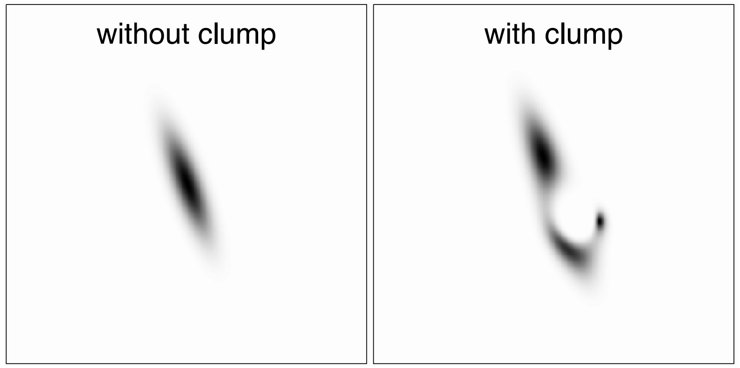


Substructure and lensing

Q) What happens if lens galaxies contain mass clumps?

A) The clumps distort the images on small scales.





(cf. Mao & Schneider 1998; Metcalf & Madau 2001; Chiba 2002)

Chuck Keeton

The Aquarius simulations have not quite enough substructure to explain quad-lens radio quasar flux anomalies -- but perhaps including baryons in simulations will help.

Effects of dark matter substructures on gravitational lensing: results from the Aquarius simulations

D. D. Xu, Shude Mao, Jie Wang, V. Springel, Liang Gao, S. D. M. White, Carlos S. Frenk, Adrian Jenkins, Guoliang Li and Julio F. Navarro MNRAS **398,** 1235–1253 (2009)

We conclude that line-of-sight structures can be as important as intrinsic substructures in causing flux-ratio anomalies. ... This alleviates the discrepancy between models and current data, but a larger observational sample is required for a stronger test of the theory.

Effects of Line-of-Sight Structures on Lensing Flux-ratio Anomalies in a ΛCDM Universe

D. D. Xu, Shude Mao, Andrew Cooper, Liang Gao, Carlos S. Frenk, Raul Angulo, John Helly MNRAS (2012)

We investigate the statistics of flux anomalies in gravitationally lensed QSOs as a function of dark matter halo properties such as substructure content and halo ellipticity. ... The constraints that we are able to measure here with current data are roughly consistent with ΛCDM N-body simulations.

Constraints on Small-Scale Structures of Dark Matter from Flux Anomalies in Quasar Gravitational Lenses

R. Benton Metcalf, Adam Amara MNRAS 419, 3414 (2012)

Substructure in lens galaxies: first constraints on the mass function

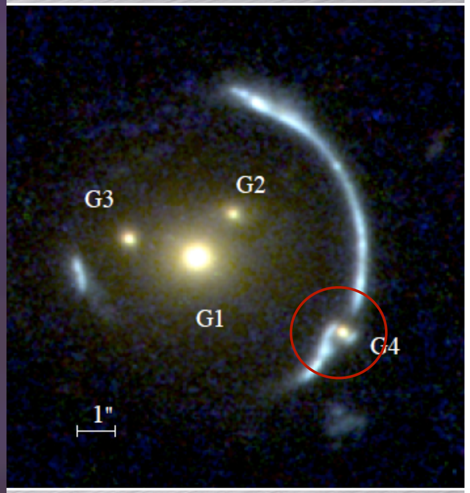
Simona Vegetti (MIT)

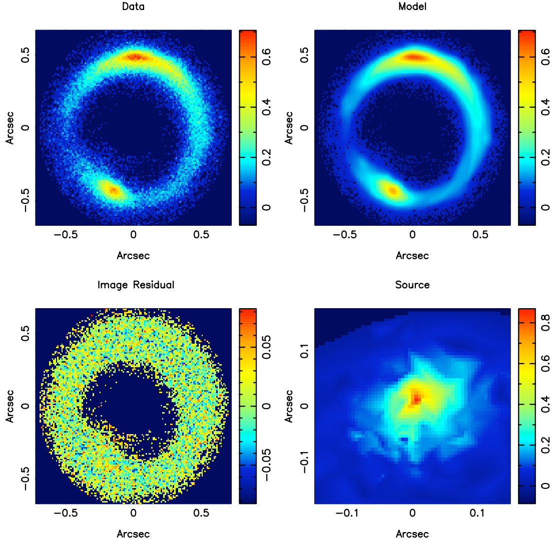
Gravitational detection of a low-mass dark satellite galaxy at cosmological distance, 2012 Nature

Talk at KITP conference “First Light and Faintest Dwarfs” Feb 2012

How do we recognise the effect of substructure?

Extended galaxy





Substructure as a truncated pseudo Jaffe

$$M_{sub} = (1.9 \pm 0.1) \times 10^{8} M_{\odot}$$

$$M(< 0.6) = (1.15 \pm 0.06) \times 10^{8} M_{\odot}$$

$$M(< 0.3) = (7.24 \pm 0.6) \times 10^{7} M_{\odot}$$

Substructure as SIS

$$M(< 0.3) = 3.4 \times 10^{7} M_{\odot}$$

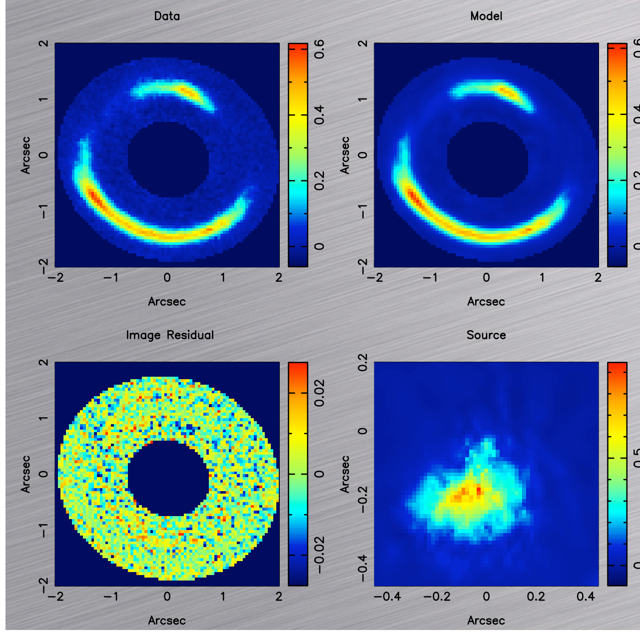
$$\sigma_v \approx 16 \ km \ s^{-1}$$

$$V_{max} \approx 27 \ km \ s^{-1}$$

$\Delta \log E = 65.0$ $12 \ \sigma \ detection$

J0946+1066 - Double ring

Power-Law smooth model + Power-Law substructure



$$M_{\rm sub} = (3.51 \pm 0.15) \times 10^{9} M_{\odot}$$

$$r_t = 1.1 \ kpc$$

$$\Delta \log \mathcal{E} = -128.0$$

equivalent to a ~16σ detection

$$M_{\rm 3D}(< 0.3) = 5.83 \times 10^{8} M_{\odot}$$

Conclusions

- Surface brightness anomalies can be used to find low mass galaxies at high z
- Simulations show that with HST quality data, 10 systems are sufficient to constrain the mass function
- Using high resolution adaptive optics data and the gravitational imaging technique we discovered an analogue of the Fornax satellite at redshift about 1
- The first constraints on the mass function are consistent with prediction from CDM (large errors ....)

Our results are consistent with the predictions from cold dark matter simulations at the 95 per cent confidence level, and therefore agree with the view that galaxies formed hierarchically in a Universe composed of cold dark matter. Vegetti et al. 2012 Nature 481, 341.

CLUMPY STREAMS FROM CLUMPY HALOS: DETECTING MISSING SATELLITES WITH COLD STELLAR STRUCTURES

Joo Heon Yoon[1]*, Kathryn V. Johnston[1], and David W. Hogg[2]

ApJ Accepted

2011 ApJ 731, 58

Dynamically cold stellar streams are ideal probes of the gravitational field of the Milky Way. This paper re-examines the question of how such streams might be used to test for the presence of "missing satellites" — the many thousands of dark-matter subhalos with masses $10^5 - 10^7 M_\odot$ which are seen to orbit within Galactic-scale dark-matter halos in simulations of structure formation in ΛCDM cosmologies. Analytical estimates of the frequency and energy scales of stream encounters indicate that these missing satellites should have a negligible effect on hot debris structures, such as the tails from the Sagittarius dwarf galaxy. However, long cold streams, such as the structure known as GD-1 or those from the globular cluster Palomar 5 (Pal 5) are expected to suffer many tens of direct impacts from missing satellites during their lifetimes. Numerical experiments confirm that these impacts create gaps in the debris' orbital energy distribution, which will evolve into degree- and sub-degree-scale fluctuations in surface density over the age of the debris. Maps of Pal 5's own stream contain surface density fluctuations on these scales. The presence and frequency of these inhomogeneities suggests the existence of a population of missing satellites in numbers predicted in the standard ΛCDM cosmologies.

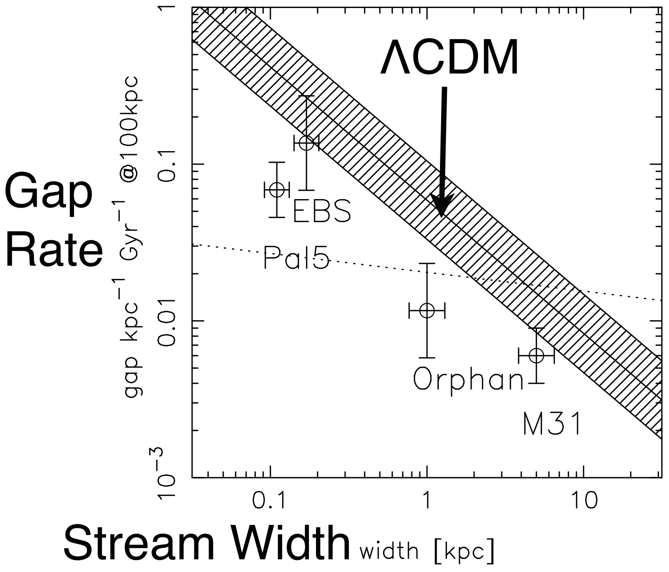


FIG. 11.— The estimated gap rate vs stream width relation for M31 NW, Pal 5, the EBS and the CDM halo prediction. All data have been normalized to 100 kpc. The width of the theoretical relation is evaluated from the dispersion in the length-height relation of Fig. 8. Predictions for an arbitrary alternative mass functions, $N(M) \propto M^{-1.6}$ normalized to have 33 halos above $10^9\,M_\odot$ is shown with a dotted line.

DARK MATTER SUB-HALO COUNTS VIA STAR STREAM CROSSINGS

R. G. Carlberg[1]   arXiv:1201.1347

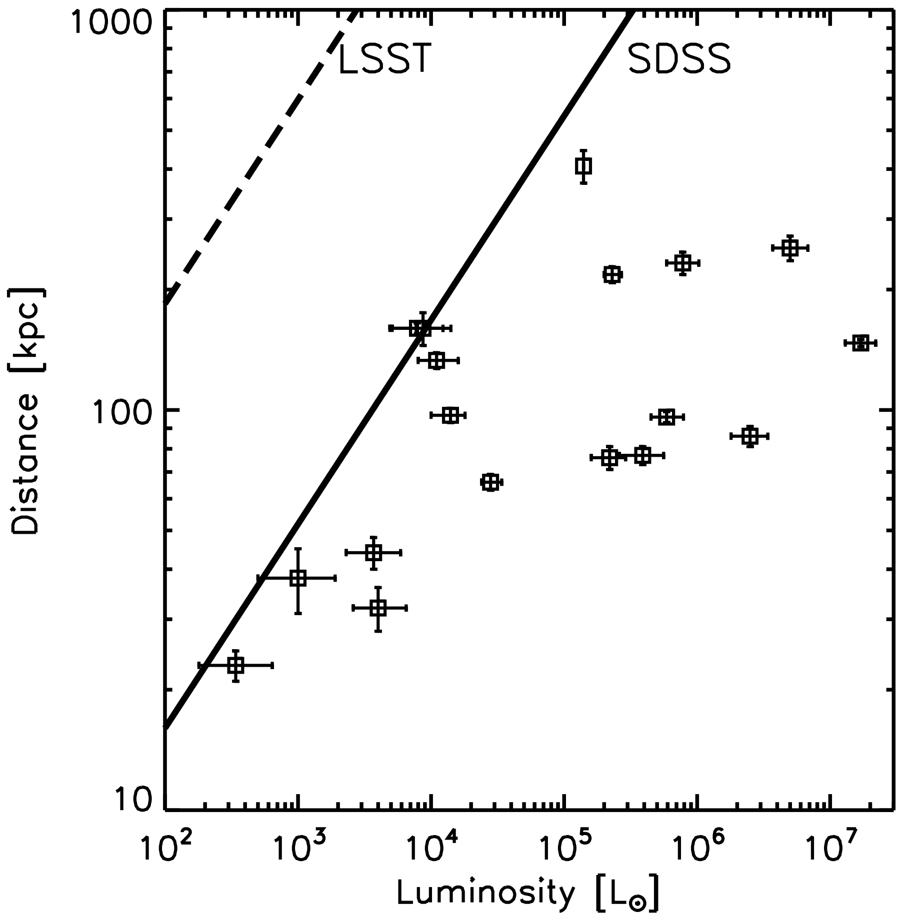
Comparison of the CDM based prediction of the gap rate-width relation with published data for four streams shows generally good agreement within the fairly large measurement errors. **The result is a statistical argument that the vast predicted population of sub-halos is indeed present in the halos of galaxies like M31 and the Milky Way.** The data do tend to be somewhat below the prediction at most points. This could be the result of many factors, such as the total population of sub-halos is expected to vary significantly from galaxy to galaxy, allowing for the stream age would lower the predicted number of gaps for the Orphan stream and possibly others as well, and most importantly these are idealized stream models.

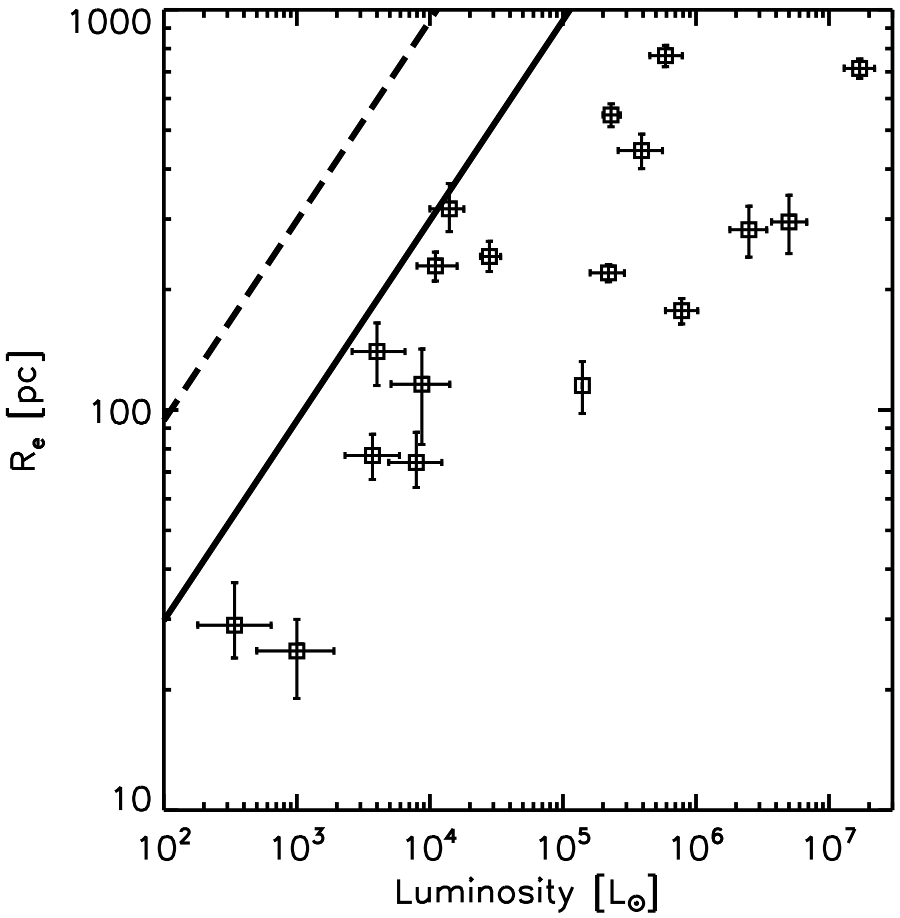
ΛCDM predicts that there is a population of low-luminosity stealth galaxies around the Milky Way. 2010 ApJ

STEALTH GALAXIES IN THE HALO OF THE MILKY WAY

James S. Bullock, Kyle R. Stewart, Manoj Kaplinghat, and Erik J. Tollerud

We predict that there is a population of low-luminosity dwarf galaxies with luminosities and stellar velocity dispersions that are similar to those of known ultrafaint dwarf galaxies but they have more extended stellar distributions (half light radii greater than about 100 pc) because they inhabit dark subhalos that are slightly less massive than their higher surface brightness counterparts. One implication is that **the inferred common mass scale for Milky Way dwarfs may be an artifact of selection bias.** A complete census of these objects will require deeper sky surveys, 30m-class follow-up telescopes, and more refined methods to identify extended, self-bound groupings of stars in the halo.





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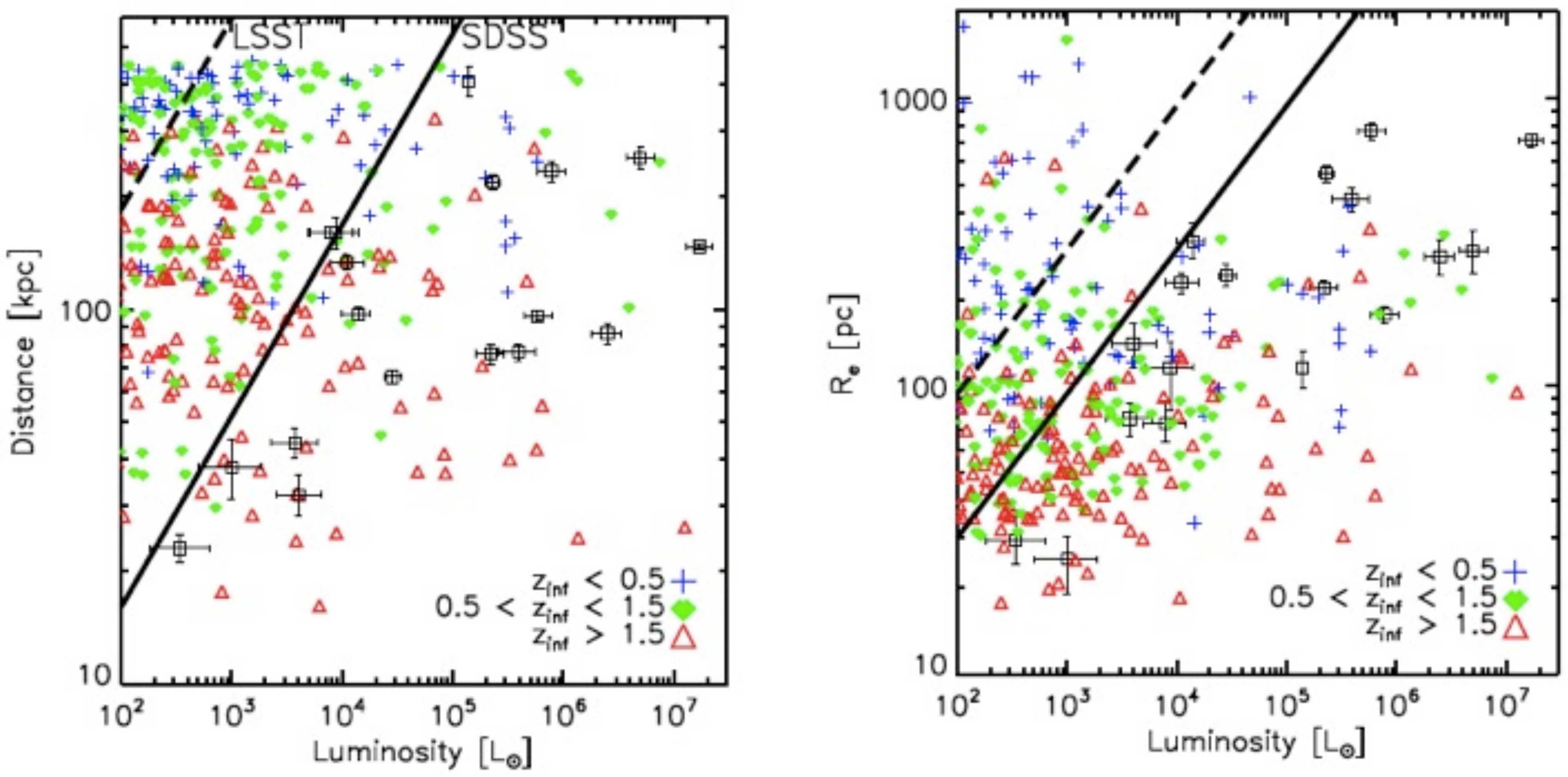
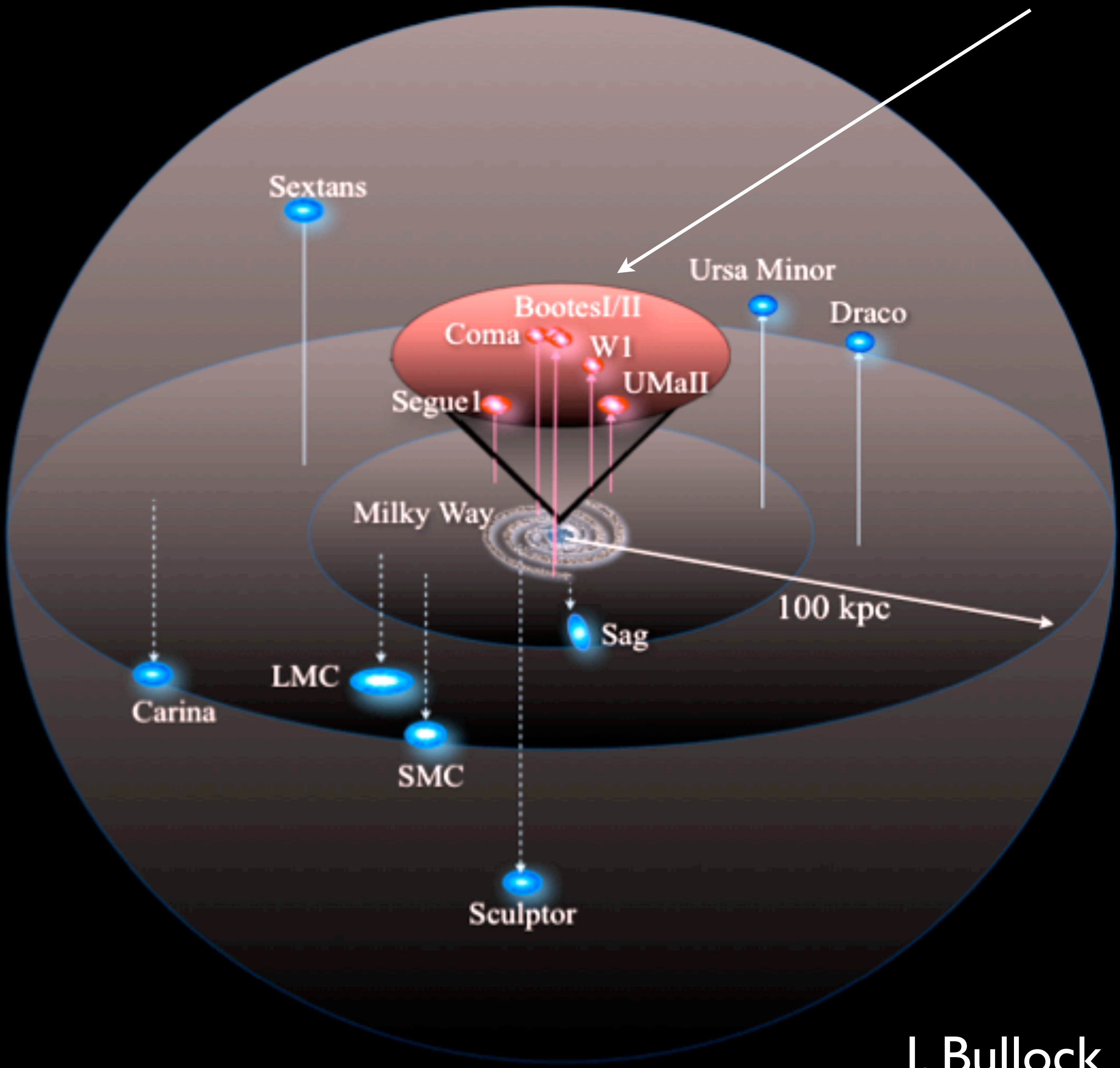


Satellite
Infall
redshift

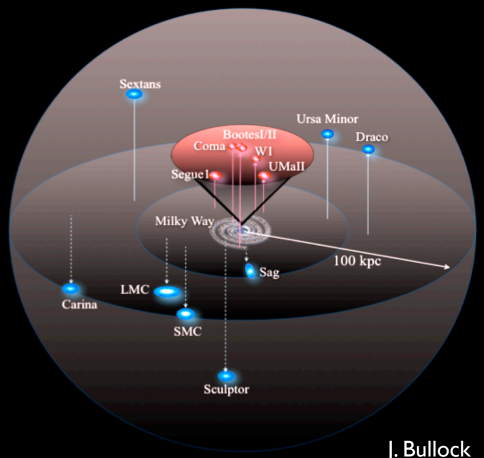
$z_{inf} < 0.5$ +
$0.5 < z_{inf} < 1.5$ ◆
$z_{inf} > 1.5$ △

SDSS satellite search

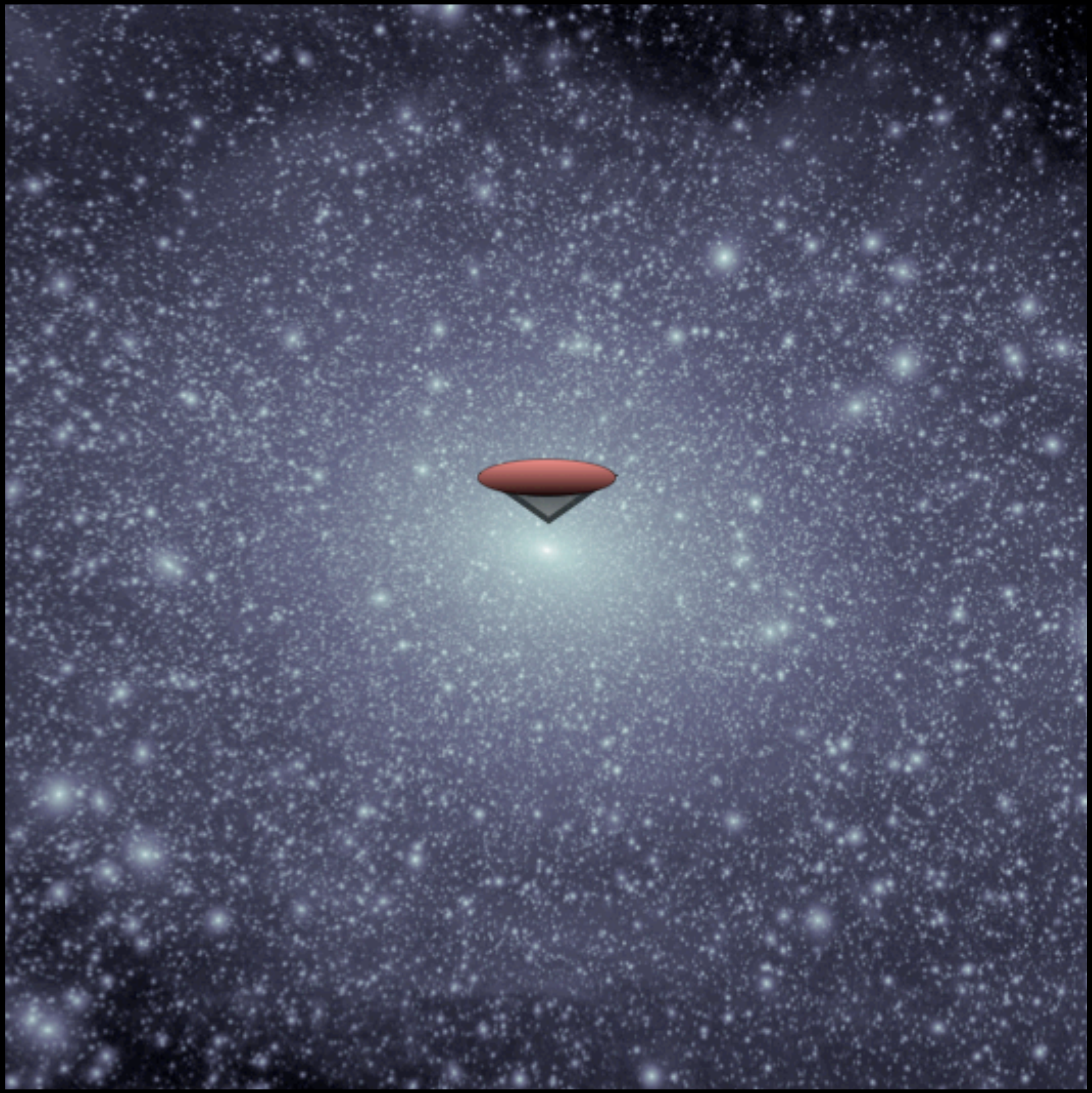


J. Bullock

The search for faint Milky Way satellites has just begun



J. Bullock



The Dark Energy Survey will cover a larger region of the Southern Sky, and LSST will go much deeper yet

Conclusions

- CMB and large-scale structure predictions of ΛCDM with WMAP5/7 cosmological parameters are in excellent agreement with observations. There are no known discrepancies.
- On galaxy and smaller scales, many of the supposed former challenges to ΛCDM are now at least partially resolved. The "angular momentum catastrophe" in galaxy formation appears to be resolved with better resolution and more realistic feedback. Cusps can be removed by starbursts blowing out central gas.
- Lensing flux anomalies and gaps in cold stellar streams appear to require the sort of substructure seen in ΛCDM simulations. However, the biggest subhalos in ΛCDM MWy-type dark matter halos do not host observed satellites. This "too big to fail" problem appears to be the most serious current challenge for ΛCDM, and may indicate the need for a more complex theory of dark matter -- or perhaps just better understanding of DM simulations and/or of baryonic physics.