Biggest Challenges to ΛCDM

Joel R. Primack
University of California, Santa Cruz

Dark Matter Ships on a Dark Energy Ocean

Matter and Energy Content of the Universe

ΛCDM

Double Dark Theory

large scale issues

Power Spectrum

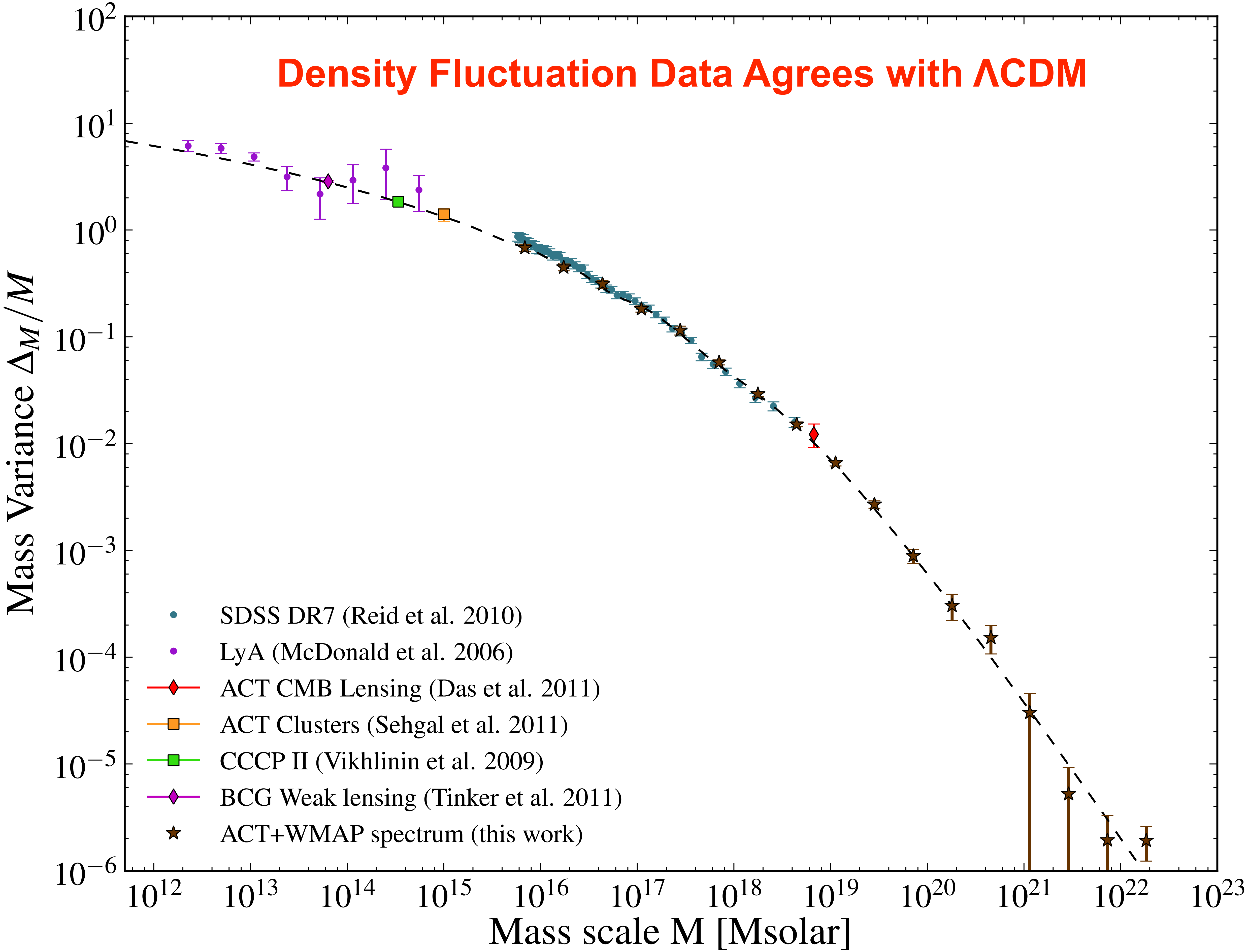
The observations on scales from the Ly alpha forest to the entire observable universe agree very well with ΛCDM.

Galaxy Correlations

The projected galaxy correlation function predicted by abundance matching from the Bolshoi simulation agrees very well with observations. The Millennium simulation overpredicts correlations at ≲1Mpc because σ_8 is too high.

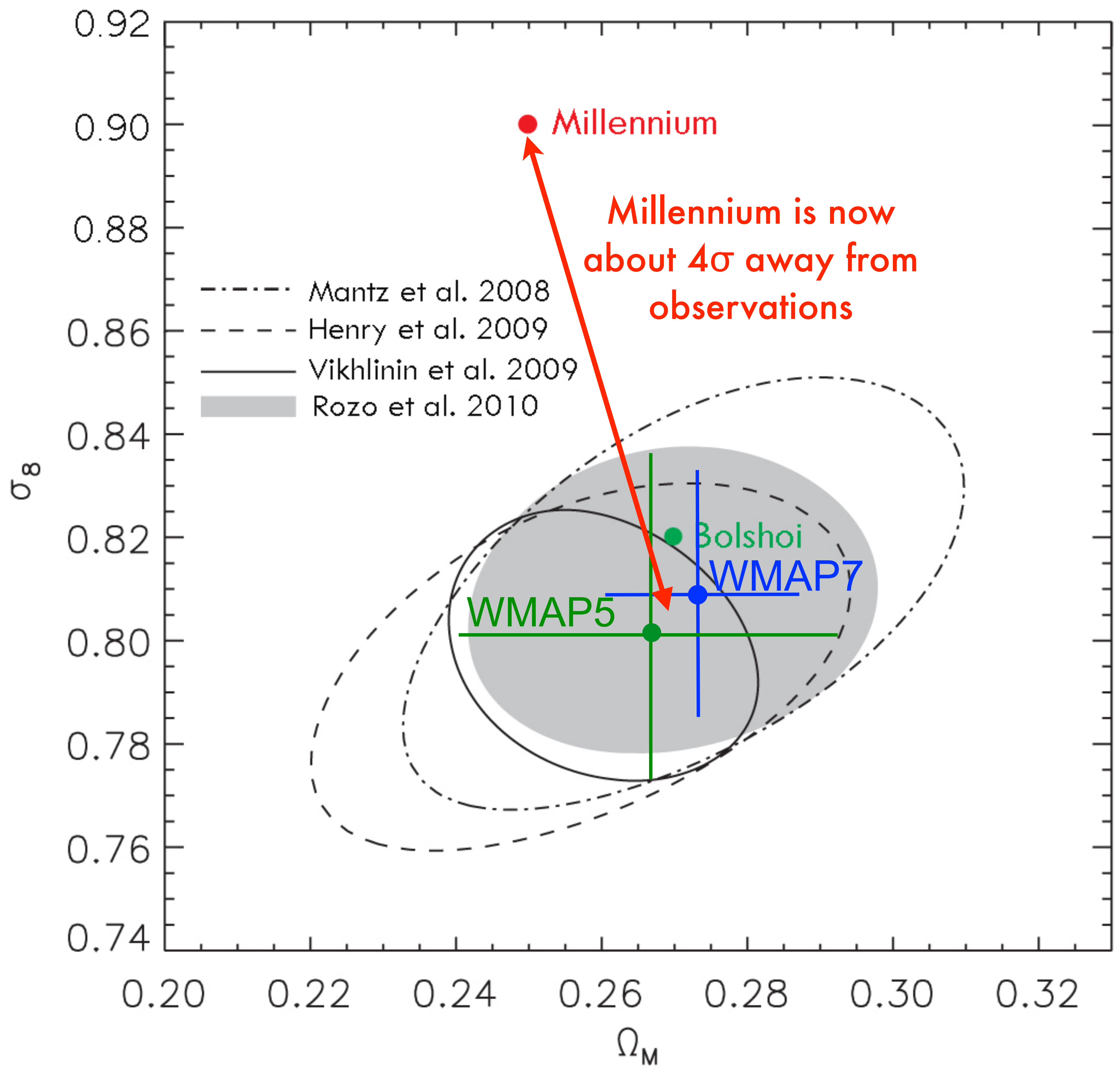
Abundance of Small Galaxies

The predicted abundance of galaxies with $V_c \gtrsim 80$ km/s is in good agreement with observations, but more galaxies are predicted with $V_c \lesssim 80$ km/s than are seen in HIPASS and ALFALFA radio surveys. But a new deep local optical survey is in better agreement with predicted abundances.

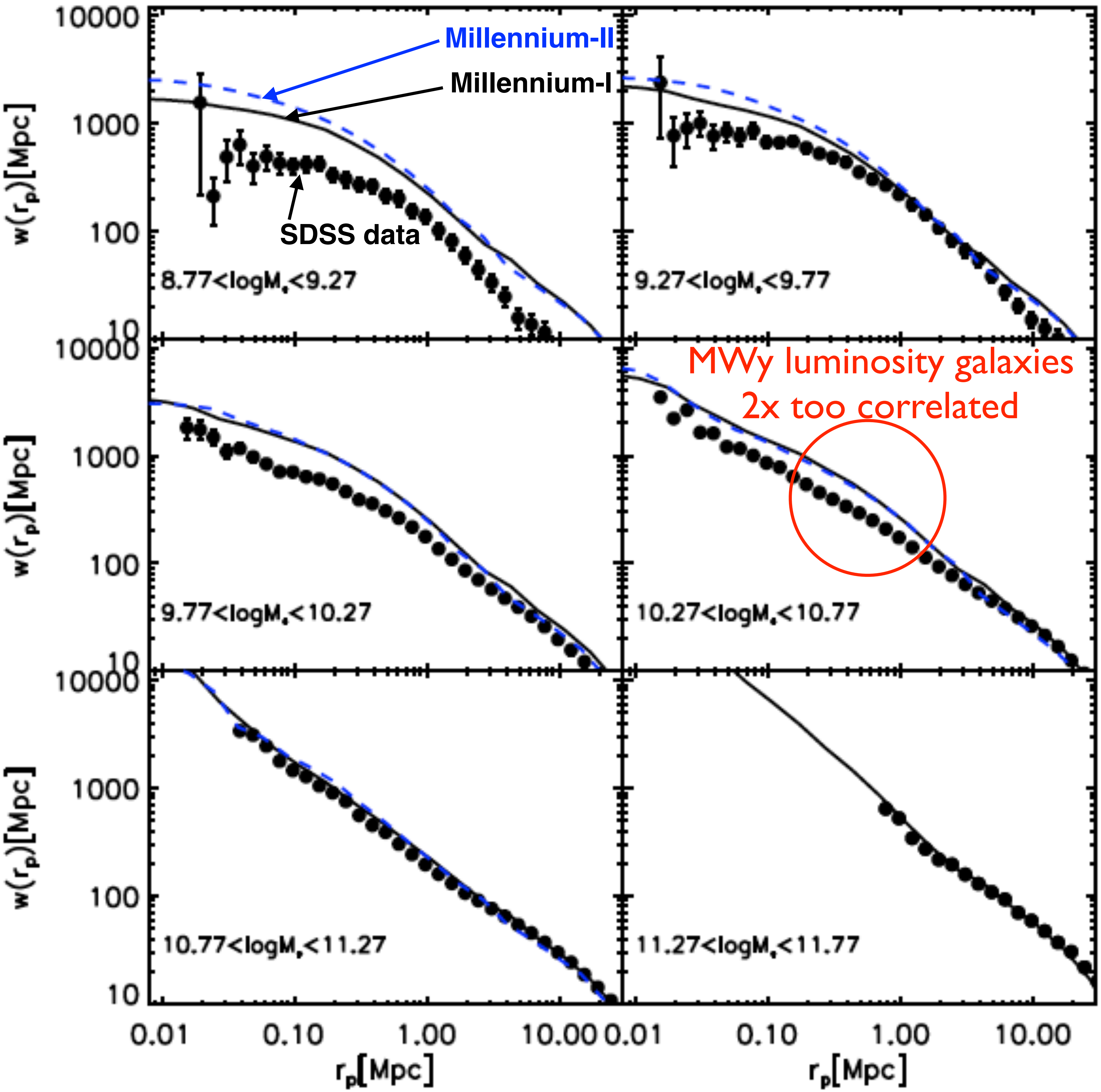


R. Hlozek et al 2011 The Atacama Cosmology Telescope: a measurement of the primordial power spectrum arXiv:1105:4487

WMAP+SN+Clusters Determination of σ_8 and Ω_M



Millennium Projected Galaxy Correlation Functions



Projected correlation functions for galaxies in different stellar mass ranges, in SAM based on Millennium I and II. Black solid and blue dashed curves give results for preferred model applied to the MS and the MS-II, respectively. Symbols with error bars are results for SDSS/DR7 calculated using the same techniques as in Li et al. (2006). The two simulations give convergent results for $M_* > 6X10^9\ M_{sun}$. At lower mass the MS underestimates the correlations on small scales.The model agrees quite well with the SDSS at all separations for $M_* > 6X10^{10}\ M_{sun}$. But **at smaller masses the correlations are overestimated substantially, particularly at small separations. The authors attribute this to the too-high $\sigma_8 = 0.90$ used in MS-I & II.**

Guo, White, et al. 2011 MNRAS

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

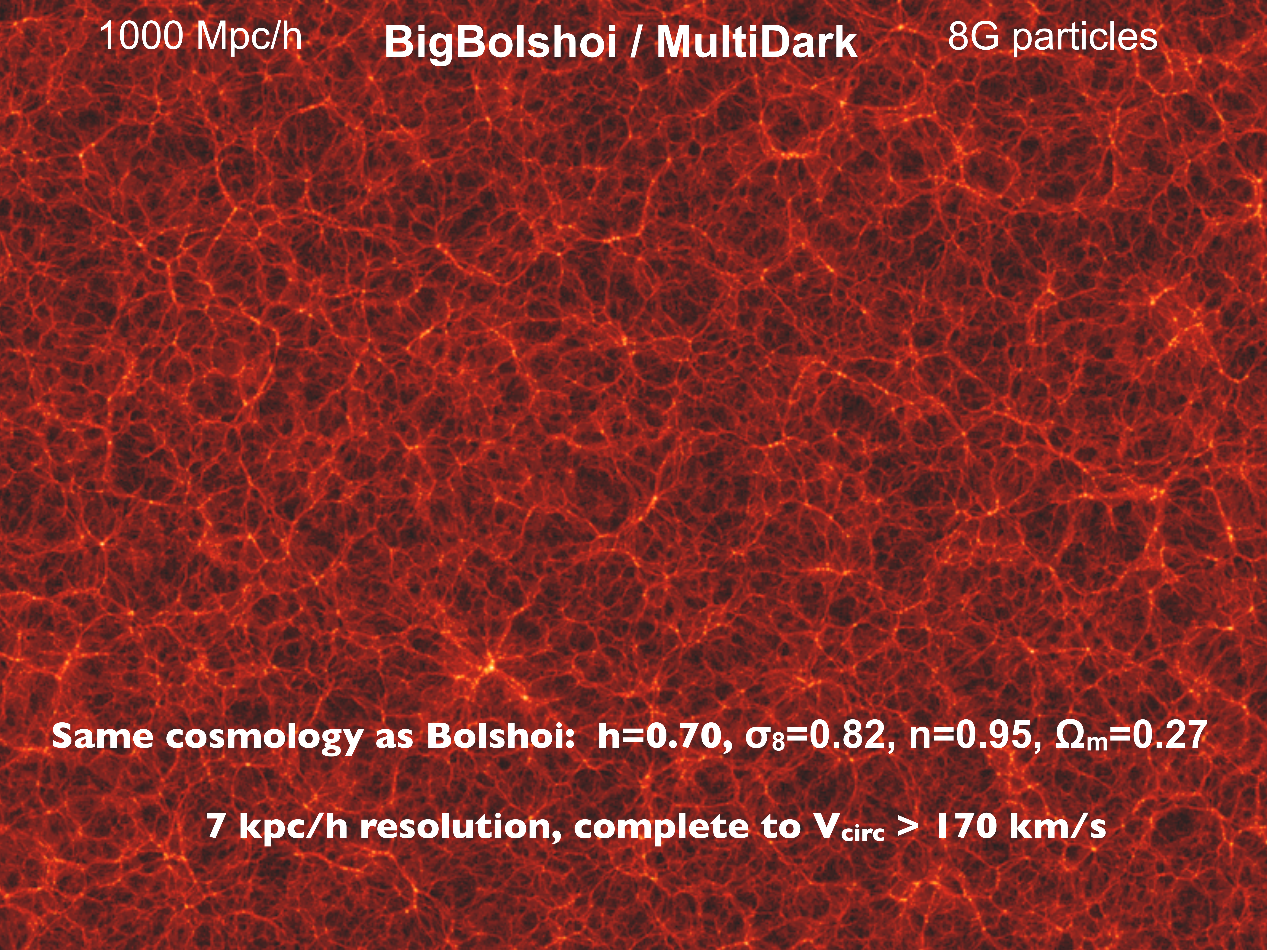
Cosmological parameters are consistent with the latest observations

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

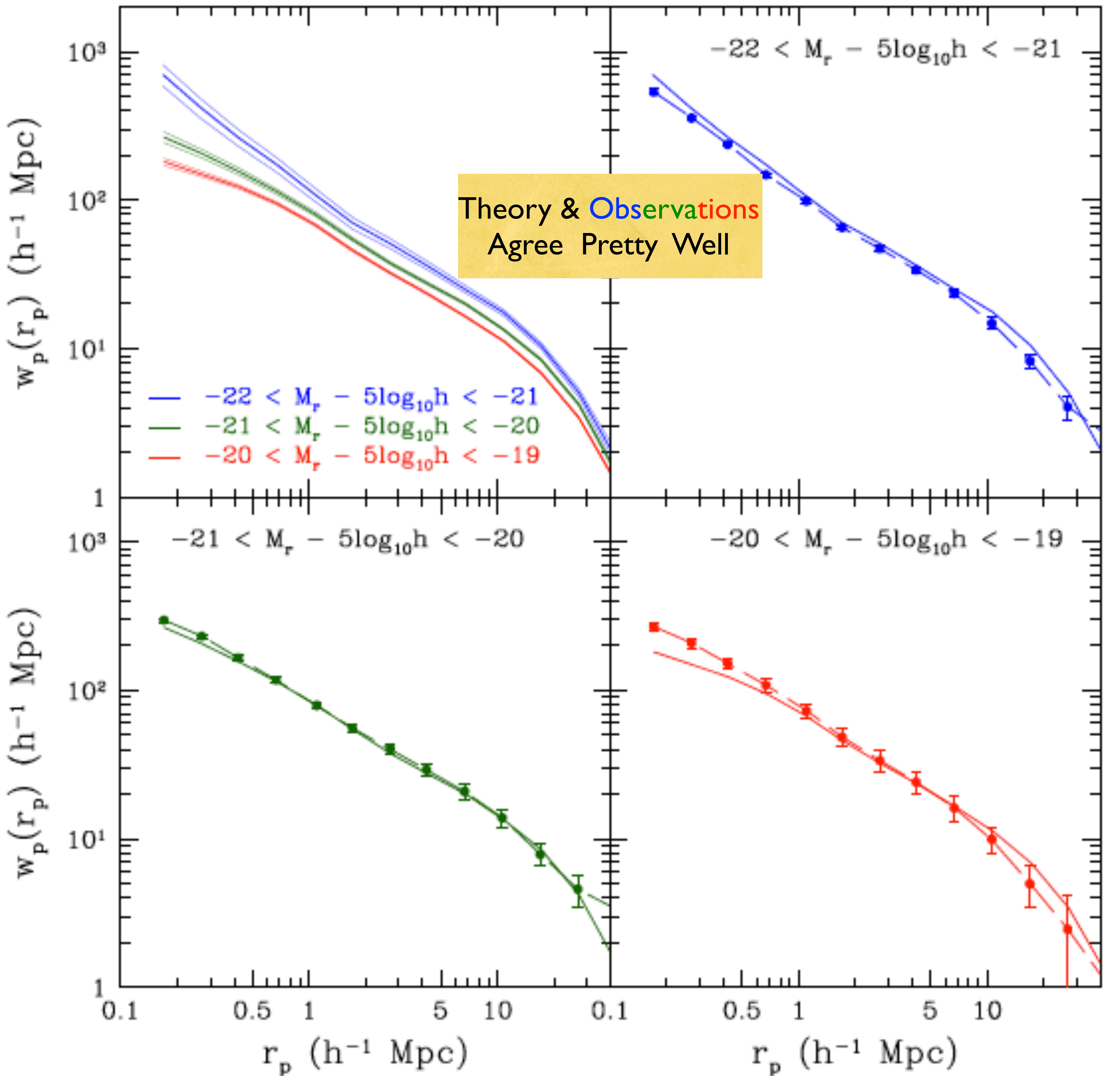
Force resolution is the same as Millennium-II, in a volume 16x larger

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 will soon be available


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

Bolshoi Projected Galaxy Correlation Functions

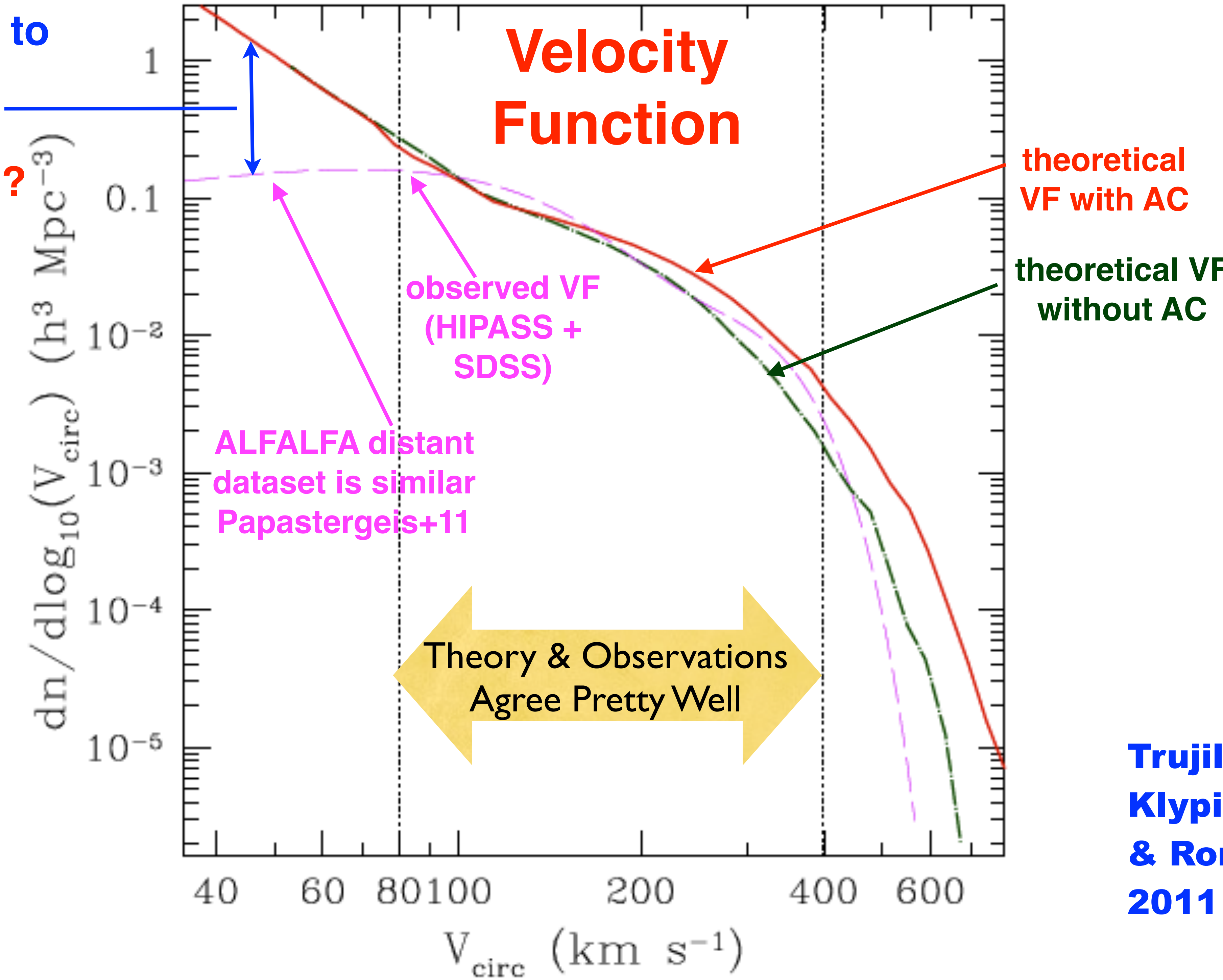


The correlation function of SDSS galaxies vs. Bolshoi galaxies using halo abundance matching, with scatter using our stochastic abundance matching method. This results in a better than 20% agreement with SDSS. *Top left:* Bolshoi correlation function in three magnitude bins, showing Poisson uncertainties 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 2011 ApJ

Bolshoi Sub-Halo Abundance Matching

Discrepancy due to incomplete observations or ΛCDM failure?



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

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.

Klypin, Karachentsev, Nasonova 2012

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

Local Volume: D <10Mpc

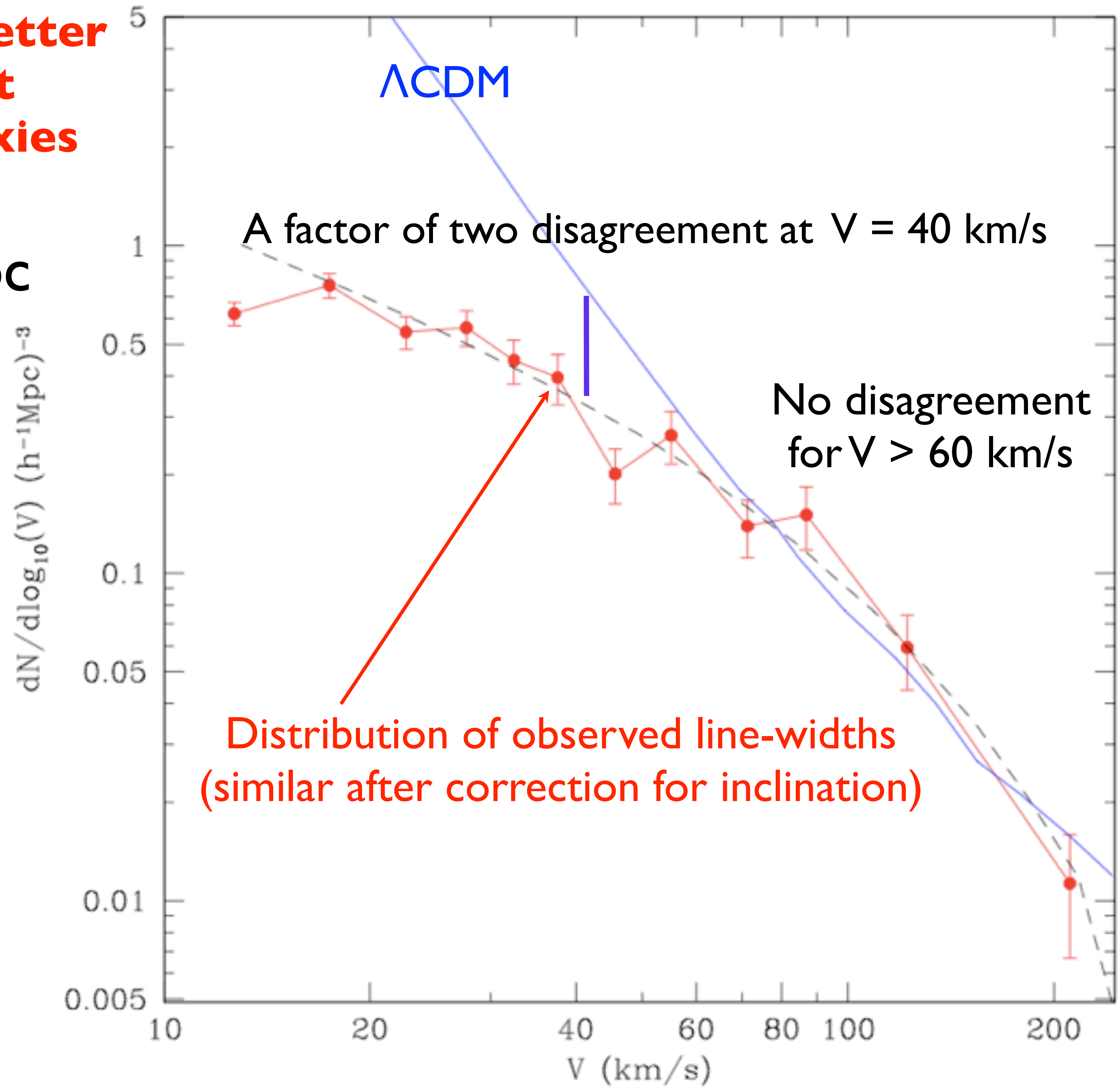
Total sample: 813 galaxies
Within 10Mpc: 686
M_B<-13 N=304
M_B<-10 N=611

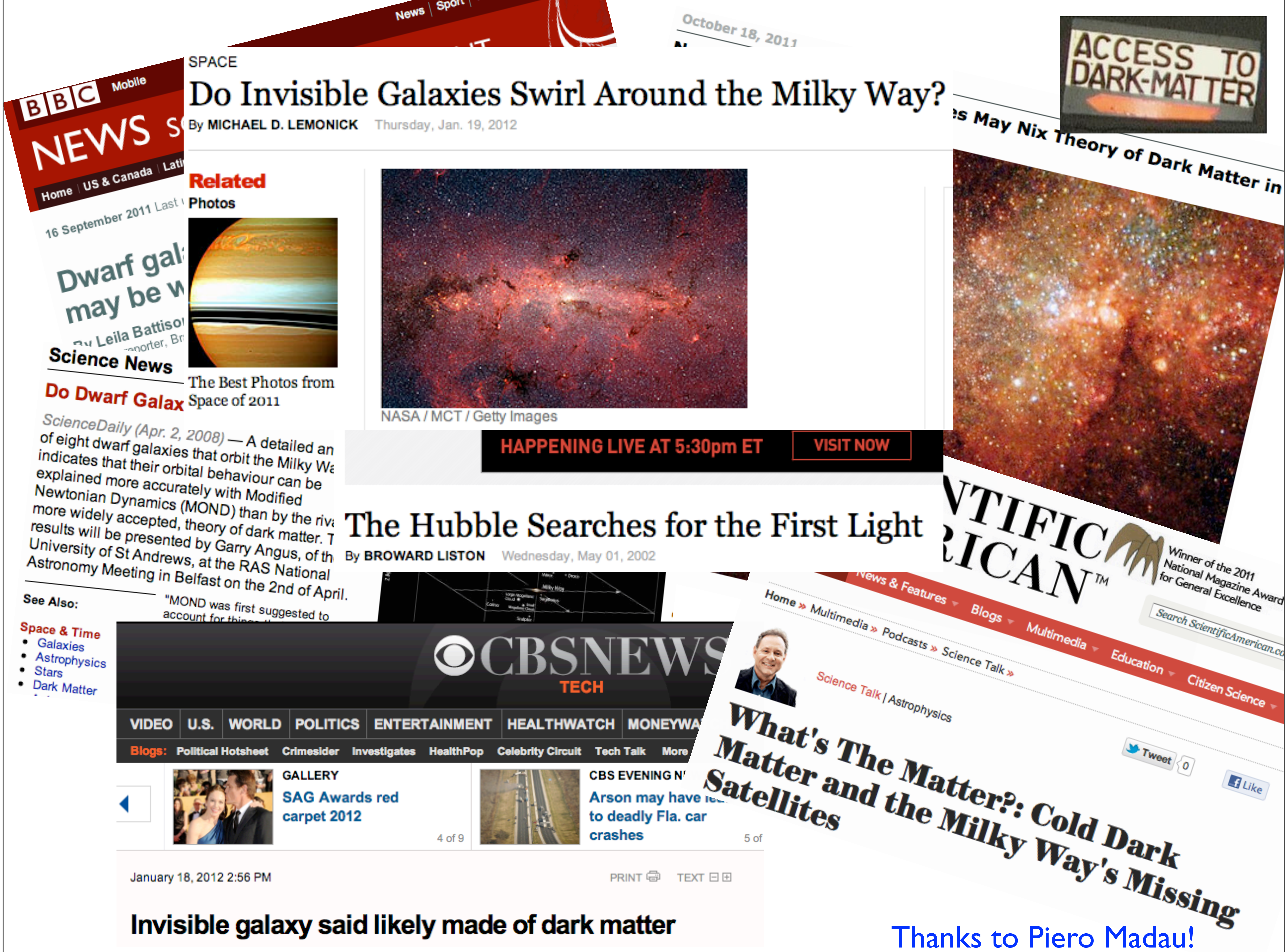
80-90% are spirals or dIrr (T>0)

Accuracy of distances are 8-10%

80% with D<10Mpc have HI linewidth

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

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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.
See Also:
"MOND was first suggested to account for thin
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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

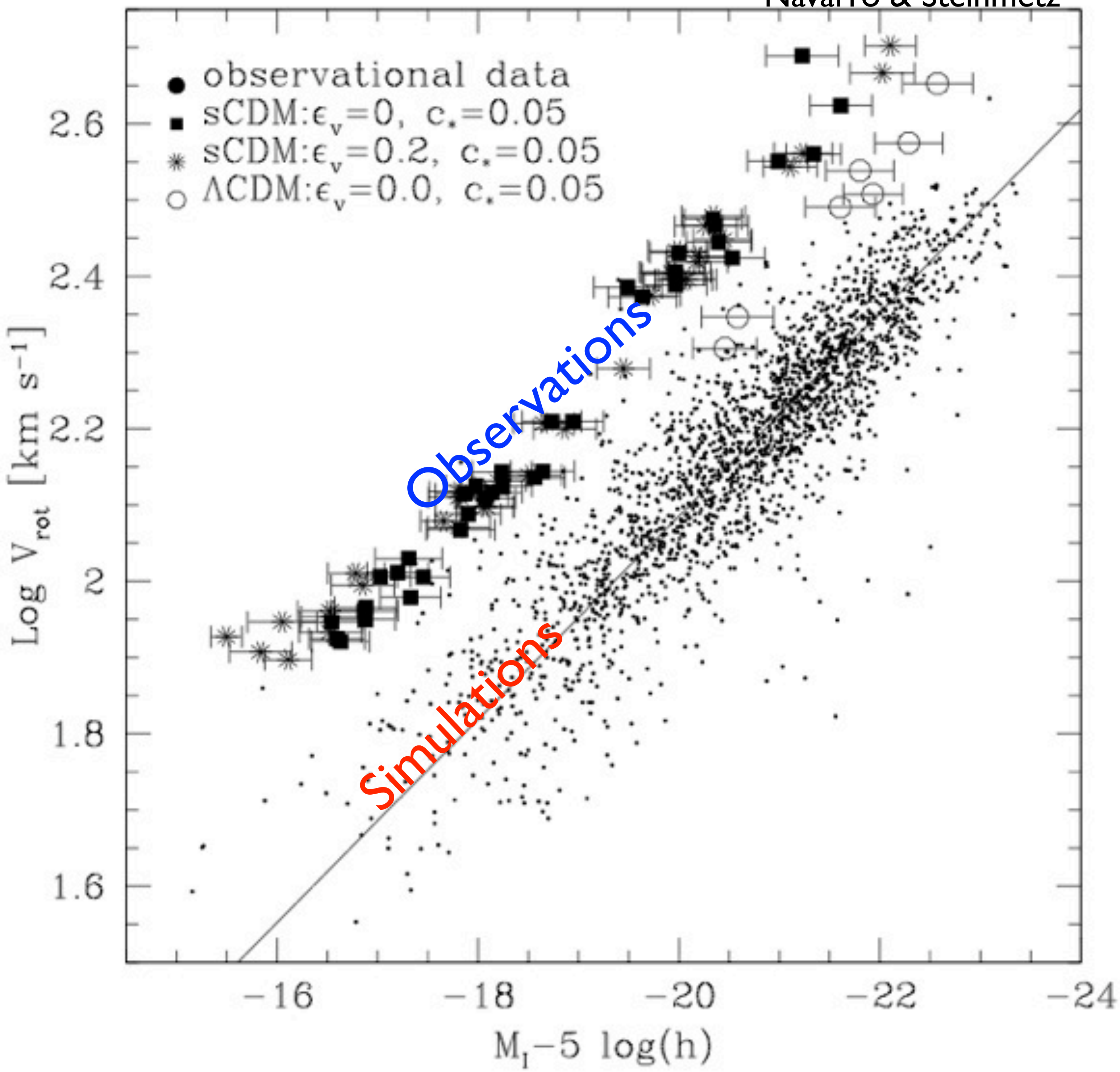
The discovery of many faint Local Group dwarf galaxies is consistent with ΛCDM predictions. Satellites, reionization, lensing flux anomalies, gaps in stellar streams, and Lyα forest data imply that WDM must be Tepid or Cooler.

Can ΛCDM Simulations Form Realistic Galaxies?

The Angular Momentum Problem

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

Navarro & Steinmetz

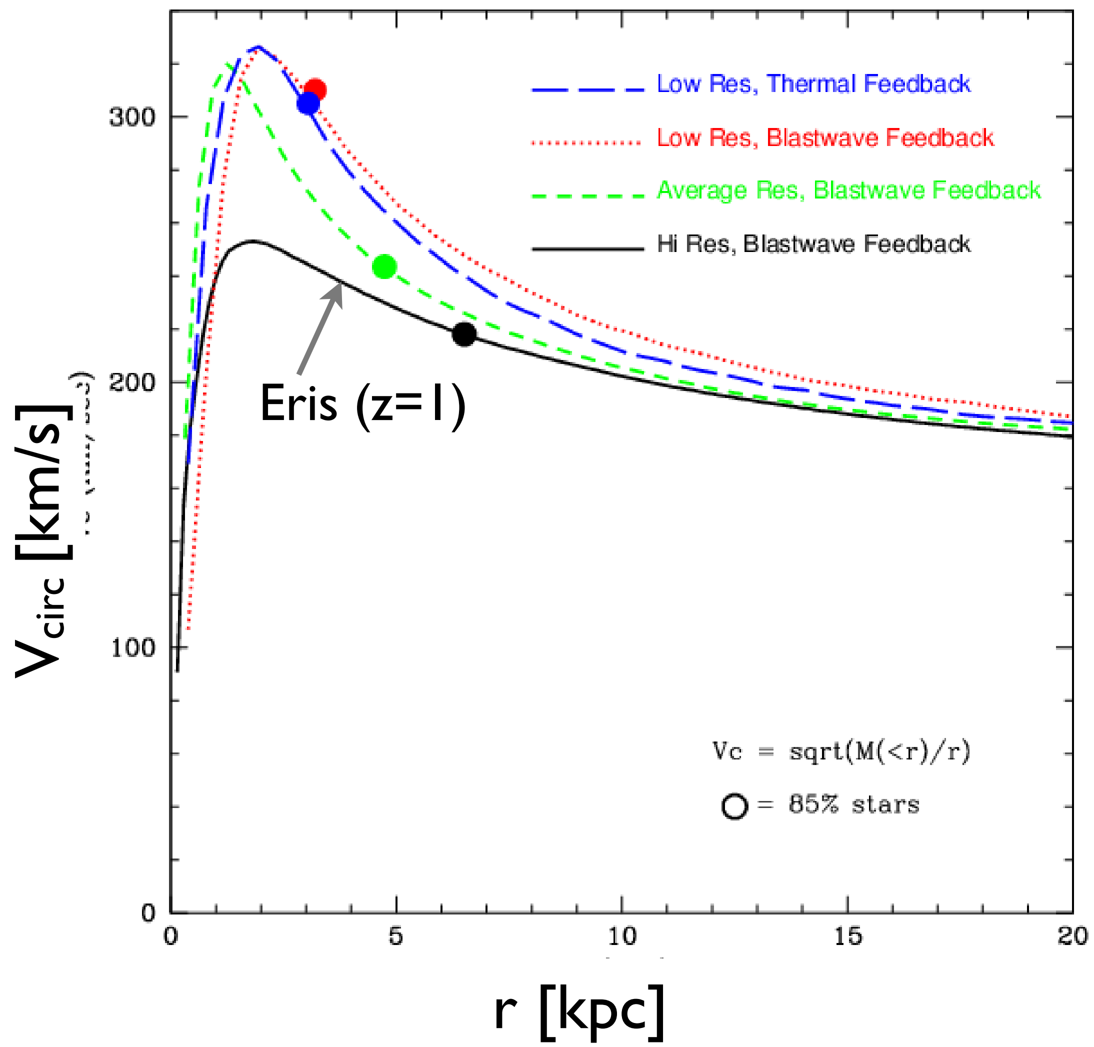


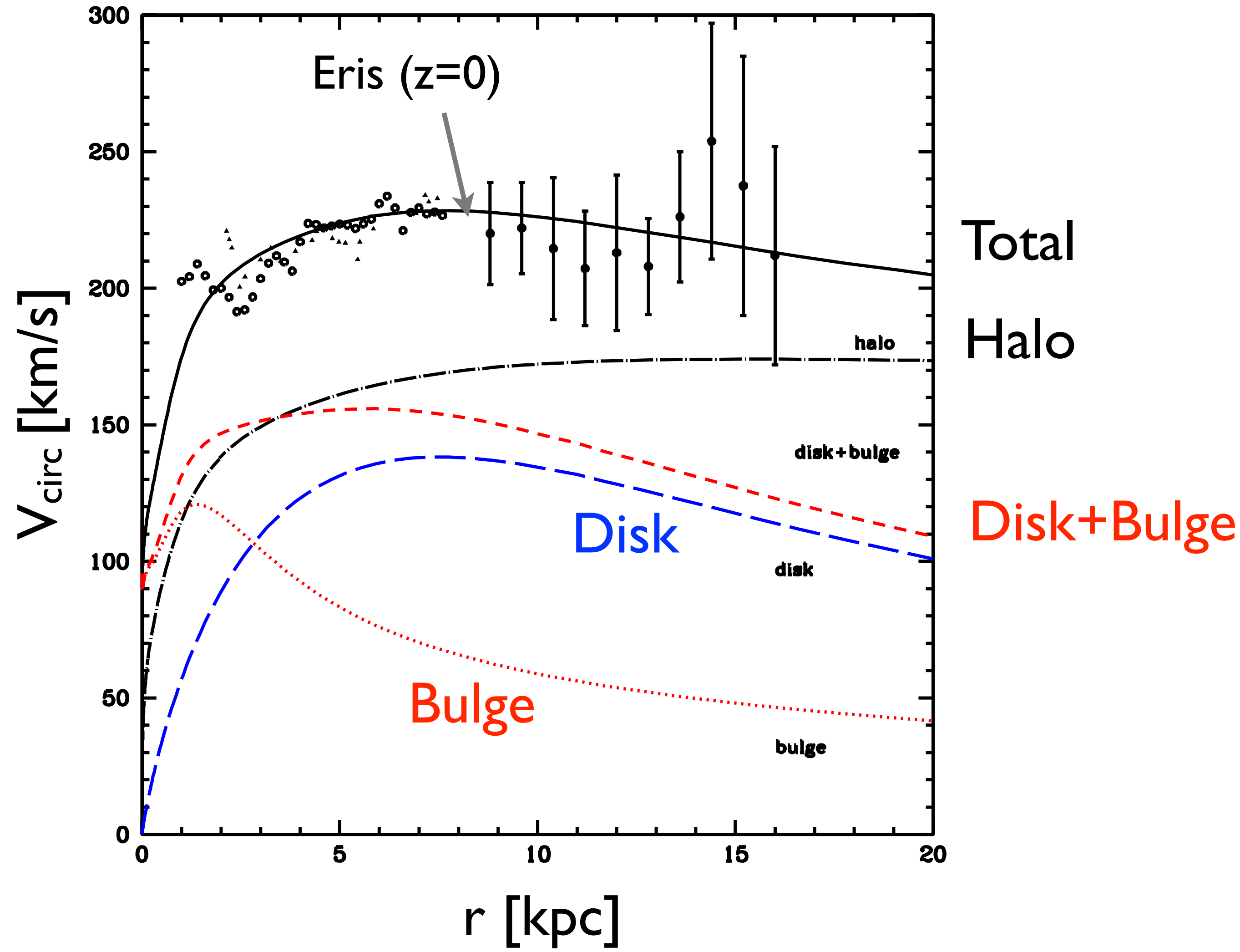
"Agreement between model and observations appears to demand substantial revision to the CDM scenario or to the manner in which baryons are thought to assemble and evolve into galaxies in hierarchical universes."

Navarro & Steinmetz 2000 ApJ

No Angular Momentum Problem in the Eris Simulation

Simulations tend to produce too many stars at the center, which translates into steeply rising rotation curves.





Solution:
* Mimic star formation as occurs in real galaxies, i.e. localized, on high-density peaks only.
* Feedback from SN becomes more efficient in removing gas from high-density regions.

These outflows remove preferentially low angular momentum material, suppressing the formation of large bulges.

Guedes, Callegari, Madau, Mayer 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 blowouts 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.

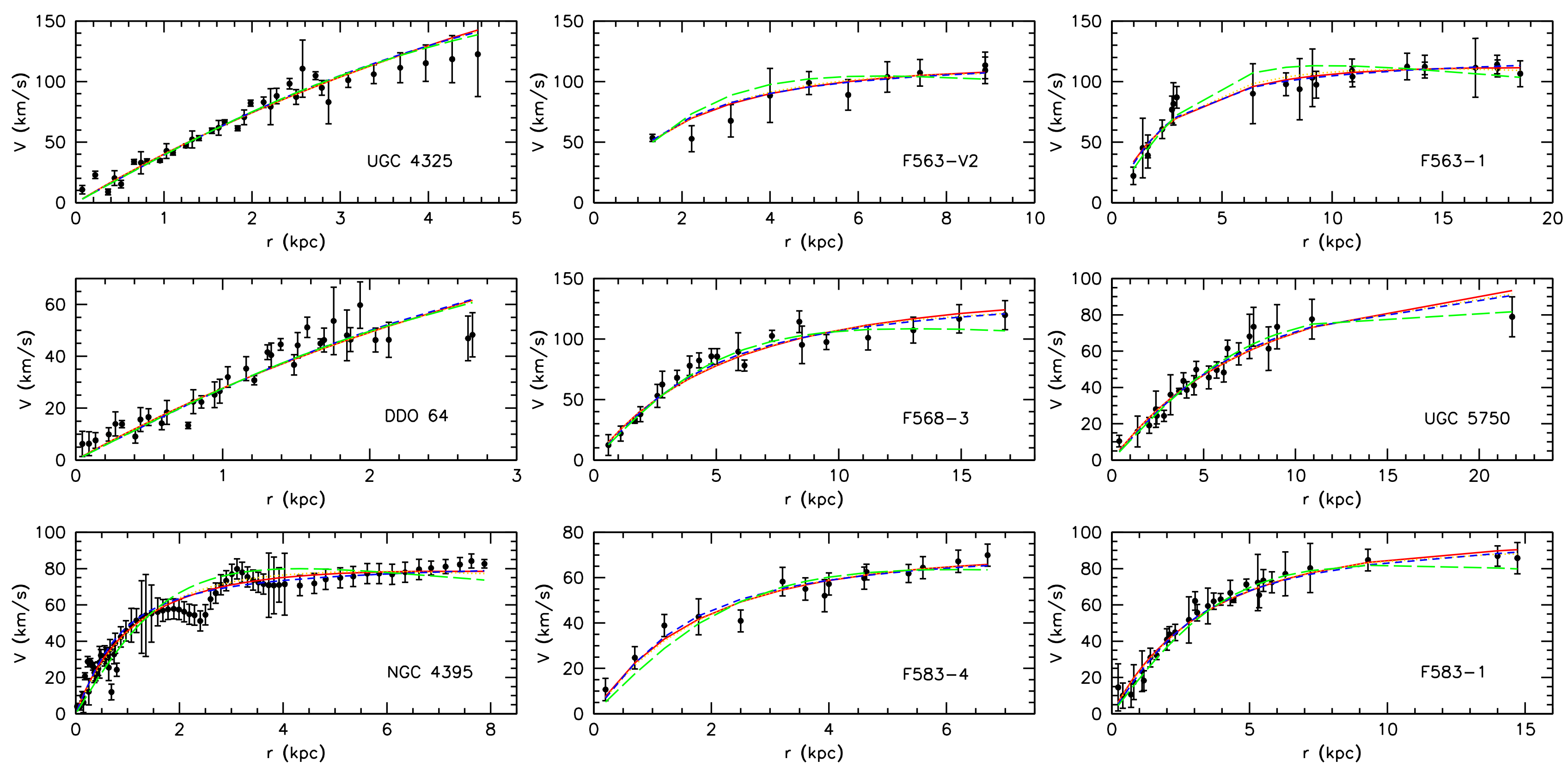
Joshua Adams poster at KITP Conference "First Light and Faintest Dwarfs" February 2012

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

Rachel Kuzio de Naray, Gregory D. Martinez, James S. Bullock, Manoj Kaplinghat **2010, ApJ, 710L, 161**

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.

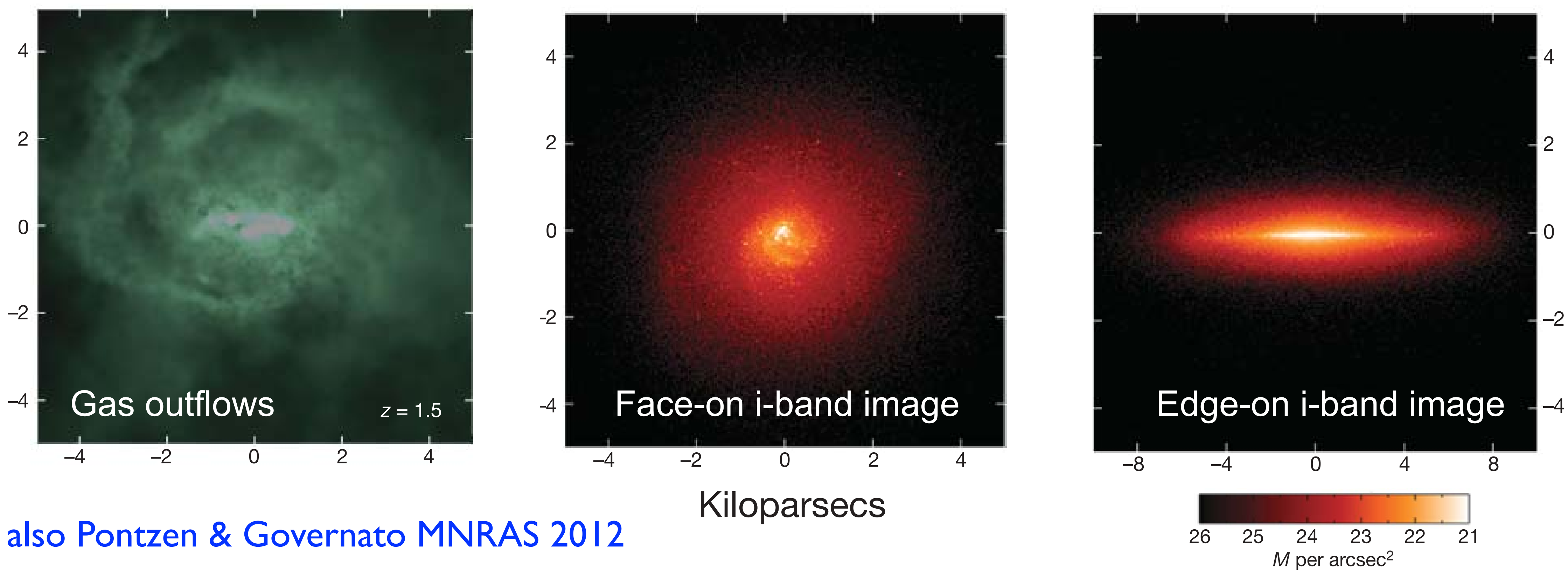


New simulations show that several episodes of gas blowout during evolution of dwarf spiral galaxies can remove cusps

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 MNRAS 2012

Cuspy No More: How Outflows Affect the Central Dark Matter and Baryon Distribution in ΛCDM Galaxies. MNRAS 2012

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]

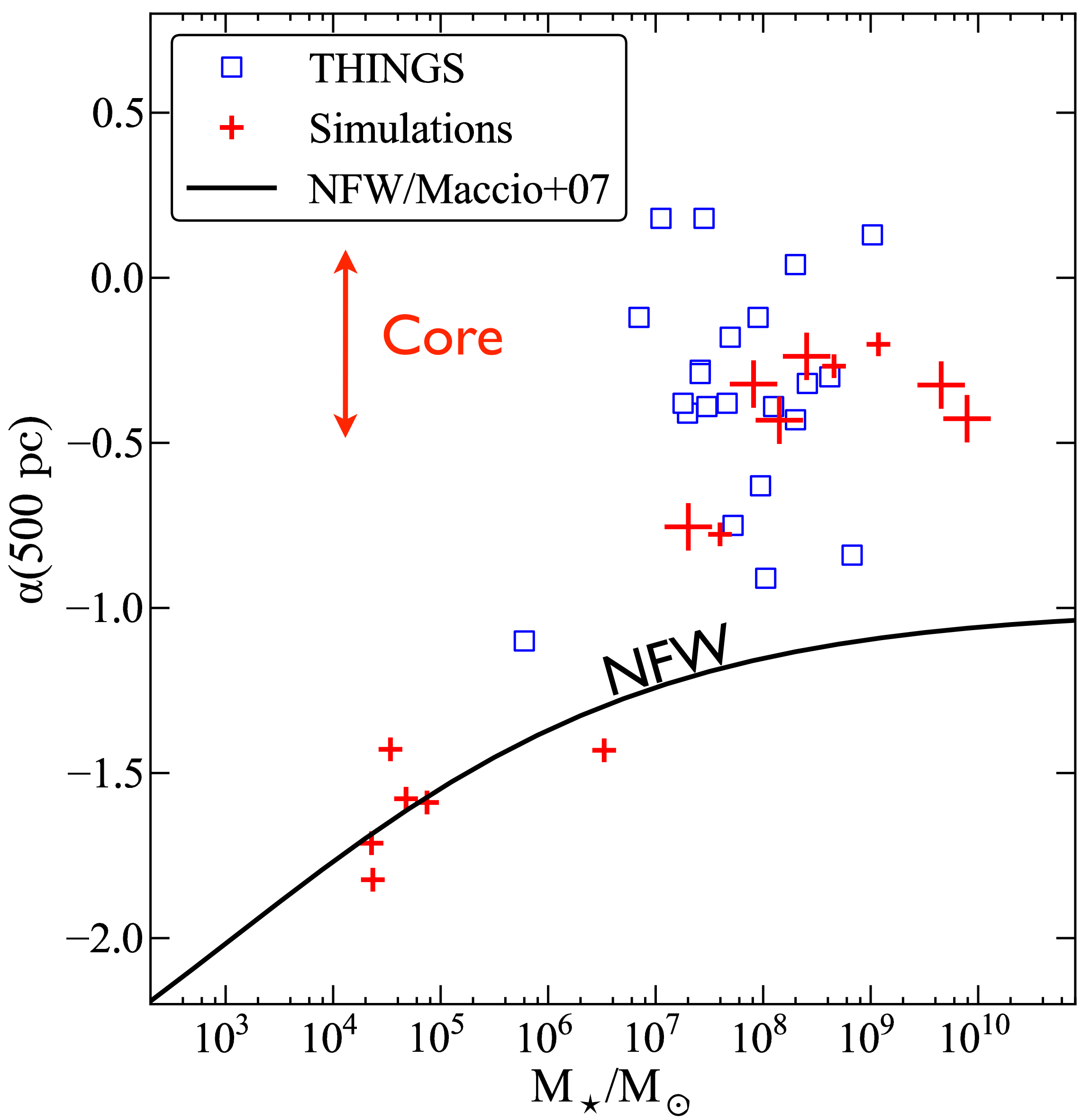


Figure 1. *The slope of the dark matter density profile α vs stellar mass measured at 500 pc and z=0 for all the resolved halos in our sample.* The Solid 'DM-only' line is the slope predicted for the same CDM cosmological model assuming i) the NFW concentration parameter trend given by Macció et al (2007) 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.

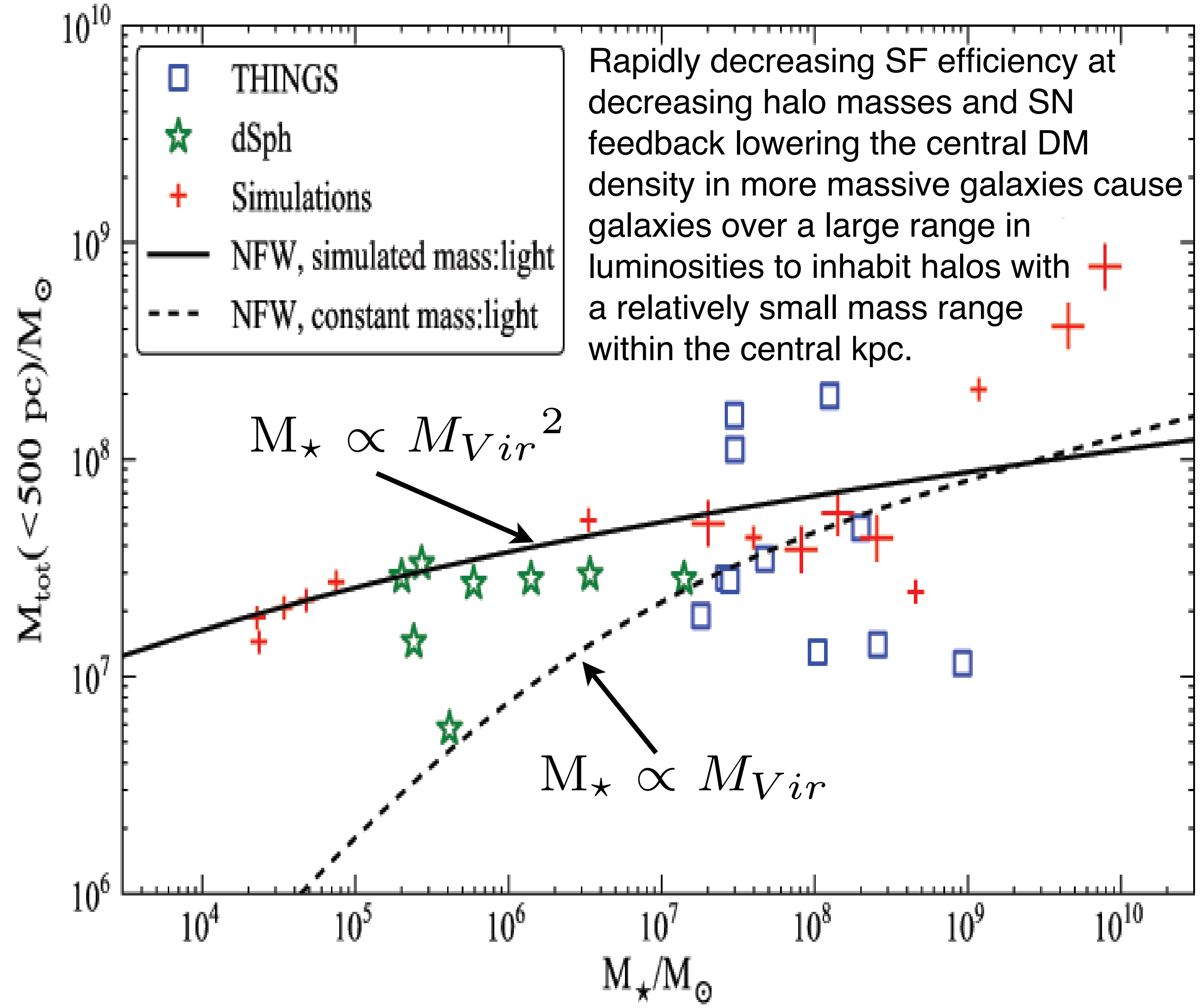


Figure 4. The total mass (baryons and DM) within the central 500 pc as a function of stellar mass: Large and small crosses: simulations. Open squares: galaxies from THINGS (Oh et al. in prep). Stars: dSph from Walker (priv. comm.). Theoretical predictions reproduce the observed flat trend from 10^5 to 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.

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.

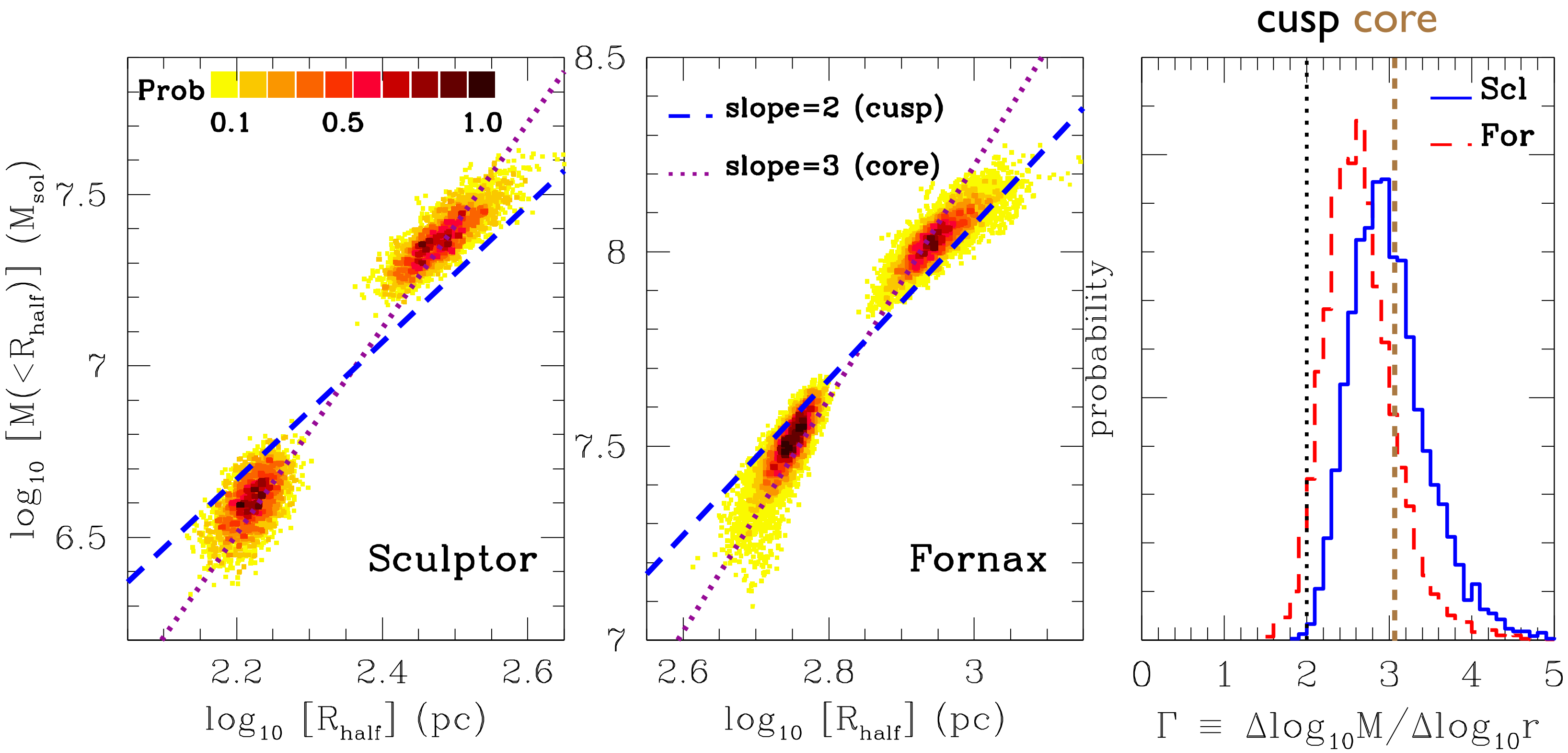


FIG. 10.— *Left, center:* Constraints on halflight radii and masses enclosed therein, for two independent stellar subcomponents in the Fornax and Sculptor dSphs. Plotted points come directly from our final MCMC chains, and color indicates relative likelihood (normalized by the maximum-likelihood value). 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 (although there may be problems with their Schwarzschild modeling). Can these dSph MWy satellite dark matter profiles can be explained by the starburst blowout mechanism?

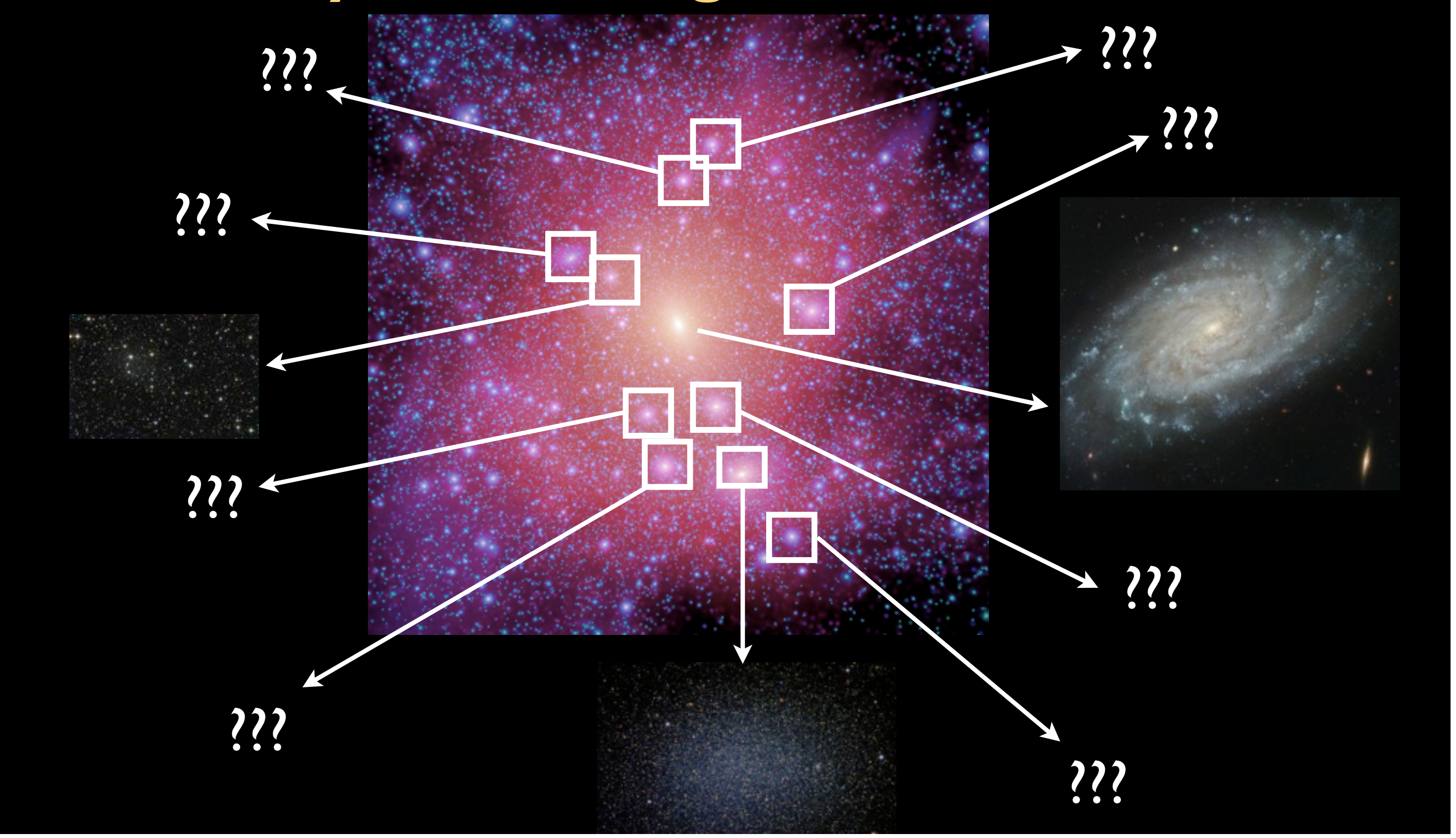
Satellites and Subhalos

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

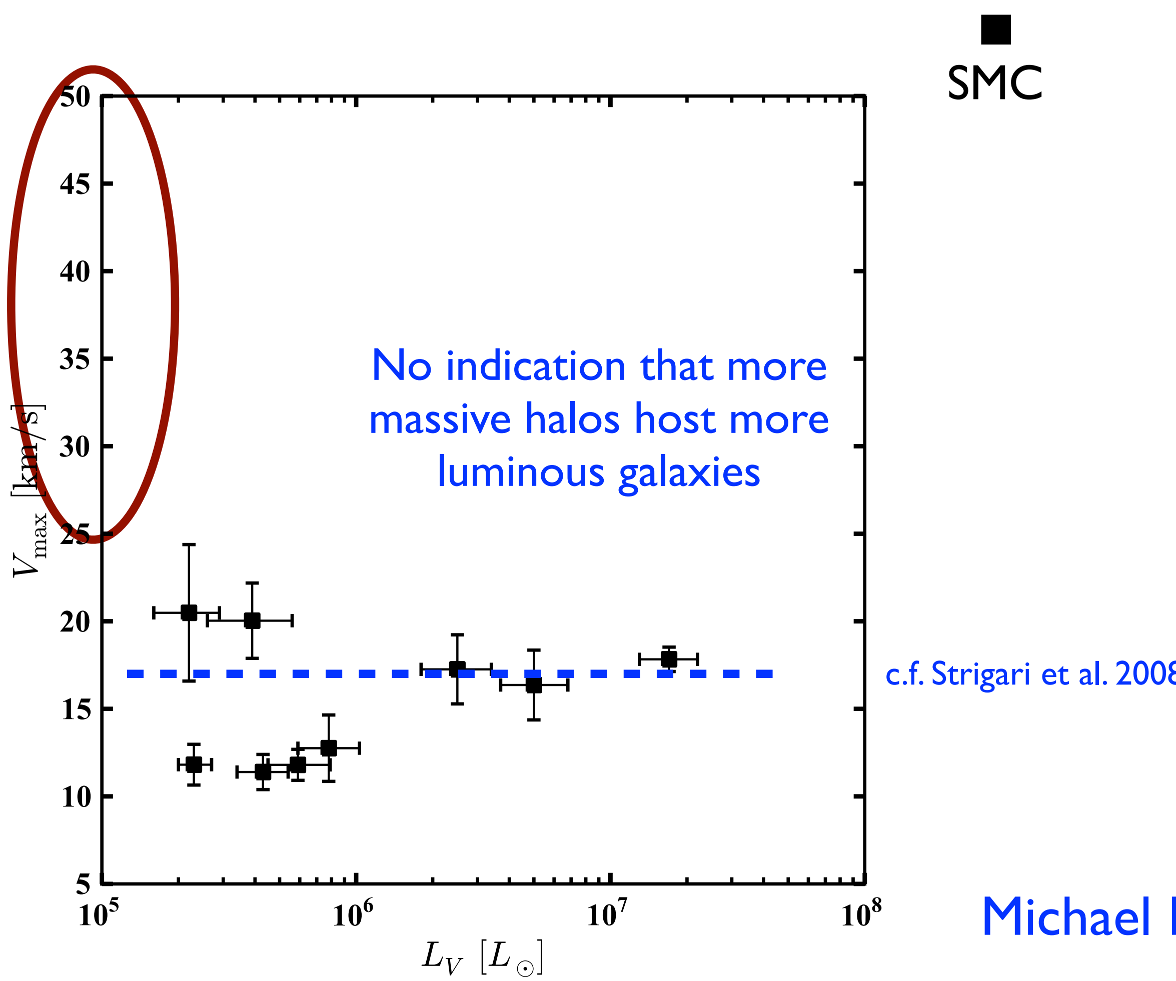
- The "too big to fail" problem appears to be the most serious current challenge for ΛCDM, and may indicate the need for a more complex theory of dark matter.
- High resolution ΛCDM simulation substructure is consistent with quad-lens radio quasar flux and galaxy-galaxy lensing anomalies and indications 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?

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 $V_{\rm max} \lesssim 25\,{\rm km/s}$
(see also Strigari, Frenk, & White 2010)

Possible Solutions to "too big to fail"

Baryons strongly modify the structure of subhalos?

The Milky Way is anomalous?

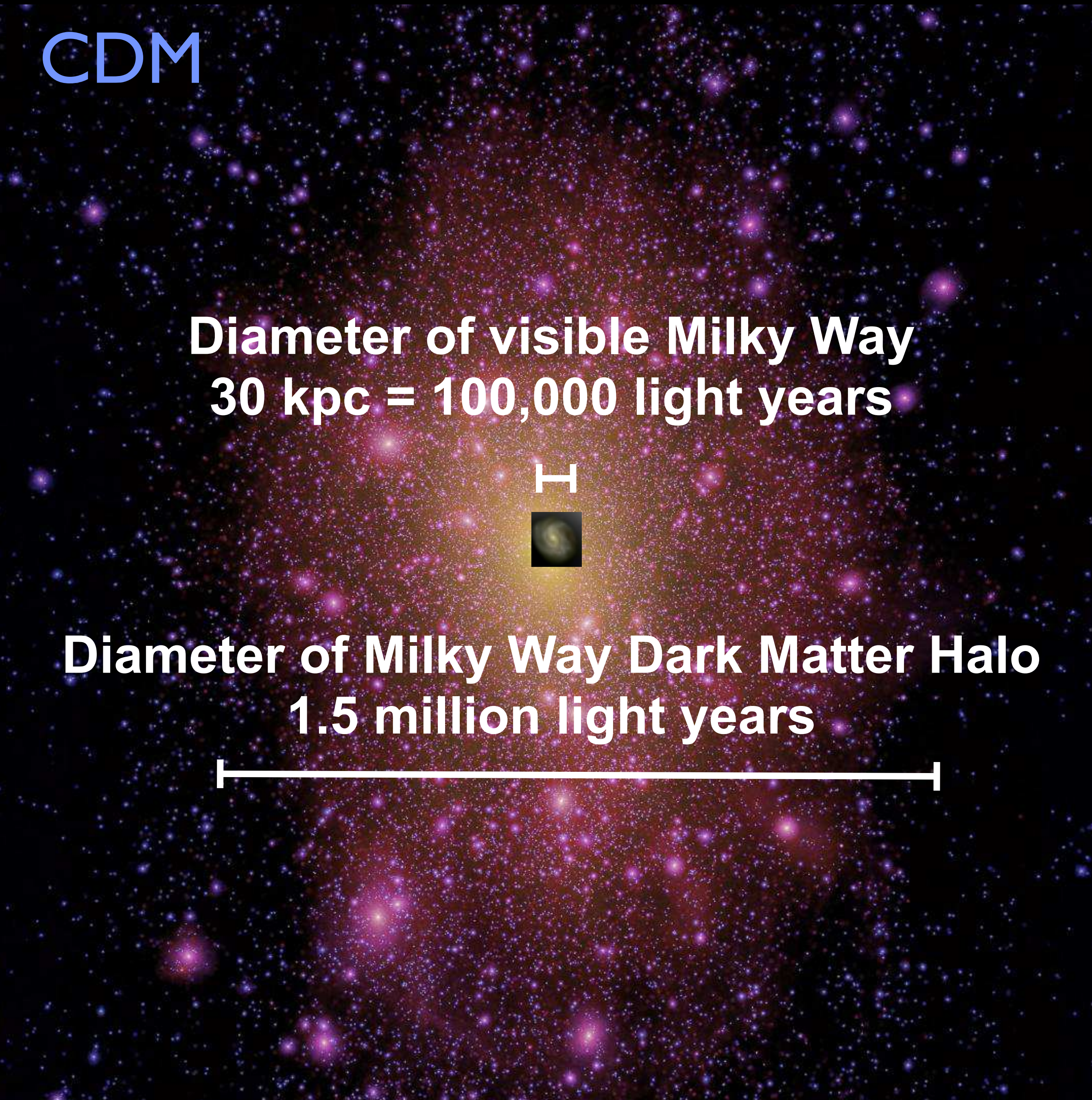
The Milky Way has a low mass dark matter halo?

Galaxy formation is stochastic at low masses?

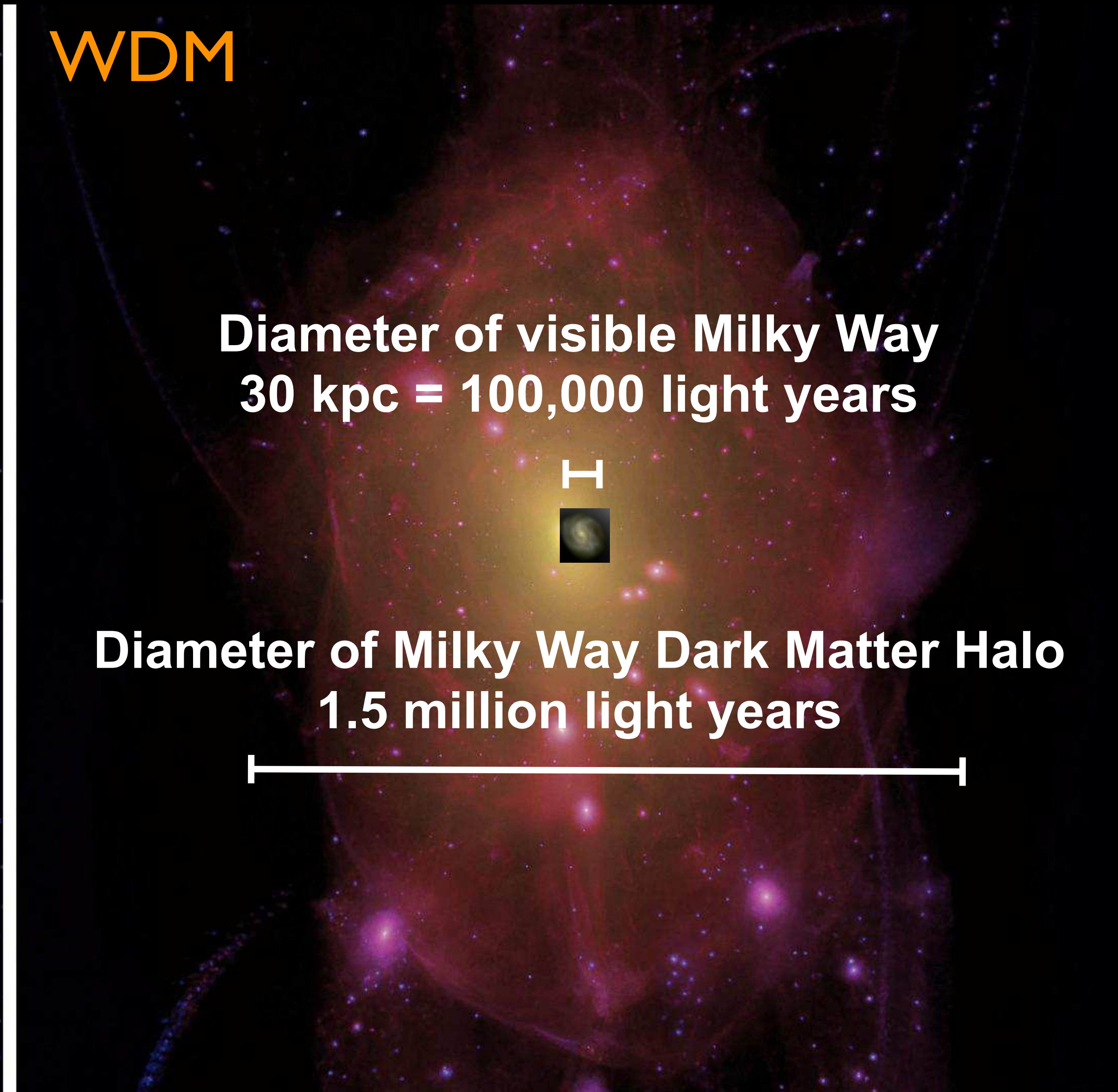
Dark matter is not just CDM -- maybe WDM or even self-interacting?

(Or maybe existing high-resolution CDM simulations are being misinterpreted?)

Michael Boylan-Kolchin, Bullock, Kaplinghat 2011, 2012



Aquarius simulation. Springel et al. 2008

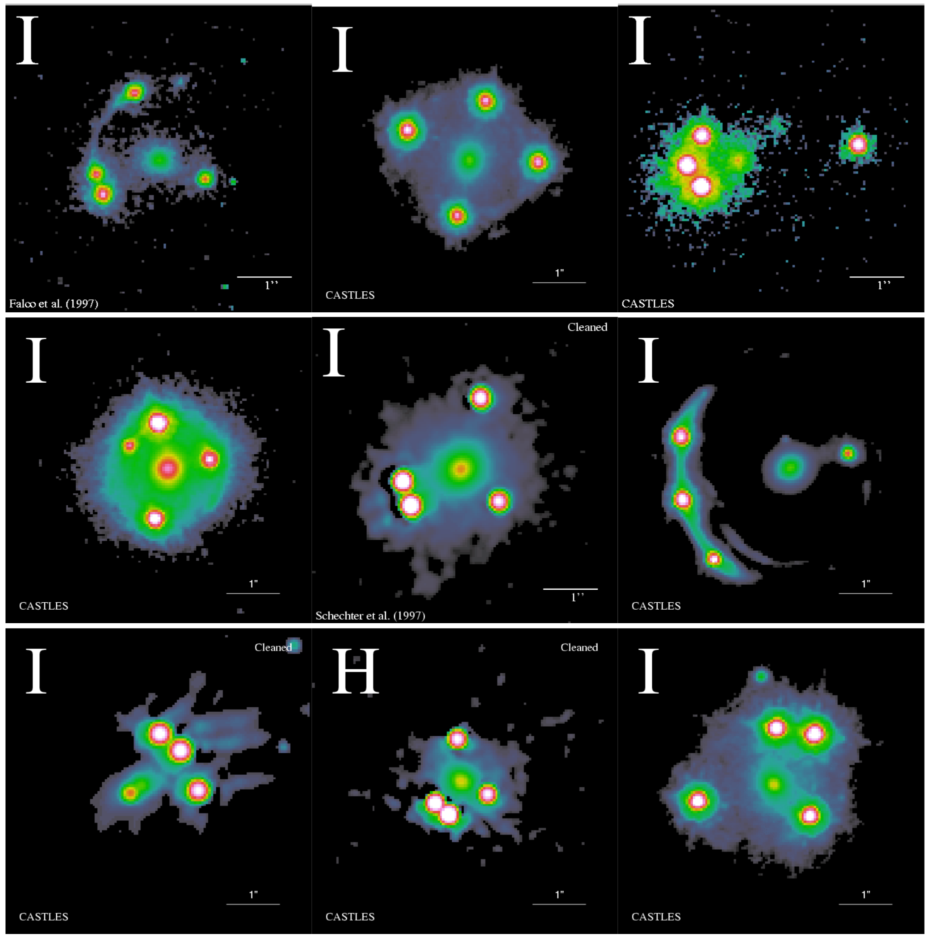


Lovell, Eke, Frenk, et al. arXiv:1104.2929

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.

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

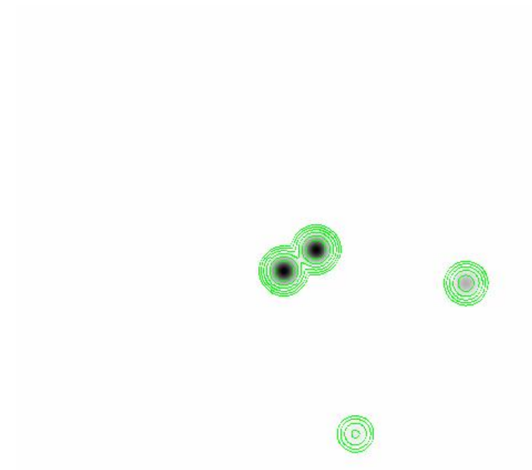
Flux ratio anomalies are generic

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

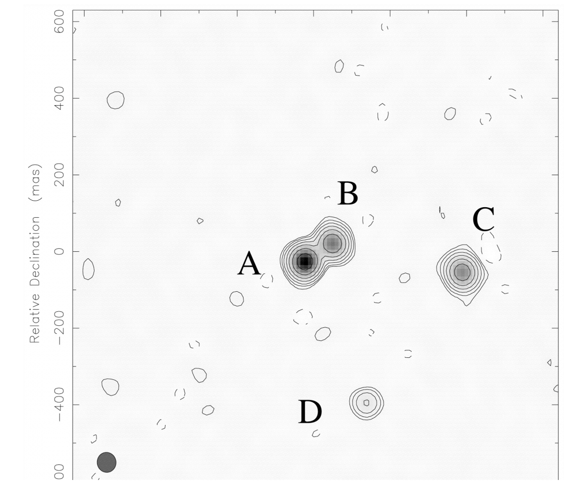
- ellipsoidal galaxy
- tidal forces from environment

But hard to explain flux ratios!

expected



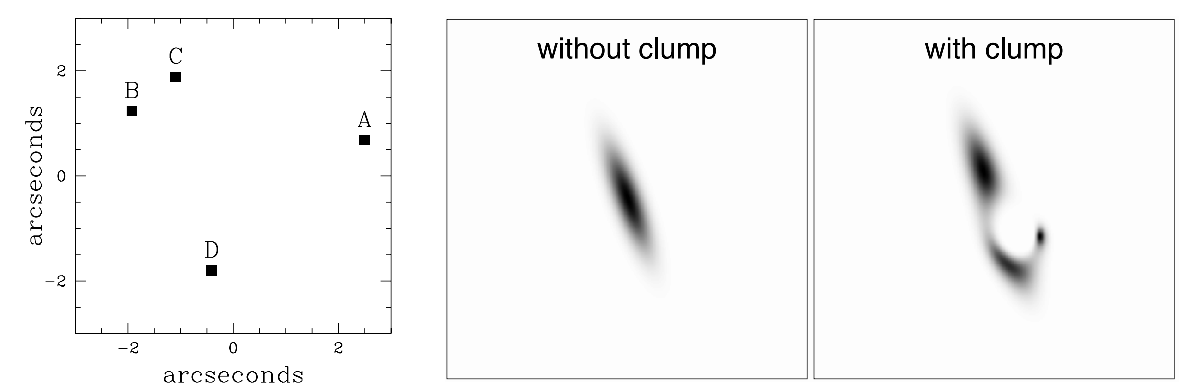
observed *(Marlow et al. 1999)*



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

Monday, May 14, 12

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

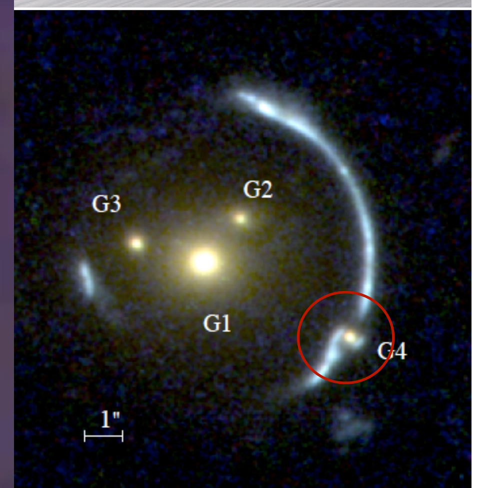
Simona Vegetti (MIT)

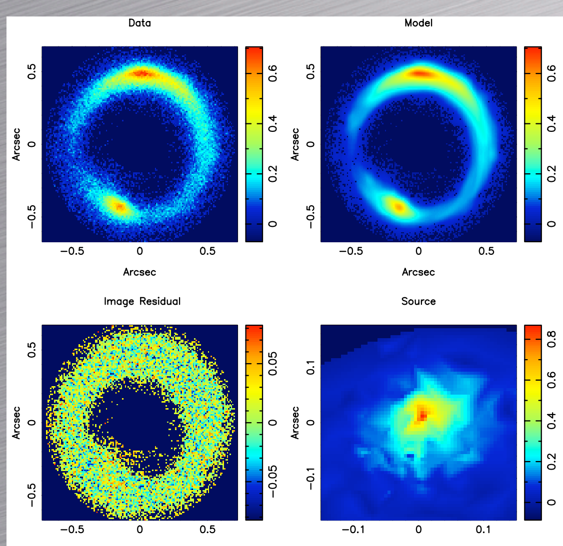
Gravitational detection of a low-mass dark satellite galaxy at cosmological distance, 2012 Nature

Talk at KITP conference "First Light and Faintest Dwarfs"

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

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

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

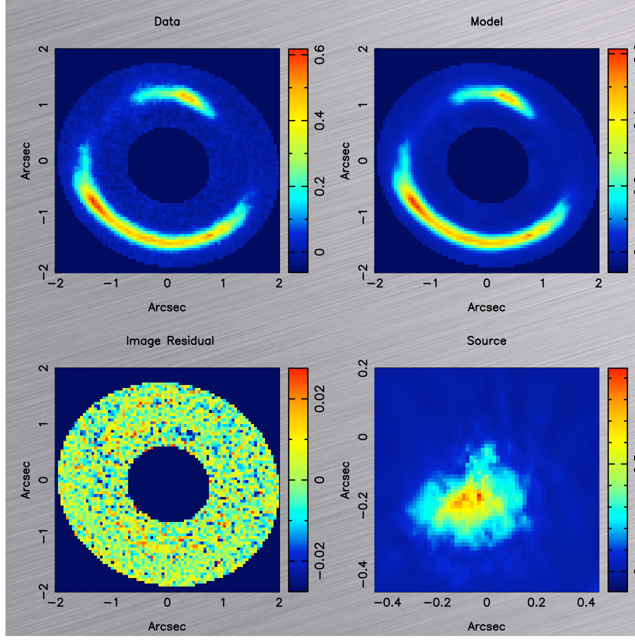
$$V_{max} \approx 27\ km\ s^{-1}$$

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

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.

J0946+1066 - Double ring

Power-Law smooth model + Power-Law substructure



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

$$r_t = 1.1\ kpc$$

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

equivalent to a ~16σ detection

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

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 ....)

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.

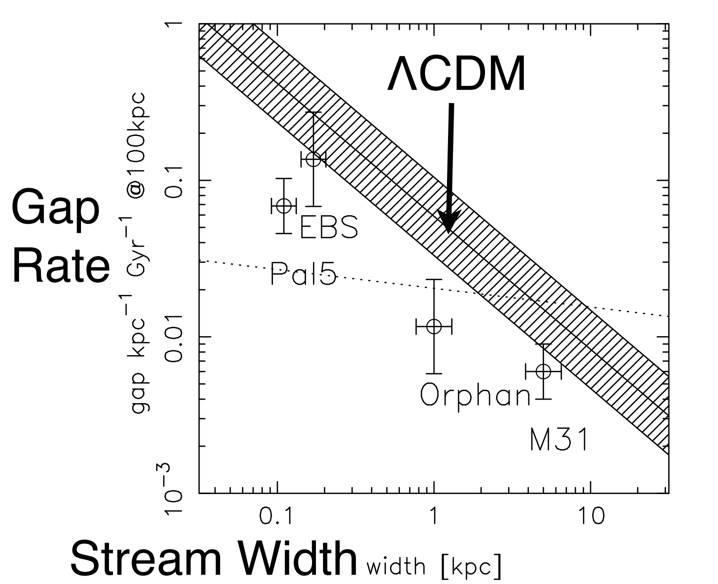


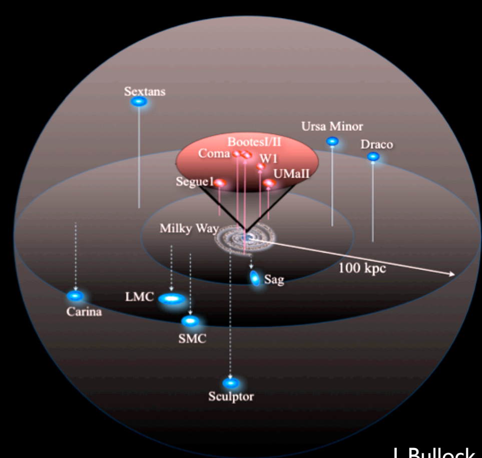
Fig. 11.— The estimated gap rate vs stream width relation for M31 NW, Pal 5, the EBS and the CDM halo prediction. All data have been normalized to 100 kpc. The width of the theoretical relation is evaluated from the dispersion in the length-height relation of Fig. 8. Predictions for an arbitrary alternative 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

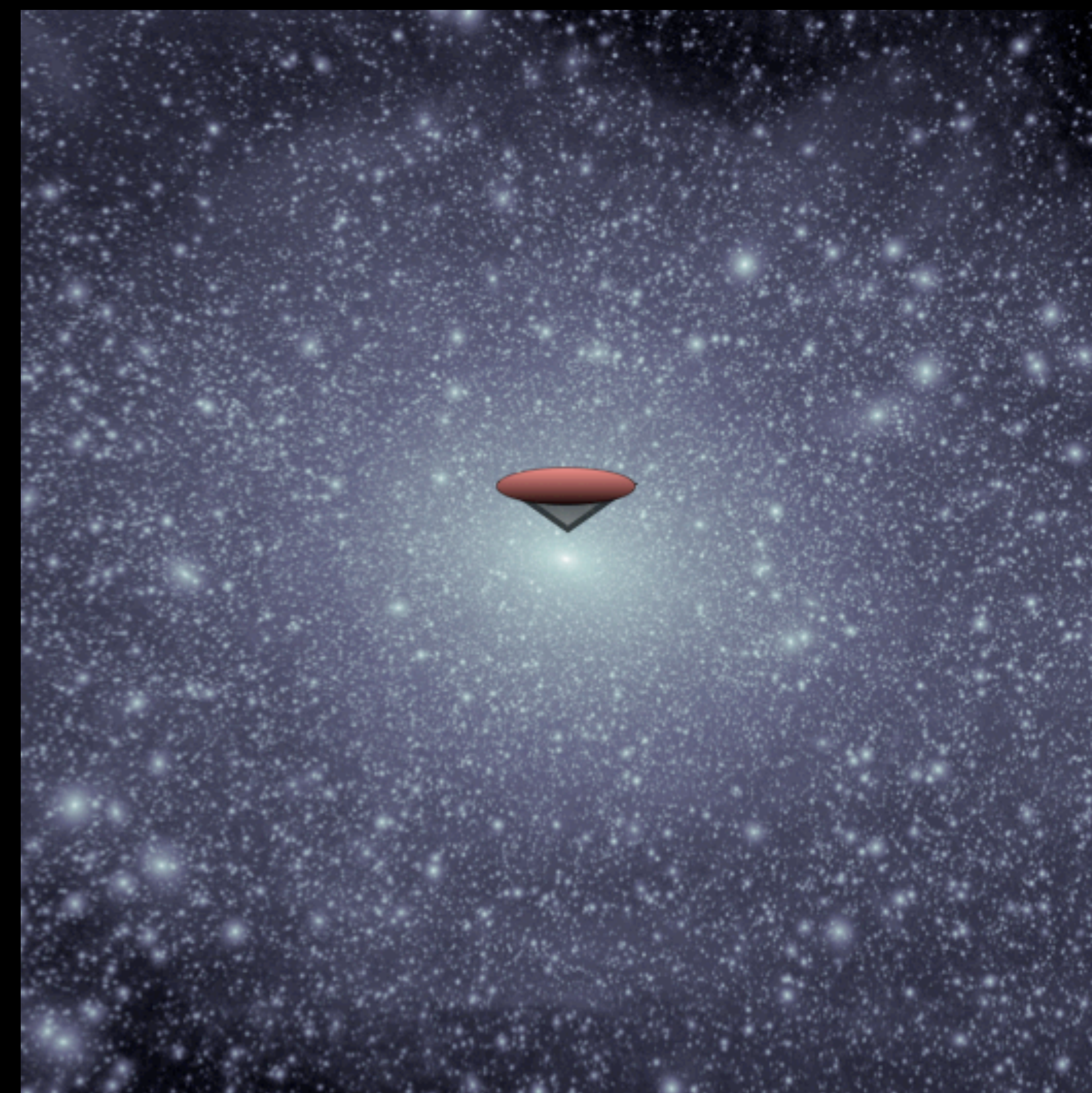
R. G. Carlberg[1] arXiv:1201.1347

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.

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.