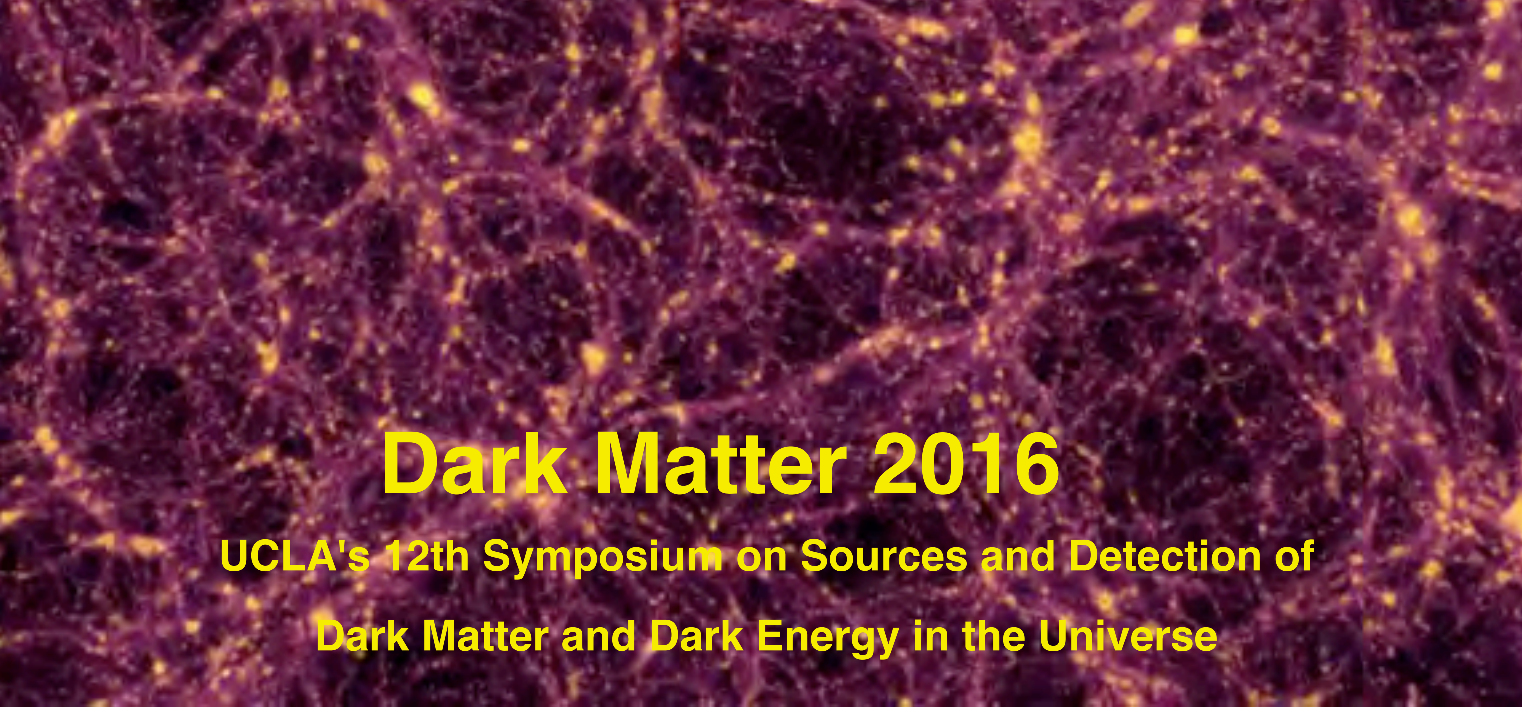


ΛCDM cosmology: successes, challenges, and opportunities for progress

Joel Primack, UC Santa Cruz

- **Successes:** CMB, Expansion History, Large Scale Structure
- **Challenges:** Cusp-Core, Too Big To Fail, Satellite Galaxies
- **Opportunities for Progress Now:** Halo Substructure by Gravitational Lensing and Stellar Motions, Early Galaxies, Reionization, Galaxies in the Cosmic Web

This series of conferences started in 1992

In my talk at the February 1992 conference at UCLA, I reported on research with my former PhD student Jon Holtzman (now chair of the NMSU Astronomy Department). Holtzman used and improved the code that George Blumenthal and I had written to calculate the linear power spectrum for CDM for our Blumenthal, Faber, Primack, & Rees 1984 Nature paper, "Formation of Galaxies and Large Scale Structure with Cold Dark Matter." In his 1989 dissertation, Holtzman calculated 96 variants of CDM, and then he and I compared the predictions with all the available large scale data such as galaxy distributions and velocities and galaxy cluster abundance. In February 1992, I reported that the available data favored two models in particular,

Cold + Hot DM (with $\Omega_{CDM} = 0.8$ and $\Omega_{\nu} = 0.2$)

and **ΛCDM** (with $\Omega_{CDM} = 0.3$ and $\Omega_{\Lambda} = 0.7$, the current values).

At Aspen in summer 1992, UCLA professor Ned Wright told me that he had practically fallen off his chair when I said that, since he had used Holtzman's thesis results to analyze the COBE DMR data, released April 29, 1992, and he had found that the same two CDM variants were favored.

THE ASTROPHYSICAL JOURNAL, 396:L13–L18, 1992 September 1

INTERPRETATION OF THE COSMIC MICROWAVE BACKGROUND RADIATION ANISOTROPY DETECTED BY THE *COBE*[1] DIFFERENTIAL MICROWAVE RADIOMETER

E. L. WRIGHT,[2] S. S. MEYER,[3] C. L. BENNETT,[4] N. W. BOGGESS,[4] E. S. CHENG,[4] M. G. HAUSER,[4] A. KOGUT,[5] C. LINEWEAVER,[6] J. C. MATHER,[4] G. F. SMOOT,[6] R. WEISS,[3] S. GULKIS,[7] G. HINSHAW,[5] M. JANSSEN,[7] T. KELSALL,[4] P. M. LUBIN,[8] S. H. MOSELEY, JR.,[4] T. L. MURDOCK,[9] R. A. SHAFER,[4] R. F. SILVERBERG,[4] AND D. T. WILKINSON[10]

Received 1992 April 21; accepted 1992 June 12

ABSTRACT

We compare the large-scale cosmic background anisotropy detected by the *COBE* Differential Microwave Radiometer (DMR) instrument to the sensitive previous measurements on various angular scales, and to the predictions of a wide variety of models of structure formation driven by gravitational instability. The observed anisotropy is consistent with all previously measured upper limits and with a number of dynamical models of structure formation. For example, the data agree with an unbiased cold dark matter (CDM) model with $H_0 = 50$ km s^{-1} Mpc^{-1} and $\Delta M/M = 1$ in a 16 Mpc radius sphere. Other models, such as CDM plus massive neutrinos [hot dark matter (HDM)], or CDM with a nonzero cosmological constant are also consistent with the *COBE* detection and can provide the extra power seen on 5–10,000 km s^{-1} scales.

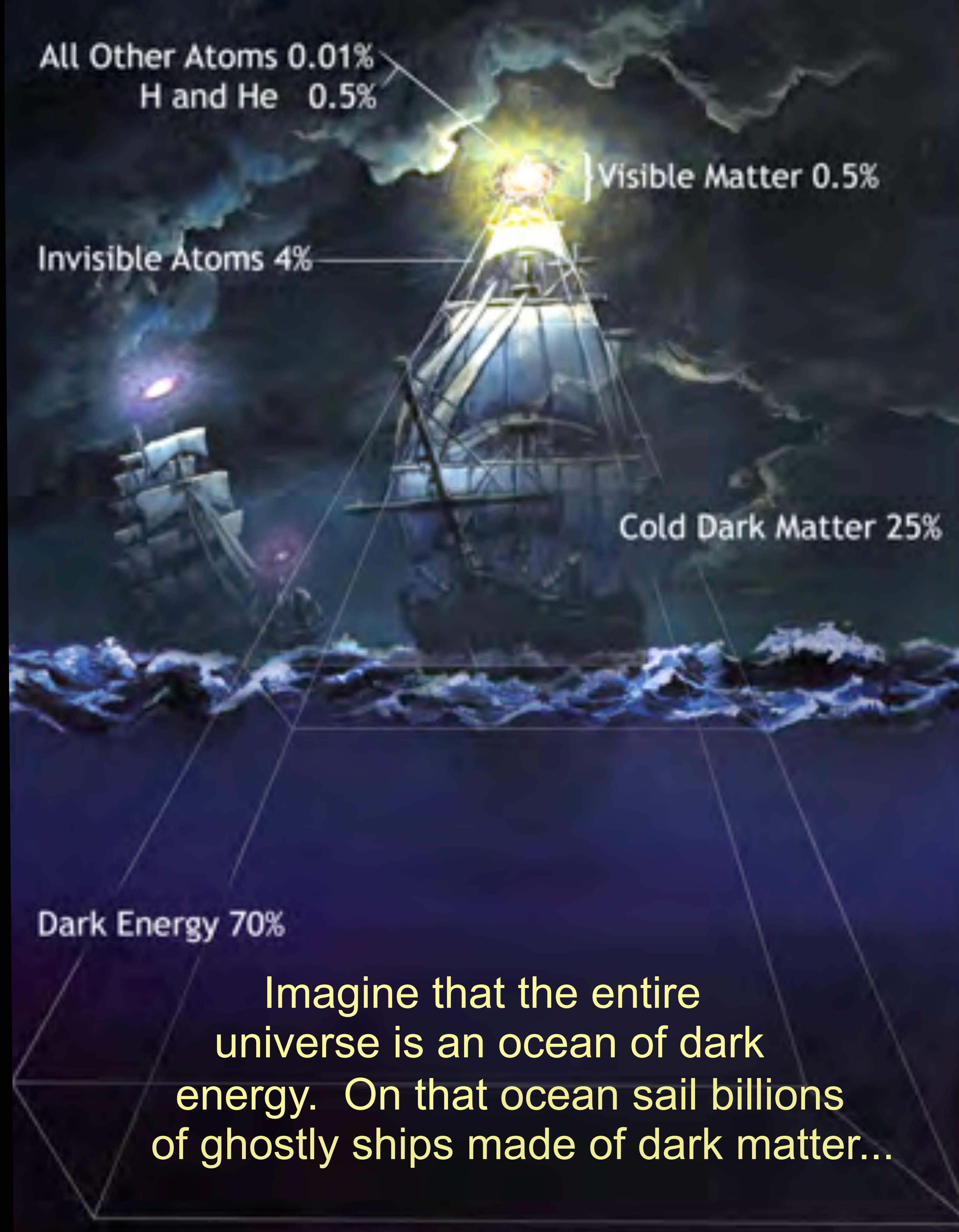
one of two CDM models in our 1984 Nature paper (the other had $\Omega_{CDM} = 0.2$)

The other two favored CDM variants were

Cold + Hot DM (with $\Omega_{CDM} = 0.8$ and $\Omega_\nu = 0.2$)
ΛCDM (with $\Omega_{CDM} = 0.3$ and $\Omega_\Lambda = 0.7$, the current values).

ΛCDM won with the 1998 discovery of accelerated expansion and high-*z* galaxies.

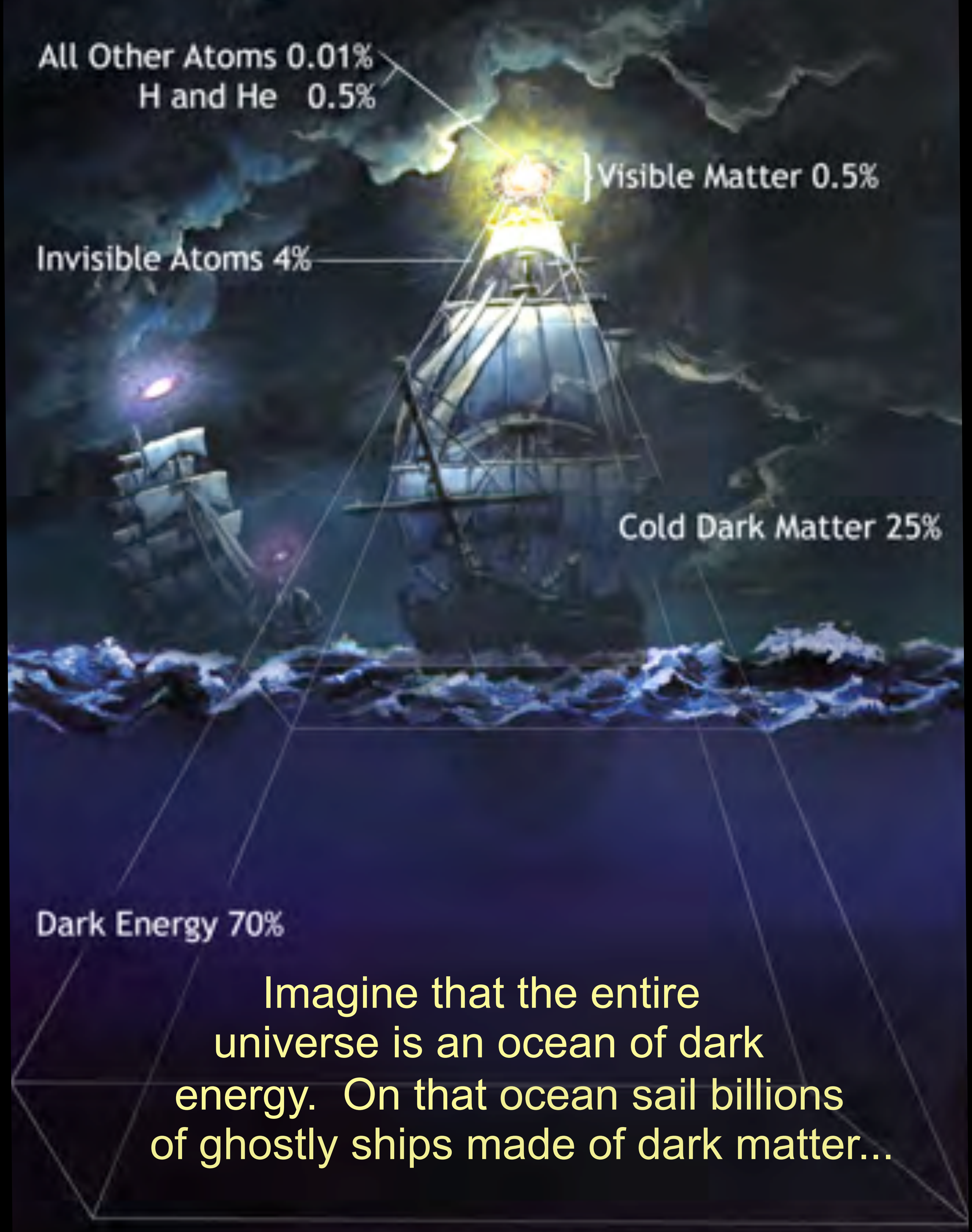
Matter and Energy Content of the Universe



Dark Matter Ships

on a

Dark Energy Ocean



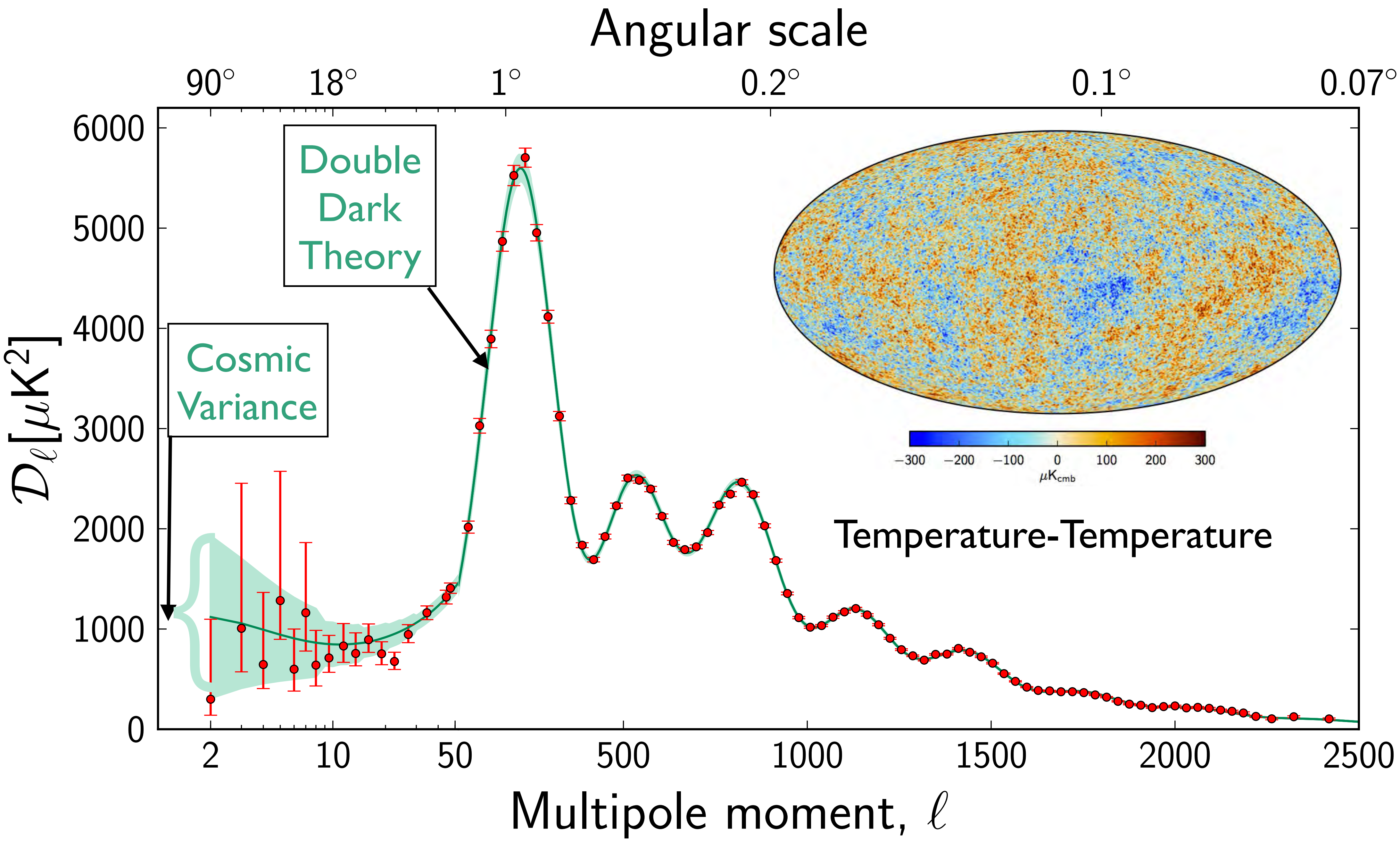
Matter and Energy Content of the Universe

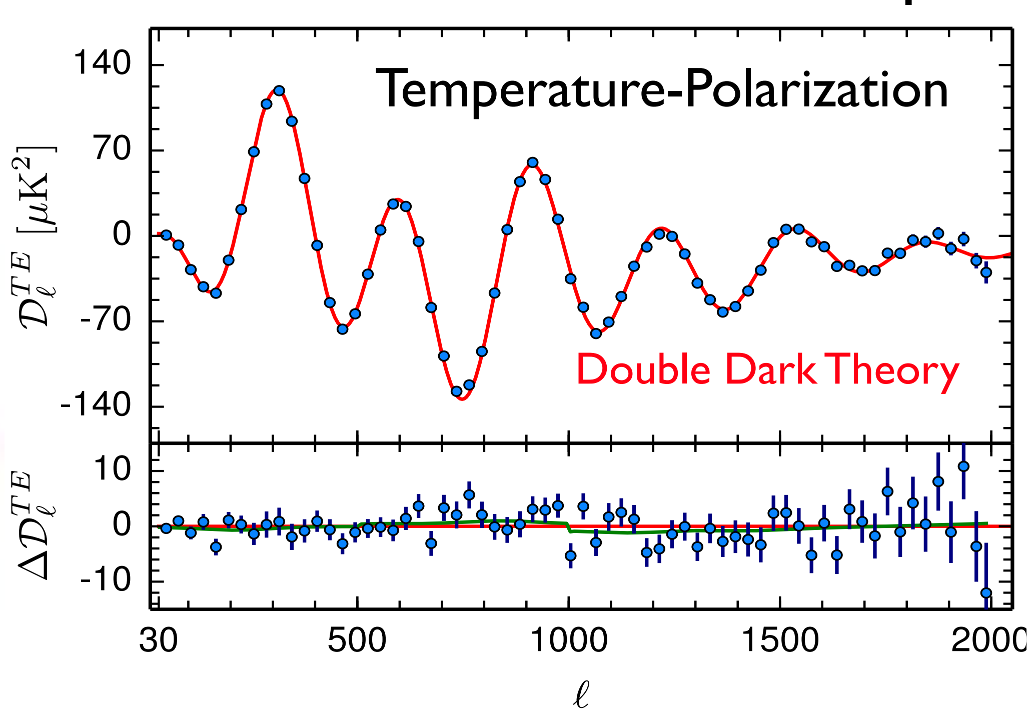
ΛCDM

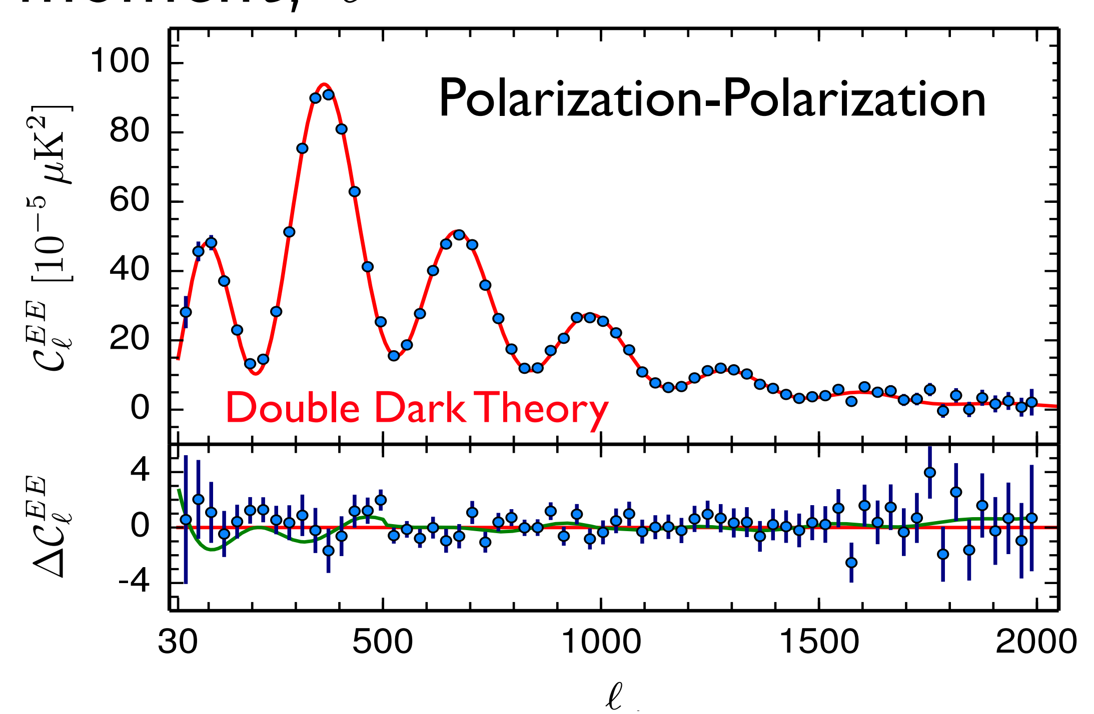
Double Dark Theory

European Space Agency PLANCK Satellite Data

Released February 9, 2015







Planck 2015 XIII Cosmology Conclusions

The six-parameter base ΛCDM model continues to provide a very good match to the more extensive 2015 *Planck* data, including polarization. This is the most important conclusion of this paper.

The *Planck TT*, *TE*, and *EE* spectra are accurately described with a purely adiabatic spectrum of fluctuations with a spectral tilt $n_s = 0.968 \pm 0.006$, consistent with the predictions of single-field inflationary models. Combining the *Planck* and BICEP2/Keck/Planck likelihoods, we find a tight constraint on tensor modes $r_{0.002} < 0.09$, strongly disfavouring inflationary models with $V(\phi) \sim \phi^2$.

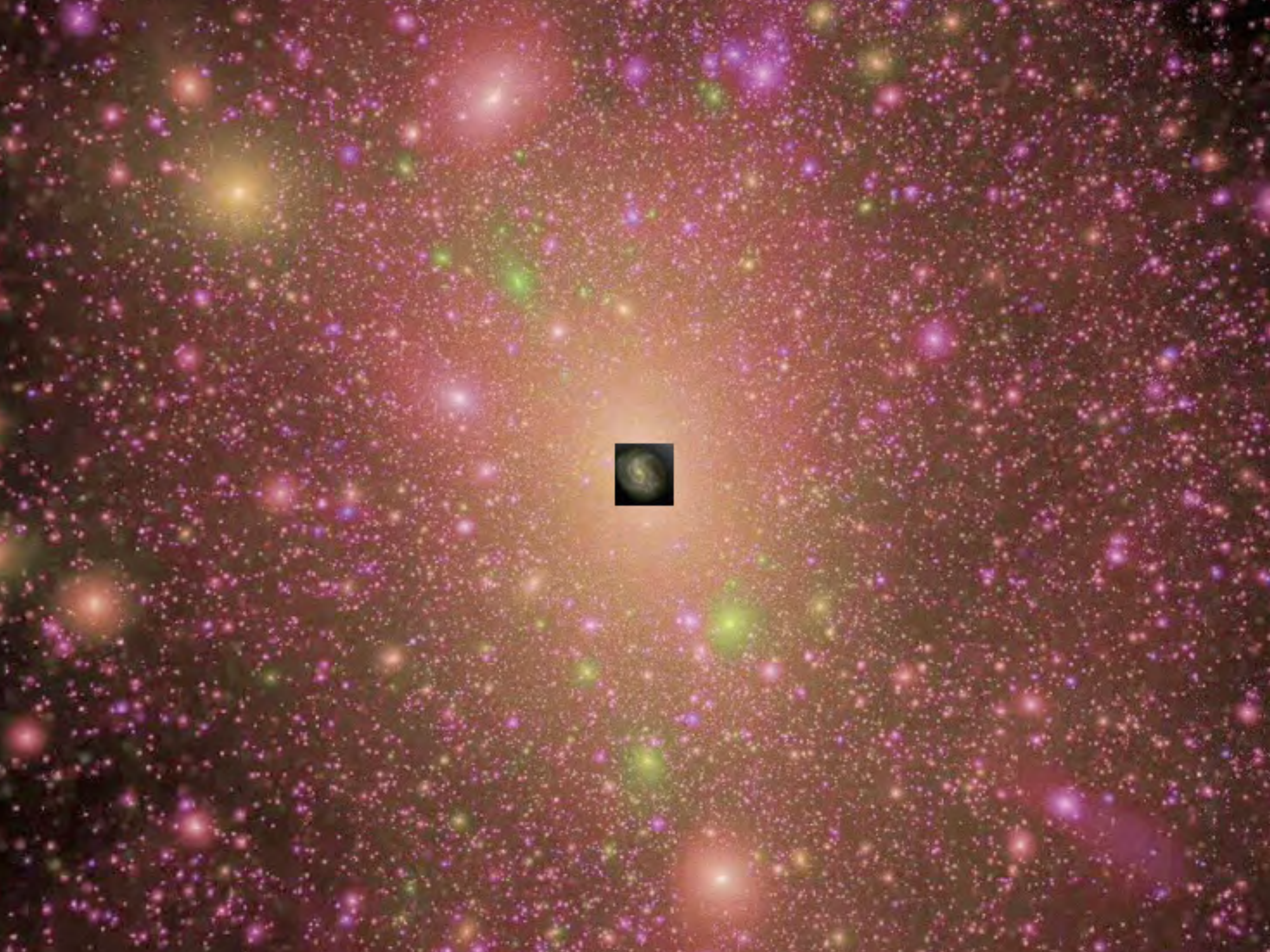
The *Planck* best-fit base ΛCDM cosmology is in good agreement with results from BAO surveys, with the recent JLA sample of Type Ia SNe, and with the recent analysis of redshift-space distortions of the BOSS CMASS-DR11.

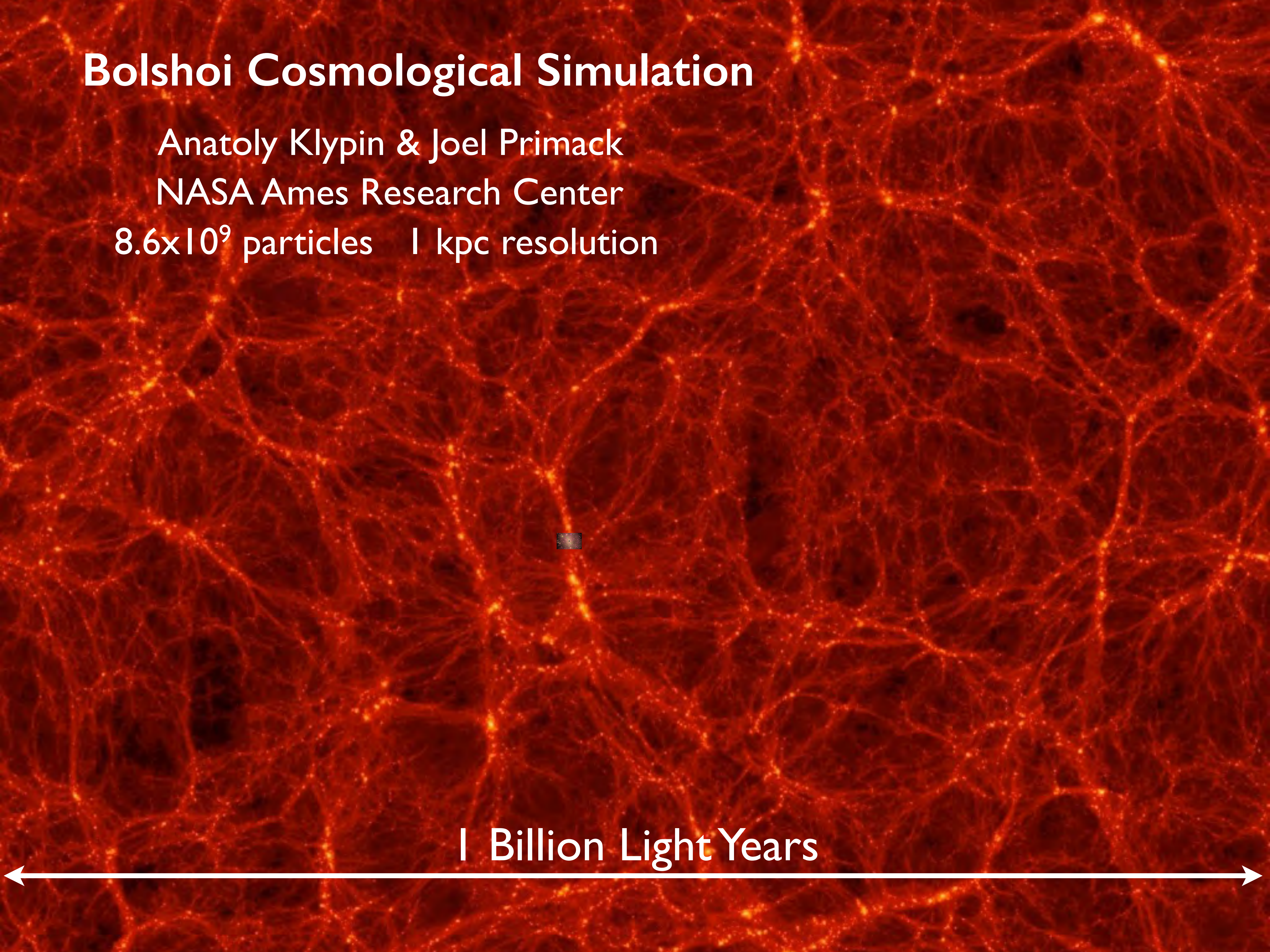
The Hubble constant in this cosmology is $H_0 = (67.8 \pm 0.9)$ km s^{-1}Mpc^{-1}. Dark energy is constrained to $w = -1.006 \pm 0.045$ and is therefore compatible with a cosmological constant, as assumed in the base ΛCDM cosmology.

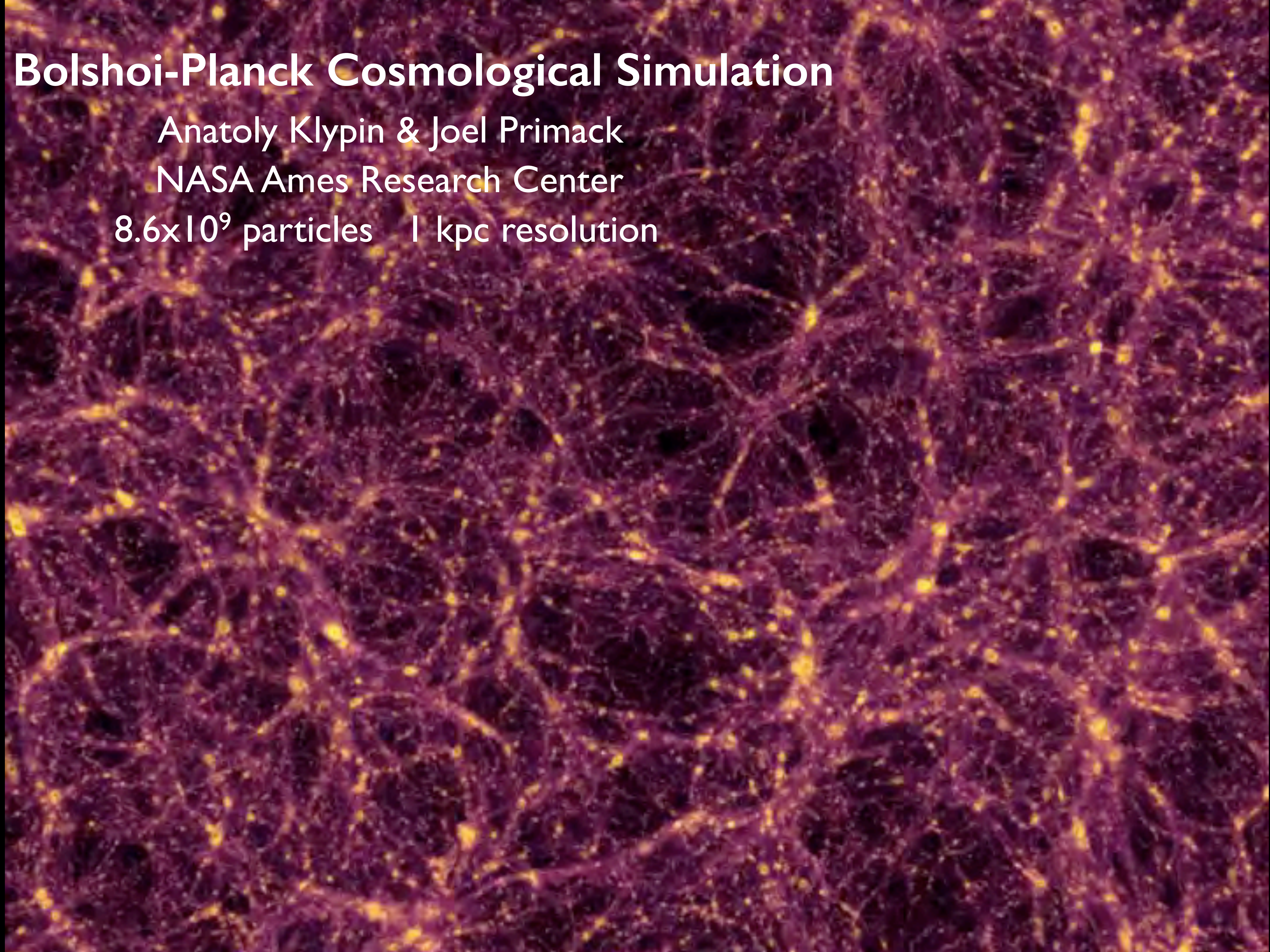
Combining *Planck* TT+lowP+lensing with BAO we find $N_{eff} = 3.15 \pm 0.23$ for the effective number of relativistic degrees of freedom, consistent with the value $N_{eff} = 3.046$ of the standard model. The sum of neutrino masses is constrained to $\sum m_\nu < 0.23$ eV. The standard theory of big bang nucleosynthesis is in excellent agreement with *Planck* data and observations of primordial light element abundances.

The analysis of 2015 *Planck* data reported in Planck Collaboration XVII (2015) sets unprecedentedly tight limits on primordial non-Gaussianity. If there is new physics beyond base ΛCDM, then the corresponding observational signatures in the CMB are weak and difficult to detect. This is the legacy of the *Planck* mission for cosmology.


Aquarius Simulation
Volker Springel
Milky Way
100,000 Light Years
Milky Way Dark Matter Halo
1,500,000 Light Years



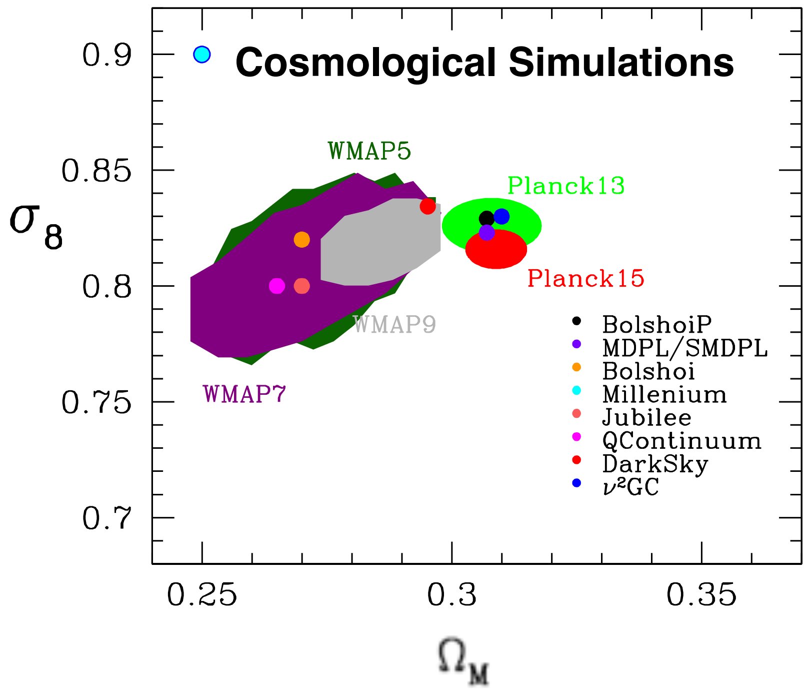

Bolshoi Cosmological Simulation
Anatoly Klypin & Joel Primack
NASA Ames Research Center
8.6x10^9 particles 1 kpc resolution
1 Billion Light Years

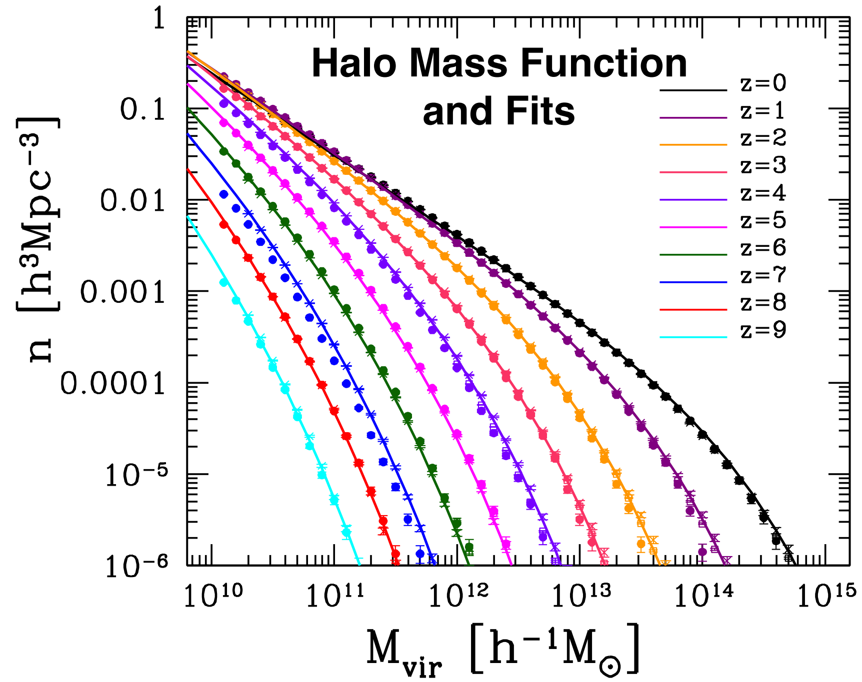

Bolshoi-Planck Cosmological Simulation
Anatoly Klypin & Joel Primack
NASA Ames Research Center
8.6x10^9 particles 1 kpc resolution

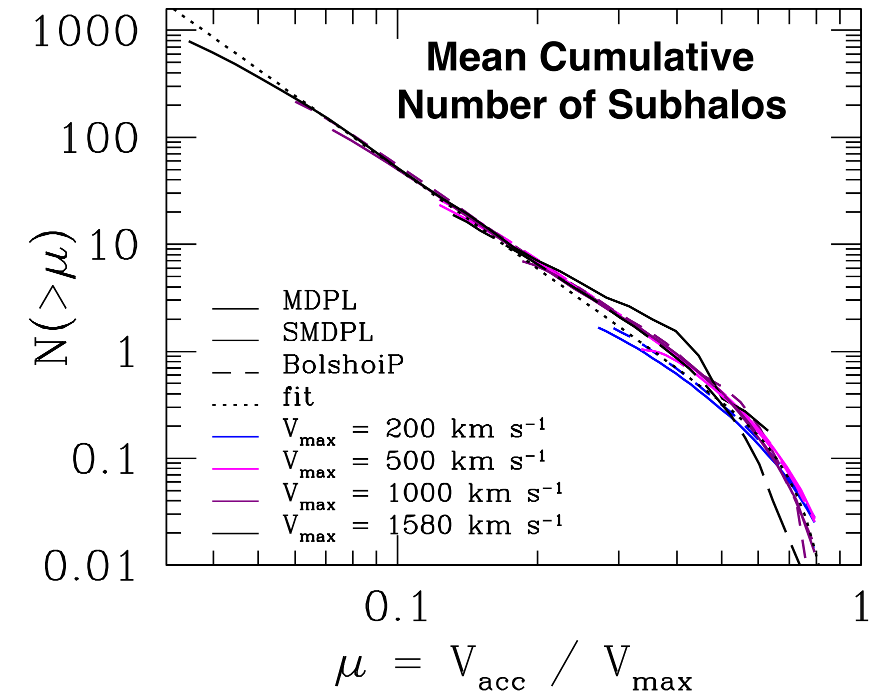
Halo and Subhalo Demographics with Planck Cosmological Parameters: Bolshoi-Planck and MultiDark-Planck Simulations

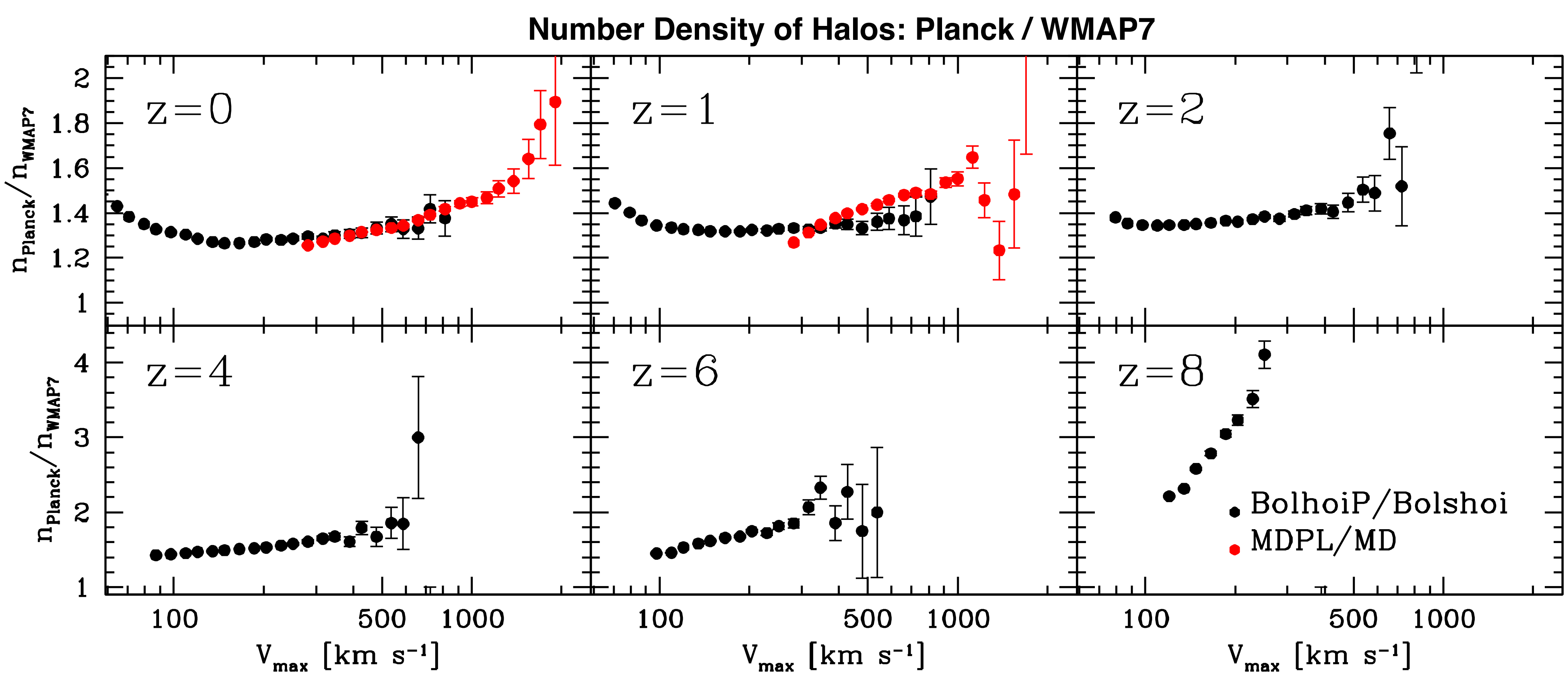
Aldo Rodrıguez-Puebla, Peter Behroozi, Joel Primack, Anatoly Klypin, Christoph Lee, Doug Hellinger

on arXiv today





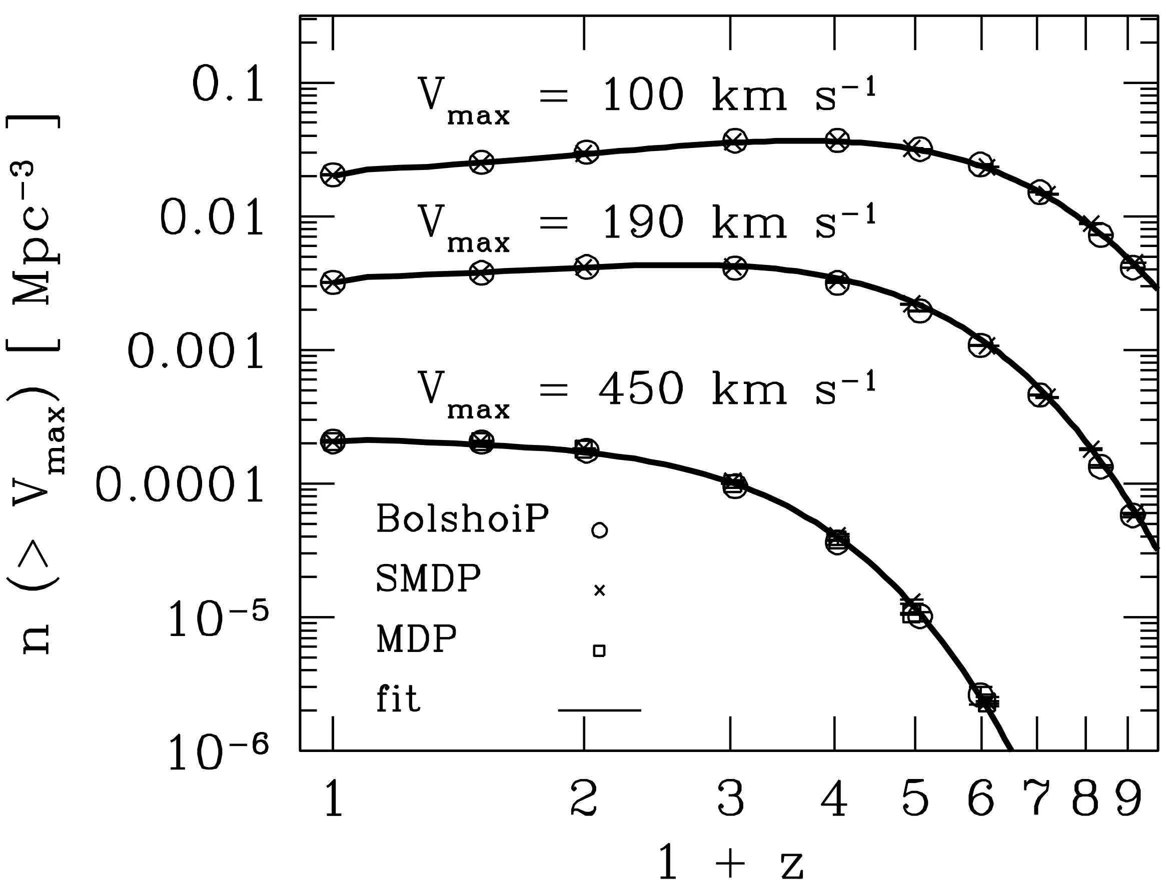




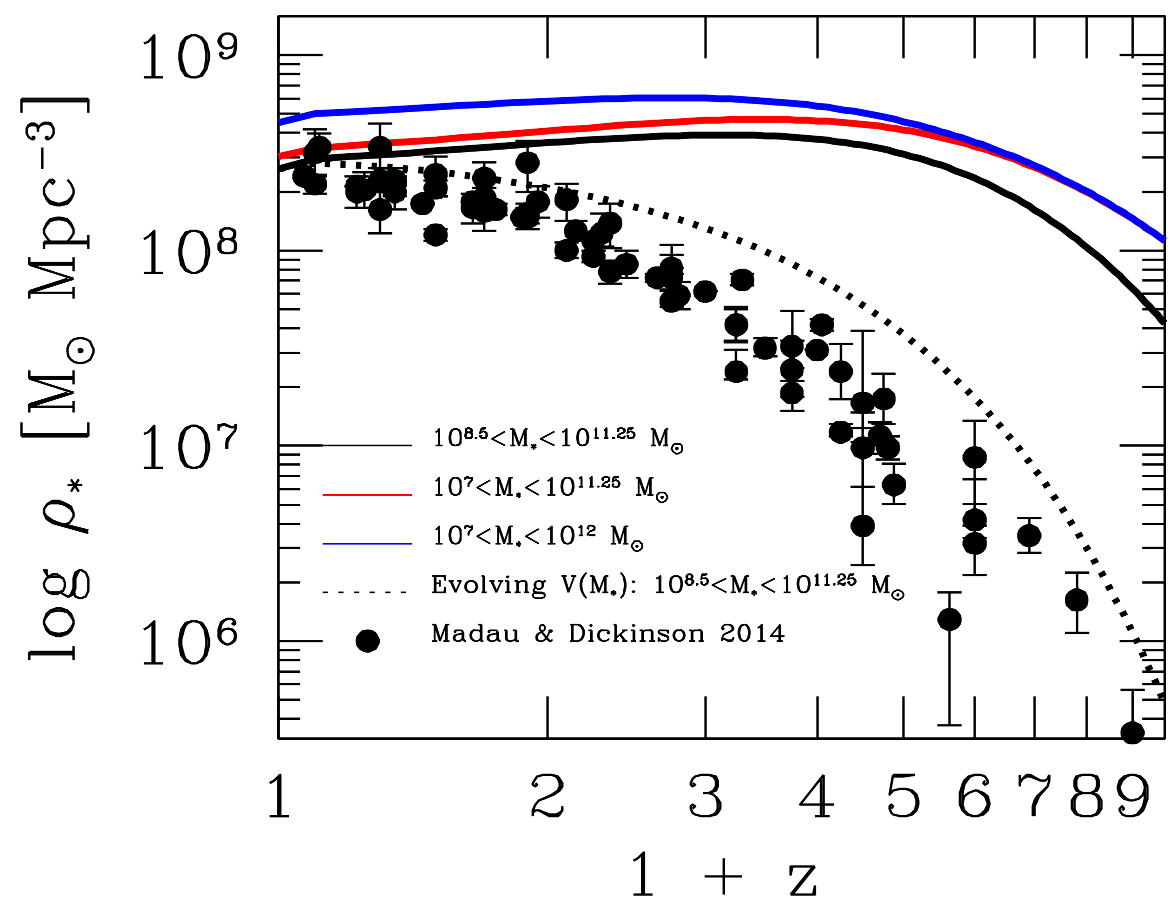
There are many more halos with the Planck cosmology, especially at high masses and redshifts.

We are now releasing the halo catalogs and merger trees from all our new cosmological simulations. The paper includes Appendices with instructions for reading these files.

Halo and Subhalo Demographics with Planck Cosmological Parameters: Bolshoi-Planck and MultiDark-Planck Simulations

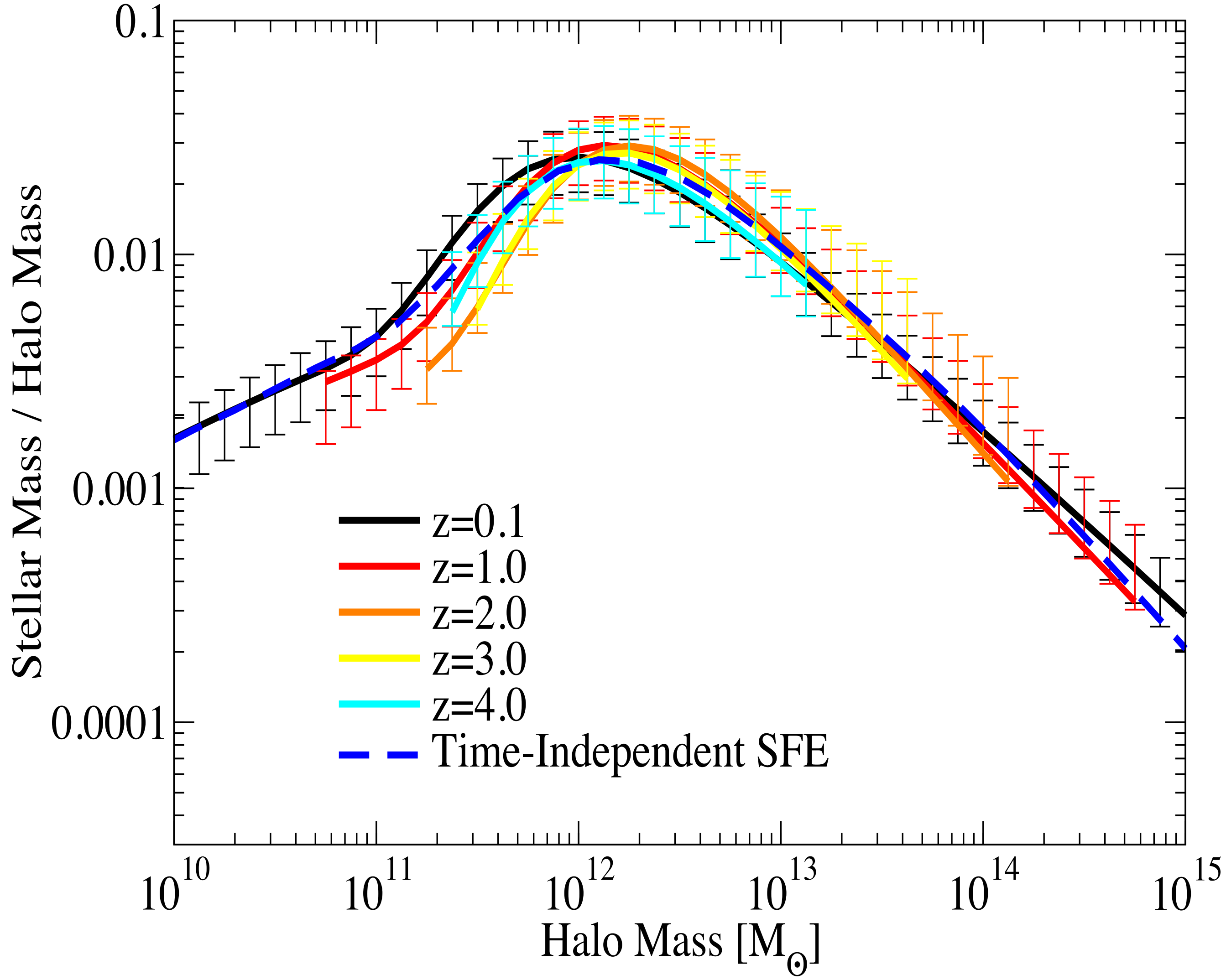


The cumulative number of halos > V_{max} is pretty constant out to redshift z ~ 4 for galaxy-mass halos. But these halos are smaller and denser, and they cannot host high-M* galaxies at high redshifts.



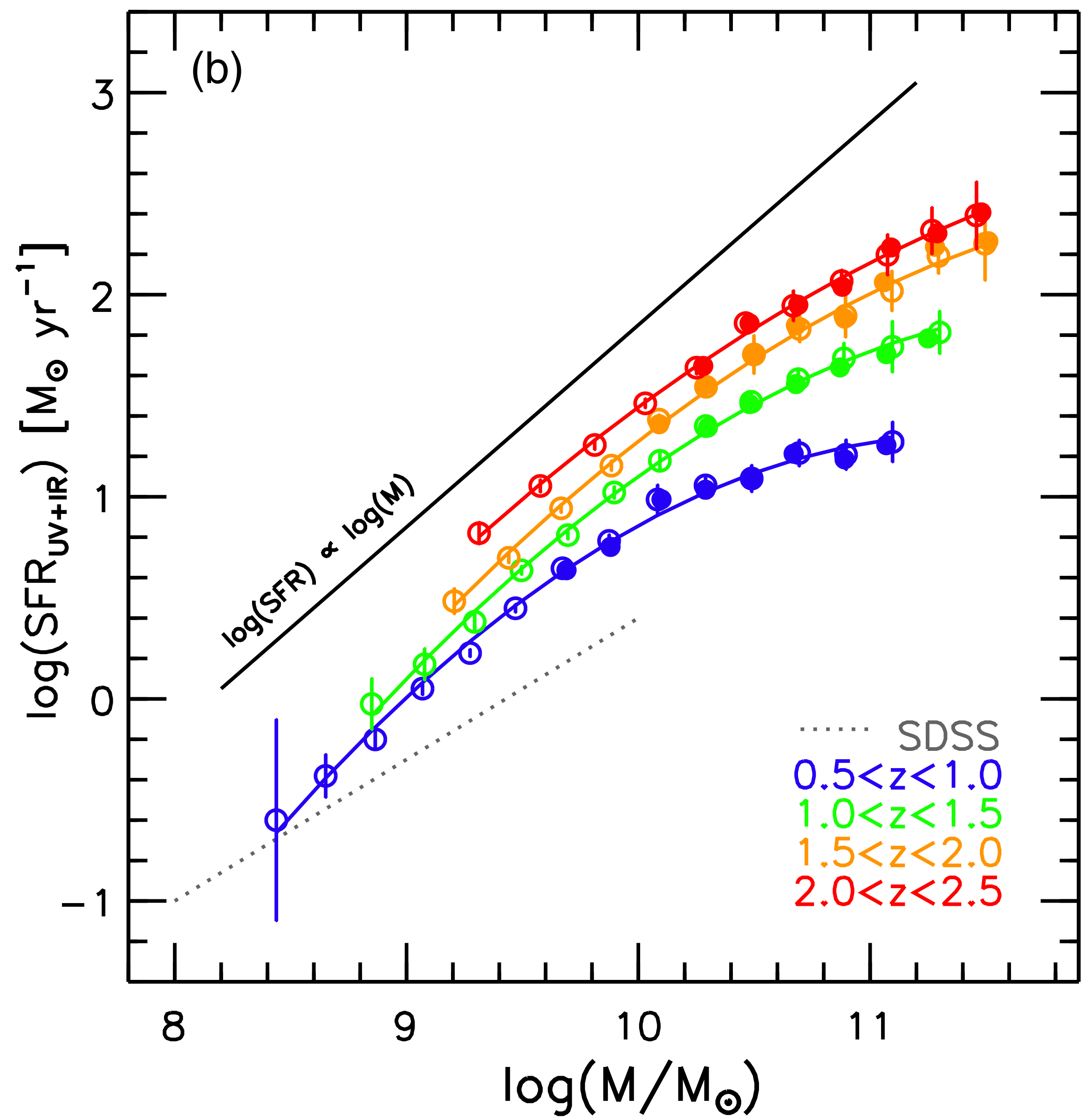
Tully-Fisher and Faber-Jackson M* ~ V^4 scaling relations for spiral and elliptical galaxies must change by z ~ 1, or they would predict far too high stellar mass density at z > 1.

Relationship Between Galaxy Stellar Mass and Halo Mass



The stellar mass to halo mass ratio at multiple redshifts as derived from observations compared to a model which has a time-independent star formation efficiency (SFE). Error bars show 1σ uncertainties. A time-independent SFE predicts a roughly **time-independent stellar mass to halo mass relationship**. (Behroozi, Wechsler, Conroy, ApJL 2013)

Star-forming Galaxies Lie on a "Main Sequence"

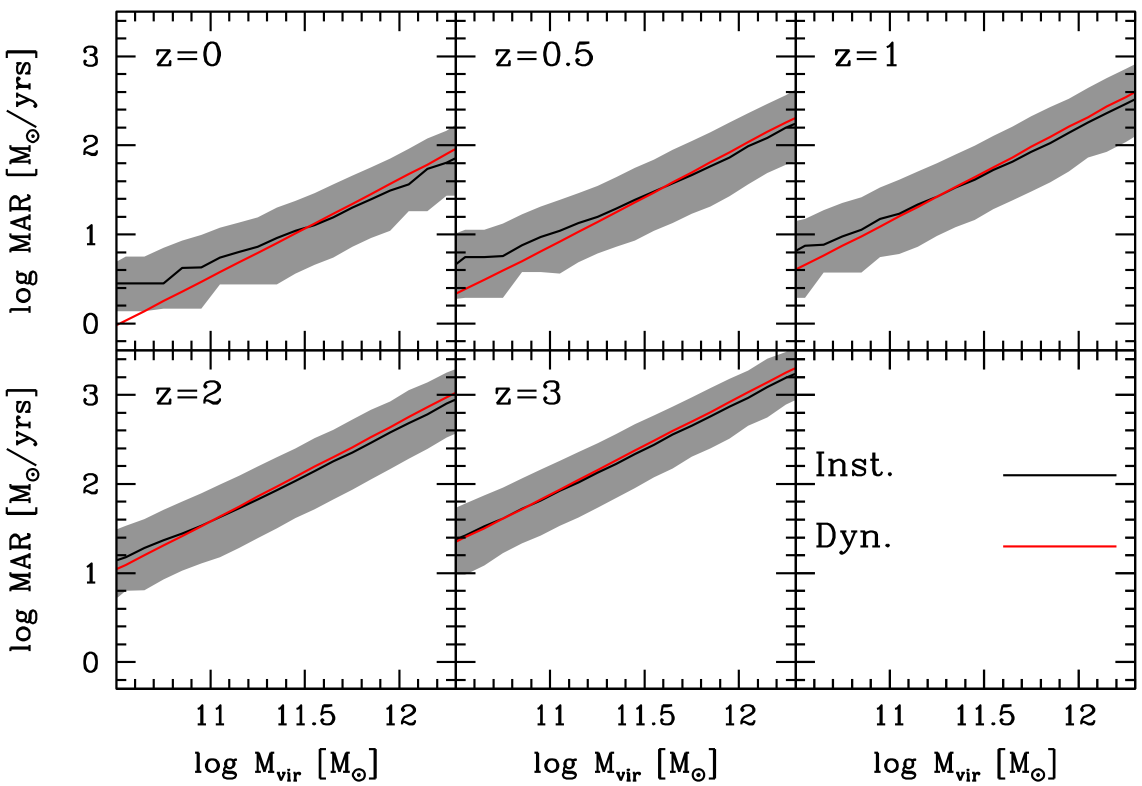


Just as the properties of hydrogen-burning stars are controlled by their mass, the galaxy star formation rate (SFR) is approximately proportional to the stellar mass, with the proportionality constant increasing with redshift up to about z = 2.5. (Whitaker et al. ApJ 2014)

Is Main Sequence SFR Controlled by Halo Mass Accretion?

by Aldo Rodríguez-Puebla, Joel Primack, Peter Behroozi, Sandra Faber MNRAS 2016

Halo mass accretion rates z=0 to 3



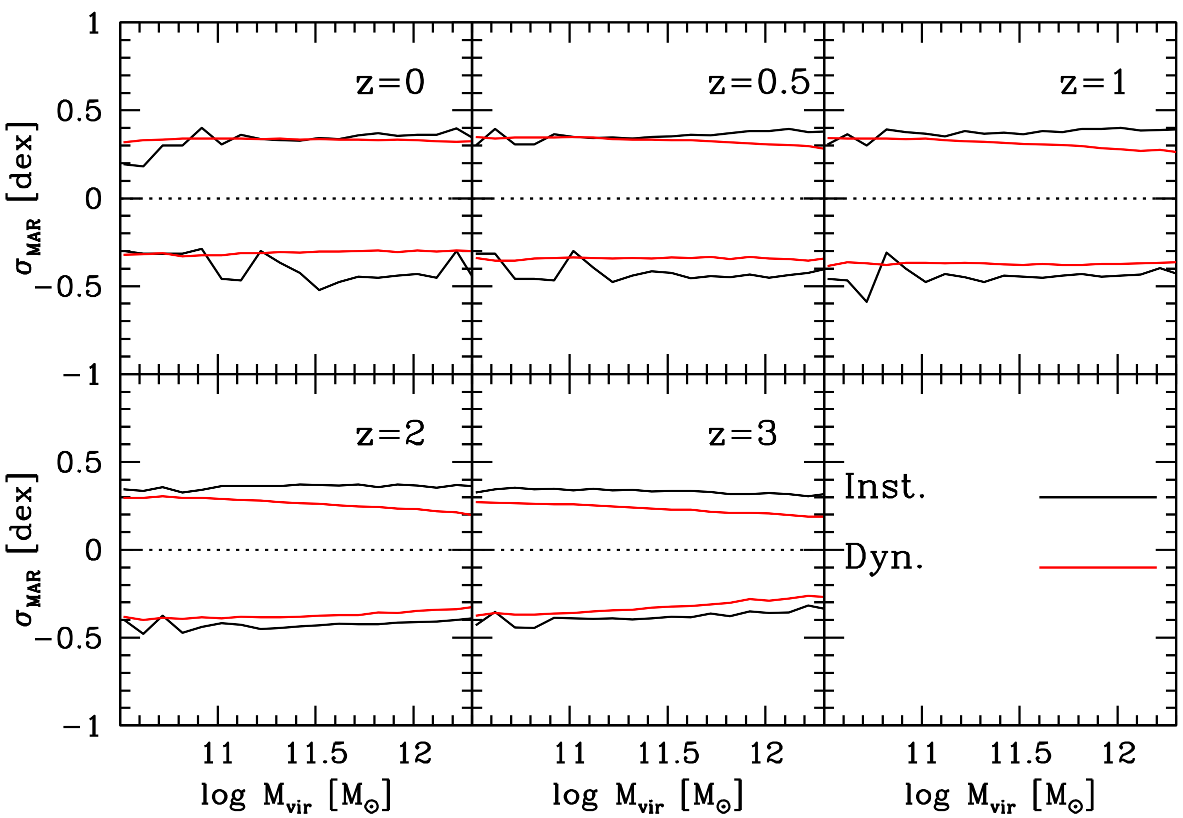
$$\frac{dM_*}{dt} = \frac{\partial M_*(M_{\rm vir}(t),z)}{\partial M_{\rm vir}}\frac{dM_{\rm vir}}{dt} + \frac{\partial M_*(M_{\rm vir}(t),z)}{\partial z}\frac{dz}{dt}$$

but if the M_*–$M_{\rm vir}$ relation is independent of redshift then the stellar mass of a central galaxy formed in a halo of mass $M_{\rm vir}(t)$ is $M_* = M_*(M_{\rm vir}(t))$. From this relation star formation rates are given simply by

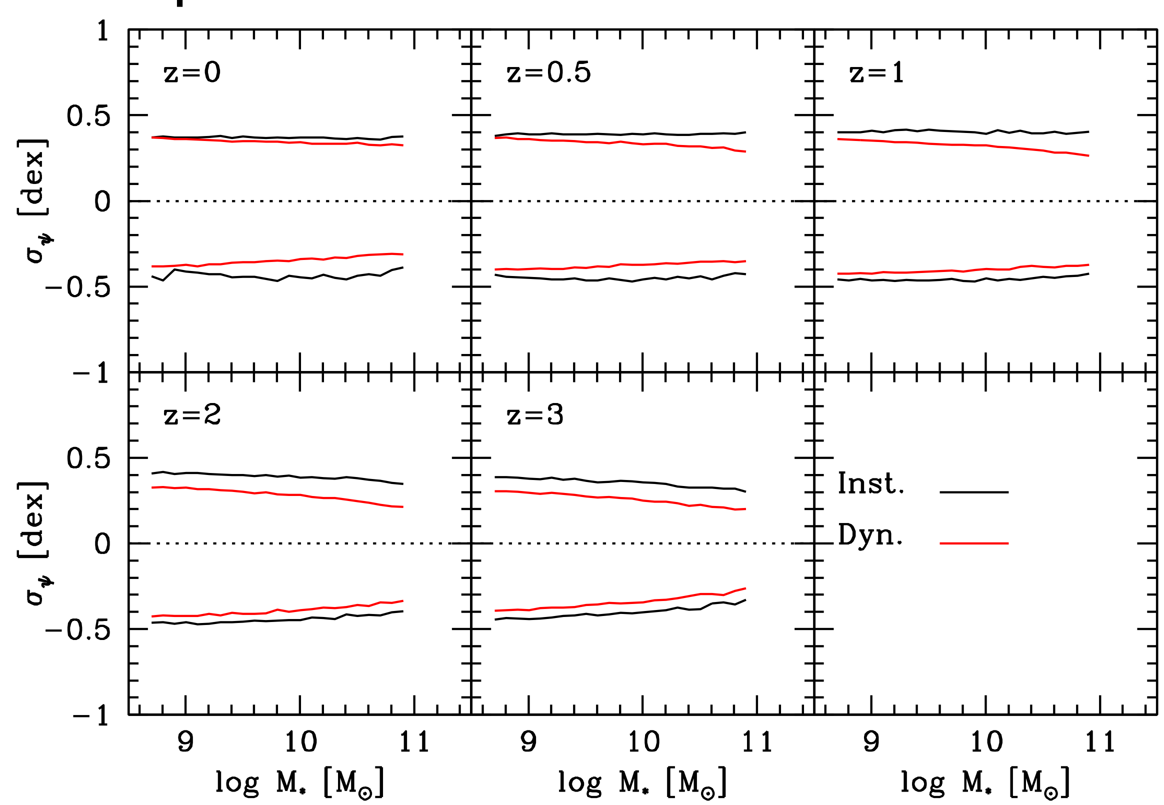
$$\frac{dM_*}{dt} = f_* \frac{d\log M_*}{d\log M_{\rm vir}}\frac{dM_{\rm vir}}{dt},$$

where $f_* = M_*/M_{\rm vir}$. We call this **Stellar-Halo Accretion Rate Coevolution (SHARC)** if true halo-by-halo.

Scatter of halo mass accretion rates



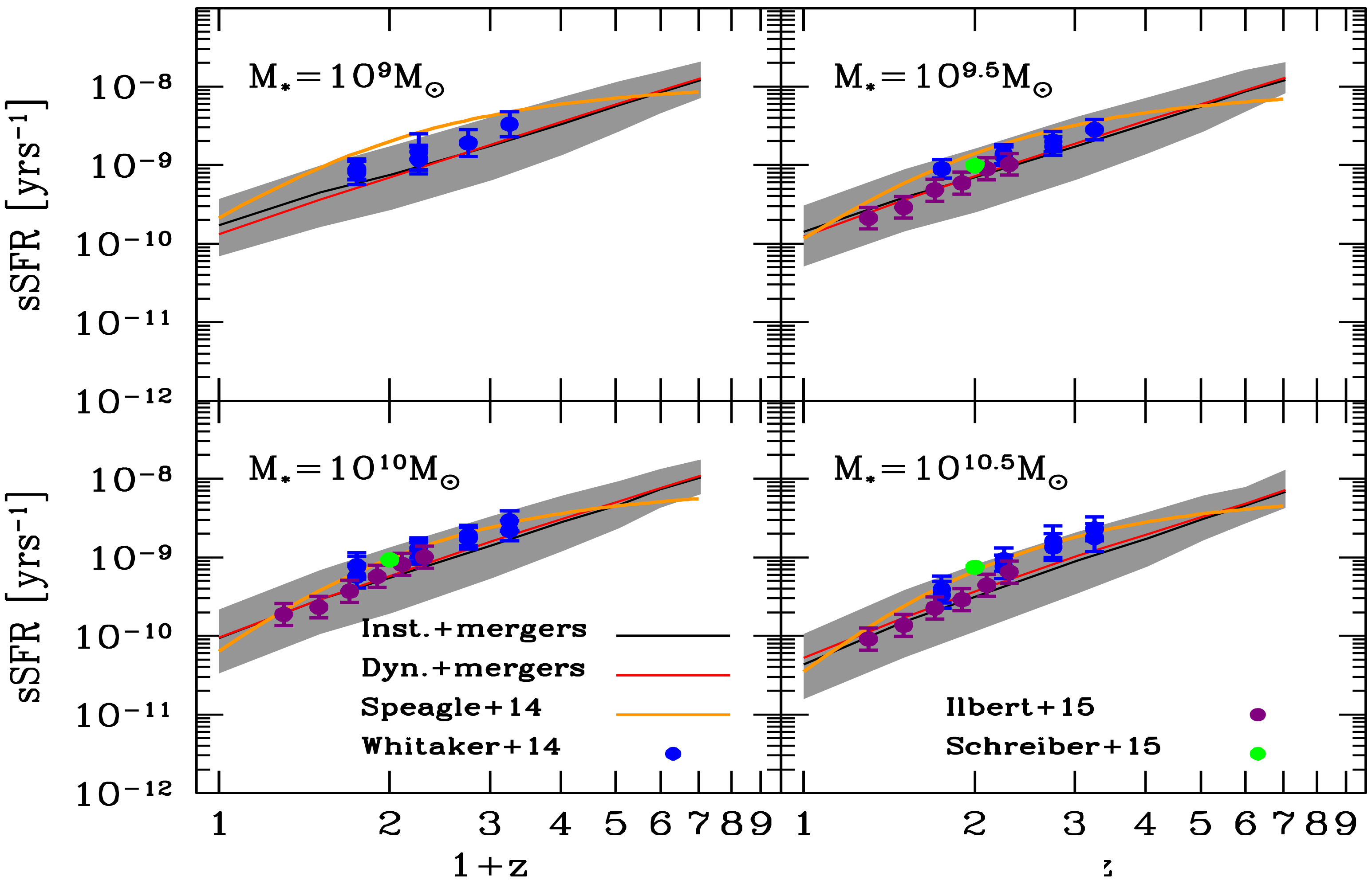
Implied scatter of star formation rates



Is Main Sequence SFR Controlled by Halo Mass Accretion?

by Aldo Rodríguez-Puebla, Joel Primack, Peter Behroozi, Sandra Faber MNRAS 2016

SHARC correctly predicts star formation rates to z ~ 4



SHARC predicts "Age Matching" (blue galaxies in accreting halos) and "Galaxy Conformity" at low z

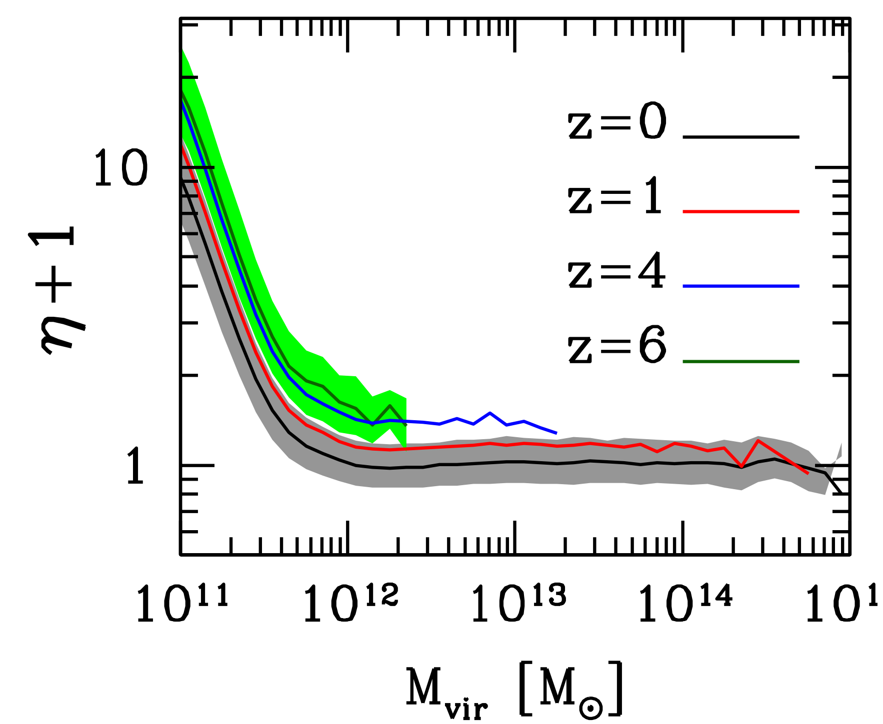
Open Questions:

Extend SHARC to higher-mass galaxies

Check predicted correlations vs. observations at high z

Can SHARC be used to measure growth rate of halos from the star formation rate, as a dark energy vs. gravity test?

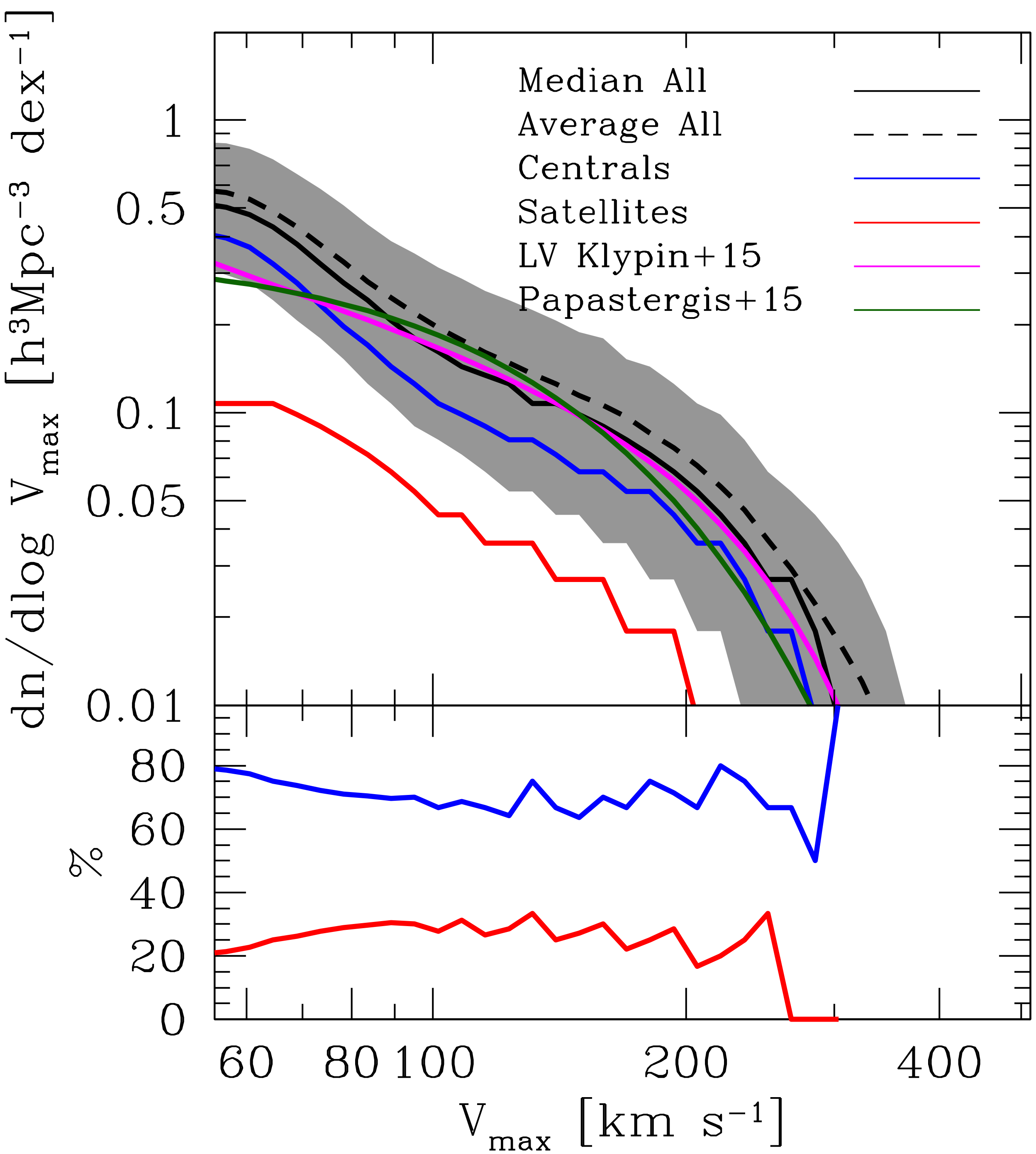
Put SHARC in "bathtub" equilibrium models of galaxy formation & predict mass loading and metallicity evolution



Net mass loading factor η from an equilibrium bathtub model (E+SHARC)

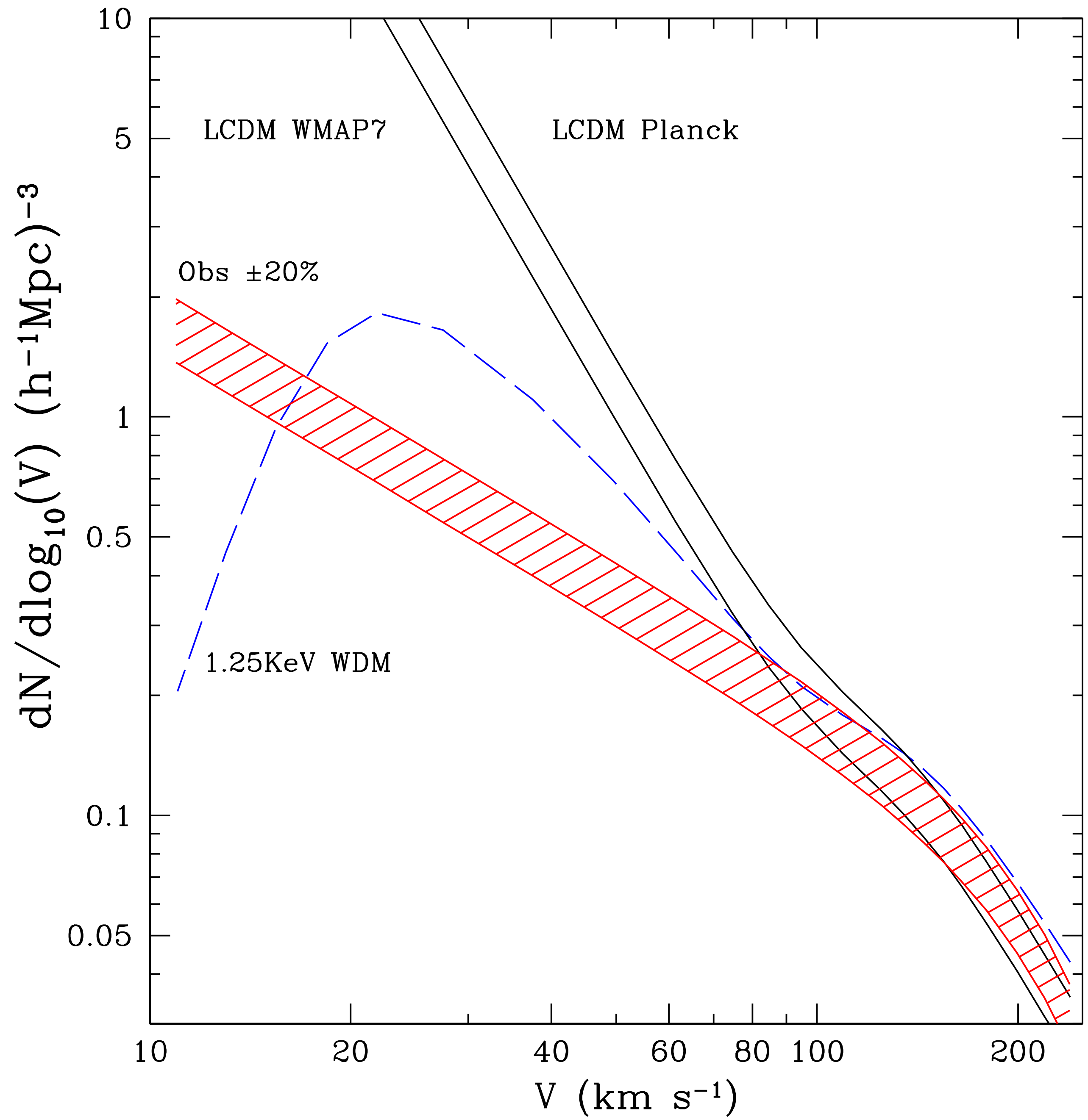
Is there a “Too Big To Fail” problem in the field?

Not down to Bolshoi-Planck simulation V_{max} > 50 km/s



Comparison of the Local Volume 3D velocity function dN/d log V from the SMDPL simulation with the observed Local Volume optical velocity function of galaxies within ~ 10 Mpc (Figure 12 of Klypin, Karachentsev et al. 2015) and the HI radio velocity function from the ALFALFA survey (Papastergis et al. 2015). The grey band is the 1σ spread around mock Milky Way centers of 10 Mpc Local Volume. (Rodriguez-Puebla et al. 2016)

Increasing discrepancy for extrapolated V_{max} < 50 km/s



Observed and theoretical estimates of the 3D velocity function of galaxies. The LCDM-*Planck* model overpredicts dwarf galaxy abundance with $V < 60$ km/s. The WDM model predicts a wrong shape for the VF; it fails by a factor of 2–3 at small velocities while still overpredicting the abundance of 30 km/s galaxies. (Klypin, Karachentsev, et al. 2015; see also Papastergis & Shankar 2015)

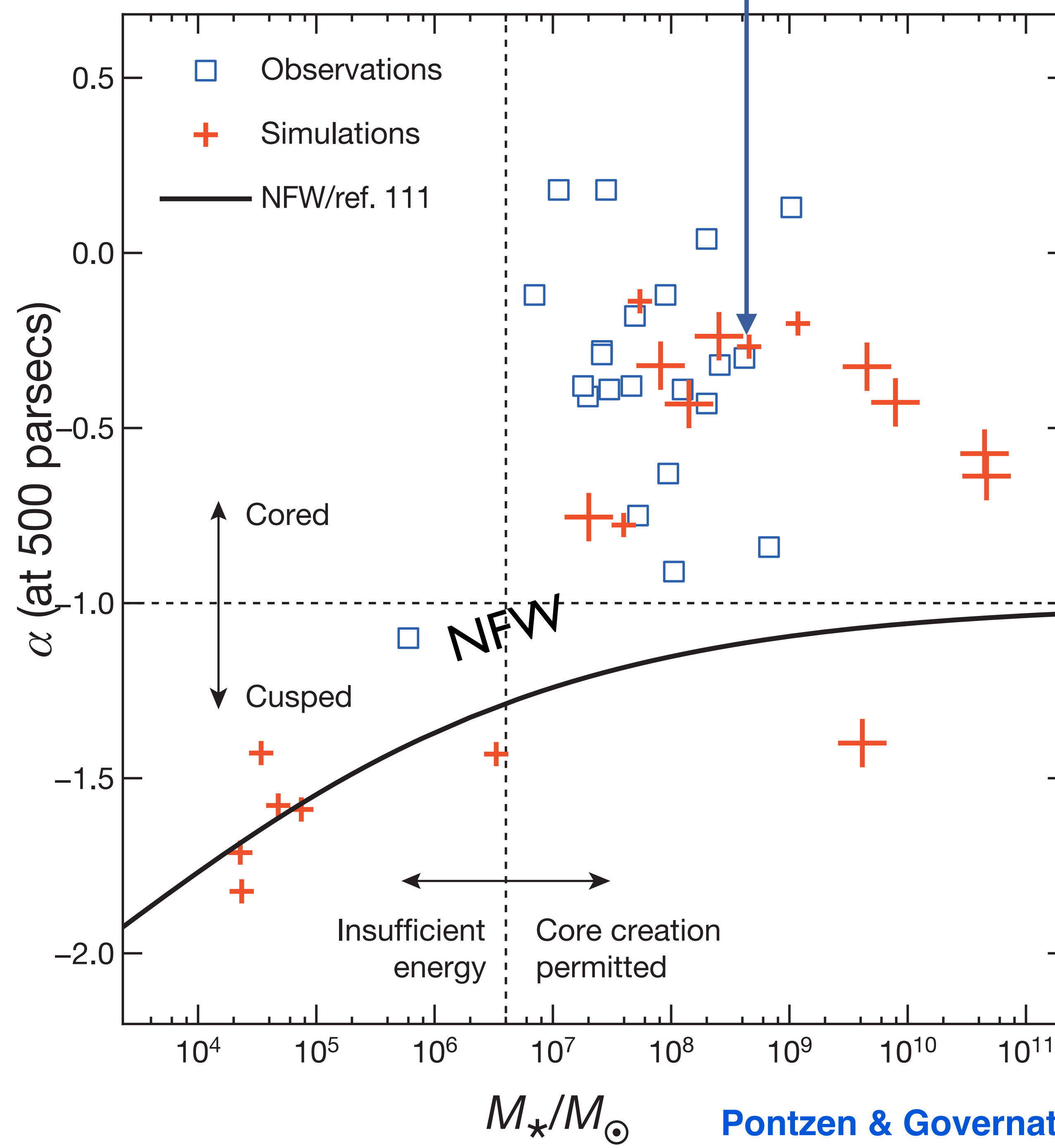
Challenges: Cusp-Core, Too Big to Fail, Satellite Galaxies

Flores & Primack94 and Moore94 first pointed out that dark matter simulations have density $\rho(r) \sim r^{\alpha}$ at small r with $\alpha \approx -1$ ("cusp") while observed small spiral galaxies and clusters appeared to have $\alpha \approx 0$ ("core").

Governato+10,13 and the *Nature* review by Pontzen & Governato14 show that in high-resolution galaxy simulations, baryonic physics softens the central DM cusp to a core as long as enough stars form, $M^* \geq 10^7\ M_{\odot}$. This happens because of repeated episodes when the baryons cool and slowly fall into the galaxy center, and are then expelled rapidly (in less than a dynamical time) by energy released by stars and supernovae.

Observers (e.g., Walker & Peñarrubia11, Amorisco & Evans12) had agreed that the larger dwarf spheroidal Milky Way satellite galaxies such as Fornax ($L \approx 1.7\times10^7\ L_{\odot}$) have cores, but recent papers (e.g., Breddels & Helmi13,14, Jardel & Gebhardt13, Richardson & Fairbairn14) have questioned this. (Reviewed in Kormendy & Freeman16.) **Thus the cusp-core question is now observational *and* theoretical.**

Adams, Simon+14 find $\rho(r) \sim r^{\alpha}$, $\alpha \approx 0.5$ for dwarf spirals, in agreement with recent high-resolution simulations with baryons.

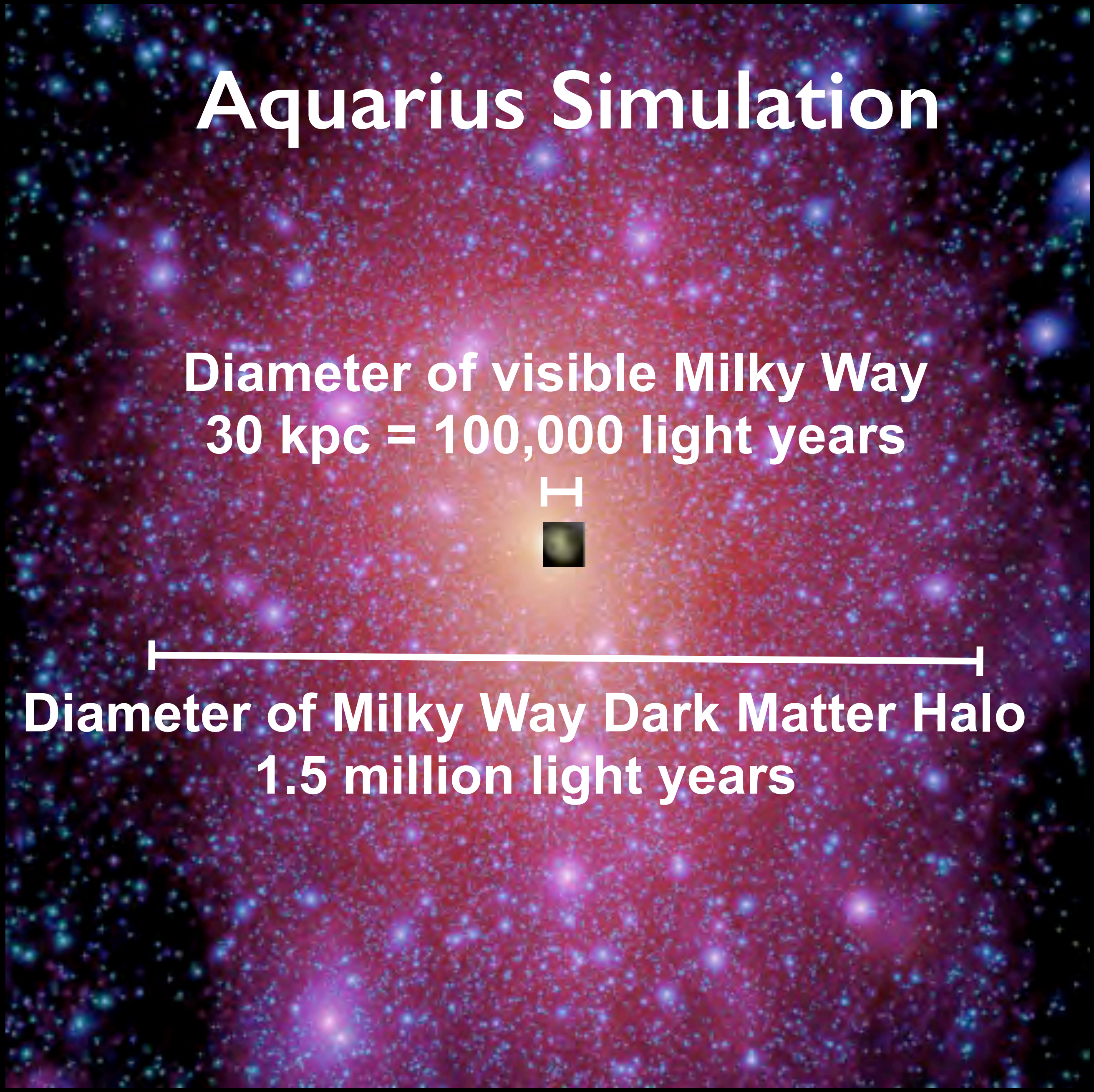


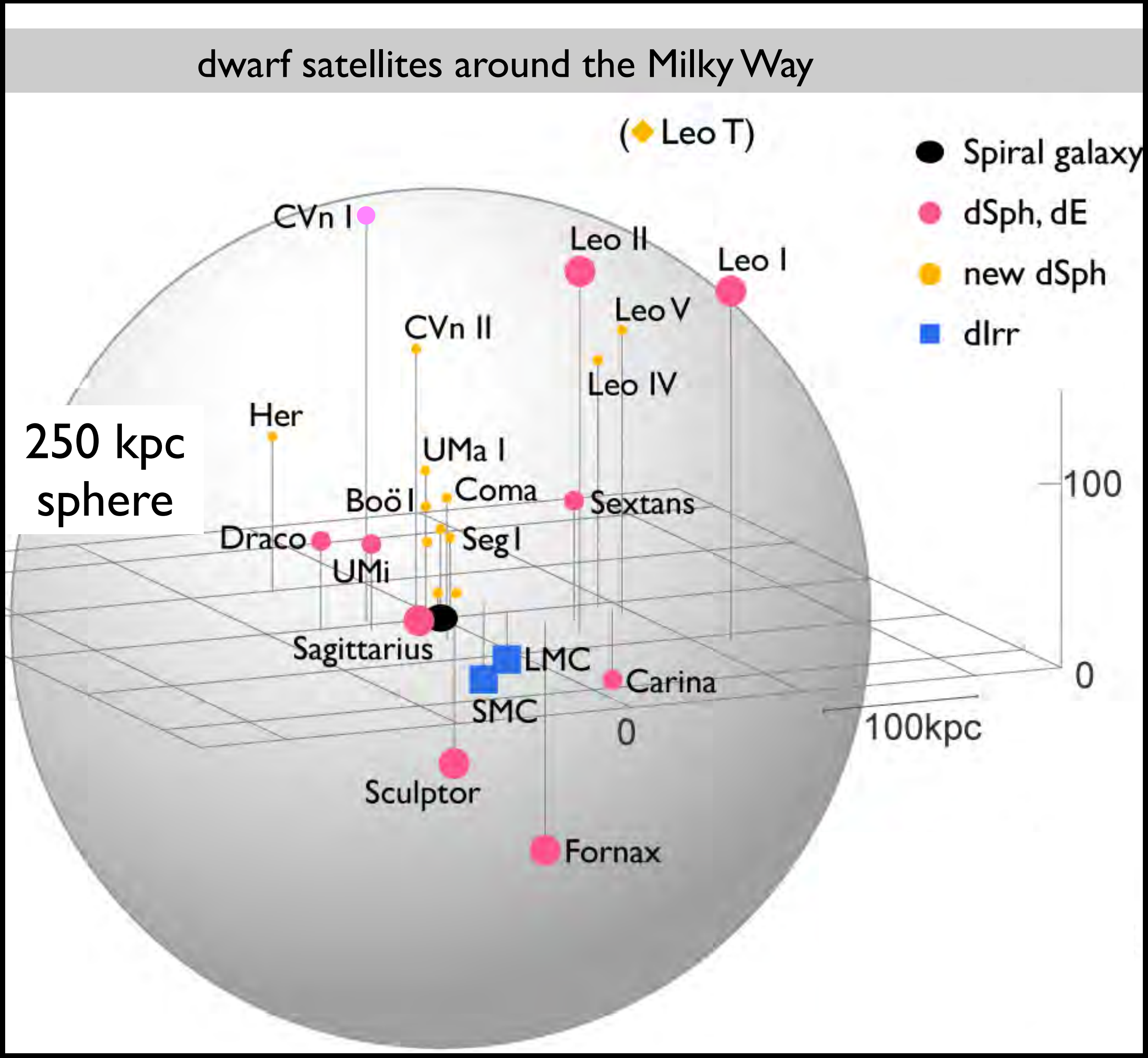
Pontzen & Governato14

“Too Big To Fail” MWy Satellite Problem

ΛCDM subhalos vs. Milky Way satellites

“Missing satellites”: Klypin et al. 1999, Moore et al. 1999





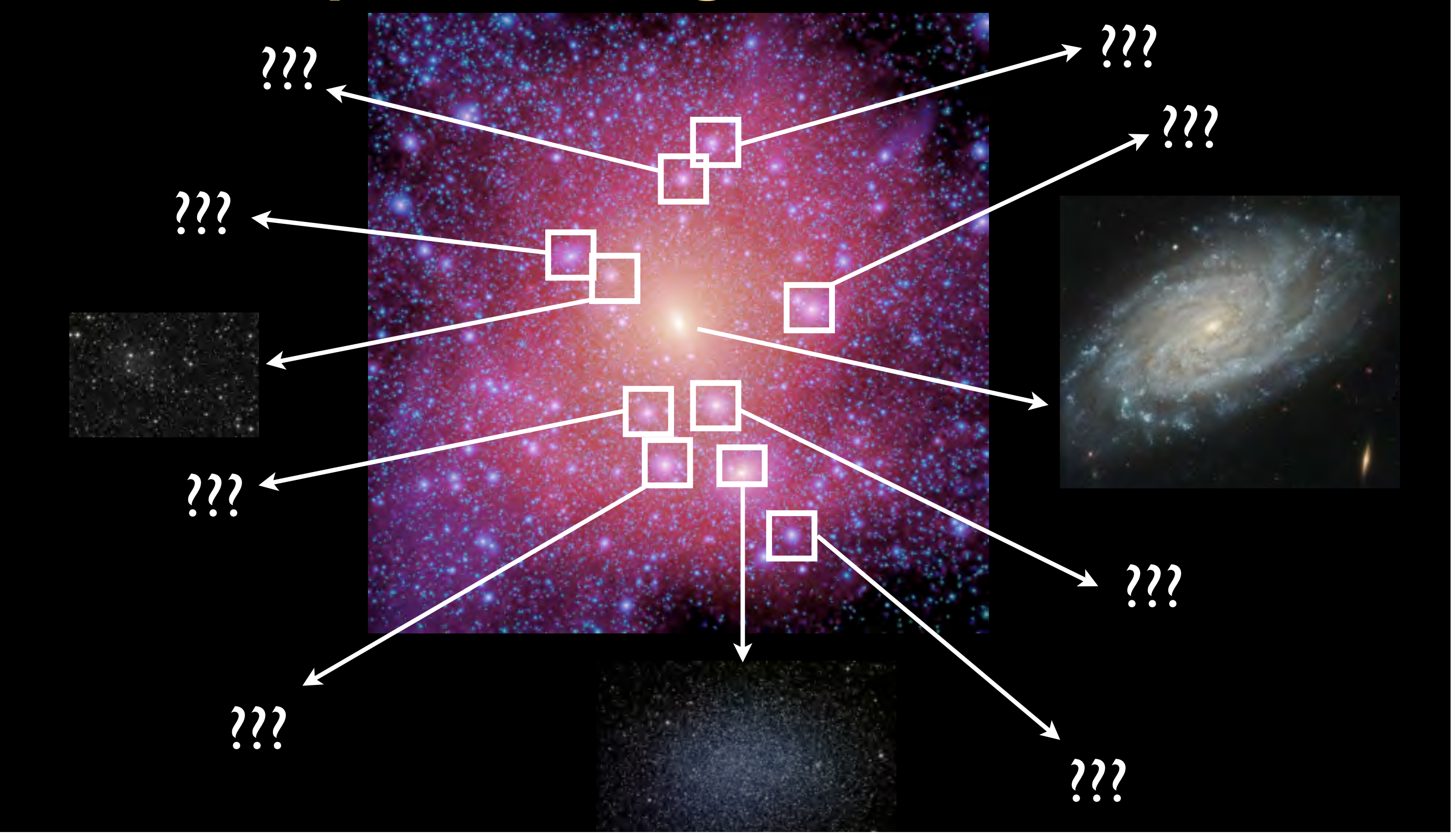
$>10^5$ identified subhalos

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

V. Springel / Virgo Consortium

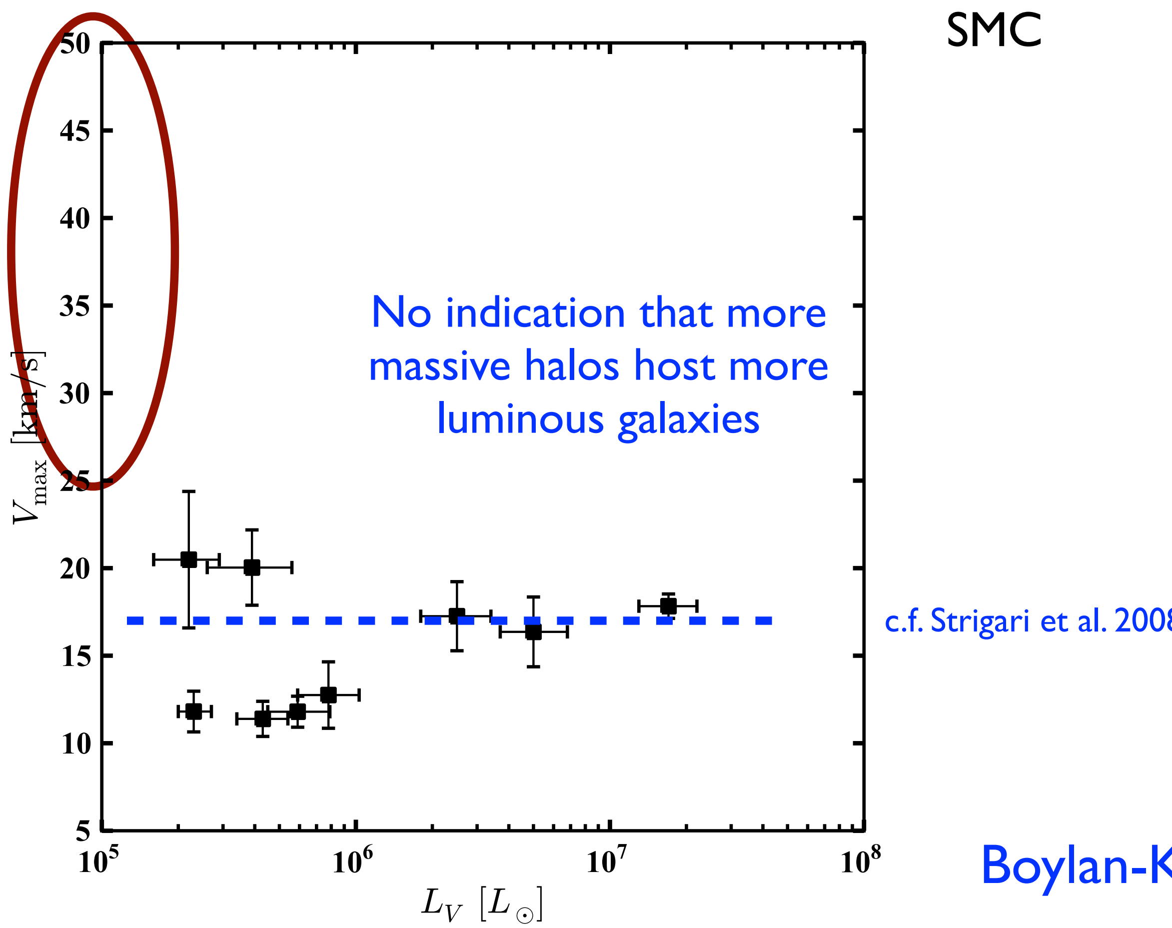
S. Okamoto

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 (?)]



c.f. Strigari et al. 2008

All of the bright MW dSphs are consistent with $V_{\rm max} \lesssim 25\,{\rm km/s}$

(see also Strigari, Frenk, & White 2010)

Boylan-Kolchin, Bullock, Kaplinghat 2011, 2012

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?

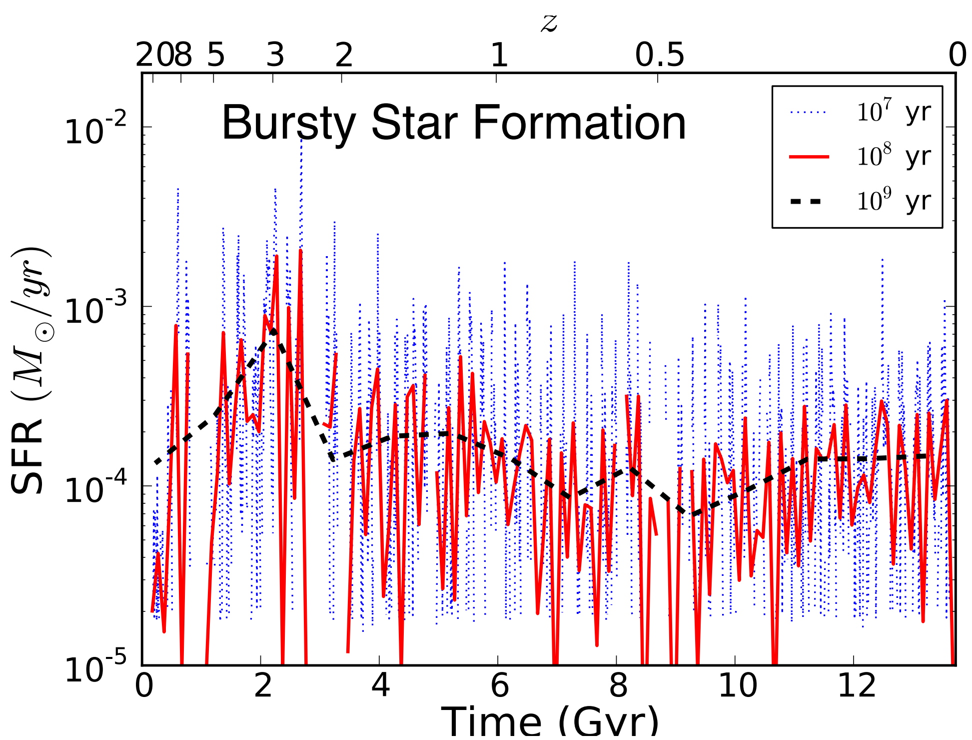
Dark matter is not just CDM -- maybe WDM (e.g., Lovell+12,13,14)?

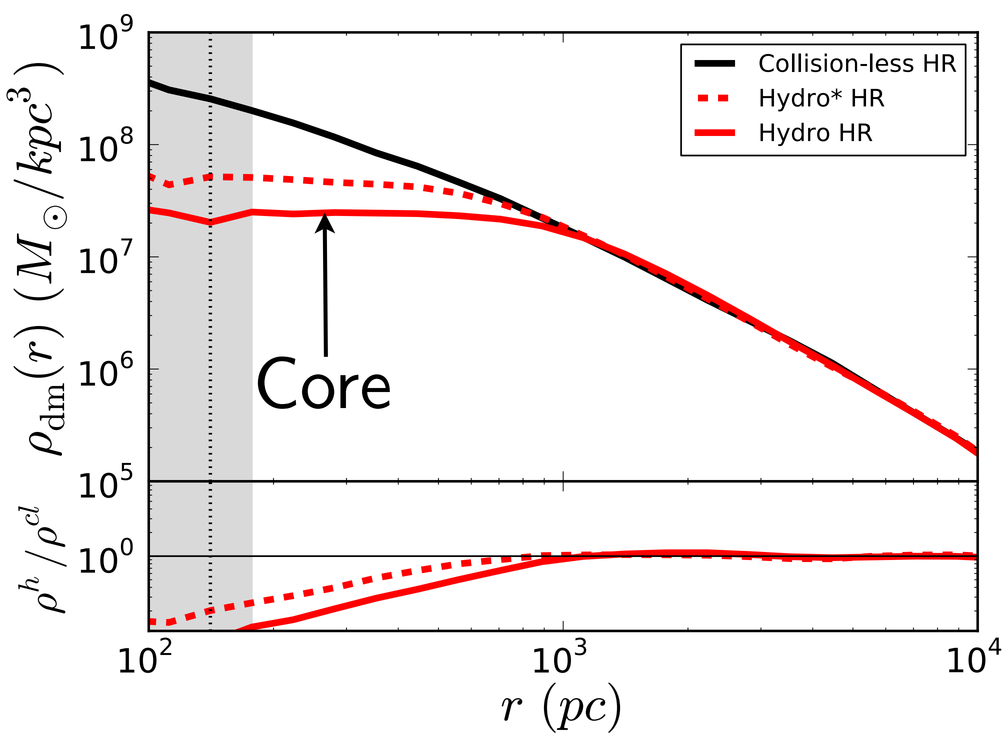
Or even self-interacting DM (Rocha+13, Peter+13, Zavala +14, Vogelsberger+14)?

But maybe just including baryons properly will do the trick.

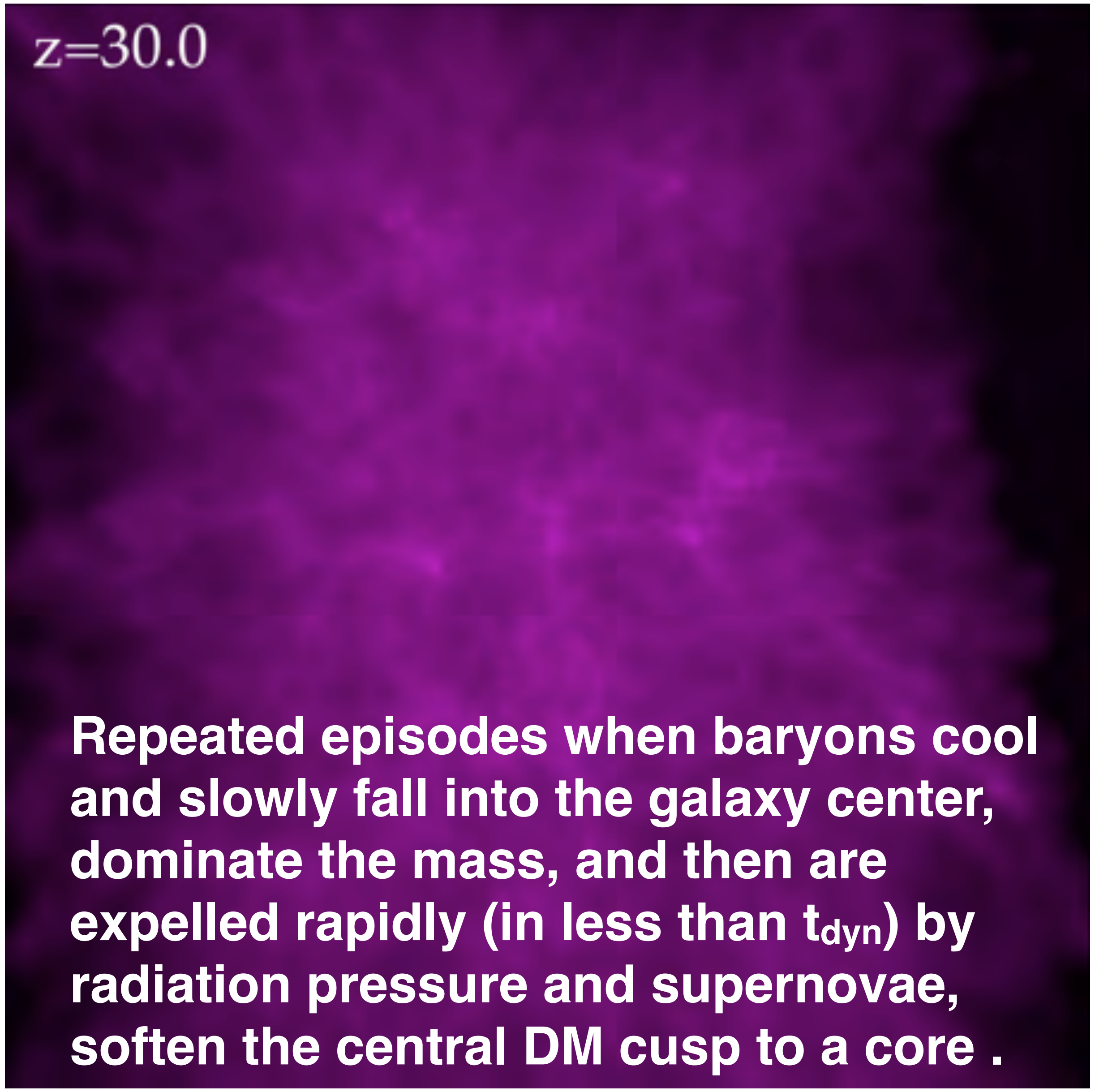
Challenges: Cusp-Core, Too Big to Fail, Satellite Galaxies

In addition to the Governato group's papers on this (including Zolotov+12, Brooks+13) there are several other recent papers (e.g., Teyssier+13, Arraki+14, Trujillo-Gome+14, DelPololo&Pace15, Simpson+15) arguing that baryonic effects convert the DM cusp to a core. **The highest-resolution simulation yet of a dwarf spiral was presented in Onorbe, Boylan-Kolchin, Bullock, et al. 2015. The continuous central star formation converted the central cusp to a core, reducing the rotation velocity, and thus resolving the TBTF challenge.**





$M_{vir} = 1E10 M_\odot$ at $z = 0$ $\quad M_* = 4 \times 10^6 M_\odot$



Onorbe, Hopkins+14 FIRE (Feedback in Realistic Environments) simulations

Challenges: Cusp-Core, Too Big to Fail, Satellite Galaxies

Some papers (e.g., Garrison-Kimmel,Rocha,Boylan-Kolchin,Bullock+13) claimed that feedback can't solve the TBTF problem. But Onorbe,Boylan-Kolchin,Bullock+15 (including some of the same authors) showed that a better treatment of feedback *can* do so, as have Maxwell,Wadsley,Couchman15 and Nipoti&Binney15.

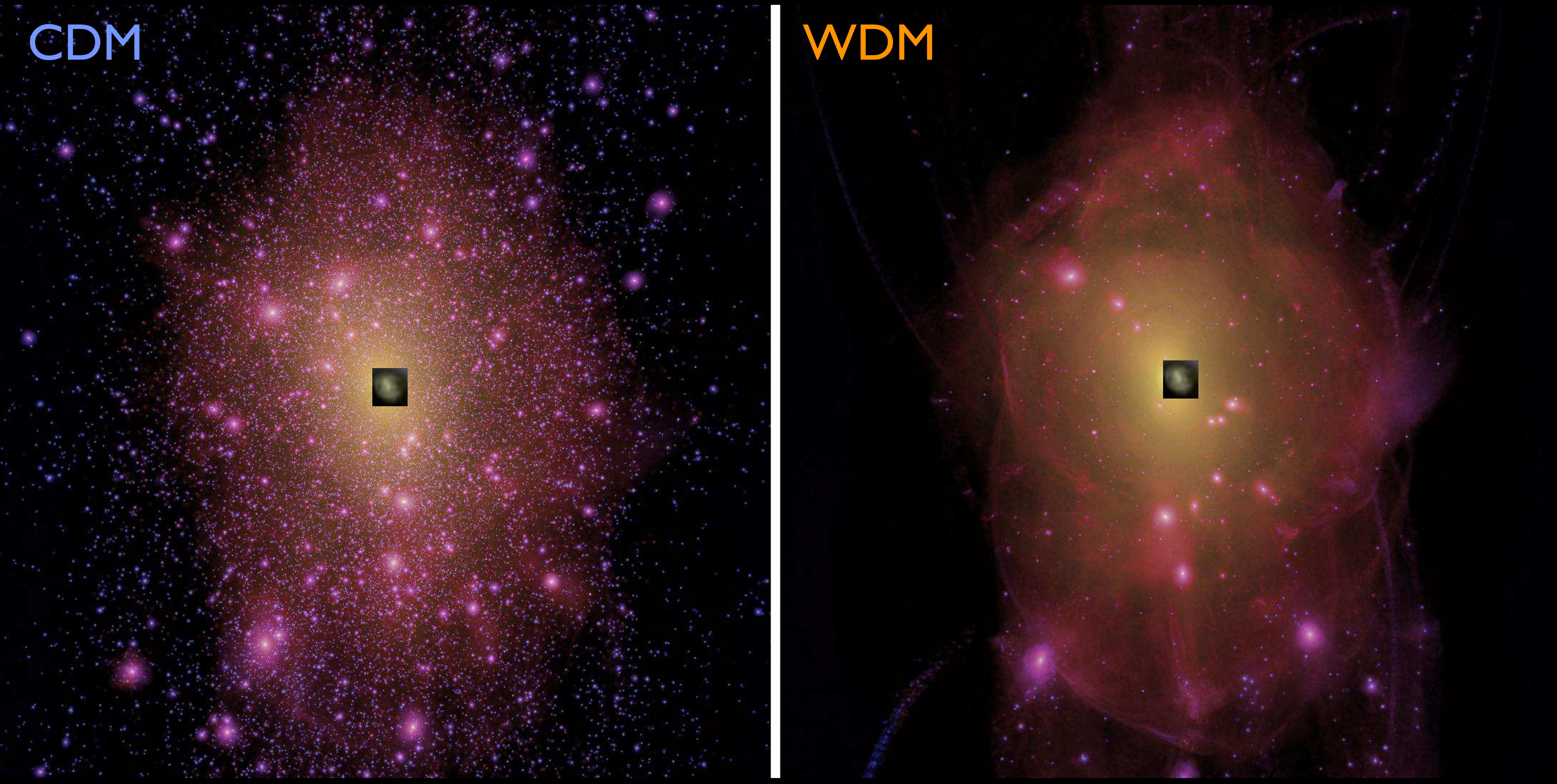
Despite the growing consensus among galaxy simulators that including baryons appears to convert the DM cusp to a core and can resolve the Too Big To Fail and Satellites challenges, papers continue to explore alternative solutions such as WDM and SIDM.

Recent Warm Dark Matter (WDM) papers

- **WDM doesn't resolve small scale problems: Schneider,Anderhalden,Maccio,Diemand14**
- **WDM constraints from lensing: Li,Frenk+1512.06507**
- **WDM constraints from reionization - strong: Schultz,Onorbe+14**
  - **- weak: Lapi&Danese15 - but this conflicts with Behroozi&Silk15**

Non-thermal (Shi&Fuller99) WDM for 3.5 keV line

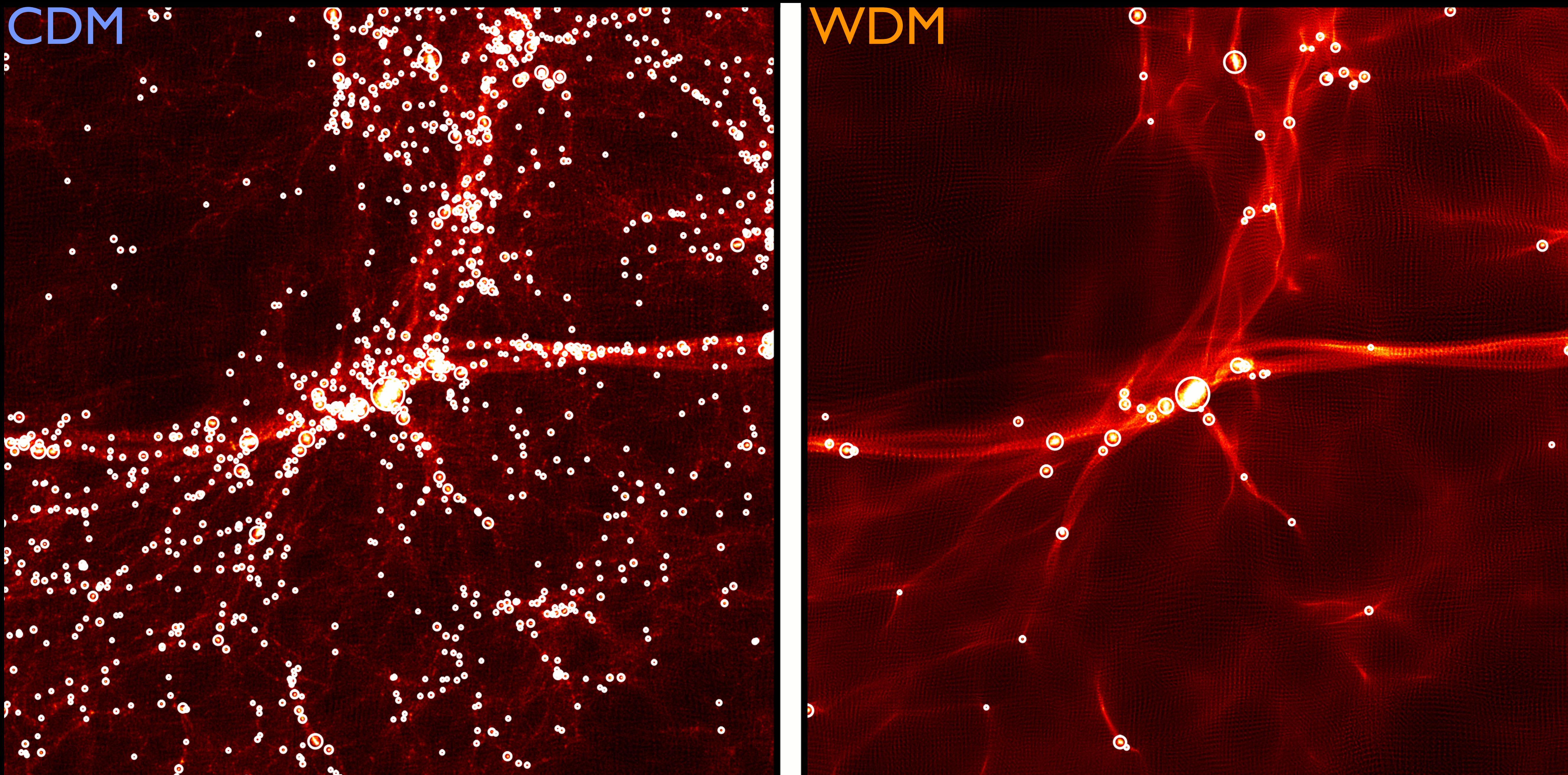
- **MWy mass > 1.2×10^{12} $M_\odot$: Lovell,Bose+1511.04078**
- **Barely produces enough satellites w/o baryons: Horiuchi+16**
- **Excluded at 2σ by Lyα Forest: Schneider1601.07553**



Aquarius simulation. Springel et al. 2008

Lovell, Eke, Frenk, et al. 2012

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+10 showed. It also won't have the subhalos needed to explain grav lensing flux anomalies and gaps in stellar streams.



WDM simulation at right has no "too big to fail" subhalos, but it is inconsistent at $>10\sigma$ with Ultra Deep Field galaxy counts. It also won't have the subhalos needed to reionize the universe unless $m_\nu^{thermal} \gtrsim 2.6$ keV (or $m_\nu^{sterile} \gtrsim 15$ keV) assuming an optimistic ionizing radiation escape fraction (Schultz, Onorbe, Abazajian, Bullock14). Faint $z=2$ galaxies exclude $m_\nu^{thermal} \lesssim 1.8$ keV and $m_\nu^{ShiFuller} \lesssim 4$ keV (Menci+16). And the Ly-α forest(Viel+13) excludes $m_\nu^{thermal} \lesssim 2$ keV at 4σ, $\lesssim 3.3$ keV at 2σ.

Challenges: Cusp-Core, Too Big to Fail, Satellite Galaxies

Some papers (e.g., Garrison-Kimmel,Rocha,Boylan-Kolchin,Bullock+13) claimed that feedback can't solve the TBTF problem. But Onorbe,Boylan-Kolchin,Bullock+15 (including some of the same authors) showed that a better treatment of feedback *can* do so, as have Maxwell,Wadsley,Couchman15 and Nipoti&Binney15.

Despite the growing consensus among galaxy simulators that including baryons appears to convert the DM cusp to a core and can resolve the Too Big To Fail and Satellites challenges, papers continue to explore alternative solutions.

Recent Warm Dark Matter (WDM) papers

- WDM doesn't resolve small scale problems: Schneider,Anderhalden,Maccio,Diemand14
- WDM constraints from lensing: Li,Frenk+1512.06507
- WDM constraints from reionization - strong: Schultz,Onorbe+14
  - weak: Lapi&Danese15 - but this conflicts with Behroozi&Silk15

Non-thermal (Shi&Fuller99) WDM for 3.5 keV line

- MWy mass > 1.2×10^{12} $M_\odot$: Lovell,Bose+1511.04078
- Barely produces enough satellites w/o baryons: Horiuchi+16
- Excluded at 2σ by Lyα Forest: Schneider1601.07553

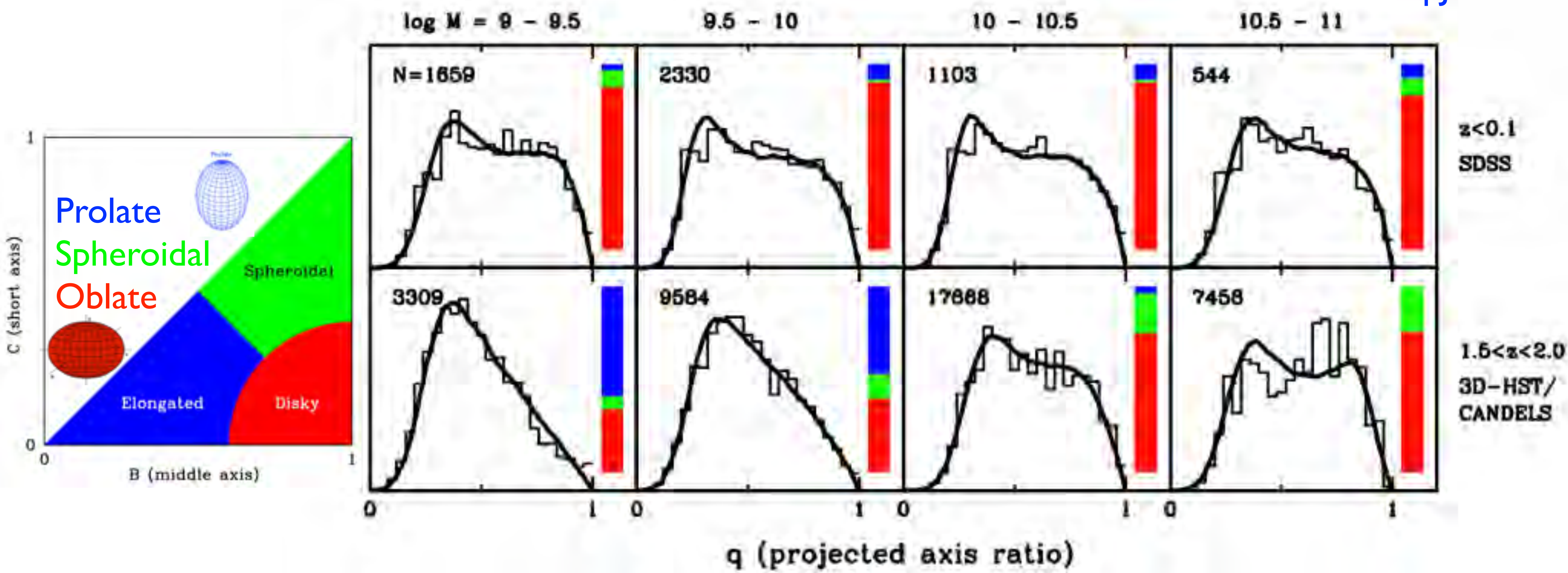
Self-Interacting Dark Matter (SIDM)

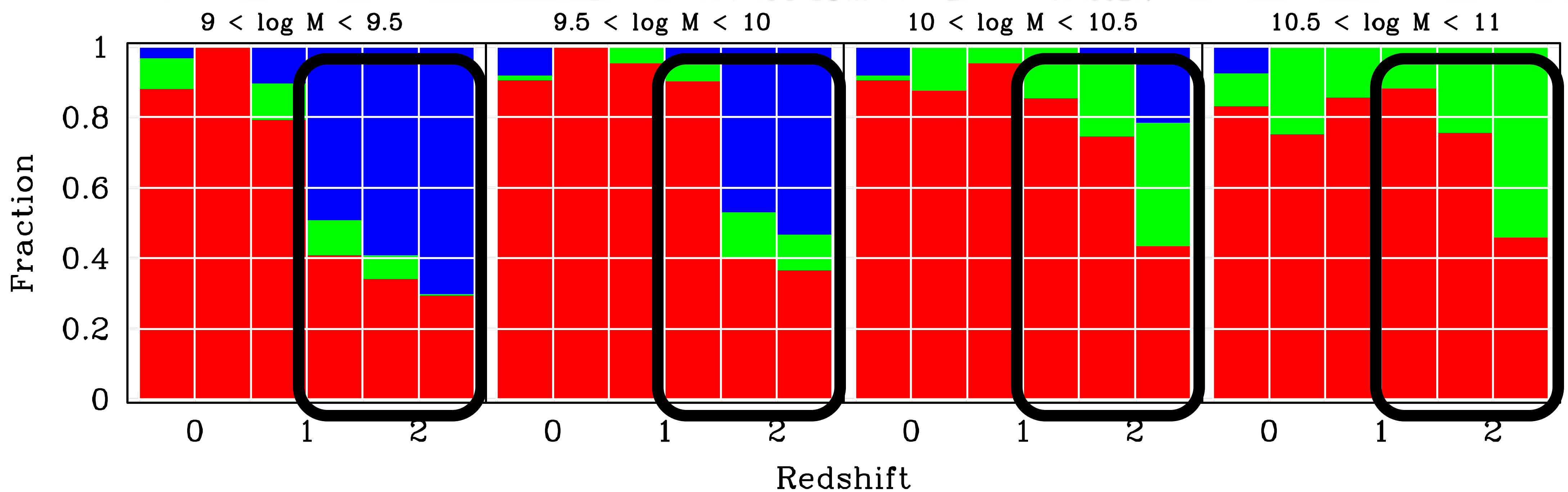
- Cluster shapes: $\sigma/m < 1$ cm^2/g : Peter+12
- Merging clusters: $\sigma/m < 1.5$ cm^2/g : Kalhoefer+15
- Velocity-dependent SIDM simulations: Vogelsberger+12, Zavela+13
- $\sigma/m = 2$ cm^2/g SIDM w baryons just like CDM, need V-dependence: Fry,Governato+15
- SIDM with V^{-4} dependence can arise from Rutherford-like scattering: Feng+09, Tulin+13
- $\sigma/m = 50$ cm^2/g for dwarf galaxies OK with V-dependence, makes them rounder: Elbert+15

But forming galaxies are not round, they are elongated (prolate, sausage-shaped)

Low-mass Forming Galaxies are Elongated (Prolate)

van der Wel+ApJ 2014



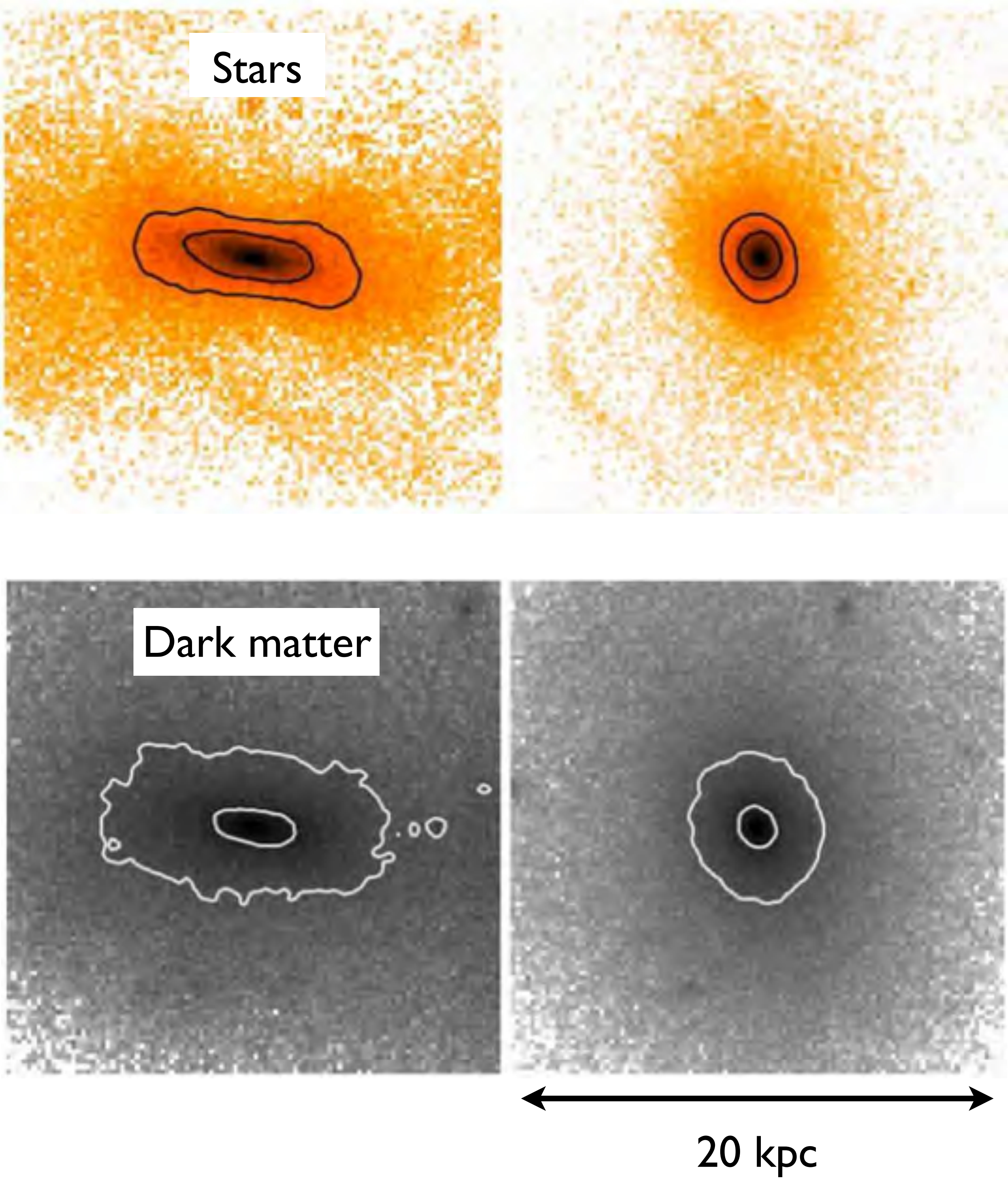


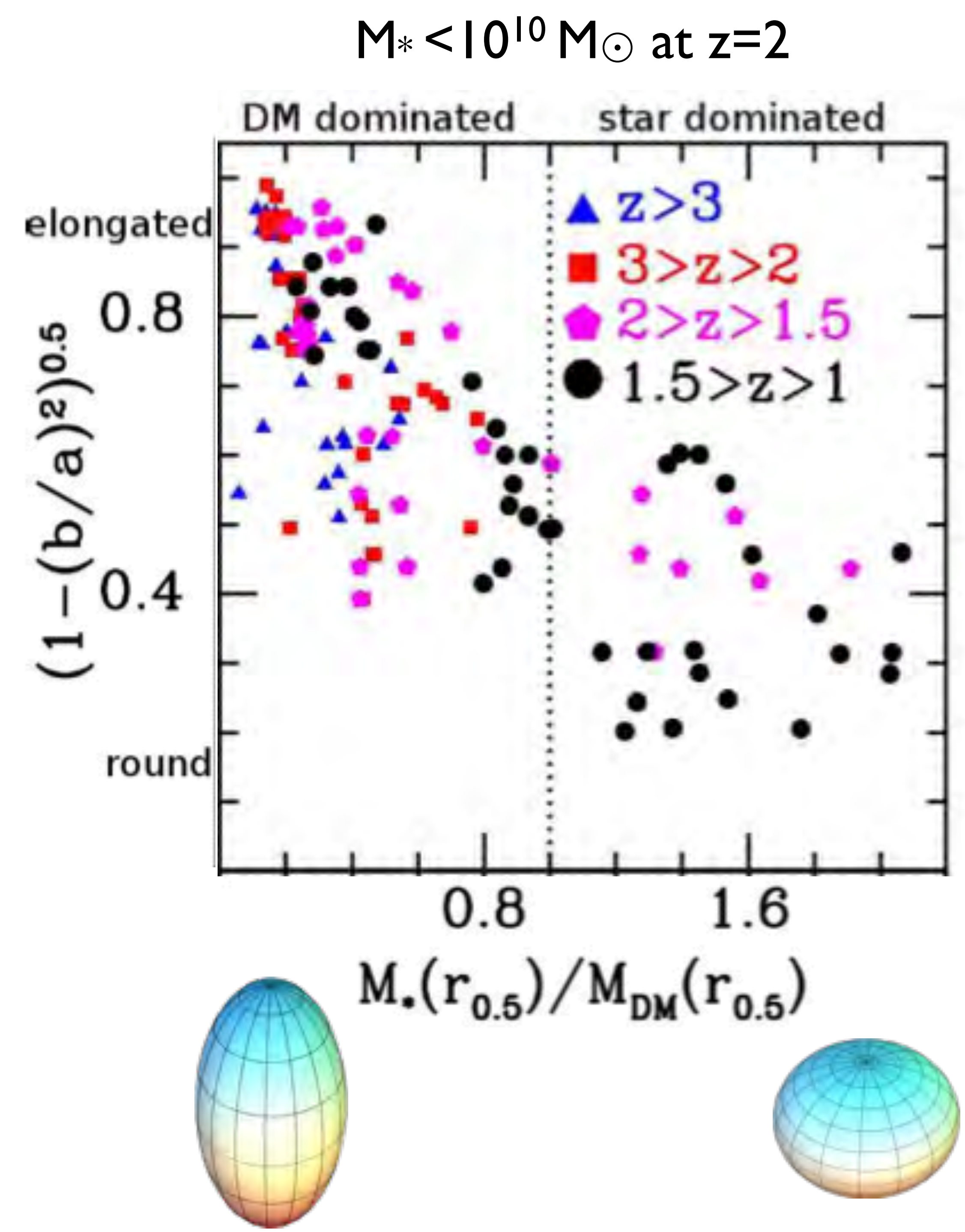
See also WHEN DID ROUND DISK GALAXIES FORM? T. M. Takeuchi et. al ApJ 2015

Formation of elongated galaxies with low masses at high redshift

High-resolution (~20 pc) cosmological zoom-in hydro simulations

Ceverino, Primack, Dekel **MNRAS 453, 408 (2015)**





See also Tomassetti, Dekel+arXiv1512062068

Gaps in Cold Stellar Streams Probe DM Halo Substructures

Direct Detection of Cold Dark Matter Substructure

Yoon, Johnston, Hogg ApJ (2011)

Density fluctuations in cold stellar streams will reflect DM substructure. Fluctuations in the Pal5 stream suggest the existence of missing satellites in numbers predicted by ΛCDM.

Dark Matter Sub-Halo Counts via Star Stream Crossings

R. G. Carlberg ApJ (2012), Carlberg,Grillmair, Hetherington ApJ (2012), Carlberg & Grillmair ApJ (2013)

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.

Feeling the pull, a study of natural Galactic accelerometers - I. Stellar Stream of Palomar 5

R. Ibata, G. Lewis, N. Martin arXiv:1512.03054

Our deep CFHT data do not support the presence of significant gaps along the stream. The origin of the difference between our results and those of Carlberg et al. (2012) is likely that it is due to variations in homogeneity of the SDSS as one approaches the limiting magnitude of that survey.

Detecting dark matter substructures around the Milky Way with Gaia

R. Feldmann, D. Spolyar MNRAS (2015)

Gaia should detect the kinematic signatures of a few starless substructures

Properties of dark subhaloes from gaps in tidal streams

D. Erdal, V. Belokurov MNRAS (2015)

SDSS, DES, *Gaia*, and LSST can measure the *complete set* of properties (including the phase-space coordinates during the flyby) of dark perturbers with $M > 10^7\ M_\odot$

Reviewed in *Tidal Streams in the Local Group and Beyond* (Springer, 2016)

More evidence for substructure in DM halos: lensing flux anomalies

Direct Detection of Cold Dark Matter Substructure

Neal Dalal & Christopher S. Kochanek ApJ 572, 25 (2002)

We devise a method to measure the abundance of satellite halos in gravitational lens galaxies and apply our method to a sample of seven lens systems. After using Monte Carlo simulations to verify the method, we find that substructure comprises $f_{sat}=0.02$ (median, $0.006<f_{sat}<0.07$ at 90% confidence) of the mass of typical lens galaxies, in excellent agreement with predictions of cold dark matter (CDM) simulations.

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 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.

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

R. Benton Metcalf, Adam Amara MNRAS 419, 3414 (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 WDM from weak lensing in anomalous quadruple lenses

K. T. Inoue, R. Takahashi, T. Takahashi, T. Ishiyama MNRAS (2015)

Observed four quadruple lenses that show anomalies in the flux ratios, we obtain constraints on the mass of thermal WDM, $m_{WDM} \geq 1.3$ keV (95 per cent CL).

More evidence for substructure in DM halos: lensing flux anomalies

How well can CDM substructures account for the observed radio flux-ratio anomalies

D. D. Xu, Dominique Sluse, Liang Gao, Jie Wang, C. Frenk, Shude Mao, P. Schneider, V. Springel MNRAS (2015)

We find that CDM substructures are unlikely to be the whole reason for radio flux anomalies.

How well can CDM substructures account for the observed radio flux-ratio anomalies

J.-W. Hsueh, C. Fassnacht, S. Vigetti, J. McKean, C. Singola, M. Auger, L. Koopmans, D. Lagattuta arXiv:1601.01671

Keck~II adaptive optics imaging and HST data reveal the lensing galaxy to have a clear edge-on disc component that crosses directly over the pair of images that exhibit the flux-ratio anomaly.

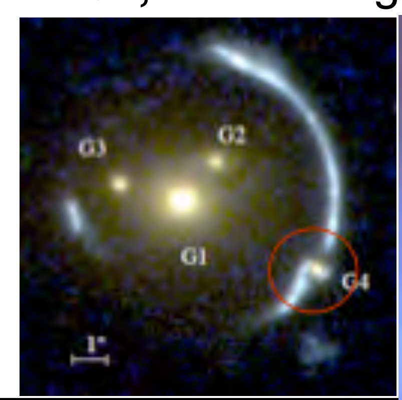
CDM Substructures in Early-Type Galaxy Halos

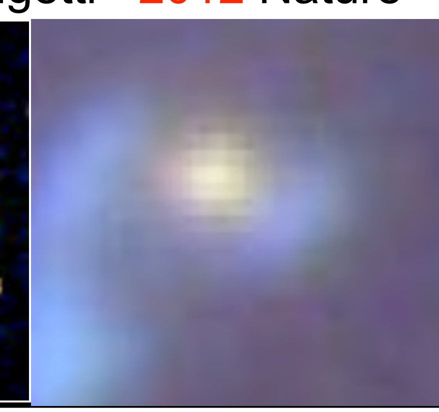
Davide Fiacconi, Piero Madau, Doug Potter, Joachim Stadel arXiv:1602.03526

Very high-resolution DM simulations of ~10^{13} $M_\odot$ halos show more substructure than previous simulations. Baryonic contraction increases the number of massive subhalos in the inner regions of the main host. The host density profiles and projected subhalo mass fractions appear to be broadly consistent with observations of gravitational lenses.

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

This group uses galaxy-galaxy lensing to look for the effects of substructure. 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.





Inference of the cold dark matter substructure mass function at $z = 0.2$ using strong gravitational lenses

S. Vegetti, L. V. E. Koopmans, M. W. Auger, T. Treu and A. S. Bolton MNRAS (2015)

No detection of substructure in 11 lens galaxies from the SDSS ACS survey. With earlier detections, the inferred fraction is consistent with the expectations from CDM simulations and with inference from flux ratio anomalies at 68% C.L.

New ways of observing dark matter halo substructure

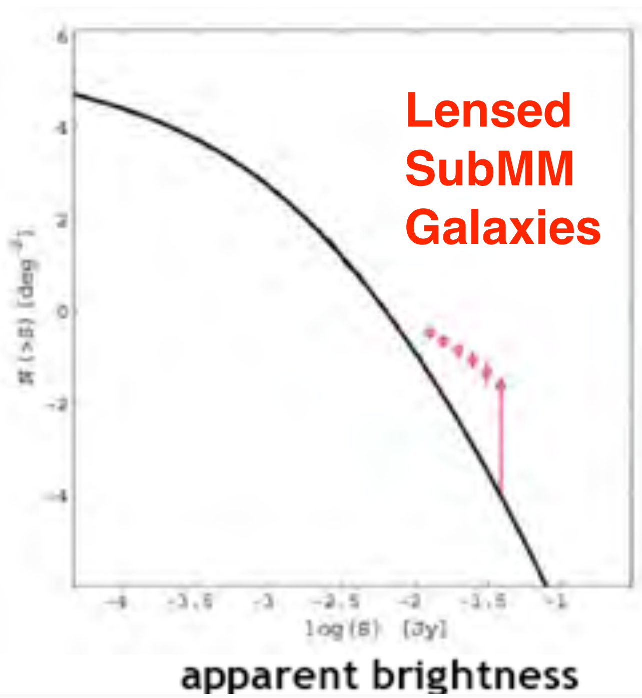
Optical lensing of quasar narrow line regions

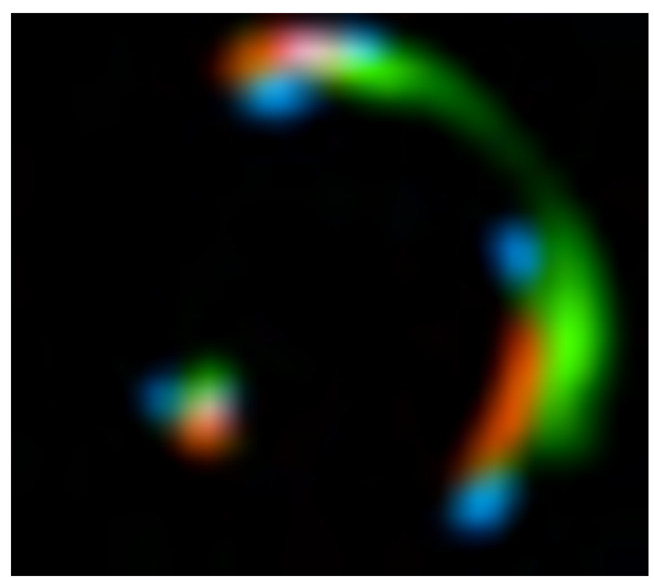
Detection of a substructure with adaptive optics integral field spectroscopy of the gravitational lens B1422+231
A. M. Nierenberg, T. Treu, S. A. Wright, C. D. Fassnacht, M. W. Auger MNRAS (2014)

In this paper we demonstrate for the first time that subhalos can be detected using strongly lensed narrow-line quasar emission, as originally proposed by Moustakas & Metcalf (2003). Many quasars have detectable narrow line emission, so this technique can really measure substructure.

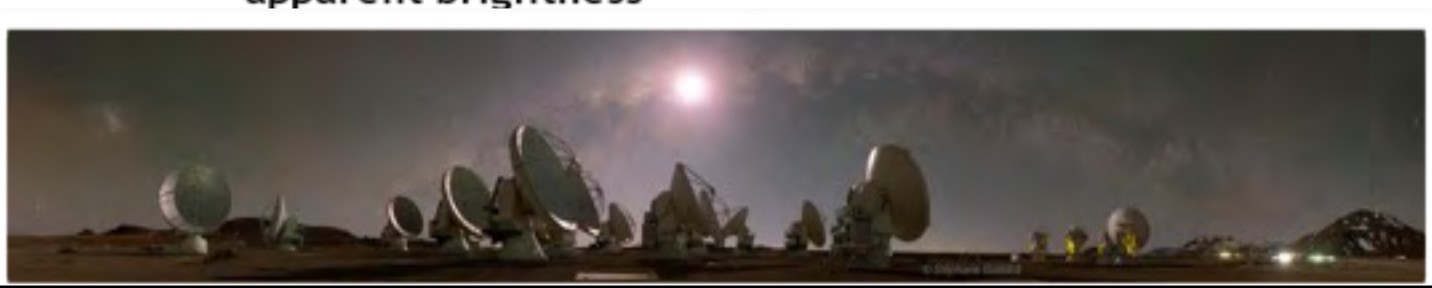
ALMA spectral detection of lensing of dusty galaxies

Dark Matter Substructure Detection Using Spatially Resolved Spectroscopy of Lensed Dusty Galaxies
Yashar Hezaveh, Neal Dalal, G. Holder, M. Kuhlen, D. Marrone, N. Murray, J. Vieira ApJ (2013)





We find that in typical DSFG lenses, there is a ~55% probability of detecting a substructure with M > 10^8 M⊙ with >5σ significance in *each lens*, if the abundance of substructure is consistent with previous lensing results.



Detection of Lensing Substructure in SDP.81
Yashar Hezaveh, Neal Dalal+ 1601.01388

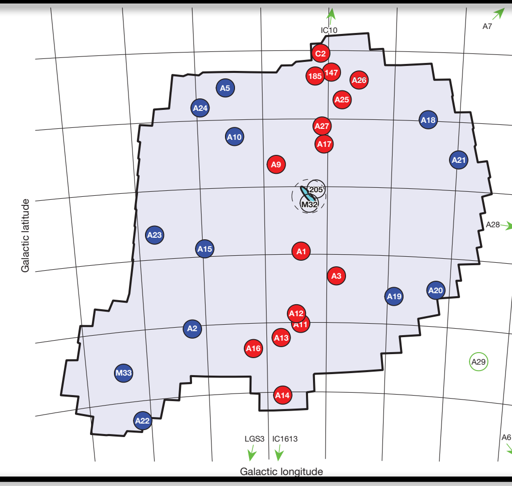
We find evidence for the presence of a $M = 10^{8.96\pm0.12} M_\odot$ subhalo with 6.9σ significance.

Rotating Planes of Galaxies About the Milky Way and Andromeda

A vast, thin plane of corotating dwarf galaxies orbiting the Andromeda galaxy

Ibata et al. Nature 2013

Intriguingly, the plane we identify is approximately aligned with the pole of the Milky Way's disk.

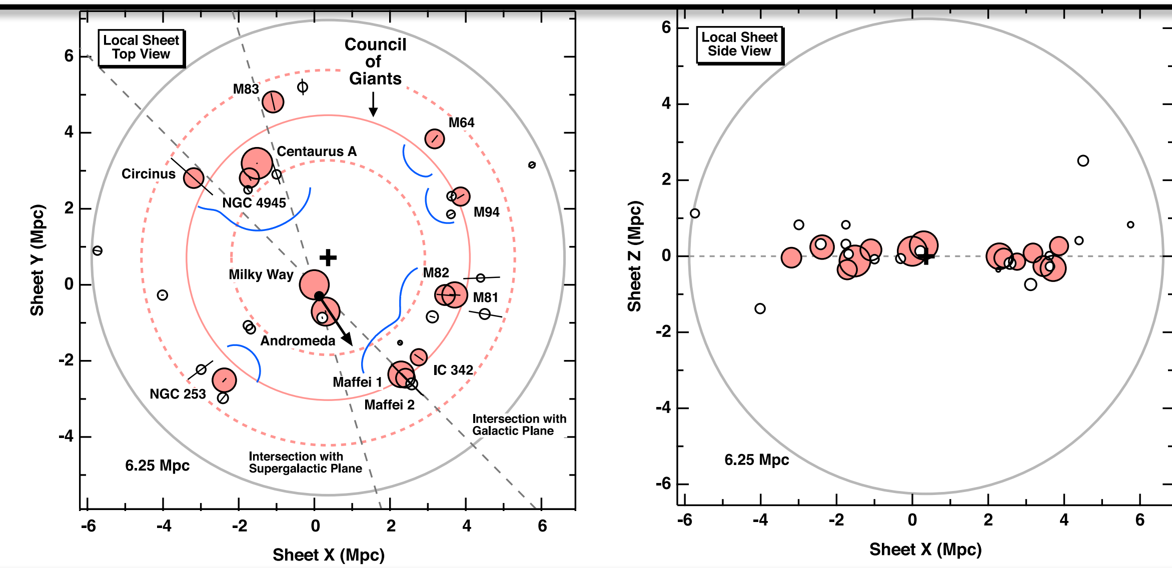


All the northern red satellites are coming towards us and all the southern ones are moving away

A Council of Giants

Marshall McCall MNRAS 2014

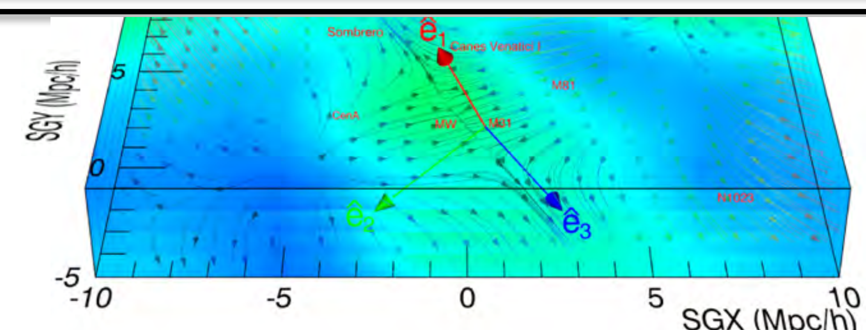
A 'Council of Giants' with a radius of 3.75 Mpc and thickness of 0.2 Mpc defines the Local Sheet, which is perpendicular to the Milky Way disk. [The planes of satellite galaxies about Andromeda and the Milky Way lie in the Local Sheet.]



Planes of satellite galaxies and the cosmic web

Libeskind, Hoffman, Tully et al. MNRAS 2015

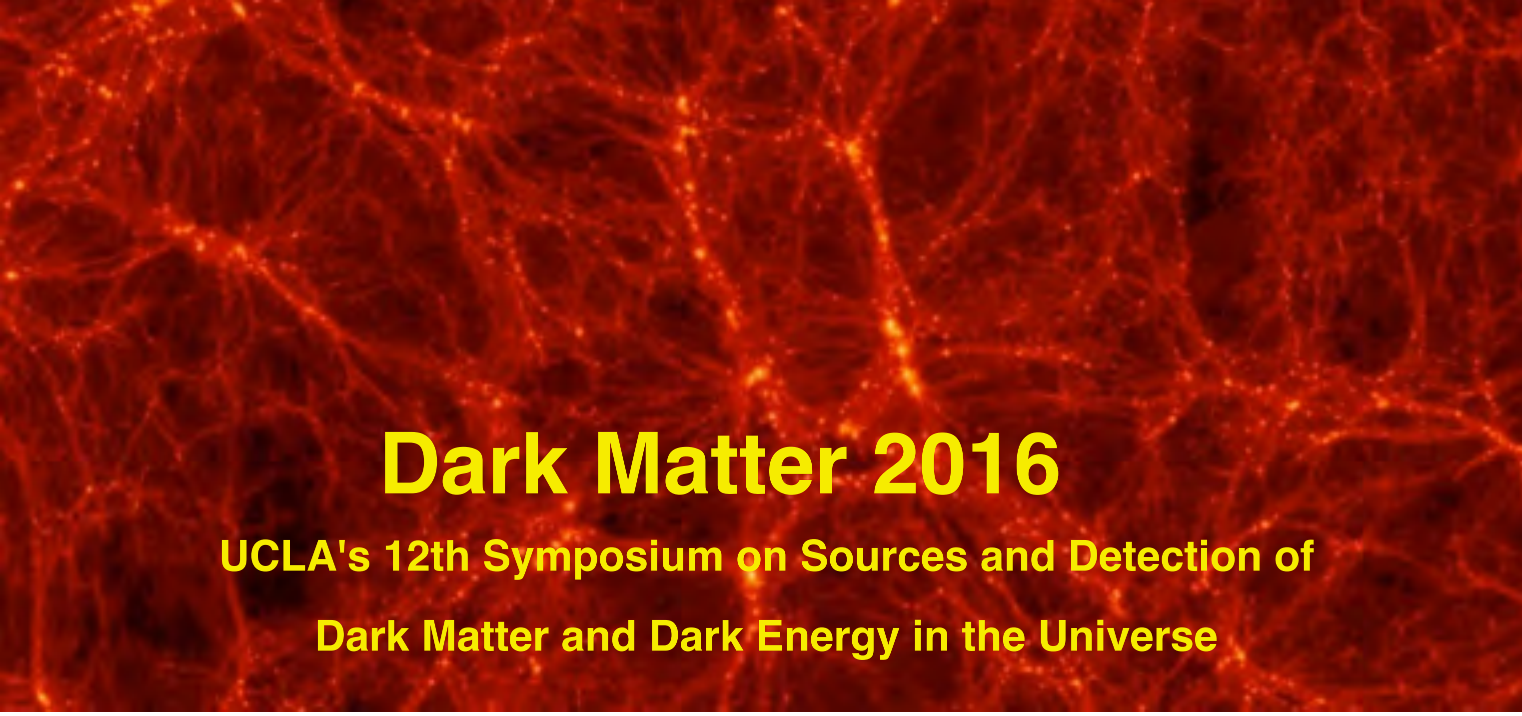
The Local Group and Centaurus A reside in a filament stretched by the Virgo cluster and compressed by the expansion of the Local Void. The alignment of satellite systems in the local Universe with the ambient shear field is thus in general agreement with predictions of ΛCDM.



Planes of satellite galaxies: when exceptions are the rule

Catun, Bose, Frenk, Qi Guo, Han, Hellwing, Sawala, Wang MNRAS 2015

~10% of simulated Local Groups have satellite planes even more prominent than observed.



ΛCDM cosmology: remaining challenges and opportunities for progress

- **Challenges:** Too Big To Fail in the Field, Distribution of DM in Galaxies like the MWy, Diversity of Galaxy Rotation Curves, Abundance of Bulgeless Galaxies, Galaxies in the Web

- **Observational Opportunities:** Measuring Halo Substructure by Gravitational Lensing and Stellar Motions, Reionization, Structure of dwarf Galaxies, Galaxies in the Cosmic Web