Kavli Institute for Theoretical Physics
University of California, Santa Barbara

Quantifying and Understanding the Galaxy — Halo Connection

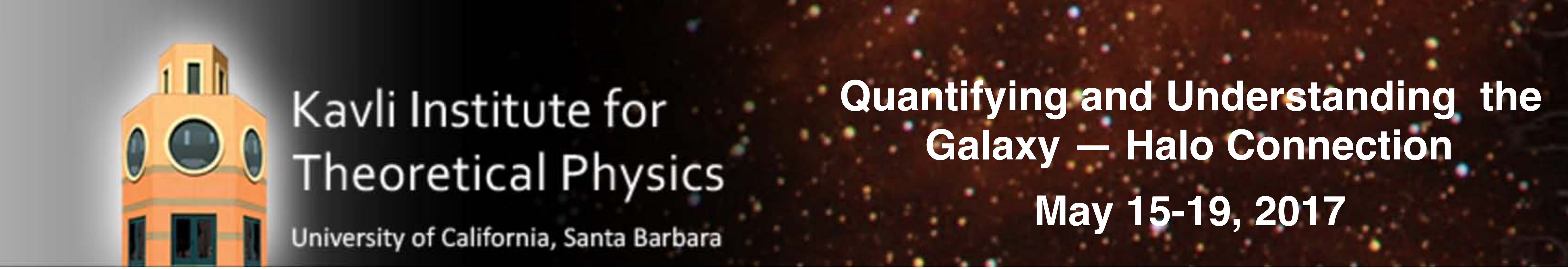
May 15-19, 2017

Coordinators: Alexie Leauthaud, Risa Wechsler, and Andrew Zentner

Scientific Advisors: Carlos Frenk, Marla Geha, Andrey Kravtsov, Romain Teyssier, and Martin White

The formation of galaxies is still one of the key unsolved problems of astrophysics and cosmology. This is because the processes involved are complex, multi-scale, and are highly non-linear. At the same time, despite the apparent complexity of these processes, observed properties of galaxies exhibit a number of striking regularities, including tight correlations between galaxy sizes, masses, luminosities, and dynamical properties. Moreover, there is a growing empirical evidence indicating that key properties of galaxies tightly correlate with properties of extended dark matter halos in which they form. Phenomenological modeling based on such empirical correlations unlocks the predictive power of large cosmological N-body simulations, enabling astrophysicists to infer the underlying dark matter distribution in the Universe and to exploit large-scale galaxy surveys as probes of cosmological physics.

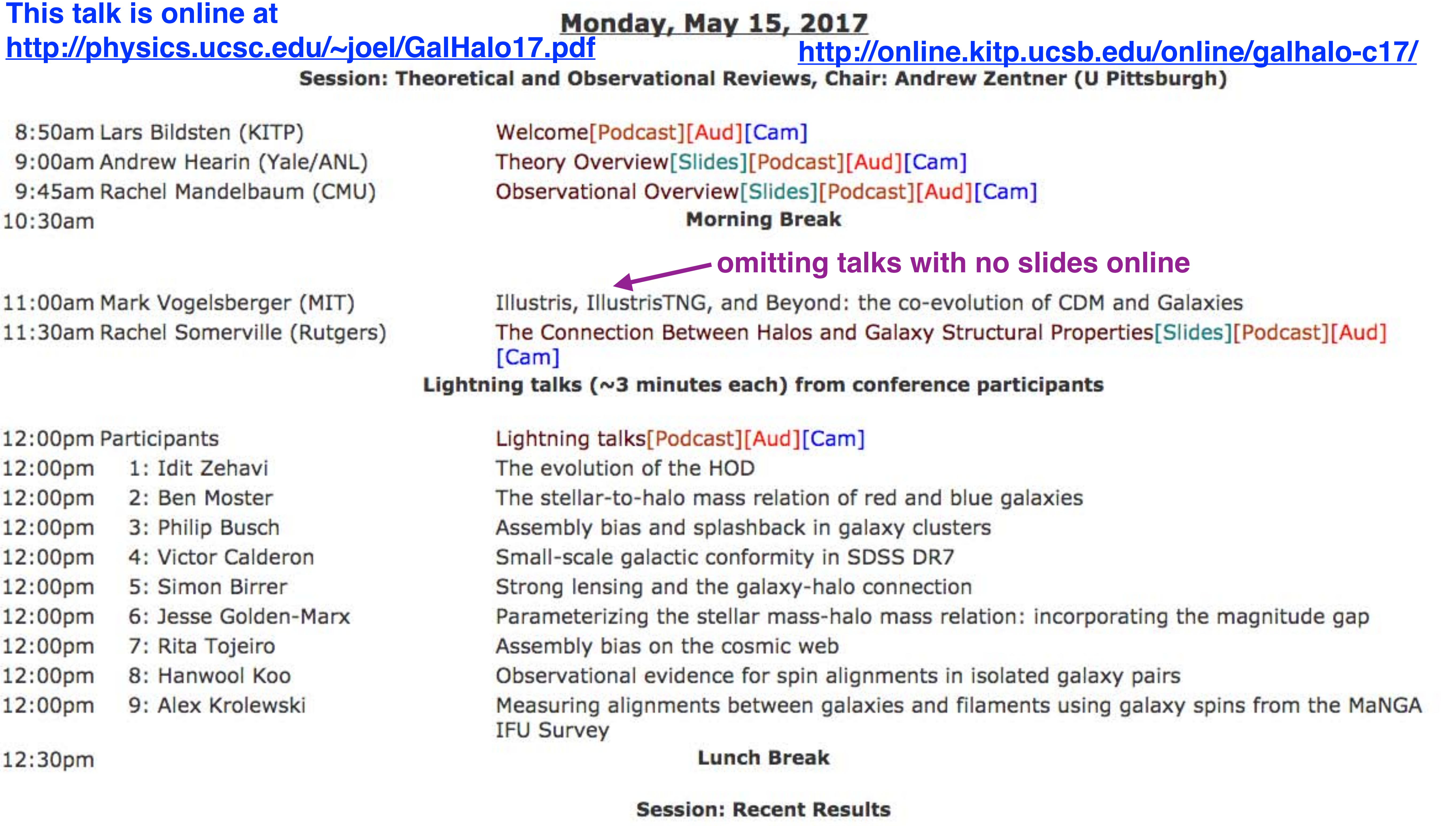
The next generation of massive, wide-field surveys will observe billions of galaxies, including galaxies from the earliest epochs of their evolution. These surveys have the potential to transform our understanding of the evolution of structure in both the galaxy distribution and the dark matter distribution, and in so doing, to answer some of the most profound questions of galaxy formation and cosmology. However, maximizing the scientific impact of these forthcoming data sets depends upon bringing phenomenological models of the galaxy-dark matter halo connection to the next level of precision. This program aims to bring together experts in the statistics of the galaxy-halo connection, cosmologists, survey scientists, and observers and theorists working on galaxy evolution to foster discussions about observational probes of the galaxy-dark matter connection and to spur on the development of next-generation theoretical methods. To brainstorm and generate ideas, we will hold a conference on the galaxy-halo connection and its role in the science of large cosmological surveys on May 15-19, 2017.



Quantifying and Understanding the Galaxy — Halo Connection

May 15-19, 2017

This talk is online at
http://physics.ucsc.edu/~joel/GalHalo17.pdf



http://online.kitp.ucsb.edu/online/galhalo-c17/

omitting talks with no slides online

Monday, May 15, 2017

Session: Theoretical and Observational Reviews, Chair: Andrew Zentner (U Pittsburgh)

8:50am	Lars Bildsten (KITP)	Welcome[Podcast][Aud][Cam]
9:00am	Andrew Hearin (Yale/ANL)	Theory Overview[Slides][Podcast][Aud][Cam]
9:45am	Rachel Mandelbaum (CMU)	Observational Overview[Slides][Podcast][Aud][Cam]
10:30am		**Morning Break**
11:00am	Mark Vogelsberger (MIT)	Illustris, IllustrisTNG, and Beyond: the co-evolution of CDM and Galaxies
11:30am	Rachel Somerville (Rutgers)	The Connection Between Halos and Galaxy Structural Properties[Slides][Podcast][Aud][Cam]

Lightning talks (~3 minutes each) from conference participants

12:00pm	Participants	Lightning talks[Podcast][Aud][Cam]
12:00pm	1: Idit Zehavi	The evolution of the HOD
12:00pm	2: Ben Moster	The stellar-to-halo mass relation of red and blue galaxies
12:00pm	3: Philip Busch	Assembly bias and splashback in galaxy clusters
12:00pm	4: Victor Calderon	Small-scale galactic conformity in SDSS DR7
12:00pm	5: Simon Birrer	Strong lensing and the galaxy-halo connection
12:00pm	6: Jesse Golden-Marx	Parameterizing the stellar mass-halo mass relation: incorporating the magnitude gap
12:00pm	7: Rita Tojeiro	Assembly bias on the cosmic web
12:00pm	8: Hanwool Koo	Observational evidence for spin alignments in isolated galaxy pairs
12:00pm	9: Alex Krolewski	Measuring alignments between galaxies and filaments using galaxy spins from the MaNGA IFU Survey
12:30pm		**Lunch Break**

Session: Recent Results

Christoph Lee will summarize the talks about halo splashback radius

Monday	3:00pm Surhud More (U Tokyo IPMU)	Assembly Bias and Splashback Radius on Cluster Scales: Observational Status
Tuesday	9:00am Benedikt Diemer (Harvard U)	Cold Dark Matter Halo Theory/Splashback Review
Friday	9:00am Philip Mansfield (U Chicago)	Halo Splashback Radius

Talks & Topics That I Will Summarize

Rachel Mandelbaum - Lensing, Assembly Bias

Priya Natarajan - HST Frontier Fields Cluster Lensing

Victor Calderon (poster) - sSSFR 2-Halo Galaxy Conformity at $z \sim 0.1$

Alison Coil - Galaxy Conformity at $z \sim 0.2 - 1$, Galaxy Clustering vs. sSFR

Guinevere Kaufmann - Gas in Halos

Andrey Kravtsov, Rachel Somerville, Fangzhao Jiang - R_{Galaxy} R_{Halo} Relation

Christoph Lee (poster) - Causes and Consequences of Halo Mass Loss

me - Structural Evolution in the Galaxy-Halo Connection, Halos vs. Density, Web

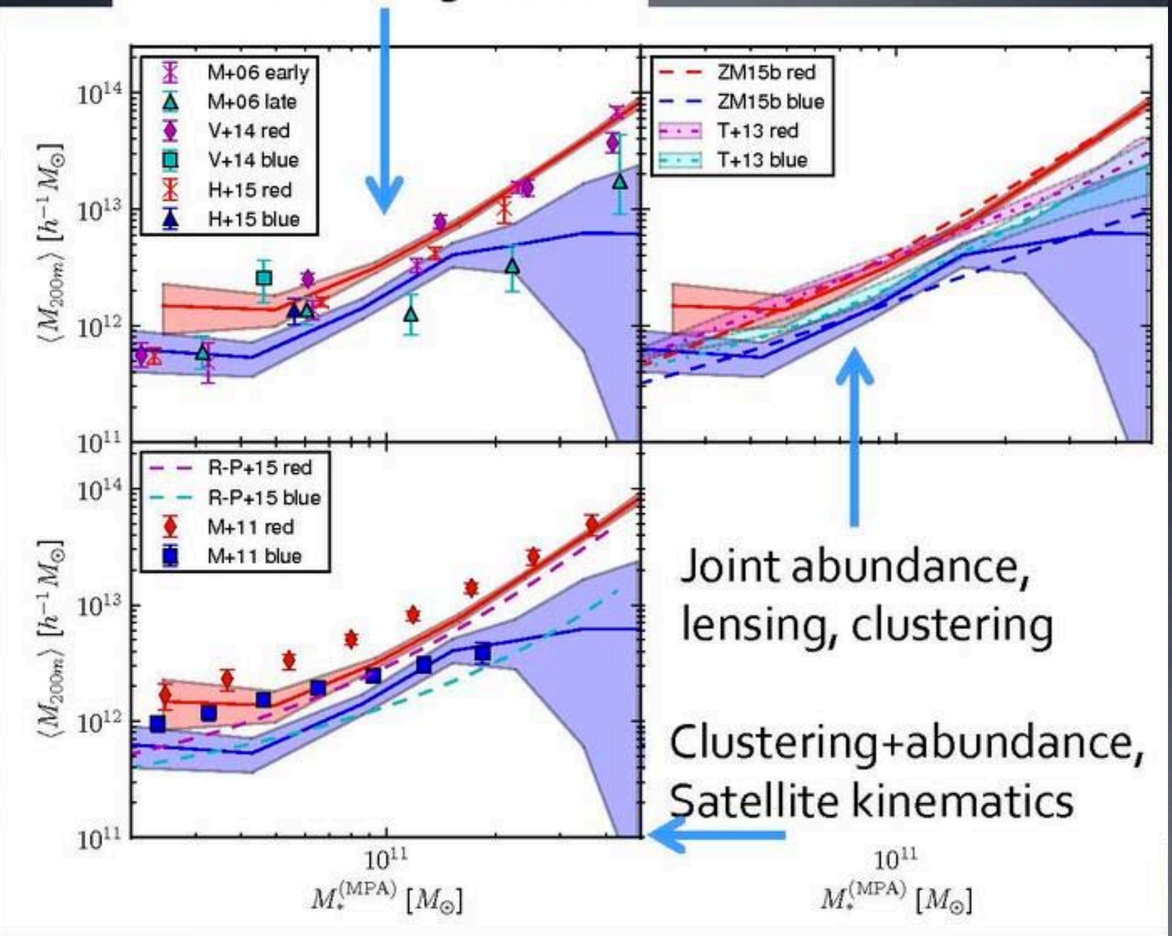
Alyson Brooks - Abundance of Dwarf Galaxies

Marla Geha - Satellites Around Galactic Analogs (SAGA Project)

Observational review: The galaxy-halo connection

Rachel Mandelbaum
Carnegie Mellon University

Previous lensing results



Joint abundance, lensing, clustering

Clustering+abundance, Satellite kinematics

Lessons so far

- Lensing tells us that **early-type central galaxies live in halos that are ~2-3x more massive than those hosting late-type central galaxies**
- Kinematics and lensing agree on this point, though with different normalization at low M*
- Clustering+abundance results agree, though high-mass normalization differs (modeling assumptions?)
- Joint lensing+clustering+abundance results agree, though SDSS and COSMOS give different results at high mass (model differences, cosmic variance in COSMOS?)

Observational review:
The galaxy-halo connection

Rachel Mandelbaum
Carnegie Mellon University

Key take-aways

- We can explain the various two-point statistics (lensing, clustering) plus marked correlations, quenching fractions with a model that relates quenching to halo mass… without assembly bias
- This model still exhibits some non-trivially interesting environmental effects in the marked correlations
    - Observed environmental effects do not automatically imply assembly bias!
- But these results do not rule out AB as a *secondary* effect on galaxy colors
    - See also decorated HODs (Hearin+15, Zentner+16)

Priya Natarajan - Insights from Cluster Lensing

HST FRONTIER FIELDS INITIATIVE
deep imaging of 6 cluster lenses

- ~40 -80 families of multiple images, ~100 images with spectroscopic redshifts (GLASS, CLASH-VLT, MUSE…)
- multi-wavelength coverage
- new insights into cluster-lenses and lensed galaxies
- what is the nature of dark matter?
- **Cluster density profiles, shapes of the cores**
  substructures
- what are the properties of the faint, high-redshift lensed galaxies?
- **Role in re-ionizing the universe, luminosit functions, magnification**
- what is the nature of dark energy?
- **Strong Lensing cosmography**

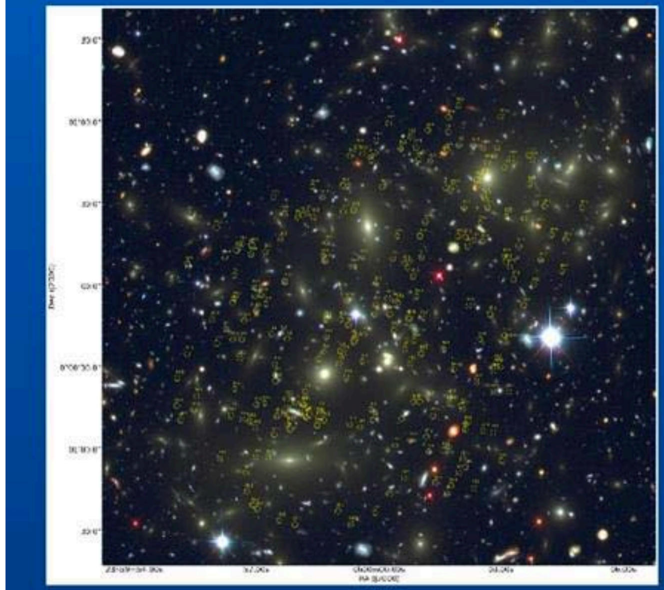
HSTFF MODEL COMPARISON PROJECT

- Teams are using various reconstruction algorithms, independently developed - parametric free-form & hybrid
- Assessing how these algorithms perform and how they compare
- Provided 2 simulated clusters where true data known for blind reconstruction, given the same inputs to all teams
- How robust are these models? strengths & limitations, improvements

Group/Author	Method	Model	Cluster	Approach	Blind
M. Bradac & A. Hoag	SWUnited	Bradac-Hoag	*Ares+Hera*	free-form	yes
J. Diego	WSLAP+	Diego-multires	*Hera*	hybrid	yes
J. Diego	WSLAP+	Diego-overfit	*Hera*	hybrid	yes
J. Diego	WSLAP+	Diego-reggrid	*Ares+Hera*	hybrid	yes
D. Lam	WSLAP+	Lam	*Hera*	hybrid	no
J. Liesenborgs, K. Sebesta & L. Williams	`Grale`	GRALE	*Ares+Hera*	free-form	yes
D. Coe	LensPerfect	Coe	*Ares*	free-form	yes
CATS	`Lenstool`	CATS	*Ares+Hera*	parametric	yes
T. Johnson & K. Sharon	`Lenstool`	Johnson-Sharon	*Ares+Hera*	parametric	yes
T. Ishigaki, R. Kawamata & M. Oguri	GLAFIC	GLAFIC	*Ares+Hera*	parametric	yes
A. Zitrin	LTM	Zitrin-LTM-gauss	*Ares+Hera*	parametric	no
A. Zitrin	PIEMDeNFW	Zitrin-NFW	*Ares+Hera*	parametric	no

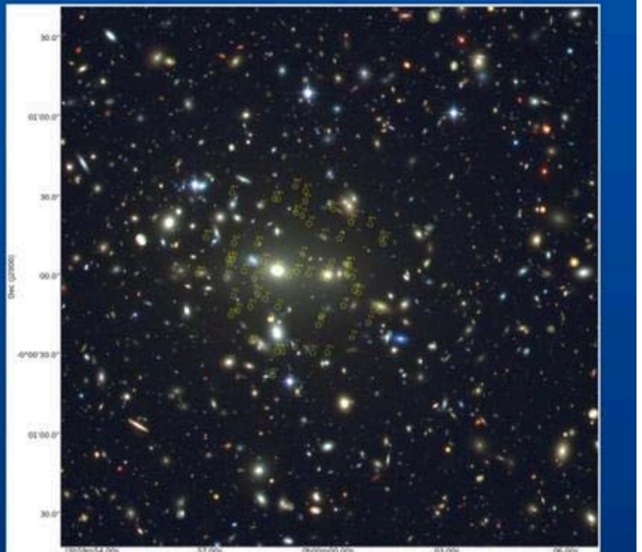
Meneghetti, Natarajan & Coe+ 16

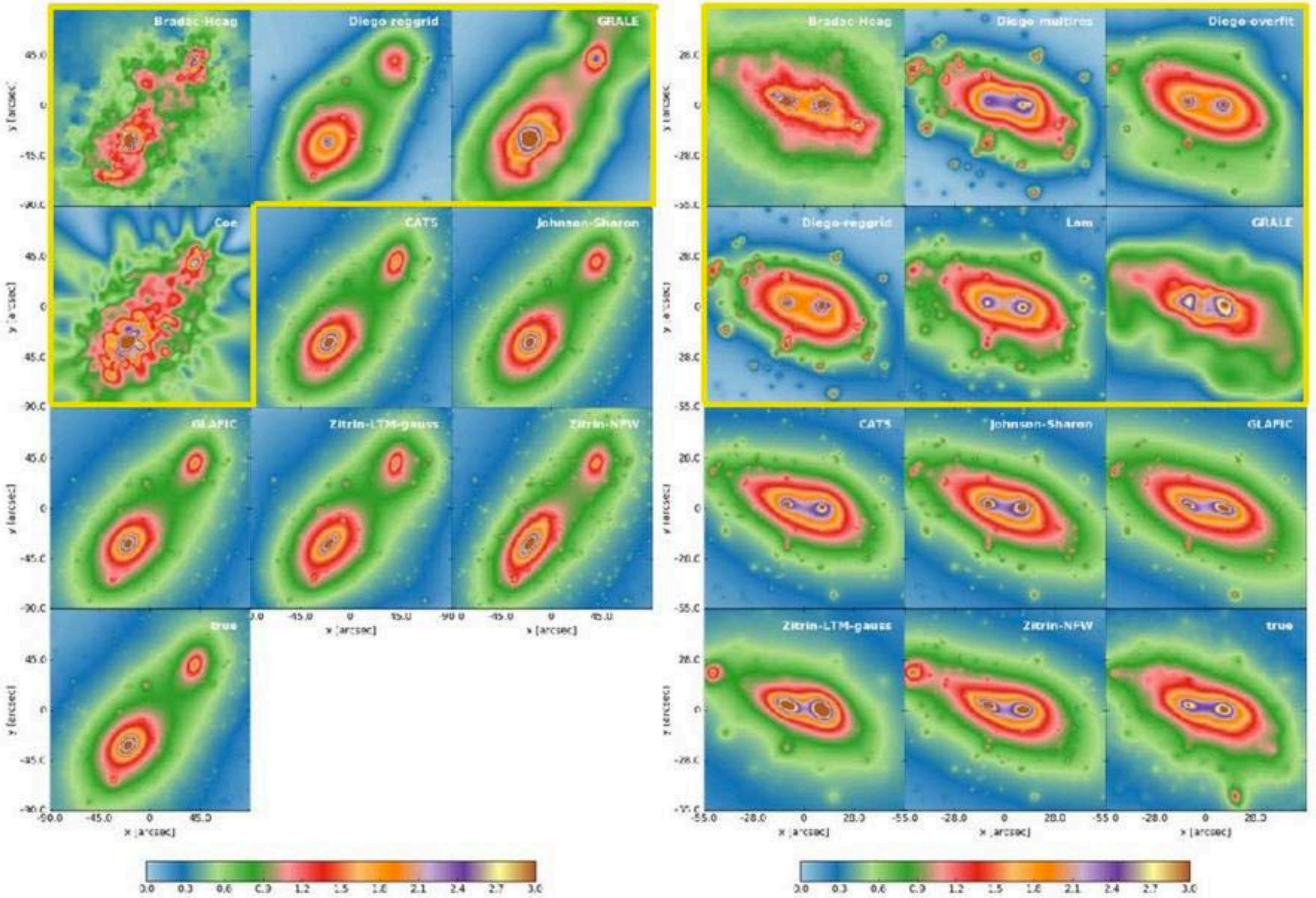
TWO SIMULATED CLUSTER LENSES
ARES & HERA



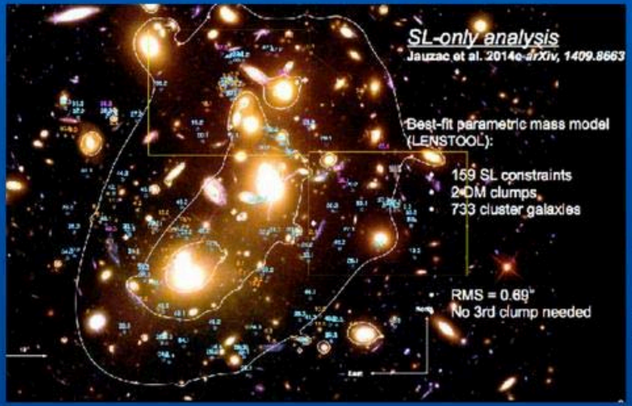
242 IMAGES OF 82 BACKGROUND SOURCES

65 IMAGES OF 19 BACKGROUND SOURCES

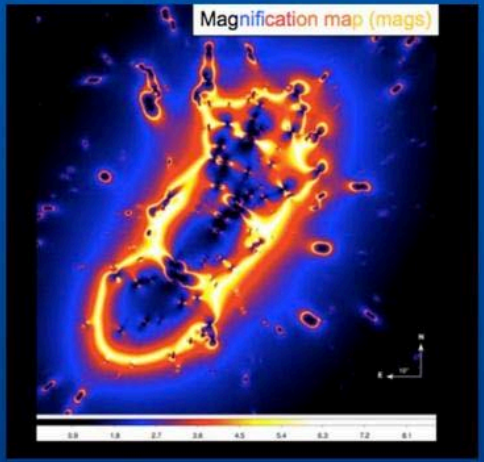


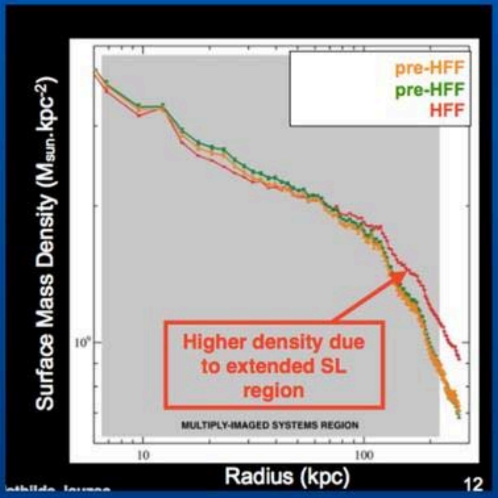


BEST-FIT MASS MODEL FOR Abell 2744

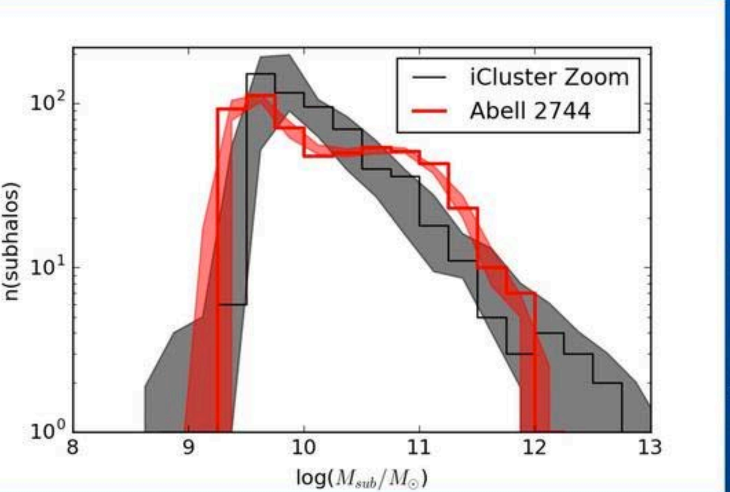


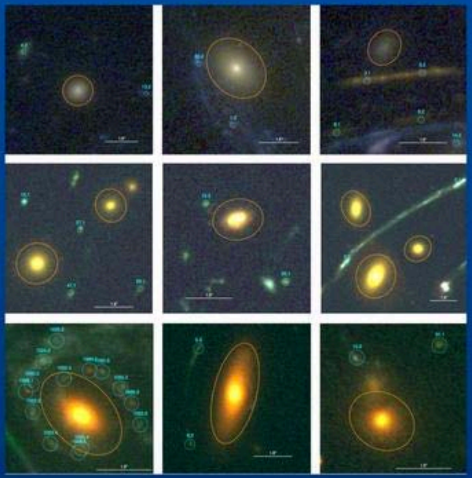
BEST-FIT MASS MODEL FOR Abell 2744





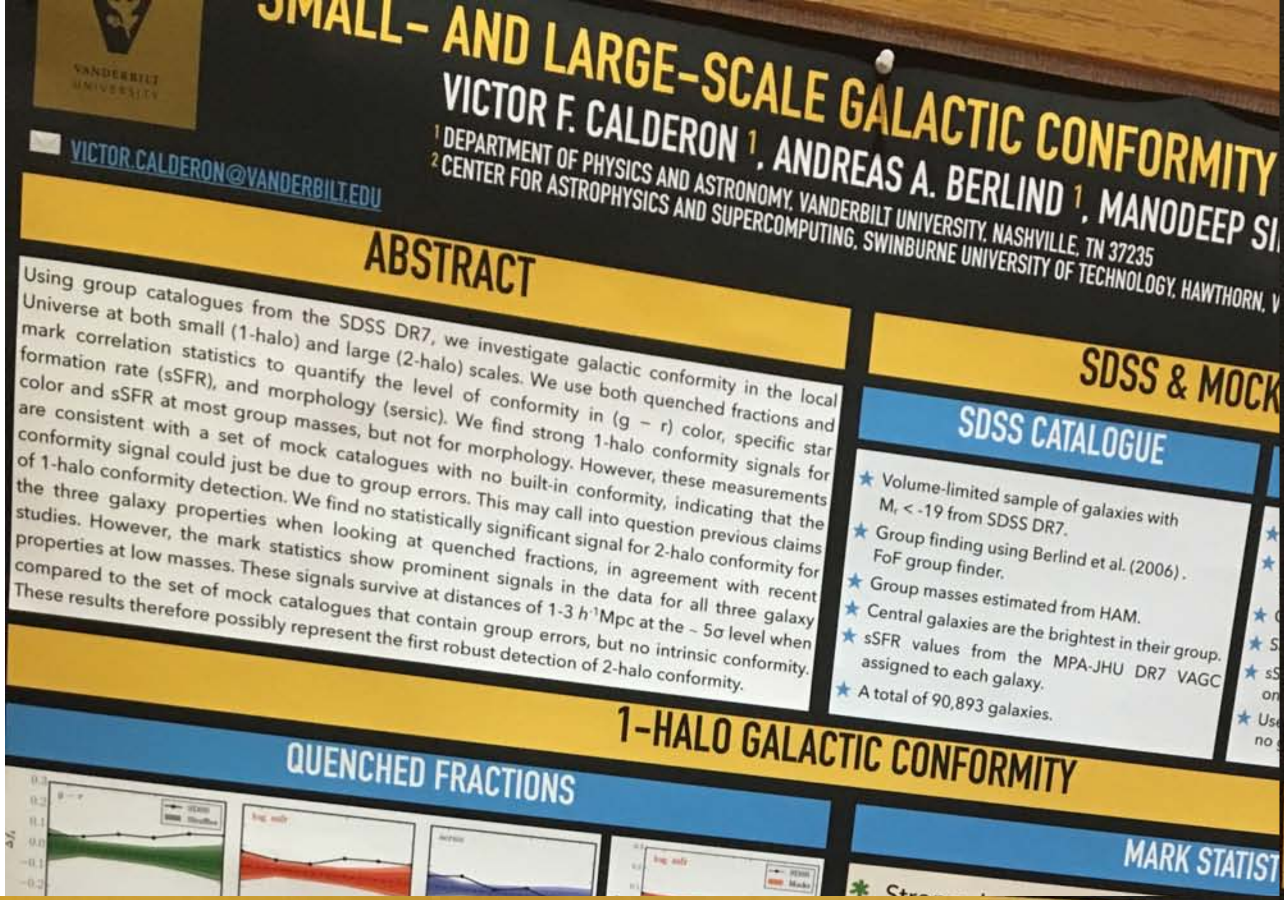
COMPARISON OF HSTFF SUBSTRUCTURE WITH LCDM PREDICTIONS





CURRENT STATUS OF RELATION BETWEEN MASS & LIGHT FROM CLUSTER-LENSES

- Light appears to trace mass with high fidelity within clusters as inferred from parametric and non-parametric lens reconstructions methods
- All lens modeling techniques have limitations even with HSTFF quality data at the present time
- Given the accuracy of the reconstruction techniques available caution advised in assessing any claims about dark clumps, displacement between light and mass in the inner regions
- The SHMF derived in the inner regions of cluster-lenses is in good agreement with theoretical LCDM expectations for parametric reconstruction methods
- The SHMF in the inner regions of cluster lenses is in very good agreement with mass matched Illustris clusters
- However the spatial distribution of sub halos in LCDM simulations is markedly different from the radial distribution inferred from lensing
- Need new formalism to address the relationship between mass and light in transient, assembling structures like massive cluster lenses



MALL- AND LARGE-SCALE GALACTIC CONFORMITY

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ABSTRACT

Using group catalogues from the SDSS DR7, we investigate galactic conformity in the local Universe at both small (1-halo) and large (2-halo) scales. We use both quenched fractions and mark correlation statistics to quantify the level of conformity in (g − r) color, specific star formation rate (sSFR), and morphology (sersic). We find strong 1-halo conformity signals for color and sSFR at most group masses, but not for morphology. However, these measurements are consistent with a set of mock catalogues with no built-in conformity, indicating that the conformity signal could just be due to group errors. This may call into question previous claims of 1-halo conformity detection. We find no statistically significant signal for 2-halo conformity for the three galaxy properties when looking at quenched fractions, in agreement with recent studies. However, the mark statistics show prominent signals in the data for all three galaxy properties at low masses. These signals survive at distances of 1-3 h^{-1}Mpc at the ~ 5σ level when compared to the set of mock catalogues that contain group errors, but no intrinsic conformity. These results therefore possibly represent the first robust detection of 2-halo conformity.

SDSS & MOCK

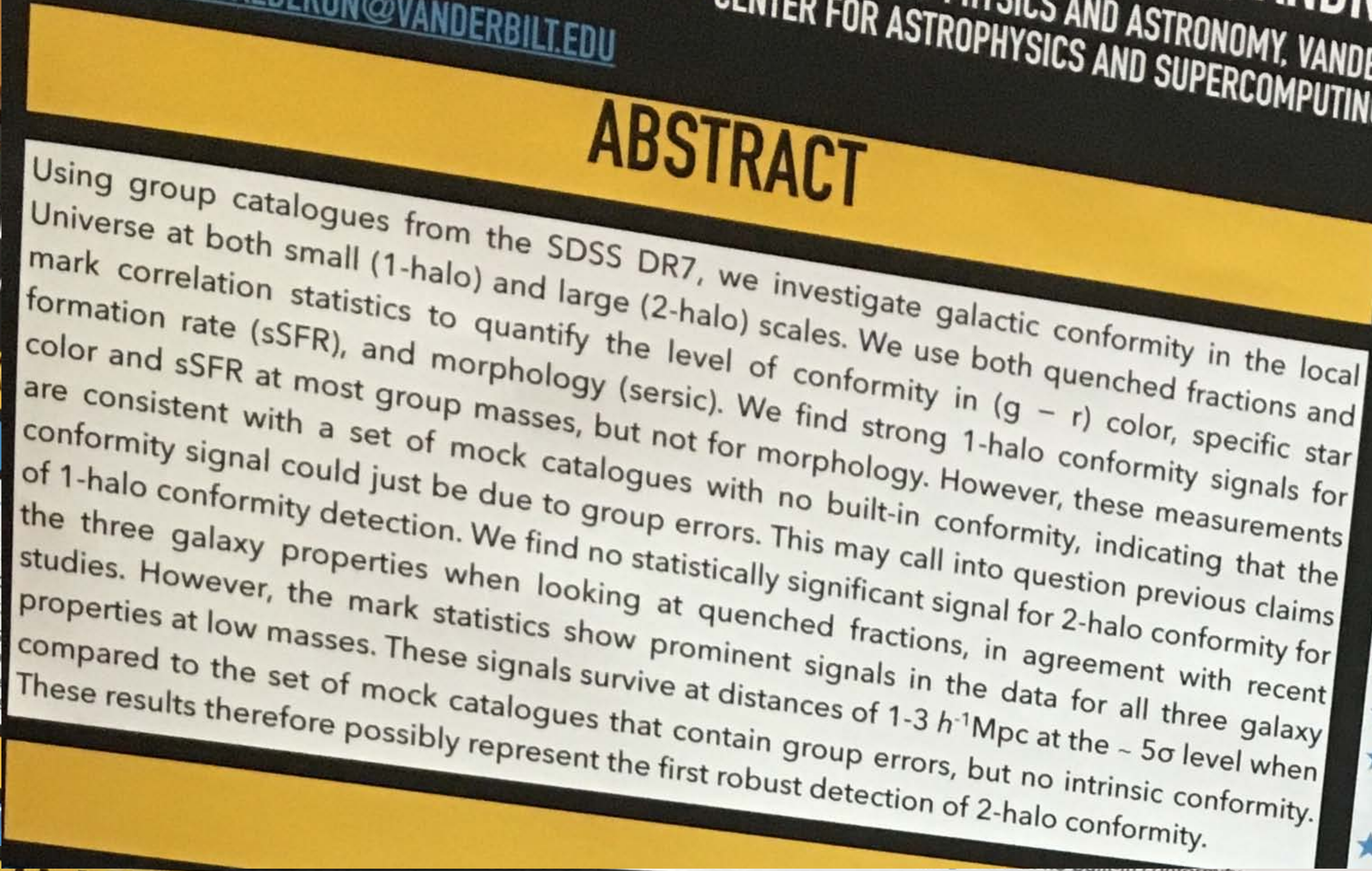
SDSS CATALOGUE

- Volume-limited sample of galaxies with $M_r < -19$ from SDSS DR7.
- Group finding using Berlind et al. (2006). FoF group finder.
- Group masses estimated from HAM.
- Central galaxies are the brightest in their group.
- sSFR values from the MPA-JHU DR7 VAGC assigned to each galaxy.
- A total of 90,893 galaxies.

1-HALO GALACTIC CONFORMITY

QUENCHED FRACTIONS

MARK STATIST



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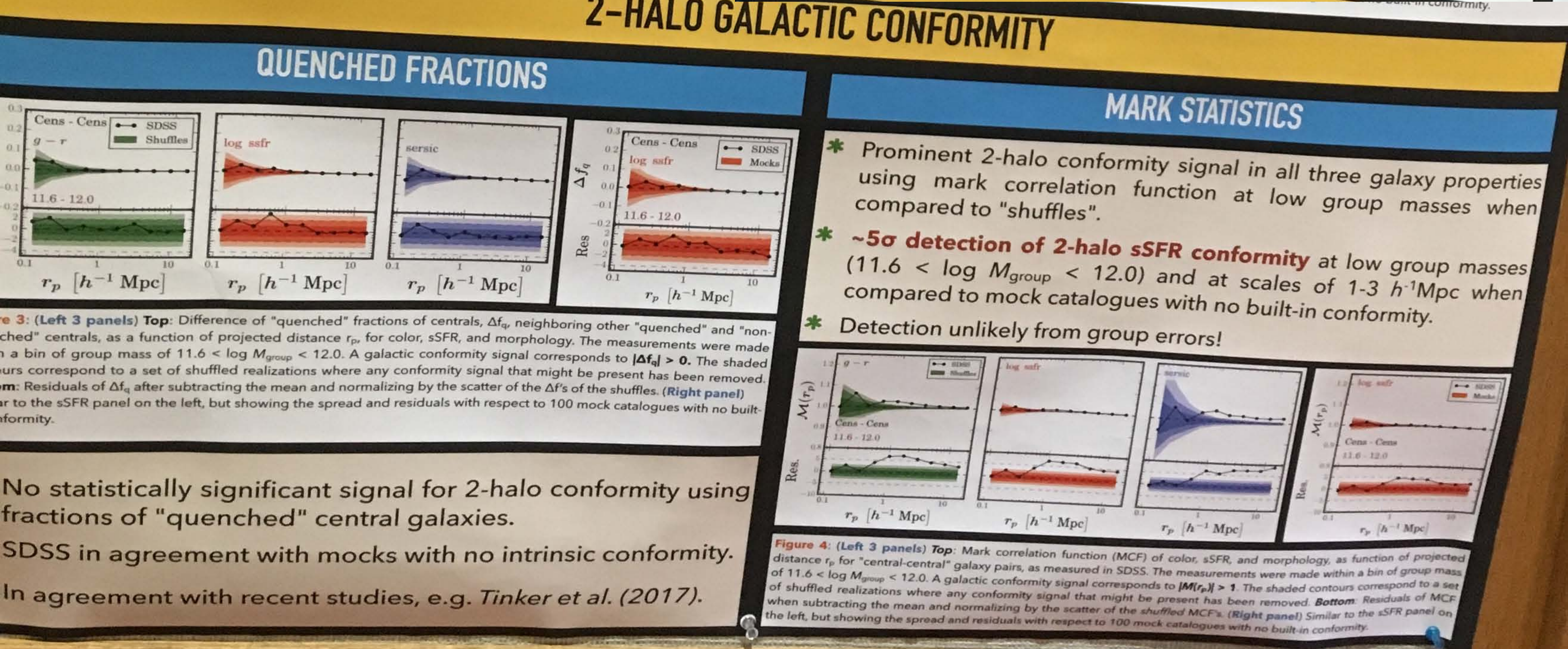

2-HALO GALACTIC CONFORMITY

QUENCHED FRACTIONS

e 3: **(Left 3 panels) Top**: Difference of "quenched" fractions of centrals, Δf_q, neighboring other "quenched" and "non-
ched" centrals, as a function of projected distance r_p, for color, sSFR, and morphology. The measurements were made
a bin of group mass of $11.6 < \log M_{group} < 12.0$. A galactic conformity signal corresponds to $|\Delta f_q| > 0$. The shaded
urs correspond to a set of shuffled realizations where any conformity signal that might be present has been removed.
m: Residuals of Δf_q after subtracting the mean and normalizing by the scatter of the Δf's of the shuffles. **(Right panel)**
r to the sSFR panel on the left, but showing the spread and residuals with respect to 100 mock catalogues with no built-
formity.

No statistically significant signal for 2-halo conformity using fractions of "quenched" central galaxies.

SDSS in agreement with mocks with no intrinsic conformity.

In agreement with recent studies, e.g. *Tinker et al. (2017)*.

MARK STATISTICS

- Prominent 2-halo conformity signal in all three galaxy properties using mark correlation function at low group masses when compared to "shuffles".
- **~5σ detection of 2-halo sSFR conformity** at low group masses ($11.6 < \log M_{group} < 12.0$) and at scales of 1-3 h^{-1}Mpc when compared to mock catalogues with no built-in conformity.
- Detection unlikely from group errors!

Figure 4: **(Left 3 panels)** ***Top***: Mark correlation function (MCF) of color, sSFR, and morphology, as function of projected distance r_p for "central-central" galaxy pairs, as measured in SDSS. The measurements were made within a bin of group mass of $11.6 < \log M_{group} < 12.0$. A galactic conformity signal corresponds to $|M(r_p)| > 1$. The shaded contours correspond to a set of shuffled realizations where any conformity signal that might be present has been removed. ***Bottom***: Residuals of MCF when subtracting the mean and normalizing by the scatter of the *shuffled* MCF's. **(Right panel)** Similar to the sSFR panel on the left, but showing the spread and residuals with respect to 100 mock catalogues with no built-in conformity.

Galactic Conformity and Clustering as a Function of sSFR to z~1

Alison Coil
UCSD

Collaborators: **Angela Berti**, Alex Mendez, Daniel Eisenstein,
Peter Behroozi, John Moustakas, Andrew Hearin

Galactic Conformity

- Observed correlation between whether a "central" galaxy is quenched and its neighbor galaxies are also quenched.
- 1-halo vs 2-halo conformity:
  - 1-halo (*intra-halo*): correlation between central and satellite galaxies being quenched
  - 2-halo (*inter-halo*): correlation between central galaxy and galaxies in *adjacent* halos being quenched

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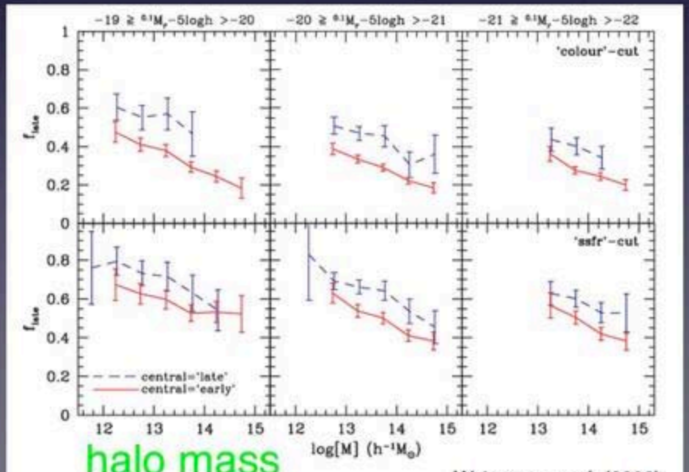
Galactic Conformity

- 1-halo conformity first observed in SDSS (Weinmann et al. 2006)
- 2-halo conformity observed and debated in SDSS (Kauffmann et al. 2013, Sin et al. 2017, Tinker et al. 2017)
- Previous z > 0.2 measurements were 1-halo only and used photometric redshifts (Kawinwanichakij et al. 2015, Hartley et al. 2015)

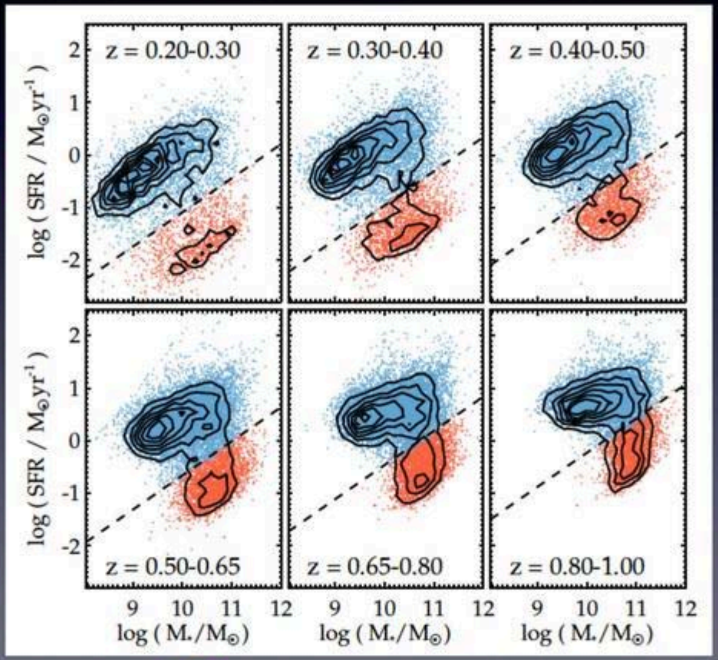


star forming fraction

halo mass

PRIMUS Conformity Sample

- 4 separate fields covering 5.5 deg^2
- 0.2 < z < 1.0
- 60,000 galaxies with spectroscopic redshifts
- Split into star forming or quiescent using evolving SFR-M* cut:



SFR

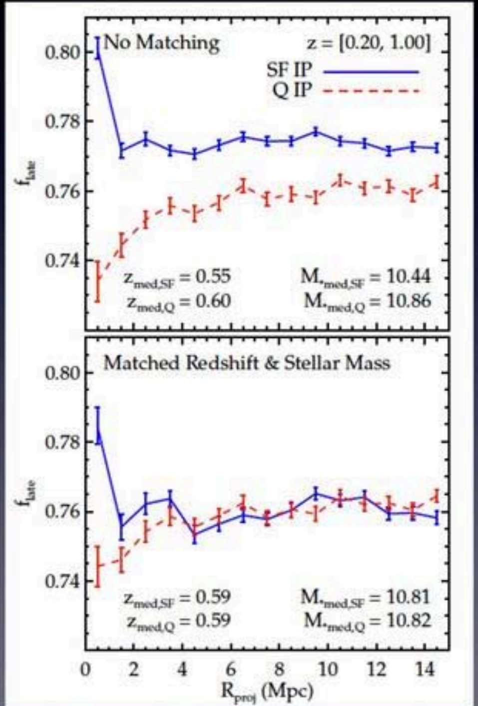
M*

Berti, Coil, et al. 2017, ApJ

Isolated Primary: Matching M* and z

- Small differences in median M* and z of the SF vs Q isolated primary samples mimics conformity signal!
- We therefore match the M* and z *distributions* of the SF and Q isolated primary galaxies
- Results in ~6,000 Q IPs and ~4,000 SF IPs

SF %



R (Mpc)

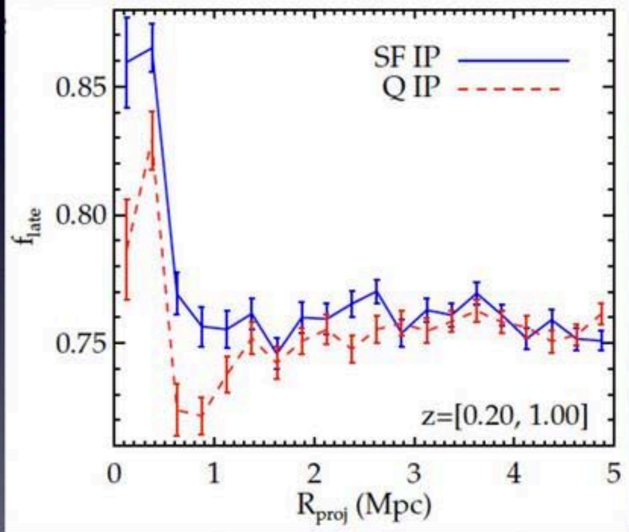
Berti, Coil, et al. 2017, ApJ

Conformity Signal at z~0.7

- f_{late} = late-type (SF) fraction of satellites / neighbors around SF and Q IPs
- Shown as a function of projected distance (R_{proj})
- Normalized signal:

$$\xi_{norm} = \frac{f_{late}^{SF\text{-}IP} - f_{late}^{Q\text{-}IP}}{\left(f_{late}^{SF\text{-}IP} + f_{late}^{Q\text{-}IP}\right)/2}$$

SF %



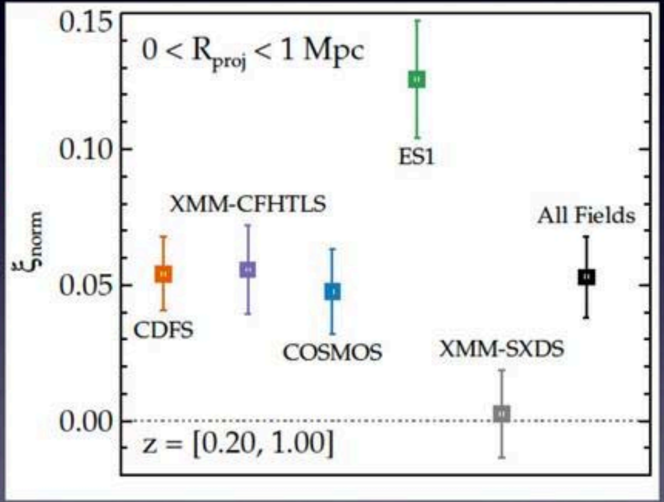
R (Mpc)

Berti, Coil, et al. 2017, ApJ

Cosmic Variance

- Substantial variation in 1-halo signal among different fields
- A meaningful measure of conformity at z > 0.2 should include several spatially separate fields

% signal



Berti, Coil, et al. 2017, ApJ

Conformity at Intermediate Redshift

- Have to be careful with differences in stellar mass and redshift distributions of SF and Q "centrals", can mimic conformity
- Cosmic variance can be substantial, want to use multiple fields
- The signal is *small*! 5% on 1-halo scales, 1% on 2-halo scales
- We're in the process now of quantifying what the contamination due to satellites is in our measurements at z~0.7, using Halotools
- The 2-halo term could be due to differences in the SMHM relation for SF and Q central galaxies…

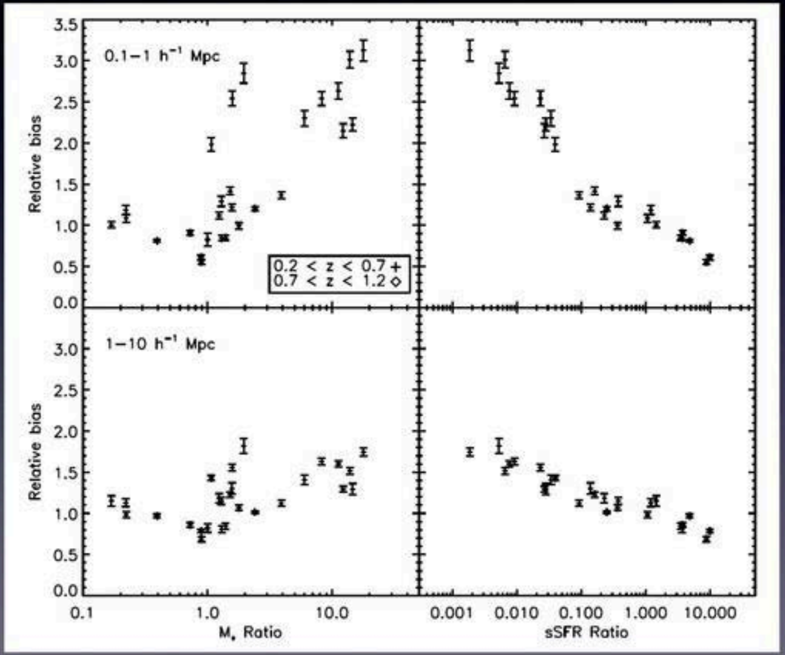
Galaxy Clustering as a function of sSFR

- Lots of papers on galaxy clustering as a function of M*
- Very few papers on clustering as a function of SFR or sSFR
- Interesting to see how galaxy clustering depends on galaxy properties <u>within</u> the SF and Q populations individually, not just between them
- Using DEEP2, Mostek, Coil et al. 2013 found that within a given M* range, star-forming galaxies <u>above</u> the MS of star formation are less clustered than star-forming galaxies <u>below</u> the MS
- Could constrain how galaxies evolve along vs across the star-forming main sequence with time

Coil, Mendez, Eisenstein, Moustakas 2017 ApJ

Relative Bias (M* ratio, sSFR ratio)

relative bias



1 halo scales

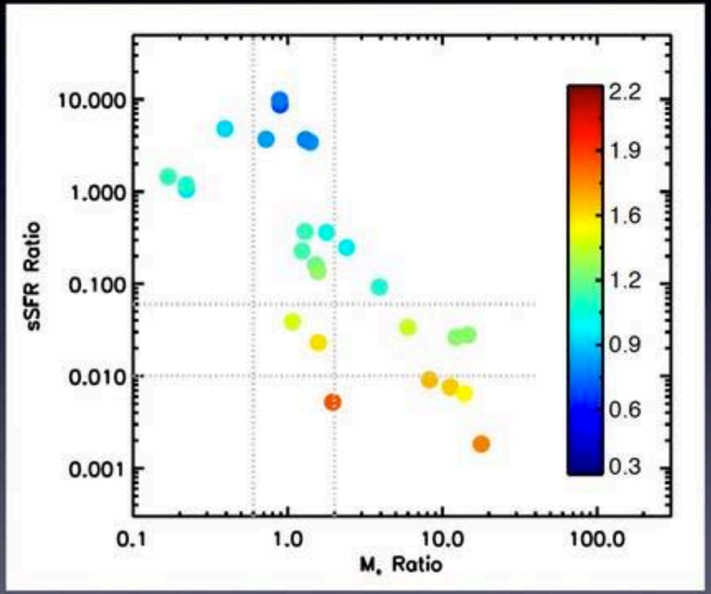
2 halo scales

stellar mass ratio

sSFR ratio

Relative Bias (M* ratio, sSFR ratio)

sSFR ratio



stellar mass ratio

color = relative bias

- At a given stellar mass ratio, the relative bias depends strongly on the sSFR ratio.
- At a given sSFR ratio, the relative bias does NOT depend strongly on the stellar mass ratio.

Clustering Conclusions

Galaxy clustering depends strongly on sSFR, not just stellar mass!

This is true <u>within</u> the star-forming and quiescent populations, individually, not just between them.

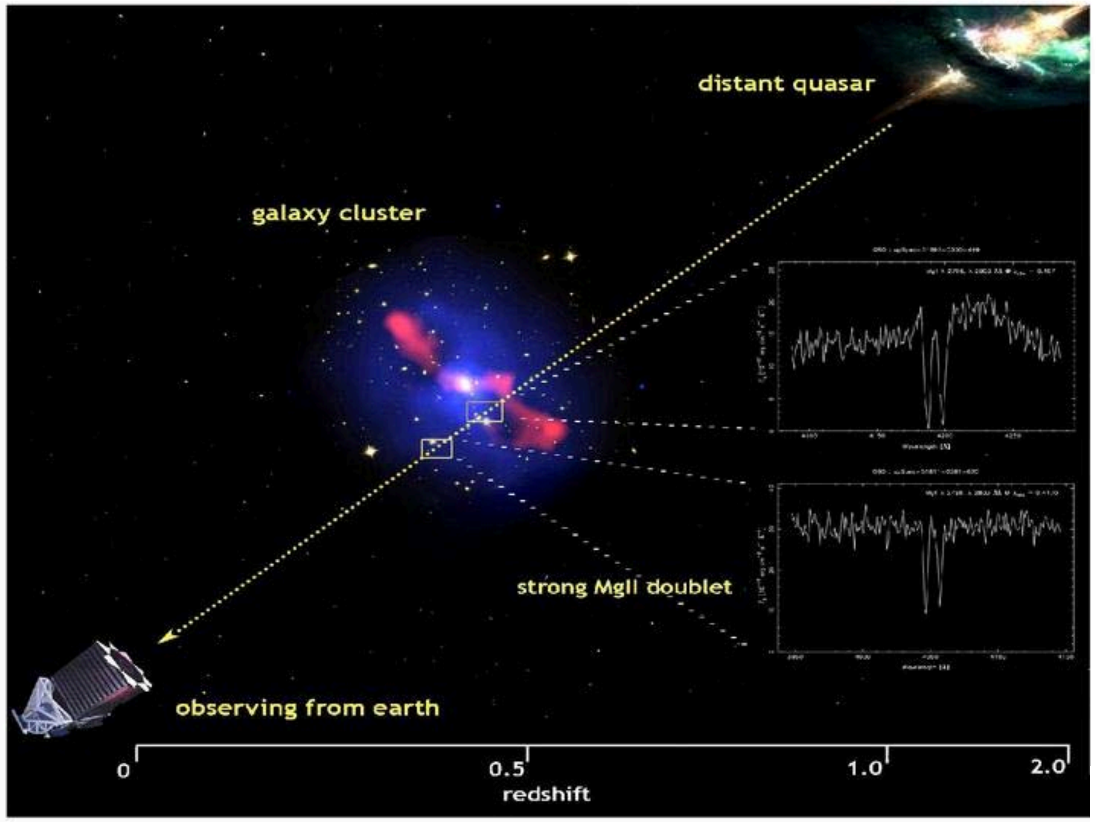
Galaxies above the main sequence of star formation are less clustered than star-forming galaxies below the main sequence. The same trend is seen within the quiescent population.

The SMHM relation likely depends on sSFR - we're testing this now with the clustering of "centrals".

These results should constrain how galaxies evolve in the sSFR-M* plane, specifically their evolution along vs across the main sequence.

Guinevere Kaufmann - Gas in Halos Overview

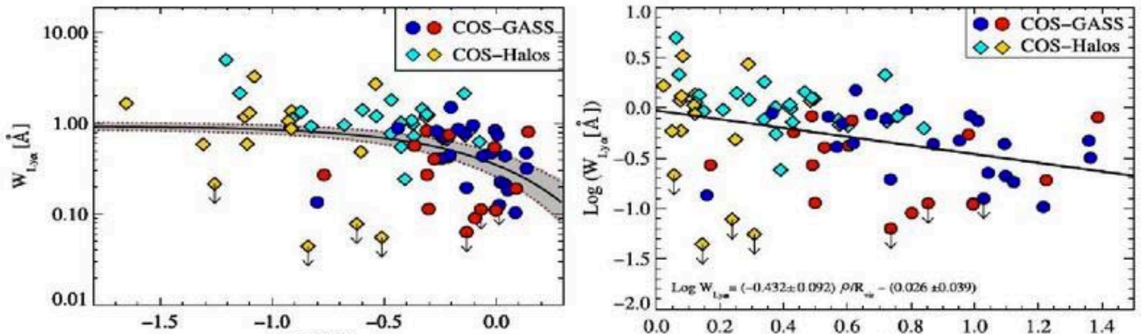
QSOs probing the circumgalactic medium (CGM) : the properties of quasar absorption lines in the vicinity of galaxies of known redshift, mass, type, SFR, etc

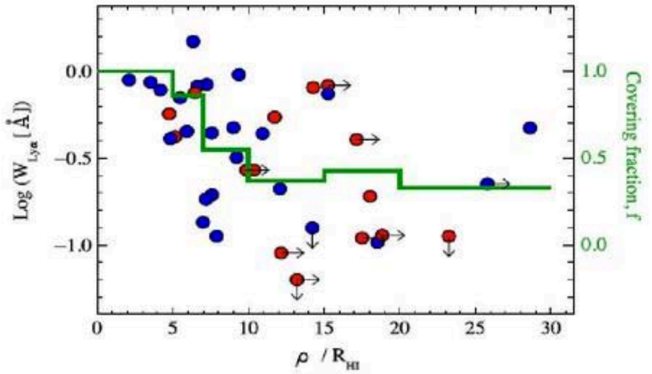


MAIN RESULTS FROM COS-GASS

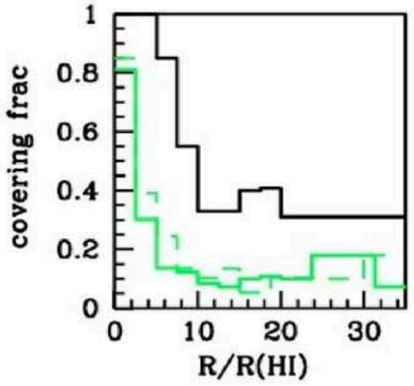
Borthakur et al 2015

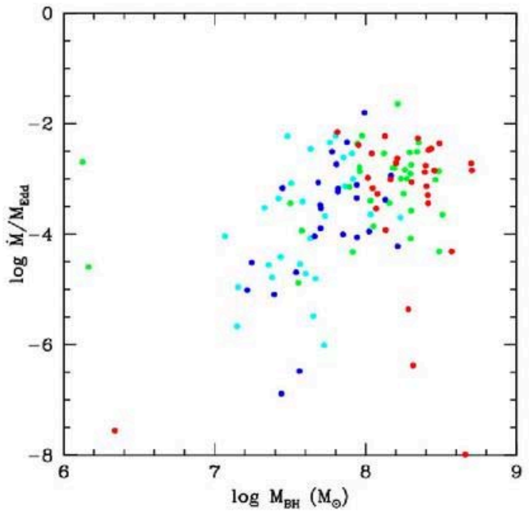
1) Lyman alpha equivalent width decreases gradually as a function of radius out to the virial radius. "Covering fraction" of clouds is ~50% even at the virial radius.



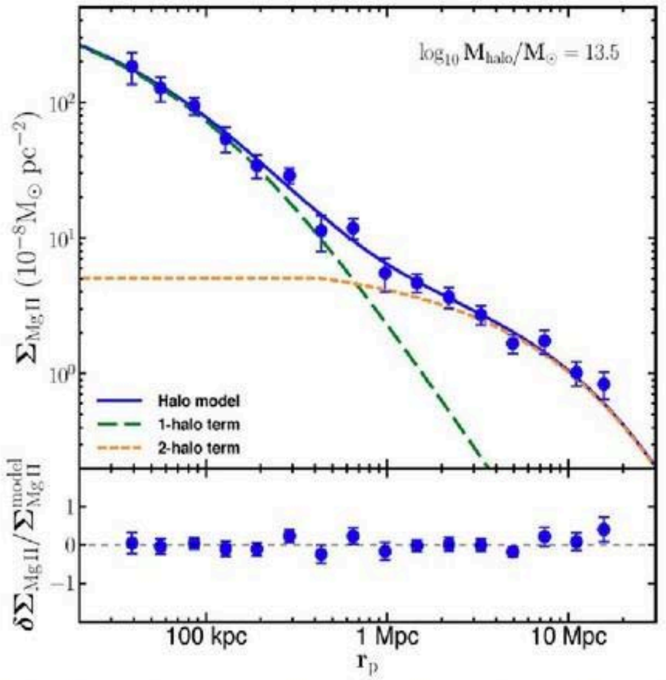


Covering fraction of neutral gas too low in Illustris compared with data: effect of AGN feedback processes

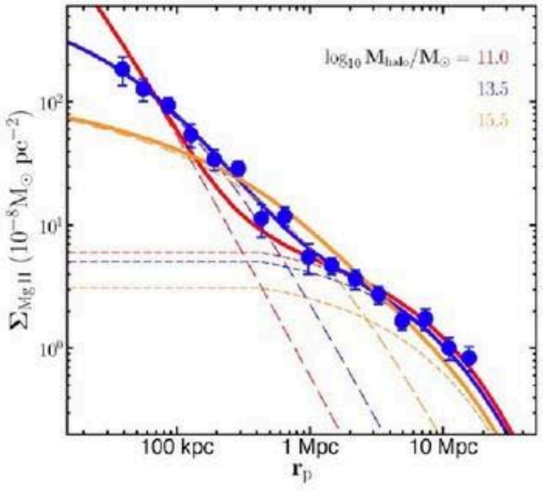




Zhu & Menard (2014): the cross correlation between MgII systems and massive galaxies



igure 5. The best fitting halo model. Upper panel shows the best fitting halo model, decomposed into one-halo and two-halo terms. Lower panel shows the ractional residuals. The halo model has three parameters: average LRG host halo mass M_{halo}, Mg II gas-to-mass ratio in the host halo $f^{1h}_{Mg\,II}$, and mean Mg II as-to-mass ratio of all galaxies $f^{2h}_{Mg\,II}$.



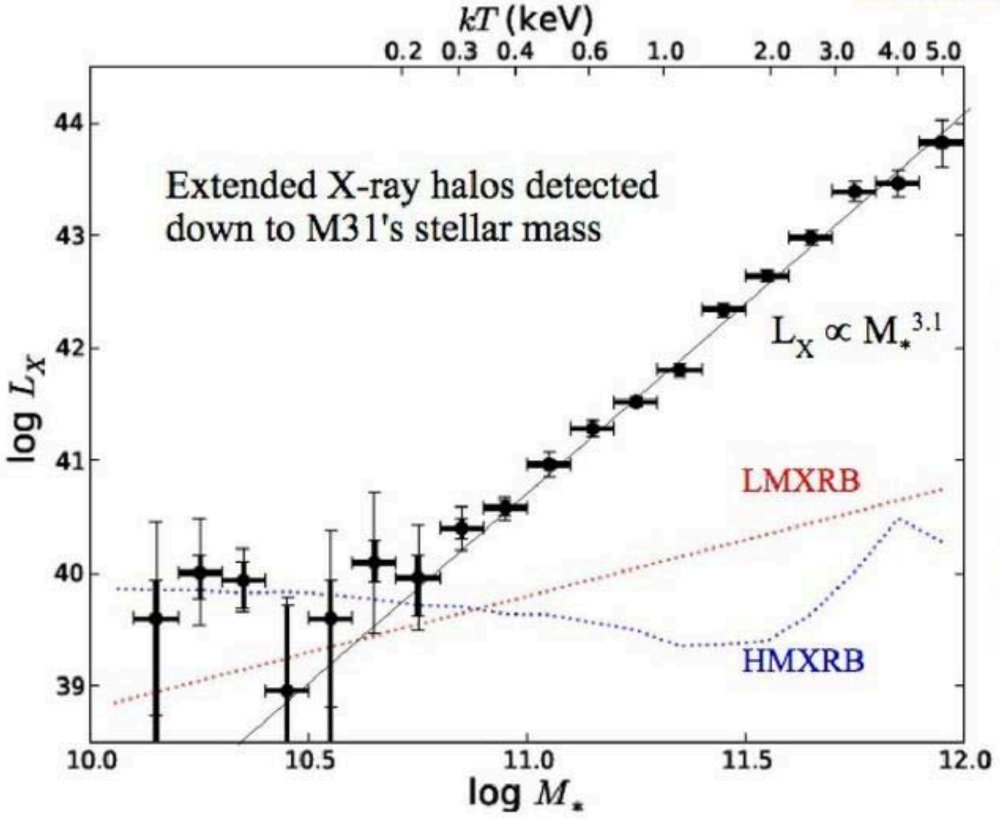
Model:

Gas distribution is assumed to trace the dark matter distribution exactly, i.e. the gas density profile in a halo of mass M has the same NFW shape as the dark matter up to a normalization factor **f_gas(M_halo)**. This model is shown to provide an adequate fit to the data if the average host halo mass of the galaxies is 10^13.5 **M⊙**.

Guinevere Kaufmann - Gas in Halos Overview

Stacked Rosat X-ray signal from LBGs

Anderson et al 2015

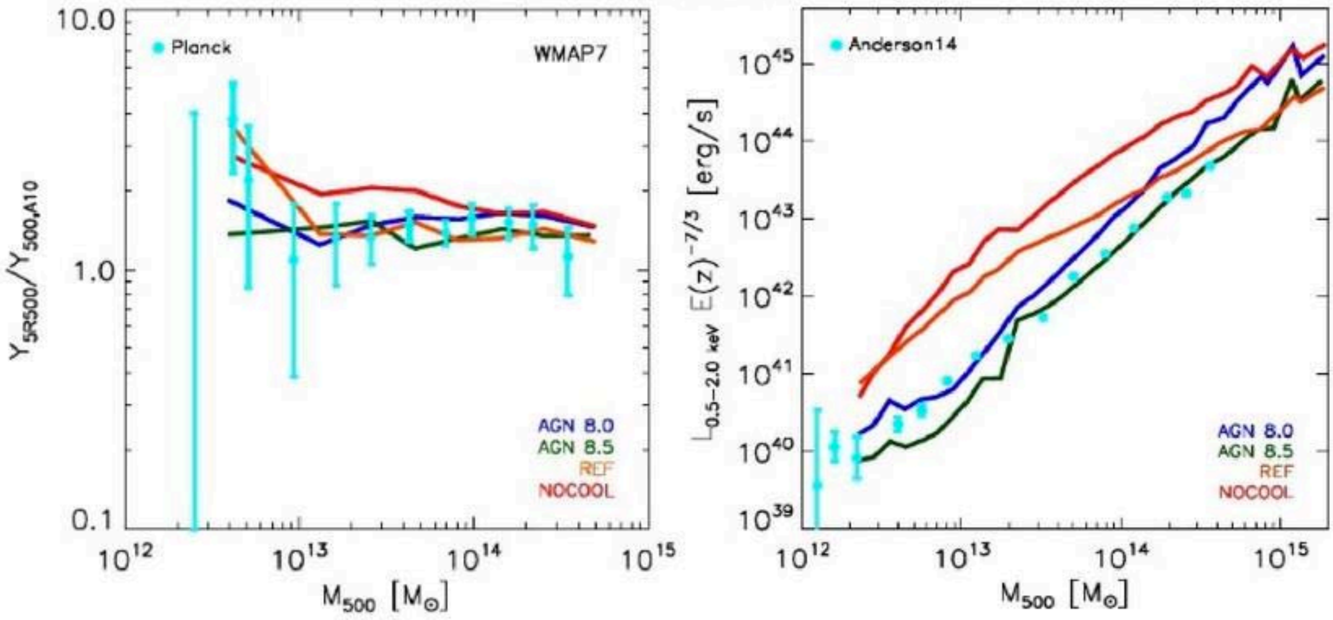


Extended X-ray halos detected down to M31's stellar mass

α = 4/3 is expected for self-similar halos with constant baryon fraction

X-ray luminosity grows much faster with mass than this

Le Brun, McCarthy & Melin 2015



AGN feedback models provide better match to X-ray data

Observational data on the circumgalactic gas provides a potentially powerful means of constraining feedback processes in galaxy formation.

Complexity arises because halo gas spans a wide range in temperature and density, so multiple tracers are necessary for full understanding.

Because of the complexity of the feedback processes, hydrodynamical simulations are required to interpret the observations. Ideally, the comparisons should involve multiple simulations with different physical prescriptions.

We also need to move beyond zero'th order characterizations of gas properties (e.g. covering fraction, column density), to measures that can probe kinematics of the gas with respect to the central galaxy.

galaxy size – halo virial radius (R_{200c}) relation of galaxies

Andrey Kravtsov

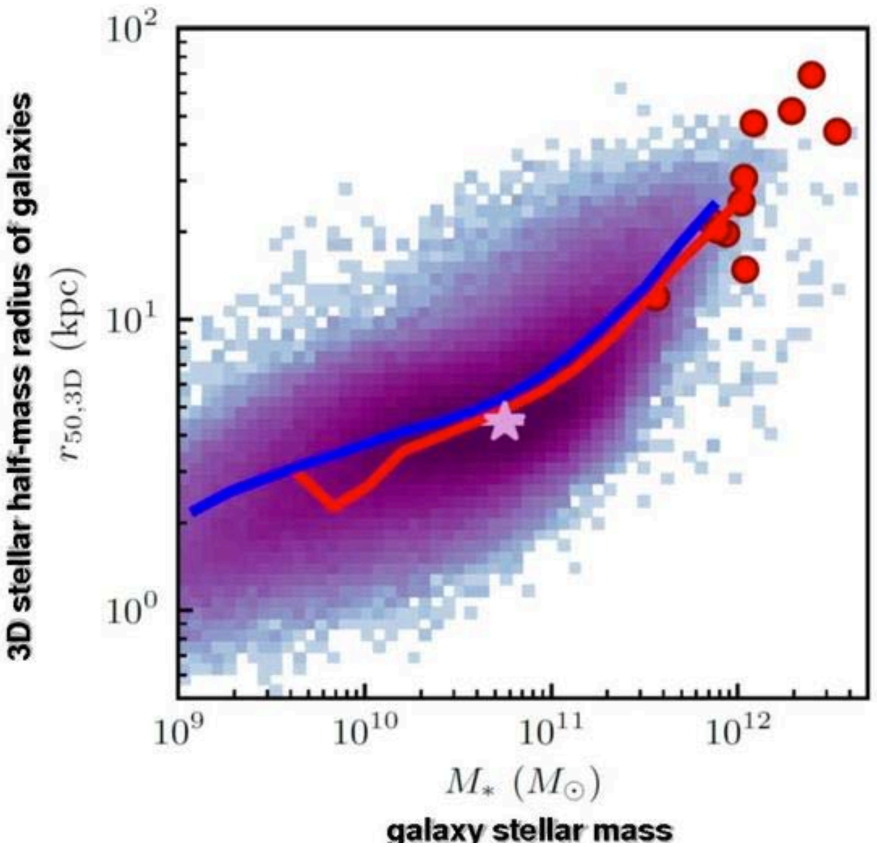
Department of Astronomy & Astrophysics
Kavli Institute for Cosmological Physics
The University of Chicago

KITP GalHalo conference
16 May 2017

“You can observe a lot just by watching.” – Yogi Berra

Galaxy size – stellar mass relation of SDSS galaxies

3d half-light radii of disk and spheroidal galaxies are not too different



compared to 9 BCGs from Kravtsov et al. 2014

and Milky Way with parameters from Licquia & Newman (2016)

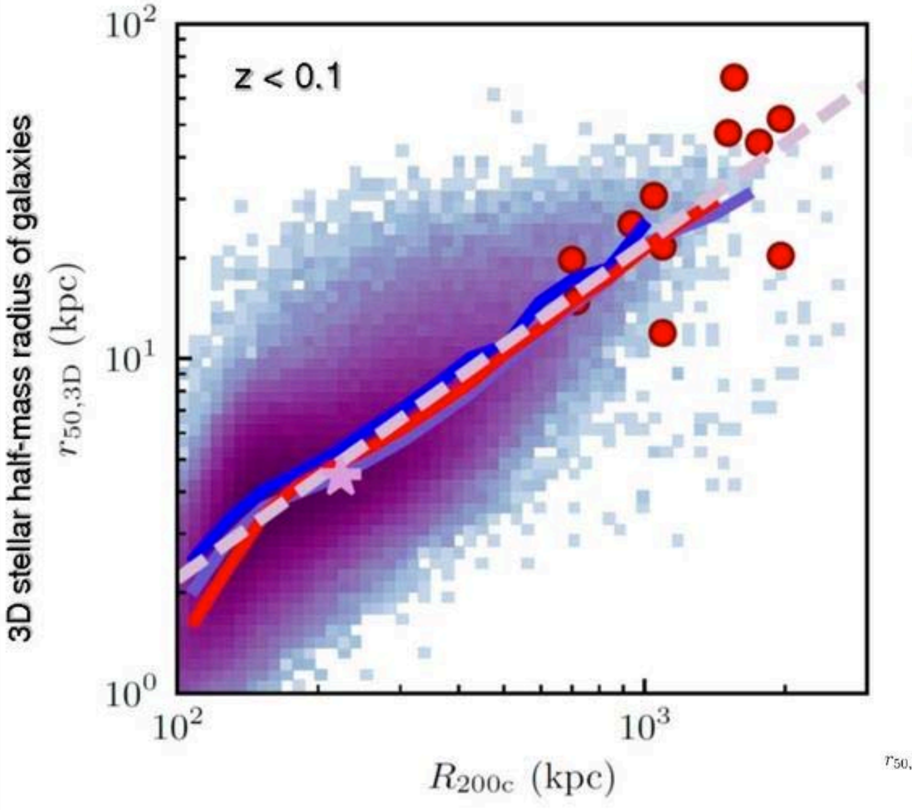
magenta 2d histogram = distribution of z<0.1 SDSS galaxies

Lines show medians for elliptical and Sc-Sd late type galaxies using morphology probabilities from Huertas-Company+ '13)

sizes and luminosities from improved SDSS photometry of Meert, Bernardi+2015
L->M* using Bell+ '03 fits

galaxy size – virial radius relation of the SDSS galaxies

both late- and early-type galaxies in SDSS follow a remarkably <u>linear relation</u> between 3d half-light radius and R_{200c}. (Kravtsov 2013; 2017; Huang+ '17; Somerville+ '17)



halo virial radius

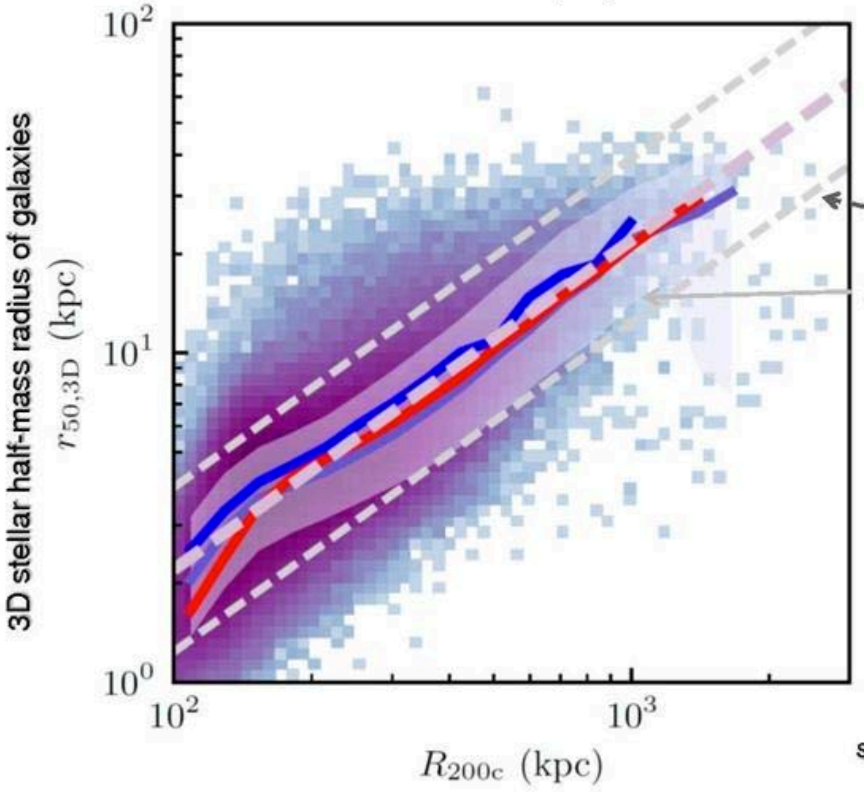
3D radius projected radius of Scd galaxies = corrected for inclination

3D radius of elliptical galaxies = de-projected radius calculated using individual galaxy Sersic indices

$$r_{50,\rm 3D} = R_{50,\rm 2D}\,(1.356 - 0.0293n + 0.0023n^2)$$

galaxy size – virial radius relation of SDSS galaxies: scatter

scatter in half-mass radius is close to expectation of the Mo, Mao & White (1998) model and distribution of spin parameters of dark matter halos



shaded band = 68% percentile range of all SDSS galaxies + assuming 0.16 dex scatter in M* at a fixed M200c

$$j_{200} = \lambda R_{200} V_{\rm circ}(R_{200})$$

$$V_{\rm circ}(R) = \sqrt{\frac{GM(<R)}{R}}$$

assume: $j(r_{50}) = j_{200}$

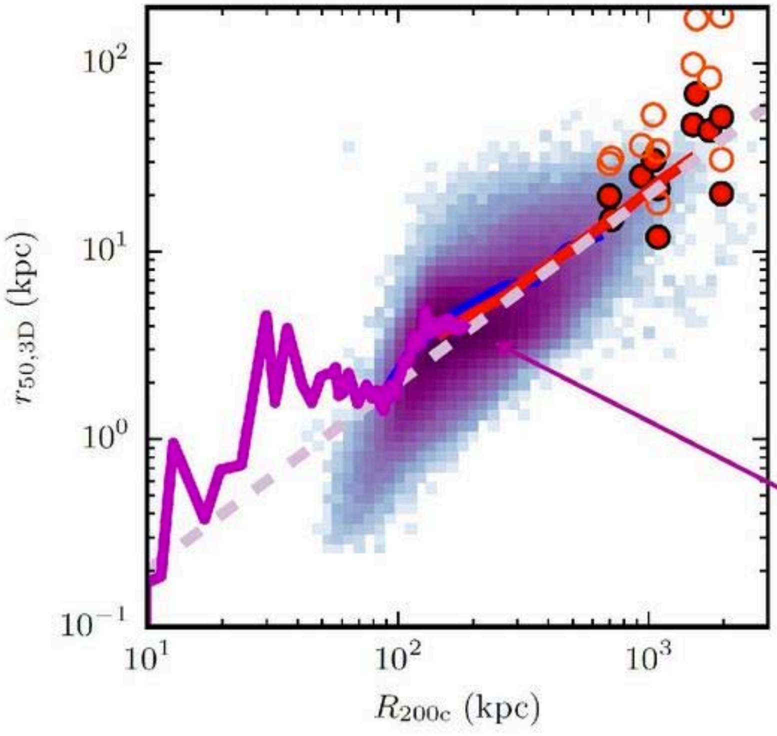
$$\rightarrow r_{50} \propto \lambda R_{200}\frac{V_{\rm circ}(R_{200})}{V_{\rm circ}(r_{50})} \propto \lambda R_{200}$$

simulations predict: $\sigma_{\log_{10}\lambda} \approx 0.25$ dex

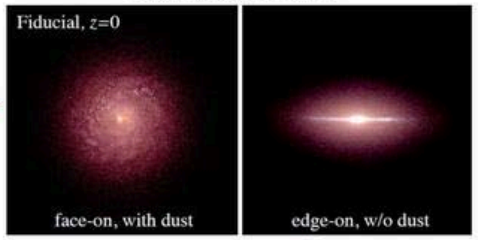
$\sigma_{\ln\lambda} \approx 0.55$

What do simulations say?

Modern galaxy formation simulations with efficient feedback have galaxies evolving along observed Reff-M* relation; they roughly follow z=0 r50-R200c relation, with possibly larger r50/R200c at high z consistent with observations



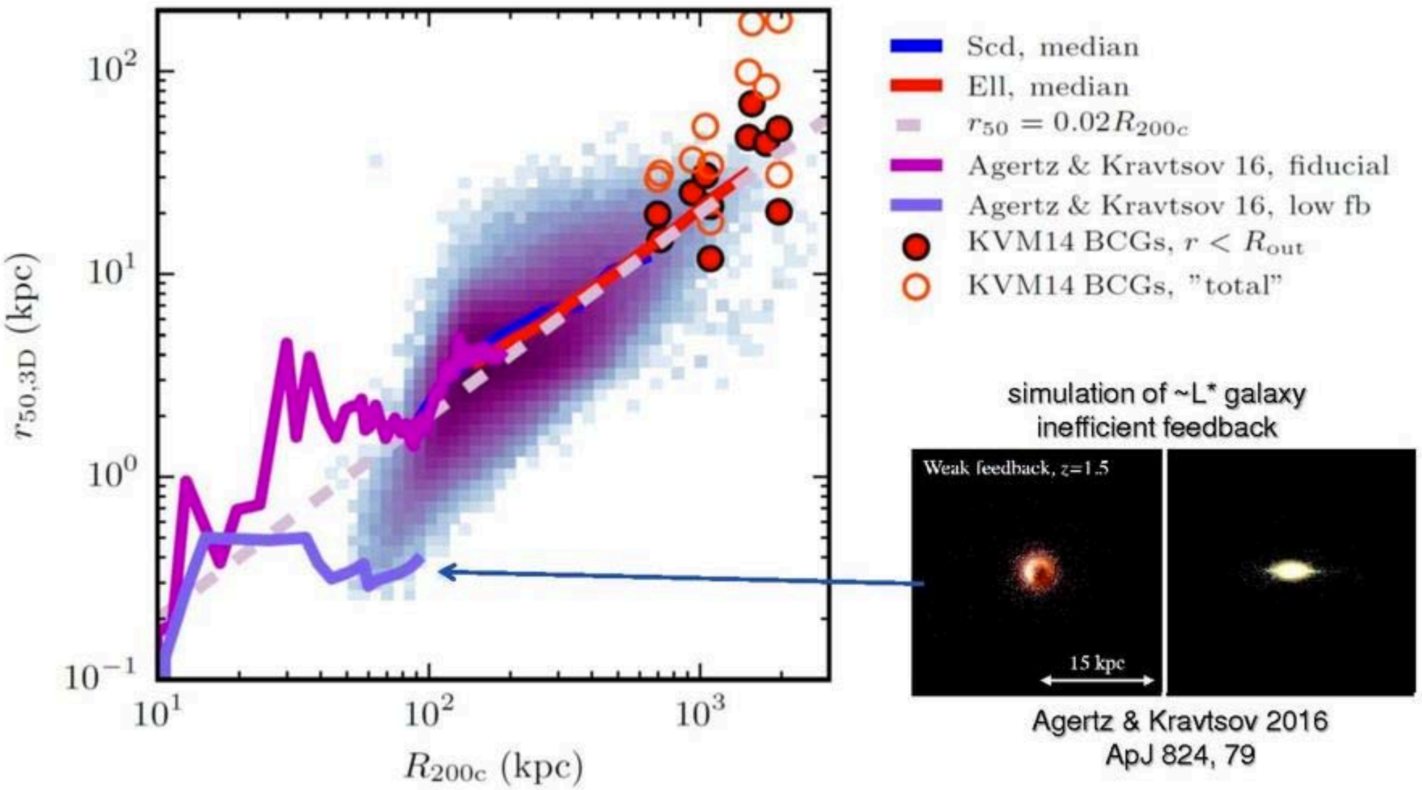
simulation of ~L* galaxy efficient feedback



Agertz & Kravtsov 2016
ApJ 824, 79
see also Sokolowska+ '16

What do simulations say?

Galaxy sizes in simulations depend on feedback being efficient;
Simulations with inefficient feedback produce galaxies that are way too compact
(and have other properties – morphologies, stellar mass, etc – that are inconsistent with observations)



simulation of ~L* galaxy
inefficient feedback

Agertz & Kravtsov 2016
ApJ 824, 79

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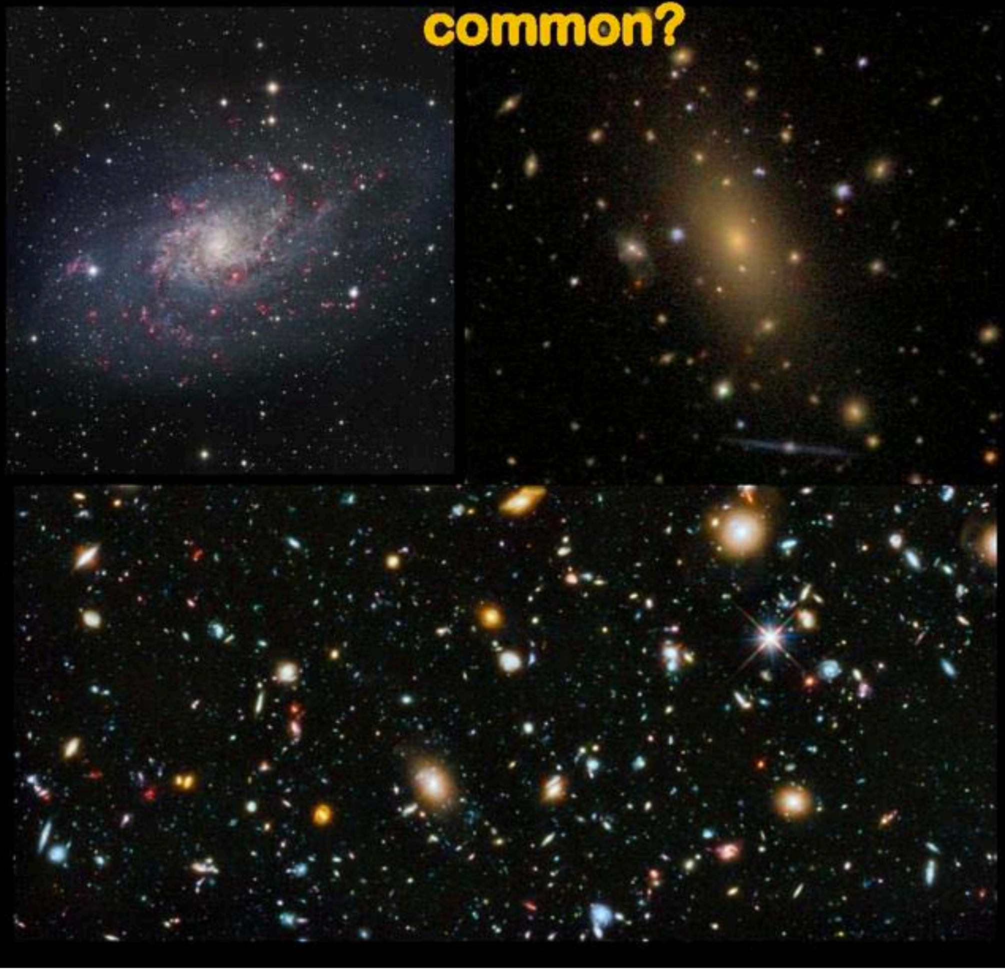
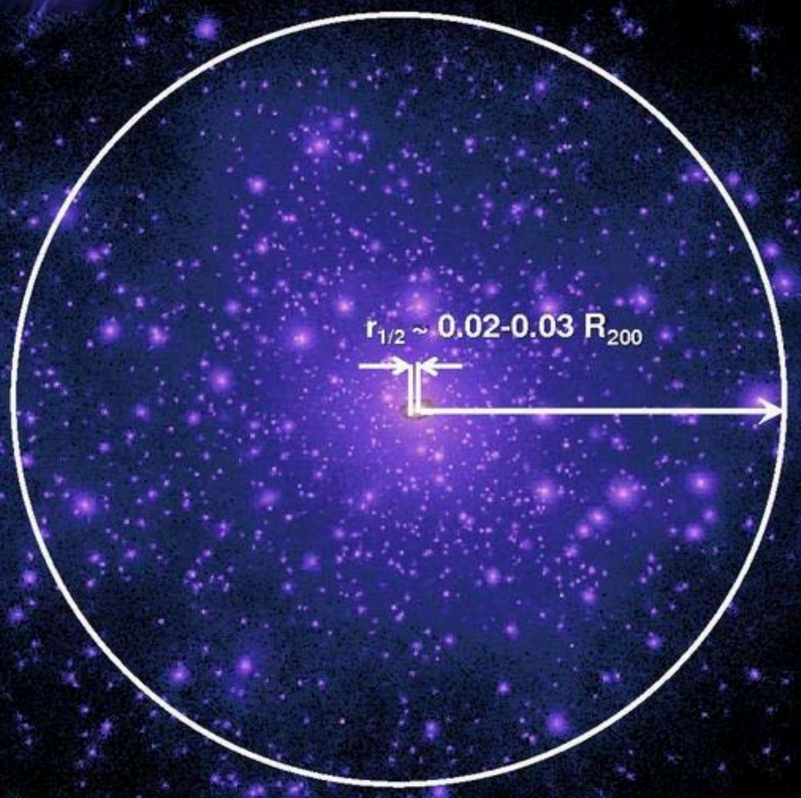
conclusions: what do these galaxies have in common?



Their half-mass radius of stars is about ~2% of R_{200c}



halo virial mass: $M_{200} = \frac{4\pi}{3} 200 \rho_{\rm crit}(z) R_{200}^3$ **where** $\rho_{\rm crit}(z) = \frac{3H^2(z)}{8\pi G}$

---

conclusions

- **normal galaxies on average have half-mass radii of stellar distribution equal to a ~0.02 of the "virial" radius R_{200} (i.e. linear $r_{1/2}$-R_{200} relation), both at z~0 and higher z.**

  This is consistent with simple picture of galaxy formation, but we know from simulations that the actual evolution is not simple and is mediated by galactic outflows.
  Why does this work for both late and early type galaxies?

- **connecting observed sizes to the halo extent is a useful way to connect galaxy evolution to evolution of host dark matter halos and processes associated with galaxy/halo evolution.**

Size-virial relation: Kravtsov 2013, ApJL 764, L31
Kravtsov 2017, in prep.
Modeling: Agertz & Kravtsov, 2016, ApJ 824, 79

The connection between halos and galaxy structural properties

rachel somerville
Rutgers University &
Center for Computational Astrophysics,
Flatiron Institute

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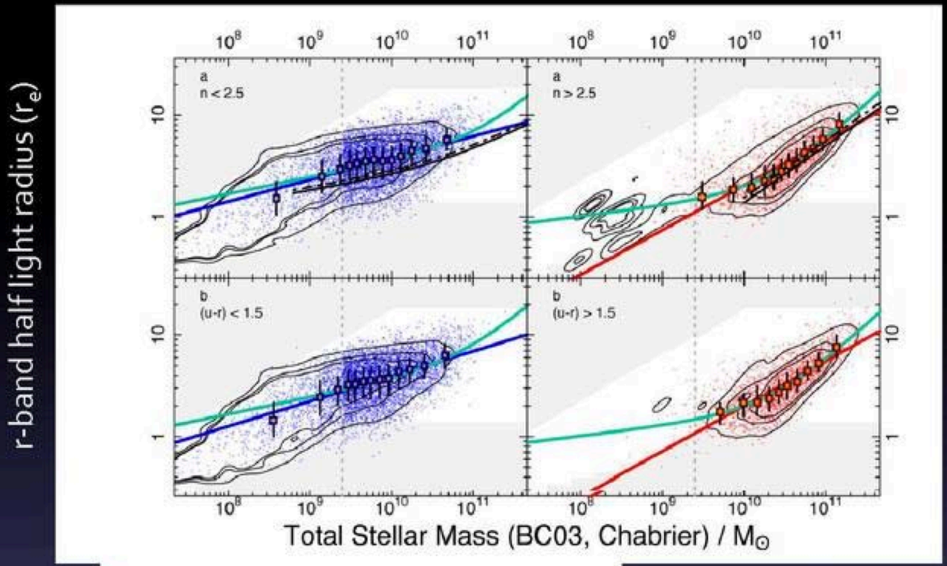
observed size-mass relation at z~0

disks

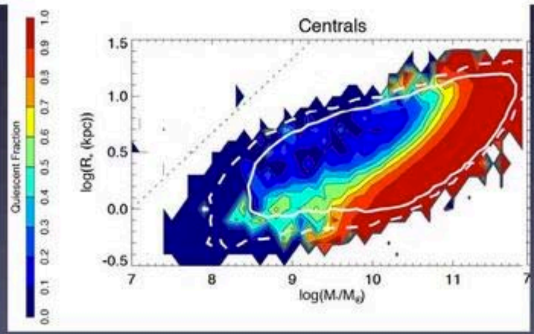
blue/
SF



spheroids

red/
quiescent

Lange et al. 2014



Omand et al. 2014

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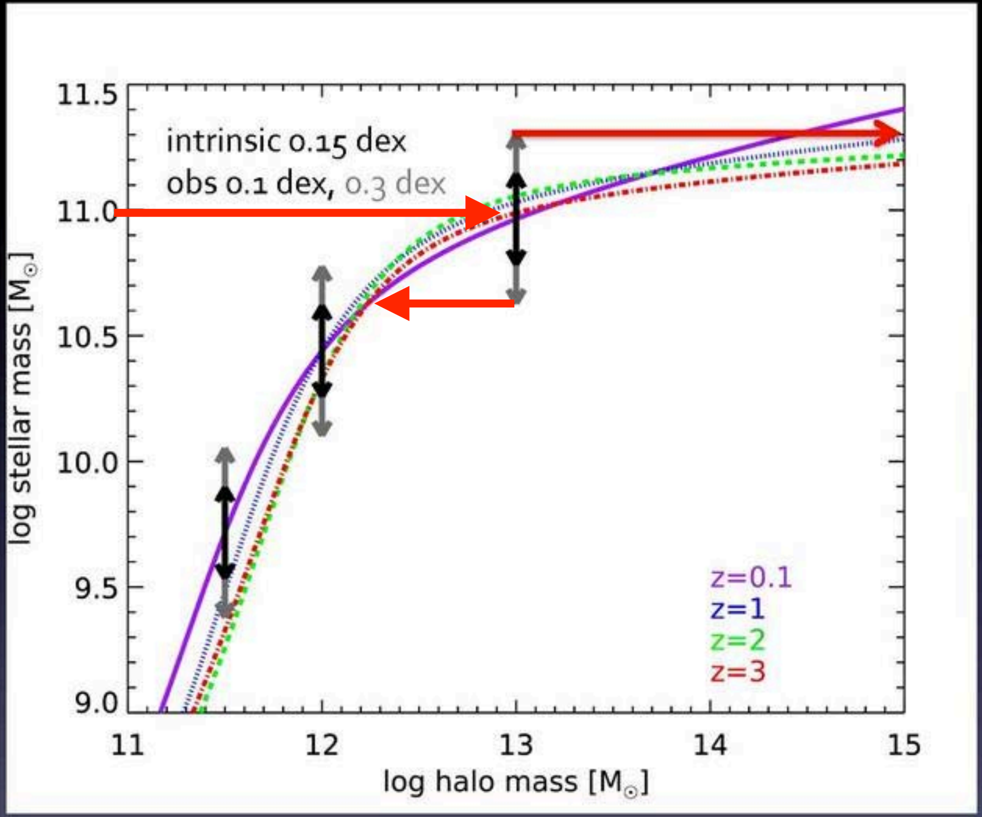
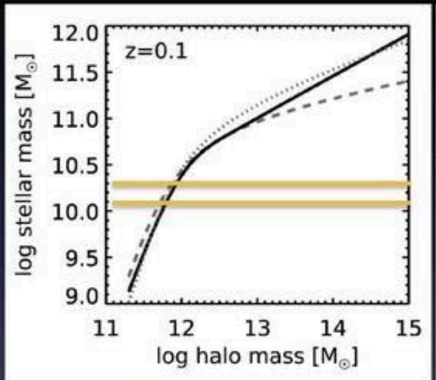
beware backwards modeling!



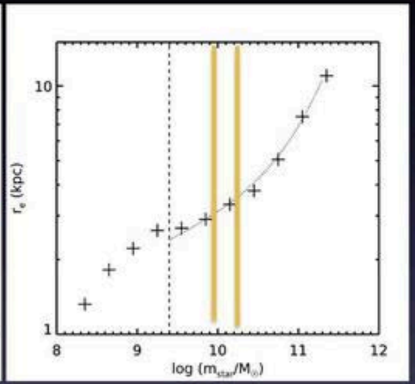
SMHM relation from Behroozi et al. 2013

Bolshoi-Planck halo catalog contains halo & sub-halo masses, spin parameters, and radii

Introducing the 'forward modeling' approach



assign stellar masses to halos (including scatter & errors)



compare $\langle R_h \rangle$ or $\langle \lambda R_h \rangle$ for halos with observed radii for galaxies in a stellar mass bin

$$\mathrm{SRHR} = \frac{\langle r_e(m_*)\rangle}{\langle R_h(m_*)\rangle}$$

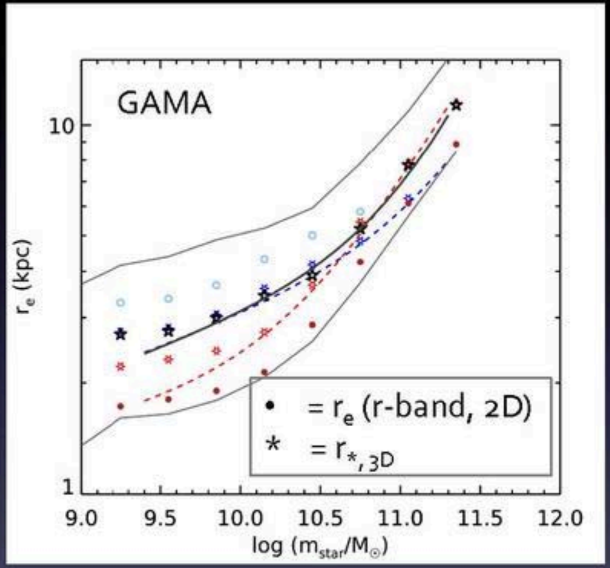
$$\mathrm{SRHR}\lambda = \frac{\langle r_e(m_*)\rangle}{\langle \lambda R_h(m_*)\rangle}$$

rss et al. arXiv:1701.03526

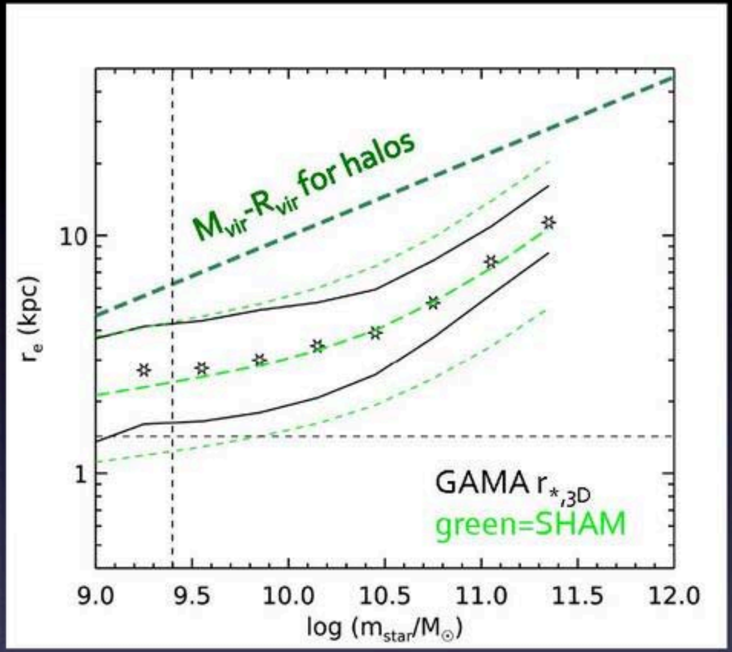
(in what follows, angle brackets denote medians)

observations

- GAMA (DR2; Liske et al. 2015) (r<19.8; 144 deg. sq.; 0.01<z<0.12)
- CANDELS (Koekemoer et al. 2011; Grogin et al. 2011) H_{160}<24.5; 0.1<z<3)
- single component Sersic fits to light profiles (r_e, n_s)
- type-dependent conversion from 2D half-light to 3D half stellar mass radii



we do not attempt to split by galaxy type in our analysis



using a constant value of SRHR=0.018 or SRHRλ=0.5, the slope of the size-mass relation appears to be beautifully reproduced by the SHAM!

lines show 16th & 84th percentiles in r_e or λR_h

rss et al. 2017

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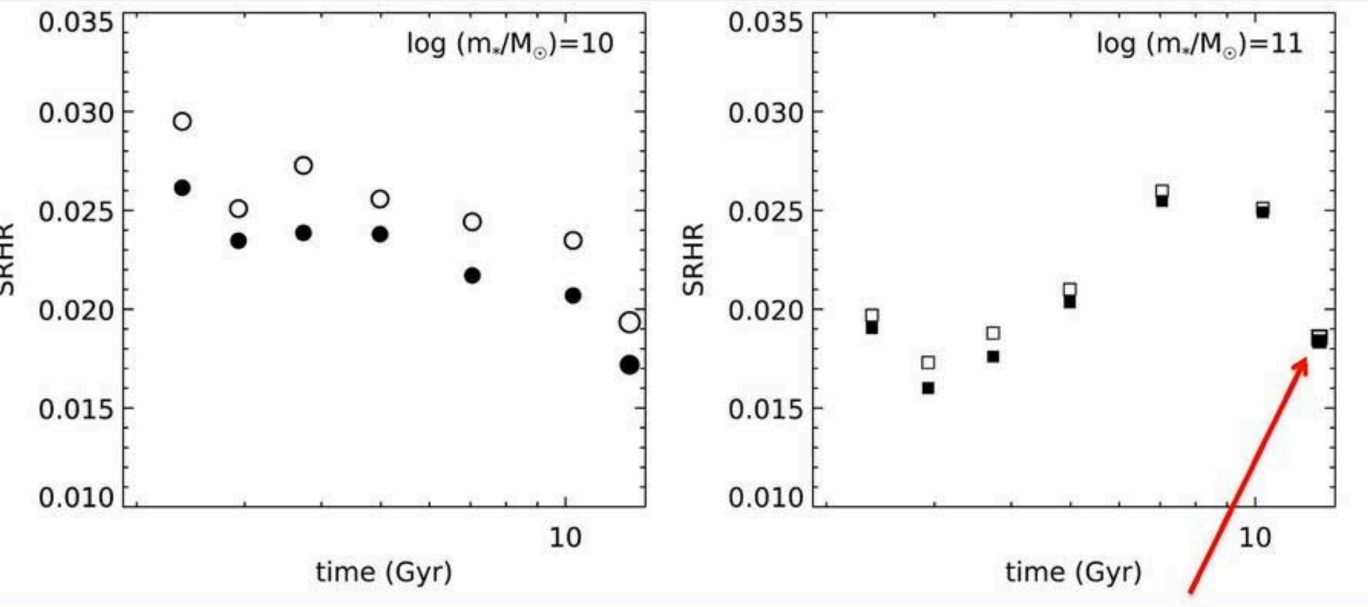
mild decrease for low-mass galaxies

mild increase for massive galaxies



empty symbols - ratio of means
filled symbols - ratio of medians

sizes underestimated due to extended light/second component?

rss et al. 2017

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summary

- intrinsic and observational scatter in SMHM must be properly accounted for in linking galaxy and halo properties
- relationship between galaxy size and halo virial radius shows hints of:
  - decrease with stellar mass above a critical mass (few 10^{10} M_{sun}) at z>1
  - decrease over cosmic time for galaxies below m_{crit}
  - increase with cosmic time for galaxies above m_{crit}
- dispersion in galaxy size at fixed mass is similar to dispersion in halo spin

Only a Weak Correlation between the Spins and Sizes of Galaxies and Their Host Halos

Fangzhou Jiang

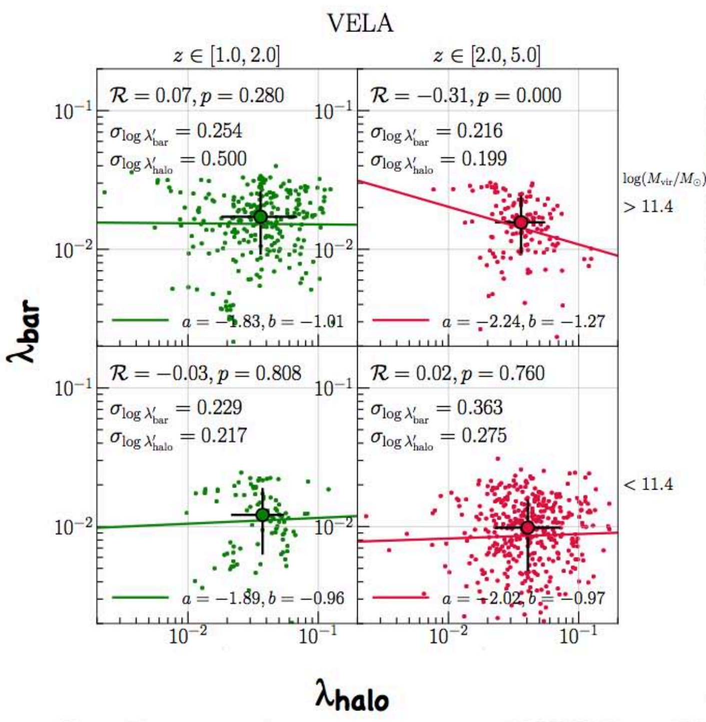
Hebrew University of Jerusalem

work in progress

Avishai Dekel, Omer Kneller, Daniel Ceverino, **Joel R. Primack**, Andrea Maccio, Aaron Dutton, **Rachel Somerville**, Shy Genel, Sharon Lapiner, Tomer Nussbaum, Omry Ginzburg

GalHalo, KITP, May 17

λ_{gal} - λ_{halo} correlation



$M_{vir} \approx 10^{11.4} M_{sun}$: characteristic mass at which galaxies "compactify" to form "blue nuggets" (BN)

regression line: $\log \lambda_g = a + (1+b) \log \lambda_h$

- No correlation between λ_{gal} and λ_{halo} at $z \geq 1$ in different M_{vir}, z bins
- λ_{gal} is higher for higher-M_{vir} (post-compaction) systems

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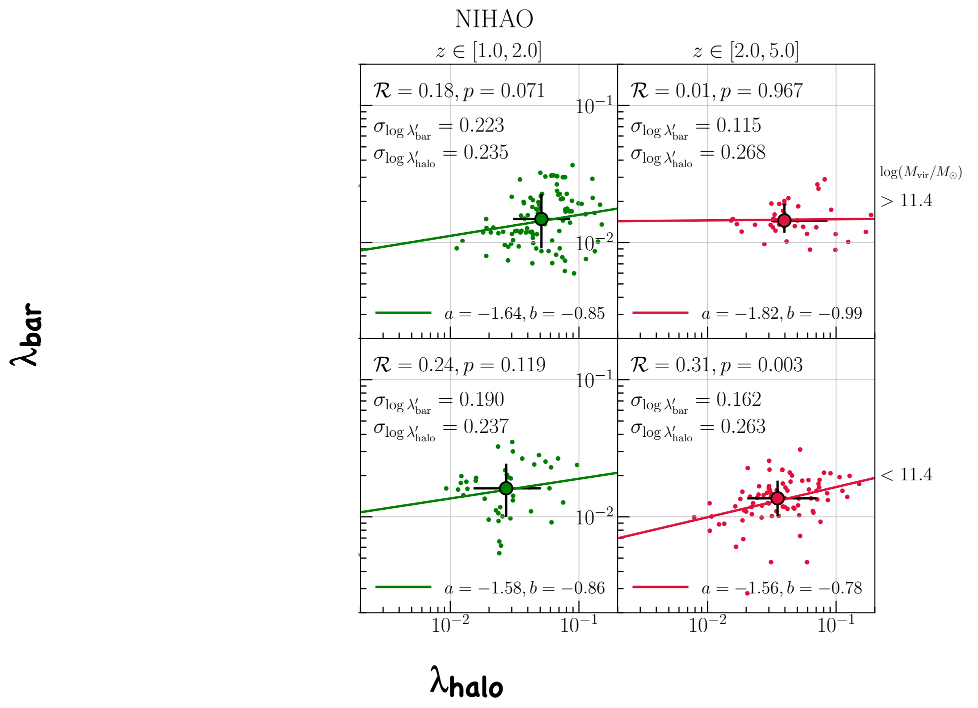
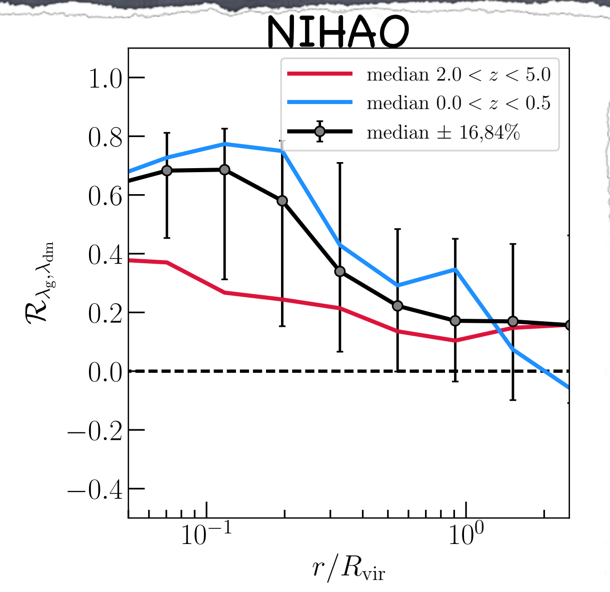
λ_{gal} - λ_{halo} correlation



regression line: $\log \lambda_g = a + (1+b) \log \lambda_h$

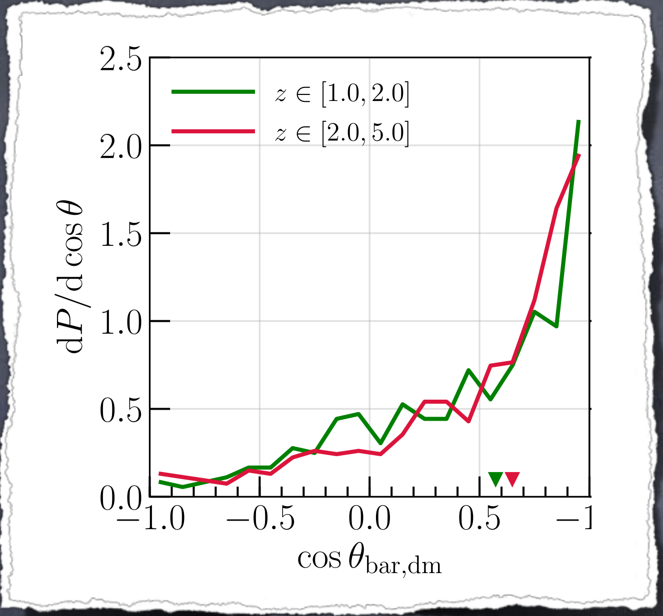
- the same, lack of correlation at $z \geq 1$
- a correlation develops towards lower z ($-1<b<0$)

λ_{gal} and $\lambda_{inner\ halo}$ still have a correlation



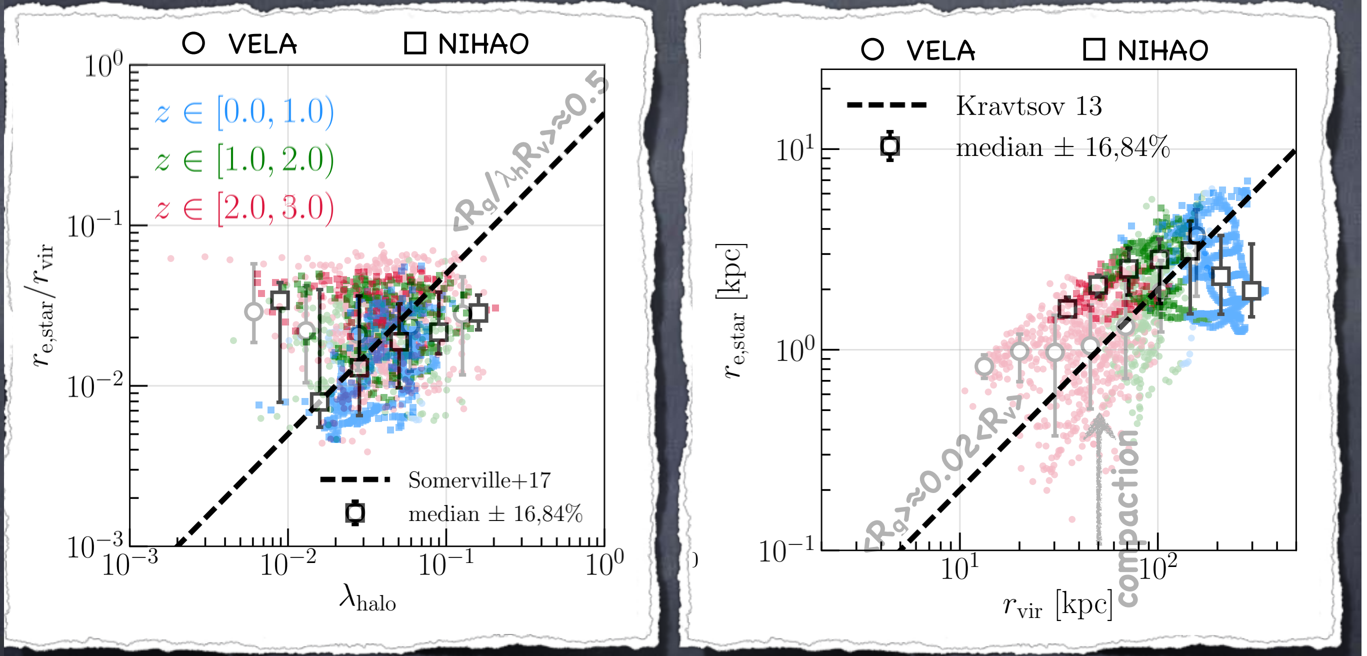
- fairly strong correlation between λ_g and $\lambda_{dm}(<r)$ for r out to $0.2R_{vir}$
- consistent with EAGLE (Zavala+16): tight correlation between the loss of sAM of the inner (0.1Rvir) DM and that of the baryons, by following Lagrangian volumes

Alignment



- strong correlation of orientation: $\langle\cos\theta\rangle$ = 0.72 (gas-DM), 0.61 (stars-DM)
- the mechanisms smearing out the λ_g - λ_h correlation should not randomize the alignment too much
- alignment weakens slightly towards lower-z, also seen in Illustris (Zjupa & Springel 2017)

Is λ_h really relevant for galaxy size?

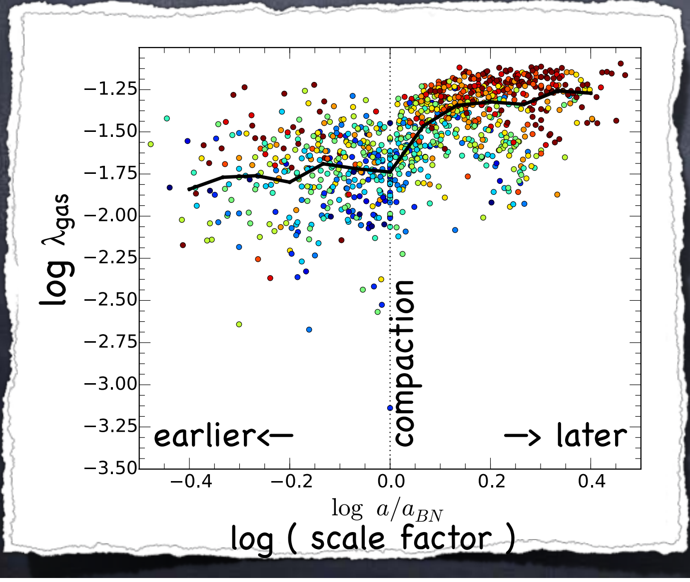


$$j_g \simeq R_g V_{\rm rot} \implies R_g \simeq \frac{j_g}{j_h}\frac{j_h}{R_{\rm vir}V_{\rm vir}}\frac{V_{\rm vir}}{V_{\rm rot}}R_{\rm vir} \simeq \lambda_h R_{\rm vir}$$

---

possible reasons for a λ_g/λ_h - λ_h anti-correlation

- **galaxy compaction** (Dekel & Burkert 14)
  - a system starts with low λ_h and thus low λ_{gas}
  - low λ_{gas} -> high Σ_{1kpc} (**compaction**)
  - "Blue Nugget" (BN) forms -> high central SFR, gas depletion
  - freshly accreted gas with high λ_{gas} forms a ring



compaction happens at a characteristic mass scale

$M_{star} \approx 10^{9.7} M_{sun}$

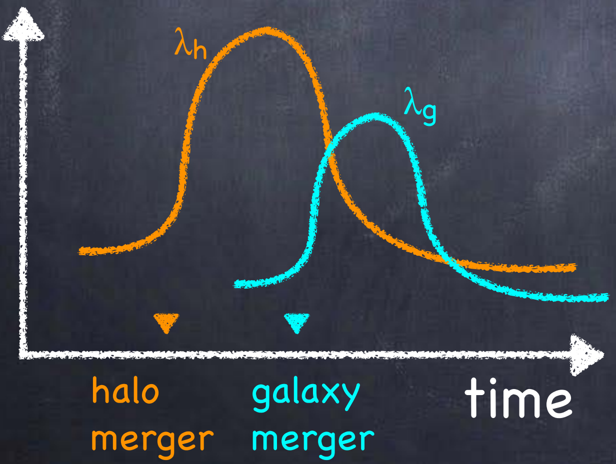
$M_{vir} \approx 10^{11.4} M_{sun}$

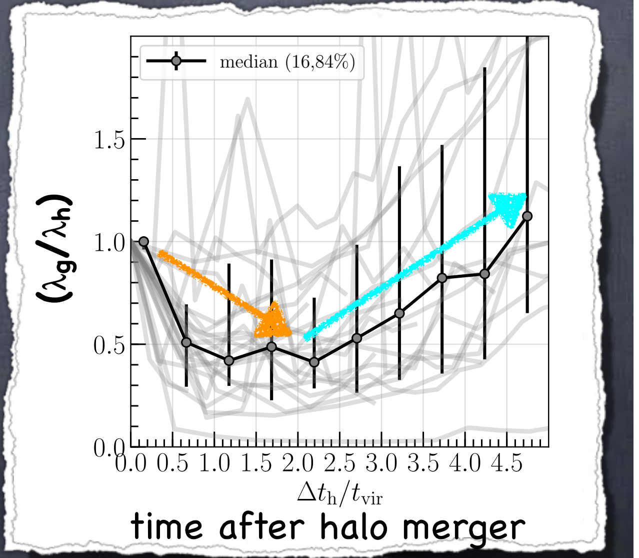
Dekel+17 in prep

---

possible reasons for a λ_g/λ_h - λ_h anti-correlation

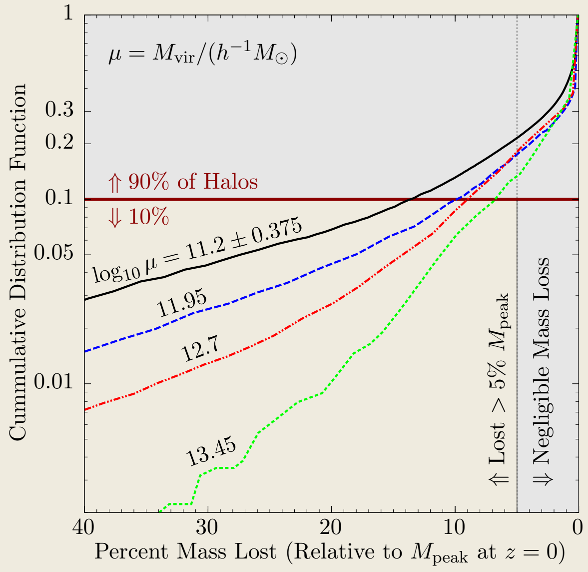
- **mergers**
  - halo mergers cause λ_h to rise (orbital AM dominating λ_h), while λ_g is untouched yet
  - halo re-virializes -> λ_h drops, while λ_g temporarily rises due to the subsequent galaxy merger



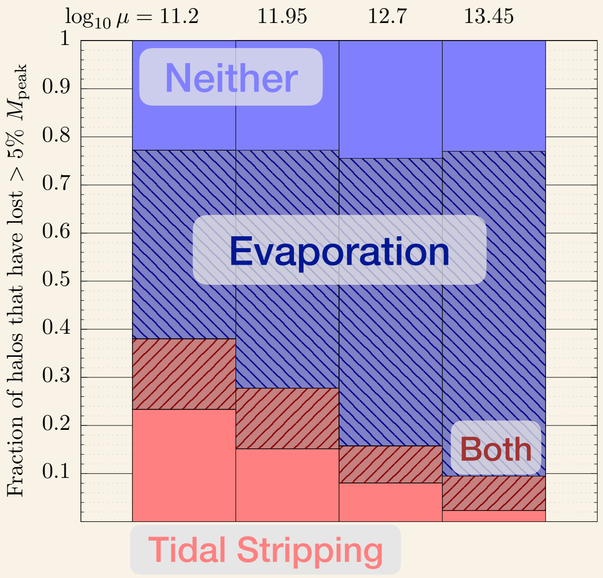


Causes & Consequences of Halo Mass Loss
Christoph Lee's Poster

2 Is halo mass loss common?



3 Why do halos lose mass?



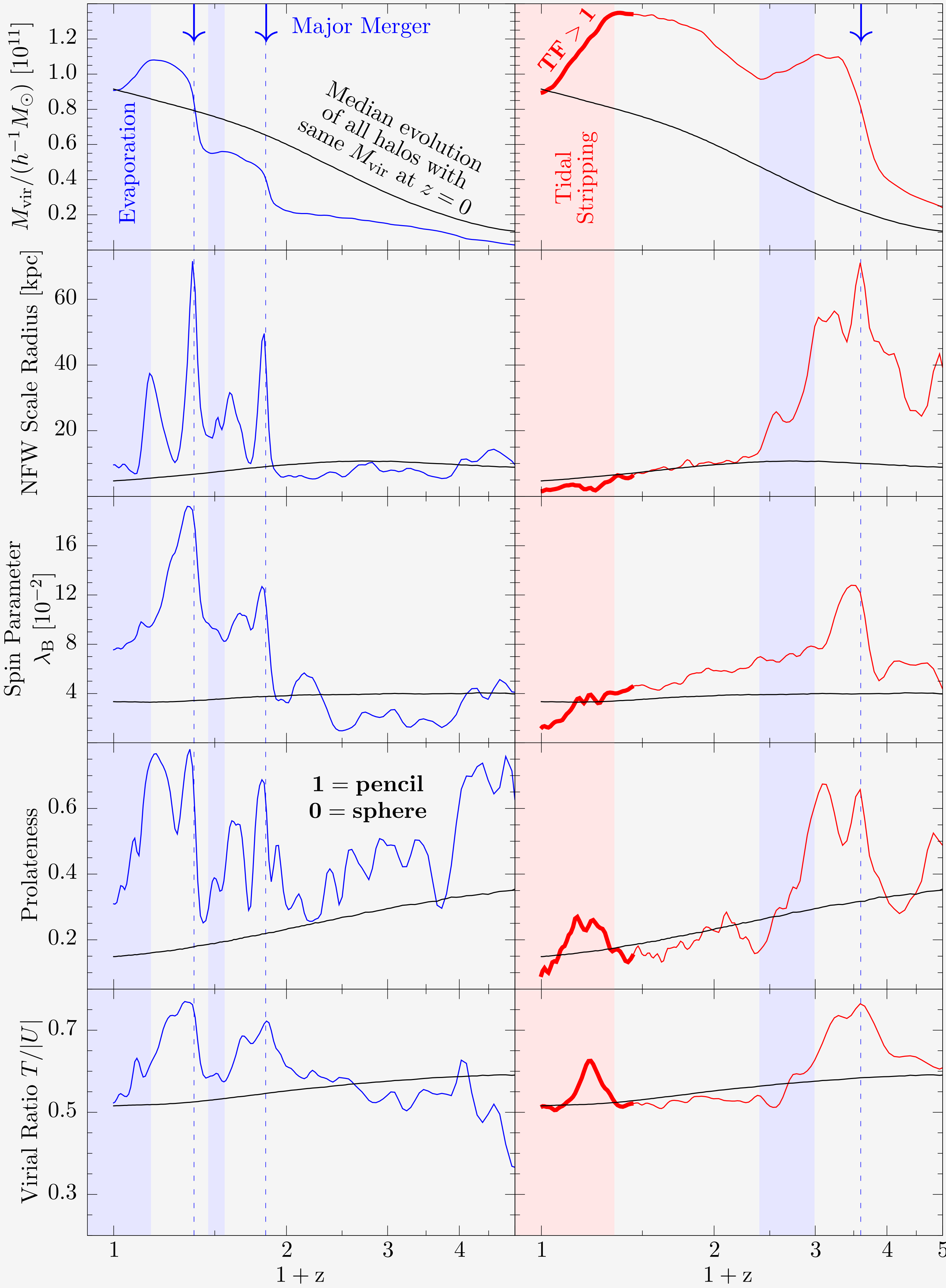
Most halos lose mass via evaporation after a major (or minor) merger. Pure tidal stripping accounts for 23% of low mass halos that have lost mass, but very few high mass halos. Some halos experience both evaporation and tidal stripping. Around 22% of halos that have lost mass neither had a recent major merger nor experienced tidal stripping (rather, these typically experienced evaporation after a minor merger).

4 What happens when halos lose mass?

Tidal Stripping:
Strong tidal force from a nearby massive halo removes loosely bound particles from a halo. 40% of tidally stripped low mass halos lose more than 20% of their peak mass. Tidally stripped halos develop:

- **Low NFW scale radius** (high concentration) due to steepening outer profile
- **Low spin parameter** due to preferential removal of high angular momentum material
- **Low prolateness** (they become rounder) due to preferential removal of particles on highly elliptical orbits.

Evaporation:
Major mergers typically cause **temporary jumps in NFW scale radius, spin parameter, and shape**. As halos relax after a merger, they shed high energy material (evaporate) and **settle back to lower values of scale radius, spin parameter, shape, and viral ratio**. After a major merger, halos typically lose 5-15% of their peak mass through evaporation.


Examples of individual halo evolution

Kavli Institute for Theoretical Physics
University of California, Santa Barbara

Quantifying and Understanding the Galaxy — Halo Connection
May 15-19, 2017

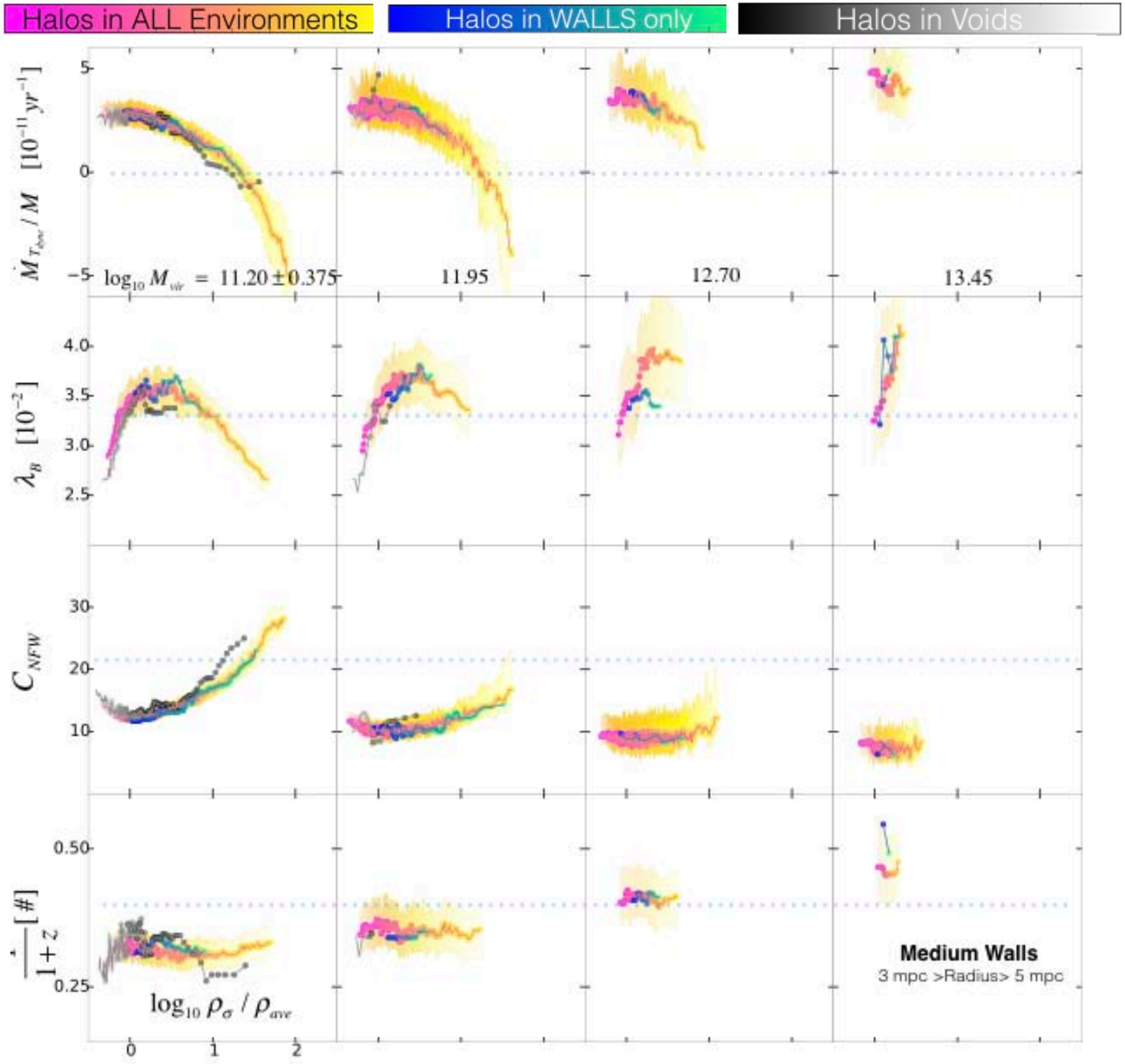
Structural Evolution in the Galaxy-Halo Connection, and Halo Properties as a Function of Environment Density and Web Location

Joel Primack

- **SHARC: ~0.3 dex dispersion in halo $\dot{M}/M \Rightarrow$ similar dispersion in $\dot{M}*/M*$ on the Main Sequence**
- **Abundance matching with radii & mergers $\Rightarrow R*{\sim}M*^{1/3}$ goes to $R*{\sim}M*^2$ after quenching, & quenching downsizing: Σ_1 grows till quenching, $\Sigma_{1,\mathrm{quench}}$ larger & at higher z for higher M***
- **Galaxy 3D half-mass radii $R*_{3D} \approx 0.5 < \lambda_{\mathrm{Bullock}} > R_{\mathrm{halo}}$ for $0 < z < 3$, but $<\lambda_{\mathrm{Peebles}}>$ ⬇ with z⬆**
- **Halo properties $\dot{M}/M$, λ, C_{NFW}, a_{LMM}, shape don't depend on web location at fixed density**
- **Spin λ 30% smaller at low density tests whether galaxy R* is determined by host halo λ**
- **Halo Mass Loss: Evaporation after Merger $\Rightarrow C_{\mathrm{NFW}}$ ⬇ & λ⬆, Tidal Stripping $\Rightarrow C_{\mathrm{NFW}}$ ⬆ & λ⬇**
- **Galaxy Luminosity-Halo Mass, Stellar Mass-Halo Mass relations are independent of density**
- **Forming galaxies are elongated & oriented along filaments, become round after compaction**

Halo Properties Independent of Web Location at the Same Density

Tze Ping Goh, Christoph T. Lee, Joel R. Primack, Miguel Aragon Calvo, Peter Behroozi, Aldo Rodríguez-Puebla, Doug Hellinger, Avishai Dekel, Kathryn Johnston (in preparation)

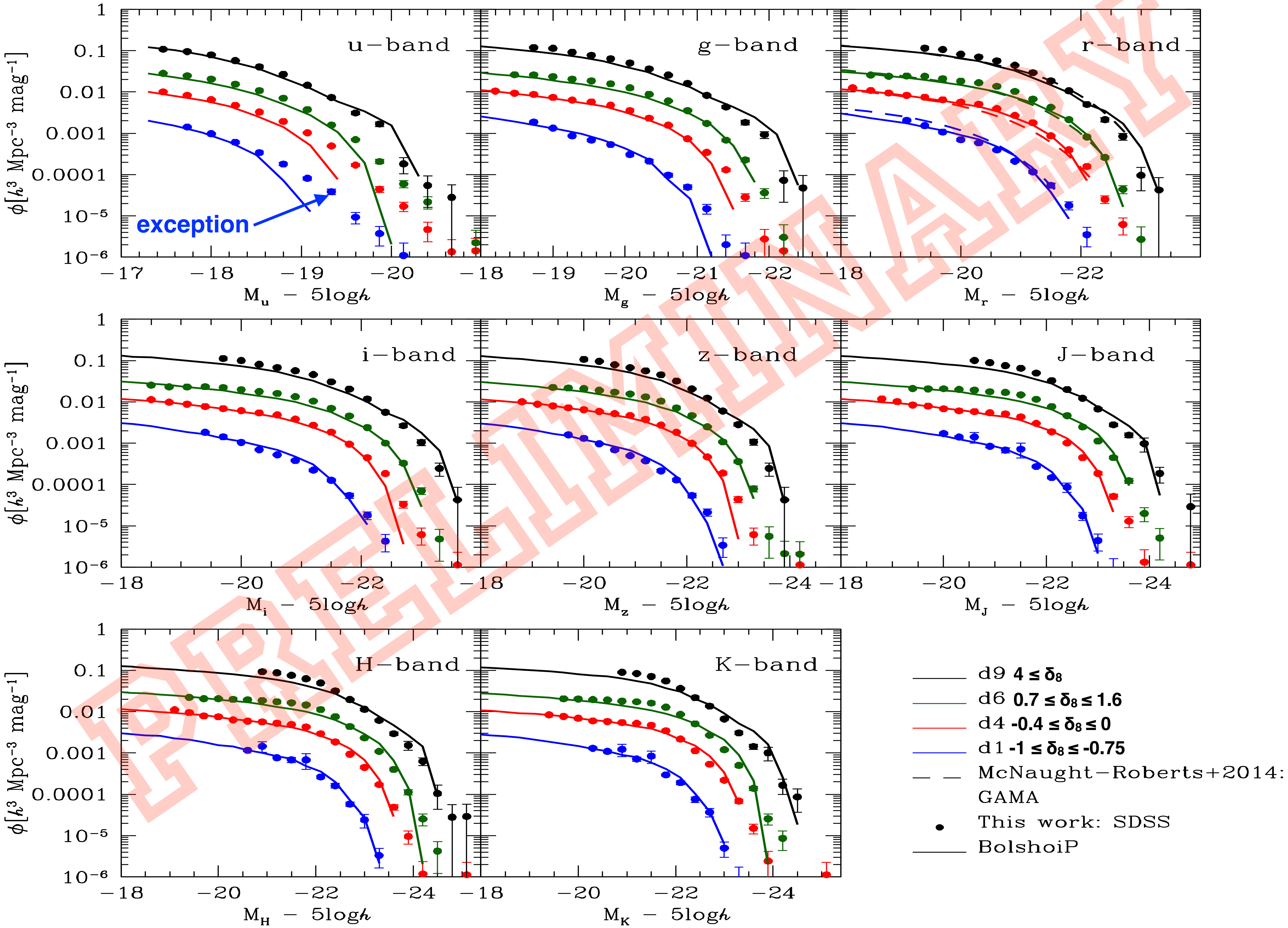


At the same environmental density, halo properties are independent of cosmic web location. It doesn't matter whether a halo is in a cosmic void, wall, or filament, what matters is the halos's environmental density. The properties studied are mass accretion rate, spin, halo concentration, scale factor of the last major merger, and prolateness. We had expected that a web's cosmic web location would matter for at least some of these halo properties. That it does not is a significant discovery.

GAMA data show that the galaxy luminosity function is also independent of web environment at fixed density (Eardley et al. MNRAS 2015). This contrasts with the finding that the halo mass function is dependent on web location at the same density using the v-web (Metuki, Liebeskind, Hoffman 2016).

Abundance Matching LF and MF Are Independent of Density

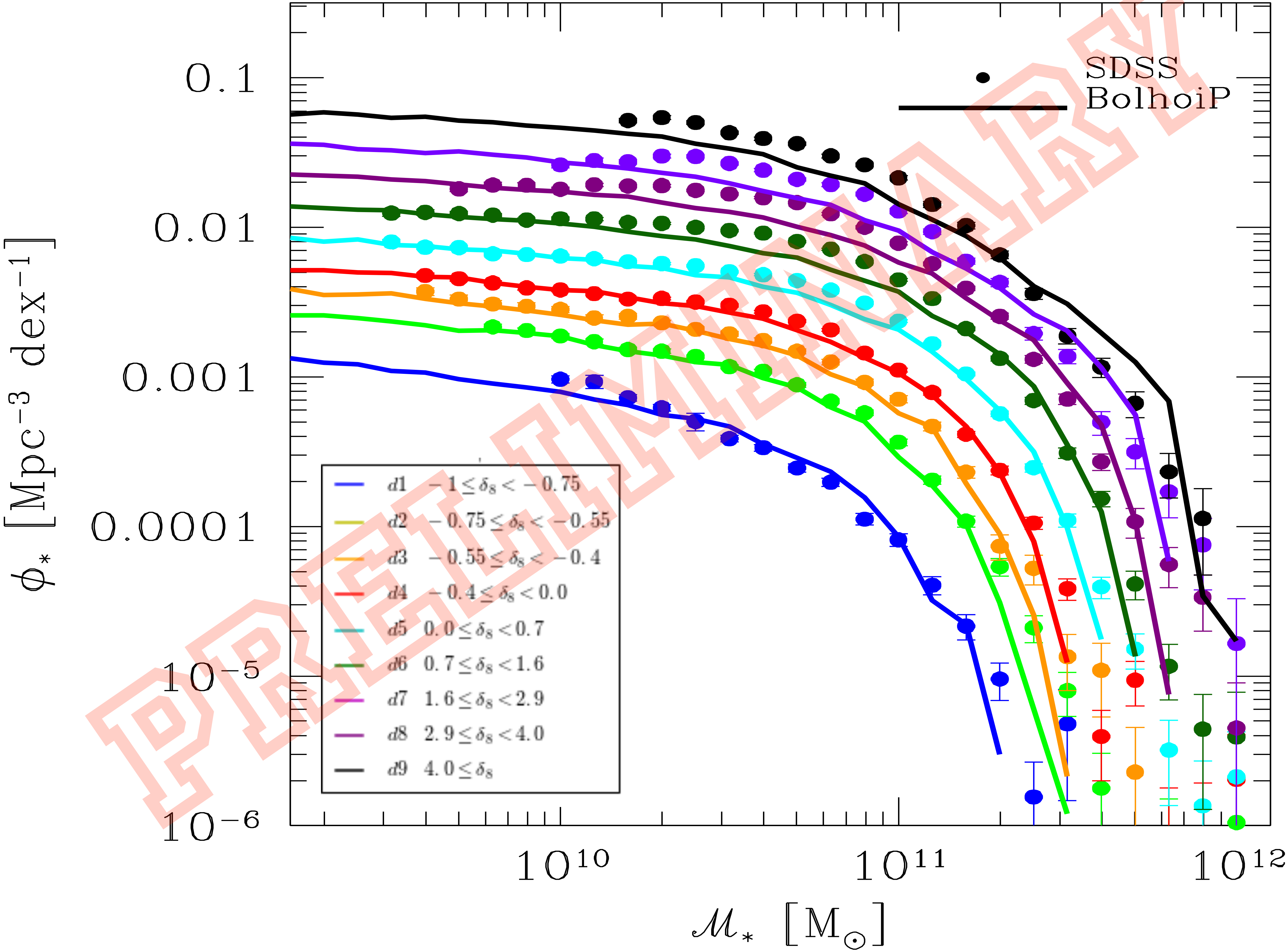
Radu Dragomir, Aldo Rodríguez-Puebla, Joel R. Primack, Christoph T. Lee,
Peter Behroozi, Doug Hellinger, Avishai Dekel (in preparation)

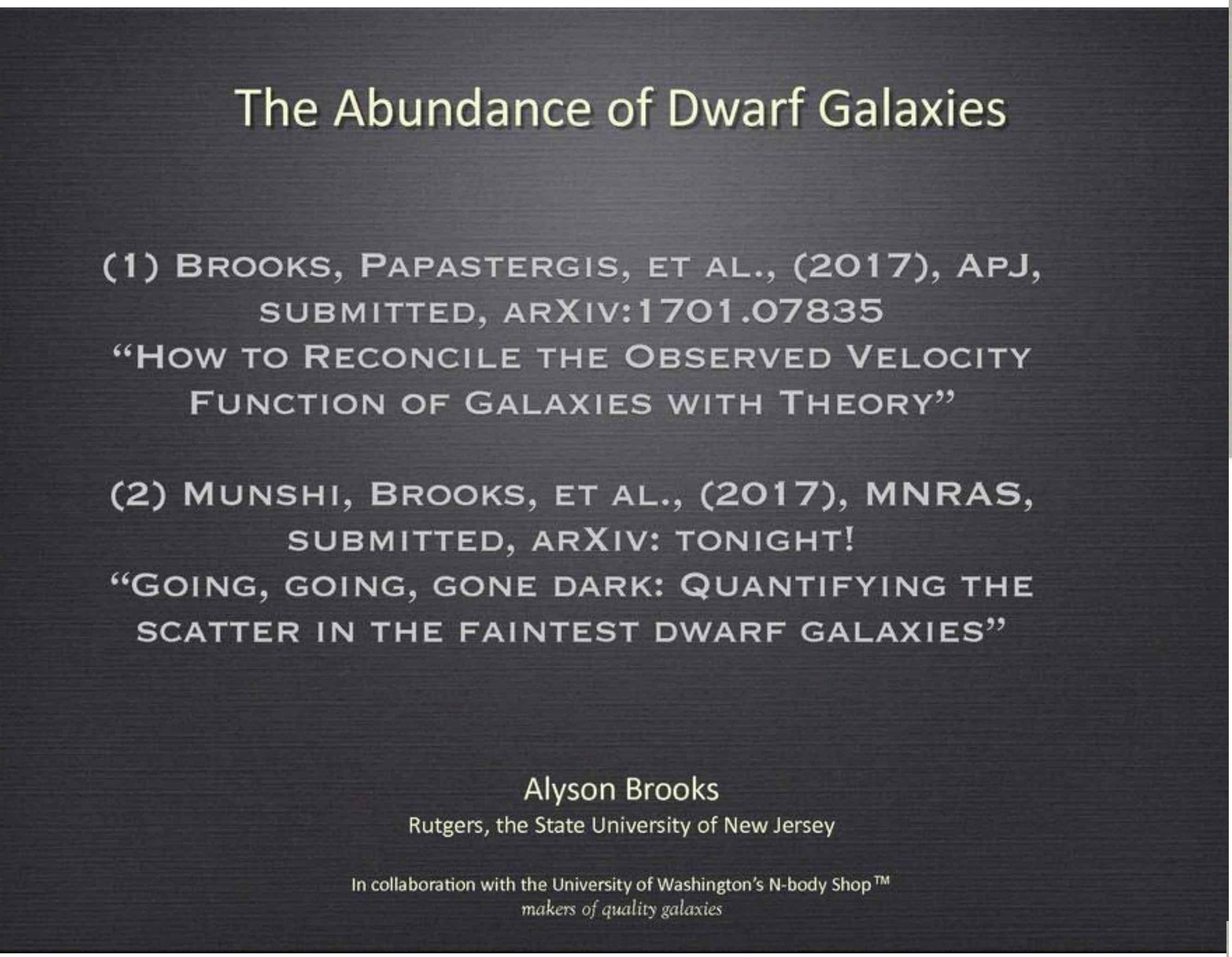


Abundance Matching LF and MF Are Independent of Density

Radu Dragomir, Aldo Rodríguez-Puebla, Joel R. Primack, Christoph T. Lee, Peter Behroozi, Doug Hellinger, Avishai Dekel

(in preparation)





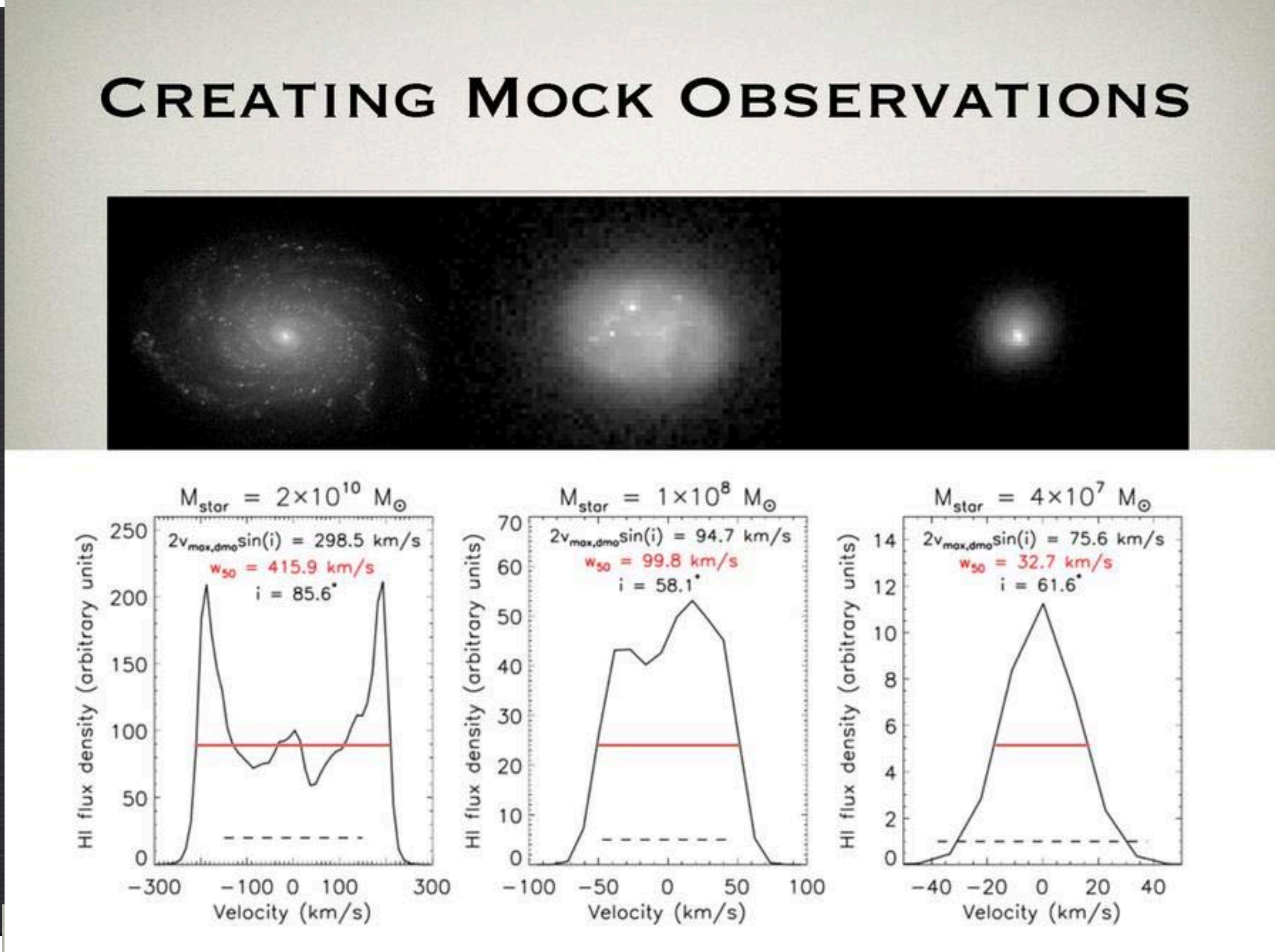
The Abundance of Dwarf Galaxies

(1) BROOKS, PAPASTERGIS, ET AL., (2017), APJ, SUBMITTED, ARXIV:1701.07835
"HOW TO RECONCILE THE OBSERVED VELOCITY FUNCTION OF GALAXIES WITH THEORY"

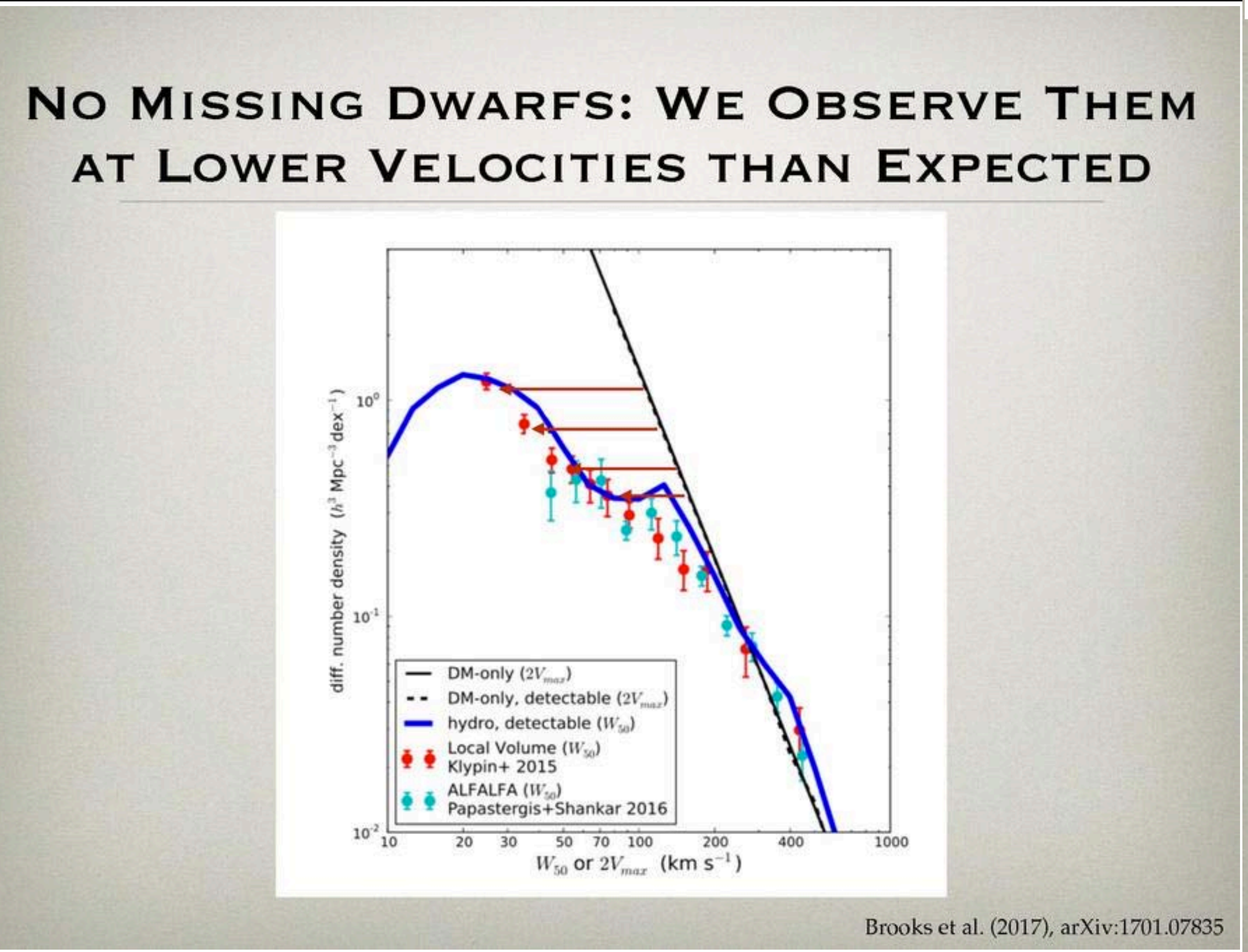
(2) MUNSHI, BROOKS, ET AL., (2017), MNRAS, SUBMITTED, ARXIV: TONIGHT!
"GOING, GOING, GONE DARK: QUANTIFYING THE SCATTER IN THE FAINTEST DWARF GALAXIES"

Alyson Brooks
Rutgers, the State University of New Jersey

In collaboration with the University of Washington's N-body Shop™
makers of quality galaxies

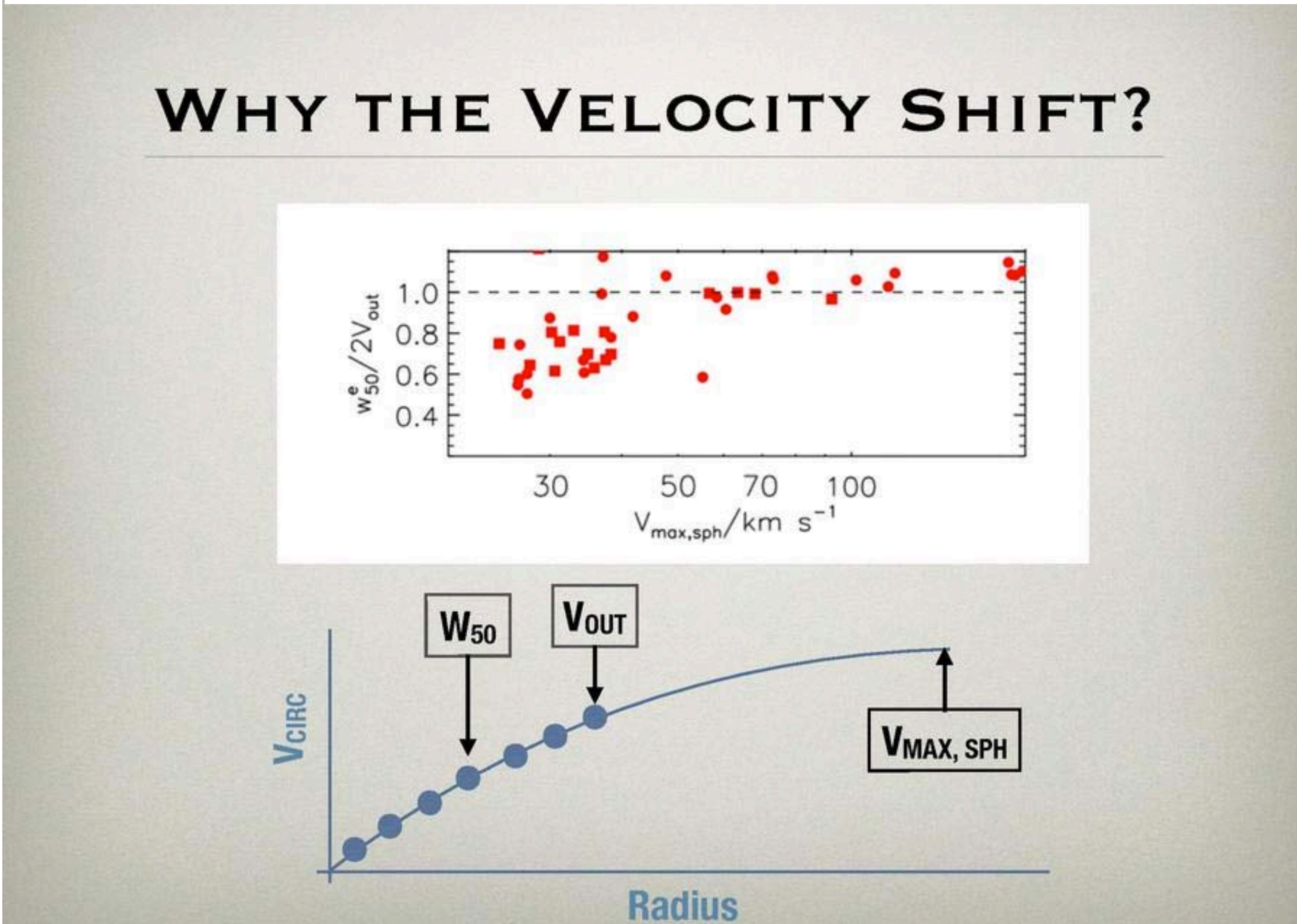


CREATING MOCK OBSERVATIONS

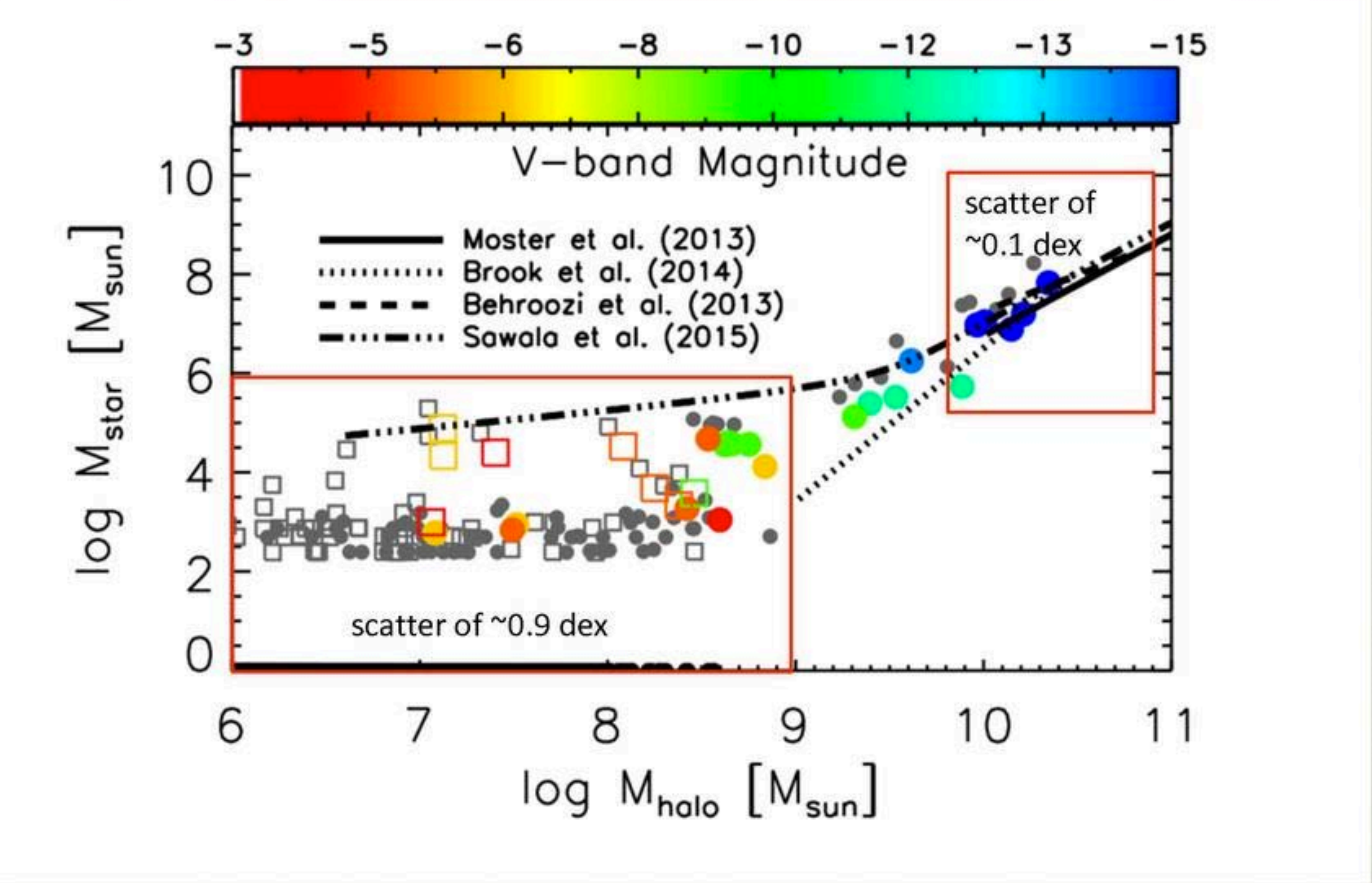


NO MISSING DWARFS: WE OBSERVE THEM AT LOWER VELOCITIES THAN EXPECTED

Brooks et al. (2017), arXiv:1701.07835

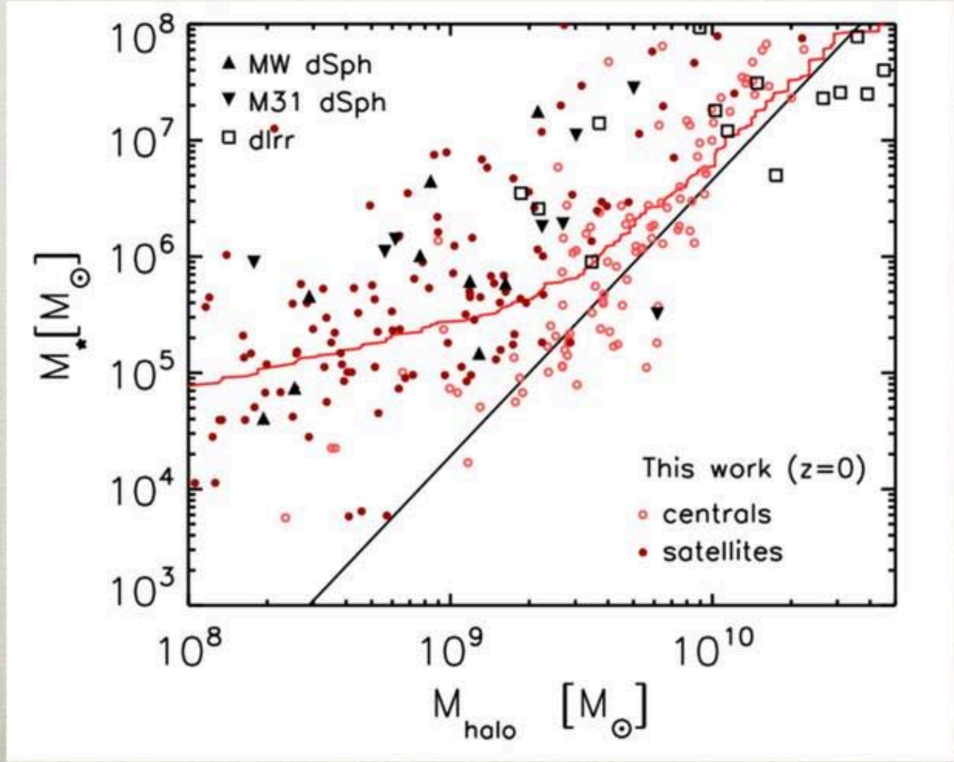


WHY THE VELOCITY SHIFT?



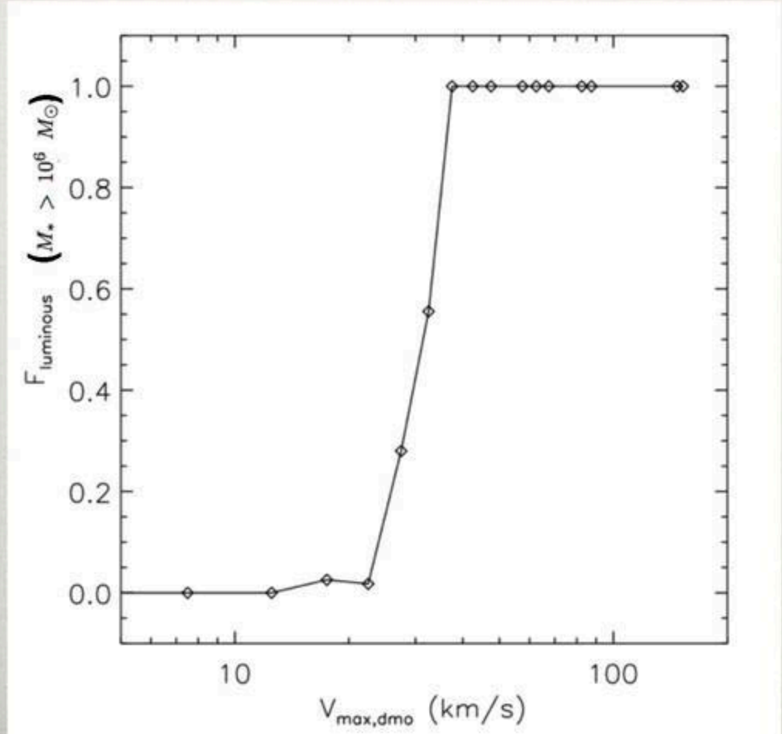
Munshi et al. (submitted)

THE "BEND" IS DUE TO THE INCLUSION OF SATELLITES



Sawala et al. 2015

ALSO CONSIDER DETECTABILITY



Brooks et al. (2017), arXiv:1701.07835

CONCLUSIONS

- Starting from the *abundance* of dwarf galaxies predicted in LCDM, the HIVF can be recovered. There is no missing dwarf problem in the field.
- The scatter in the SMHM relation in low mass halos increases with decreasing halo mass. There is no one-to-one assignment of stellar mass to halo mass.
- The "bend" at low halo masses found by Sawala et al. (2015) is due to the inclusion of satellites.
- The increased scatter at low masses leads to a prediction of a steeper stellar mass function in the ultra-faint dwarf galaxy mass range, currently being probed by DES, HSC, MagLiteS, etc, and by LSST in the future.

The SAGA Project:
Satellites Around Galactic Analogs

Marla Geha (Yale)
Risa Wechsler, Yao-Yuan Mao

Erik Tollerud, Ben Weiner, Ben Hoyle
and the SAGA team

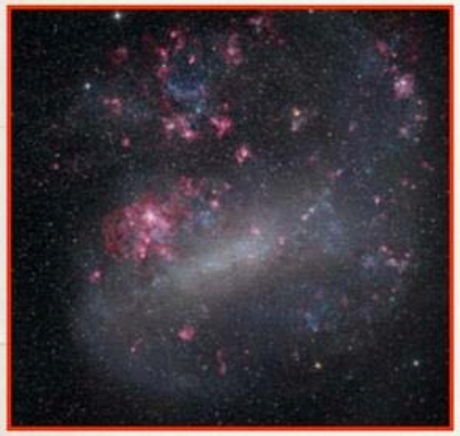
Paper and pretty images available at sagasurvey.org

Submitted on astro-ph 29.96 minutes ago.

The SAGA Project (Satellites Around Galactic Analogs)

SAGA Overall Goal:
Characterize the satellite populations down to M_r = -12.3 around 100 Milky Way-like galaxies.

LMC: $M_r = -18.5$



SMC: $M_r = -17.1$

Sgr: $M_r = -13.8$

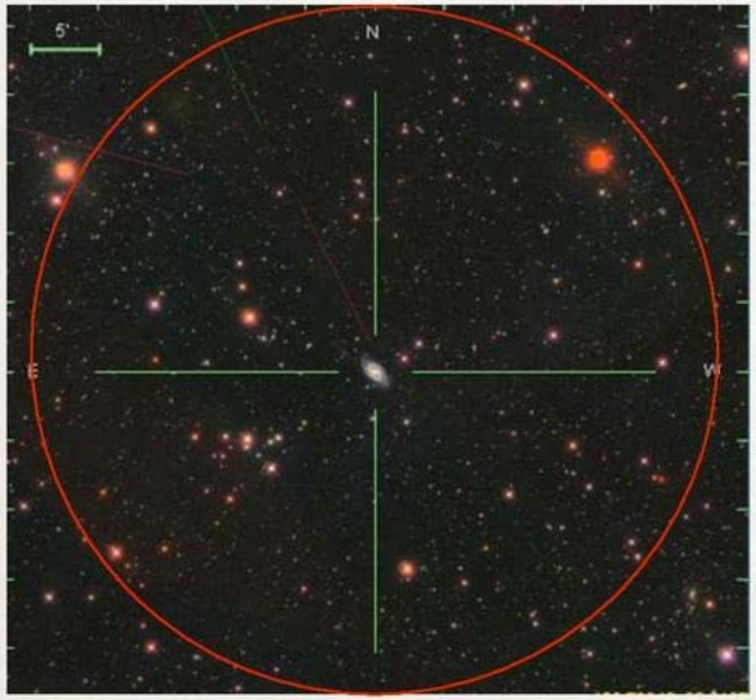
For: -13.7

Leo I: -12

Inside the Milky Way viral radius of 300 kpc, there are 5 satellites to $M_r = -12.3$
LMC/SMC are only star formation satellites.

The SAGA Project: Defining a Milky Way Analog

The virial radius of the Milky Way is **300 kpc**. Want to survey satellites inside this radius.

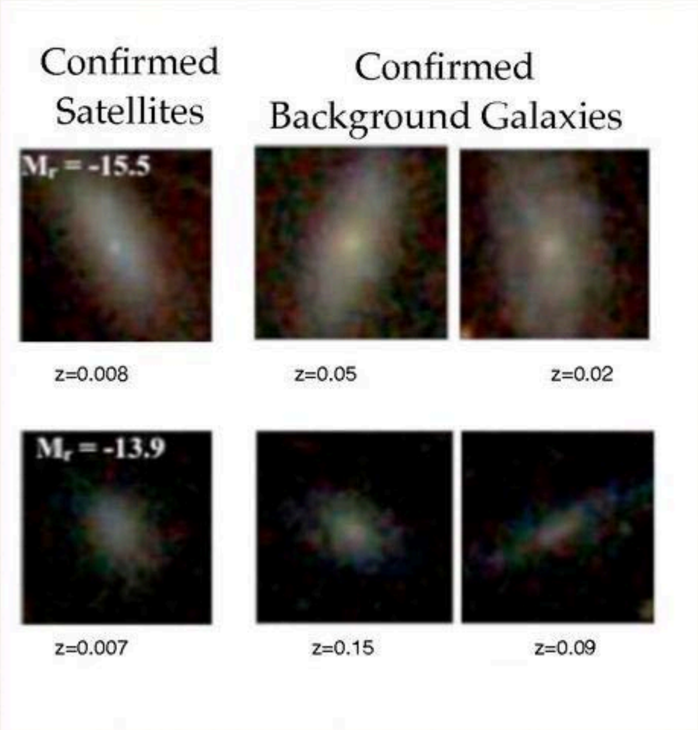


At 20 Mpc, a physical radius of 300 kpc is equivalent to ~ 1 degree

At 40 Mpc, r = 21 is equivalent to $M_r = -12.3$

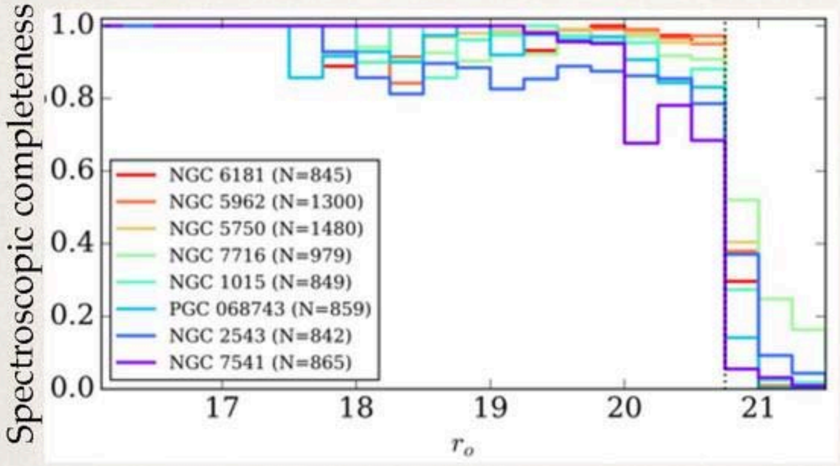
Within 1 deg, there are typically 10,000 objects down to r = 21

The SAGA Project: Photometric Redshifts @ Low-z



Photometric redshifts are not very informative at these redshifts.
D = 20 - 40 Mpc
z = 0.005 - 0.01

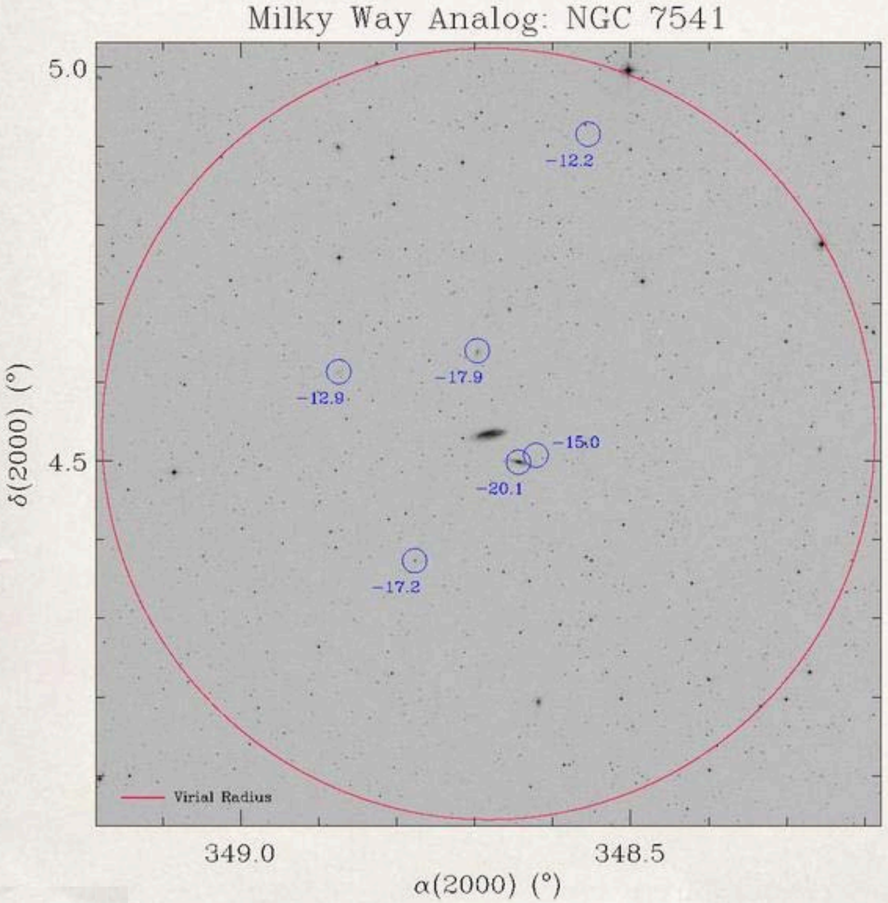
The SAGA Project: Completeness



8 MW hosts
with > 82% gri
completeness to $r_o < 20.75$

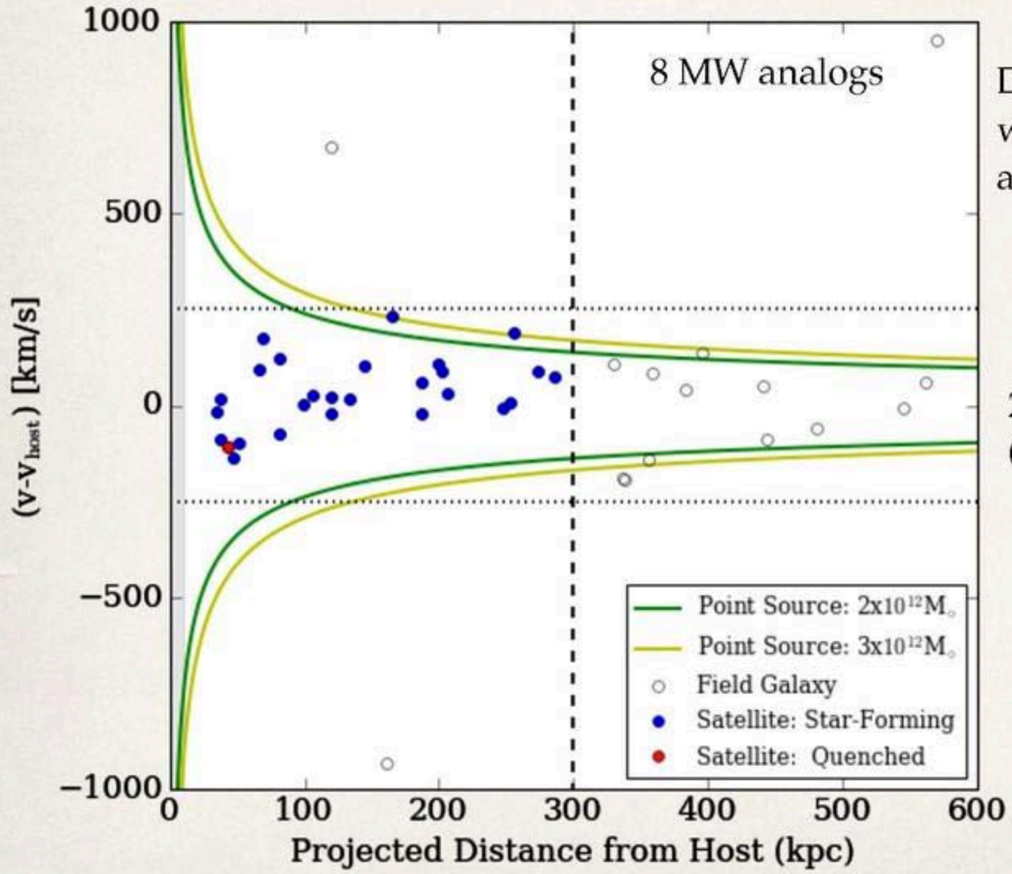
(1) SAGA Name	(2) NGC Name	(9) N_{sats}	(10) N_{tot} $r_o < 20.75$	(11) N_{gri} $r_o < 20.75$
Gilgamesh	NGC 5962	2	2995	98% [illegible]271/1300)
Odyssey	NGC 6181	9	1850	97% ([illegible]19/845)
Dune	NGC 5750	1	3557	97% ([illegible]33/1480)
AnaK	NGC 7716	2^1	2356	94% ([illegible]7/979)
Narnia	NGC 1015	2	1976	92% ([illegible]8/849)
OBrother	PGC 068743	4	1740	90% ([illegible]0/859)
StarTrek	NGC 2543	2	1719	85% ([illegible]16/842)
Catch22	NGC 7541	5^2	2198	82% [illegible]06/865)

The SAGA Project



6 satellites
(3 discovered)

The SAGA Project: Satellite Radial Distribution



Define satellite as galaxy
w/in projected virial radiu
and +/- 250 km/s

27 satellites around 8 host
(14 new satellites)

26 of 27 satellites are star forming

The SAGA Project: Satellite Luminosity Function