Title: Galaxy Evolution from Galaxy Clustering

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Abstract: While understanding the evolution of galaxies is one of the major themes of contemporary astronomy, most empirical studies focus only on the evolution of distribution functions (e.g., the luminosity function), effectively treating galaxies in isolation. The new generation of large imaging and spectroscopic surveys make it possible to measure the clustering of galaxies with different physical properties as a function of redshift, providing complementary information to traditional distribution function studies. This approach is especially powerful, because most theoretical models of galaxy evolution are based on the underlying distribution of dark matter halos and they make strong predictions for clustering evolution. To link galaxies to dark matter halos from the observed galaxy clustering, I will introduce the halo occupation distribution (HOD), which characterizes the relation between galaxies and dark matter halos by the probability distribution that a halo of virial mass M contains N galaxies of a given type, together with the spatial and velocity distributions of galaxies within halos. I will present HOD modeling results for galaxy clustering measured in several surveys, including the SDSS (z~0), the DEEP2 (z~1), and the NOAO Deep Wide-Field Surveys (0<z<1). I will demonstrate that, by linking galaxies to dark matter halos, HOD modeling of galaxy clustering opens a new direction in studying galaxy evolution (and cosmology).

Galaxy Evolution from Galaxy Clustering

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Yale Center for Astronomy and Astrophysics

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Feb 3, 2011

Collaborators

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Andreas Berlind	(Vanderbilt)	Michael Brown	(Monash)
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Jeremy Tinker	(NYU)	Martin White	(Berkeley)
David Weinberg	(OSU)	Yipeng Jing	(SHAO)
Jaiyul Yoo	(ETH/Berkeley)	Mike Kuhlen	(Berkeley)
Idit Zehavi	(CWRU)	Doug Rudd	(Yale)

Galaxy Evolution

- What is the assembly history of a galaxy? What does it depend on?
- What drives the evolution of galaxies?
- What is the relation between galaxies and dark matter halos?
- What is the origin of the bimodal distribution of galaxies? How do different populations evolve?
- How does the evolution of central and satellite galaxies differ?

Approaches to Study Galaxy Evolution

- Hydrodynamical Simulations of Galaxy Formation
- Semi-Analytic Model of Galaxy Formation
- Observations and Empirical Modeling of Galaxy Distribution Functions

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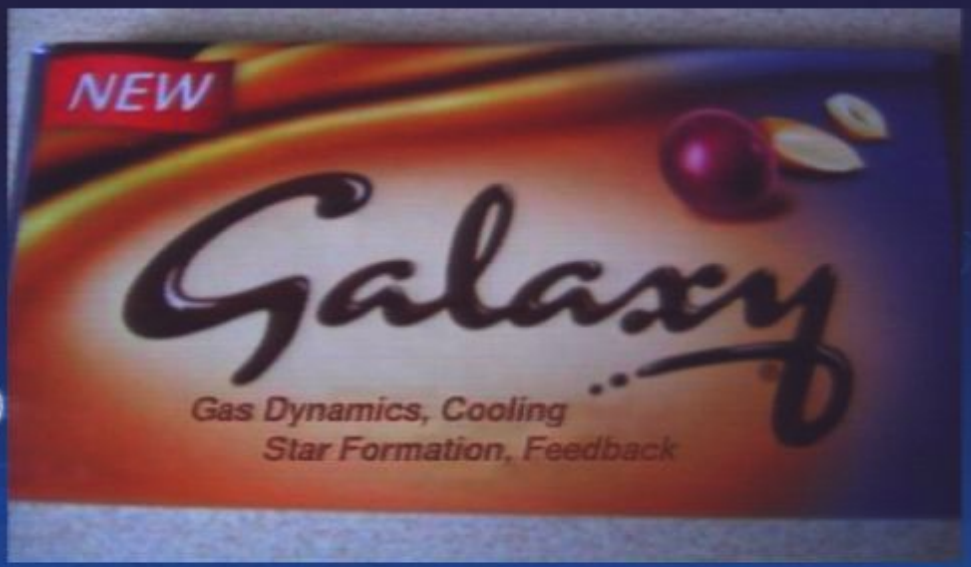
Main difficulty in theory of galaxy formation:

Gastrophysics

(baryon-related processes)



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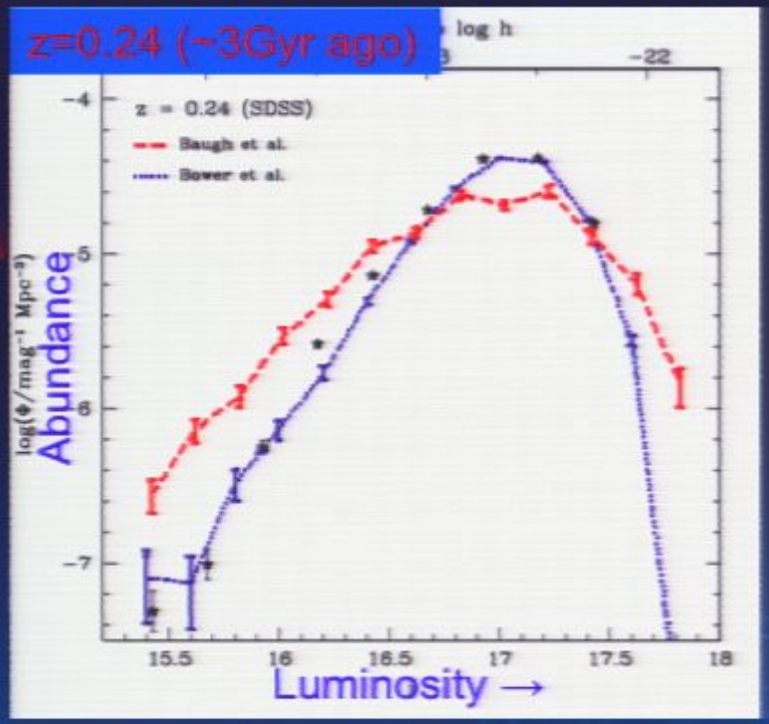

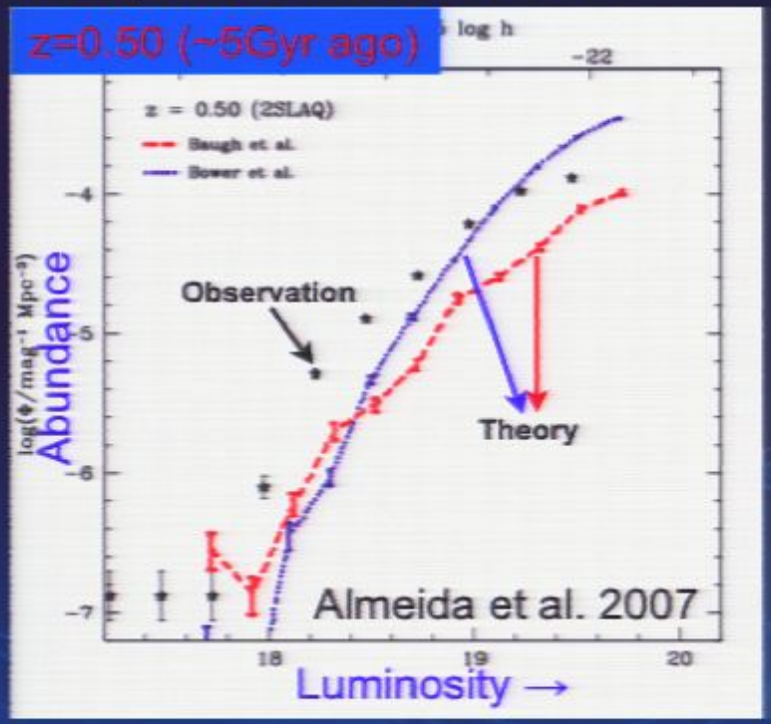

Theory is far from complete.

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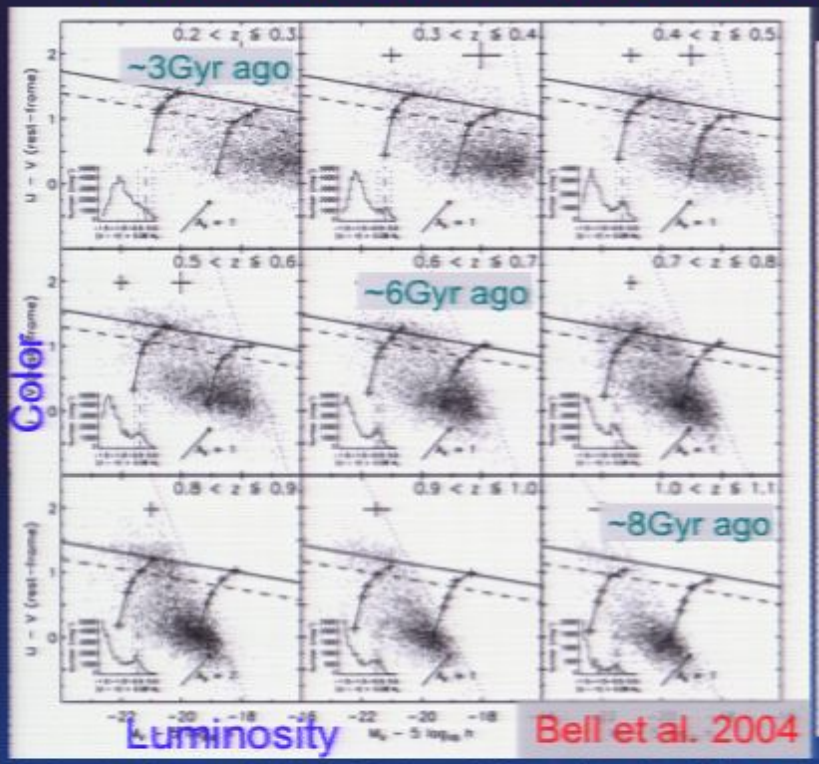
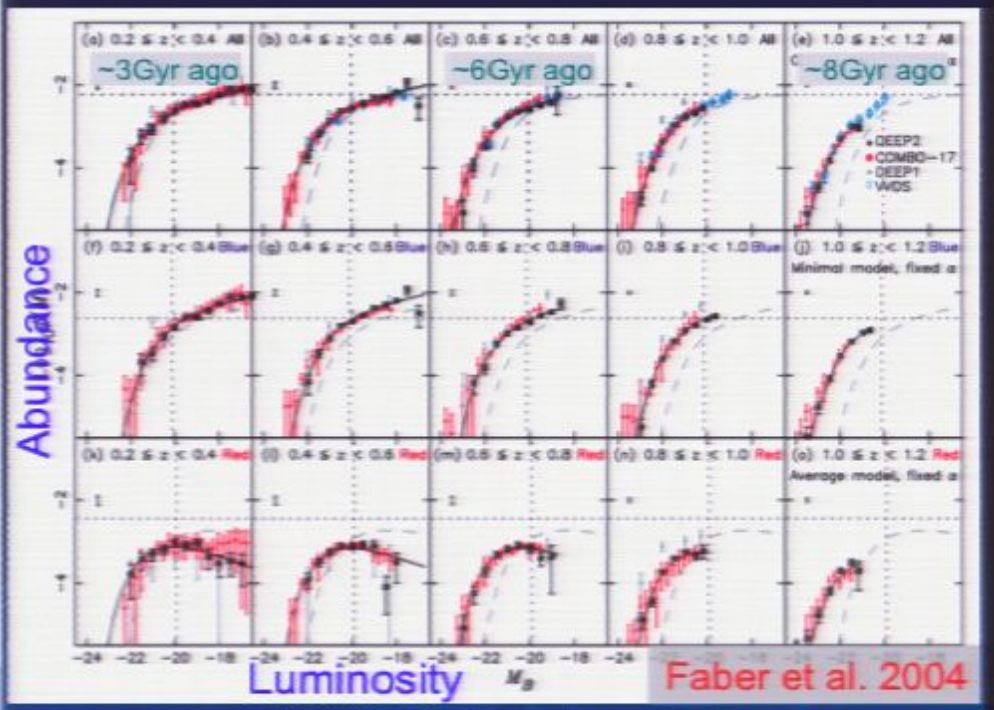


Evolution of the Color-Magnitude Diagram



Evolution of the Luminosity Functions

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In between theory and observation

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In between theory and observation

Make use of observed galaxy clustering and theory of dark matter halo growth

observation: bright side

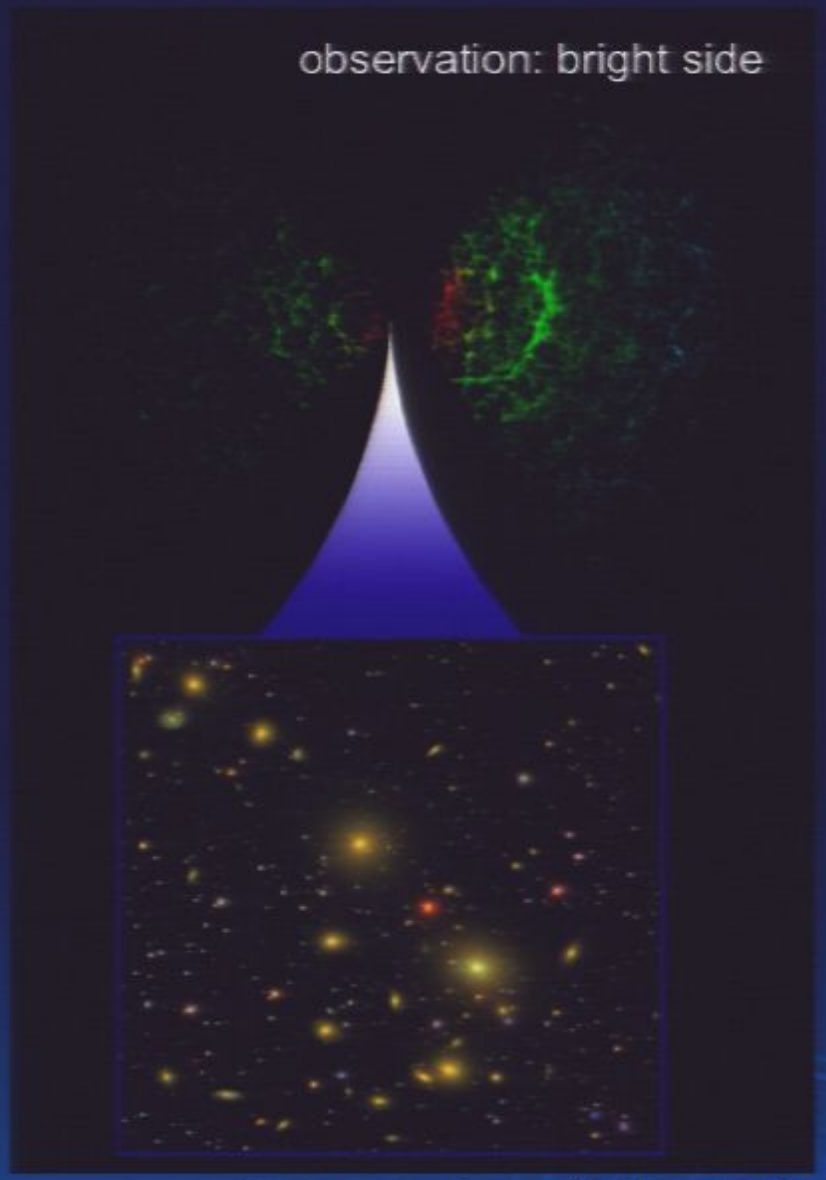


image courtesy: M. Tegmark

theory: dark side

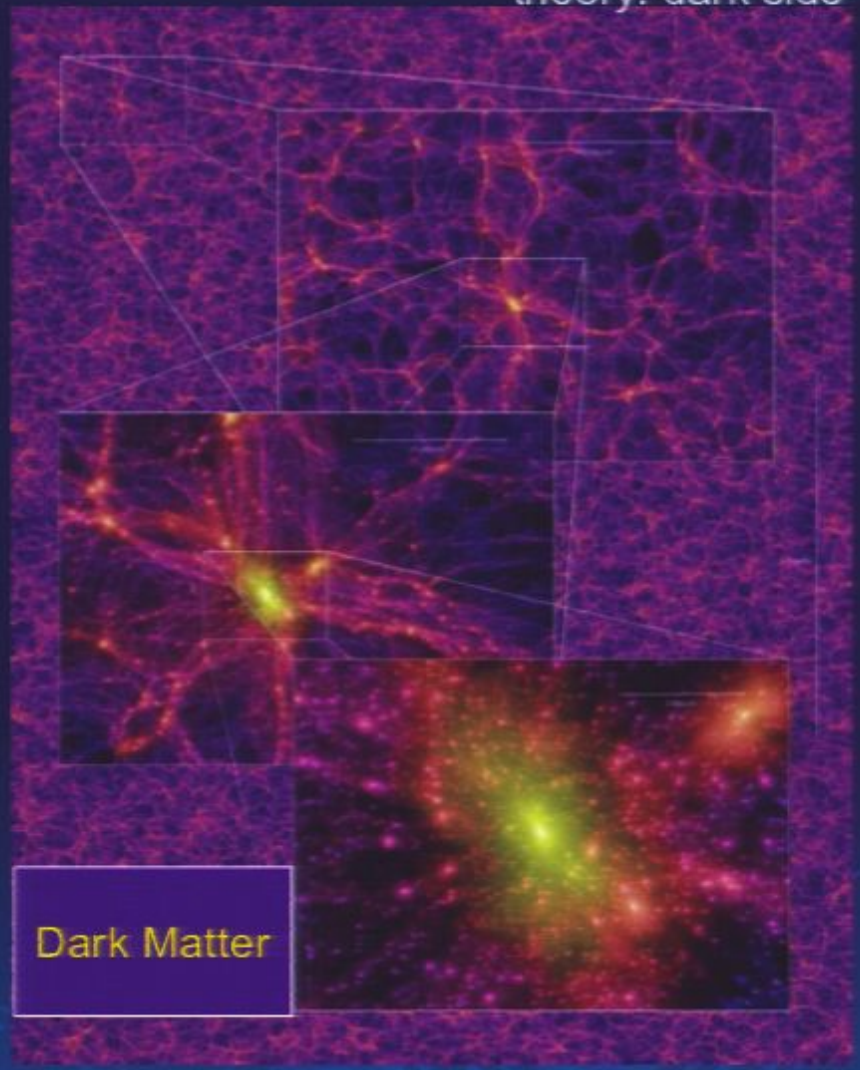
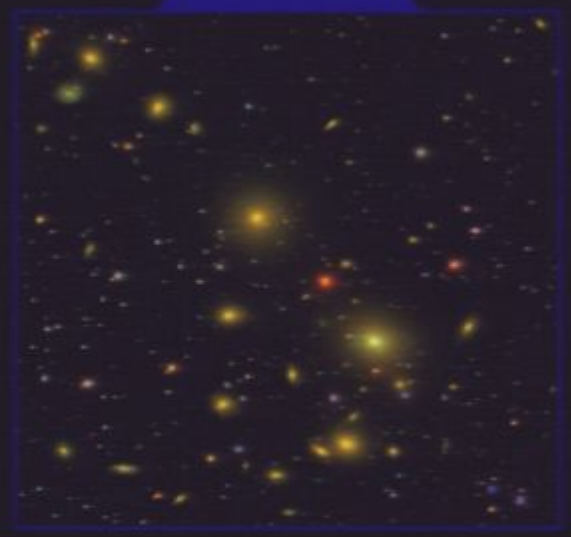


image courtesy: V. Springel

Dark matter halo:

- a bound dark matter structure of typical overdensity ~200
- in approximate dynamical equilibrium
- forming in a dissipationless gravitational collapse
- formation insensitive to baryonic physics
- site for galaxy to form and evolve
- can host a single galaxy or a group/cluster of galaxies



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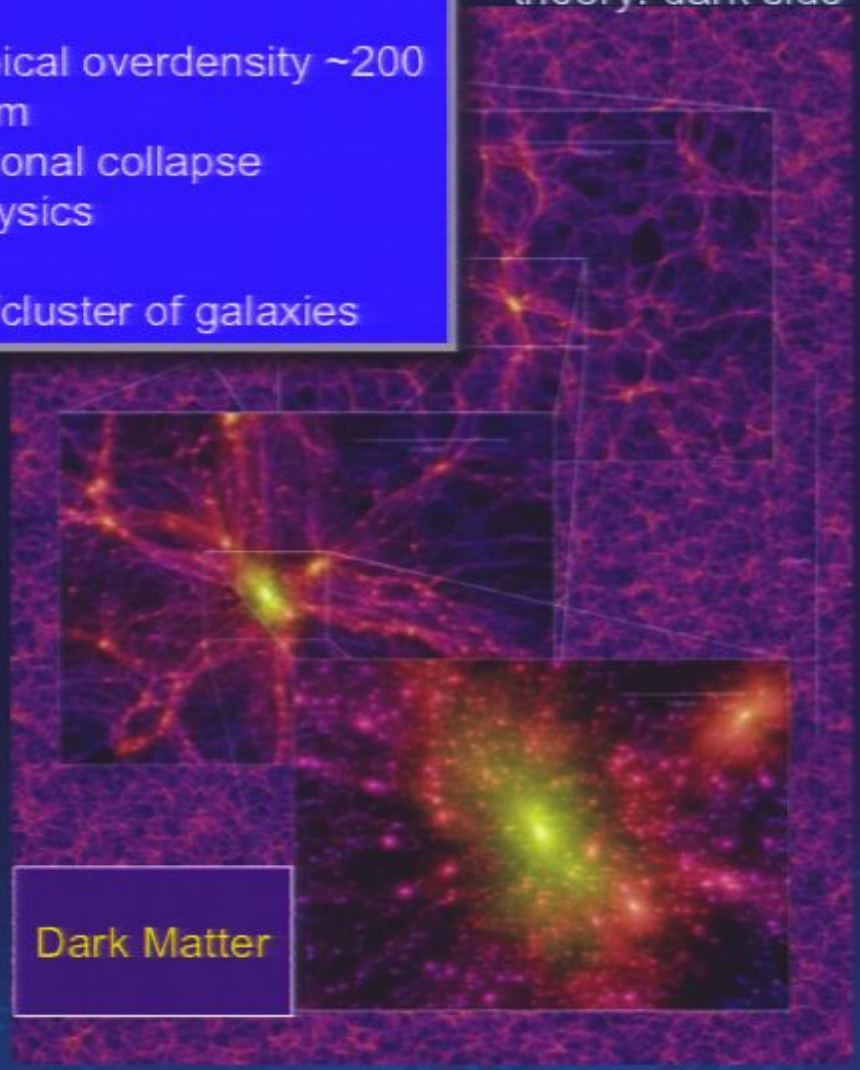

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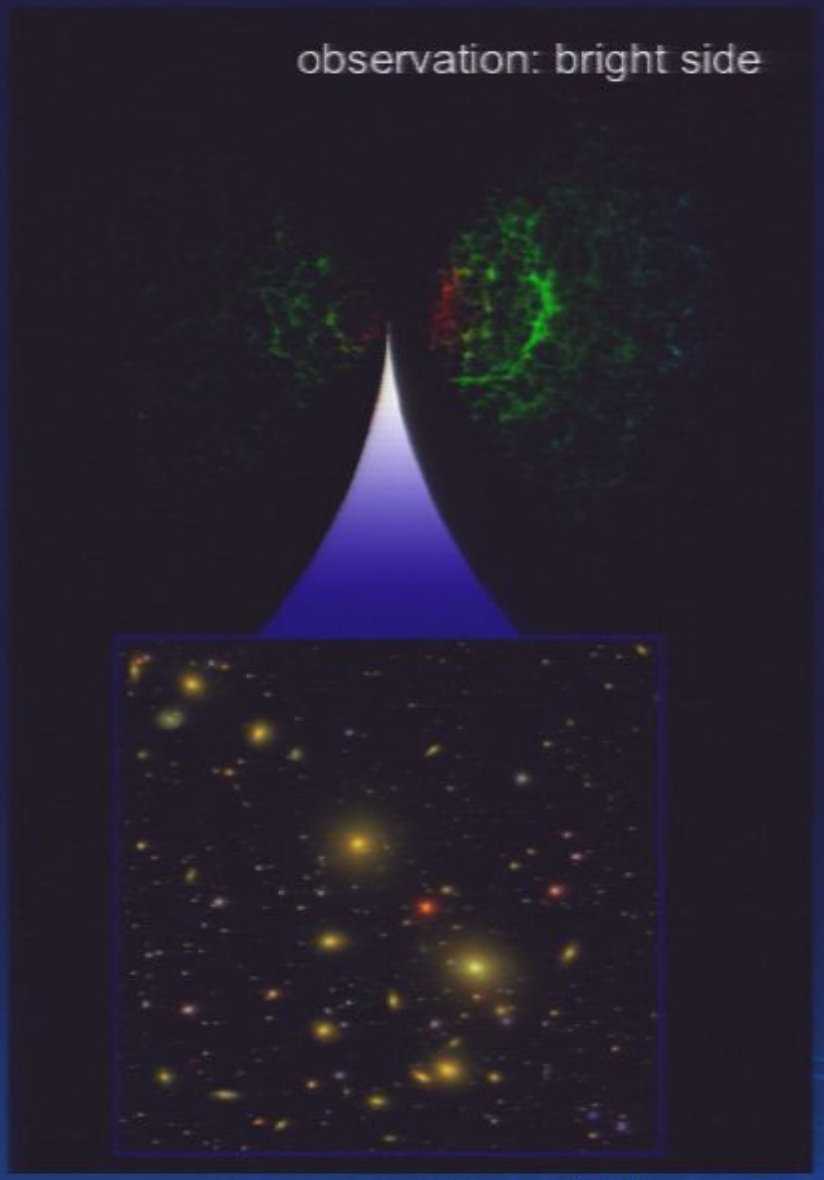

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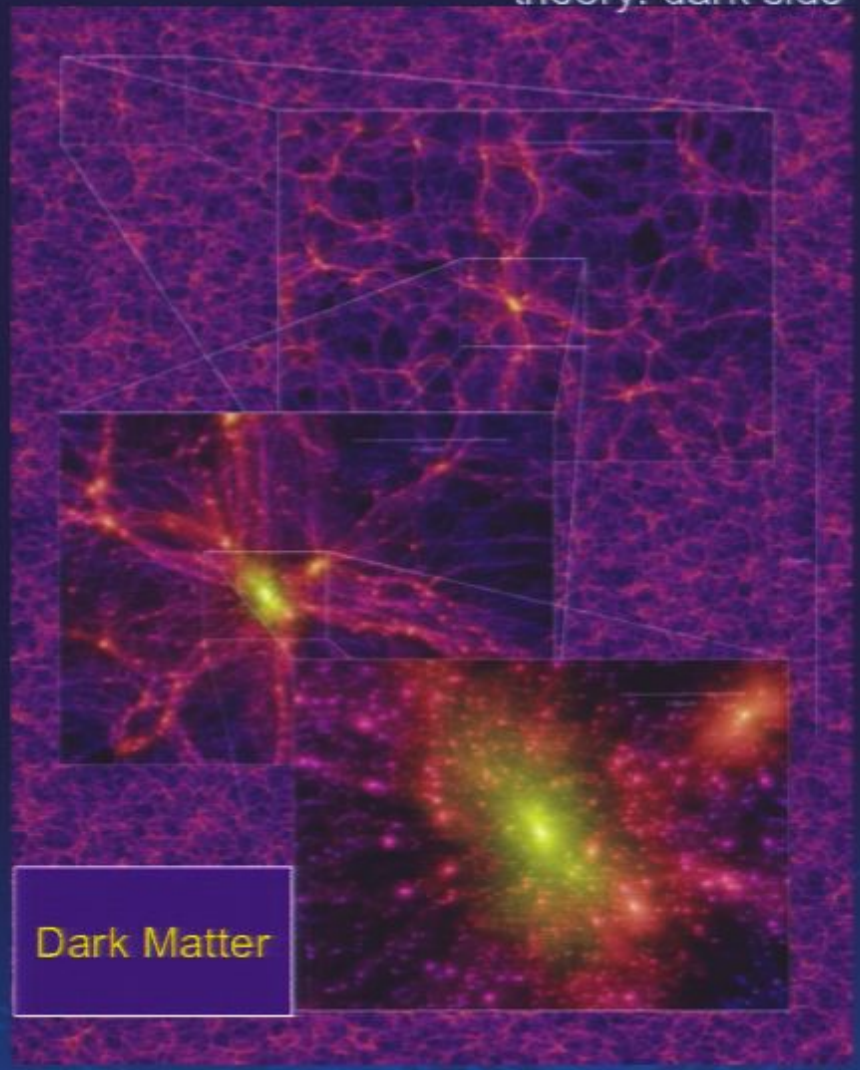

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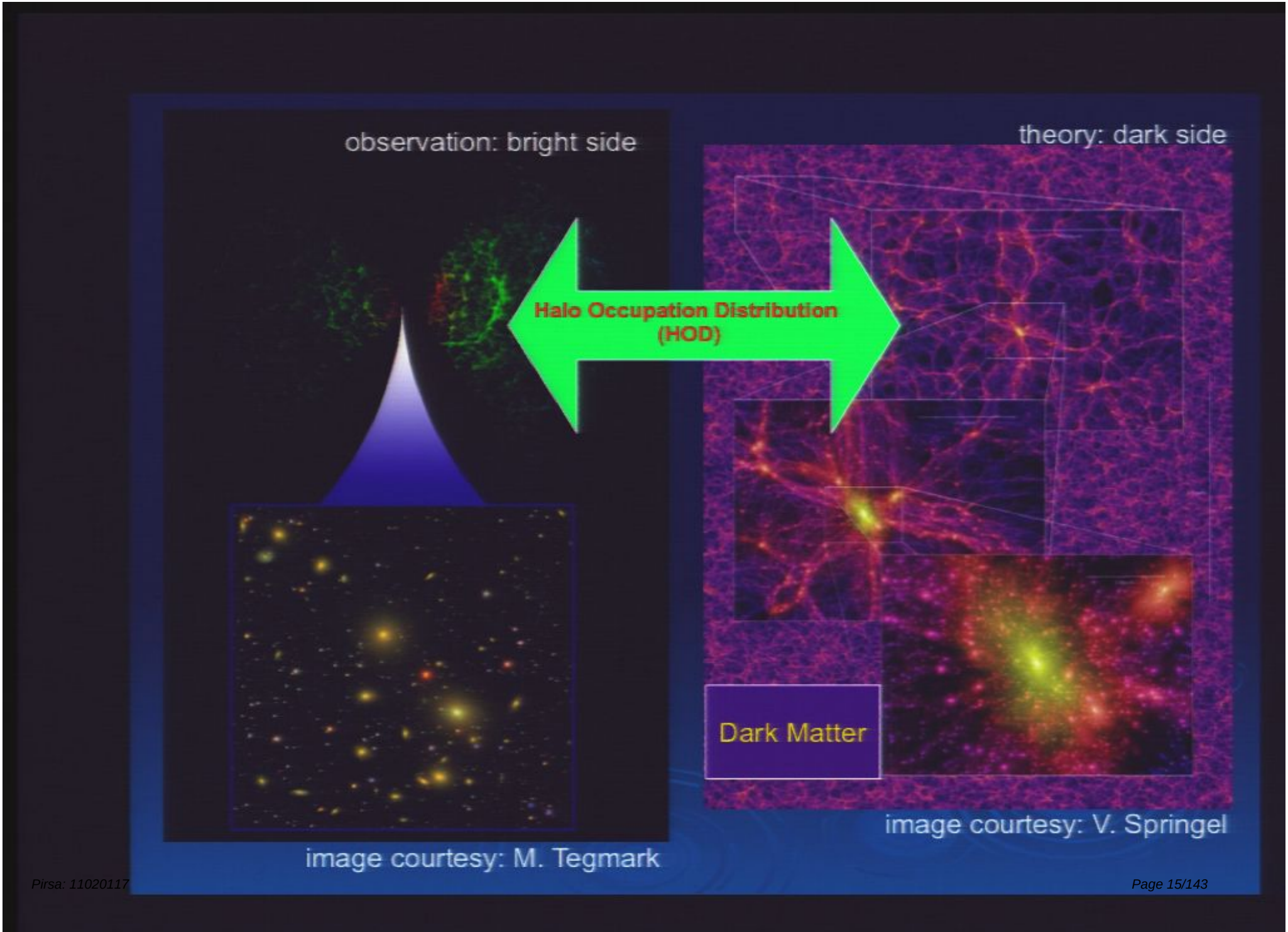
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Halo Occupation Distribution
(HOD)
Dark Matter
image courtesy: M. Tegmark
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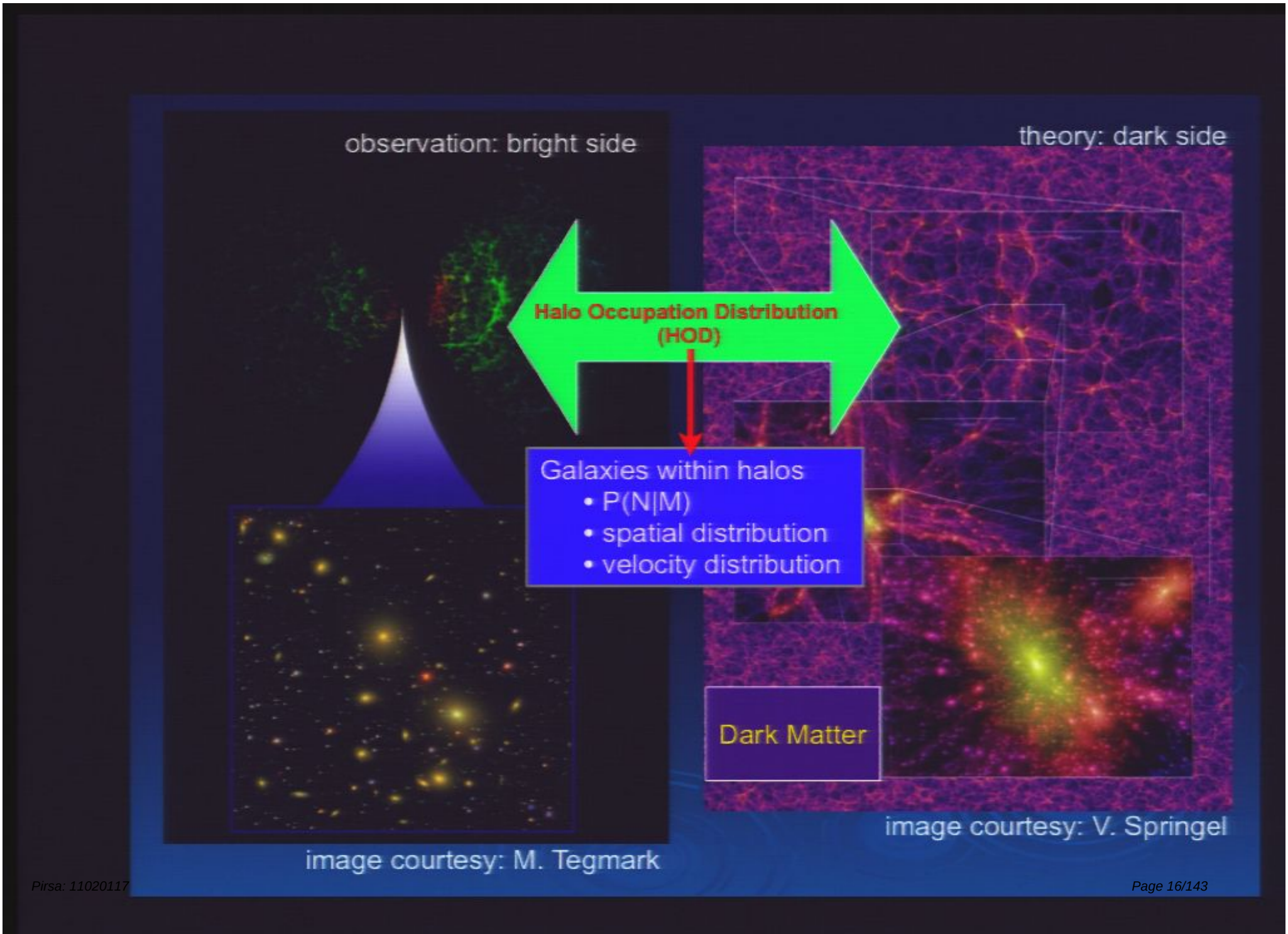
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Halo Occupation Distribution
(HOD)
Galaxies within halos
• P(N|M)
• spatial distribution
• velocity distribution
Dark Matter
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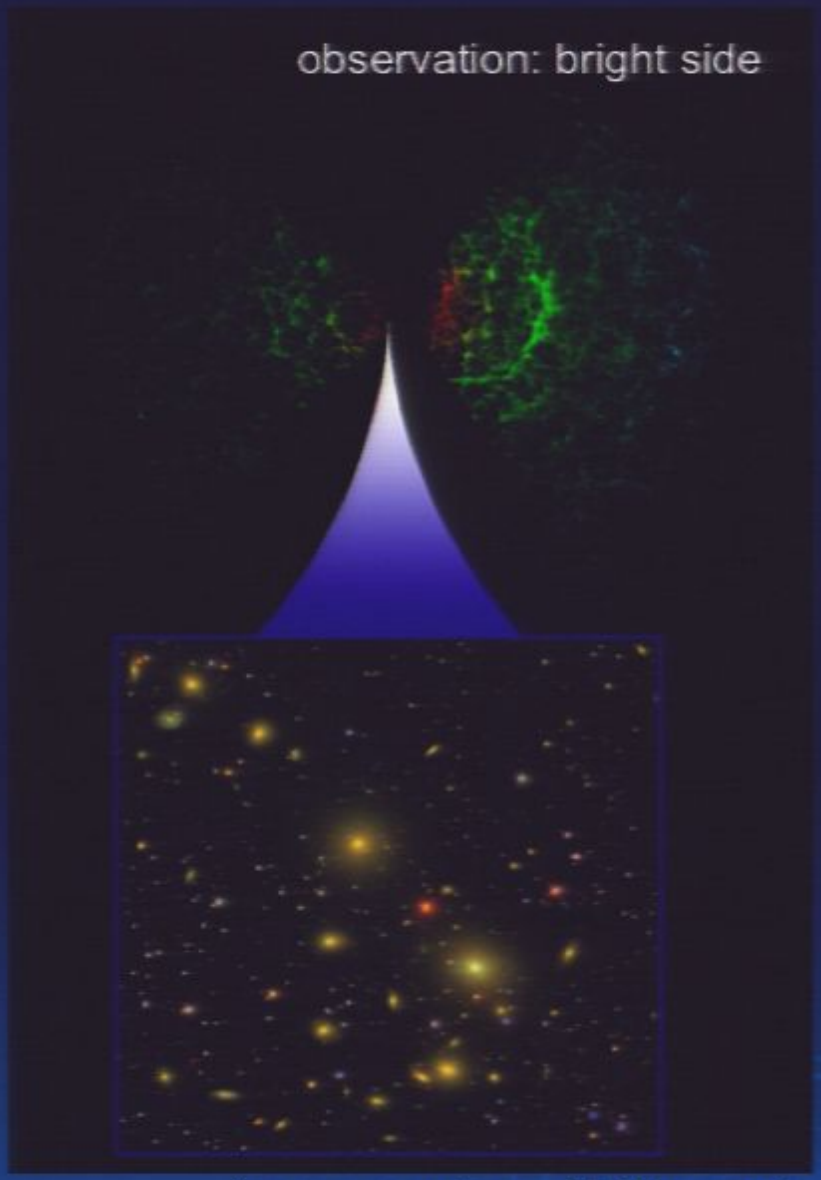

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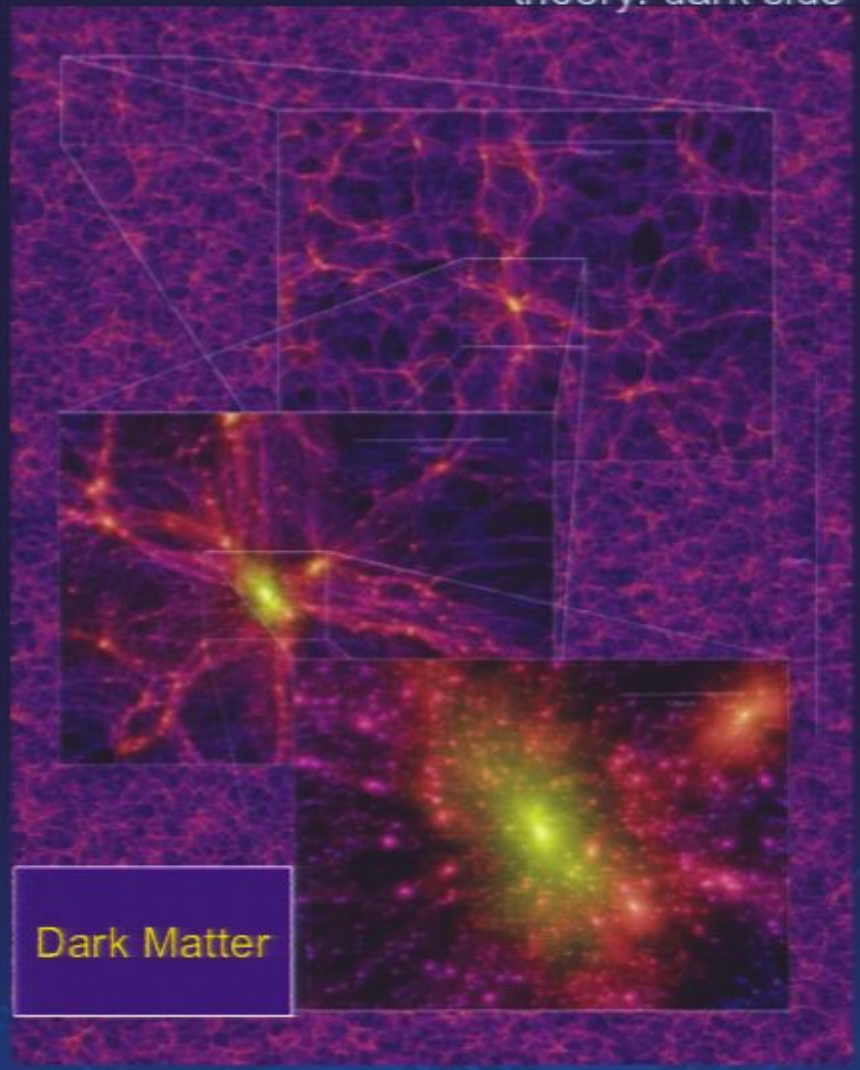

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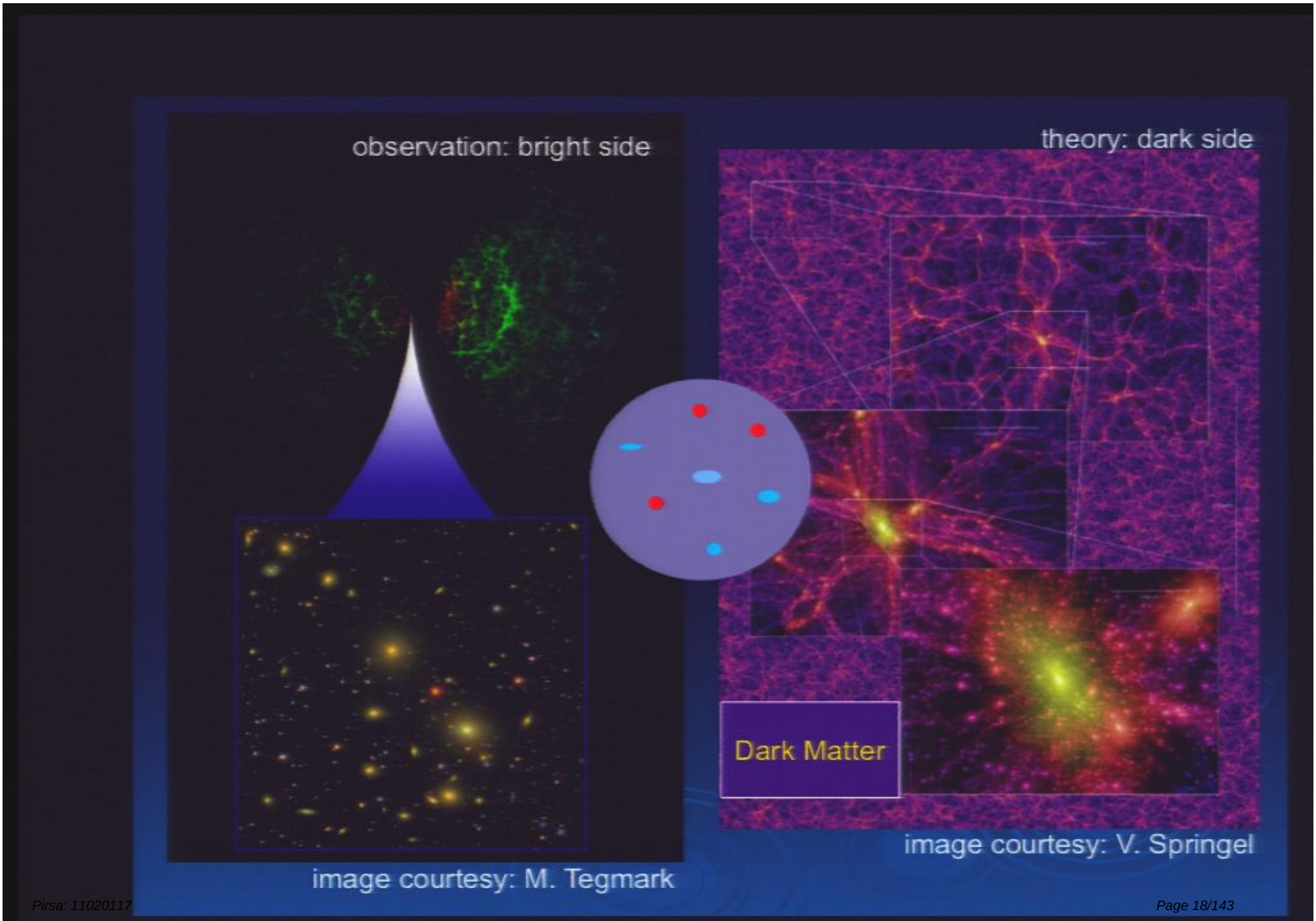
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Halo Occupation Distribution (HOD)

- not a galaxy formation model, but a tool to empirically infer the relation between galaxies and dark matter halos
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Weakness?

Halo Occupation Distribution (HOD)

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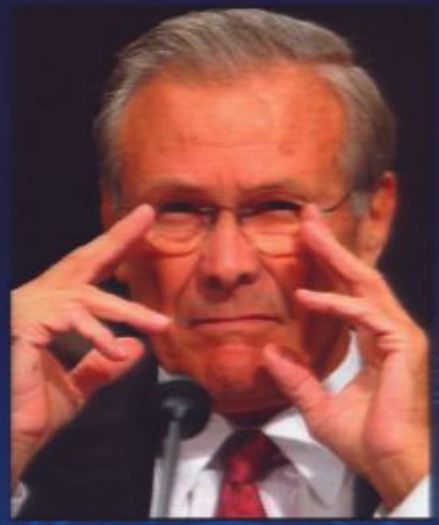
HOD modeling:

make use of known knowns to probe known unknowns and to reveal unknown unknowns.



known knowns

observed galaxy clustering

theory of dark matter evolution

known unknowns

relations between galaxies and dark matter halos

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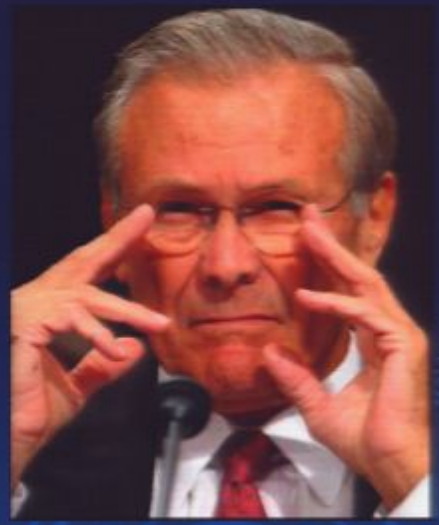

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unknown unknowns

properties in galaxy formation and evolution

- HOD: Theory Expectations

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- Low-z Results from Sloan Digital Sky Survey (SDSS)
- High-z Results, Galaxy Evolution (SDSS+DEEP2, NOAO-DWFS)
- HOD Modeling and Cosmology

HOD - Theoretical predictions

predictions of galaxy formation models

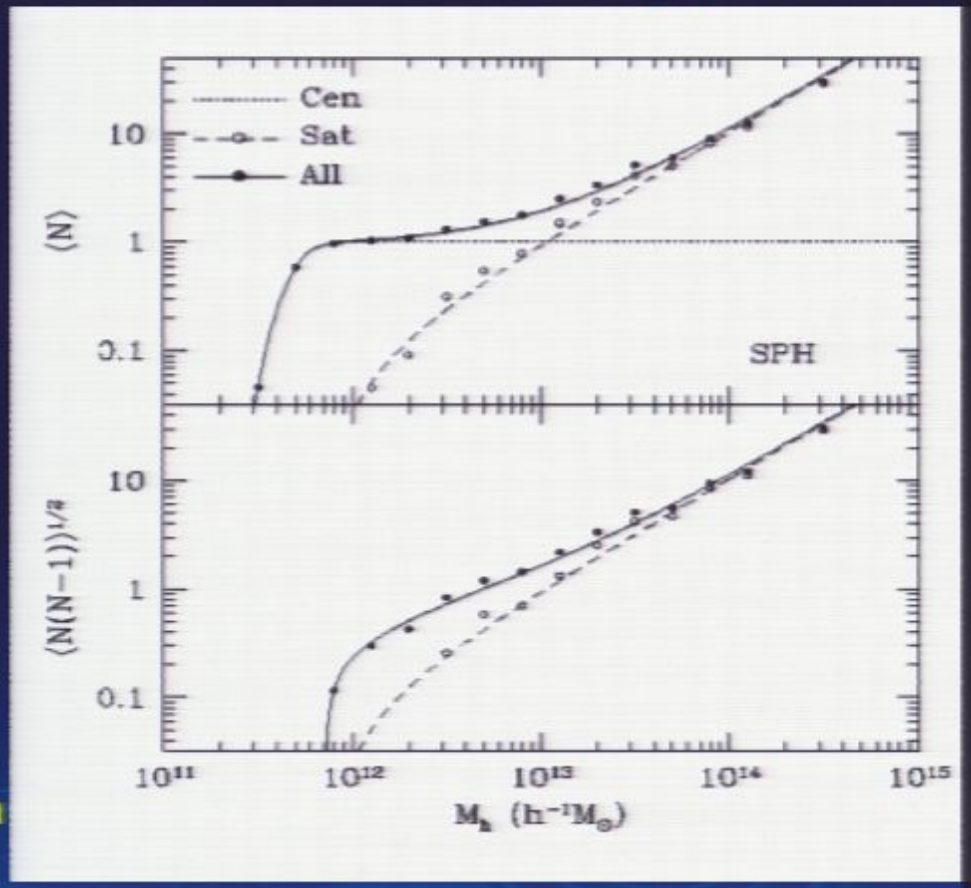
important and physically meaningful to separate CENTRAL and SATELLITE galaxies

For a sample of galaxies more luminous than L_{min}

* Mean occupation function of *central* galaxies:
  step-like function

* Mean occupation function of *satellite* galaxies:
  powerlaw-like function
  scatter following Poisson distribution

Zheng et al. 2005



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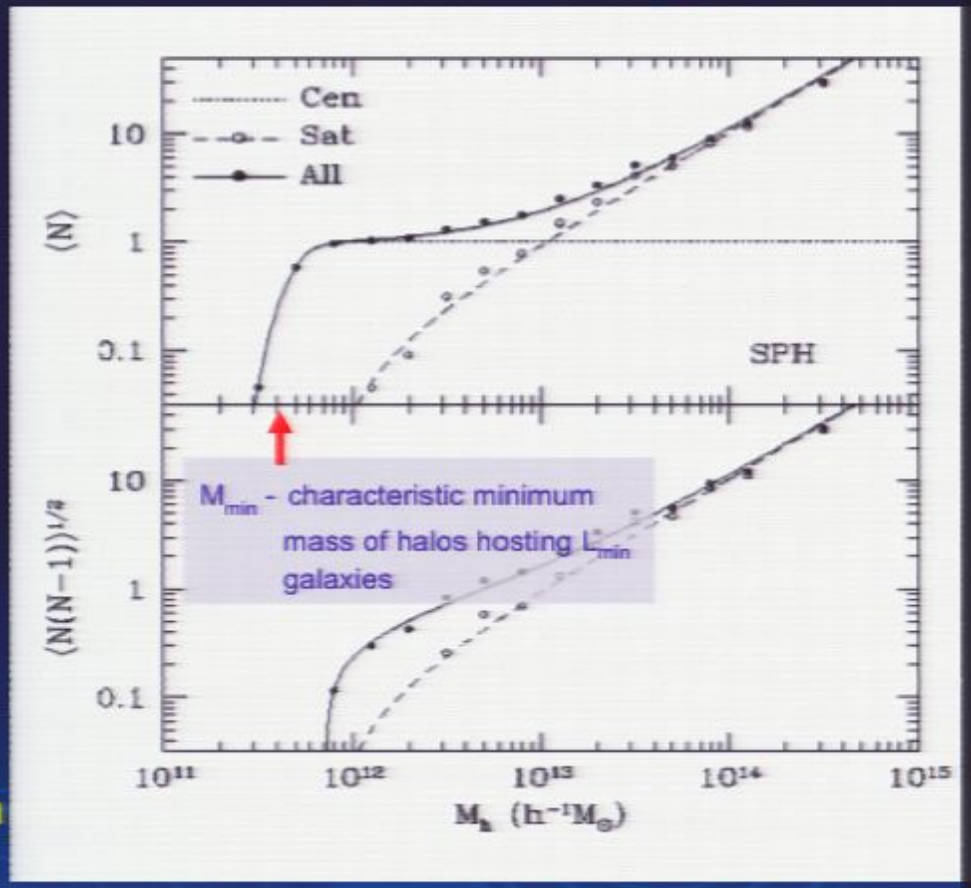

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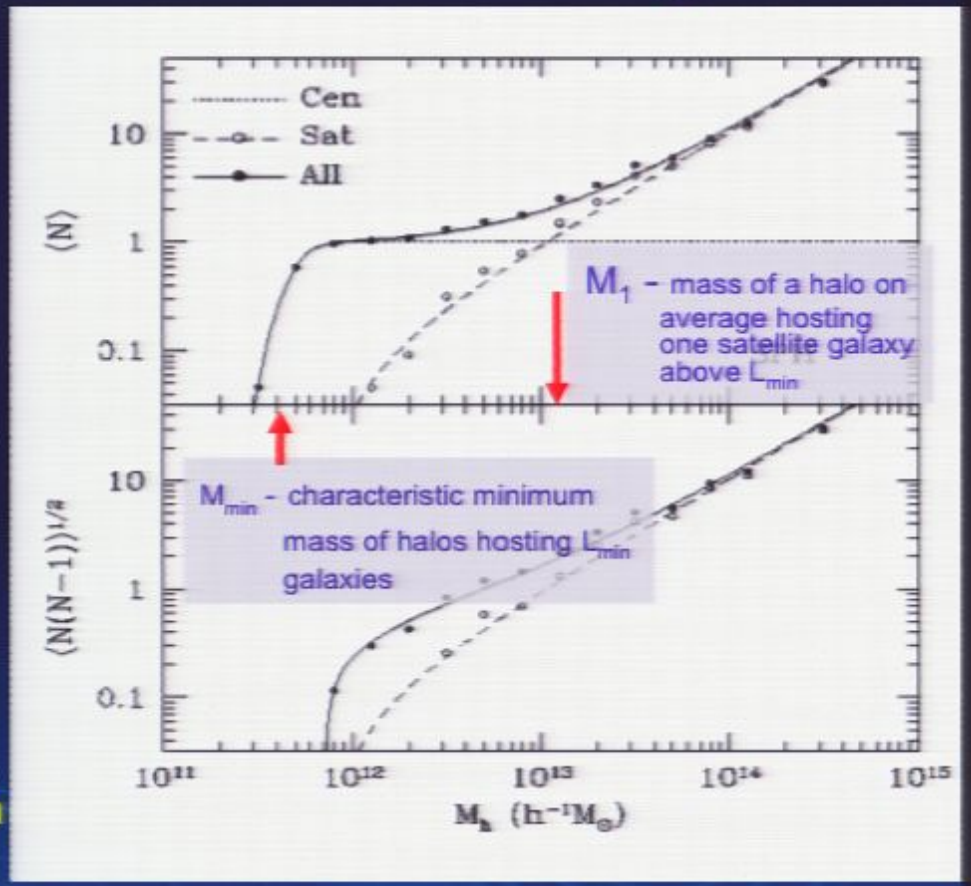

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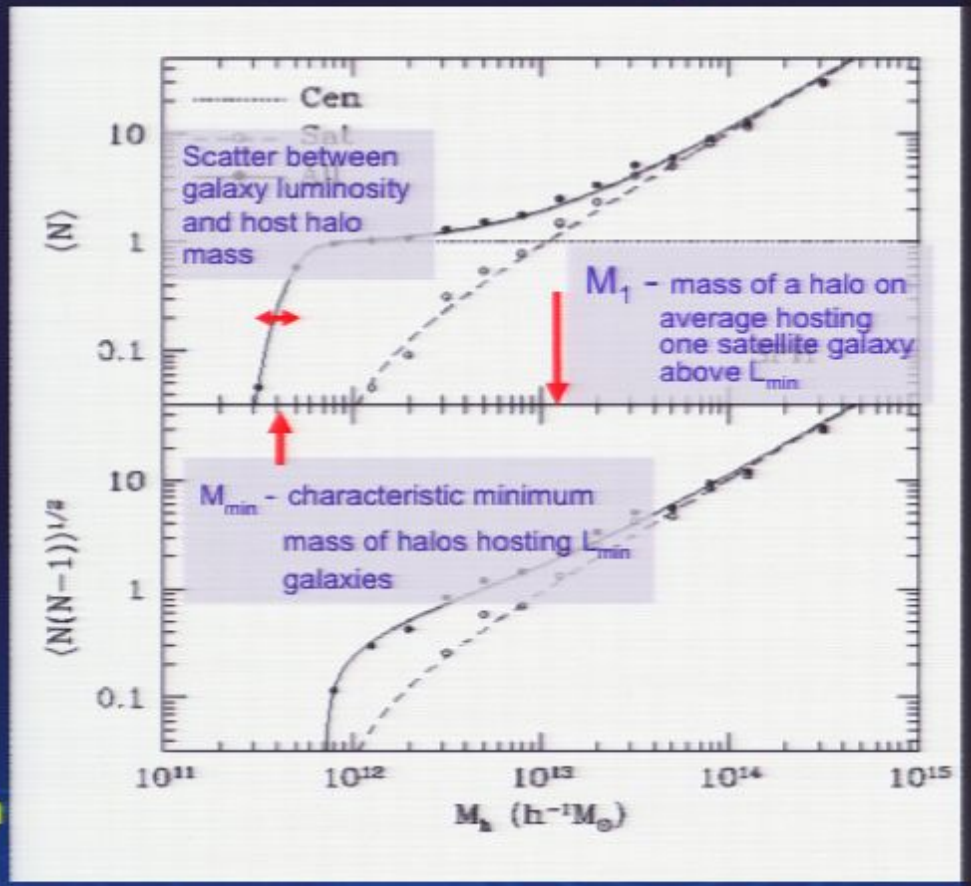
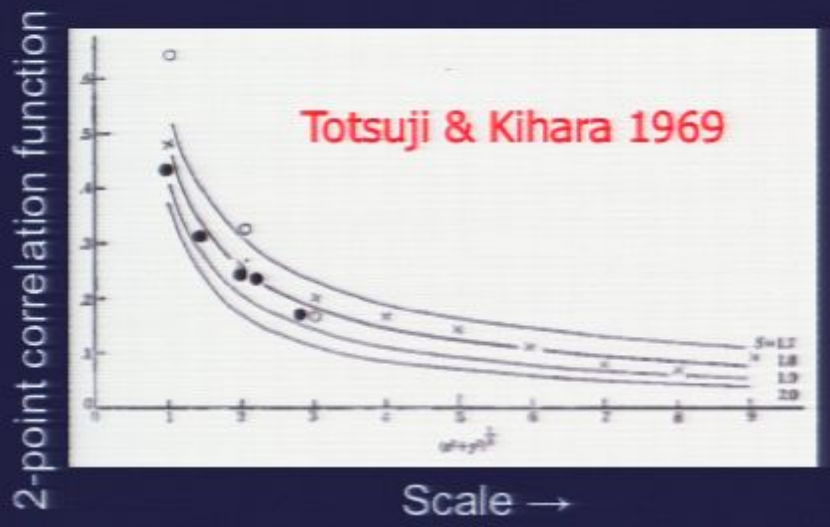
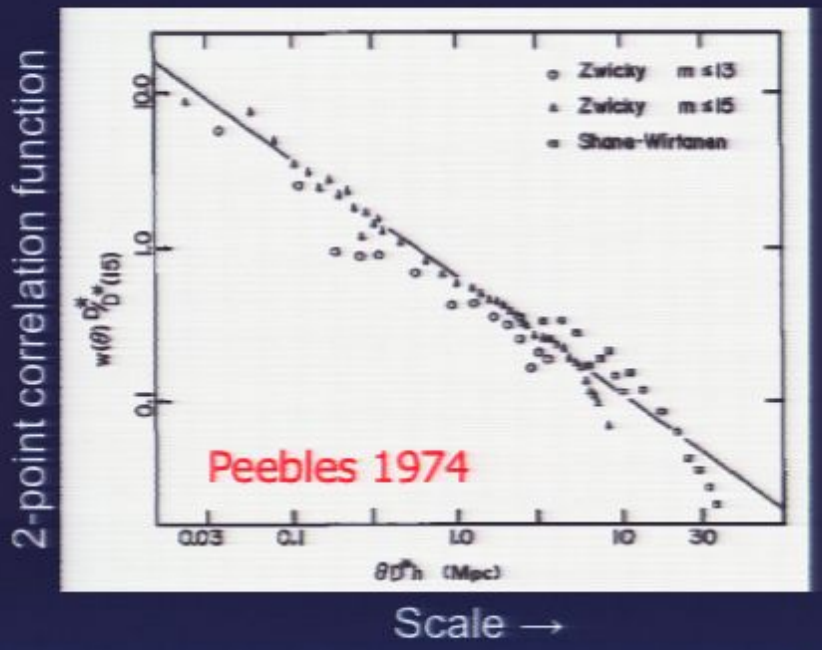


Departures from a power law in the galaxy correlation function





long-standing quantitative result in galaxy clustering --

power-law form of the two-point correlation function of galaxies

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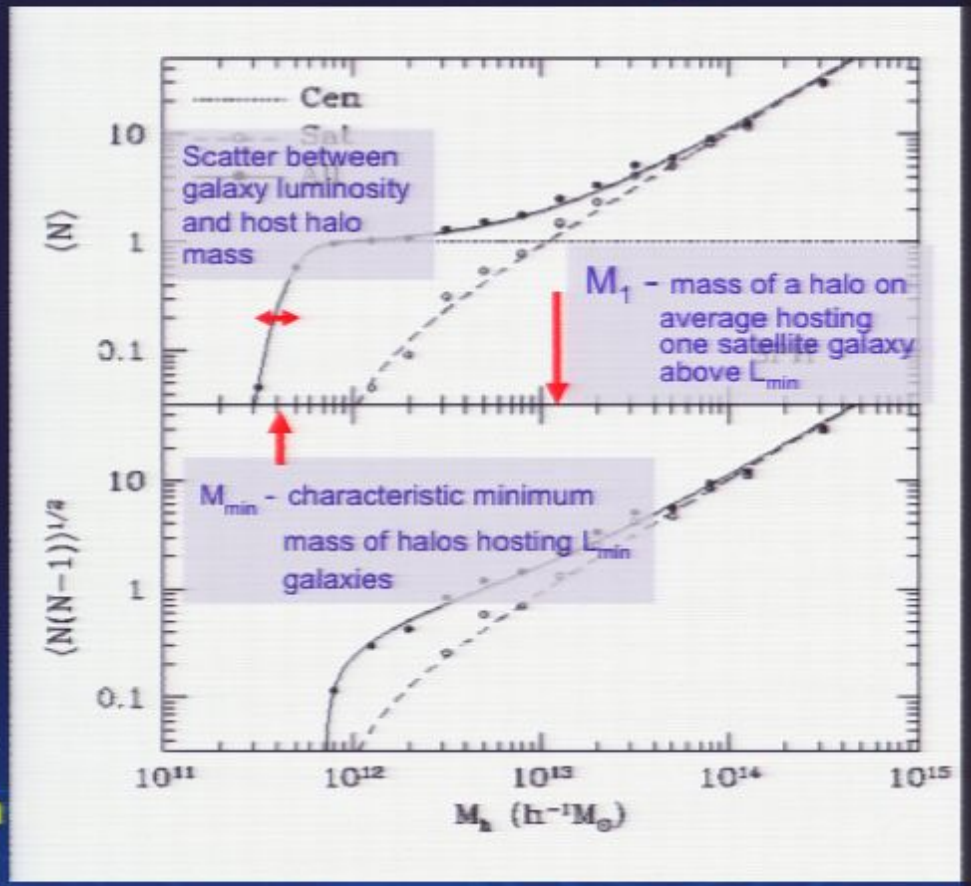

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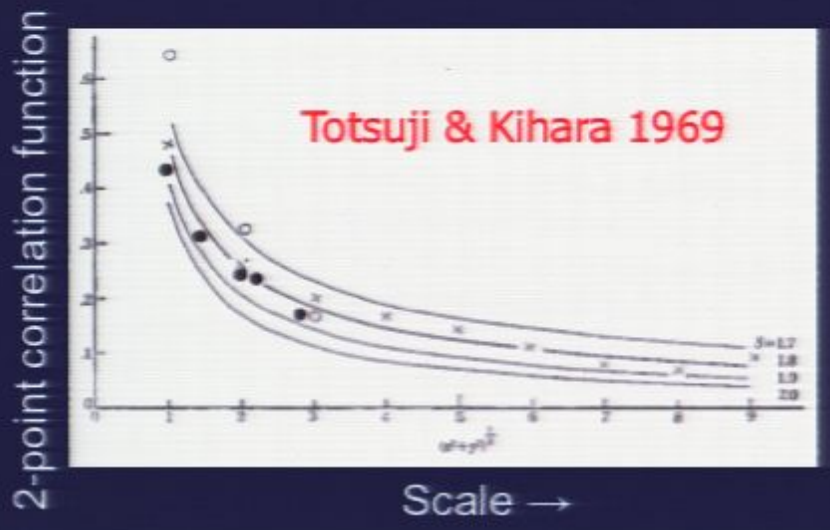

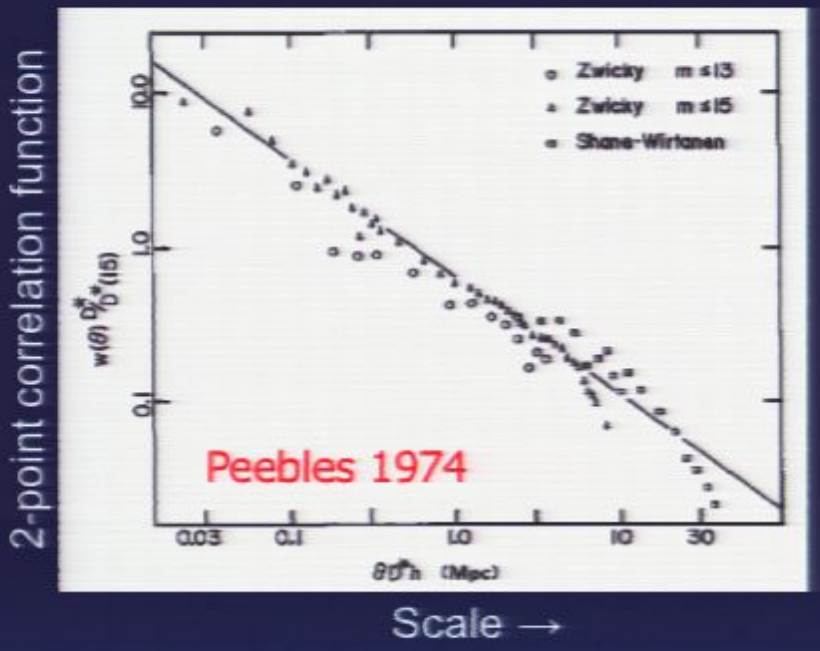

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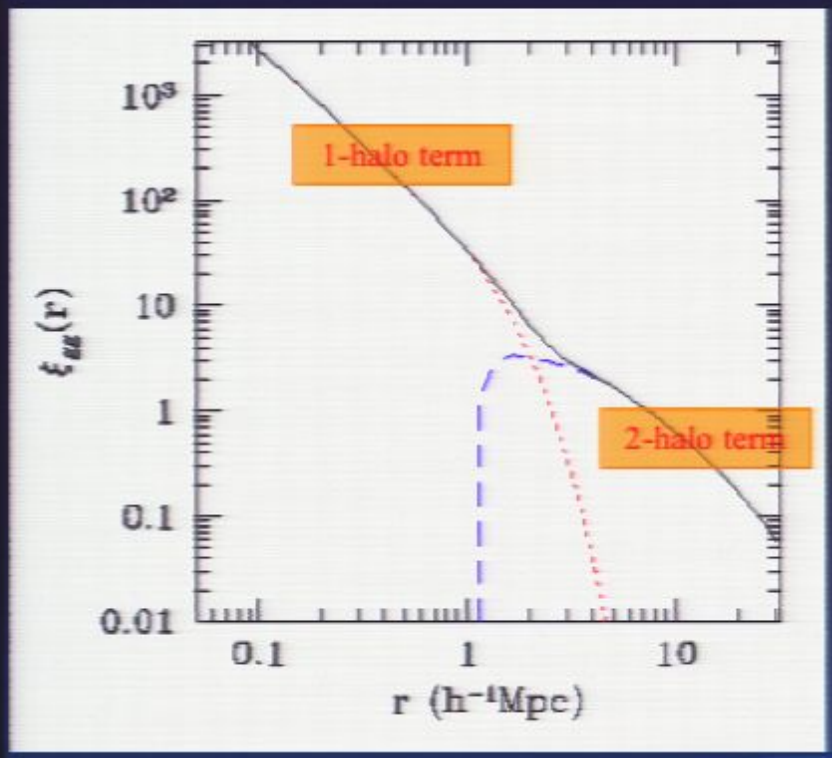
Two-point correlation function of galaxies

Excess probability w.r.t. random distribution of finding galaxy pairs at a given separation



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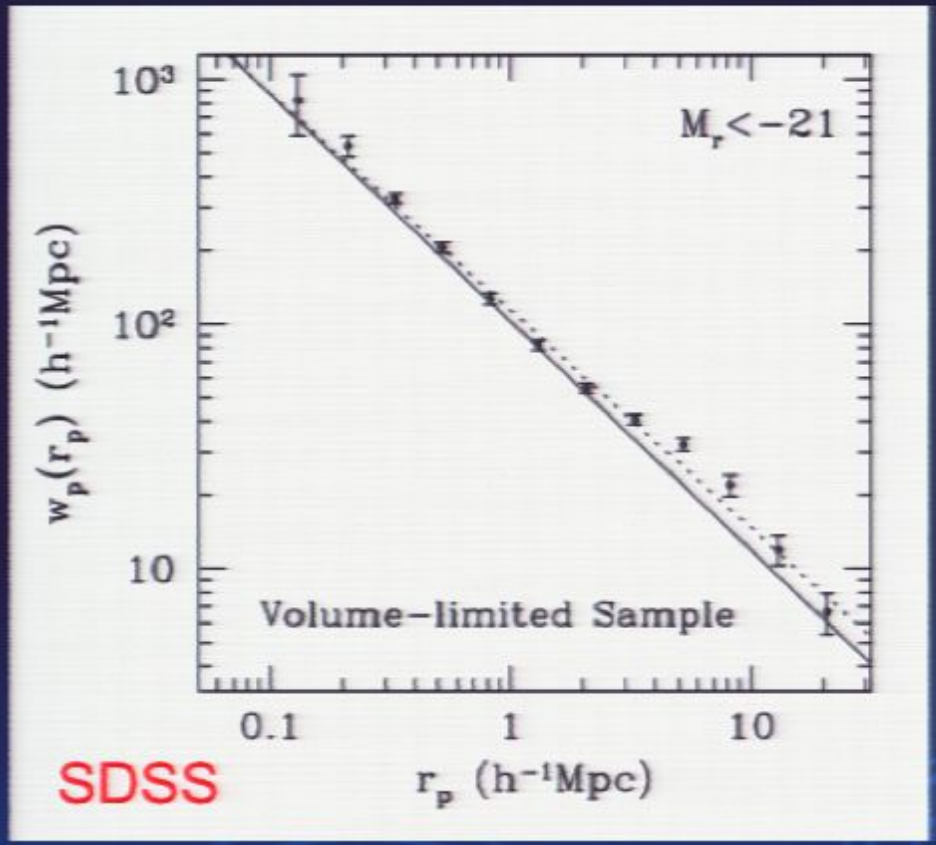

Zehavi, Weinberg, Zheng et al. 2005

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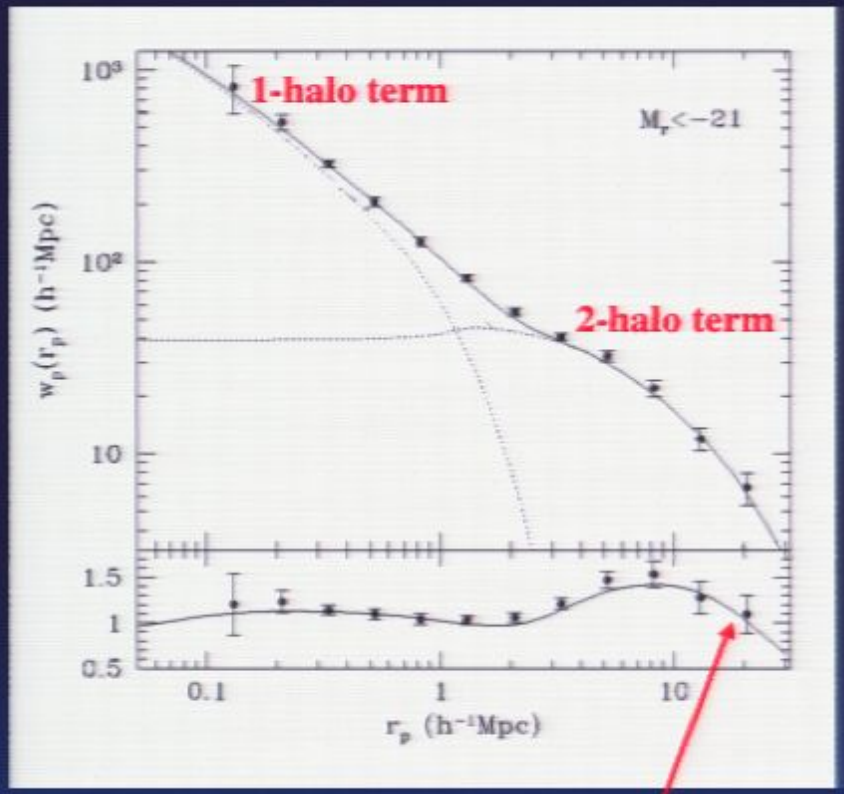

Divided by the best-fit power law

ΛCDM + HOD modeling:

- naturally explains shape of correlation function observed in SDSS
- converts galaxy pair counts to the relation between galaxies and DM halos

Zehavi, Weinberg, Zheng, et al. 2005

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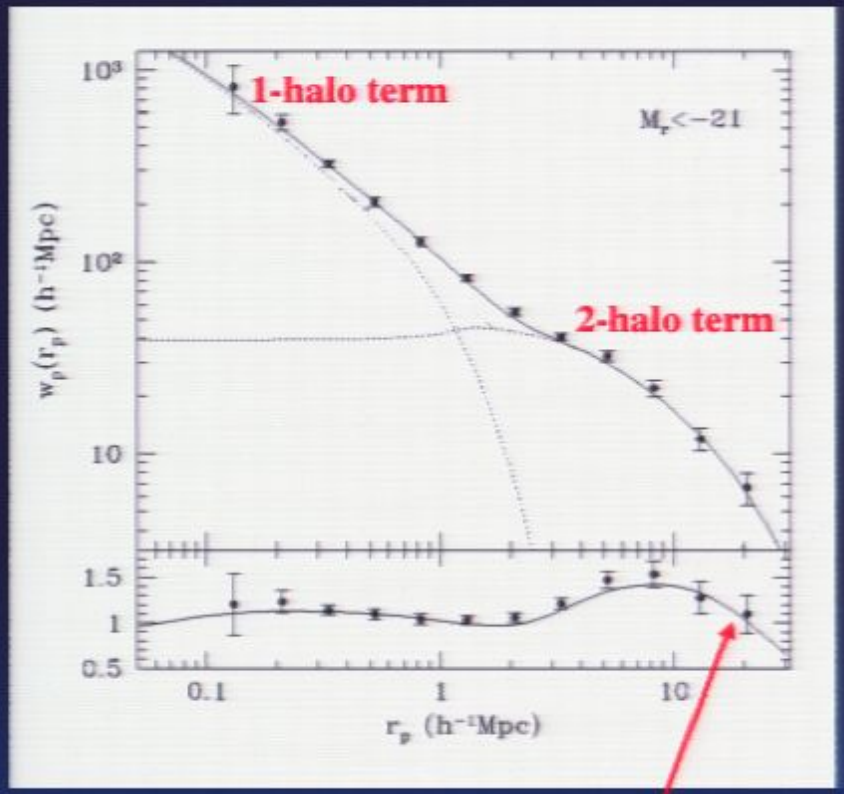

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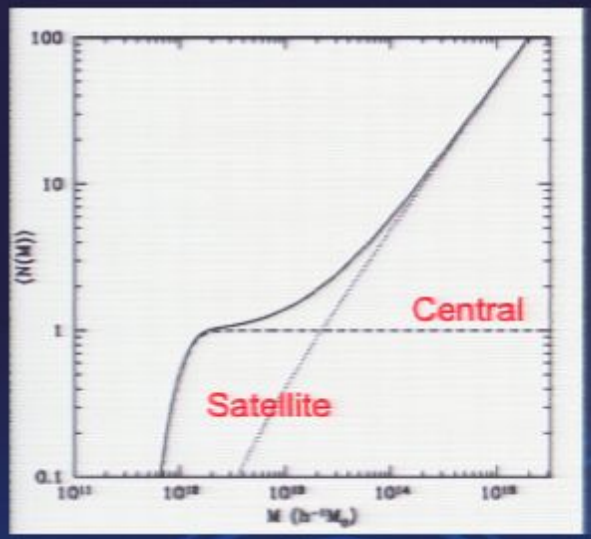

Zehavi, Weinberg, Zheng, et al. 2005

Departures from a power law in the galaxy correlation function

Daddi et al. (2003), clustering of z~3 red galaxies
(power-law extrapolation from small to large scales
➡ remarkably strong clustering)

Puzzle:

one-galaxy-per-halo ➡ $M>10^{13}h^{-1}M_{sun}$,

while density of such halos << observed galaxy density

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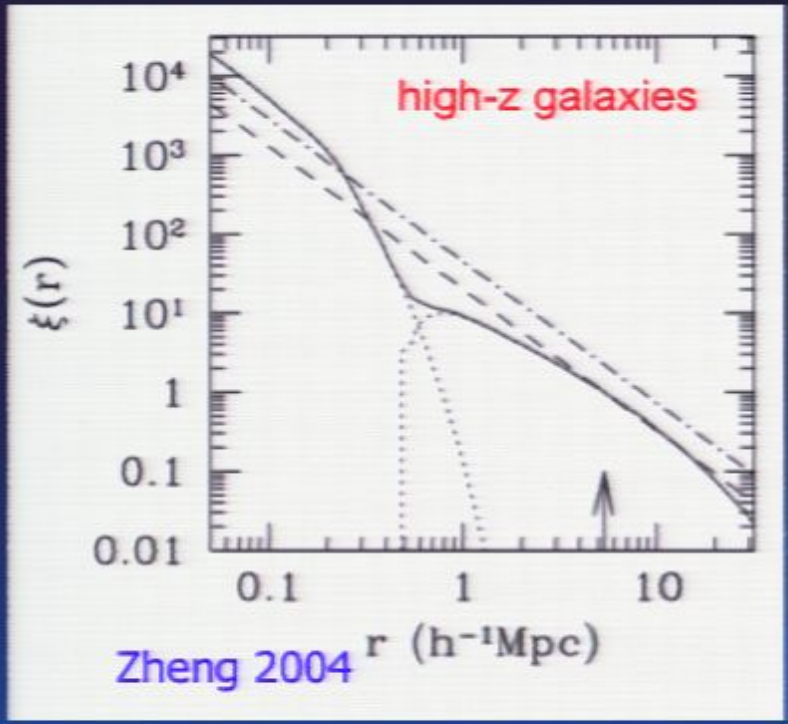

Zheng (2004), HOD modeling

Puzzle Resolved:

strong departure from a power law multiple galaxies per halo, strong clustering on small scales

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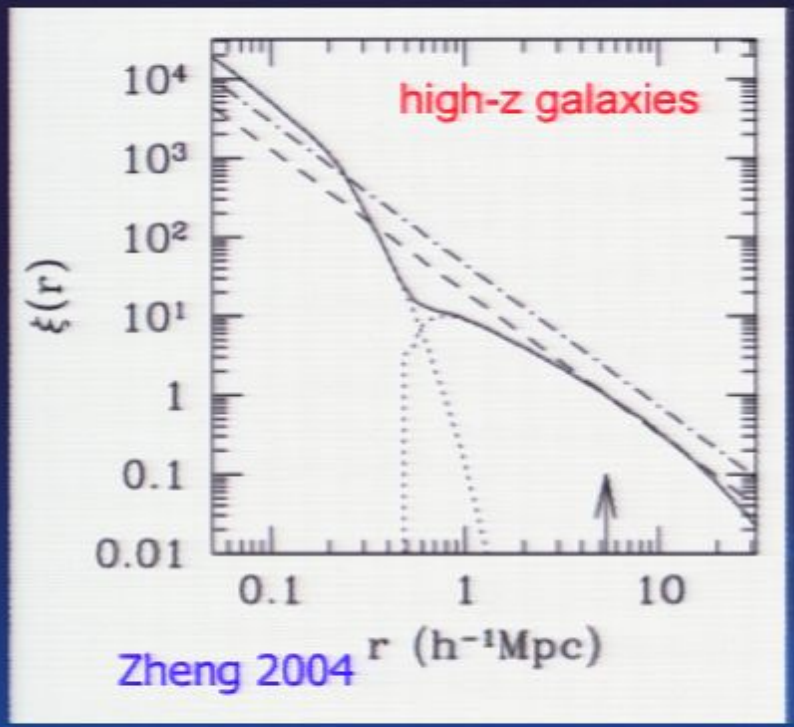

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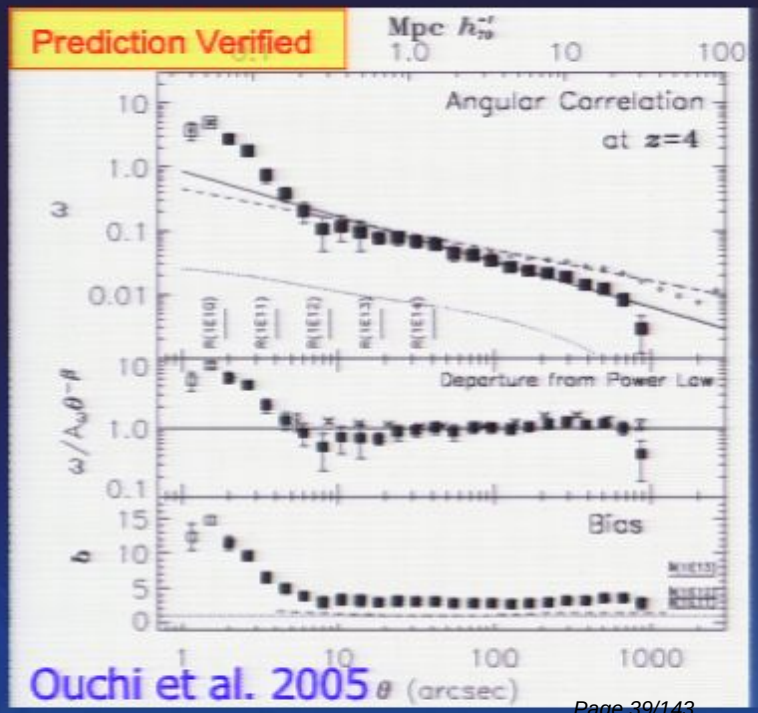
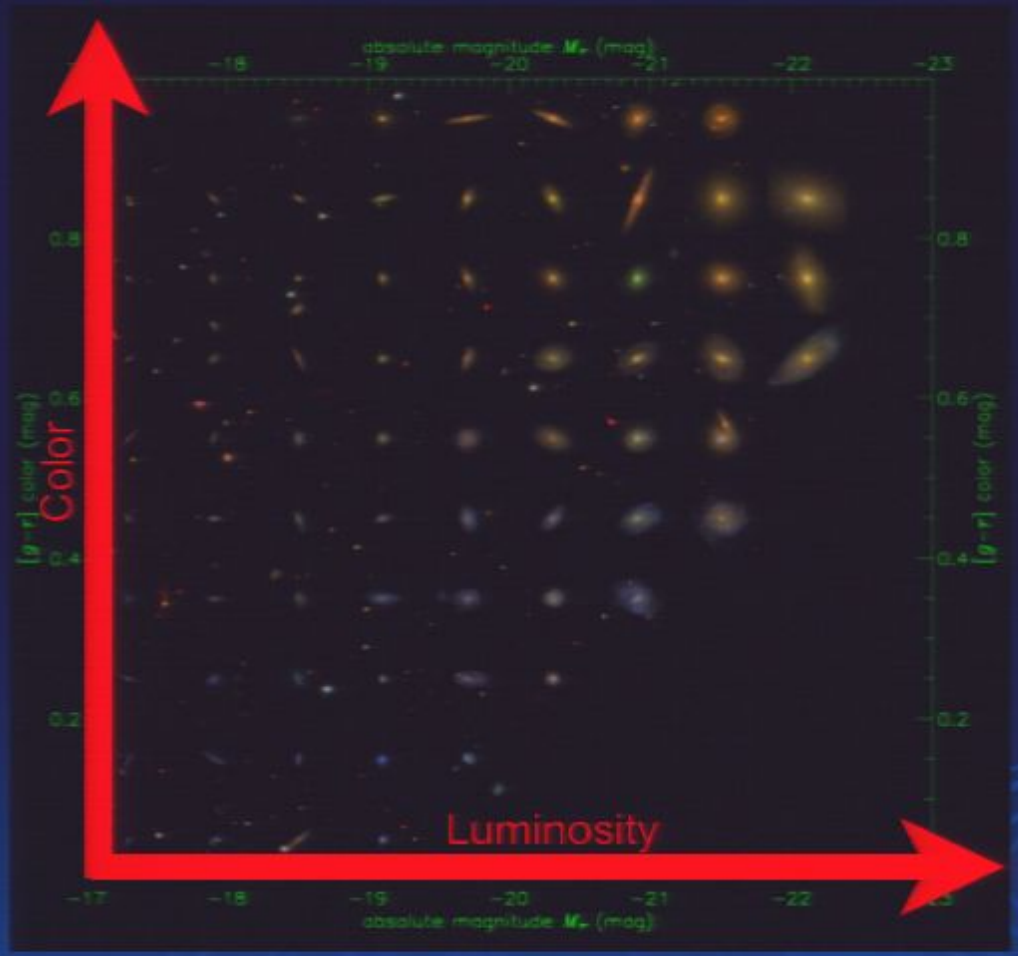


Ouchi et al. 2005

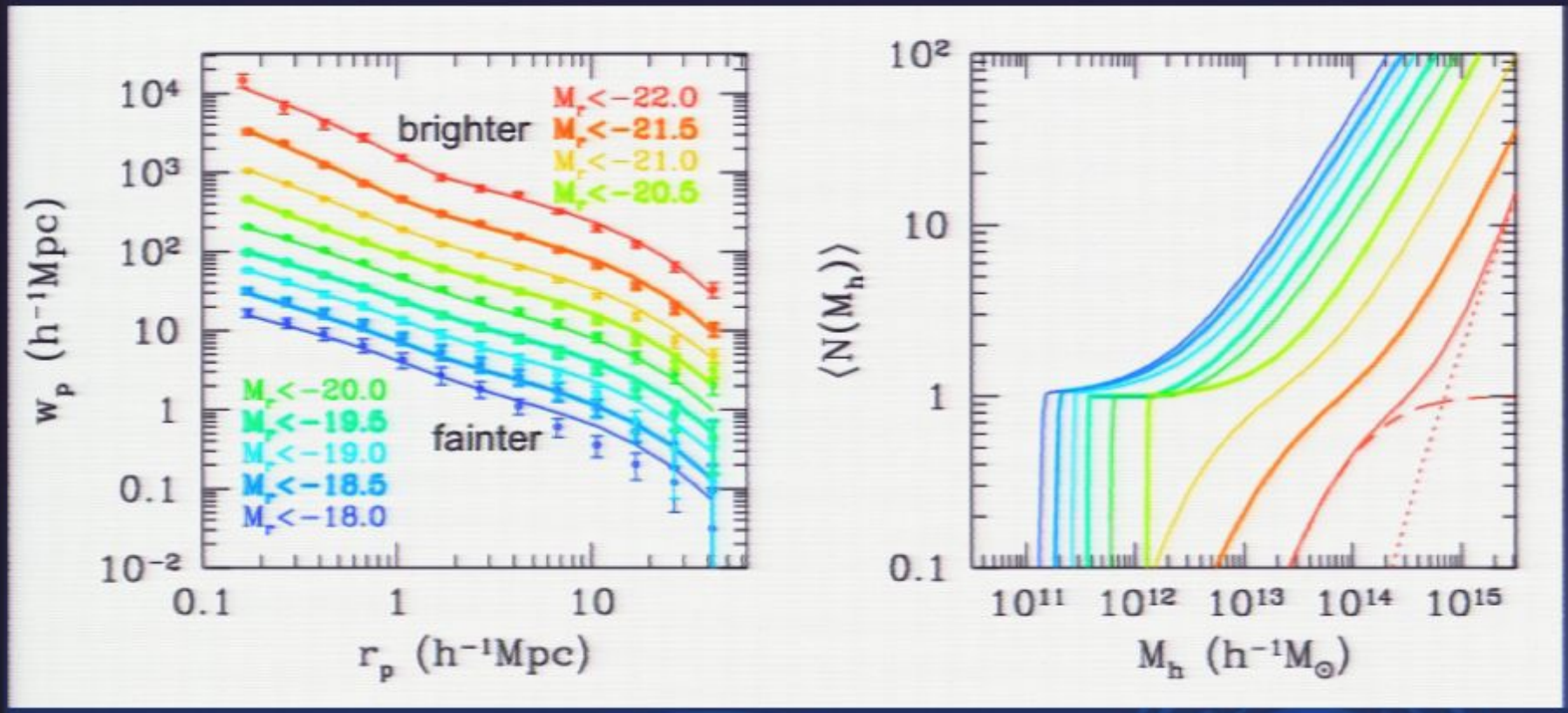
Galaxy correlation function
- Luminosity and color dependence



Hogg & Blanton

~ low stellar mass ~ high stellar mass

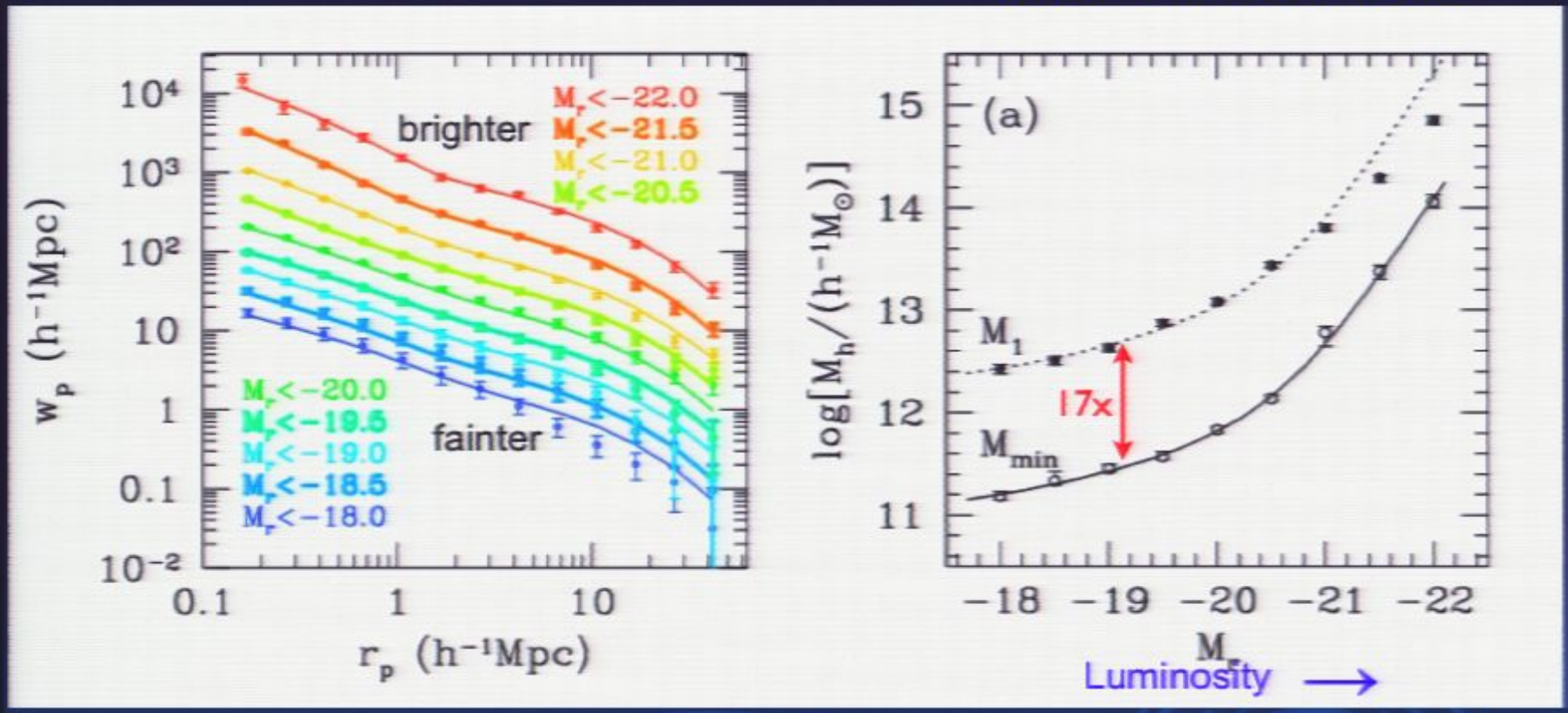
Luminosity dependence of galaxy clustering



Zehavi, Zheng, et al. 2010

Luminosity dependence of galaxy clustering

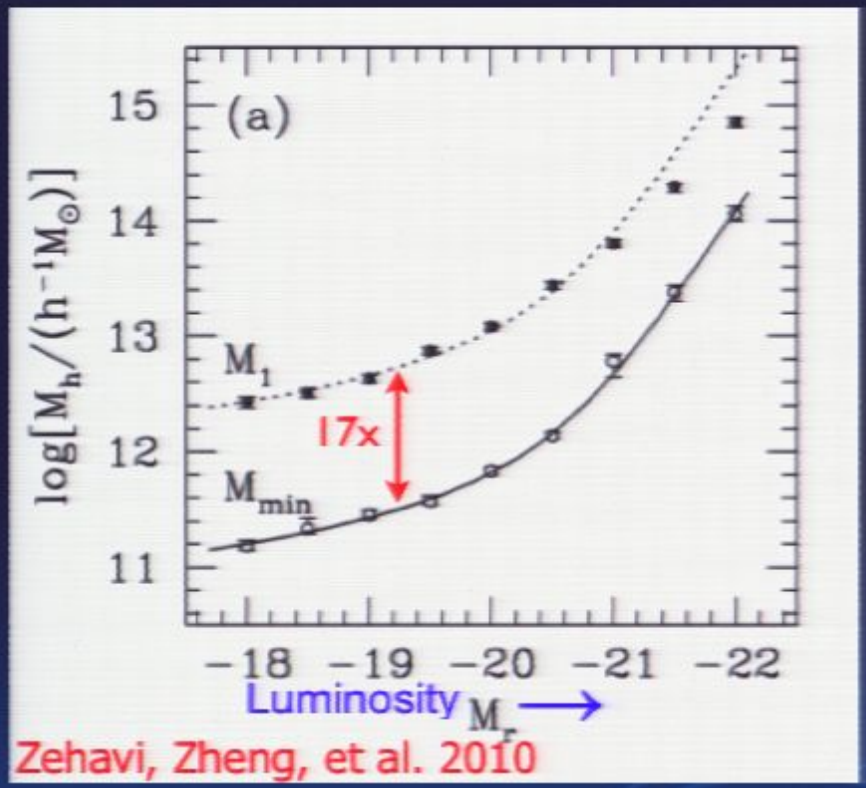
Constant ratio of M_1 to M_{min}



Zehavi, Zheng, et al. 2010

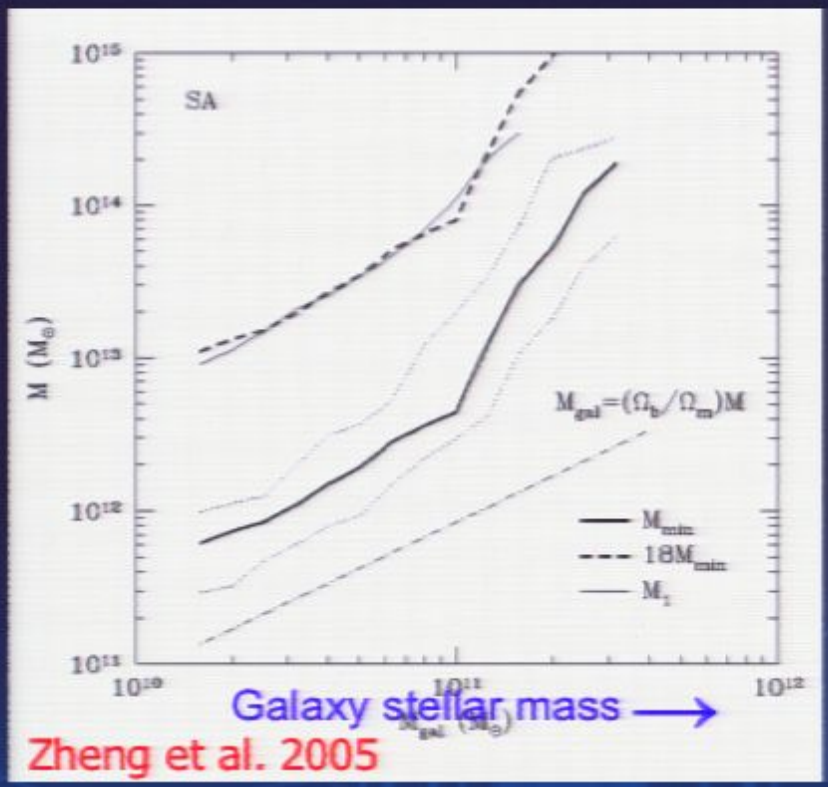
Luminosity dependence of galaxy clustering

Observation



Zehavi, Zheng, et al. 2010

Theory

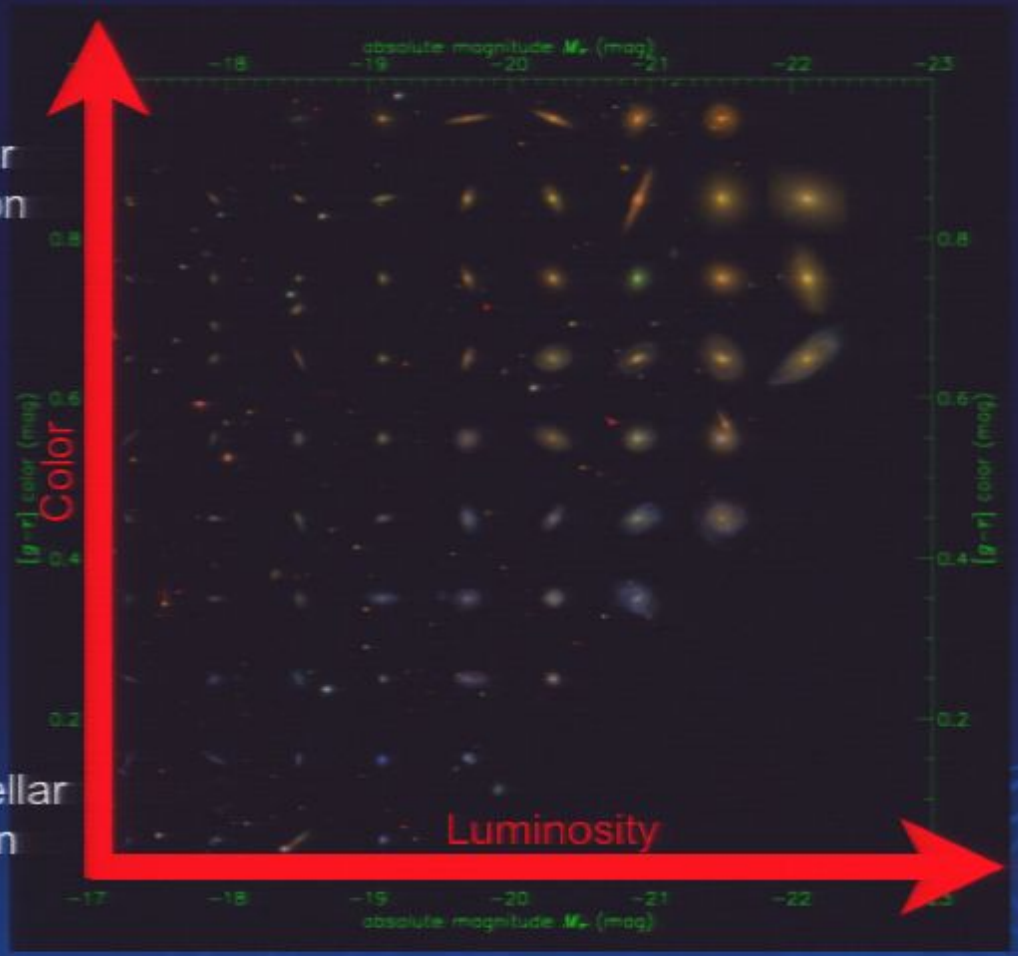


Zheng et al. 2005

HOD parameters vs galaxy luminosity

Galaxy correlation function
- Luminosity and color dependence

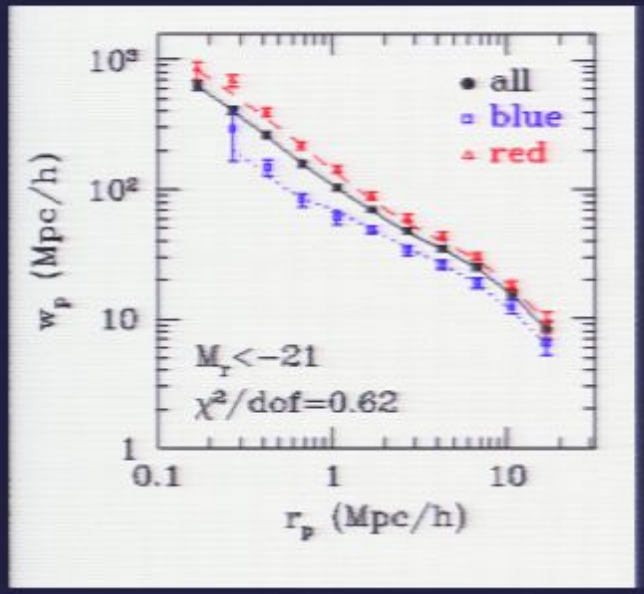
~ old stellar population



~ young stellar population

Hogg & Blanton

Color dependence of galaxy clustering

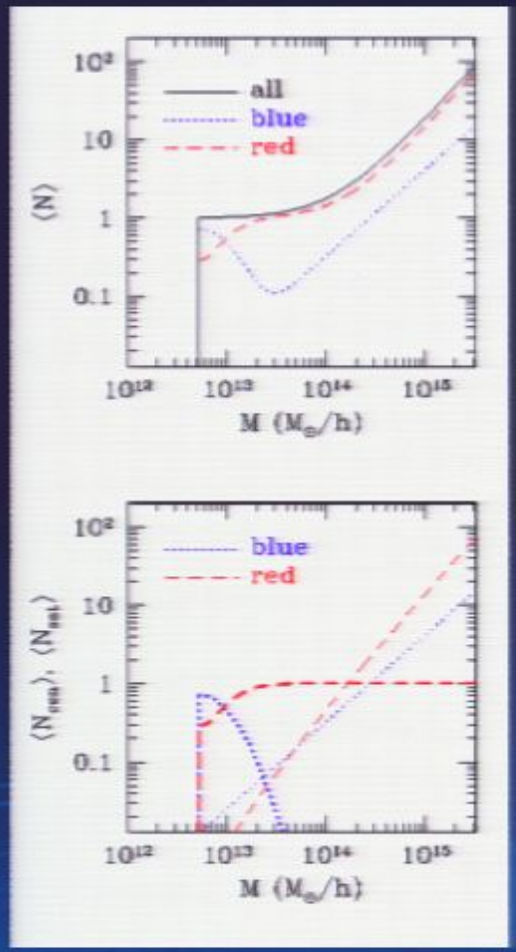


Zehavi, Zheng, et al. 2005
Zehavi, Zheng, et al. 2010

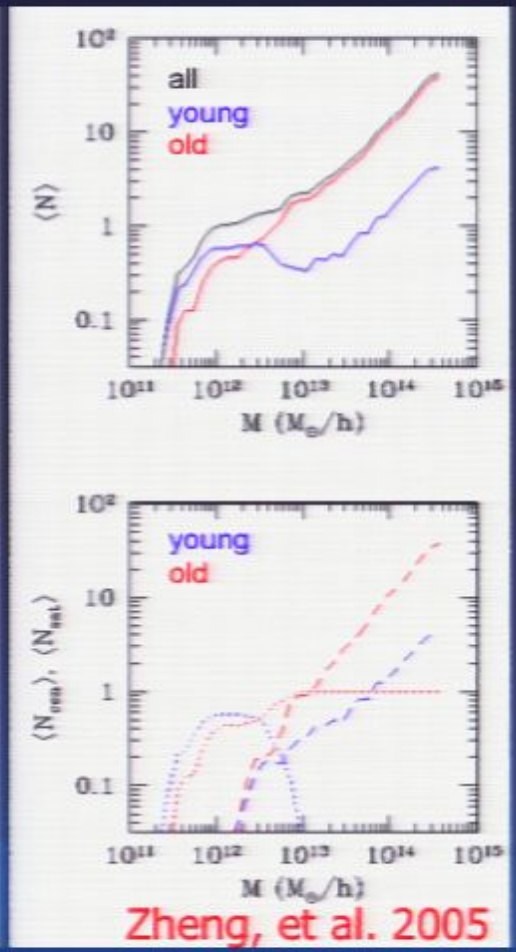
Matching observed clustering requires:

- color-halo mass relation for central galaxies
- higher red fraction for satellite galaxies

Observation



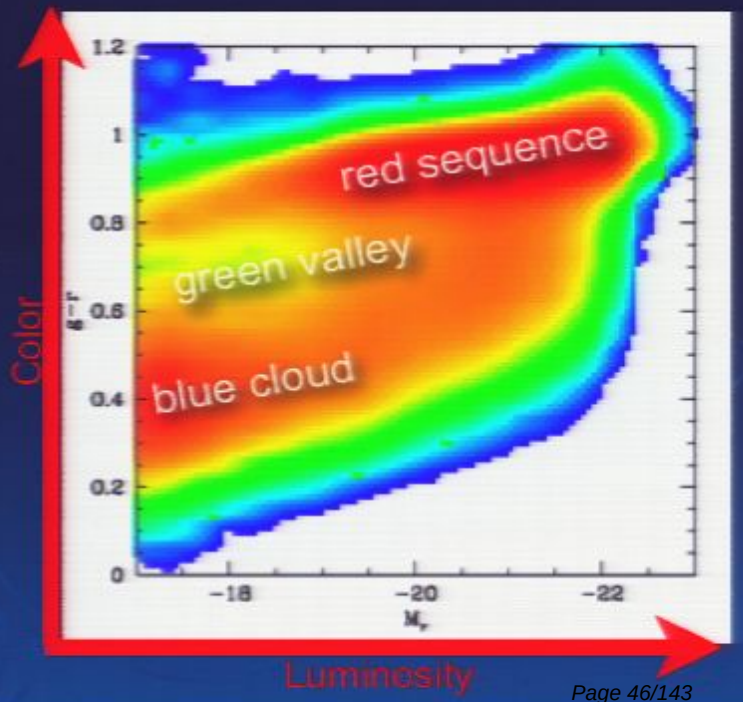
Theory



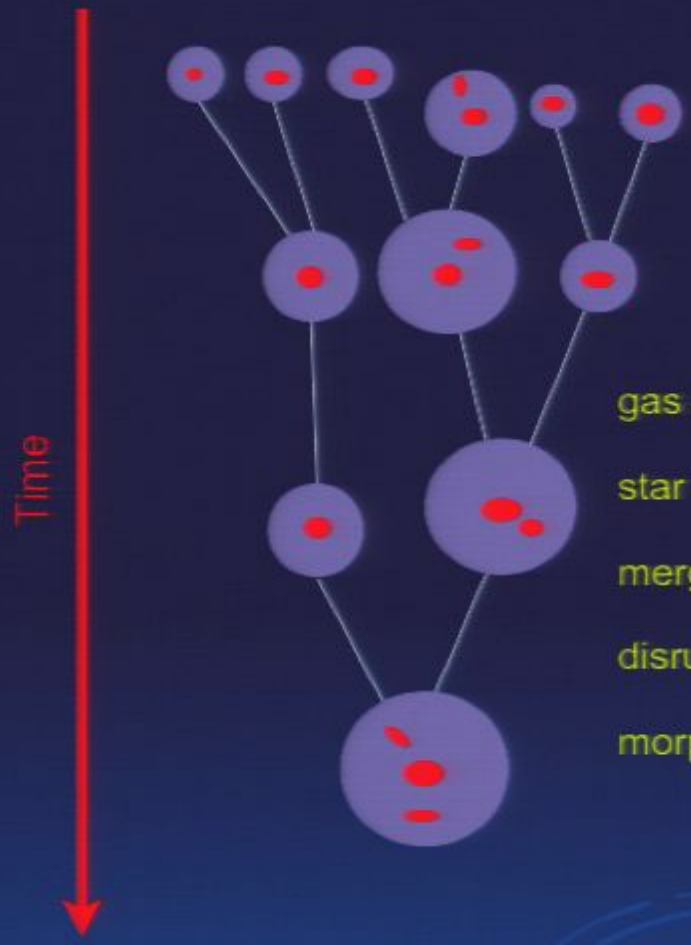
Zheng, et al. 2005

HOD modeling of SDSS galaxy clustering

- Demonstration of the existence of a break in the galaxy correlation function
  Naturally expected within HOD
- Rich color/luminosity dependence in galaxy clustering
  Relation between galaxy properties and halo mass
- Ongoing analyses of DR7 data
  Expect more detailed understanding of the galaxy-halo connection
  (color/luminosity, central/satellite)
  Zheng, et al. in prep.



Going to Higher Redshifts (Earlier Times)



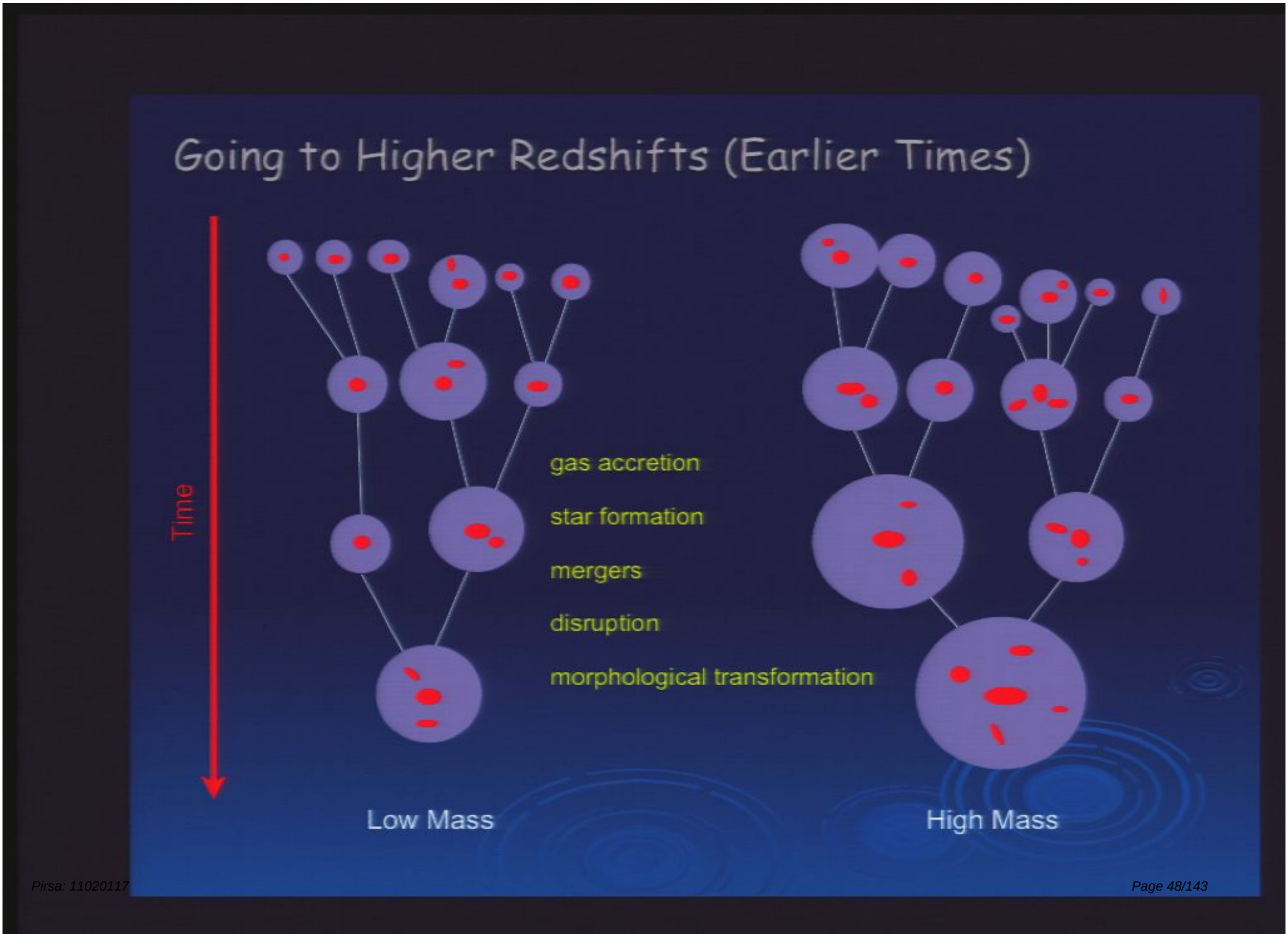
gas accretion

star formation

mergers

disruption

morphological transformation


Going to Higher Redshifts (Earlier Times)
Time
gas accretion
star formation
mergers
disruption
morphological transformation
Low Mass
High Mass

HOD Modeling

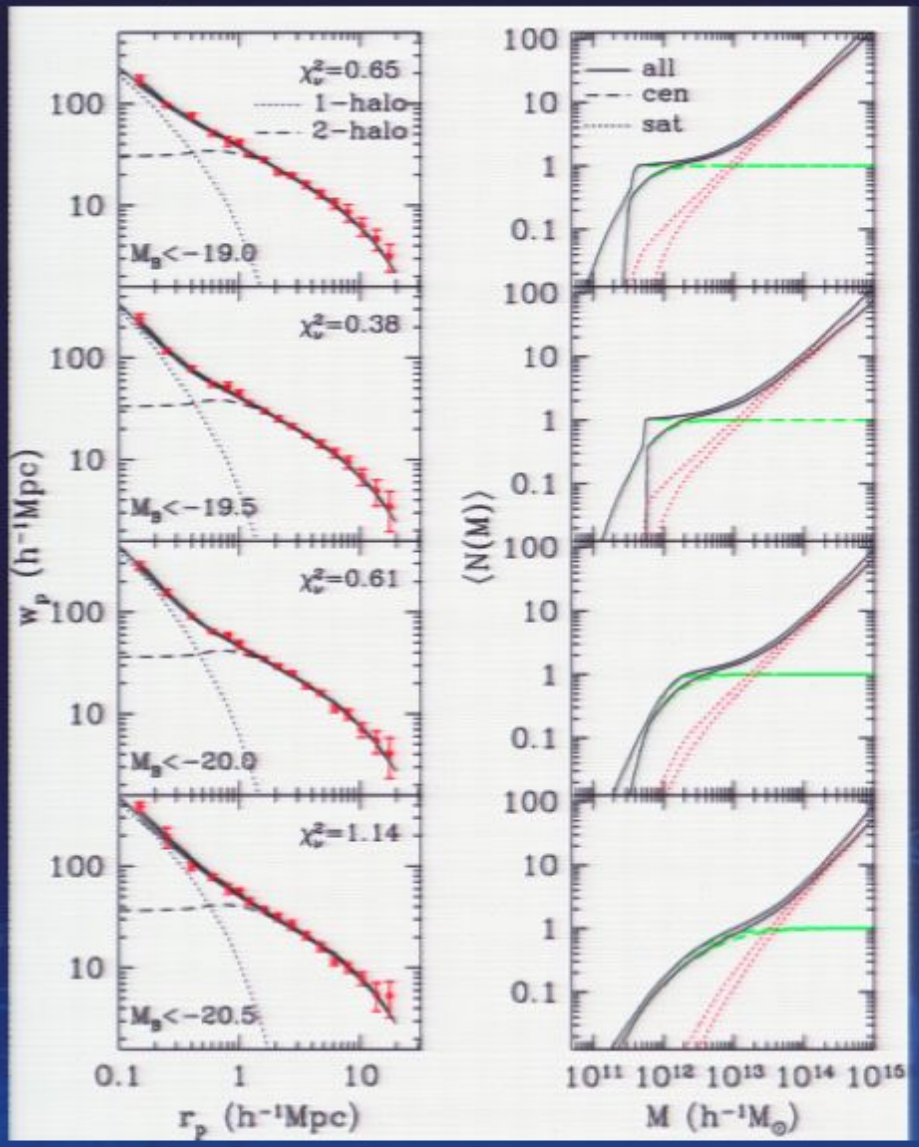
SDSS (z~0) [Now]

DEEP2 (z~1) [~7.5Gyr ago]

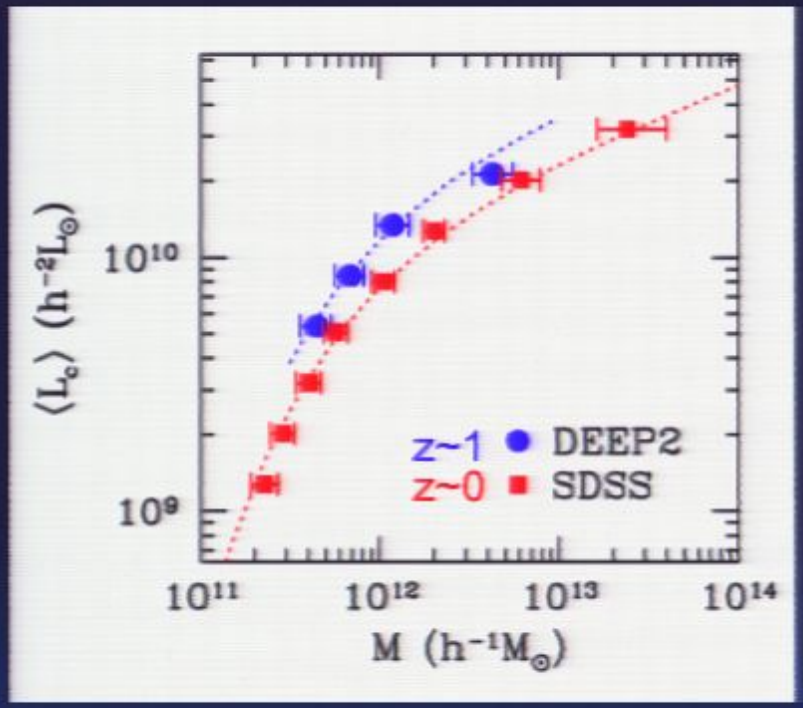
Luminosity

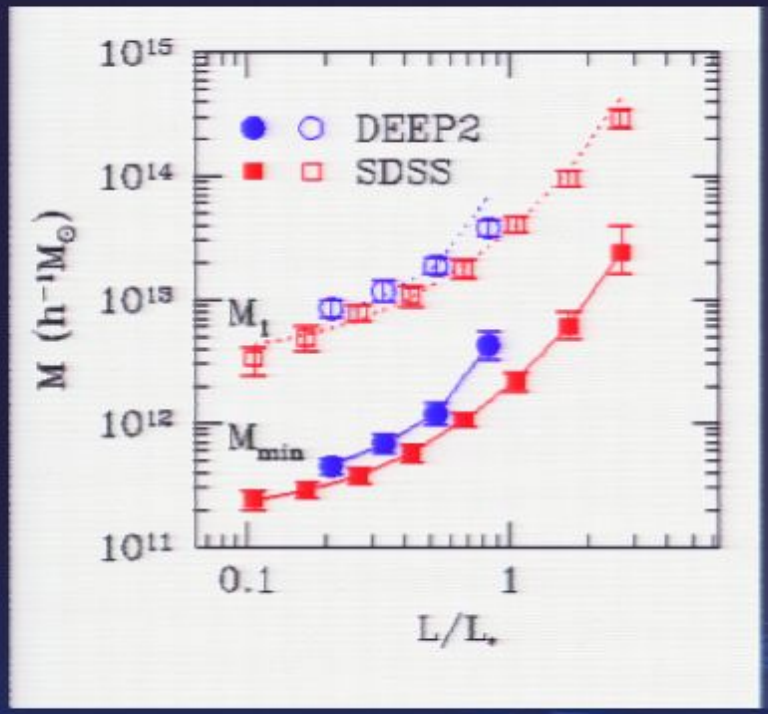
DEEP2 galaxies
z~1

Zheng, Coil, & Zehavi 2007



Galaxy luminosity and mass scales





Zheng, Coil, & Zehavi 2007

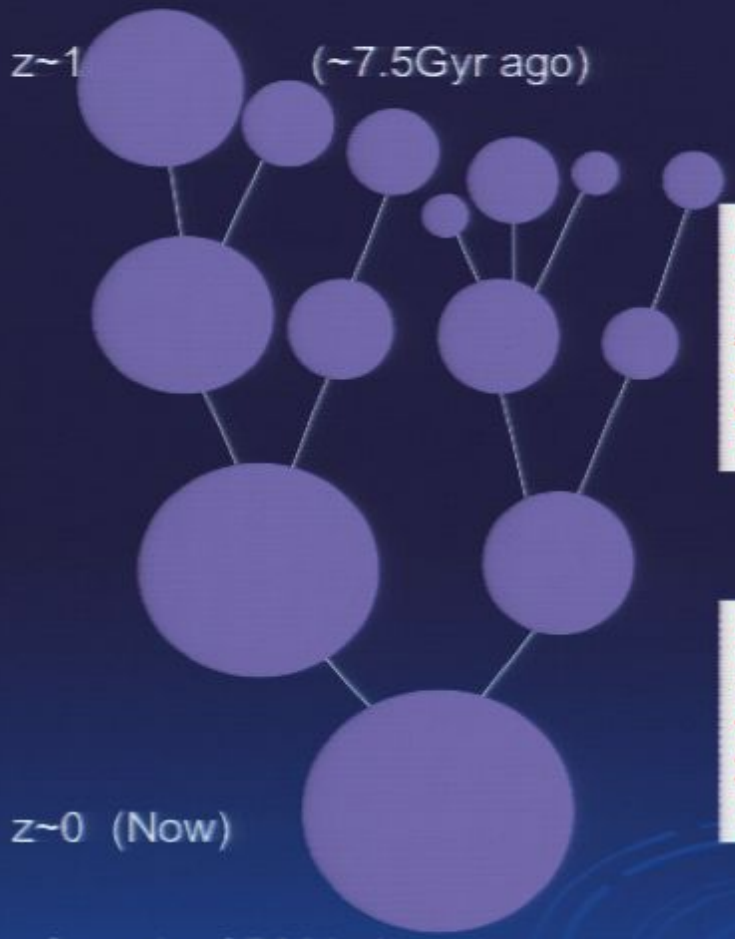
M_1/M_{min} ratio similar at z~1 and z~0
steep increase of L_c with halo mass at low mass end

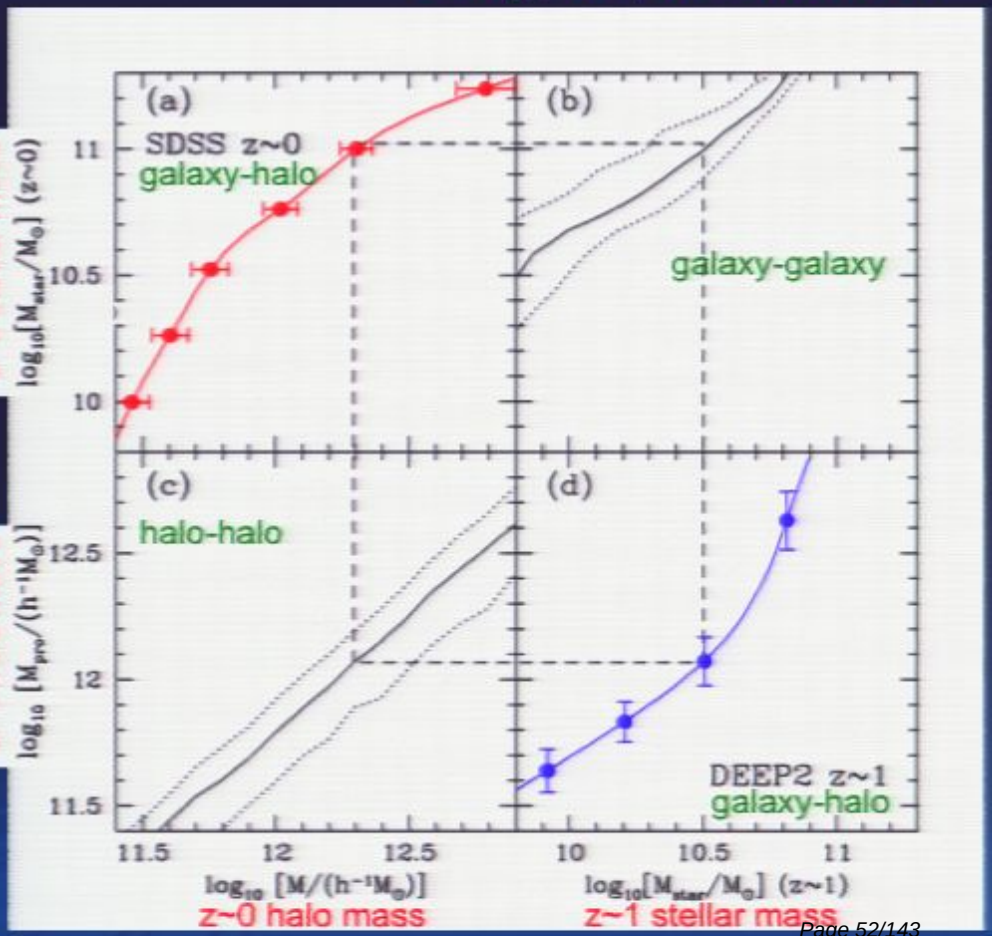
Halo-Galaxy z~1 (~7.5Gyr ago)

Halo-Galaxy z~0 (Now)

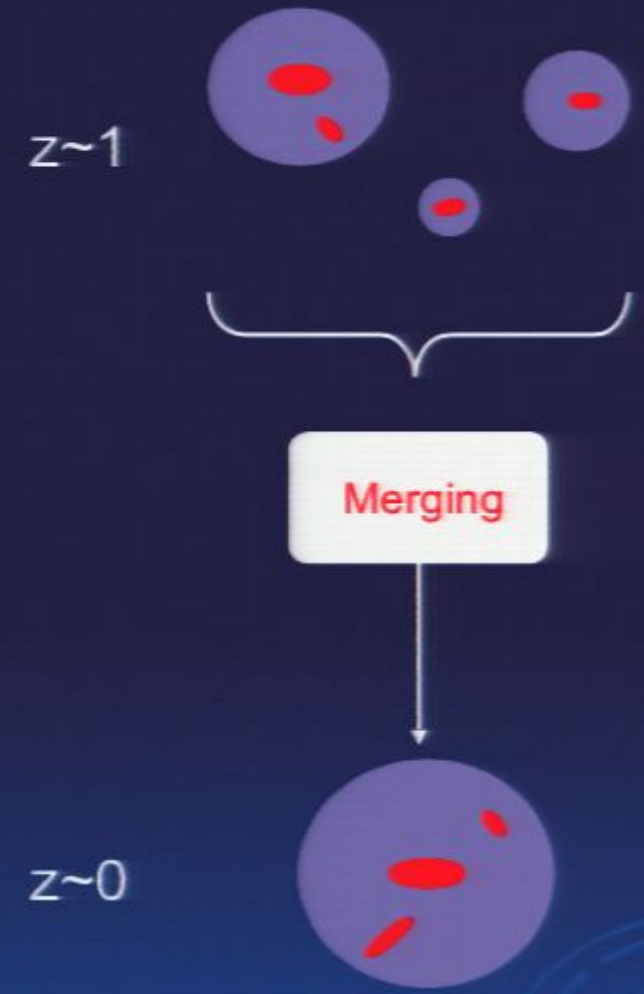
Establishing an evolution link between z~1 DEEP2 and z~0 SDSS galaxies

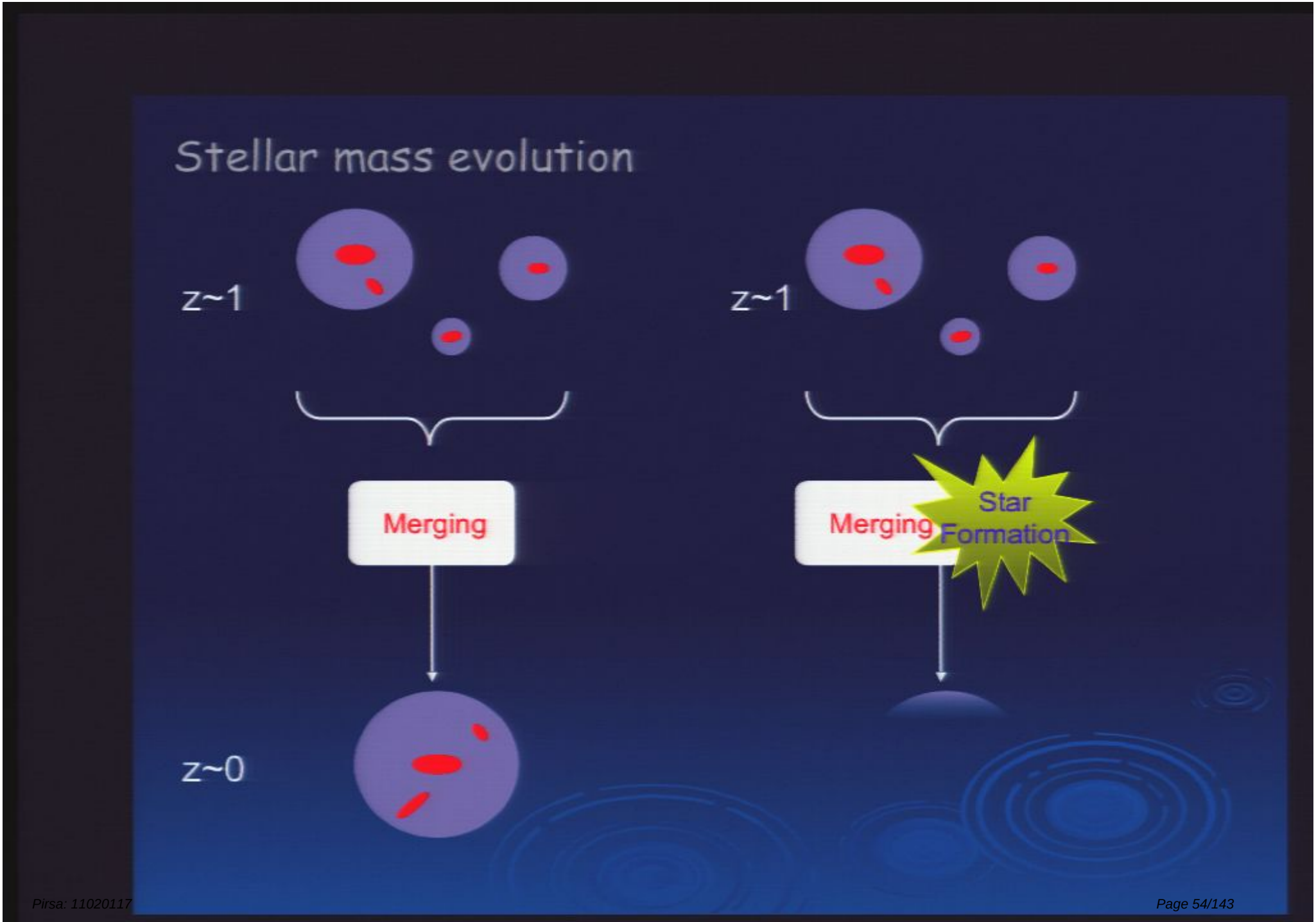
Zheng, Coil, & Zehavi 2007



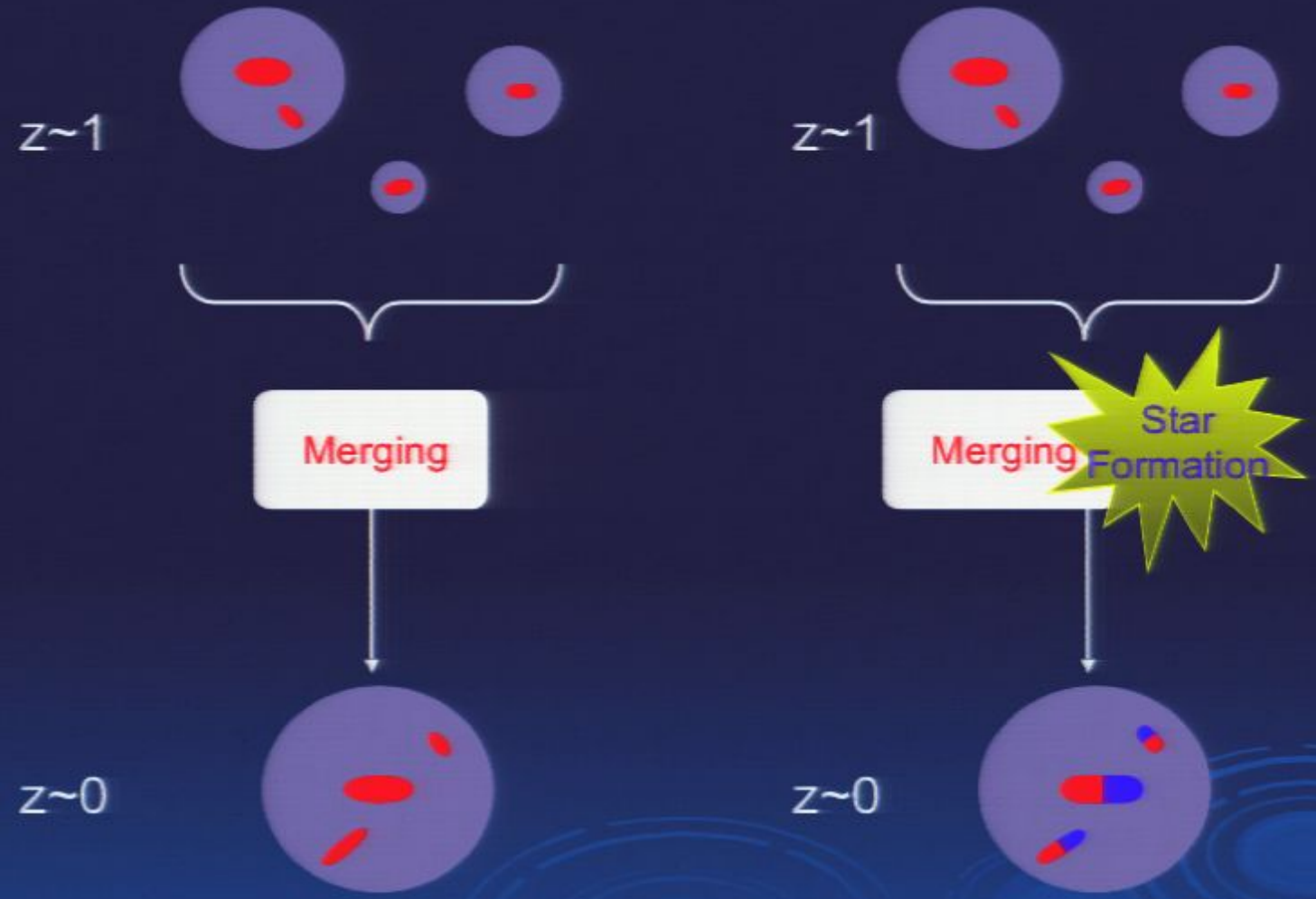


Stellar mass evolution

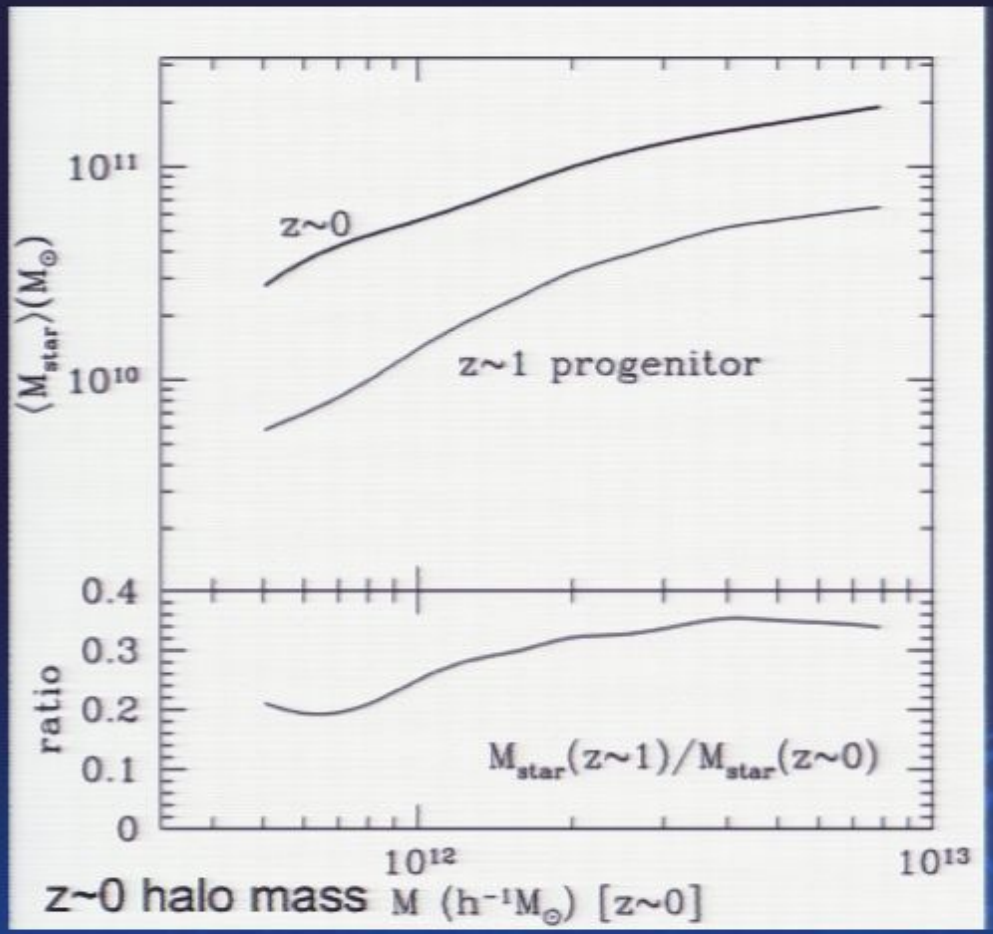



Stellar mass evolution
z~1
z~1
Merging
Merging
Star Formation
z~0

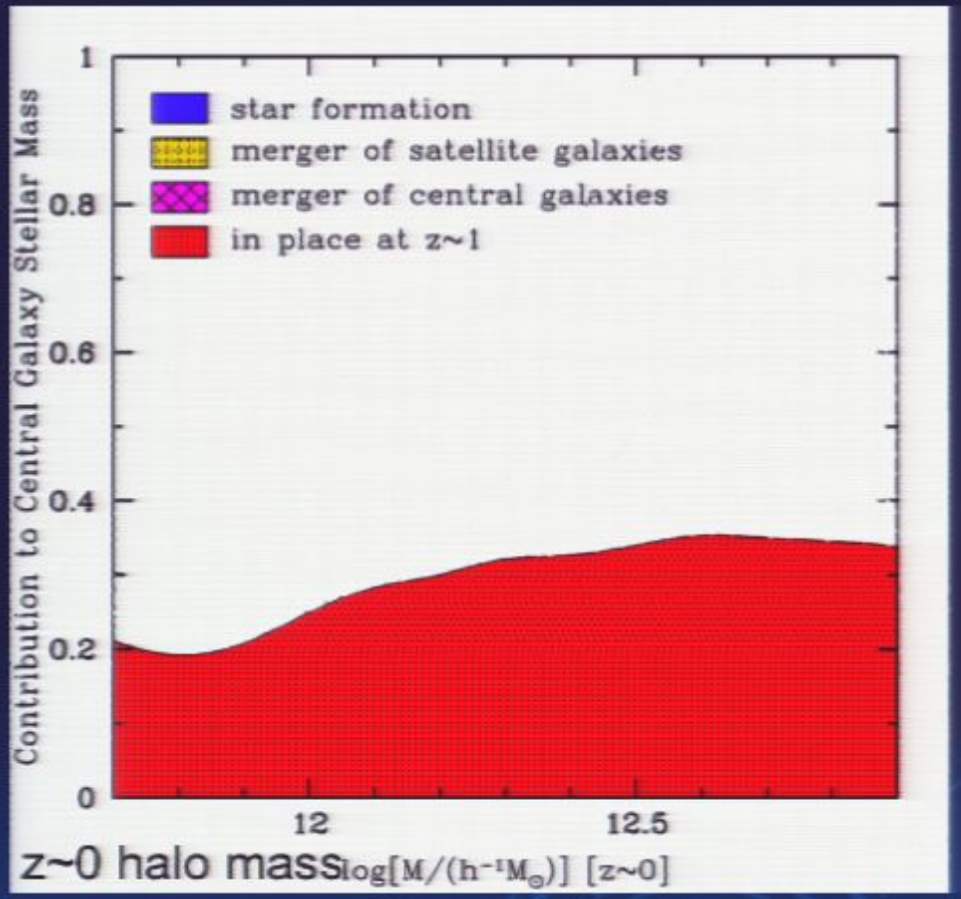
Stellar mass evolution



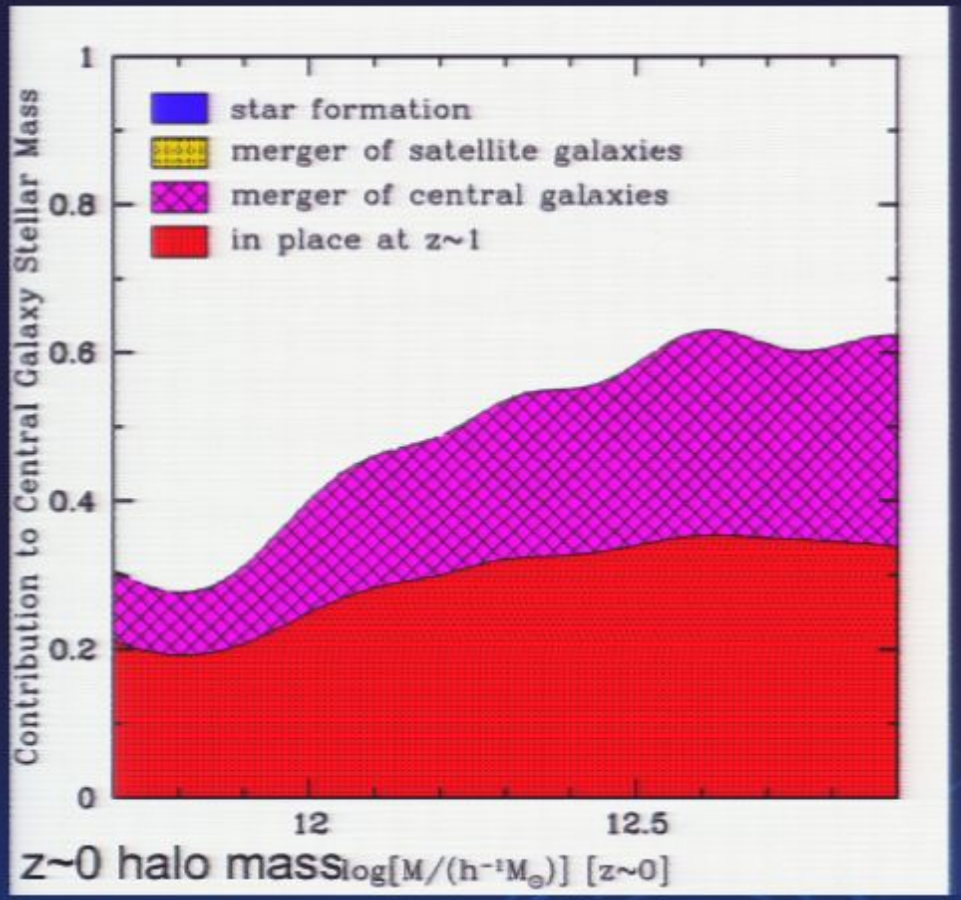
Stellar mass evolution (z~1 to z~0) as a function of halo mass



Zheng, Coil, & Zehavi 2007



Zheng, Coil, & Zehavi 2007



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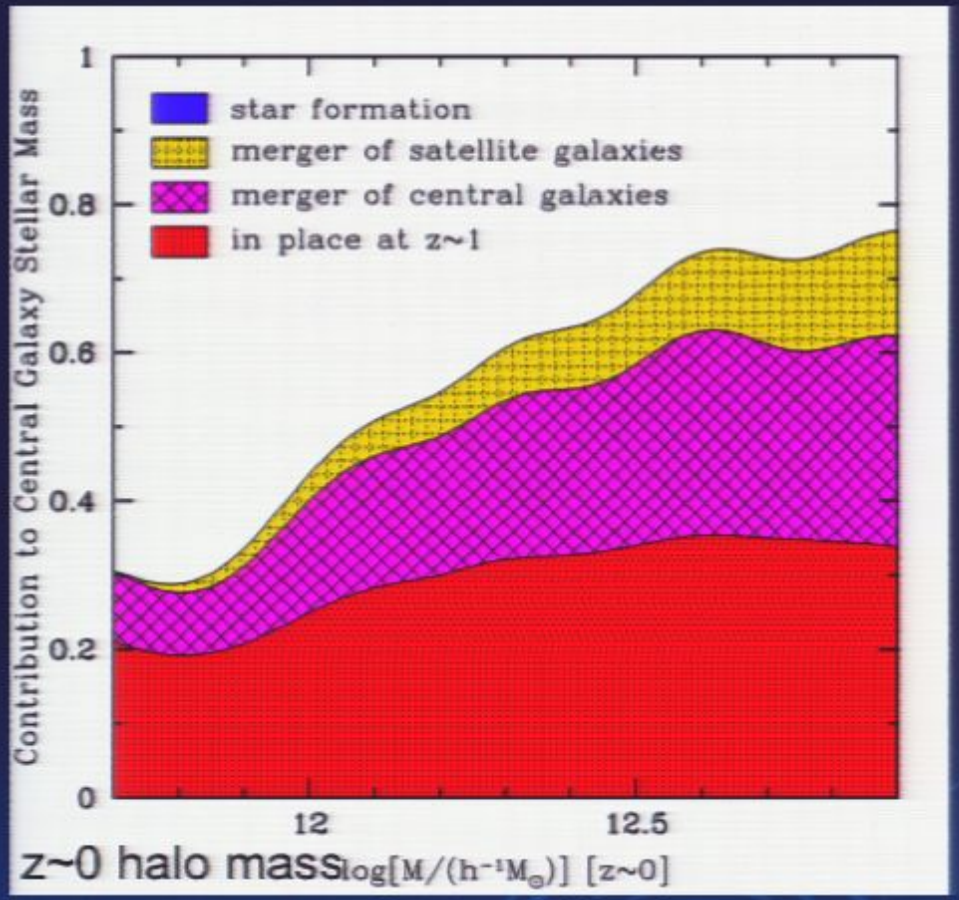

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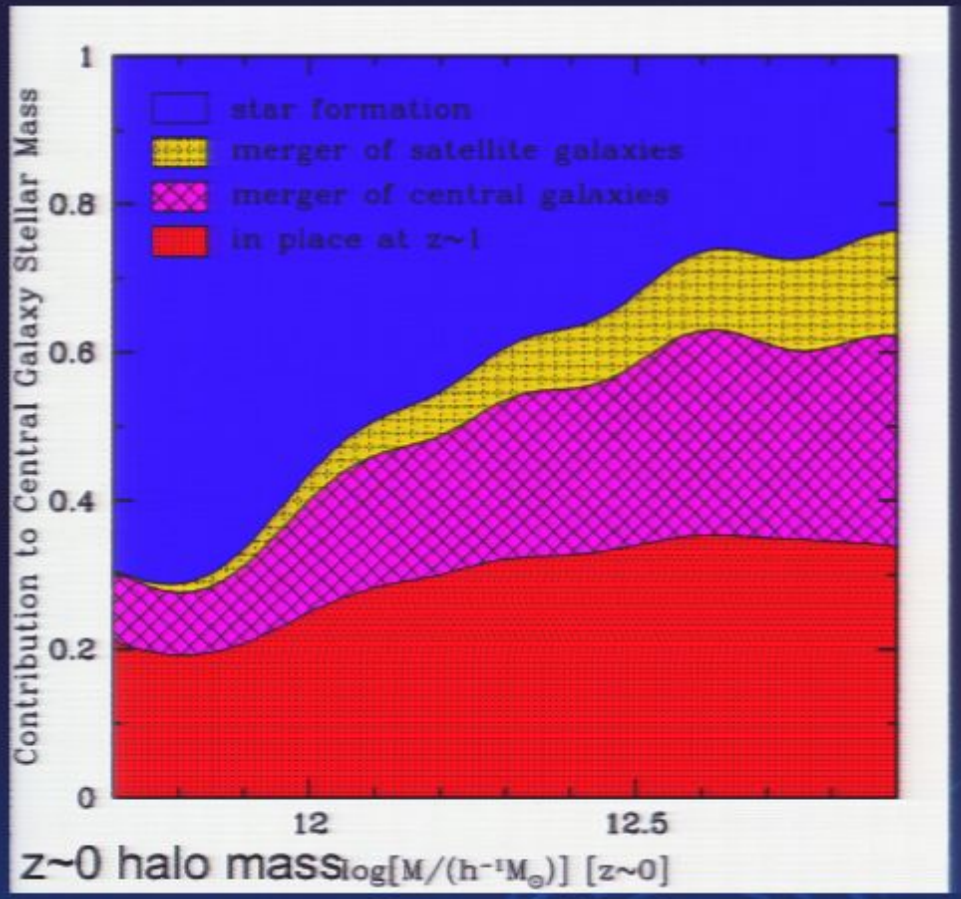


Zheng, Coil, & Zehavi 2007

Results:

For central galaxies in z~0 $M \sim 5 \times 10^{11}\ h^{-1} M_{sun}$ halos,
~70% of their stars form after z~1

For central galaxies in z~0 $M \sim 10^{13}\ h^{-1} M_{sun}$ halos,
~25% of their stars form after z~1

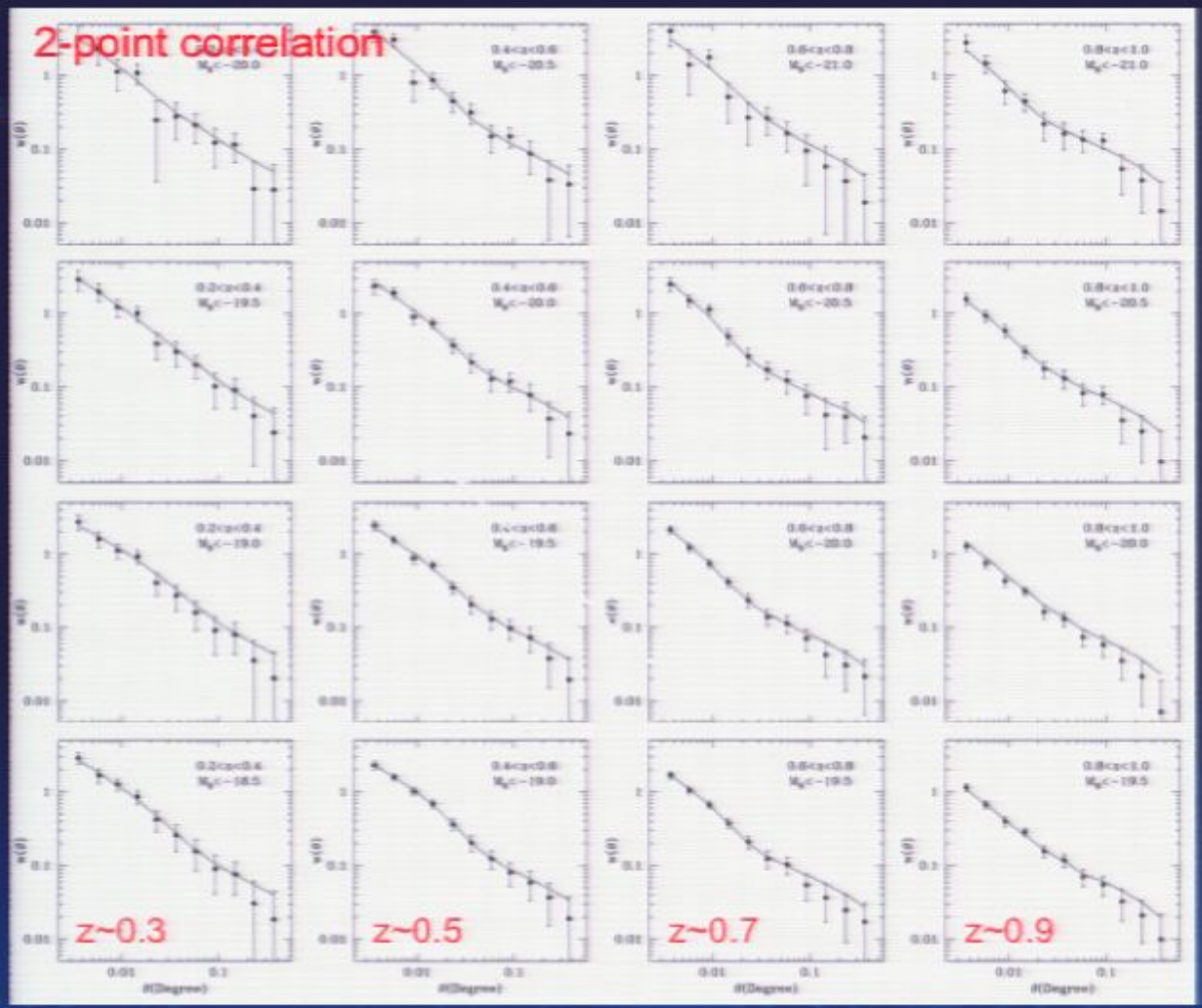
Fardal et al. 2006 — global SFH, 40-50% stars formed after z~1

Panter et al. 2007 — stellar population modeling of z~0 SDSS galaxies,
60% of the stars in galaxies with stellar mass 2×10^{10} M_{sun}
25% of the stars in galaxies with stellar mass 2×10^{11} M_{sun}
formed between z~0.8 and z~0

Noeske et al. 2007 — SFR (during the SF phase) $\propto M_{star}^{2/3}$ [$(1\text{-}5) \times 10^{10}$ M_{sun}]
consistent with our integration results [ours has a 20% lower normalization $\Rightarrow$ SF is the dominant mode of stellar mass growth for $(1\text{-}5) \times 10^{10}$ M_{sun} galaxies]

Clustering of red galaxies at different redshifts

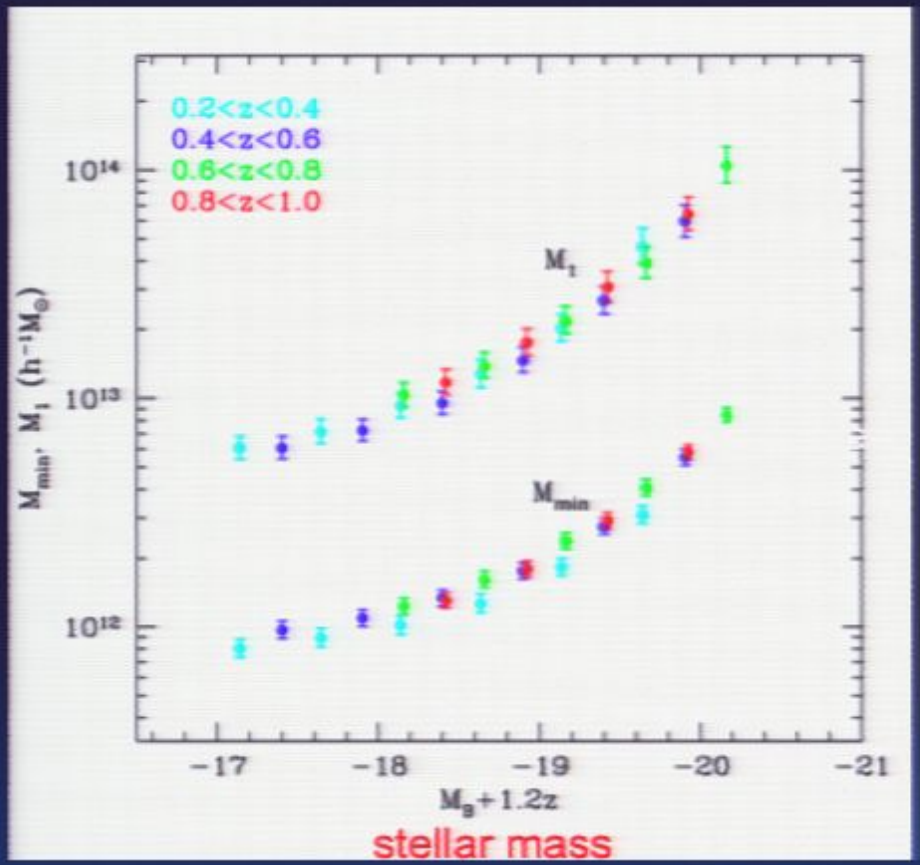
Galaxies in massive halos



NOAO Deep Wide Field Survey
(NOAO-DWFS)

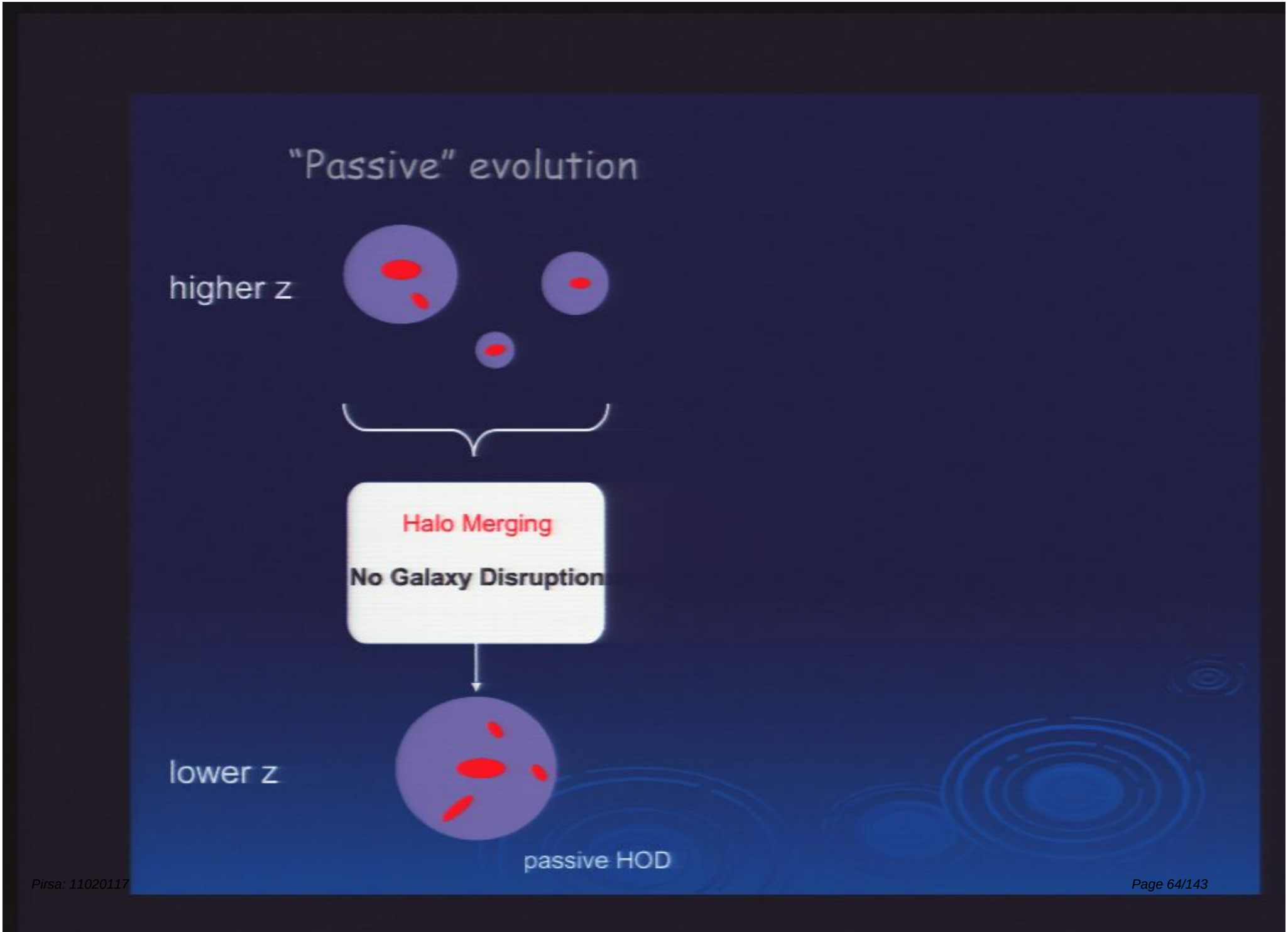
Brown, Zheng, et al. 2008

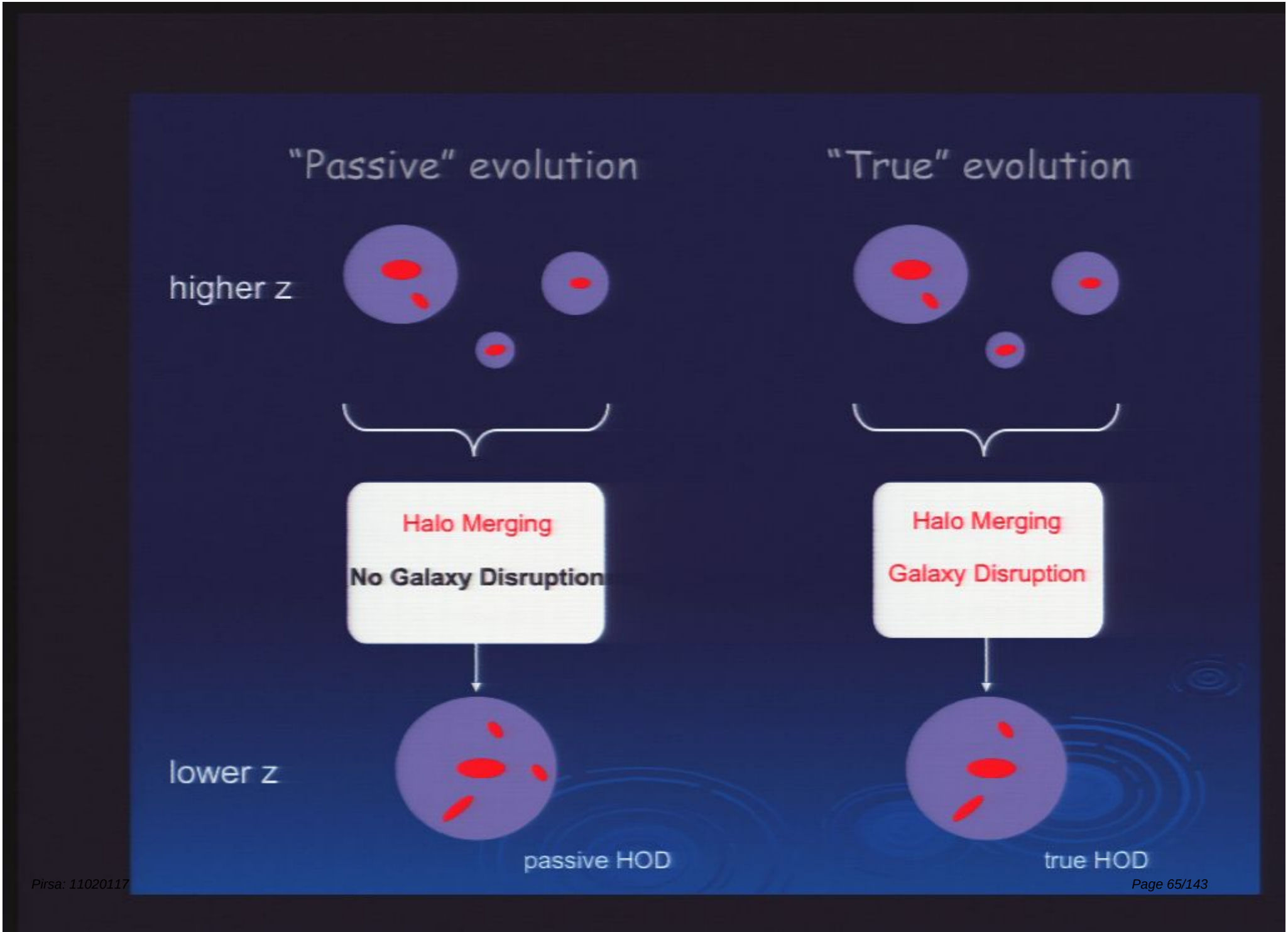
HODs of red galaxies at different redshifts (NOAO-DWFS)



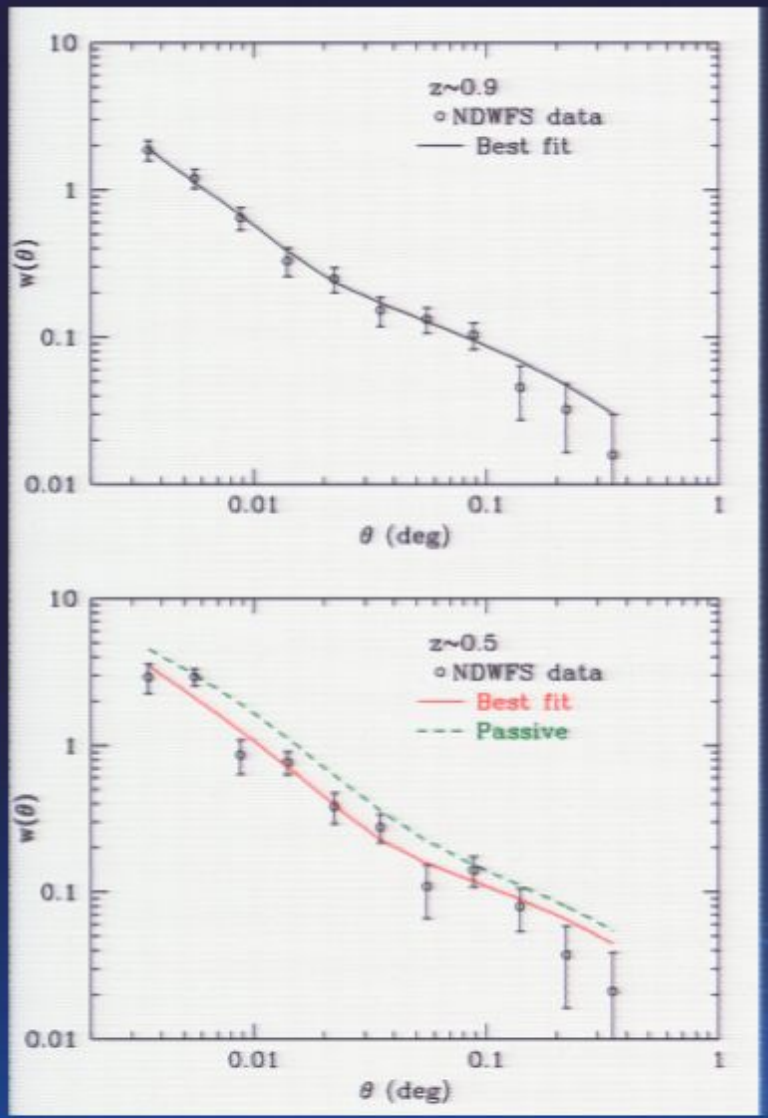
- M_{min}-M_1 scaling
- similar halo mass scales in terms of stellar mass
- flattening at ~10^{12} $h^{-1}M_{sun}$
- $M_{star} \propto M^{0.3}$ at high mass end
- decomposition of LF

Brown, Zheng, White, et al. 2008


"Passive" evolution
higher z
Halo Merging
No Galaxy Disruption
lower z
passive HOD


"Passive" evolution
"True" evolution
higher z
Halo Merging
No Galaxy Disruption
Halo Merging
Galaxy Disruption
lower z
passive HOD
true HOD

Evolution of luminous red satellite galaxies (NOAO-DWFS)



Compare the "passive" HOD with the "true" HOD

From z~0.9 to z~0.5,
~1/3 of the satellite galaxies in massive halos undergo merging or disruption.

These satellites may contribute to

Central galaxy growth [merging]
Intra-cluster light (ICL) [disruption]

White, Zheng, Brown, Dey, & Jannuzi 2007

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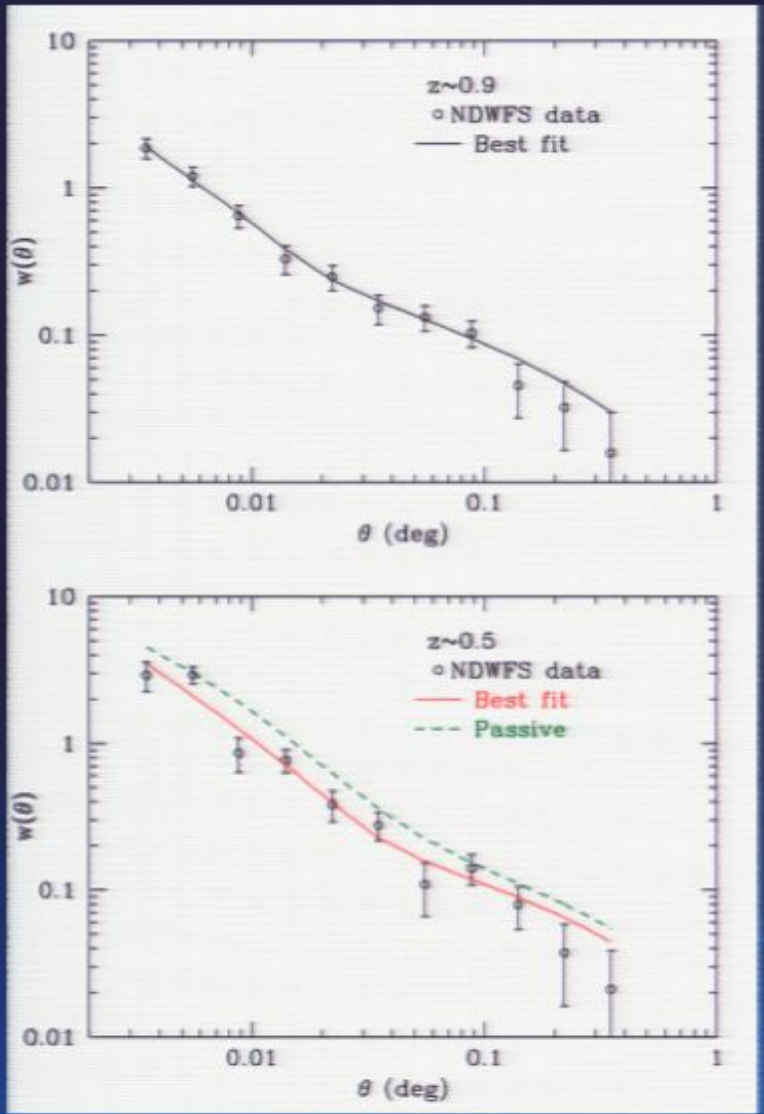

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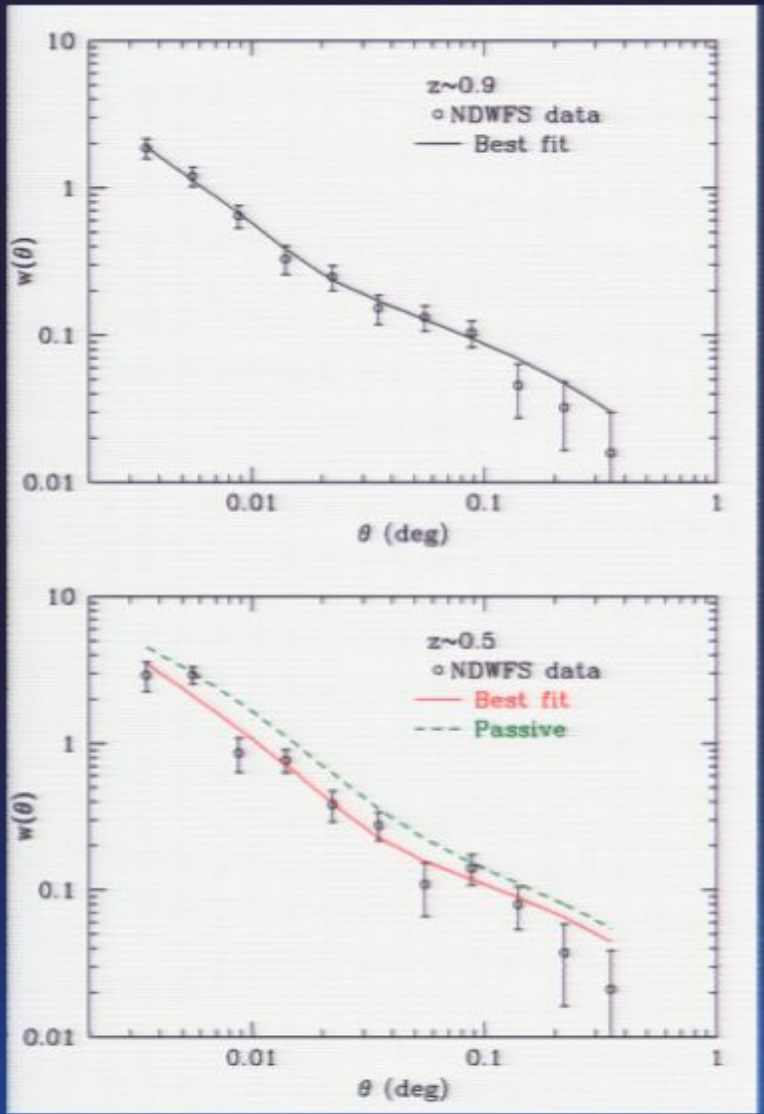

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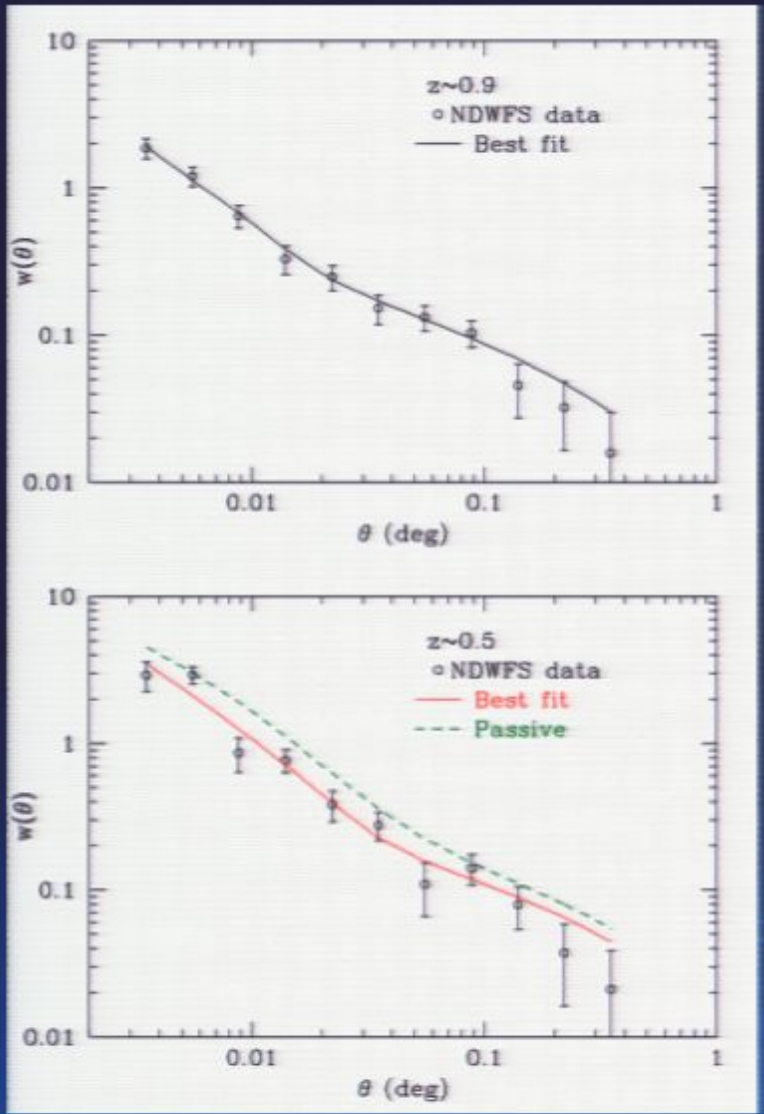

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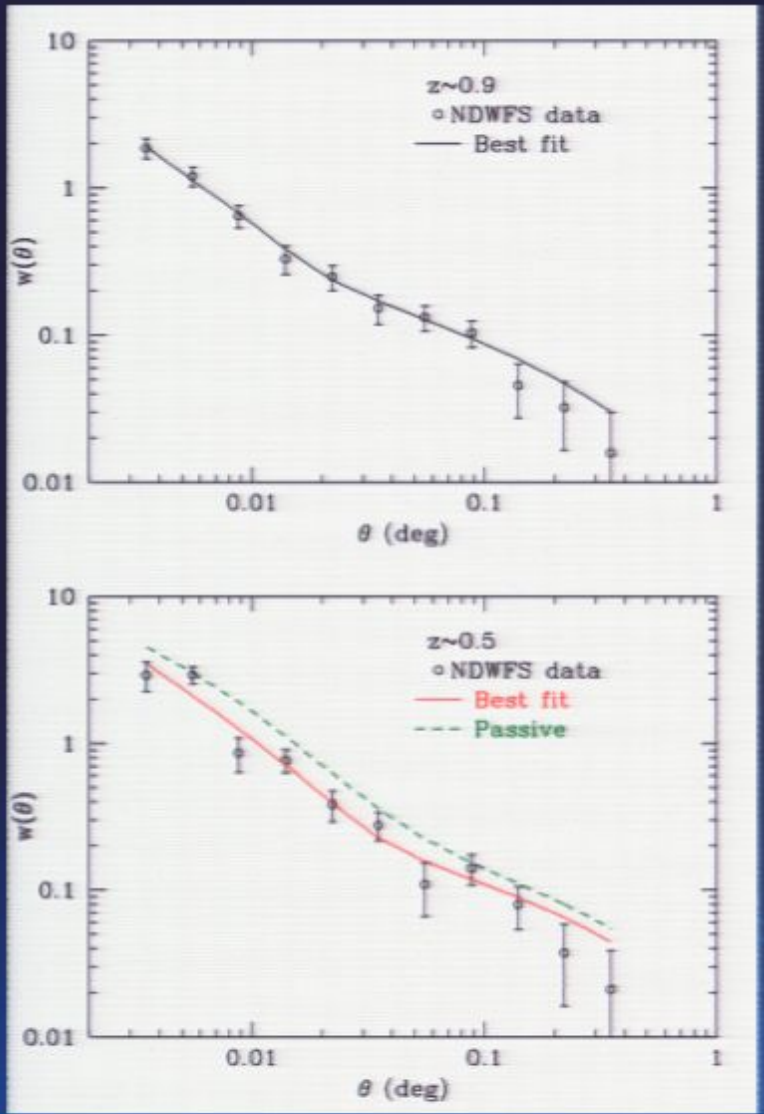

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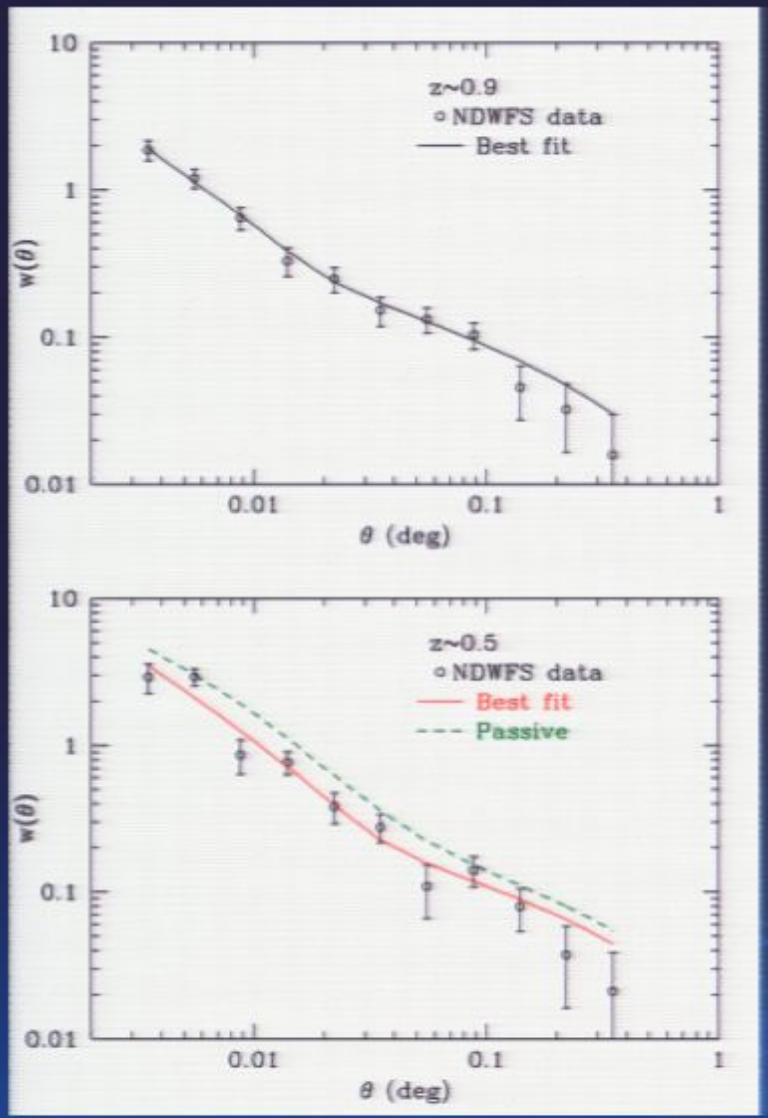

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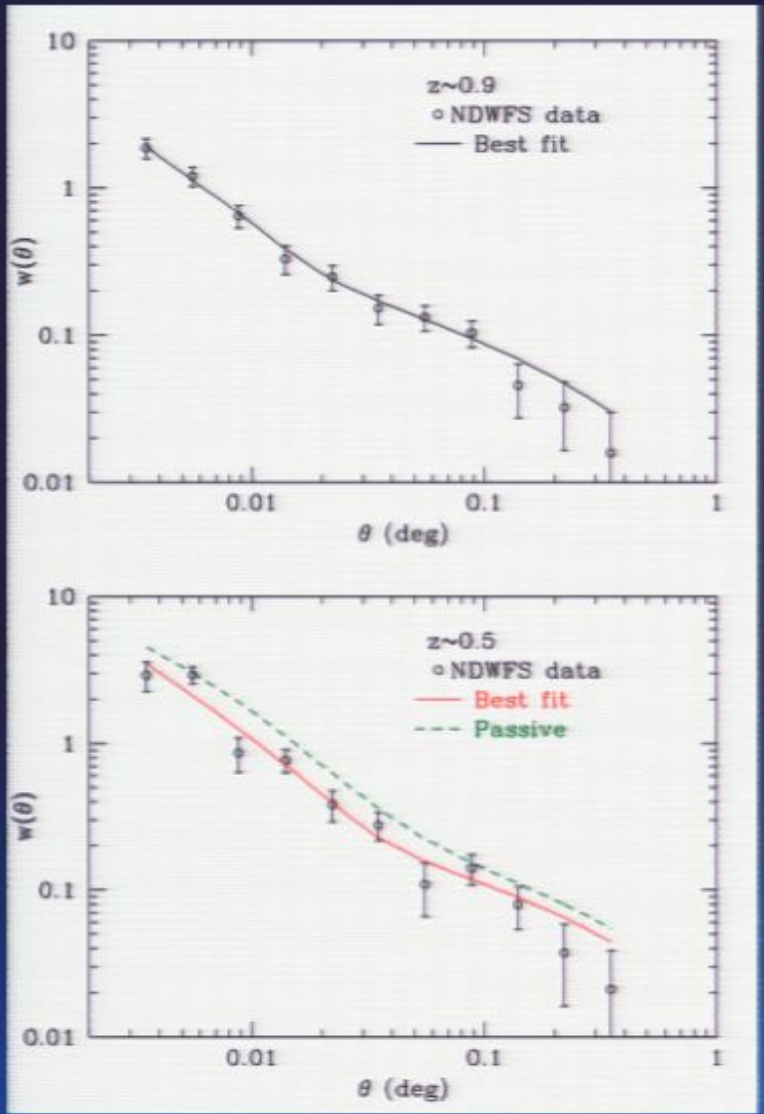

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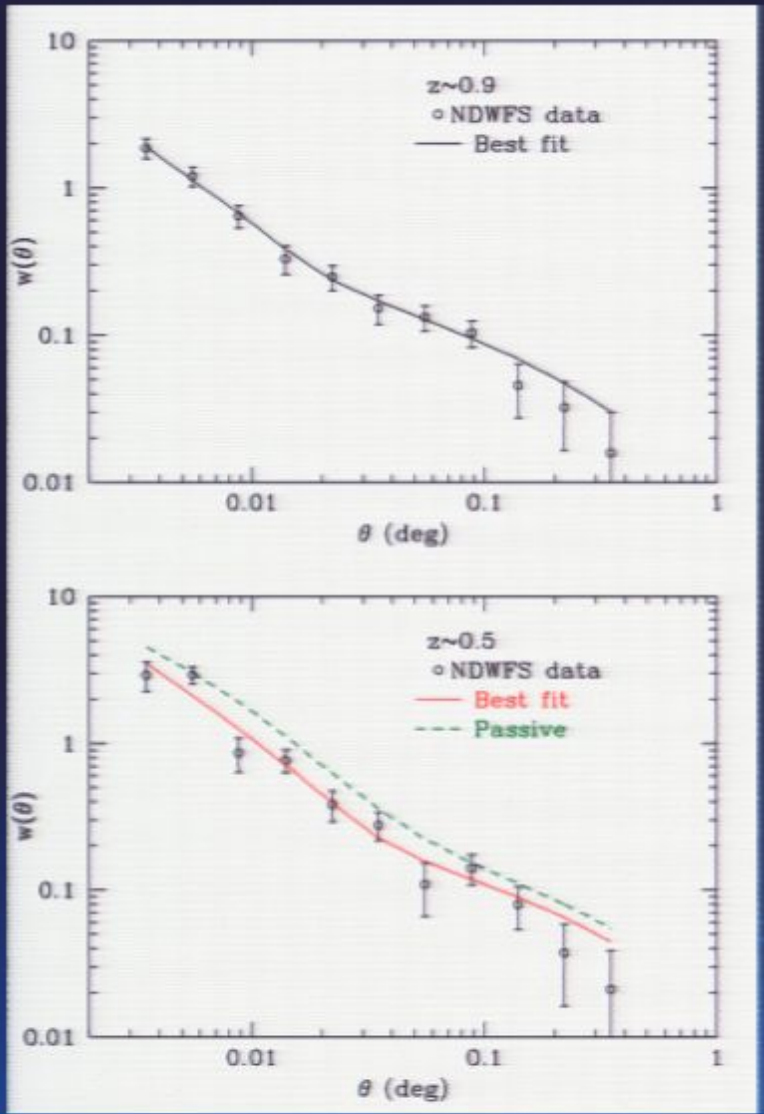

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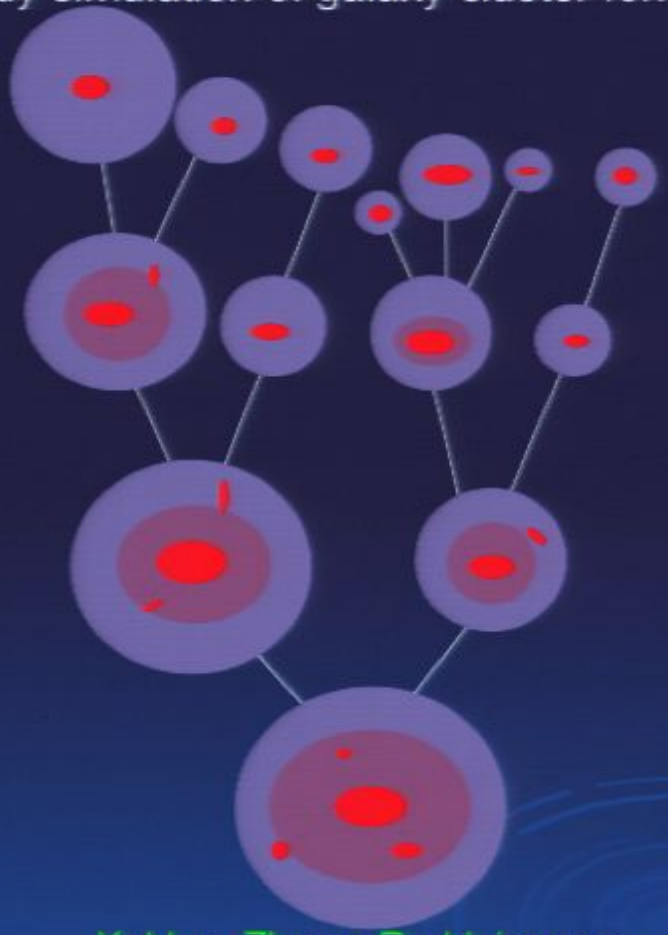
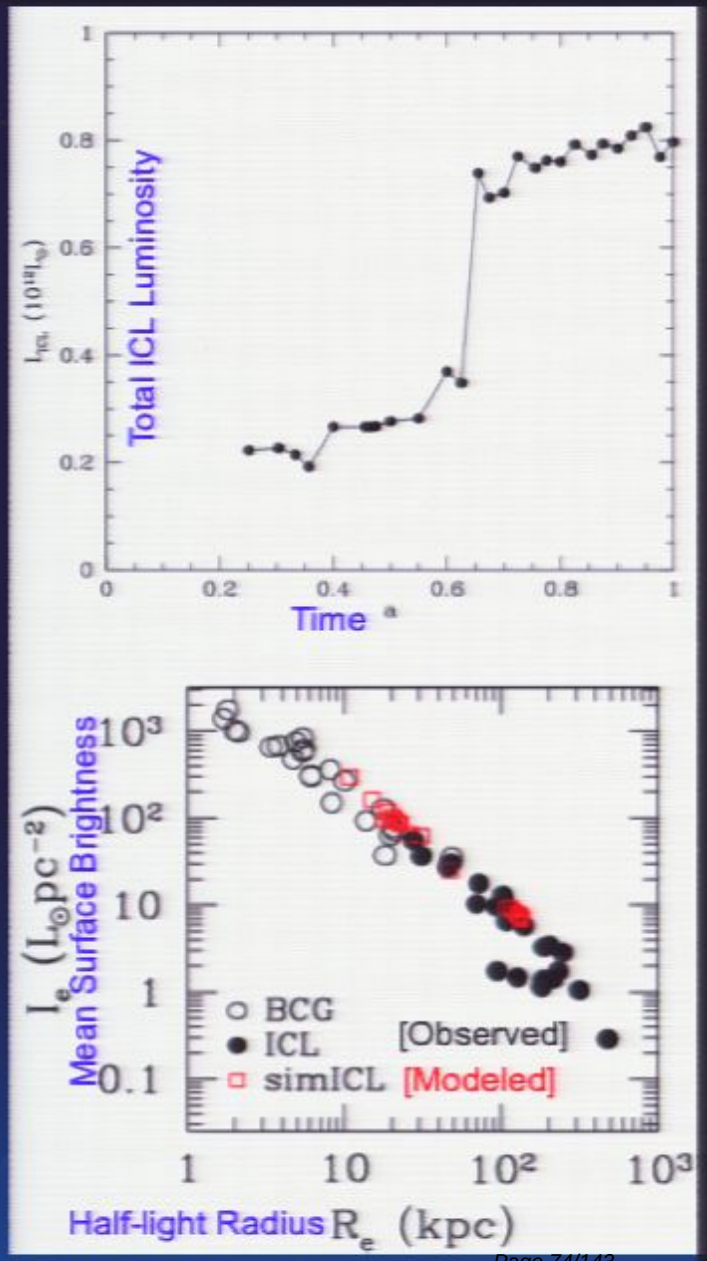
White, Zheng, Brown, Dey, & Jannuzi 2007

Formation and Properties of ICL

empirically inferred HODs + high-resolution
N-body simulation of galaxy cluster formation.



Kuhlen, Zheng, Rudd, in prep.



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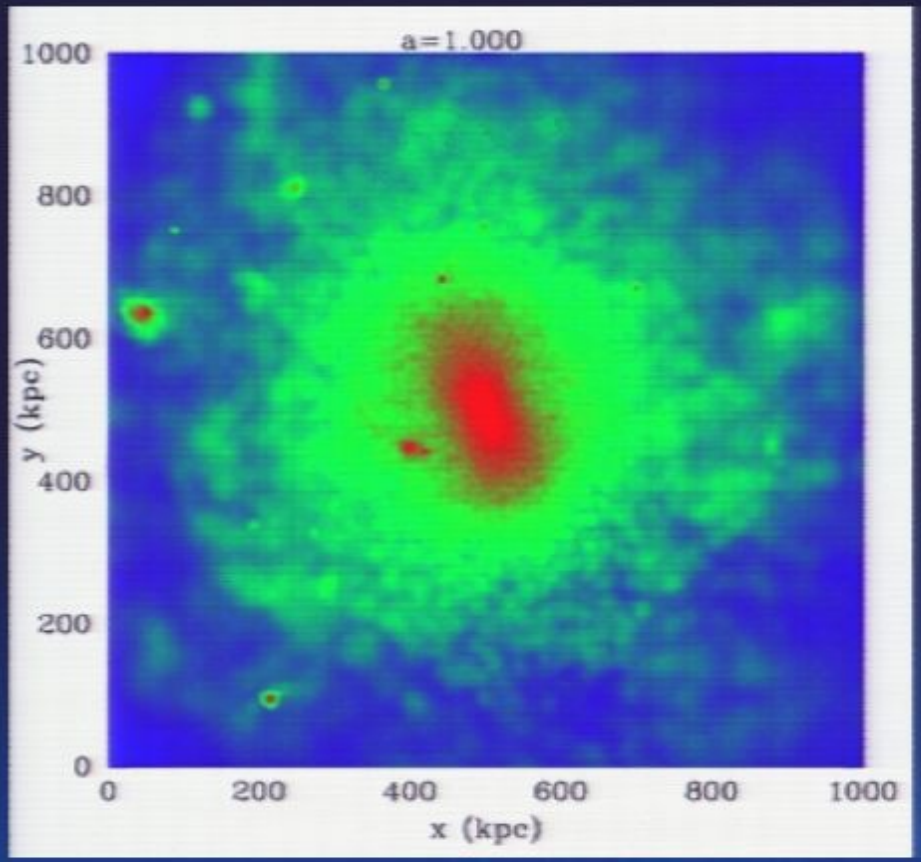

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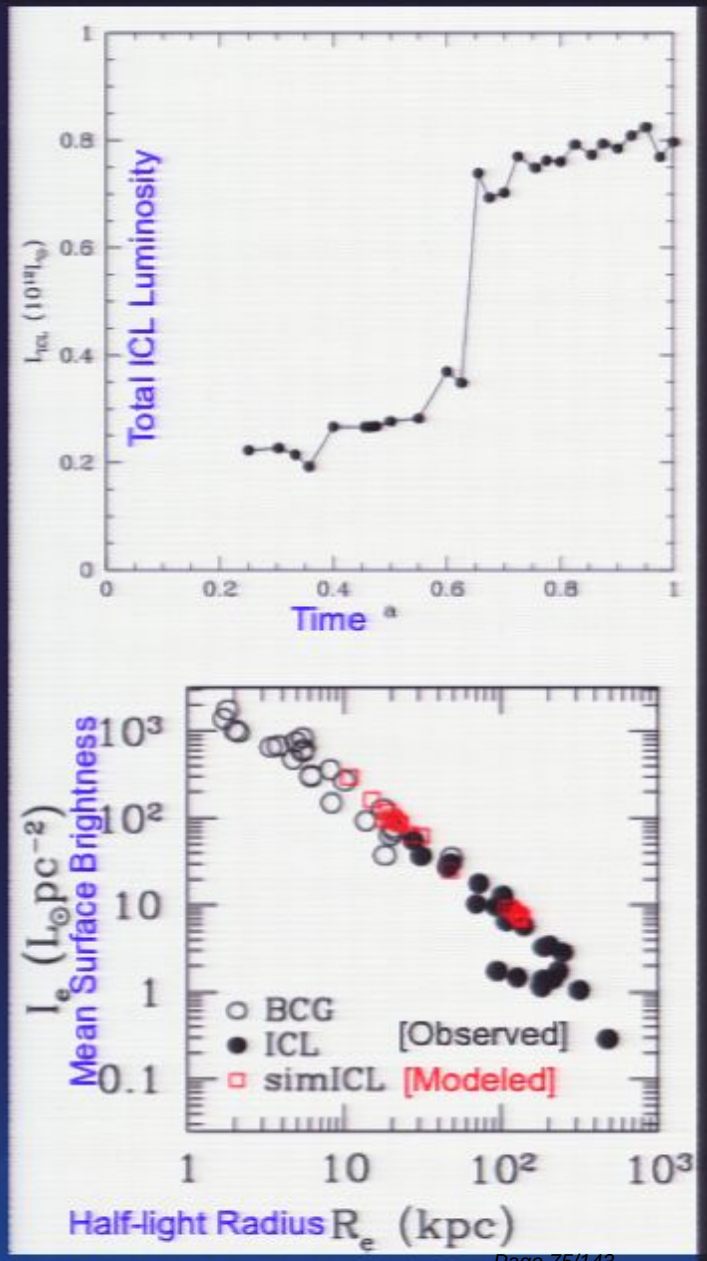

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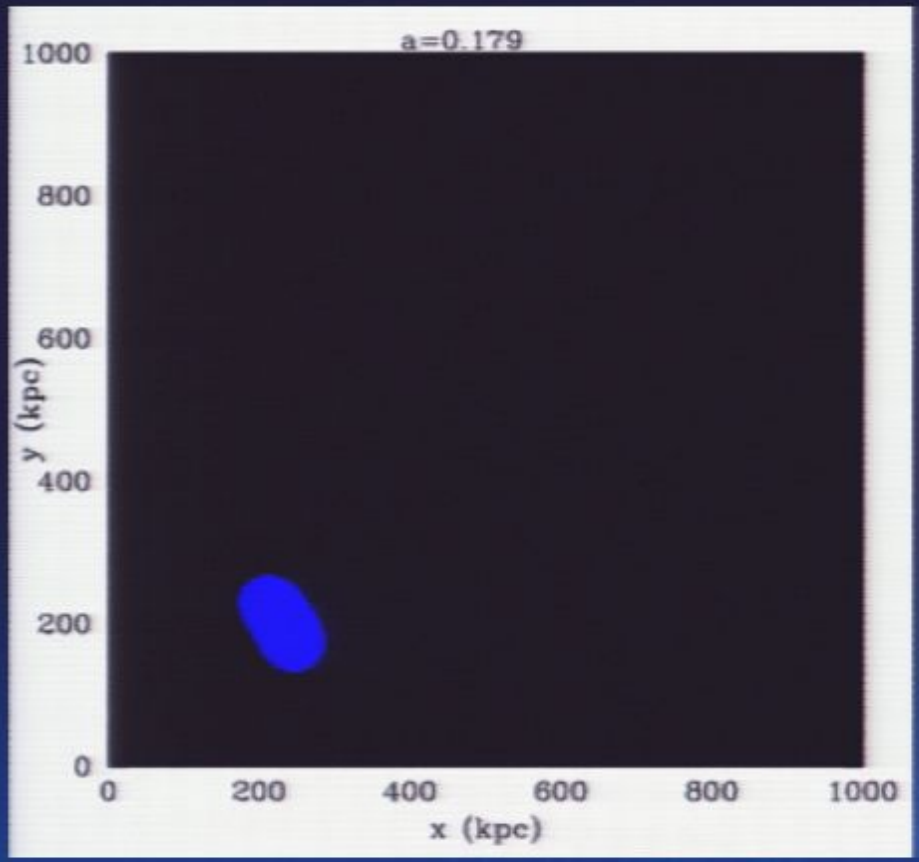

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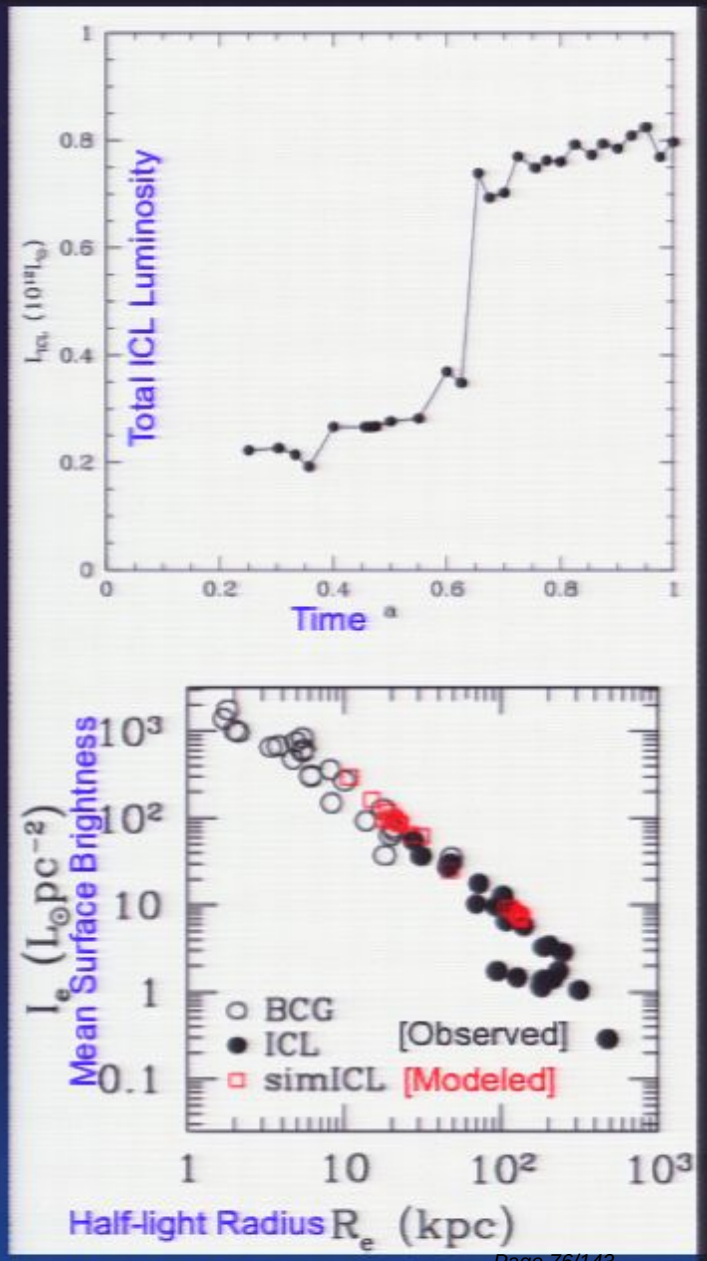

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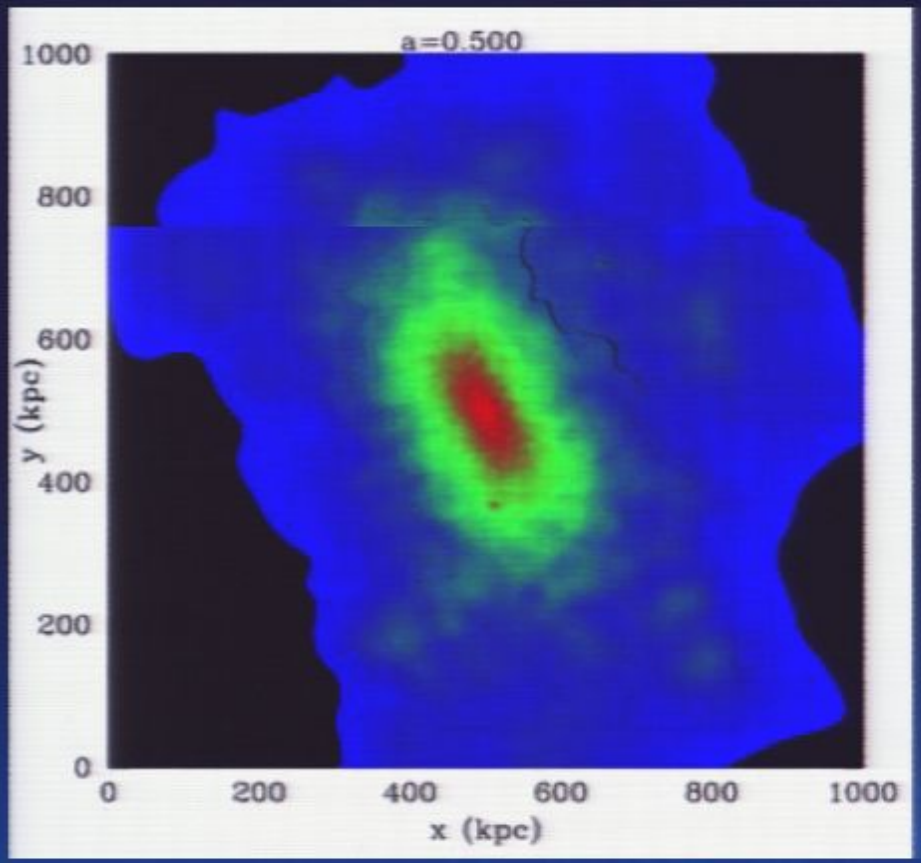

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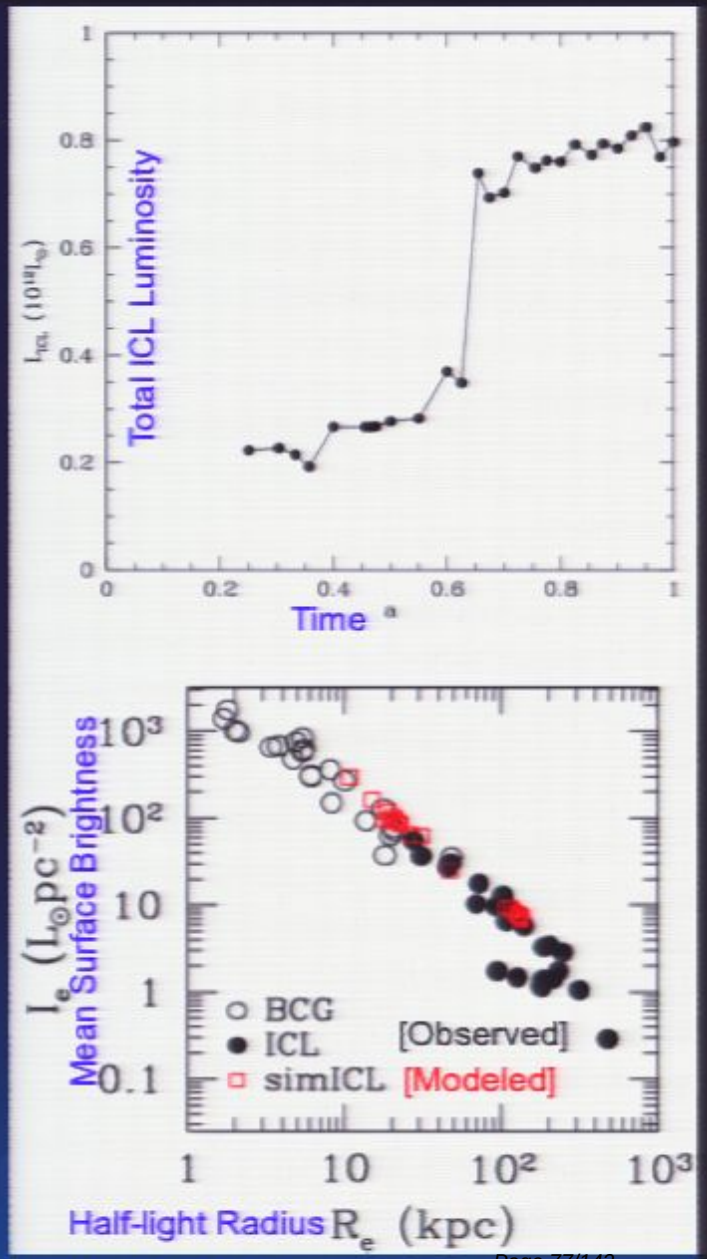

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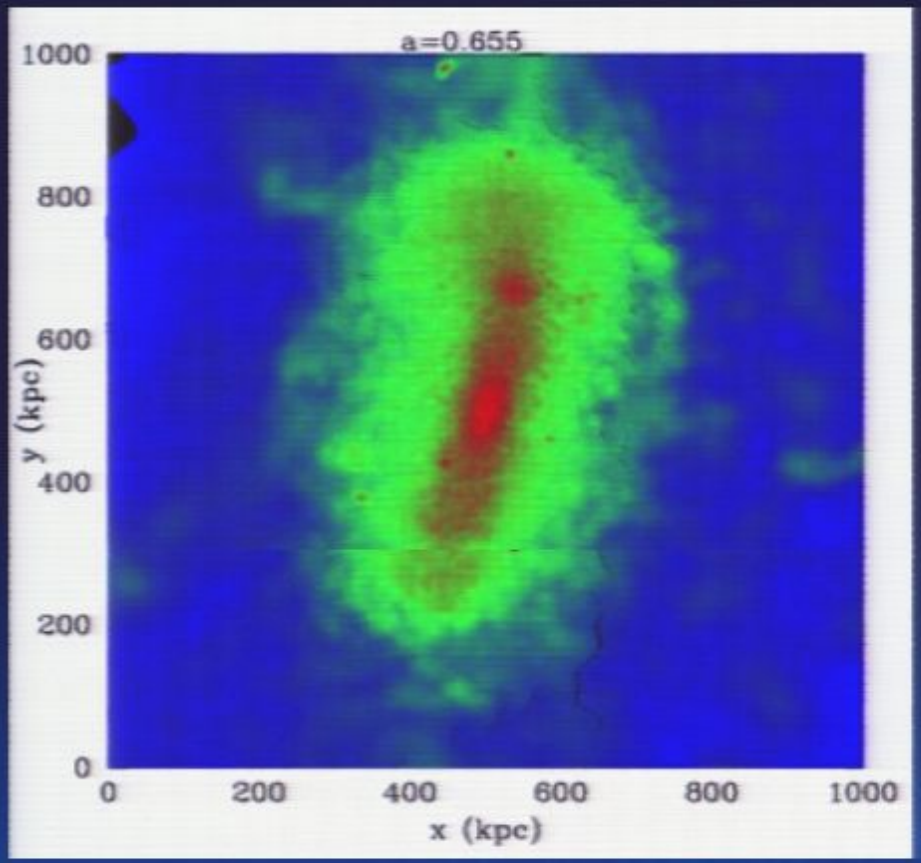

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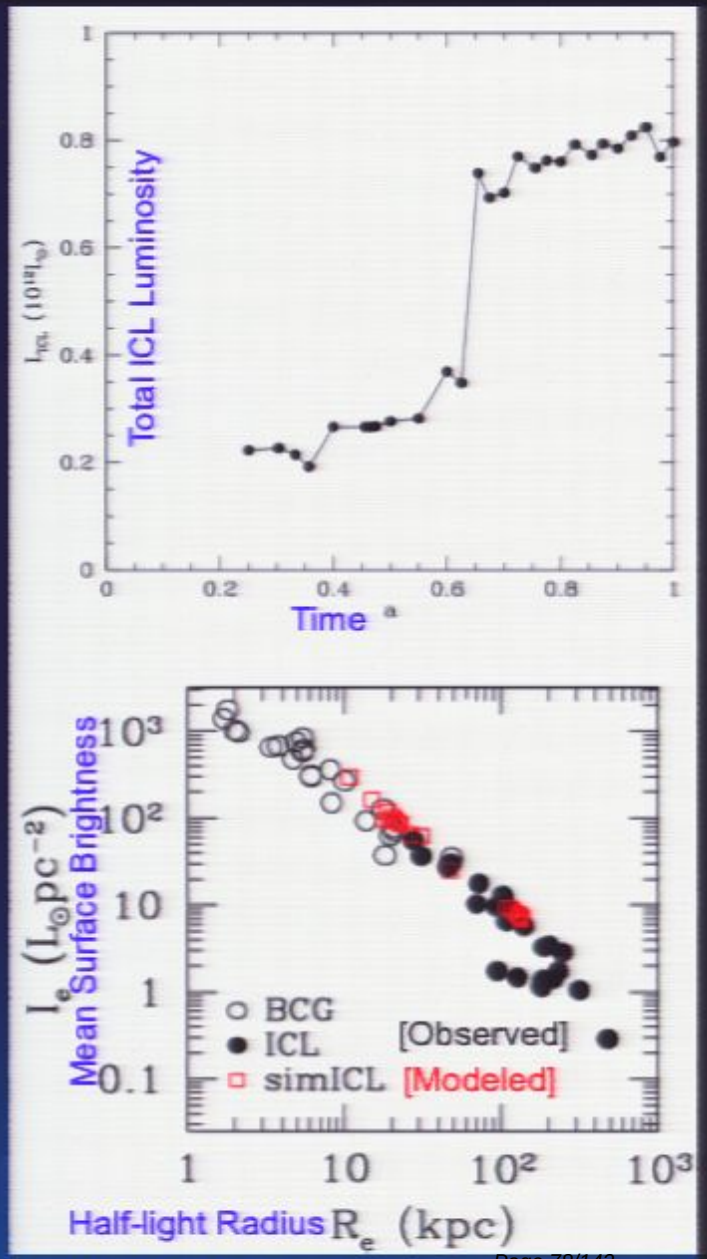

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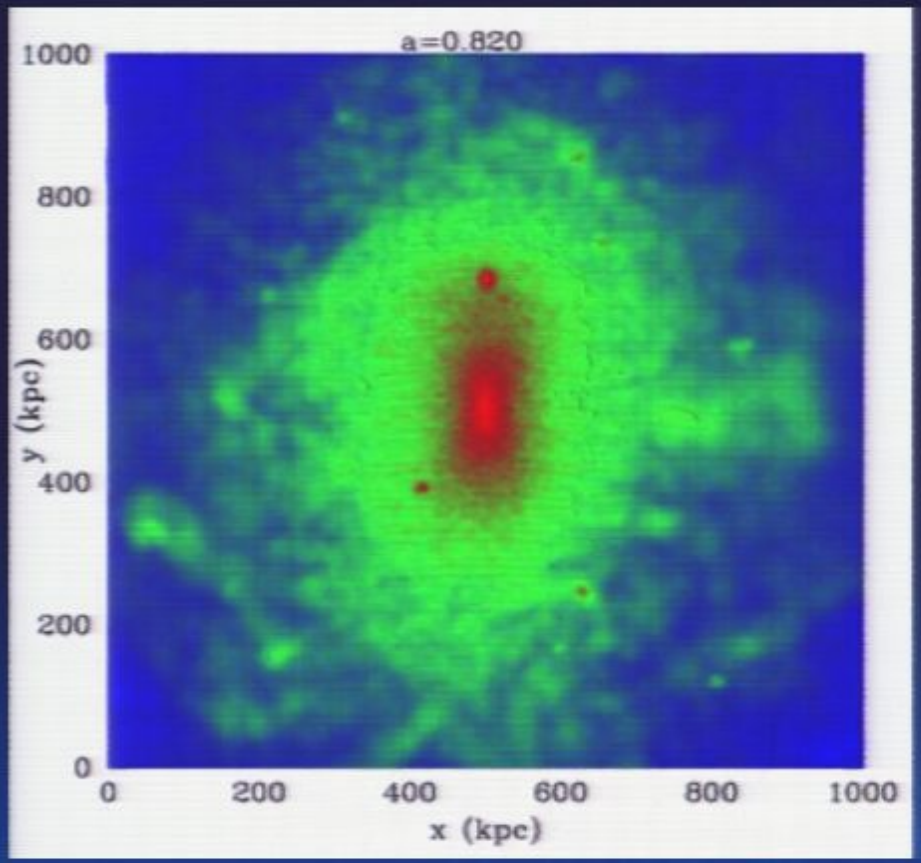

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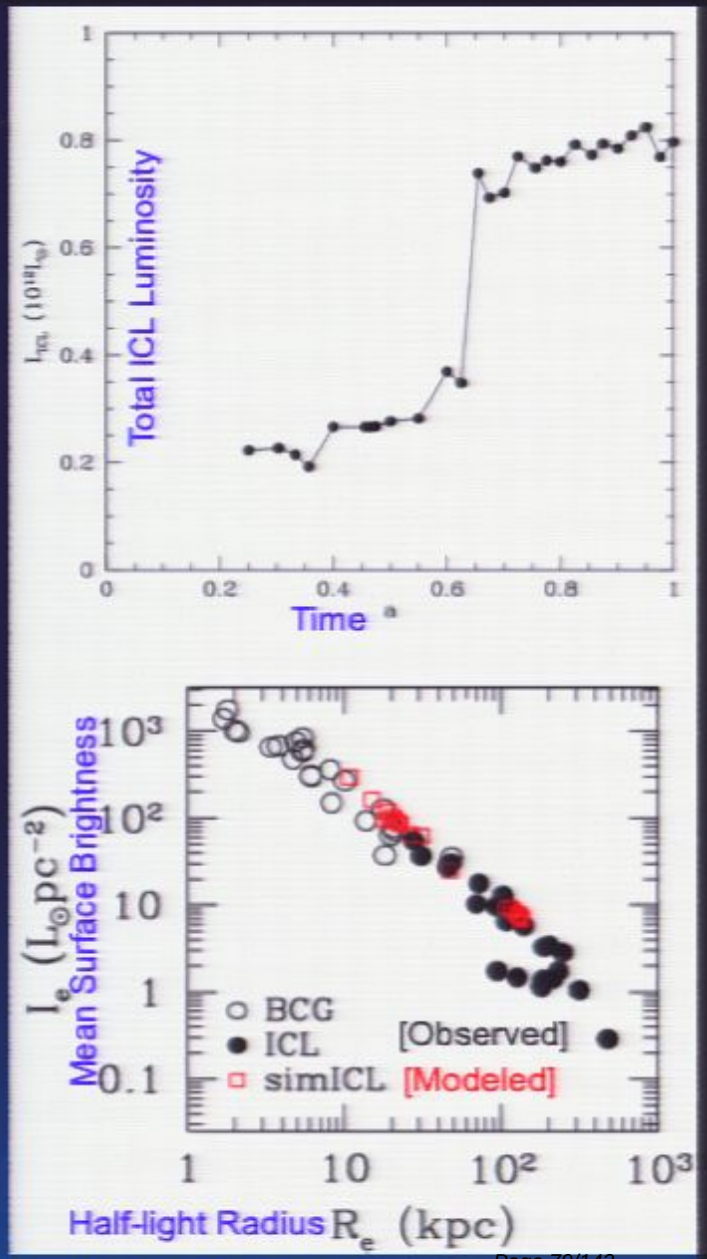
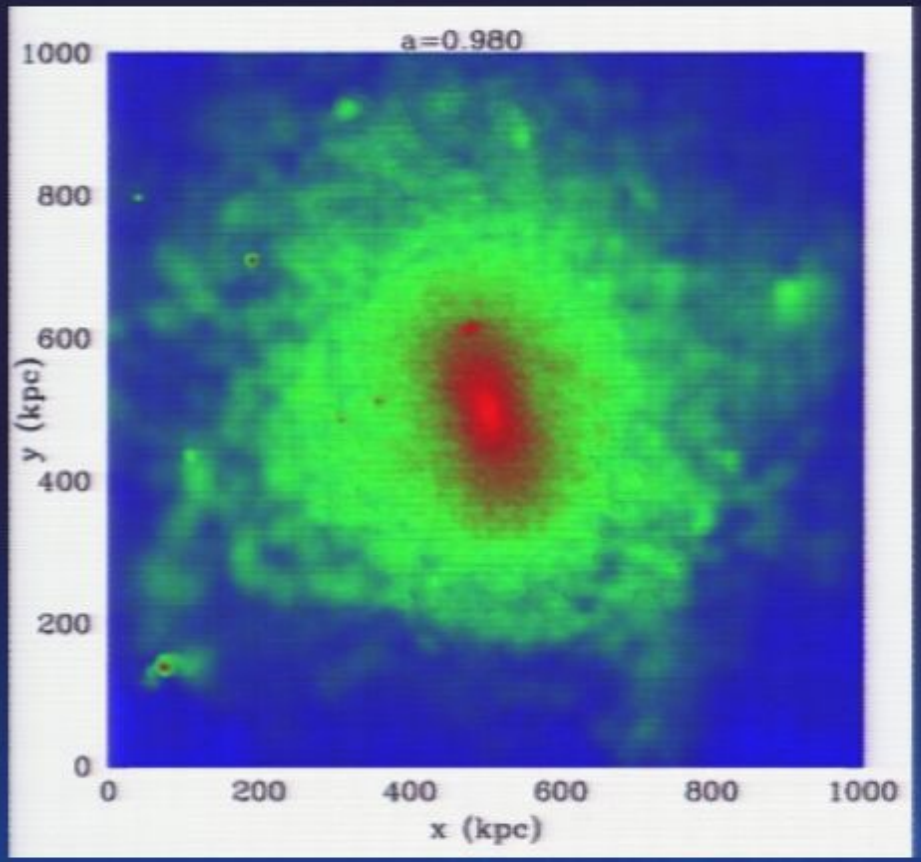


Formation and Properties of ICL

empirically inferred HODs + high-resolution
N-body simulation of galaxy cluster formation.



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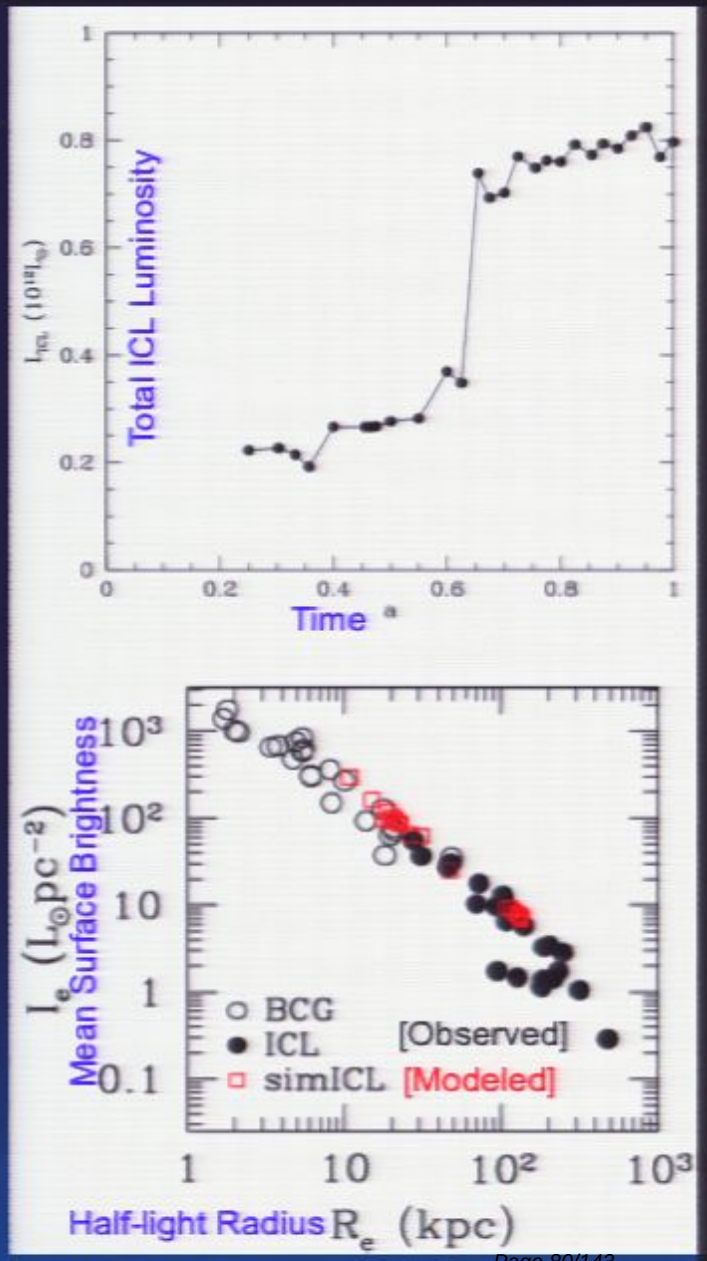

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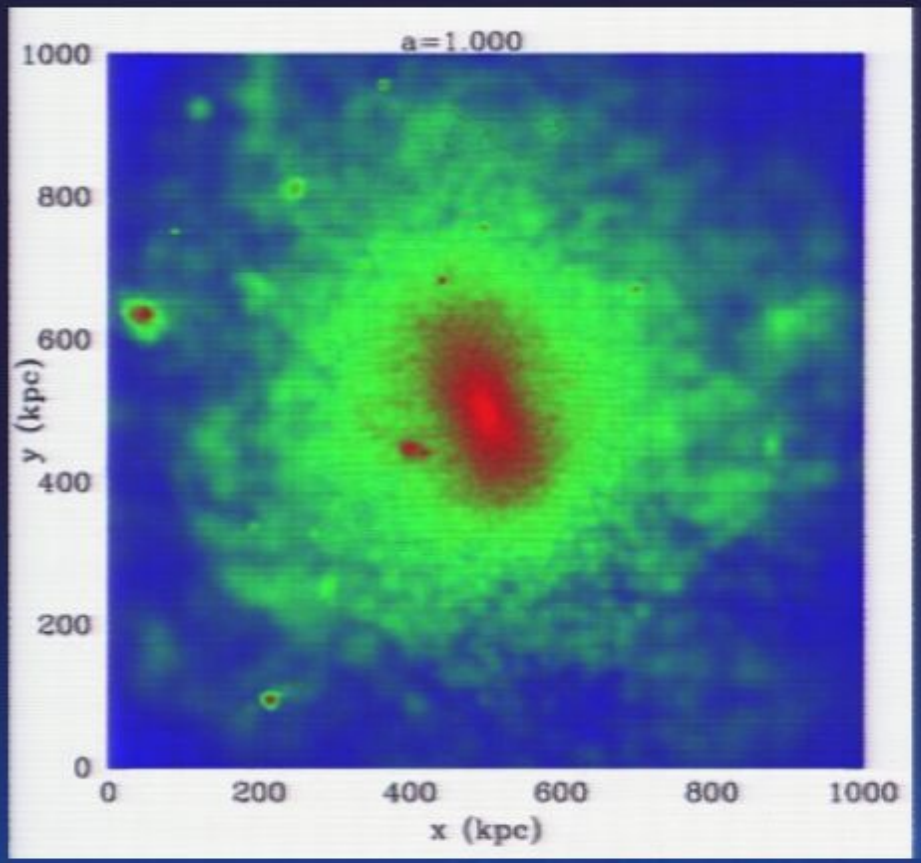

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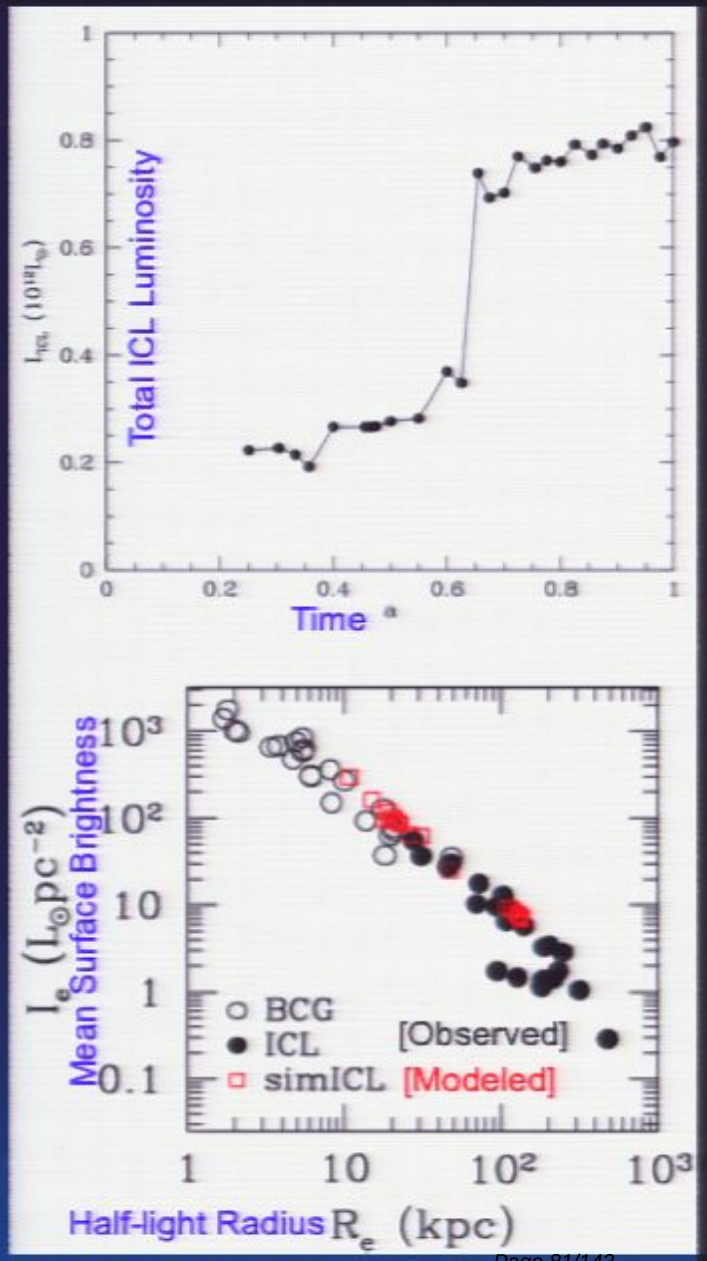

HOD modeling and cosmology

Using galaxy clustering to constrain cosmology

Worry: degeneracy between galaxy bias and cosmology?

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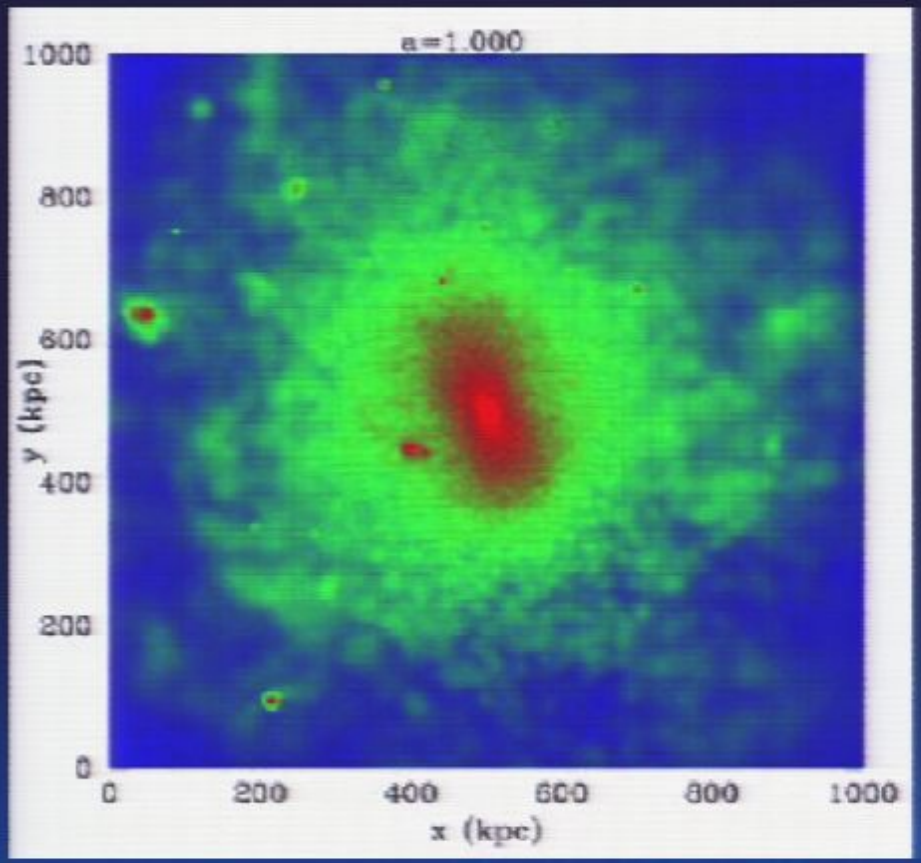

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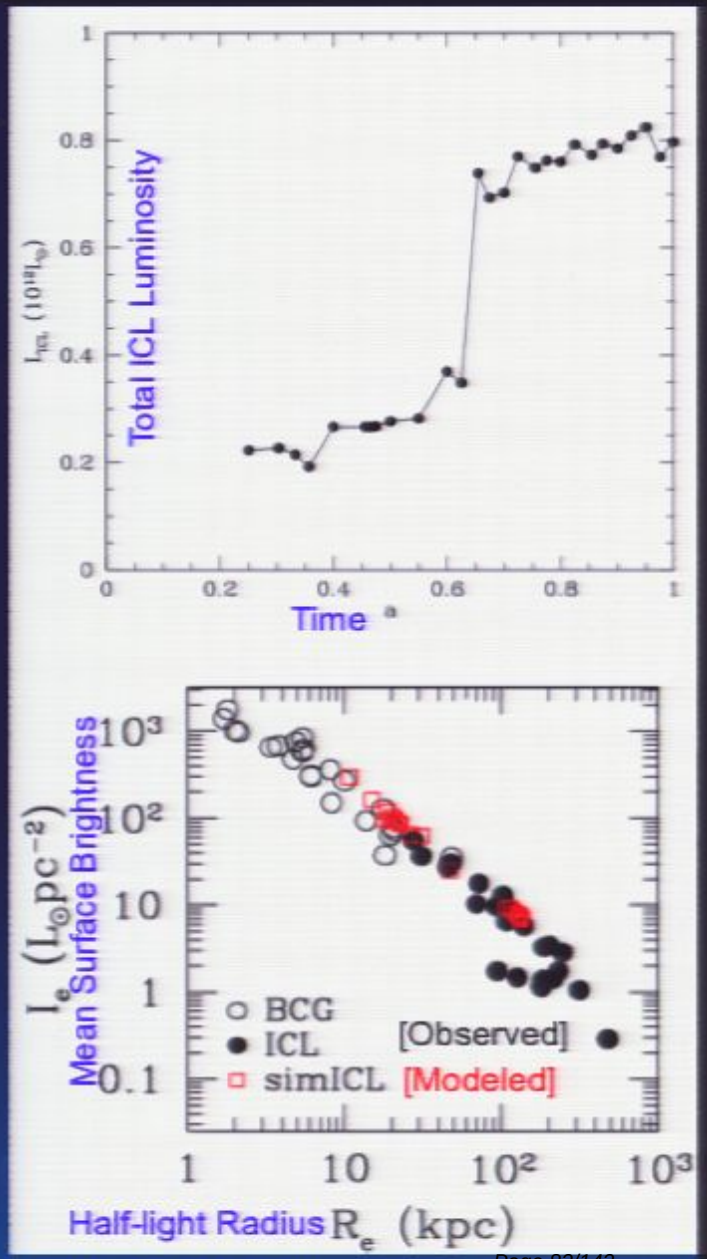

HOD modeling and cosmology

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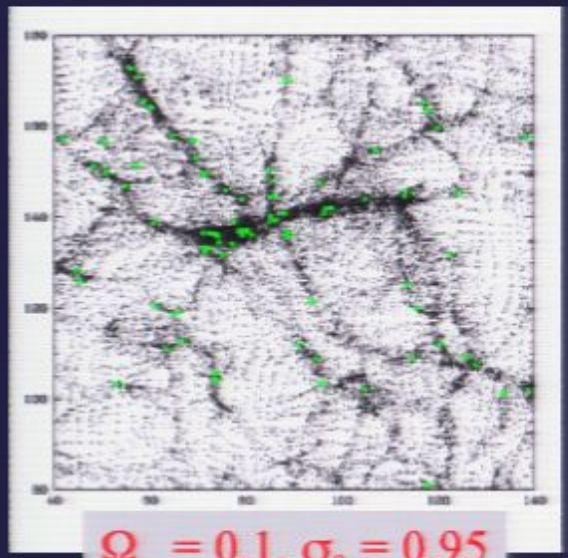
HOD modeling and cosmology

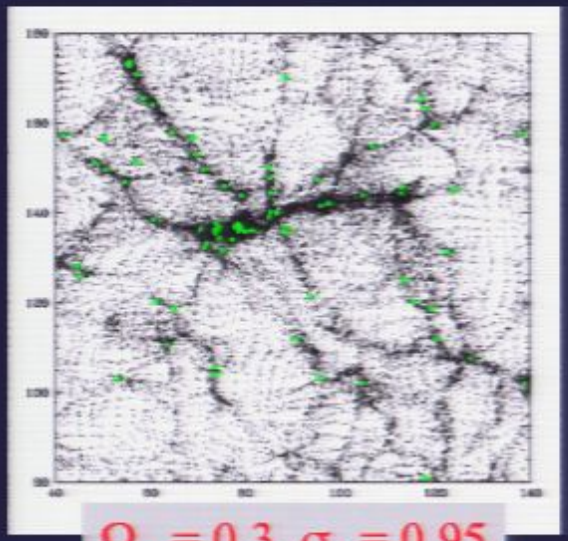
Using galaxy clustering to constrain cosmology

Worry: degeneracy between galaxy bias and cosmology?

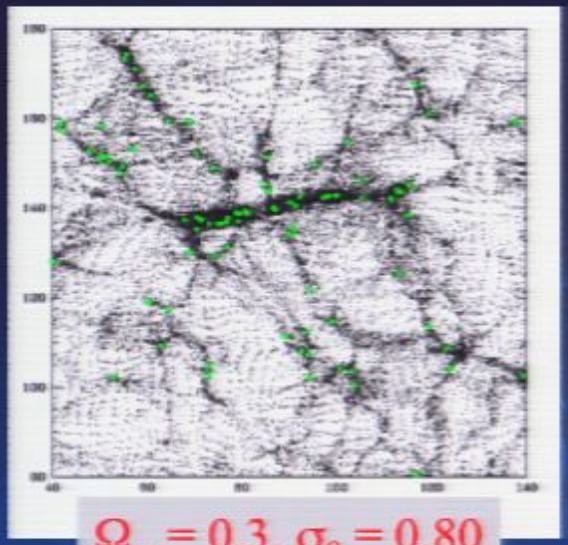
• galaxy
• dark matter



$\Omega_m = 0.1, \sigma_8 = 0.95$



$\Omega_m = 0.3, \sigma_8 = 0.95$



$\Omega_m = 0.3, \sigma_8 = 0.80$

HOD modeling and cosmology

Ω_m: matter density parameter
σ_8 : normalization of matter fluctuation power spectrum

Tinker, Weinberg, Zheng, & Zehavi et al. 2006

HOD modeling and cosmology

Zheng & Weinberg 2007

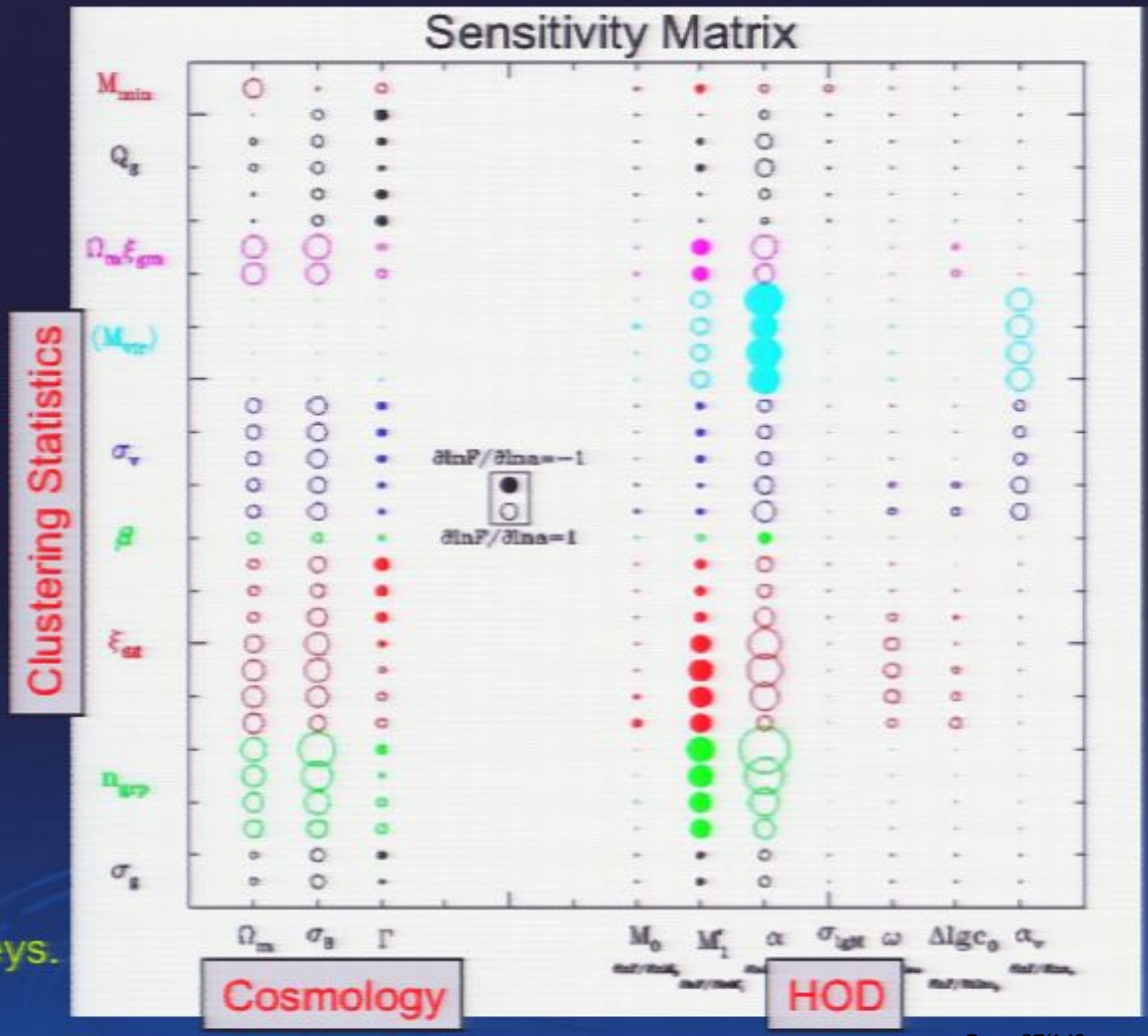
clustering observable

$$\frac{\partial \ln F}{\partial \ln p}$$

cosmology or HOD parameter

positive

negative



HOD and Cosmology are NOT degenerate.

HOD modeling can greatly amplify the cosmological power of galaxy redshift surveys.

HOD modeling and cosmology

Main results from several applications

- Cosmological constraints from CMB+HOD modeling of w_p [quasi-linear and non-linear scales]
  similar to those from CMB+$P_g(k)$ [linear scales]
  Abazajian, Zheng, et al. (2005)

- HOD modeling of w_p + M/L of large scale structures
  $(\sigma_8/0.9)(\Omega_m/0.3)^{0.6} = 0.75 \pm 0.06$
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- CLF modeling of $r_0(L)$+M/L of clusters
  $\Omega_m = 0.25 \pm 0.04$ and $\sigma_8 = 0.78 \pm 0.06$
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- HOD modeling explains shape of power spectrum of SDSS luminous red galaxies (scale-dependent bias)
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?

WMAP1+SNIa+LAF+P(k)
$(\sigma_8/0.9)(\Omega_m/0.3)^{0.6} = 0.96 \pm 0.06$

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! Consistent with WMAP3 (Before the release of WMAP3 results)

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Future Work

SDSS, final dataset

* improvements in studying color/luminosity/morphology dependence
* relation between galaxy bi-modality and dark matter halos
* environmental effects
* low-z baseline for galaxy evolution study
* improvements in cosmological constraints based on HOD modeling

Data at higher redshifts (existing or forthcoming)

* NOAO-DWFS ($2 \times 9 deg^2$ +blue galaxies) $0<z<1$ [also AGES]
* COSMOS ($2 deg^2$) $0.5<z<6$ [$z<3$ for z-COSMOS]
* VVDS ($0.61 deg^2$) $0.2<z<2.1$
* DEEP2 ($4 \times 1 deg^2$) $0.65<z<1.5$
* LBG $z \sim 4$

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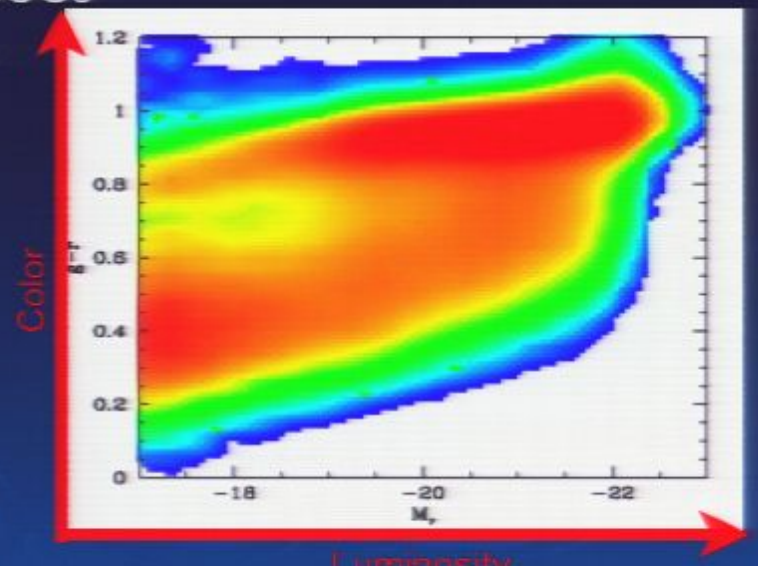
* LBG $z\sim4$

a systematic study of galaxy evolution over a large range of redshifts through HOD modeling

Future Work

What we expect to learn:

- continuous history of stellar mass growth, separated into mergers and star formation, as a function of halo mass
- origin and evolution of bi-modal distribution, as a function of halo mass
- difference in central/satellite evolution tracks
- ICL history and relation to the growth of BCGs
- environmental effects in galaxy evolution
- star formation quenching time scales, mass scales, and mechanism



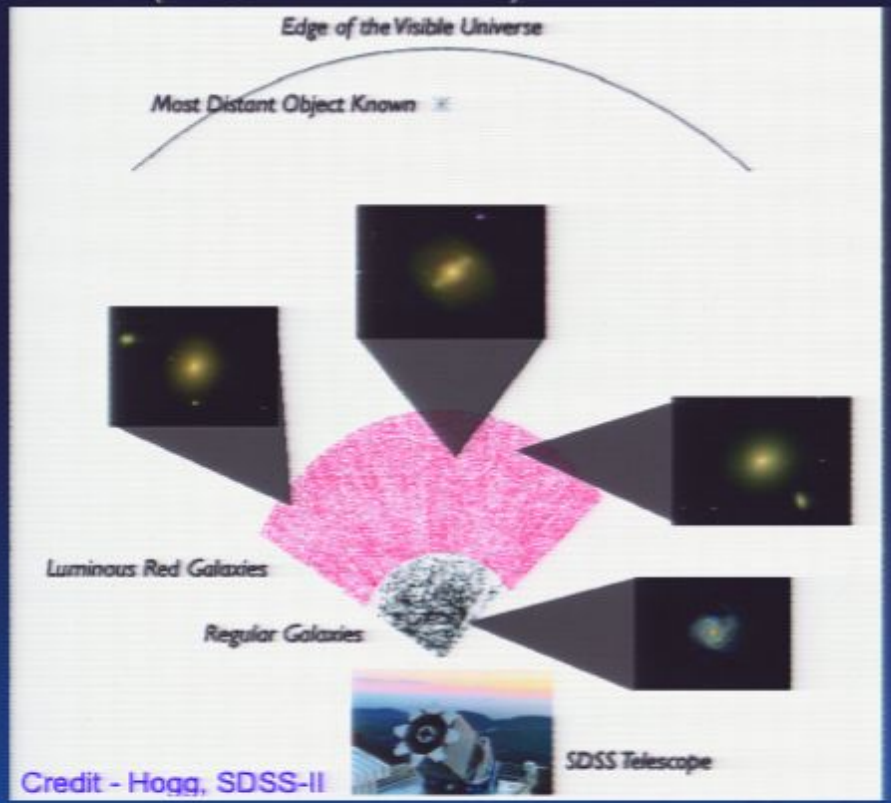
Future Work

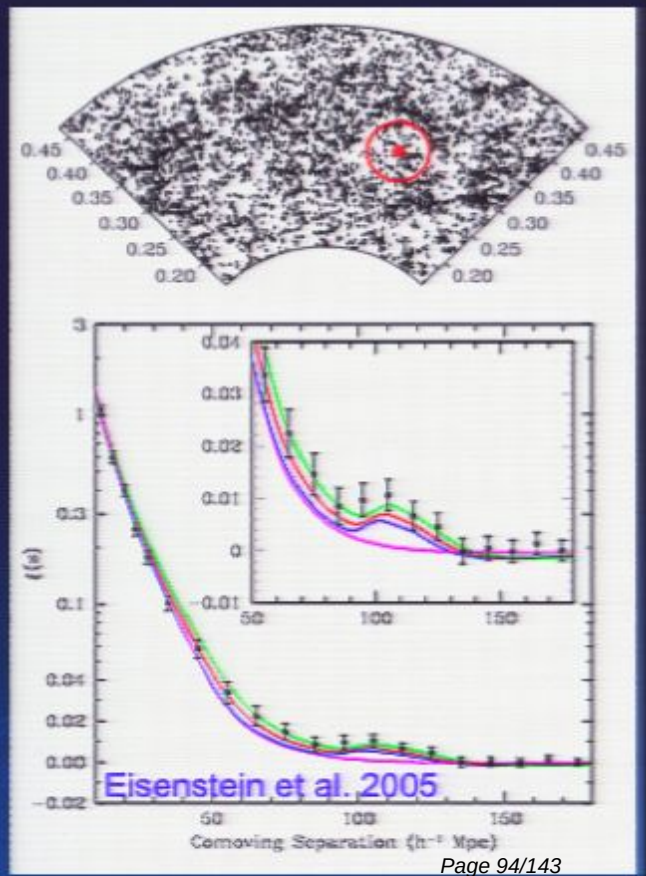
SDSS-III (10,000 deg^2)

BOSS (Baryon Oscillation Spectroscopic Survey)

cosmic expansion from BAO measurement; 1.5 million Luminous Red Galaxies to z~0.7

LAMOST (4m, 4000 fibers)

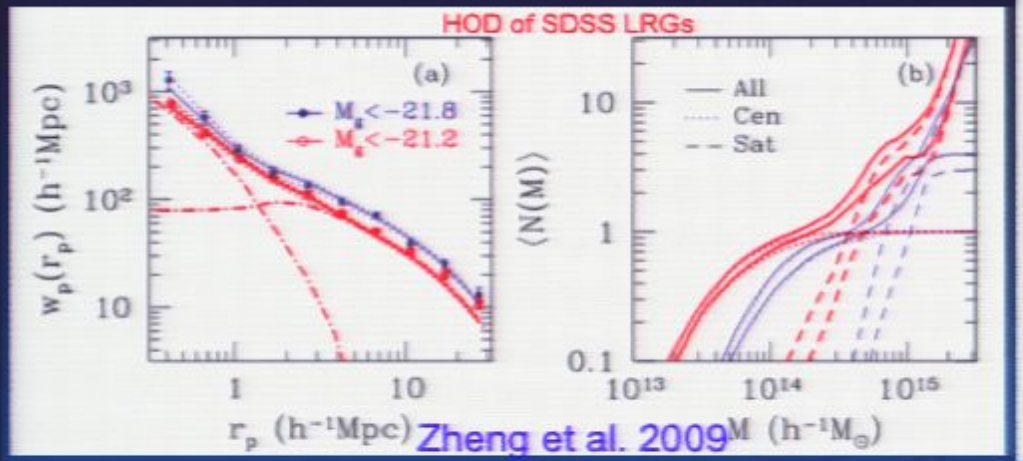


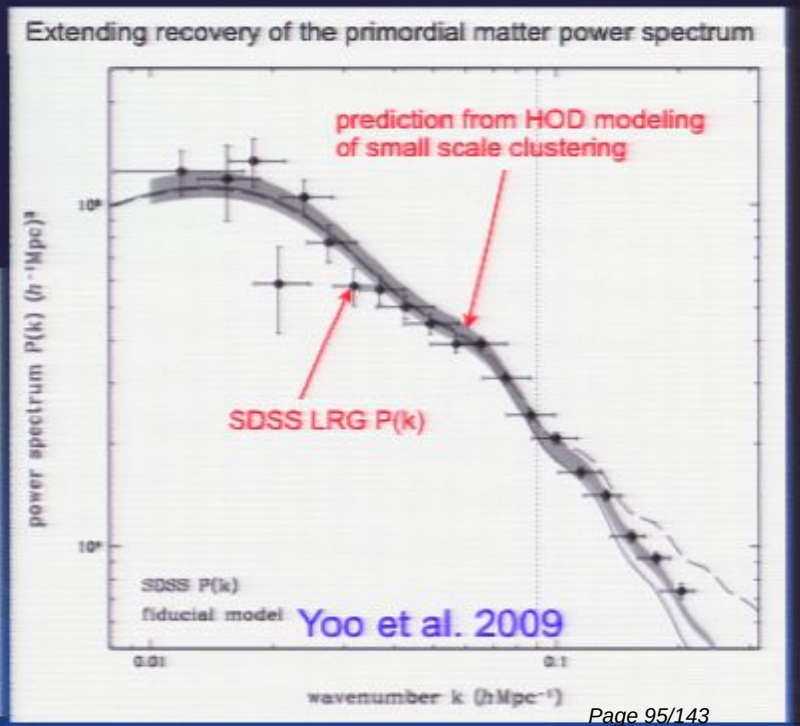


Luminous Red Galaxies (LRGs)

- luminous, detectable at large redshifts
- high clustering amplitude
- good for photo-z estimates (imaging surveys)

- powerful probe of cosmology
- important role in next generation surveys
- evolution of massive galaxies





Future Work

DES (Dark Energy Survey, $0.2<z<1.3$, 5000 deg^2)

LSST ($0<z<2$, 20,000 deg^2)

PAN-STARRS ($0<z<1.5$, $z>3$, 1200 deg^2 [30,000 deg^2])

...

These ambitious surveys will produce a hugh amount of data.

Besides constraining cosmology (esp. DE), the statistical power of the data will allow us to study galaxy evolution from galaxy clustering in great detail and put stringent constraints on galaxy formation models.

Galaxy Evolution

largely answered
partly answered
yet to be answered

- What is the assembly history of a galaxy? What does it depend on?
- What drives the evolution of galaxies?
- What is the relation between galaxies and dark matter halos?
- What is the origin of the bimodal distribution of galaxies? How do different populations evolve?
- How does the evolution of central and satellite galaxies differ?



Summary

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  - a new view of the galaxy correlation function; departures from a power law as the 1-halo to 2-halo term transition
  - correlation of galaxy luminosity with halo mass; remarkable scaling relation between M_{min} and M_1
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