The Galaxy-Halo Connection

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OUTLINE

LECTURE 1

- A primer on Structure Formation
- The Halo Model
- Halo Occupation Modeling
  - Halo Occupation Distribution (HOD)
  - Conditional Luminosity Function (CLF)
  - Subhalo Abundance Matching (SHAM)

LECTURE 2

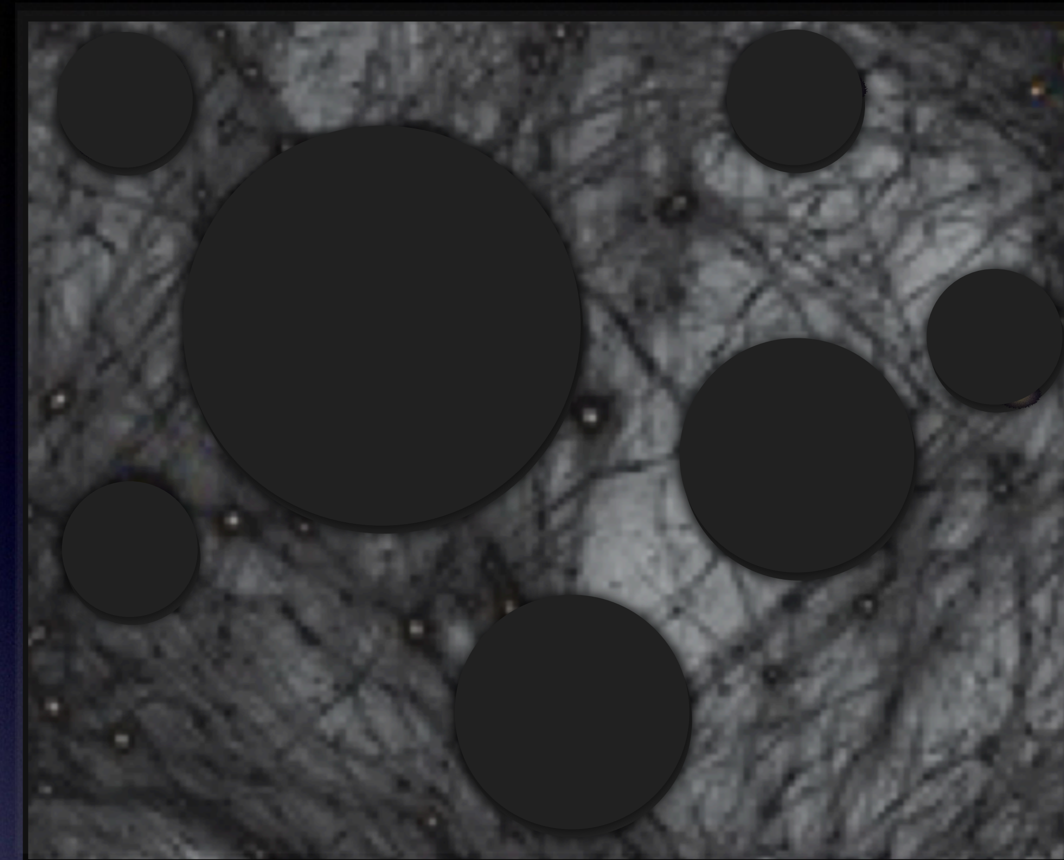
- Empirical Constraints
  - Galaxy clustering
  - Galaxy-Galaxy lensing
  - Satellite kinematics
- Galaxy-Halo Connection
  - Stellar Mass-Halo Mass Relation (SHMR)
  - Scatter in SHMR
  - Satellite Galaxies
- Cosmological Constraints
  - The S_8 tension
- Issues & Concerns
  - Artificial Subhalo Disruption & Orphans
  - Baryonic Effects
  - Assembly Bias

Constraints from clustering

From Clustering to Galaxy-Halo Connection

Analytical Halo Model

$$
\begin{aligned}
\xi(r) &= \xi^{1\mathrm{h}}(r) + \xi^{2h}(r) \\
\xi^{1\mathrm{h}}(r) &= \frac{1}{\bar{\rho}^2} \int \mathrm{d}M\, M^2\, n(M) \int \mathrm{d}^3\vec{y}\, u(\vec{x}-\vec{y}|M)\, u(\vec{x}+\vec{r}-\vec{y}|M) \\
\xi^{2\mathrm{h}}(r) &= \frac{1}{\bar{\rho}^2} \int \mathrm{d}M_1\, M_1\, b(M_1)\, n(M_1) \int \mathrm{d}M_2\, M_2\, b(M_2)\, n(M_2) \times \\
&\quad \int \mathrm{d}^3\vec{y}_1 \int \mathrm{d}^3\vec{y}_2\, u(\vec{x}-\vec{y}_1|M_1)\, u(\vec{x}+\vec{r}-\vec{y}_2|M_2)\, \xi^{\mathrm{lin}}_{\mathrm{mm}}(\vec{y}_1-\vec{y}_2)
\end{aligned}
$$



For given $\Phi(L\,|\,M)$ and $n_{\rm sat}(r\,|\,M)$, compute the two-point correlation function and compare to observations

cosmology $\rightarrow$ $\left\{\right.$

- halo mass function $n(M)$
- halo bias function $b_h(M)$

$\left.\right\} \rightarrow \xi_{\rm hh}(r\,|\,M)$

From Clustering to Galaxy-Halo Connection

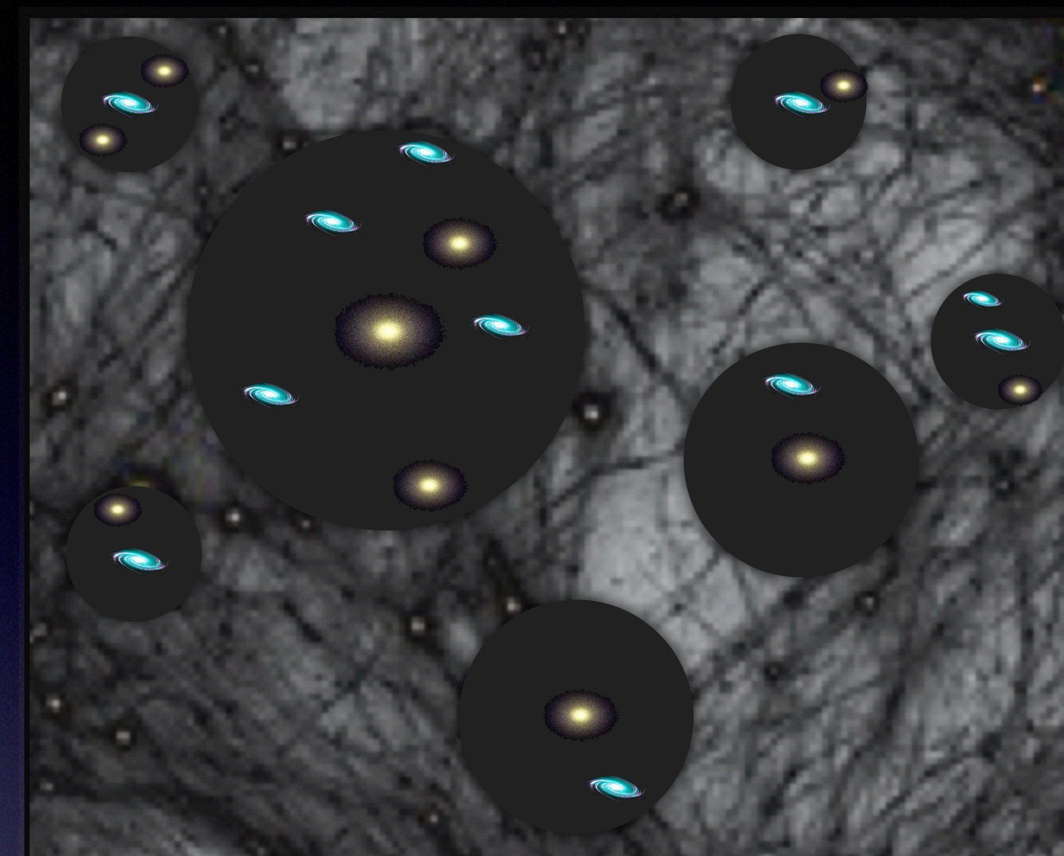
Analytical Halo Model

$$\xi(r) = \xi^{1h}(r) + \xi^{2h}(r)$$

$$\xi^{1h}(r) = \frac{1}{\bar{\rho}^2}\int \mathrm{d}M\, M^2\, n(M) \int \mathrm{d}^3\vec{y}\, u(\vec{x}-\vec{y}|M)\, u(\vec{x}+\vec{r}-\vec{y}|M)$$

$$\xi^{2h}(r) = \frac{1}{\bar{\rho}^2}\int \mathrm{d}M_1\, M_1\, b(M_1)\, n(M_1) \int \mathrm{d}M_2\, M_2\, b(M_2)\, n(M_2) \times \int \mathrm{d}^3\vec{y}_1 \int \mathrm{d}^3\vec{y}_2\, u(\vec{x}-\vec{y}_1|M_1)\, u(\vec{x}+\vec{r}-\vec{y}_2|M_2)\, \xi^{\rm lin}_{\rm mm}(\vec{y}_1-\vec{y}_2)$$

For given $\Phi(L\,|\,M)$ and $n_{\rm sat}(r\,|\,M)$, compute the two-point correlation function and compare to observations



prior | model | observables

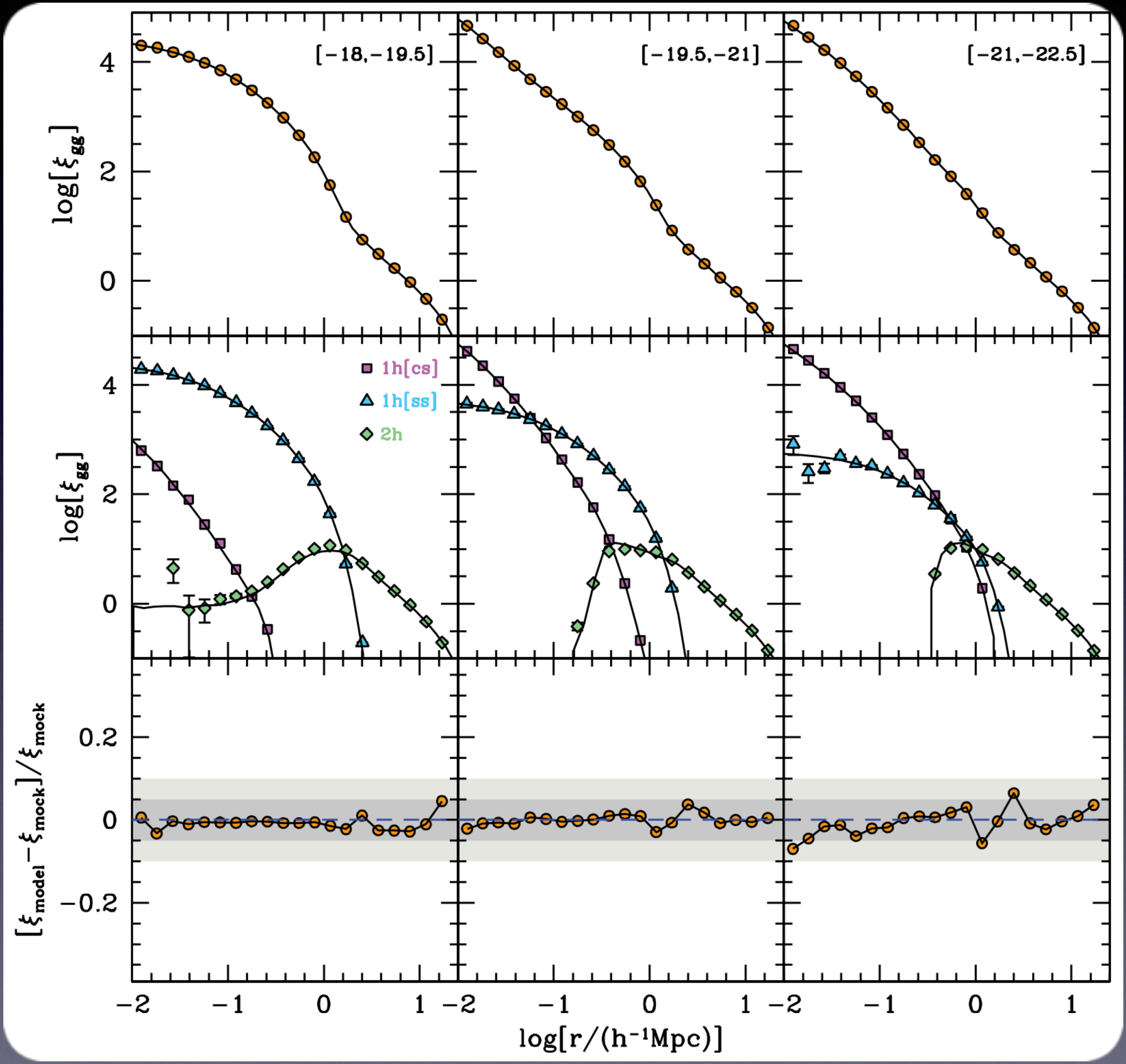
cosmology → { • halo mass function $n(M)$; • halo bias function $b_h(M)$

• halo occupation model $\Phi(L|M)$

→ $\Phi(L)$, $\xi_{\rm gg}(r|L)$

Bayesian Engine

Testing with Mock Data



source: vdBosch et al. 2013

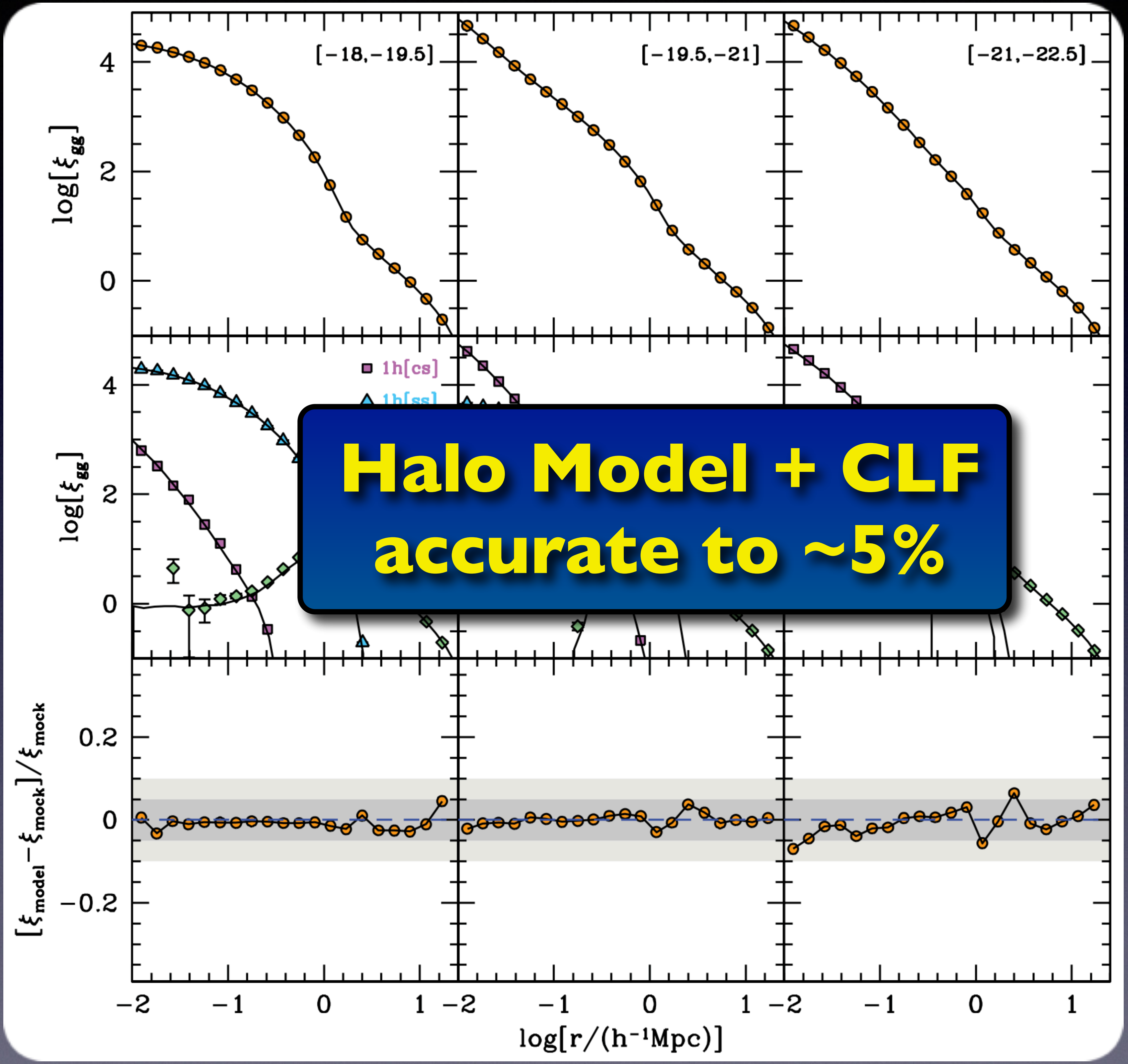
Populate dark matter halos in N-body simulation with mock galaxies using CLF

Construct mock SDSS

Measure clustering in mock SDSS data

Predict clustering using analytical model with same CLF and compare

Testing with Mock Data



source: vdBosch et al. 2013

Populate dark matter halos in N-body simulation with mock galaxies using CLF

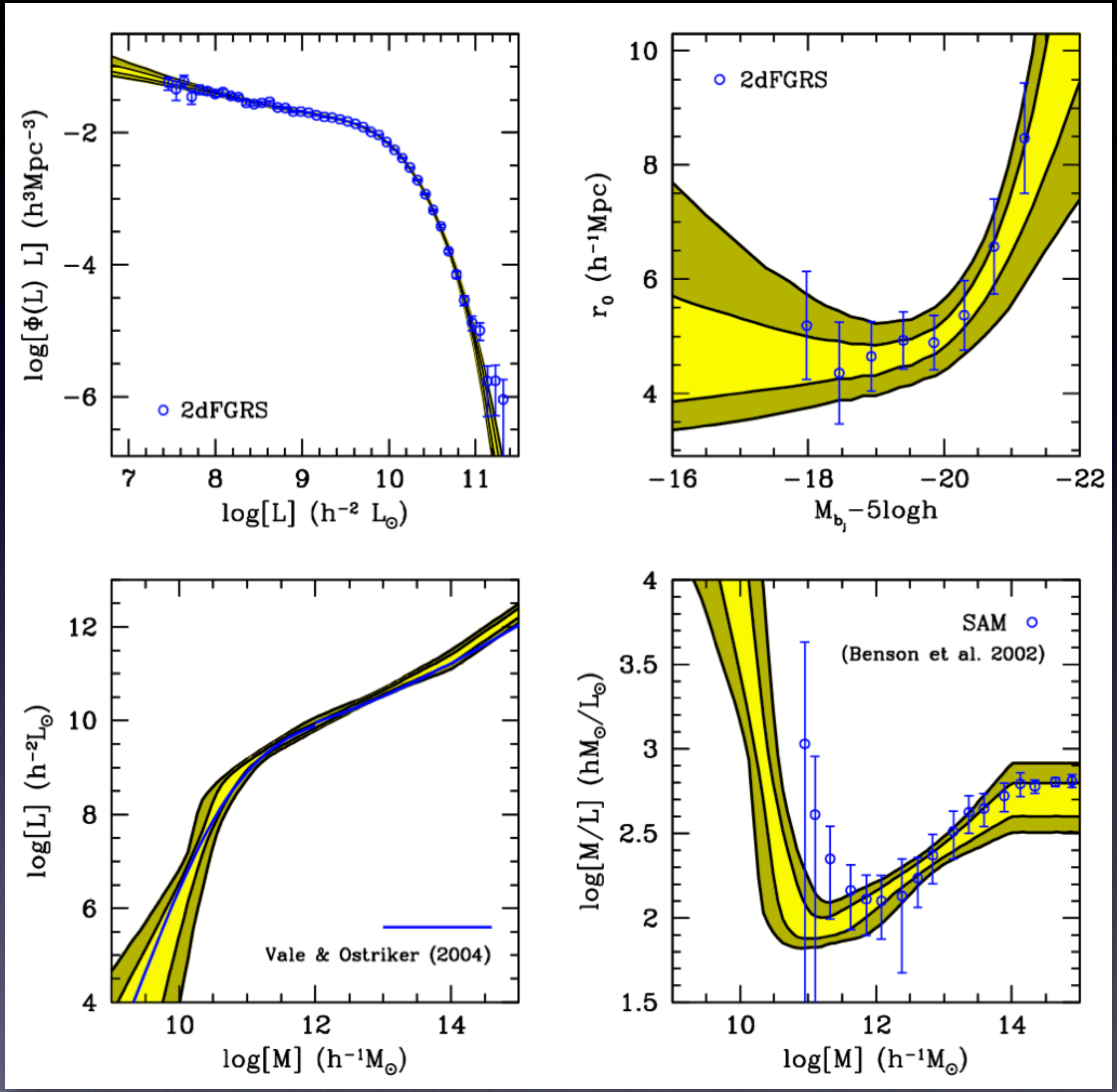
Construct mock SDSS

Measure clustering in mock SDSS data

Predict clustering using analytical model with same CLF and compare

Constraints on Halo Occupation Statistics

2004

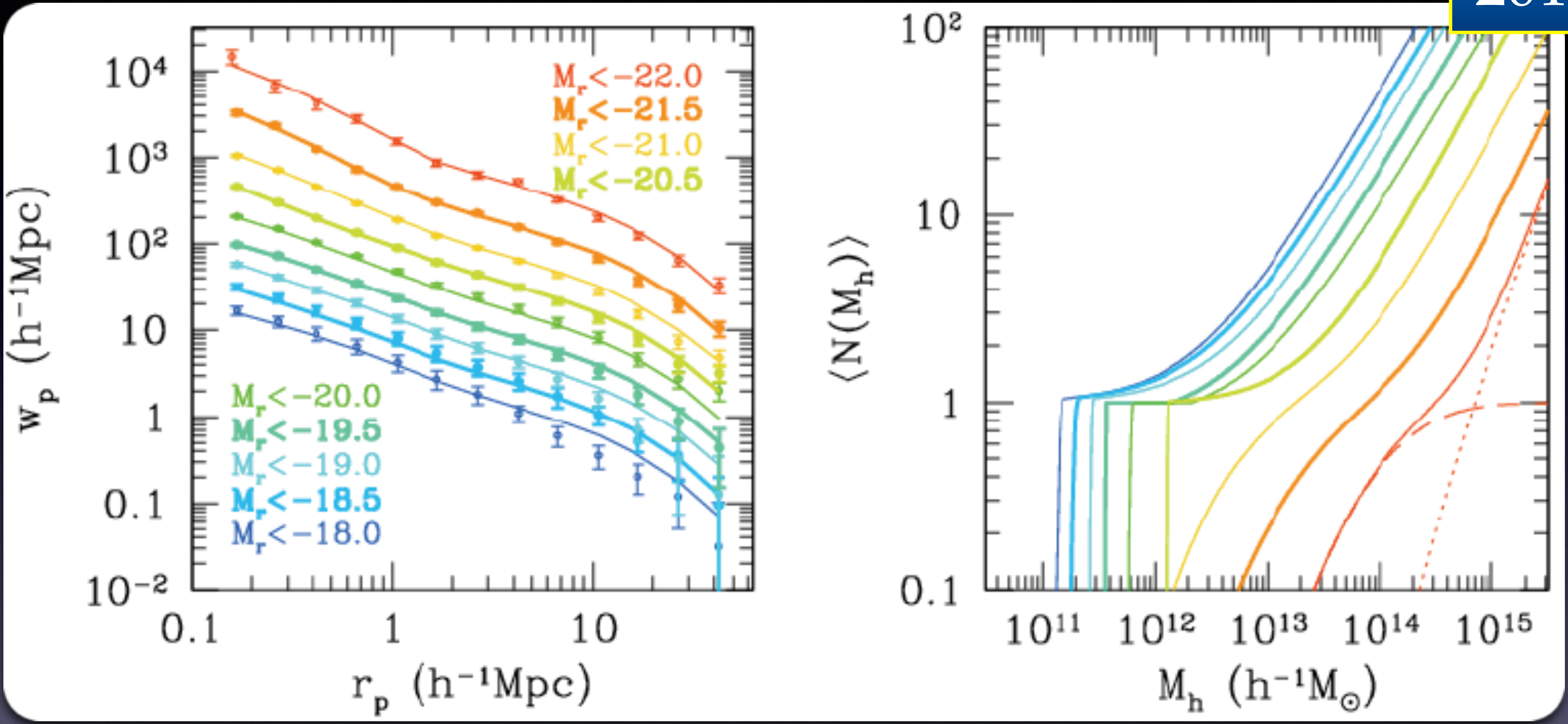


vdBosch, Yang & Mo 2004

One of the first, clustering-based constraints, on galaxy-halo connection

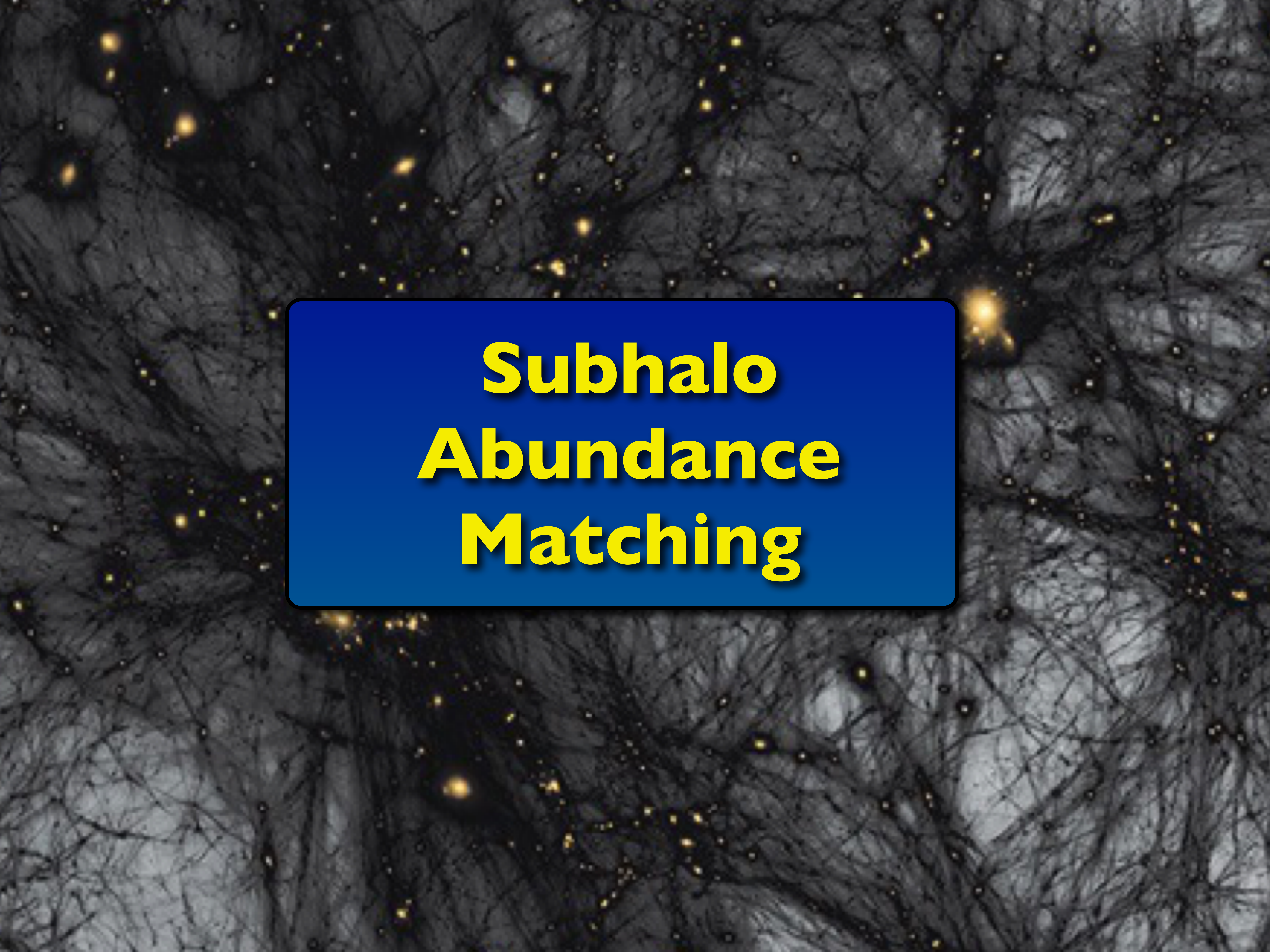
Constraints on Halo Occupation Statistics

2011



Source: Zehavi et al. 2011

Simple HOD models can accurately fit the (projected) correlation functions for 9 different SDSS luminosity threshold samples…



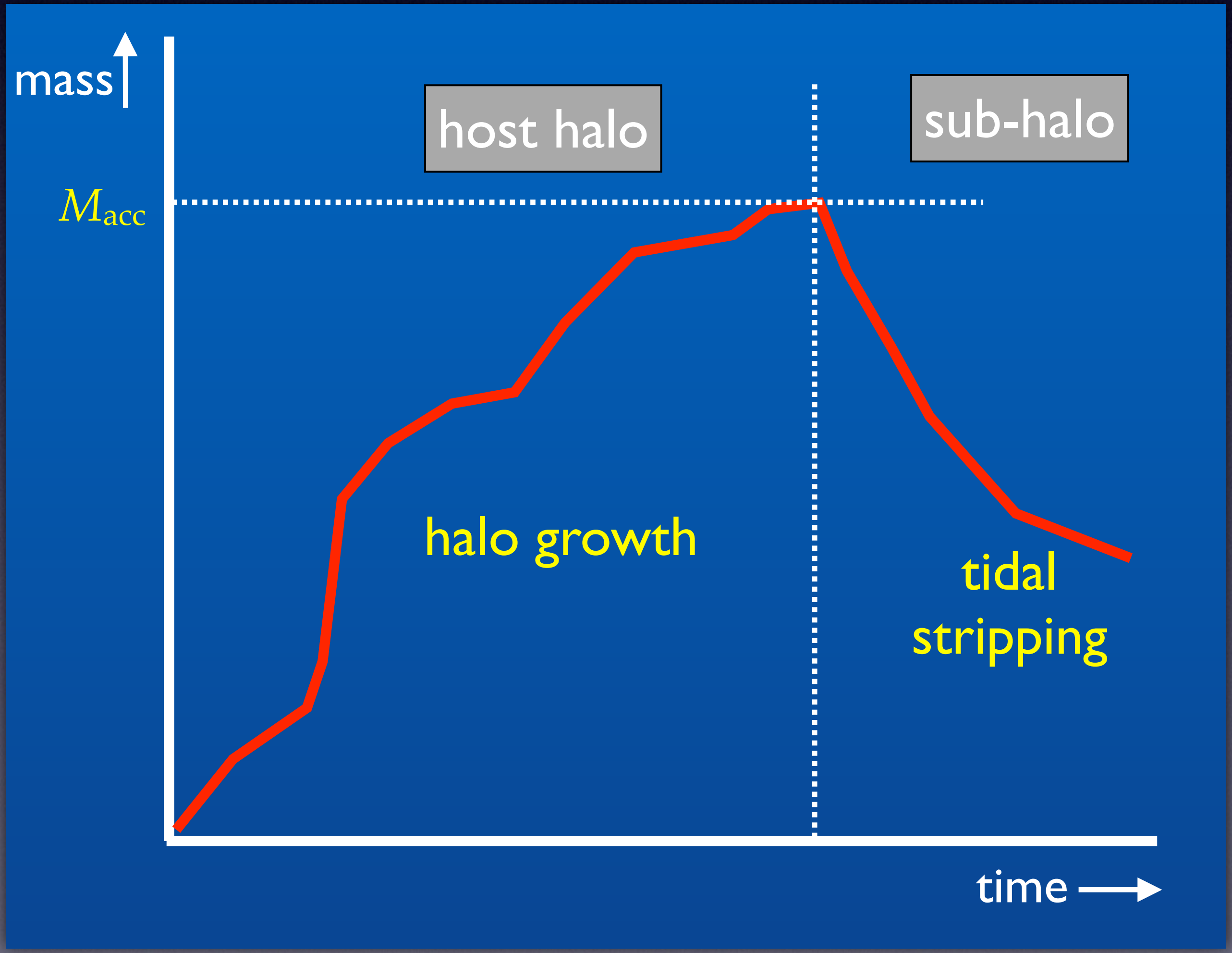
Subhalo Abundance Matching

Subhalo Abundance Matching

Key Premises

- Galaxies form and reside in halos (including subhalos)
- There exist some halo property(ies) that are tightly correlated with the properties of the galaxies they host

  i.e., L is strongly correlated with M



Ansatz

For satellite galaxies, their present-day luminosity/stellar mass is strongly correlated with their halo mass at accretion, M_{acc}

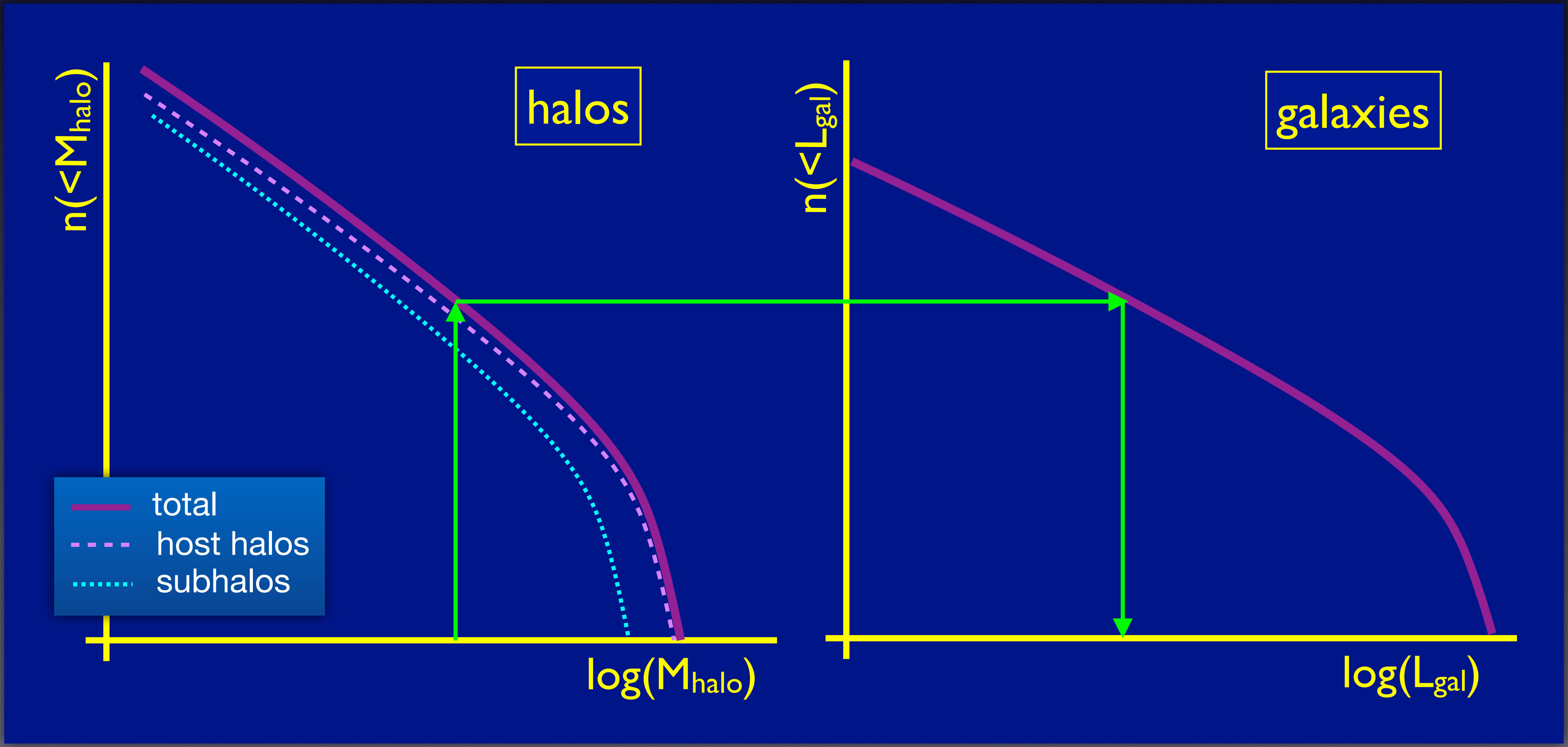
Motivation

Satellite galaxies quench after infall and tides mainly strip dark matter

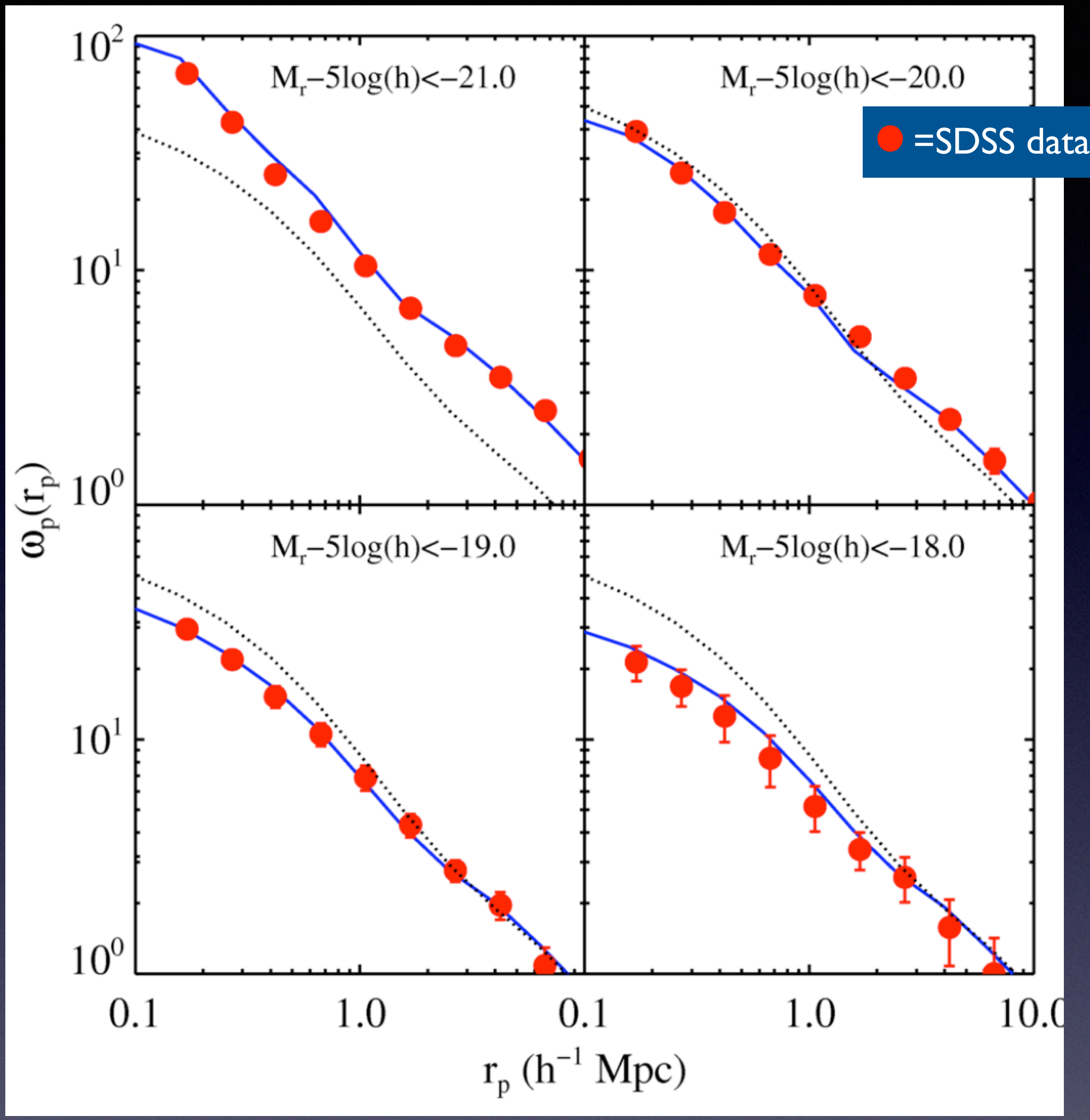
Subhalo Abundance Matching

- From N-body simulation, obtain cumulative mass function of halos + subhalos (for latter, use mass at infall)
- From a galaxy redshift survey, obtain cumulative mass or luminosity function of galaxies
- Match rank orders…..done

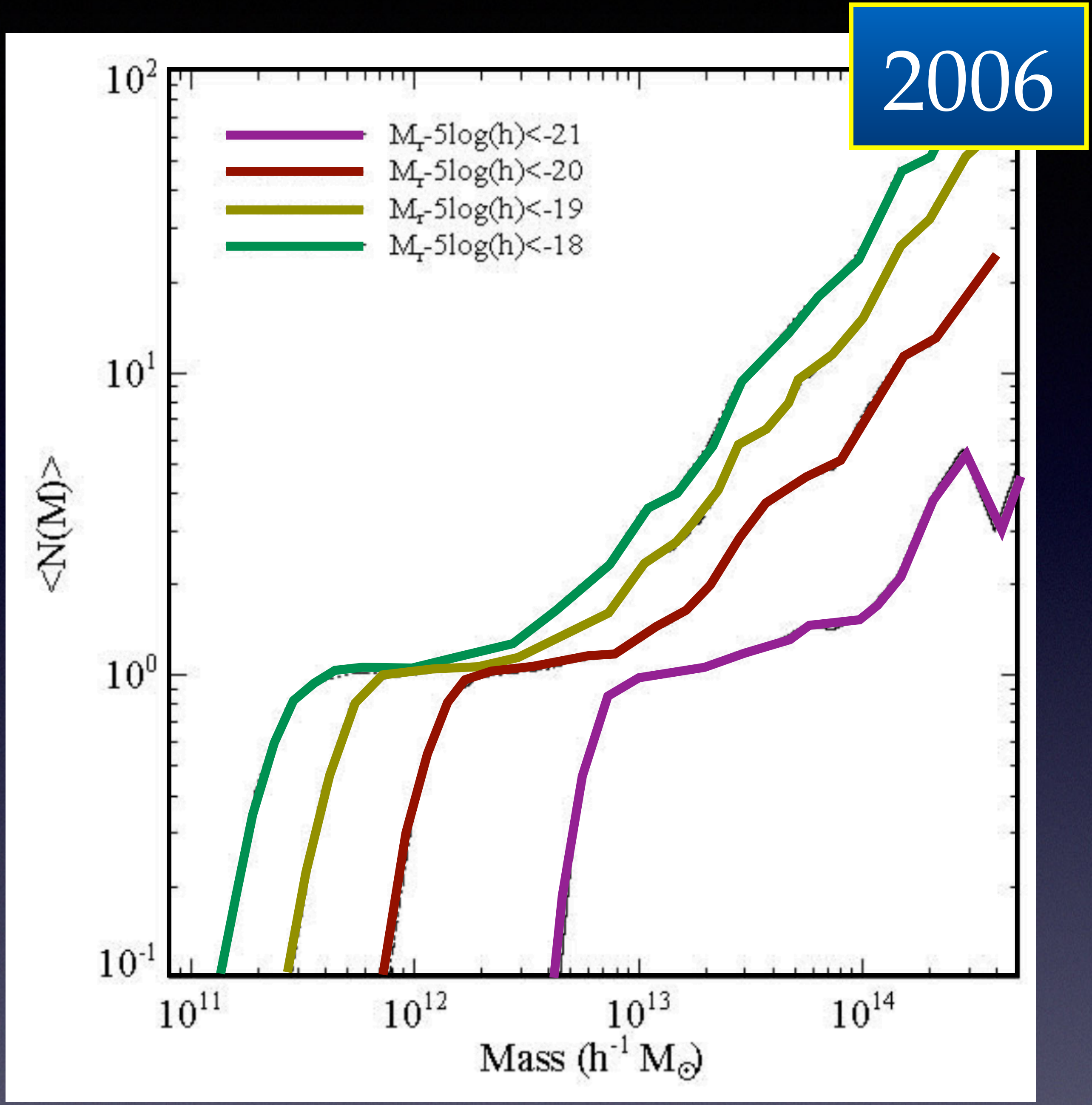
Kravtsov et al. 2004; Vale & Ostriker 2006, 2007; Conroy et al. 2006



Subhalo Abundance Matching

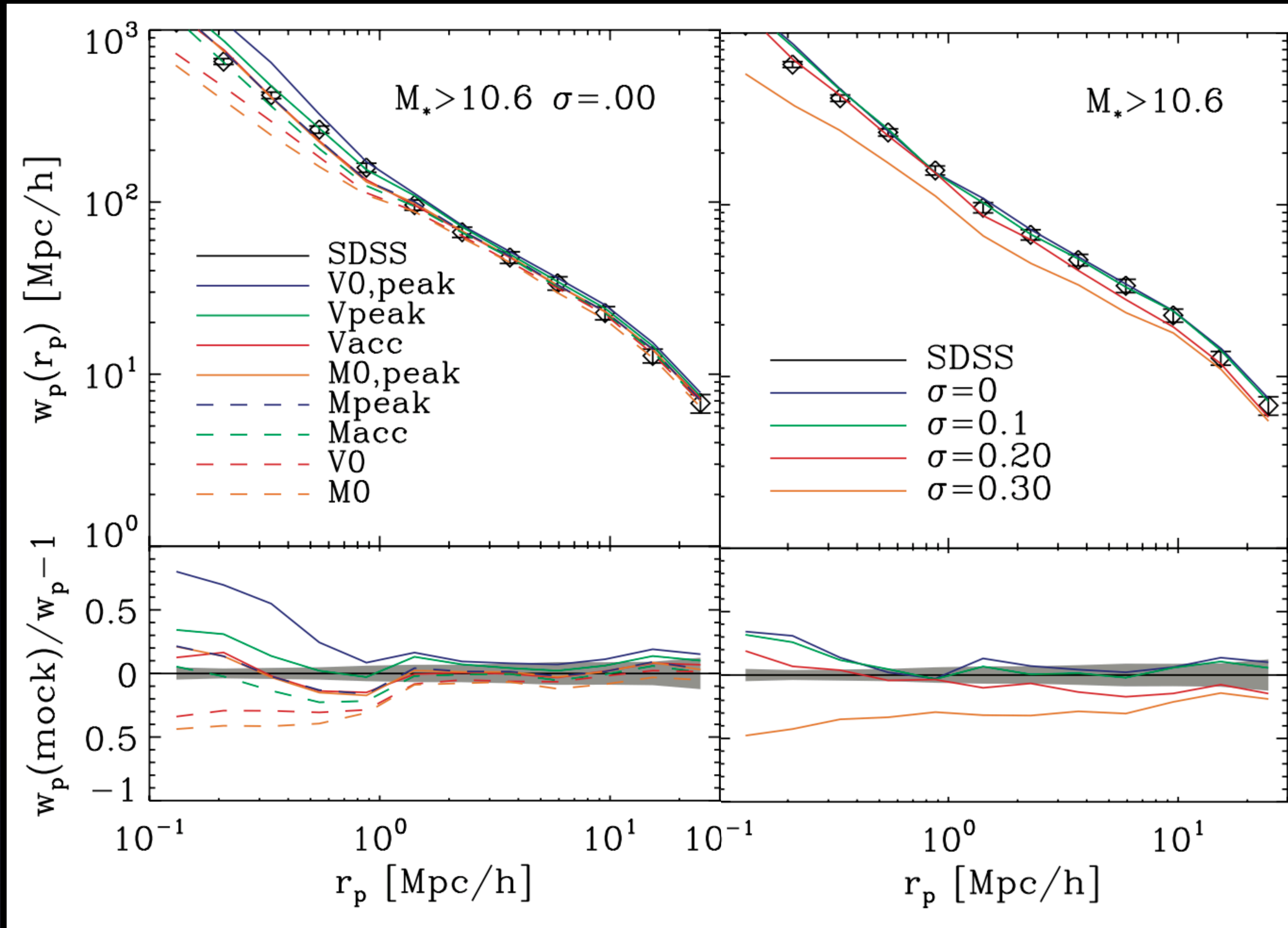


Source: Conroy, Wechsler & Kravtsov 2006



…suggests that satellites indeed stop forming stars at infall (quenching)…

Subhalo Abundance Matching



Source: Reddick et al. 2013

Downsides of SHAM

- Only works for complete samples of galaxies
- Requires N-body simulations
- artificial disruption; SHAM to be complemented with orphan treatment

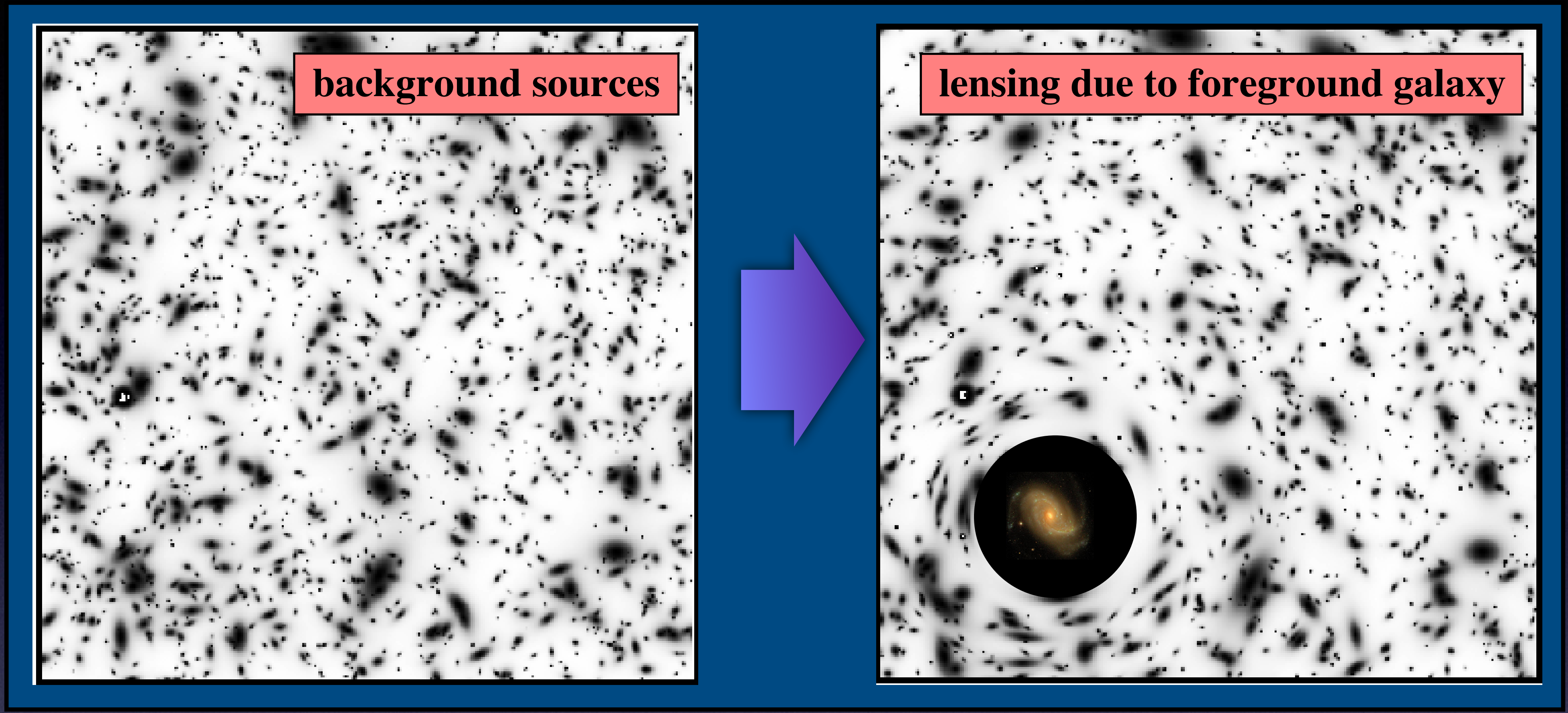
Campbell, vdB et al. 2018

SHAM has only 2 degrees of freedom: halo property & scatter

Galaxy-Galaxy Lensing

Galaxy-Galaxy Lensing

The mass associated with galaxies lenses background galaxies



Lensing causes correlated ellipticities, the tangential shear, $\gamma_{\rm t}$, which is related to the excess surface density, $\Delta\Sigma$, according to

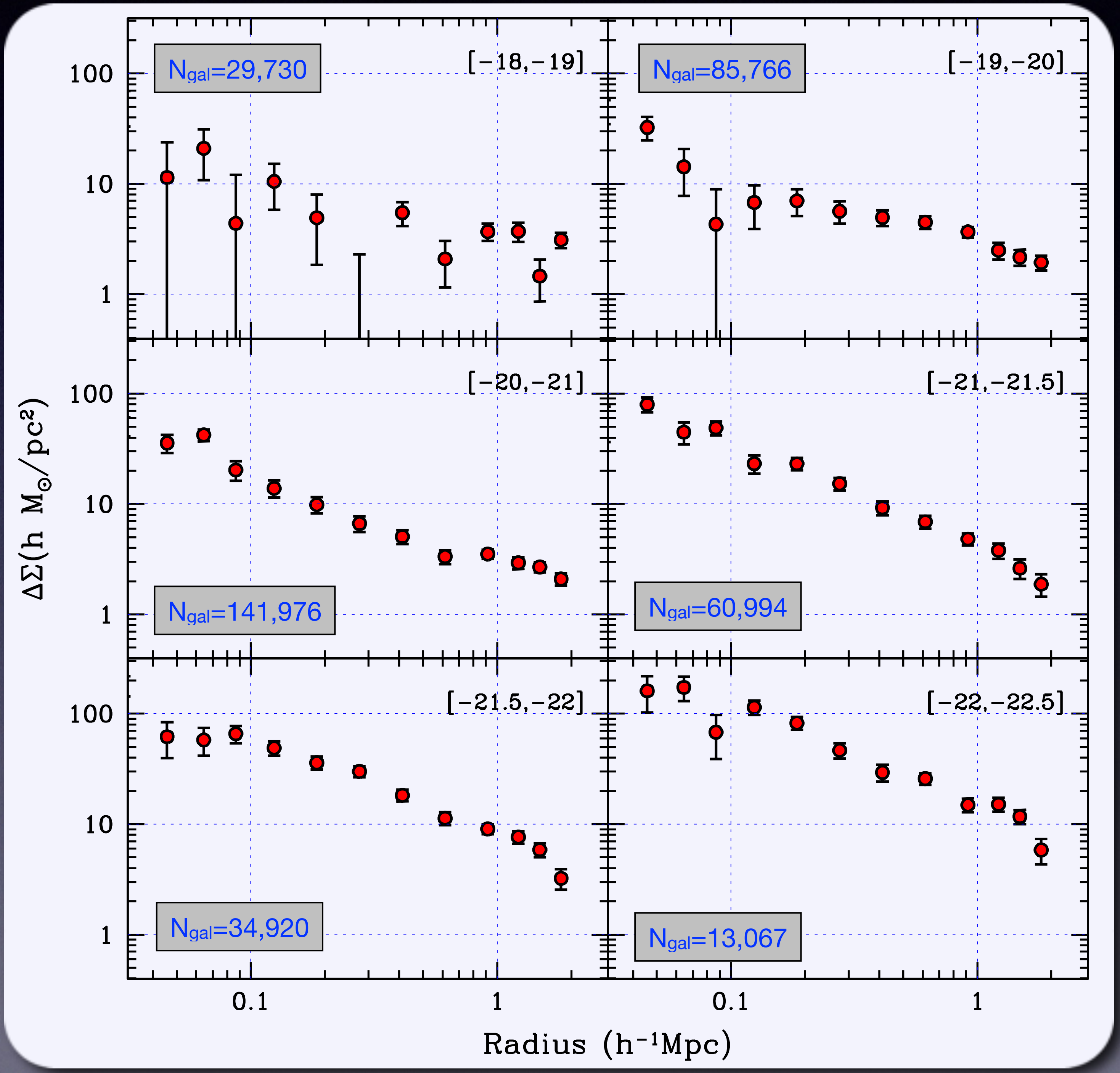
$$\gamma_{\rm t}(R)\Sigma_{\rm crit} = \Delta\Sigma(R) = \bar{\Sigma}(< R) - \Sigma(R)$$

$\Delta\Sigma$ is line-of-sight projection of galaxy-matter cross correlation

$$\Sigma(R) = \bar{\rho}\int_0^{D_{\rm s}} [1 + \xi_{\rm g,dm}(r)]\, {\rm d}\chi$$

Galaxy-Galaxy Lensing

- Number of background sources per lens is limited
- Measuring shear with sufficient S/N requires stacking of many lenses



Mandelbaum et al. 2006

Galaxy-Galaxy Lensing

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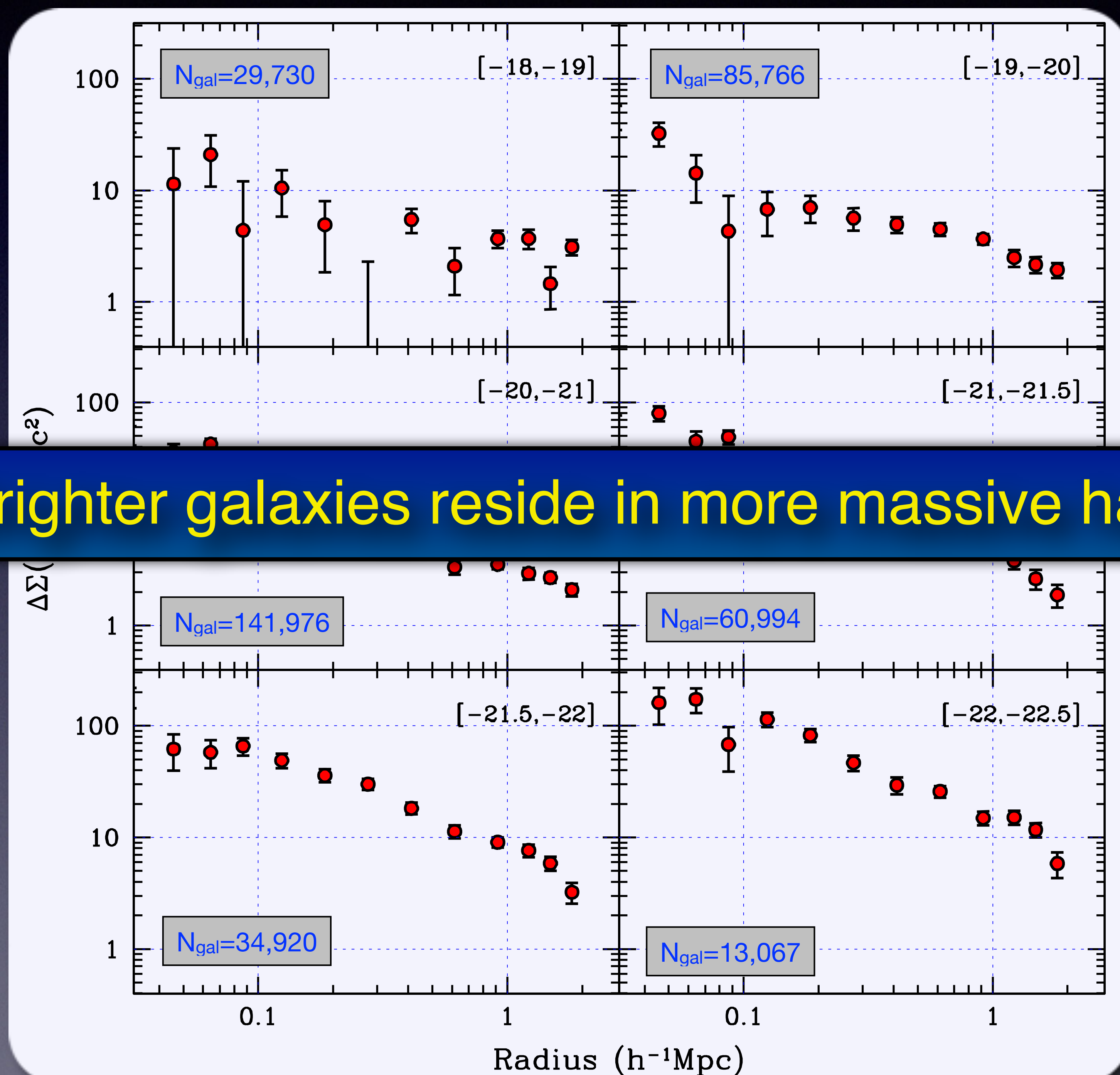
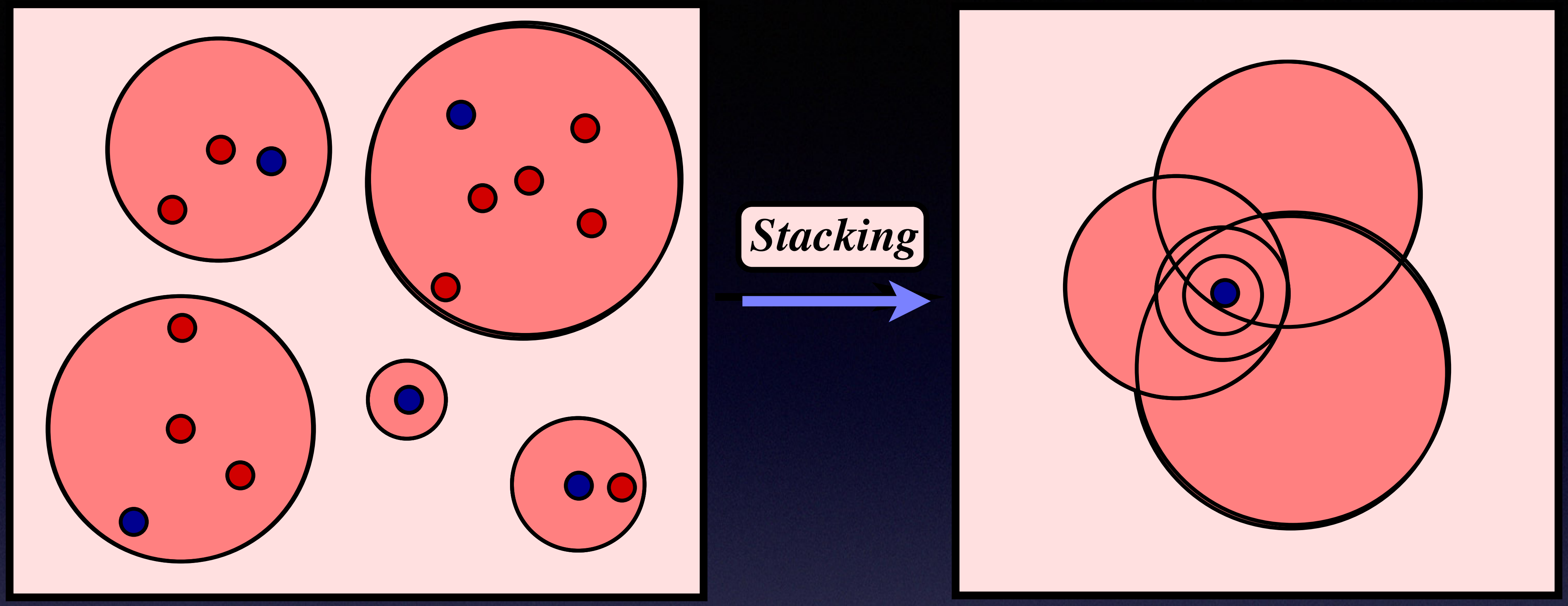


Brighter galaxies reside in more massive haloes

Mandelbaum et al. 2006

Galaxy-Galaxy Lensing



Because of stacking, it is not straightforward to interpret lensing signal

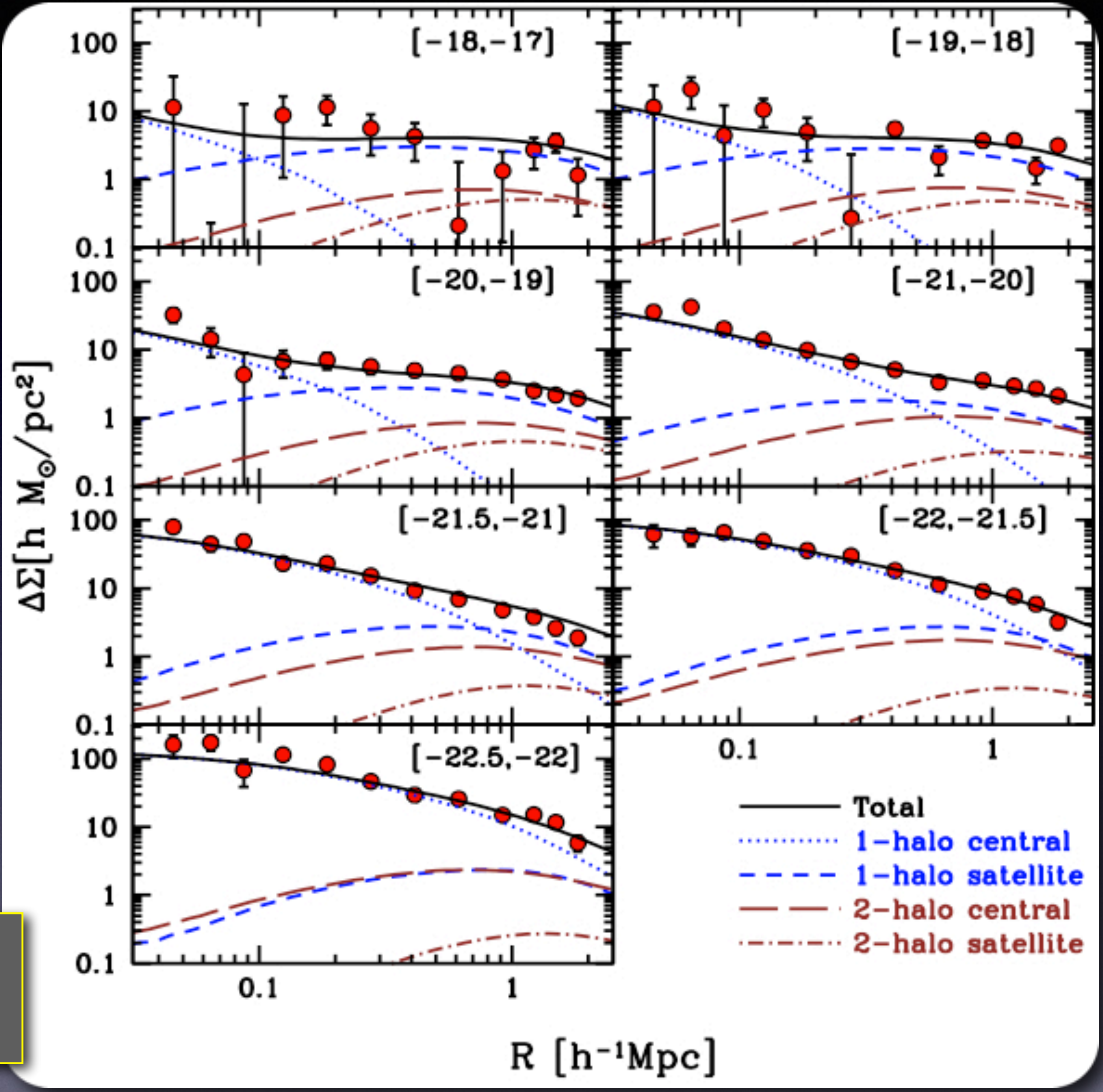
In order to model the data, what is required is:

$P_{\rm cen}(M|L)$ $P_{\rm sat}(M|L)$ $f_{\rm sat}(L)$

These can all be computed from the CLF...

For a given $\Phi(L|M)$ we can predict the lensing signal $\Delta\Sigma(R|L_1, L_2)$

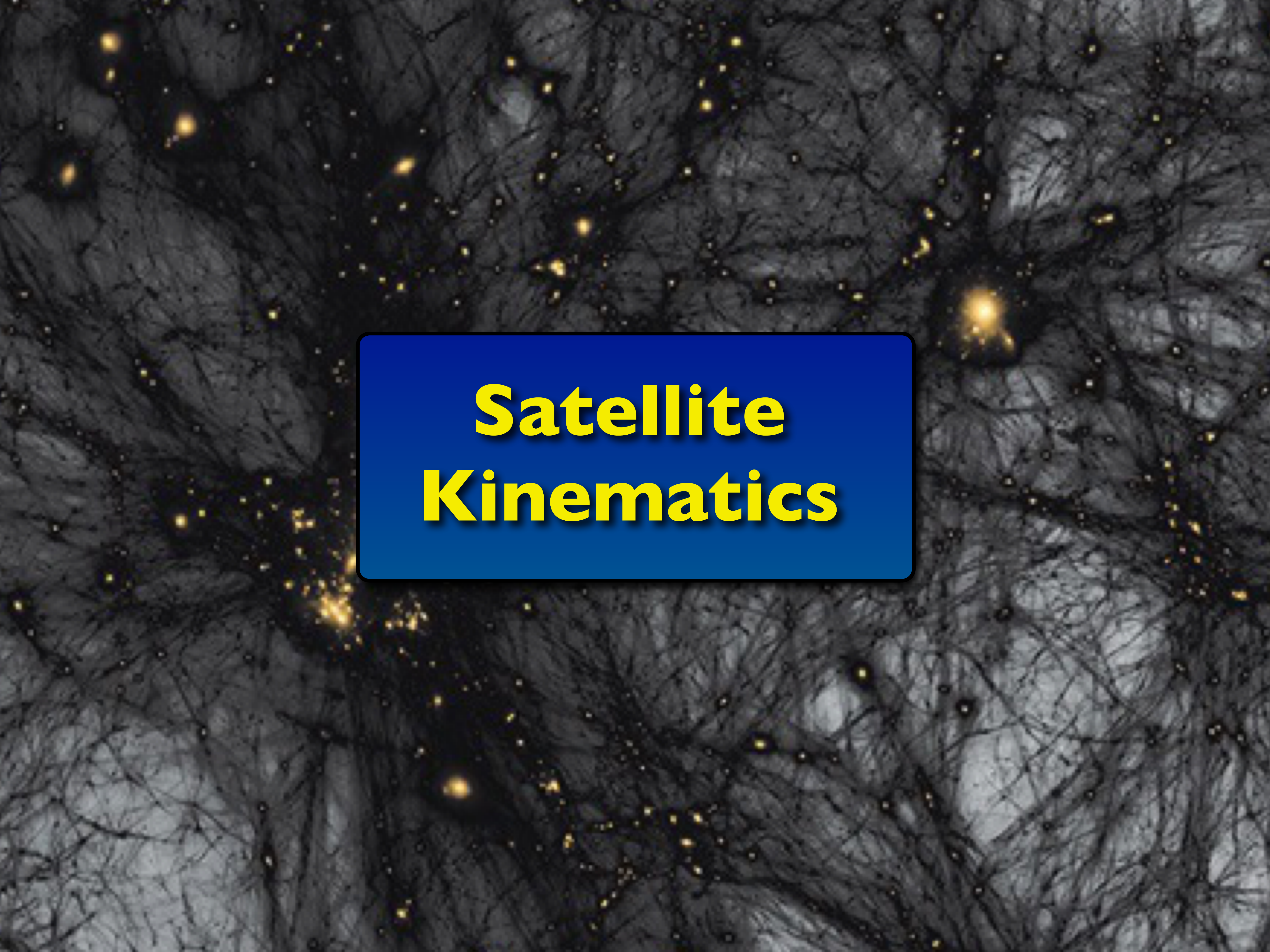
Galaxy-Galaxy Lensing



Data:
SDSS measurements by Mandelbaum+06

Cacciato, vdB et al. 2009

Galaxy-Galaxy Lensing can constrain halo occupation statistics



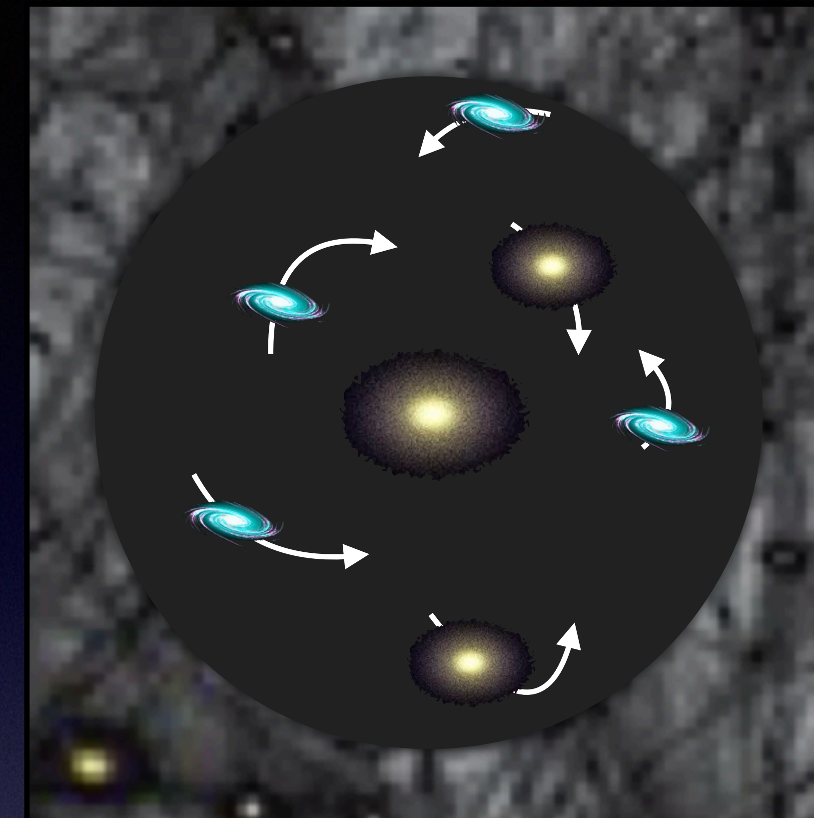
Satellite Kinematics

Probing Halo Mass with Satellite Kinematics

$$2K + W = 0$$

Virial Theorem

$$M \propto \frac{\langle R \rangle \, \sigma^2}{G}$$



Die Rotverschiebung von extragalaktischen Nebeln

von F. Zwicky.

(16. II. 33.)

Um, wie beobachtet, einen mittleren Dopplereffekt von 1000 km/sek oder mehr zu erhalten, müsste also die mittlere Dichte im Comasystem mindestens 400 mal grösser sein als die auf Grund von Beobachtungen an leuchtender Materie abgeleitete[1]). Falls sich dies bewahrheiten sollte, würde sich also das überraschende Resultat ergeben, dass $\boxed{\text{dunkle Materie}}$ in sehr viel grösserer Dichte vorhanden ist als leuchtende Materie.

Zwicky, **1933**, Helv. Phys. Acta, 6, 110

Probing Halo Mass with Satellite Kinematics

$$2K + W = 0$$

Virial Theorem

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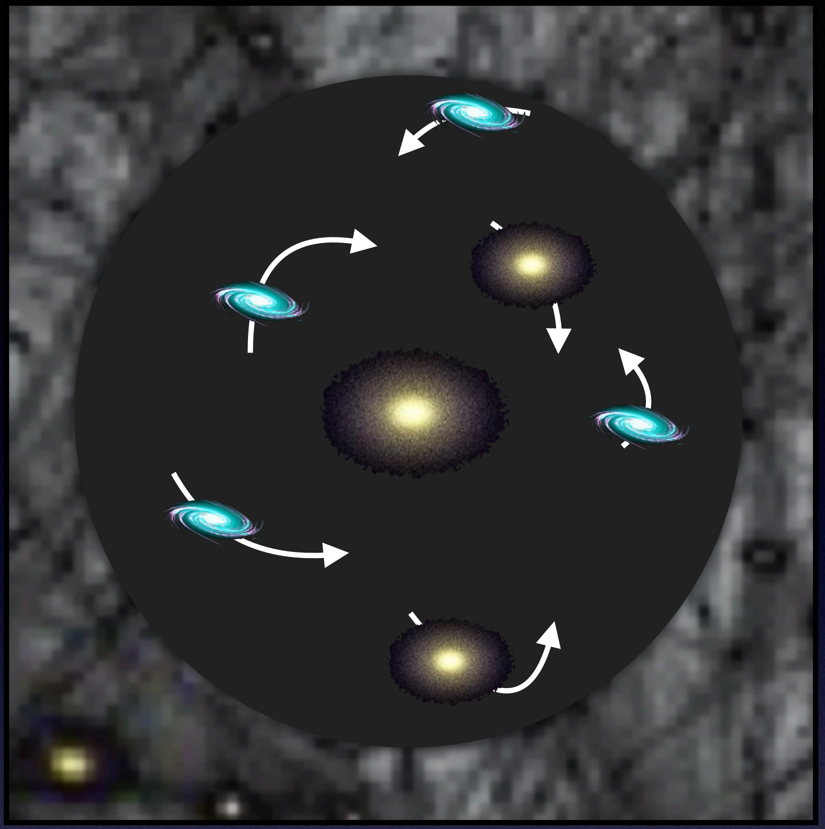


Spherical Jeans Equations

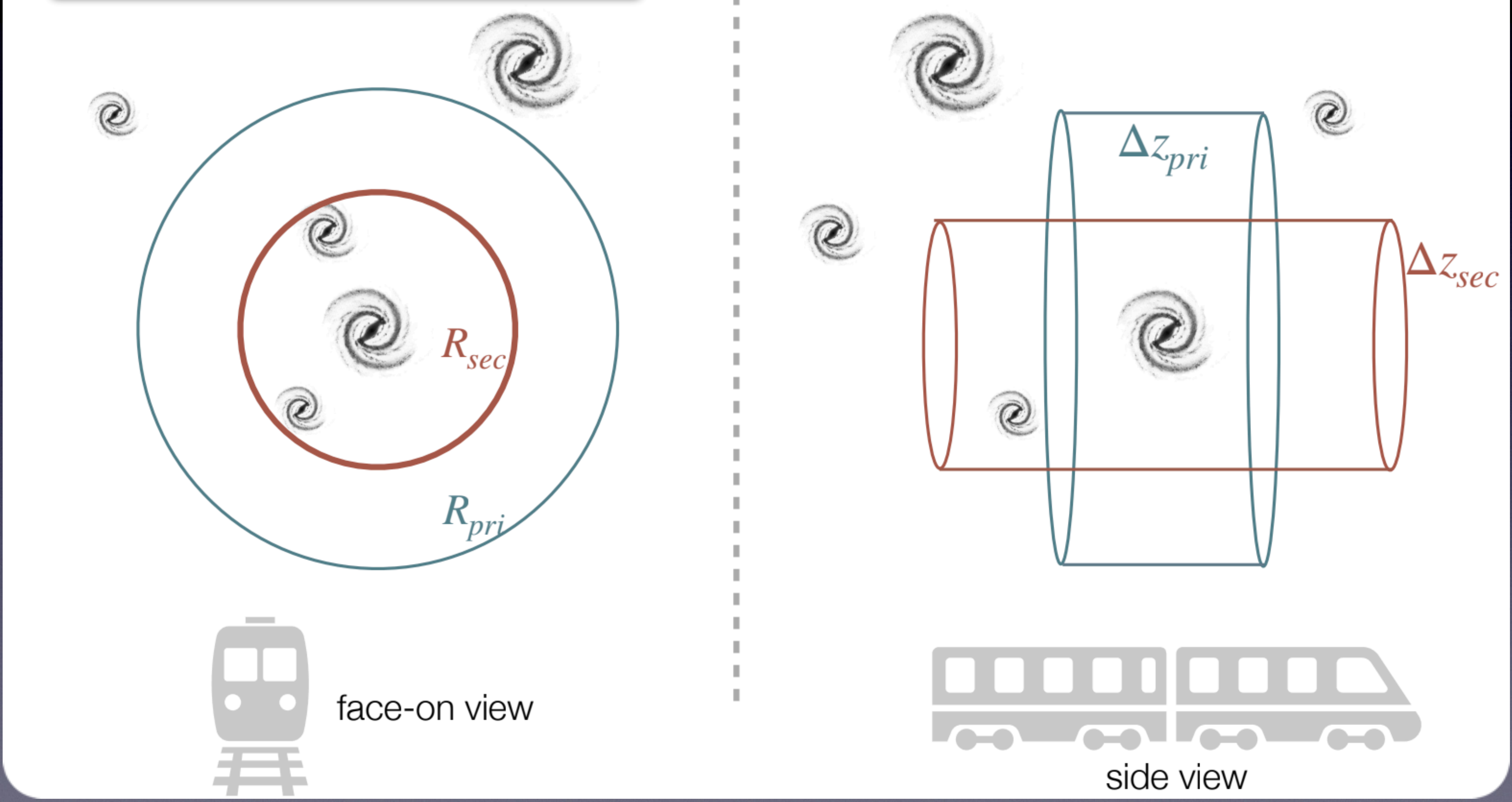
$$M(r) = -\frac{r\sigma_r^2}{G}\left[\frac{\mathrm{d}\ln n_{\rm sat}}{\mathrm{d}\ln r} + \frac{\mathrm{d}\ln \sigma_r^2}{\mathrm{d}\ln r} + 2\beta\right]$$

anisotropy parameter $\beta = 1 - \frac{\sigma_{\rm t}^2}{2\sigma_{\rm r}^2}$

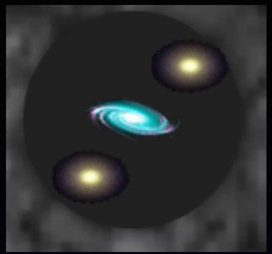
Selecting Centrals & Satellites

Centrals (`primaries') are the brightest galaxies in their cylinder. Others are satellites (`secondaries')

Cylinder sizes are optimized for purity and completeness (using mocks)

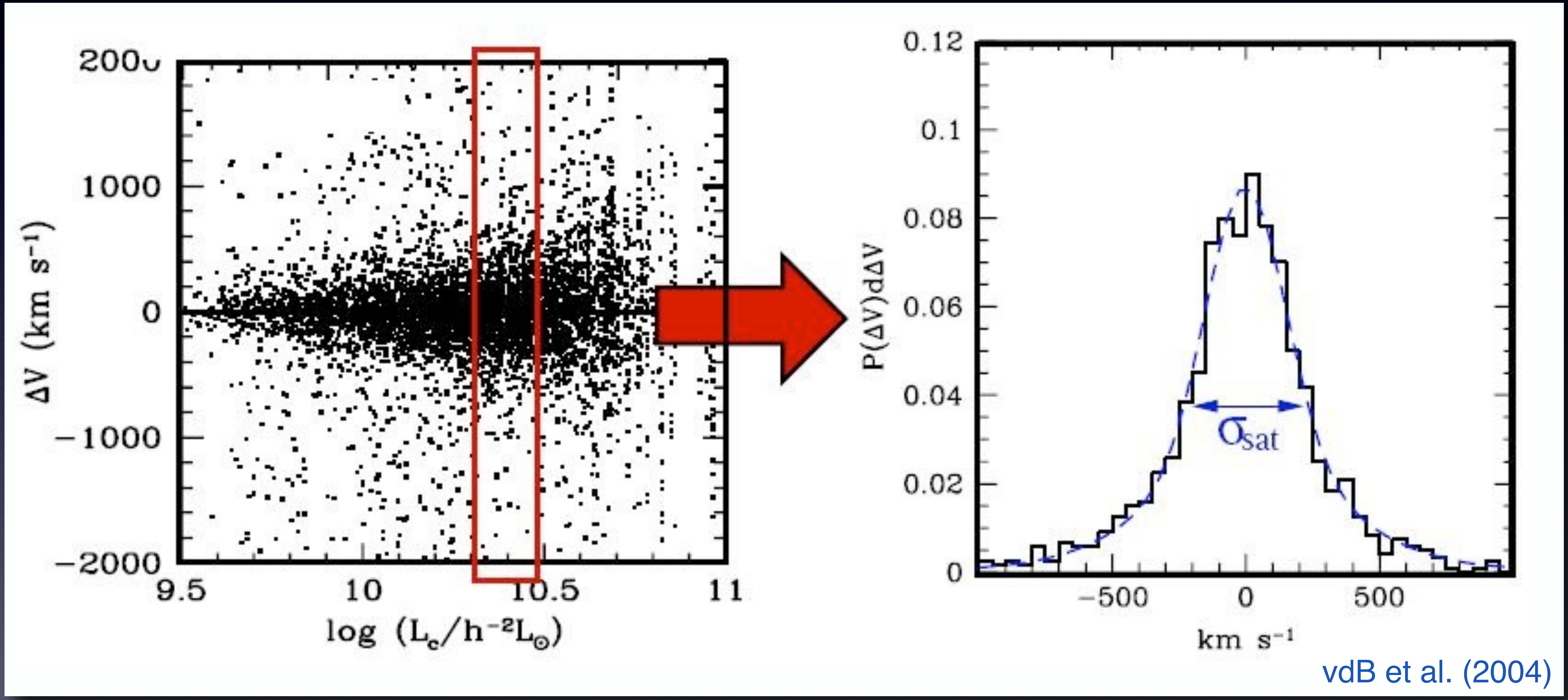


Satellite Kinematics



Select centrals and their satellites from a redshift survey

Using redshifts, determine $\Delta V = V_{\rm sat} - V_{\rm cen}$ as function of $L_{\rm c}$



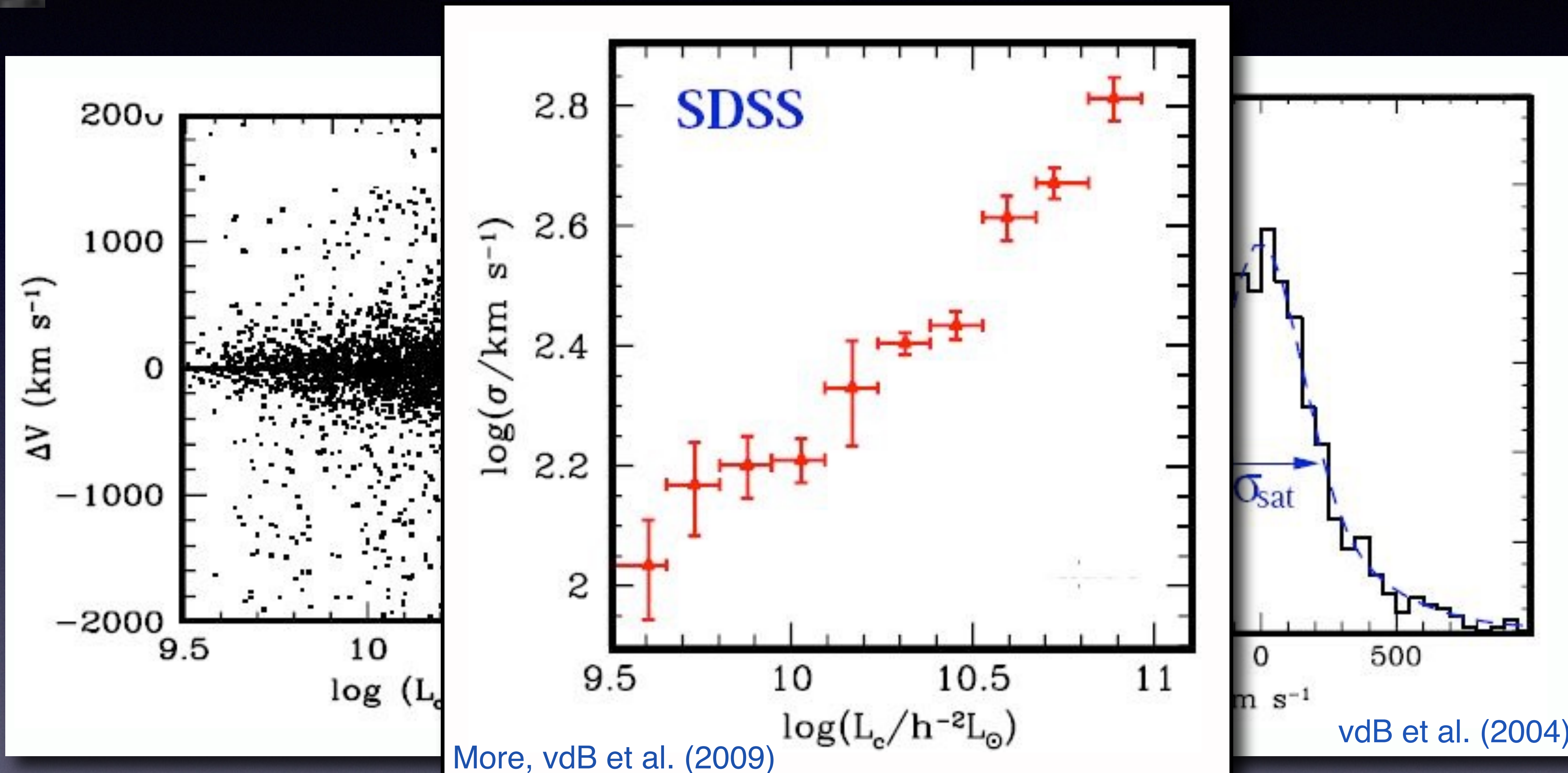
Compute satellite velocity dispersion, $\sigma_{\rm sat}$, as function of $L_{\rm c}$

Use $\sigma_{\rm sat}(L_{\rm c})$ to constrain $\Phi(L_{\rm c}|M)$

Satellite Kinematics

Select centrals and their satellites from a redshift survey

Using redshifts, determine $\Delta V = V_{\rm sat} - V_{\rm cen}$ as function of $L_{\rm c}$



More, vdB et al. (2009)

vdB et al. (2004)

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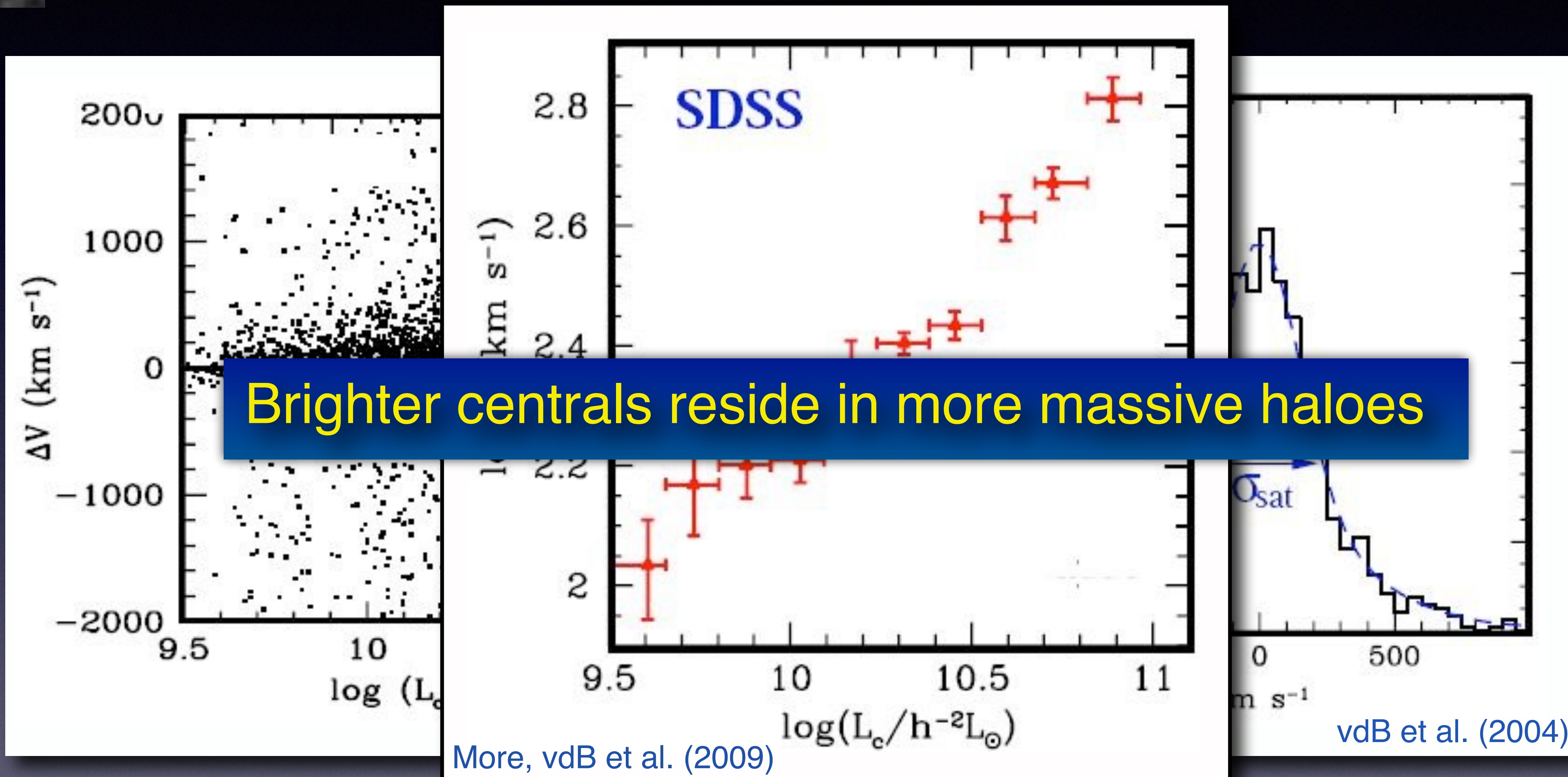
Use $\sigma_{\rm sat}(L_{\rm c})$ to constrain $\Phi(L_{\rm c} | M)$

Satellite Kinematics

Select centrals and their satellites from a redshift survey

Using redshifts, determine $\Delta V = V_{\rm sat} - V_{\rm cen}$ as function of $L_{\rm c}$



More, vdB et al. (2009)

vdB et al. (2004)

Brighter centrals reside in more massive haloes

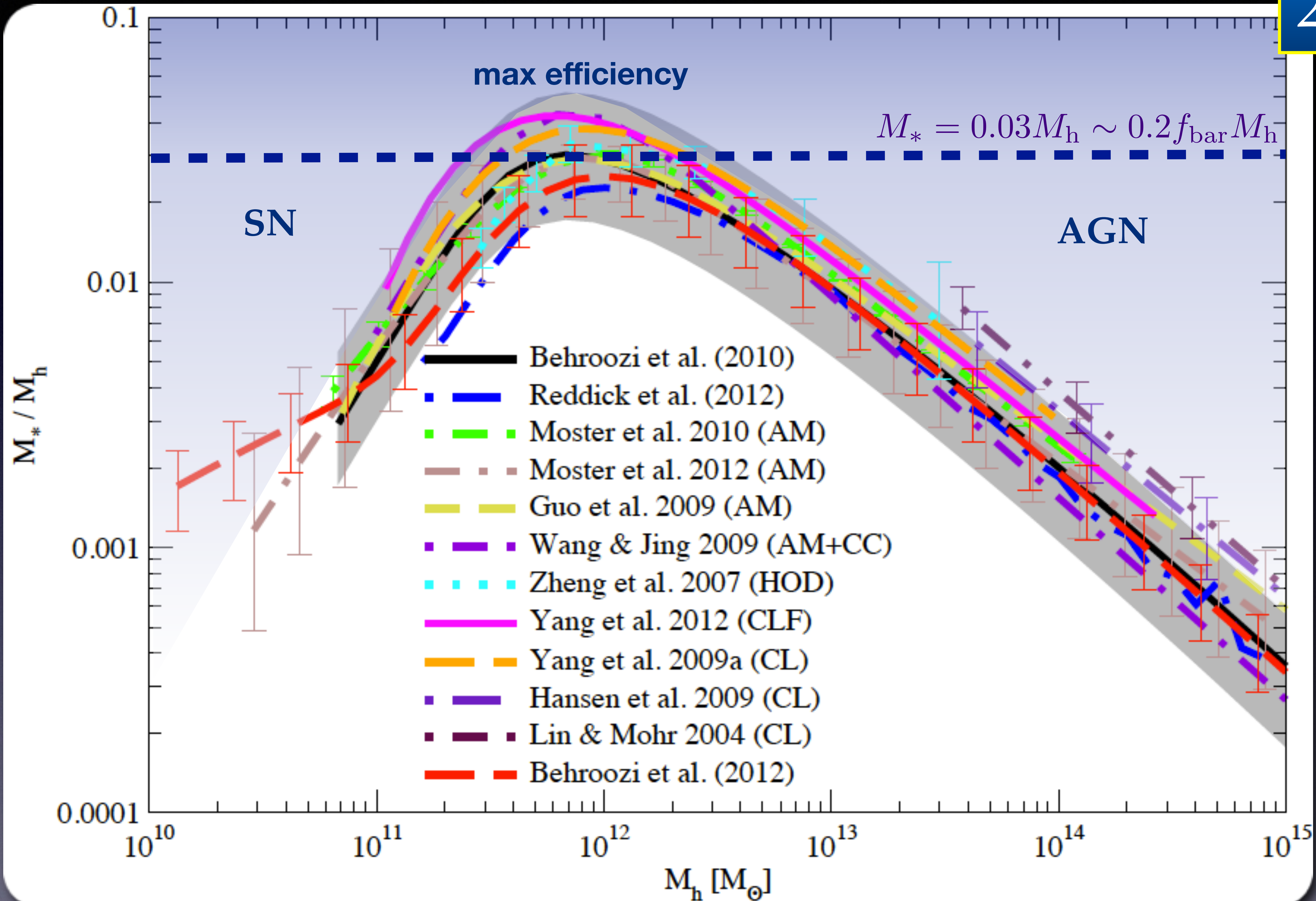
Compute satellite velocity dispersion, $\sigma_{\rm sat}$, as function of $L_{\rm c}$

Use $\sigma_{\rm sat}(L_{\rm c})$ to constrain $\Phi(L_{\rm c}|M)$

Constraints on the Galaxy-Halo Connection

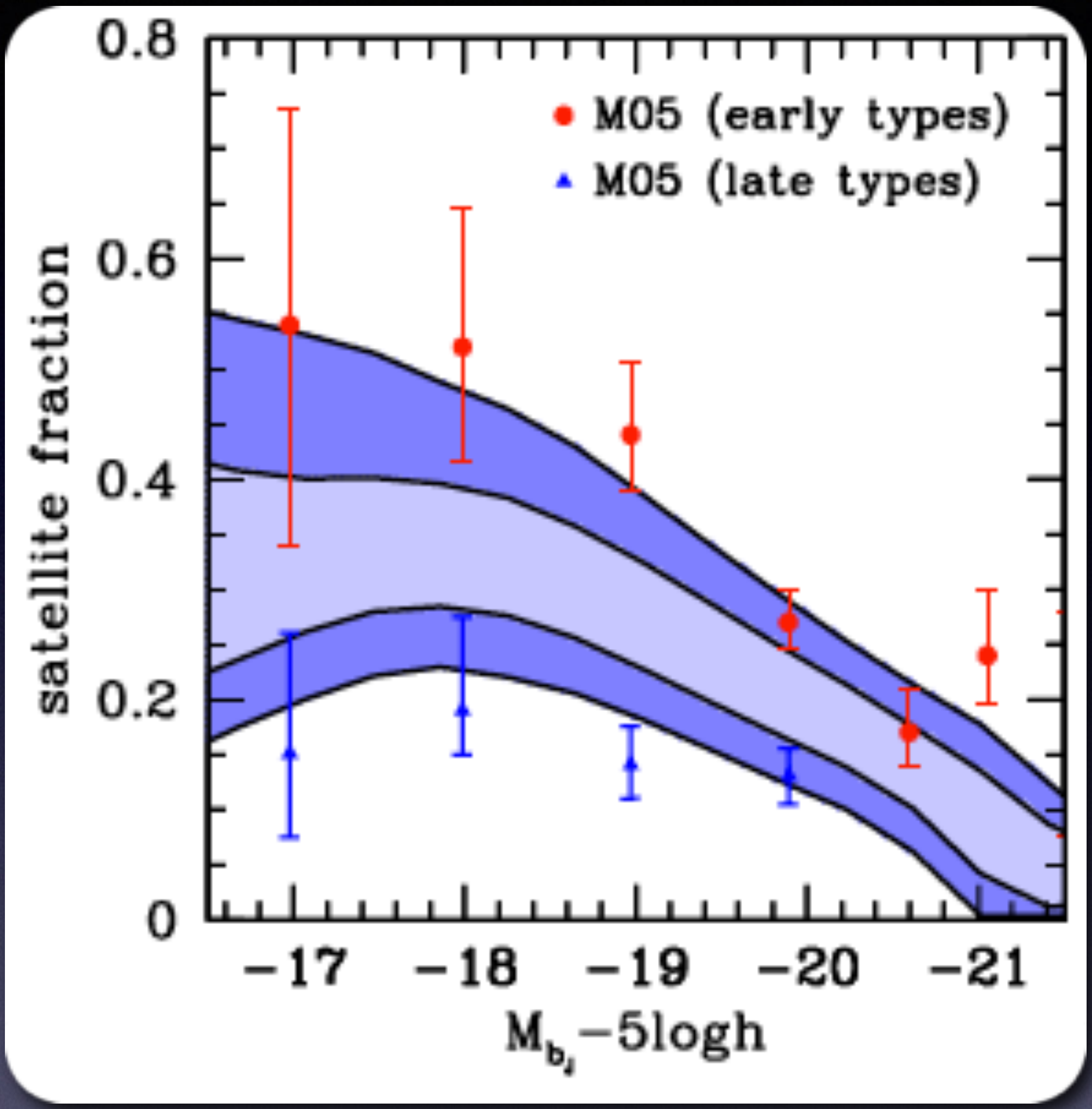
The Stellar Mass - Halo Mass Relation

2013

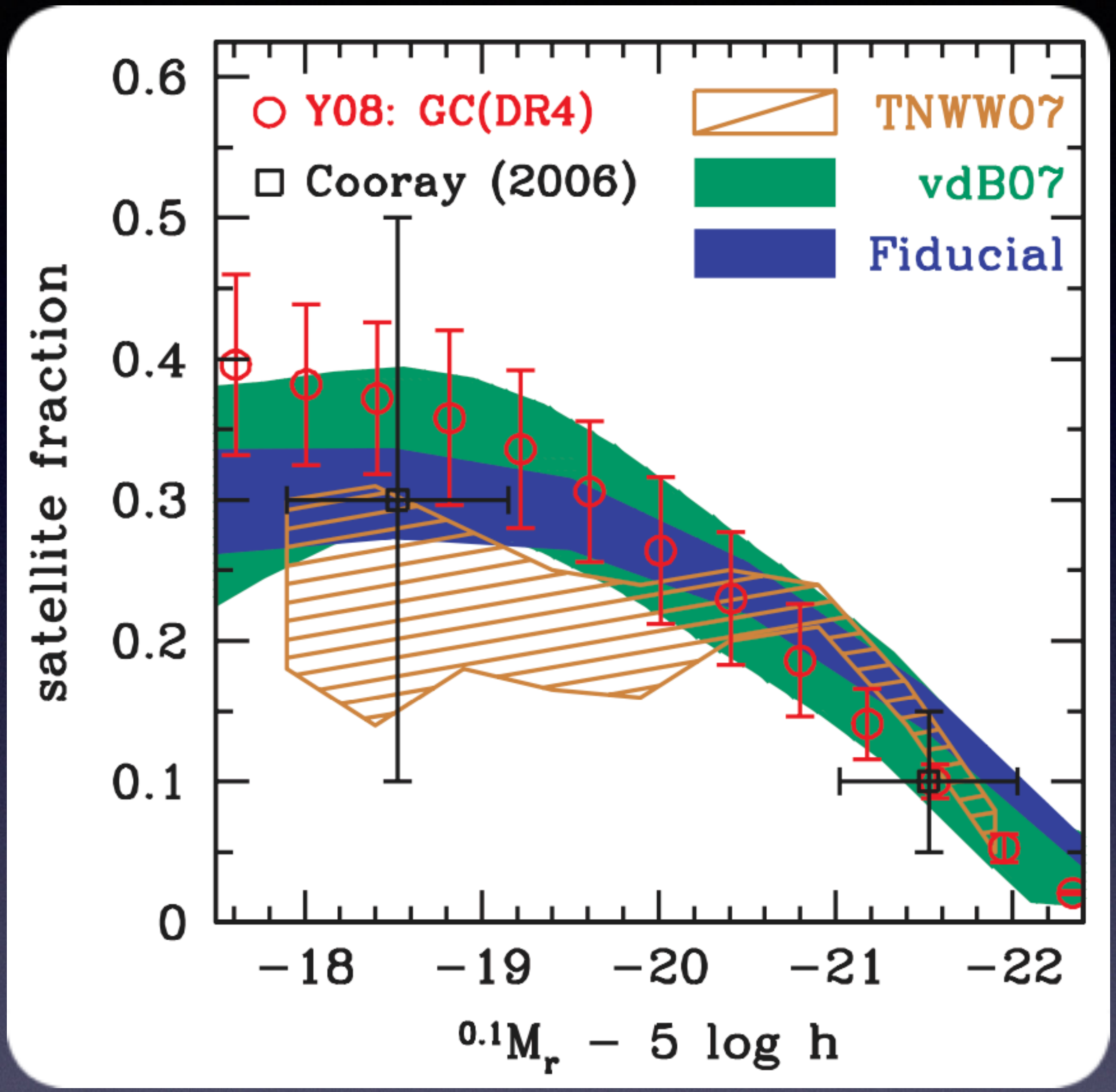


Source: Behroozi, Wechsler & Conroy, 2013

Satellite Fractions



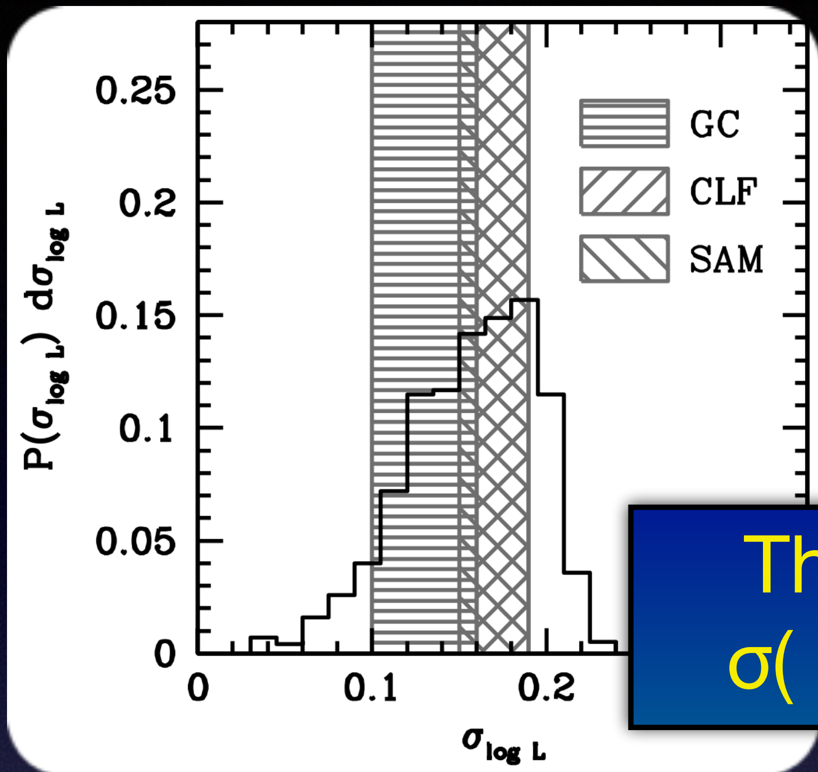
Source: van den Bosch et al. 2007



Source: Cacciato, vdB et al. 2013

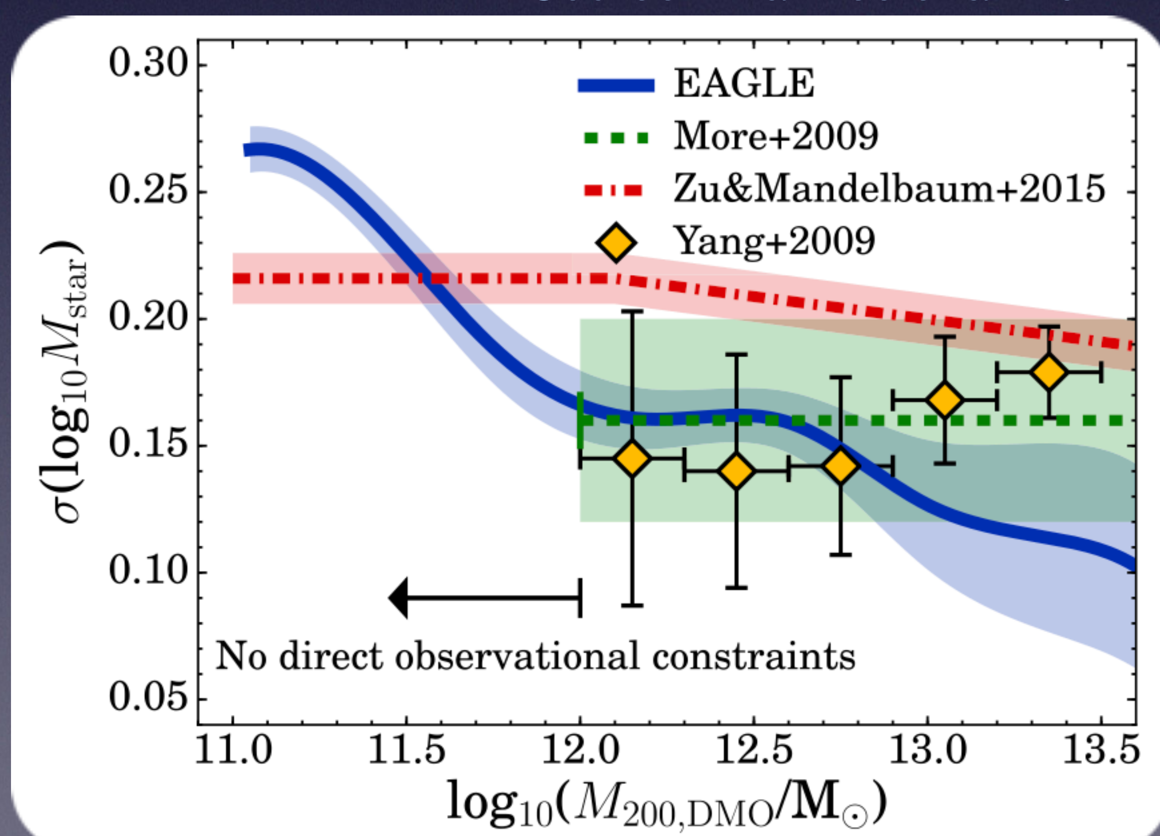
Majority of galaxies of a given luminosity (or stellar mass) are centrals.

Scatter in the SHMR

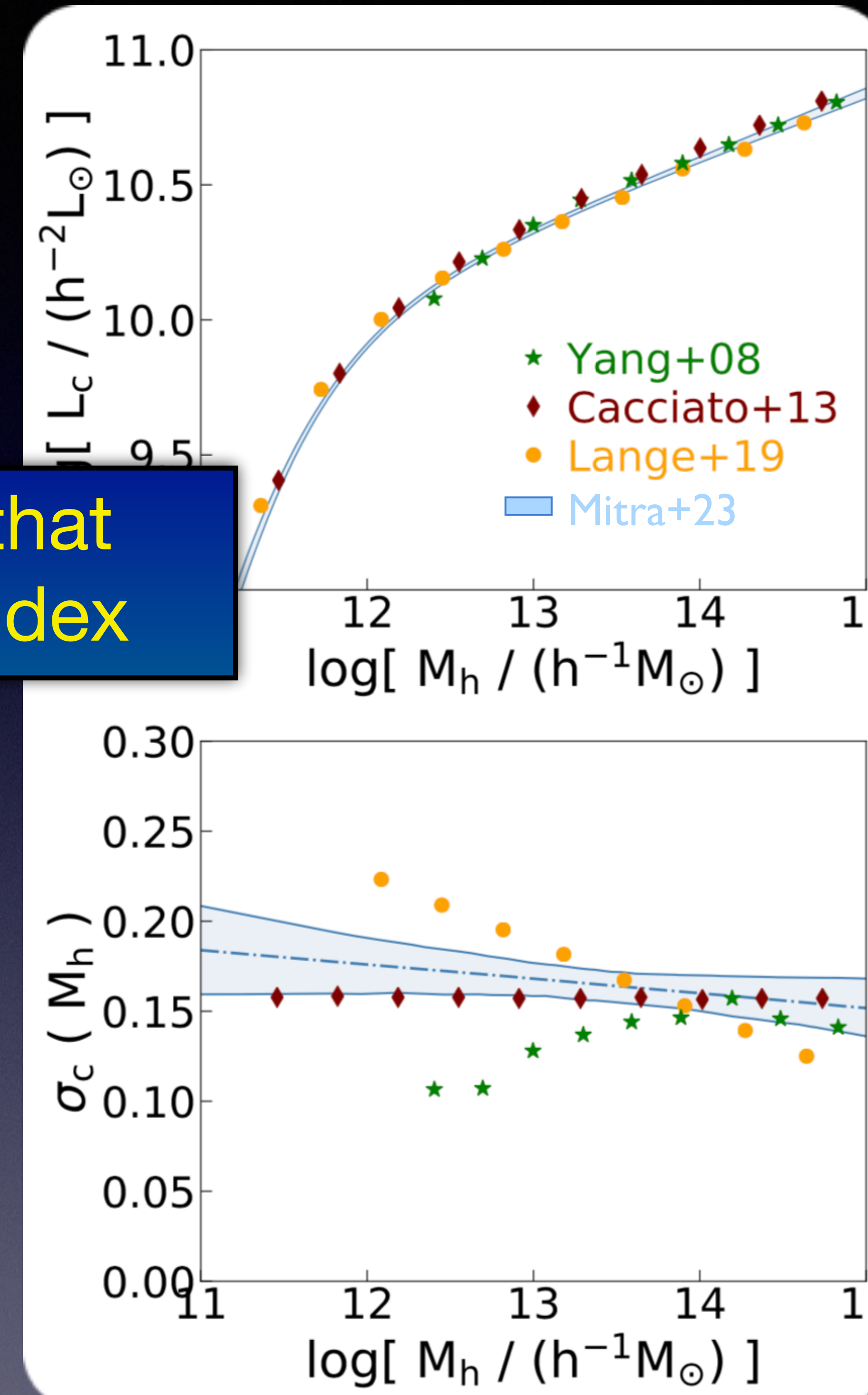


There is a clear consensus that
$\sigma(\log L_c \,|\, \log M_h) \sim 0.15\text{-}0.2$ dex

Source: More, vdB et al. 2009

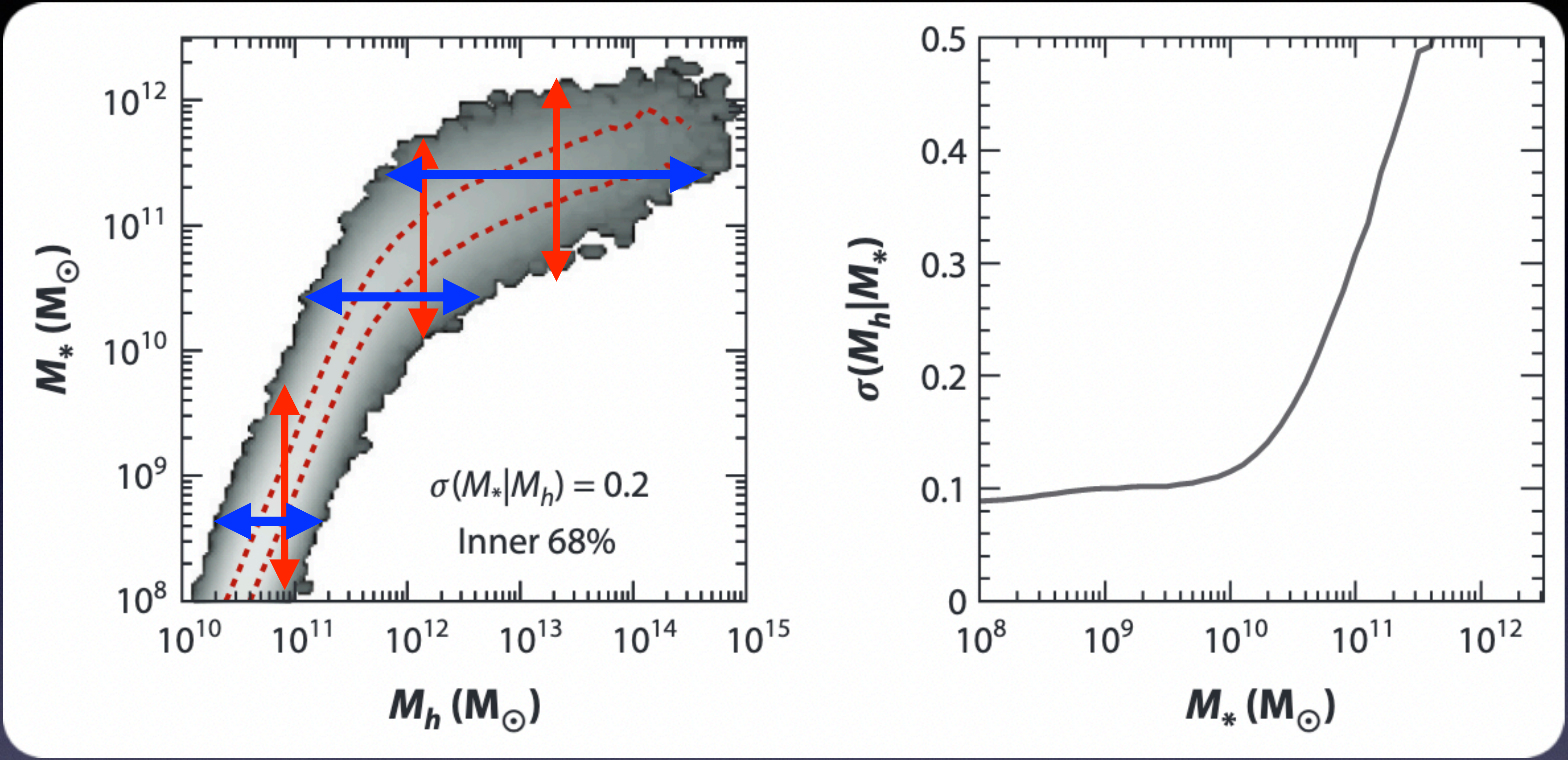


Source: Matthee et al. 2017



Mitra, vdB et al, 2023, in prep.

Scatter in SHMR



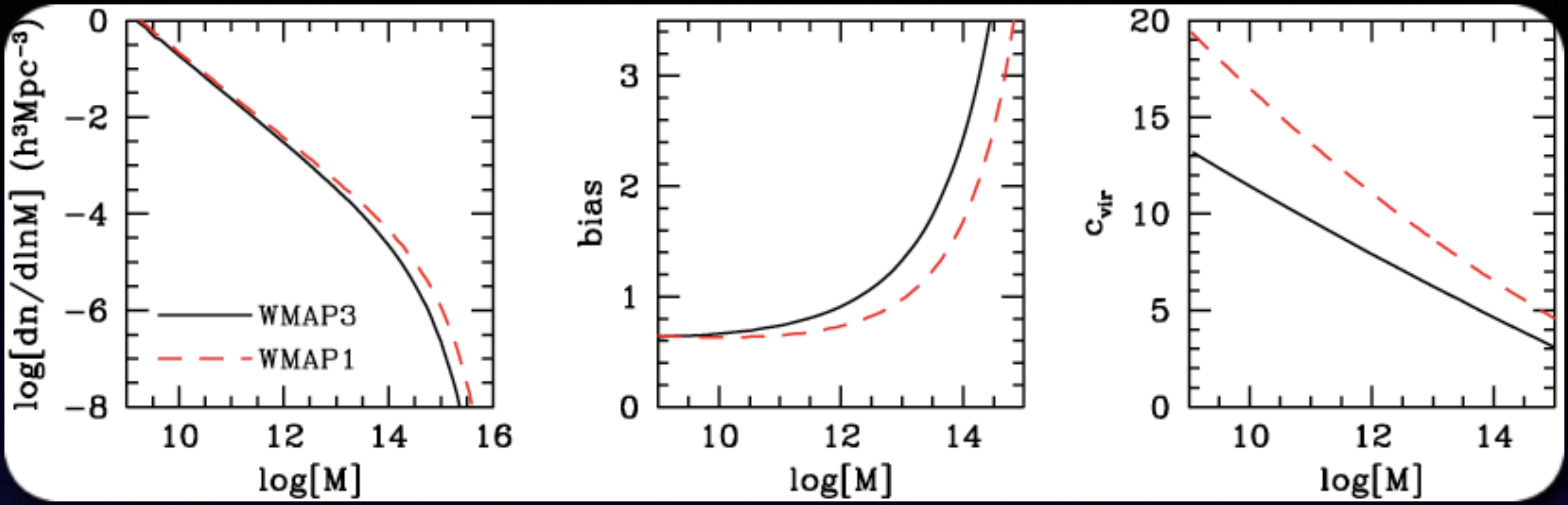
Source: Wechsler & Tinker 2018

Scatter in halo mass at fixed luminosity increases strongly with stellar mass

Beware when stacking galaxies by stellar mass

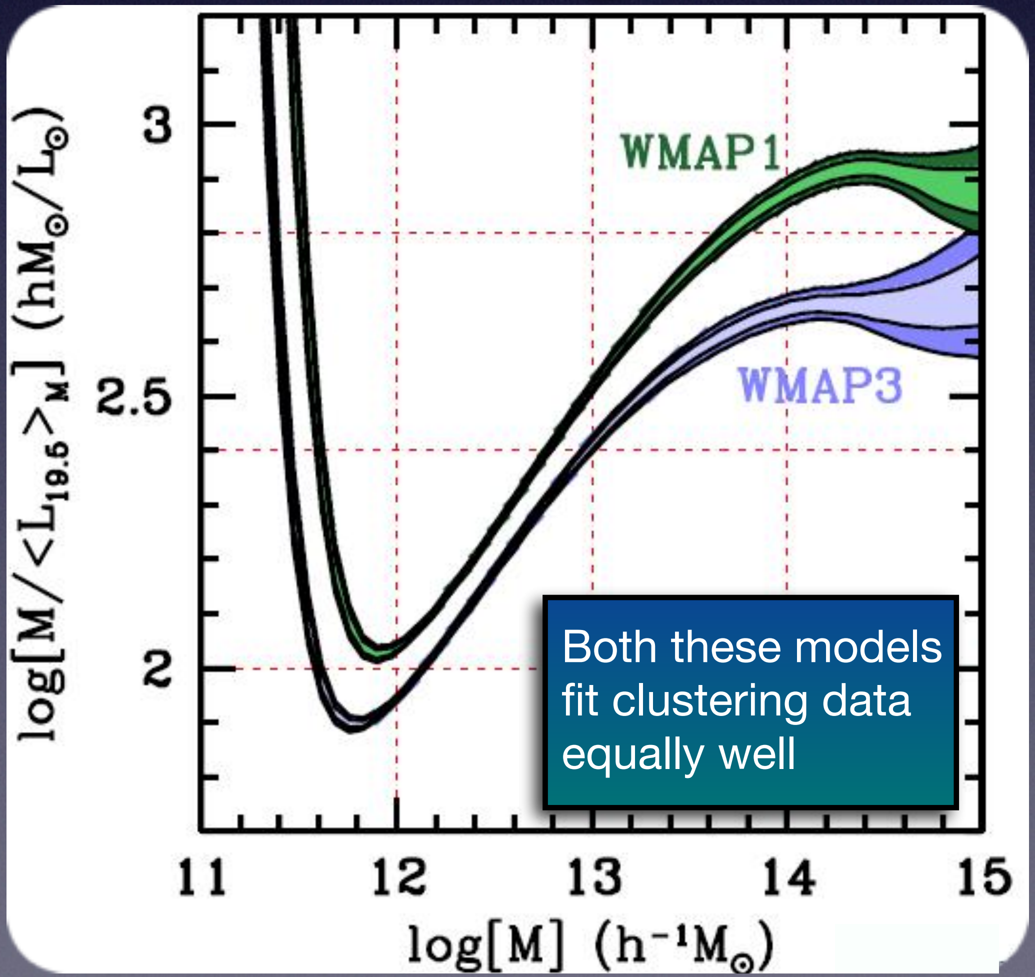
Constraining Cosmology

Cosmology Dependence



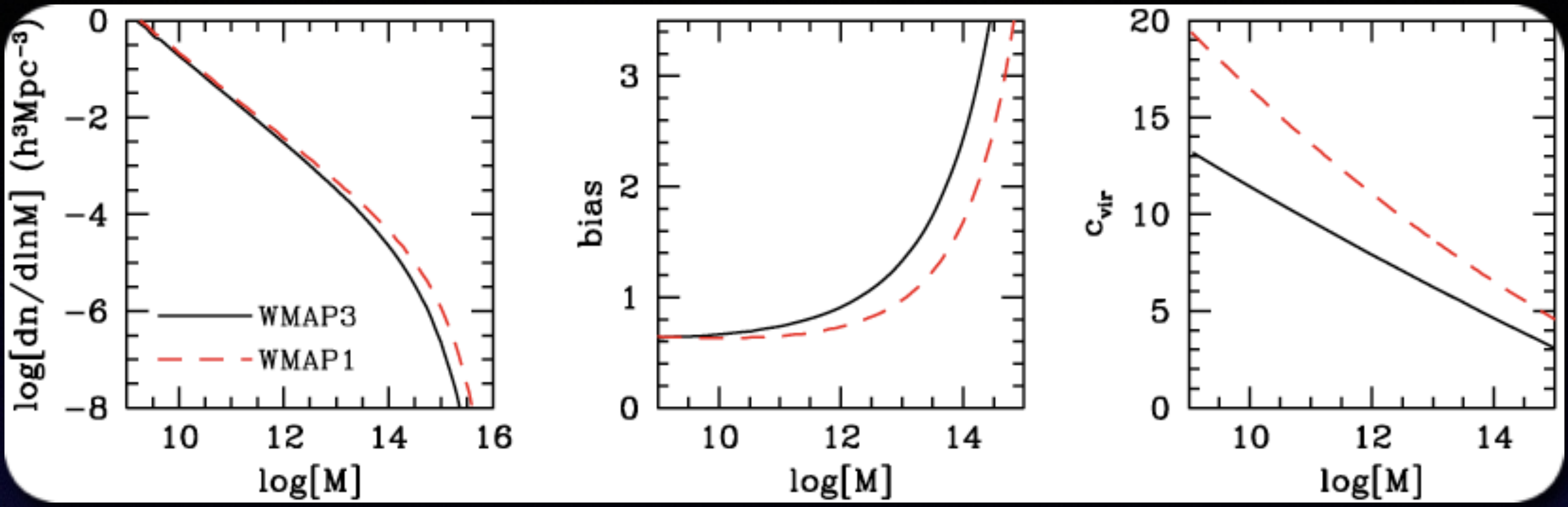
WMAP1
Ω_m=0.3 σ_8=0.9

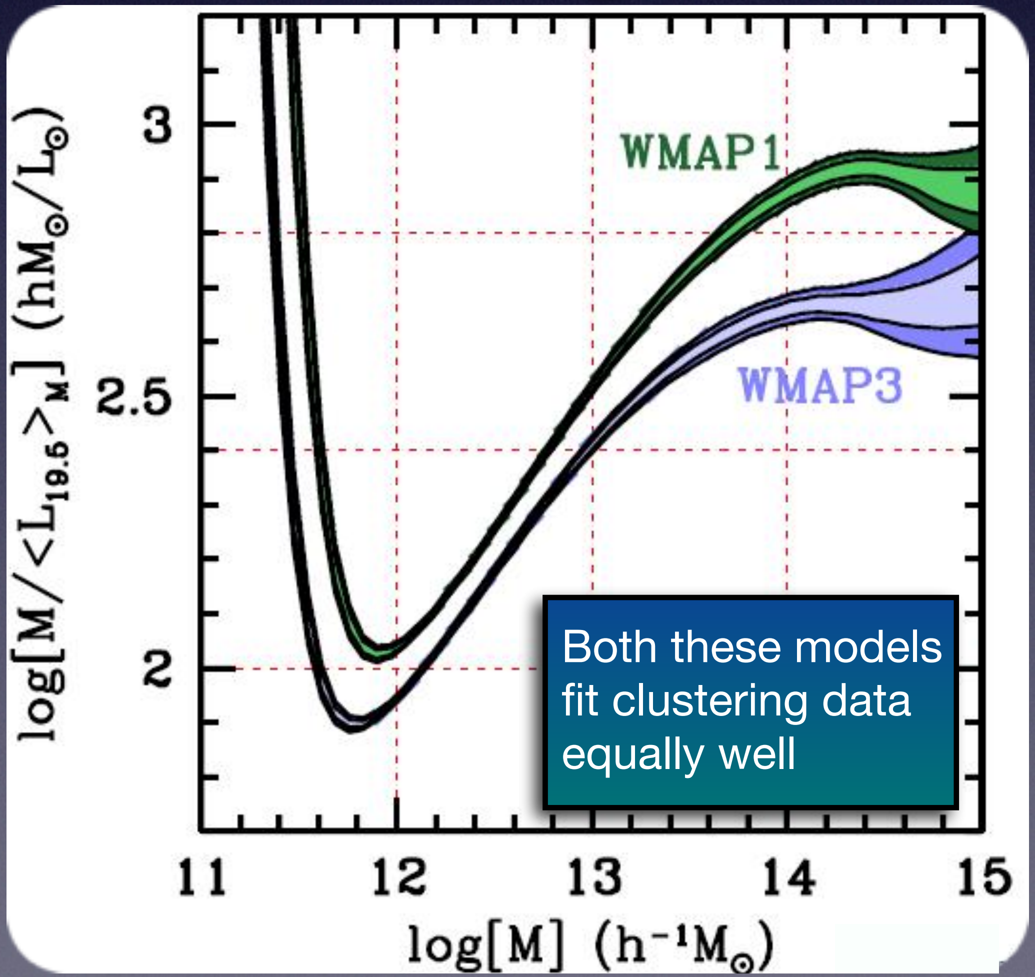
WMAP3
Ω_m=0.24 σ_8=0.74



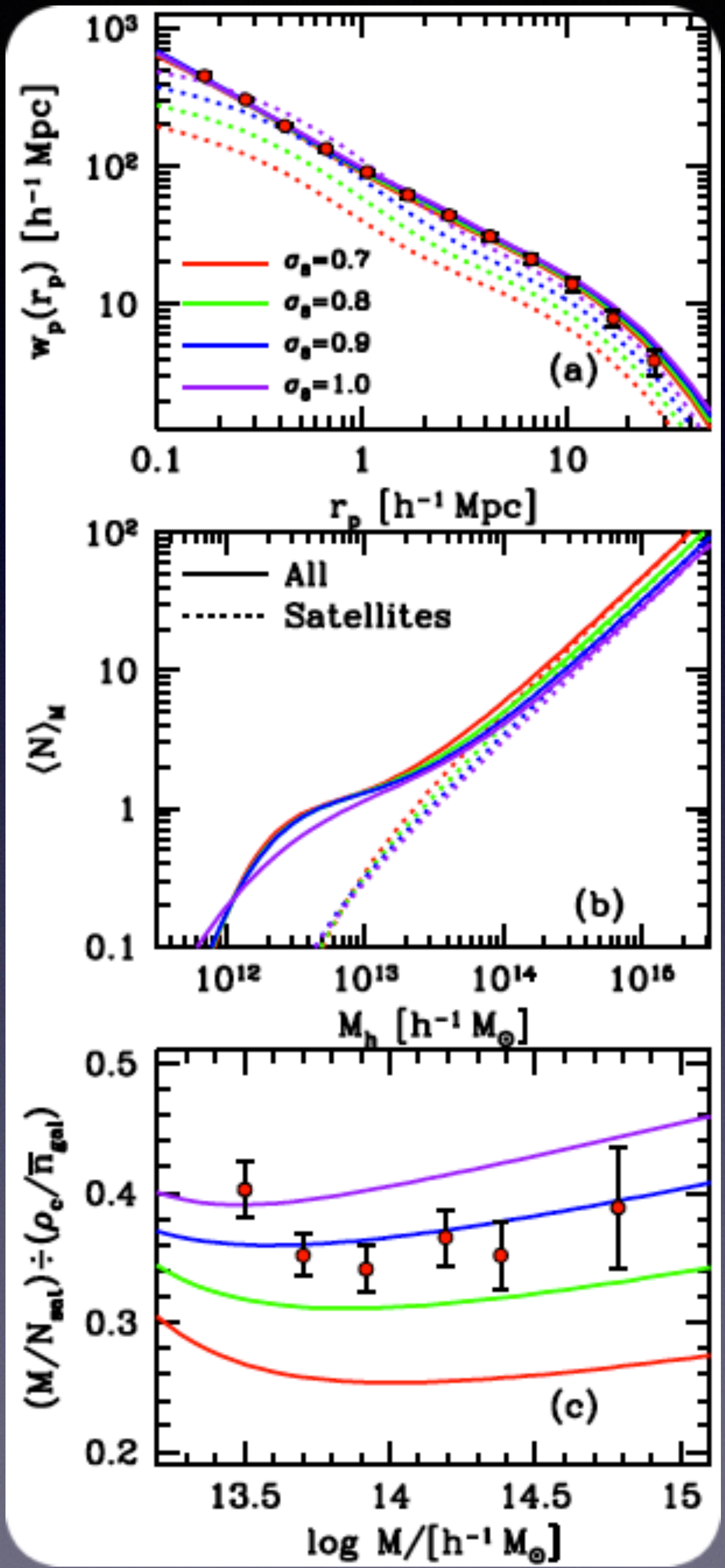
Source: Cacciato et al. 2009

Cosmology Dependence





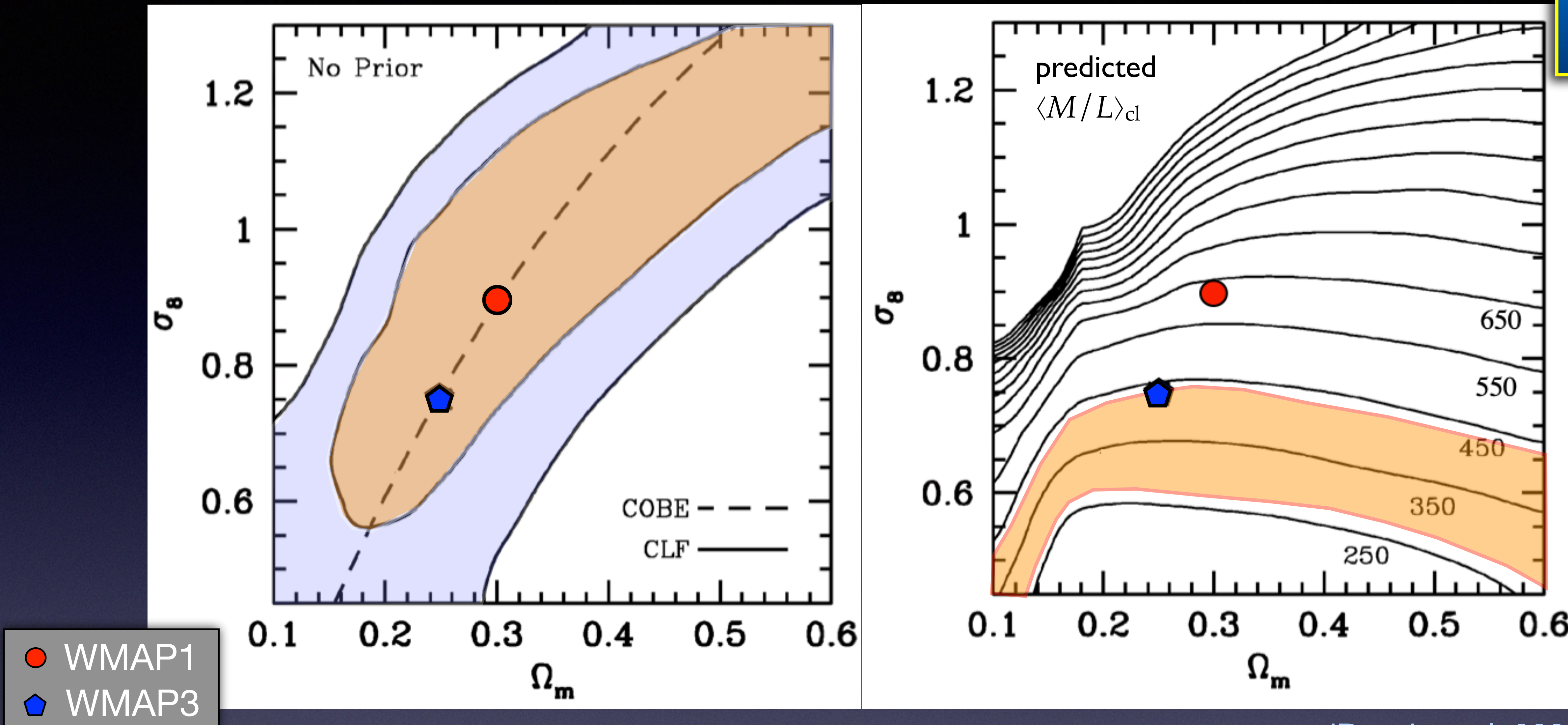
Source: Cacciato et al. 2009



Source: Tinker et al. 2012

Cosmology Dependence

2003



source: vdBosch et al. 2003

Observational constraints $\langle M/L \rangle_{cl} = 350 \pm 70\ (M/L)_\odot$ suggest low values for Ω_m and σ_8

Carlberg+96; Bahcall+00;

These were early manifestations of the S_8 tension

see also Yang et al. 2004; Tinker et al. 2005

Cosmology Dependence

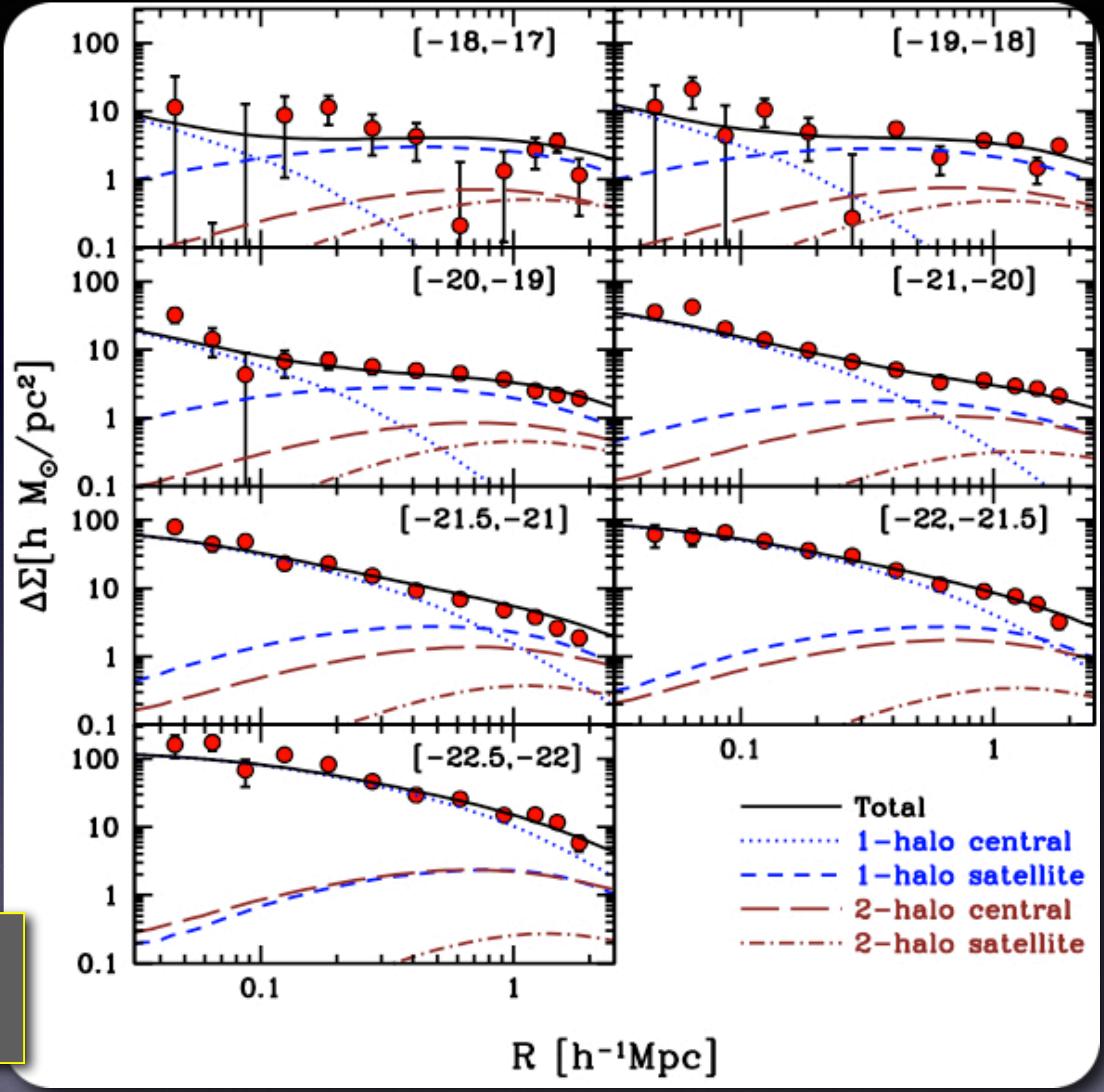
Breaking degeneracies between cosmology and galaxy-halo connection requires methods that directly constrain halo mass

Galaxy-Galaxy lensing

Redshift-space distortions (RSD)

Satellite kinematics

Galaxy-Galaxy Lensing

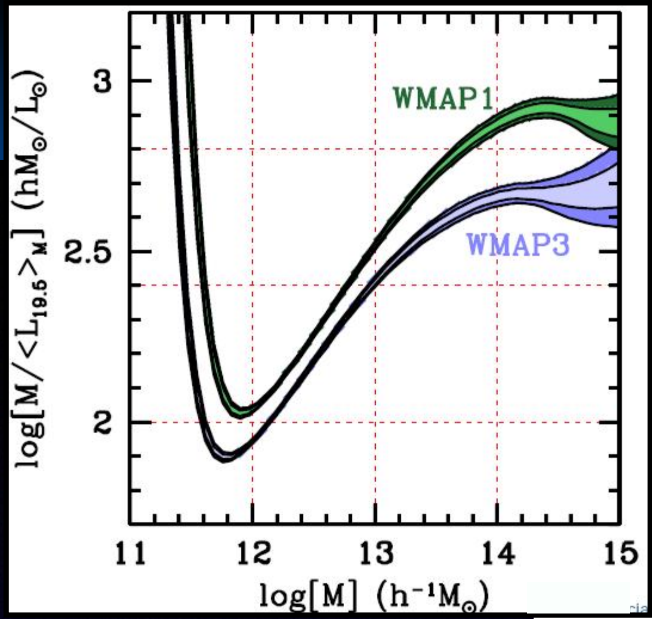


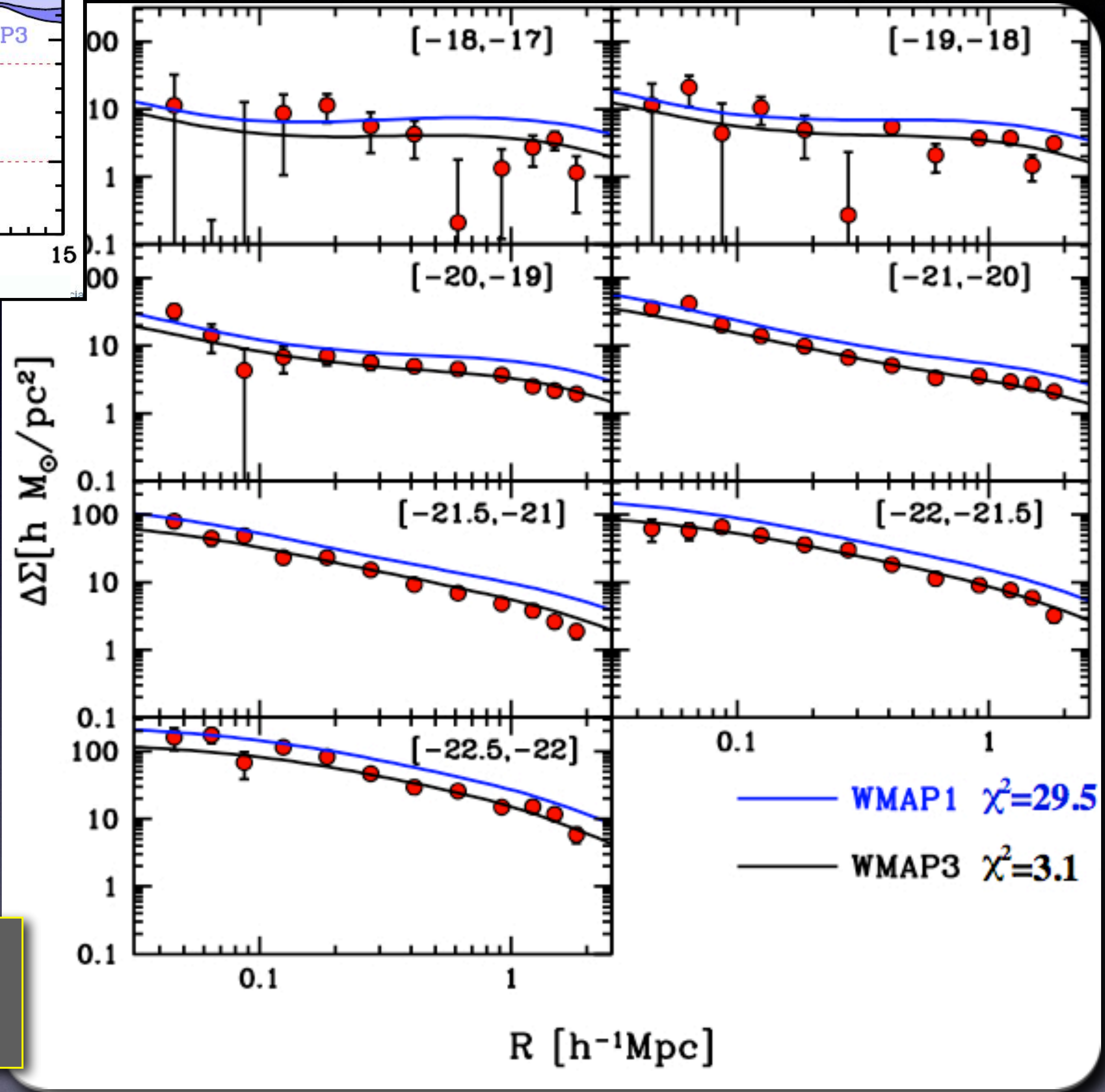
Data:
SDSS measurements by Mandelbaum+06

Cacciato, vdB et al. 2009

NOTE: this is not a fit, but a prediction based on CLF

Galaxy-Galaxy Lensing





WMAP1
Ω_m=0.3 σ_8=0.9

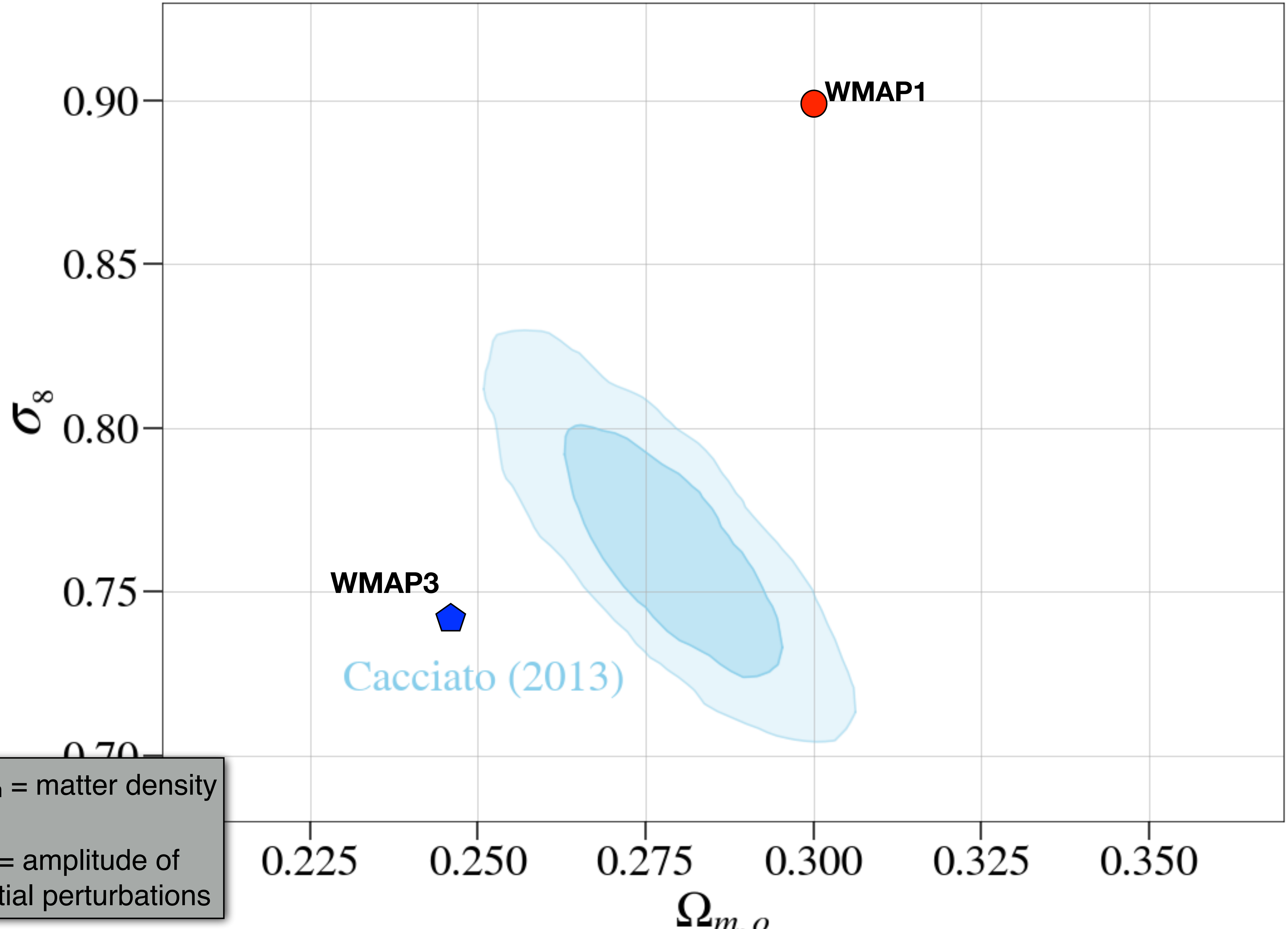
WMAP3
Ω_m=0.24 σ_8=0.74

Data:
SDSS measurements
by Mandelbaum+06

Cacciato, vdB et al. 2009

Combination of clustering & lensing can constrain cosmology!!!

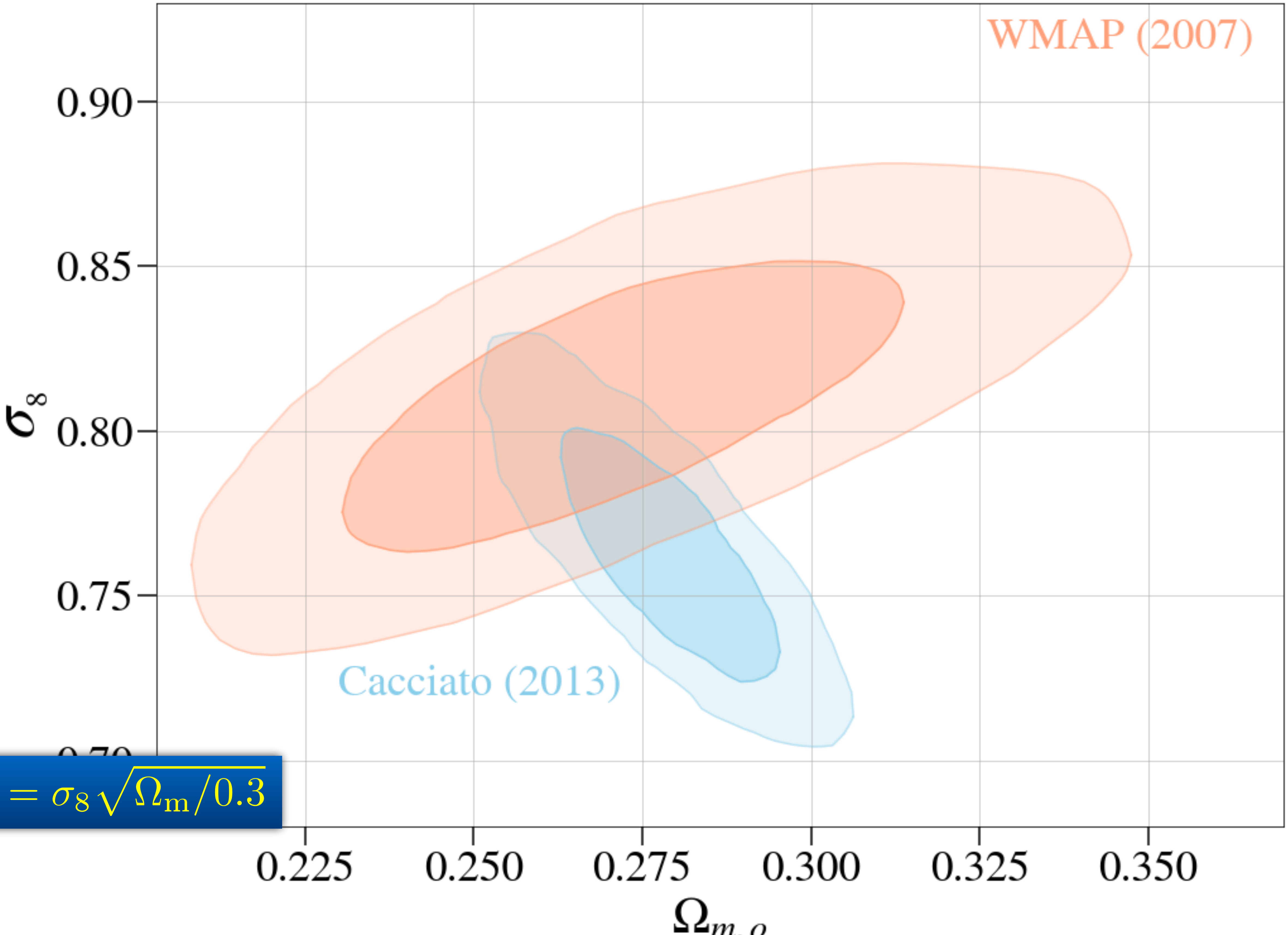
The S_8 Tension



Ω_m = matter density

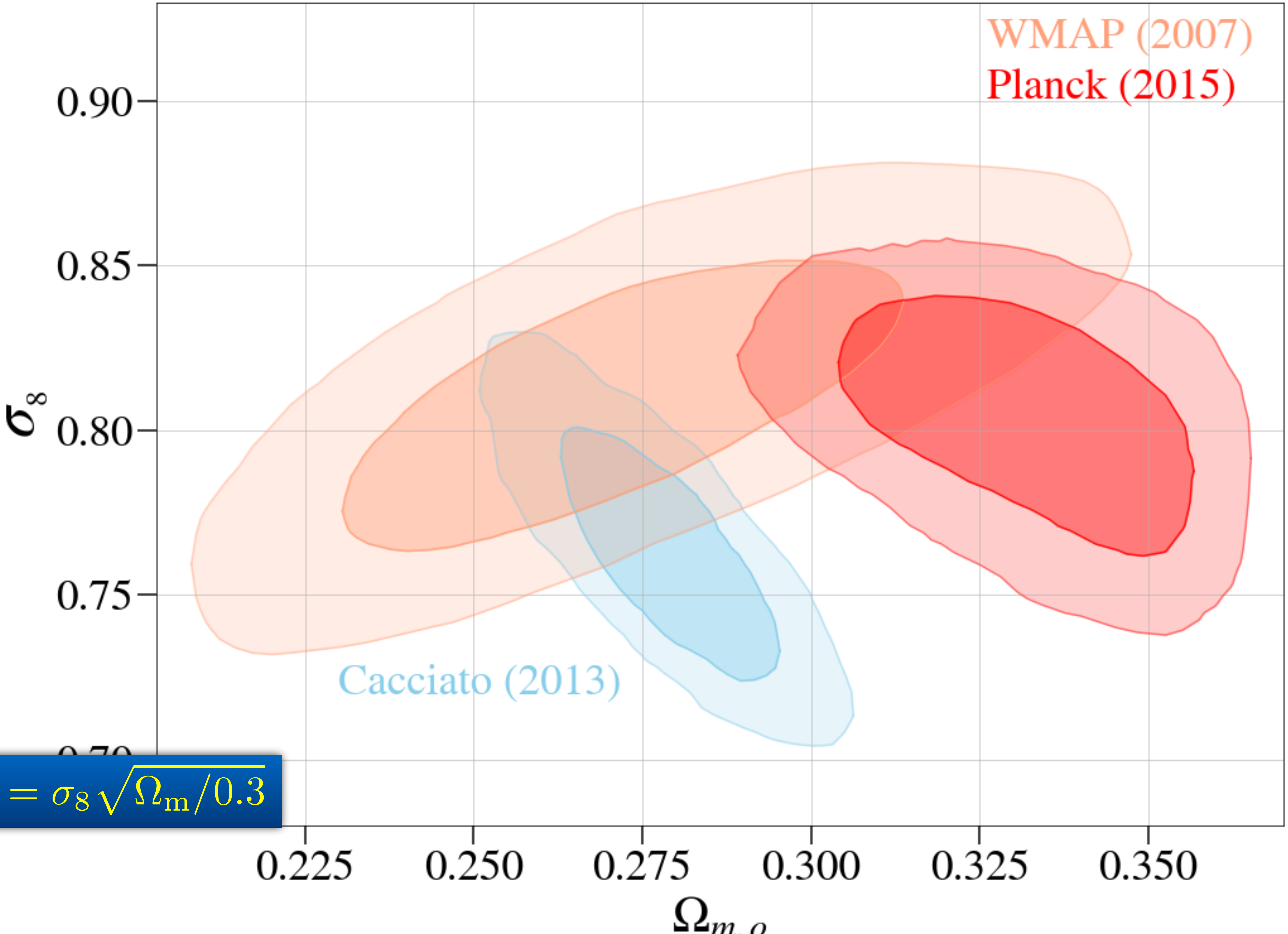
σ_8 = amplitude of initial perturbations

The S_8 Tension



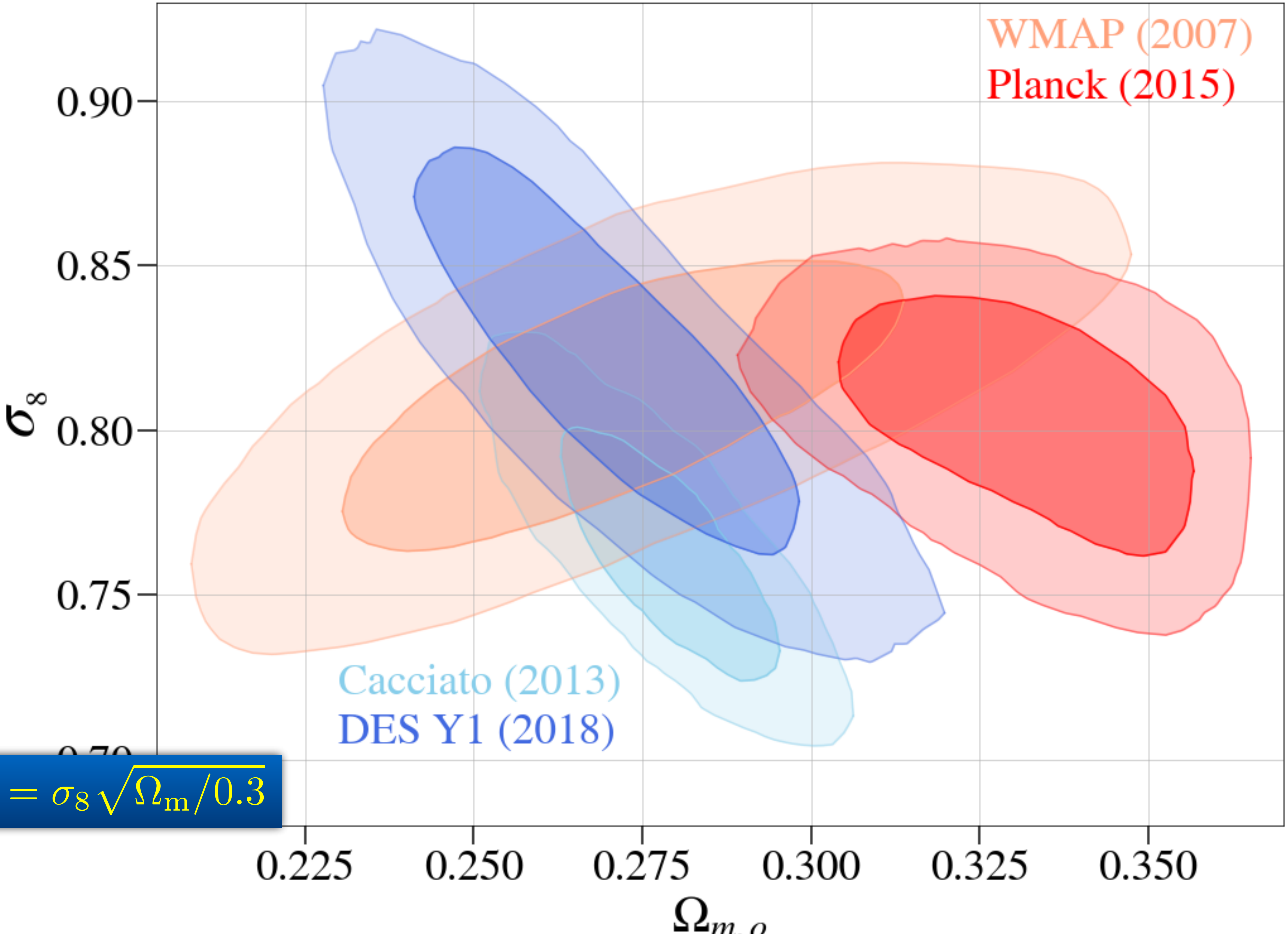
$$S_8 = \sigma_8 \sqrt{\Omega_{\rm m}/0.3}$$

The S_8 Tension



$$S_8 = \sigma_8 \sqrt{\Omega_{\rm m}/0.3}$$

The S_8 Tension



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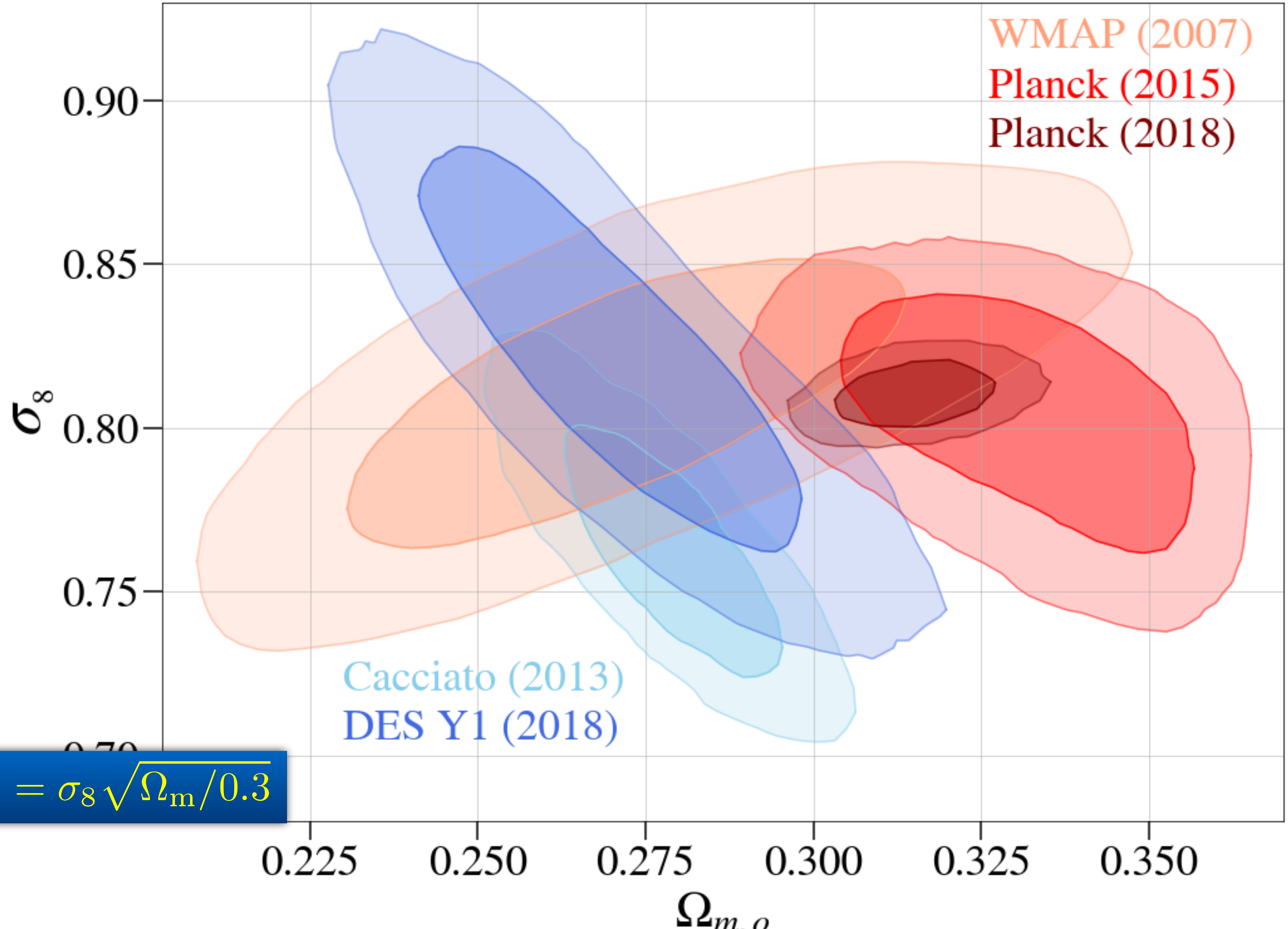

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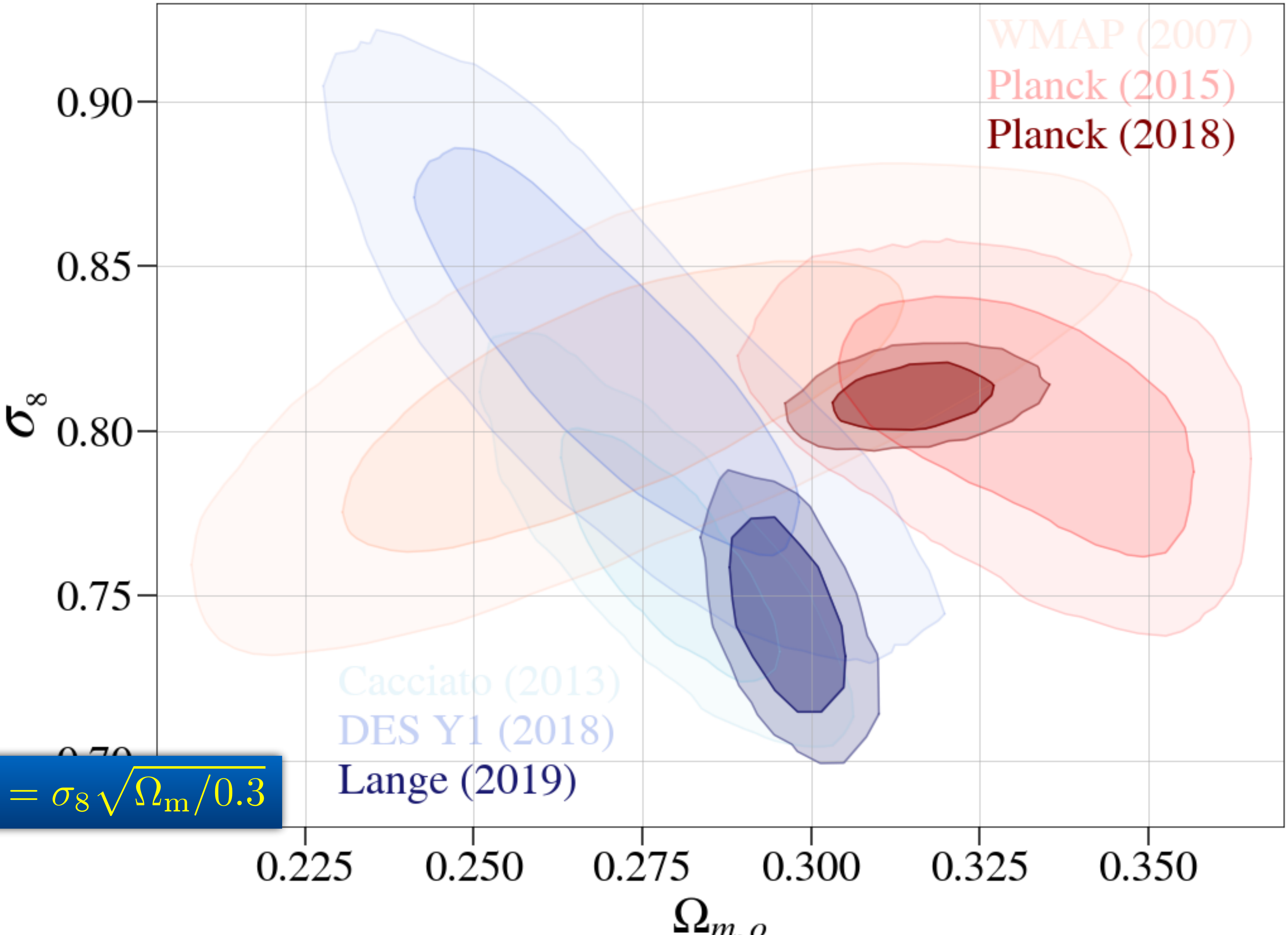

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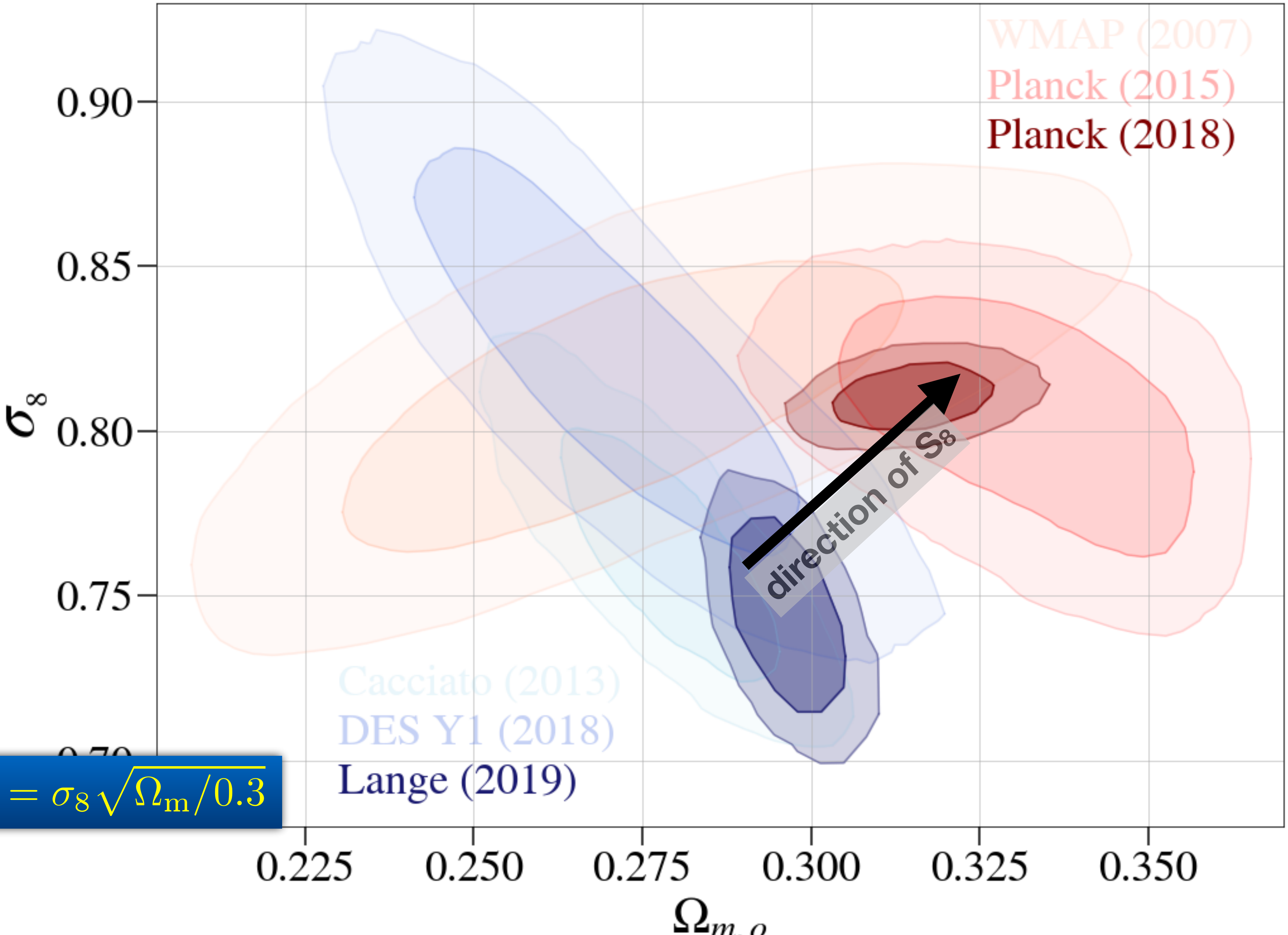
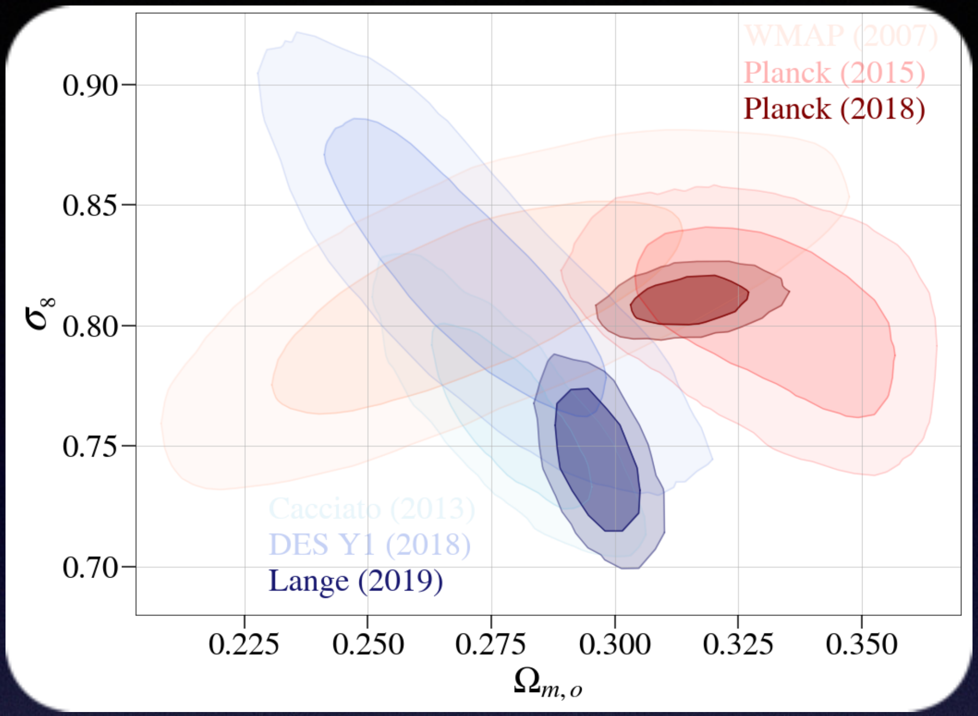


$$S_8 = \sigma_8 \sqrt{\Omega_\mathrm{m}/0.3}$$

The S_8 Tension = "Lensing is Low" problem



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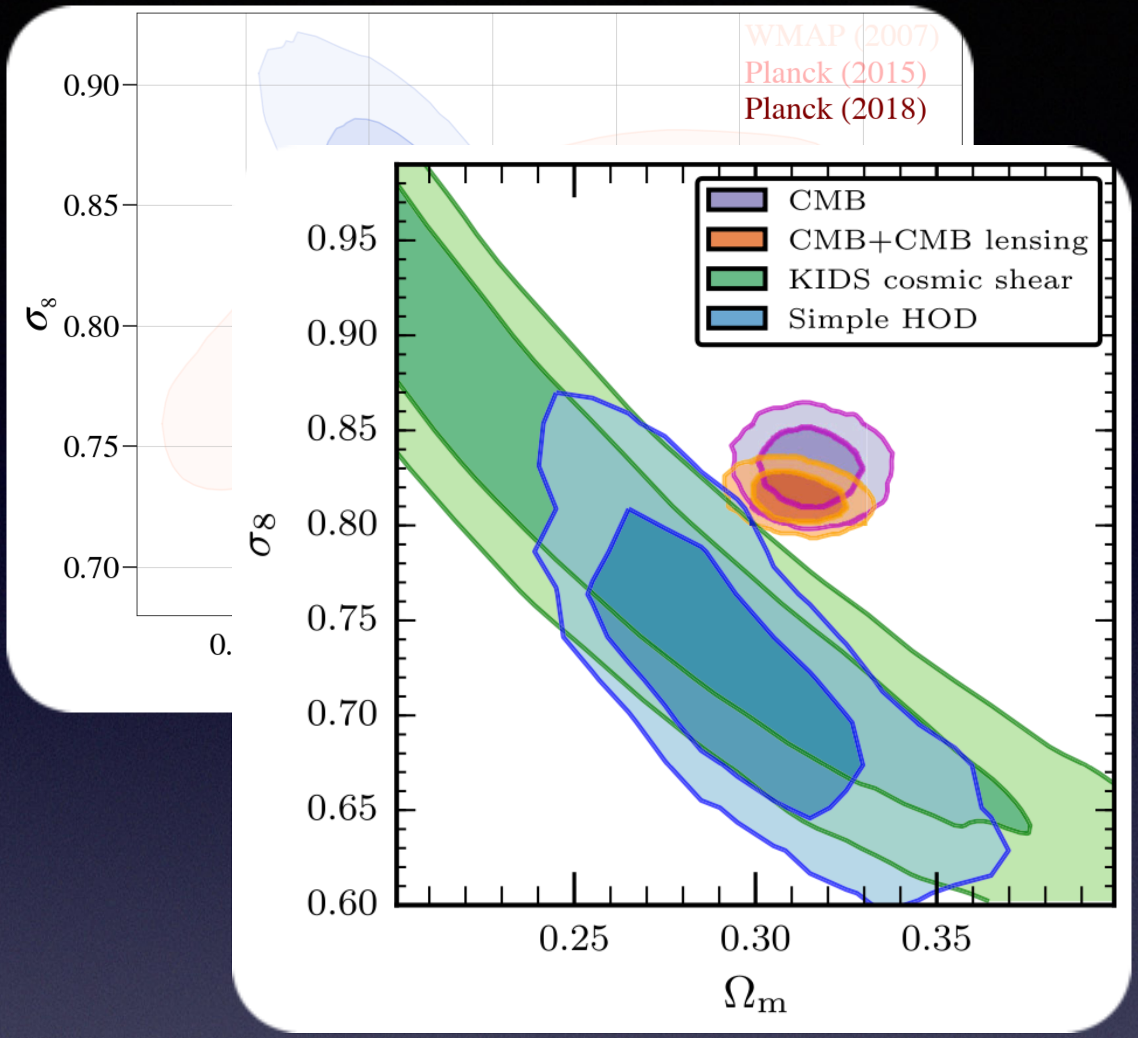
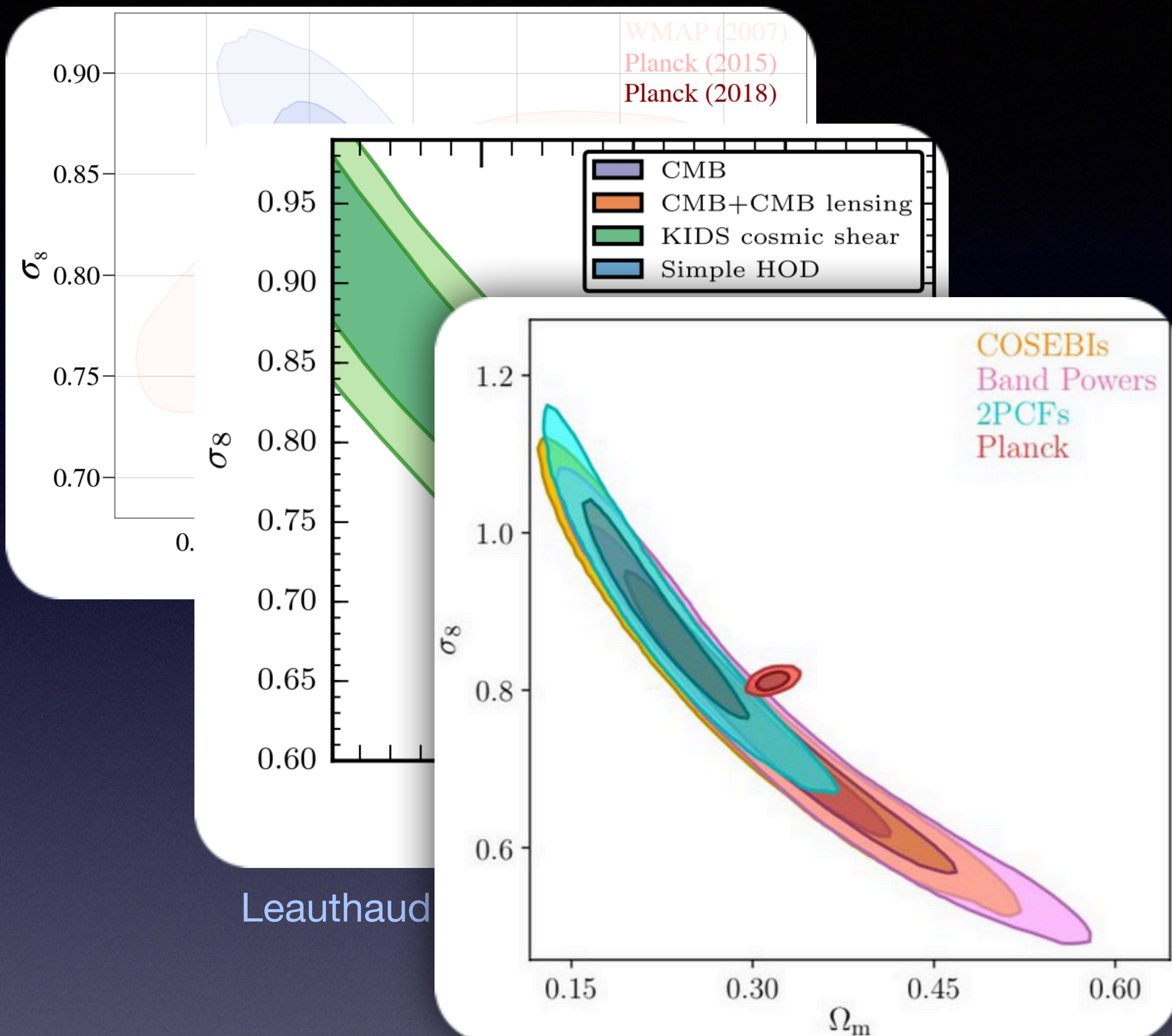


Leauthaud et al. (2017) BOSS-CMASS

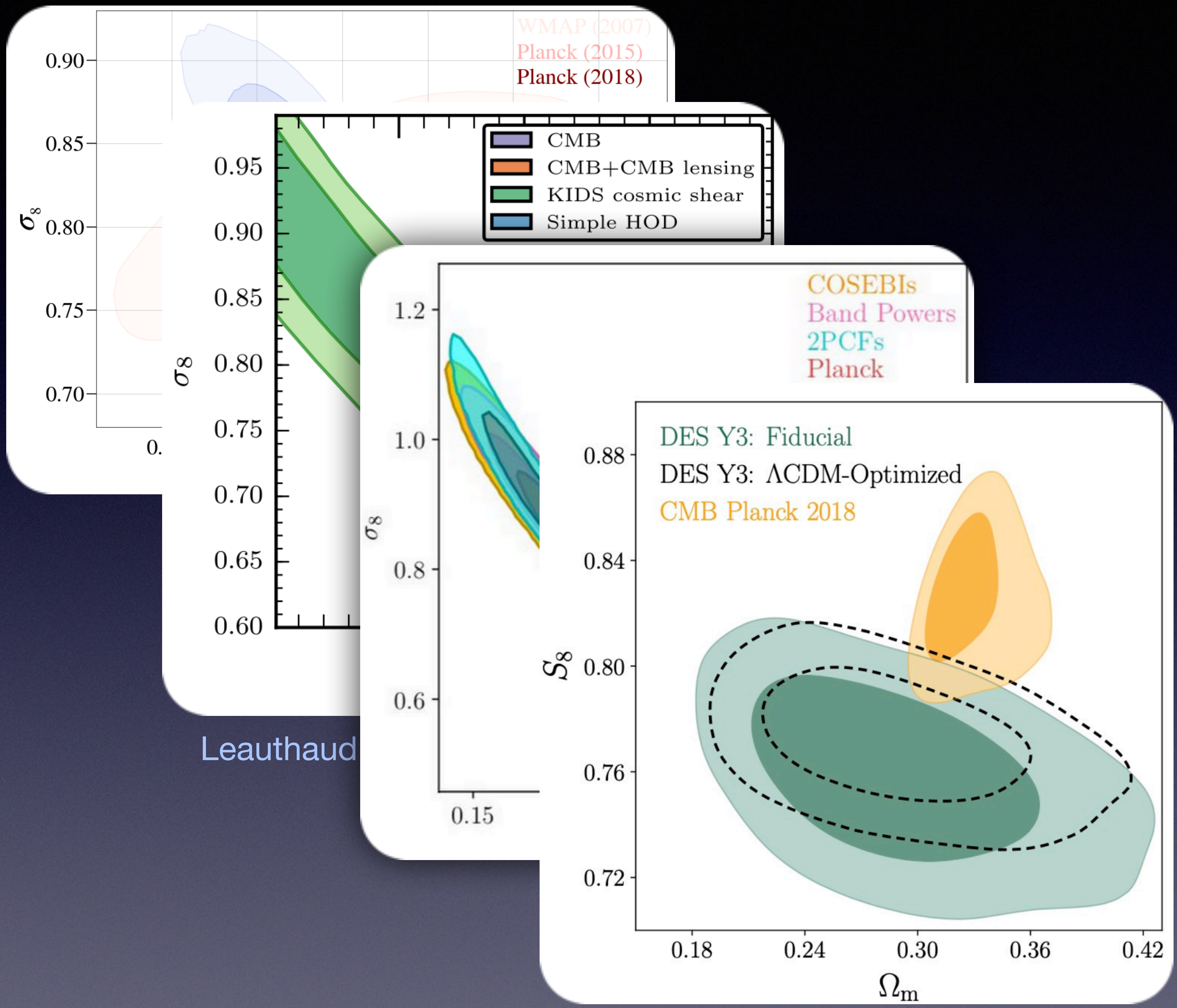
The S8 Tension = “Lensing is Low” problem



Leauthaud

Asgari et al 2020 (KIDS-1000)

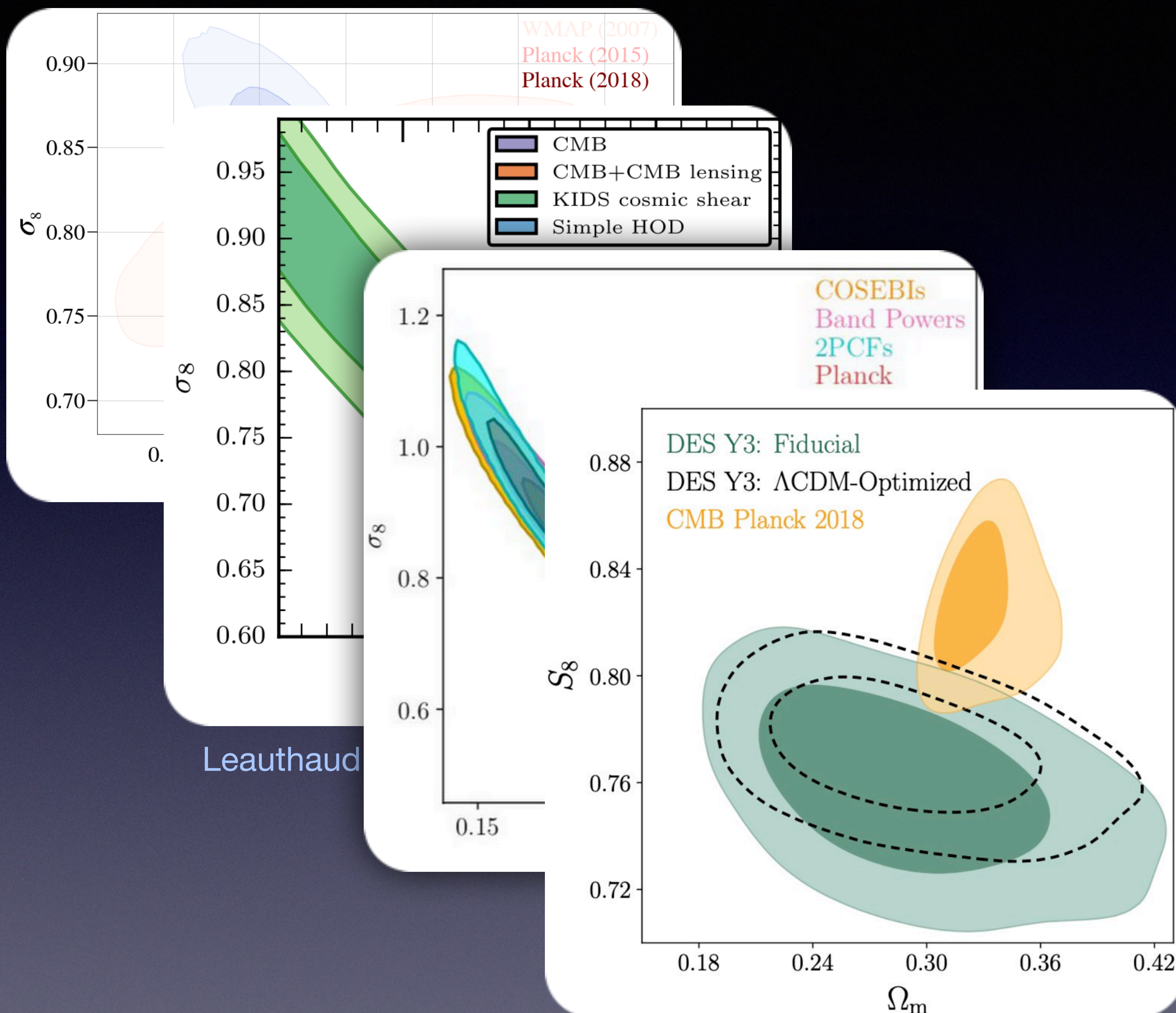
The S_8 Tension = "Lensing is Low" problem



Leauthaud

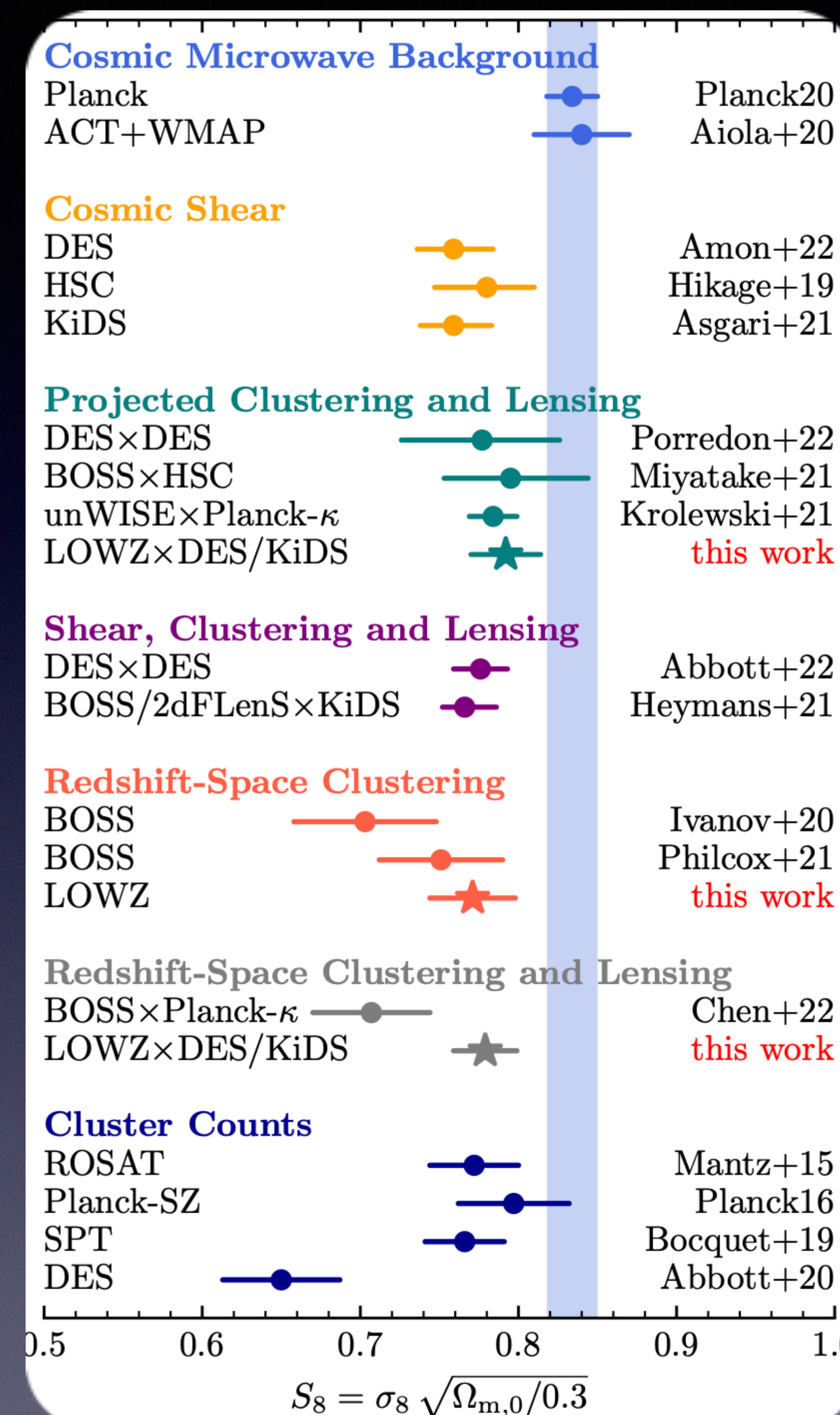
Amon et al. (2022) DES Y3

The S_8 Tension = "Lensing is Low" problem



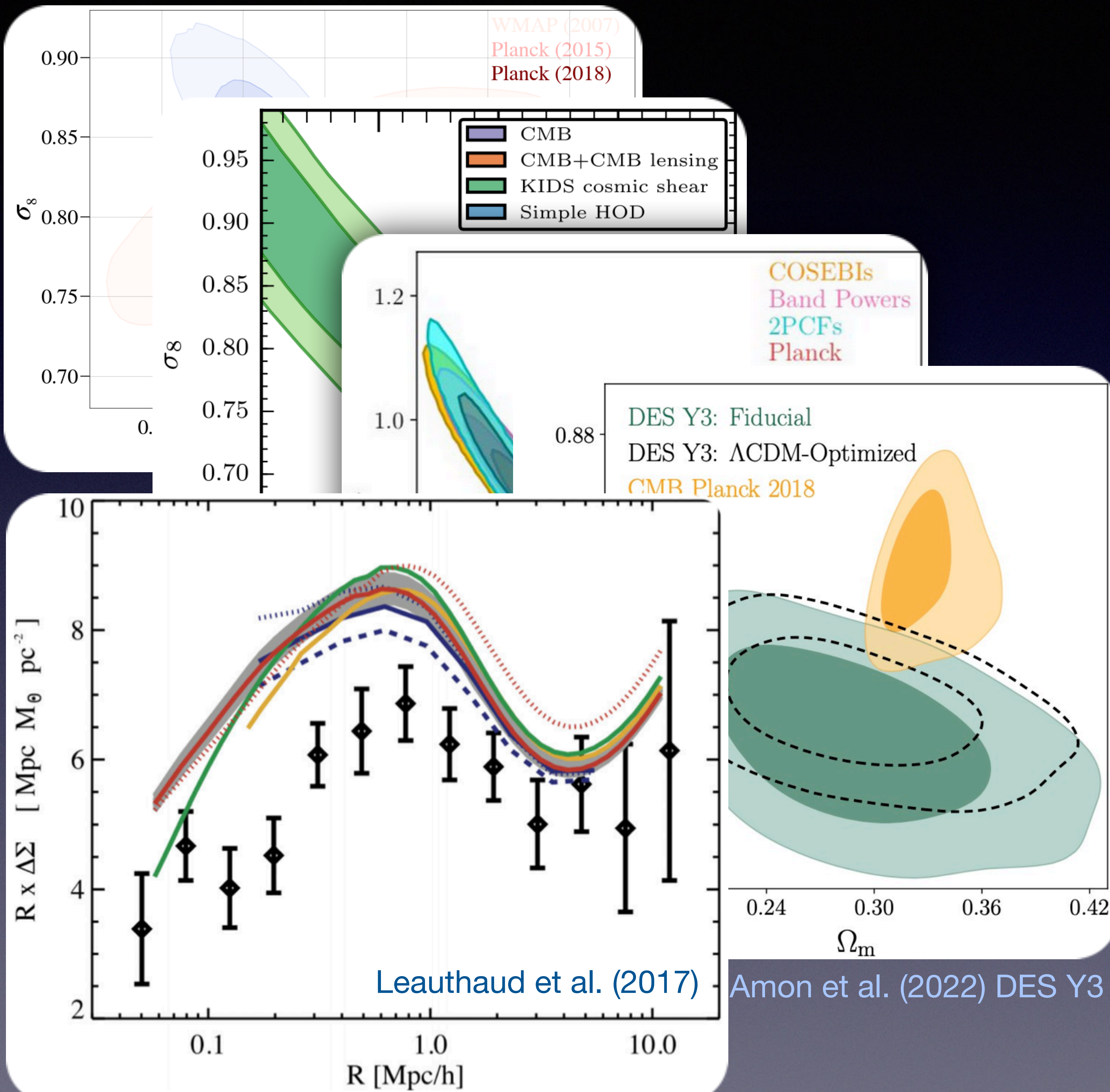
Leauthaud

Amon et al. (2022) DES Y3

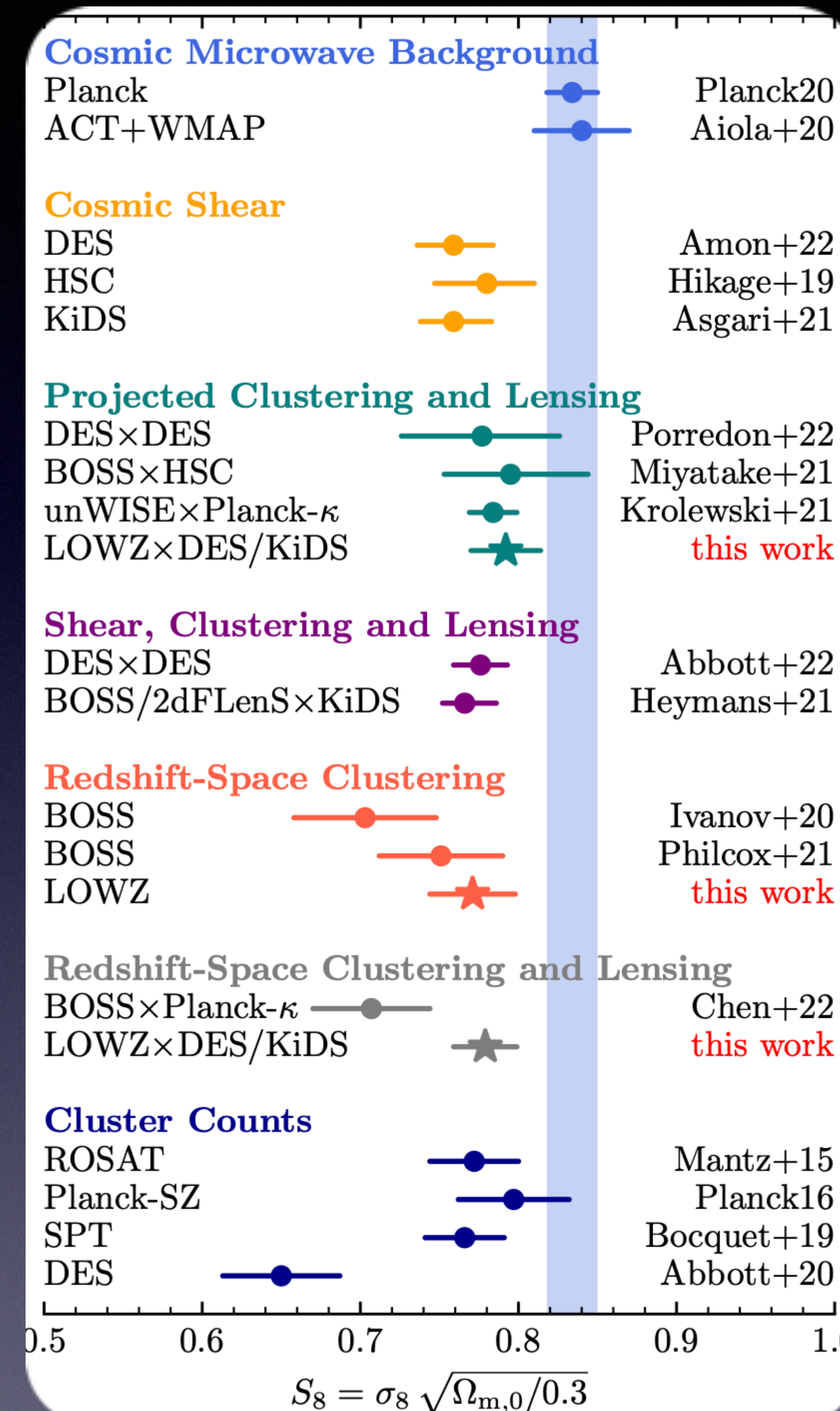


Lange,…,vdB,.. et al. (2023)

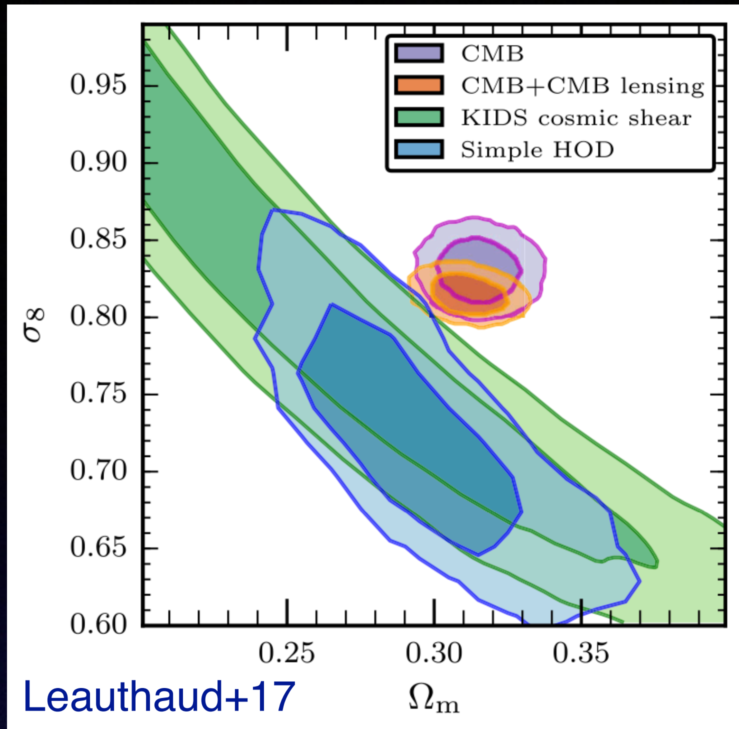
The S_8 Tension = “Lensing is Low” problem

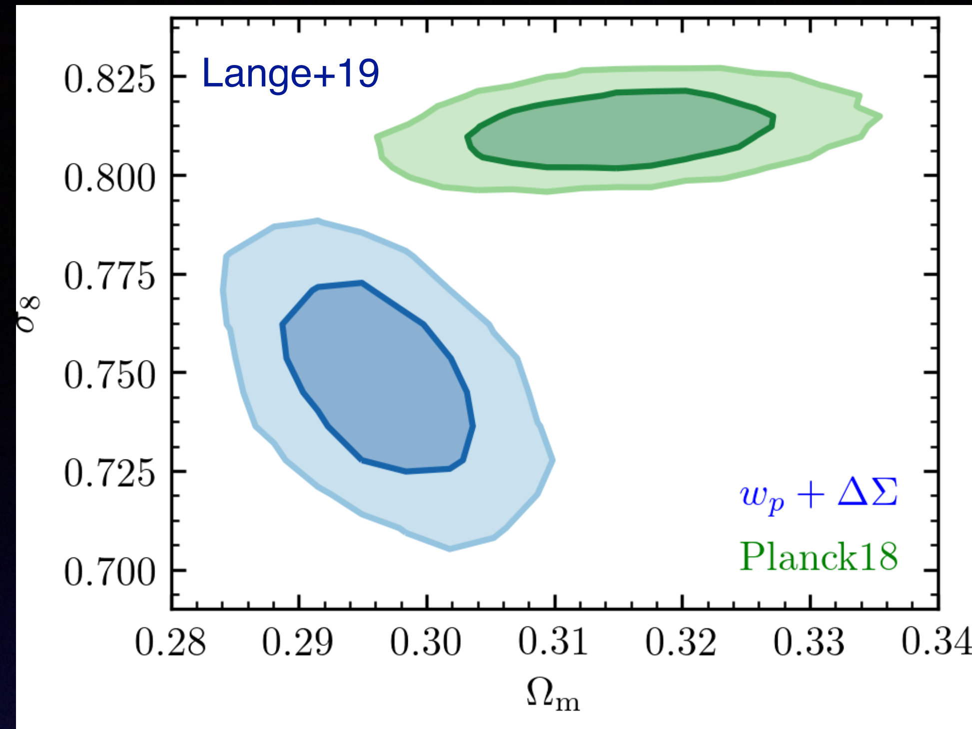


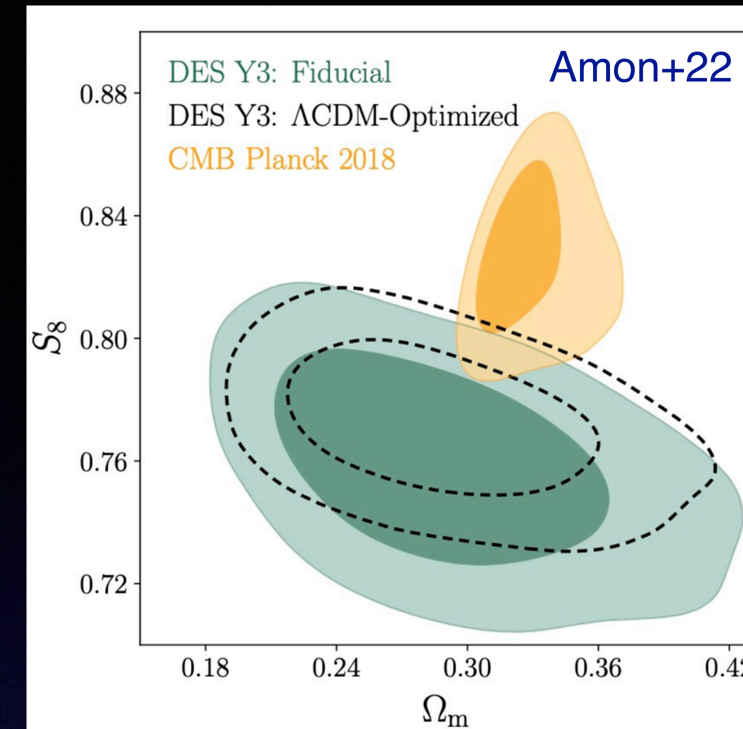
Amon et al. (2022) DES Y3



Lange,…,vdB,.. et al. (2023)







There is a persistent tension between observations of the low-z Universe and Planck CMB results.

- Systematic error in Planck analysis?

  there is also tension with respect to Hubble parameter…

- New physics beyond the 6-parameter "vanilla" LCDM model?

  neutrino mass, dark matter is warm/fuzzy/self-interacting,…

- Systematic errors in lensing shear measurements?

- Systematic errors in modeling of clustering and/or lensing?

  assembly bias, impact of baryons,…

The Dark Side of Halo Occupation Modelling


WARNING: things are about to get ugly and depressing
stop listening if you suffer from anxiety or heart conditions

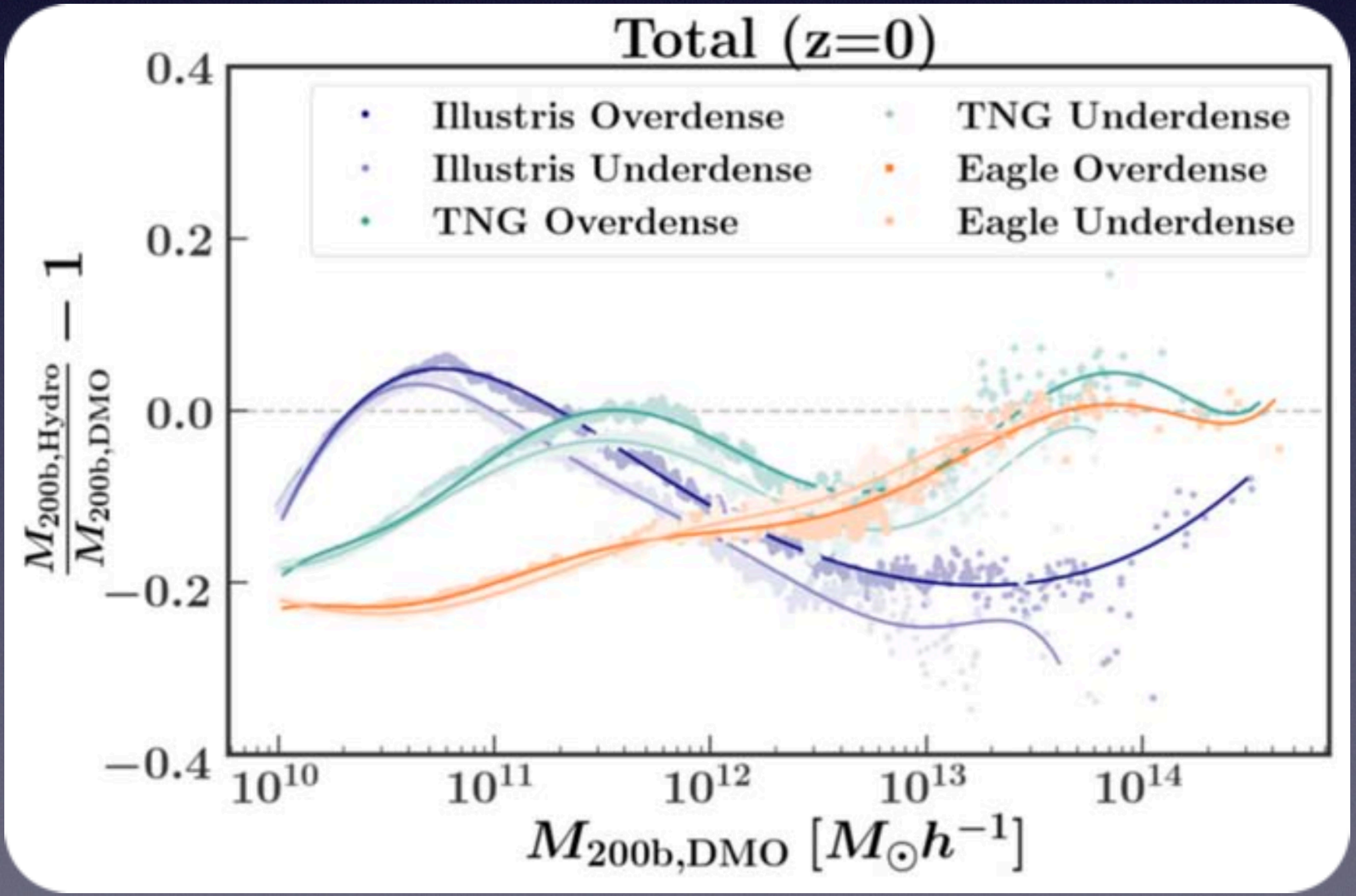
Baryonic Effects

Throughout, it is assumed that dark matter halos follow a NFW profile.

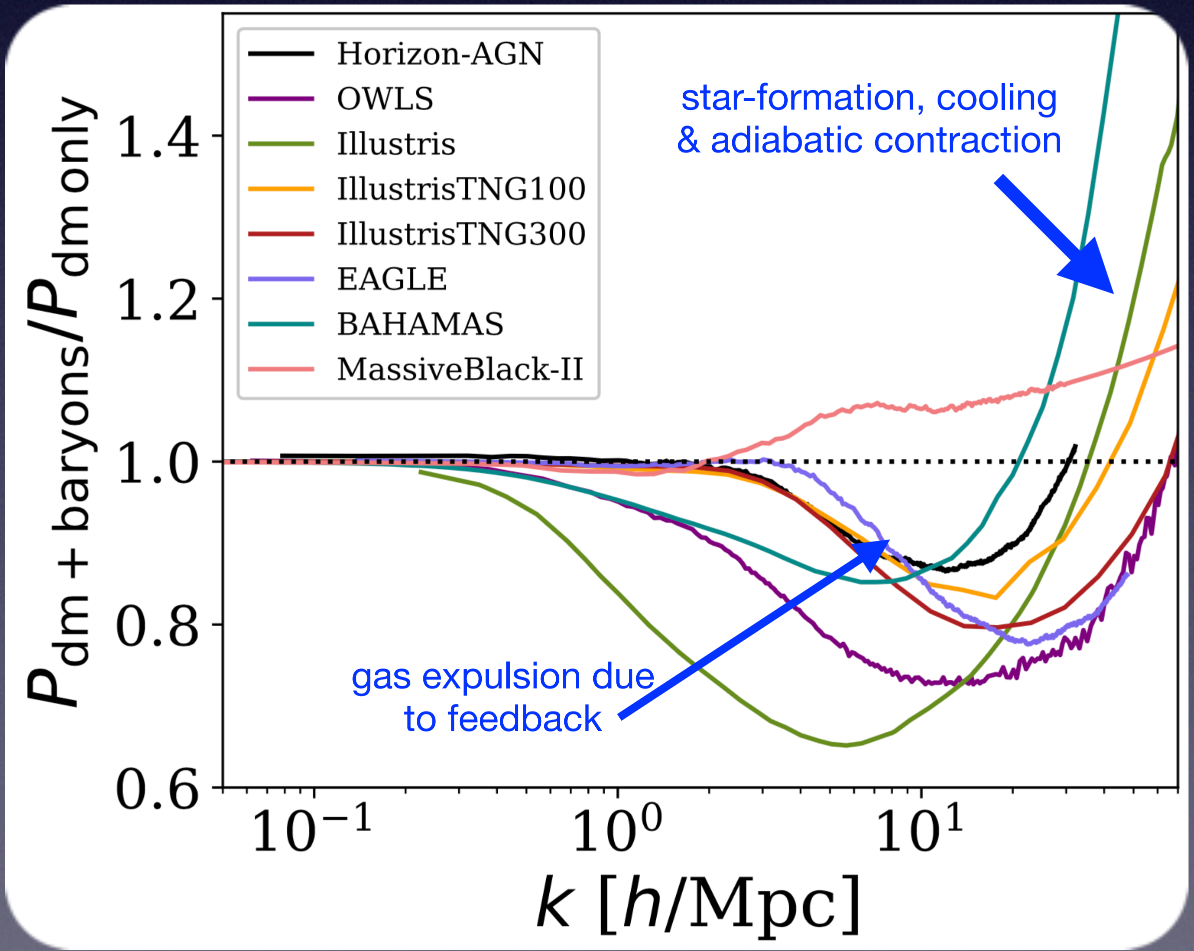
This is motivated by results from N-body, dark-matter-only (DMO) simulations.

However, hydro-dynamical simulations show that galaxy formation physics impacts both the masses and density profiles of dark matter halos…

Zentner et al. 2008; van Daalen et al. 2011, Sawala et al. 2013, Martizzi et al. 2016
Springel et al. 2017, Schneider et al. 2019, Chisari et al. 2019, Beltz-Mohrmann & Berlind 2021



source: Beltz-Mohrmann & Berlind (2021)



source: Chisari et al. (2019)

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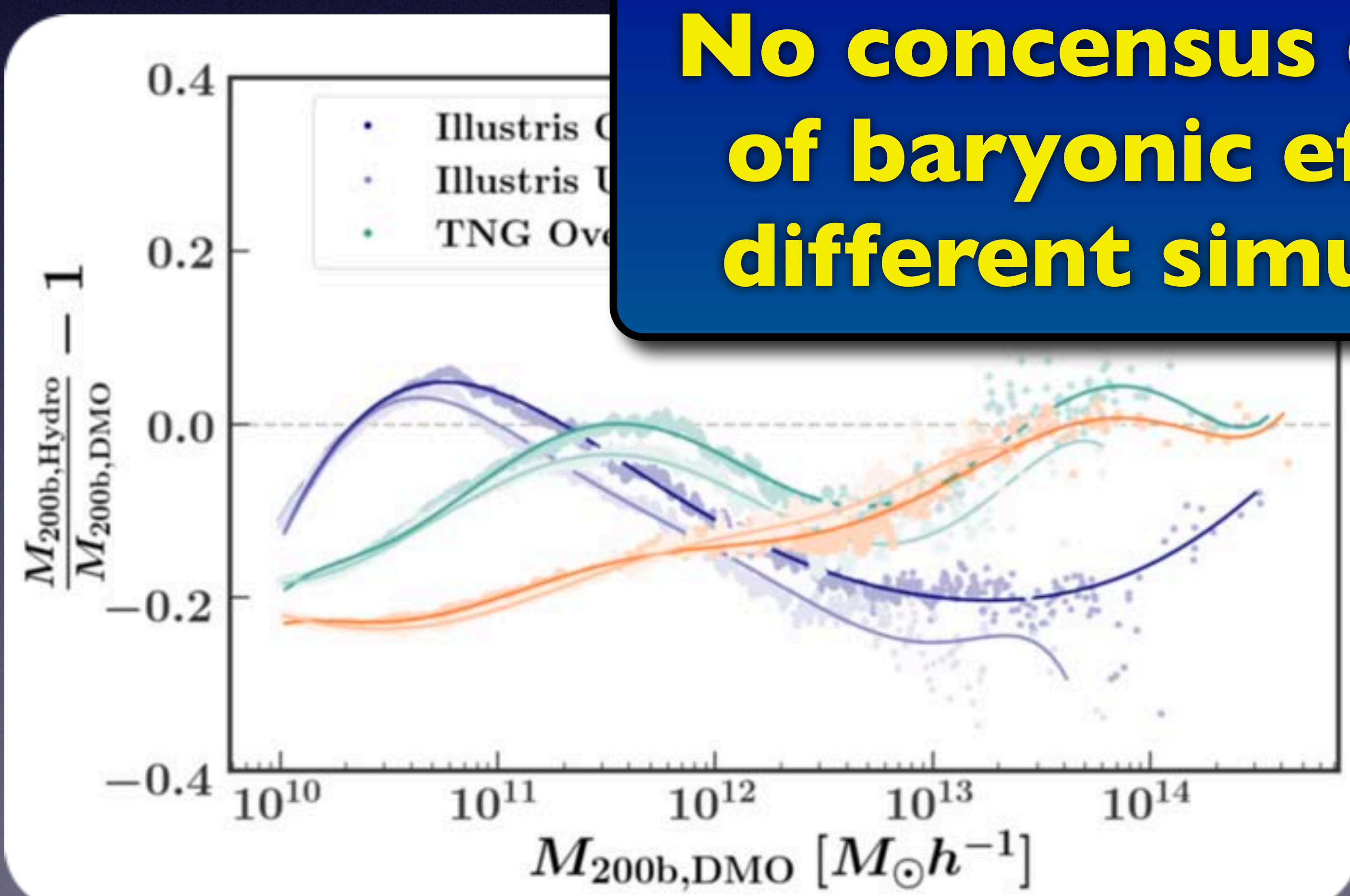
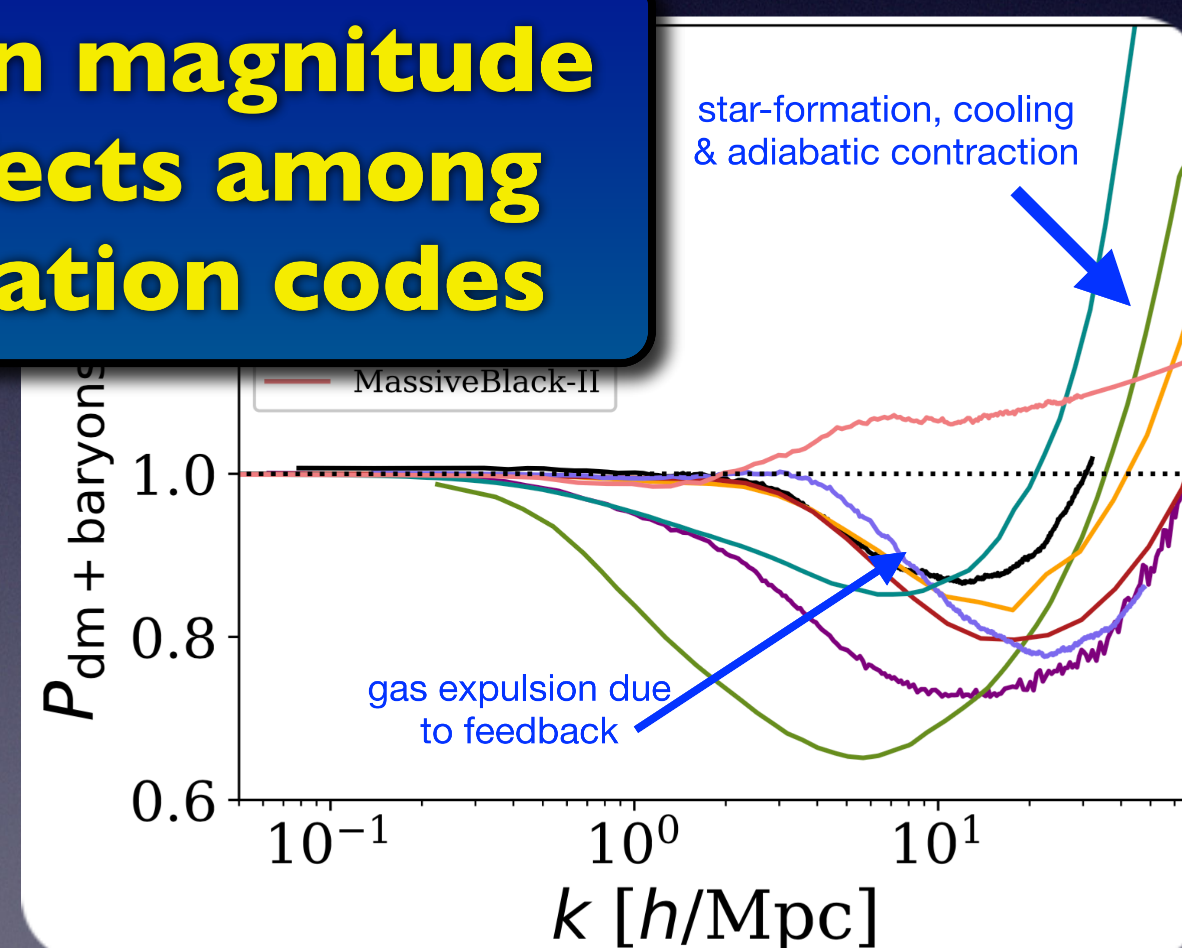


source: Beltz-Mohrmann & Berlind (2021)

No concensus on magnitude of baryonic effects among different simulation codes



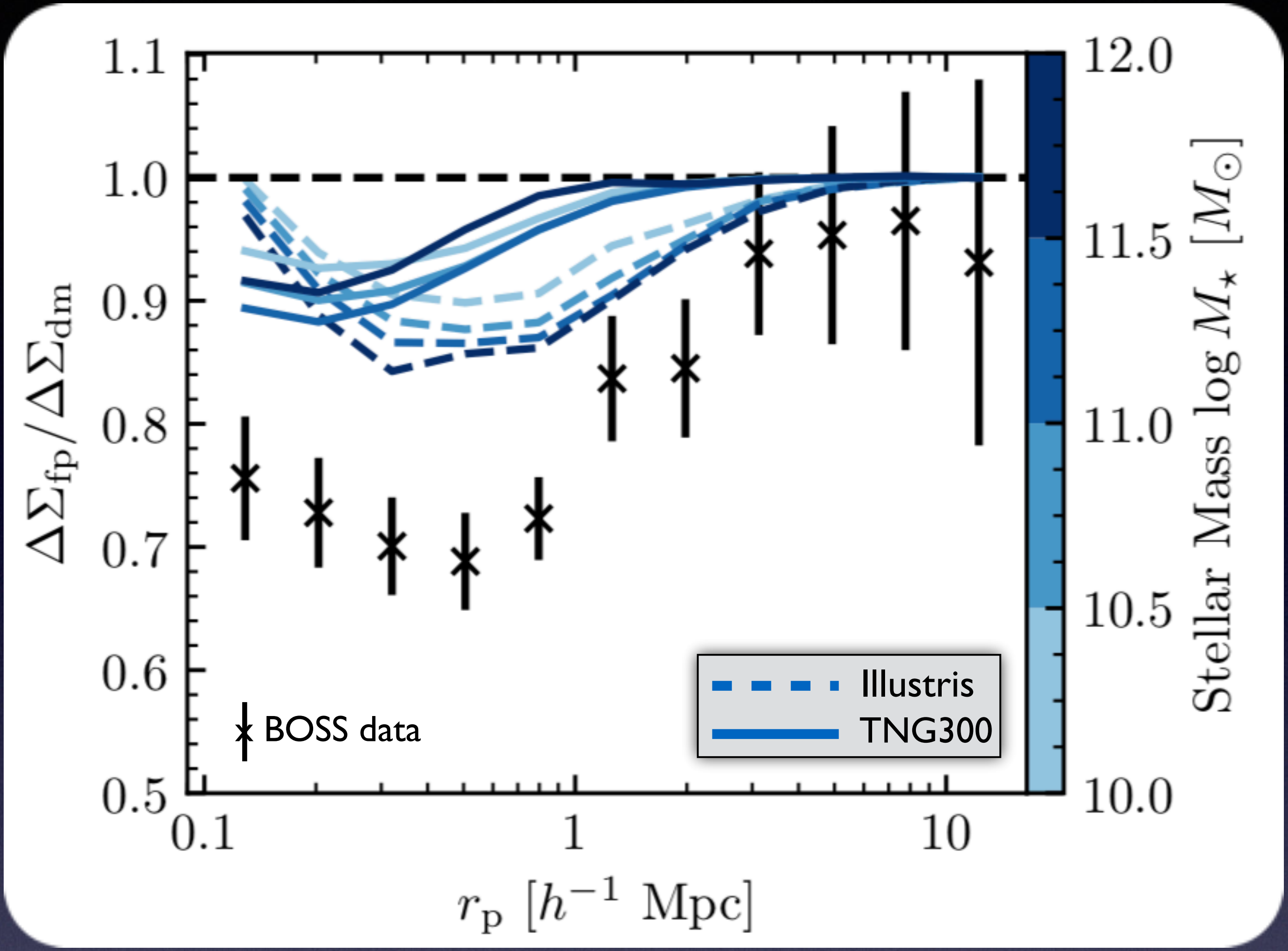
source: Chisari et al. (2019)

Baryonic Effects vs S_8 Tension

'Feedback' reduces ESD on small scales ($\lesssim$ 1 Mpc).

Not accounted for in most clustering/lensing analyses

Effect diminishes, but seems unable to fully solve "lensing is low"

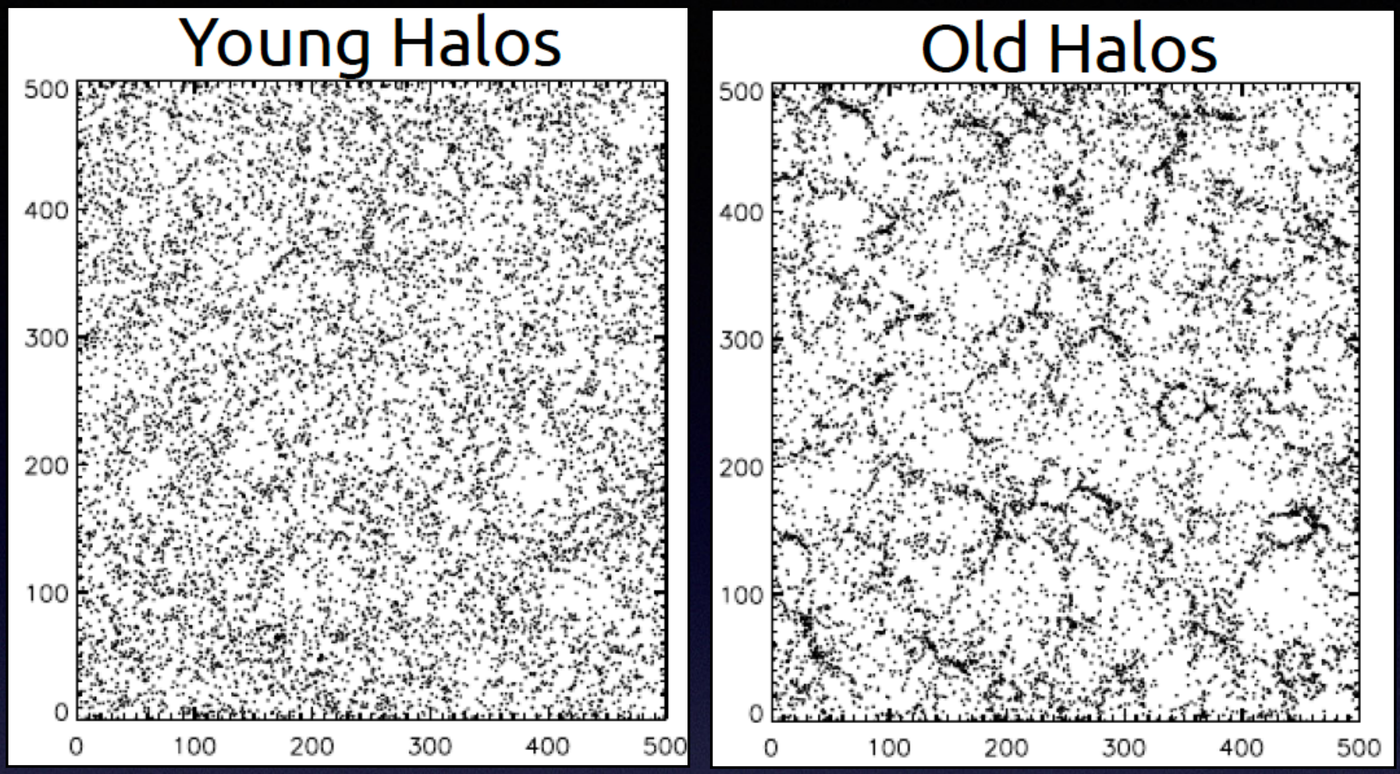


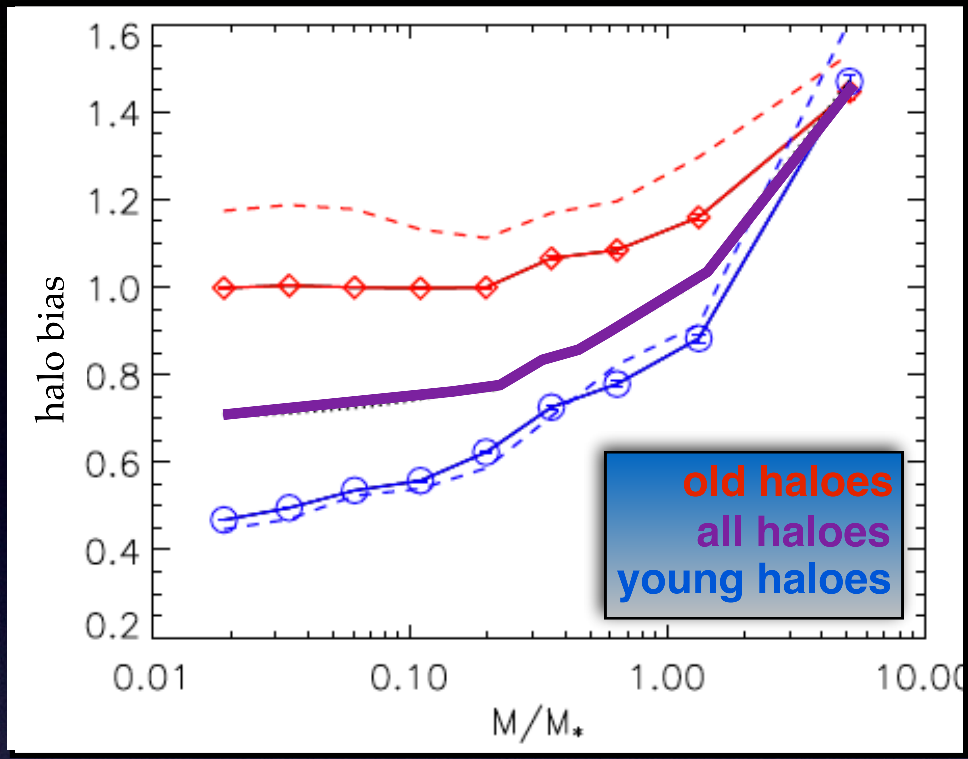
source: Lange et al. (2019)

Main Challenge:

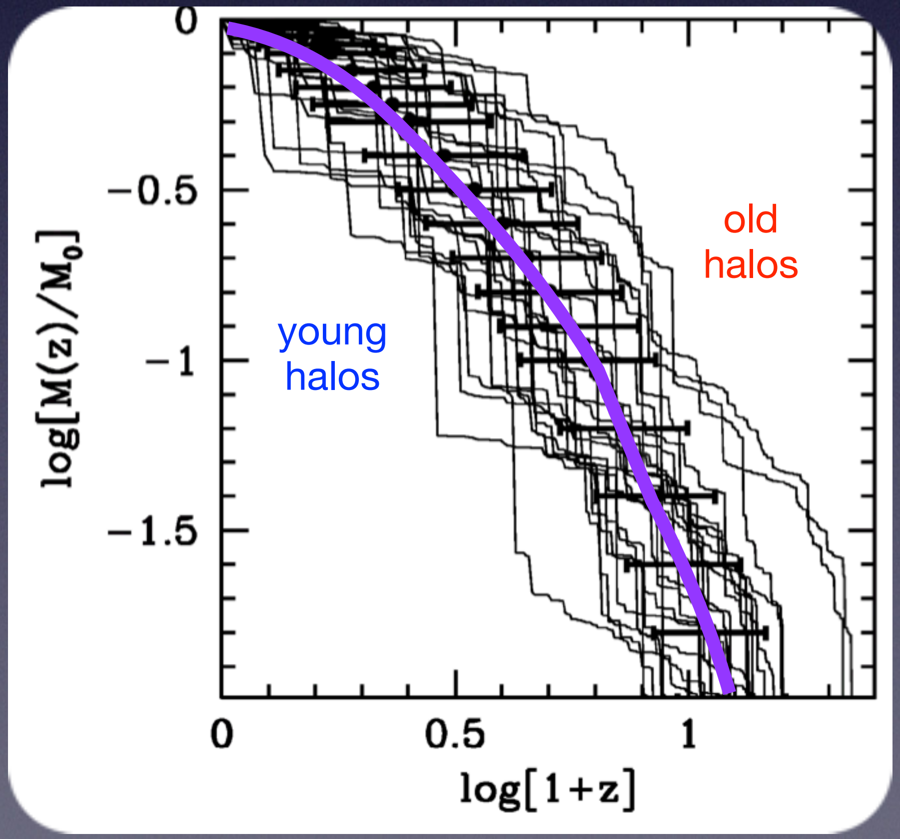
- There is (and likely never will be) concensus among simulations as to the magnitude of the effect.
- Assume simulations bracket truth and marginalize over uncertainties
- Simultaneously model & observe stars (galaxies) and gas (CGM).

Halo Assembly Bias





source: Gao et al. 2005



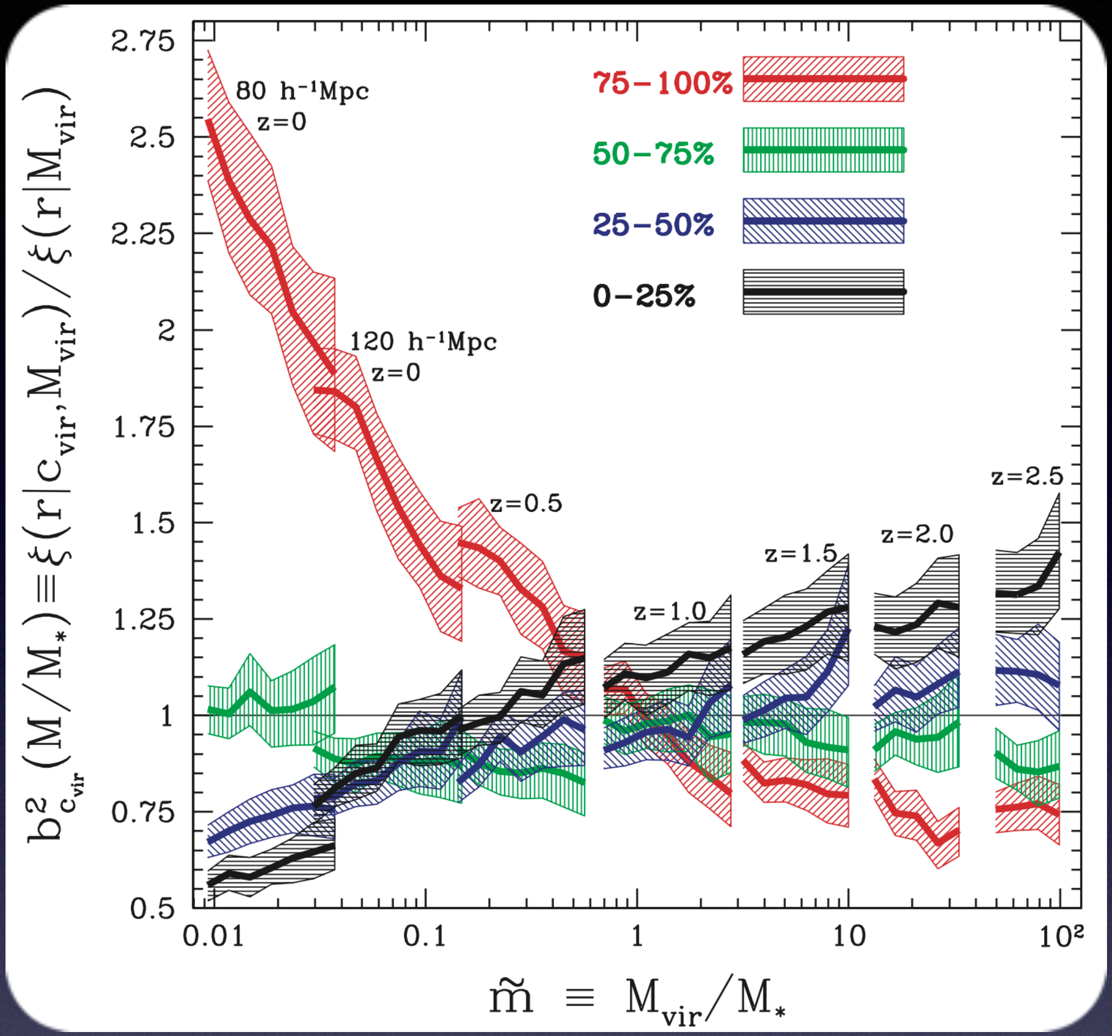
source: van den Bosch (2002)

Halo bias, at fixed mass, depends on halo age

At low masses: halos that assemble earlier are more strongly clustered

Gao et al. 2005

Halo Assembly Bias



Source: Wechsler et al. 2006

Halo bias also depends on halo concentration…

Wechsler et al. 2006

In fact, N-body simulations have shown that halo bias depends on virtually <u>every</u> halo property…

- spin parameter (angular momentum)
- environment
- halo shape

Gao & White 2007, Lacerna & Padilla 2012
Villareal et al. 2017, Mao et al. 2018, Salcedo et al 2018

Clustering strength is not a clean indicator of halo mass

The Origin of Halo Assembly Bias

What is the origin of Halo Assembly Bias?

Correlations between halo properties.

Halos of a given mass that assemble earlier

- are more centrally concentrated
- have smaller spin parameter
- have less (surviving) substructure
- are more spherical

Wechsler et al. 2002; Vitvitska et al. 2002
Gao et al. 2004, vdBosch 2005
Allgood et al. 2006; Jiang & vdBosch 2017

Tides from nearby halos or large-scale structure [arrested development]

Desjacques 2008; Dalal et al. 2008; Hahn et al. 2009; Wang et al. 2011
Hearin et al. 2016; Paranjape et al. 2018; Mansfield & Kravtsov 2019

Contamination with Splashback halos [environmental stripping]

Wang et al. 2009; Li et al. 2013; Wetzel et al. 2015; Hearin et al. 2015
Sunayama et al. 2016; Tucci et al 2020; Mansfield & Kravtsov 2020

Galaxy Assembly Bias

Halo Assembly Bias: the effect that the clustering of halos at fixed mass depends on secondary halo properties

aka secondary halo bias

Mass-Only Ansatz: the assumption, made up to now, that halo occupation statistics depend only on halo mass

Galaxy Assembly Bias: at fixed halo mass, the occupation statistics depend on secondary halo properties that show halo assembly bias

i.e. $P(L|M,x) \neq P(L|M)$ or $\langle N|M,x\rangle \neq \langle N|M\rangle$ when $b(M,x) \neq b(M)$

GAB GAB HAB

Galaxy Assembly Bias is a violation of the Mass-Only ansatz

Galaxy Assembly Bias

Why do we care about galaxy assembly bias?

- provides important insight into galaxy formation

- ignoring GAB can bias the inferred galaxy-halo connection

Empirical Fact:
red galaxies are more strongly clustered than blue galaxies of same stellar mass.

without GAB:
red galaxies reside in <u>more massive</u> halos than their blue couterparts

with GAB:
red galaxies reside in <u>older halos</u> than their blue counterparts, but of <u>same mass</u>

See Zentner, Hearin & vdB (2014) for an explicit example

- ignoring GAB can bias cosmological inference

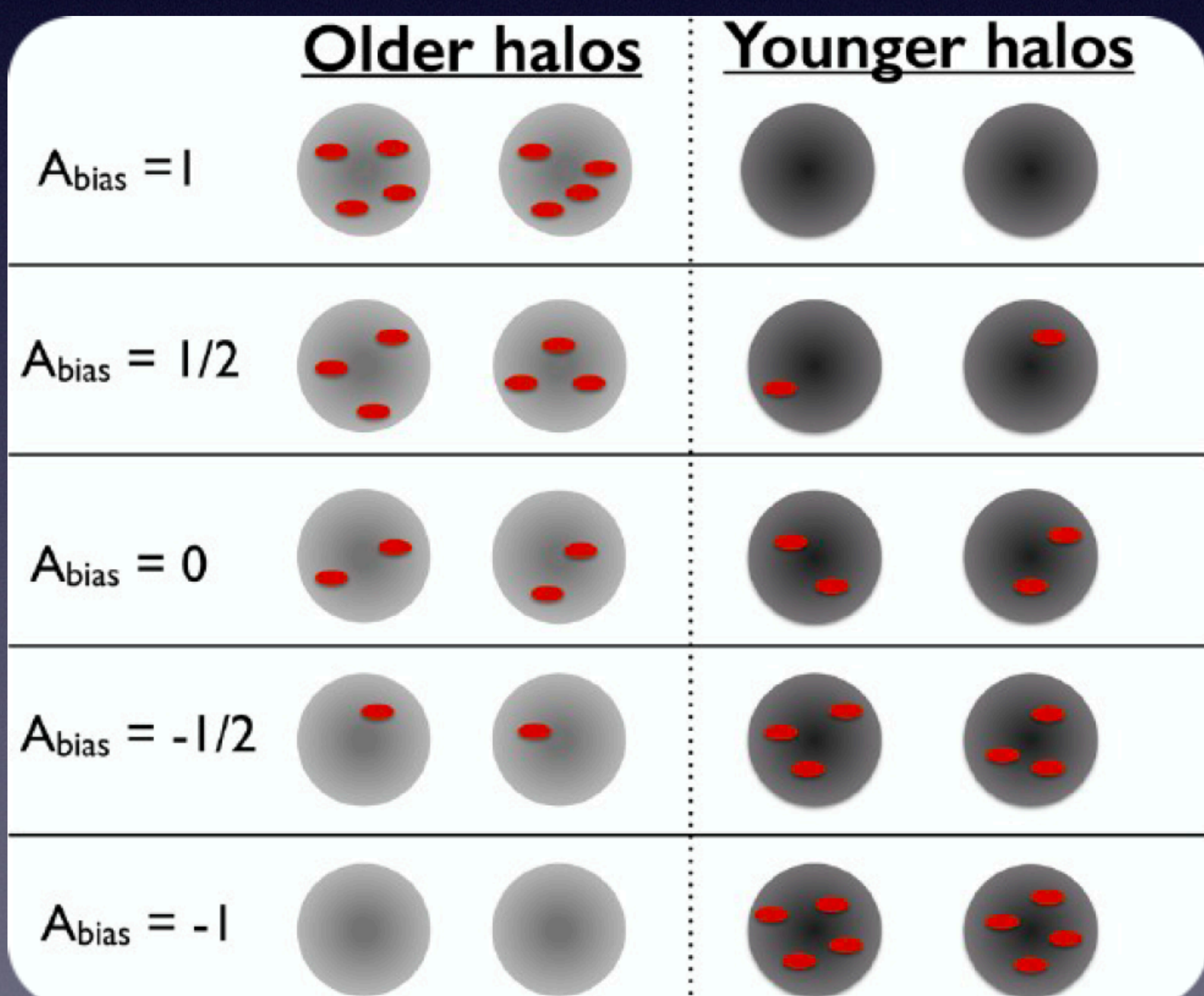
might the S_8 tension be a manifestation of galaxy assembly bias

Modeling Galaxy Assembly Bias

How can one model galaxy assembly bias?

- generalize halo occupation models: $P(L\,|\,M) \rightarrow P(L\,|\,M,x)$
  $\langle N\,|\,M\rangle \rightarrow \langle N\,|\,M,x\rangle$
- quantify relevant halo bias $b(M) \rightarrow b(M,x)$

Bottleneck: we (currently) lack an analytical/theoretical model for $b(M,x)$



source: Hearin et al. 2016

Virtually all models that include assembly bias are simulation-based

decorated-HOD (dHOD) Hearin, Zentner, vdB et al. 2016

$$\langle N\,|\,M,x_{\rm high}\rangle = \langle N\,|\,M\rangle + \delta N$$
$$\langle N\,|\,M,x_{\rm low}\rangle = \langle N\,|\,M\rangle - \delta N$$

GRAND-HOD Yuan et al. 2018

inject x-dependence into HOD parameters
Walsh & Tinker 2019; Xu et al. 2020

flexible Abundance Matching
Lehmann et al. 2017; Contreras et al. 2021, 2023

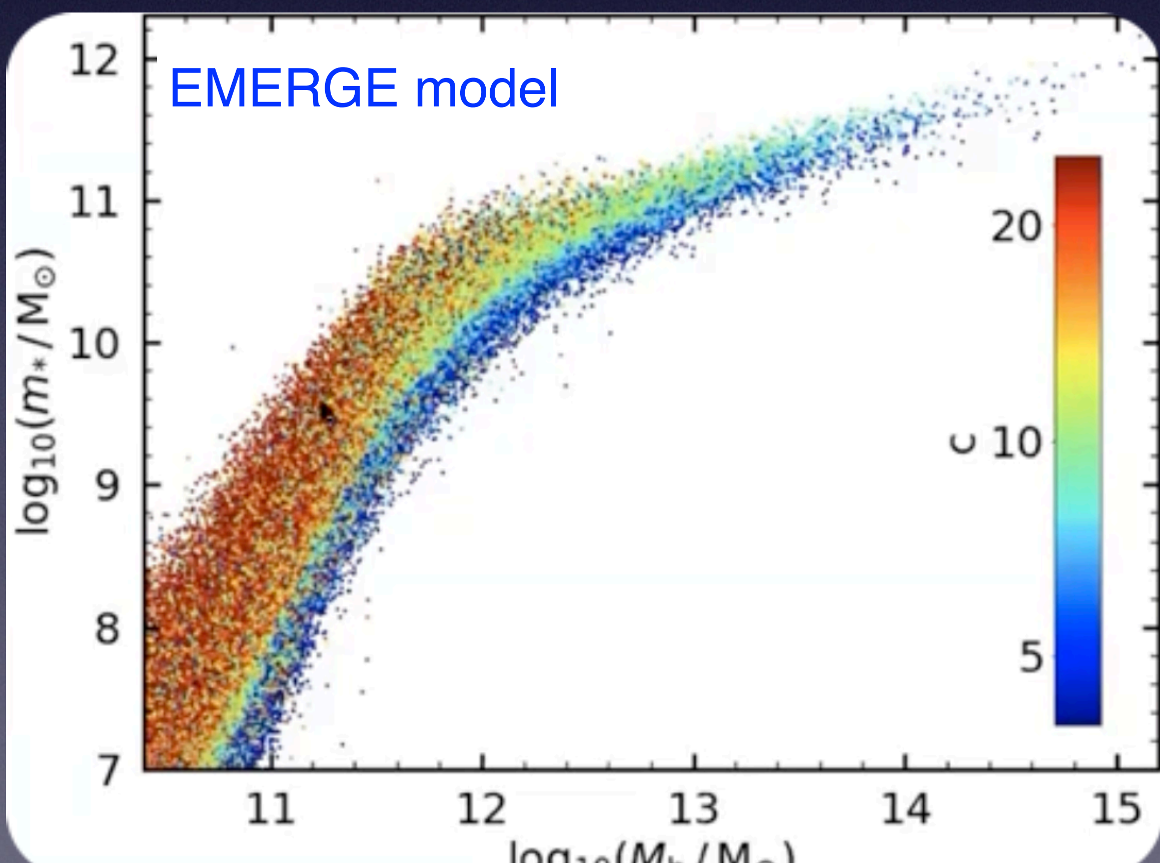
Conditional Abundance Matching (CAM)
Hearin & Watson 2013

Galaxy Assembly Bias

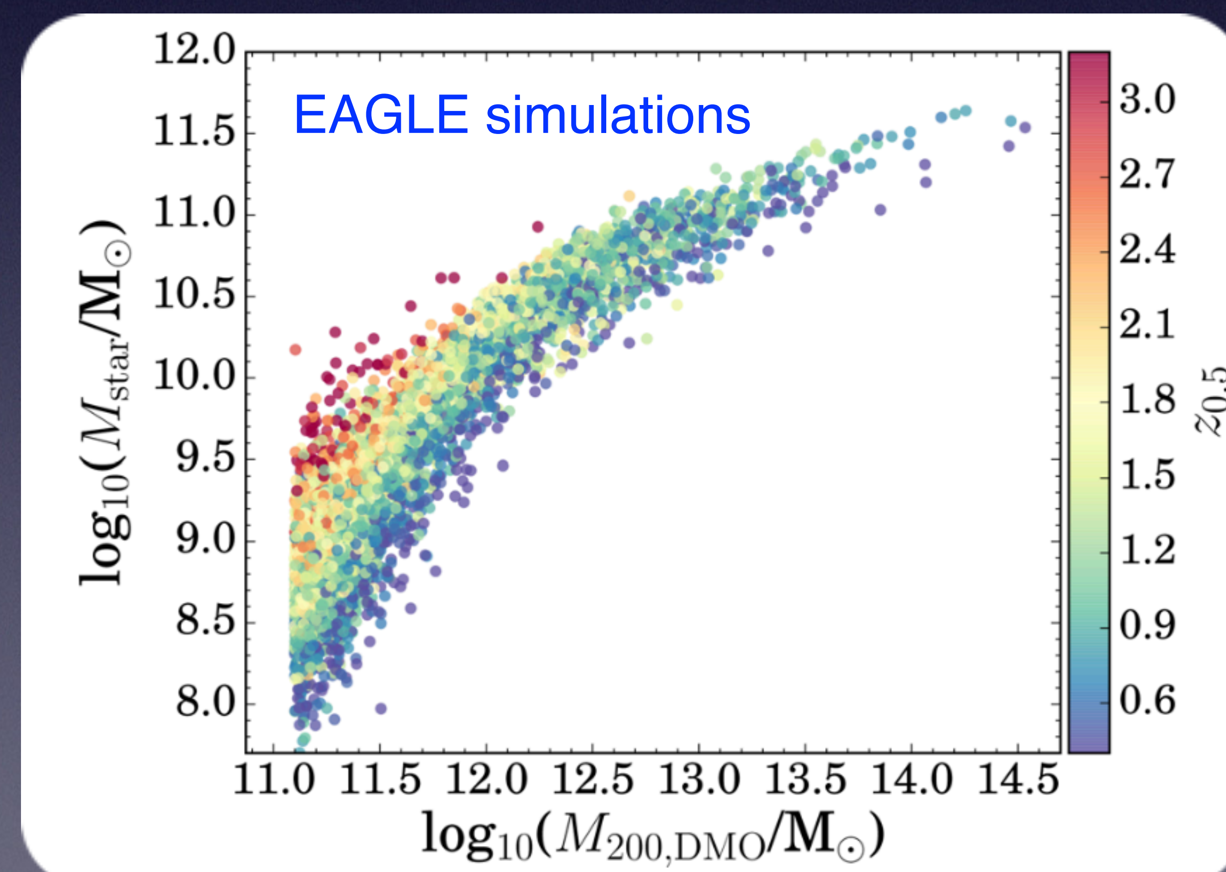
Do we expect galaxy assembly bias?

- there is NO reason to assume that there is NO galaxy assembly bias
- it seems only logical that the properties of a galaxy depend on the assembly history, spin, and shape of its dark matter halo
- SAMs, SIMs and empirical models all `predict' different levels of GAB

Artale et al. 2018; Zehavi et al. 2018; Bose et al. 2019; Contreras et al. 2019; Xu & Zheng 2020



source: Moster et al. 2018

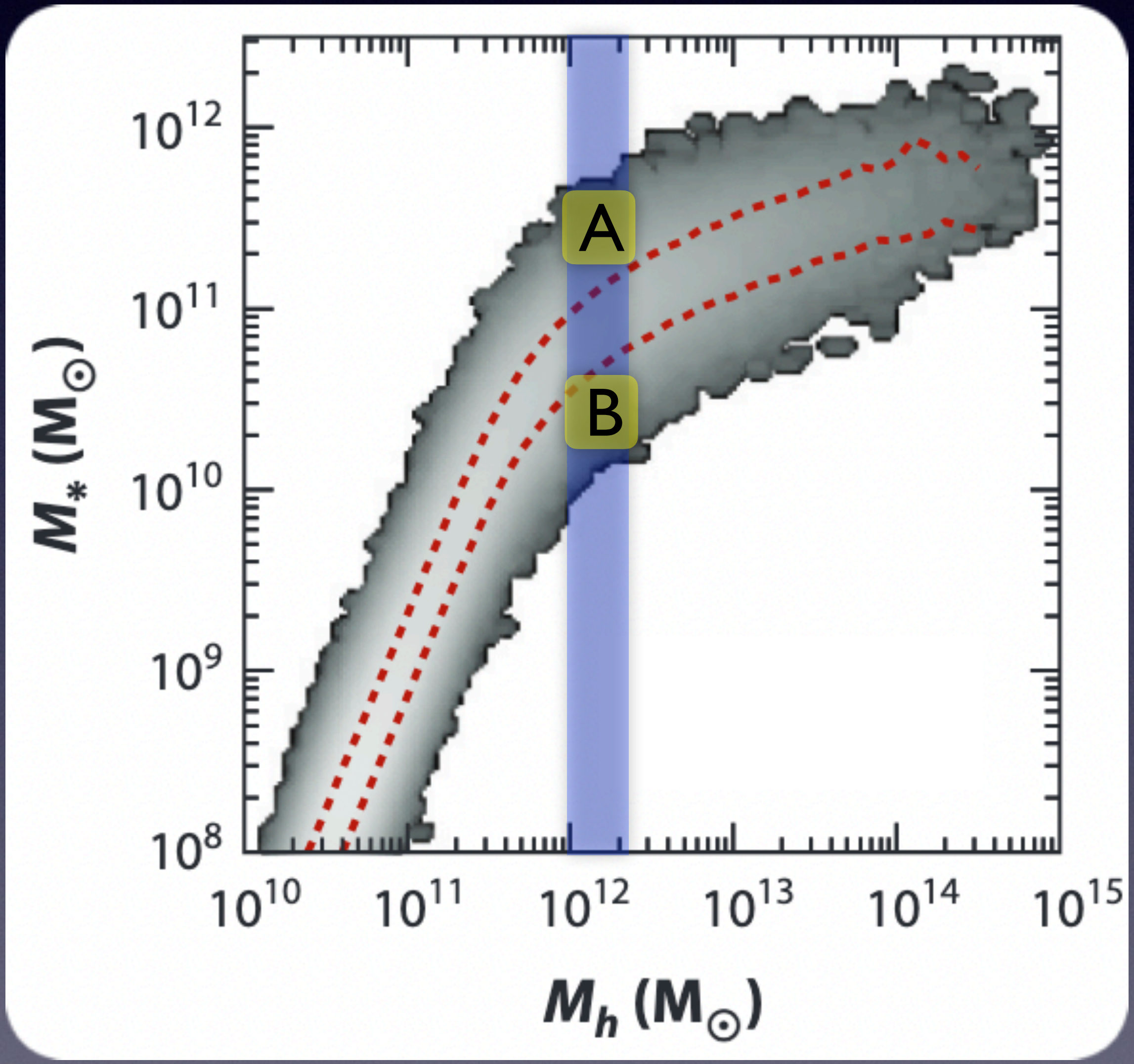


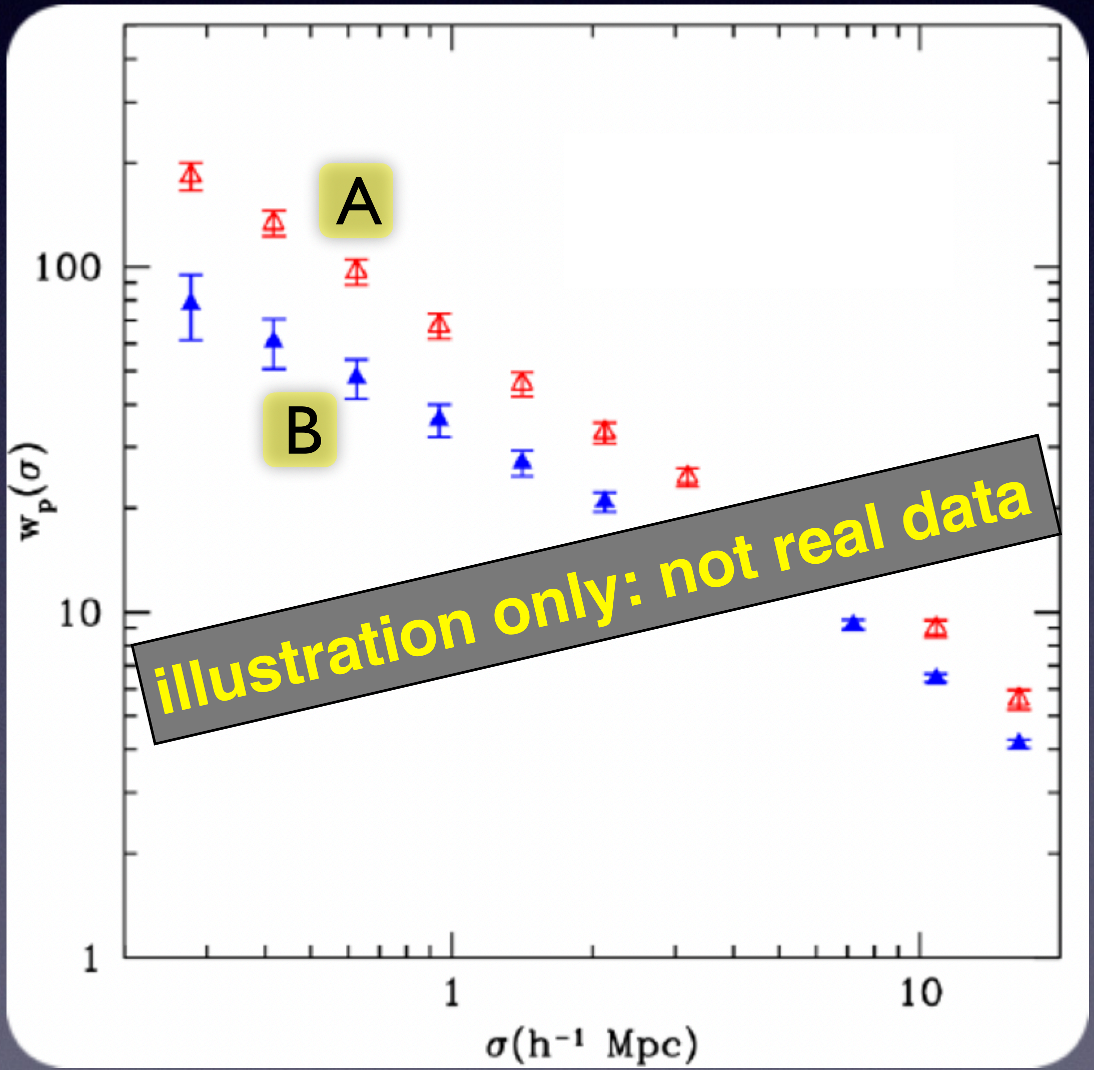
source: Matthee et al. 2017

Galaxy Assembly Bias

Have we observationally detected galaxy assembly bias?

- direct detection: requires demonstration that different subsets of the same halo mass are clustered differently





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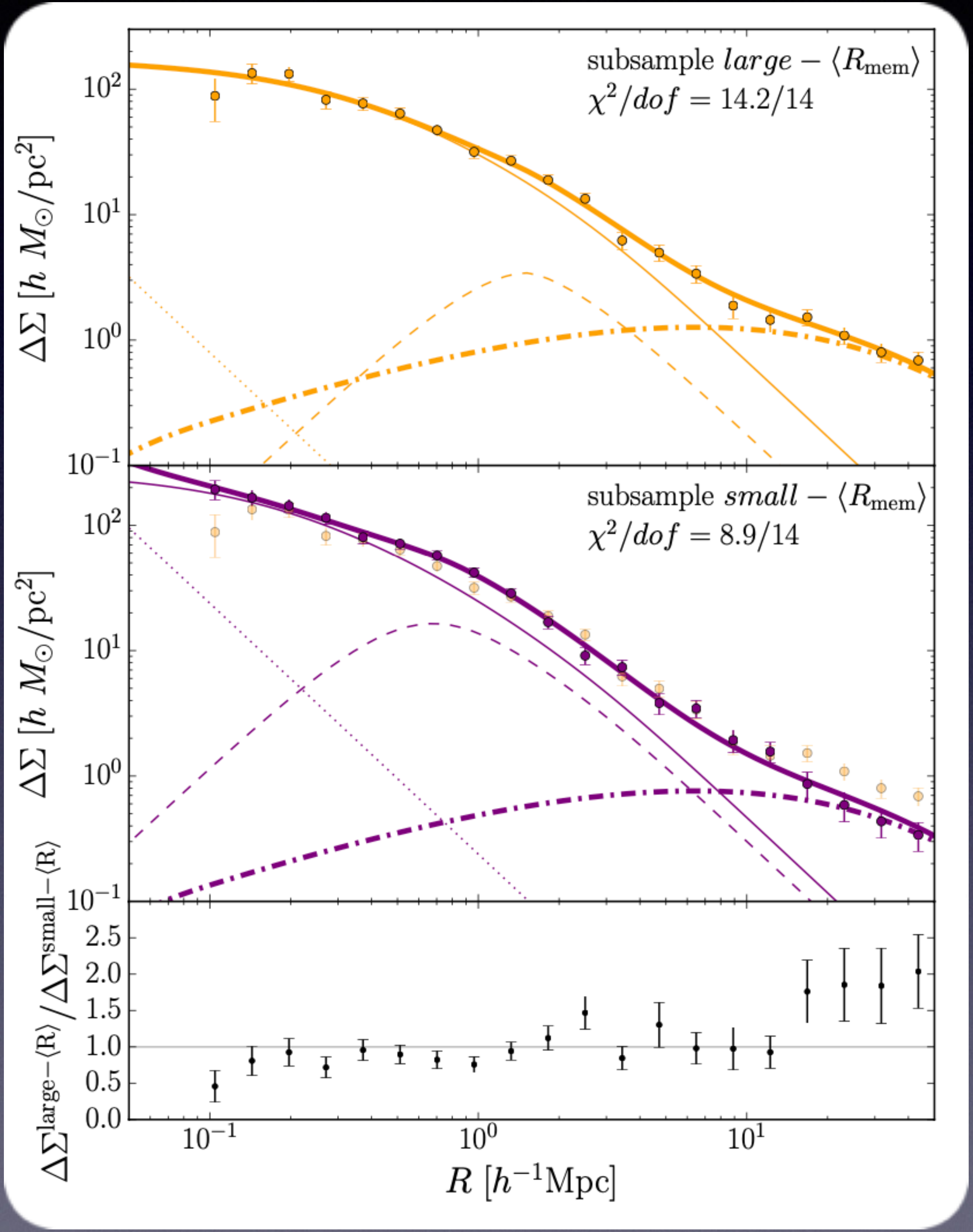
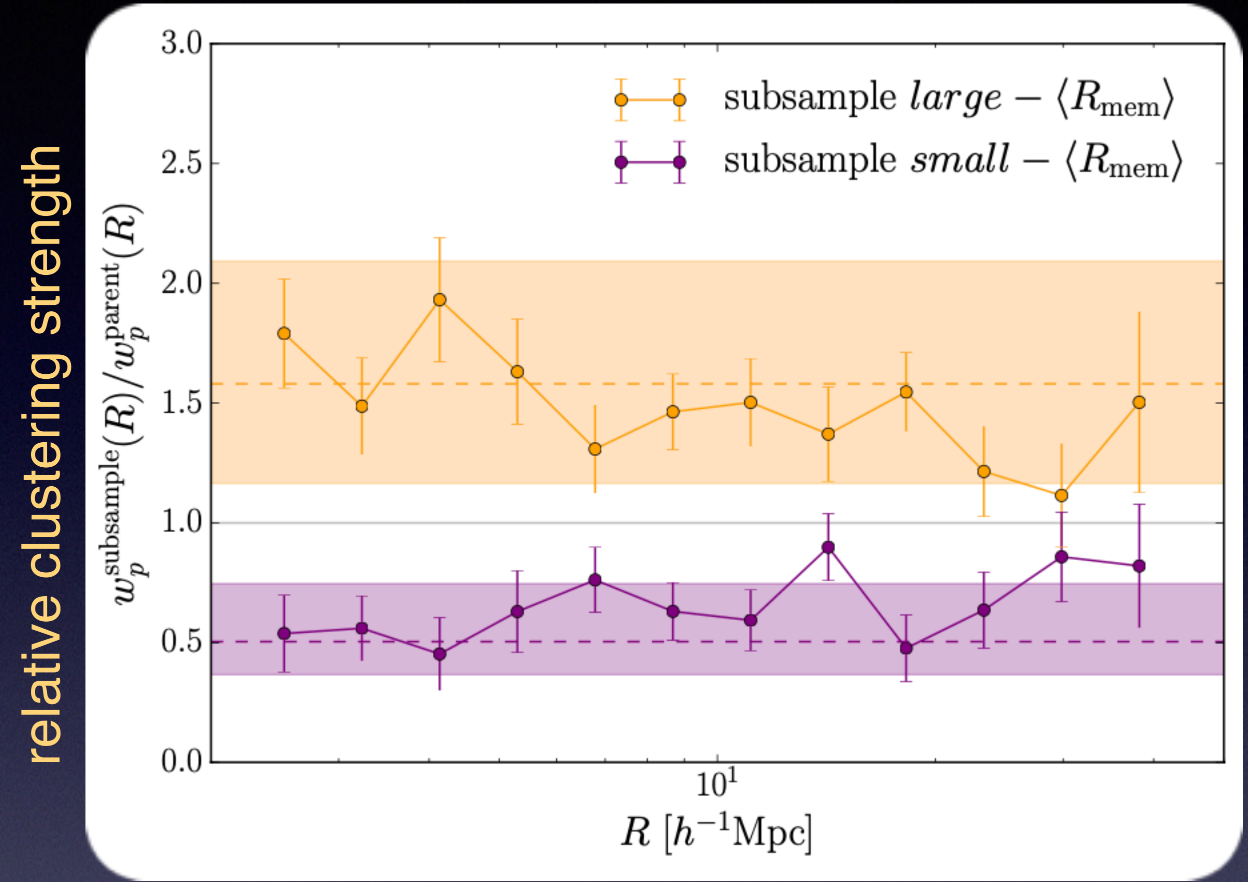


source: Miyatake et al. 2016



Miyatake et al. 2016

two cluster samples with equal g-g lensing (=equal mass) display different clustering.

signal larger than expected

effect can be explained with projection effects

Busch et al. 2017; Zu et al. 2017; Sunayama et al. 2020

Galaxy Assembly Bias

Have we observationally detected galaxy assembly bias?

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MNRAS **452**, 1958–1969 (2015) doi:10.1093/mnras/stv1358

Beyond halo mass: galactic conformity as a smoking gun of central galaxy assembly bias

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[2] *Kavli Institute for Cosmological Physics, 5640 South Ellis Avenue, The University of Chicago, Chicago, IL 60637, USA*
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ABSTRACT

Quenched central galaxies tend to reside in a preferentially quenched large-scale environment, a phenomenon that has been dubbed *galactic conformity*. Remarkably, this tendency persists out to scales far larger than the virial radius of the halo hosting the central. Therefore, conformity manifestly violates the widely adopted assumption that the dark matter halo mass $M_{\rm vir}$ exclusively governs galaxy occupation statistics. This paper is the first in a series studying the implications of the observed conformity signal for the galaxy–dark matter connection. We show that recent measurements of conformity on scales $r \sim 1$–5 Mpc imply that central galaxy quenching statistics cannot be correctly predicted with the knowledge of $M_{\rm vir}$ alone. We also demonstrate that ejected (or 'backsplash') satellites cannot give rise to the signal. We then invoke the age matching model, which is predicated on the co-evolution of galaxies and haloes. We find that this model produces a strong signal, and that central galaxies are solely responsible. We conclude that large-scale 'two-halo' conformity represents a smoking gun of *central galaxy assembly bias*, and indicates that contemporary models of satellite quenching have systematically overestimated the influence of post-infall processes.

Key words: galaxies: evolution – galaxies: haloes – cosmology: theory – dark matter – large-scale structure of Universe.

Galactic Conformity:

red/quenched galaxies are typically surrounded by red/quenched galaxies

Weinmann, vdB et al. 2006; Kauffmann et al 2013
Kawinwanichakij et al. 2016; Berti et al. 2017

on small scales: 1-halo conformity
on large scales: 2-halo conformity

Hearin et al. 2015

Group finder errors and projection effects can masquerade as conformity

Campbell, vdB et al. 2015; Paranjape et al. 2015
Calderon et al. 2018; Zu & Mandelbaum 2017

Ongoing debate.....
Challenge is to control for halo mass.

Galaxy Assembly Bias

Have we observationally detected galaxy assembly bias?

- direct detection: requires demonstration that different subsets of the same halo mass are clustered differently

- indirect detection: include GAB in occupation models and see if it improves fits to data. This typically requires multiple types of data (i.e., clustering + lensing) to break degeneracies.

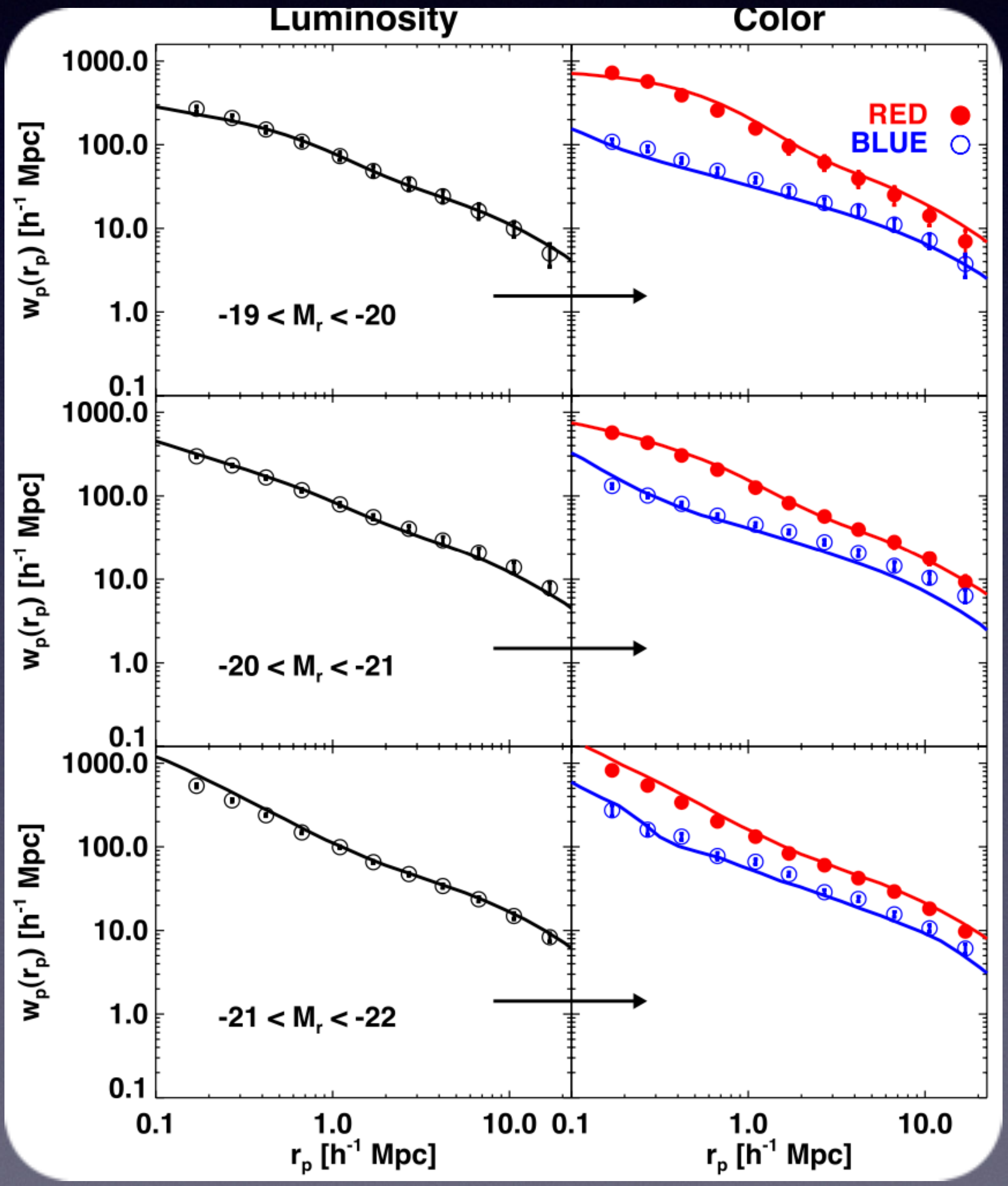
Hearin & Watson 2013; Hearin+14; Lehmann+17; Zentner+19; Lange +19
Vakili & Hahn 2019; Salcedo+19; Yuan+21; Wang+22; Beltz-Mohrmann+23

Galaxy Assembly Bias

Age Matching‡

Step 1: using an N-body simulations, abundance match L to V_{max}.
Step 2: in bins of L, abundance match color to halo assembly time; reddest to oldest
Step 3: compute clustering as function of L and color and compare to data

Hearin & Watson 2013; Hearin et al. 2014



source: Hearin & Watson 2013

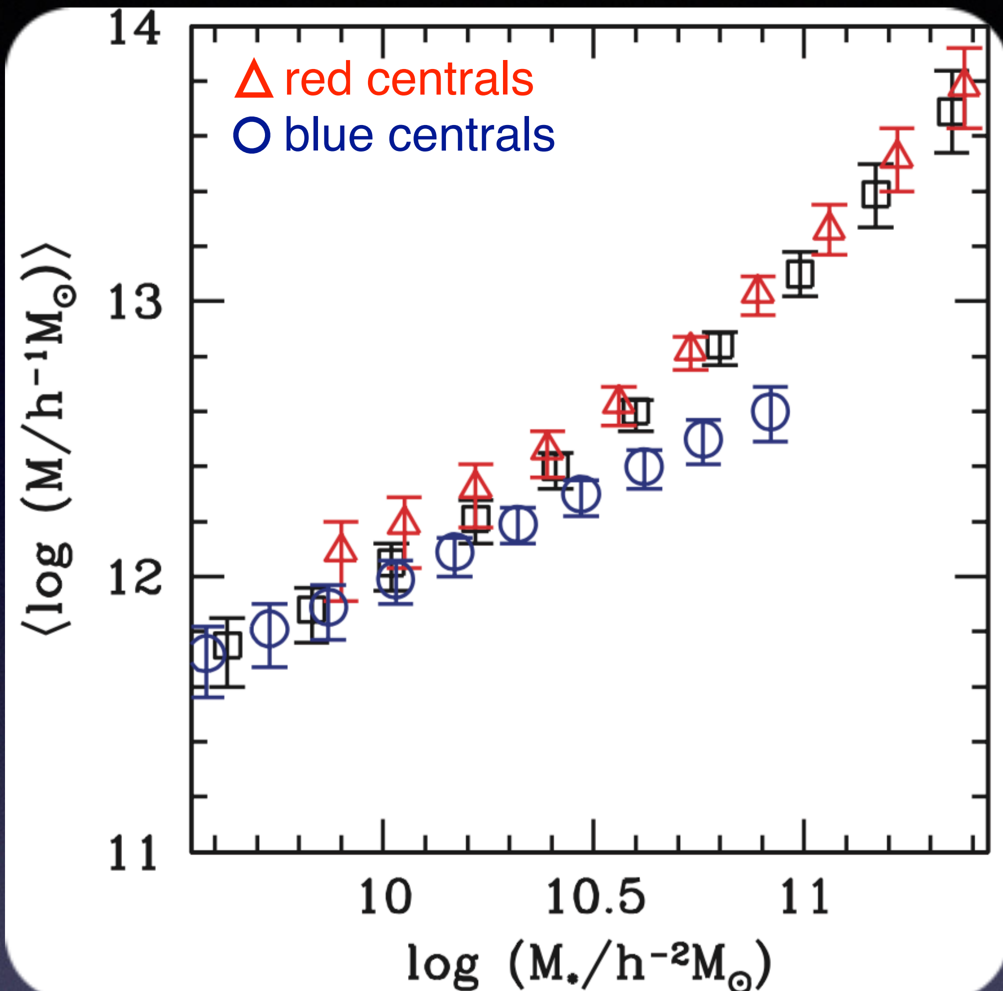
Age Matching accurately fits clustering of red and blue galaxies.

Proof of galaxy assembly bias ??

‡an example of conditional abundance matching (CAM)]

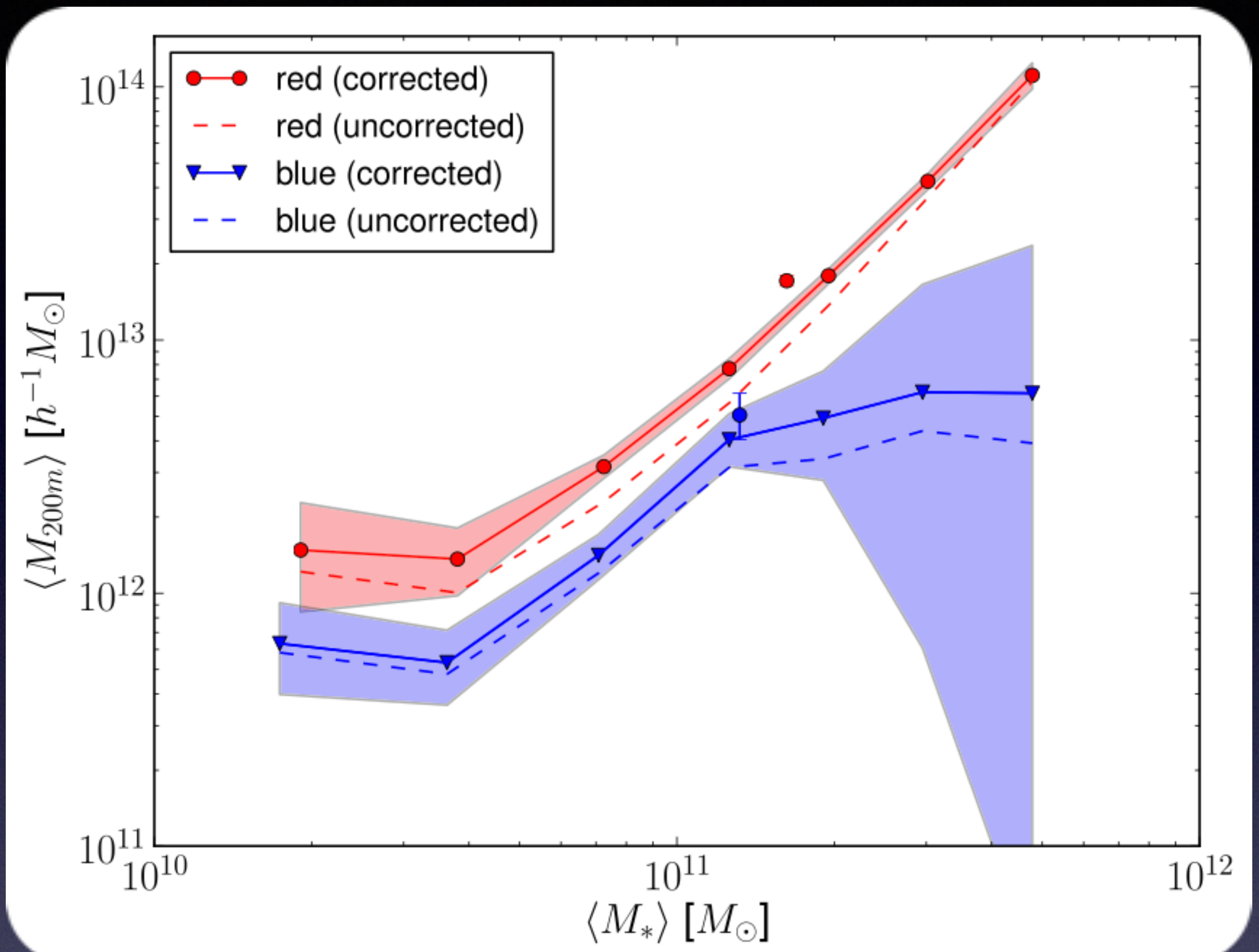
Galaxy Assembly Bias

Satellite Kinematics



source: More, vdB et al. 2011

Galaxy-Galaxy Lensing



source: Mandelbaum et al. 2016

Satellite kinematics and galaxy-galaxy lensing shows that red centrals live in more mass halos, which can also explain their different clustering…

see also Rodríguez-Puebla et al. 2015; Zu & Mandelbaum 2015; Lange, vdB et al. 2019

Degeneracies are common and make it difficult to find unambiguous evidence for galaxy assembly bias

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Hearin & Watson 2013; Hearin+14; Lehmann+17; Zentner+19; Lange +19
Vakili & Hahn 2019; Salcedo+19; Yuan+21; Wang+22; Beltz-Mohrmann+23

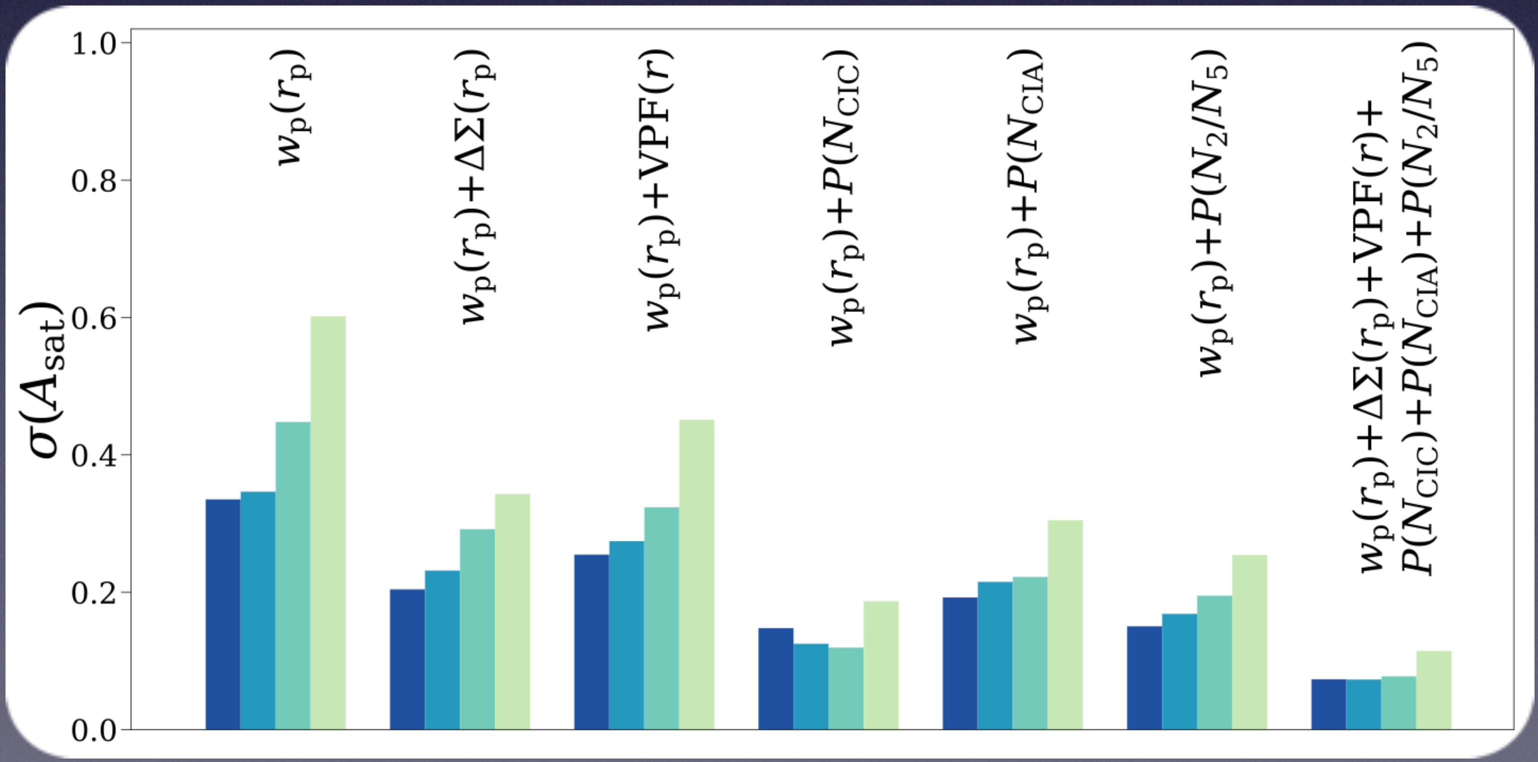
- data that is particularly good at breaking degeneracies

void-probability function

Walsh & Tinker 2019

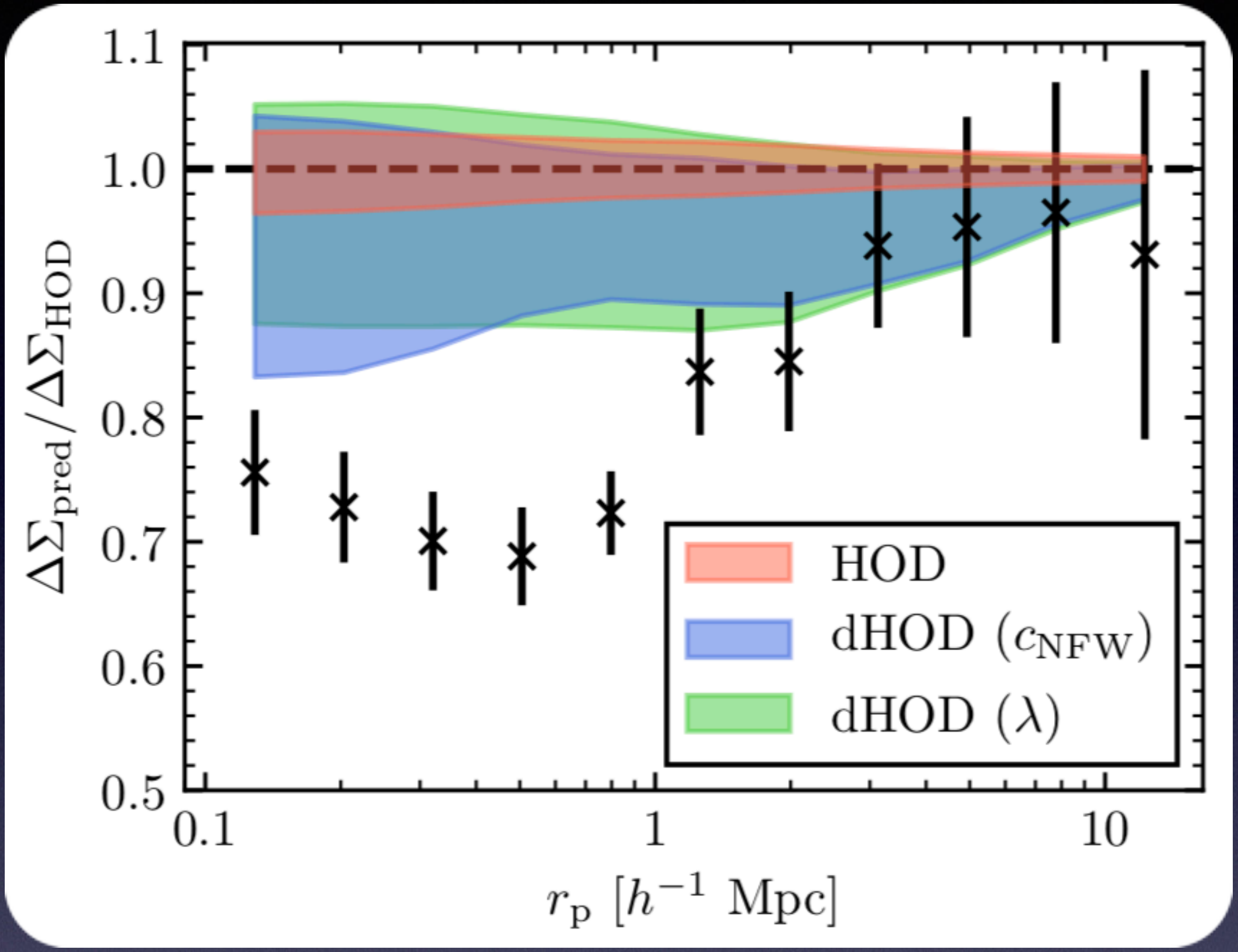
counts-in-cells

Wang et al. 2019

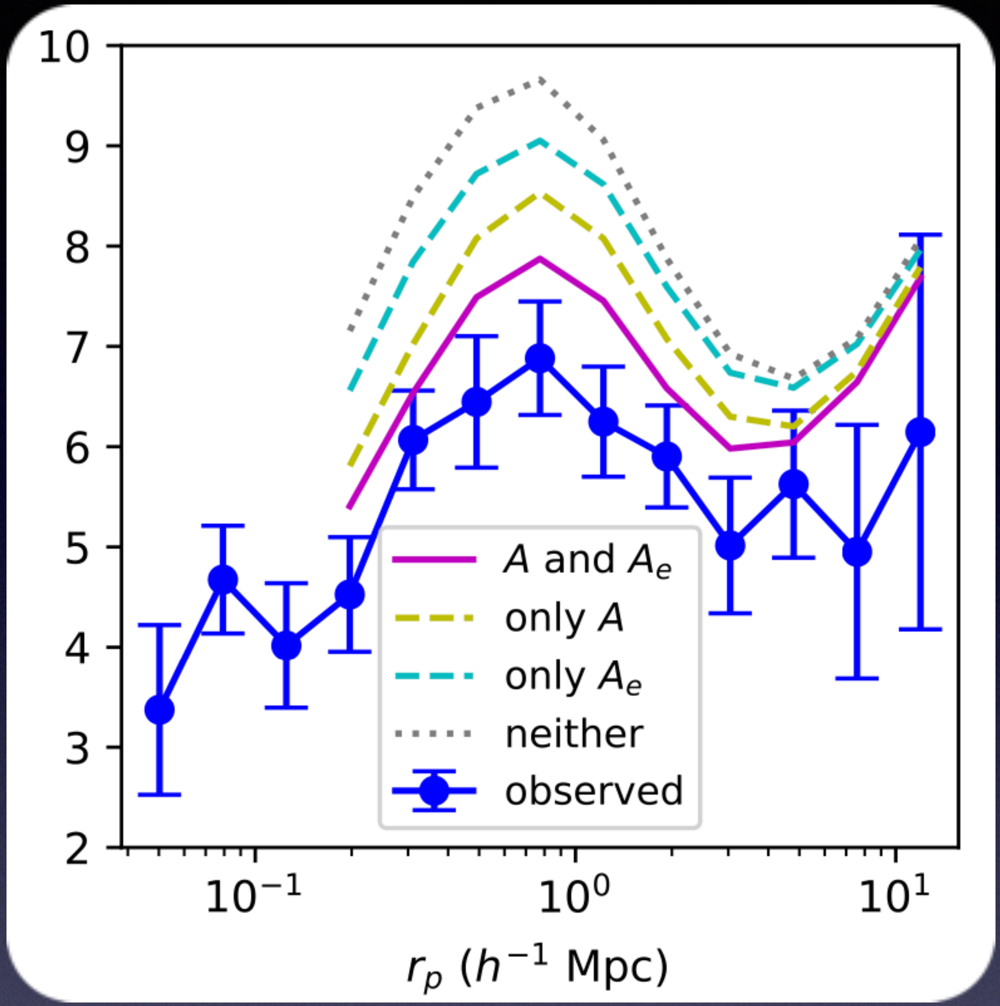


source: Wang et al. 2019

Assembly Bias vs. S_8 Tension



source: Lange et al. 2019

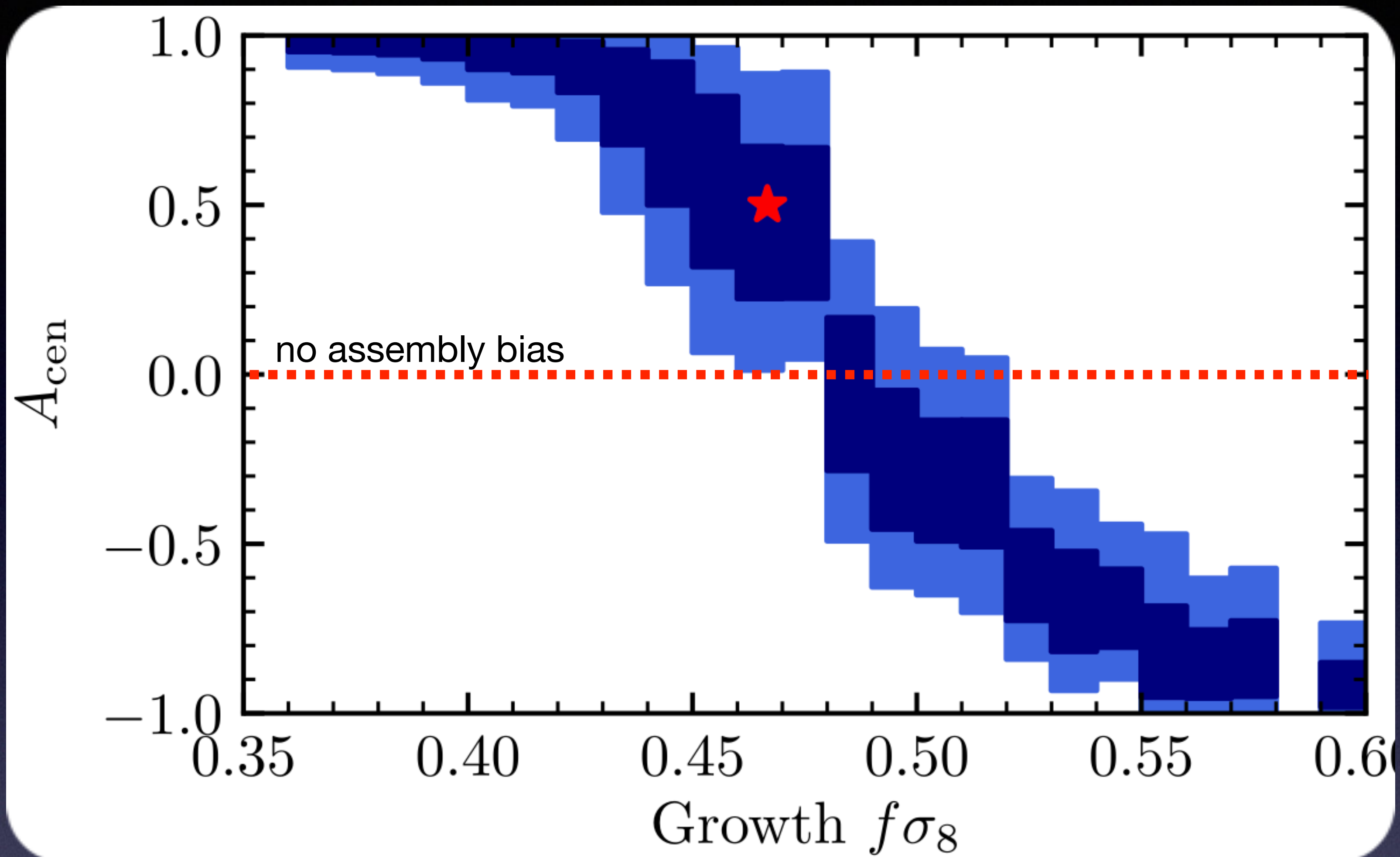


source: Yuan et al. 2021

Assembly bias unable to explain the lensing discrepancy?

The $64,000 Question

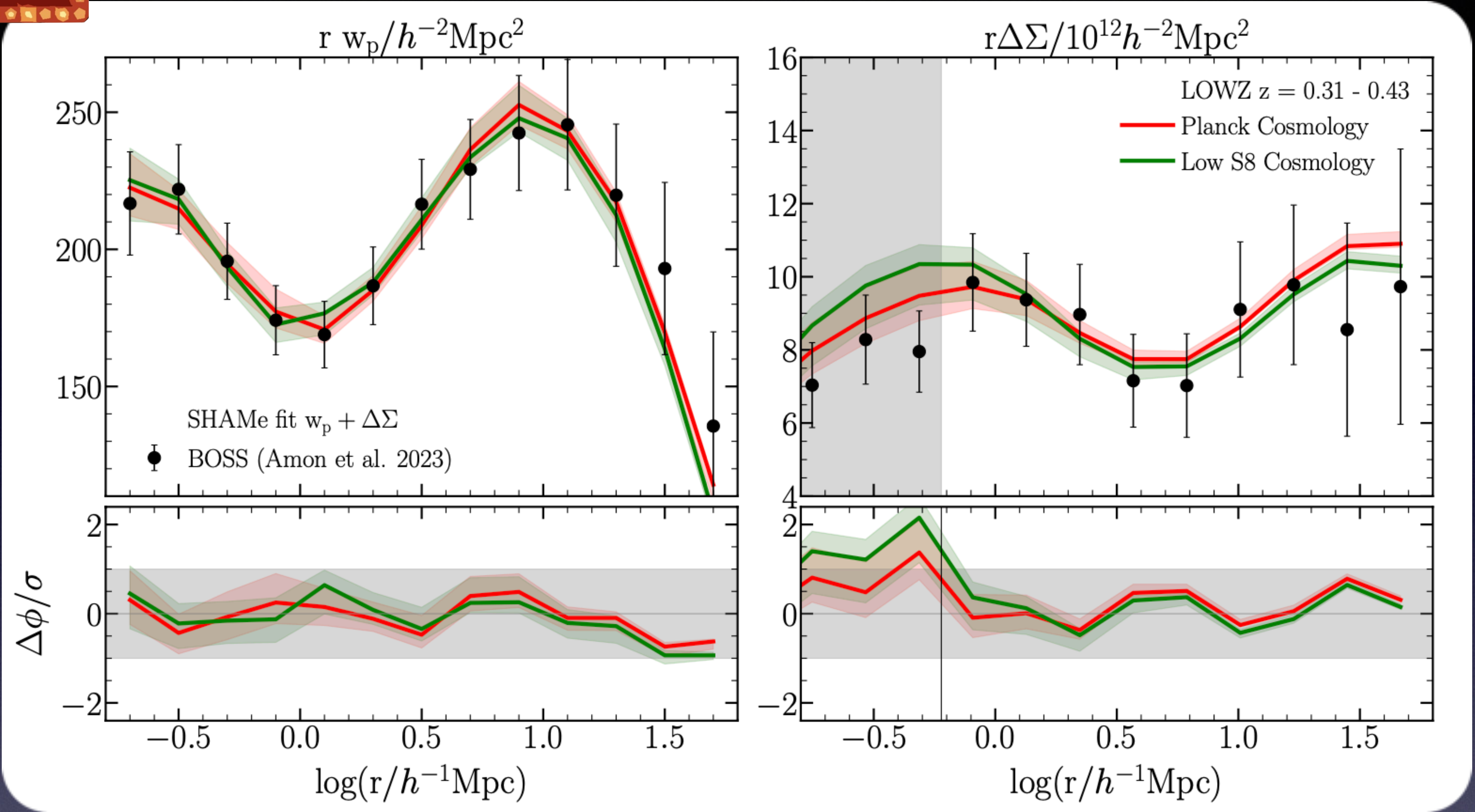
Assembly Bias vs. S_8 Tension



Source: Lange et al. 2019

Assembly bias is degenerate with cosmological parameters

Assembly Bias vs. S_8 Tension



Source: Contreras et al. 2023

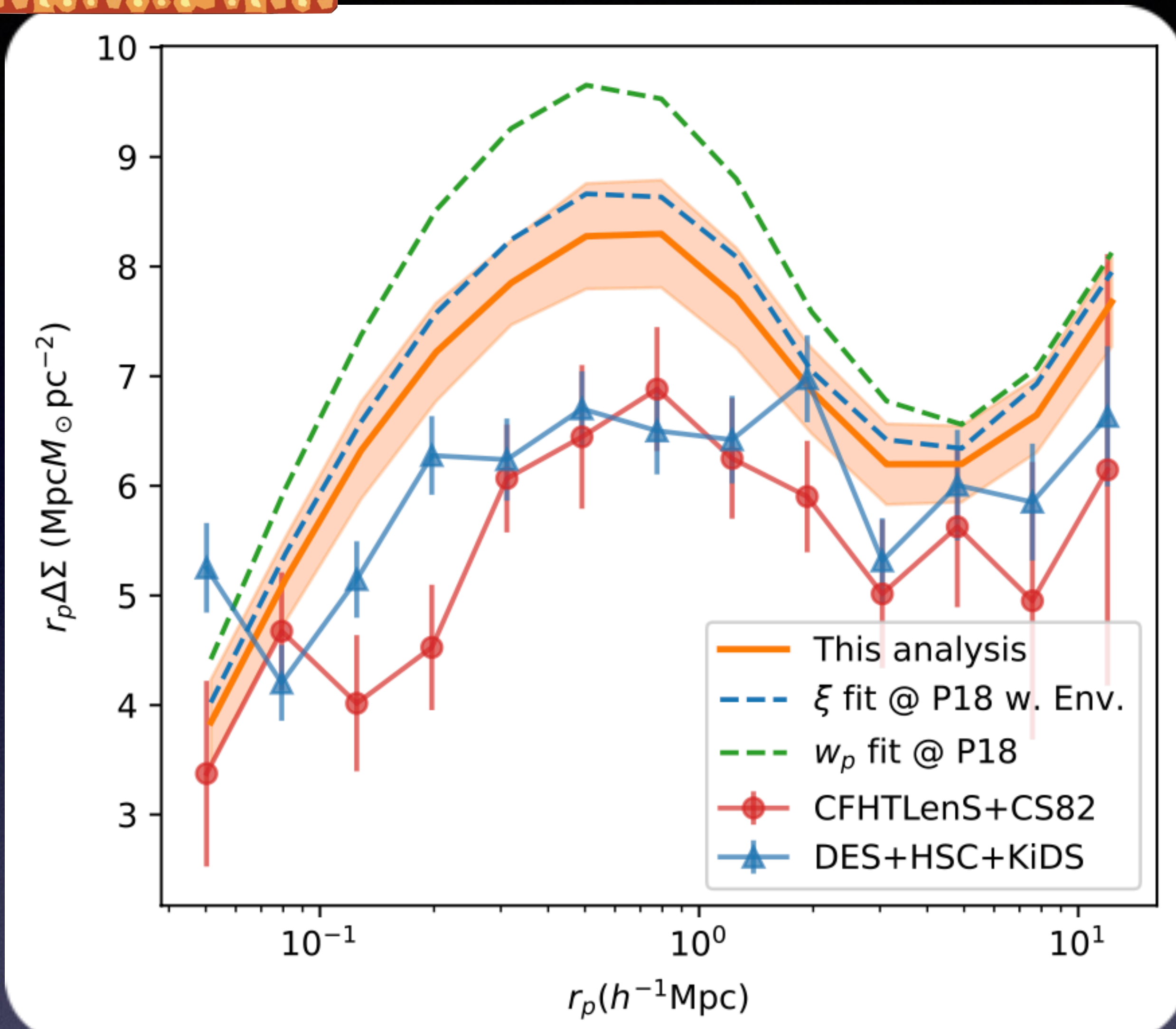
SHAMe: includes treatment of orphan galaxies
secondary halo property used is large-scale environmental density

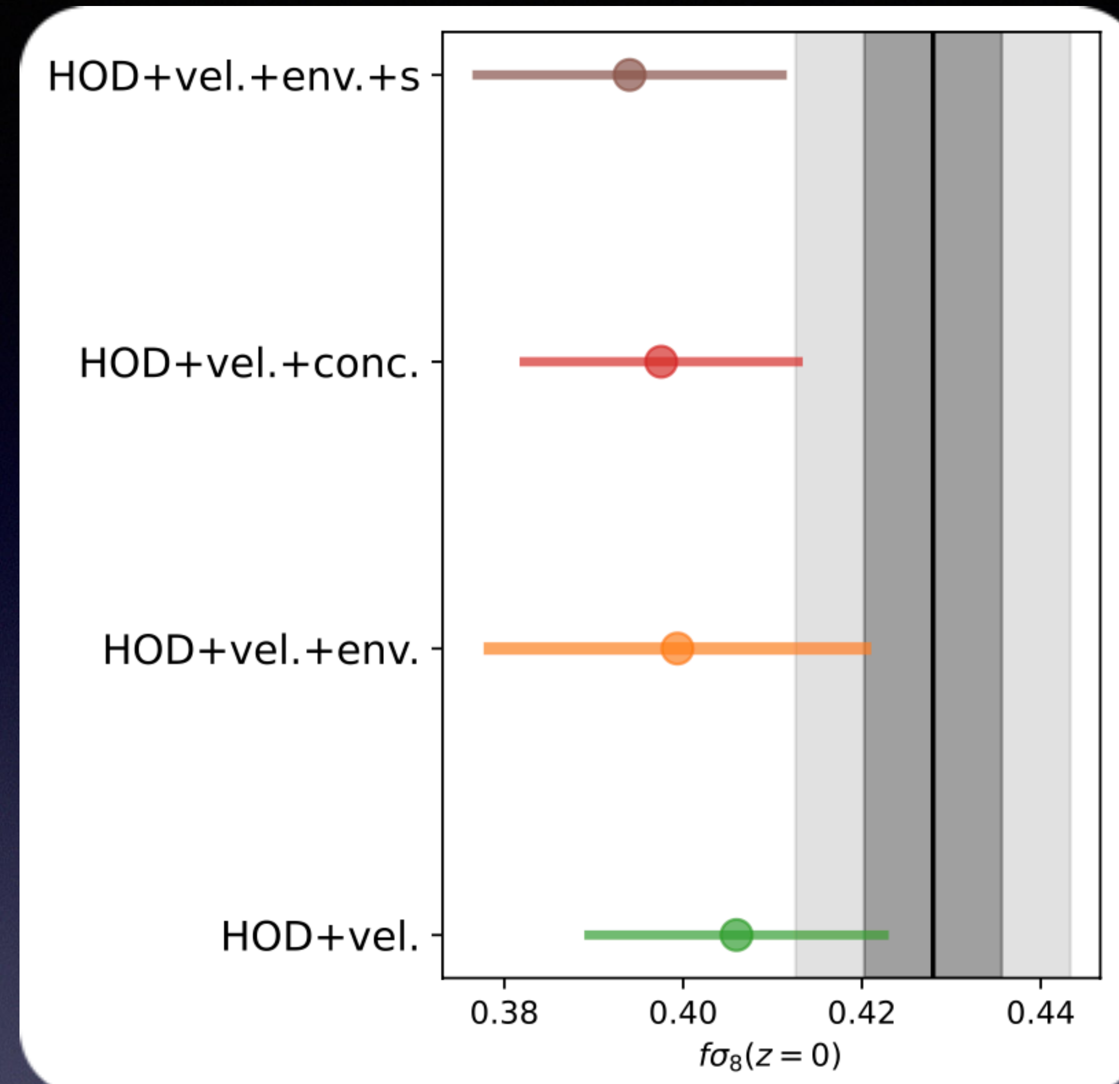
Assembly bias is degenerate with cosmological parameters and is flexible enough to solve the S8 tension?

see also Chaves-Montero et al. 2023

The $64,000 Question

Assembly Bias vs. S_8 Tension





Source: Yuan et al. 2022

flexible HOD + emulator: flexible radial profile of satellites
HOD has environment dependence to model galaxy assembly bias

Inconsistent with results of Contreras et al. 2023
The tension continues….

lesson learned (again)

"Inconsistency is the only thing in which men are consistent"

[Horace Smith]

The Galaxy-Halo Connection

Constrain Cosmology marginalize over galaxy formation	**Fix Cosmology** learn about galaxy formation
Assembly Bias is a condemnation	Assembly Bias is a blessing
N-body simulations are a must but what about orphans?	N-body simulations are a must but what about orphans?
Emulators & Cosmological Evidence Modeling lots of progress in recent years	Only a few simulations needed to beat cosmic variance
Will we be able to break degeneracies? uncertain	Will we be able to break degeneracies? probably
How to deal with baryonic effects? marginalization or include gas?	How to deal with baryonic effects? marginalization or include gas?
Can we (ever) reach 1% accuracy? maybe; beat cosmic variance [see Angular & Pontzen 2016]	No need for 1% accuracy
How to convince critics that marginalization is sufficiently general?	No marginalization