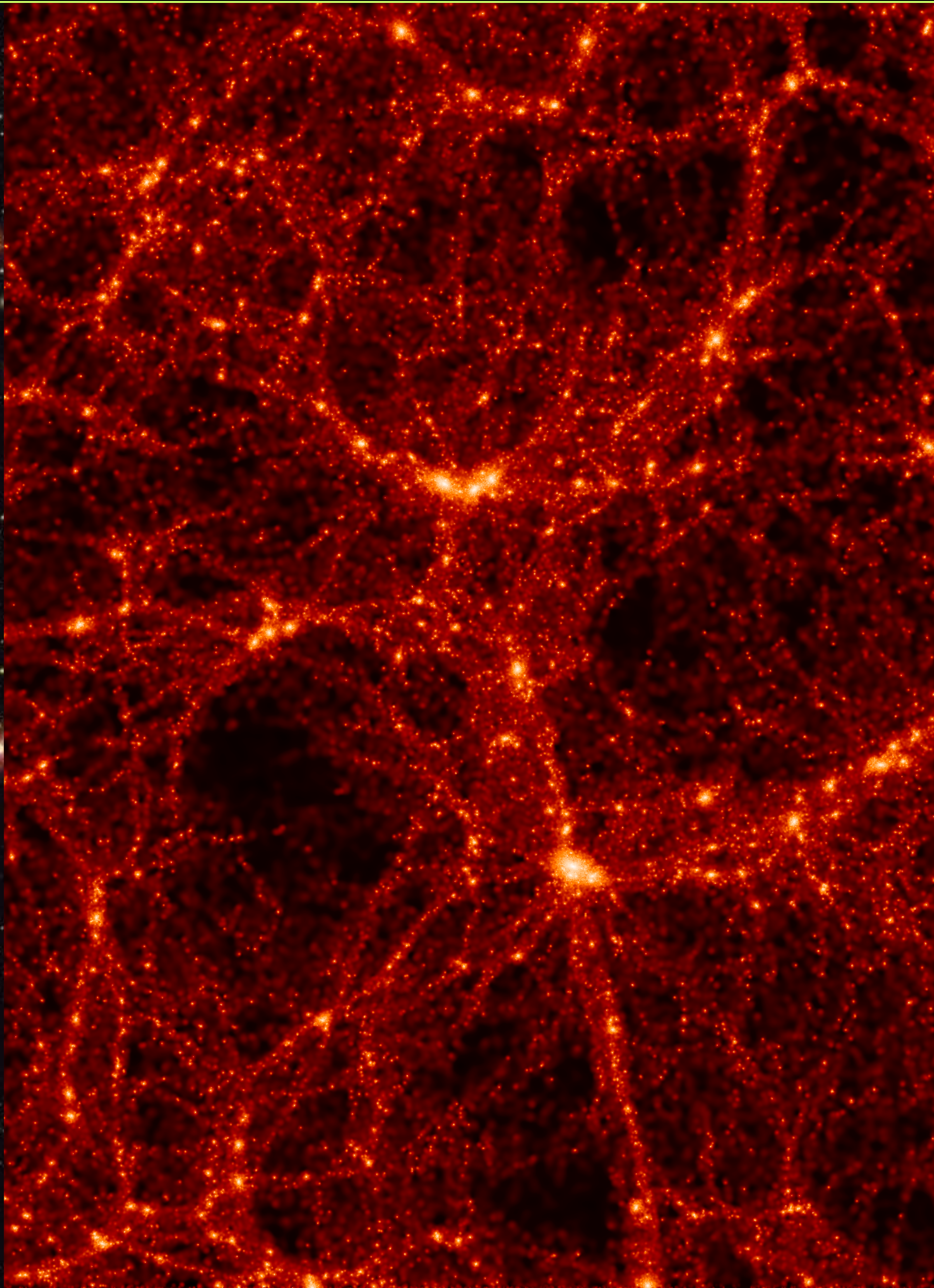
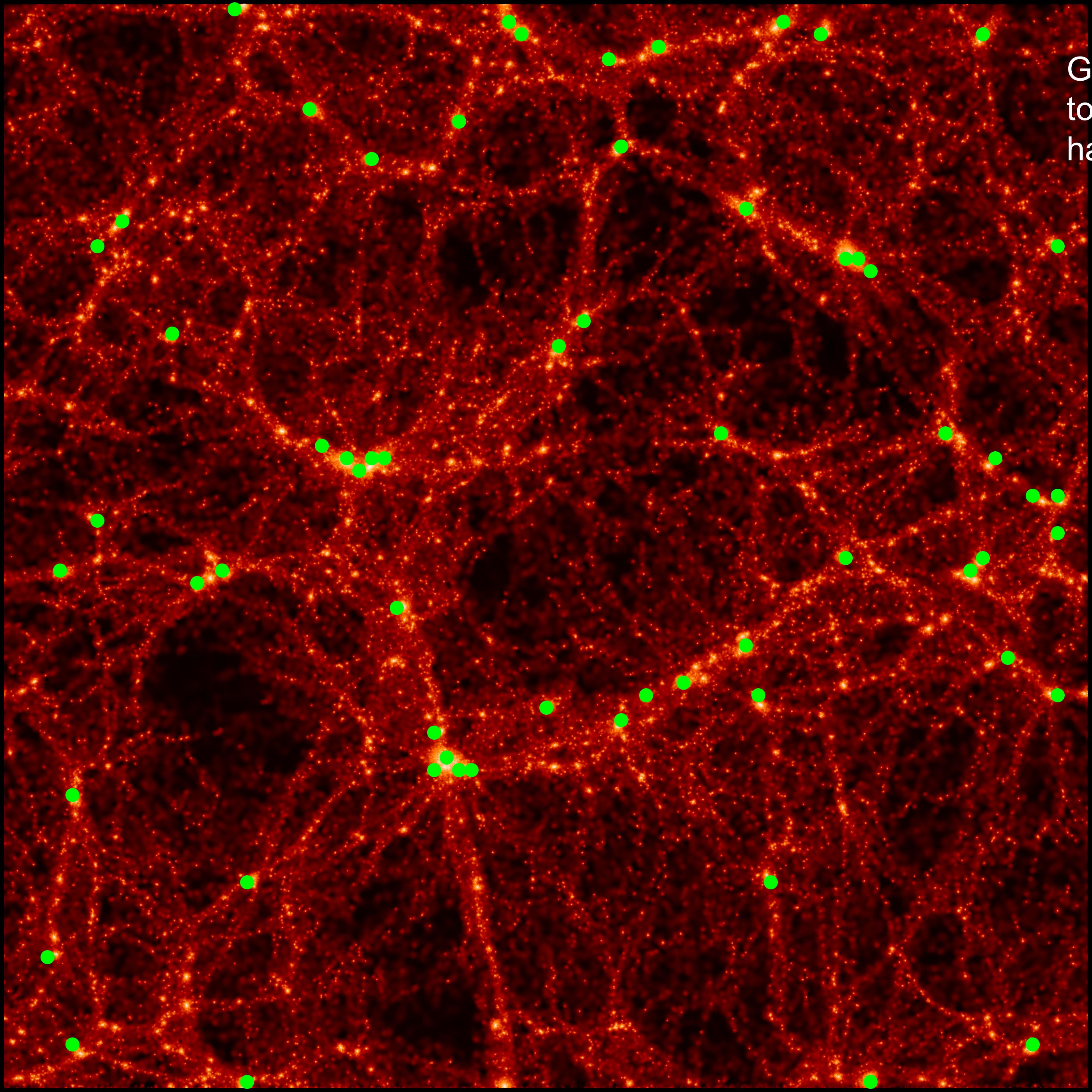
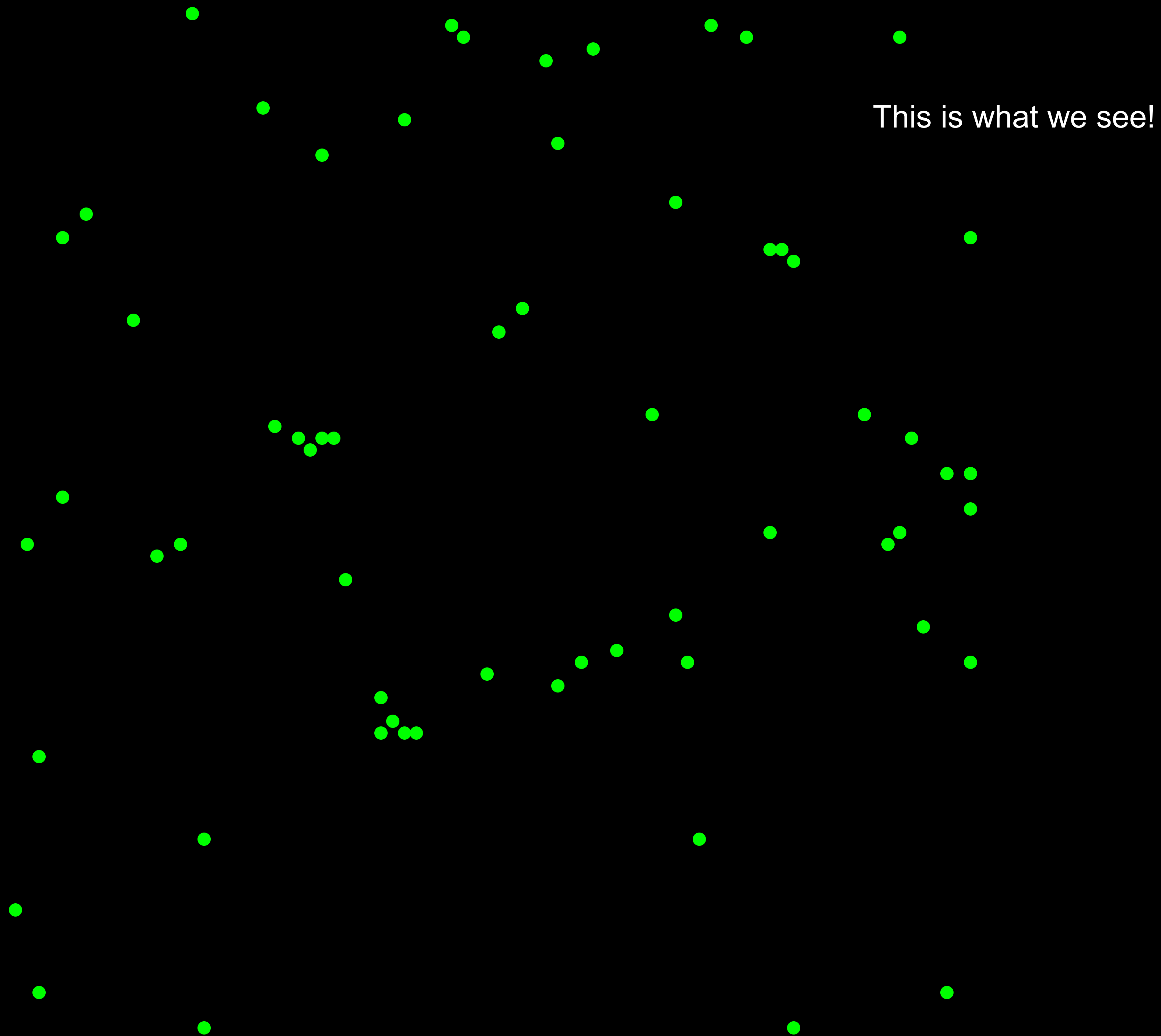
From dark matter to galaxies



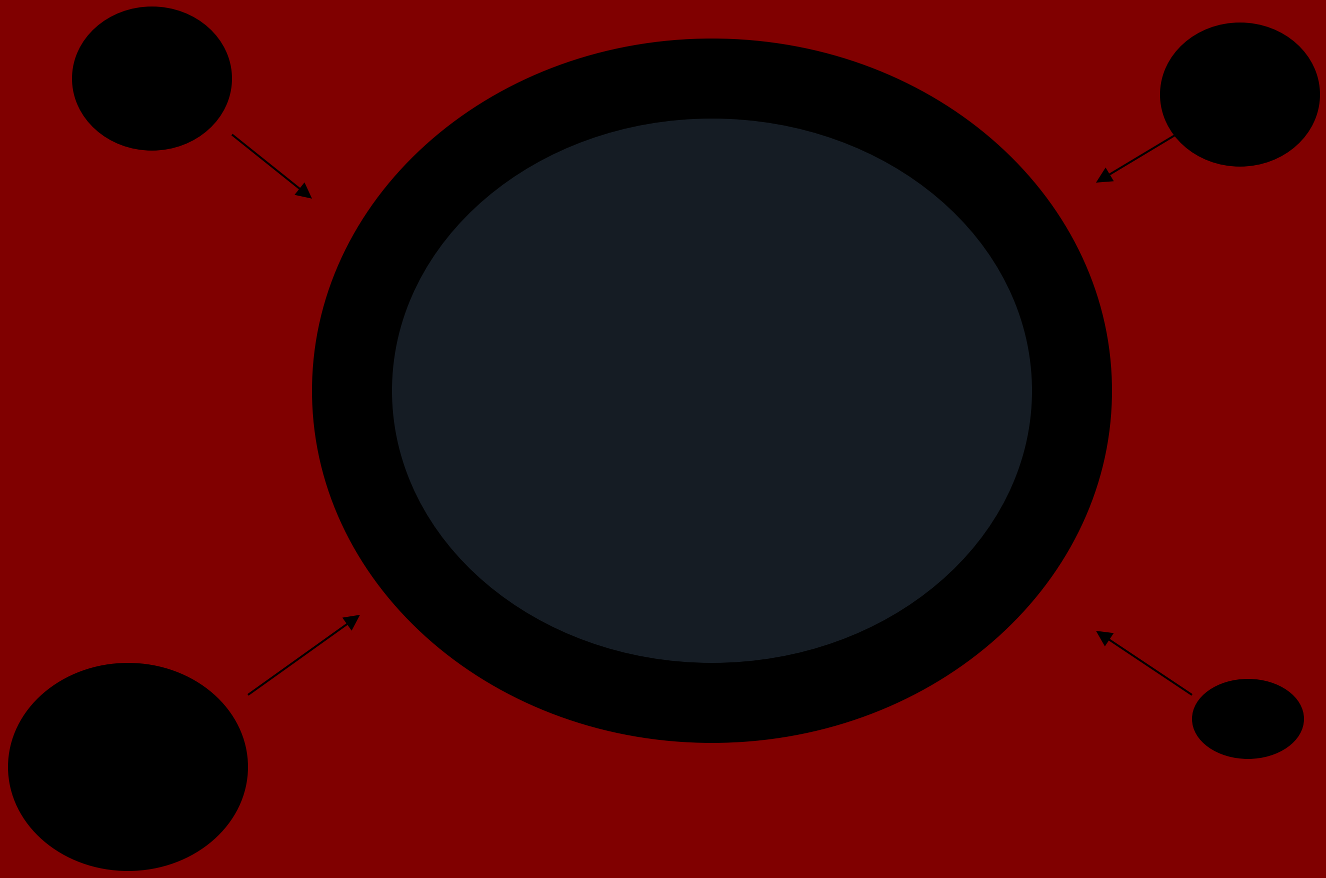


Galaxies are assumed to form in dark matter halos.


This is what we see!

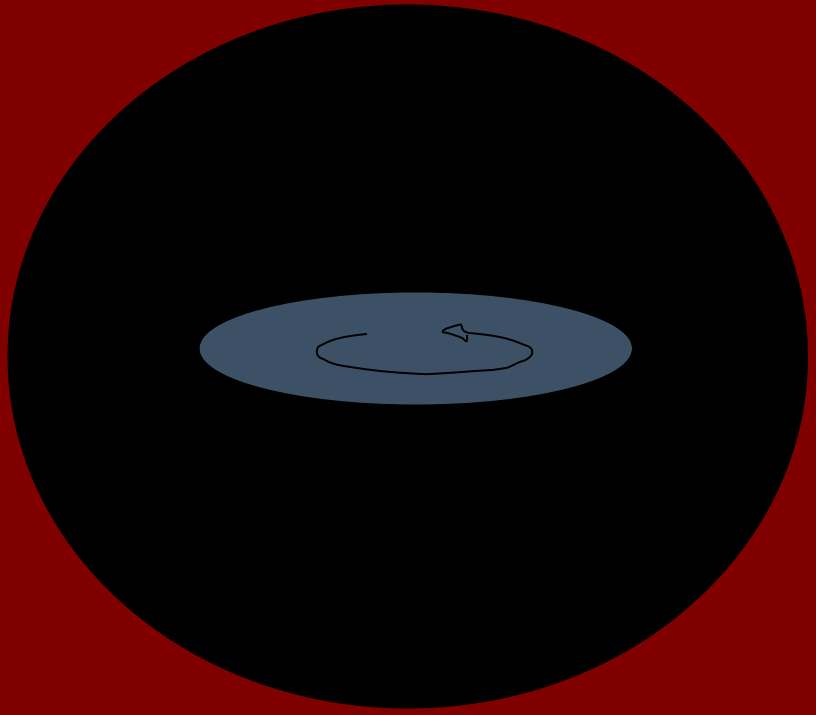
Galaxy formation theory in a nutshell

A dark matter halo forms. Inside the halo is hot/warm gas.
The gas has some angular momentum.



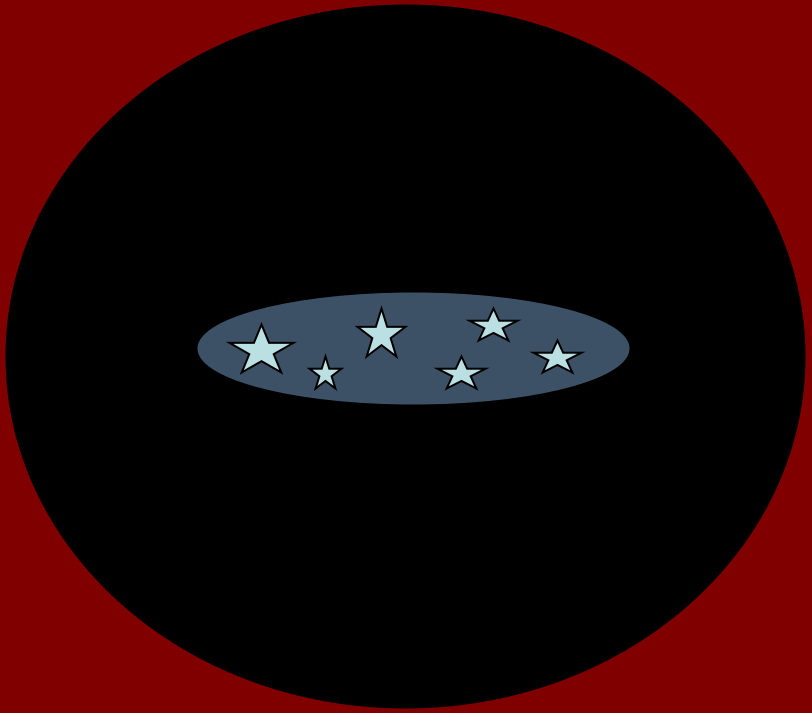
Galaxy formation theory in a nutshell

Gas cools inside the halo and settles into a rotating disk.



Galaxy formation theory in a nutshell

Stars form from the cold dense gas.



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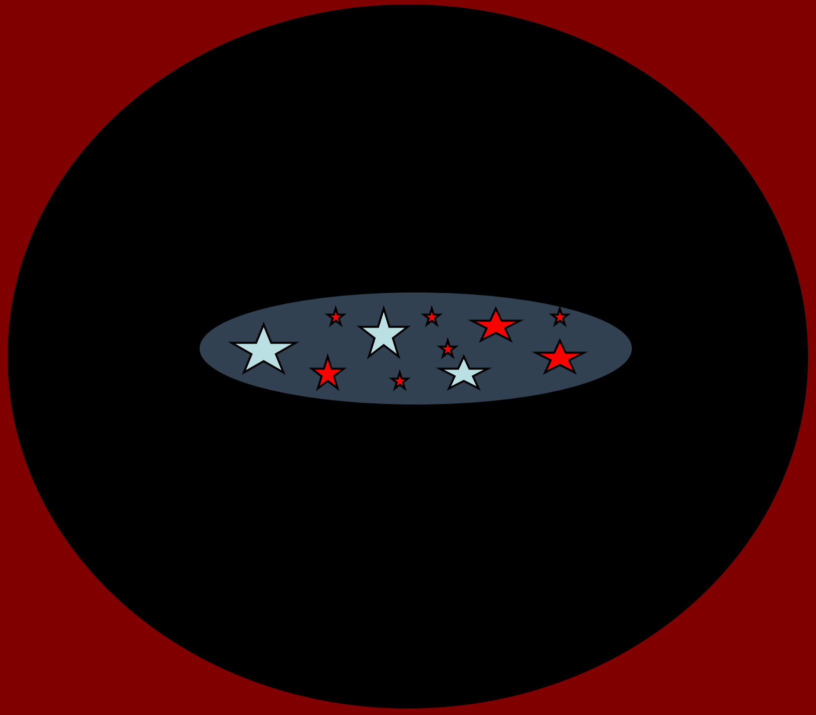
Galaxy formation theory in a nutshell

Stellar populations grow old and fade, new stars are born.
Gas undergoes heating and cooling.



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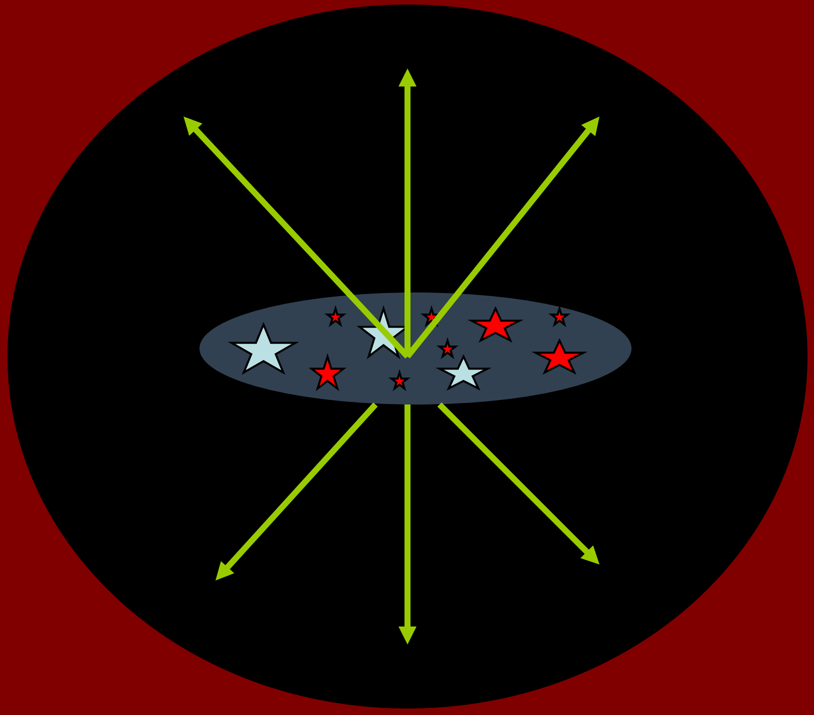
Galaxy formation theory in a nutshell

Energy feedback due to supernovae or a massive central black hole can reheat the gas or blow it out of the galaxy. This can end star formation.



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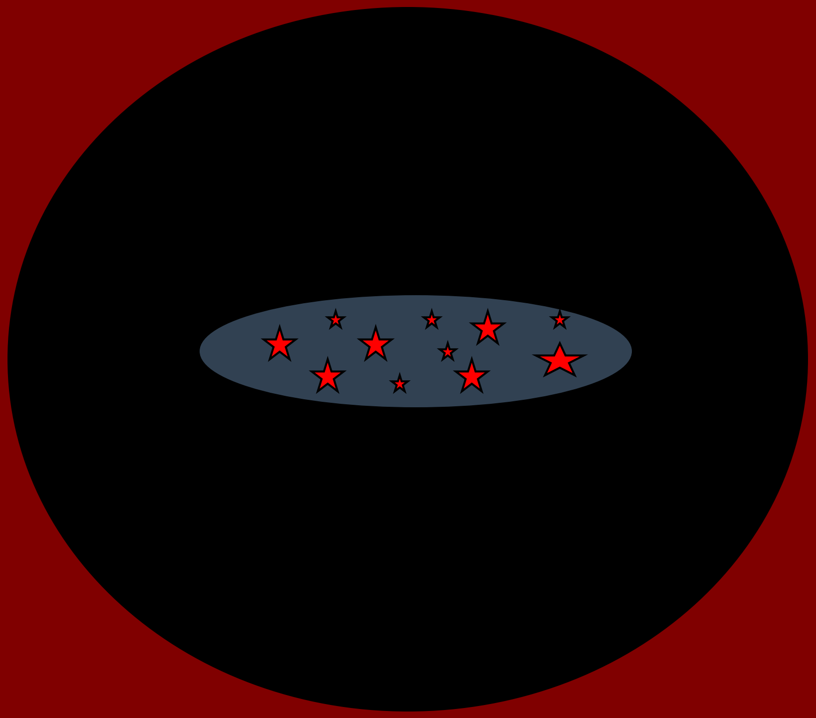
Galaxy formation theory in a nutshell

The galaxy gets dimmer and redder.



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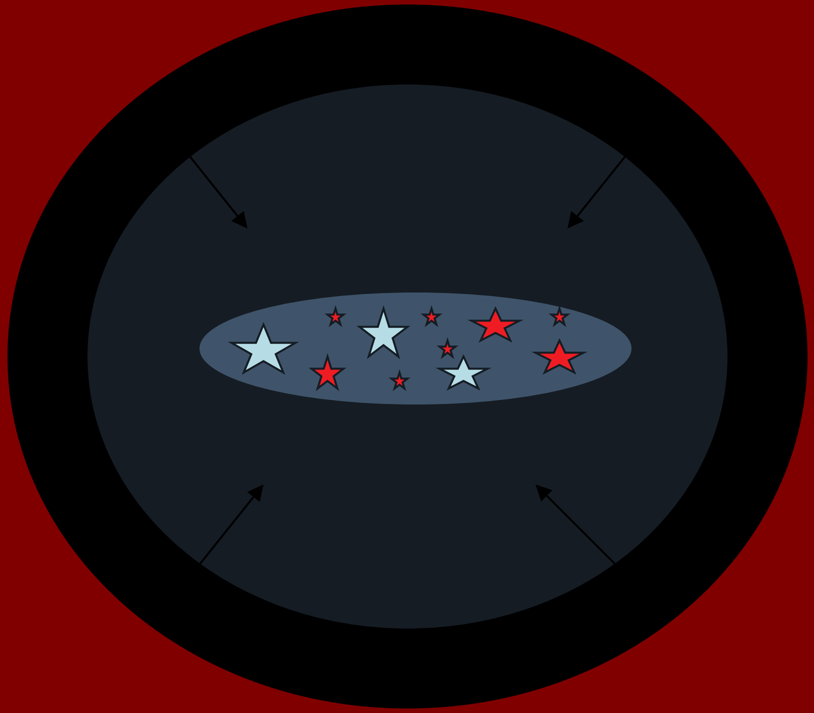
Galaxy formation theory in a nutshell

If the halo is in a gas-rich environment, more gas can fall into the halo from the inter-galactic medium.



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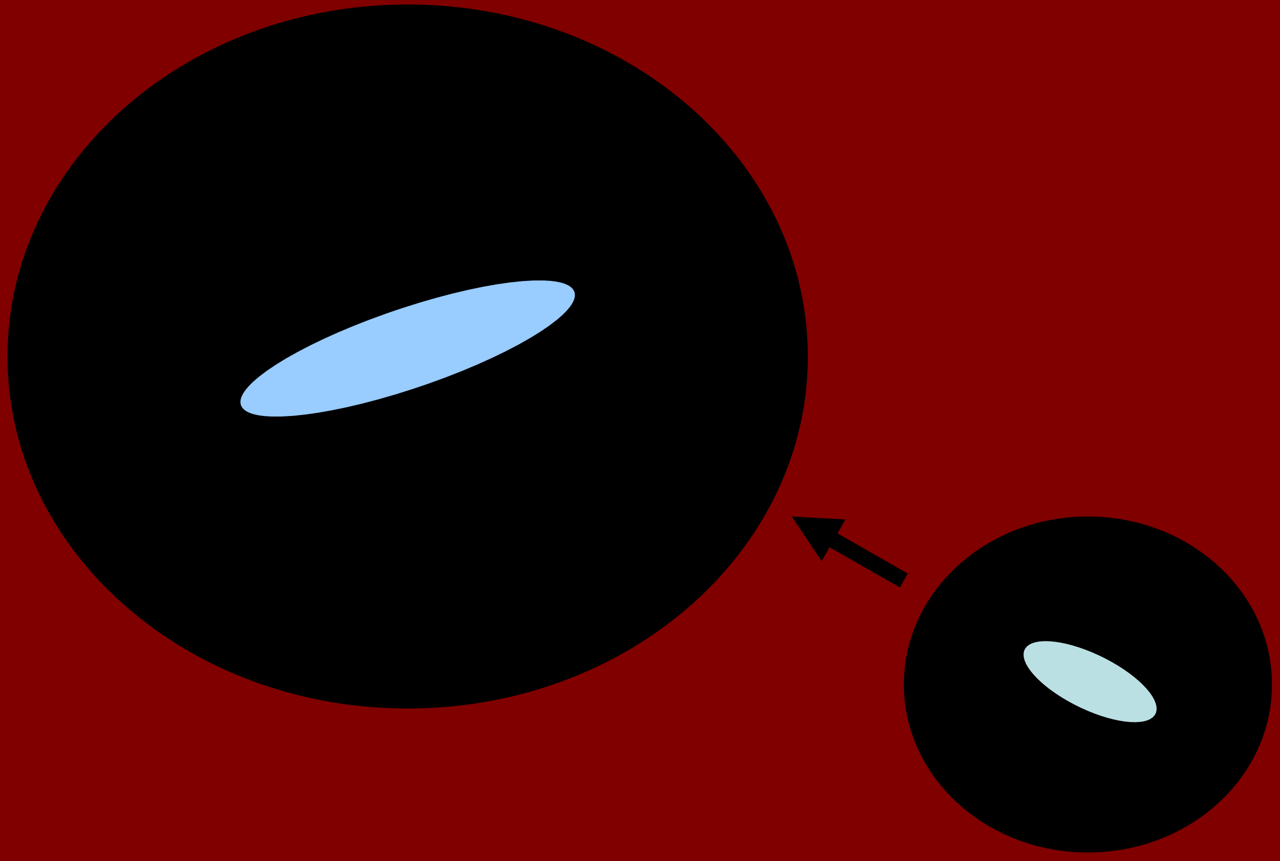
Galaxy formation theory in a nutshell

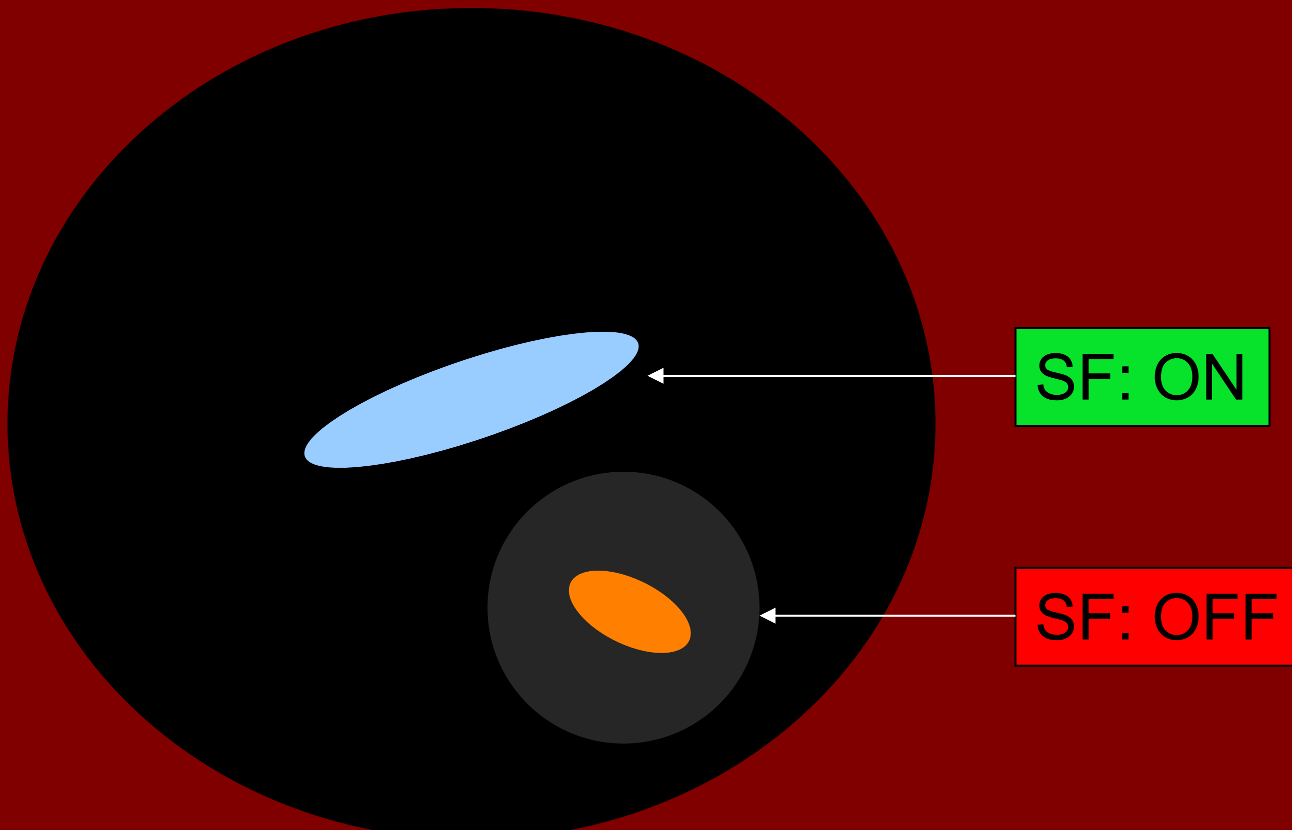
If the halo merges with another halo containing a galaxy, the smaller galaxy becomes a satellite.



Galaxy formation theory in a nutshell

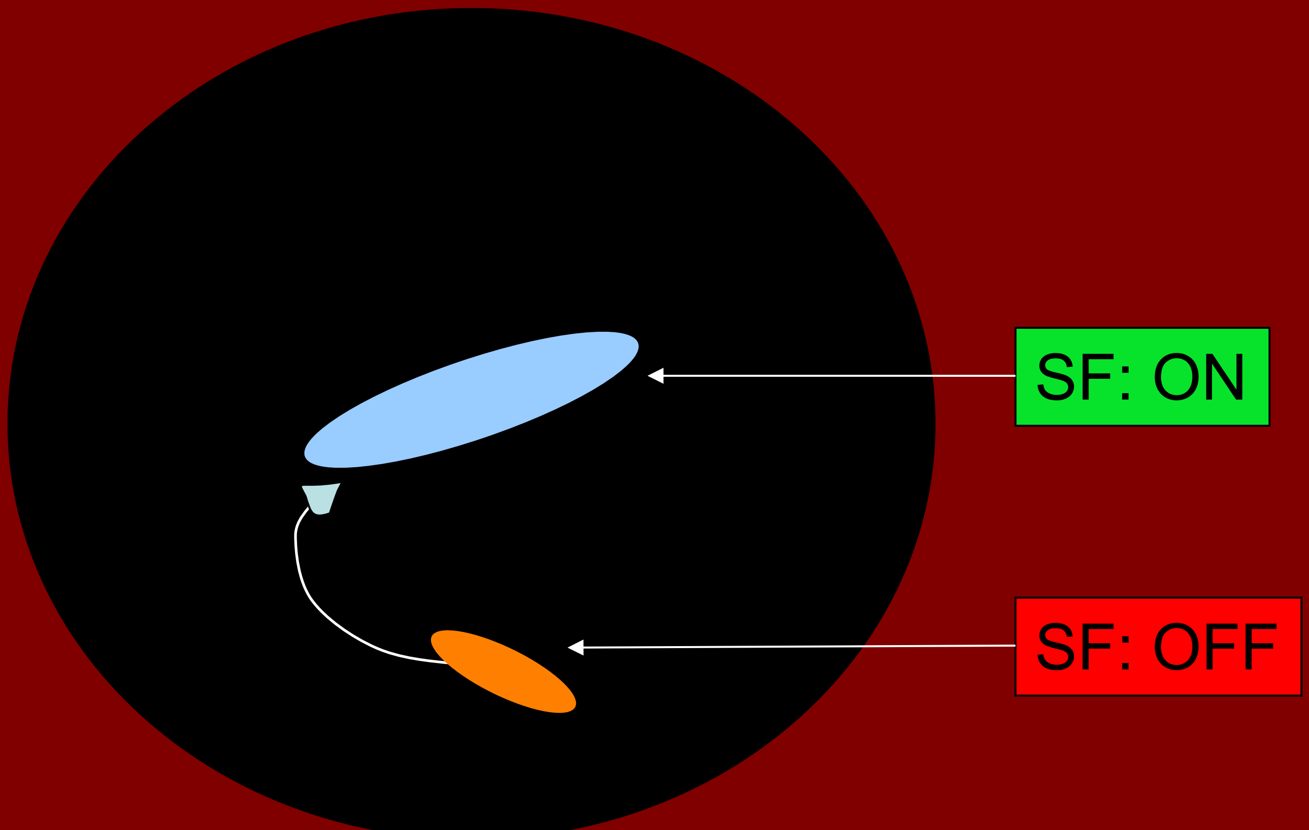
If the main halo is massive enough, it can contain hot gas that might ram-pressure strip the gas out of the satellite galaxy, thereby ending its star formation.

the halo merges with another halo containing a galaxy, the smaller galaxy becomes a satellite.



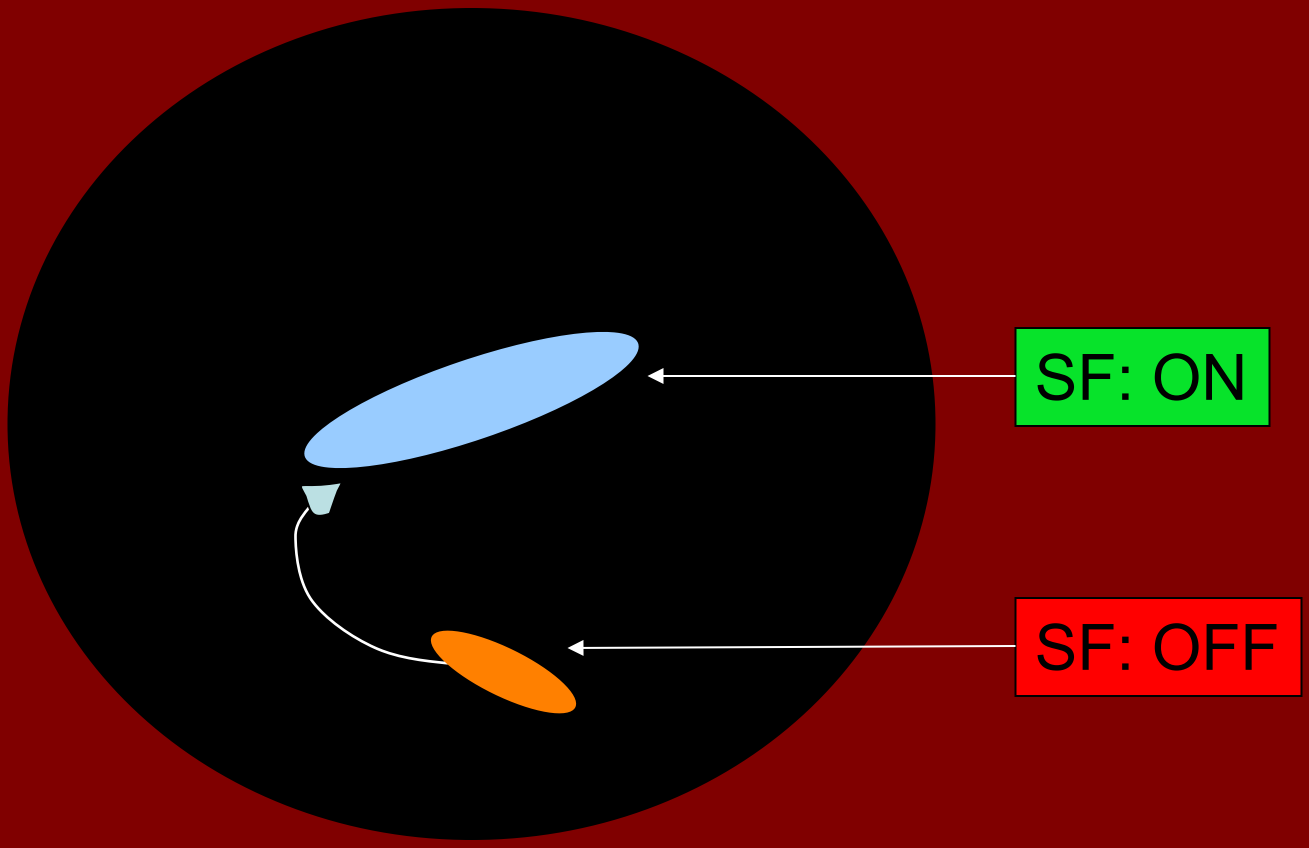
Galaxy formation theory in a nutshell

Eventually, the subhalo will be destroyed via tidal stripping and the satellite galaxy will spiral in due to dynamical friction.



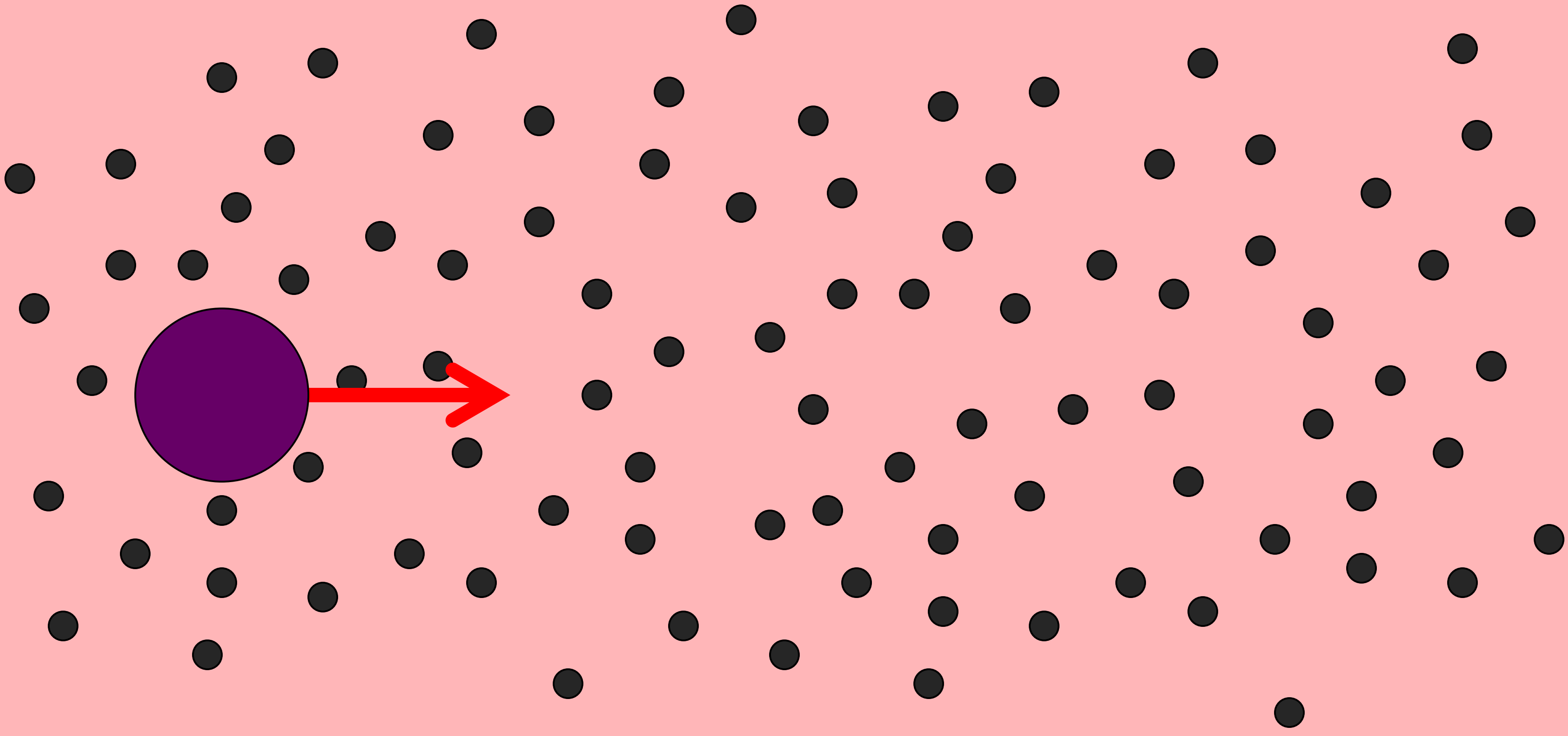
Galaxy formation theory in a nutshell

Eventually, the subhalo will be destroyed via tidal stripping and the satellite galaxy will spiral in due to dynamical friction.



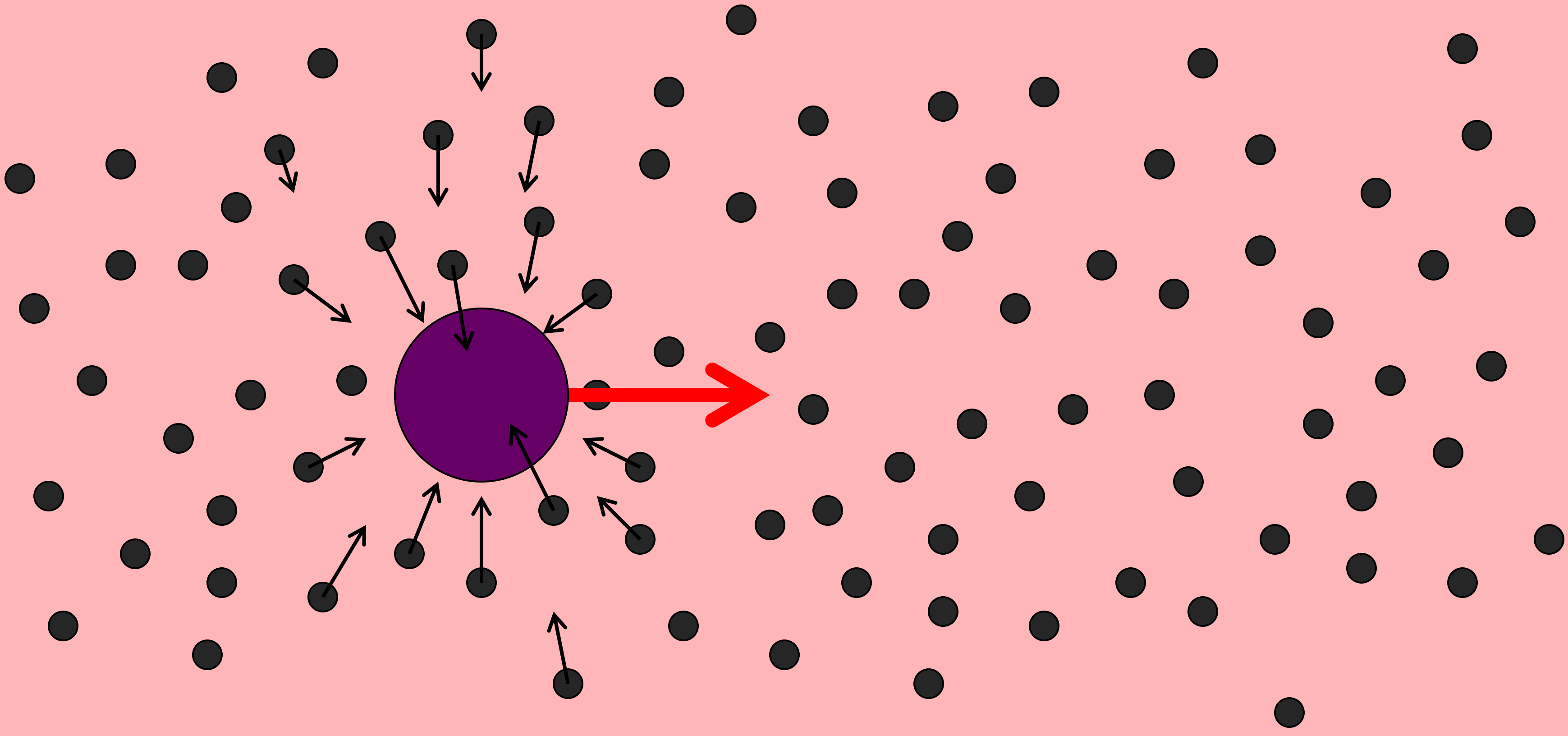
Dynamical Friction

Dynamical friction is a force experienced by a massive body moving within a sea of lower mass particles.



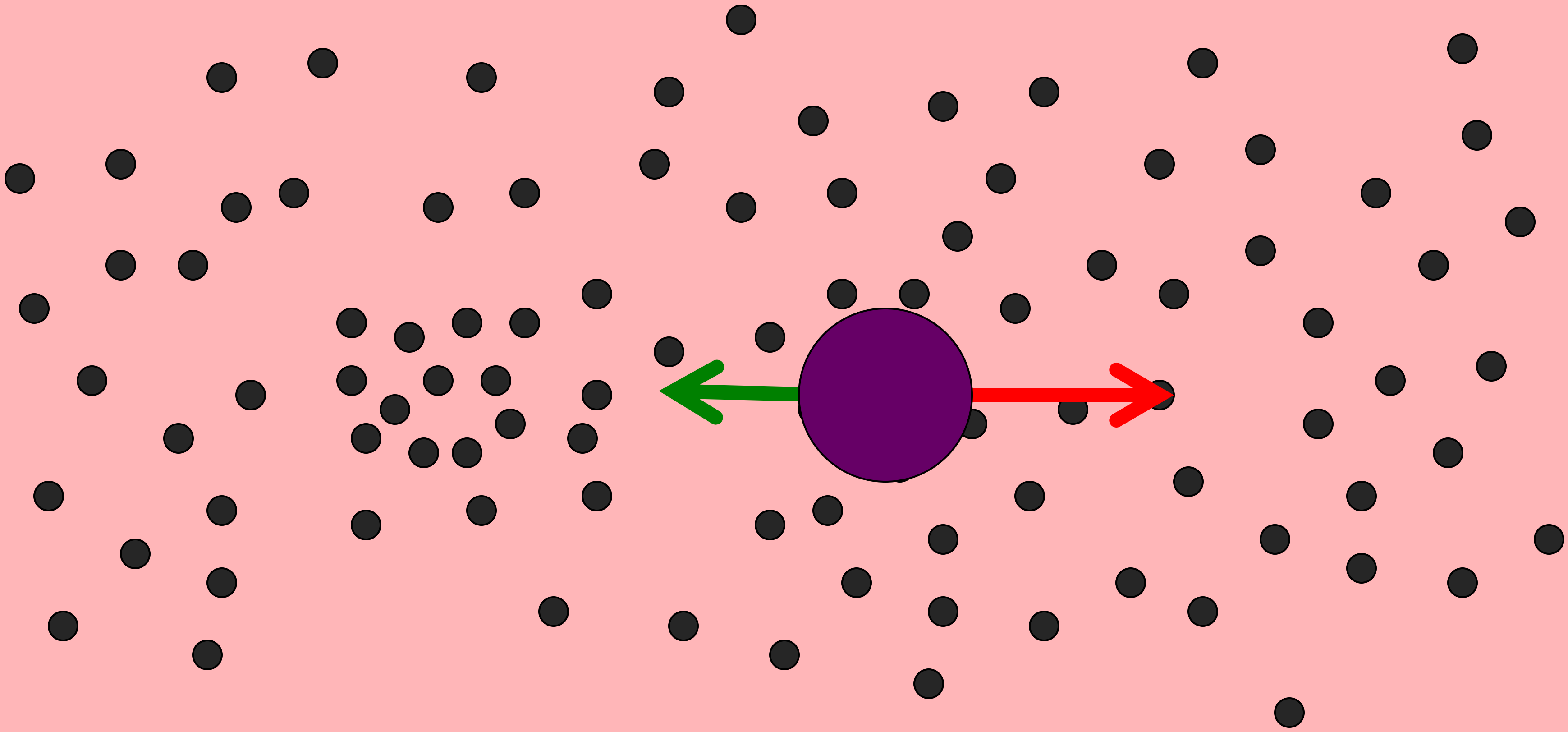
Dynamical Friction

Dynamical friction is a force experienced by a massive body moving within a sea of lower mass particles.



Dynamical Friction

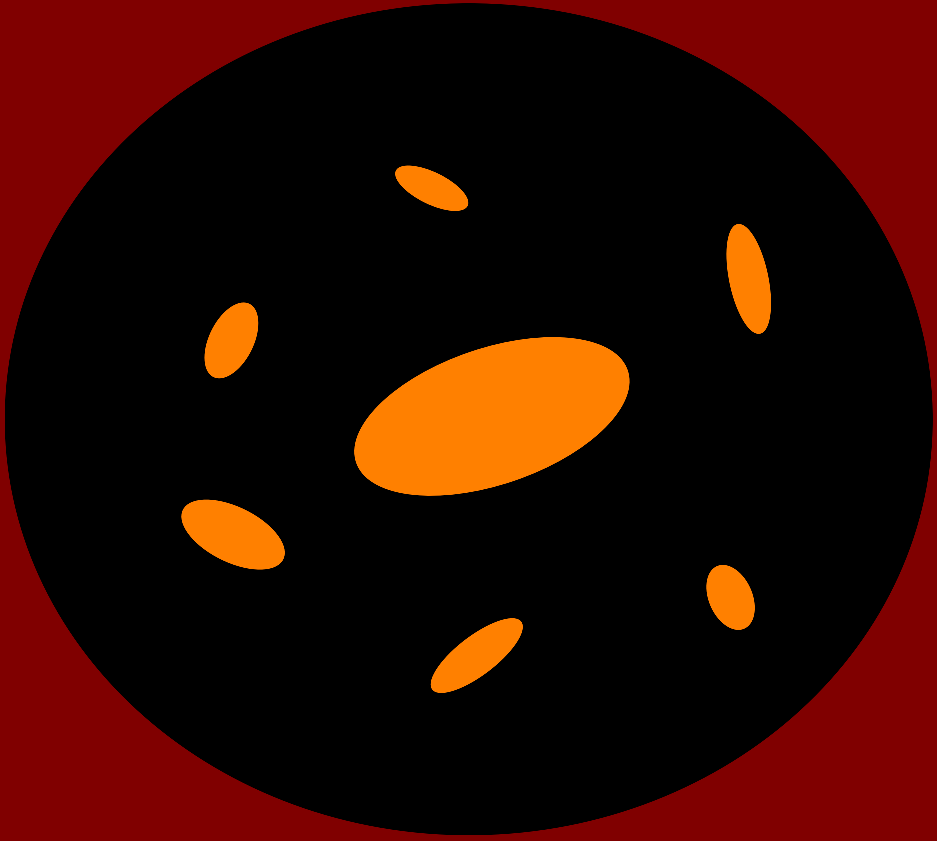
The body creates a wake of particles behind it, which creates a drag force.



Friction is high if mass of body is large and body moves slowly.

Galaxy formation theory in a nutshell

In high mass halos, halo mergers happen frequently, but dynamical friction timescales are long, resulting in galaxy clusters.



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Galaxy formation theory in a nutshell

Key questions:

•What is the initial distribution of gas within halos and how does it cool?(e.g., multiphase medium)

•How do stars form exacty? (e.g., conditions for star formation, dependence of IMF on environment, metallicity)

•How does supernova feedback work? (e.g., thermal vs. kinetic energy injection, efficiency)

•How does AGN feedback work?

•How does merging affect galaxies' star formation and morphology?

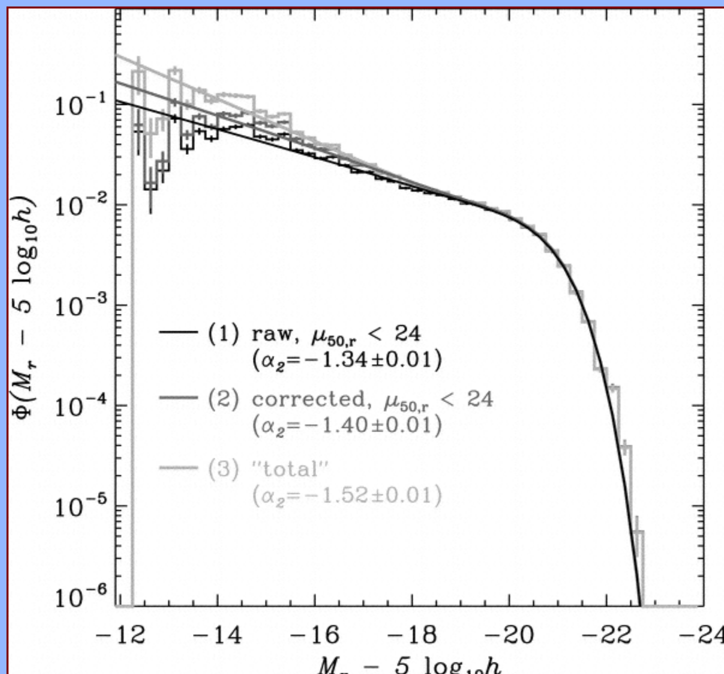
•How does fresh gas in the IGM feed galaxies?

Lots of unknowns!

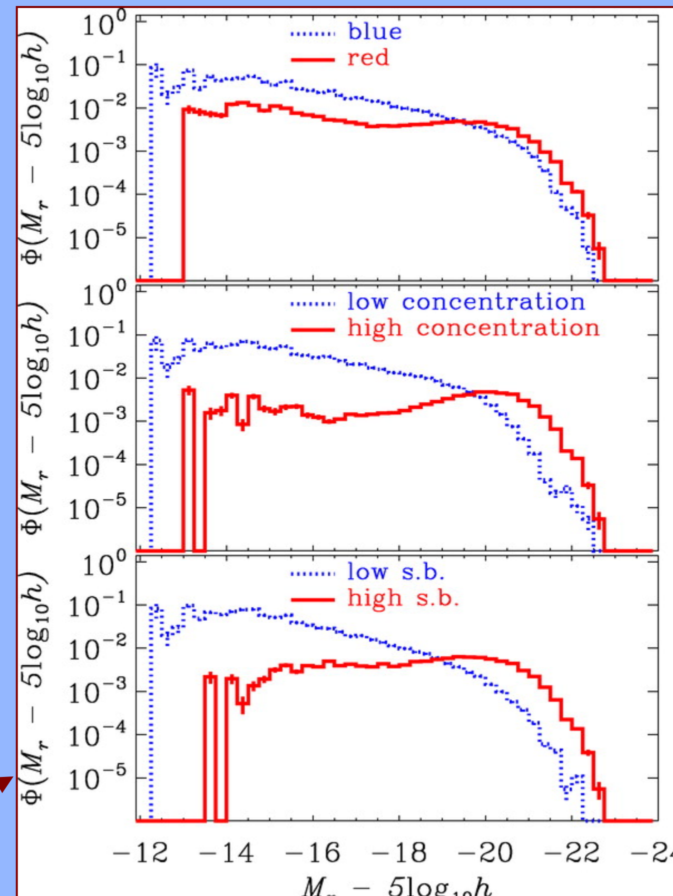
But also lots of data describing the distribution of galaxies!

Large surveys: Measurements of Galaxy Clustering

First Moments $\langle \delta(\vec{x}) \rangle$



Blanton et al. (2005)

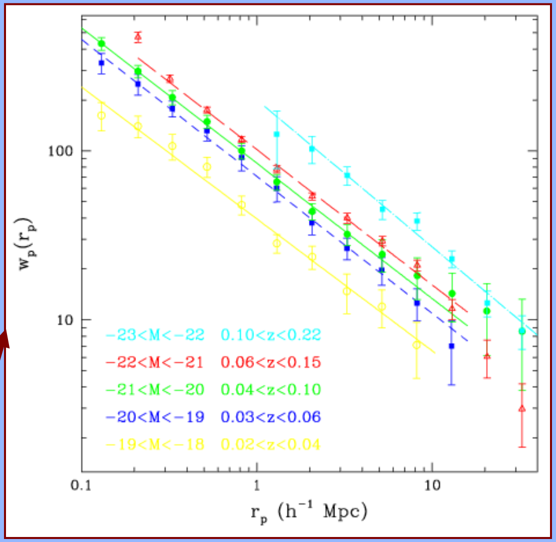


Luminosity Functions

Large surveys: Measurements of Galaxy Clustering

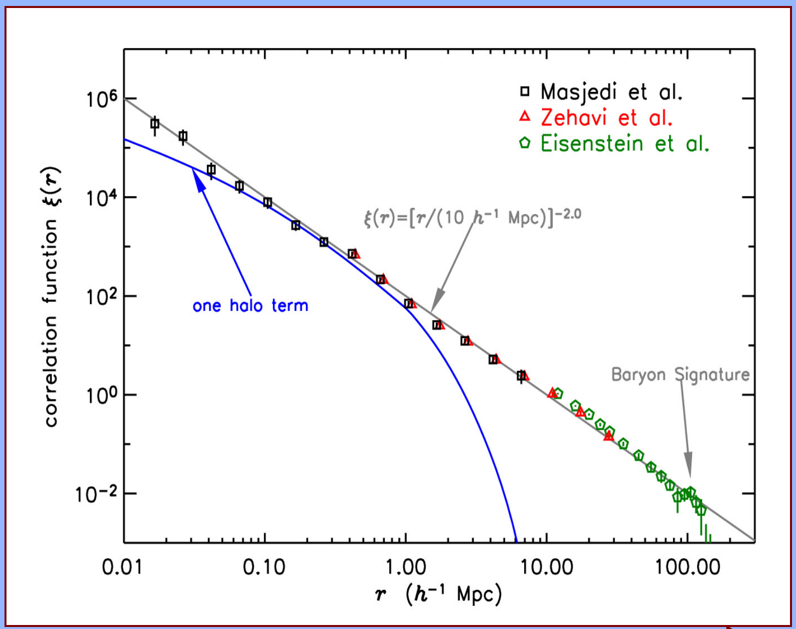
Second Moments $\langle \delta(\vec{x})\delta(\vec{x}+r) \rangle$

$w_p(r_p)$

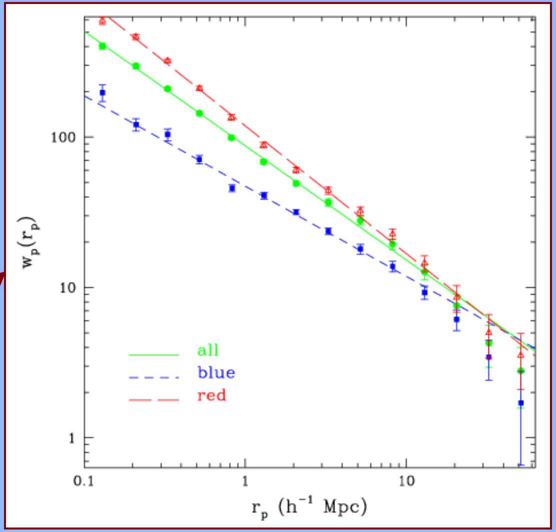


Zehavi et al. (2005)

$\xi_{gg}(r)$



Masjedi et al. (2006)

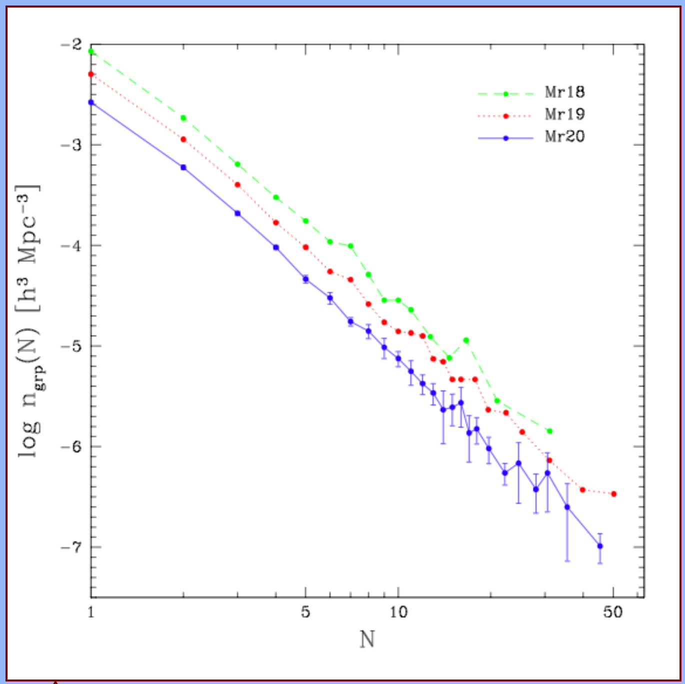


Correlation Functions

Large surveys: Measurements of Galaxy Clustering

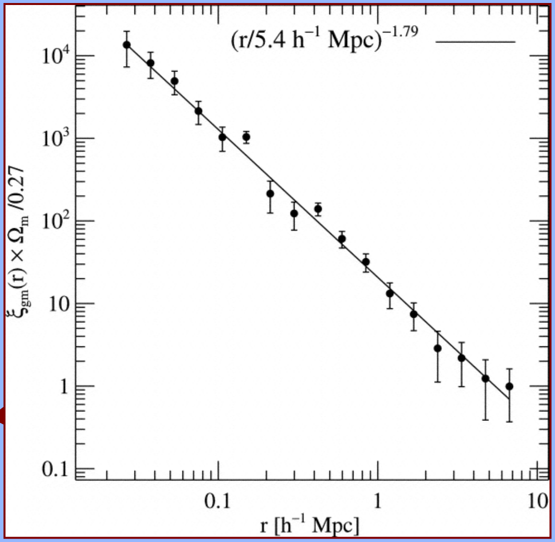
Higher Moments and Other Statistics

$n_{grp}(N)$



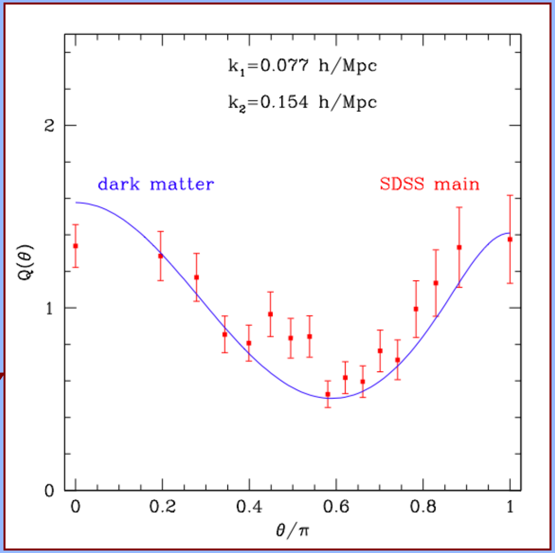
Berlind et al. (2006)

$\xi_{gm}(\rho)$



Sheldon et al. (2005)

$Q(\vartheta)$



Scoccimarro et al. (2006)

Galaxy-Mass Correlations

Group Multiplicity Function

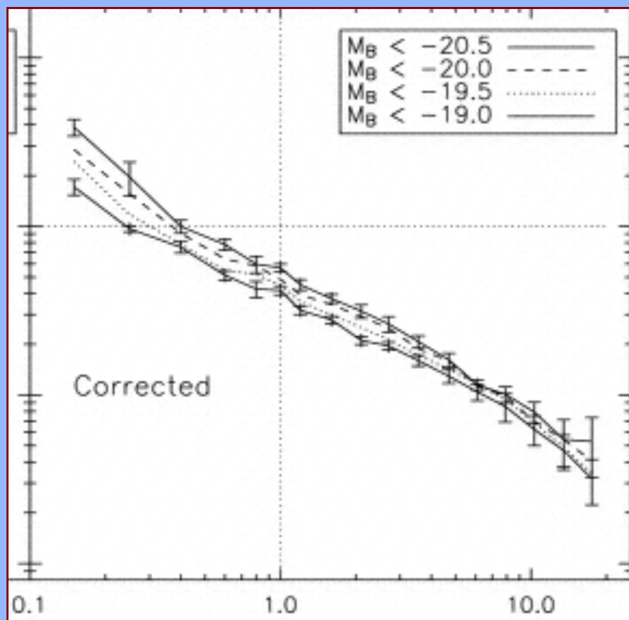
Bispectrum

Large surveys: Measurements of Galaxy Clustering

High Redshift

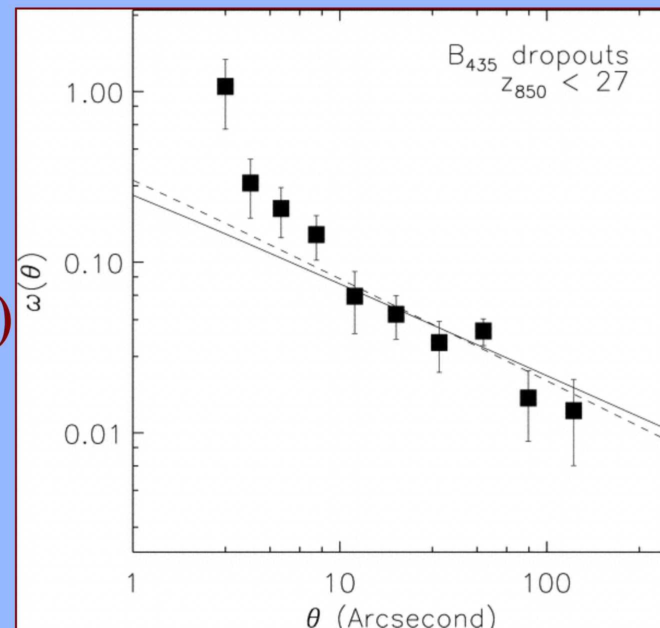
GOODS

$w_p(r_p)$



Coil et al. (2006)

$\omega(\theta)$

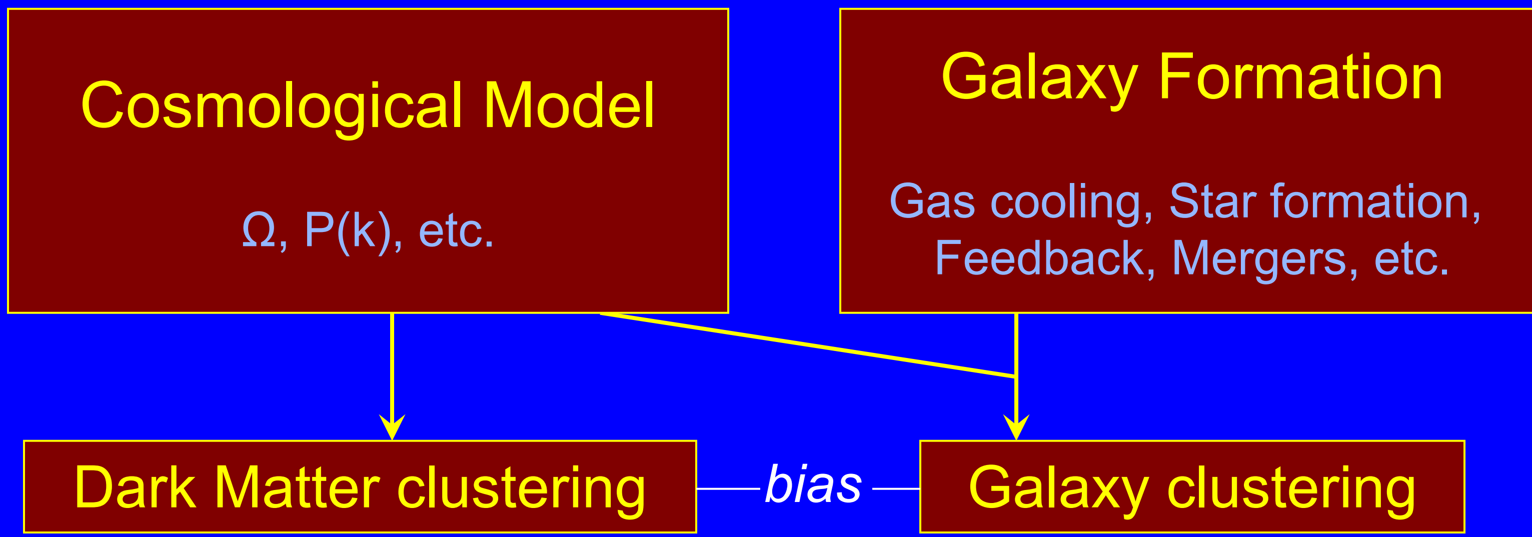


Lee et al. (2006)

Z ~ 1

z ~ 4

Galaxy clustering data contains information about cosmology and galaxy formation/evolution.



How can we extract this information from the data?

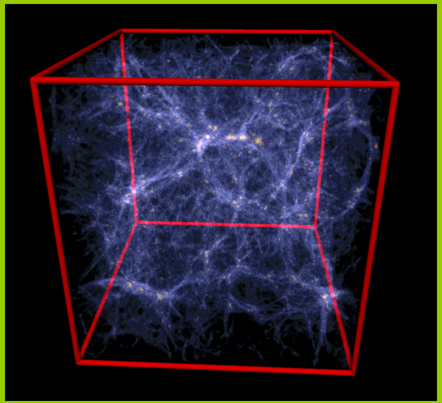
e.g., what does a particular shape of $\xi(r)$ for bright red galaxies tell us about how these galaxies formed? Can we use this statistic to constrain cosmological parameters?

Ab-initio Predictions

Hydrodynamic Simulations of Dark Matter + Gas

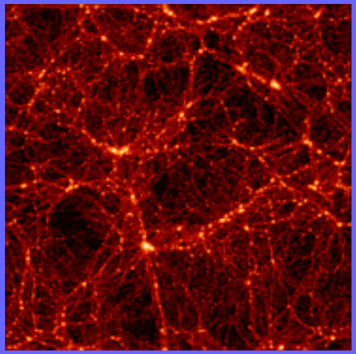
Gravity and Hydrodynamics + Heating and Cooling + Prescriptions for Star Formation and Feedback =

(Sub-grid physics)

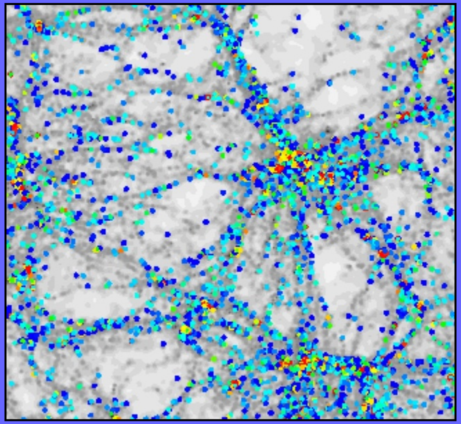


Springel et al.

Semi-Analytic Models



+ Prescriptions for: Gas distribution, Gas Cooling, Star Formation, Feedback, Galaxy Mergers + more in DM halos =



Virgo Consortium

RAMSES code (AMR)

RAMSES code (AMR)

GASOLINE code (SPH)

Gas Rich Mergers and Disk Galaxy Formation

Galaxy formation simulations created at the

N-body shop

makers of quality galaxies

key: gas- green new stars- blue old stars- red

credits:

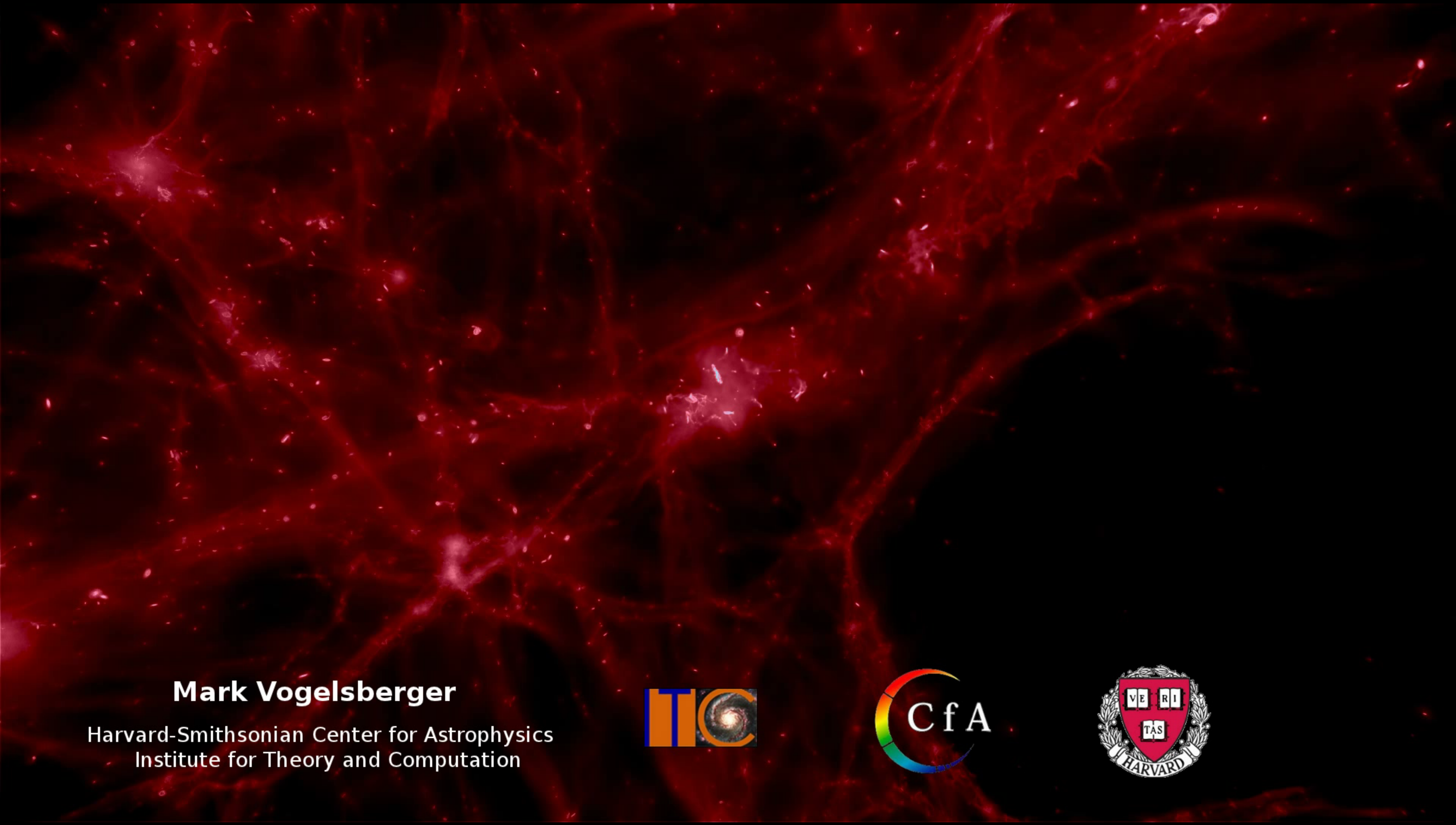
Fabio Governato (University of Washington)
Alyson Brooks (University of Washington)
James Wadsely (McMaster University)
Tom Quinn (University of Washington)
Chris Brook (University of Washington)

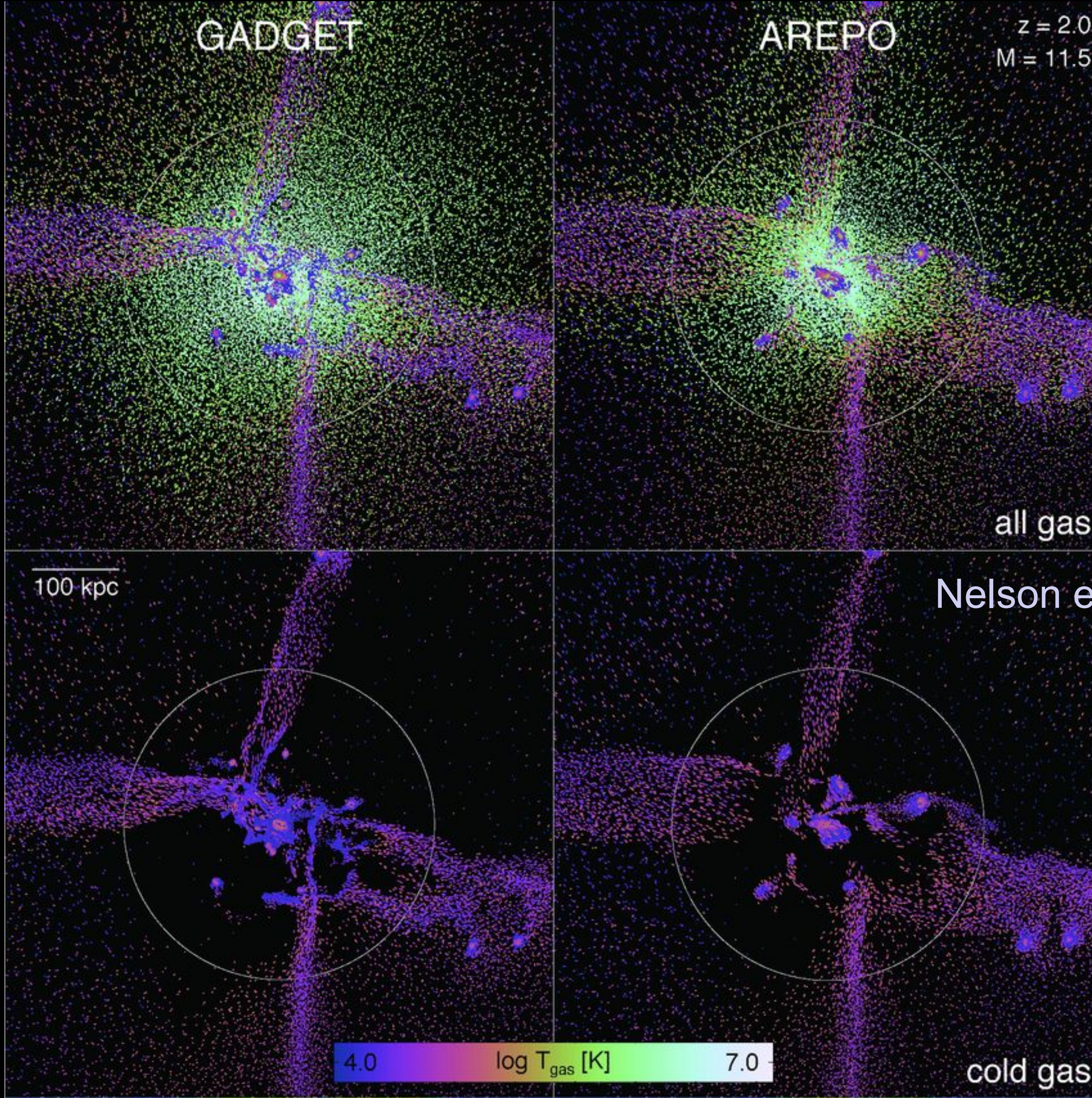
Simulation run on Columbia (NASA Advanced Supercomputing)

contact: fabio@astro.washington.edu

AREPO code (Moving Mesh)

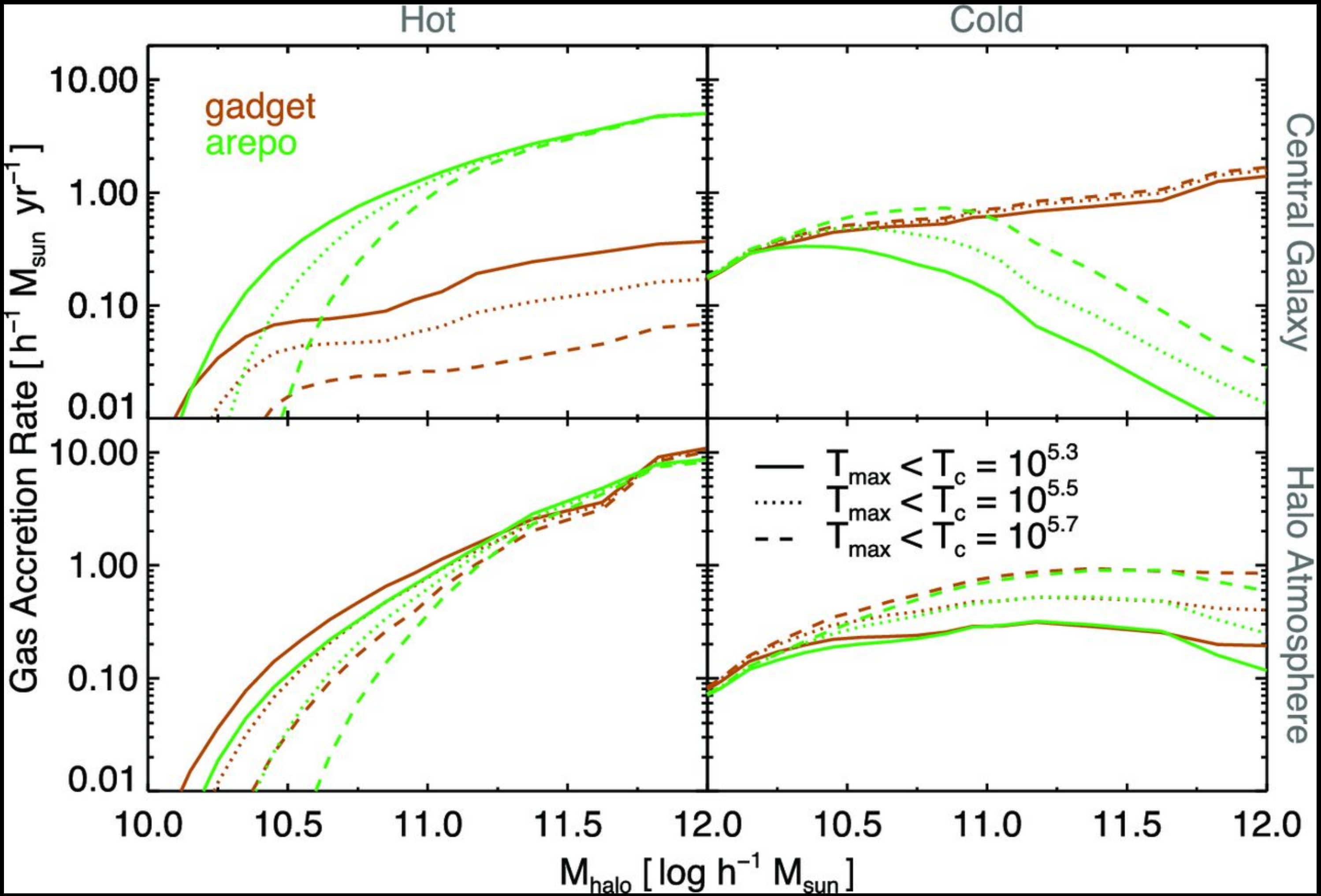
AREPO code (Moving Mesh)



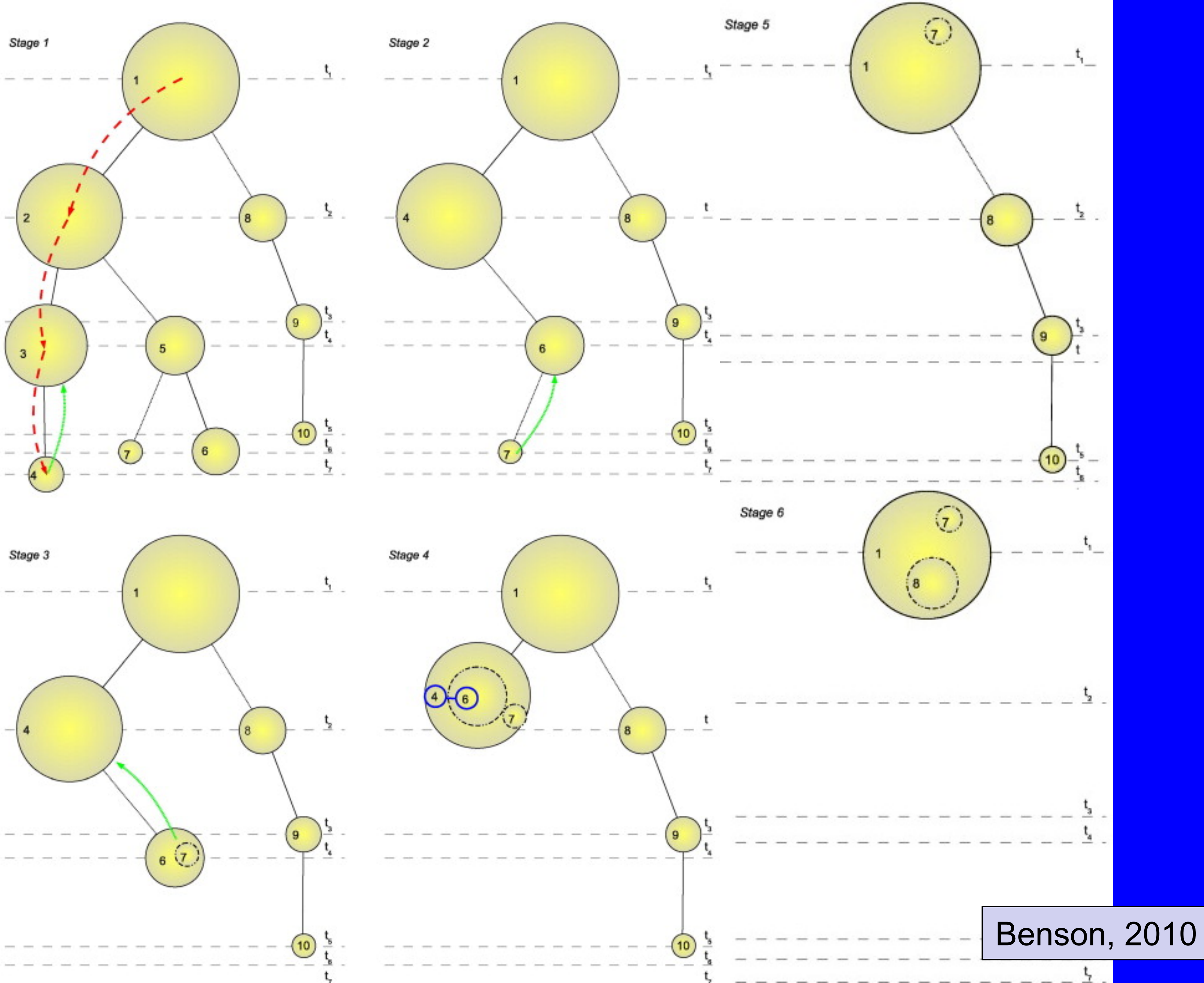


Nelson et al. (2013)

Moving Mesh vs. SPH - Gas accretion



Nelson et al. (2013)


Stage 1
Stage 2
Stage 3
Stage 4
Stage 5
Stage 6
Benson, 2010

Parameter	Value	Reference
[H_0]	70.2 km/s	§4.2; (Komatsu et al., 2010)
[Omega_0]	0.2725	§4.2; (Komatsu et al., 2010)
[Omega_DE]	0.7275	§4.2; (Komatsu et al., 2010)
[Omega_b]	0.0455	§4.2; (Komatsu et al., 2010)
[T_CMB]	2.72548 K	§4.2; (Komatsu et al., 2010)
[accretionDisksMethod]	ADAF	§4.3
[adafAdiabaticIndex]	1.444	§4.3
[adafEnergyOption]	pure ADAF	§4.3
[adafRadiativeEfficiency]	0.01	§4.3
[adafViscosityOption]	fit	§4.3
[adiabaticContractionGnedinA]	0.8	§4.8
[adiabaticContractionGnedinOmega]	0.77	§4.8
[barInstabilityMethod]	ELN	§4.7
[blackHoleSeedMass]	100	§3.1.2
[blackHoleWindEfficiency]	0.001	§3.1.2
[bondiHoyleAccretionEnhancementHotHalo]	1	§3.1.2
[bondiHoyleAccretionEnhancementSpheroid]	1	§3.1.2
[bondiHoyleAccretionTemperatureSpheroid]	100	§3.1.2
[coolingFunctionMethod]	atomic CIE Cloudy	§4.5.1
[coolingTimeAvailableAgeFactor]	0	§4.5.5
[coolingTimeSimpleDegreesOfFreedom]	3	§4.5.4
[darkMatterProfileMethod]	NFW	§4.6.1
[darkMatterProfileMinimumConcentration]	4	§3.8.2
[diskOutflowExponent]	2	§4.23
[diskOutflowVelocity]	200 km/s	§4.23
[effectiveNumberNeutrinos]	4.34	§4.4.2
[galacticStructureRadiusSolverMethod]	adiabatic	§4.8
[haloMassFunctionMethod]	Tinker2008	§4.4.6
[haloSpinDistributionMethod]	Bett2007	§4.6.3
[hotHaloOutflowReturnRate]	1.26	§3.2.2
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[imfSalpeterYieldInstantaneous]	0.02	§4.12.2
[imfSelectionFixed]	Salpeter	§4.12.1
[isothermalCoreRadiusOverVirialRadius]	0.1	§4.10

Benson, 2010

[majorMergerMassRatio]	0.1	§4.9.1
[mergerRemnantSizeOrbitalEnergy]	1	§4.9.2
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[mergerTreeBuildCole2000MassResolution]	$5 \times 10^9 M_\odot$	§4.16
[mergerTreeBuildCole2000MergeProbability]	0.1	§4.16
[mergerTreeConstructMethod]	build	§4.14
[minorMergerGasMovesTo]	spheroid	§4.9.1
[modifiedPressSchechterFirstOrderAccuracy]	0.1	§4.15
[modifiedPressSchechterG0]	0.57	§4.15
[modifiedPressSchechterGamma1]	0.38	§4.15
[modifiedPressSchechterGamma2]	-0.01	§4.15
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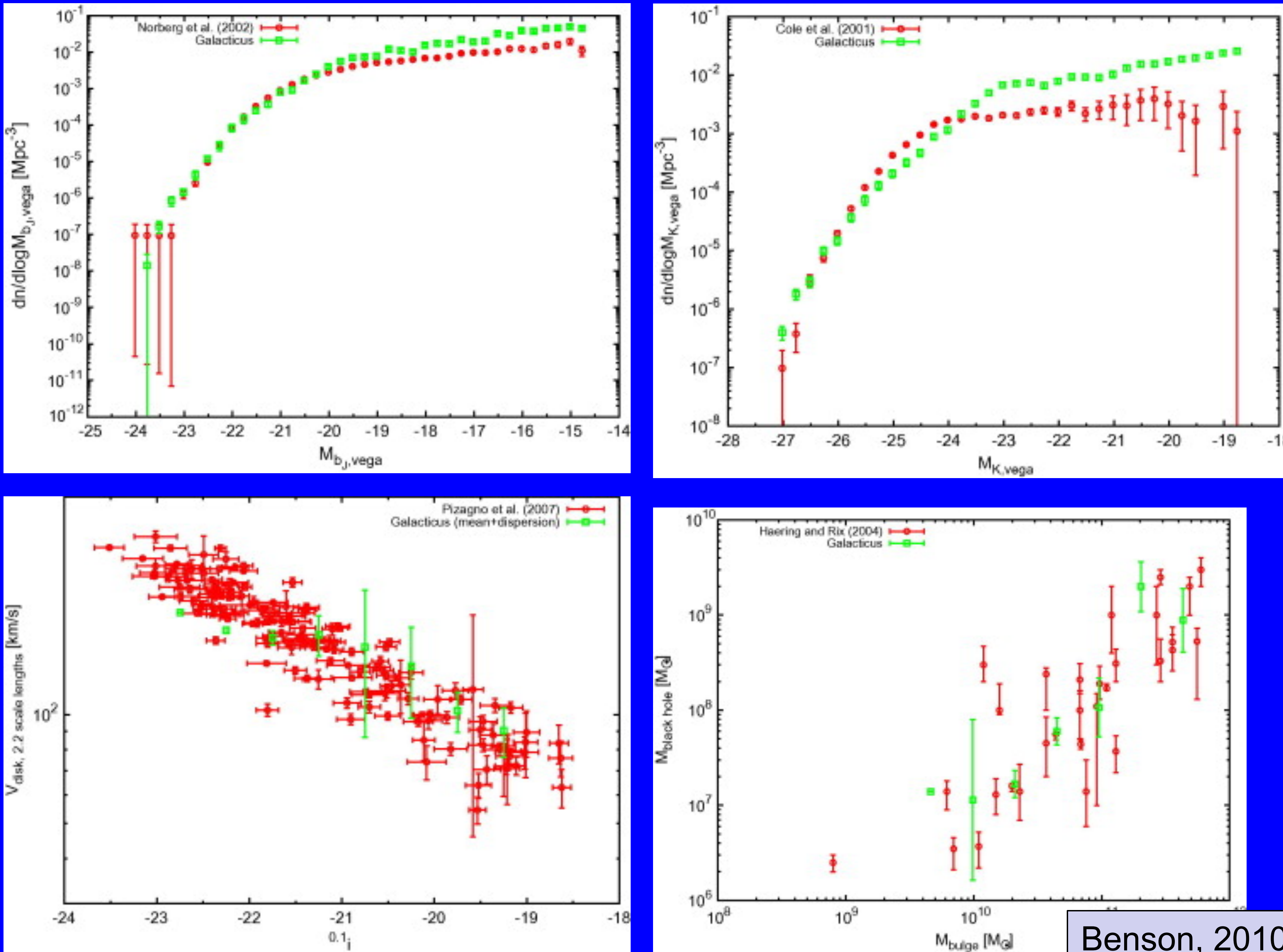
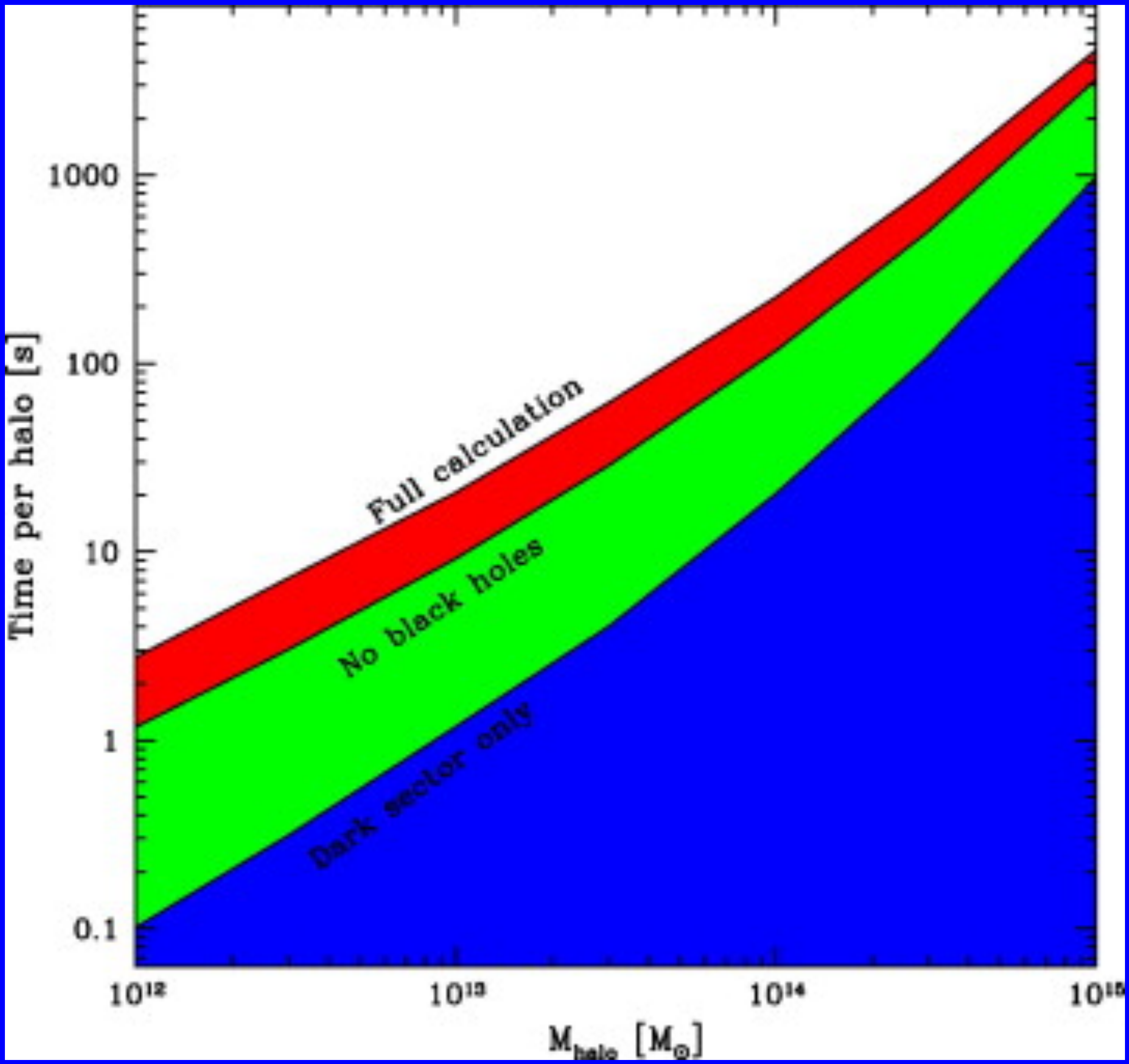
[powerSpectrumReferenceWavenumber]	1 Mpc^{-1}	§4.4.1; (Komatsu et al., 2010)
[powerSpectrumRunning]	0	§4.4.1; (Komatsu et al., 2010)
[randomSpinResetMassFactor]	2	§3.7.2
[reionizationSuppressionRedshift]	9	§4.1
[reionizationSuppressionVelocity]	30 km/s	§4.1
[satelliteMergingMethod]	Jiang2008	§4.22.1
[sigma_8]	0.807	§4.4.1 & §4.4.2
[spheroidEnergeticOutflowMassRate]	1	§3.4.2
[spheroidOutflowExponent]	2	§4.23
[spheroidOutflowVelocity]	50 km/s	§4.23
[spinDistributionBett2007Alpha]	2.509	§4.6.3
[spinDistributionBett2007Lambda0]	0.04326	§4.6.3
[stabilityThresholdGaseous]	0.9	§4.7
[stabilityThresholdStellar]	1.1	§4.7
[starFormationDiskEfficiency]	0.01	§4.17
[starFormationDiskMinimumTimescale]	0.001 Gyr	§4.17
[starFormationDiskVelocityExponent]	-1.5	§4.17
[starFormationSpheroidEfficiency]	0.1	§4.17
[starFormationSpheroidMinimumTimescale]	0.001 Gyr	§4.17
[starveSatellites]	true	§3.2.2
[stellarPopulationPropertiesMethod]	instantaneous	§4.18
[summedNeutrinoMasses]	0	§4.4.2
[transferFunctionMethod]	Eisenstein + Hu	§4.4.2
[virialDensityContrastMethod]	spherical top hat	§4.4.5

Benson, 2010



Norberg et al. (2002)
Galacticus
dn/dlogM_bJ,vega [Mpc^-3]
M_bJ,vega
Cole et al. (2001)
Galacticus
dn/dlogM_K,vega [Mpc^-3]
M_K,vega
Pizagno et al. (2007)
Galacticus (mean+dispersion)
V_disk, 2.2 scale lengths [km/s]
0.1i
Haering and Rix (2004)
Galacticus
M_black hole [M_⊙]
M_bulge [M_⊙]

Benson, 2010



Time per halo [s]
1000
100
10
1
0.1
Full calculation
No black holes
Dark sector only
10^{12}
10^{13}
10^{14}
10^{15}
M_{halo} [$M_\odot$]

Benson, 2010

Forward approach is not practical

- Hydrodynamic simulations take too long + cannot resolve much of the important physics → make many assumptions.

- Semi-analytic models have too many free parameters and do not necessarily include all the relevant physics.

For constraining cosmological parameters: too many uncertainties in galaxy formation physics. We can predict dark matter clustering to fairly high precision, but we have trouble going from DM to galaxies.

For constraining galaxy formation physics: difficult to understand how parameters affect clustering statistics. *e.g., what does it mean if a model predicts a 3-point correlation function that is too high for faint red galaxies?*

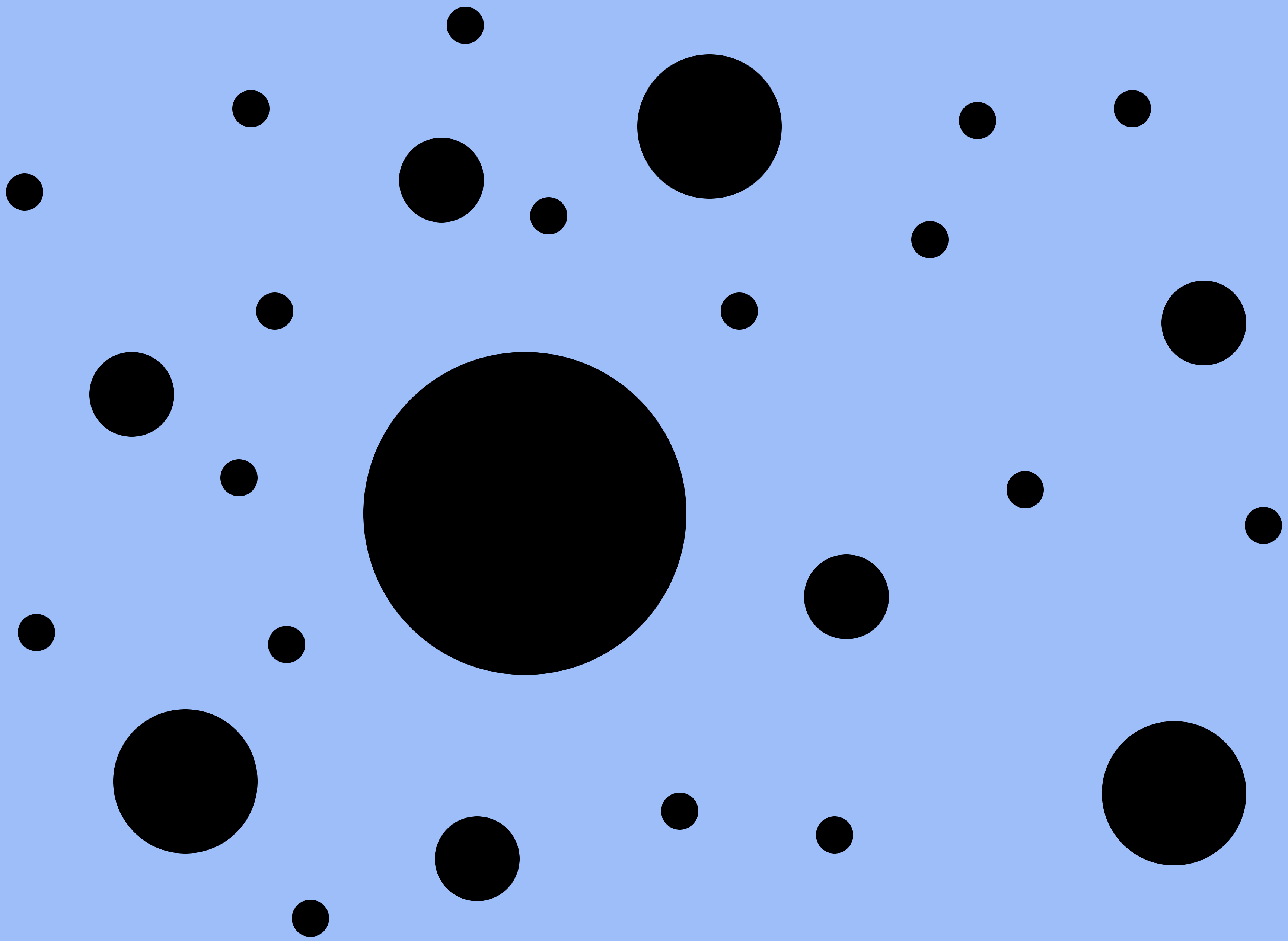
“Halo Occupation” Bias

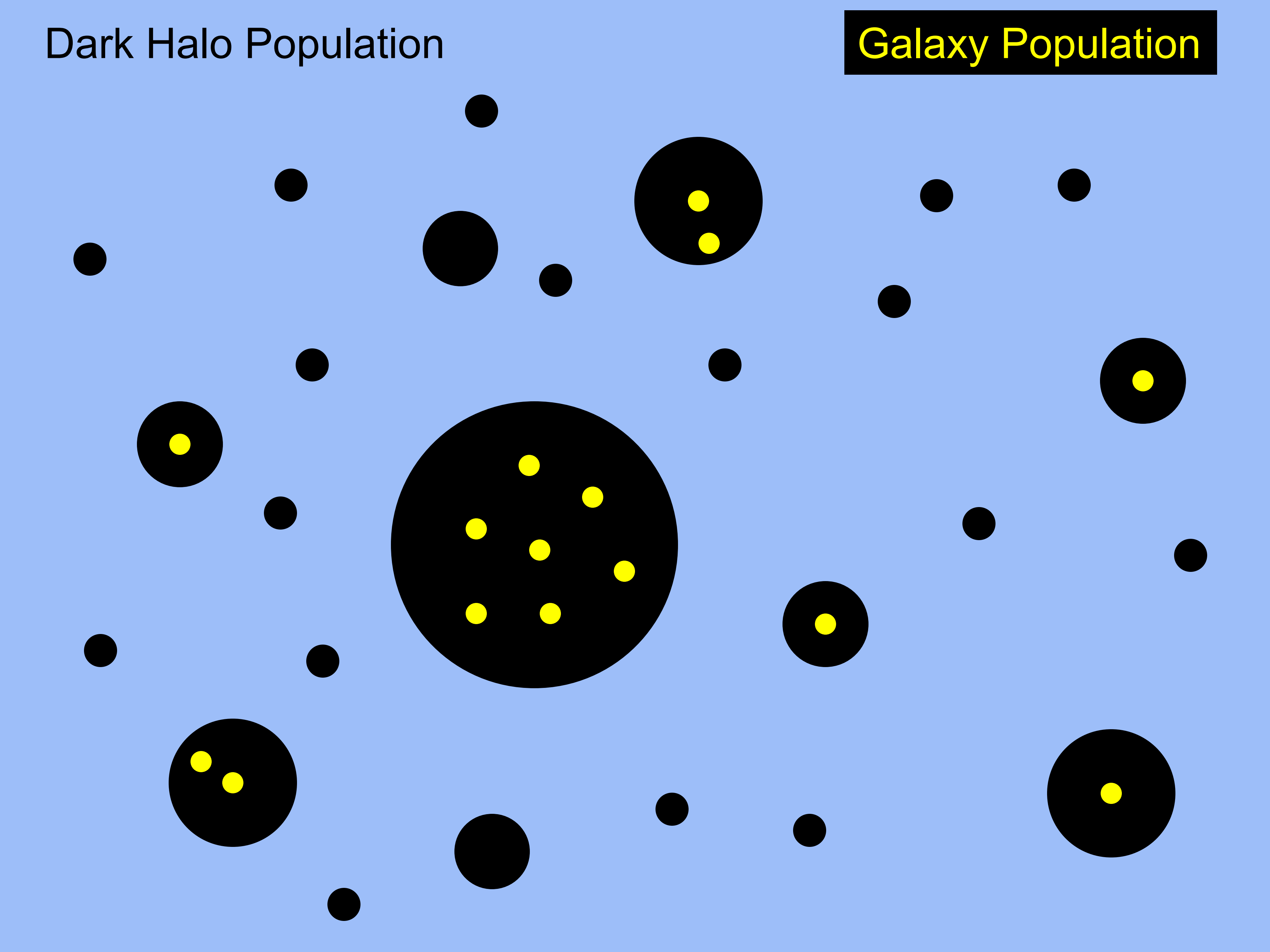
1. All galaxies live in DM halos
2. The galaxy content of a halo is statistically independent of the halo’s larger scale environment (depends only on mass)

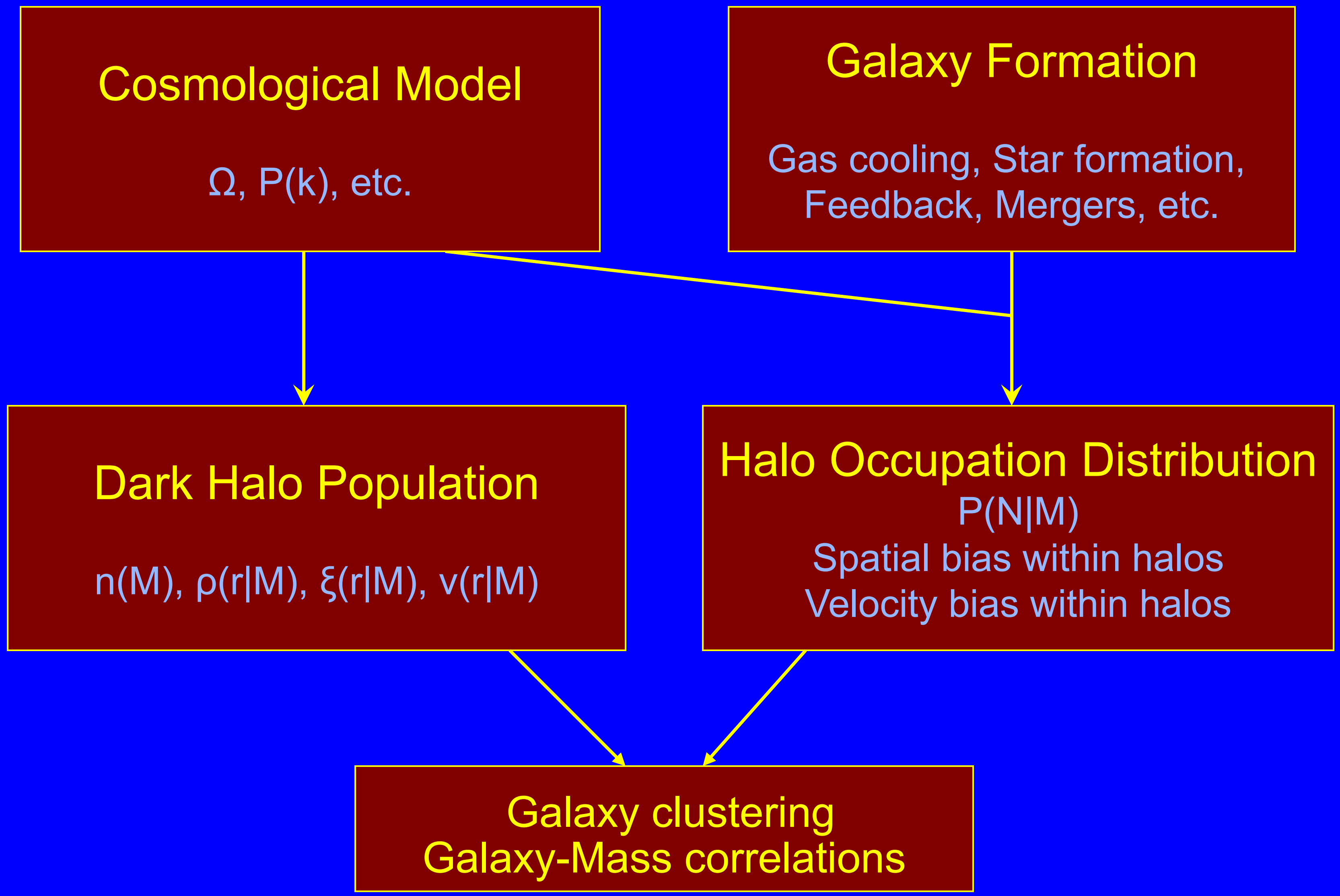
The bias of any class of galaxies (luminosity, type, etc.) is fully defined by the Halo Occupation Distribution (HOD):

- The probability distribution $P(N|M)$ that a halo of mass M contains N galaxies of that class.
- The relation between the spatial distributions of galaxies and DM within halos.
- The relation between the velocity distributions of galaxies and DM within halos.

Dark Halo Population




Dark Halo Population
Galaxy Population


Cosmological Model
Ω, P(k), etc.
Galaxy Formation
Gas cooling, Star formation, Feedback, Mergers, etc.
Dark Halo Population
n(M), ρ(r|M), ξ(r|M), v(r|M)
Halo Occupation Distribution
P(N|M)
Spatial bias within halos
Velocity bias within halos
Galaxy clustering
Galaxy-Mass correlations

Why is the Halo Occupation Distribution (HOD) the right way to think about bias?

- **Complete:** It tells us everything a theory of galaxy formation has to say about galaxy clustering (all statistics, all scales).
- **Physically illuminating:** Discrepancies offer guidance about their physical origin.
- **Observationally powerful:** Description of bias at the level of systems in dynamic equilibrium, where methods can constrain mass.

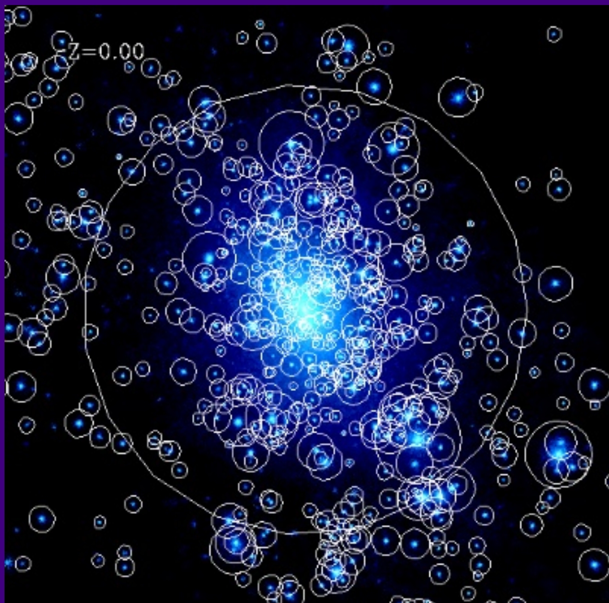
Nice conceptual division between roles of “cosmological model” and “theory of Galaxy formation”.

The basic approach.

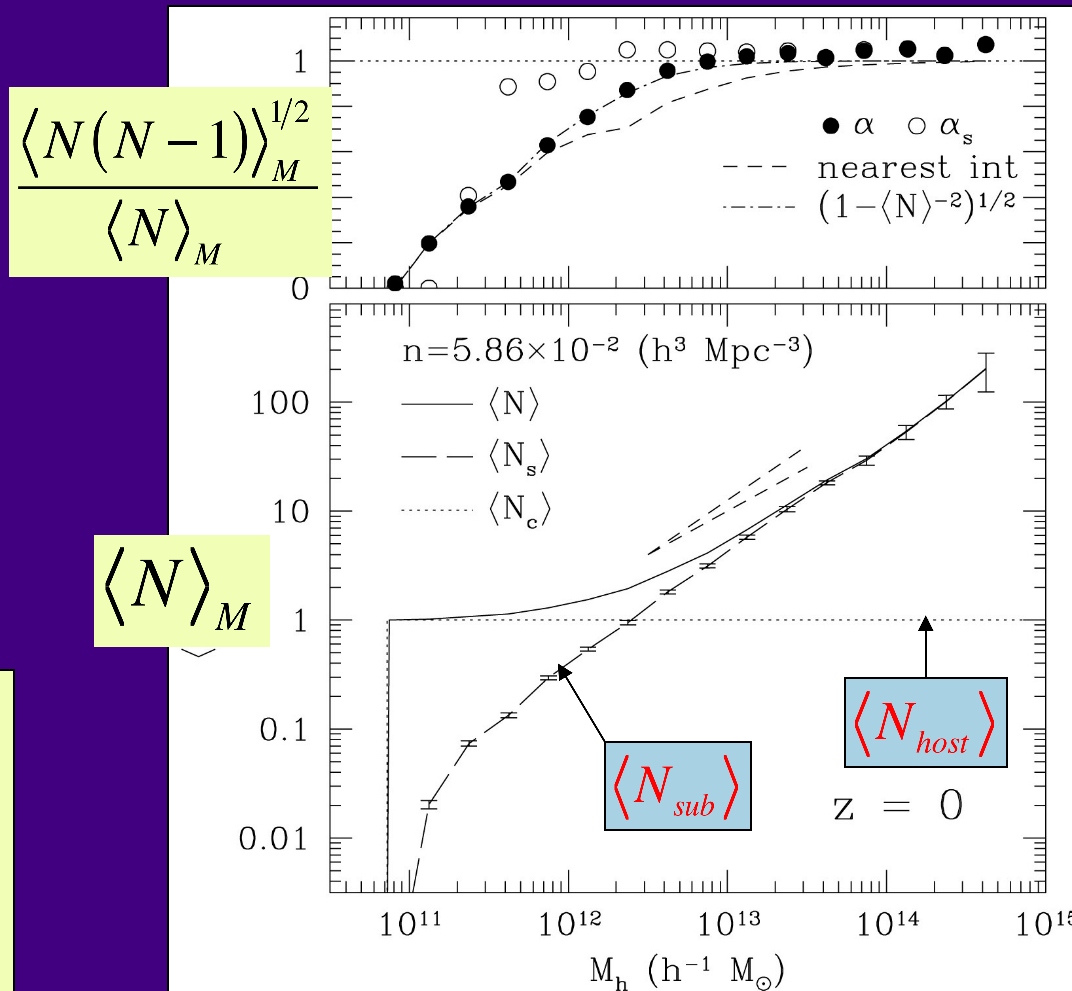
- We know how to go from cosmological parameters to halo properties.
- Parameterize the HOD (and thus our ignorance about galaxy formation).
- Develop machinery to compute galaxy clustering statistics given halo properties (mass function, etc.) + HOD.
- Fit cosmological + HOD parameters (or HOD parameters at fixed cosmology) to galaxy clustering measurements.
- Use measured HODs to gain insight into galaxy formation.

How do we parameterize the HOD?

N-body



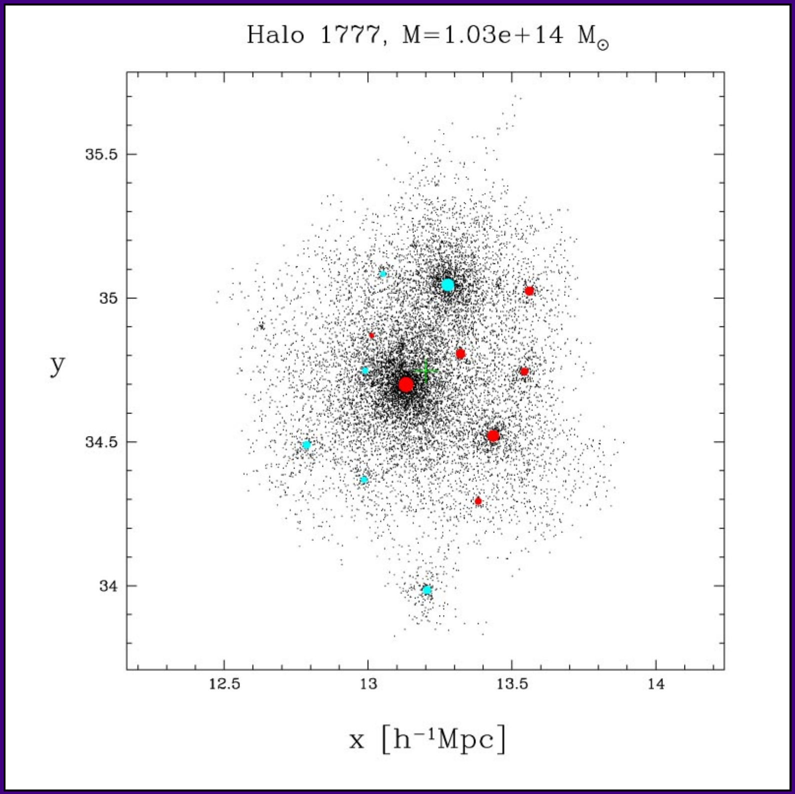
- HOD for halos + subhalos.
- $\langle N_{sub} \rangle$ is a power law with slope ~1.
- Distribution about $\langle N_{sub} \rangle$ is Poisson.

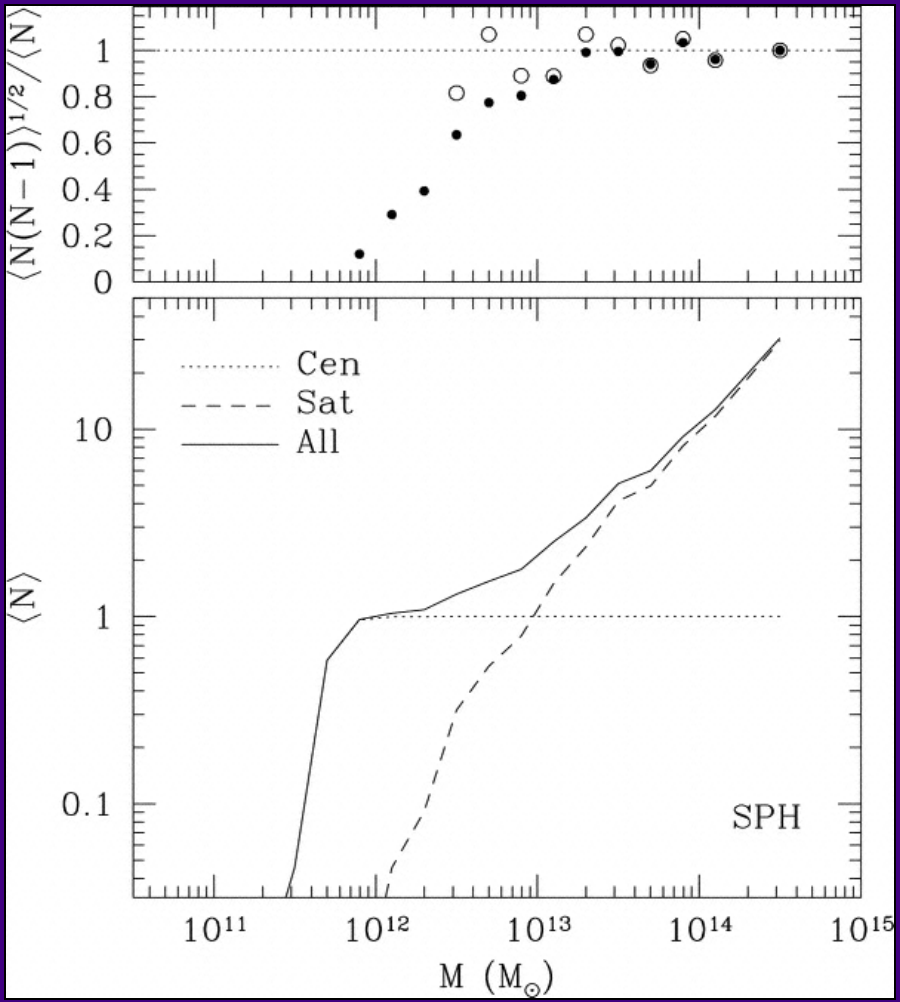


Kravtsov, Berlind et al. (2004)

How do we parameterize the HOD?

SPH

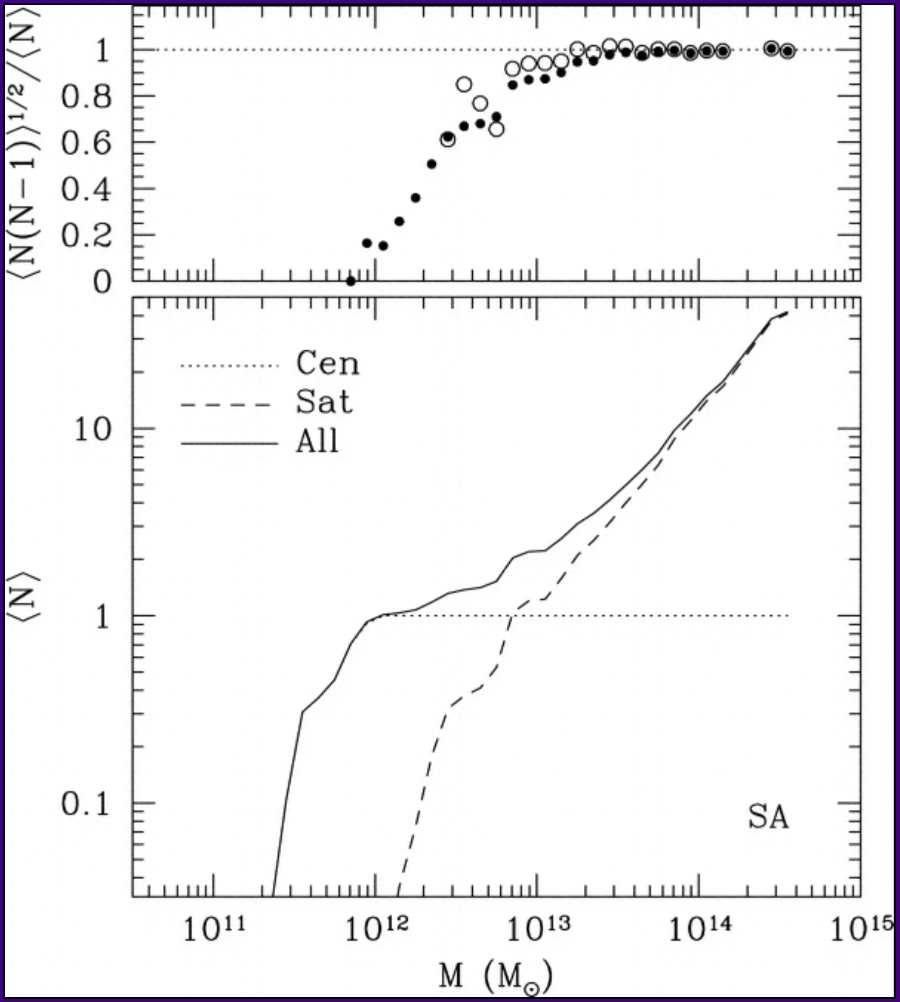




Zheng, Berlind et al. (2005)

How do we parameterize the HOD?

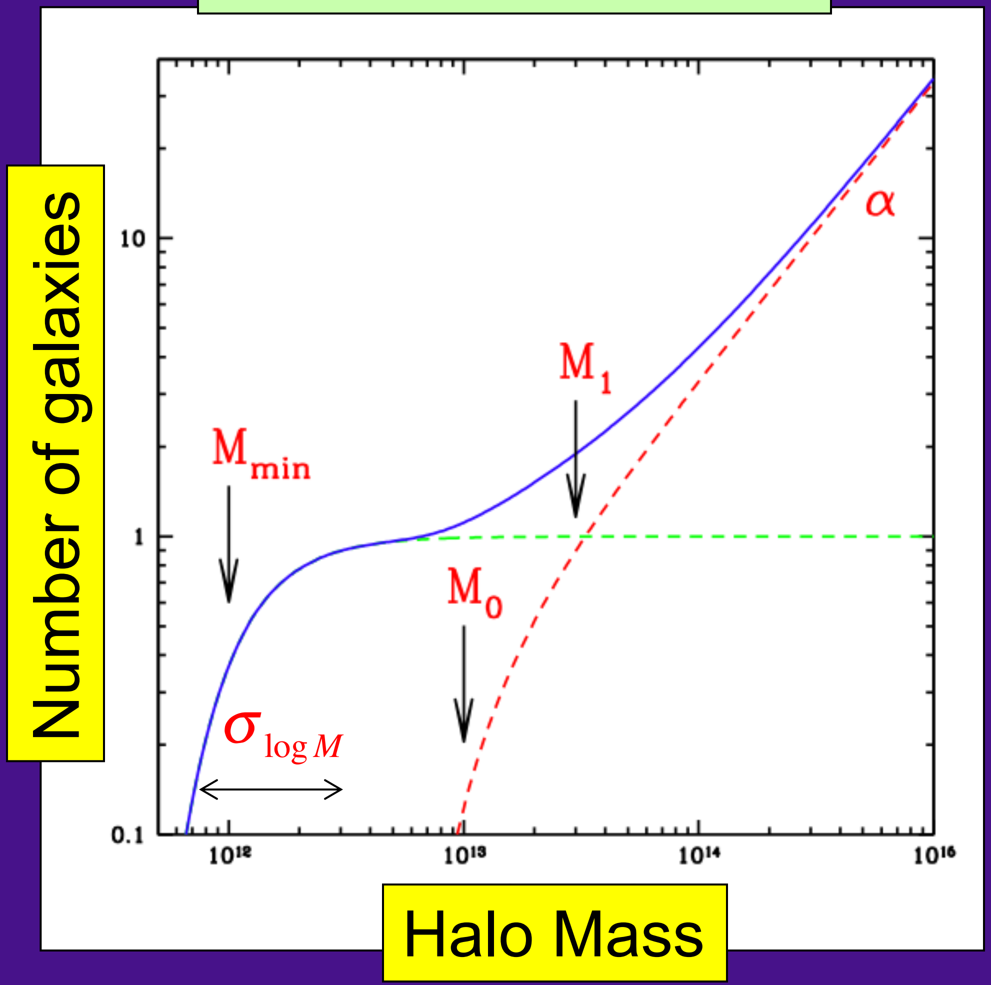
Semi-Analytic

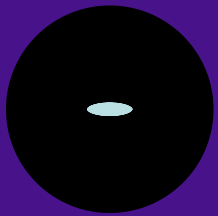


Zheng, Berlind et al. (2005)

How do we parameterize the HOD?

$$\langle N \rangle = \langle N_{cen} \rangle + \langle N_{sat} \rangle$$



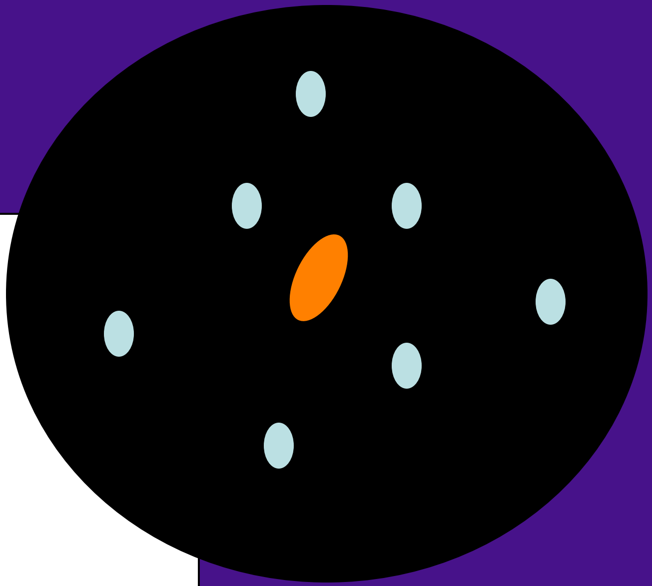


How do we parameterize the HOD?

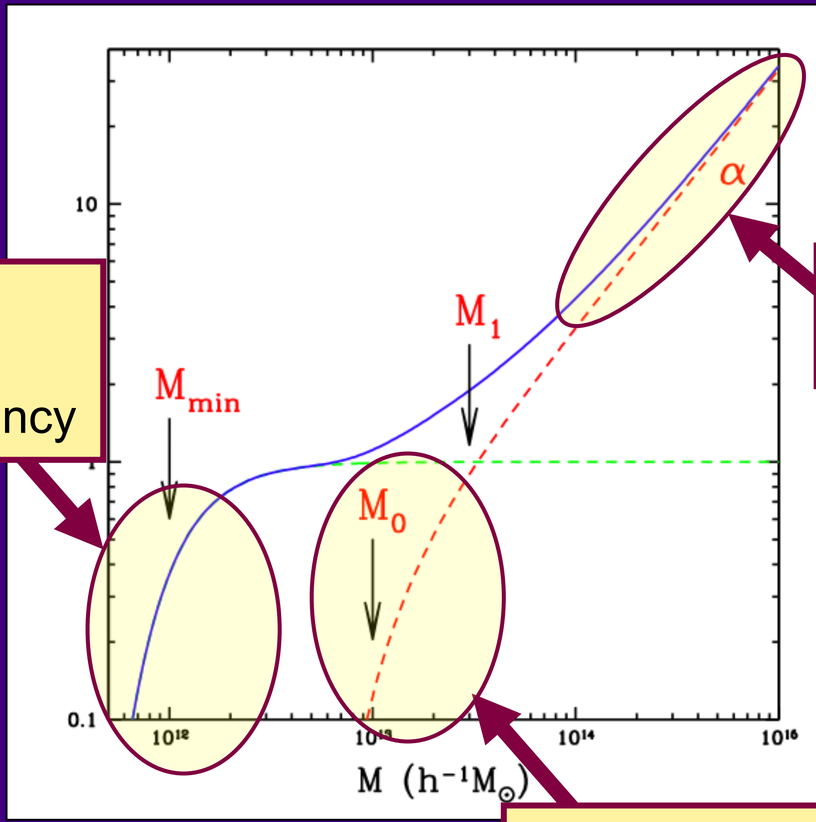
Assume:

- Central galaxy resides at halo center

- Satellite galaxies trace the DM density distribution within the halo



The HOD contains information about physics!

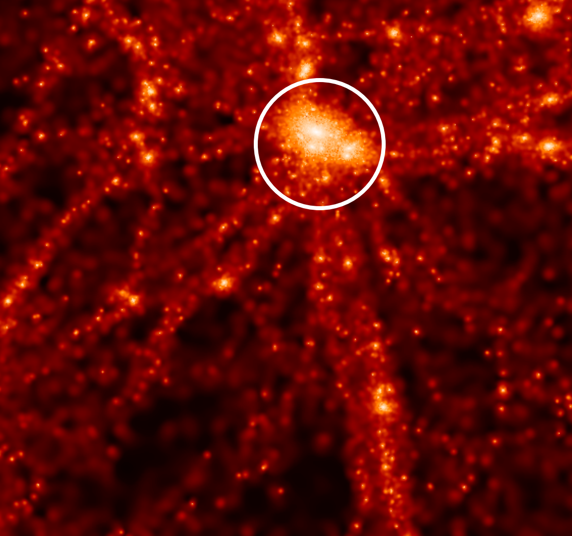


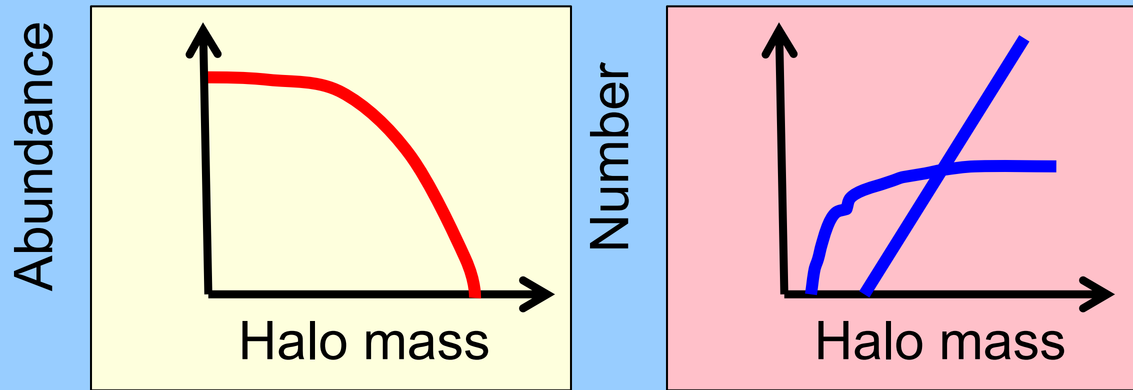
Baryon/DM fraction
Gas cooling
Star formation efficiency

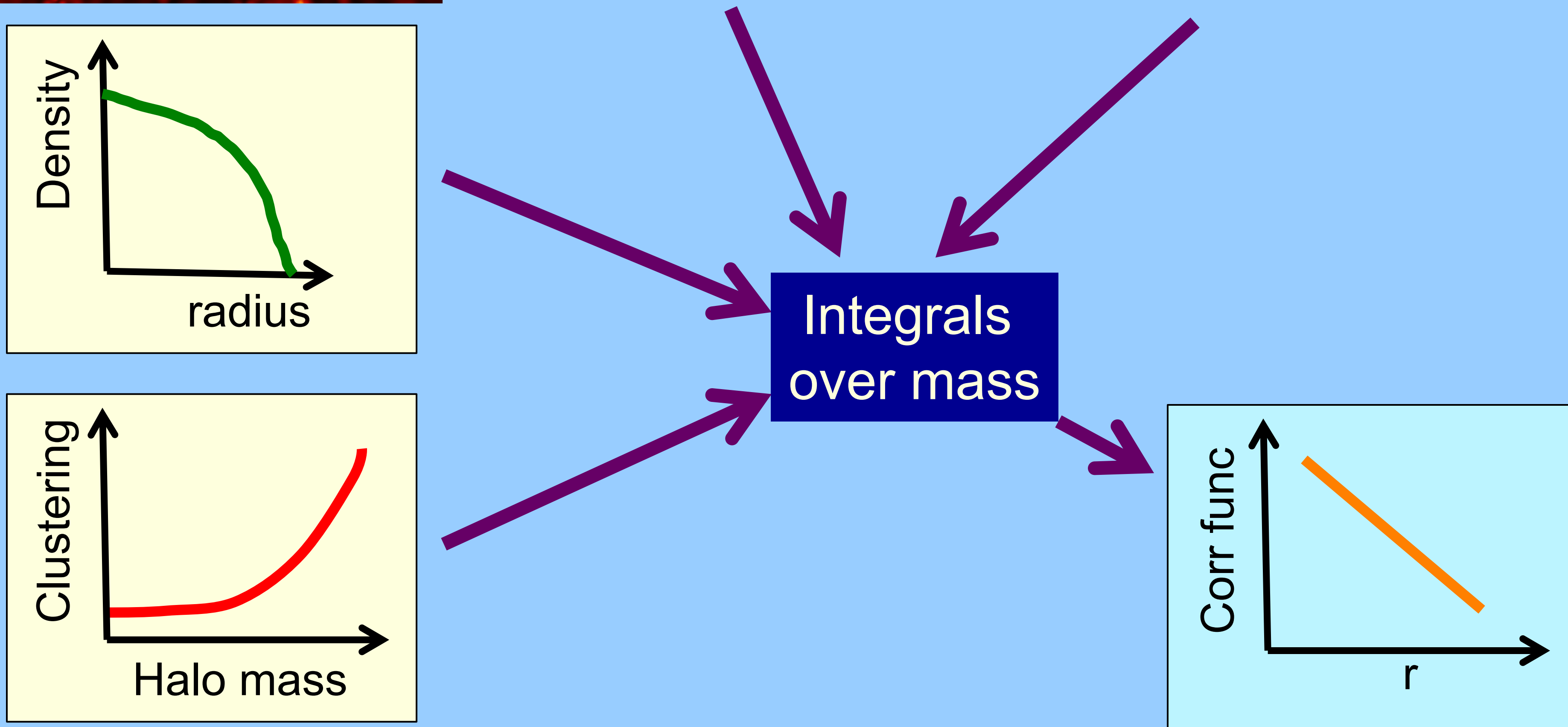
Dynamical friction
Tidal disruption

DM halo merger statistics

The Analytic Halo Model







How do we compute clustering statistics?

Number density

$$n_g = \int_0^\infty dM \frac{dn}{dM} \langle N \rangle_M$$

Berlind & Weinberg (2002)

How do we compute clustering statistics?

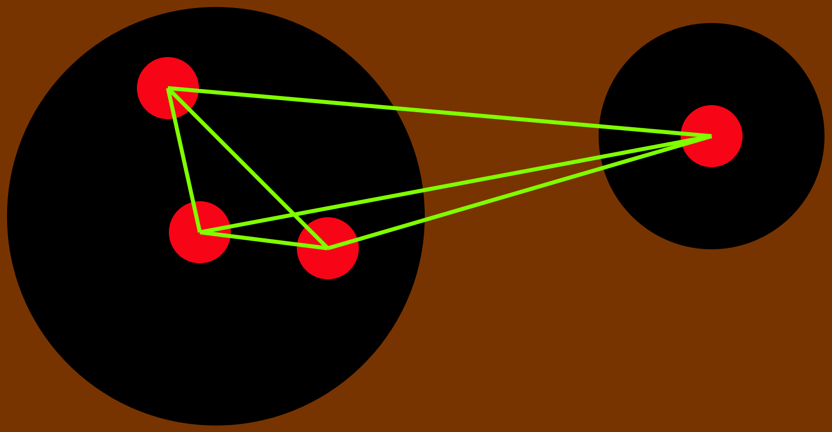
2-pointCorrelation function

Small scales: All pairs come from same halo.
1-halo term

$$1+\xi_g^{1h}(r)=\left(2\pi r^2 n_g^2\right)^{-1}\int_0^\infty dM\,\frac{dn}{dM}\frac{\langle N(N-1)\rangle_M}{2}\lambda(r|M)$$

Large scales: Pairs come from separate halos.
2-halo term

$$\xi_g(r)=b_g{}^2\xi_m(r)$$

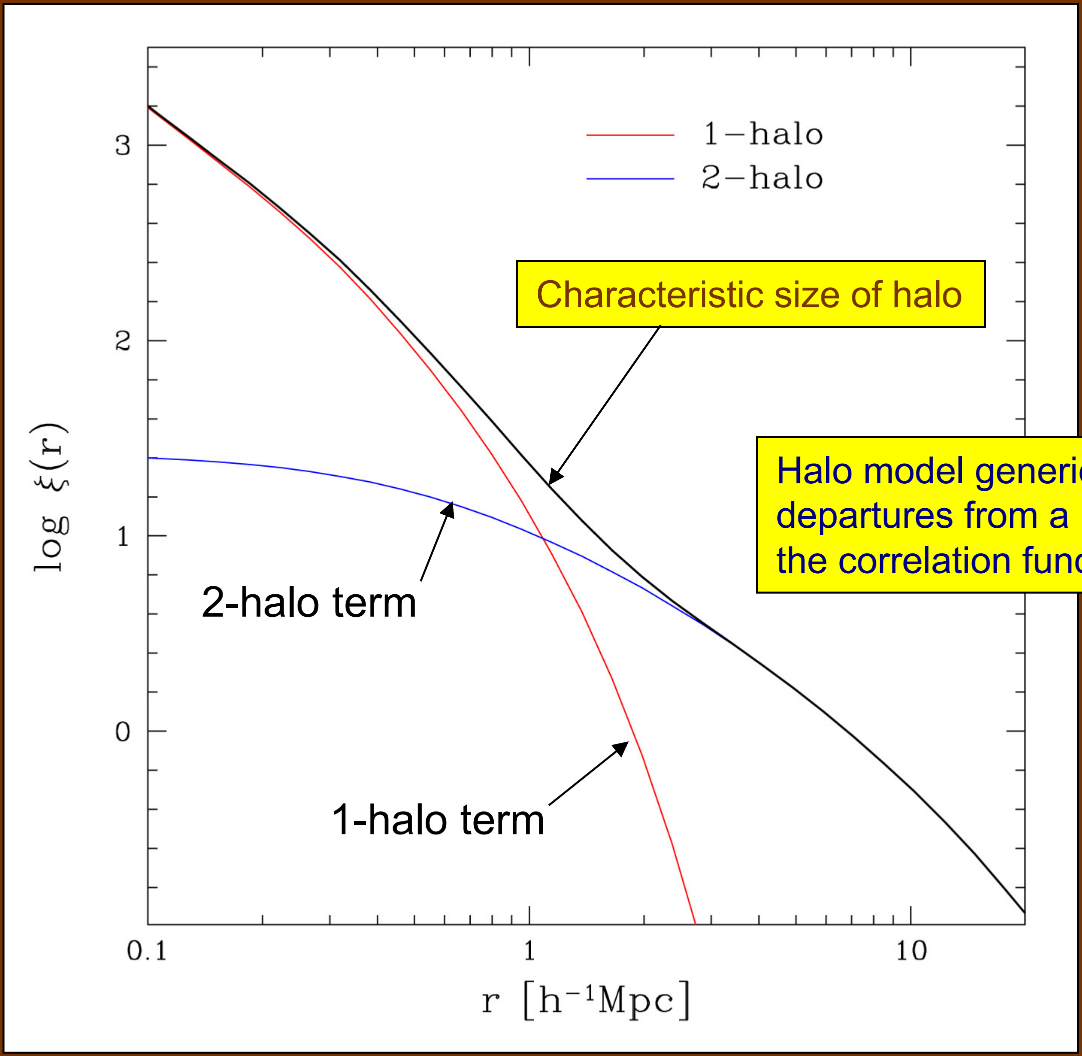


$$b_g=n_g^{-1}\int_0^\infty dM\,\frac{dn}{dM}\langle N\rangle_M b_h(M)$$

Berlind & Weinberg (2002)

How do we compute clustering statistics?

2-point correlation function



Halo model generically predicts departures from a power law in the correlation function.

How do we compute clustering statistics?

N-point correlation functions

3-point function has 3 terms: 1-halo, 2-halo, 3-halo
1-halo term depends on <N(N-1)(N-2)>

Redshift-space and velocity statistics

Need model for velocity distribution in DM halo
+ velocity bias for galaxies

Luminosity function

$$\Phi(L) = \int_0^\infty dM \, \frac{dn}{dM} \langle N(M, L) \rangle$$

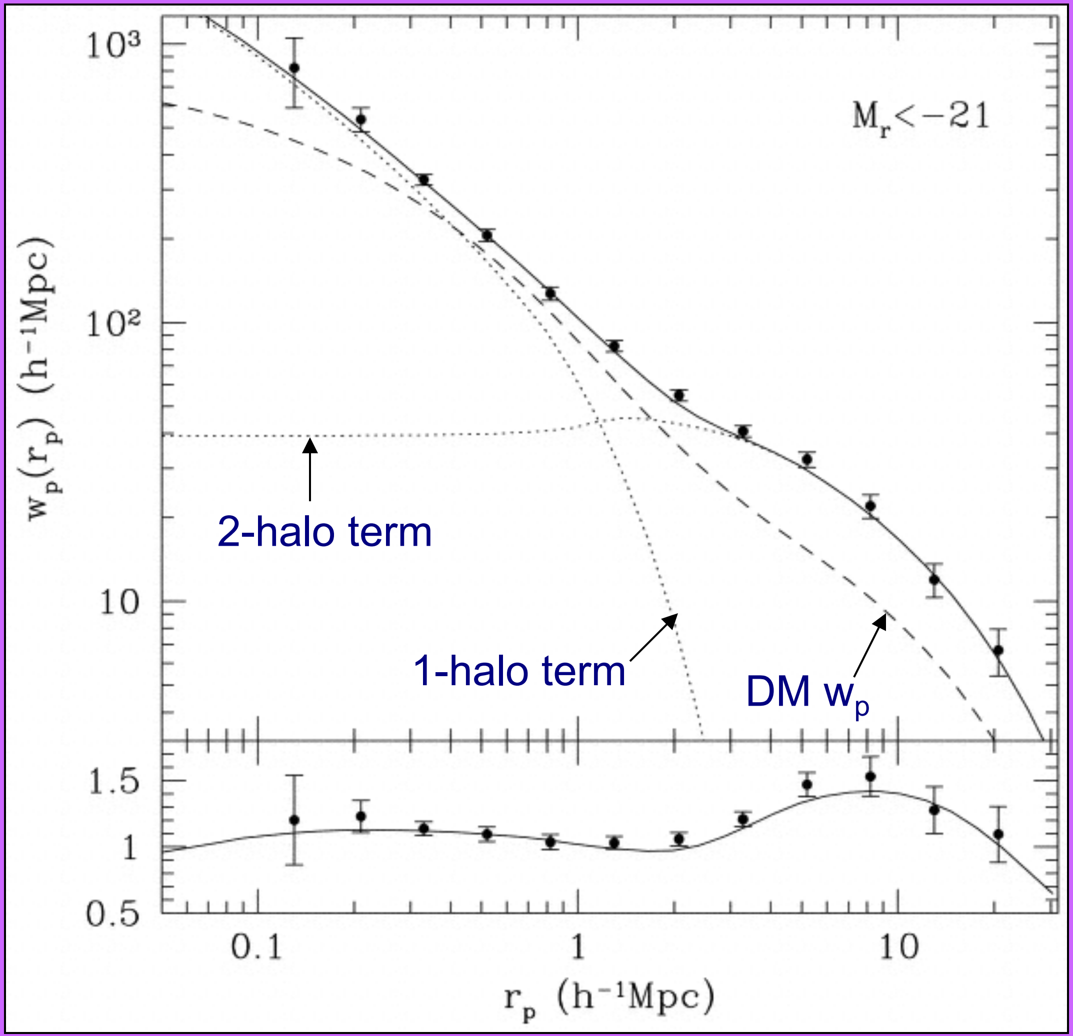
How do we compute clustering statistics?

Improvements to standard halo model

- Non-linear P(k) in 2-halo term
- Scale dependence of halo bias: b(M,r)
- Halo exclusion
- Non-spherical halos
- Non-NFW profiles
- Dependence of b(M) and/or P(N|M) on halo assembly history
- Parameterize P(N|M) for non-trivial galaxy populations

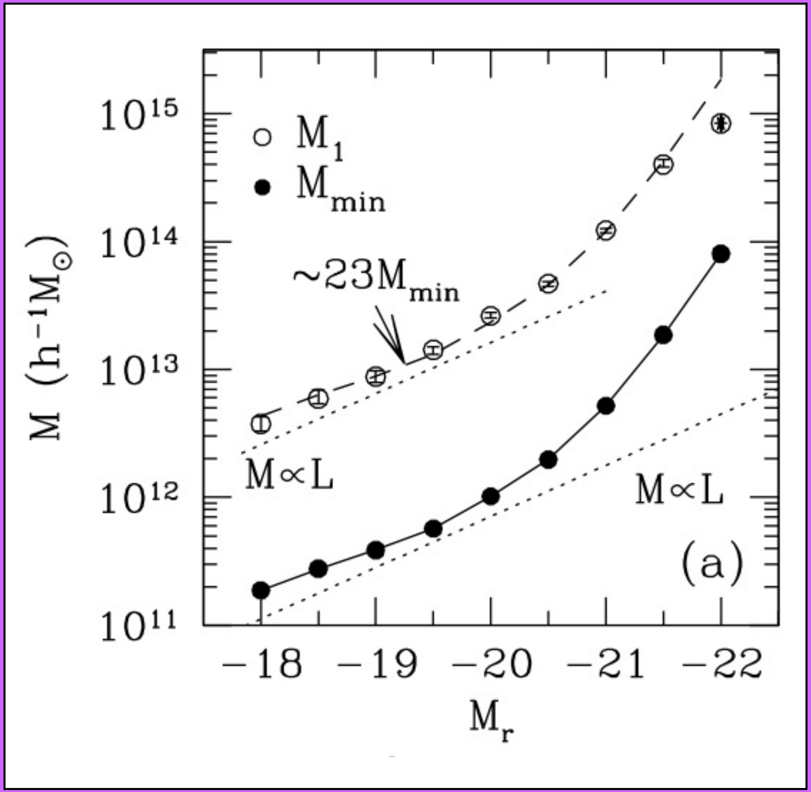
Measurements of the HOD

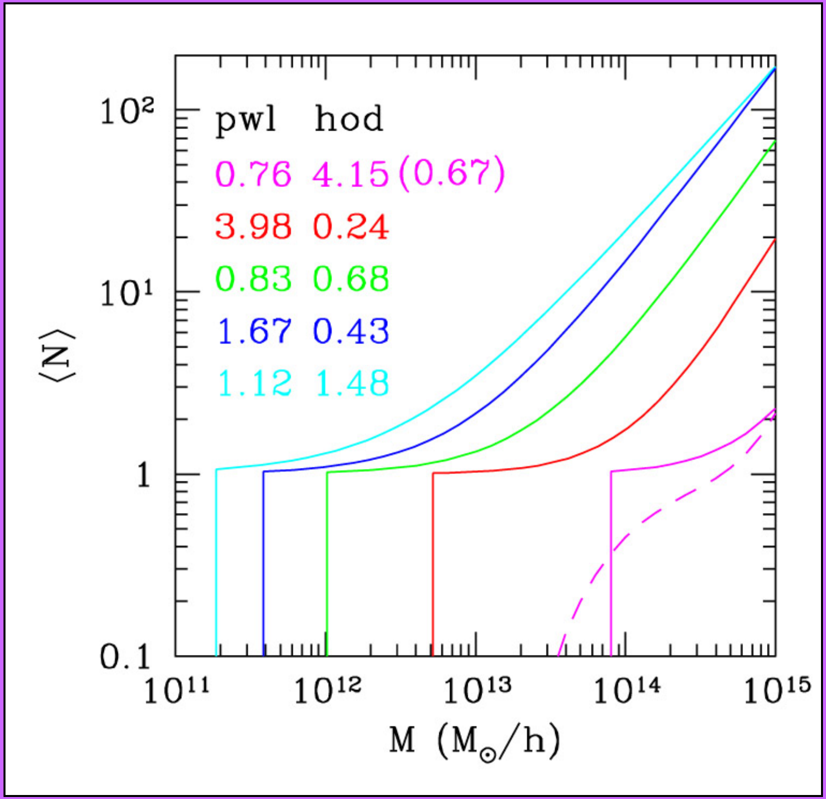
Deviation from power law detected. Halo model gives a good fit to the data. (χ^2/*dof = 0.93 vs. 6.12 for plaw*)



Zehavi et al. (2004)

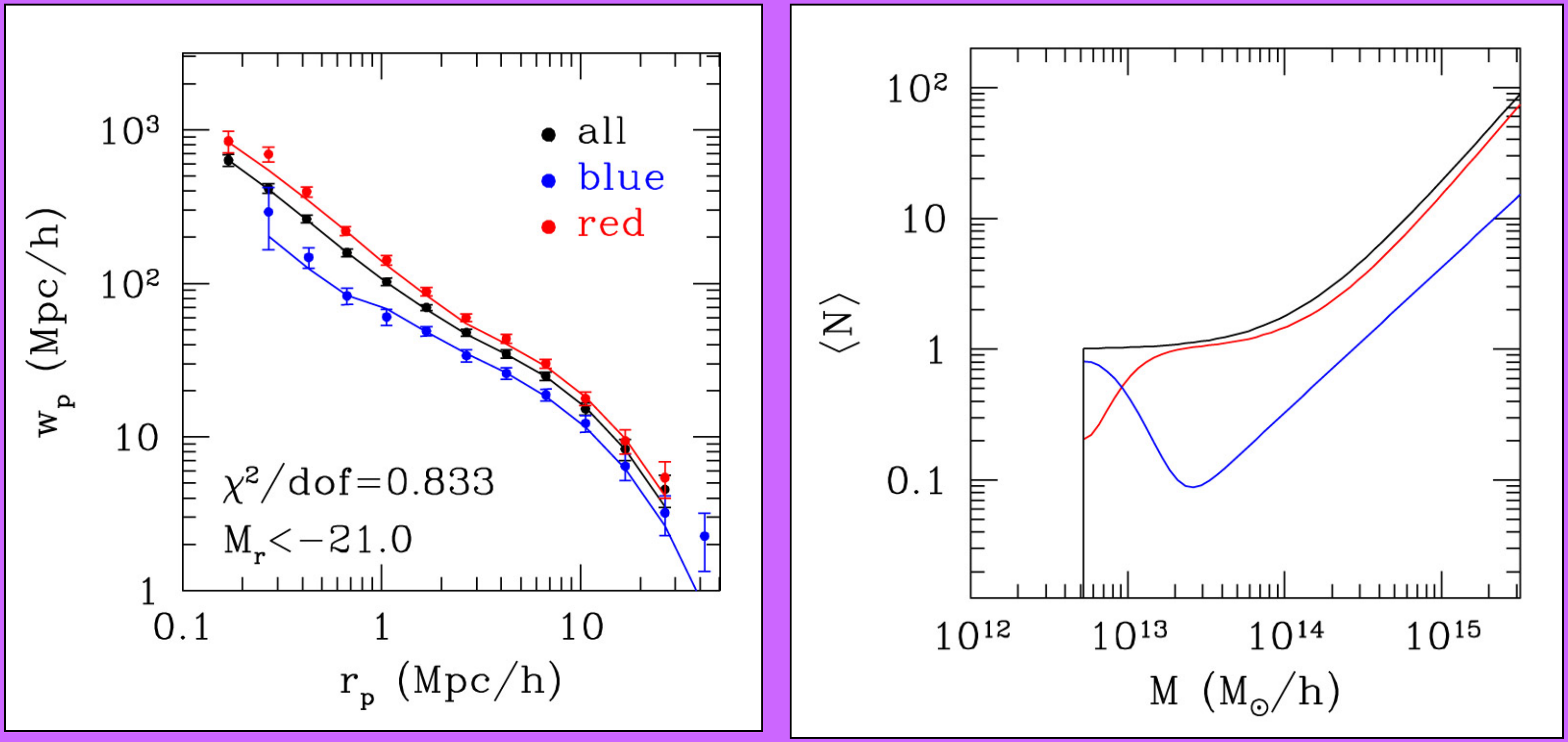
Measurements of the HOD





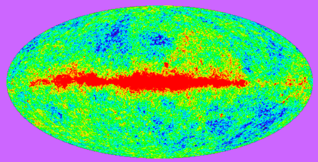
Zehavi et al. (2005)

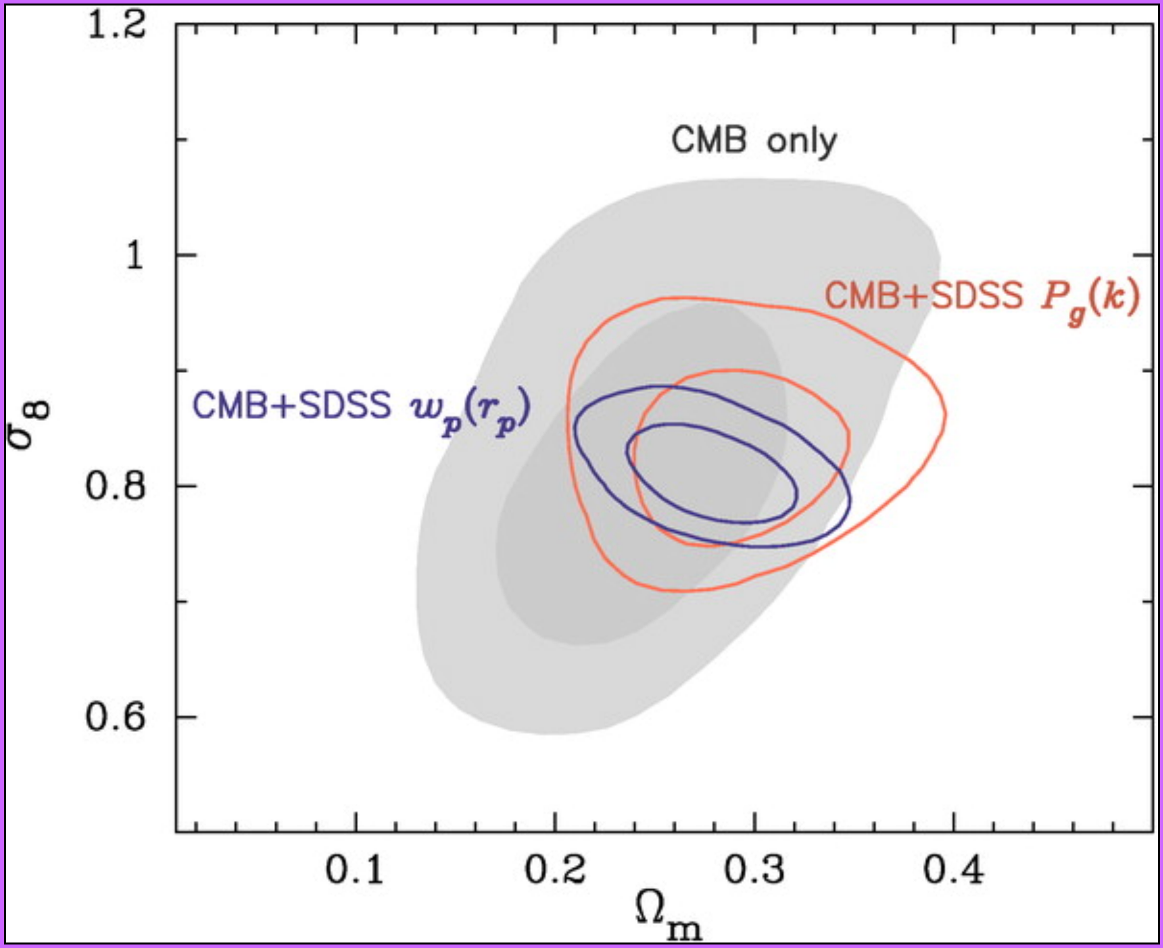
Measurements of the HOD



Zehavi et al. (2005)

Measurements of cosmology





Abazajian et al. (2003)

Testing the halo model assumptions

1. All galaxies live in halos.

2. The statistical content of halos depends only on halo mass.

   i.e., *P(N|M)* is sufficient, as opposed to *P(N|M,X)*

   Recent work shows that halo bias $b_h(M)$ depends on halo assembly history at fixed mass. If *P(N|M)* also shows this dependence, then standard halo model will be incorrect.

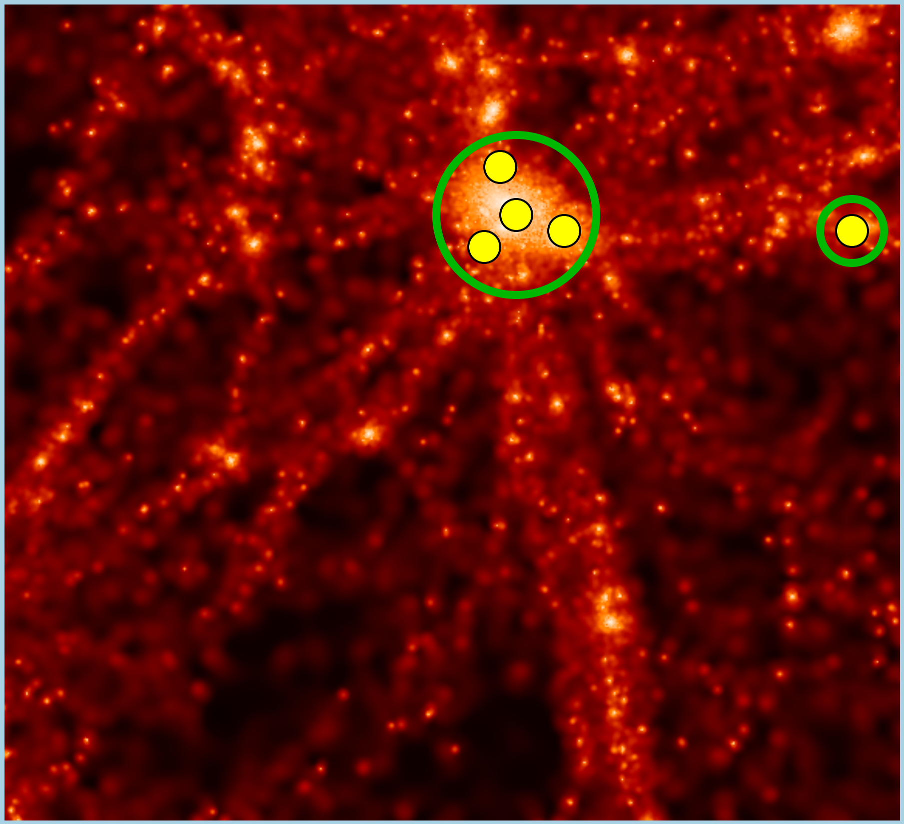
   Measurements of this are not conclusive. This systematic effect needs to be addressed if galaxy clustering is to be used for precision cosmology.

3. The dark halo properties are not affected by baryons

   This is almost certainly not true, but the extent of this problem is unclear.

Alternative to the analytic halo model approach

Populate an N-body simulation with an HOD to compute clustering statistics instead of using analytic formulas.



Alternative to the analytic halo model approach

Populate an N-body simulation with an HOD to compute clustering statistics instead of using analytic formulas.

Advantages:

- Halo clustering, abundances, and profiles are correct on all scales above the simulation's resolution limit.
- Can calculate any clustering statistic.

Disadvantages:

- Not good for very small scale clustering.
- Much more computationally intensive.

Alternatives to the halo model / HOD approach

Use a Conditional Luminosity Function (CLF) to model the luminosity dependence of clustering.

$$\Phi(L) = \int_0^\infty dM \frac{dn}{dm} \Phi(L|M) \qquad \langle N \rangle_M = \int_{L_{\min}}^\infty dL \Phi(L|M)$$

Advantages:

- Don't have to assume a form for <N(M)>
- More ambitious: model the luminosity dependence explicitly

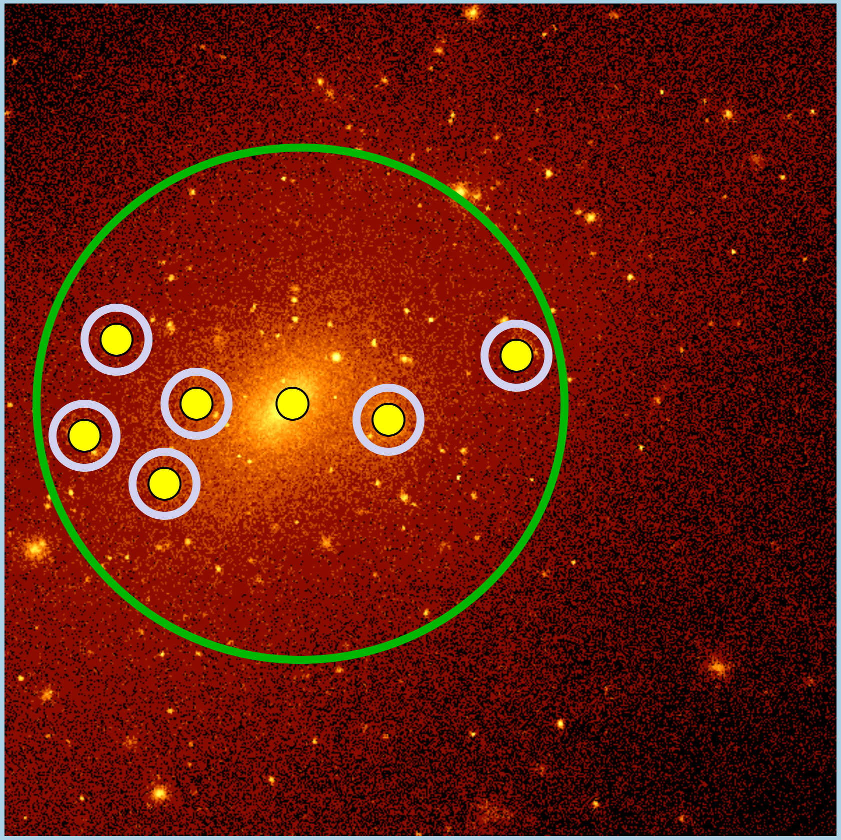
Disadvantages:

- Have to assume a form for $\phi(L|M)$
- More ambitious: luminosity dependence is model dependent

Methods are very similar and complementary.

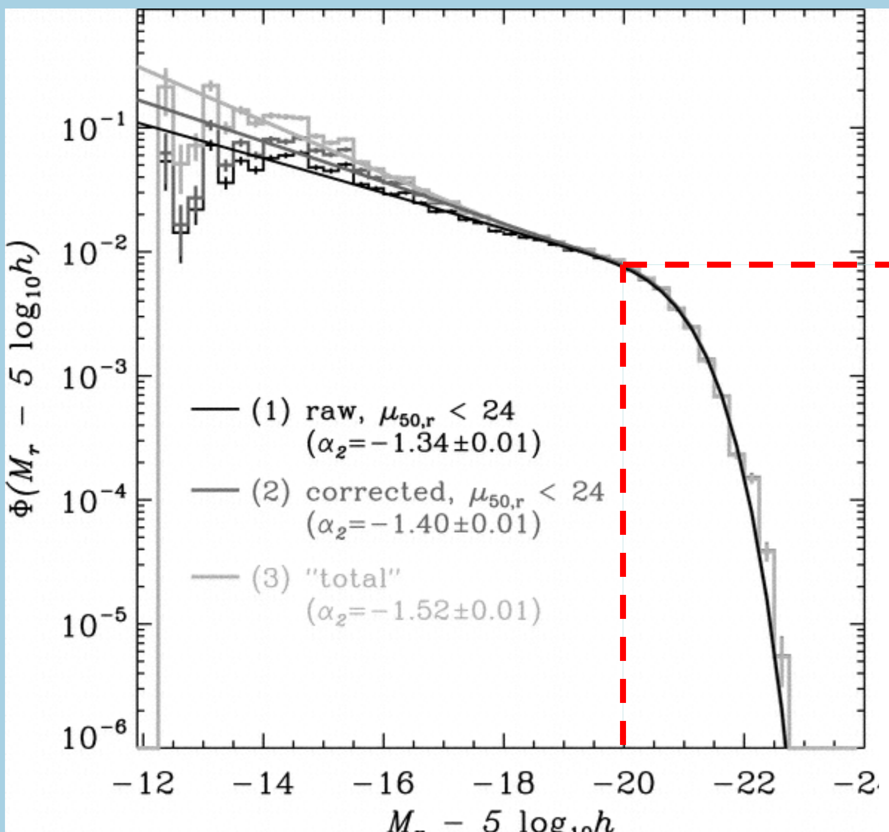
Alternatives to the halo model / HOD approach

Use a high resolution N-body simulation to place galaxies in halos + subhalos, assuming relations between galaxy and subhalo properties. (i.e., use subhalo distribution instead of HOD)



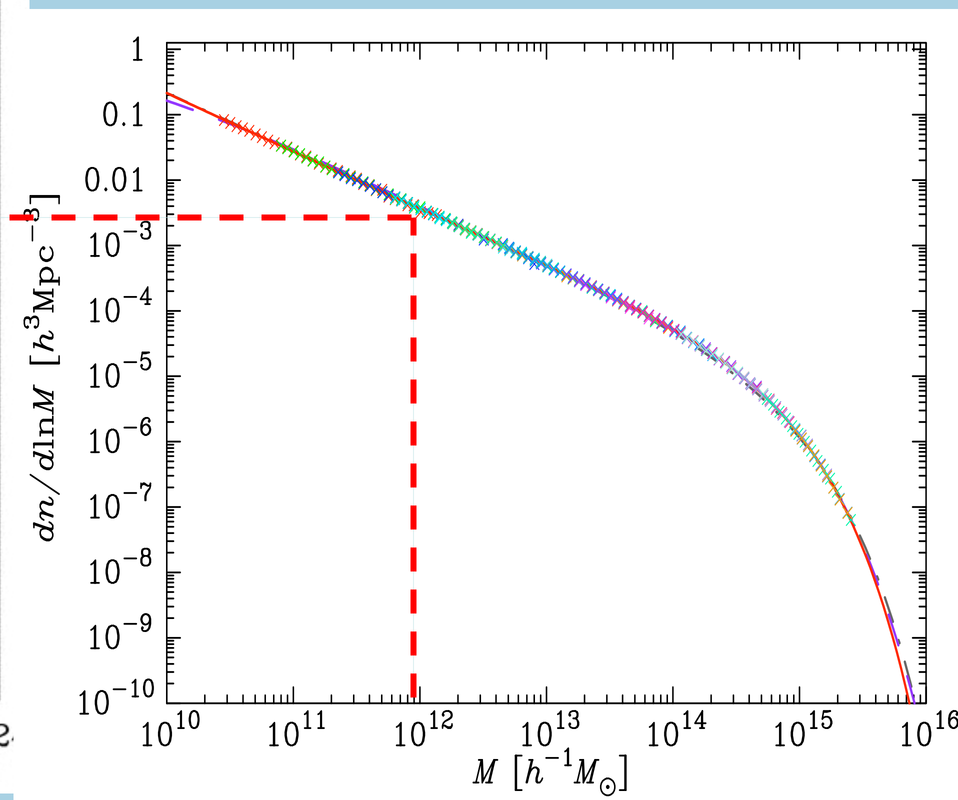
Halo/Subhalo Abundance Matching

Galaxy luminosity function

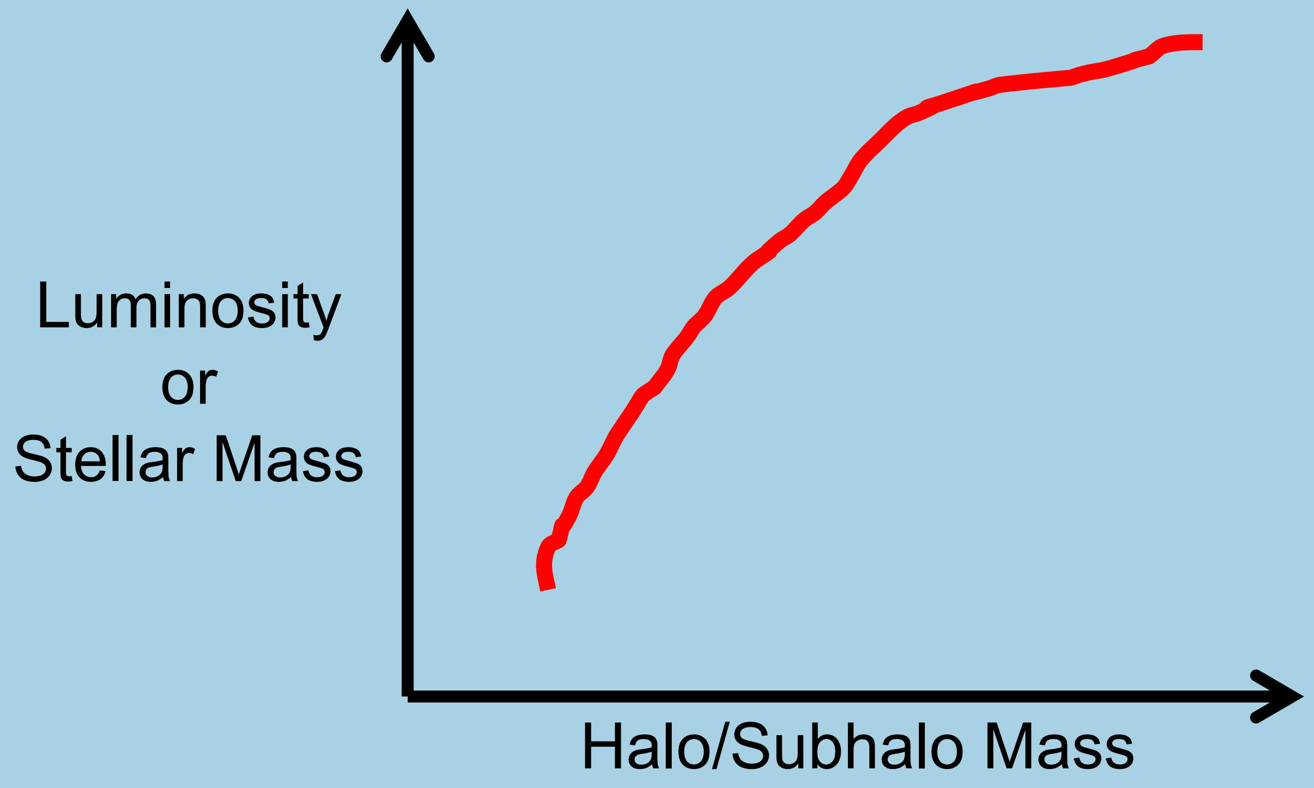


Halo mass function

(including subhalos)

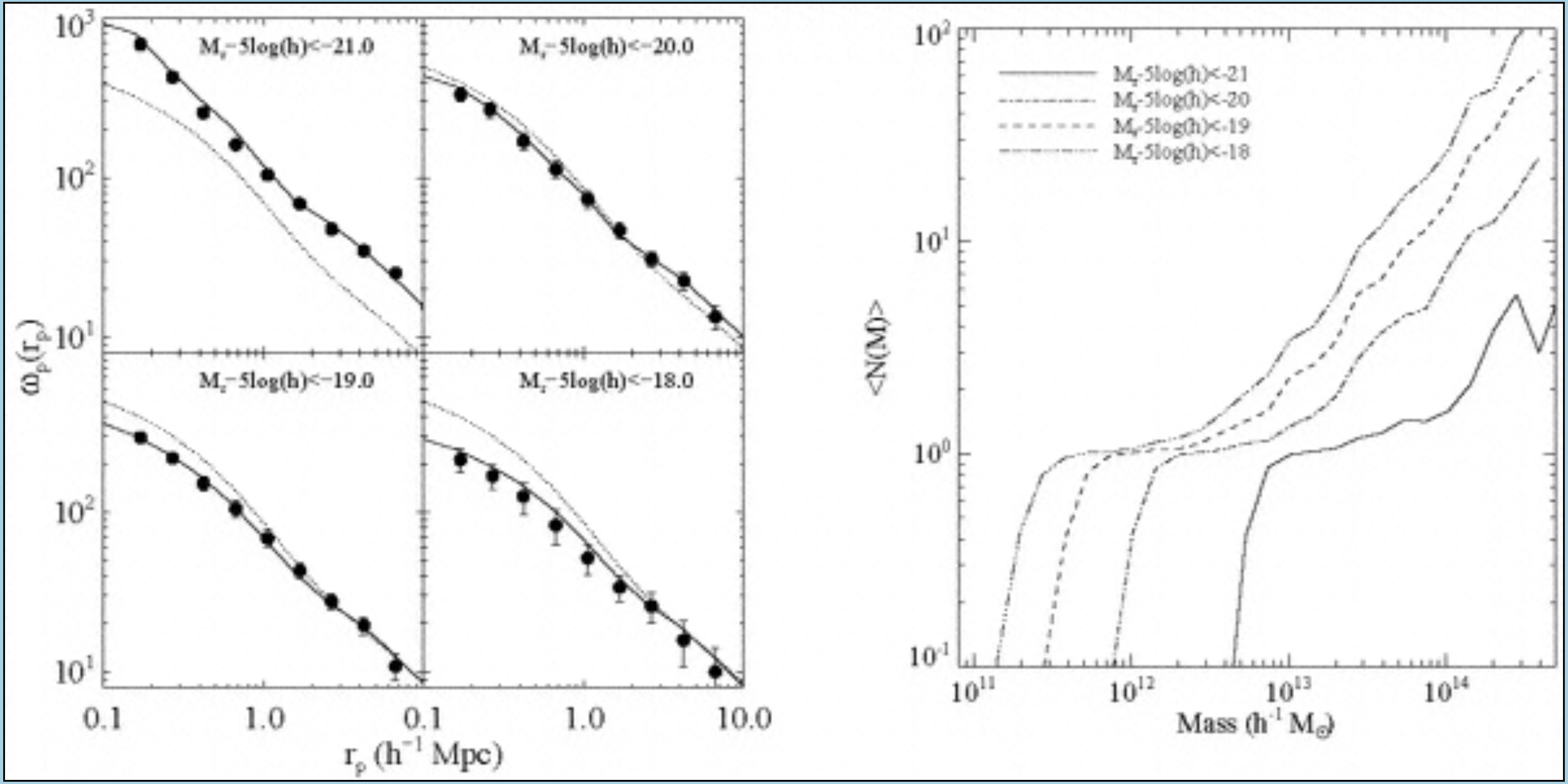


Halo/Subhalo Abundance Matching



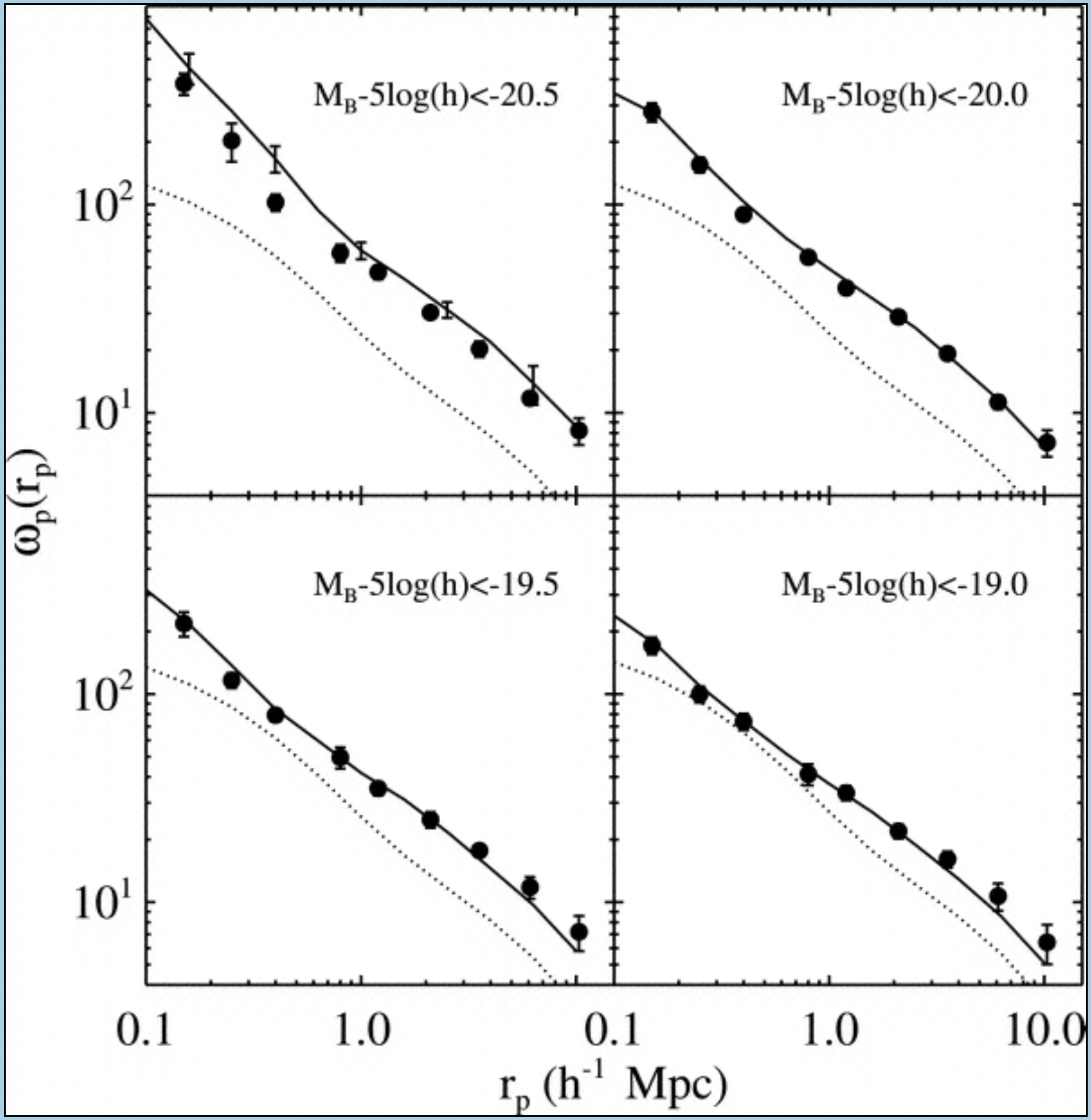
Halo/Subhalo Abundance Matching

SDSS
z~0



Conroy et al. (2006)

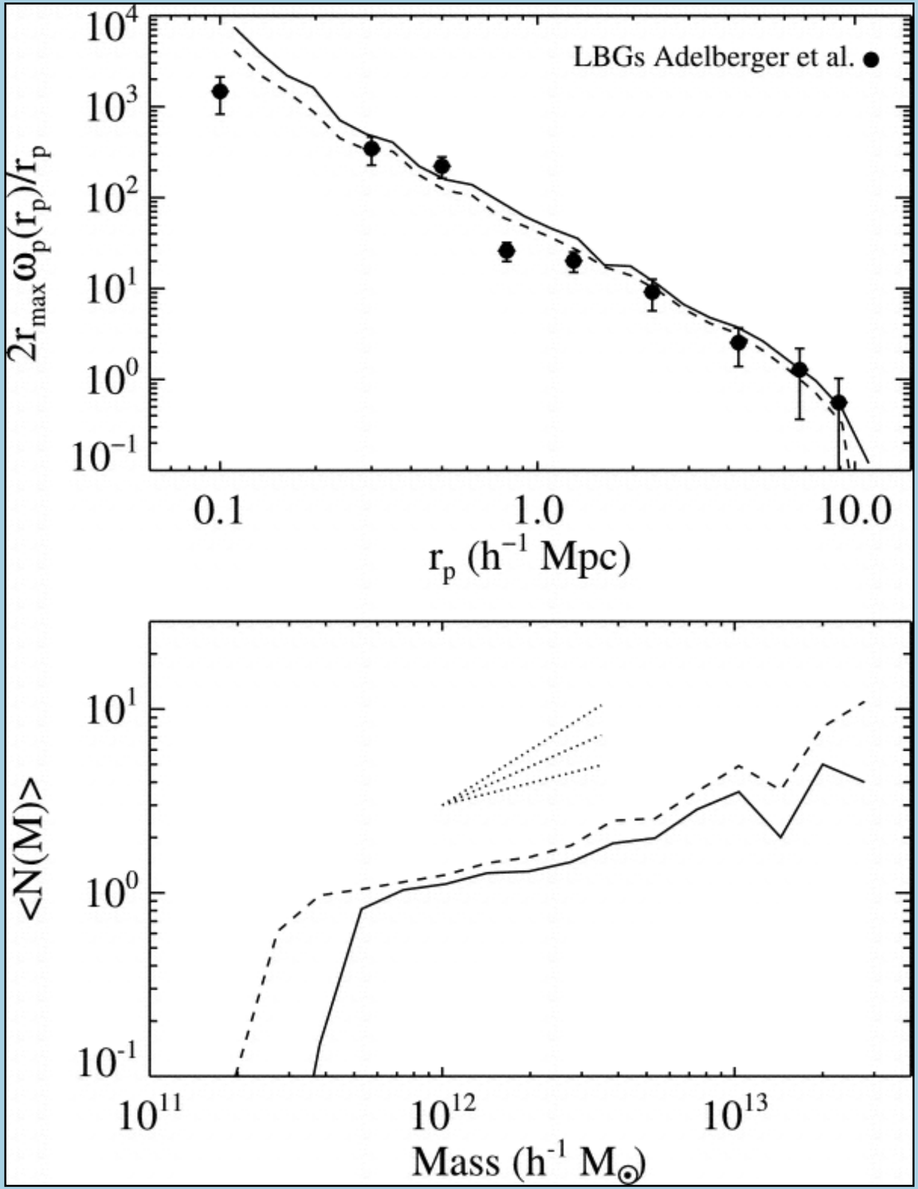
Halo/Subhalo Abundance Matching



DEEP2
z~1

Conroy et al. (2006)

Halo/Subhalo Abundance Matching

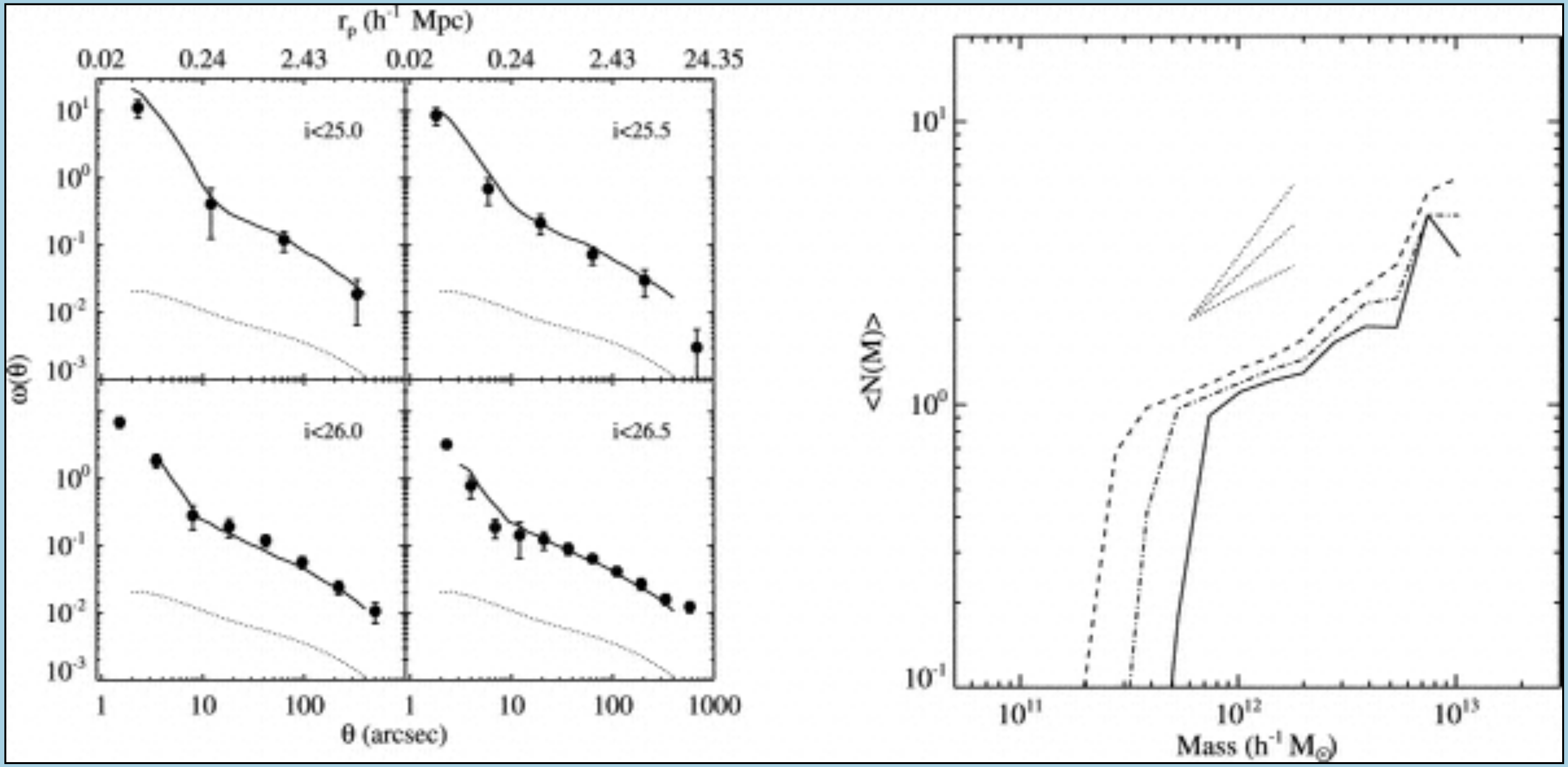


LBGs
z~3

Conroy et al. (2006)

Halo/Subhalo Abundance Matching

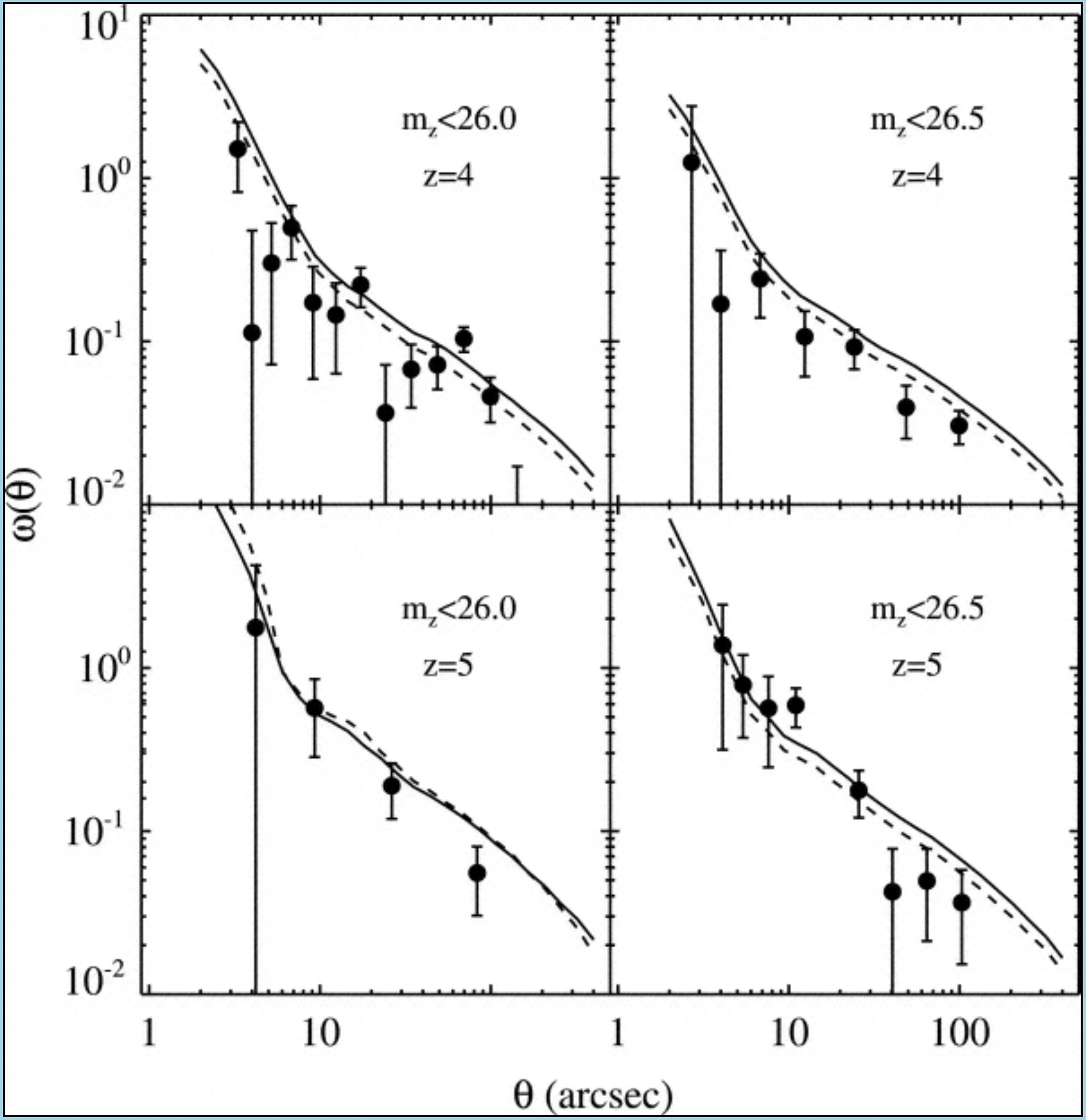
Subaru
z~4



Conroy et al. (2006)

Halo/Subhalo Abundance Matching

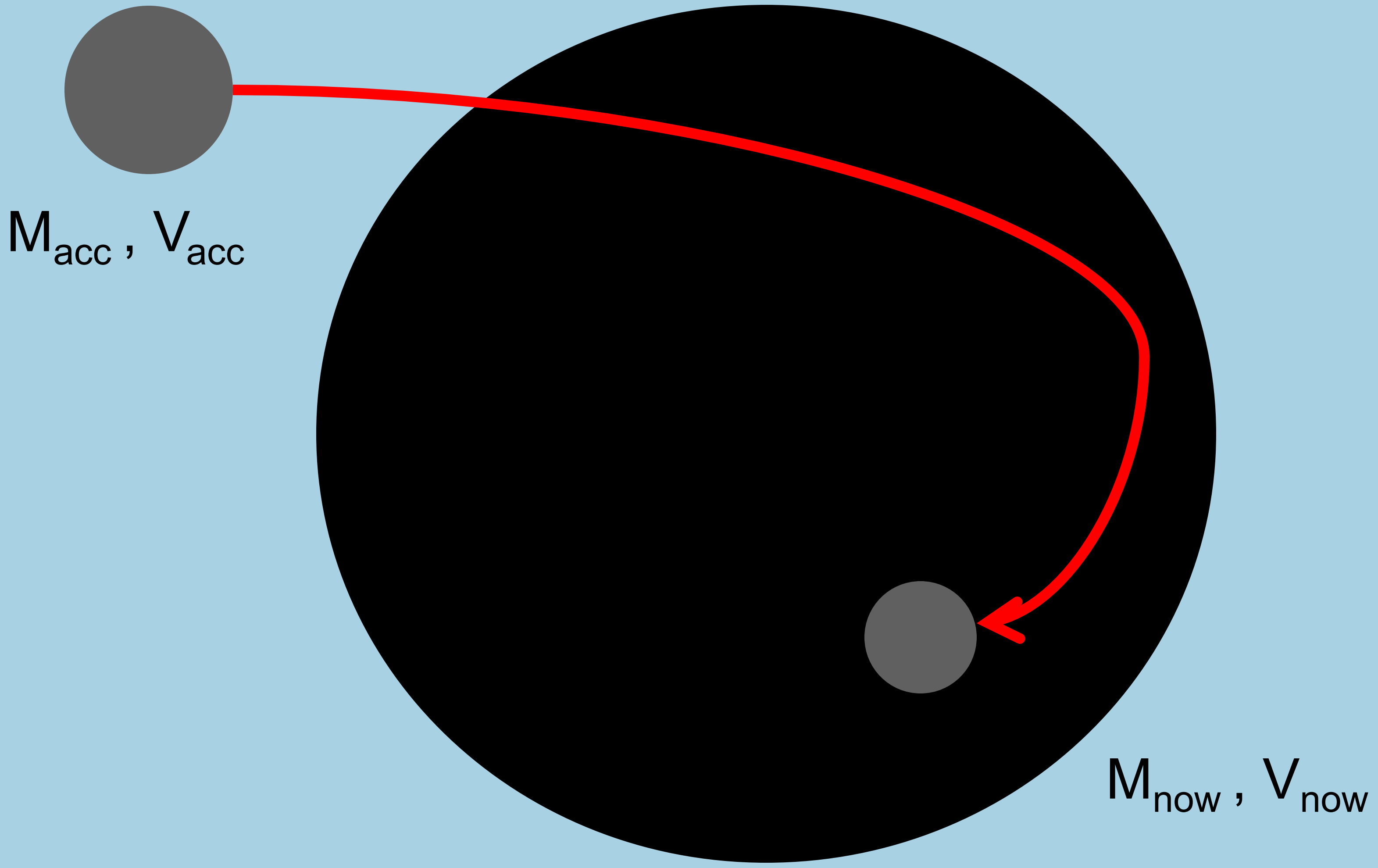
GOODS
z~4-5



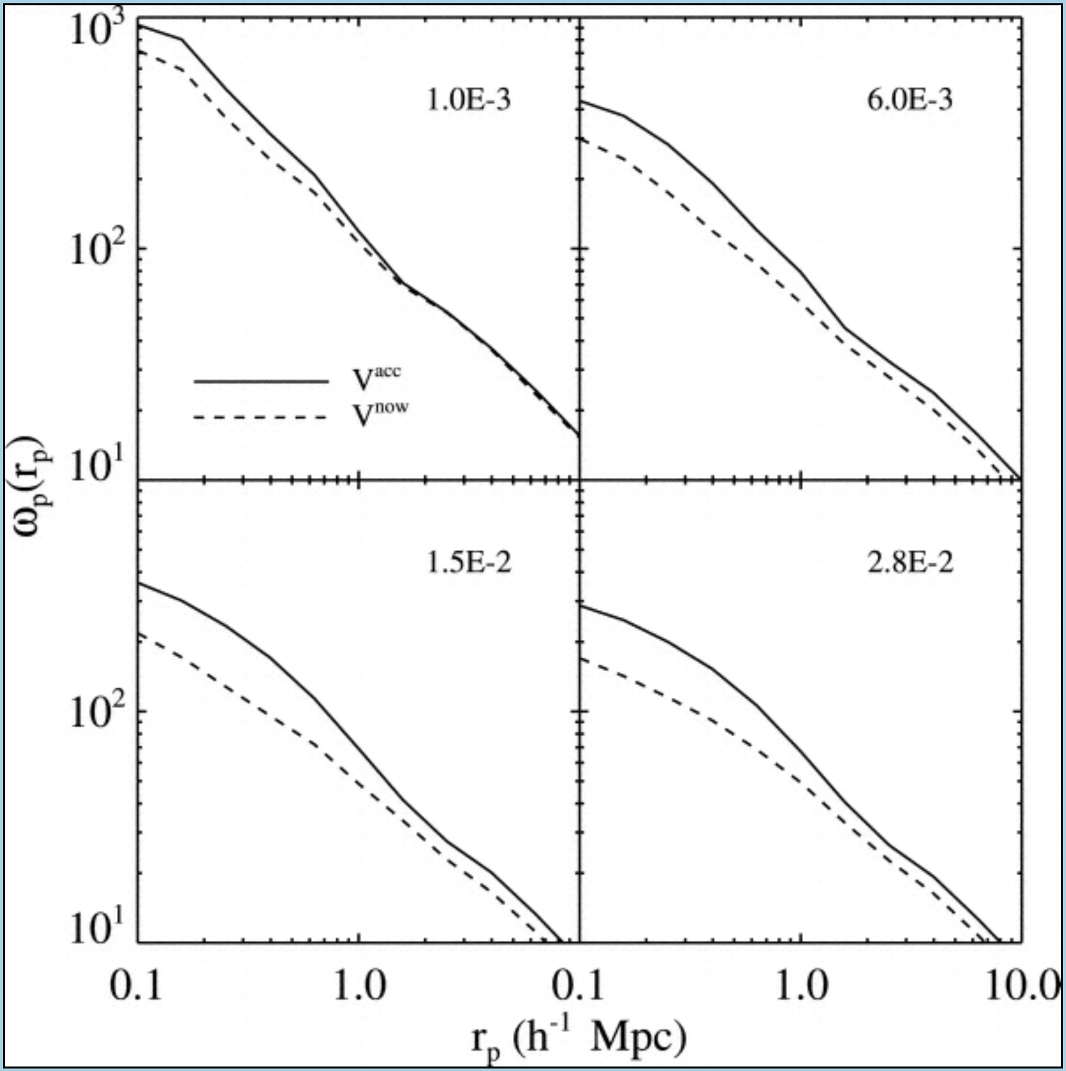
Conroy et al. (2006)

Halo/Subhalo Abundance Matching

What subhalo property should be used?

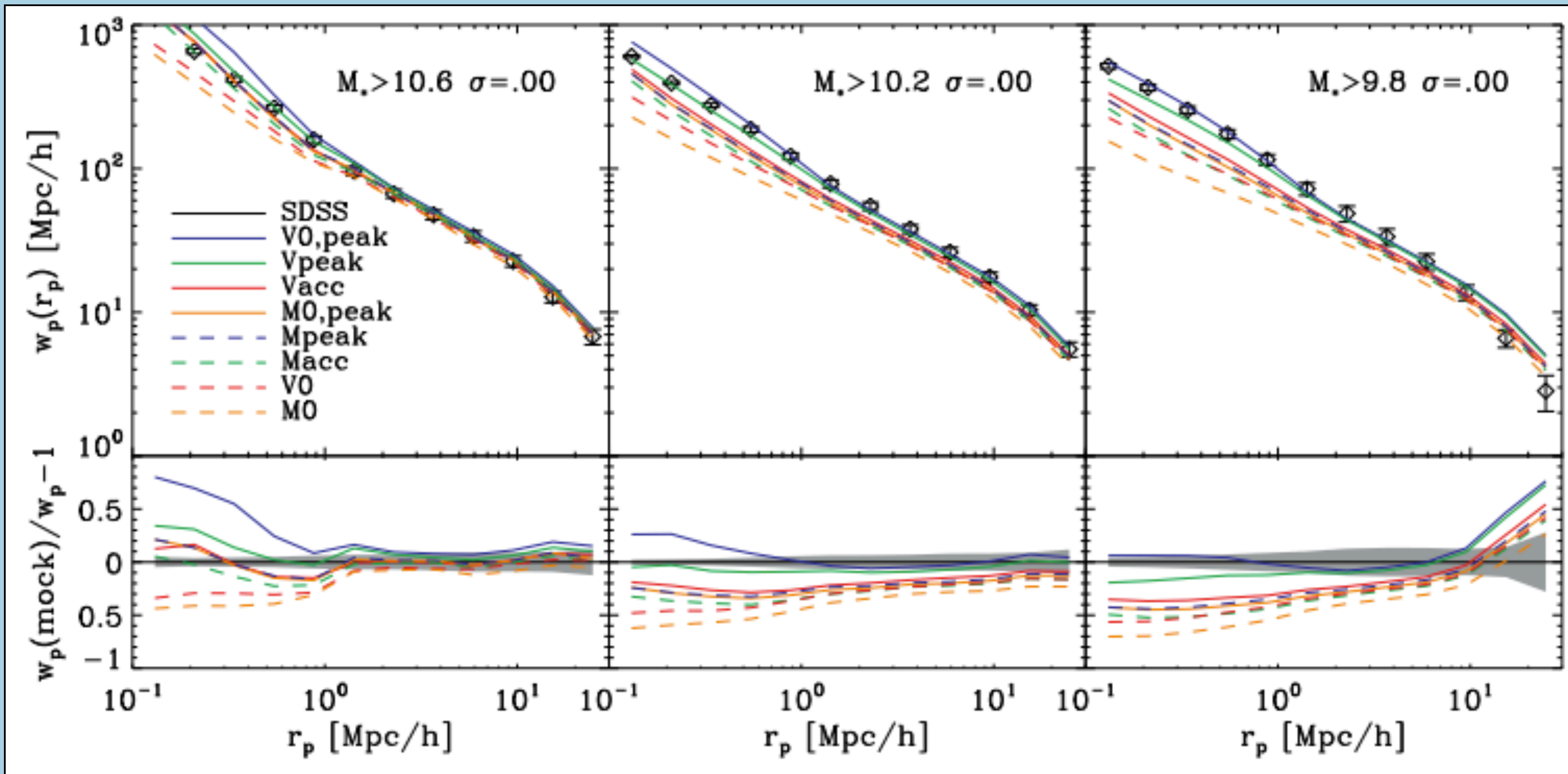


Halo/Subhalo Abundance Matching



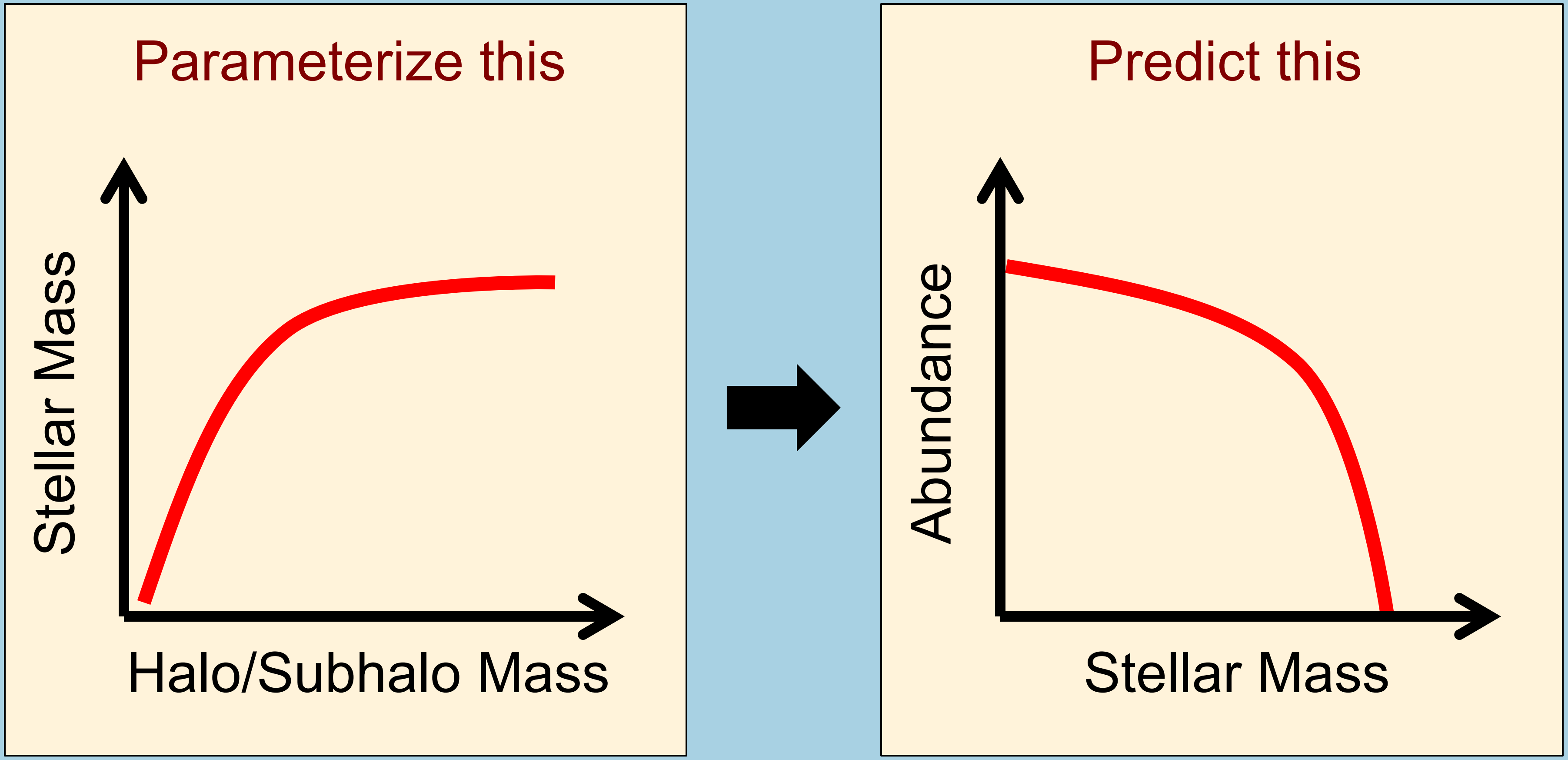
Conroy et al. (2006)

Halo/Subhalo Abundance Matching

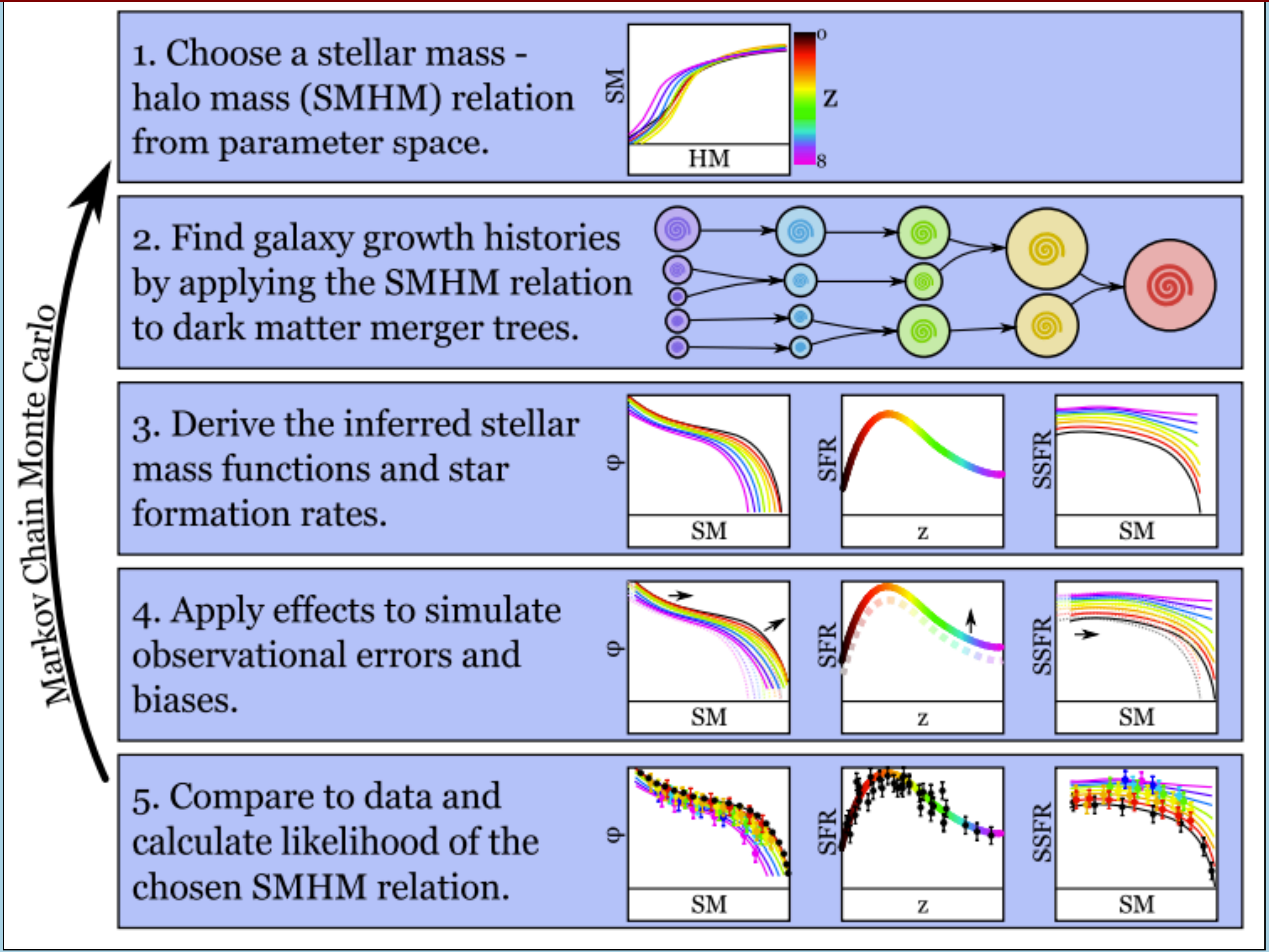


Reddick et al. (2013)

Or do a forward approach



The modeling is getting very ambitious

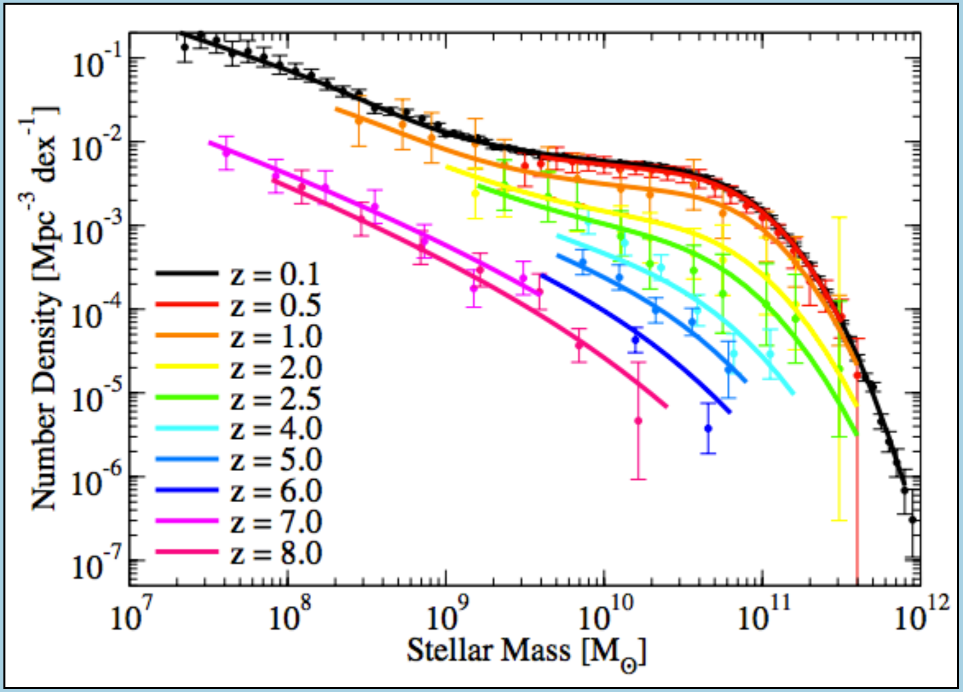


Behroozi et al. (2013)

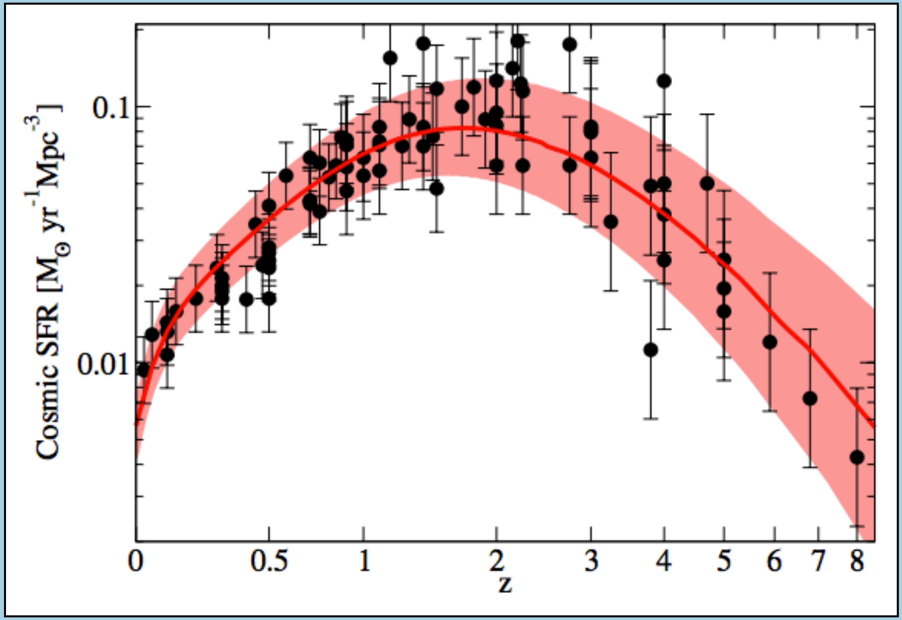
The modeling is getting very ambitious

Fit model at all redshifts to:

(1) stellar mass function

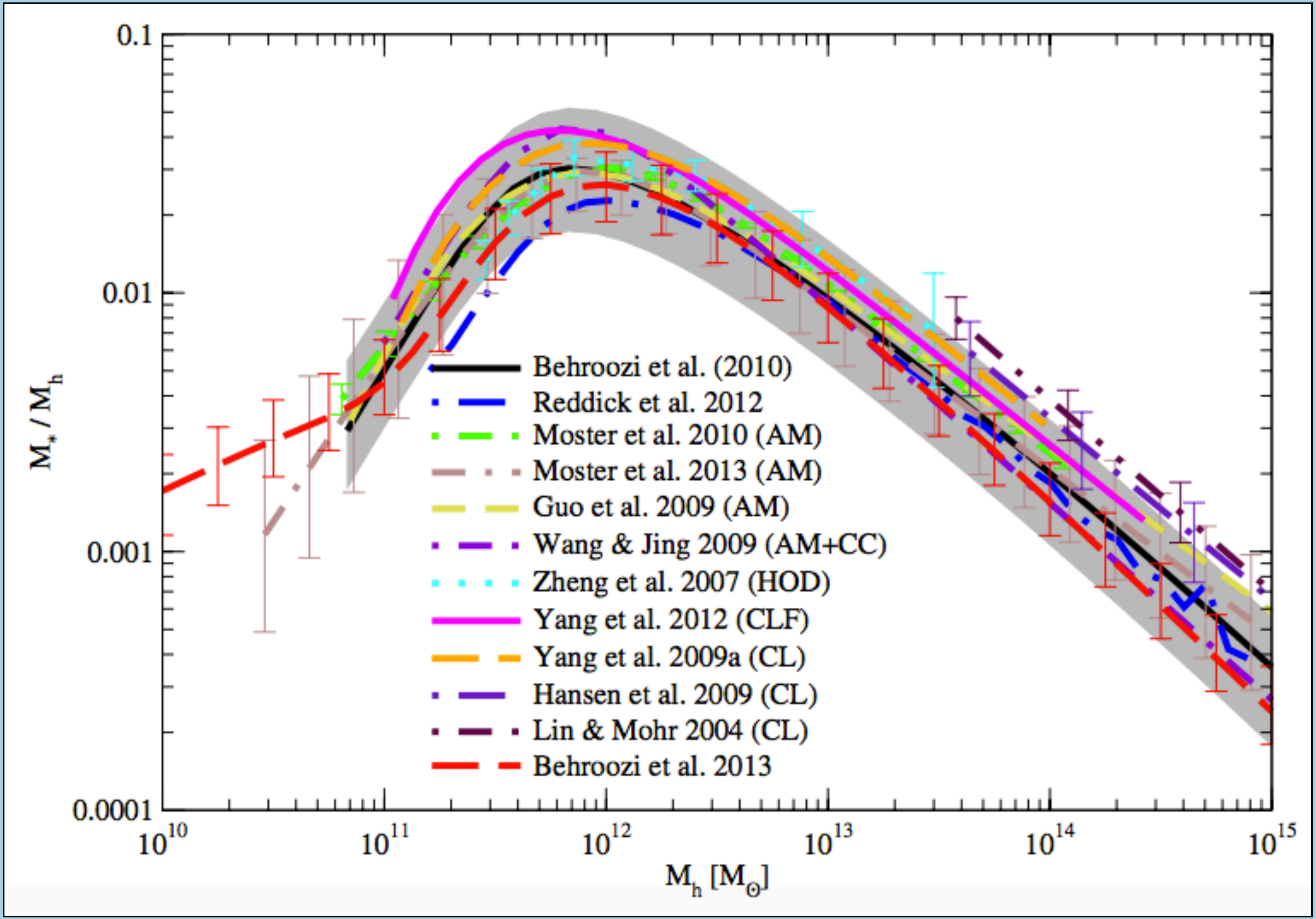


(2) star formation rate



Behroozi et al. (2013)

The modeling is getting very ambitious



Behroozi et al. (2013)

Describing vs. Understanding

HOD/HAM/CLF are excellent statistical tools for *describing* the wealthof galaxy clustering data: for translating complicated statistics into a more physically informative language.

It is still essential that we *understand* the physics behind the data: gas cooling, star formation, feedback, etc. For this we need ab-initio models such as hydrodynamic simulations and semi-analytic models.

The methods are highly complementary.

SYNOPSIS

- Galaxy properties
- Stellar populations
- Distance measures
- Hubble expansion and z-space distortions
- Redshift surveys
- Galaxy environments
- Galaxy groups and clusters
- Galaxy clustering statistics
- Cosmological parameters
- Expansion history of the universe
- Growth of perturbations
- N-body simulations
- Dark matter halos
- Galaxy formation
- The halo model