Galaxy formation and distribution in a cosmological context

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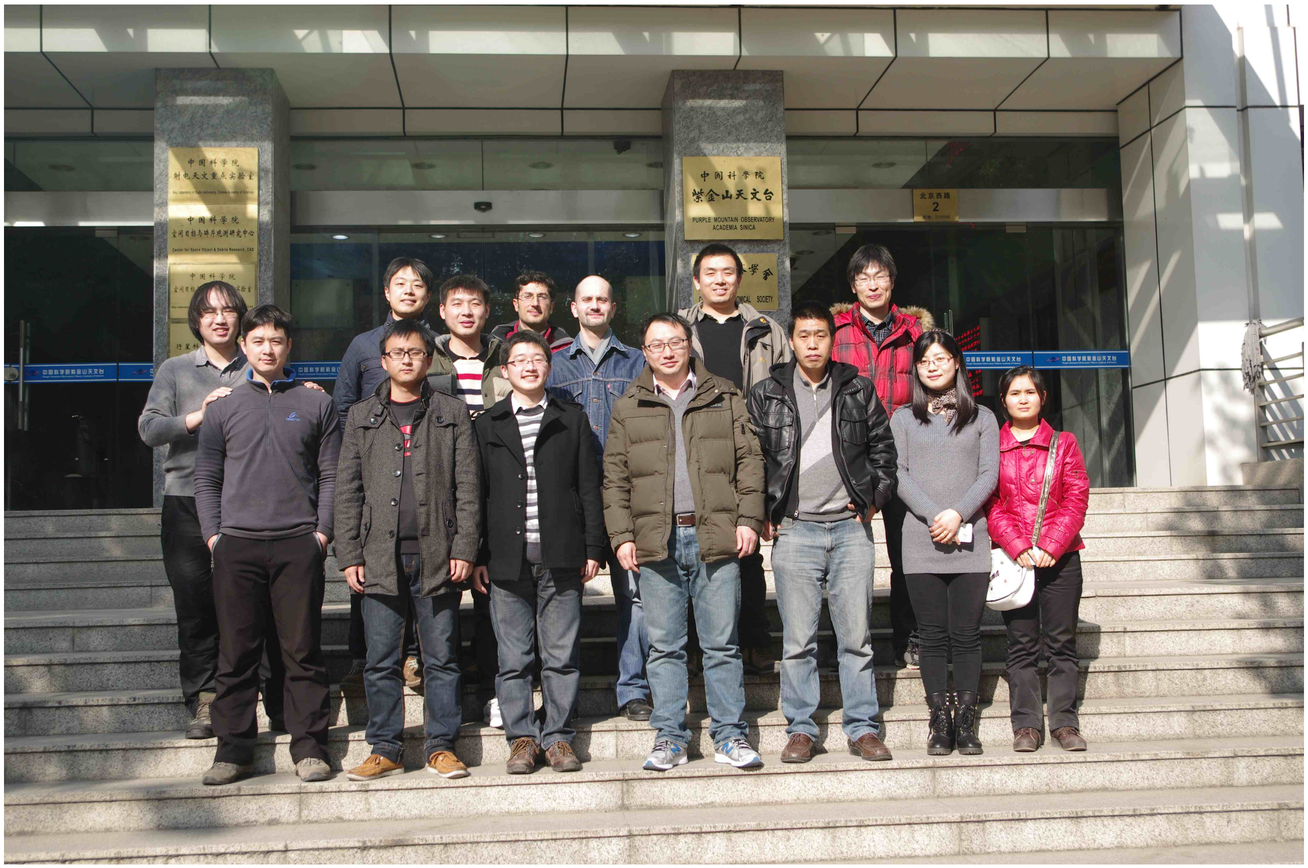
Galaxy and Cosmology group at PMO (theory)

partner group with max-planck-institute for astronomy (Heidelberg, Germany)



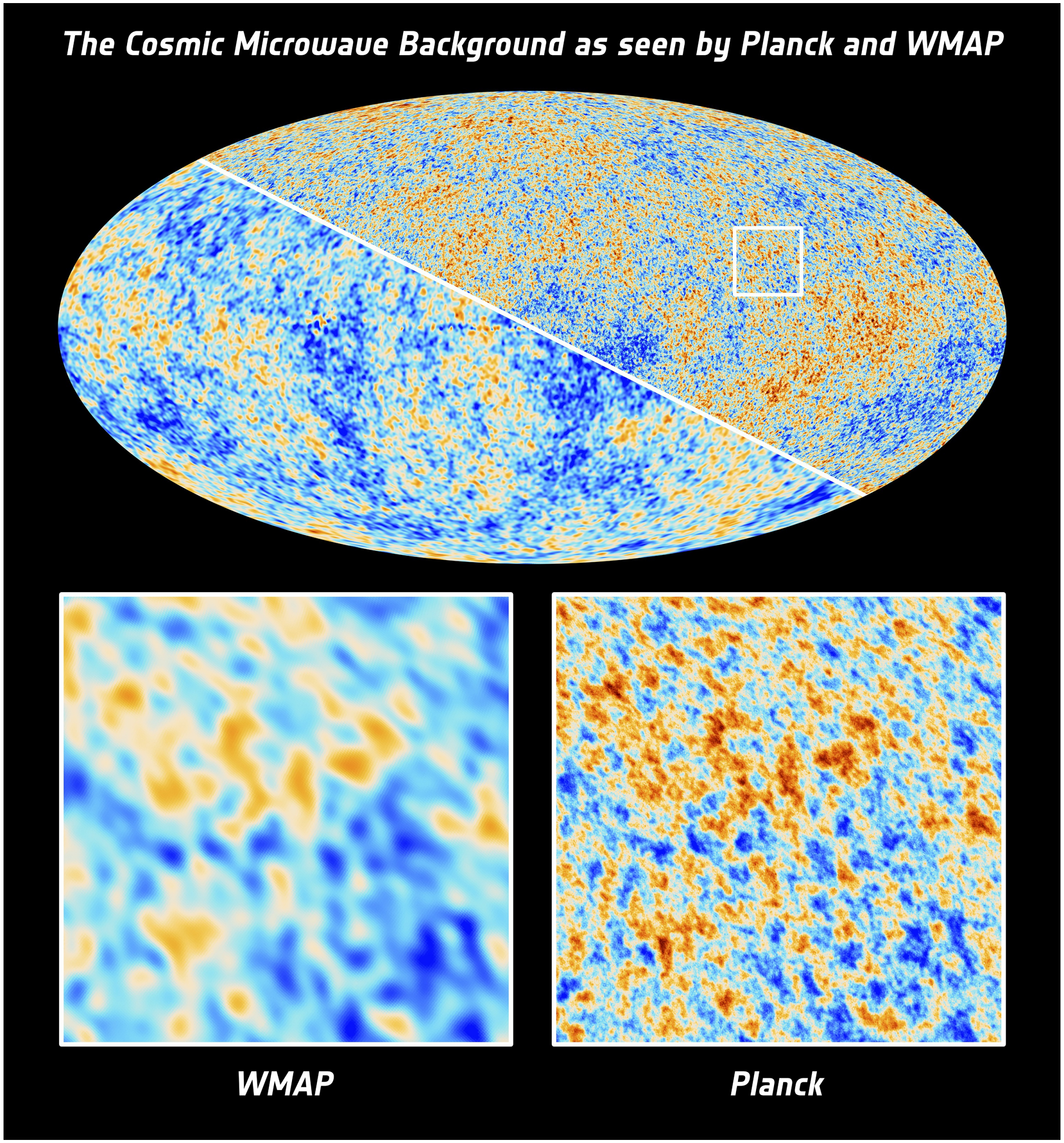
成员staff：康熙（研究员），李国亮（研究员），王蕾（助研）
博士后(postdoc): Alessio Romeo, Emanuele Contini, 褚哲，
研究生：10名

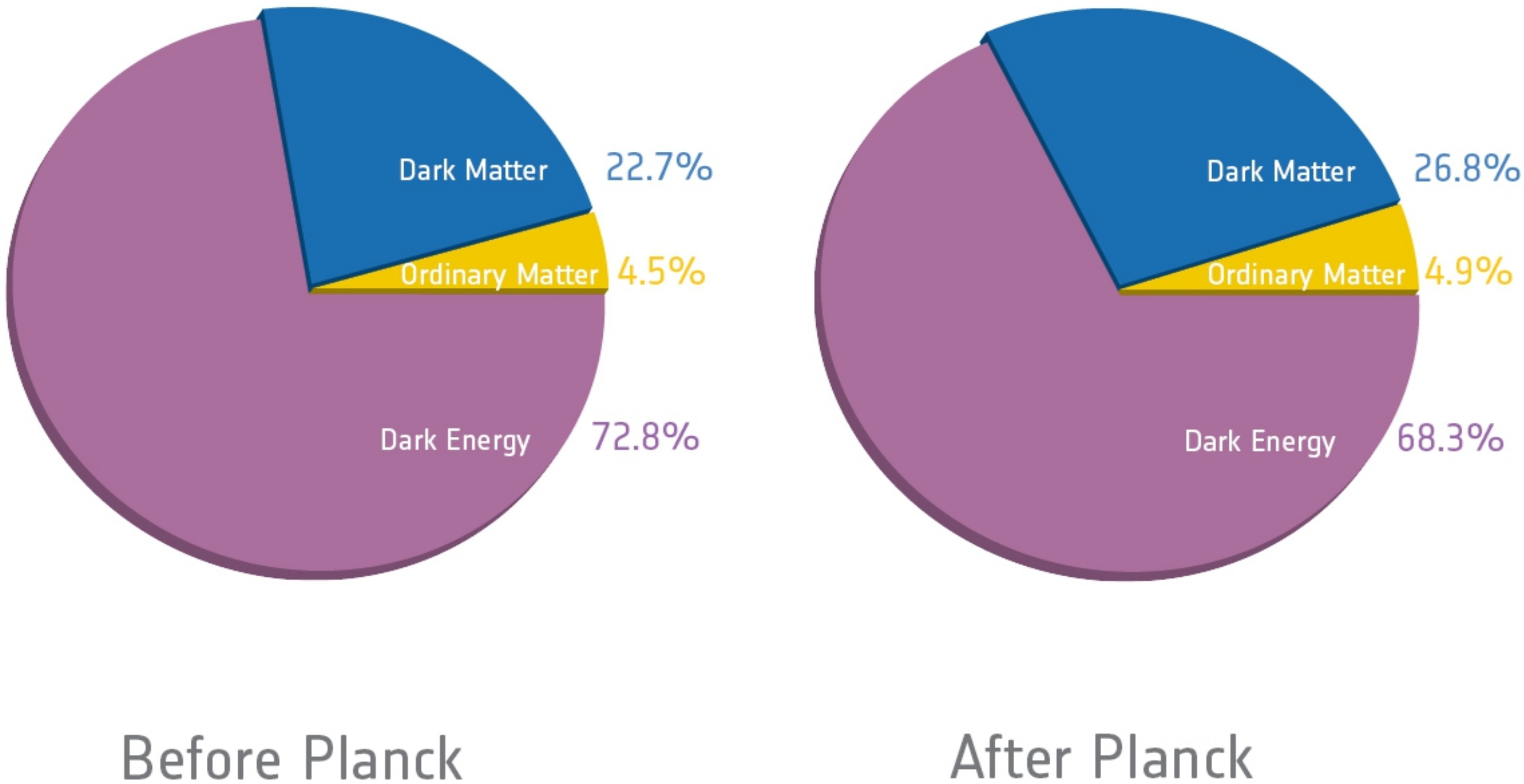
Research interests in our group

- Semi-analytical model for galaxy formation
- Numerical simulation of galaxy cluster
- N-body simulation of galaxy merger
- Large scale structure analysis
- Gravitational lensing (strong + weak)

Outline

- Structure formation
- Models for galaxy formation
- Several types of galaxy distribution
- milky way as a local lab
- Summary


The Cosmic Microwave Background as seen by Planck and WMAP
WMAP
Planck

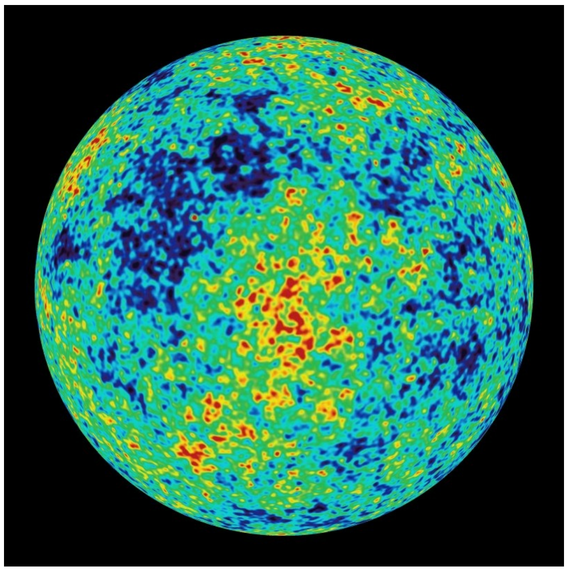


The Universe is also expanding 7% slower than before and is 80,000,000 years older!

Z~1000 ($\Delta T/T \sim 10^{-5}$)

Z~100

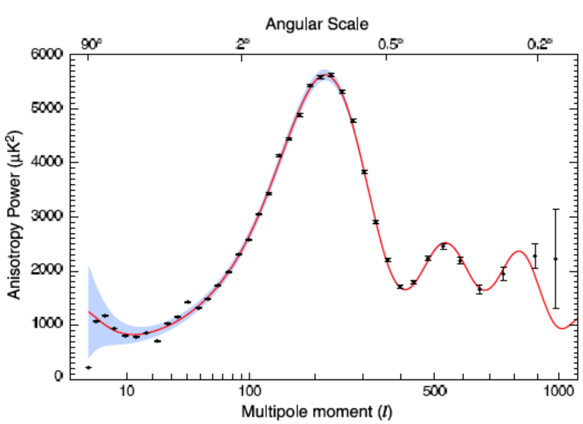
Z=0



linear perturbation theory

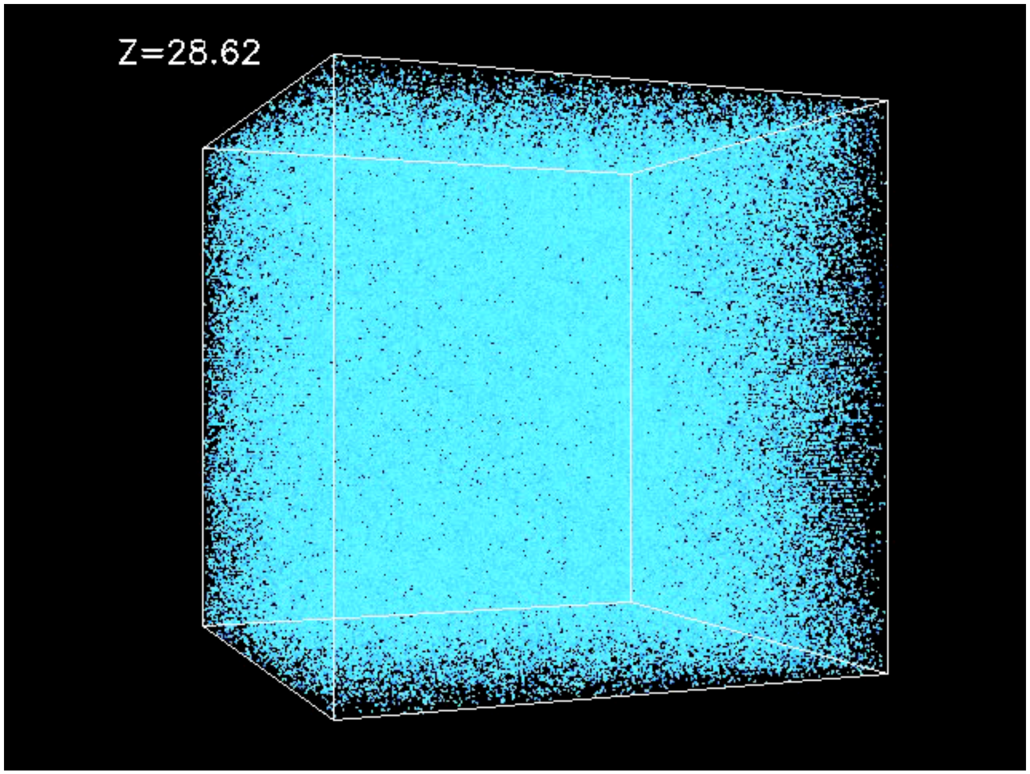
Non-linear

N-body Simulation



structure formation in N-body simulation

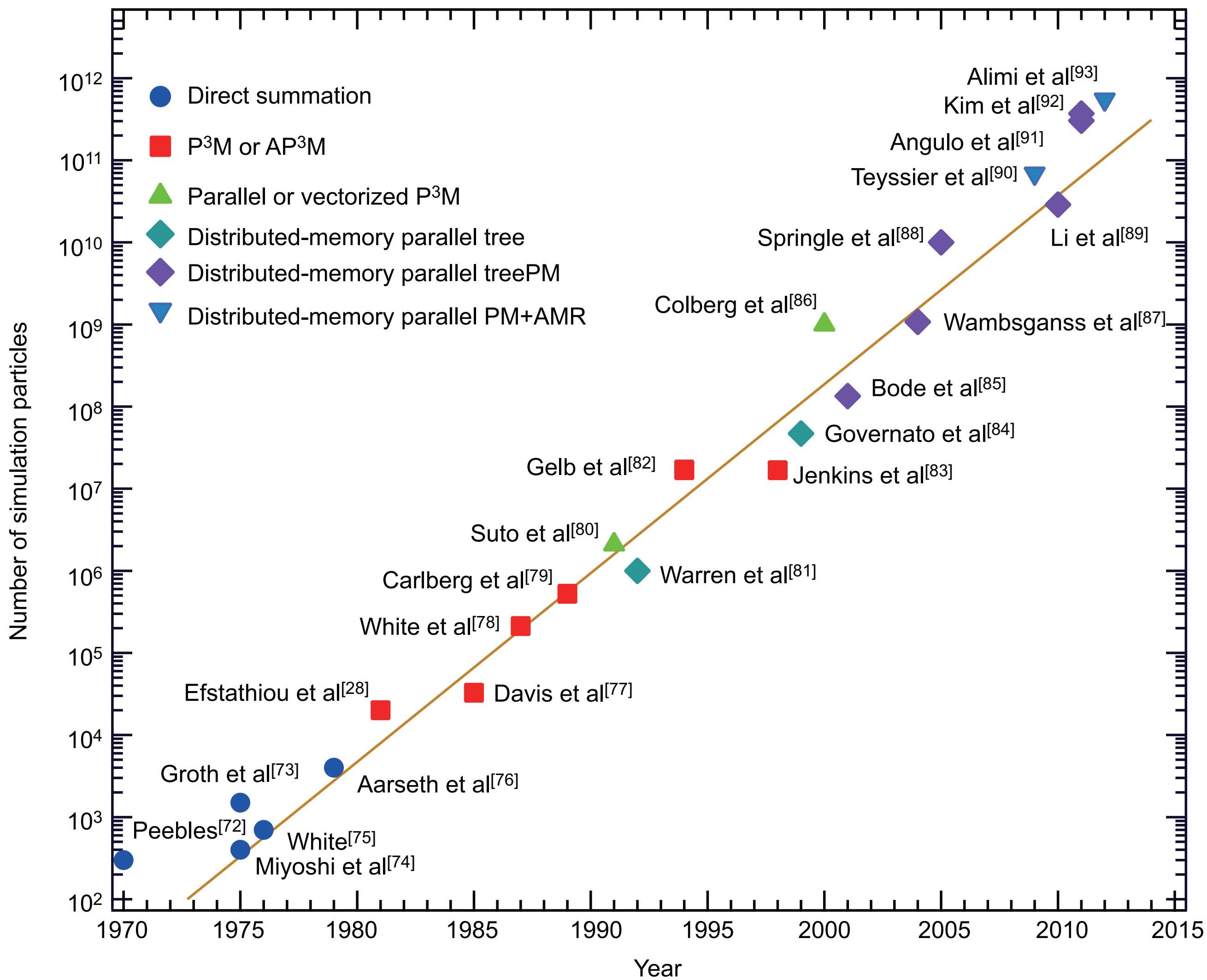
large scale



small scale

Gravitational instability is the driver of structure formation

N evolves with time



Computational Cosmology Consortium of China (C4)

盘古模拟

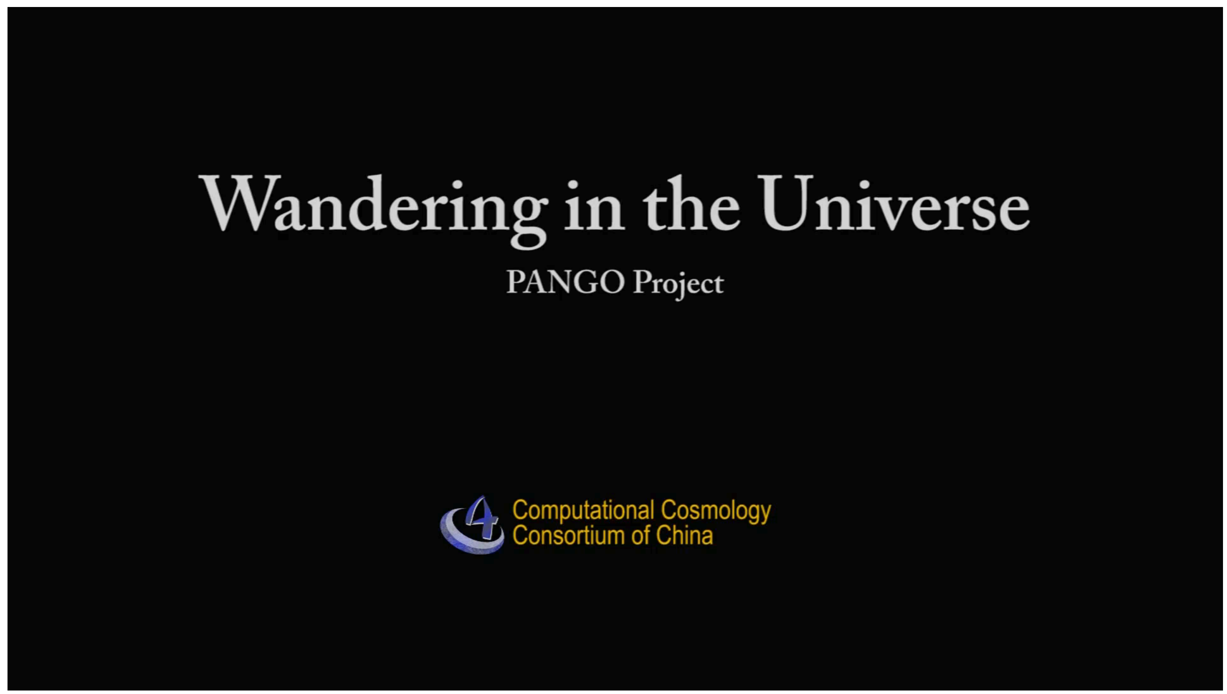
Members:

Purple Mountain Observatory
National Astronomical Observatory
Shanghai Astronomical Observatory
Shanghai Jiaotong University
Zhongshan University
Super-Computing Center of CAS

Facilities: ShenTeng 7000 (12,000 cores)

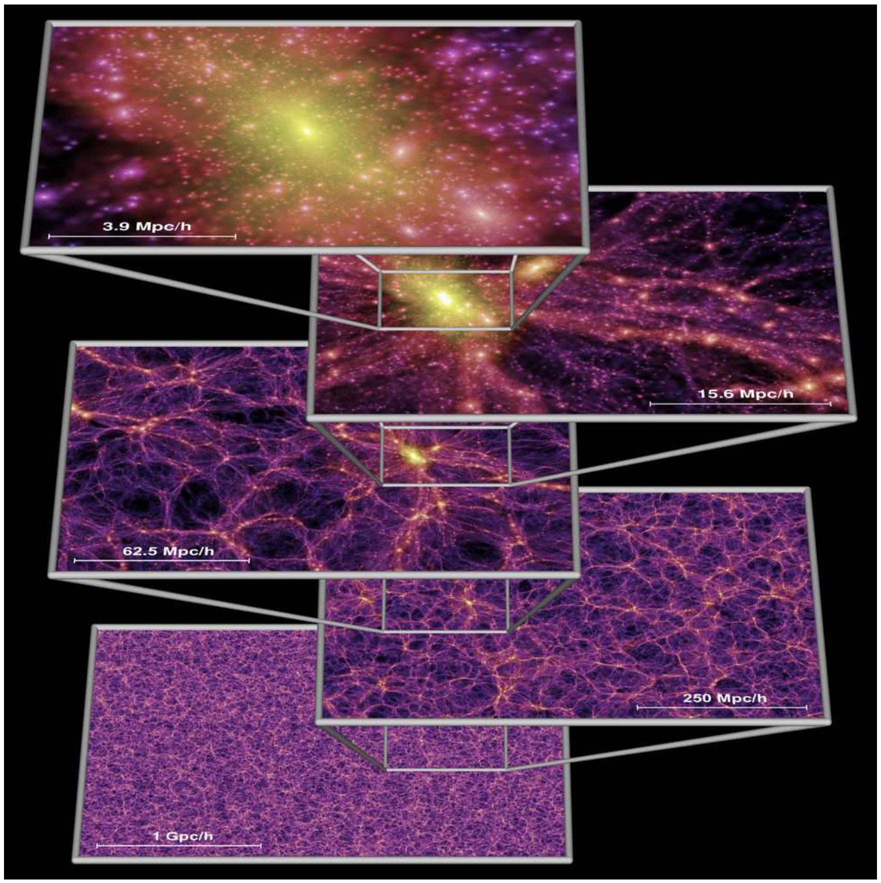
Pangu simulation

N=30 billion, Box Size=1000 Mpc/h, WMAP5 cosmology
Using 2048 cores, 1 Million CPU hours, 6TB memory, Data Volume:40 TB



Running cosmological simulation is very expensive

Hierarchic Structure of the universe



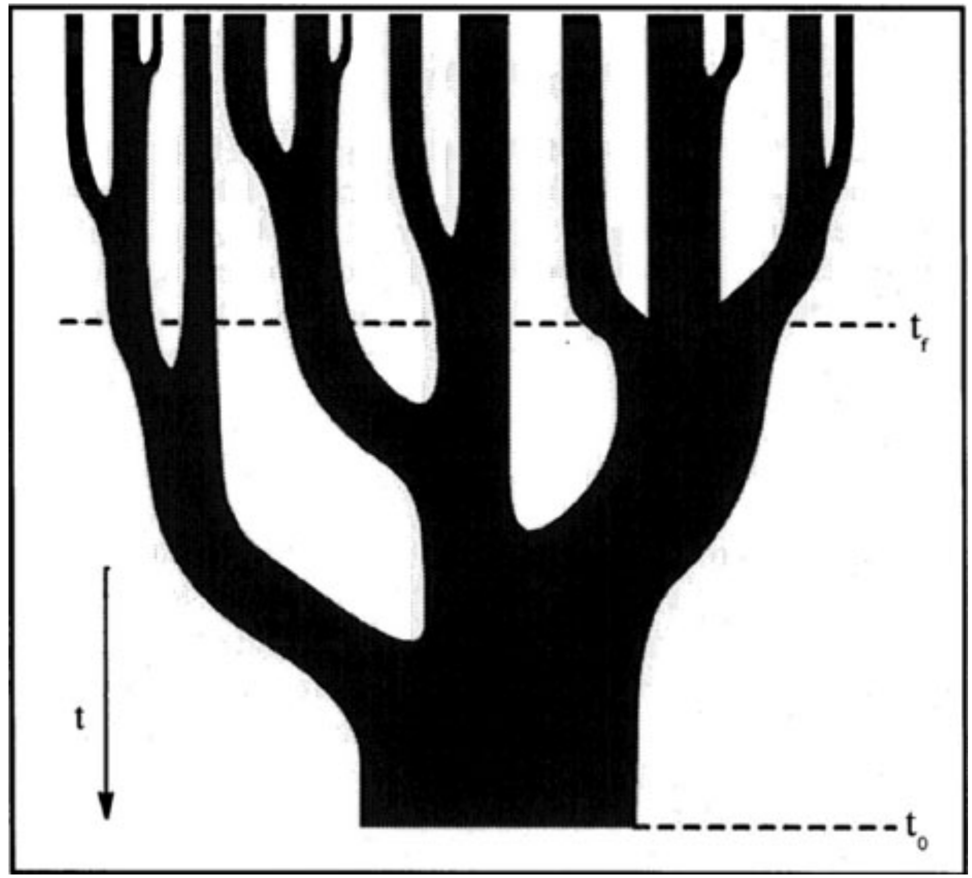
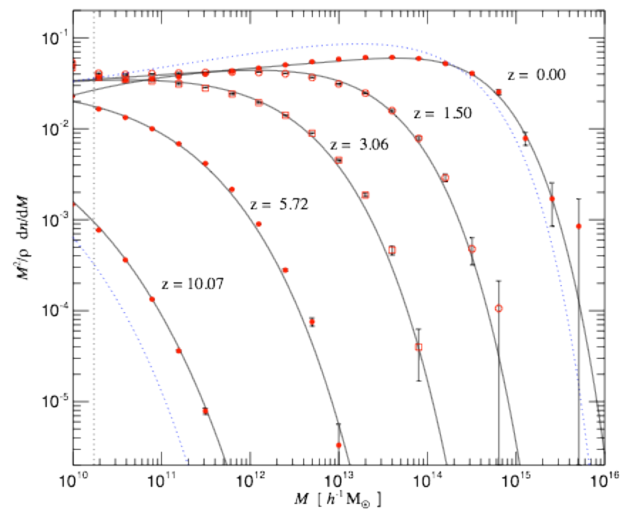
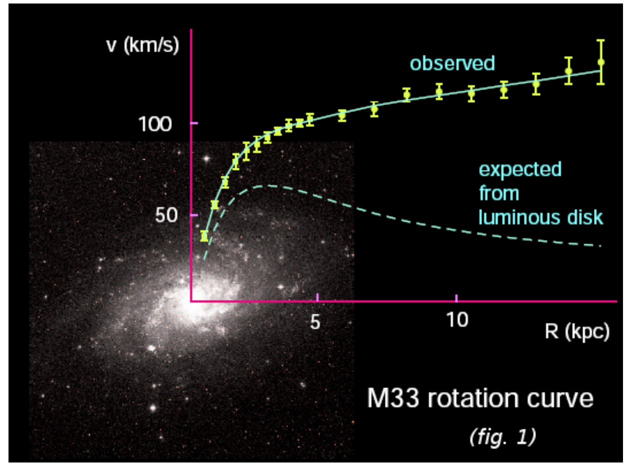


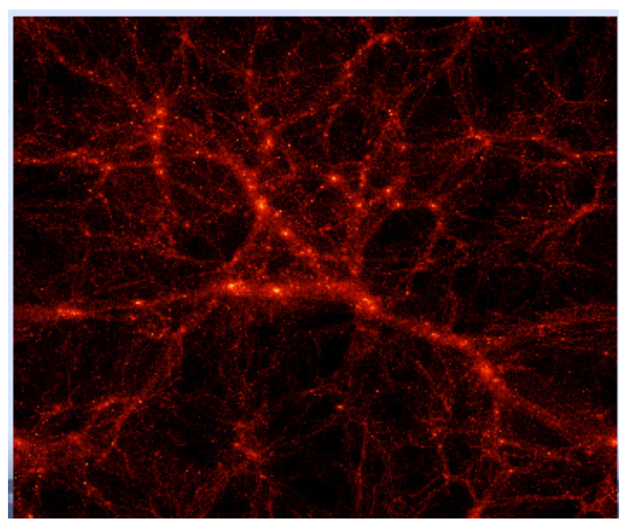
Image from Millennium Simulation

Using N-body simulation to study



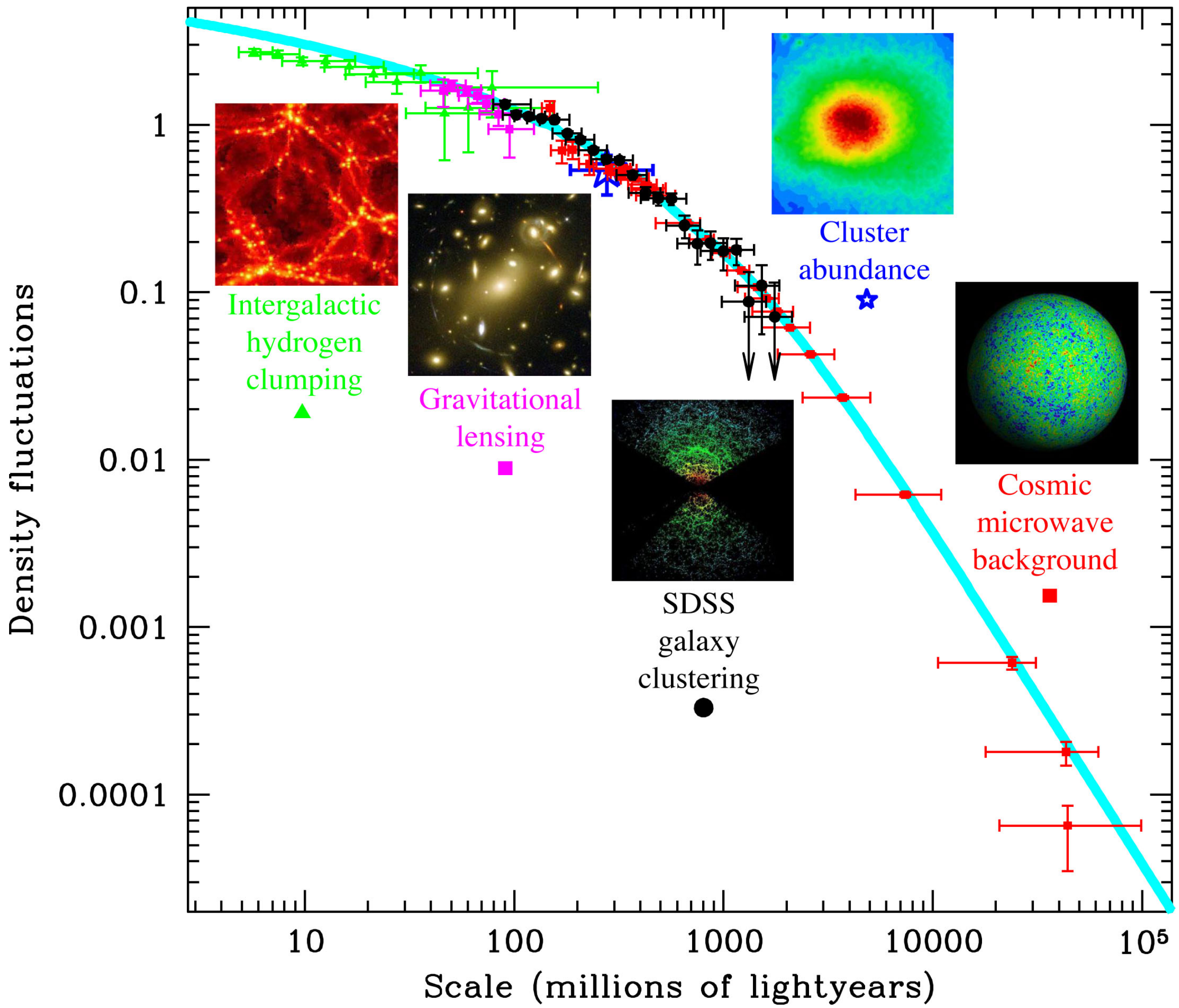


- Halo mass function
- Galaxy rotation curve
- Subhalo mass function
- Cosmic web properties: filament, voids, sheets
- Dark matter power spectrum

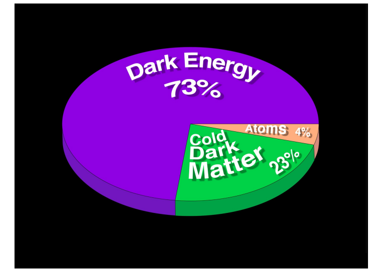


We can also:
Investigate the effects of dark matter and dark energy on the structure formation

Concordance Λ-CDM Model



Credit: Max Tegmark



+

τ, n_s, σ_8

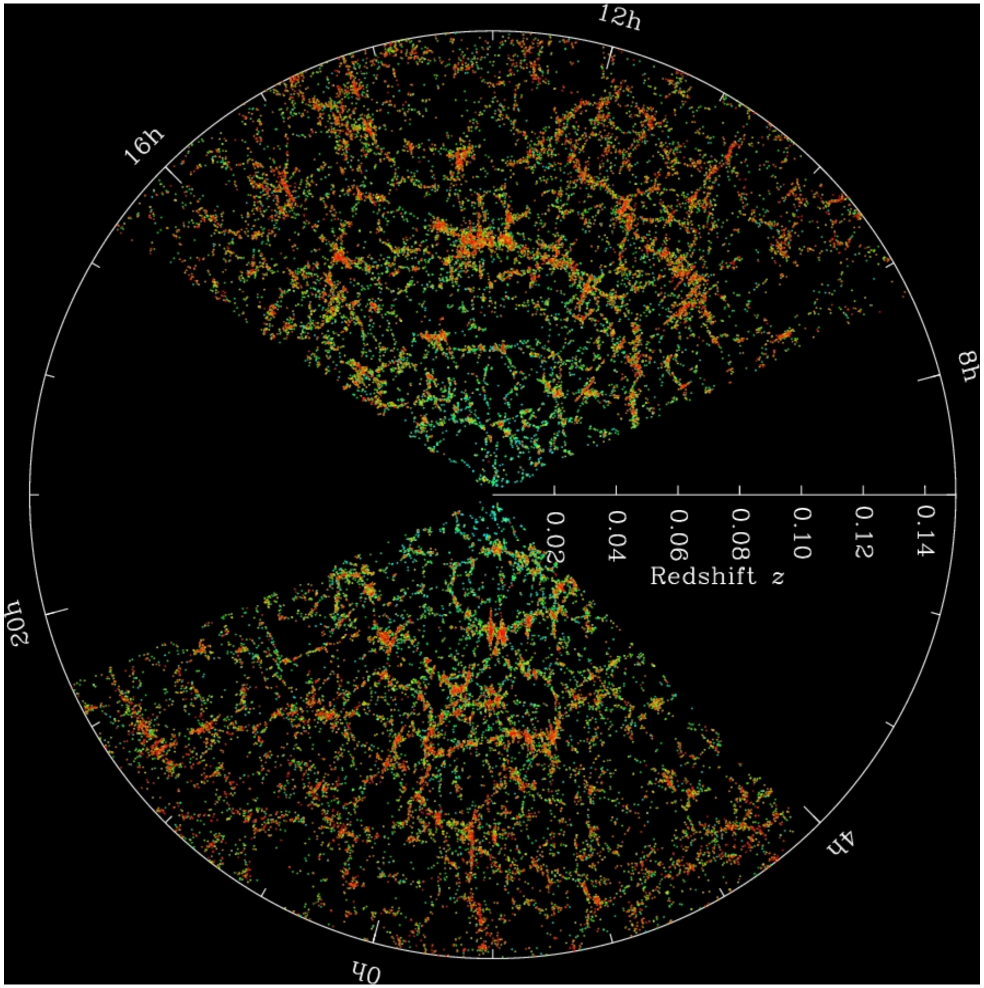
Still not clear:

- Nature of DE
- WDM vs CDM

Goal of next generation sky survey: BAO, Weak-lensing, redshift-distortion

Outline

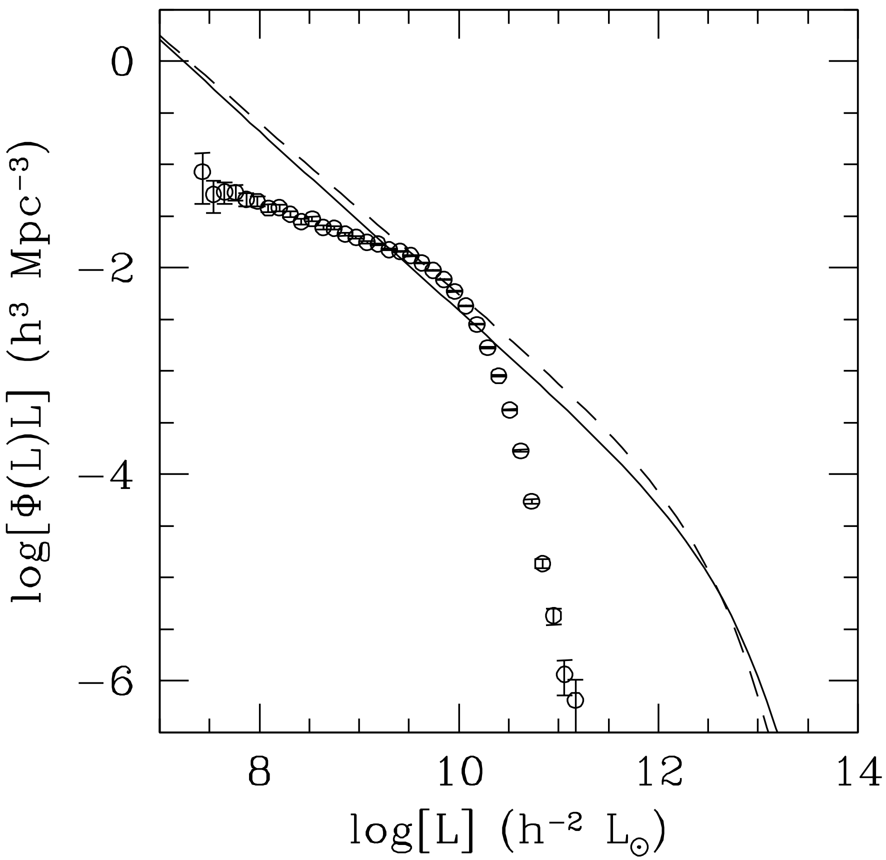
- Structure formation
- Models for galaxy formation
- Several types of galaxy distribution
- Various tests (milky way as a local lab)
- Summary



利用SDSS巡天，我们已经直接观测到了100多万个星系，精确地测量了其统计性质：数目－光度，质量，颜色，形态，空间分布等

模拟宇宙学背景下星系的形成（统计上）是当前星系宇宙学的重要研究方向

luminosity function: theorists have been struggling with it for about 20 years



Yang et al. 2003

Line: theory
points: data

how to link them?
we need models for galaxy population formation

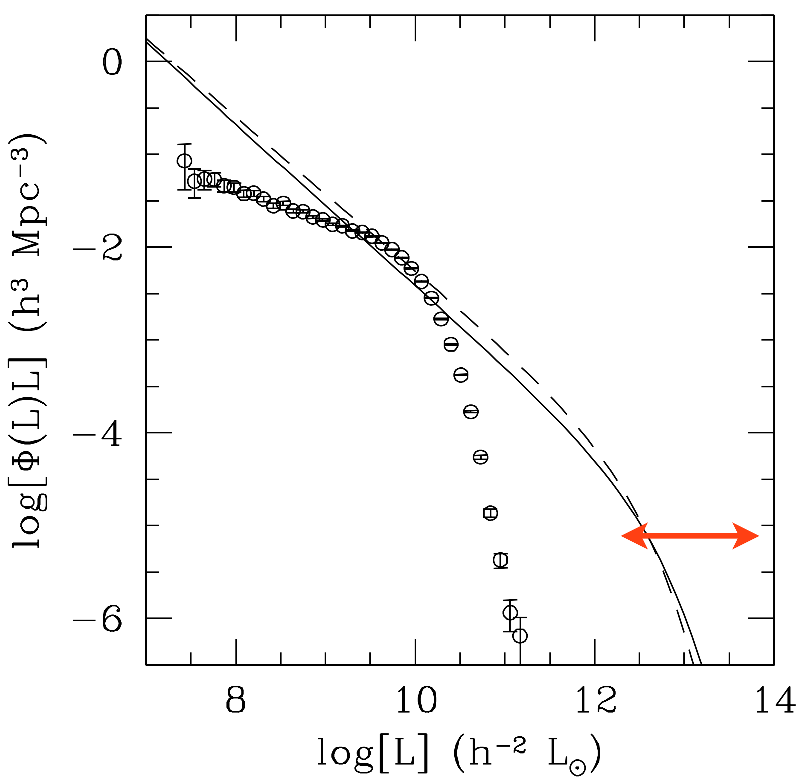
interpreting galaxy distribution

- Abundance matching: using dark matter halo(subhalo) properties (often at accretion) with abundance match to galaxy population (no free parameters, still no physics)
- HOD/CLF: halo occupation distribution,conditional luminosity function: put galaxy(with given stellar mass/luminosity) in dark matter halo (local observations are inputs, no physics input)

modeling galaxy formation

- Hydra-simulation: with gas, star formation included, advantage: model gas dynamics directly, but star formation, feedback still included by hand, problems: sub-grid physics, resolution effect, over-cooling, time consuming
- Semi-analytical model: combine dark matter halo merger trees with simple description of galaxy physics, advantages: computation easy to produce large sample of galaxy population, easy to change cosmology & model parameters (too many free parameters)

Abundance matching (using stellar mass function only)



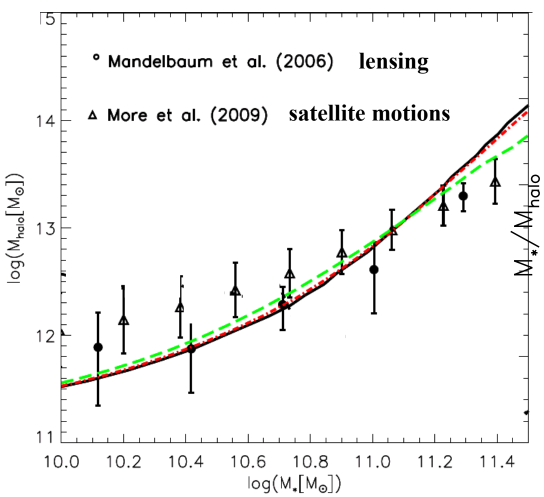
- n(>m_star)=n(>M_halo)
- current models have included subhalos and orphan galaxies, using halo mass at accretion(M_{acc})

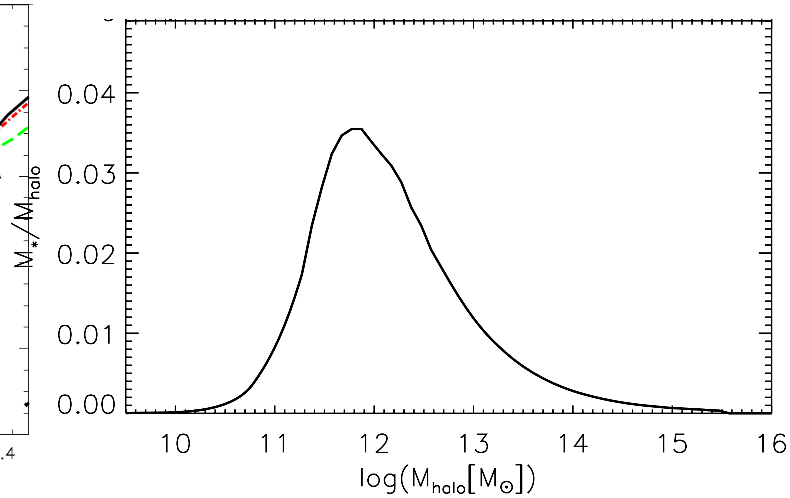
predictions from Abundance matching

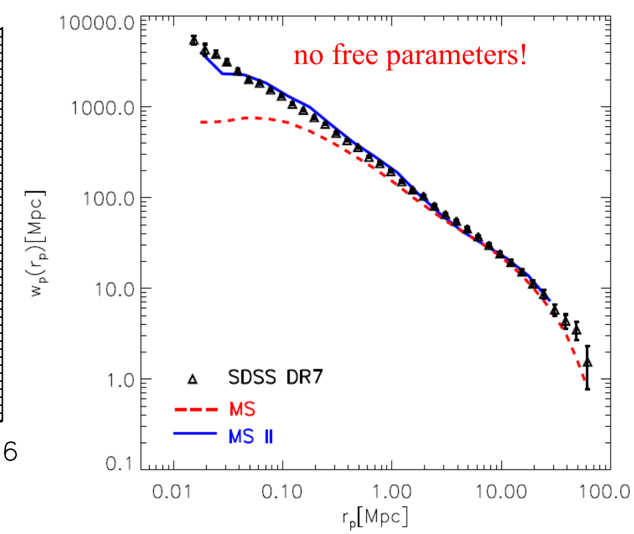
stellar-halo mass relation

star formation efficiency

galaxy clustering

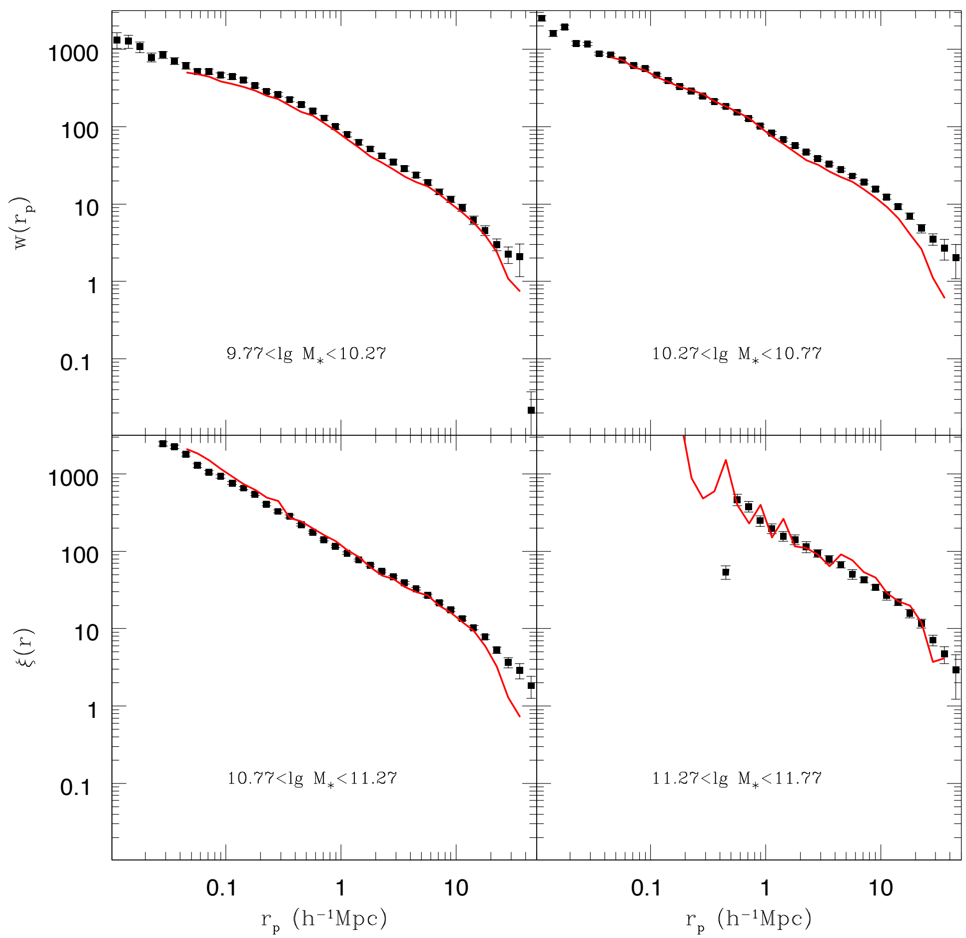






Guo et al. 2010

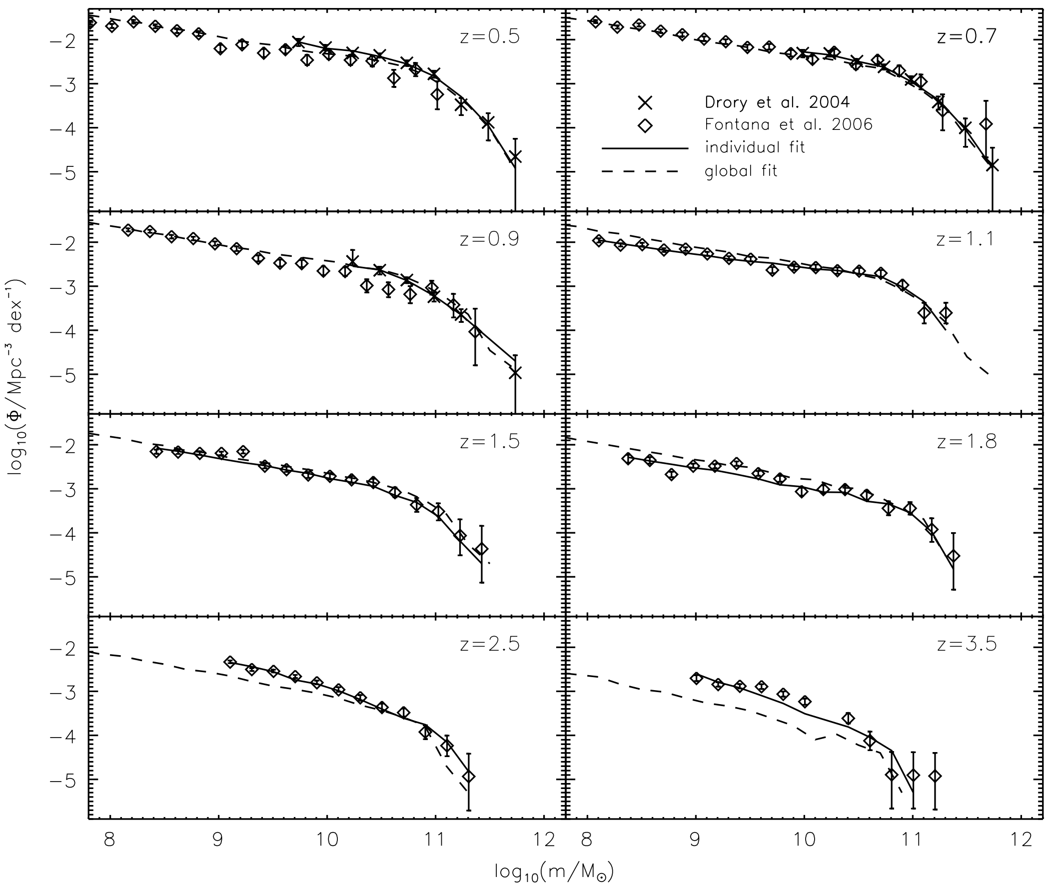
Abundance matching:
galaxy clusterings

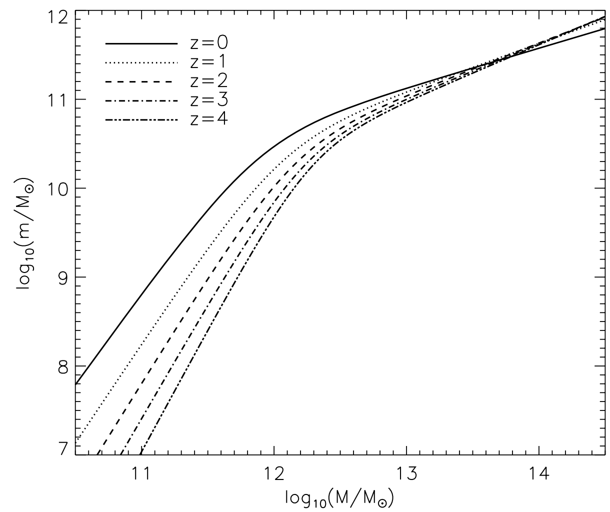


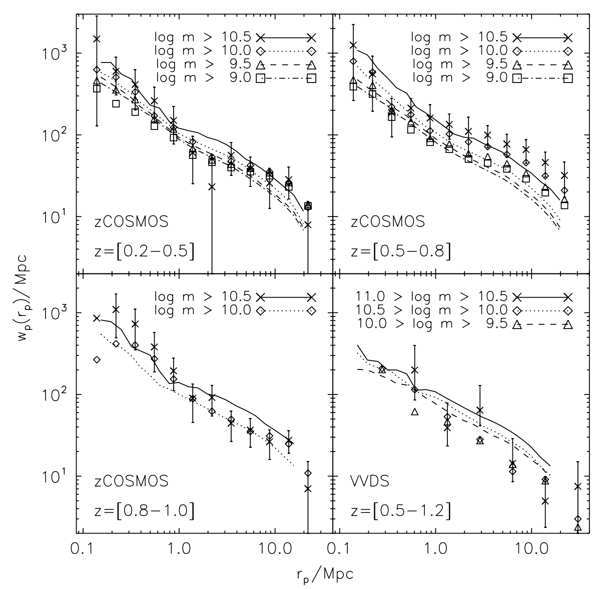
good agreement in different stellar mass bins

Kang et al. 2012

Abundance matching
(high-redshift)

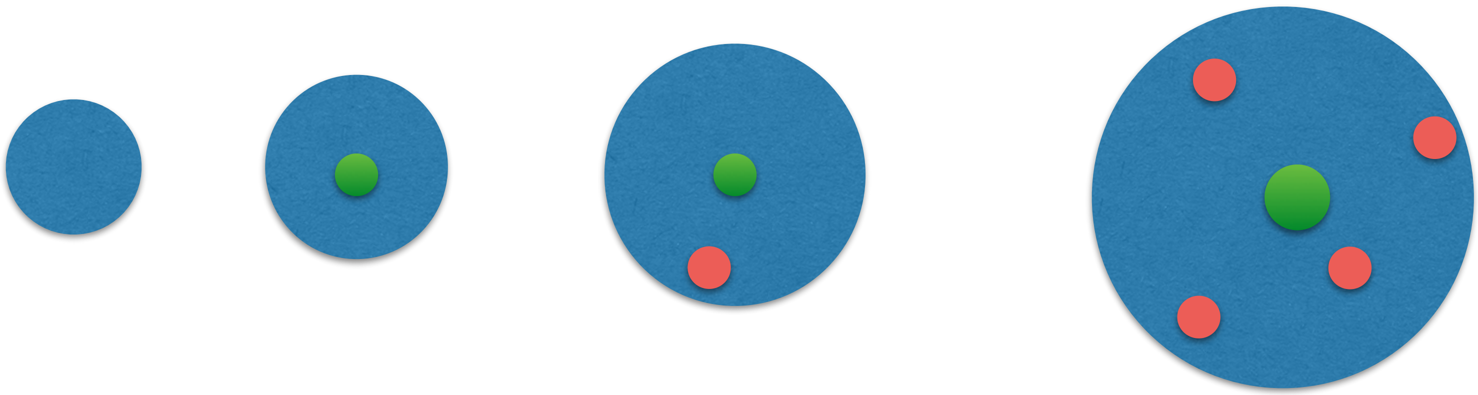






Moster et al. 2010

HOD/CLF (Halo Occupation Distribution)



$N_c(M), N_s(M)$
$L_c(M), L_s(M)$
$\rho_s(r)$

+

Halo mass function

Halo clustering

Galaxy density distribution

Compare with observations:

- galaxy stellar mass function
- galaxy clustering

→ Constraining model parameters

HOD or CLF can

describe the galaxy distribution
describe the star formation history

However, no physics, do not tell us why

we need models describing galaxy formation !

Structure of SAMs

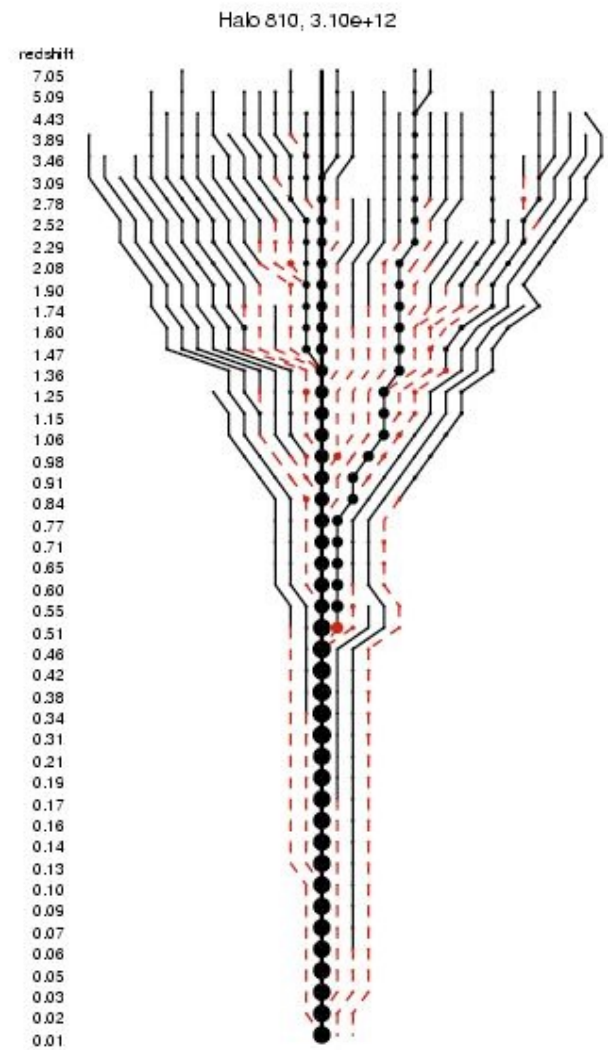
- Formation of dark matter (sub)halos

- Baryonic physics (most uncertain)

Formation of dark matter (sub)halos

- Directly from N-body simulations

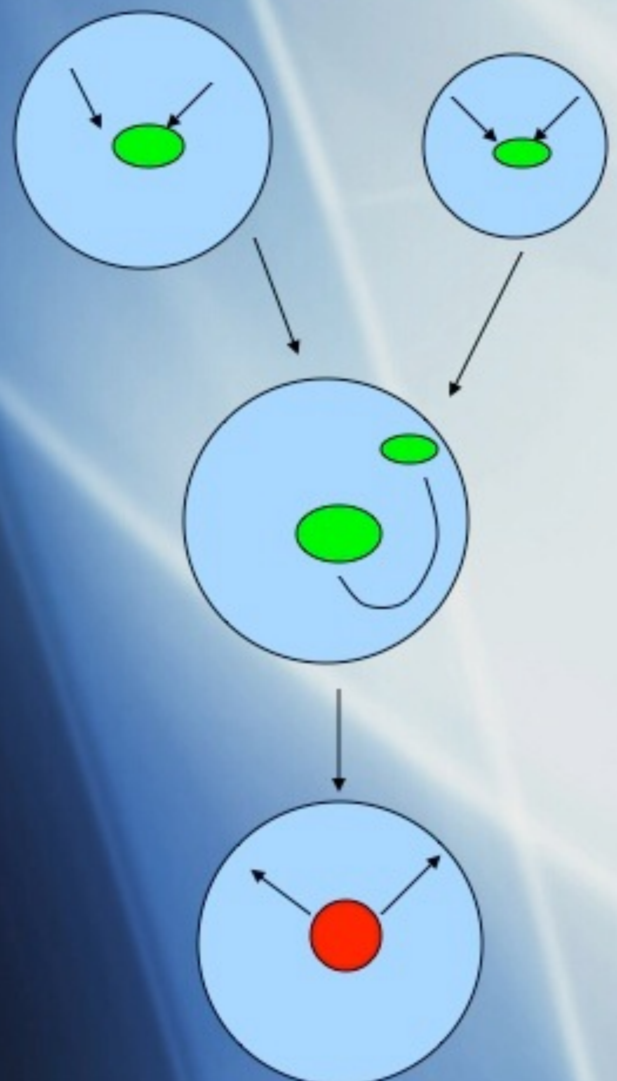
- EPS theory (high-resolution, no spatial information)

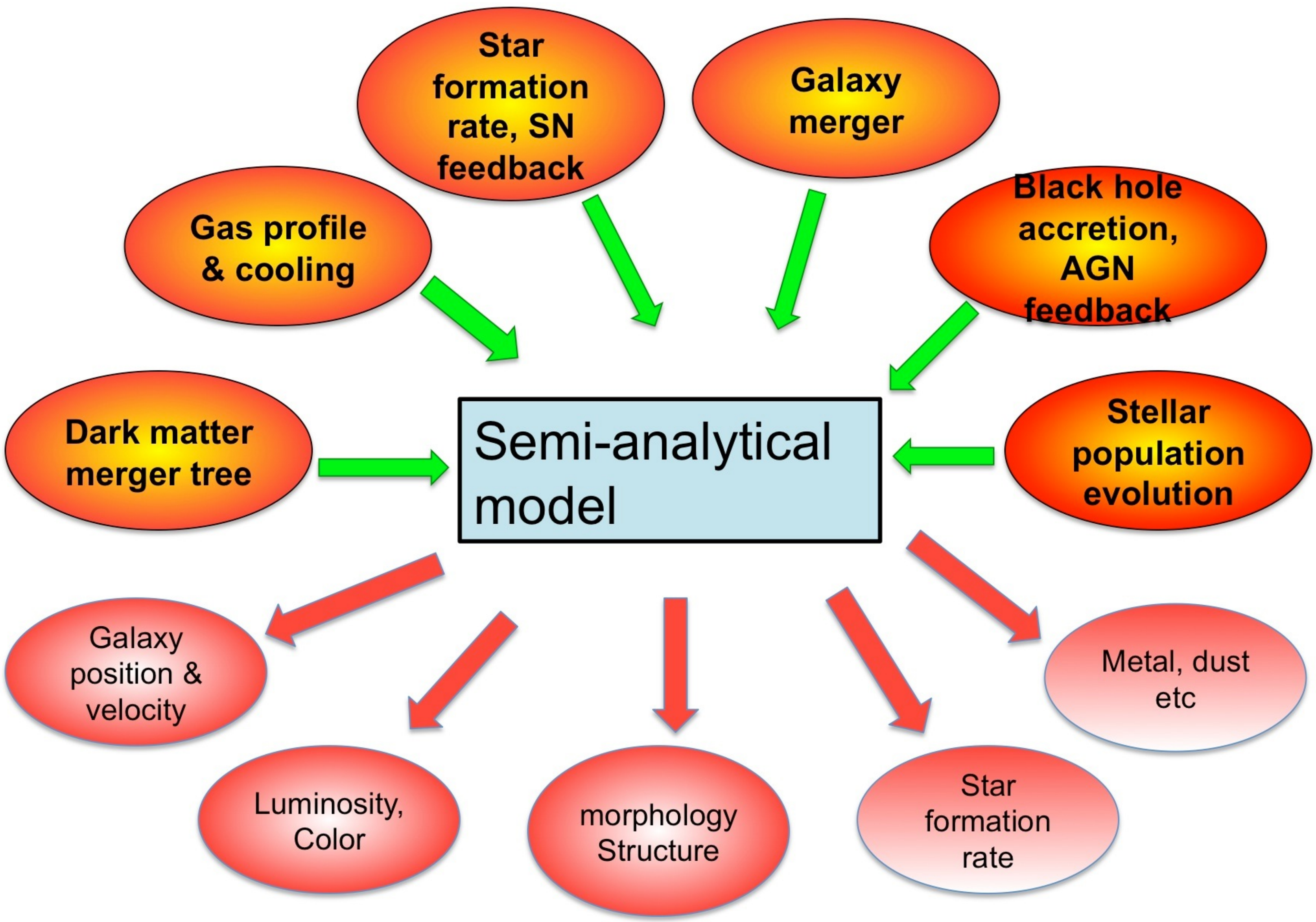


Halo merger trees are fully determined given cosmological model, initial conditions

Baryon process: part1

- Gas shocked heated to halo virial temperature
- Angular momentum conservation, r ~ 0.05R
- Satellite merge with central after a dynamical friction time
- Star form both in disk (efficiency not well constrained) and during merger, (merger trigger more stars formed)
- Major merger trigger bulge form, most gas consumed, others blow out (dear, red ellipticals)

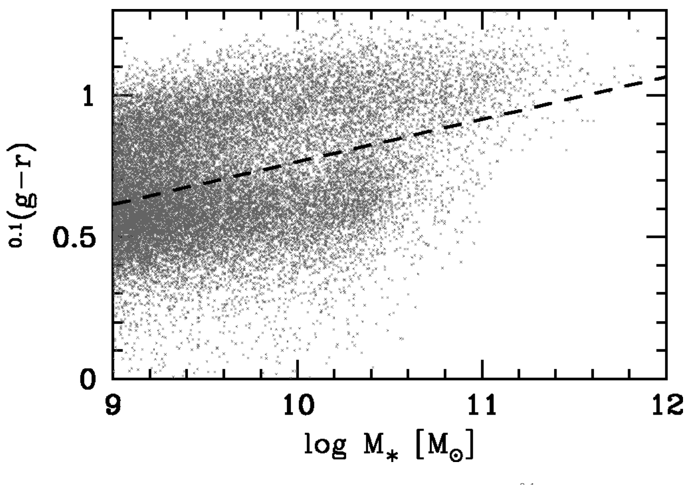


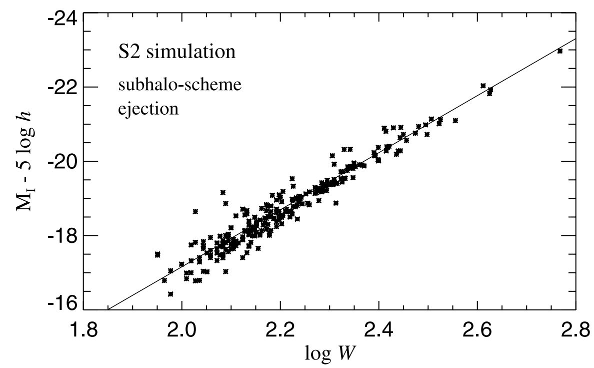

Star formation rate, SN feedback
Galaxy merger
Gas profile & cooling
Black hole accretion, AGN feedback
Dark matter merger tree
Semi-analytical model
Stellar population evolution
Galaxy position & velocity
Luminosity, Color
morphology Structure
Star formation rate
Metal, dust etc

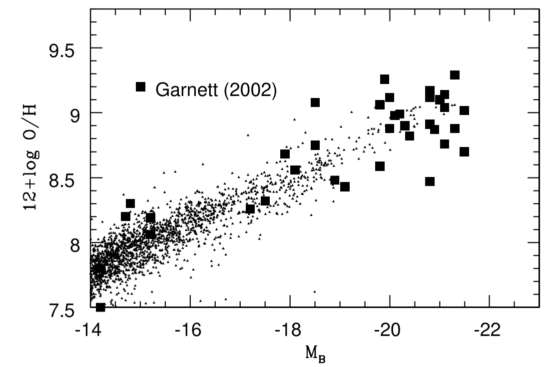
Main baryonic process (not very clear)

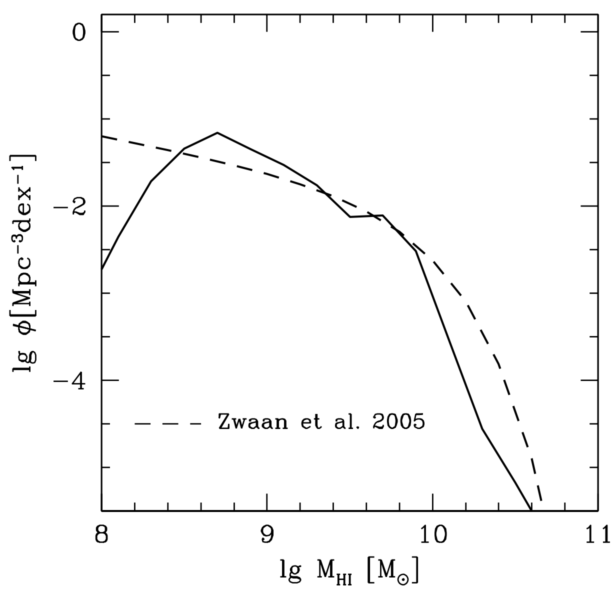
- Cold gas accumulation: how many gas can cool in given halo (gas accretion manner?)
- Star formation efficiency (mass dependency, redshift evolution?)
- SN feedback , Black Hole feedback (fate of reheated gas, BH accretion rate?)
- Central galaxy ->satellite: ram-pressure stripping, stellar stripping, disruption, merger rate (partly understood)
- Stellar population evolution (IMF?)
- Others: galaxy merger, morphology transform, star burst,,,

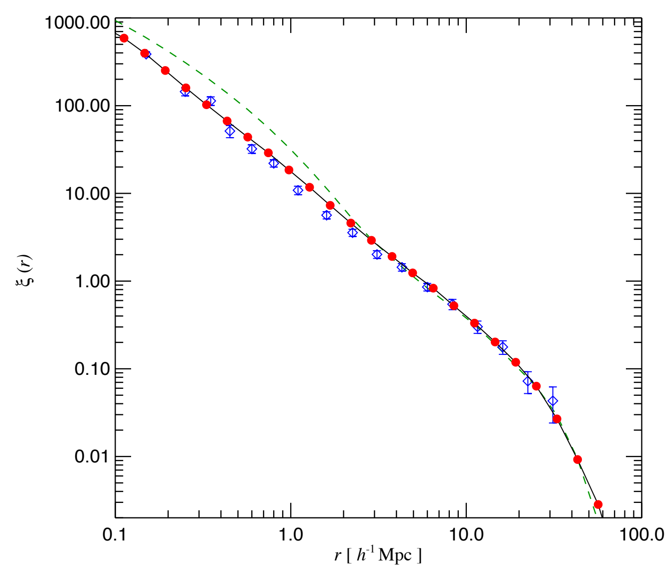
SAM predictions

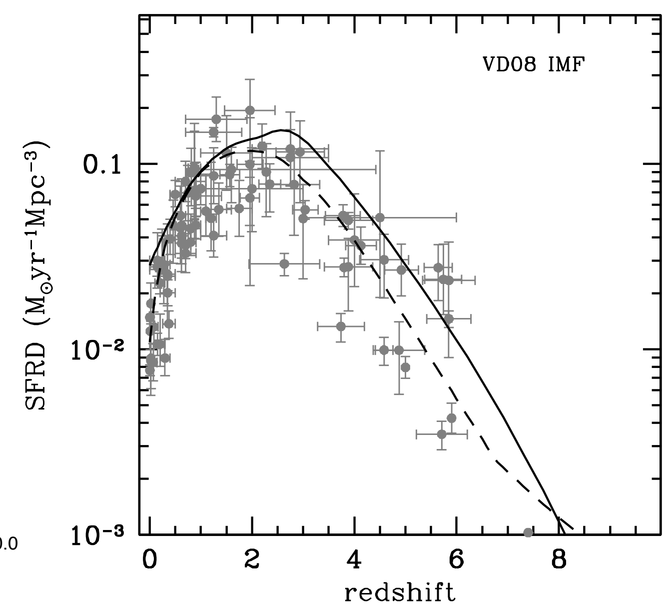




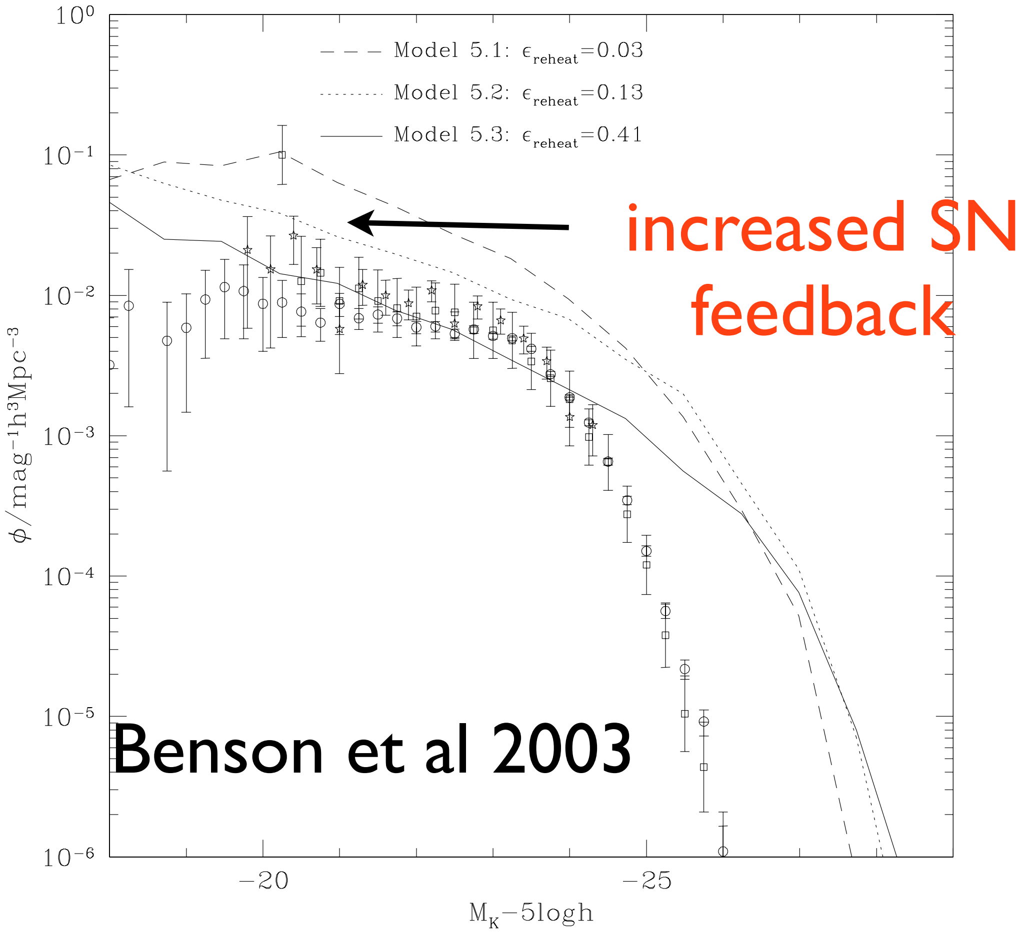


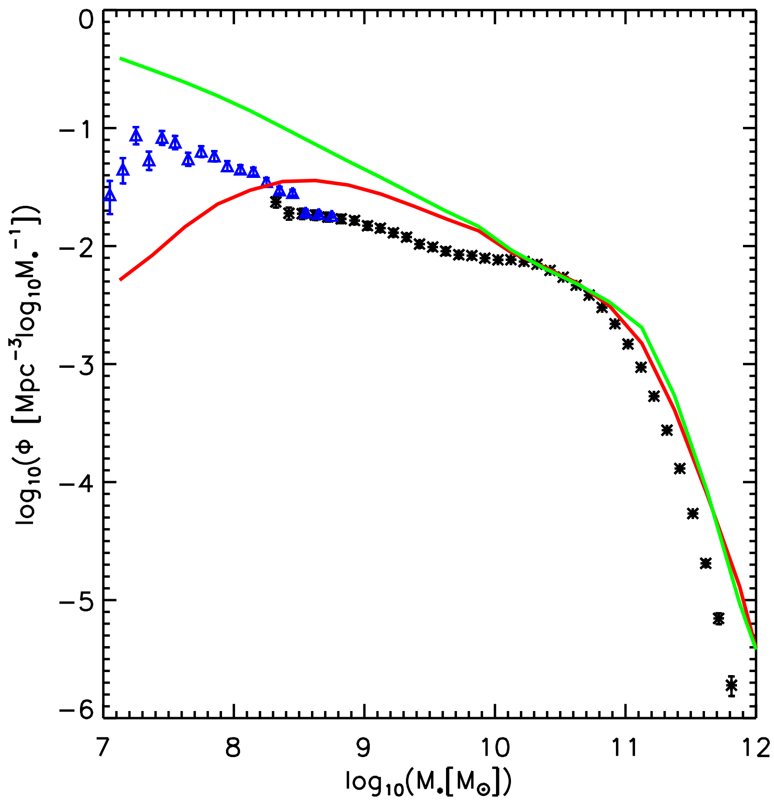






What we have learned from SMF?





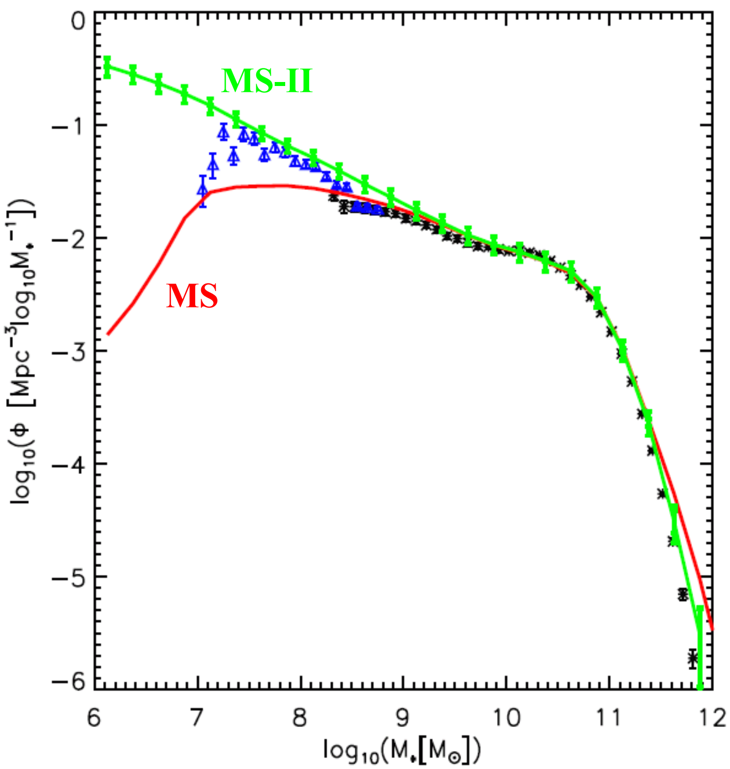
Delucia et al. 2007

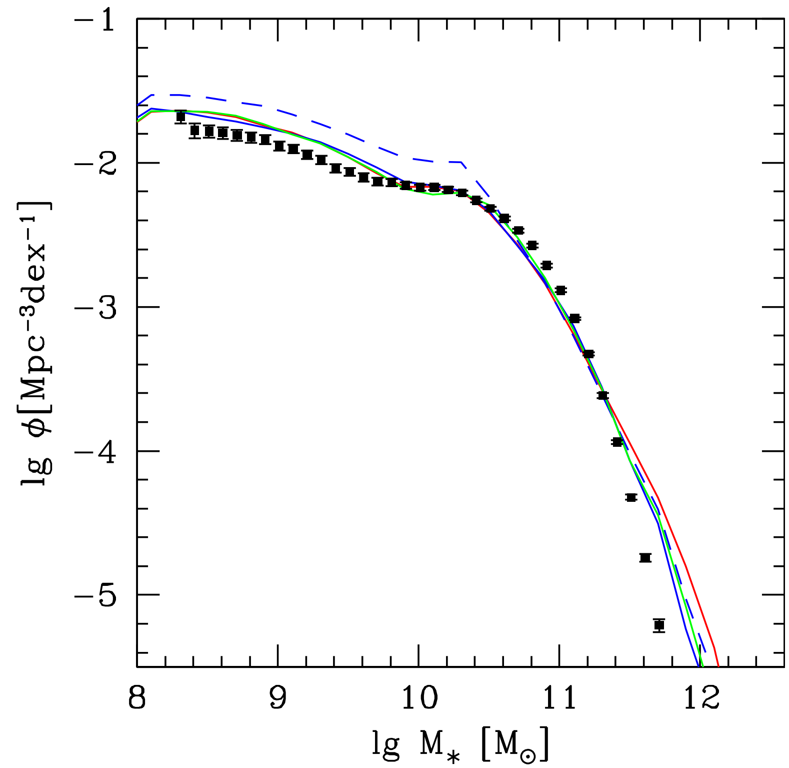
A flat faint end can be obtained if:

SN feedback efficiency is $\sim V^{-\alpha}$ ($\alpha > 2$),

(Cole et al. 2000)

What we have learned from SMF?





A:Guo etal 2010

B:Kang et al. 2012

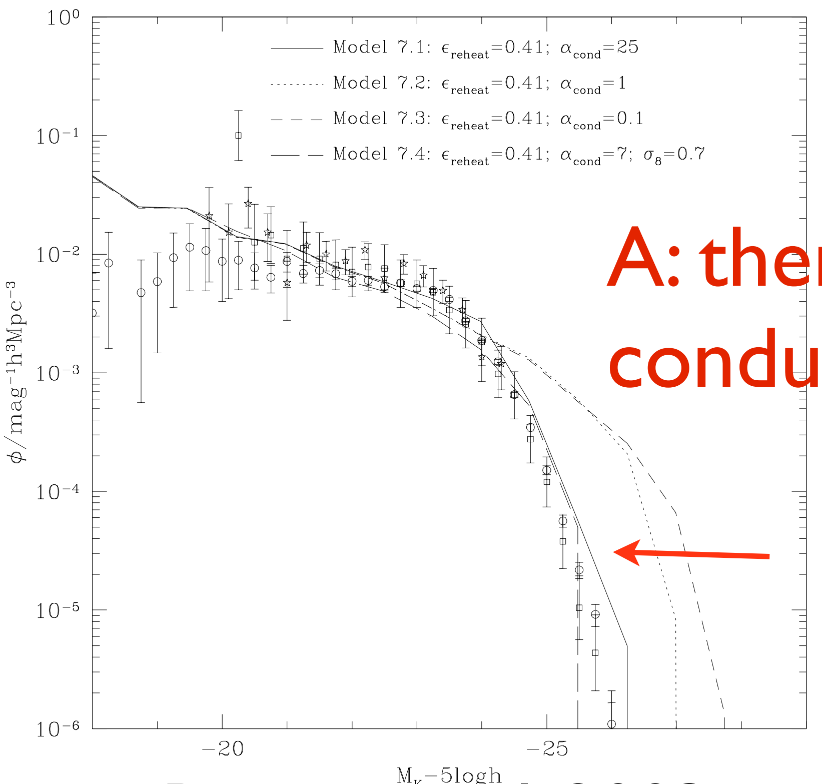
A flat faint end can be obtained if:

A:gas re-incorporation time is longer

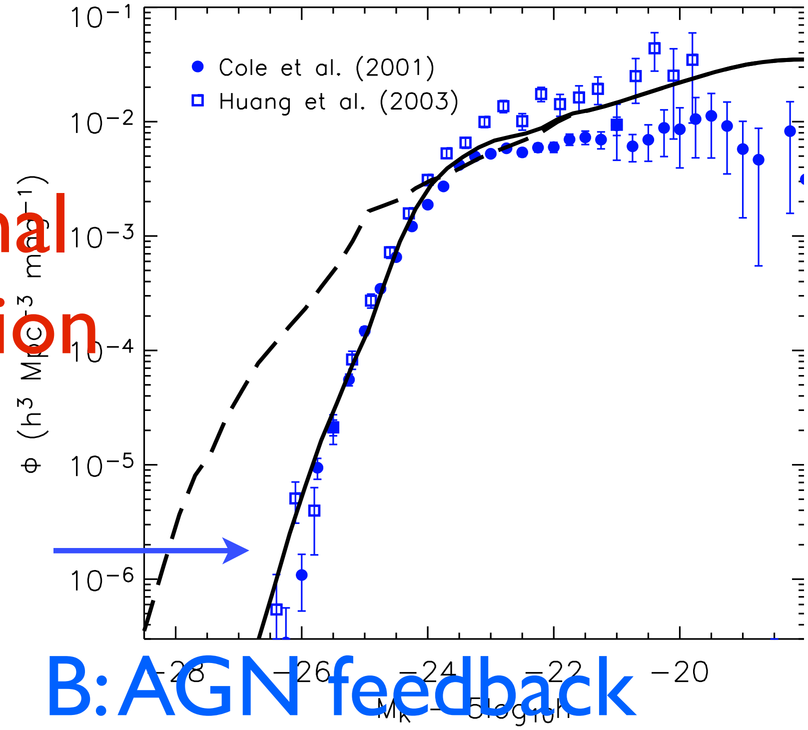
B:gas cooling is lower in small halo

B: $M_{cool}=fM_{hot}/t_{dyn}$

What we have learned from SMF?



Benson et al. 2003



Croton et al. 2006

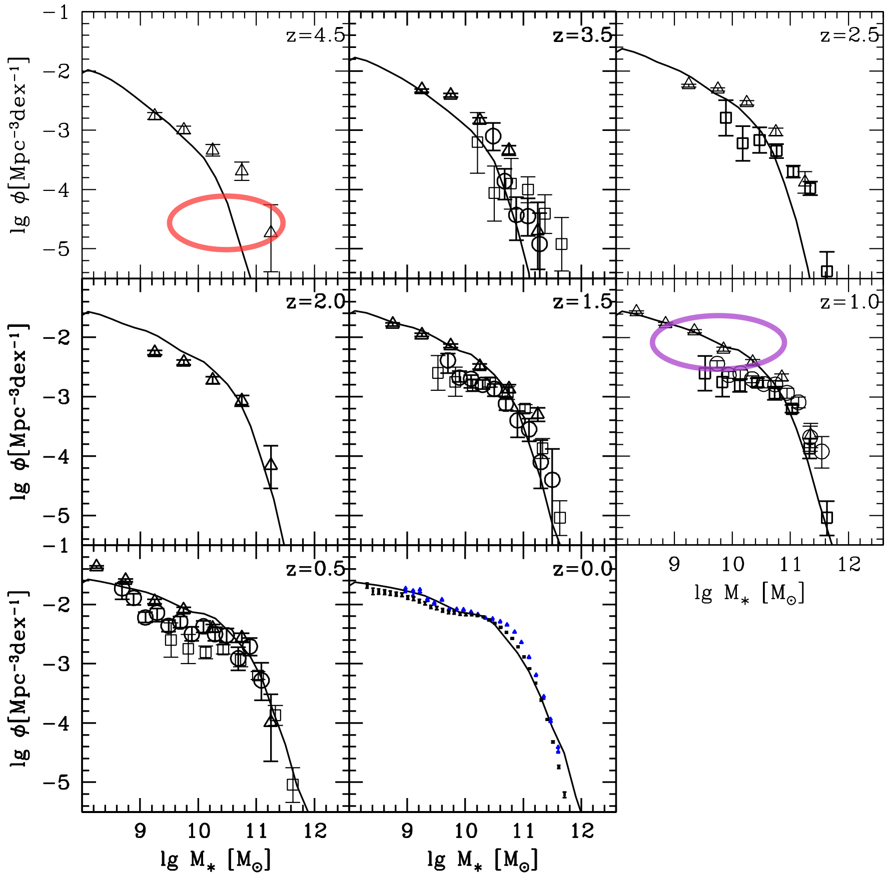
A sharp decline at the bright end can be obtained if:

A: high thermal conduction in cluster

B: AGN feedback is incorporated

Problem 1: Stellar mass functions at z>0

Kang et al. 2010, ApJ



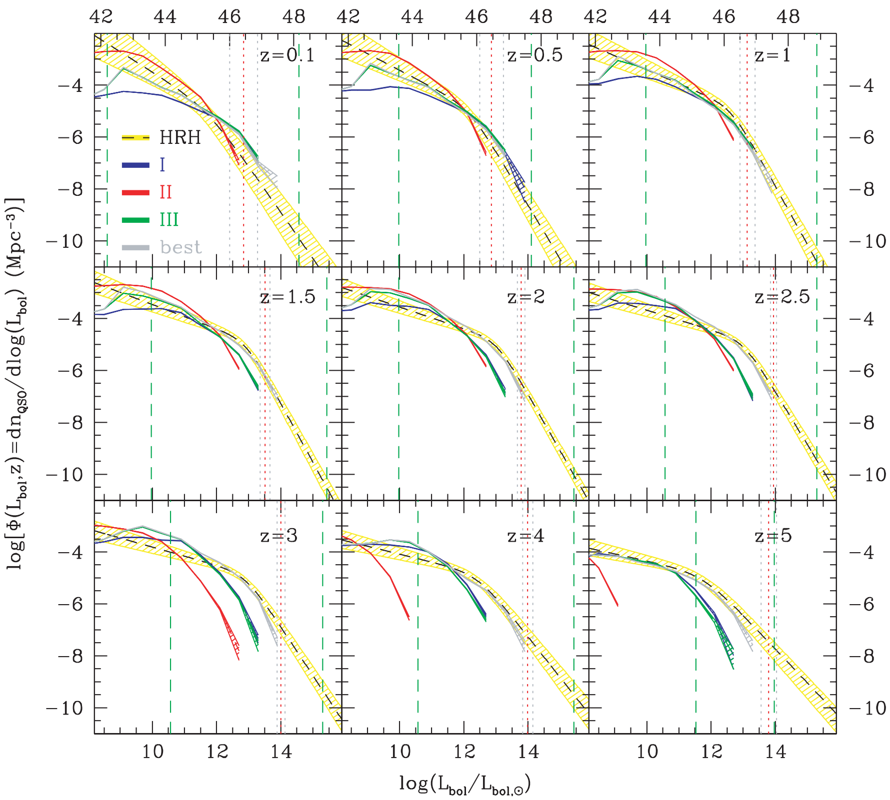
- •Model under-predict number of massive galaxies at z>2
- •be aware of Cosmic variance and stellar mass estimation uncertainty

- •Too many galaxies at M_*=10^10 at z>0 (But Faint end is not well constrained, discrepancies among data and recent COSMOS results has more faint galaxies)

Large uncertainty on SMF at massive end (Bernardi+ 2013,depending on how to fit light distribution) and faint end (survey magnitude limit etc)

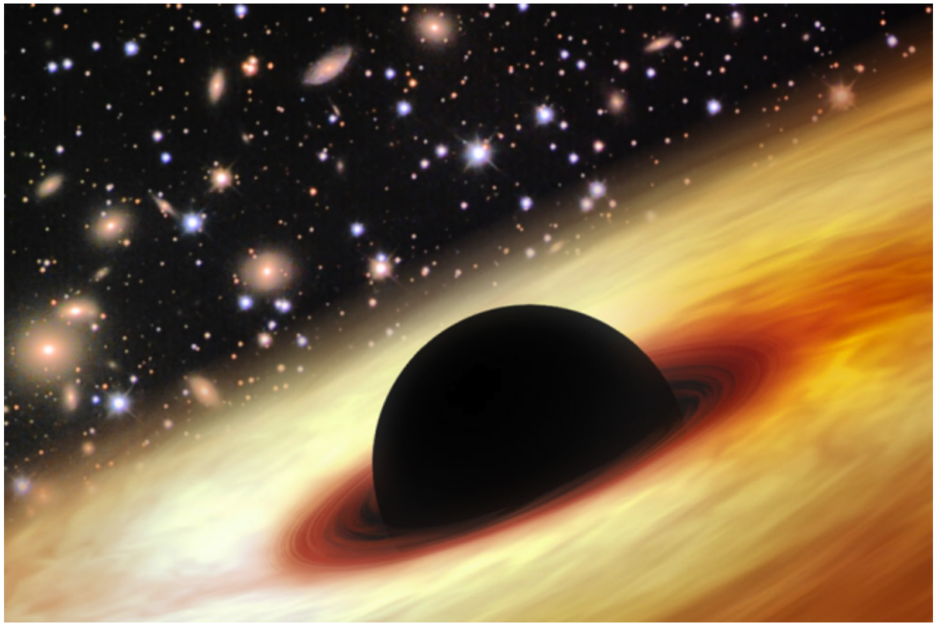
Predictions on QSOs

QSO Luminosity functions



Marulli et al. 2008

Most luminous QSO at z=6.3 (BH: 10^10 solar mass)



吴学兵 et al. 2015 Nature

How to relate the growth of BH with galaxy formation?

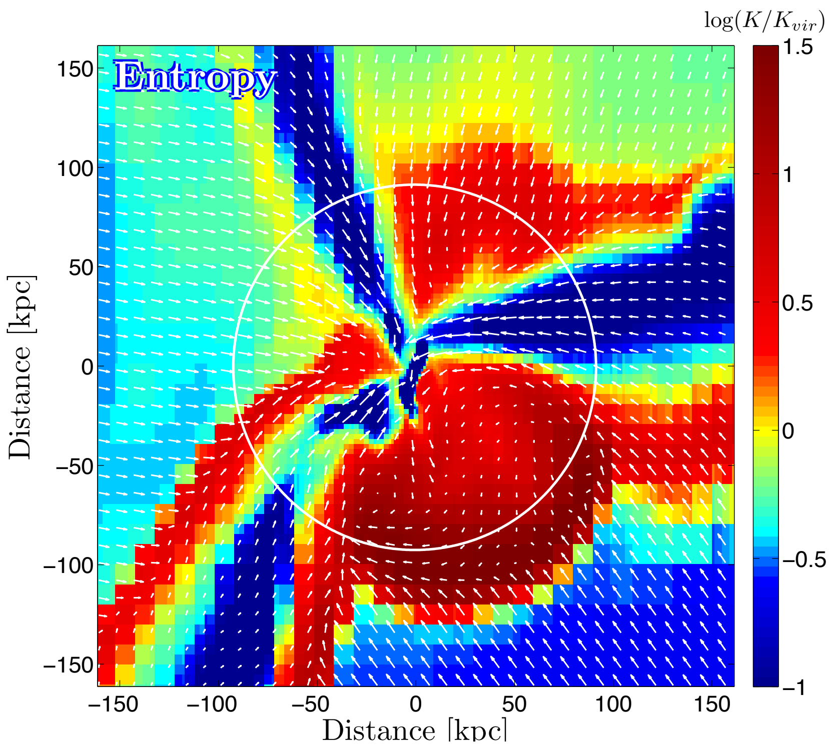
In SAM, QSO growth occur with major mergers

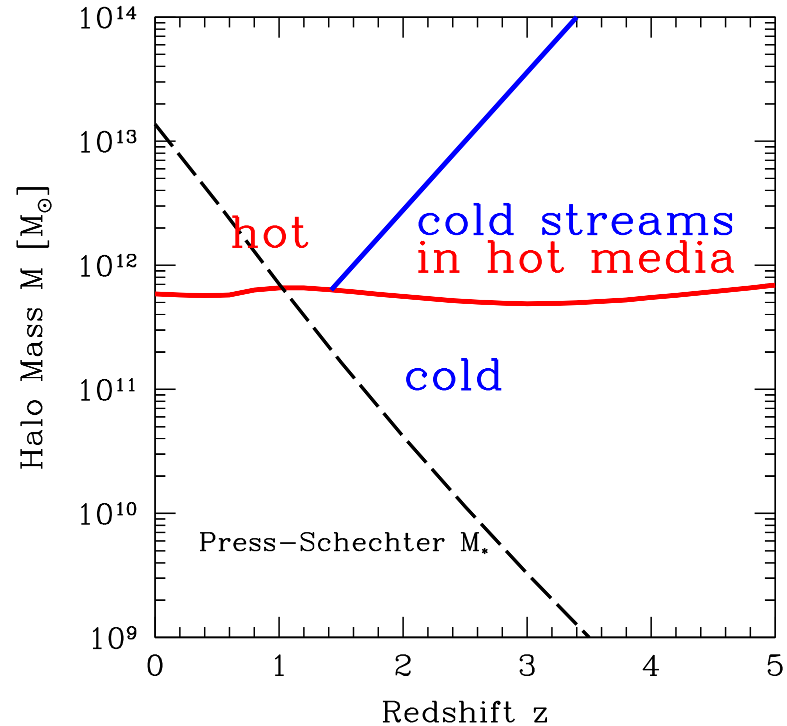
BH accretion more efficient at high-z?

Any other source of rapid BH accretion?

Even the gas cooling at high-z is quite different

Cold flow at high-z, massive haloes:

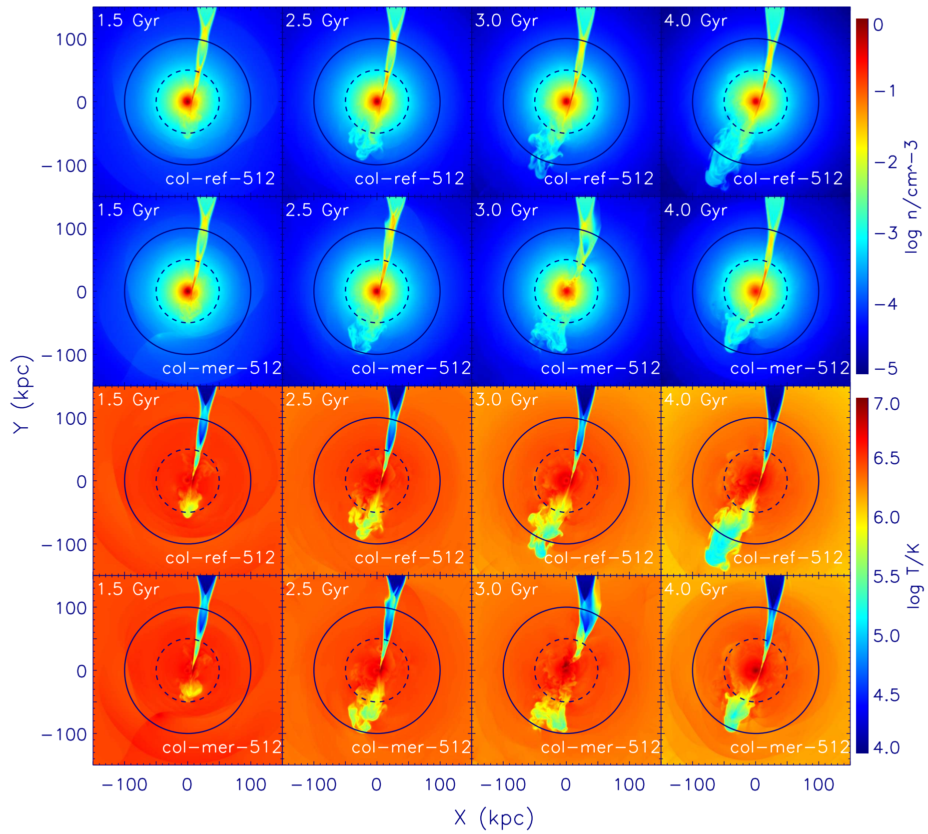




Dekel etal. 2009

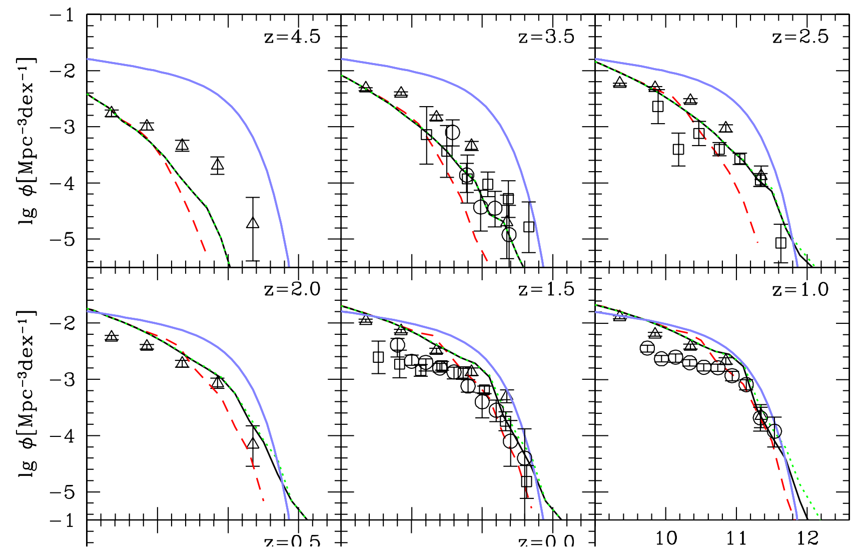
Gas goes to halo center in form of cold flow, faster than conventional cooling formula: $M_{hot}(r_{cool})/t_{cool}$

High-z galaxy suffers many mergers, and difficult to observed)
Is cold flow stable?



Wang, Kang+ 2014, MNRAS

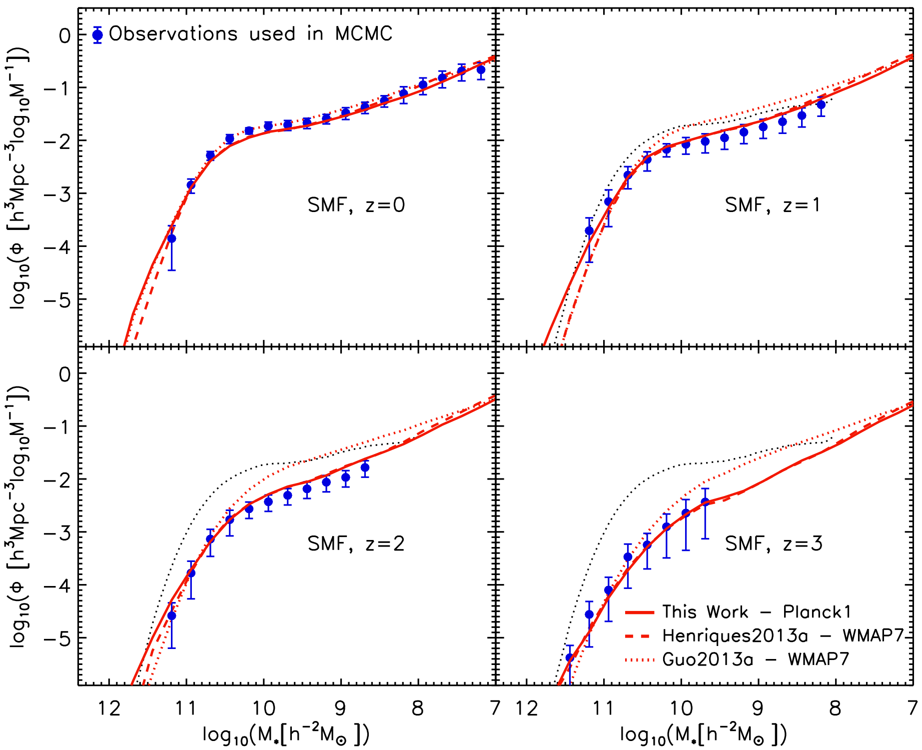
Our toy model shows: cold flow can maintain its stability if continuous cold flow is sustained



Kang et al. 2010 ApJ: rapid cold accretion produce more massive galaxies

Could deep survey around luminous QSO identify the nearby filamentary structure around?

Problem 2: low-mass galaxies (big & real problem)



Low-mass galaxy problem is solved if

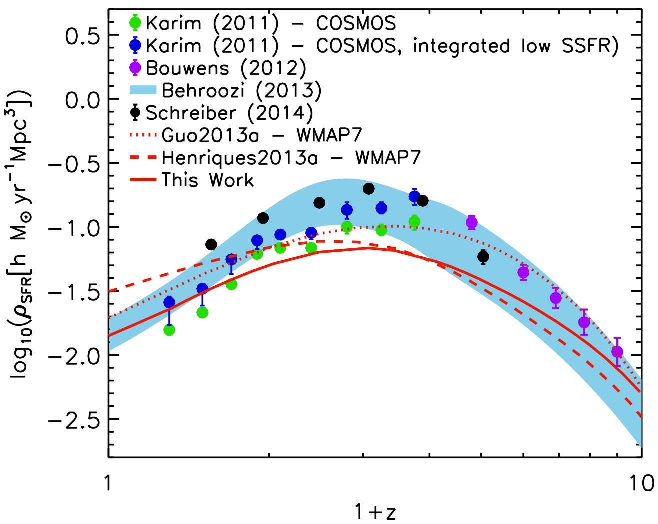
- gas re-incorporate time is longer
- star formation threshold is lower
- ram-pressure is suppressed
- However, SFRH is still not right!

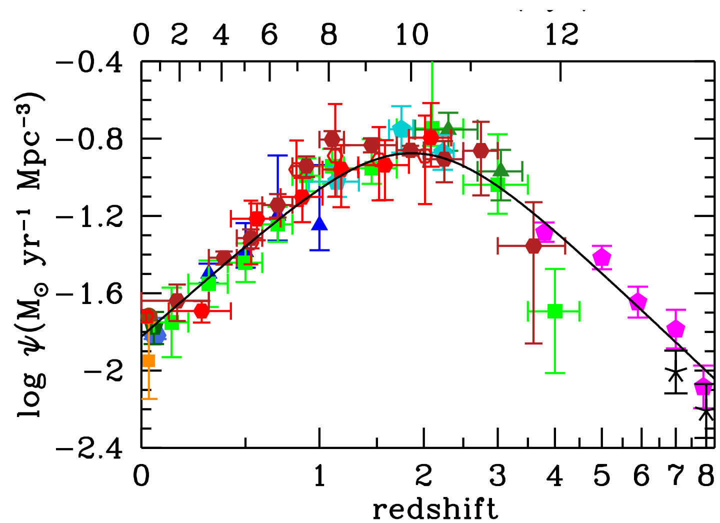
Henriques et al. 2014 (Munich model)

Solutions are inconsistent with Hydro simulations by illustris

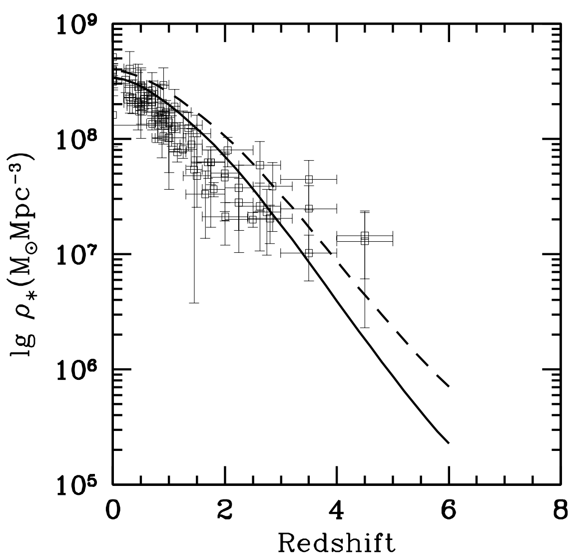
- gas cooling is full traced
- supernova feedback is maximized

Problem 3: Cosmic Star Formation History
(not a problem of SAM, but data itself)

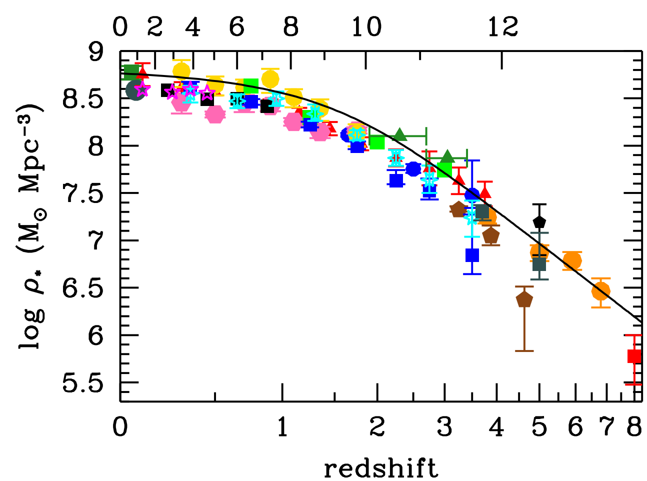




henriques et al. 2014



Kang et al. 2010



Madau & Dickinson 2014, ARAA

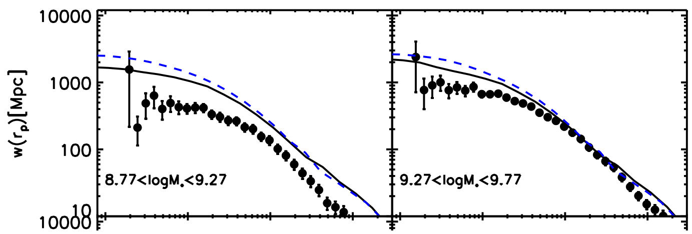
previous work under-estimated SMD
(using a too flat faint-end slope)

Physics affecting satellite galaxies

- Ram-pressure stripping: galaxy color
- Tidal stripping & disruption: red satellite fraction, intra-cluster light
- Supernova feedback efficiency: satellite galaxy mass
- Cosmic re-ionization: abundance of low-mass satellites
- Dark matter property: abundance/kinematics of satellites

Problems for low-mass galaxies

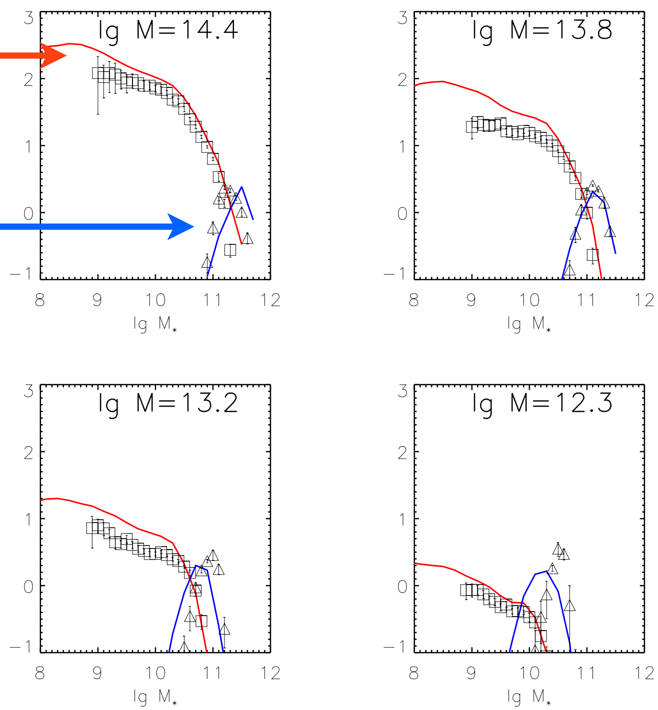
2 points correlation function



Guo et al. 2010 MNRAS

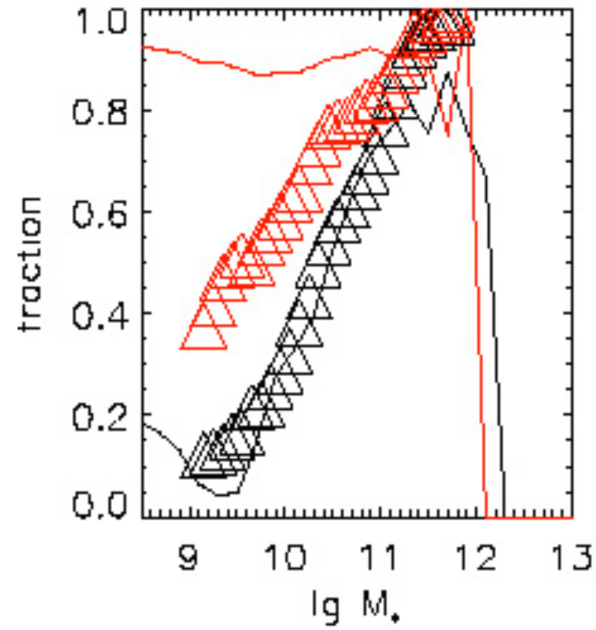
Satellites

Centrals

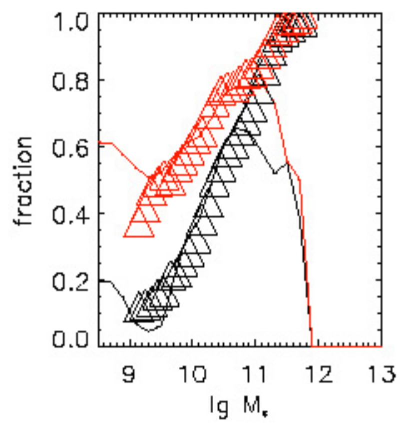


Kang 2014 MNRAS

red fraction



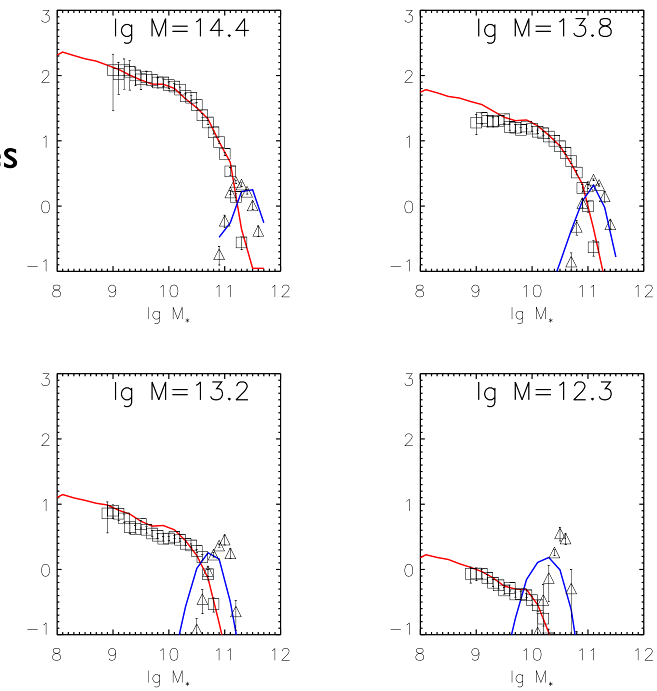
Too many low-mass & red satellite galaxies in Almost all Sam models !!!



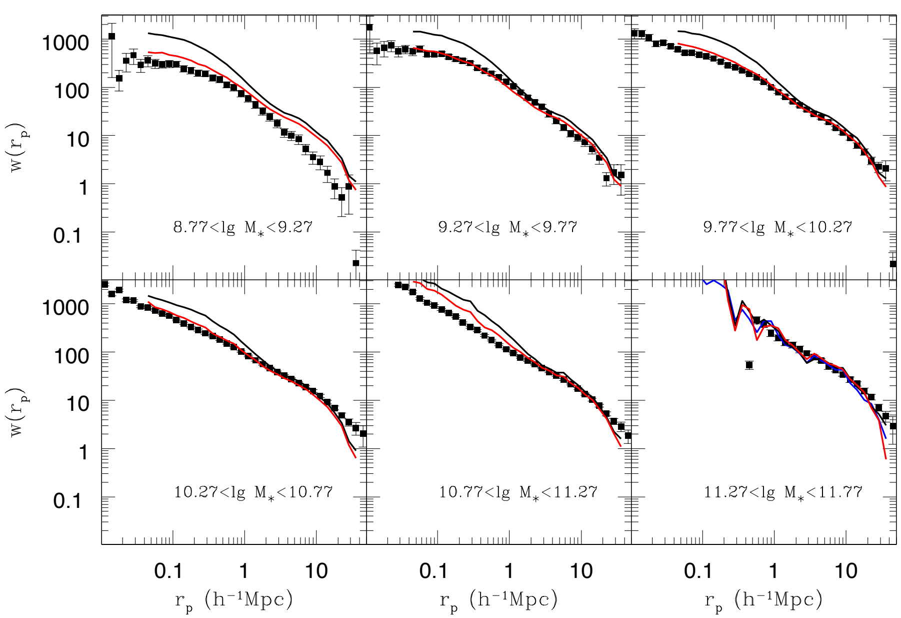
A: Non-instantaneous stripping

of hot halo gas in satellites lasting about 3 Gyr

\+ Some fraction of satellites being disrupted



Kang & van den Bosch 2008

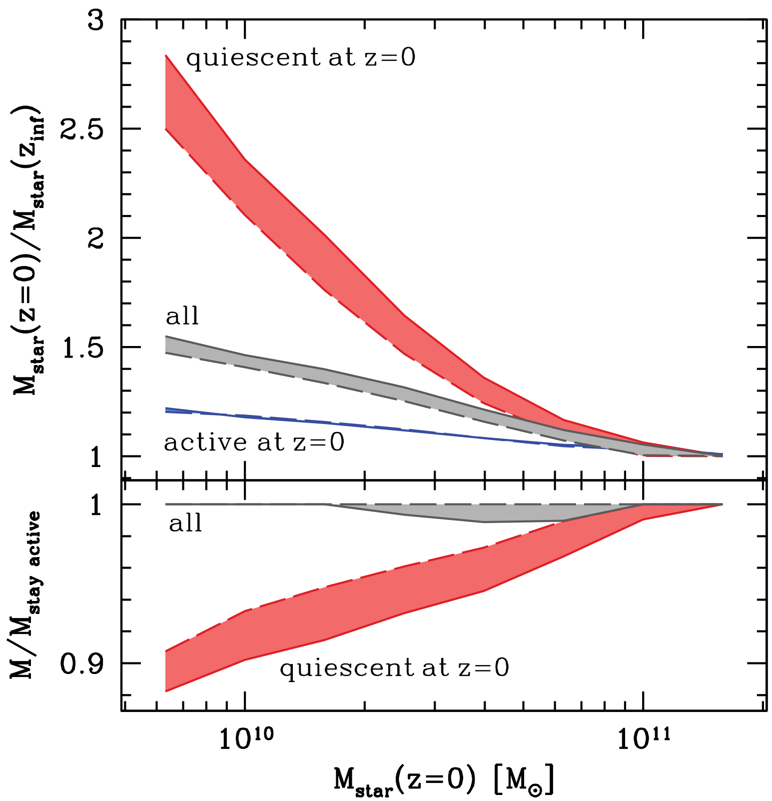


Kang 2014 MNRAS

B: The supernova feedback efficiency should be a local effect: Vreheated=Vdisk previous models assume $V_{reheated}=V_{host}$ (temperature of the host halo)

Effect A & B have opposite effects on satellite mass

constraints on satellite mass growth

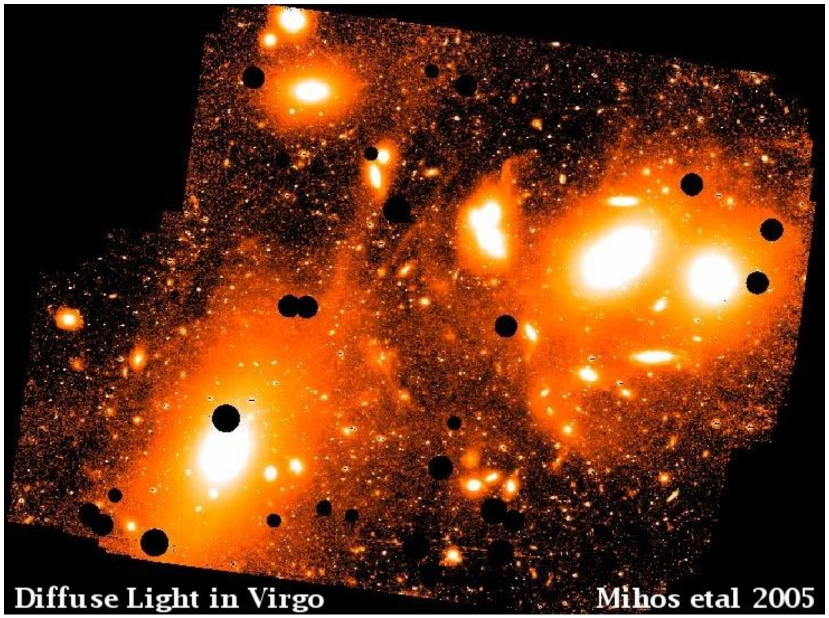


mass growth of satellites after infall should be very limited (at most by factor of 2)

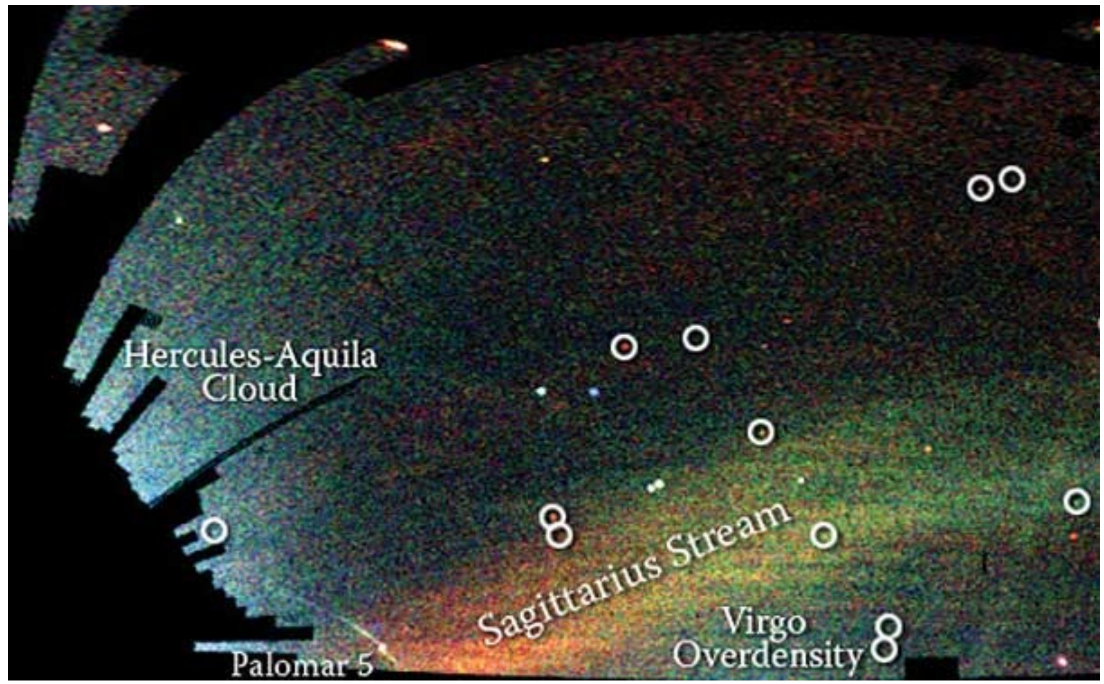
One possible solution to the too-many red satellites problem: strong stripping and disruption

Wetzel et al. 2013

diffuse stellar light and tidal stream



Virgo cluster

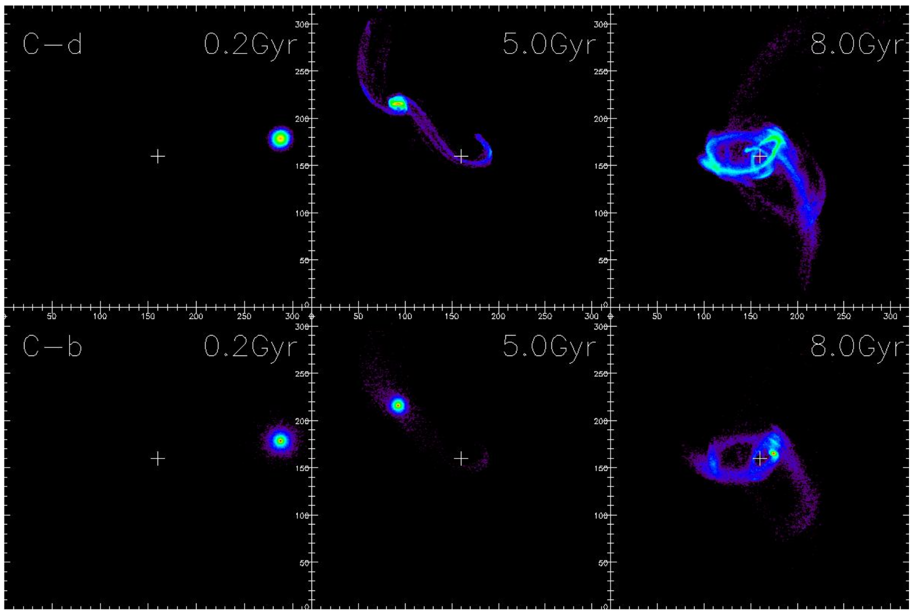


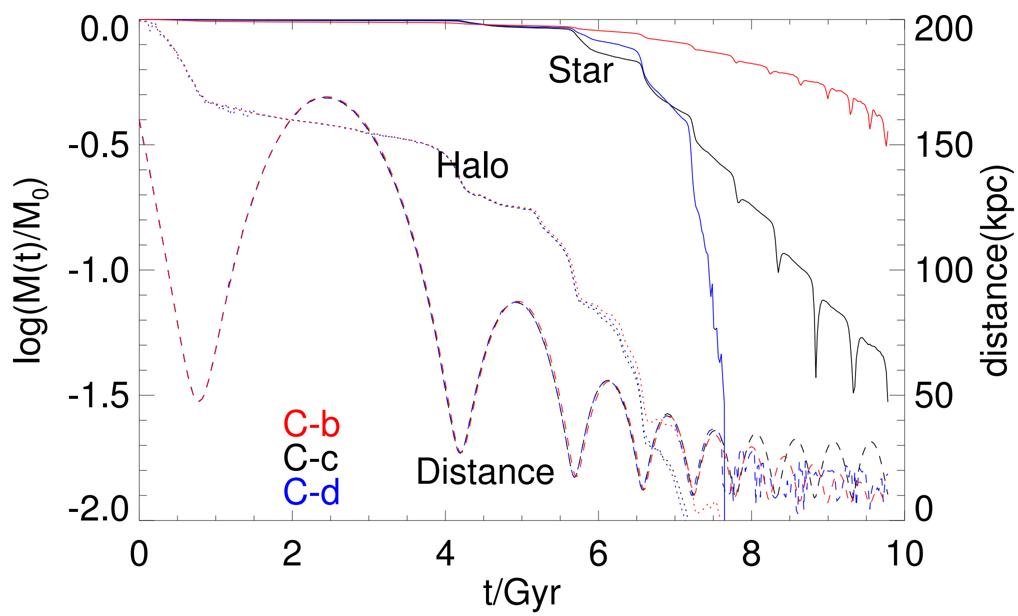
Milky Way

tidal stripping and disruption is included in SAM
but in a very simple way
dependence on galaxy morphology?

N-body simulation of tidal stripping

Chang, Kang+, 2013, MNRAS





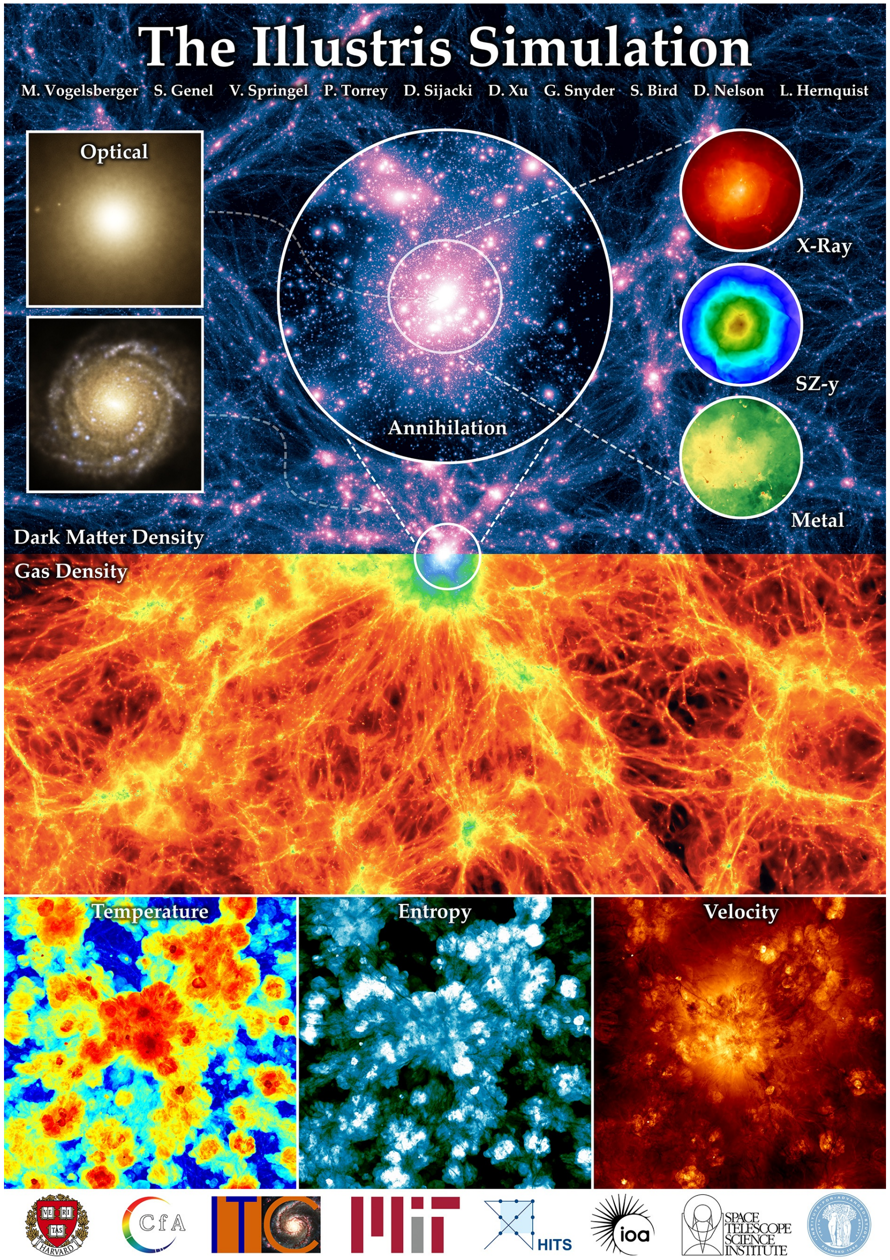
stripping efficiency depends on galaxy morphology !

interpreting galaxy distribution

- Abundance matching: using dark matter halo(subhalo) properties (often at accretion) with abundance match to galaxy population (no free parameters, still no physics)
- HOD/CLF: halo occupation distribution,conditional luminosity function: put galaxy(with given stellar mass/luminosity) in dark matter halo (local observations are inputs, no physics input)

modeling galaxy formation

- Hydra-simulation: with gas, star formation included, advantage: model gas dynamics directly, but star formation, feedback still included by hand, problems: sub-grid physics, resolution effect, over-cooling, time consuming
- Semi-analytical model: combine dark matter halo merger trees with simple description of galaxy physics, advantages: computation easy to produce large sample of galaxy population, easy to change cosmology & model parameters (too many free parameters)



Illustris: a state-of-the-art cosmological hydrodynamical simulation of galaxy formation. Including almost everything! (AREPO code)

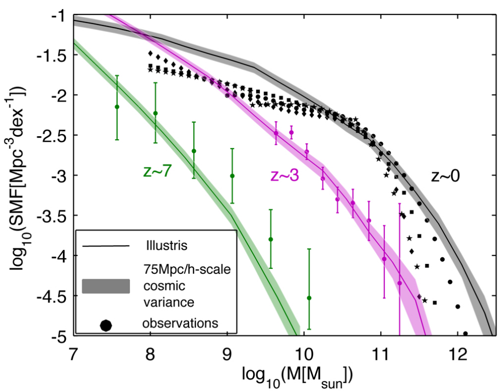
A big step forward to model galaxy formation in Lab

End of hydro-simulation of galaxy formation?

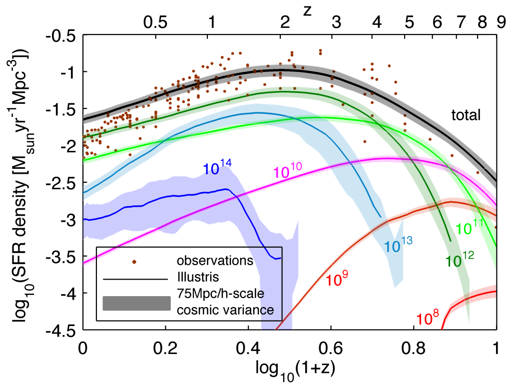
Vogelsberger et al. Nature, 2014:

AREPO (AMR): $(75Mpc/h)^3$ with 12 billion particles,19 Million CPU hours, peak memory: 25TB

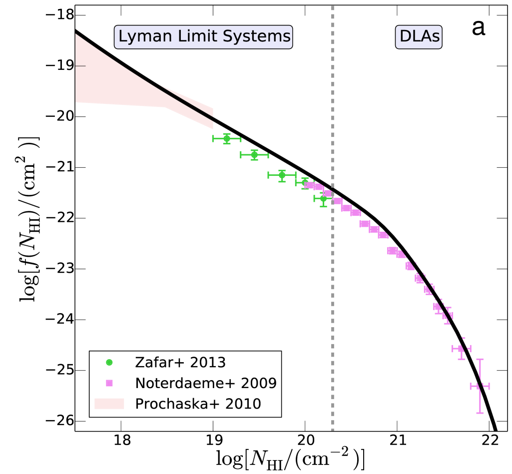
predictions from illustris

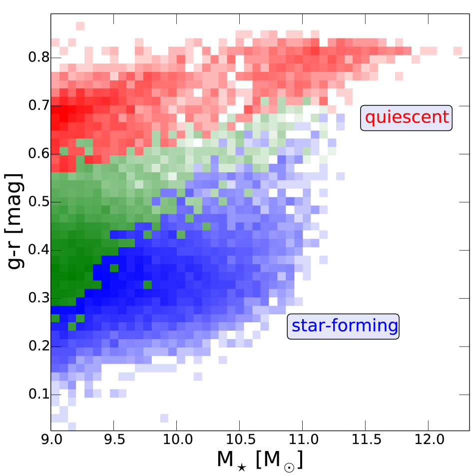


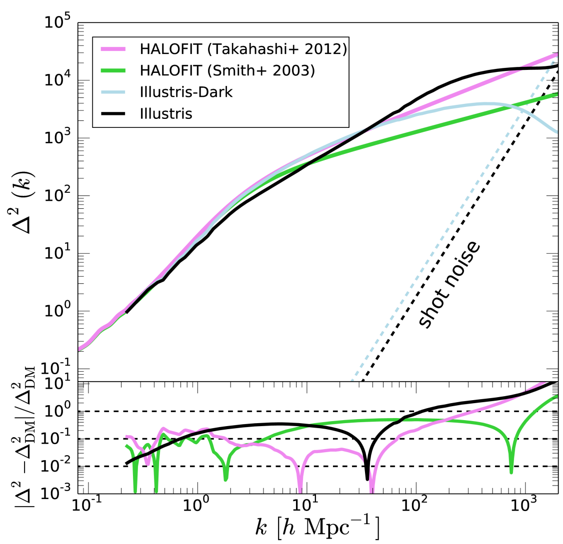
(d) Stellar mass functions, 106.5 Mpc cosmic variance

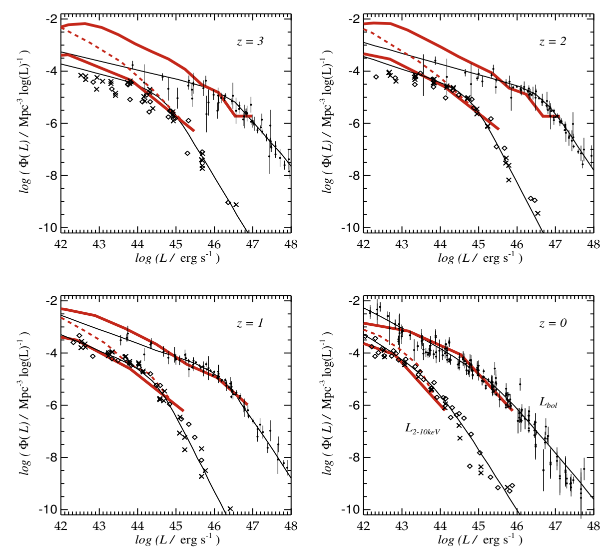


(c) Cosmic SFR density, 106.5 Mpc cosmic variance





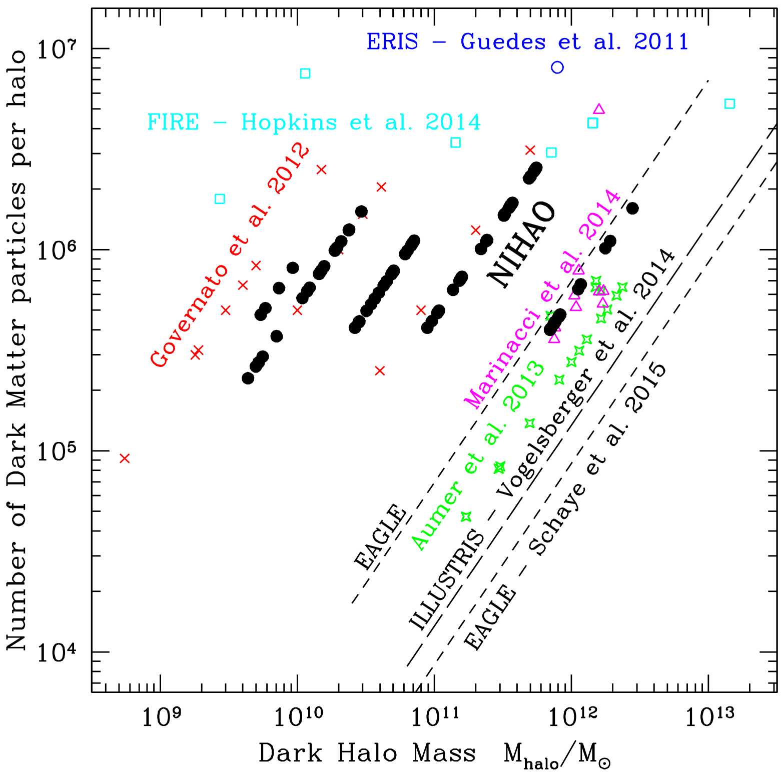


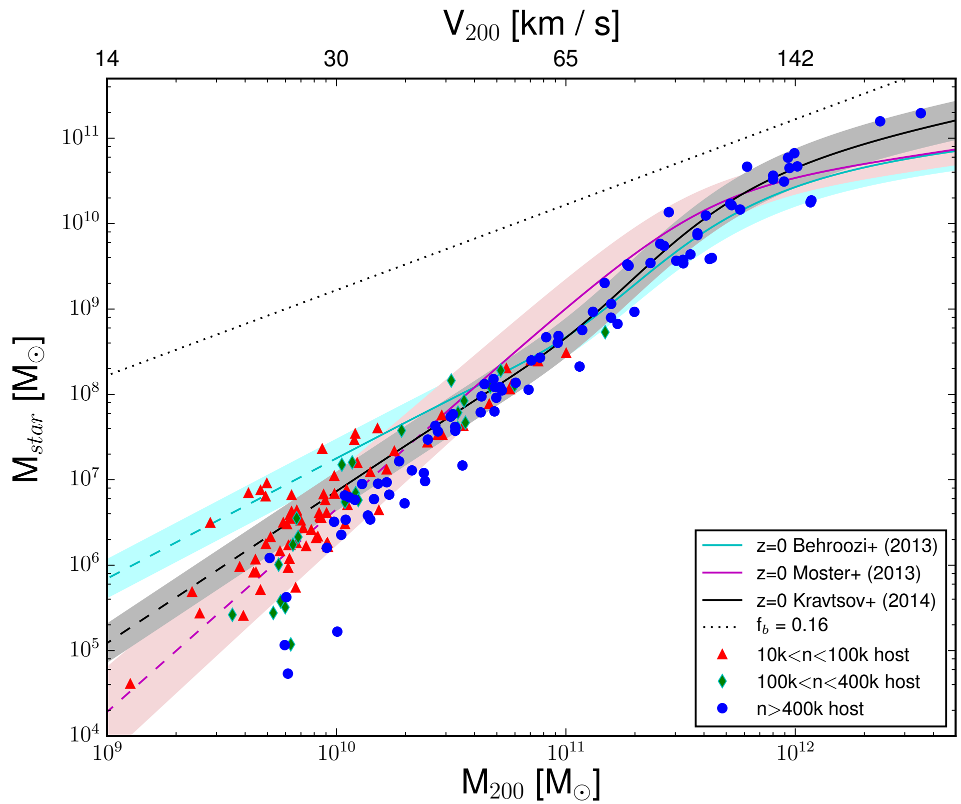


Illustris Simulation well reproduces many properties of local and high-z galaxies, however

- The formation of low-mass galaxies is still too fast
- The energy feedback from SN and SMBH should be very strong and efficient
- Extremely computational cost, not possible to explore: cosmology parameters, dark matter property, physics of star formation

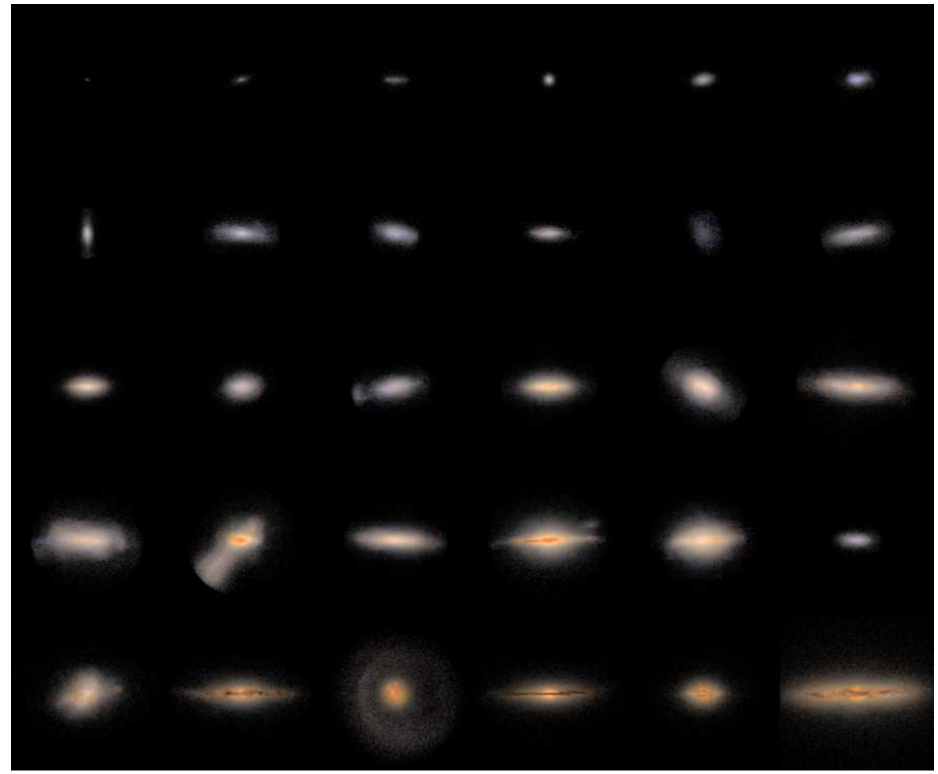
NIHAO compared to ILLUSTRIS





NIHAO resolves low-mass galaxies with much high resolutions

NIHAO (你好） project: Numerical Investigation of a Hundred Astrophysical Objects (collaboration between PMO and MPIA)

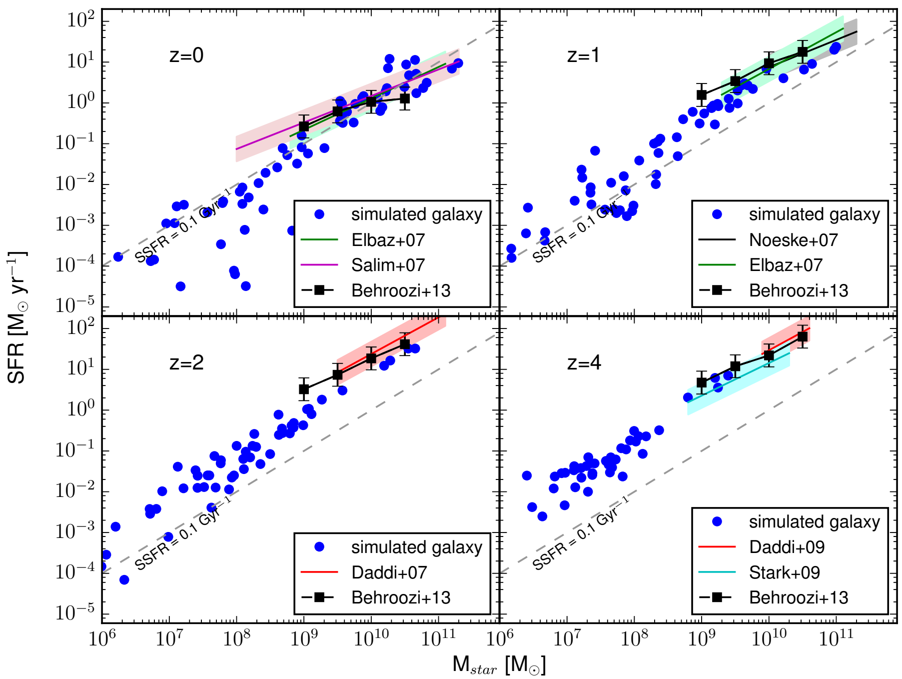


Hydro-dynamical simulation: star formation, feedback from supernova and Early Stellar Feedback (ionizing feedback from massive stars prior to SN explosion)

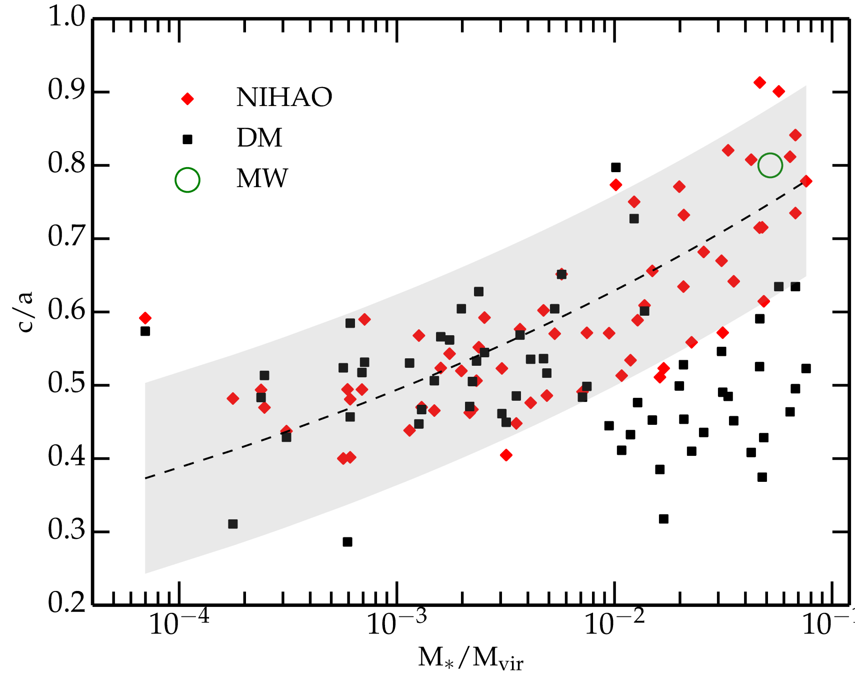
Wang L+Kang X et al., arXiv: 1503:04818
Butsky I+Kang X et al., arXiv: 1503.04814
Tollet E+Kang X et al., in preparation

NIHAO: predictions

SFR vs Mstar relations



Halo shape



- Well reproduce the main sequence relation
- haloes are rounder in hydro-simulation

Outline

- Structure formation
- Models for galaxy formation
- Several types of galaxy distribution
- Various tests (milky way as a local lab)
- Summary

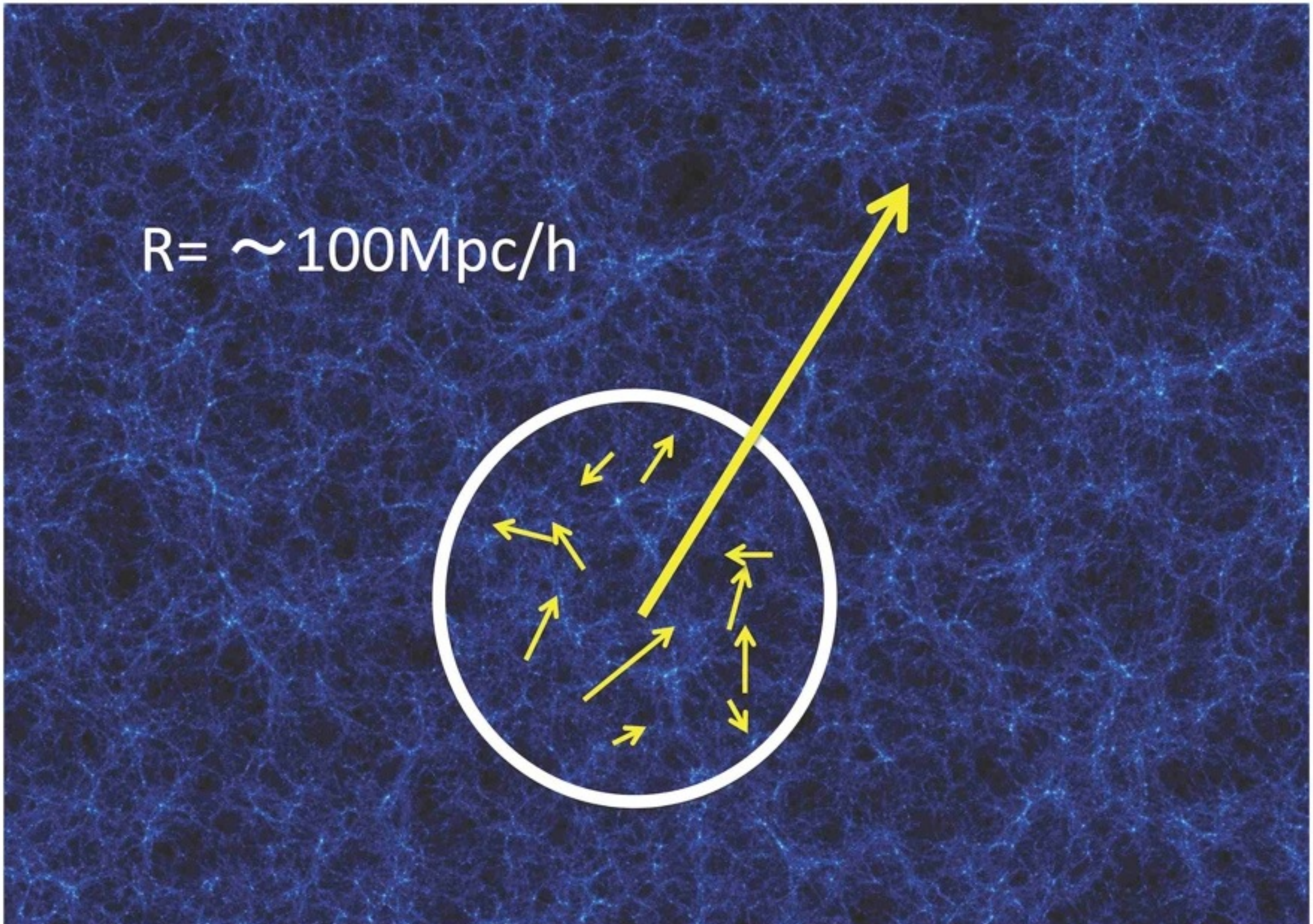
Does the distribution of galaxy reconcile with CDM?

Position distribution

- Bulk Flow (first order statistics)
- Galaxy two-point correlation function (second order)

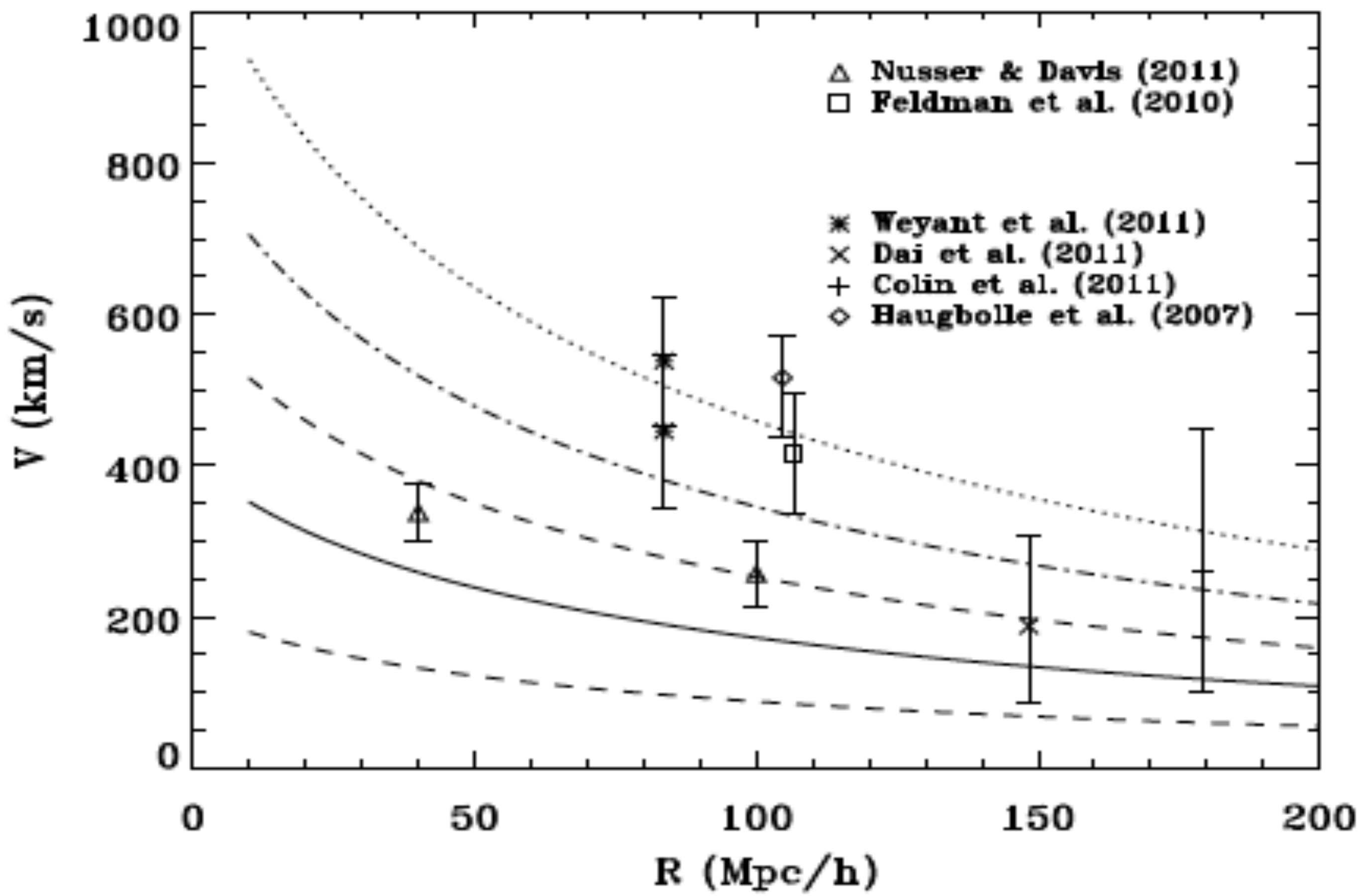
Shape distribution

- Satellite-central alignment
- Galaxy-Galaxy alignment
- Galaxy distribution with LSS

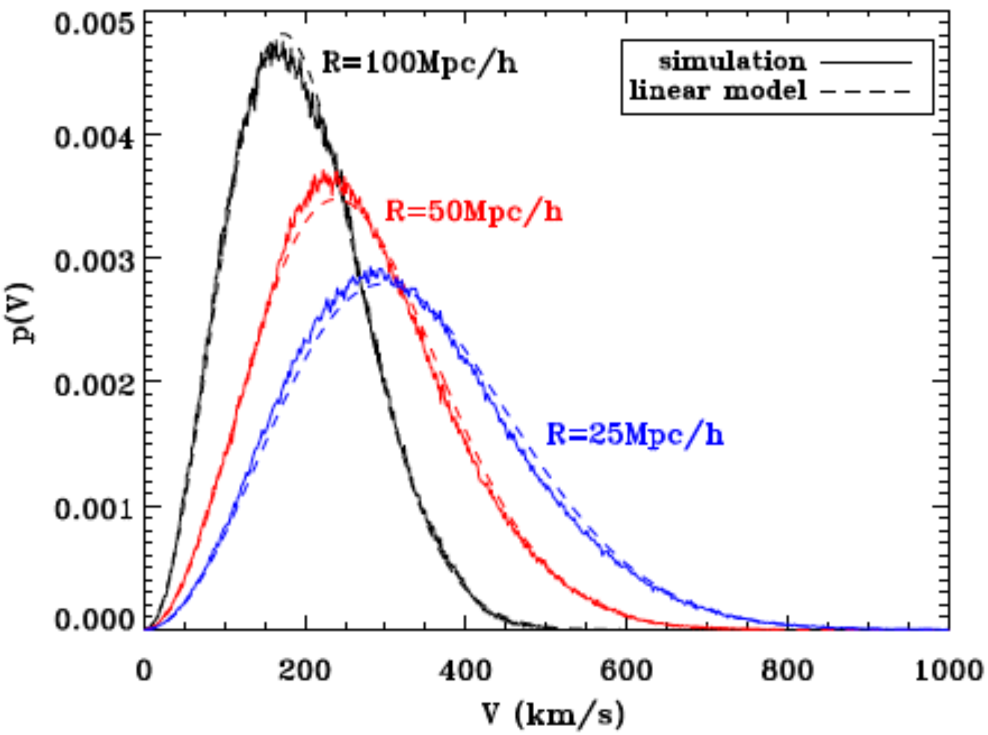


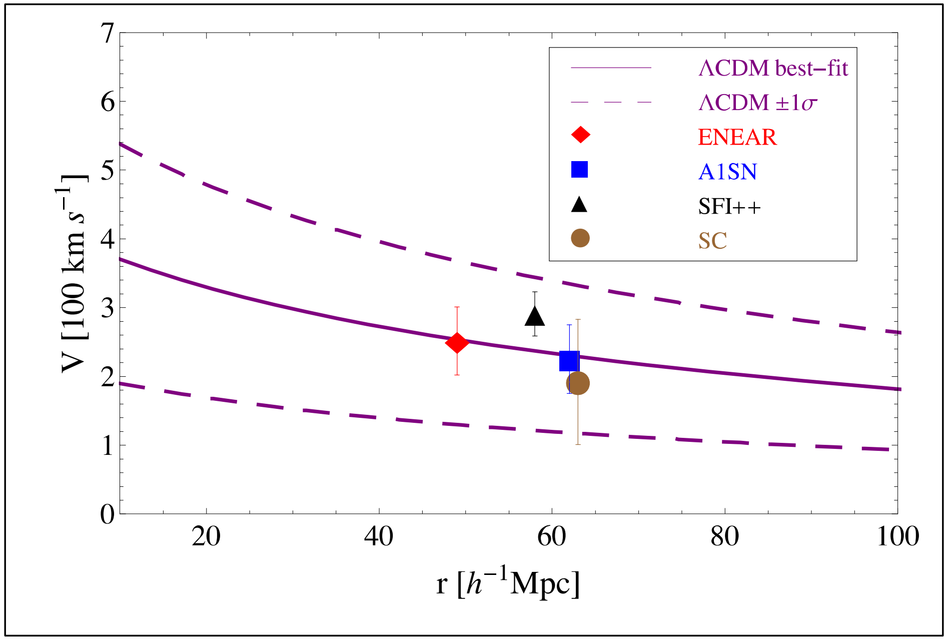
Bulk flow is the average of peculiar velocity of dark matter, galaxy or galaxy cluster enclosed in volume

Measurement of bulk flow



CDM predicts lower bulk flow?



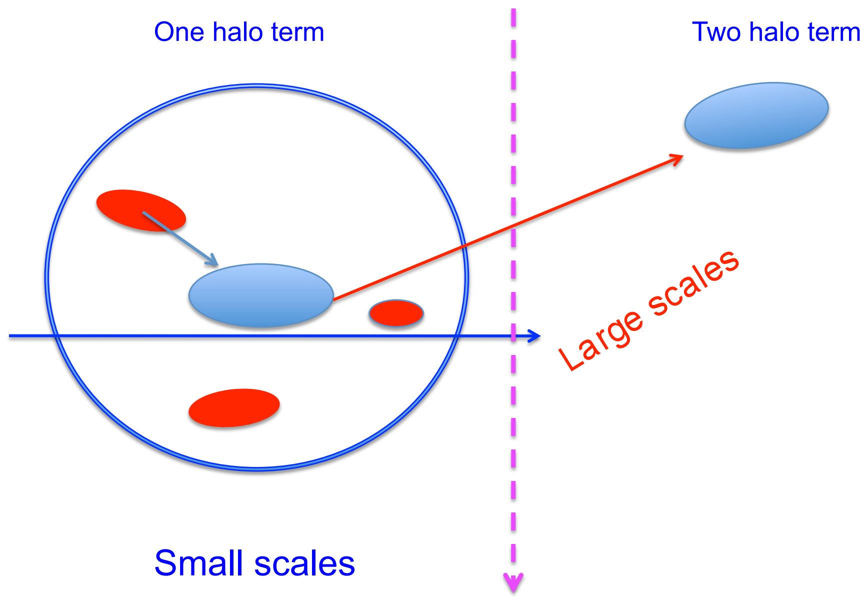


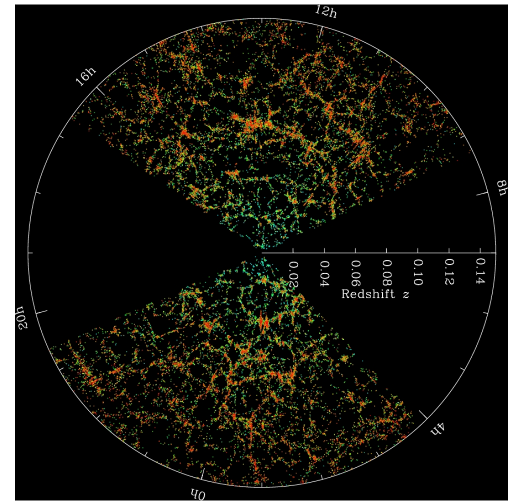
Bulk flow follows Maxwellian distribution, fits well the prediction by linear theory

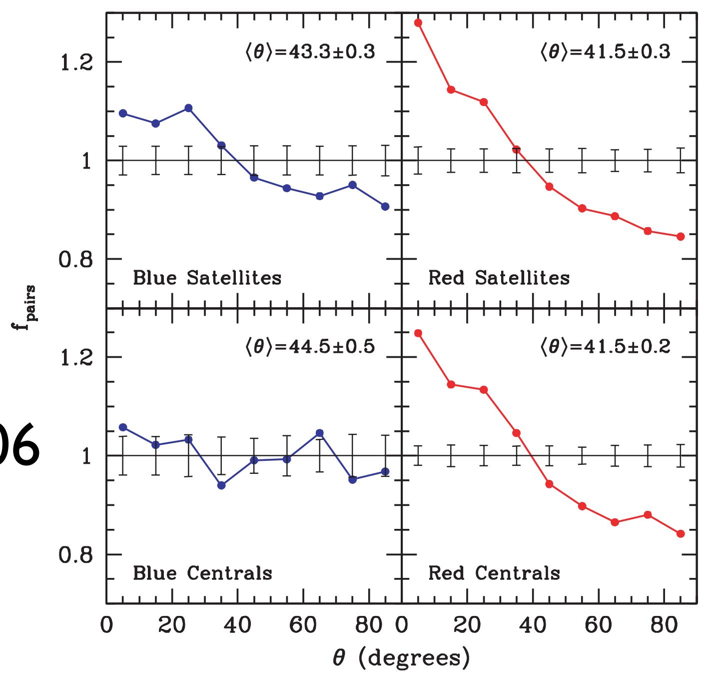
Our results agree with new data

C4, 2012, ApJ

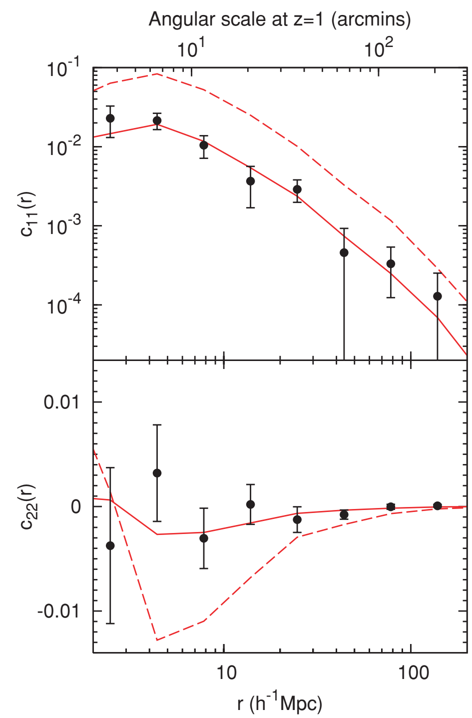
Several types of galaxy alignment







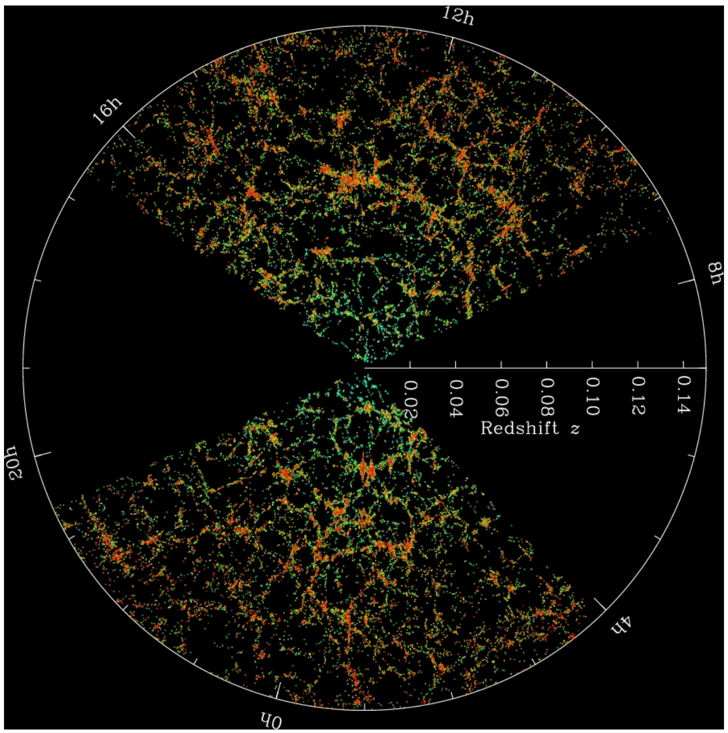
Yang+ 2006



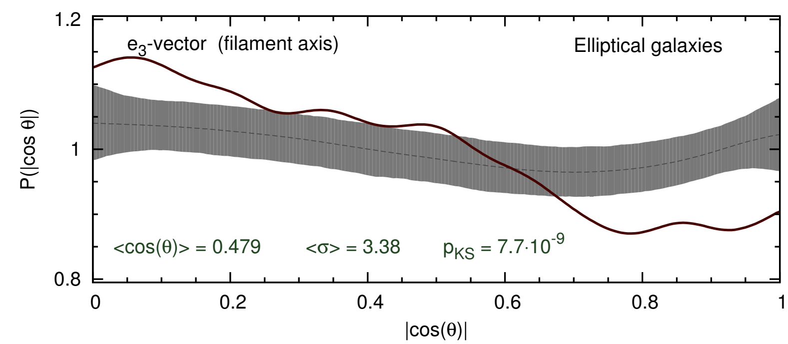
Teppi & Jing 2009

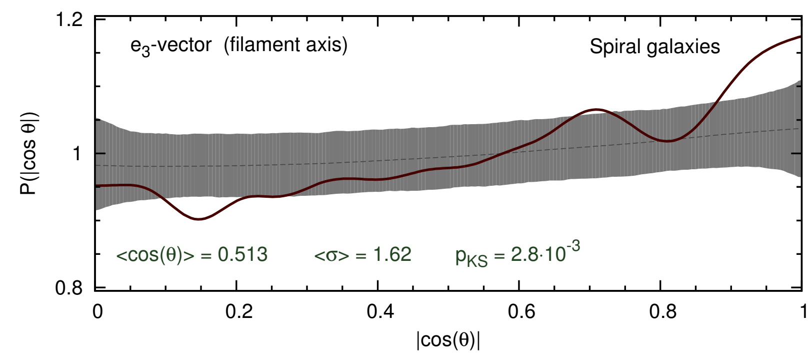
galaxy spin and LSS

SDSS



Galaxy Spin to Filament

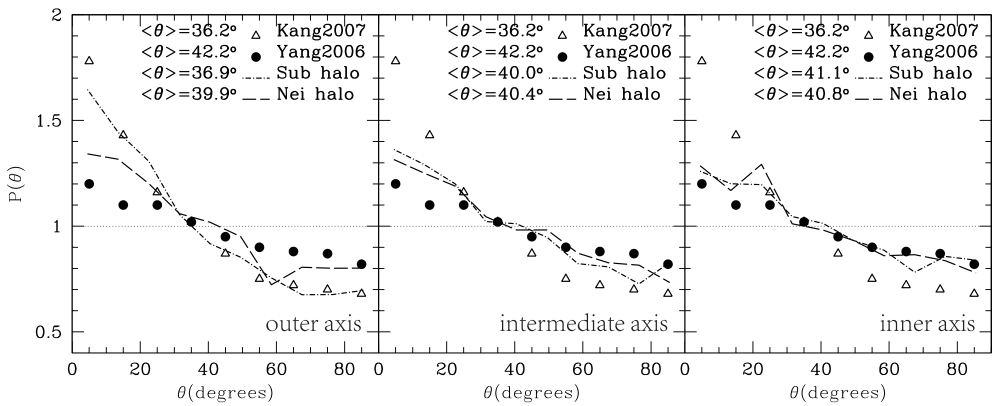


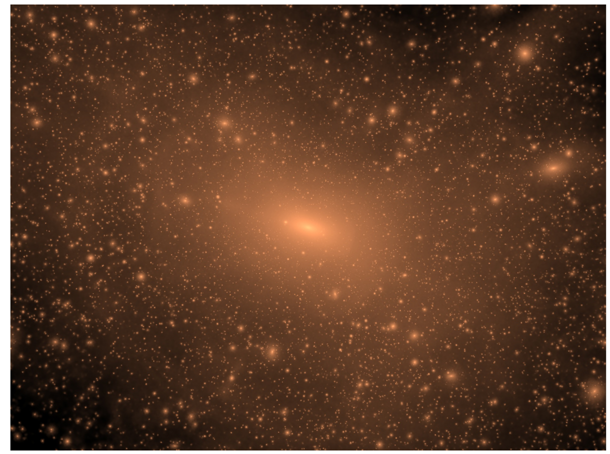


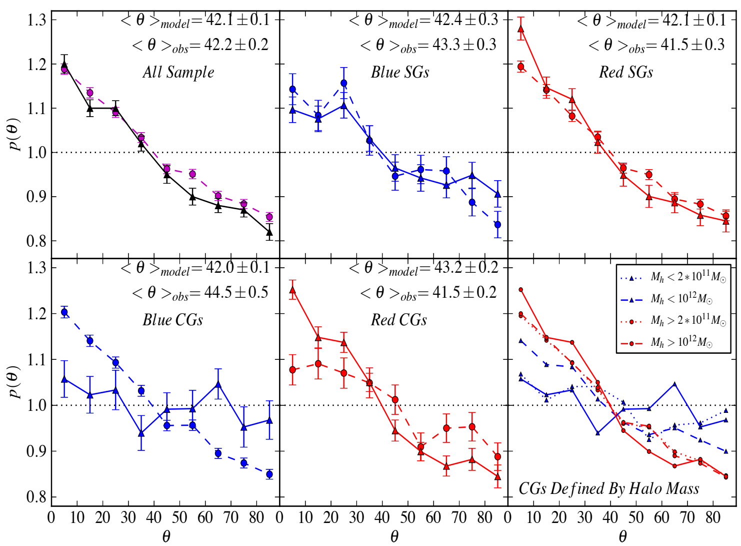
Tempel & Libeskind 2013
Also see Zhang et al. 2014

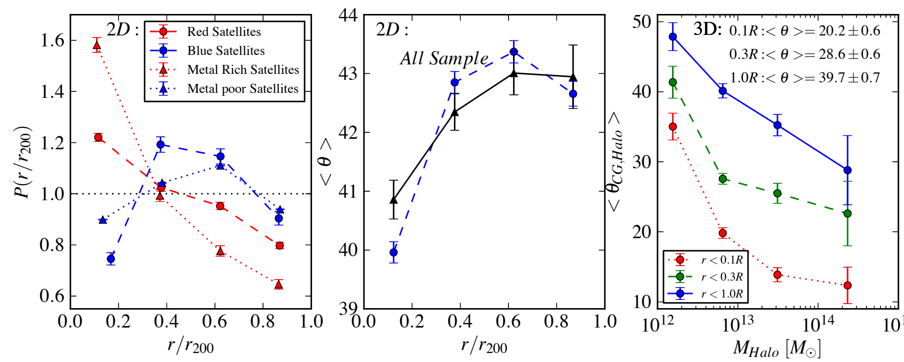
galaxy alignment (shape correlation)

satellites distribution around central galaxy







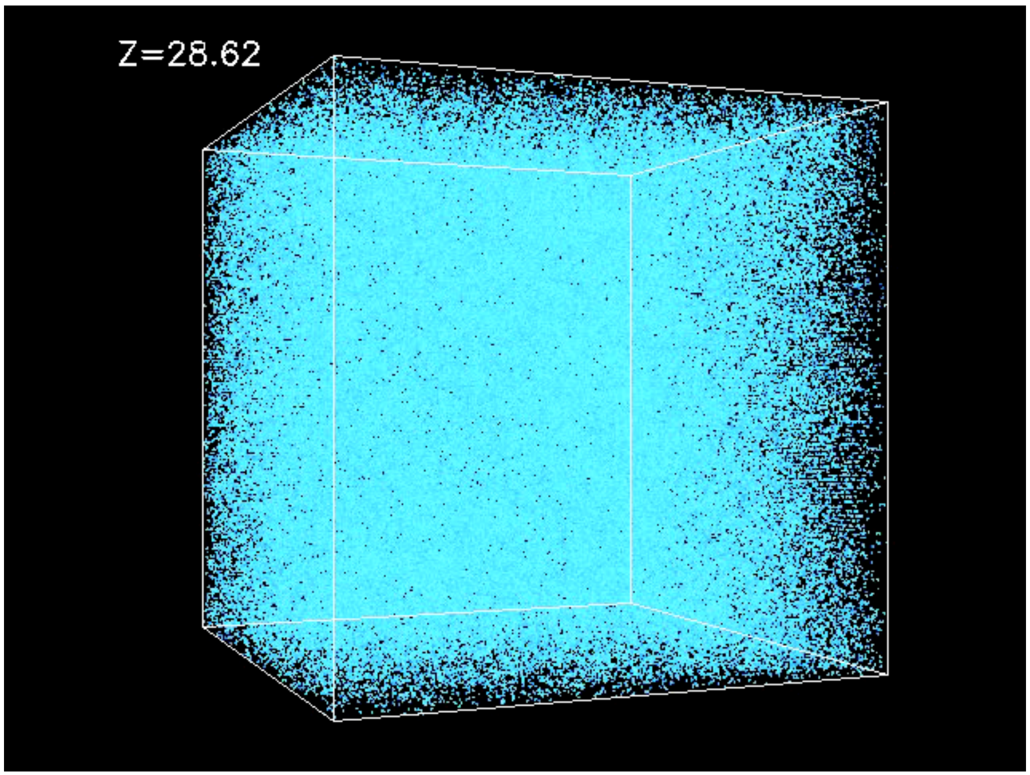


alignment is from halo tri-axial shape
and mis-alignment between galaxy & halo
(internal evolution)

Kang,Lin et al. 2007,2014a, 2014b

any primordial alignment?

Cosmic Web

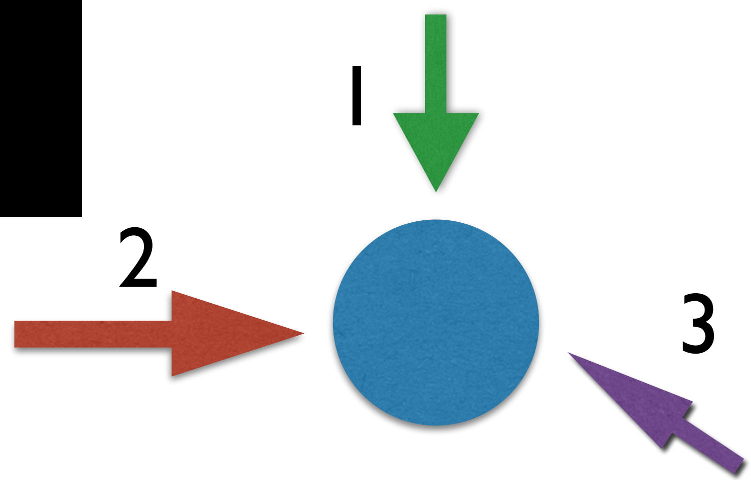


Zel'dovich approximation

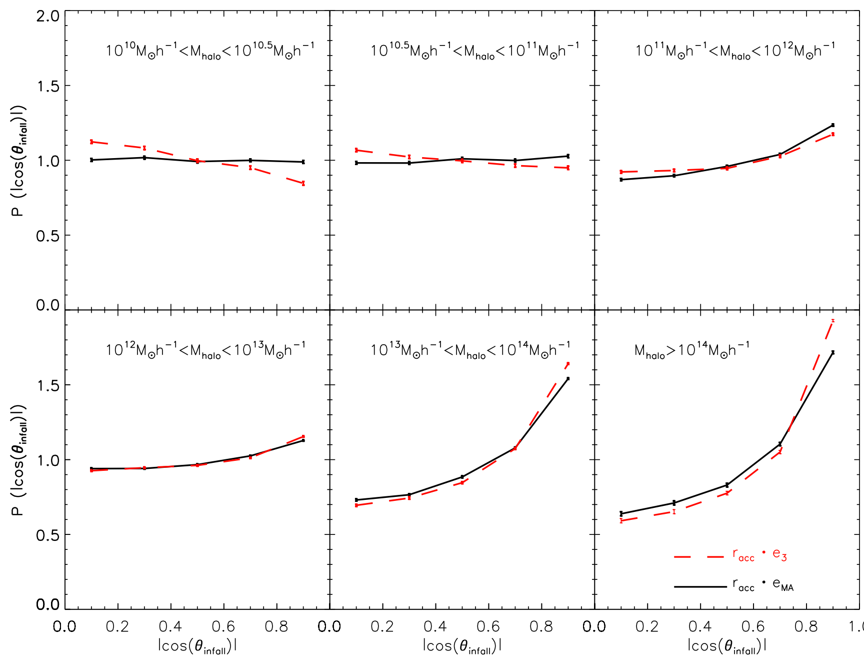
$$\mathbf{x}(t) = \mathbf{q} + D(t)\ \nabla\psi(\mathbf{q}) \ ,$$

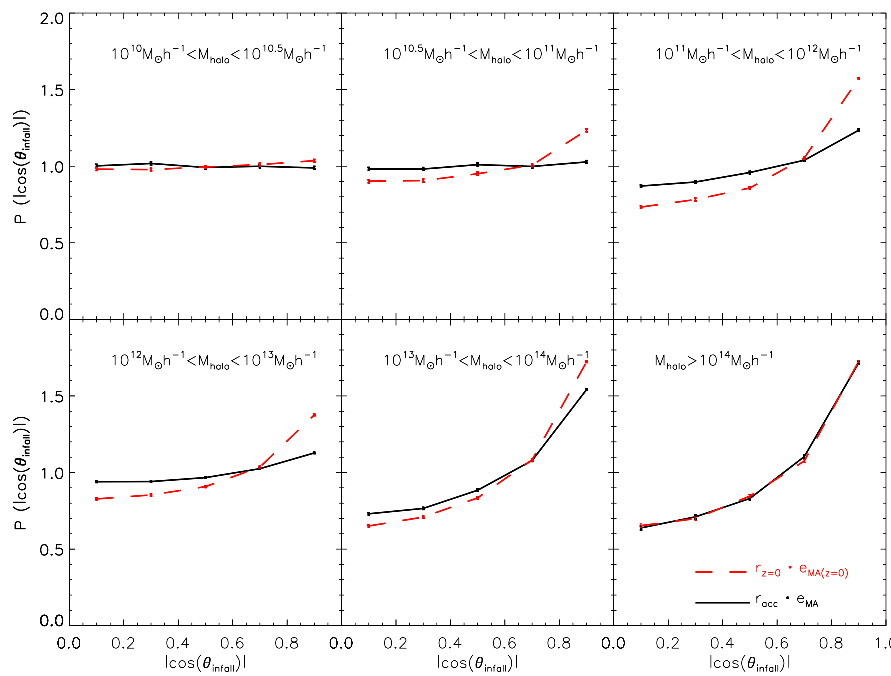
$$\rho(\mathbf{x}) = \frac{\bar{\rho}}{[1 - D\ \lambda_1(\mathbf{q})]\ [1 - D\ \lambda_2(\mathbf{q})]\ [1 - D\ \lambda_3(\mathbf{q})]}$$

Sheet—>Filament—>Node



is subhalo accretion universal?

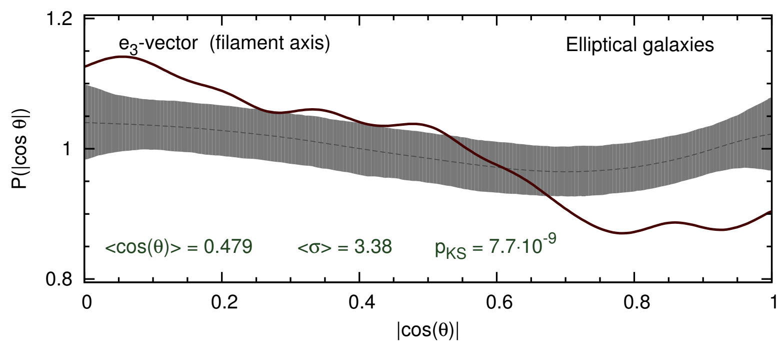


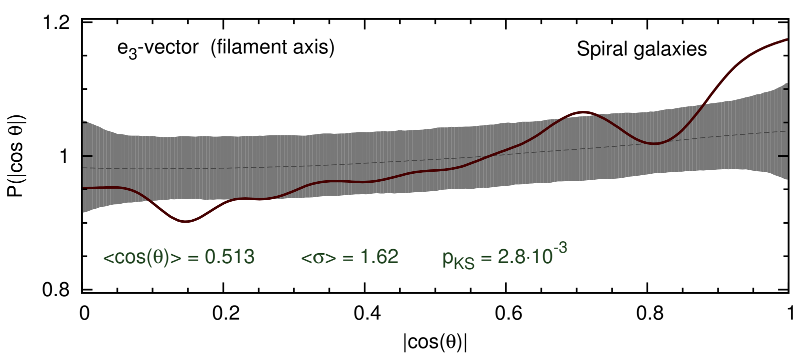


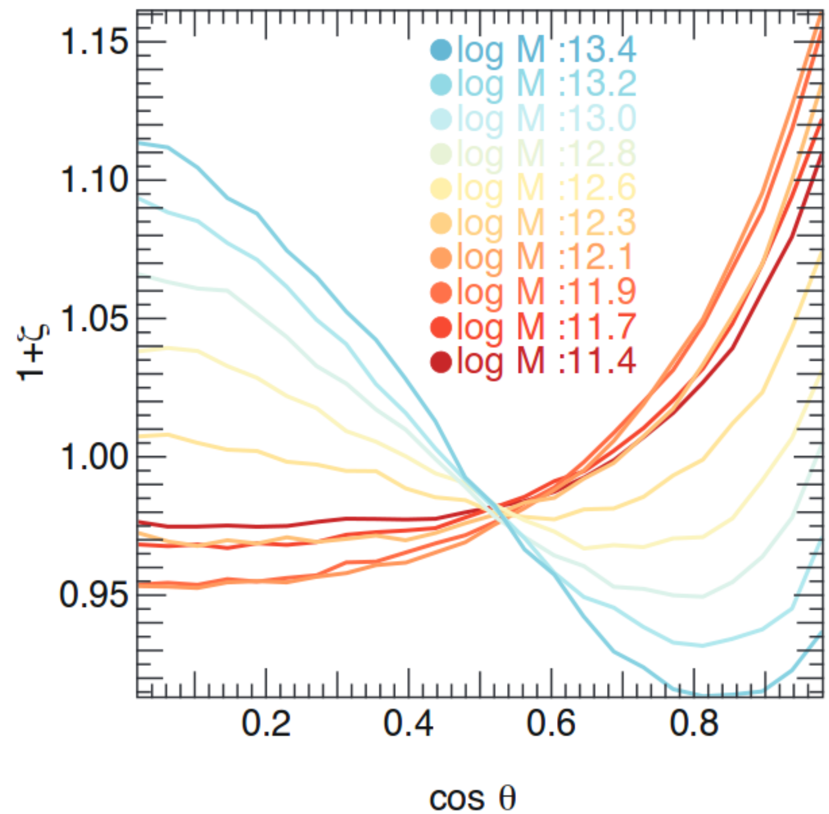
Kang & Wang in preparation, 2015

- subhaloes are accreted along halo major axis
- subhaloes are accreted along e3 only in massive haloes

galaxy/halo spin with LSS

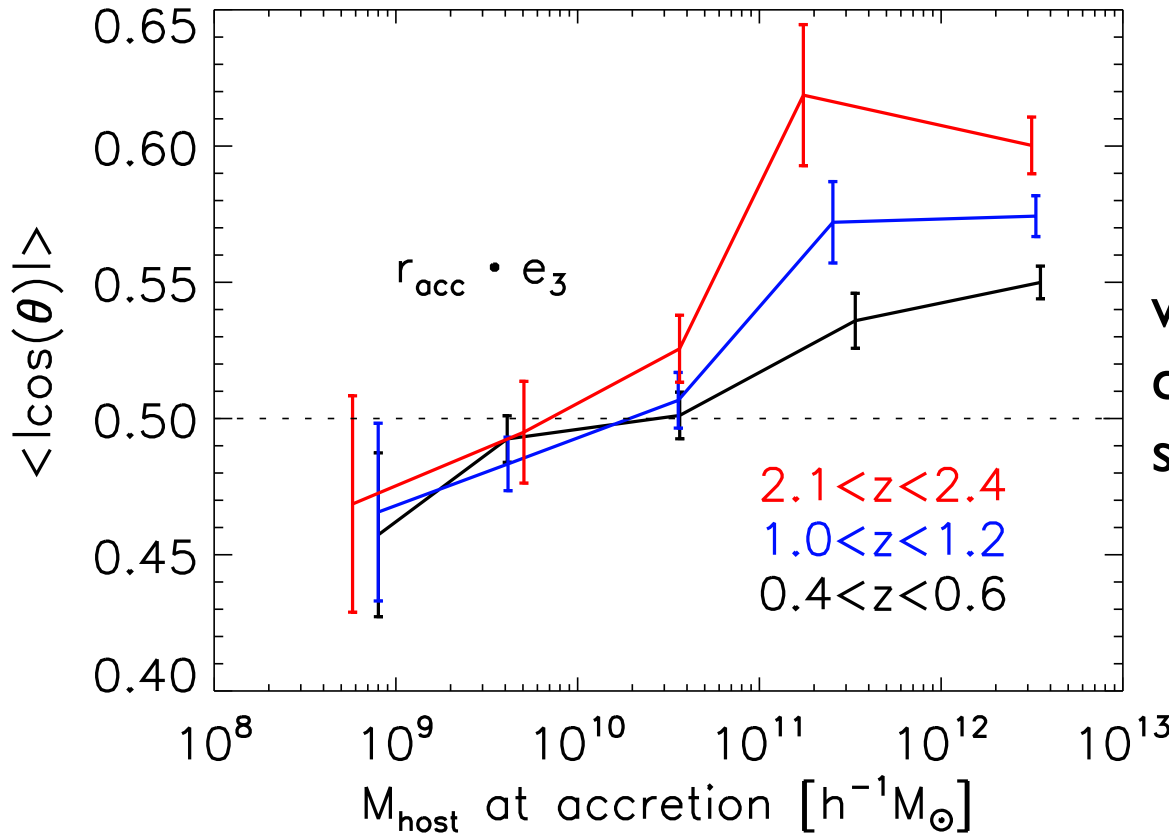






TTT theory predicts: halo spin is perpendicular to e3 (or filament)

alignment between subhalo accretion and filament



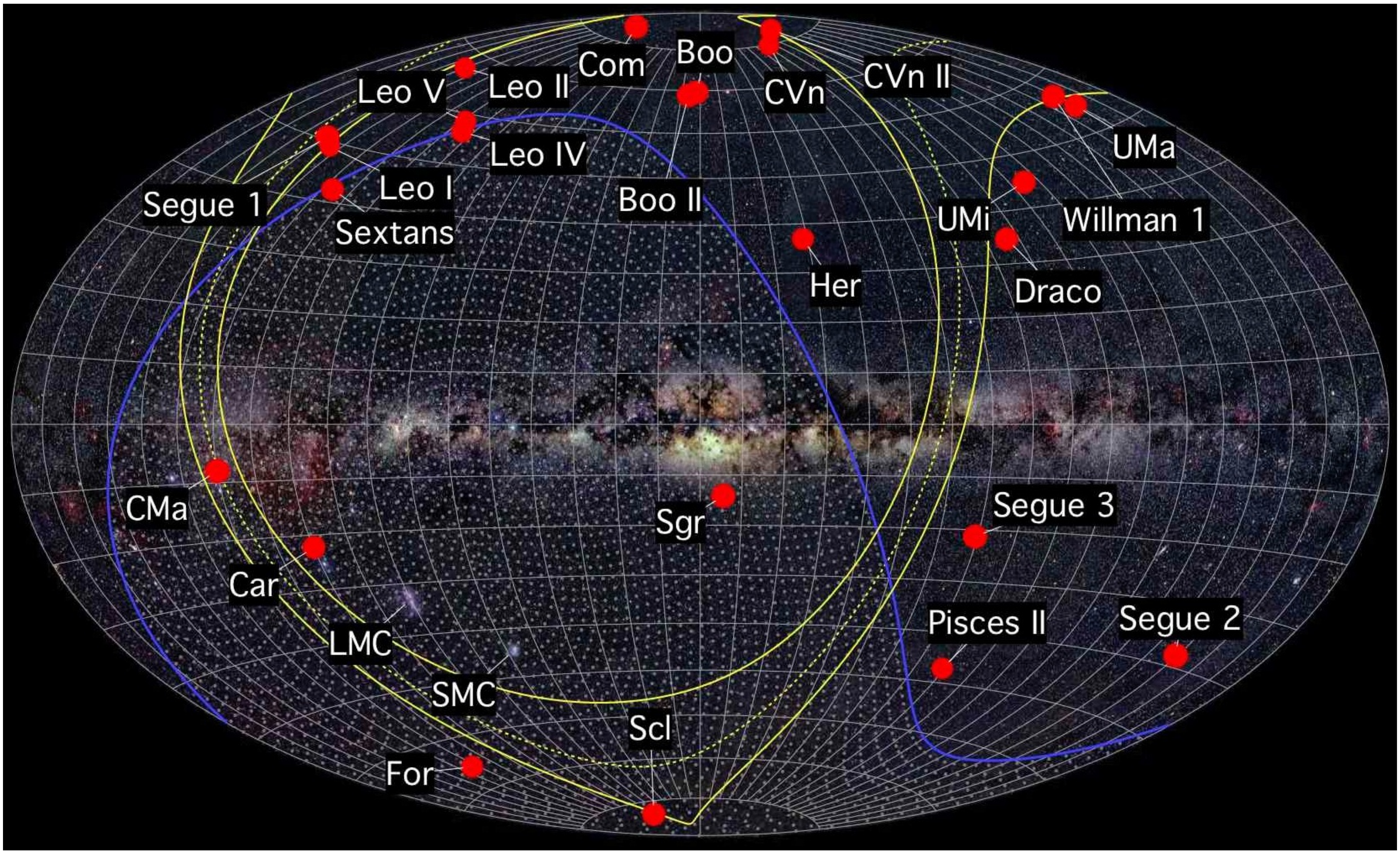
Kang & Wang , 2015 in preparation

well explains the observed correlation between galaxy spin and LSS

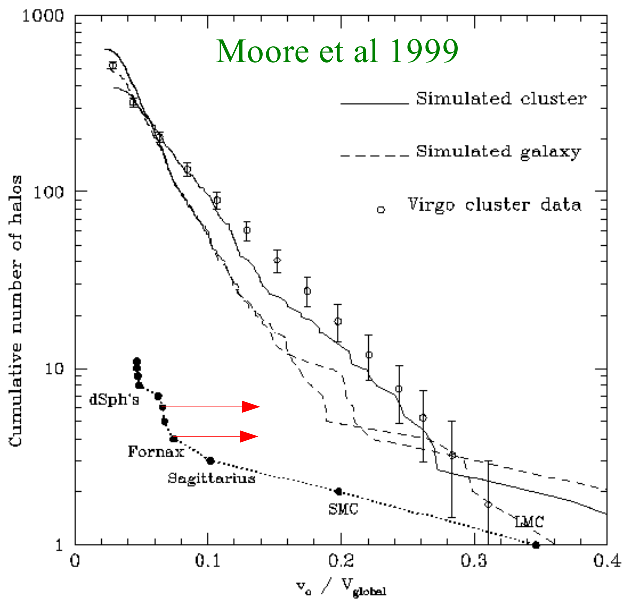
if the orbit angular momentum is transfered to halo spin, it is naturally expected that:

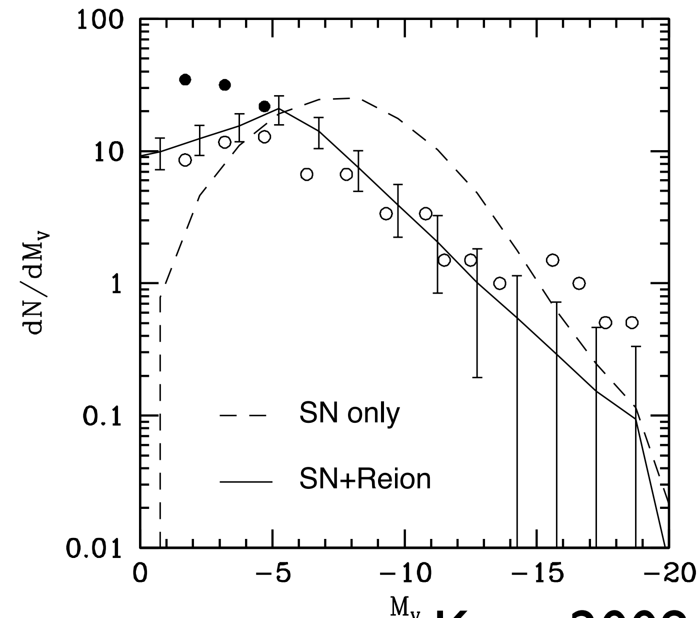
- for massive haloes, spin is perpendicular to filament
- for low-mass haloes, spin is parallel to filament

Our Milky Way is a good laboratory to test CDM and model for galaxy formation



Missing satellite problem of the Milky Way

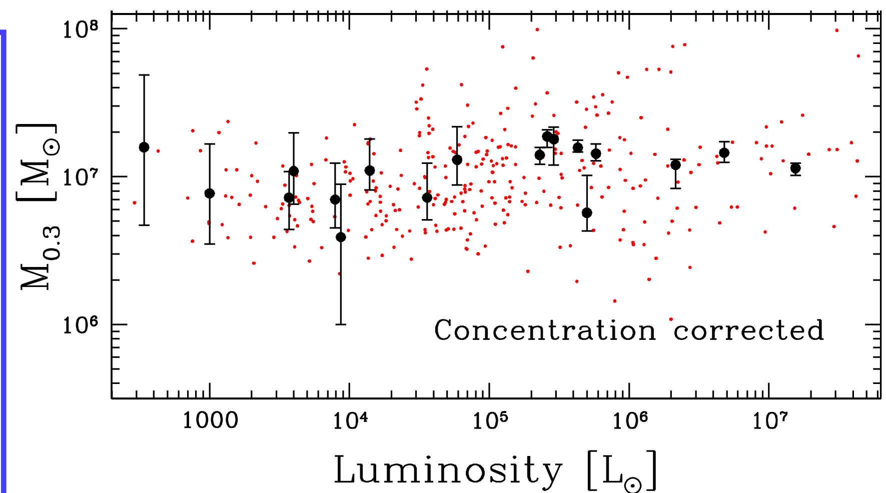




Kang 2008

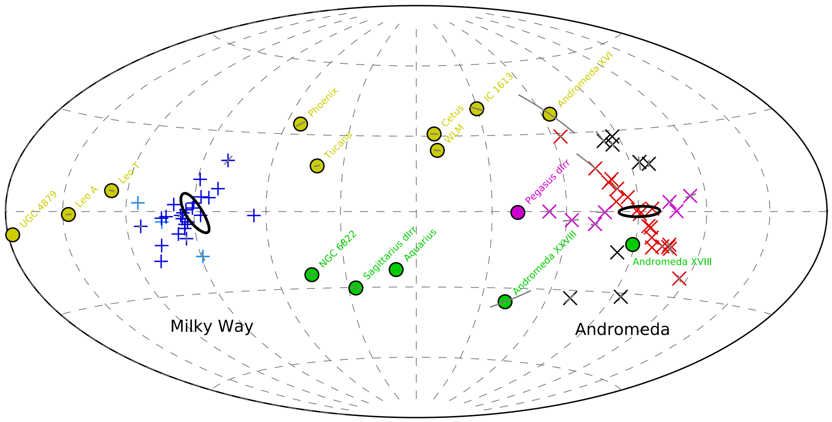
The luminosity function of MW can be obtained:

- Cosmic re-ionization suppress gas cooling in low-mass halo (V<50 km/s or M<10^9 solar mass)
- Most MW satellites are in ~10^9 solarmass haloes at accretion

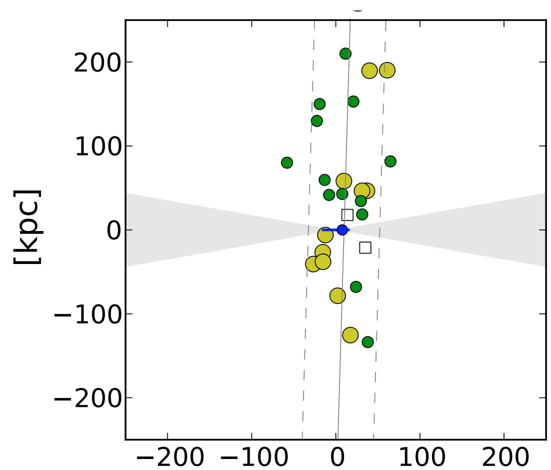


Maccio,Kang &Moore, 2008

The spatial distribution of MW/M31 satellites is also a mystery



Observed Sats of MW/M31

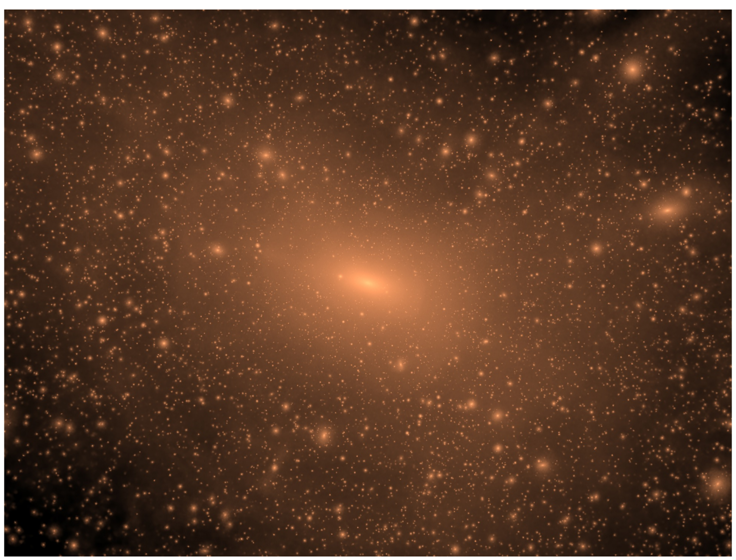


Kroupa etal. 2010

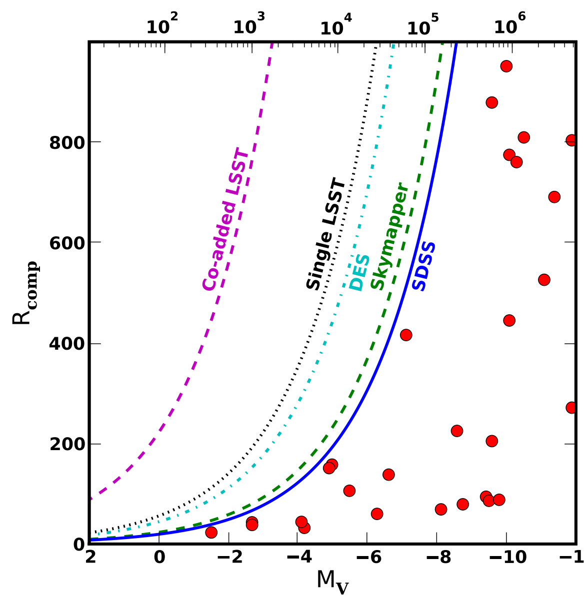
Satellites are

- in thin/great plane
- co-orbiting

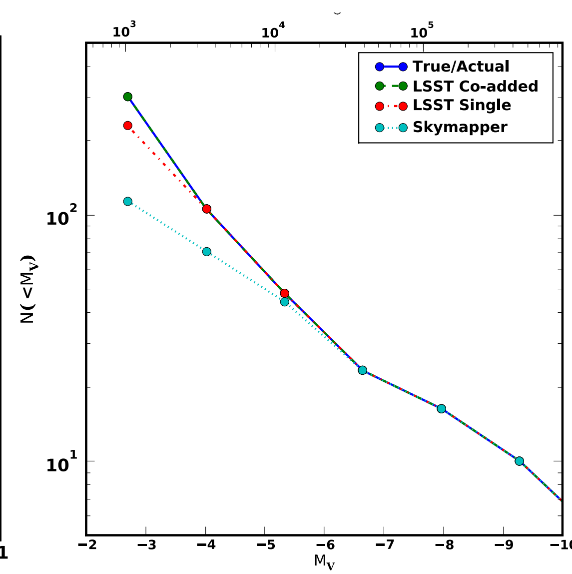
Inconsistent with CDM predictions (<1%chance)



predicted distribution of subhalos by CDM



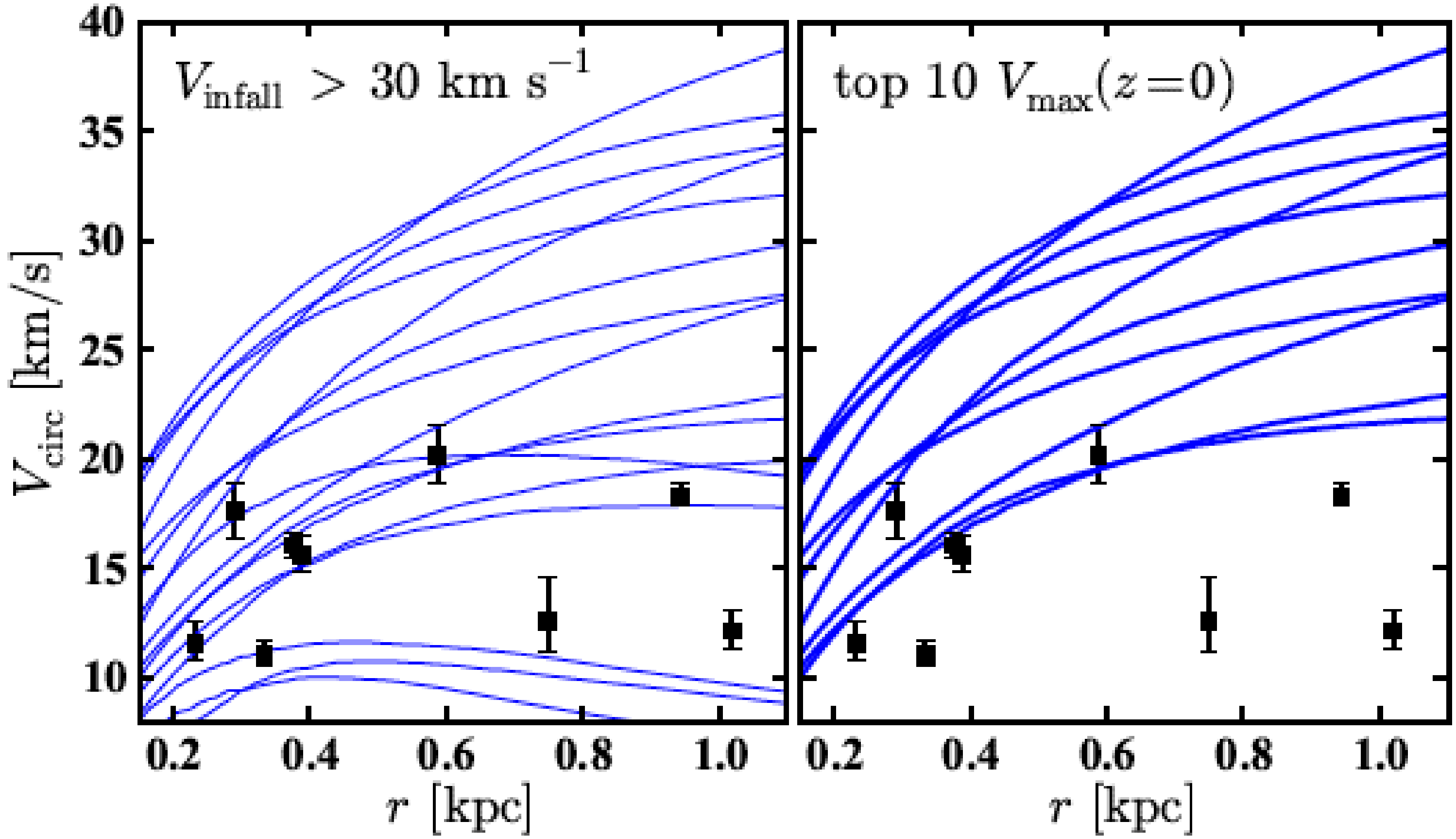
Tollerud etal.2008



The story could be very different if future deep survey will discover more sats

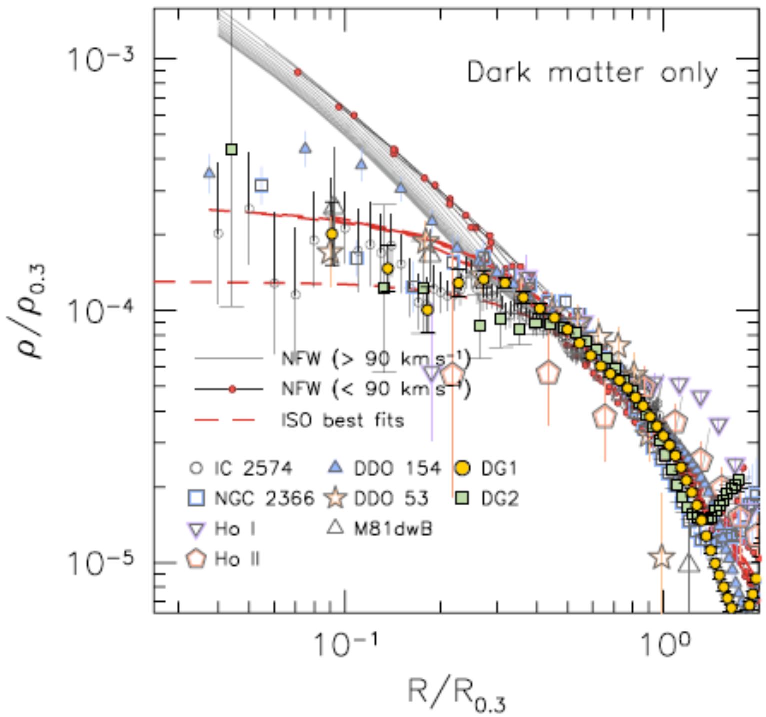
Too big to fail

Boylan-Kolchin et al 2012

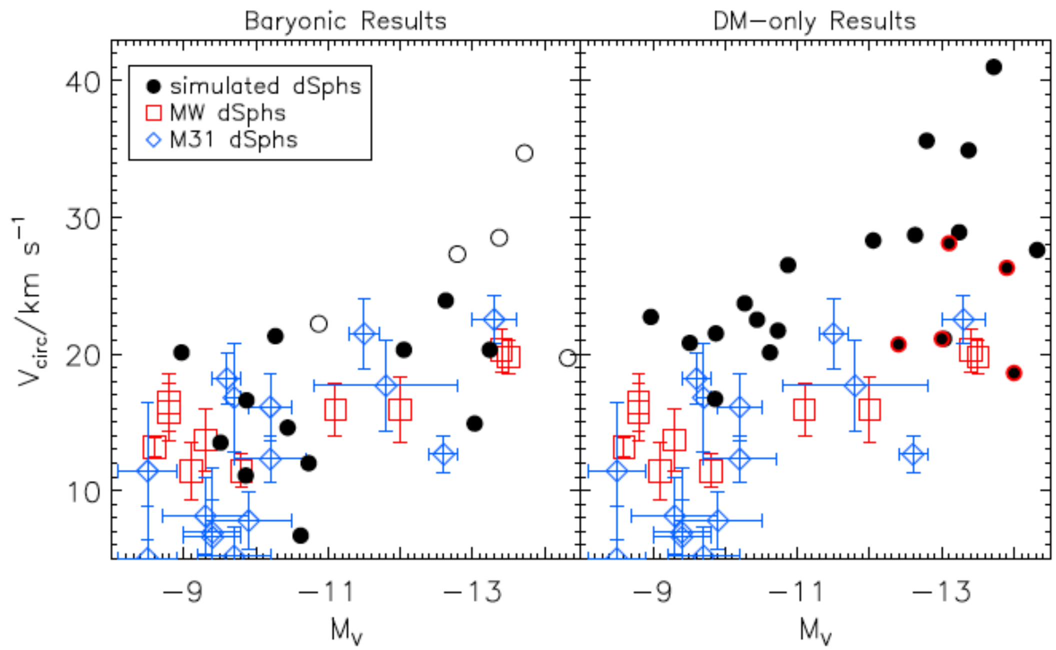


cusp vs core?

baryon effect?



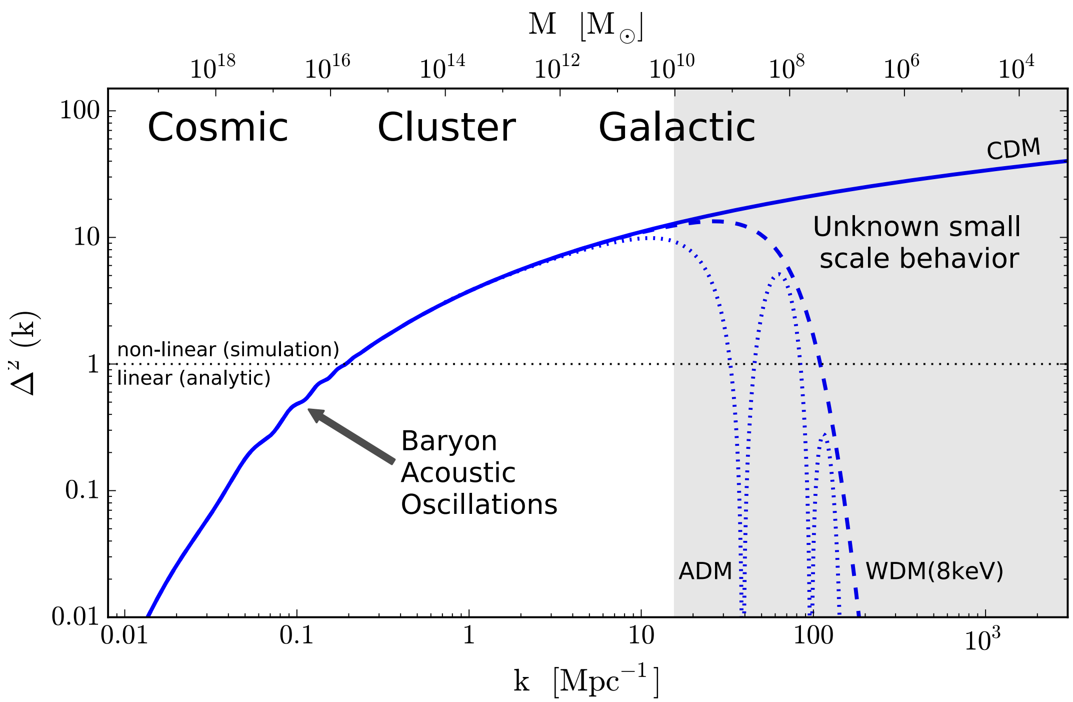
Oh et al. 2011

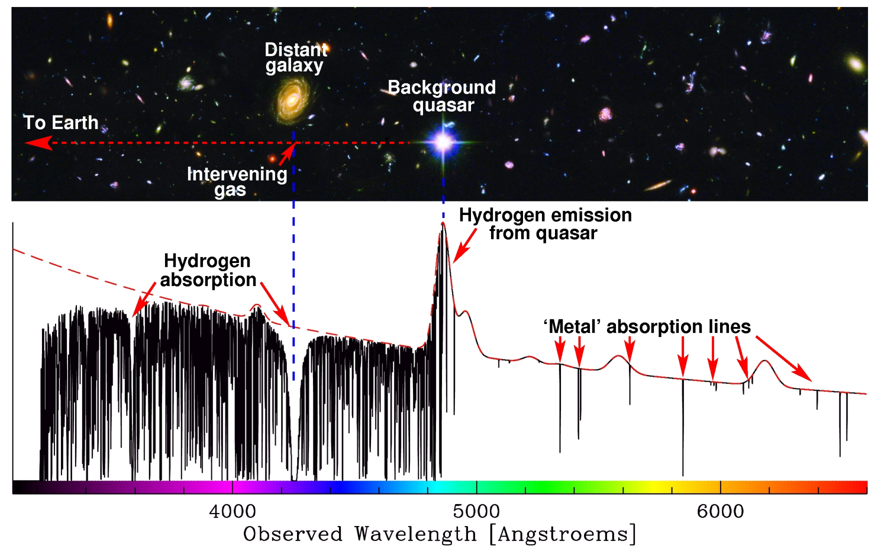


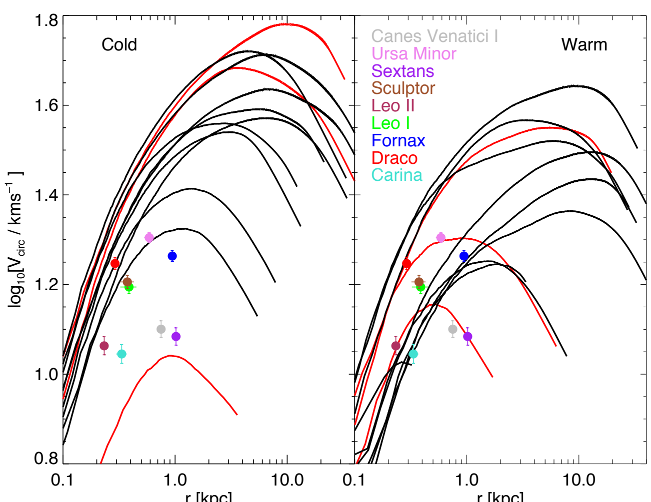
brooks & zolotov 2014

Baryonic effects seem to be more favorable to solve the small-scale crisis

solution: WDM? (not clear)

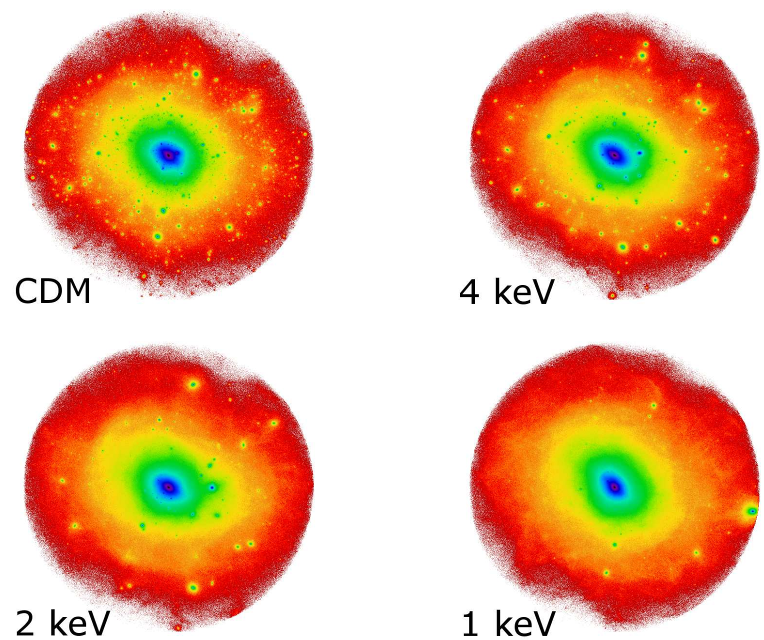




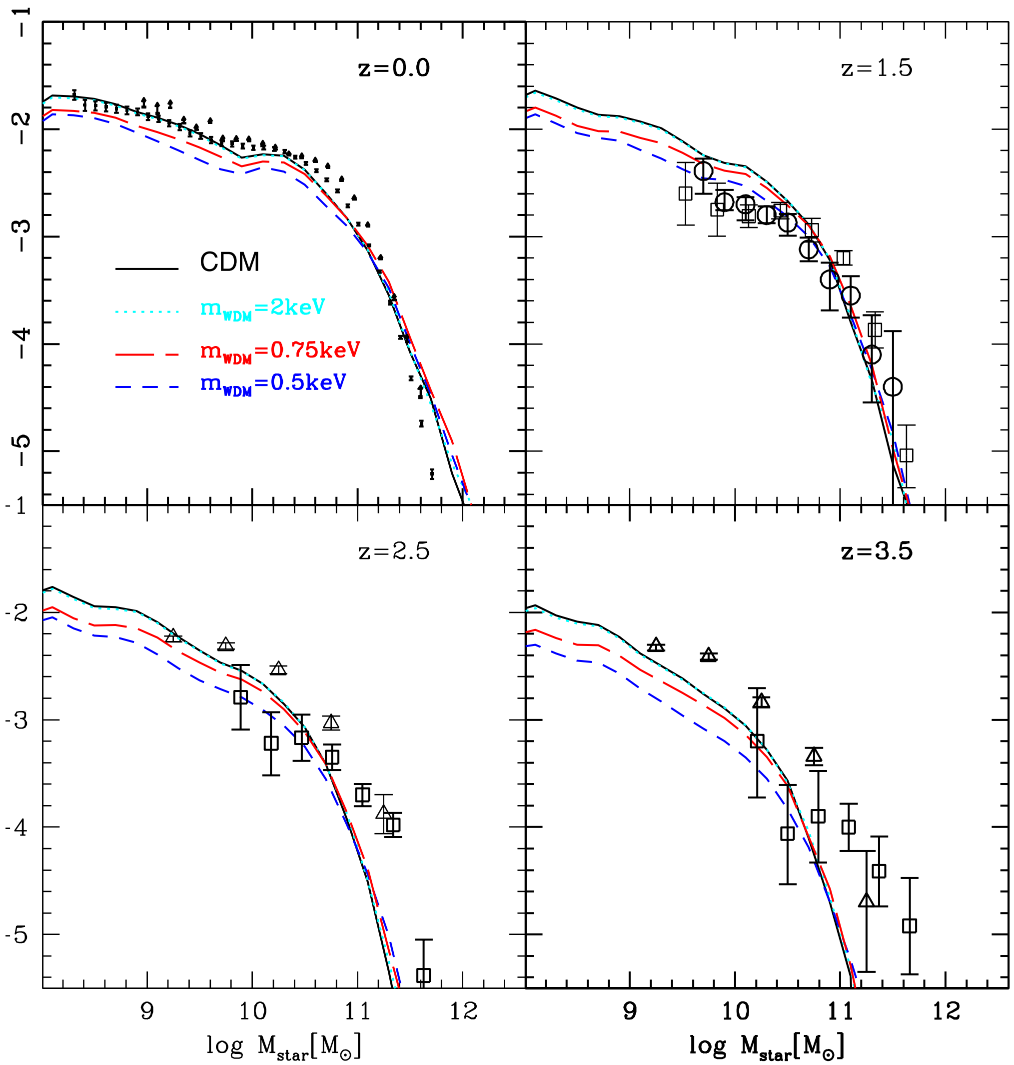


Lovell etal. 2012

m_{wdm}=2kev



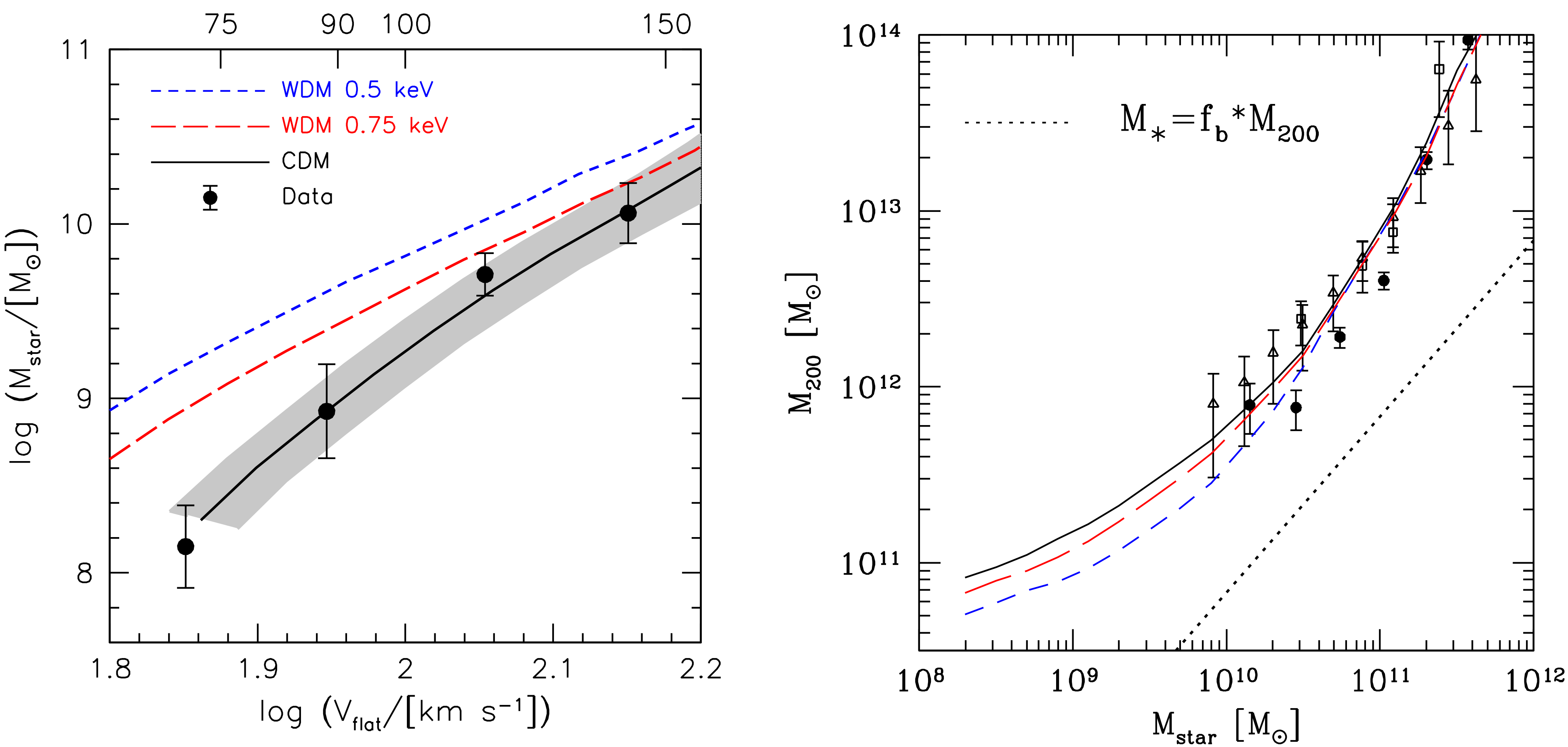
constrain WDM using galaxy formation model



Fewer galaxy at M=10^10 solar mass

Kang et al. 2012 MNRAS
Kang et al. 2013, ApJ

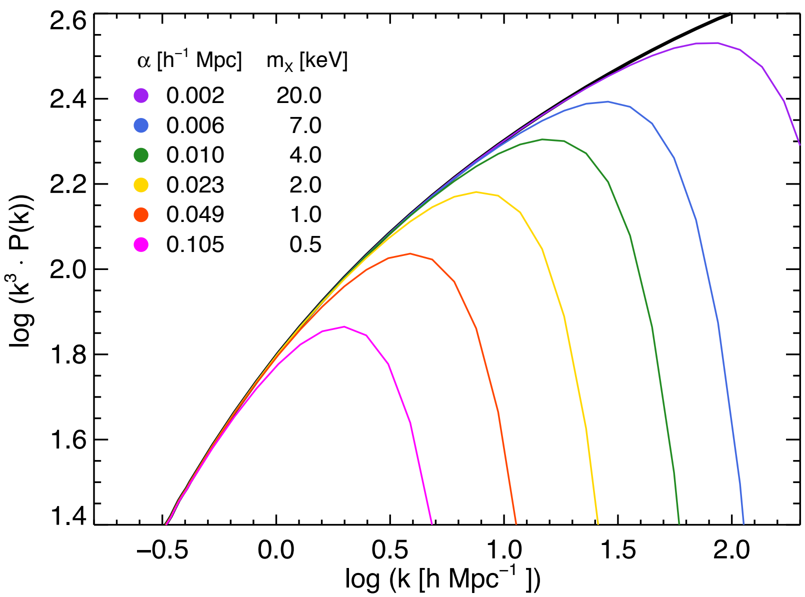
constrain WDM mass using galaxy formation

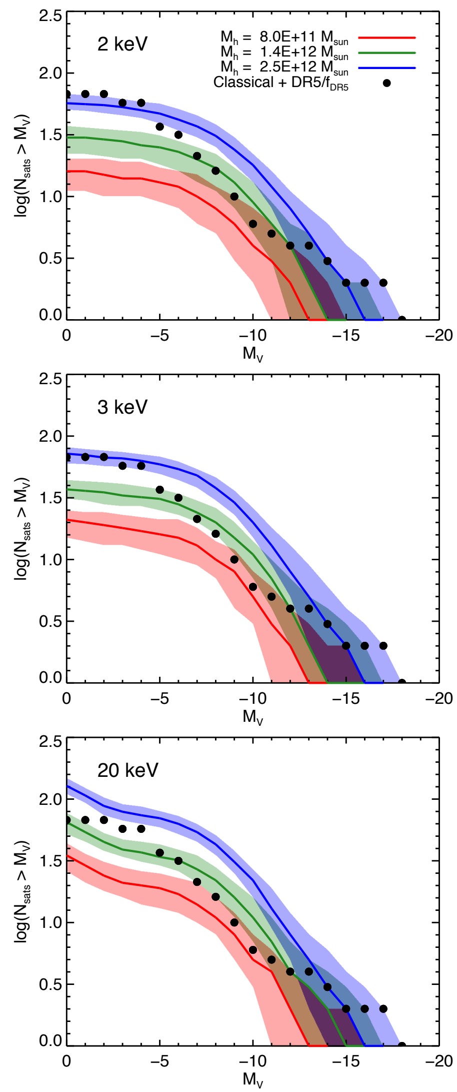


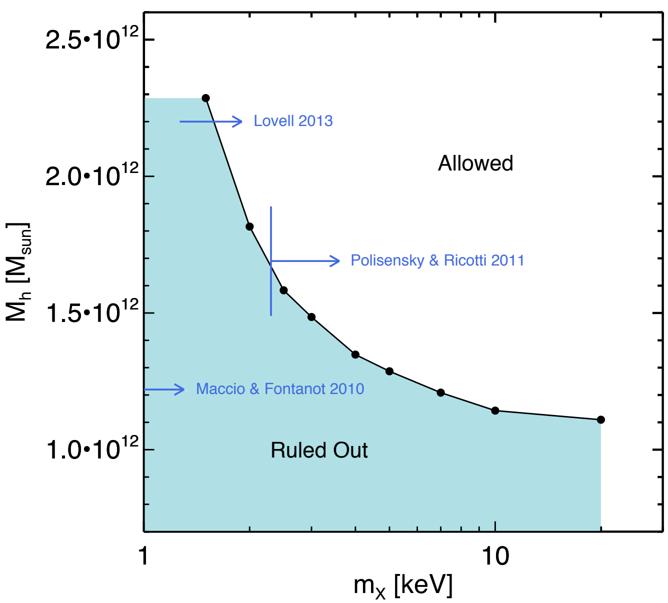
Kang et al. 2013, ApJ

Our model still supports CDM

constrain WDM mass using MW satellites







Kennedy et al. 2013

Summary

- The standard LCDM model (cosmological constant + cold dark matter) works well on large scales.
- On small scales, LCDM still works better (Warm dark matter VS baryonic effect)

- semi-analytical model and hydro-dynamical simulation are both useful to model galaxy formation in cosmological context, SAM is more fast to explore physical process
- The number of low-mass galaxies at high-z is crucial to understand the physics of galaxy formation: gas cooling, feedback, tidal disruption

- Our Milky Way may be an anomaly (outlier statistically, depending on future survey of satellites distribution: number counts, spatial distribution, kinematics etc)

Thanks for your attention !