The Dark Matter - Galaxy Connection: HOD Estimation from Large Volume Hydrodynamical Simulations

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THE DARK MATTER - GALAXY CONNECTION

HOD

SYNERGIES WITH LARGE GALAXY SURVEYS

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Some OPEN QUESTIONS IN GALAXY grouping

- Why do galaxies gather the way they do?
- Do satellites trace the underlying DM halo?
  - To what extend?
- HOD: What can we expect from a Galaxy with a certain stellar mass?
  (DM halo?, Satellite galaxies...)

COMPUTER EXPERIMENTS AS A TESTBED TO STUDY

DARK MATTER – GALAXY CONNECTION

INTRODUCING COSMOLOGICAL SIMULATIONS

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GALAXY FORMATION IN A COSMOLOGICAL CONTEXT: STEPS

1.- Cosmological Model; Spectrum of pert. field

2.- Halo Formation & Statistics

3.- Gas Physics & Thermodynamics

4.- Gas Acumulation & Star Formation

(about **1 kpc** = 3.26 l.yr = 0.3x10^20 m)

5.- Short Scale Stellar Processes + BH

6.- Element formation + Diffusion

INTRINSIC OBJECT

7.- Observational Manifestation (light emission)

1, 2, 3: Large Scale, from Fundamental Physics

5, 6, 7: Require Models

4 : KEY STEP: models, numerical, observations

WHAT SIMULATIONS DO

FUNDAMENTAL PHYSICS 

- Follow mass density evolution under gravity and hydrodynamics

TRACE GALAXIES AND DM IN DIFFERENT SCALES

Isolated, Groups, Clusters

- Accretion and assembly of galaxies
- Gas cooling and heating

 **coupled evol. Of LSS, galaxies, gas accumulation**

+ MODELS 

Star Formation, BHs, Element Formation

SYNERGY WITH LARGE VOLUME GALAXY SURVEYS

COMPUTING CHALLENGES

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SCIENCE OBJECTIVES

- **statistical properties of galaxies:** galaxy groupings , mass and luminosity functions, their dependence on environment and on morphological type, their evolution with redshift ....

  >>> LARGE VOLUMES

- **Local & young object information:** imaging; SEDs; obscured star formation at high z

  element formation <<<

  >>> HIGH RESOLUTION

HUGE DYNAMICAL RANGE

- Fair determination of **sample statistical properties**

  Periodic box size > 80 Mpc side

  (otherwise clustering poorly represented) (Power & Knebe)

Fair determination of individual galaxy properties

Space resolution ≈ 2 – 0.2 kpc; Mass resolution

HUGE DYNAMICAL RANGE > 5×10^5

HUGE NUMBER OF DM+GAS PARTICLES

PARALLEL HYDRO CODES

- GADGET (Springer et al. 06)
- GASOLINE (Wadsley et al. 04)
- Ramses (Teyssier et al. 08)
- P-DEVA (Martinez-Serrano 08)

P-DEVA

THE CODE

AP3M + SPH_{2L} + DDR + Q_{ij}

OpenMP

. Kennicutt-Schmidt SF algorithm

. Stellar Physics subresolution modelling (Chemical feedback)

. Self-consistent element formation (Q_{ij}) & cooling (DDR)

. Conservation Laws >>

careful implementation of the neighbour searching algorithm in SPH

2 loops >> highly CPU time consuming !!

P-DEVA

THE RUNS

EQUILIBRIUM BOX SIZE /RESOLUTION

- 80 Mpc periodic box side >>
  cosmological convergence
- Initial Conditions : WMAP+BAO+SZ+SNEall+ SSDS, running
- 2 x 512^3 DM & baryon particles
  (2.4 & 12.5 x 10^7 $M_\odot$)
- Space resolution: 2 kpc gravity; 1 kpc hydro
- Resampling possible (mass & space resolution increased):
  3 x 40 Mpc^3 sub-boxes brought up to z=0

WHY LARGE GALAXY SURVEYS ARE NECESSARY ?

Not only galaxy statistics ...

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The dark-matter vs galaxy connection

- decipher important clues about the role DM plays in galaxy formation processes.
- DIRECT PROBES of DM in galaxy haloes at r>50 kpc
- G-G lensing
- Satellite kinematics
- INDIRECT PROBES: HOD

ProtoG location relative to the cosmic-web:

- alignments
- AM acquisition → shapes
- morphology
- kinematics

Yes… galaxy statistics…

Halo Occupation Distribution

Study of the occupation attending:

- Halo mass, host mass, satellite mass…

$$\Phi\left(M_*\middle|M_h\right) = \Phi_c\left(M_*\middle|M_h\right) + \Phi_s\left(M_*\middle|M_h\right)$$

CENTRAL **SATELLITE**

Conditional stellar mass function

Number of galaxies with stellar mass in the interval

$M_* \pm dM_*/2$

Separate contributions from central galaxies and satellites

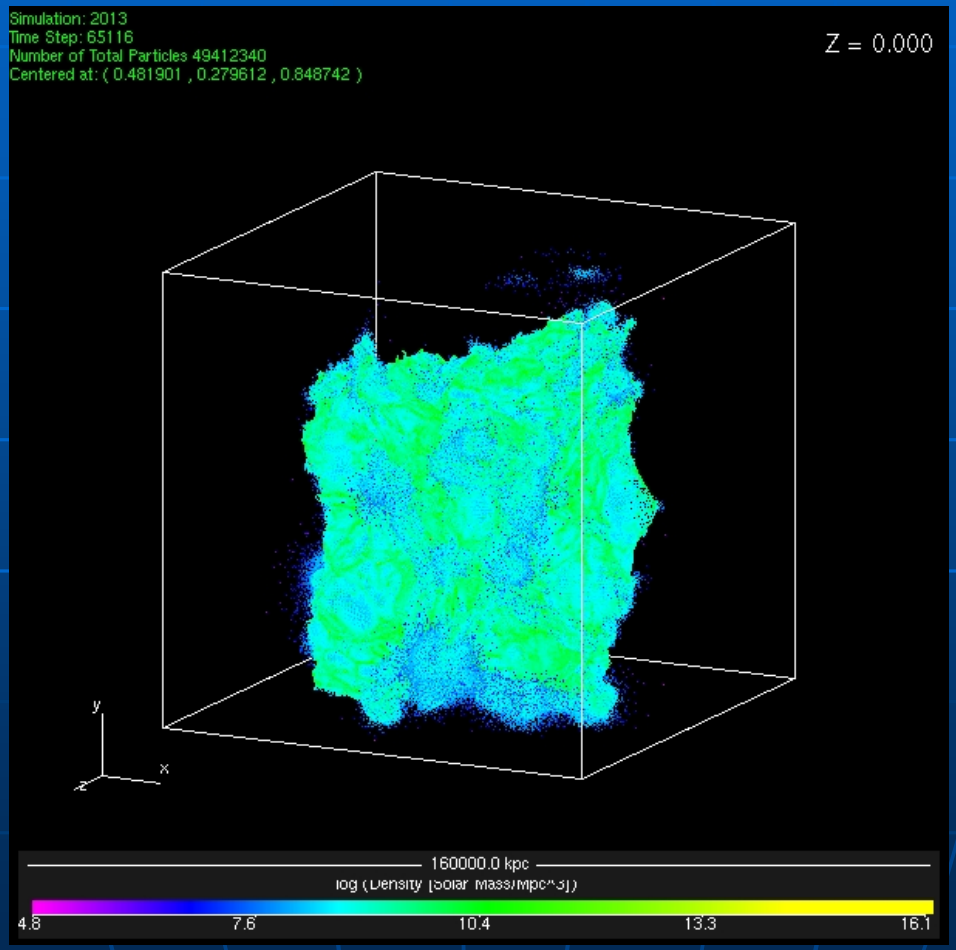
Halo Occupation Distribution

What we really work with:

- $\left\langle N_{cen}\left(M_h|char\right)\right\rangle$ average number of ¨char¨ central galaxies hosted by halos of mass M_h. ("char" can correspond to a mass threshold or a mass bin)
- $\left\langle N_{sat}\left(M_h|char\right)\right\rangle$ average number of ¨char¨ satellite galaxies hosted by halos of mass M_h.

HOD PROVIDES A WIDE RANGE OF POSSIBILITIES TO CONNECT DM & GALAXY DISTRIBUTIONS

Results from large-volume hydro simulations



What is necessary to perform this work with simulations?

AUTOMATIZATION

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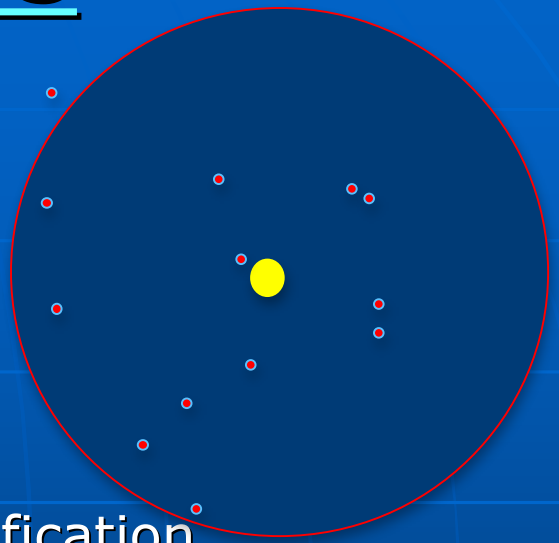
Object Finding in LVHS



- What do we find?
  - "Virtual Galaxies": star + gas,
  - With : sizes, masses, dynamics OK
  - Embeded in DM haloes
  - Orbiting satellites.

No trivial problem: VG & satellite identification

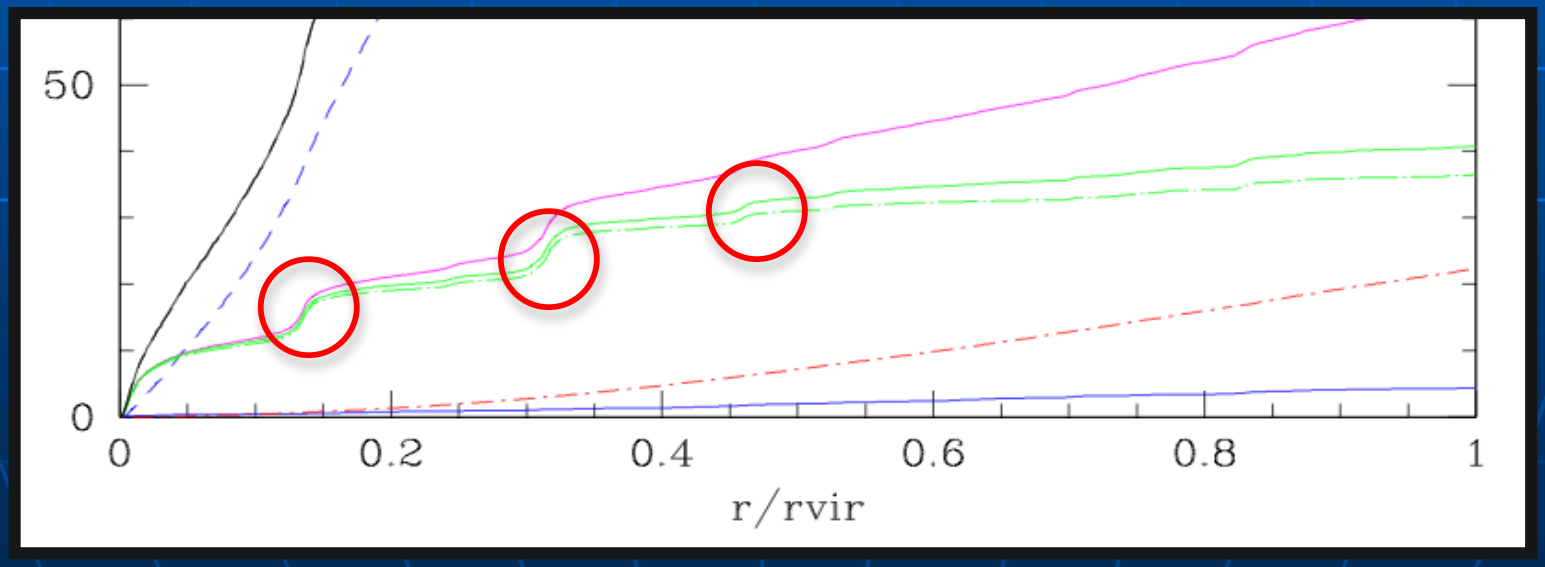
- FOF – Friends of Friends (Davies et al. [1985])
  - Automatic object Finder
  - Linking length, *b*
  - Gives the object centers
  - HOST Selection criterion $M_* \geq 10^{1.5}\ M_\odot$

Still **SATELLITE IDENTIFIER ??**

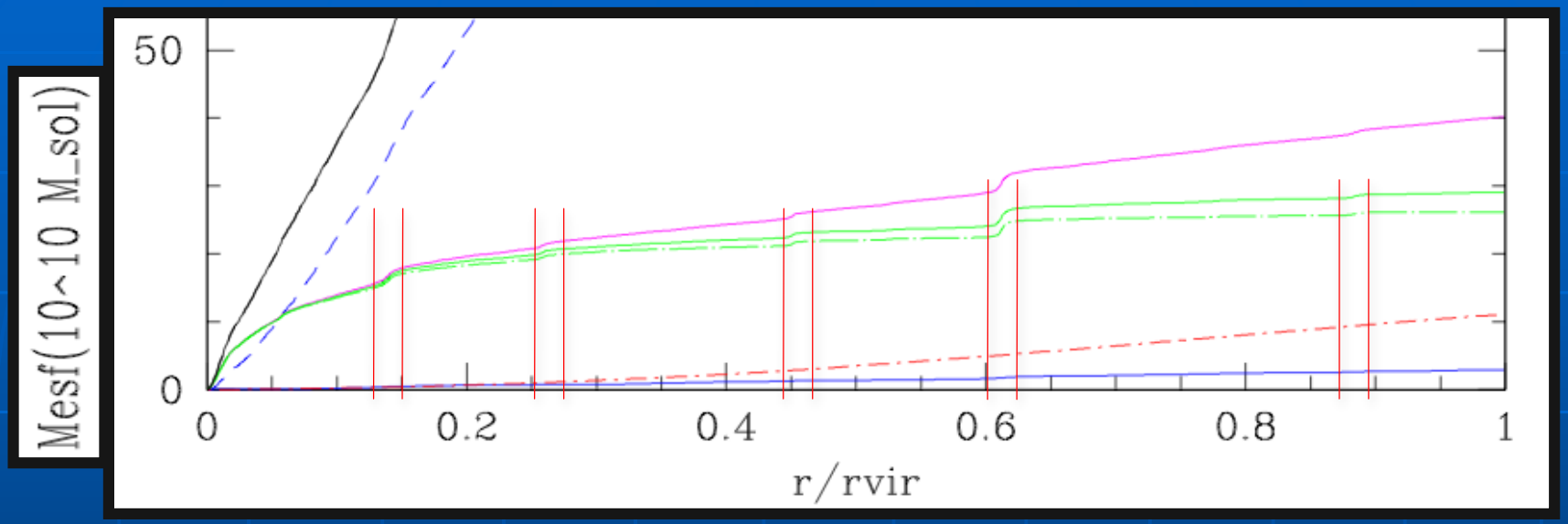
MEASURING STELLAR MASSES & SATELLITE IDENTIFICATION

- Virial masses
- Virial radii (Bryan & Norman)
- 3D integrated mass profiles (IMPs)
  - How does a satellite shows up in a IMP?

JUMP !!!



JUMP DETECTOR ALGORITHM (Casado et al. in prep)



Method based on:

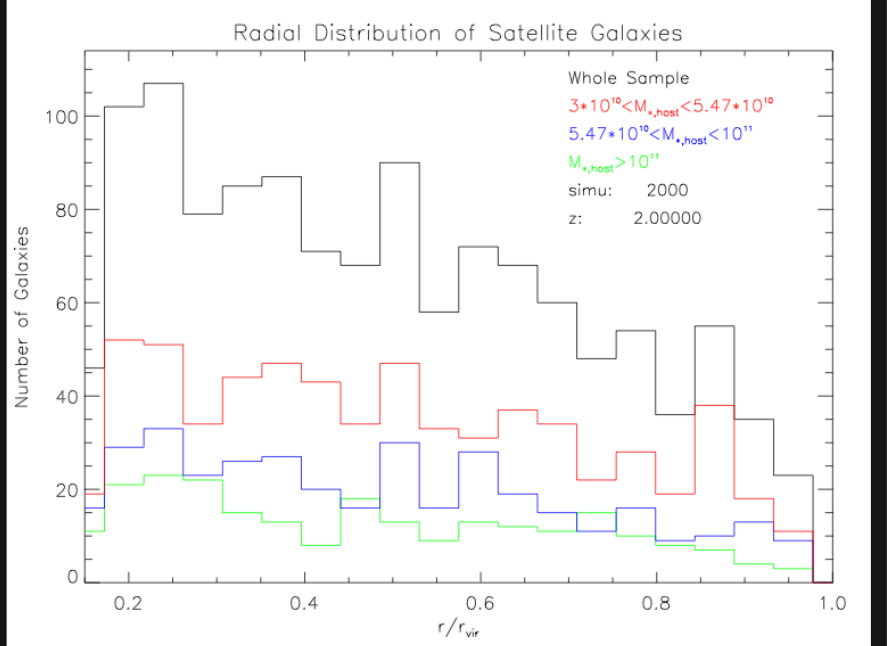
- detection of changes in the IMP function and derivatives.
- optimized to detect satellites and avoid mergers in substructure and projection effects.
- Also useful to detect mergers in the central halo object and study the accuracy of the mass estimation and virial radii.
- Fast and cheap way to detect satellites and substructure.

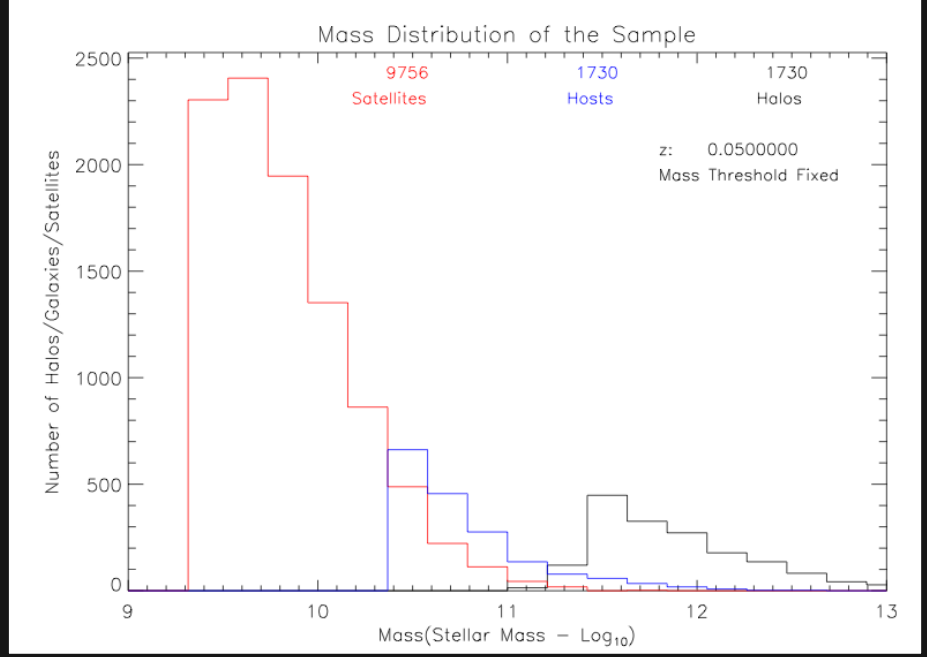
What do we get out of it?

Statistical study:

-Radial distribution of satellites, mass distribution, study of number of merging objects…

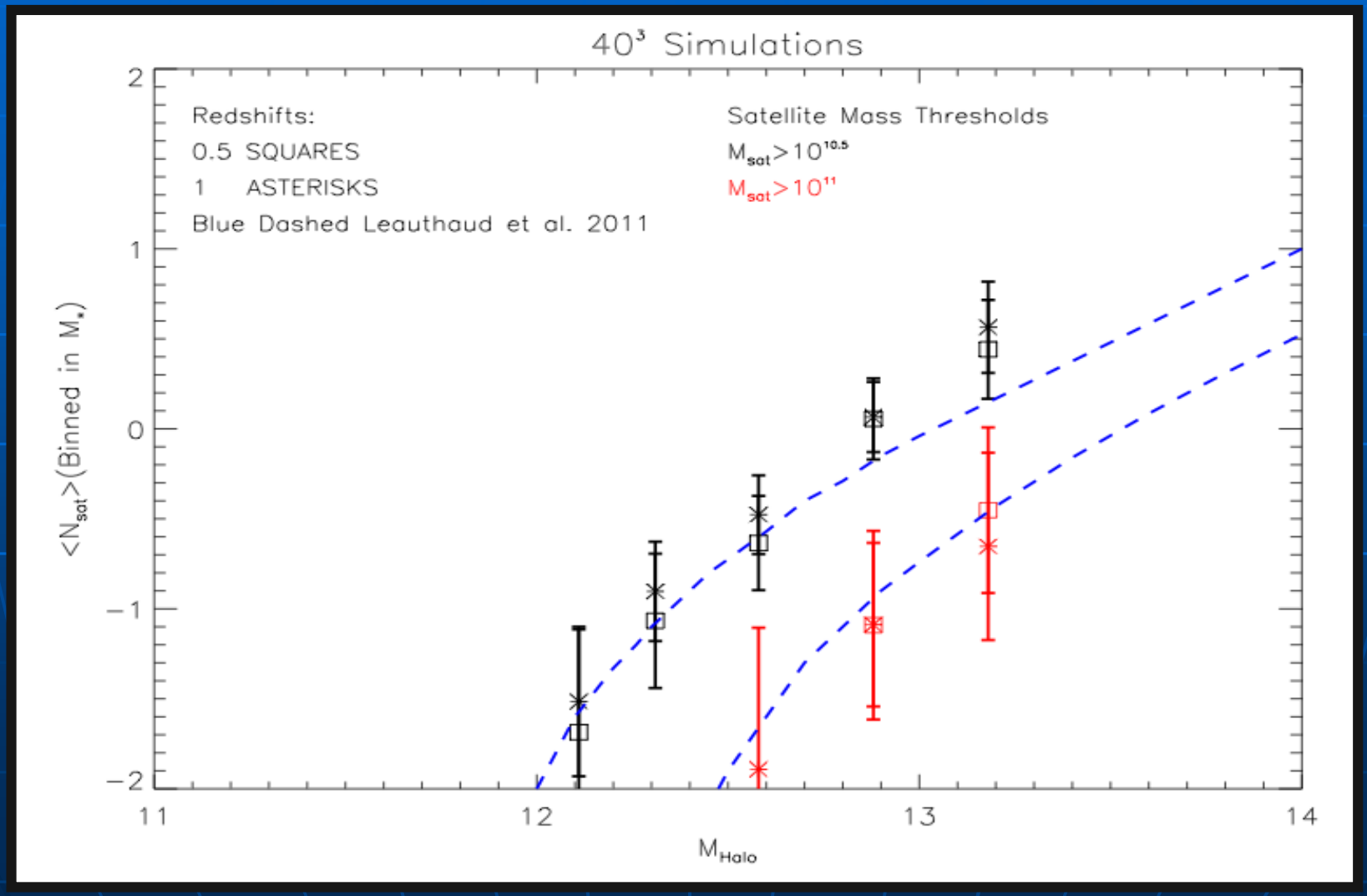
A LARGE VARIETY OF STUDIES AVAILABLE



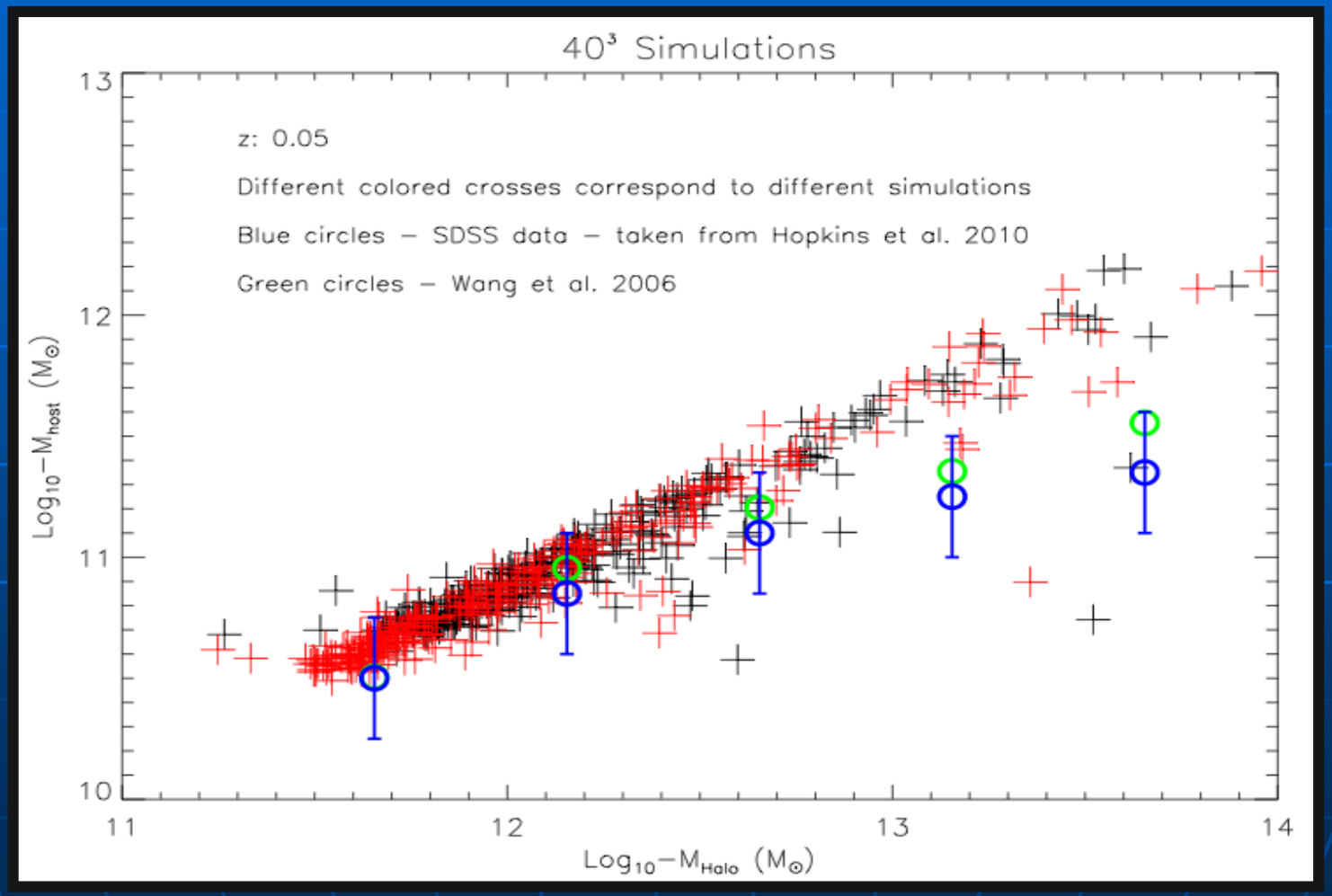


AND, of course **HOD studies**

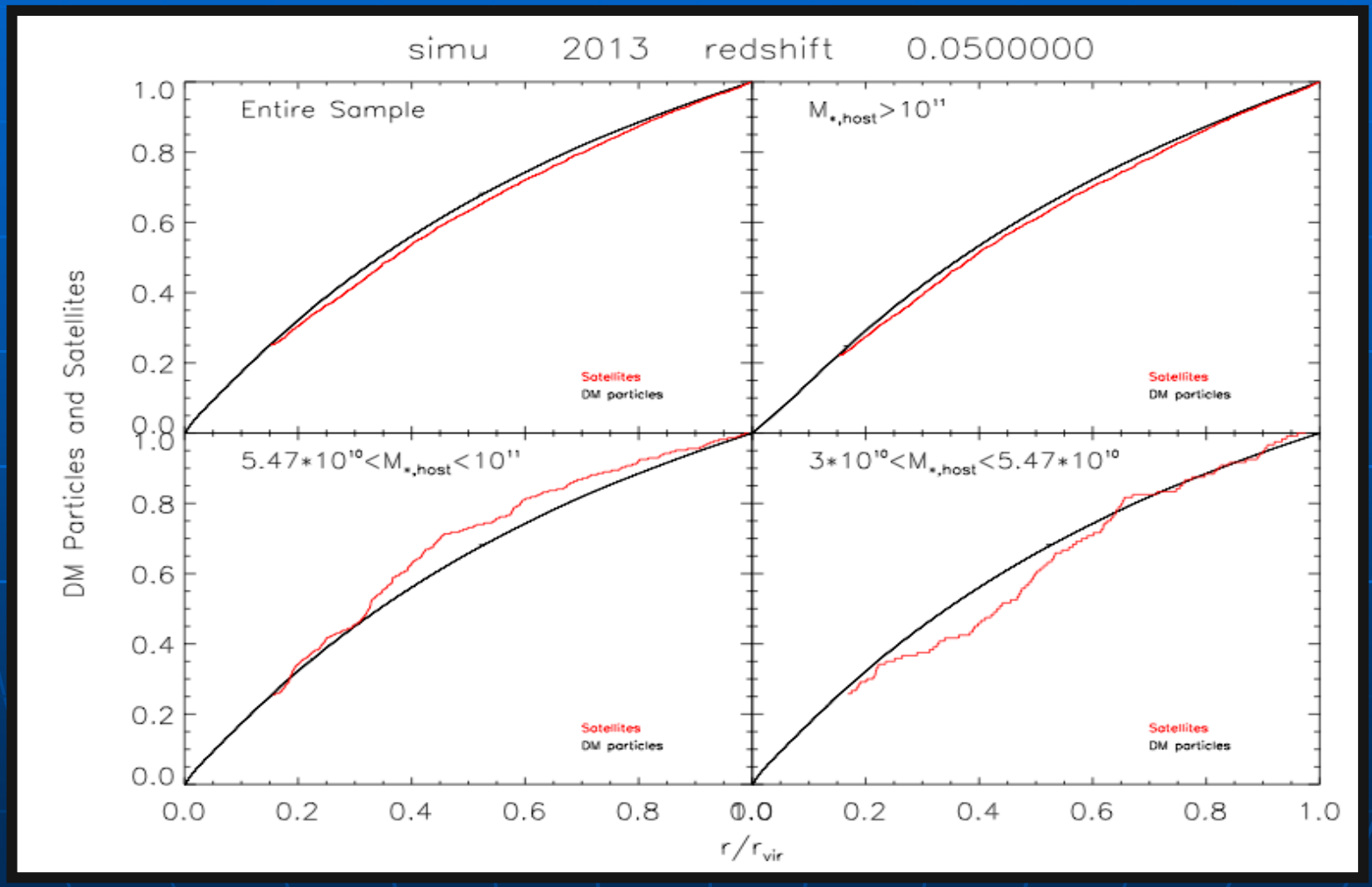
$\left\langle N_{sat}\left(M_h / M_{sat,*}\right)\right\rangle$ From GALFOBS



$M_{central,*}$ vs M_{halo} From GALFOBS



DO SATELLITES TRACE THE HALO (DARK) MASS DISTRIBUTION?



They probably do !!

HOD

Leauthaud et al. 2011 & 2012

Theoretical Framework
(MODEL + BEST FITTING WITH COSMOS SURVEY)

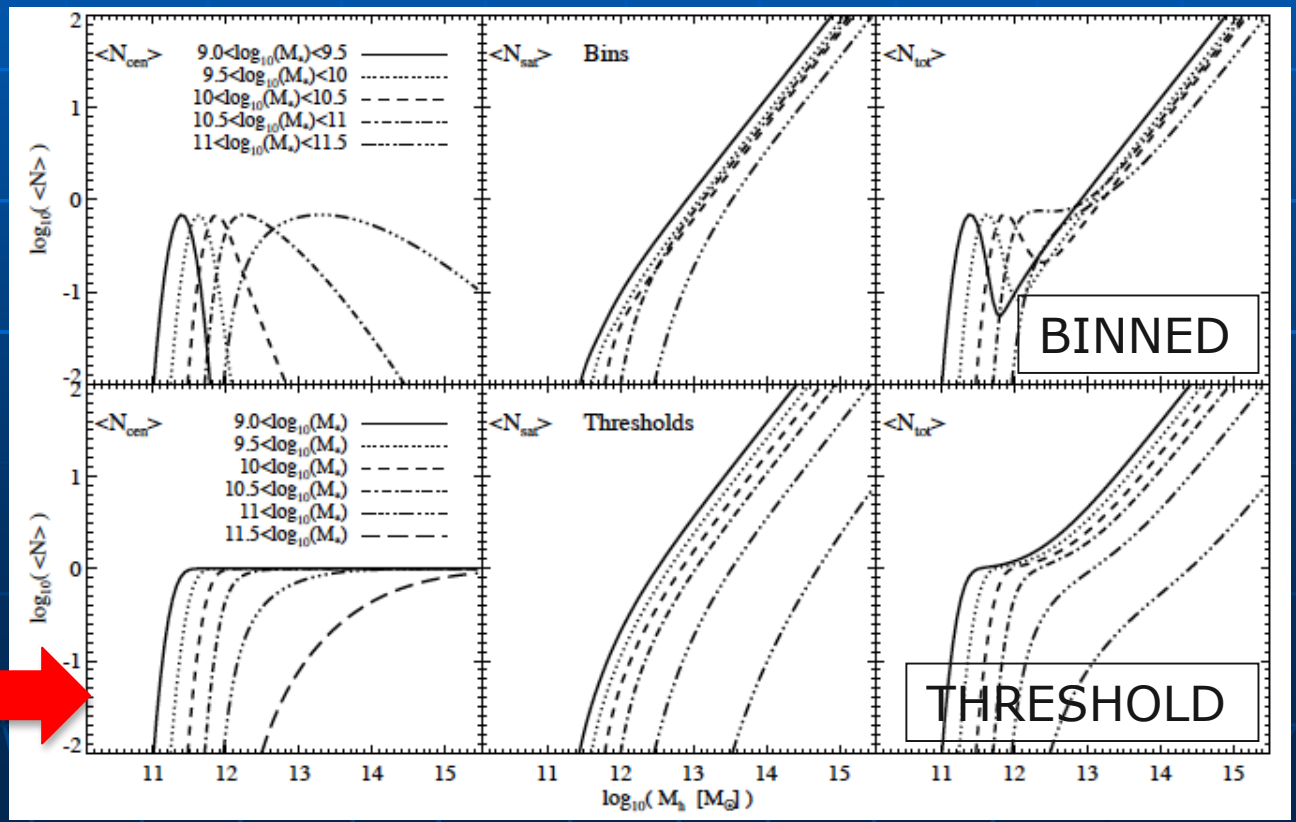
Based on log-normal probability distribution function for the stellar-to-halo mass relation (SHMR) → { 2 parameters for central gal. + 3 for satellites

MODEL

(5 parameters)

- Galaxy-galaxy lensing
- Galaxy clustering $\omega(\theta)$
- Galaxy stellar mass function

BEST FITTING COSMOS SURVEY 0.48<z<0.74



SUMMARY

For DM – Galaxy connection **group statistics are very important.**

Large surveys are required
with accurate z determination
with accurate mass, velocity & positions.

Observational estimations of HOD are still at their infancy

Combining Results from Large Galaxy Surveys and Simulations will lead to a better understanding of the Dark Matter – Galaxy Connection