13th Potsdam Thinkshop
Near Field Cosmology
2016, March 29 – April 3, Obergurgl Tyrol Austria

Leibniz-Institut für Astrophysik Potsdam

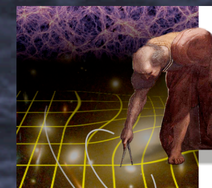
UAM UNIVERSIDAD AUTONOMA DE MADRID

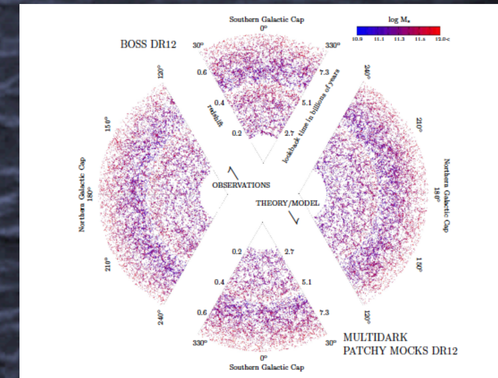
The MultiDark Simulation Project:

Large Volume Simulations for Near Field Cosmology

Gustavo Yepes
Universidad Autónoma de Madrid

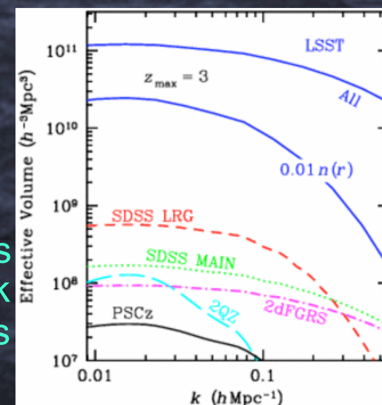
Why Large N-body simulations are needed?

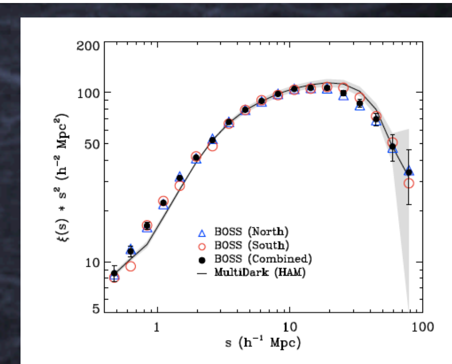




- **Plenty of Large Volume Galaxy Surveys (**DES, KIDS, BOSS, eBOSS
- DESI, JPAS, Euclid…

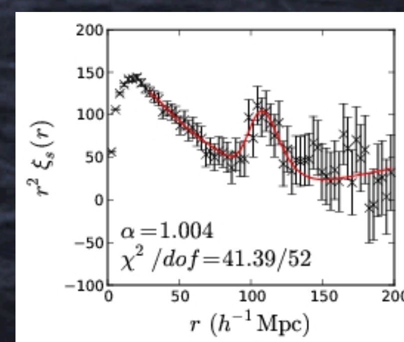
- They will probe 10-100 Gpc^3 volumes



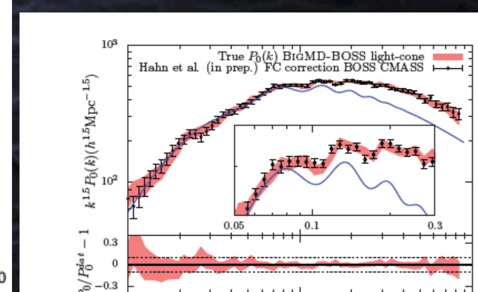


- Need to resolve halos hosting the faintest galaxies of these surveys to produce realistic mock catalogues. Higher z surveys imply smaller galaxies and smaller halos->more mass resolution.

- Fundamental tool to compare clustering properties of galaxies with theoretical predictions from cosmological models at few % level. Not possible only with LPT. Must do the full non-linear evolution for scales 100+ Mpc (BAO, P(k), RSD, 2pcf of galaxies)



- *BAO in BOSS,*
- *100Mpc scale*

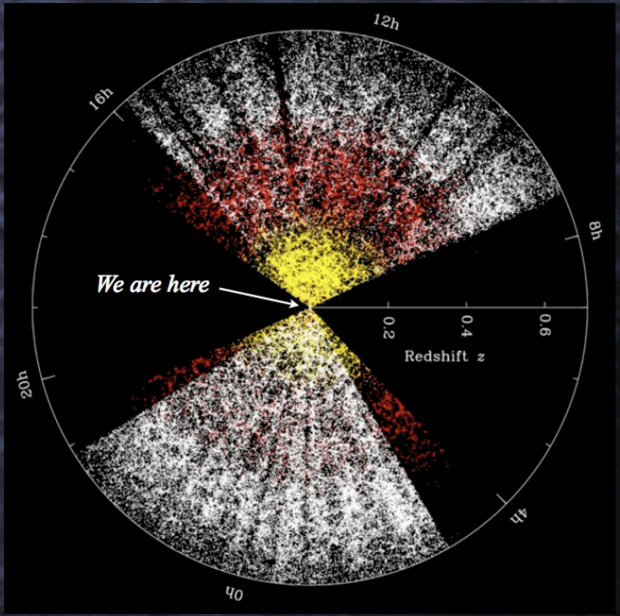


- *P(k) from Dr12 and BiGMD*
- *Rodriguez-Torres et al 2015*

- **Galaxy Biases**: Large mass resolution is needed if internal sub-structure of dm halos has to be properly resolved to map halos to galaxies.
- e.g. Using the *Halo Abundance Matching* technique (e.g. Trujillo et al 2011).

Why Large N-body simulations are needed

- **Large Volume Galaxy Surveys**
- A real example: BOSS (z=0.1..0.7)
- Box size to host full BOSS survey : 3.5 h^{-1} Gpc



- BOSS completed down to LRG galx with
- V_{cir} >350 km/s -> M_{vir} ~5x10^12 Msun.
- To properly resolve the peak of the Vrot in a dark matter halo we need a minimum of few 100 particles. High-force resolution to properly model halos and subhalos hosting LRG's

Dark Energy Spectroscopic Instrument

- Then, a proper representation N-body realization of a BOSS survey will need > 7000^3 particles.

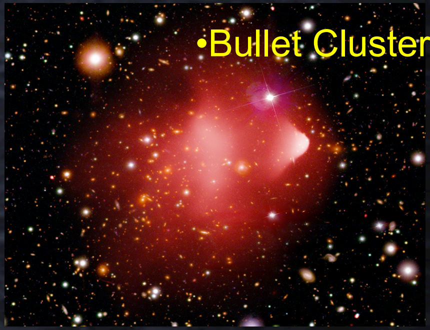
LSST
Large Synoptic Survey Telescope

- DESI, Euclid , LSST will probe to z>1.5
- Larger Boxes: > 4/h Gpc
- Npart > 10,000^3
- Smaller host halos (~10^12) for ELG's

Why Large N-body simulations are needed?

- **Cosmic Abundance of extremely rare galaxy clusters.**

- In LCDM Need very large computational volumes to find one of the extreme interacting clusters recently found in SZ or X-rays + Lensing dat: e.g Bullet cluster, El Gordo.



•For a Bullet-like object, assuming that pairwise velocity is >3000 km/s then volumes typical of 5Gpc and above are needed but with moderate number of particles ~3000^3 . (Thomson & Nagamine 2012) .

•For EL Gordo, at z=0.87, considerable much larger volumes need to be simulated. More than 6 Gpc and > 7000^3 particles

Why Large N-body simulations are needed?

- **Near Field Cosmology:**

  - **Statistics of Local Group Analogs (LGA).**

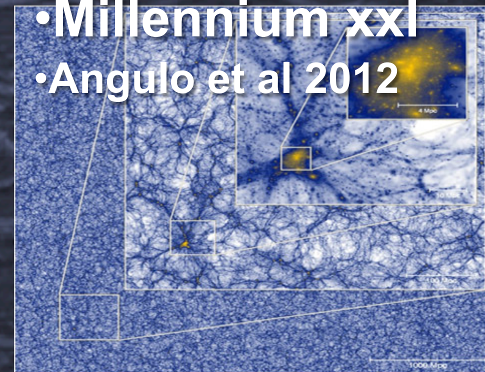
  - **Understand environmental effects on the properties of LGA's**

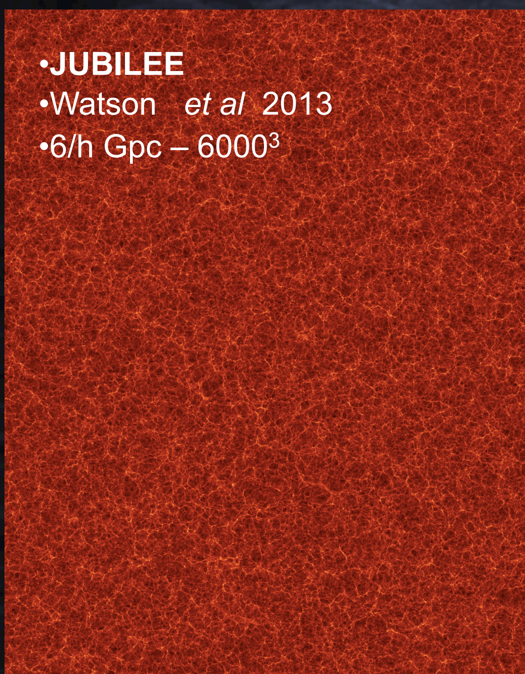
    - **Proximity to a Virgo Cluster**
    - **Presence of a Void or a big filament (Local Supecluster)**

  - **Estimate the special features of our LG by comparing**

    - **LGA's found in Constrained Simulations (CLUES)**
    - **LGA's found in large volume random realizations**

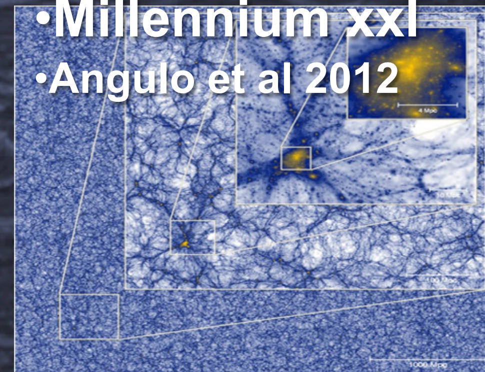
Dark Matter Cosmological Simulations

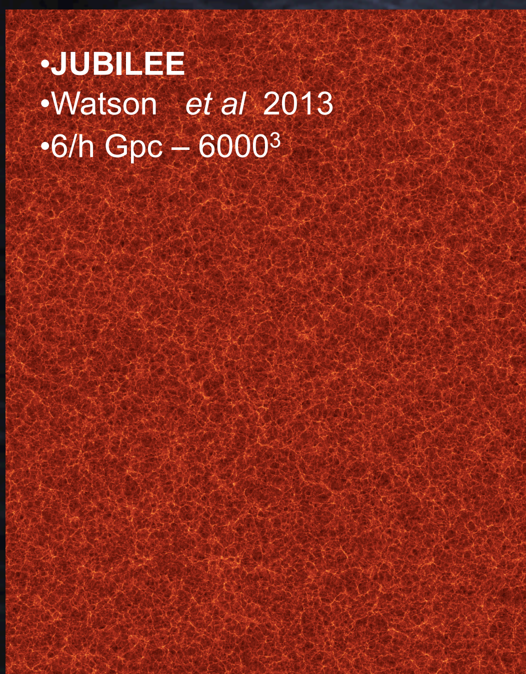




•Millennium I (WMAP1-GAD) 500 /h Mpc 10 billion particles
•Millennium II (WMAP1 –GAD) 100/h Mpc 10 billion particle
•Millenium XXL (WMAP1-GAD) 3 /h Gpc 303 billion particles
•Bolshoi (WMAP7-ART) 250/h Mpc 8 billion particles
•Multidark (WMAP7-ART) 1 /h Gpc 8 billion particles
•*Las Damas (WMAP7-GAD) 2.5/h Gpc*
•MICE -GC (WMAP5-GAD) 3 /h Gpc 68 billion particles
•Horizon (FR) (WMAP3-RAMSES) 2 /h Gpc 68 billion particles
•Horizon (KR) (WMAP5-GOTPM) 10.7 /h Gpc 372 billion.
•DEUS (FR) (WMAP7-RAMSES) 21/h Gpc 550 billion particles
•**JUBILEE (WMAP7-CP3M) 6/h Gpc 216 billion particles**
•***BigMD (PLANCK-GAD) 2.5/h Gpc 56.6 billion particles***
•***MultiDark (PLANCK-GAD) 1.0/h Gpc 56.6 billion particles***
•***OUTER RIM ((PLANCK-HAAC) 4.0/h Gpc 1.1 trillion particles***
•***DARK SKY (PLANCK-2HOT) 8.0/h Gpc 1.1 Trillion particles***

Dark Matter Cosmological Simulations





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From dark halos to galaxies

- A Full self-consistent galaxy formation simulation is orders of magnitudes more computationally expensive than dark matter only simulations.

- Not yet possible to simulate large computational volumes (> 1Gpc^3) with baryons and proper resolution

- Need to map halos to galaxies using approx. models:
  - ✓ Halo Occupation Distribution (HOD)
  - ✓ Halo Abundance Matching (HAM)
  - ✓ Semi Analytical Modelling (SAM)

MULTIDARK SIMULATION PROJECT

•The *old* MULTIDARK Simulations

• **Multidark run:**

•Volume: 1/h Gpc volume.

•N particles: 2048^3 particles

•Force Resolution: 7 kpc/h

•*Cosmological Parameters:*

•Ω_M=0.27, 0.29, 0.31

•σ_8= 0.82, 0.9

•n_s = 0.95

•zinit= 65

•ART N-body code

• (Kravtsov & Klypin 97)

•Both FOF and BDM halo catalogues for 80+ redshifts.

•Accurate determination of internal profiles of halos and substructures.

•HAM to select galaxies (Nuza et al 2013)

•Matching LRG clustering of BOSS 2pcf..

•DATABASE

•http://www.multidark.org

•The MULTIDARK Simulation Suite

•**PRACE proposal** 2012: G. Yepes (PI), S. Gottloeber, A. Klypin, F.Prada, S. Hess

•22.5 million cpu hours in SuperMUC@ LRZ.

•DATABASES

•http://www.multidark.org

• http://www.cosmosim.org

• Publicly available now!!

• **BigMD suite:**

•Volume: 2.5/h Gpc volume.

•N particles: 3840^3 particles

•Force Resolution: 10 kpc/h

•N timesteps > 6000 (max $\Delta t < 0.001$)

•*Cosmological Parameters:*

• Ω_M=0.27, 0.29, 0.31

• σ_8= 0.82, 0.9

• n_s = 0.95

• zinit= 100

•**First Planck Cosmology runs:**

•Ω_M=0.3071, σ_8= 0.8225, n_s=0.96

•Zinit=100

•Multidark & Small MD Planck1

•Box = 1/h Gpc and 400/h Mpc@ 3840^3

•Force = 5 kpc/h – 3kpc

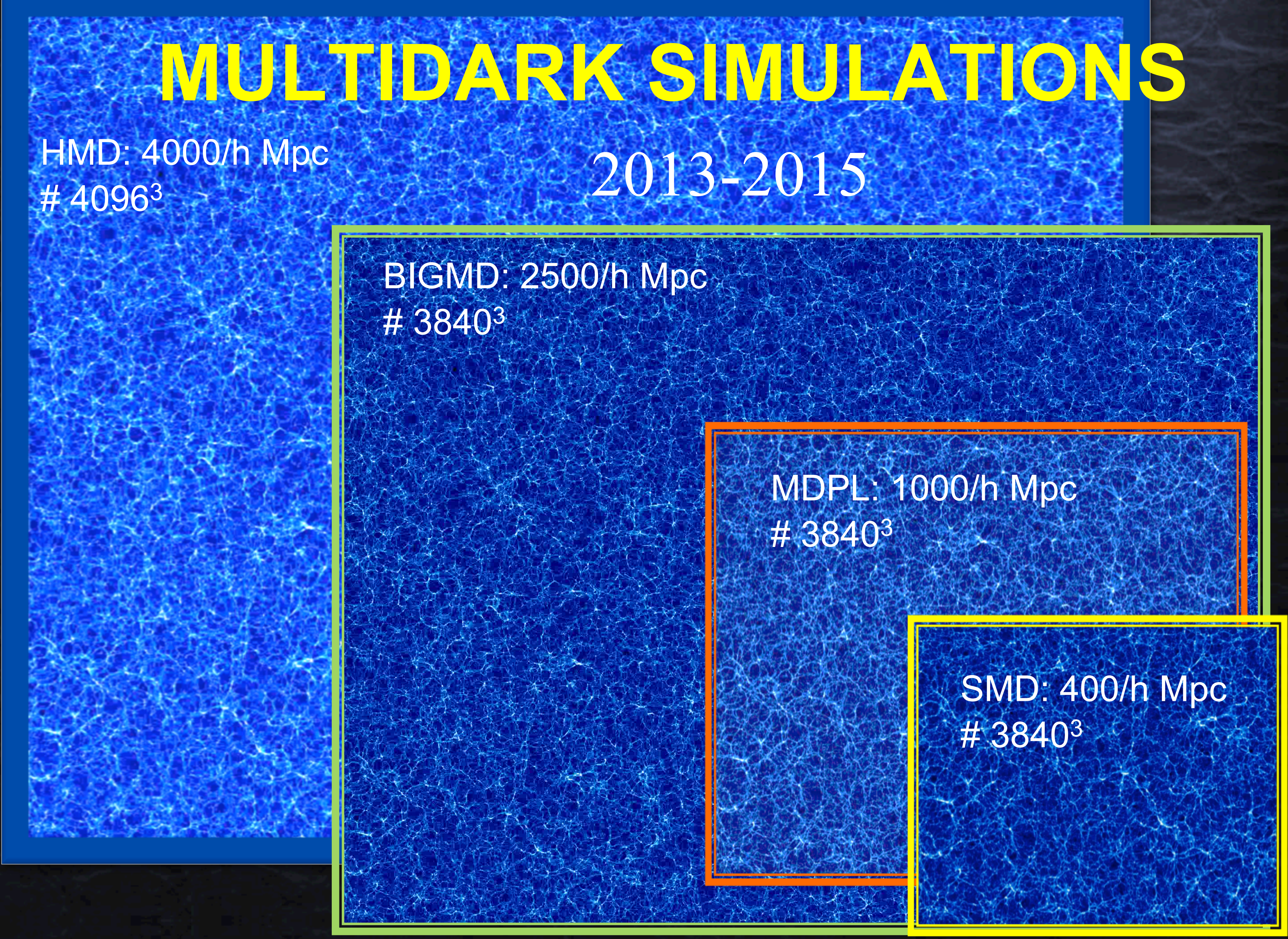
•Zinit=120-150

•130 timesteps stored.

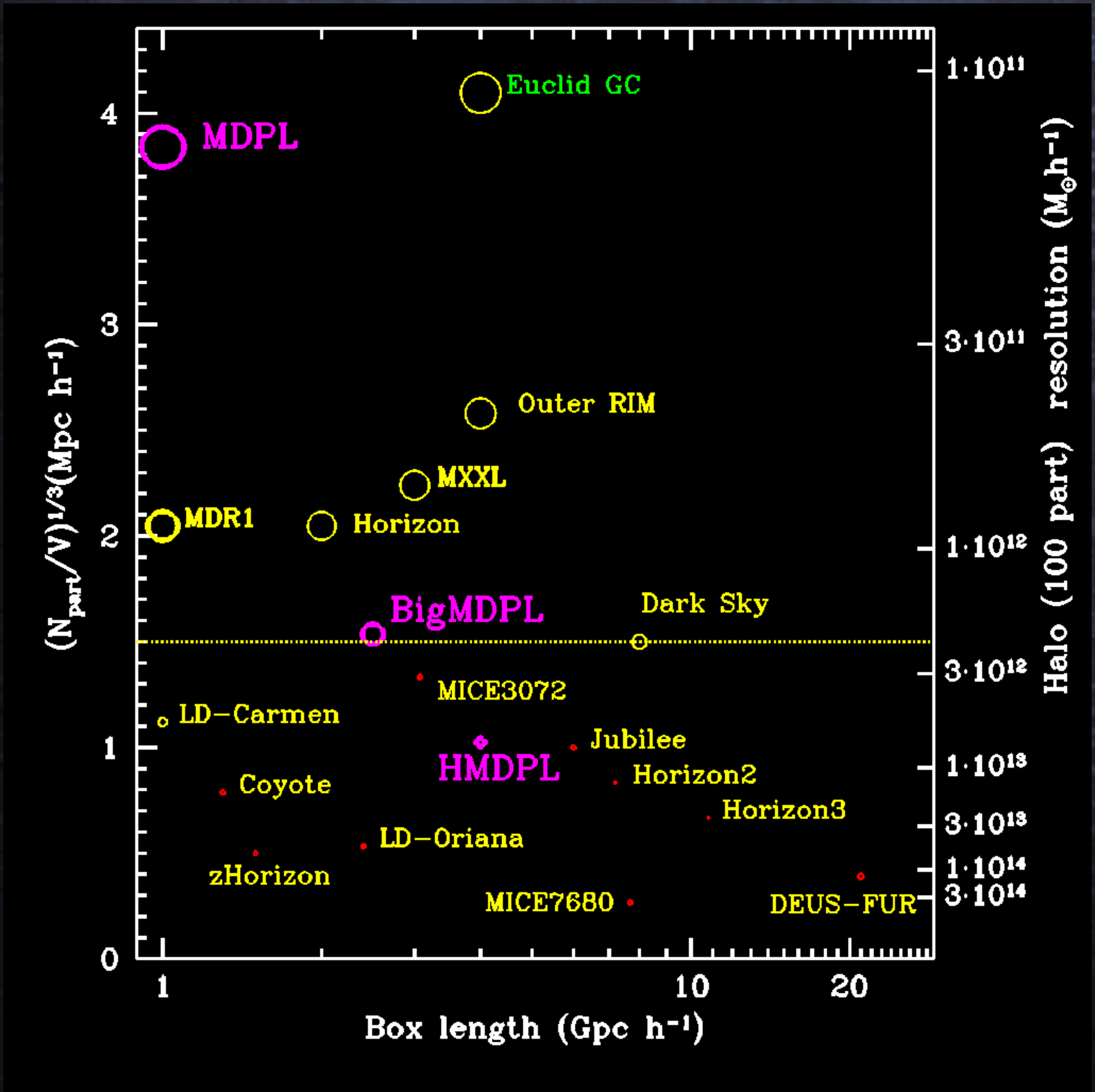
•**FOF, BDM and ROCKSTAR** halos.

MULTIDARK SIMULATIONS

2013-2015



Current S.o.A Cosmological Simulations



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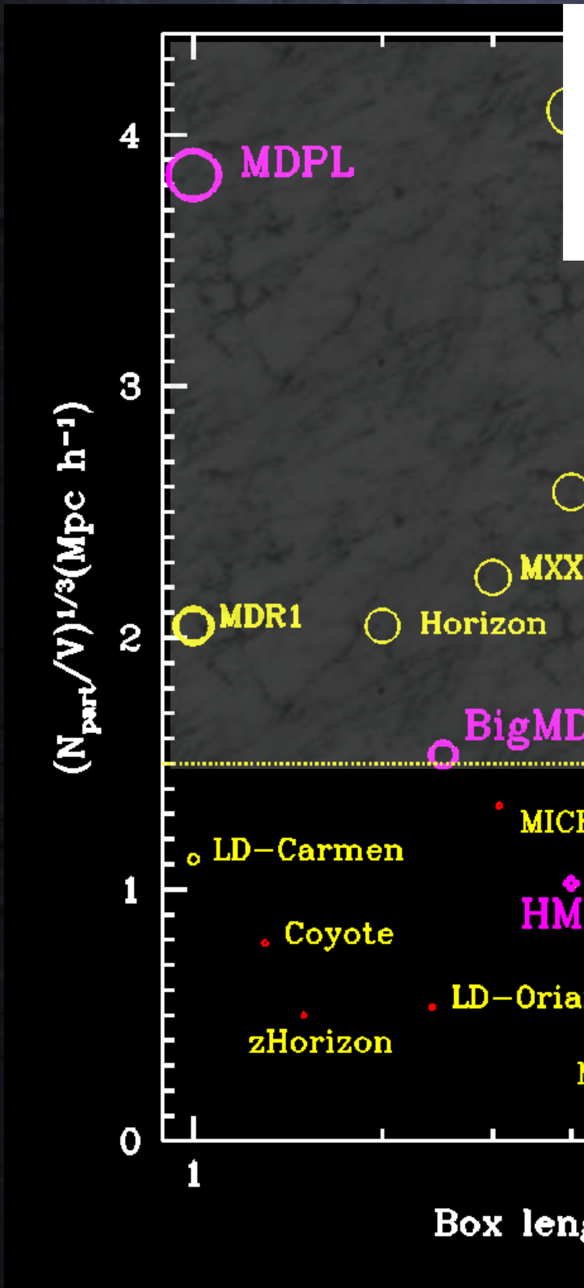

Halo Abundance Matching: accuracy and conditions for numerical convergence

Arxiv:1310.3740

Anatoly Klypin[1*], Francisco Prada[2,3,4], Gustavo Yepes[5], Steffen Heß[6], Stefan Gottlöber[6]

Numerical precision needed for the Halo Abundance Matching Technique (HAM).

Halos and subhalos selected by V_{max}.

Convergence studies for correlation functions to measure clustering using Bolshoi and MD ART simulations and BigMD Gadget.

Main conclusions:

Need high mass and force resolution to achieve this: (0.1-0.3)*rs, rs = scale radius of resolved subhalo. Progenitor of subhalos must be resolved with ~150 particles.

Contrary to previous results from Millenium sims (Guo & White 2013) who claimed that HAM needed halos resolved with 3000 or more particles for convergence.

•More than 1 PBYTE of RAW DATA PRODUCED DURING 2013-15

Name	Cosmology	Ω_m	Ω_Λ	Ω_b	σ_8	n_s	Box [Mpc/h]	Particles	Mass range (min/max halo mass, [M_{sun}/h])	Force resolution	Data in DB
Bolshoi [Query]	WMAP 5	0.27	0.73	0.047	0.82	0.95	250	2048^3	$2.7*10^9 – 8*10^{14}$	1.0 kpc/h	BDM, FOF, Profiles, Particles, Density
MDR1 [Query] (MDark_2048_om0.27)	WMAP 5	0.27	0.73	0.047	0.82	0.95	1000	2048^3	$1.7*10^{11} – 1.6*10^{15}$	7.0 kpc/h	BDM, FOF, Profiles, Particles, Mtree, Substructure, Density
MDPL [in progress] (MD_3840_Planck1)	Planck 1	0.31	0.69	0.048	0.82	0.96	1000	3840^3	$3.0*10^{10} – 4.2*10^{15}$	13 kpc/h (for high z) – 5 kpc/h (low z)	BDM, FOF
BigMDPL [coming soon] (BigMD_3840_Planck1)	Planck 1	0.31	0.69	0.048	0.82	0.96	2500	3840^3	$4.7*10^{11} – 6*10^{15}$	30 kpc/h (high z) – 10 kpc/h (low-z)	[nothing yet]
BigMDPLnw [coming soon] (BigMD_3840_Planck1_NW, no baryonic wiggles)	Planck 1	0.31	0.69	0.048	0.82	0.96	2500	3840^3	$4.7*10^{11} – 6*10^{15}$	30 kpc/h (high z) – 10 kpc/h (low-z)	[nothing yet]
BigMD27 [coming soon] (BigMD_3840_om0.27)	WMAP 5	0.27	0.73	0.047	0.82	0.95	2500	3840^3	$4.2*10^{11} – 5.5*10^{15}$	30 kpc/h (high z) – 10 kpc/h (low-z)	[nothing yet]
BigMD29 [coming soon] (BigMD_3840_om0.29)	–	0.29	0.71	0.047	0.82	0.95	2500	3840^3	$4.4*10^{11} – 5.6*10^{15}$	30 kpc/h (high z) – 10 kpc/h (low-z)	[nothing yet]
BigMD31 [coming soon] (BigMD_3840_om0.31)	–	0.31	0.69	0.047	0.82	0.95	2500	3840^3	$4.1*10^{11} – 5.8*10^{15}$	30 kpc/h (high z) – 10 kpc/h (low-z)	[nothing yet]

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2015: The Huge MULTIDARK RUN: 4/h Gpc and 4096^3 particles

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BigMD31 [coming soon] (BigMD_3840_om0.31)	–	0.31	0.69	0.047	0.82	0.95	2500	3840^3	$4.1*10^{11} – 5.8*10^{15}$	30 kpc/h (high z) – 10 kpc/h (low-z)	[nothing yet]

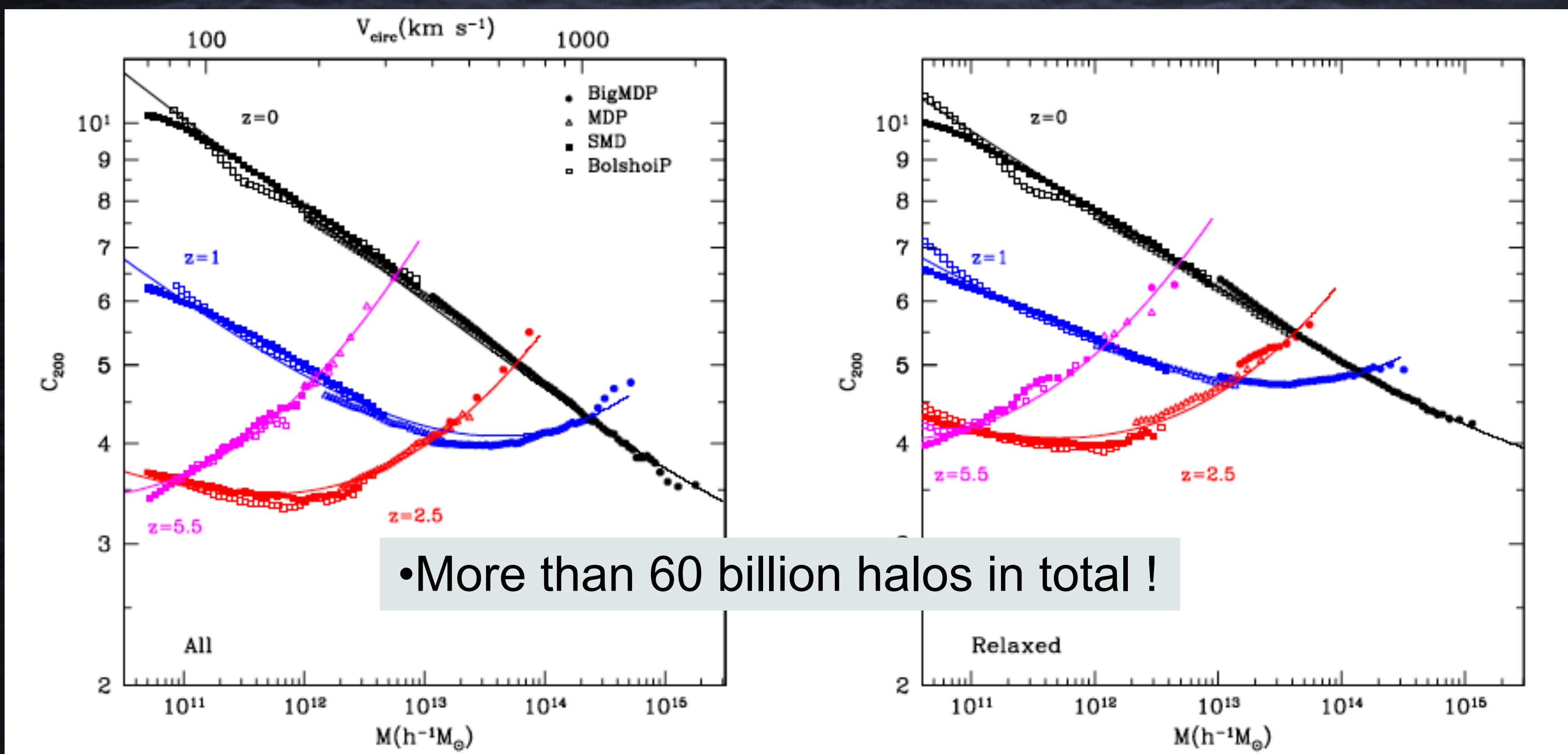
SOME MULTIDARK SIMULATION RESULTS

Multidark SImulations: Calibrating c-M relation

MultiDark simulations: the story of dark matter halo concentrations and density profiles.

•ArXiv/1411.4001

Anatoly Klypin[1⋆], Gustavo Yepes[2], Stefan Gottlöber[3], Francisco Prada[4,5,6], and Steffen Heß[3]



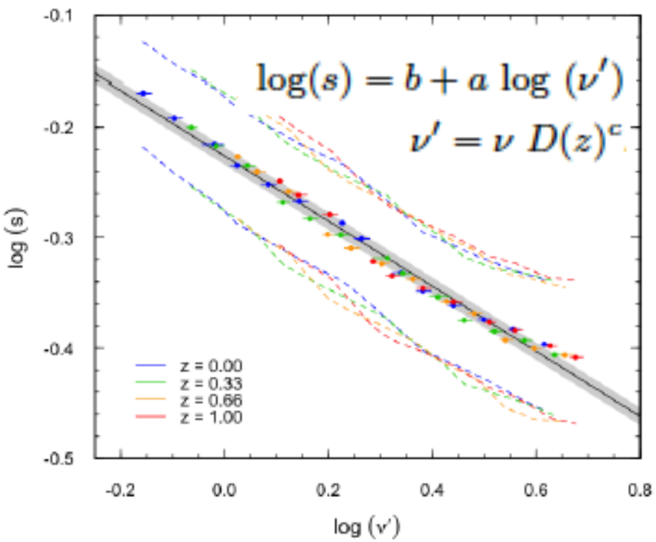
•More than 60 billion halos in total !

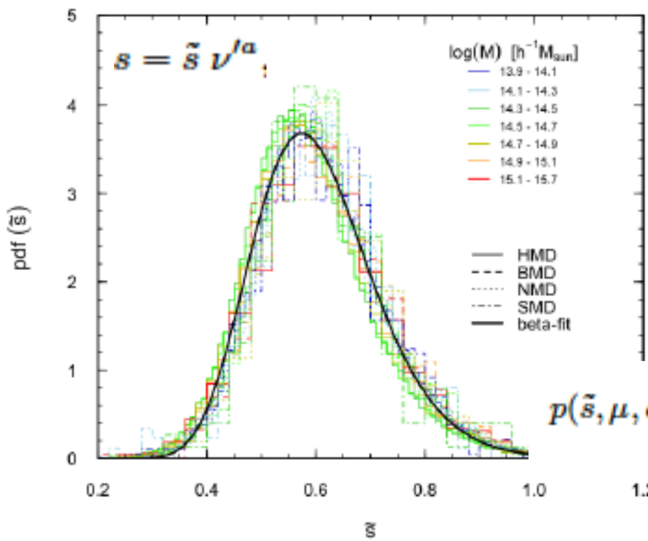
Multidark SImulations: Shapes of DM halos

On the shape of dark matter halos from MultiDark Planck simulations

ArXiv/1603.02256

Jesús Vega[1,2⋆], Gustavo Yepes[1,3] and Stefan Gottlöber[4]





$$p(\tilde{s}, \mu, \sigma) = \frac{1}{\tilde{s}\sqrt{2\pi}\sigma} \exp\left(-\frac{(\ln \tilde{s} - \mu)^2}{2\sigma^2}\right)$$

Axis ratio (s) can be described by an universal function of rescaled peak density independent of redshift

Lensing Maps from BigMD

- Use of GLAMER Ray tracing code in a light cone of BigMD:
- Comparision with VIPERS and SDSS STRIPE 82

MultiDarkLens Simulations: weak lensing light-cones and data base presentation

arXiv:1511.08211

Carlo Giocoli[1] ⋆, Eric Jullo[1], R. Benton Metcalf[2], Sylvain de la Torre[1], Gustavo Yepes[3], Francisco Prada[4,5,6] Johan Comparat[3,4], Stefan Göttlober[7], Anatoly Kyplin[8], Jean-Paul Kneib[9,1], Margarita Petkova[10], HuanYuan Shan[9], Nicolas Tessore[2]

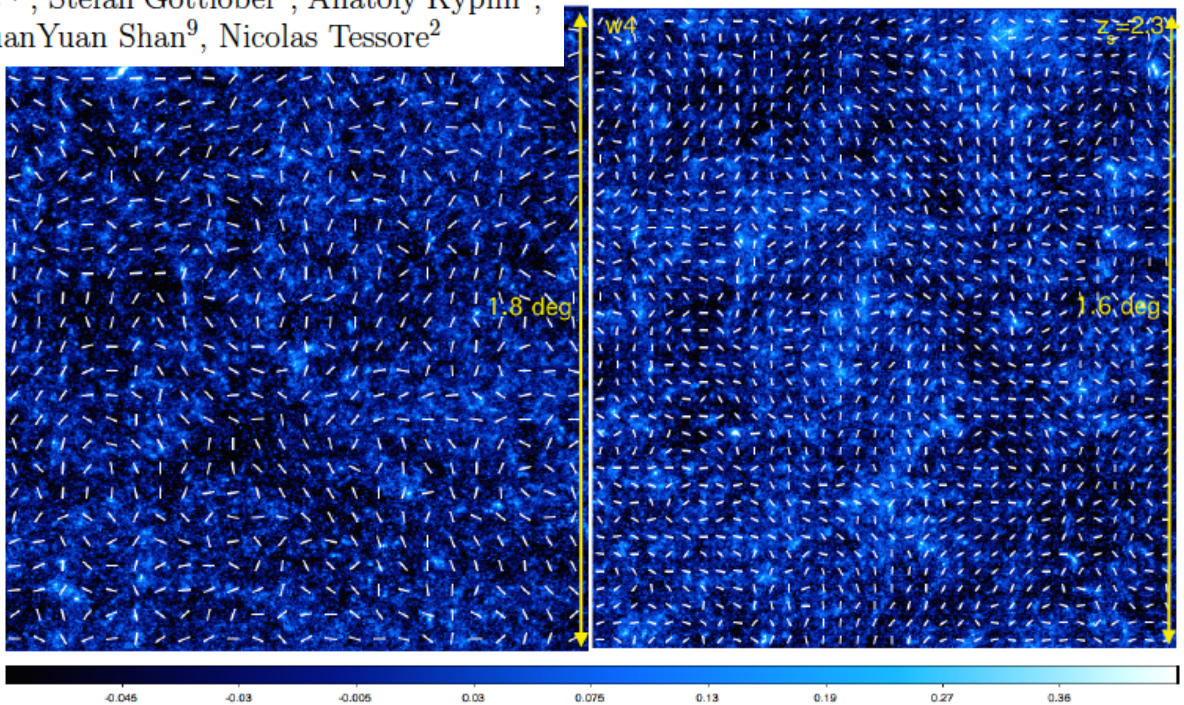
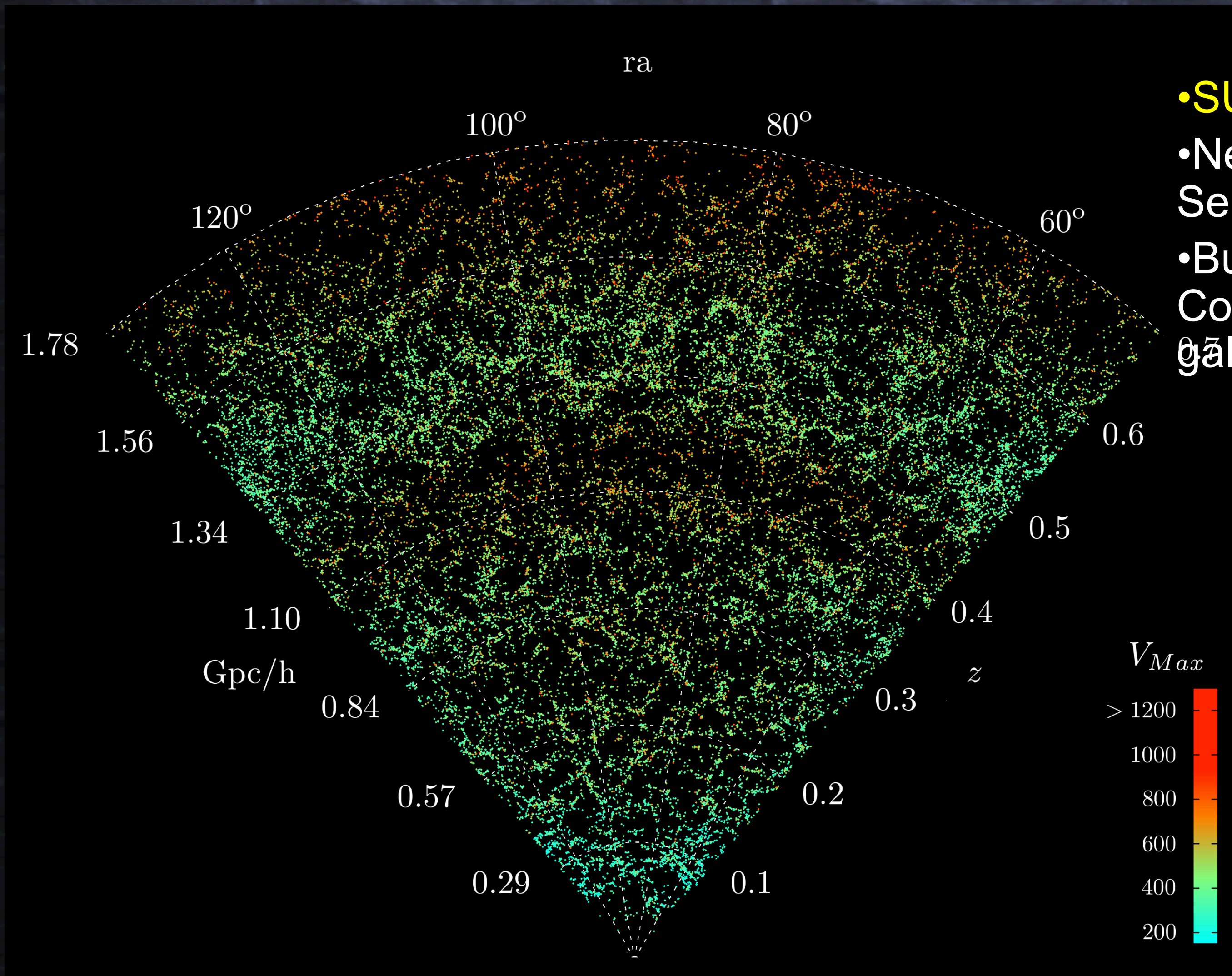


Figure 9. Convergence maps for sources at redshift $z_s = 2.3$ for a square region the w1 (left) and the w4 (right) fields. In this case we show sticks – that in each panel have the same size – representing the direction of the corresponding shear field.

•SUGAR: creating Realistic Light cone mocks for BOSS LRG’s

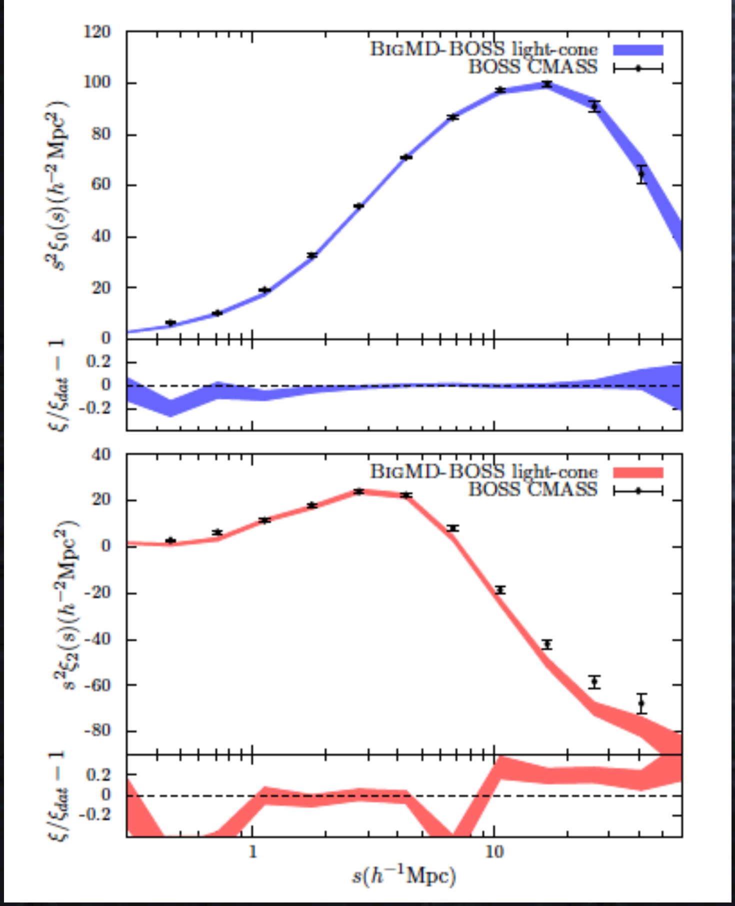


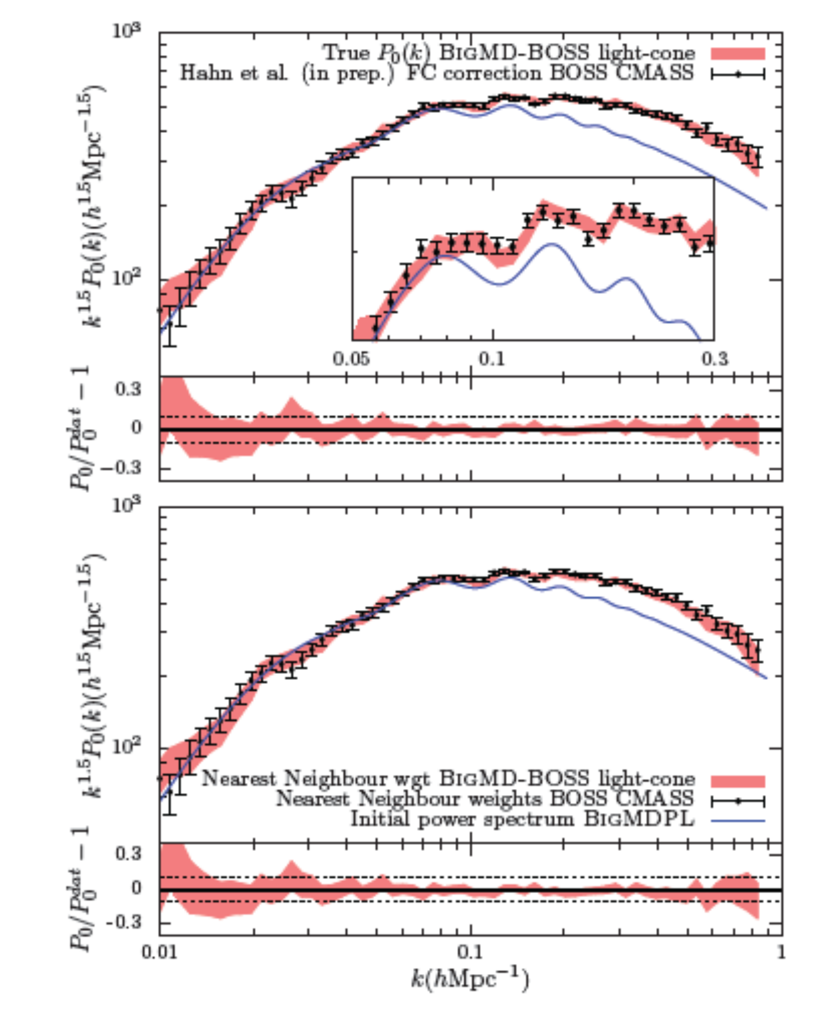
- SUrvey GenerAtoR :
- New code developed by Sergio Rodriguez to
- Build high fidelity Light Cone mocking BOSS LRG galaxies

The clustering of galaxies in the SDSS-III Baryon Oscillation Spectroscopic Survey: Modeling the clustering and halo occupation distribution of BOSS-CMASS galaxies in the Final Data Release

Arxiv-1509.06404

Rodriguez-Torres, et al 2015





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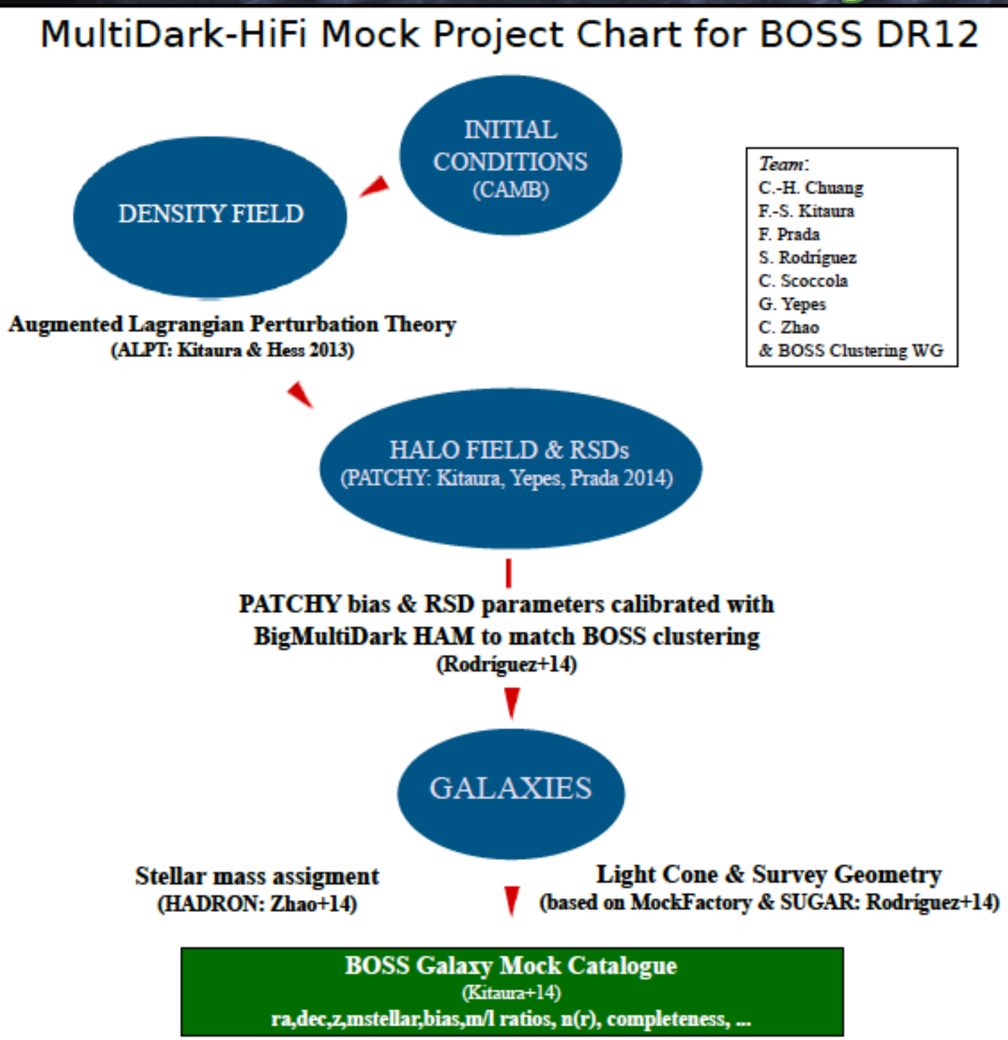
AIP Leibniz-Institut für Astrophysik Potsdam

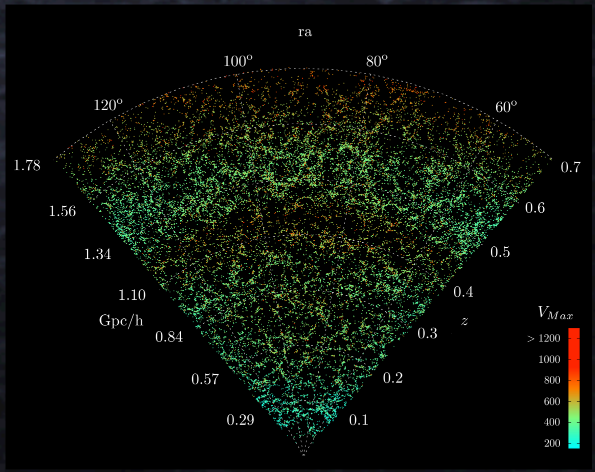
清華大學 Tsinghua University

BSC Barcelona Supercomputing Center Centro Nacional de Supercomputación

The Mock Factory for BOSS LRG's



- Generation of high-fidelity mocks for final data release DR12 of BOSS Survey:
  - More than 2000+ light-cones for CMASS North and South + LOWz North and South
- A total of **192,000 Gpc^3** volume simulated using PATCHY
  - (2LPT+bias model)
- (Kitaura et al 2016, MNRAS, 456,4156



Multidark Simulations: Determining the bias of ELG's

arXiv:1507.04356v1

Clustering properties of g-selected galaxies at $z \sim 0.8$

Ginevra Favole[1,2] *†, Johan Comparat[1,2,5], Francisco Prada[3,1,2,4], Gustavo Yepes[5], Eric Jullo[6], Anna Niemiec[6], Jean-Paul Kneib[7,6], Sergio A. Rodríguez-Torres[1,2,5], Anatoly Klypin[8], Ramin A. Skibba[9], Cameron K. McBride[10], Daniel J. Eisenstein[10], David J. Schlegel[3], Sebastián E. Nuza[11], Chia-Hsun Chuang[1,2], Timothée Delubac[12,7], Christophe Yèche[12], Donald P. Schneider[13,14]

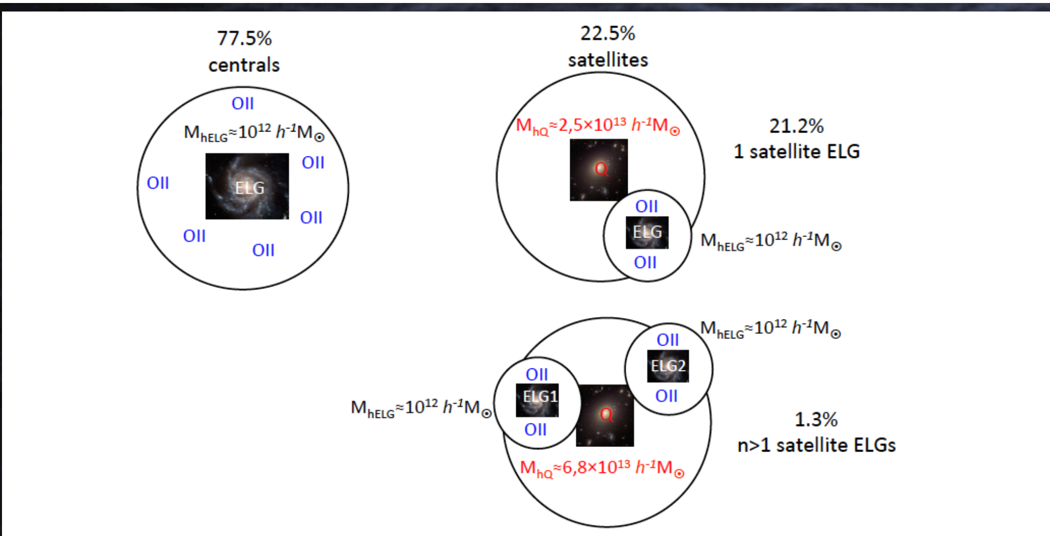


Figure 7. Schematic diagram of possible ELG configurations. ELGs at $z \sim 0.8$ typically live in halos of mass $M_h \sim (1 \pm 0.5) \times 10^{12}\, h^{-1} \mathrm{M}_\odot$ and 22.5% are satellites belonging to larger halos, whose central galaxy is quiescent. Among these satellite configurations, 21.2% of parent halos with $M_{hQ} \sim 2.5 \times 10^{13}\, h^{-1} \mathrm{M}_\odot$ host one satellite ELG, and only 1.3% of parents host more than one satellite ELG. The maxium number of satellites, $n = 1.8$, is achieved in the highest-mass case, $M_{hQ} \sim 6.8 \times 10^{13}\, h^{-1} \mathrm{M}_\odot$. See the text for details.

Modified SHAM in MPDPL Light cones:

ELG's live in halos of M ~10^12 /h Msun @ z= 0.8

Near Field Cosmology

- Use MultiDark simulations to identify Local Group Analogs (LGA):
  - Need at least 1000 particles to reliably identify MW and M31 halos.
  - **SMDPL** (400/h Mpc) and **NMDPL** (1Gpc)
    - 9.6x10^7 /h Msun - 1.5x10^9/h Msun
- Select LGA's according to different searching criteria: isolation, dynamics, distance to Virgo systems…
- Comparison with CLUES LGA's

Near Field Cosmology

The impact of the nearest cluster on Local Group analogs

Christoph Behrens[1★], Noam I. Libeskind[2], Gustavo Yepes[3], Peter S. Behroozi[4,5], and Stefan Gottlöber[2]

•MNRAS, 2016,submitted

ABSTRACT

Using a large N-body simulation, we select pairs of halos that resemble the two most massive members of the Local Group, the Milky Way and M31. We focus on the influence of the nearest cluster on the properties and evolution of these Local Group analogs (LGAs), e.g. on their relative velocities and accretion histories. We find that the tangential velocity of M31 and Milky Way analogs is on average lower if the LGA is very isolated. The radial velocity, however, is mostly affected by the distance between Milky Way and M31; tangential velocities of more than 100 km/s are very unlikely in general. We also find that LGAs close to a cluster (< 10 Mpc) grew slower on average in the last 4 Gyr.

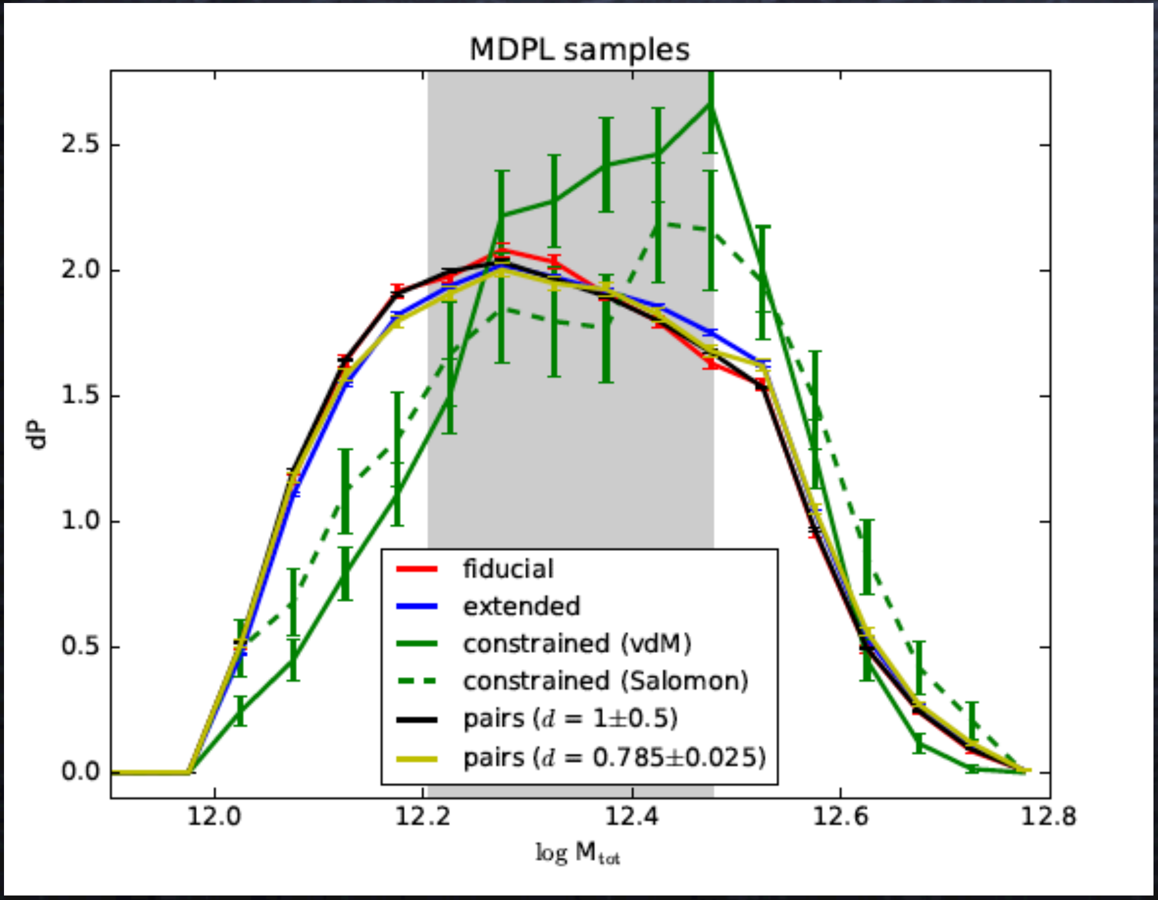
Simulation	box size [Mpc]	Number of particles	Initial redshift,	m_p [$M_\odot$]	ϵ [kpc]
MDPL	1476	3840^3	120	2.2×10^9	7.4
SMDPL	590	3840^3	120	1.4×10^8	2.2

Table 2. Overview of the selection criteria for the LGA samples. From left to right, we state the name of the sample, the distance between MW and M31, the total mass, the radius of isolation, the distance to the nearest cluster, the radial velocity, the tangential velocity, and the number of groups selected from the MPDL (SMDPL) simulation.

Sample name	d [Mpc]	M_{tot} [10^{12} $M_\odot$]	d_{iso} [Mpc]	d_c [Mpc]	v_r [km/s]	v_t [km/s]	N
fiducial	1 ± 0.5	3.5 ± 2.5	3	10 - 20	< 0		54706 (3381)
extended	1 ± 0.5	3.5 ± 2.5	1.5	1.5 - 30	< 0		362023 (23230)
constrained van der Marel	0.785 ± 0.025	3.5 ± 2.5			-109.4 ± 4.4	< 34.3	1387 (94)
constrained Salomon	0.785 ± 0.025	3.5 ± 2.5			-87.5 ± 13.8	164.4 ± 61.8	767 (56)
isolated MWs		1.75 ± 1.25	3	3 - 30			1806405 (113956)

Near Field Cosmology

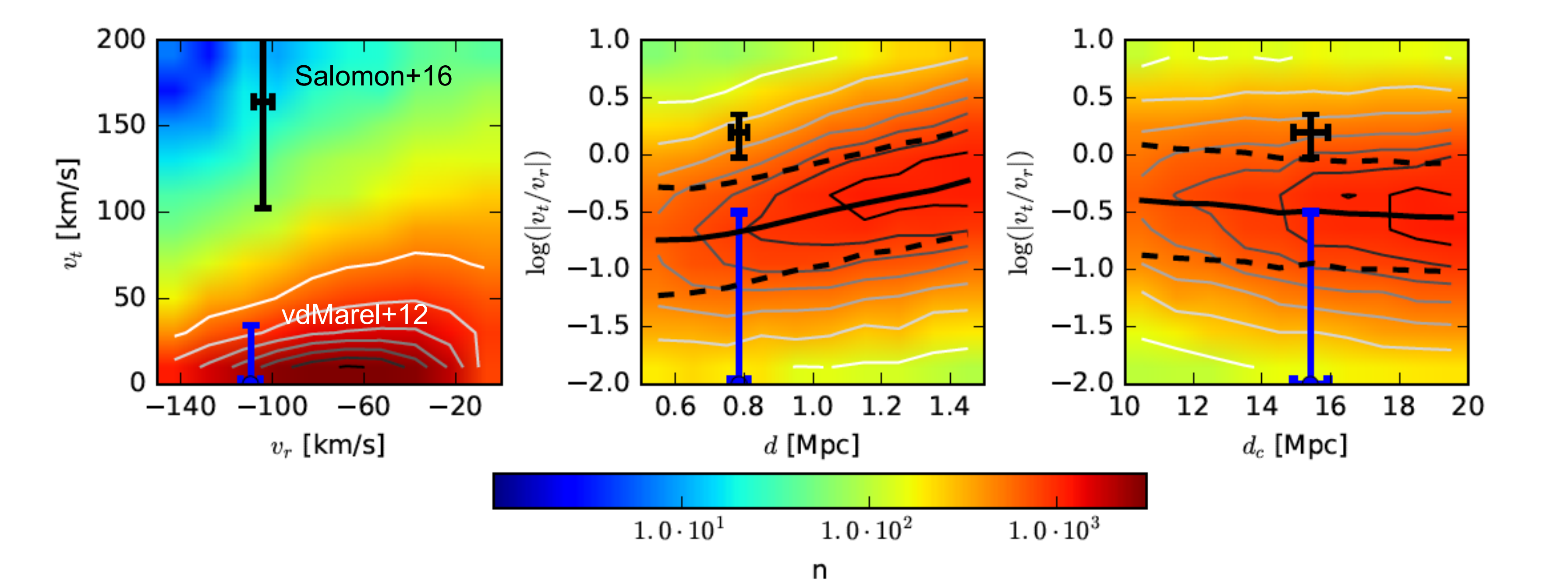
The mass of the LGA's



- Observational constrained samples tend to predict higher total masses.
- $\langle LogM_{vdM} \rangle$=12.33
- $\langle LogM_{Sal} \rangle$ = 12.37

Near Field Cosmology

The relative velocity of LGA's from MDPL



•Distribution of LGA's fiducial sample for tangential to radial, distance between MW and M31 and distance to nearest cluster.

•Higher vt/vr for larger d,. Weak dependence on distance to clusters: the closer the cluster the larger vt/vr.

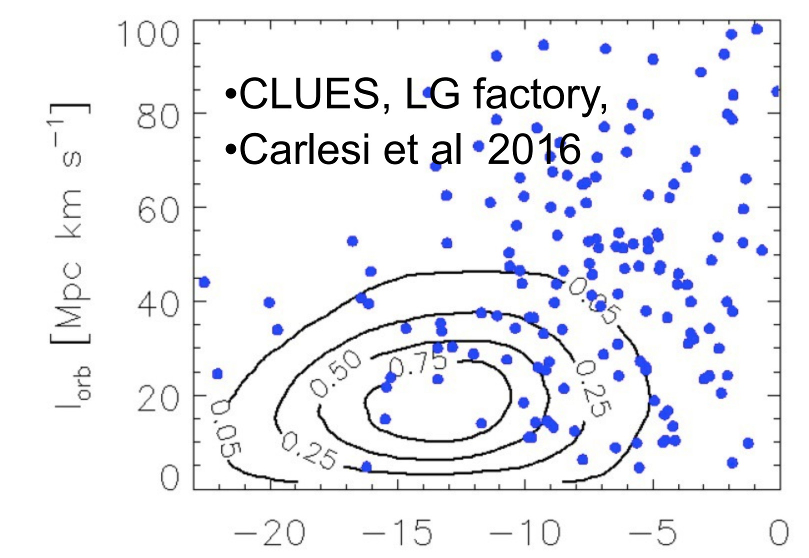
•Salomon+16 observational points (black) are very unlikely Only 7% of LGA's vt>100km/s. But see Carlesis's talk on results of vtan from CLUES LG factory…

Near Field Cosmology

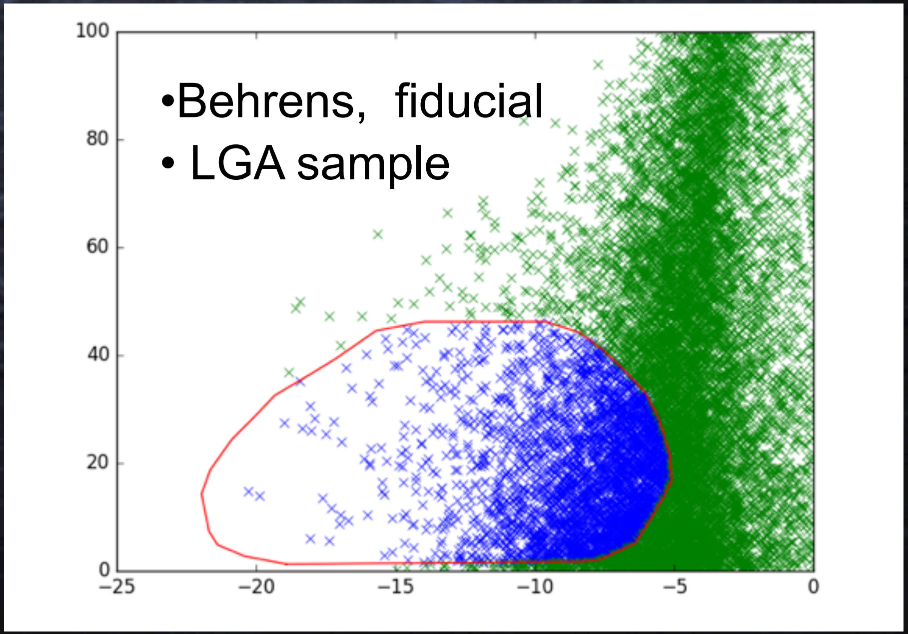
•The distribution of orbital values: reduced internal energy and specific angular momentum

$$e = \frac{1}{2}(v_t^2 + v_r^2) - \frac{GM_{tot}}{d}.$$

•14% lie within 95%

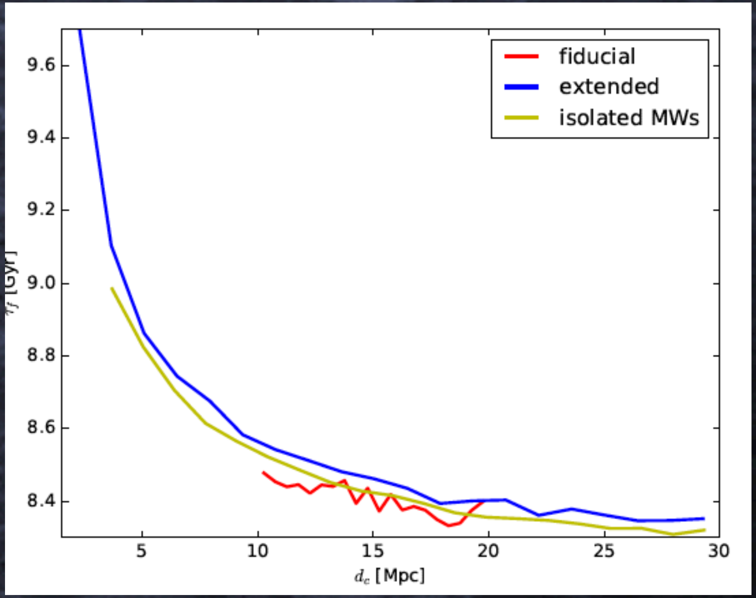


•27% lie within 95%

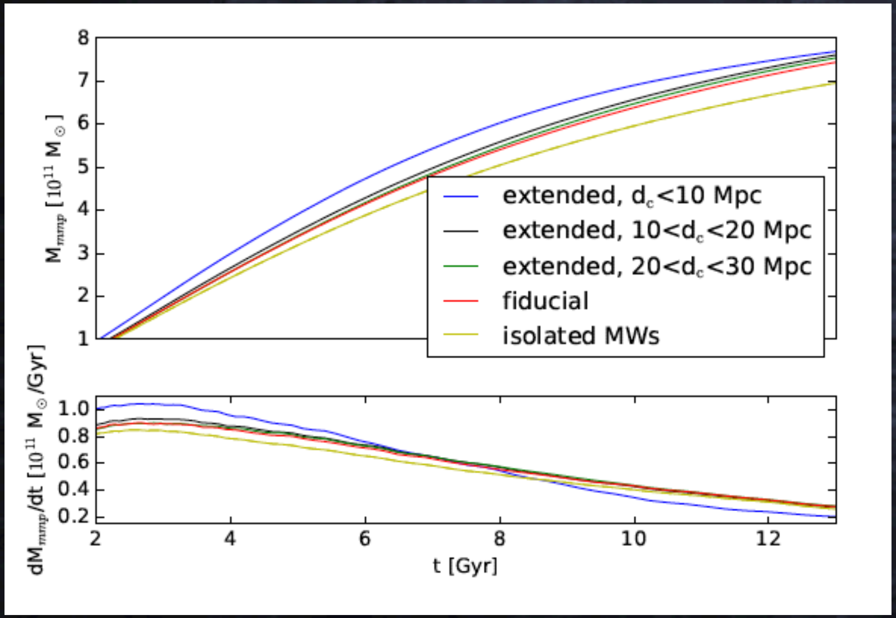


Near Field Cosmology

•MEAN FORMATION TIME FOR LGA's



•Average Mass accretion history of LGA's

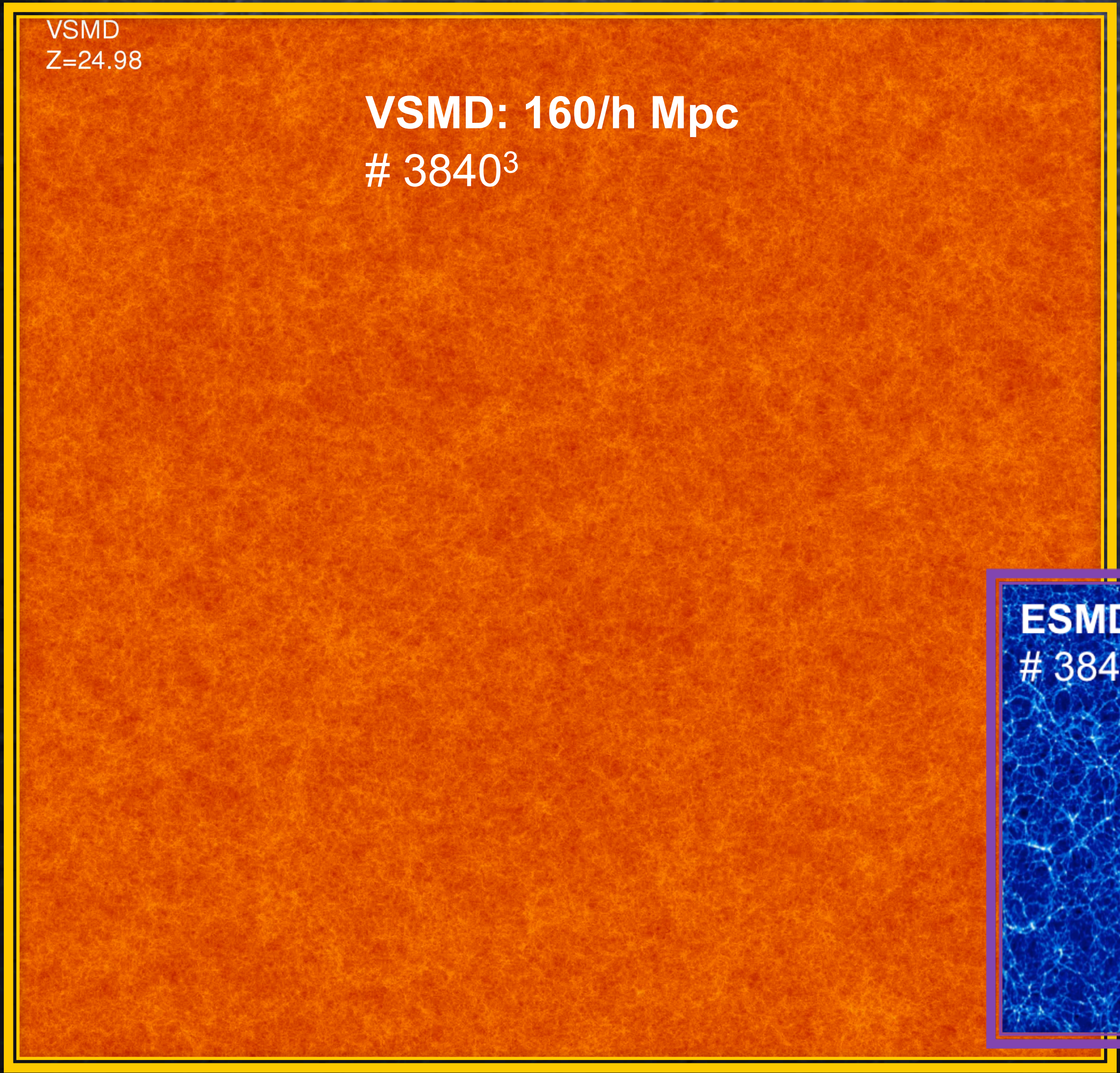


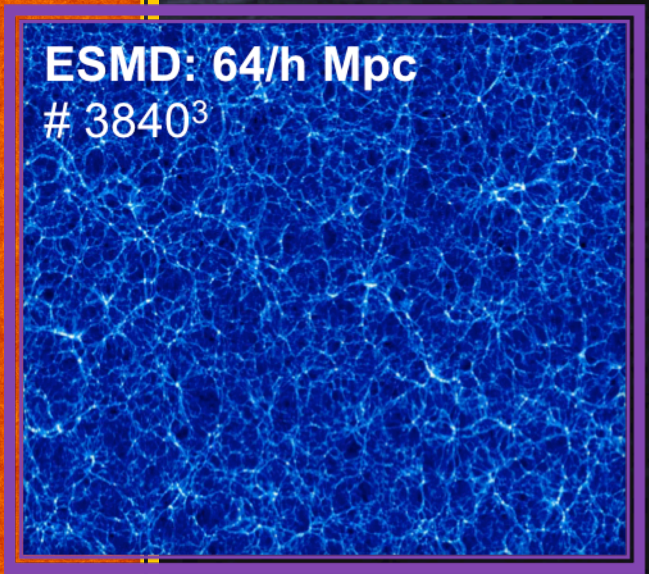
•LGA's close to a cluster grow faster at the beginning, but then slows down . Those far away from clusters grow mass faster in the last 4-5 Gyear

Near Field Cosmology

- For future work:
  - Explore influence of other cosmography elements in the properties of LGA’s.
  - Going to smaller scales:
    - Study the importance of LMC or M33 in the characteristics of LGA’s.

NEW MULTIDARK SIMULATIONS





New runs

2016

Extend smaller scales

NEW MULTIDARK SIMULATIONS

New runs 2016

Extend to smaller mass scales

VSMD: Mp= 6 x10^6 /h Msun

ESMD: Mp=4x10^5 /h Msun

Project: *High redshift galaxies and the epoch of reionization.*

with, P. Dayal , P Behroozi, N. Libeskind, S. Gottlober and G. Yepes

CONCLUSIONS

- Large Volume N-body are indispensable tools:
  - for comparison of model predictions with data from upcoming large galaxy surveys.
  - Estimating cosmic variance errors in clustering and lensing statistics.
  - For calibrating methods to populate galaxies in halos (SHAM, HOD; SAM)
  - For extracting similar objects to the nearby ones (LG, Virgo) and compare their properties with those obtained from CLUES simulations.

- **MultiDark Simulation Project:** aims at producing a consistent set of simulation boxes all within the same Planck cosmological parameters and covering a wide range of mass and spatial resolution. (more than 5 orders of magnitude)

- Promote the use of simulated data among the community:

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- Promote the use of simulated data among the community:

YOU ARE VERY WELCOME TO USE THE MULTIDARK DATA PRODUCTS.