Cosmological N-body simulations for large galaxy surveys: Towards trillion particles and beyond

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Universidad Autónoma de Madrid

COSMORENATA Meeting, Valencia, June 2013

Do we need trillion+ particle simulations?

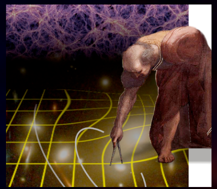
Plenty of Large Volume Galaxy Surveys (DES, KIDS, BOSS, LSST, BigBOSS, JPAS, PAU, Euclid…

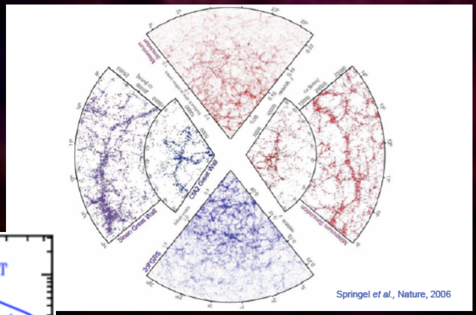
They will probe 10-100 Gpc^3 volumes

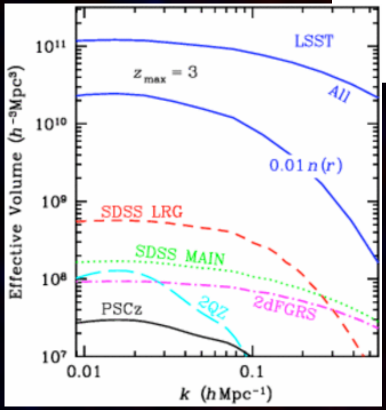
- Need to resolve halos hosting the faintest galaxies of these surveys to produce realistic mock catalogues. Higher z surveys imply smaller galaxies and smaller halos->more mass resolution.

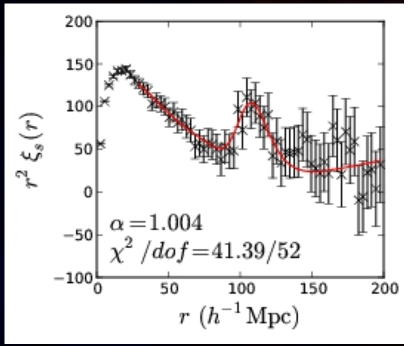
- Fundamental tool to compare clustering properties of galaxies with theoretical predictions from cosmological models at few % level. Not possible only with largrangian perturbation theory. Must do the full non-linear evolution for scales 100+ Mpc (BAO, zero crossing, 2pcf of galaxies)

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).

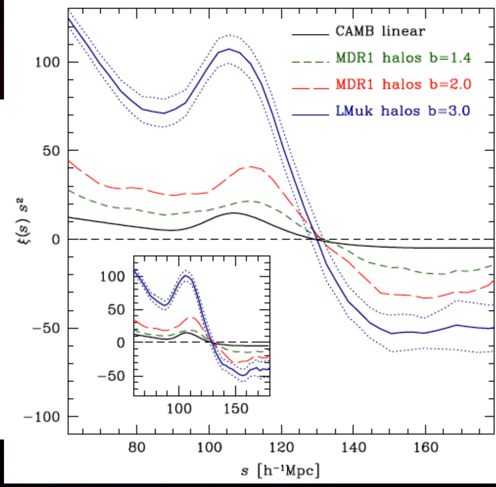






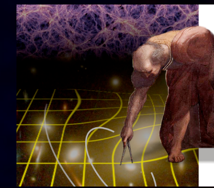


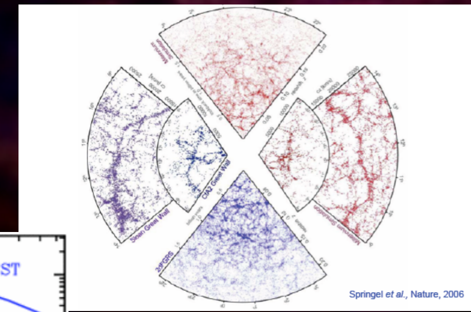
BAO in BOSS, 100Mpc scale



Zero crossing of CF. 130Mpc Prada et al 2012

Do we need trillion+ particle simulations?





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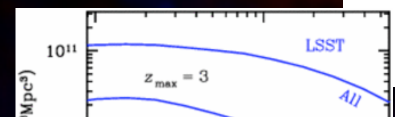

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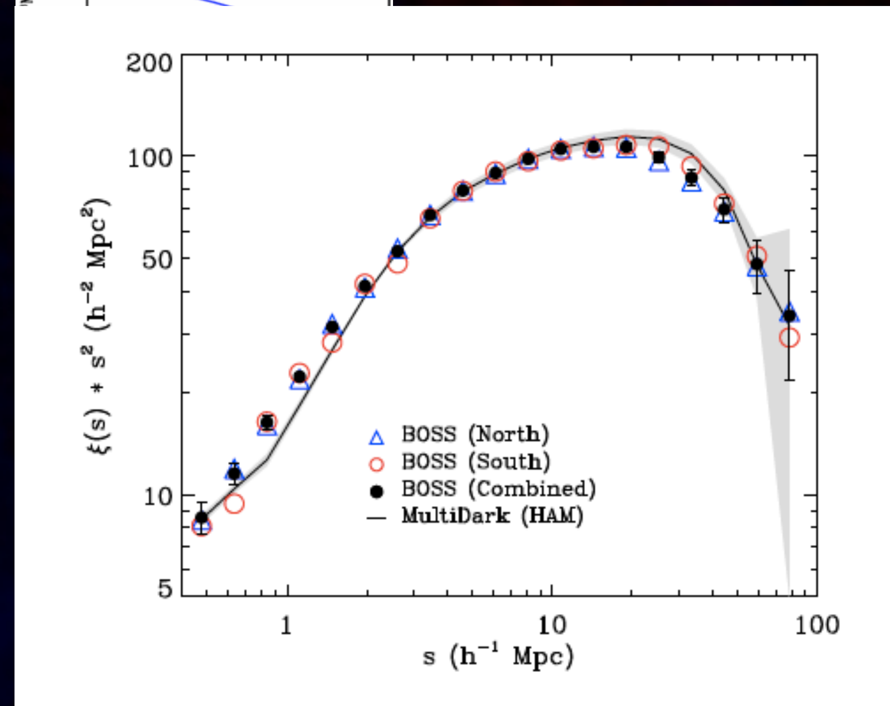

BAO in BOSS, 100Mpc scale

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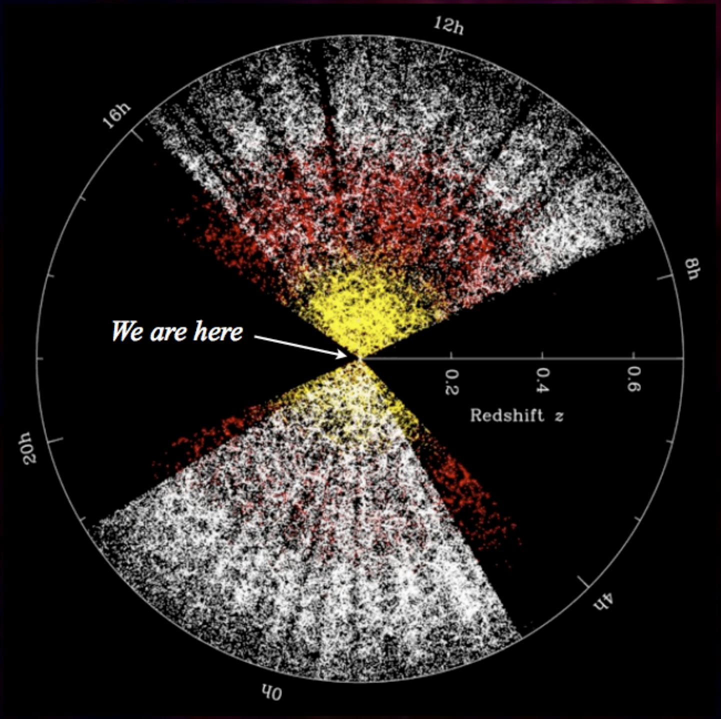
Large Volume Galaxy Surveys

A real example: BOSS (z=0.1..0.7)

Box size to host full BOSS survey : 3.5 h^-1 Gpc

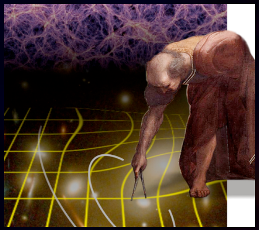
BOSS completed down to galx with V_{cir} >350 km/s - > M_{vir} ~5x10^12 Msun.

To properly resolve the peak of the Vrot in a dark matter halo we need > 100 particles.
High-force resolution to properly model subhalos



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

BigBOSS, Euclid ,LSST will go to z>1.5
Larger Boxes: > 6/h Gpc
Npart > 10,000^3



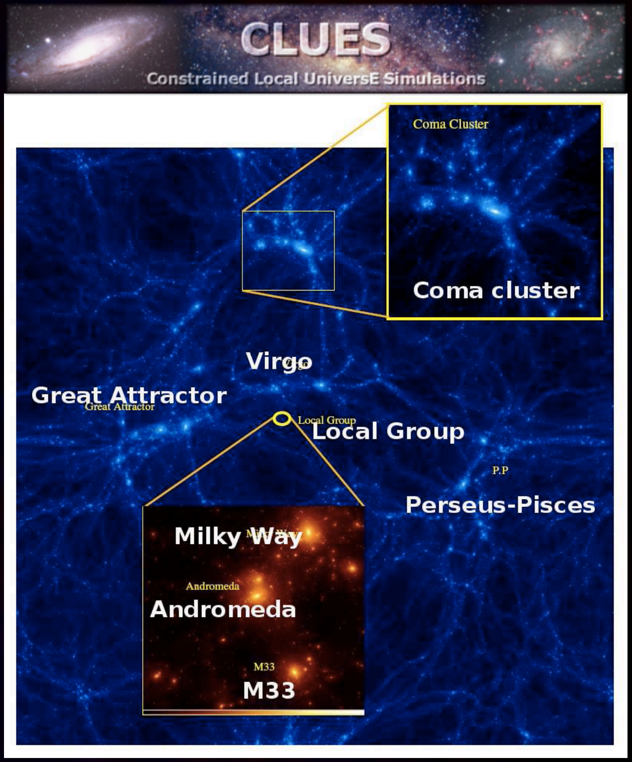
Do we need trillion+ particle simulations?

LSS structure formation in the cosmic reionization epoch
(e.g. Iliev et al 2006, 2010).

Large cosmological volumes with huge dynamical range to resolve the tiny CDM mini-halos that host the first population of stars. (~1-5x10^5 Msun). Not-full RT treatment of course. Only DM simulations to find sources of UV radiation. Then RT is done as a postprocessing

Fortunately, only have to integrate in time up to z=6.

An example: Reionization of the Local group (Iliev et al 2011) we used a 64 Mpc box with 1024^3 particles.
Resolving only ~10^9 Msun halos.
Desired resolution: 3x10^5 Msun minihalos:10,000^3
A trillion particles…



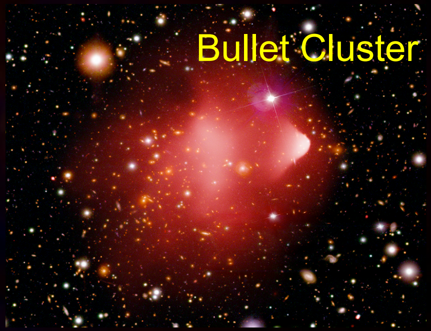
Do we need trillion+ particle simulations?

Cosmic Abundance of extreme rare objects

In LCDM Need very large computational volumes to find one of the extreme interacting objects 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



From dark halos to galaxies

A Full self-consistent galaxy formation simulation is order of magnitude more computational expensive than dark matter only simulations.

Not yet possible to simulate large computational volumes (> 1Gpc^3) with baryons.

Need to map halos to galaxies using models:

- Halo Occupation Distribution (HOD)
- Halo Abundance Matching (HAM)
- Semi Analytical modeling (SAM)

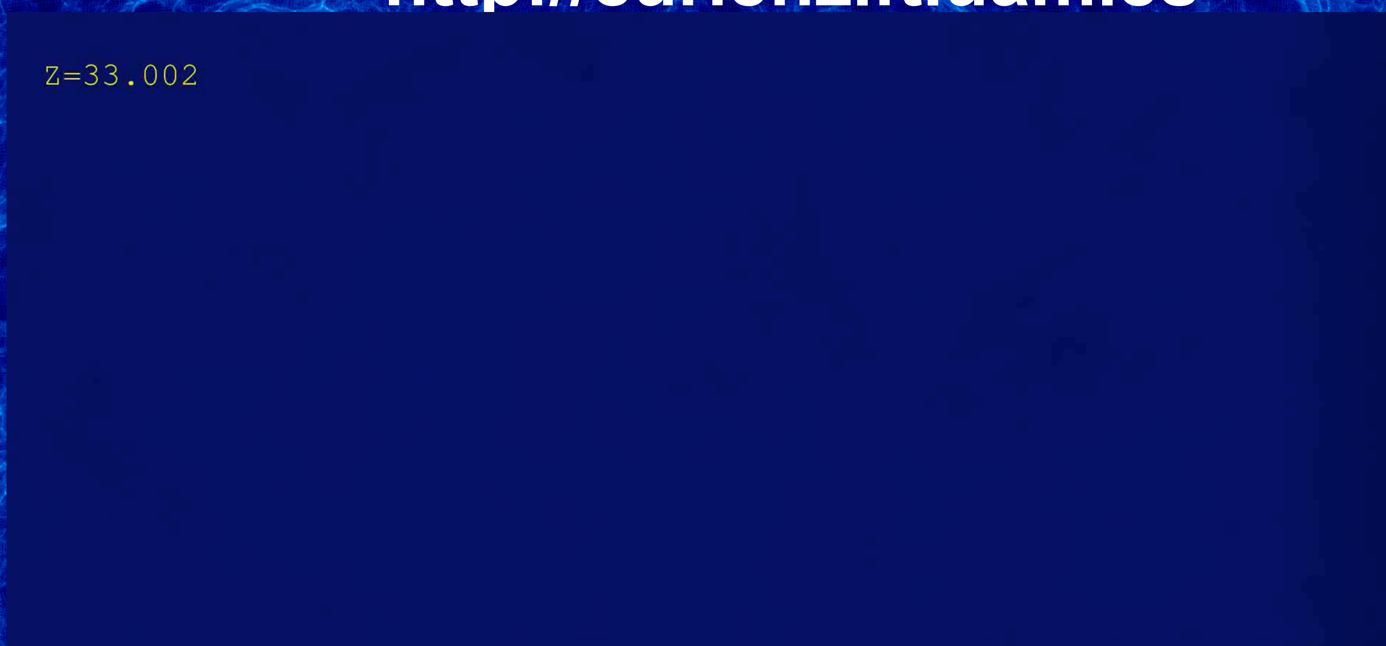
CURIE UNIVERSE:
GALAXY FORMATION SIMULATION

Gasdynamics and N-body in 200/h Mpc box with 2--16 billion particles(gas +stars+dark matter)

+

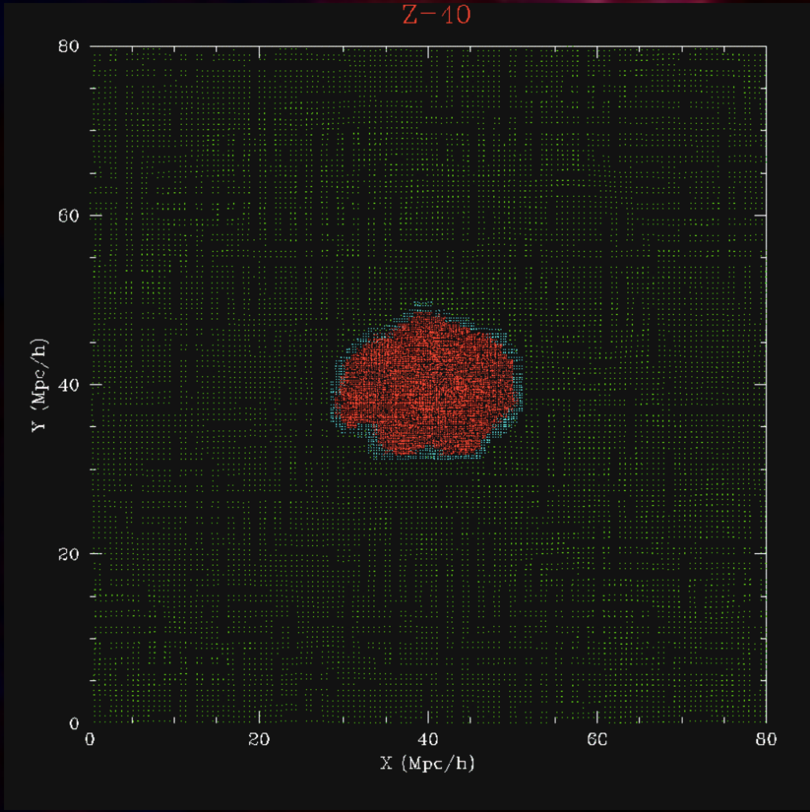
Detailed modelling of baryonic physics.

http://curiehz.ft.uam.es



AN ALTERNATIVE: MULTIMASS ZOOMED SIMULATIONS

- Select objects in large volumes and resimulate them with high resolution + baryons.
- Make a simulated catalog
- Re-Simulated areas from large computational boxes by resampling particles of increasing mass away from the refined region:
    - Original initial conditions up to 4096^3 particles in a big box.
    - Trace back particles of selected objects to identify region to be resimulated with very high resolution
    - **Very easy way of parallelization.**



THE MUSIC PROJECT

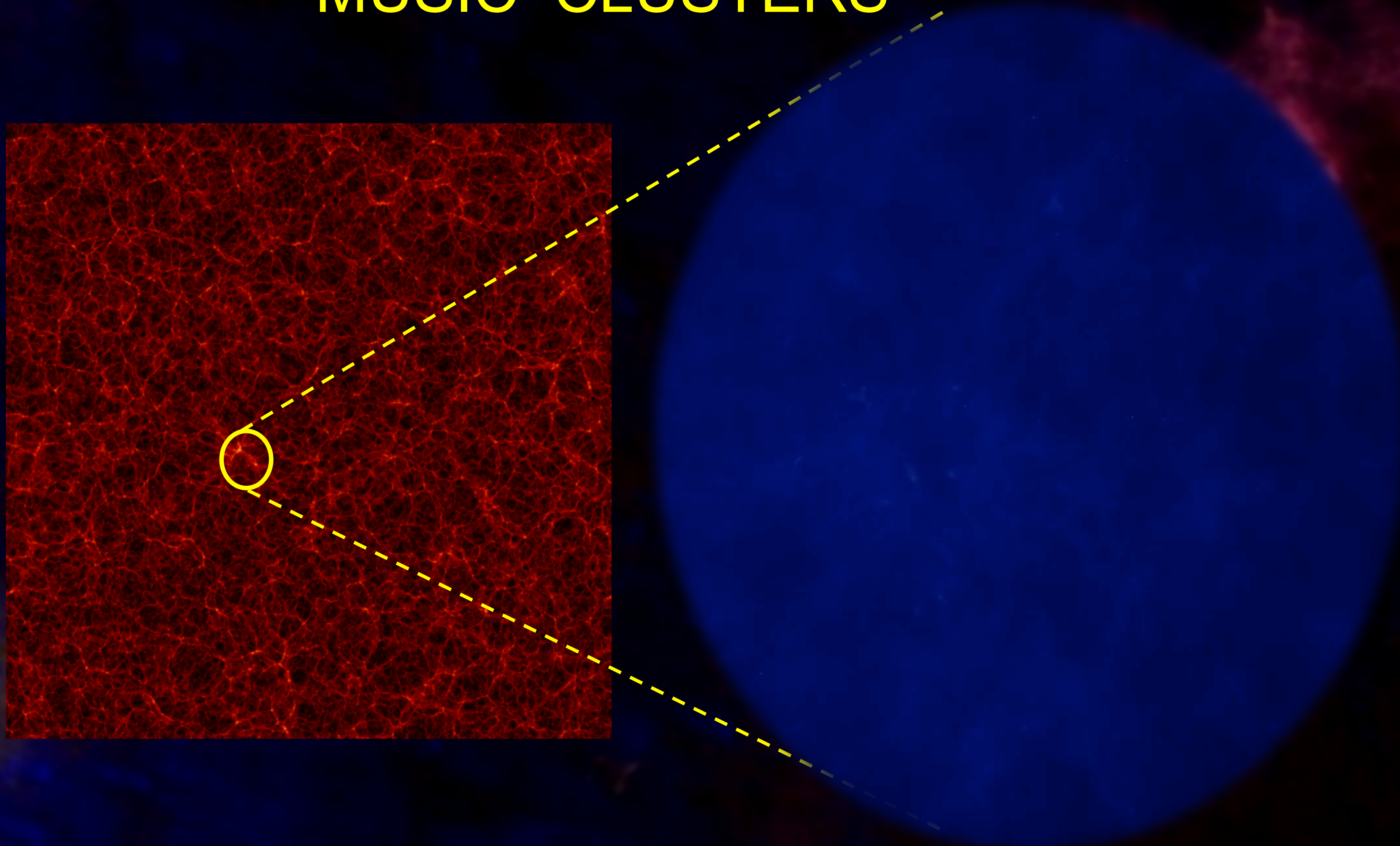
Compile an extended sample of high-resolution radiative gasdynamical resimulations of clusters:

http://music.ft.uam.es

Two selection criteria:

- Based on the dynamical state:
  - Bullets vs. Relaxed cluster (from MN simulation)
- A complete volume limited sample:
  - Selection of all clusters above a given mass cutoff.
  - Extracted from large N-body volumes: MULTIDARK simulation.

MUSIC CLUSTERS

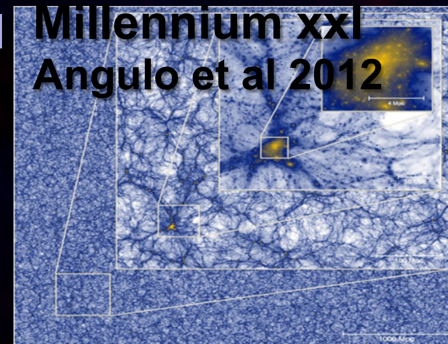


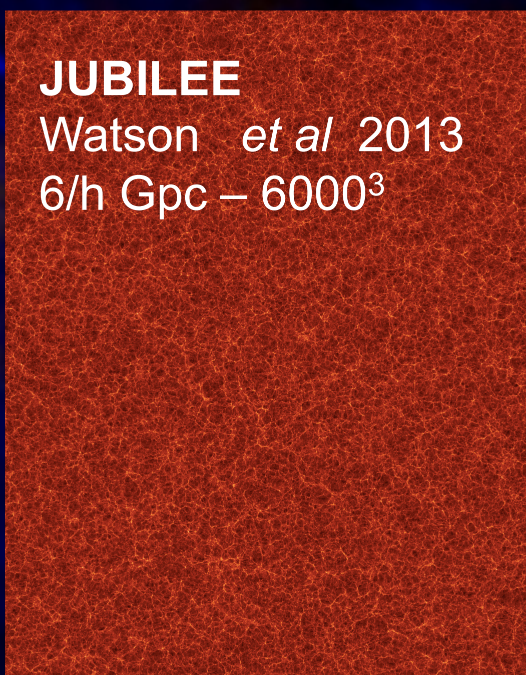
- We selected all the cluster-size halos more massive than $M > 10^{15}\ h^{-1}\ M_{sun}$ (282) at z=0. 8 times more particles ($m_{DM}=1.03 \times 10^{9}\ h^{-1}\ M_{sun}$ and $m_{gas}=1.82 \times 10^{8}\ h^{-1}\ M_{sun}$) than original Multidark simulation (eq. to 4096^3) including radiative physics (i.e cooling , UV photoionization, star formation and SN thermal and kinetic feedbacks in form of galactic winds). **More than 2000 clusters and groups in database.**

LARGE DARK MATTER N-BODY COSMOLOGICAL SIMULATIONS:

PRESENT STATUS

Current S.o.A 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	(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***
MultiDark2	***(PLANCK-GAD)***	***1.0/h Gpc***	***56.6 billion particles***

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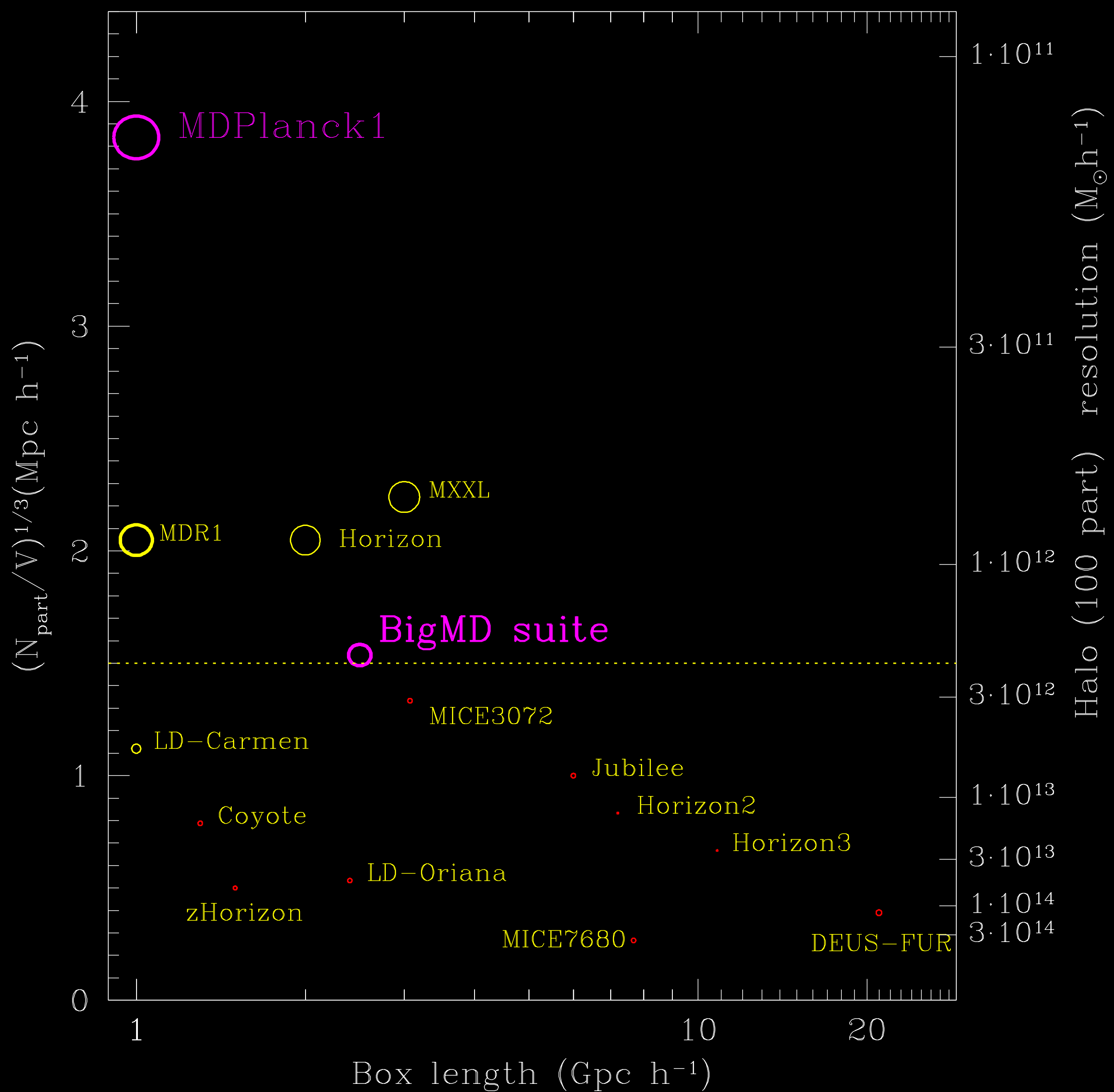

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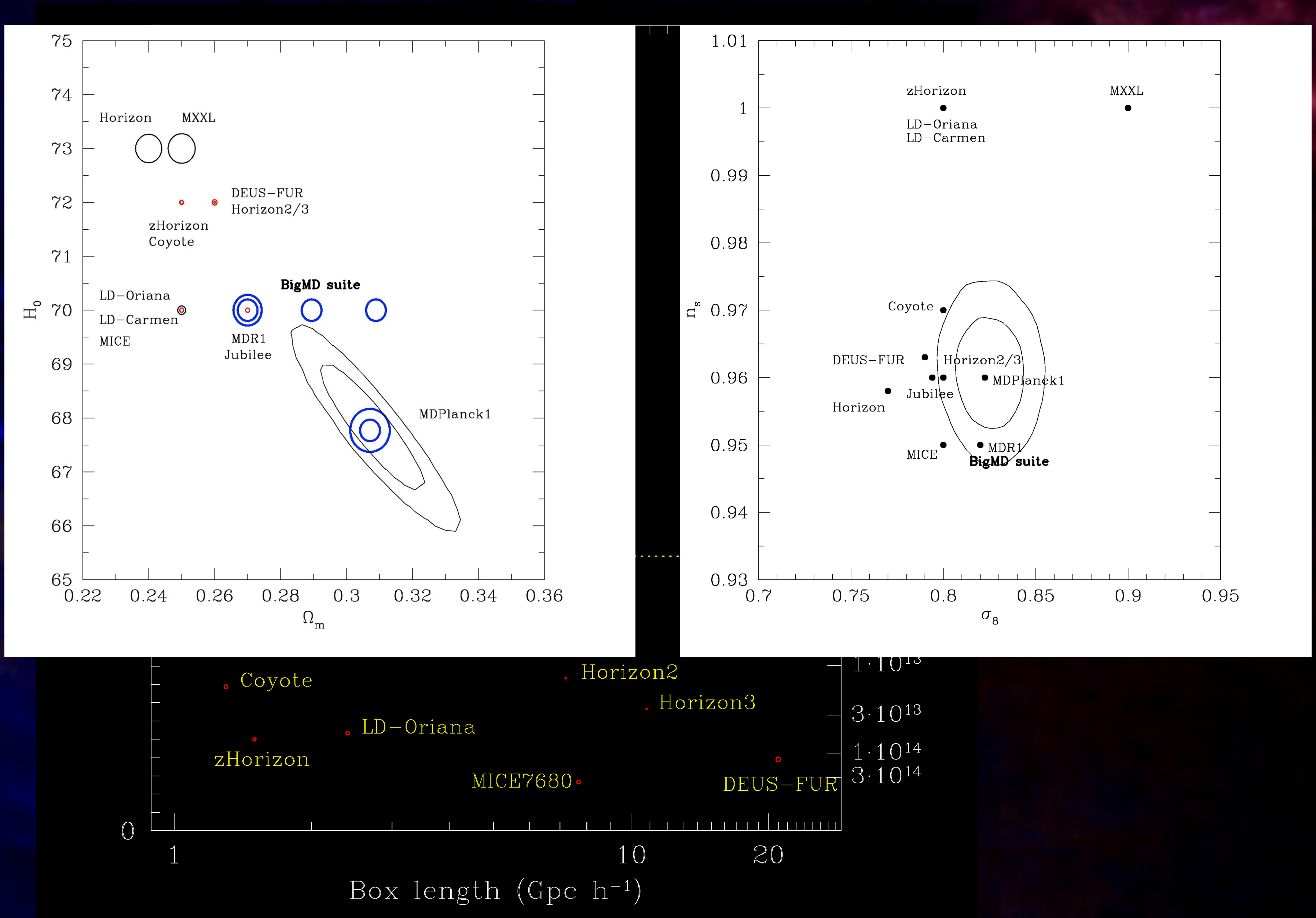

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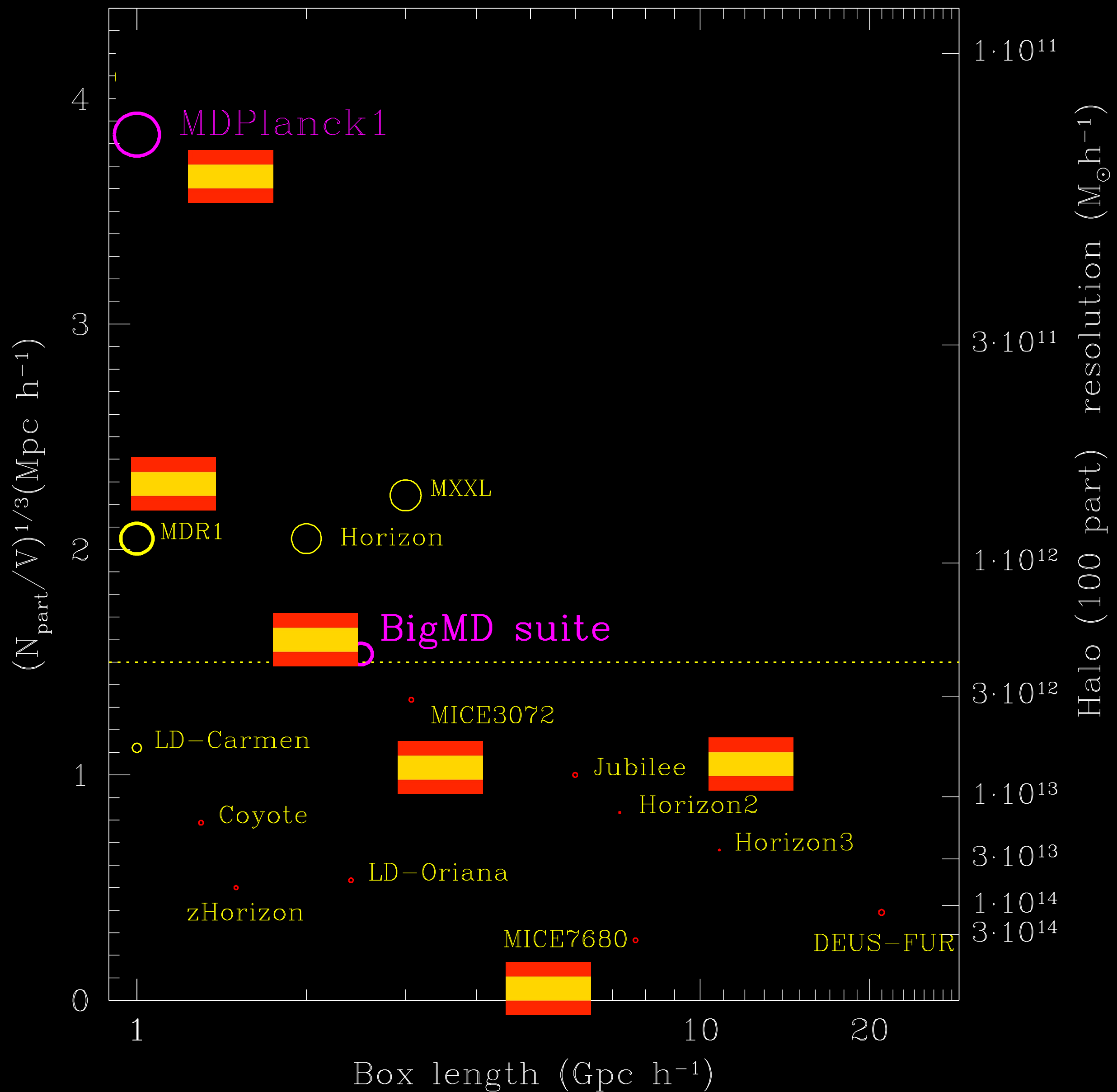

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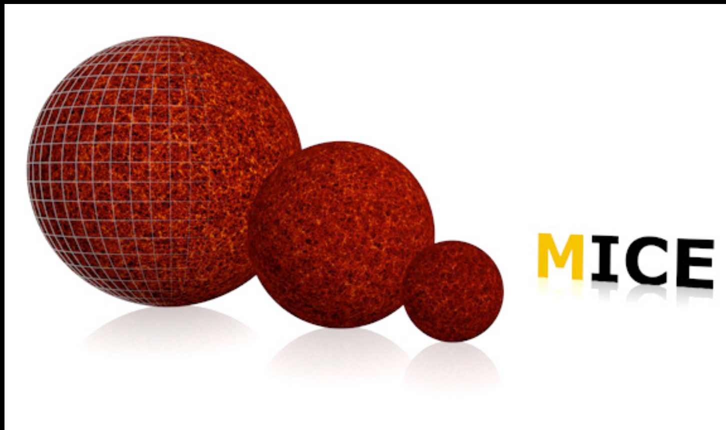


Marenostrum Institut de Ciències de l'Espai Simulations

http://maia.ice.cat/mice/

Simulation	Ω_m	Ω_b	h	n_s	Ω_Λ	σ_8	w	Number of realizations	Status	CPU Time (hours)
MICE179	0.25	0.044	0.7	0.95	0.75	0.8	-1	1	Completed	26000
MICE384	0.25	0.044	0.7	0.95	0.75	0.8	-1	1	Completed	17600
MICE768-2LPT	0.25	0.044	0.7	0.95	0.75	0.8	-1	1	Completed	17000
MICE768	0.25	0.044	0.7	0.95	0.75	0.8	-1	1	Completed	17000
MICE1200	0.25	0.044	0.7	0.95	0.75	0.8	-1	20	Completed	19200
MICE1200-2LPT	0.25	0.044	0.7	0.95	0.75	0.8	-1	1	Completed	19500
MICE1536	0.25	0.044	0.7	0.95	0.75	0.8	-1	1	Completed	14800
MICE1536-W1.0	0.25	0.044	0.7	0.95	0.75	0.8	-1	1	Completed	7000
MICE1536-W0.8	0.25	0.044	0.7	0.95	0.75	0.8	-0,8	1	Completed	7000
MICE3072-LR	0.25	0.044	0.7	0.95	0.75	0.8	-1	1	Completed	25000
MICE3072-HR	0.25	0.044	0.7	0.95	0.75	0.8	-1	1	Completed	370000
MICE3072-GC	0.25	0.044	0.7	0.95	0.75	0.8	-1	1	Completed	3100000
MICE4500	0.25	0.044	0.7	0.95	0.75	0.8	-1	1	Completed	25200
MICE4500-W0.8	0.25	0.044	0.7	0.95	0.75	0.8	-0,8	1	Completed	26200
MICE7680	0.25	0.044	0.7	0.95	0.75	0.8	-1	1	Completed	370000
Total	-	-	-	-	-	-	-	34	-	4061500

Grand Challenge Run:
3/h Gpc @ 4096^3 particles
Force resolution 50 kpc/h

The MULTIDARK Simulations

MultidarkD 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 catalogs 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

DATABASE
http://www.multidark.org

The Big-MULTIDARK Simulation Suite

PRACE proposal 2012: G. Yepes (PI), F. Prada, S. Gottloeber, A. Klypin, S. Hess, C. Scoccola, S. Rodriguez, C.-H Chuang.

22.5 million cpu hours in SuperMUC@ LRZ.

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 Planck1

Box = 1/h Gpc @ 3840^3

Force = 5 kpc/h

Zinit=120

80 timesteps stored in each run

FOF and BDM halos. Light Cones

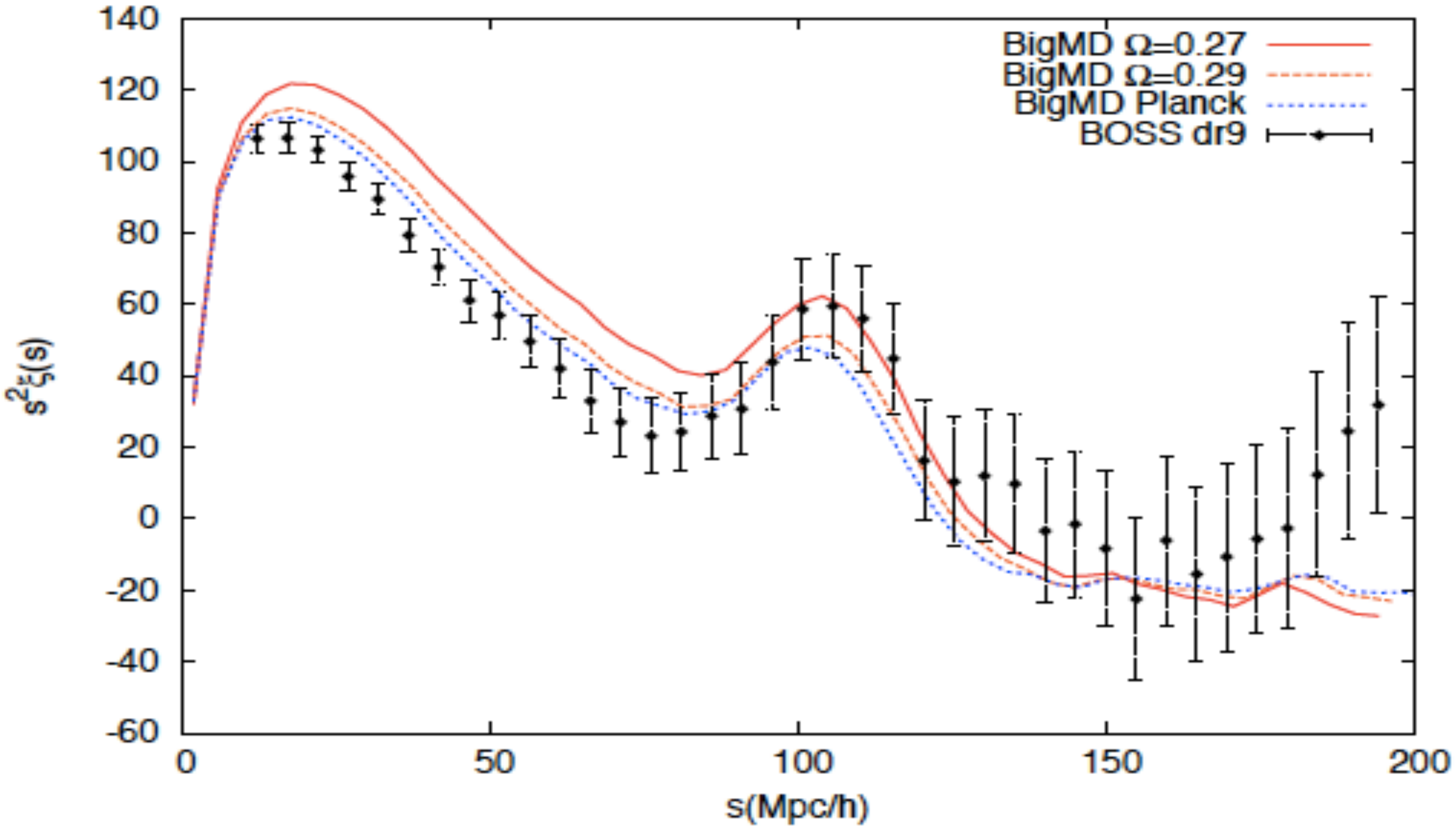
DATABASES

http://www.multidark.org

BigMD products

Publicly available soon

The Big-MULTIDARK Simulation Suite



URA 3: Snapshot z=0.5053 with number density $3.6\times10^{-4}h^3/\text{Mpc}^3$

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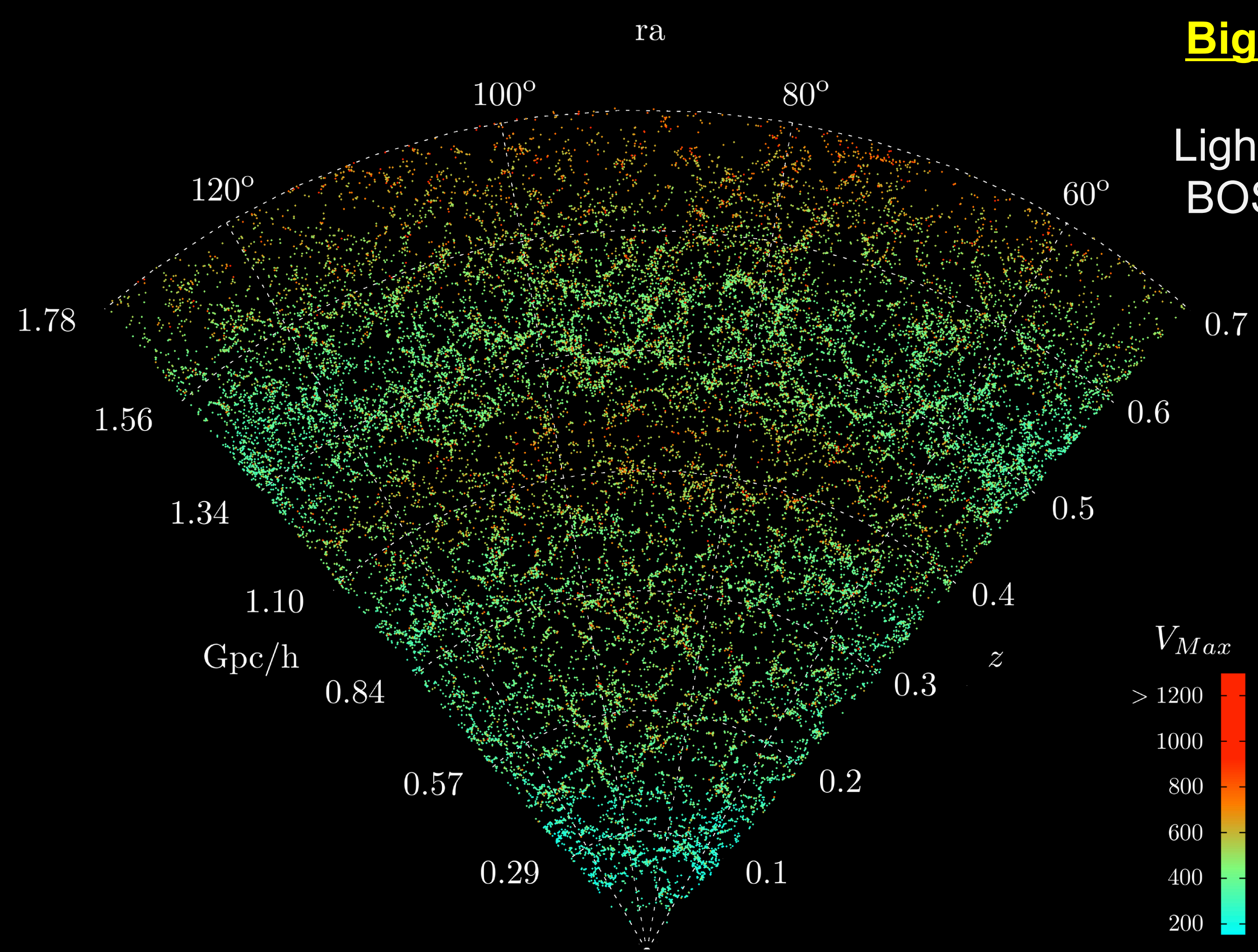

BigMD suite:

Light Cone mocking
BOSS LRG galaxies

Leibniz-Institut für Astrophysik Potsdam

US University of Sussex

UAM UNIVERSIDAD AUTONOMA DE MADRID

IFCA Instituto de Física de Cantabria

The Jubilee Simulation

A Coherent Hubble Volume Simulation for All-Sky ISW predictions and Large Scale Surveys

The JUBiLEE (JUropa huBbLE volumE) project

Stefan Gottlöber[1], Illian Iliev[2],
Gustavo Yepes[3], Steffen R. Knollmann[3],
José María Diego[4], Enrique Martínez González[4], Patricio Vielva[4]
[1]Astrophysikalisches Institut Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany
[2]Astronomy Centre, University of Sussex, Brighton BN1 9QH, United Kingdom
[3]Grupo de Astrofísica, Departamento de Fisica Teorica, Modulo C-15, Universidad Autónoma de Madrid, Cantoblanco E-28049, Spain
[4]Instituto de Fisica de Cantabria, Avda. Los Castros s/n, 39005 Santander, Spain

One of the largest simulated volumes in the current most favored cosmology.

- **6/h Gpc** = 20 billons light-years
- Second largest number of particles
  - **6000^3** ~ 216 billion particles
  - **$12{,}000^3$**~1.6 trillion mesh for PM
- Covers all the universe from z=1
- N-body simulation CUBEP^3M code
- Use 8000 nodes of Juropa:
  - Node=8 Cpus and 24 Gbytes
- Each snapshot = 6 Tbytes. More than 30 snapshots stored
- Scientific results:
  - Measuring of ISW
  - Cross correl. ISW LSS from LRG.
- Halos finding: AHF
- ISW from potential in a 12000^3 mesh
- Starting z=100.

Leibniz-Institut für Astrophysik Potsdam

University of Sussex

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The Jubilee Simulation

arXiv:1305.1976v1

Statistics of extreme objects in the Juropa Hubble Volume simulation*

William A. Watson[1]†, Ilian T. Iliev[1], Jose M. Diego[2], Stefan Gottlöber[3], Alexander Knebe[4], Enrique Martínez-González[2], Gustavo Yepes[4]

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[2] *IFCA, Instituto de Física de Cantabria (UC-CSIC). Avda. Los Castros s/n. 39005 Santander, Spain*
[3] *Leibniz-Institute for Astrophysics, An der Sternwarte 16, 14482, Potsdam, Germany*
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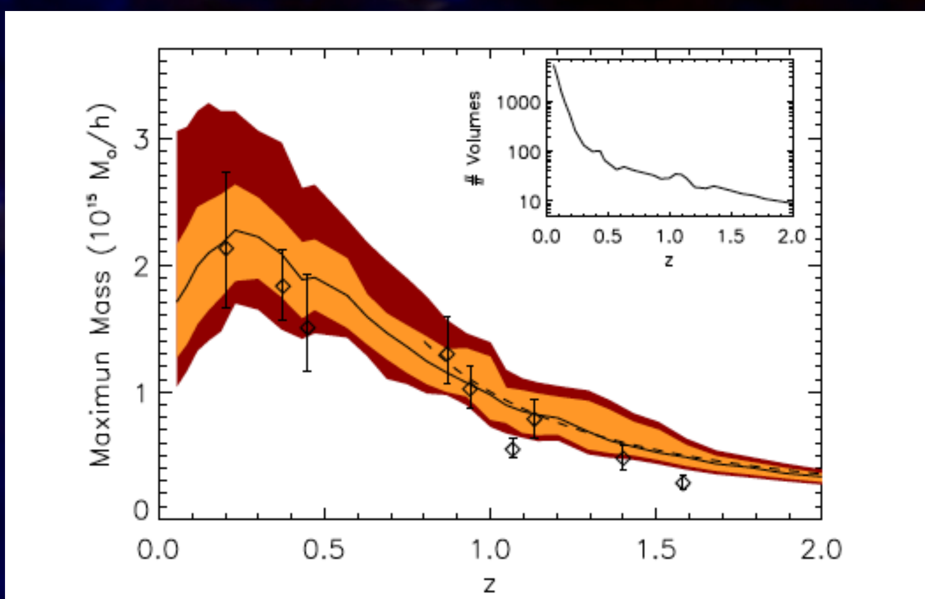
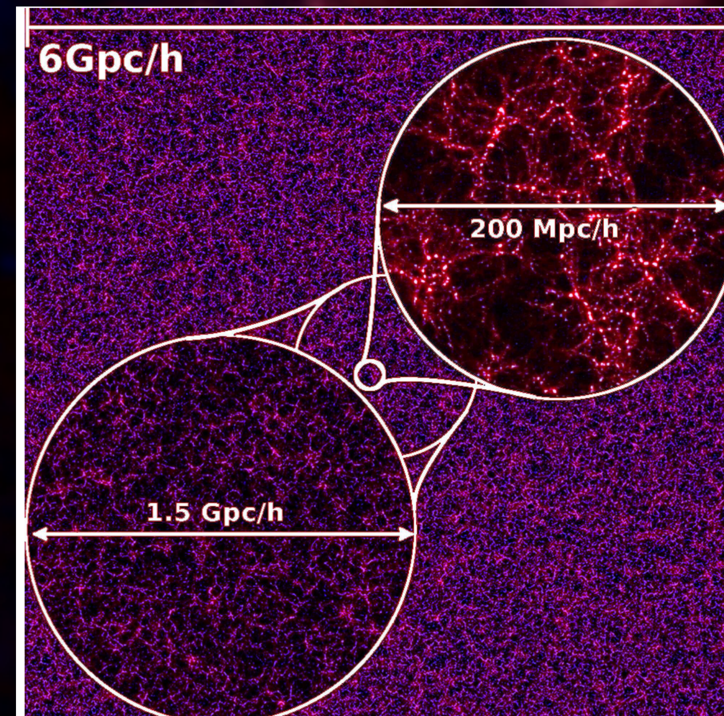
2013





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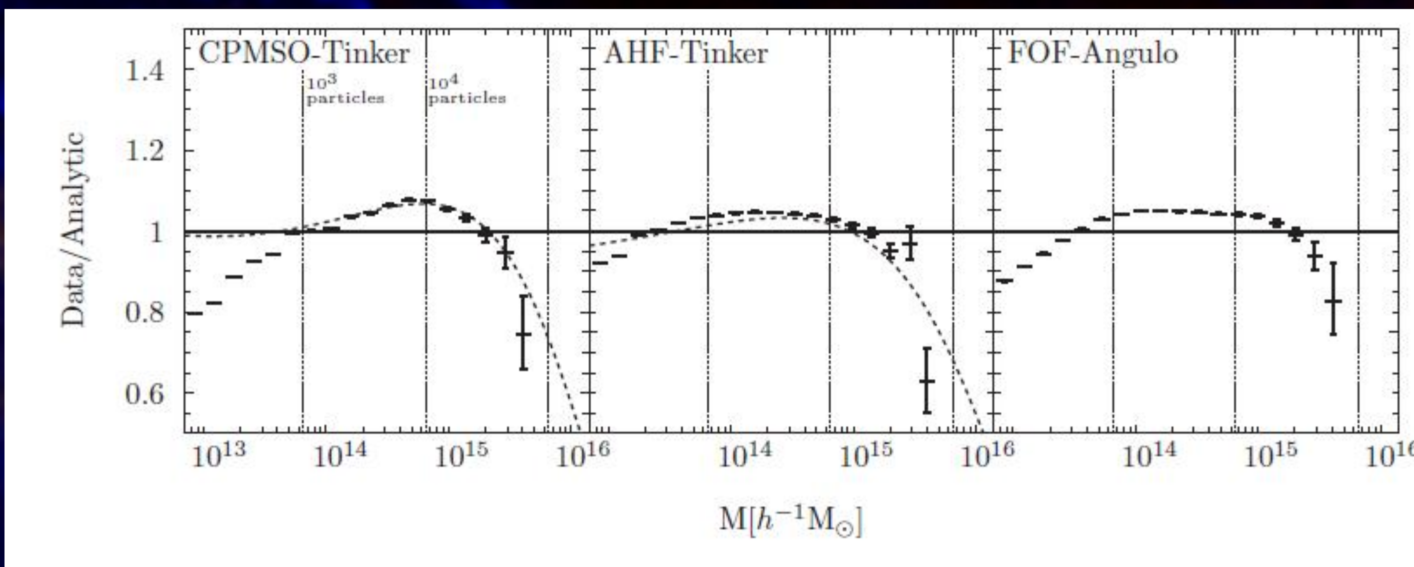
2013

Mass functions



Less extreme clusters than analytical mass functions (Tinker, Angulo, others).

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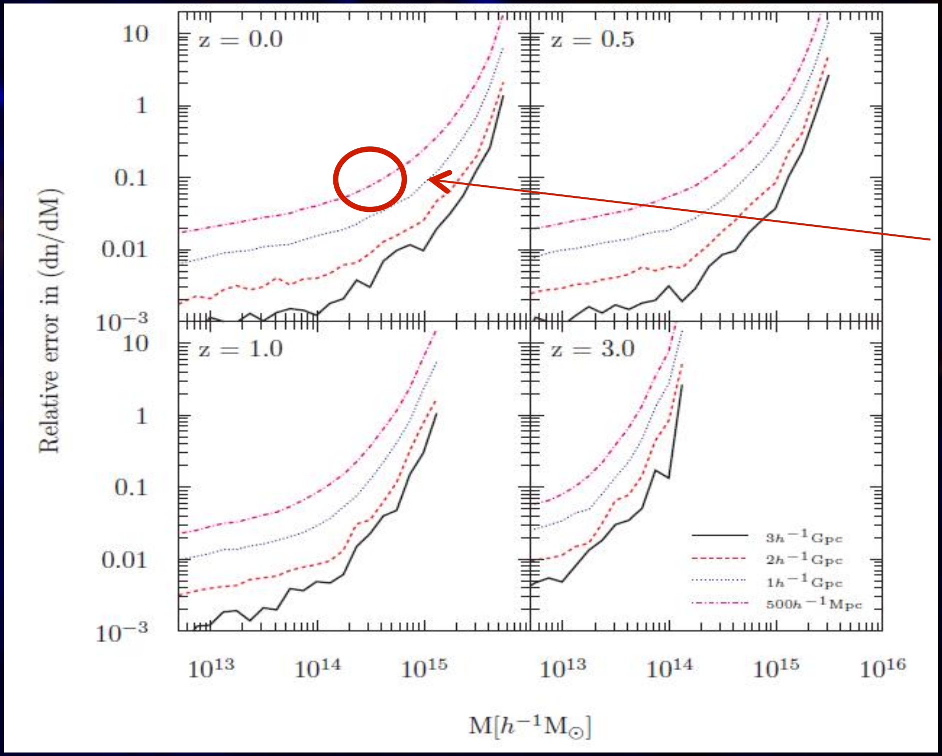
Cosmic Variance



10% error for local (z<0.1) counts.

Cosmic Variance=Poisson?

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Statistics of extrer
simulation*

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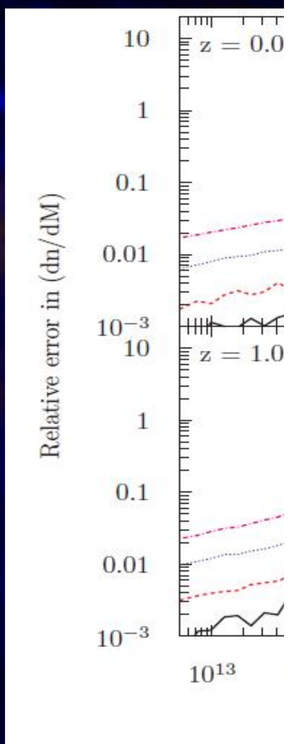

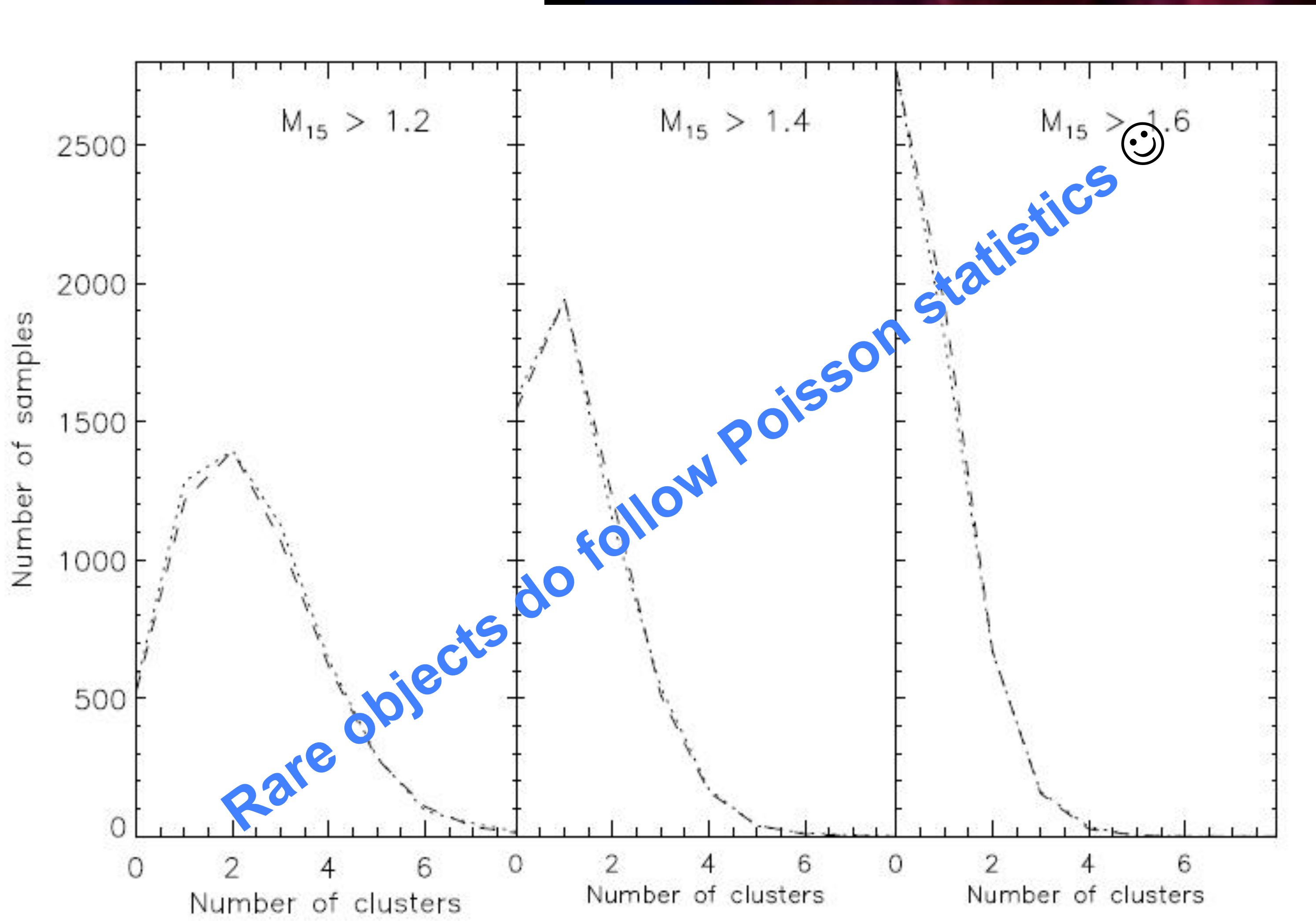

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Statistics of extreme objects in the Jupropa Hubble Volume simulation*

William A. Watson[1]†, Ilian T. Iliev[1], Jose M. Diego[2], Stefan Gottlöber[3], Alexander Knebe[4], Enrique Martínez-González[2], Gustavo Yepes[4]

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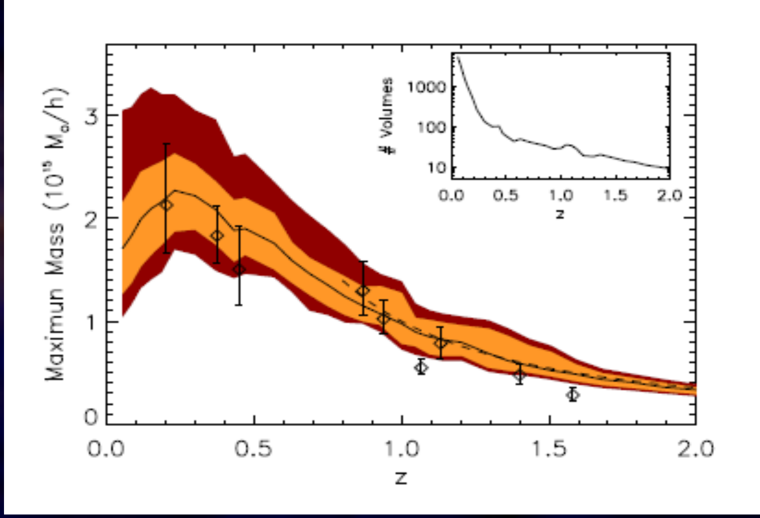
[3] Leibniz-Institute for Astrophysics, An der Sternwarte 16, 14482, Potsdam, Germany
[4] Universidad Autónoma de Madrid, Grupo de Astrofísica, 28049, Madrid, Spain

2013

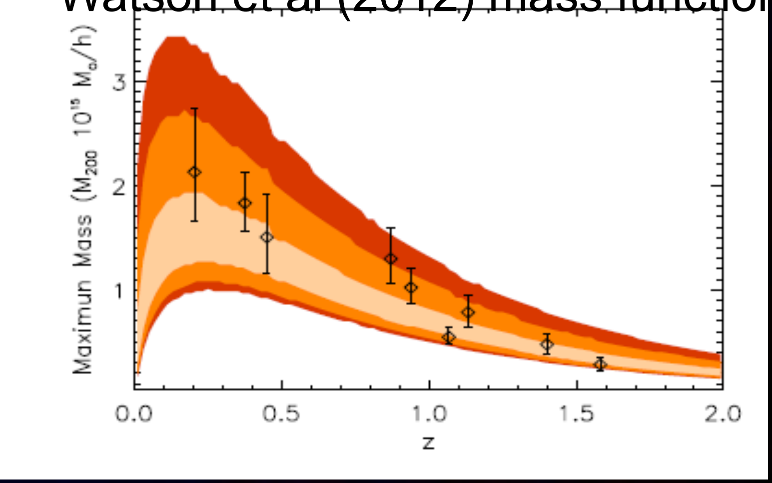
EXTREME OBJECT STATISTICS

Simulation



Analytical

Watson et al (2012) mass function



Small tension between predictions and observations of very extreme objects

How many are too many?

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The Jubilee Simulation

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Statistics of extreme objects in the Juropa Hubble Volume simulation★

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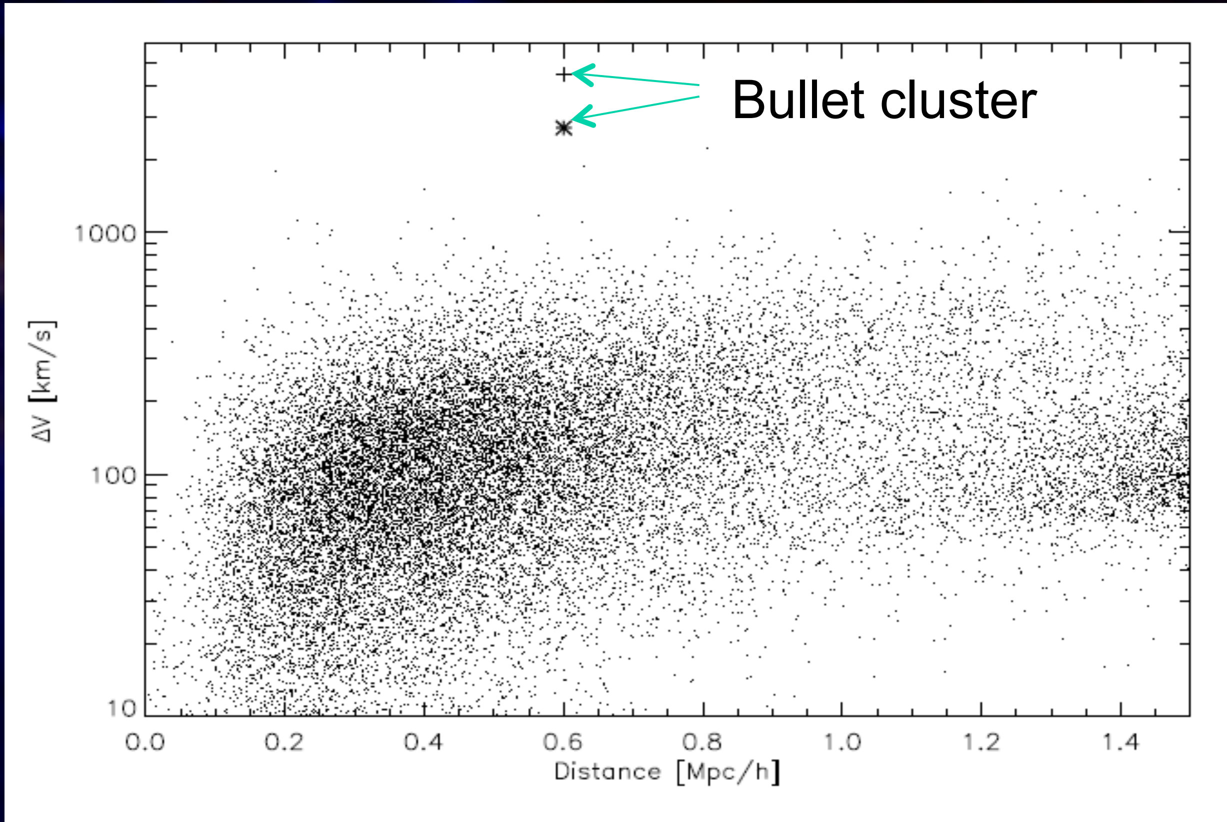
Pairwise velocity



Relative pairwise velocity of halo pairs with M > 7x10^13 Msun /h at z = 0.3

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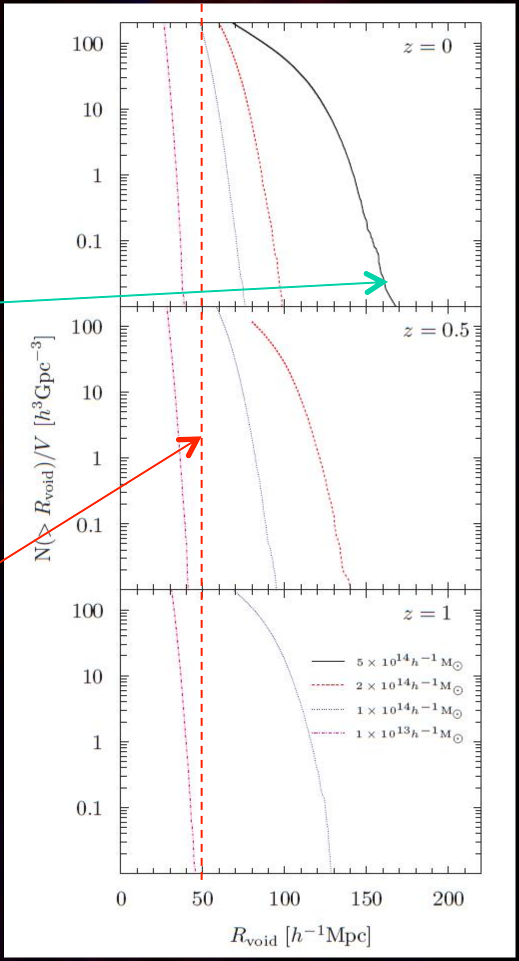
VOID STATISTICS



Local void acting as DE ?

Only one in a million observers would see the effect

40-50 Mpc/h cut-off (10^{13} Msun/h)

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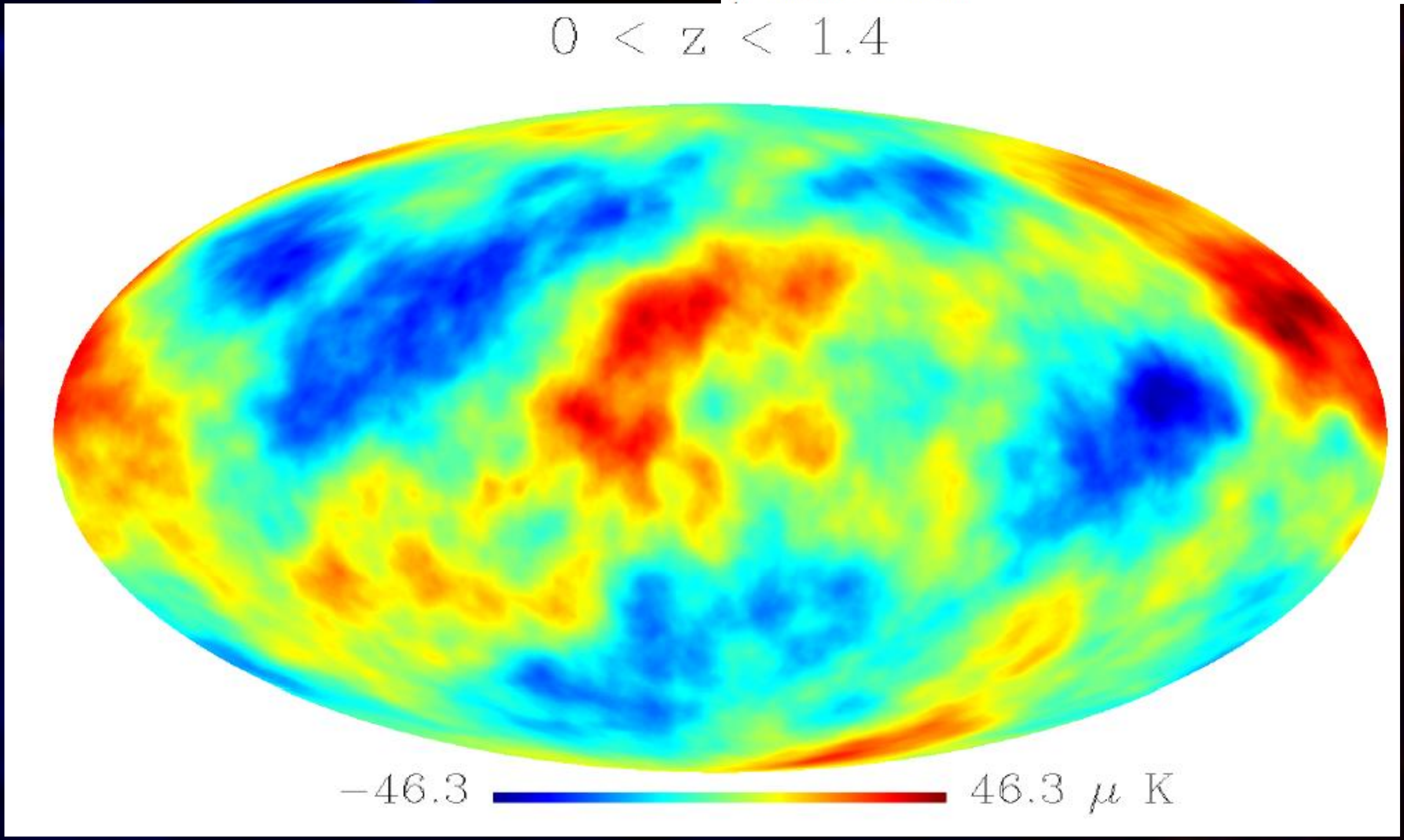
Upcoming results on ISW

The Integrated Sachs-Wolfe effect and its cross-correlation with large-scale structure

W. A. Watson[1*] J. M. Diego[2] S. Gottlöber[3] I. T. Iliev[1] A. Knebe[4] G. Yepes[4]
R. B. Barreiro[2] J. González-Nuevo[2] S. Hotchkiss[5] E. Martínez-González[2]
S. Nadathur[6] P. Vielva[2]



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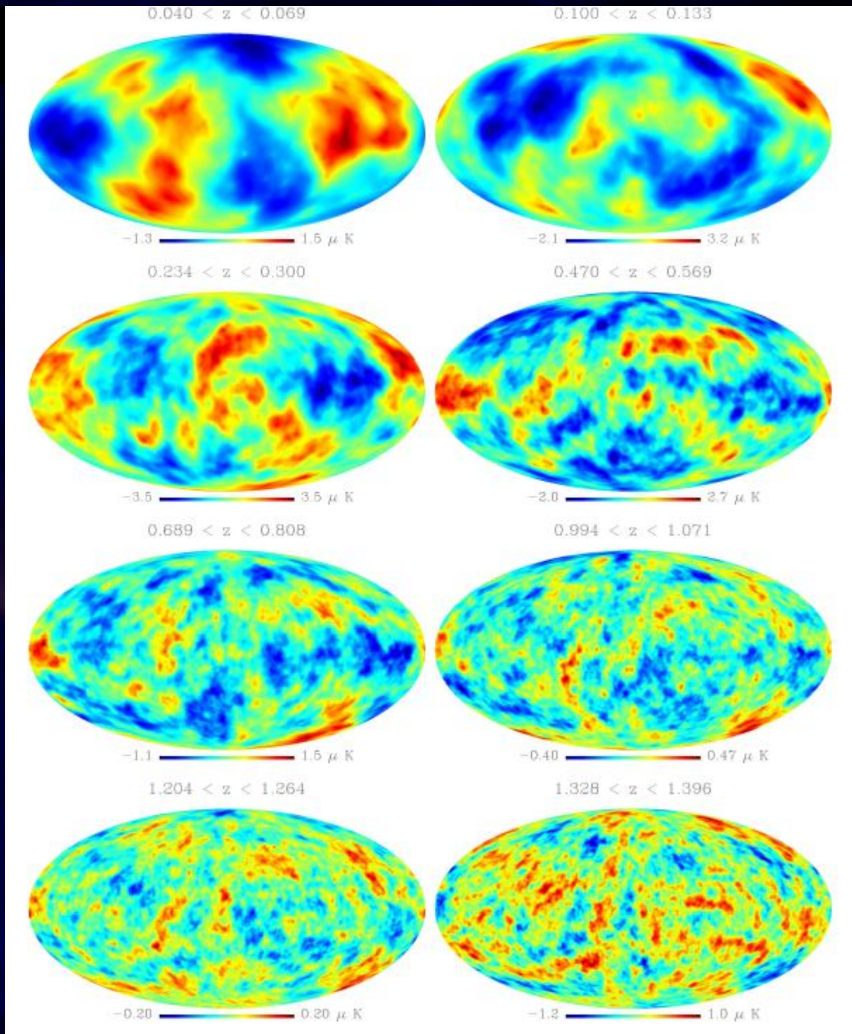

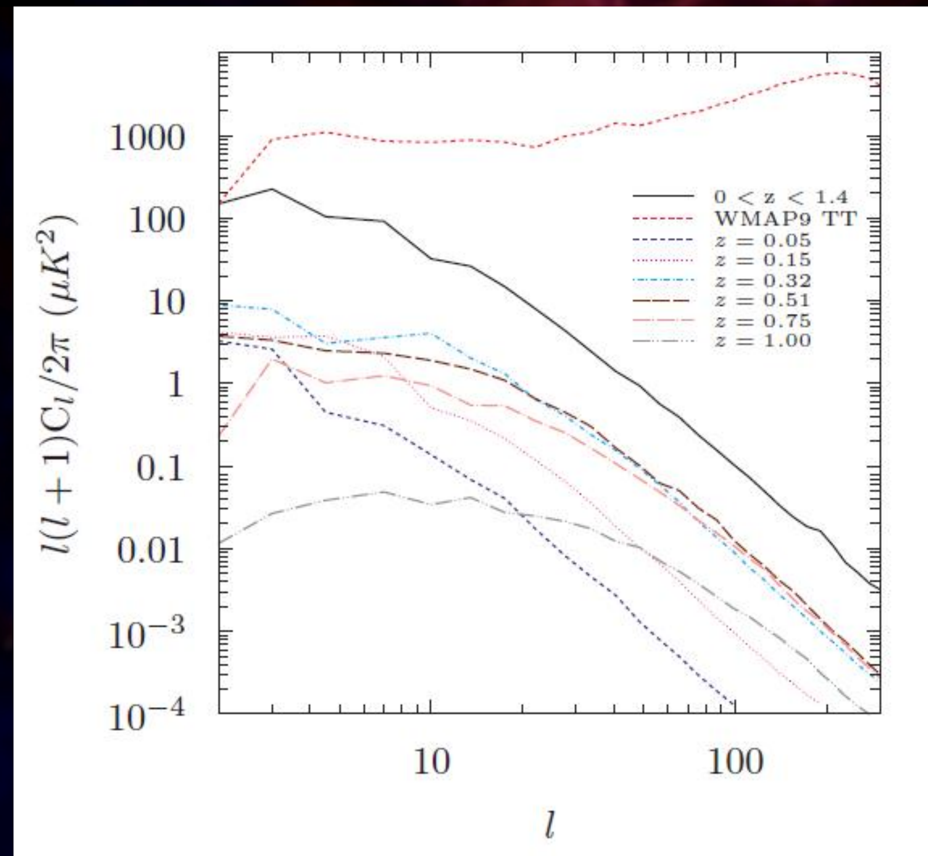

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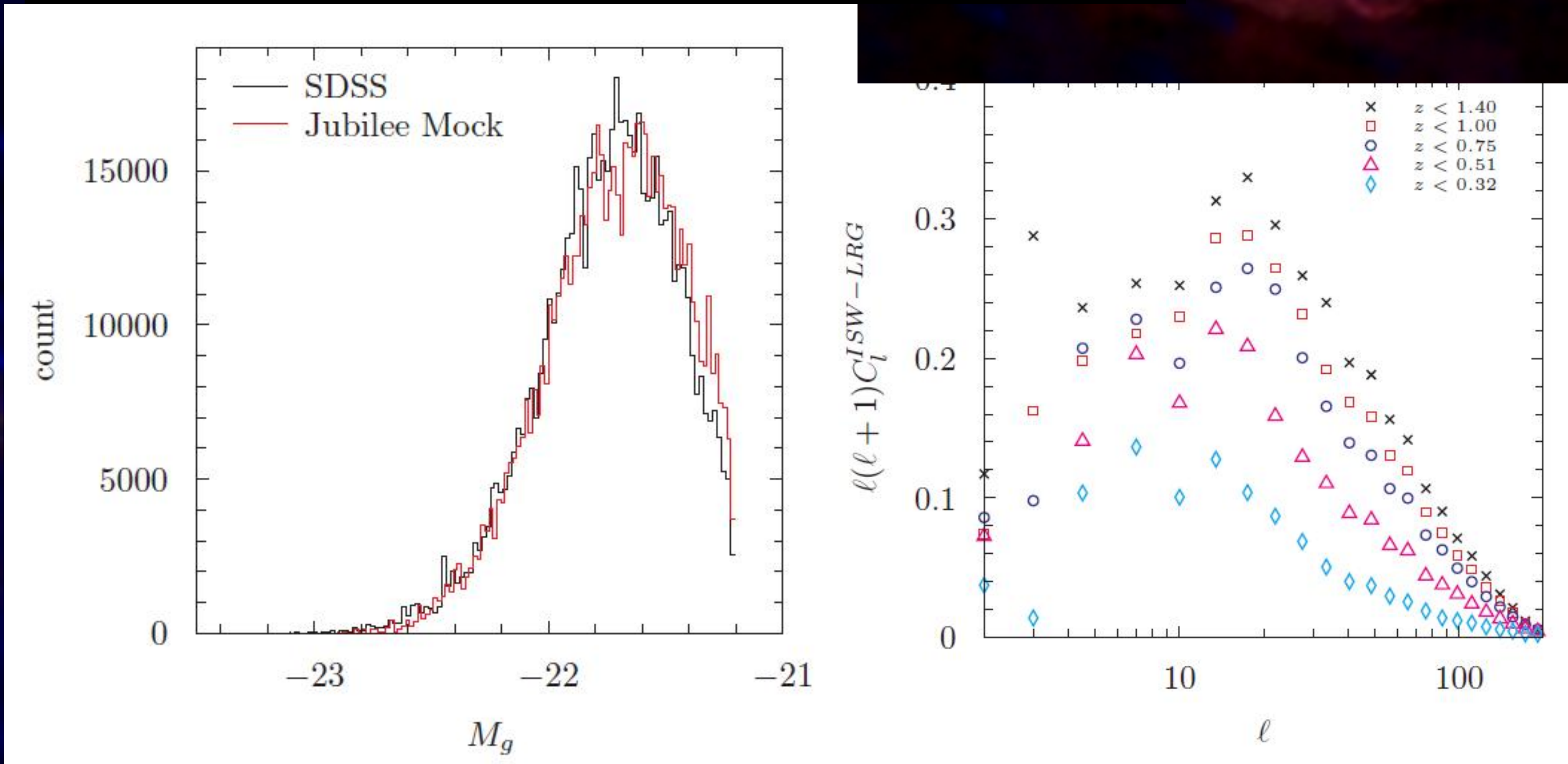
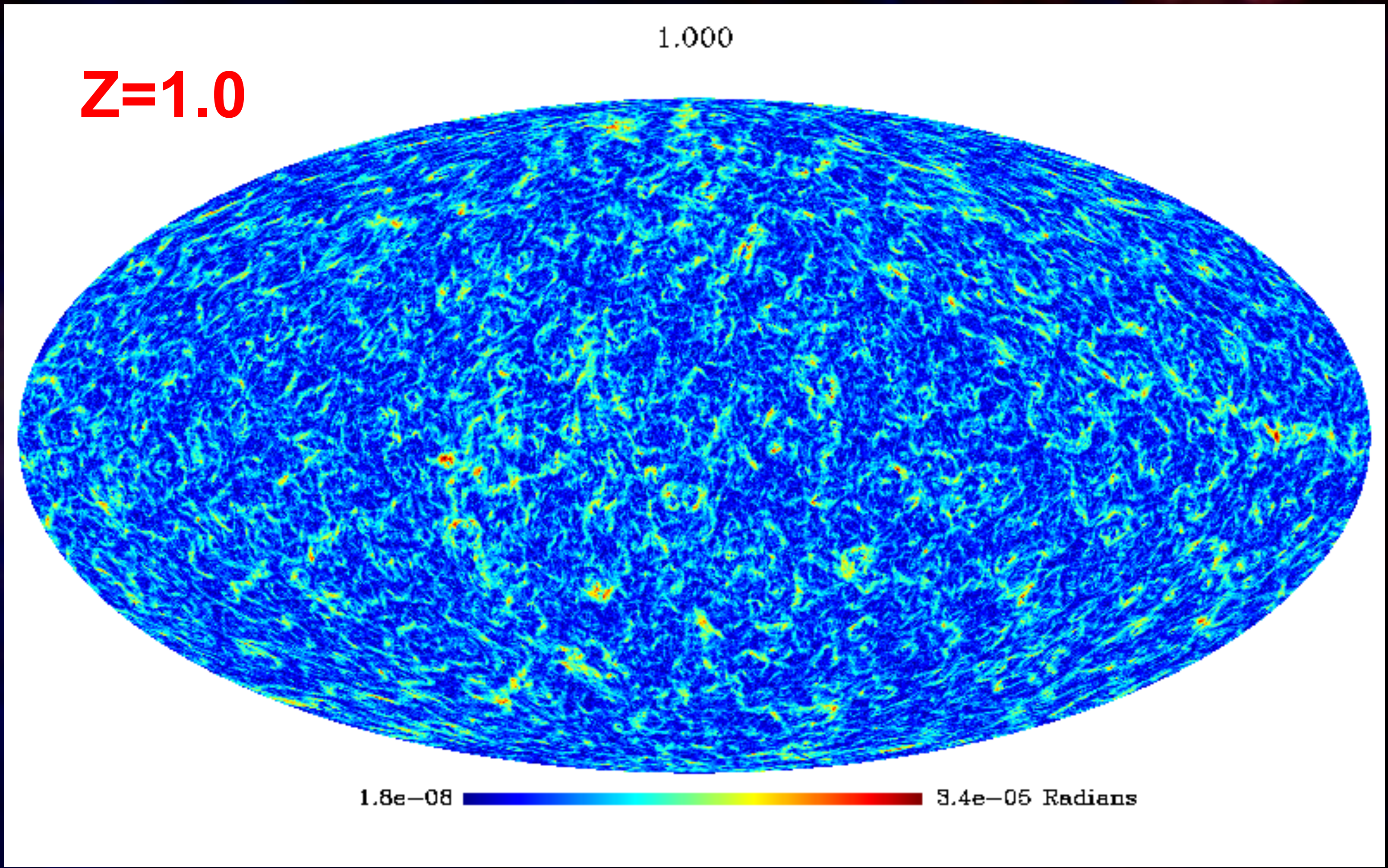
Cross-correlation between ISW and LRGs



The Jubilee Simulation

GRAVITATIONAL LENSING MAPS



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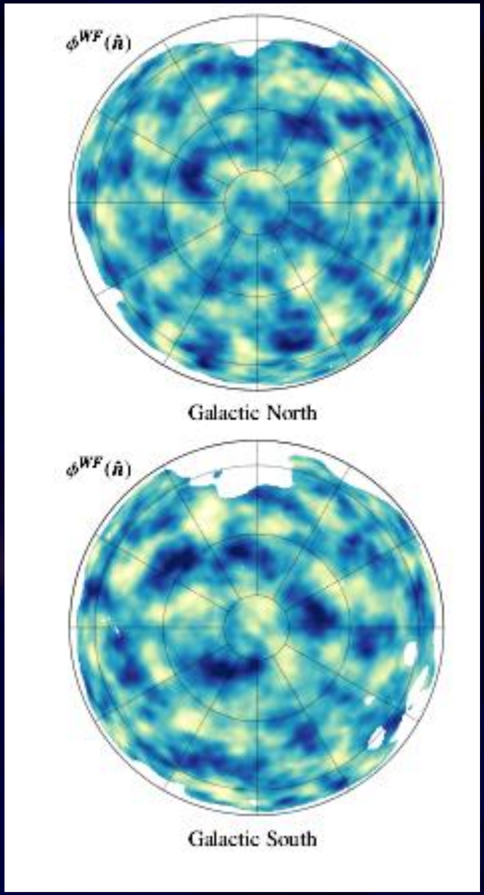
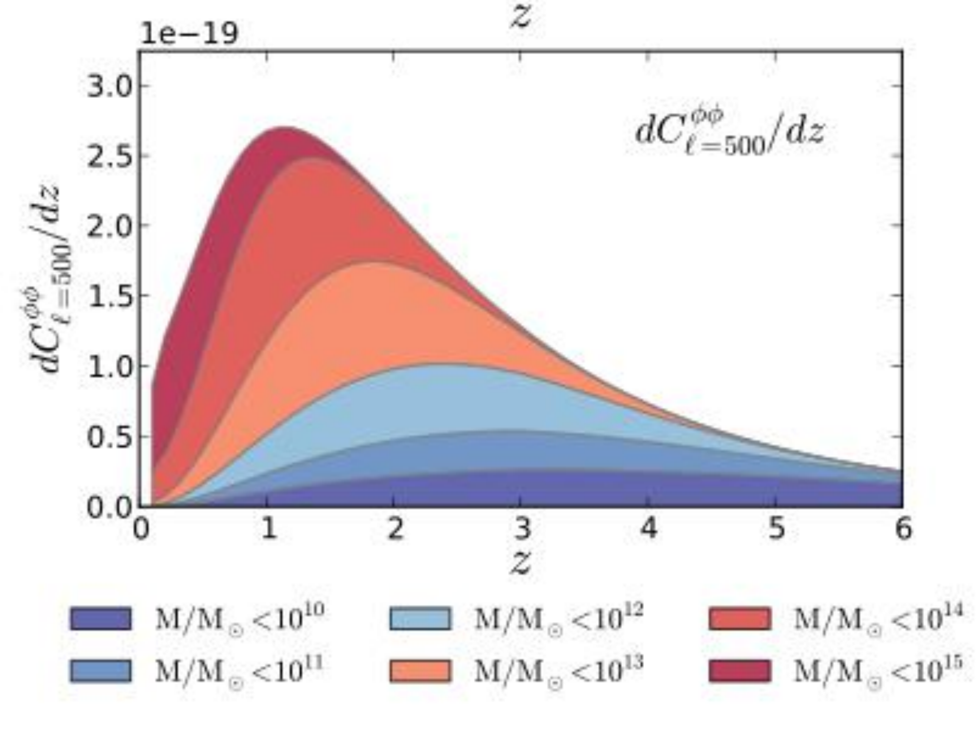
Simulation of the (CMB) lensing potential requires large volumes





Planck

All-sky lensing maps together with associated catalogs needed for key future missions and surveys.

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The Jubilee Simulation

[redacted]

DATA PRODUCTS AVAILABLE

http://jubilee-project.org

http://jubilee.ft.uam.es/

Fedora Project Red Hat Free Content

Home - Jubilee Project

Jubilee Project

JUropa huBbLE volumE simulation project

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Juropa Hubble Volume Simulation Project

216 billion particles in a 6/h Gpc volume.

The ***Jubilee project*** consists of two of the largest N-body simulations done up to date. Two volumes of **3072 Mpc** and **6000 Mpc** respectively with same mass and spatial resolution.

These simulations were intended to be used primarily to compute an all-sky map of the Integrated Sachs-Wolfe effect (or ISW) but also to produce catalogs of luminous red galaxies (or LRG), radio and IR galaxies as well as all sky maps the Sunyaev-Zel'dovich (or SZ) and lensing effects.

Future data sets like Planck and surveys like BOSS, Pan-STARRS, DES, KIDS, BigBoss, J-PAS or EUCLID will require coherent simulated data derived from very large N-body simulations that include the above effects and a catalog of simulated galaxies. A large volume is needed in order to properly simulate the largest scales of the ISW and also to study the impact of cosmic variance on future LSS surveys.

The simulations were done in the Juropa supercomputer at the Jülich Supercomputer Center in Germany using the CUBEP3M parallel N-body code.

The participating members of the project are:

Stefan Gottlöber

Ilian Iliev and William Watson

Gustavo Yepes

Enrique Martínez González and J. M. Diego

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The Jubilee Simulation

DatabaseName.TableName	Number of Rows	Size
jubilee6GpcAHF.AHFz0000	459,100,385	80 GB
jubilee6GpcAHF.AHFz0509	381,971,966	66 GB
jubilee6GpcAHF.AHFz1000	305,292,843	52 GB
jubilee6GpcAHF.AHFz6000	990,672	175 MB

The tables structure is as follow (underline means the column is indexed):

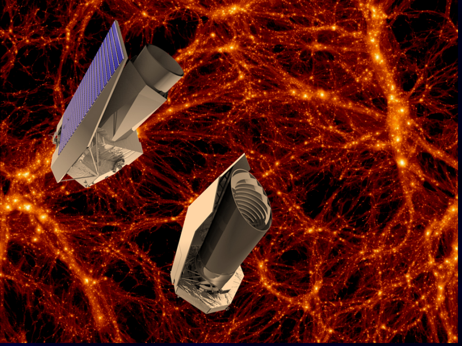
Field	Type	Units	Description
<u>HaloId</u>	bigint(20)		Unique identifier in the table. (Primary key)
npart	int(11)		Number of particles in halo
fMhires	float		Halo contamination
Xc	float	kpc/h	Position
Yc	float		
Zc	float		
VXc	float	km/s	Peculiar velocity of halo
VYc	float		
VZc	float		
Mvir	float	$M_\odot$/h	Mass of halo
Rvir	float	kpc/h	Virial radius
Vmax	float	km/s	Max velocity
Rmax	float	kpc/h	Position of rotation curve maximum
sigV	float	km/s	3D velocity dispersion
lambda	float		Spin parameter (Bullock et al. 2001 definition)
Lx	float	$\|L\|=1$	Orientation of angular momentum vector
Ly	float		
Lz	float		
Eax	float	$\|E_a\|=1$	
Eay	float		
Eaz	float		
b	float	b/a	Second largest axis of moment of inertia tensor
Ebx	float	$\|E_b\|=1$	
Eby	float		
Ebz	float		
c	float	c/a	Third largest axis of moment of inertia tensor
Ecx	float	$\|E_c\|=1$	
Ecy	float		
Ecz	float		
ovdens	float		Overdensity at virial radius
nbins	int(11)		Number of bins used for the profile
Ekin	float	$M_\odot$/h (km/sec)^2	Kinetic energy
Epot	float	$M_\odot$/h (km/sec)^2	Potential energy
mbp_offset	float	kpc/h	Offset between most bound particle and halo centre
com_offset	float	kpc/h	Offset between centre-of-mass and halo centre
r2	float	kpc/h	Position where ρr^2 peaks
lambdaE	float		Classical spin parameter (Peebles' definition)
v_esc	float	km/sec	Escape velocity at Rvir
Phi0	float	(km/sec)^2	ϕ0 (cf. unbinding procedure)

DatabaseName.TableName	Number of Rows	Size
jubilee6GpcSO.SOz0000	542,225,296	19 GB
jubilee6GpcFOF.FOFz0509	510,195,856	18 GB
jubilee6GpcFOF.FOFz1000	445,147,825	16 GB

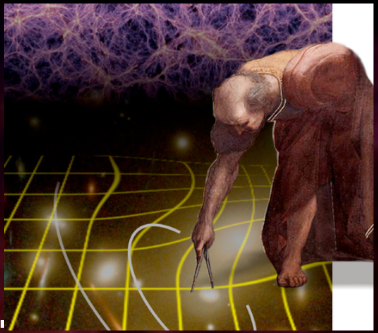
The tables structure is:

Field	Type	Units	Description
<u>HaloId</u>	bigint(20)		Unique identifier in the table. (Primary key)
<u>Mvir</u>	float		
x	float		Position
y	float		
z	float		
Vx	float		Velocity
Vy	float		
Vz	float		

- Haloes catalogs based on AHF, SO and FoF
- AHF catalogs. Few redshifts but very complete
- SO catalogs. More basic info but for 100+all redshifts
- Peculiar velocities useful for z-corrections



ESA EUCLID

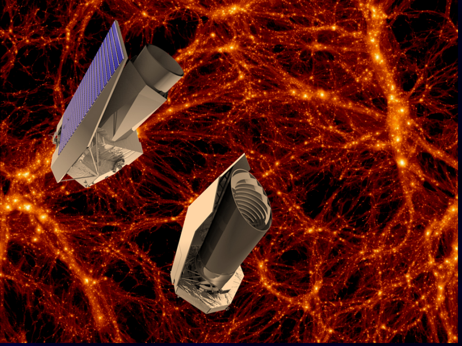


EUCLID is one of ESA's M-class mission scheduled to be launched in 2019.

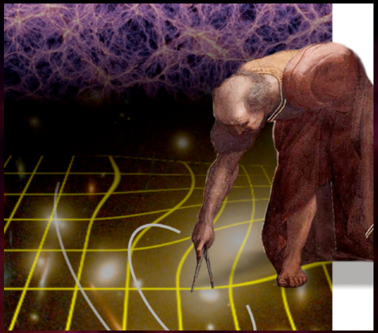
Main purpouse is to investigate the nature of the dark energy from the clustering of galaxies in a large volume of the Universe (up to z ~1.5)

Need huge demands of numerical simulations to

- Compare between cosmological model predicitions and observational results
- As templates for design of observational strategies
- Grand challeng goal: try too make predictions to % level from N-body results.



ESA EUCLID



EUCLID Software Working Group:

Coordinators: P. Fosalba & R. Teyssier

More than 50 scientists specialist in computational astrophysics.

Euclid Grand Challenge: 4/h Gpc @ 16000^3)

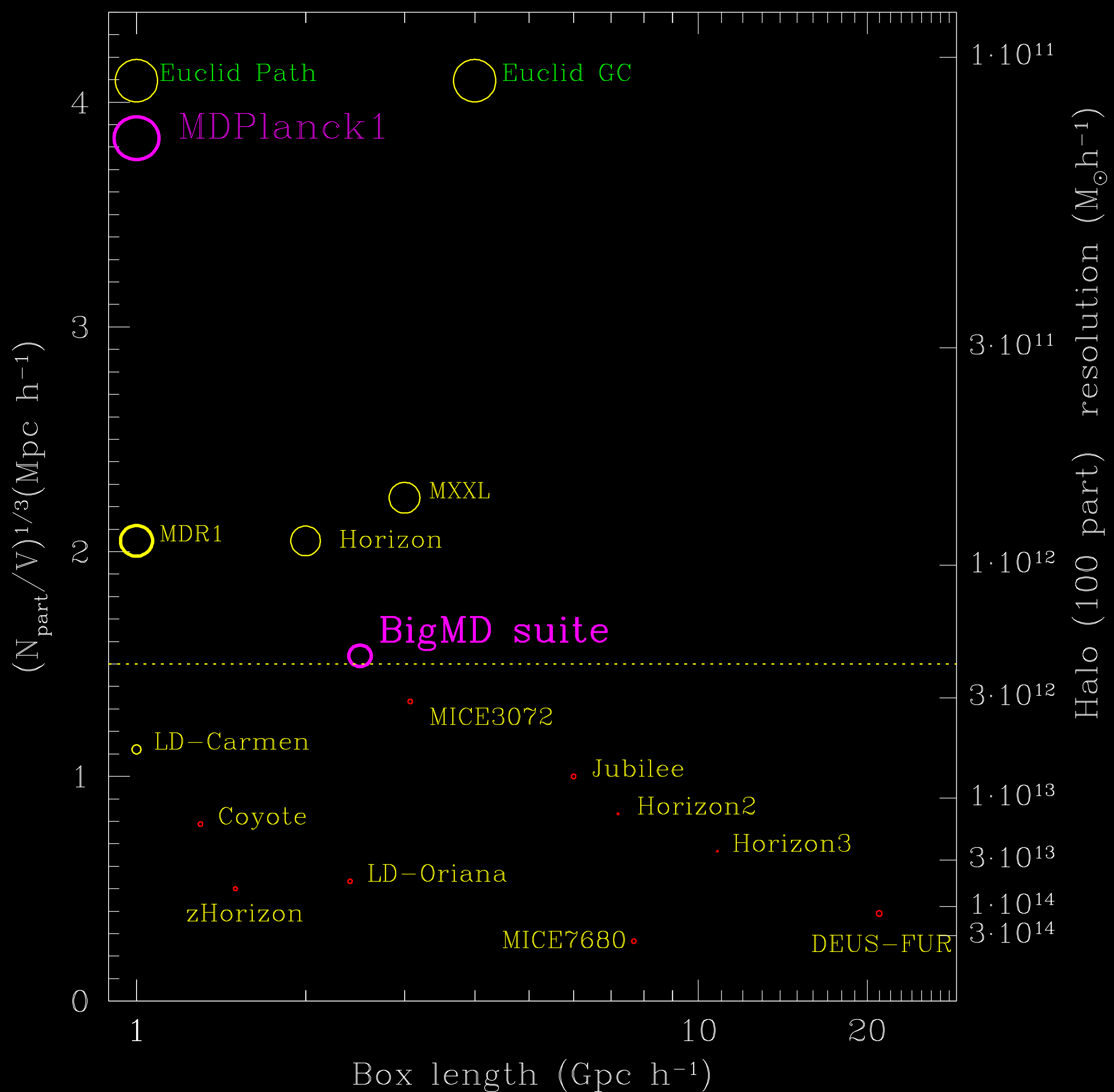
Code testing, scalabiity, comparison of results:

RAMSES, GADGET, CUBEP3M, PKDGRAV

Postprocessing, Data managements.

Proposal to PRACE for access supercomputing resources for running Euclid pathfinder simulation (1 Gpc @ 4096^3)

Current S.o.A Cosmological Simulations



RELIABILITY OF N-BODY CODES

It remains to be shown whether present N-body codes can effectively use 10's of thousands of mpi task simultaneously for sufficiently large time without MPI errors hanging the runs.

The probability of a communication error is increasing dramatically with the number of MPI tasks used, so all the computation will be lost since last checkpoint unless we provide some sort of fault-tolerance method in MPI codes.

DATA MANAGEMENT

For 10^12 particle simulation we expect to have a minimum of 30Tbytes per snapshot.

Total number of snapshots can range between 10 to 100, so we will need to store 300 Tbytes to 3 Pbytes.

Halo finding can be done on the fly (eg. Subfind) or as postprocessing tool (e.g AHF; Rockstar, FoF, BDM etc). They also have to show that they can cope with this amount of particles in an efficient way.

Must show that results do not depend on halo identification algorithm (Knebe et al 2010)

DATA MANAGEMENT

- This amount of data that is generated in large simulations poses new problems:
  - Data storage: SC do not care about the long term storage and access of simulated results.
  - Network bandwidth still not fast enough to get the data out of the SC to a local facility..
  - Need to have access to the data for a longer period than the duration of the simulation run. Sometimes a simulation is producing interesting results years after it was done.
  - Simulations are usually done in different SC scatterd accross Europe, or the world..How to centralize the access to the raw data?.

CONCLUSIONS

- 10^{12}+ particle simulations for different cosmological models are indispensable for current and upcoming galaxy surveys.
- It is really necessary to coordinate efforts between the different collaborations and not repeating same big runs again and again (e.g. Euclid SWG). The same simulation can be used to extract mocks for several surveys with different selection functions and geometries.
- So far the SC centers have not paid attention to the data managements of simulated results. Some sort of central repository for simulation datasets could be an ideal solution. This might be another big HPC infrastructure.
- Some kind of standarization of the analysis and format of data has to be done.

THANK YOU