Formation of Large Scale Structure

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Bogota
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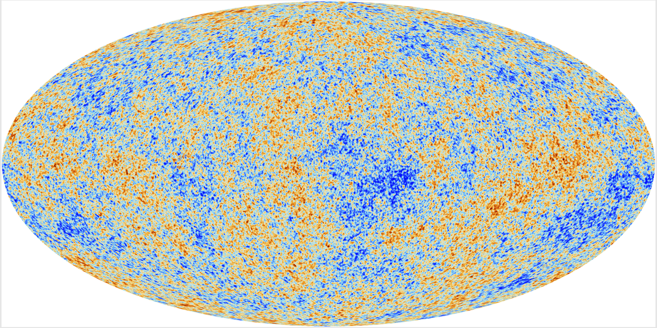
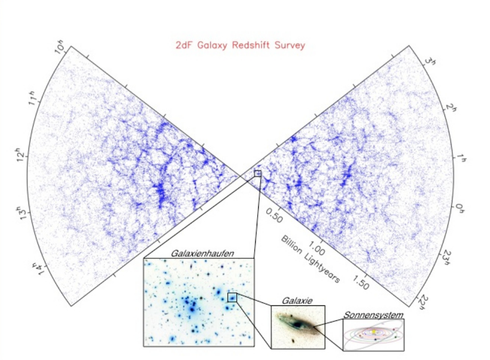
Cosmic Microwave Background (CMB) radiation

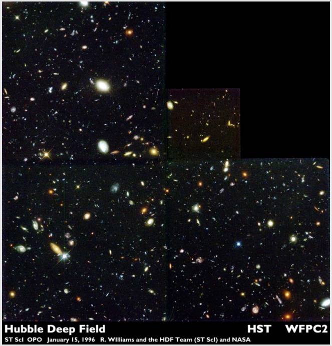


The Cosmic Microwave Background - as seen by Planck. Credit: ESA and the Planck Collaboration

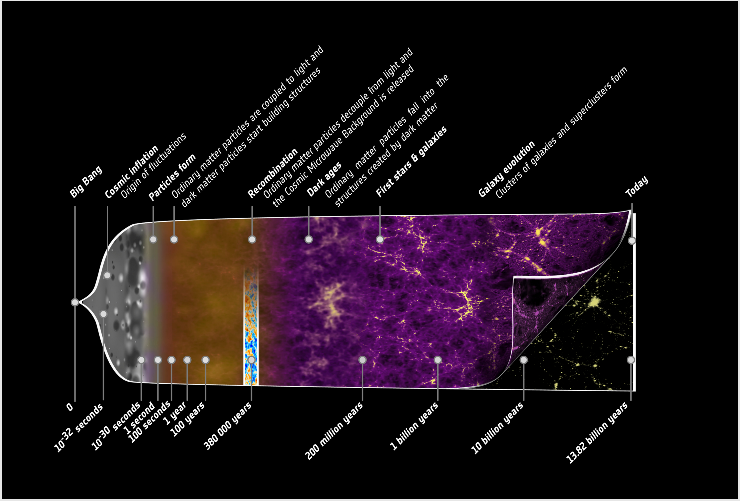
The universe about 13.5 billion years ago (a few hundred thousands years after big bang). Baryon matter content: 75% of hydrogen, about 25% of helium, about 0.01% of deuterium, trace amounts (on the order of 10^{-10}) of lithium and beryllium.

The visible universe - Large Scale Structure





Structures on all scales (LSS: clusters,filaments, voids, different galaxies) down to the solar system.



Credit: ESA and the Planck Collaboration

The evolution of structure

- About 13.5 billion years ago the universe was almost homogeneous with tiny density fluctuations of the order of 10^{-5}.
- Now we observe at large scales the cosmic web into which a large diversity of galaxies is embedded.
- The tiny initial fluctuations grew by gravitational instability.
- Besides gravitation gas-dynamical processes play an important role.
- $\Longrightarrow$ **We need supercomputers**

General relativity

Sitzungsberichte der Königlich Preussischen Akademie der Wissenschaften vom 11. November 1915

Zur allgemeinen Relativitätstheorie

"Setzen wir nun fest, daß die Feldgleichungen der Gravitation lauten sollen
$G_{\mu\nu} = -\kappa\ T_{\mu\nu}$,
so haben wir allgemein kovariante Feldgleichungen gewonnen."

Albert Einstein (1879 - 1955)

And two years later

Sitzungsberichte der Königlich Preussischen Akademie der Wissenschaften vom 8. Februar 1917

Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie
"Im folgenden führe ich den Leser auf dem von mir selbst zurückgelegten, etwas holperigen Wege, weil ich nur so hoffen kann, daß er dem Endergebnis Interesse entgegenbringe."

...

$G_{\mu\nu} - \lambda g_{\mu\nu} = -\kappa \left(T_{\mu\nu} - \frac{1}{2} g_{\mu\nu} T \right)$

"... das letztere (*das Zusatzglied* $\lambda g_{\mu\nu}$) haben wir nur nötig, um eine quasistatische Verteilung der Materie zu ermöglichen, wie es der Tatsache der kleinen Sterngeschwindigkeiten entspricht."

Friedmann equations

metric of the homogeneous and isotropic universe:

$$ds^2 = c^2dt^2 - a^2(t)\left(\frac{dr^2}{1-kr^2} + (d\theta^2 + \sin^2\theta d\phi^2)\right)$$

scale factor $a(t)$

$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{kc^2}{a^2} = \frac{8\pi G}{3}\rho$$

$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) < 0$ (i.e. expansion always slows down)

gravitational constant: G

density and pressure: ρ, p

Alexander Friedman(n) (1888 - 1925)

Friedman, A (1922), *Über die Krümmung des Raumes*, Z. Phys. 10, 377

The Universe expands

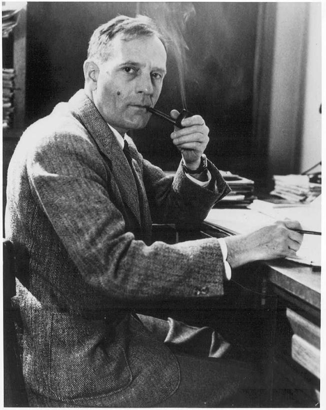
1929

Observational result:

The radial velocity of galaxies is proportional to their distance.

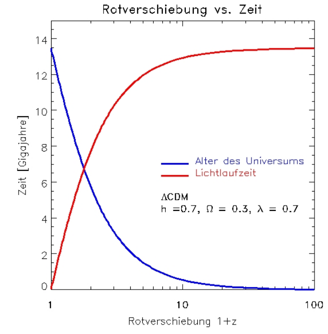
$v = H_0 \times r$

H_0: Hubble constant at present t_0



Edwin Hubble (1898 - 1953)

Redshift



The redshift is used as measure of distance and/or time

redshift $z = \frac{\Delta\lambda}{\lambda_0}$

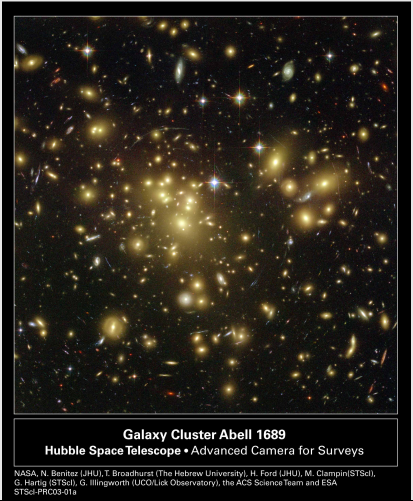
radial velocity $v = H \times r$

(H ... Hubble constant)

$z = v/c$ (if $v << c$)

The radial distance is a function of redshift which depends on the parameters of the cosmological model.

Dark Matter



Observed by gravitational lensing

- Galaxy cluster Abell 1689
- Gravitational lensing of Abell 1689 as predicted by GR
- The gravitative mass is much larger than all the mass seen in light and X-ray

Indirect observations

- rotation curves of galaxies
- rms velocities of galaxies in clusters

Jan Oort, dark matter 1932

BULLETIN OF THE ASTRONOMICAL INSTITUTES OF THE NETHERLANDS.

1932 August 17 Volume VI. No. 238.

COMMUNICATION FROM THE OBSERVATORY AT LEIDEN.

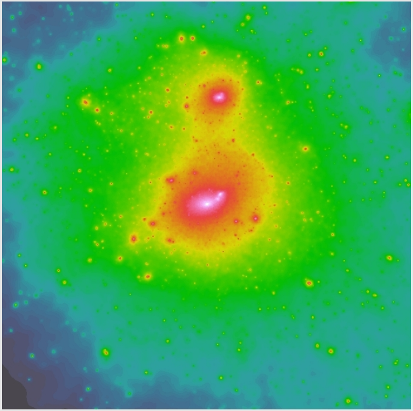
The force exerted by the stellar system in the direction perpendicular to the galactic plane and some related problems, by *J. H. Oort.*

11. *The amount of dark matter.*

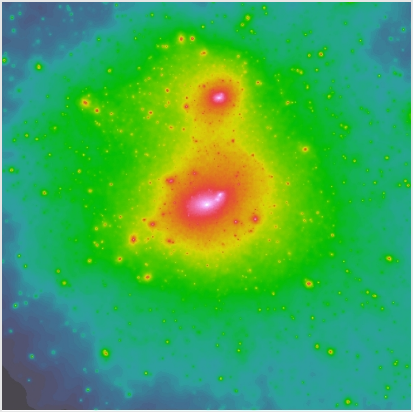
From the results found for the decrease of $K(z)$ with z we may derive an approximate value of the total density of matter, Δ, in the neighbourhood of the sun. Let us suppose that we are situated inside

It is a pleasant duty to express my gratitude to the members of the computing staff of the Observatory, especially to Messrs. PELS and KRIEST who are responsible for the major part of the computational work involved in the above investigation.

Halos of Dark Matter



Halos of Dark Matter



Halo: a glow or ring of light around a head or person in art

What is a halo in cosmology?

- a potential well filled with dark matter (and baryons)
- decoupled from cosmological expansion
- density: $\rho \approx \rho_{\rm vir} \approx 300 \times \bar{\rho} \approx 100 \times \rho_{\rm crit}$
- triaxial

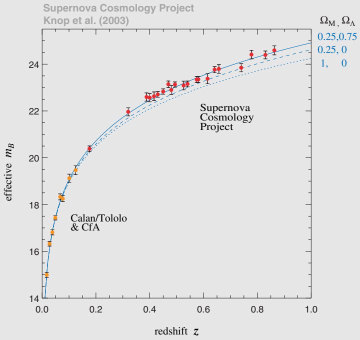
Dark Matter

What do we know?

- about 85 per cent of all matter must be dark
- dark matter is responsible for the large scale structure
- all galaxies and clusters live in dark matter halos
- probably not in all dark matter halos live galaxies
- dark matter must be made of
  - **weakly** interacting
  - non-baryonic
  - more or less cold $\Longrightarrow$ **small scale structure**

  particles

Dark Energy



Observed by distant supernovae

- observed magnitude vs. distance
- high redshift supernovae are fainter than expected in standard cosmology
- therefore further away
- $\Longrightarrow$ **Accelerating force**

Dark Energy

What do we know?

- about 70 per cent of the total energy in the universe is unknown
- this dark energy is responsible for the acceleration of expansion
- experiments are planned to measure the evolution of the dark energy
  - Simplest explanation: Cosmological constant (= vacuum energy = additional constant term in Einstein's field equation)
  - some still unknown (scalar) field similar to the (still unknown) field which drives inflation
  - something else

Dark Energy (or cosmological constant Λ)

Friedmann equation with dark energy

$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{kc^2}{a^2} = \frac{8\pi G}{3}(\rho + \rho_{\mathrm{DE}})$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2} + \rho_{\mathrm{DE}} + \frac{3p_{\mathrm{DE}}}{c^2}\right)$$

cosmological constant = vacuum energy ($p_\Lambda = -\rho_\Lambda c^2$)

Recent observations have shown $-0.8 \lesssim \frac{\rho_{DE} c^2}{p_{DE}} \lesssim -1.2$

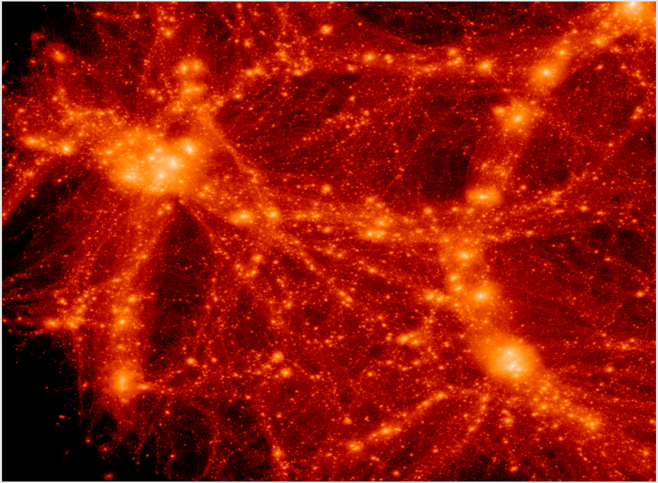
Dark Matter and Dark Energy

- We need
  - dark matter to explain the formation of structure in the universe
  - dark energy to explain the accelerated expansion
  - supercomputers to simulate the clustering of dark matter
- We know that
  - all galaxies and clusters live in dark matter halos
  - probably not in all dark matter halos live galaxies
  - dark matter simulations are a good first approximation to study galaxies

Expansion and comoving coordinates

- Background expansion according to General Relativity (Friedman equation)
- Constant vacuum energy leads to accelerated expansion about 7 Gigayears after Big Bang
- Periodic boundary conditions
- Physical coordinates vs. comoving coordinates (movies do not show expansion)

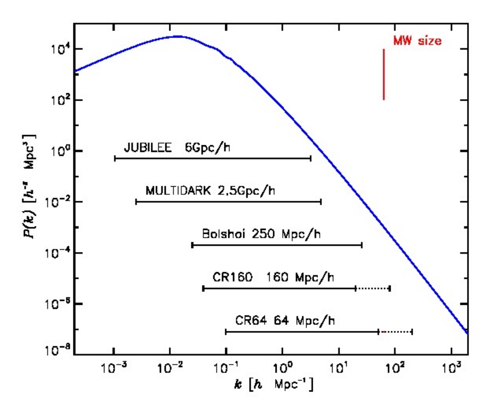
Structure formation on all scales



Large-scale structure

Individual haloes

Power spectrum of the density fluctuations



Linearly evolved power spectrum

Possible representation in different simulation boxes and with different resolution

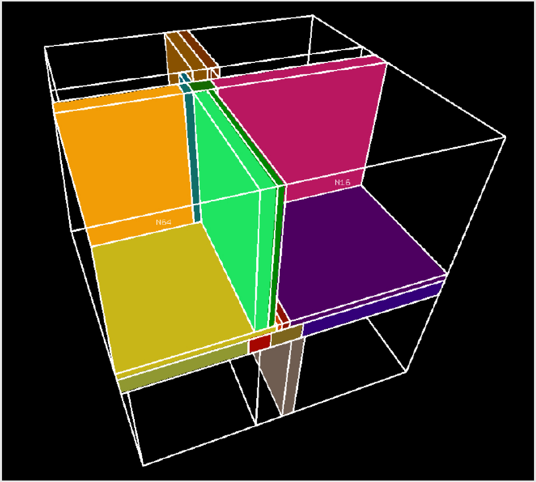
The computational problem

- The Universe
  - Few hundred billion MW type galaxies
- The Milky Way
  - Hundred billion stars
- A solar mass
  - 10^{55} dark matter particles
- Our largest simulation
  - 216 billion particles
- Dark matter (easy to handle)
  - Baryons (observed)

The numerical challenge

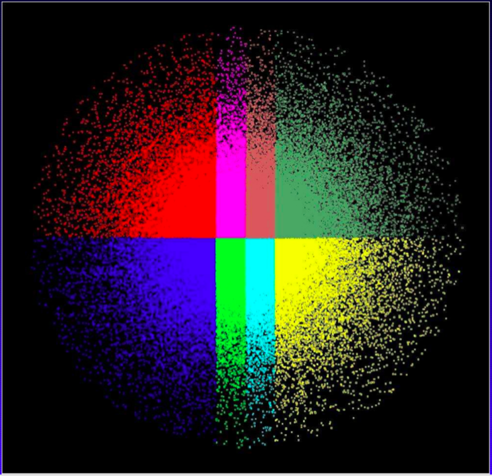
Billions of interacting particles distributed to thousands of cores

The numerical challenge as solved in ART



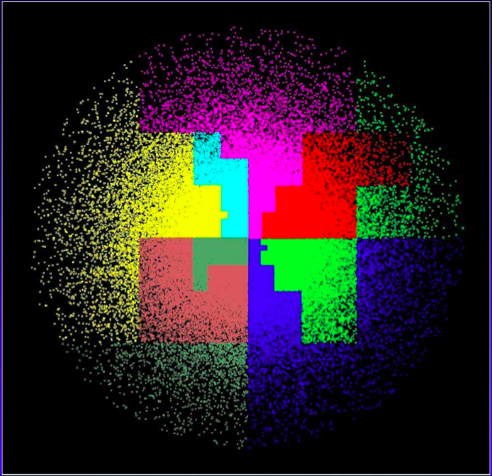
The Numerical Challenge

Gadget1



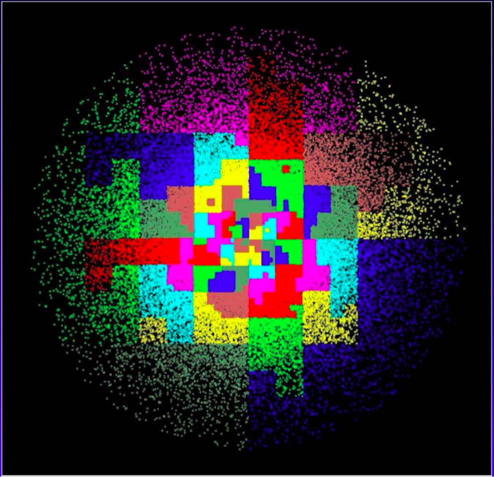
The Numerical Challenge

Gadget2



The Numerical Challenge

Gadget3



The numerical challenge

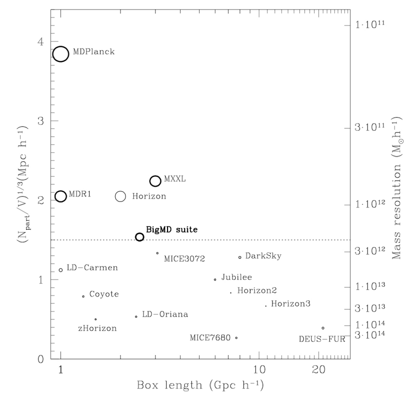
- find objects in the distribution of billion of particles
- halo finder
  - Friends of Friends
    - first halofinder
    - 6D
    - hierarchical FOF
    - merging history
    - AFOF
  - Spherical Overdensity
    - halos + subhalos + subsubhalos ...
    - spherical
    - merging history

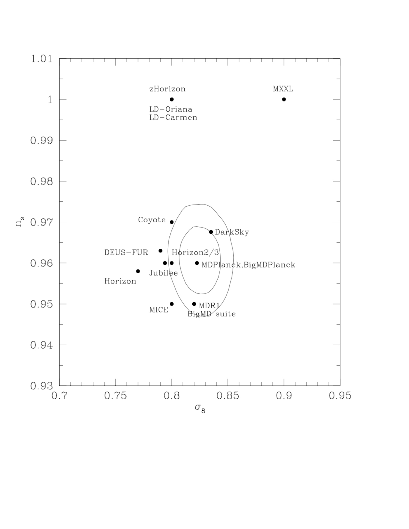
JUBiLEE: JUropa huBbLE volumE

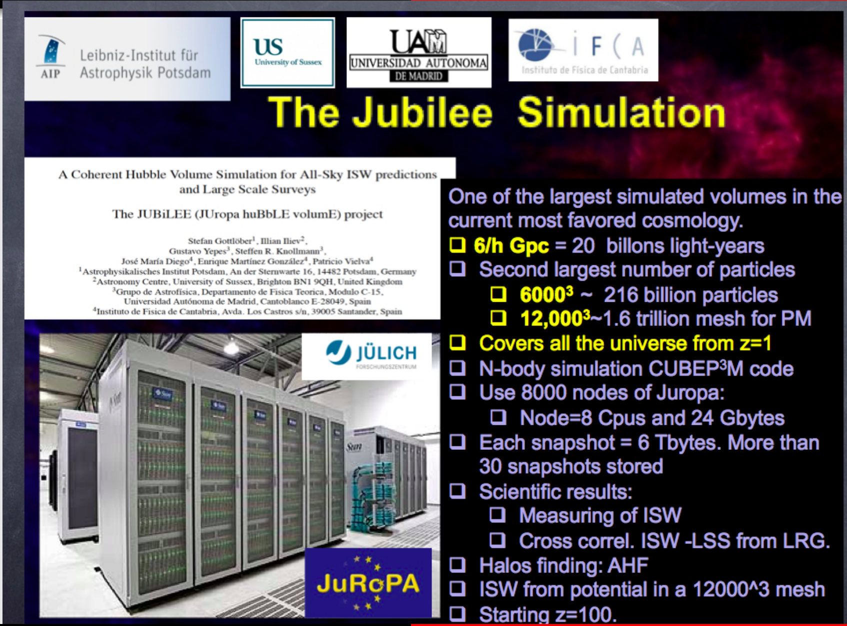
An N-body simulation with 216 billion particles

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

Large Cosmological Simulations



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DE MADRID
i F (A
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
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JÜLICH
FORSCHUNGSZENTRUM
JuRoPA
One of the largest simulated volumes in the current most favored cosmology.
6/h Gpc = 20 billons light-years
Second largest number of particles
6000³ ~ 216 billion particles
12,000³~1.6 trillion mesh for PM
Covers all the universe from z=1
N-body simulation CUBEP³M 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.

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 of 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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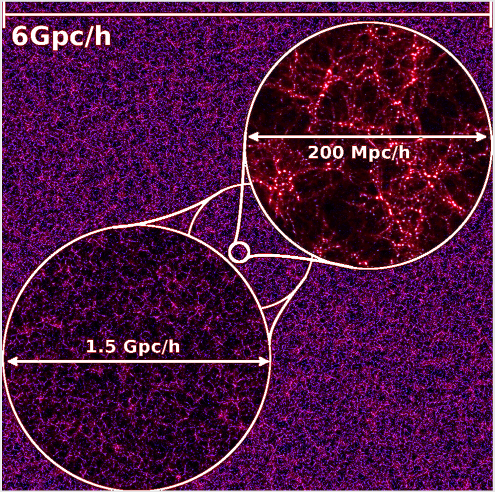
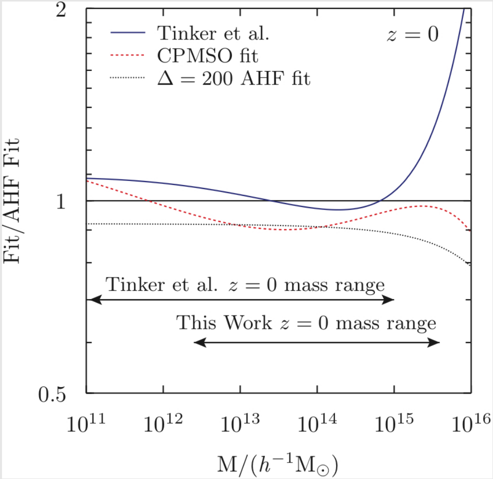
Jubilee at $z = 0$



Mass functions

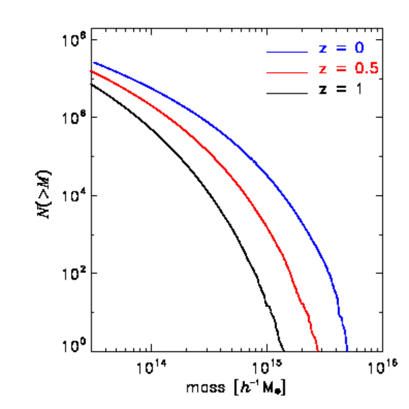


Overprediction of very massive clusters of galaxies by the Tinker fit

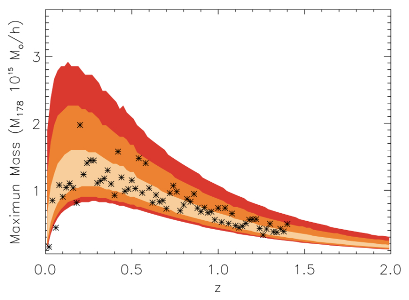
Watson etal, MNRAS 433 (2013), 1230

Most massive objects

Mass function of FOF halos in Jubilee

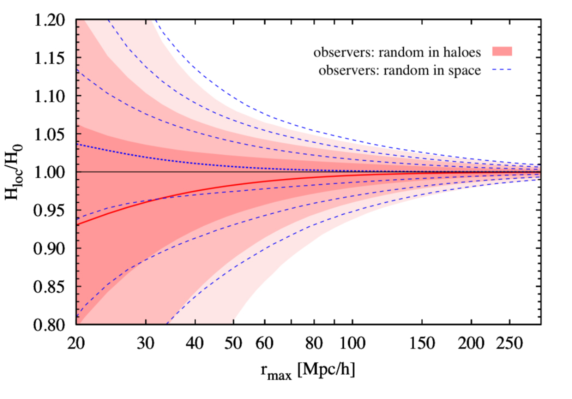


Extreme value statistics (Harrison & Coles 2011) and clusters observed in Jubilee



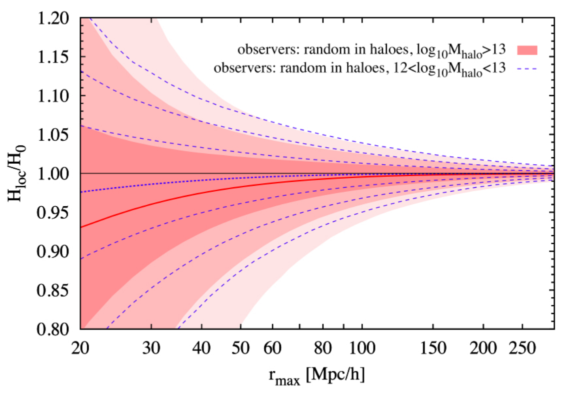
Watson etal, MNRAS 437 (2014), 3776

Probability distribution of the local Hubble parameter

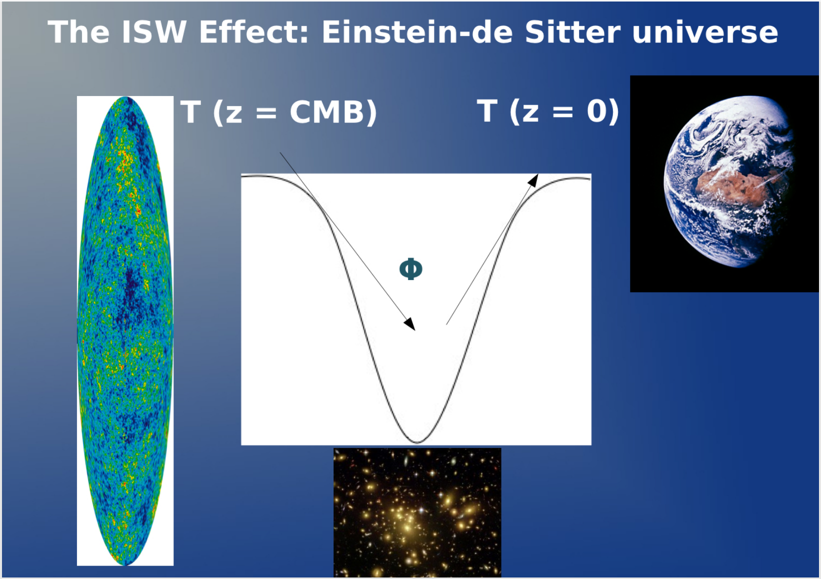


Wojtak etal, MNRAS 438 (2014), 1805

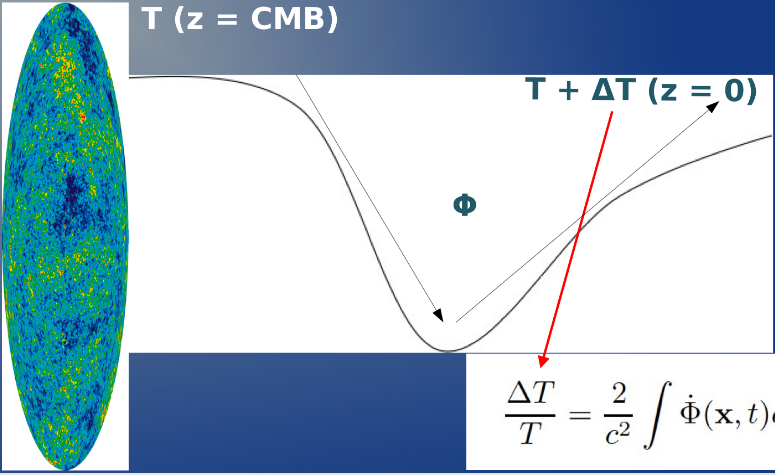
Probability distribution of the local Hubble parameter



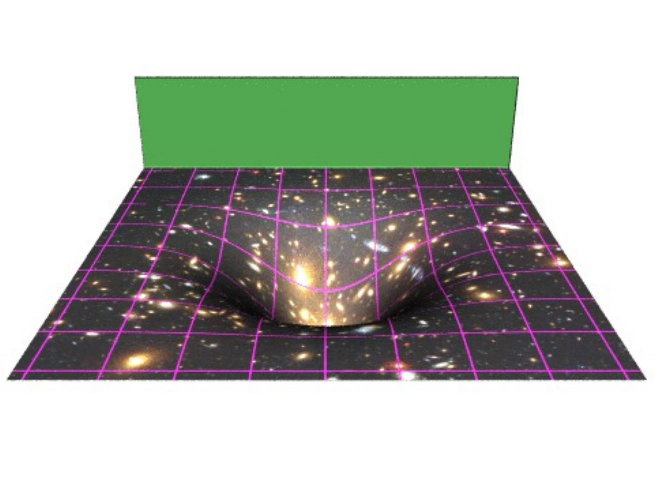
Wojtak etal, MNRAS 438 (2014), 1805


The ISW Effect: Einstein-de Sitter universe
T (z = CMB)
T (z = 0)
Φ

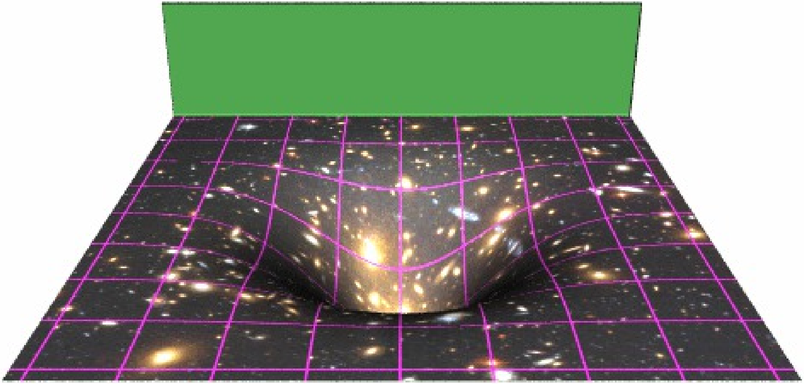
The ISW Effect: ΛCDM universe

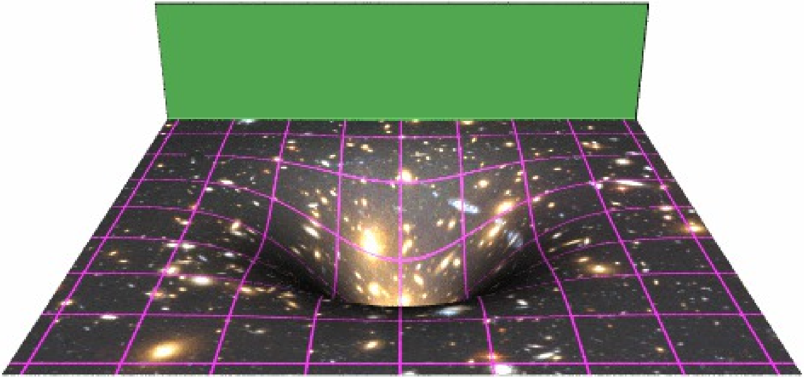


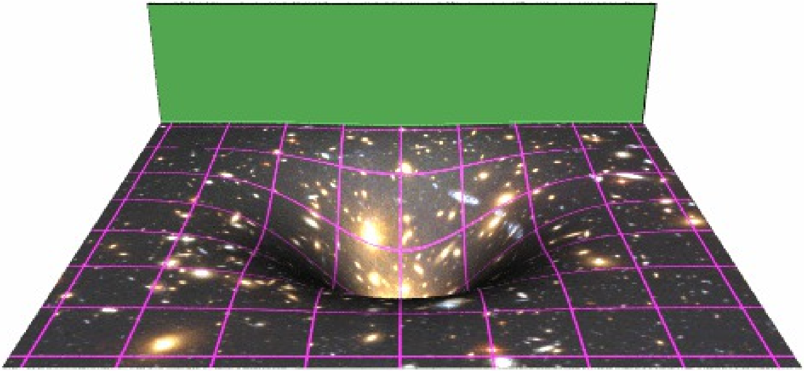
$$\frac{\Delta T}{T} = \frac{2}{c^2} \int \dot{\Phi}(\mathbf{x}, t) dt$$

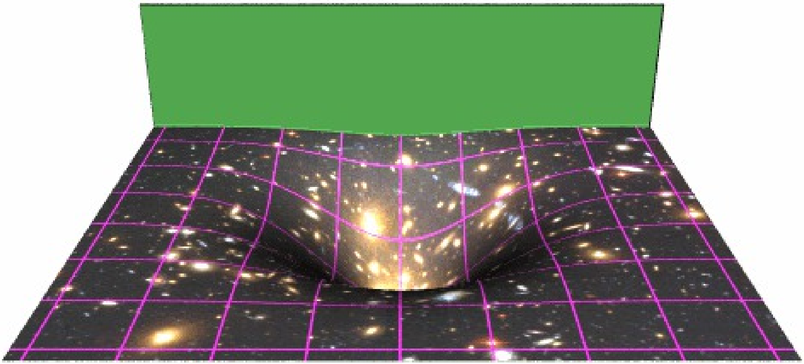


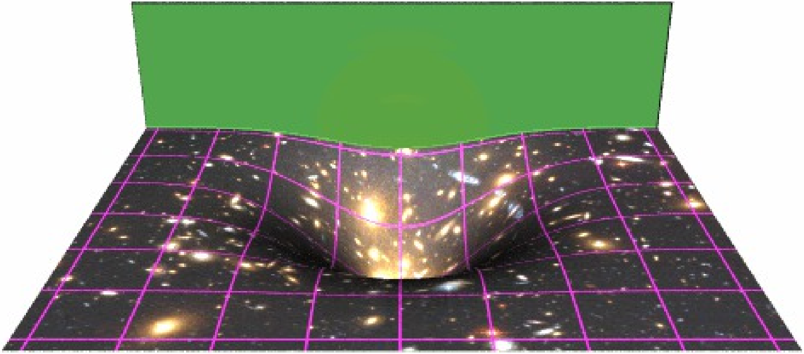
credit: IfA Hawaii, COSMOWAVE

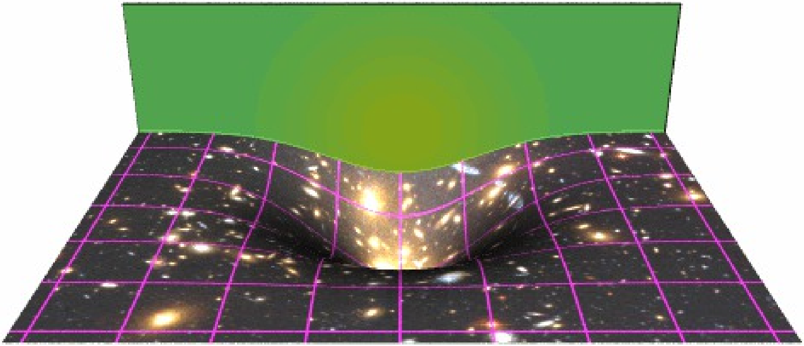


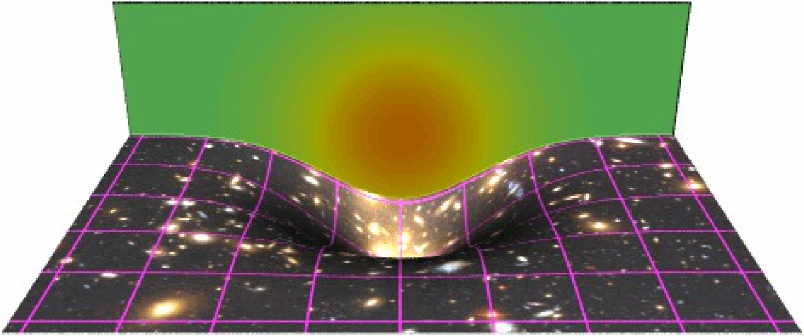


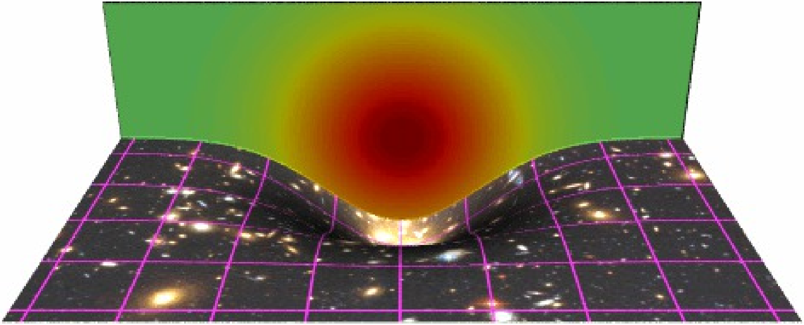


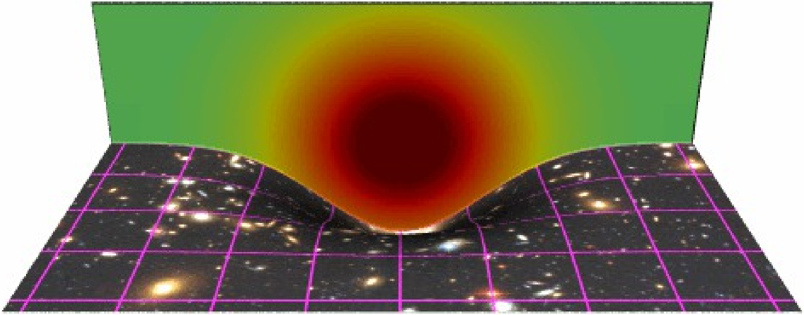


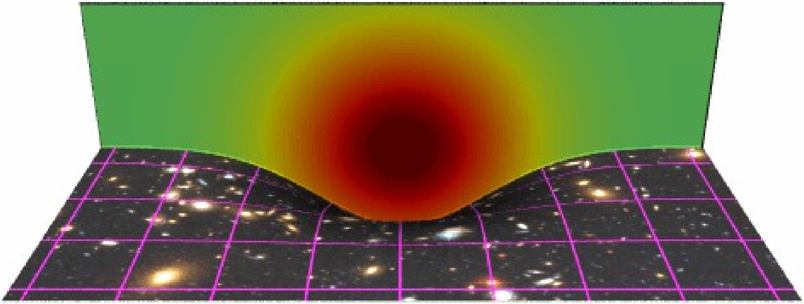


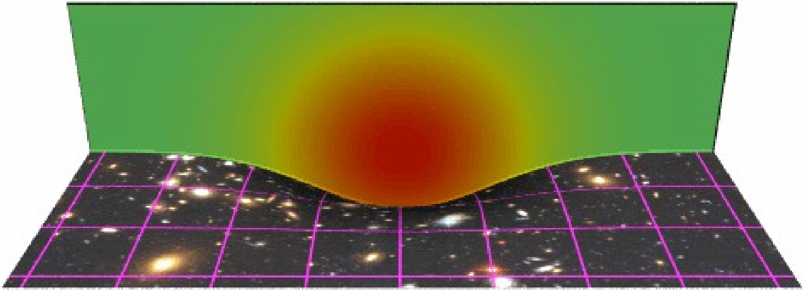


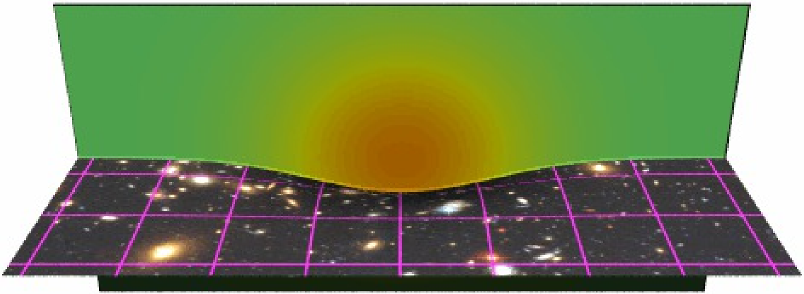


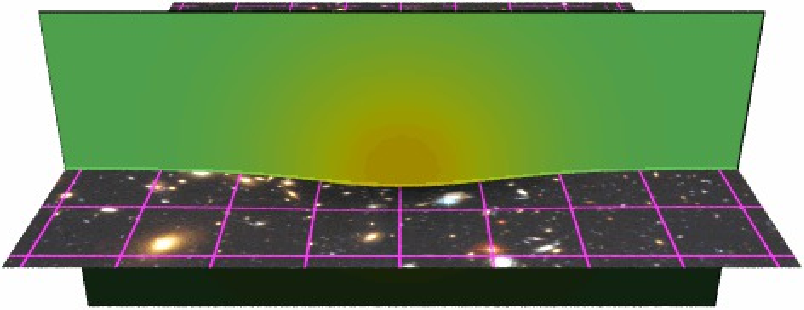


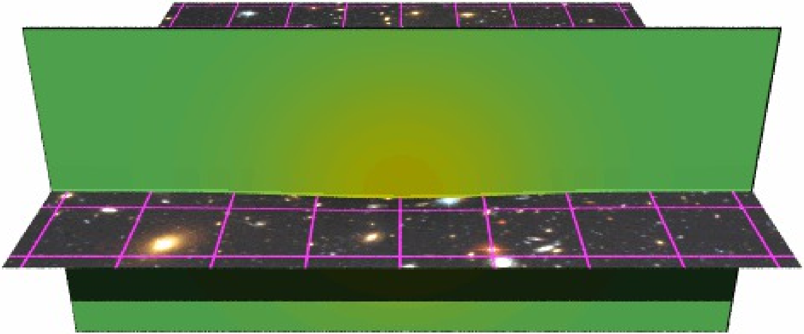


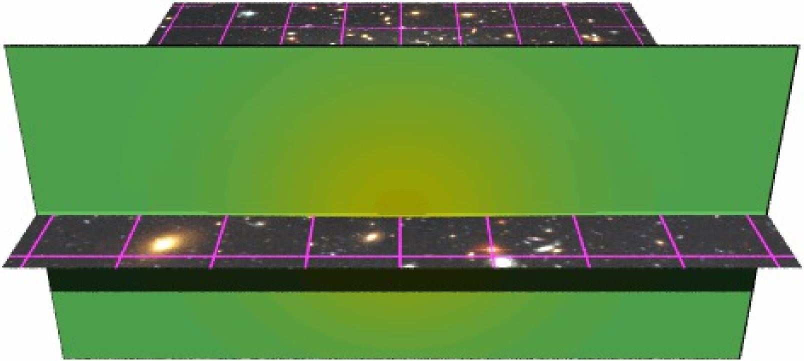


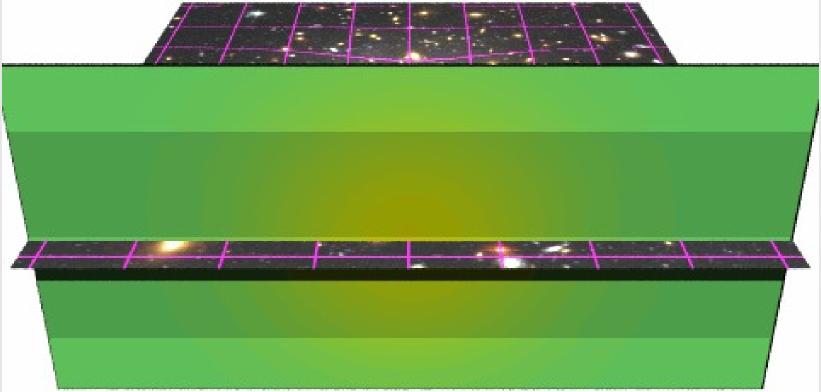


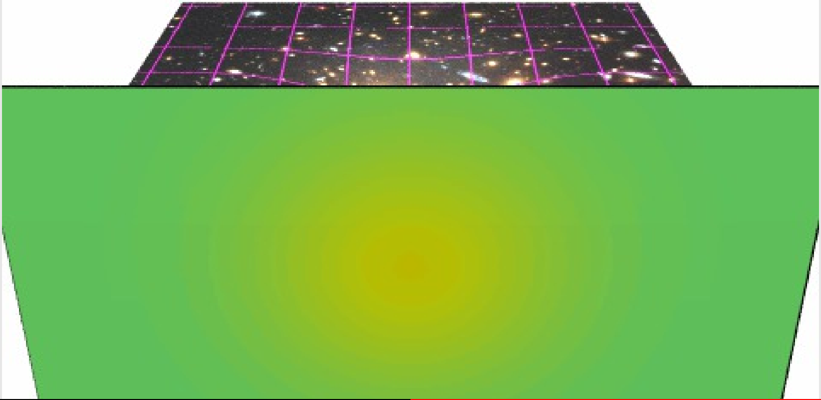




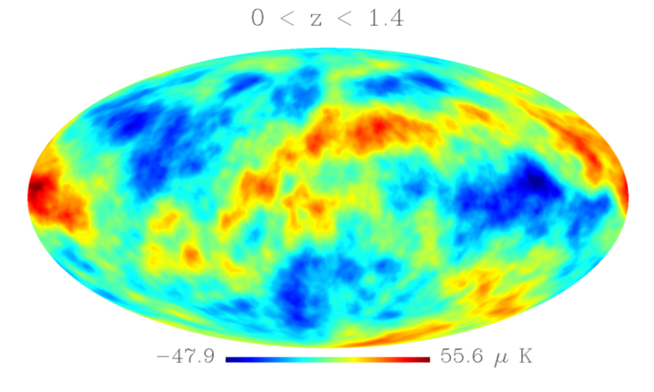






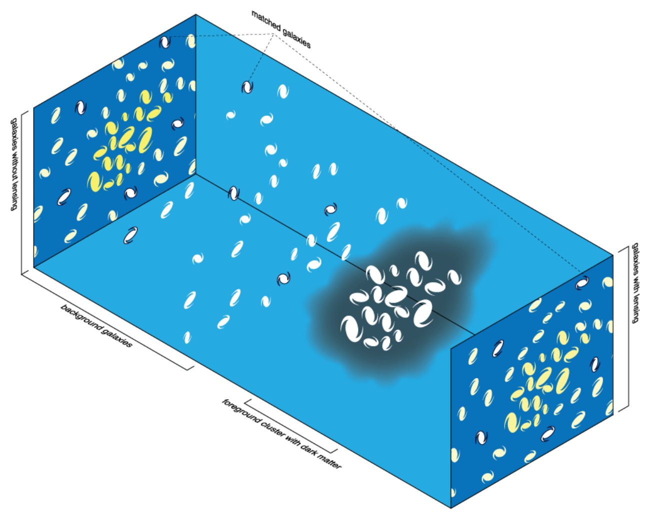


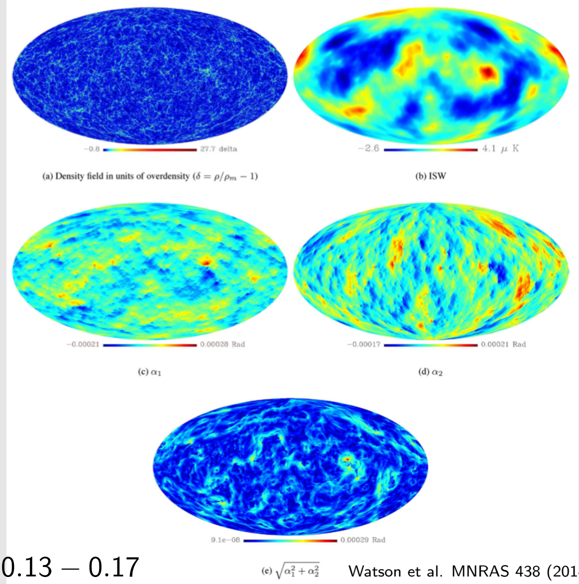
Jubilee full sky ISW signal



Full-sky map of the predicted secondary CMB anisotropies due to the ISW effect.

Weak lensing





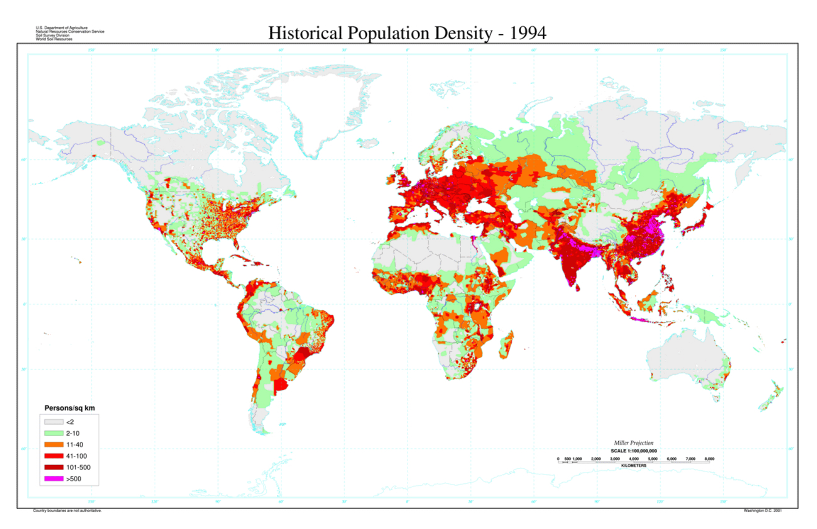
shell $z = 0.13 - 0.17$

Watson et al. MNRAS 438 (2014), 412

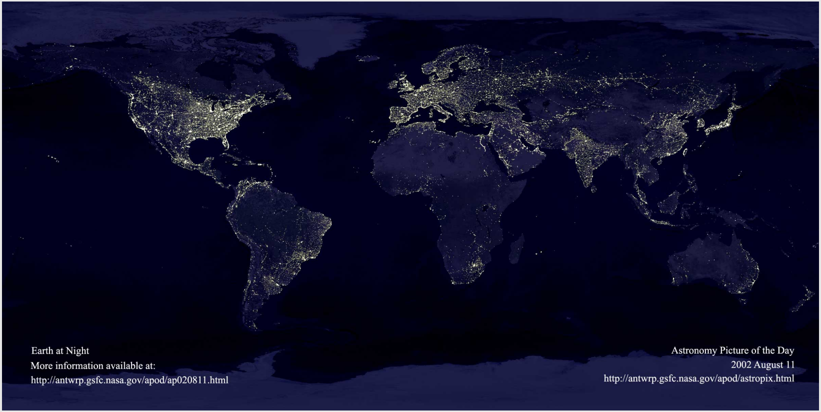
Luminous Red Galaxies (LRGs)

How to put galaxies into a dark matter only simulation?

Earth population density



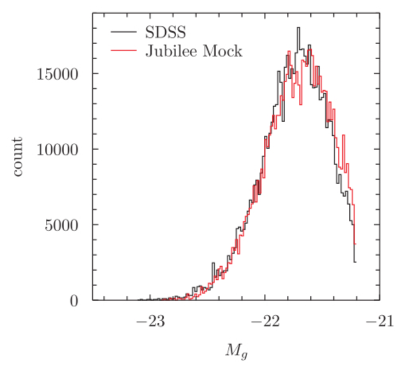
Light at night

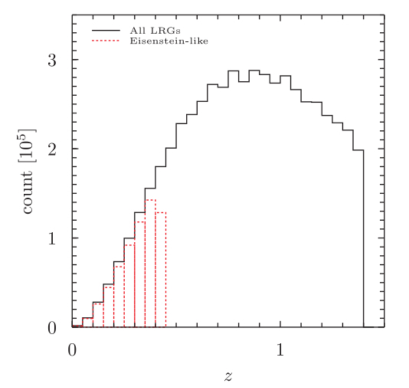


Mock catalogs of LRGs

- Halo Occupation Distribution (HOD) model to select halos which host LRGs
- simple relationship between mass and luminosity: $L \propto M^{\alpha}$, $\alpha = 0.3, 0.5, 1$ in different mass ranges

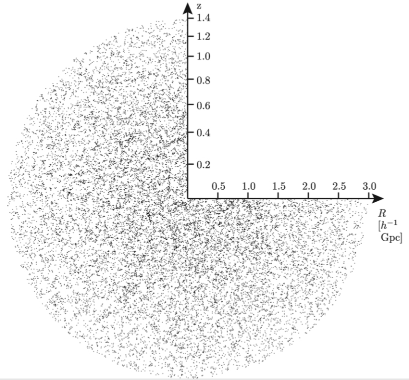
Mock catalogs of LRGs

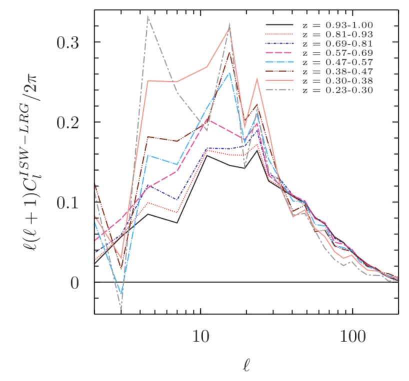




Histogram comparing SDSS LRGs with Jubilee mock LRGs (left) and Jubilee entire sky catalog (right).

ISW correlation with LSS





Left: LRG distribution in a slice of $20h^{-1}\mathrm{Mpc}$.
Right: Cross-correlation between ISW and LRGs.

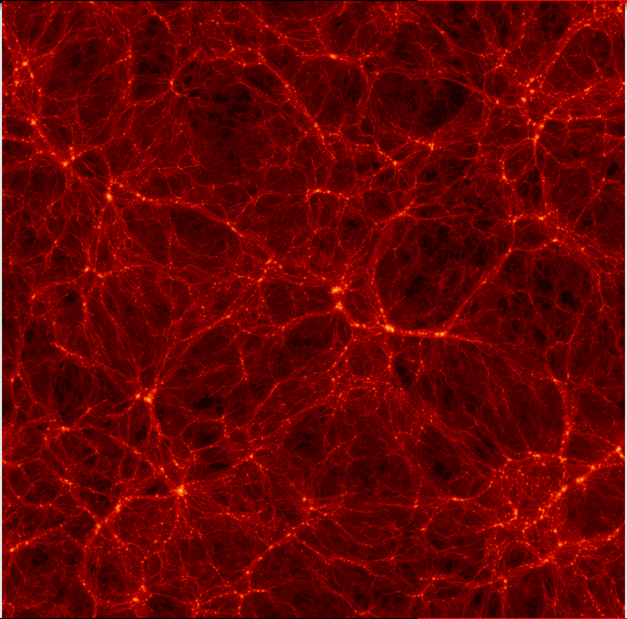
The MultiDark project

A series of DM only simulations

from $250h^{-1}\mathrm{Mpc}$ to $4000h^{-1}\mathrm{Mpc}$ boxes

with 2048^3 to 4096^3 particles

Cosmic Web in 175x130 h^{-1}Mpc



2048^3
$250h^{-1}\mathrm{Mpc}$
WMAP5

B
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h
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i

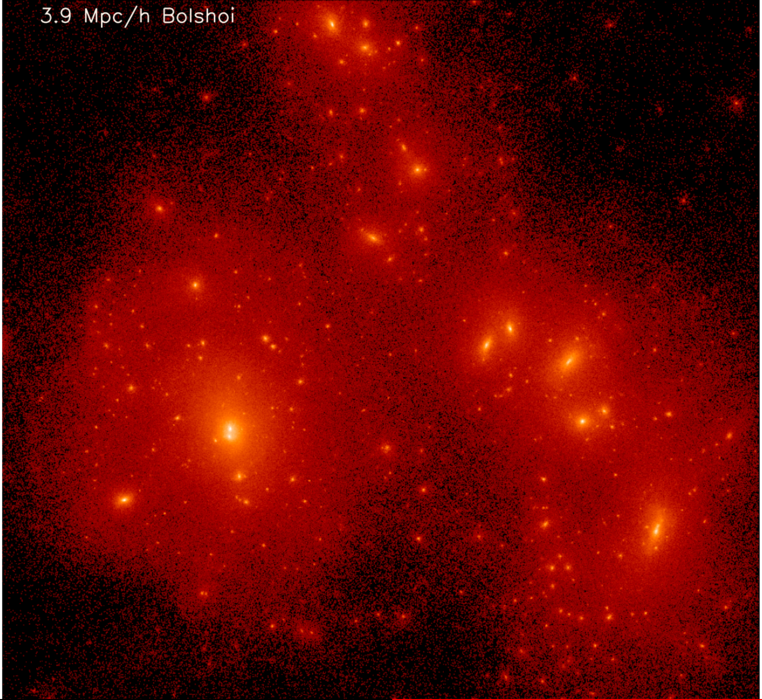
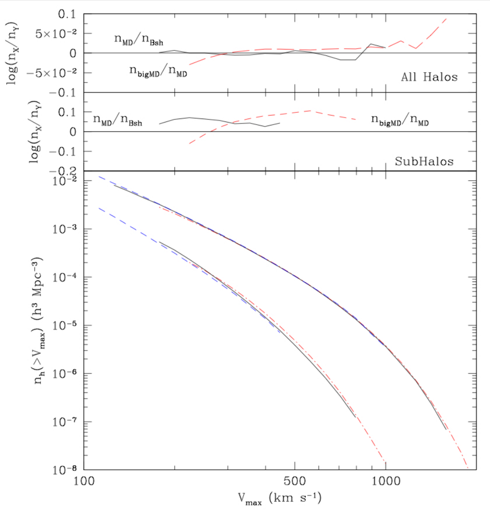

3.9 Mpc/h Bolshoi

Table : Numerical and cosmological parameters for the simulations. The columns give the simulation identifier, the size of the simulated box in $h^{-1}\,\mathrm{Gpc}$, the number of particles, the mass per simulation particle m_p in units $10^{10}h^{-1}\,M_\odot$, the Plummer equivalent gravitational softening length ϵ in units of physical $h^{-1}\,\mathrm{kpc}$, the adopted values for Ω_{Matter}, Ω_{Baryon}, Ω_Λ , the clustering at $8h^{-1}\,\mathrm{Mpc}$, σ_8, the spectral index n_s and the Hubble constant H_0 in $\mathrm{km/s/Mpc}$. The GADGET-2 code has been used, for the simulations with 2048^3 the ART code.

Simulation	box	particles	m_p	ϵ	Ω_M	Ω_B	Ω_Λ	σ_8	n_s	H_0
HugeMDPL	4.0	4096^3	8.0	50.0	0.307	0.048	0.693	0.829	0.96	67.8
BigMD27	2.5	3840^3	2.1	10.0	0.270	0.047	0.730	0.820	0.95	70.0
BigMD29	2.5	3840^3	2.2	10.0	0.289	0.047	0.711	0.820	0.95	70.0
BigMD31	2.5	3840^3	2.4	10.0	0.309	0.047	0.691	0.820	0.95	70.0
BigMDPL	2.5	3840^3	2.4	10.0	0.307	0.048	0.693	0.829	0.96	67.8
BigMDPLnw	2.5	3840^3	2.4	10.0	0.307	0.048	0.693	0.829	0.96	67.8
MDPL	1.0	3840^3	0.15	5	0.307	0.048	0.693	0.829	0.96	67.8
MultiDark (A)	1.0	2048^3	0.87	7.0	0.270	0.047	0.730	0.820	0.95	70.0
SMDPL	0.4	3840^3	0.0096	1.5	0.307	0.048	0.693	0.829	0.96	67.8
BolshoiP (A)	0.25	2048^3	0.015	1.0	0.307	0.048	0.693	0.829	0.96	67.8
Bolshoi (A)	0.25	2048^3	0.013	1.0	0.270	0.047	0.730	0.820	0.95	70.0

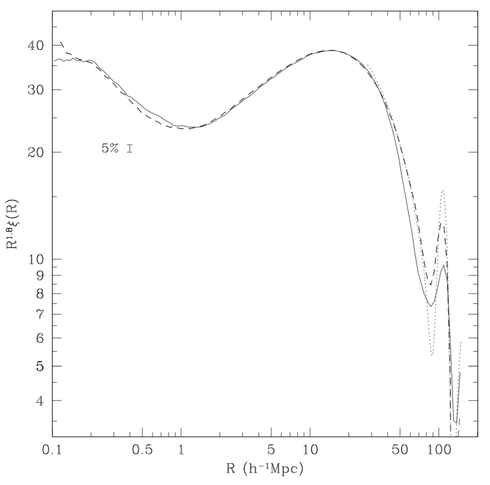
Velocity function of halos



Velocity functions in simulations with different resolution

- solid line: $1h^{-1}\mathrm{Gpc}$, 3840^3
- dot-dashed line: $2.5h^{-1}\mathrm{Gpc}$, 3840^3
- dashed line: $0.4h^{-1}\mathrm{Gpc}$, 2048^3

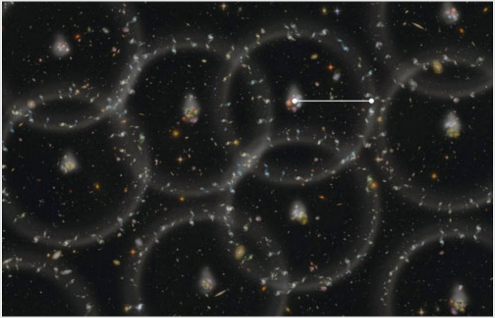
Correlation function of halos



Correlation function of halos with $v_{\max} > 240\,\mathrm{km\ s^{-1}}$

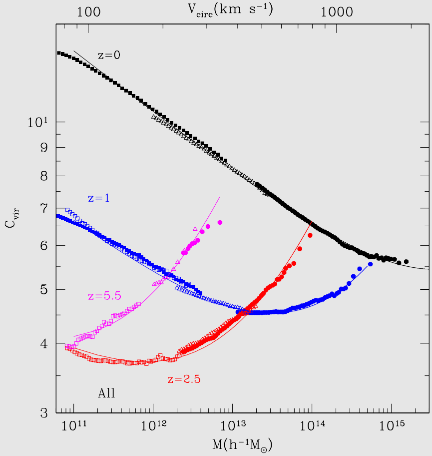
- full lined: $1h^{-1}\mathrm{Gpc}$, 3840^3
- dashed line: $2.5h^{-1}\mathrm{Gpc}$, 3840^3
- dotted line: linear $\xi(r)$ with bias 1.3

Baryonic oscillations (BAO)



Cartoon of BAOs from the BOSS web page

Concentration of halos at different redshifts



Filled squares - SMD
Open squares - BolshoiP
Triangles - MD
Filled circles -BigMD

MUSIC: MUltiDark SImulation of galaxy Clusters
(including gasdynamics into MultiDark)

MUSIC

MUSIC
Marenostrum
MUltidark
SImulations
of galaxy
Clusters

THE MUSIC DATASET

(Sembolini et al., MNRAS, 2013, 429,323)

MARENOSTRUM (MUSIC-1) resimulated clusters
•164 (82 relaxed clusters – 82 'bullet-like')
Only few objects with M > 10^{15} $h^{-1}M_{SUN}$

} cooling + SFR resimulations
(model: Springel & Hernquist, 2003)

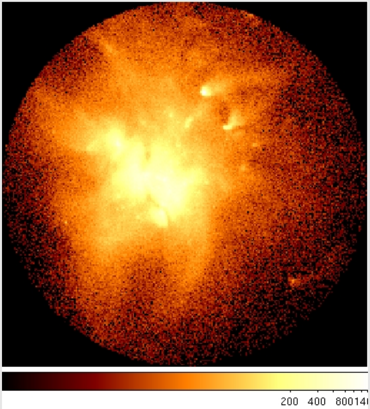
MULTIDARK (MUSIC-2) resimulated clusters
•283 lagrangian regions
•> 500 clusters M > 10^{14} $h^{-1}M_{SUN}$
•> 2000 objects M > 10^{13} $h^{-1}M_{SUN}$

} cooling + star formation (CSFR) & non radiative (NR)resimulations

Many objects with M > $10^{15} h^{-1}$ M_{SUN}
m_{DM}=$9.01\times10^8 h^{-1}M_{SUN}$ - m_{SPH}=$1.9\times10^8 h^{-1}M_{SUN}$
Each cluster described by several millions of particles

700 resimulated clusters with M > 10^{14} $h^{-1}M_{SUN}$ **largest dataset**
of hydrodynamical simulations of galaxy clusters
Large statistics to study baryonic properties and calibrate
scaling relations

MUSIC



- the most massive cluster in the MultiDark simulation as would be seen by Chandra(ACIS-S)
- colored according to photon counts

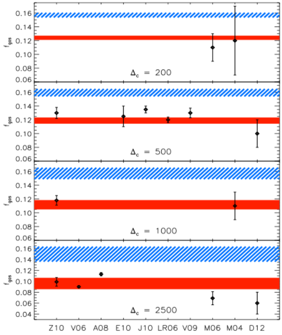
Veronica Biffi (2014)

MUSIC

GAS FRACTION : COMPARISON WITH OBSERVATIONS

CSFR clusters:

- Δ_c=500 f_{gas} = (0.118±0.005)
- f_{gas} compatible with observations at all overdensities (LaRoque 2006 (LR06); Maughan 2006 M(06); Vikhlinin 2006 (V06); Ettori 2010 (E10); Zhang 2010 (Z10))
- f_{star} higher than observational data (0.05 vs 0.01, effect of overcooling?)



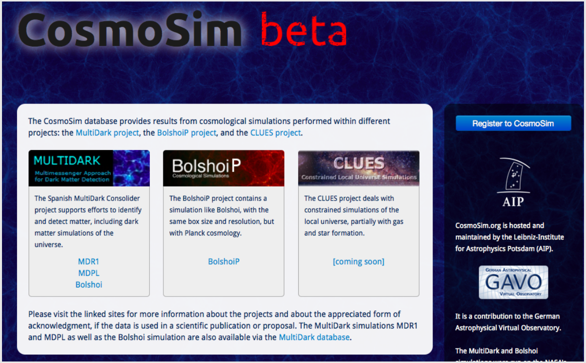
Sembolini et al. 2013

The CosmoSim database at AIP

The challenge — big data

- results from > 150 million core hours (17,000 years)
    - petabytes of raw data
    - terabytes of processed data
    - distributed in archives of different supercomputer centers
    - restricted access (mainly for project participants)
- Where did we run and store simulations
    - NAS Ames (columbia, pleiades)
    - LRZ Munich (hitachi, altix, supermuc)
    - JSC Juelich (jump, juropa)
    - BSC Barcelona (MareNostrum)
    - CEA (curie)

CosmoSim database



http://www.cosmosim.org/

Kristin Riebe, Adrian Partl, Harry Enke

Project supported by MultiDark and the German Astrophysical Virtual Observatory (GAVO)

Simulations performed at LRZ Munich, BSC Barcelona, JSC Juelich, NAS Ames

DB contains catalogs of objects as well as raw data

- FOF
  - catalogs at 4 different linking lengths
    which correspond to different overdensities
  - FOF objects and subhalos
  - supercluster (and clusters within them)
  - merging tree
- spherical overdensity halos (BDM, Rockstar)
  - catalogs (halos and sub-halos)
  - profiles
  - merging trees (coming)
- particles
  - particles on a 1024^3 grid
  - particles of FOF objects (different redshifts, more added on request)

Database Spring 2015

- 31 Tb data + 14 Tb index
- 329 billion rows
- 189 users
- about 2.24 million successful queries
- 450 billion rows (9.5 Tb) downloaded

A very useful tool

TOPCAT

Tool for OPerations on Catalogues And Tables

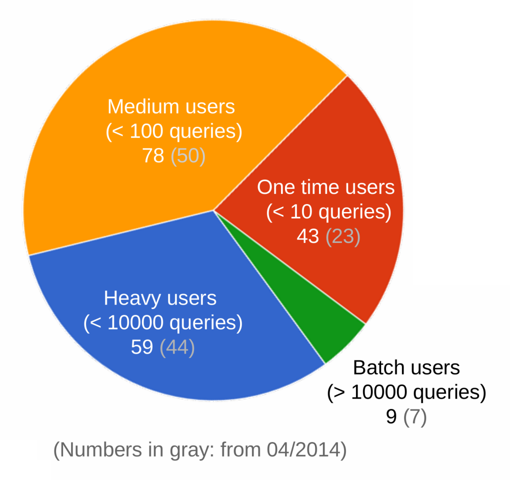
Does what you want with tables

Latest (see Version History for details)

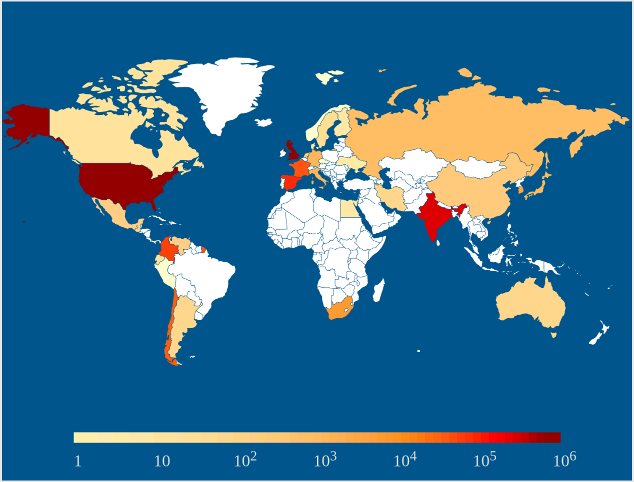
Version 4.2-3 released 14 April 2015

http://www.star.bris.ac.uk/m̃bt/topcat/

Database user statistics

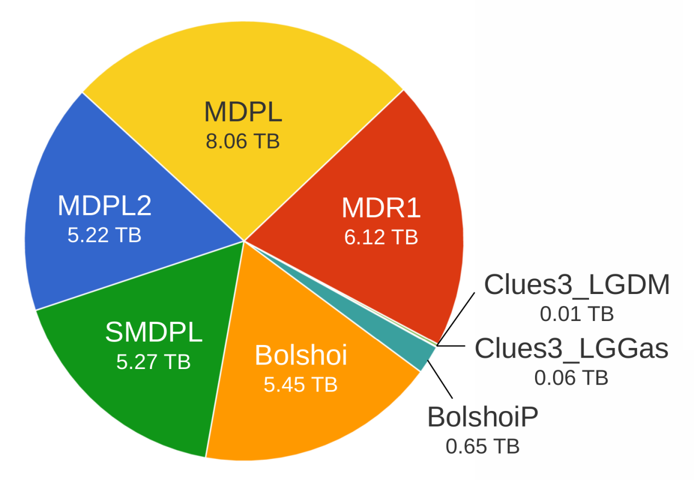


Database user statistics



Number of queries per country

Database datavolume



Summary

Numerical simulations on modern supercomputers are an important tool to study the formation of the observed structures in the universe.
They have been the driving force behind much of the theoretical progress in our understanding of the evolution of structure in the Universe.
Databases become more important in the analysis of large simulations.
There is plenty to do for you!!!!

Proyecto de porvenir

Hay mucho para hacer!