From Large Volume Simulations to Near Field Cosmology

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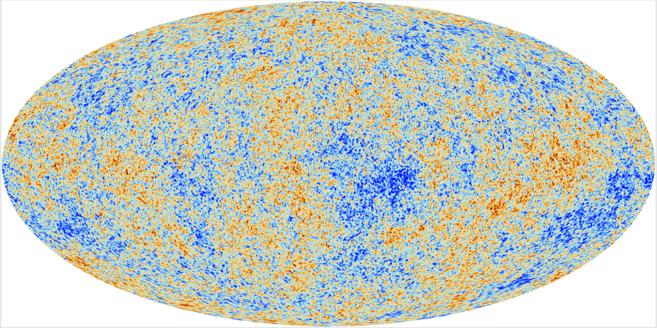
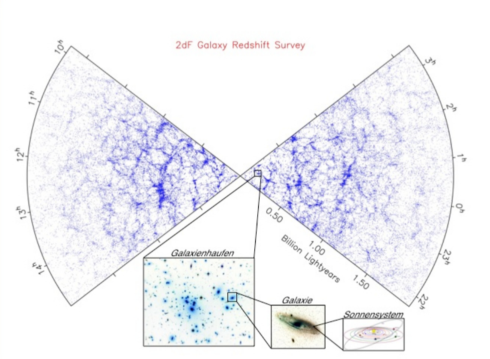
Cosmic Microwave Background (CMB) radiation

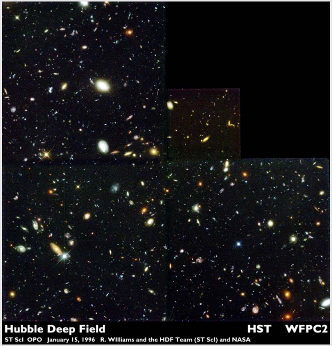


The Cosmic Microwave Background - as seen by Planck. Credit: ESA and the Planck Collaboration

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.

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.
- $\Longrightarrow$ **To describe the formation of structures we need supercomputers**

Dark Energy and Dark Matter

- about 70 per cent of the total energy in the universe is unknown
- this dark energy is responsible for the acceleration of expansion
  - Simplest explanation: Cosmological constant (= vacuum energy = additional constant term in Einstein's field equation)
- about 85 per cent of all matter must be dark
- dark matter is responsible for the formation of large scale structure
- dark matter must be made of
  - weakly interacting non-baryonic more or less cold $\Longrightarrow$ **small scale structure**

  particles

Jan Oort, 1932, computational astrophysics with dark matter

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.

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 - gravity only)
  - Baryons (observed but difficult to handle - gravity + hydro + subgrid models - HESTIA simulations)

The numerical challenge in dark matter only simulations

- run simulations with billions of particles
- find objects in the distribution of billions of particles
- halo finder
  - Friends of Friends
    - first halofinder
    - hierarchical FOF and/or 6D
    - merging history
  - Spherical Overdensity
    - halos + subhalos + subsubhalos ...
    - merging history
- put galaxies into dark matter halos (semianalytical models, abundance matching, ...)

From Large Volumes to Near Field Cosmology

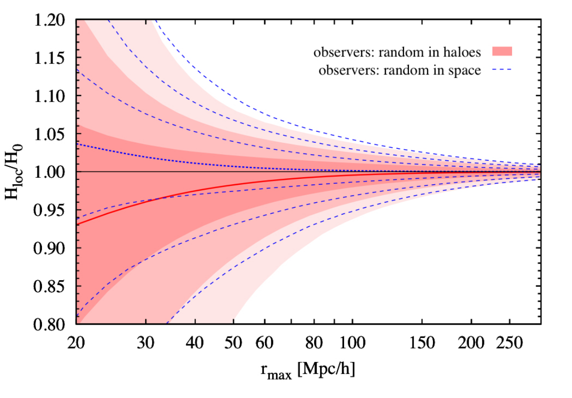
JUBiLEE: JUropa huBbLE volumE

An N-body simulation with 216 billion particles

in a volume of $(6000h^{-1}\mathrm{Mpc})^3$

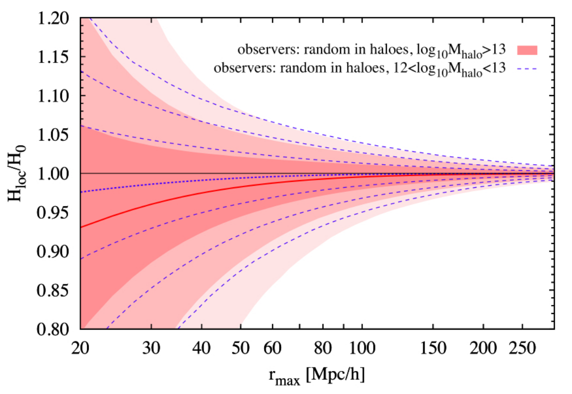
http://jubilee.ft.uam.es/

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 MultiDark project

A series of DM only simulations

from $64h^{-1}\mathrm{Mpc}$ to $4000h^{-1}\mathrm{Mpc}$ boxes

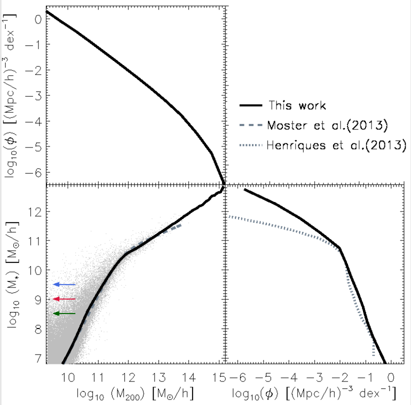
with 3840^3 or 4096^3 particles

assuming Planck cosmology

Table of MulitiDark simulations

Simulation	box $[h^{-1}\,\mathrm{Mpc}]$	particles	$m_p\ [h^{-1}\,M_\odot]$	$\epsilon\ [h^{-1}\,\mathrm{kpc}]$
HMD	4000	4096^3	8.0×10^{10}	50.0
BigMD	2500	3840^3	2.4×10^{10}	10.0
MD	1000	3840^3	1.5×10^{9}	5
SMD	400	3840^3	9.6×10^{7}	1.5
VSMD	160	3840^3	6.2×10^{6}	1.0
ESMD	64	2048^3	2.6×10^{6}	1.0
ESMD	64	4096^3	3.2×10^{5}	

Semianalytical (SAG) dwarfs in SMD



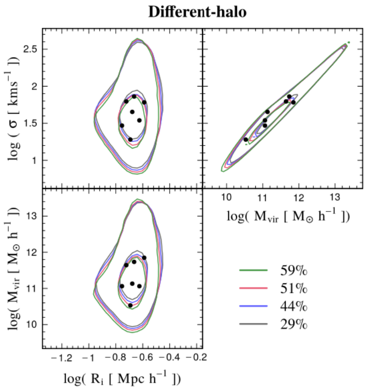
Yaryura et al, in prep.

Systems of dwarfs

- FOF with fixed kinking length of $0.4h^{-1}\mathrm{Mpc}$
- three samples with different maximum stellar mass (i.e. if any of the members of the FOF-group has a higher stellar mass the FOF-group is excluded)
  - $\log_{10}(M_{\max}[\mathrm{M}_\odot\ h^{-1}]) = 8.5$, 366713 systems
  - $\log_{10}(M_{\max}[\mathrm{M}_\odot\ h^{-1}]) = 9.0$, 606320 systems
  - $\log_{10}(M_{\max}[\mathrm{M}_\odot\ h^{-1}]) = 9.5$, 850856 systems

Yaryura et al, in prep.

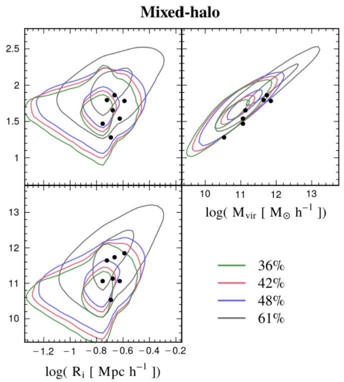
Dwarf associations



Associations: All dwarfs are in different DM halos. Black filled circles: seven dwarf galaxy associations from Tully et al. 2006

Yaryura et al, in prep.

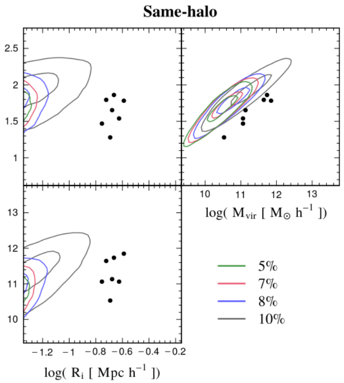
mixed sample



Black filled circles: seven dwarf galaxy associations from Tully et al. 2006

Yaryura et al, in prep.

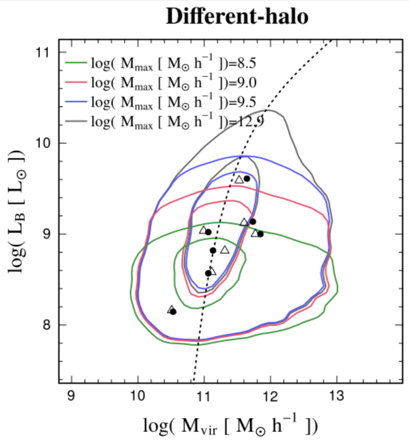
Groups of dwarfs

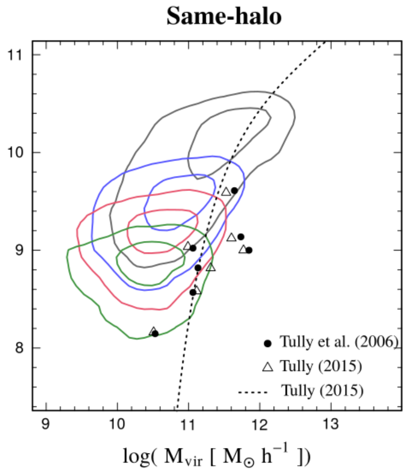


Groups: All dwarfs are in the same DM halo. Black filled circles: seven dwarf galaxy associations from Tully et al. 2006

Yaryura et al, in prep.

B-band luminosity vs. virial mass

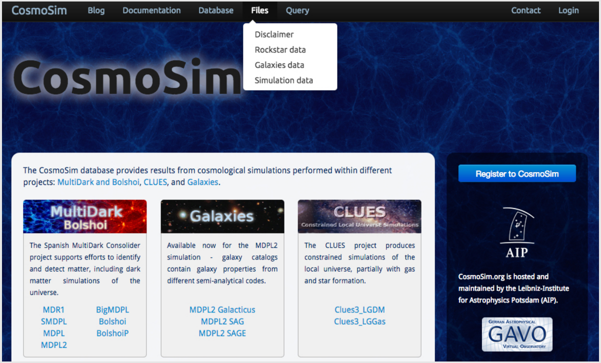




Associations and groups of dwarfs, Yaryura et al, in prep.

The CosmoSim database at AIP

CosmoSim database



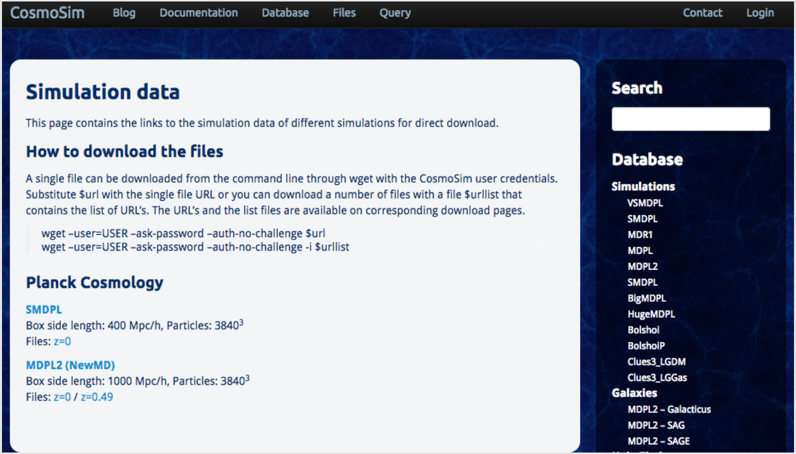
http://www.cosmosim.org/

Kristin Riebe, Anastasia Galkin, Adrian Partl, Jochen Klar, Harry Enke

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

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

CosmoSim simulation data



https://www.cosmosim.org/cms/files/simulation-data

Simulations performed at LRZ Munich

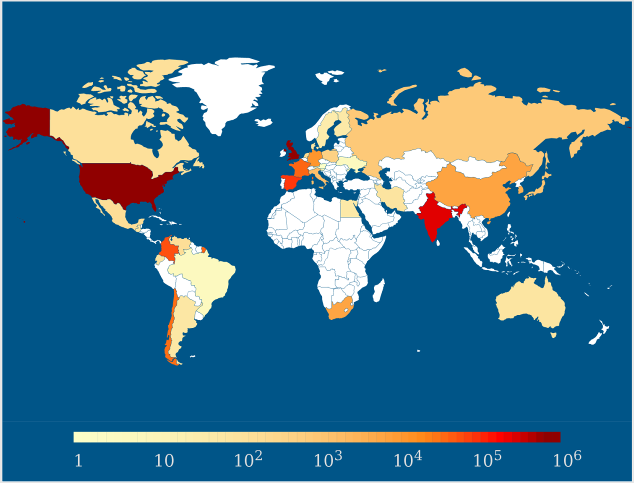
DB contains catalogs of objects as well as raw data

- FOF
  - catalogs at 4 different linking lengths (different overdensities)
  - FOF objects and subhalos
  - supercluster (and clusters within them)
  - merging tree
- spherical overdensity halos (BDM, Rockstar)
  - catalogs (halos and sub-halos)
  - profiles, shapes, spins, etc.
  - merging trees
- galaxies (SAMs described in Knebe et al. MNRAS **474** (2018) 5206)
  - GALACTICUS
  - SAG
  - SAGE

Database, August 2019

- 45 Tb data + 19 Tb index
- 378 billion rows
- 764 registrations
  - 317 users with more than 10 queries
  - 108 users with more than 100 queries
- millions of successful queries
- 1.8 Tb in user tables

Database user statistics



Number of queries per country (Spring 2017)

Near Field Cosmology

Why are we interested in the Local Universe?

- The local neighbourhood of the Milky Way is the most well known piece of the universe.
- Thus it is an ideal place to test on small scales models of structure formation against observations, for example number of dwarfs in the local volume.
- However, the local universe is not a representative part of the universe. It is dominated by the Local Group with two massive galaxies, the huge Local Void and a few clusters which build together the Laniakea Supercluster (Brent Tully, lani = sky, heaven, akea = broad, wide).
- Constrained simulations are an ideal tool to compare theoretical predictions (computer experiments) with local observations

A short (and incomplete) history of constrained simulations

- Kolatt T. et al. APJ 458 (1996), 419, "Simulating our Cosmological neighborhood: Mock catalogs for velocity analysis"
- Bistolas V., Hoffman Y., APJ 492 (1998), 439 "Nonlinear constrained realisations of the large scale structure"
- Klypin A. et al, APJ 596 (2003), 19, "Constrained Simulations of the Real Universe: the Local Supercluster"
- Lavaux G., MNRAS 406 (2010), 1007 "Precision constrained simulation of the local universe"
- Heß S. et al., MNRAS 435 (2013), 2065 "Simulating Structure Formation of the Local Universe"
- Wang H. et al., APJ 794 (2014), "ELUCID - Exploring the Local Universe with reConstructed Initial Density field I: Hamiltonian Markov Chain Monte Carlo Method with Particle Mesh Dynamics"

CLUES

AIP

CLUES
Constrained Local UniversE Simulations

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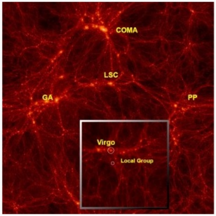
CLUES – Constrained Local UniversE Simulations

The Local Group and its environment is the most well observed region of the universe. Only in this unique environment can we study structure formation on scales as small as that of very low mass dwarf galaxies. The main goal of the CLUES-project is to provide constrained simulations of the local universe designed to be used as a numerical laboratory of the current paradigm. The simulations will be used for unprecedented analysis of the complex dark matter and gasdynamical processes which govern the formation of galaxies. The predictions of these experiments can be easily compared with the detailed observations of our galactic neighborhood.

Executive Board of the Collaboration:
Jenny Sorce, Noam Libeskind, Alexander Knebe, Hélène Courtois, Gustavo Yepes, Yehuda Hoffman, Stefan Gottlöber



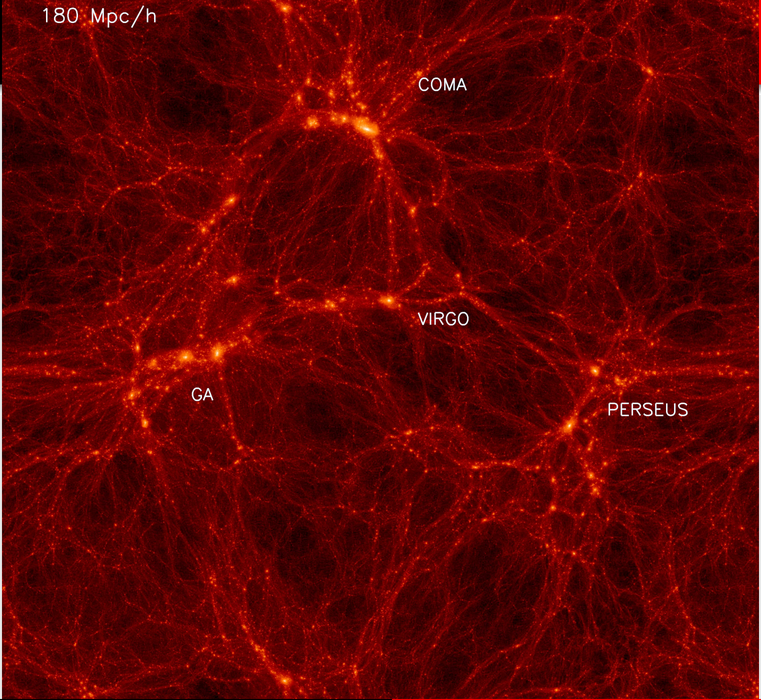
Dark matter distribution in our Local Universe in two different simulations: a box with 160 Mpc/h side length (big picture) and with 64 Mpc/h side length (inset panel).

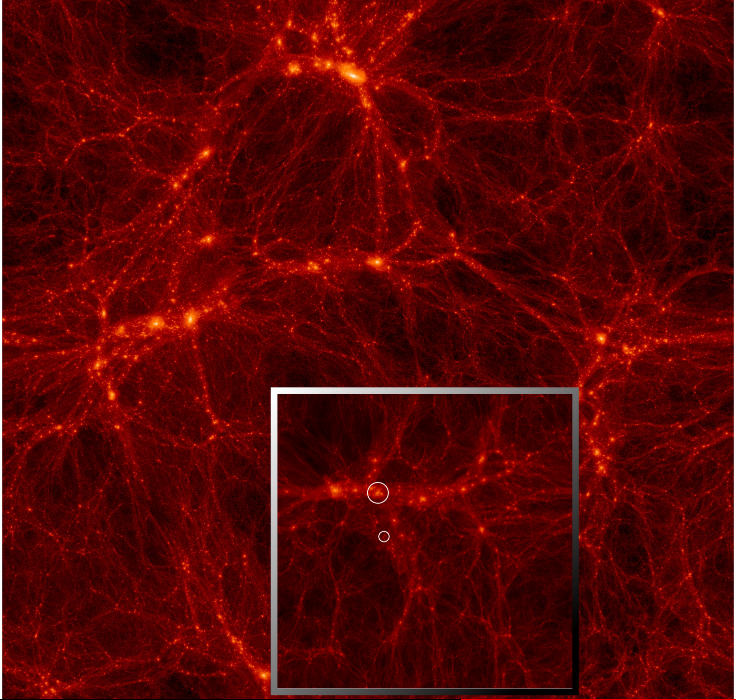
See the Image Gallery for more information and further images.

Observational data and constraints for CLUES

- Wiener Filter (Zaroubi et al., 1995)
- Hoffman-Ribak algorithm (Hoffman & Ribak, 1991)
- Radial velocity field (MARK III, Willick et al., 1997, Tonry 2001, Karachentsev 2004)
- Nearby cluster positions (Reiprich & Böhringer, 2002)

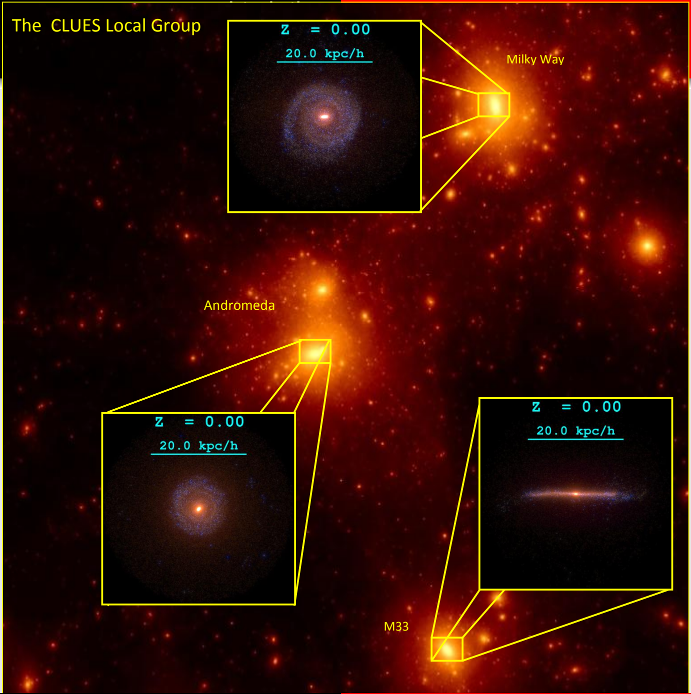
- CosmicFlows-2 (Tully et al. 2013)
- Reverse Zeldovich Approximation (Doumler et al. 2012, Sorce et al 2014)
- Grouping of velocity data (Tully 2014, Sorce,Tempel 2017)
- Malmquist bias correction (Sorce 2015)
- CosmicFlows-3 (Tully, Courtois, Sorce 2016)


180 Mpc/h
COMA
VIRGO
GA
PERSEUS



$160 h^{-1}$Mpc
Anatoly
Klypin

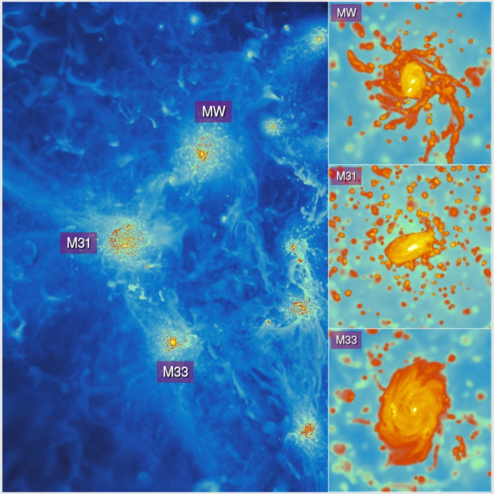
$64 h^{-1}$Mpc
Gustavo
Yepes



The CLUES Local Group
Z = 0.00
20.0 kpc/h
Milky Way
Andromeda
Z = 0.00
20.0 kpc/h
Z = 0.00
20.0 kpc/h
M33

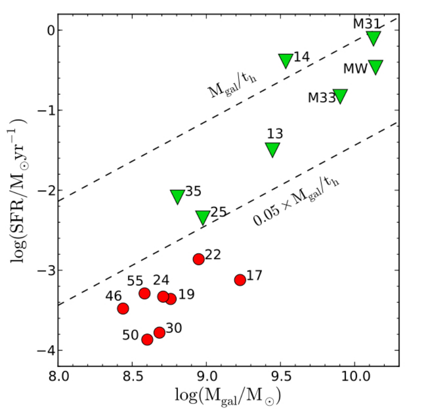
The Local Group simulations

Gas distribution in the local group



- box $64h^{-1}\mathrm{Mpc}$
- 4096^3 particles locally
- DM particles: $2.1 \times 10^5 h^{-1}\mathrm{M}_\odot$
- gas particles: $4.4 \times 10^4 h^{-1}\mathrm{M}_\odot$
- force resolution: $0.15h^{-1}\mathrm{kpc}$

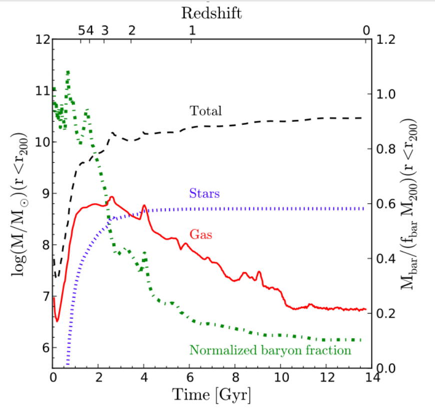
Dwarfs in the Local Group



Alejandro Benitez-Llambay et al. (2013)

- isolated dwarfs without interactions with one of the massive galaxies in the past
- all within a sphere of R = 1.5 Mpc/h of the center of the Local Group
- triangles: galaxies that form stars at rates comparable to their past average
- circles: star formation has largely ceased

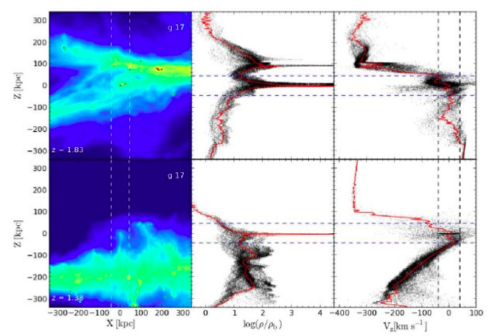
Dwarfs in the Local Group



Alejandro Benitez-Llambay et al. (2013)

- masses within the virial radius of galaxy "30"
- sudden loss of baryons at $z \approx 2$
- ram pressure arising from crossing a large-scale pancake

Cosmic web stripping

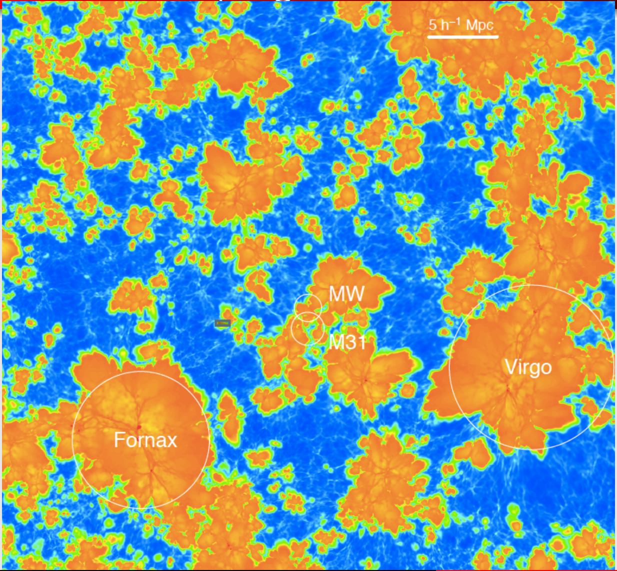


Alejandro Benitez-Llambay et al. (2013), movies made by Alejandro

- gas from the halo is removed by the cosmic web environment due to ram pressure
- **Cosmic Web Stripping**

Reionisation of the Local Group

Cosmic Dawn (Virgo, Fornax, Andromeda, Milky Way)

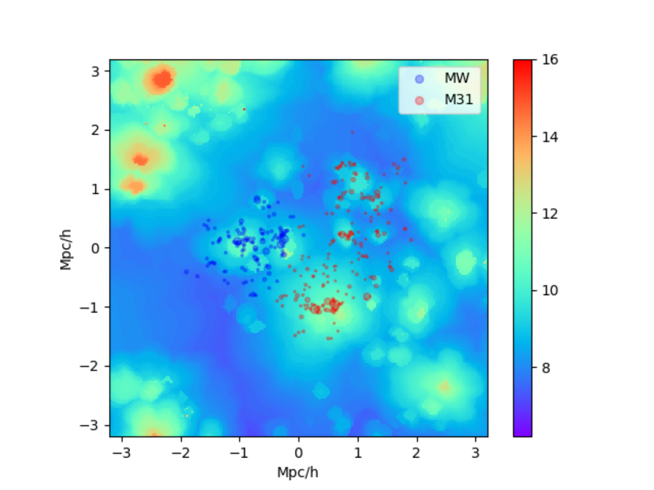


4096^3 particles in $64h^{-1}$Mpc box

Temperature distribution at z$=$ 6.15

orange: photo-heated,ionized
blue: cold, neutral

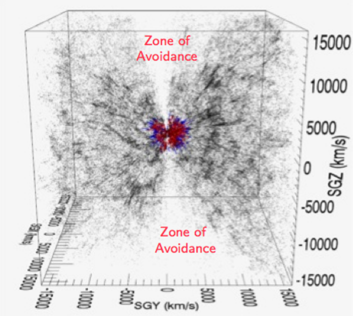
Pierre Ocvirk et al. (2016)



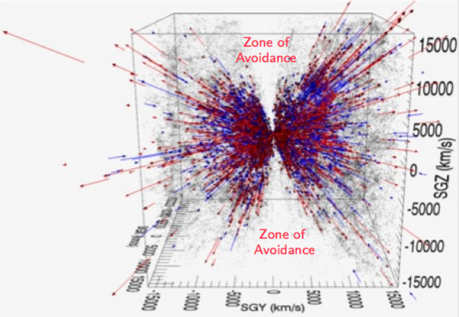
Dominique Aubert: CODA I-AMR radiative hydrodynamics simulation

CLUES with CosmicFlows

CosmicFlows

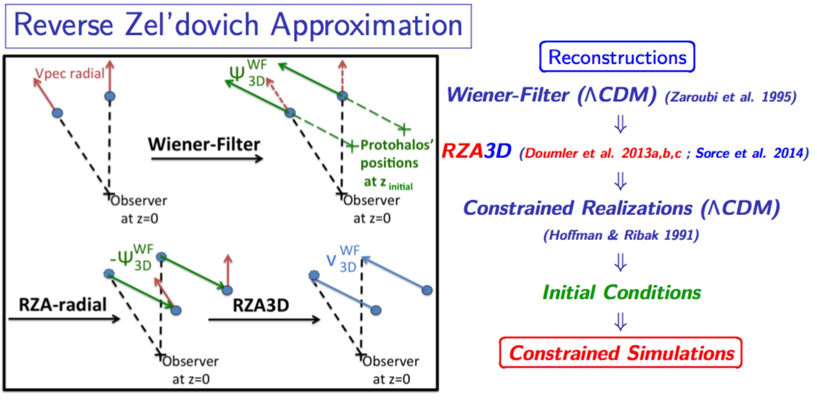


Cosmicflows-1
about 2000 constraints
Tully et al. 2008



Cosmicflows-2
about 8000 constraints
Tully et al. 2013

RZA

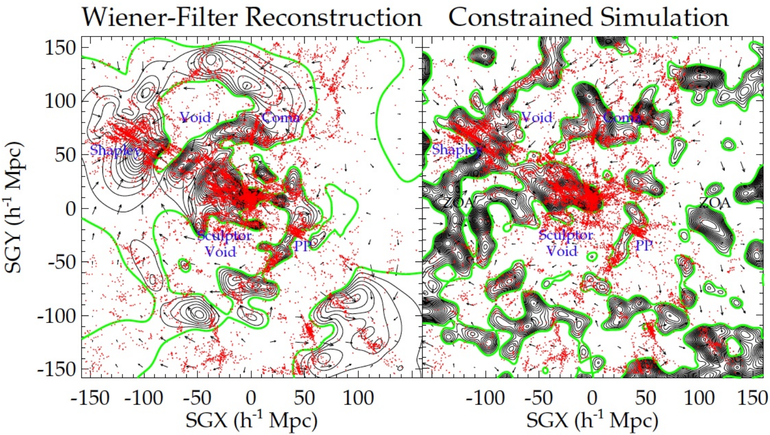


Jenny Sorce (2014)

CLUES with CF2

Sorce et al. 2016a

At z = 0



Observations for comparisons: redshift catalog ●

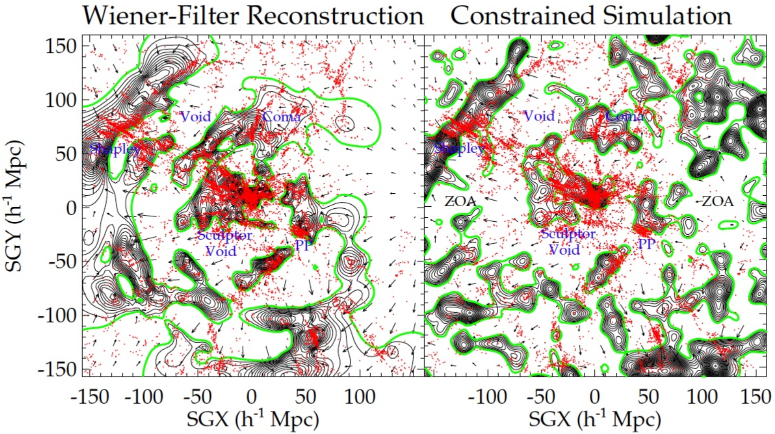
Observations to constrain = Peculiar Velocities: CF2 catalog

Reconstruction: L=500 h^{-1} Mpc, n=256^3, linear field (contours, arrows)

Simulation: L=500 h^{-1} Mpc, n=512^3, full field (contours, arrows)

Using CF3

At z = 0



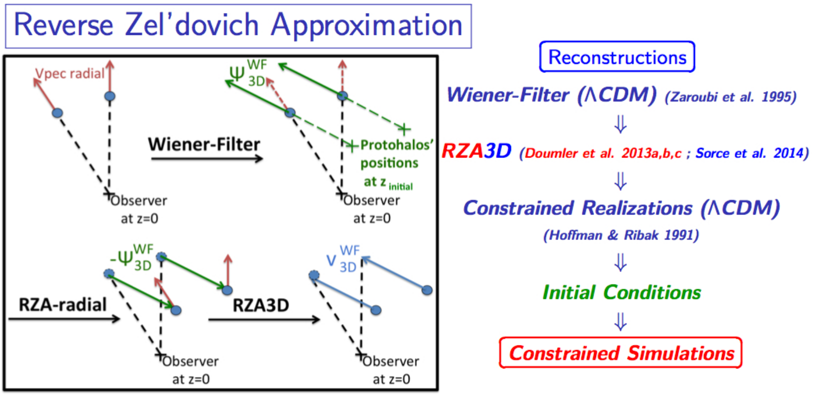
Observations for comparisons: redshift catalog ●

Observations to constrain = Peculiar Velocities: **CF3** catalog

Reconstruction: L=800 h^{-1} Mpc, n=256^3, linear field (contours, arrows)

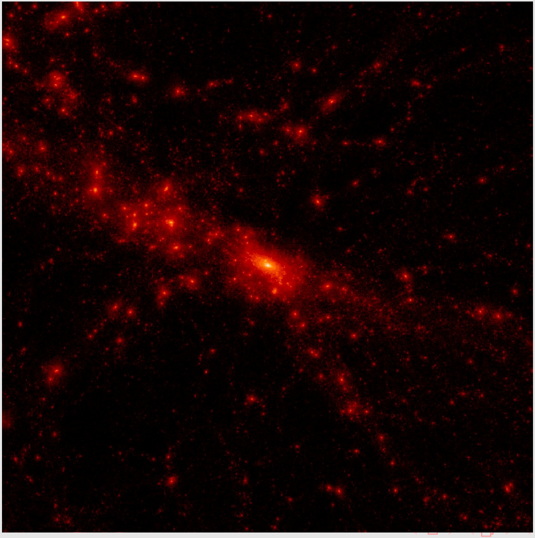
Simulation: L=500 h^{-1} Mpc, n=512^3, full field (contours, arrows)

RZA

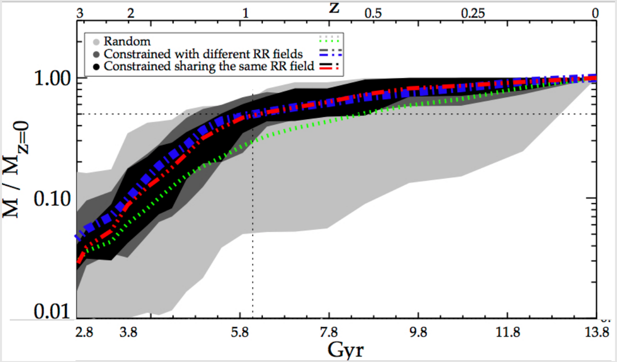


Jenny Sorce (2014)

Virgo cluster in CF2 constrained simulations

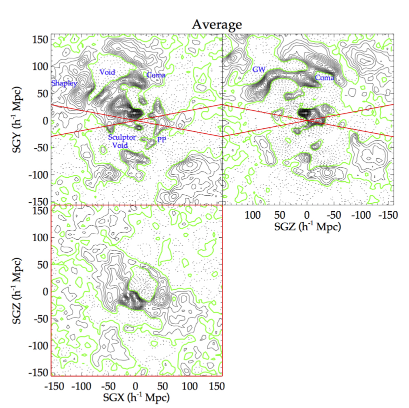


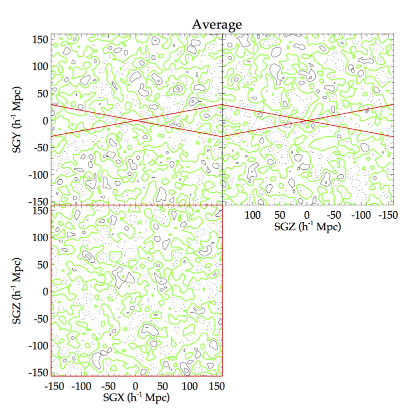
Virgo merging history



Jenny Sorce et al (2016)

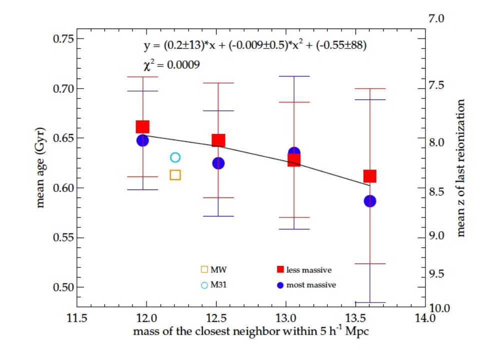
Predicting structures in the ZOA





Averaged overdensity fields (black solid contours) of 200 constrained (left) and 200 random (right) realizations in slices centered on the observer (Sorce et al 2017).

Reionisation as function of environment



Mean redshift of reionisation of Local Group simulacra

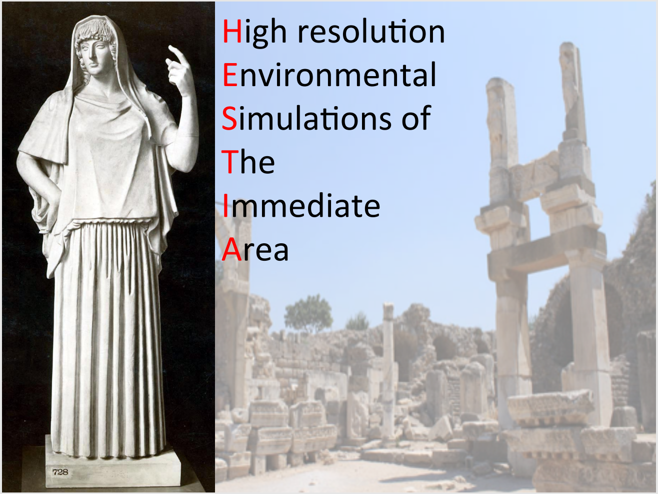
Jenny Sorce et al (in prep.)

The Local Group factory

- What is the local group factory?
  - a series of DM only constrained simulations of the Local Volume with different small scale structure
- Why do we need a local group factory?
  - correct relative masses of the LG members
  - correct relative distances of the LG members
  - correct infall velocity of the LG members
  - quite merging history

Edoardo Carlesi et al (2016)

HESTIA: Noam's talk



Thanks to my collaborators

Yamila Yaryura

Summary

- Constrained numerical simulations are an important tool to study the formation of local structures like the Virgo cluster and the Local Group as well as local dwarfs and the Local Void.
- The CosmicFlows data together with improved reconstruction technique substantially improved and will further improve the quality of our constrained simulations
- An increasing number of both constrained and unconstrained simulations are available at the CosmoSim database of AIP.