

# The CLUES-Project

## Constrained Local UniversE Simulations

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Copenhagen  
May 11, 2015

# Collaborators

- the CLUES collaboration
- <http://www.clues-project.org/people.html>  
“A collaboration is nothing without the people contributing to it, sharing ideas and working together”

# CLUES



**AIP** 

**CLUES** People Simulations Talks Articles Image Gallery Movies Observations

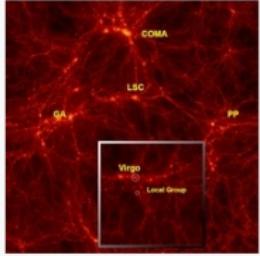
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## CLUES - Constrained Local UniversE Simulations

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.

[Stefan Gottlöber](#) [Hélène Courtois](#) [Yehuda Hoffman](#) [Anatoly Klypin](#) [Gustavo Yepes](#)



*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.*

[News](#)

# CLUES authors



## ① Constrained Simulations

## ② The Local Volume simulations

## ③ The Local Group simulations

## ④ Outlook

# 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

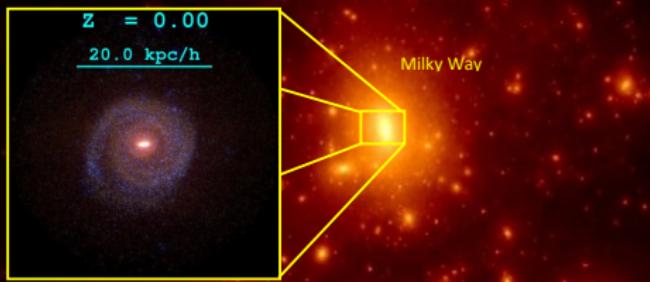
- Kolatt T. et al. APJ 458 (1996), 419, “Simulating our Cosmological neighborhood: Mock catalogs for velocity analysis”
- Bistolas V., Hoffman Y., APJ 492 (1998), 439 “Nonlinear constrained realisations of the large scale structure”
- Klypin A. et al, APJ 596 (2003), 19, “Constrained Simulations of the 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”



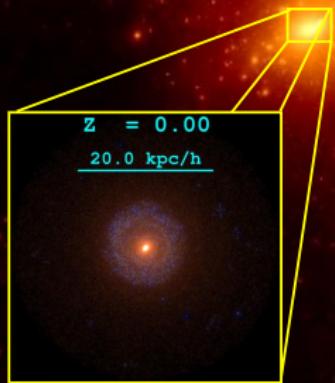
# CLUES

Constrained Local UniversE Simulations

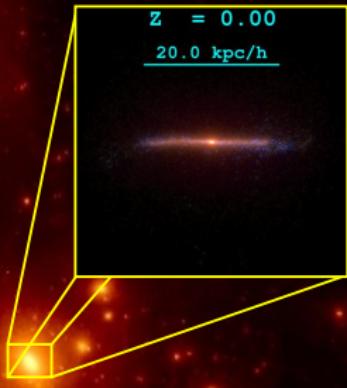
## The CLUES Local Group



Andromeda



M33



# 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 (Courtois, Tully 2013)
- Reverse Zeldovich Approximation (Doumler et al. 2012, Sorce et al 2014)
- Grouping of velocity data (Tully 2014)
- Malmquist bias correction (Sorce 2015, Saturday afternoon discussion)

180 Mpc/h

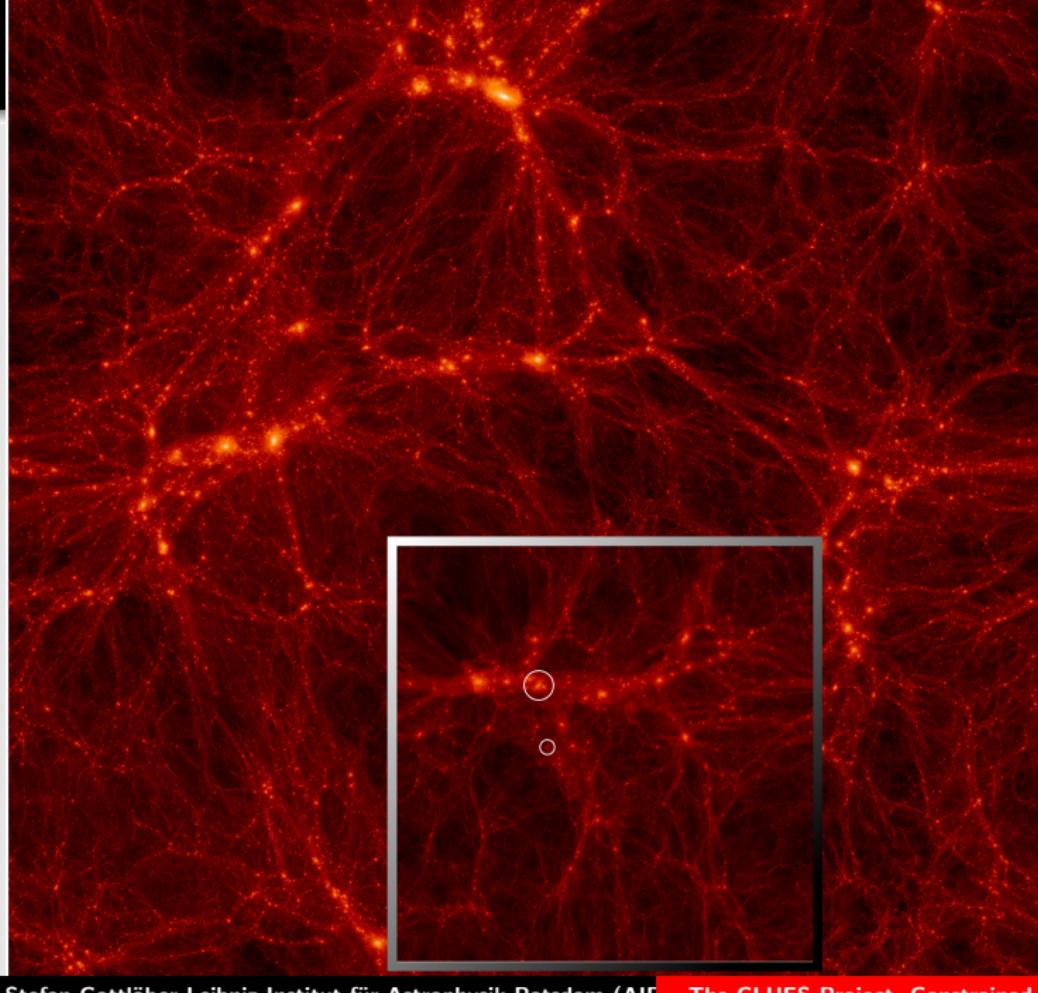
COMA

VIRGO

GA

PERSEUS



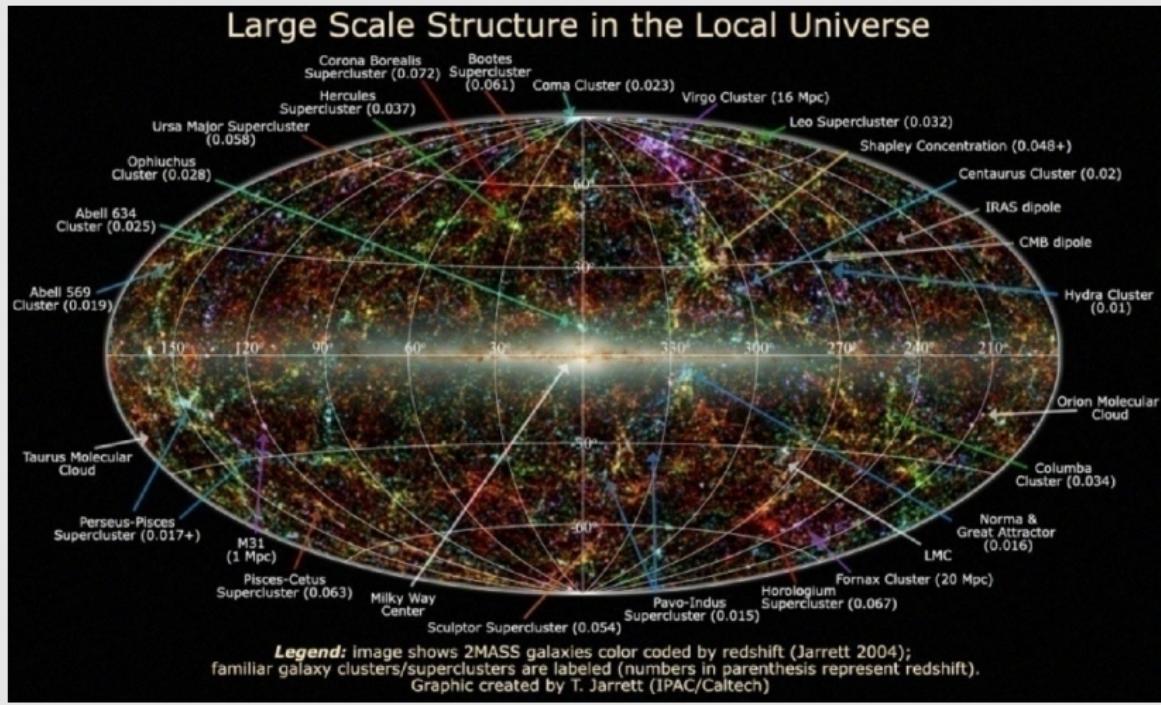


$160 h^{-1}\text{Mpc}$   
Anatoly  
Klypin

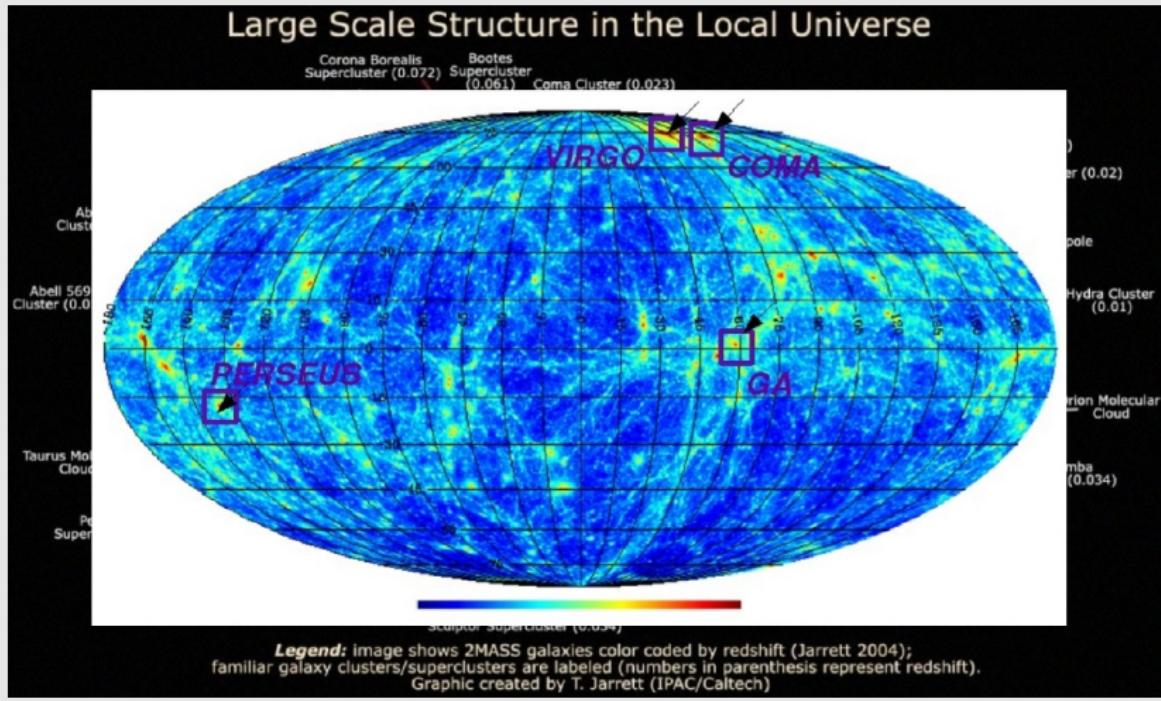
$64 h^{-1}\text{Mpc}$   
Gustavo  
Yepes

# The Local Volume simulations

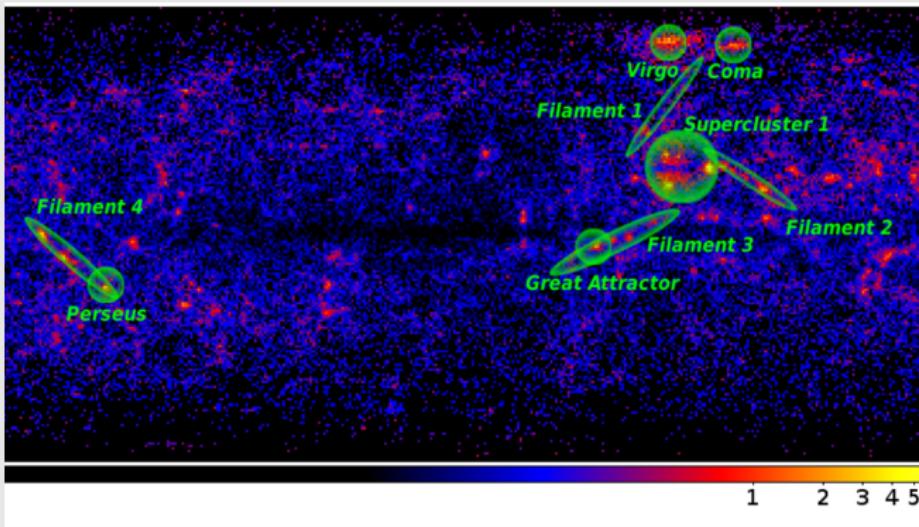
# The Local Volume



# The Local Volume



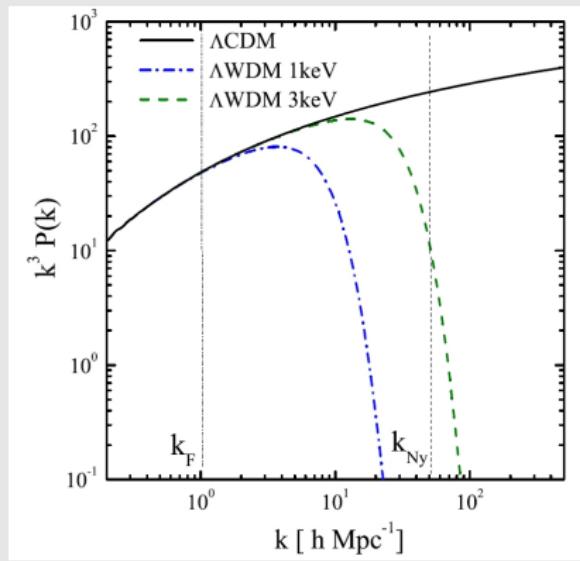
# Fermi Simulation



Gamma-ray photon counts (100 MeV - 10 GeV) which Fermi would detect in 5 years of an all sky survey

Cuesta et al. ApJ 2011

# Cold vs. Warm Dark Matter

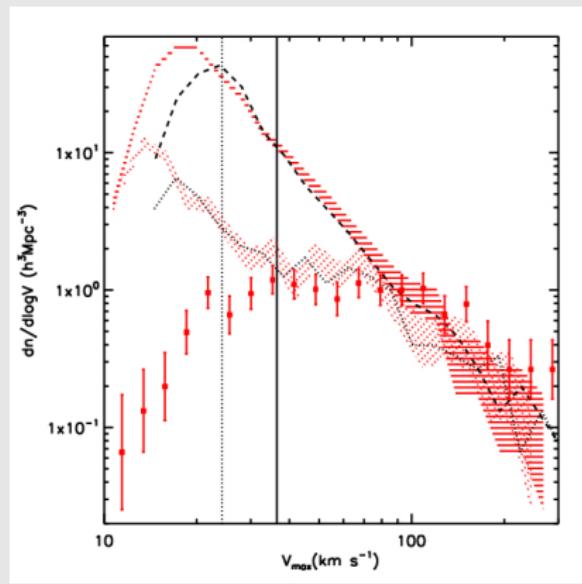


WMAP3

- $h = 0.73$
- $\Omega_m = 0.24$
- $\Omega_{bar} = 0.042$
- $\sigma_8 = 0.75$
- $n = 0.95$
- $m_{WDM} = 1 \text{ keV}$  lower limit
- $k_{\text{peak}} = 3.7 h \text{ Mpc}^{-1}$

less small scale power  $\implies$  less small scale structure

# ALFALFA observations in Virgo direction



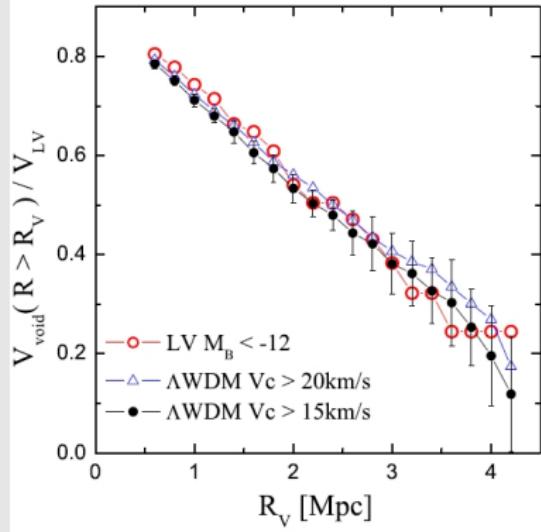
Zavala et al. (2009)

## velocity function

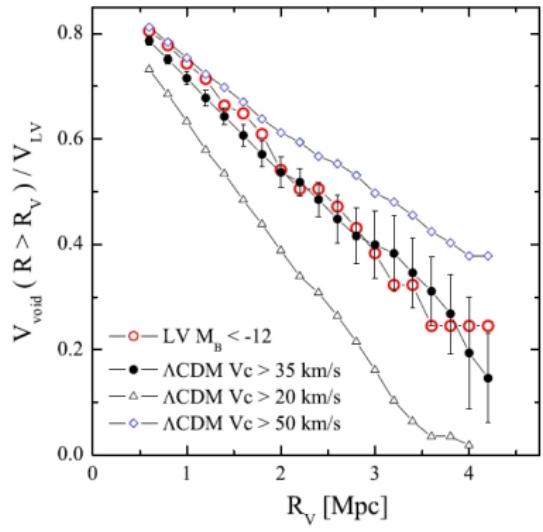
- squares with error bars: galaxies taken from the ALFALFA catalog with distances lower than  $20h^{-1}\text{Mpc}$
- predictions from the constrained simulation
  - $\Lambda\text{CDM}$ : dashed red area
  - $\Lambda\text{WDM}$ : dotted red area
  - dashed/dotted line: disk baryon fraction as function of halo mass (SN feedback)

# Spectrum of mini-voids in the local volume $R < 8h^{-1}\text{M}_\odot$

Warm Dark Matter



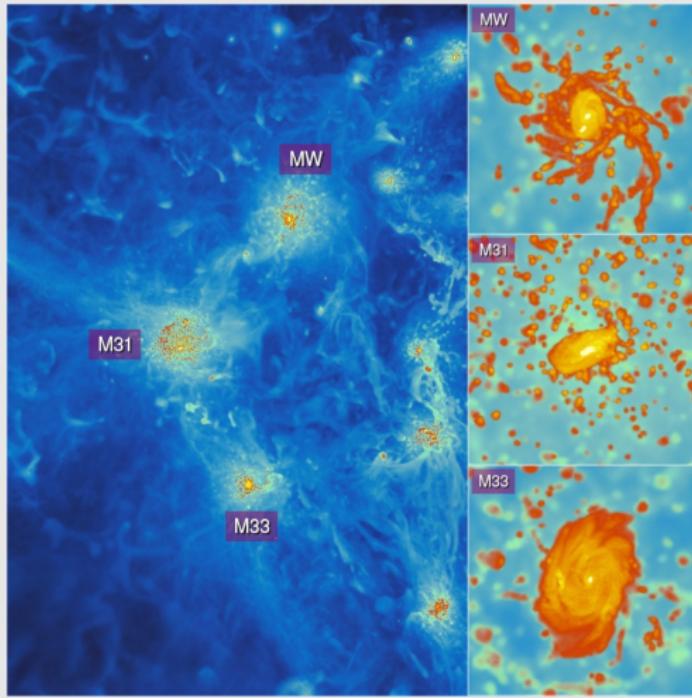
Cold Dark Matter



Tikhonov and Klypin (2009), Tikhonov et al. (2009)

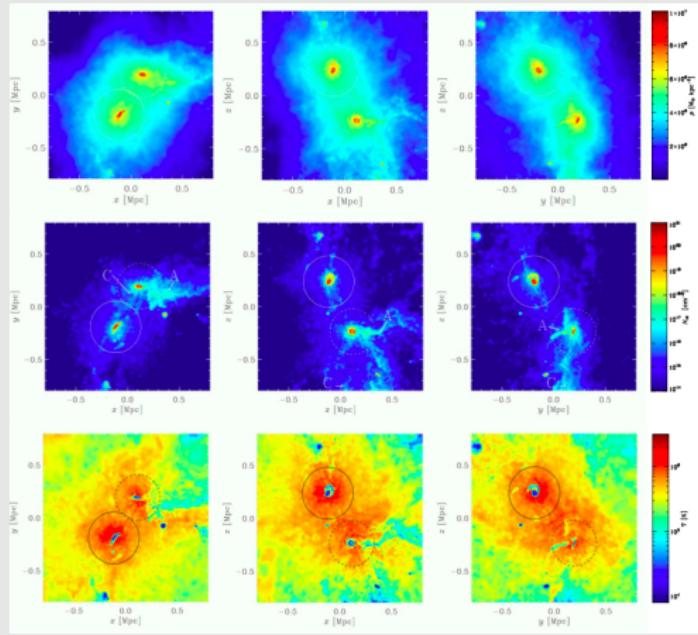
# The Local Group simulations

# Gas distribution in the local group



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

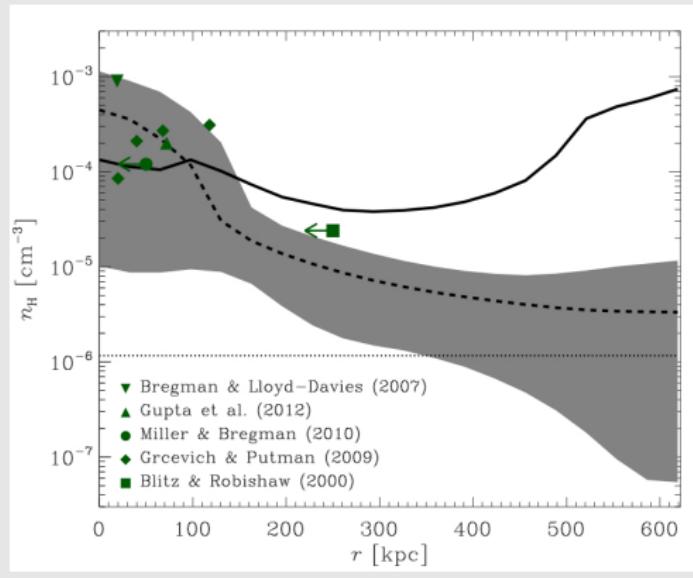
# Gas distribution in the local group



Nuza et al. (2013)

- gas density (upper panel)
- HI column density (middle panel)
- temperature (lower panel)
- virial radius (circles)

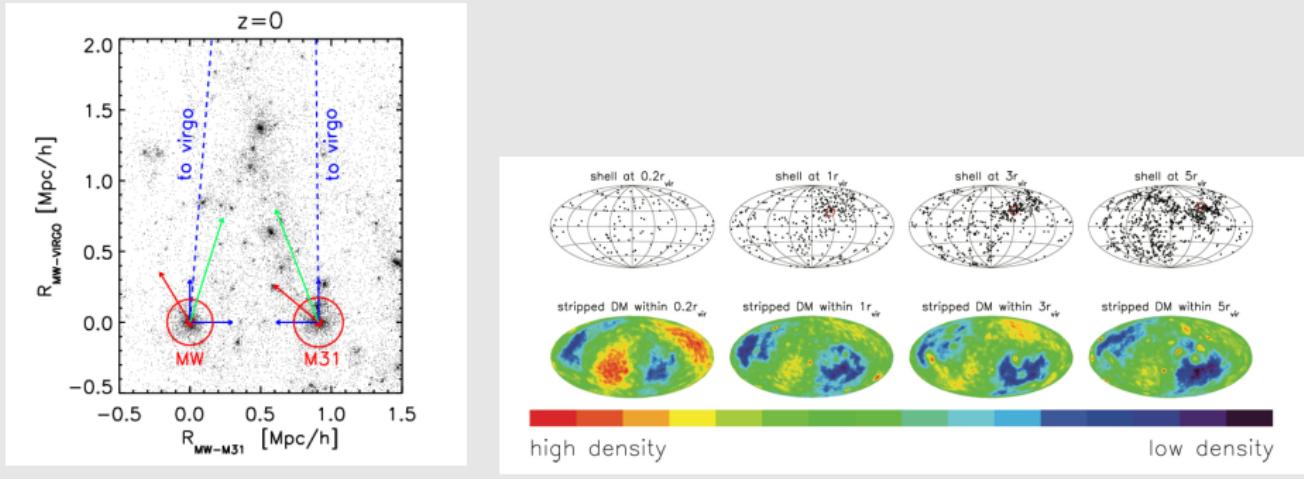
# Gas distribution in the local group



Nuza et al. (2013)

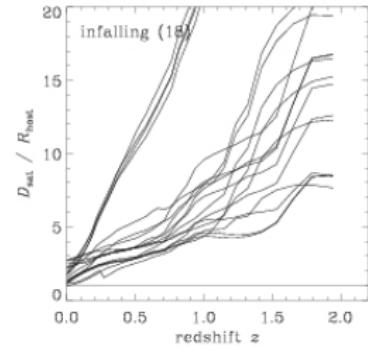
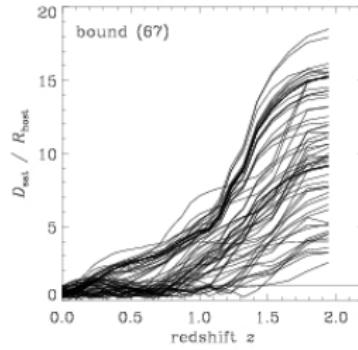
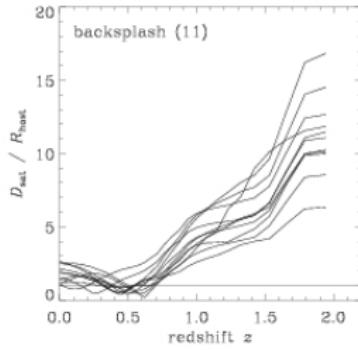
- hydrogen number density profile
- shaded area:standard deviation over random directions
- thick line: direction to Andromeda

# Preferential infall



Libeskind et al. (2011)

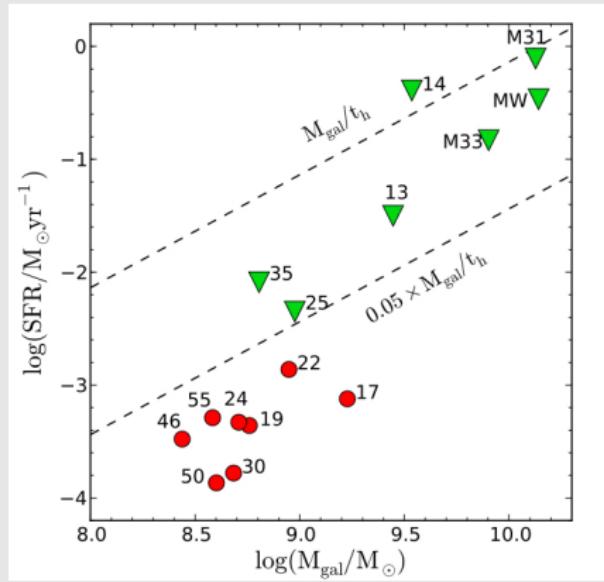
# Backsplash galaxies



a substantial fraction of halos outside of the virial radius of the massive host halos have been inside the virial radius before, and there are **renegades** too

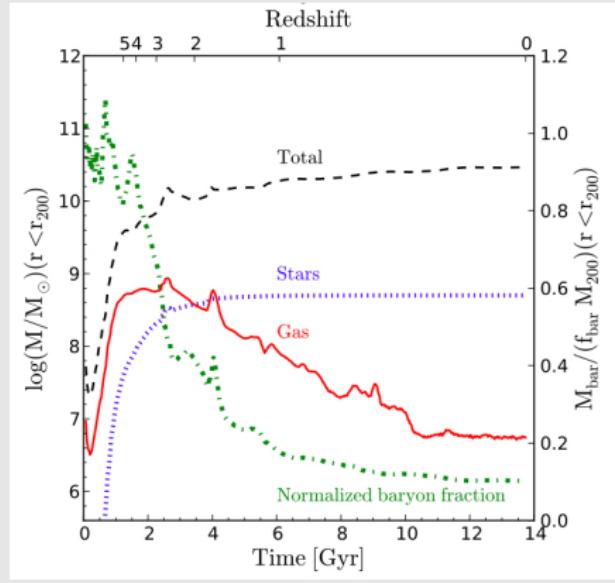
Knebe et al. 2011

# Dwarfs in the Local Group



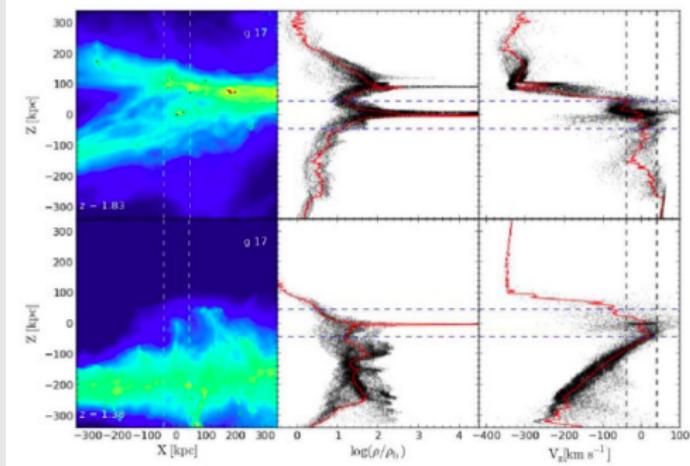
- isolated dwarfs without interactions with one of the massive galaxies in the past
- all within a sphere of  $R = 1.5 \text{ Mpc}/\text{h}$  of the center of the Local Group
- triangles: galaxies that form stars at rates comparable to their past average
- circles: star formation has largely ceased

# Dwarfs in the Local Group



- 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

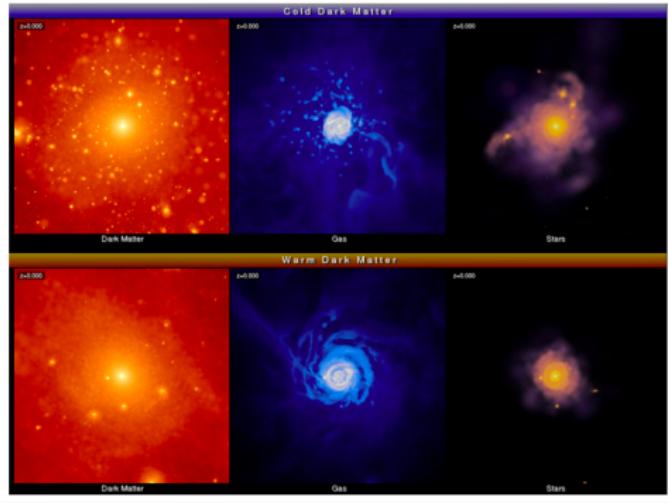
# Cosmic web stripping



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

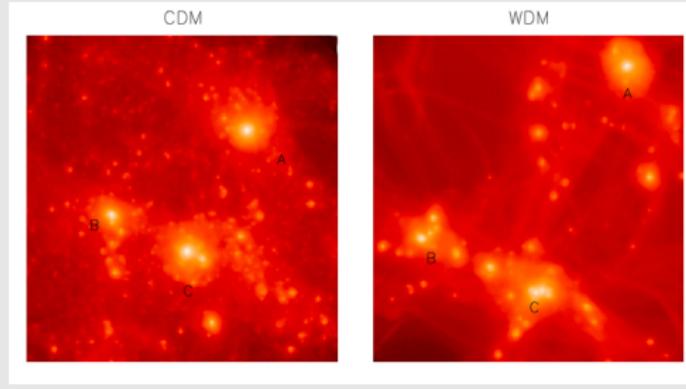
- gas from the halo is removed by the cosmic web environment due to ram pressure
- **Cosmic Web Stripping**

# Cold vs Warm Dark Matter



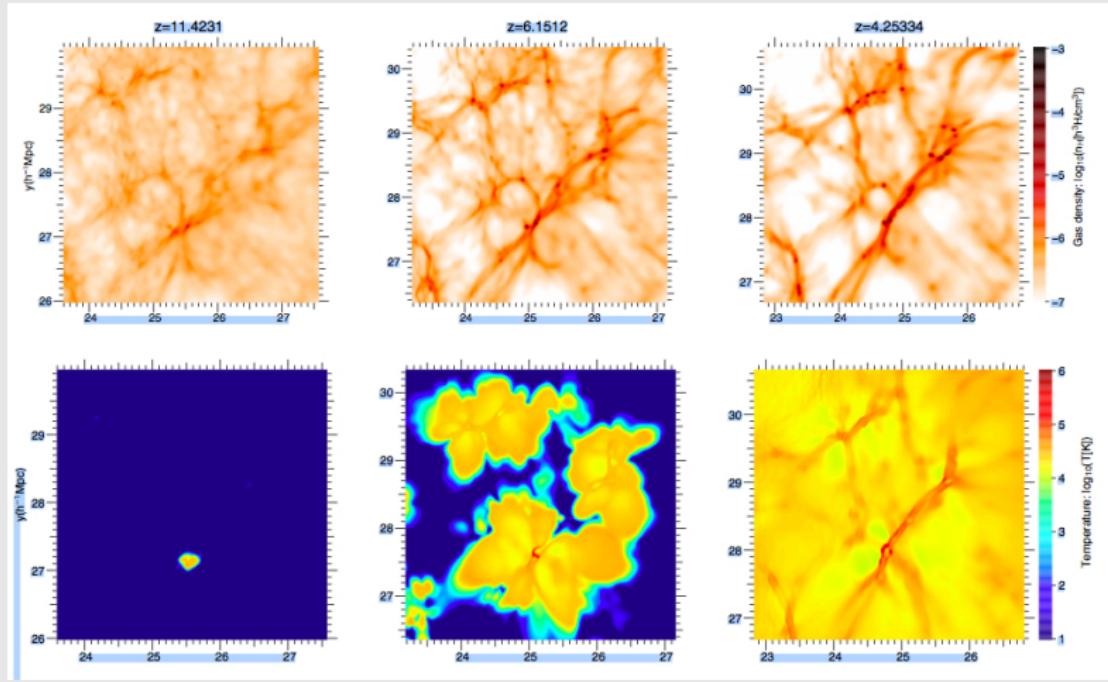
- more substructures in the dark matter distribution of the “CDM galaxy”
- also more substructures in gas and stars

# Cold vs Warm Dark Matter



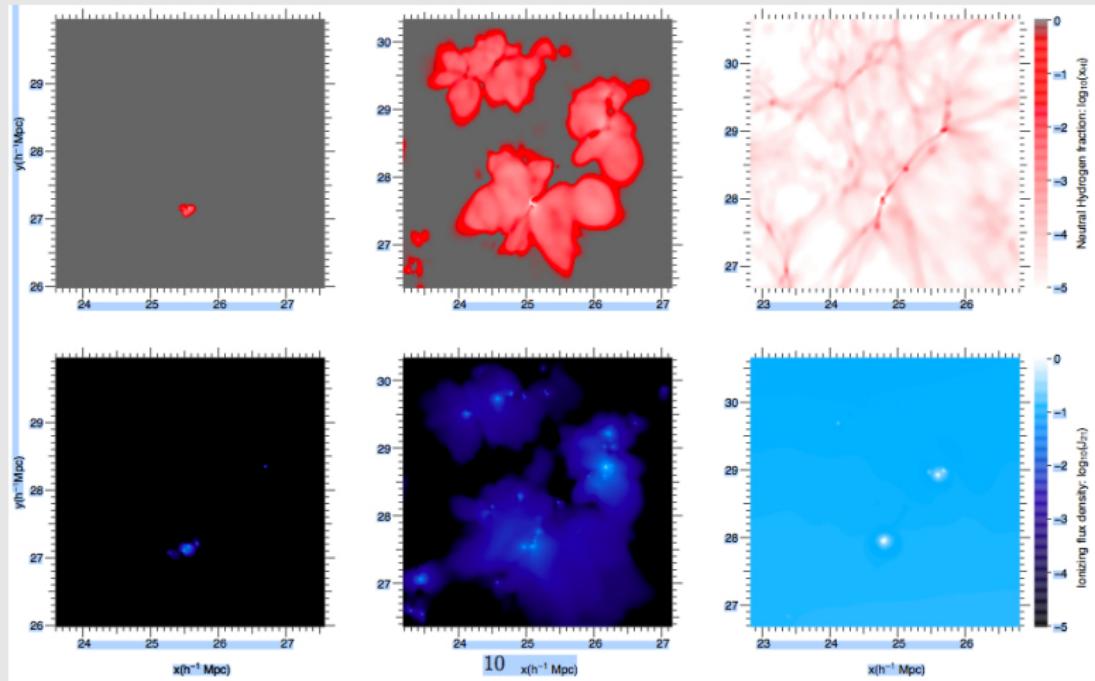
- different dynamics in the CDM and WDM “local groups”
- still expanding in WDM

# The reionization history of Andromeda



Pierre Ocvirk

# The reionization history of Andromeda

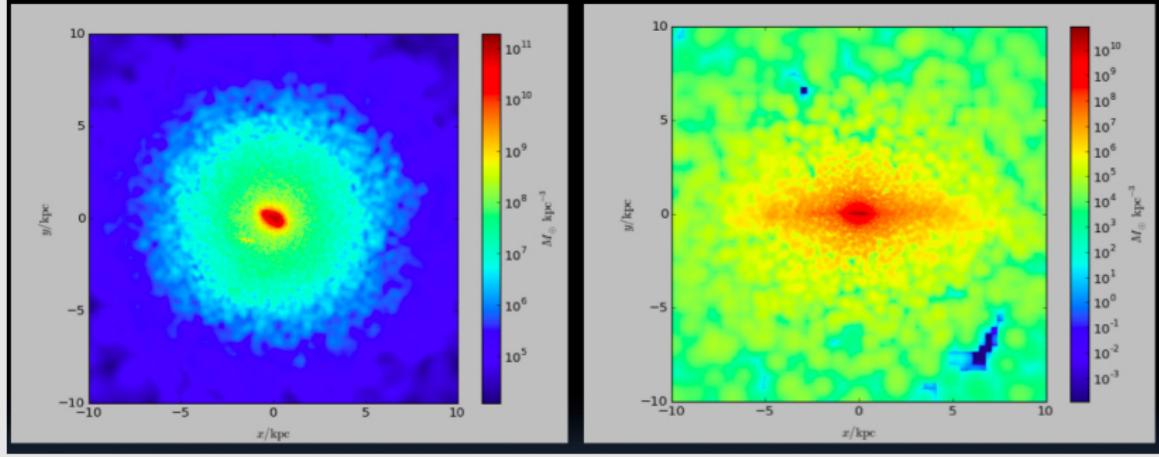


Pierre Ocvirk

# CLUES with Gasoline

# CLUES@DARK

## GASOLINE CLUES WMAP3 “MW”



Chris Brook, Arianna Di Cintio

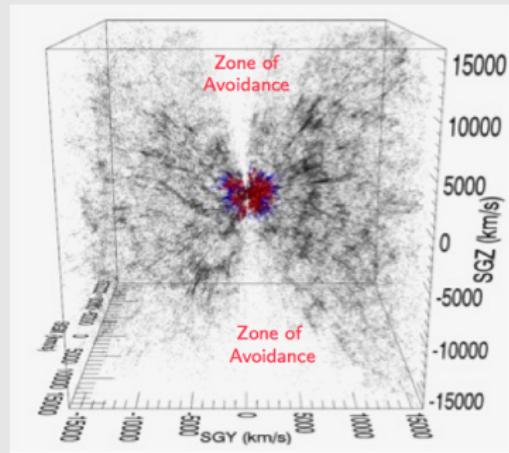
# CLUES@DARK

- new set of CLUES simulations using Gasoline
  - DM profiles vs. baryonic physics
  - LG properties vs. feedback scenario
- selfinteracting DM in CLUES

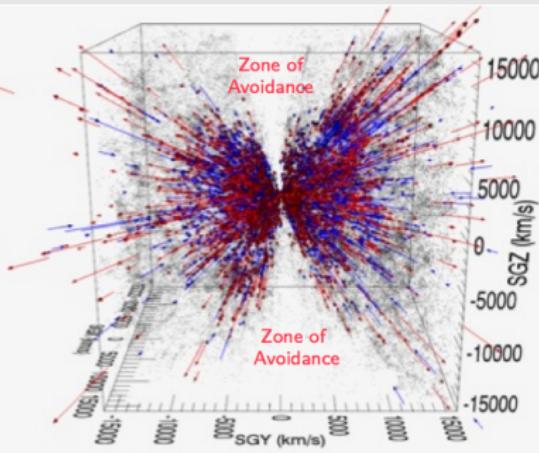
Arianna Di Cintio

# Simulations based on CosmicFlows2 data and the Reverse Zeldovich Approximations (RZA)

# CosmicFlows



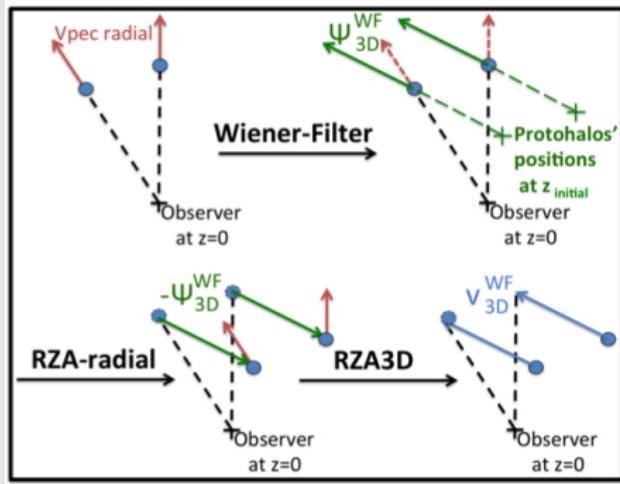
**Cosmicflows-1**  
about 2000 constraints  
*Tully et al. 2008*



**Cosmicflows-2**  
about 8000 constraints  
*Tully et al. 2013*

# RZA

## Reverse Zel'dovich Approximation



### Reconstructions

**Wiener-Filter ( $\Lambda CDM$ )** (Zaroubi et al. 1995)



**RZA3D** (Doumler et al. 2013a,b,c ; Sorce et al. 2014)



**Constrained Realizations ( $\Lambda CDM$ )**

(Hoffman & Ribak 1991)



**Initial Conditions**



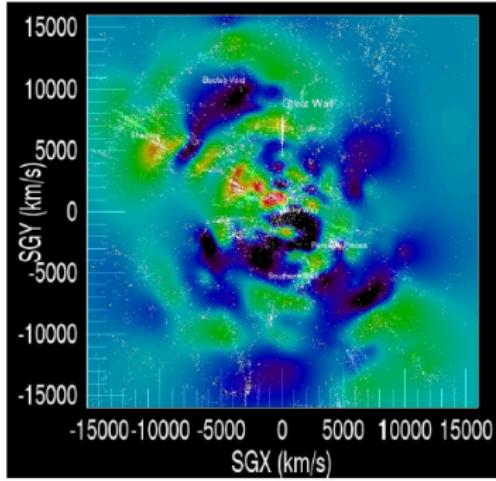
**Constrained Simulations**

Jenny Sorce (2014)

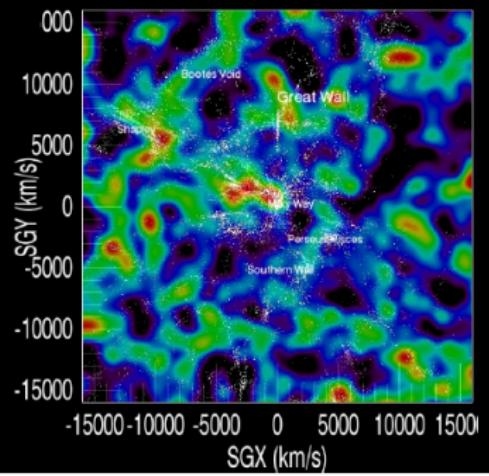
# Constr

## The Large Scale Structure

At  $z = 0$ ,  
Reconstruction



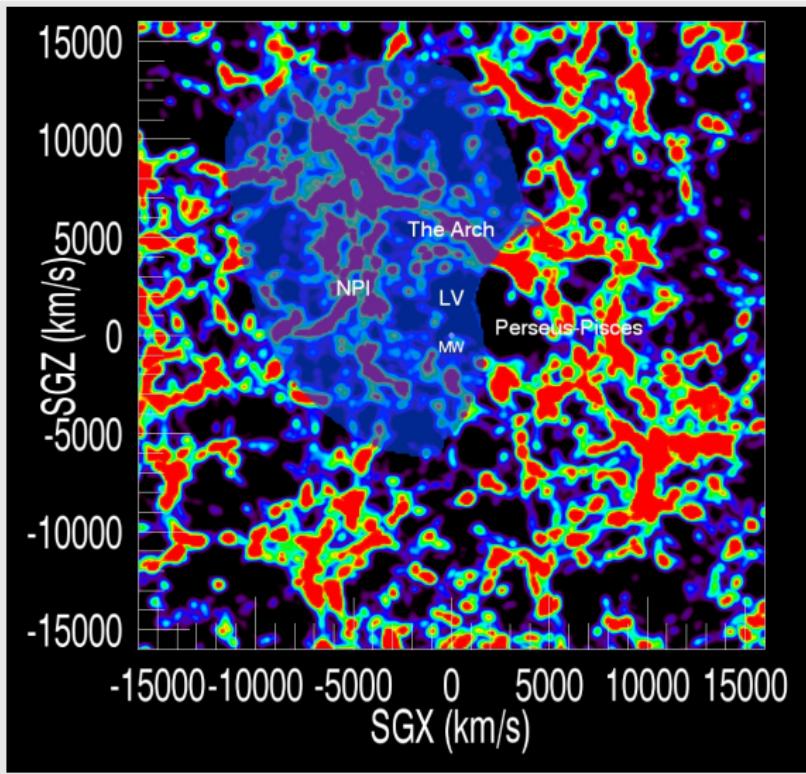
Simulation



Periodic Boundary Conditions,  $L=500 h^{-1} \text{ Mpc}$ ,  $n^3=512^3$

Jenny's talk

# Constrained simulations from Cosmic Flows 2

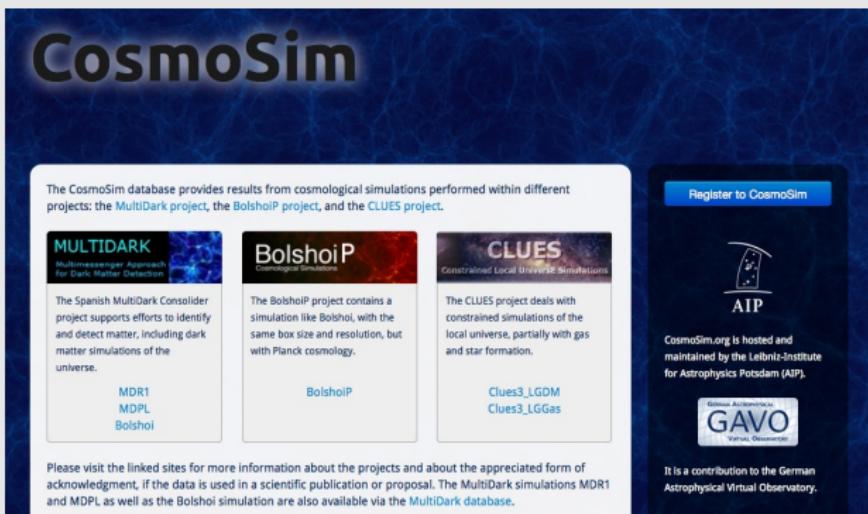


# Constrained Local Group(s)

- set of CLUES simulations  $100h^{-1}\text{Mpc}$  box size  
 $512^3$  particles,  $m_p = 0.6 \times 10^9 h^{-1} M_\odot$
- Local Group identification
- LG properties compared to randomly selected LGs

Edoardo Carlesi

# CosmoSim database



The CosmoSim database provides results from cosmological simulations performed within different projects: the MultiDark project, the BolshoiP project, and the CLUES project.

**MULTIDARK**  
Multimessenger Approach for Dark Matter Detection

The Spanish MultiDark Consilier project supports efforts to identify and detect matter, including dark matter simulations of the universe.

MDR1  
MDPL  
Bolshoi

**BolshoiP**  
Cosmological Simulations

The BolshoiP project contains a simulation like Bolshoi, with the same box size and resolution, but with Planck cosmology.

BolshoiP

**CLUES**  
Constrained Local Universe Simulations

The CLUES project deals with constrained simulations of the local universe, partially with gas and star formation.

Clues3\_LGDM  
Clues3\_LGGas

Please visit the linked sites for more information about the projects and about the appreciated form of acknowledgment, if the data is used in a scientific publication or proposal. The MultiDark simulations MDR1 and MDPL as well as the Bolshoi simulation are also available via the [MultiDark database](#).

[Register to CosmoSim](#)

CosmoSim.org is hosted and maintained by the Leibniz-Institute for Astrophysics Potsdam (AIP).

**GAVO**  
German Astrophysical Virtual Observatory

It is a contribution to the German Astrophysical Virtual Observatory.

<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

# CLUES topics



# Advertisement



Near Field Cosmology, University Center Obergurgl  
March 29 - April 3, 2016

# Summary

- **Constrained numerical simulations are an important tool to study the formation of the observed structures in the local universe. In particular locally observed dwarfs are a target of such simulations.**
- **The CF2 data together with the improved reconstruction technique substantially improve the quality of our constrained simulations**
- **An increasing number of both constrained and unconstrained simulations are available at the CosmoSim database of AIP.**