Constrained Simulations
The original CLUES simulations
The new CLUES simulations

Constrained simulations of the Local Universe
The CLUES-Project

Stefan Gottlöber

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Quy Nhon
July 8, 2016

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CosmoSim database

http://www.cosmosim.org/   Kristin Riebe, Harry Enke
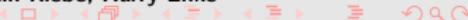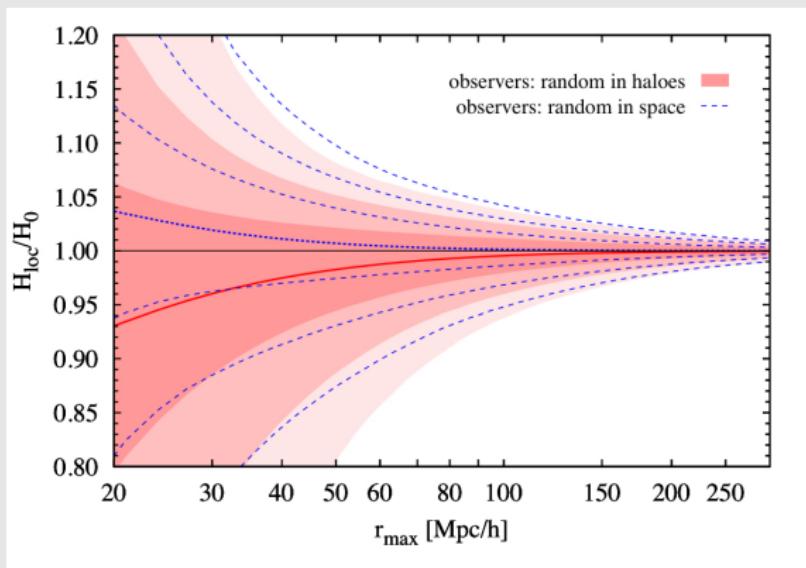
Stefan Gottlöber Leibniz-Institut für Astrophysik Potsdam (AIP)   Constrained simulations of the Local Universe The CLUES-Pro

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Probability distribution of the local Hubble parameter

Wojtak etal, MNRAS 438 (2014), 1805

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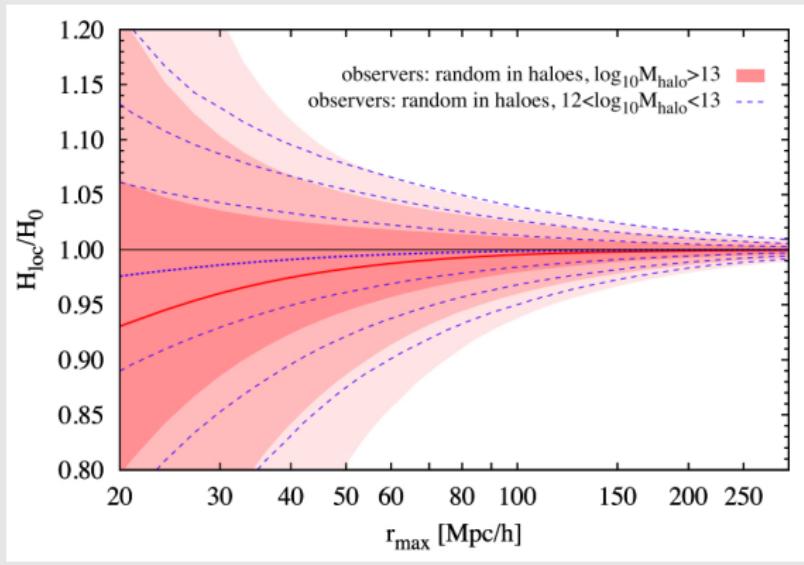
CLUES – Constrained Local UniversE Simulations

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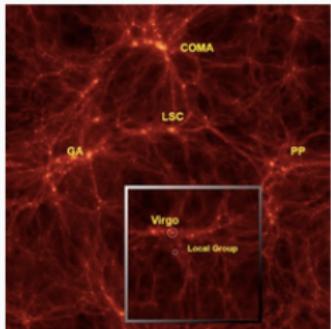
Dark matter distribution in our Local Universe in two different simulations: a box with 160 Mpc/h side length (big picture) and with 64 Mpc/h side length (inset panel).

See the Image Gallery for more information and further images.

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Collaborators

- Yehuda Hoffman (HU, Jerusalem)
- Gustavo Yepes (UAM, Madrid)
- Brent Tully (IfA, Hawaii)
- Noam Libeskind (AIP, Potsdam)
- Helene Courtois (IPNL, Lyon)
- Jenny Sorce (AIP, Potsdam)
- Edoardo Carlesi (HU, Jerusalem)
- Alejandro Benitez-Llambay (Cordoba)
- Matthias Steinmetz (AIP, Potsdam)
- and the CLUES collaboration

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Why are we interested in the Local Universe?

- The local neighbourhood of the Milky Way is the most well known piece of the universe.
- It is the ideal place to compare on small scales models of structure formation with observations.
- It is dominated by the Local Group with two massive galaxies, the huge Local Void and a few nearby clusters.
- Constrained simulations are an ideal tool to study this environment.

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CLUES

Constrained Local UniversE Simulations

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GA

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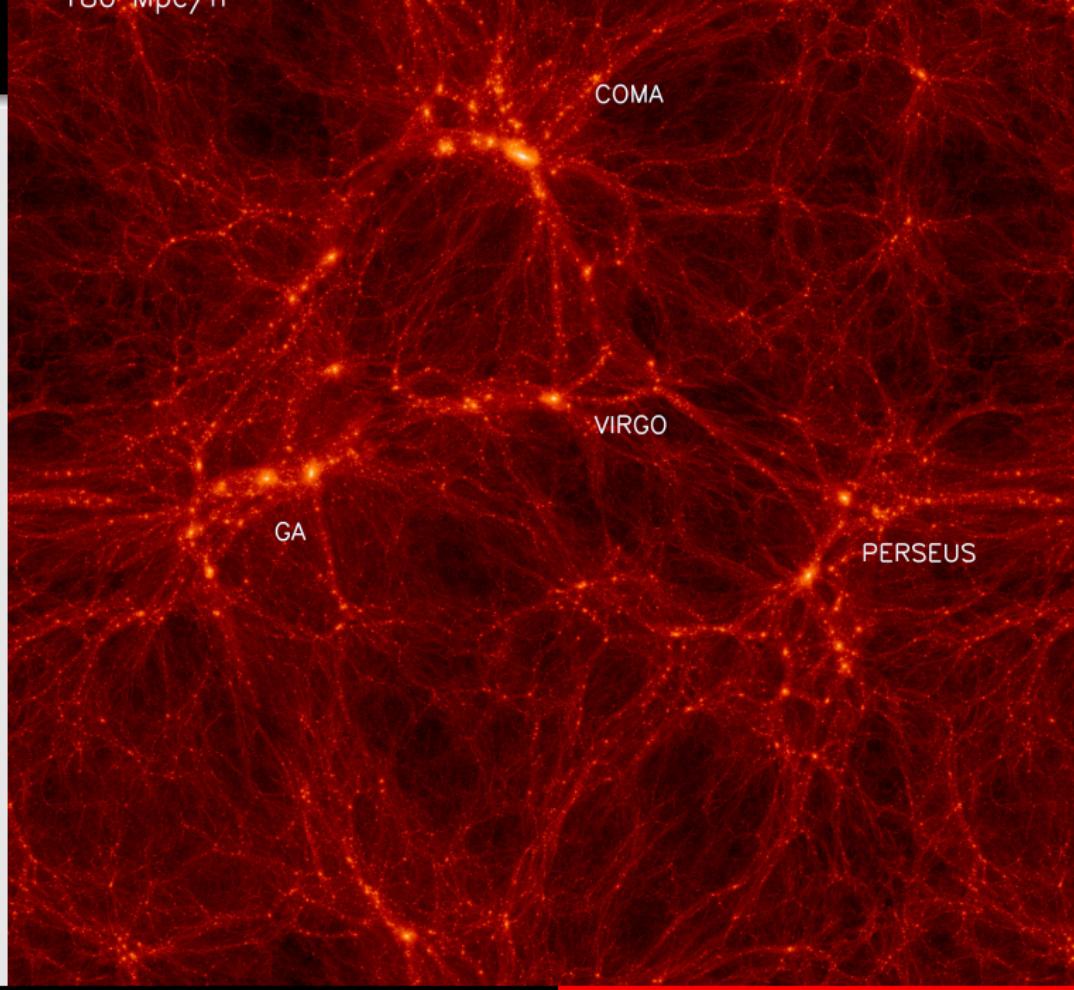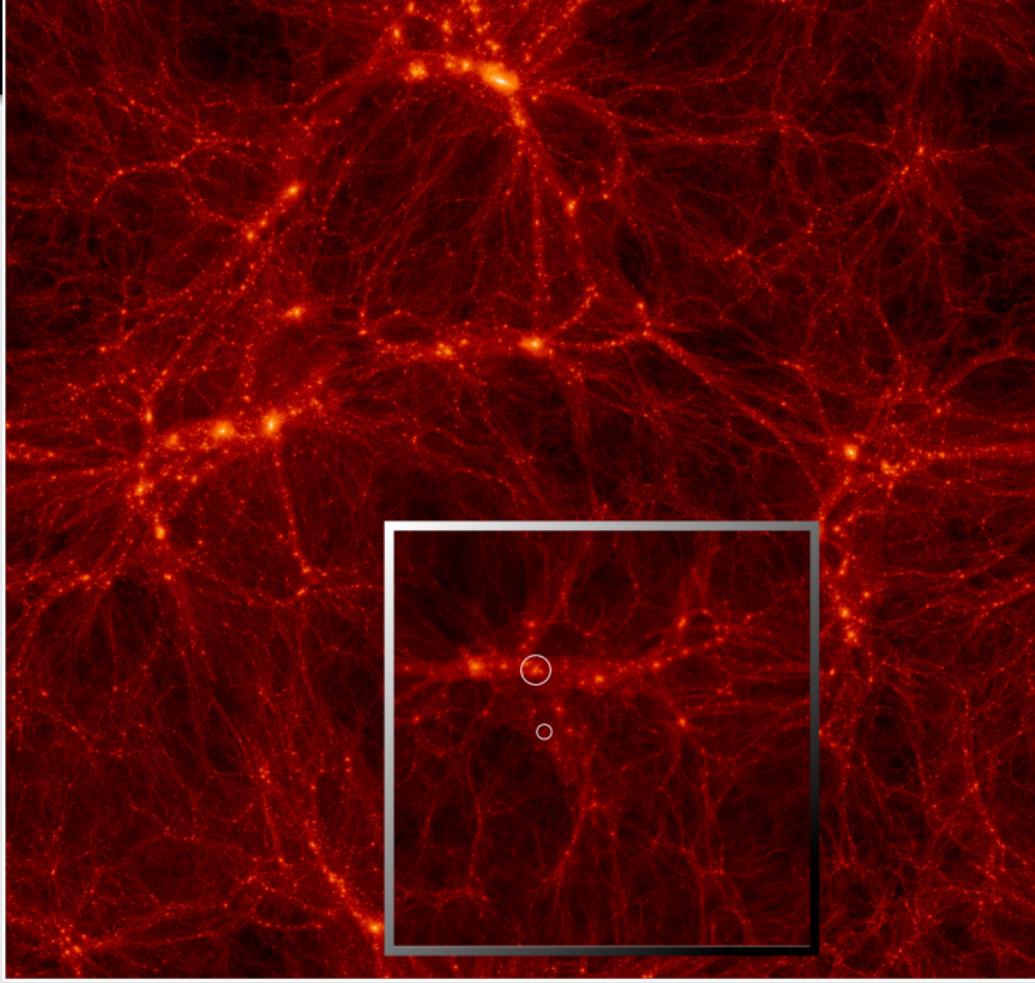
$160h^{-1}\mathrm{Mpc}$
Anatoly
Klypin

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

The CLUES Local Group

Z = 0.00
20.0 kpc/h

Milky Way

Z = 0.00
20.0 kpc/h

Andromeda

Z = 0.00
20.0 kpc/h

M33

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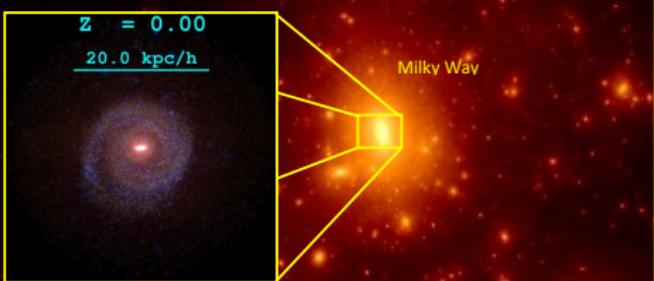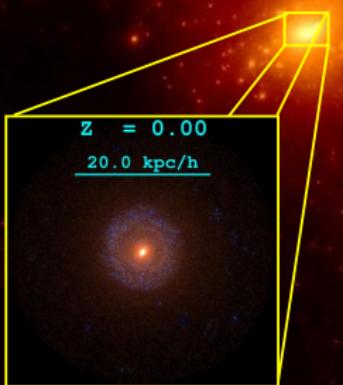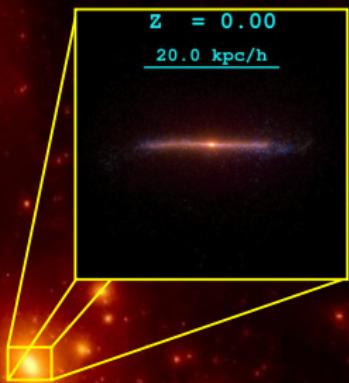
Observational data and constraints for CLUES

- 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)

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The Local Volume simulations

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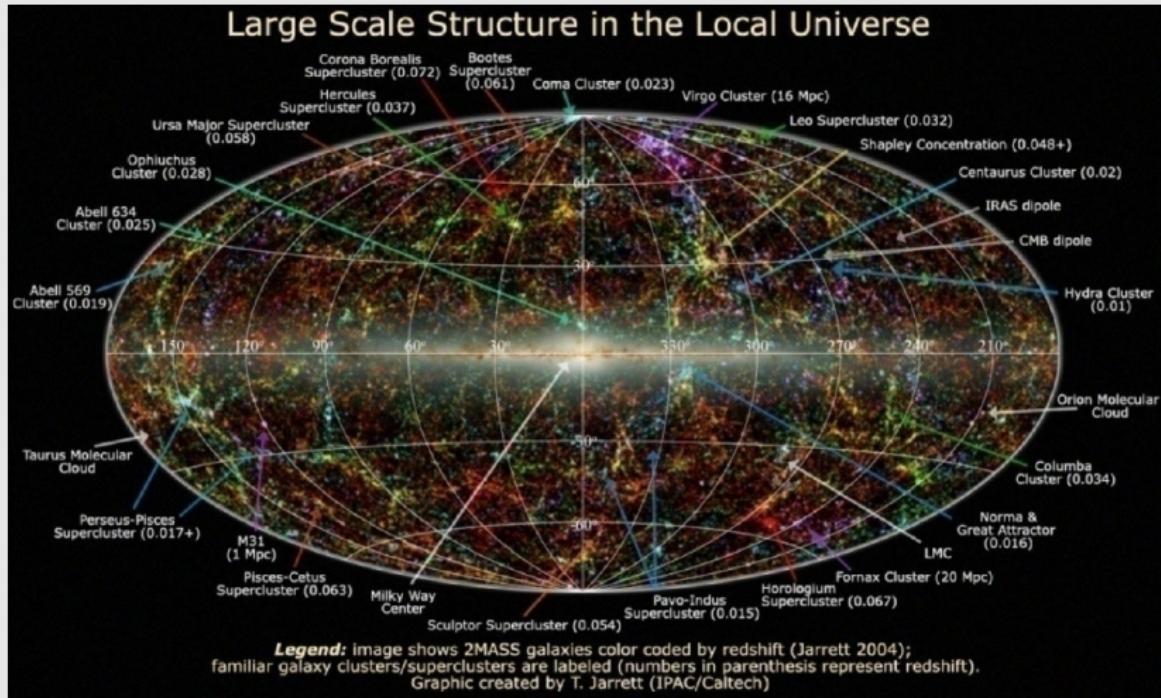
The Local Volume

Large Scale Structure in the Local Universe

Legend: image shows 2MASS galaxies color coded by redshift (Jarrett 2004);
familiar galaxy clusters/superclusters are labeled (numbers in parenthesis represent redshift).
Graphic created by T. Jarrett (IPAC/Caltech)

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The Local Volume

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Spectrum of mini-voids in the local volume $R < 8h^{-1}\mathrm{M}_\odot$
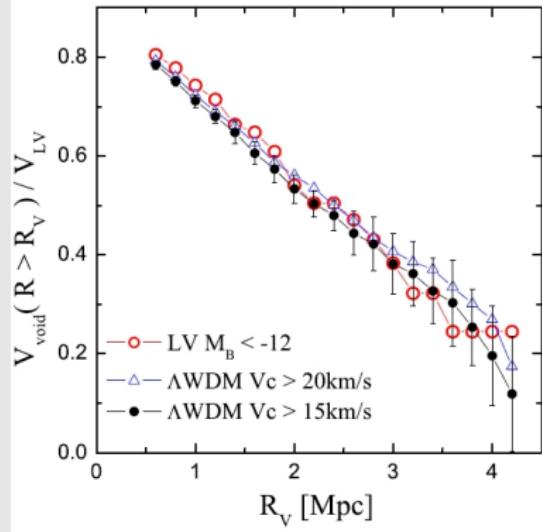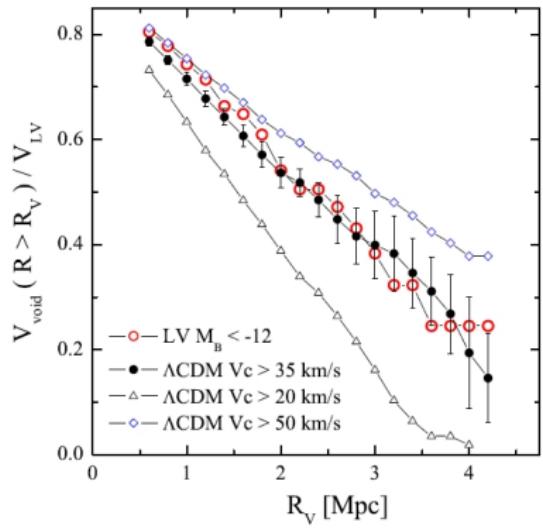
Tikhonov and Klypin (2009), Tikhonov et al. (2009)

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Also studied in the past using CLUES LV simulations

- *Dark Matter decay and annihilation in the Local Universe: CLUES from Fermi*, Cuesta et al ApJ 726 (2010) L6
- *The velocity function in the local environment from ΛCDM and ΛWDM constrained simulations*, Zavala et al ApJ 700 (2009) 1779

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The Local Group simulations

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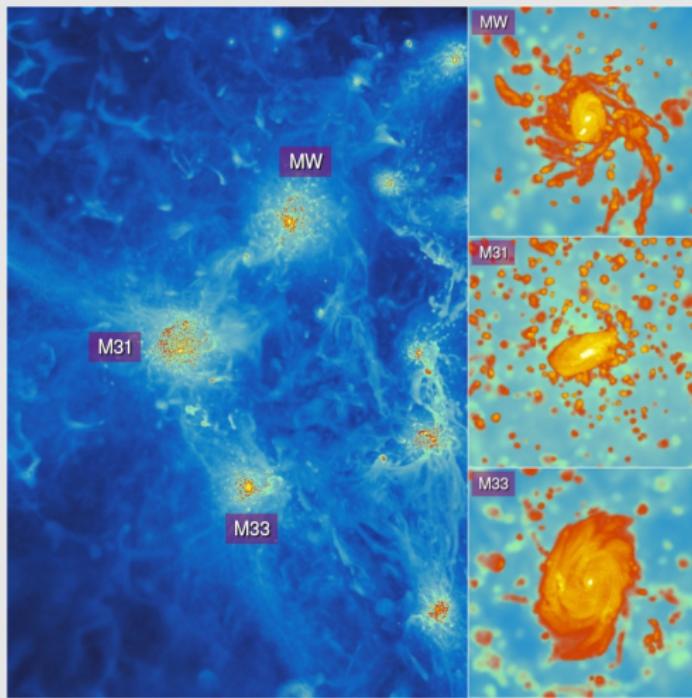
- box $64h^{-1}\mathrm{Mpc}$
- 4096^3 particles locally
- DM particles:
  $2.1 \times 10^5 h^{-1}\mathrm{M}_\odot$
- gas particles:
  $4.4 \times 10^4 h^{-1}\mathrm{M}_\odot$
- force resolution:
  $0.15h^{-1}\mathrm{kpc}$

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Nearby dwarfs
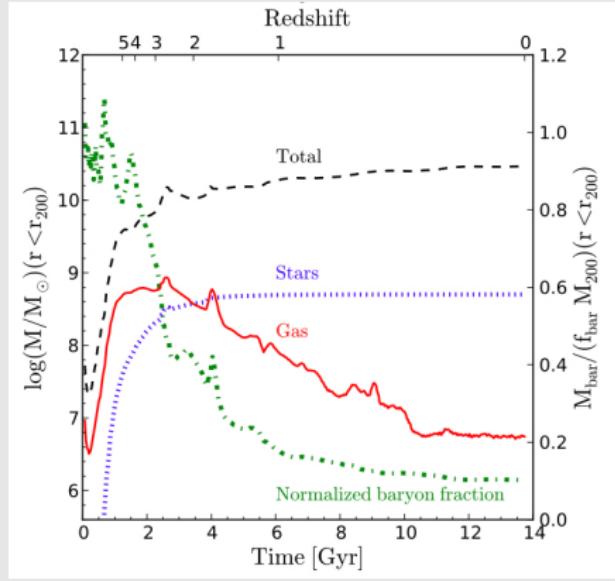
- not associated with Andromeda or MW
- masses within the virial radius of galaxy 30
- sudden loss of baryons at $z \approx 2$
- ram pressure arising from crossing a large-scale pancake

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**The original CLUES simulations**
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Cosmic web stripping
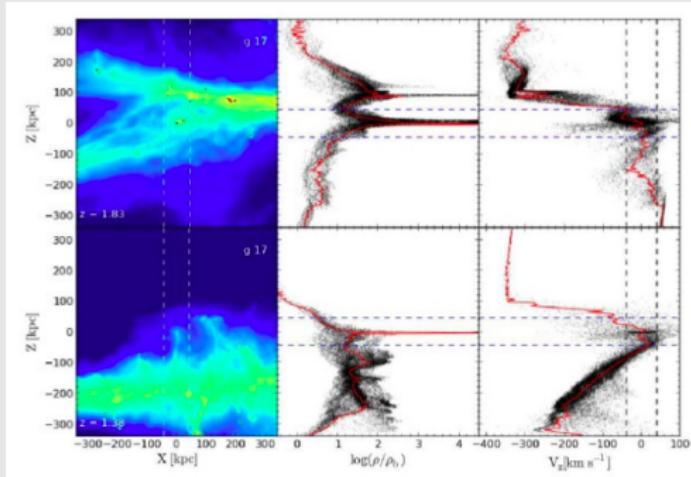
Alejandro Benitez-Llambay et al. (2013), movies made by Alejandro

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

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Cosmic Dawn (Virgo, Fornax vs. Cen A, M81)
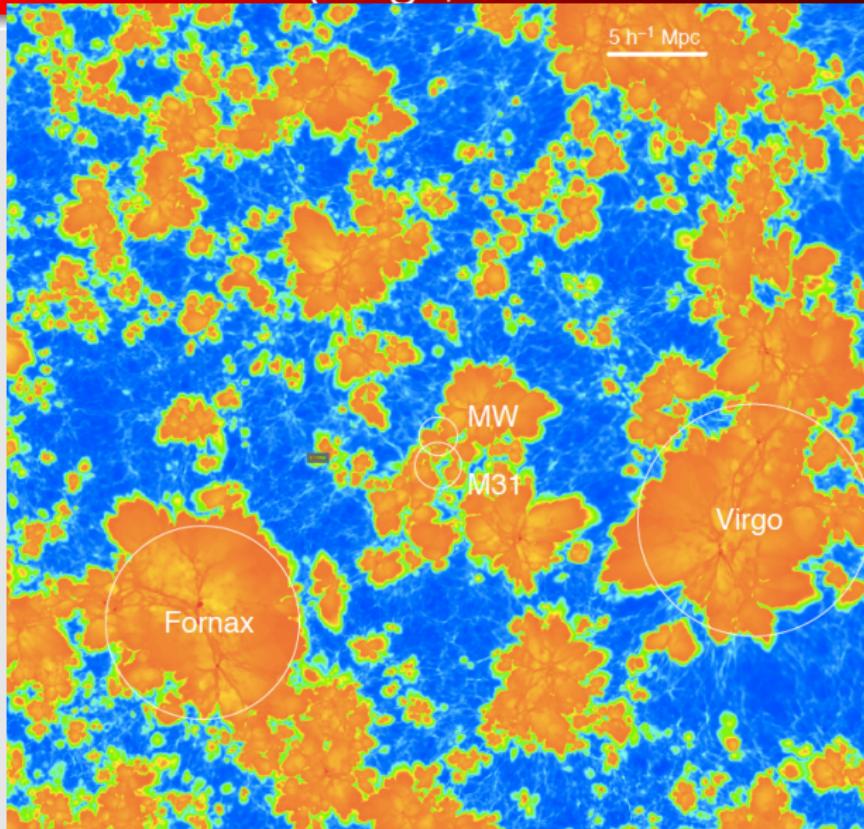
4096^3 particles in $64h^{-1}$Mpc box

Temperature distribution at z= 6.15

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

Ocvirk et al, submitted to

MNRAS

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Also studied in the past using CLUES LG simulations

- *The distribution of gas in the Local Group from constrained cosmological simulations: the case for Andromeda and the Milky Way galaxies*, Nuza et al. MNRAS 441 (2014), 2593
- *Vast planes of satellites in a high resolution simulation of the Local Group: comparison to Andromeda*, Gillet et al, APJ 800 (2015), 34
- *The Imprint of Reionization on the Star Formation Histories of Dwarf Galaxies*, Benitez-Llambay et al, MNRAS 450 (2015) 4207

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New CLUES simulations

**observational constraints: CosmicFlows data
(talk of Brent)**

**improved algorithm: Reverse Zeldovich Approximations (RZA)
(a series of papers of Timur Doumler and Jenny Sorce)**

**bias minimization
(Jenny Sorce 2015)**

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RZA

Reverse Zel'dovich Approximation
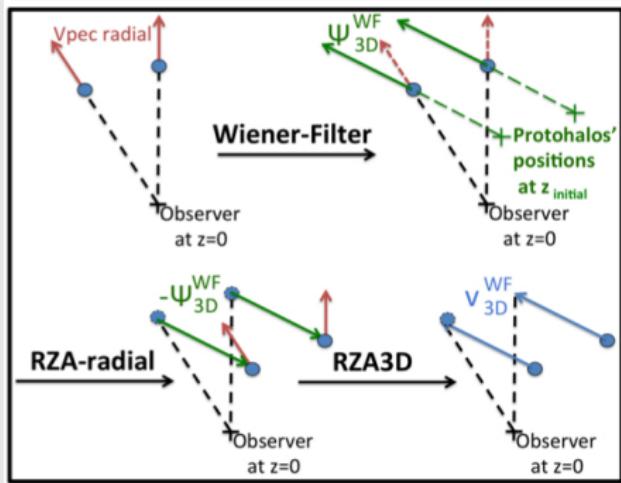
Reconstructions

Wiener-Filter (ΛCDM) (Zaroubi et al. 1995)
⇓
RZA3D (Doumler et al. 2013a,b,c ; Sorce et al. 2014)
⇓
Constrained Realizations (ΛCDM)
(Hoffman & Ribak 1991)
⇓
Initial Conditions
⇓
Constrained Simulations

Jenny Sorce (2014)

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Constrained simulations of the Local Universe (Jenny's talk)

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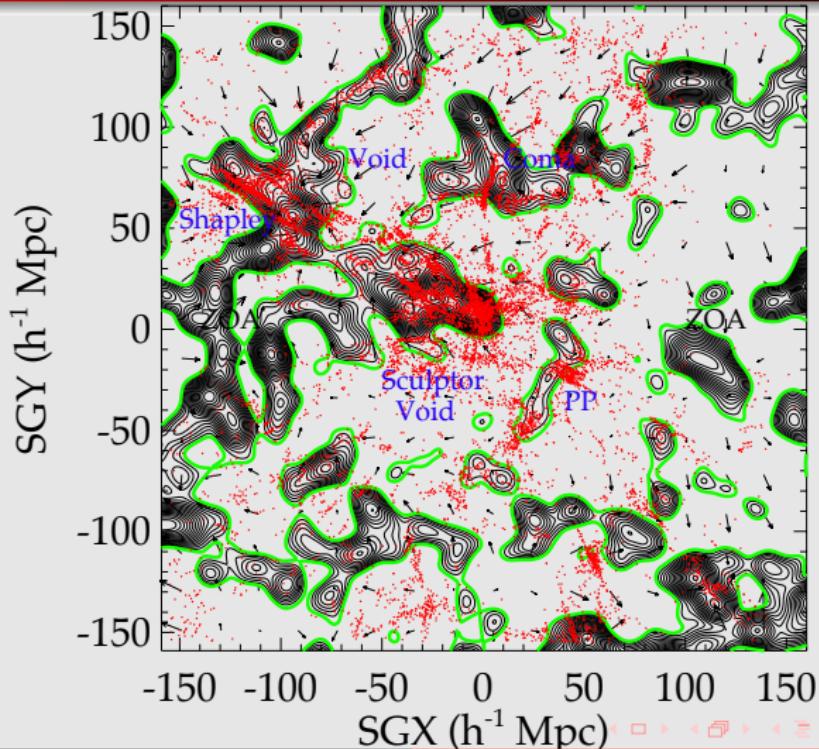
Constrained simulations of the Local Group (Edoardo's talk)

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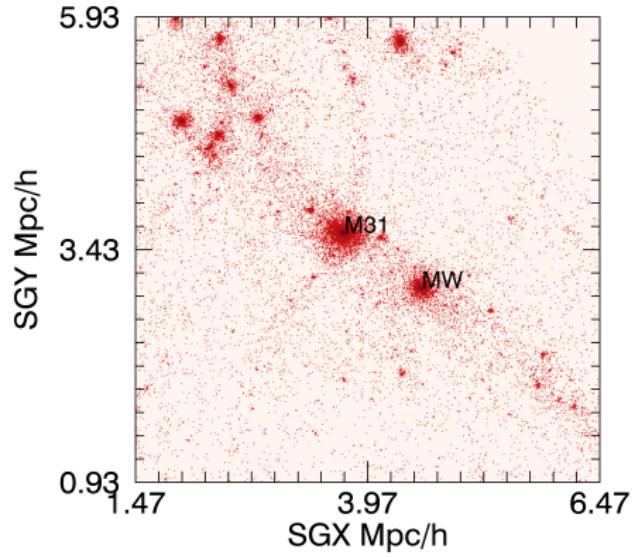
outlook: box of 500 Mpc/h
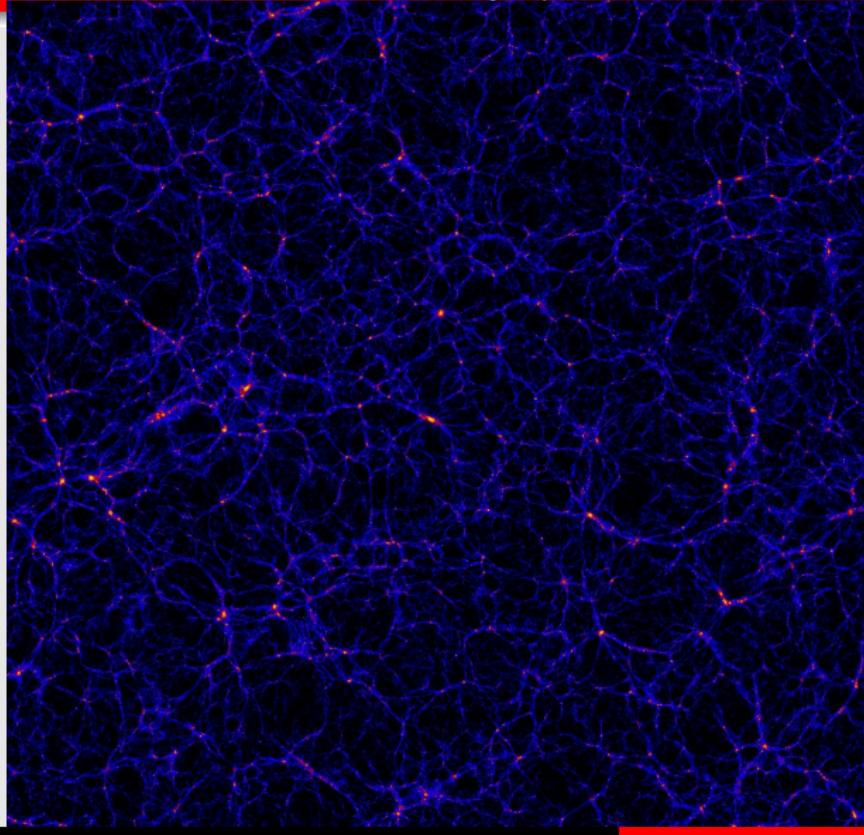
3072^3 particles
$M_p =$
$3.7 \times 10^8 M_s/h$

Simulation
performed by
Klaus Dolag and
Jenny Sorce

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outlook: : zoom R = 120 Mpc/h
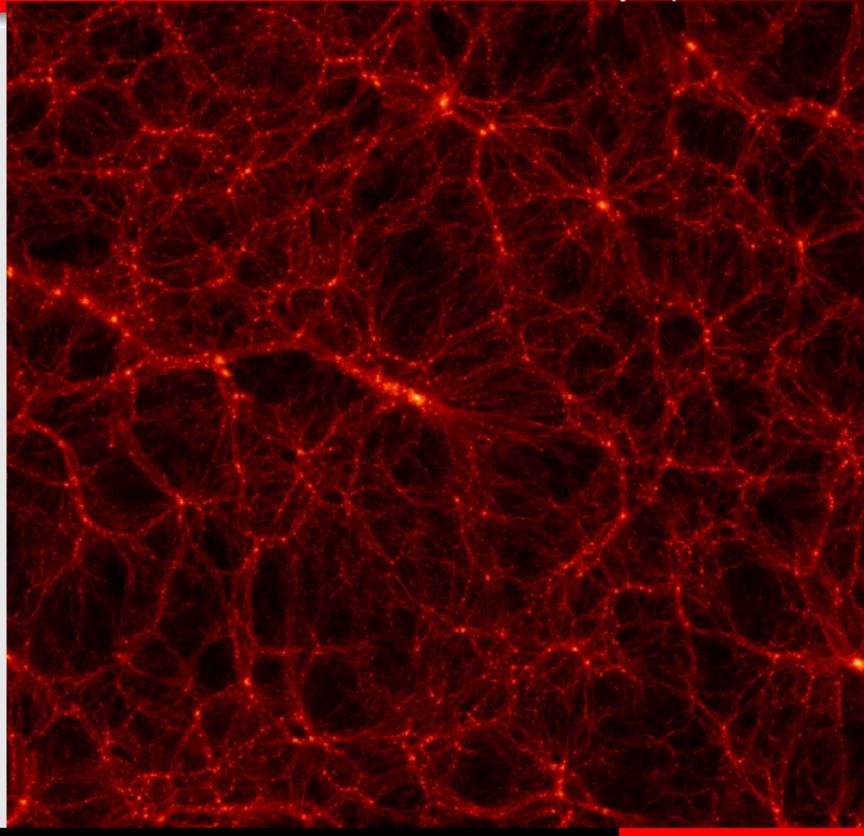
6144^3 particles
$M_p = 4.6 \times 10^7 M_s/h$

Simulation performed by Klaus Dolag and Jenny Sorce

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Virgo (next talk)

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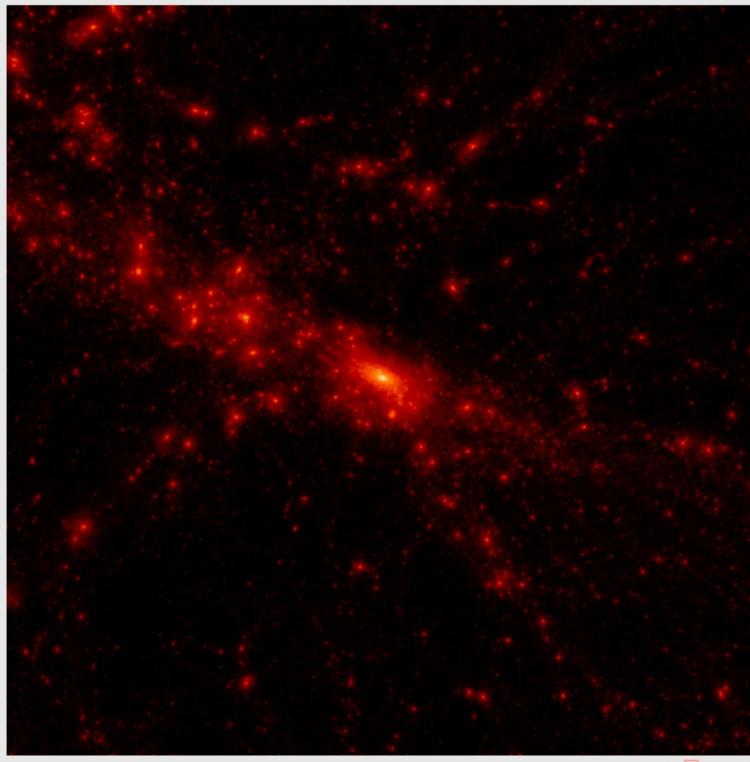
Summary

- **Constrained numerical simulations are an important tool to study the formation of the observed structures in the local universe.**

- **The CF2 data together with the new reconstruction algorithm substantially improve the quality of our constrained simulations**

- **Looking forward to a great future with CF3**