The CLUES-Project
Constrained Local UniversE Simulations

Stefan Gottlöber
Leibniz-Institut für Astrophysik Potsdam (AIP)

Potsdam
August 26, 2014

Collaborators

- Yehuda Hoffman (HU, Jerusalem)
- Gustavo Yepes, Alexander Knebe, Arianna DiCintio (UAM, Madrid)
- Brent Tully (IfA, Hawaii)
- Helene Courtois (IPNL, Lyon)
- Jenny Sorce (IPNL, Lyon and AIP, Potsdam)
- Alejandro Benitez-Llambay, Mario Abadi (Cordoba)
- Julio Navarro (Victoria)
- Noam Libeskind, Steffen Heß, Francisco Kitaura, Matthias Steinmetz (AIP, Potsdam)
- and others

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Constrained Local UniversE Simulations

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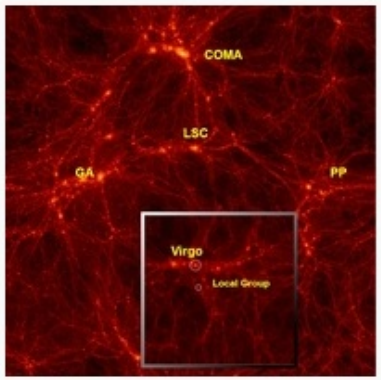
CLUES - Constrained Local UniversE Simulations

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.

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

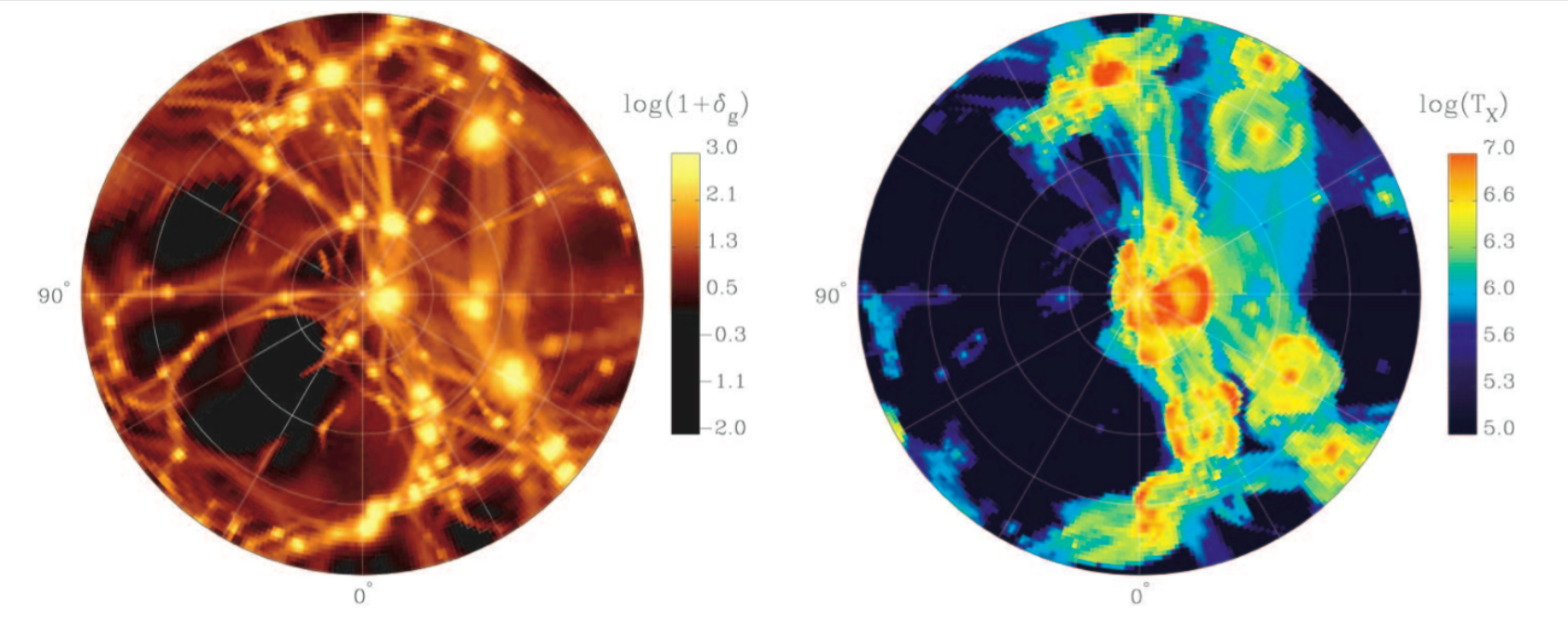
Why are we interested in the Local Universe?

- 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 (Klypin 2014).
- 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., astro-ph/1407.3451 (2014), "ELUCID - Exploring the Local Universe with reConstructed Initial Density field I: Hamiltonian Markov Chain Monte Carlo Method with Particle Mesh

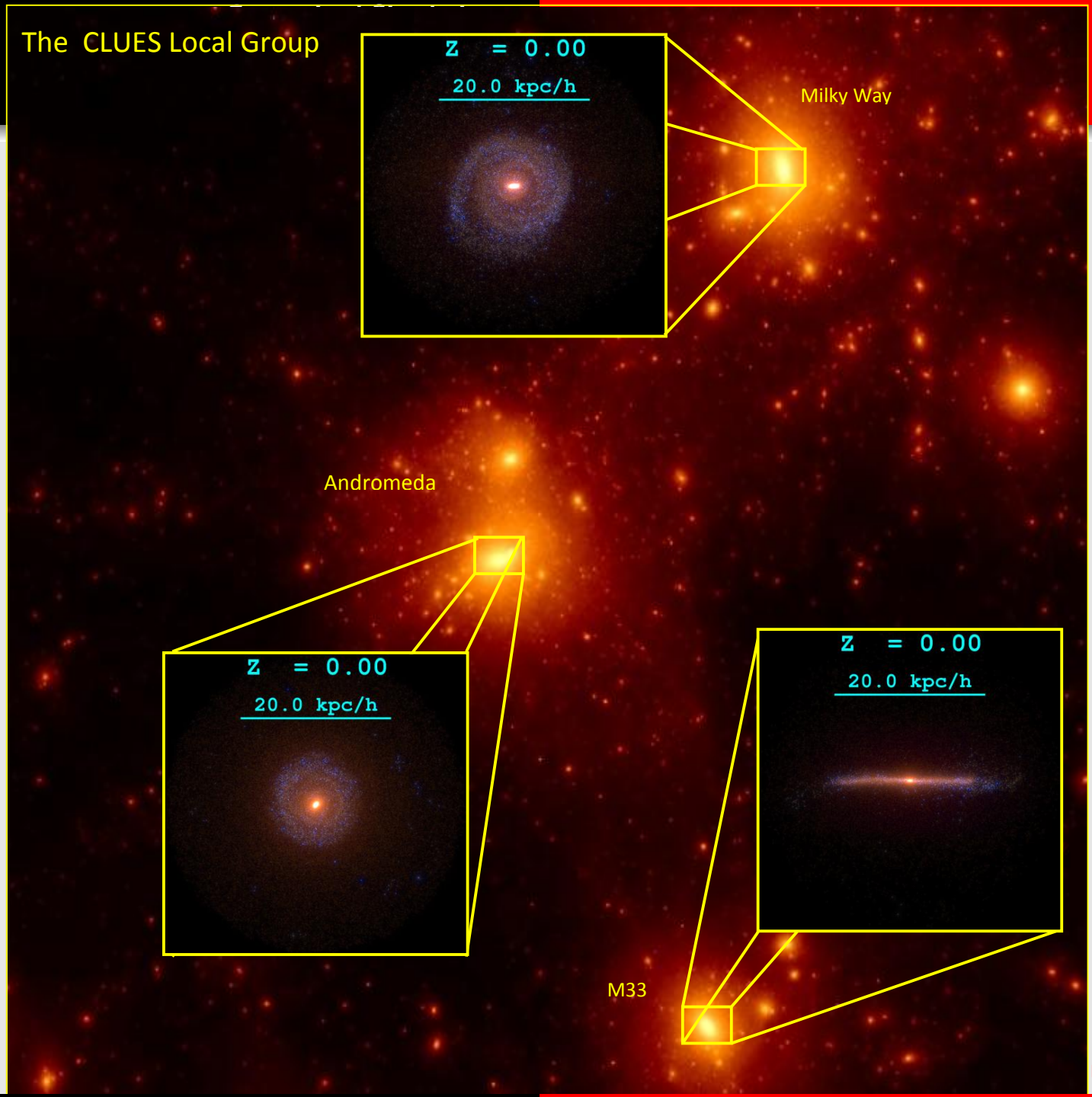
Constrained simulations



- left: Sky map of the density in the Local Supercluster (Virgo close to the center, Local Void in the bottom left quadrant)
- right: Sky map of X-ray emission-weighted temperature
  - Kravtsov A. et al. APJ 563 (2002), 571 "Constrained Simulations of the real universe II. Observational signatures of intergalactic gas in the local supercluster region"

CLUES

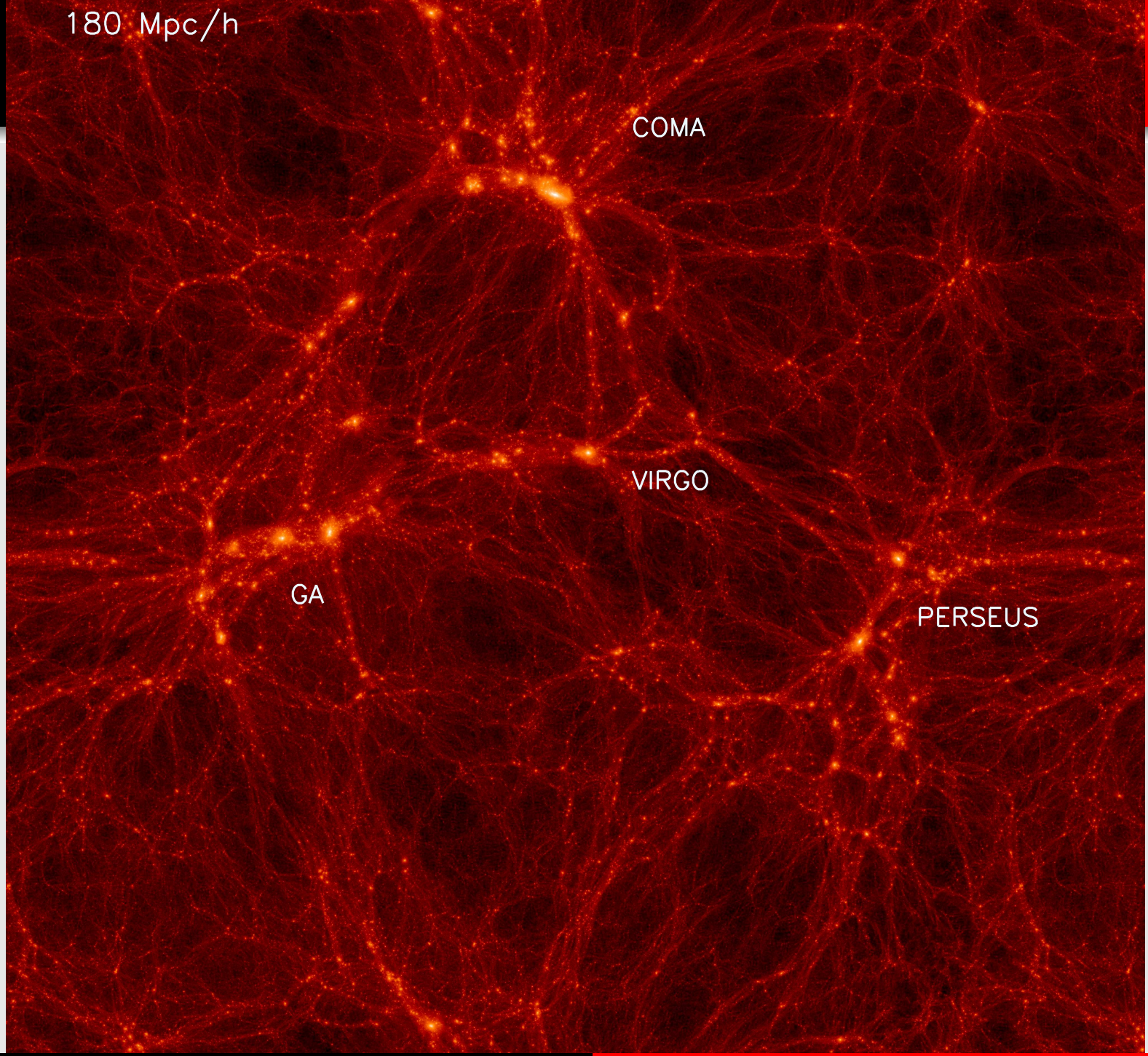
Constrained Local UniversE Simulations

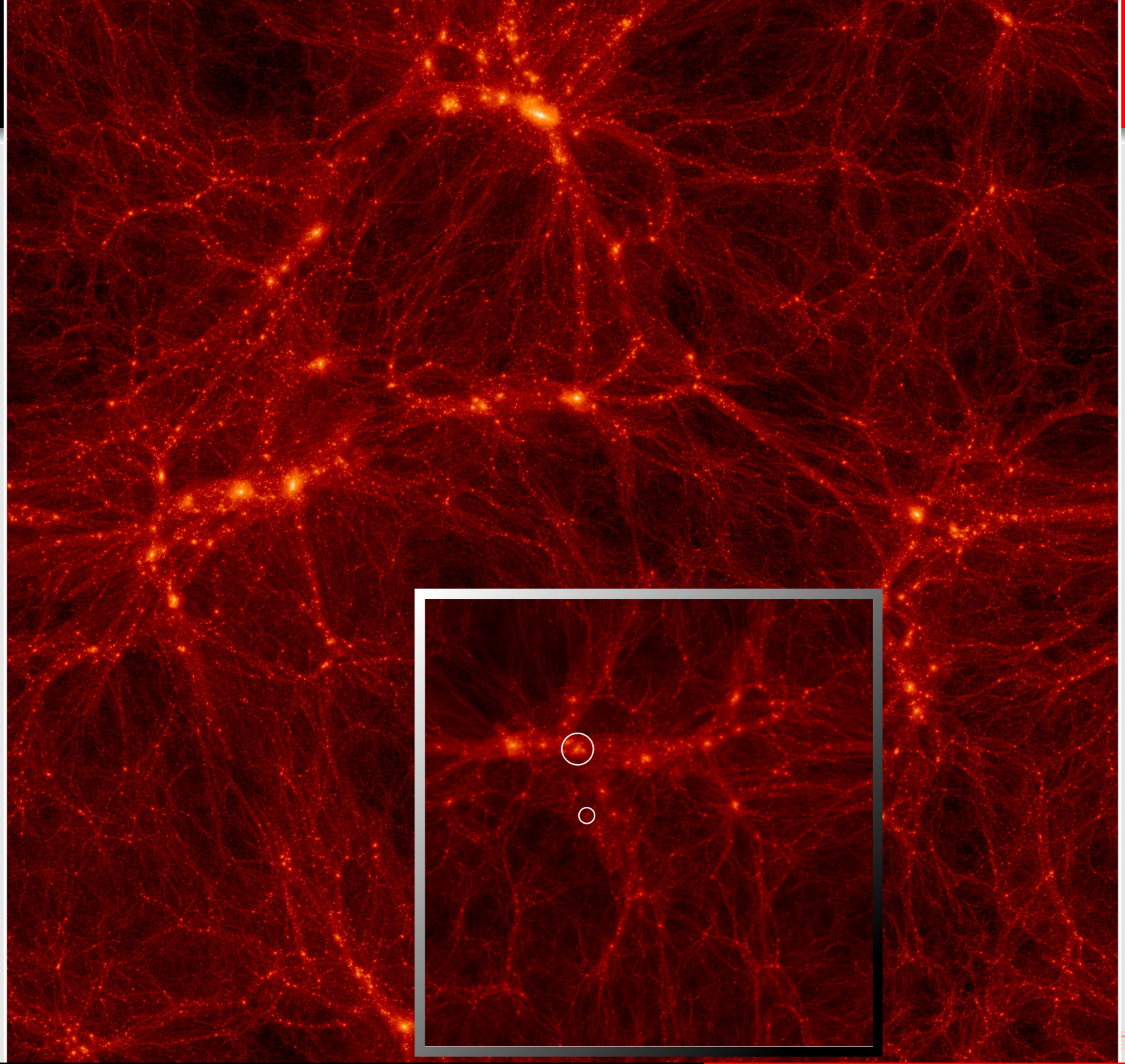

The CLUES Local Group
Z = 0.00
20.0 kpc/h
Milky Way
Andromeda
Z = 0.00
20.0 kpc/h
Z = 0.00
20.0 kpc/h
M33

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)


180 Mpc/h
COMA
VIRGO
GA
PERSEUS

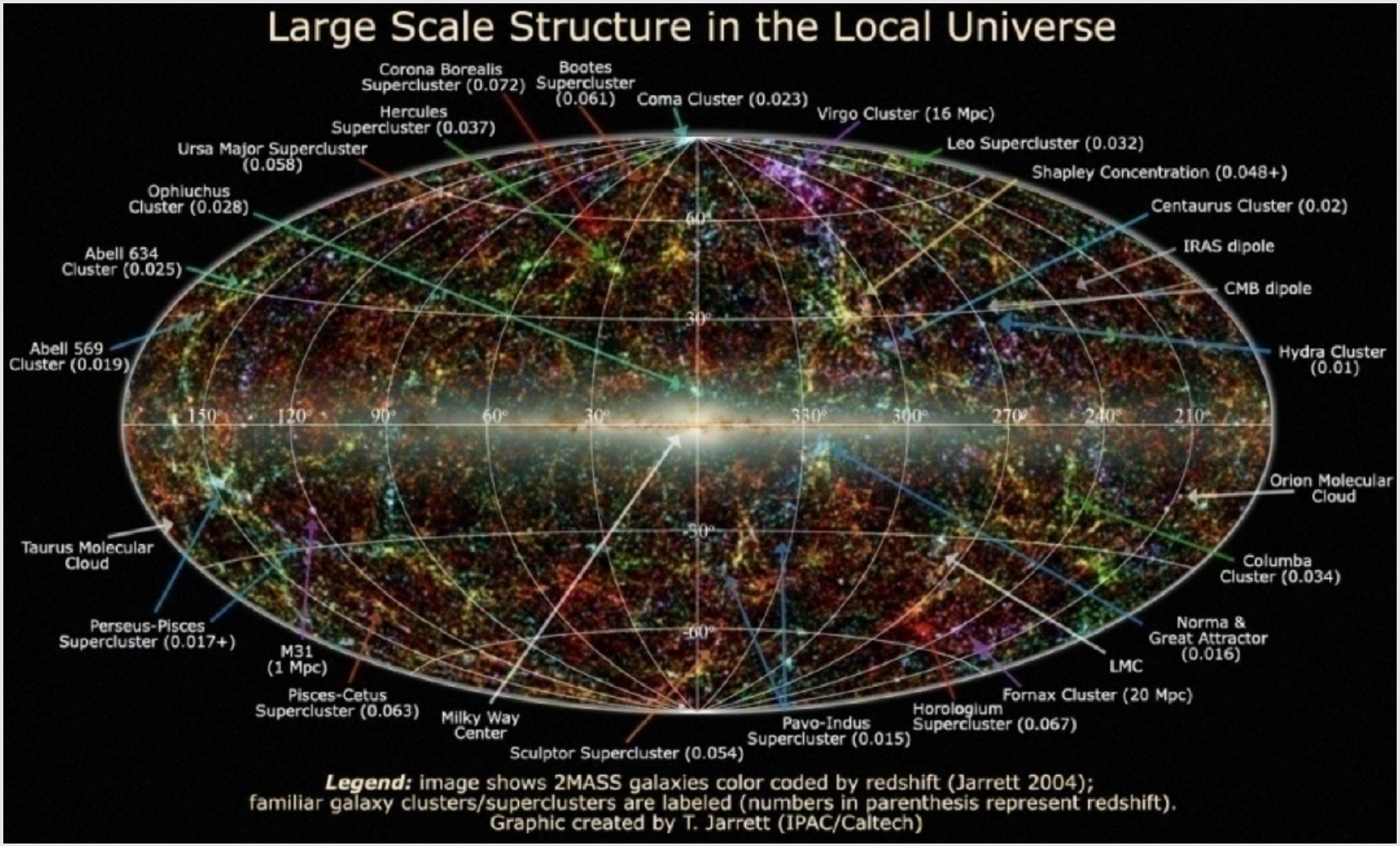


$160h^{-1}\mathrm{Mpc}$
Anatoly
Klypin

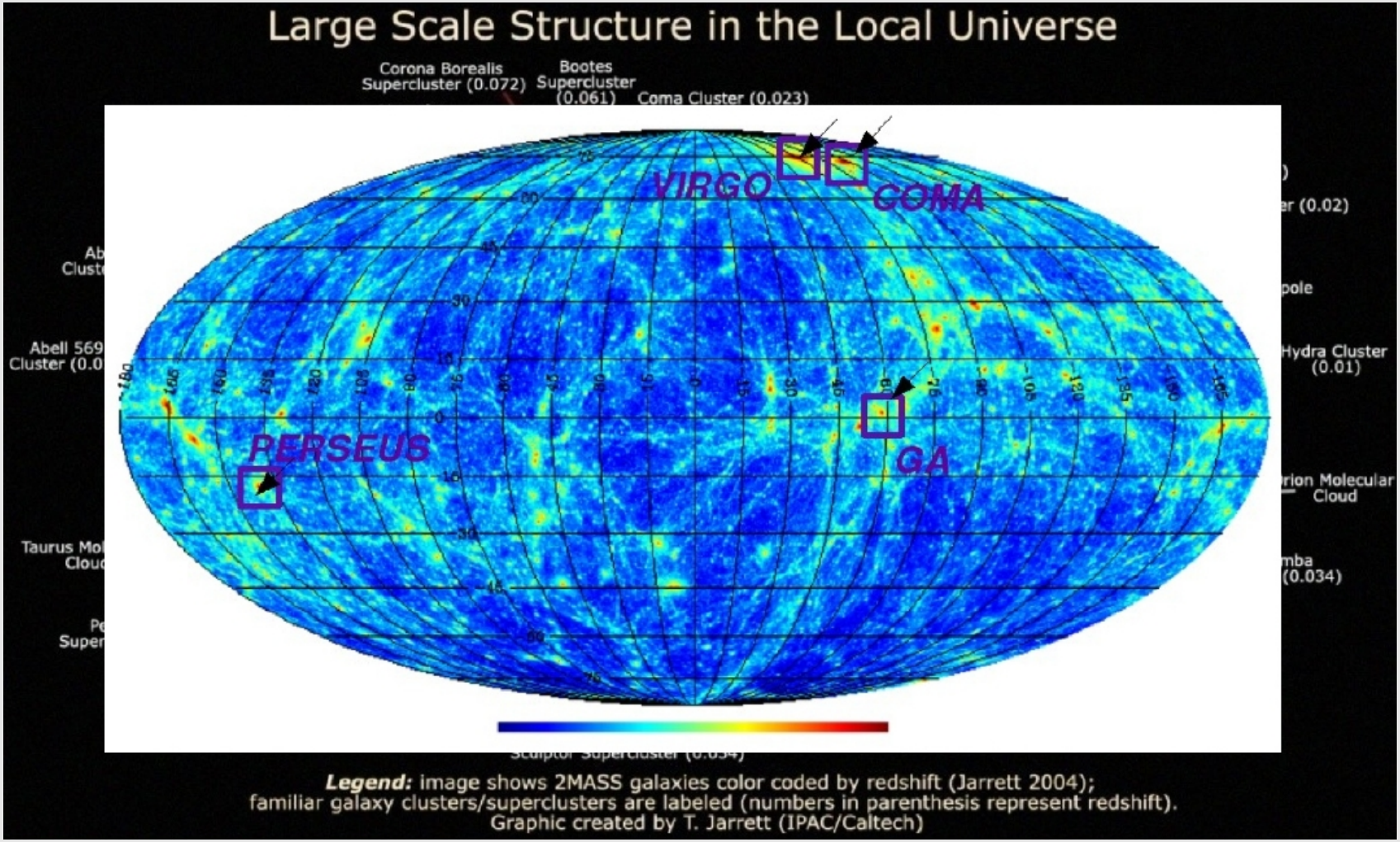
$64h^{-1}\mathrm{Mpc}$
Gustavo
Yepes

The Local Volume simulations

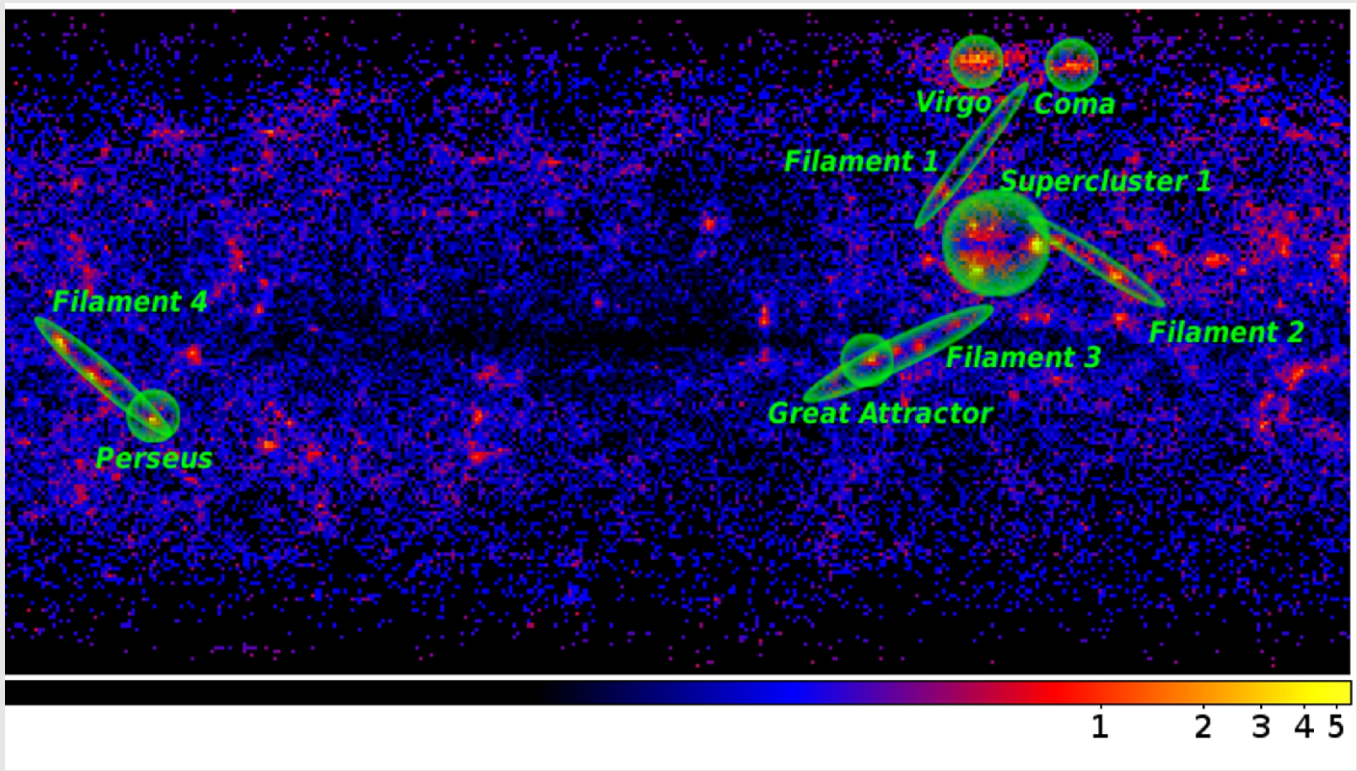
The Local Volume



The Local Volume



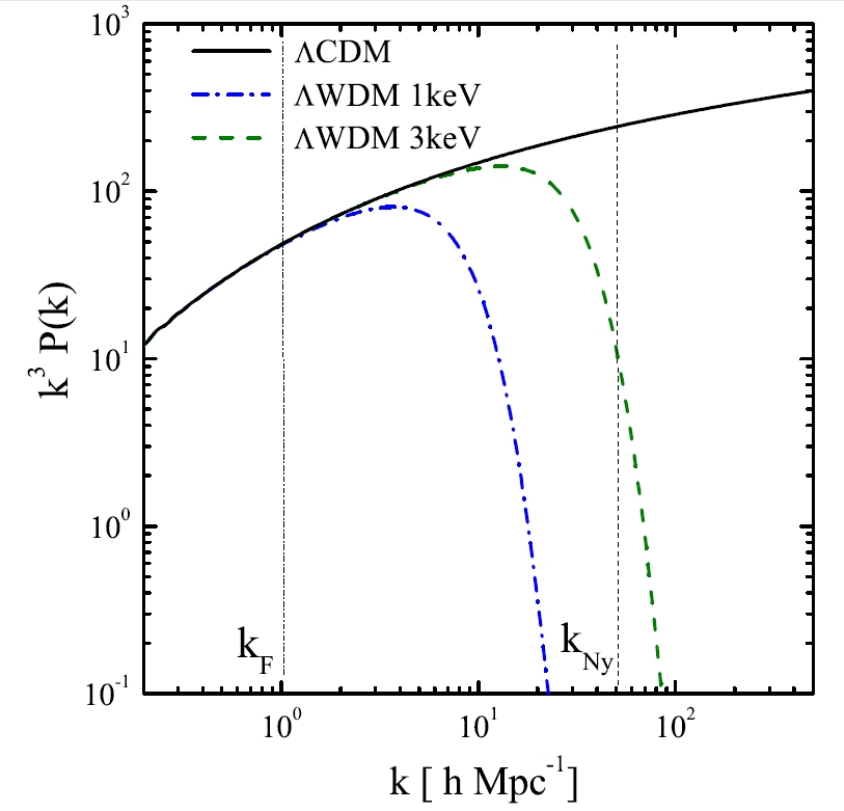
Fermi Simulation



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

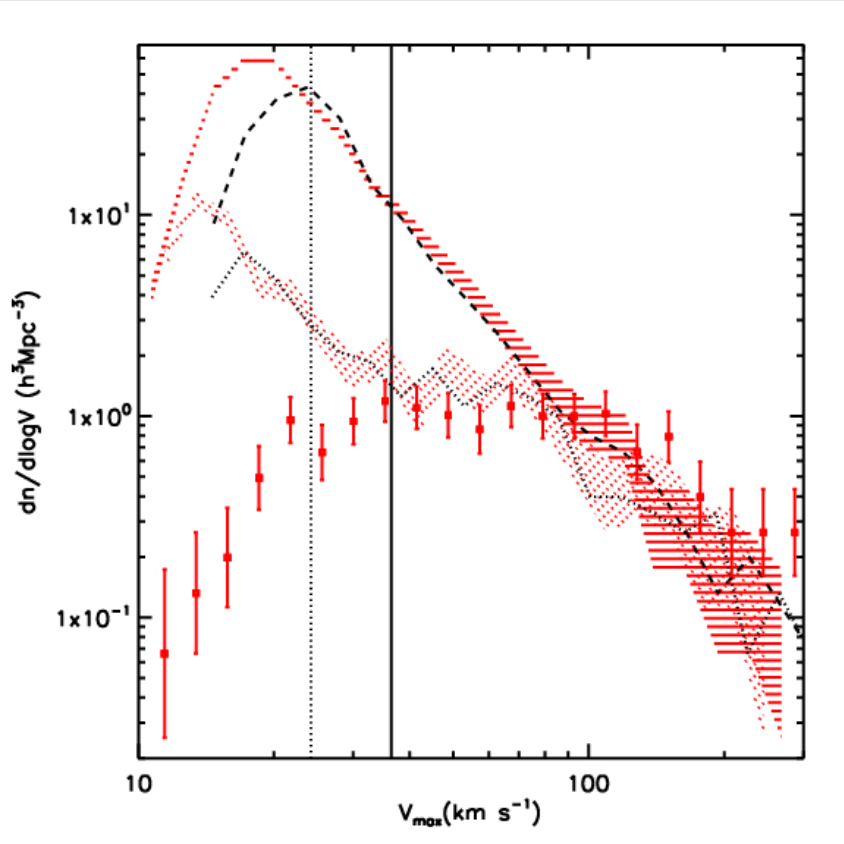


WMAP3

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

less small scale power $\Longrightarrow$ less small scale structure

ALFALFA observations in Virgo direction



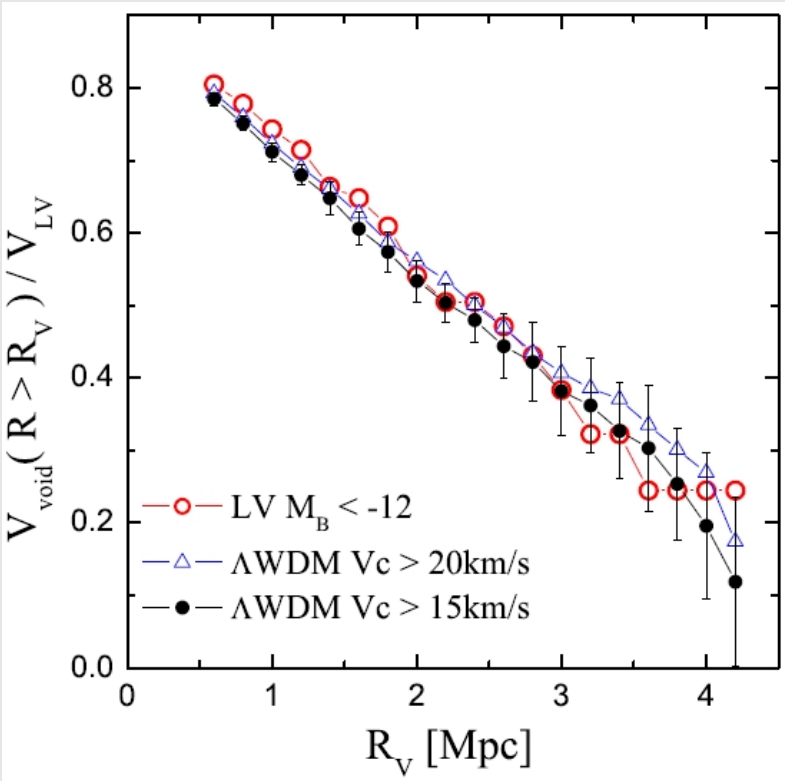
Zavala et al. (2009)

velocity function

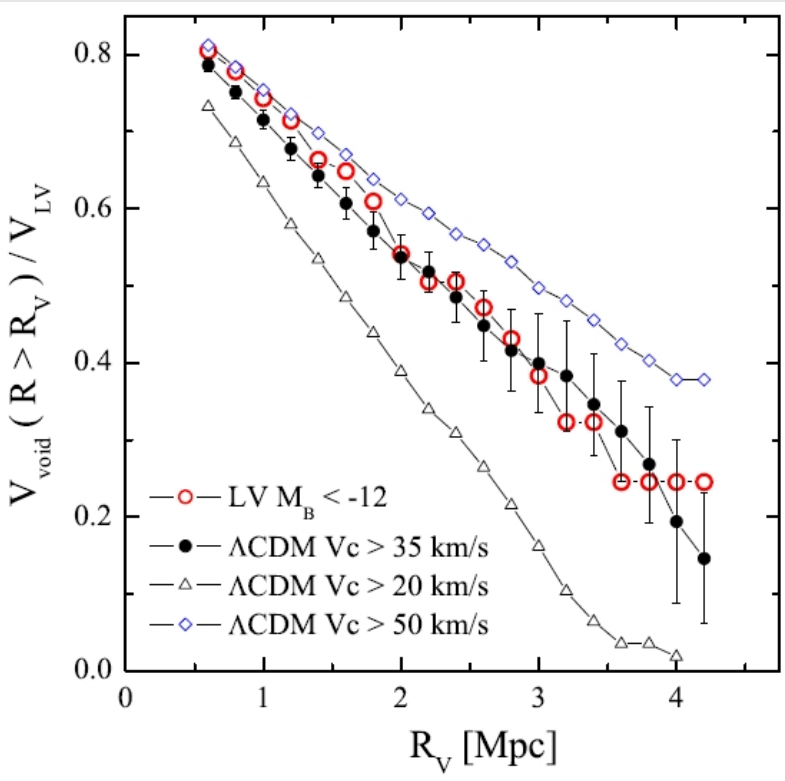
- squares with error bars: galaxies taken from the ALFALFA catalog with distances lower than $20h^{-1}\mathrm{Mpc}$
- predictions from the constrained simulation
  - ΛCDM: dashed red area
  - ΛWDM: dotted red area
  - dashed/dotted line: disk baryon fraction as function of halo mass (SN feedback)

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

Warm Dark Matter



Cold Dark Matter



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

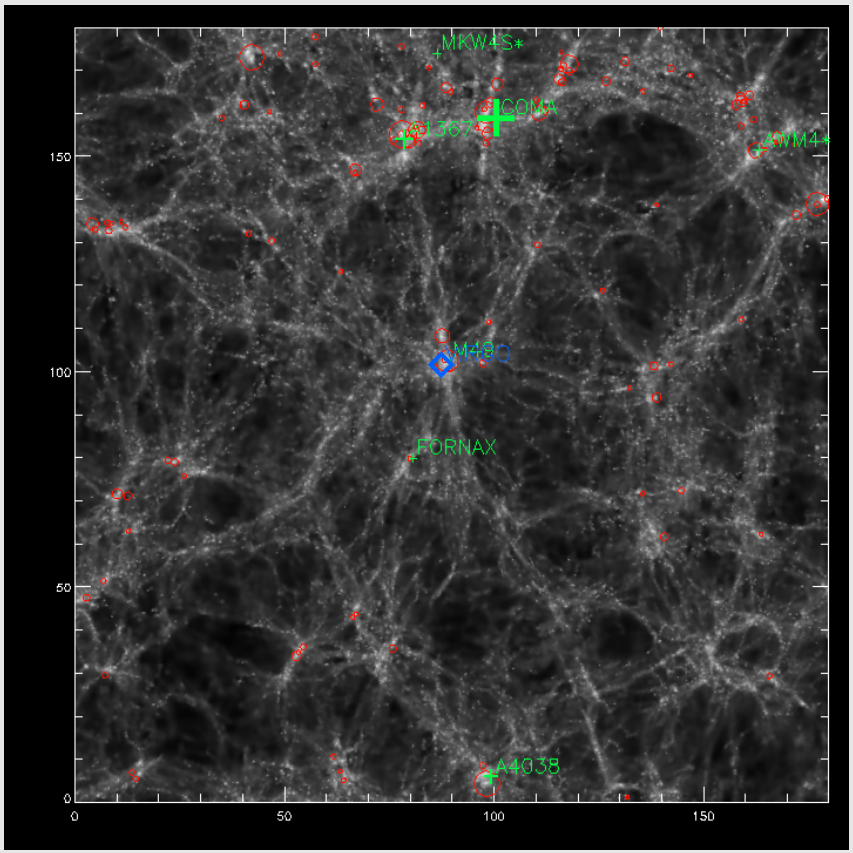
KIGEN - an alternative method

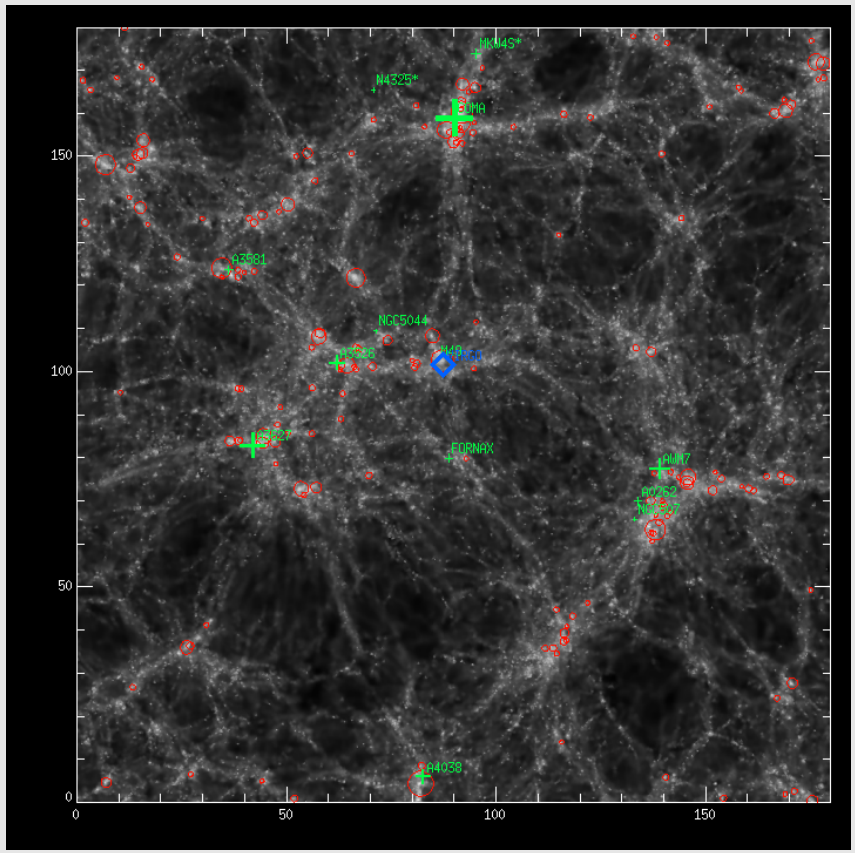
Reconstruction of Gaussian initial conditions with KIGEN (Kitaura 2012)

- observational data: 2MRS redshift survey
  - full sky (small ZOA)
  - positions and redshifts are used
- KIGEN algorithm
  - assuming LCDM priors
  - constructing the redshift zero distribution by Augmented Lagrangian Perturbation Theory (ALPT) (Kitaura, Heß 2013)
  - comparison with the observed galaxy distribution
  - selecting the best tracers
  - iterative improvement of the ICs until convergence

A 180 Mpc/h CR box

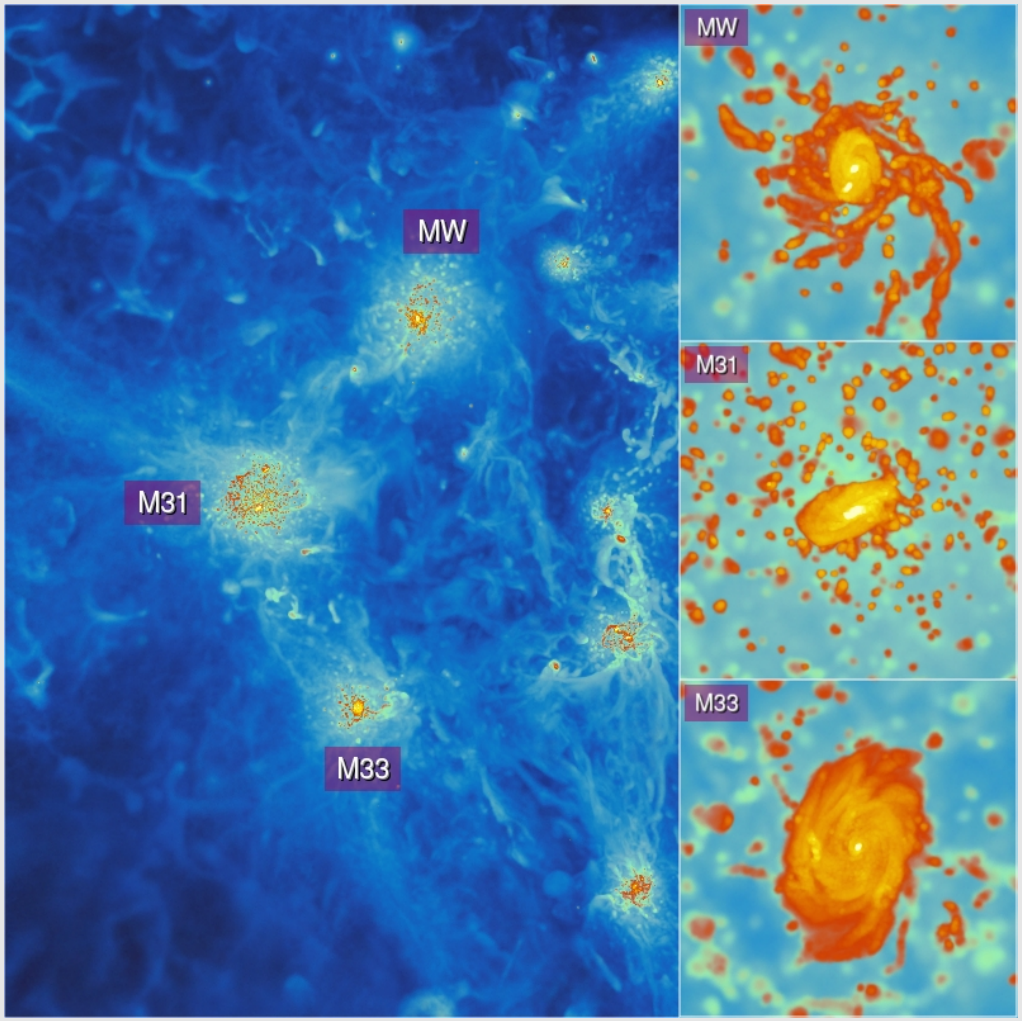
The simulated local universe (Heß S. et al., 2013)





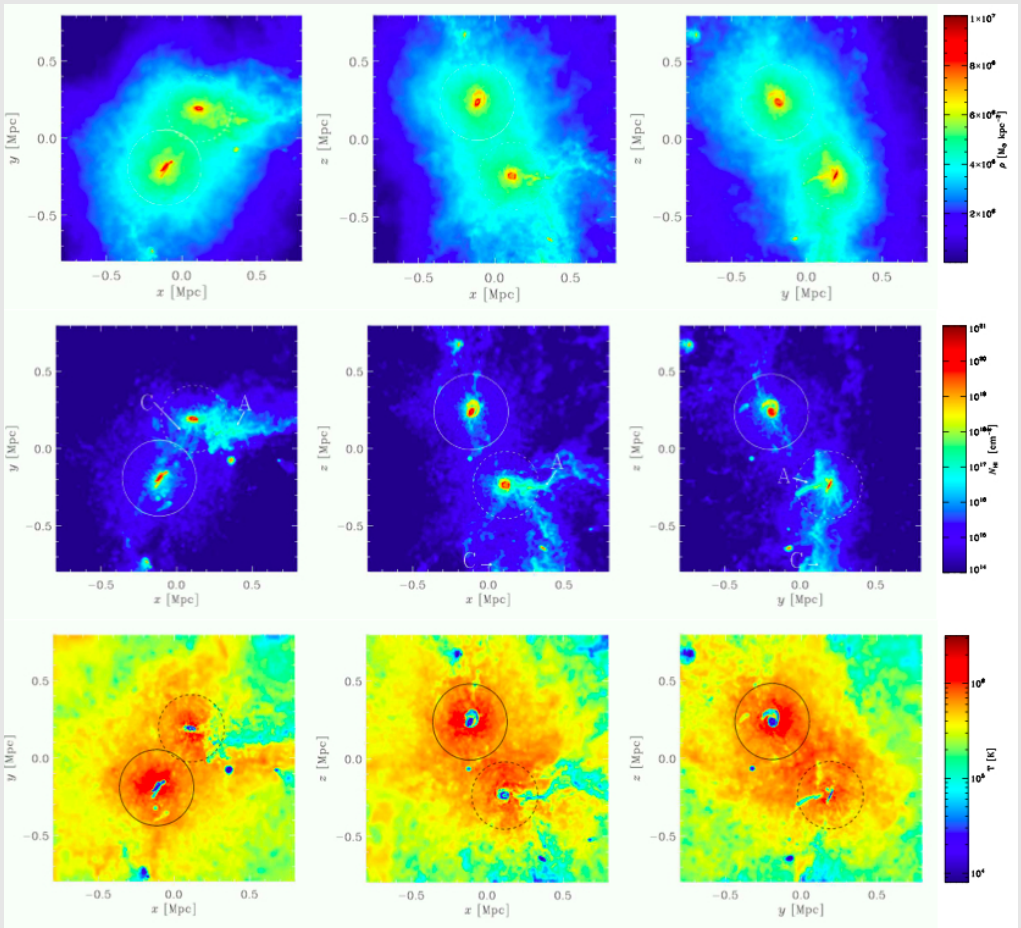
The Local Group simulations

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: $0.15h^{-1}\mathrm{kpc}$

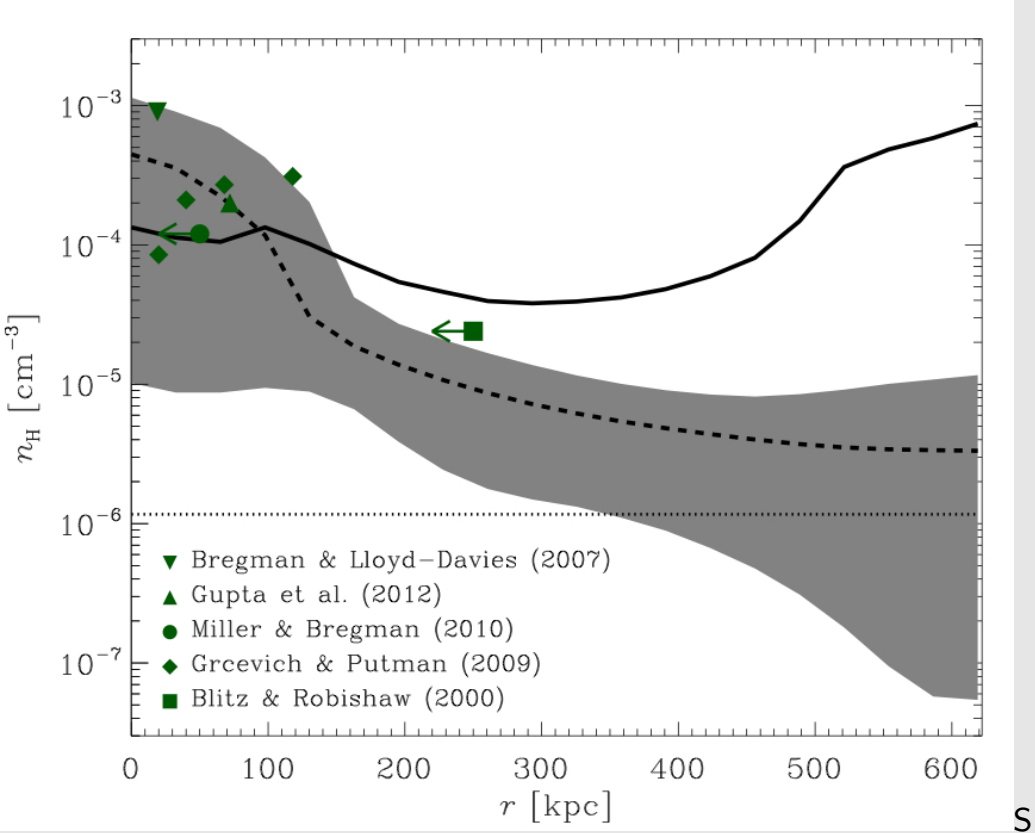
Gas distribution in the local group



S. 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

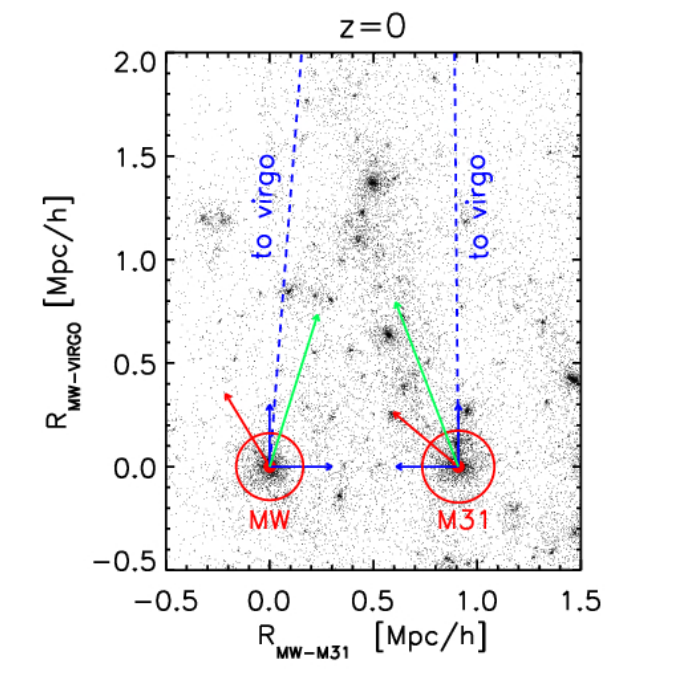


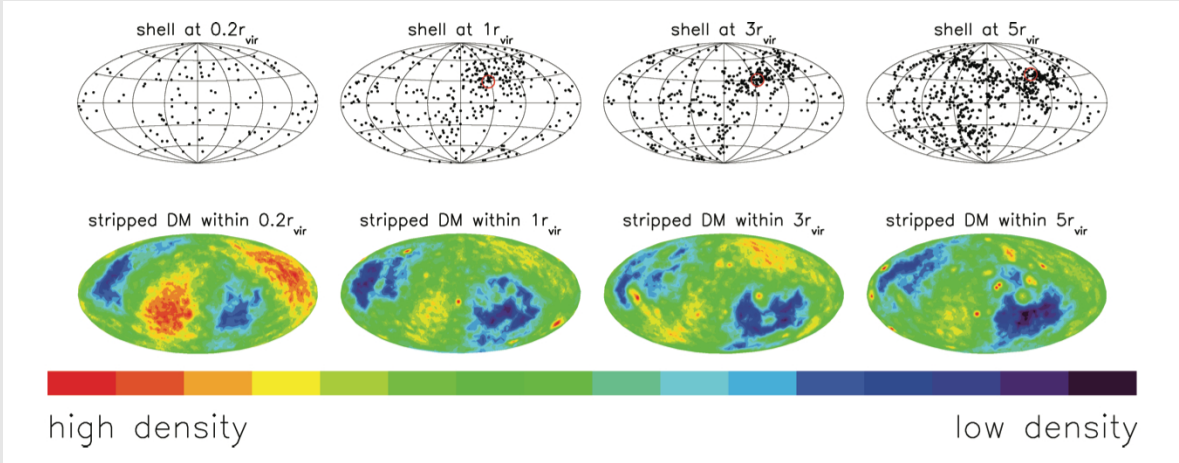
s.

Nuza et al. (2013)

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

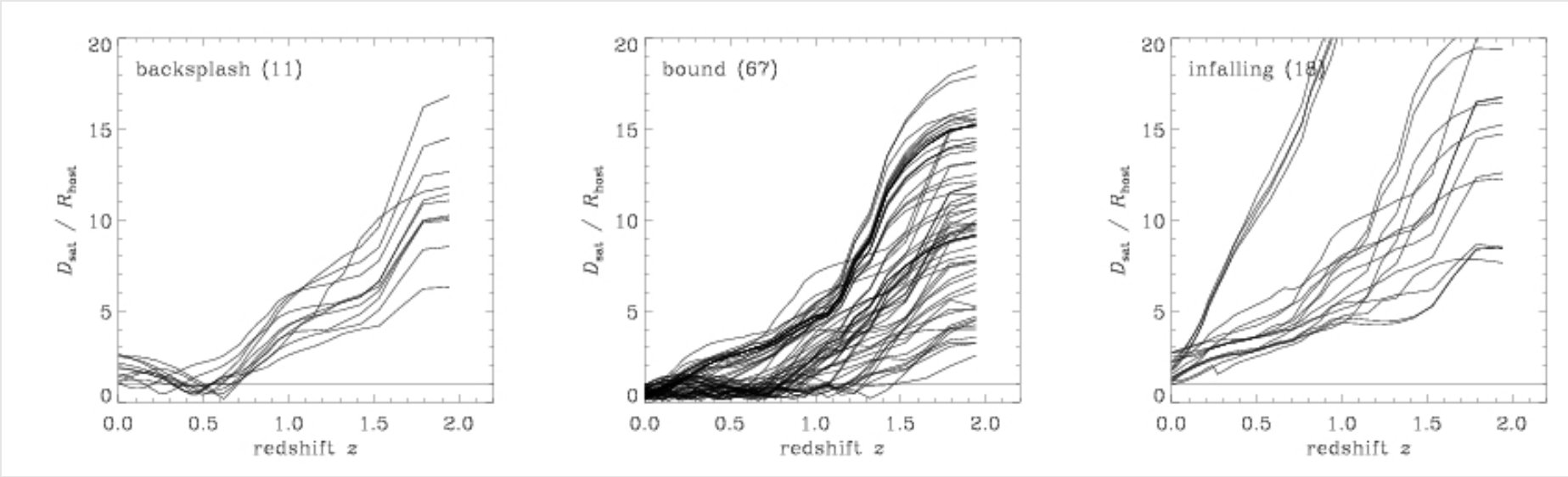
Preferential infall





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

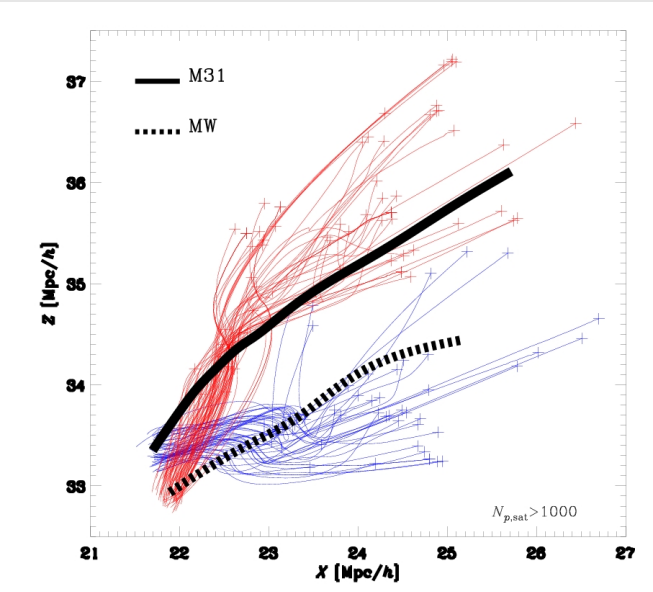
Knebe et al. MNRAS 2011

Renegade galaxies

z	$=$	0.0	0.05	0.16	0.23	0.29	0.68
$D_{\mathrm{MW-M31}}$	$=$	545	600	700	750	800	1000
N	$=$	128	107	26	7	1	0
p	$=$	5%	4%	1%	<1%	<1%	0%

The number of renegade satellites (with $N_{p,\mathrm{sat}} \geq 20$, $M_{sat} > 4.1 \times 10^6 h^{-1}\mathrm{M}_\odot$) as a function of redshift z and distance $D_{\mathrm{MW-M31}}$ (as measured in h^{-1}kpc), respectively.

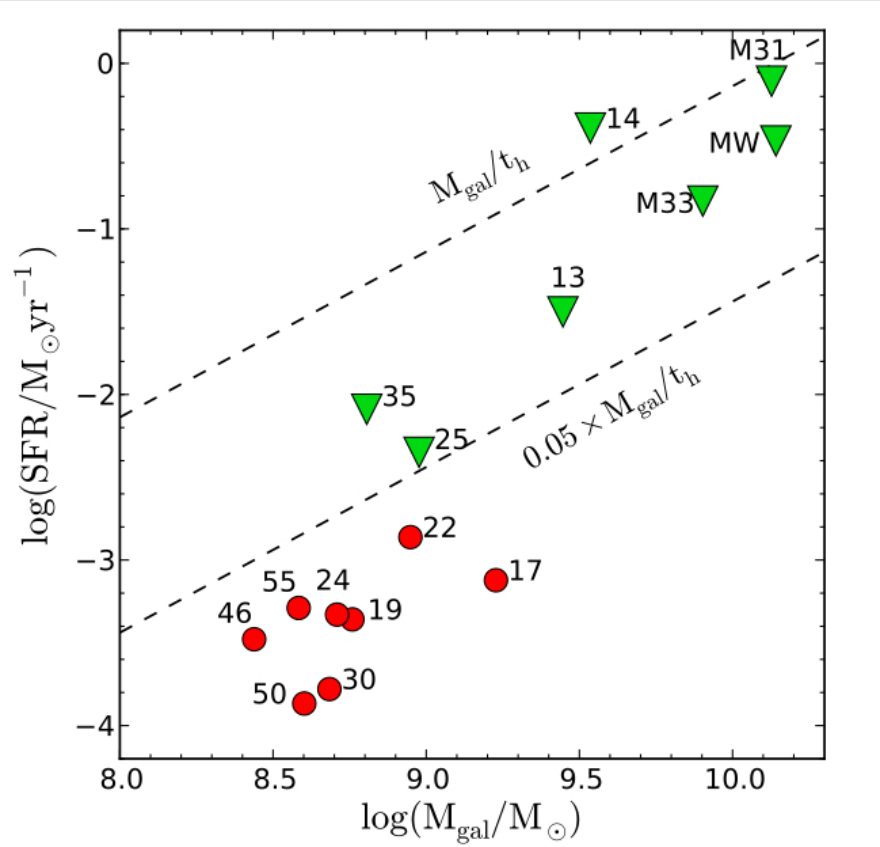
infall of satellites



renegade satellites

Knebe et al. 2011

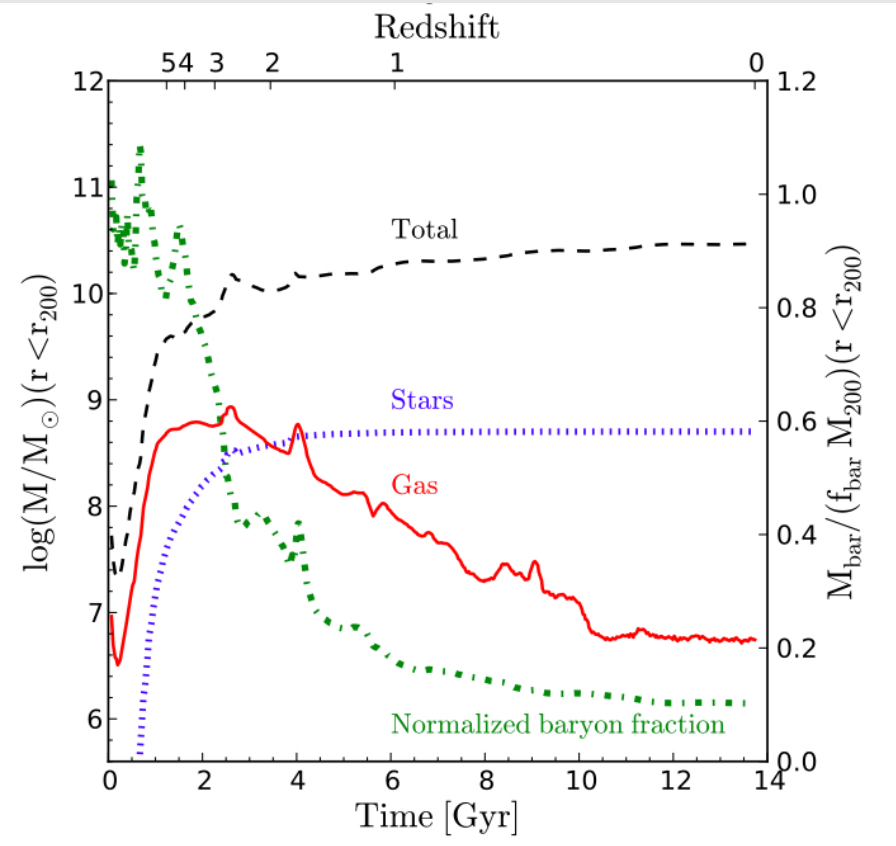
Dwarfs in the Local Group



- isolated dwarfs without interactions with one of the massive galaxies in the past
- all within a sphere of R = 1.5 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

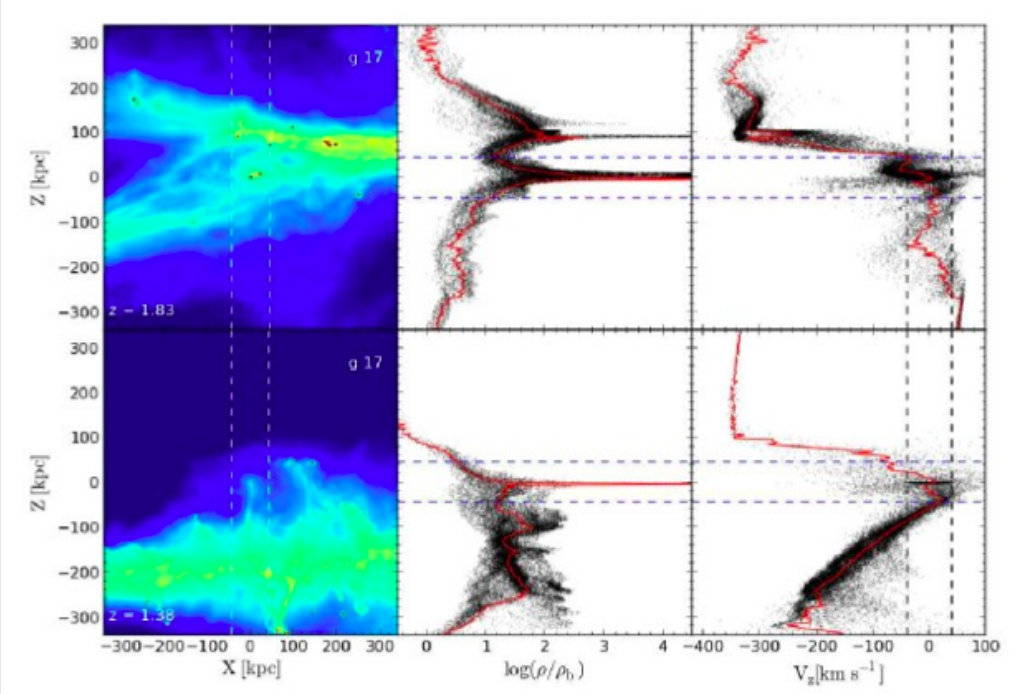
Alejandro Benitez-Llambay et al. (2013)

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

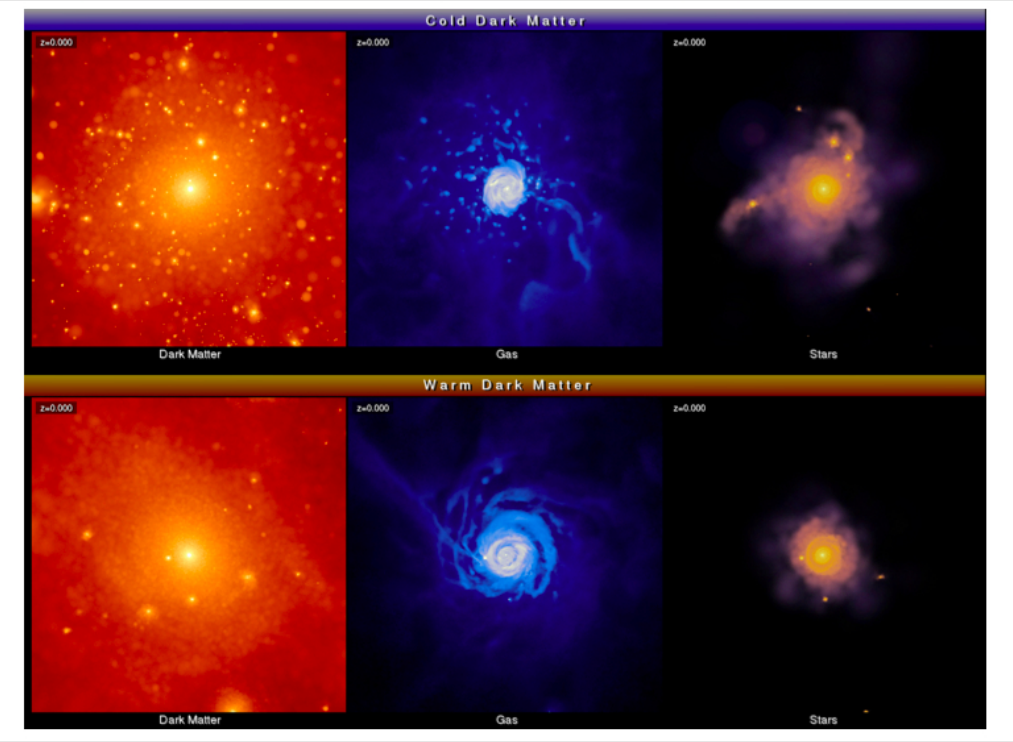
Cosmic web stripping



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

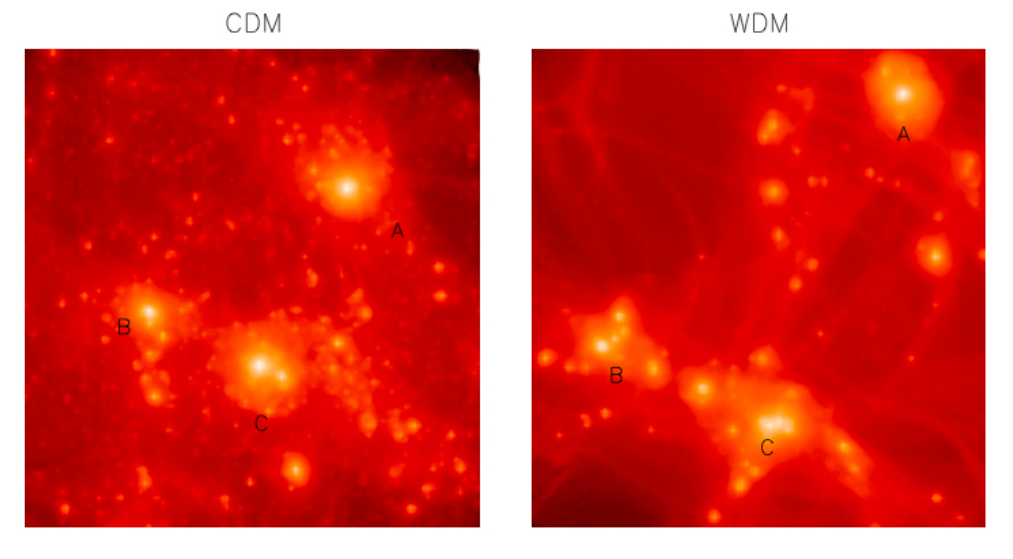
- gas from the halo is removed by the cosmic web environment due to ram pressure
- **Cosmic Web Stripping**

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

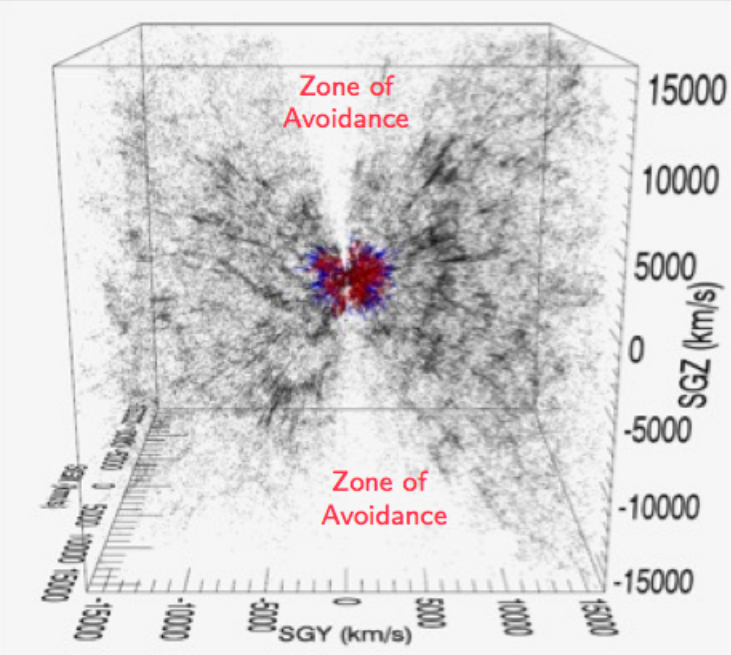
The evolution of the Local volume

XII. Dwarf galaxies and reionization (Thursday morning)

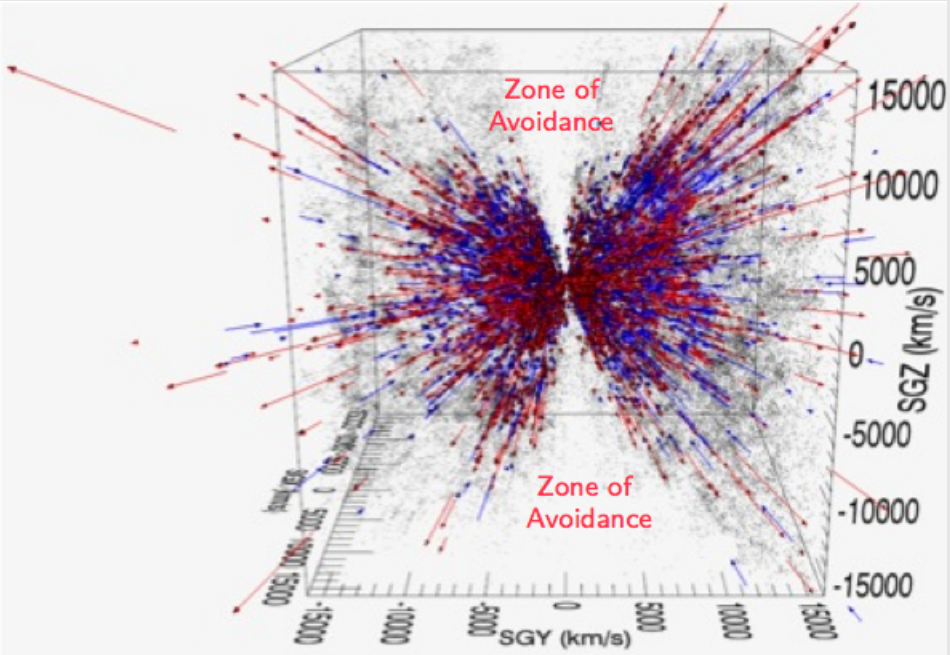
- Ilian Iliev: Radiative feedback of the first objects and its effects on galaxy formation and the IGM
- Pierre Ocvirk: A hydro–radiative solution to the missing satellite problem?
- Alejandro Benitez-Llambay: The imprint of reionization on the star formation histories of dwarf galaxies

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

CosmicFlows

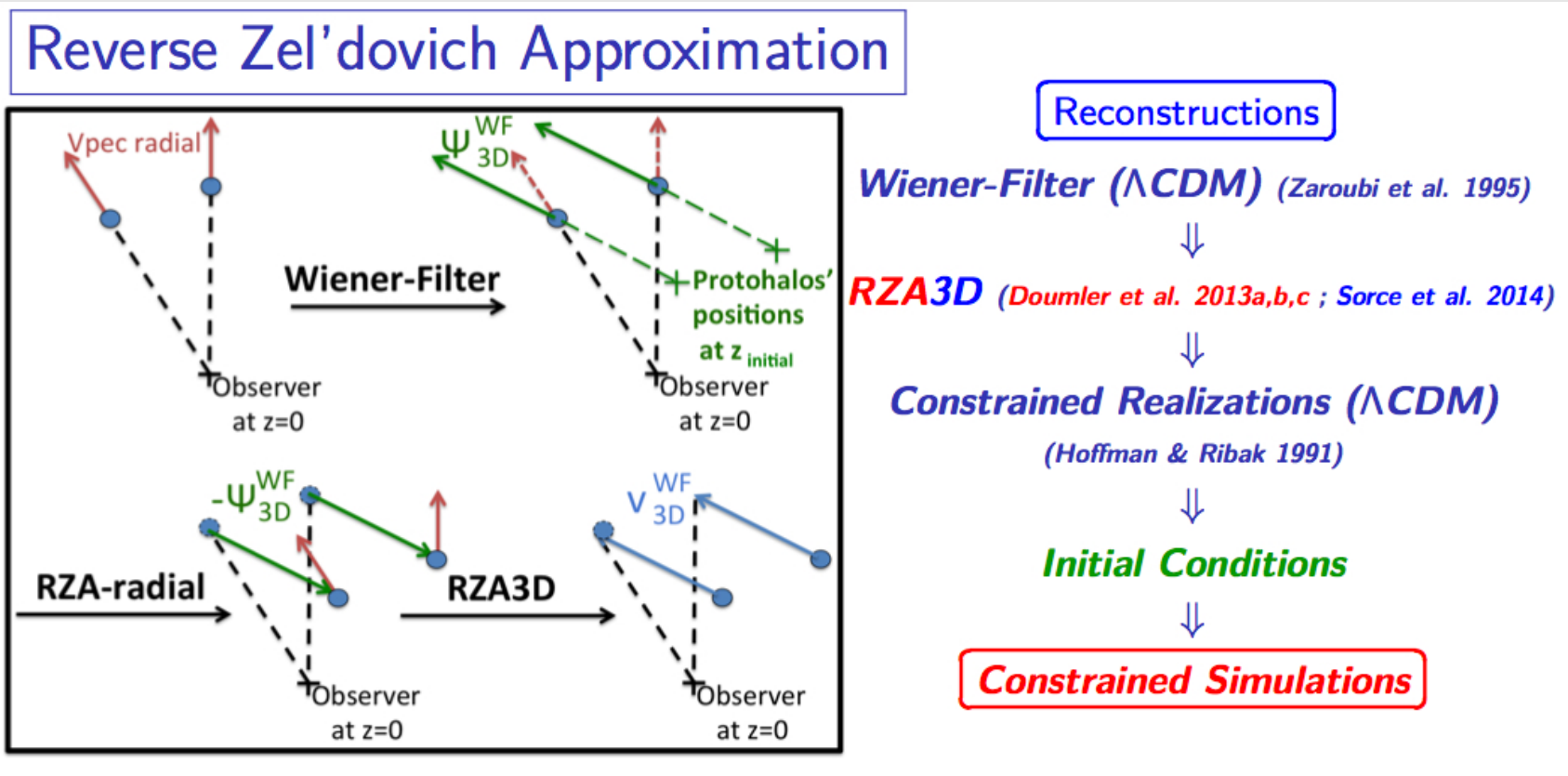


Cosmicflows-1
about 2000 constraints
Tully et al. 2008



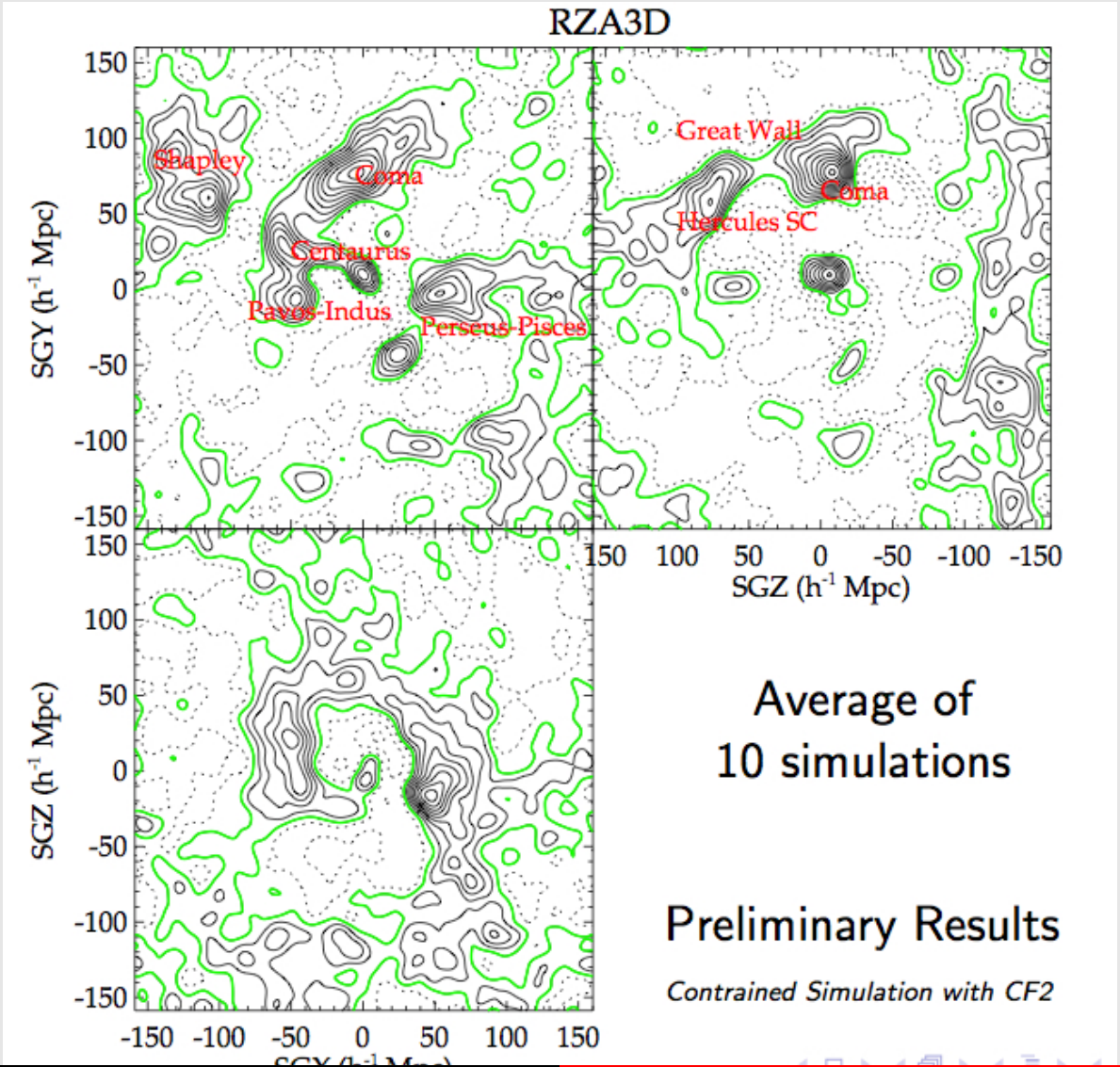
Cosmicflows-2
about 8000 constraints
Tully et al. 2013

RZA

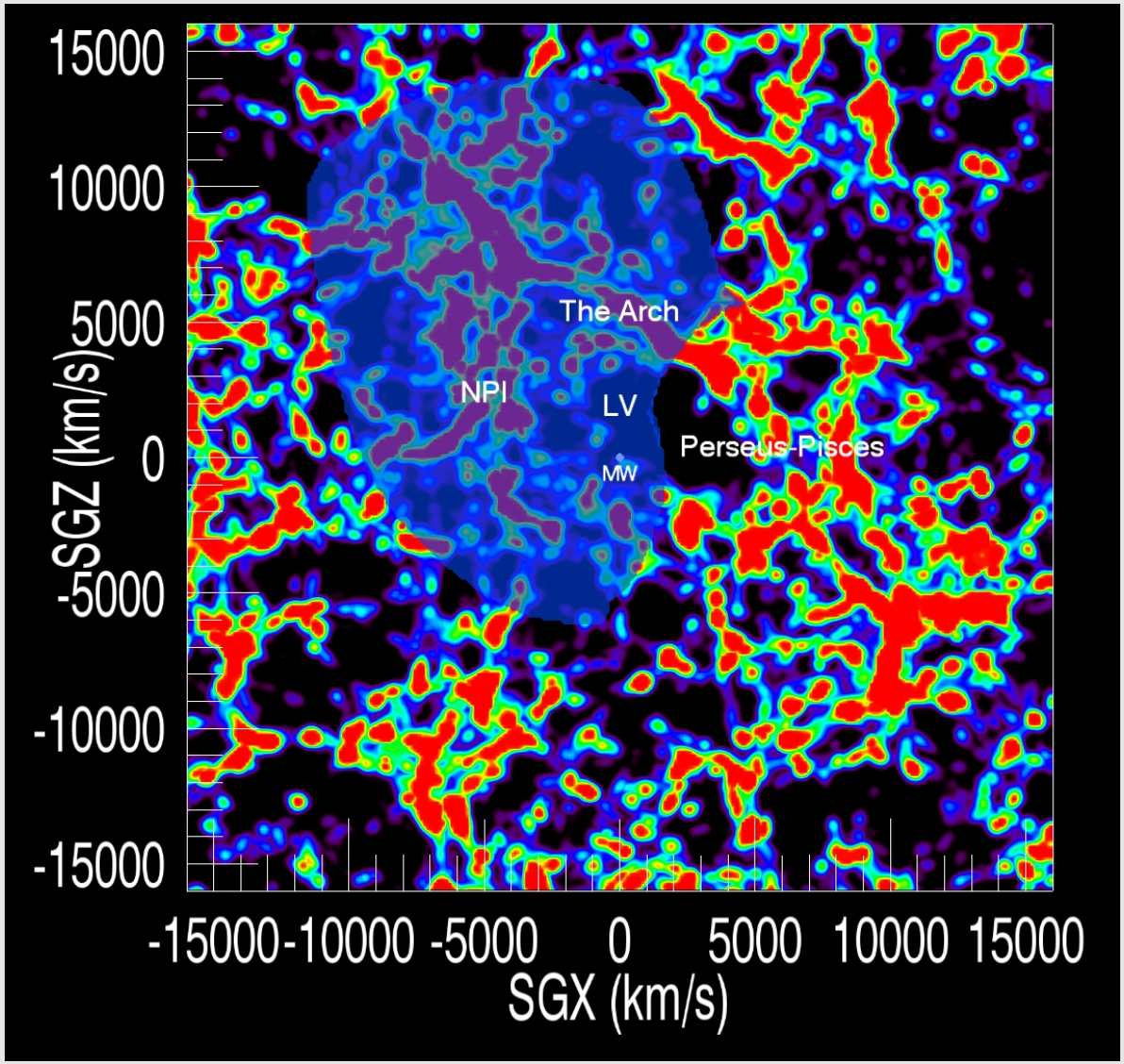


Jenny Sorce (2014)

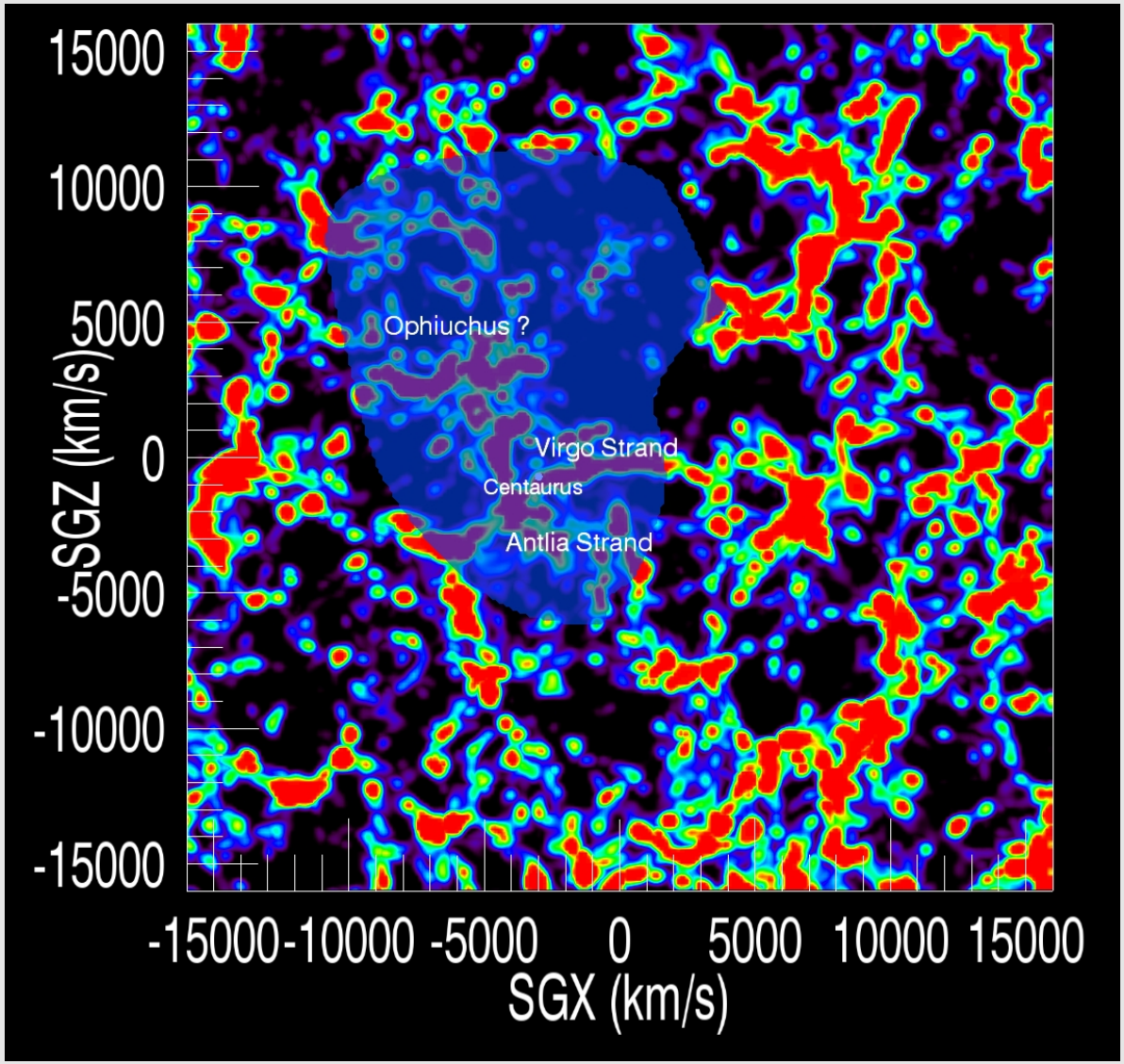
Constrained simulations from Cosmic Flows 2



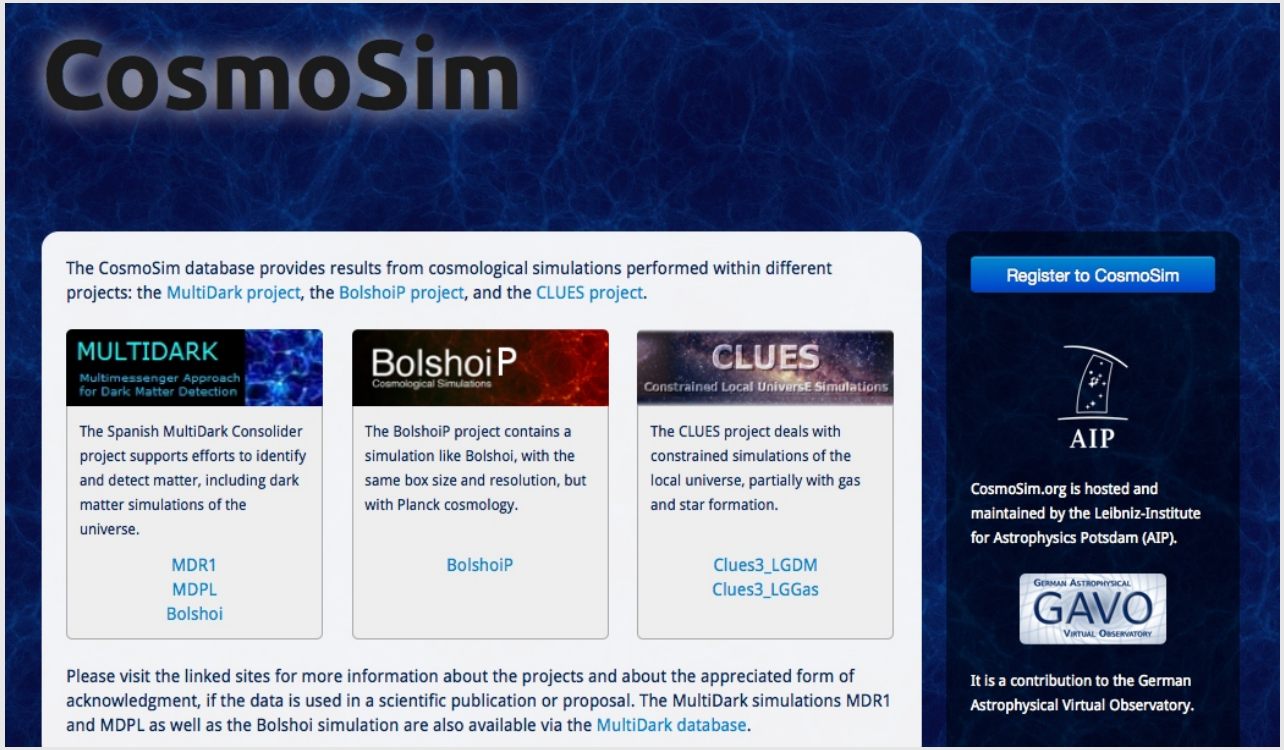
Constrained simulations from Cosmic Flows 2



Constrained simulations from Cosmic Flows 2



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

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.