Formation of Small Scale Structure or Near Field Cosmology

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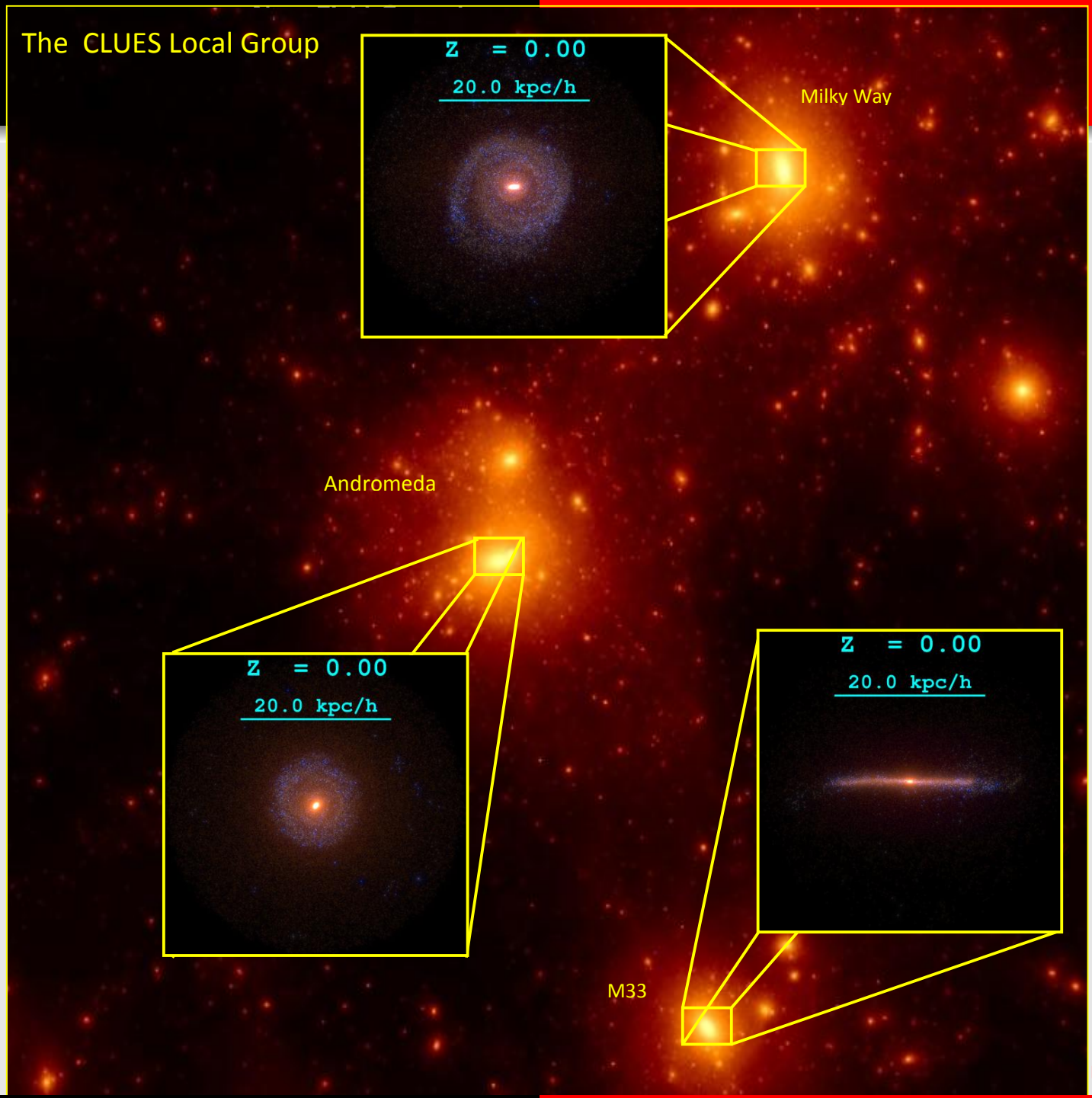
Limitations of present day simulations

- Representative volume ($> 500h^{-1}\mathrm{Mpc}$) $\Longleftrightarrow$ desired resolution ($< 0.1h^{-1}\mathrm{kpc}$) $\Longrightarrow$ impossible on present computers
- Mass range ($10^8 ... 10^{15} h^{-1}\mathrm{M}_\odot$) $\Longleftrightarrow$ mass resolution (> 1000 particles) $\Longrightarrow$ impossible on present computers
- there are also limits of present day observations
- $\Longrightarrow$ simulate a smaller volume representative for the neighborhood of Milky Way

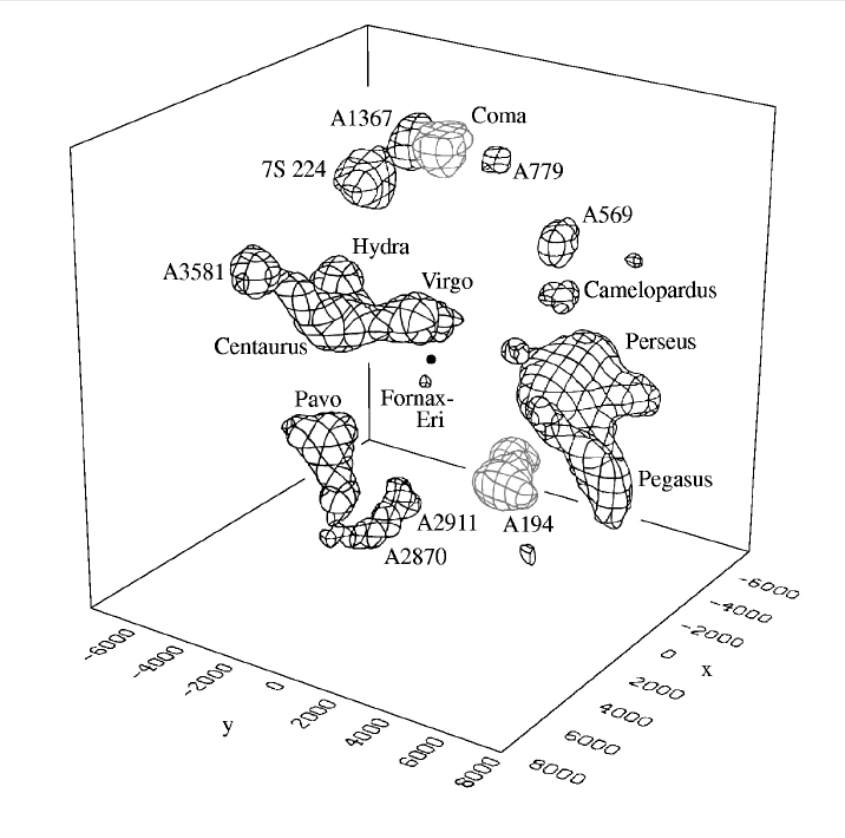
CLUES

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

Why are we interested in constrained simulations?

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.
However, the local universe is not a representative part of the universe.

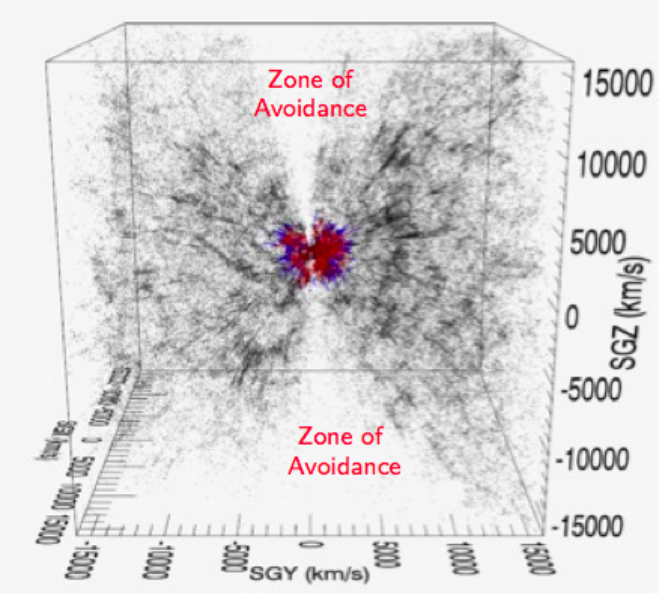


Hudson (1993)

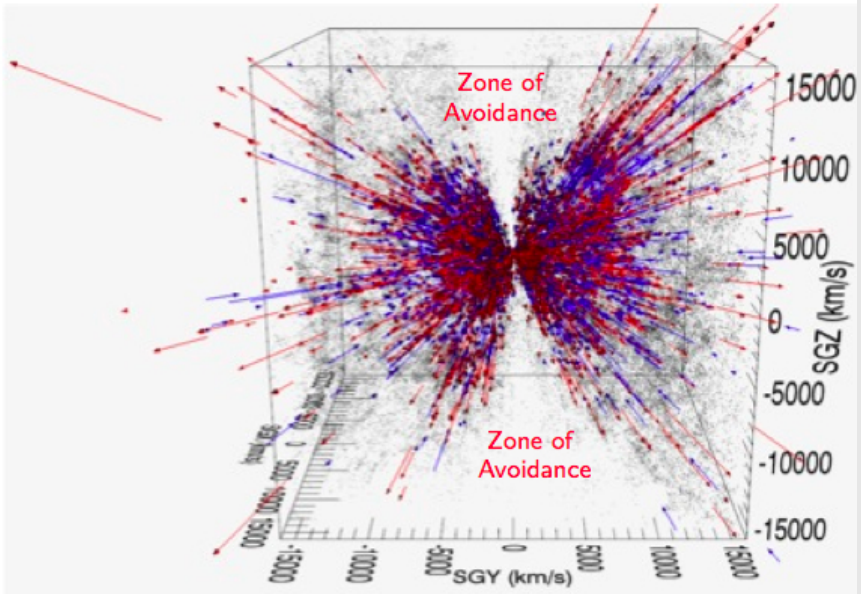
Cosmic Flows data

CF1 and CF2: Evolution of Cosmicflows Catalogs

Galaxies with measured radial peculiar velocities



Cosmicflows-1
about 2000 constraints
Tully et al. 2008



Cosmicflows-2
about 8000 constraints
Tully et al. 2013

With each catalog, improvements of :

- **quality** (*e.g. accuracy*)
- **quantity** (*e.g. farther, Zone of Avoidance*)

Black dots: XSCZ redshift catalog

Construction of catalogs

How Catalogs Are Built

$$v_{obs} = H_0 \times \mathbf{d} + v_{pec\ radial} \quad (1)$$

redshift — constant — distance — velocity

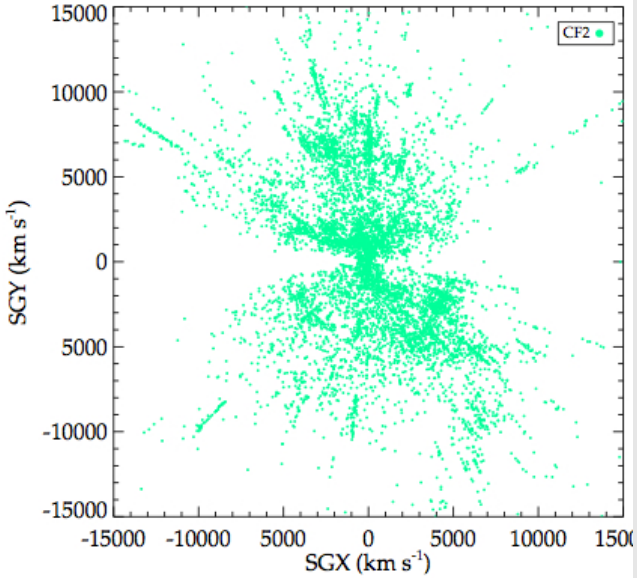
$$m - M = 5 log_{10}(\mathbf{d}(Mpc)) + 25 \quad (2)$$

$\begin{cases} m \leftrightarrow \textbf{Photometry} \\ M \leftrightarrow \textbf{ITFR} : L \propto v_{HI}^{\alpha} \end{cases}$ — Observations / Calibrations

Mainly (Tully & Fisher 1977)

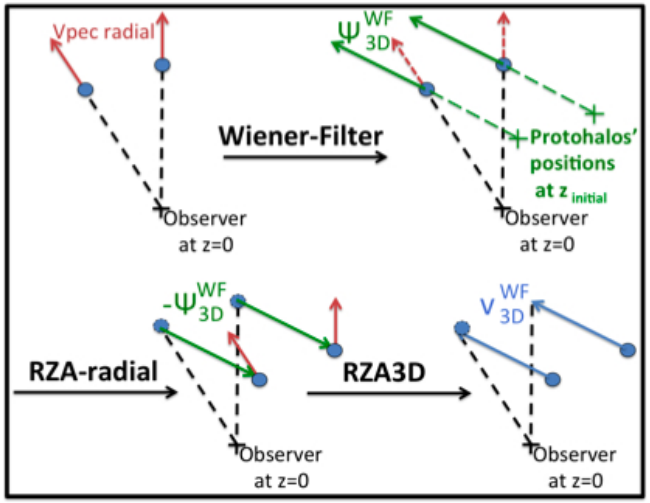
$\overset{(2)}{\hookrightarrow} \mathbf{d} \overset{(1)}{\rightarrow}$ radial $v_{pec} \rightarrow$ Cosmicflows Catalogs $\rightarrow$ e.g. CF1, CF2

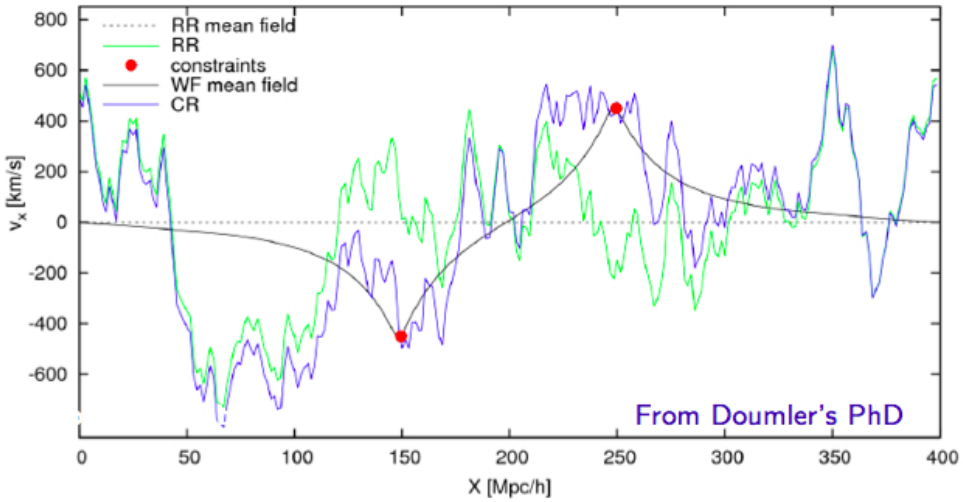
$\Rightarrow$ **Constrained Simulations** methods, mocks, observational data



CF2

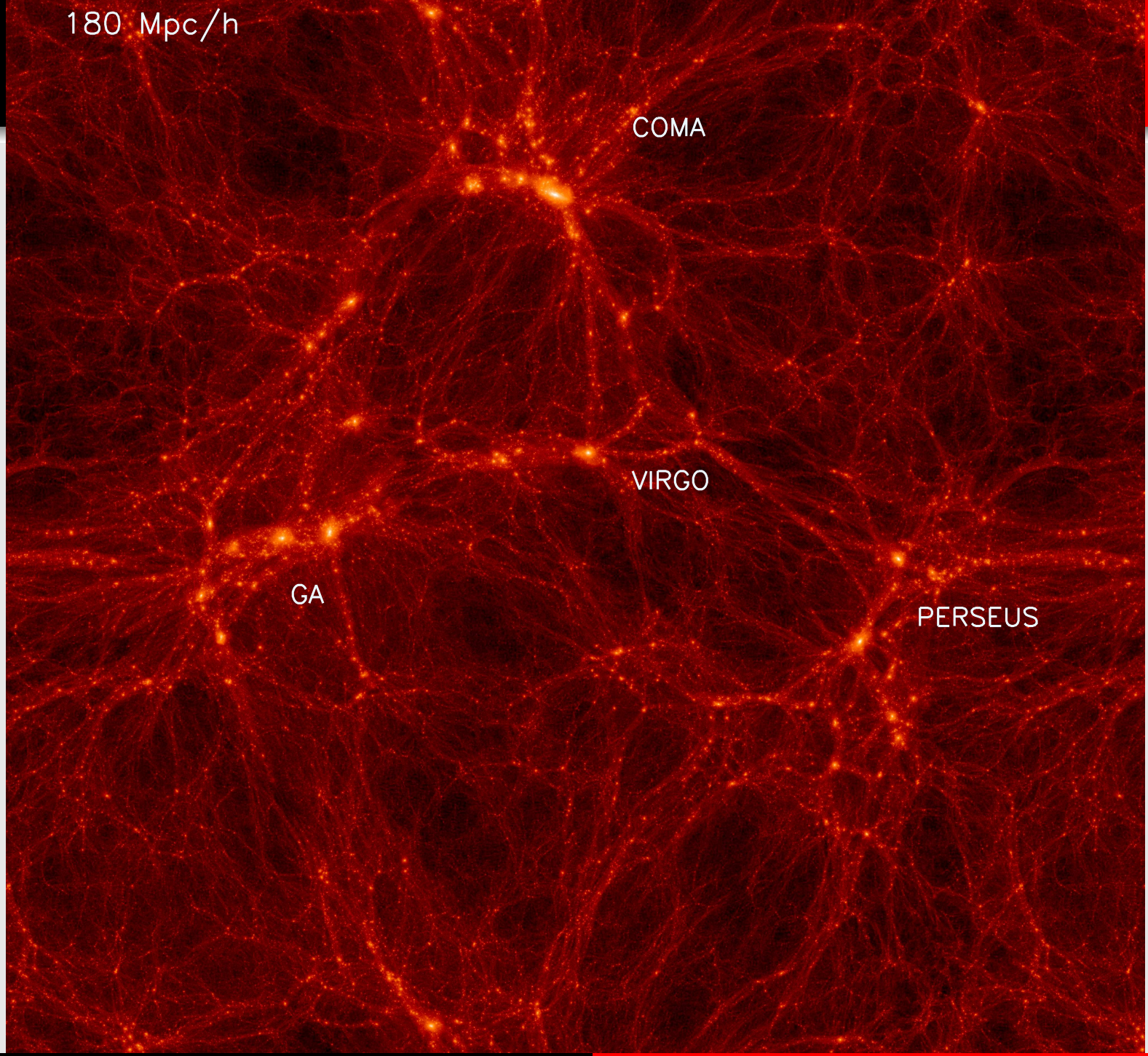
Constrained initial conditions (Jenny Sorce)

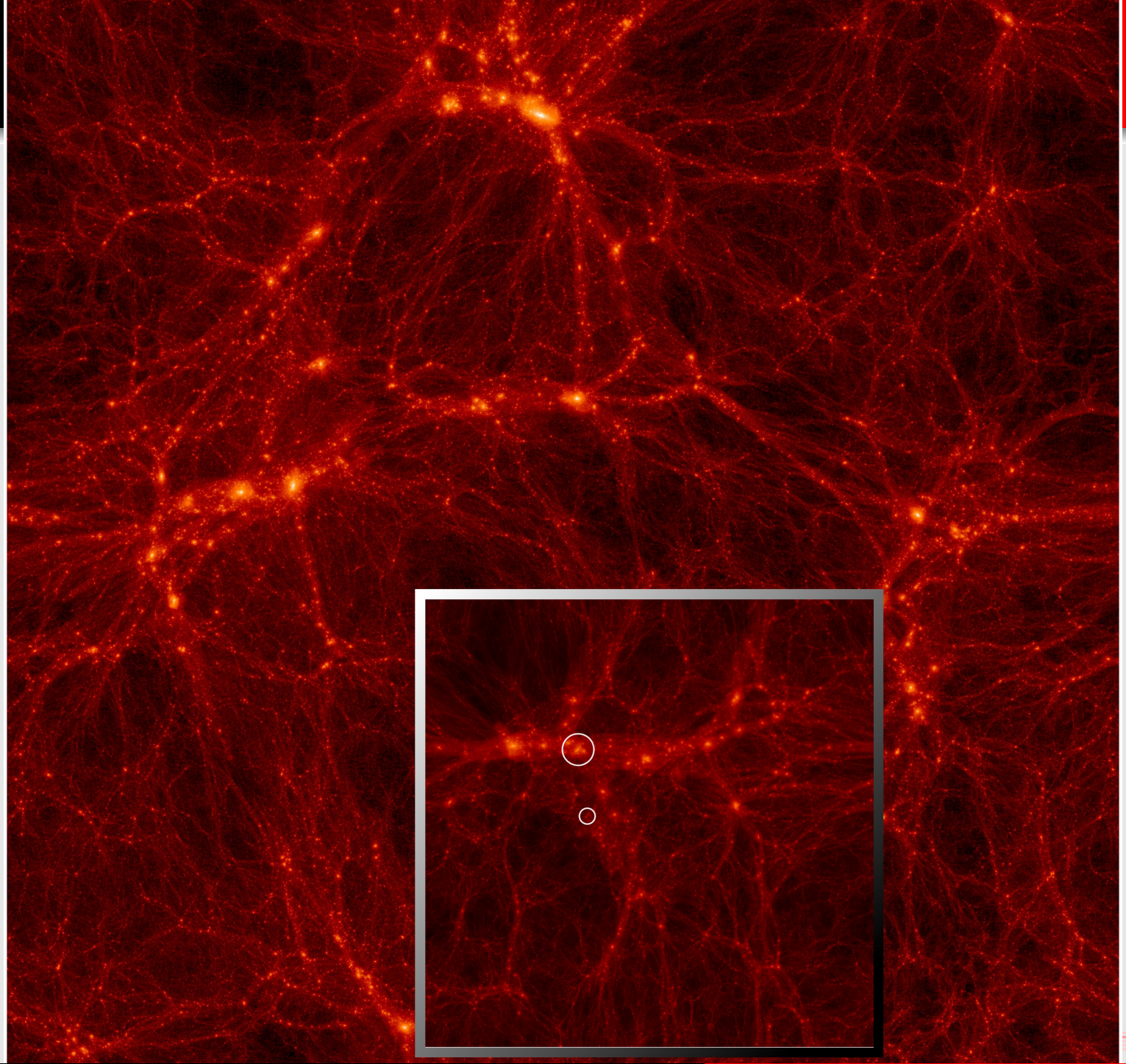




Cosmicflows-2 → WF → RZA → CR (∼ WF+RR) → white noise → increase resolution (random small scale features) → convert back white noise to build initial conditions → run constrained simulations

Linear Theory at 1^{st} order valid down to 2 h^{-1} Mpc


180 Mpc/h
COMA
VIRGO
GA
PERSEUS



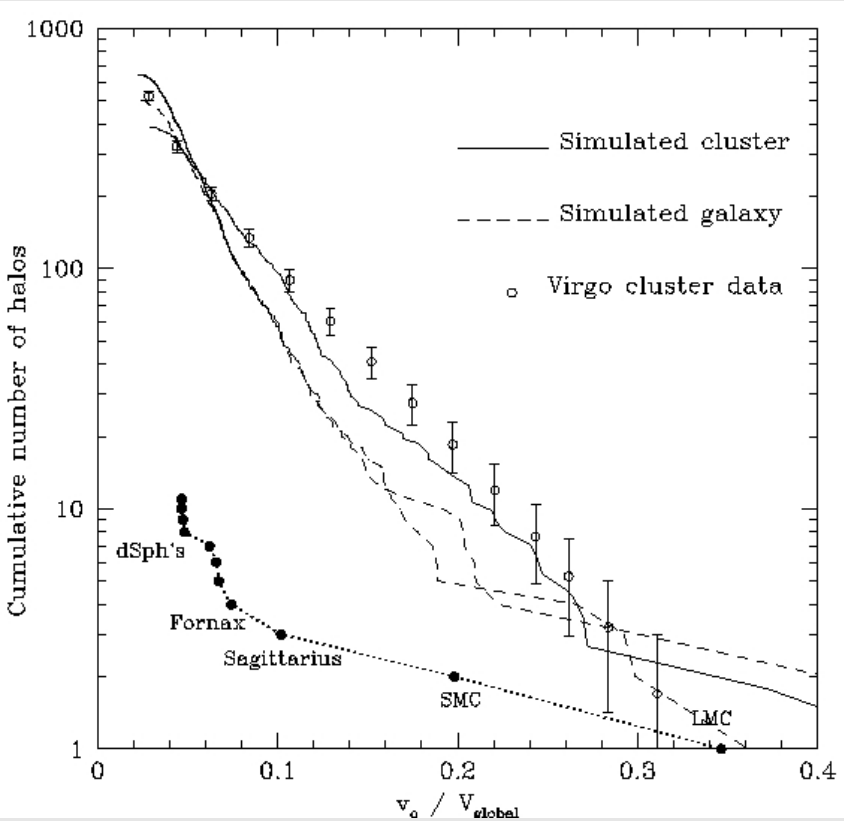
$160h^{-1}\mathrm{Mpc}$

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

The Local Volume simulations

Small scale structure with Warm Dark matter

Missing satellites

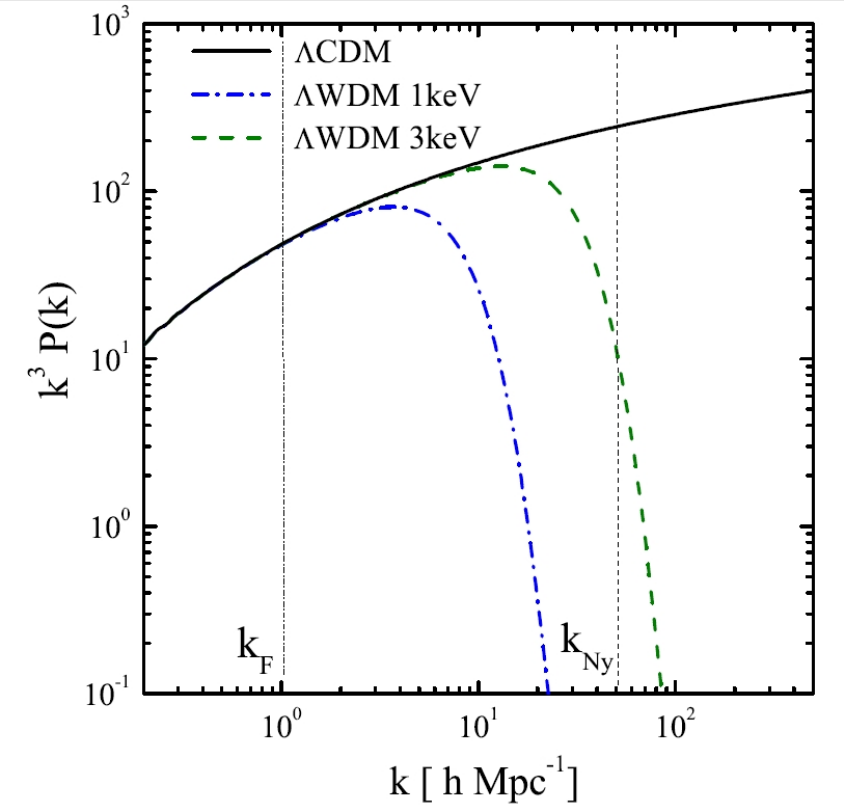


The number of observed satellites is an order of magnitude smaller than the predicted number of subhalos.

possible solutions:

- DM subhalos are more massive than assumed
- suppression of star formation
- no scale invariance of the power spectrum
  - Warm Dark Matter (small scale power erased)
  - a different inflationary model

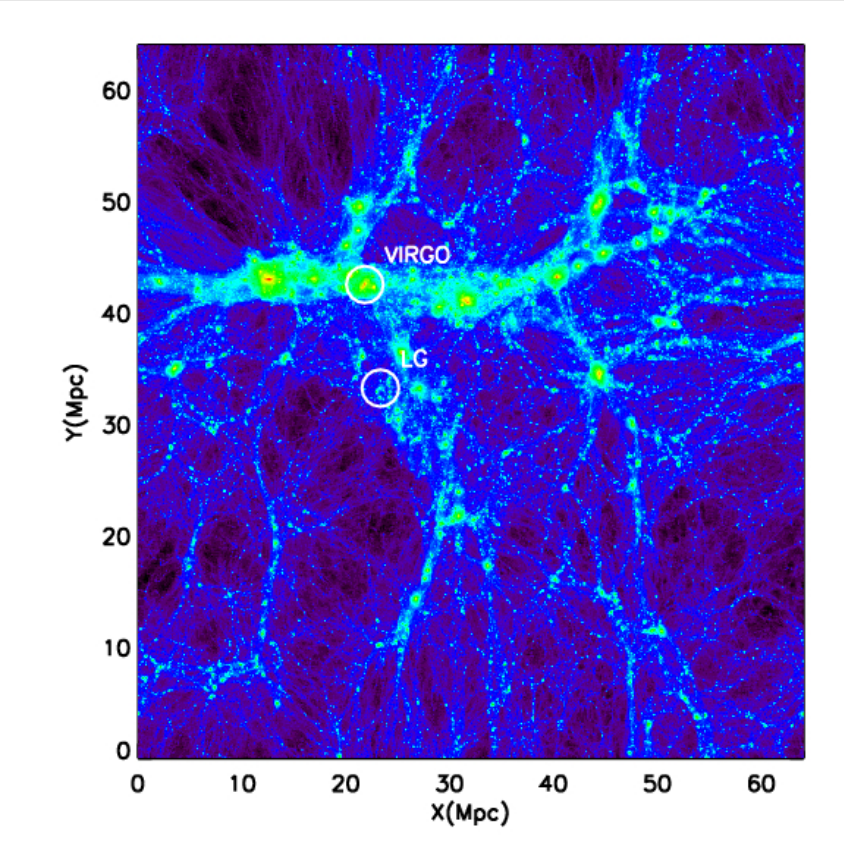
Cold vs. Warm Dark Matter



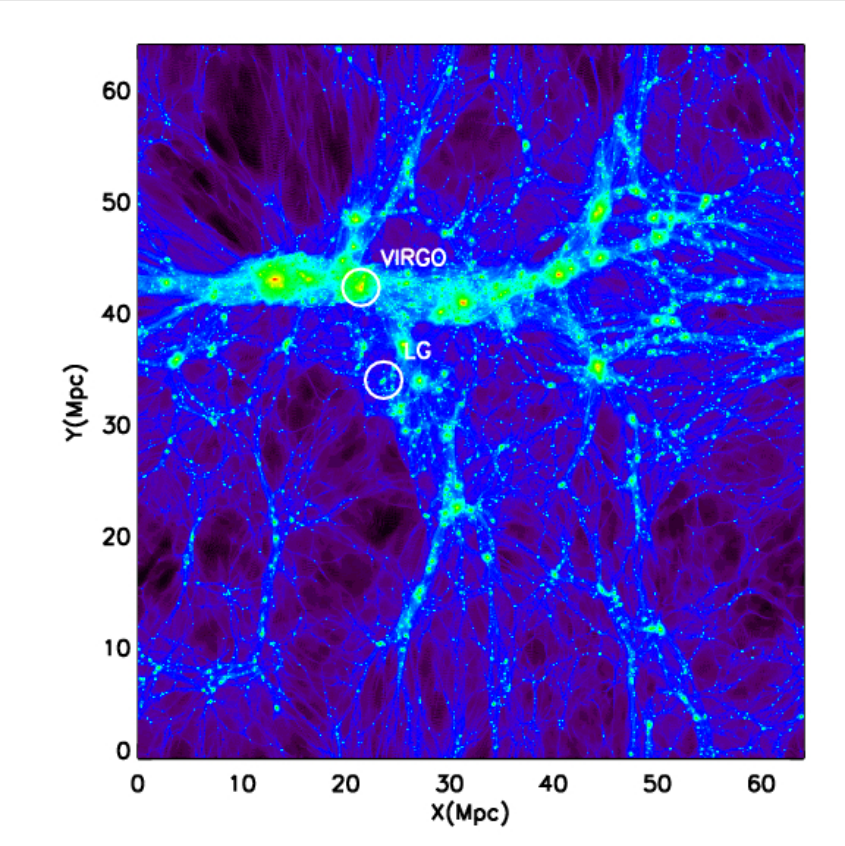
WMAP3

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

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



CDM



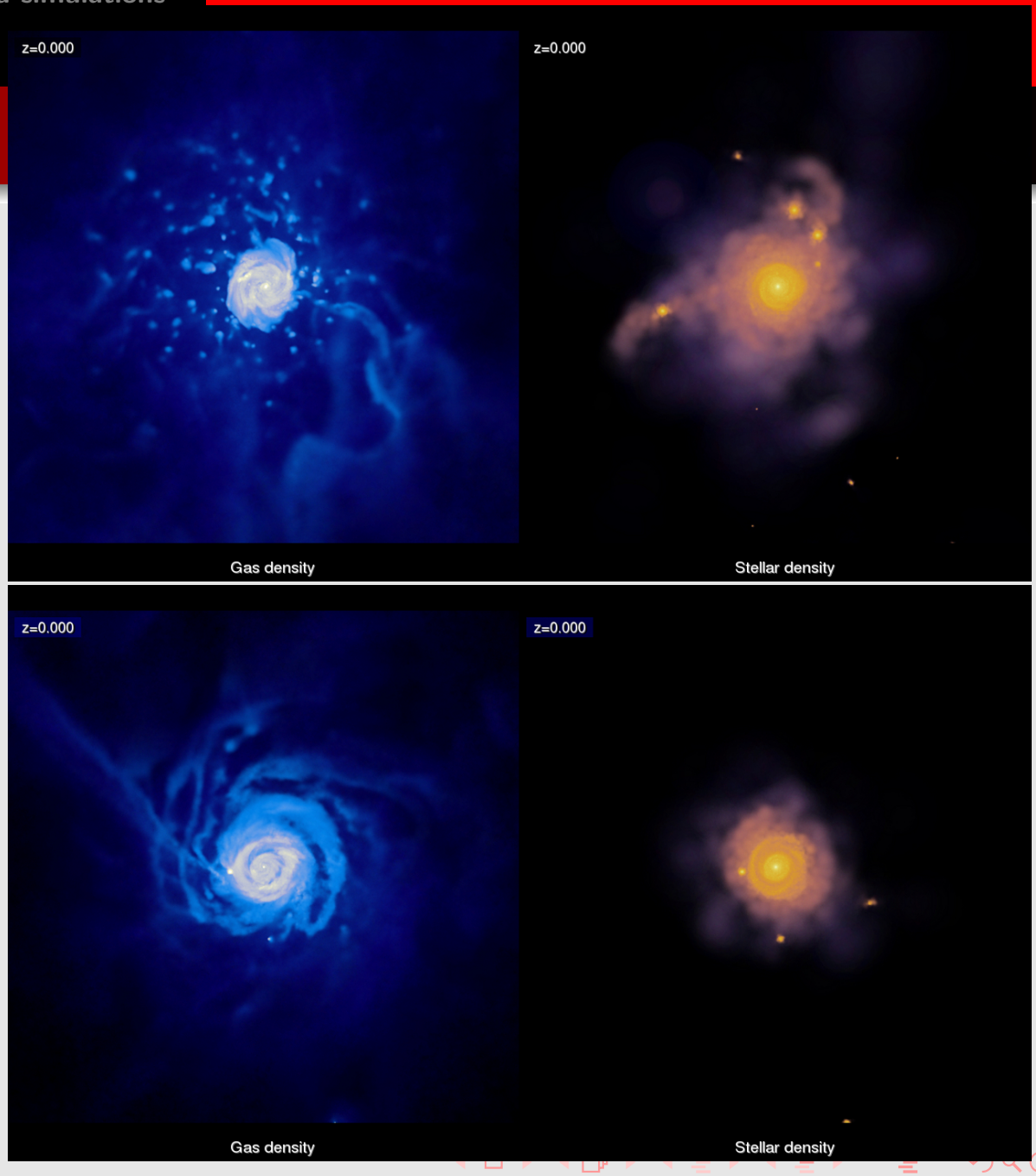
WDM

How does the nearby universe look like for an observer situated at the simulated MW?

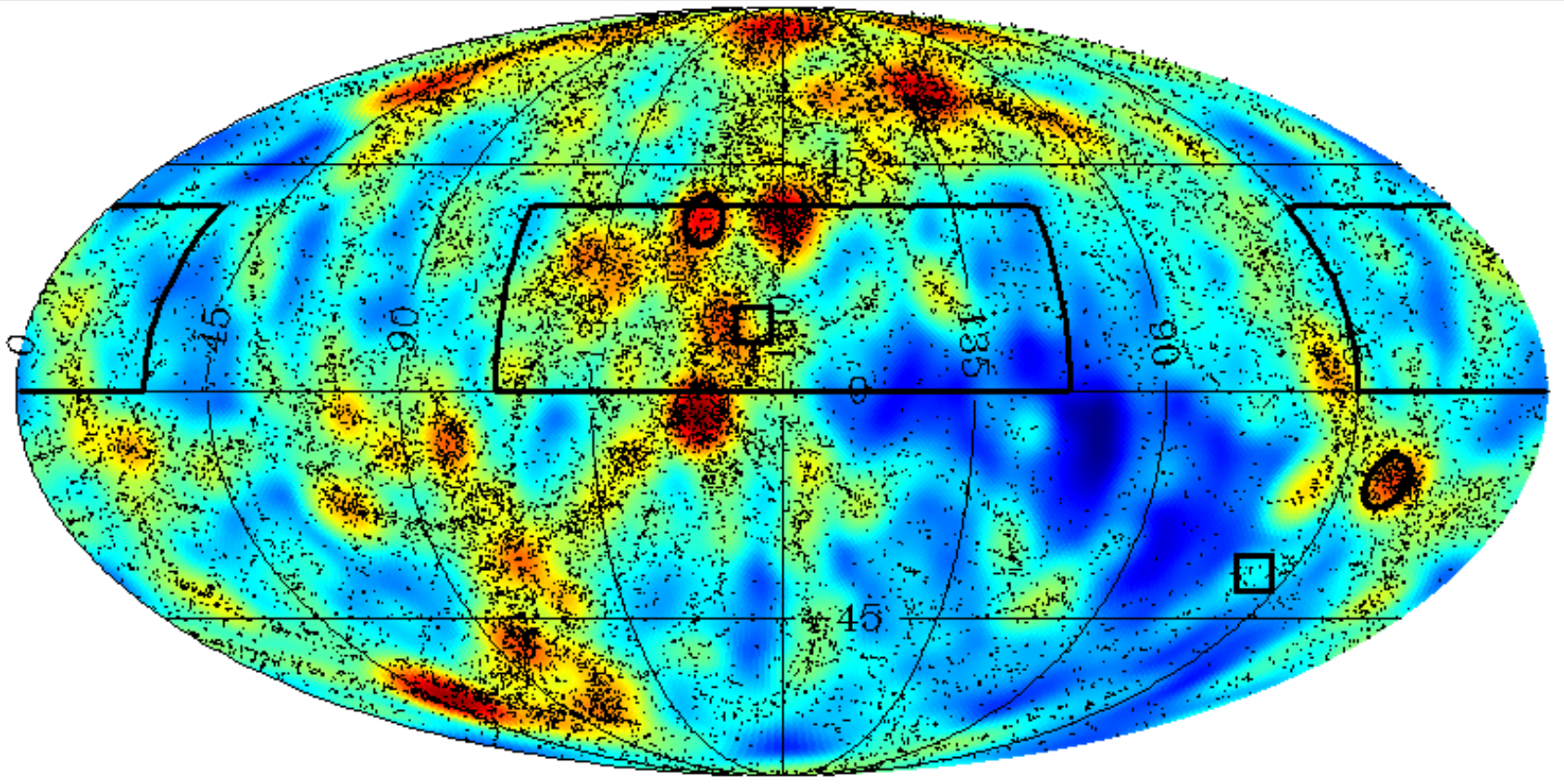
The Local Group

CDM

WDM

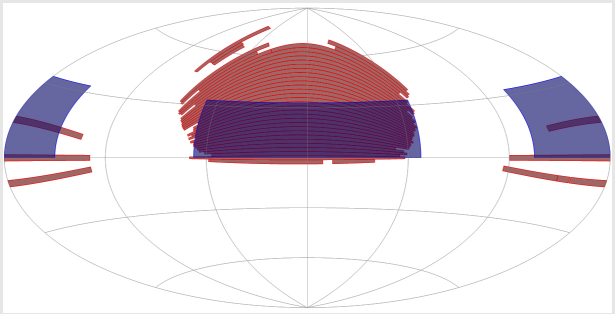


Simulated sky map (Virgo/Fornax best fit)



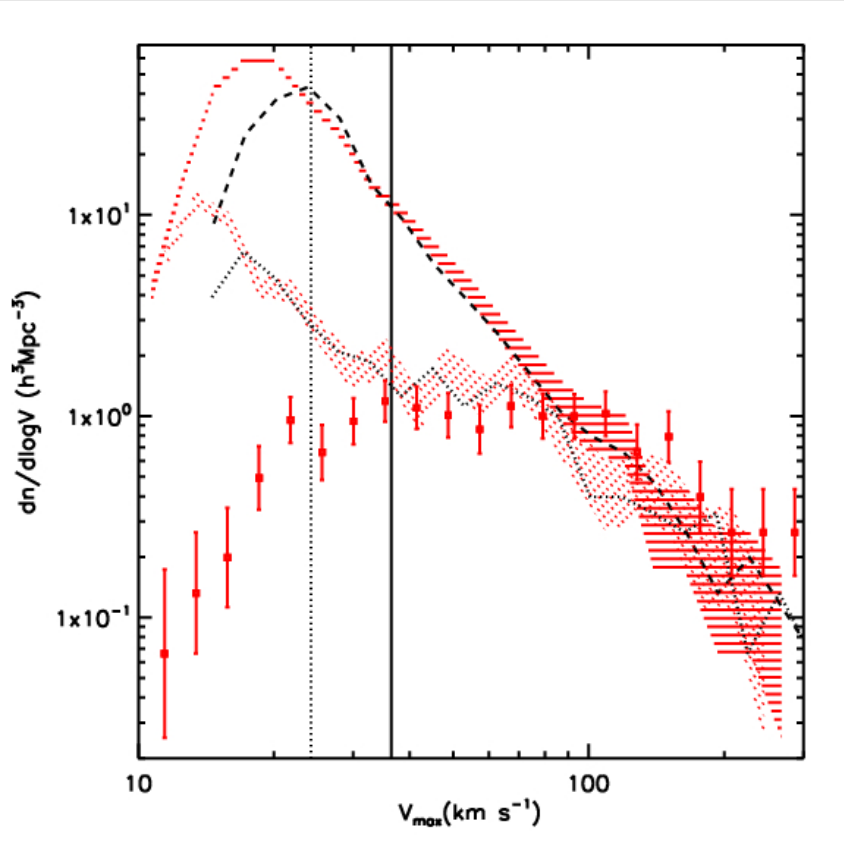
dots: halos with $M > 5 \times 10^9 h^{-1} \mathrm{M}_\odot$
squares: Virgo and Fornax, circles: their simulated counterparts

Arecibo Legacy Fast ALFA (ALFALFA) survey



- blind HI survey, started February 4, 2005 (6-7 years expected)
- detection of 20,000 galaxies expected within 200 Mpc
- gas rich galaxies with only a few or no stars ("dark")
- two arrays (Virgo and anti-Virgo)

ALFALFA observations in Virgo direction

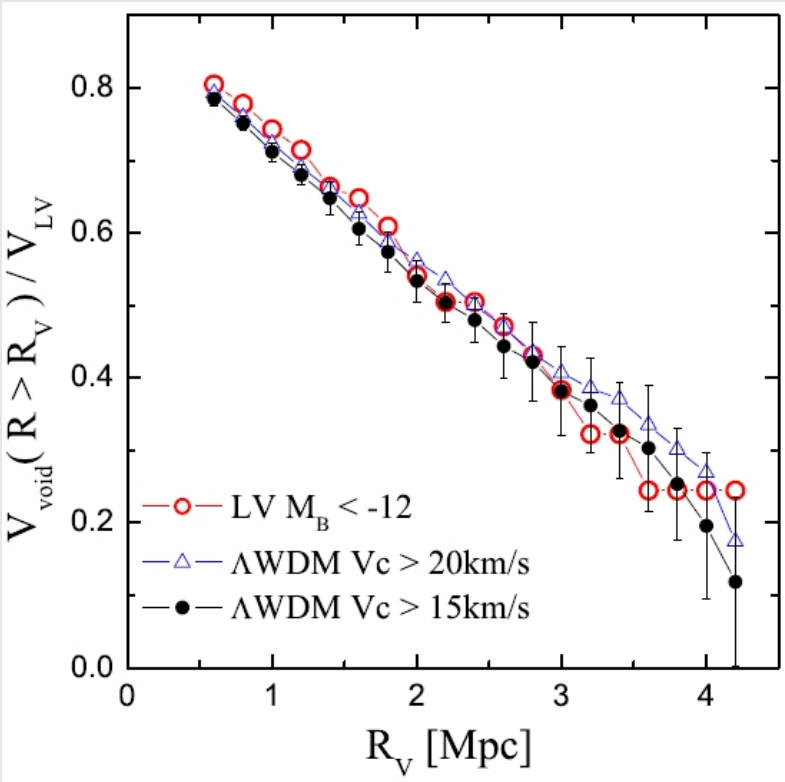


Zavala et al. (2009)

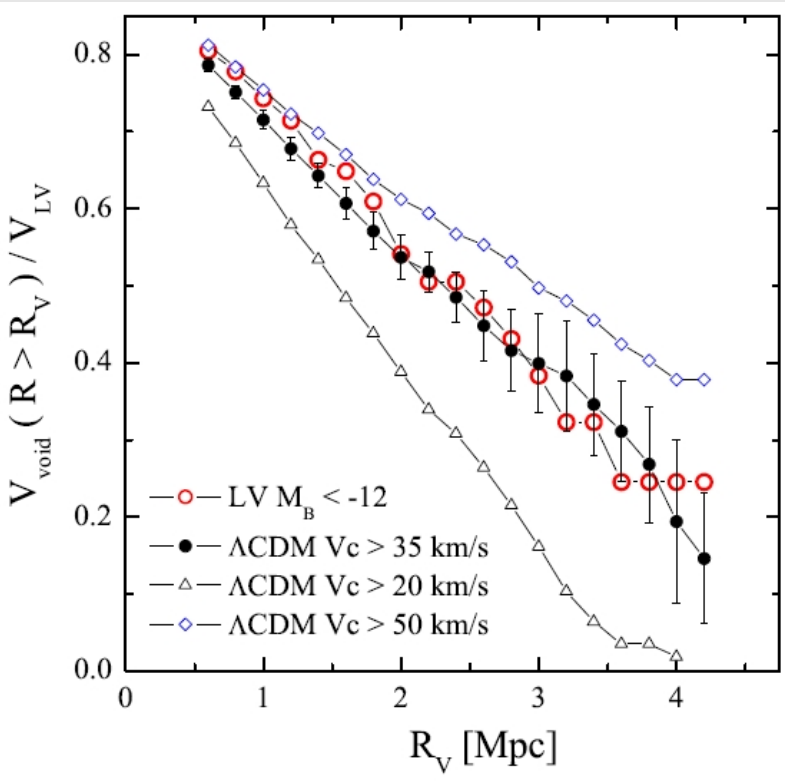
velocity function

- 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

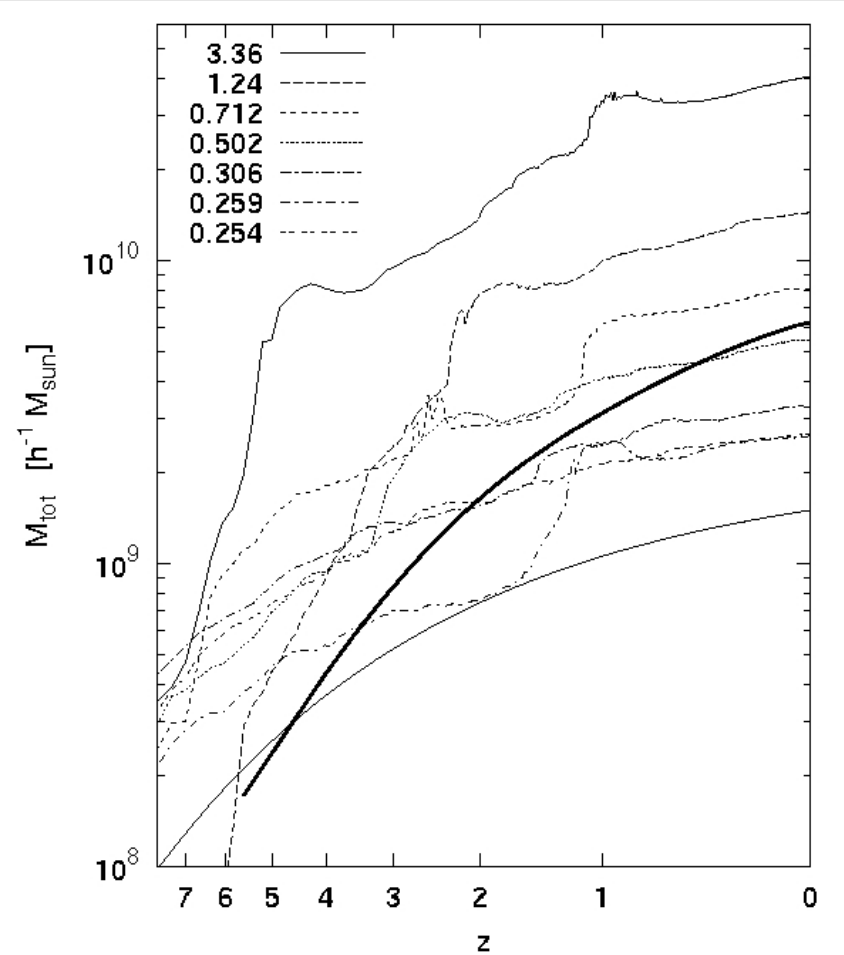


Cold Dark Matter

Tikhonov et al. (2009)

The observed spectrum of mini-voids could be easily explained with Warm Dark Matter halos, but do these halos contain galaxies?

Critical mass M_c of star formation



Hoeft et al. (2006)

- uniform UV-background (Haardt, Madau 1996)
- critical mass $M_c(z)$ for halos with low gas fraction (thick solid line)
- mass accretion history of seven halos (mass in $10^{10}h^{-1}\mathrm{M}_\odot$)
- mean mass accretion history of a $1.4 \times 10^{9}h^{-1}\mathrm{M}_\odot$ halo

no star formation right of the thick solid line

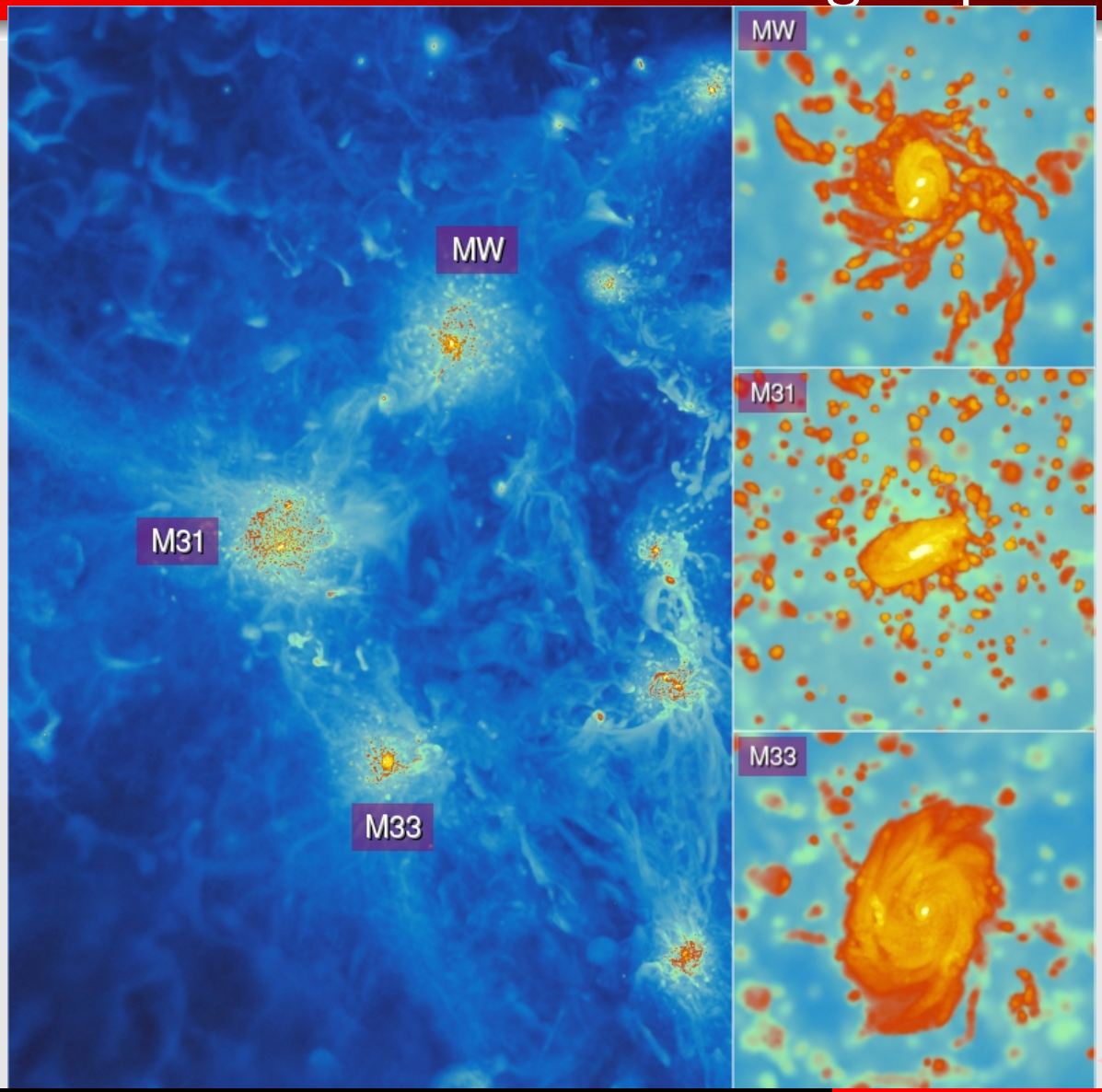
CDM: LG WDM: LG

The Local Group simulations

Local Group simulations

- box $64h^{-1}\mathrm{Mpc}$ constrained simulation
- $r = 2h^{-1}\mathrm{Mpc}$ sphere contains:
- Local Group (MW, M33, M31) 2048^3 particles
  - mass resolution DM: $1.6 \times 10^6 h^{-1}\mathrm{M}_\odot$
  - mass resolution gas: $3.5 \times 10^5 h^{-1}\mathrm{M}_\odot$
  - force resolution: $0.3h^{-1}\mathrm{kpc}$
- Local Group (MW, M33, M31) 4096^3 particles
  - mass resolution DM: $2.1 \times 10^5 h^{-1}\mathrm{M}_\odot$
  - mass resolution gas: $4.4 \times 10^4 h^{-1}\mathrm{M}_\odot$
  - force resolution: $0.15h^{-1}\mathrm{kpc}$

Gas distribution in the local group

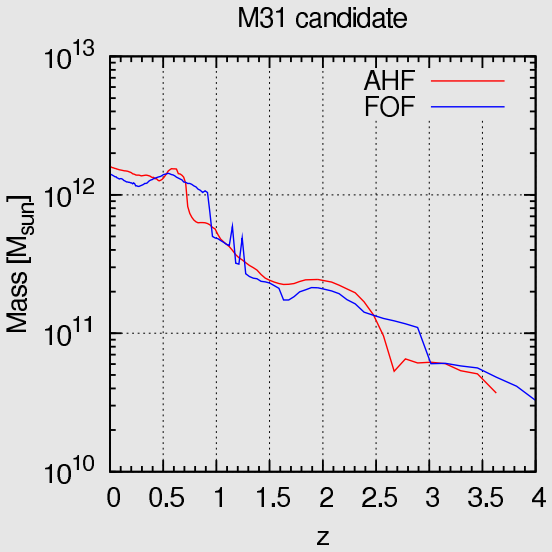


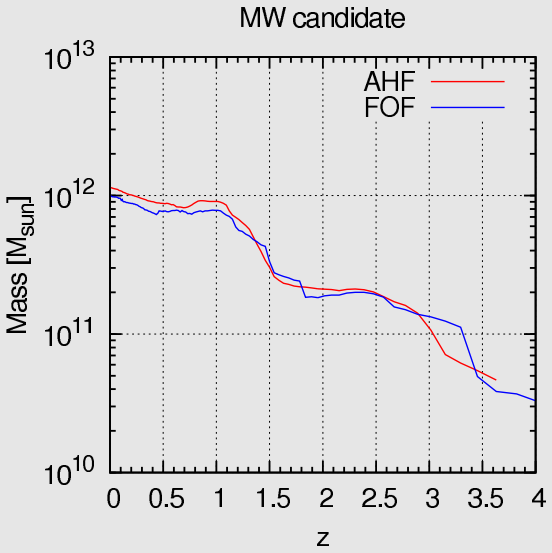
flying to M33

gas evolution in the LG

Kristin Riebe

Evolution of M31 and MW





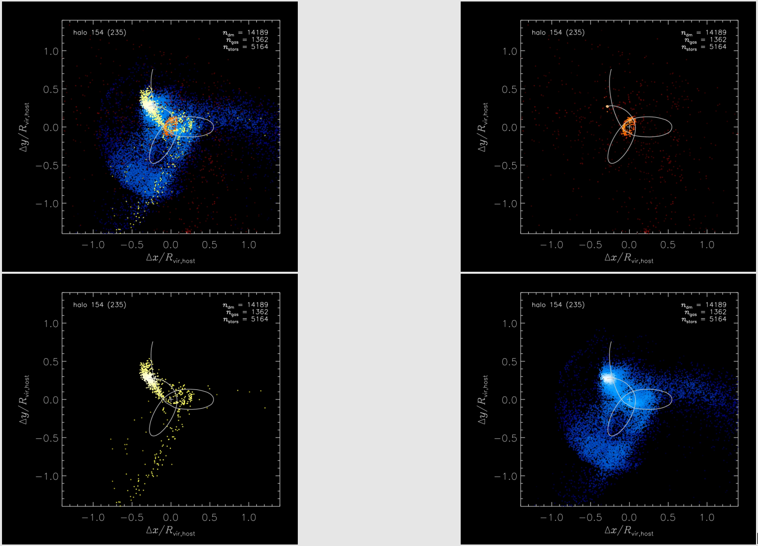
infall of M31 satellites

mass accretion histories of the dark matter halos hosting the Milky Way and M31

infall of MW satellites

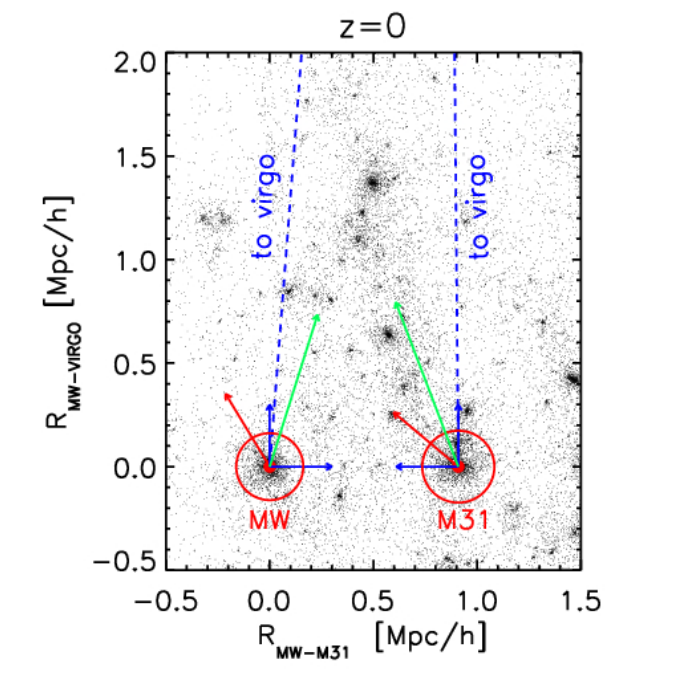
Steffen Knollmann

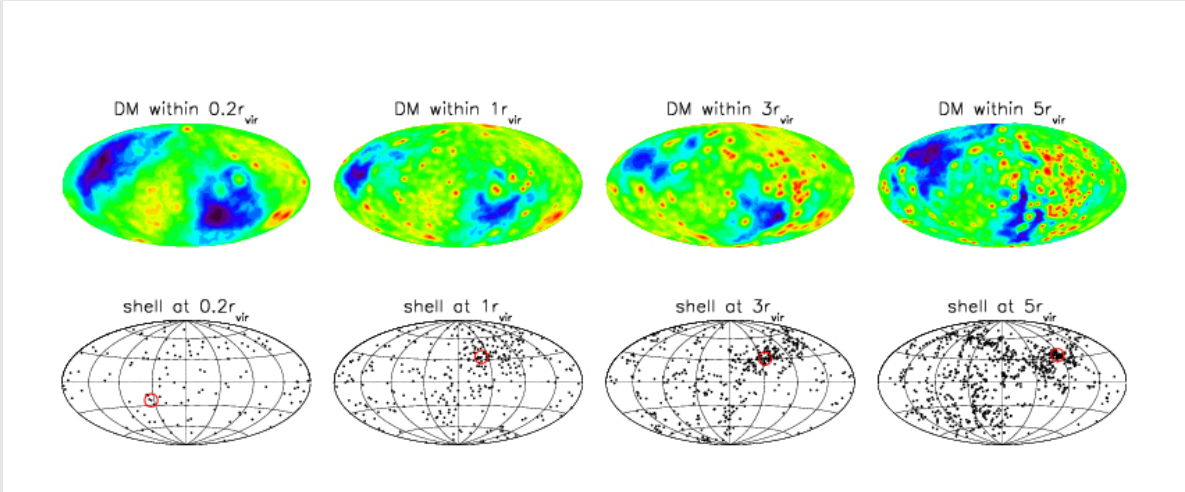
Tidal streams of a satellite (infall at $z = 0.845$)



Kristin Riebe

Preferential infall





Libeskind et al. (2010)

Summary

Constrained numerical simulations are an important tool to study the formation of small scale structure in the nearby universe structure.