Constrained Local UniversE Simulations
The CLUES-project

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Rencontres de Moriond
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Cosmological simulations
Constrained simulations
The Local Group simulations
Small scale structure and Warm Dark Matter

CLUES collaborators

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- and many more (see http://www.clues-project.org)
1. Cosmological simulations

2. Constrained simulations

3. The Local Group simulations

4. Small scale structure and Warm Dark Matter
Cosmological simulations
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Cosmic Microwave Background (CMB) radiation

The first structures 13 Gigayears ago.
Their non-linear evolution is studied by cosmological simulations.
Ingredients of simulations

- Dark Matter (21%)
- Dark Energy (74 %)
- Baryons (5%)
  - Computational very expensive
  - "sub-grid" physics not (yet) well modeled
    - star formation
    - chemical evolution
    - formation of super-massive black holes and their influence on galaxies
    - magnetic fields
    - ...
  - Post-processing of DM simulations (semianalytical models)
Cosmological simulations
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2048^3
250h^{-1}Mpc
WMAP5

Constrained Local UniversE Simulations (CLUES)

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Bolshoi - mass function

- large samples of different objects
- different environments
- galaxies (SAM) available
Limitations of present day simulations

- Representative volume \((> 500 h^{-1} \text{Mpc})\) \(\iff\) desired resolution \((< 0.1 h^{-1} \text{kpc})\) \(\implies\) impossible on present computers

- Mass range \((10^8 \ldots 10^{15} h^{-1} \text{M}_\odot)\) \(\iff\) mass resolution \((> 1000\) particles\) \(\implies\) impossible on present computers

\(\implies\) simulate a smaller volume representative for the neighborhood of Milky Way
CLUES

Constrained Local Universe Simulations
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)
Observational data and constraints

- Constraining Gaussian random fields (Hoffman & Ribak, 1991)
- Nearby cluster positions (Reiprich & Böhringer, 2002)
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160\,h^{-1}\text{Mpc}

64\,h^{-1}\text{Mpc}
The Local Group simulations
Local Group simulations

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

Constrained Local UniversE Simulations (CLUES-project)
Gas distribution in the local group

flying to M33

gas evolution in the LG

Kristin Riebe
Evolution of M31 and MW

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

Steffen Knollmann
Tidal streams of a satellite (infall at $z = 0.845$)
Baryons vs. Dark Matter

Density profile

Libeskind et al. (2009)

Satellite distribution

Libeskind et al. (2009)
Preferential infall

Libeskind et al. (2010)
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
Cosmology with Warm Dark Matter
**Cold vs. Warm Dark Matter**

**WMAP3**
- $h = 0.73$
- $\Omega_m = 0.24$
- $\Omega_{\text{bar}} = 0.042$
- $\sigma_8 = 0.73$
- $n = 0.95$
- $m_{\text{WDM}} = 1\text{keV}$ lower limit
- $k_{\text{peak}} = 3.7h\text{Mpc}^{-1}$

less small scale power $\Rightarrow$ less small scale structure
How does the nearby universe look like for an observer situated at the simulated MW?
Simulated sky map (Virgo/Fornax best fit)

dots: halos with $M > 5 \times 10^9 h^{-1} M_\odot$
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

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)

Zavala et al. (2009)
Spectrum of mini-voids in the local volume $R < 8h^{-1}M_\odot$

- Warm Dark Matter
  - Tikhonov et al. (2009)
- Cold Dark Matter
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

- 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 $10^{10} h^{-1} M_\odot$)
- mean mass accretion history of a $1.4 \times 10^9 h^{-1} M_\odot$ halo

(no star formation right of the thick solid line)

Hoeft et al. (2006)
Constrained simulations are a useful tool to study the local universe.

Satellites tend to enter our galaxy from a preferred direction. The matter stripped from these subhalos retains a memory of that direction.

The velocity function of nearby ALFALFA galaxies as well as the spectrum of mini-voids in the Local Volume point to a possible problem of the ΛCDM model on small scales. Warm Dark Matter could be one solution to this long standing problem of overabundance of small scale structure (but there are also alternative explanations).