Simulating our Cosmic Home using Galaxy Flows

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Collaborations Cosmicflows & CLUES

Large Scale Structure and Galaxy Flows
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**ΛCDM works well on large scales**

Because the Universe is ‘quite’ **homogeneous on large scales**

in order to test ΛCDM, any simulation with:

- a reasonable boxsize to capture the large structures
- a reasonable resolution to resolve the large structures

is enough to show that **ΛCDM works well on large scales** (i.e. that the observed LSS resembles the simulated LSS)

2dF redshift survey, Colless 1999 & Millennium runs, Springel et al. 2005 and 2008

(Other recent and on-going surveys presented by Jeremy Mould, Christina Magoulas, Matthew Colless)
But problems...  

... on the **small scales**, e.g.:

- missing satellite galaxies and dwarfs (Klypin et al. 1999; Moore et al. 1999; Zavala et al. 2009), etc
- size of voids (Tikhonov & Klypin 2009)
- preferential distribution of the Milky Way’s satellites in a pancake shape-like rather than an isotropic distribution (Kroupa et al. 2005) (mentioned by Xi Kang)
But problem...

... we reside in a given environment,

thus our measurements, conclusions, local and far observations might be biased by its characteristics, e.g.:

- variation of the ‘local’ Hubble Constant with density (Wojtak et al. 2014)

- impact of the gravitational redshift due to the local gravitational potential (Wojtak et al. 2015)
But problem...

... the best and most detailed observations are only available close-by for comparisons!
To summarize

The Universe might well look like this...
To summarize

we have the details only for this one...
To summarize

and it does not look like the others when looking at the details!
To summarize
and it does not look like the others when looking at the details!
Two solutions
First solution

Very large and high resolution simulations to select similar environmental conditions or/and similar objects e.g.

MilleniumXXL, Angulo et al. 2012

Courtesy of G. Yepes
First solution

Very challenging / demanding because huge computer resources are required in terms of:

- time
- memory
- storage
Second solution: followed in this talk

Constrained simulations of the best-observed volume, i.e. our local environment

Simulations resembling the Local Universe to make direct comparisons on multi-scales (down to the dwarfs)

Reduction of the cosmic variance
The Local Universe

Motivation

Building Constrained ICs

The local LSS

The Virgo cluster

Preliminary results

Conclusion

The Local Universe

Simulating the Local Universe
The Local Universe

- Coma
- Shapley
- Zone of Avoidance
- Perseus
- Pisces
- Laniakea

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Virgo Supercluster

Laniakea
The Local Universe

Local Group

Virgo Cluster

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Milky Way
Andromeda
Local Group
Ingredients to get Constrained Simulations
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- observations:
  radial peculiar velocities
  Brent Tully’s talk
Ingredients to get Constrained Simulations

- observations:
  radial peculiar velocities
  Brent Tully’s talk

- simulations:
  backward method
  Yehuda Hoffman’s & Stefan Gottlöber’s talks

(see Guilhem Lavaux’s talk for forward methods)
Summary of the method

1. Radial peculiar velocity catalog
2. Minimization of the biases
   - Reverse Zel’dovich Approximation
   - Constrained Realization Technique
     (prior = power spectrum)
3. Constrained Initial Conditions
4. Simulation run

- Constrained with positions at z>0!

**Observed today!**

- Tully 2015
- Sorce 2015

**Observed today!**

- Zaroubi et al. 1995
  (see Yehuda Hoffman’s and Romain Graziani’s talks)

- Doumler et al. 2013
- Sorce et al. 2014

- Hoffman & Ribak 1991

- Tully et al. 2013

**Observations**

**Biases minimization** (including grouping)

**Reconstruction**

**Re-location & Replacement**

**Random Details**

**Initial Conditions**

**Simulation**
Summary of the method

1. **Radial peculiar velocity catalog**
2. **Minimization of the biases**
3. **Reverse Zel’dovich Approximation**
4. **Constrained Realization Technique** (prior = power spectrum)
5. **Constrained Initial Conditions**

Constrained with positions at z>0!

- **Observed today!**
- **Tully et al. 2013**
- **Tully 2015**
- **Sorce 2015**
- **Zaroubi et al. 1995**
  (see Yehuda Hoffman’s and Romain Graziani’s talks)
- **Doumler et al. 2013**
  **Sorce et al. 2014**
- **Hoffman & Ribak 1991**

Simulation run
The local LSS: CLUES with CF2

At $z = 0$

Observations for comparisons: redshift catalog
Observations to constrain: Peculiar Velocities
Reconstruction: $L=500 \; h^{-1} \text{ Mpc}$, $n=256^3$, linear field
Simulation: $L=500 \; h^{-1} \text{ Mpc}$, $n=512^3$, full field

Structures in the ZOA:
- Renée Kraan-Korteweg’s,
- Anja Schroeder’s and
- Khaled Said’s talks
How did the Local Universe form?

Sorce et al. 2016a
The Laniakea Supercluster, the zero velocity surface

Reconstruction

One Constrained Simulation

Plot made with Daniel Pomarède’s SDvision software
How did the Virgo cluster form?

- Shift $\sim 3-4 \ h^{-1} \ Mpc$
- Mass within $\sim [0.5, 2]$ estimated mass (Ludlow & Porciani 2011)
How did the Virgo cluster form?


Sorce et al. 2016b
How did the Virgo cluster form?

Dark Matter Haloes - Virgo Candidates: Particles at $z=5$. 

Sorce et al. 2016b
How did the Virgo cluster form?

Dark Matter Haloes - Virgo Candidates: Particles at $z=2$. 

Sorce et al. 2016b
How did the Virgo cluster form?

Dark Matter Haloes - Virgo Candidates: Particles at $z = 0.5$
How did the Virgo cluster form?

Dark Matter Haloes - Virgo Candidates: Particles at $z = 0.25$
How did the Virgo cluster form?

Dark Matter Haloes - Virgo Candidates: Particles at $z = 0$. 

Sorce et al. 2016b
How did the Virgo cluster form?

Dark Matter Haloes - Virgo Candidates:
• Similar formation / evolution

One color per redshift:
10, 5, 2, 0.5, 0.25, 0

Jenny Sorce (AIP)
A preferential direction of infall

Motivation Building Constrained ICs The local LSS The Virgo cluster Preliminary results Conclusion

Autocorrelation function:
\[ \frac{D(\alpha\alpha)}{D(\alpha\alpha_r)} - 1 \]

Sorce et al. 2016b

Infalling particles
Particles within \( R_{200} \)
All particles

\[ D(\alpha\alpha): \text{distribution of angle } \alpha \]
\[ D(\alpha\alpha_r): \text{distribution of angle } \alpha_r \]

Particles within 6 \( h^{-1} \) Mpc at \( z=0 \)
A preferential infall: Aitoff

In Supergalactic coordinates,

- redshift catalog
- infalling particles
A quiet formation history over the last gigayears

Similar merging histories: a quiet history over the last 7 Gigayears.
The Local Group

The Local Group factory
Carlesi, Sorce et al. 2016

Higher tangential velocity preferred

Sohn et al. 2016: 17 ± 4 km s\(^{-1}\)
Salomon et al. 2016: 64 ± 61 km s\(^{-1}\)
Preliminary results with CF3

At $z = 0$

Wiener-Filter Reconstruction    Constrained Simulation

Observations for comparisons: redshift catalog
Observations to constrain = Peculiar Velocities: CF3 catalog
Reconstruction: $L=800 \ h^{-1} \ Mpc, n=256^3$, linear field (contours, arrows)
Simulation: $L=500 \ h^{-1} \ Mpc, n=512^3$, full field (contours, arrows)
Observations for comparisons: redshift catalog

Observations to constrain = Peculiar Velocities: CF2 catalog

Reconstruction: L=500 h^{-1} Mpc, n=256^3, linear field (contours, arrows)

Simulation: L=500 h^{-1} Mpc, n=512^3, full field (contours, arrows)
Conclusion & Prospectives

Problems:

... on the small scales

... we reside in a local environment

... the best and most detailed observations are only available close by for comparisons!

Solutions to study, etc them:

Use **constrained simulations**!

(A lot is, will be or can be available! Just ask)
Thank you, Merci, Danke, Gracias, Grazie, Spasibo, Mahalo, Xièxie, Arigatô, Toda, Tak, Dank u, Obrigada, Cám Ōn ...