Observatoire astronomique de Strasbourg

Leibniz-Institut für Astrophysik Potsdam

Near Field Cosmology

From an Observational to a Numerical local Universe

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CPPM, Marseille, December the 4th

Observatoire de Strasbourg / Leibniz-Institut für Astrophysik Potsdam

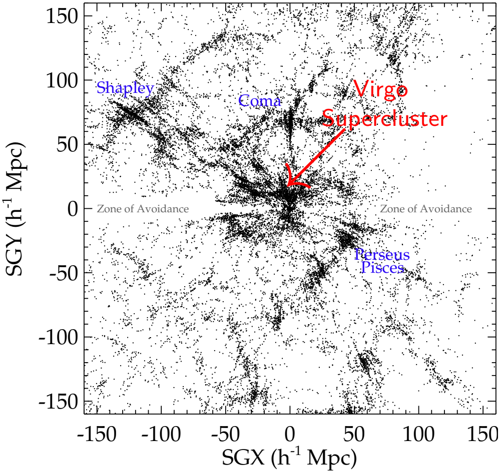
Definitions (IAU Division H)

• **Near Field Cosmology**: "[...] increasing interest in studying the **local Universe** **(near field)** as distinct from the high redshift universe (far field)."

• **local Universe**: "defined by the distance ($\sim$10 Mpc) over which stellar populations in galaxies can be resolved by the HST. [...] **extend to include Virgo** ($\sim$15 Mpc) [...] to cover the full range of galaxy environments, from voids to massive groups and clusters. **In an era of ELTs,** [...] **possible to extend** [...] to even **greater distances**."

The local Universe in this talk

Size of the LSS, walls, etc: 100's of Mpc

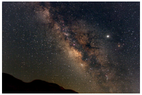


Virgo Supercluster

Virgo Cluster
distance: ∼15 Mpc

Local Group
size: ∼2 Mpc

Milky Way
size: ∼30 kpc



Andromeda
distance:
∼750 kpc

$1 \text{ pc} = 3.0857 \times 10^{13} \text{ km} = 3.26 \text{ light-years}$

Studying & Understanding the Universe

THEORIES: Cosmological models

e.g. ΛCDM

$H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$

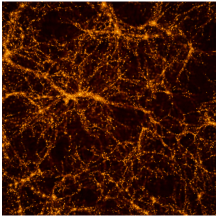
↙ ↗ ↖ ↘

OBSERVATIONS

Measurements of luminosity, velocity, etc of galaxies

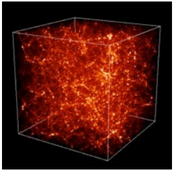
← →

SIMULATIONS



Following numerically the evolution of structures, etc from **early redshift until today**

Cosmological simulations



From Gaussian random fields (initial conditions: CMB) to dark matter halos + galaxies = dark matter + hydrodynamics

Basic equations ruling the dynamics (plus expansion = supercomoving variables) **and periodic boundaries**

$\frac{\partial f}{\partial t} + \mathbf{u}.\nabla f - \nabla\Phi.\nabla_u f = 0$	Vlasov : dark matter, stars **Collisionless**
$\frac{\partial \rho_b}{\partial t} + \nabla.(\rho_b \mathbf{u}) = 0$	Continuity : gas
$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}.\nabla).\mathbf{u} = -\nabla\Phi - \frac{\nabla p}{\rho_b}$	Euler : gas **Collisional**
$\frac{\partial \varepsilon}{\partial t} + \mathbf{u}.\nabla\varepsilon = -\frac{p}{\rho_b}\nabla.\mathbf{u}$	Energy : gas
$p = (\gamma - 1)\varepsilon\rho_b$	Equation of state : gas
$\nabla^2\Phi = 4\pi G\left[\int f d^3u + \rho_b\right]$	Poisson : everything

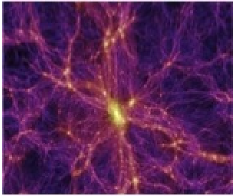
+ subgrid models

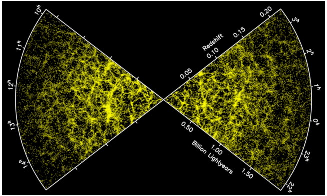
PM long range
Tree or AMR short range

Courtesy J. Devriendt (Adapted)

Simulations vs. Observations

ΛCDM works **well** on large scales (simulations vs. observations):





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

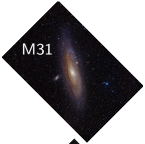
But **problems** on the small scales, e.g.:

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

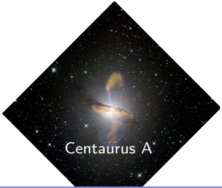
Is this due to the fact that we reside in a given environment?

Our **measurements, conclusions, local and far observations** might be **biased** by its particularities, e.g.:

- variation of the ‘local’ Hubble Constant with density (Wojtak et al. 2014)
- impact of gravitational redshift due to local gravitational potential (Wojtak et al. 2015)



but it is the best and most observed Volume → Focus ! → detailed observations, map, expansion (H_0)



To summarize

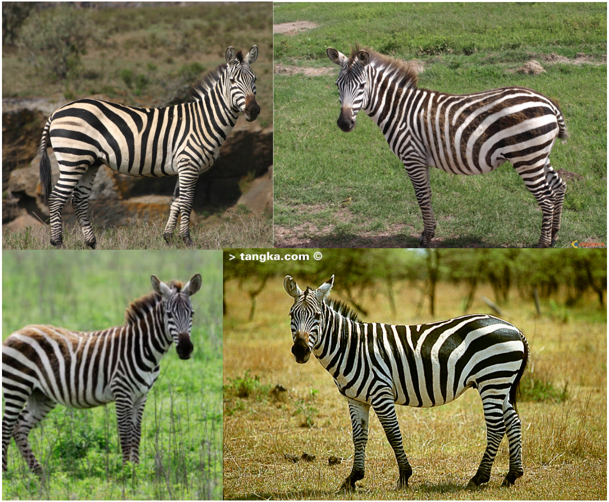
The Universe might well look like this...

To summarize

we have the details only for this one...

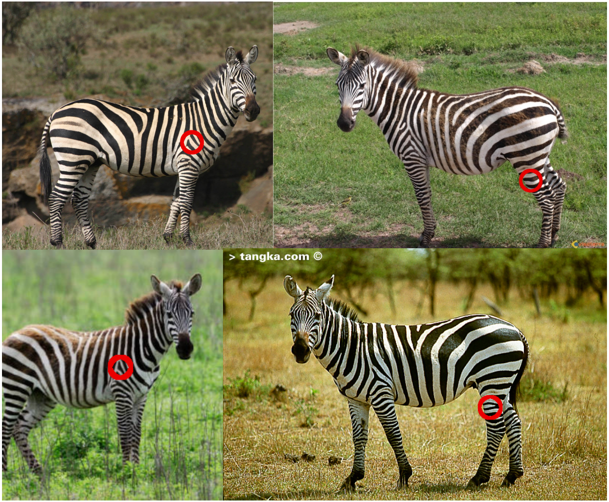
To summarize

and it does not look like the others when looking at the details !



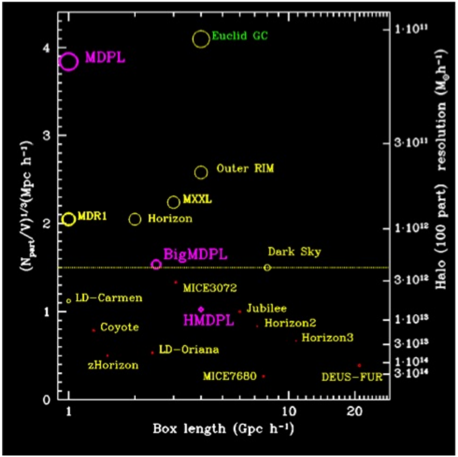
To summarize

and it does not look like the others when looking at the details !



Two solutions

First solution



Courtesy of G. Yepes

Need:

- very **large and high resolution** simulations: **small scales** in all **large scale** environments possible
- even **better with baryons** (e.g Cui & Zhang 2017 for a review)

⇒ Very challenging / demanding huge computer resources required:

- time
- memory
- storage

Second solution: Constrained Simulations

PATH INTEGRAL METHODS FOR PRIMORDIAL DENSITY PERTURBATIONS: SAMPLING OF CONSTRAINED GAUSSIAN RANDOM FIELDS

EDMUND BERTSCHINGER
Center for Theoretical Physics, Center for Space Research, and Department of Physics, Massachusetts Institute of Technology
Received 1987 August 17; accepted 1987 September 10

ABSTRACT

Path integrals may be used to describe the statistical properties of a random field such as the primordial density perturbation field. In this framework the probability distribution is given for a Gaussian random field subjected to constraints such as the presence of a protovoid or supercluster at a specific location in the initial conditions. An algorithm has been constructed for generating samples of a constrained Gaussian random field on a lattice using Monte Carlo techniques. The method makes possible a systematic study of the density field around peaks or other constrained regions in the biased galaxy formation scenario, and it is effective for generating initial conditions for *N*-body simulations with rare objects in the computational volume.

"This identical twin of yours... Can you describe him?"

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

=

Reduction of the **cosmic variance**

Typical vs. Constrained Initial Conditions:

$\sqrt{P(k)}$w(k) with P=power spectrum and w=white noise.
In the second case, particle **velocity and position** are **constrained**.

Ingredients to get Constrained Simulations

observations

simulations

Ingredients to get Constrained Simulations

- **Redshifts or peculiar velocities** ← observations

simulations

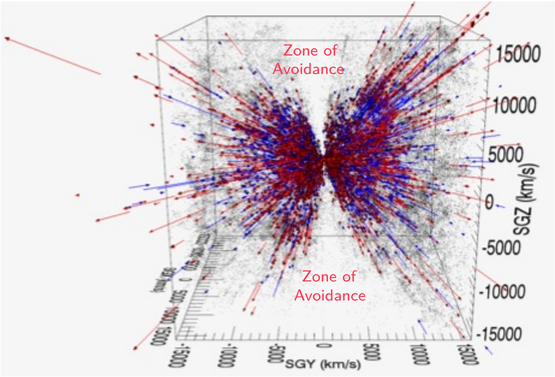
Ingredients to get Constrained Simulations

- **Redshifts or peculiar velocities** ← observations

- **Method/Technique** ← simulations

  e.g. Kitaura 2013, Jasche & Wandelt 2013, etc
  Wang et al. 2014, Hoffman & Ribak 1991

Observational constraints: peculiar velocities



Cosmicflows-2
about 8000 constraints
Tully et al. 2013

$$v_{obs} = H_0 \times \mathbf{d} + v_{pec\ radial}$$

redshift — constant — distance — velocity

$$\Delta v_{pec\ radial} = H_0 \Delta d$$

From **direct** distance measurements:

- high linearity
- large-scale correlation
- direct tracers of the underlying gravitational field

Catalogs of radial peculiar velocities (i.e. Hubble expansion substracted)

Black dots: XSCZ redshift catalog

Building Constrained Initial Conditions

Radial peculiar velocity catalog

↓

Grouping & Minimization of the biases

↓

Reverse Zel'dovich Approximation

↓

Constrained Realization Technique
(prior = power spectrum)

↓

Constrained Initial Conditions

Simulation ↓ run

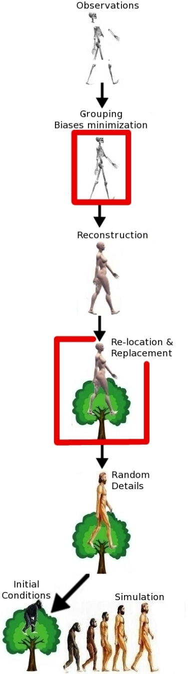
Tully et al. 2013

Tully 2015, Sorce & Tempel 2017, Sorce 2015

Zaroubi et al. 1995

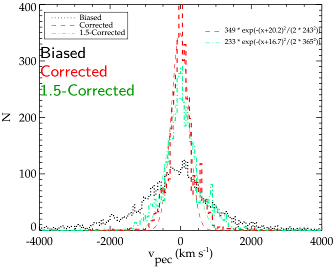
Doumler et al. 2013
Sorce et al. 2014b

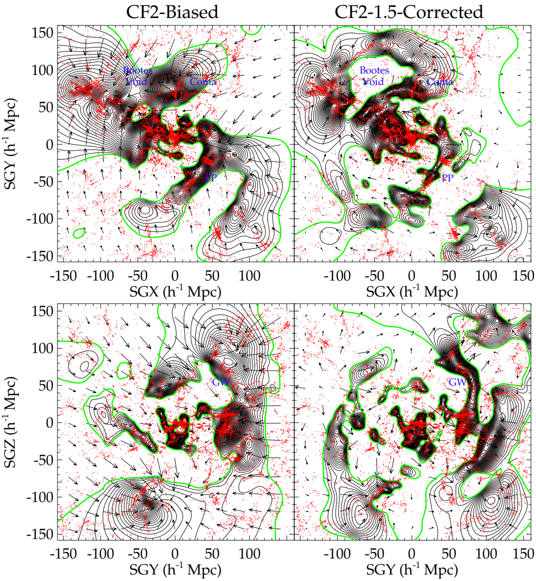
Hoffman & Ribak 1991



Minimization of biases

Sorce 2015





- General infall suppressed
- Structures more sharply defined

Building Constrained Initial Conditions

Radial peculiar velocity catalog — Tully et al. 2013

↓

Grouping & Minimization of the biases — Tully 2015, Sorce & Tempel 2017, Sorce 2015

↓

Reverse Zel'dovich Approximation — Zaroubi et al. 1995

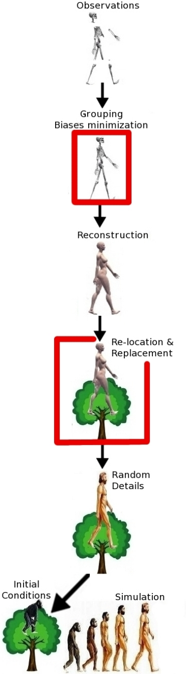
↓

Constrained Realization Technique (prior = power spectrum) — Doumler et al. 2013, Sorce et al. 2014b

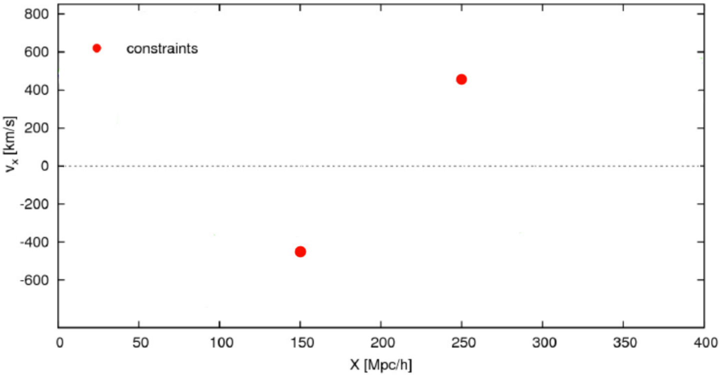
↓

Constrained Initial Conditions — Hoffman & Ribak 1991

Simulation ↓ run



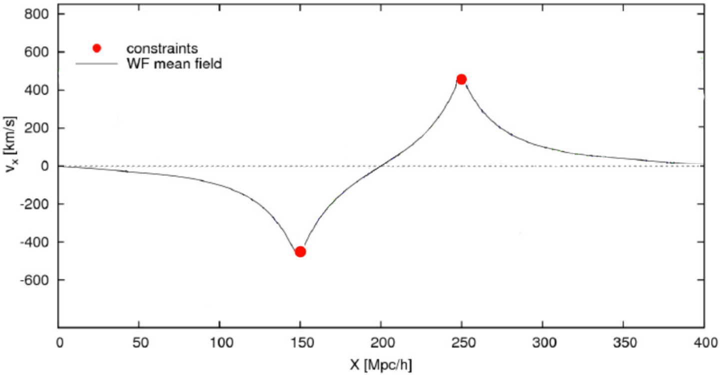
Wiener-Filter or Reconstruction Technique



Wiener-Filter reconstruction = **Linear Minimal Variance Estimator** (valid down to 2 h^{-1} Mpc) using noisy, sparse data and a model (Zaroubi et al. 1995)

$$\text{Example :}\ v_x^{WF}(\mathbf{X}) = \sum_{i=1}^{n} \langle v_x(\mathbf{X}) C_i \rangle \sum_{j=1}^{n} \langle C_i C_j \rangle^{-1} (C_j)$$

Wiener-Filter or Reconstruction Technique



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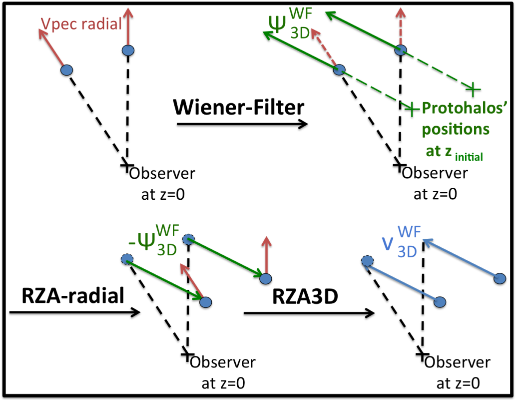
Reverse Zel'dovich Approximation

(Doumler et al. 2013 and Sorce et al. 2014)



Reverse Zel'dovich Approximation:

$$\vec{x}_{init}^{RZA} = \vec{r} - \frac{\vec{v}}{H_0 \ f(t_{init})}$$

$$\text{growth rate} : f(t) = \frac{d\ (ln\ D(t))}{d\ (ln\ a(t))} \quad \begin{matrix}\text{growth factor} \\ \text{scale factor}\end{matrix}$$

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

Building Constrained Initial Conditions

Radial peculiar velocity catalog — Tully et al. 2013

↓

Grouping & Minimization of the biases — Tully 2015, Sorce & Tempel 2017, Sorce 2015

↓

Reverse Zel'dovich Approximation — Zaroubi et al. 1995

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Constrained Realization Technique (prior = power spectrum) — Doumler et al. 2013, Sorce et al. 2014b

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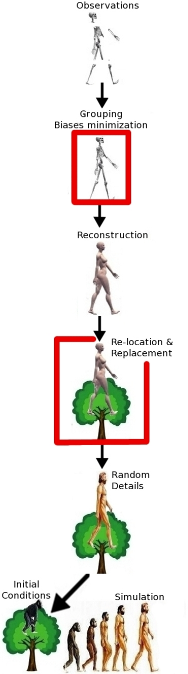
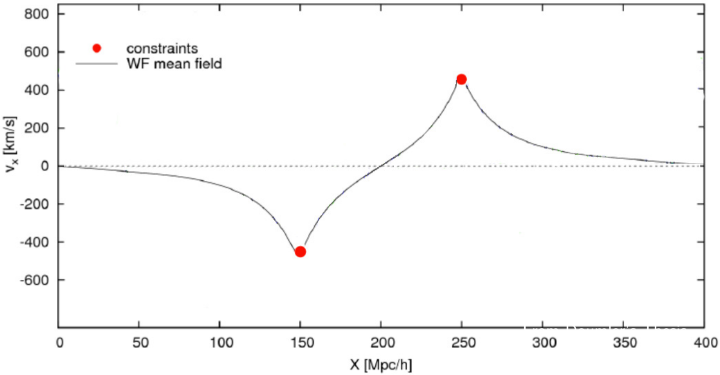
Constrained Initial Conditions — Hoffman & Ribak 1991

Simulation ↓ run



Wiener-Filter or Reconstruction Technique



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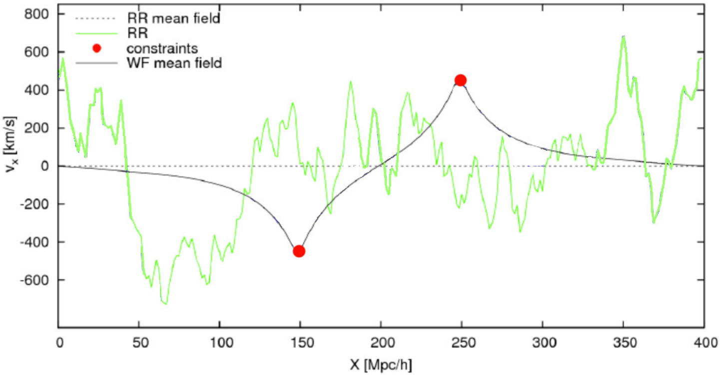
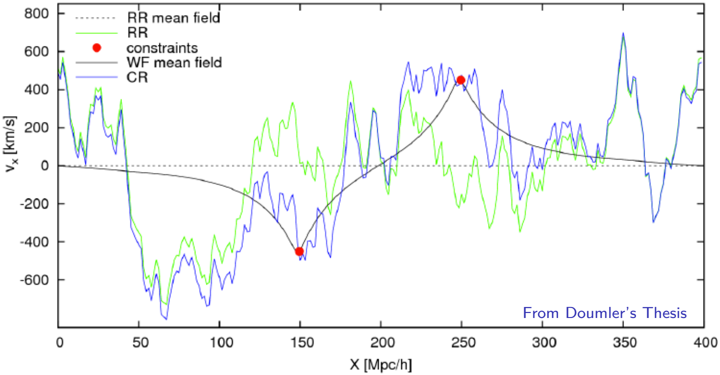
Constrained Realization Technique



Constrained Realizations ≈ Wiener-Filter + Random Realization to compensate for the missing Power Spectrum (Hoffman & Ribak 1991)

$$\text{Example}: v_x^{CR}(\mathbf{X}) = v_x^{RR}(\mathbf{X}) + \sum_{i=1}^{n} \langle v_x(\mathbf{X}) C_i \rangle \sum_{j=1}^{n} \langle C_i C_j \rangle^{-1} (C_j - \overline{C_j})$$

Constrained Realization Technique



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Building Constrained Initial Conditions

Radial peculiar velocity catalog

↓

Grouping & Minimization of the biases

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Reverse Zel'dovich Approximation

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Constrained Realization Technique
(prior = power spectrum)

↓

Constrained Initial Conditions

Simulation ↓ run

Tully et al. 2013

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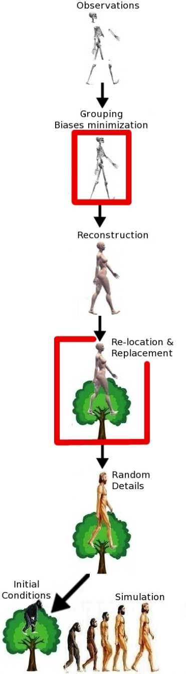
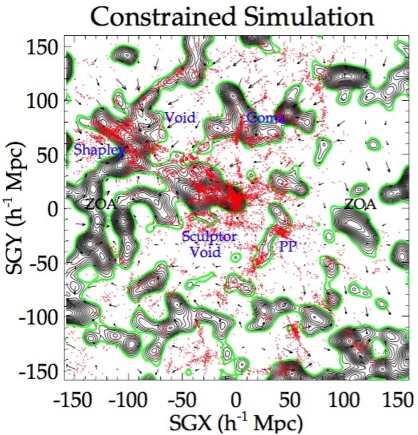
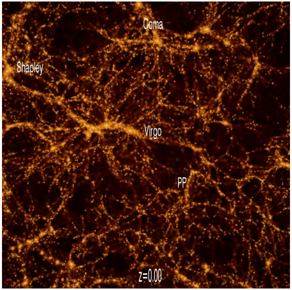


How did the Local Universe form?

Sorce et al. 2016a

At z=0





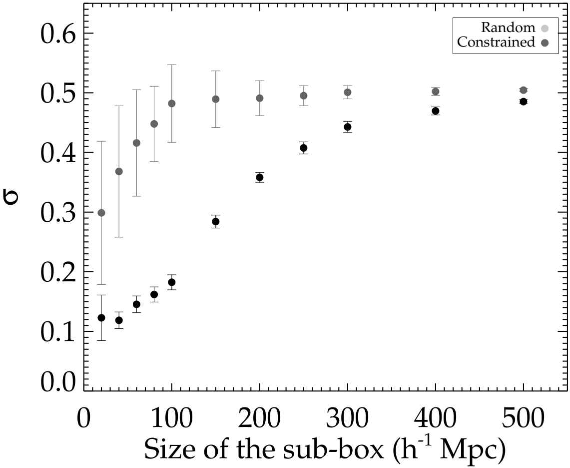
Observations for comparisons: redshift catalog •

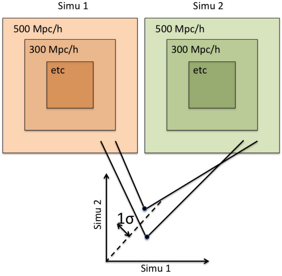
Observations to constrain = Peculiar Velocities: CF2 catalog

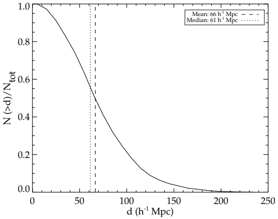
Simulation: L=500 h^{-1} Mpc, n=512^3, full field (contours, arrows)

Robust Large-Scale Environment

Sorce et al. 2016a







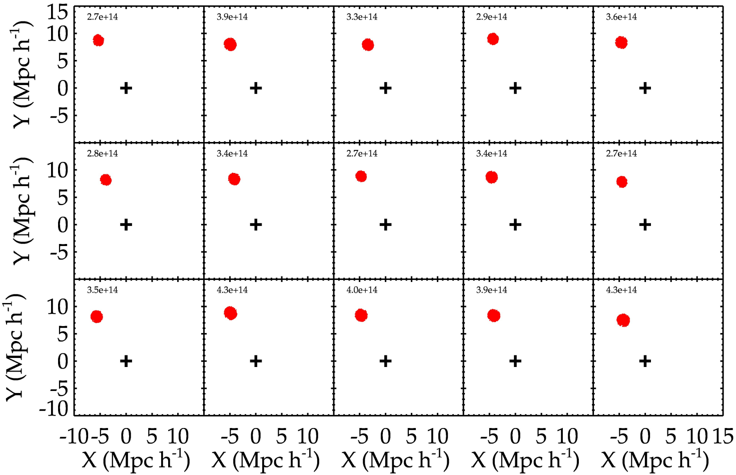
Smoothing: 5 h^{-1} Mpc

Mean and scatter of 1-σ scatters in cell-to-cell comparisons

Robust Large-Scale Environment $\rightarrow$ to study local structures and objects


Can we zoom-in?
What about the clusters?

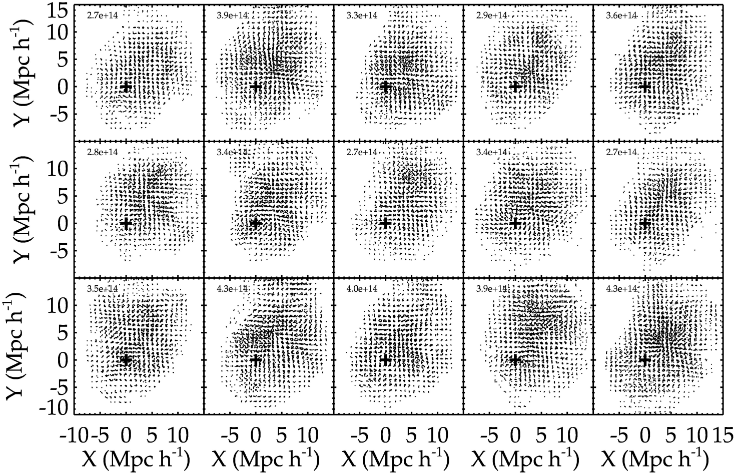
How did the Virgo cluster form?



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

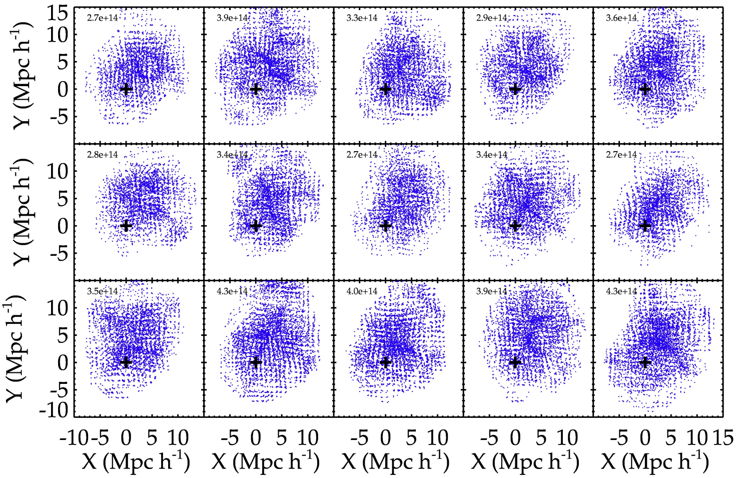
- Shift ∼ 3-4 h^{-1} Mpc
- Mass within ∼ [0.5,2] estimated mass (Ludlow & Porciani 2011) M_{200}

How did the Virgo cluster form?



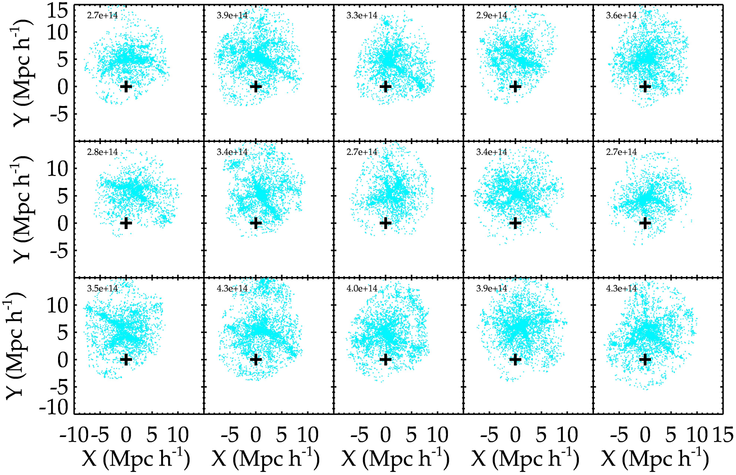
Dark Matter Haloes - Virgo Candidates: Particles at z= 10.

How did the Virgo cluster form?



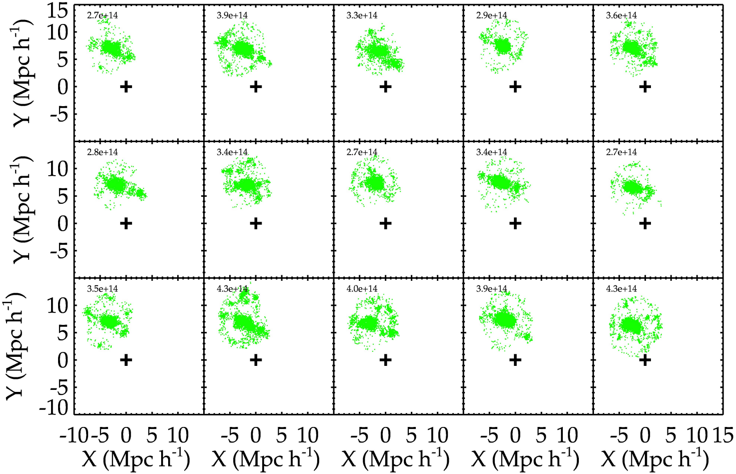
Dark Matter Haloes - Virgo Candidates: Particles at z= 5.

How did the Virgo cluster form?



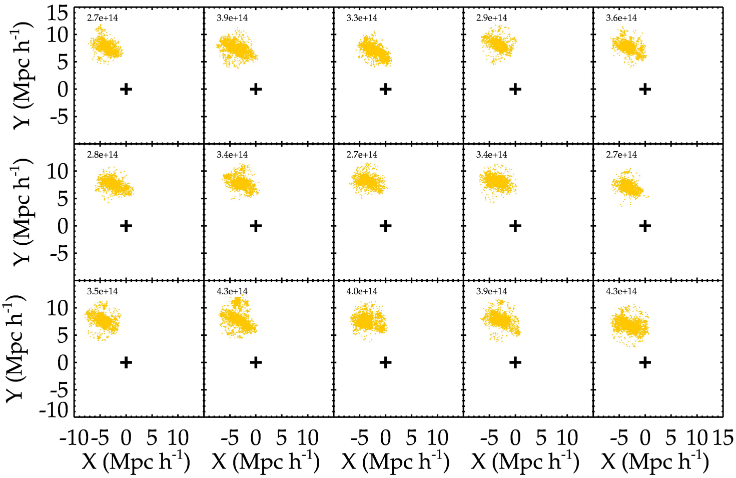
Dark Matter Haloes - Virgo Candidates: Particles at z= 2.

How did the Virgo cluster form?



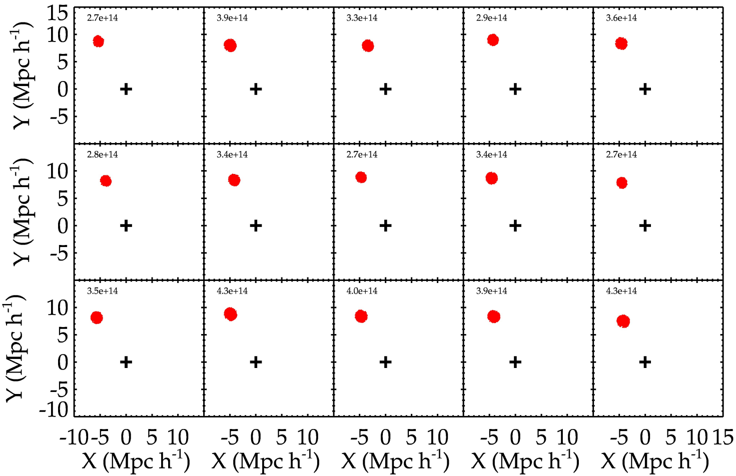
Dark Matter Haloes - Virgo Candidates: Particles at z= 0.5

How did the Virgo cluster form?



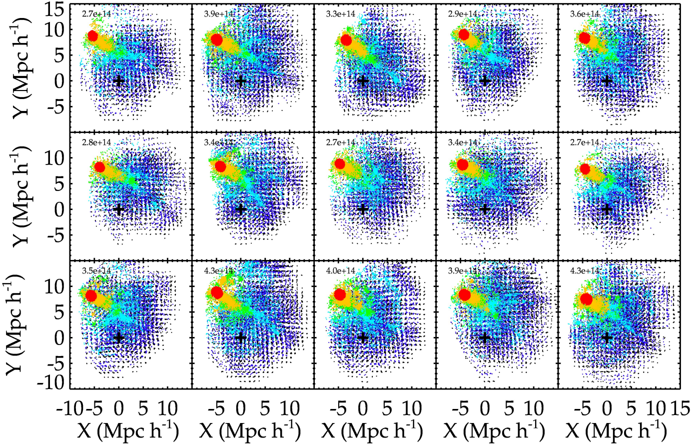
Dark Matter Haloes - Virgo Candidates: Particles at z= 0.25

How did the Virgo cluster form?



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

How did the Virgo cluster form?



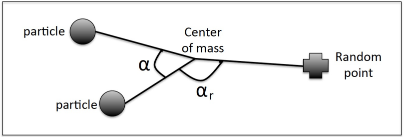
Dark Matter Haloes - Virgo Candidates:

- Similar formation / evolution

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

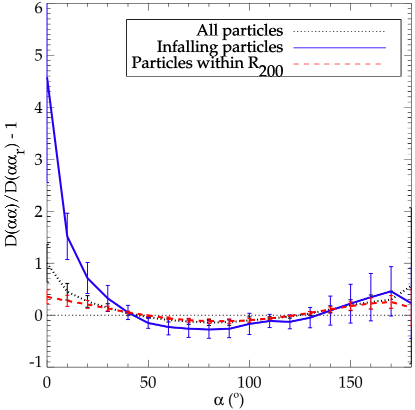
A preferential direction of infall

Sorce et al. 2016b



$D(\alpha\alpha)$: distribution of angle α
$D(\alpha\alpha_r)$: distribution of angle α_r

Autocorrelation function:
$D(\alpha\alpha)/D(\alpha\alpha_r)$ - 1



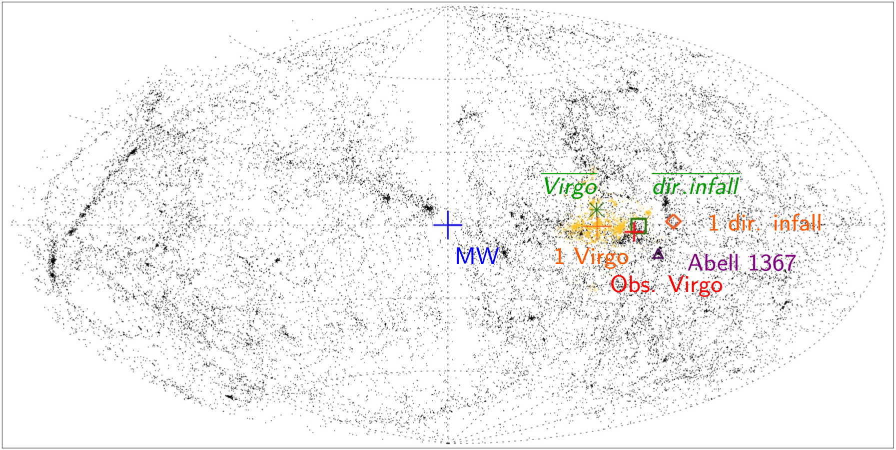
Particles within 6 h^{-1} Mpc at z=0

A preferential infall: Aitoff

Sorce et al. 2016b

In Supergalactic coordinates,

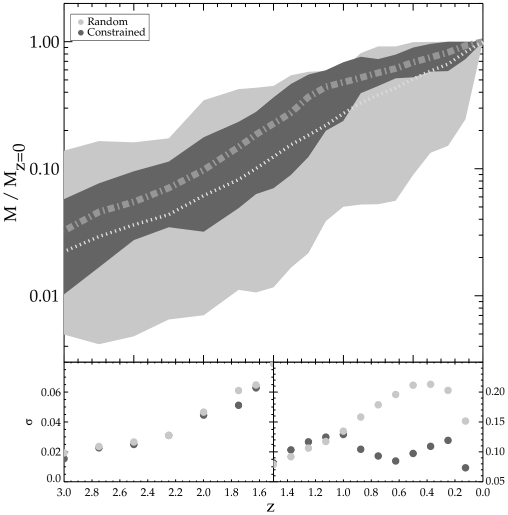
- redshift catalog
- infalling particles



West & Blakeslee (2000)

A quiet formation history over the last gigayears

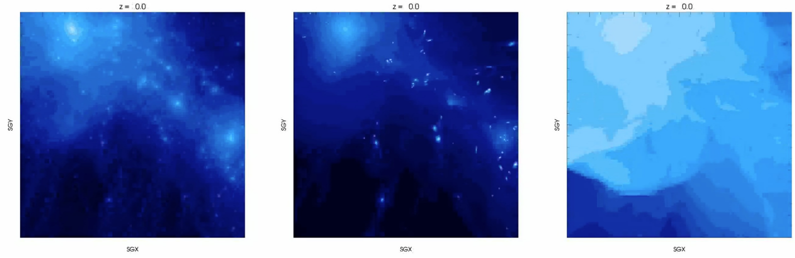
Sorce et al. 2016b



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

What else?

- Zone of Avoidance (Sorce et al. 2017): **Vela** Supercluster (Kraan-Korteweg et al. 2017)
- Virgo (Sorce et al. in prep.): **likeliness, substructures, zoom-in hydro.**, etc
- Local Group (e.g. Carlesi, Sorce et al. 2016) & Reionization (Ocvirk et al in prep., Sorce et al. in prep.): **mass ratio, tangential velocity**, etc
- 3^{rd} catalog: **preliminary** results



Conclusions & Prospects

Problems on the small scales

→ local environment

→ best and most detailed observations for comparisons!

Solutions: constrained simulations (A lot is, will be or can be available !)

Prospectives:

- hydrodynamical constrained simulations (**full or zoom** Bertschinger 2001): detailed comparisons with **galaxy** populations to **improve models**
- foreground effect (SZ & SW): **un-bias** large surveys, reach **precision cosmology**

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Toda, Obrigada, Dank u,

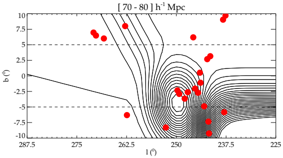
Tak, Cám Ơn, Dziękuję, ...

Latest Results

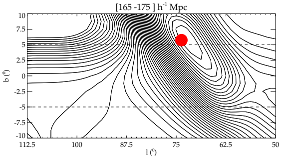
Structures in the Zone of Avoidance

**Using local Universe-like simulations
to predict structures in the Zone of Avoidance**

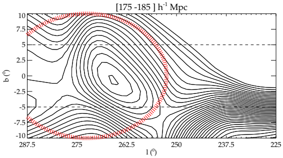
Average density field (contours) of constrained realizations of the local Universe. 3 slices of the Zone of Avoidance at different distances from us:



Puppis 3 cluster
red filled circles = galaxies (CDS-VizieR)
(Chamaraux & Masnou 2004)



Cygnus A cluster
red filled circles = cluster (CDS-VizieR)
(CIZA project, Ebeling et al. 2002)



Vela Supercluster
ellipse = predictions from observations
(Kraan-Korteweg et al. 2017)