Observatoire astronomique
de Strasbourg

AIP Leibniz-Institut für
Astrophysik Potsdam

Near Field Cosmology

From an Observational
to a Numerical local Universe

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Fuerteventura, Spain, September 2017

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Introduction

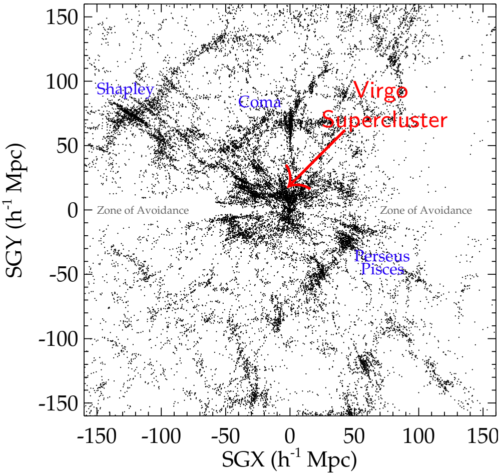
Definition (IAU Division H):

- **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 (∼10 Mpc) over which stellar populations in galaxies can be resolved by the HST. [...] **extend to include Virgo** (∼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 lecture

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

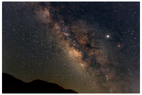


Virgo Supercluster

Virgo Cluster
distance: ∼15 Mpc

Local Group
size: ∼2 Mpc

Milky Way
size: ∼30 kpc



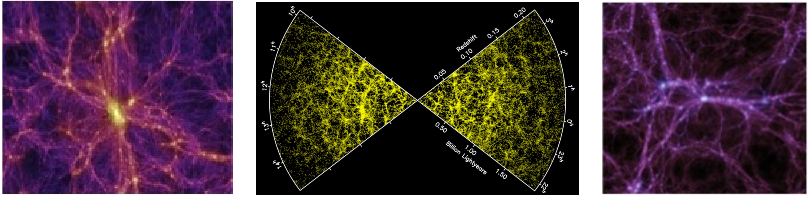
Andromeda
distance:
∼750 kpc

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

Motivation

See also Rien van der Weijgaert's lecture for simulated/observed LSS

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



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

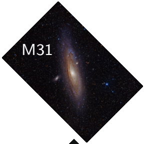
But **problems** on the small scales, e.g.:

- 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)

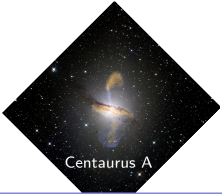
Is this due to the fact that we reside in a given environment?

Our **measurements, conclusions, local and far observations** might be **biased** by its 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)



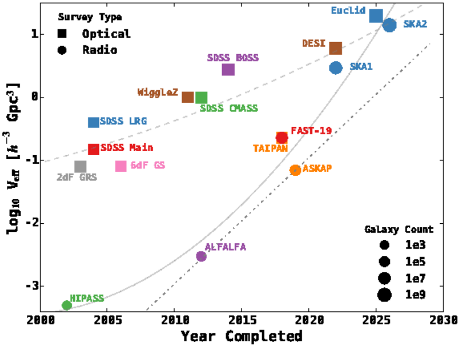
but it is the best and most observed Volume → Focus ! → detailed observations, map, expansion (H_0)



Observational

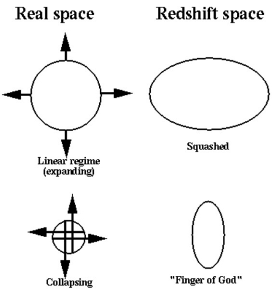
Mapping the local Universe

From redshift survey to distance measurements:



$\Rightarrow$ redshift survey approximate distance measurements: $d \sim v/H_0$

See Will Percival & Yi Zheng's lectures for detailed explanations



Kaiser 1987; Hamilton 1997
also non-linear motions

$z_{obs} = (\lambda_r - \lambda_e)/\lambda_e$

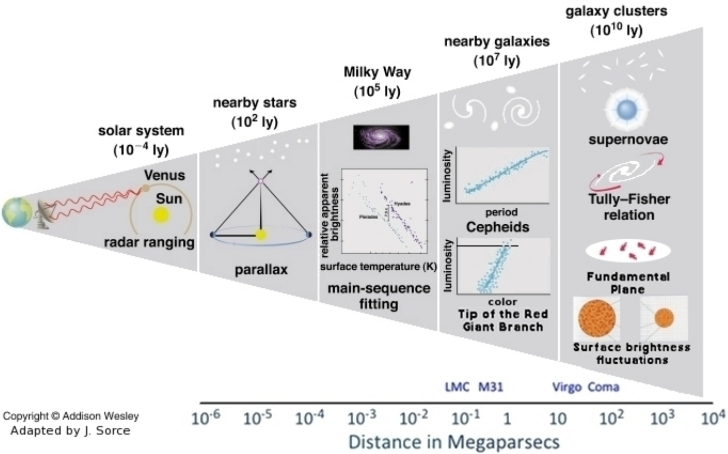
but $\lambda_r \neq a \times \lambda_e$ because of v_{pec}

$\mathbf{v_{tot} = H_0 d + v_{pec}}$

$(\neq cz_{obs} = (1+cz_{exp})(1+cz_{pec})-1)$

direct distance measurements $\Rightarrow$ distance indicators (and eventually access v_{pec})

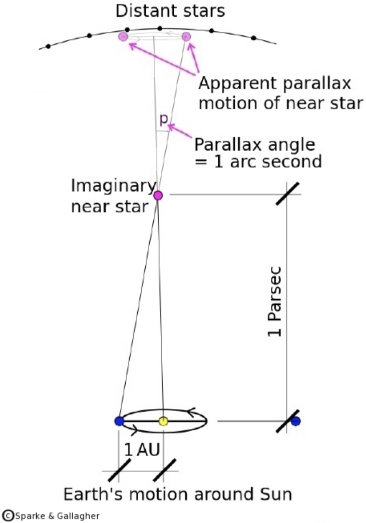
Cosmic ladder & a few examples



standard candle: celestial object with **absolute magnitude** assumed to **not vary with age/distance**.

distance modulus: μ = m - M = 5 $\log_{10}$(d(Mpc)) + 25 (m → measure, M → distance indicator)

Parallax: apparent motion of stars caused by Earth's motion



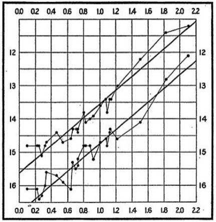
First measured in 1838 by Besser with an heliometer (two semi-lenses, adjustable until superimposition)

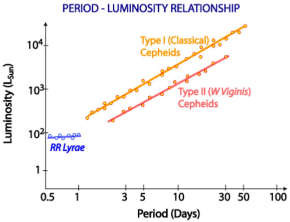
$$d=1/p \text{ pc}$$

(pc: distance at which a star has p=1")

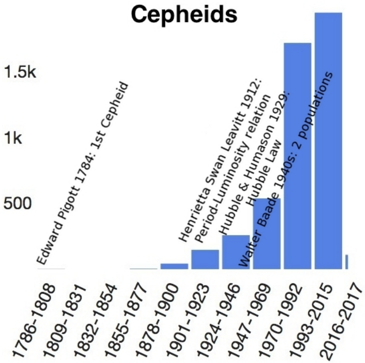
Cepheids - standard candle: $\mu \propto \log_{10}(P)$

Cepheid: star **varying** in brightness with a **well-defined** stable **period** and amplitude.





Luminosity vs. Period (logarithmic scales):
Left: Cepheids in the SMC (Leavitt 1912) - Right: credit: ATNF

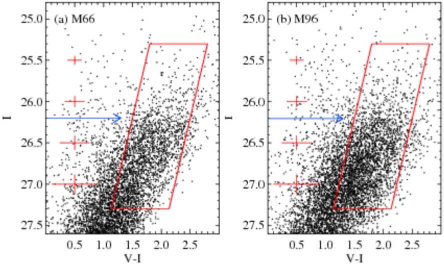


- More: metallicity (Webb et al. 1998), etc
- Big projects: e.g. HST key project (Freedman et al. 2001)

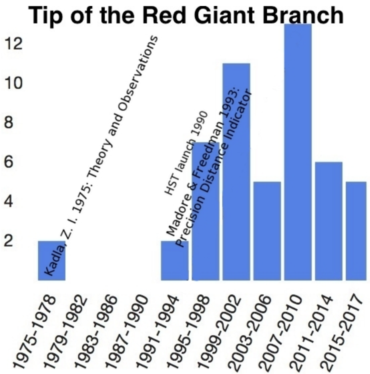
κ-mechanism (opacity increases with temperature): atmosphere moves inward⇒denser & more opaque⇒heats up⇒pressure pushes the layer back out (repeat)

TRGB - standard candle: $M_I \sim$-4.0

TRGB: Tip of the Red Giant Branch.



Lee et al. 2013 - edge-detection = sharp discontinuity



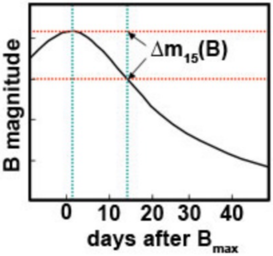
- More: metallicity (Mager et al. 2008), etc
- Big projects: e.g. Carnegie-Chicago Hubble project (Hatt et al. 2017)

Helium core at pressure and temperature to undergo nuclear fusion⇒temperature increases⇒sharp discontinuity in the evolutionary track of the star on the HR diagram.

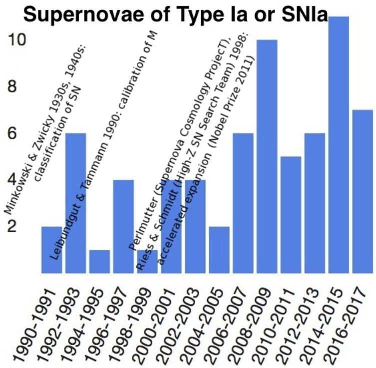
SNIa - standard candle: M_V=-19.3

See Yun Wang's lecture for detailed explanations

SNIa: occurs in **binary** systems in which one of the stars is a low rotation rate carbon-oxygen **white dwarf** with $M_{\rm limit} = 1.44 M_\odot$



Credit: Swinburne University of Technology

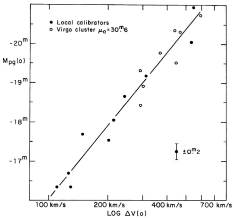


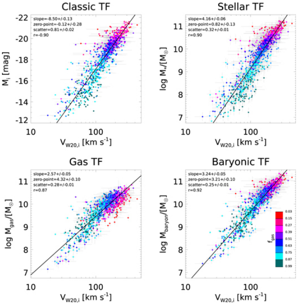
- More: environment (Rigault et al. 2013), etc
- Big projects: e.g. Nearby Supernovae Factory (Aldering et al. 2002)

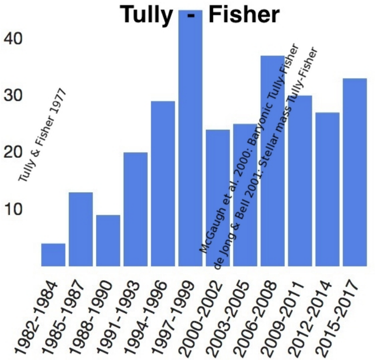
Mass accretion from companion⇒core reaches carbon-$T_{\rm fusion}$ close to $M_{\rm limit}$⇒SN explosion: C&O converted into heavier elements within a few s., T=billions of deg., released energy unbinds the star⇒shock wave, particles at ∼6% of light-speed (most accepted scenario).

Tully-Fisher: $M \propto \log_{10}(v)$

classic TF: luminosity - rotation rate.







Tully & Fisher 1977 - Bradford et al. 2017

$M_{\mathrm{baryonic}} = M_* + M_{\mathrm{gas}}$

- More: color, sample (Sorce et al. 2013, Sorce & Guo 2016)
- Big projects: e.g. cosmicflows with Spitzer (Sorce et al. 2014)

Virial theorem: $2E_k + E_p = 0 \Rightarrow M/R \propto v^2$

if M/L=cst then $L \propto v^2 R$
if $L \propto R^2$ (SB definition)

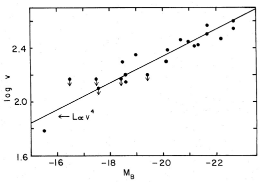
then $R^2 \propto v^2 R$ (or $R \propto v^2$)

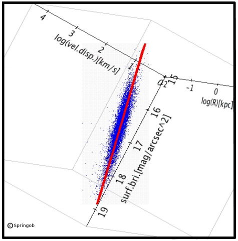
finally $L \propto v^4$

NB: Classic TF applicable to spiral galaxies (pending normalization for the others)

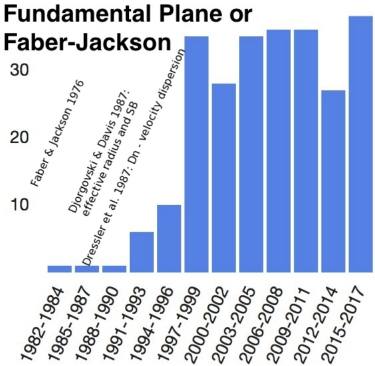
Faber-Jackson & Fundamental Plane

Faber-Jackson: luminosity-velocity dispersion (simple version).
Fundamental plane: usually R_{eff}, $<SB>_{\rm eff}$, σ.





Faber & Jackson 1976 - Credit: 6dFGS collaboration



Dn: diameter within which SB=20.75mag/arcsec^2

- Big projects: 6dF, 6dFGS (Colless et al. 2001, Springob et al. 2014)

Virial theorem: $2E_k+E_p=0 \Rightarrow M/R \propto \sigma^2$

if M/L=cst then $L \propto \sigma^2 R$
if $L \propto R^2$ (SB definition)

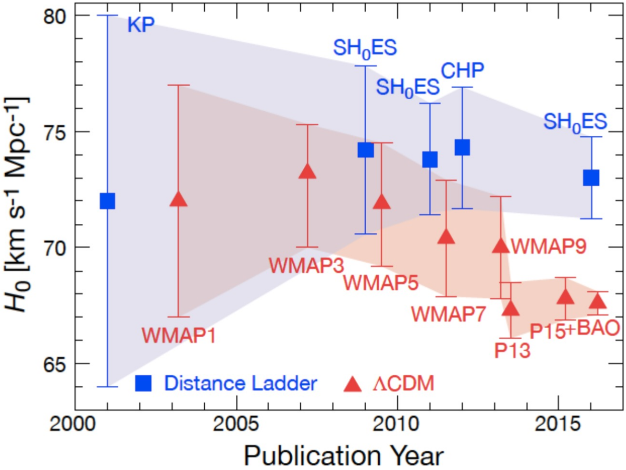
then $R^2 \propto \sigma^2 R$ (or $R \propto \sigma^2$)

finally $L \propto \sigma^4$

NB: Fundamental plane and variants applicable to elliptical galaxies

H_0: a never ending history?

distance indicators ⇒d⇒ When d>>, $H_0 \sim v_{tot}/d$ but local vs. cosmological (CMB) H_0:



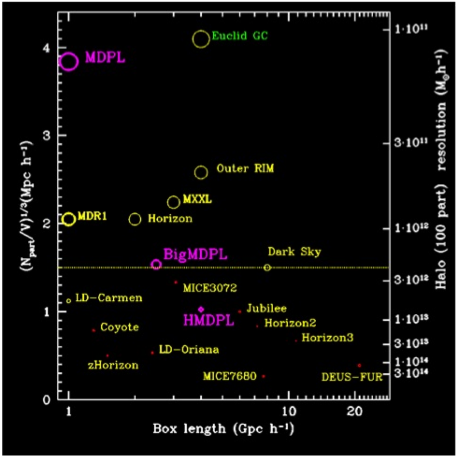
Credit: Freedman 2017

Cosmic variance, another cosmo. model, etc ⇒ test with cosmological simulations

Numerical

Simulations: an overview

See Raul Angulo's lecture for detailed information



Courtesy of G. Yepes

Need:

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

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

- time
- memory
- storage

Another option: Constrained Simulations

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

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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

constraints = observations

initial conditions for simulations

Ingredients to get Constrained Simulations

- **Redshifts or peculiar velocities**

$\leftarrow$ constraints = observations

initial conditions for simulations

Ingredients to get Constrained Simulations

- **Redshifts or peculiar velocities** ← constraints = observations
- **Method/Technique** ← initial conditions for simulations

Redshift vs. Peculiar velocities

Redshift:

PROS:

- Easy

CONS:

- fingers-of-god, kaiser effects, etc

- luminosity bias

Peculiar velocities:

CONS:

- Challenging

- Homogeneous and heterogeneous Malmquist biases, lognormal error

PROS:

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

Techniques and applications: History

See also Francisco Kitaura's lecture

Bayes 1761 — Posterior: prior * likelihood

Wiener 1942 — Predictions or Removal of noise from incomplete information

Bertschinger 1987 — BBKS gene-ralization, POTENT

Hoffman & Ribak 1991 — CR: residual estimate

Zaroubi et al. 1995 — reconstruction of the LSS with WF

van der Weijgaert & Bertschinger 1996 — CR for ICs

Klypin et al. 2003 — Mark III vpec + density constraints

Lavaux 2010 — 2MASS redshift survey

Kitaura & Angulo 2012 (start 2008) — Hamiltonian sampling of the posterior

Hess, Kitaura & Gottloeber 2013 — 2MRS redshift survey (augmented LPT: Kitaura & Hess 2013)

Jasche & Wandelt 2013 — On going PLUS project

Wang et al. 2014 – 2016 — On going ELUCID Project (SDSS)

Sorce et al. 2014-2017 — detailed explanations hereafter

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

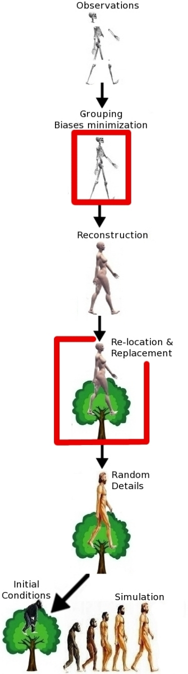
Tully et al. 2013

Tully 2015, Sorce & Tempel 2017, Sorce 2015

Zaroubi et al. 1995

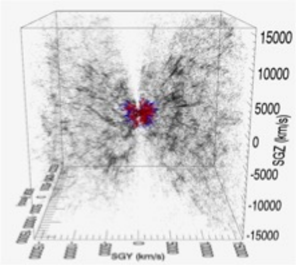
Doumler et al. 2013 Sorce et al. 2014b

Hoffman & Ribak 1991

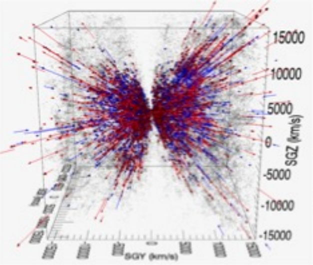


Cosmicflows: Observational datasets

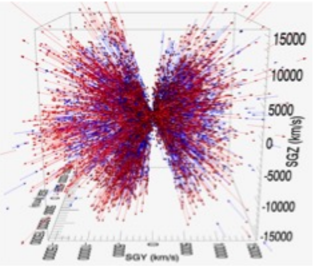
CF1
Tully et al. 2008



CF2
Tully,...,Sorce et al. 2013



CF3
Tully,...,Sorce 2016

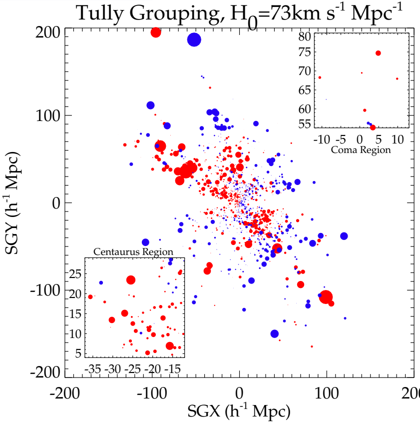


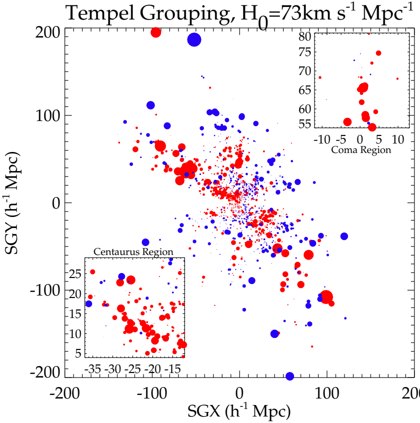
	CF1	CF2	CF3
Radial peculiar velocities	$\sim$ 1,8000	$\sim$ 8,000	$\sim$ 17,000
Max. d (Mpc)	$\sim$ 50	$\sim$ 300	$\sim$ 370
Mean d (Mpc)	$\sim$ 15	$\sim$ 60	$\sim$ 90

Courtesy D. Pomarède

Grouping

Sorce & Tempel 2017





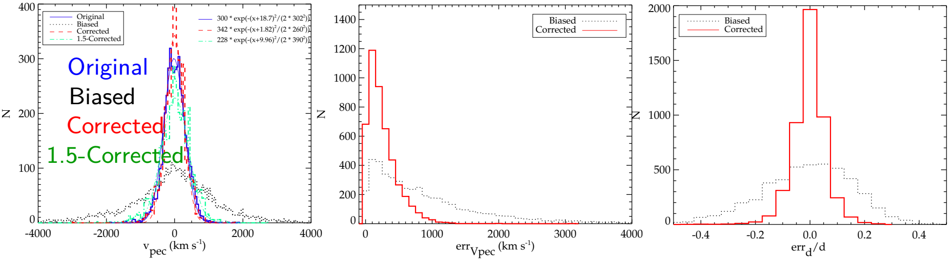
$$\mu_g = \frac{\sum w \times \mu}{\sum w} \; ; \; \sigma_{\mu g} = \sqrt{\frac{1}{\sum w}} \text{ where } w = \frac{1}{\sigma_\mu^2},$$

$$d_g = 10^{\frac{\mu_g - 25}{5}} \; ; \; \sigma_{dg} = \sigma_{\mu g} \times \frac{\log(10)}{5}$$

$$v_{pec\ g} = v_{tot\ g} - H_0 \times d_g \; ; \; \sigma_{vpec\ g} = \sigma_{dg} \times d_g \times H_0$$

Minimization of the biases

Sorce 2015



Iterations on:

$$\textit{if}\ \ v_{pec} > 0,\ \ v_{pec\ c} = (1-w)[p(v_{pec} - \sigma_{v_{pec}}) + (1-p)(v_{pec} + \sigma_{v_{pec}})] + w\, v_{pec}$$

$$\textit{if}\ \ v_{pec} < 0,\ \ v_{pec\ c} = (1-w)[p(v_{pec} + \sigma_{v_{pec}}) + (1-p)(v_{pec} - \sigma_{v_{pec}})] + w\, v_{pec}$$

then multiplication by 1.5

- p: probability $v_{pec} \notin$ theoretical Gaussian (from the mock) (Sheth and Diaferio, 2001)
- w: weighted uncertainty on v_{pec}

After correction:

- distances computed accordingly: $d_c = (v_{obs} - v_{pec\ c})/H_0$
- 5% fractional error on distances assumed.

Wiener-Filter

Linear minimum variance estimator between data C_j and model: $f_i = \sum_{j=1}^{n} a_j C_j$

$$f_i = \sum_{j=1}^{n} \sum_{i=1}^{n} \langle f_i C_i \rangle \langle C_i C_j \rangle^{-1} C_j$$

$\langle AB \rangle$: correlation functions involving the prior model P(power spectrum)

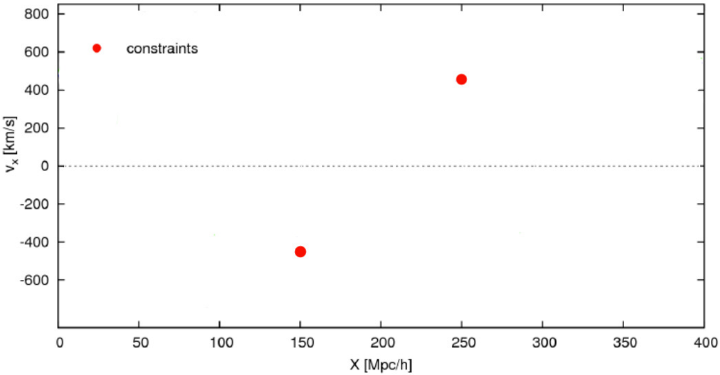
For $f=\delta$ or v and C=v with "j_is" the common Bessel functions:

$$\langle \delta(\mathbf{r}')v_\alpha(\mathbf{r}'+\mathbf{r})\rangle = \frac{\dot{a}f}{(2\pi)^3}\int_0^\infty \frac{ik_\alpha}{k^2}P(\mathbf{k})e^{-i\mathbf{k}.\mathbf{r}}d\mathbf{k} = -\dot{a}f\hat{r}_\alpha \frac{1}{2\pi^2}\int_0^\infty k^2 j_0(\mathbf{kr})P(\mathbf{k})d\mathbf{k}$$

$$\langle v_\alpha(\mathbf{r}')v_\beta(\mathbf{r}'+\mathbf{r})\rangle = \frac{(\dot{a}f)^2}{(2\pi)^3}\int_0^\infty \frac{k_\alpha k_\beta}{k^4}P(\mathbf{k})e^{-i\mathbf{k}.\mathbf{r}}d\mathbf{k} = (\dot{a}f)^2[\Psi_T\delta^K_{\alpha\beta}+(\Psi_R-\Psi_T)\hat{r}_\alpha\hat{r}_\beta]$$

where $\Psi_T = \frac{1}{2\pi^2}\int_0^\infty \frac{j_1(\mathbf{kr})}{\mathbf{kr}}P(\mathbf{k})d\mathbf{k}$ and $\Psi_R = \frac{1}{2\pi^2}\int_0^\infty [j_0(\mathbf{kr}) - \frac{2j_1(\mathbf{kr})}{\mathbf{kr}}]P(\mathbf{k})d\mathbf{k}$.

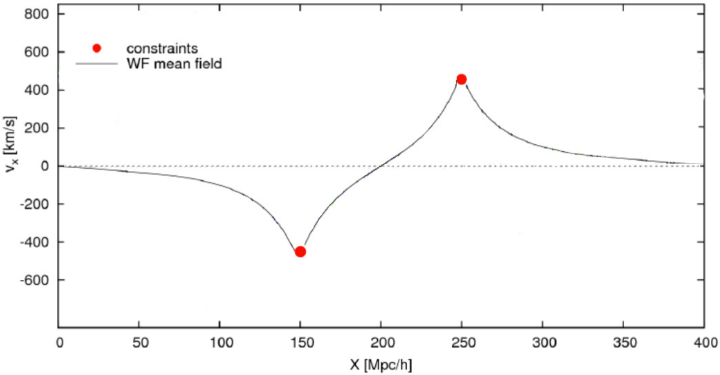
Wiener-Filter or Reconstruction Technique



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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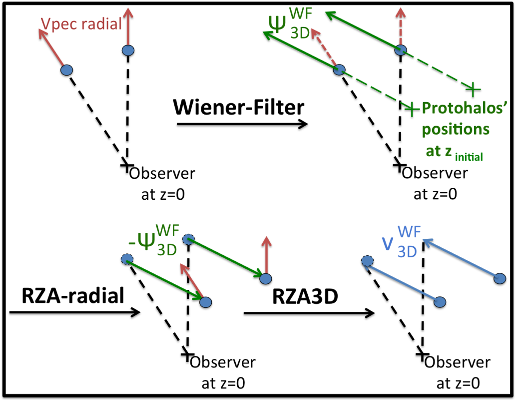
Reverse Zel'dovich Approximation

(Doumler et al. 2013 and Sorce et al. 2014 & cf. Rien van der Weijgaert's lecture for 'nice' stories)



Reverse Zel'dovich Approximation:

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

$$\text{growth rate} : f(t) = \frac{d \, (ln \, D(t))}{d \, (ln \, a(t))}$$

growth factor
scale factor

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

Constrained Realization (CR)

1. **WF** for random constraints $\tilde{C}_j$ of a random field $\tilde{f}^{RR}$:

$$\tilde{f}^{WF} = \sum_{j=1}^{n}\sum_{i=1}^{n}\langle f_i\tilde{C}_i\rangle\langle\tilde{C}_i\tilde{C}_j\rangle^{-1}\tilde{C}_j = \sum_{j=1}^{n}\sum_{i=1}^{n}\langle f_i C_i\rangle\langle C_i C_j\rangle^{-1}\tilde{C}_j$$

(correlation functions depend only on the prior model)

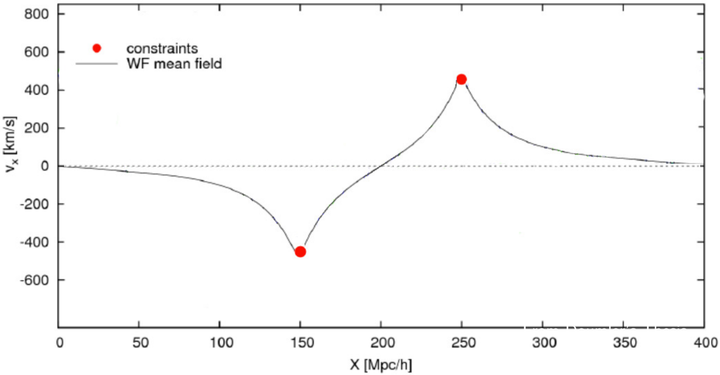
2. **Residual:**

$$\tilde{R} = \tilde{f}^{RR} - \tilde{f}^{WF} = \tilde{f}^{RR} - \sum_{j=1}^{n}\sum_{i=1}^{n}\langle f_i C_i\rangle\langle C_i C_j\rangle^{-1}\tilde{C}_j$$

3. **Constrained realization field:**

$$f^{CR} = f^{WF} + \tilde{R} = \tilde{f}^{RR} + \sum_{j=1}^{n}\sum_{i=1}^{n}\langle f_i C_i\rangle\langle C_i C_j\rangle^{-1}(C_j - \tilde{C}_j)$$

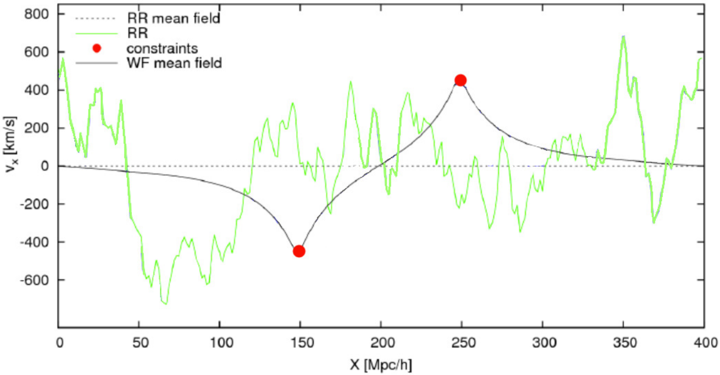
Wiener-Filter or Reconstruction Technique



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)

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

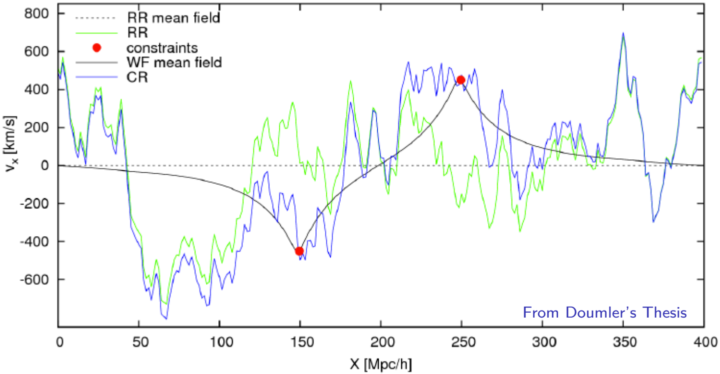
Constrained Realization Technique



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



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

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

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

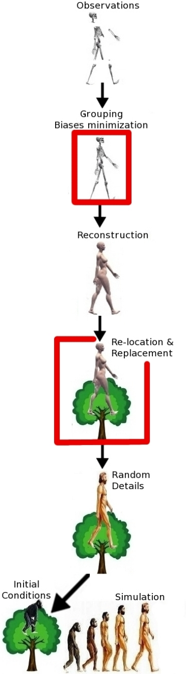
↓

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

↓

Constrained Initial Conditions — Hoffman & Ribak 1991

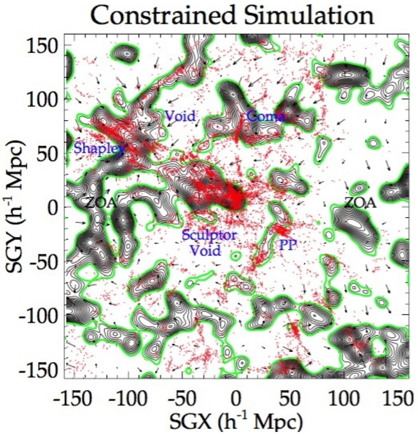
Simulation ↓ run

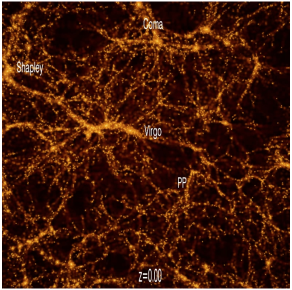


How did the Local Universe form?

Sorce et al. 2016a

At z=0





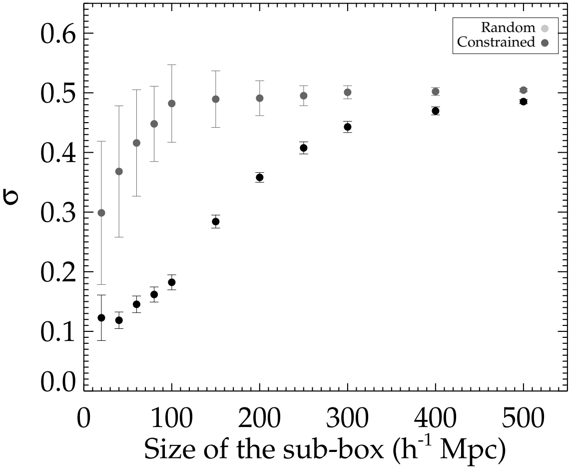
Observations for comparisons: redshift catalog •

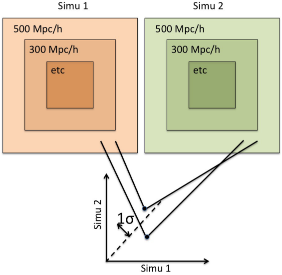
Observations to constrain = Peculiar Velocities: CF2 catalog

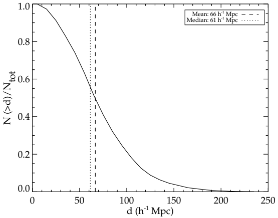
Simulation: L=500 h^{-1} Mpc, n=512^3, full field (contours, arrows)

Robust Large-Scale Environment

Sorce et al. 2016a







Smoothing: 5 h^{-1} Mpc

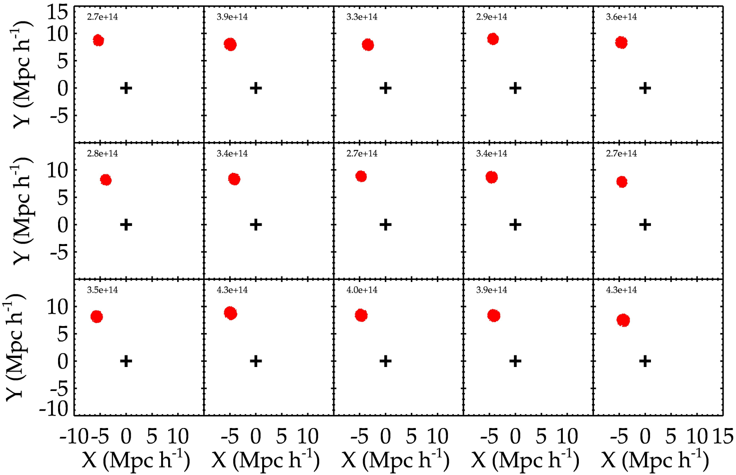
Mean and scatter of 1-σ scatters in cell-to-cell comparisons

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

Can we zoom-in?

What about the clusters?

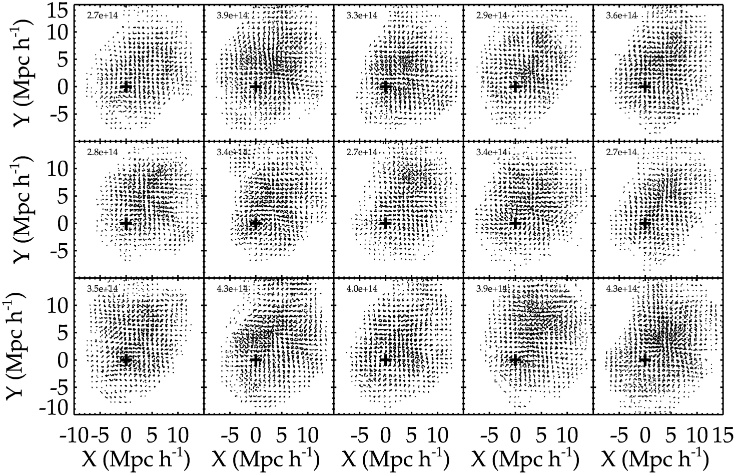
How did the Virgo cluster form?



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

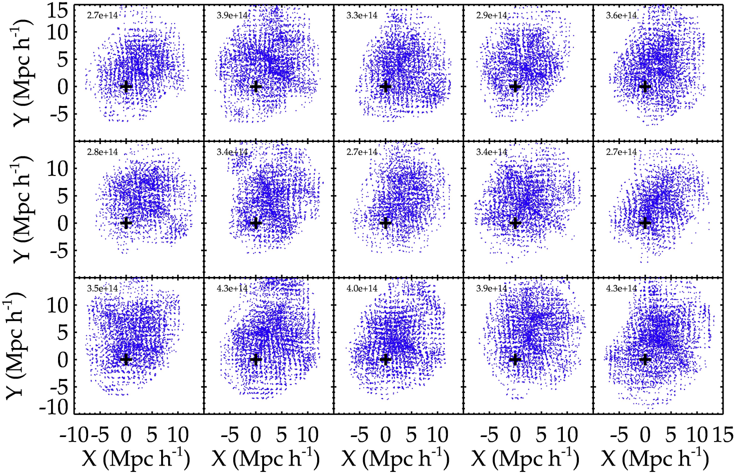
- Shift $\sim$ 3-4 h^{-1} Mpc
- Mass within $\sim$ [0.5,2] estimated mass (Ludlow & Porciani 2011) M_{200}

How did the Virgo cluster form?



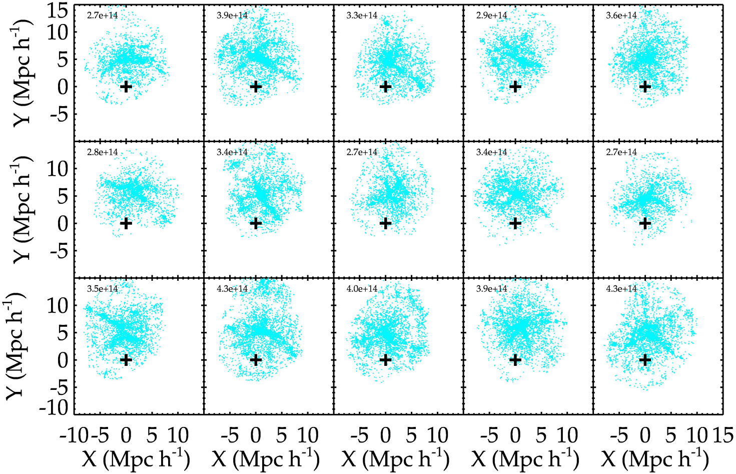
Dark Matter Haloes - Virgo Candidates: Particles at z= 10.

How did the Virgo cluster form?



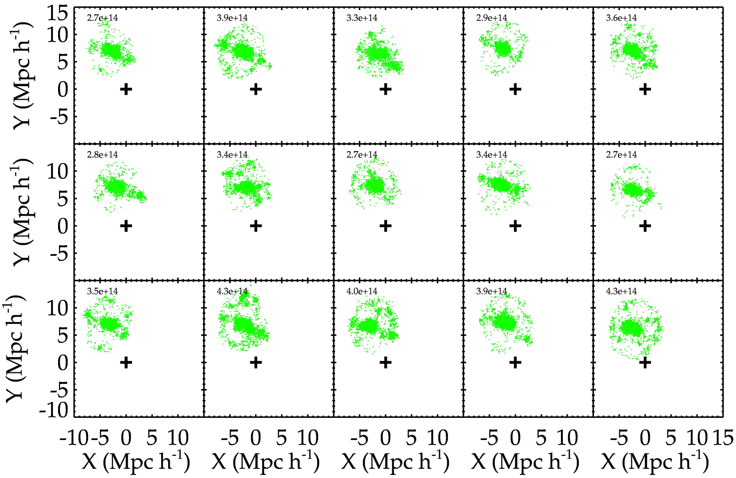
Dark Matter Haloes - Virgo Candidates: Particles at z= 5.

How did the Virgo cluster form?



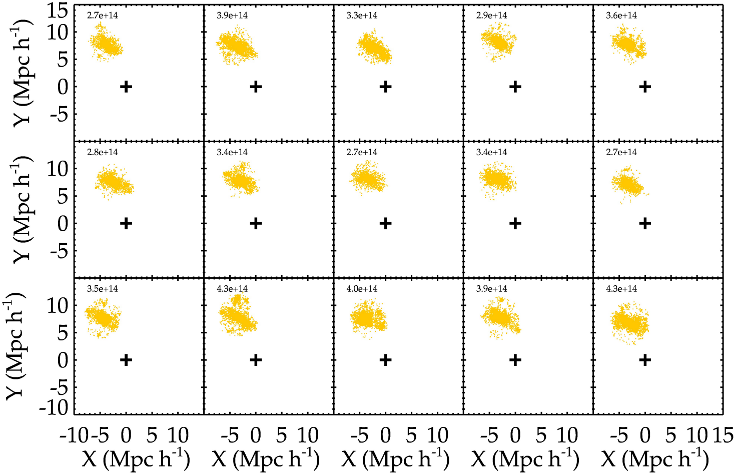
Dark Matter Haloes - Virgo Candidates: Particles at z= 2.

How did the Virgo cluster form?



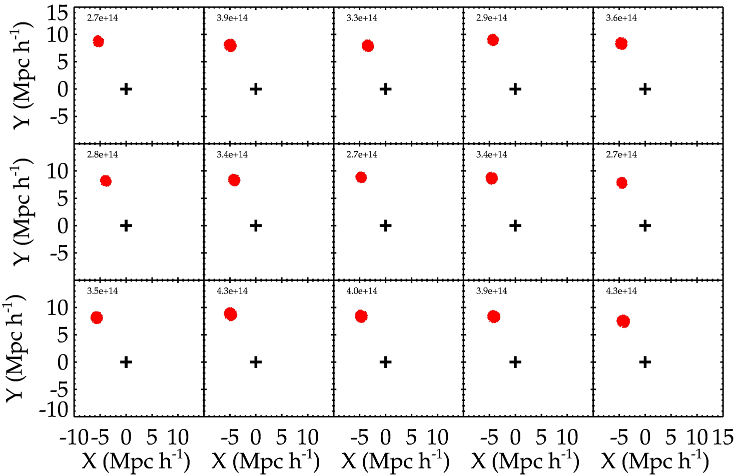
Dark Matter Haloes - Virgo Candidates: Particles at z= 0.5

How did the Virgo cluster form?



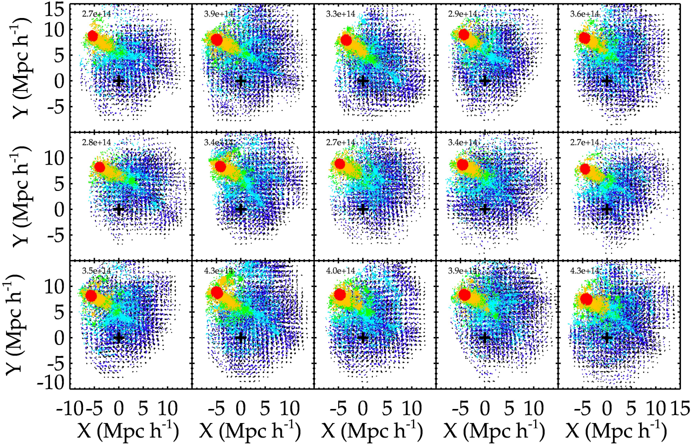
Dark Matter Haloes - Virgo Candidates: Particles at z= 0.25

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

Want more?

- Zone of Obscuration (Sorce et al. 2017): e.g. **Vela** Supercluster (Kraan-Korteweg et al. 2017)
- Virgo (Sorce et al. 2016b, Sorce et al. in prep.): e.g. **preferential direction of infall, merging history**, etc
- Local Group (e.g. Carlesi, Sorce et al. 2016) & Reionization (Ocvirk et al in prep., Sorce et al. in prep.): e.g. **mass ratio, tangential velocity**
- 3^{rd} catalog: **preliminary** results

⇒ Come to discuss & see poster & more movies

Near Field Cosmology: summary

Observational side:

- Redshifts (pros/cons)
- Peculiar velocities (via distance indicators, pros/cons)

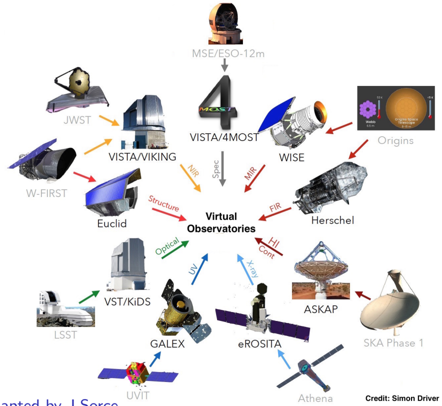
Numerical side:

- Reduction of the cosmic variance (1^{st} Bertschinger 1987)
- Several techniques & applications (backwards/forwards, redshifts/velocities/both)

⇒ wide range of studies possible through comparisons & statistics

Near Field Cosmology and beyond: prospectives

Observational side:



Adapted by J.Sorce

Numerical side:

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

Acknowledgements

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Toda, Tak, Dank u,

Obrigada, Cám Ơn, Dziękuję, ...