Do we need a new cosmological model ?

GMO-CLONES, a solution to the precision era dilemma

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Centre de Recherche Astrophysique de Lyon

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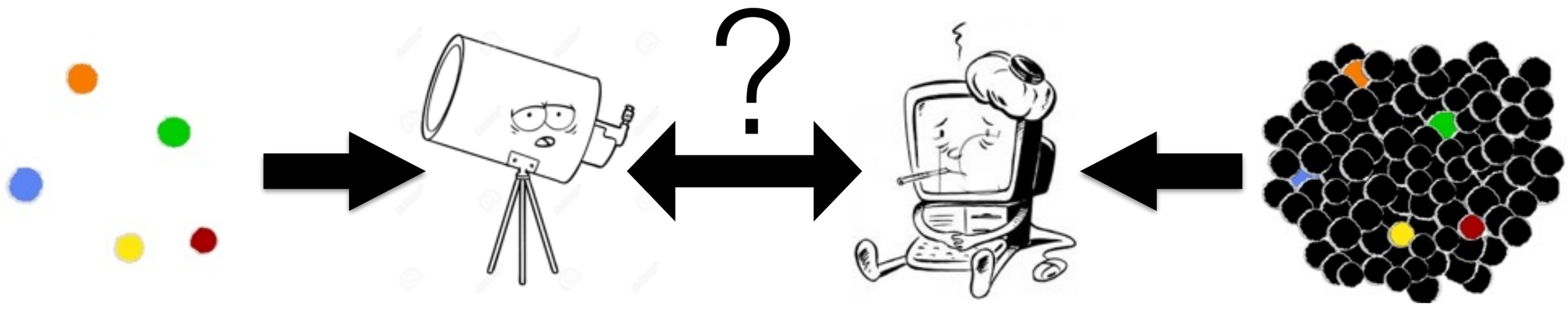
Collaborators: **Blaizot, Richard, Tresse (CRAL), Dubois (IAP), Hahn (OCA), de La Torre (LAM), Pontzen, Peiris, Rey (UCL), Ocvirk (ObAS)**

Motivation : ΛCDM? ➤ Current strategy

Observations

Simulations



Directly Observable Universe

Cosmological Model

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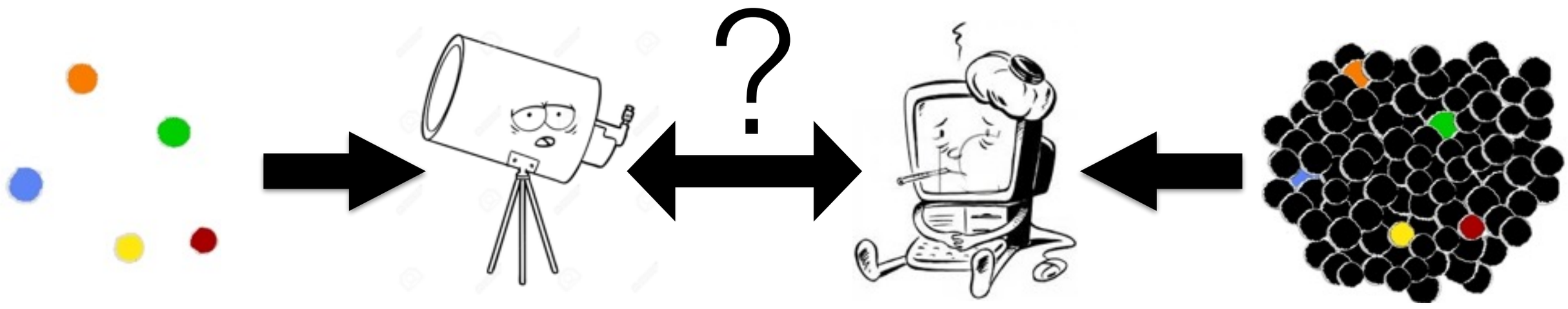


Directly Observable Universe

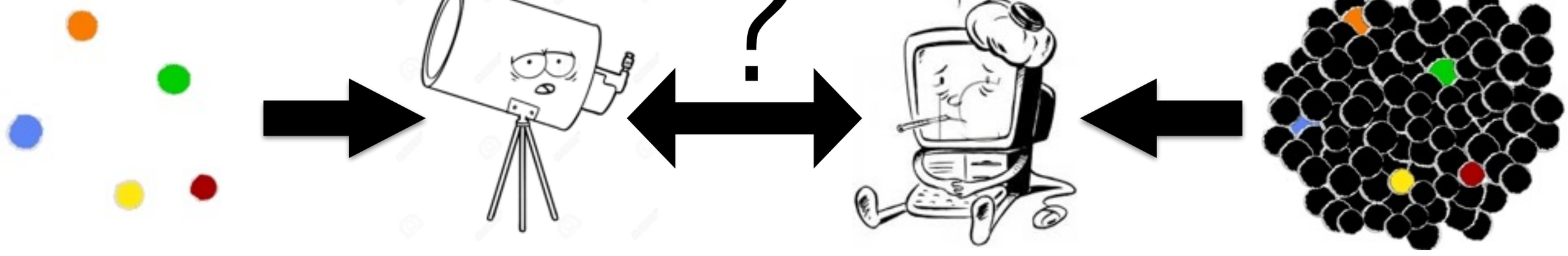
If all goes well…
it is a perfect match

Cosmological Model

Motivation : ΛCDM? In practice

Observations

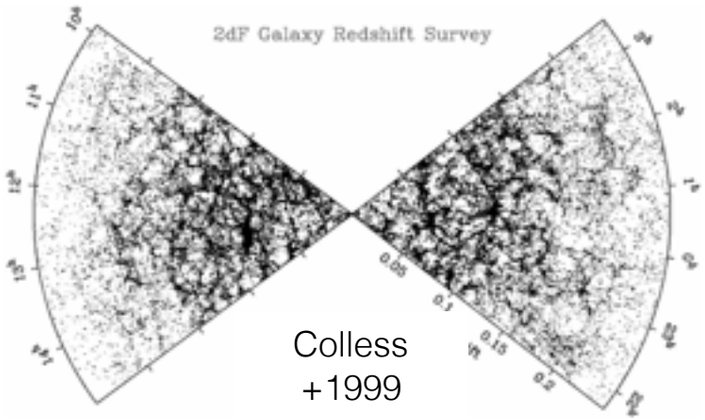
Simulations



Directly Observable Universe

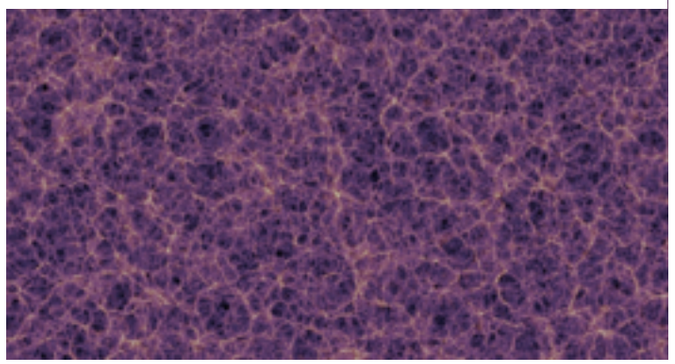
Overall: ΛCDM ☑

Cosmological Model



Colless +1999

Springel+2005,2008, Dubois+2016, etc

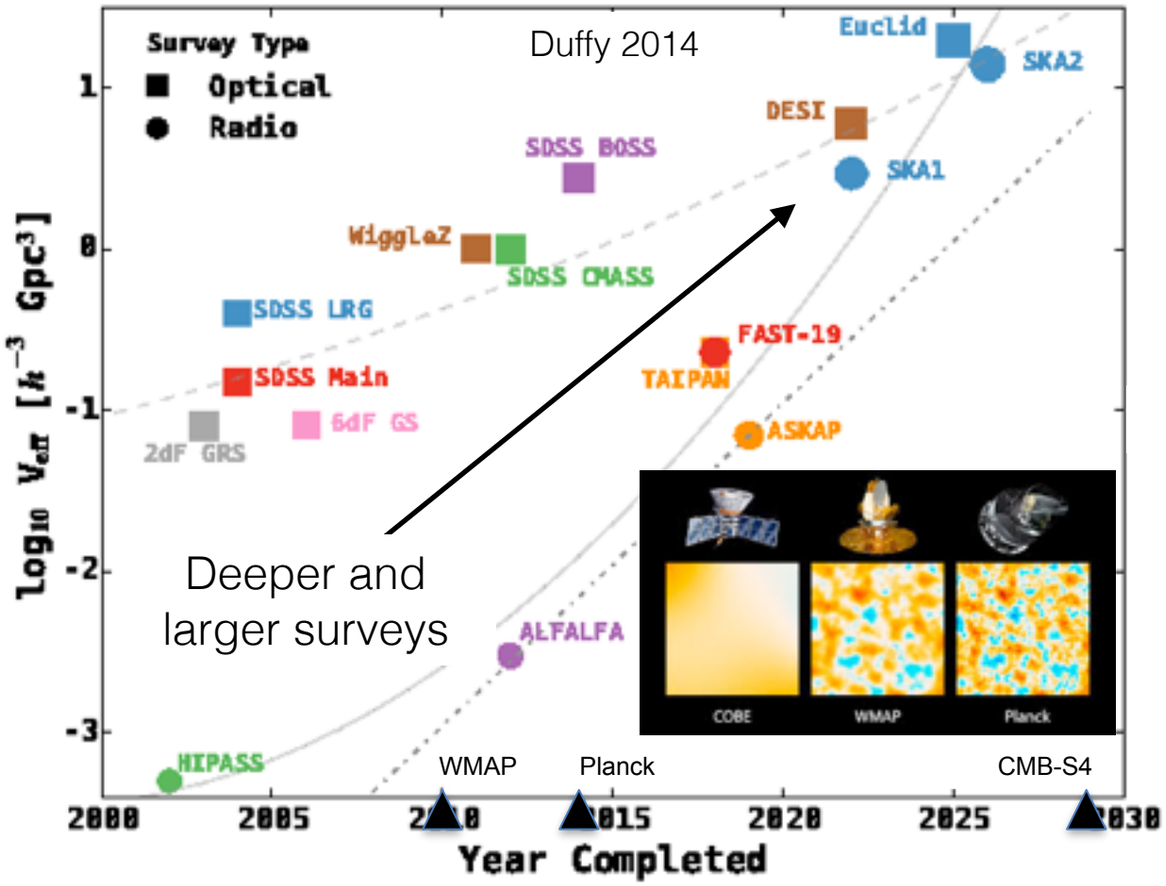


Motivation : ΛCDM? Toward precision cosmology

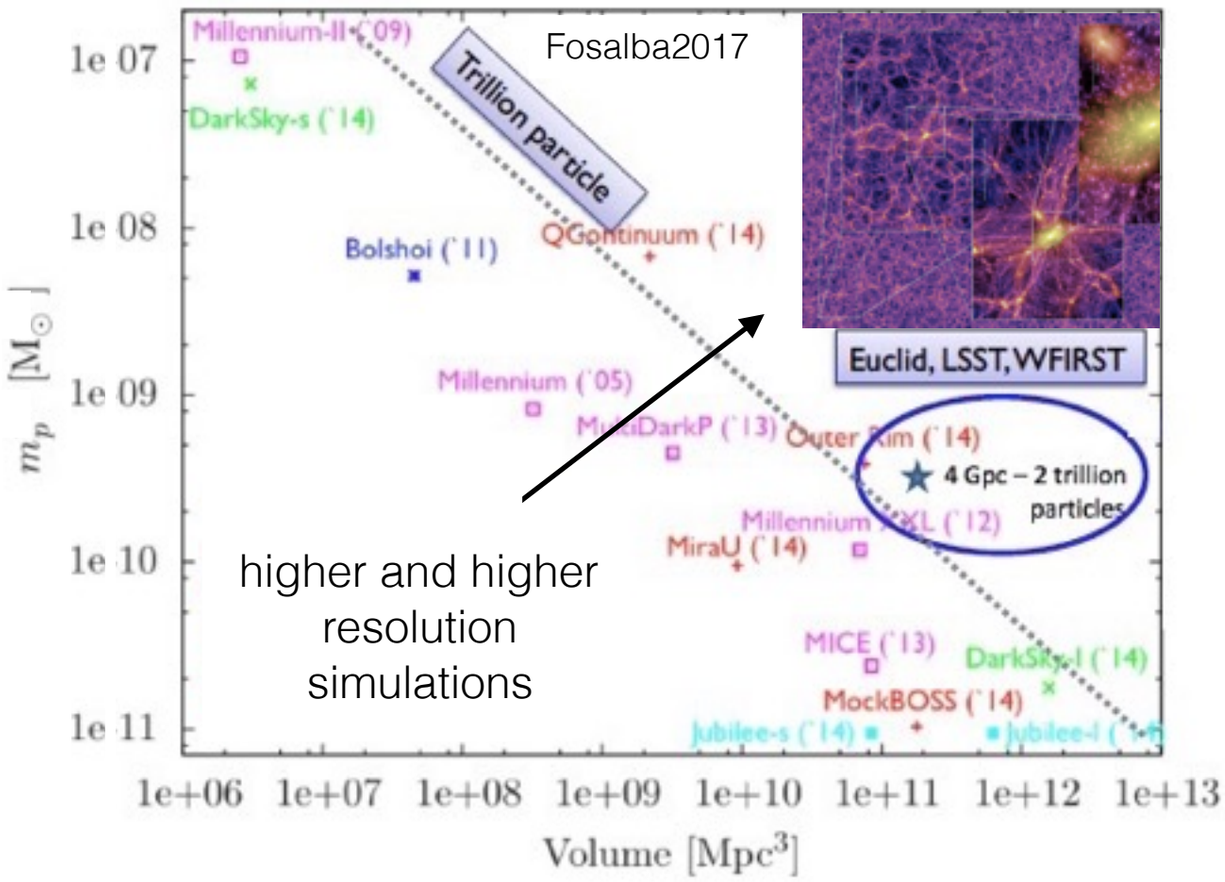
Precision Era:
1-2% precision

ΛCDM checked on all scales

Observational

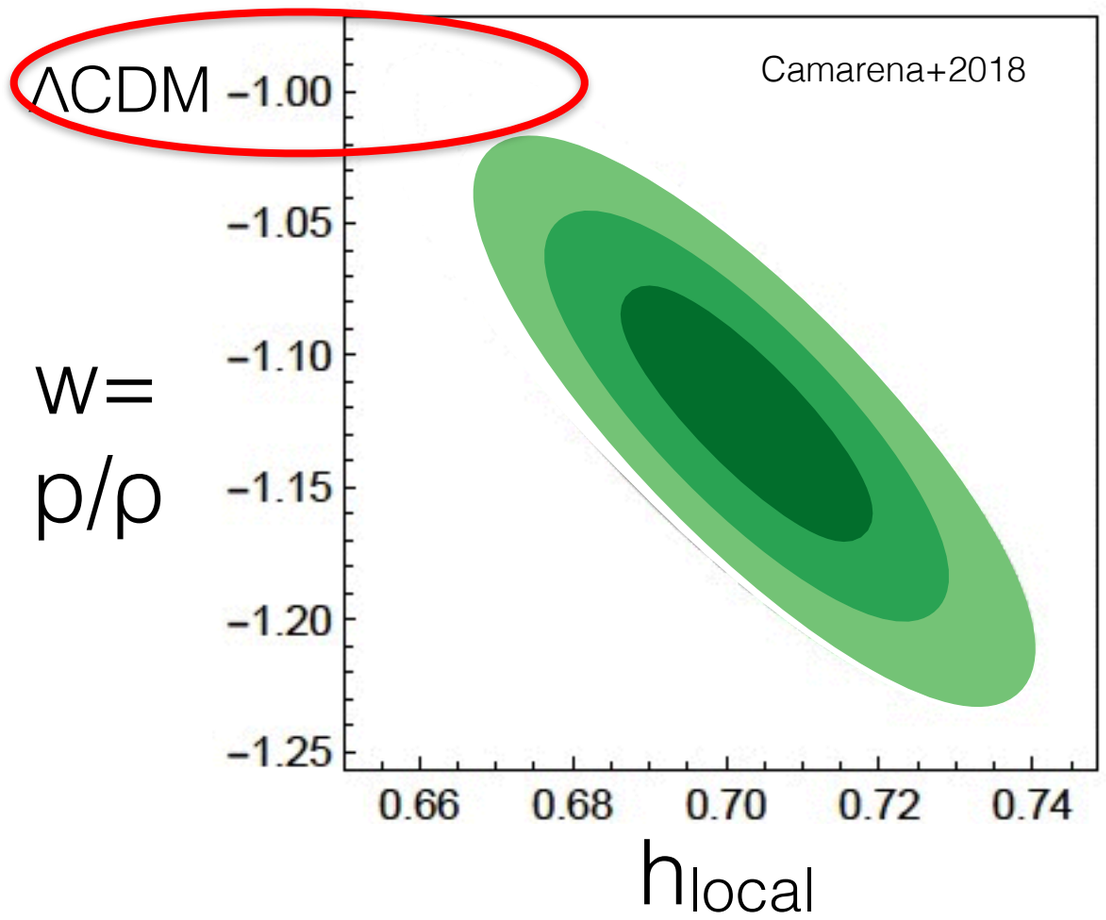


Numerical



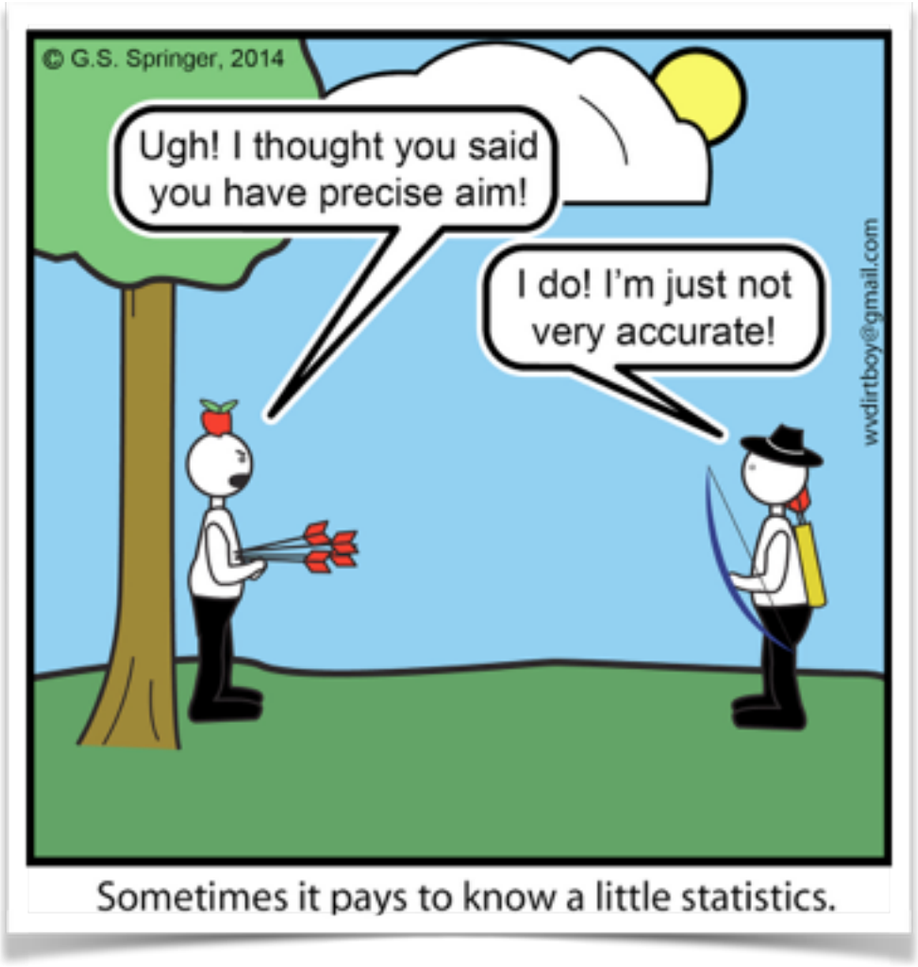
Motivation : ΛCDM? but with more precision come some tensions !

Example: Equation of state of the dark energy



Motivation : ΛCDM?

Precision is not accuracy !



Precision is not accuracy: environmental biases?

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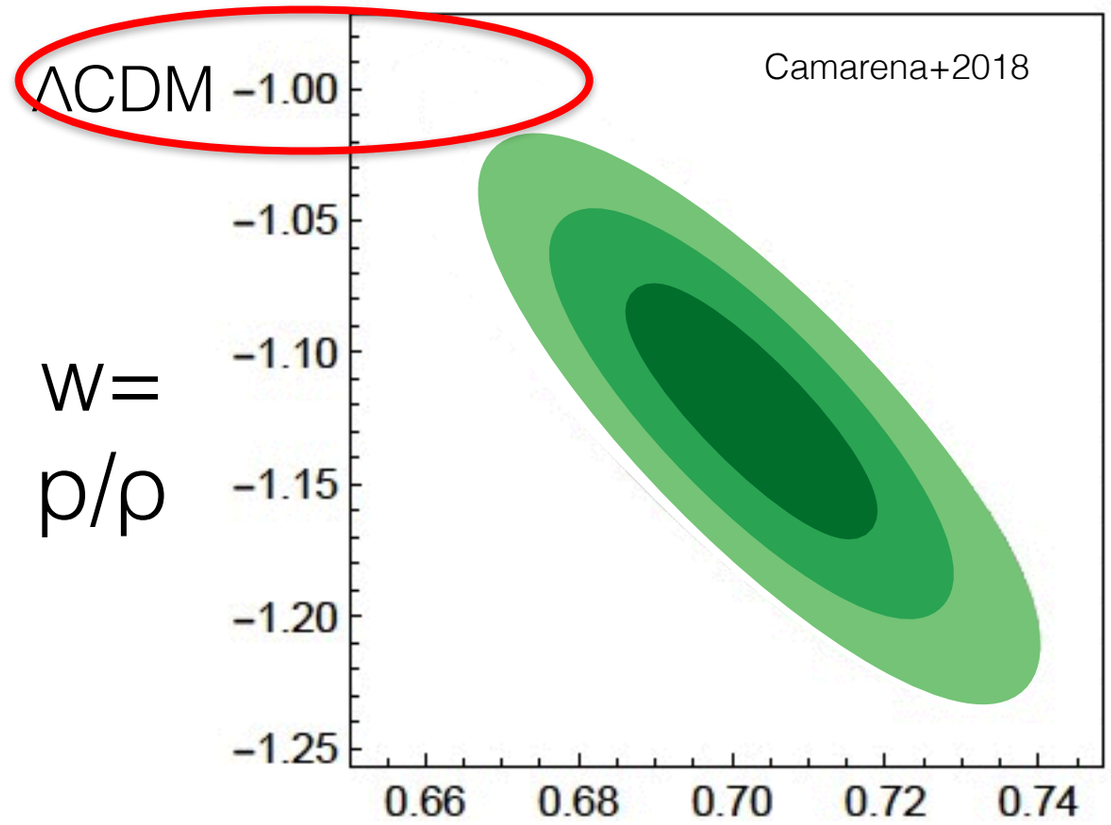
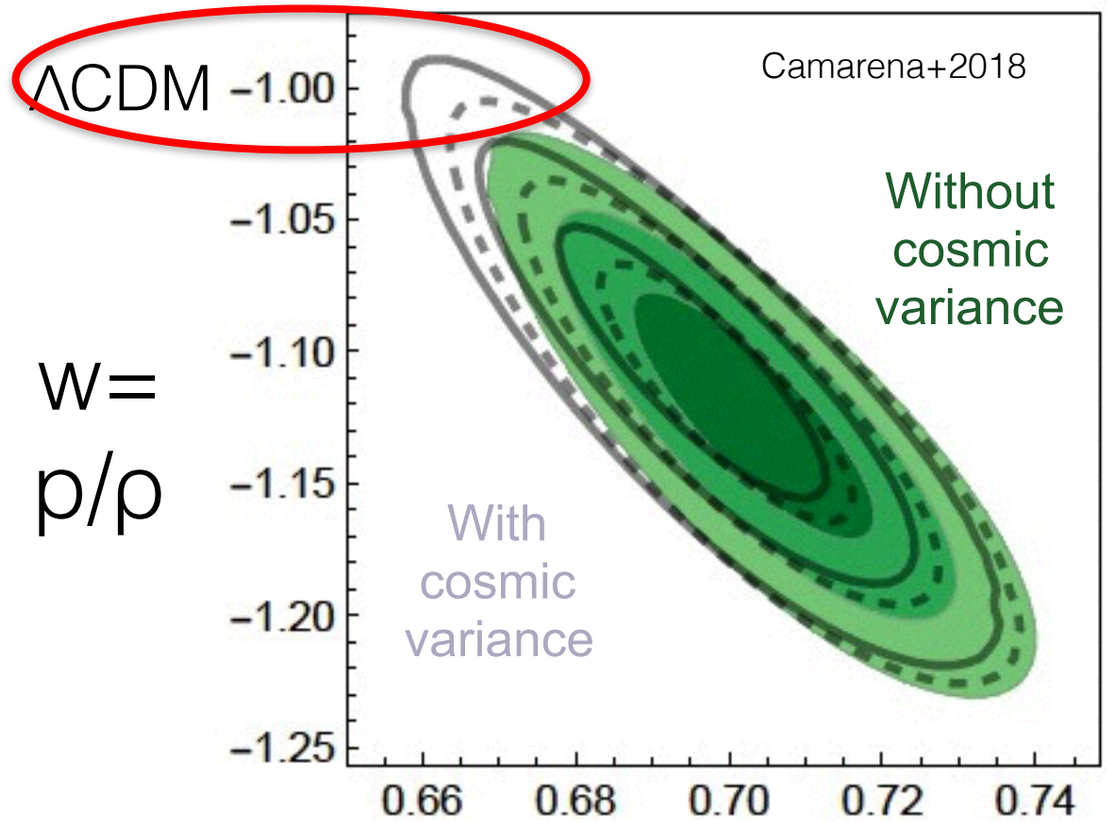


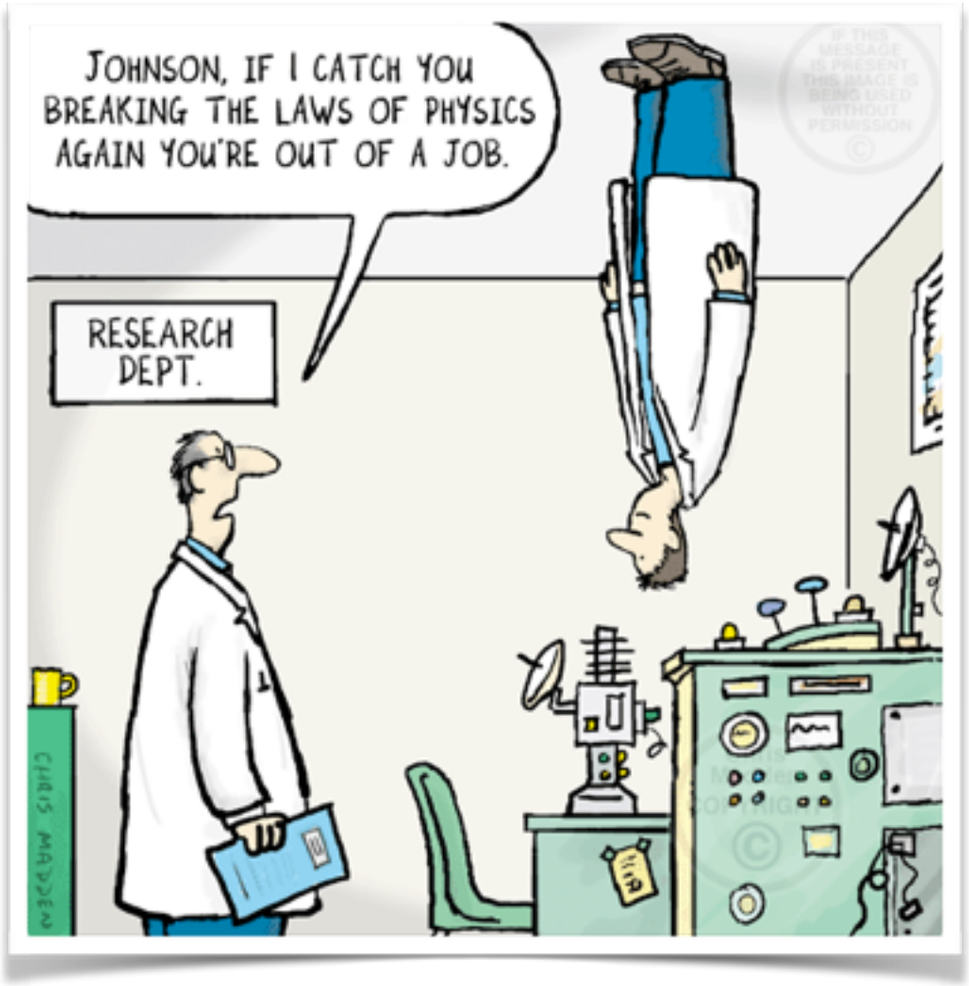
Motivation : ΛCDM? Both precision and accuracy are required!

Example: Equation of state of the dark energy



Accuracy:
1% bias non-negligible

When observations challenge ΛCDM

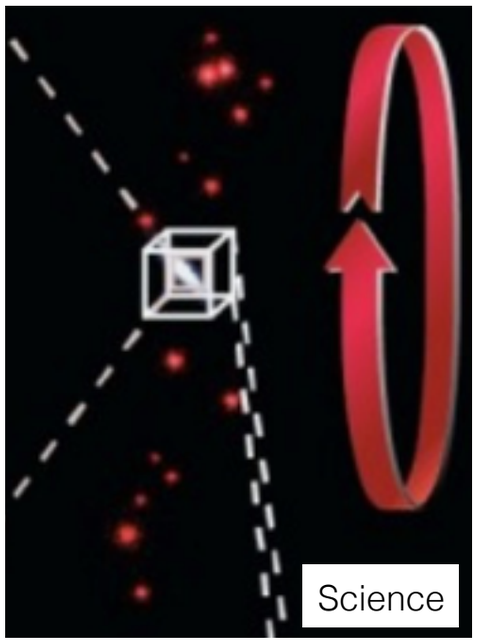


ΛCDM questioned? ➤ Precision cosmology

A few examples

Small scales

Thin disks of satellites



Observed… not simulated

Famaey+2013, Bullock+2017

local scales

local / global H_0

Freedman+2017

Large scales

CMB

North/South Asymmetry

Francis+2010

very unlikely…

e.g. Schwarz+2016

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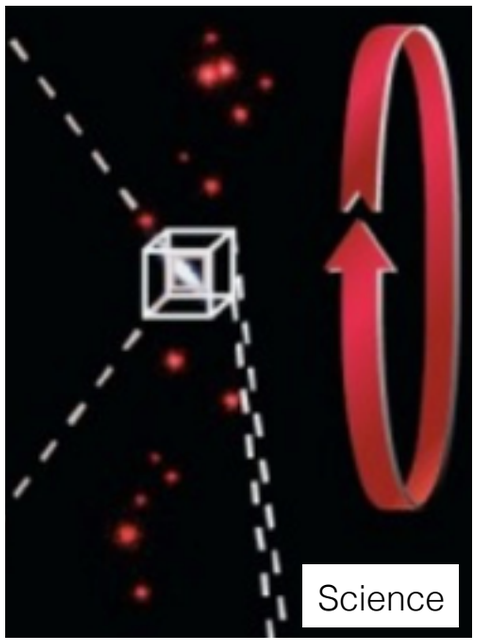

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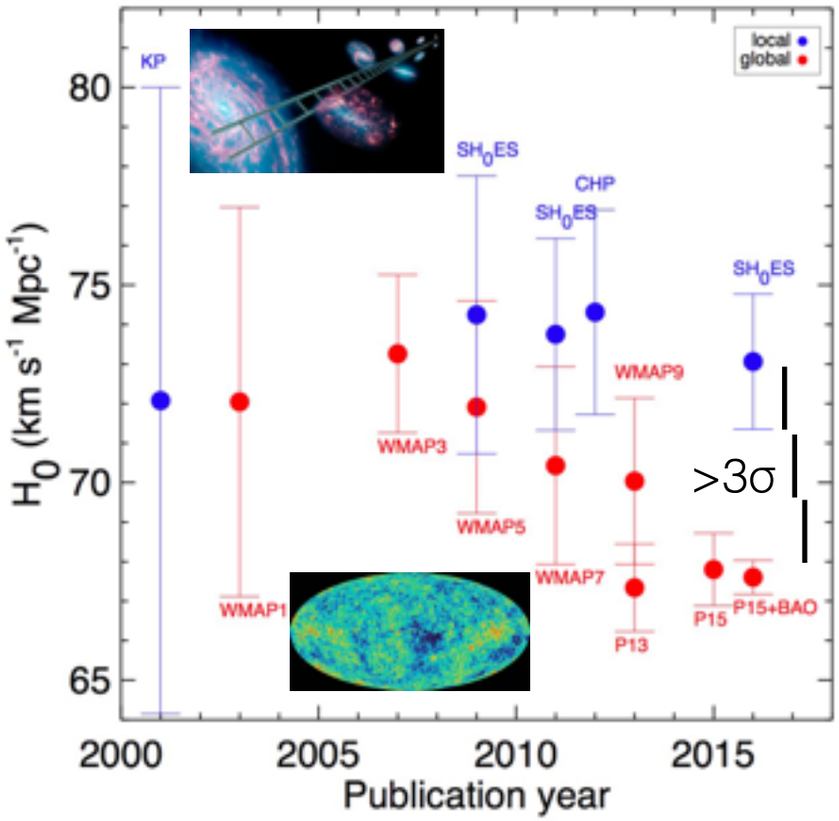

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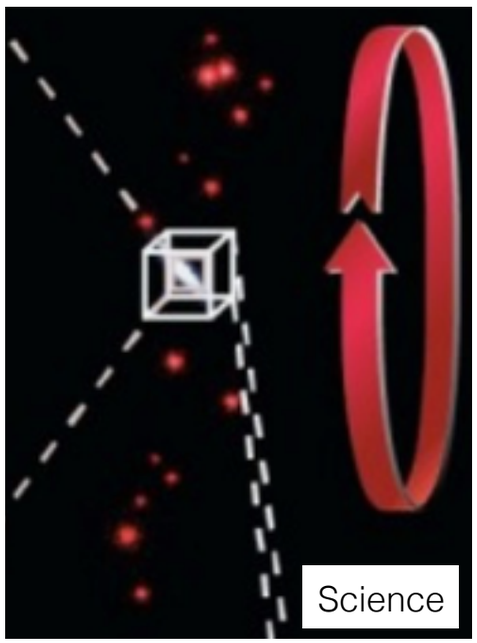

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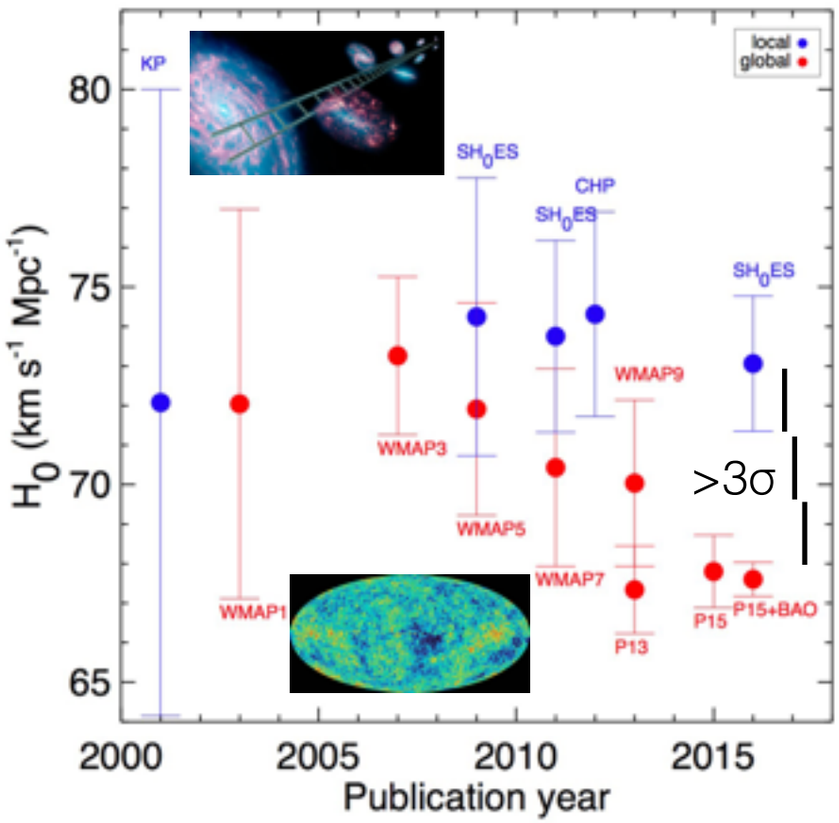

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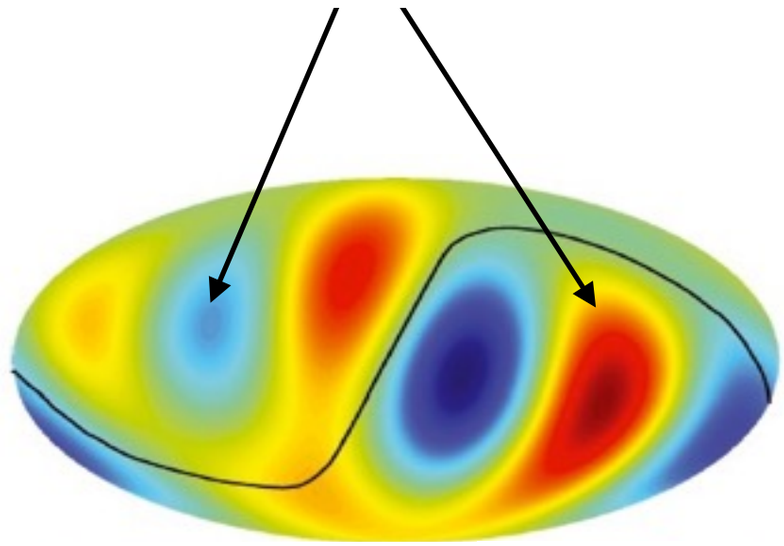

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ΛCDM questioned? Precision cosmology

More examples…

Small scales

local void emptier
with larger galaxies

Simulated

Observed

local scales

local / global cosmological
parameter values

Planck SZ / CMB

σ_8: 0.77±0.02 / 0.834±0.027

Ω_m: 0.29±0.02 / 0.314±0.020

Large scales

CMB

Lack of angular correlation
at large angles

Even more examples: local correlations slope and scatter, missing satellites, cold spot, etc

ΛCDM questioned? ➤ Precision cosmology

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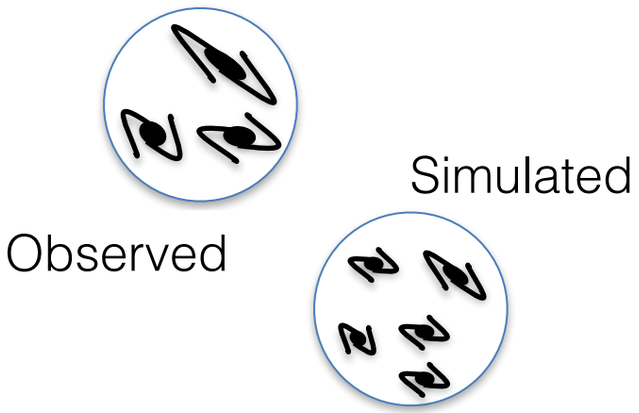

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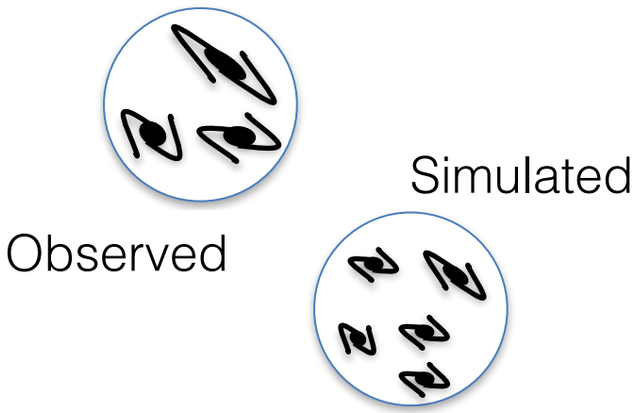

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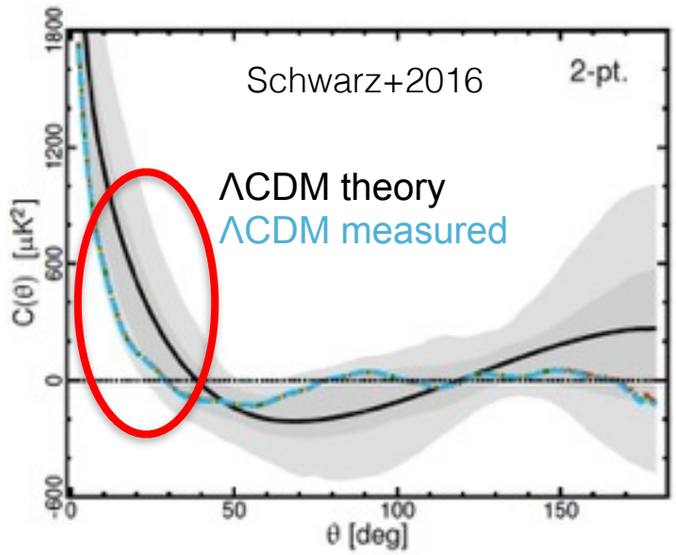


Lack of angular correlation at large angles

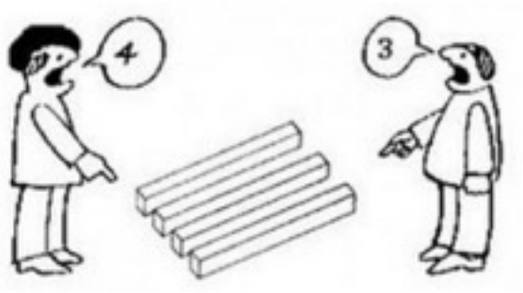
Even more examples: local correlations slope and scatter, missing satellites, cold spot, etc

Questions?

Small scales

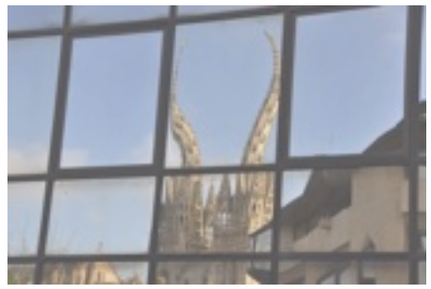
Are we comparing apple to apple?

local scales



Are we a neutral observer?

Large scales



What about a foreground effect?

Local-induced biases

How can our local environment bias our ‘’perception’’ at the 1-2% level preventing us from reaching 1-2% precision?

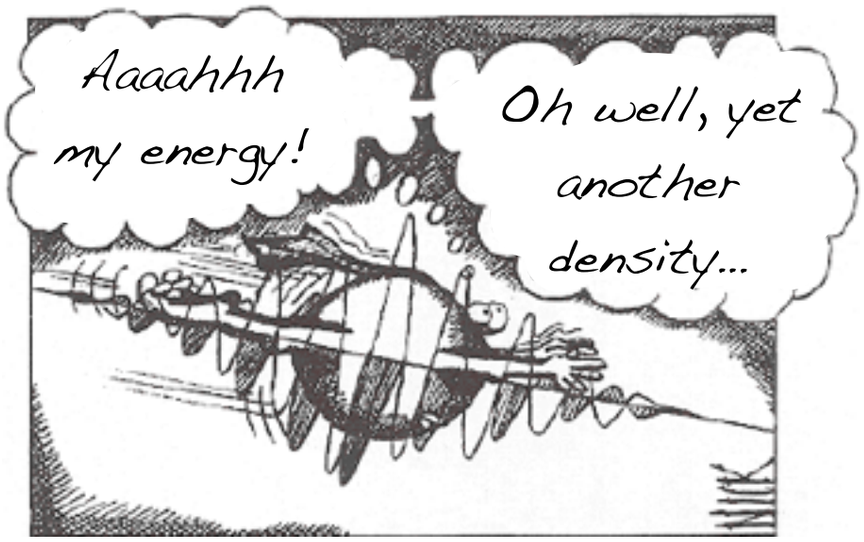
Small scales

Clear… correlation with environment

local scales

A neutral environment?
Very unlikely…

Large scales



Photons travel a lot before reaching us…

and eventually this can decrease *or increase* tensions with ΛCDM !

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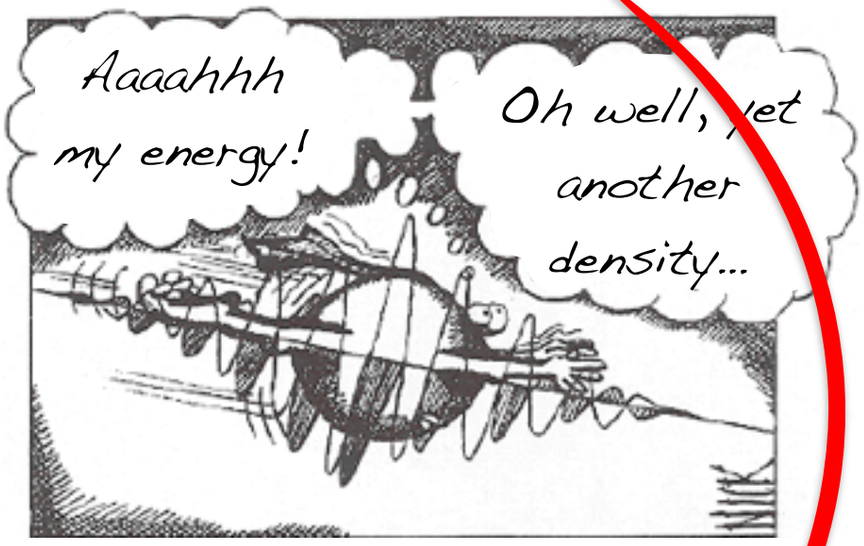

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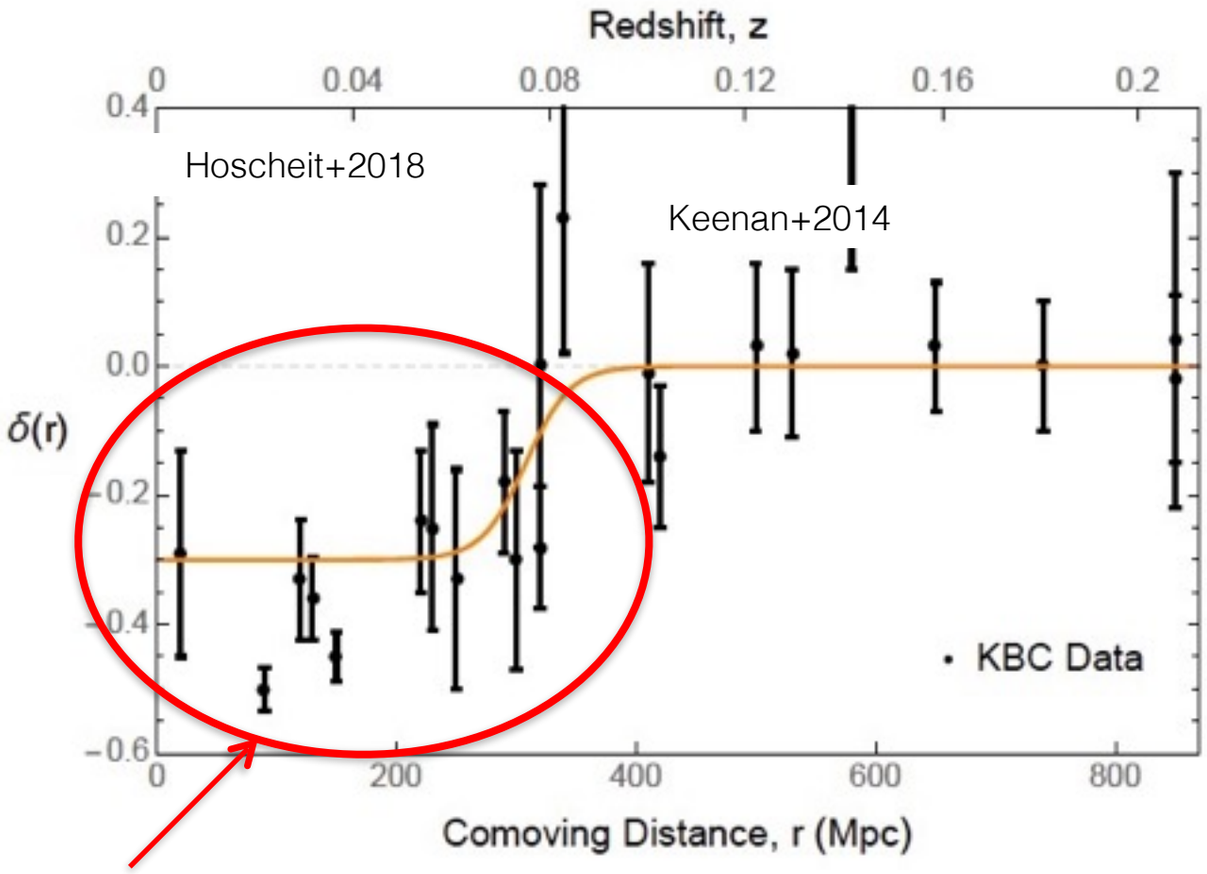
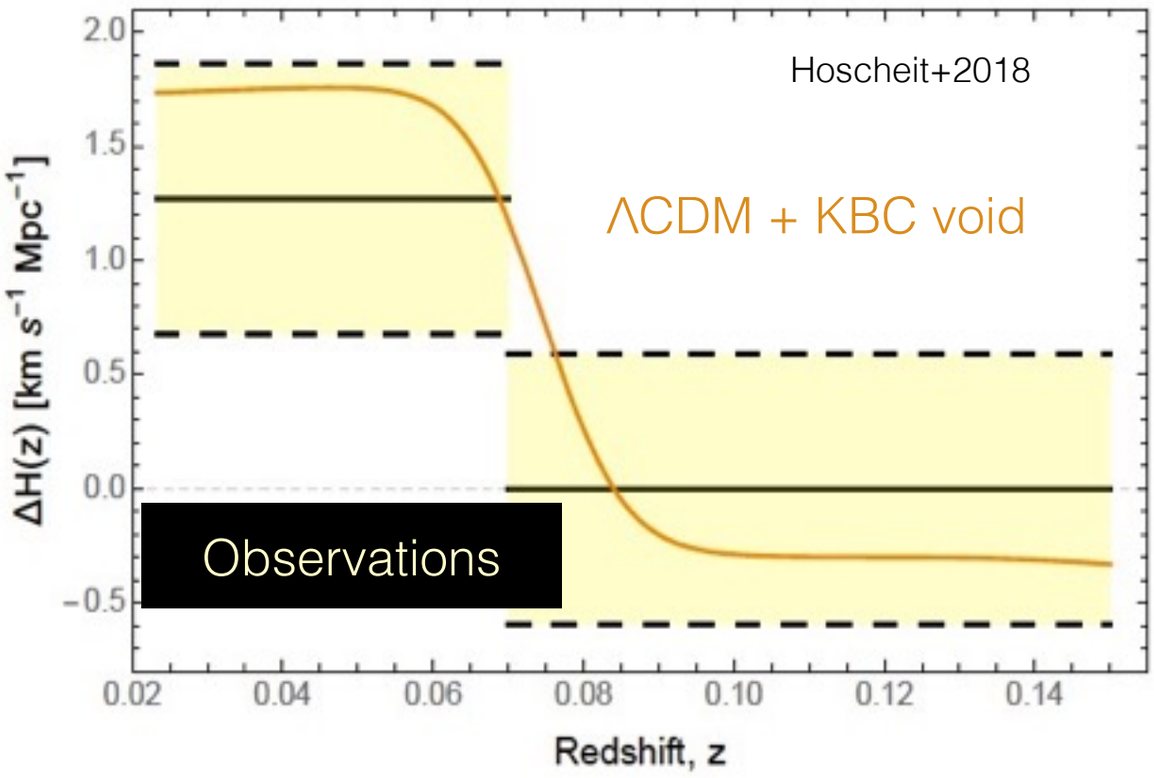
and eventually this can decrease *or increase* tensions with ΛCDM !

Local-induced biases on the local scales

A simple example: we live in a spherical underdensity

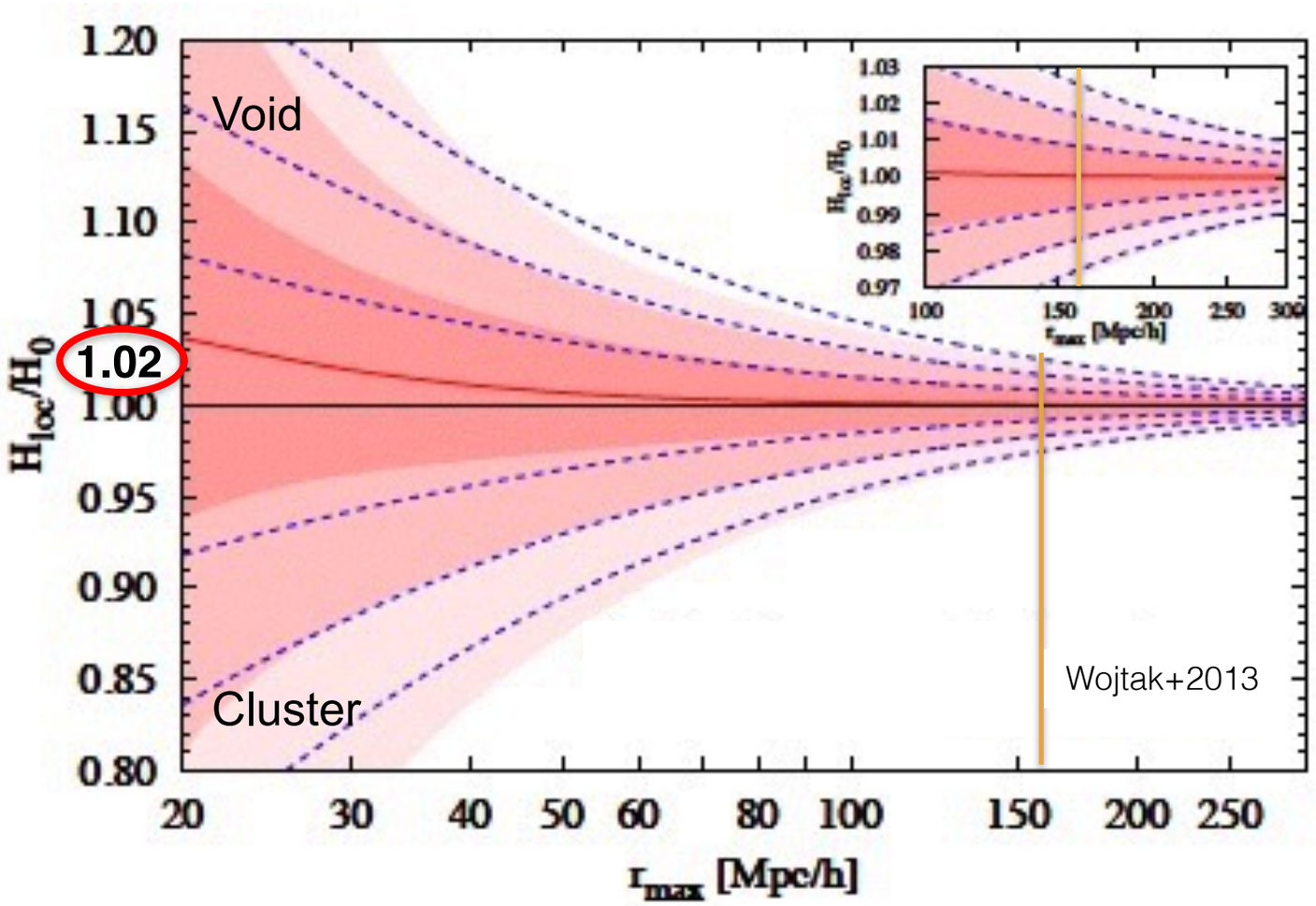


An example: Hint at a local underdensity up to z=0.07



Local-induced biases → on the local scales

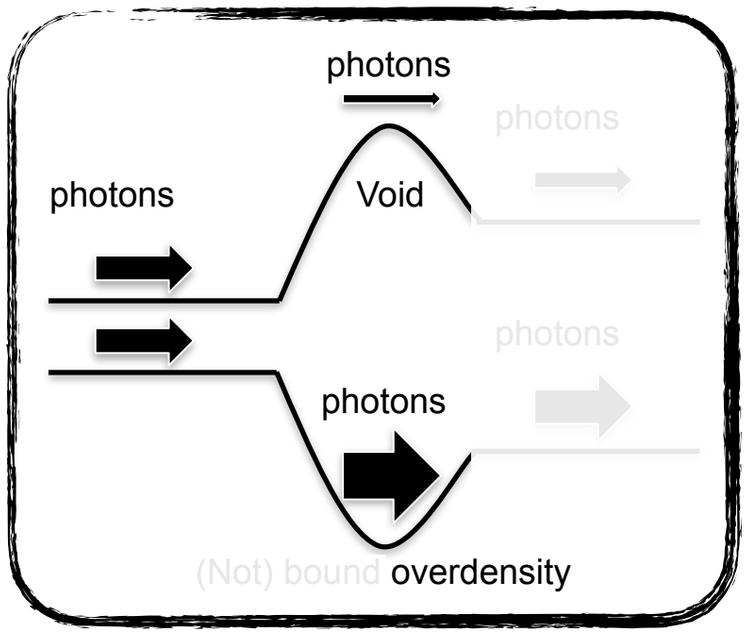
As many effect values as environments



For an average environment: a 2% bias !

Local-induced biases on the large scales

Gravitational redshifts and the large scale surveys



As many effect values as environments

Value: [10^{-5} - 10^{-4}]

For an average environment: a 1-2% bias !

Local-induced biases on the large scales

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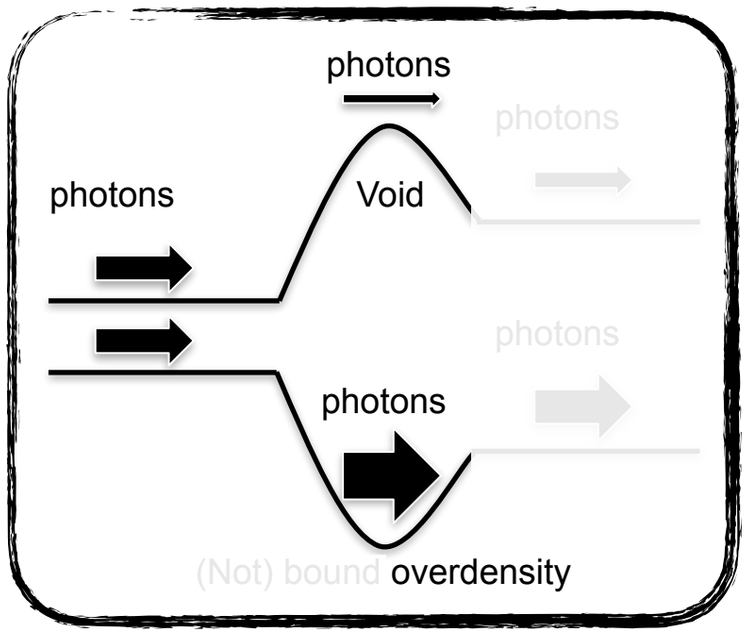

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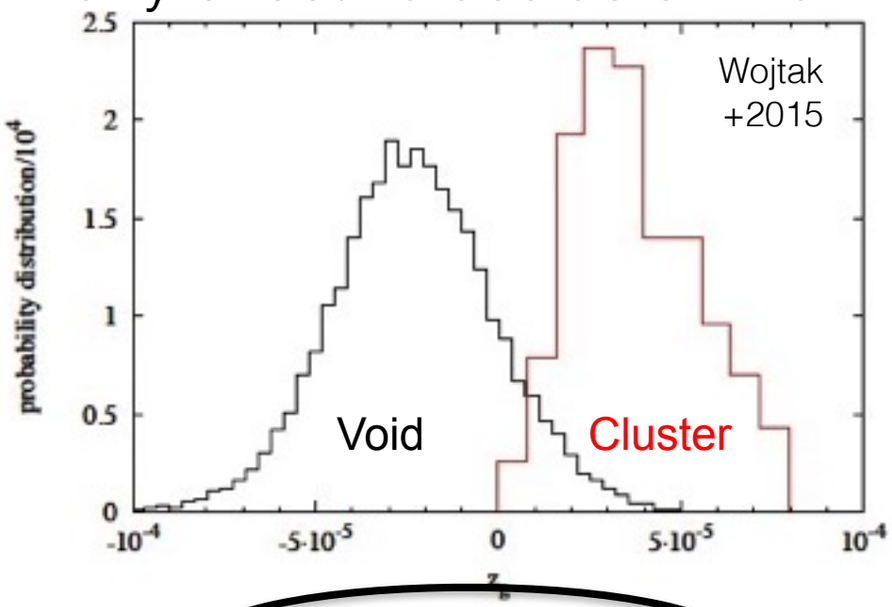

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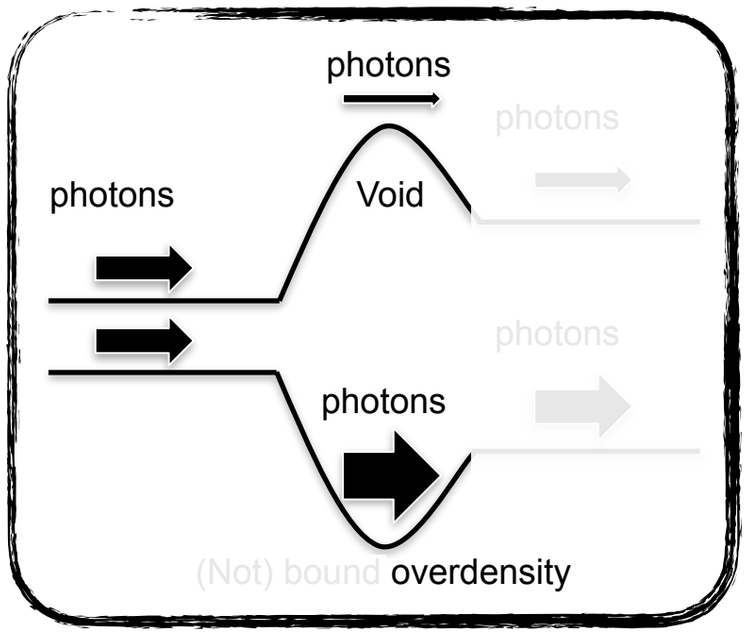

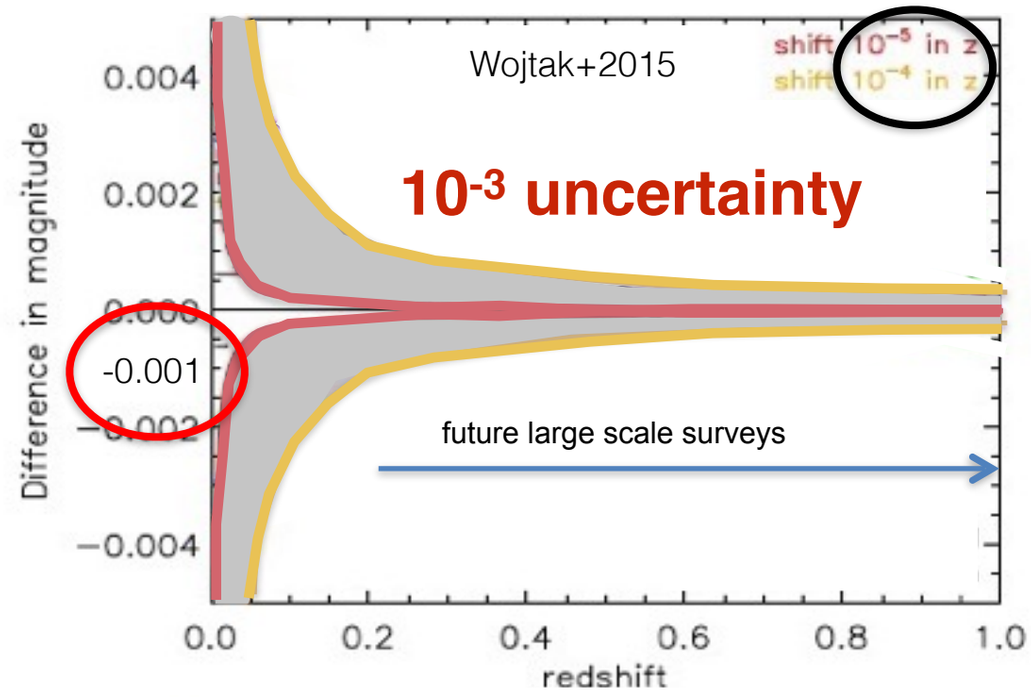

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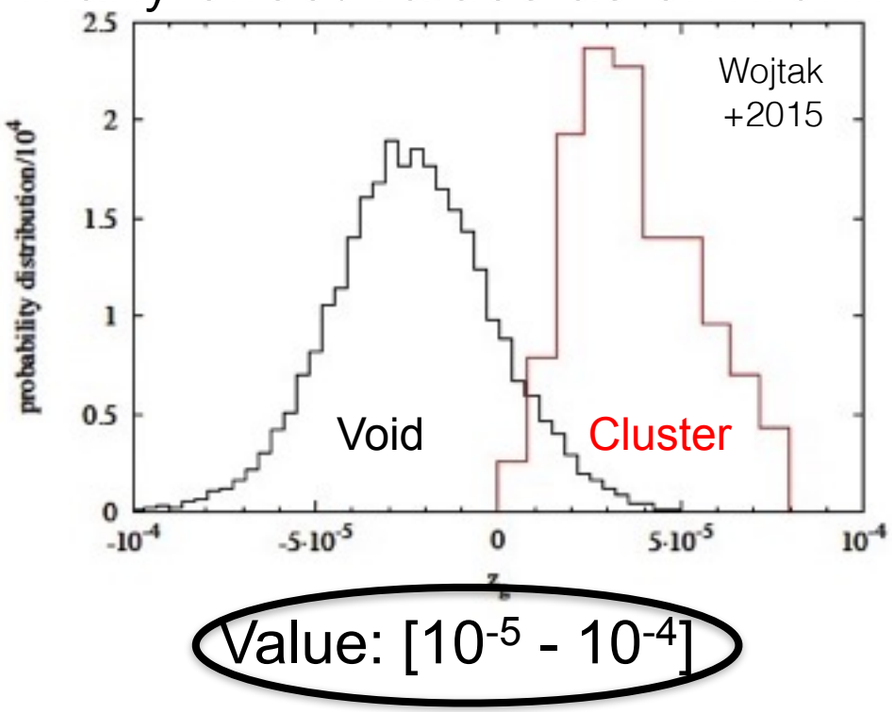

Value: [10^{-5} - 10^{-4}]

Required Precision !

For an average environment: a 1-2% bias !

Local-induced biases on the large scales

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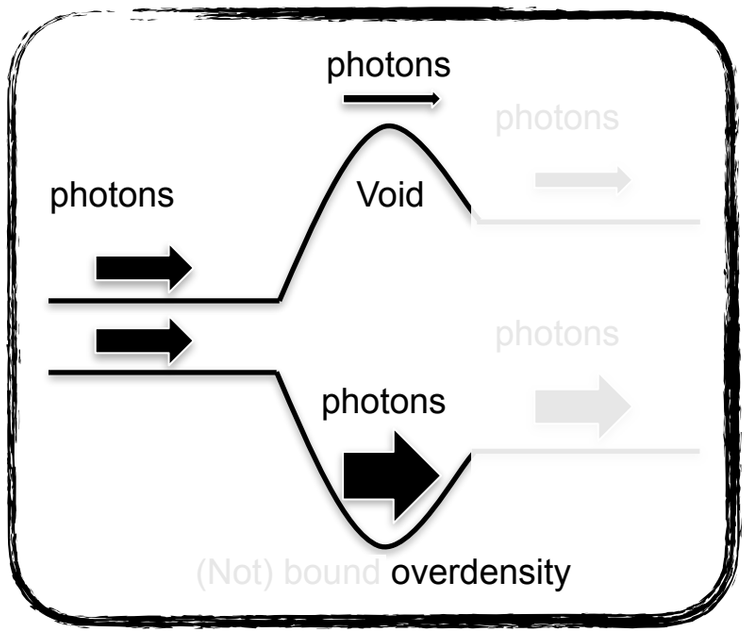

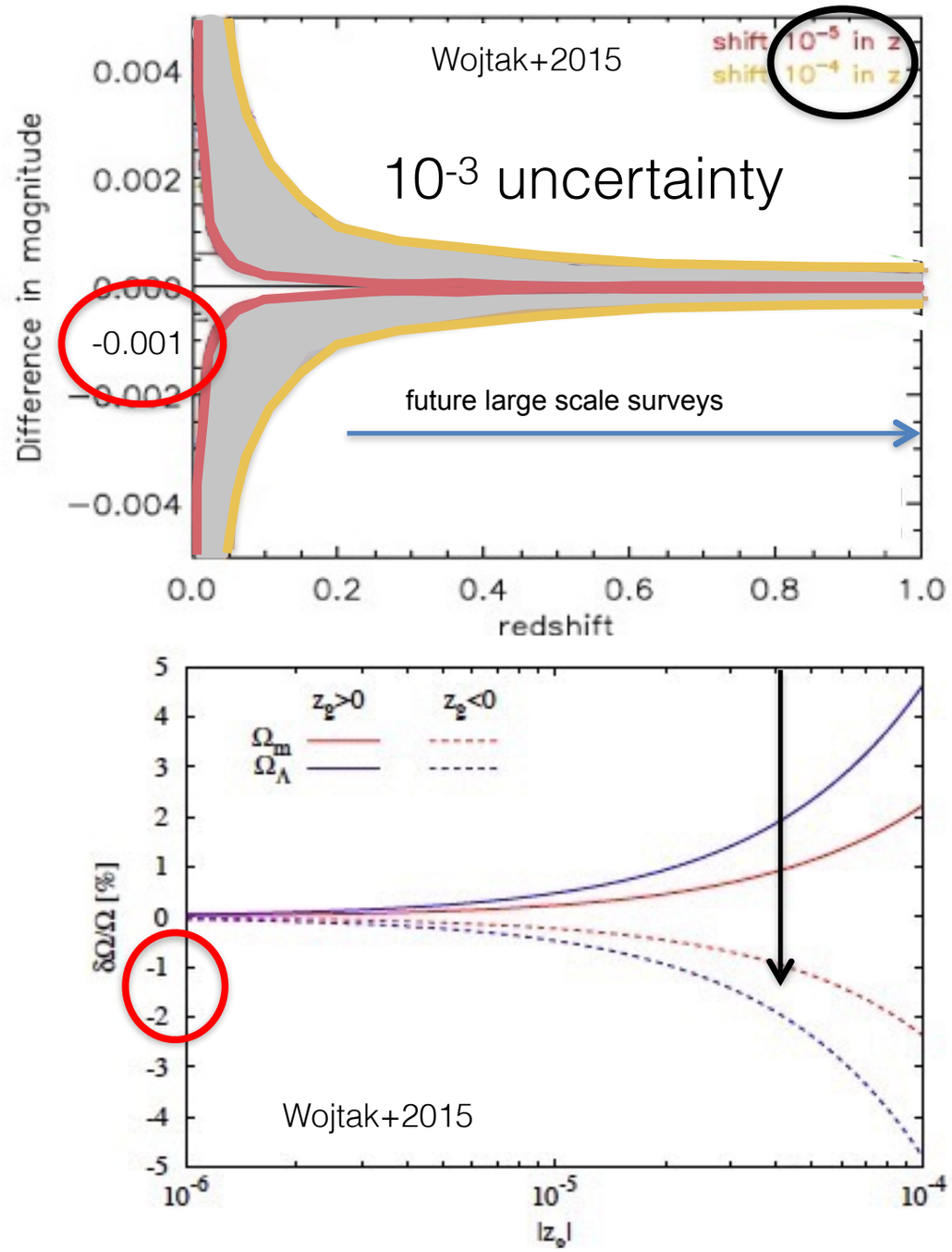

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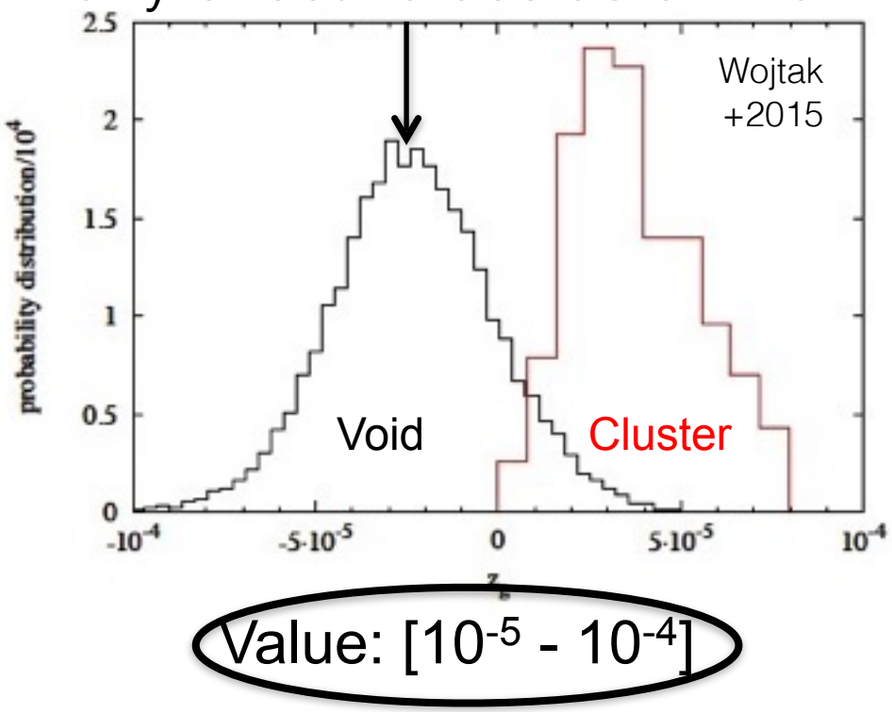

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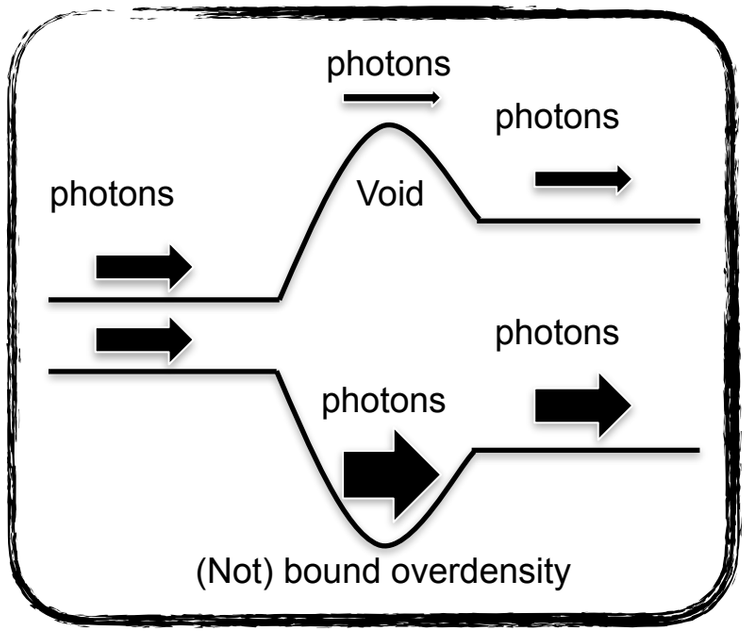
For an average environment: a 1-2% bias !

Local-induced biases on the large scales

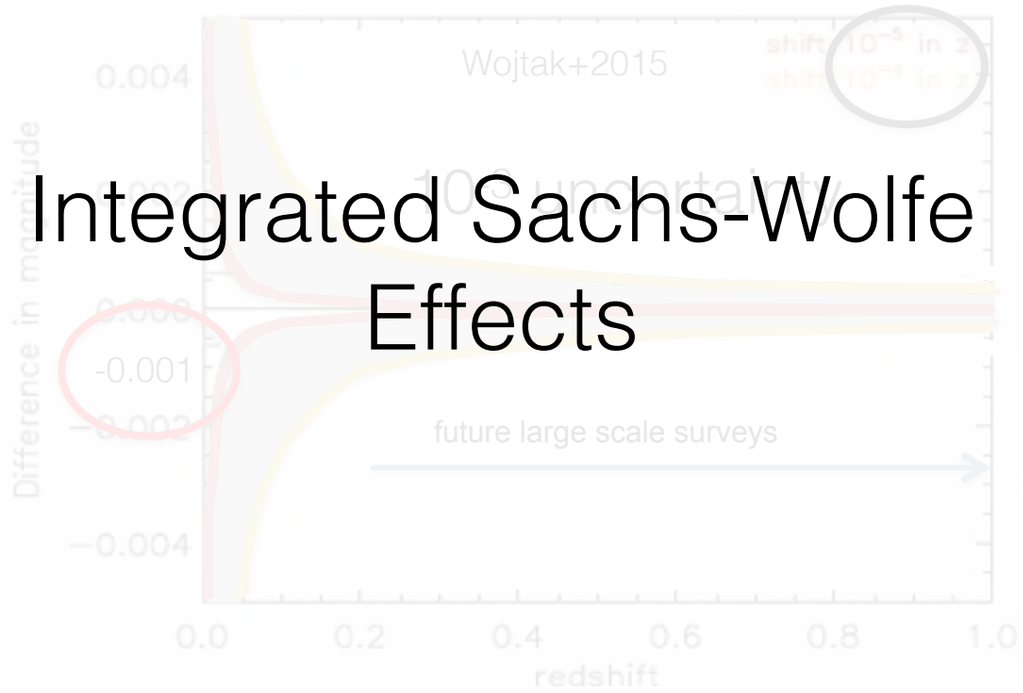
Gravitational redshifts and the large scale surveys



Integrated Sachs-Wolfe Effects

As many effect values as environments

Value: $[10^{-5} - 10^{-4}]$

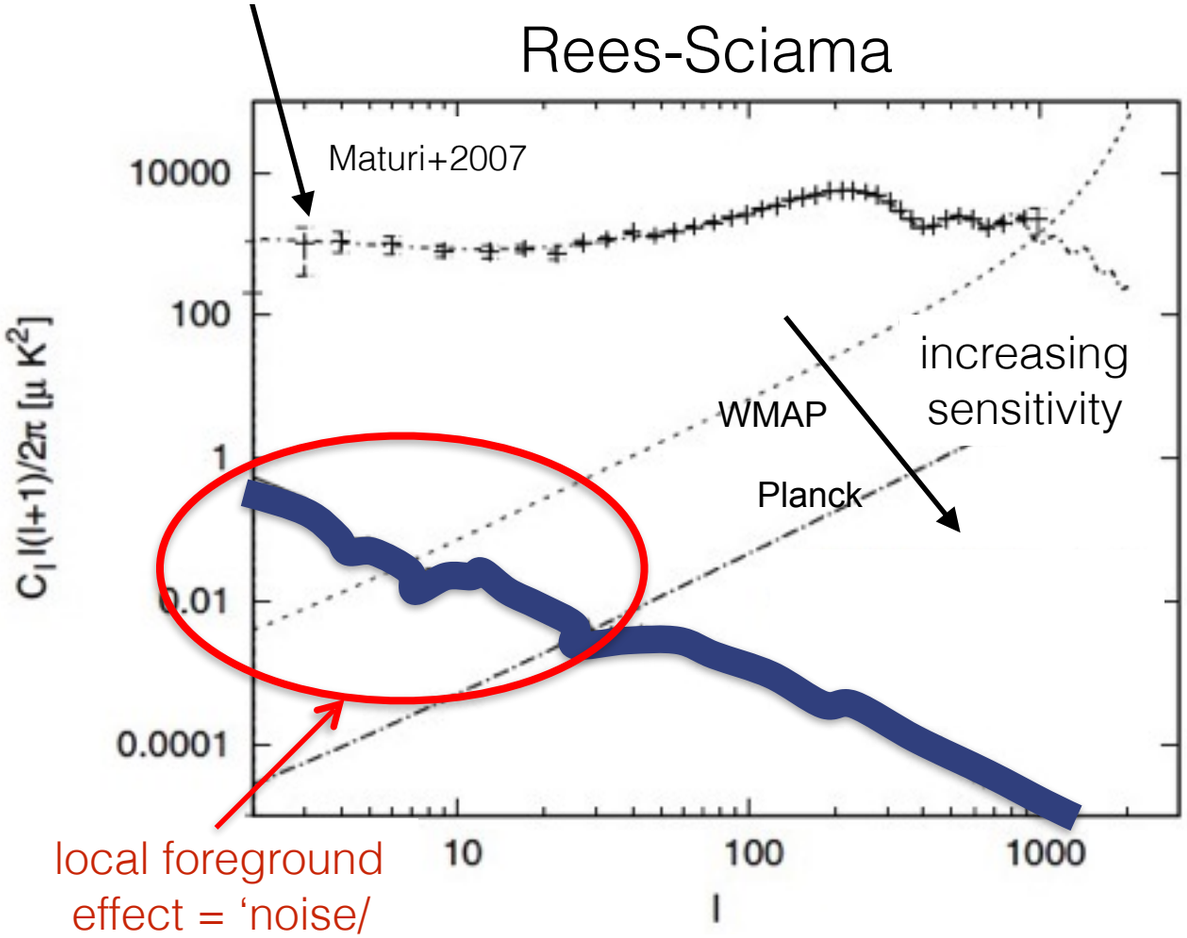


For an average environment: a 1-2% bias !

Local-induced biases on the large scales

Gravitational redshift, Sunyaev Zel'dovich and the CMB

increasing precision
= reducing error bars



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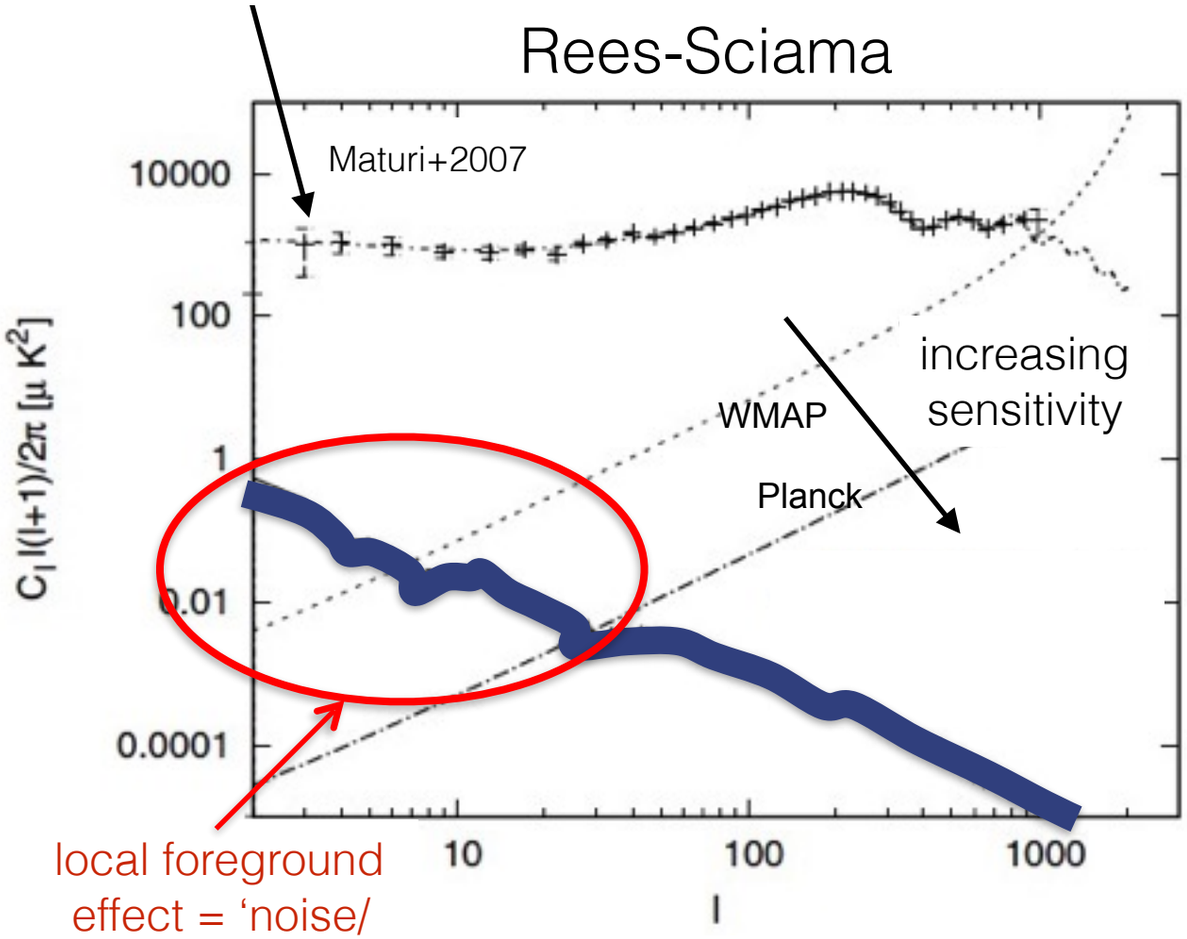
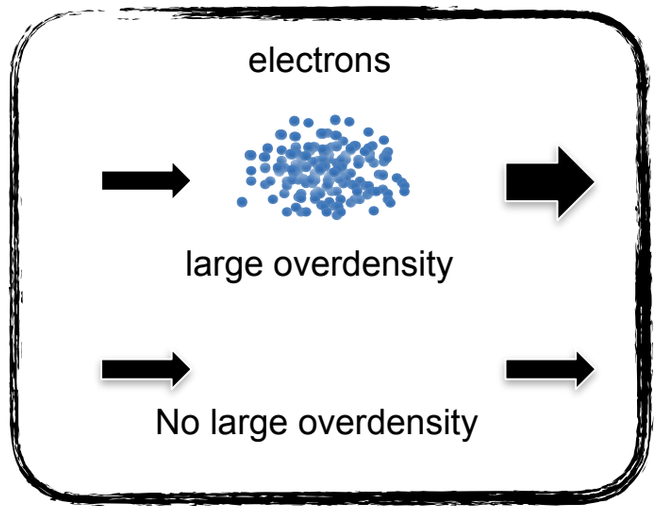
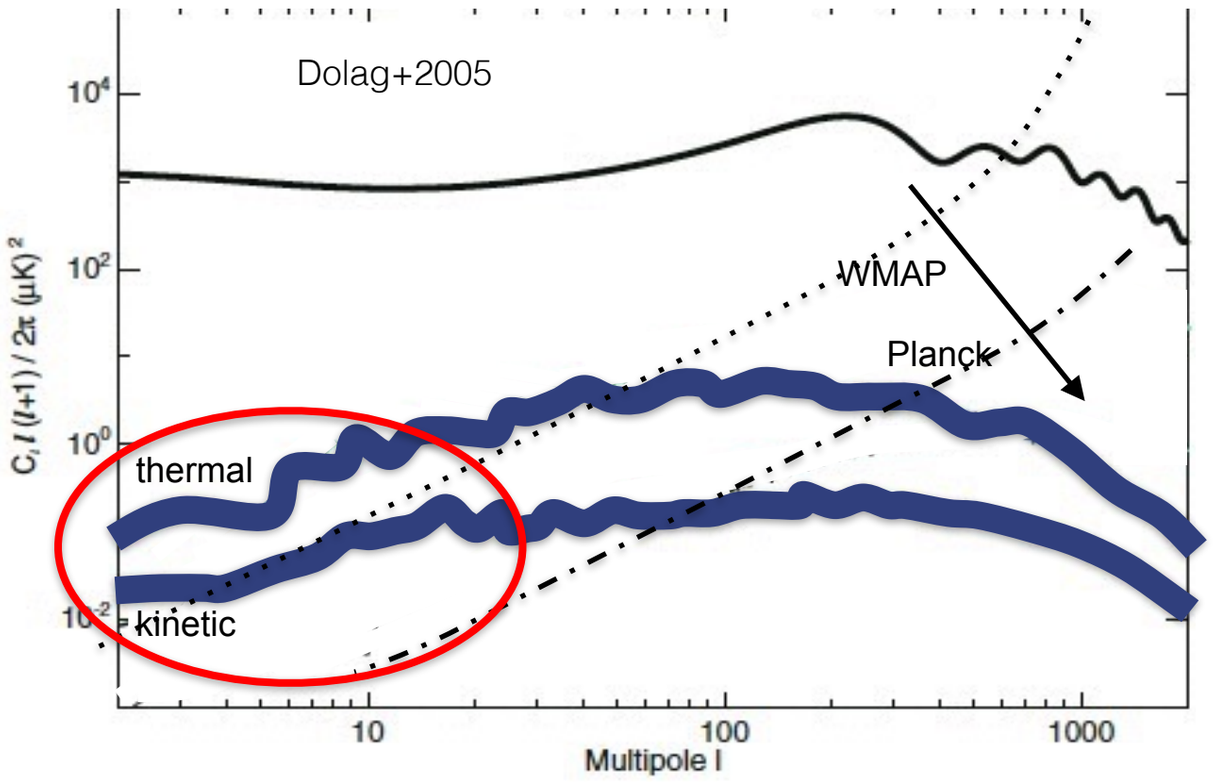
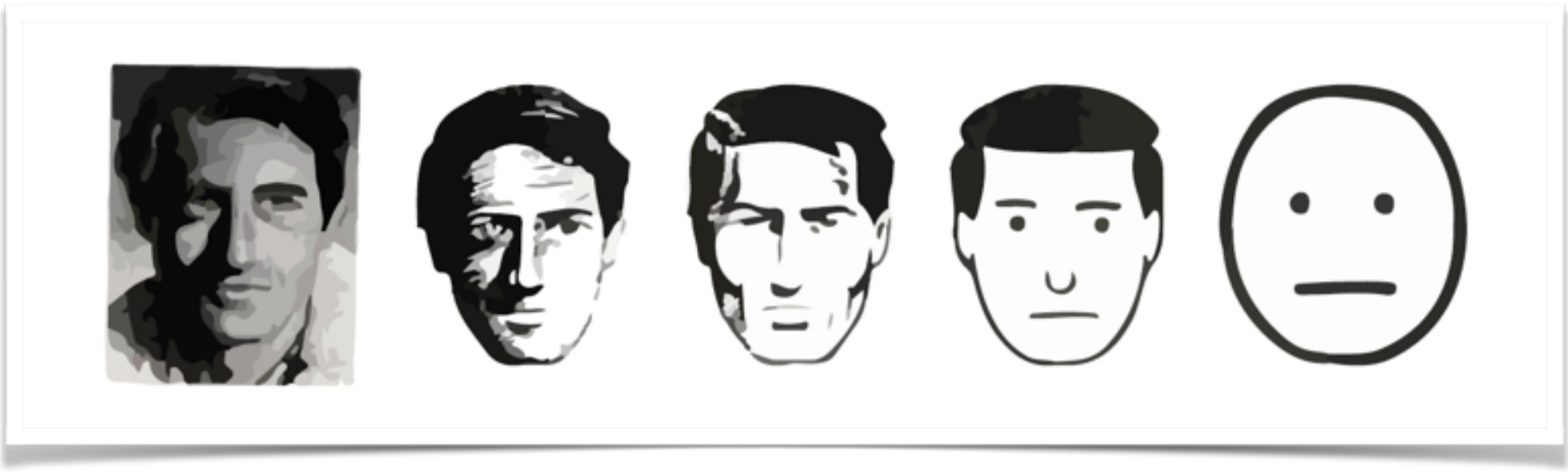


local foreground effect = 'noise/ bias'





A crude modeling is a beginning…

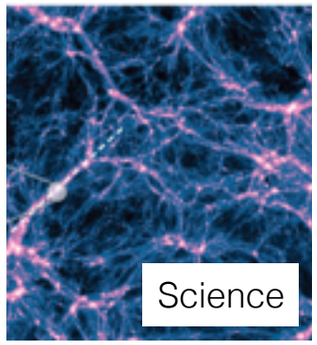


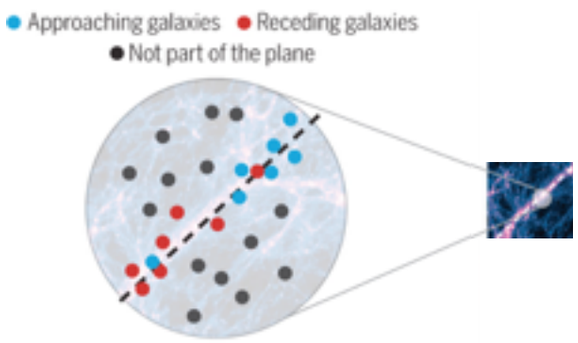
but not nearly enough…

Accounting for the effects ▶ crude modeling

A few examples

Small scales





Do we live in a filament that reproduces exactly that thin plane?

Local scales

In what kind of density do we live exactly?

Large scales

broken North/South asymmetry

Francis+2010

But correction from redshift surveys only…

Accounting for the effects ➤ crude modeling

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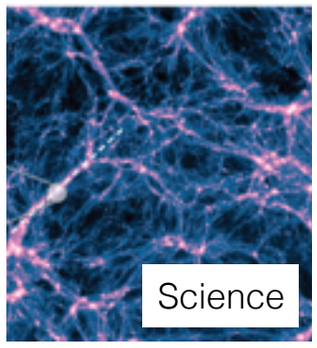
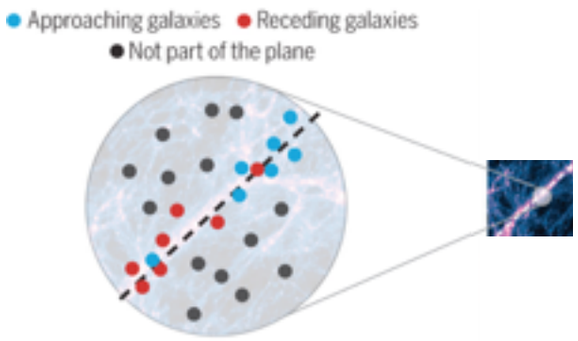
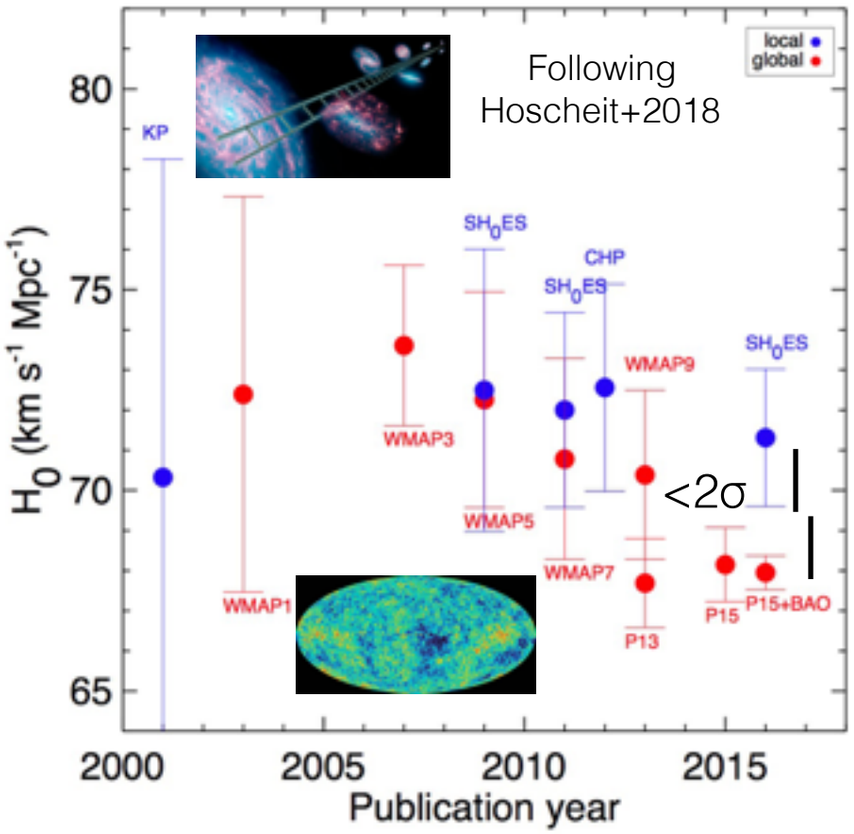




Do we live in a filament that reproduces exactly that thin plane?

Local scales



In what kind of density do we live exactly?

Large scales

broken North/South asymmetry

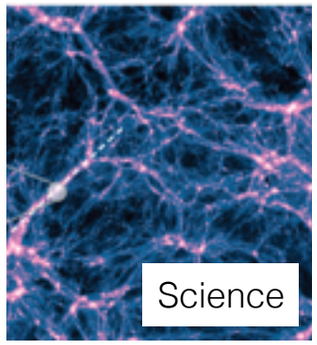
Francis+2010

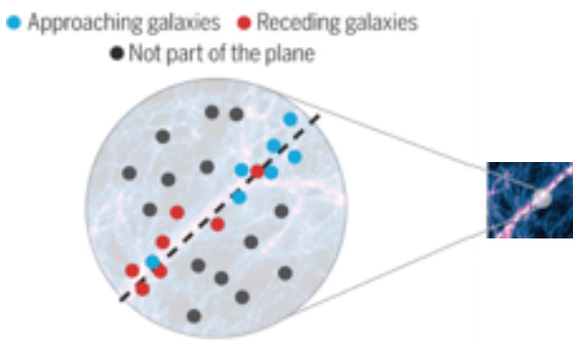
But correction from redshift surveys only…

Accounting for the effects ➤ crude modeling

A few examples

Small scales





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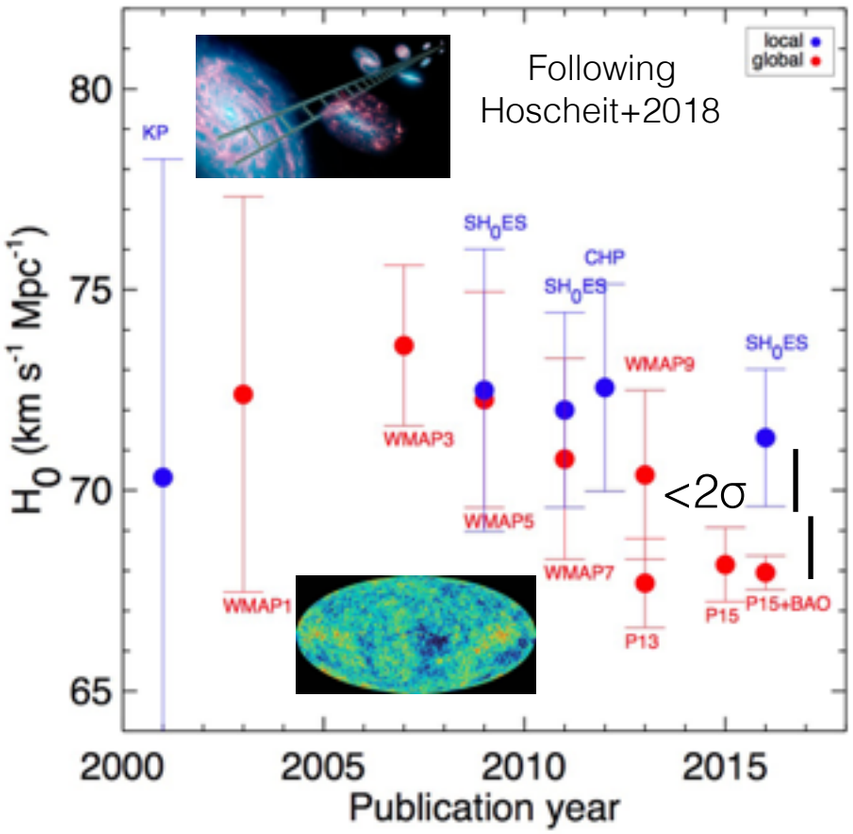
Local scales



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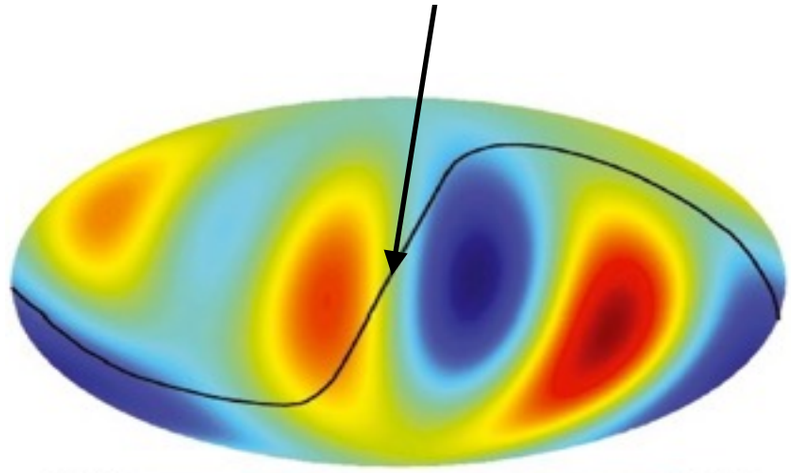

Francis+2010

But correction from redshift surveys only…

Importance of our local environment !

We need a very acute knowledge of the total *local* distribution of matter (map)

to reach an accurate precision cosmology:

- **on the small scale: compare apple to apple**
- **on the local scale: become a neutral observer**
- **on the large scale: correct for foreground effects**

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Observations

to reach an accurate precision cosmology:

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Observations — **Simulations**

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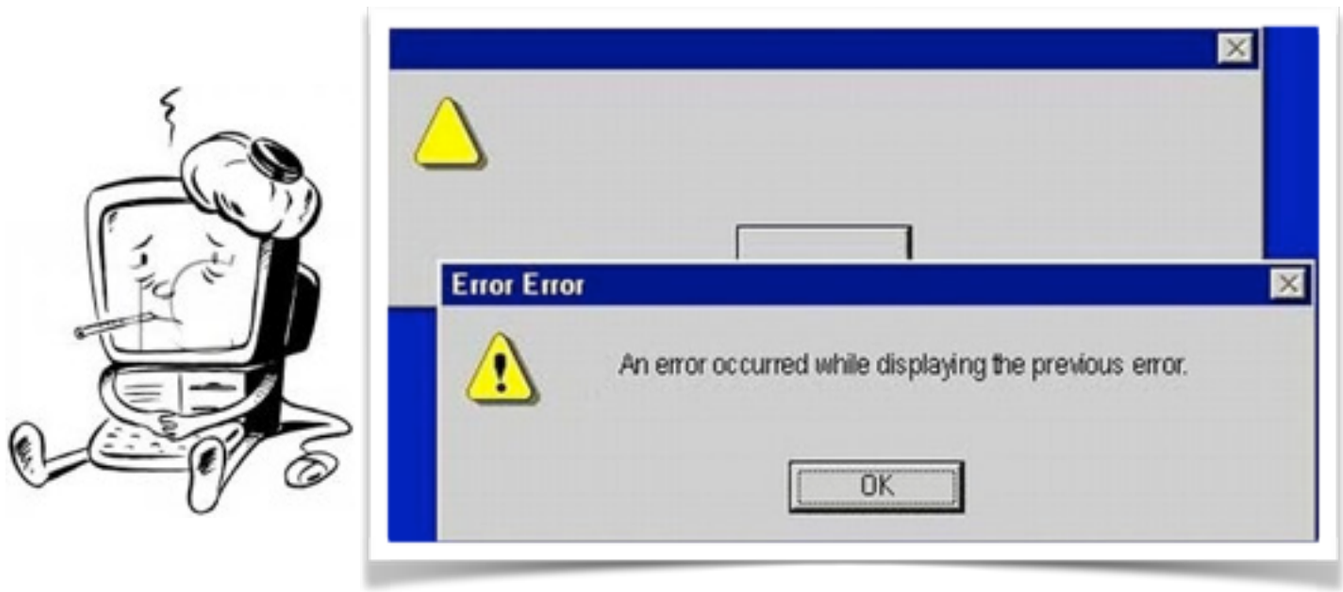
→ **Initial conditions of the local Universe**

Obtaining the initial conditions of the local Universe



Local Universe's initial conditions → constrained initial conditions

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 [illegible] effective for generating initial conditions for *N*-body simulations with rare objects in the computational volume

Bayes1761 Wiener1942 Hoffman & Ribak 1991 Zaroubi+1995 van der Weijgaert & Bertshinger 1996

Constraints / Work	Redshift surveys	peculiar velocities + density	peculiar velocities
Kitaura2008,2012, 2013 Hess+2013	☑		
Lavaux2010, Jasche+2013-tdy	☑		
Wang+2014-tdy	☑		
Klypin+2003		☑	
Sorce+2014-tdy			☑

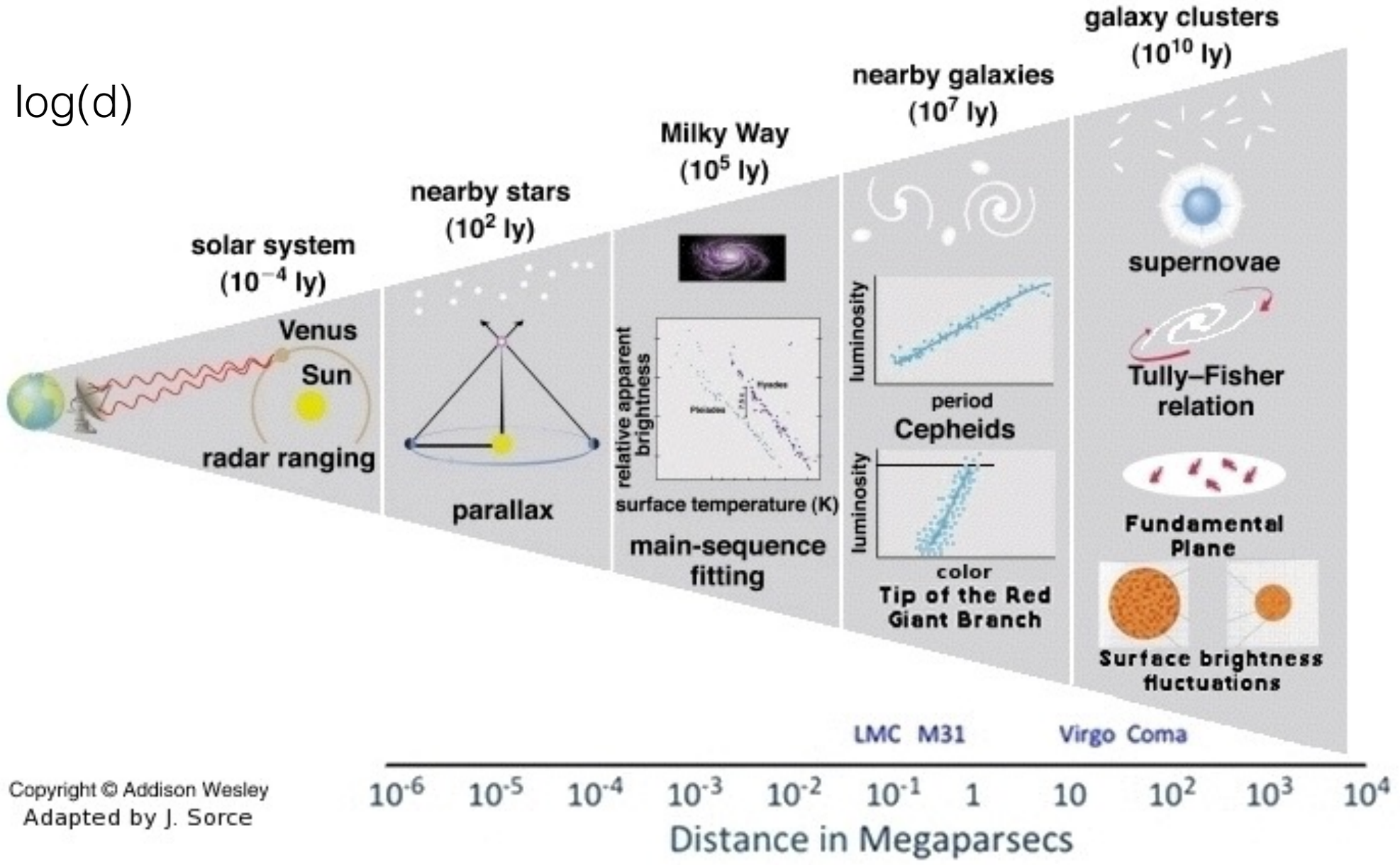
no luminosity bias

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

Peculiar velocities

direct distance measurements

m-M ∝ log(d)



Peculiar velocities

direct distance measurements

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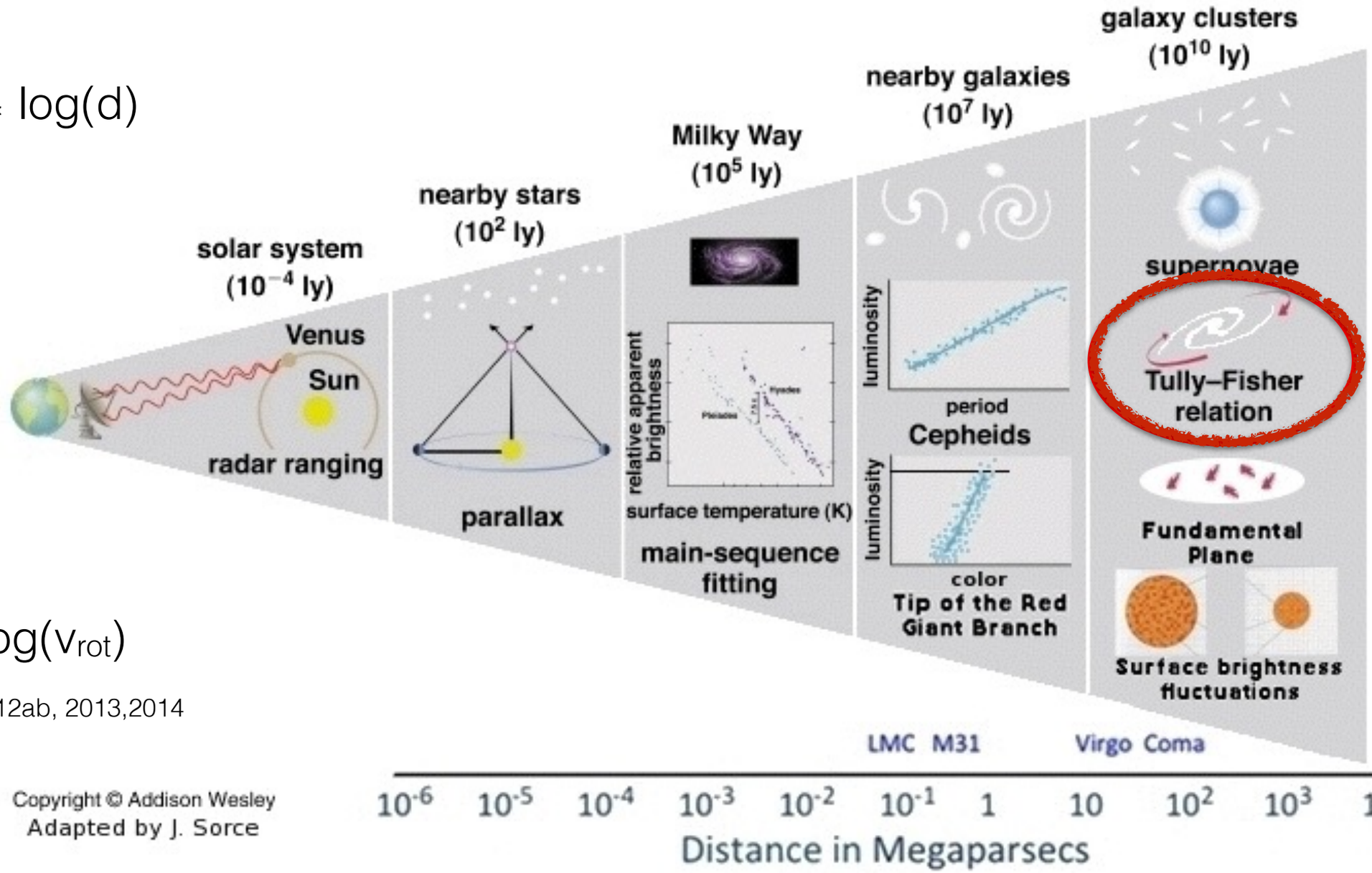
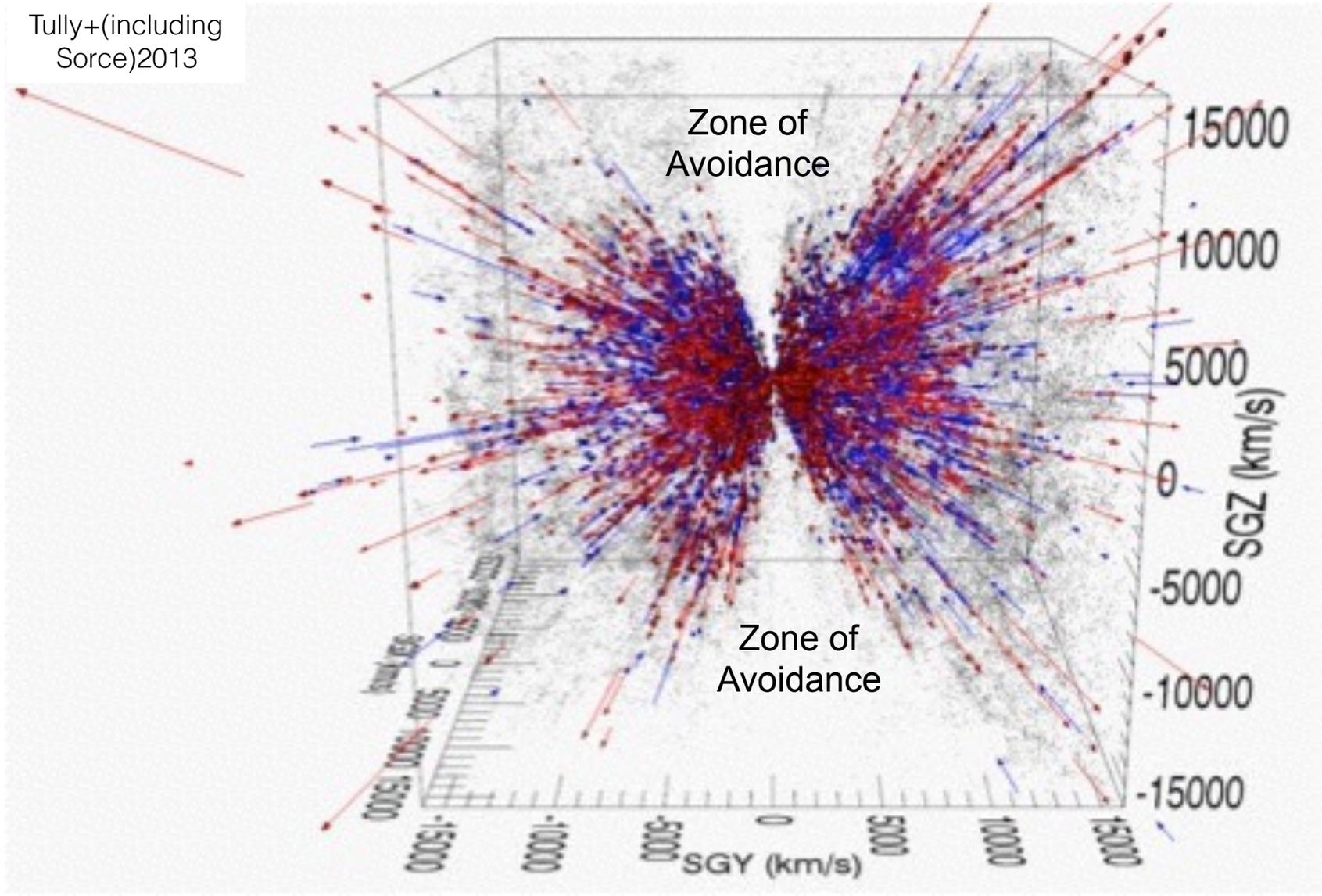


M ∝ log(v_{rot})

e.g. Sorce+2012ab, 2013,2014

Peculiar velocities catalog

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



- Account for the entire underlying gravitational field
- Correlated on large scale
- Highly linear

Method

Radial peculiar velocity catalog

Grouping

Minimization of biases

Wiener filtering

Reverse Zel'dovich Approximation

Constrained realization

Constrained initial conditions

Sorce & Tempel 2017,2018

Sorce 2015, 2018

Doumler+2013 Sorce+2014

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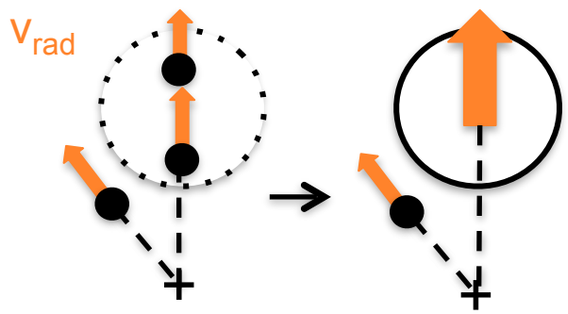

Distance (modulus) of the group and its uncertainty

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

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

Peculiar velocity of the group and its uncertainty

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

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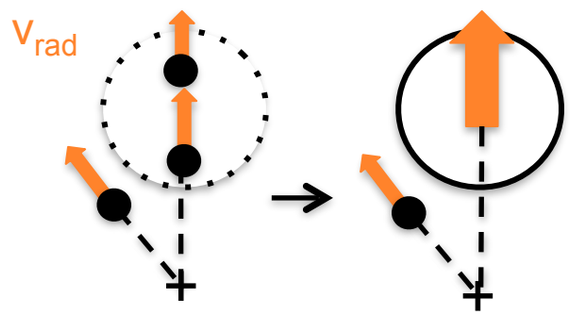

Distance (modulus) of the group and it ertainty

$$\mu_g = \frac{\sum w \times \mu}{\sum w} \; ; \; \sigma_{\mu g} = \sqrt{\quad}$$

$$d_g = 10^{\frac{\mu}{5}}$$

The biggest difficulty is to determine the groups !

Pec .ie group and its uncertainty

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

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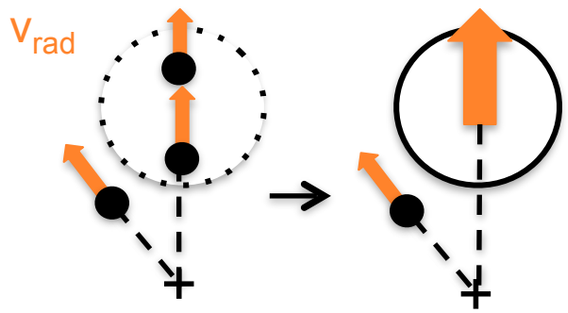
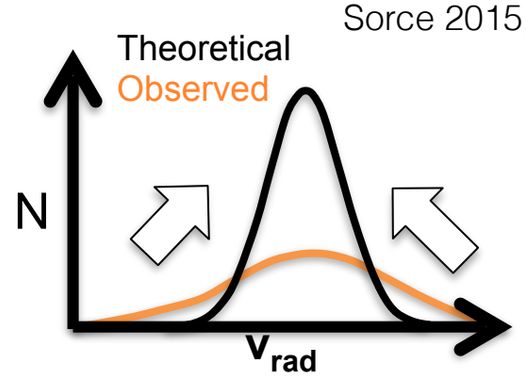
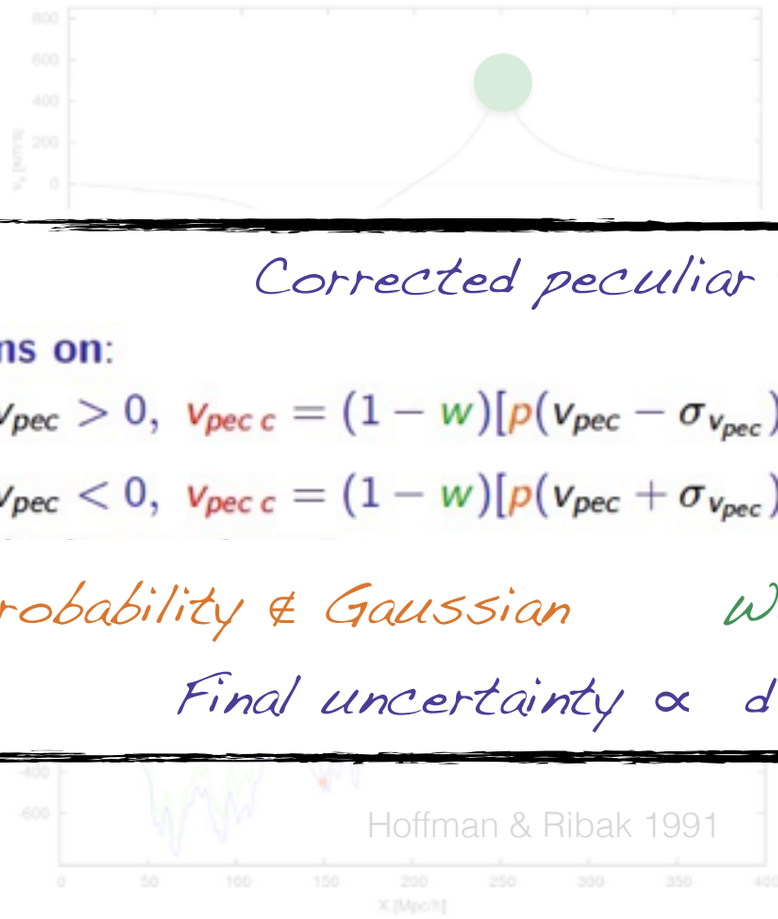


Sorce 2015, 2018





Corrected peculiar velocities

Iterations on:

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

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

Probability & Gaussian *Weighted uncertainty*

Final uncertainty $\propto$ *d &* $n_{constraints}$

Method

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↓

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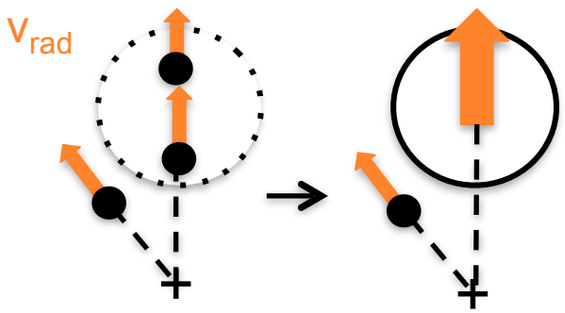
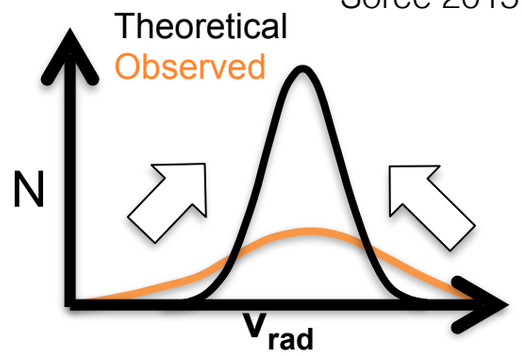
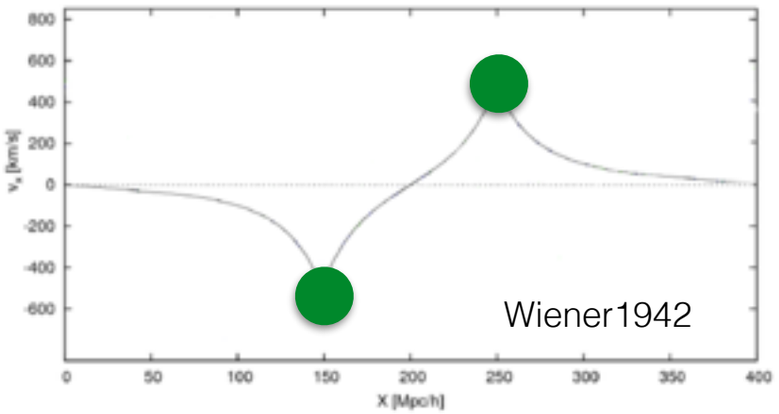
Sorce & Tempel 2017,2018



Sorce 2015, 2018





Doumler+2013 Sorce+2014

Linear minimum variance estimator

Model *Data = constraints*

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

Correlation functions

Method

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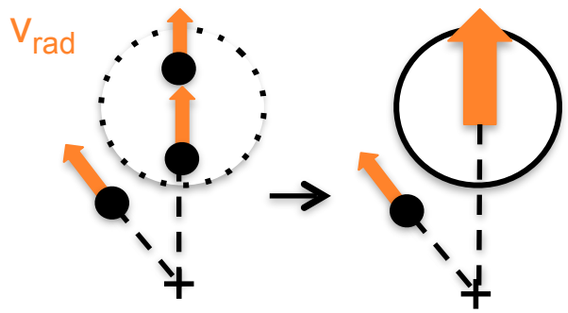
Sorce & Tempel 2017,2018



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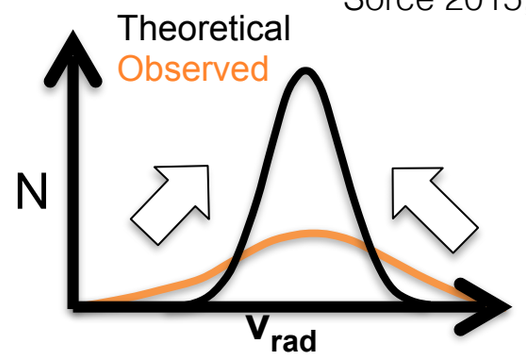

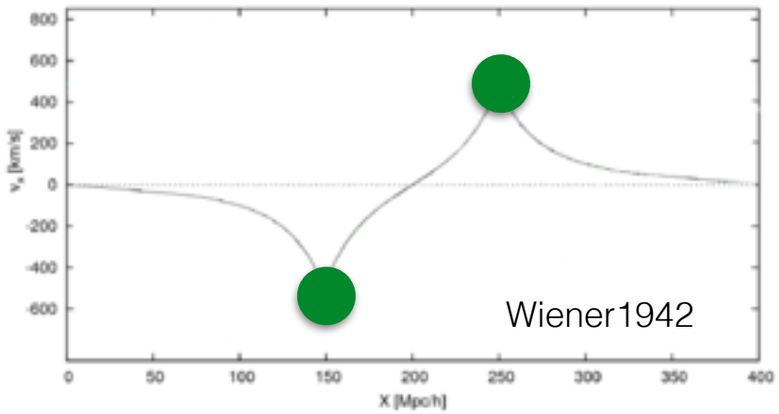

Doumler+2013 Sorce+2014

power spectrum

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

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

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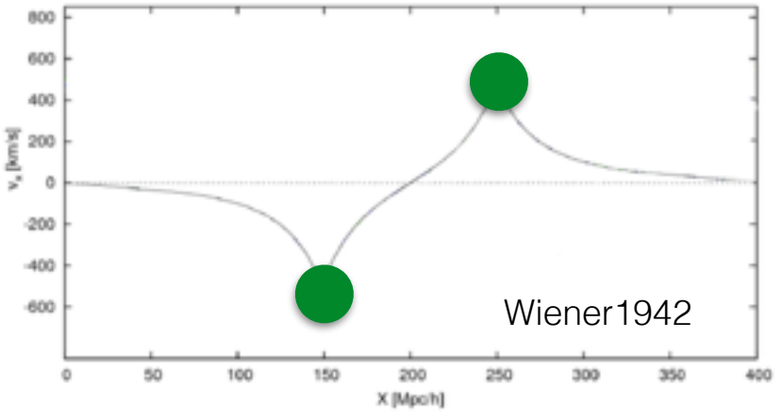
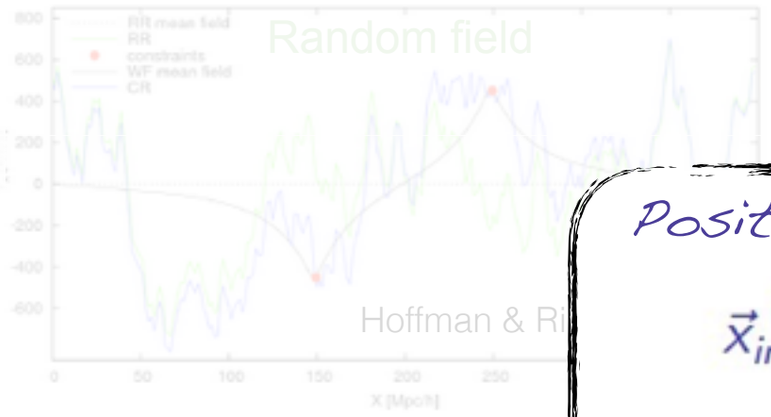
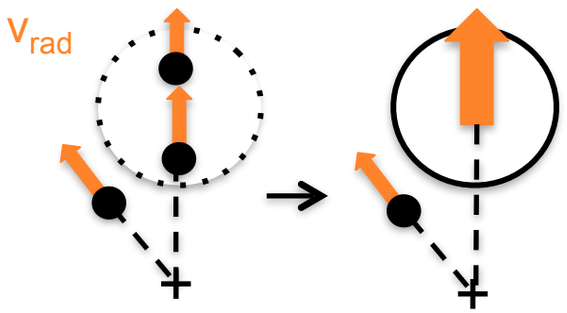




Sorce & Tempel 2017,2018



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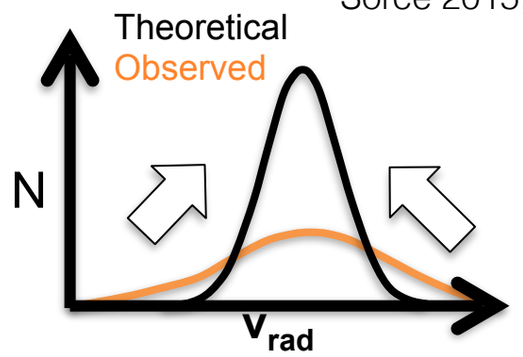

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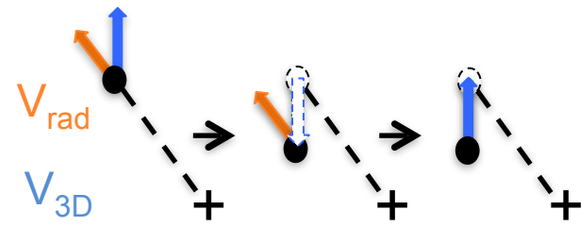

Position of the progenitors

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

growth rate

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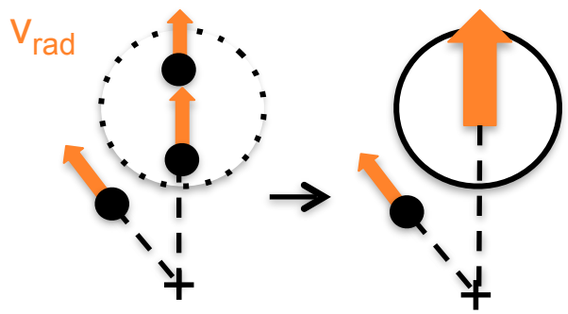
Sorce & Tempel 2017,2018

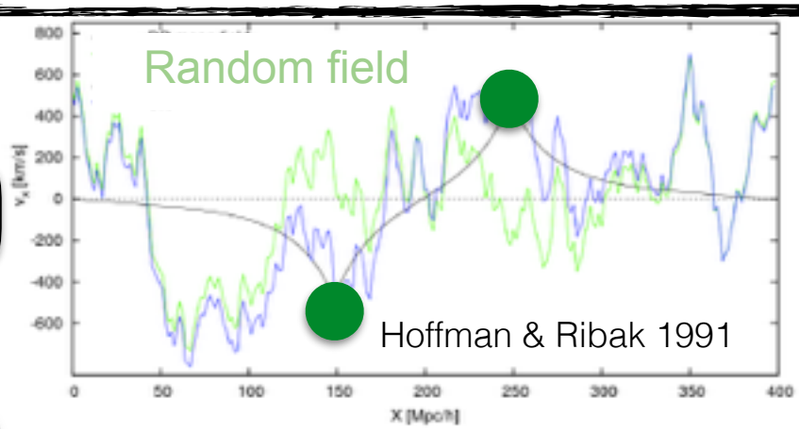


Constrained Realization: Estimate of the residual

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

Correlation functions depend only on the model

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



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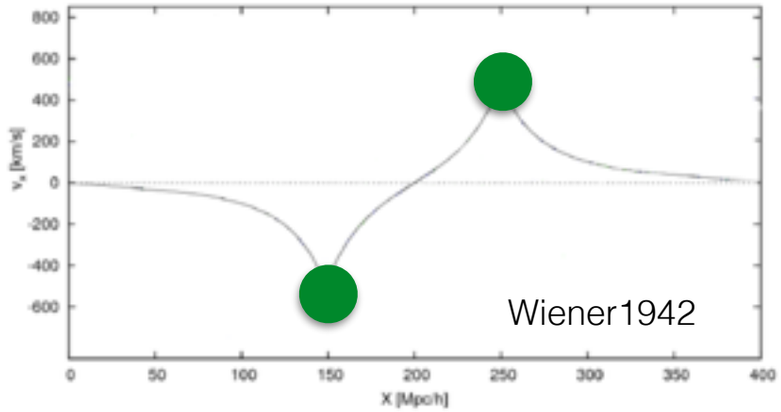
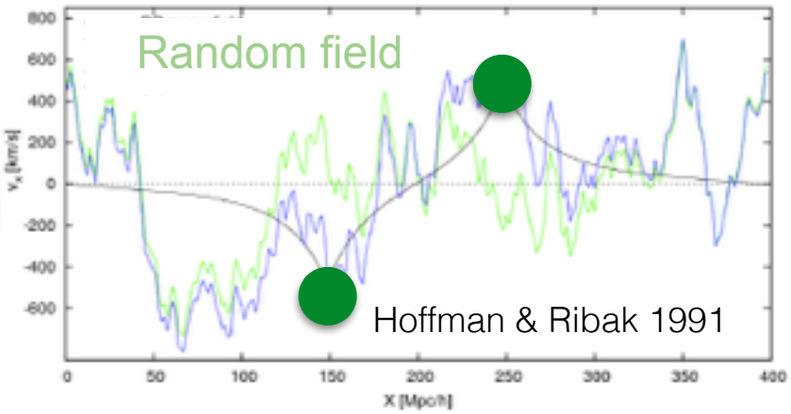
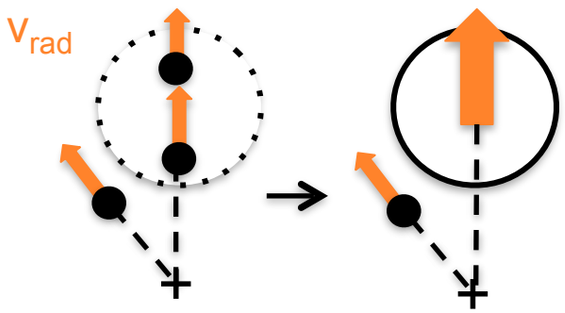




Sorce & Tempel 2017,2018



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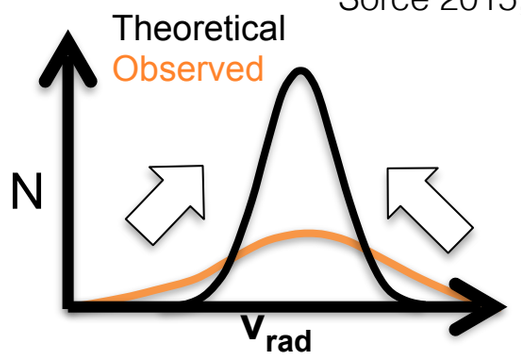

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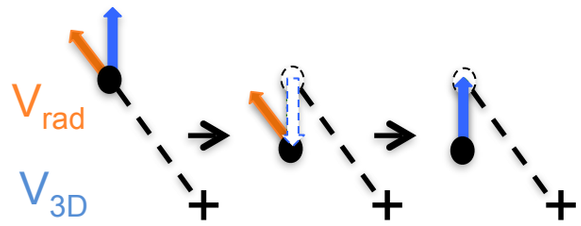
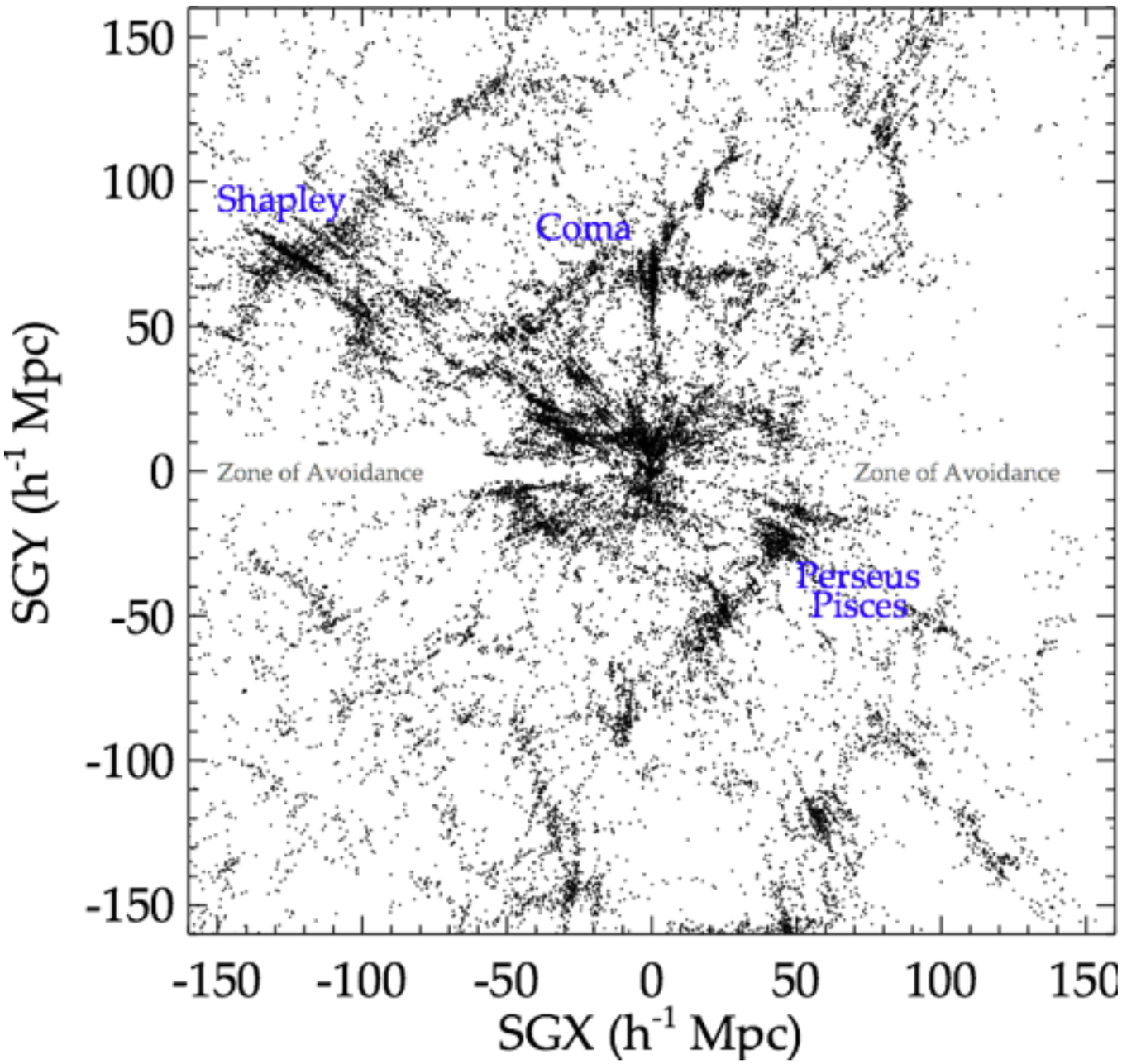


A non-linear map of the local Universe

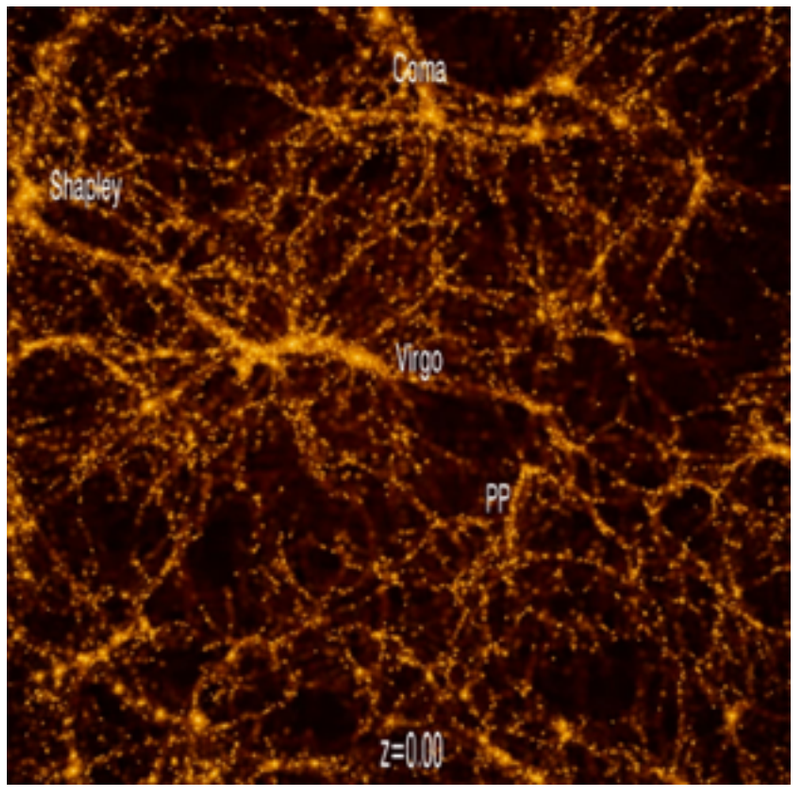
Using the same folding techniques as road maps greatly delayed the gene mapping research.

Results: the local large scale

z=0, large scale Sorce+2016



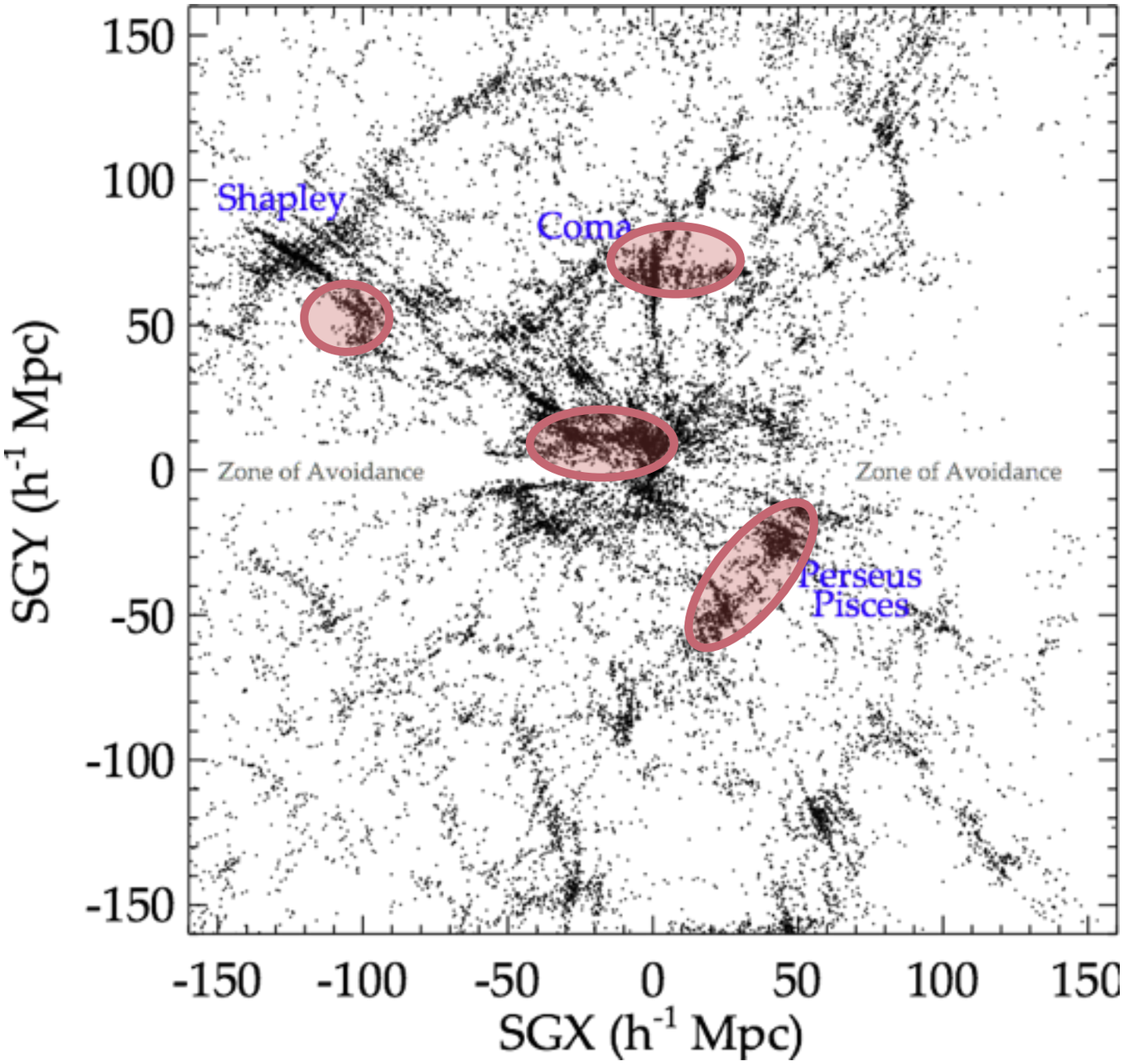
Note the fingers of gods



500 Mpc/h, 1024^3 particles,
DM only, Planck cosmology

Results: the local large scale

z=0, large scale Sorce+2016



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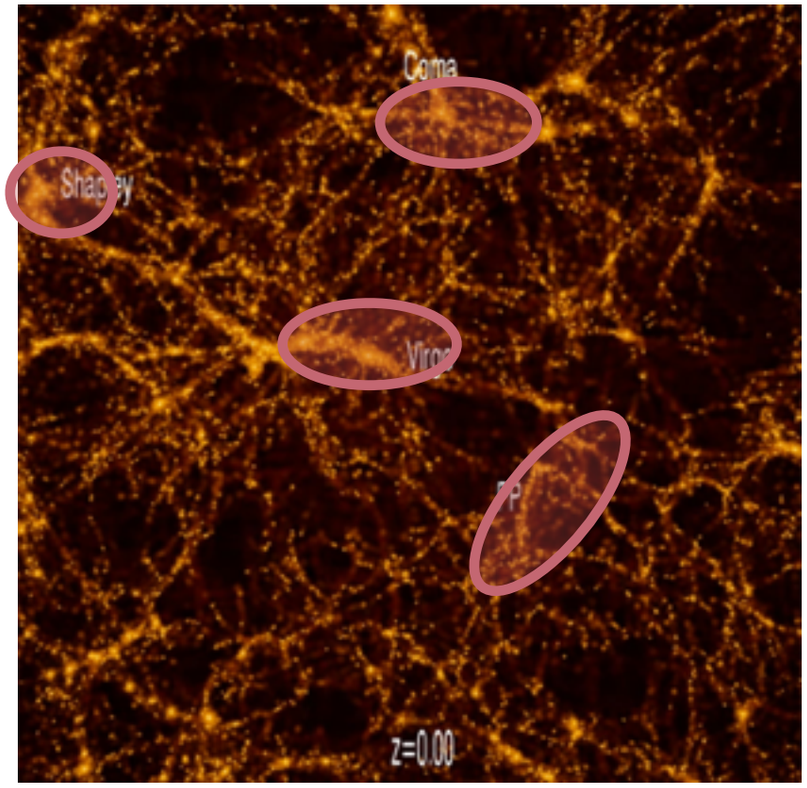

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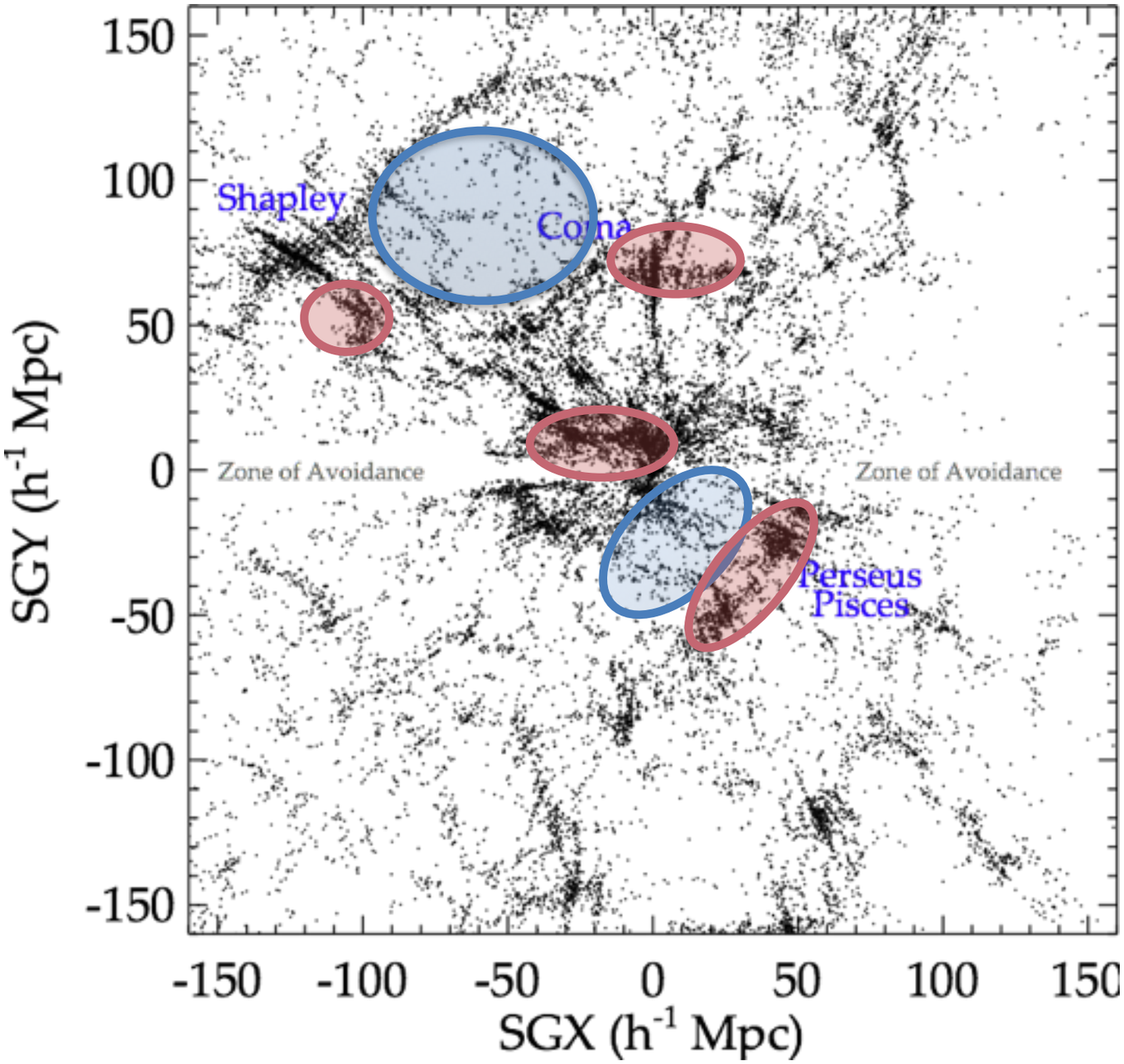

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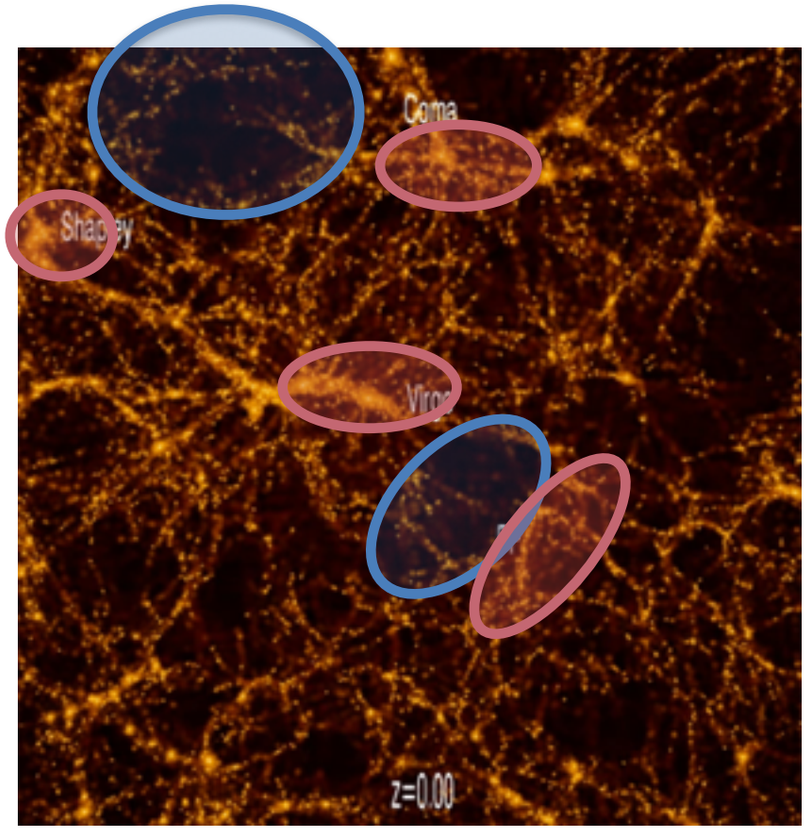

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Results: the local large scale

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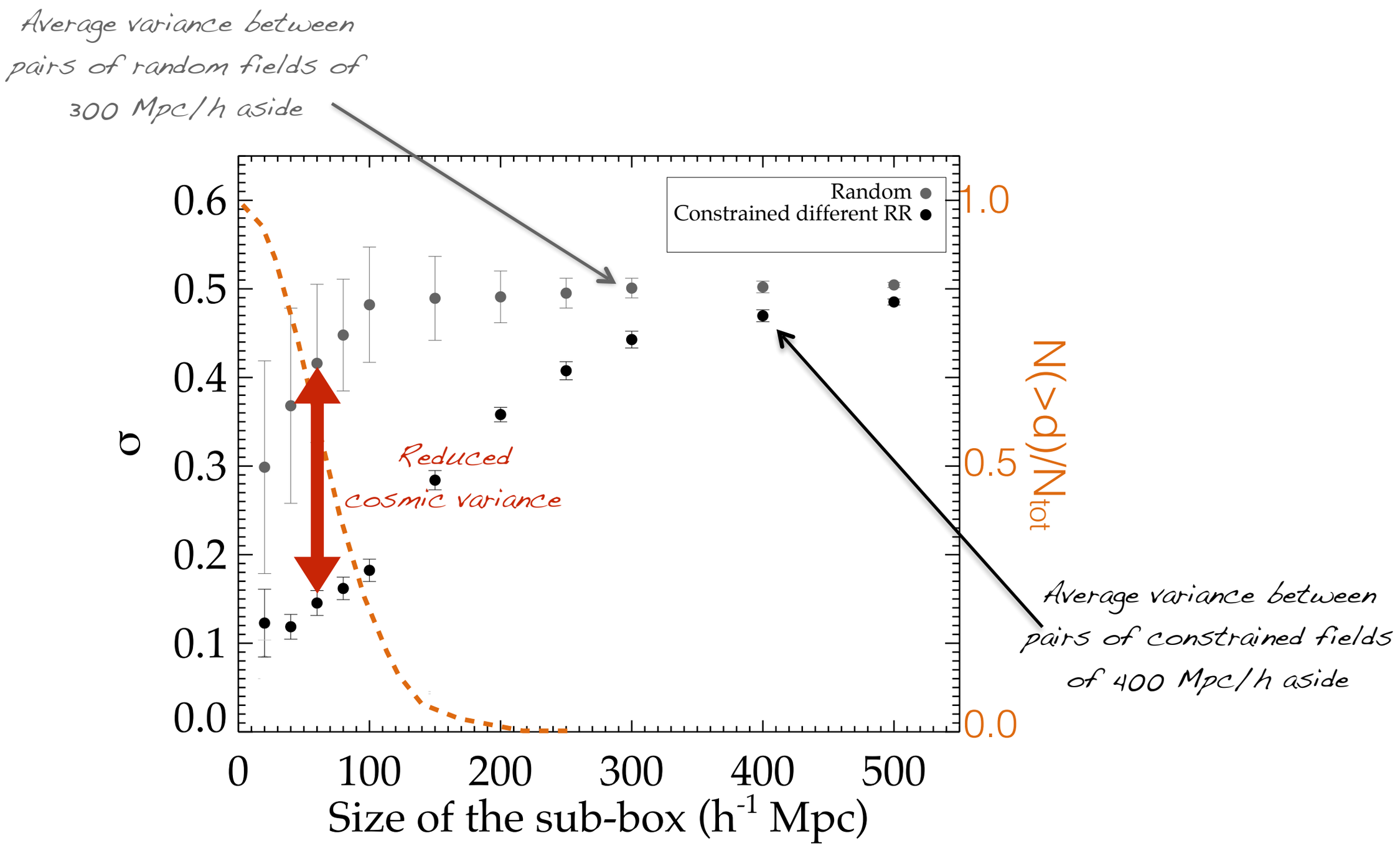
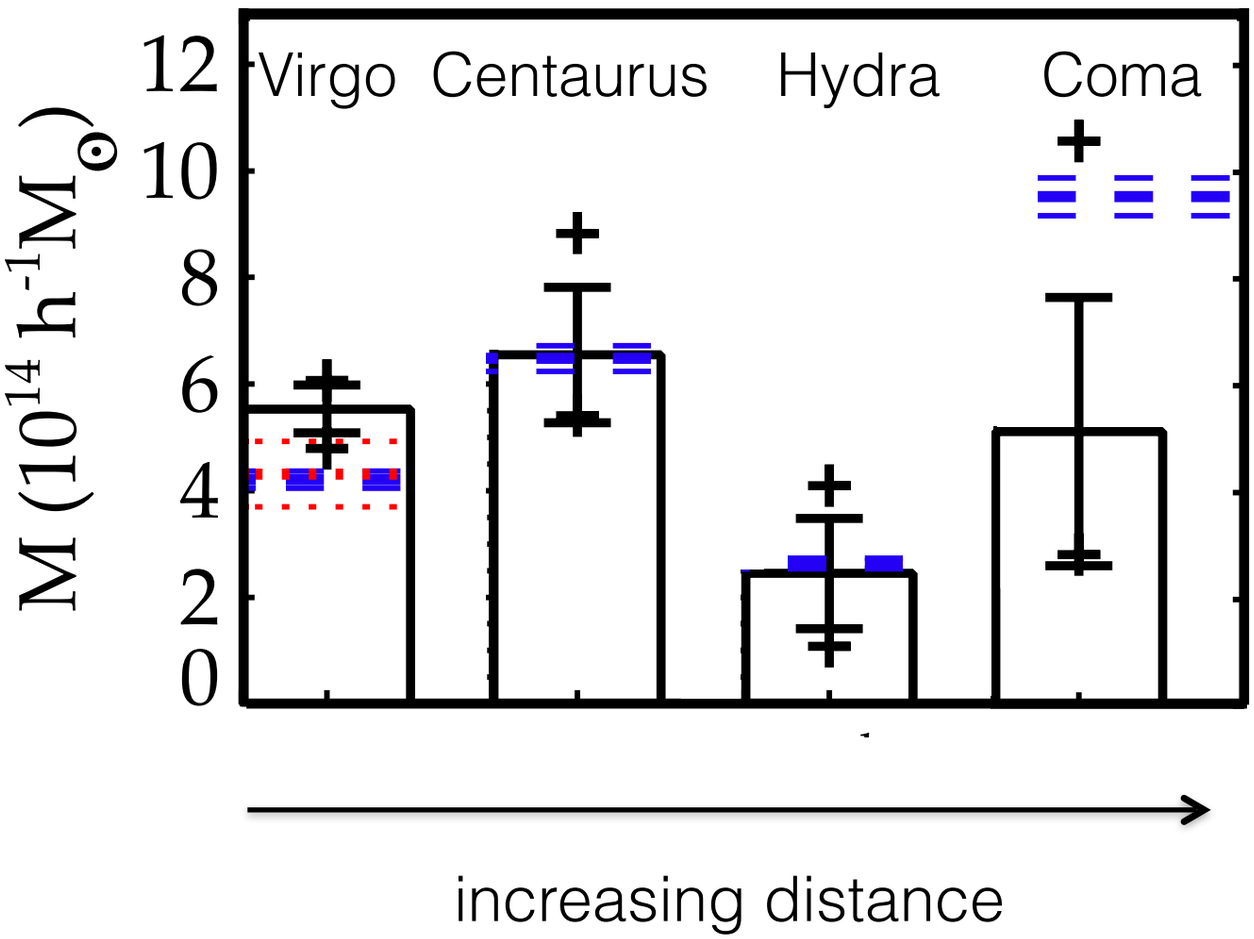


Results: the local clusters

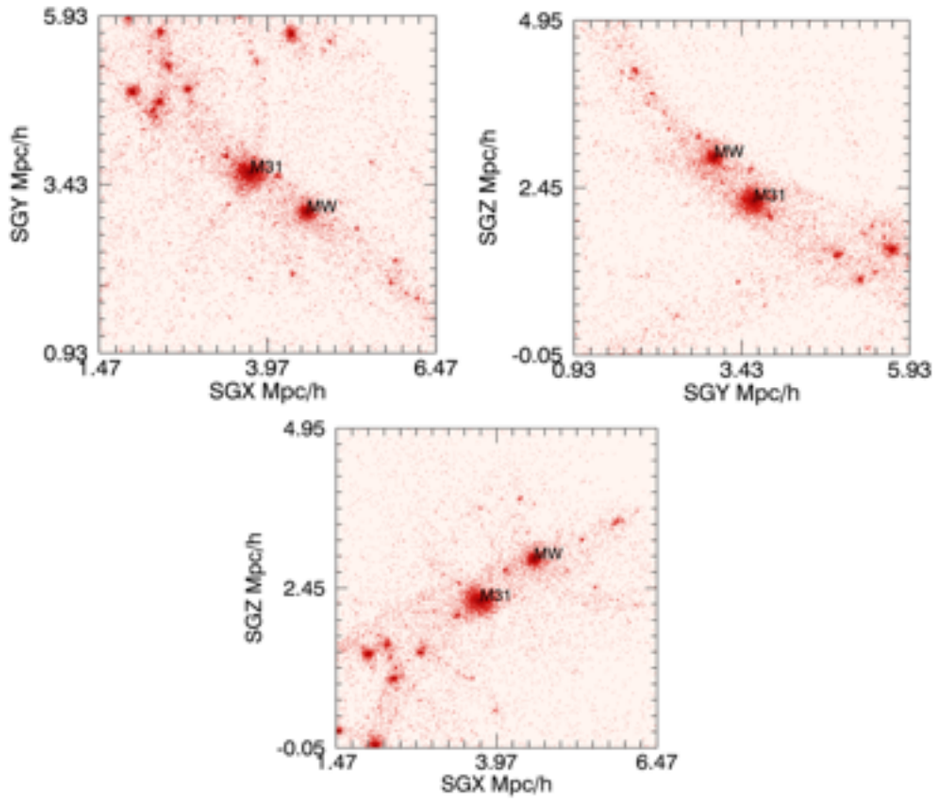
z=0, cluster scale Sorce 2018

Dark matter halos = counterparts of observed local clusters



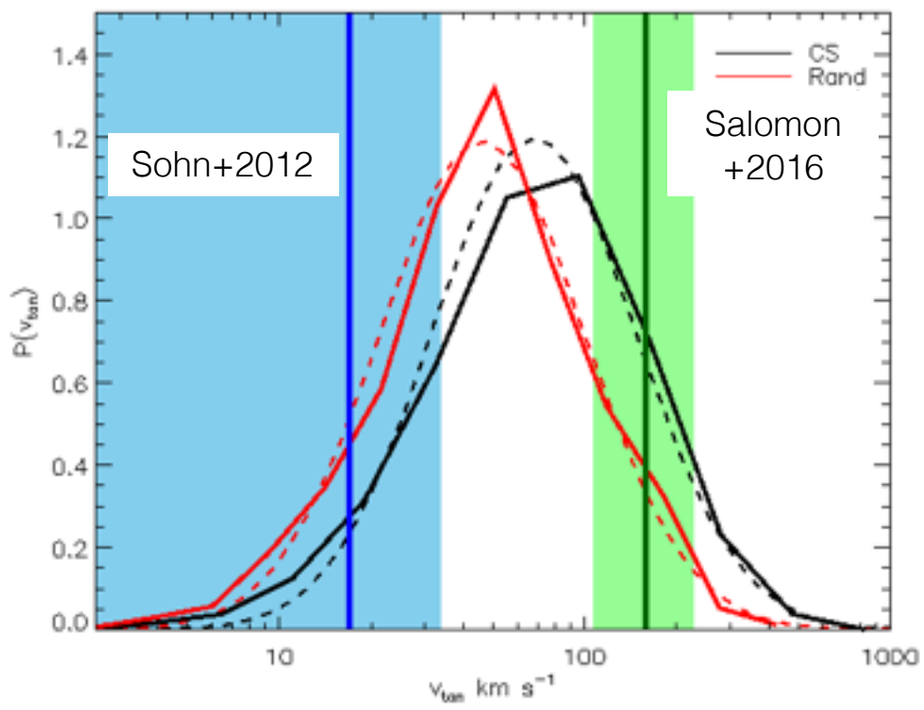
Results: the Local Group

z=0, group scale



induced by the local environment,
not directly constrained
(non-linear scales)

An example of application: in favor of a higher tangential velocity

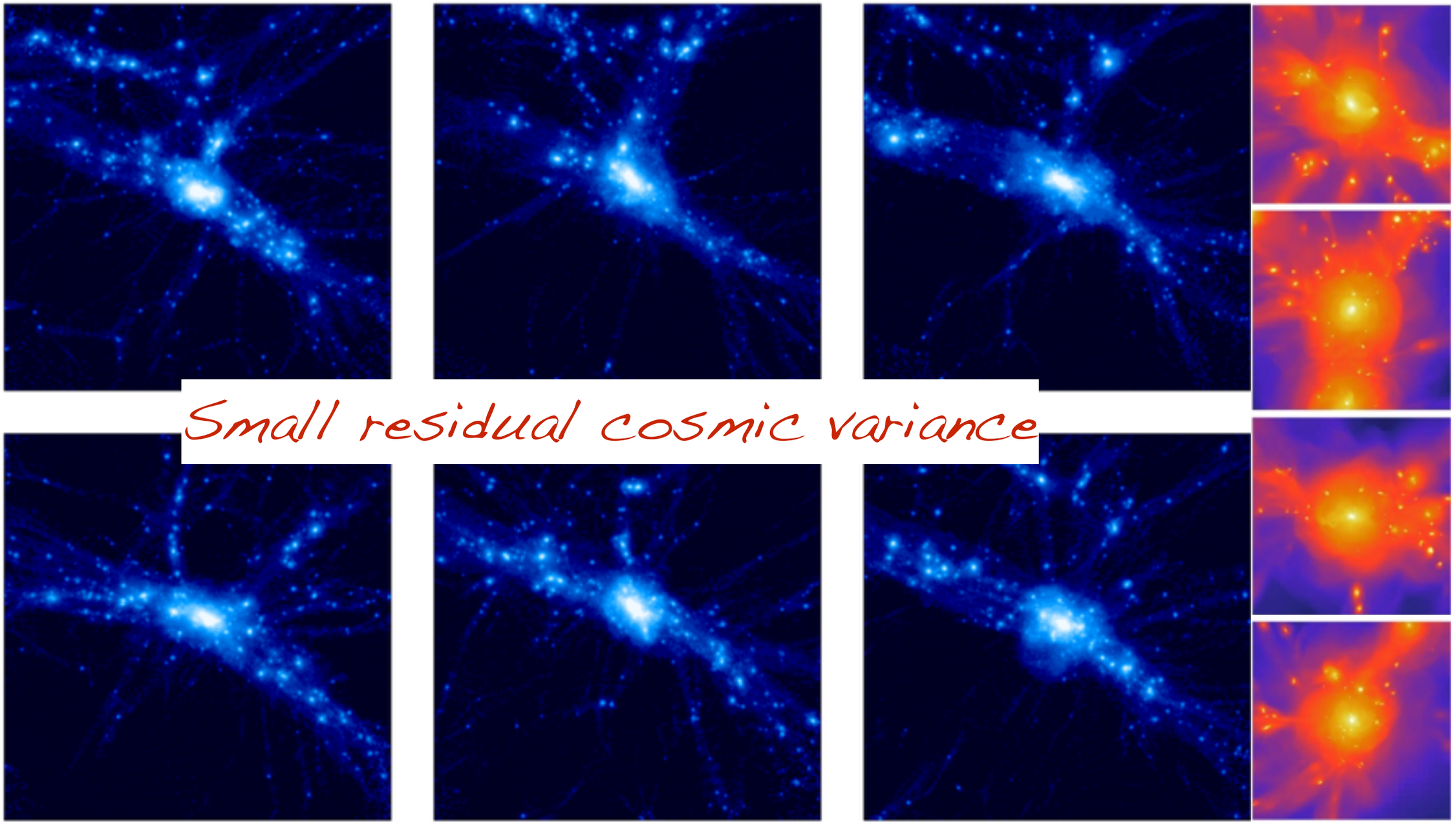


Carlesi,Sorce+2016
Carlesi,Hoffman,Sorce+2016
Carlesi,Hoffman,Sorce+2017

Let's dig into the Virgo cluster of galaxies

Observed Virgo, Simulated Virgo & Random clusters

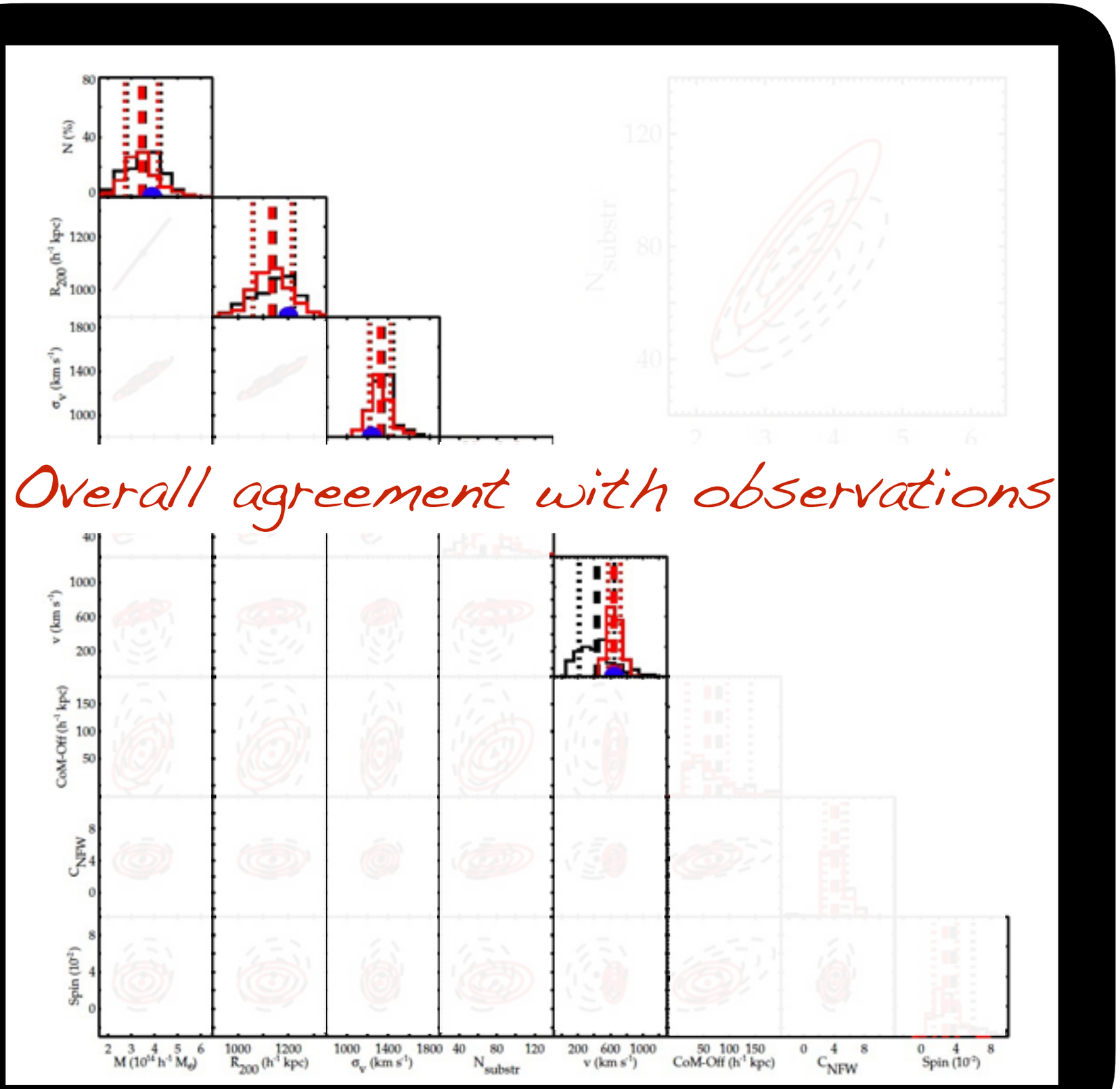
Let's dig into the Virgo cluster of galaxies



Rhapsody (Hahn +2017)

500 Mpc/h, 2048^3 particles effective (20 Mpc/h zoom), 3.8 kpc/h, DM only, Planck cosmology

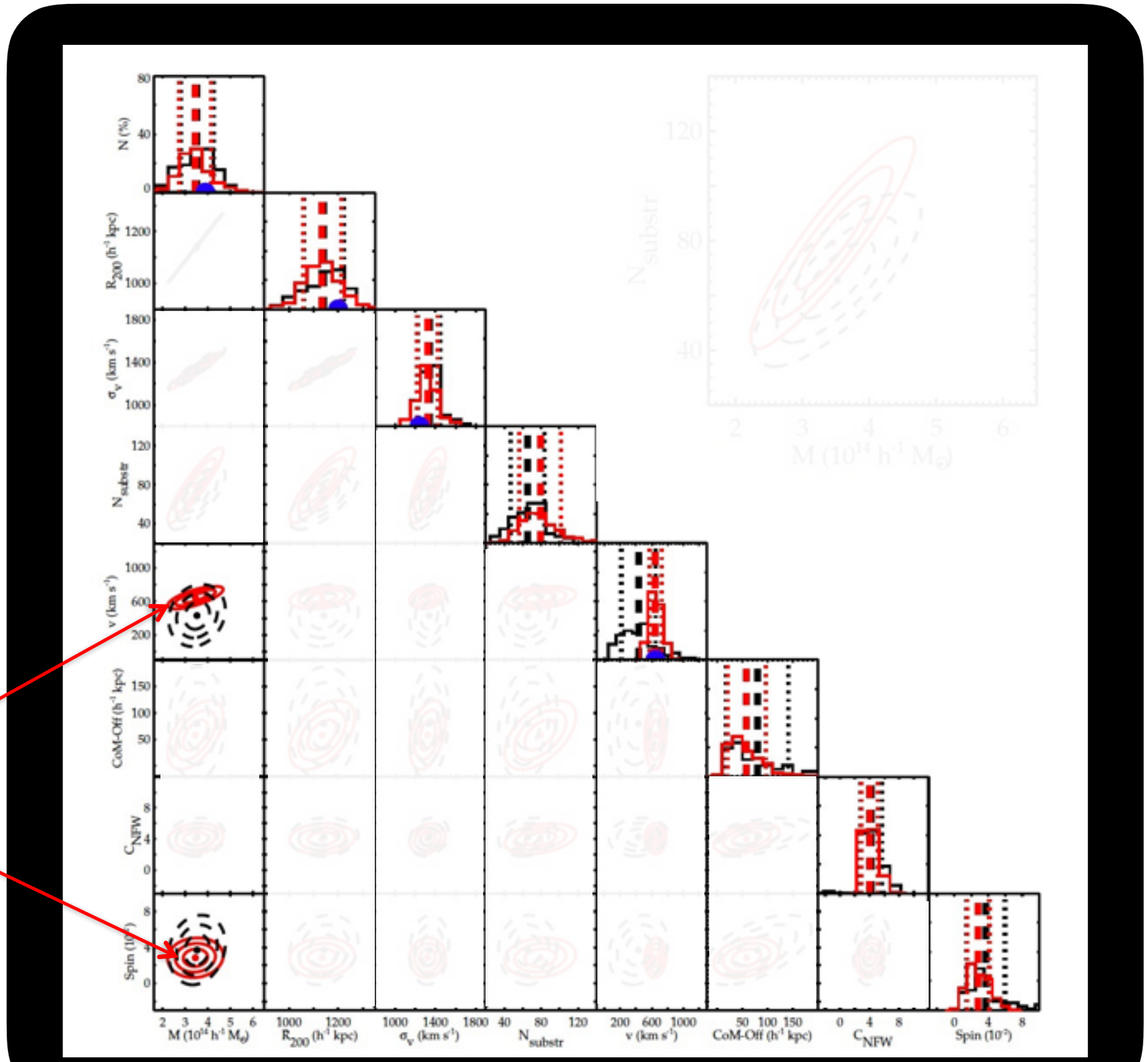
Let's dig into the Virgo cluster of galaxies



Overall agreement with observations

Sorce, Blaizot, Dubois submitted

Let’s dig into the Virgo cluster of galaxies



Velocity

Spin

→ Environment

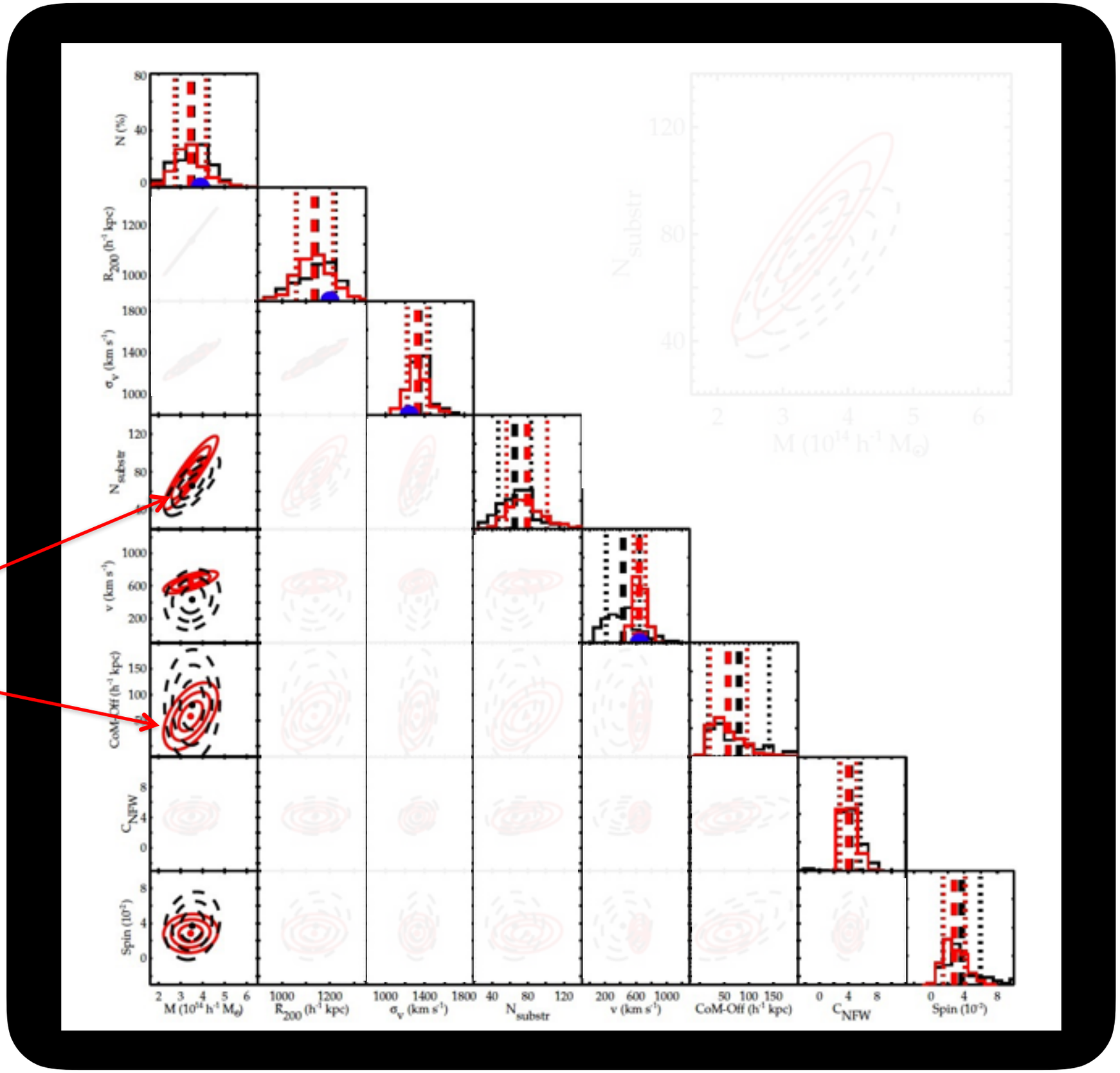
Sorce, Blaizot, Dubois submitted

Let's dig into the Virgo cluster of galaxies

Number of substructures

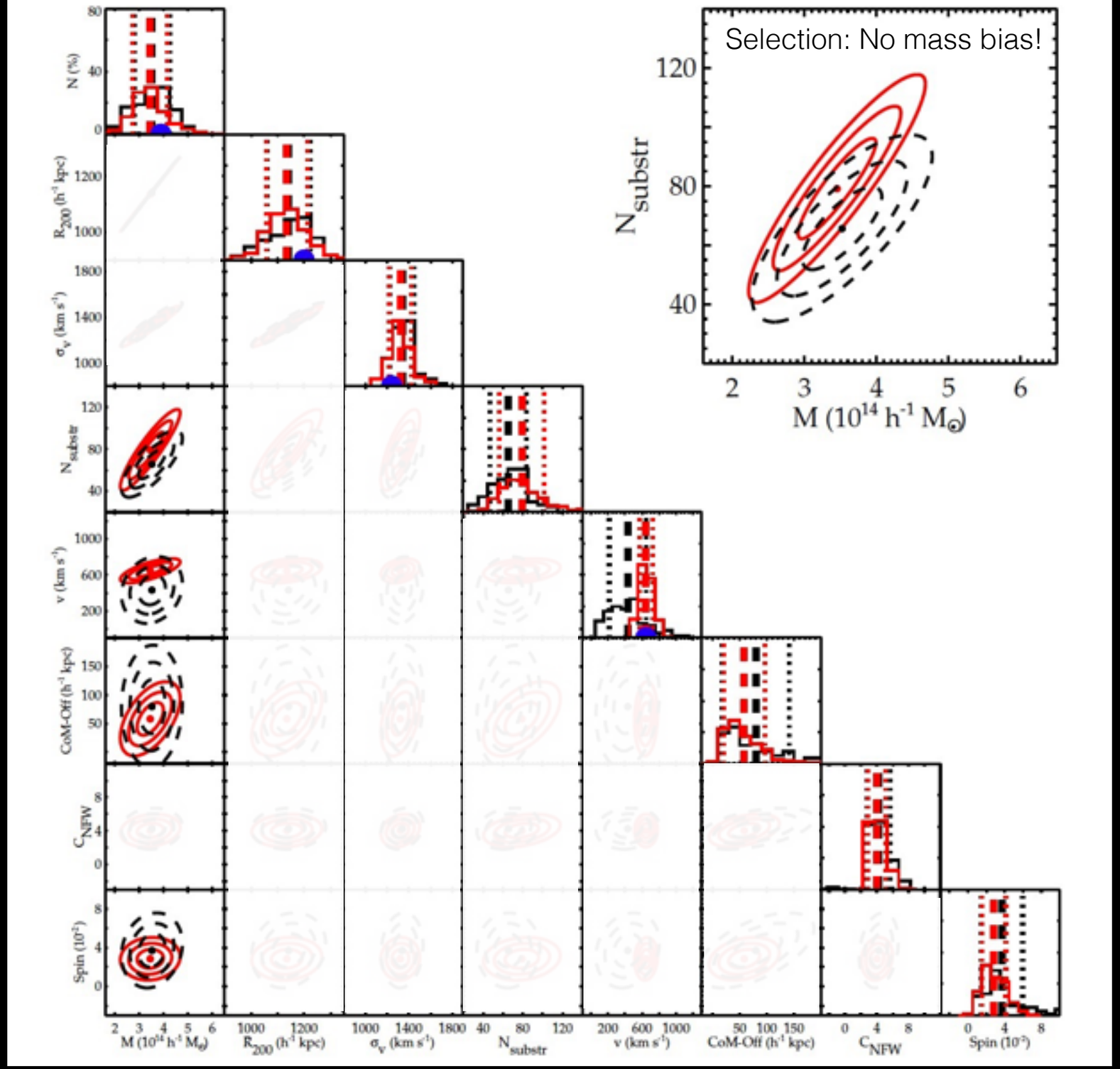
Center of mass offset wrt spherical center

➙ History



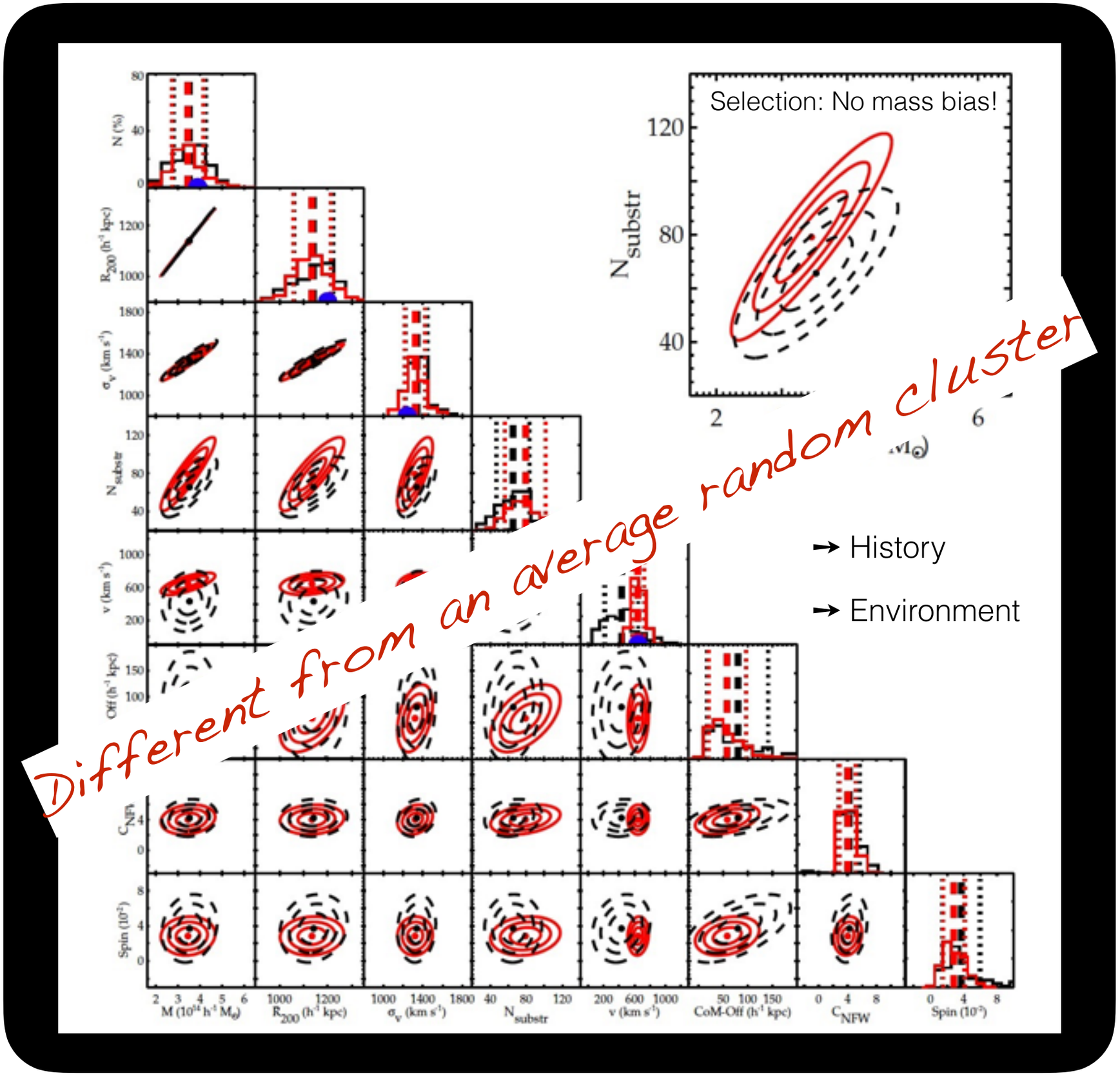
Sorce, Blaizot, Dubois submitted

Let's dig into the Virgo cluster of galaxies



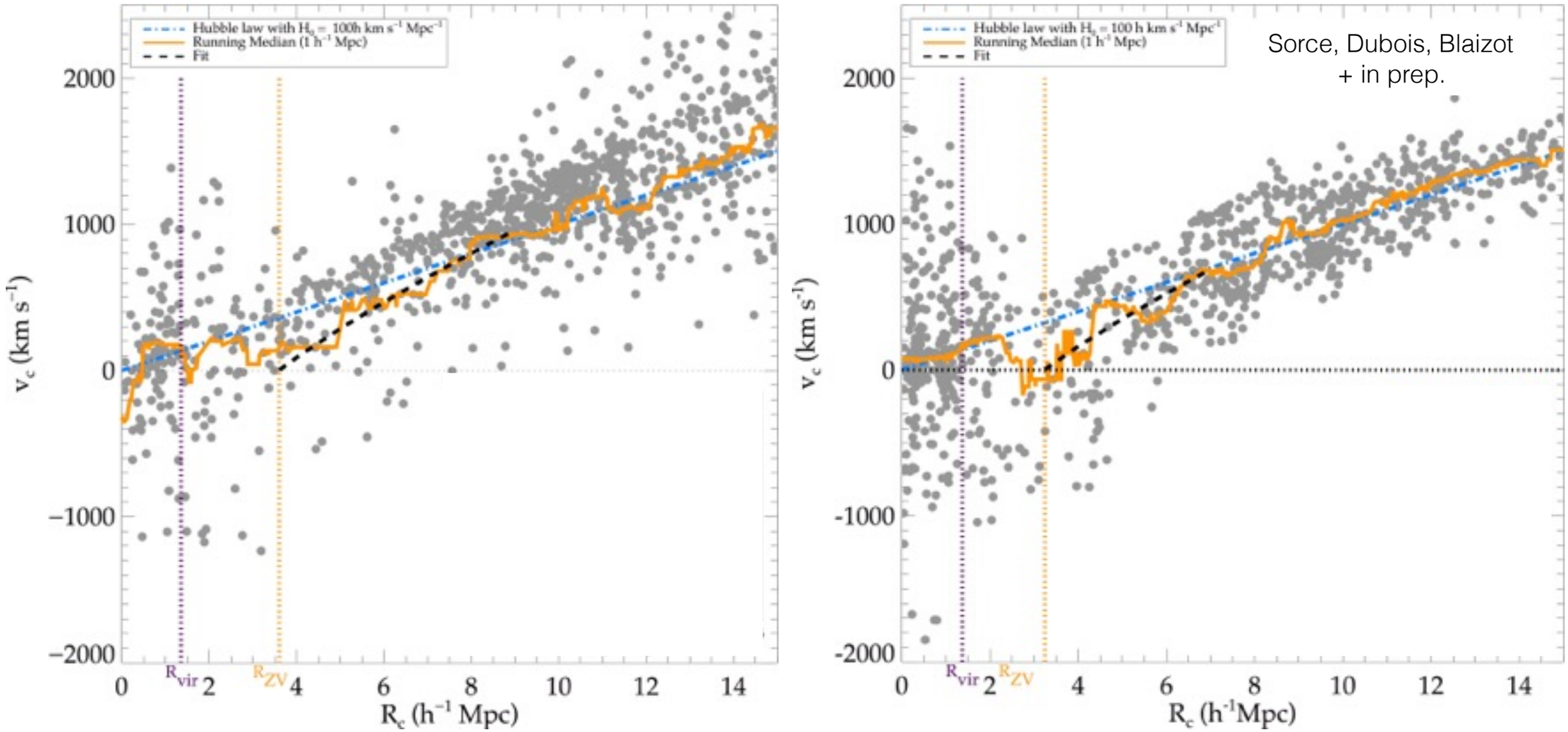
Sorce, Blaizot, Dubois submitted

Let's dig into the Virgo cluster of galaxies



Sorce, Blaizot, Dubois submitted

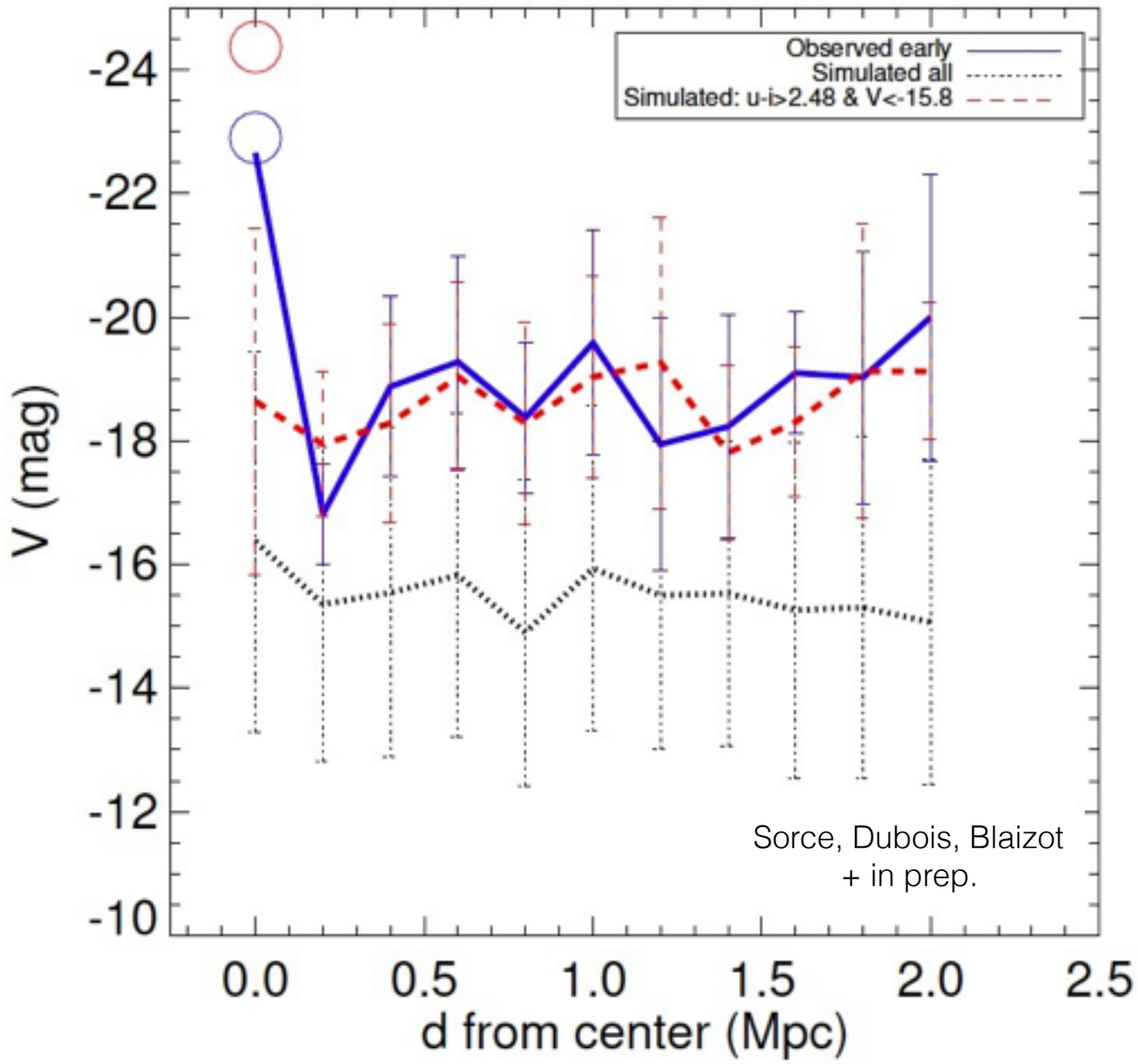
Let's dig into the Virgo cluster of galaxies



500 Mpc/h, 8192^3 particles effective (20 Mpc/h zoom), 0.24 kpc/h hydrodynamics: SN and AGN feedback, Planck cosmology

Overall agreement with observations

Let's dig into the Virgo cluster of galaxies

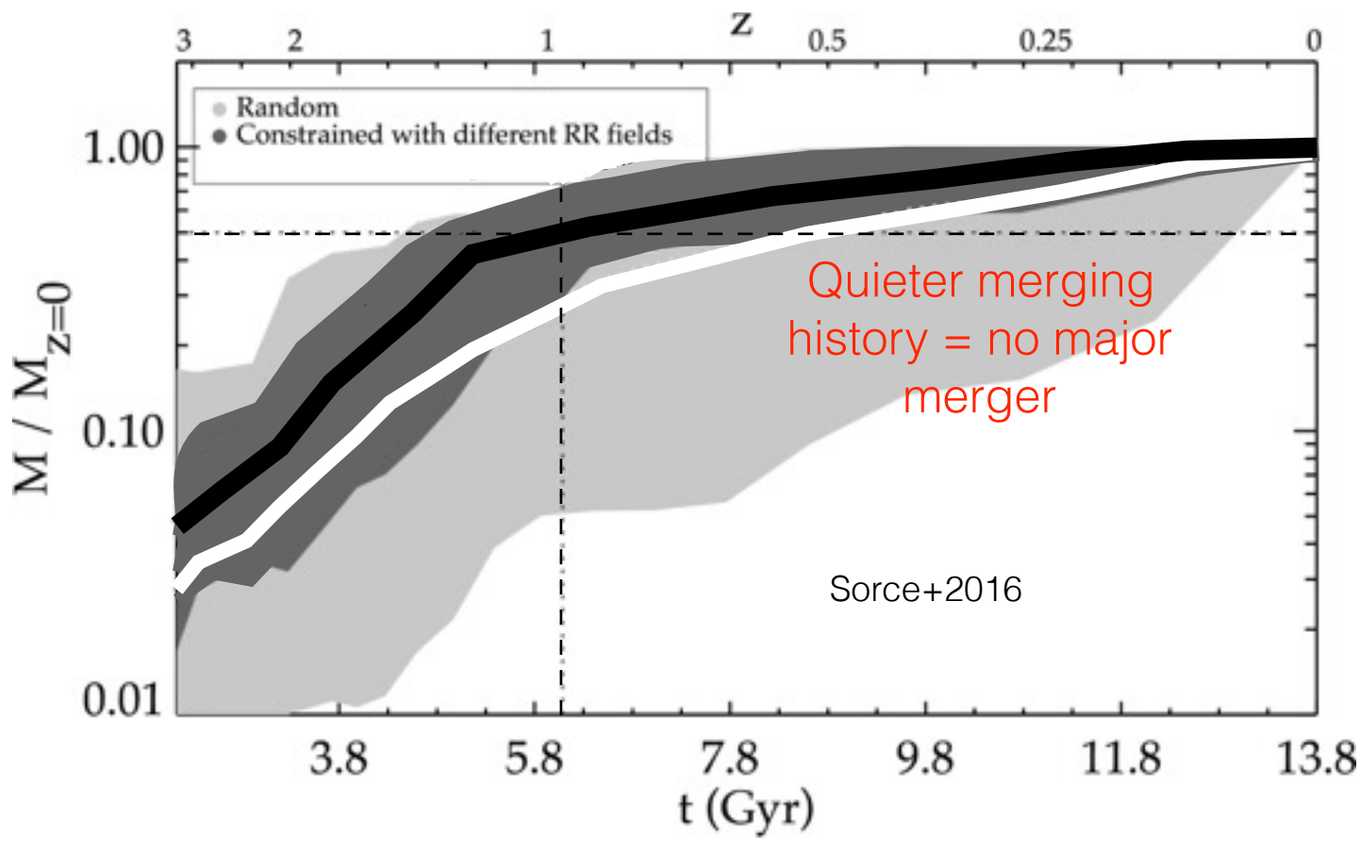


Overall agreement with observations

Let's dig into the Virgo cluster of galaxies

Boselli+2008,2014: from observation, only small mergers within the past few Gyrs

From simulation

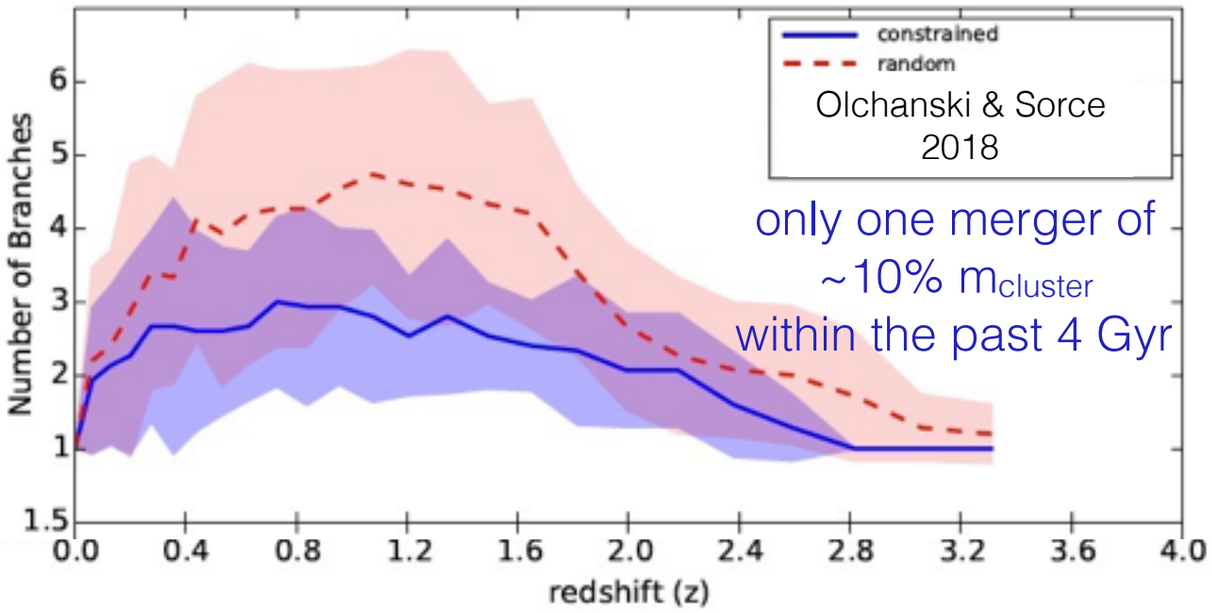


500 Mpc/h, 512^3 particles, DM only, Planck cosmology

Agreement with observational predictions

Let's dig into the Virgo cluster of galaxies

Lisker+2018: from observation, remnant of a group of ~10% $m_{cluster}$ that infall 2-3 Gyr ago



500 Mpc/h, 512^3 particles, DM only, Planck cosmology

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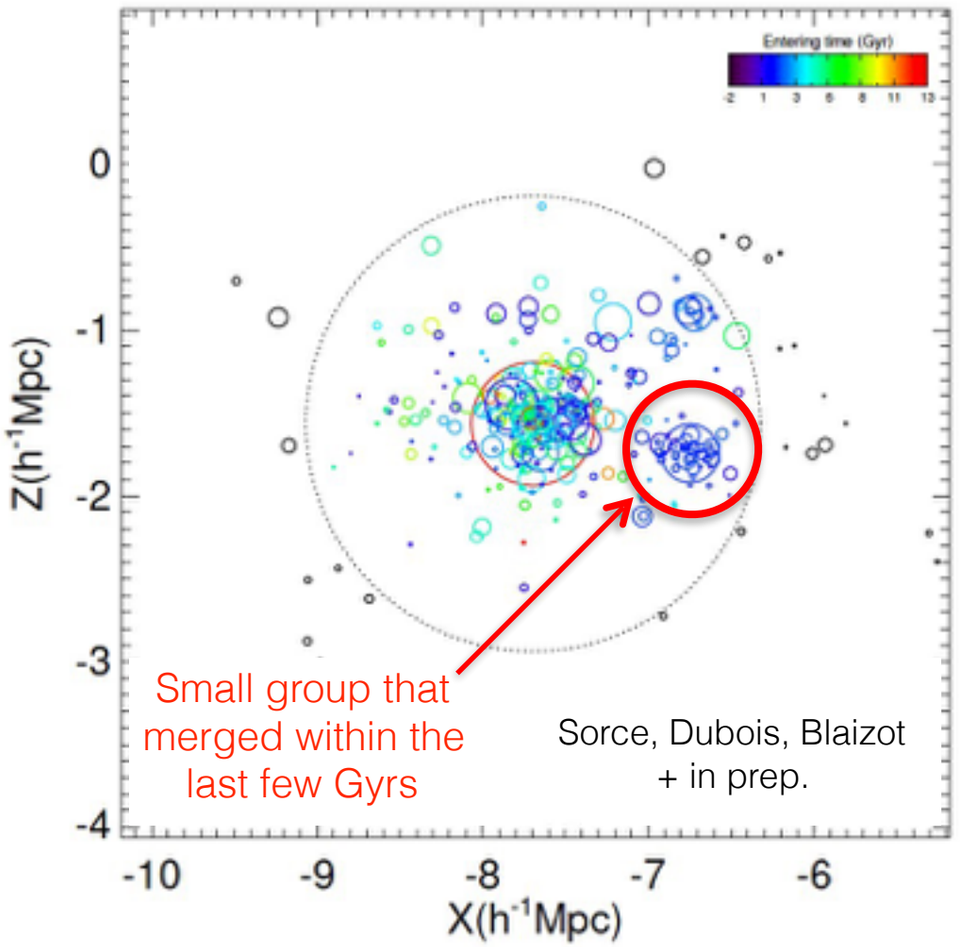
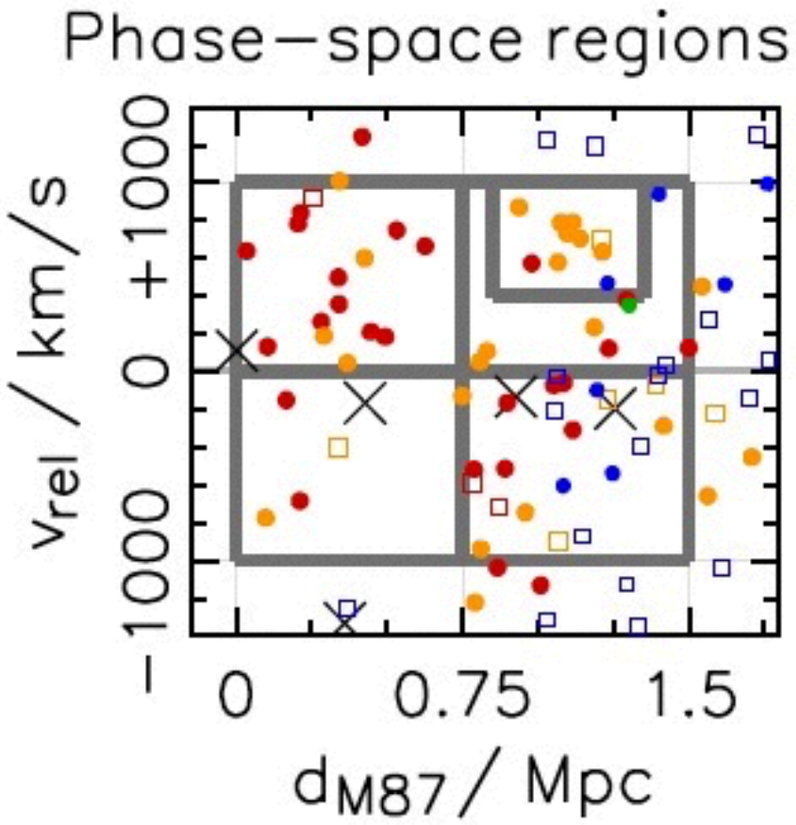


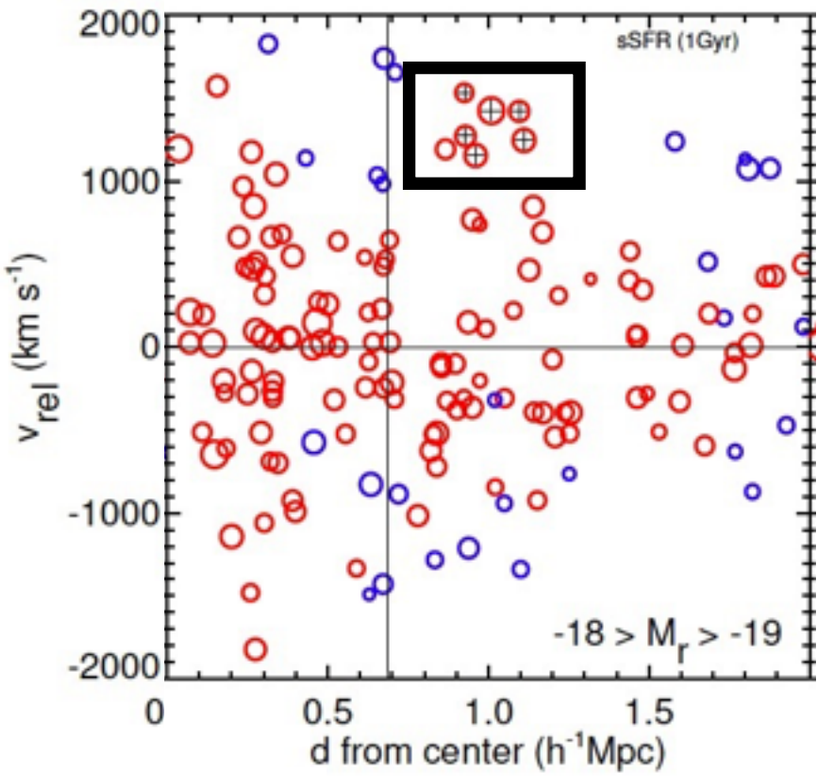
500 Mpc/h, 8192^3 particles effective (20 Mpc/h zoom), 0.24 kpc/h - Hydrodynamics: SN and AGN feedback, Planck cosmology

Agreement with observational predictions

Let's dig into the Virgo cluster of galaxies



Lisker+2018

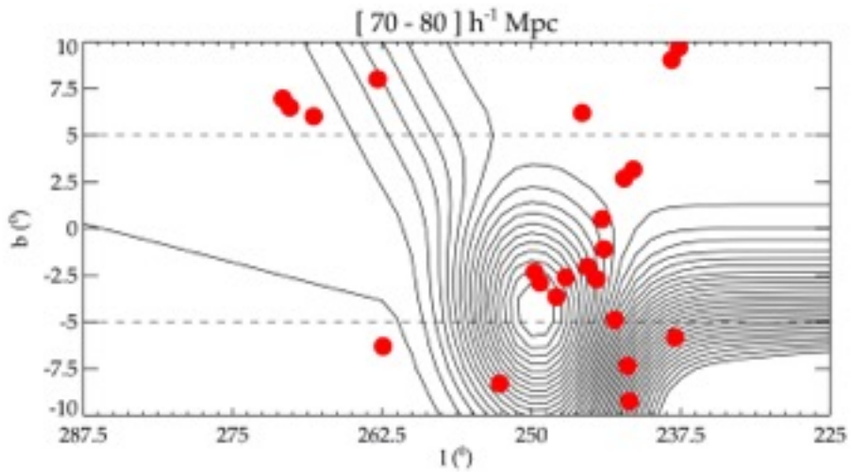


Sorce, Dubois, Blaizot
+ in prep.

Agreement with observational predictions

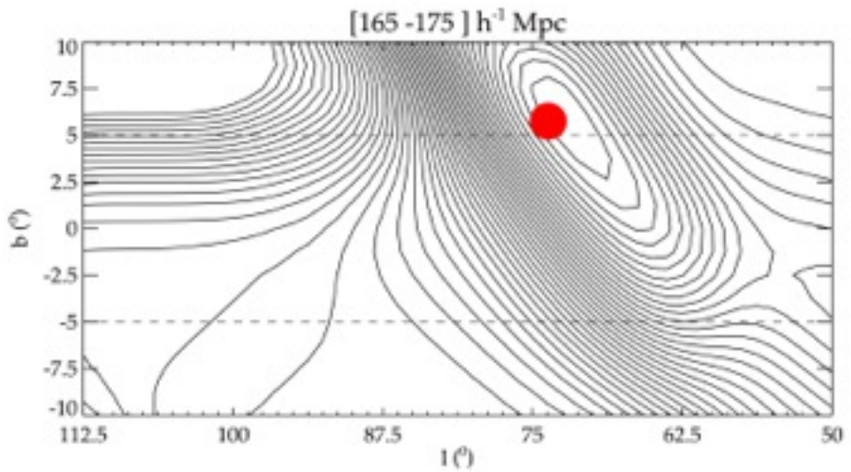
A few more applications: The Zone of Avoidance

Sorce+2017



Puppis-3 Cluster

Chamaraux & Masnoux 2004



Cygnus A Cluster

Ebeling+2002

ΛCDM challenges hidden in the Zone of Avoidance?

- number of superclusters

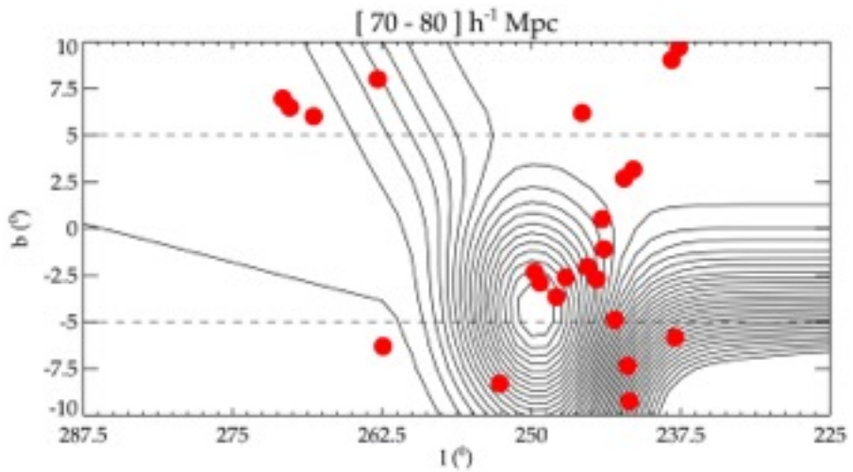
- longest structures

Vela Supercluster

Kraan-Korteweg+2017

A few more applications: The Zone of Avoidance

Sorce+2017



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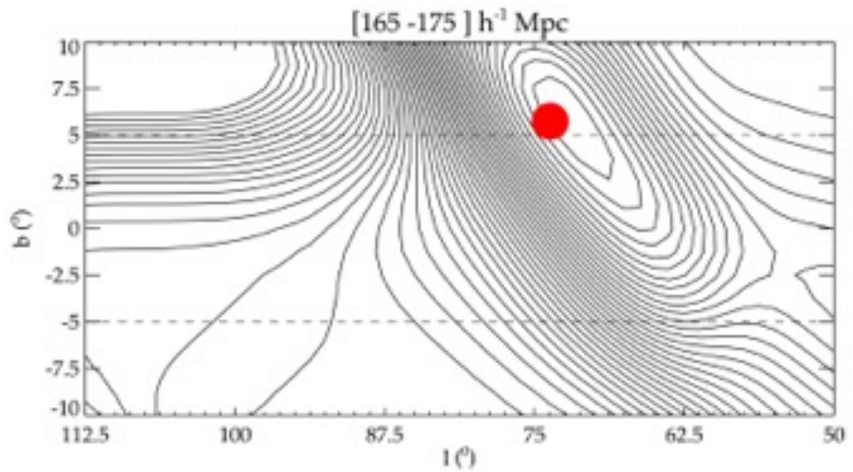

Cygnus A Cluster

Ebeling+2002

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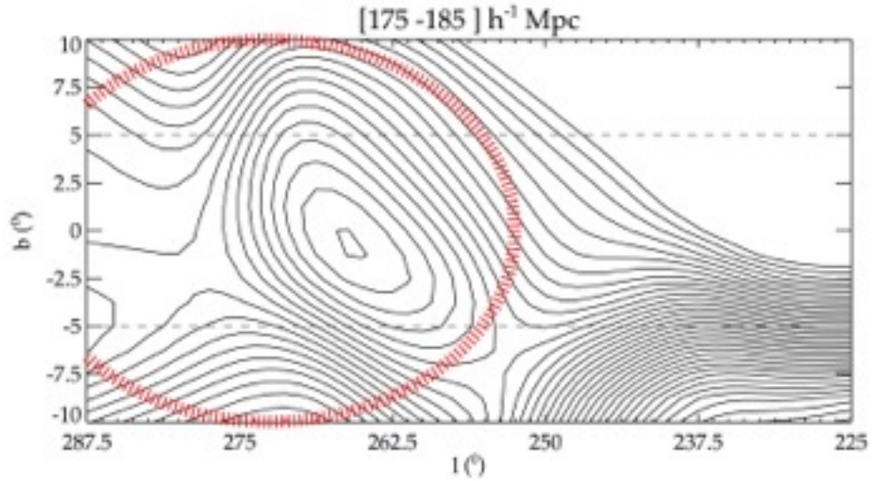
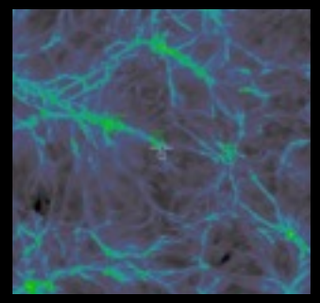


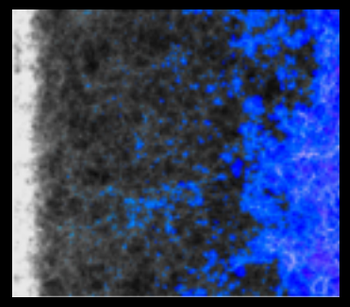
Vela Supercluster

Kraan-Korteweg+2017

A few more applications: …



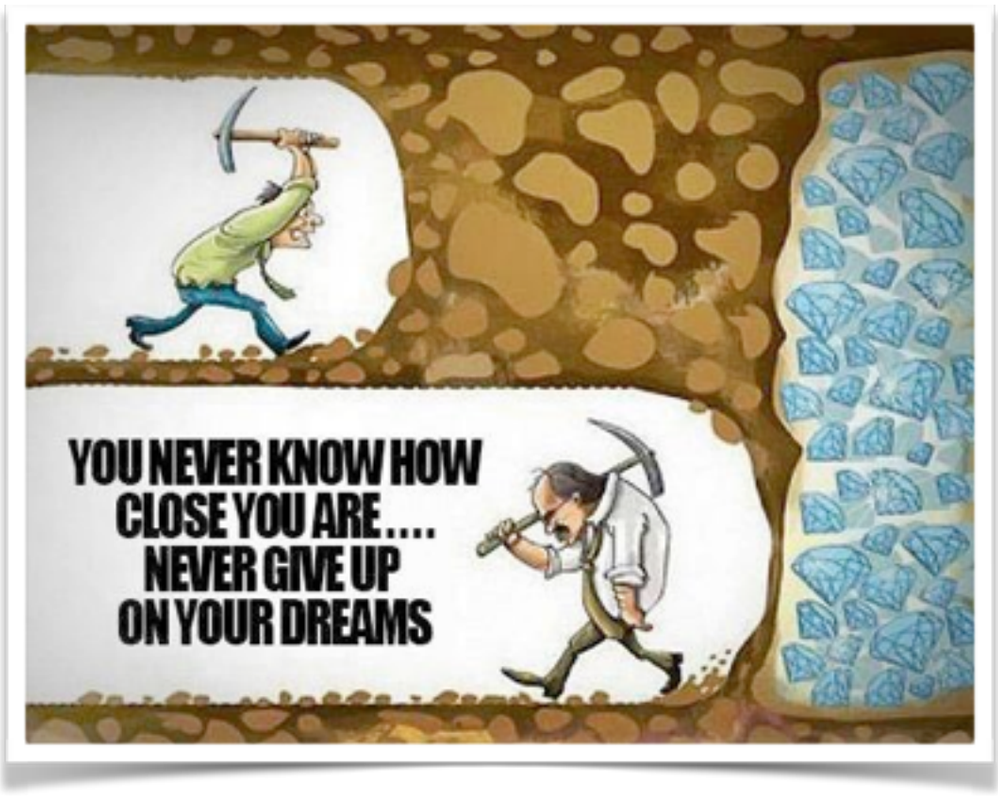
Cosmic Rays in the local Universe
(Hackstein+2018)



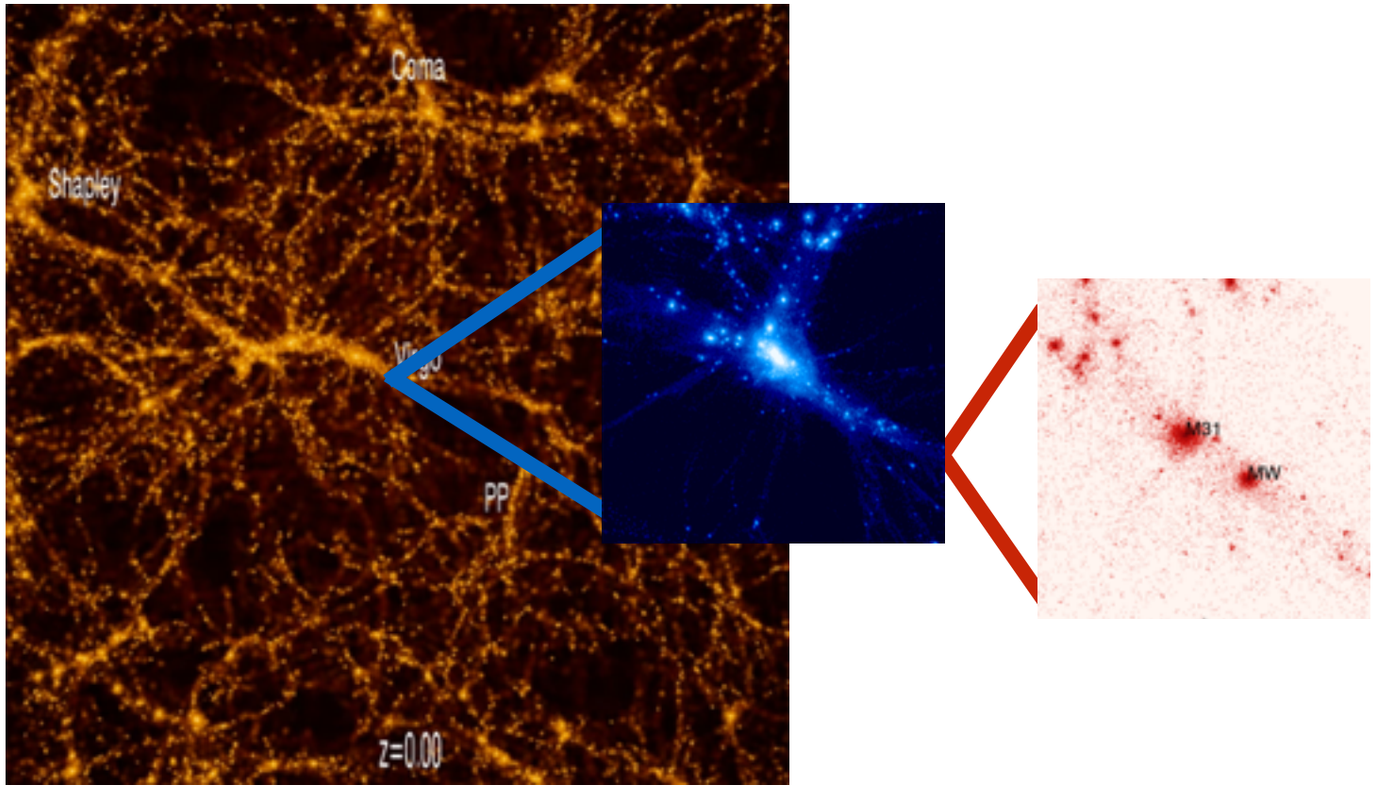
Reionization of the local Universe
(Ocvirk+ submitted)
(Sorce+ in prep.)

and
more…

Summary: where do we stand?
How far have we come?



Summary of validity



Work \ Constraints	large scales	cluster scales	local group scales
Kitaura2008,2012,2013 Hess+2013	☑	☑ no statistics	
Lavaux2010, Jasche+2013-tdy	☑		
Wang+2014-tdy	☑	☑ not nearby, no statistics	
Klypin+2003	☑	☑ mass 'by hand'	☑ induced
Sorce+2014-tdy	☑	☑	☑ induced

luminosity bias !

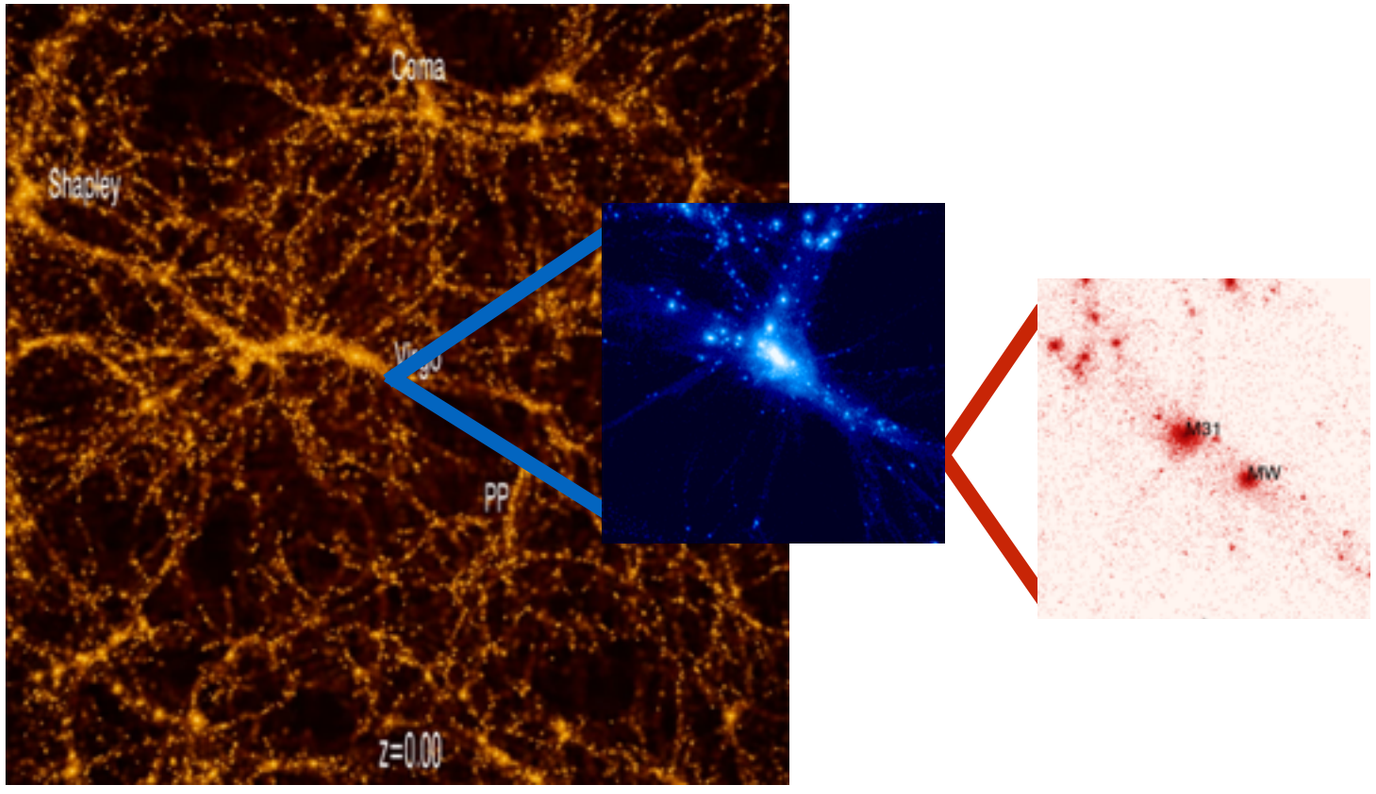
e.g. for the **Virgo cluster** Sorce+2016b, Sorce +submitted, Sorce+in prep. **including the past history**!

e.g. Carlesi,Sorce+2016
Carlesi,Hoffman,Sorce+2016
Carlesi,Hoffman,Sorce+2017

GM… What?


© Mike Baldwin / Cornered
CLONING
$600.
CARTOONSTOCK
.com
Search ID: mban1808.
"It just seems wrong to me. I don't think I could live with myself."

Summary and Prospectives



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GMO-CLONES	☑	☑	☑

luminosity bias !

e.g. for the **Virgo cluster** Sorce+2016b, Sorce +submitted, Sorce+in prep. **including the past history**!

Suite of constrained initial conditions of different resolutions, sizes and focus

e.g. Carlesi,Sorce+2016
Carlesi,Hoffman,Sorce+2016
Carlesi,Hoffman,Sorce+2017

Take home message

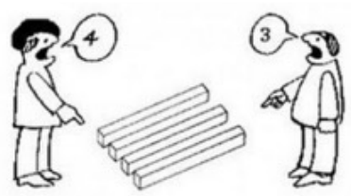
Do we need a new cosmological model?

To answer, nowadays (this is on-going)

Small scales

Simulations of Galaxy formation & evolution

Local scales



local estimates of cosmological parameters

Large scales

CMB high sensitivity experiment and large scale surveys

Biased Precision Cosmology

Take home message

Do we need a new cosmological model?

GMO-CLONES

initial conditions for

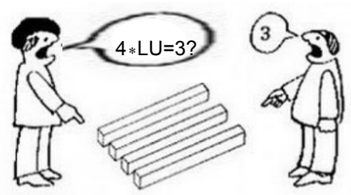
numerical specialists, theorists and observers

Small scales

Simulations of Galaxy formation & evolution:

- reproduction
- calibration

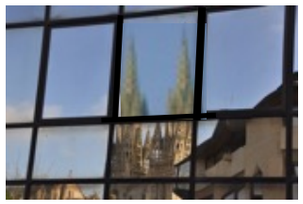
Local scales



unbiased local estimates of cosmological parameters

Accurate Precision Cosmology

Large scales



CMB high sensitivity experiment and large scale surveys : foreground effect correction

Acknowledgements

Thank you, Merci, Grazie,
Gracias, Danke, спаси́бо,
Mahalo, 谢谢, ありがとう,
תודה, Obrigada, Dank u,
Tak, Cảm ơn, Dziękuję,
Kiitos, Aitäh, …*

* Missing your ‘thanks’ spelling? It means I did not get the chance yet to visit your country but I am looking forward to do so !
(exceptions in red: I have not been but I have had the opportunity to learn how to say it)