Do we need a new cosmological model ?

GMO-CLONES, a solution to the precision era dilemma

Jenny Sorce

Centre de Recherche Astrophysique de Lyon

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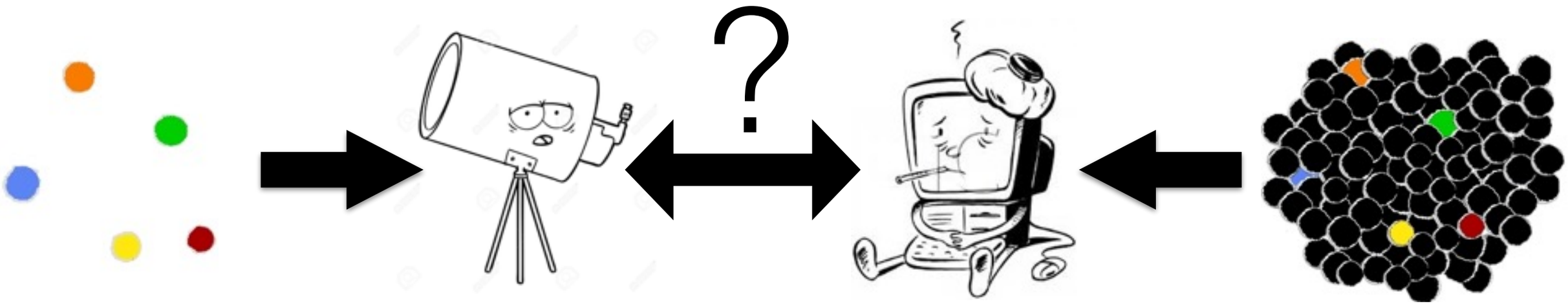
Collaborators: **Blaizot, Richard, Tresse (CRAL), Dubois (IAP), Hahn (OCA), de La Torre (LAM), Pontzen, Peiris, Rey (UCL), Ocvirk (ObAS)**

Motivation : ΛCDM? ➤ Current strategy

Observations

Simulations



Directly Observable Universe

Cosmological Model

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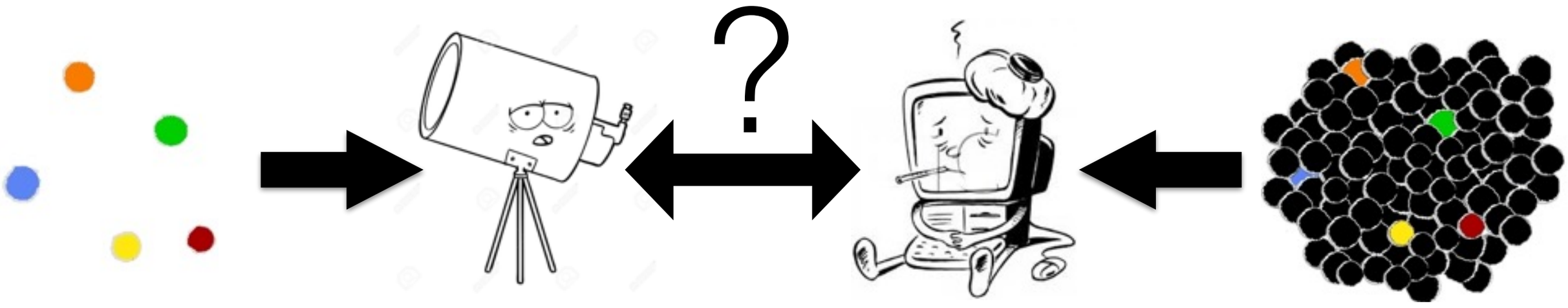

Directly Observable Universe

If all goes well…
it is a perfect match

Cosmological Model

Motivation : ΛCDM? In practice

Observations

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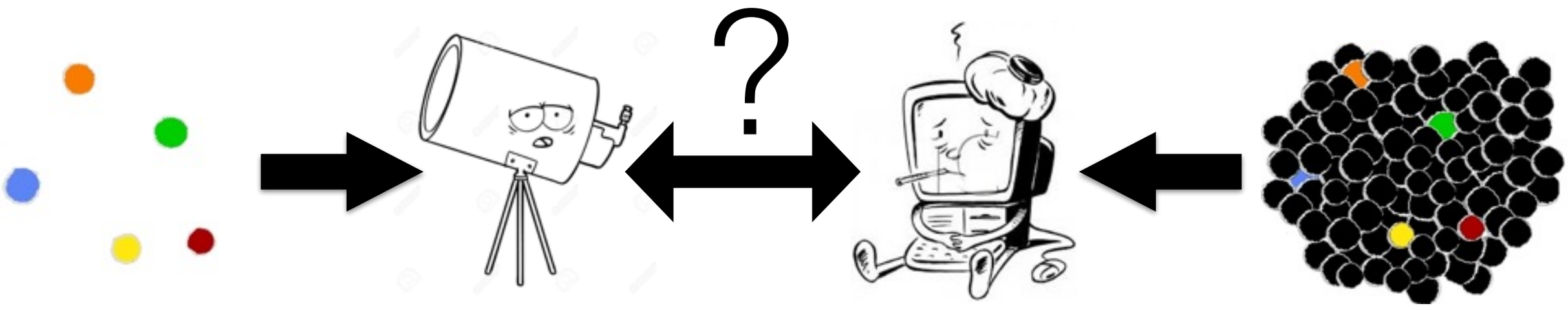

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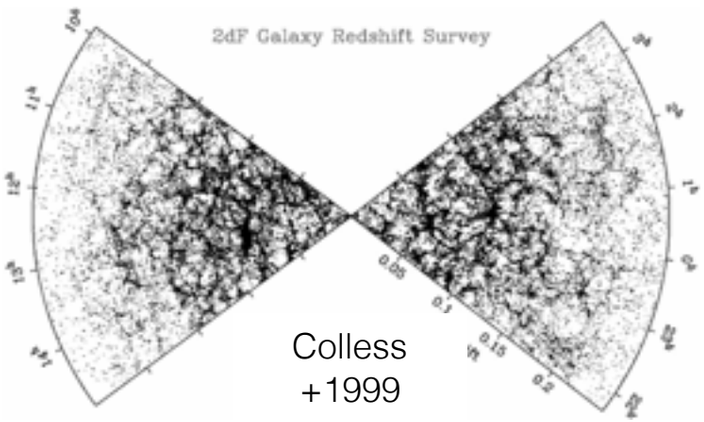
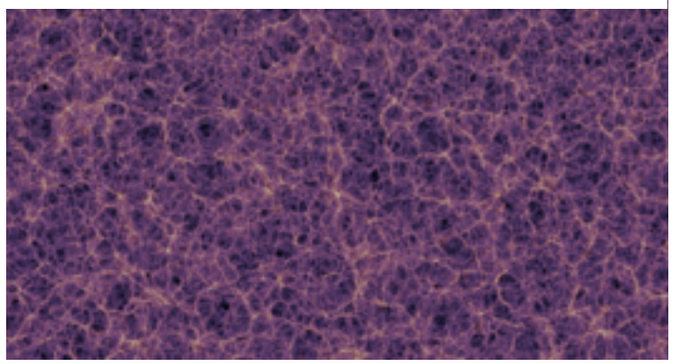


Colless +1999

Overall: ΛCDM ☑

Cosmological Model

Springel+2005,2008, Dubois+2016, etc

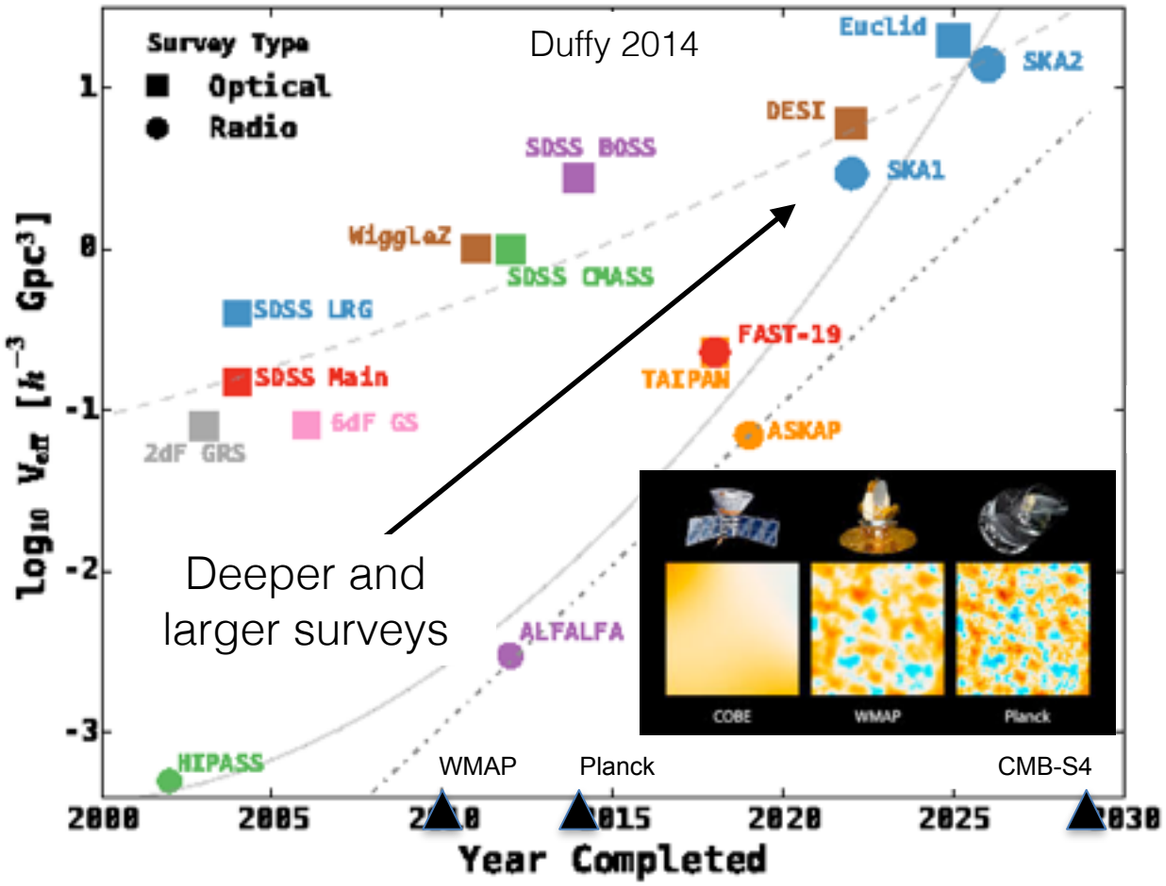


Motivation : ΛCDM? Toward precision cosmology

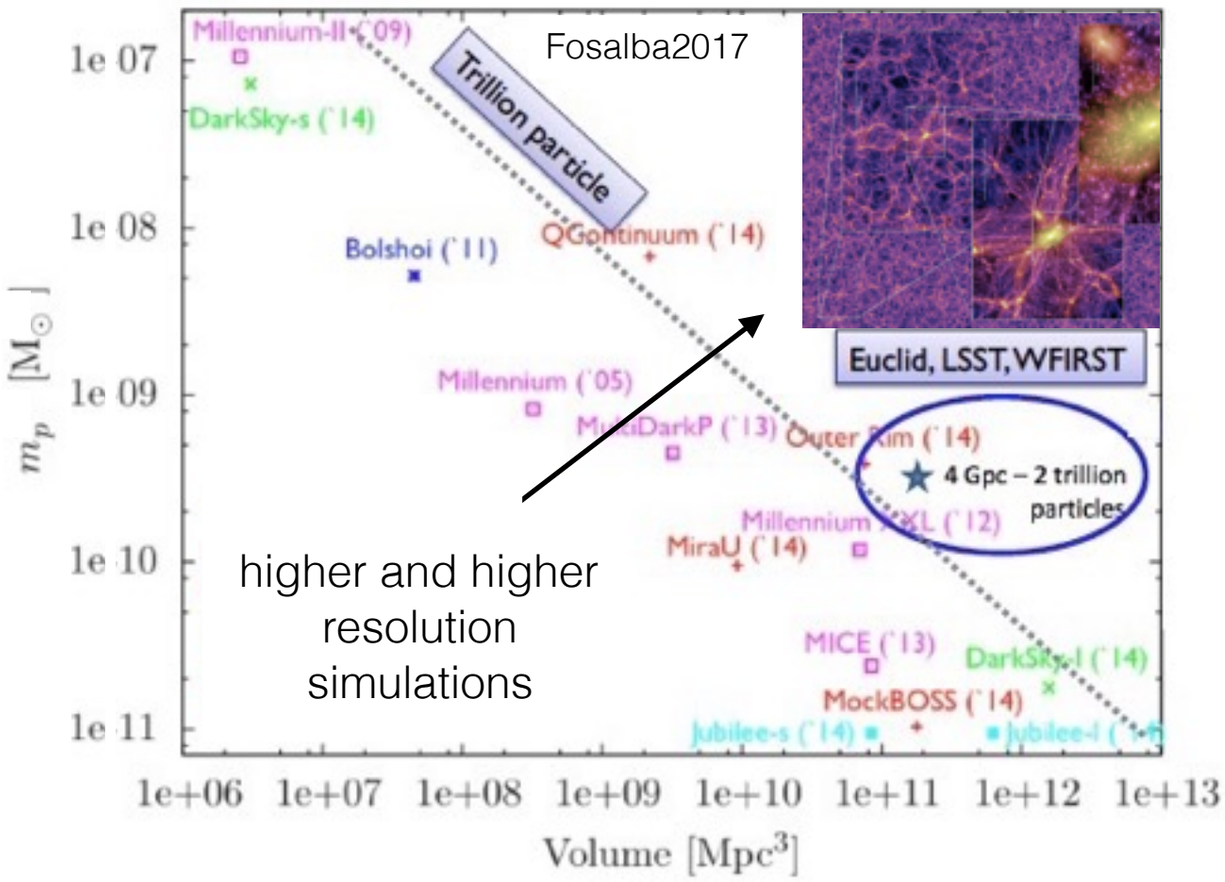
Precision Era:
1-2% precision

ΛCDM checked on all scales

Observational

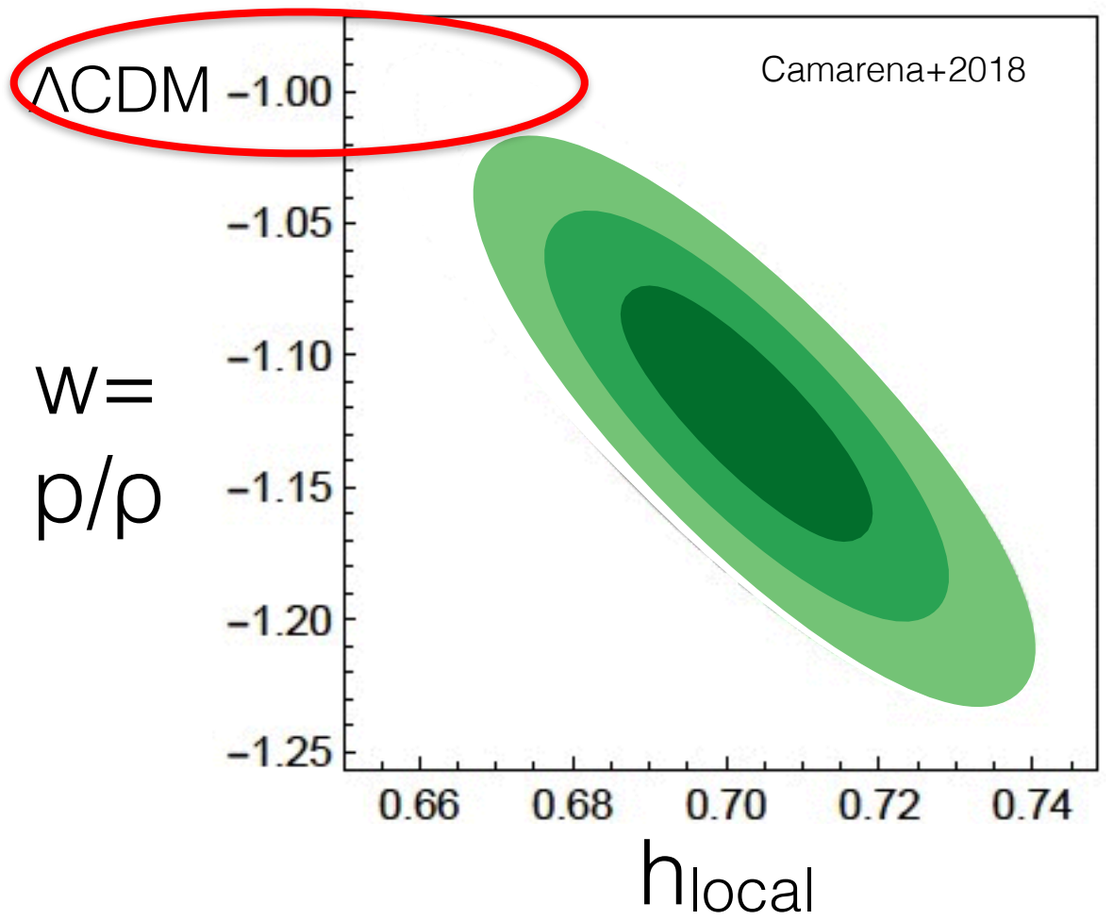


Numerical



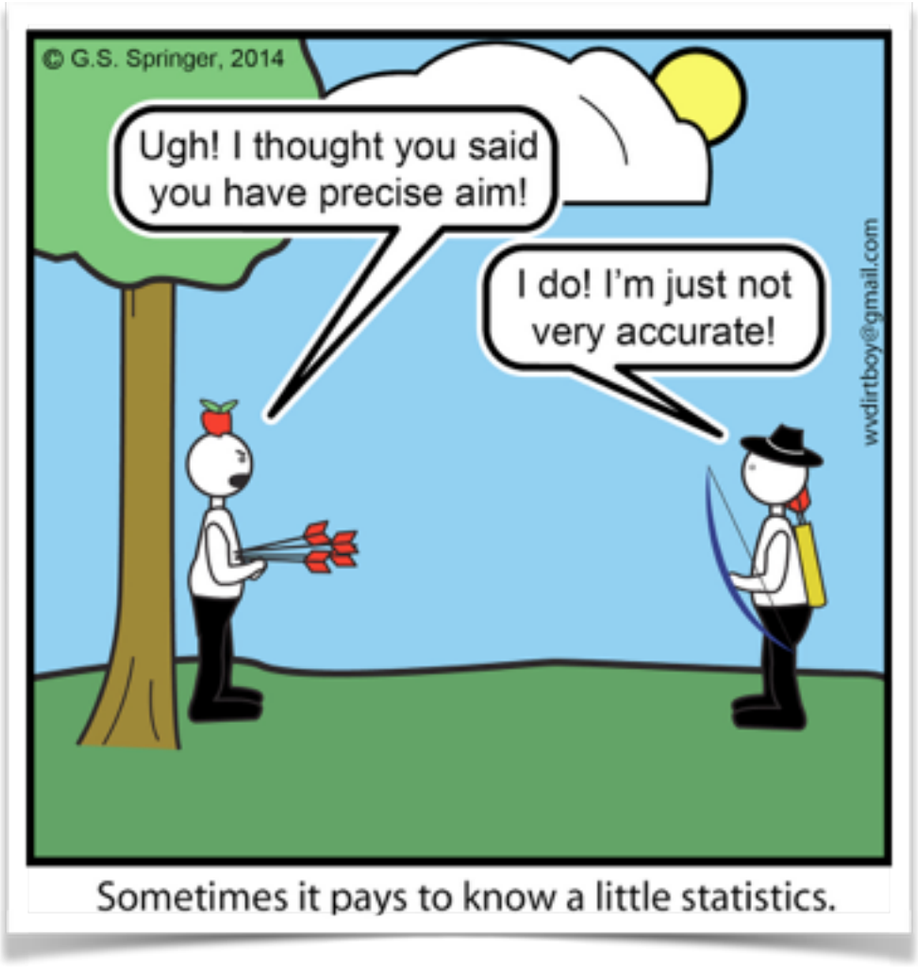
Motivation : ΛCDM? but with more precision come some tensions !

Example: Equation of state of the dark energy



Motivation : ΛCDM?

Precision is not accuracy !



 Precision is not accuracy: environmental biases?

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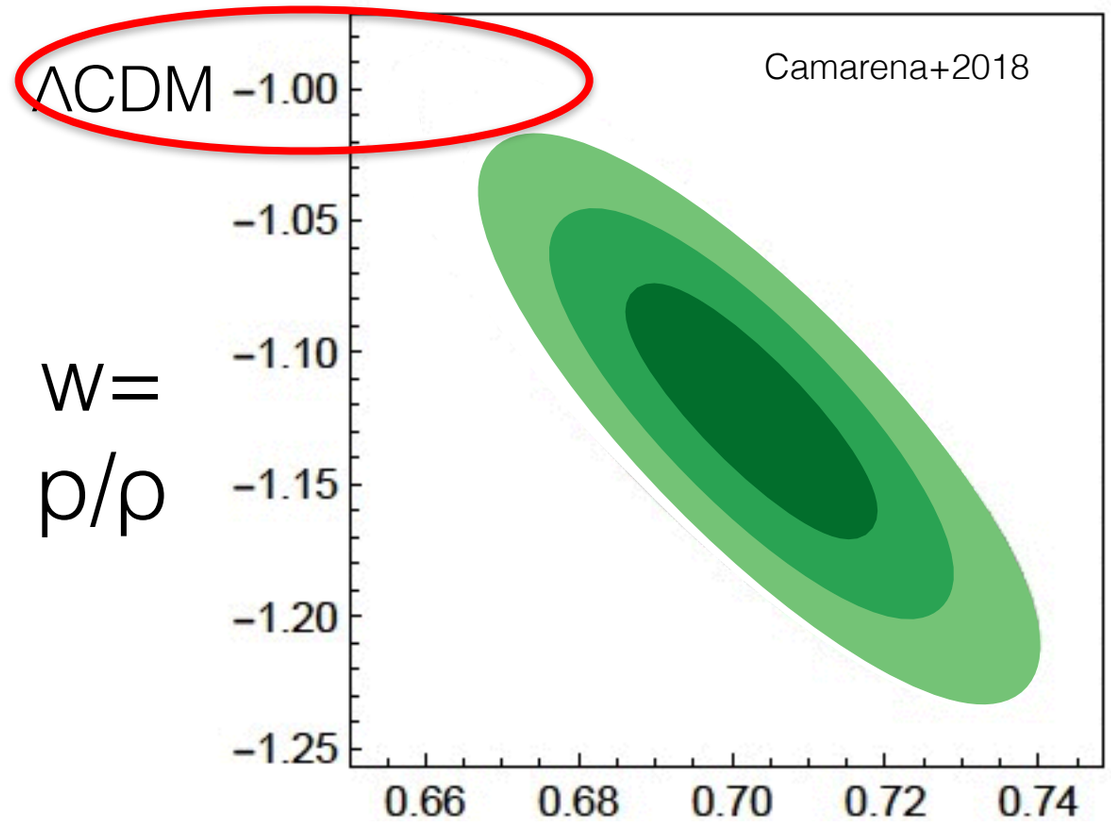
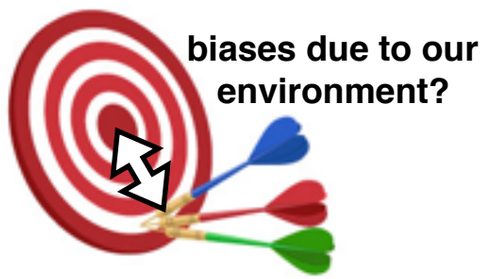
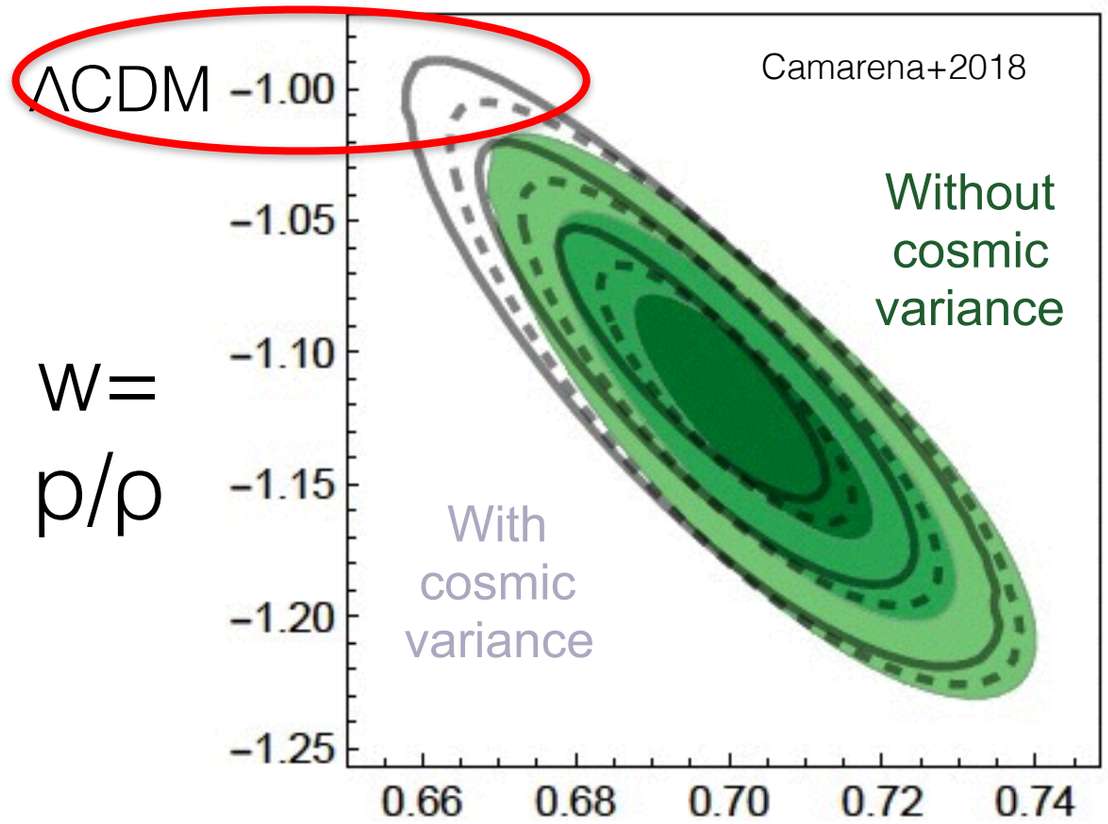




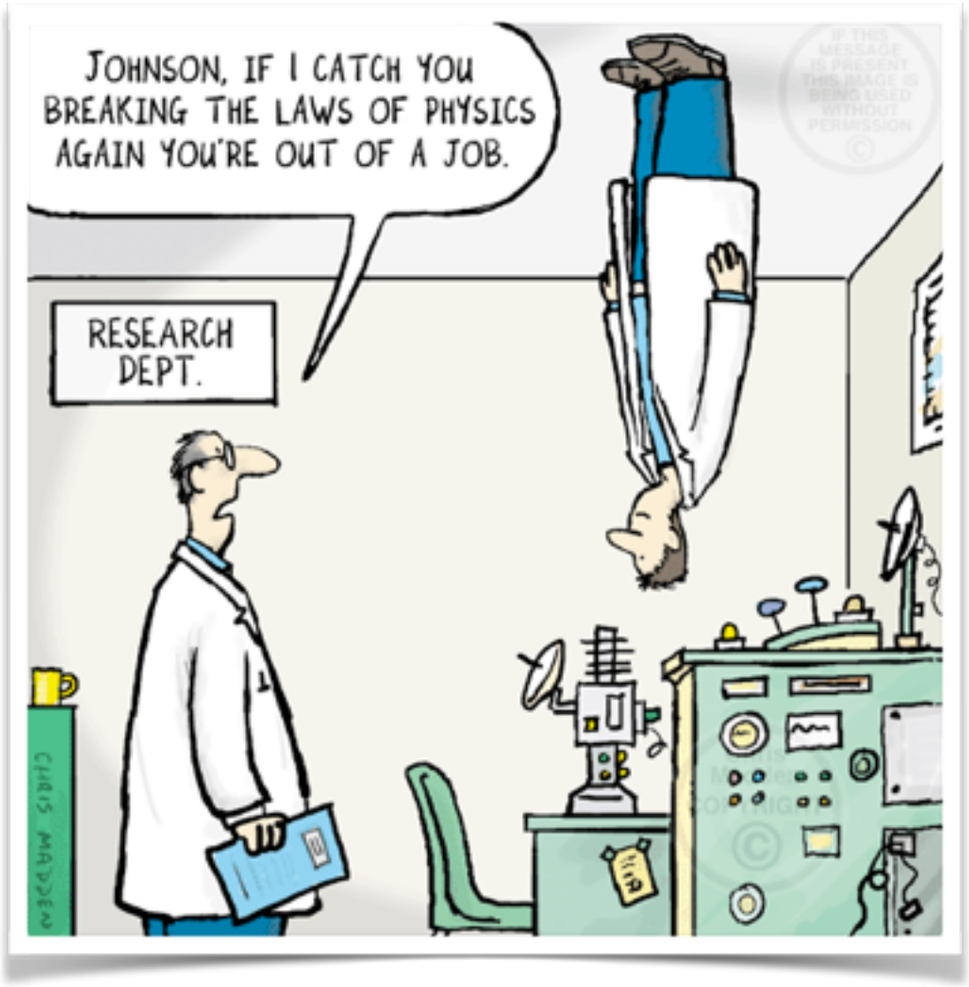
Motivation : ΛCDM? Both precision and accuracy are required!

Example: Equation of state of the dark energy



Accuracy:
1% bias non-negligible

When observations challenge ΛCDM

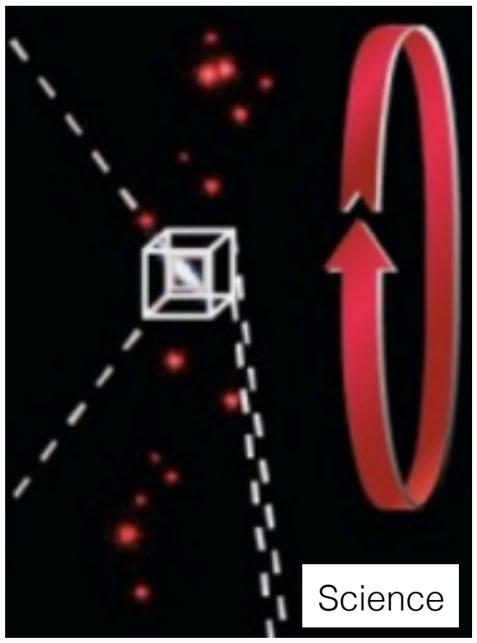


ΛCDM questioned? ➤ Precision cosmology

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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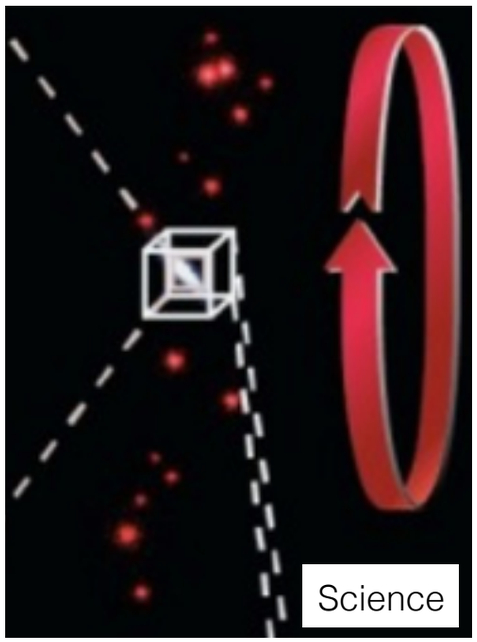

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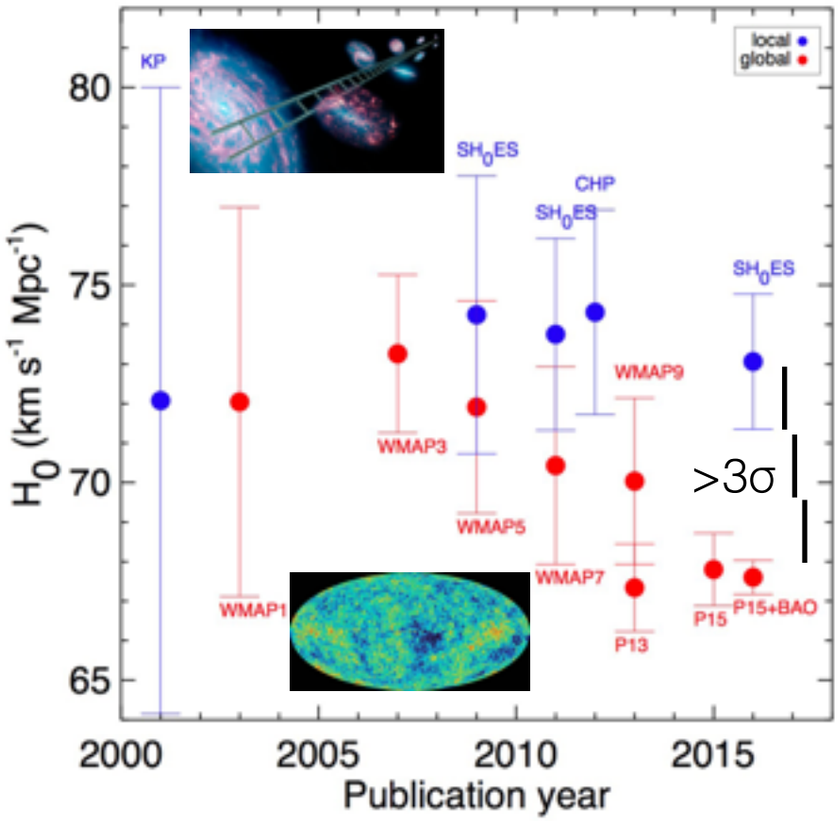

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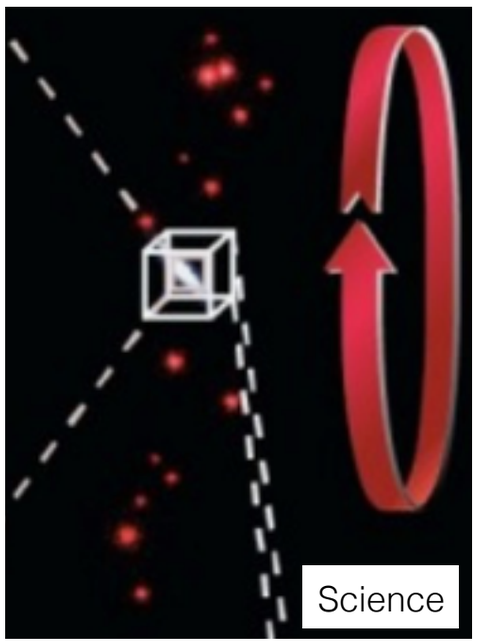

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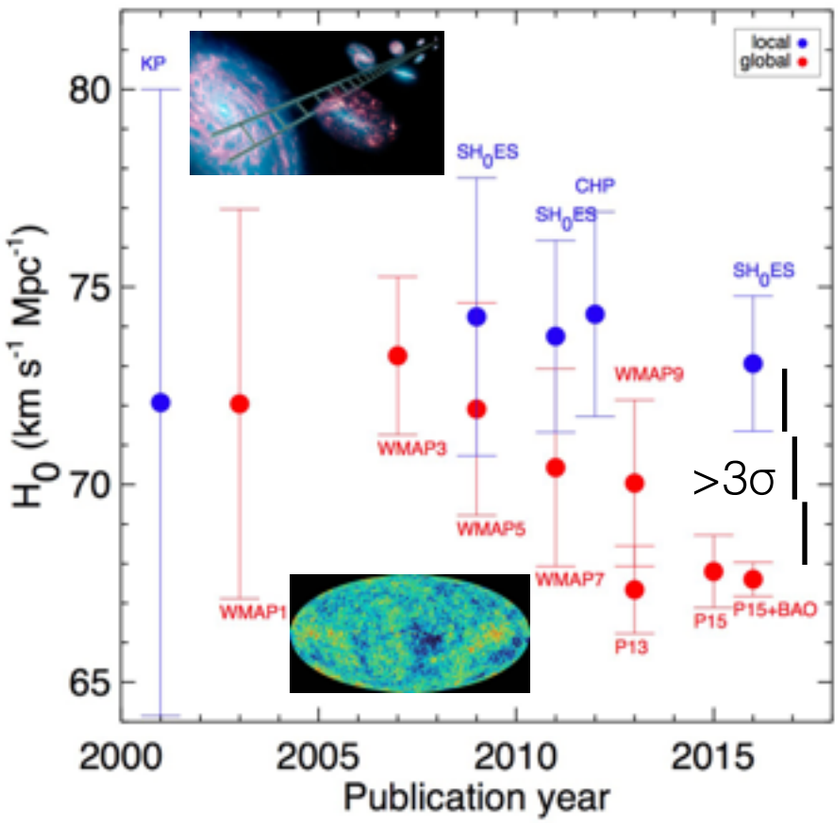

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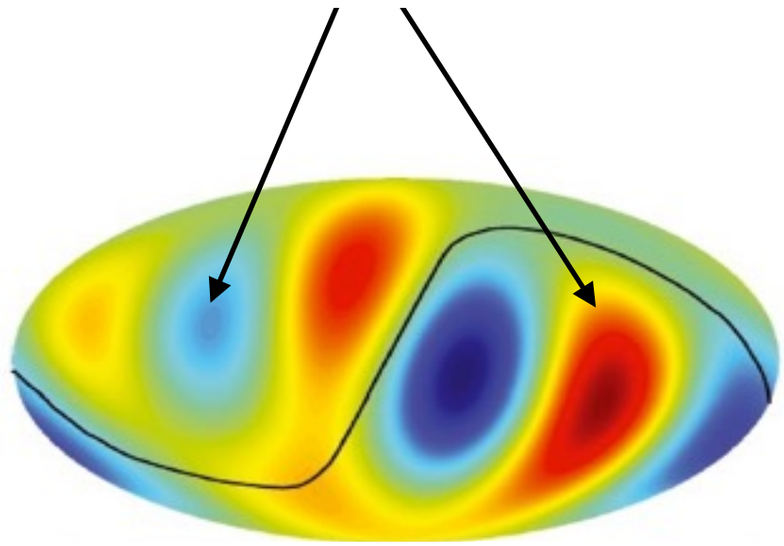

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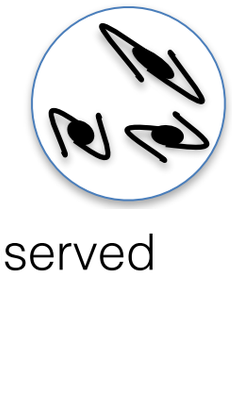
ΛCDM questioned? Precision cosmology

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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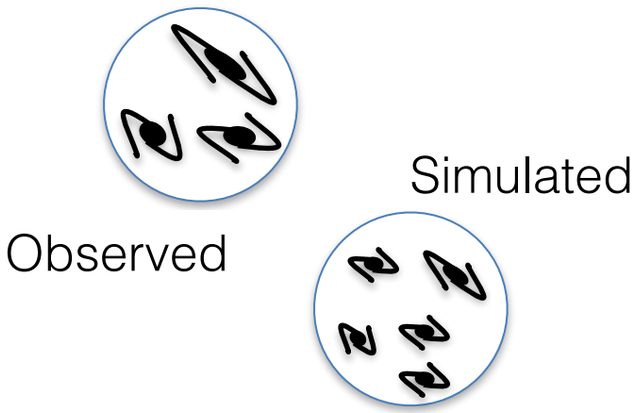

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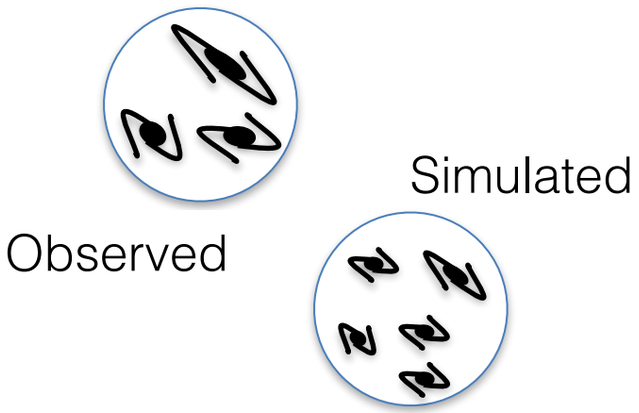

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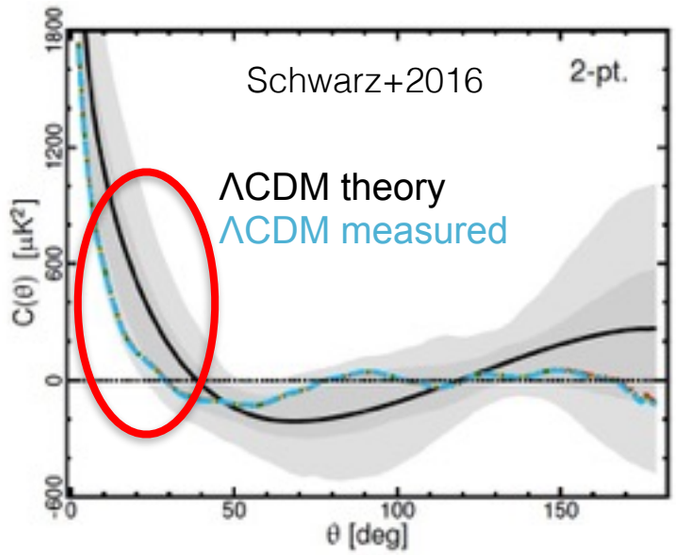

Lack of angular correlation at large angles

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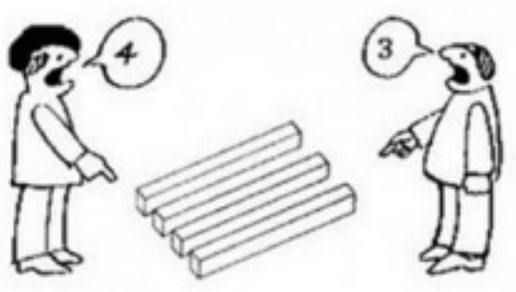
Questions?

Small scales

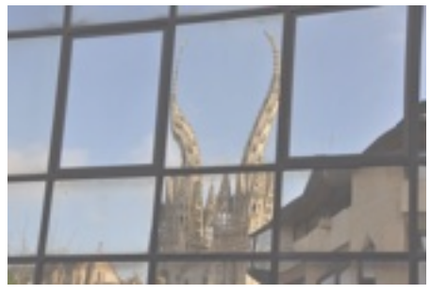
Are we comparing apple to apple?

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?

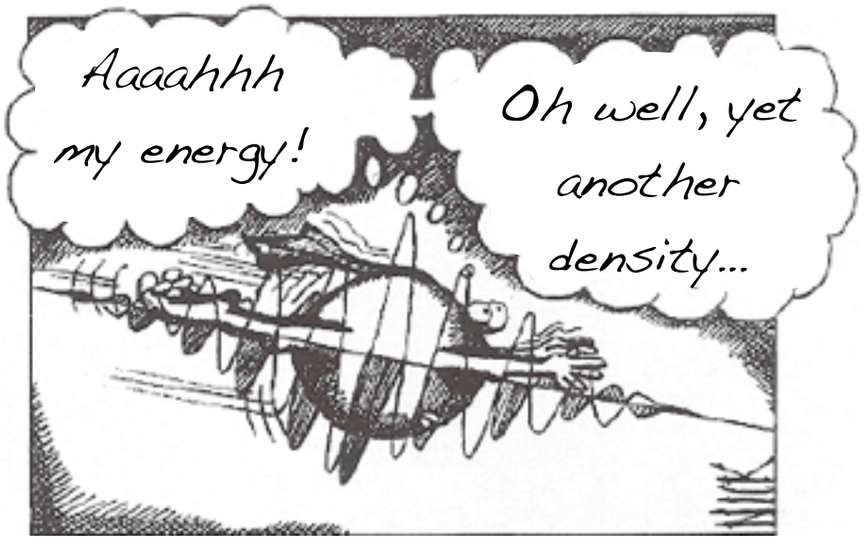
Small scales

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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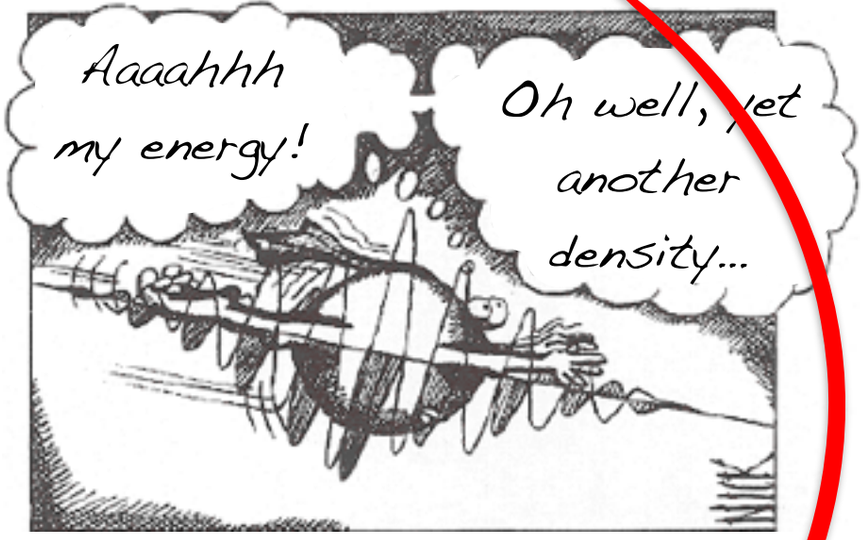

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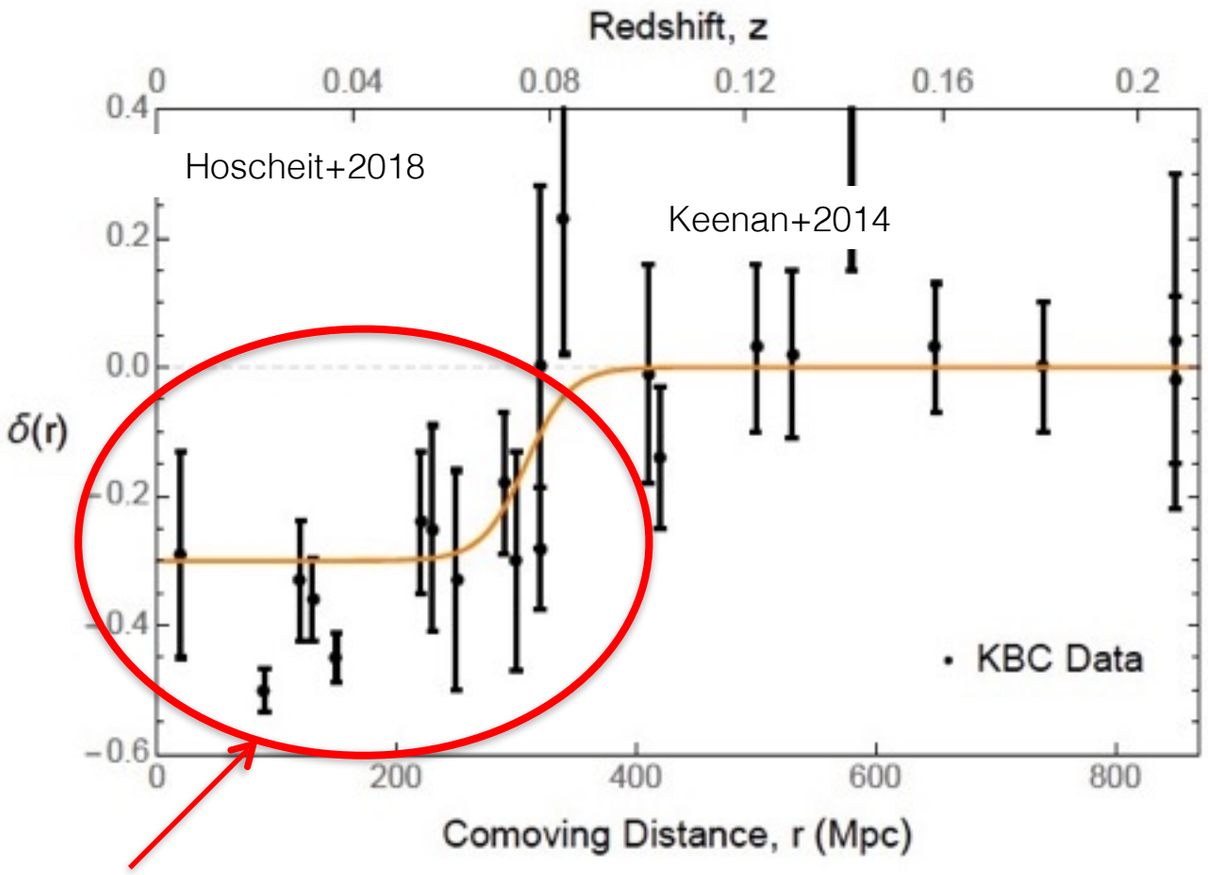
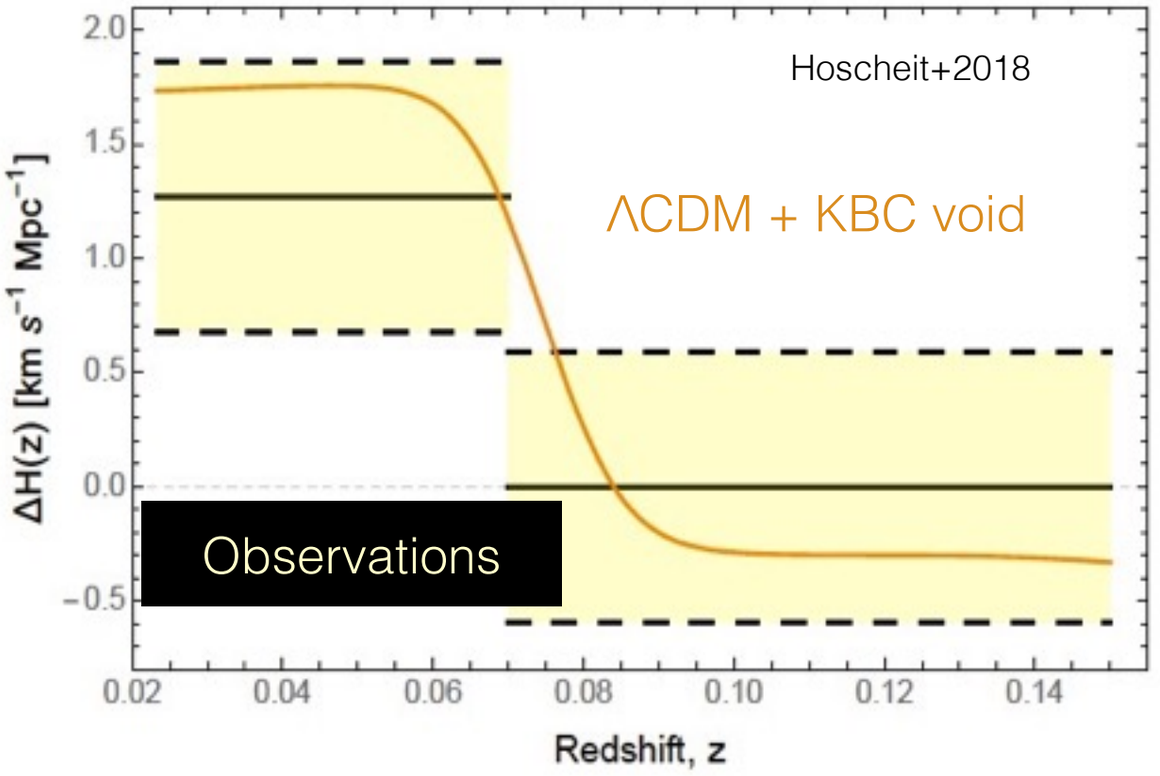
and eventually this can decrease *or increase* tensions with ΛCDM !

Local-induced biases on the local scales

A simple example: we live in a spherical underdensity

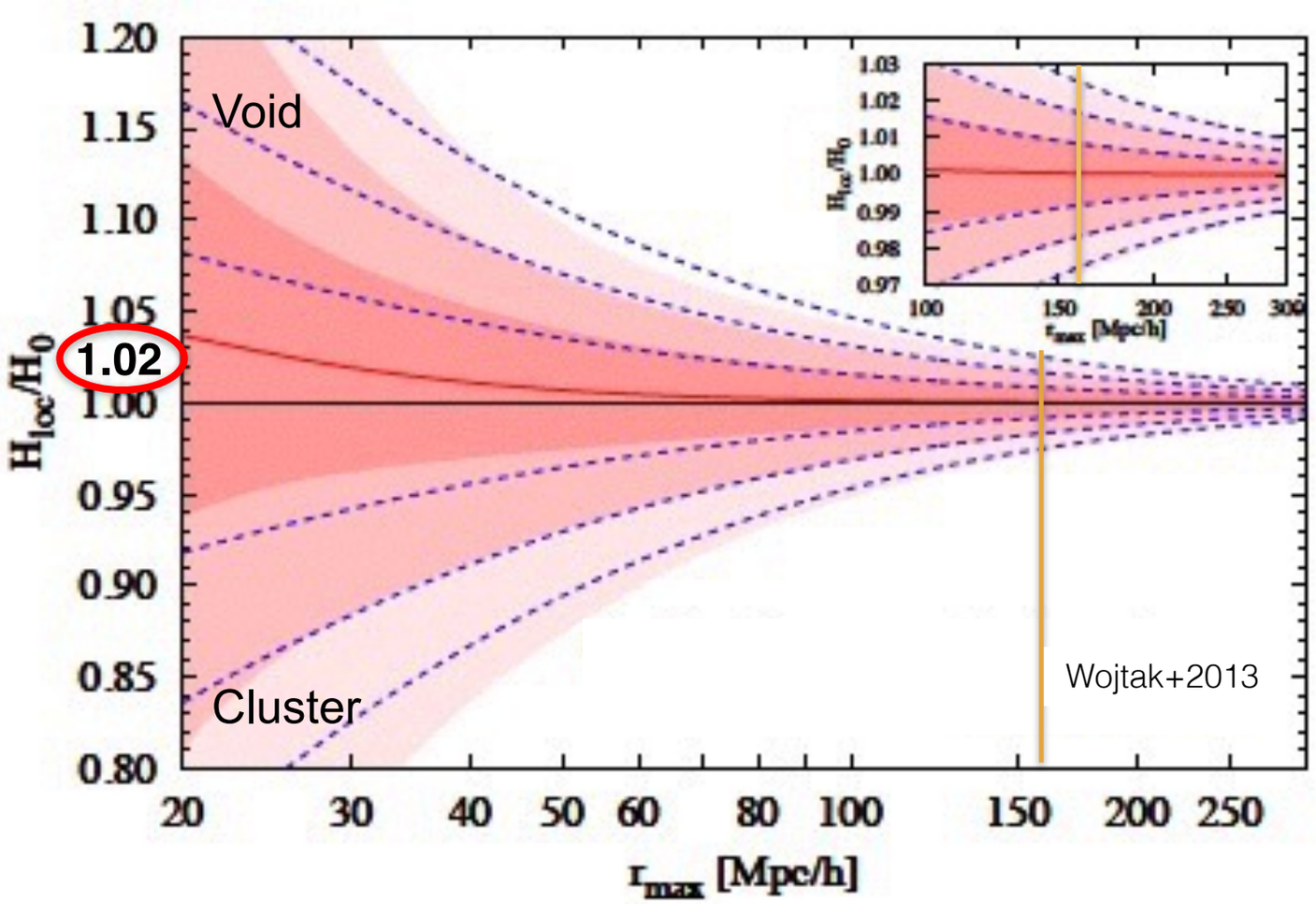


An example: Hint at a local underdensity up to z=0.07



Local-induced biases on the local scales

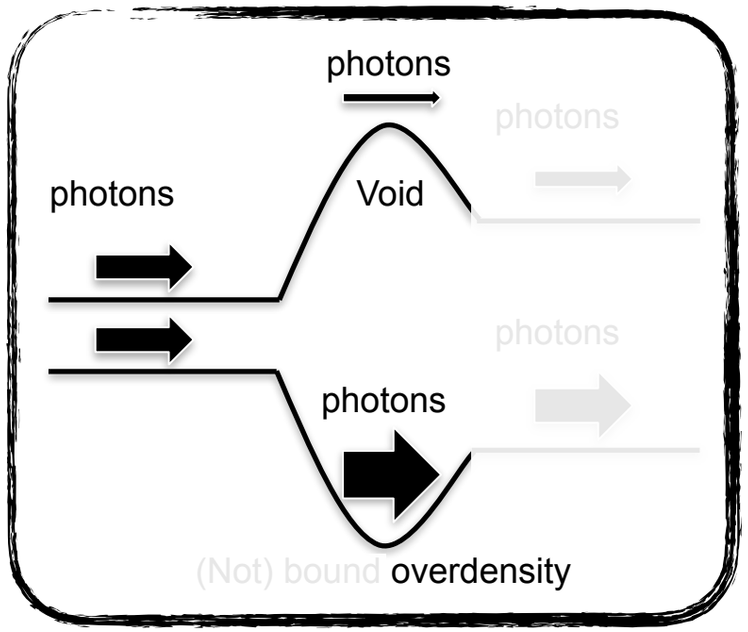
As many effect values as environments



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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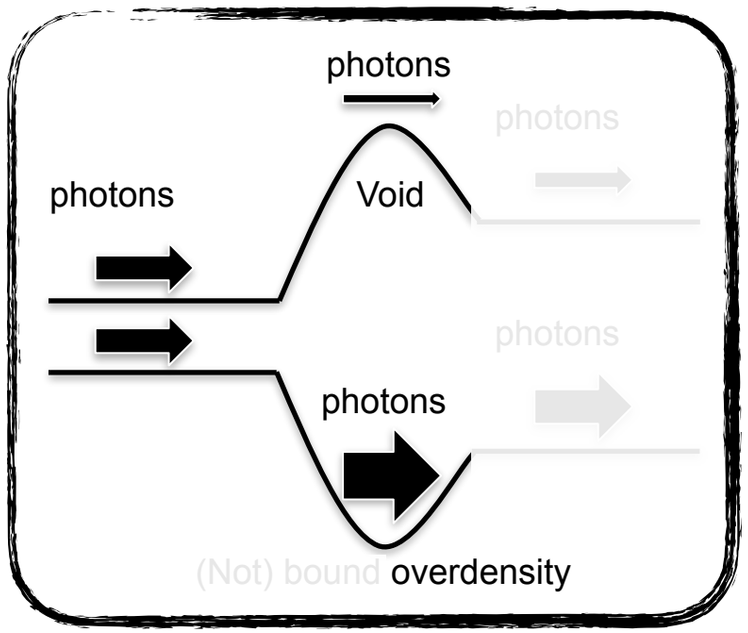

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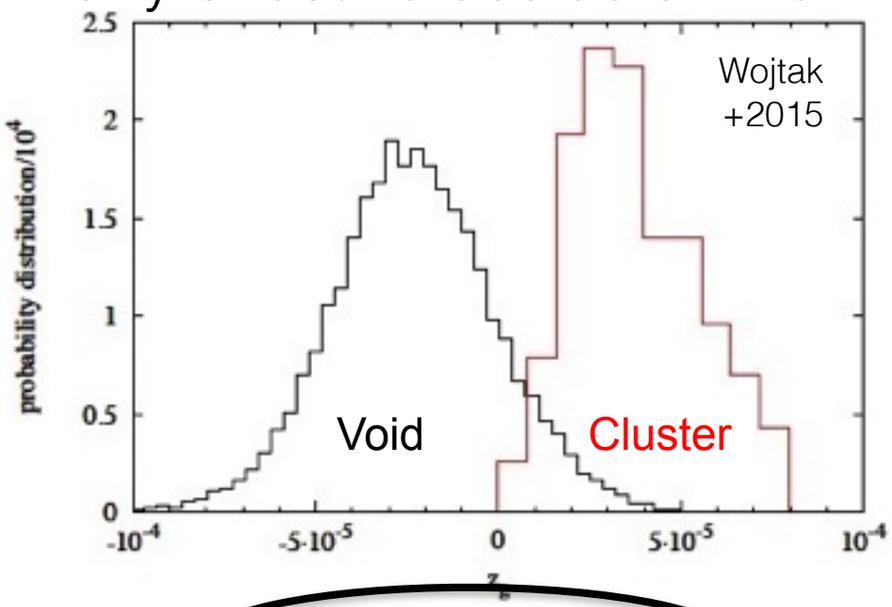

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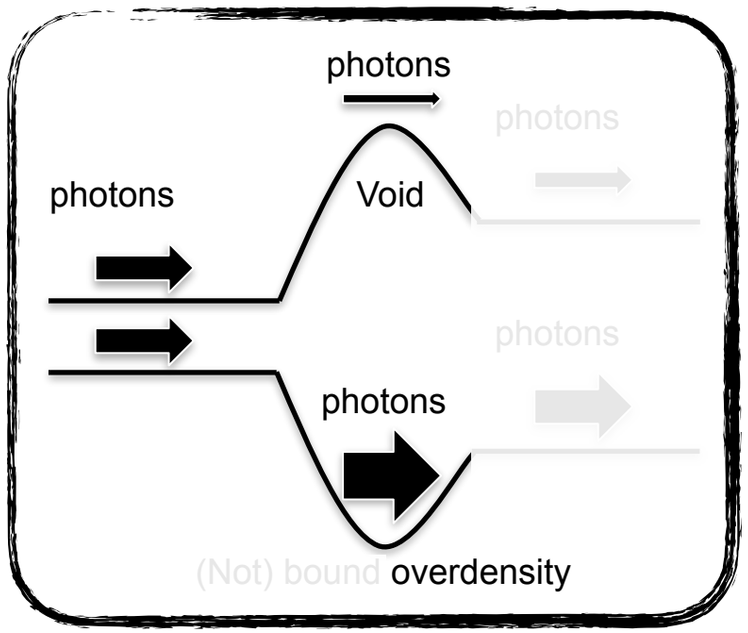

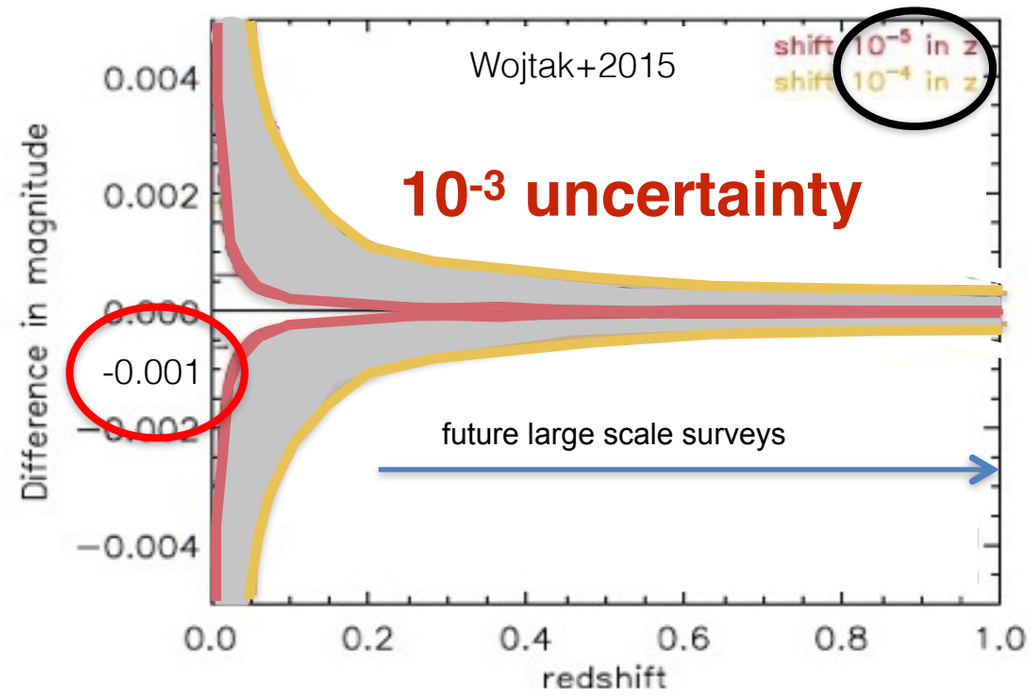

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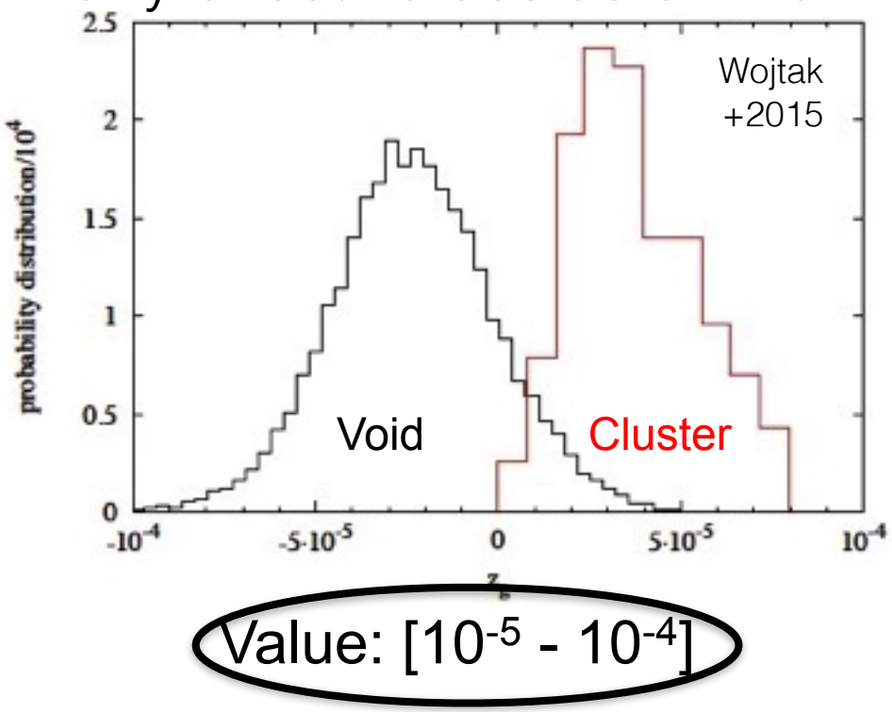

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Required Precision !

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

Local-induced biases on the large scales

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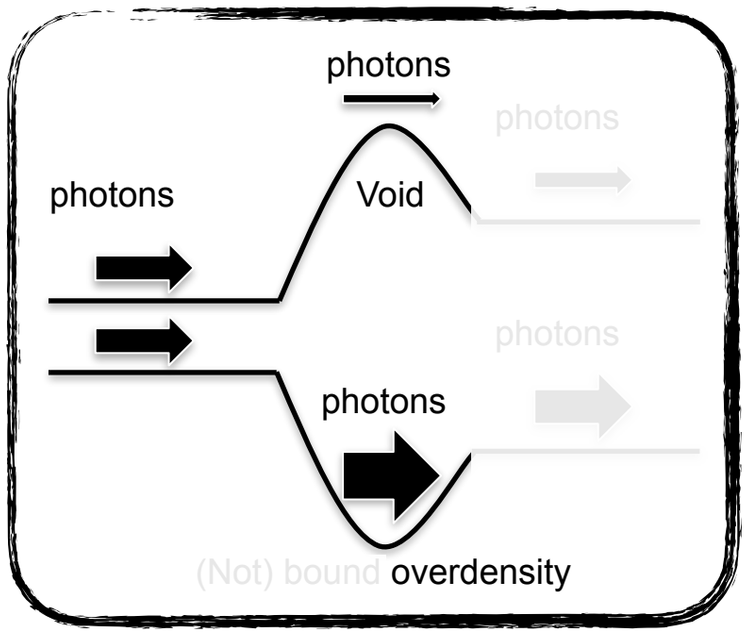

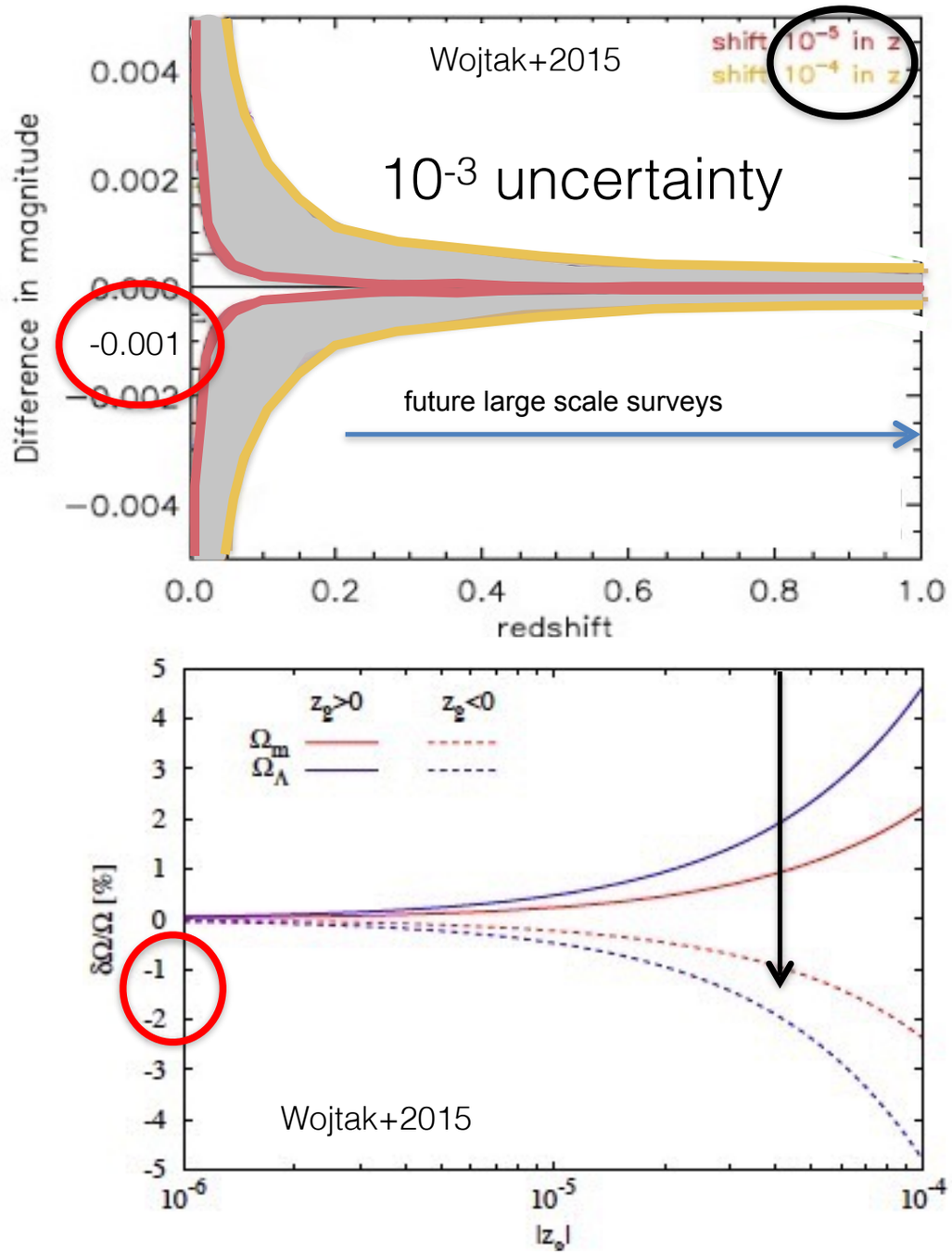

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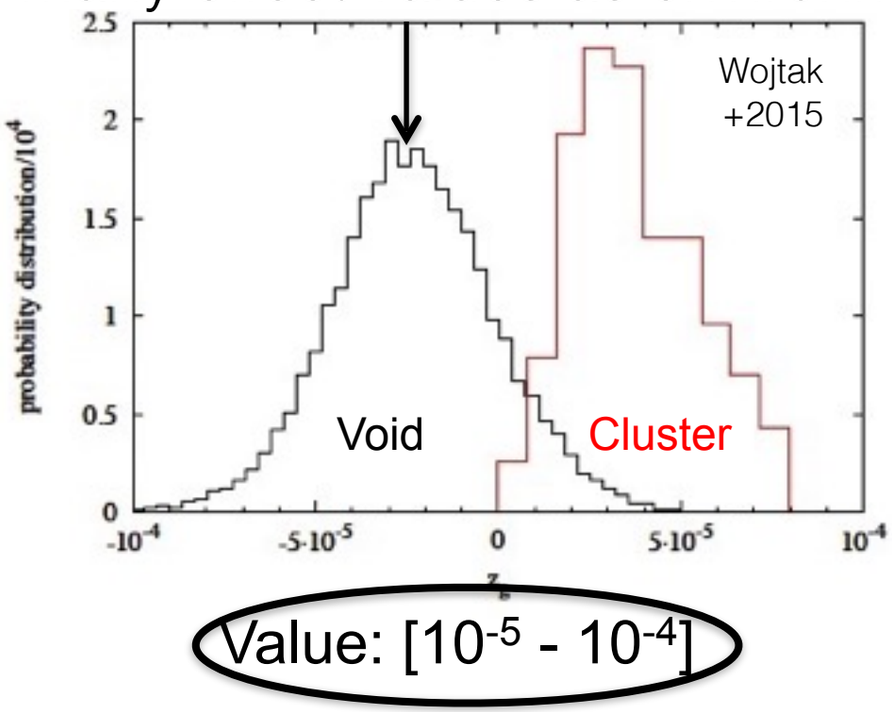

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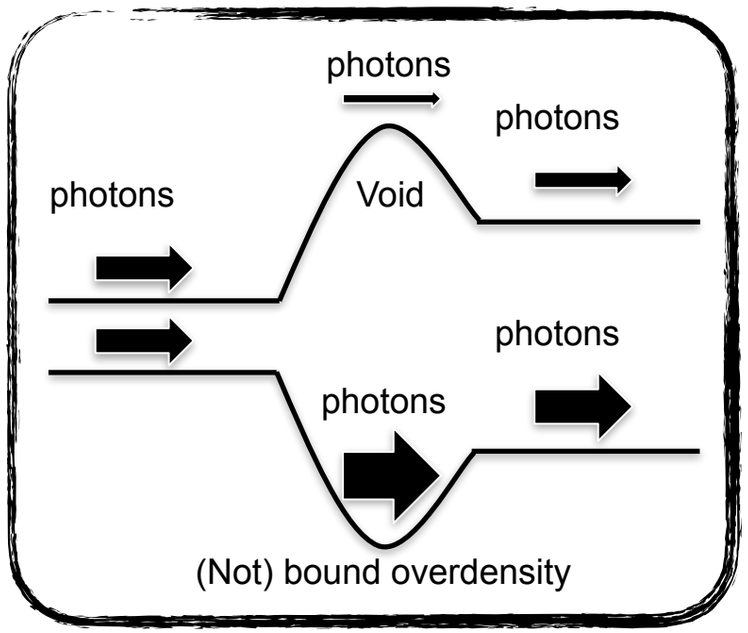
For an average environment: a 1-2% bias !

Local-induced biases on the large scales

Gravitational redshifts and the large scale surveys



Integrated Sachs-Wolfe Effects

As many effect values as environments

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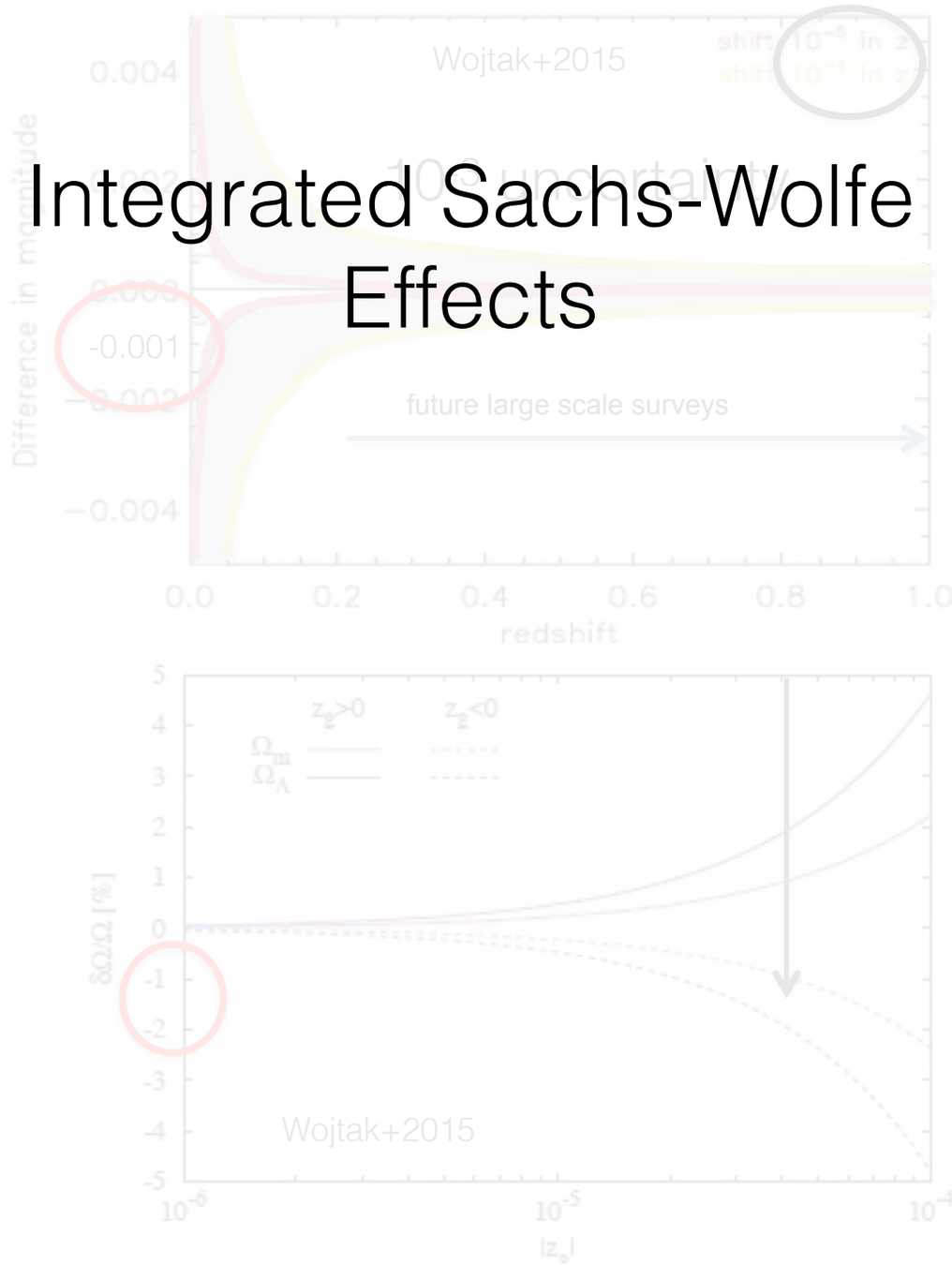
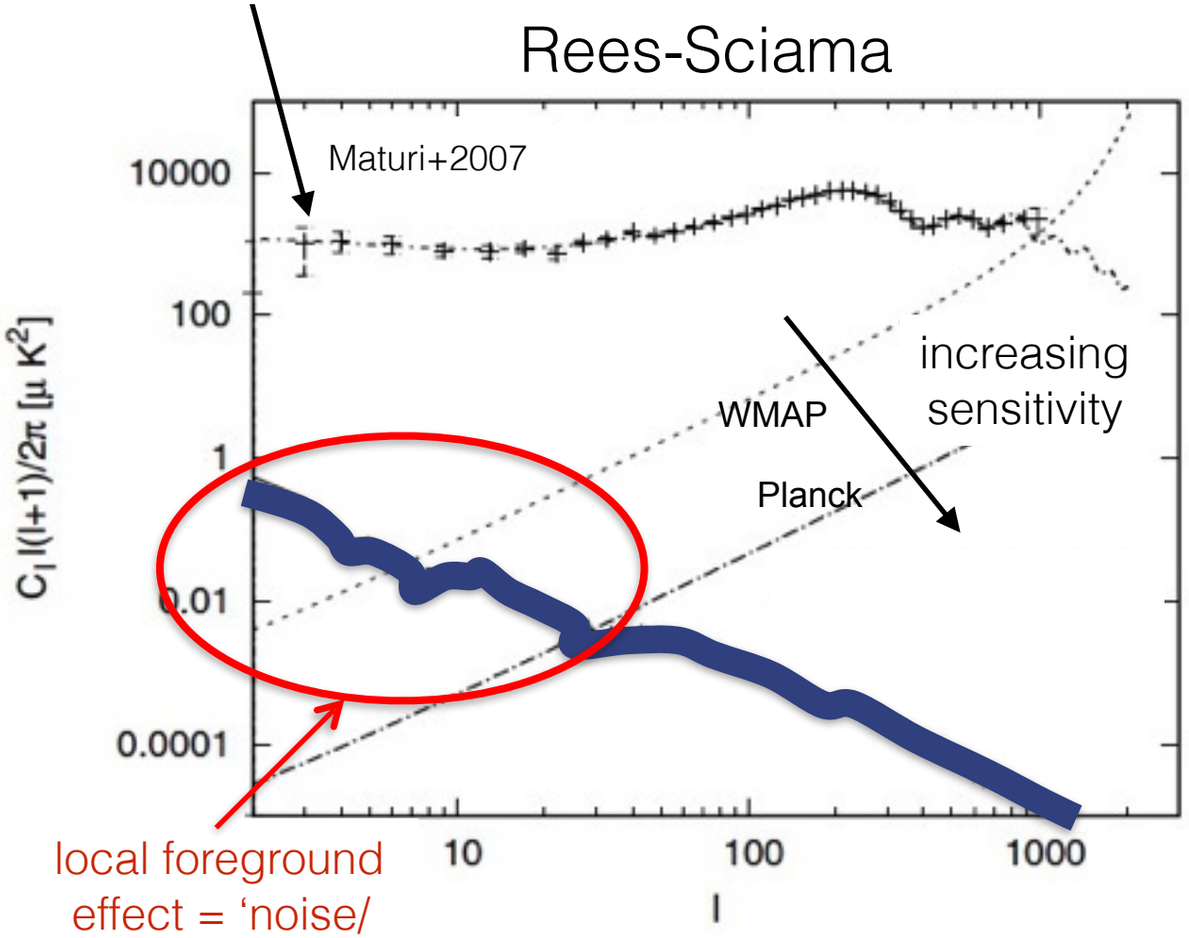


For an average environment: a 1-2% bias !

Local-induced biases on the large scales

Gravitational redshift, Sunyaev Zel'dovich and the CMB

increasing precision
= reducing error bars



local foreground effect = 'noise/ bias'

Local-induced biases on the large scales

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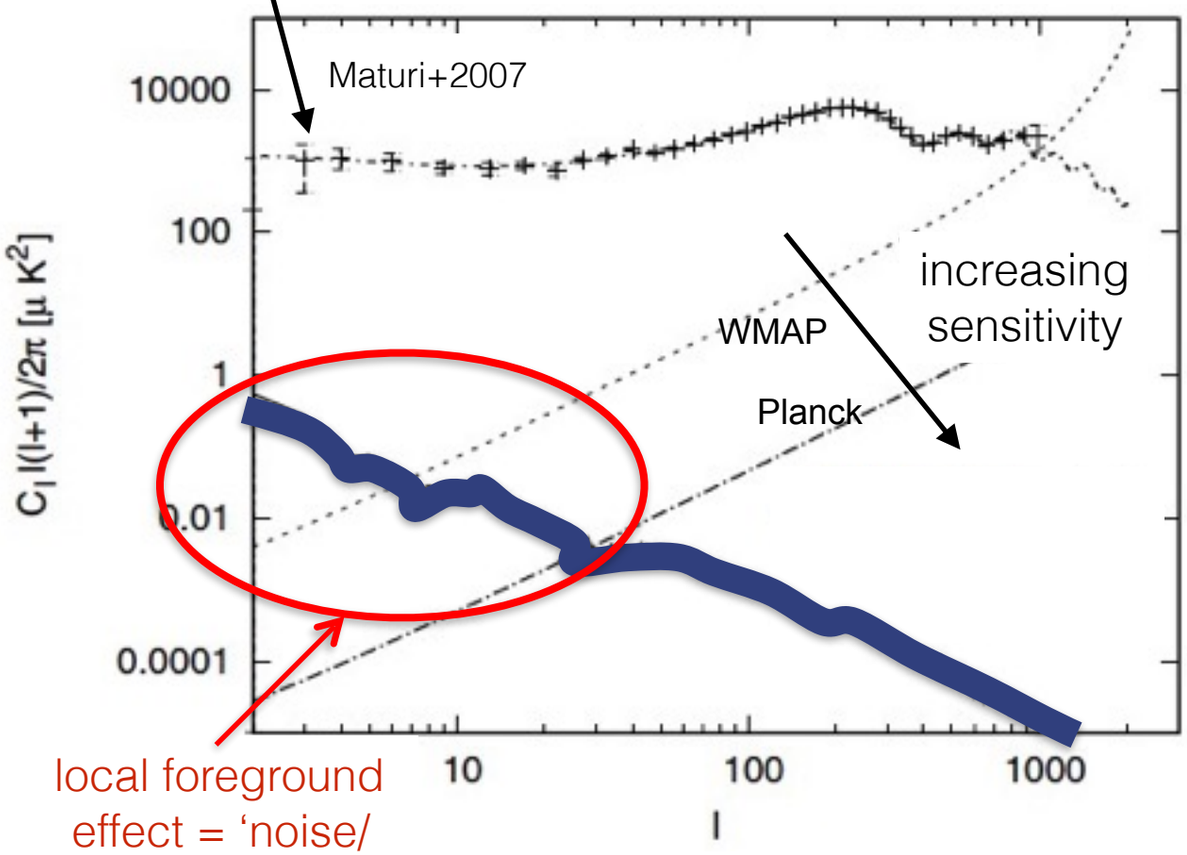
Rees-Sciama



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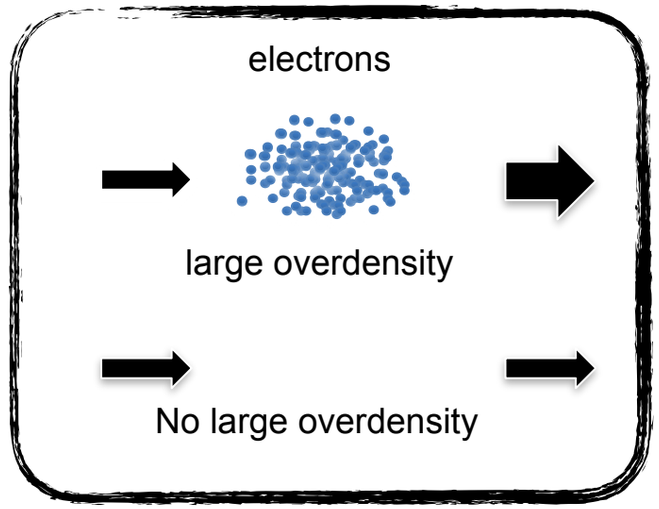
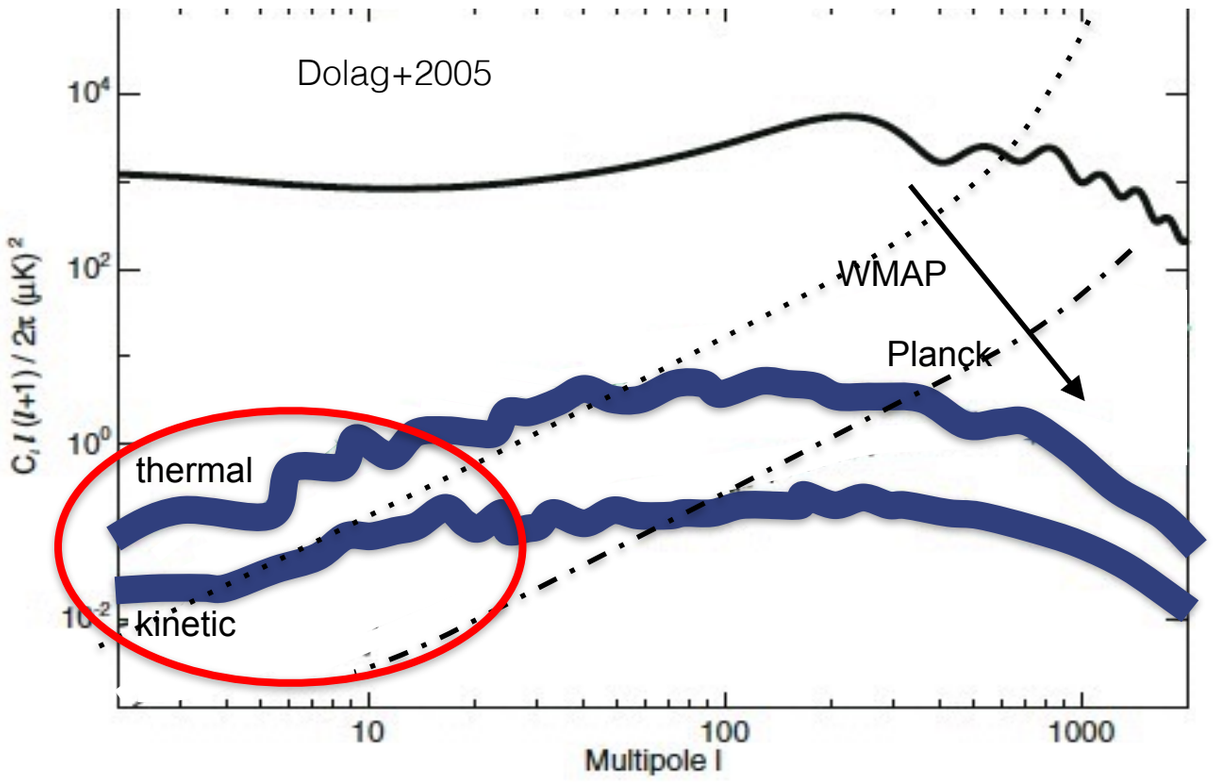
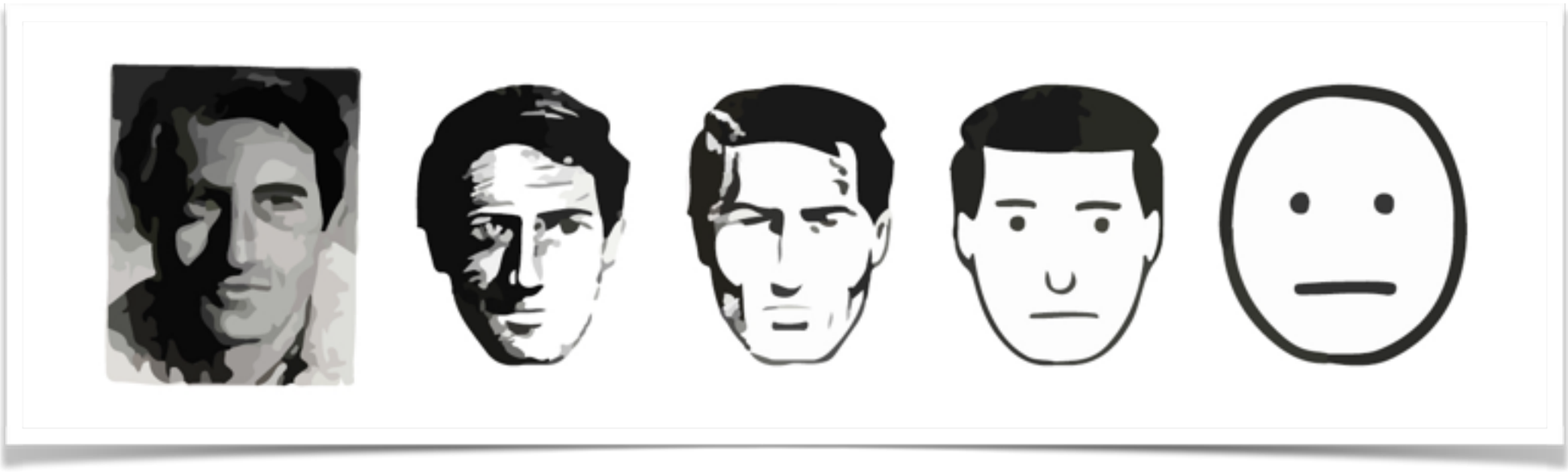




A crude modeling is a beginning…

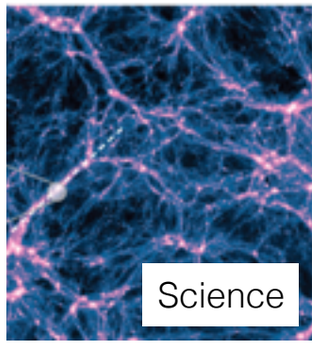


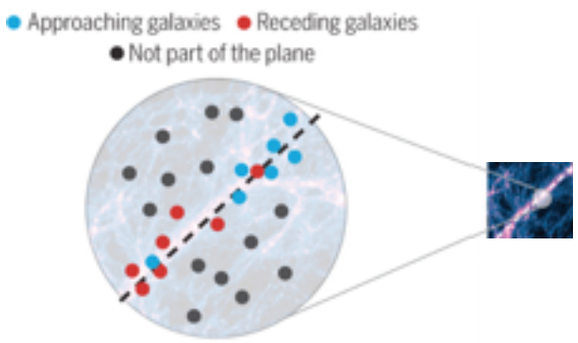
but not nearly enough…

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

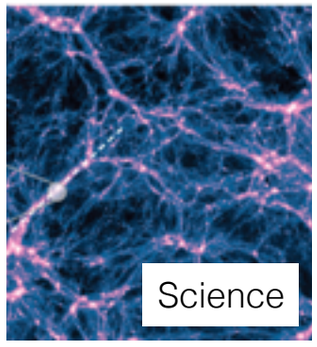
Francis+2010

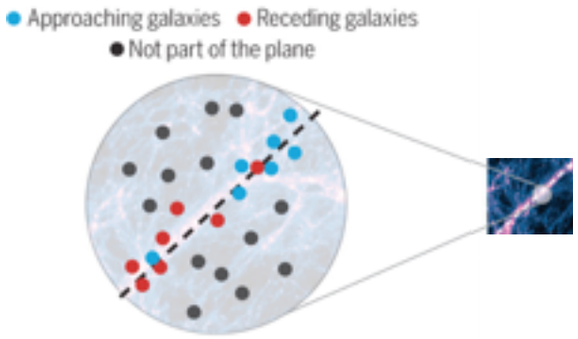
But correction from redshift surveys only…

Accounting for the effects ➤ crude modeling

A few examples

Small scales





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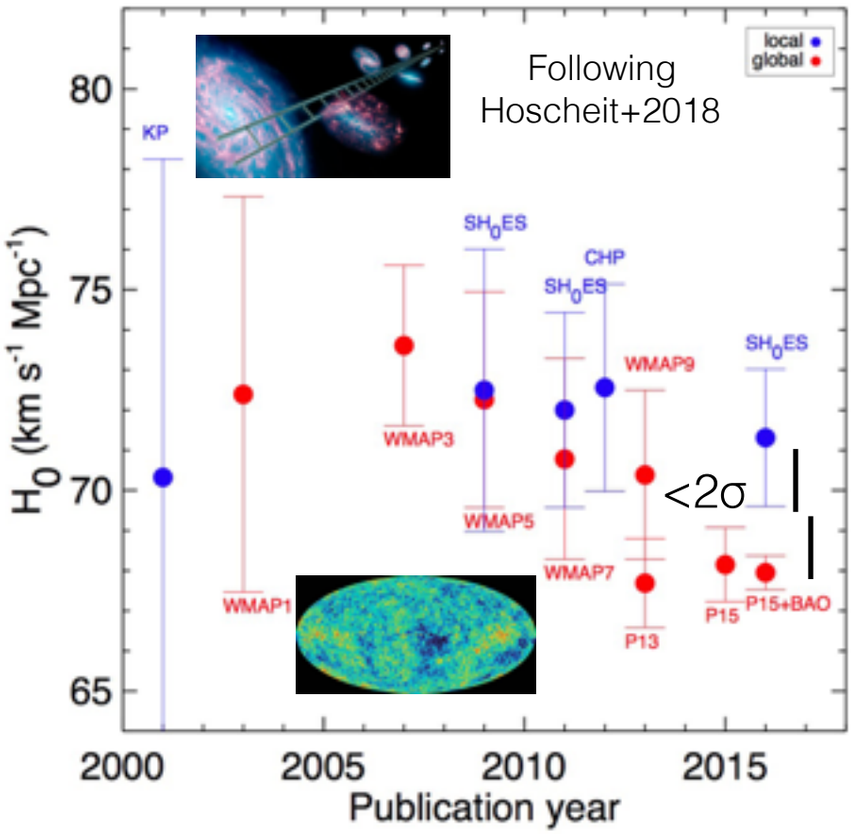

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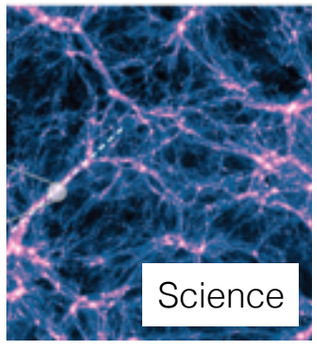

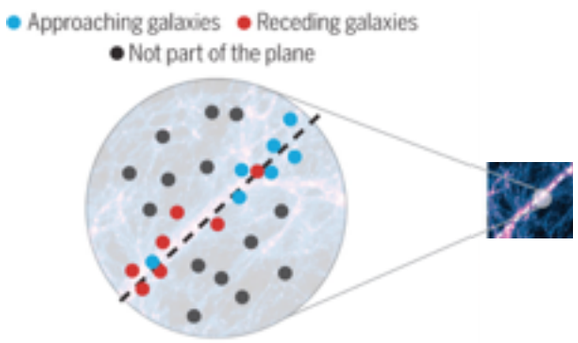

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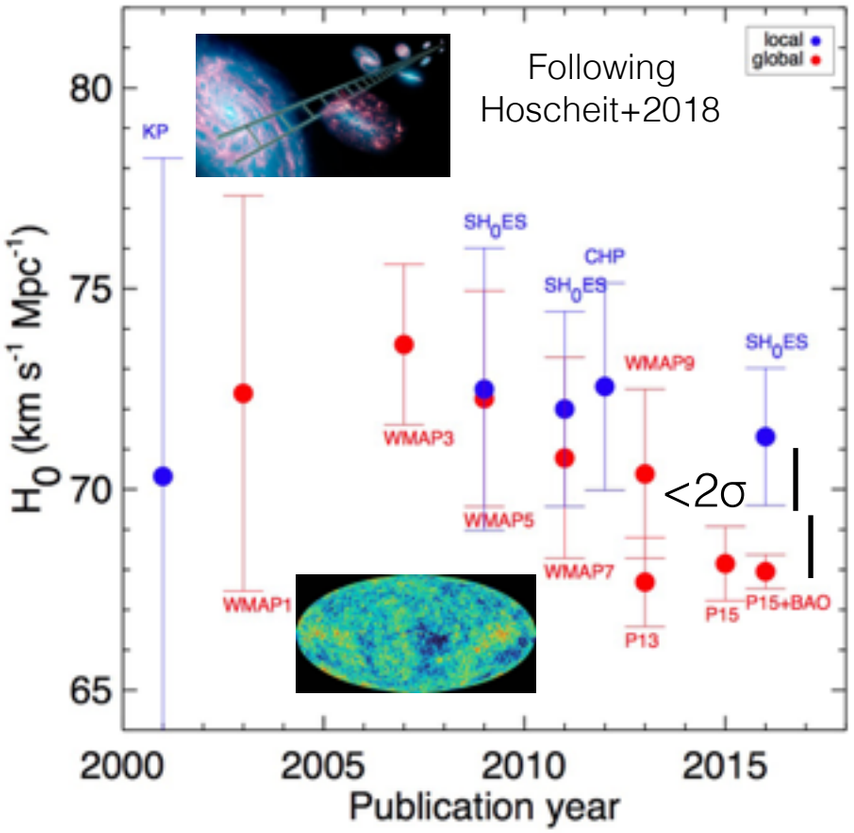

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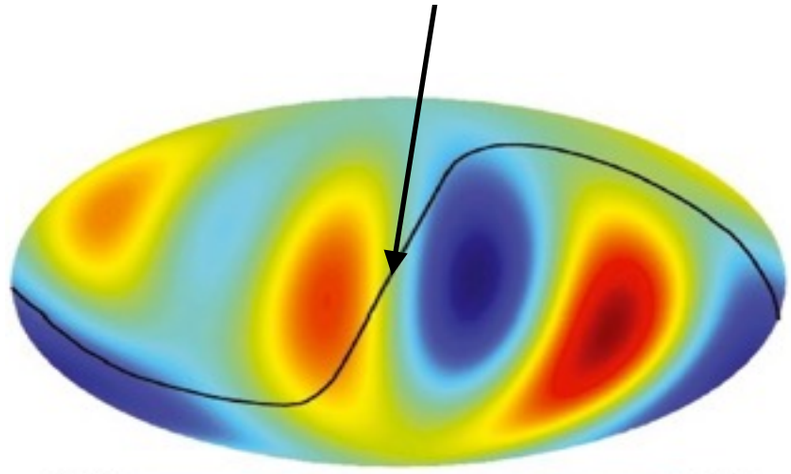

Francis+2010

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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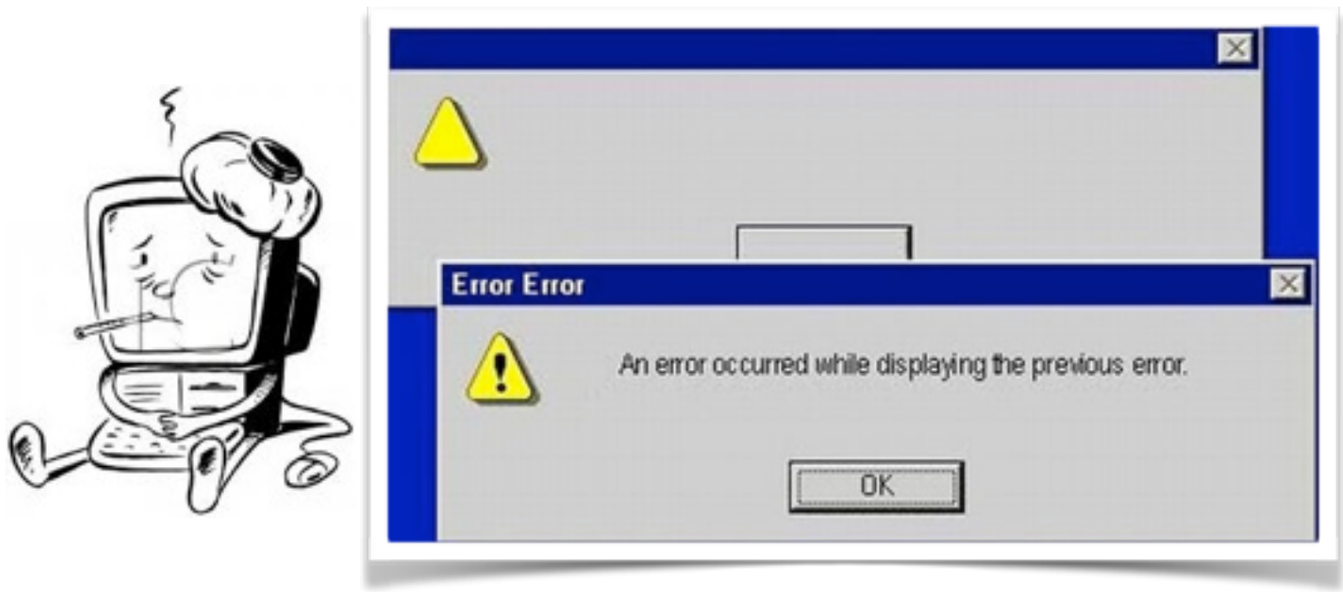
→ **Initial conditions of the local Universe**

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			☑

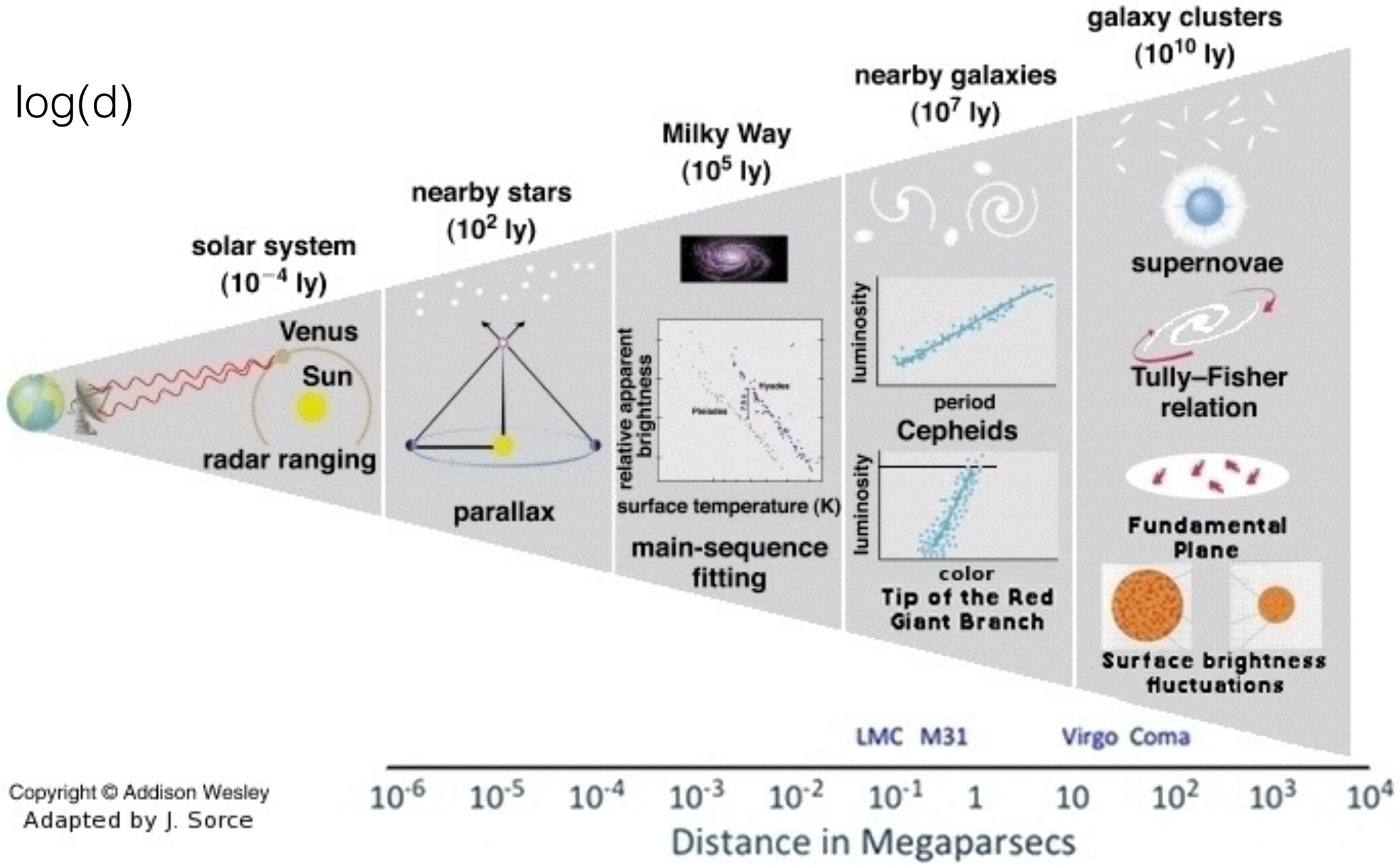
no luminosity bias

"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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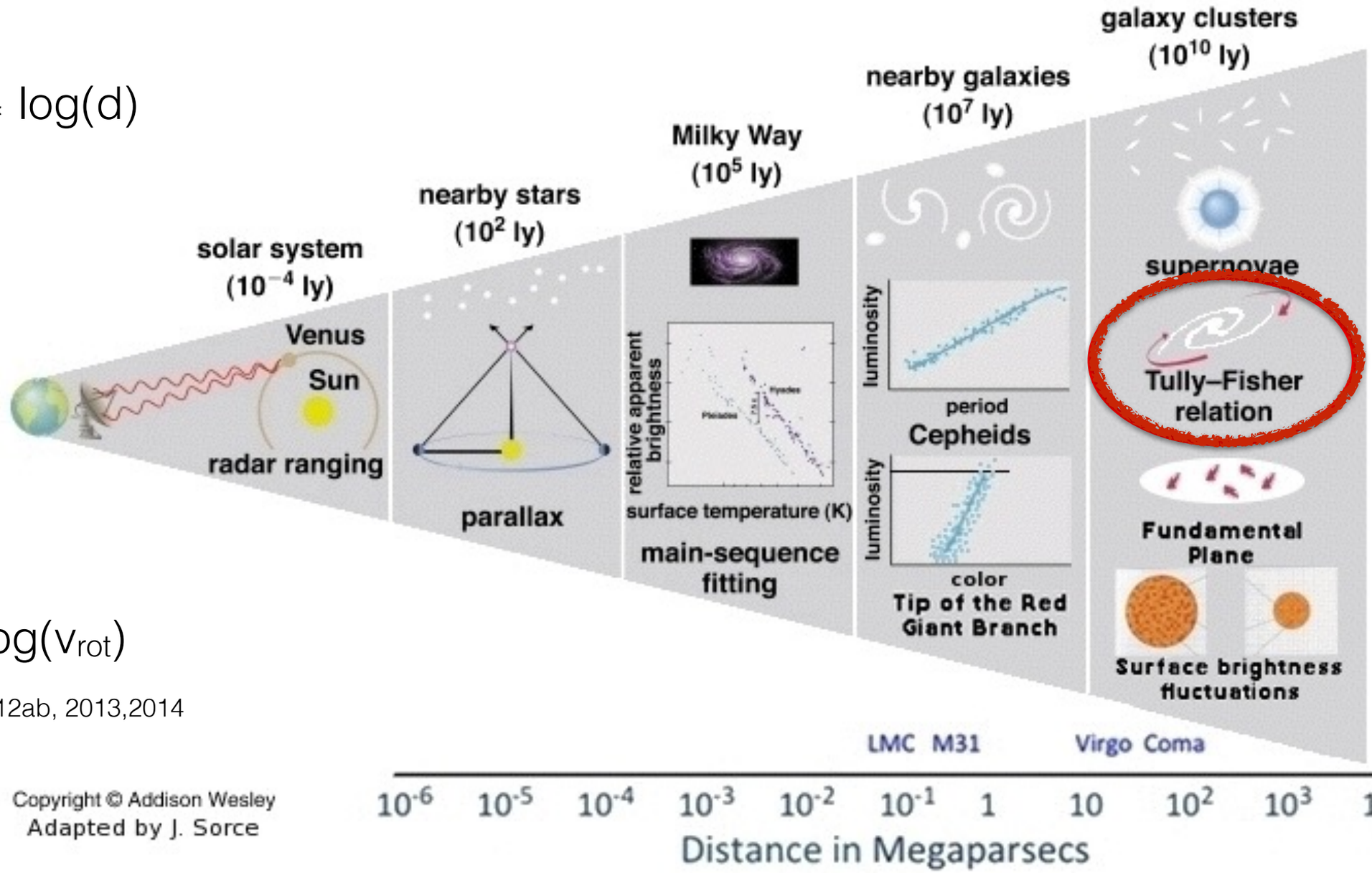
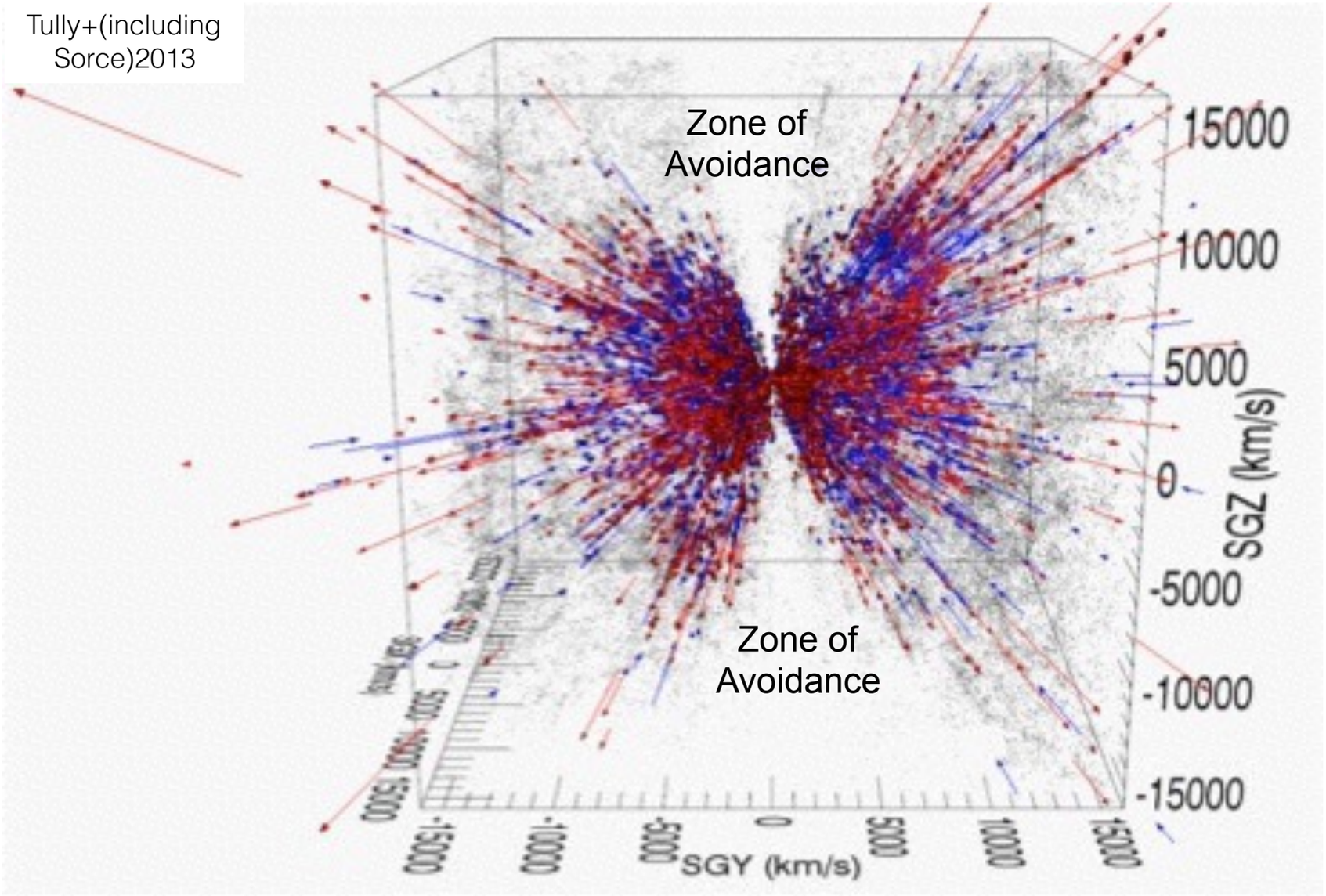


M ∝ log(v_{rot})

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

Peculiar velocities catalog

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



- 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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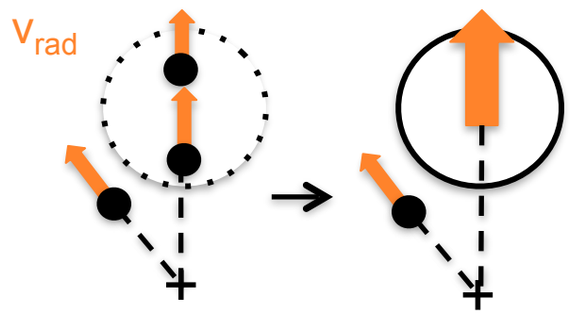

Distance (modulus) of the group and its uncertainty

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

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

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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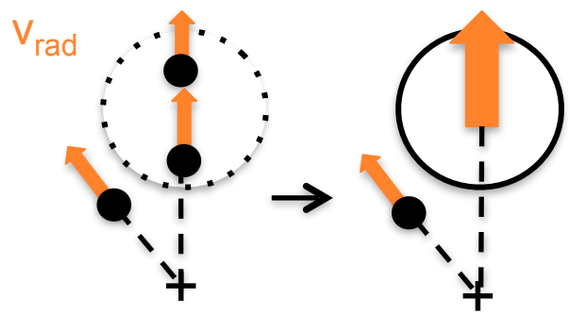

Distance (modulus) of the group and it ertainty

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

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

The biggest difficulty is to determine the groups !

Pec .ie group and its uncertainty

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

Method

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↓

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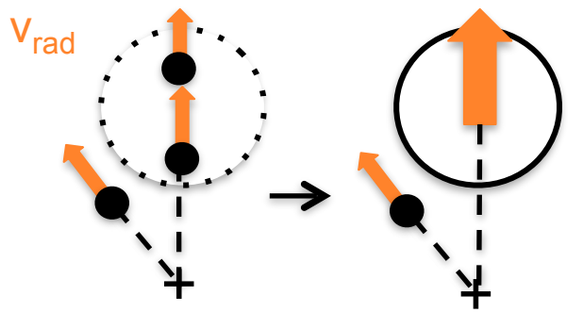
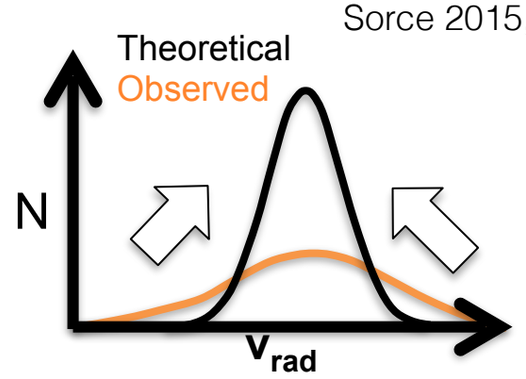
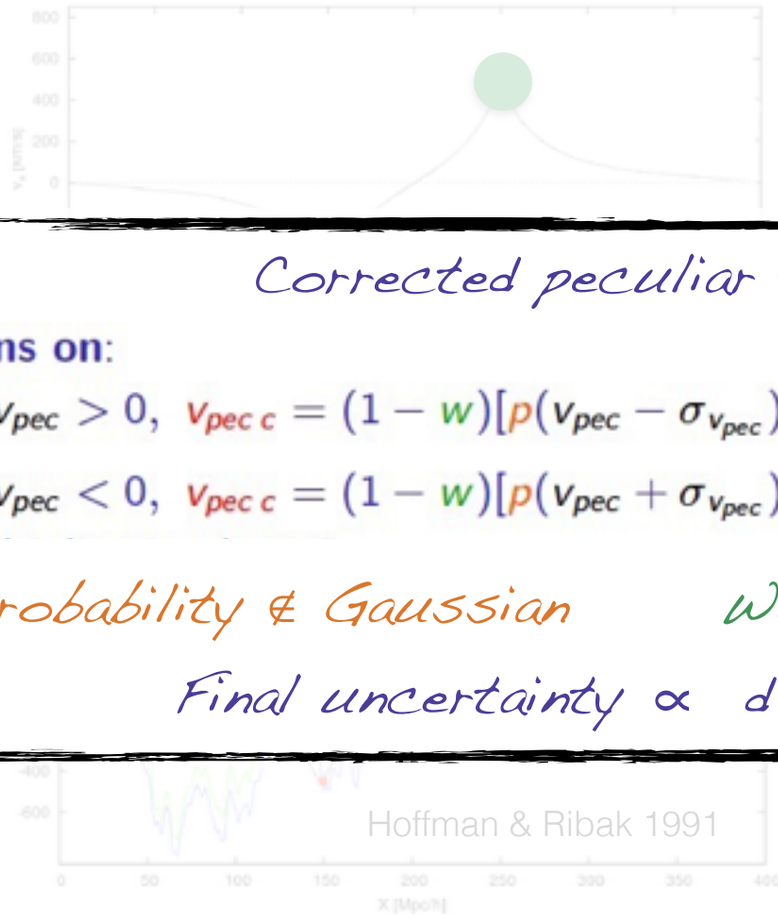


Sorce 2015, 2018





Corrected peculiar velocities

Iterations on:

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

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

Probability & Gaussian *Weighted uncertainty*

Final uncertainty ∝ d & $n_{constraints}$

Method

Radial peculiar velocity catalog

↓

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↓

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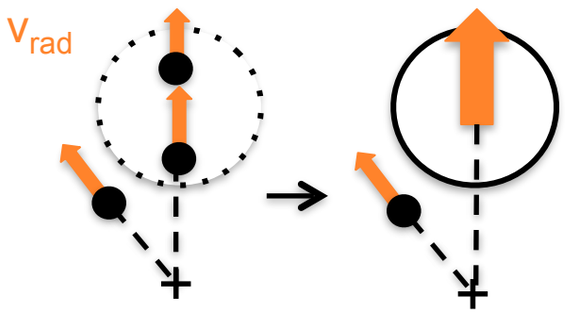
Sorce & Tempel 2017,2018



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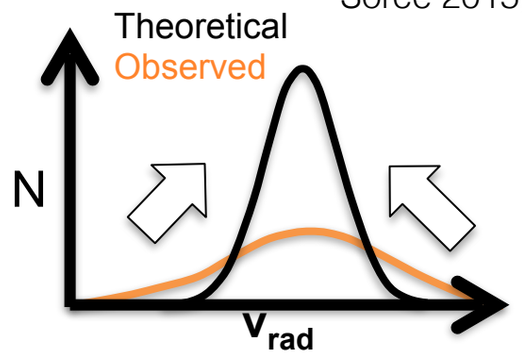

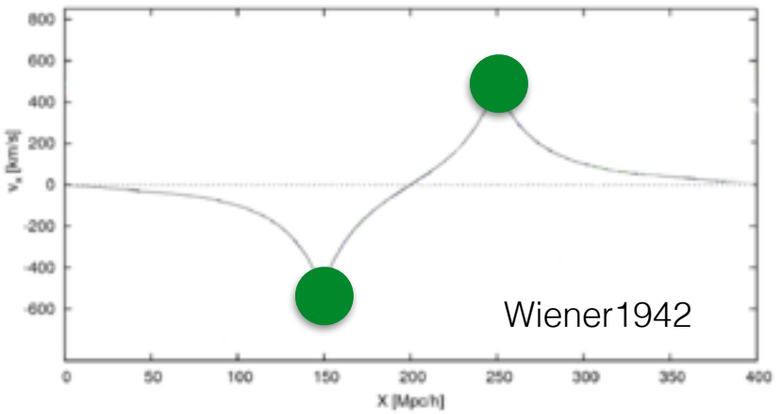

Doumler+2013 Sorce+2014

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

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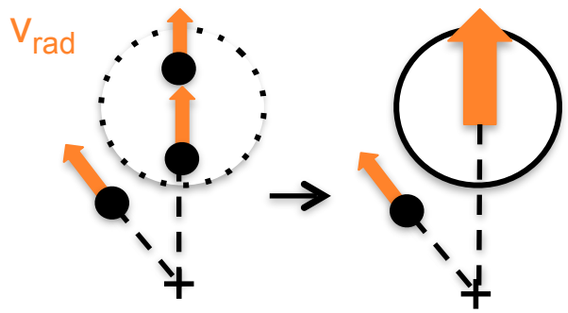

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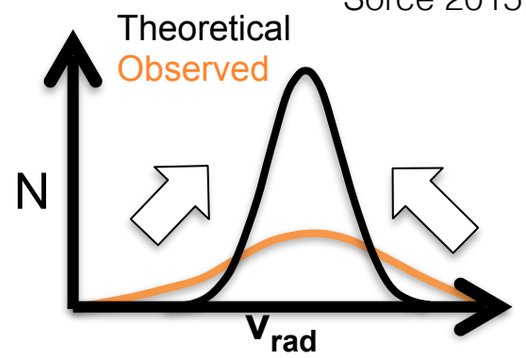

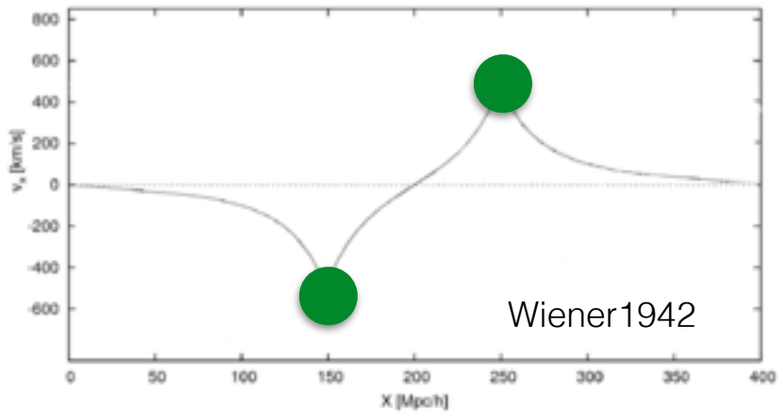

Doumler+2013 Sorce+2014

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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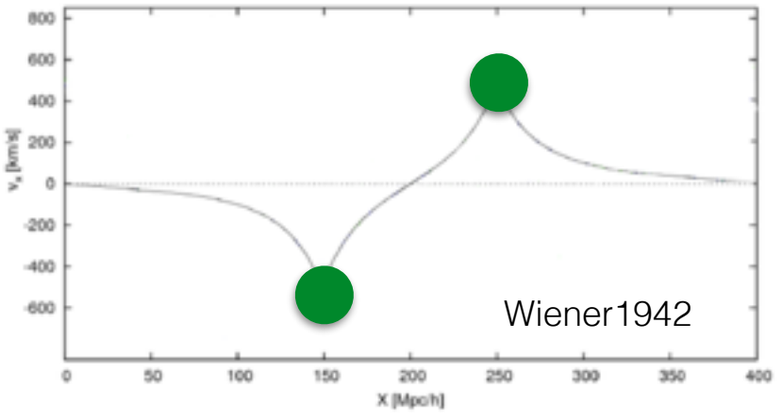
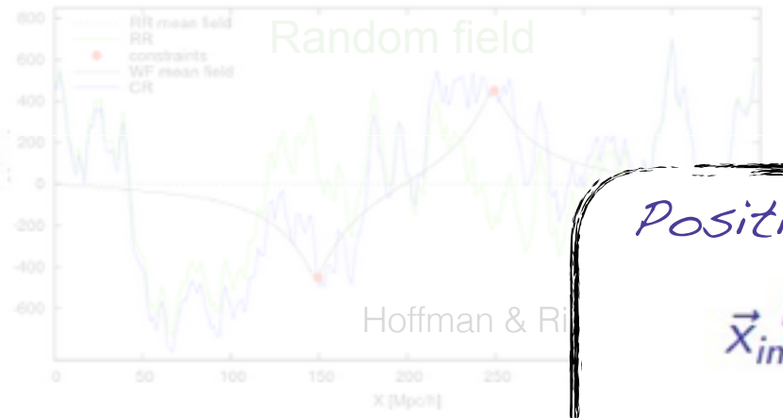
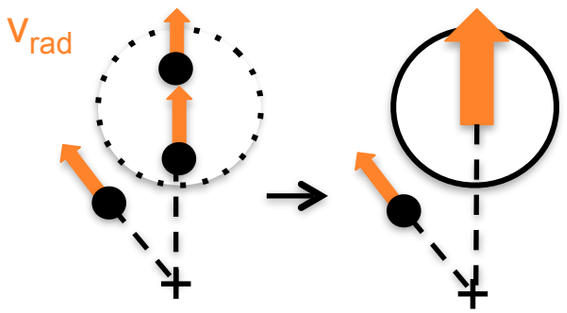




Sorce & Tempel 2017,2018



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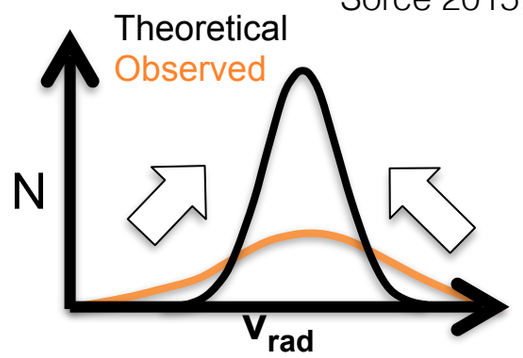

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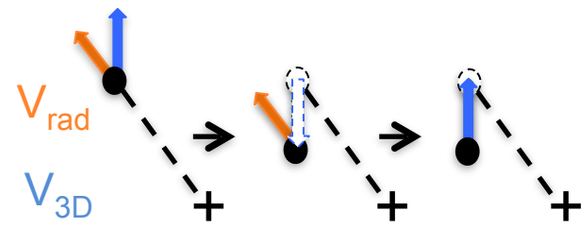

Position of the progenitors

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

growth rate

Method

Radial peculiar velocity catalog

↓

Grouping

↓

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↓

Wiener filtering

↓

Reverse Zel'dovich Approximation

↓

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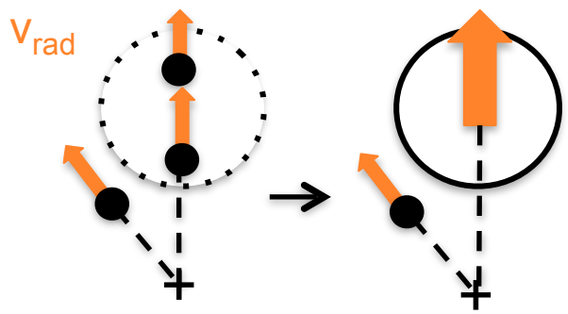
↓

Constrained initial conditions

Sorce & Tempel 2017,2018

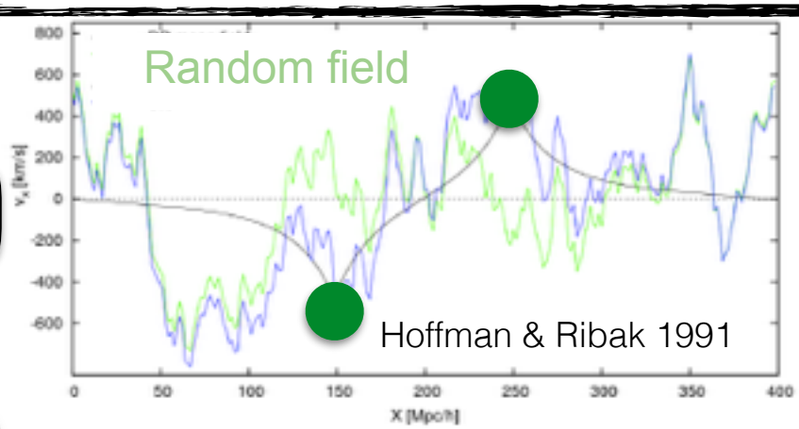


Constrained Realization: Estimate of the residual

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

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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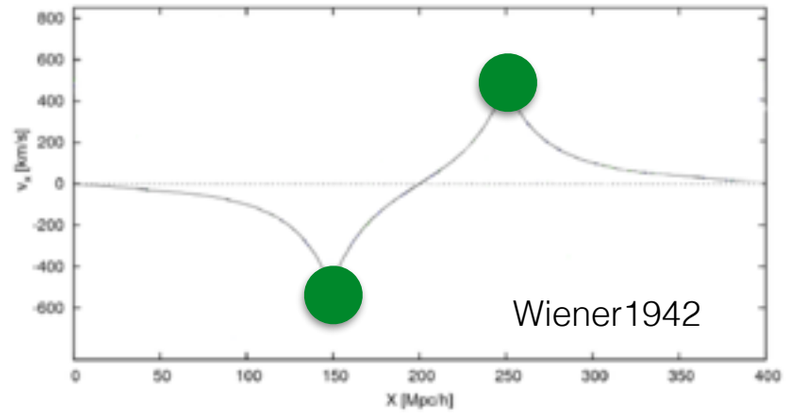
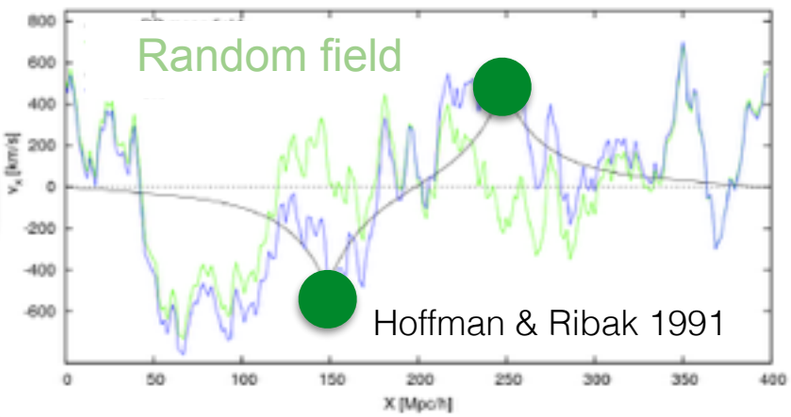
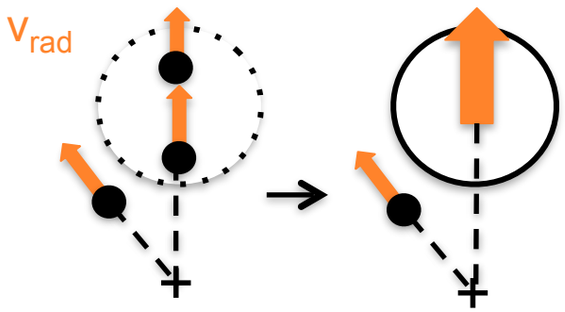
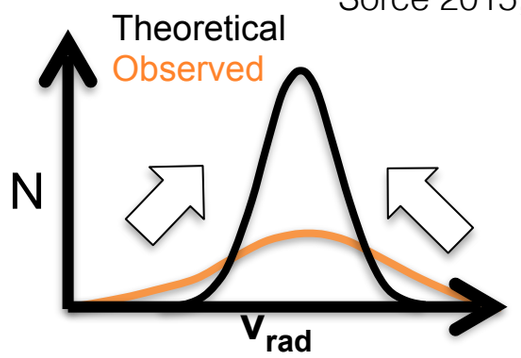




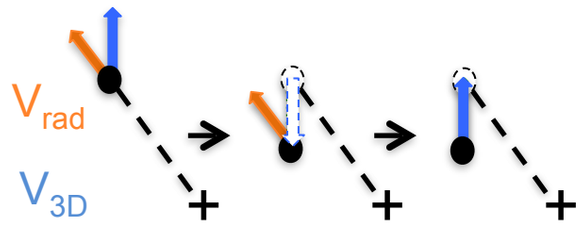
Sorce & Tempel 2017,2018



Sorce 2015, 2018



Doumler+2013 Sorce+2014

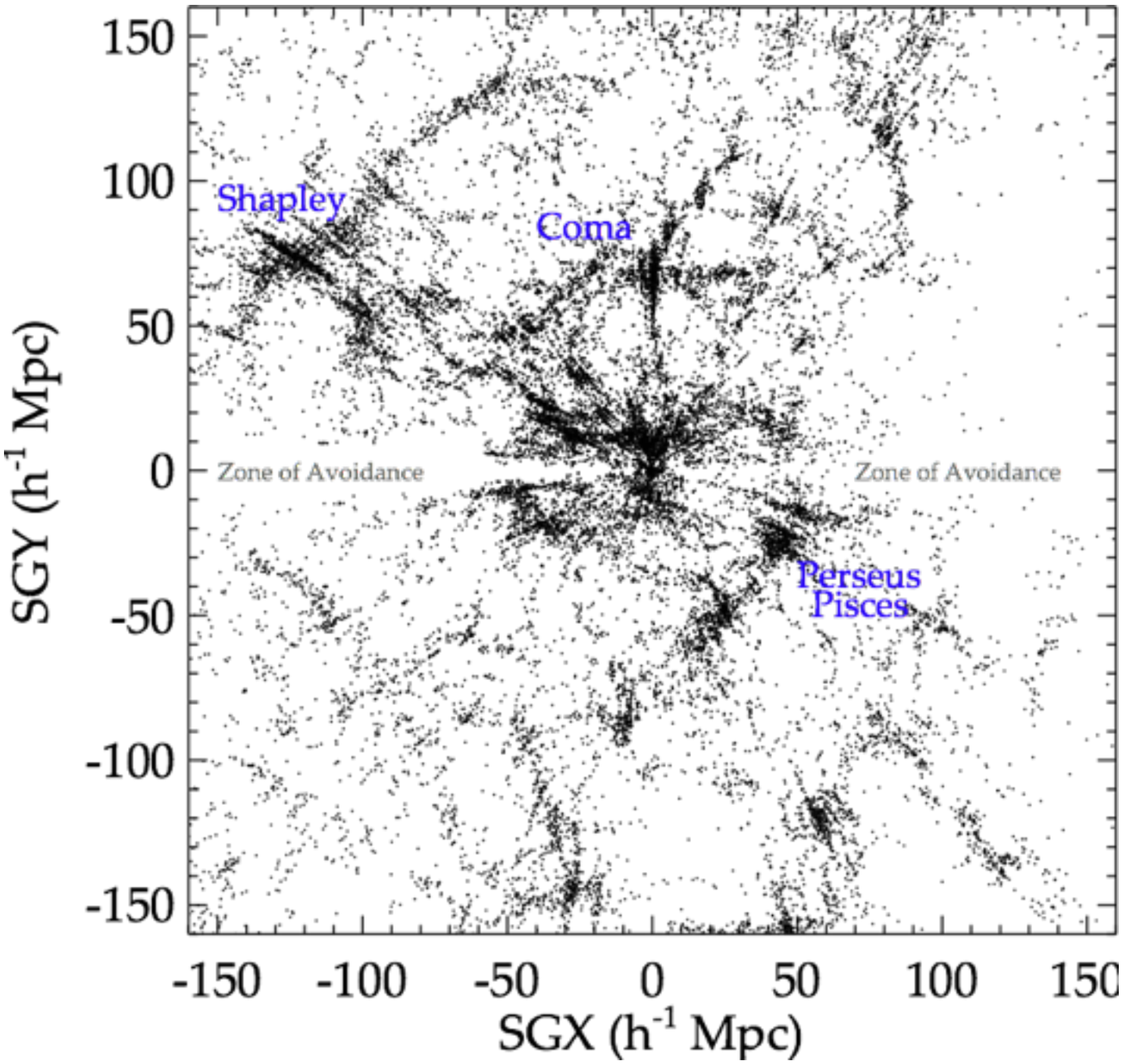


A non-linear map of the local Universe

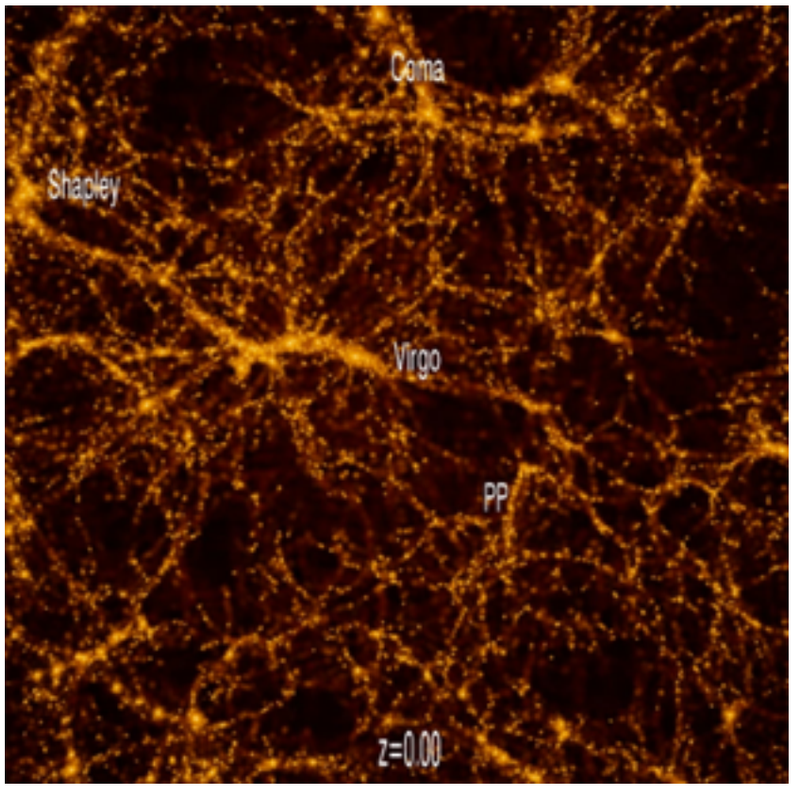
Using the same folding techniques as road maps greatly delayed the gene mapping research.

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

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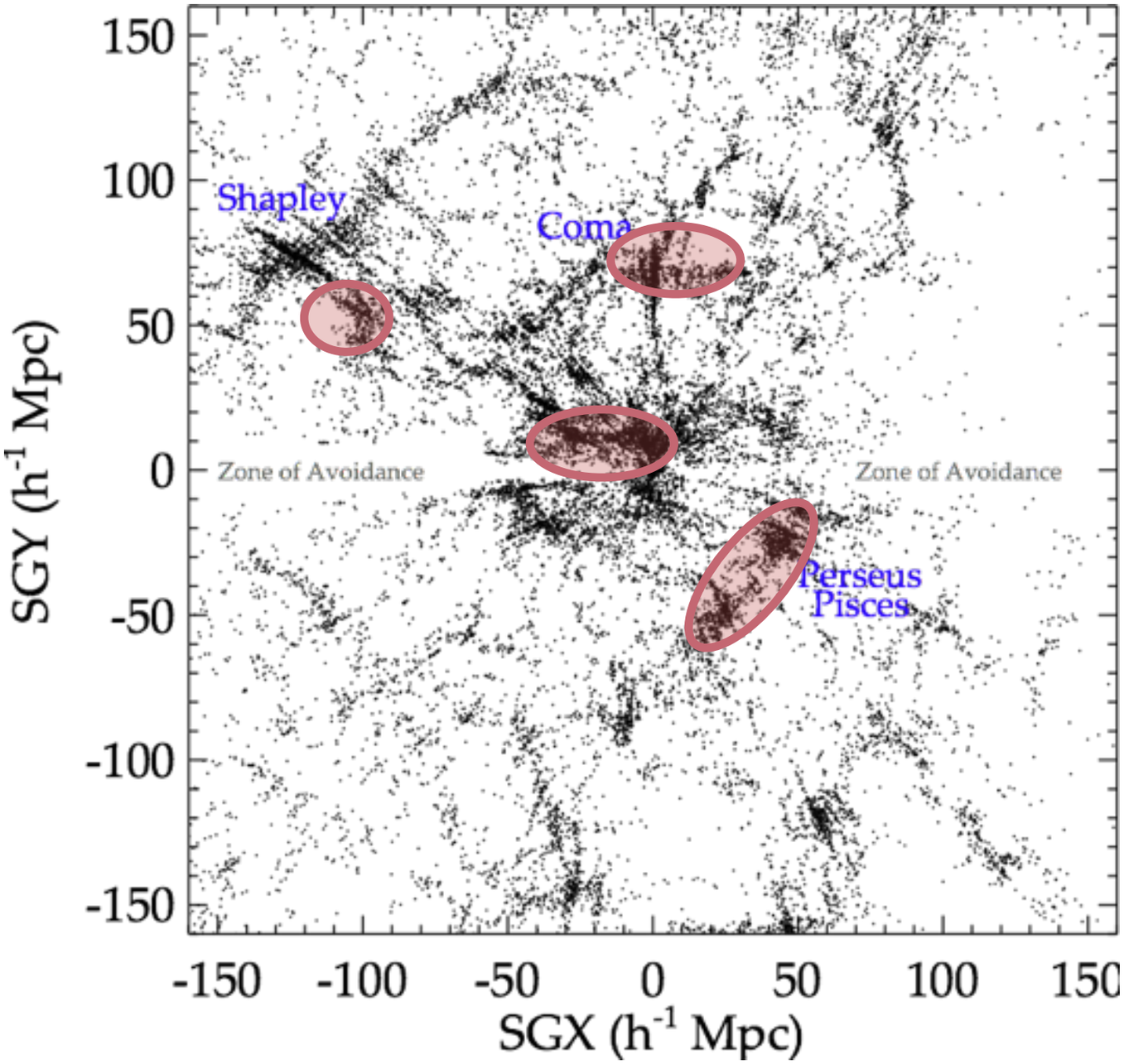

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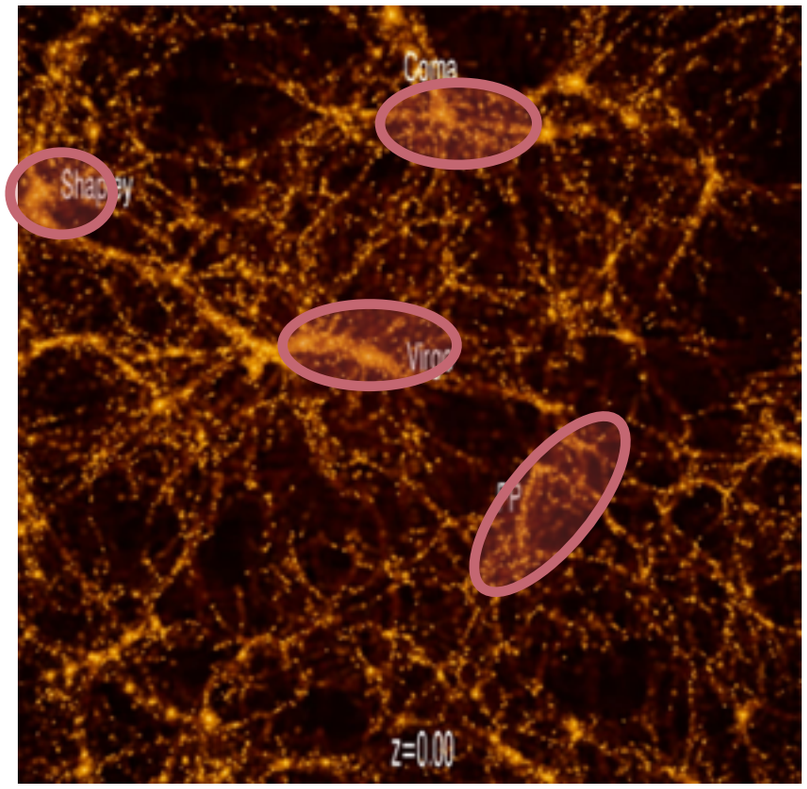
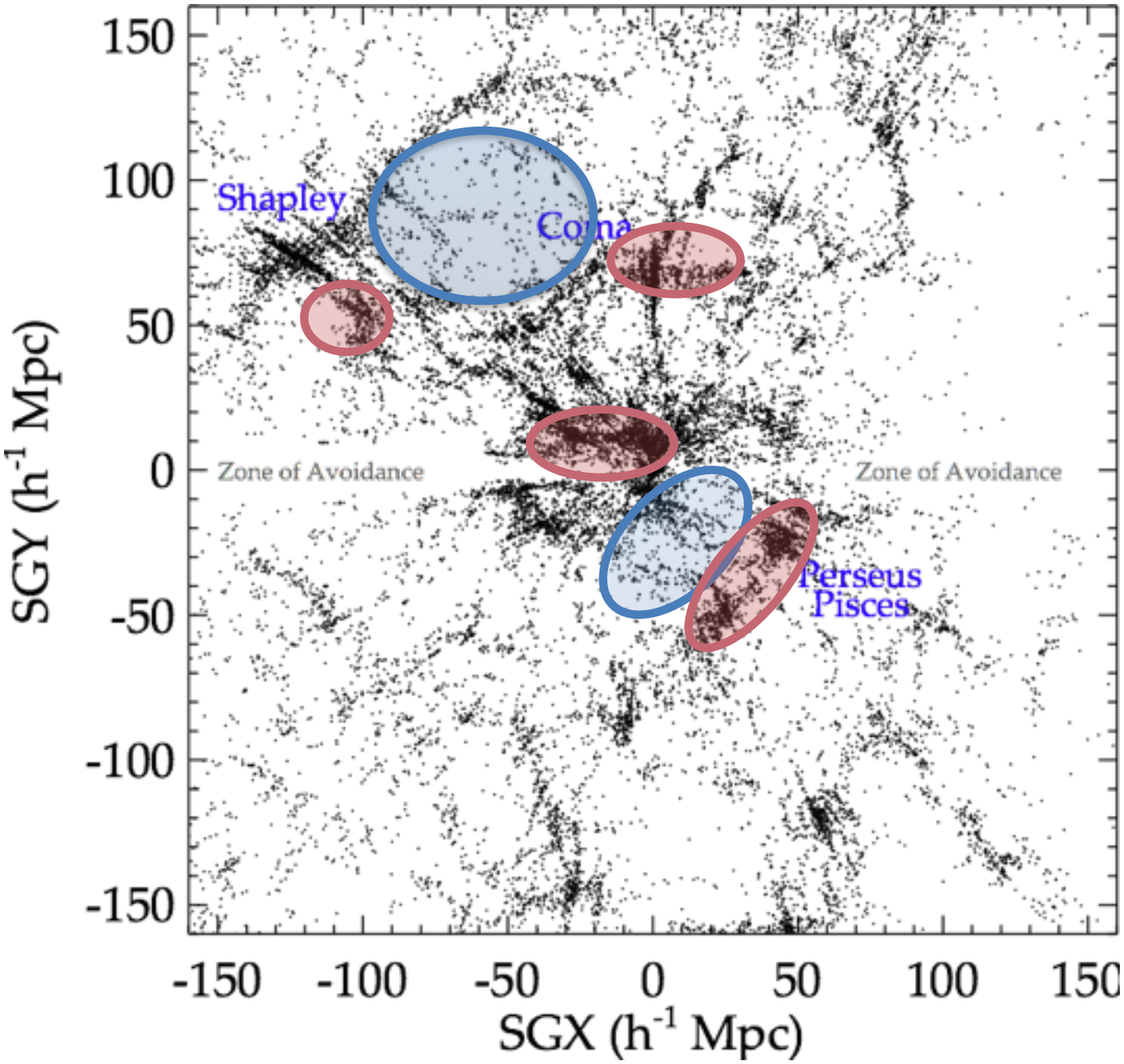


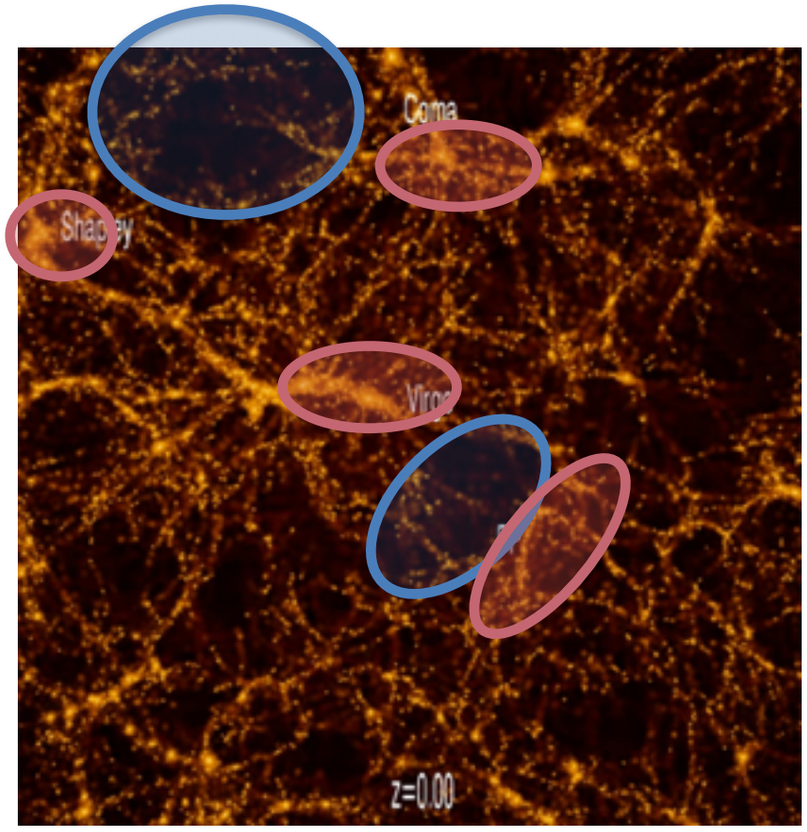
500 Mpc/h, 1024^3 particles,
DM only, Planck cosmology

Results: the local large scale

z=0, large scale Sorce+2016



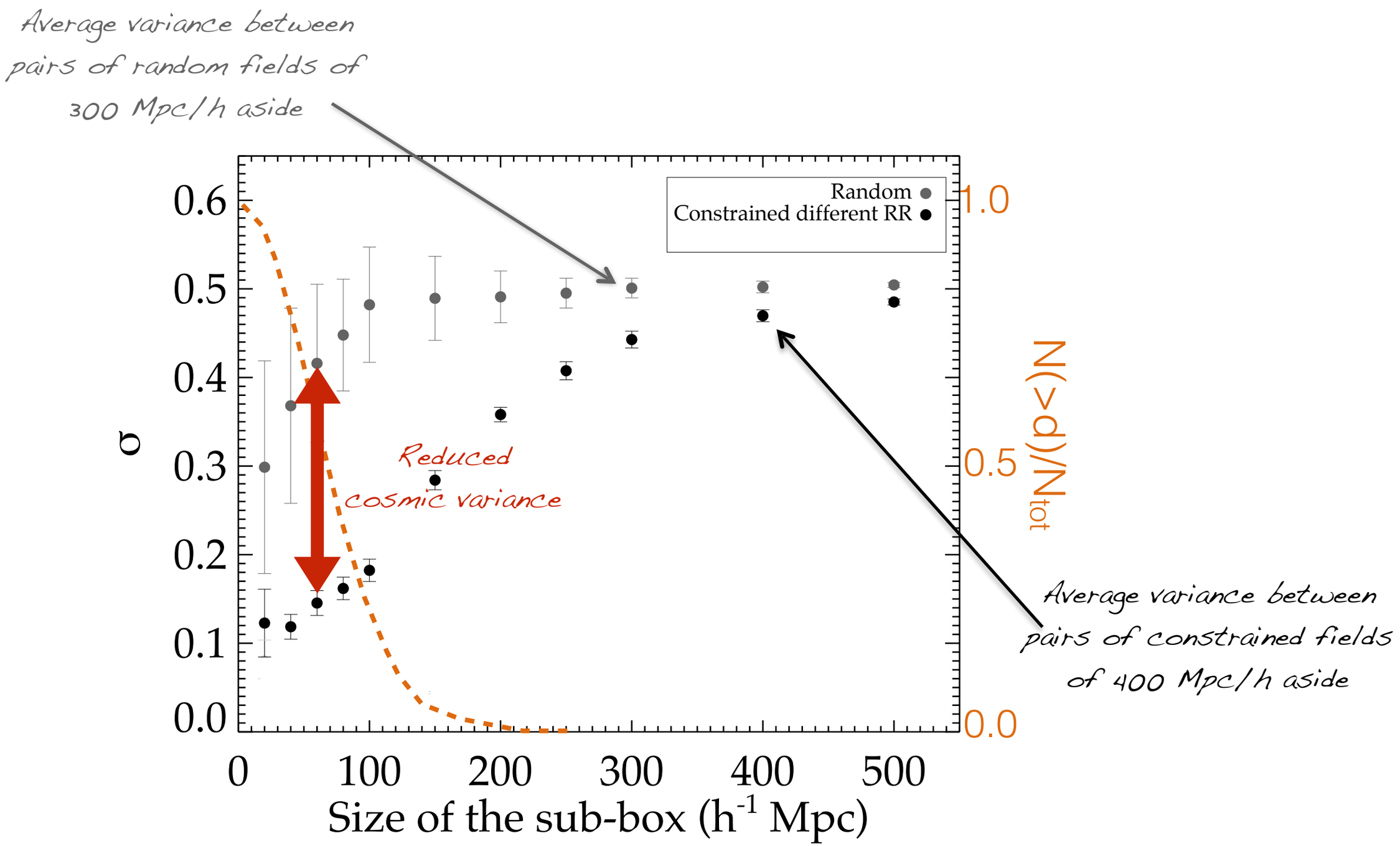
Note the fingers of gods



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

Results: the local large scale

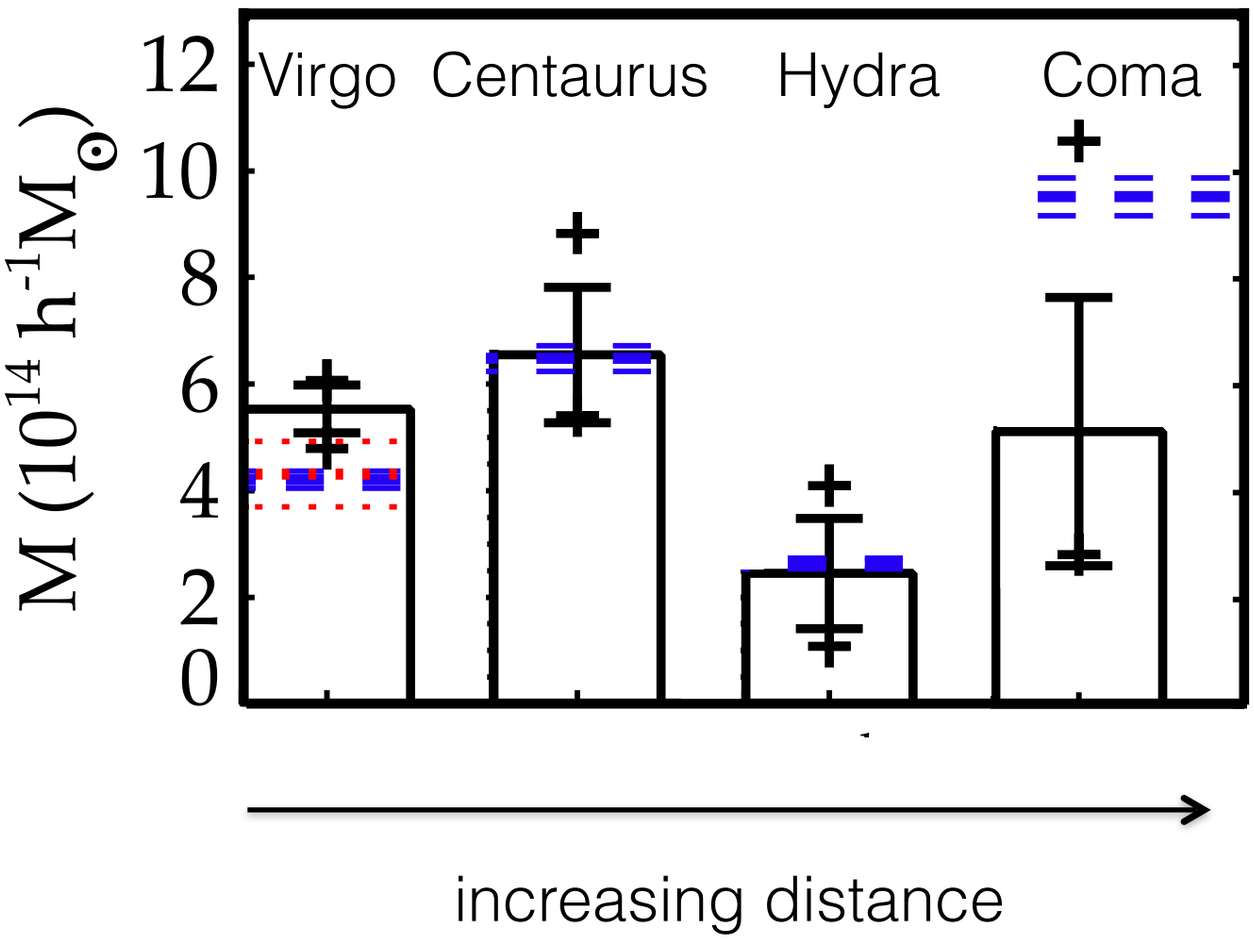
z=0, large scale Sorce+2016



Results: the local clusters

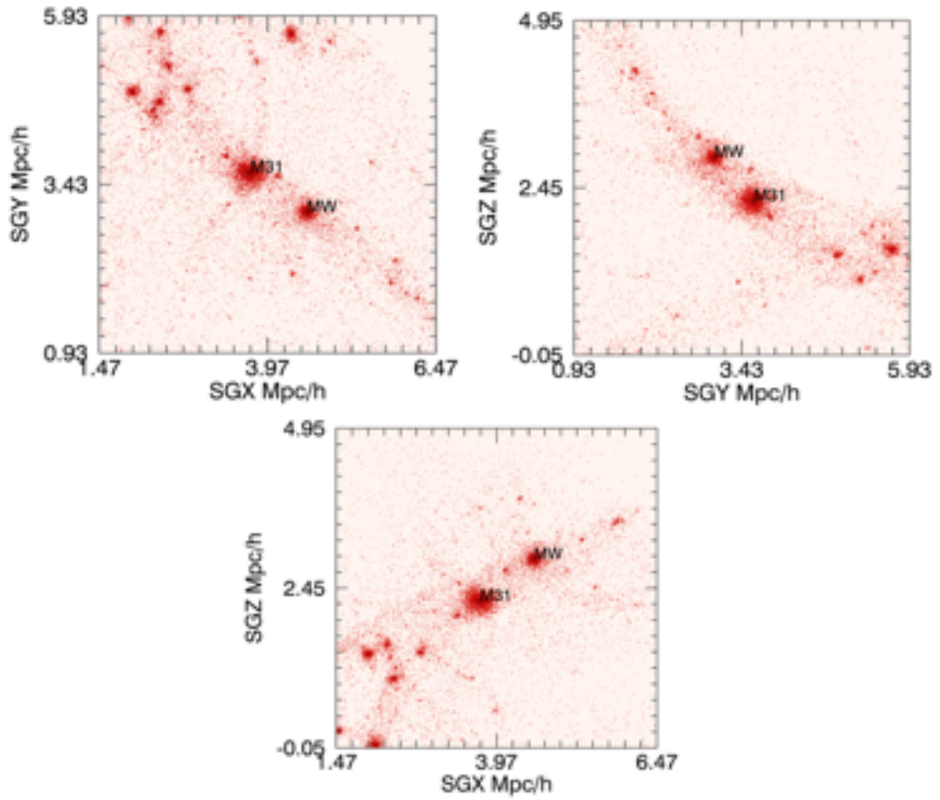
z=0, cluster scale Sorce 2018

Dark matter halos = counterparts of observed local clusters



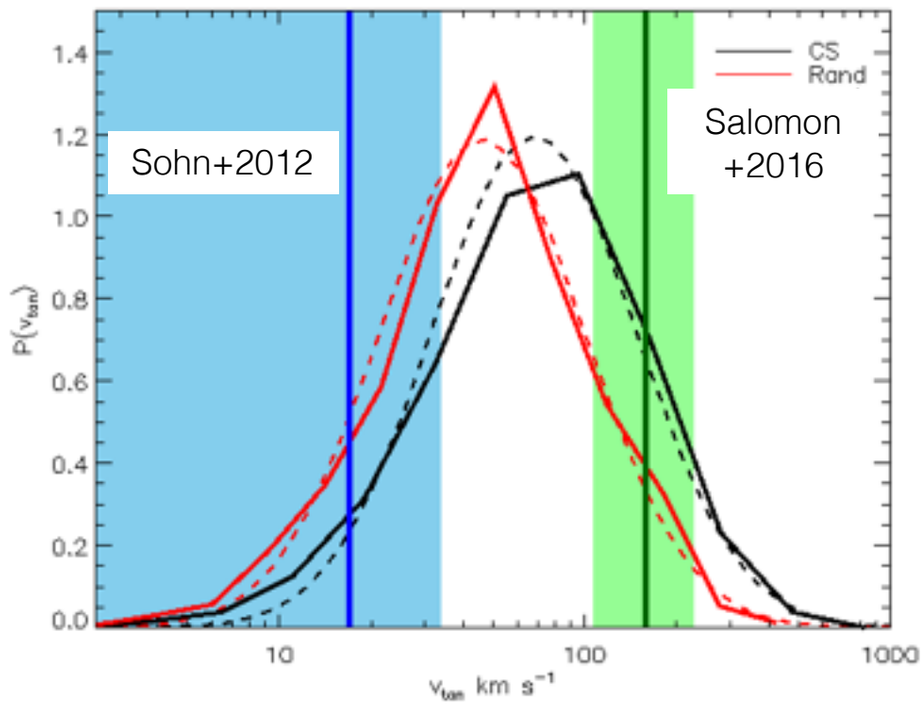
Results: the Local Group

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

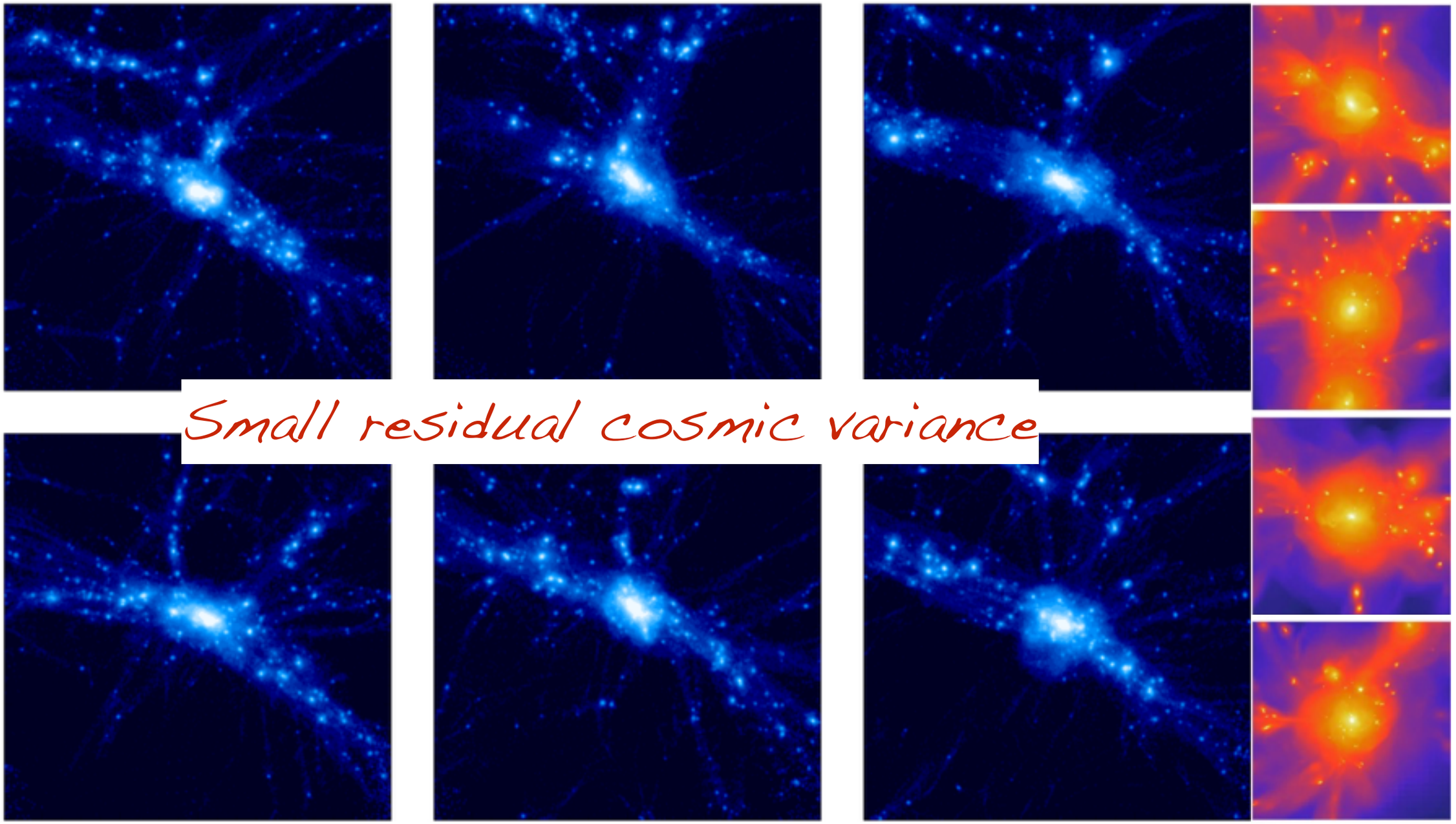


Carlesi,Sorce+2016
Carlesi,Hoffman,Sorce+2016
Carlesi,Hoffman,Sorce+2017

Let's dig into the Virgo cluster of galaxies

Observed Virgo, Simulated Virgo & Random clusters

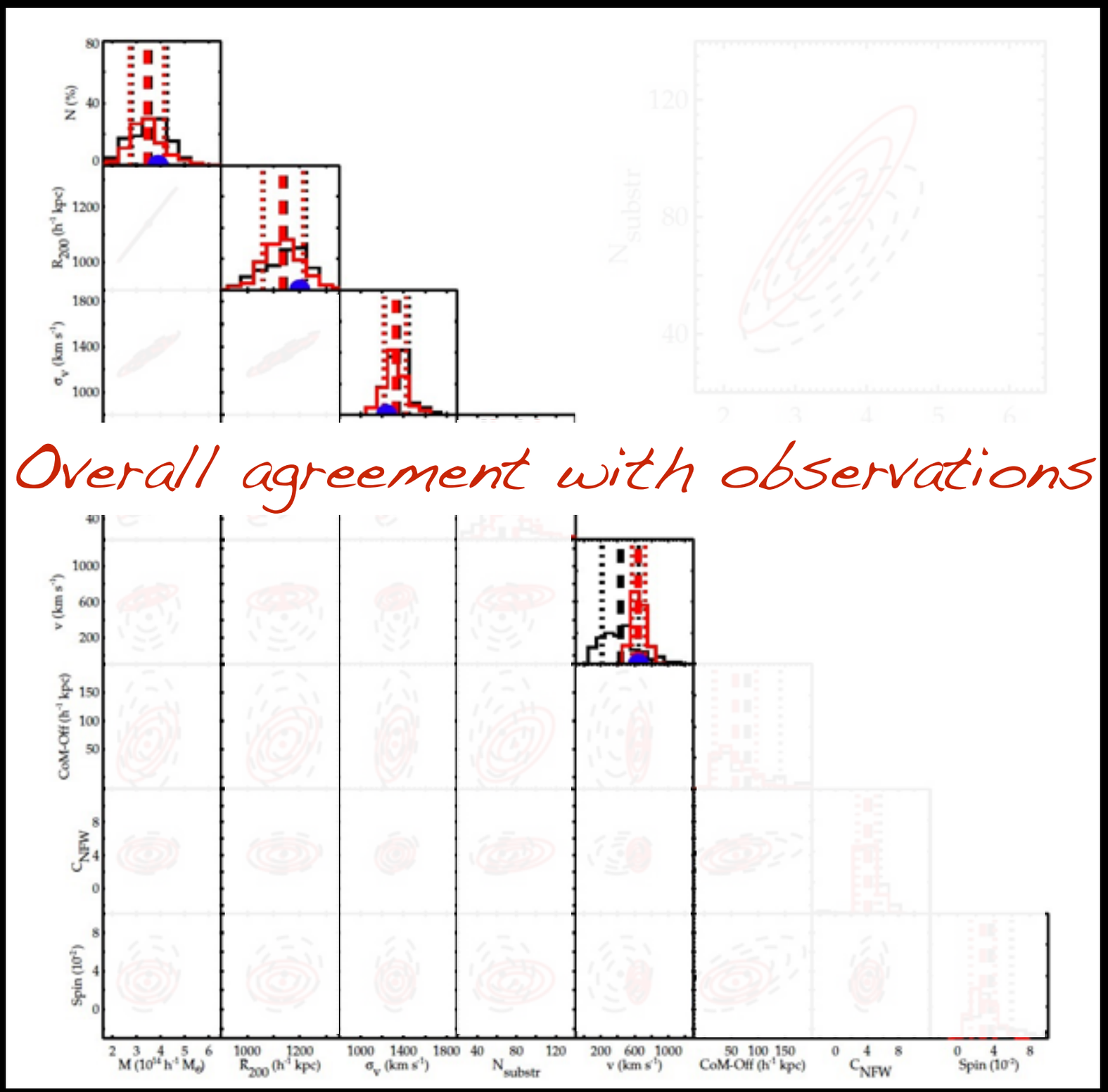
Let's dig into the Virgo cluster of galaxies



Rhapsody (Hahn +2017)

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

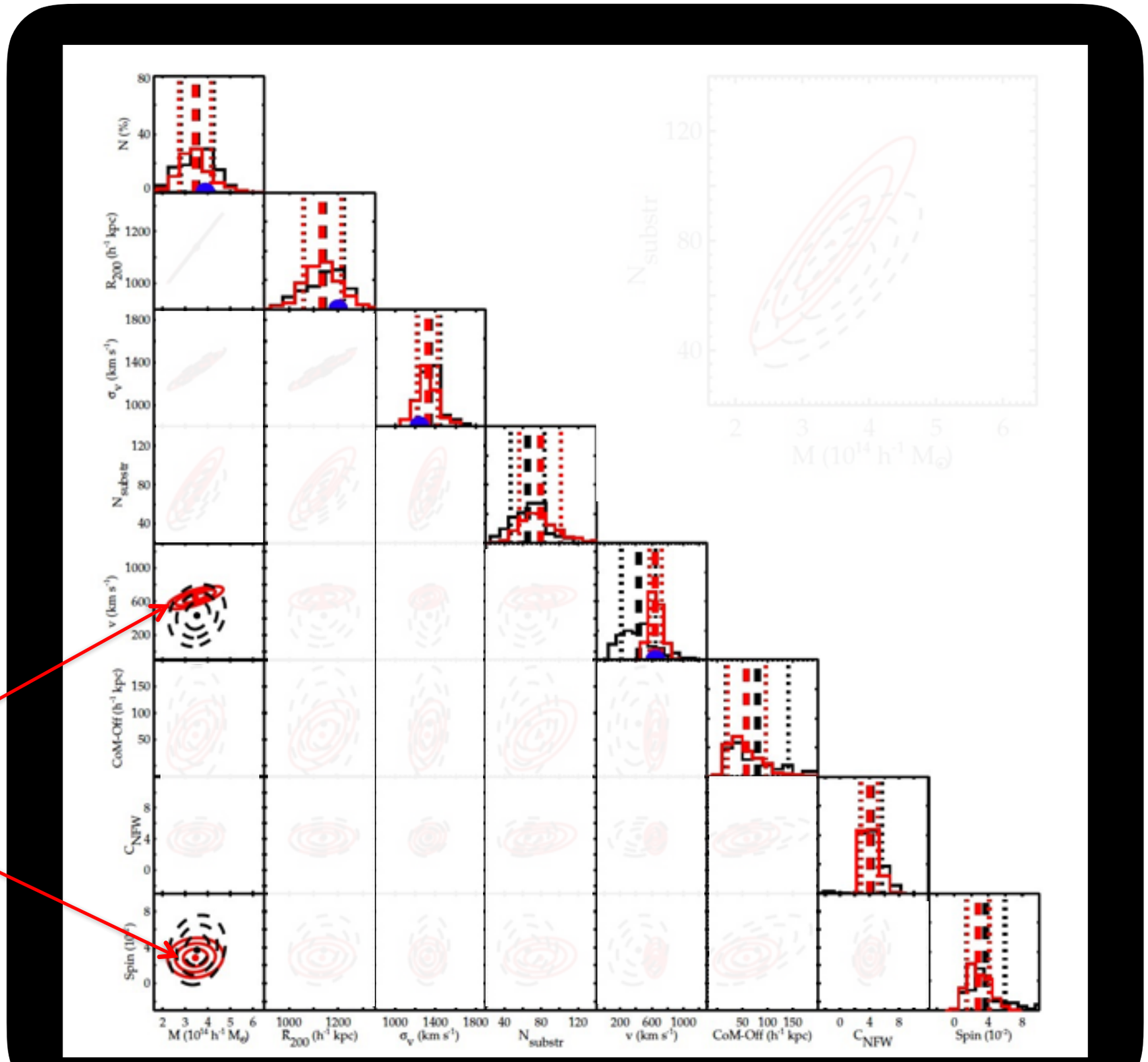
Let's dig into the Virgo cluster of galaxies



Overall agreement with observations

Sorce, Blaizot, Dubois submitted

Let’s dig into the Virgo cluster of galaxies



Velocity

Spin

→ Environment

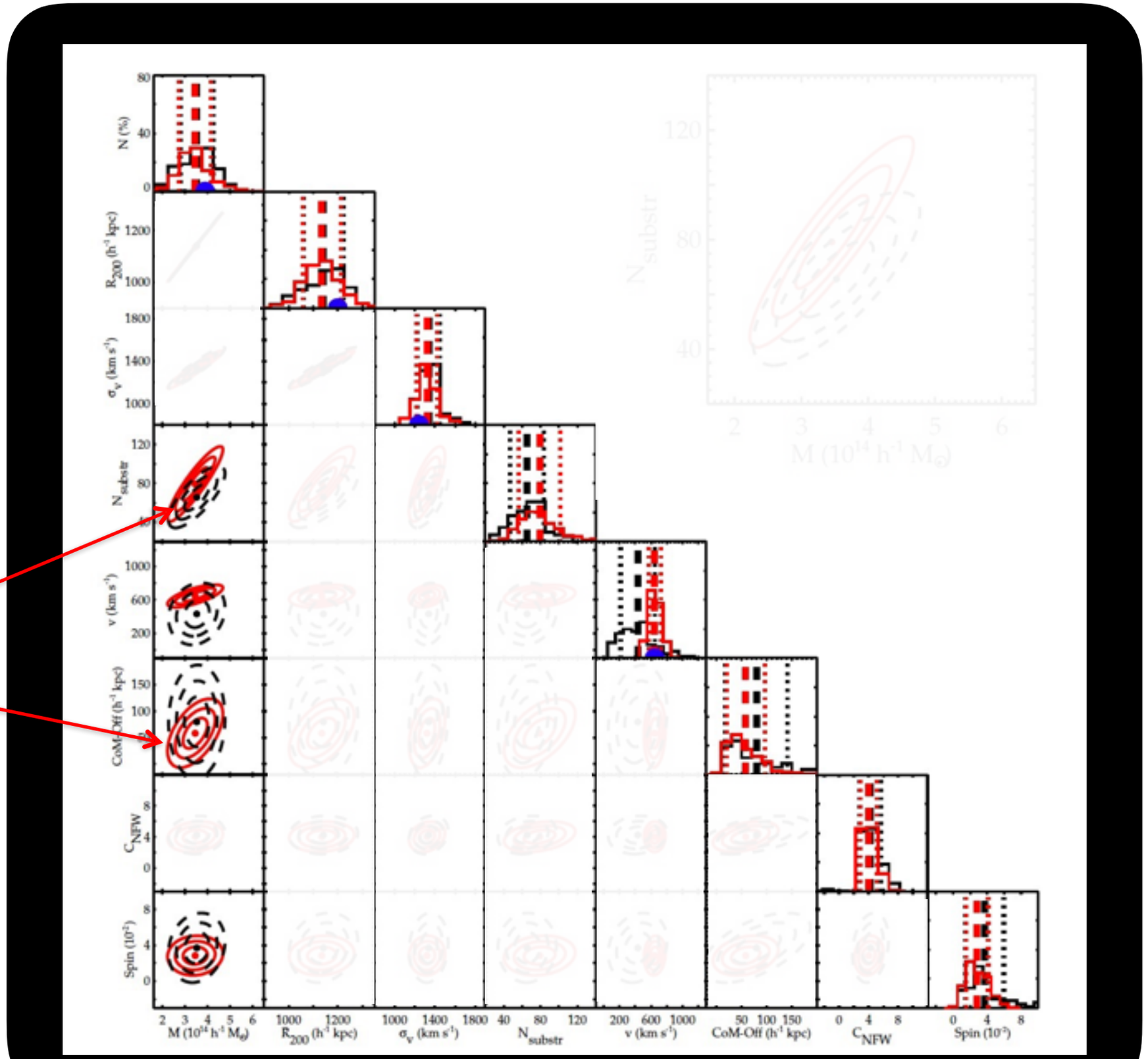
Sorce, Blaizot, Dubois submitted

Let's dig into the Virgo cluster of galaxies

Number of substructures

Center of mass offset wrt spherical center

➙ History



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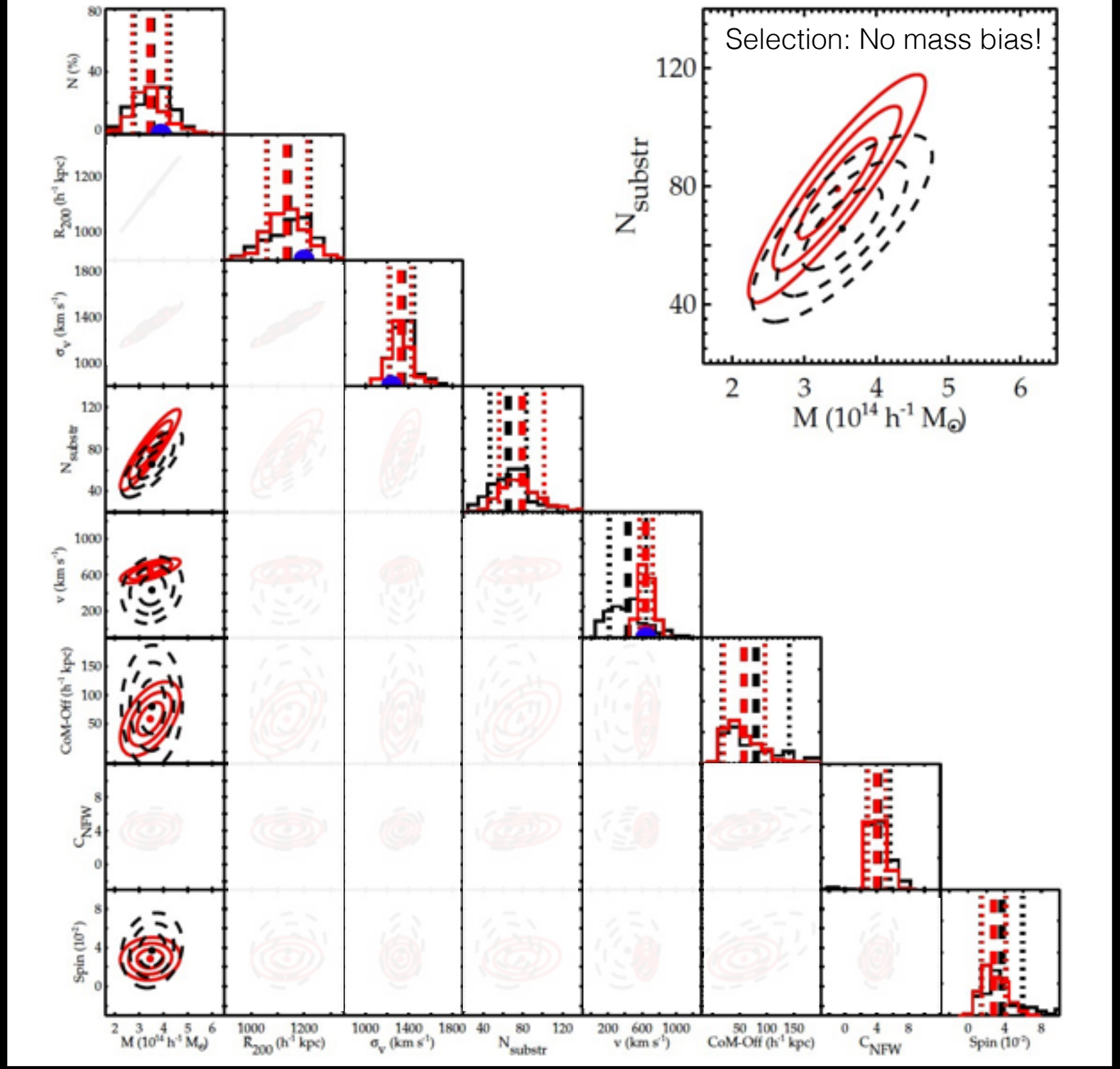
Let's dig into the Virgo cluster of galaxies



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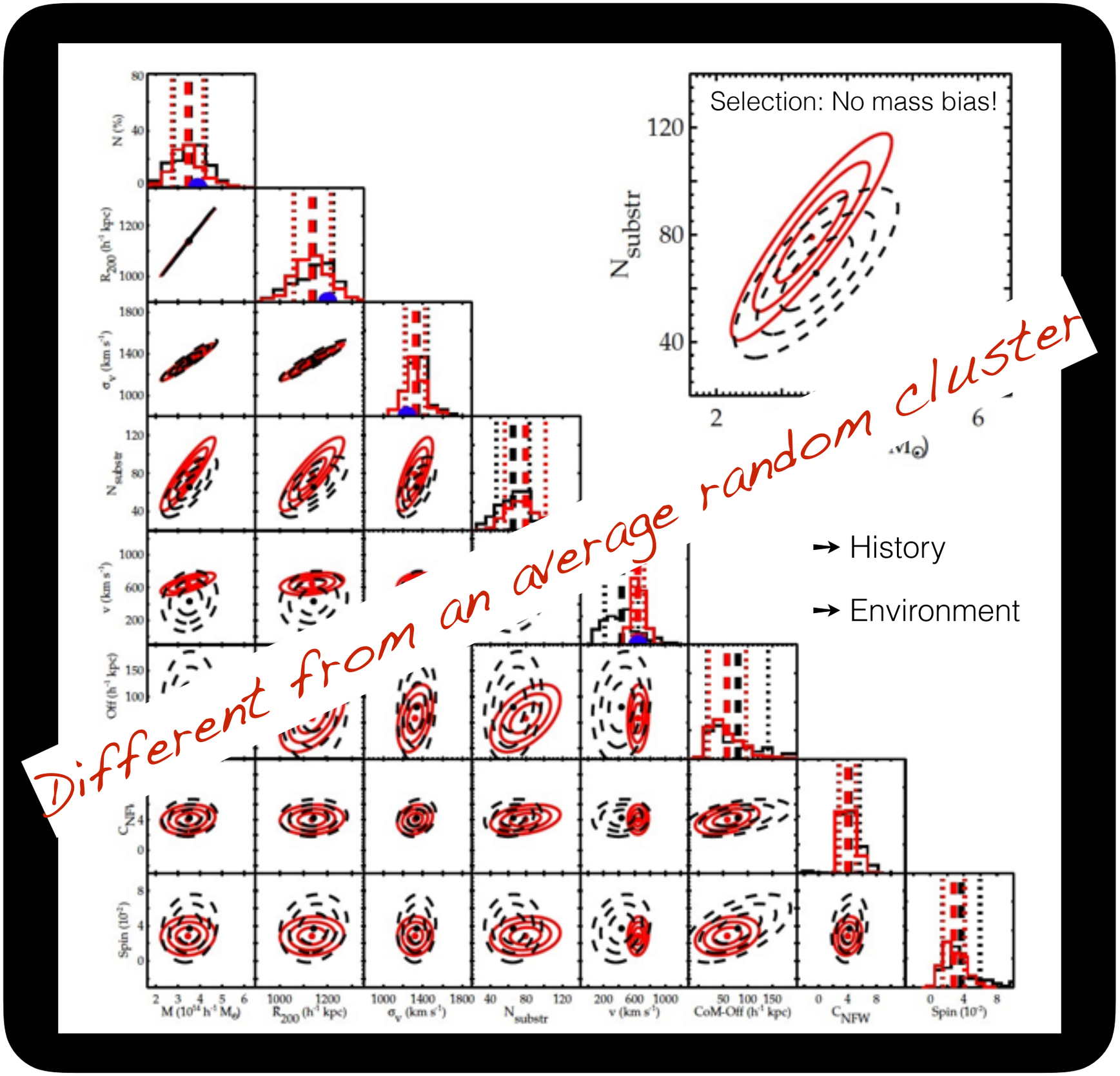
Let's dig into the Virgo cluster of galaxies



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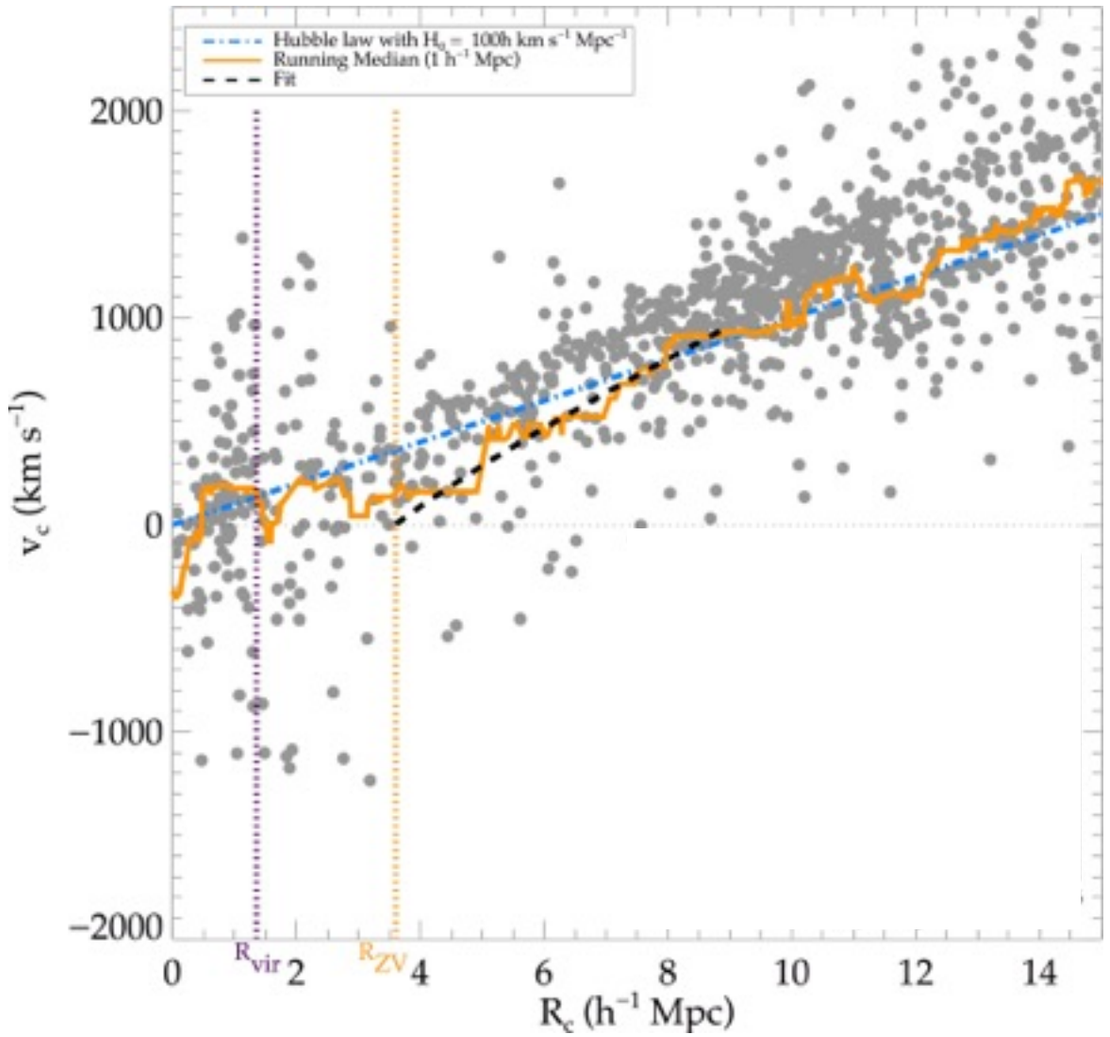
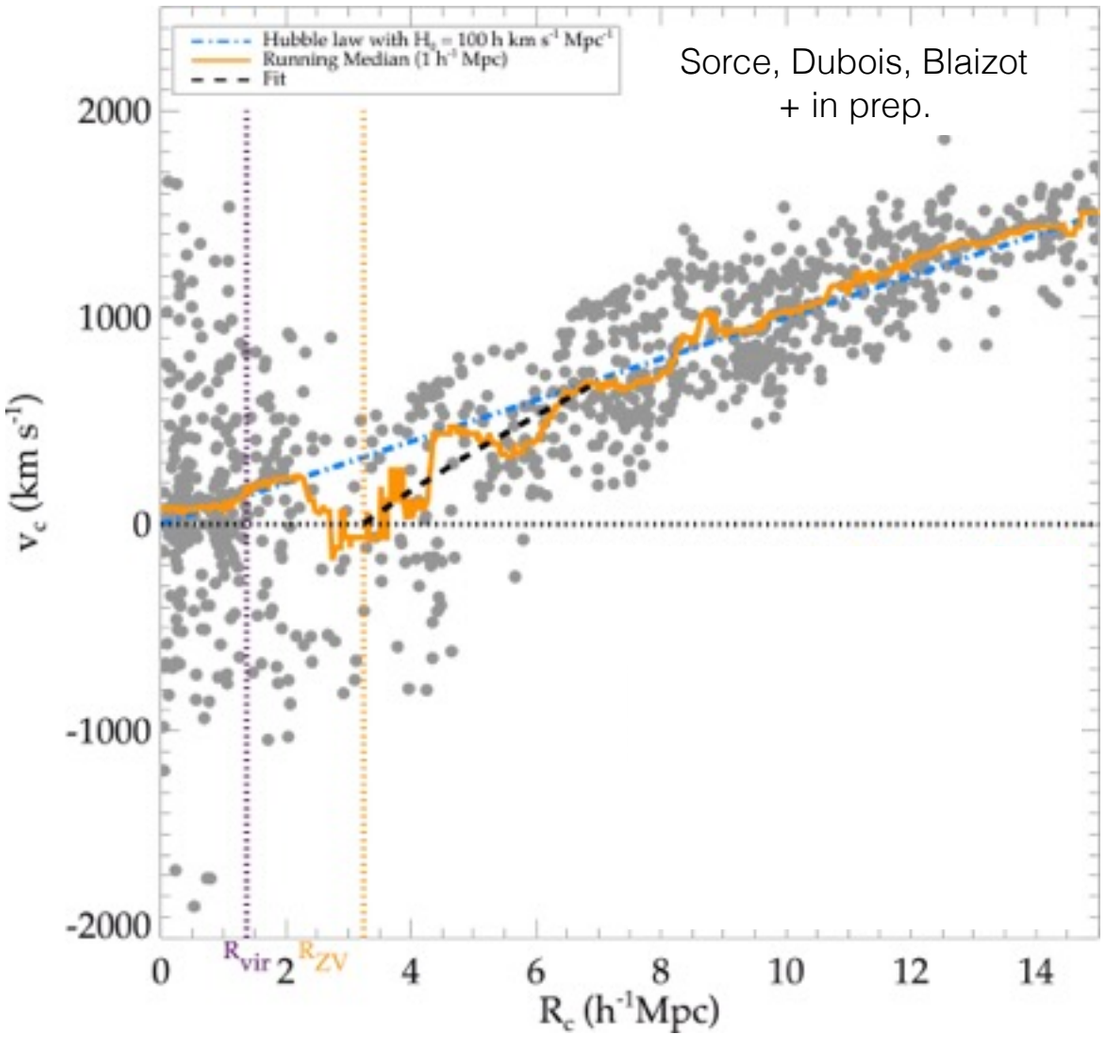
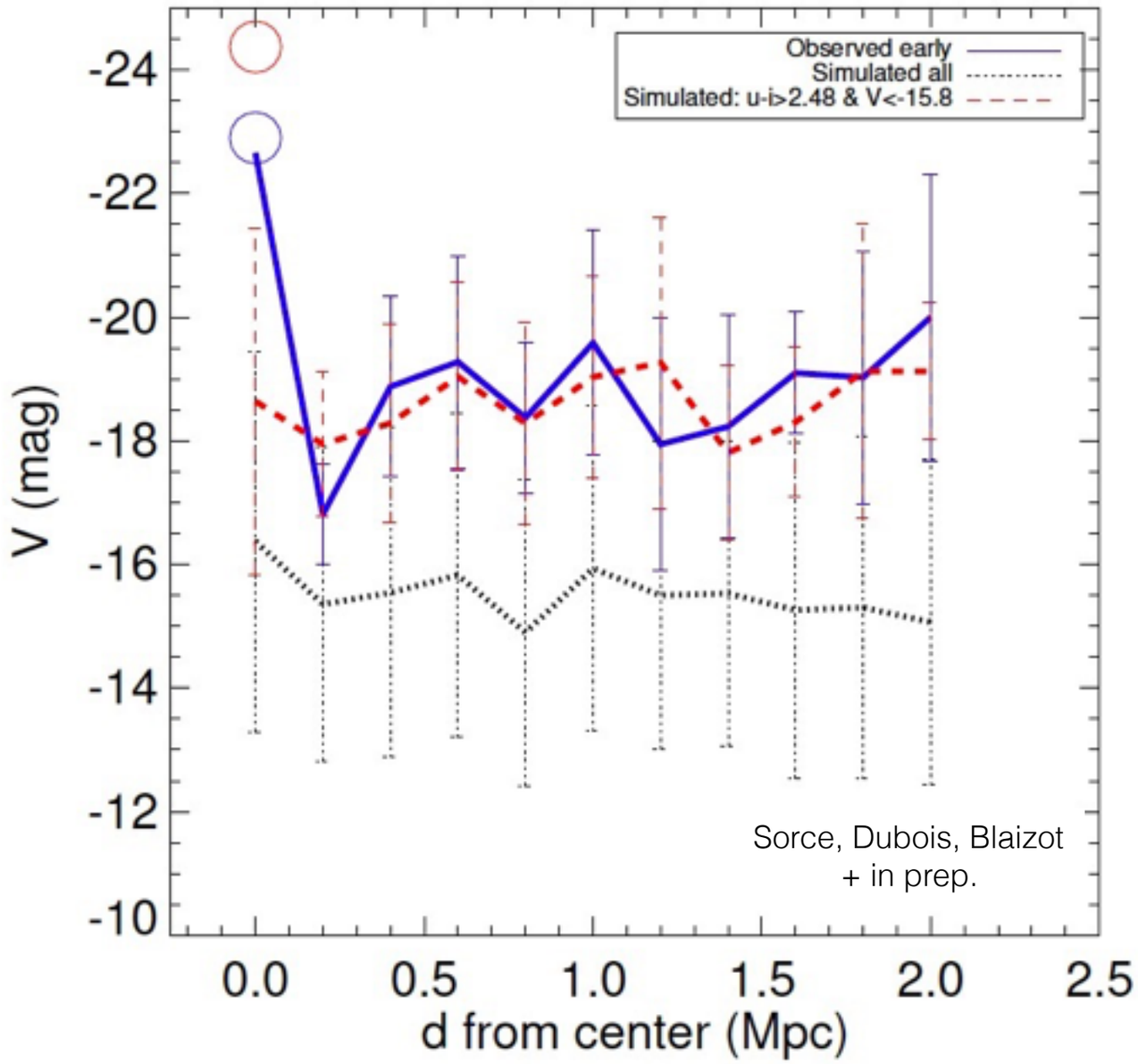




500 Mpc/h, 8192^3 particles effective (20 Mpc/h zoom), 0.24 kpc/h hydrodynamics: SN and AGN feedback, Planck cosmology

Overall agreement with observations

Let's dig into the Virgo cluster of galaxies

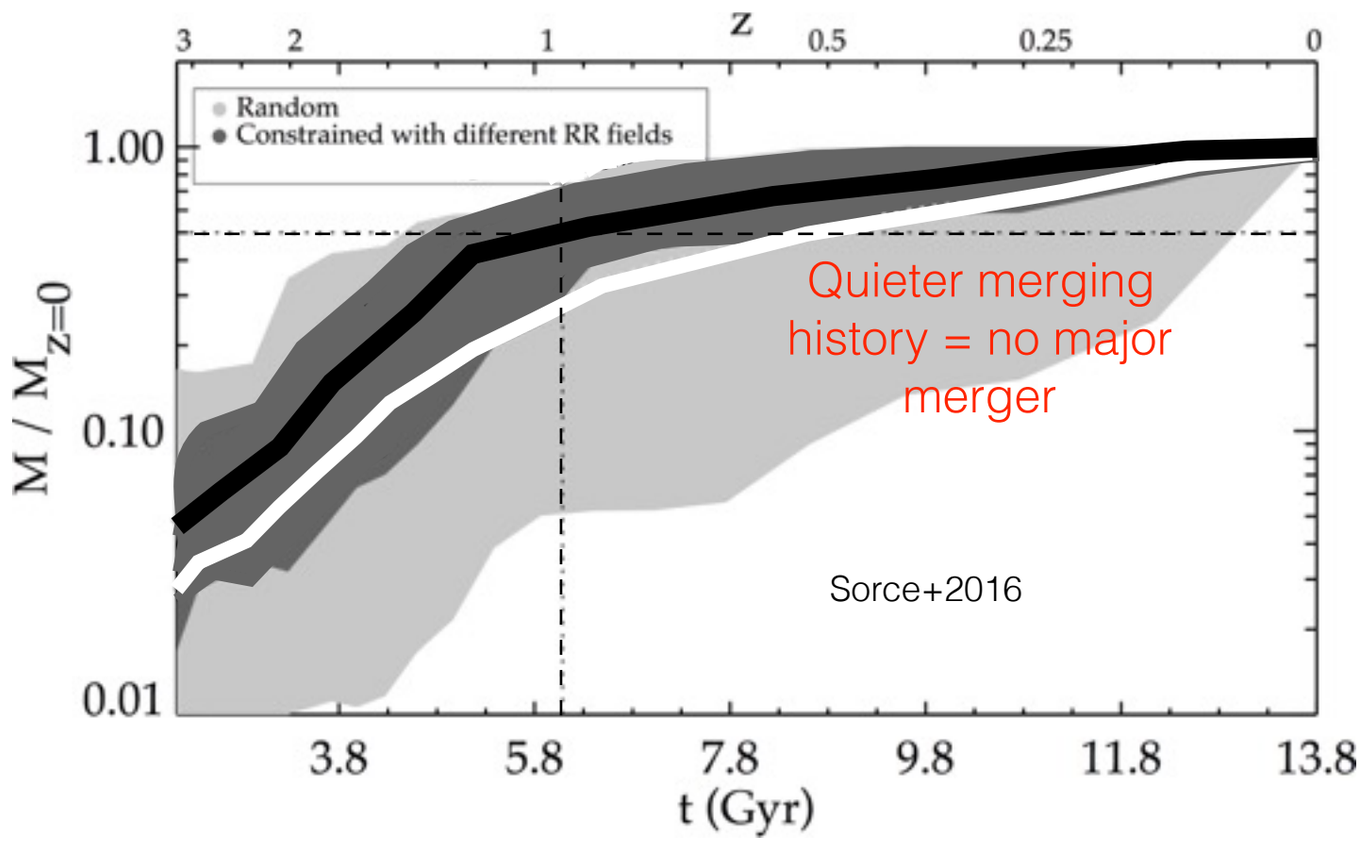


Overall agreement with observations

Let's dig into the Virgo cluster of galaxies

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

From simulation



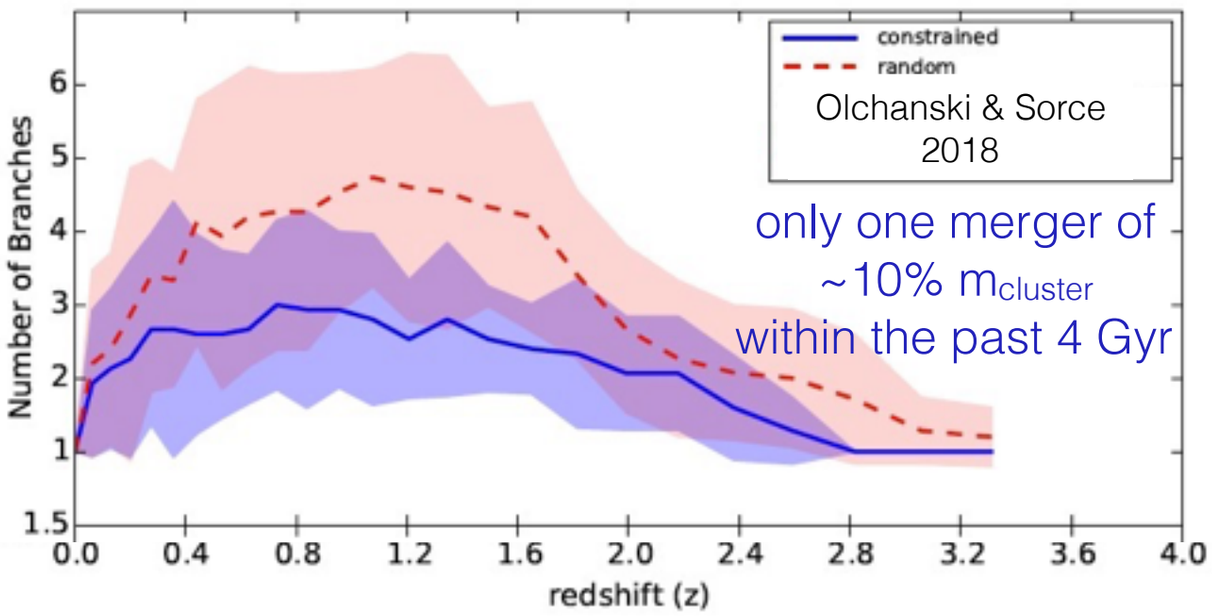
500 Mpc/h, 512^3 particles, DM only, Planck cosmology

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

From simulation



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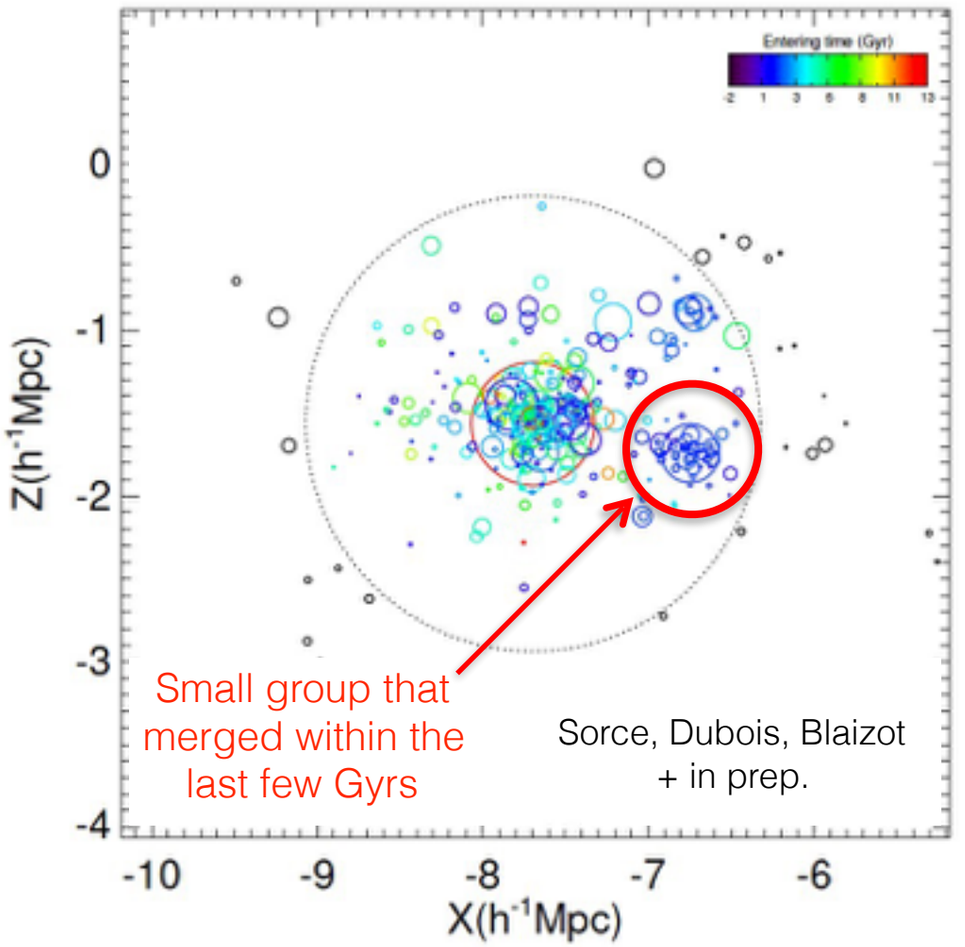

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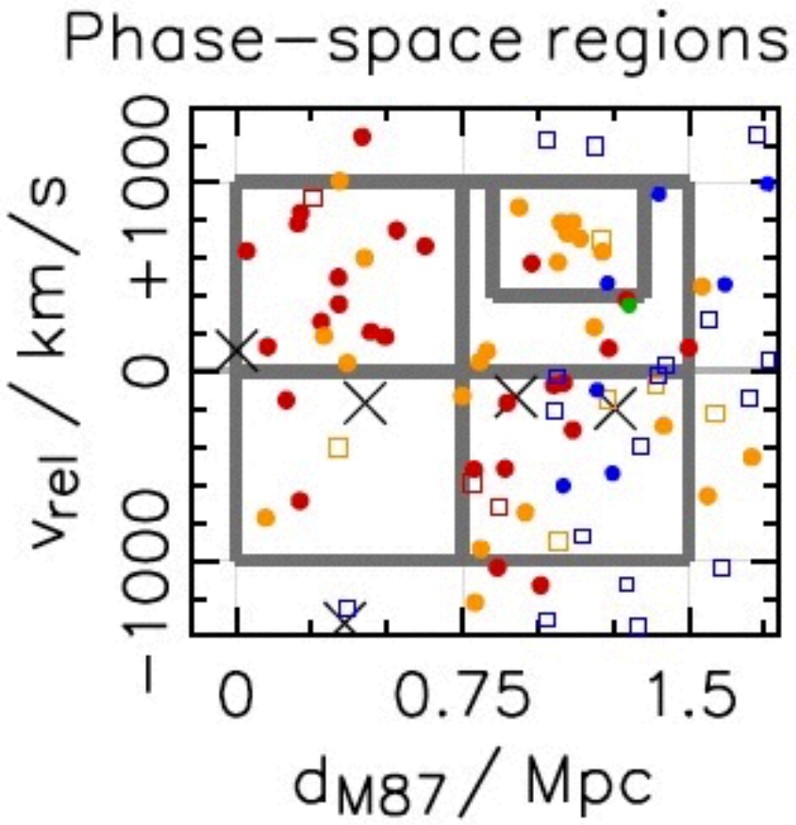
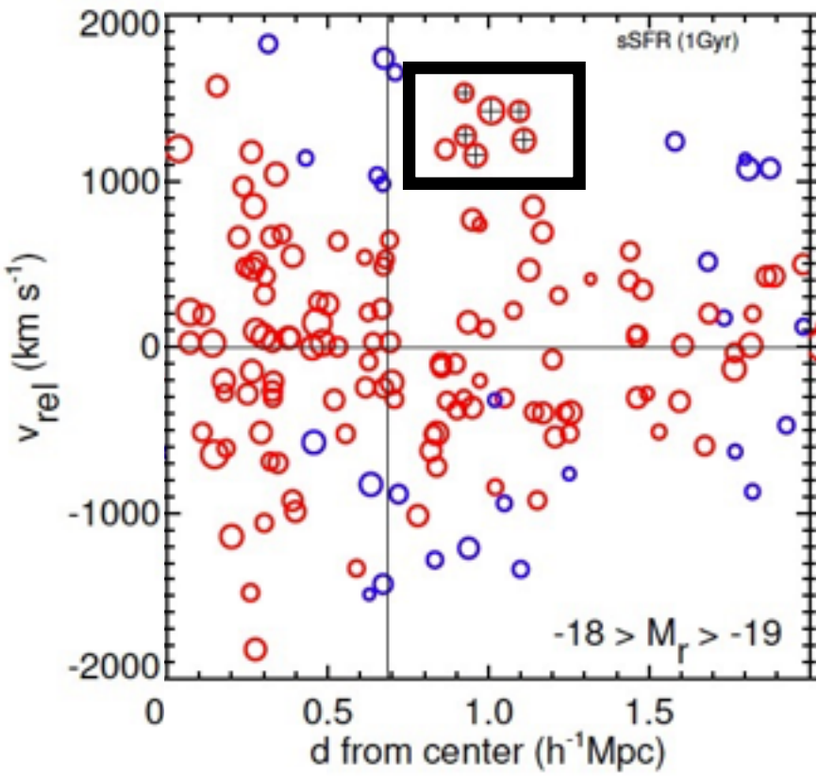


Lisker+2018

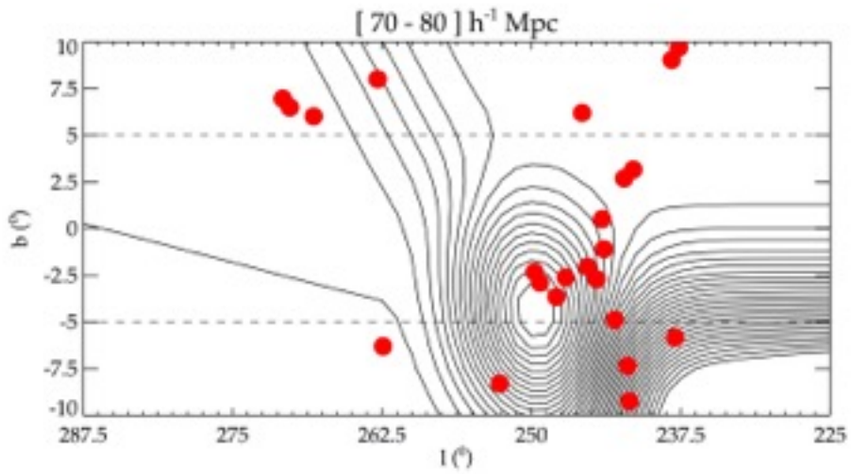


Sorce, Dubois, Blaizot
+ in prep.

Agreement with observational predictions

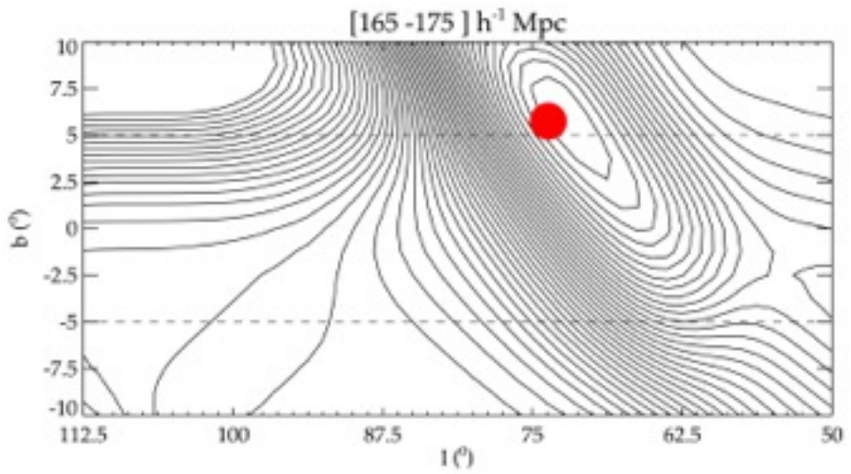
A few more applications: The Zone of Avoidance

Sorce+2017



Puppis-3 Cluster

Chamaraux & Masnoux 2004



Cygnus A Cluster

Ebeling+2002

ΛCDM challenges hidden in the Zone of Avoidance?

- number of superclusters

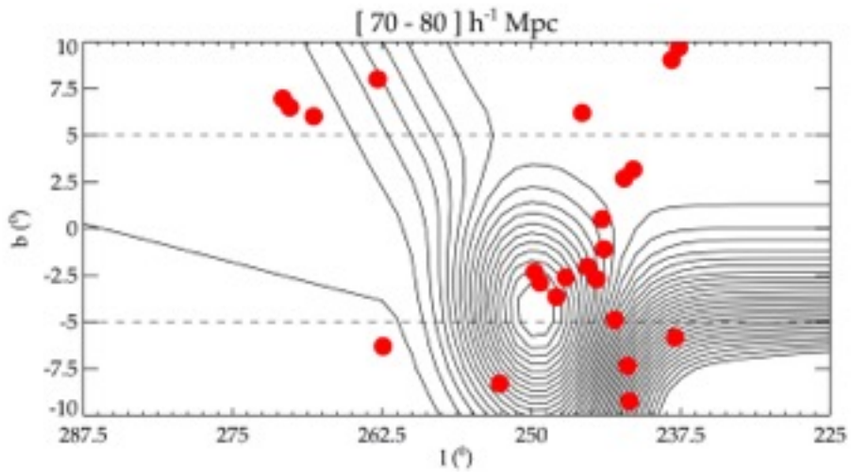
- longest structures

Vela Supercluster

Kraan-Korteweg+2017

A few more applications: The Zone of Avoidance

Sorce+2017



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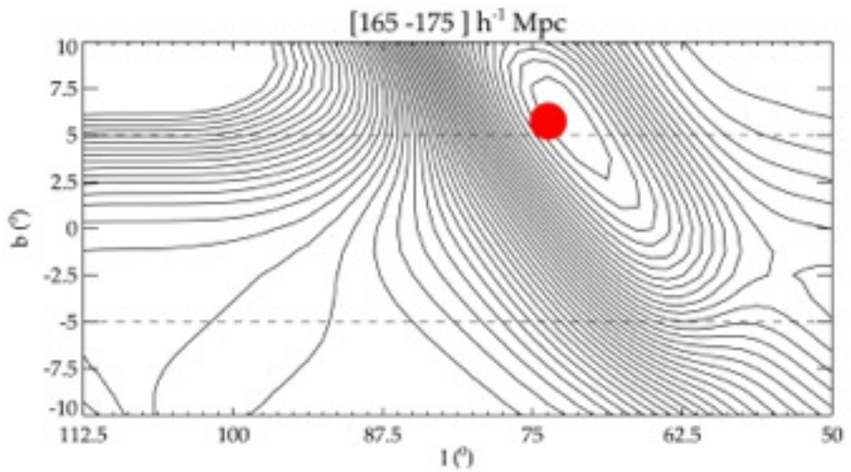

Cygnus A Cluster

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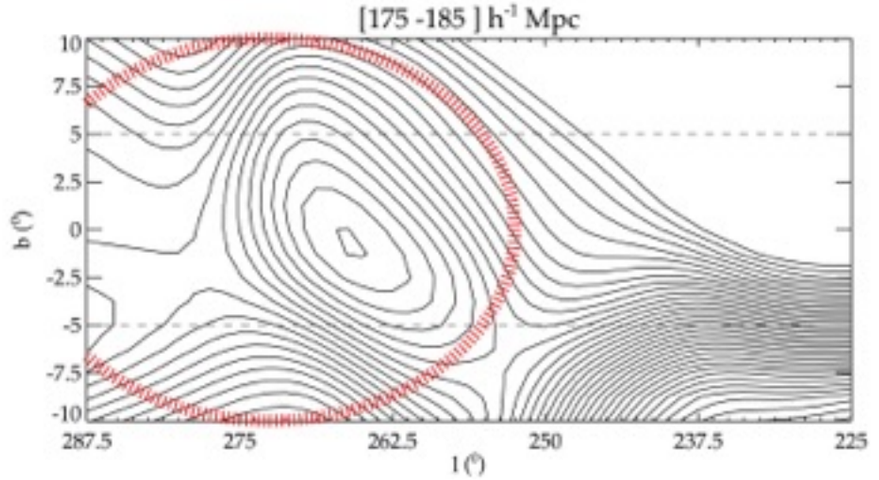
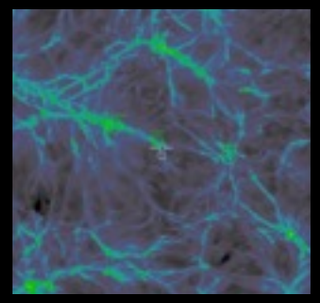


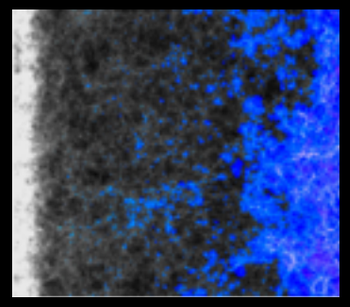
Vela Supercluster

Kraan-Korteweg+2017

A few more applications: …



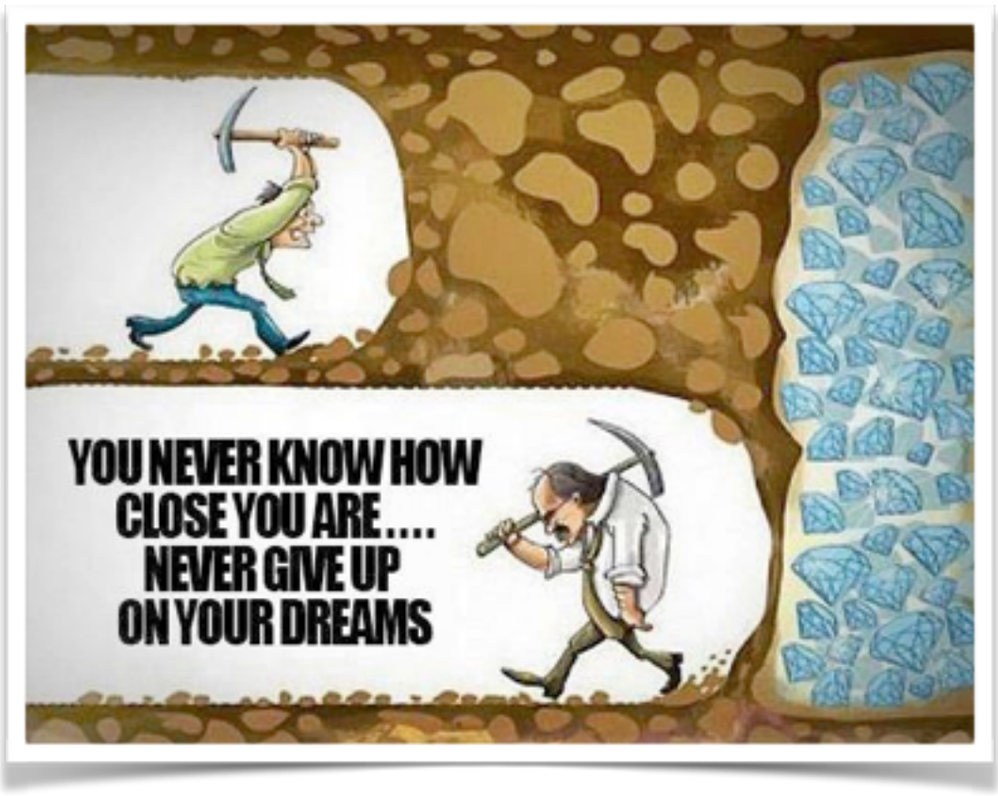
Cosmic Rays in the local Universe
(Hackstein+2018)



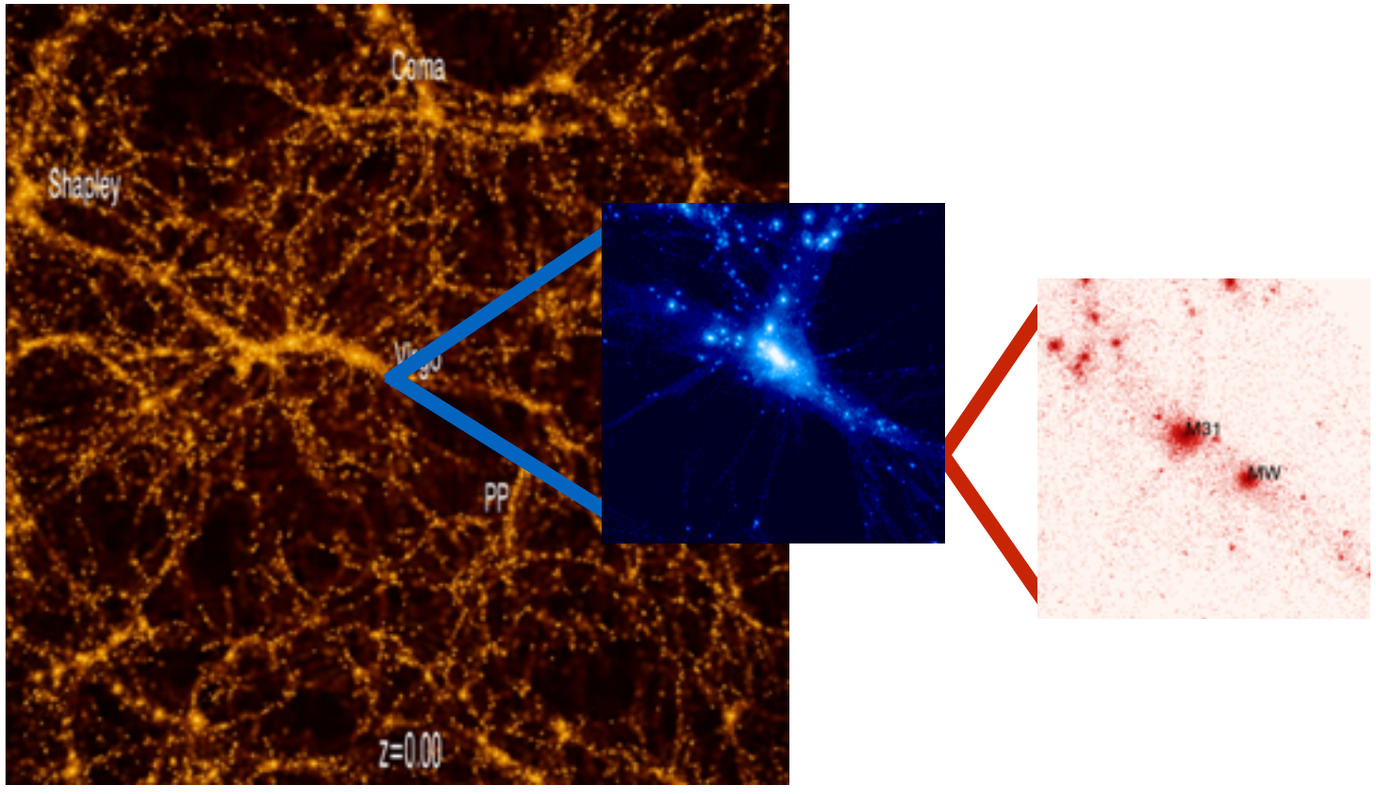
Reionization of the local Universe
(Ocvirk+ submitted)
(Sorce+ in prep.)

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 !

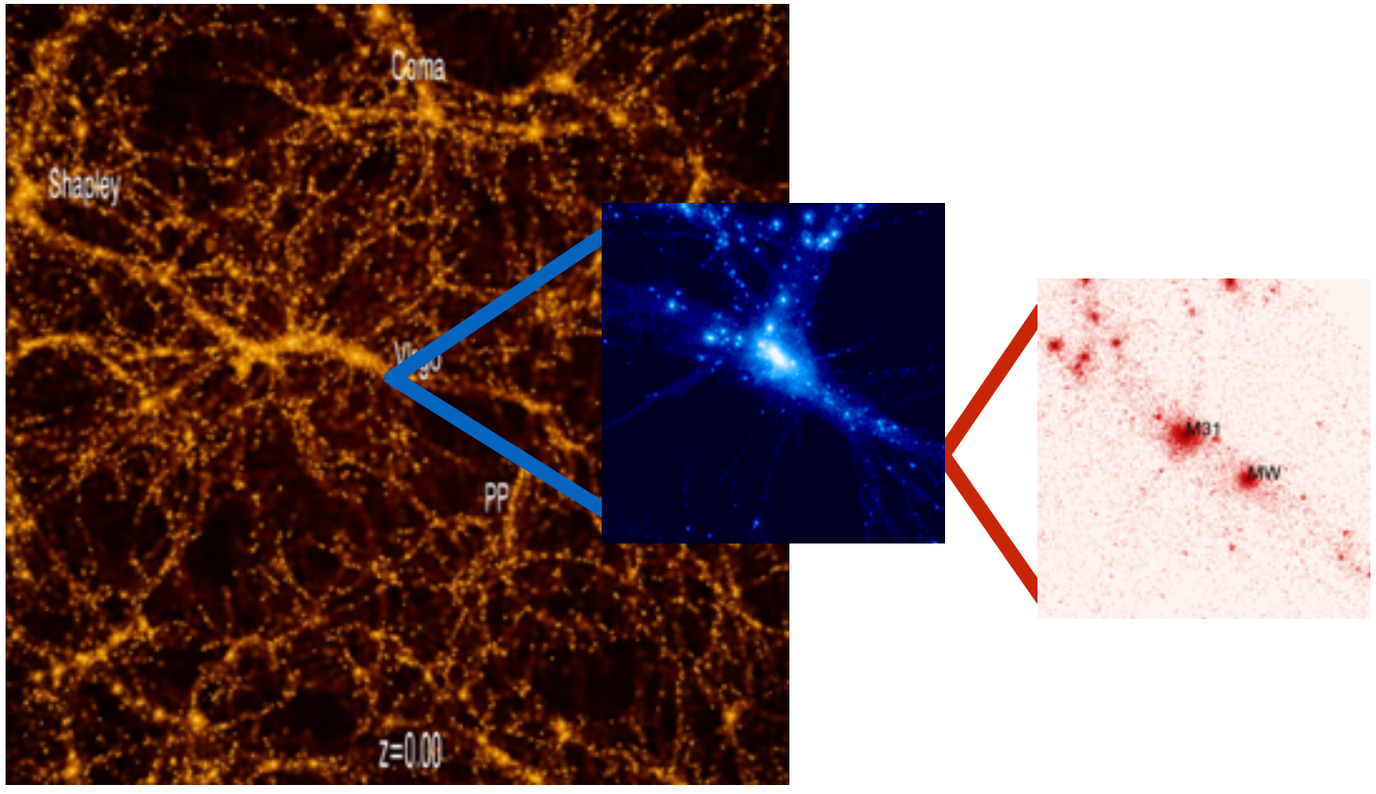
e.g. for the **Virgo cluster** Sorce+2016b, Sorce +submitted, Sorce+in prep. **including the past history**!

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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Sorce+2014-tdy	☑	☑	☑ induced
GMO-CLONES	☑	☑	☑

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

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

Take home message

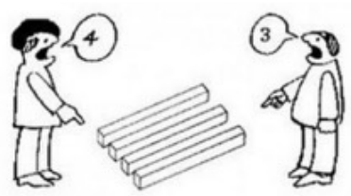
Do we need a new cosmological model?

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

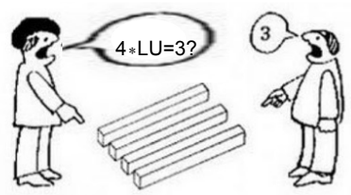
numerical specialists, theorists and observers

Small scales

Simulations of Galaxy formation & evolution:

- reproduction
- calibration

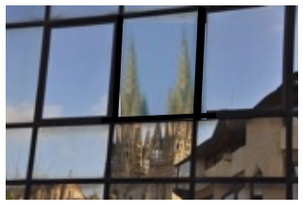
Local scales



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)