Cosmological Simulations

Numerical CLONES

In memory of Cécile Renault

Jenny Sorce

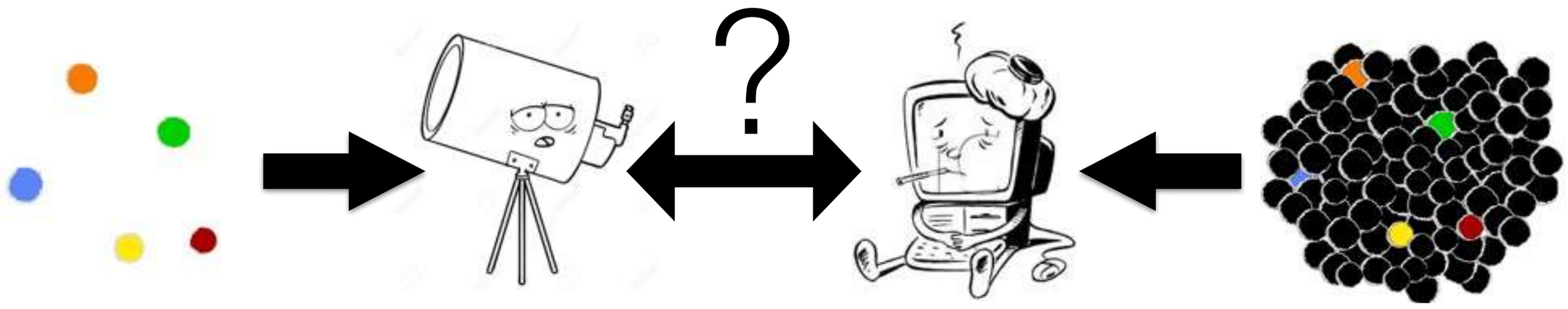
Centre de Recherche Astrophysique de Lyon

Webinar dark energy - May 11th 2021

Motivation : ΛCDM? ➤ Current strategy

Observations

Simulations



Directly Observable Universe

Cosmological Model

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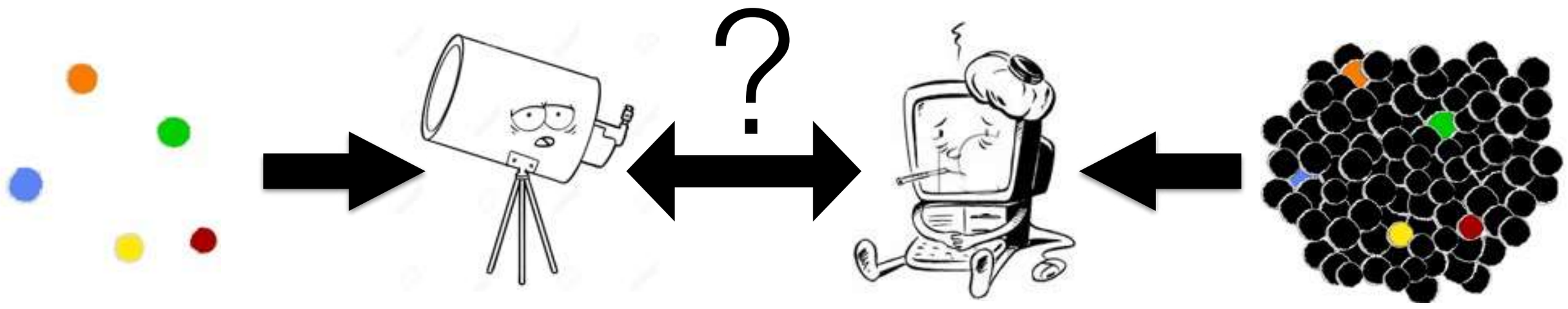


Directly Observable Universe

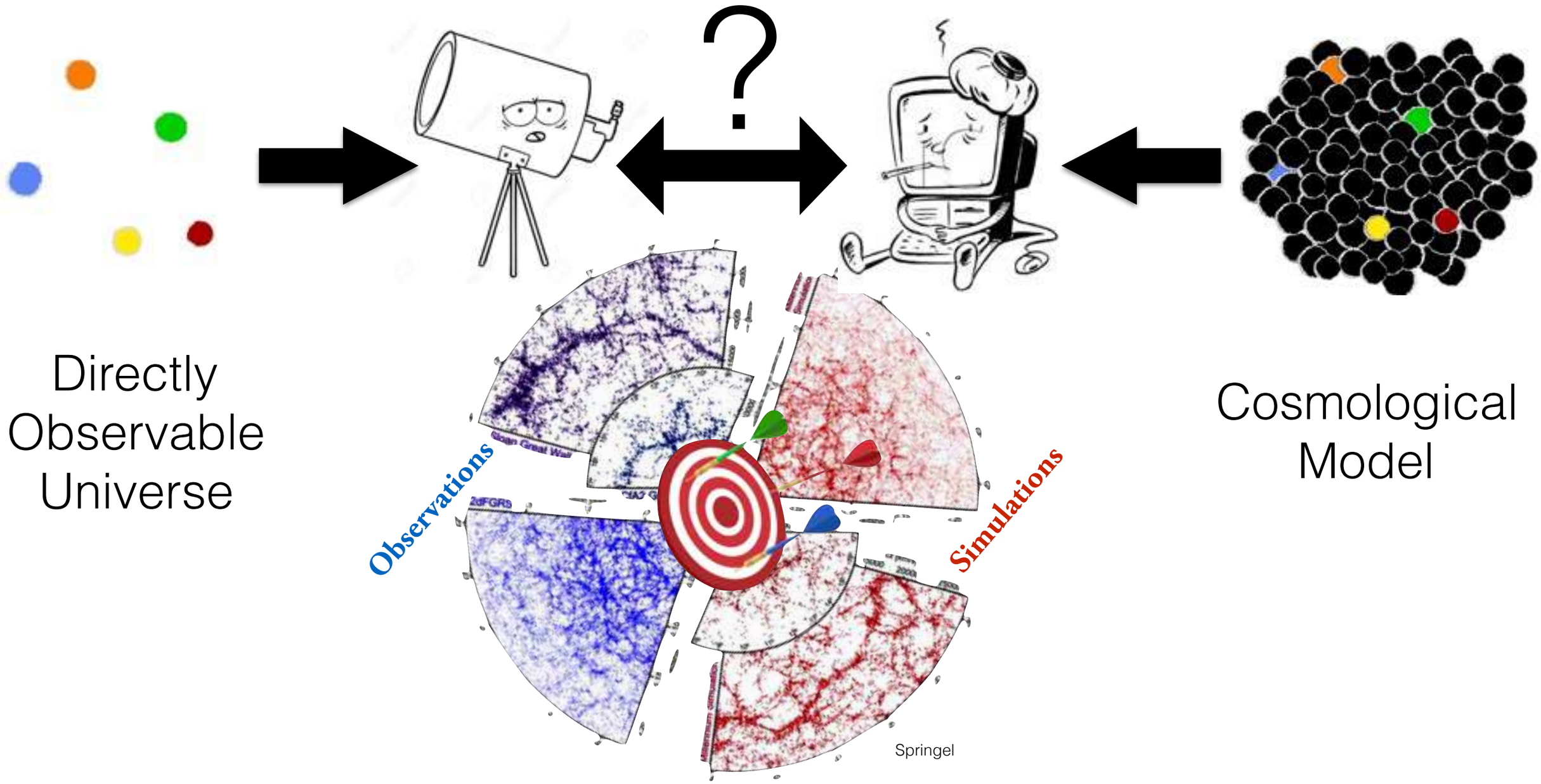
Cosmological Model

If all goes well…
it is a perfect match

Motivation : ΛCDM? In practice

Observations

Simulations



Directly Observable Universe

Cosmological Model

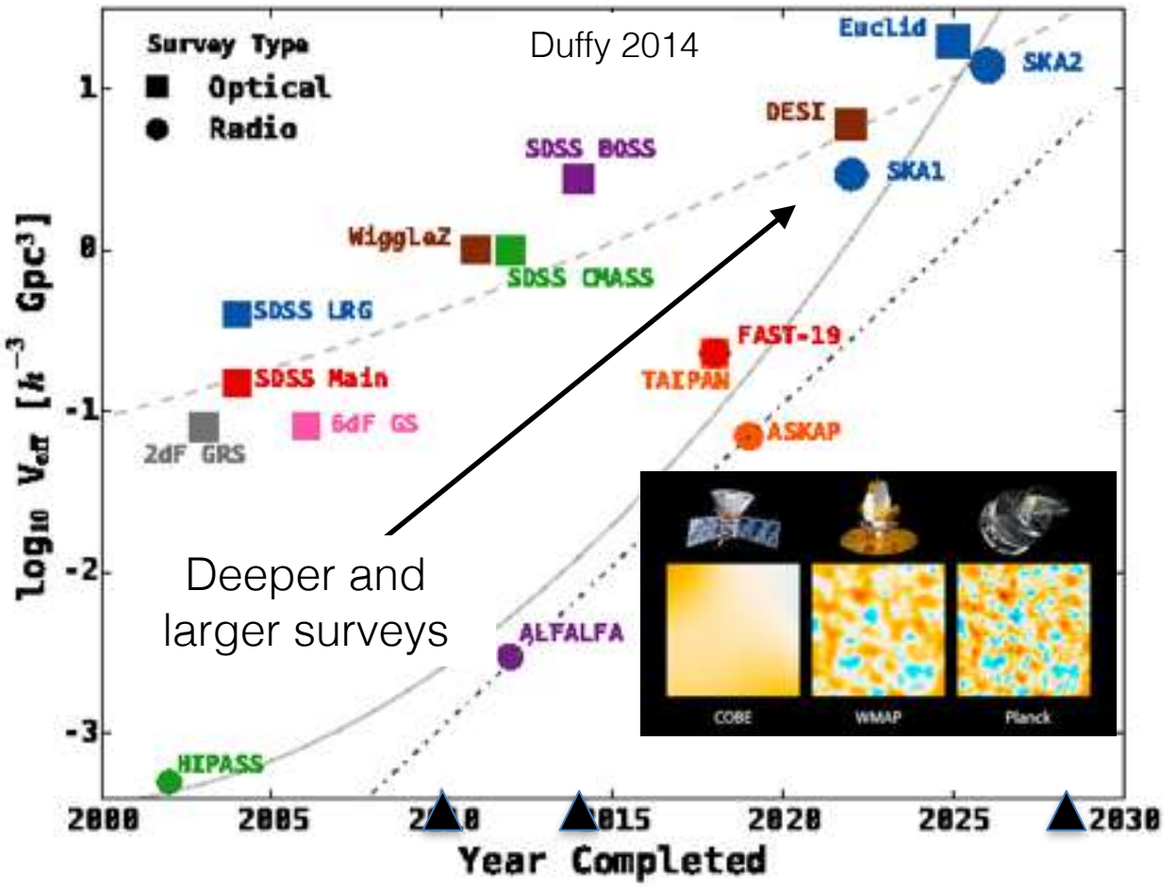
Overall: ΛCDM ☑

Motivation : ΛCDM? Toward precision cosmology

Precision Era:
1-2% precision

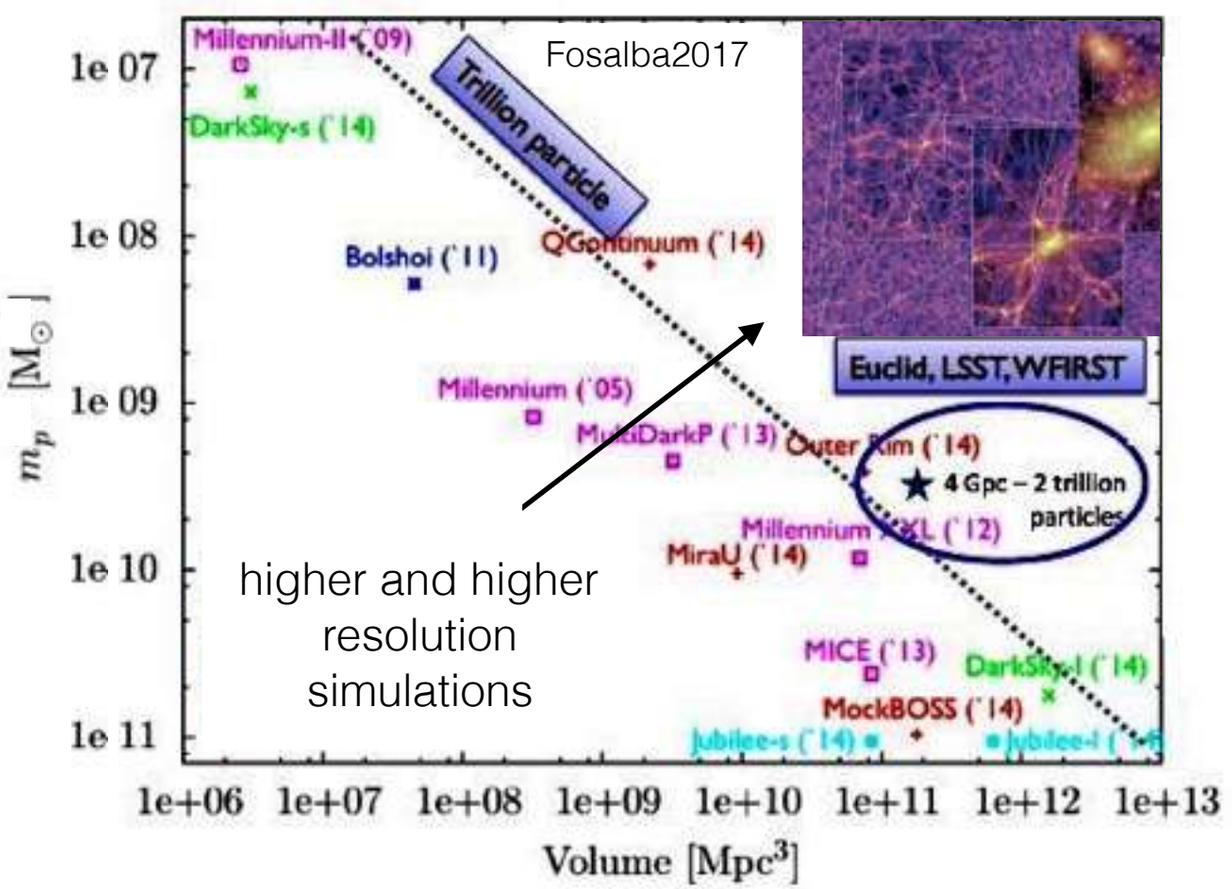
ΛCDM checked on all scales

Observational



Duffy 2014

Dark matter only



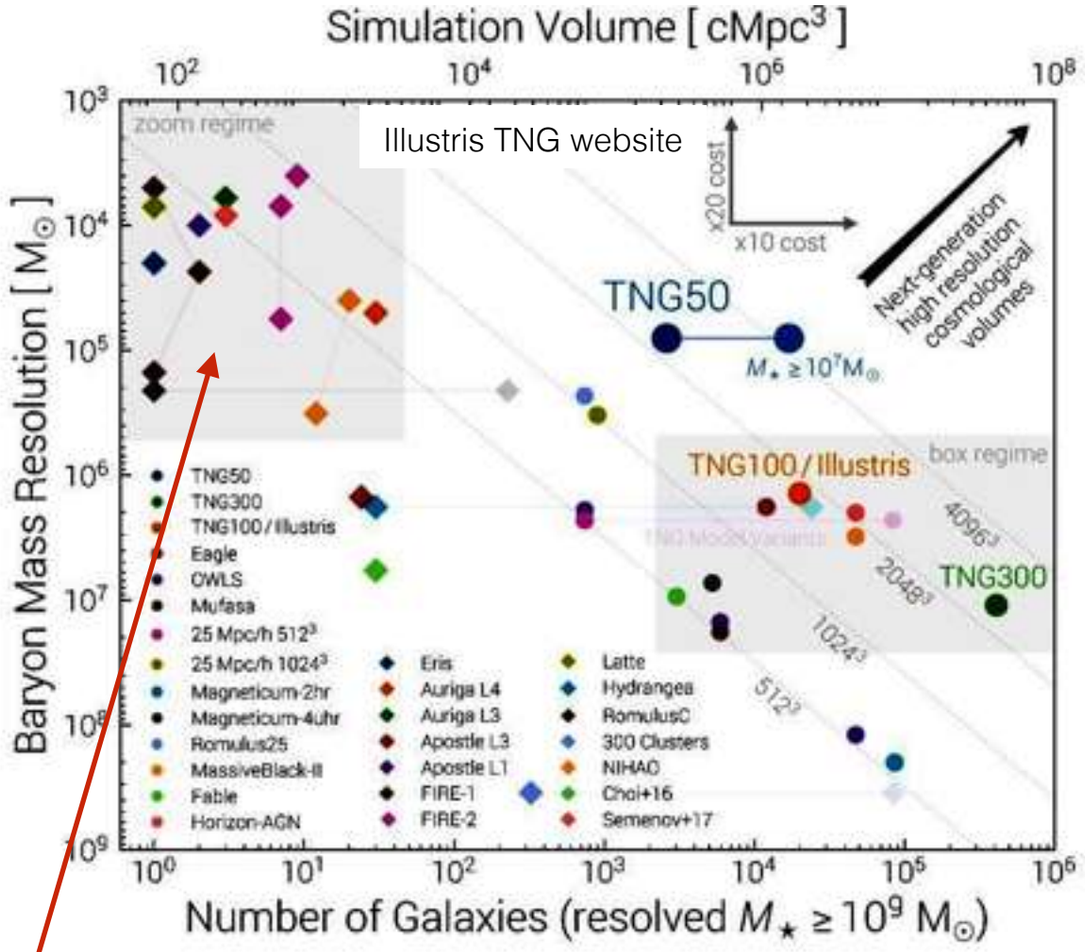
Fosalba2017

Motivation : ΛCDM? Toward precision cosmology

Precision Era:
1-2% precision

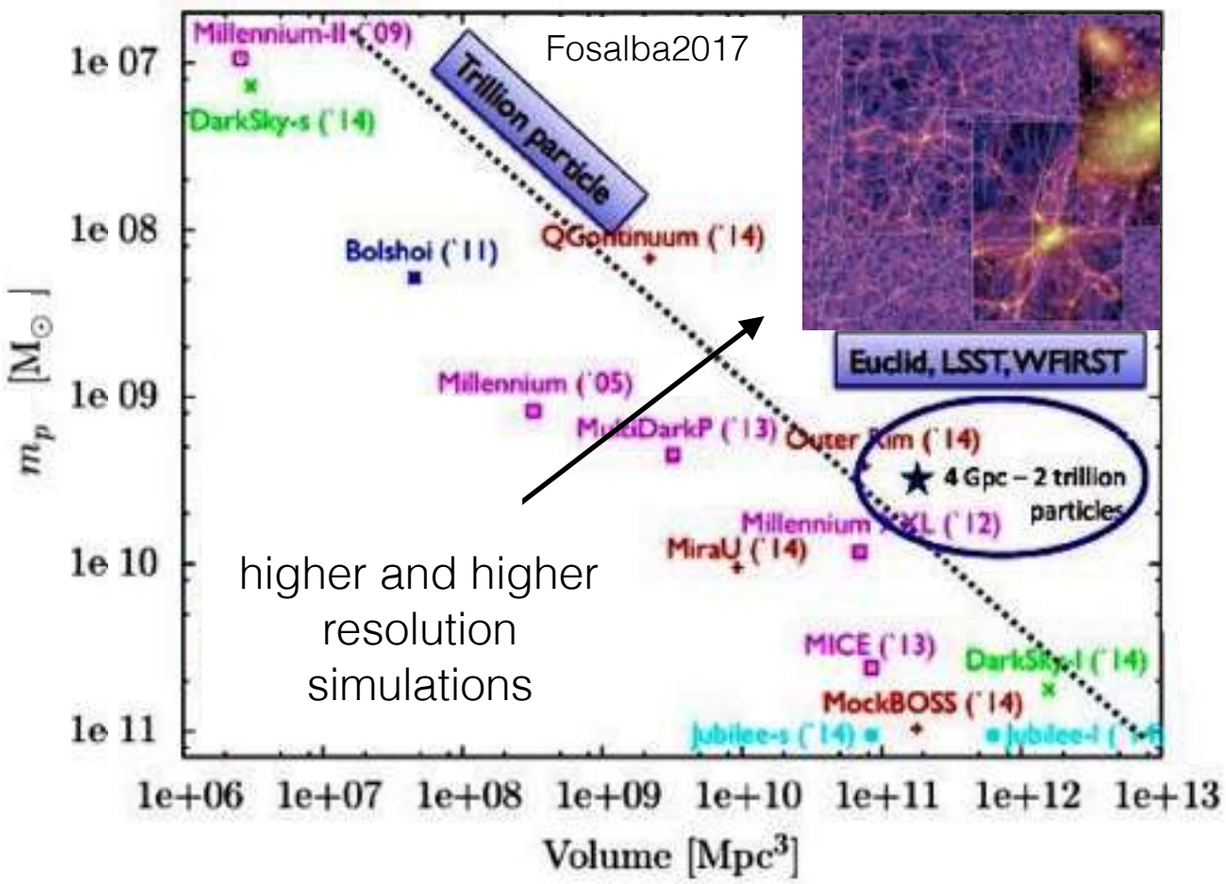
ΛCDM checked on all scales

With baryons



Zoom Simulations to retain large scale effects

Dark matter only



Motivation : ΛCDM? Toward precision cosmology

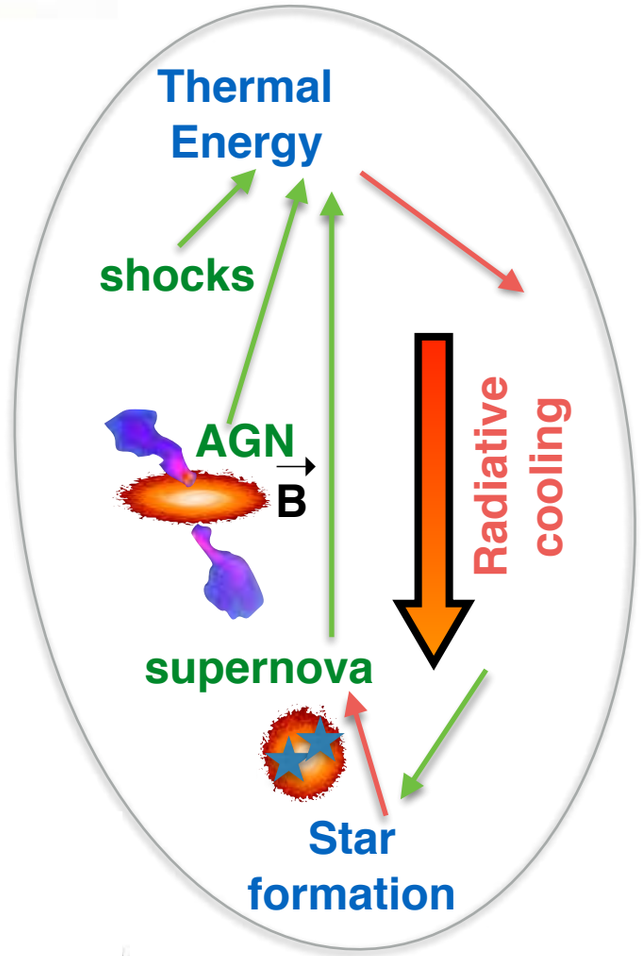
Precision Era:
1-2% precision

What is in there?

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

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

+ subgrid models



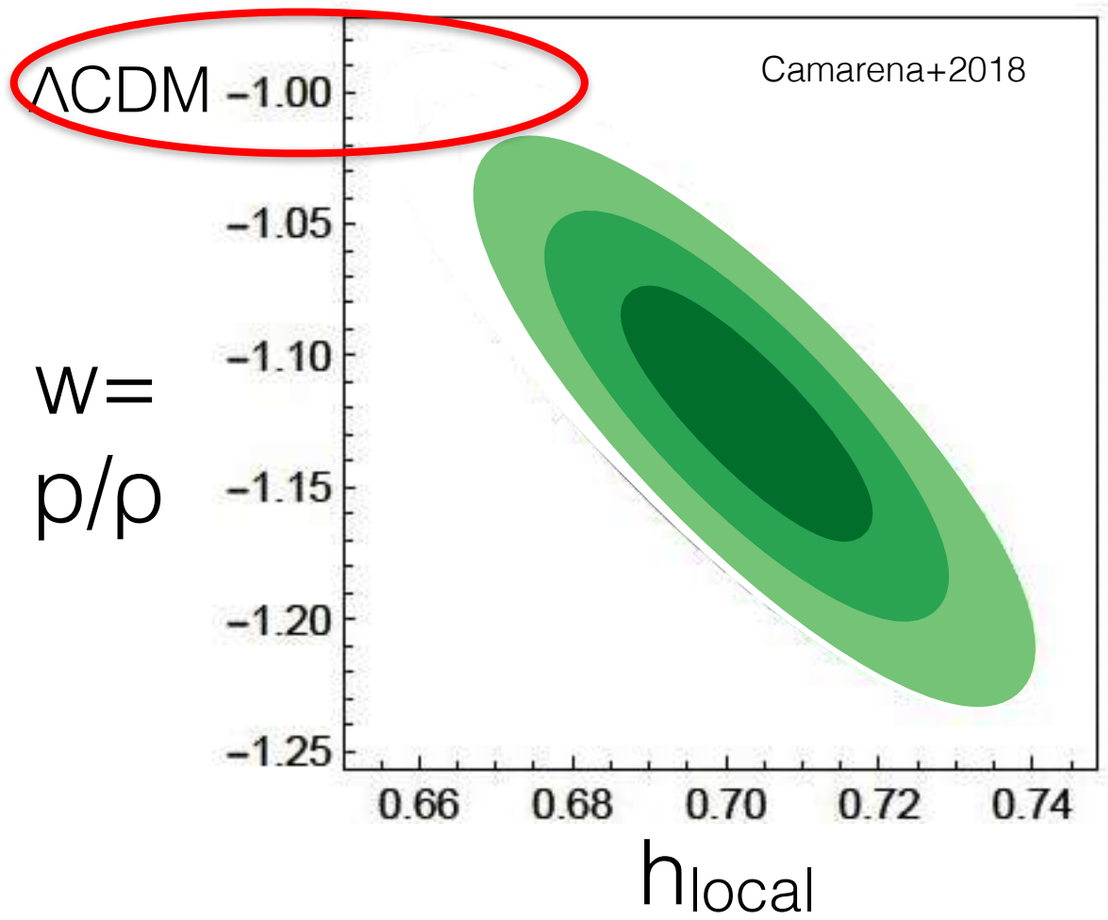
+ Cosmic Rays, etc

What more can we do wrt these typical simulations and why ?

 with more precision come some tensions !

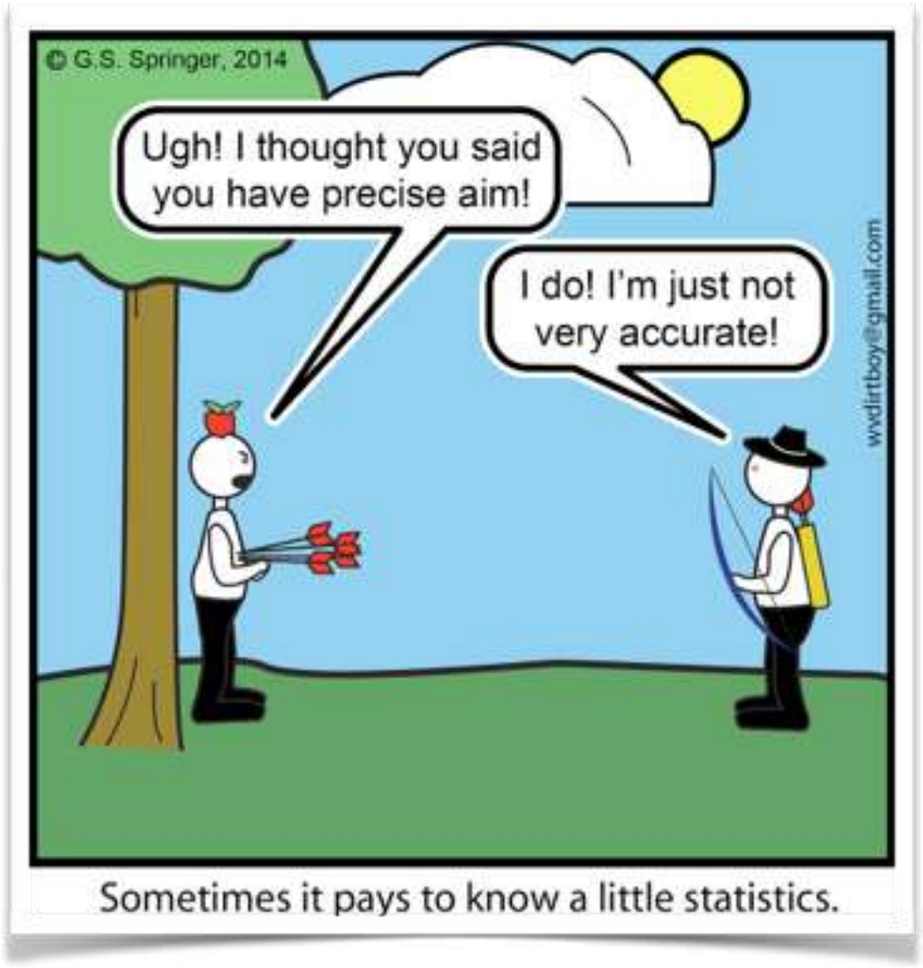
Let's start with why

Example: Equation of state of the dark energy



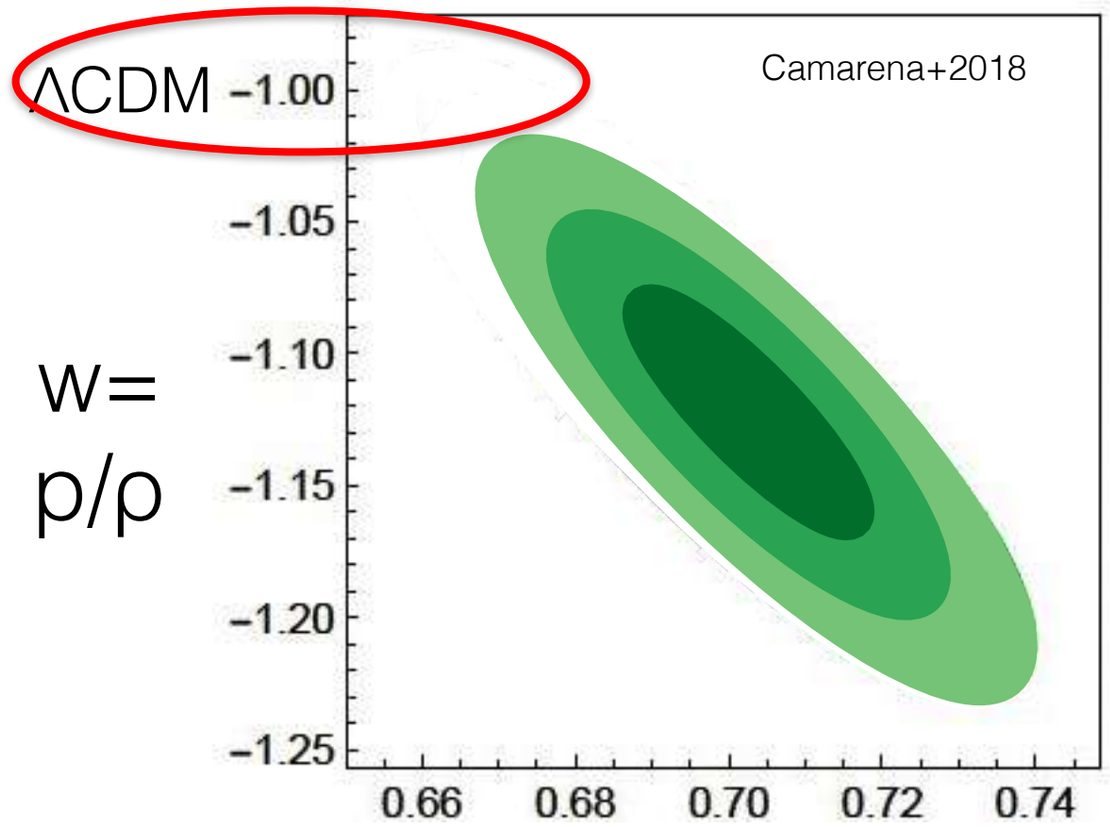
Motivation : ΛCDM?

Precision is not accuracy !



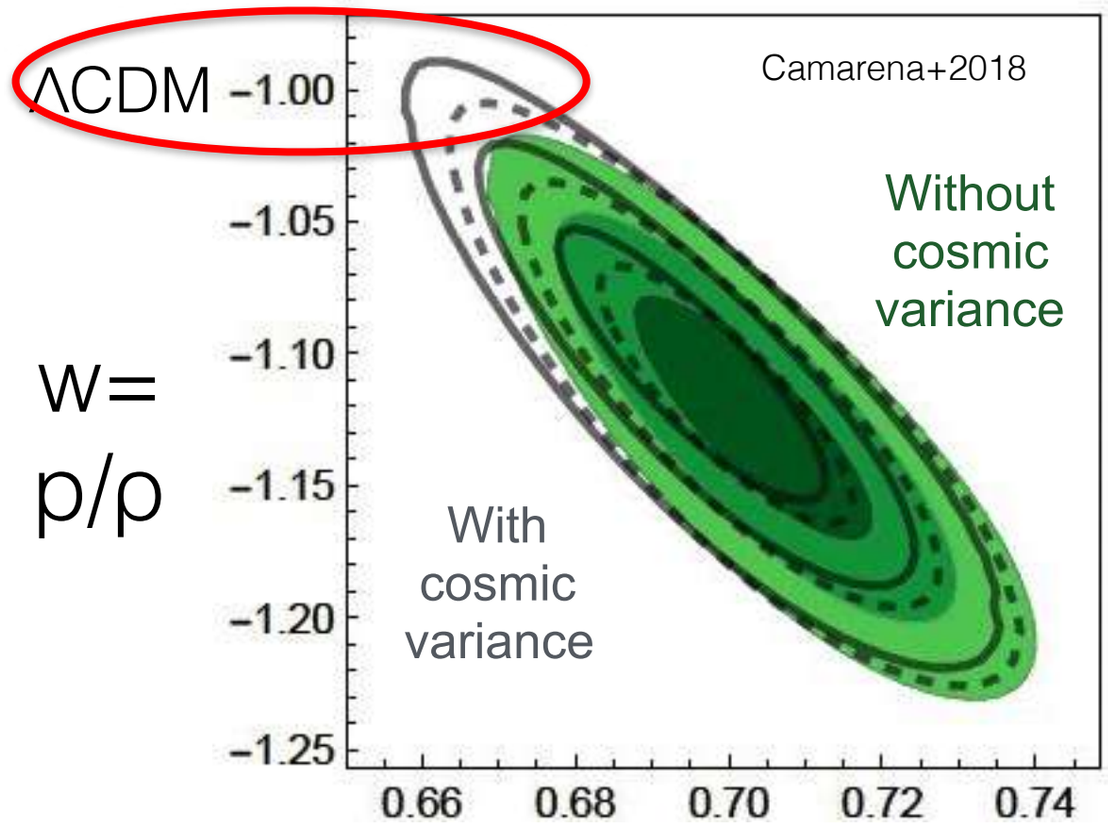
Motivation : ΛCDM? Precision is not accuracy: environmental biases?

Example: Equation of state of the dark energy



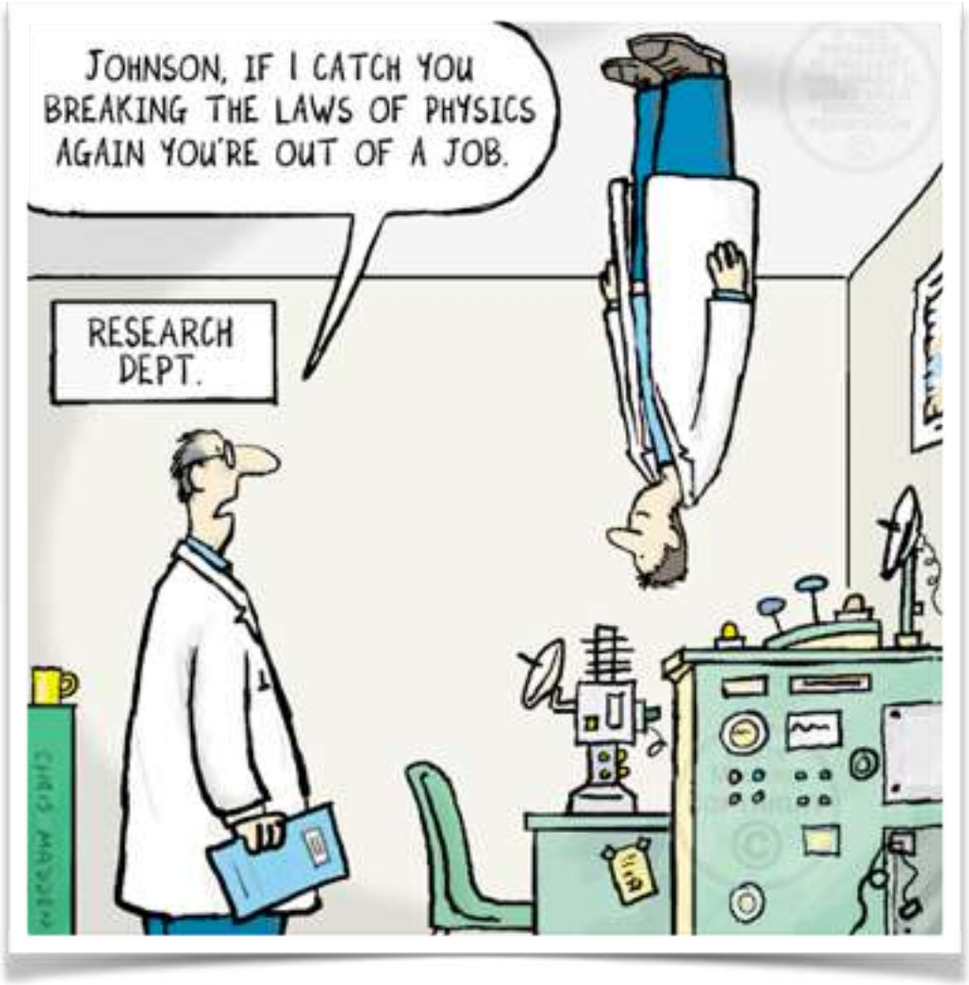
Motivation : ΛCDM? Both precision and accuracy are required!

Example: Equation of state of the dark energy



Accuracy:
1% bias non-negligible

When observations challenge ΛCDM

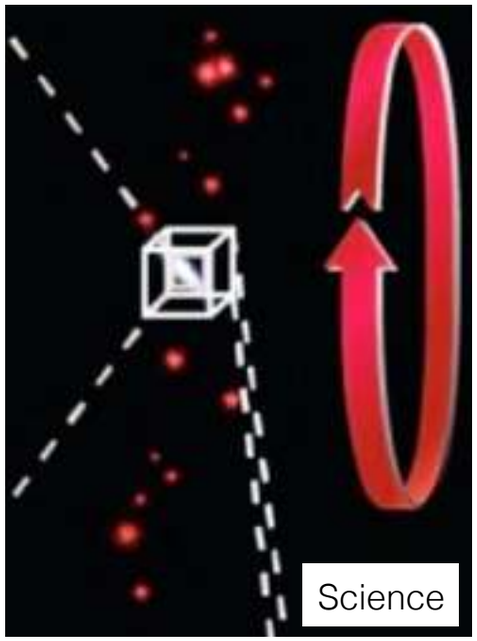


ΛCDM questioned? Precision cosmology

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

ΛCDM questioned? Precision cosmology

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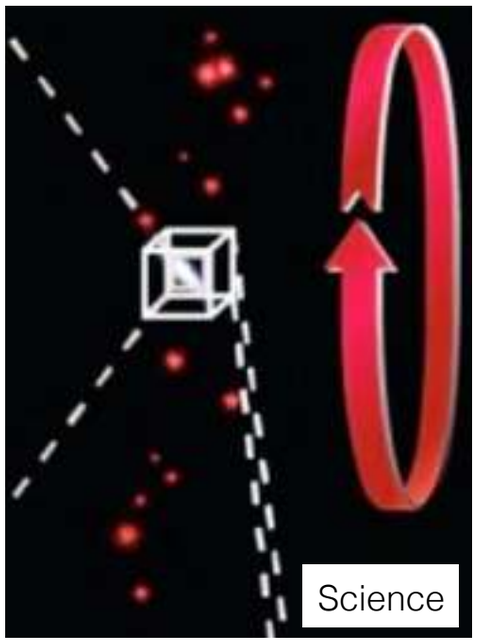

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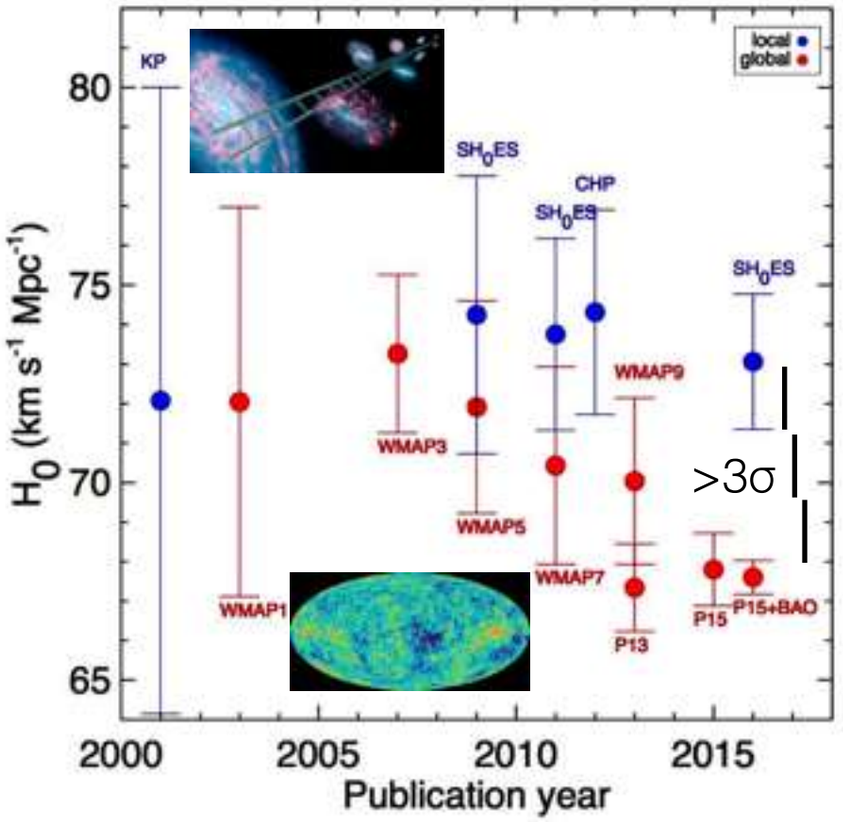

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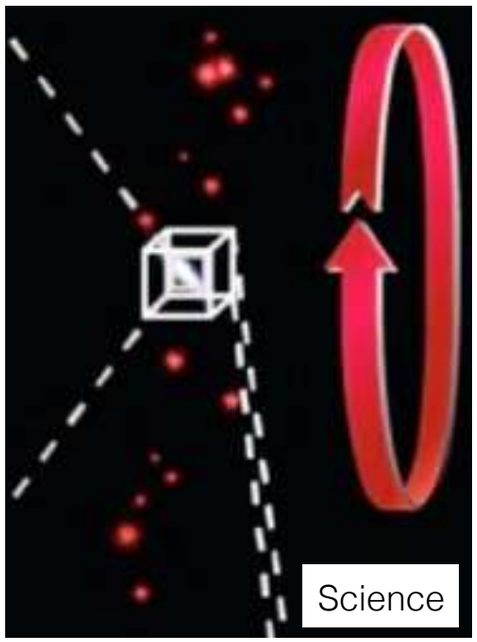

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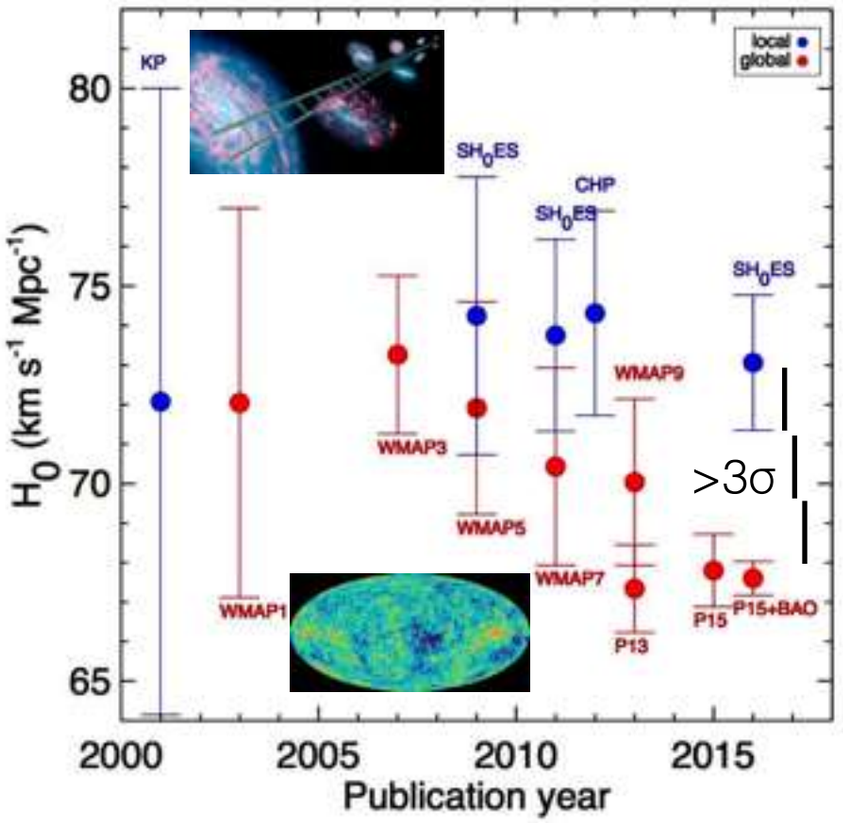

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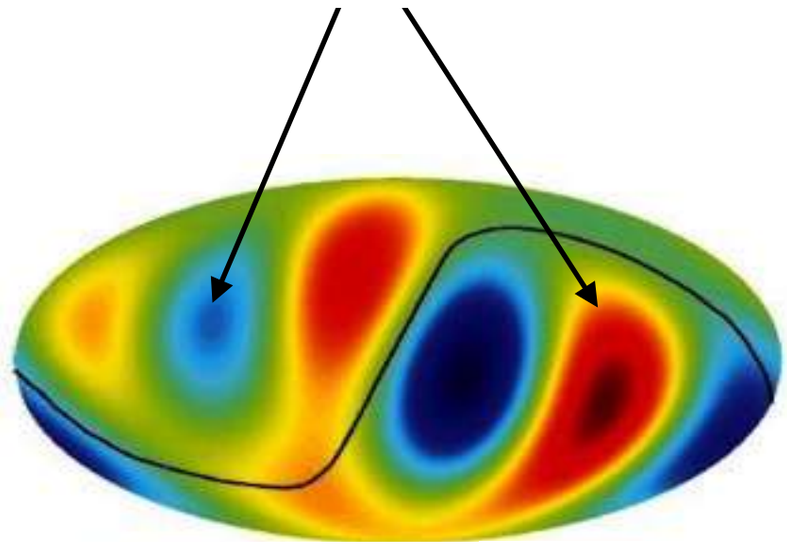


Francis+2010

very unlikely…

e.g. Schwarz+2016

More examples: local void emptier with larger galaxies, CMB/galaxy clusters σ_8, lack of angular correlation at large scales

local correlations slope and scatter, missing satellites, cold spot, etc

Local-induced biases ?

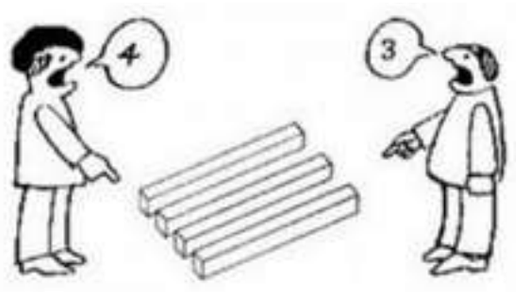
Can our local environment bias our ‘’perception’’ at the 1-2% level preventing us from reaching 1-2% accuracy…

Small scales

Are we comparing
apple to apple?
Do we understand enough?

Correlation with environment

Local scales



Are we a neutral observer?

A neutral environment?
Very unlikely…

Large scales

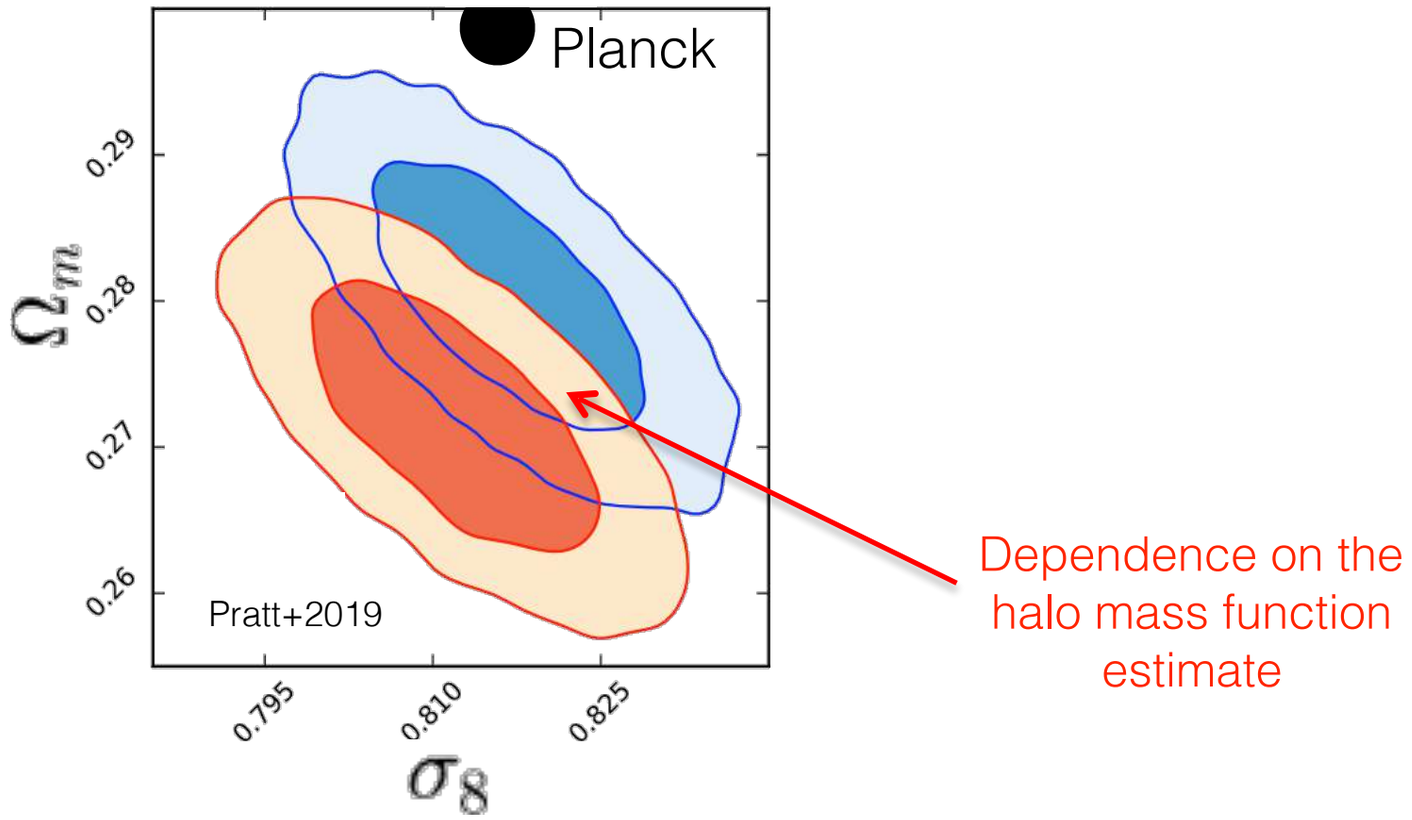
What about foreground effects?

Photons travel a lot
before reaching us…

and eventually decrease *or increase* tensions with ΛCDM ?

Local-induced biases ? on the small scales

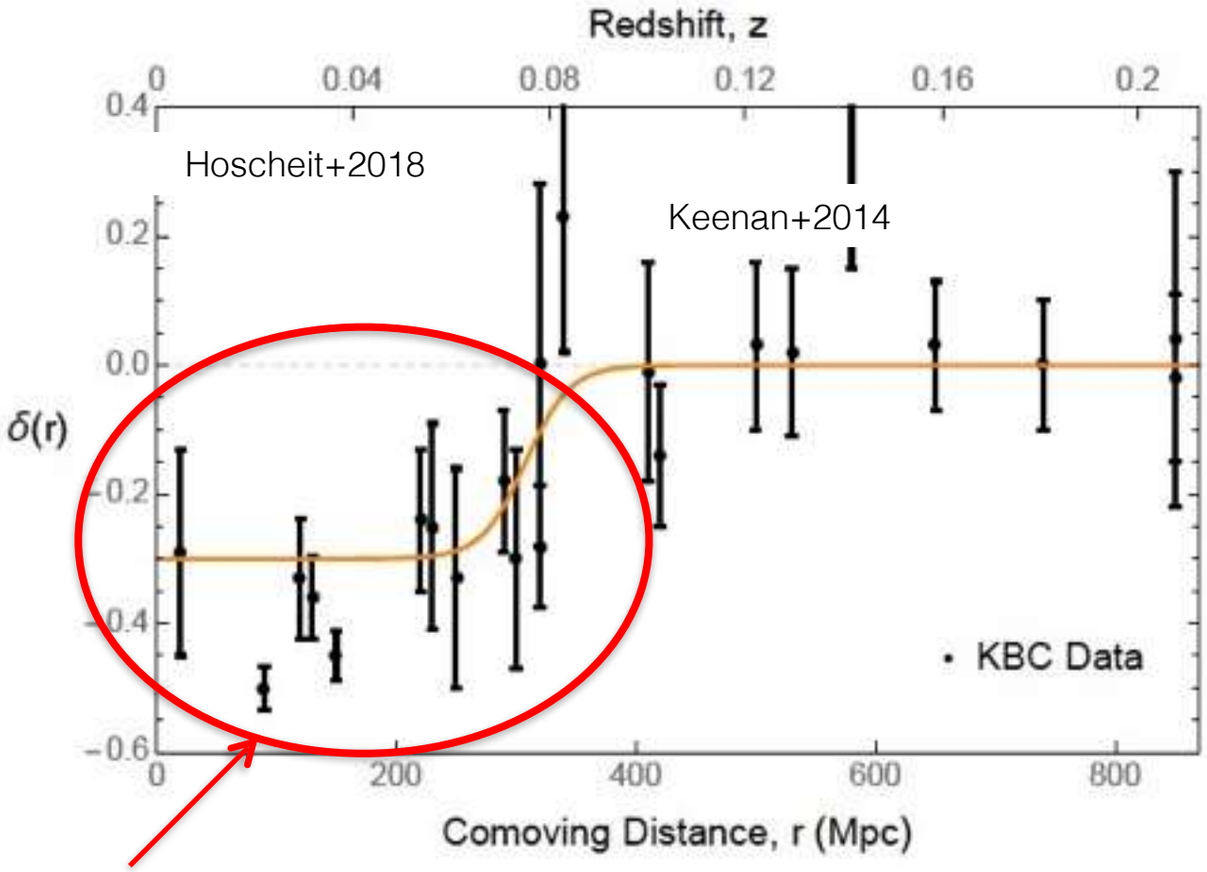
Everything relies on the mass estimate of galaxy clusters



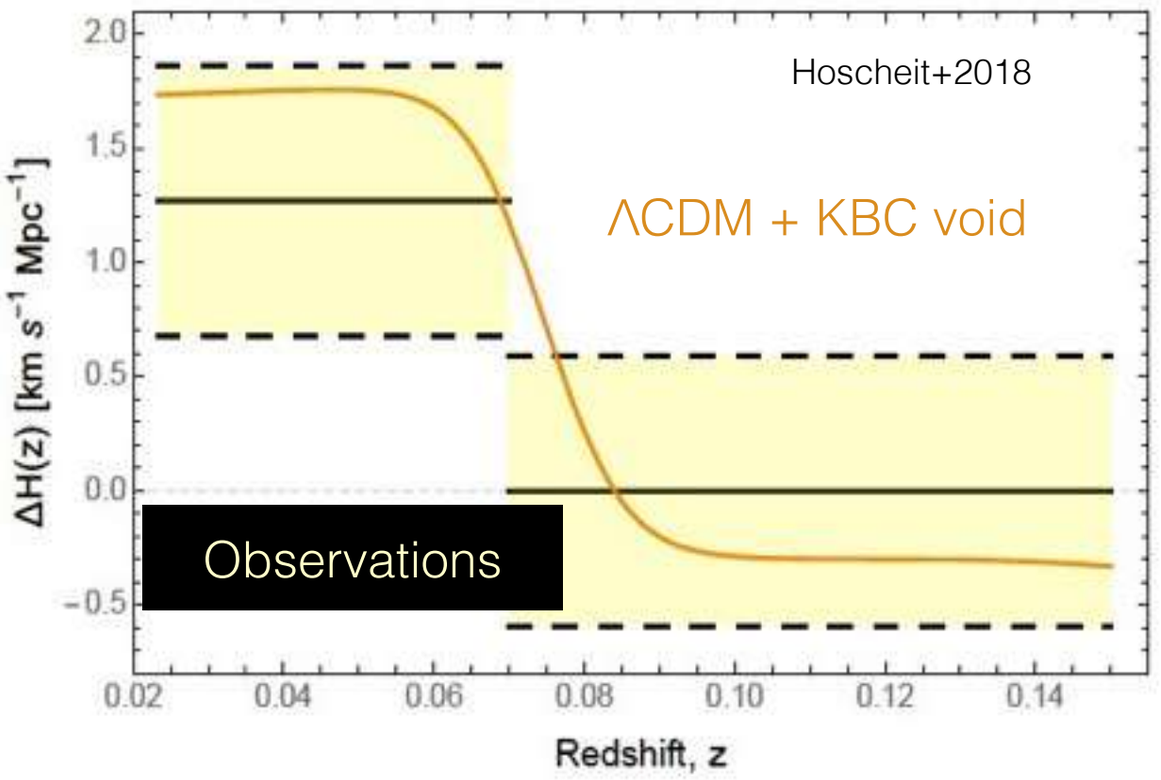
Need to understand these physics laboratories before using them as cosmological probes
Best known are closeby & Dependence on the environment !

Local-induced biases ? on the local scales

A simple example: if we live in a spherical underdensity

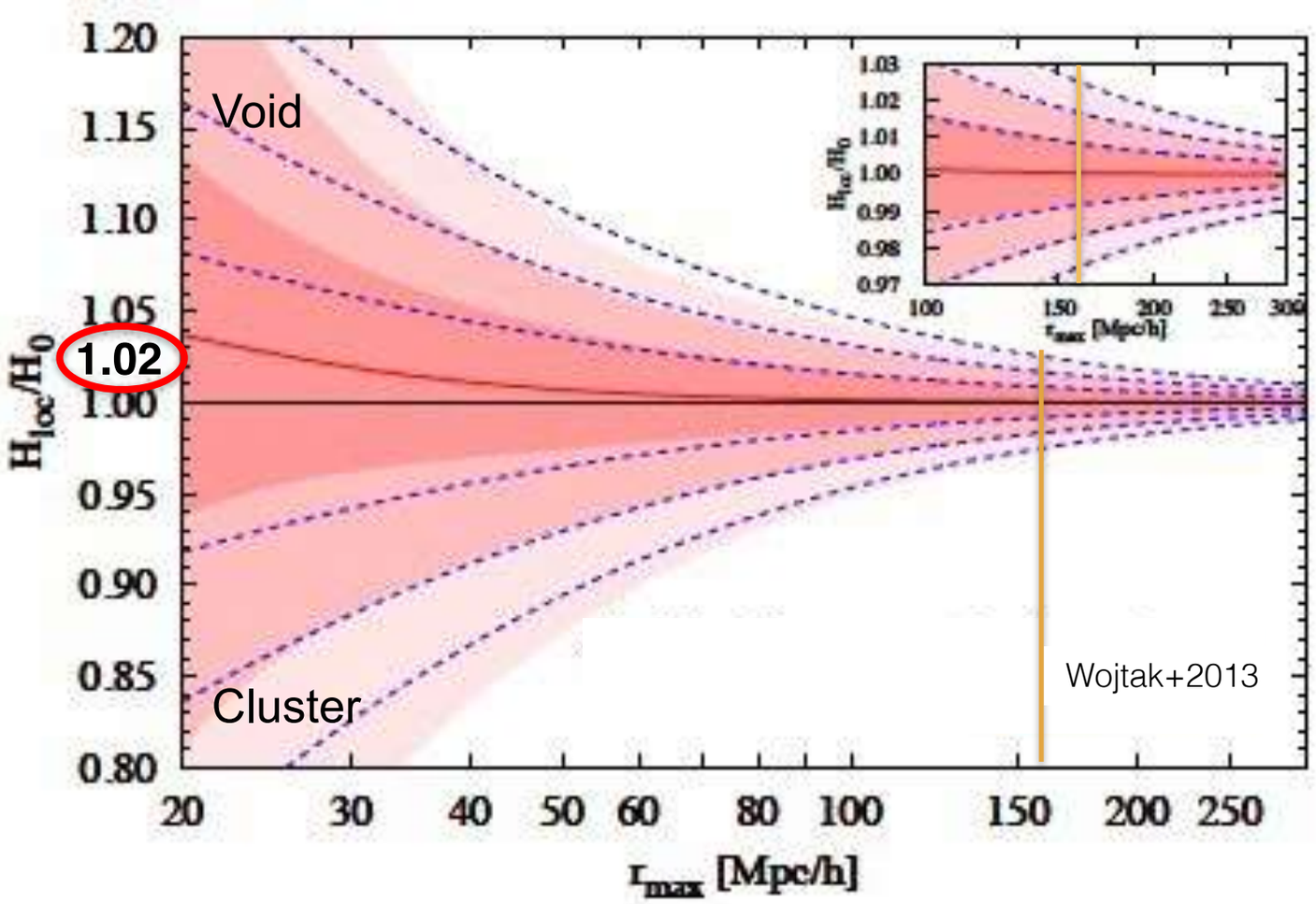


An example: Hint at a local underdensity up to z=0.07



Local-induced biases ? ➤ on the local scales

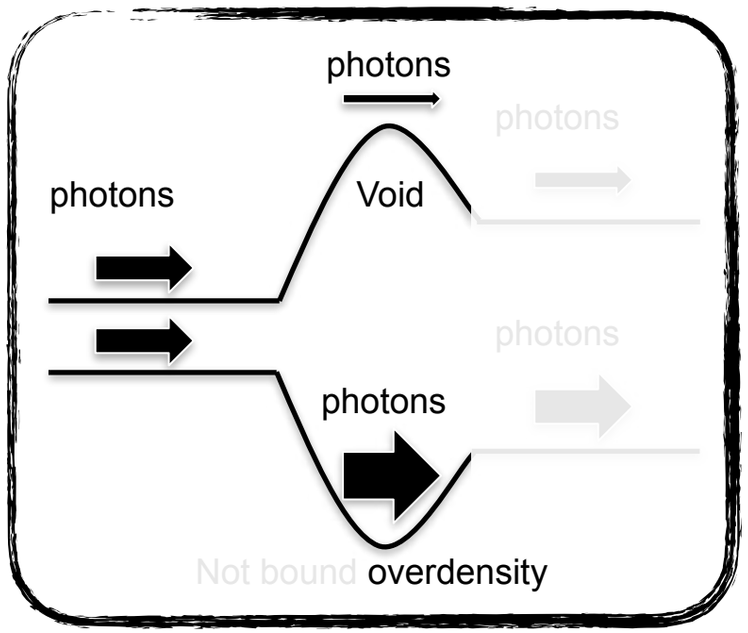
As many effect values as environments



For an average environment: a 2% bias !

Local-induced biases ? on the large scales

Gravitational redshifts and the large scale surveys



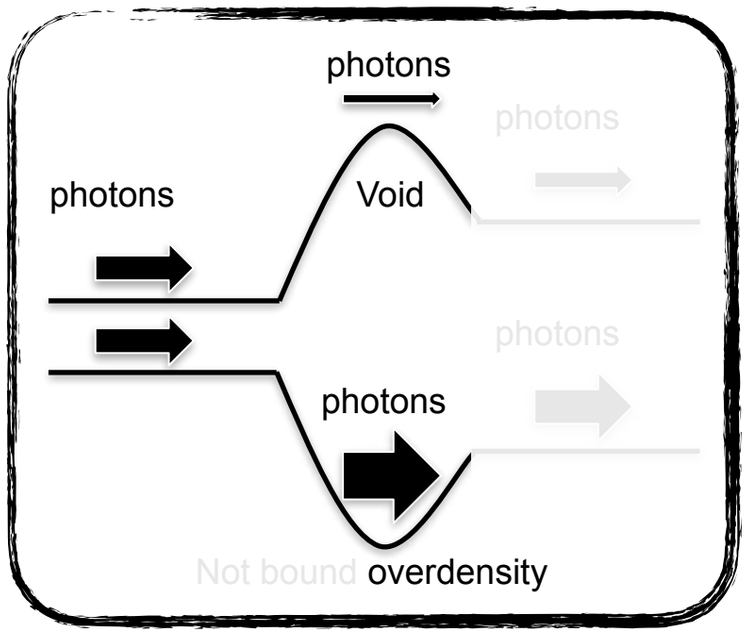
As many effect values as environments

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

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

Local-induced biases ? on the large scales

Gravitational redshifts and the large scale surveys



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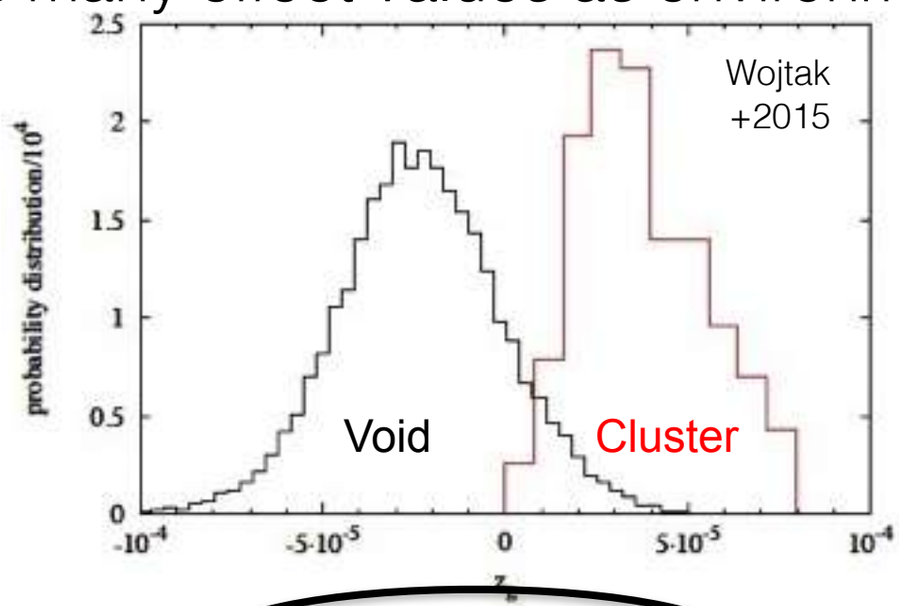

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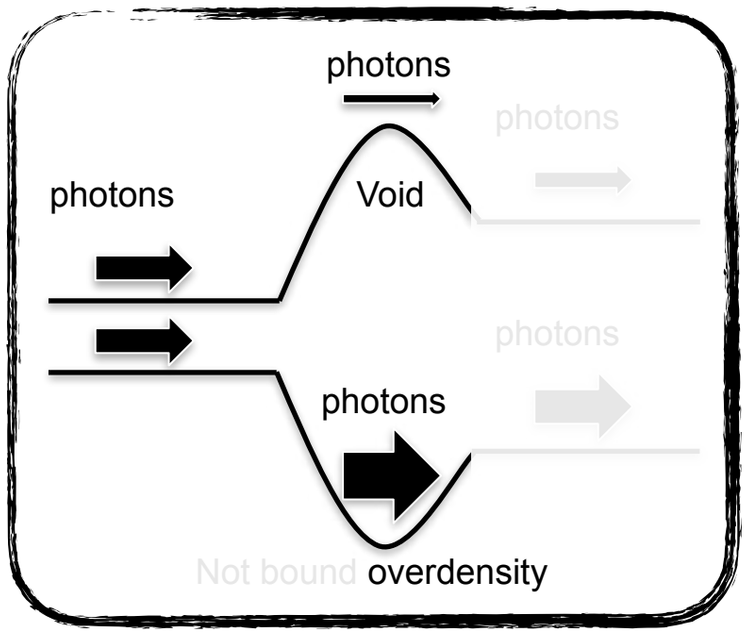

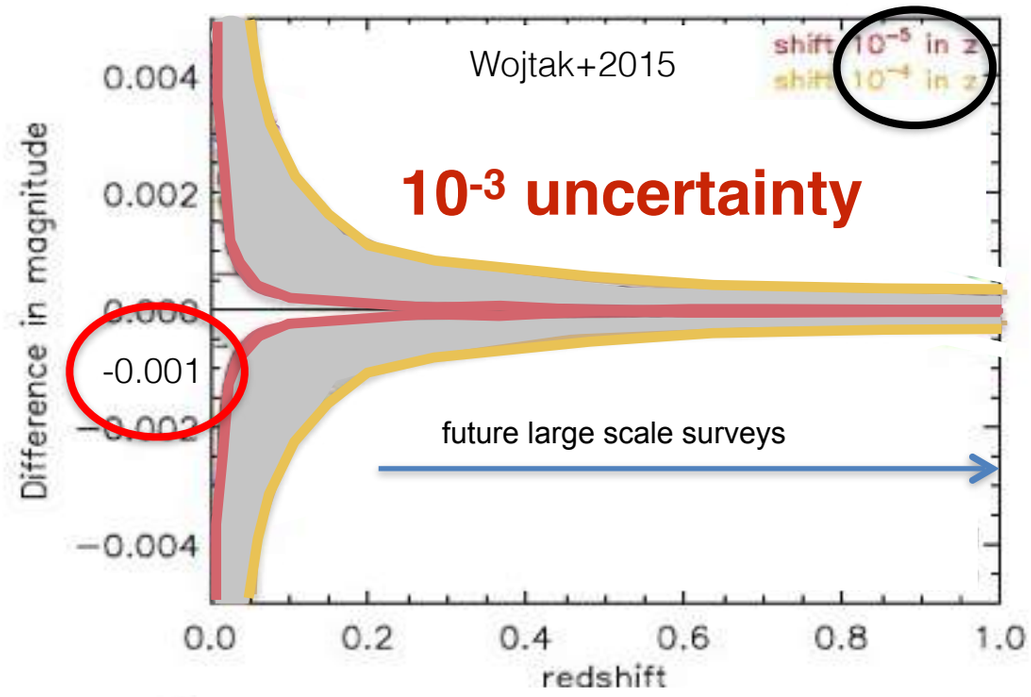

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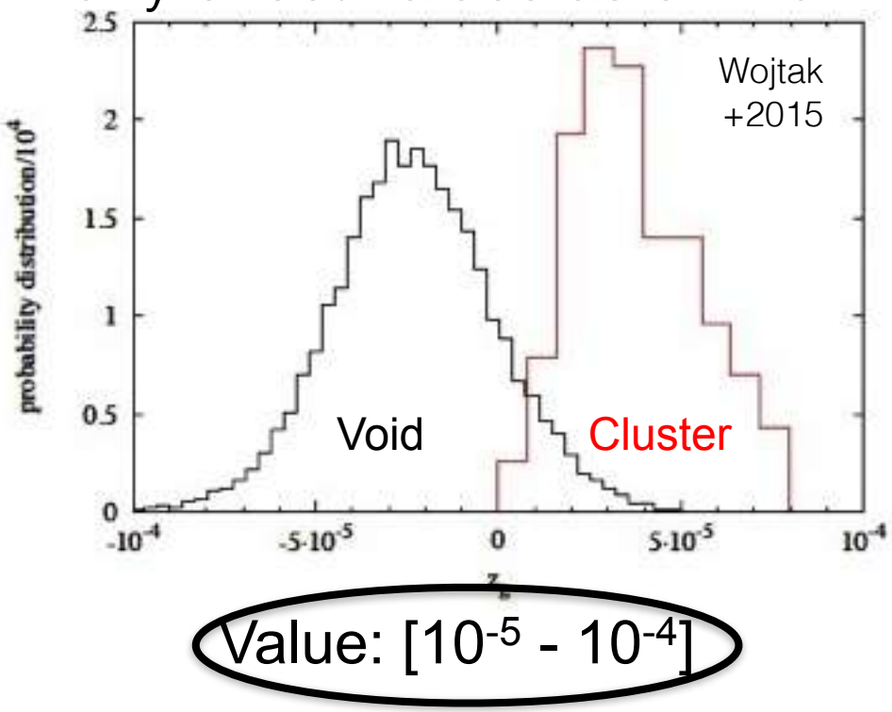


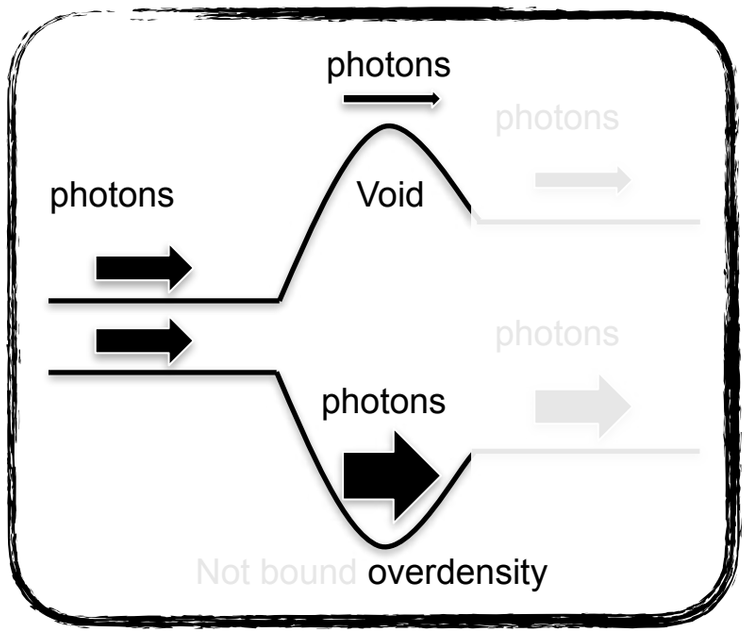
Value: [10^{-5} - 10^{-4}]

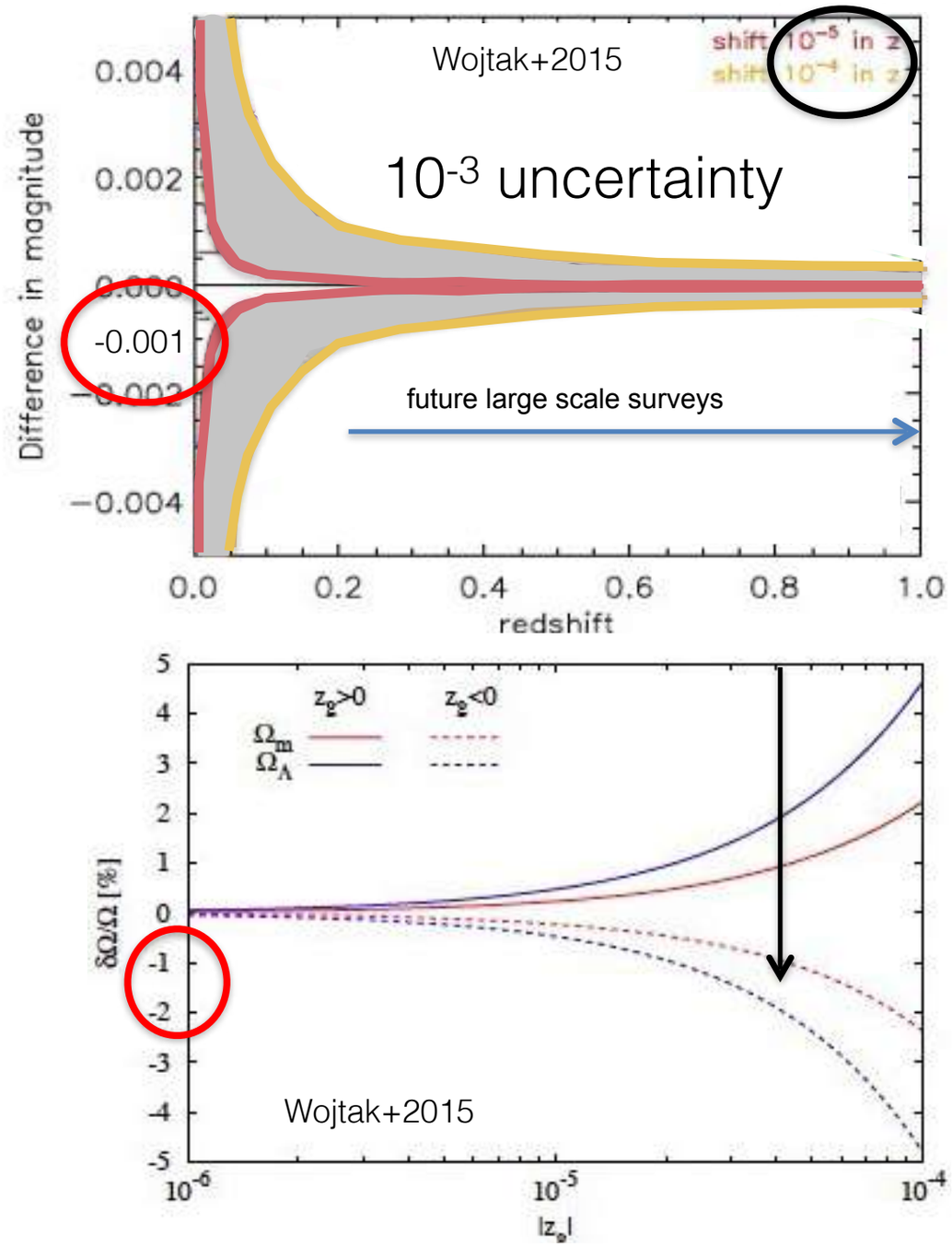
Required Precision !

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

Local-induced biases ? on the large scales

Gravitational redshifts and the large scale surveys





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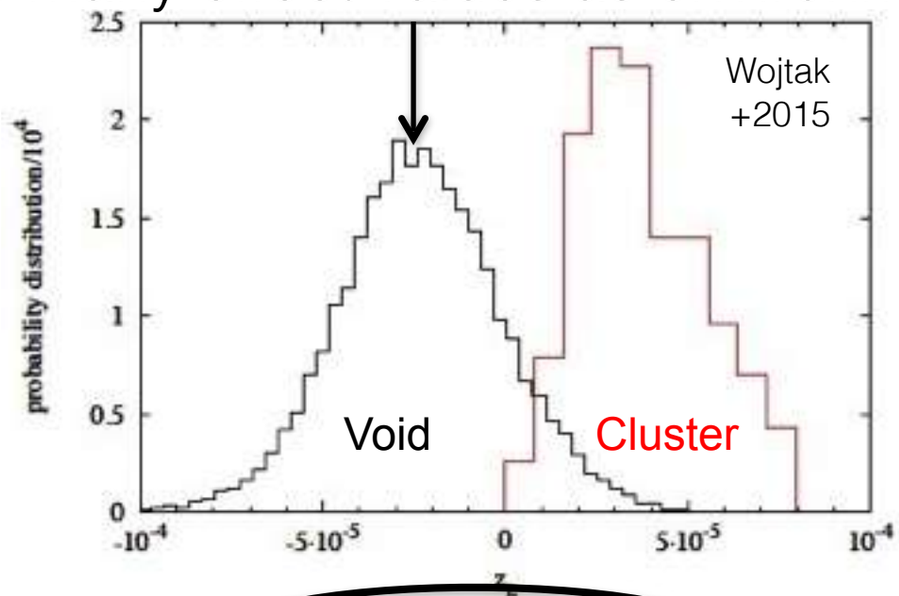

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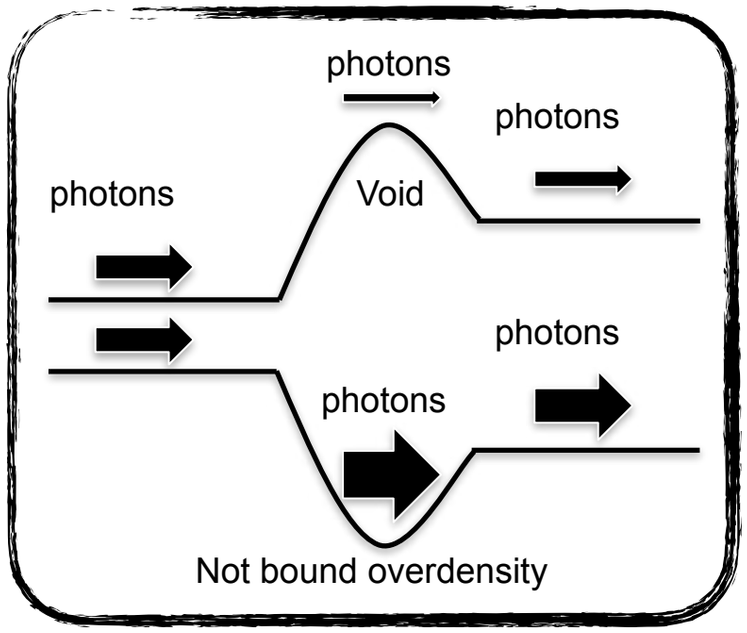
For an average environment: a 1-2% bias !

Local-induced biases ? on the large scales

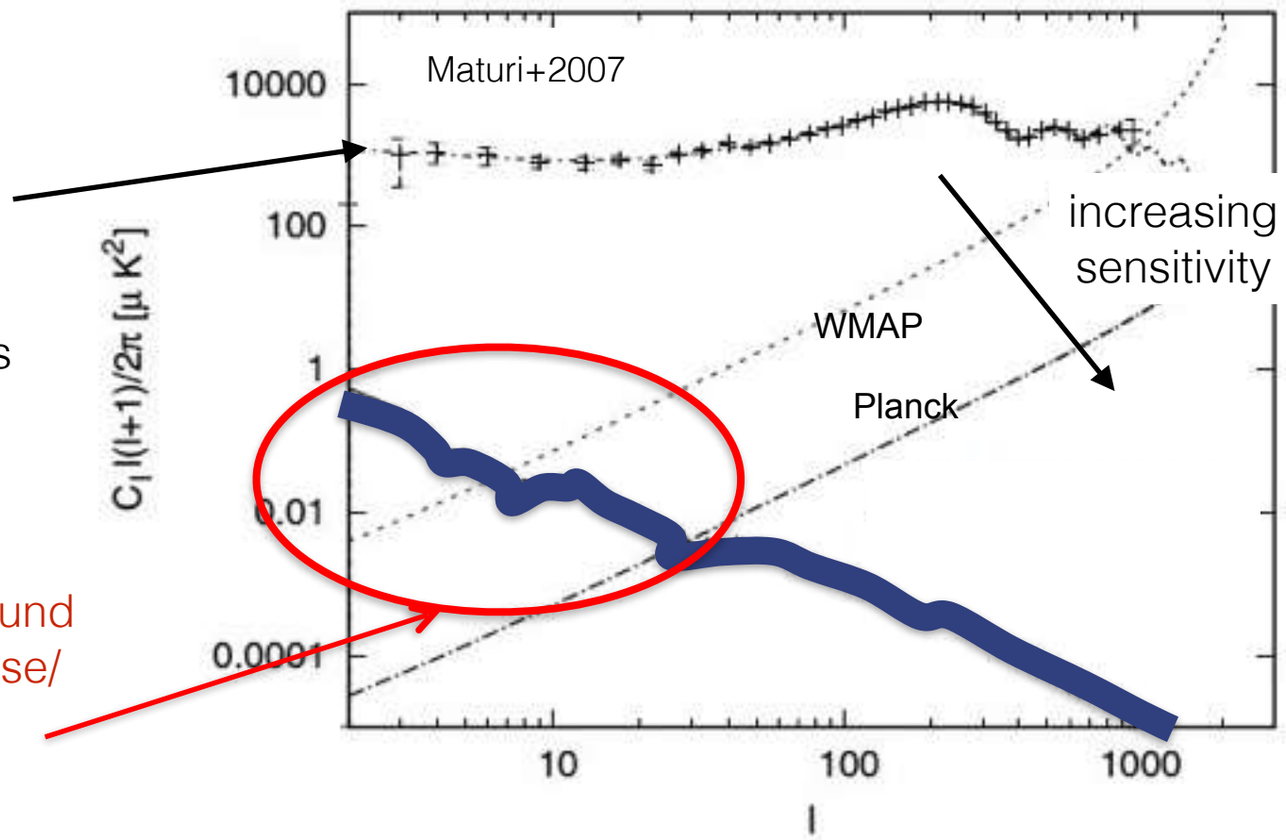
Gravitational redshifts and the CMB



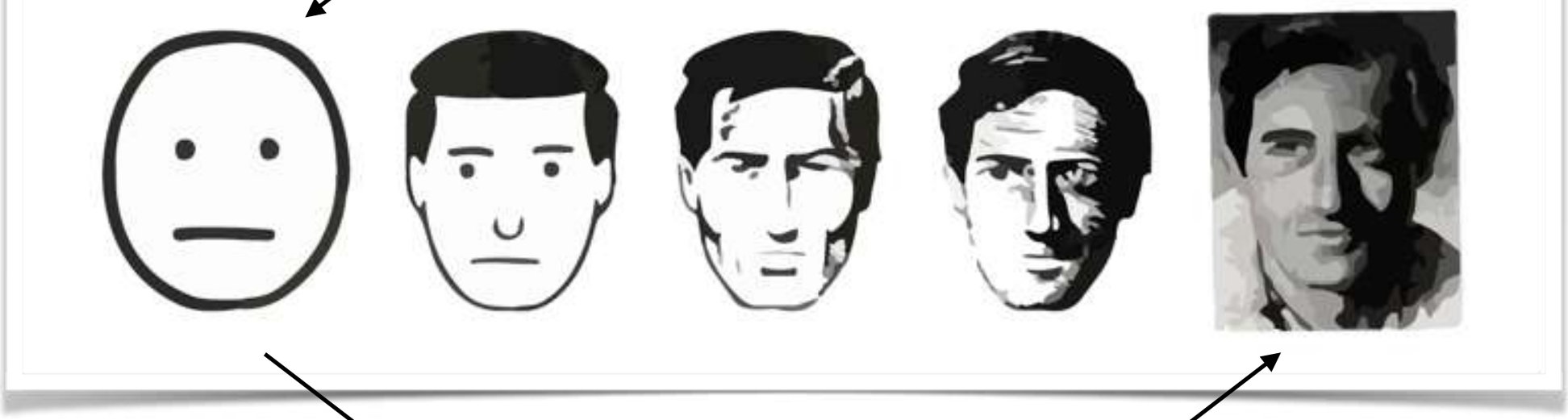
Integrated Sachs-Wolfe & Rees-Sciama Effects

increasing precision = reducing error bars

local foreground effect = ‘noise/ bias’



A crude modeling is a beginning…

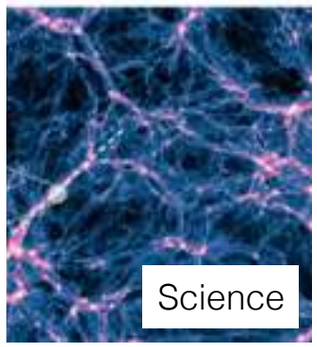


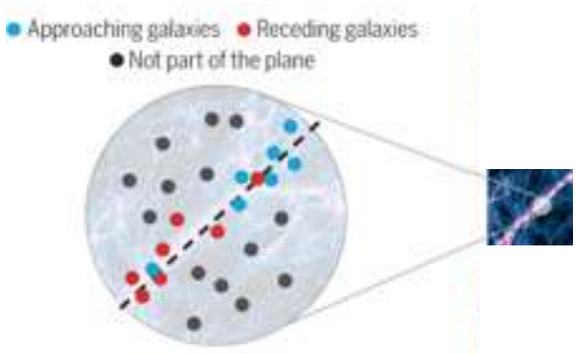
but not nearly enough…

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

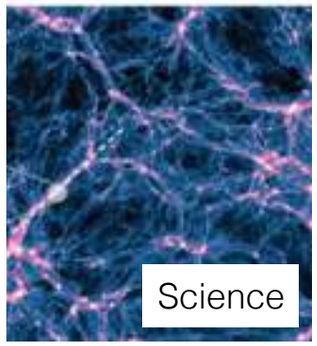
Francis+2010

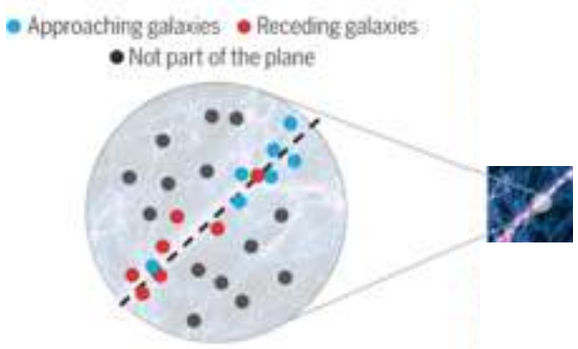
But correction from redshift surveys only…

Accounting for the effects ➤ crude modeling

A few examples

Small scales





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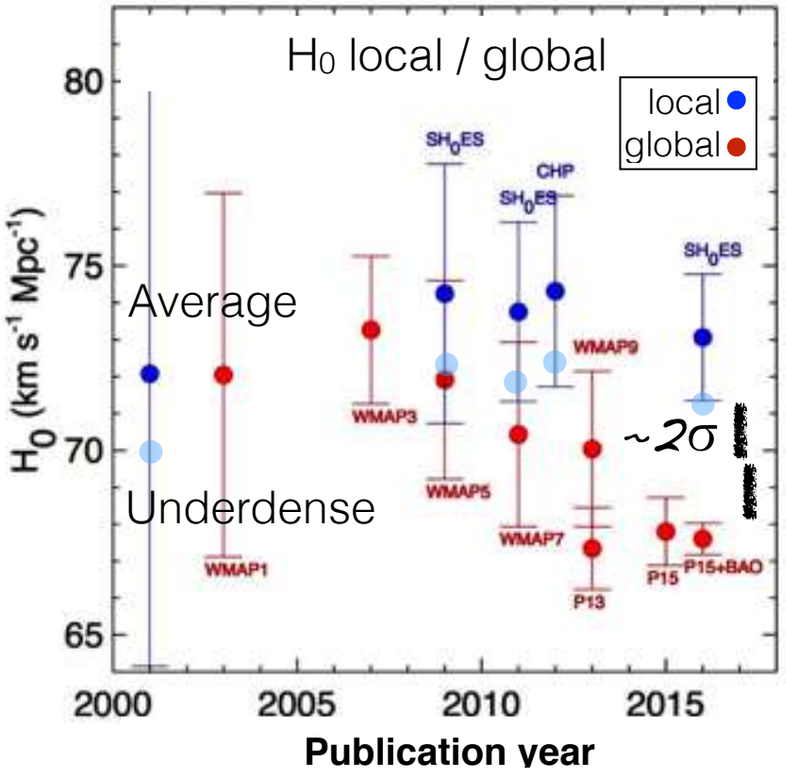

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Accounting for the effects > crude modeling

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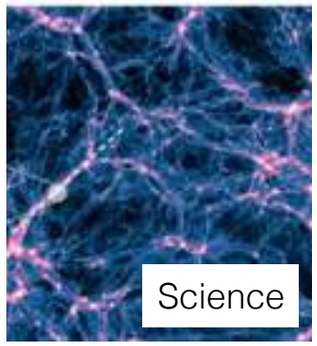

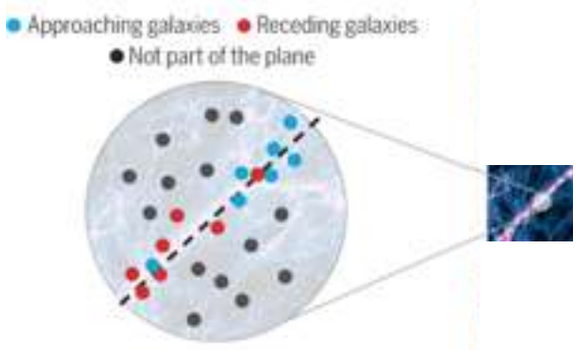

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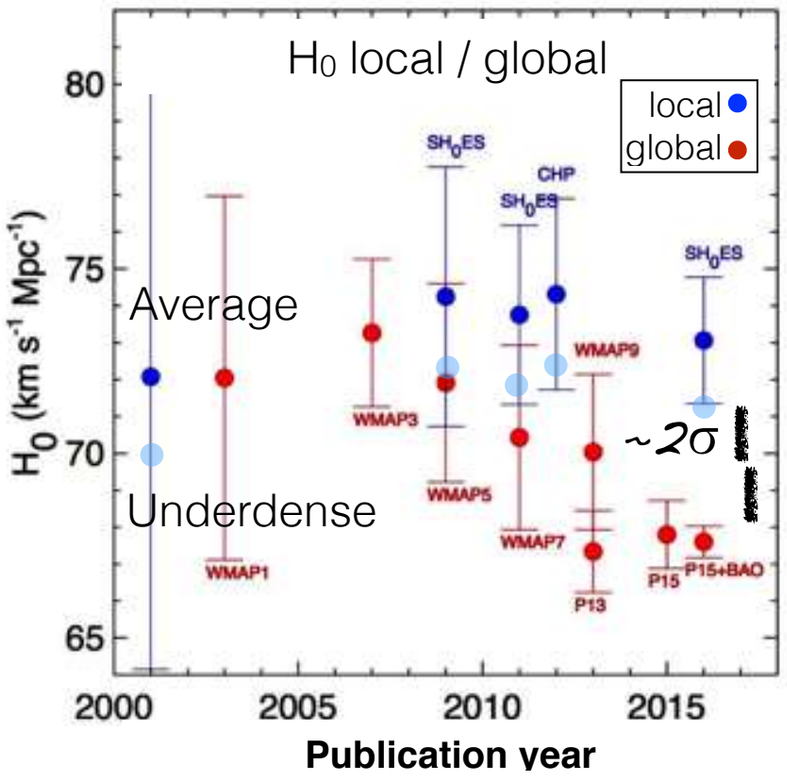

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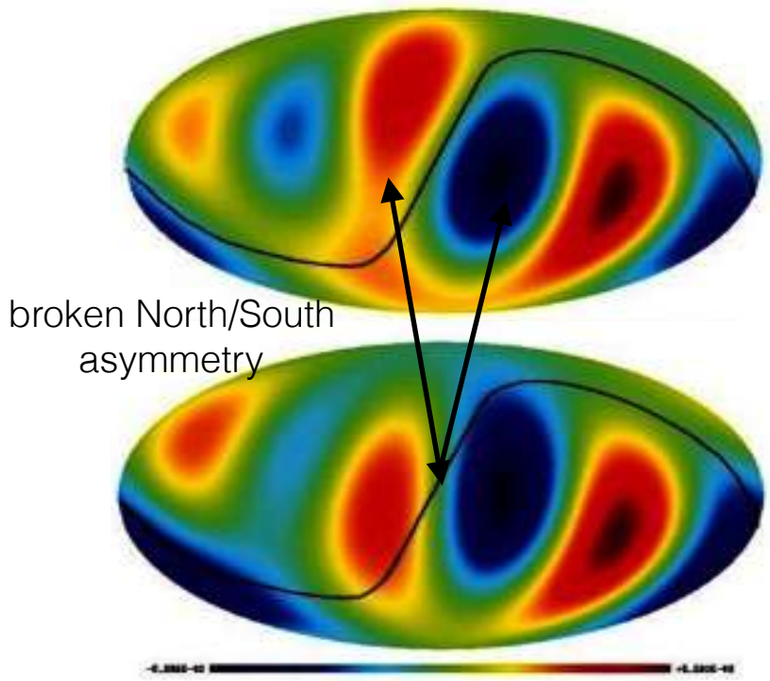

Francis+2010

But correction from redshift surveys only…

That concludes why we might want to do more

Summary

Let's continue with what more wrt typical simulations can we do or reformulating how can we build a local modeling in order to account for the local-induced biases?

CLONES = Constrained LOcal & Nesting Environment Simulations

Local Universe's initial conditions ➤ constrained initial conditions

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

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Received 1987 August 17; accepted 1987 September 10

ABSTRACT

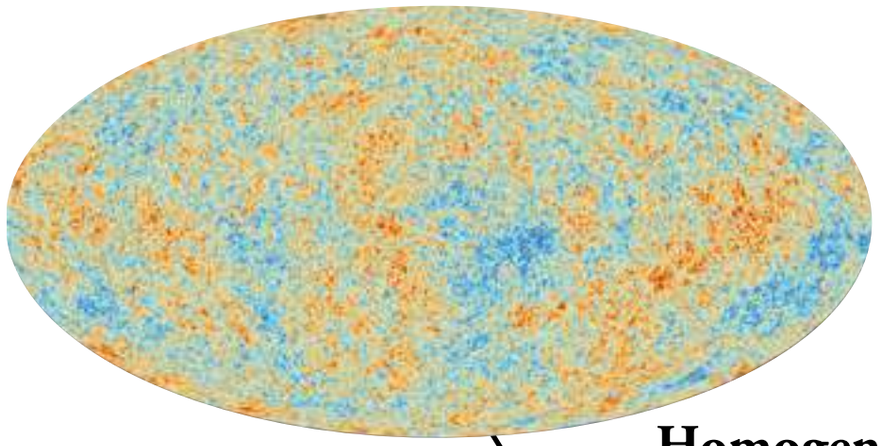
Path integrals may be used to describe the statistical properties of a random field such as the primordial density perturbation field. In this framework the probability distribution is given for a Gaussian random field subjected to constraints such as the presence of a protovoid or supercluster at a specific location in the initial conditions. An algorithm has been constructed for generating samples of a constrained Gaussian random field on a lattice using Monte Carlo techniques. The method makes possible a systematic study of the density field around peaks or other constrained regions in the biased [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

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

Local Universe's initial conditions → constrained initial conditions

Part of the Universe at 13.7 light-Gyr
Photons received today have been emitted when it was ~380 000 yrs. old

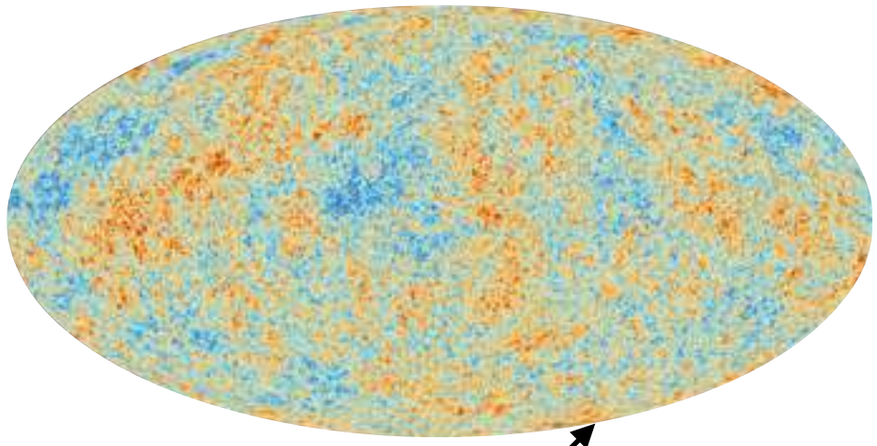


Homogeneous and Isotropic Universe

Probability excess to have an object at a distance r from another = autocorrelation of the density contrast = Fourier transform of the power spectrum

$$\xi(\mathbf{r}) = \langle \delta(\mathbf{x})\delta(\mathbf{x}+\mathbf{x}') \rangle = \frac{1}{(2\Pi)^3} \int_0^\infty P(\mathbf{k}) e^{-i\mathbf{k}.\mathbf{r}} d\mathbf{k}$$

Gaussian initial density field



white noise $w(\mathbf{k})$ and power spectrum are sufficient to get a …
RANDOM realization
= whatever part of the Universe

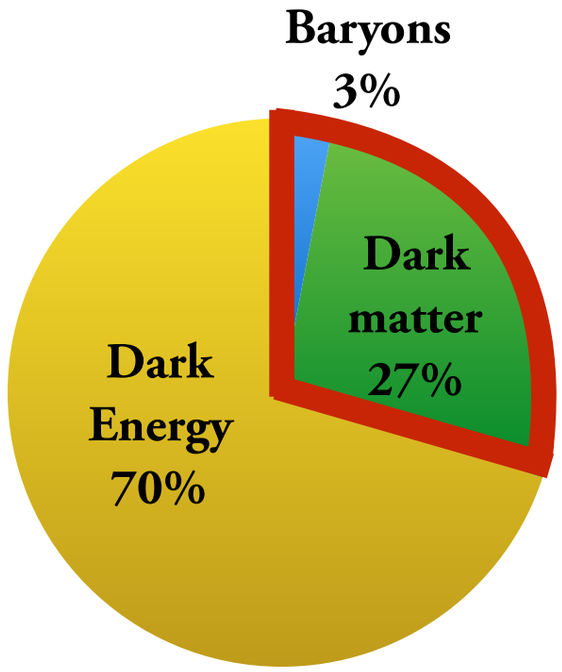
$$\delta(\mathbf{k}) = \sqrt{P(\mathbf{k})}.\omega(\mathbf{k})$$

Applying local constraints

Constrained initial conditions

Local Universe's initial conditions constrained initial conditions

Work \ Constraints	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

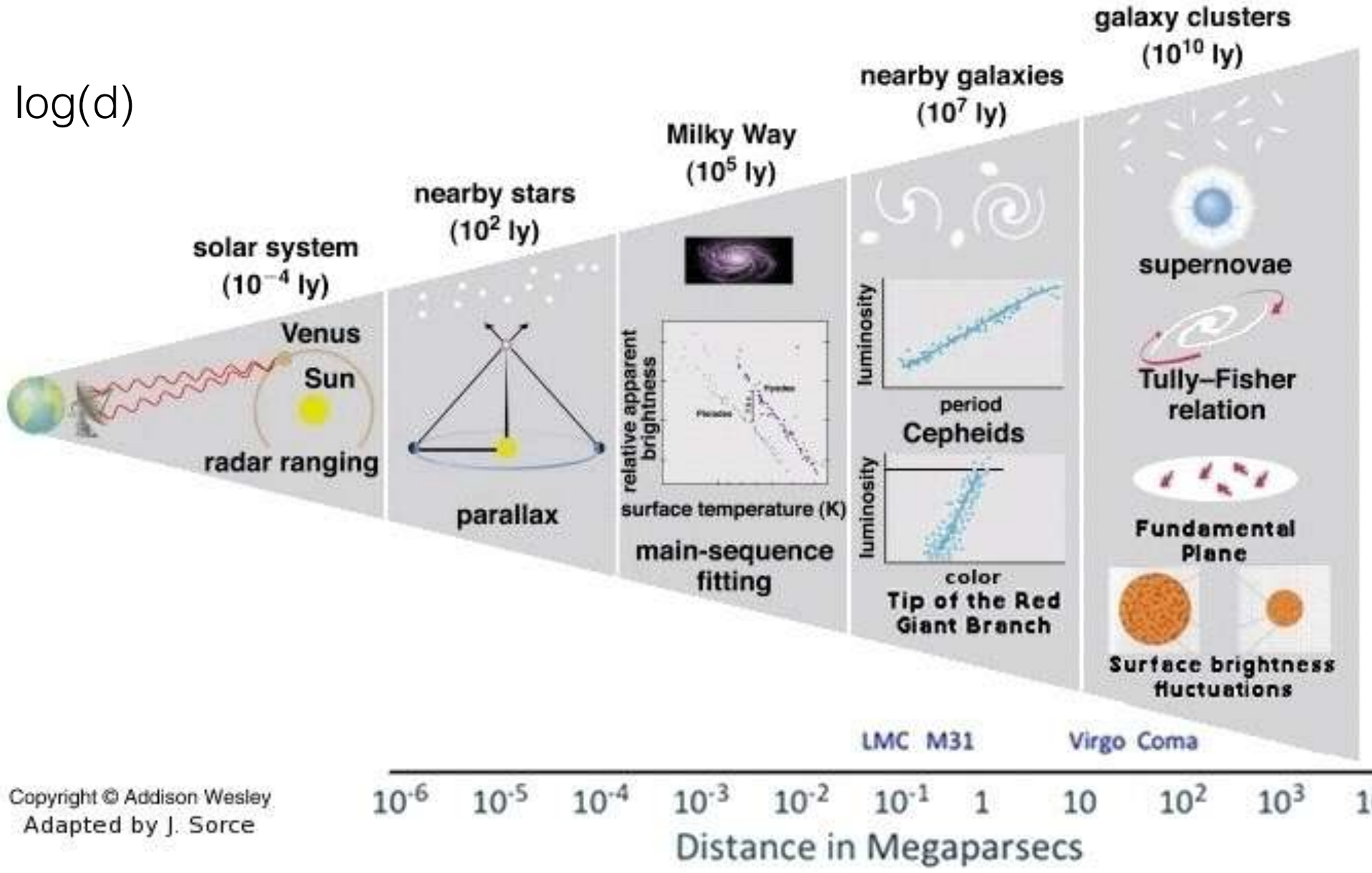
- Account for the entire underlying gravitational field
- Correlated on large scale
- Highly linear

e.g. Tully+(including Sorce)2013, Tully+(including Sorce)2016

Peculiar velocities catalog → direct distance measurements

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

$$m - M \propto \log(d)$$



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Adapted by J. Sorce

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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~~Radial peculiar velocity~~ catalog

distance catalog

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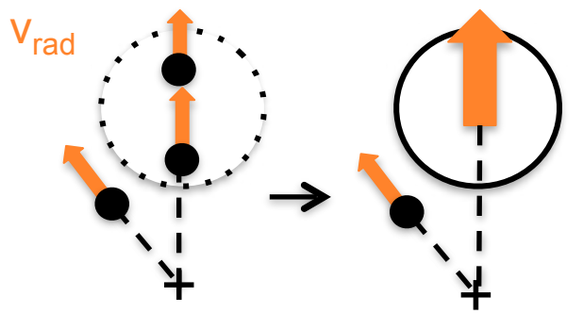

Distance (modulus) of the group and its uncertainty

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

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

Peculiar velocity of the group and its uncertainty

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

Hoffman & Ribak 1991

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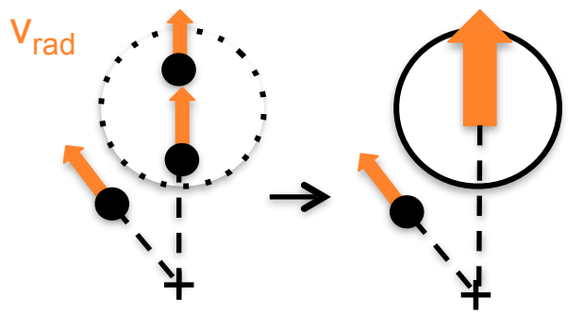

Distance (modulus) of the group and it

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

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

The difficulty is to determine properly the groups !

ie group and its uncertainty

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

Hoffman & Ribak 1991

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↓

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↓

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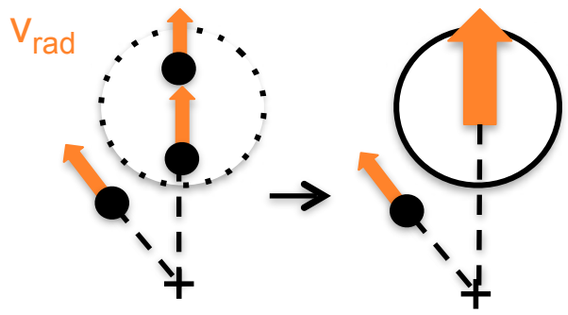
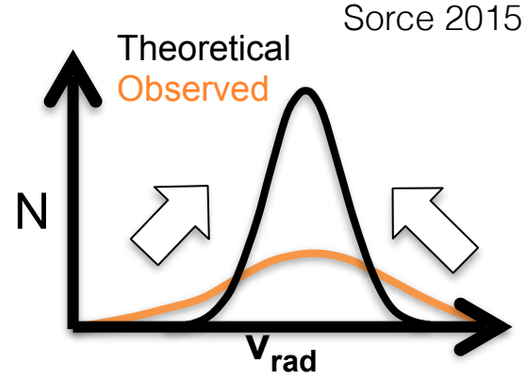
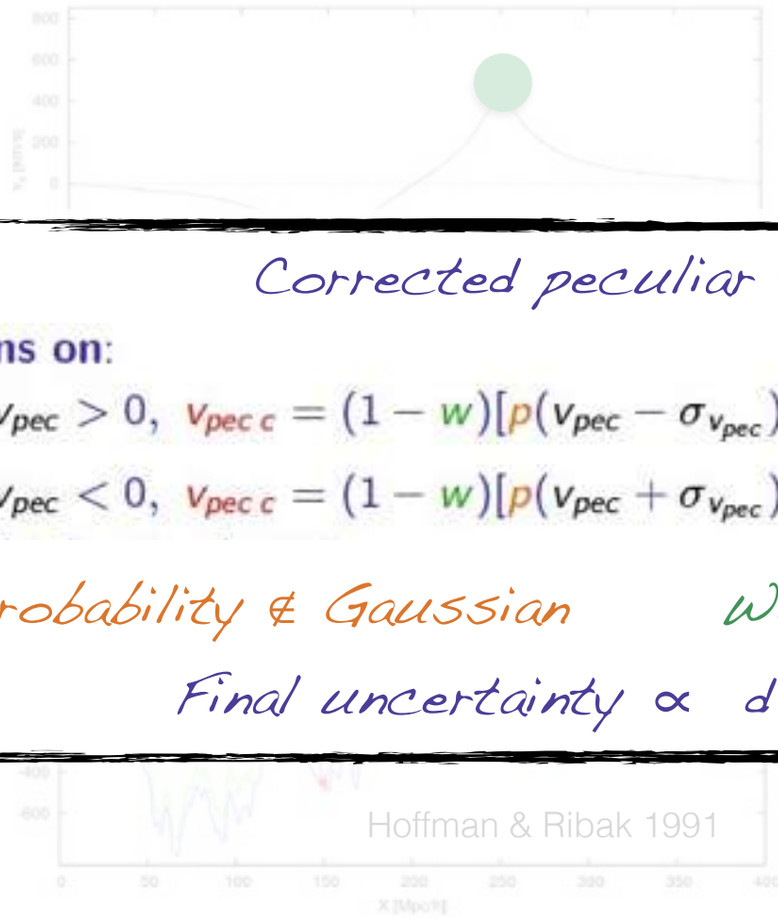


Sorce 2015, 2018





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 & $n_{constraints}$*

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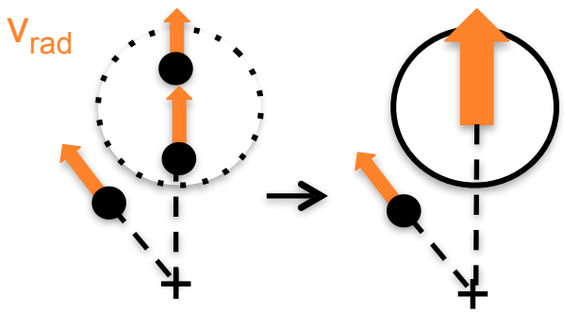
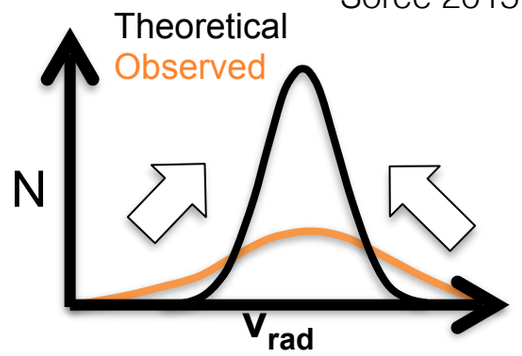
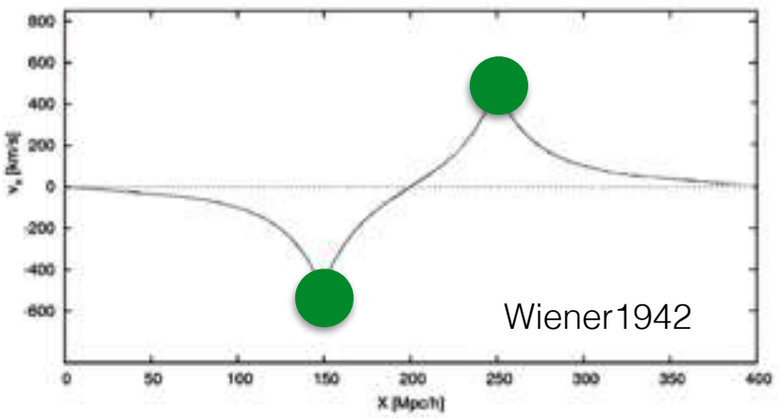


Sorce 2015, 2018





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

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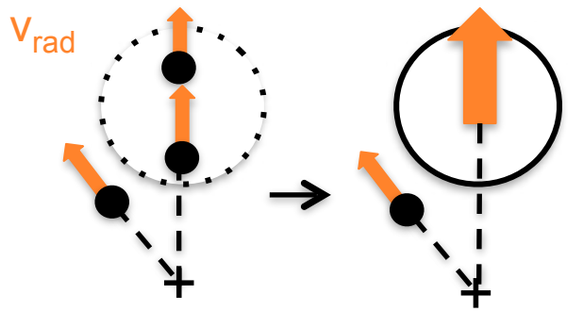
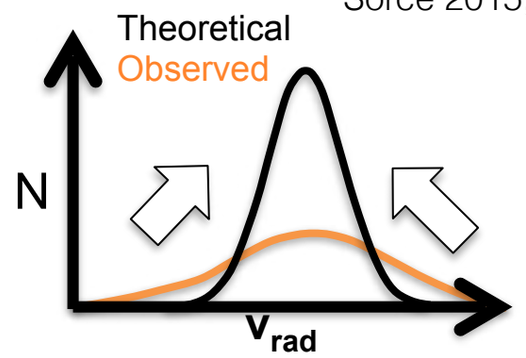
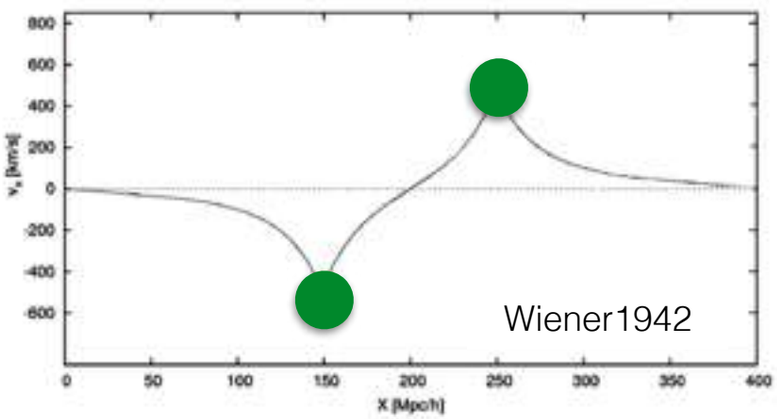


Sorce 2015, 2018





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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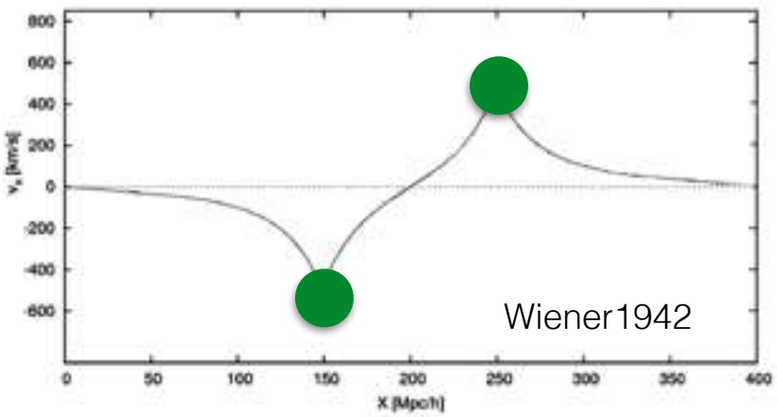
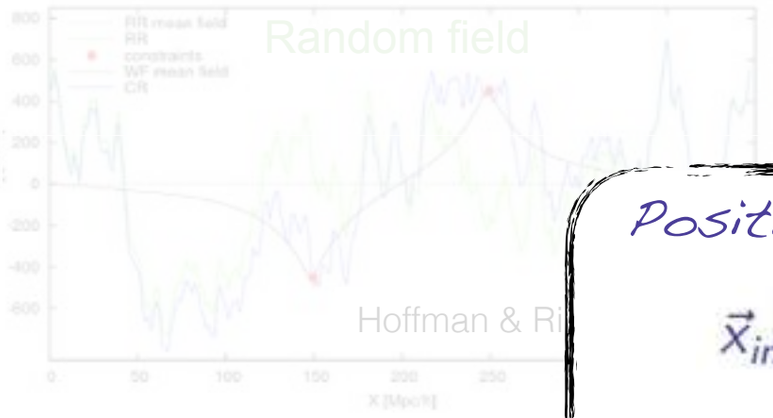
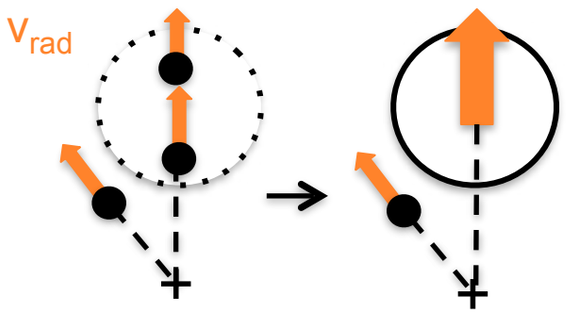
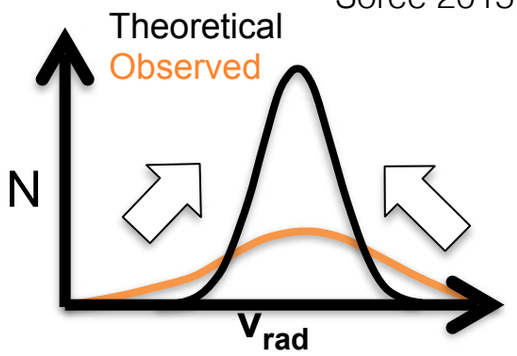




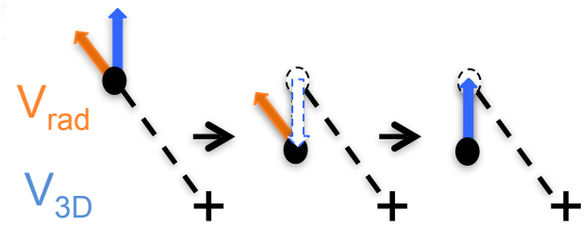
Sorce & Tempel 2017,2018



Sorce 2015, 2018



Doumler+2013 Sorce+2014



Position of the progenitors

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

growth rate

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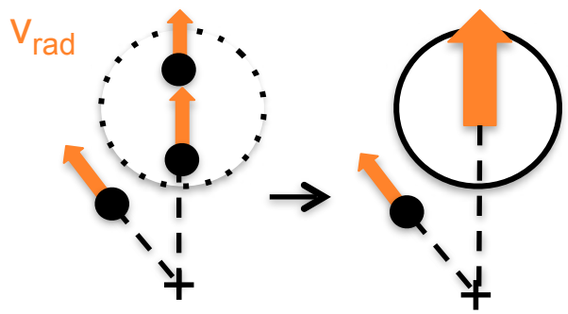
Sorce & Tempel 2017,2018

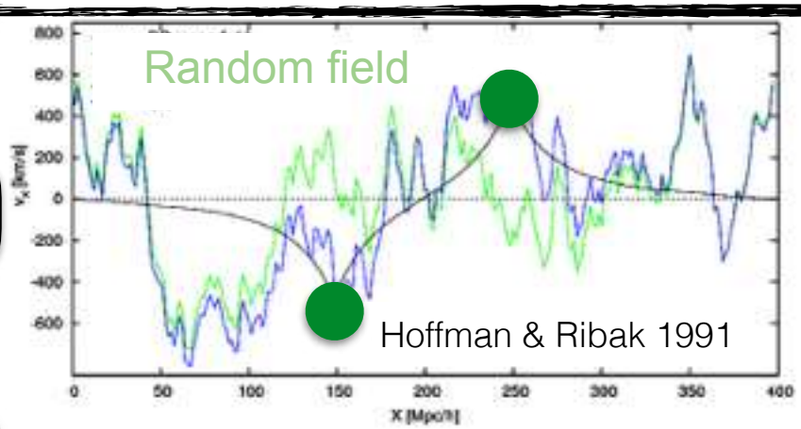


Constrained Realization: Estimate of the residual

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

Correlation functions depend only on the model

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



V_{3D}

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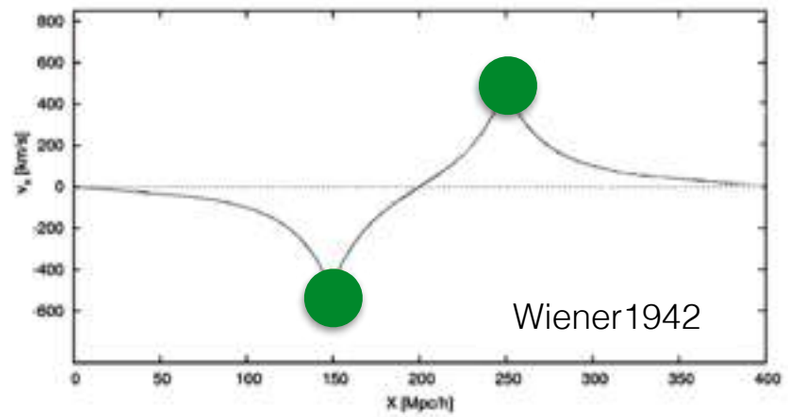
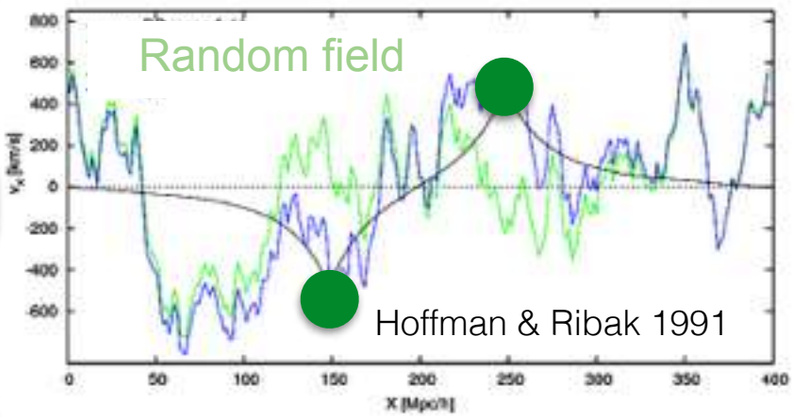
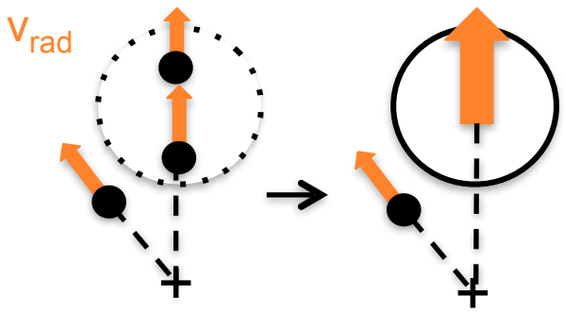
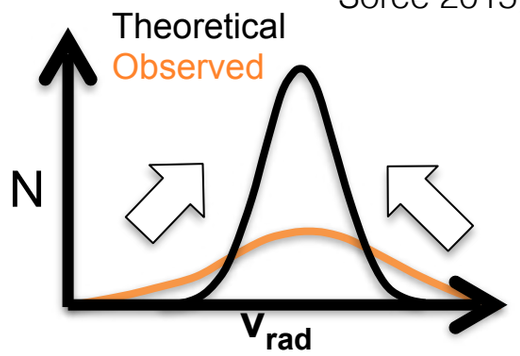




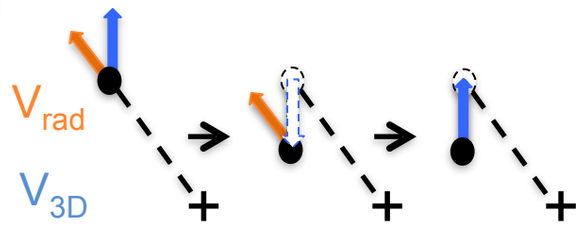
Sorce & Tempel 2017,2018



Sorce 2015, 2018

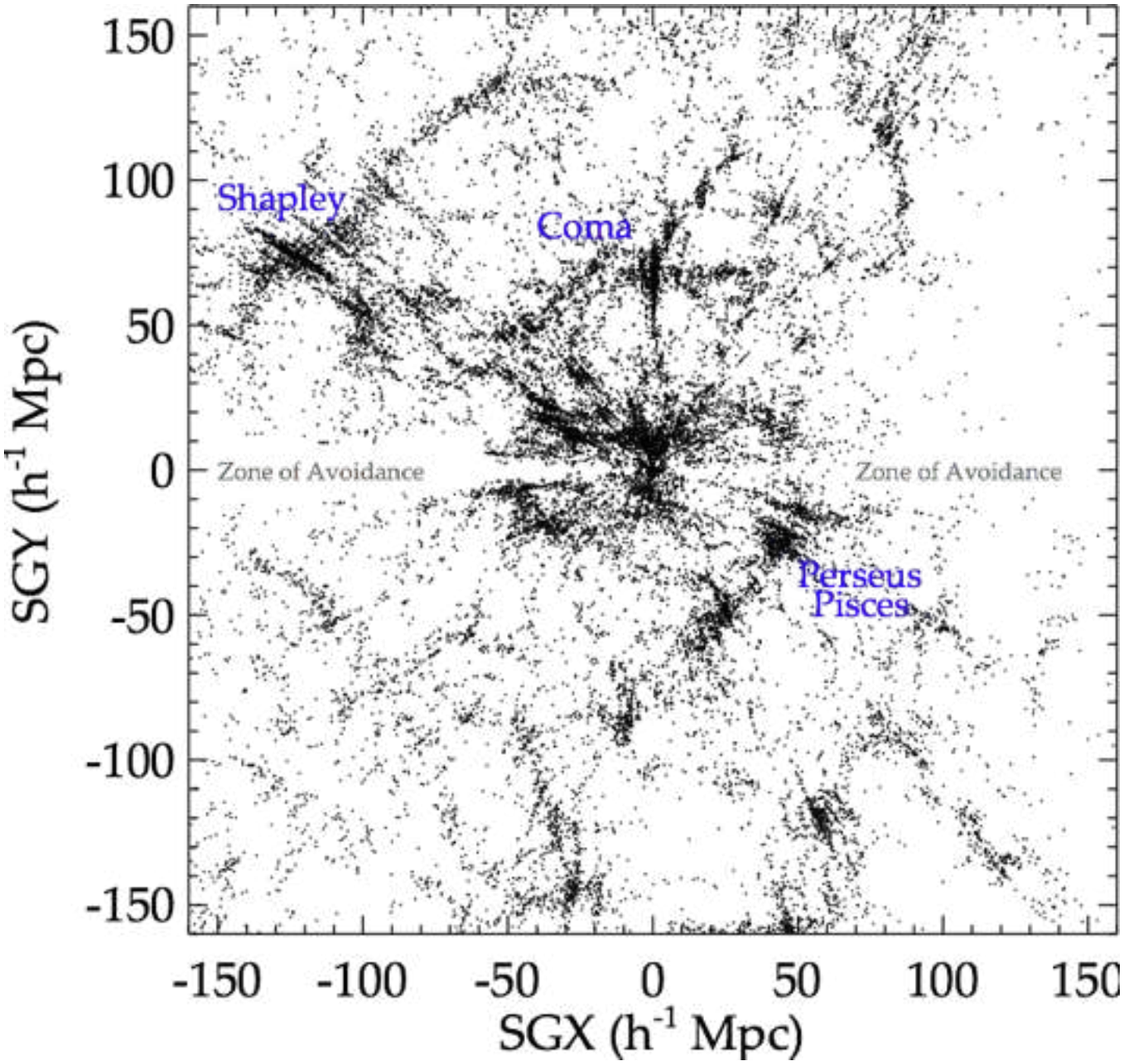


Doumler+2013 Sorce+2014

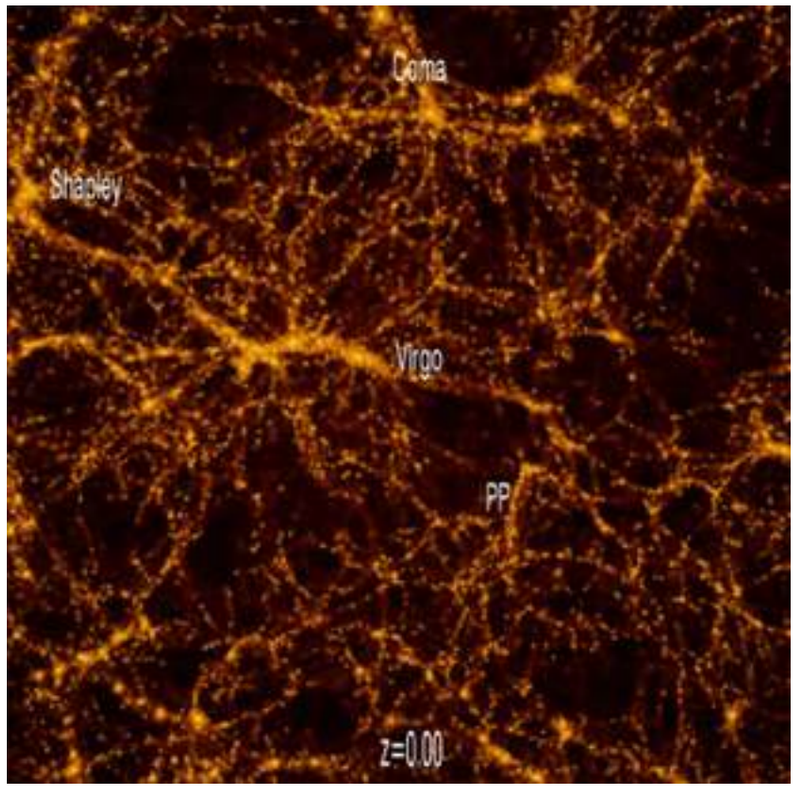


Results: the local large scale CLONE

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 CLONE

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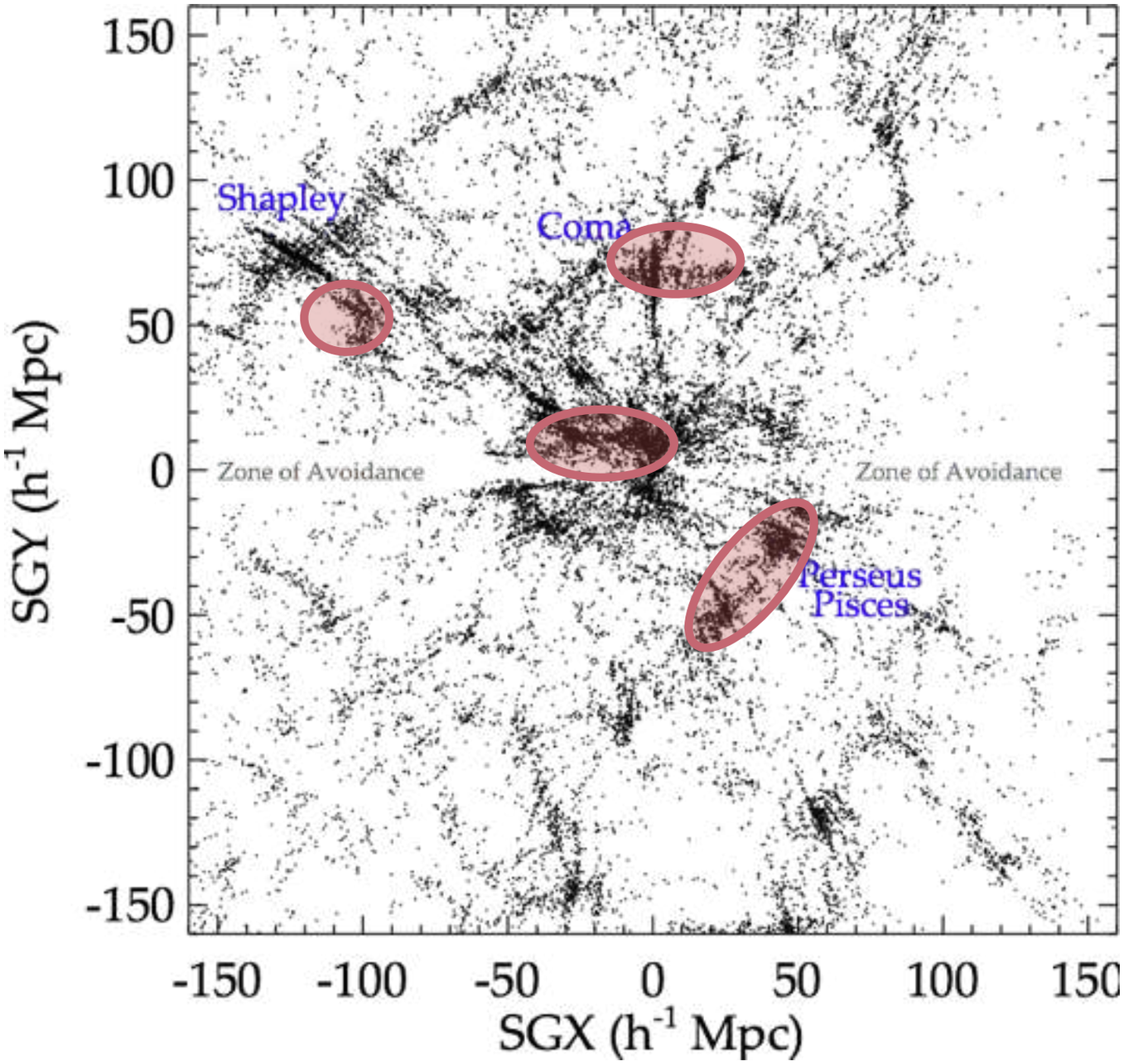

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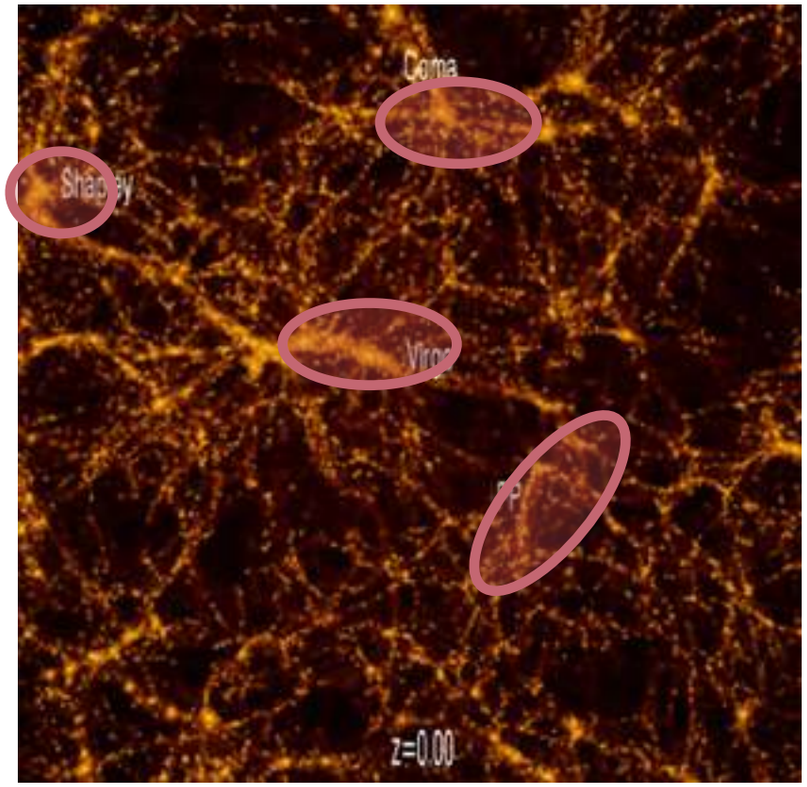

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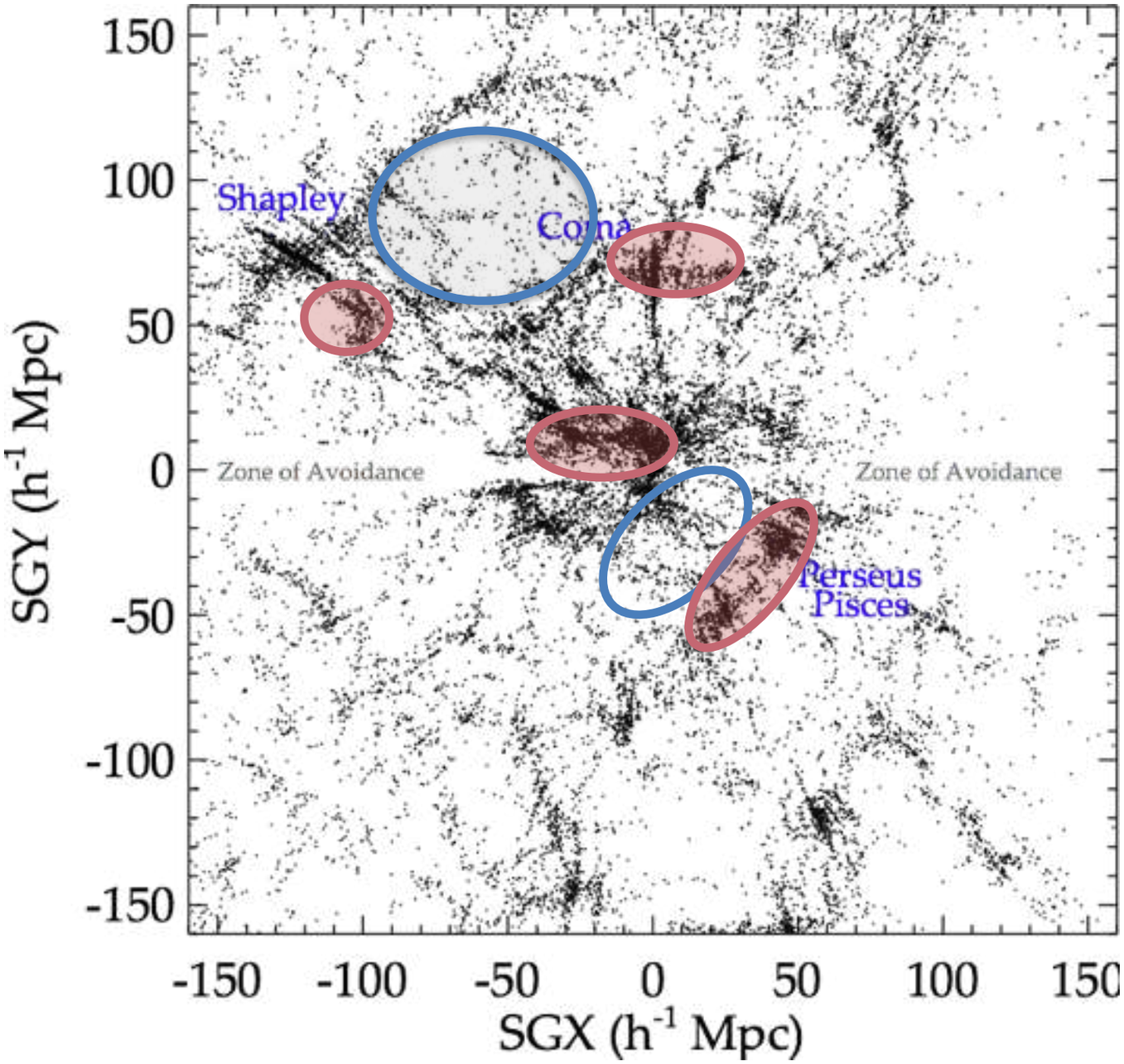
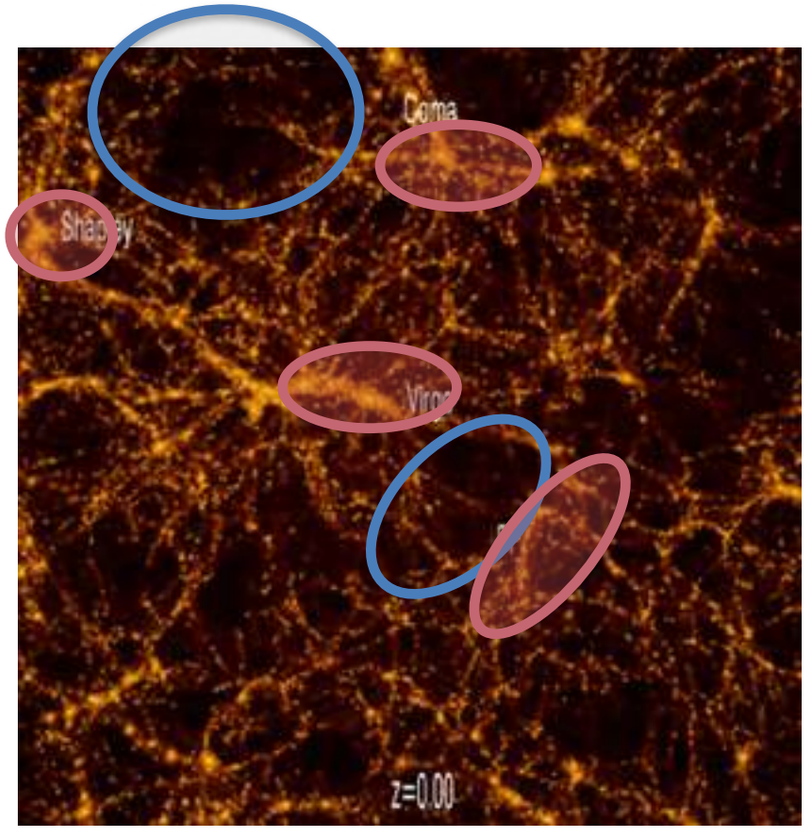


Note the fingers of gods



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

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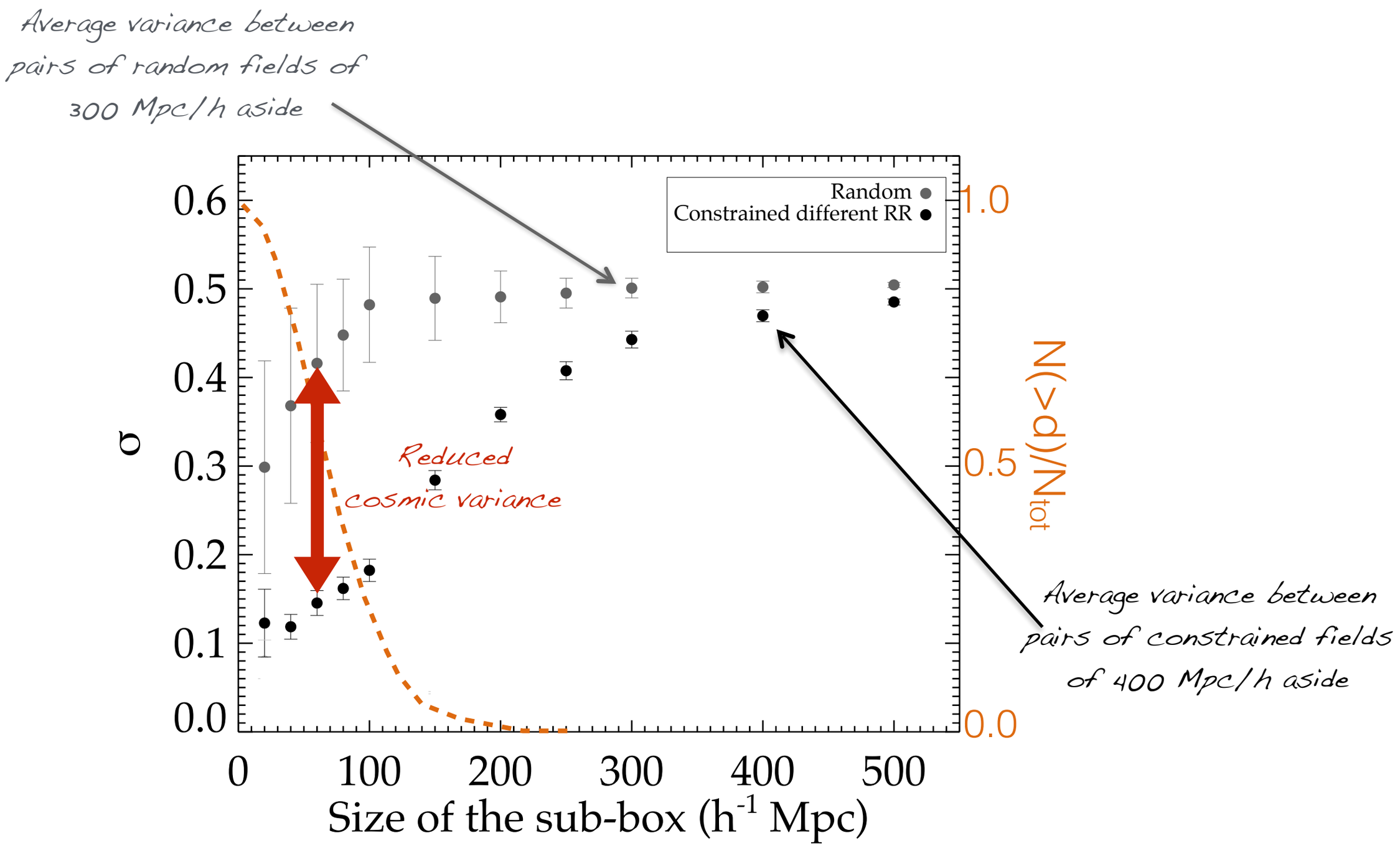
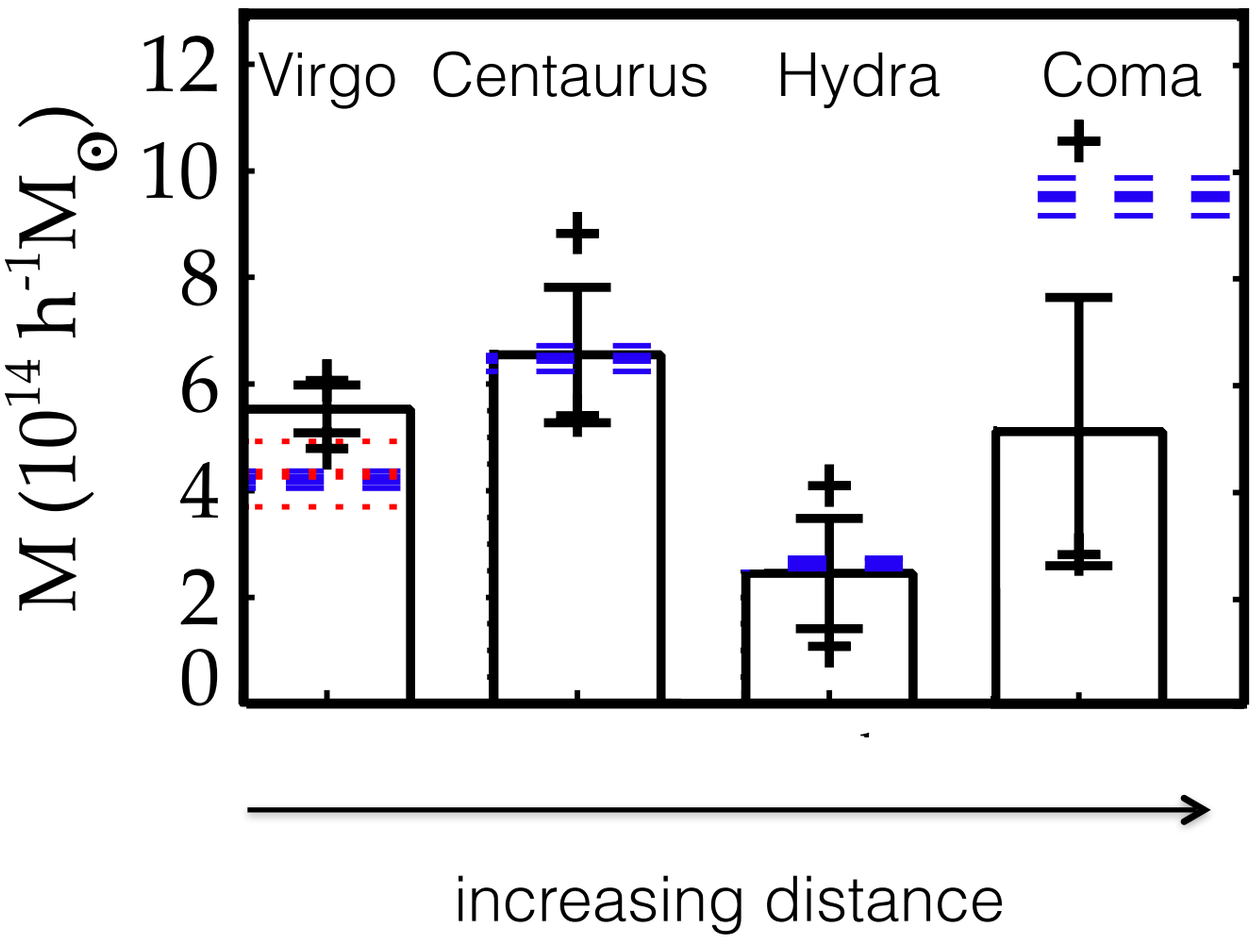
z=0, large scale Sorce+2016



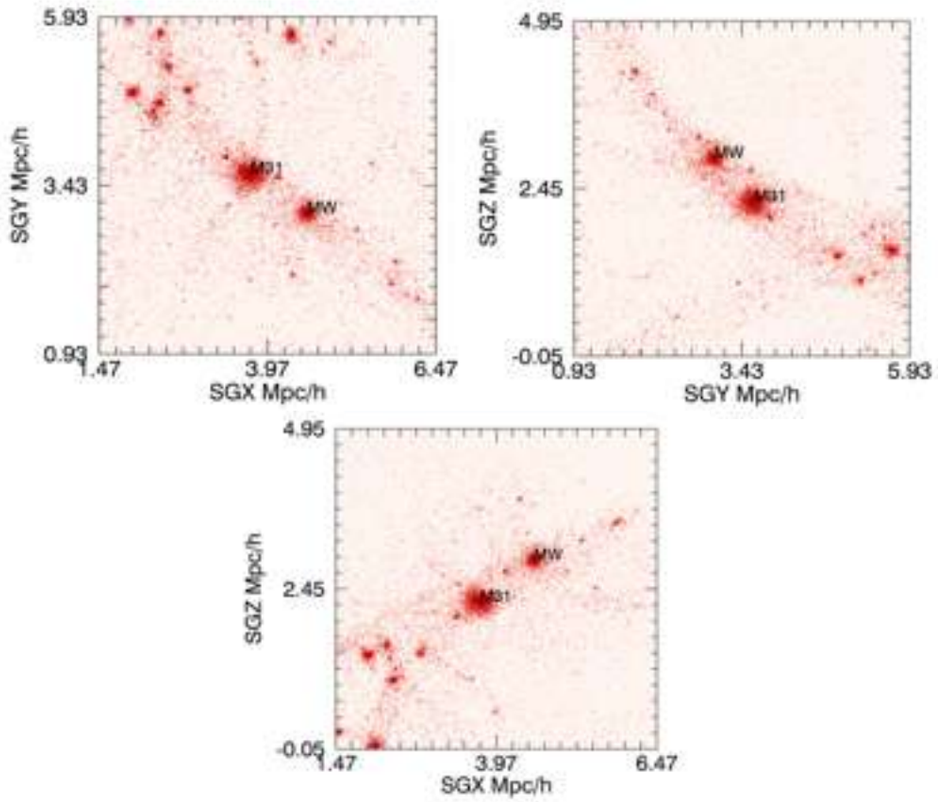
Results: the local clusters CLONES

z=0, cluster scale Sorce 2018

Dark matter halos = counterparts of observed local clusters

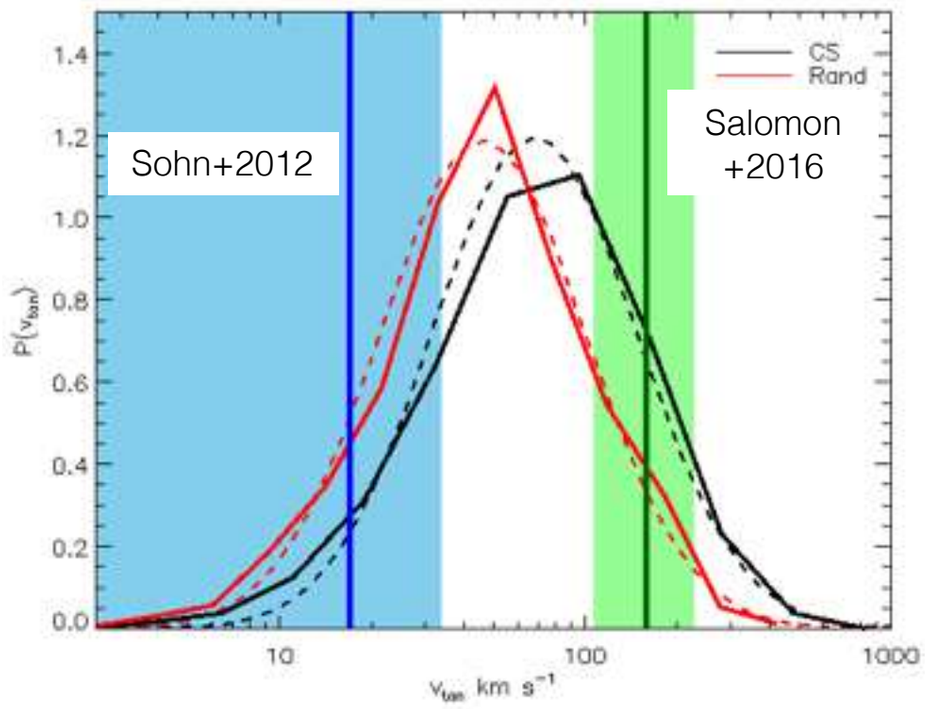


Results: the Local Group CLONES = HESTIA z=0, group scale



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

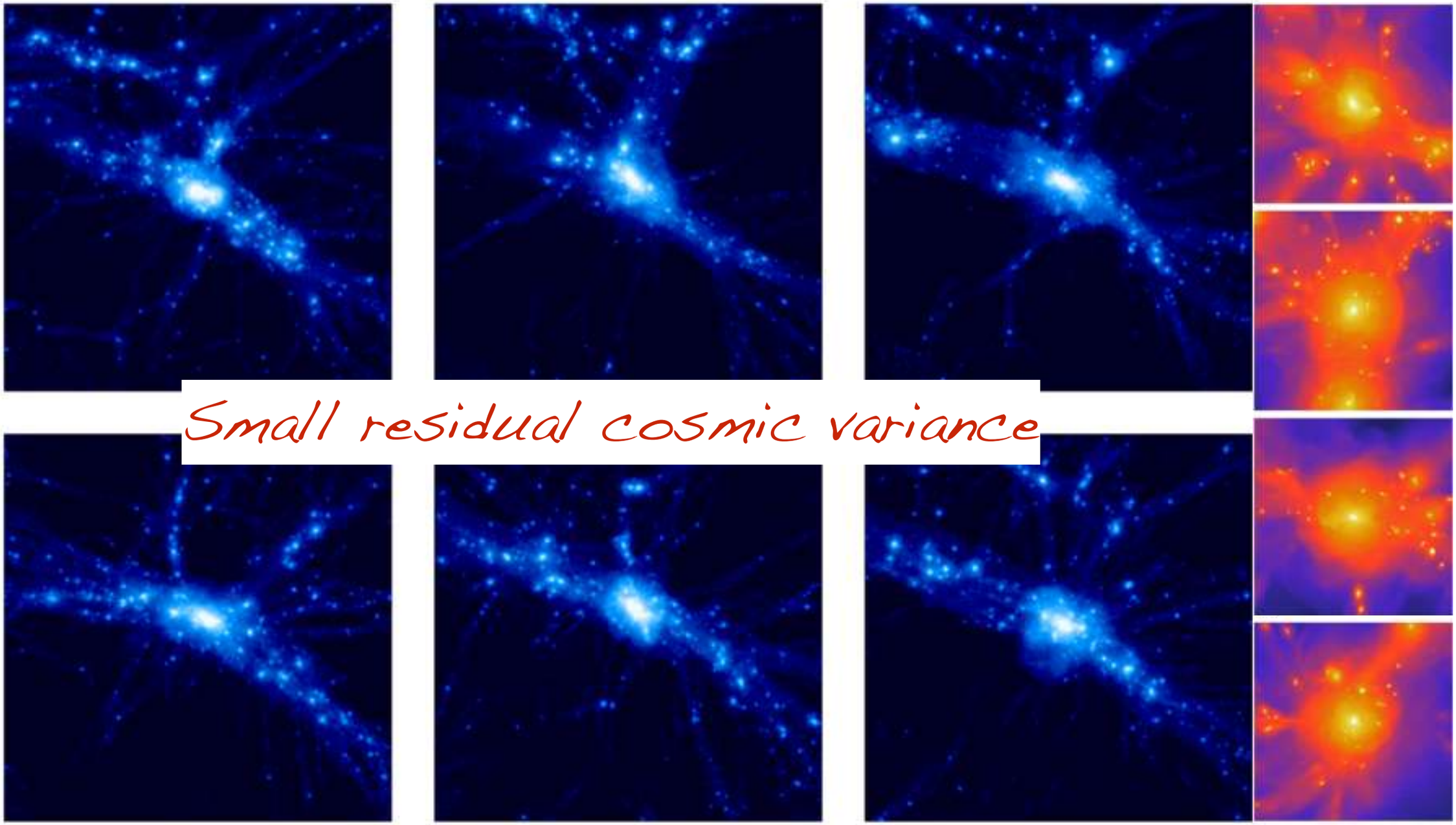
An example of
application: in favor of a
higher tangential velocity



Carlesi,Sorce+2016
Carlesi,Hoffman,Sorce+2016
Carlesi,Hoffman,Sorce+2017
Libeskind+(including Sorce)2020

The Virgo galaxy cluster CLONE

Simulated Virgo & Random clusters

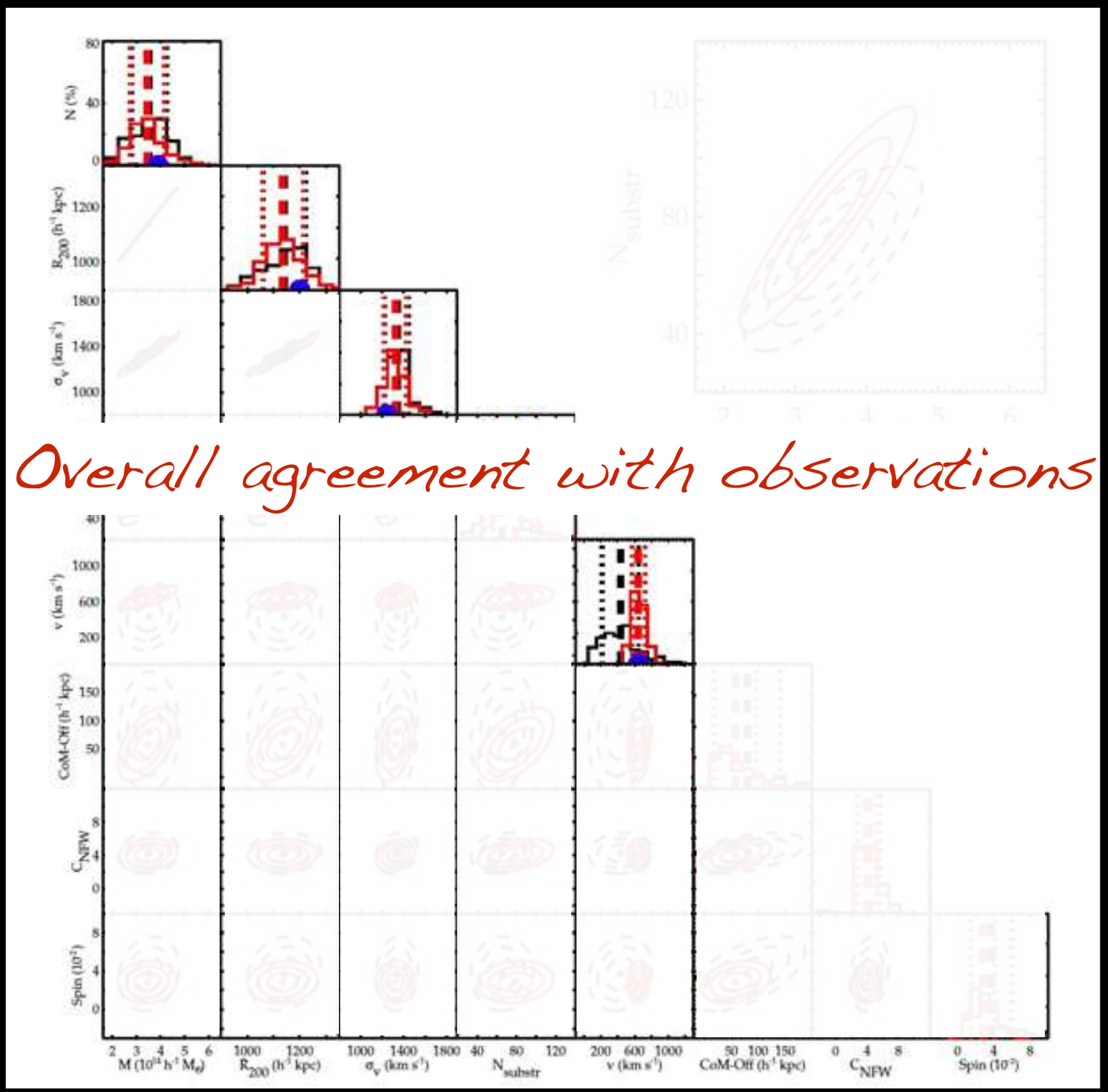


Small residual cosmic variance

Rhapsody (Hahn +2017)

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

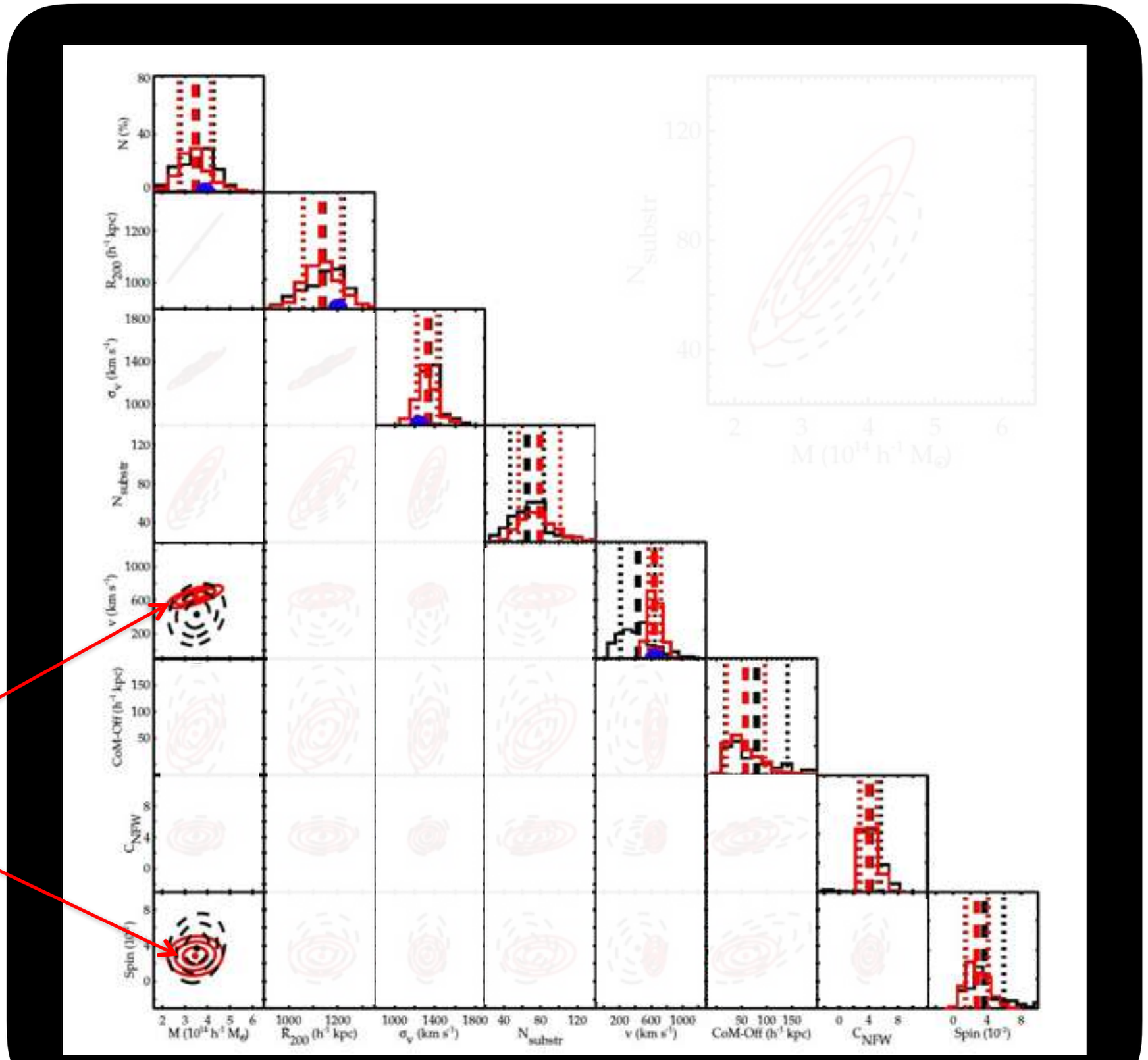
The Virgo galaxy cluster CLONE



Overall agreement with observations

Sorce, Blaizot, Dubois 2019

The Virgo galaxy cluster CLONE



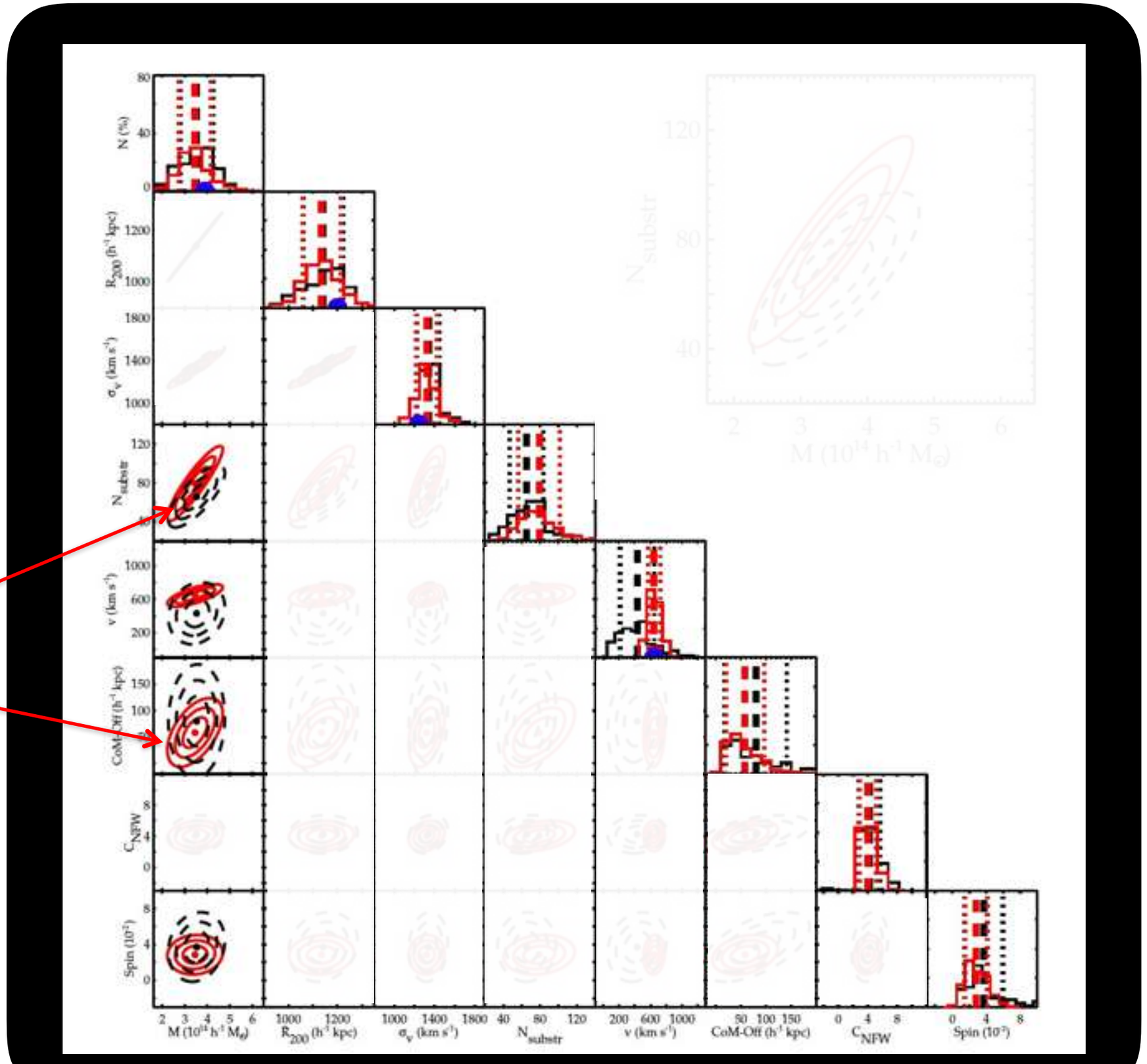
Velocity

Spin

→ Environment

Sorce, Blaizot, Dubois 2019

The Virgo galaxy cluster CLONE



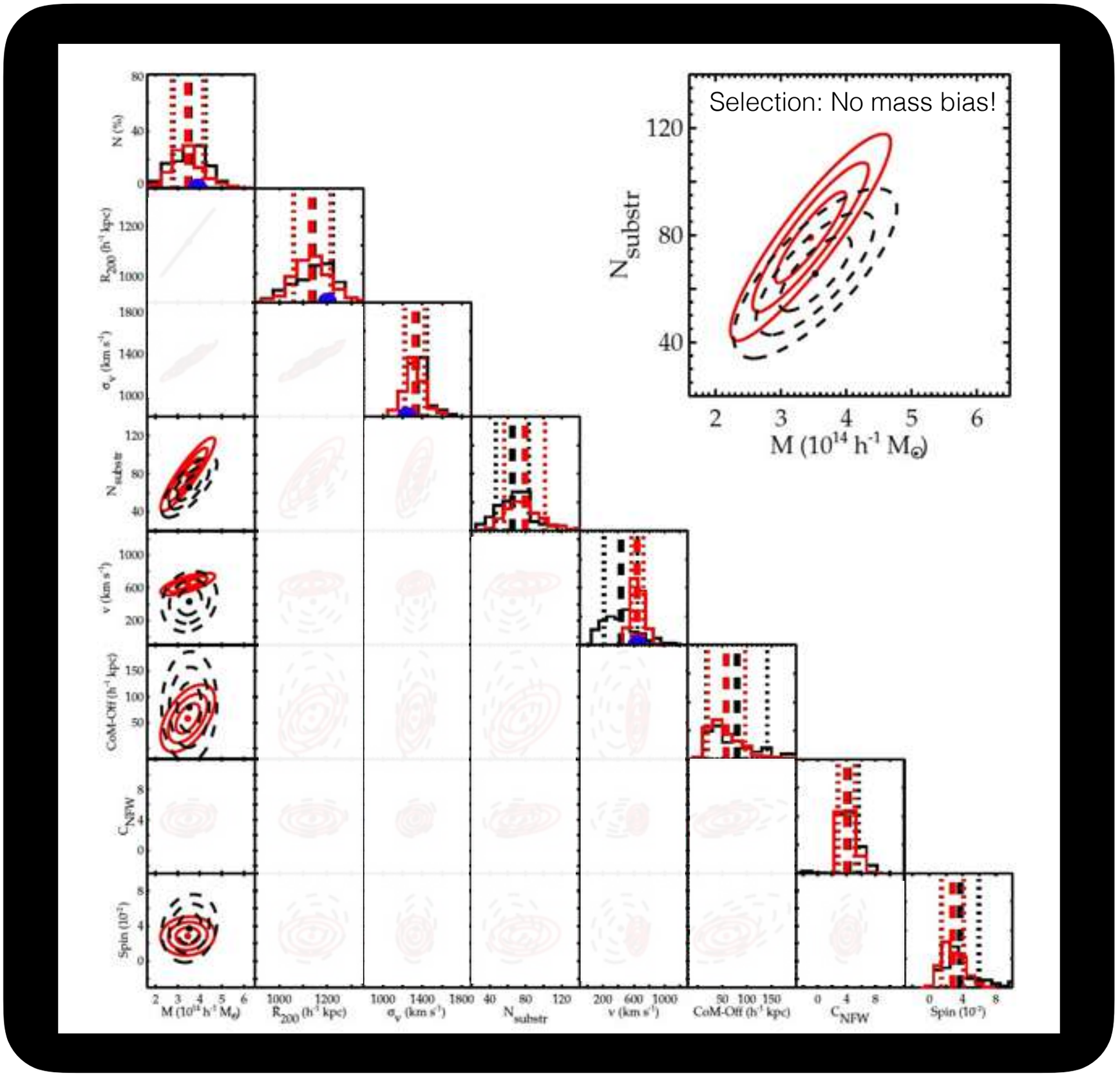
Number of substructures

Center of mass offset wrt spherical center

➙ History

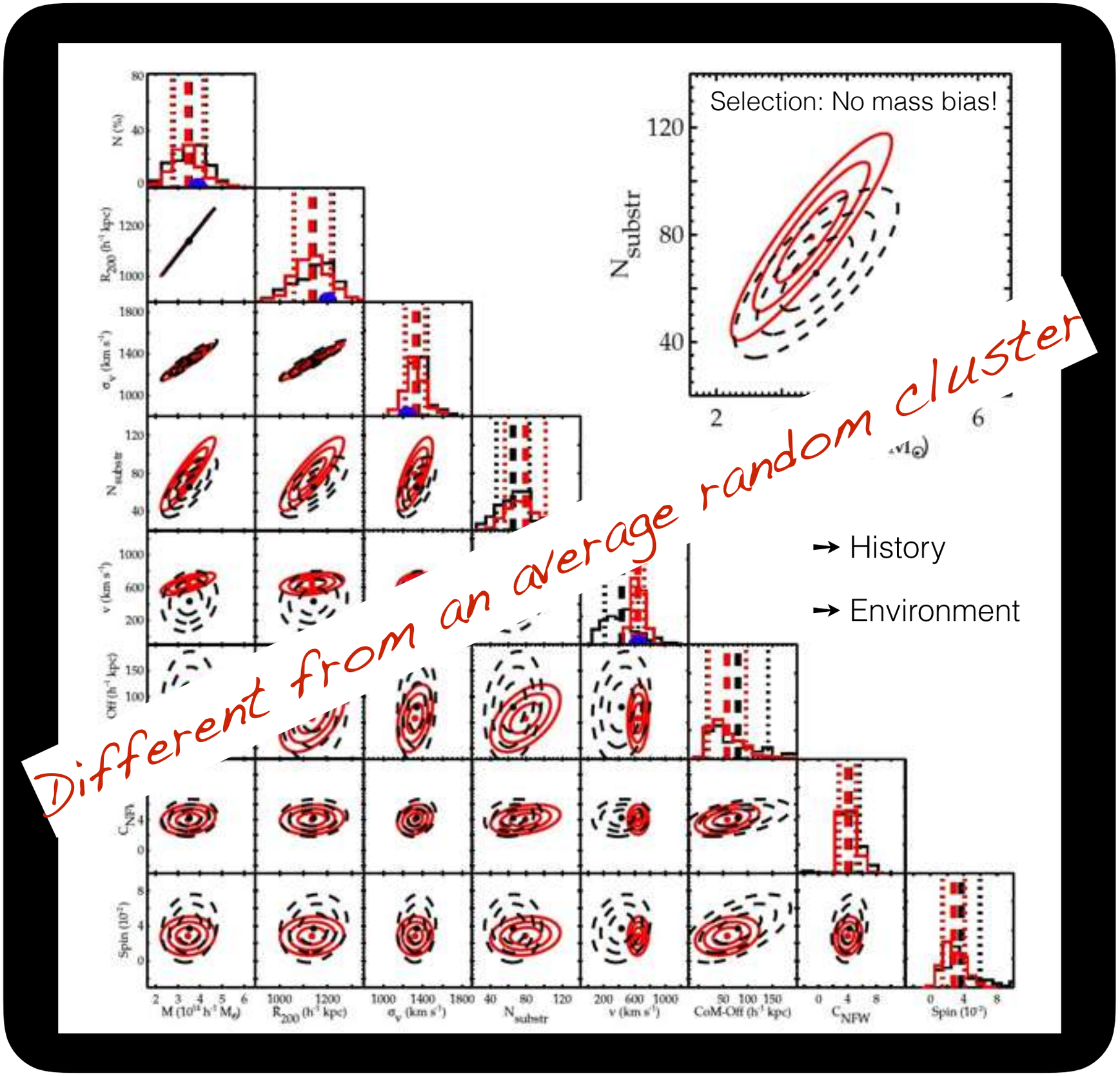
Sorce, Blaizot, Dubois 2019

The Virgo galaxy cluster CLONE



Sorce, Blaizot, Dubois 2019

The Virgo galaxy cluster CLONE

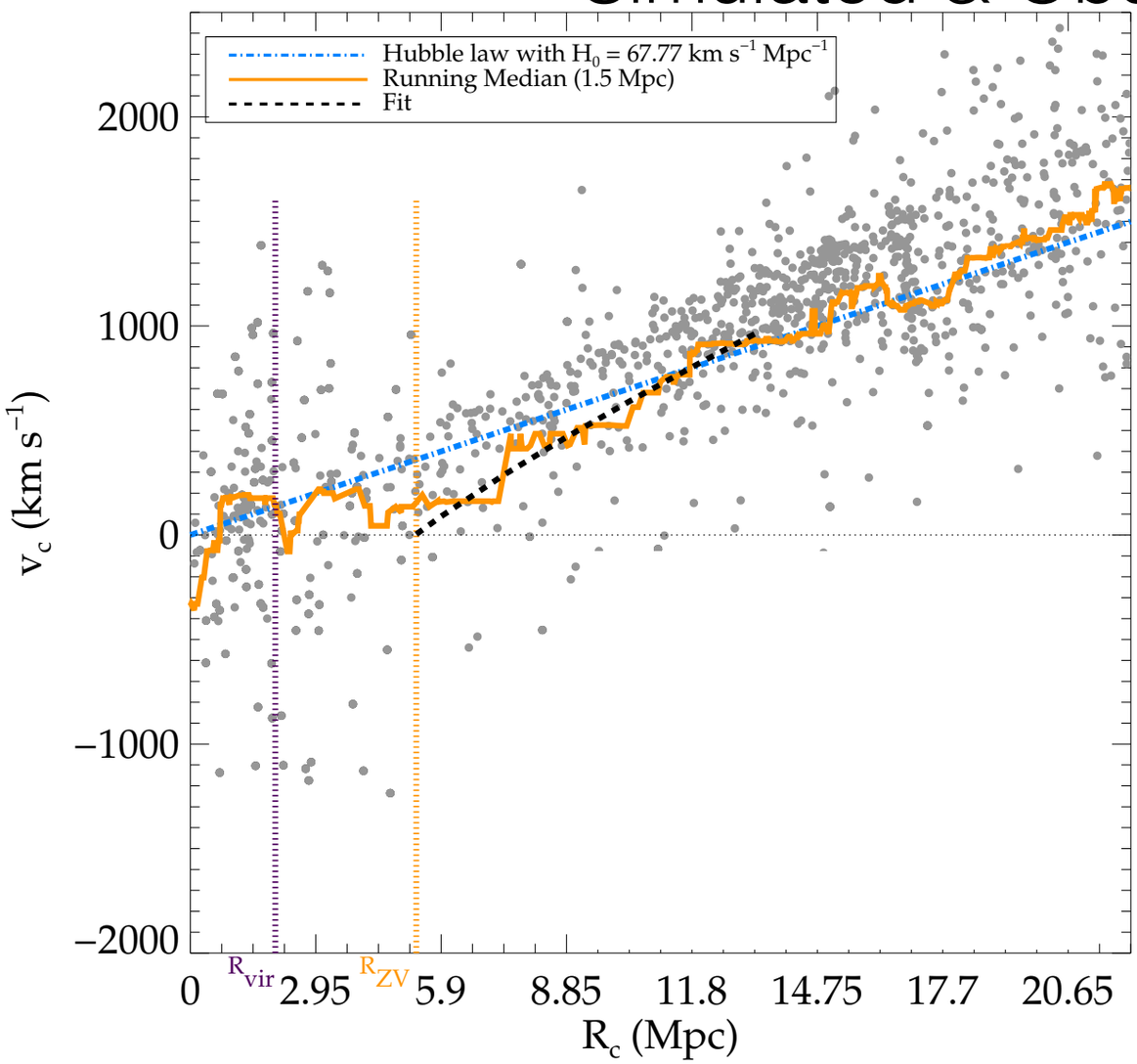


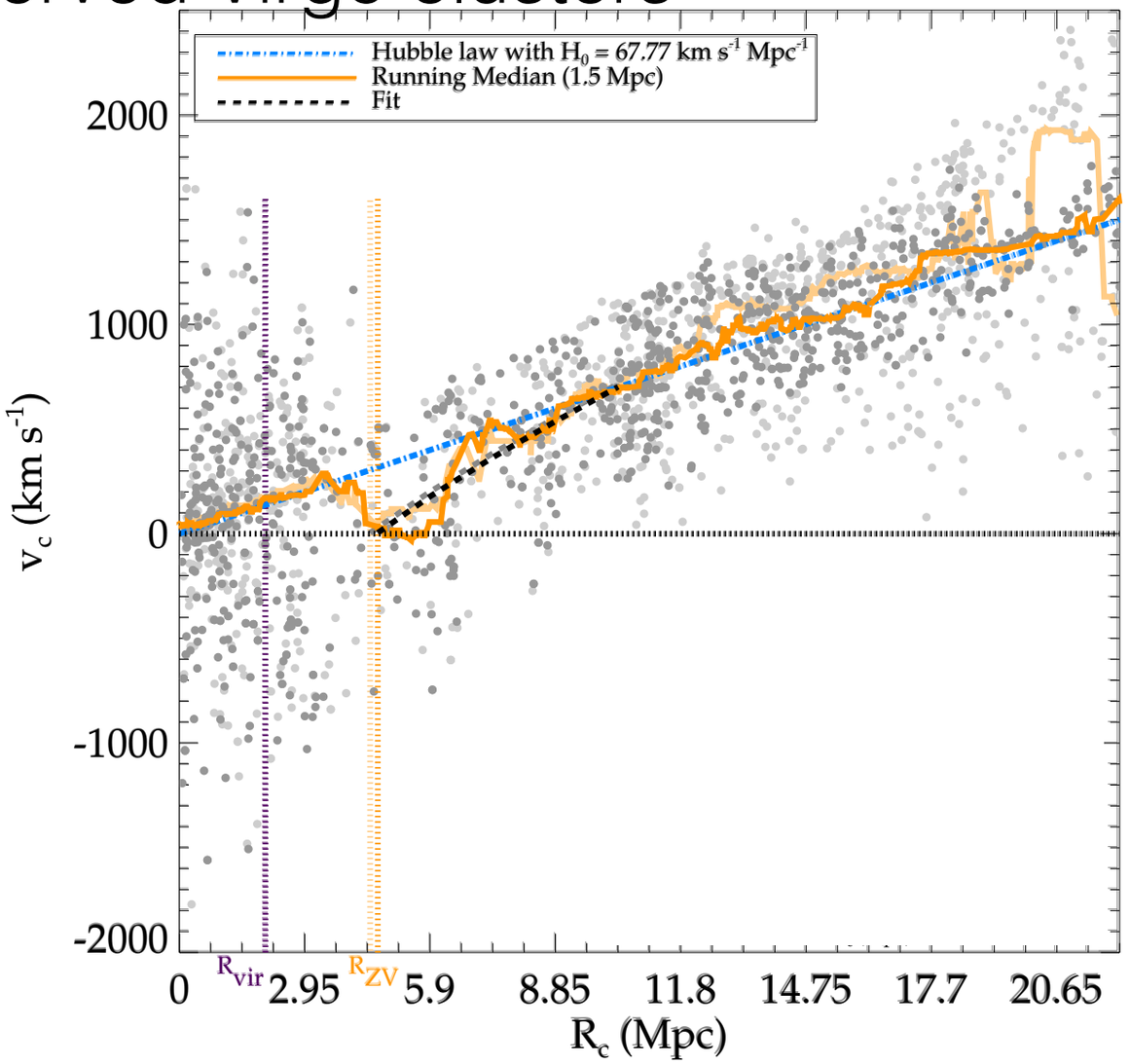
Sorce, Blaizot, Dubois 2019

The Virgo galaxy cluster CLONE

Sorce+2021

Simulated & Observed Virgo clusters



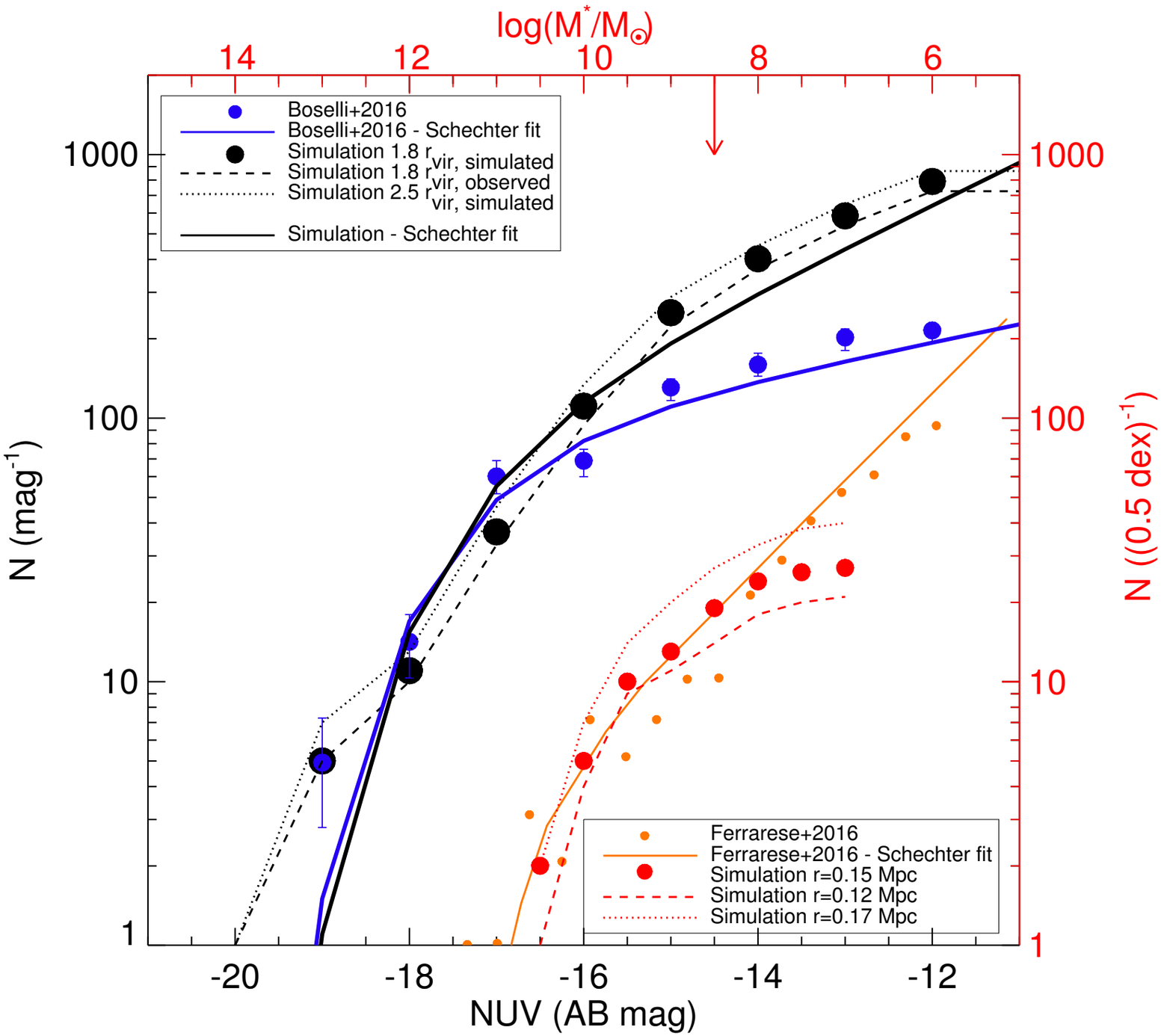


500 Mpc/h, 8192^3 particles effective (20 Mpc/h zoom), 0.24 kpc/h hydrodynamics: SN and AGN feedback, Planck cosmology

Overall agreement with observations

The Virgo galaxy cluster CLONE

Sorce+2021



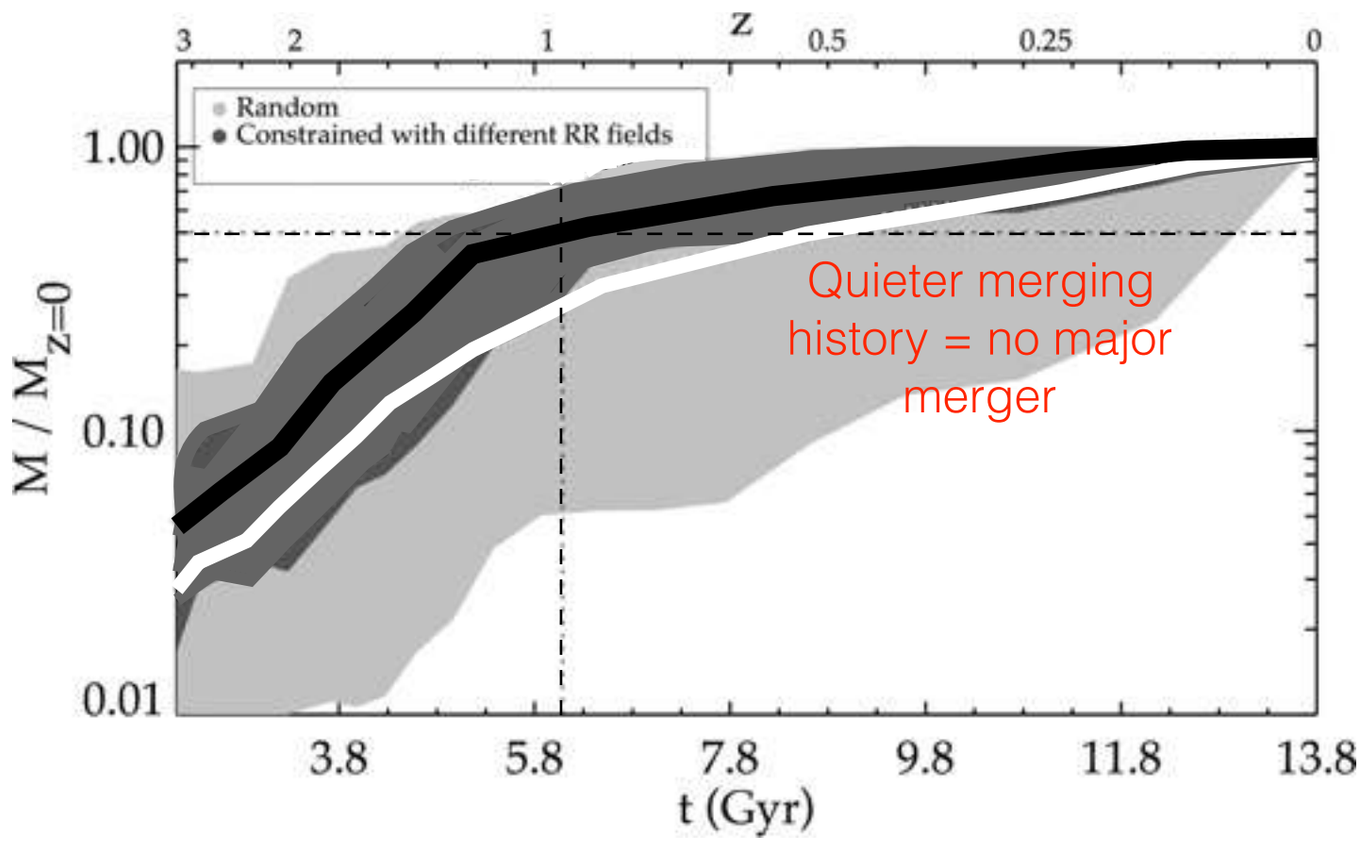
Overall agreement with observations

The Virgo galaxy cluster CLONE

Sorce+2016

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

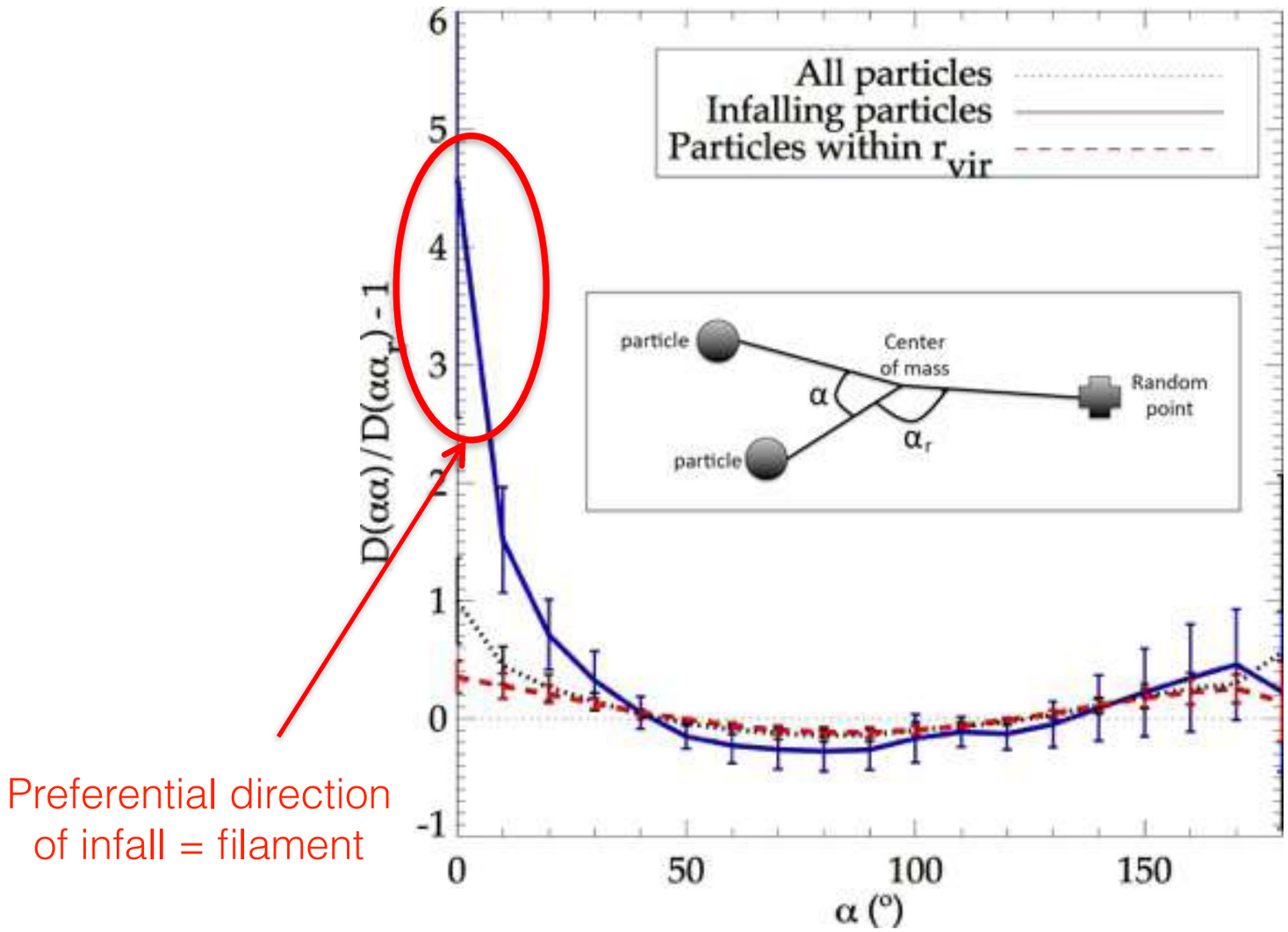
Agreement with observational predictions

The Virgo galaxy cluster CLONE

Sorce+2016

West & Blakeslee 2000 : from observation, formation along a filament

From simulation



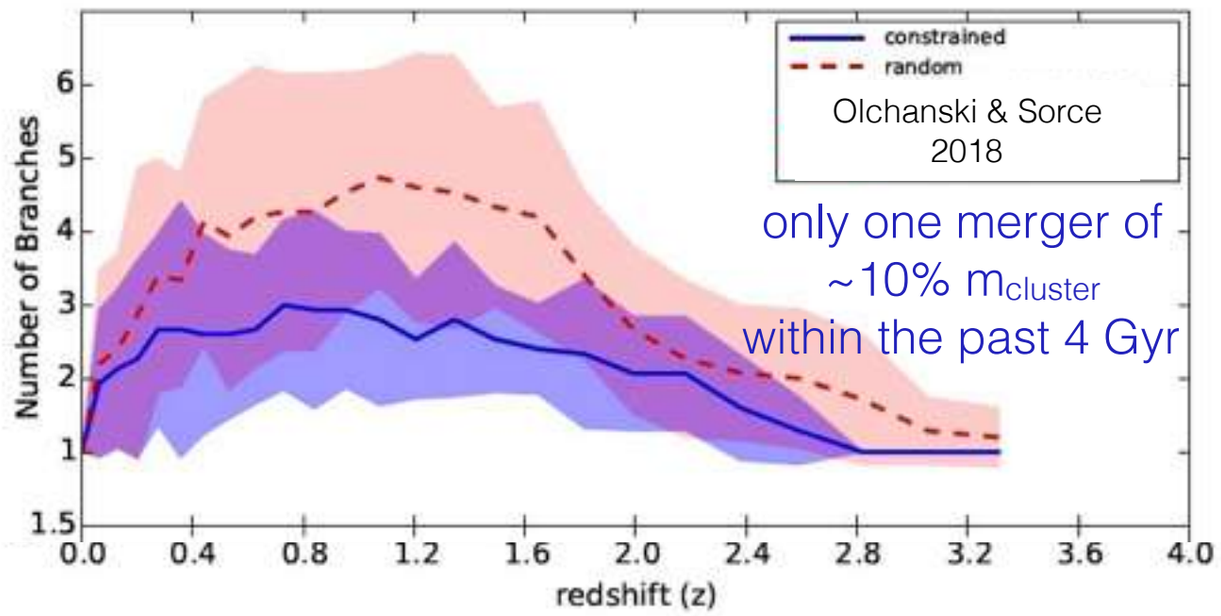
Preferential direction of infall = filament

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

Agreement with observational predictions

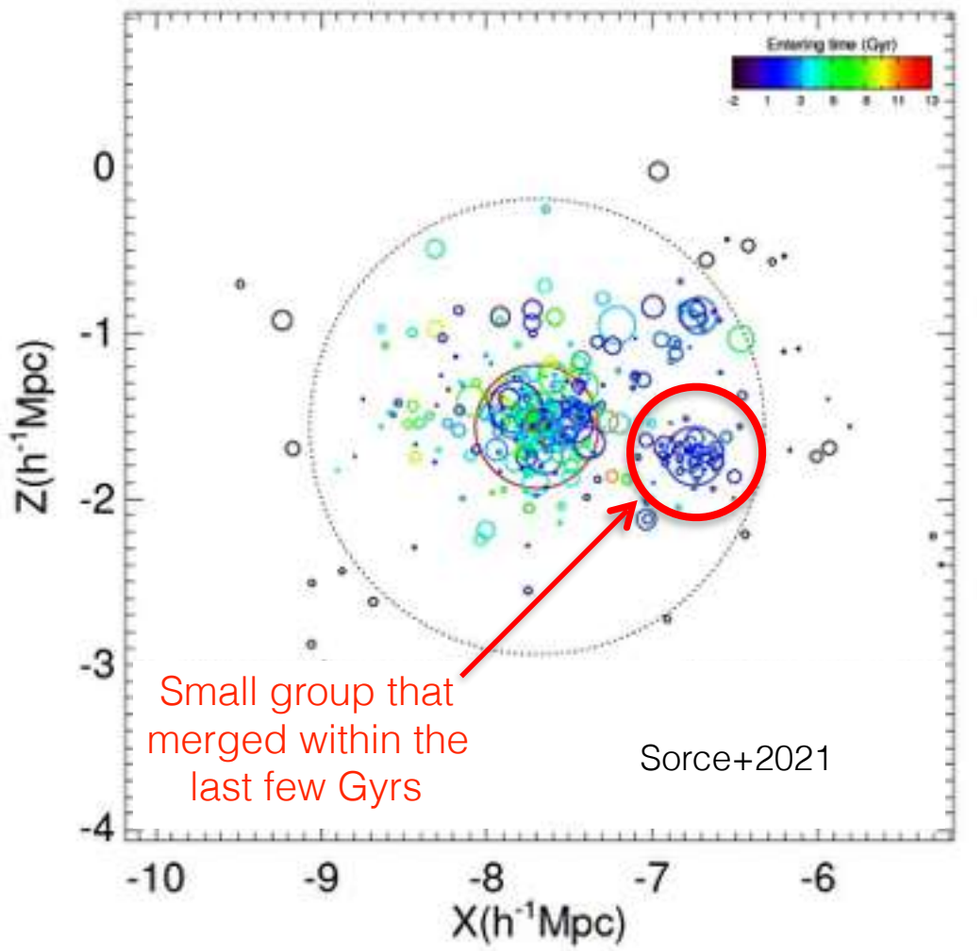
The Virgo galaxy cluster CLONE

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

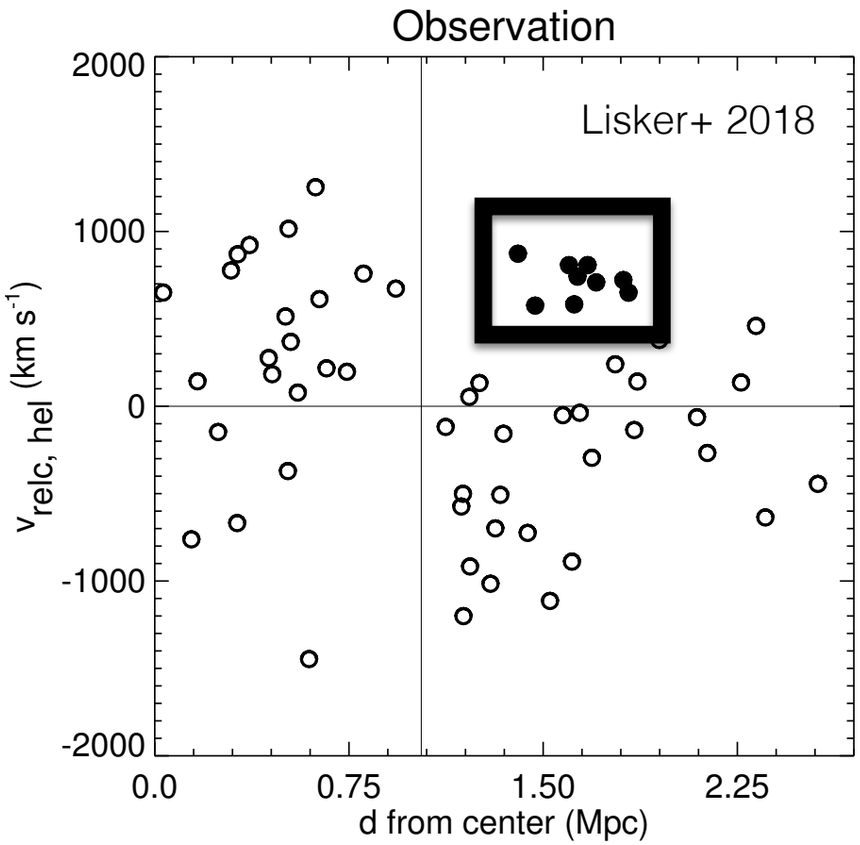
From simulation



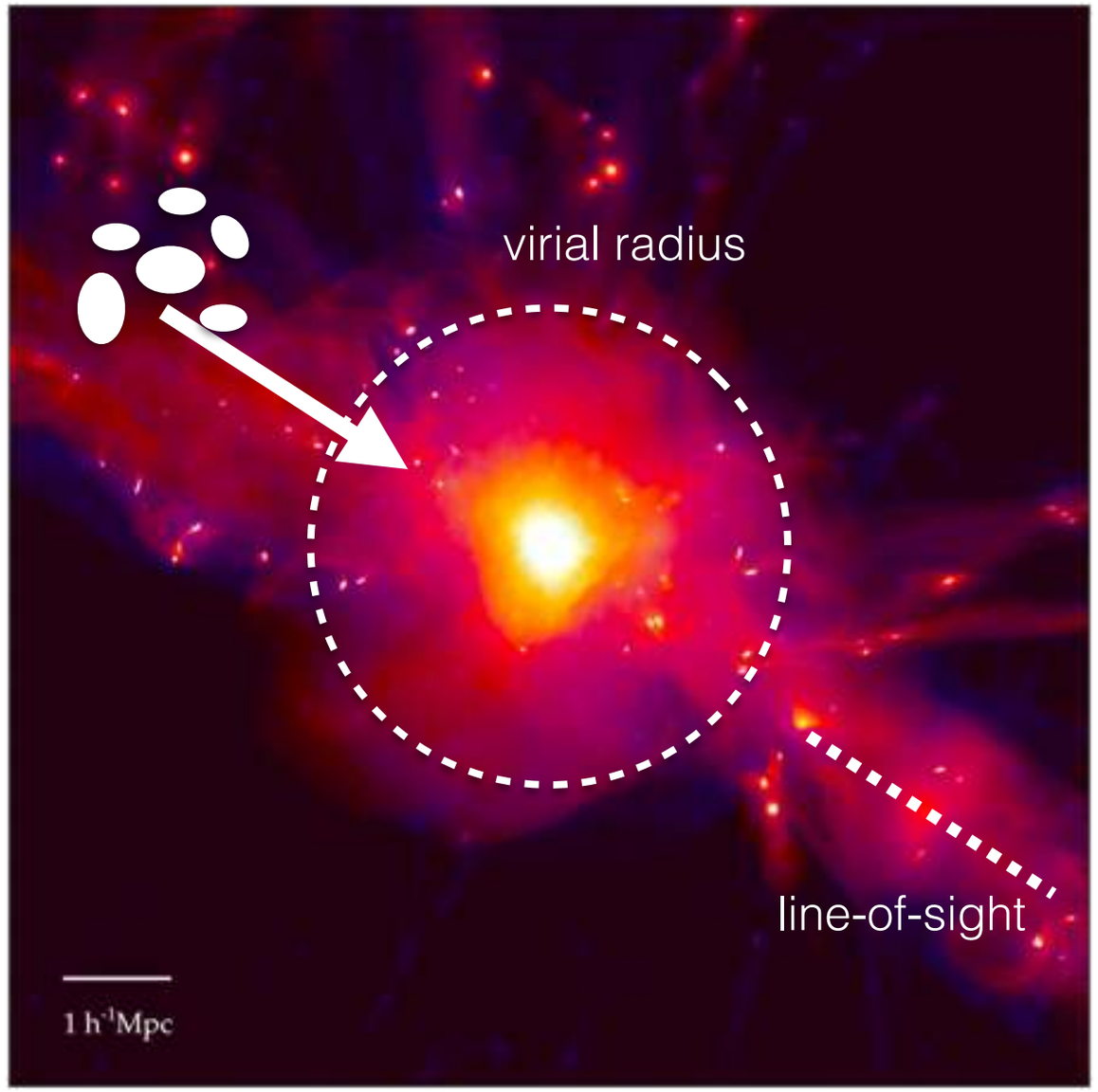
500 Mpc/h, 8192^3 particles effective (20 Mpc/h zoom), 0.24 kpc/h - Hydrodynamics: SN and AGN feedback, Planck cosmology

Agreement with observational predictions

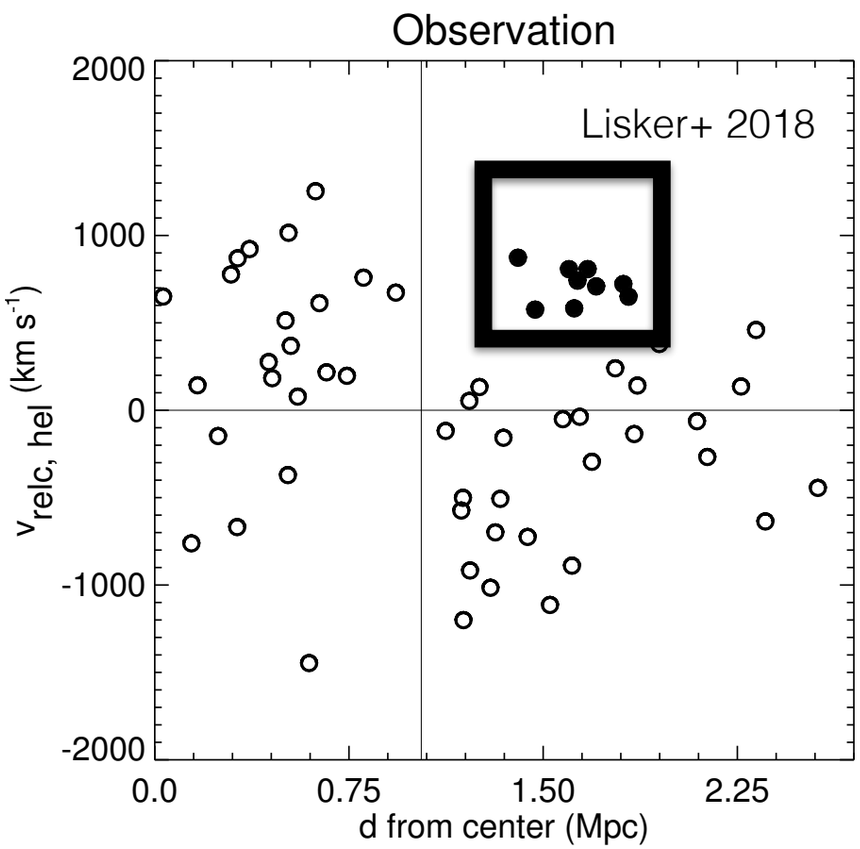
The Virgo galaxy cluster CLONE

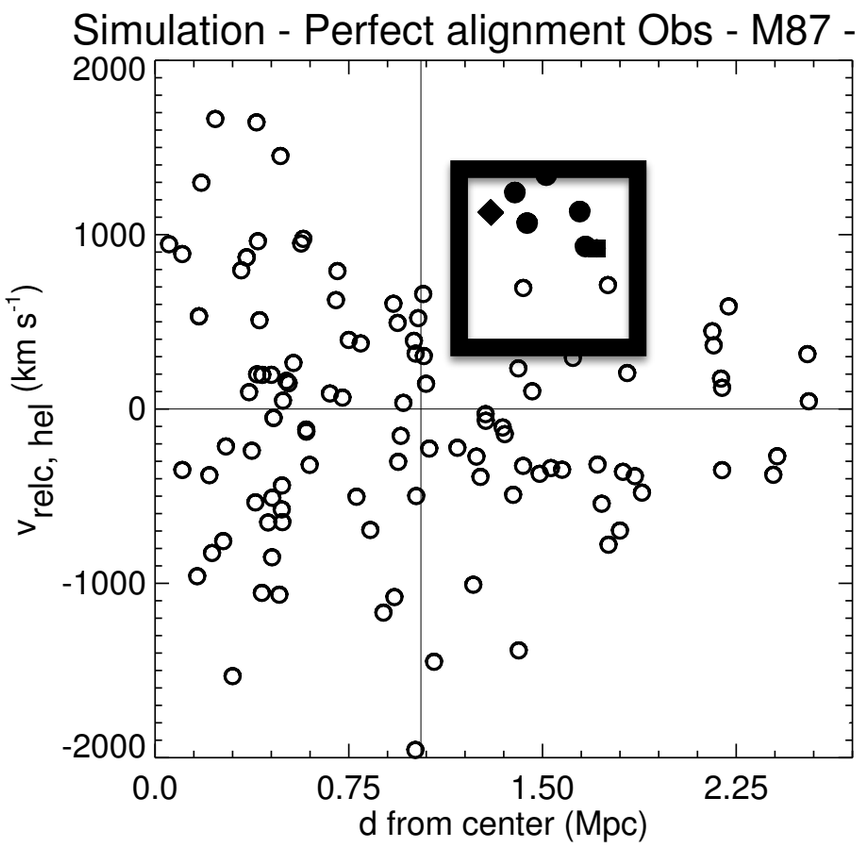


Group of galaxies that fell within the line-of-sight?



The Virgo galaxy cluster CLONE

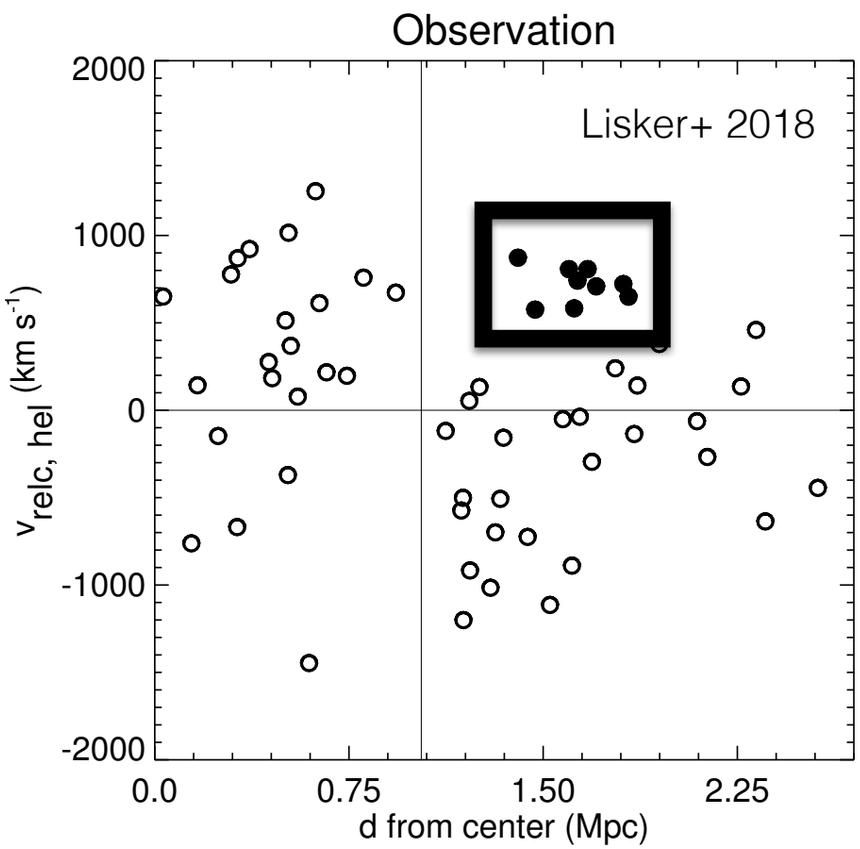


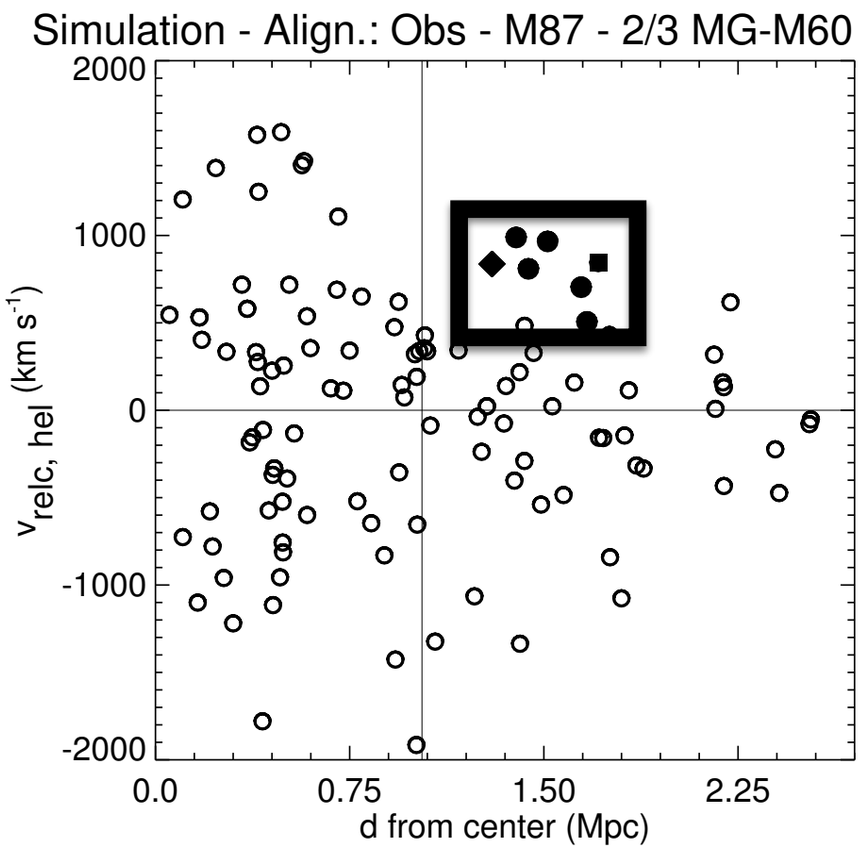


Group of galaxies that fell within the line-of-sight?

Sorce+2021

The Virgo galaxy cluster CLONE





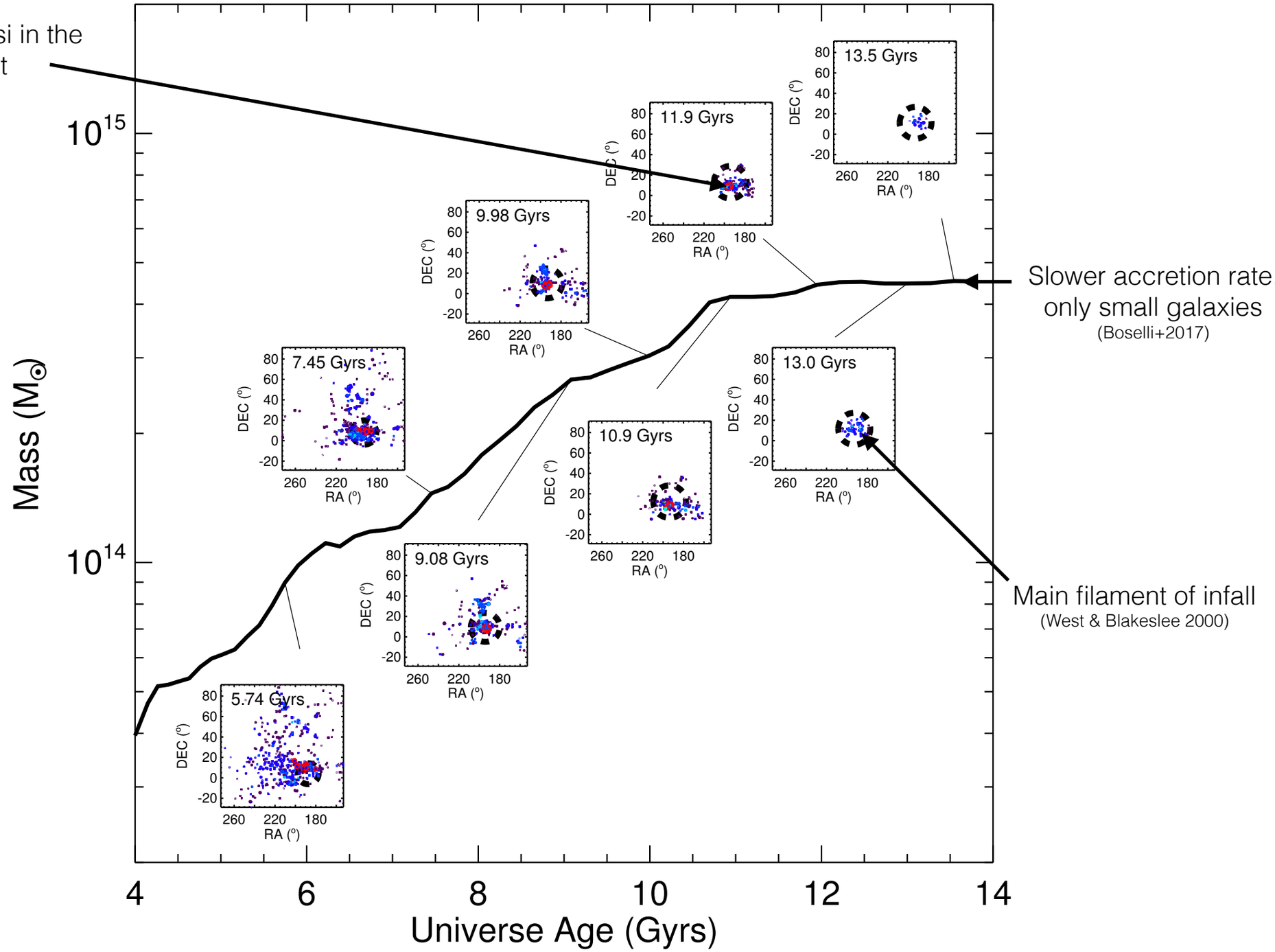
Group of galaxies that fell quasi within the line-of-sight

Sorce+2021

Agreement with observational predictions

The Virgo galaxy cluster CLONE

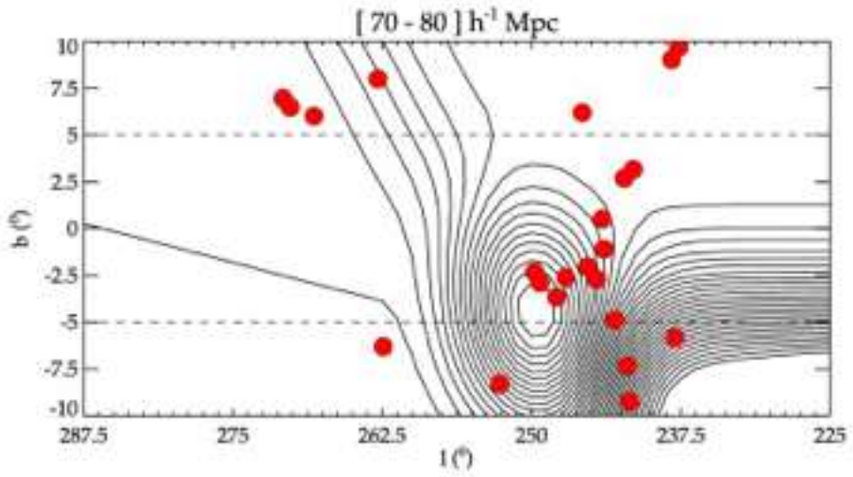
Sorce+2021



Agreement with observational predictions

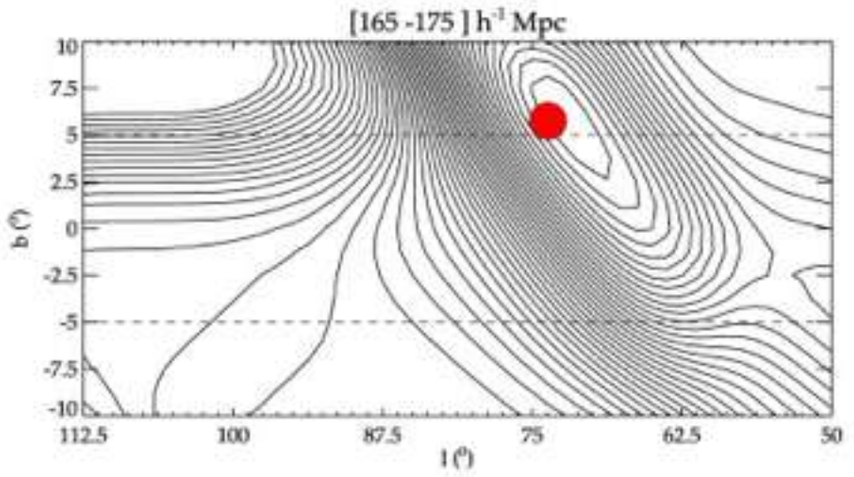
The Zone of Avoidance CLONE

Sorce+2017



Puppis-3 Cluster

Chamaraux & Masnoux 2004



Cygnus A Cluster

Ebeling+2002

ΛCDM challenges hidden in the Zone of Avoidance?

- number of superclusters

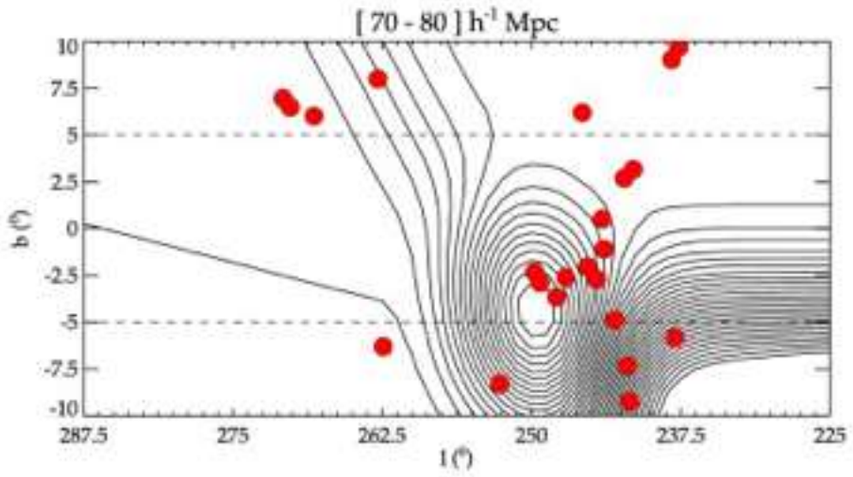
- longest structures

Vela Supercluster

Kraan-Korteweg+2017

The Zone of Avoidance CLONE

Sorce+2017



Puppis-3 Cluster

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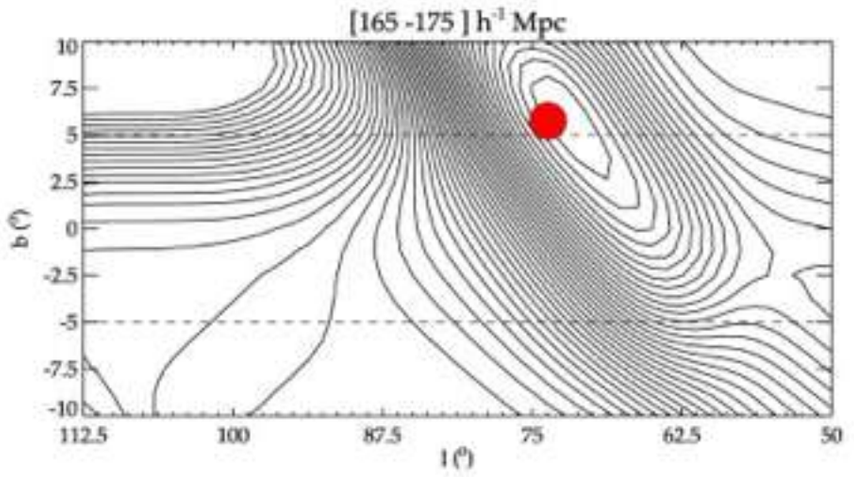

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Ebeling+2002

ΛCDM challenges hidden in the Zone of Avoidance?

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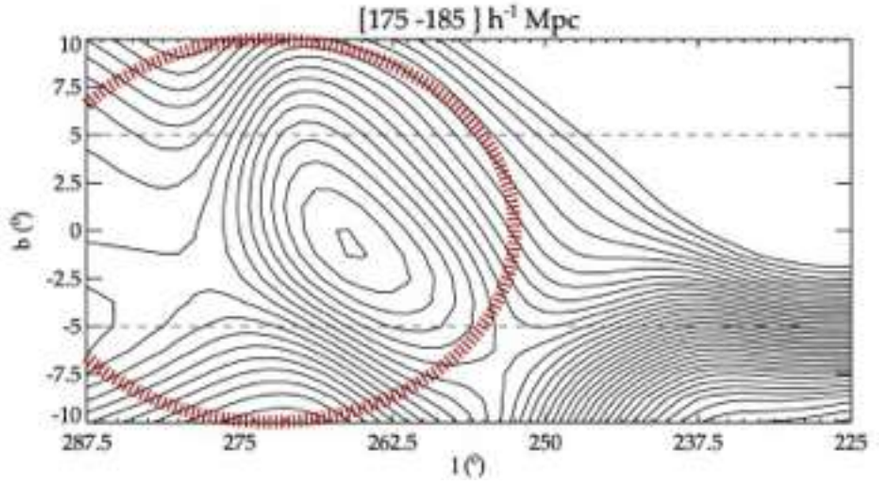
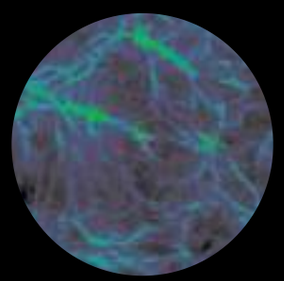


Vela Supercluster

Kraan-Korteweg+2017

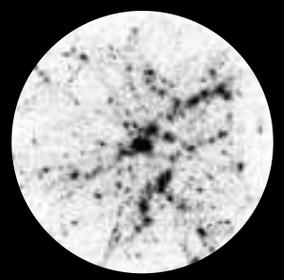
Some other examples: …



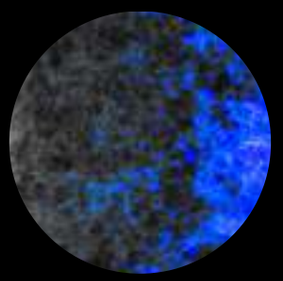
Cosmic Rays in the local Universe
(Hackstein+2018)

SLOW : local galaxies
(Sorce, Dolag +)

and
more…



Coma connectivity
(Malavi, Aghanim, Sorce+)



Reionization of the local Universe (CoDa)
(Ocvirk+2020, Lewis+2020, etc)

Take home message

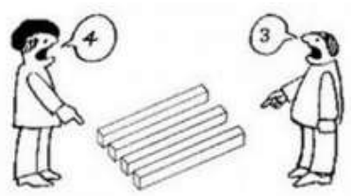
Tensions = Do we need a new cosmological model?

To answer, nowadays : comparisons between typical cosmological simulations and observations

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

Tensions = Do we need a new cosmological model?

CLONES

initial conditions for

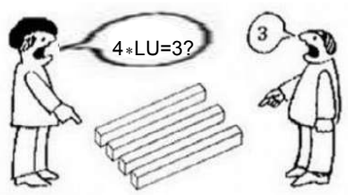
numerical specialists, theorists and observers

Small scales

Simulations of Galaxy formation & evolution:

- reproduction
- calibration

Local scales



unbiased local estimates of cosmological parameters

Large scales

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

Accurate Precision Cosmology

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, diolch, dankewol,

ಧನ್ಯವಾದಗಳು, …*

* 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)