Toward accurate precision cosmology

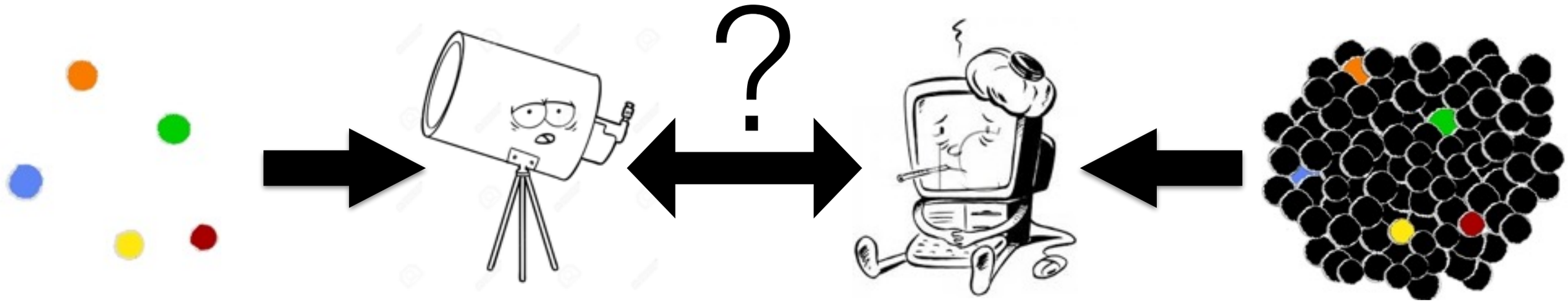
with CLONES' help

Jenny Sorce
Guest researcher at AIP, Potsdam
IASF Milano - November, 9th 2021

Motivation : ΛCDM? ➤ Current strategy

Observations

Simulations



Directly Observable Universe

Cosmological Model

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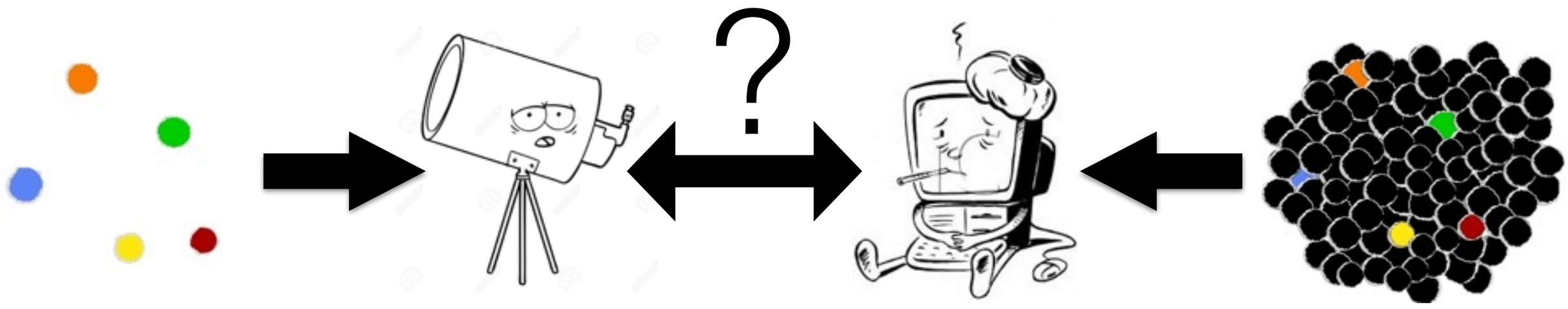


Directly Observable Universe

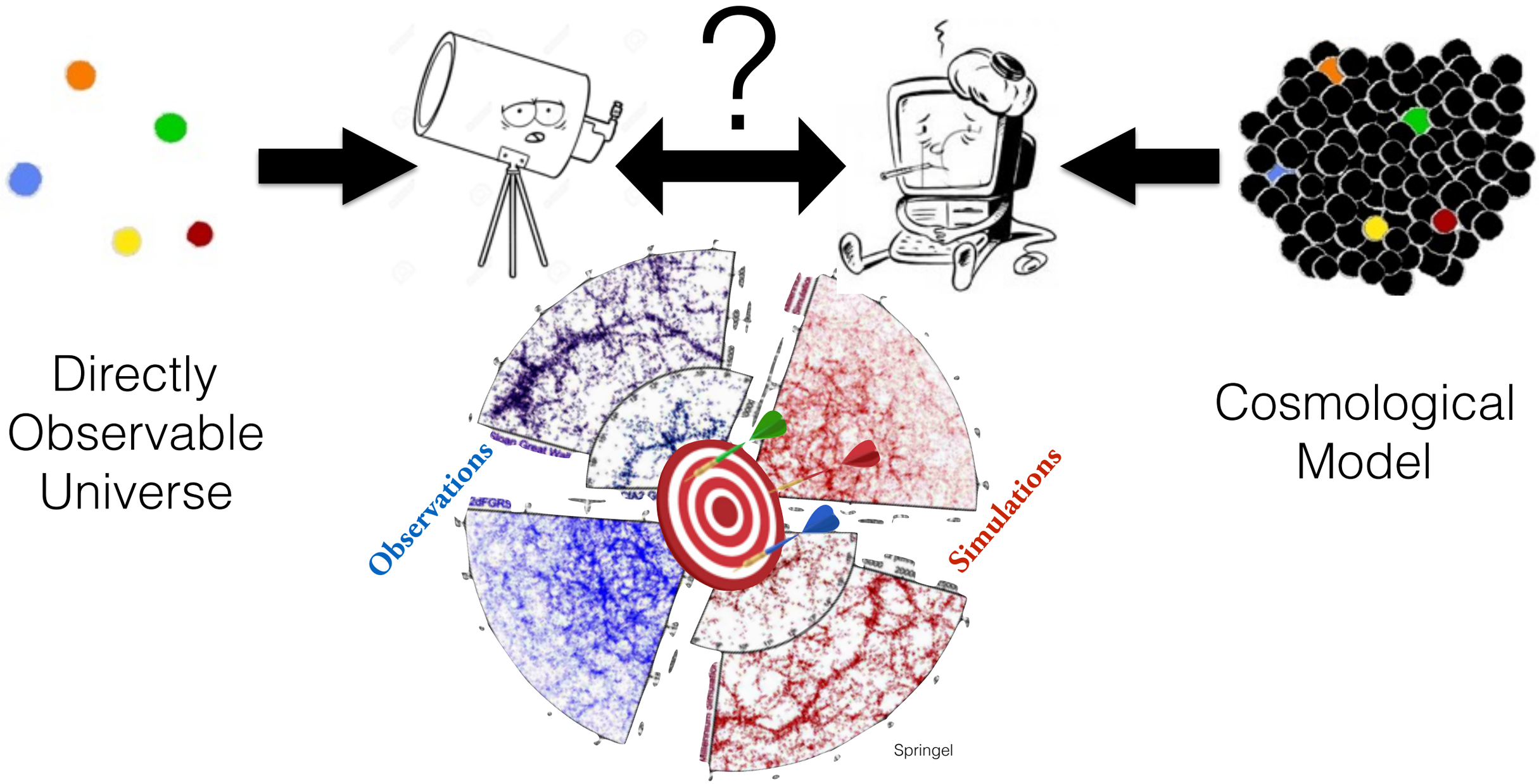
Cosmological Model

If all goes well…
it is a perfect match

Motivation : ΛCDM? In practice

Observations

Simulations



Directly Observable Universe

Cosmological Model

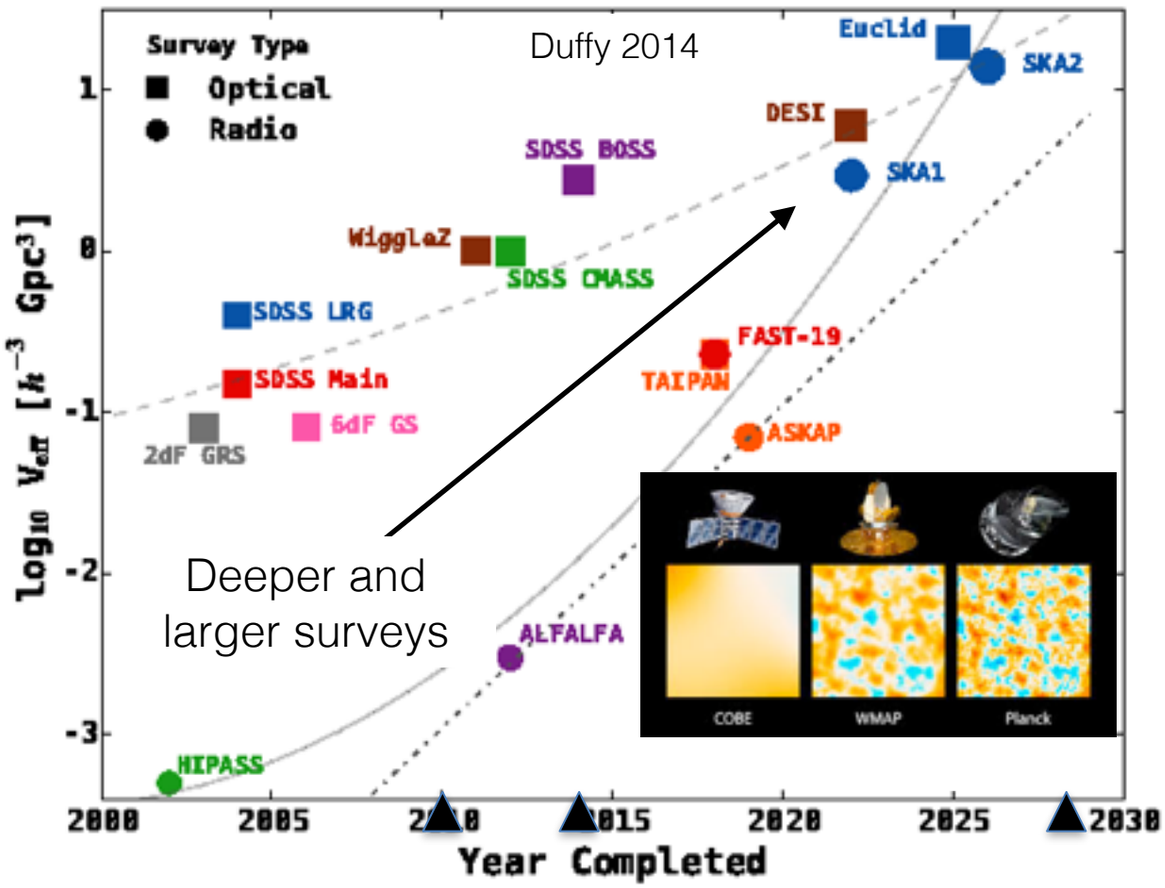
Overall: ΛCDM ☑

Motivation : ΛCDM? Toward precision cosmology

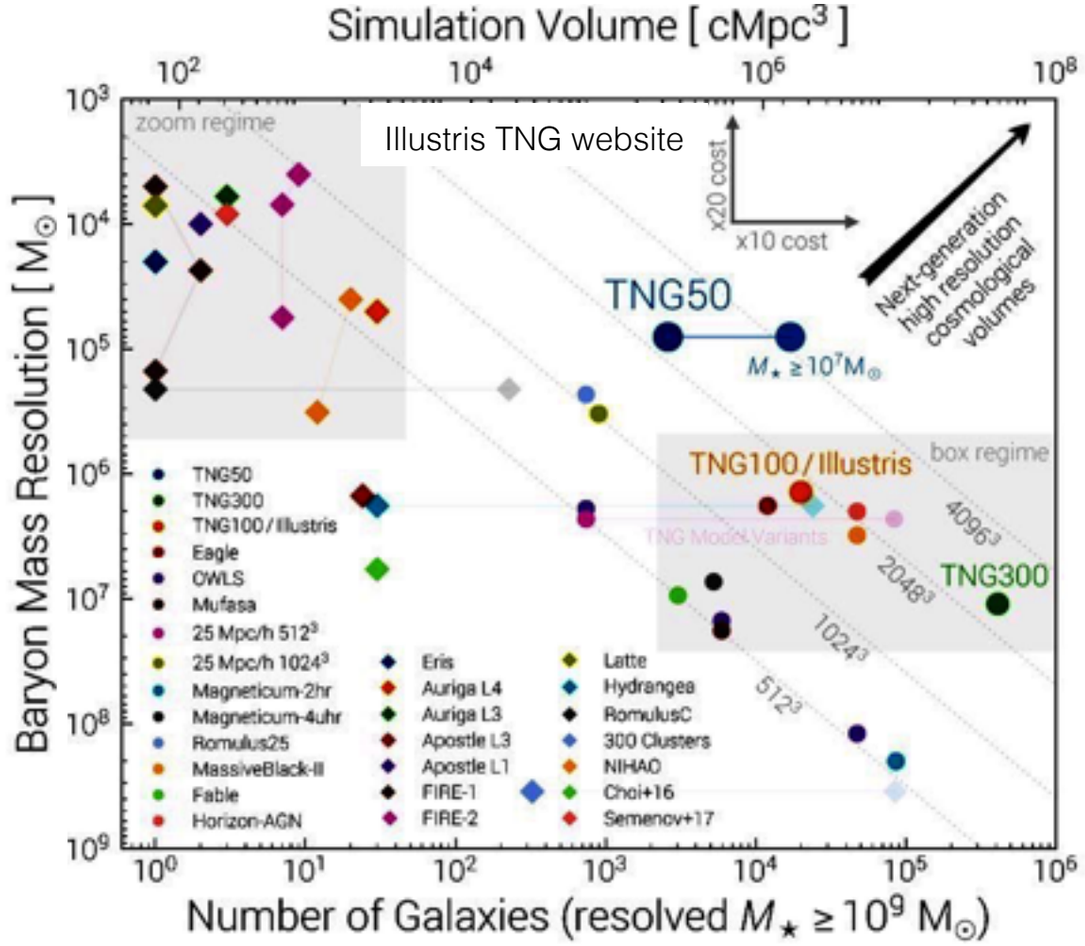
Precision Era:
1-2% precision

ΛCDM checked on all scales

Observations

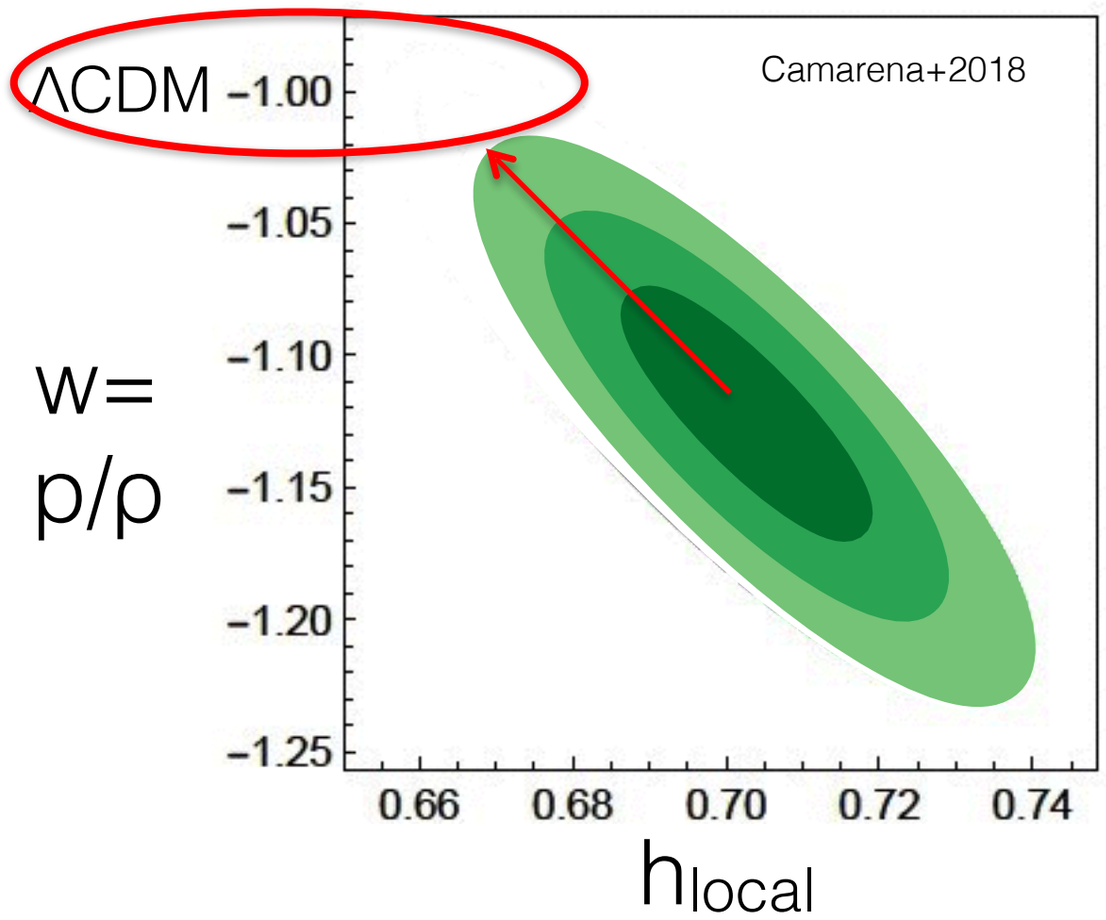


Simulations



ΛCDM questioned? with more precision comes some tensions !

Example: Equation of state of the dark energy

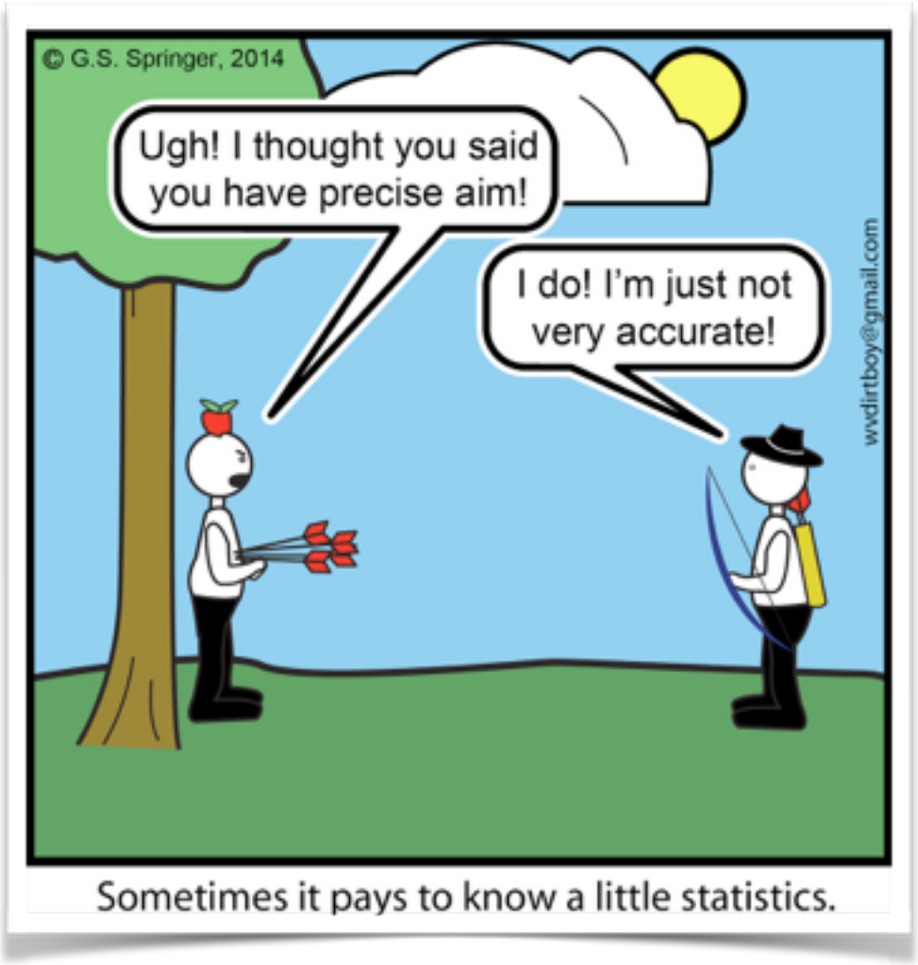


given H precise value unlikely with a likelihood without cosmic variance

our cosmic Home:
Volume of ~ 300-400 Mpc
centered on us

ΛCDM questioned?

Precision is not accuracy !



ΛCDM questioned? → environmental biases?

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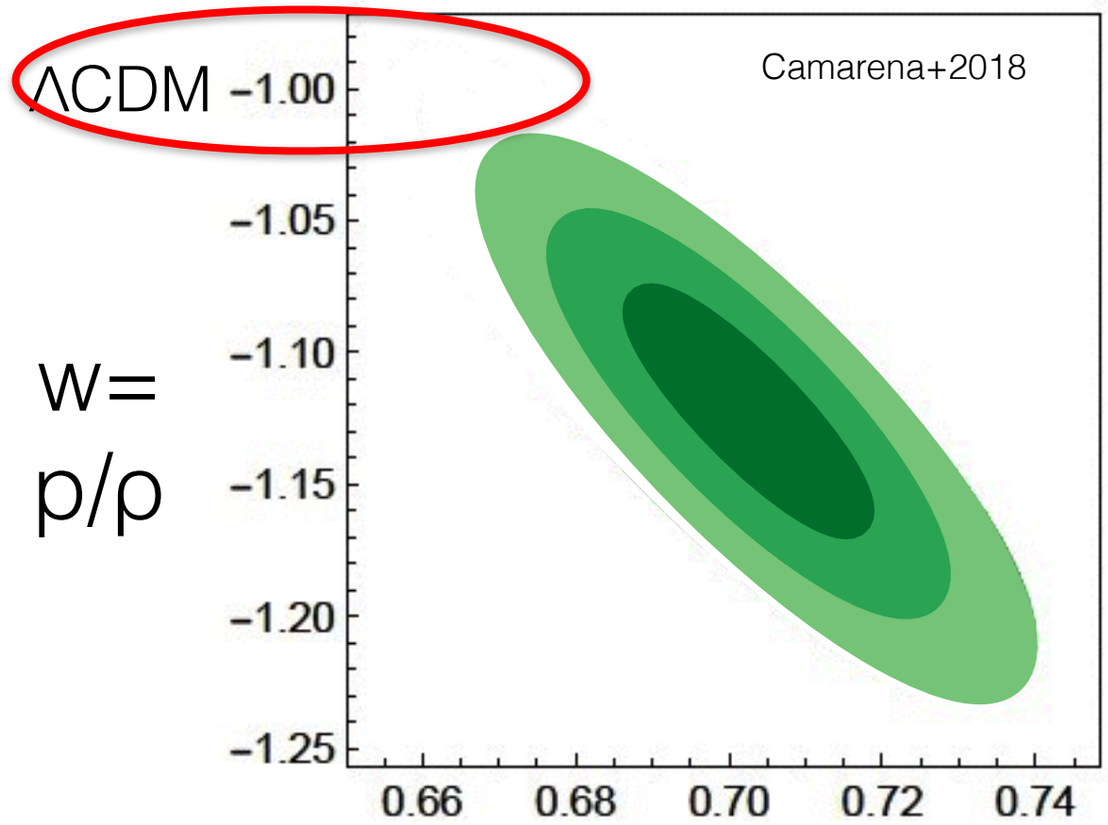
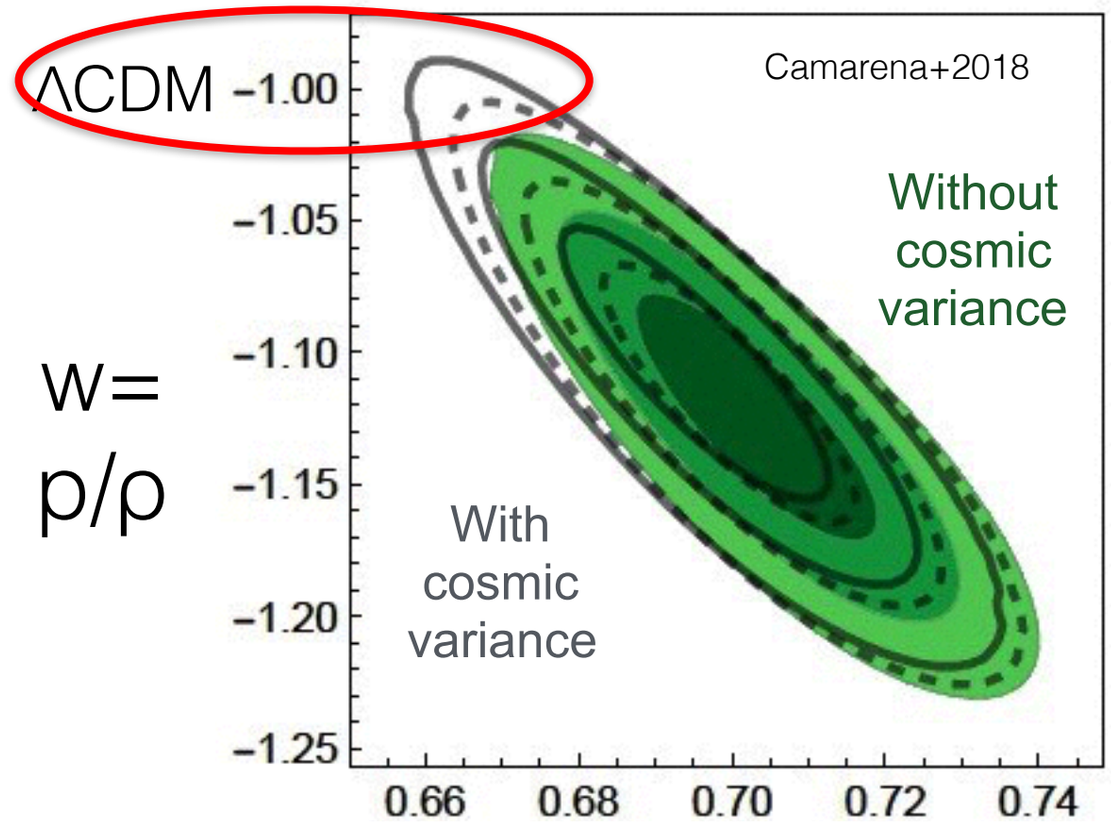


ΛCDM questioned?

Both precision and accuracy are required!

Example: Equation of state of the dark energy

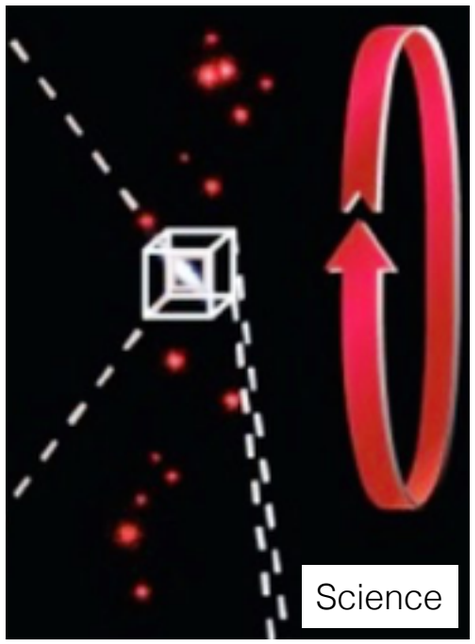


Accuracy:
1% bias non-negligible

ΛCDM questioned? A few other 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

Francis+2010

very unlikely…

ΛCDM questioned? A few other examples

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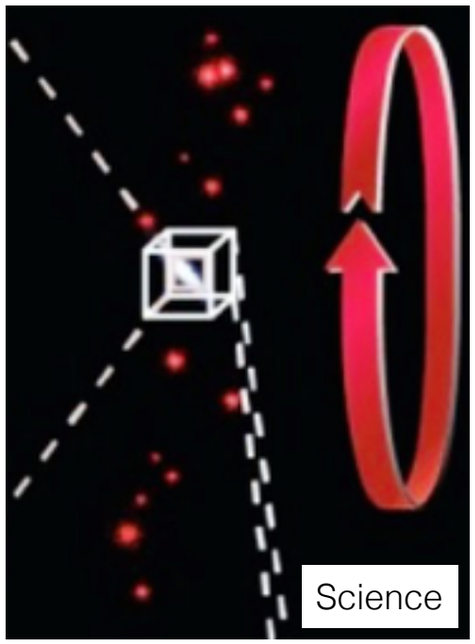

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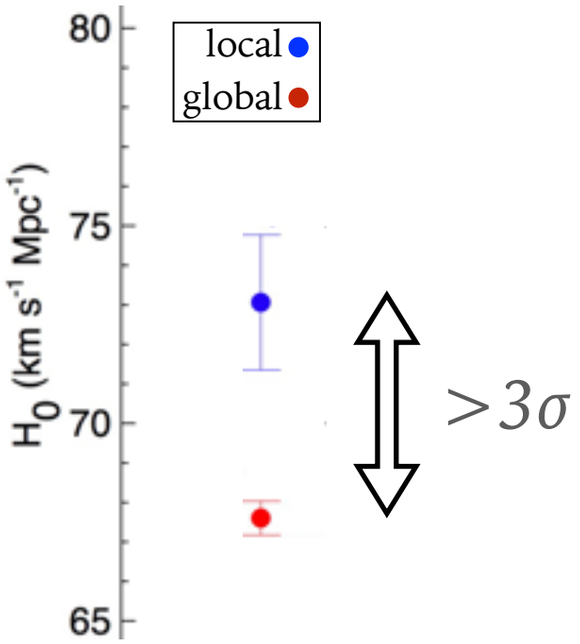

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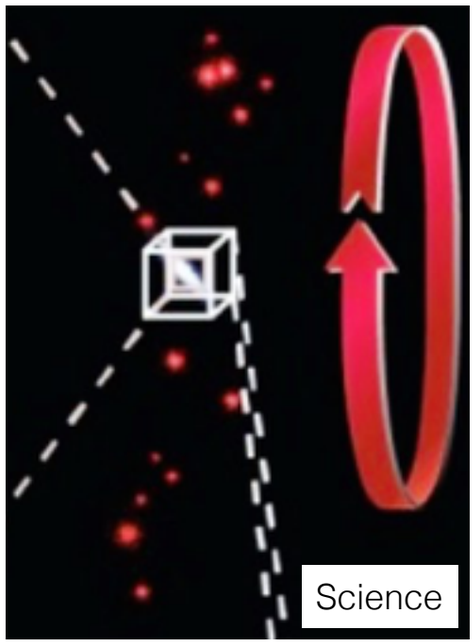

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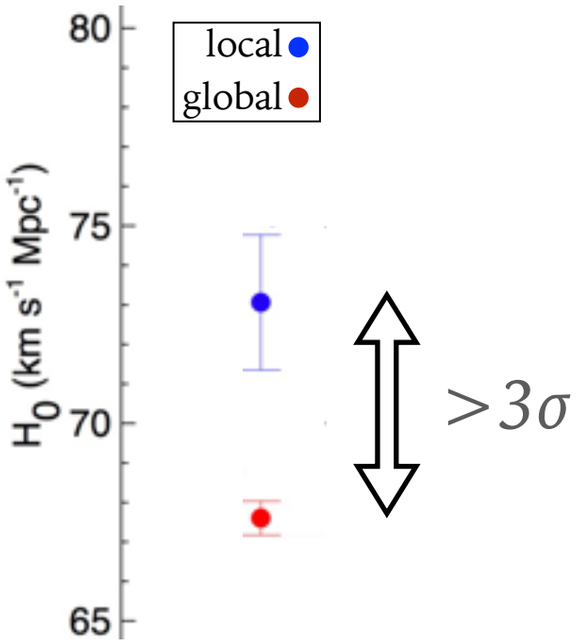

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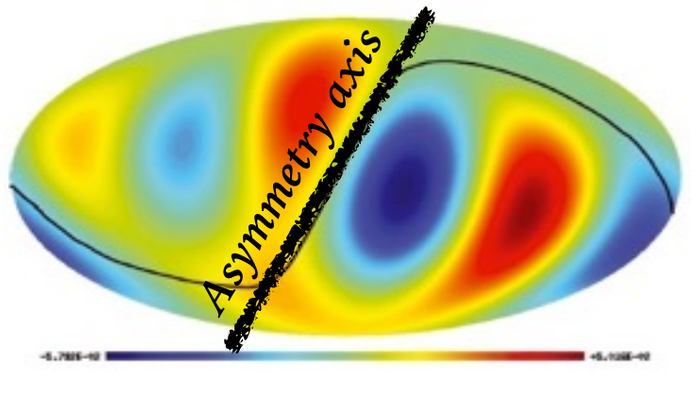


Francis+2010

very unlikely…

Local-induced biases ?

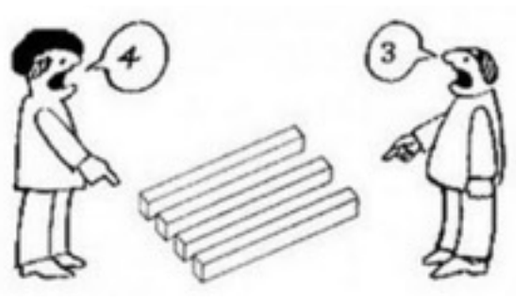
Can our local environment bias our ‘’perception’’ at the 1-2% level preventing us from reaching 1-2% accuracy…

Small scales

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

Correlation with environment

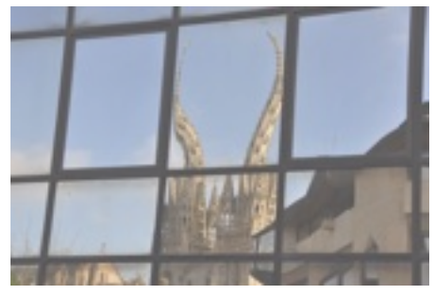
Local scales



Are we a neutral observer?

A neutral environment?
Very unlikely…

Large scales



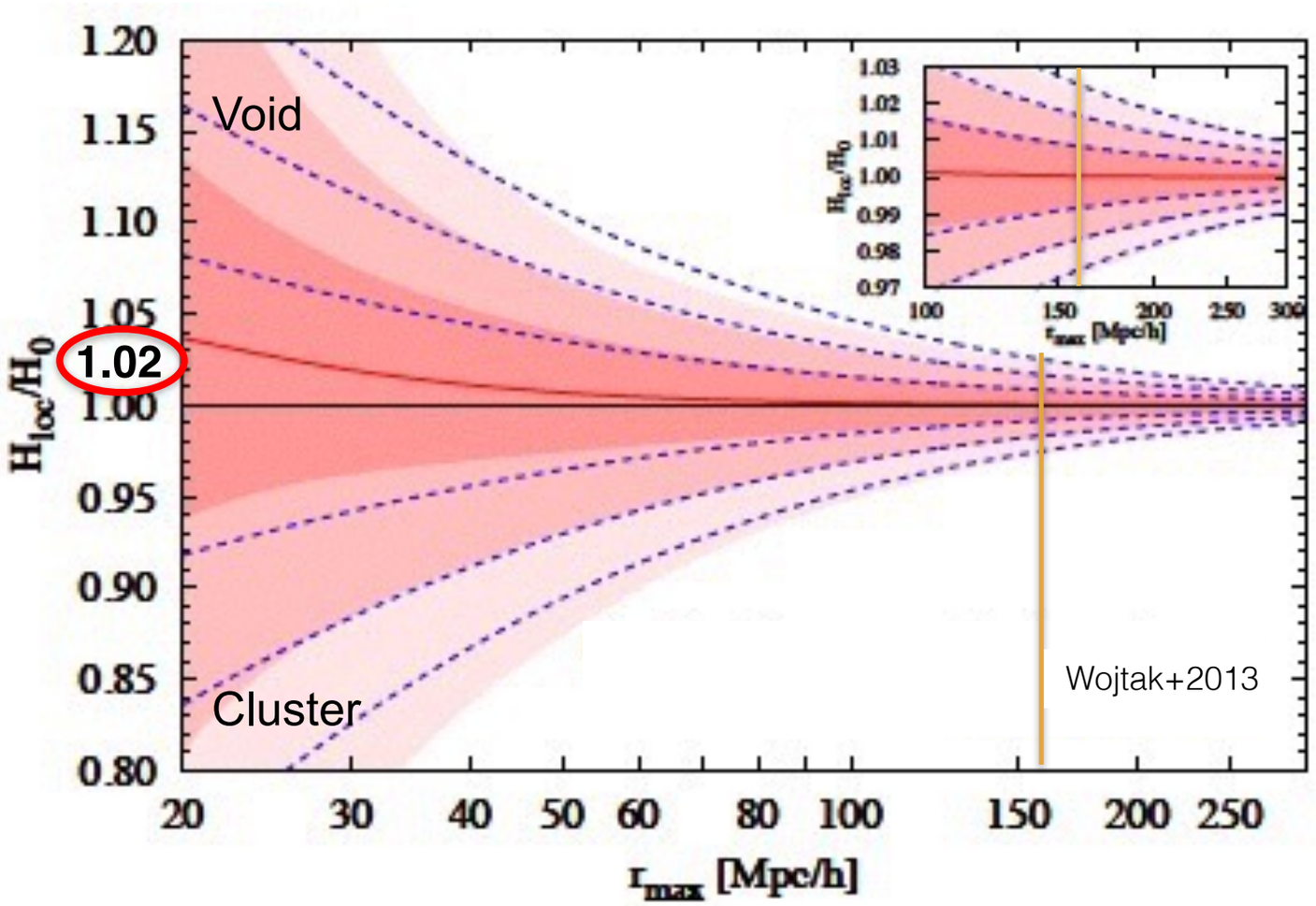
What about foreground effects?

Photons travel a lot
before reaching us…

and eventually decrease *or increase* tensions with ΛCDM ?

Local-induced biases ? on the local scales

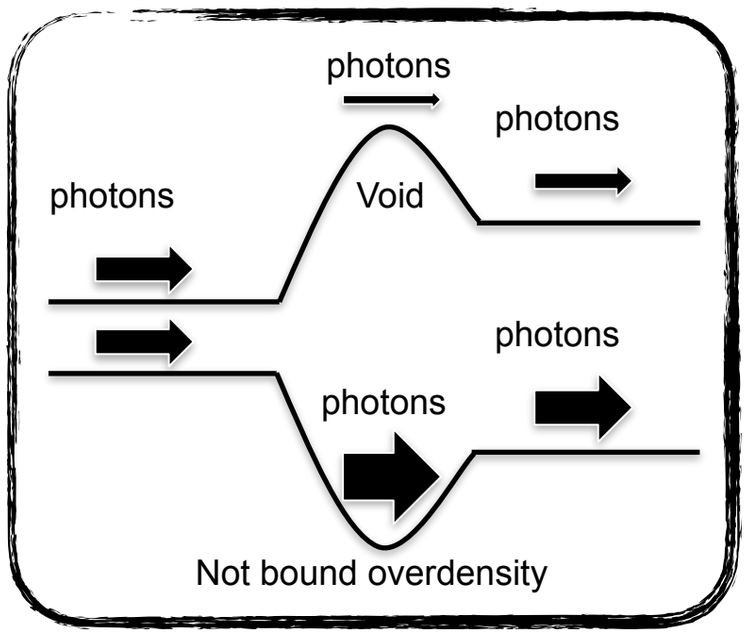
As many effect values as environments



For an average environment: a 2% bias !

Local-induced biases ? on the large scales

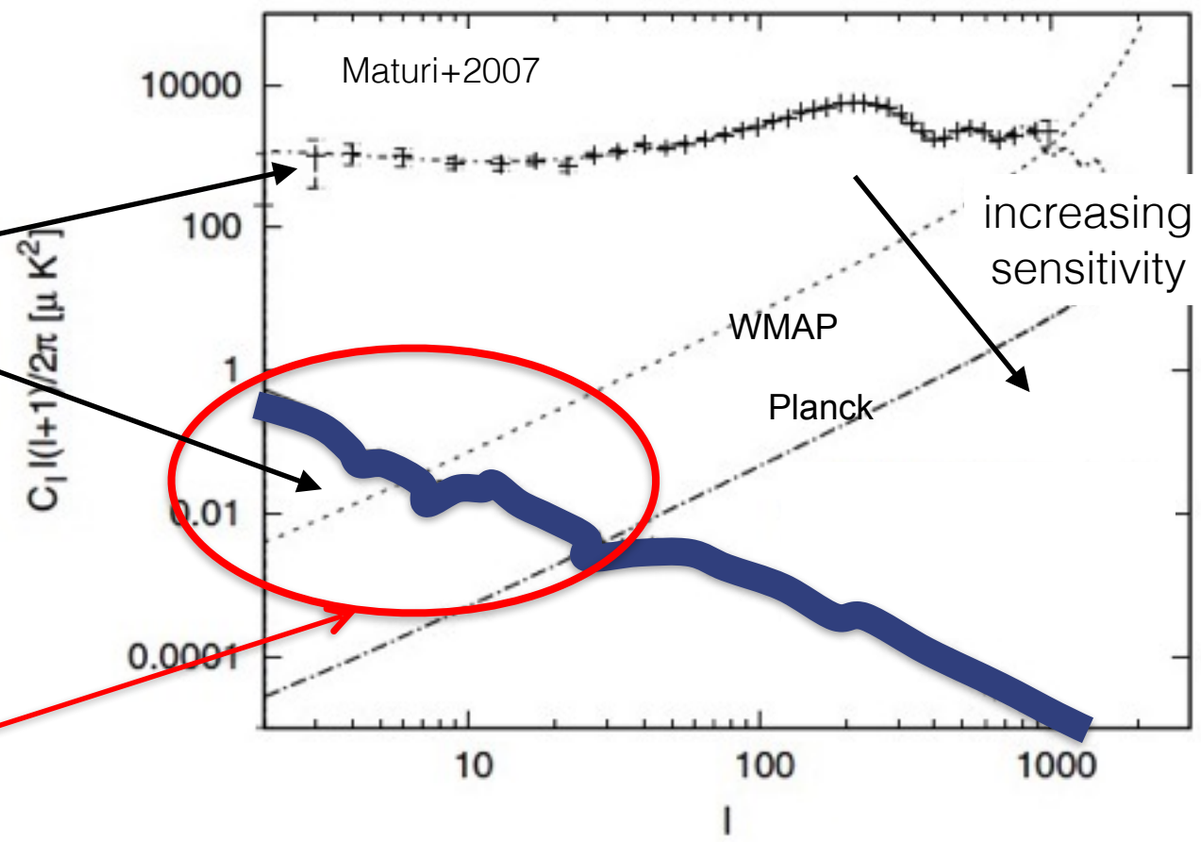
Gravitational redshifts and the CMB



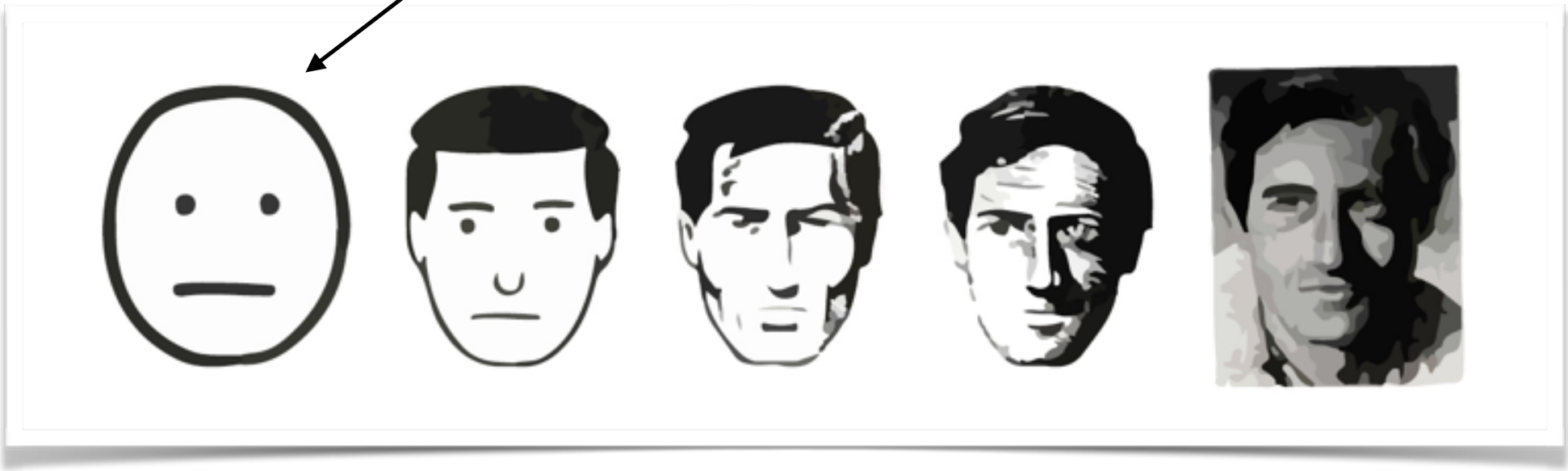
Integrated Sachs-Wolfe & Rees-Sciama Effects

reducing error bars = increasing precision

local foreground effect = 'noise/ bias'



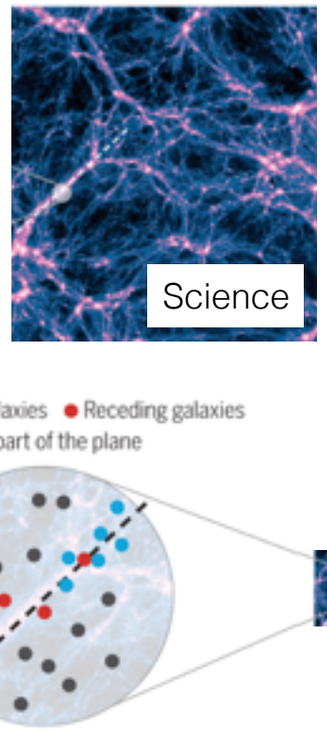
A crude modeling is a beginning…



Accounting for the effects ➤ crude modeling

Small scales

Thin disks of satellites



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

local scales

local / global H_0

In what kind of density do we live exactly?

Large scales

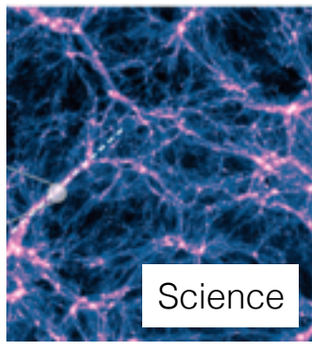
CMB

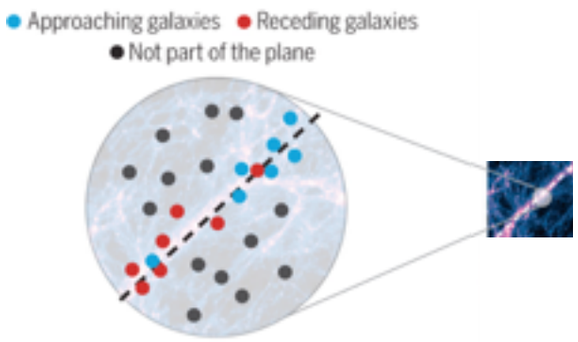
But correction from redshift surveys only…

Accounting for the effects ➤ crude modeling

Small scales

Thin disks of satellites





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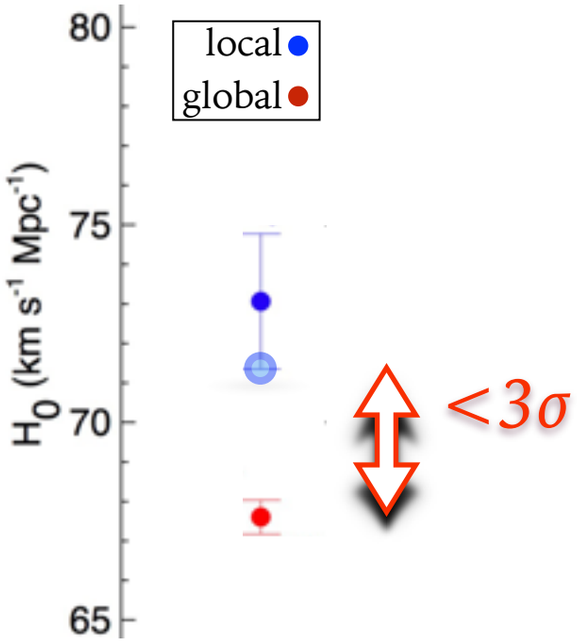

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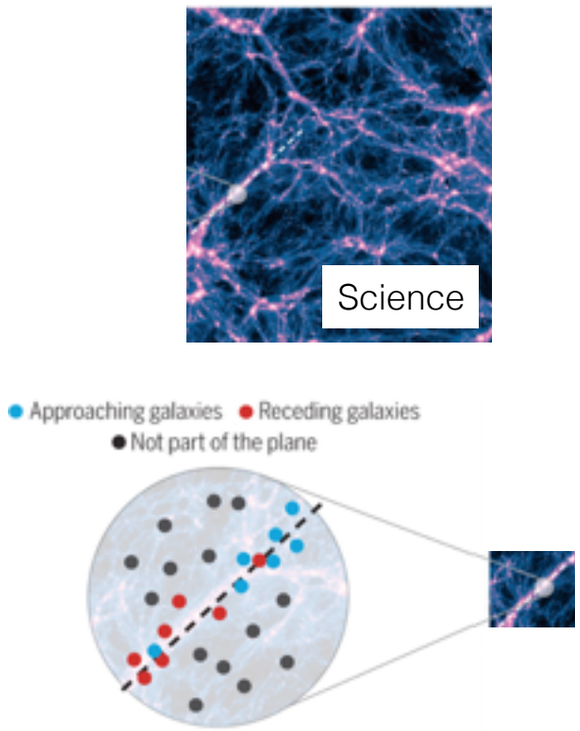

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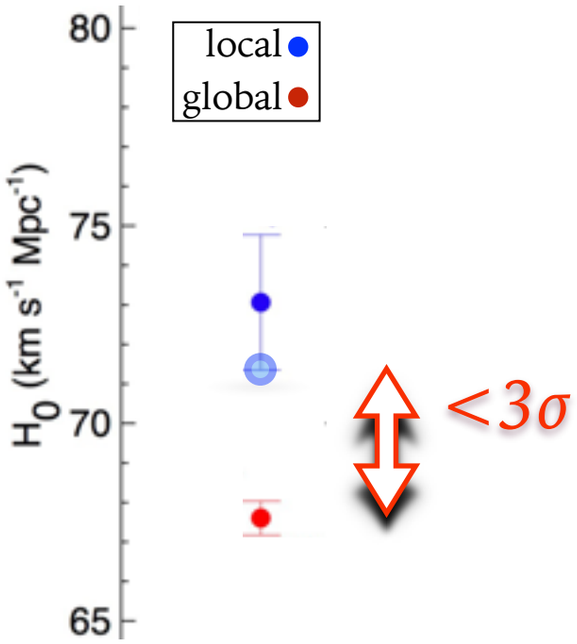

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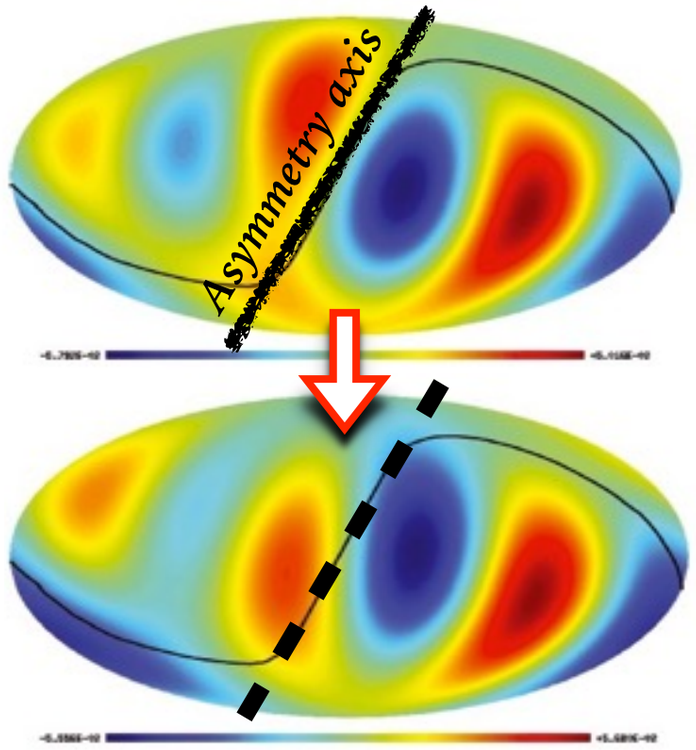
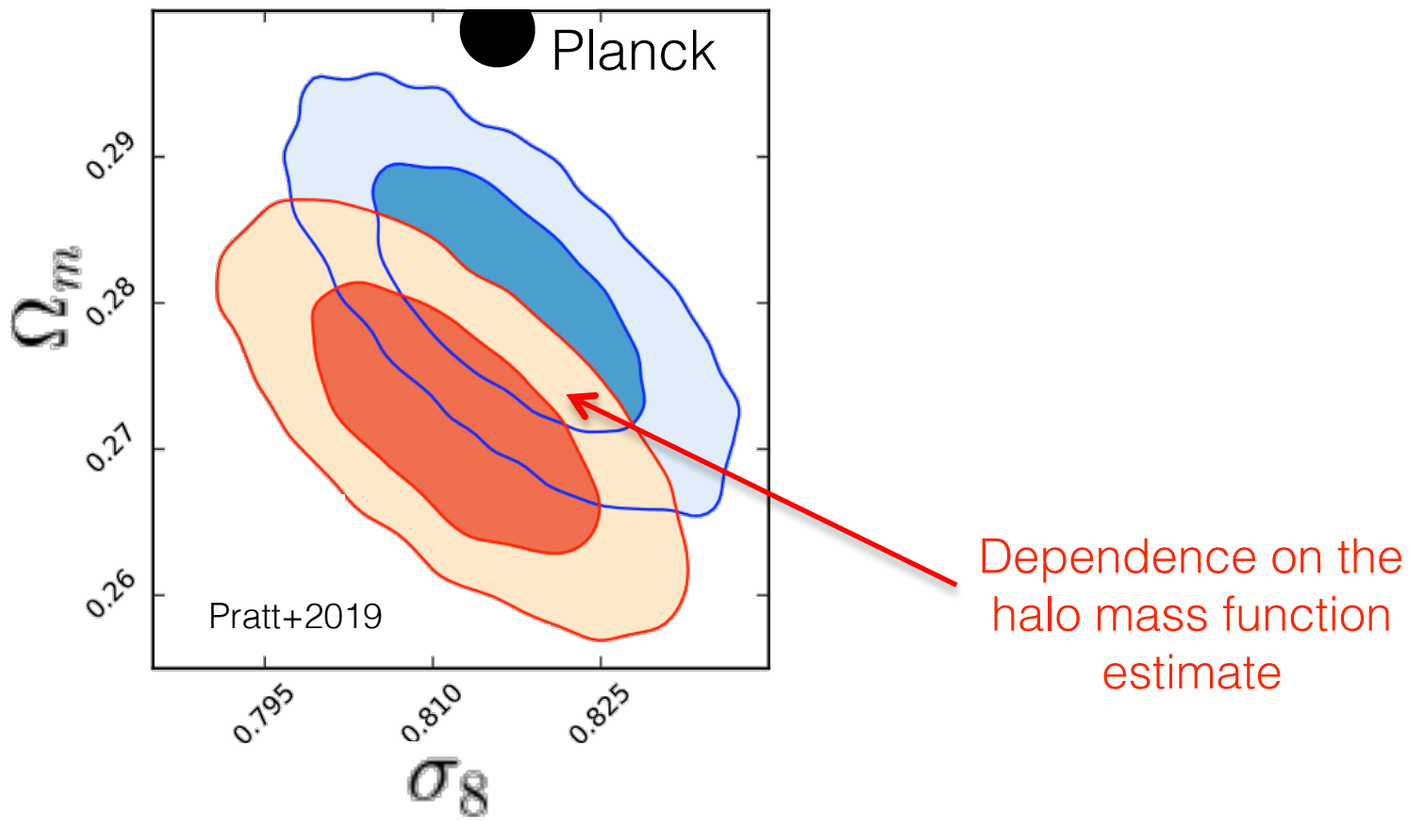


But correction from redshift surveys only…

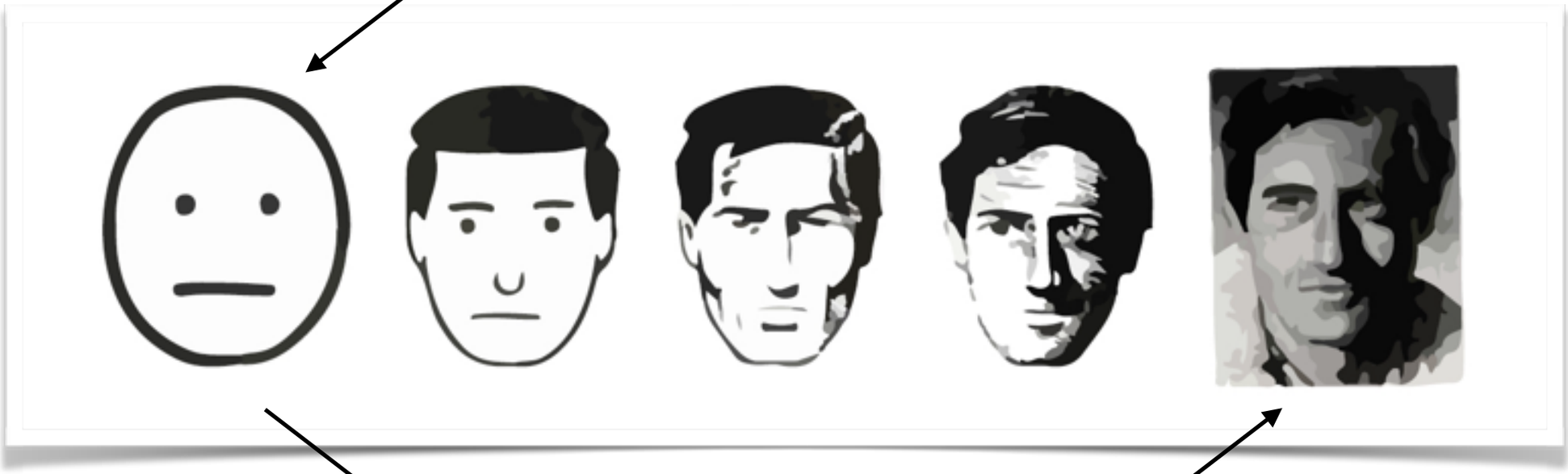
Local-induced biases ? one more example

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 !

A crude modeling is a beginning…



but not nearly enough…

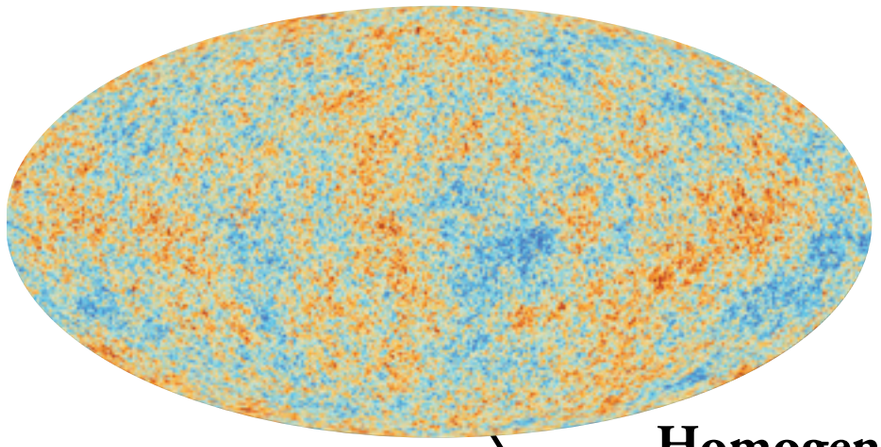
Summary

Need a good 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

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

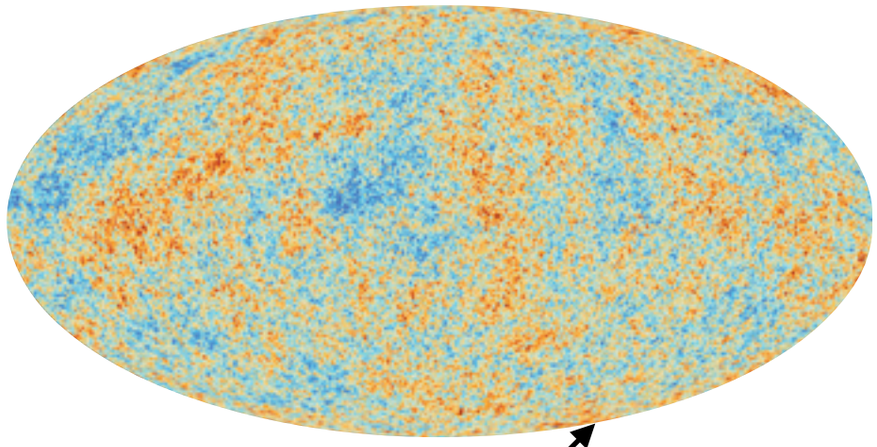


Homogeneous and Isotropic Universe

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

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

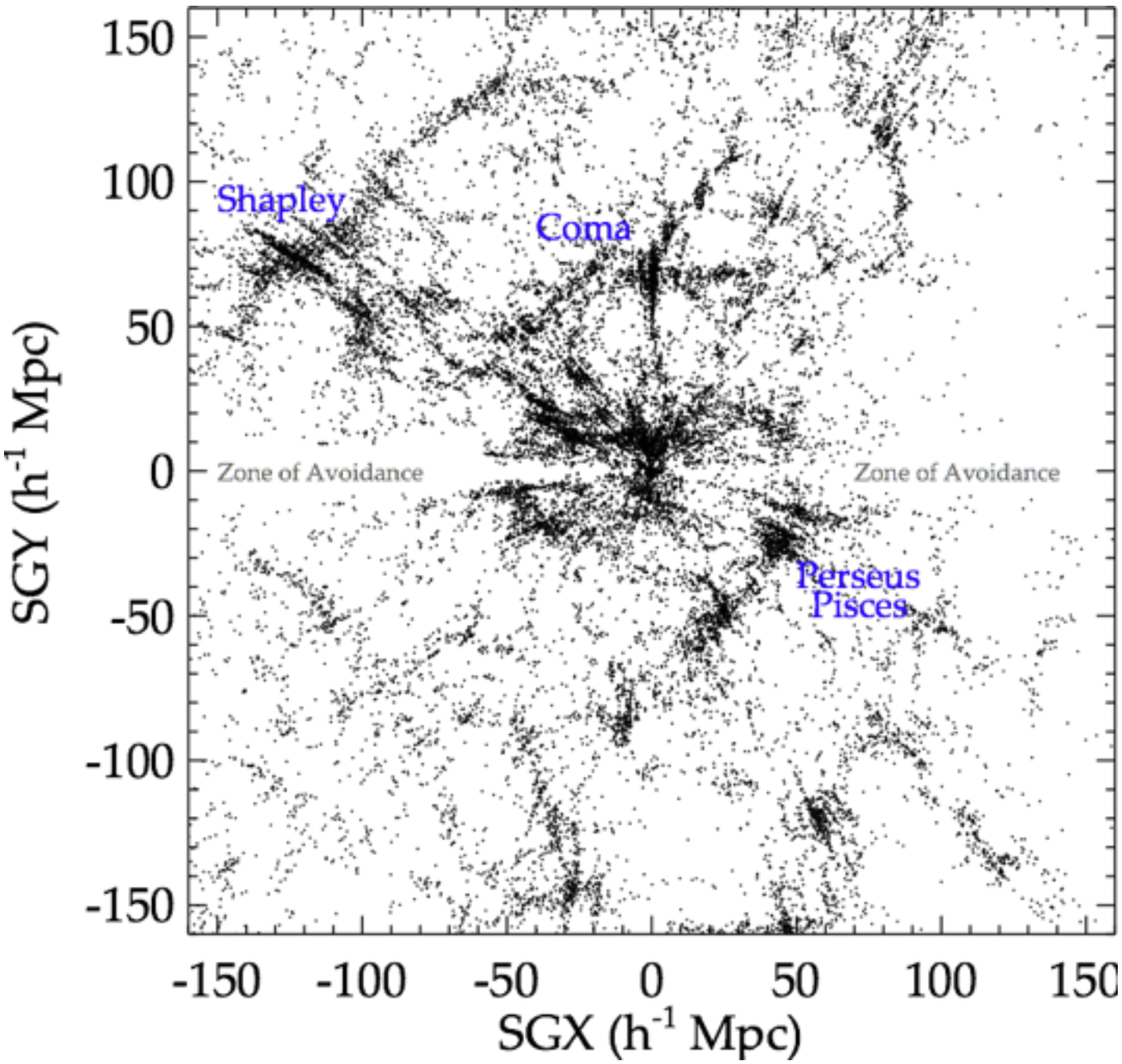
Method

For another time, let's look at some results

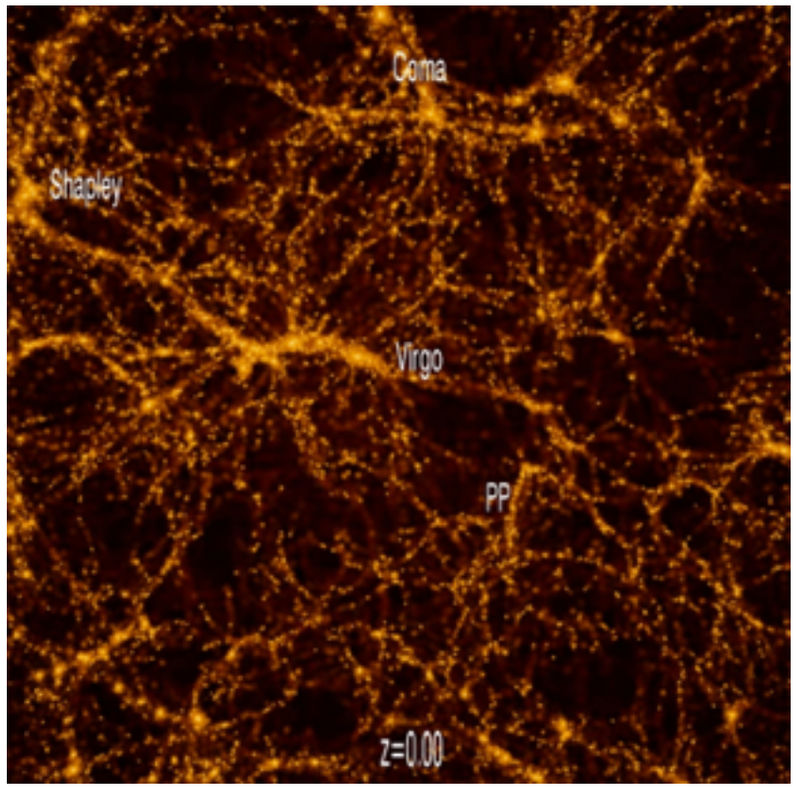
or look at e.g.
Sorce & Tempel 2017,2018
Sorce 2015, 2018
Doumler+2013
Sorce+2014
Hoffman & Ribak 1991
Wiener1942

Results: the local large scale CLONE

z=0, large scale Sorce+2016



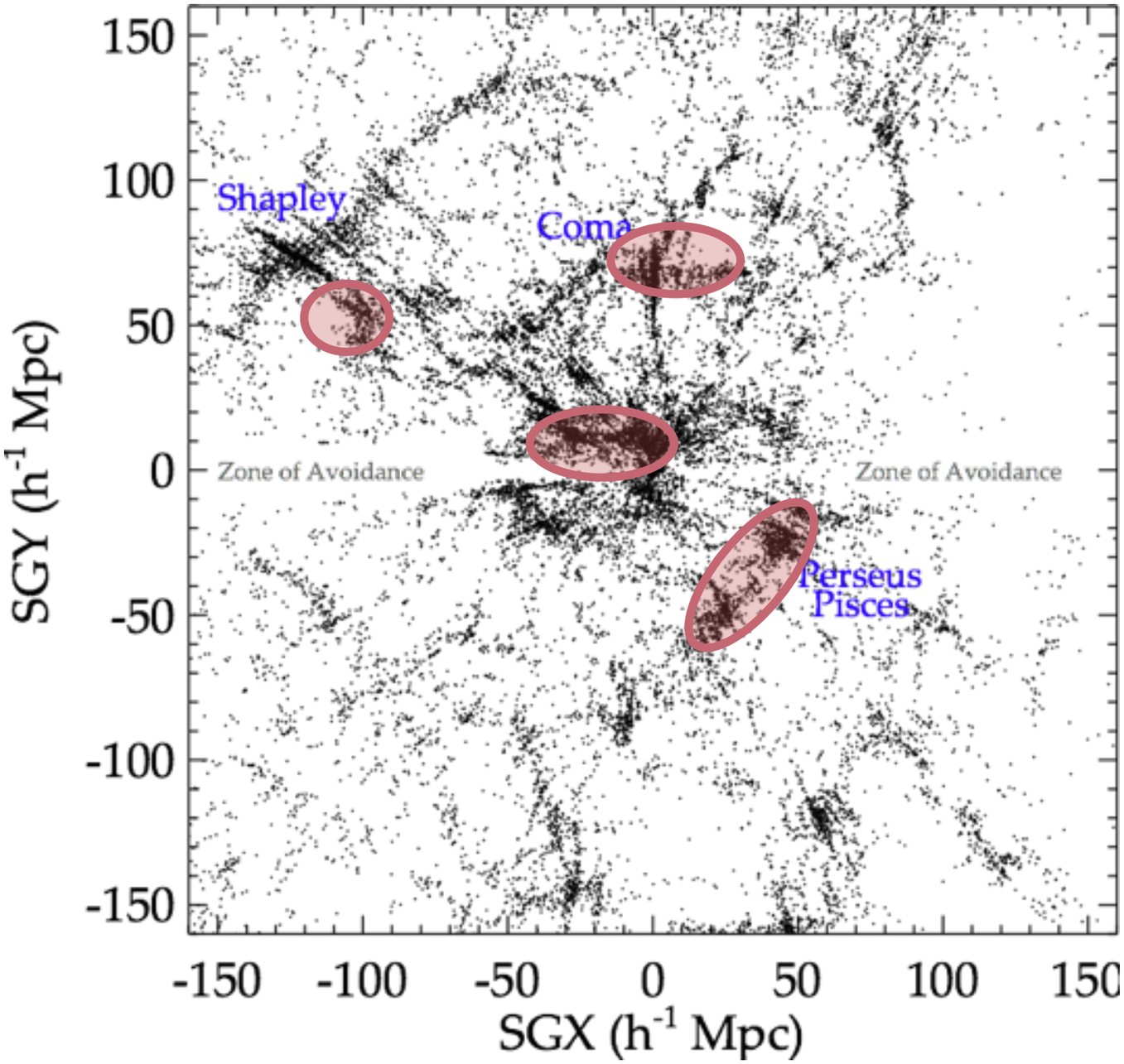
Note the fingers of gods



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

Results: the local large scale CLONE

z=0, large scale Sorce+2016



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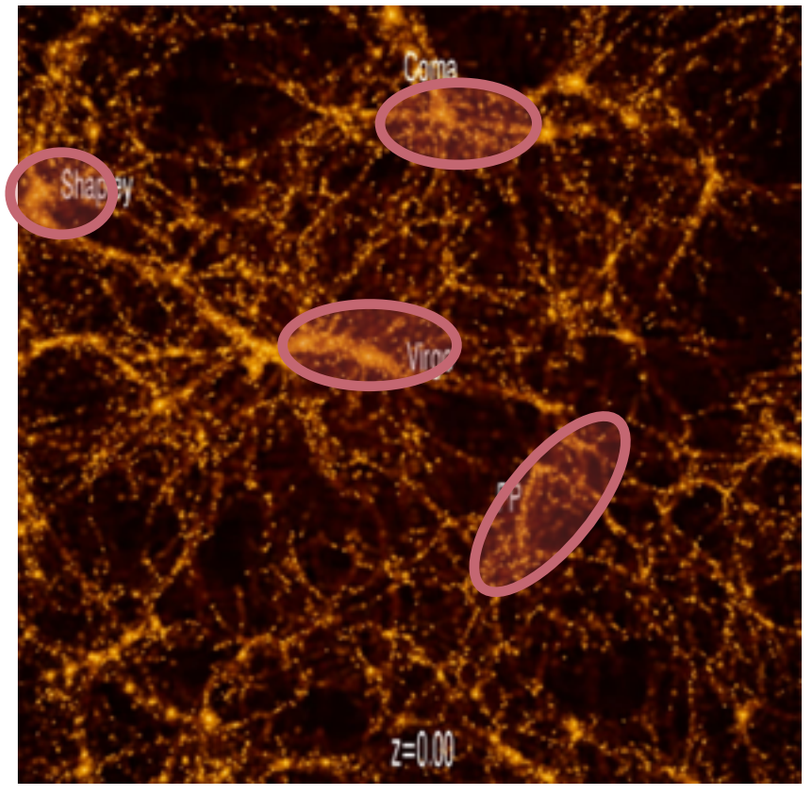

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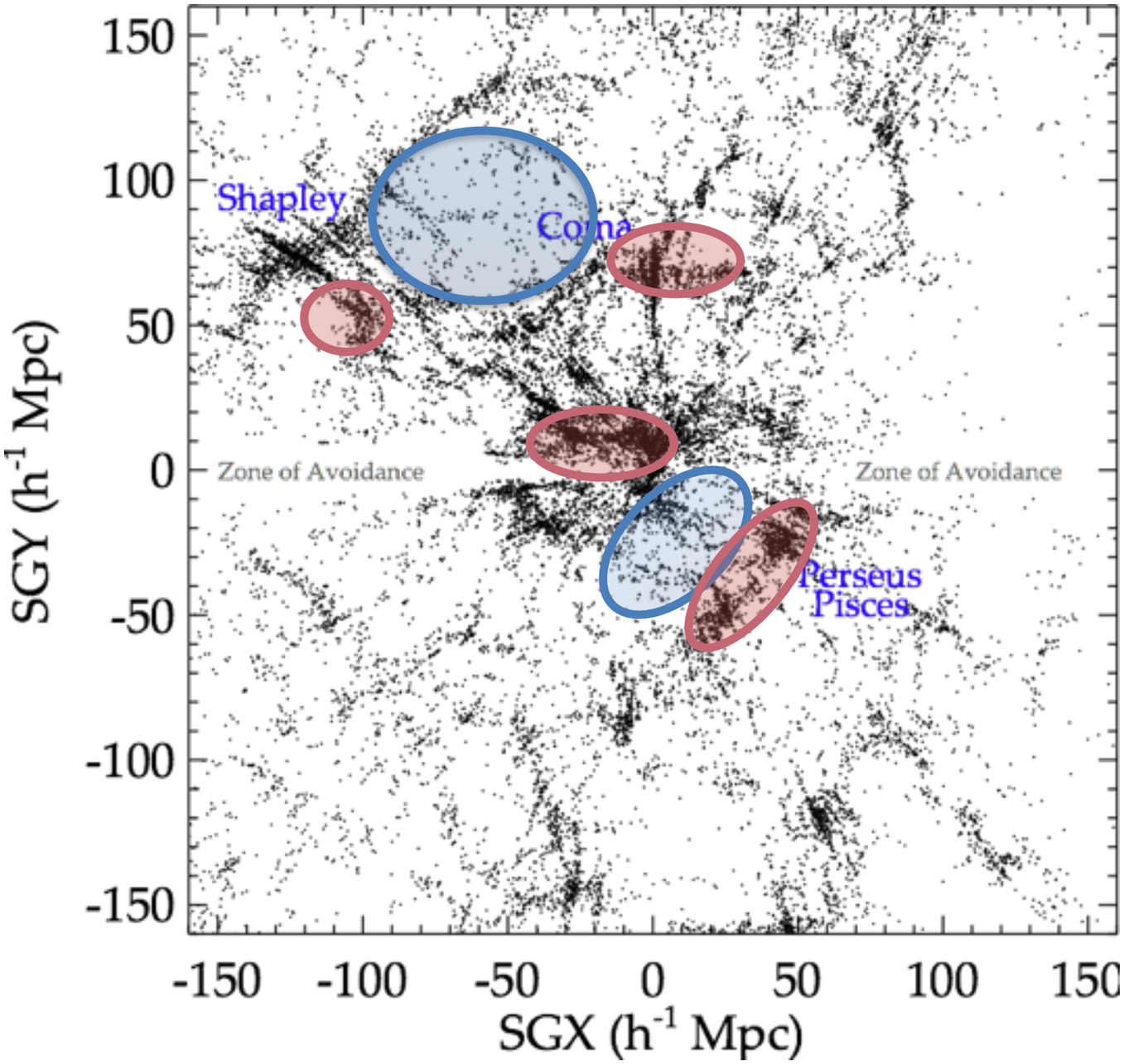

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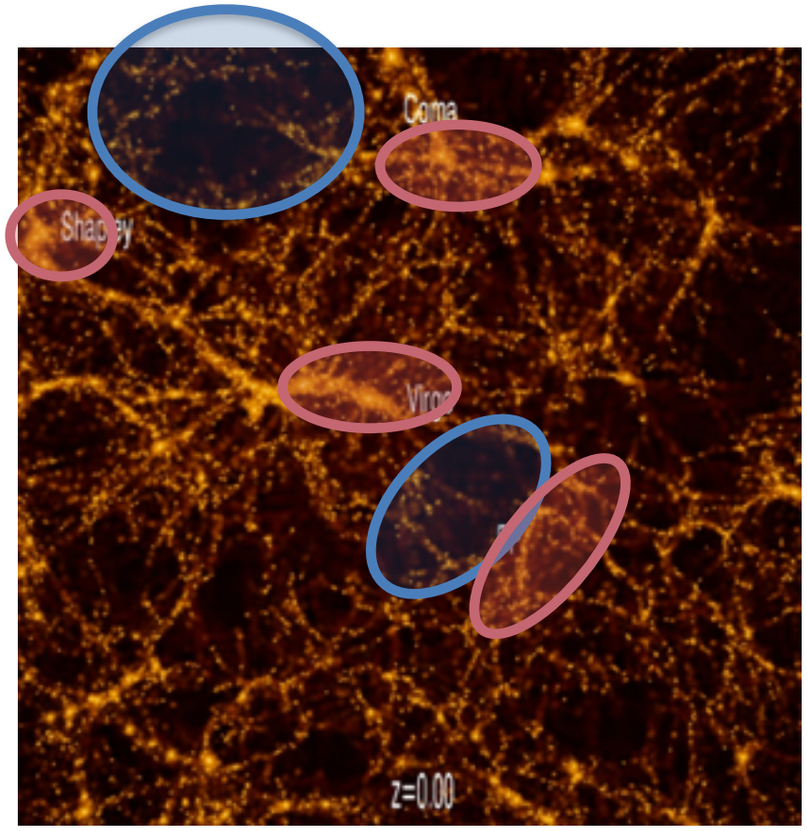
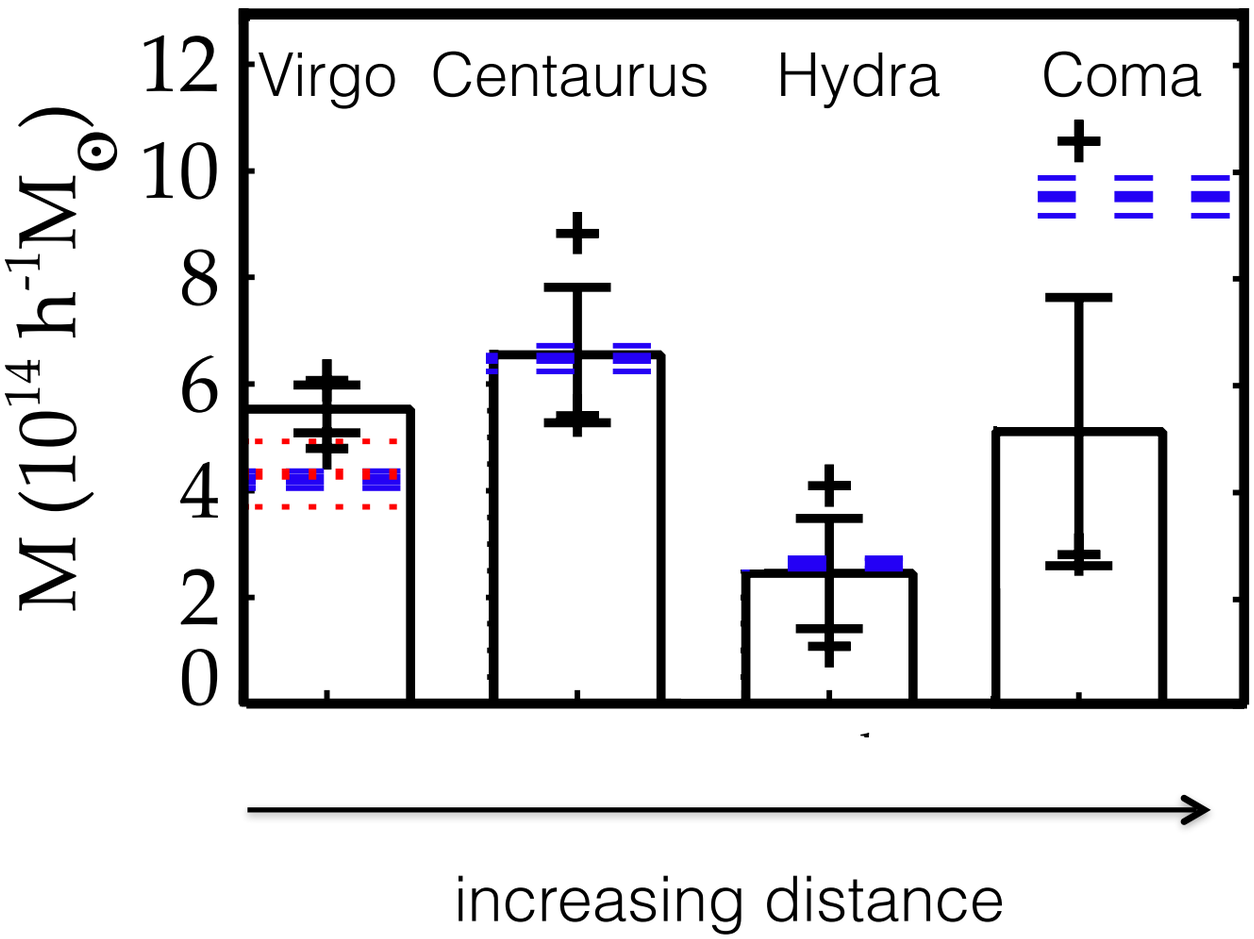


500 Mpc/h, 1024^3 particles,
DM only, Planck cosmology

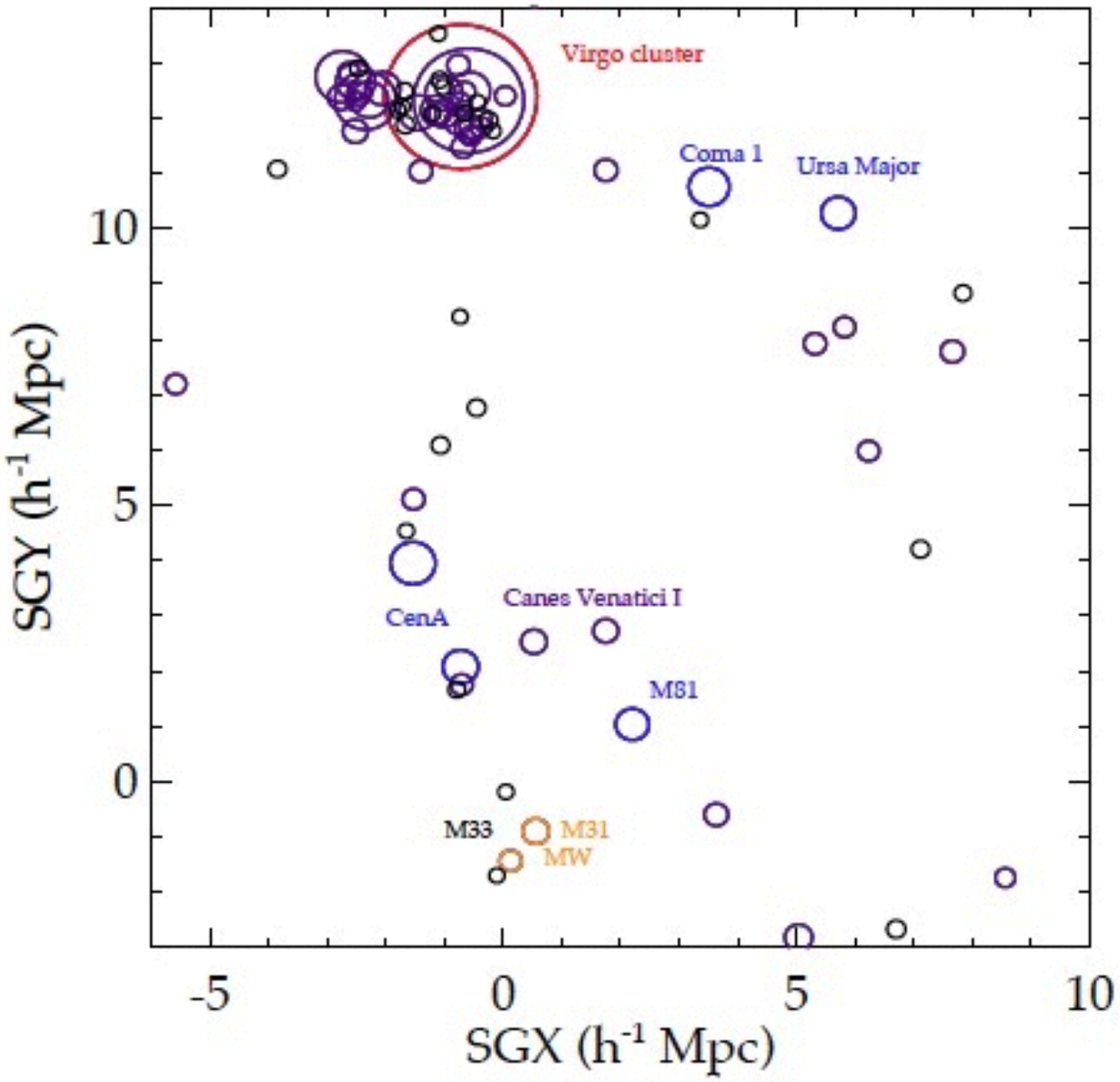
Results: the local clusters CLONES

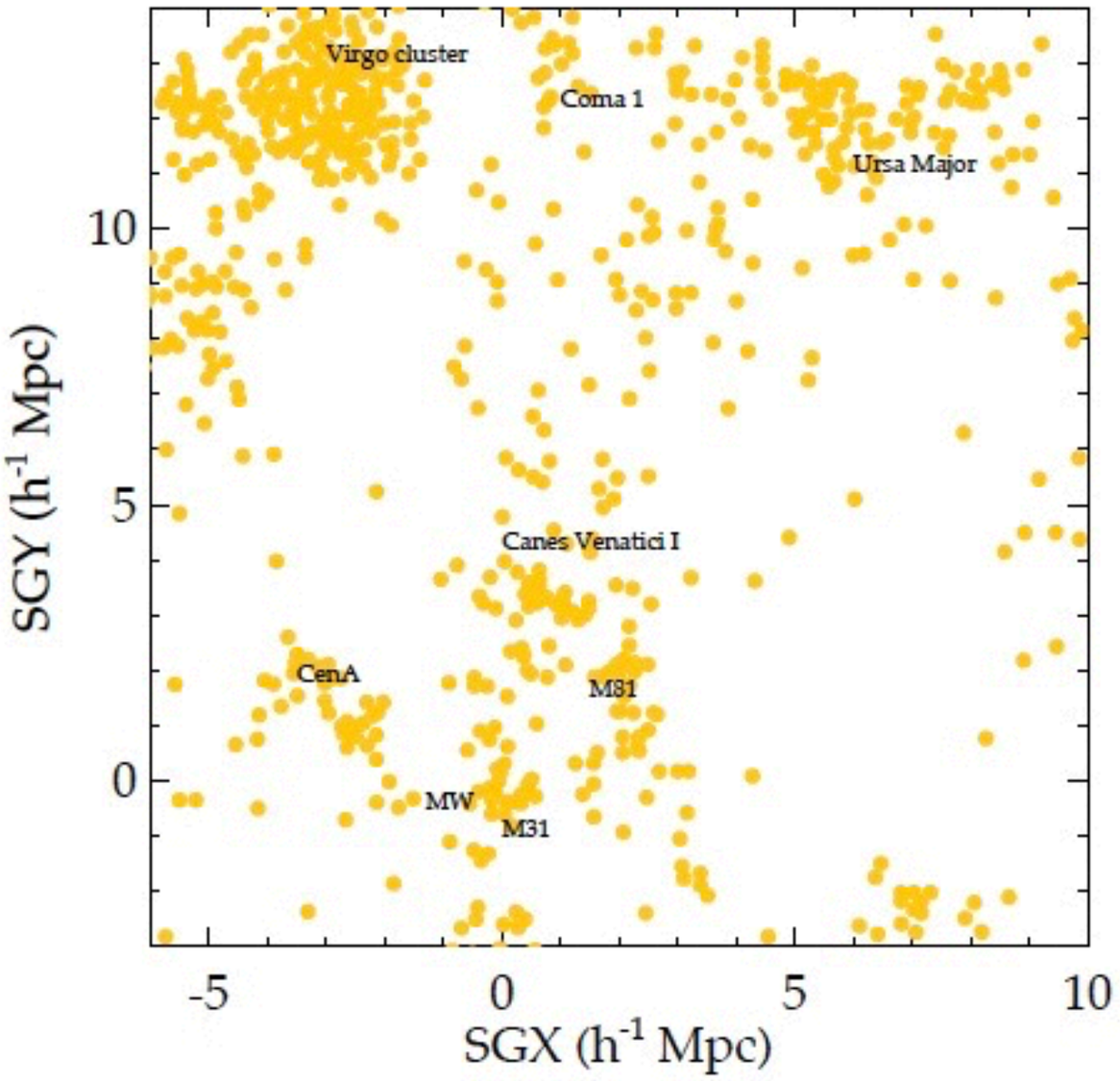
z=0, cluster scale Sorce 2018

Dark matter halos = counterparts of observed local clusters



Results: the *inner* local Universe CLONE ➤ z=0

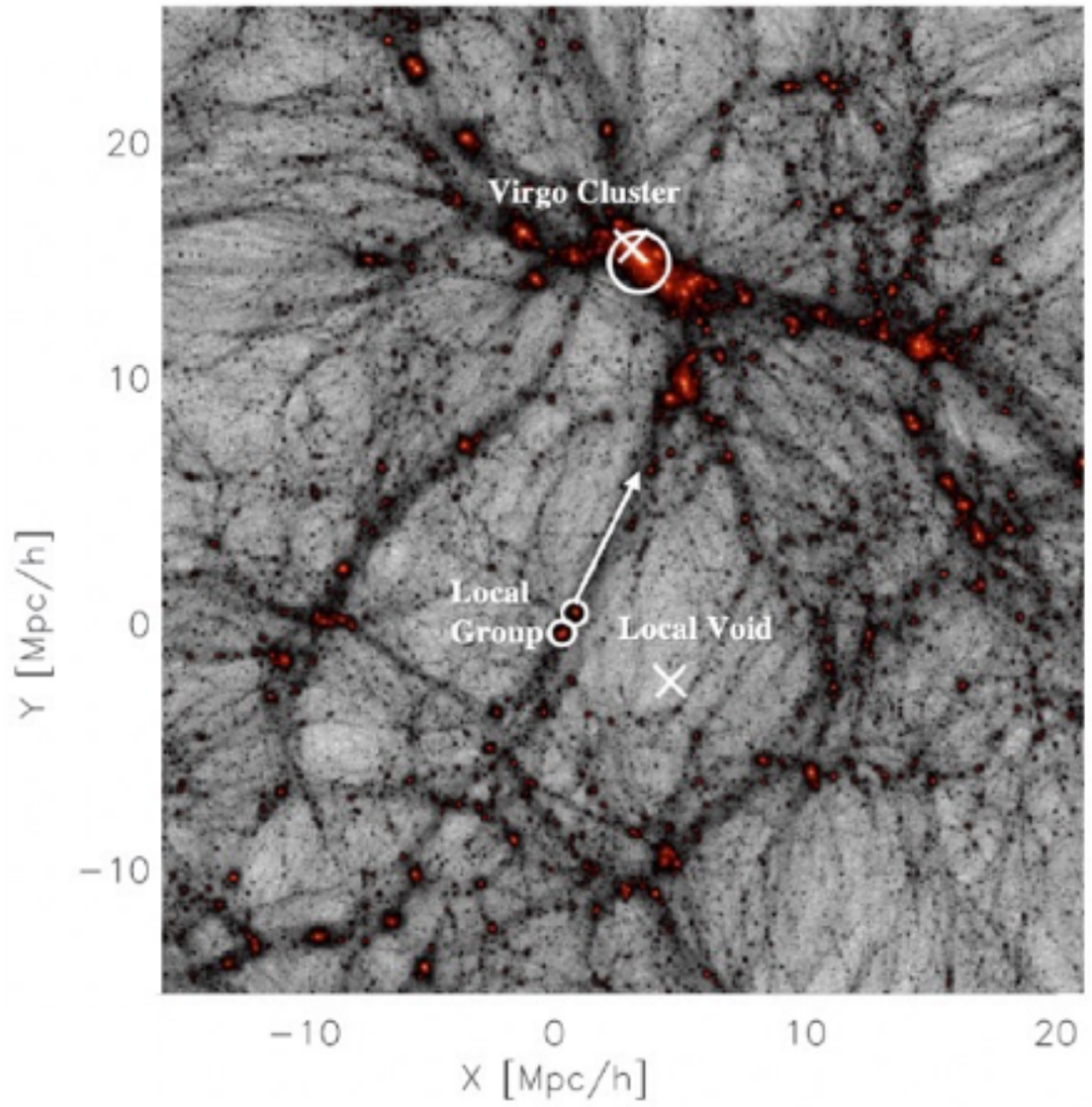




64 Mpc/h, 2048^3 particles, DM only, Planck cosmology

Ocvirk, Aubert, Sorce + 2020

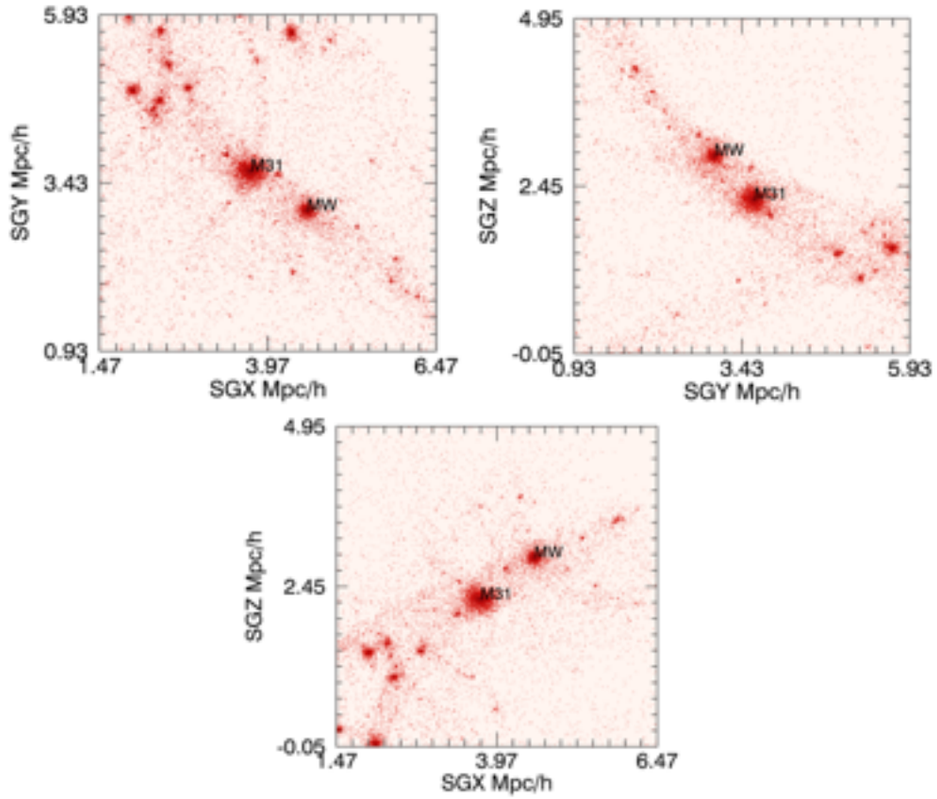
Results: the Local Group CLONES = HESTIA z=0, group scale



100 Mpc/h, 4096^3 particles effective (5 Mpc/h zoom), hydrodynamical, 340 pc, Planck cosmology

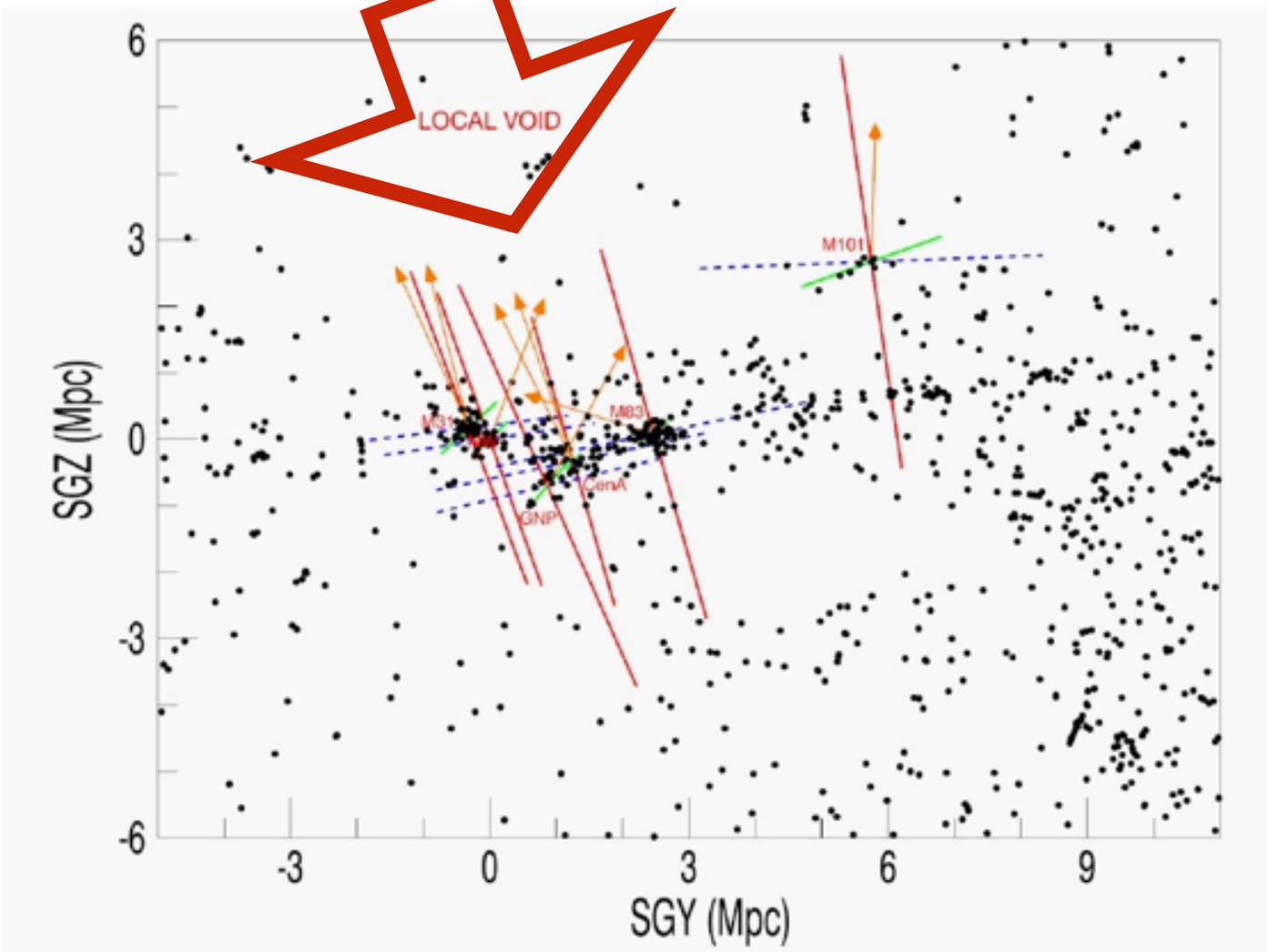
Carlesi,Sorce+2016
Carlesi,Hoffman,Sorce+2016
Libeskind+(including Sorce)2020

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



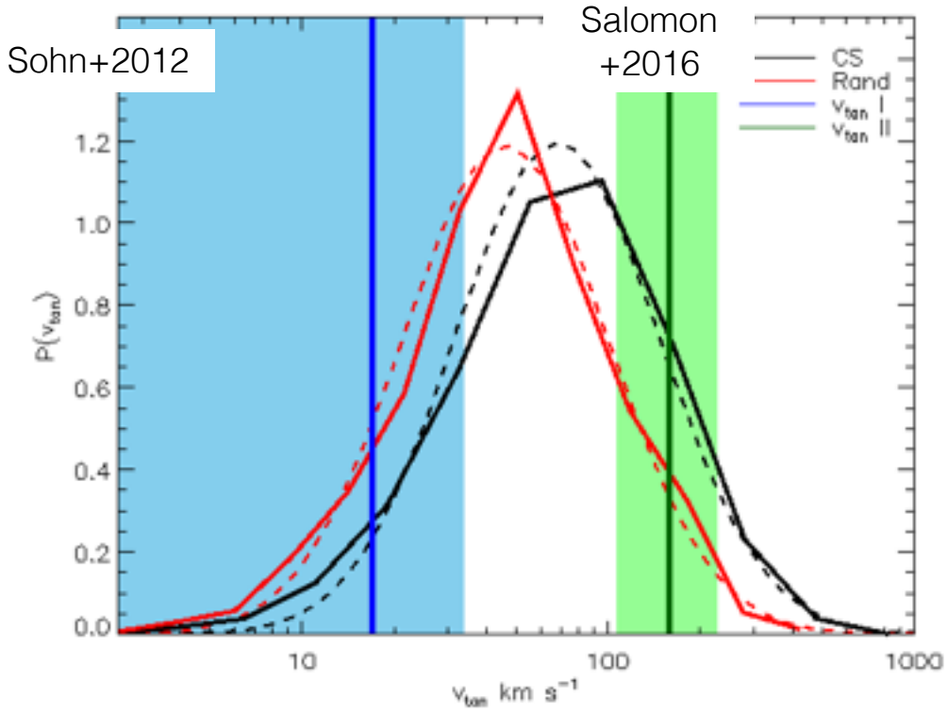
100 Mpc/h, 512^3 particles effective (5 Mpc/h zoom), DM only, Planck cosmology

Applications: the Local Group CLONES



normal of planes of satellites aligned with the direction of greater compression

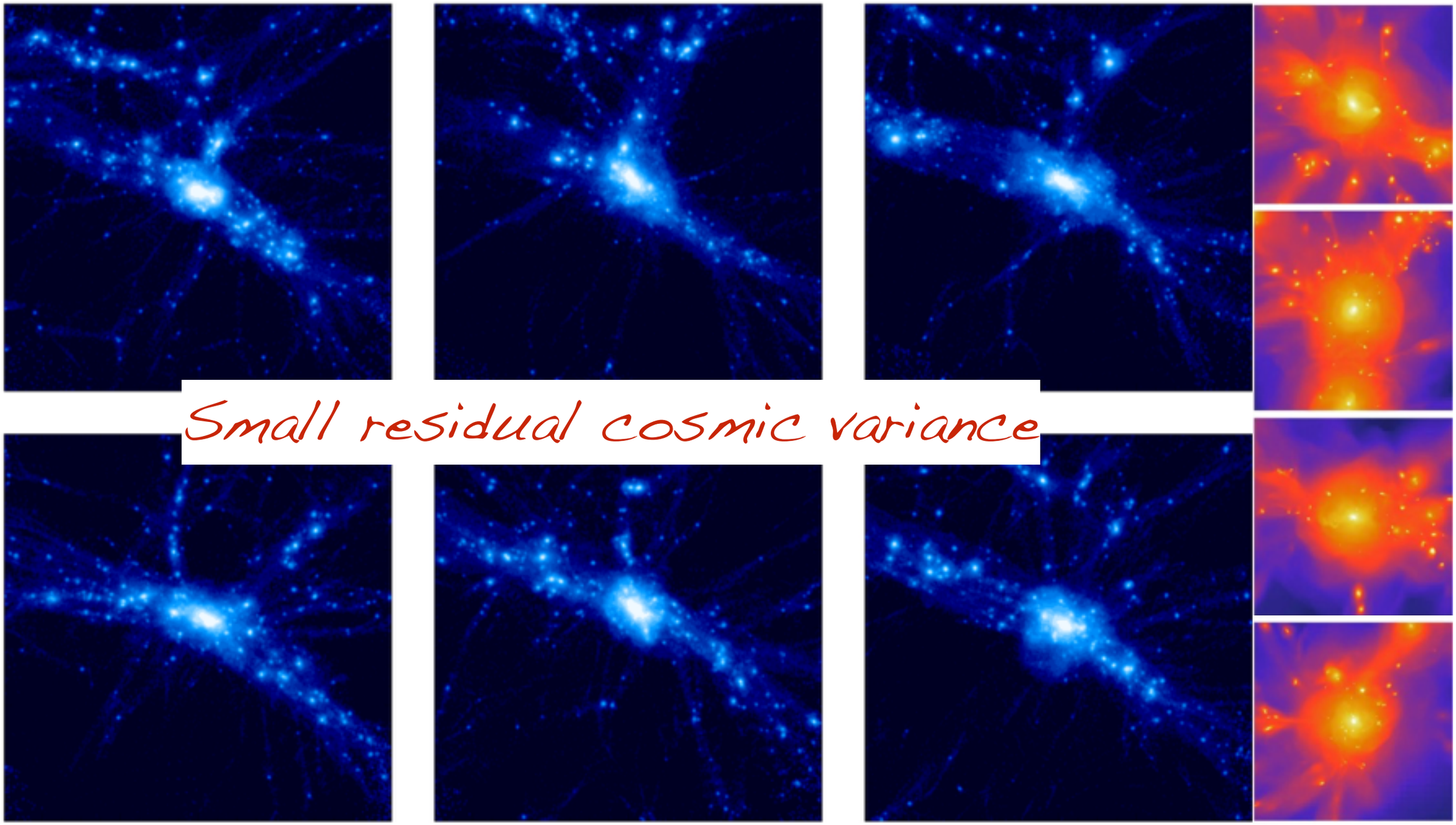
in favor of a higher tangential velocity for M31



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

Applications: the Virgo cluster CLONE

Simulated Virgo & Random clusters



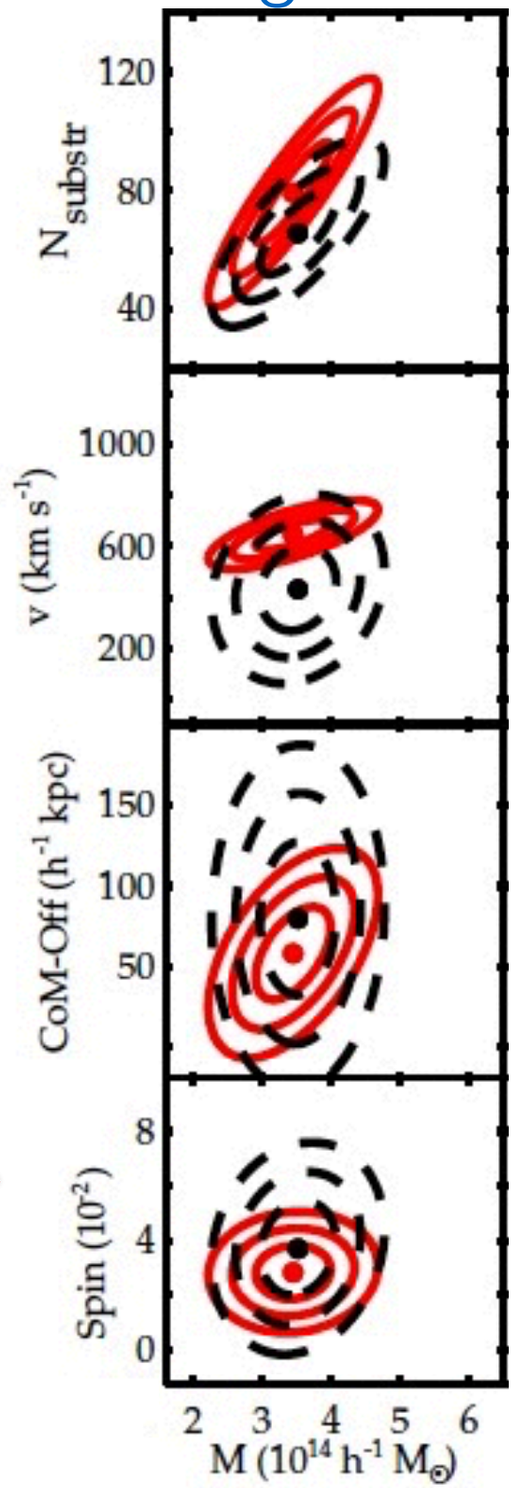
Small residual cosmic variance

Rhapsody (Hahn +2017)

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

Applications: the Virgo cluster CLONE

Simulated Virgo & Random clusters



Number of substructures

Center of mass offset wrt spherical center

➞ History

Velocity

Spin

➞ Environment

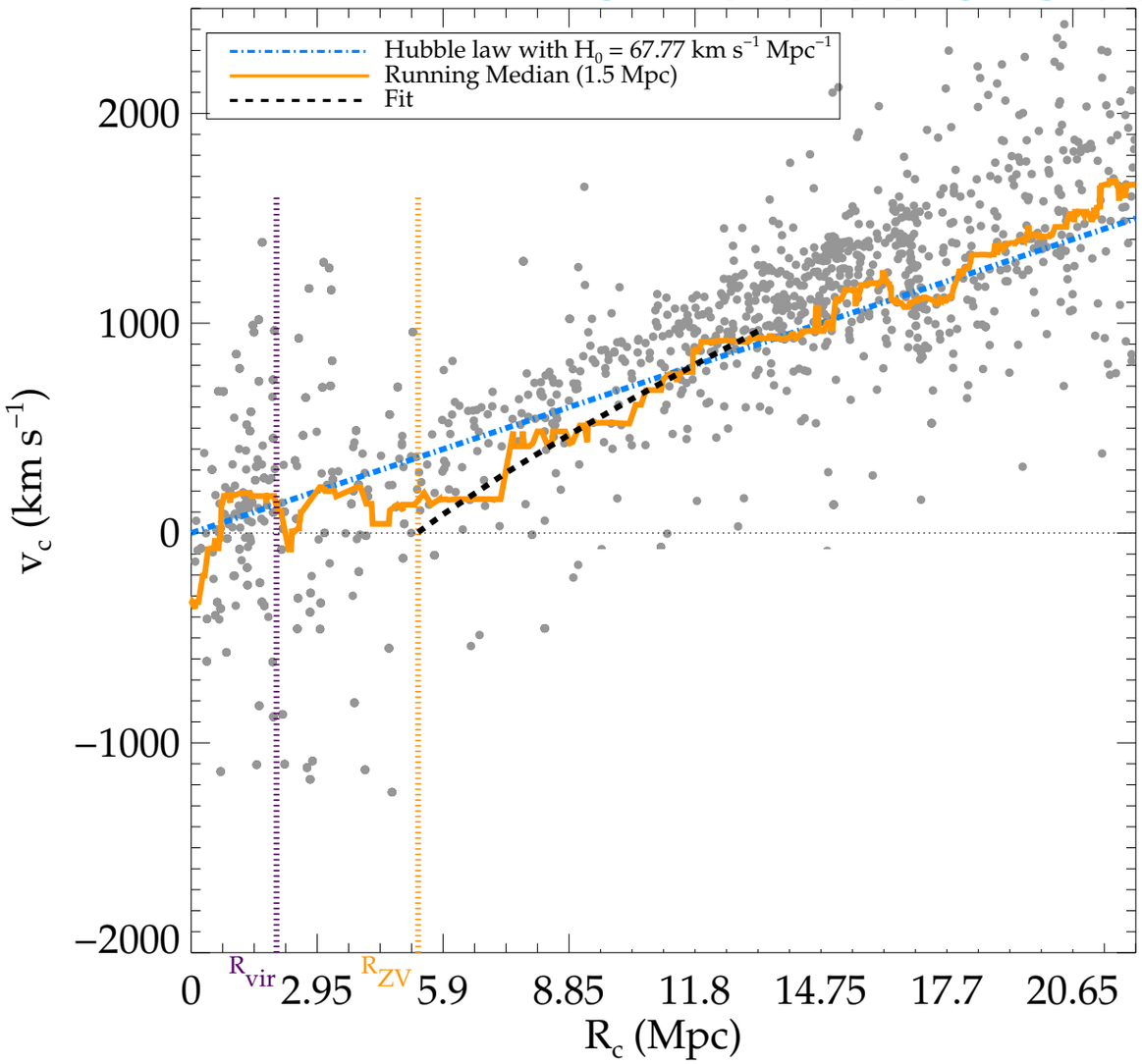
Sorce, Blaizot, Dubois 2019

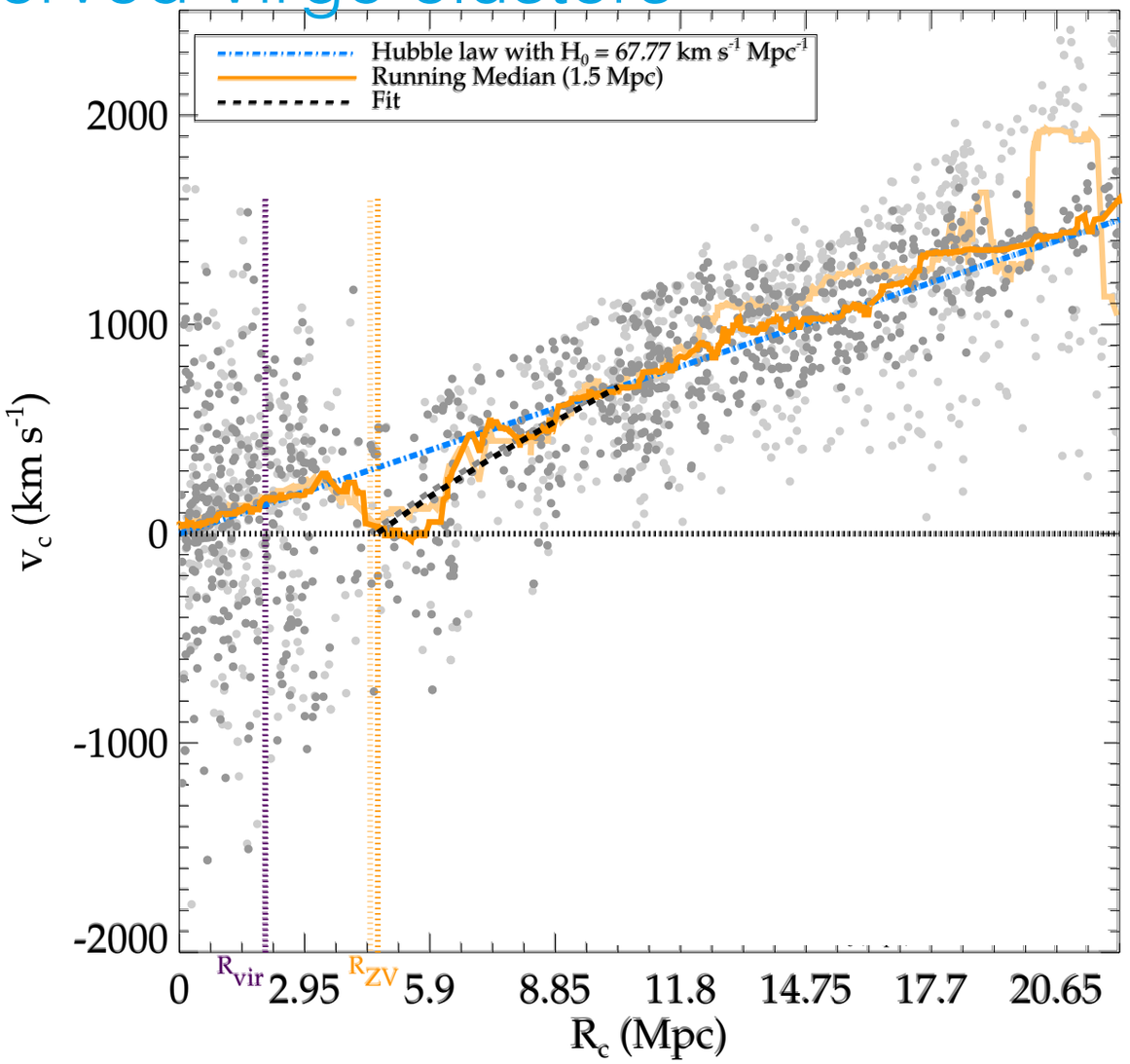
Different from an average random cluster

Applications: the Virgo cluster CLONE

Sorce+2021

Simulated & Observed Virgo clusters





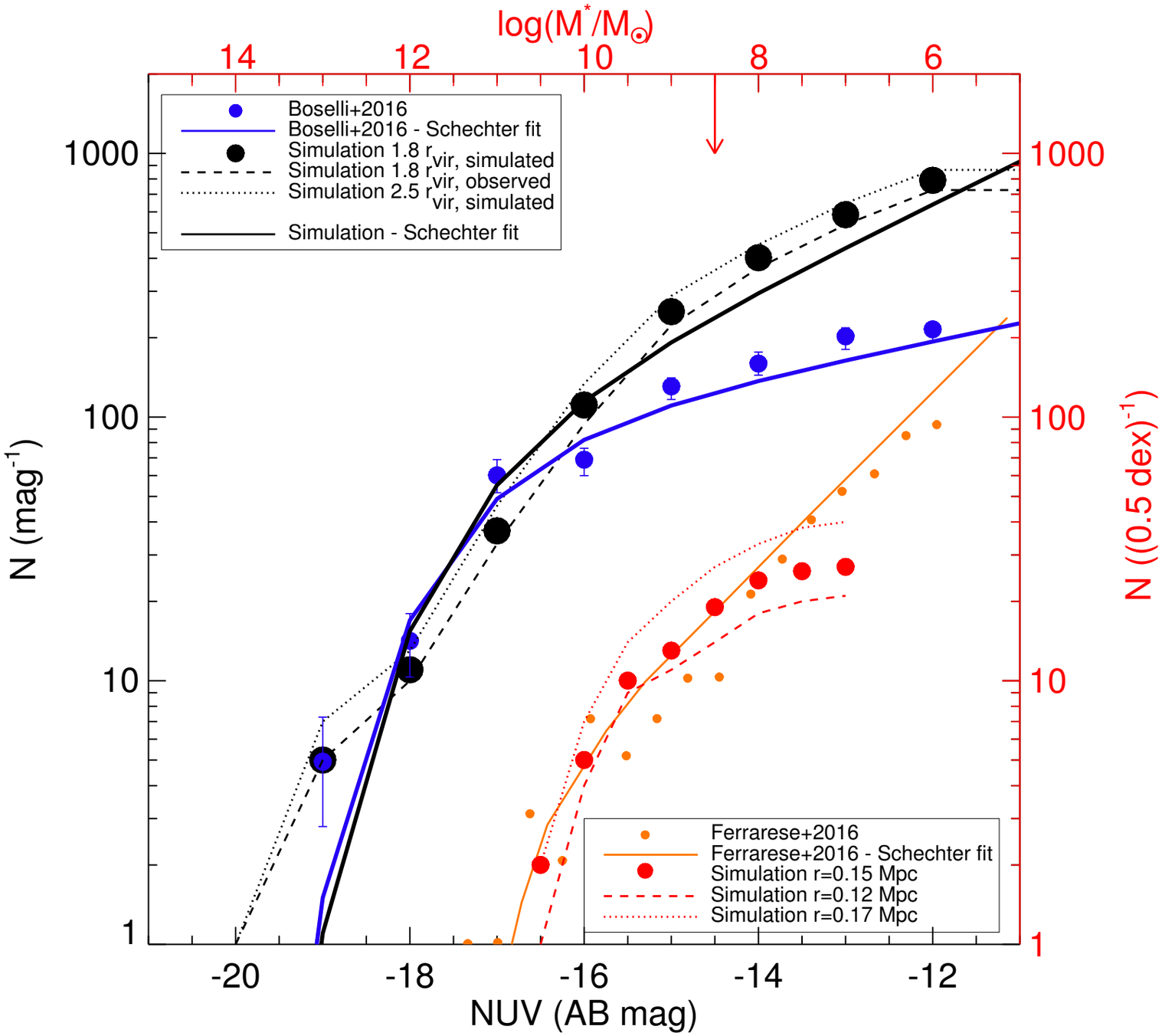
500 Mpc/h, 8192^3 particles effective (20 Mpc/h zoom), 0.24 kpc/h hydrodynamics: SN and AGN feedback, Planck cosmology

Overall agreement with observations

Applications: the Virgo cluster CLONE

Sorce+2021

Simulated & Observed Virgo clusters



Overall agreement with observations

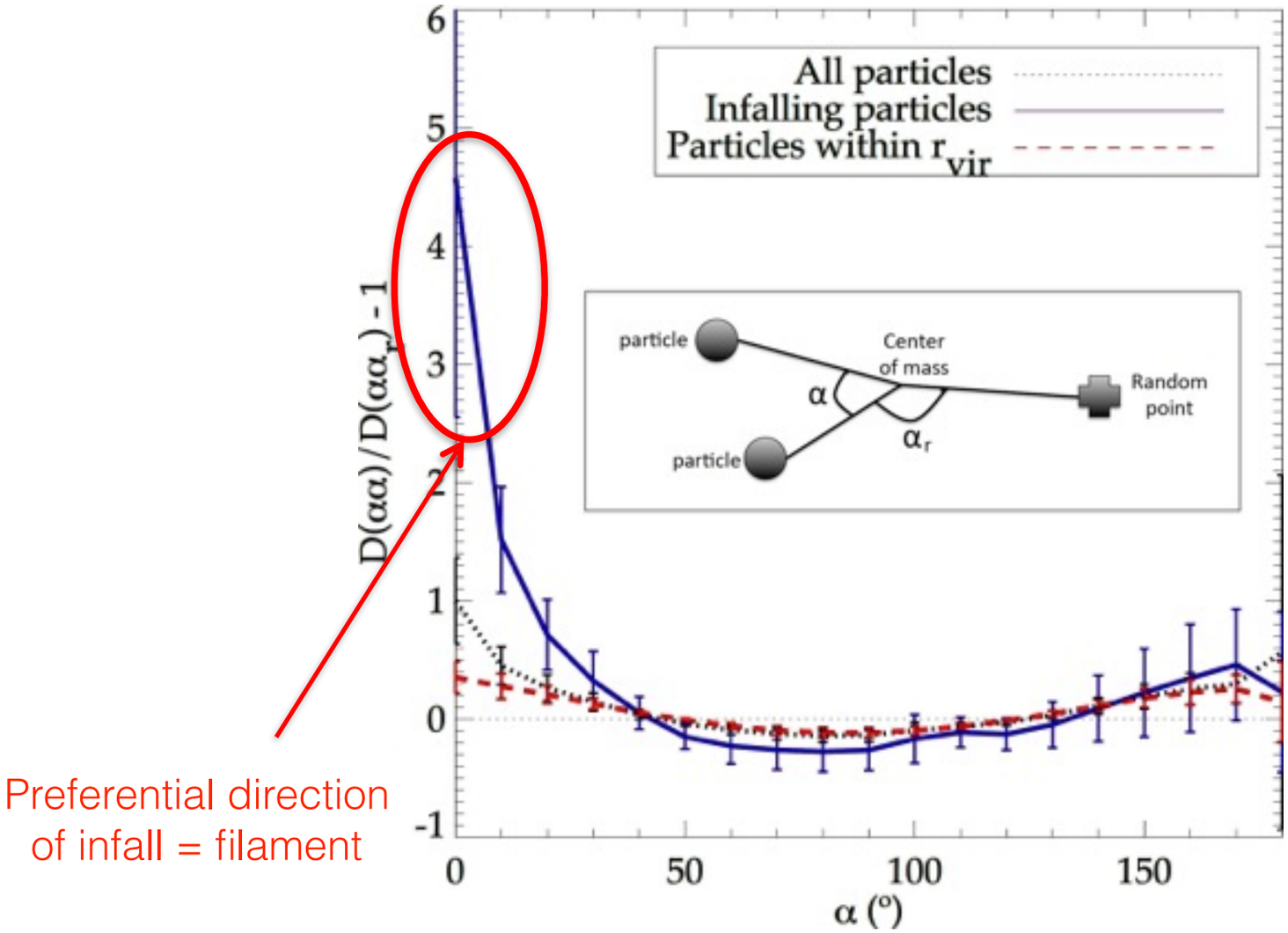
Applications: the Virgo cluster CLONE

Sorce+2016

Simulated & Observed Virgo clusters

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

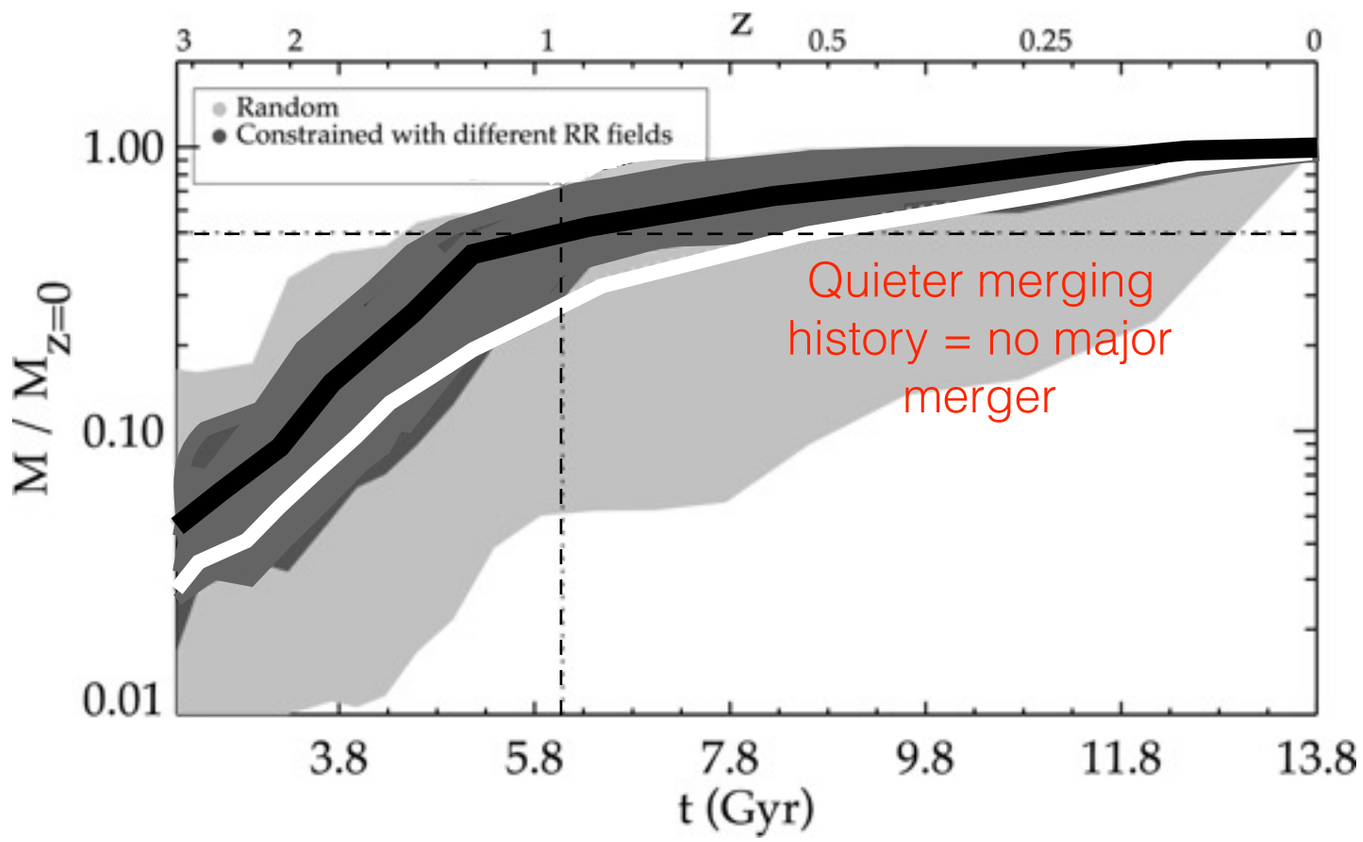
Applications: the Virgo cluster CLONE

Sorce+2016

Simulated & Observed Virgo clusters

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

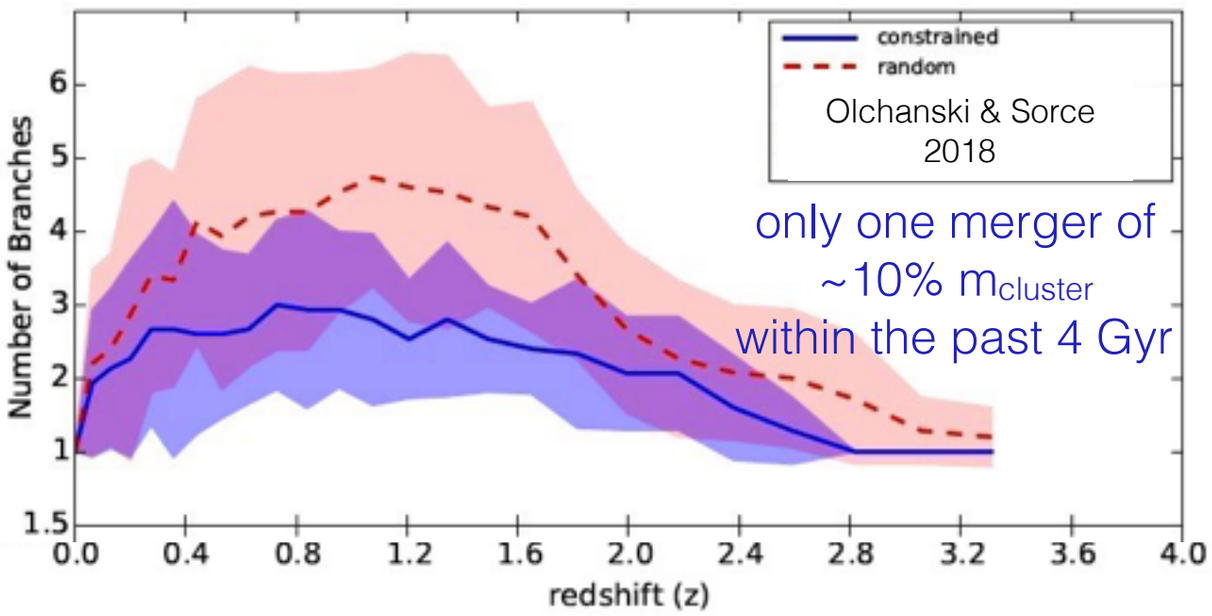
Agreement with observational predictions

Applications: the Virgo cluster CLONE

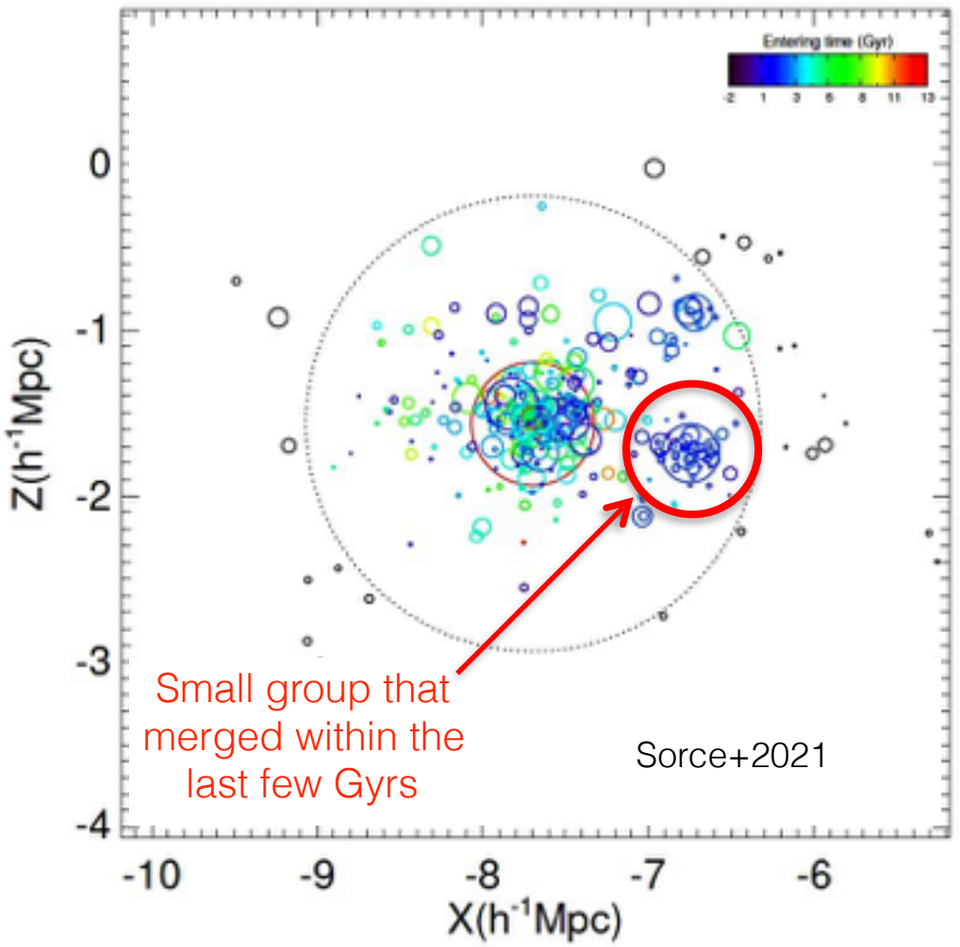
Simulated & Observed Virgo clusters

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

From simulation



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

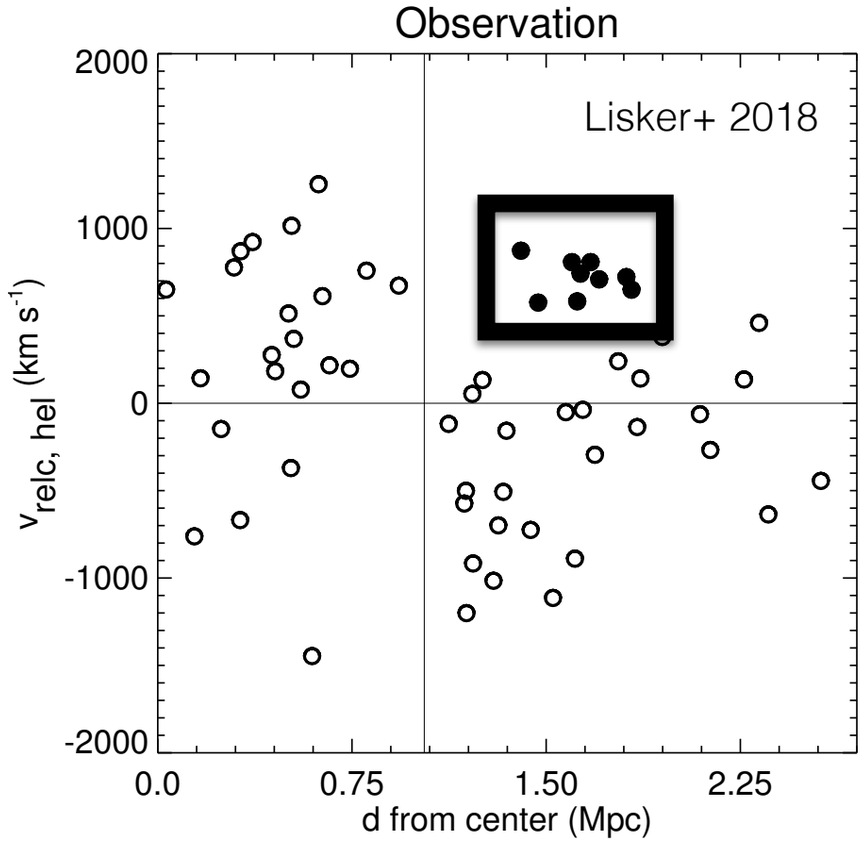


500 Mpc/h, 8192^3 particles effective (20 Mpc/h zoom), 0.24 kpc/h - Hydrodynamics: SN and AGN feedback, Planck cosmology

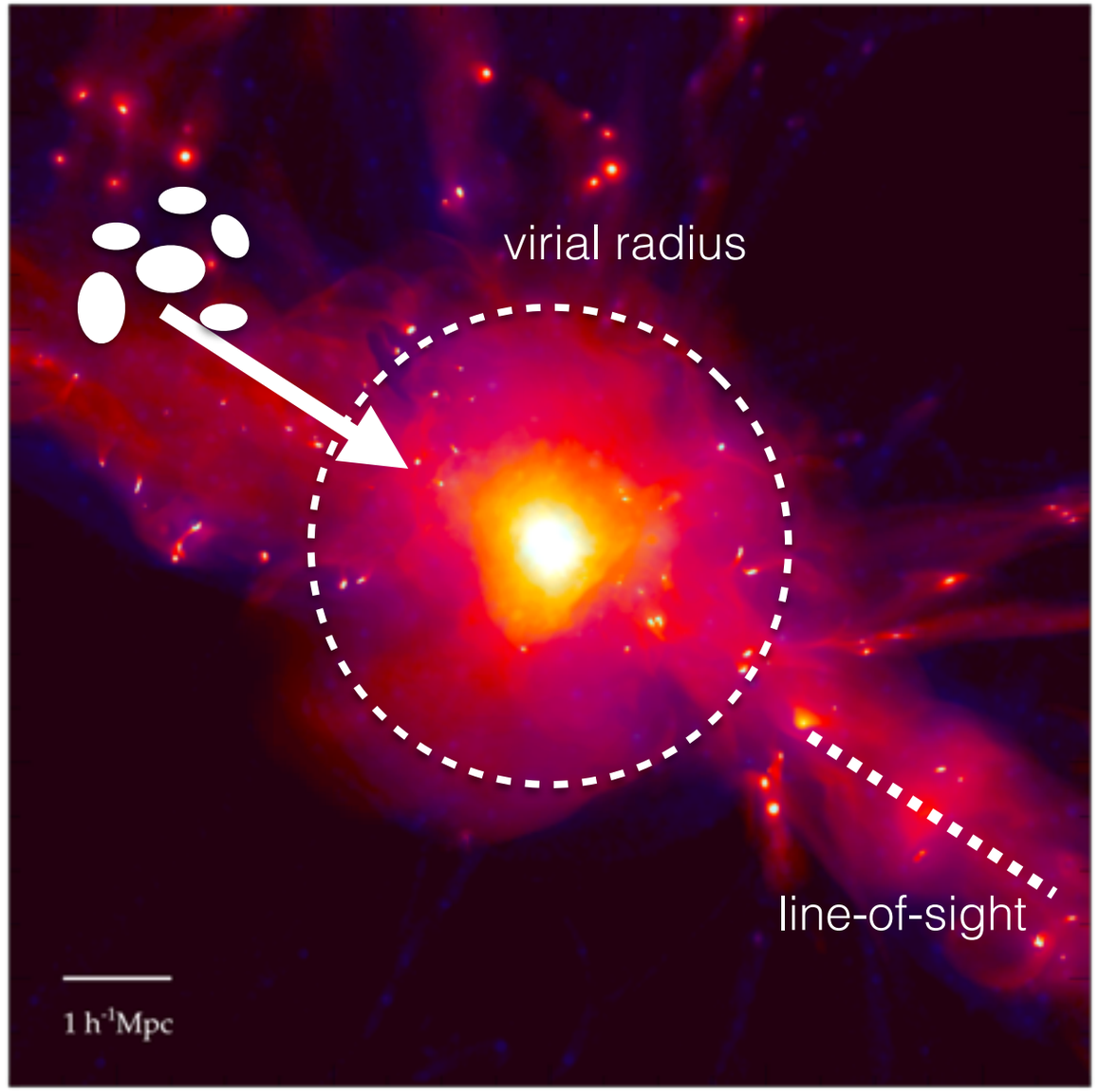
Agreement with observational predictions

Applications: the Virgo cluster CLONE

Simulated & Observed Virgo clusters

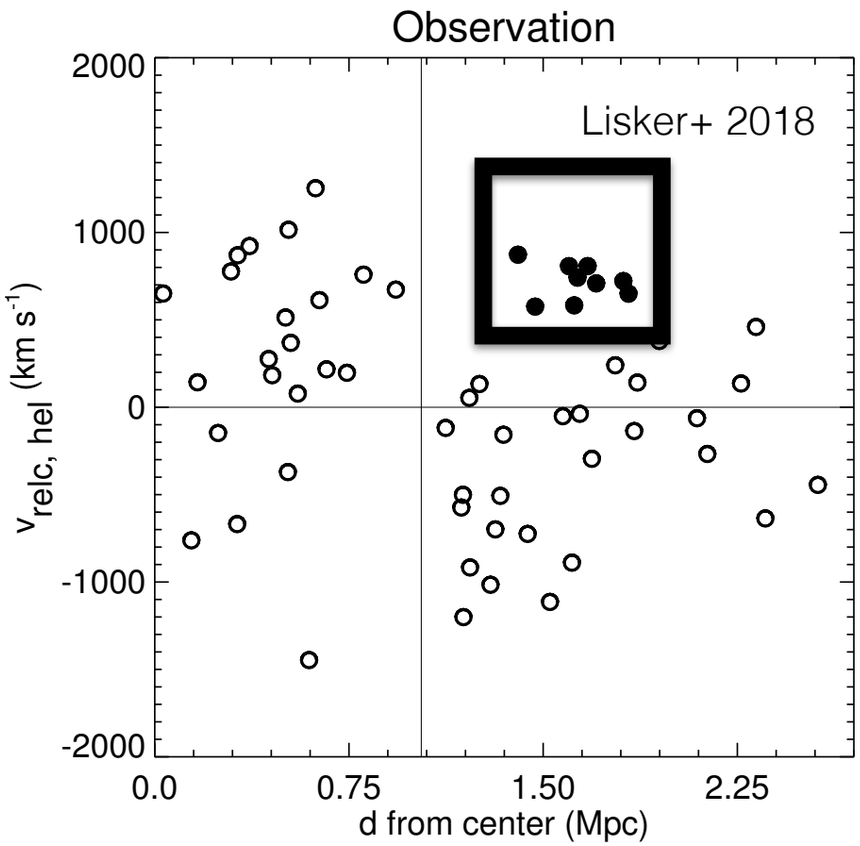


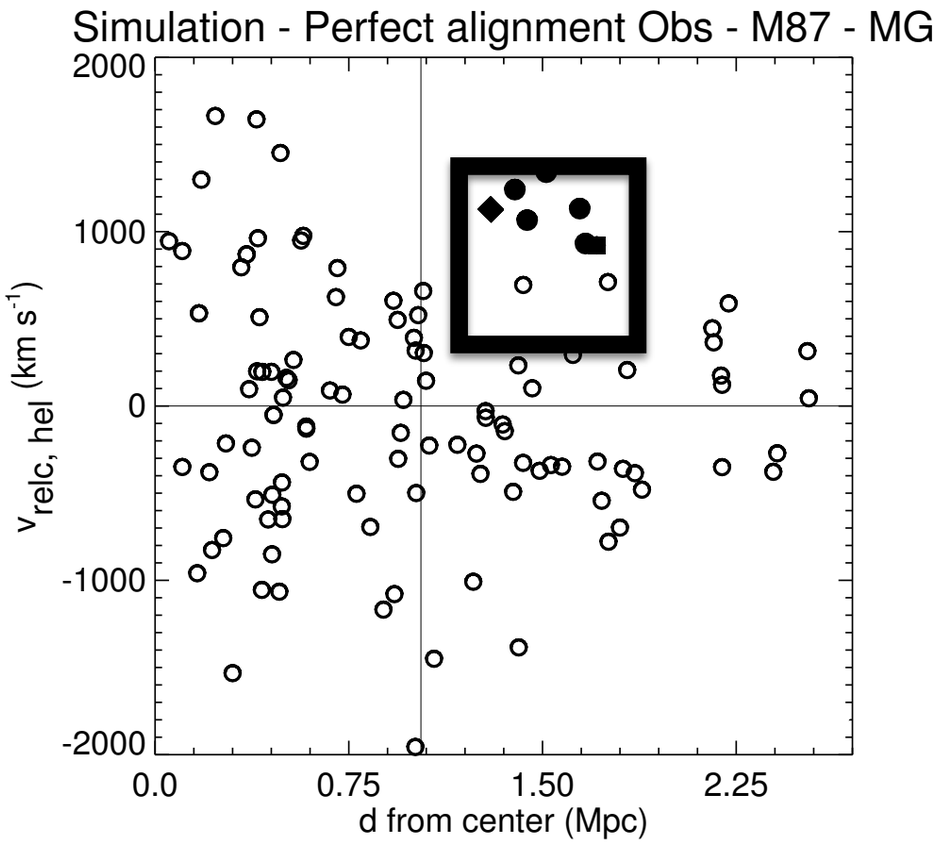
Group of galaxies that fell within the line-of-sight?



Applications: the Virgo cluster CLONE

Simulated & Observed Virgo clusters



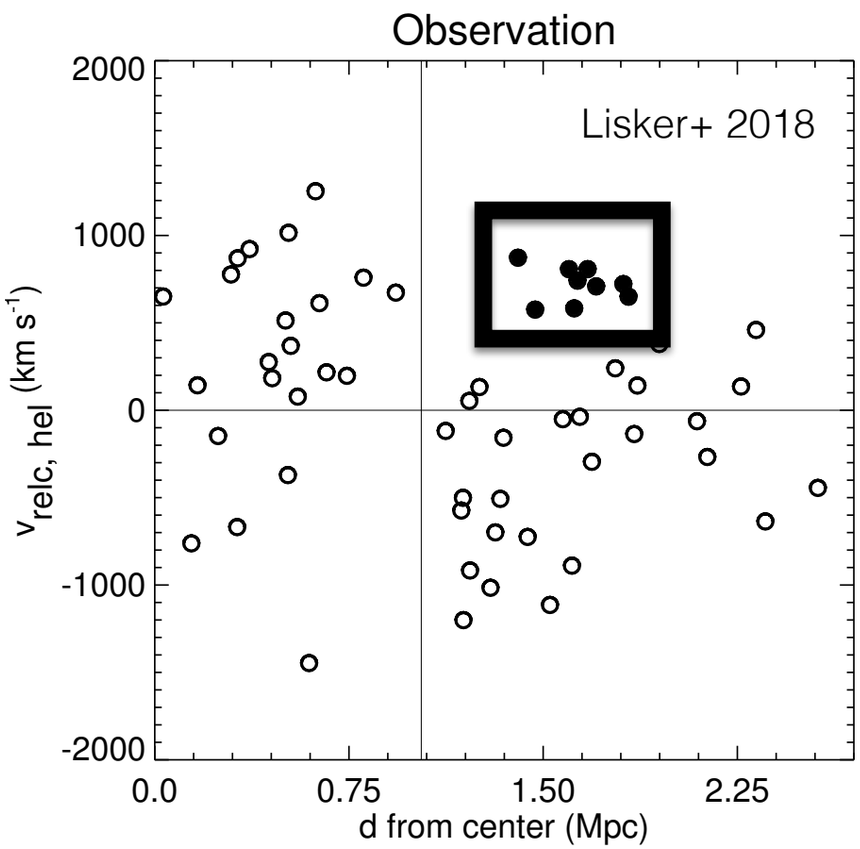


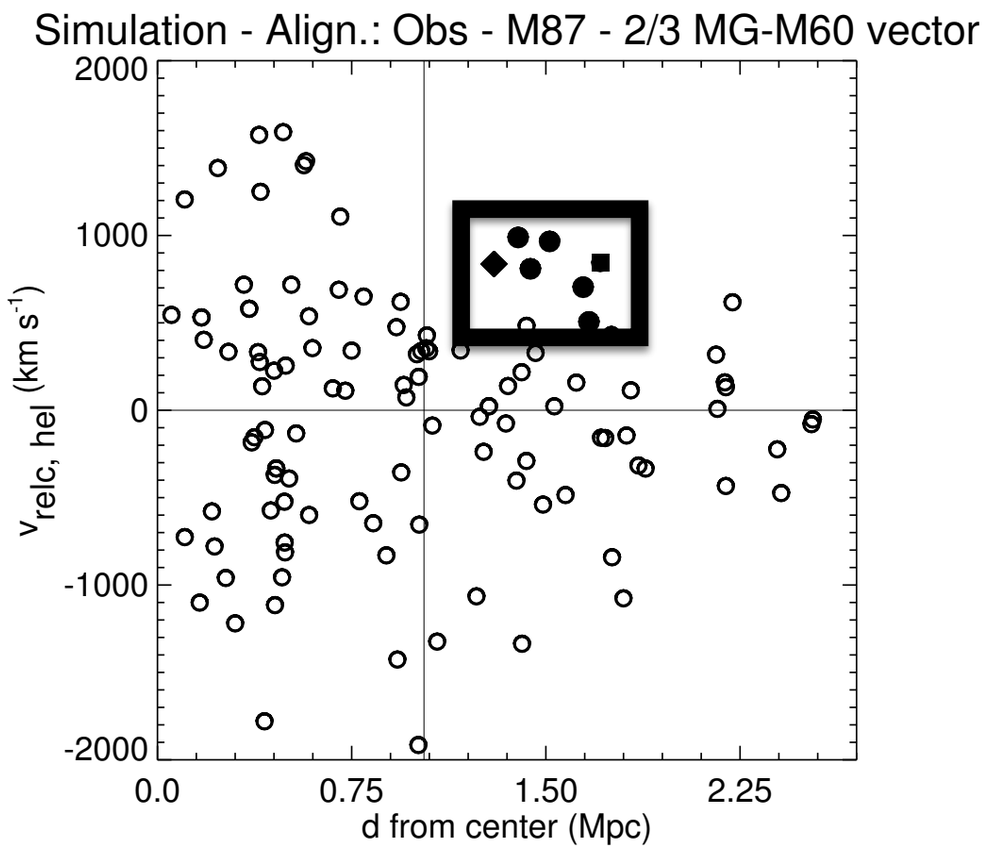
Group of galaxies that fell within the line-of-sight?

Sorce+2021

Applications: the Virgo cluster CLONE

Simulated & Observed Virgo clusters





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

Sorce+2021

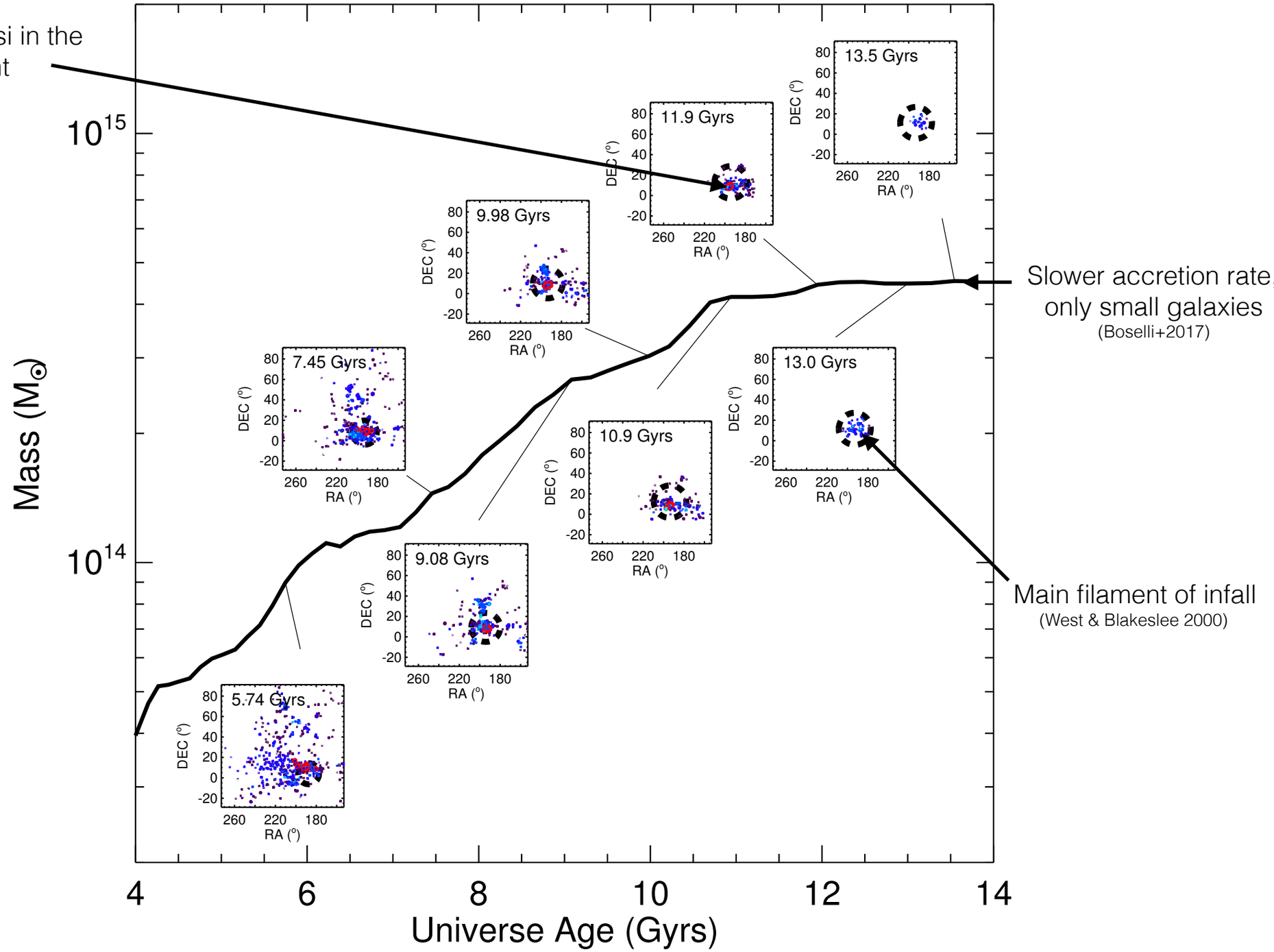
Agreement with observational predictions

Applications: the Virgo cluster CLONE

Sorce+2021

Simulated & Observed Virgo clusters

Small group quasi in the line of sight
(Lisker+2018)



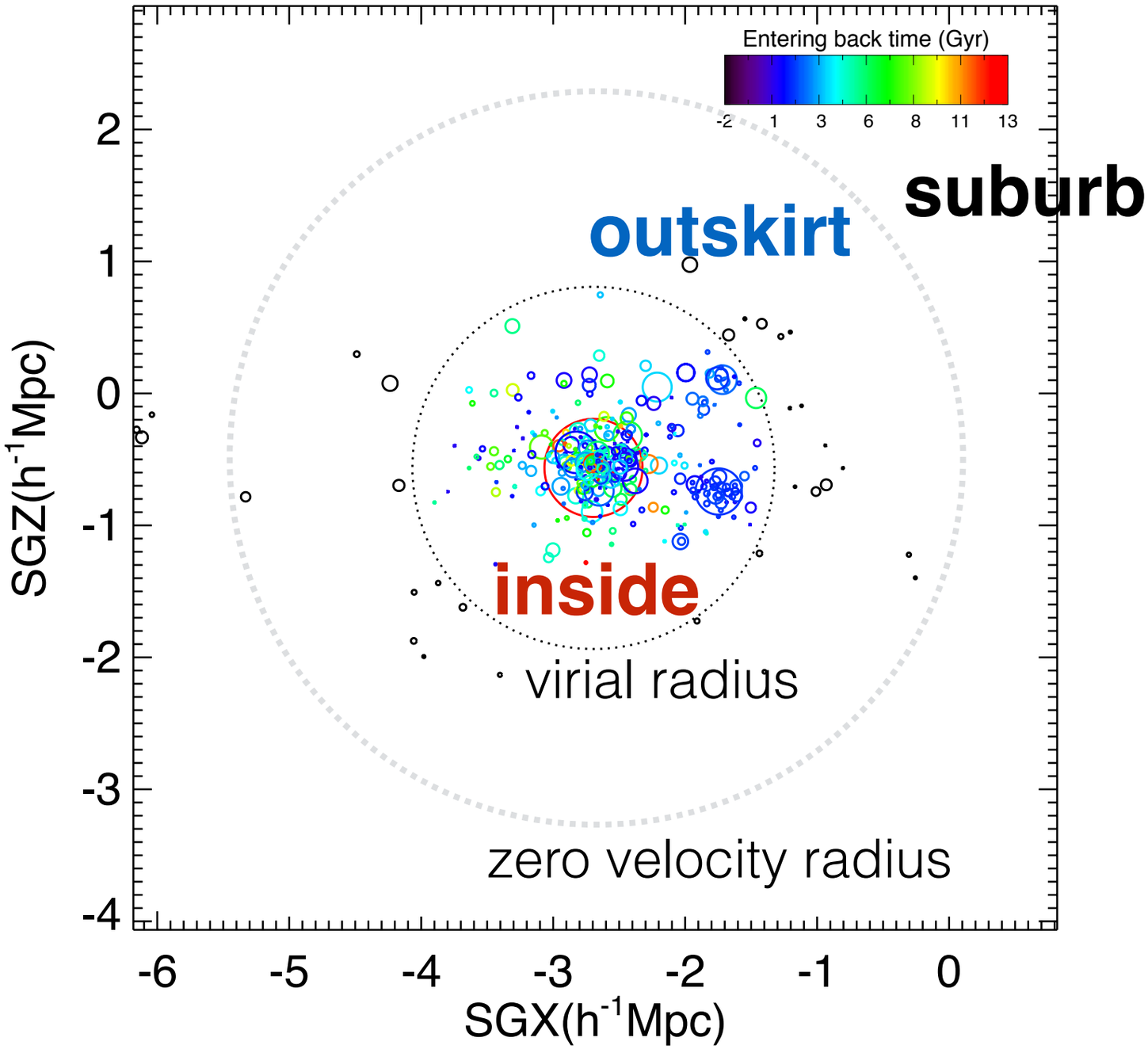
Slower accretion rate, only small galaxies
(Boselli+2017)

Main filament of infall
(West & Blakeslee 2000)

Agreement with observational predictions

Applications: the Virgo cluster CLONE

Definitions of galaxy populations in a cluster environment

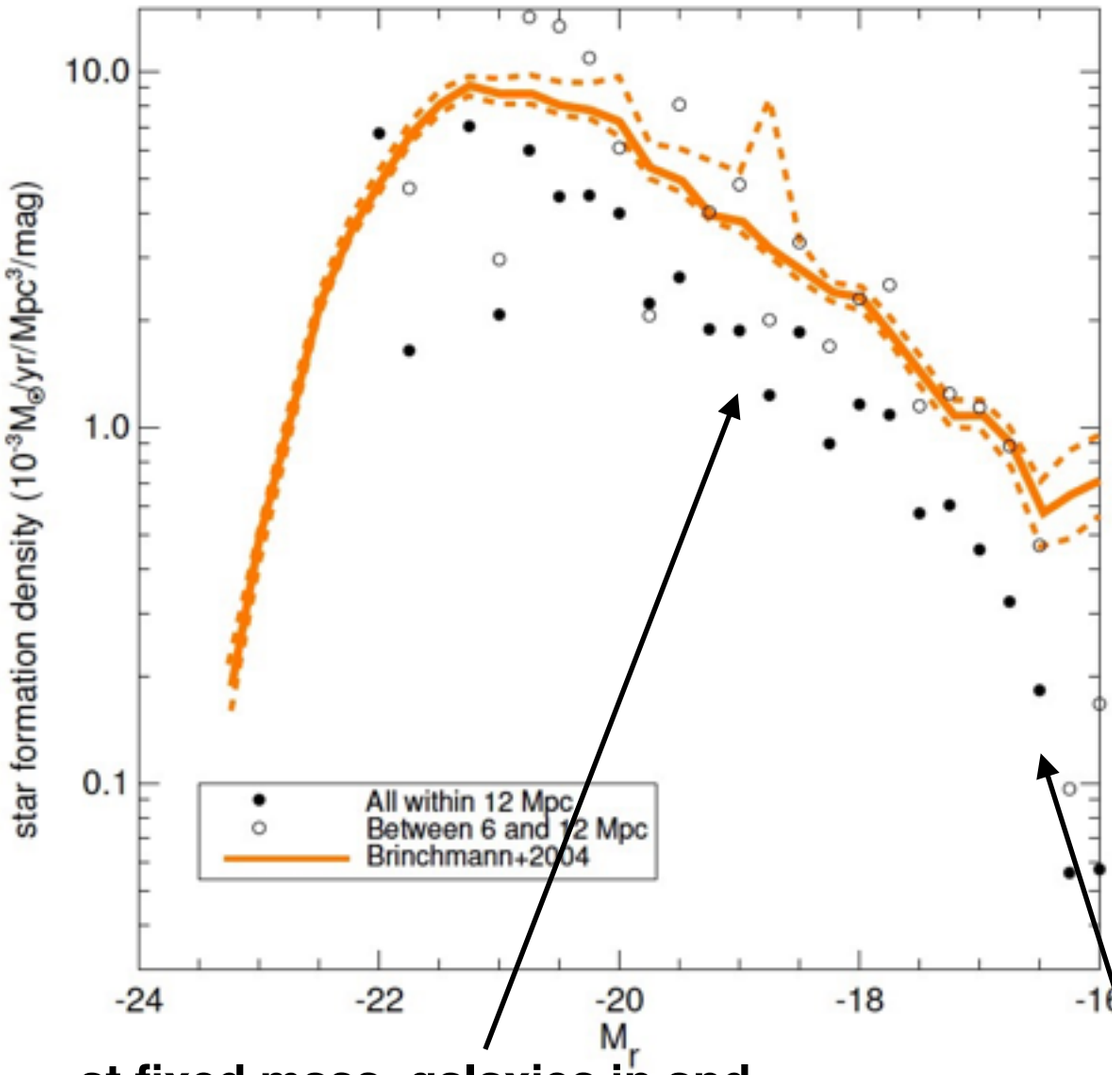


Applications: the Virgo cluster CLONE

Preliminary

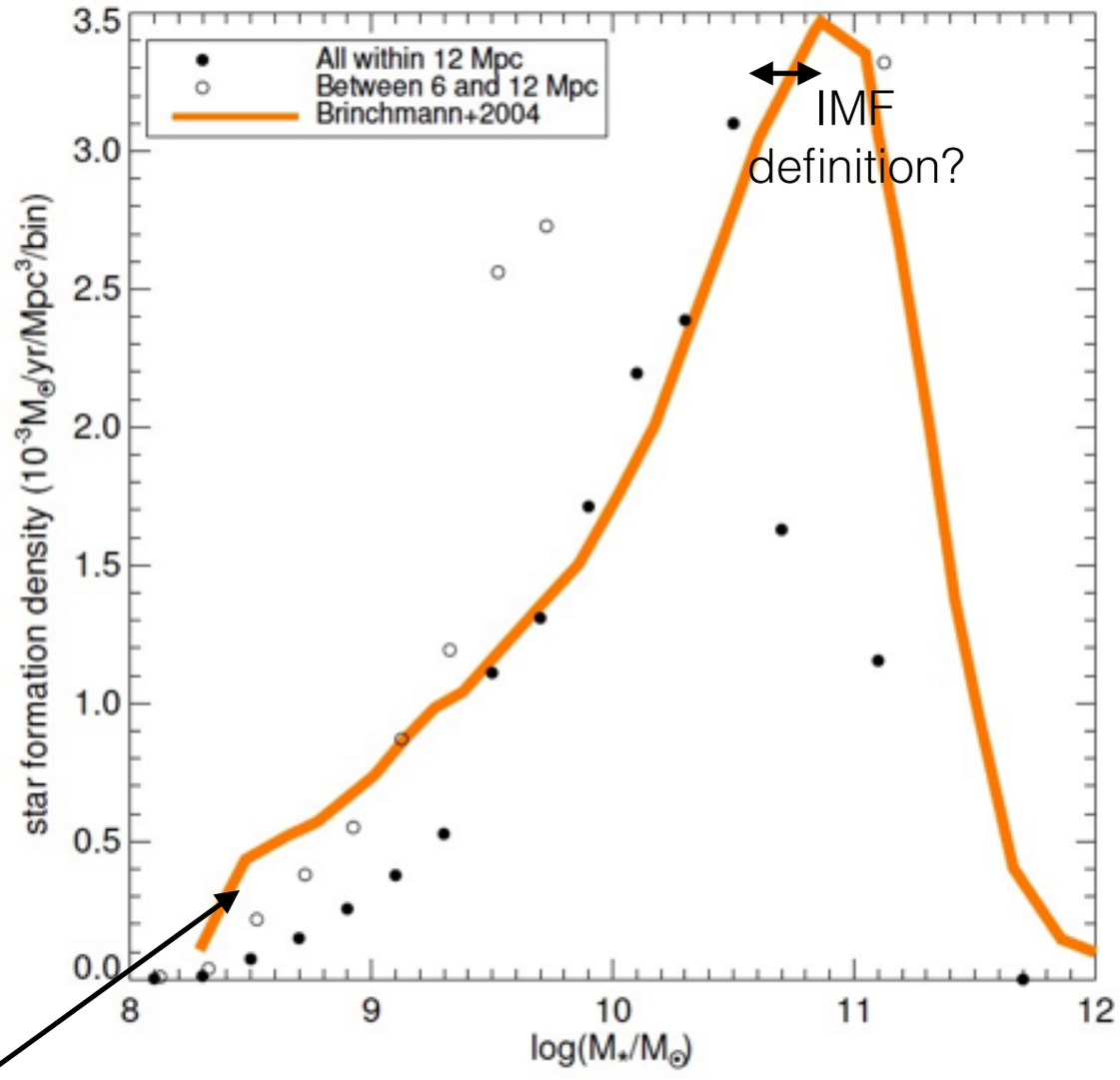
Simulated Virgo & Observed galaxies

Star formation density: field vs. cluster



at fixed mass, galaxies in and around clusters 1) form less / no stars, ~~2) are less numerous~~

Sorce+ in prep.



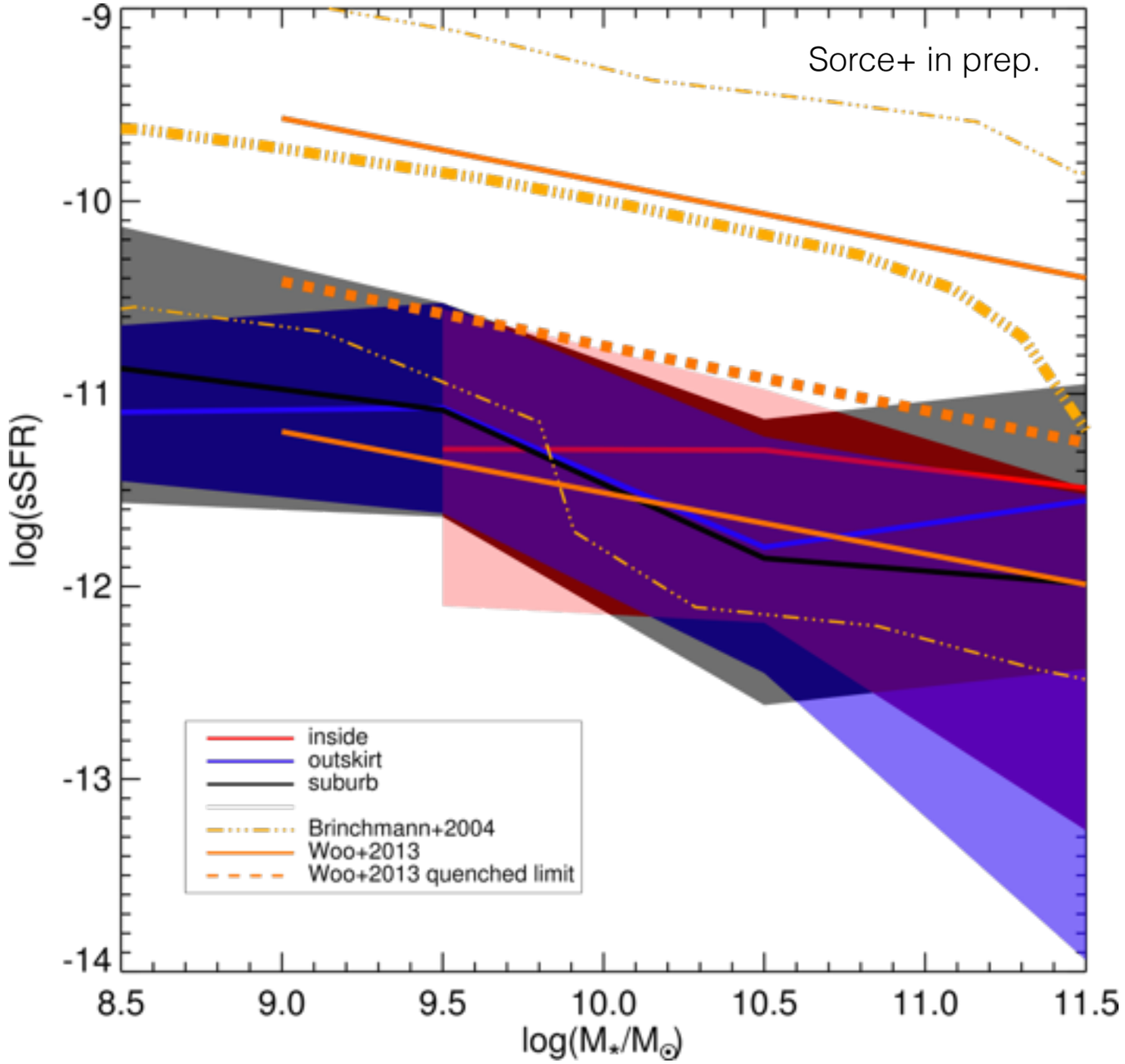
resolution limit + low mass galaxies in clusters 1) more likely to be quenched, ~~2) less numerous~~?

Applications: the Virgo cluster CLONE

Preliminary

Simulated Virgo & Observed galaxies

specific Star Formation Rate: field vs. cluster



At fixed stellar mass, galaxies in clusters **form less stars**

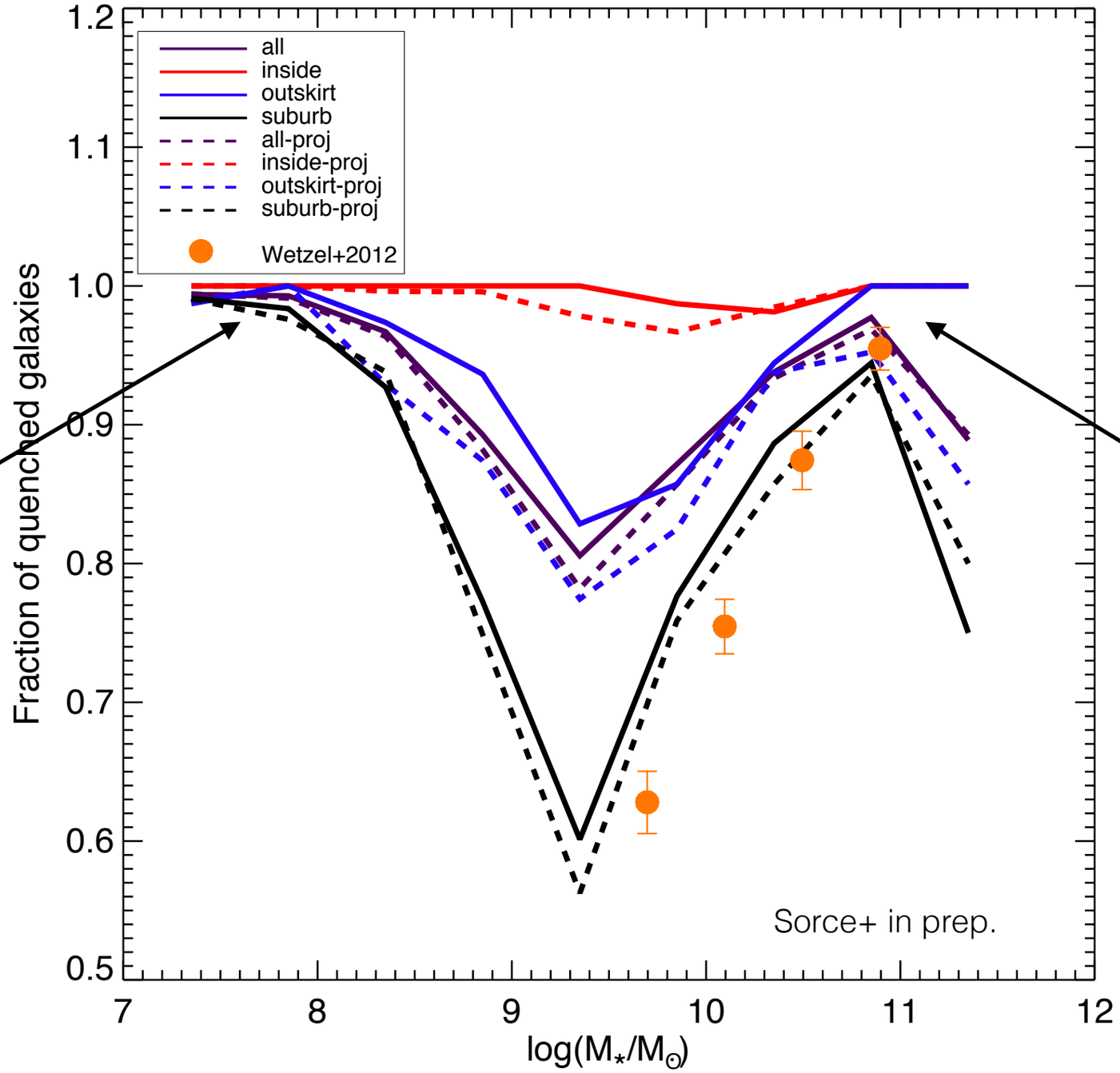
Applications: the Virgo cluster CLONE

Preliminary

Simulated Virgo & Observed galaxies

Likeliness to be quenched depends on stellar mass and distance to the cluster

the smallest galaxies are ‘pre-processed’



the largest galaxies need to get close to the cluster center

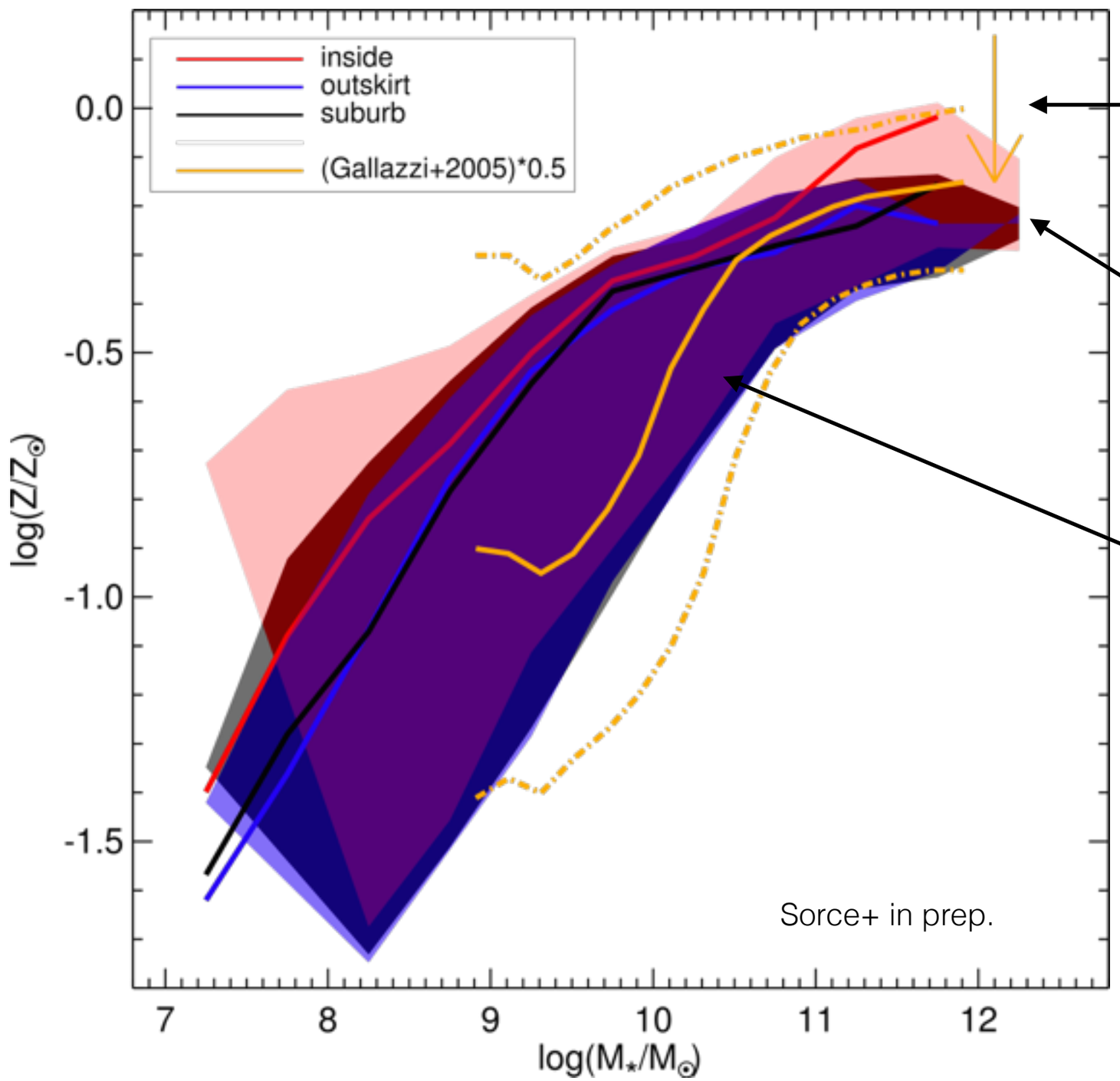
Fraction of quenched galaxies too high: quenching happens too fast? -> **dependence & mechanism**?

Applications: the Virgo cluster CLONE

Preliminary

Simulated Virgo & Observed galaxies

Metallicity of galaxies: field vs. cluster



Metallicities are too small by a factor 2: IMF = metal yield & mass return, aperture?

Scatter = metallicity not solely mass related

Transition regime = change in probability to be quenched

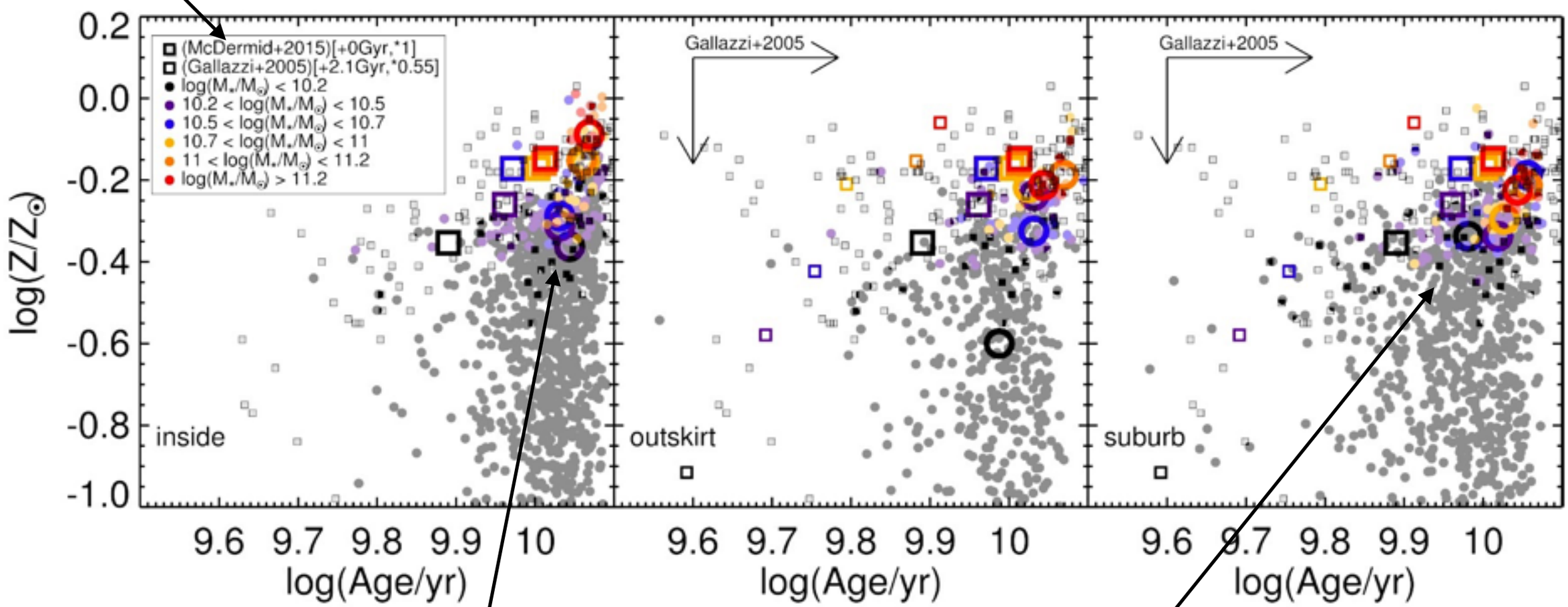
Applications: the Virgo cluster CLONE

Preliminary

Simulated Virgo & Observed galaxies

Metallicity vs. Age of galaxies: field vs. cluster

ATLAS3D no shift: early type, larger aperture



Galaxies in the cluster are older, low metallicity ≠ young

The correlation is stronger outside the cluster

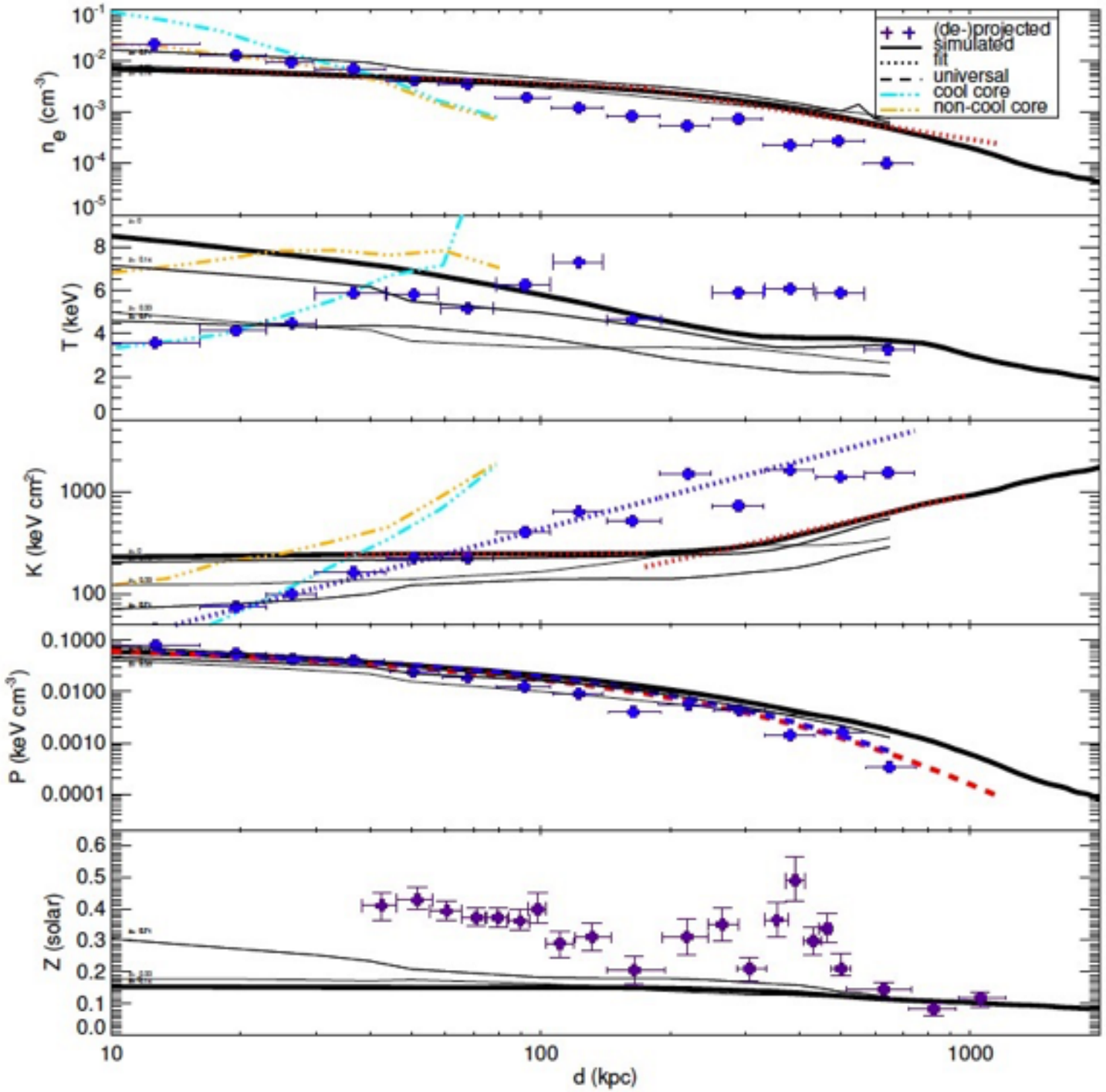
Sorce+ in prep.

Applications: the Virgo cluster CLONE

Extremely Preliminary

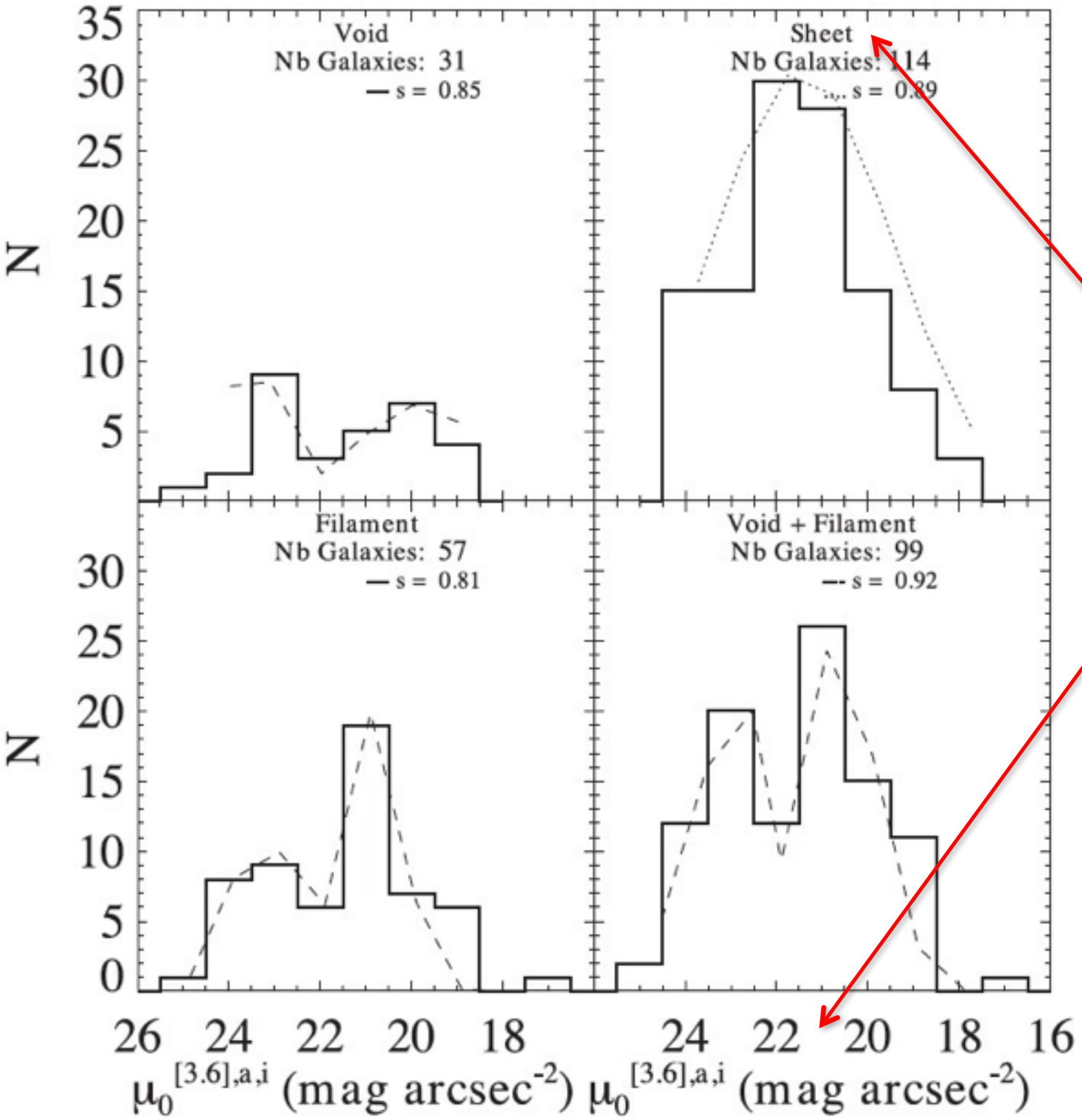
Simulated Virgo & Observed Virgo

Hot Gas in the core



Applications: the LSS CLONE & galaxies

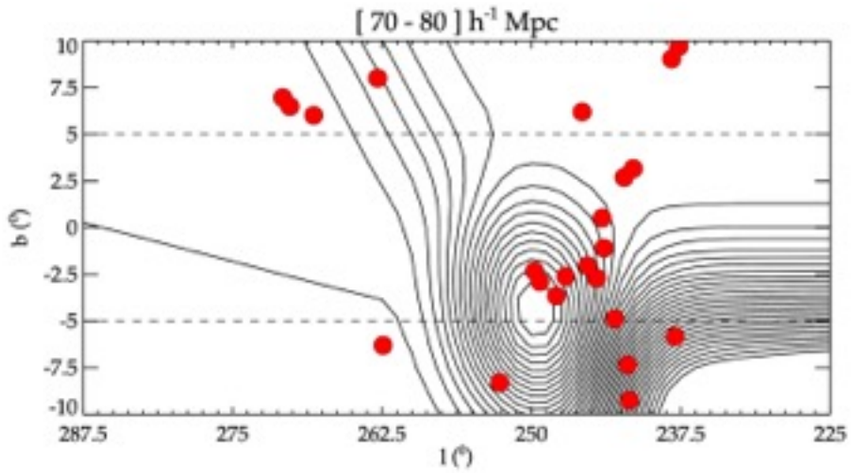
Sorce+2017



Intermediate disk central surface brightness galaxies (as much DM as baryons in their center = less stable) more likely to be in sheets = environment with less activities

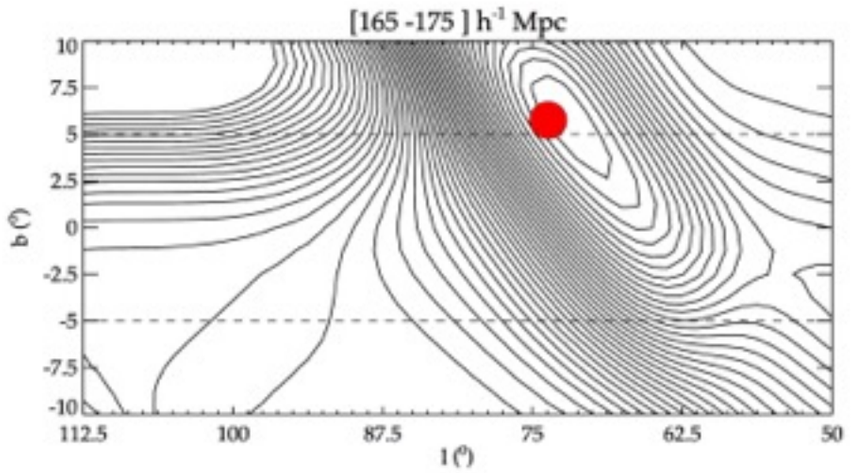
Applications: the Zone of Avoidance

Sorce+2017



Puppis-3 Cluster

Chamaraux & Masnoux 2004



Cygnus A Cluster

Ebeling+2002

ΛCDM challenges hidden in the Zone of Avoidance?

- number of superclusters

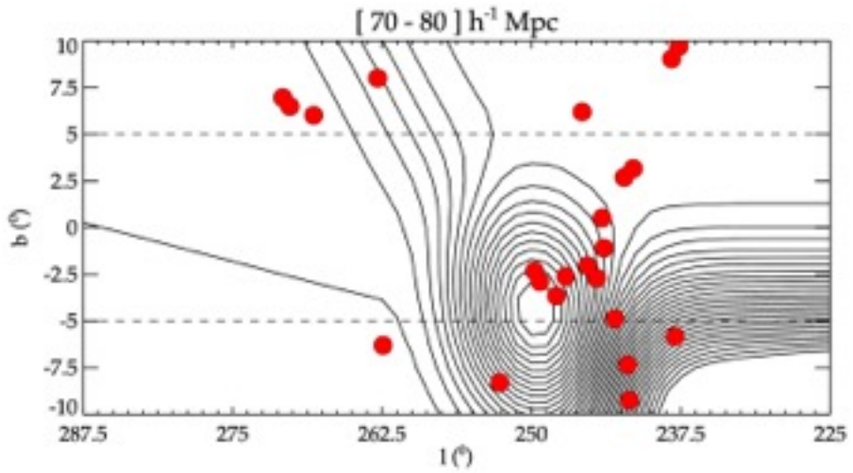
- longest structures

Vela Supercluster

Kraan-Korteweg+2017

Applications: the Zone of Avoidance

Sorce+2017



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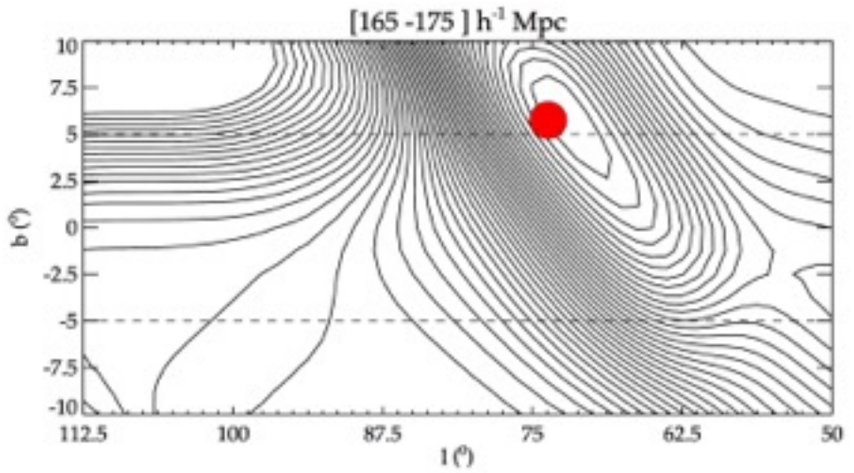

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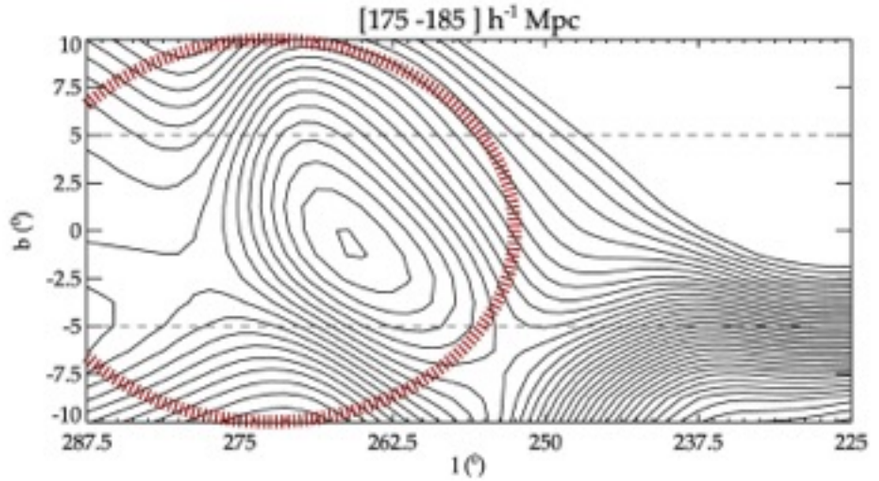
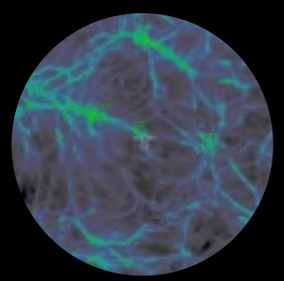


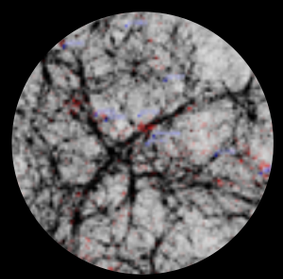
Vela Supercluster

Kraan-Korteweg+2017

Some other examples: …

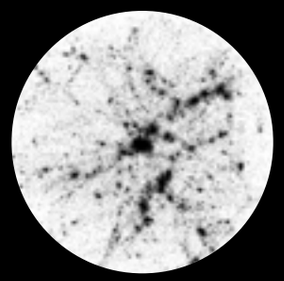


Cosmic Rays in the local Universe
(Hackstein+2018)

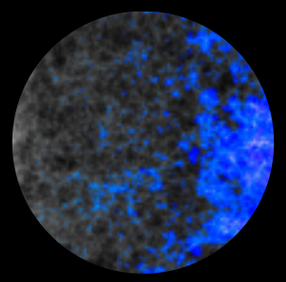


SLOW : local galaxies
(Sorce, Dolag +)

and
more…



Coma connectivity
(Malavi, Aghanim, Sorce+)



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

Take home message

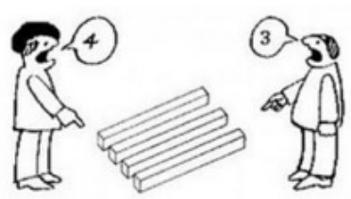
Tensions = Do we need a new cosmological model?

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

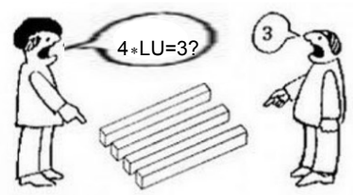
numerical specialists, theorists and observers

Small scales

Simulations of Galaxy formation & evolution:

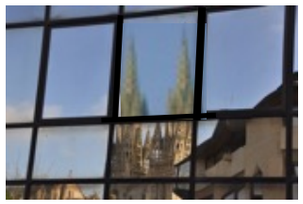
- reproduction
- calibration

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)