Shape and connectivity of clusters
Impact of dynamical state and accretion history

Céline Gouin

Institut d'Astrophysique Spatiale, France

Main collaborators: N. Aghanim, M. Douspis, T. Bonnaire

Observing the millimeter Universe with the NIKA2 camera
01/07/2021

Introduction to galaxy clusters:
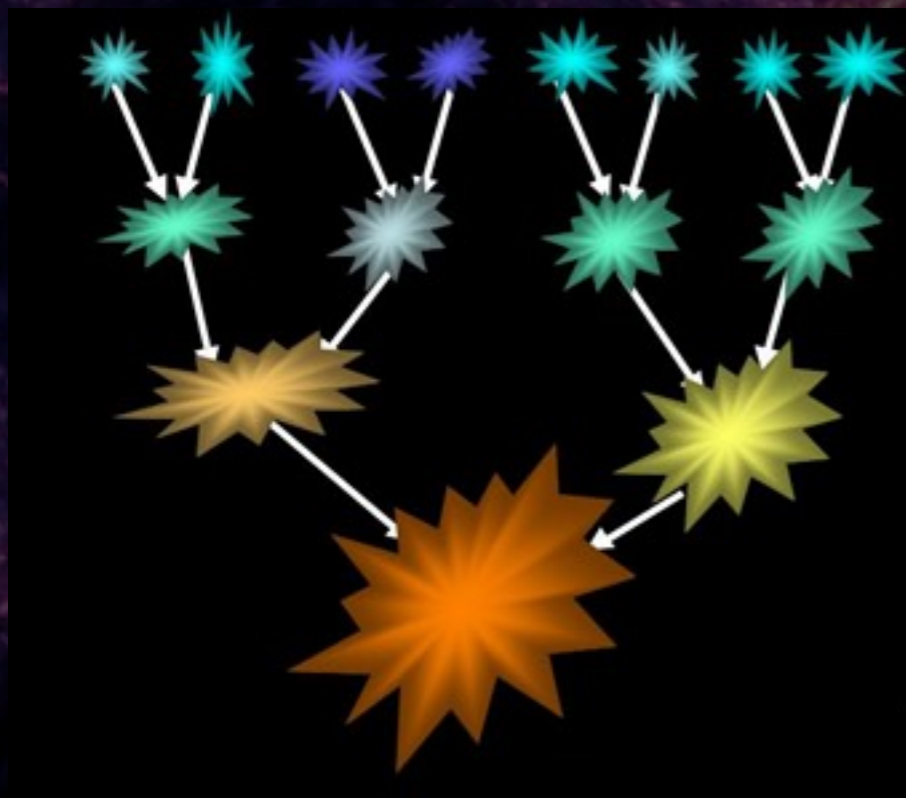## The bulding up of Galaxy cluster environements

Nodes of Cosmic web:

- Located at the intersection of cosmic filaments

- Most recently formed structures

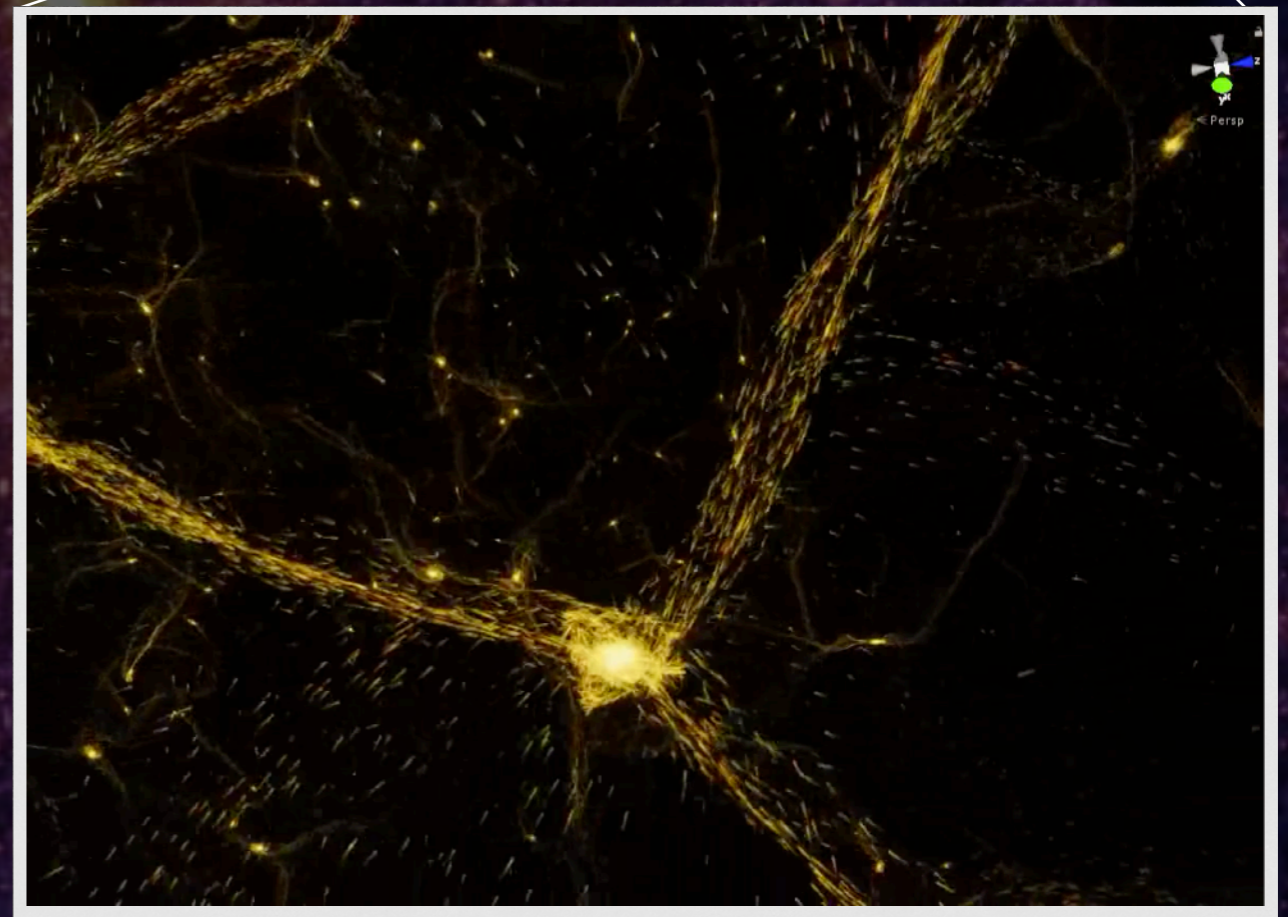- Matter flow from void to wall, then via filaments into clusters

Pichon et al, 2009
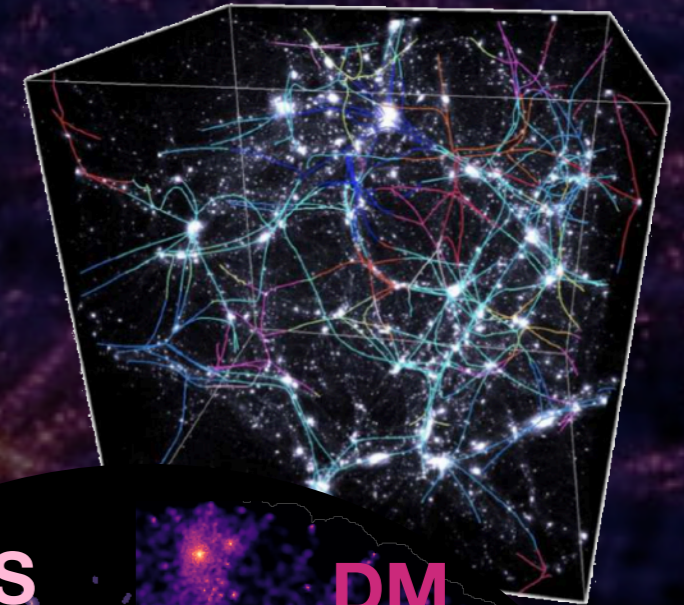
Hierarchical structure formation scenario

time

Credit to Miguel Aragon Calvo

1

Galaxy cluster environments
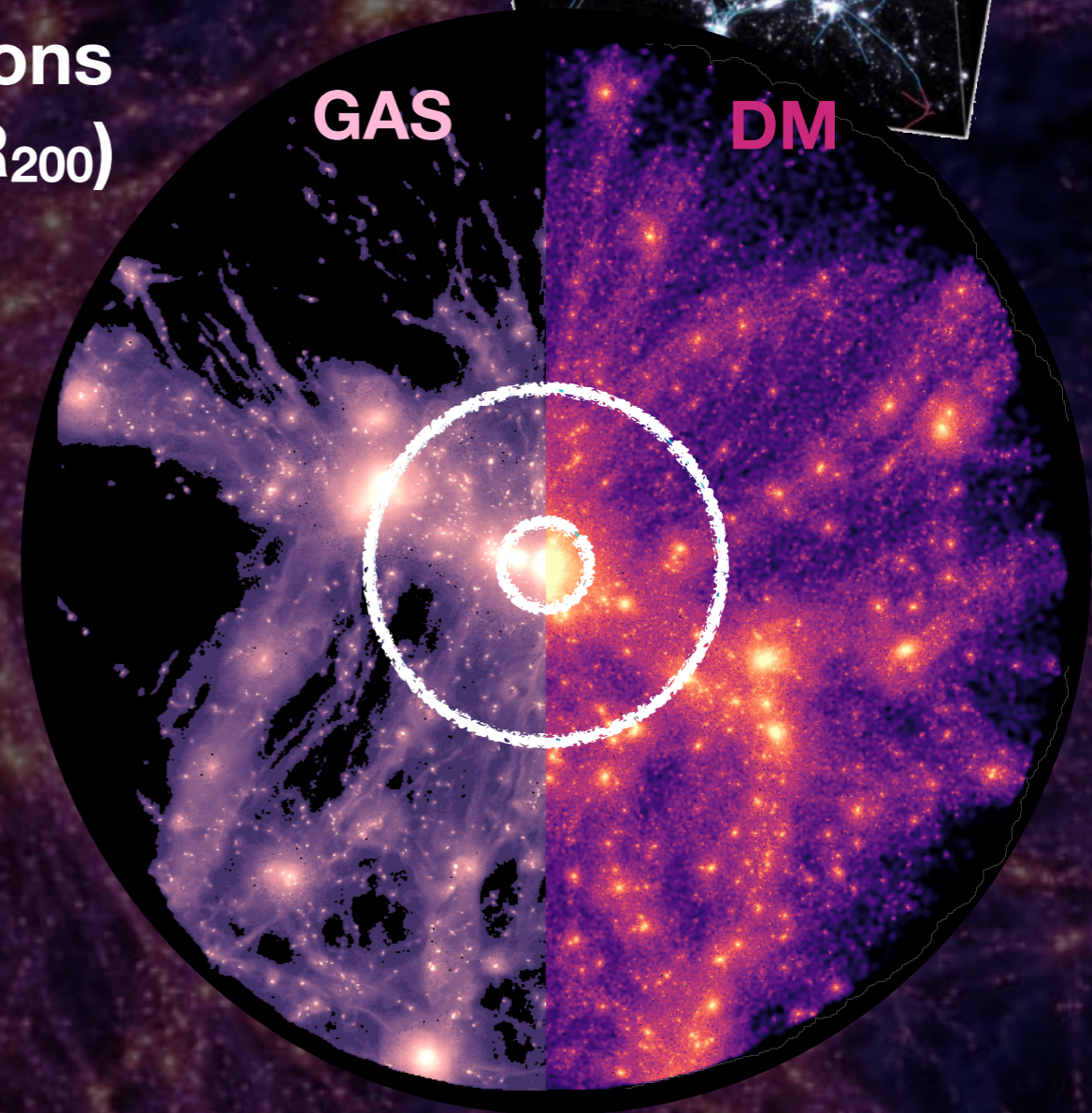## from their center to the LSS

Unique laboratories

- *gas physics*

- *galaxy evolution*

- *growth of the structures*

Cosmic Web
(> 4 R_{200})

**In-falling regions
(from 1 to 4 R_{200})**

GAS

DM

Galaxy clusters
(~1 R_{200})

Galaxy cluster environments
from their center to the LSS

Unique laboratories

- *gas physics*
- *galaxy evolution*
- *growth of the structures*

*How does the connection of
clusters to the cosmic web
influence their properties ?*

Cosmic Web
($> 4\ R_{200}$)

In-falling regions
(from 1 to 4 R_{200})

Galaxy clusters
($\sim 1\ R_{200}$)

GAS   DM

Galaxy cluster environments
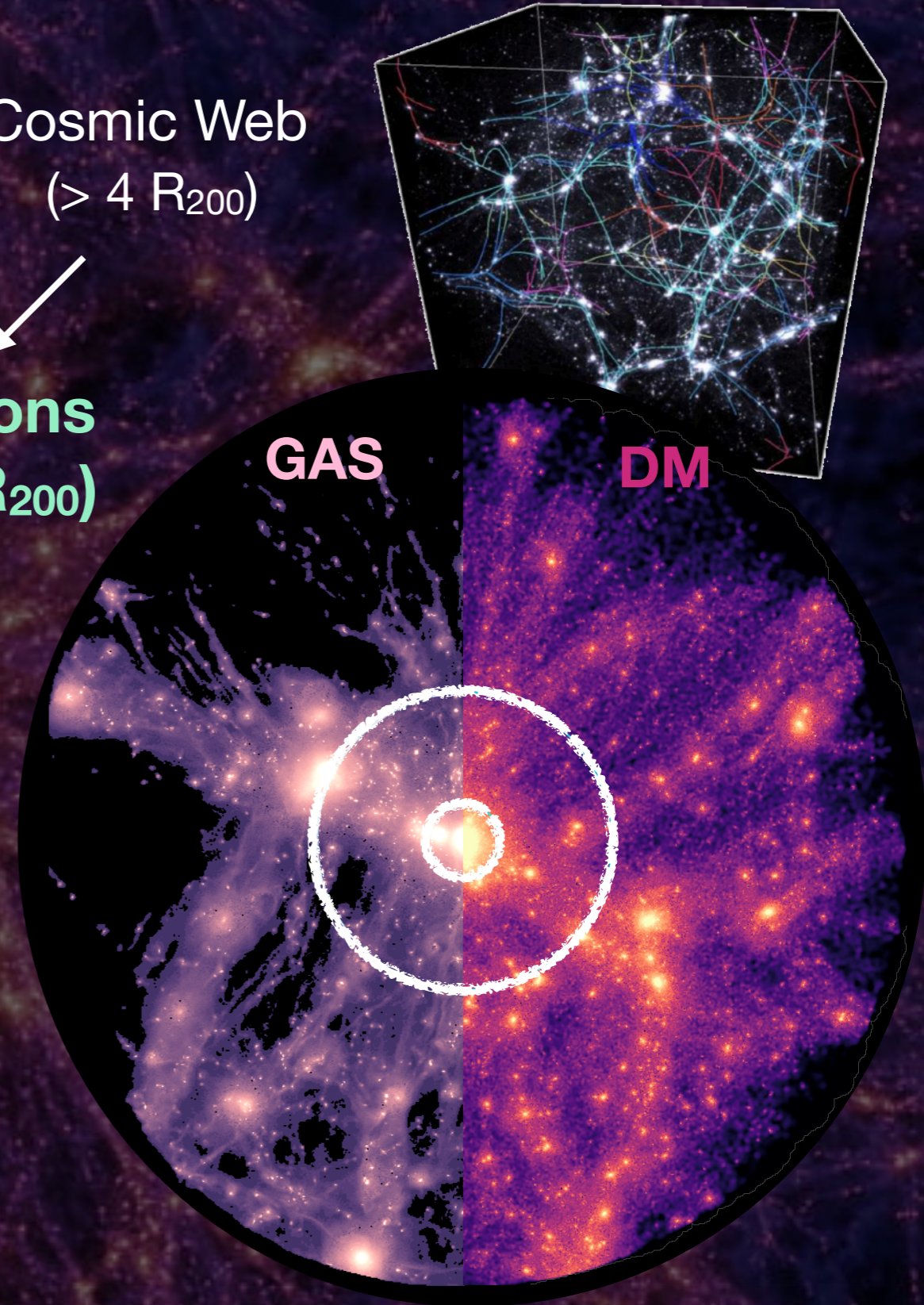from their center to the LSS

Unique laboratories

– *galaxy evolution*

In-falling regions (from 1 to 4 R_{200})

‣ Environemental effect on galaxies

‣ Connection between LSS and clusters

Gouin +20

Galaxy clusters
(~1 R_{200})

‣ Morphology

1. How accretion processes affect
galaxies properties during their infall ?

Galaxy cluster environments
from their center to the LSS

Unique laboratories

– *growth of the structures*

Galaxy clusters
(~1 R_{200})

‣ **Morphology**

‣ **Dynamical state**

‣ **Accretion history**

In-falling regions (from 1 to 4 R_{200})

‣ **Connection between LSS and clusters**

Gouin +21

2. How the connection of clusters
to the cosmic web influences
the bulding up of clusters?

Probing the azimuthal environment of galaxies around clusters
 from their center to the LSS
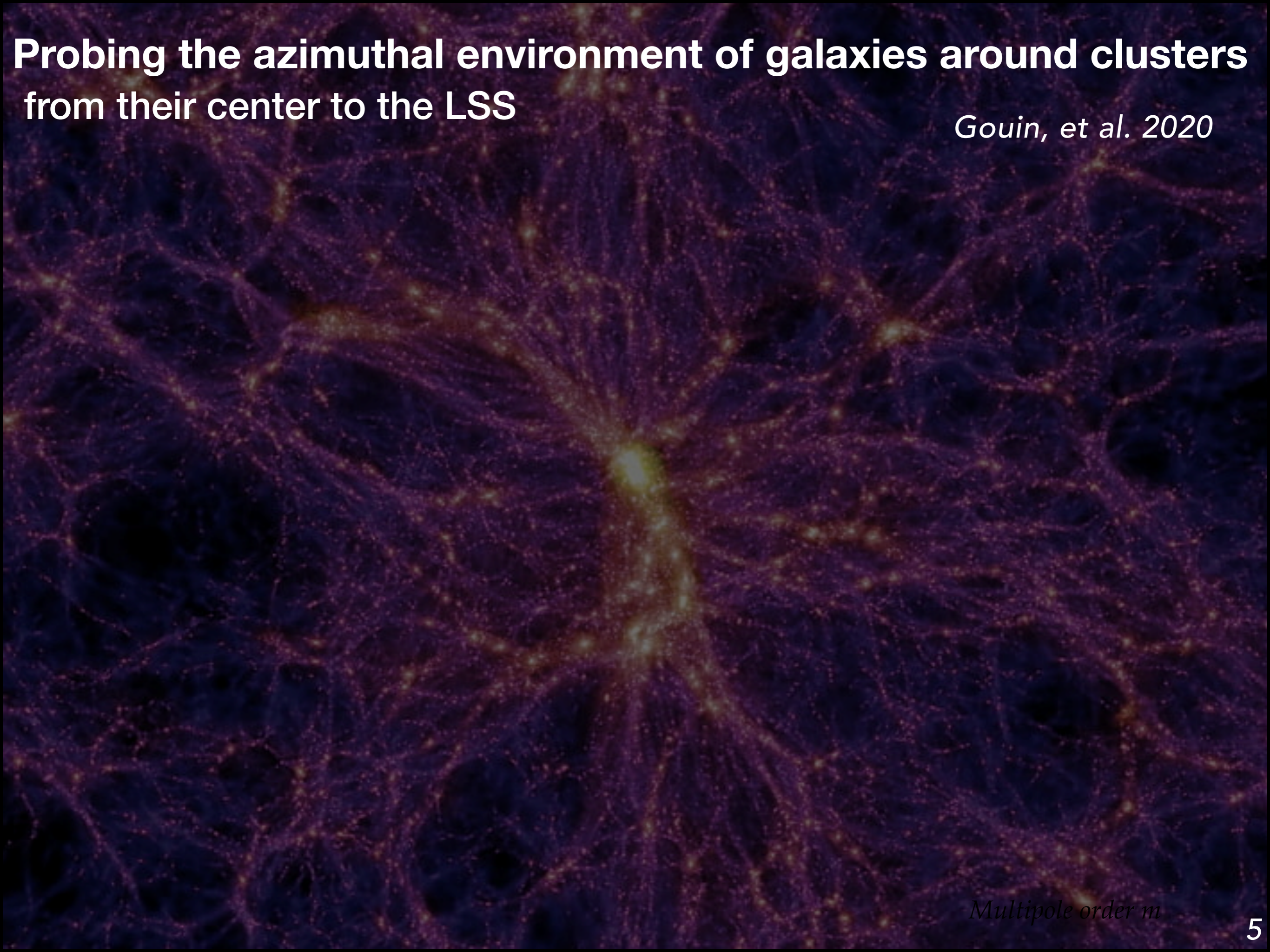
Gouin, et al. 2020

Multipole order m

Probing the azimuthal environment of galaxies around clusters
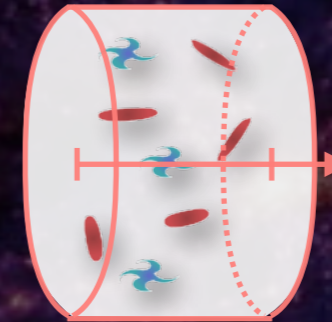## from their center to the LSS
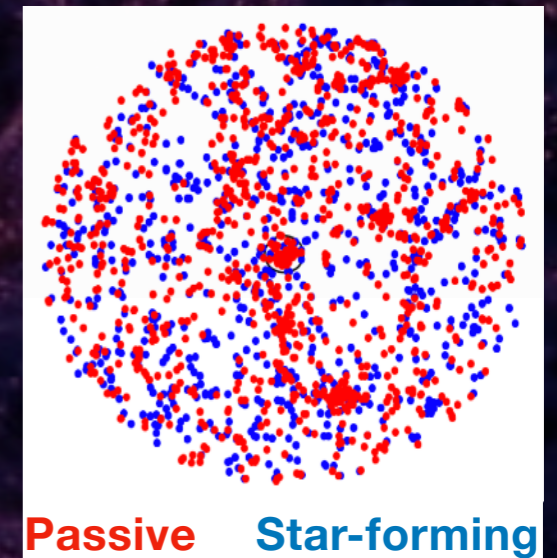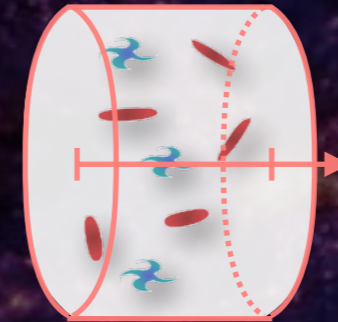
Gouin, et al. 2020

Dataset

Obsevational dataset for low-z clusters

- Galaxies form Wise X SCOSMOS between 0.1<z<0.3 (Bilicki et al, 2016)

~**6400 Clusters** from SDSS (Wen et al, 2012)

Redshift slices around clusters

2D galaxy map around clusters

Passive **Star-forming**

Multipole order m

5

Probing the azimuthal environment of galaxies around clusters
from their center to the LSS

Gouin, et al. 2020

Redshift slices around clusters
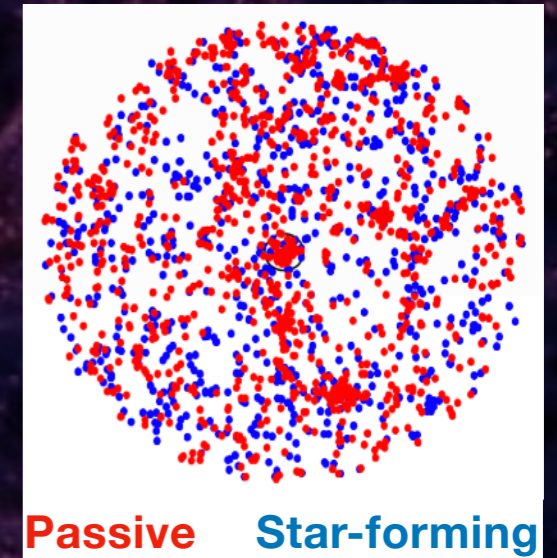
2D galaxy map around clusters

Dataset

Obsevational dataset for low-z clusters

- Galaxies form Wise X SCOSMOS between 0.1<z<0.3 (Bilicki et al, 2016)

~**6400 Clusters** from SDSS (Wen et al, 2012)

Passive   **Star-forming**

Simulated dataset

Light-cone of Magneticum (Dolag et al. 2015)

Multipole order m

Probing the azimuthal environment of galaxies around clusters
from their center to the LSS

Gouin, et al. 2020

Dataset

Obsevational dataset for low-z clusters

- Galaxies form Wise X SCOSMOS between 0.1<z<0.3 (Bilicki et al, 2016)
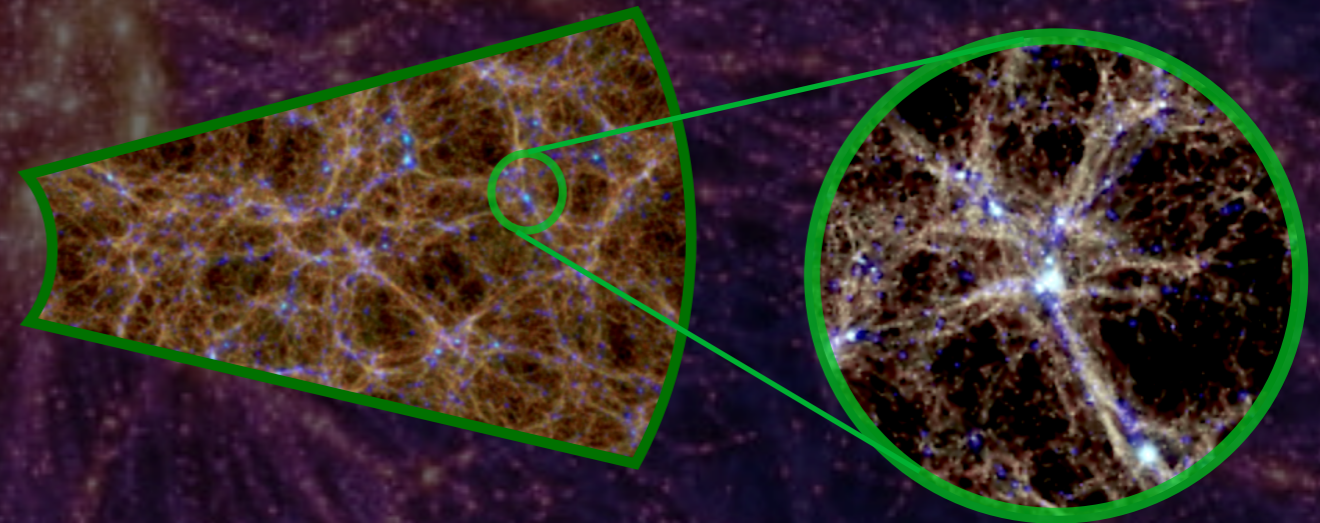
~**6400 Clusters** from SDSS (Wen et al, 2012)

fraction of SF galaxies

Redshift slices around clusters

2D galaxy map around clusters

Passive   Star-forming

Simulated dataset

Light-cone of Magneticum (Dolag et al. 2015)

Multipole order m

5

Probing the azimuthal environment of galaxies around clusters
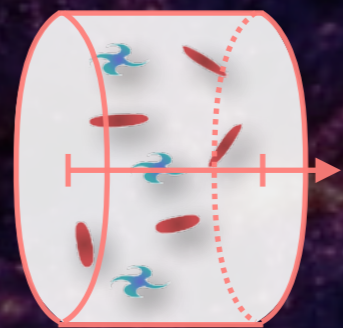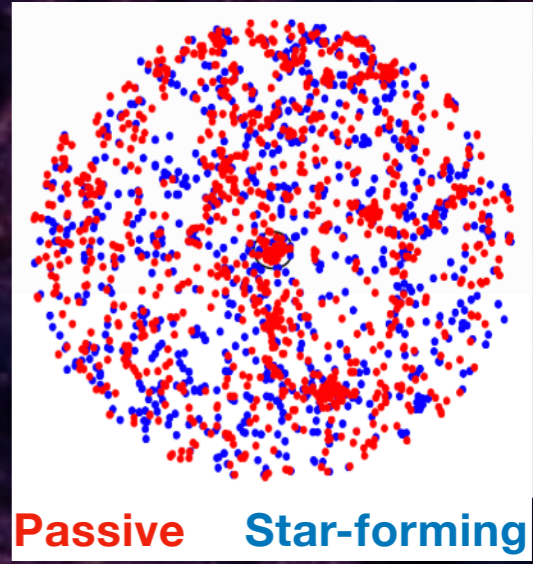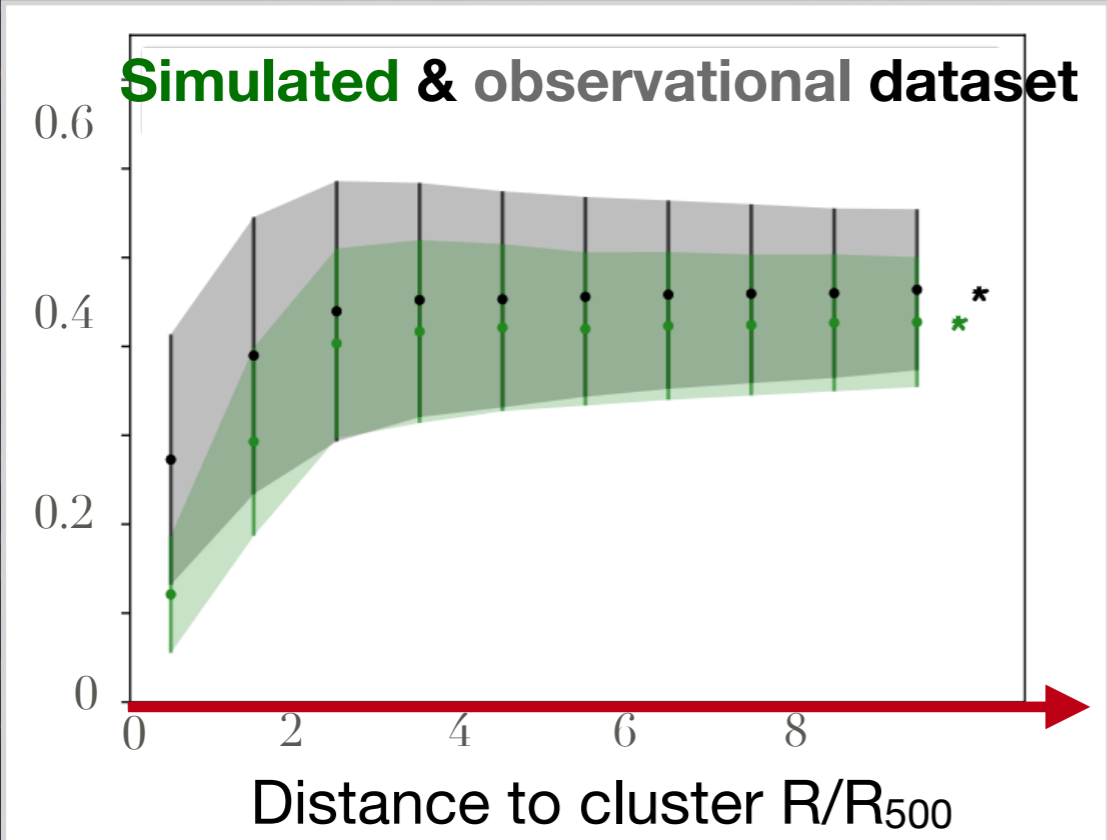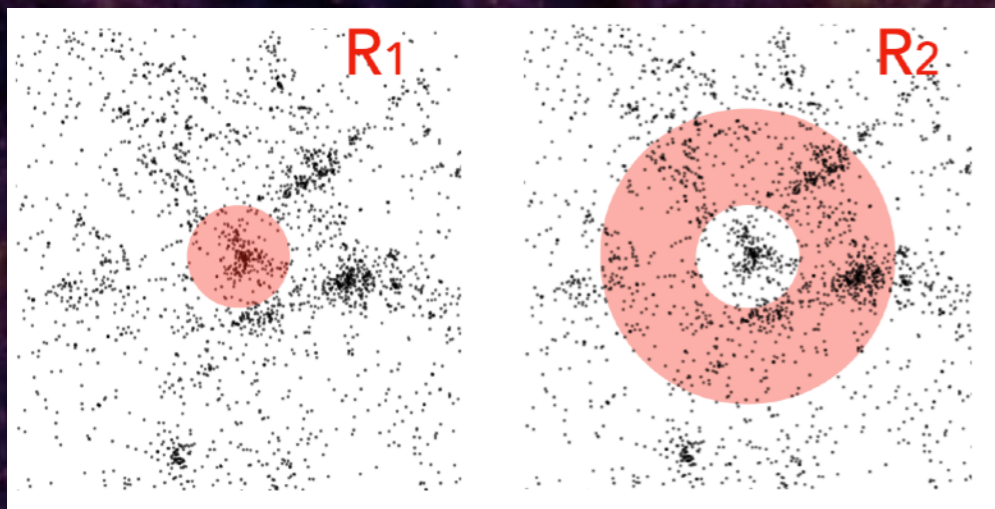## from their center to the LSS

Gouin, et al. 2020

Azimuthal average of galaxy distribution

Harmonic decomposition of 2-D distribution around galaxy clusters (Schneider et al, 1997)

$$Q_m(\Delta R) = \int_{\Delta R} R \, dR \int_0^{2\pi} d\phi \, e^{im\phi} \, \Sigma_g(R, \phi)$$

Multipole order m

Gouin et al 2020 (Galaxies), Gouin et al 2018 (DM), Codis et al 2018 (GRF)

Probing the azimuthal environment of galaxies around clusters
from their center to the LSS

Gouin, et al. 2020

Azimuthal average of galaxy distribution

Harmonic decomposition of 2-D distribution around galaxy clusters (Schneider et al, 1997)

$$Q_m(\Delta R) = \int_{\Delta R} R \, dR \int_0^{2\pi} d\phi \, e^{im\phi} \, \Sigma_g(R, \phi)$$

*to **statistically highlight angular symmetries (anisotropy)***

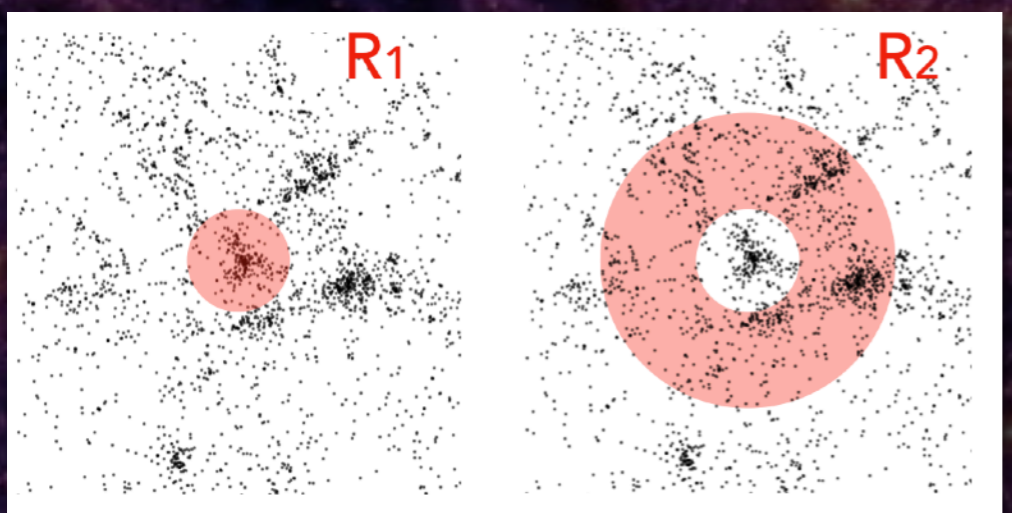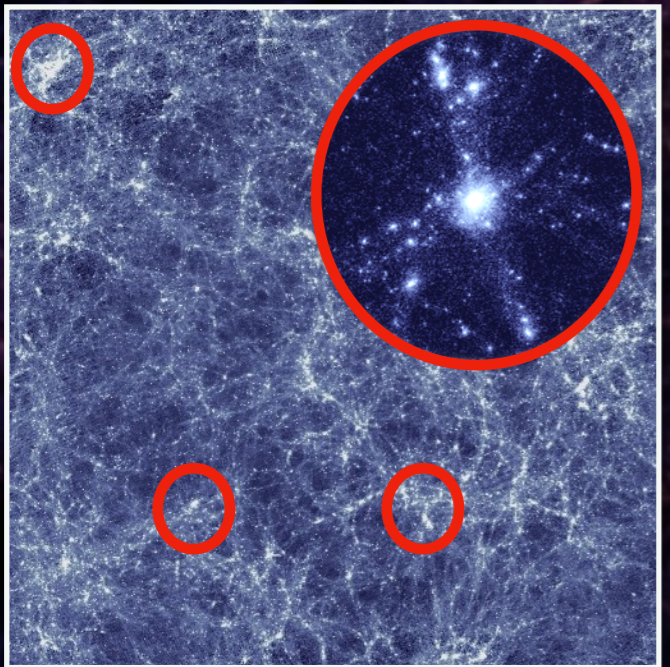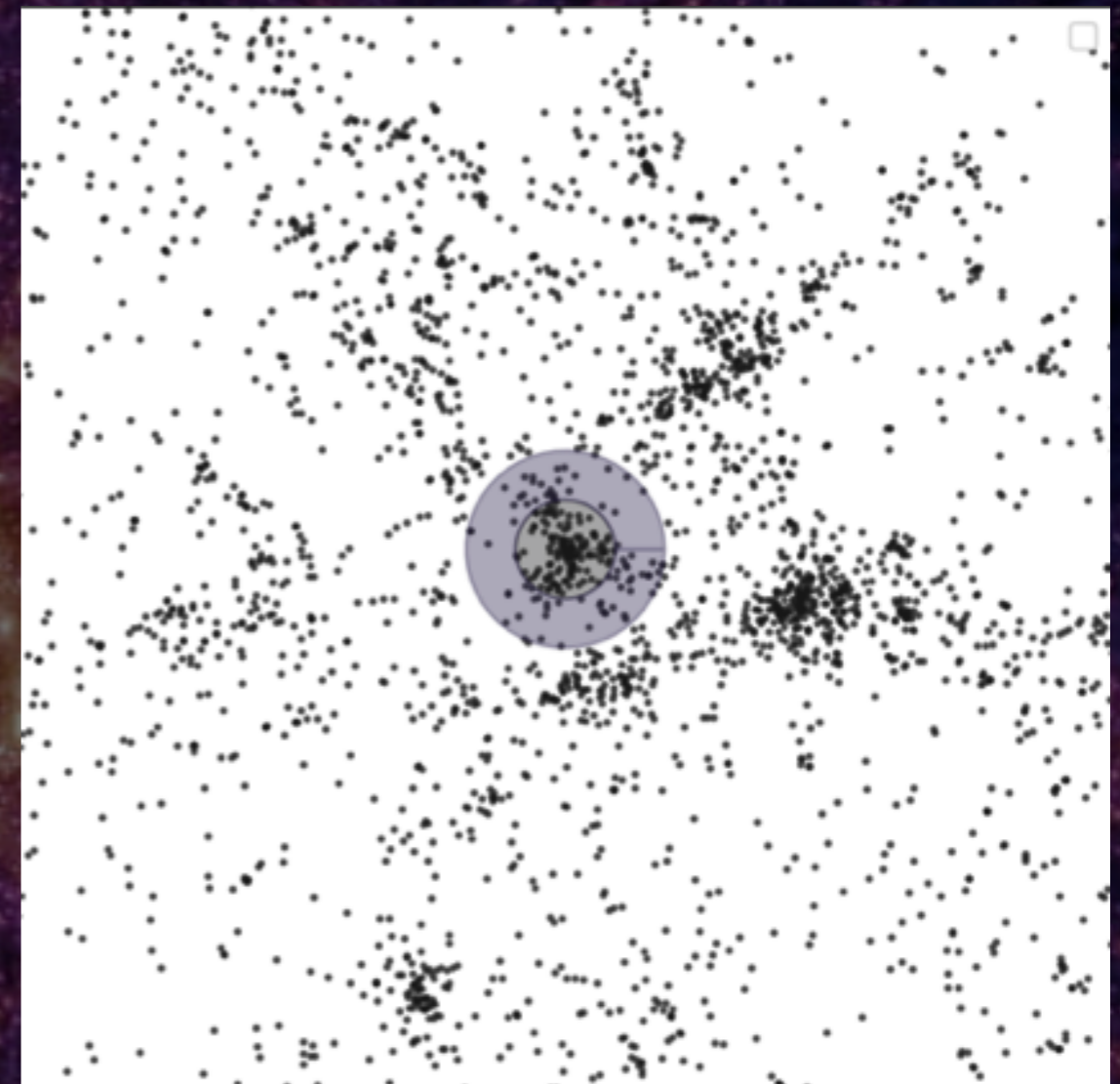$$Q_m \longrightarrow \langle |Q_m|^2 \rangle \qquad \textit{Multipole order m}$$

Gouin et al 2020 (Galaxies), Gouin et al 2018 (DM), Codis et al 2018 (GRF)

Probing the azimuthal environment of galaxies around clusters
from their center to the LSS

Gouin, et al. 2020

Results - *Radial evolution of angular features around clusters (simulation)*

$\widetilde{Q}_m$

R = [0-1] R500
R = [1-2] R500

Elliptical cluster shape
[0-2] R500

Quadrupole

m=2

2

$\widetilde{Q}_m$

1

2   4   6   8   10   Multipoles

1   2   3   4   5   6   7   8   (Multipole orders)

1   2   3   4   5   6   7   8   .... Multipole orders

Probing the azimuthal environment of galaxies around clusters
from their center to the LSS

Gouin, et al. 2020

Results - *Radial evolution of angular features around clusters (simulation)*

Complex anisotropic structures

Filamentary patterns
[2-8] R500

R = [2-3] R500
R = [3-4] R500
R = [4-5] R500
R = [5-6] R500
R = [6-7] R500
R = [7-8] R500

Multipoles

1   2   3   4   5   6   7   8   (Multipole orders)

Gouin et al, 2020   8

Probing the azimuthal environment of galaxies around clusters
from their center to the LSS

Gouin, et al. 2020

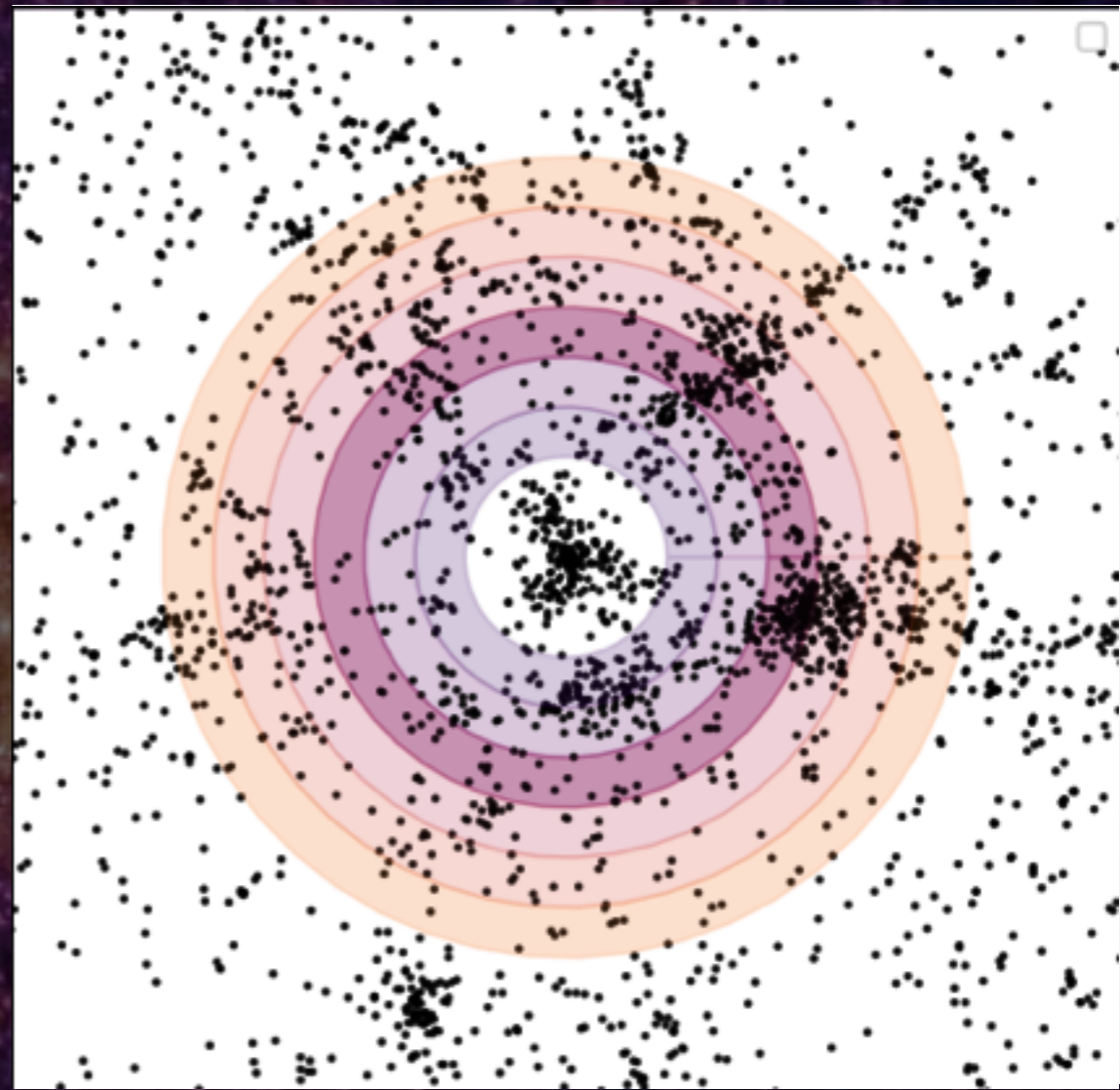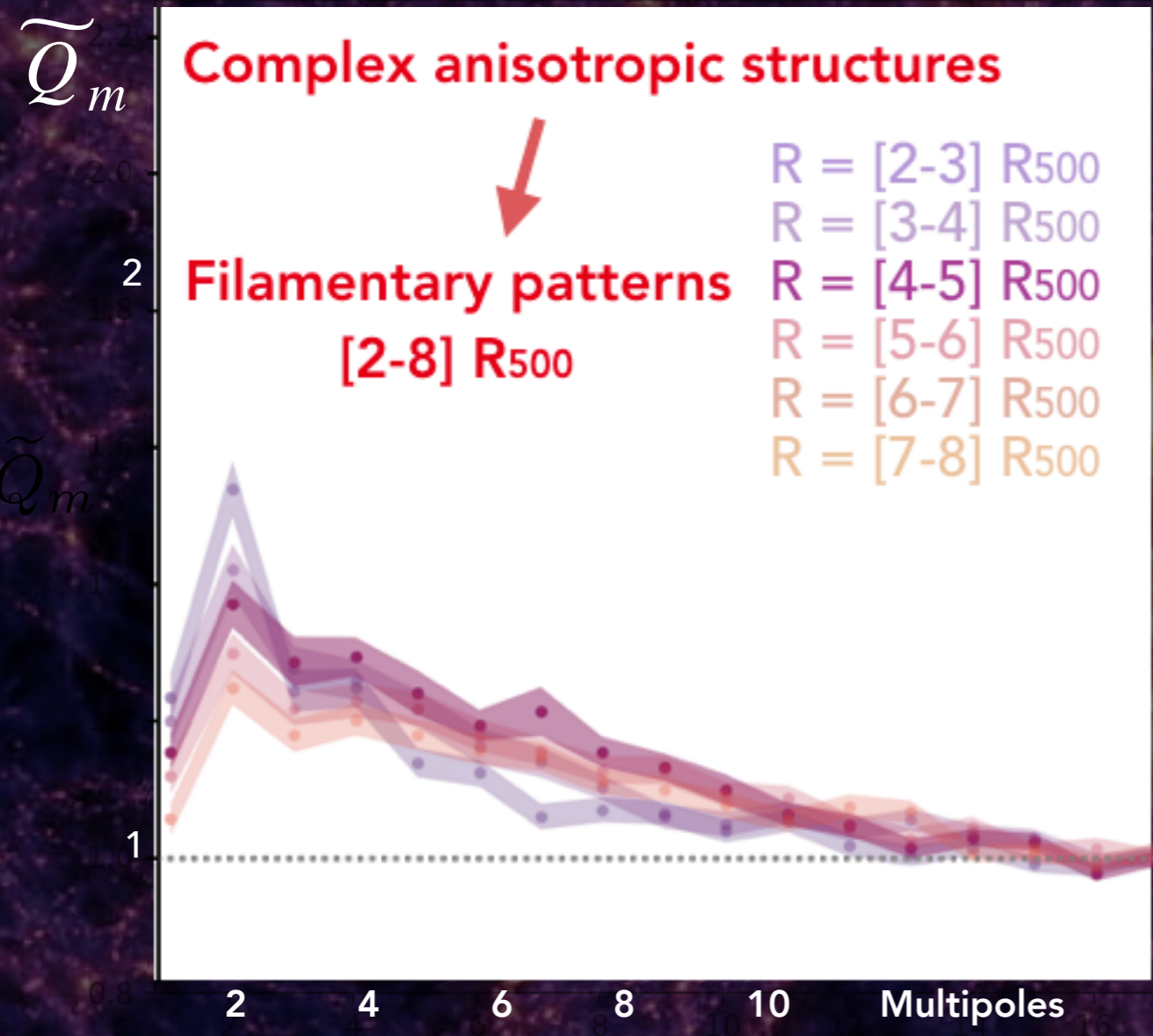**Results - *Radial evolution of angular features around clusters (observation)***

R=[0-2]R$_{500}$

R=[2-8]R$_{500}$

$\widetilde{Q}_n\widetilde{Q}_m$

Quadrupole

m=2

Ellispoidal shape

Filamentary pattern

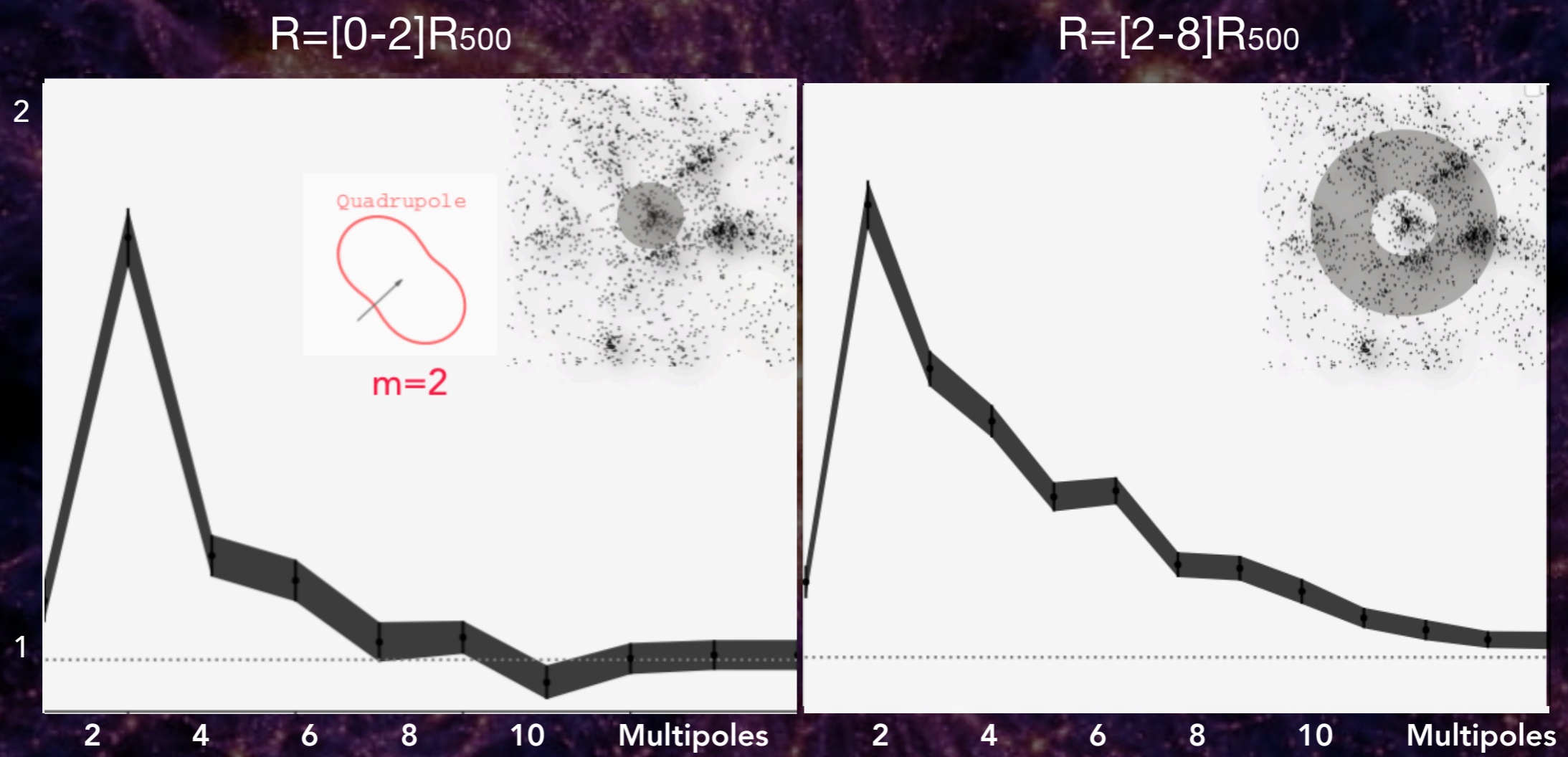1   2   3   4   5   6   7   8   (Multipole orders)

Probing the azimuthal environment of galaxies around clusters
from their center to the LSS

Gouin, et al. 2020

Results - *Radial evolution of angular features around clusters (observation)*
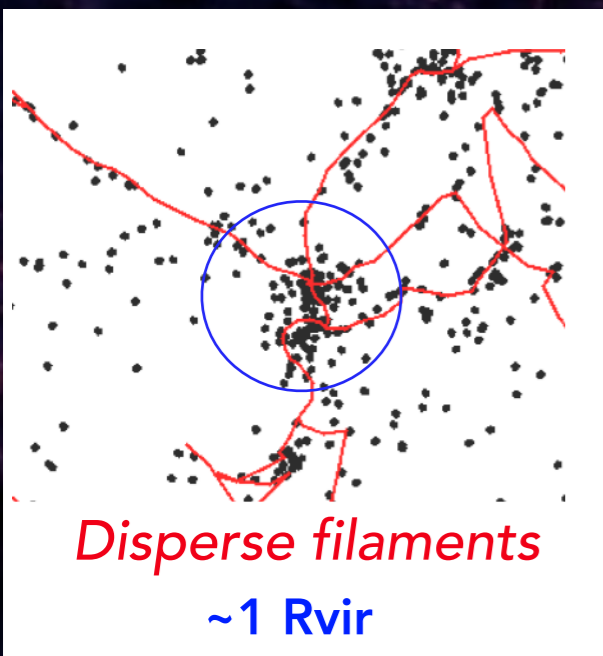
Mean angular scale

$$m_{mean} = 4.2 \pm 0.1$$
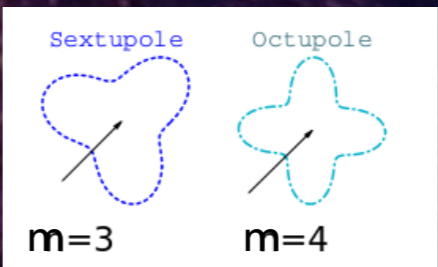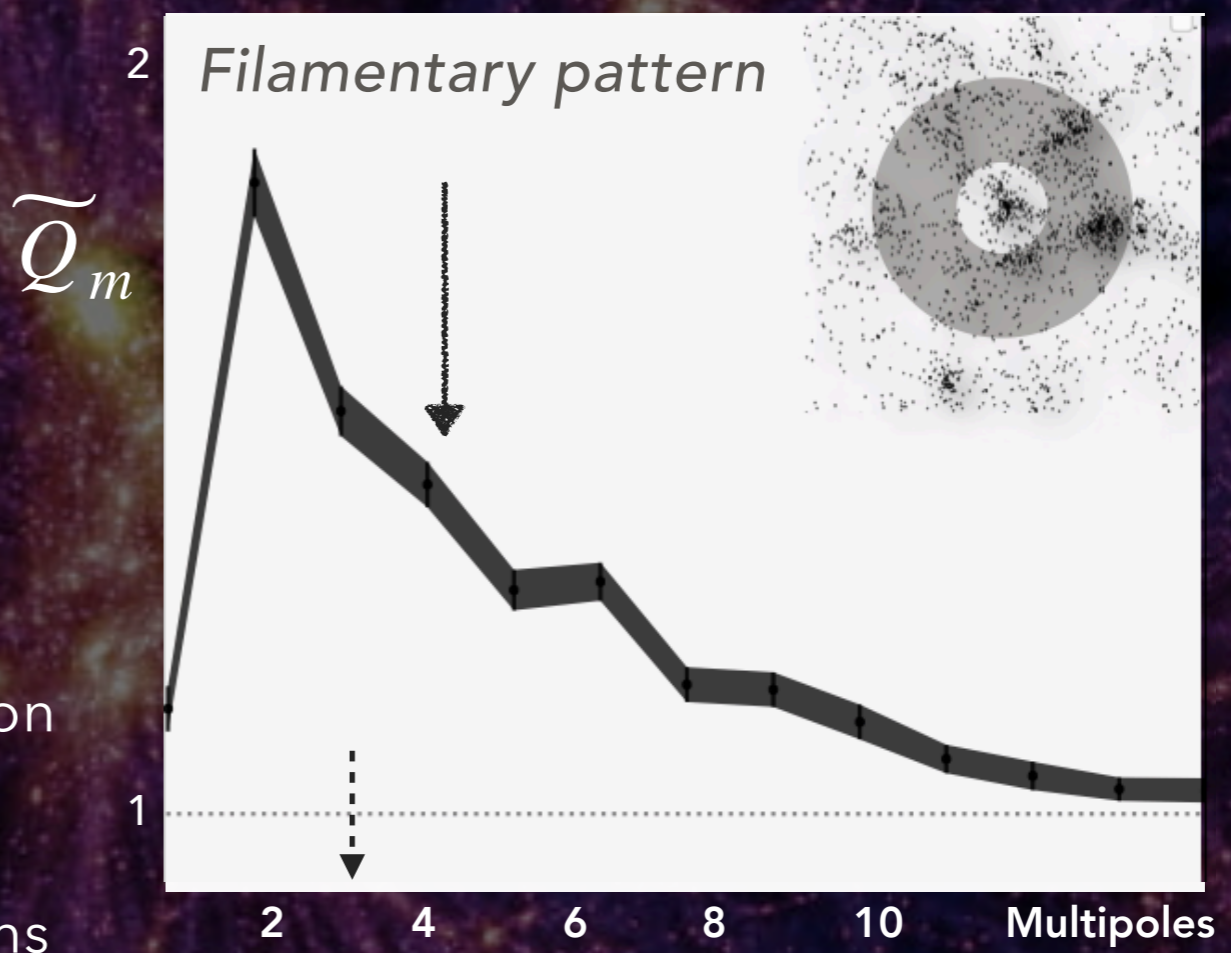
Median angular scale

$$m_{median} = 3.1 \pm 0.1$$

$\widetilde{Q}_m$

Connectivity (2D) in litterature

Disperse filaments

~1 Rvir

~**3.7** in DM simulation
(Codis 2018)

~**3 - 4** in observations

(Sarron et al 2019,
Malavasi et al 2019,
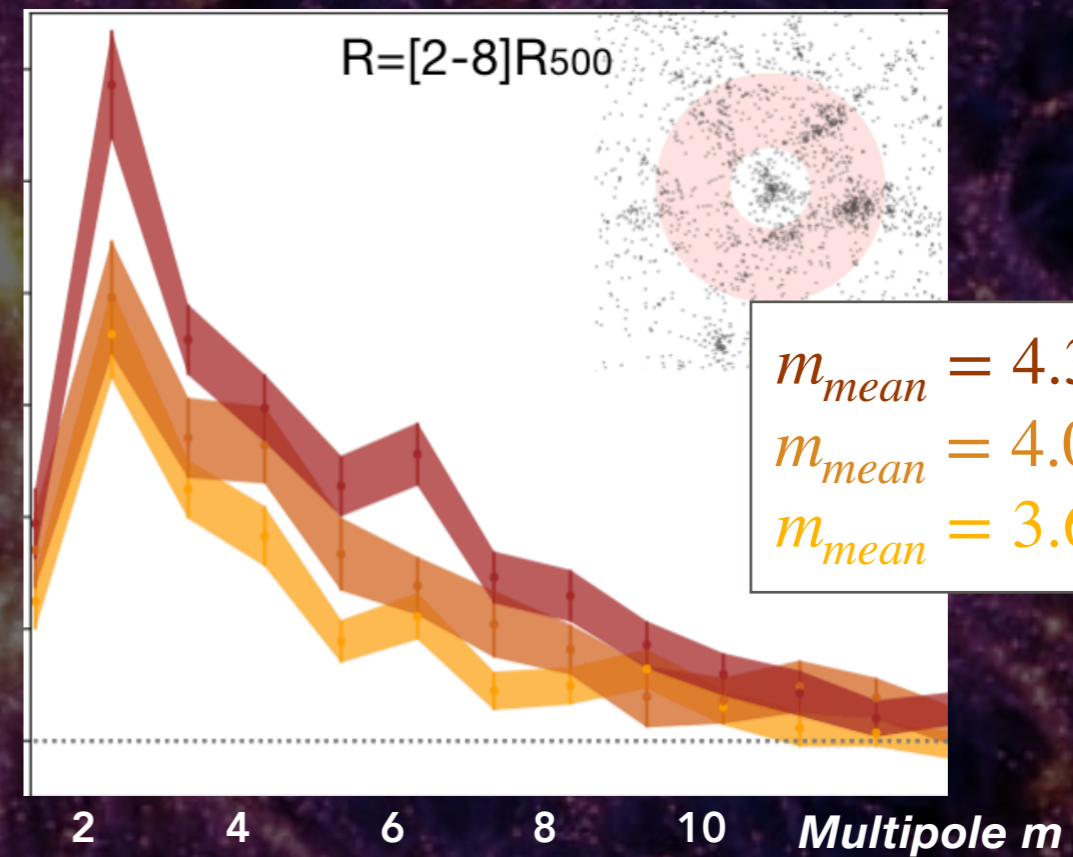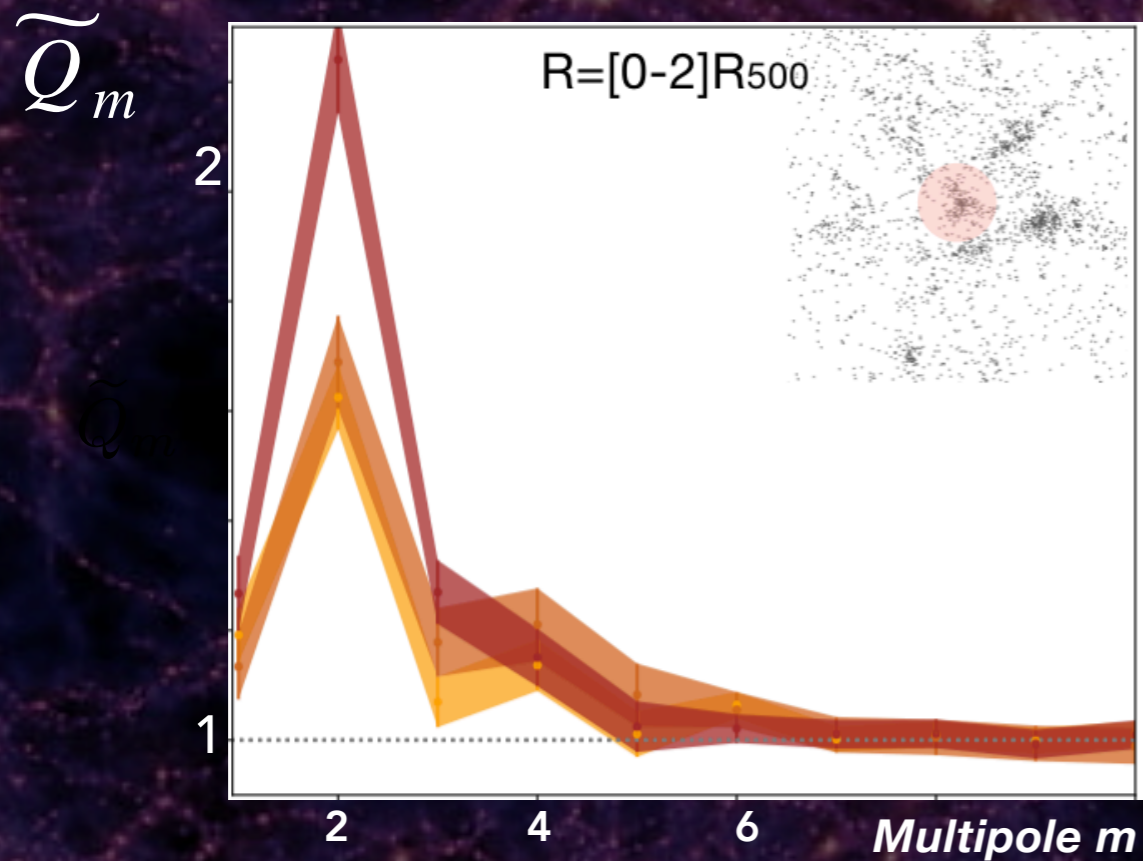Darragh-Ford et al 2019)

R=[2-8]R$_{500}$

$\widetilde{Q}_m$

Filamentary pattern

2

1

2   4   6   8   10   **Multipoles**

Sextupole   Octupole

m=3   m=4

1   2   3   4   5   6   7   8   ....   Multipole orders

Gouin et al, 20

Probing the azimuthal environment of galaxies around clusters
from their center to the LSS

Gouin, et al. 2020

Results - *Dependancy on cluster mass (observation)*

$20 < richness \leq 25$ $25 < richness \leq 30$ $richness > 30$

$M_{200} \sim 1.2 \times 10^{14} M_{\odot}$ $M_{200} \sim 1.6 \times 10^{14} M_{\odot}$ $M_{200} \sim 2.7 \times 10^{14} M_{\odot}$

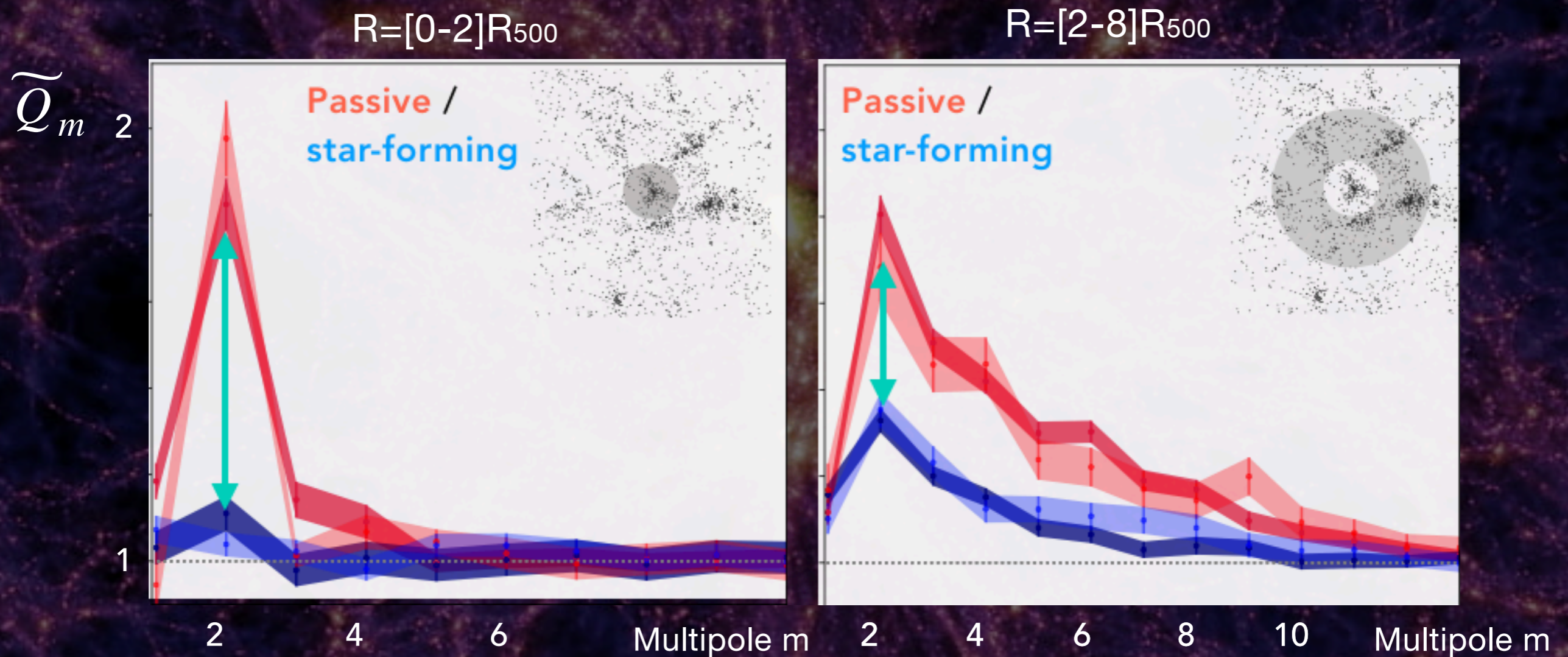
$m_{mean} = 4.38 \pm 0.13$
$m_{mean} = 4.01 \pm 0.20$
$m_{mean} = 3.63 \pm 0.27$

The elliptical shape is more
marked in richer clusters

Richer clusters have stronger filamentary
pattern with higher mean angular scale

11

Probing the azimuthal environment of galaxies around clusters
from their center to the LSS

Gouin, et al. 2020

Which type of galaxy trace the asymmetries in galaxy distribution?
The role of cluster environment ?

R=[0-2]R$_{500}$

R=[2-8]R$_{500}$

$\widetilde{Q}_m$

Passive /
star-forming

Passive /
star-forming

Multipole m

Multipole m

The contribution of SF galaxies increases with cluster distance

*A gradient of SF activity in anistropic structures, from cluster centre to the filaments?*

Probing the azimuthal environment of galaxies around clusters
from their center to the LSS

Gouin, et al. 2020

Which type of galaxy trace the asymmetries in galaxy distribution?
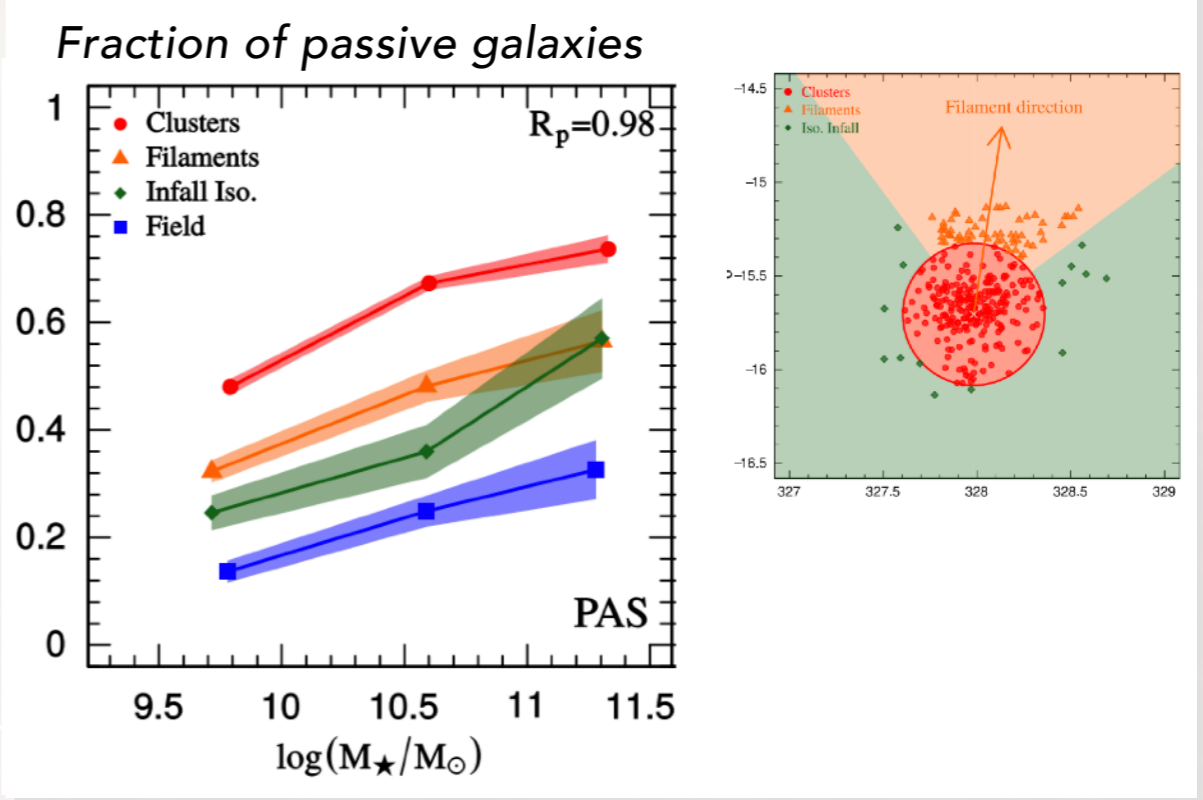**The role of cluster environment ?**

An gradient of SF activity in asymmetric structures from cluster centre to the LSS

Passive galaxies in cosmic filaments are located closer to clusters than their SF counterpart (for low-z clusters)
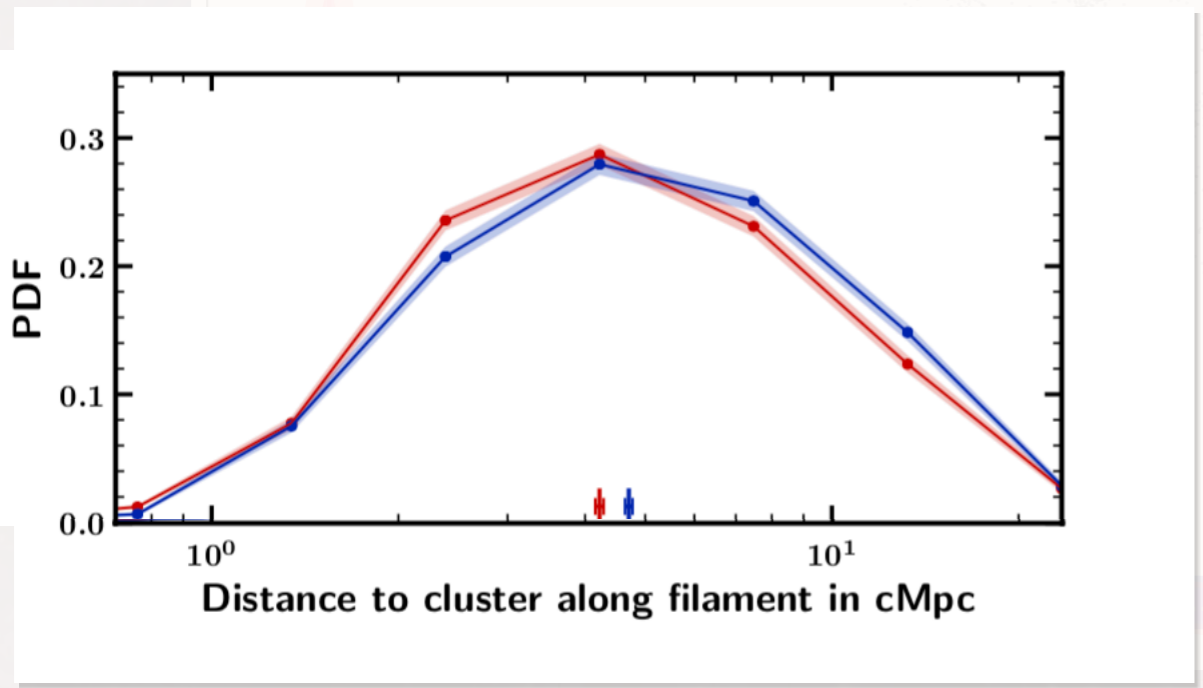
Sarron et al. (2019)

Galaxies in filaments are systematically more quenched than their counterparts infalling from other directions

Fraction of passive galaxies
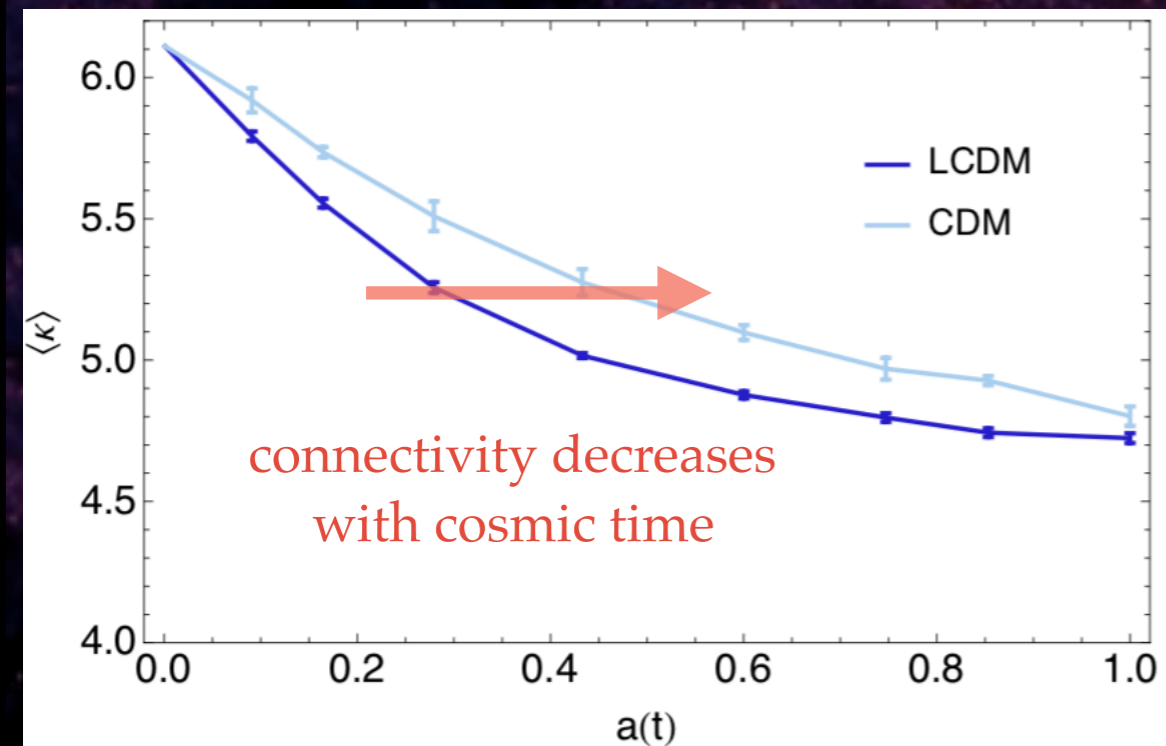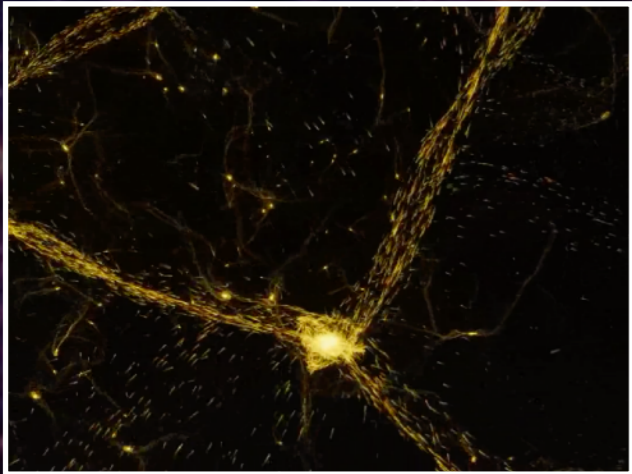
Salerno et al. (2020)

See also Kraljic et al, 2018 ; Lotz et al 2018; …

Galaxy cluster environments
from their center to the LSS

2. How *the connection of clusters to the cosmic web influences the bulding up of clusters?*

Galaxy cluster environments
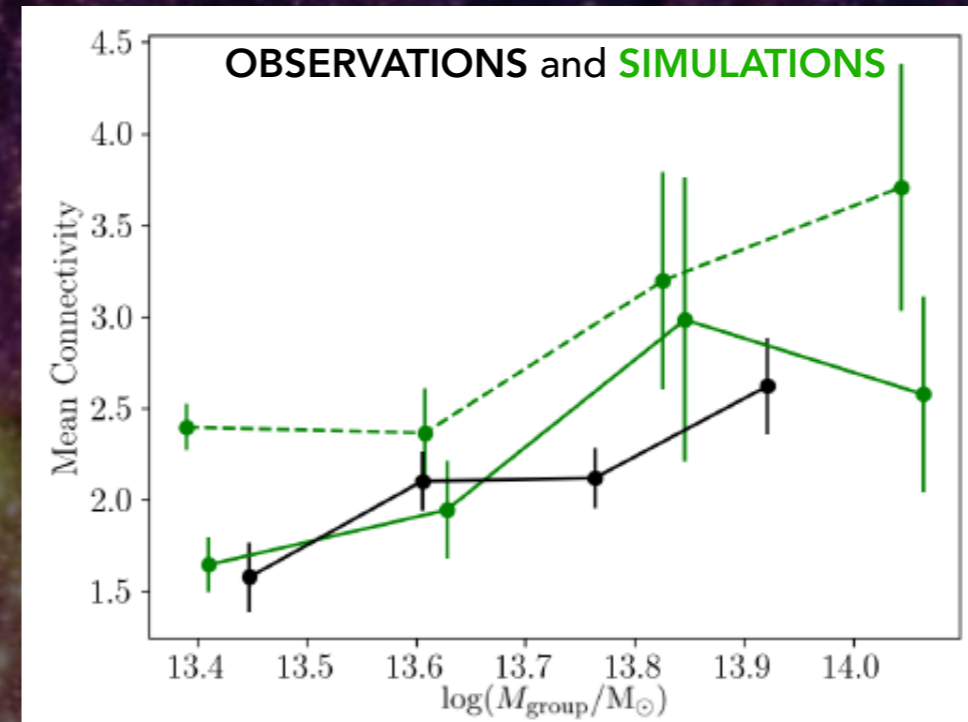## from their center to the LSS
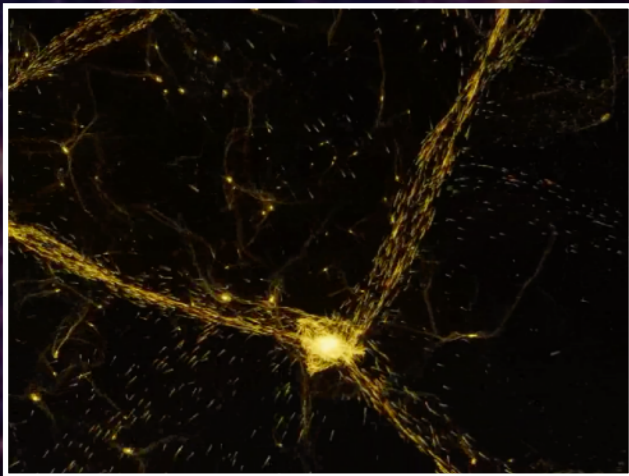

2. How *the connection of clusters to the cosmic web influences the bulding up of clusters?*

connectivity decreases
with cosmic time

LCDM
CDM

$\langle \kappa \rangle$

a(t)

Codis, et al. 2018 (GRF theory & N-body simulation)

Galaxy cluster environments
from their center to the LSS

2. H*ow the connection of clusters to the cosmic web influences the bulding up of clusters?*

Darragh Ford et al. 2019 (HorizonAGN and COSMOS)

More massive, more connected

connectivity increases with the mass

*Codis, et al. 2018 (GRF theory & N-body simulation)
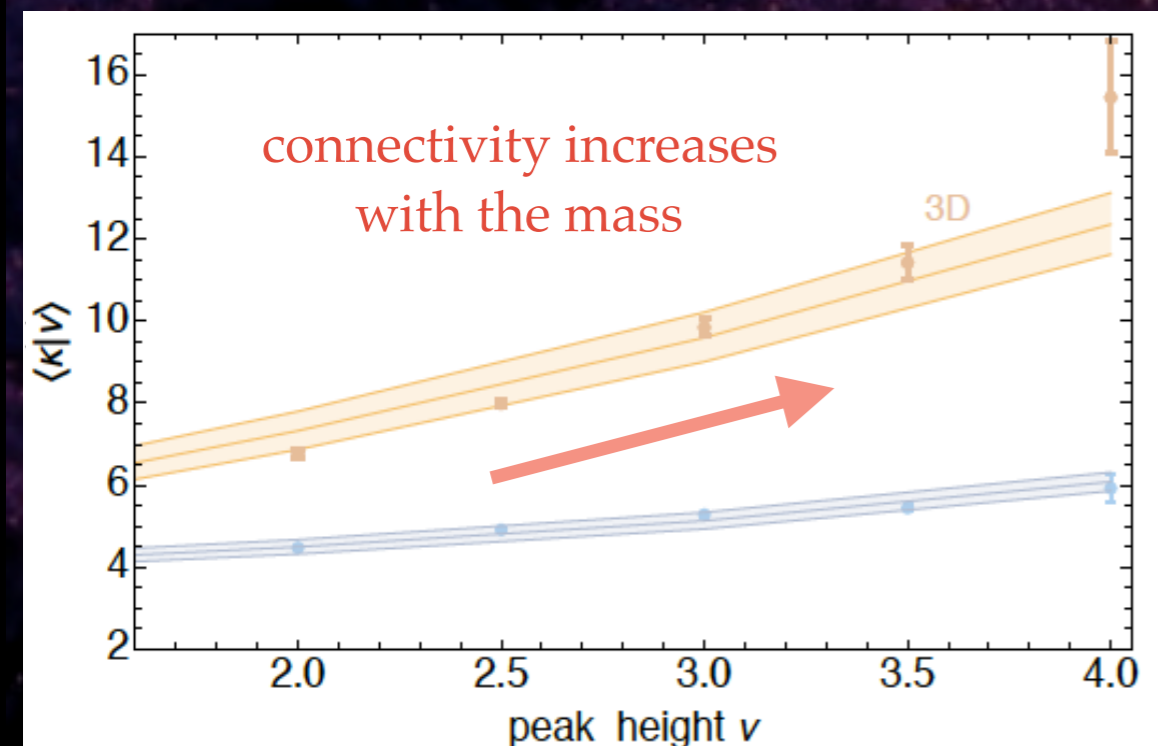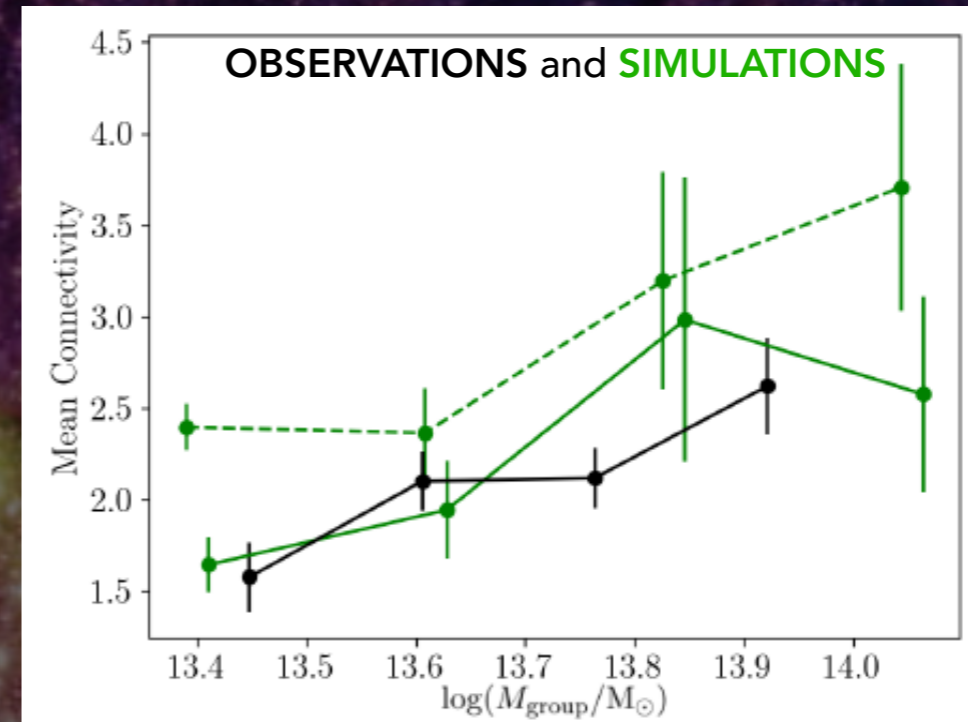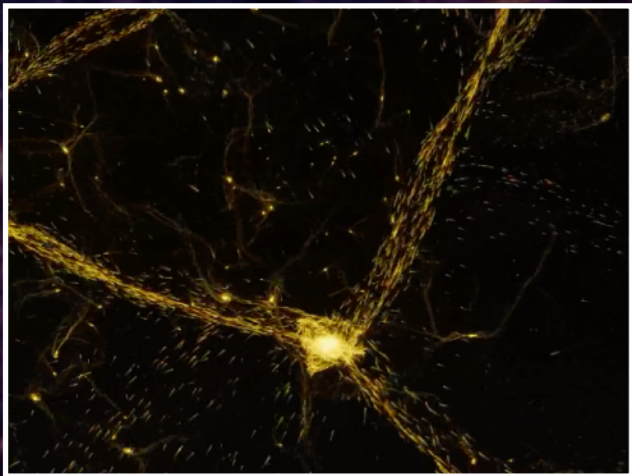see Aragón-Calvo et al. 2010; Pichon et al. 2010;*

Galaxy cluster environments
from their center to the LSS

2. H*ow the connection of clusters to the cosmic web influences the bulding up of clusters?*

Darragh Ford et al. 2019 (HorizonAGN and COSMOS)

connectivity increases
with the mass

3D

More massive, more connected

Codis, et al. 2018 (GRF theory & N-body simulation)

Merging event

Galaxy cluster environments
from their center to the LSS

2. How *the connection of clusters to the cosmic web influences the bulding up of clusters?*

Dynamical state

fraction of substructure

center offset

virial ratio

Kuchner, et al. 2020

Level of relaxation

Massive clusters are more dynamically unelaxed on average

ThreeHundred simulations

Galaxy cluster environments
from their center to the LSS

2. How *the connection of clusters to the cosmic web influences the bulding up of clusters?*
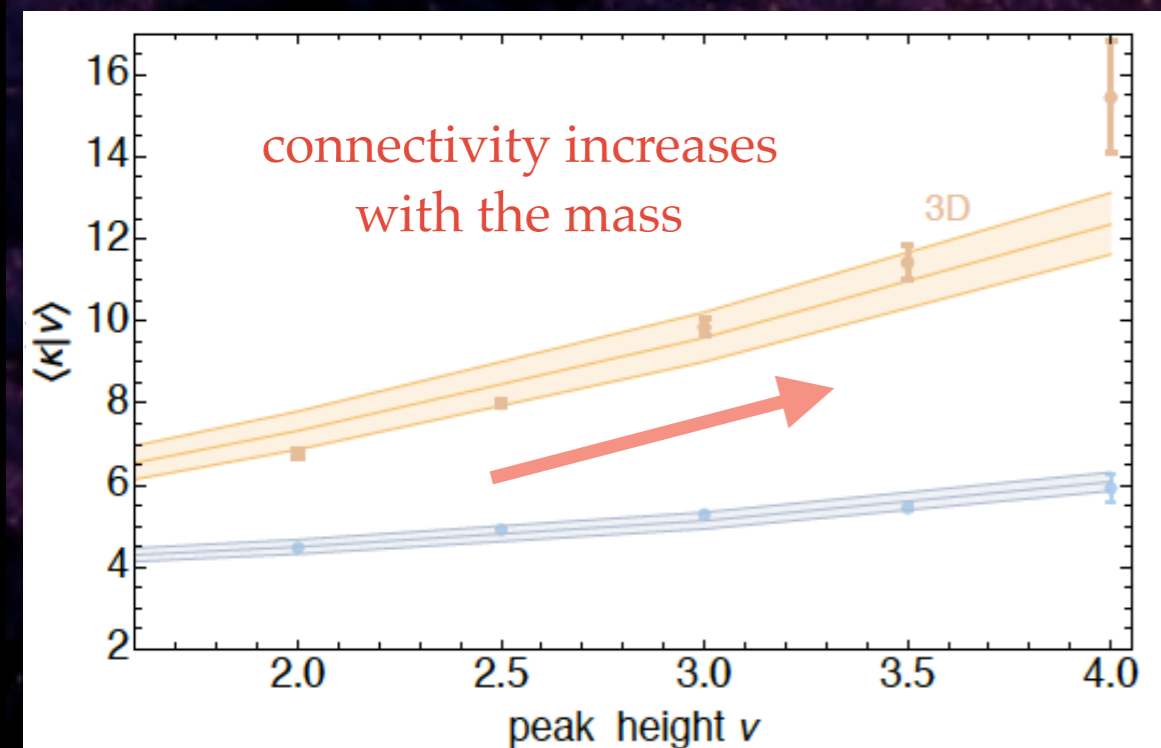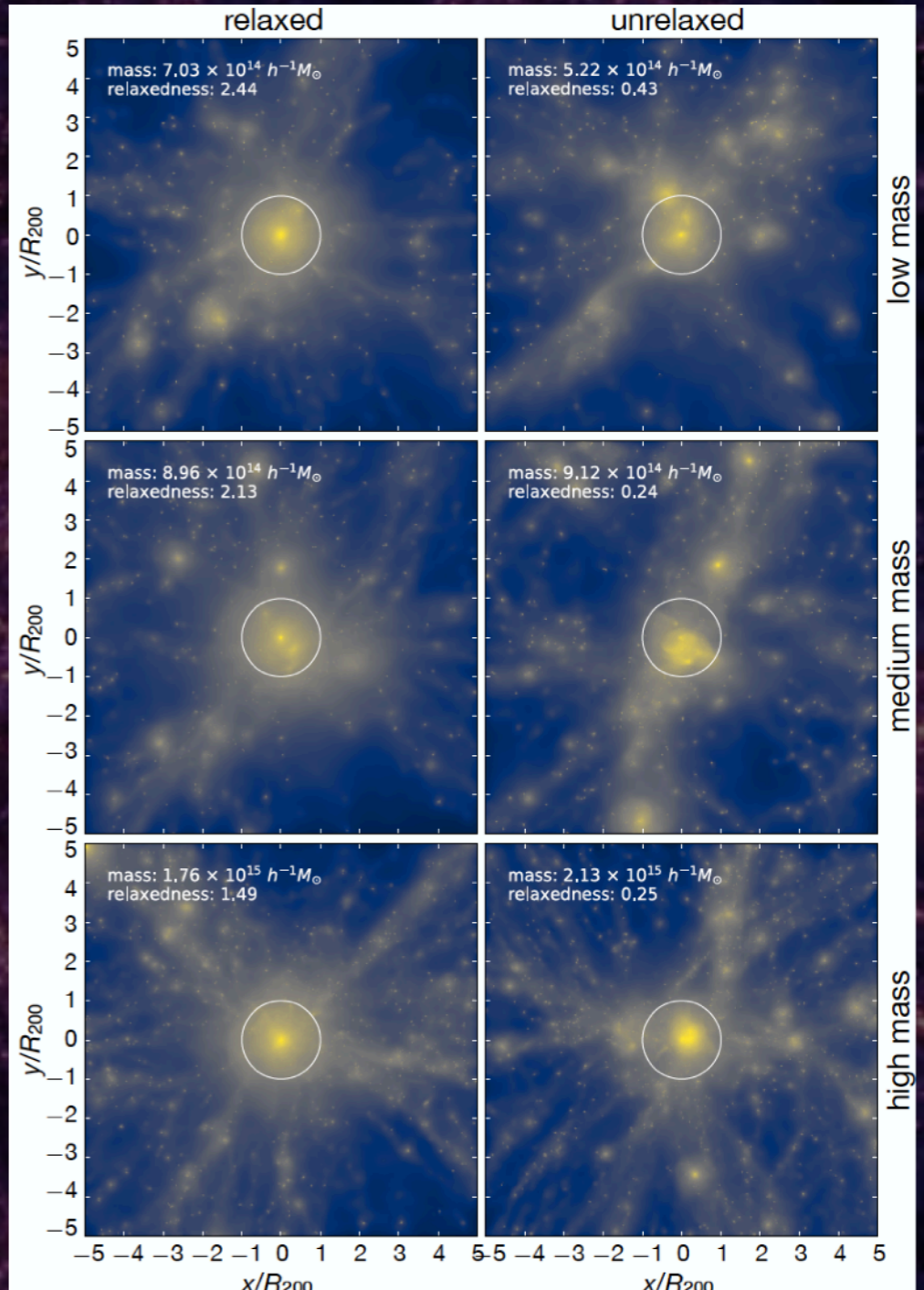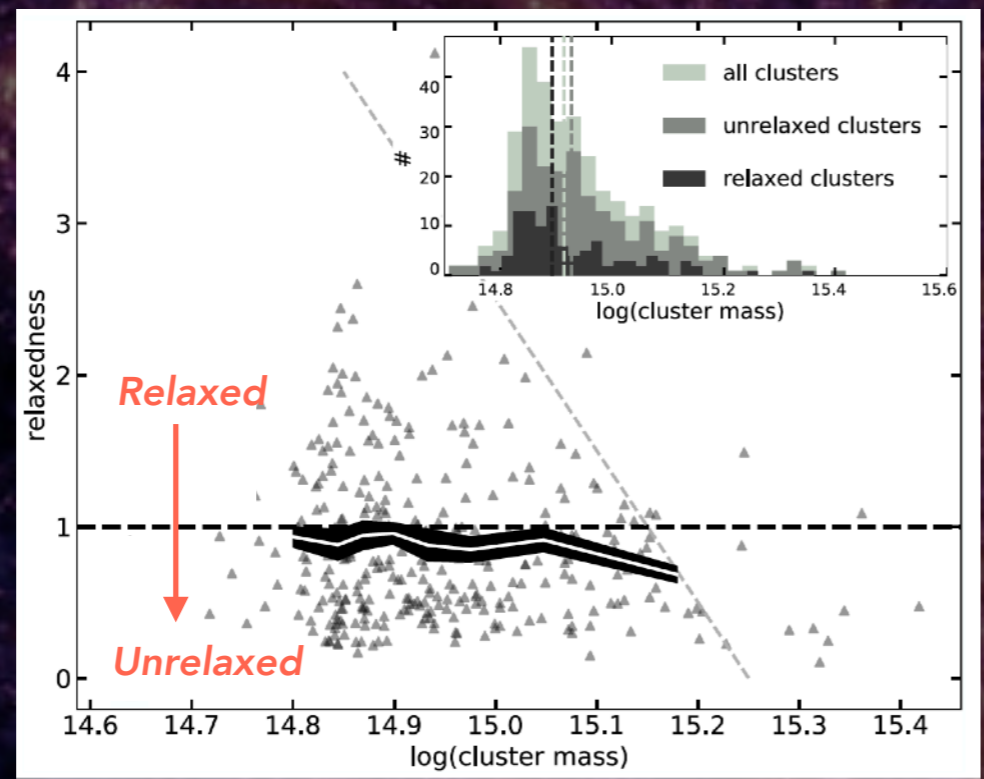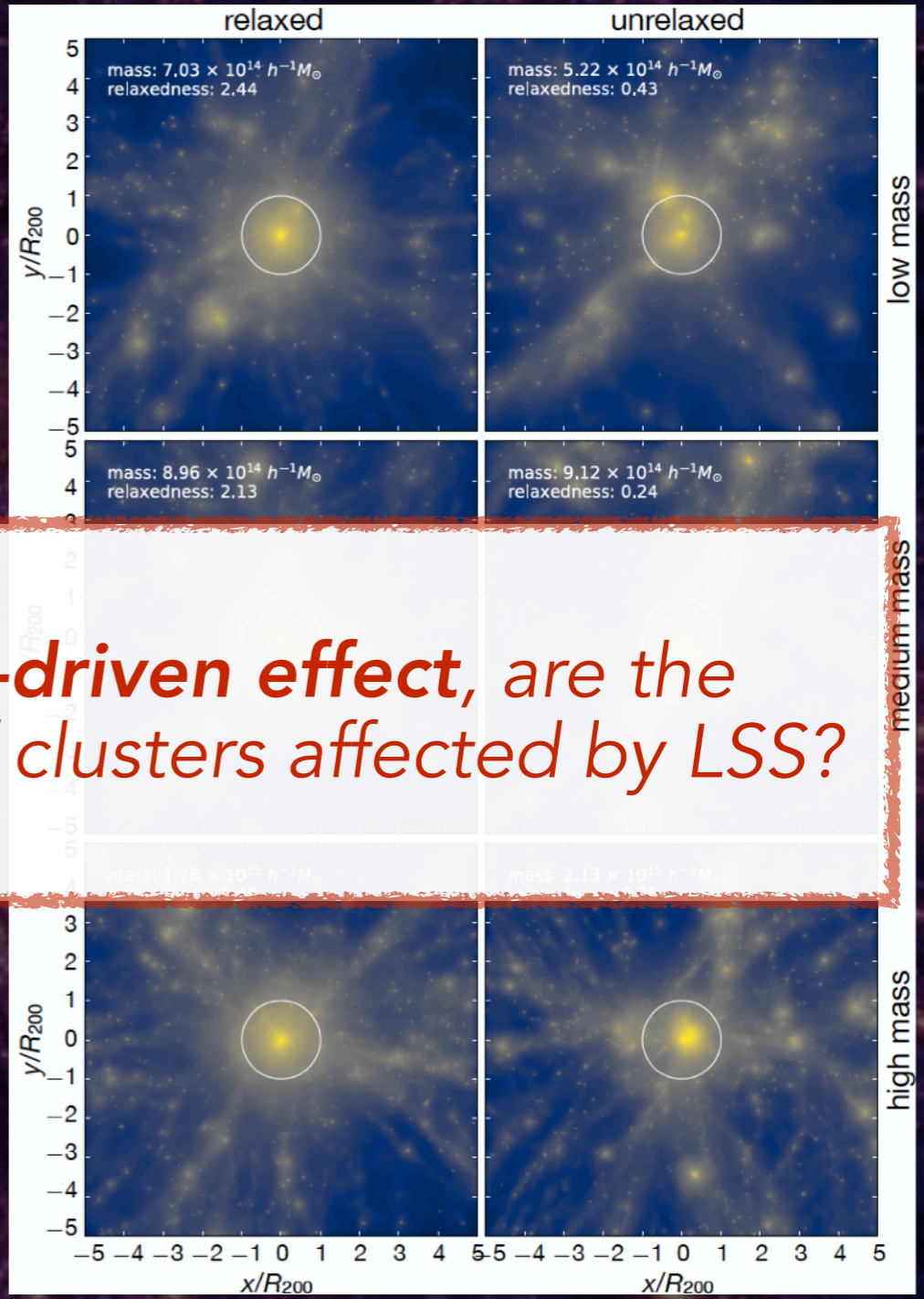
<u>Dynamical state</u>

fraction of substructure

center offset

virial ratio

Kuchner, et al. 2020

Level of relaxation

Relaxed

Unrelaxed

Beyond this mass-driven effect, *are the physical properties of clusters affected by LSS?*
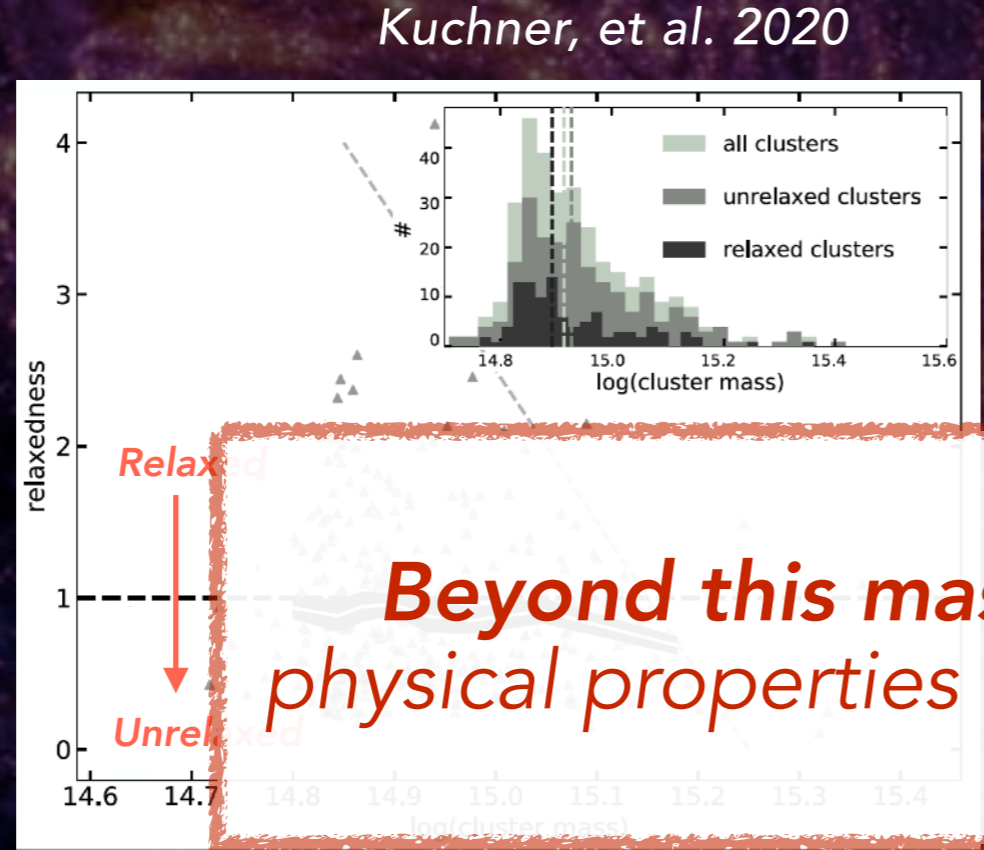
Massive clusters are more dynamically unelaxed on average

Shape and connectivity of clusters
Impact of dynamical state and accretion history

Gouin, et al. 2021

IllustrisTNG simulation

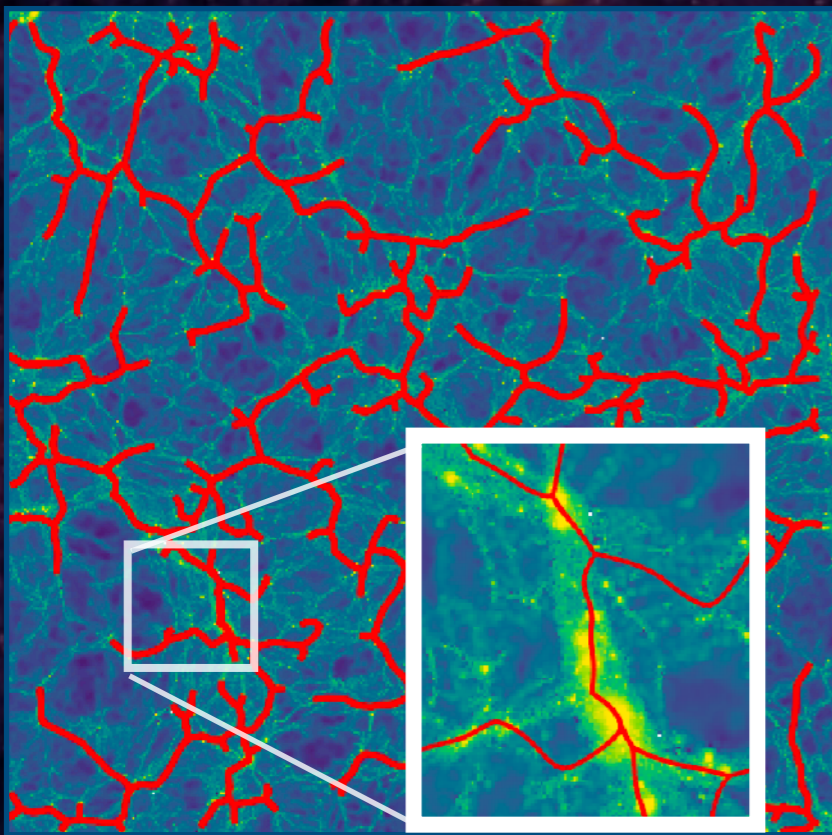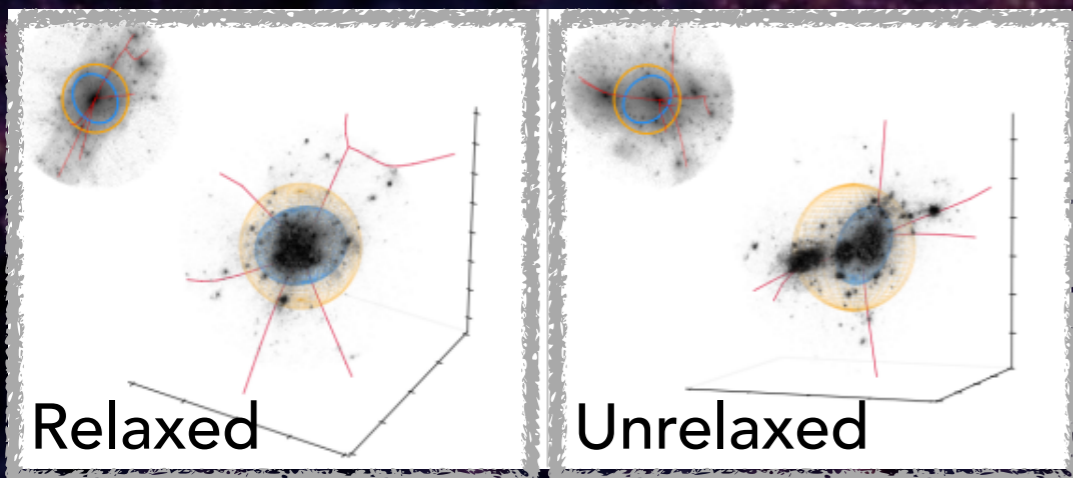*T-ReX algorithm* *Bonnaire et al (2020)*

~2400 groups/clusters with $M_{200}>10^{13}Mo/h$

Relaxed

Unrelaxed

2. How *the connection of clusters to the cosmic web influences the bulding up of clusters?*
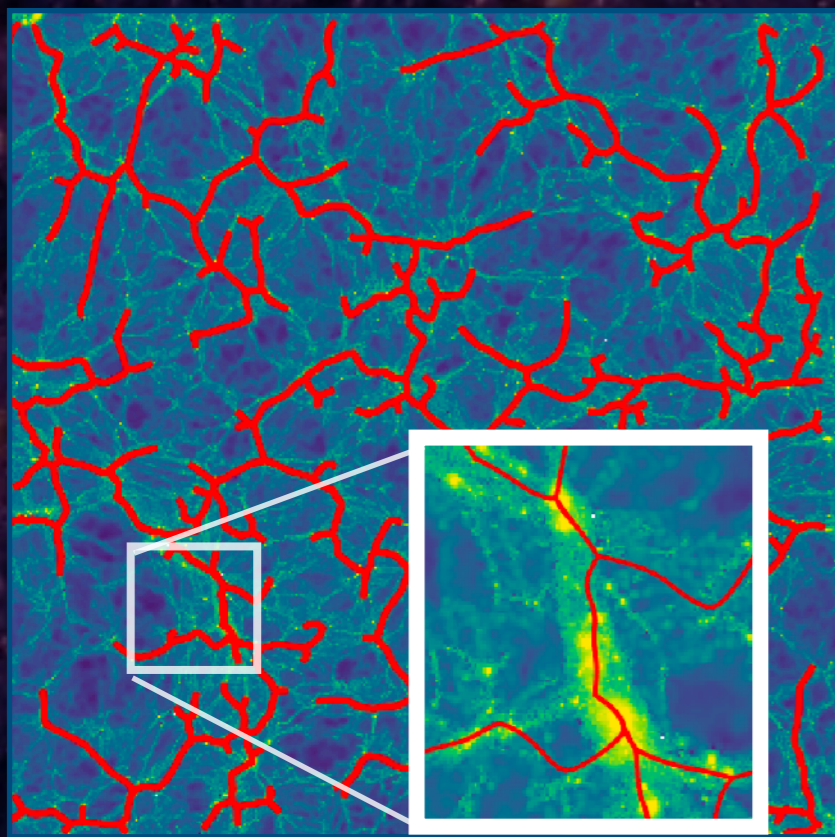
Shape and connectivity of clusters
Impact of dynamical state and accretion history

Gouin, et al. 2021

IllustrisTNG simulation

2. How *the connection of clusters to the cosmic web influences the bulding up of clusters?*
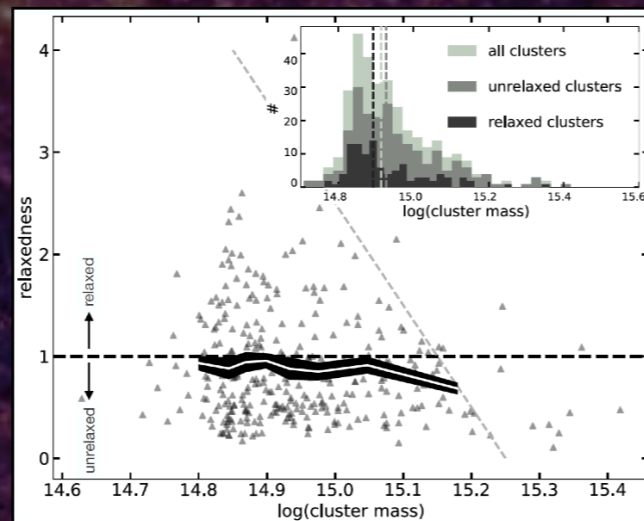
Kuchner, et al. 2020

Relaxedness - Mass
(depending on Connectivity)

$\kappa > 3$
$\kappa = 3$
$\kappa = 1,2$

Relaxed

Unrelaxed

T-ReX algorithm *Bonnaire et al (2020)*

~2400 groups/clusters with $M_{200} > 10^{13} Mo/h$
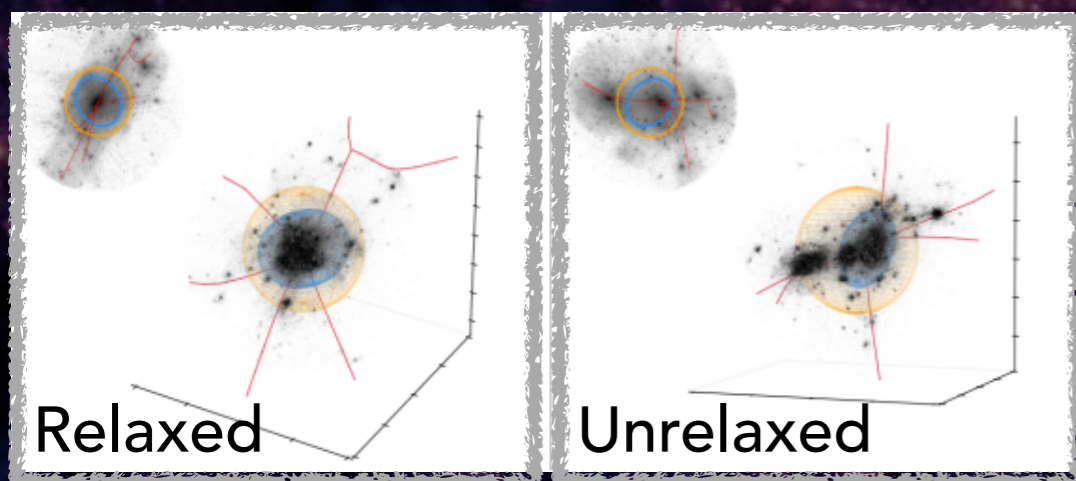
Relaxed   Unrelaxed

**Independantly of the mass,
highly connected clusters are less relaxed
than low-connected clusters**

Shape and connectivity of clusters
Impact of dynamical state and accretion history

Gouin, et al. 2021

IllustrisTNG simulation

T-ReX algorithm Bonnaire et al (2020)

~2400 groups/clusters with $M_{200} > 10^{13}$ Mo/h

Relaxed   Unrelaxed
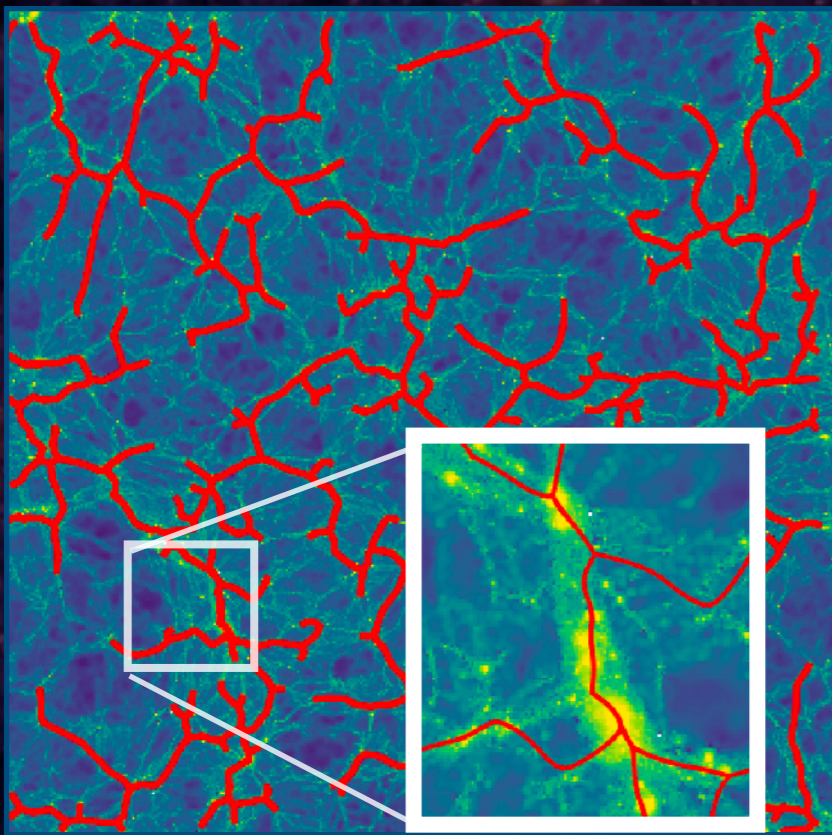
2. How *the connection of clusters to the cosmic web influences the bulding up of clusters?*

Mass growth - Mass relation (depending on Connectivity)
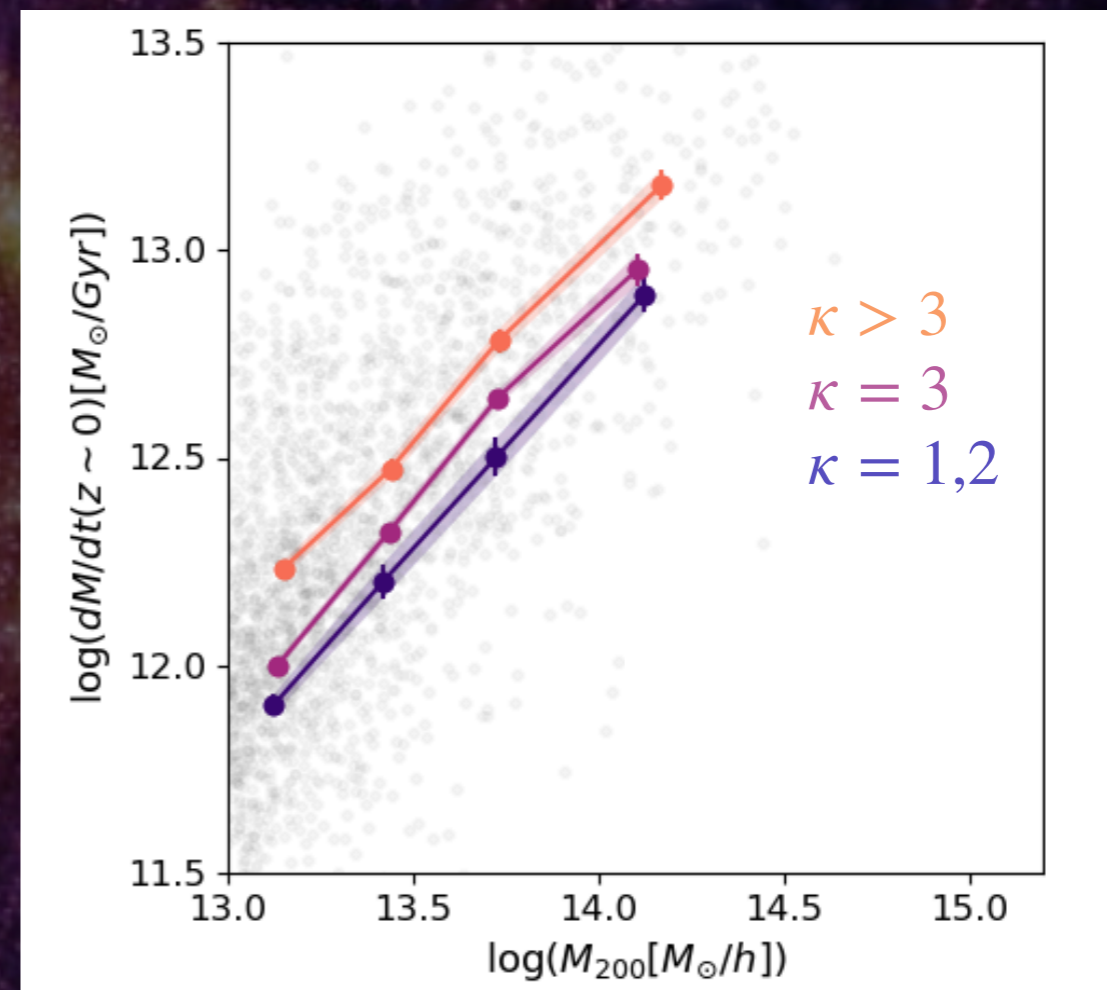
$\kappa > 3$
$\kappa = 3$
$\kappa = 1,2$

**Independantly of the mass,
highly connected clusters grow faster**

Shape and connectivity of clusters
Impact of dynamical state and accretion history

Gouin, et al. 2021

IllustrisTNG simulation

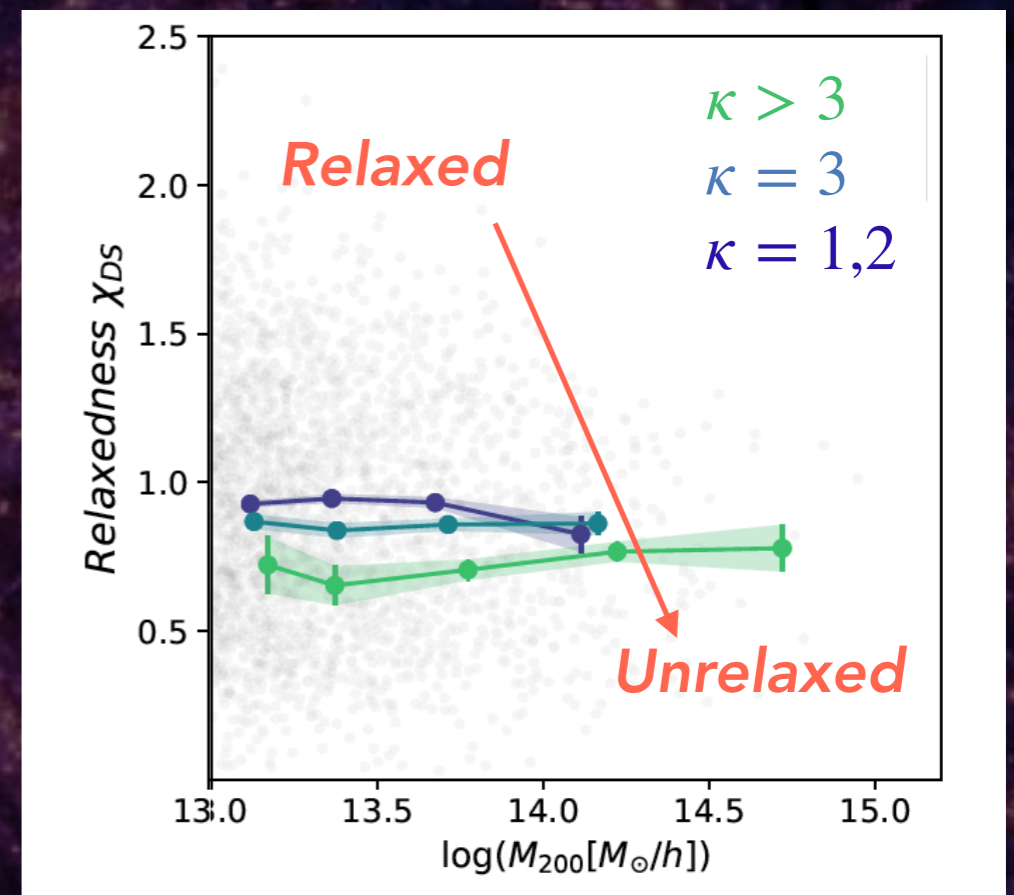*T-ReX algorithm* Bonnaire et al (2020)

~2400 groups/clusters with $M_{200} > 10^{13}$Mo/h

$\epsilon \sim 0.3$ $\epsilon \sim 0.05$

Ellipticity

2. How *the connection of clusters to the cosmic web influences the bulding up of clusters?*

Ellipticity-Mass relation (depending of Connectivity)

$\kappa > 3$
$\kappa = 3$
$\kappa = 1,2$

Ellipticity

$\log(M_{200}[M_\odot/h])$

**Independantly of the mass,
highly connected clusters are more elliptical**

Shape and connectivity of clusters
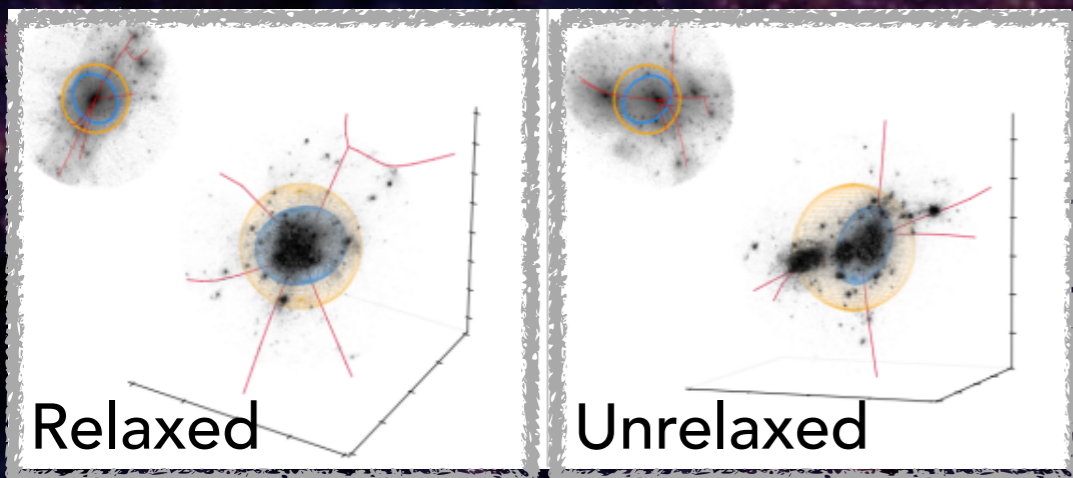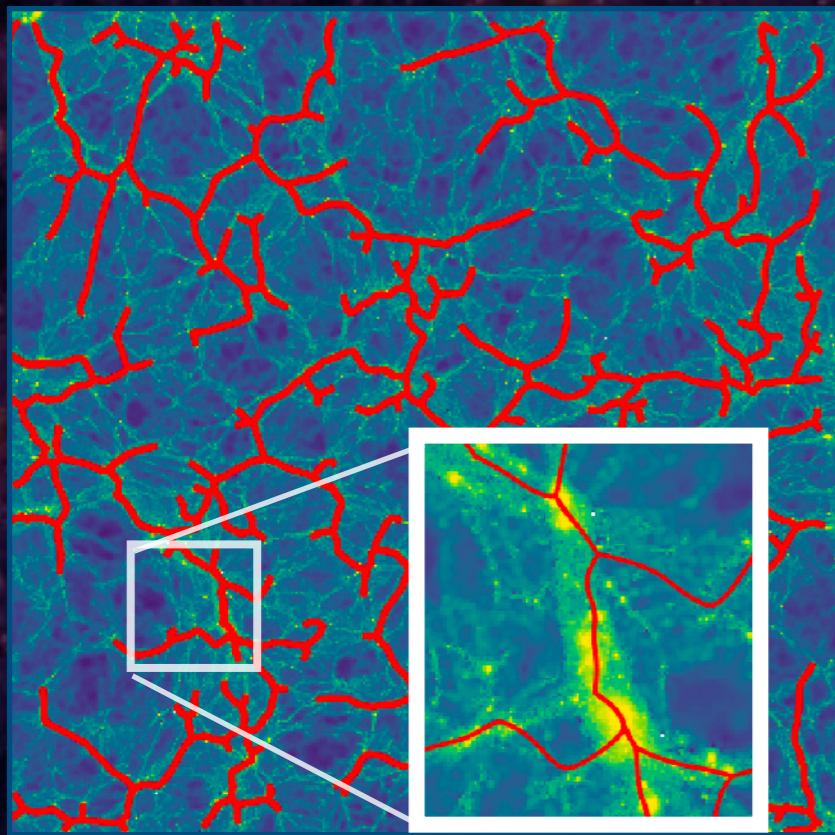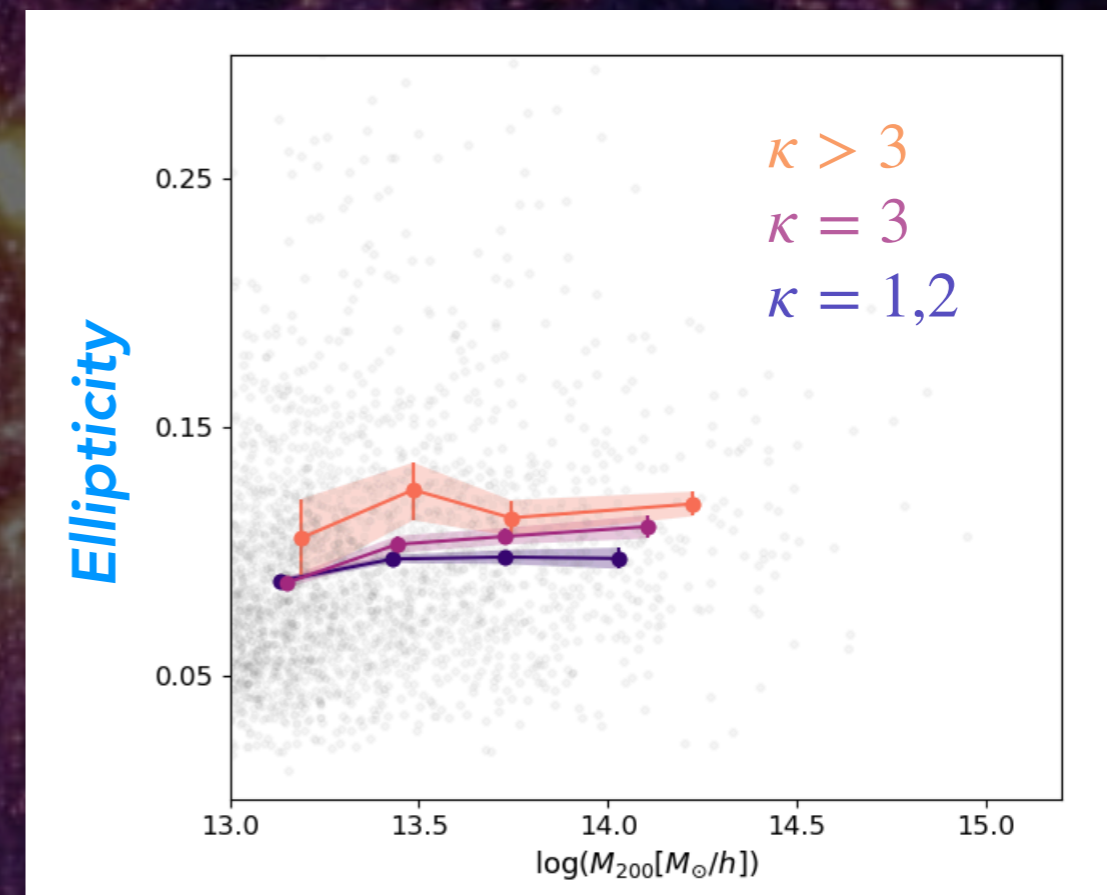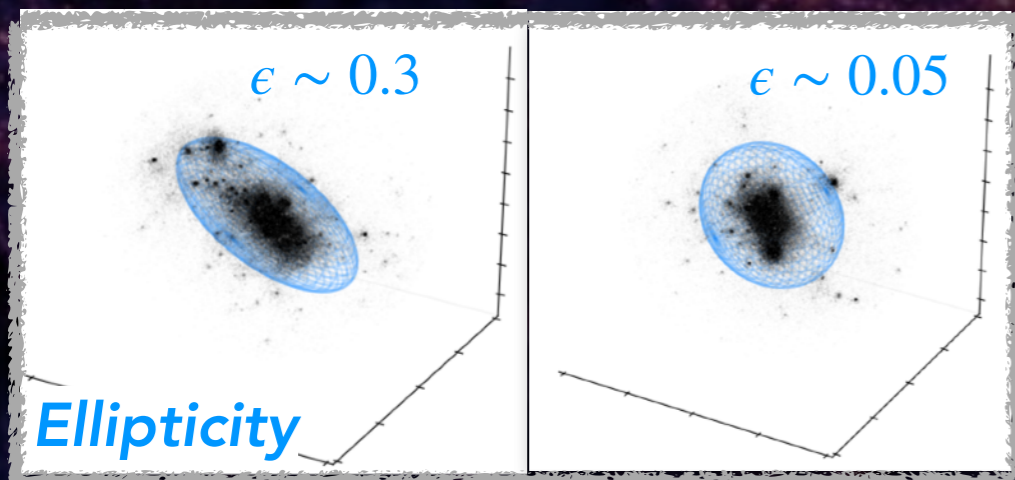# Impact of dynamical state and accretion history

2. H*ow the connection of clusters to the cosmic web influences the bulding up of clusters?*

Gouin, et al. 2021

Dynamical-Evolutionary state dependancy

• *the formation redshift*

Mass accretion rate $\quad \Gamma = \dfrac{\Delta \log(M_{200m})}{\Delta a}$

Formation redshift $\quad M(z_{form}) = \dfrac{M(z=0)}{2}$

Mass accretion rate

Relaxed

Unrelaxed

Formation redshift
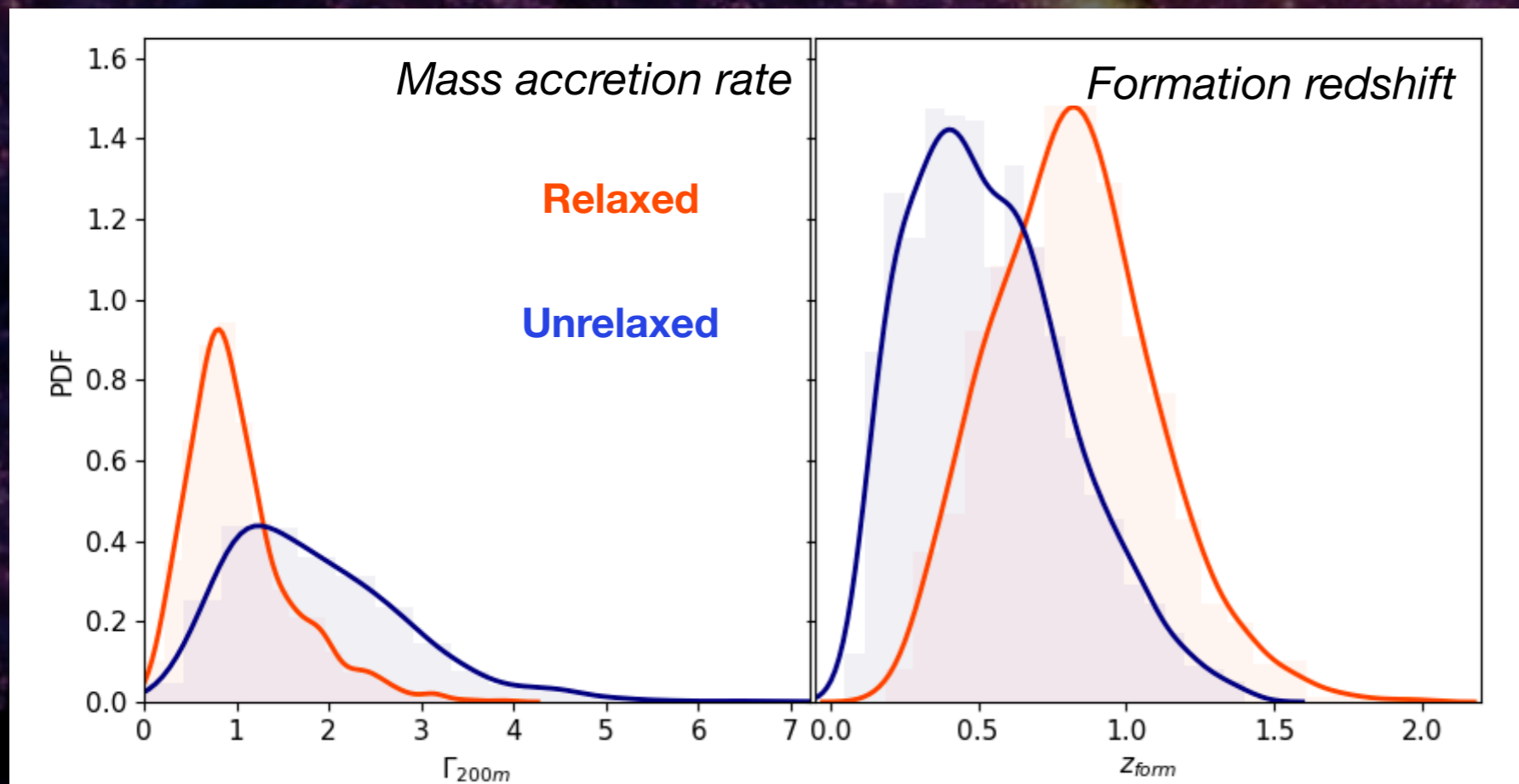
Unrelaxed groups are formed more recently and are in fast accreting phase

See also Power et al. (2012), Diemer et al (2014) Mostoghiu et al. (2019)

Shape and connectivity of clusters
Impact of dynamical state and accretion history

2. How the connection of clusters to the cosmic web influences the bulding up of clusters?

Gouin, et al. 2021

Dynamical-Evolutionary state dependancy

• *the formation redshift*

Mass accretion rate $\quad \Gamma = \dfrac{\Delta \log(M_{200m})}{\Delta a}$

Formation redshift $\quad M(z_{form}) = \dfrac{M(z=0)}{2}$

Relaxed
$z_{form} > 0.7$
$\Gamma < 1.5$

Unrelaxed
$z_{form} < 0.4$
$\Gamma > 2$

Unrelaxed groups are formed more recently and are in fast accreting phase

Early-formed slow accretion phase relaxed clusters

Recently-formed fast accretion phase unrelaxed clusters

Shape and connectivity of clusters
Impact of dynamical state and accretion history
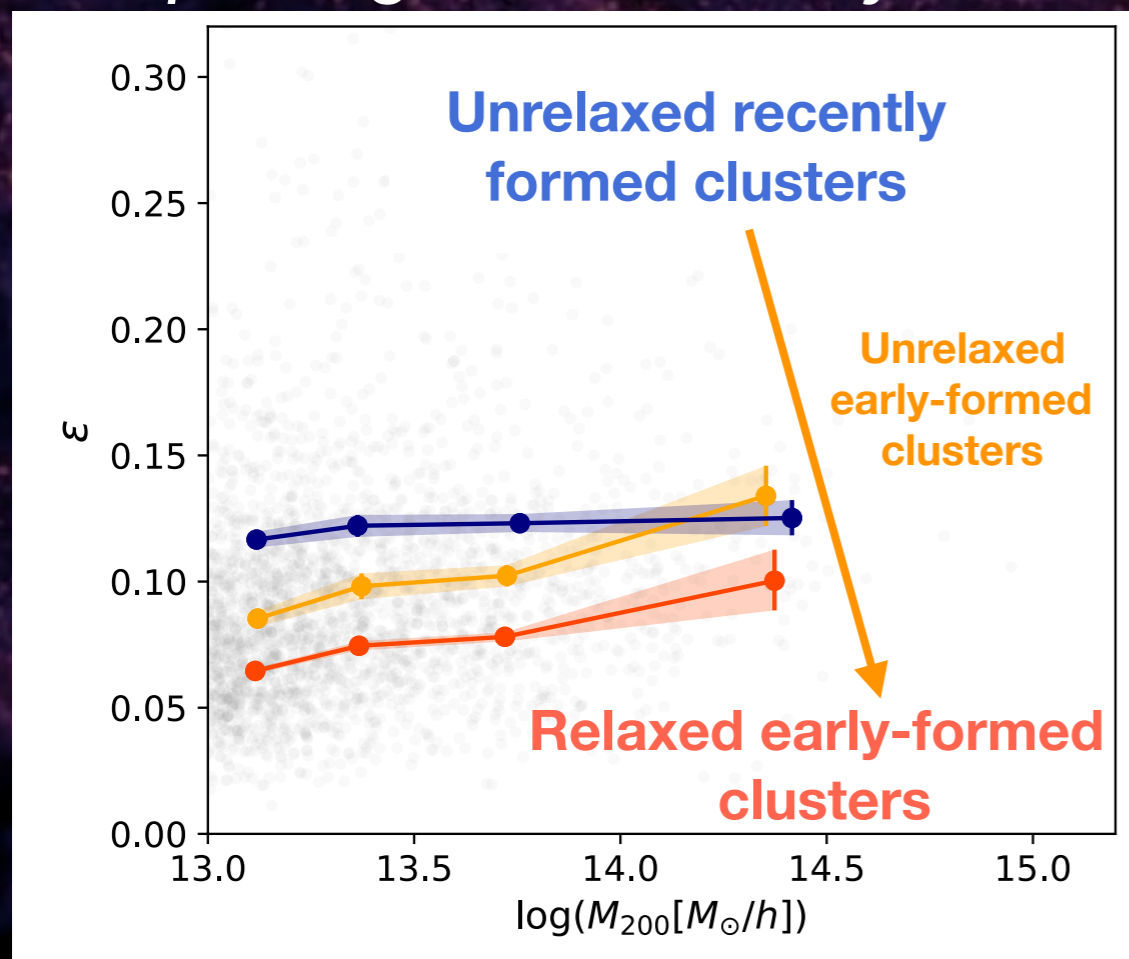
2. H*ow the connection of clusters to the cosmic web influences the bulding up of clusters?*
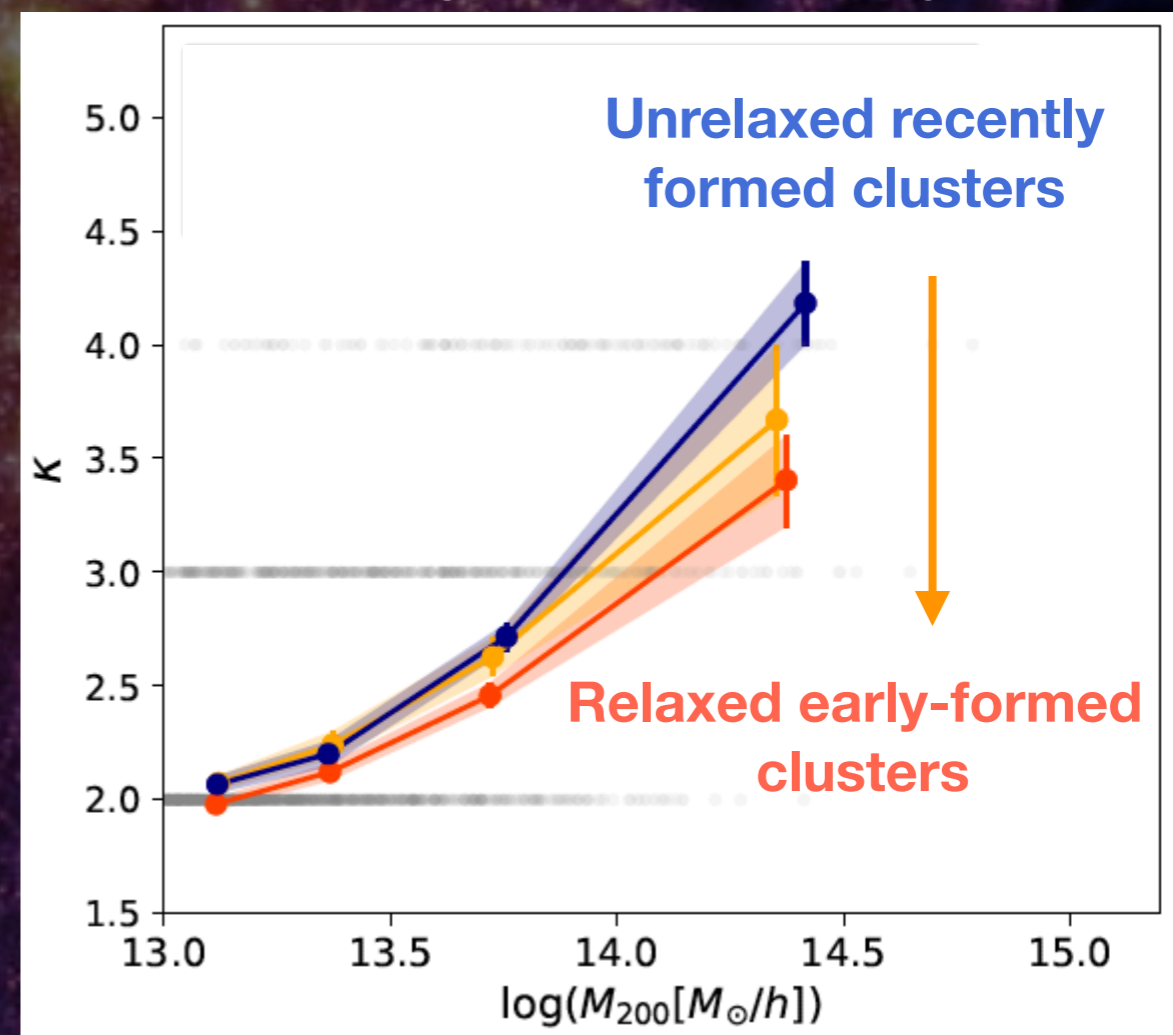
Gouin, et al. 2021

Dynamical-evolutionary state dependancy
Ellipticity and connectivity of clusters are resulting from different mass assembly histories

*Ellipticity-Mass relation
(depending on evolutionary state)*

*Connectivity-Mass relation
(depending on evolutionary state)*

Shape and connectivity of clusters
Impact of dynamical state and accretion history

2. How the connection of clusters to the cosmic web influences the bulding up of clusters?

Gouin, et al. 2021

Different environments traduce different evolutionary state of clusters

Illustrate our finding in observations

A2142 cluster (Einasto et al. 2020)

- elongated shape
- large number of substructures
- merging system
- ➡ **Recently formed type of objects**

COMA cluster (Malavasi et al. 2020)

- more spherical
- high concentration & low accretion rate
- ➡ **Early formed type of objects**

Unrelaxed young fast-accreting clusters

A2142

Coma

Relaxed early-formed clusters

κ

$\log(M_{200}[M_{\odot}/h])$

Gouin, et al. 2021

Shape and connectivity of clusters
Impact of dynamical state and accretion history

Gouin, et al. 2021

2. How the connection of clusters to the cosmic web influences the bulding up of clusters?

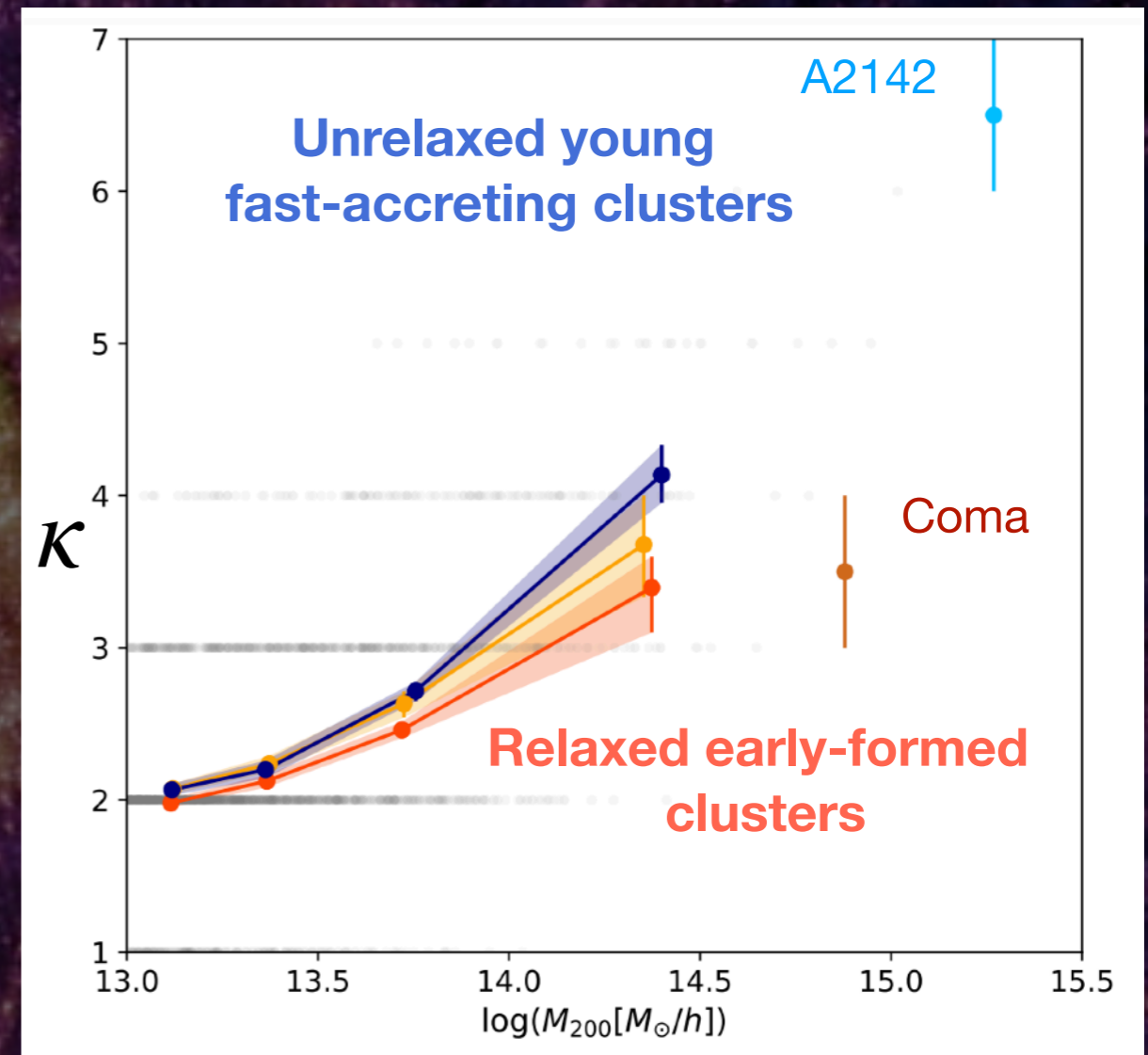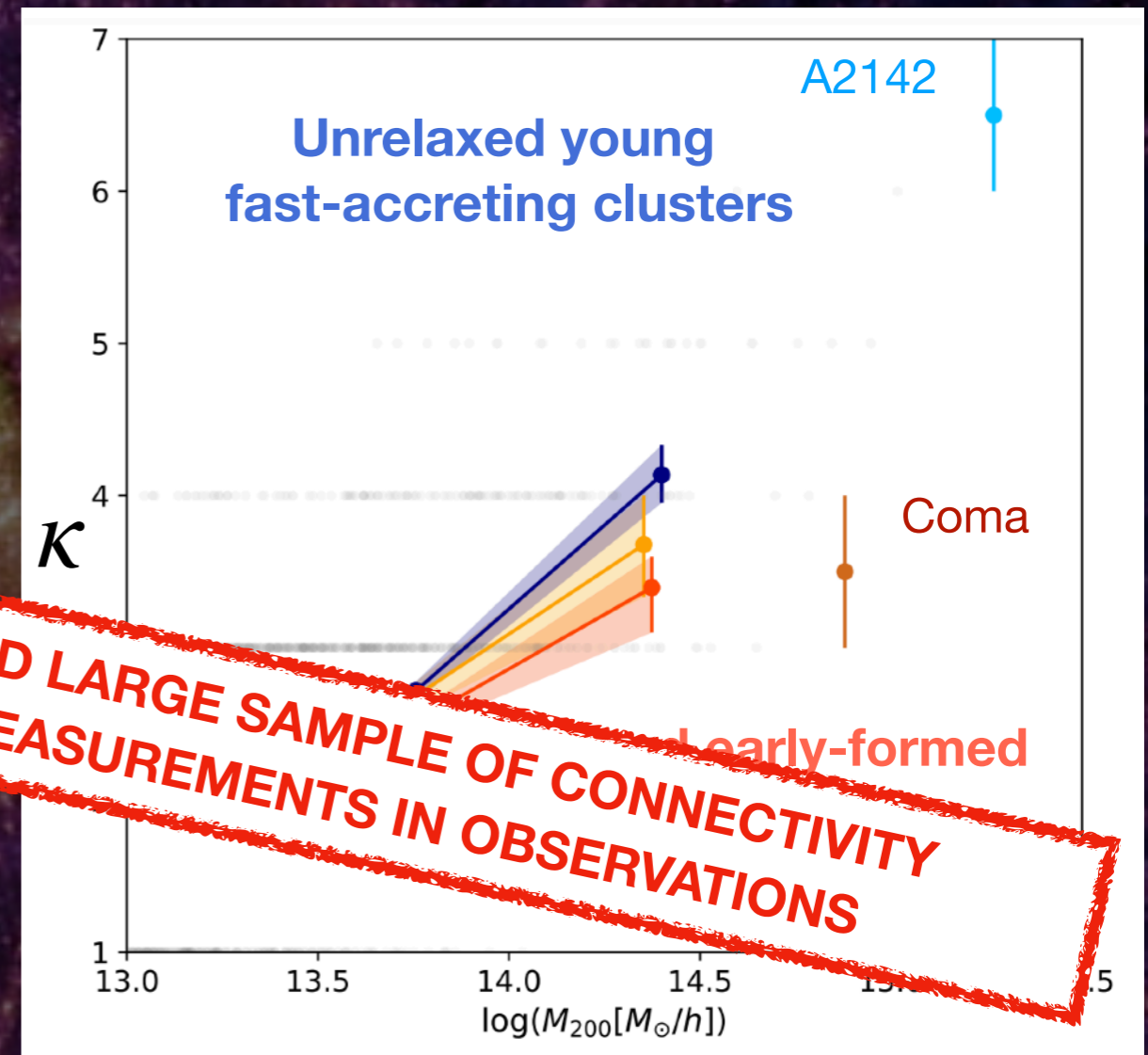**Different environments traduce different evolutionary state of clusters**

Illustrate our finding in observations

A2142 cluster (Einasto et al. 2020)

- elongated shape
- large number of substructures
- merging system
- ➡ **Recently formed type of objects**

COMA cluster (Malavasi et al. 2020)

- more spherical
- high concentration & low accretion rate
- ➡ **Early formed type of objects**

Gouin, et al. 2021

NEED LARGE SAMPLE OF CONNECTIVITY MEASUREMENTS IN OBSERVATIONS

Conclusions

In-falling regions in cluster outskirts (from 1 to 4 R_{200})

▸ **Azimuthal environment of galaxies around clusters**

Gouin+20

- ▸ Angular features detected in harmonic space

- ▸ Galaxies tend to be **preferentially quenched inside filaments** around clusters

▸ **The connectivity of clusters depending of their properties**

Gouin+21

- ▸ **Beyond the trend governed by the mass**, we exhibited additional contribution of cluster environment on their properties (dynamic, Morphology, growth rate).

- ▸ Large scatter in shape and connectivity of clusters can be explained by **mass assembly history**