KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Lecture 2

Effect of the multi-scale web filaments on galaxy evolution

Daniela Galárraga-Espinosa

Kavli-IPMU Fellow
Tokyo-Japan

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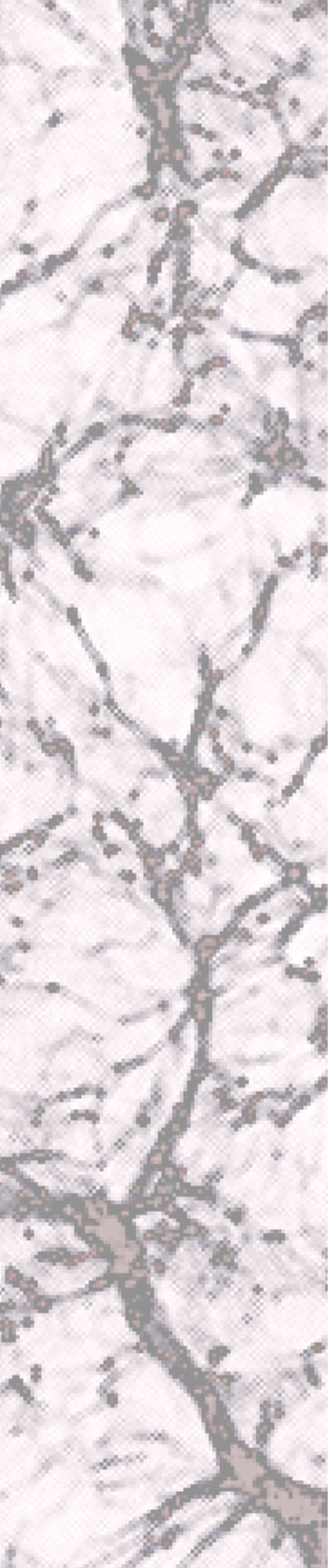
daniela.galarraga@ipmu.jp

Disclaimer

This lecture will not be about galaxy evolution (internal processes, inflows, outflows, …).

It will be about linking **galaxy** *observable* properties and the *observable* **cosmic web.**
Studies done by the Cosmic Web community, many pioneering works, but many naive views.

For the theory on galaxy evolution, wait for Peeter's talk (day 4)



Effect of the multi-scale web filaments on galaxy evolution

Plan of the lecture

1) Results: First generation *(general excitement)*

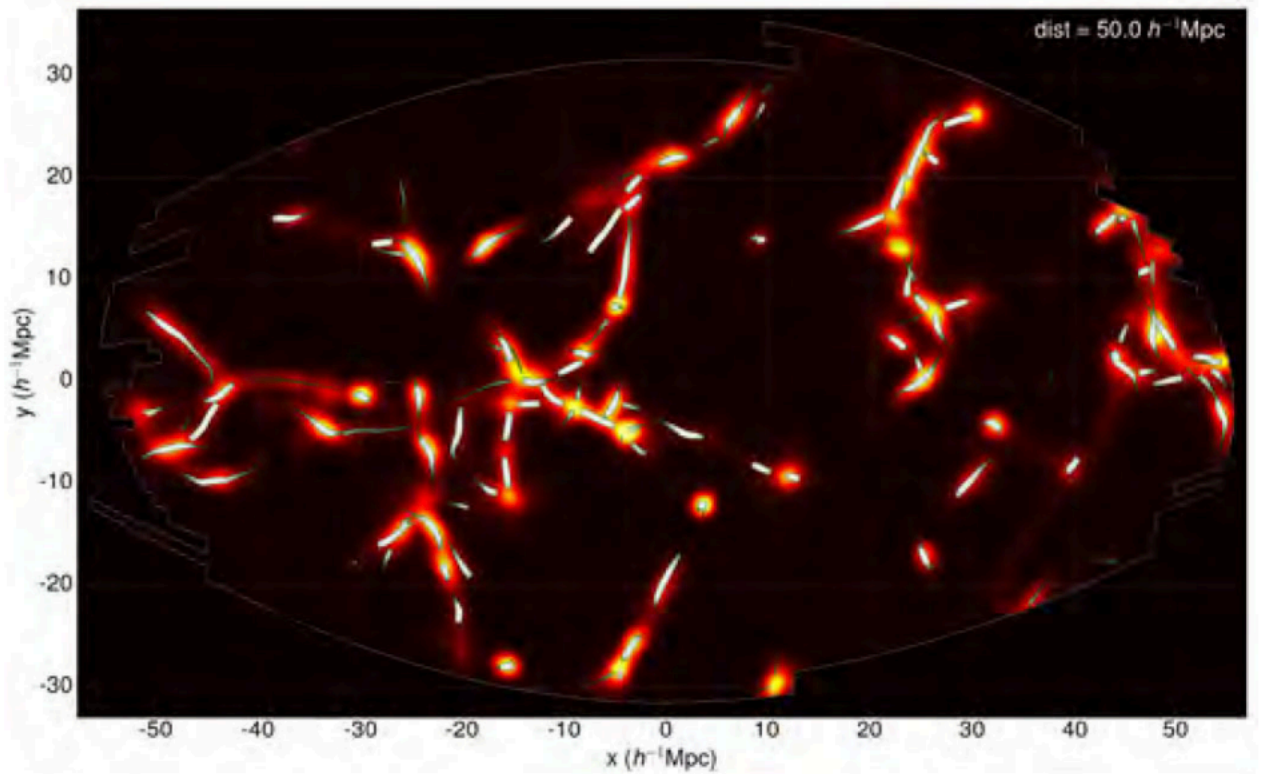
2) Results: Second generation

3) Current picture *(insights from the galaxy evolution community)*

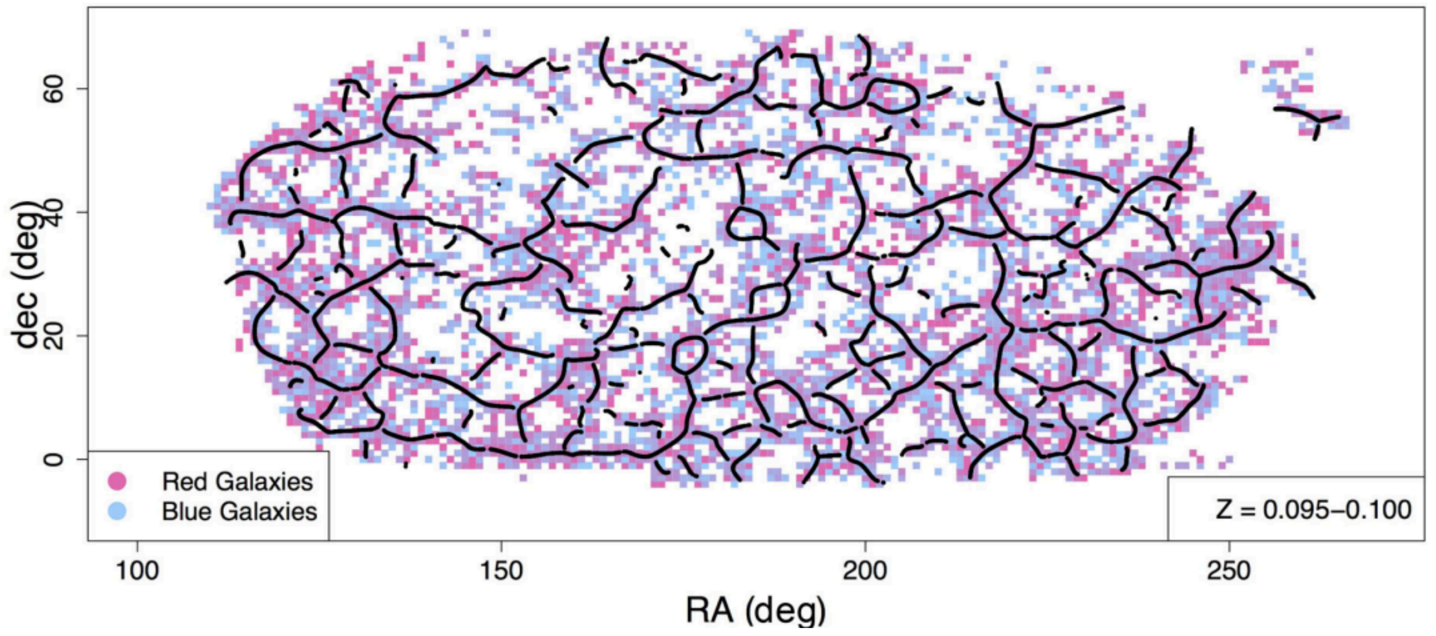
4) Summary: a complicated puzzle

We have data! Let’s identify the cosmic web

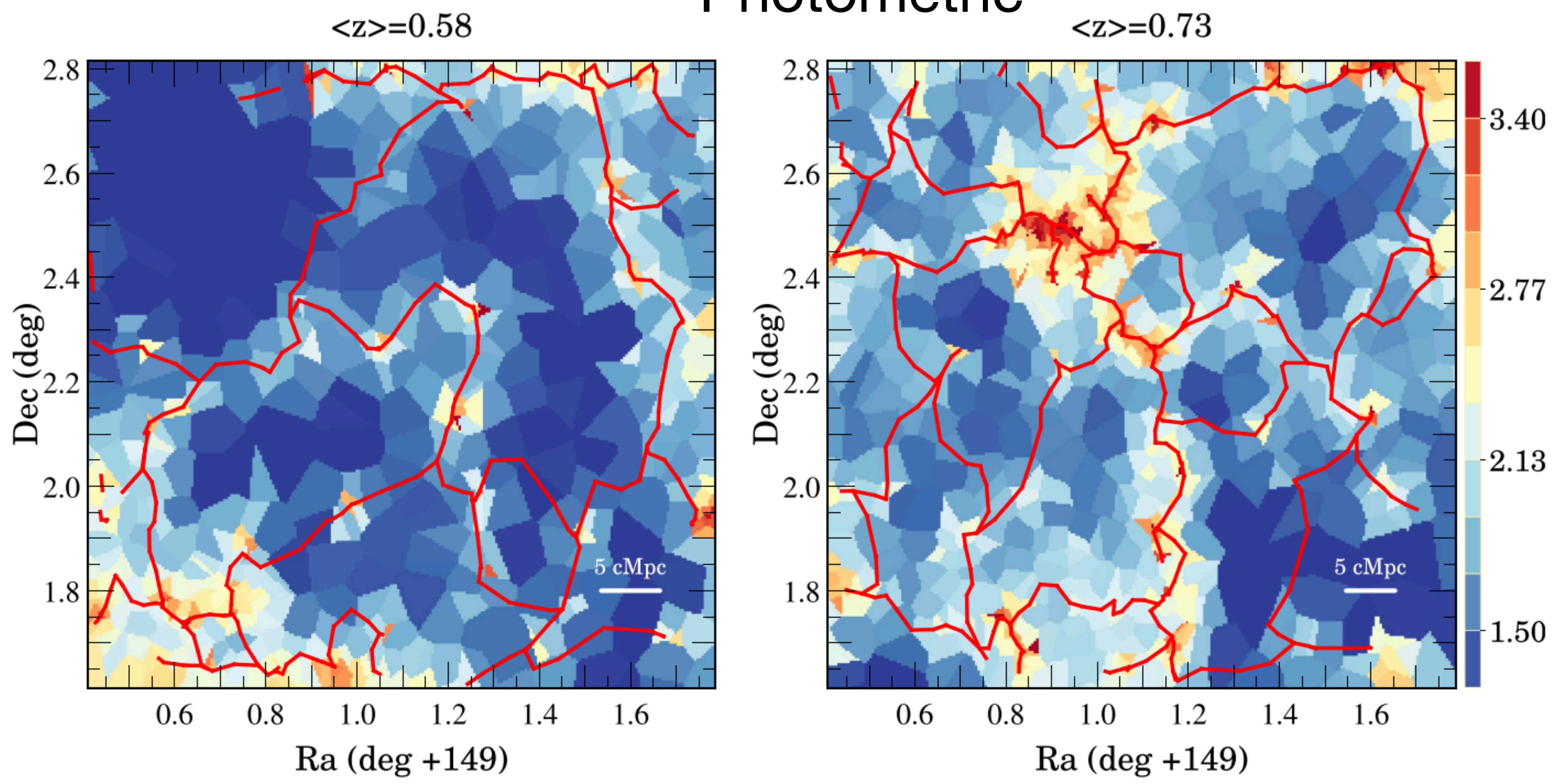
SDSS (Tempel et al. 2014)



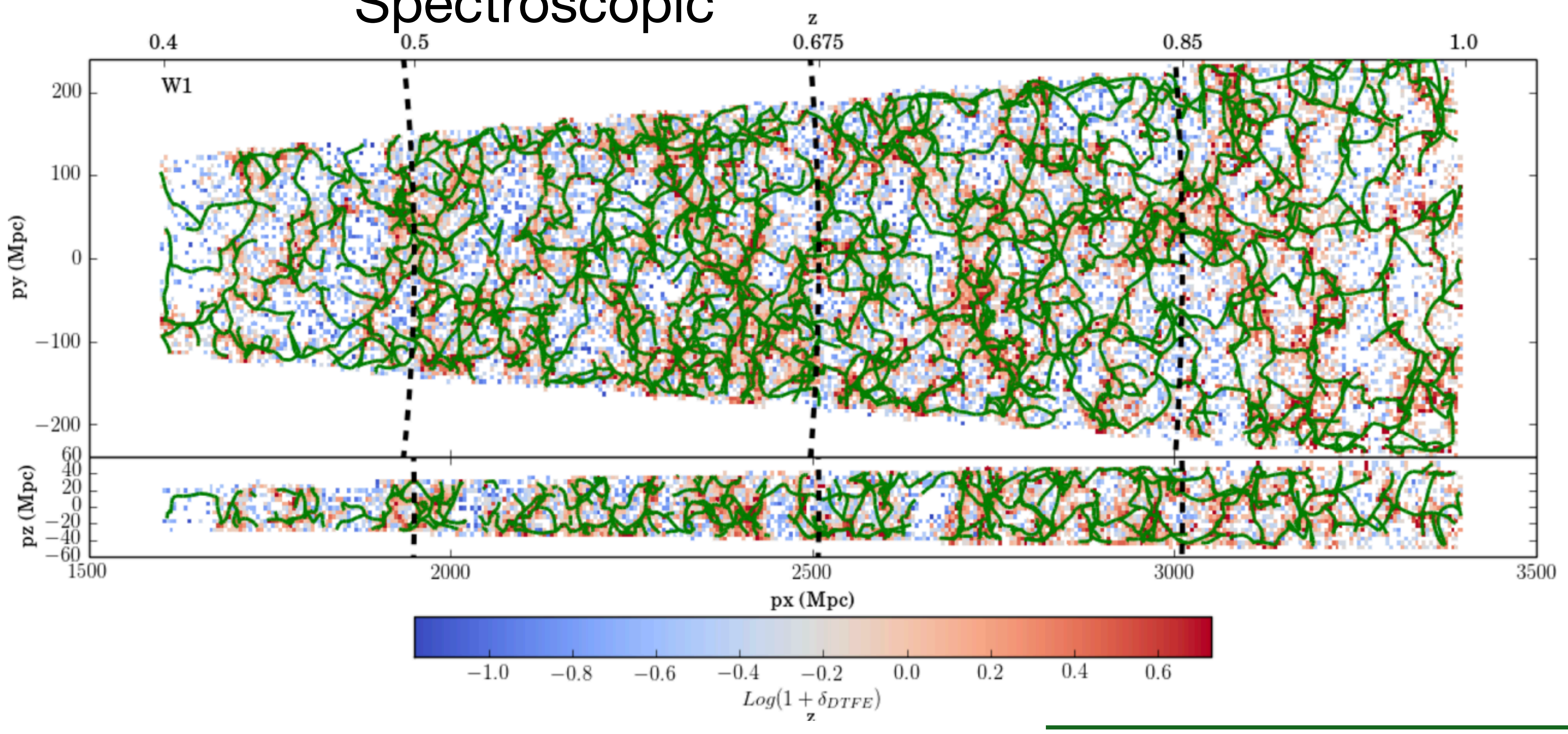
SDSS (Chen et al. 2017)



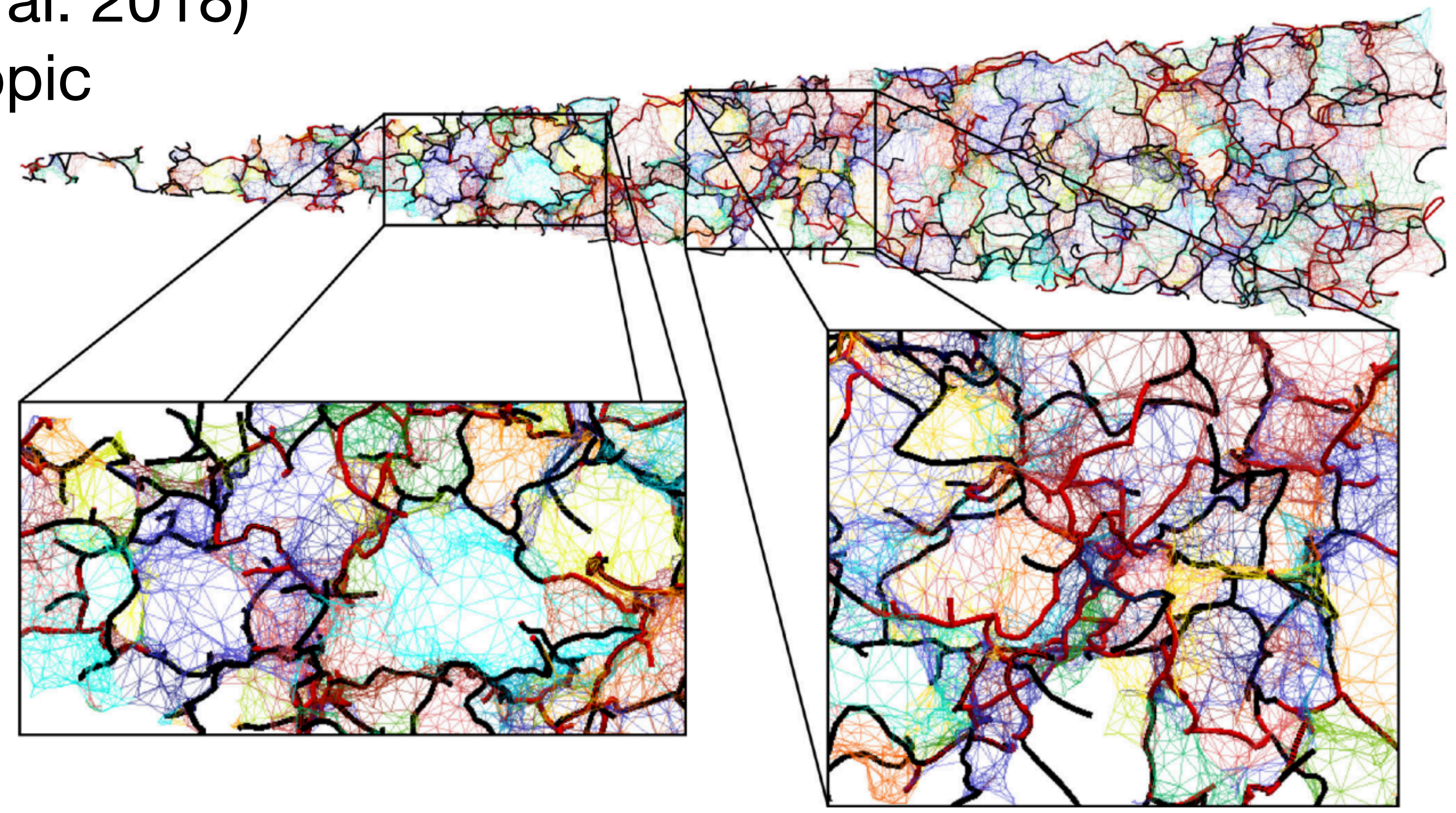
COSMOS (Laigle et al. 2018)
Photometric



VIPERS (Malavasi et al.2017)
Spectroscopic



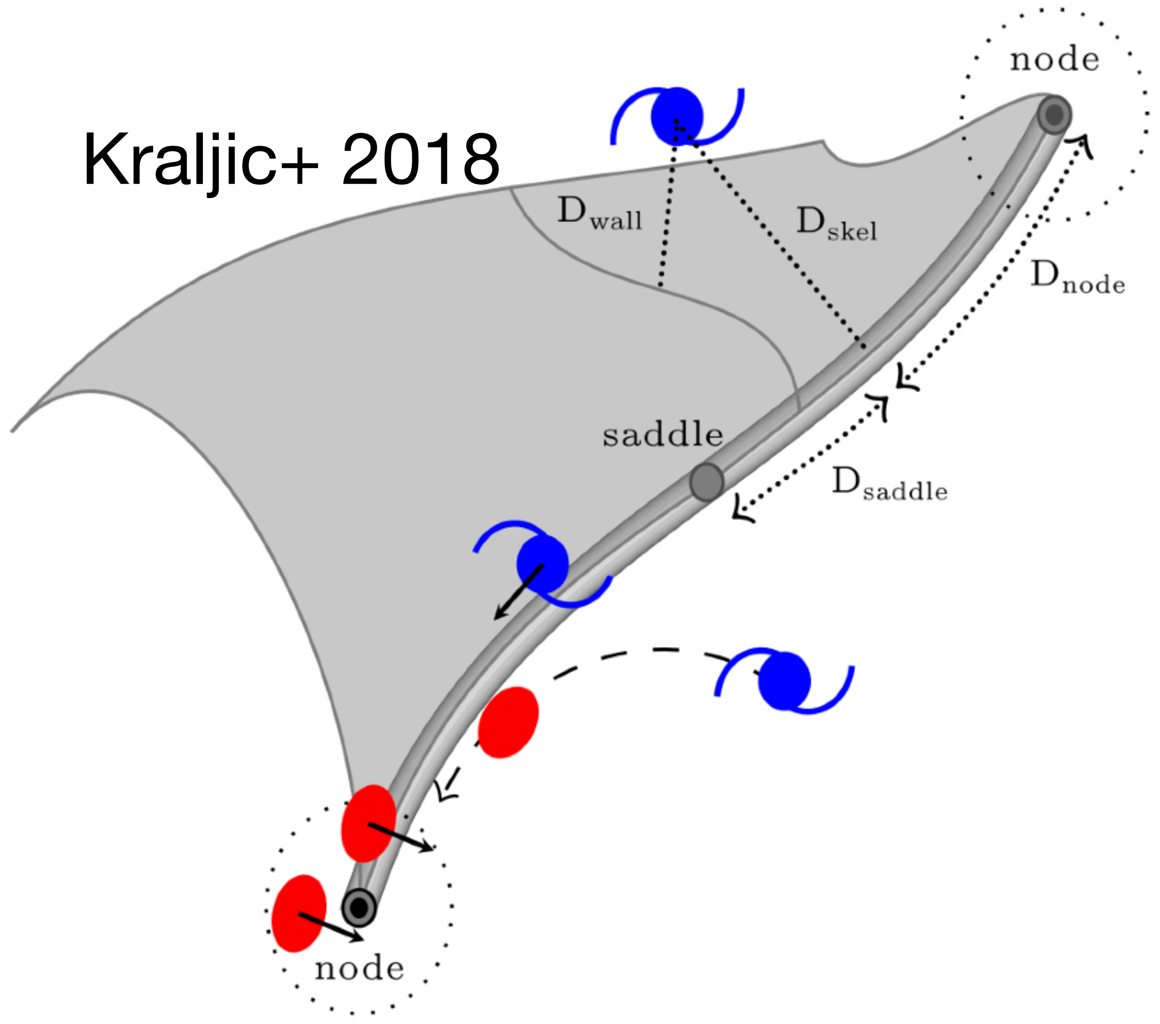
GAMA (Kraljic et al. 2018)
Spectroscopic



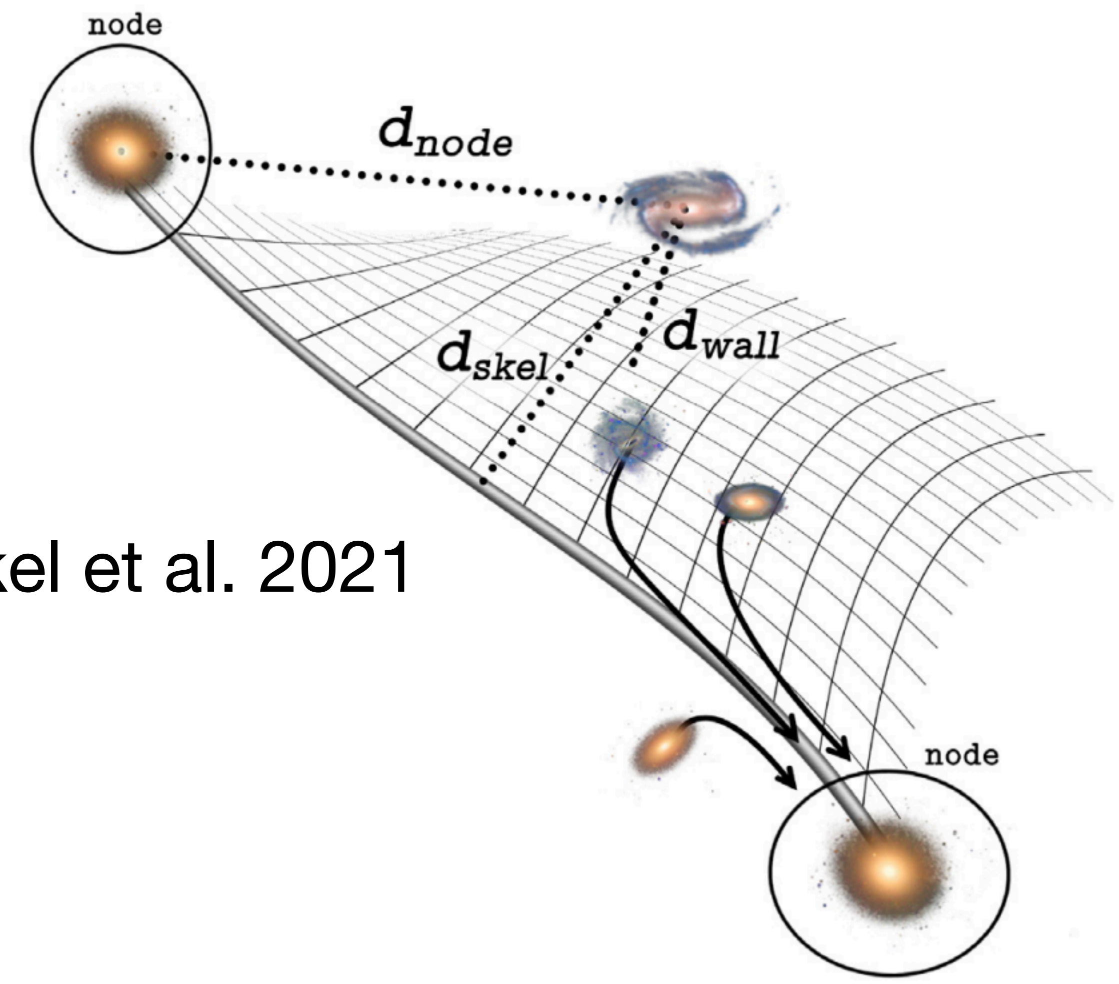
And many others!

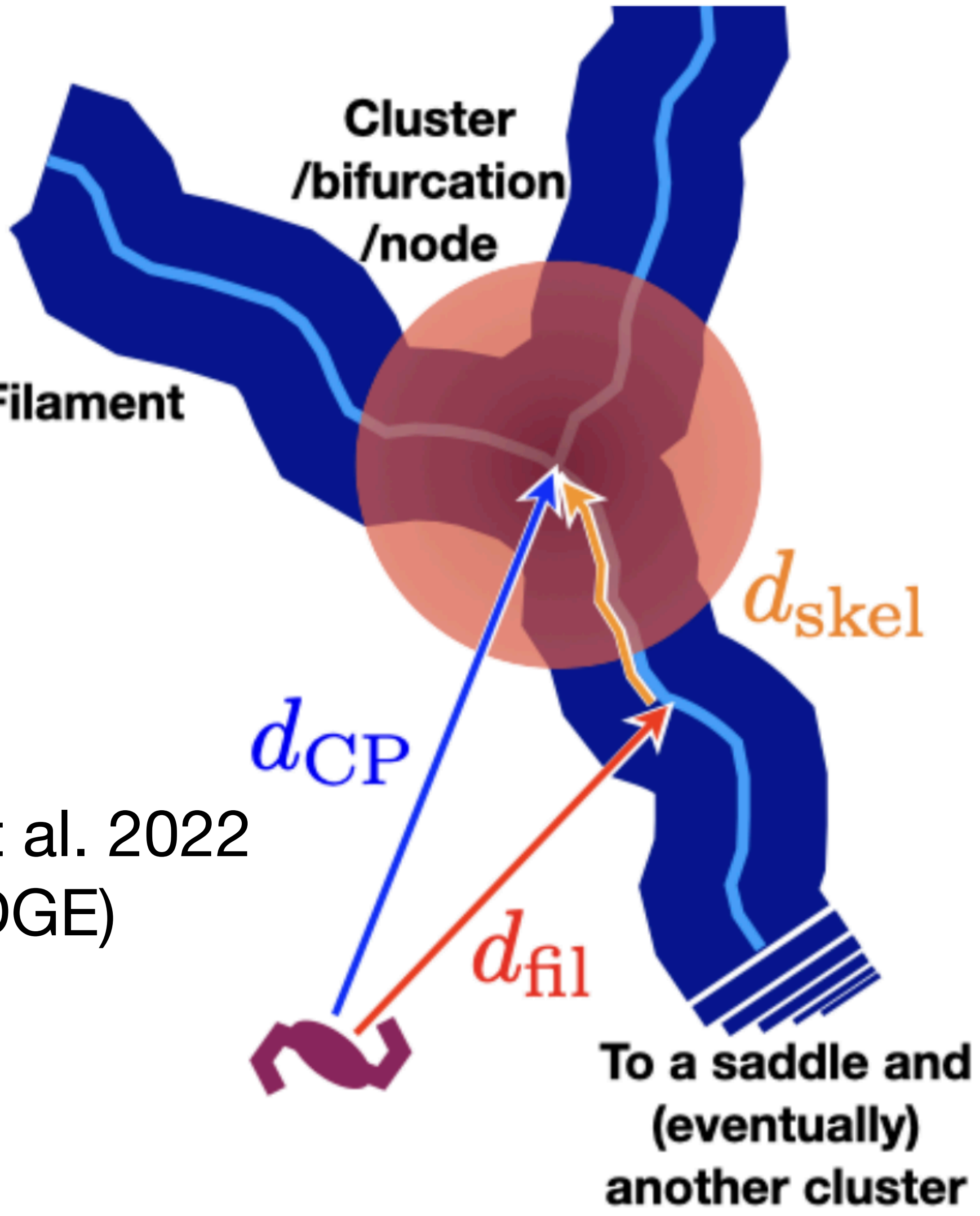
Do filaments influence galaxy properties?

Kraljic+ 2018



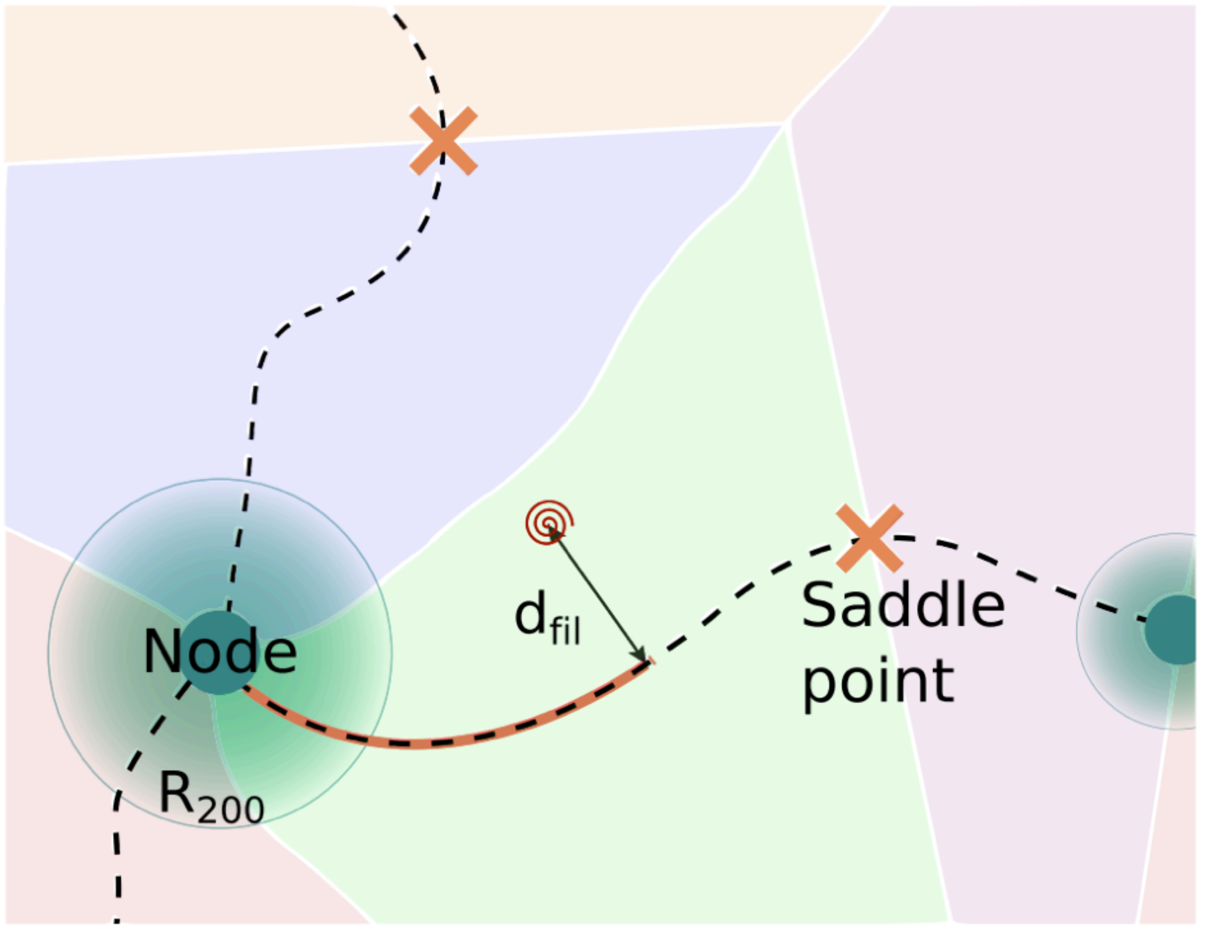
Winkel et al. 2021





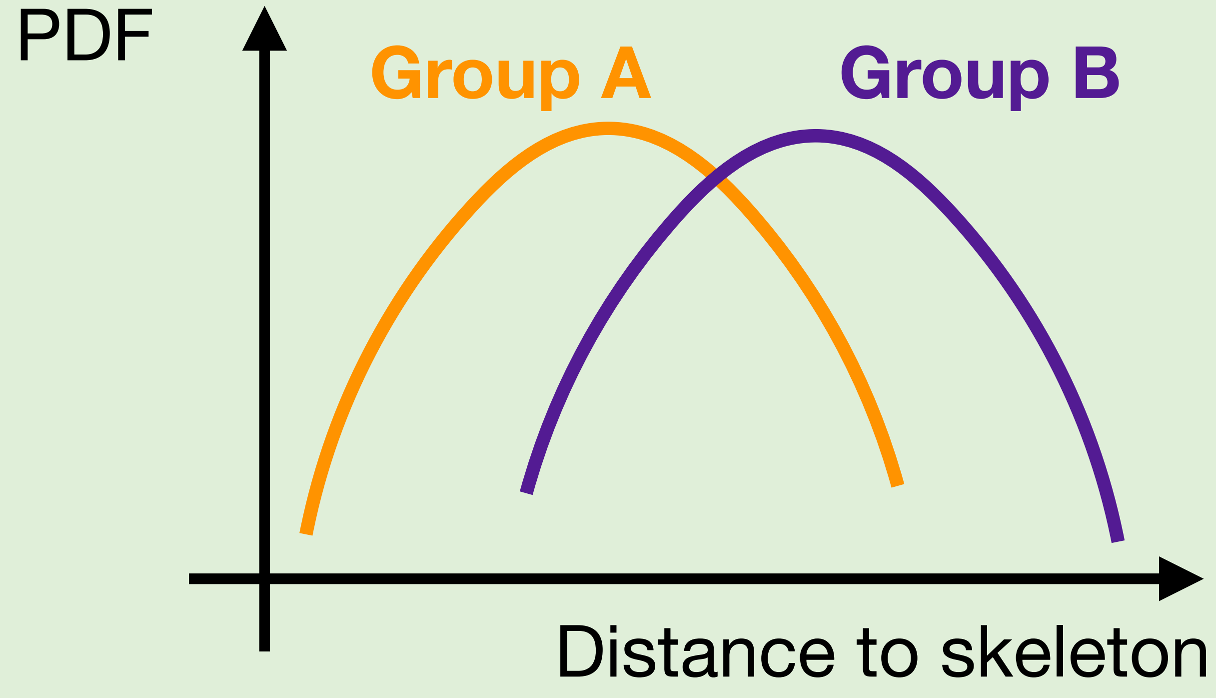
Malavasi et al. 2022
(incl. DGE)

Rost et al. 2021



Method:

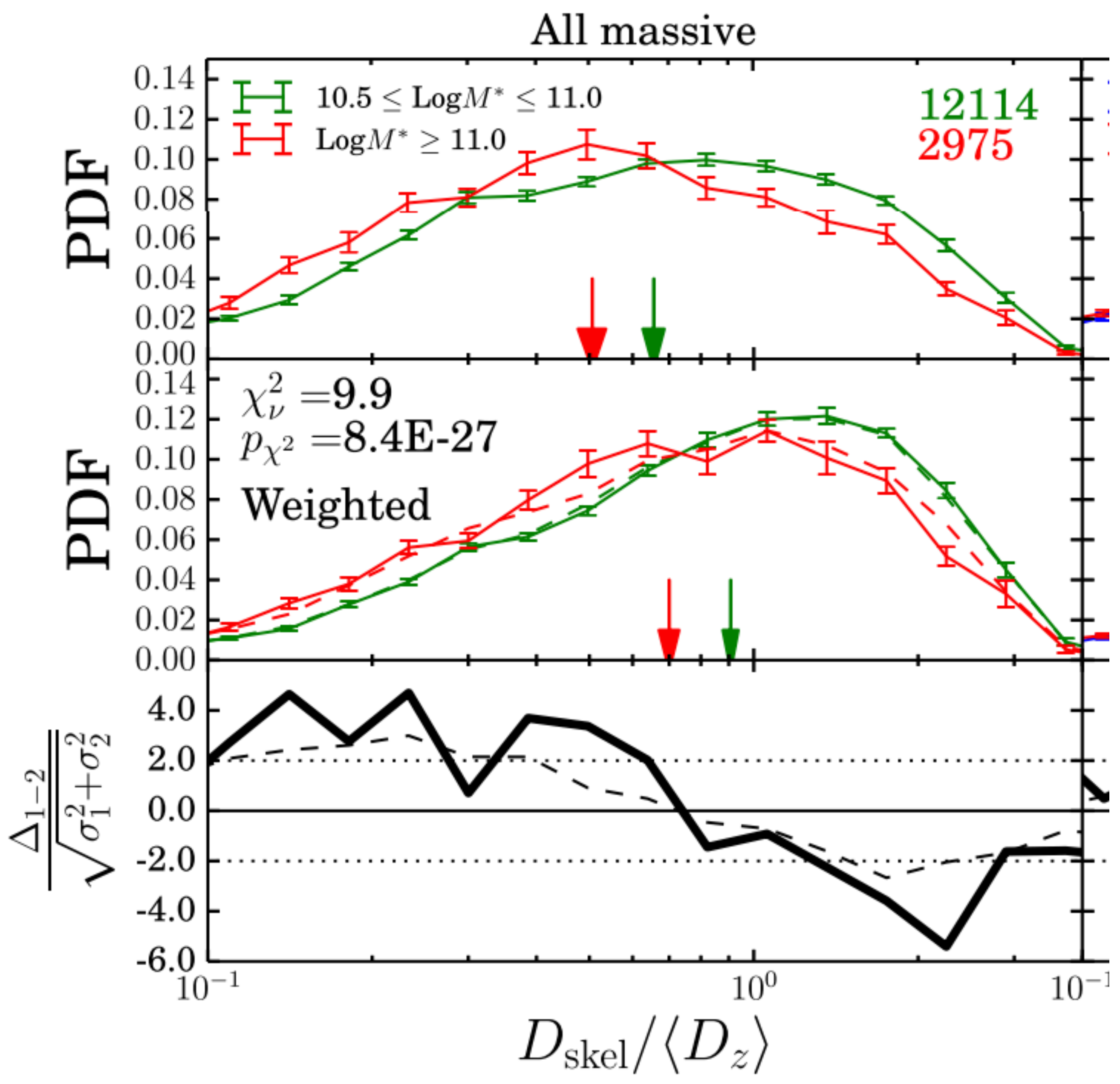
1. Compute distances of galaxies to the skeleton.
2. Separate galaxies in groups **A** and **B**, based on a property of interest
3. Analyse the distribution of distances of A vs that of B



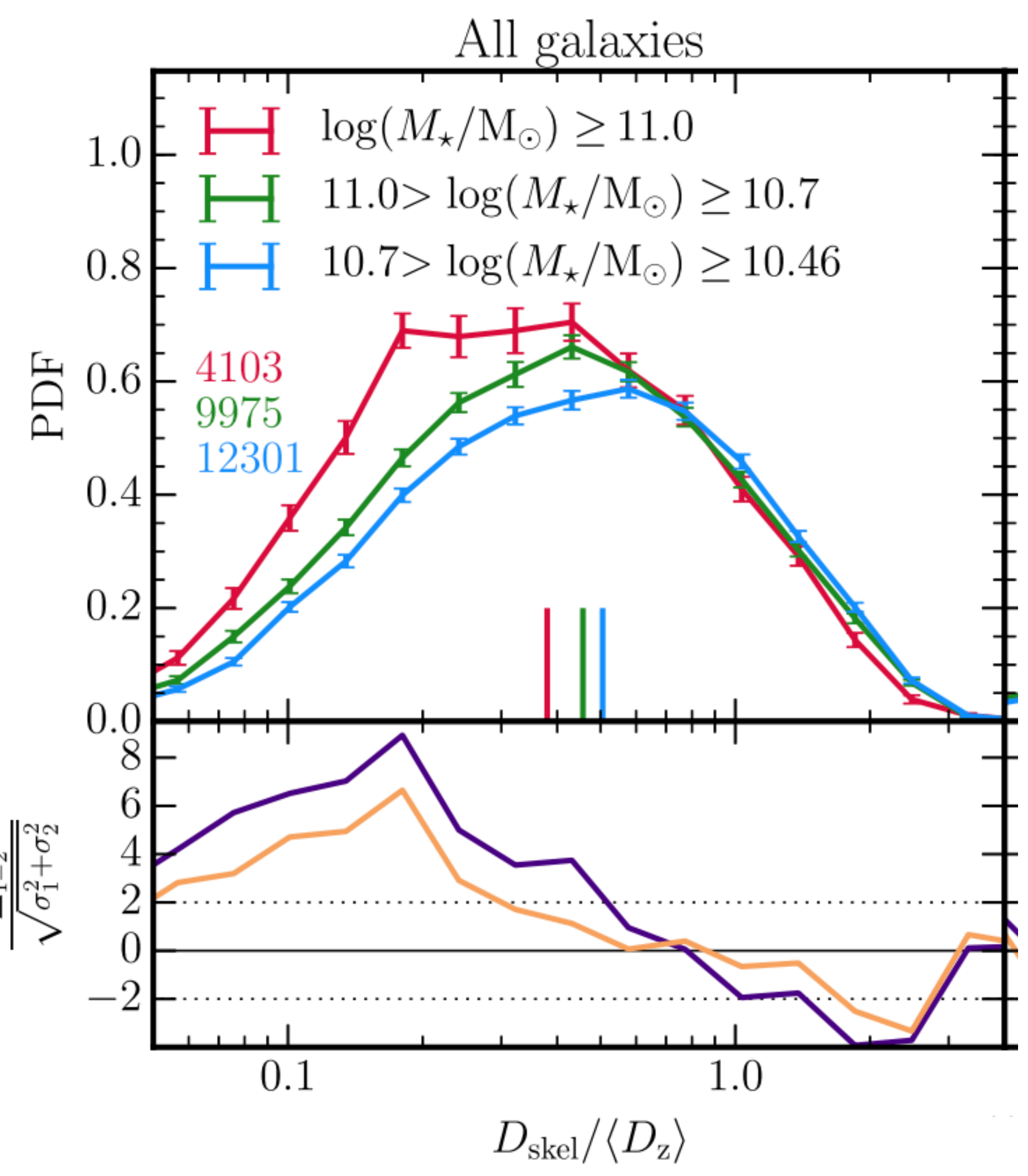
If differences (gradients): the skeleton has an impact on the studied property

Stellar mass

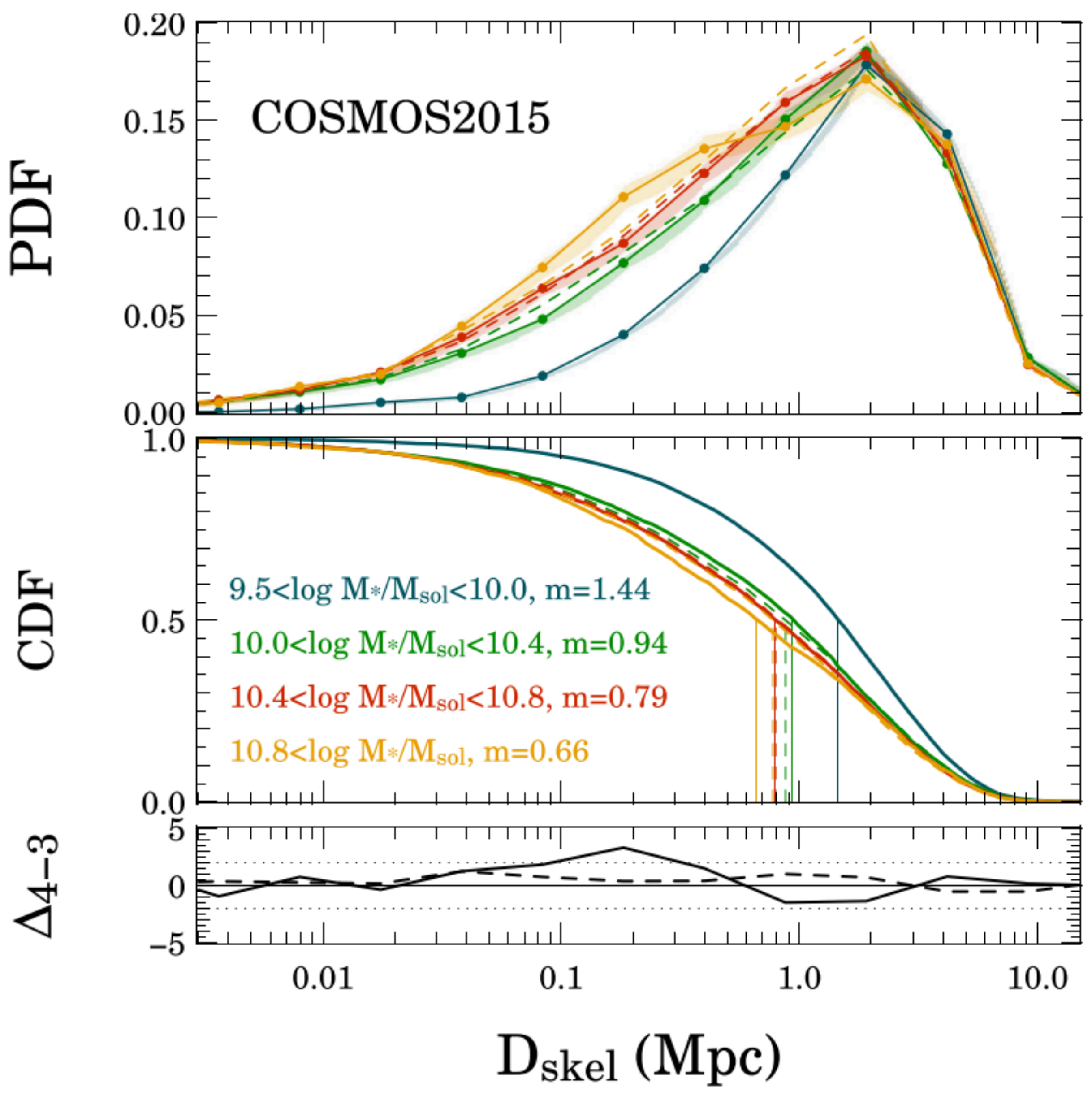
VIPERS (Malavasi et al.2017)



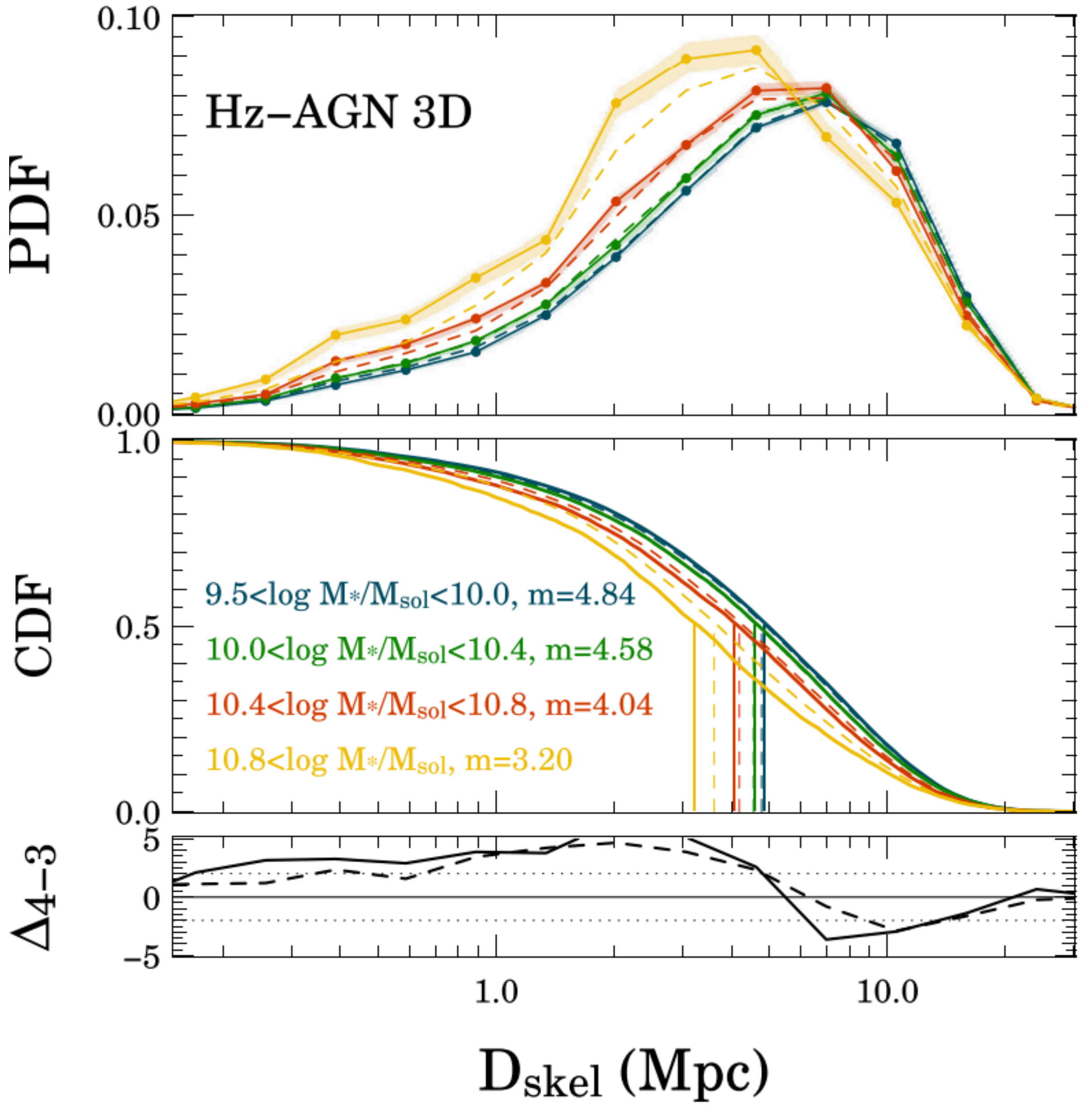
GAMA (Kraljic et al. 2018)



COSMOS2015 (Laigle et al. 2018)



Horizon-AGN (Laigle et al. 2018)



Galaxies in nodes are discarded.

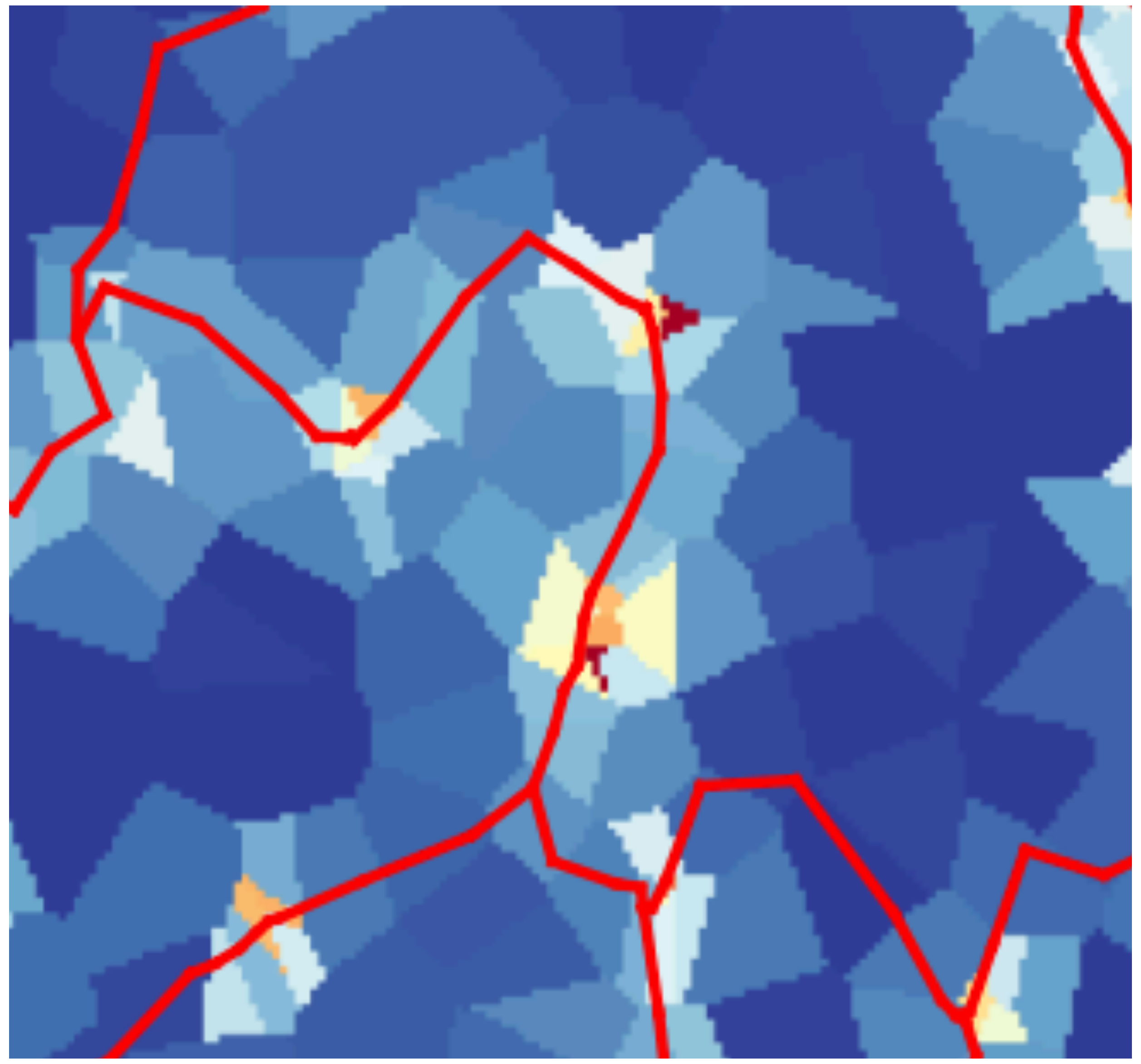
"Weak but statistically significant segregation effect inside the filaments"

Mass gradients towards filaments:
the most massive galaxies are closer to the filament center than the low mass ones.

Other studies: Sarron et al. 2019

A density-driven effect? ...

Example of density estimation $\rho_{\rm DTFE}$



Well established: galaxy properties correlate with local galaxy density

- **morphology–density** relation *(Dressler 1980)*: galaxies with early-type morphologies are more abundant in regions of high local galaxy density, such as cluster cores.
- **colour–density** relation *(e.g. Baldry et al. 2006; Bamford et al. 2009)*
- **star formation–density** *(e.g. Hashimoto et al. 1998; Kauffmann et al. 2004)*

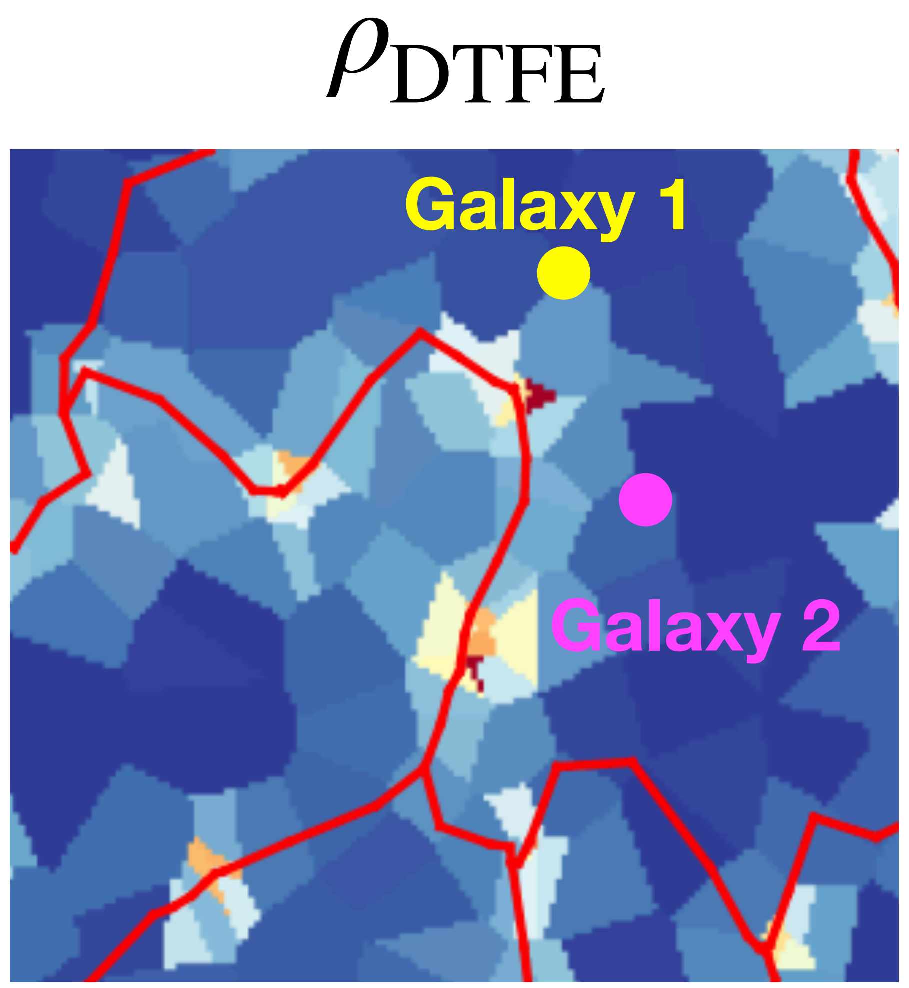
Are the gradients driven entirely by processes correlated with **local density**

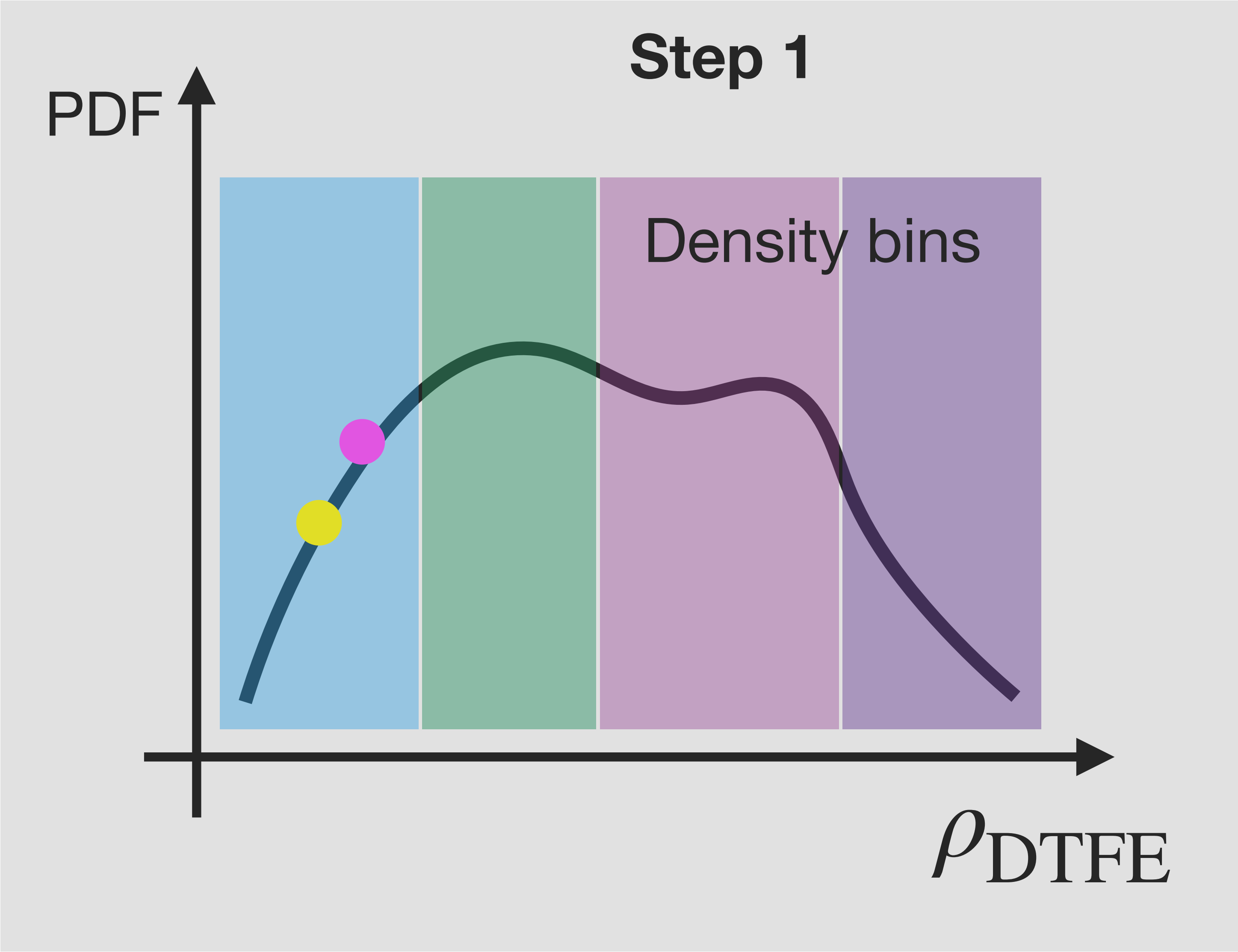
or

are they influenced by the geometry, topology, and physics of the Cosmic Web?

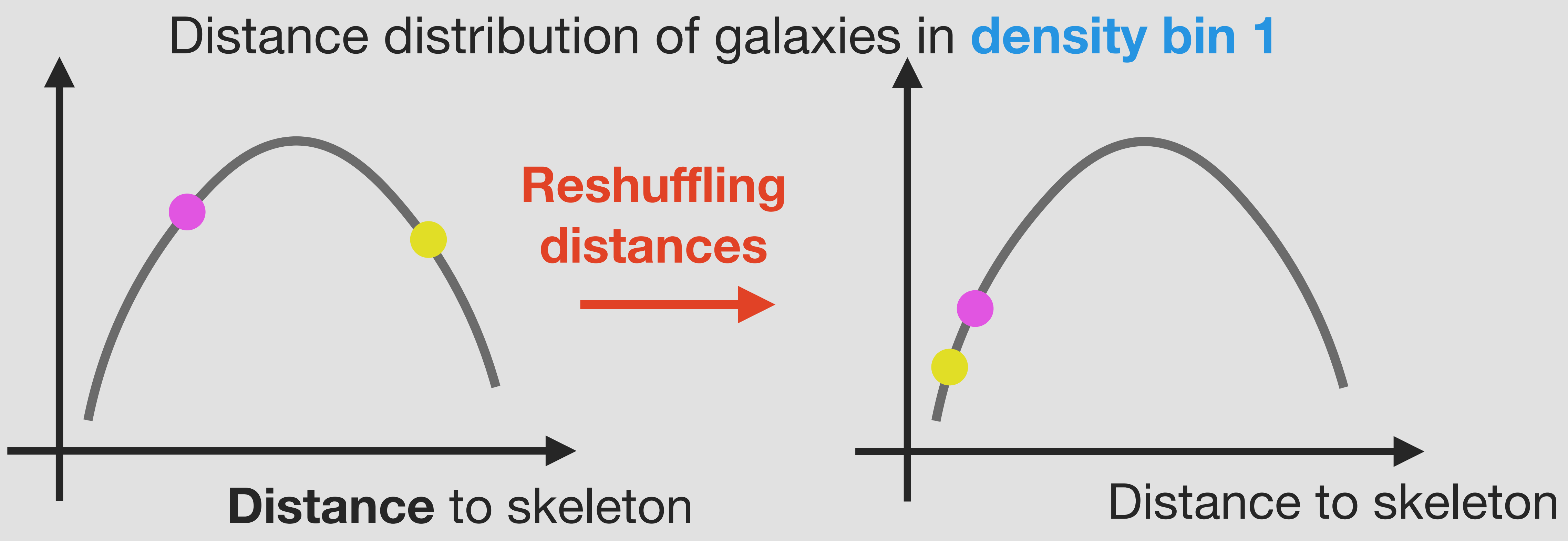
A density-driven effect? ...

Try to separate effects driven by the **mass-density relation**





Step 2



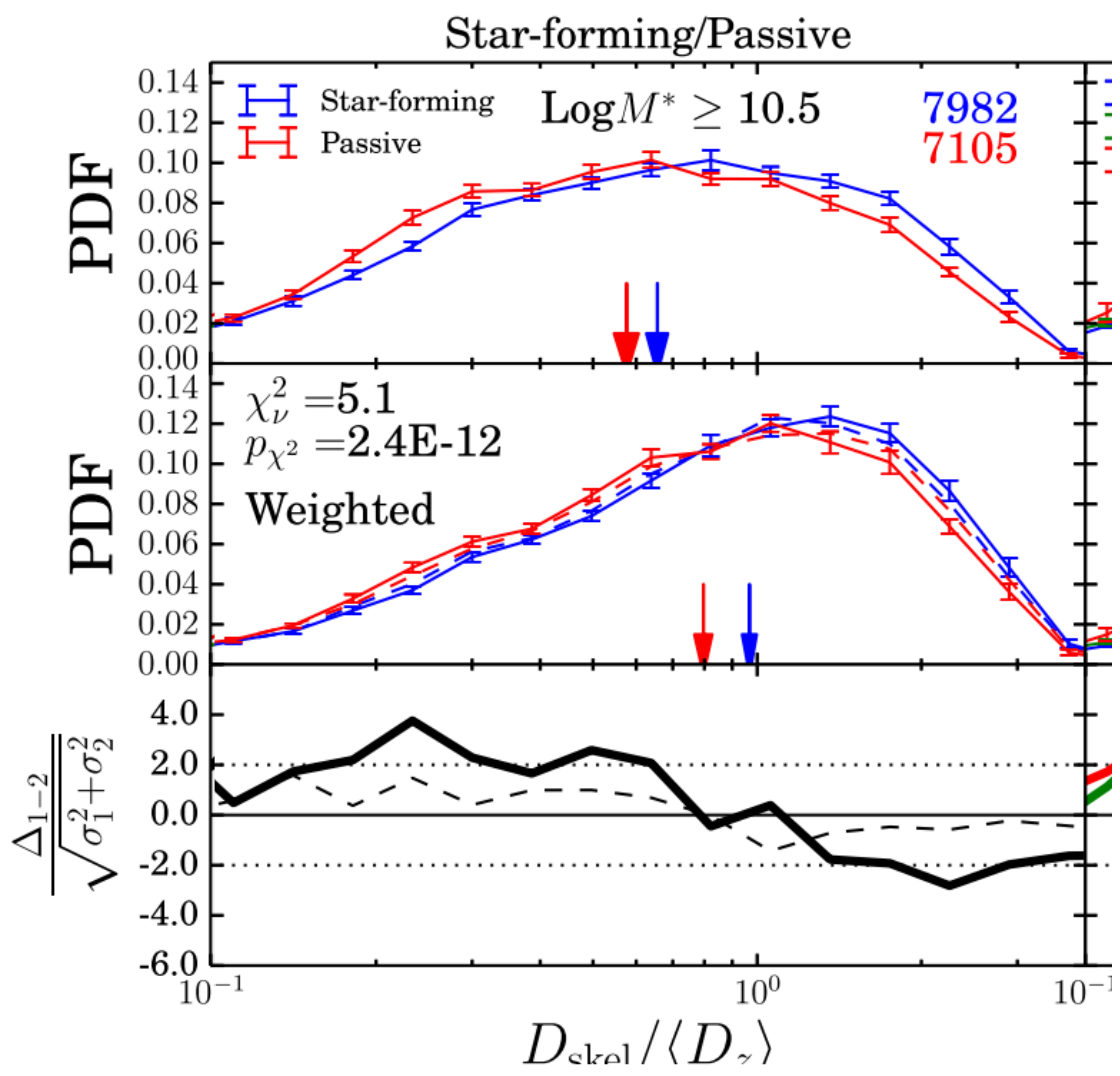
- If gradients are identical —> it’s all about density —> geometry of the environment does not matter
- If differences, but gradients are still there —> the filaments have an effect

“This operation preserves the mass–density relation; hence, the role played by the background density. However, within a density bin, it moves galaxy positions with respect to the filaments”. (Laigle et al. 2018)

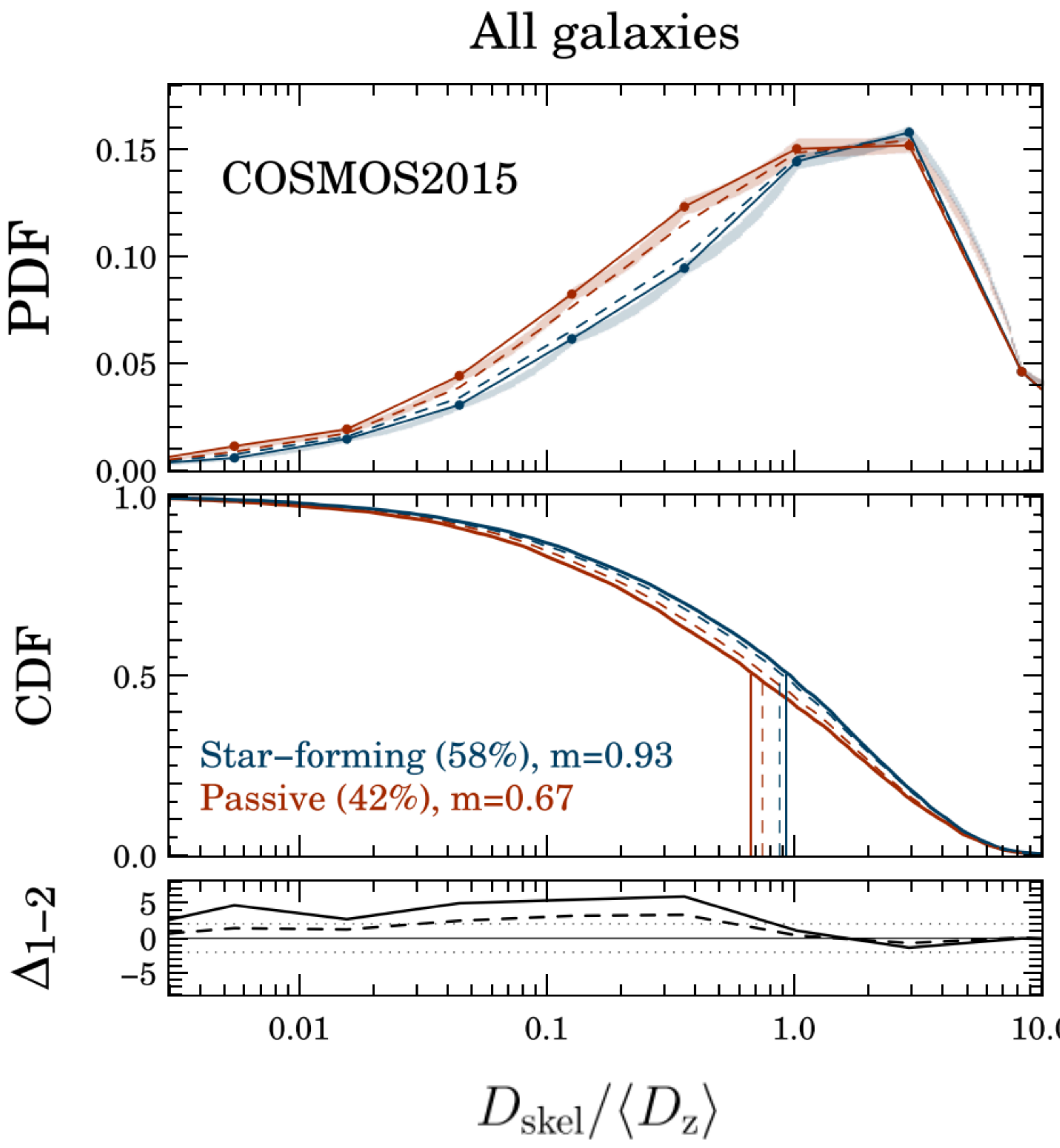
—> **Result**: gradients cannot be entirely explained by the mass–density relation.
The particular geometry of the large-scale environment itself plays a role

Galaxy colors, star-formation rates

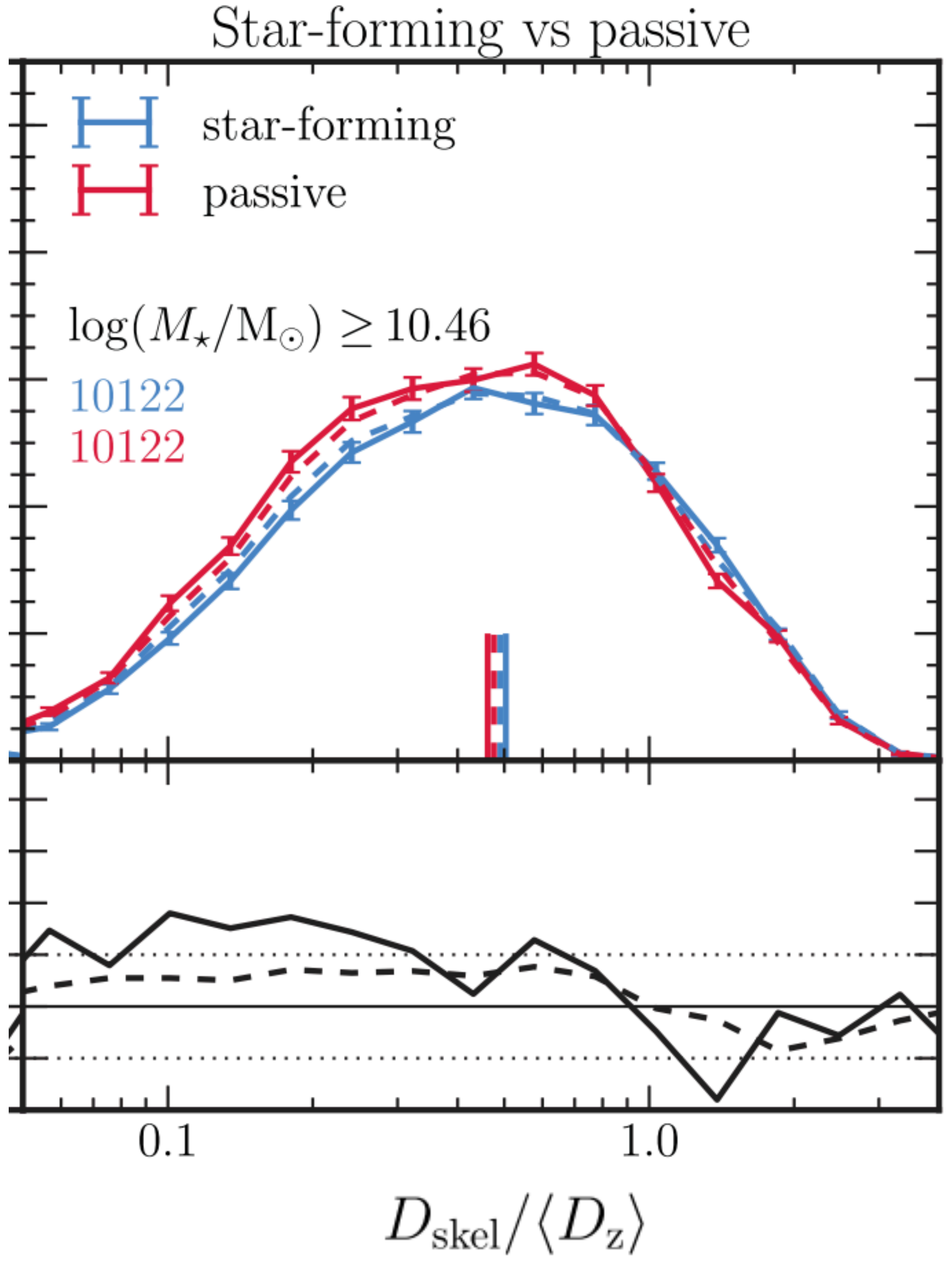
VIPERS (Malavasi et al.2017)



COSMOS2015 (Laigle et al. 2018)



GAMA (Kraljic et al. 2018)



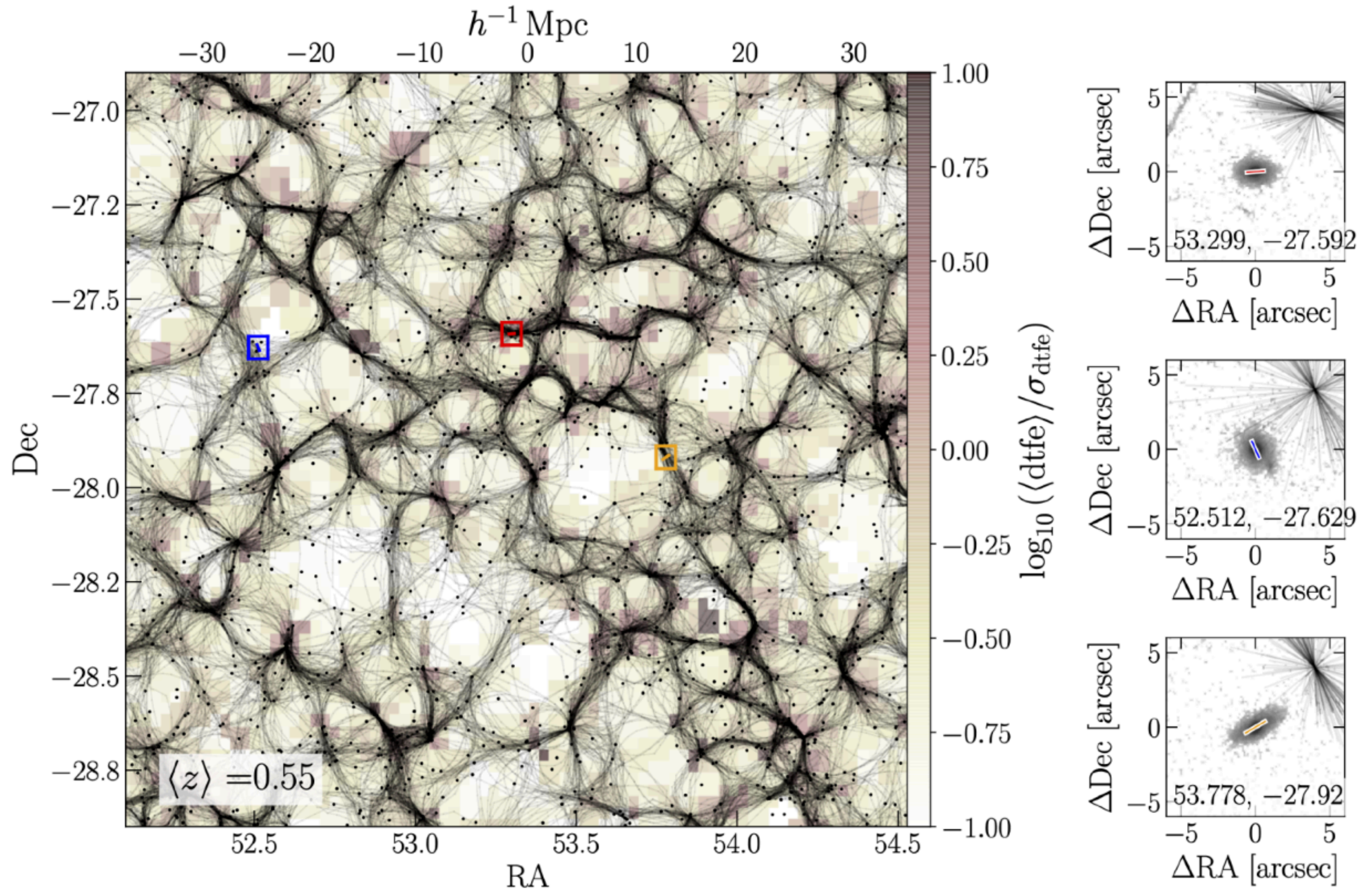
Color and SFR gradients towards filaments:
Redder and less star-forming galaxies are closer to the filament center than bluer and more star-forming ones.

Morphology

Laigle+ 2025 (submitted)
EUCLID collaboration, Q1 data

- EUCLID Deep Fields (photometric)
- Filaments detected in thick tomographic redshift slices (170 Mpc/h)
- redshift range 0.5 < z < 0.9,

using about 100 000 galaxies more massive than 1010M⊙



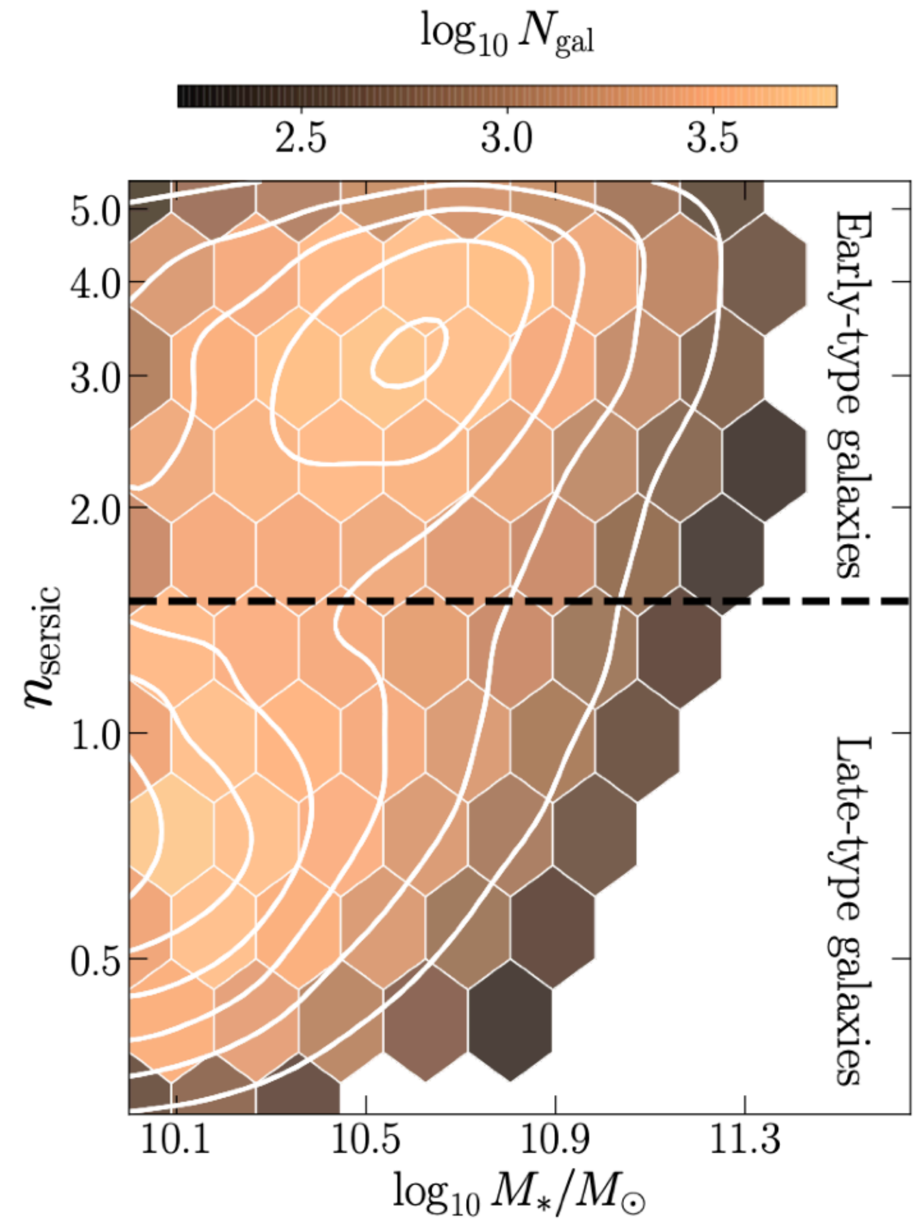
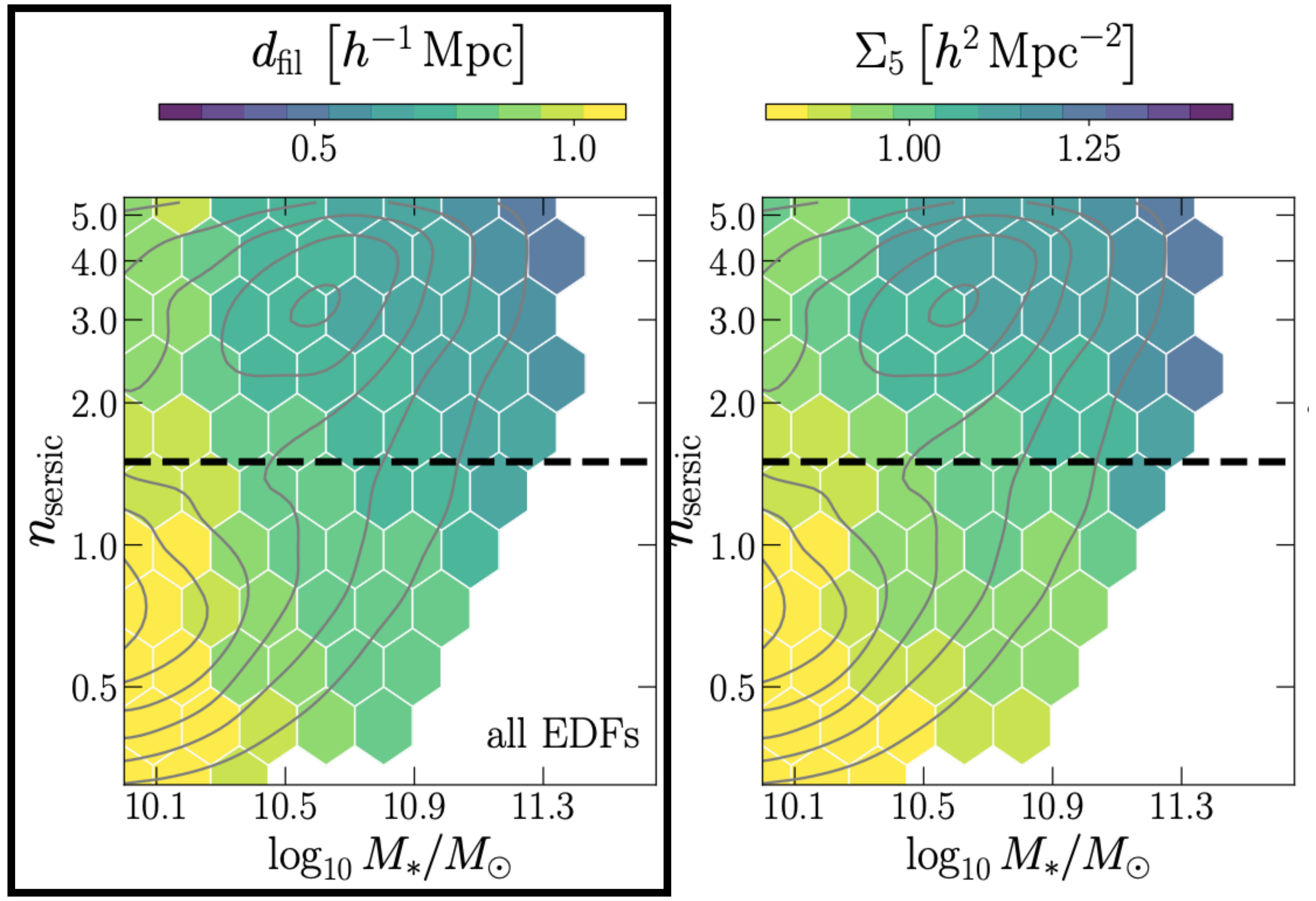


Fig. 1. Galaxy distribution in the plane of Sérsic index versus mass for all galaxies in our fiducial sample in the EDFs at $0.5 < z < 0.9$. The black dashed line corresponds to the boundary for the early-type galaxy domain. Density contours are overlaid in white.

Early type galaxies are on average closer to filaments than late-type galaxies (even at fixed stellar mass).



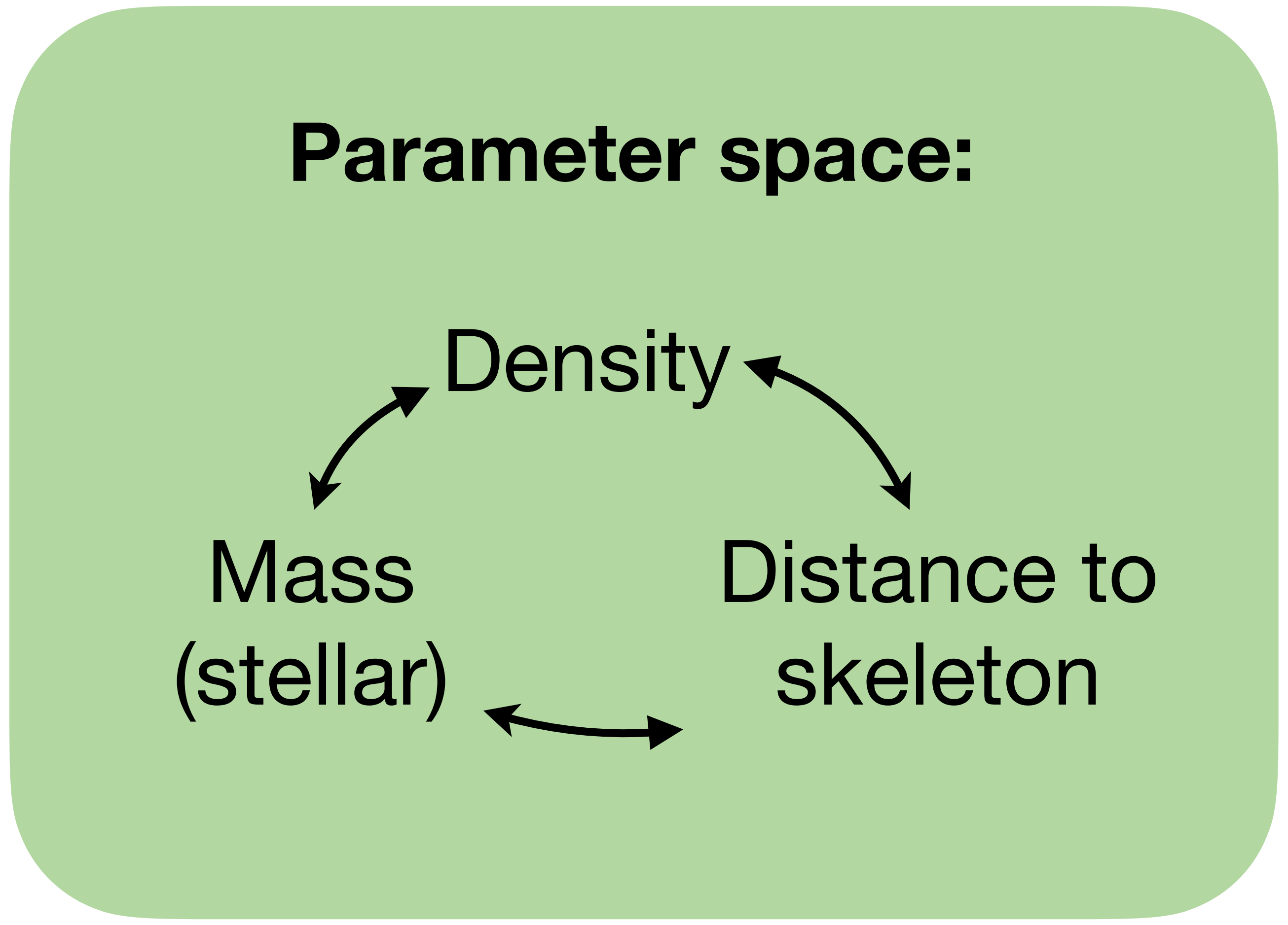
"We note that the gradients in distance to filaments and density are similar, but not completely equivalent, suggesting that distance to filaments and density are not completely interchangeable"

Other (contradictory) results

- *Kleiner et al. (2017):* the most massive galaxies in filaments (log(Mstar/M) > 11) have **enhanced HI** fractions relative to the field population,
- **'Cosmic Web Enhancement'** *(Vulcani et al. 2019)*: sufficiently massive galaxies can **rejuvenate** their gas supply through accretion from cosmic filaments.
- Galaxies in filaments have enhanced SF rates *(e.g. Fadda et al. 2008; Darvish et al. 2014)*…

But sample sizes, cosmic variance, and different characterisations of the environment

—> Hard to settle on a conclusion.



Main issue: local density and filament proximity are inherently correlated!

So, reshuffling galaxies within density bins may **still retain geometric correlations**

—> It is difficult to isolate the filament's "geometric" effect from the density-driven effect.

Other works about mass and SFR

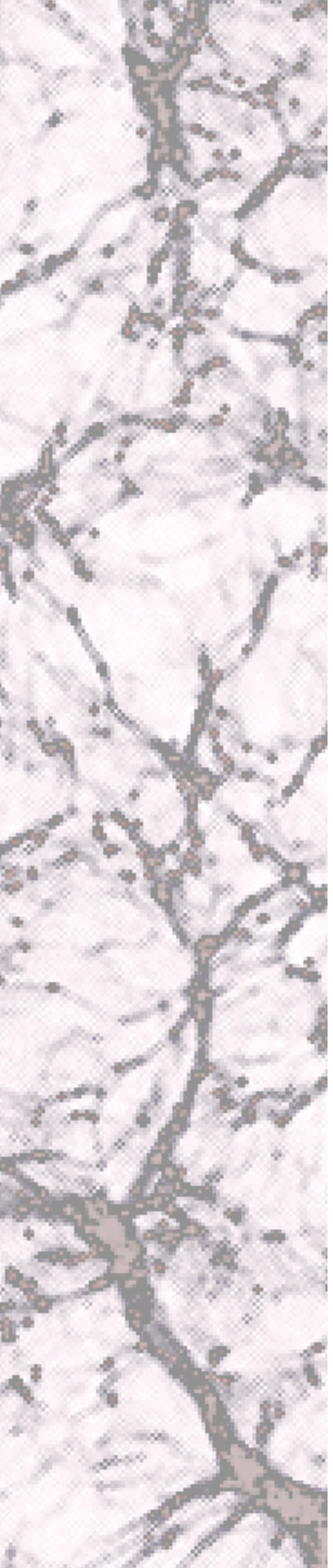
Other studies:
- Martínez, Muriel & Coenda 2016 (preprocessing)
- Alpaslan+ 2016 (GAMA)
- Kuutma+ 2017 (SDSS)
- Chen et al. 2017 (SDSS)
- Kraljic et al. 2018
- Mahajan, Singh & Shobhana 2018
- Sarron et al. 2019 (CFHTLS)
- Kraljic+ 2019
- Darragh-Ford+ 2019;
- Liao & Gao 2019;
- Bonjean+ 2018 (WISExSCOS, one bridge between clusters)
- Singh, Mahajan & Bagla 2020
- Santiago-Bautista+ 2020
- Singh+ 2020
- Song+ 2021
- Castignani et al. 2022b
- Malavasi+ 2022
- Kotecha+ 2022
- Donnan, Tojeiro & Kraljic 2022
- Jhee+ 2022
- Parente et al. 2024
- Bulichi, Dave & Kraljic (2024)
- Hasan+ 2024
- O'Kane+2024

And many others!

Research groups all around the world (a lot of interest)

Observations:
SDSS, GAMA, COSMOS, CFHTLS, surveys
Individual pointings

Simulation
Simba, EAGLE, IllustrisTNG simulations.



Effect of the multi-scale web filaments on galaxy evolution

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1) Results: First generation *(general excitement)*

2) Results: Second generation *(density?)*

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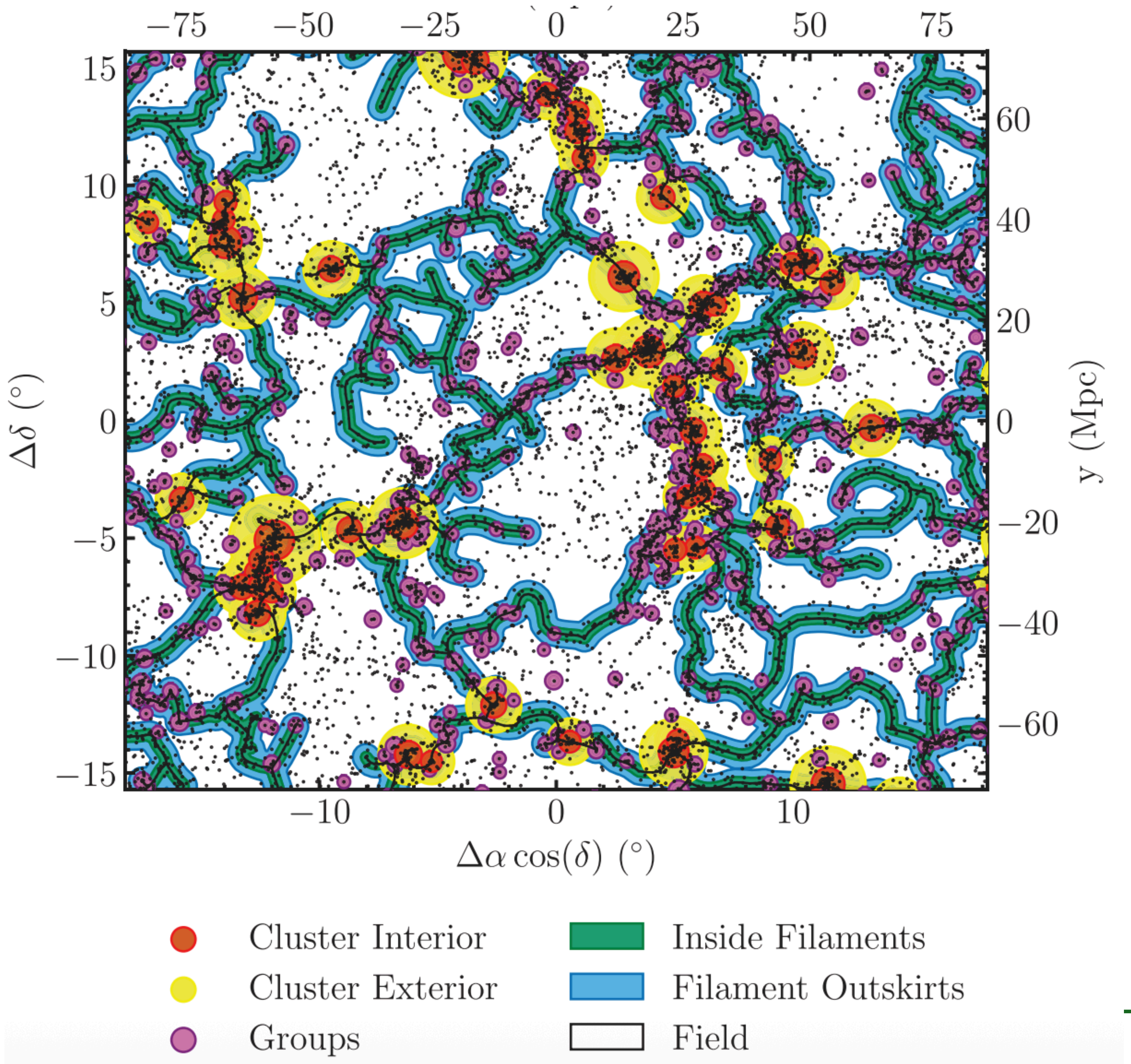
4) Summary: a complicated puzzle

Final study in the SDSS

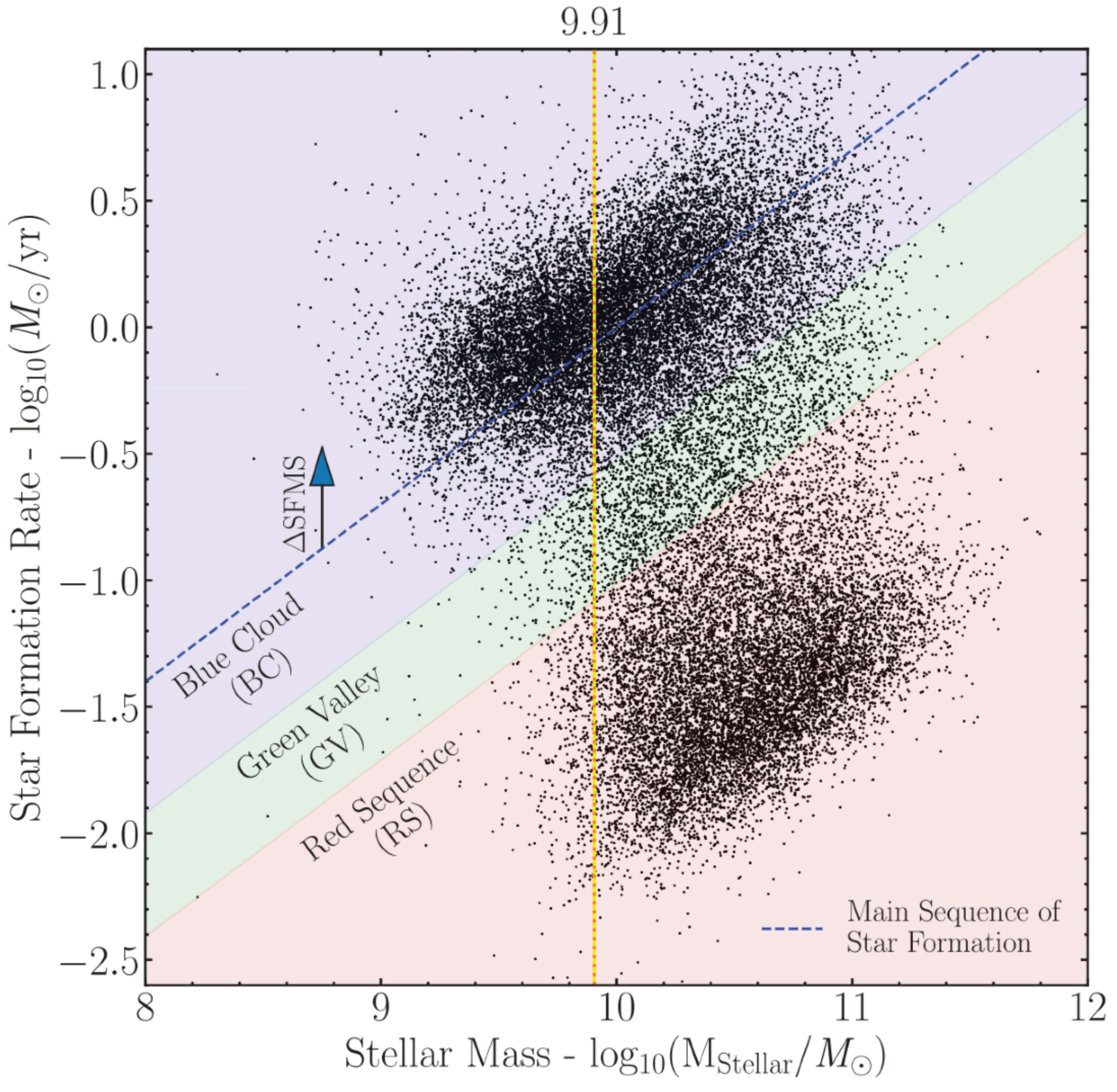
The effect of cosmic web filaments on galaxy evolution **(O'Kane et al. 2024)**

- SDSS DR8 Main Galaxy Sample
- 16 fields centred on galaxy clusters, but pretty large! (100x100 Mpc^2)
- 2D extractions of cosmic filaments (slices of thickness: Delta z=0.1) using DisPerSE
- Separation of different cosmic web environments



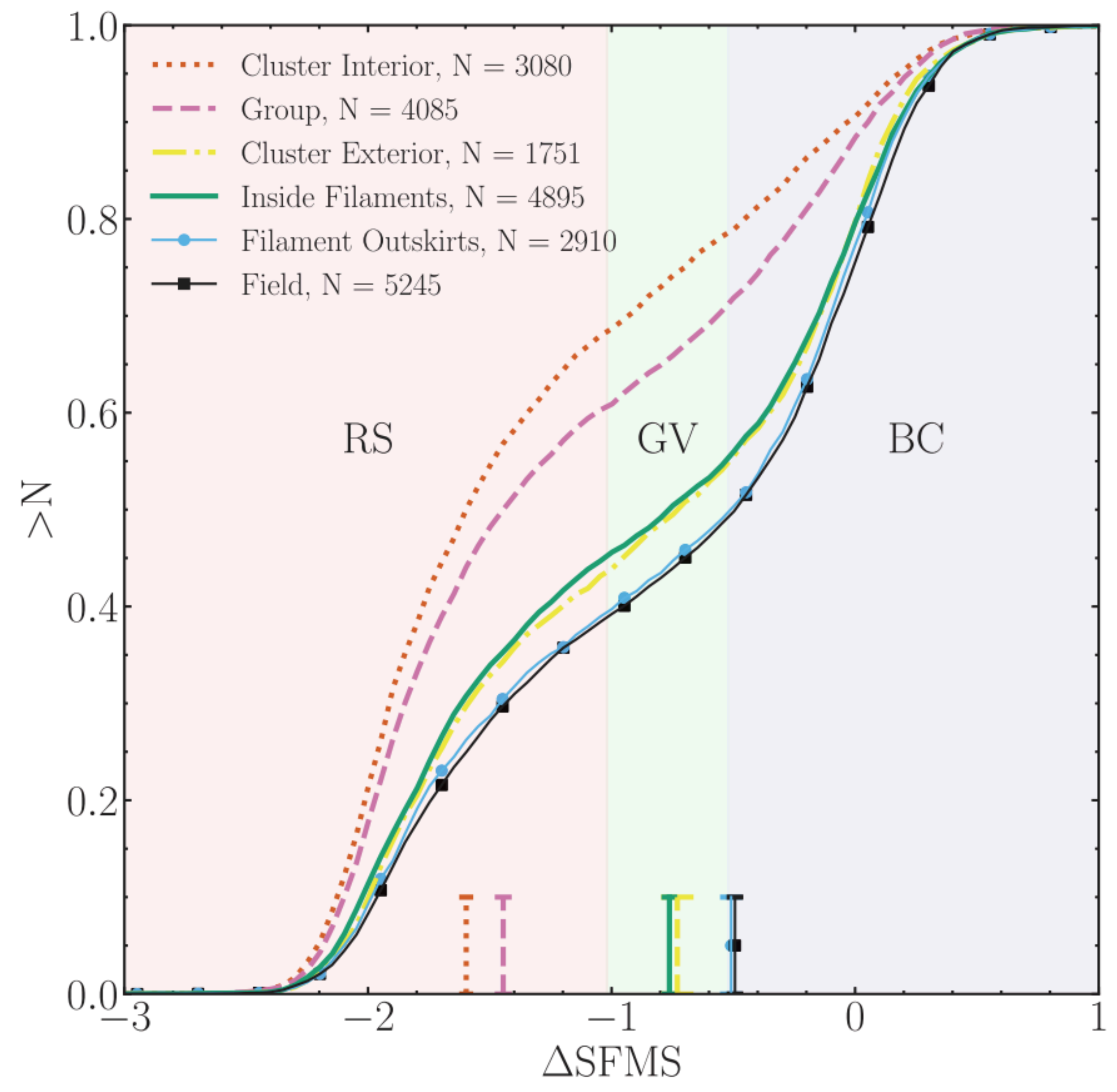
Metric for star-formation suppression

ΔSFRMS = vertical logarithmic distance to the Main Sequence



> 0 —> enhancement in star formation
< 0 —> suppression wrt star-forming galaxies on the main sequence.

First (raw/naive) result:



Expected trends are recovered: Compared to field galaxies, SF is progressively suppressed in filaments, groups, and clusters (respectively)

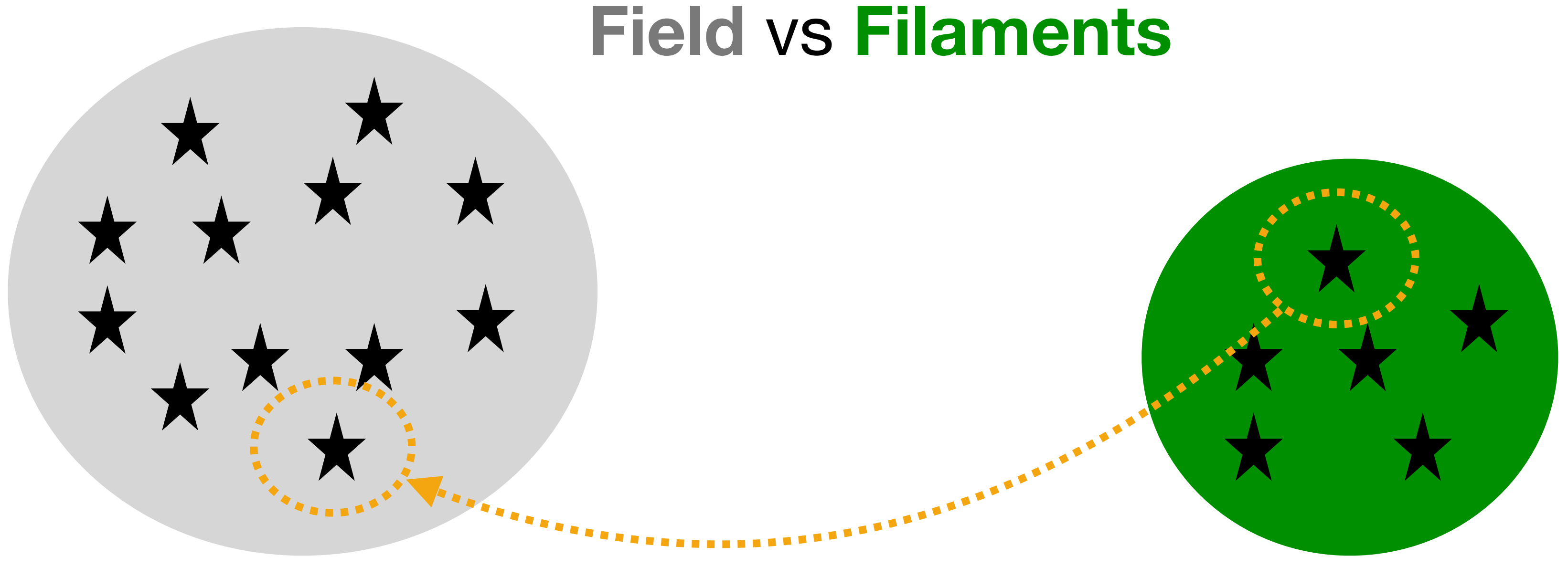
What drives this effect?

Let's control for mass

Mass-matching

Goal: to account for the different stellar mass distributions in each cosmic environment.

Field vs Filaments



Galaxy with the closest mass
(within 0.1 dex)

—> Compare their ΔSFRMS

Repeat this for all environments (pairwise environment comparison).

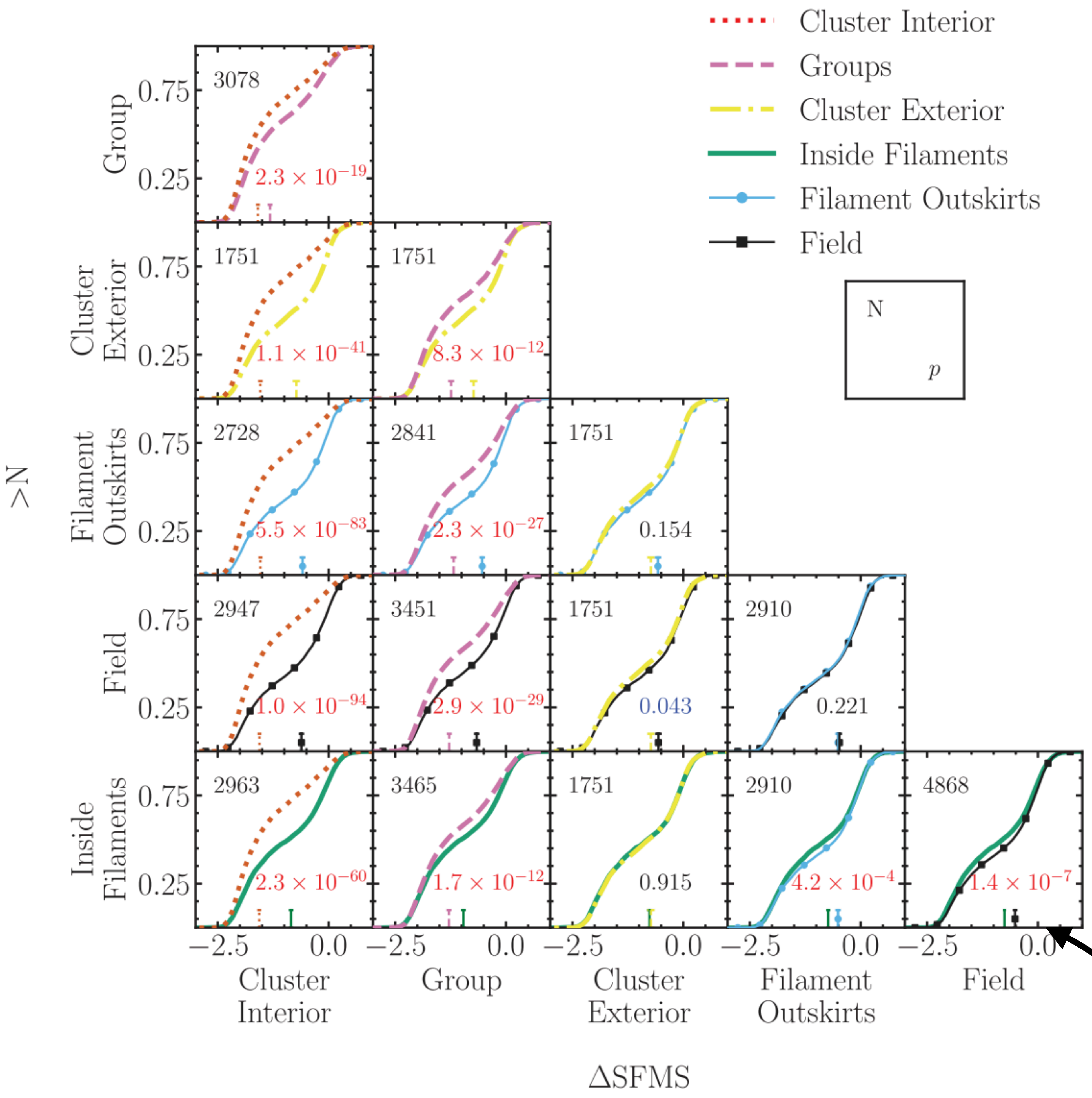


Figure 5. Pairwise comparisons of the ΔSFMS cumulative distributions for each environmental pair using the mass-matched samples only. Medians of each distribution are shown as vertical lines with their respective 1σ errors. In each panel, the number of galaxies in each population is shown in the top left. Using Kolmogorov–Smirnov statistics, the probability that both distributions are identical is shown in the lower right. Significant p-values ($p < 0.05$) are coloured in blue and highly significant p-values ($p < 0.01$) are coloured in red. The comparisons between the distributions of galaxies inside filaments and those within cluster interiors and the field, show highly significant differences ($p < 0.01$). Further showing that when matching in stellar mass, filaments appear as an intermediary environment between the clusters and the field.

"The increased star formation suppression within filaments, in comparison with the field, agrees with the results of past studies such as Mart´ınez et al. (2016), Kraljic et al. (2018), and Laigle et al. (2018), as well as simulation work (e.g. Bulichi et al. 2024)."

O'Kane et al. 2024

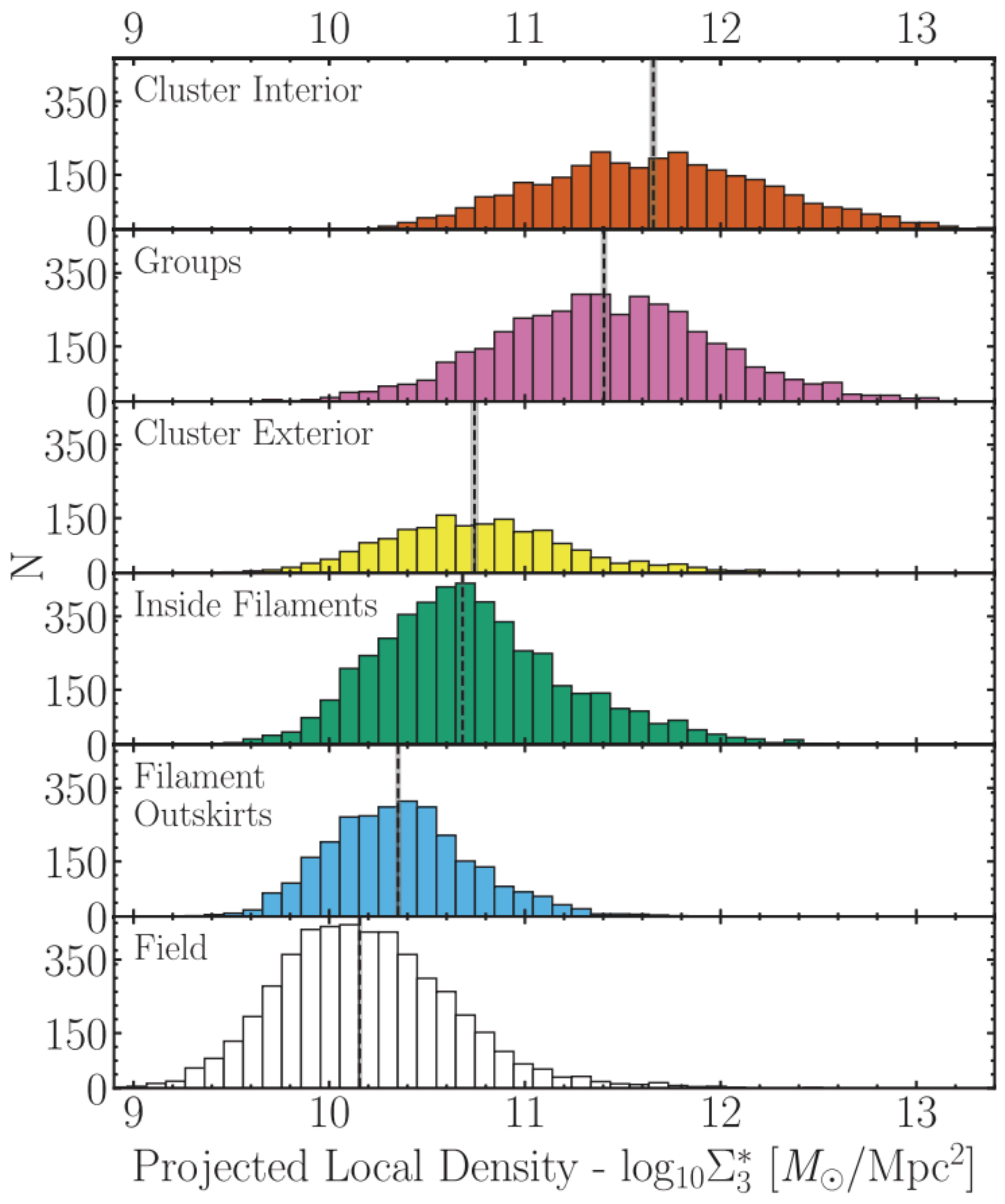
What drives this effect?

Mass AND local density matched samples

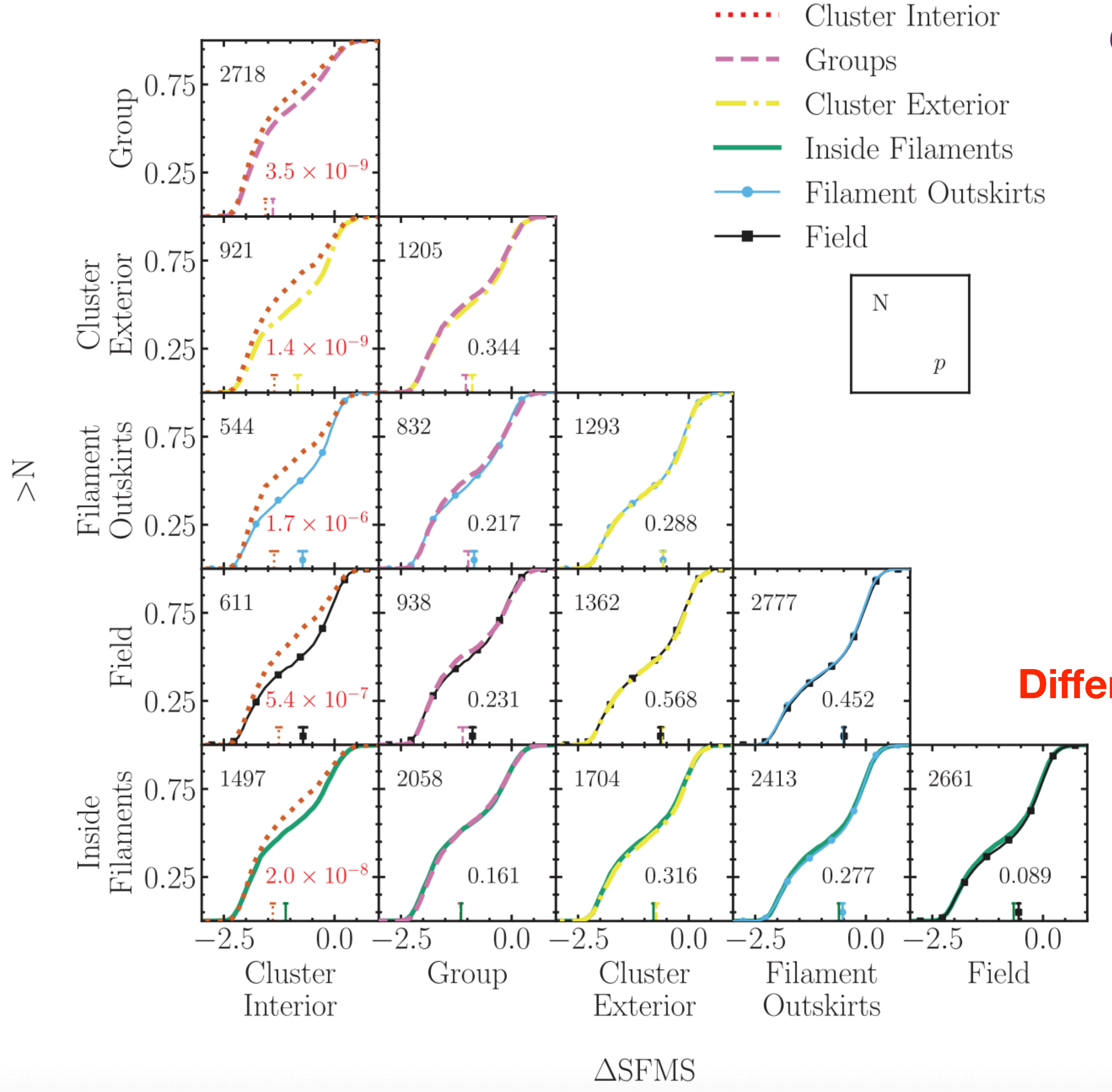
- Density defined to probe the small scales (3rd nearest neighbour, ~1 Mpc)

$$\Sigma_3^* = M_3/\pi R_3^2$$

Local density distributions (good check)



O'Kane et al. 2024



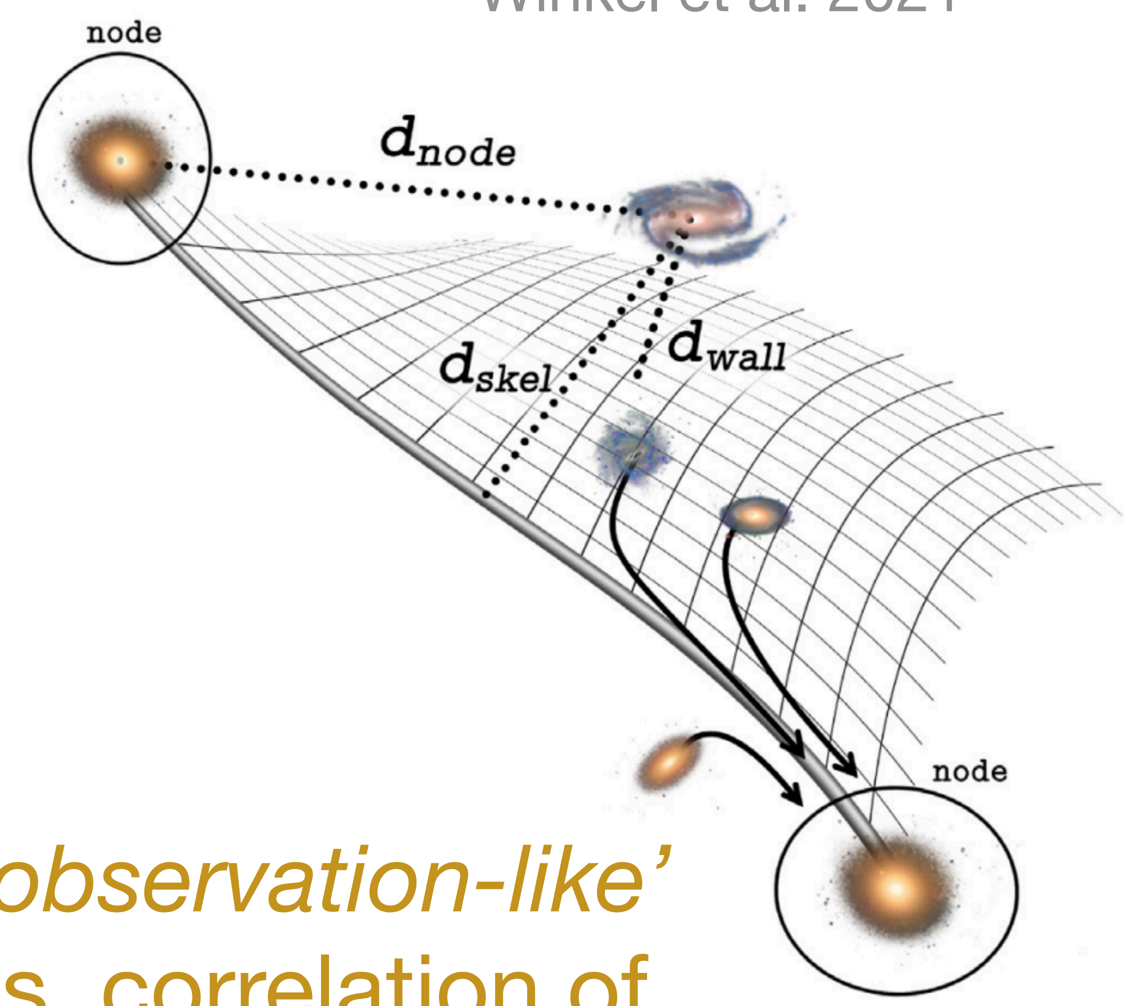
Differences vanish!

"The ΔSFRMS distribution for the filament populations appears statistically indistinguishable from that of the field population when matching in stellar mass and local galaxy density."

Differences in ΔSFRMS can be entirely parametrized by a local galaxy density index Σ_3^*. In other words, galaxies in filaments are subject to environmental processes that correlate well with local galaxy density."

Summary of results in the literature

Winkel et al. 2021



Many studies find that galaxies closer to filaments are
- More massive
- Redder in colour
- With reduced star formation

…compared to field galaxies

Also, they find that filaments "pre-process" galaxies before falling into clusters.

—> Do filaments really matter, or we're just measuring effects of density?

Most of those studies have tried to disentangle the effect of density

Density estimation: many ways!
- Delaunay tessellation (with and without smoothing)
- Distance to nearest neighbour (how many?)
- Density within a radius (e.g. within 8 Mpc, Kraljic+ 2018)

Complication: many scales!
- **Small-scale density** (~<1 Mpc) → linked to recent, stochastic processes like mergers, tidal interactions, feedback
- **Large-scale density** (~>5 Mpc) → reflects the long-term environment, like formation history, gas accretion patterns

What are the relevant scales? What is the sphere of influence of a galaxy? (see e.g. *Ayromlou+ 2023*, the "closure radius")

Studies in **simulations** in an *'observation-like'* fashion (e.g. statistical analysis, correlation of property A with B).

—> We discovered trends, but not the physics behind them.

—> Hard to grasp the actual processes.

—> Comparison with observations not obvious because:
- Different choice of tracers
- Different methods (sometimes with arbitrary calibrations: finders are applied without quantitative tests to ensure the robustness of the extracted skeleton)
- Different filaments (so a fair comparison between results is almost impossible)

—> DisPerSE is widely used.

But maybe DisPerSE filaments ≠ physical (true) filaments.

Little theoretical experiment

"Exploring the causal effect of cosmic filaments on dark matter haloes"

Storck et al. 2025 (incl. DGE)

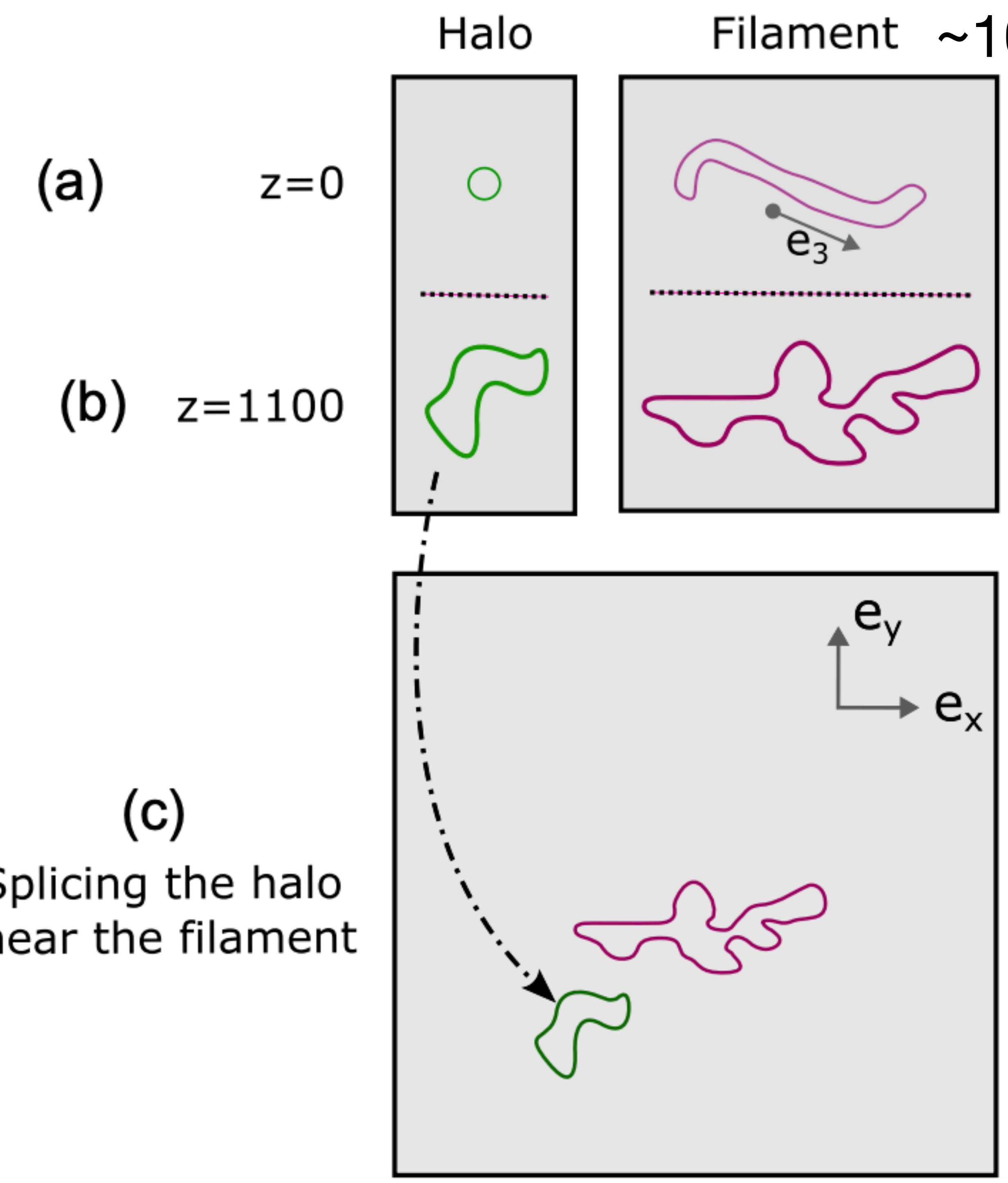
What is really impacted by the cosmic web?

Numerical experiment designed to **splice**/insert a halo at a given location with respect to a large cosmological filament

Method

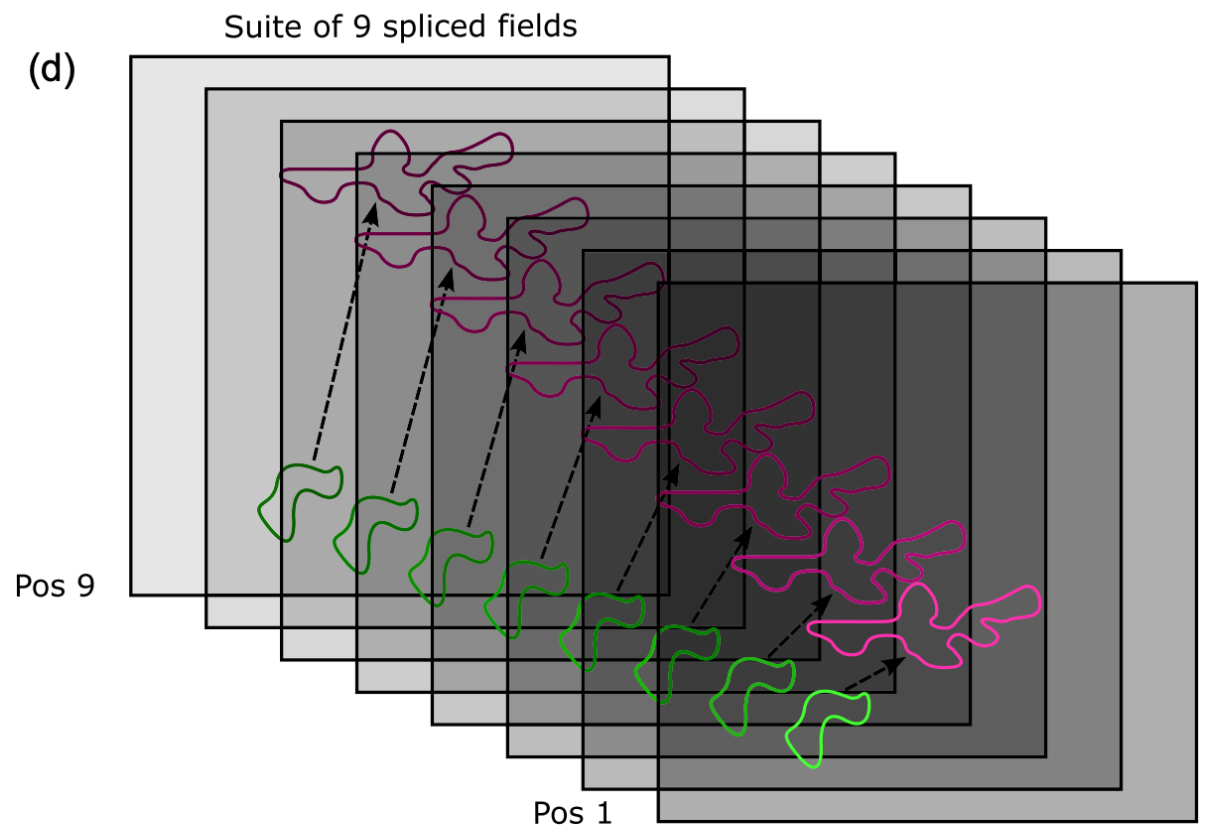
1) Identification of Lagrangian regions

~10 Mpc long

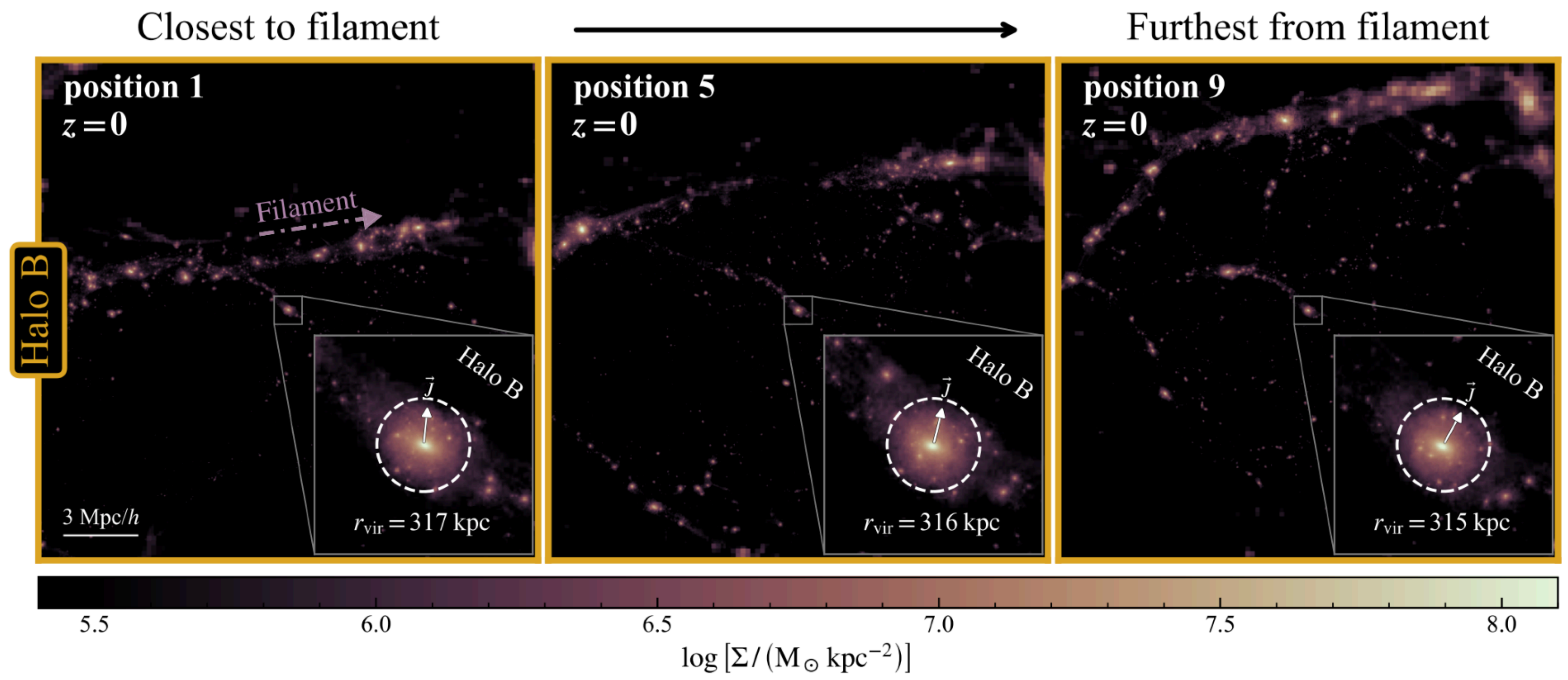


Splicing ~ surgery of the virtual Universe

2) Repeat for 9 different distances of the halo wrt filament



Visual results



$1.5 < M_{\rm halo}/10^{12}\,M_\odot < 3.5$

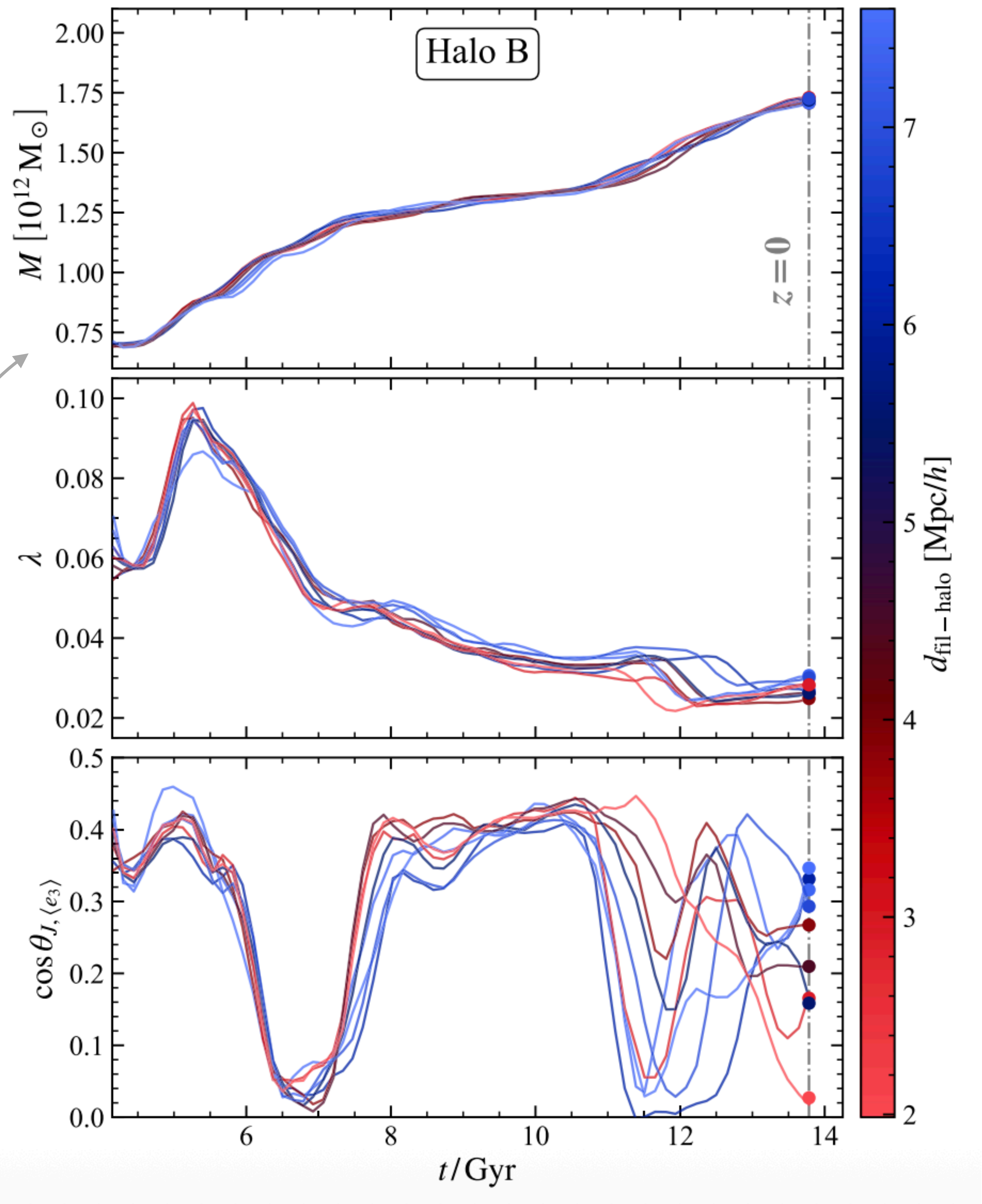
Storck et al. 2025

Track properties:

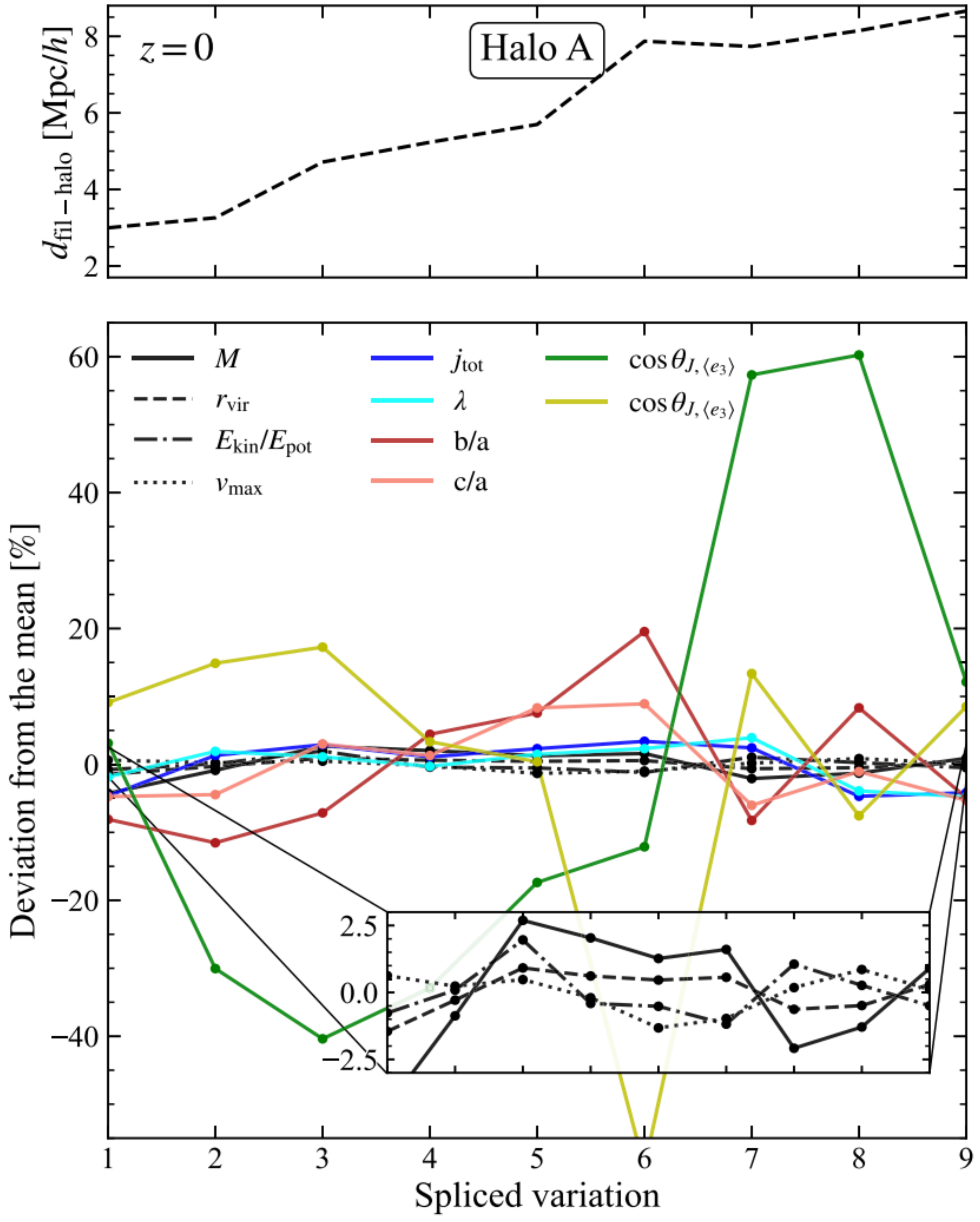
- Mass
- Viral radius
- Ratio between Kinetic and potential energy
- Maximum rotational velocity
- Total specific angular momentum
- Spin parameter
- Morphology/ shapeparameters (b/a, c/a)
- Spin alignment: orientation wrt filament

"Mass is essentially set by the initial density and tides in the Lagrangian patch, and remains largely unaffected by the non-linear evolution of halo's environments"

Example: time evolution of properties



Result for the 5 haloes:

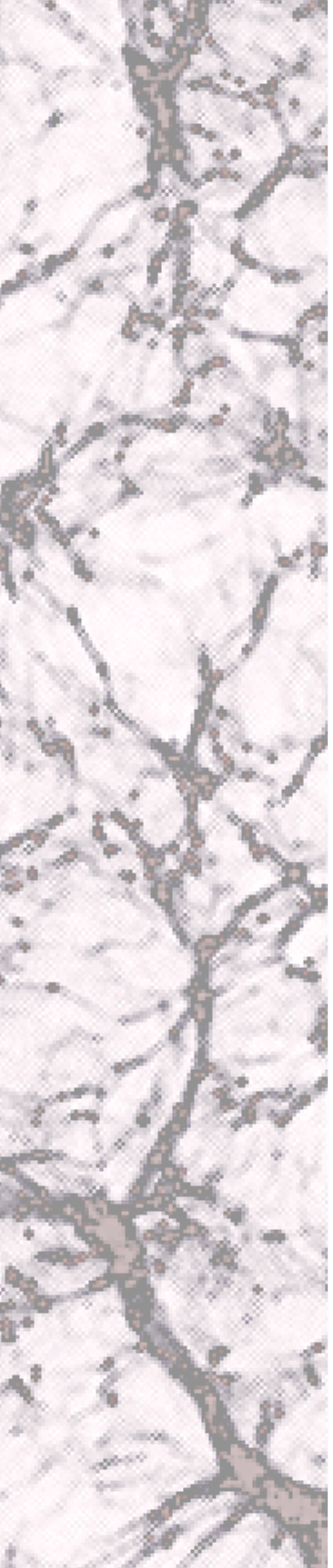


Conclusions:

(i) **Mass** and **virialization parameters** are relatively insensitive (sub % fluctuations)

(ii) **Angular momentum** and DM halo **morphology**: mildly sensitive (fluctuations < 10 %).

(iii) The **orientation** of the halo and of its angular momentum with respect to the nearest cosmological filament: highly sensitive (fluctuations 10-80%)



Effect of the multi-scale web filaments on galaxy evolution

Plan of the lecture

1) Results: First generation *(general excitement)*

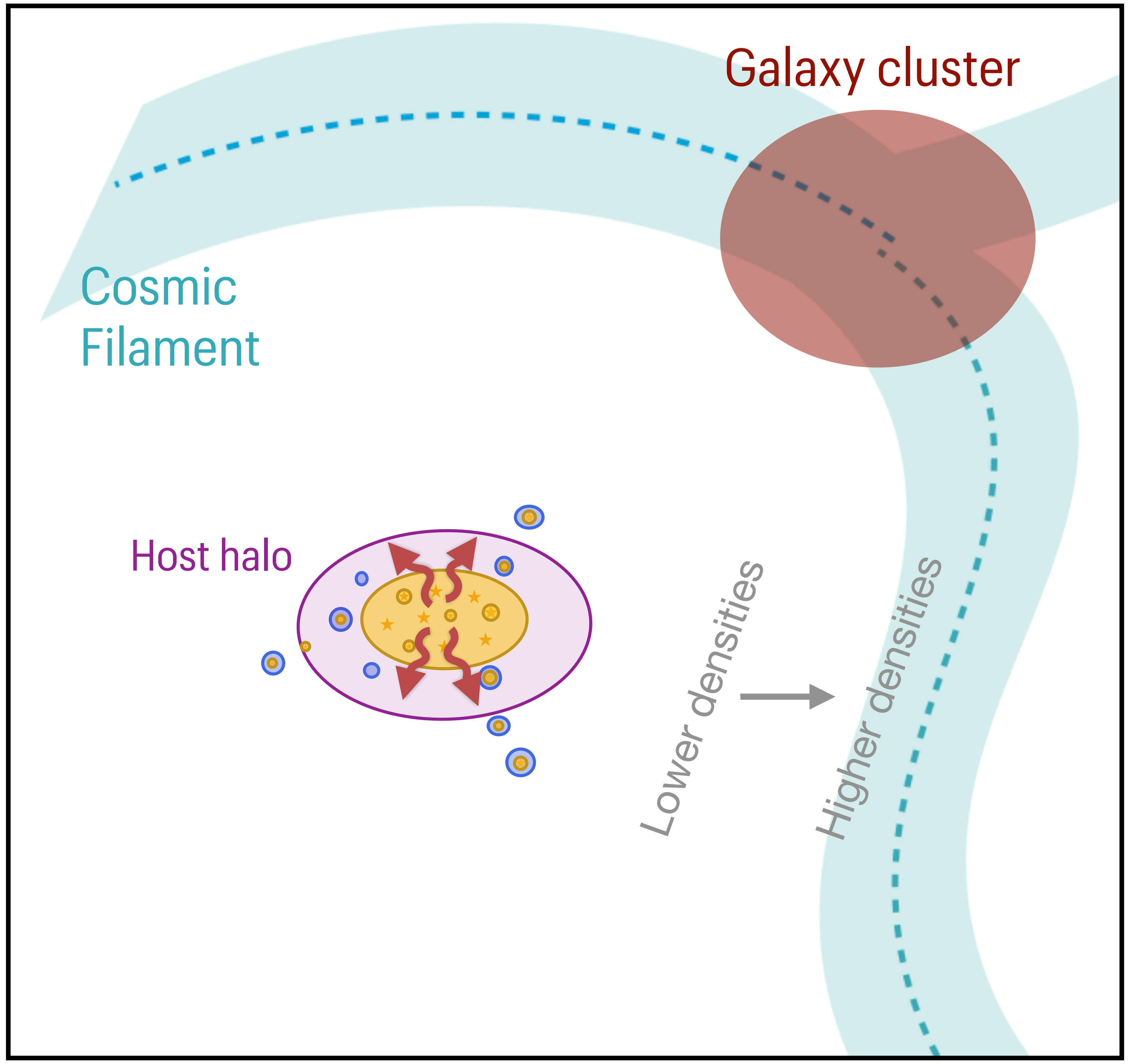
2) Results: Second generation *(density?)*

3) Current picture *(insights from the galaxy evolution community)*

4) Summary: a complicated puzzle

More insights (from galaxy evolution community)...

Simplified cartoon of the neighbourhood of a galaxy:



Complex parameter space:

- central or satellite?
- AGN active?
- Super novae feedback?
- Gas in Circum-galactic medium
- Turbulence & Cosmic rays

- Halo mass
- Cosmic web environment
- Local density
- ...

More insights (from galaxy evolution community)...

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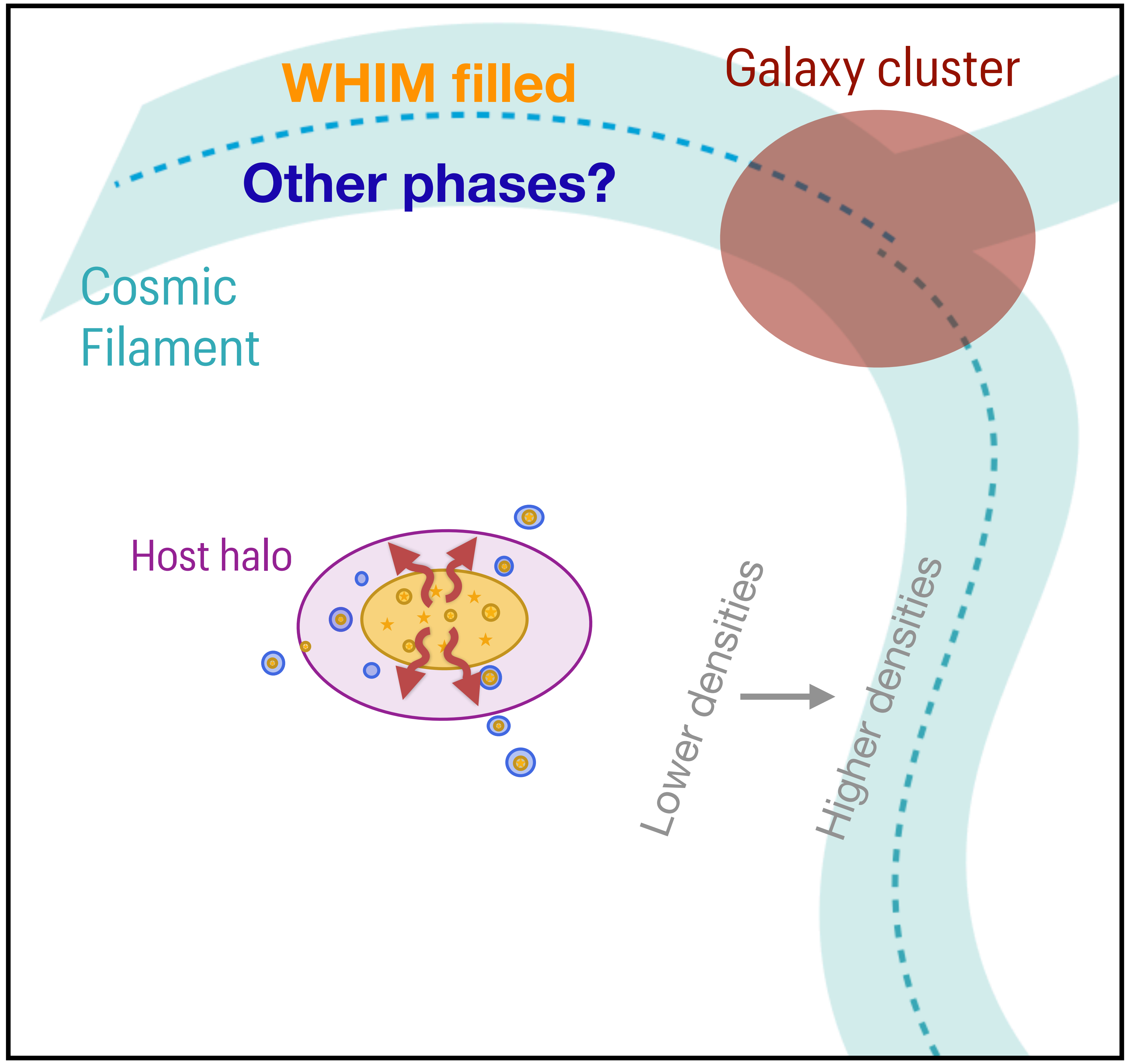


z=0 **Higher redshifts**

Complex parameter space:

- central or satellite?
- AGN active?
- Super novae feedback?
- Gas in Circum-galactic medium
- Turbulence & Cosmic rays

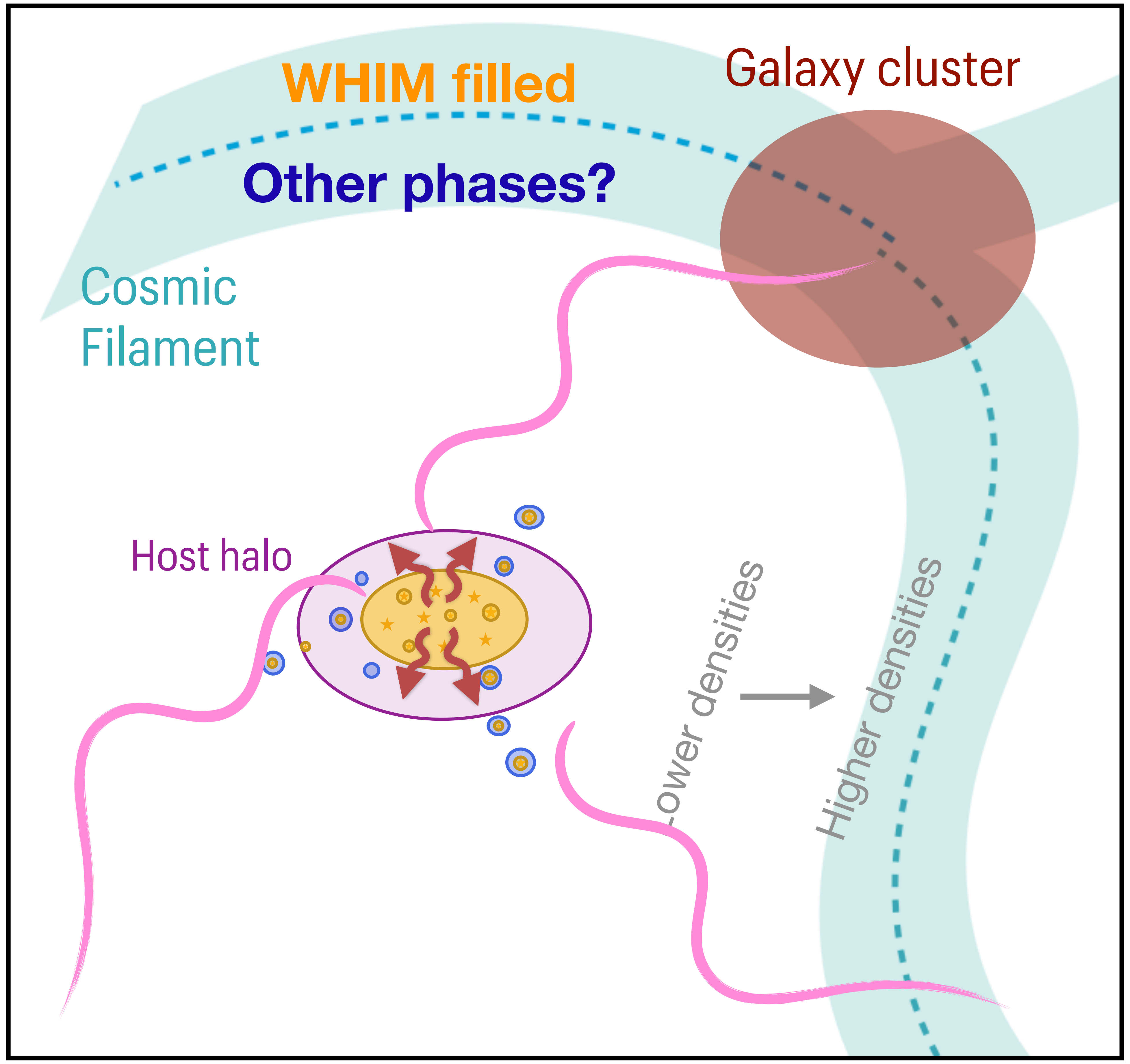
- Halo mass
- Cosmic web environment
- Local density
- ...

Within the **hierarchical formation model**, the assembly histories of galaxies are expected to be affected by the **past large-scale environment.**

Galaxy properties: should be affected by this history while (maybe) also correlating with the present environment.

More insights (from g Cosmic web n community)...

Simplified cartoon of the neighbourhood of a galaxy:



z=0 **Higher redshifts** **Multi-scale web!**

Complex parameter space:

- central or satellite?
- AGN active?
- Super novae feedback?
- Gas in Circum-galactic medium
- Turbulence & Cosmic rays

- Halo mass
- Cosmic web environment
- Local density
- ...

Within the **hierarchical formation model**, the assembly histories of galaxies are expected to be affected by the **past large-scale environment.**

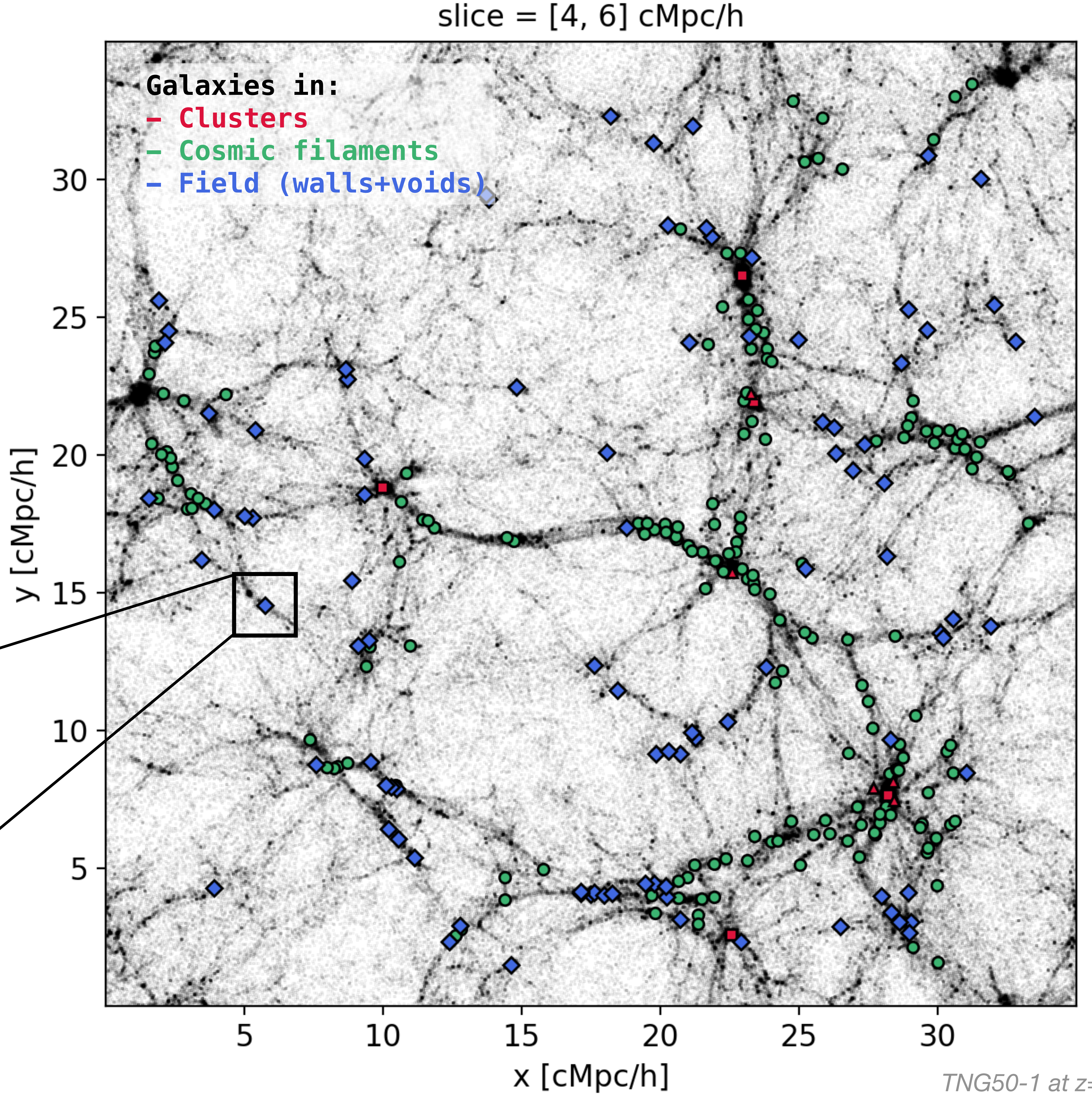
Galaxy properties: should be affected by this history while (maybe) also correlating with the present environment.

Galaxy evolution: a multi-scale problem

- **Problem: understanding quenching of star-formation.**
  Hard because huge parameter space, many intrinsic correlations!
  (halo mass, local density, SN & AGN feedback, …)
  + Galaxies are not isolated, they are embedded in the large-scale cosmic web!

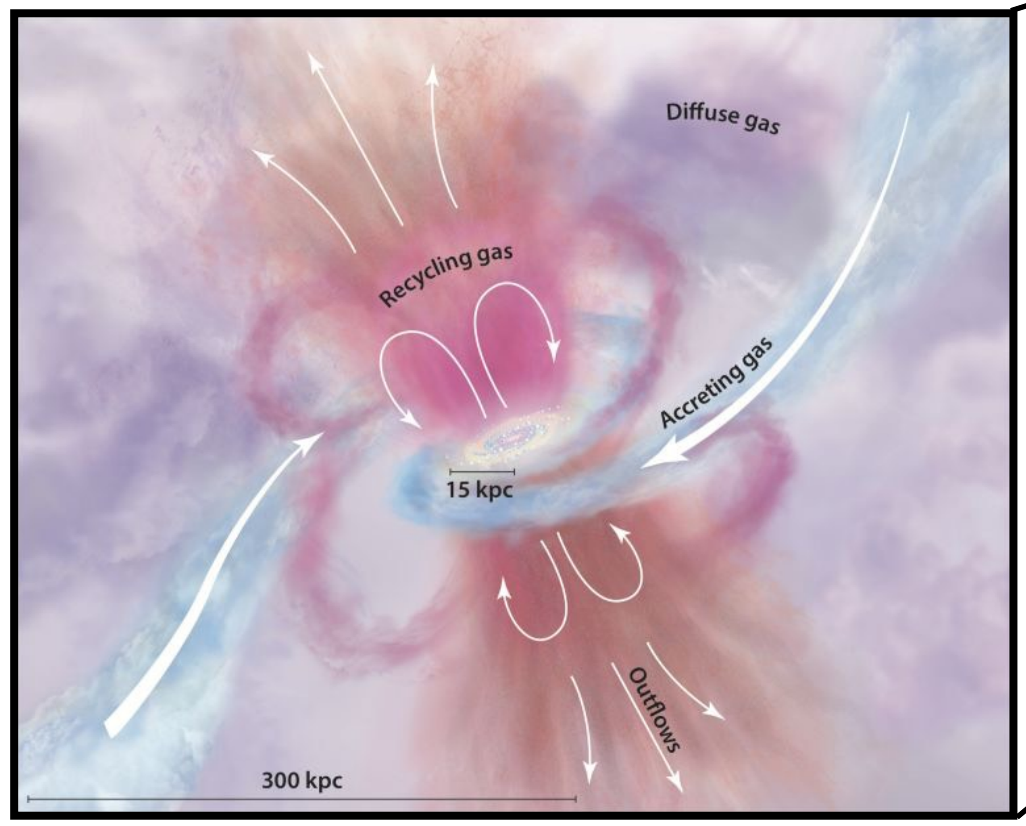
- **We need to** look at <u>accretion</u> and <u>availability</u> of **cold gas**

- Theory —> accretion from *external reservoirs* at high z, via **filamentary streams**



TNG50-1 at z=2

Birnboim & Dekel 2003; Kereš+ 2005; Ocvirk+ 2008; Dekel+ 2009; Bauermeister+ 2010; Pichon+ 2011; Faucher-Giguère & Kereš 2011; Faucher-Giguère+ 2011; Danovich+ 2012; Nelson+ 2013; Prescott+2015; Stewart+ 2017; Zabl+2019; Ramsøy+ 2021, Lu+2024, …



Tumlinson+ 2017

How?

Inspired from (large-scale) cosmic web studies (e.g. Codis+2028; Darragh Ford+ 2019; Kraljic+ 2020; Gouin+2020, 2021)

"Flows around galaxies I" (Galárraga-Espinosa, Garaldi & Kauffmann 2023)

1) Central galaxies from TNG50-1

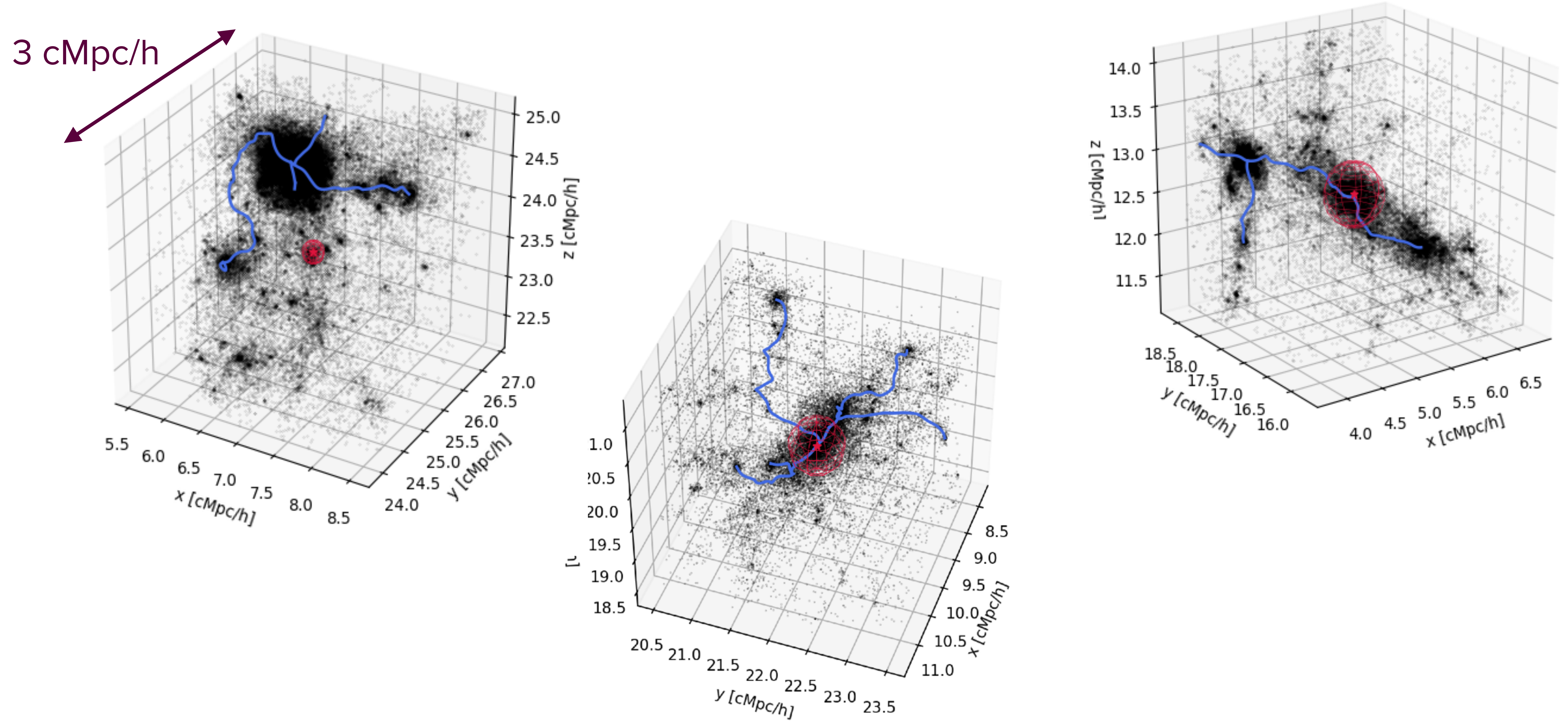
- $M_* \geq 10^8\,\mathrm{M}_\odot/h$
- At **z=2** (peak of SF activity)
- Select **only star-forming**

—> **2942 centrals**

2) Filaments/streams detected in 3 cMpc/h environments, using the DM density.

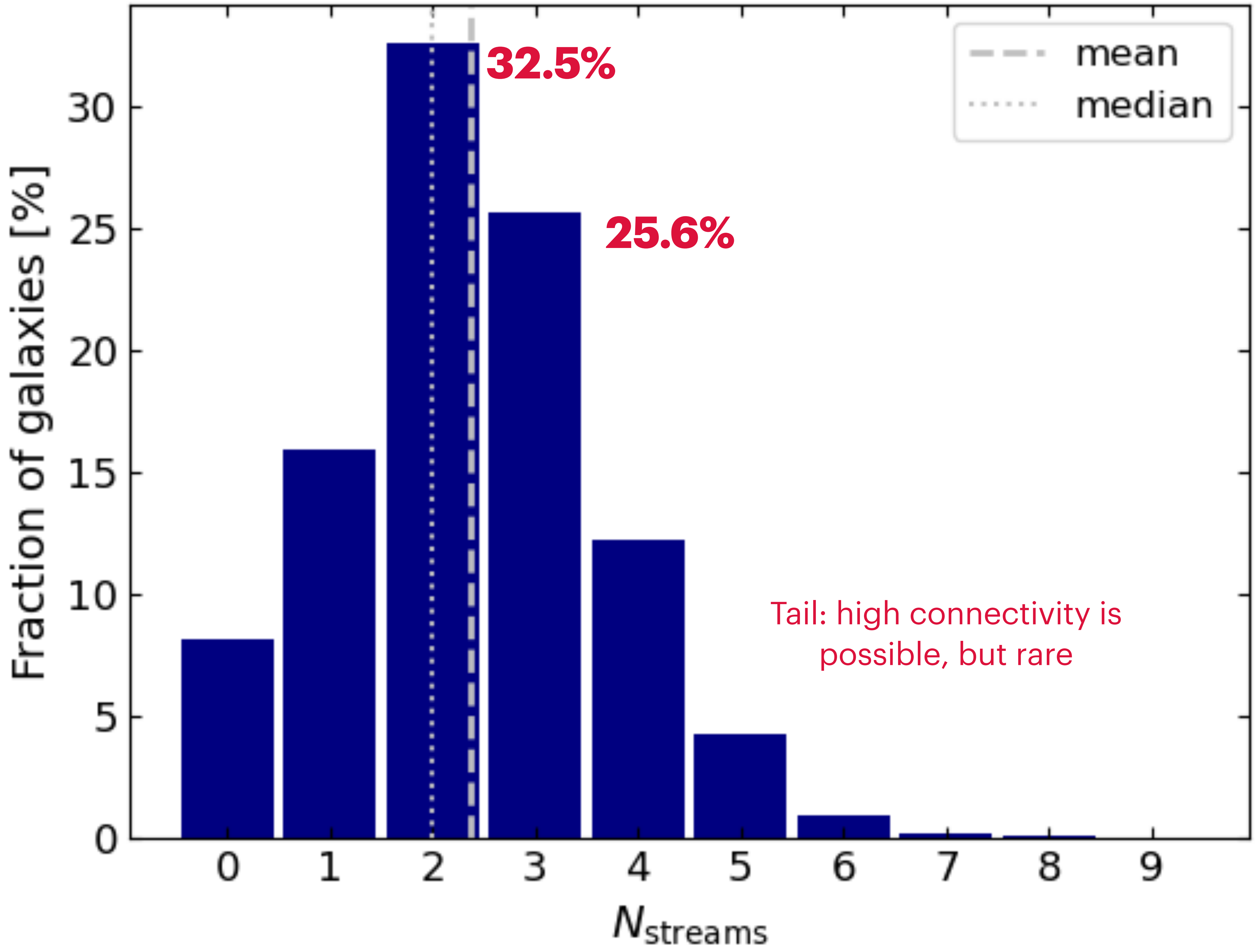
—> Goal: detect the local potential wells

—> filament finder: DisPerSE (Sousbie+ 2011, Sousbie 2011)



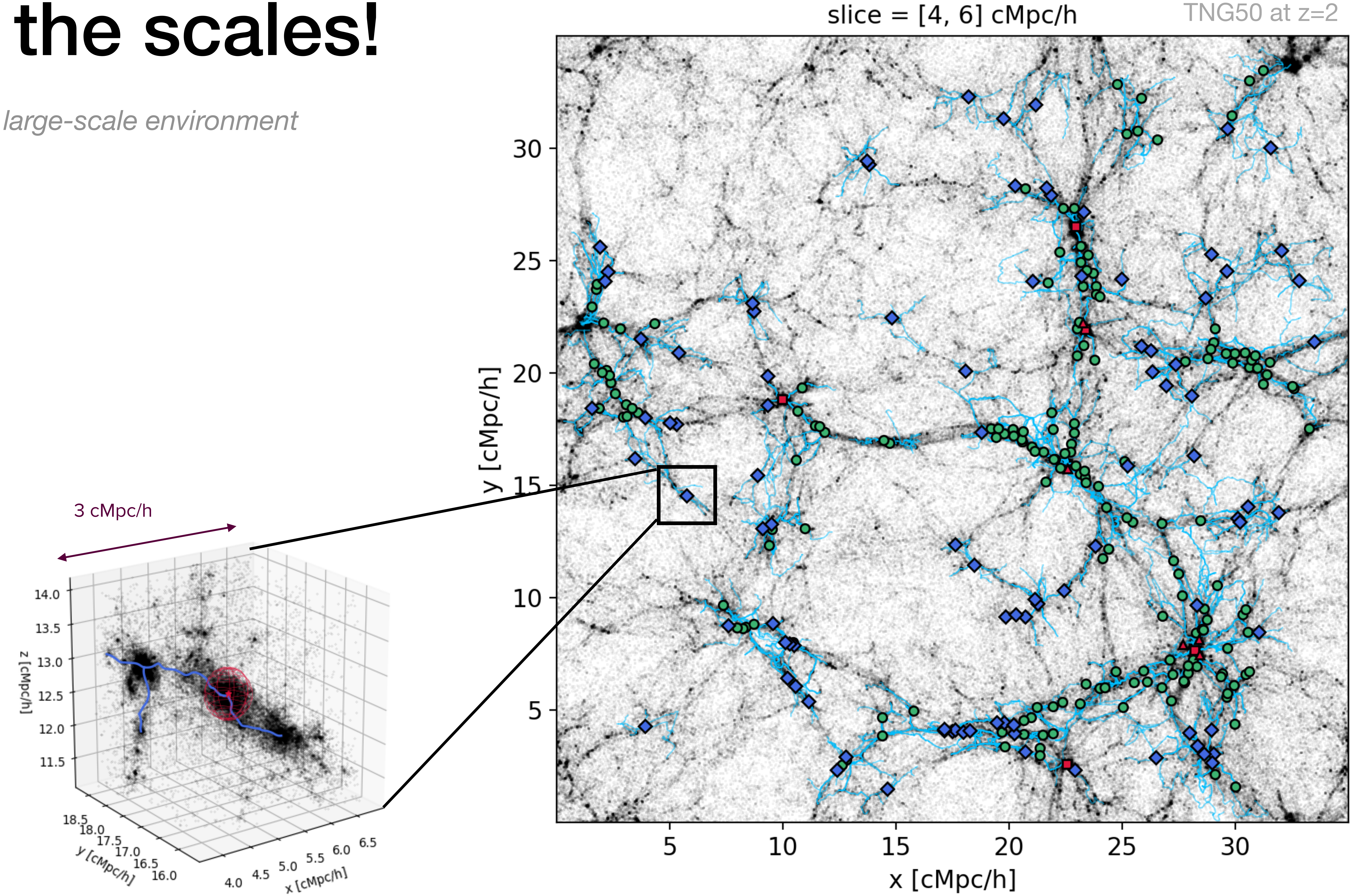
3) The observable: Galaxy connectivity

= Number of streams intersecting Rvir



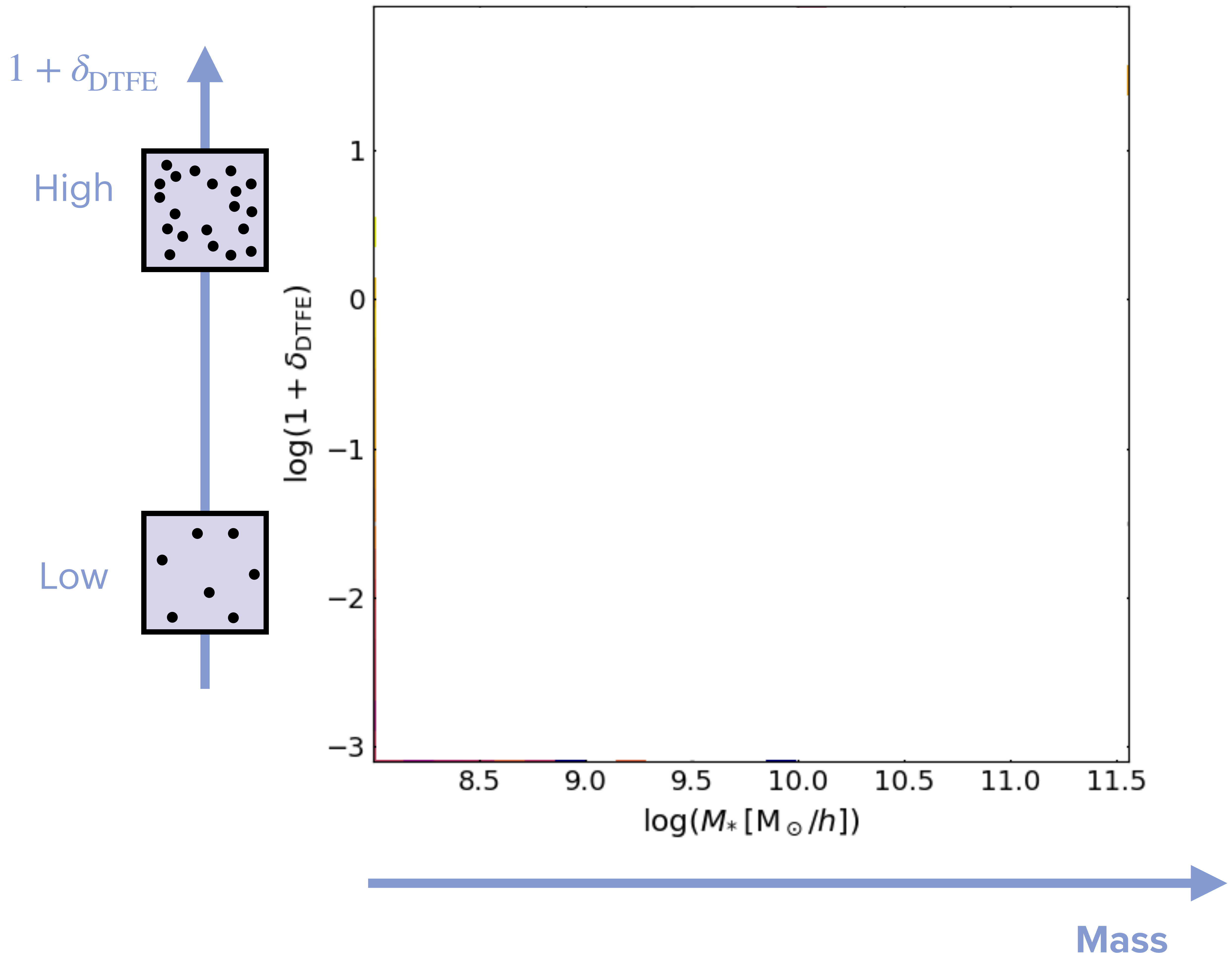
Mind the scales!

Local web vs large-scale environment



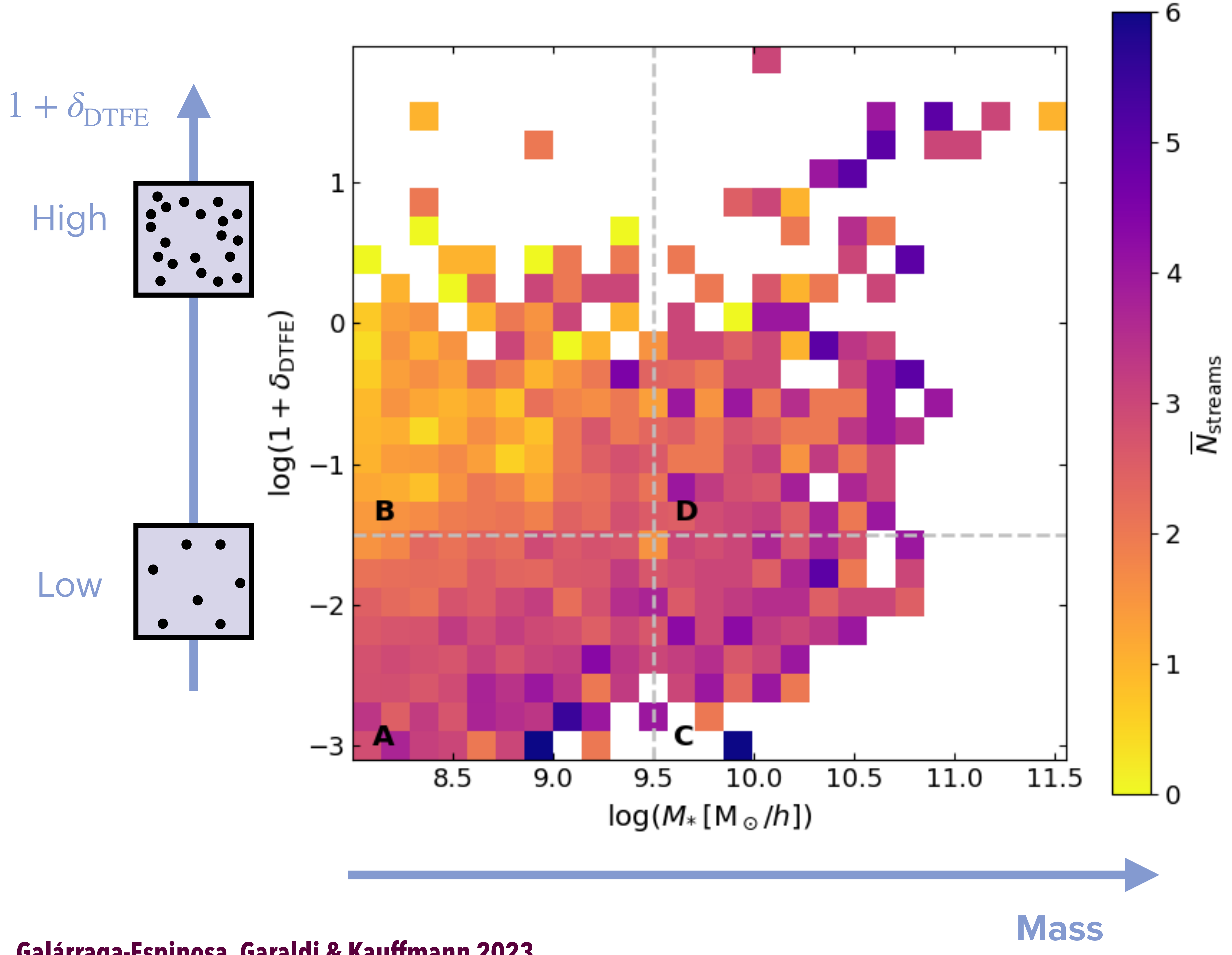
Connectivity : any secondary dependences?

Mean connectivity in the mass-overdensity plane



Connectivity : any secondary dependences?

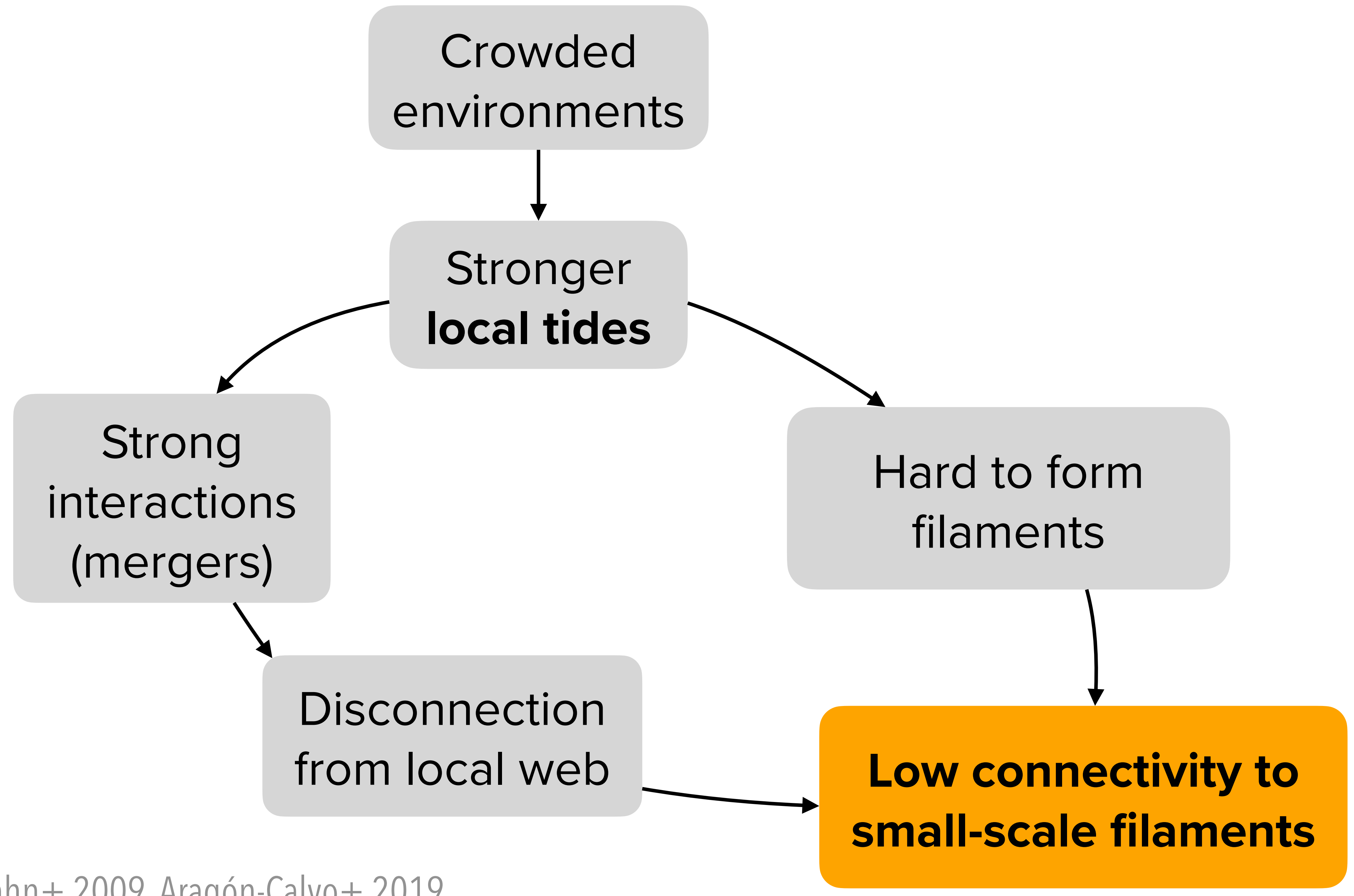
Mean connectivity in the mass-overdensity plane



Galárraga-Espinosa, Garaldi & Kauffmann 2023

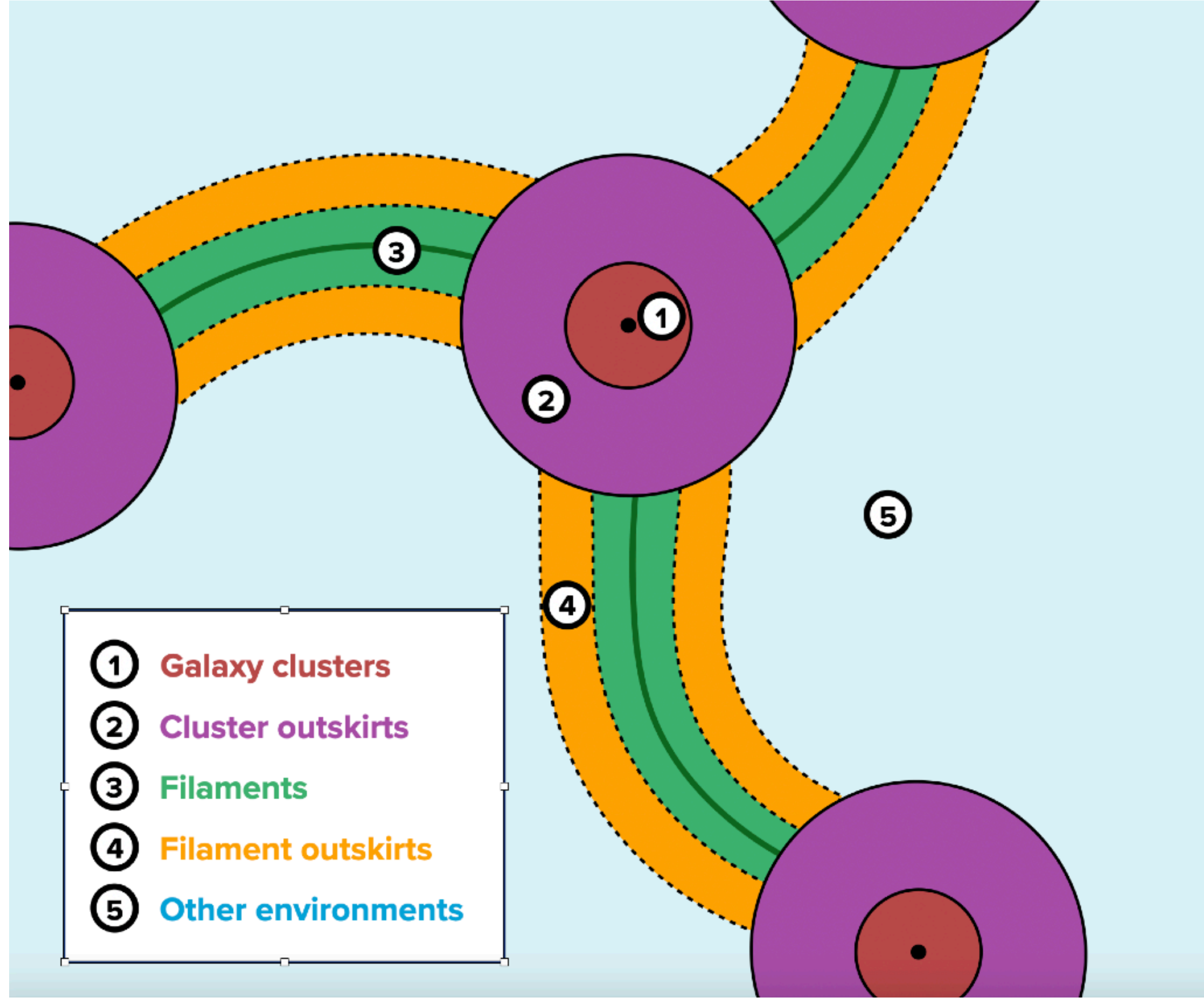
1. **Increase with <u>mass</u>**
   - Explained by peak theory (Codis+2018) and seen in galaxy clusters (Aragón-Calvo+ 2010, Darragh-Ford+ 2019, Sarron+ 2019, Malavasi+ 2020, Kraljic+ 2020, Gouin+2021, Boldrini+ 2024)
   - Here: extension to lower mass haloes

2. **Decrease with <u>local density</u> for low mass galaxies!**

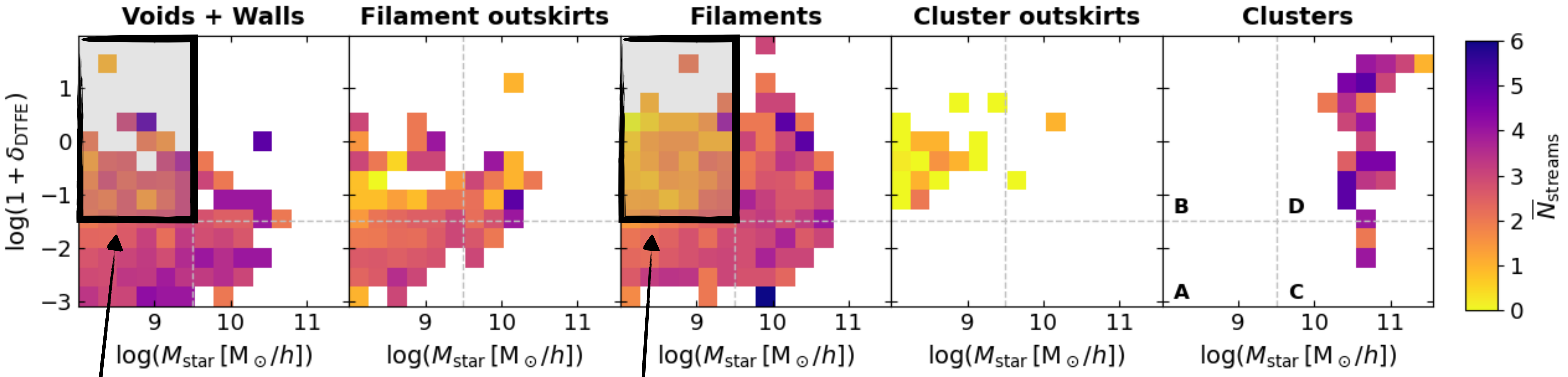


Hahn+ 2009, Aragón-Calvo+ 2019

Variations with large-scale environment?



Connectivity of galaxies in different cosmic web environments



mean = 2.34 ± 0.09

mean = 1.43 ± 0.05

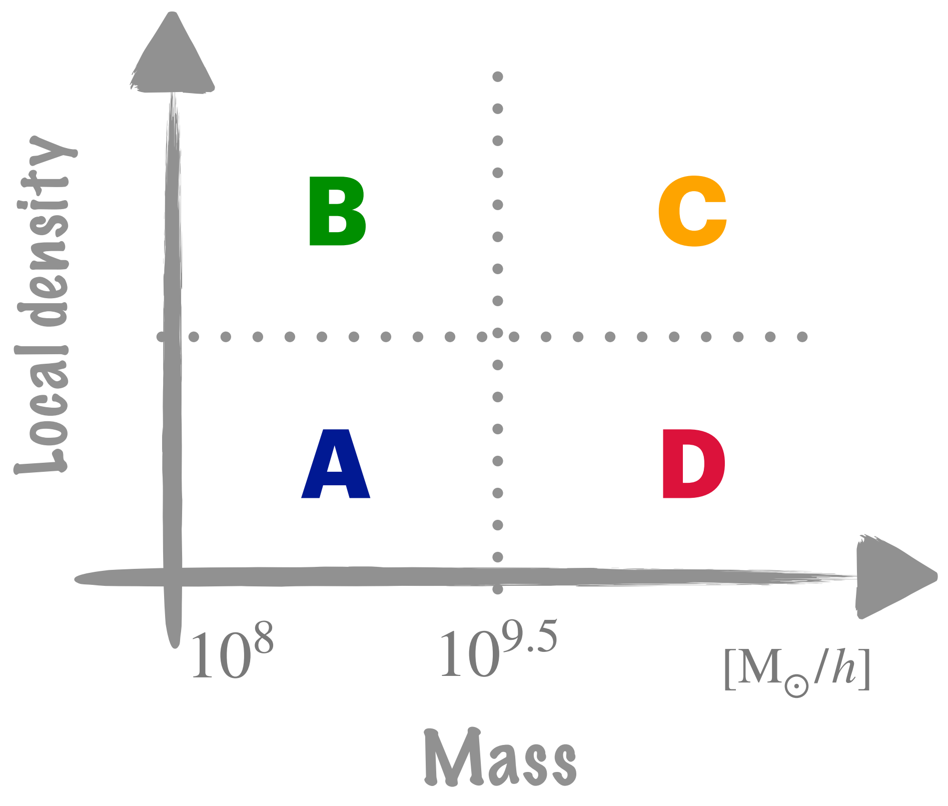
=> ***8.48σ difference***

Variations due to effects of cosmic tides

(different strengths in different locations in the Cosmic Web)

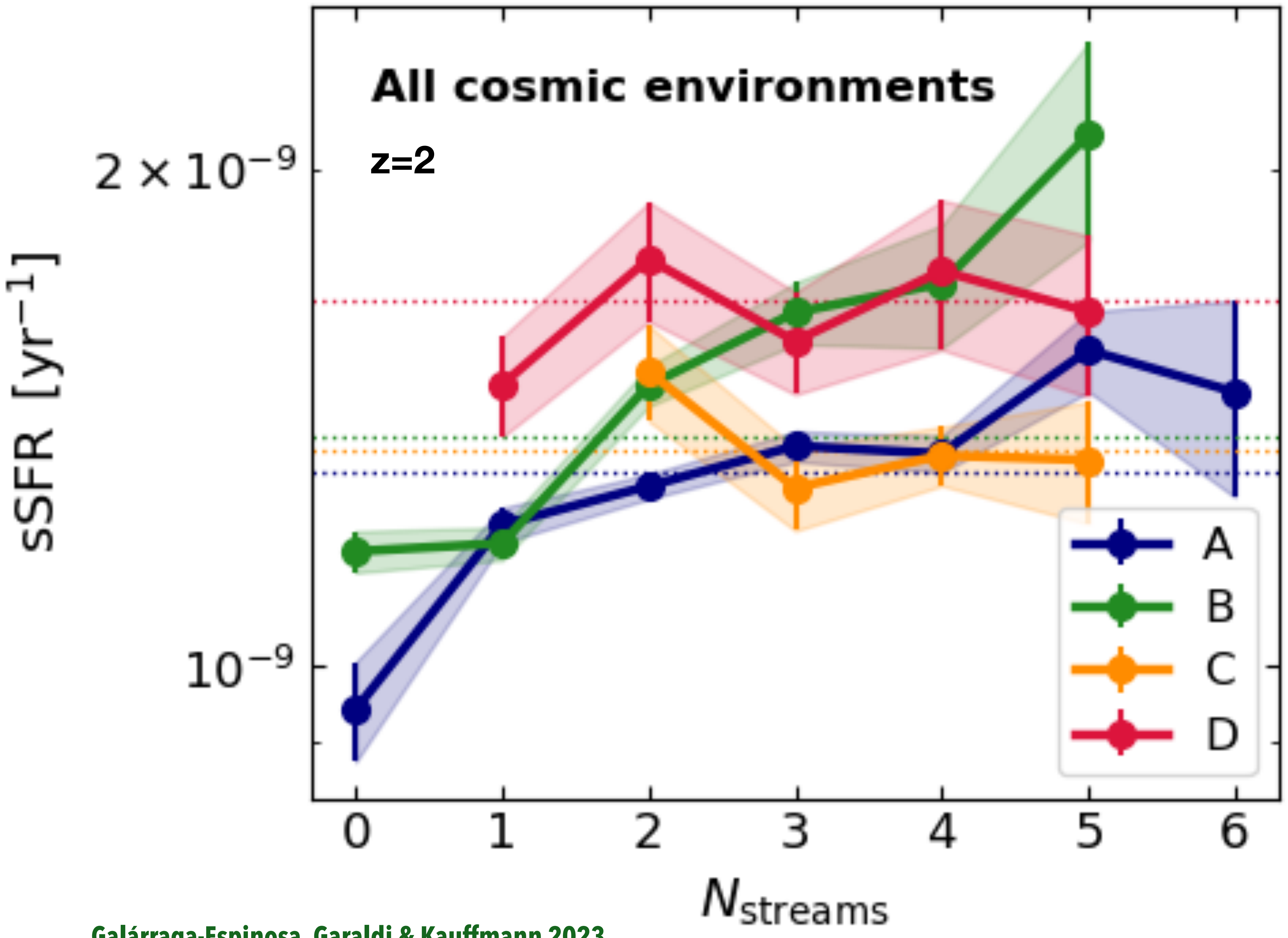
Borzyszkowski+ 2017; Musso+ 2018; Paranjape+ 2018; Kraljic+ 2020; Kuchner+ 2020, Jhee+ 2022:…

Galárraga-Espinosa, Garaldi & Kauffmann 2023



Relation with SFR

Mean sSFR vs connectivity



Galárraga-Espinosa, Garaldi & Kauffmann 2023

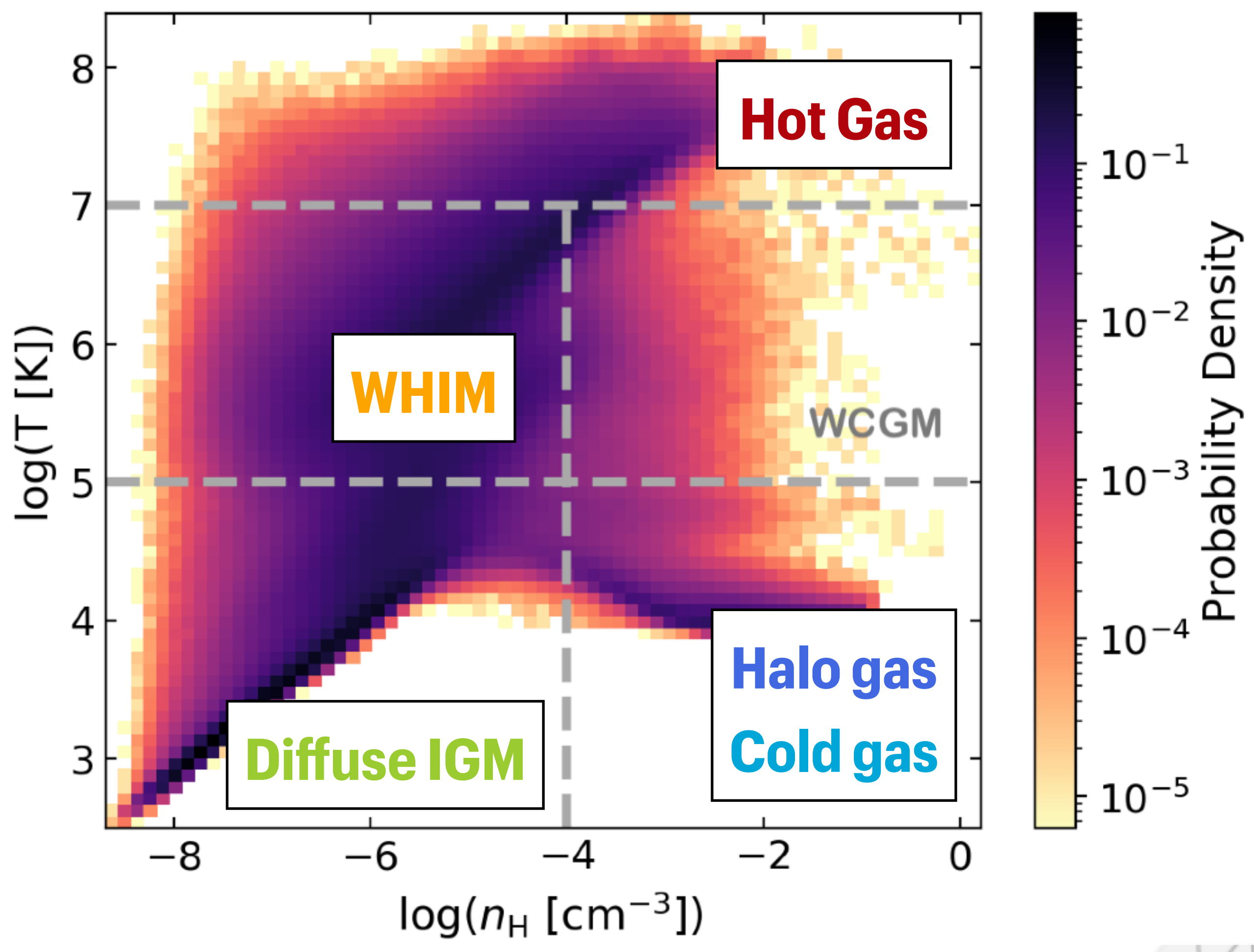
1) sSFR significantly boosted for <u>low mass</u> galaxies (A: 5.84σ, B: 5.92σ)

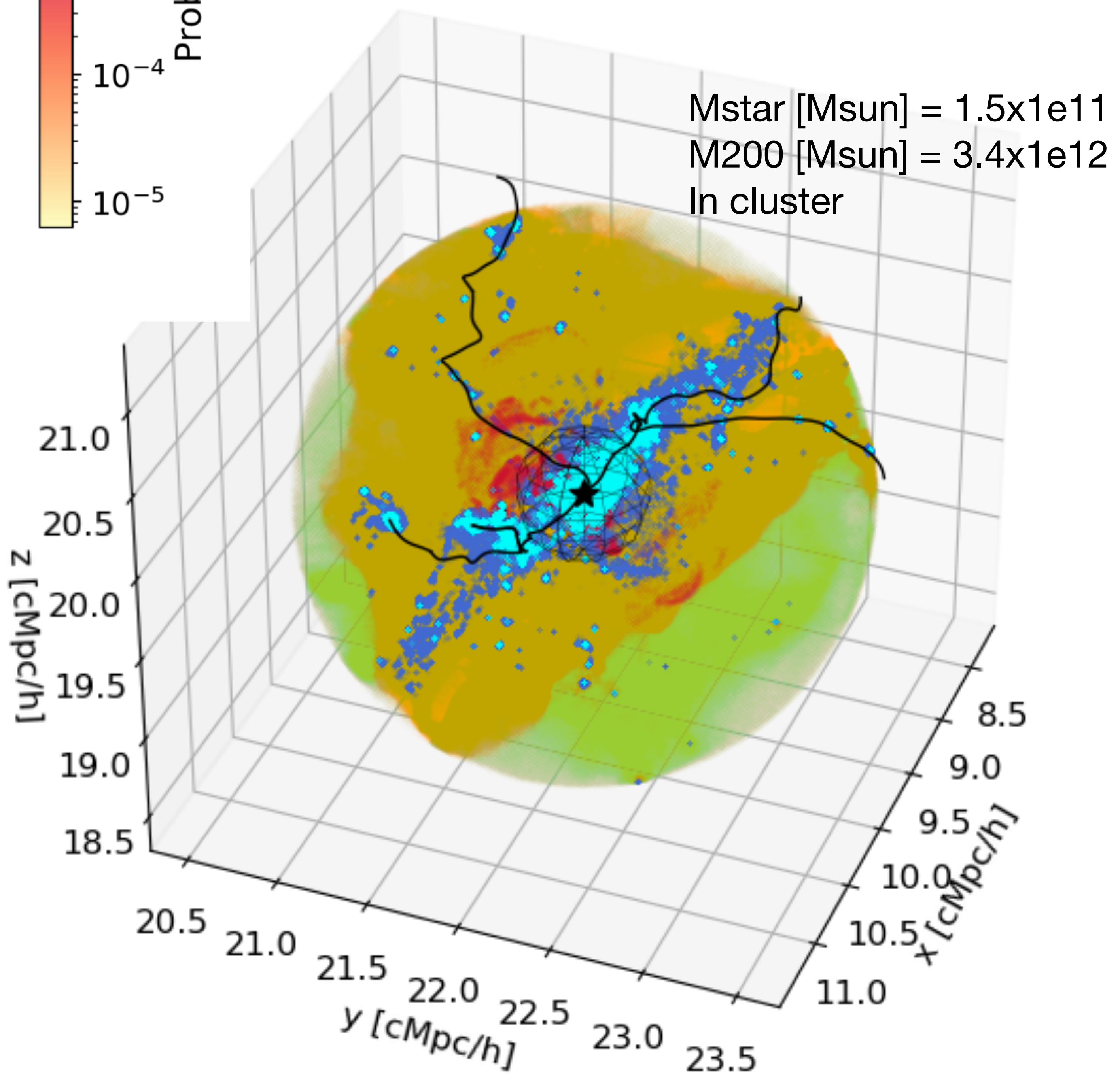
larger number of streams
=> more accretion of cold material (anisotropic accretion)
=> boost galaxy star-formation

2) No trend for <u>high mass</u> galaxies. Accretion via streams not efficient? "Dry" streams?

Which gas phase is in those DM filaments (z=2)?

***"Flows around galaxies II"* (in preparation)**





Msc. Silvia Rueda Vargas
6 months internship @MPA
Now PhD student @ESO-Garching

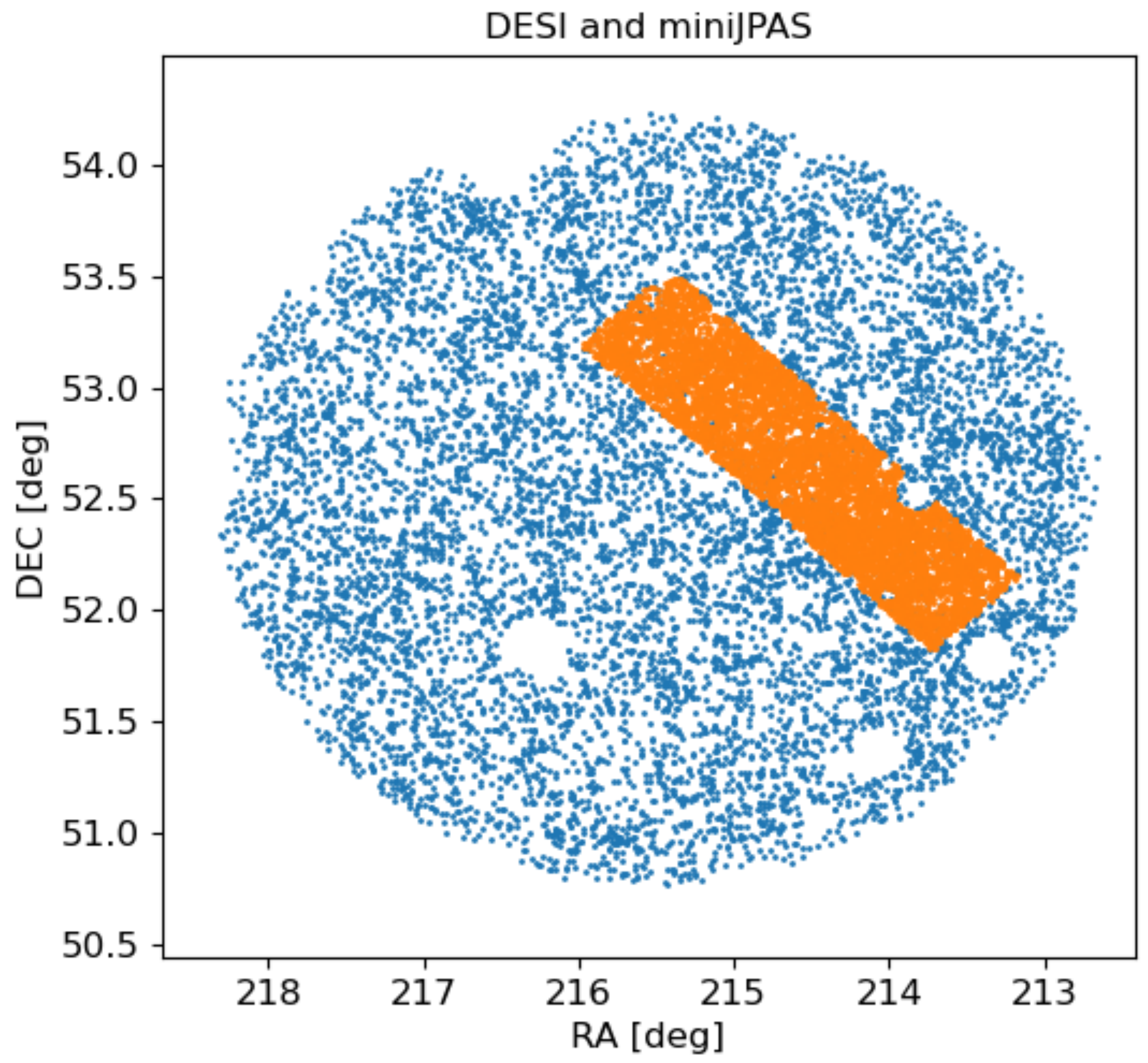
Can we observe this?

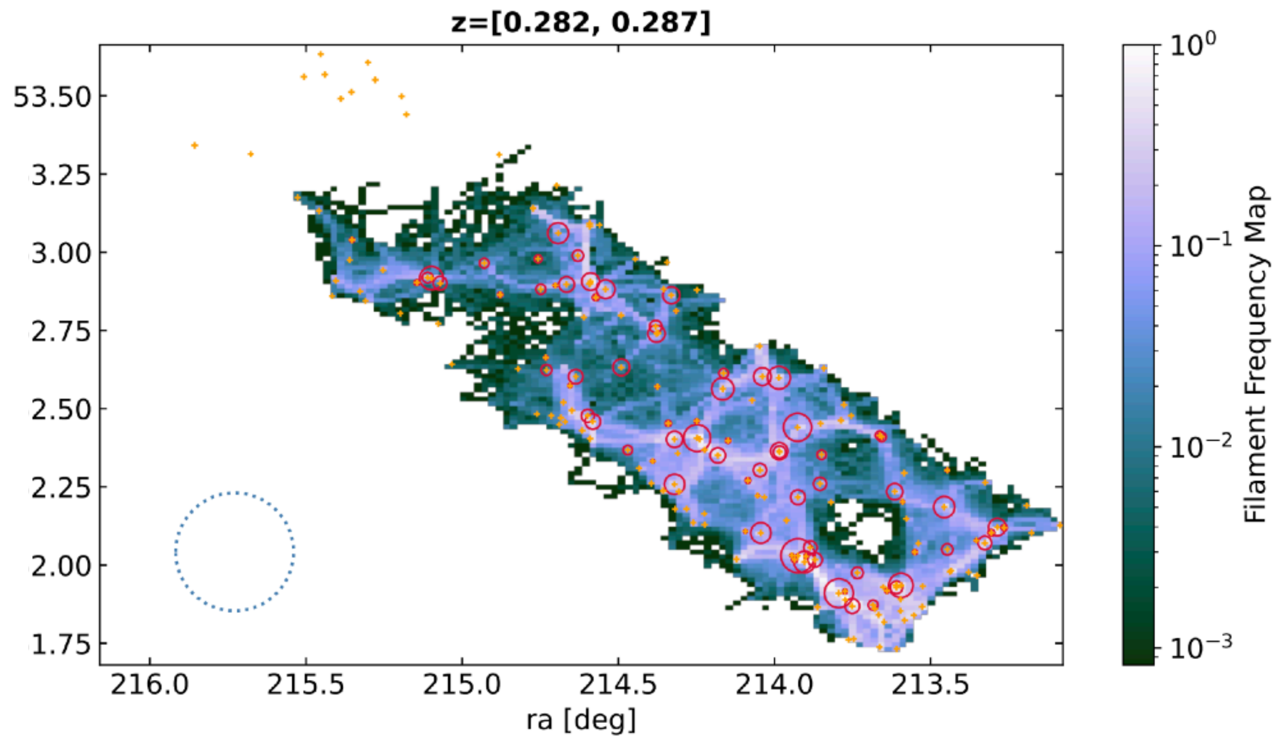
Galarraga-Espinosa et al. 2025 (submitted)

Unveiling the small-scale web around galaxies with miniJPAS and DESI: the role of local connectivity in star formation

Daniela Galárraga-Espinosa[1,2]★, Guinevere Kauffmann[1], Silvia Bonoli[3,4], Luisa Lucie-Smith[5], Rosa M. González Delgado[6], Elmo Tempel[7,8], Raul Abramo[9], Siddharta Gurung-López[10,11], Valerio Marra[12,13,14], Jailson Alcaniz[15], Narciso Benitez, Saulo Carneiro[15], Javier Cenarro[16,17], David Cristóbal-Hornillos[16], Renato Dupke[15], Alessandro Ederoclite[16,17], Antonio Hernán-Caballero[16,17], Carlos Hernández-Monteagudo[18,19], Carlos López-Sanjuan[16,17], Antonio Marín-Franch[16,17], Claudia Mendes de Oliveira[20], Mariano Moles[16], Laerte Sodré Jr[20], Keith Taylor[21], Jesús Varela[16], and Hector Vázquez Ramió[16,17]

z<1





Positive trend between small-scale connectivity and SFR for MW-mass galaxies!

Effect of the multi-scale web filaments on galaxy evolution

Plan of the lecture

1) Results: First generation *(general excitement)*

2) Results: Second generation *(density?)*

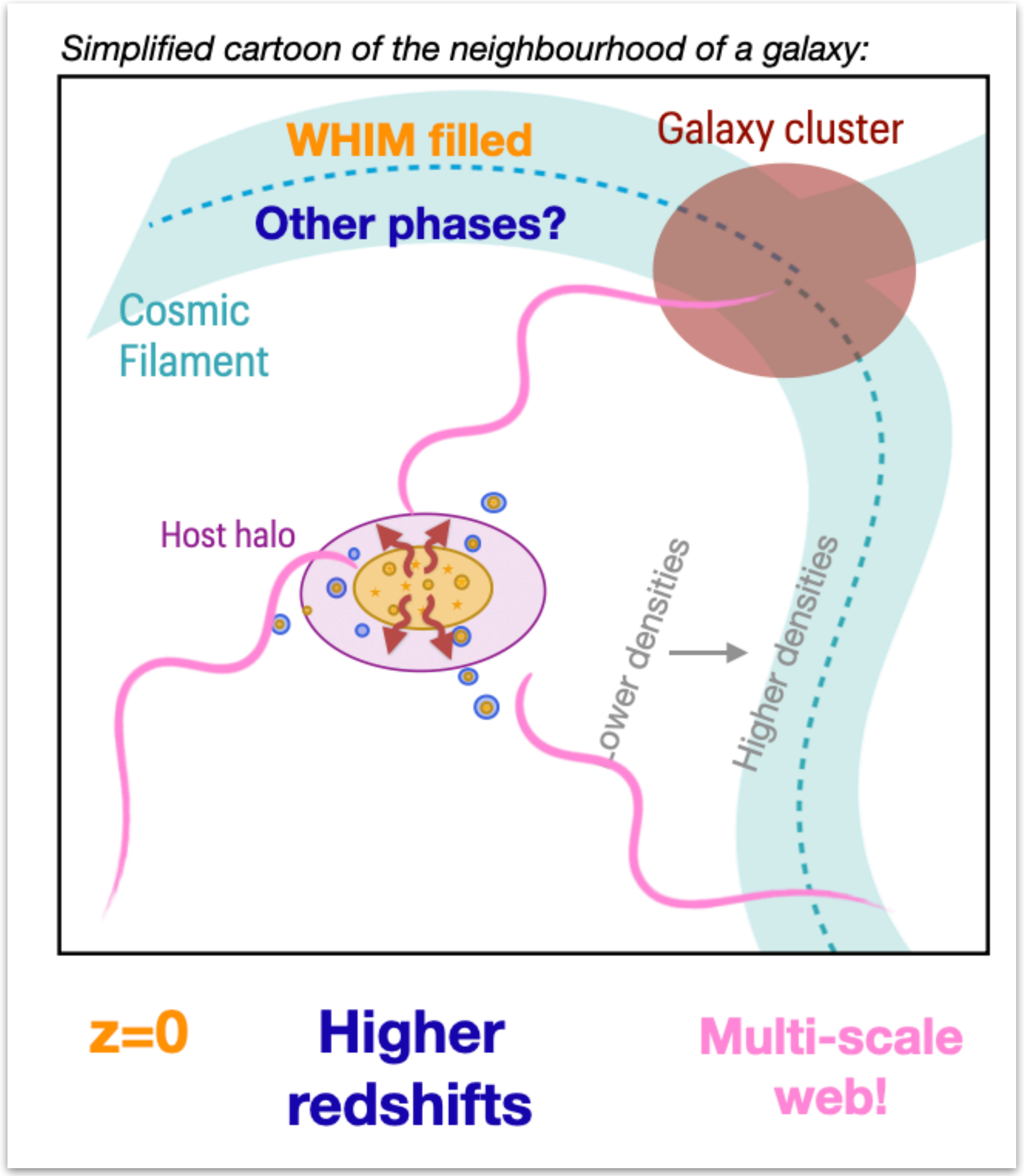
3) Current picture *(insights from the galaxy evolution community)*

4) Summary: a complicated puzzle

Where we stand in 2025

- **Understanding galaxies is complicated**
    - Multi-parameter space
    - Multi-scale
    - Time evolution: galaxies, cosmic web gas

- **Our best try: multi-wavelength observations**
    - Optical galaxy surveys (Elmo's talk)
    - X-rays
    - Radio
    - IR



- **Joint effort/communication between different communities is needed:**
    - Cosmic web community: needs to consider smaller-scale processes + gas
    - Galaxy evolution community: needs to understand that galaxies form and evolve in a web

- **But**: to learn about the processes, we need to be able to connect to fundamental theory (Job's talk)