KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

The astrophysics of large-scale structures in the era of eROSITA, Euclid, SPT-3G: the emergence of the cosmic web
September 9th, 2025

Properties of **cosmic filaments** from **numerical simulations**

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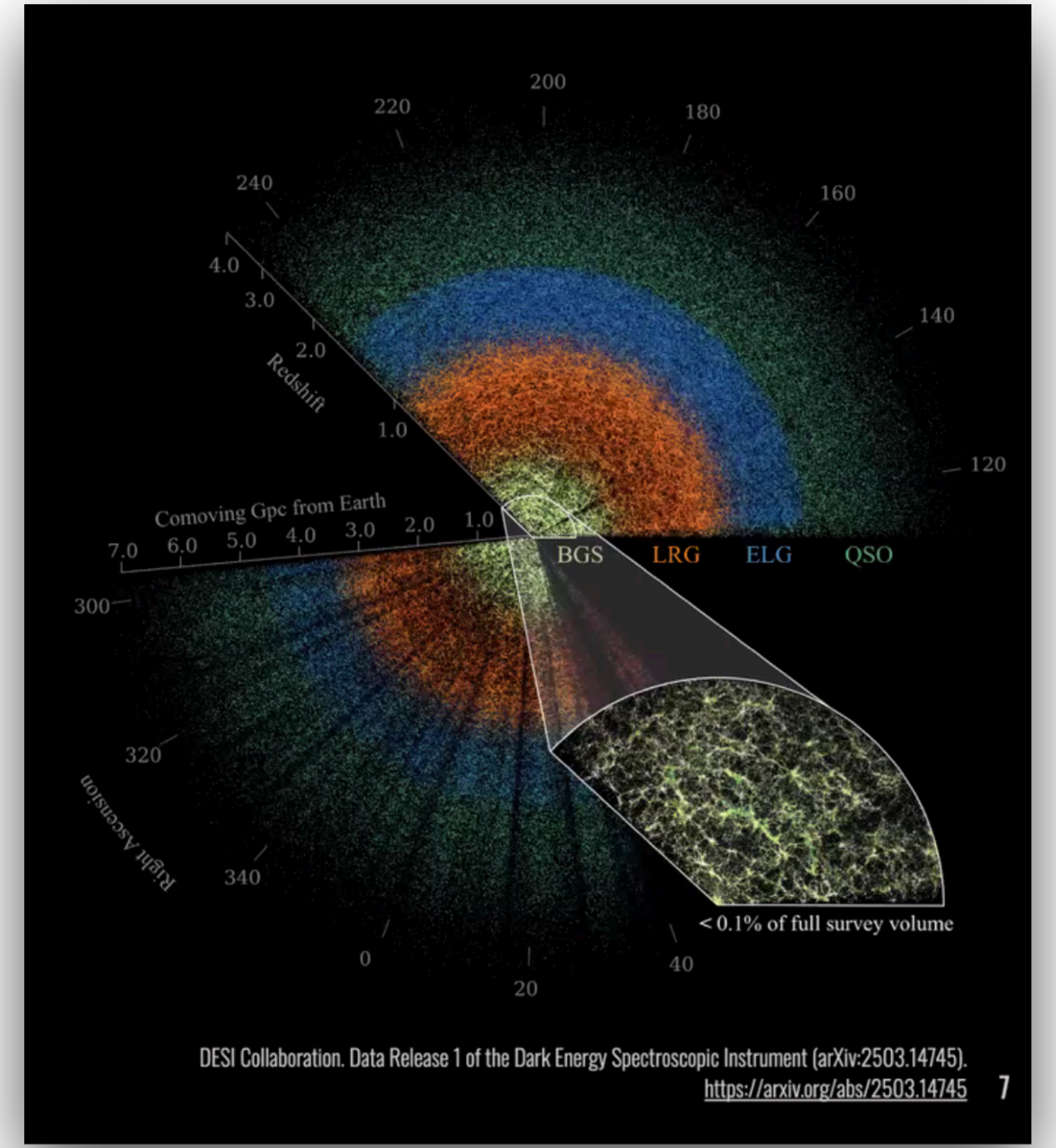
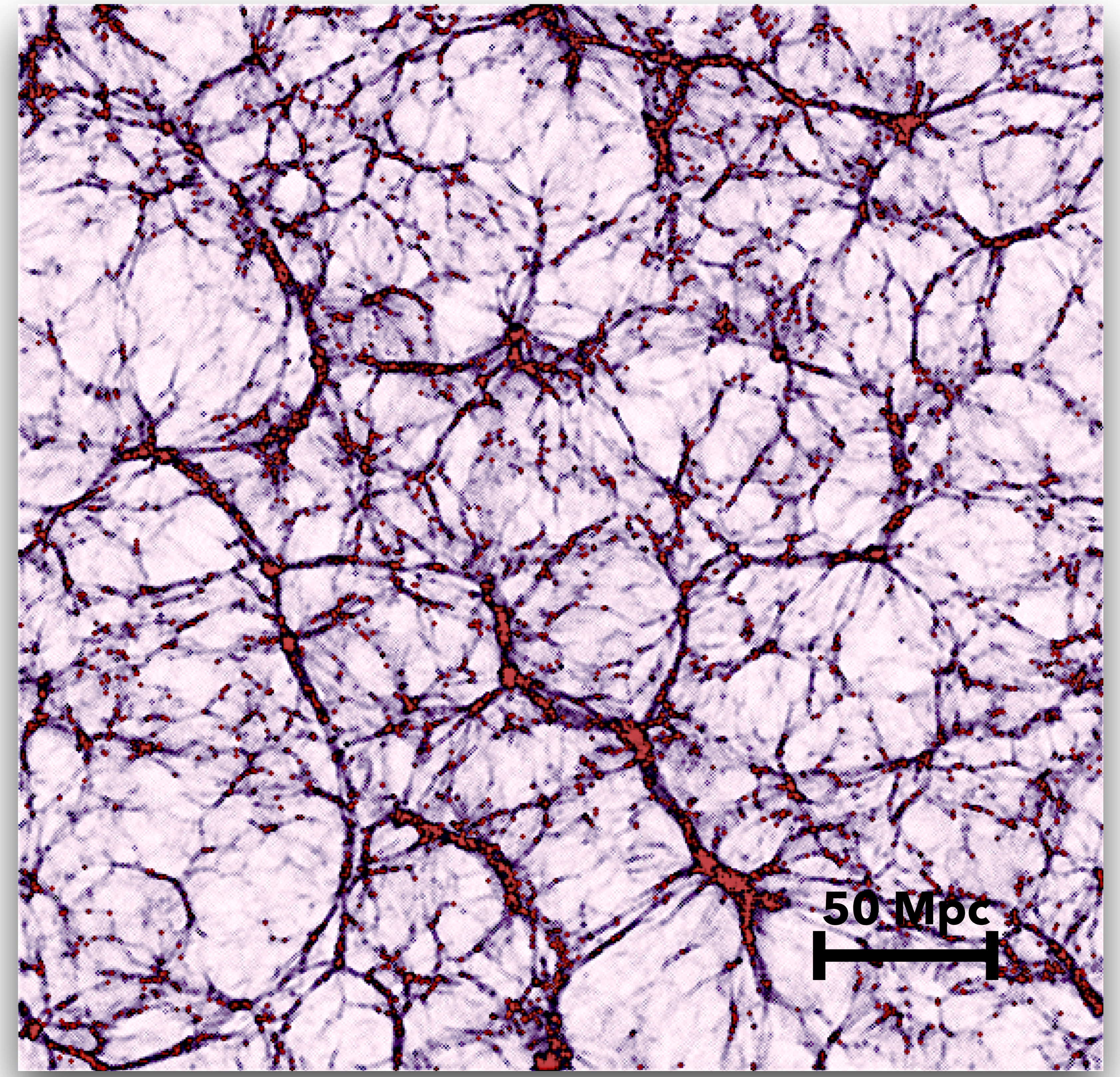
The cosmic web

The distribution of galaxies at the large scales *traces* the cosmic skeleton

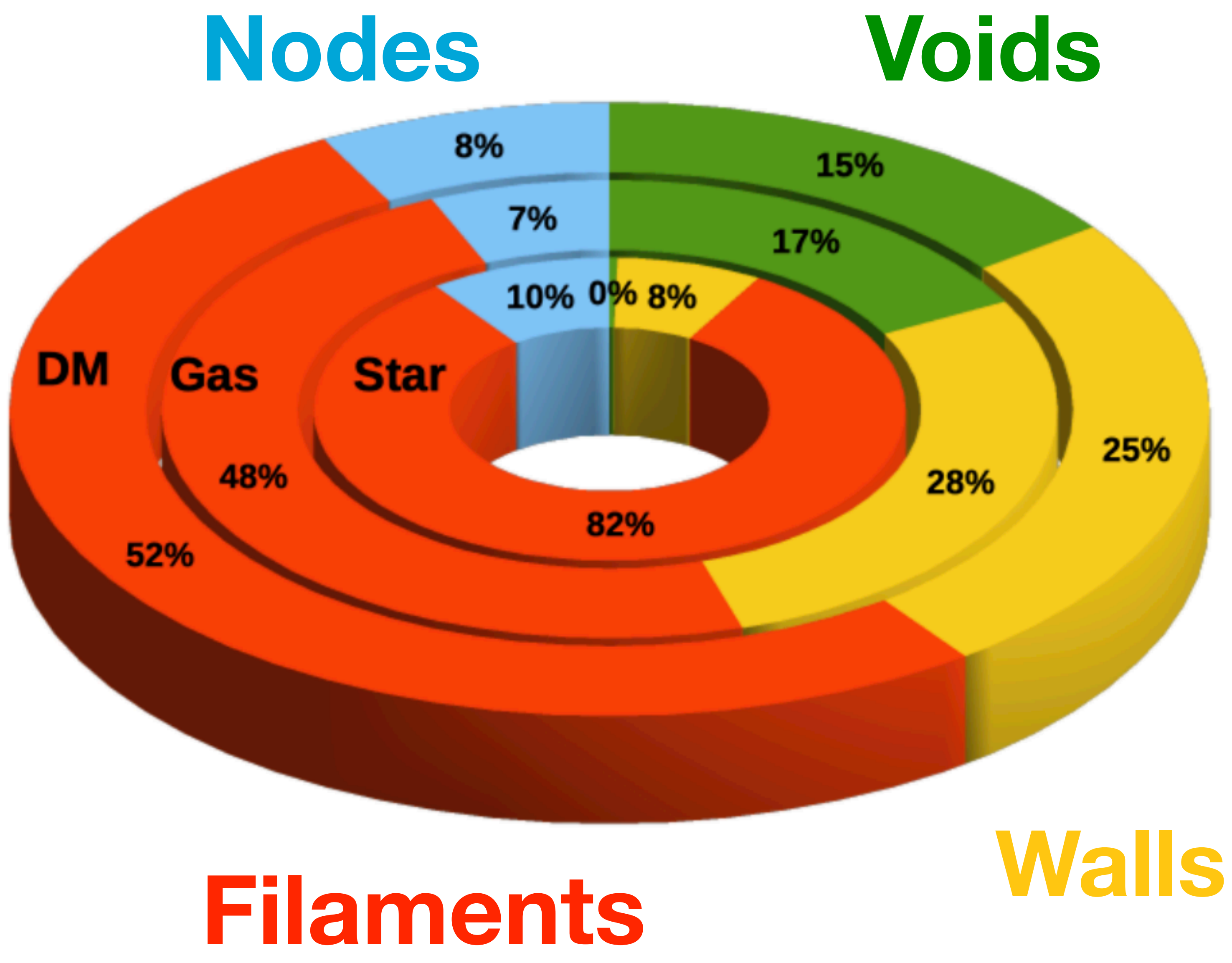


We can simulate the cosmic web



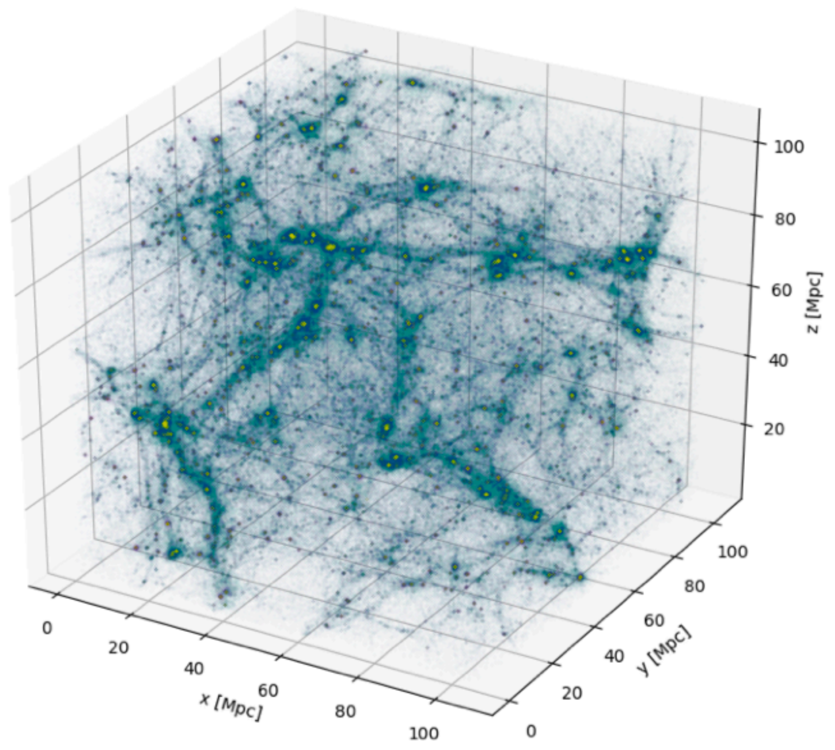
Slice of the IllustrisTNG simulation (Nelson+ 2019, Pillepich+ 2019): z=0

Matter distribution at large-scales



Ganeshaiah Veena+ 2019

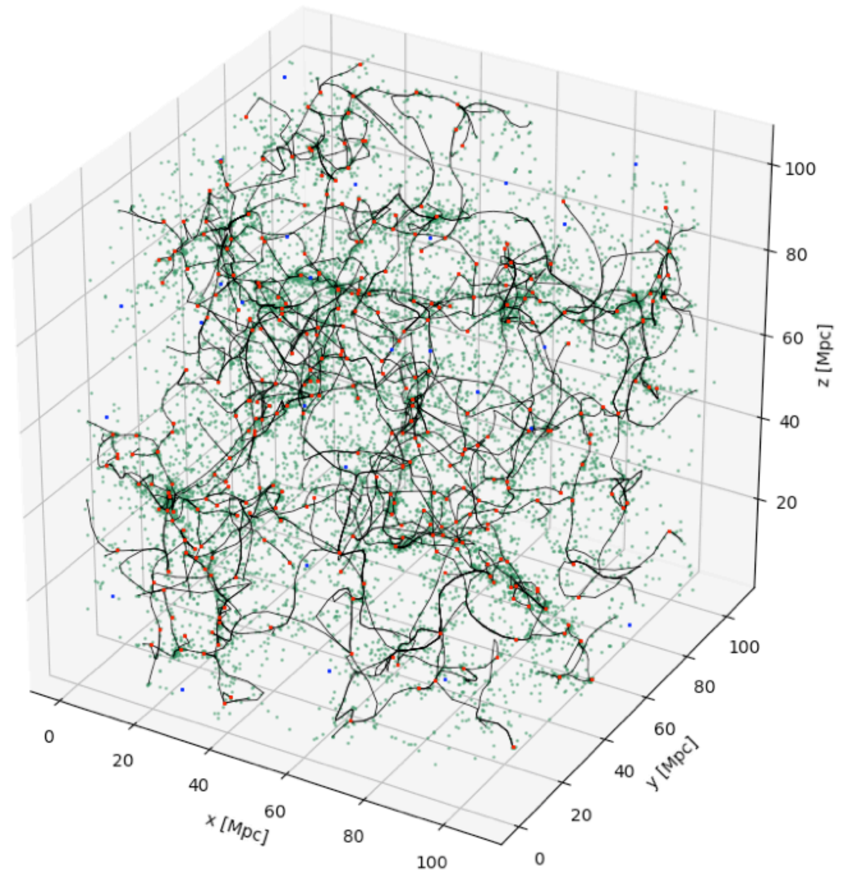
Filament characterisation methodology

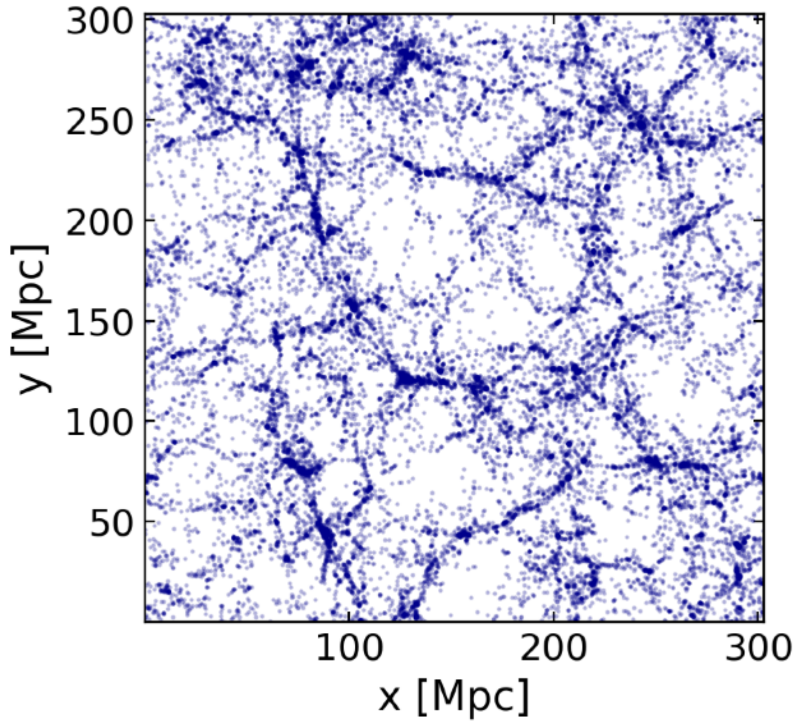


Hydro-dynamical numerical simulations

Filament catalogues

Using filament finder **DisPerSE**

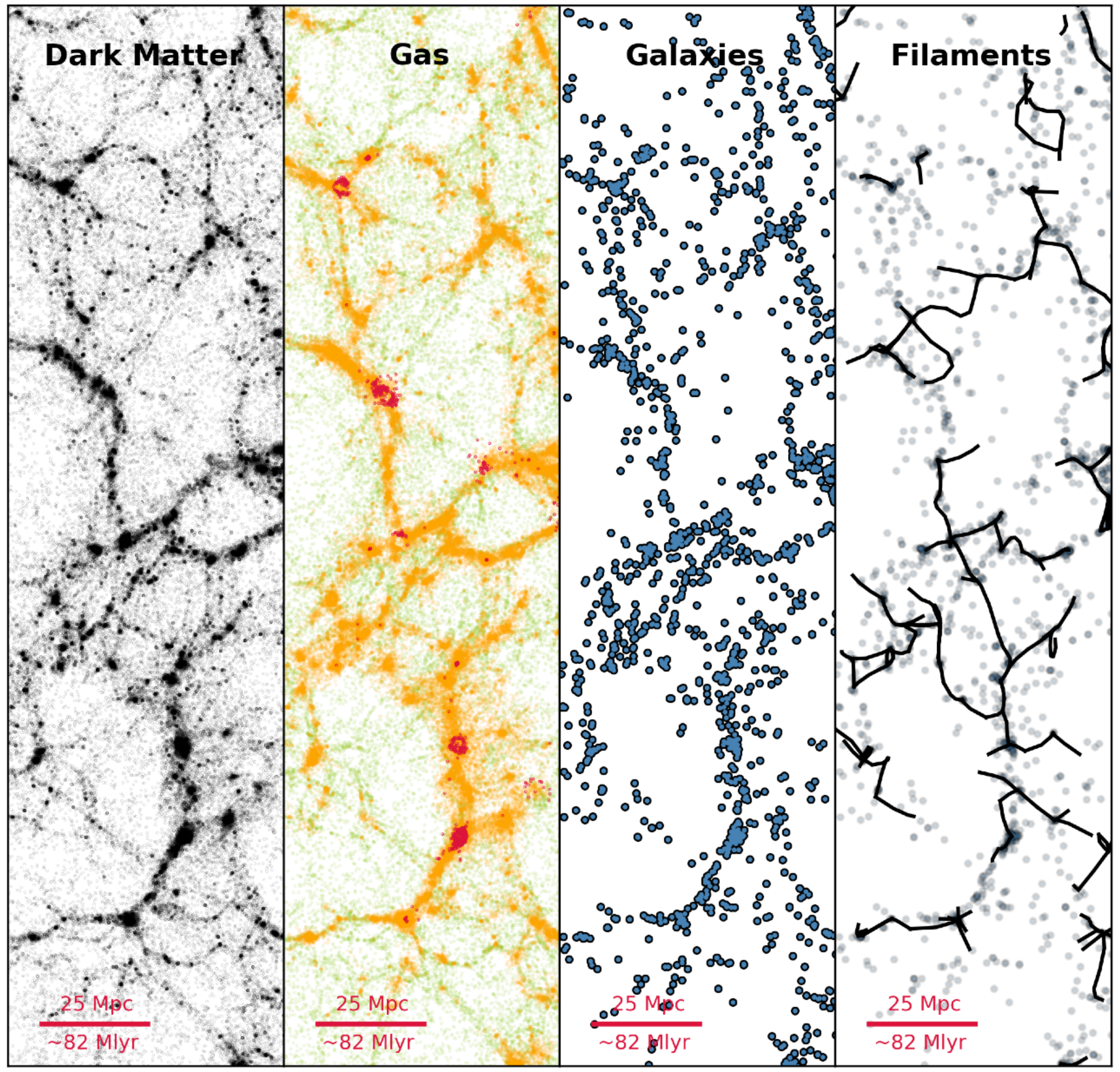




Galaxy distributions

Following an observational approach

Analysis of matter properties around filaments



Cosmic filament characterisation

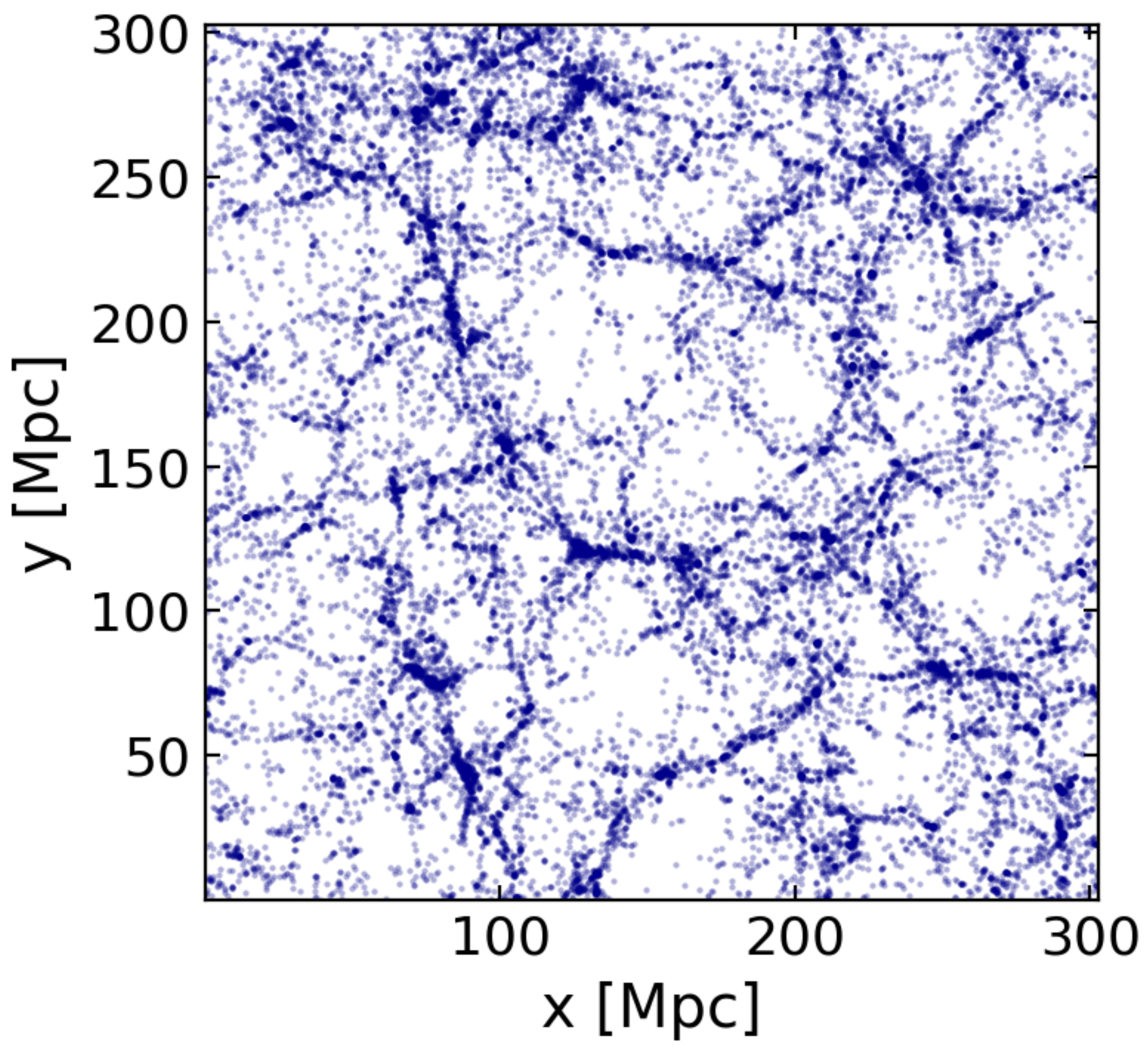
Finding the filaments

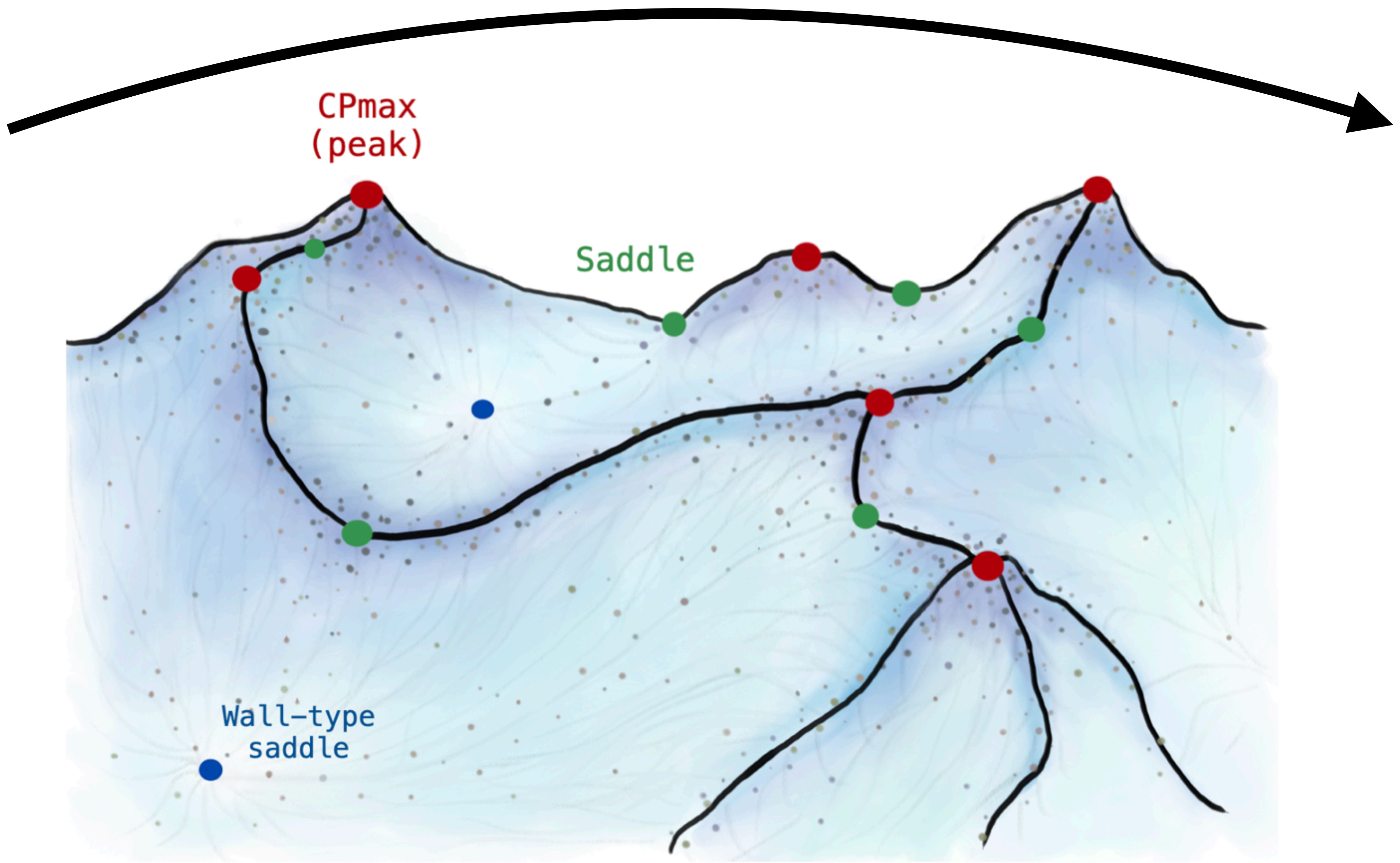
Publicly available code

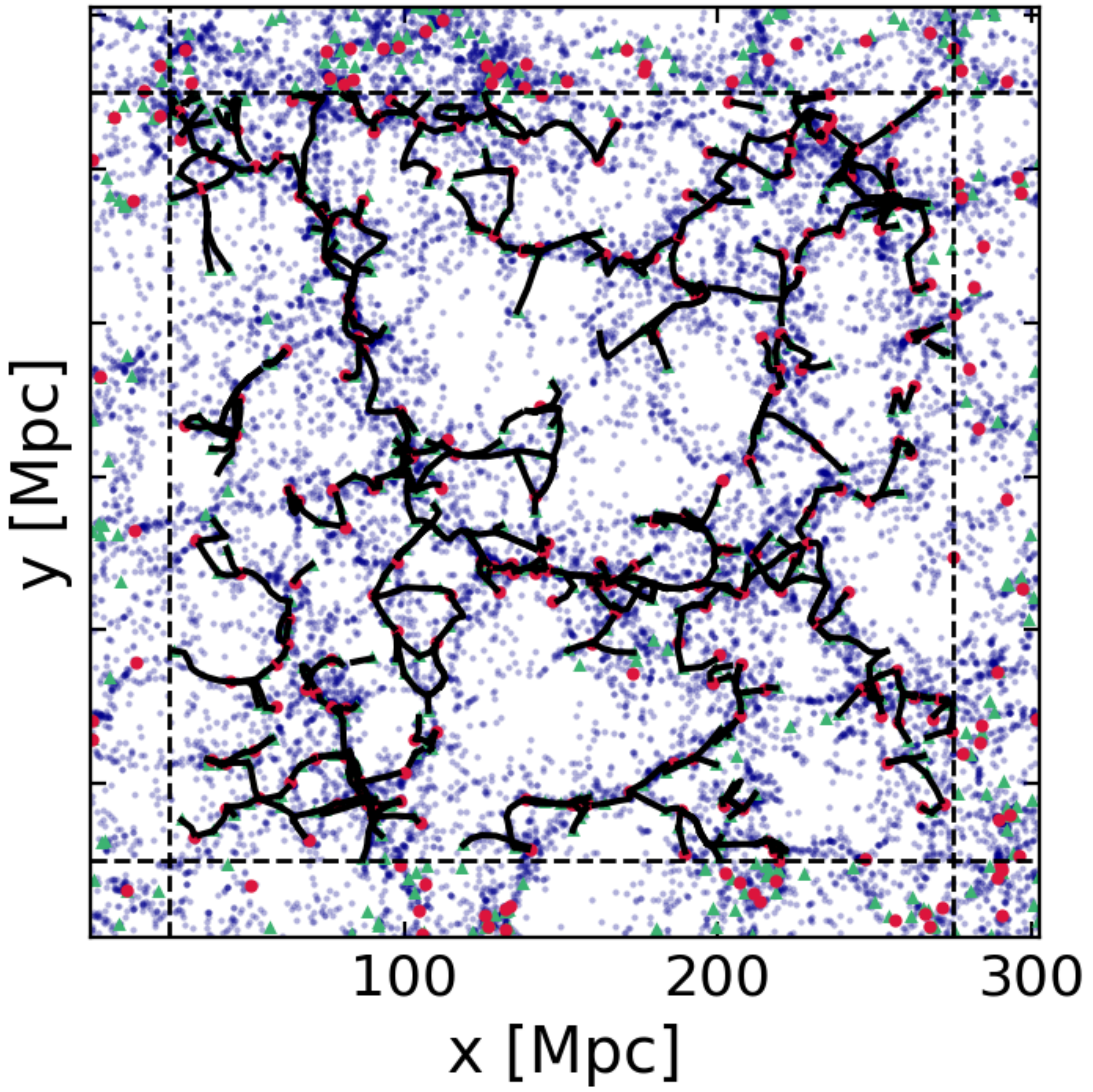
Using galaxy distributions (following an <u>observational</u> approach)

DisPerSE

(Sousbie+ 2011, Sousbie 2011)







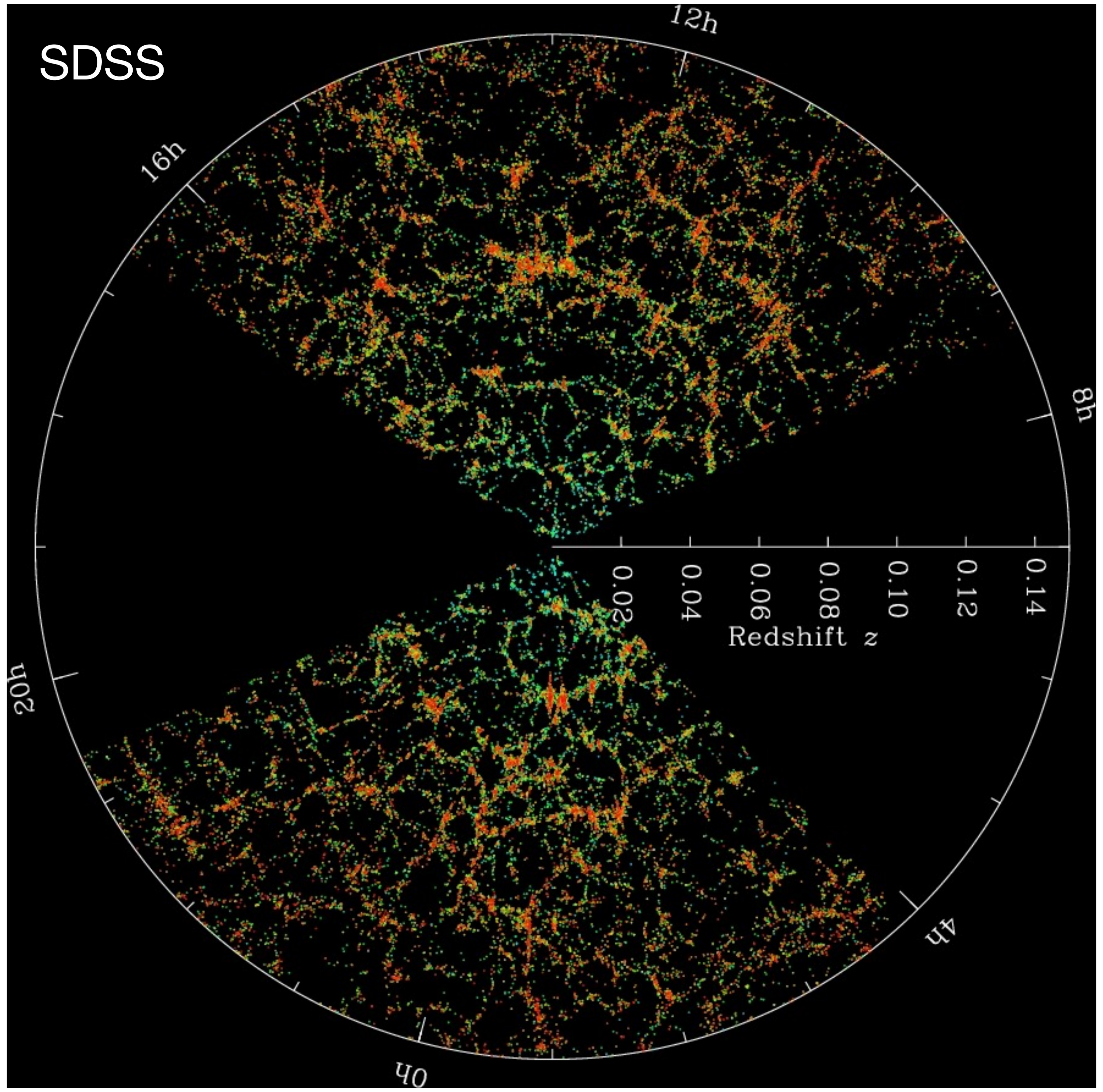
Galaxy selection in mass

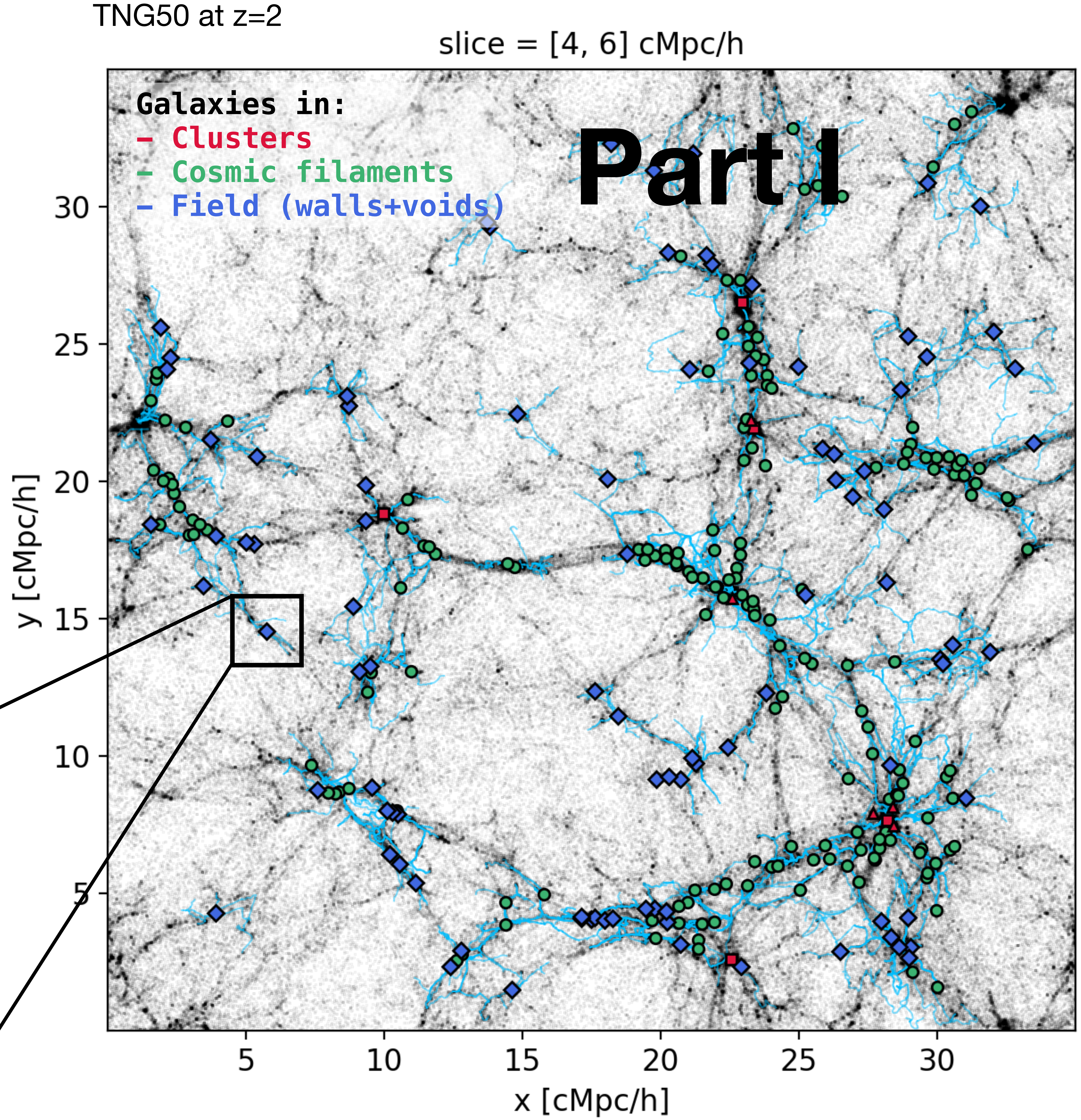
$M_* > 10^9\ \mathrm{M}_\odot$

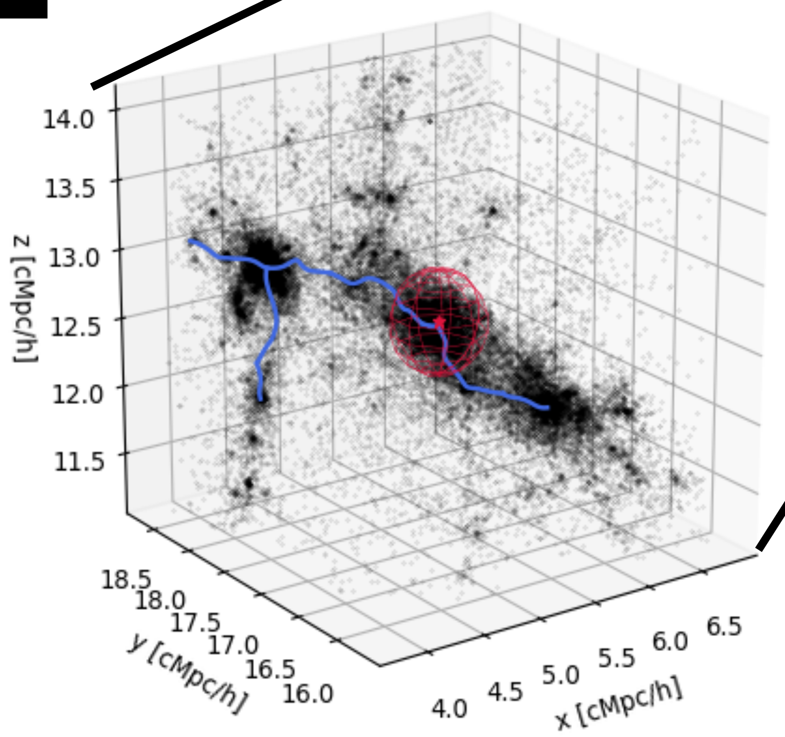
1 parameter (persistence ratio): **physically-motivated calibration**

Filaments = ridges of the density field,
connecting **maximum density** critical points to **saddles**

Mind the scales!







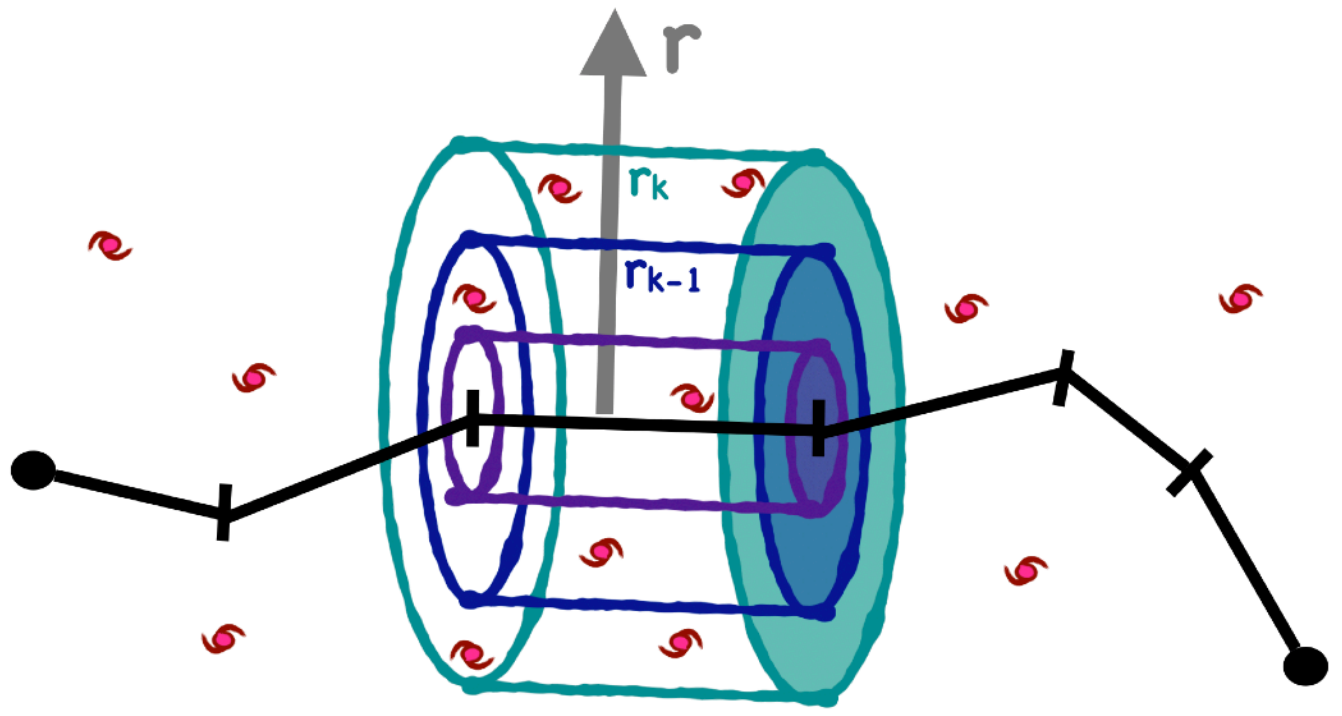
Part II

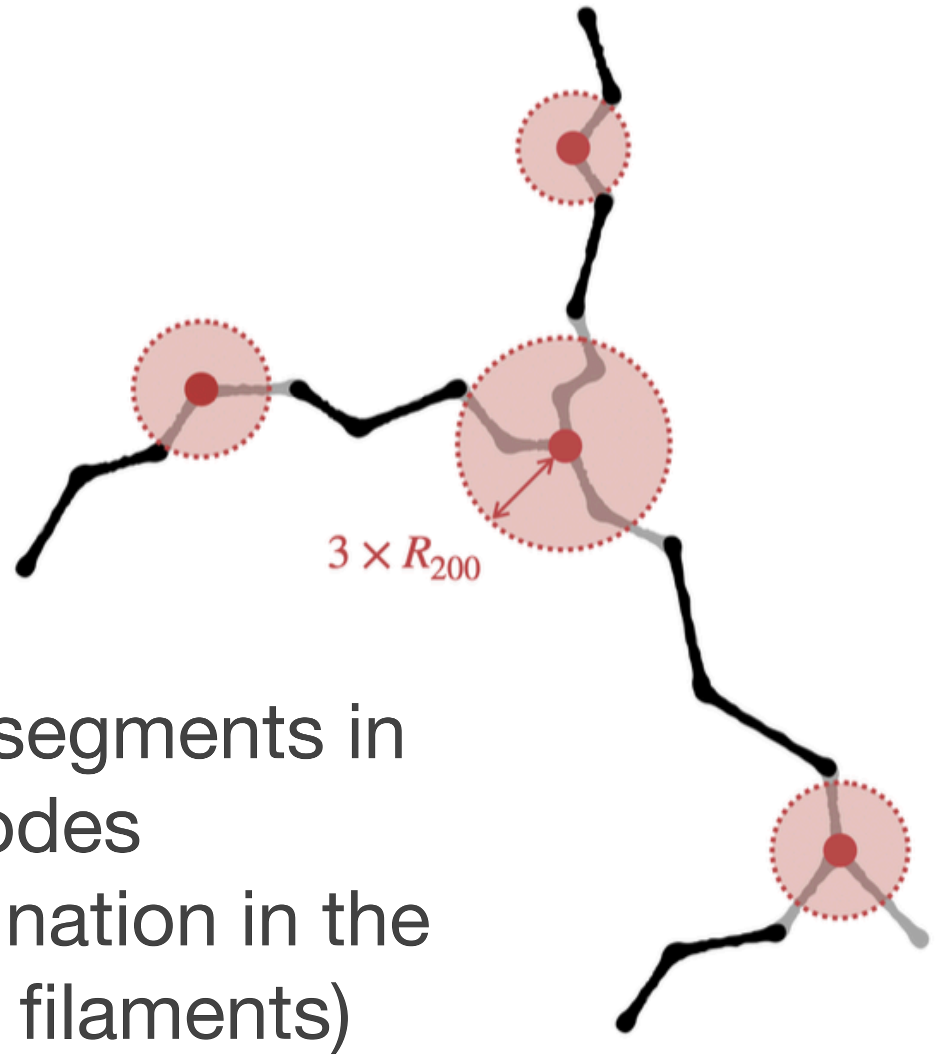
Part I
Filaments in the Large-Scale structure

Distribution of galaxies around filaments

Method:

Number density of galaxies: n(r)





Remove segments in nodes
(= contamination in the study of filaments)

Distribution of galaxies around filaments

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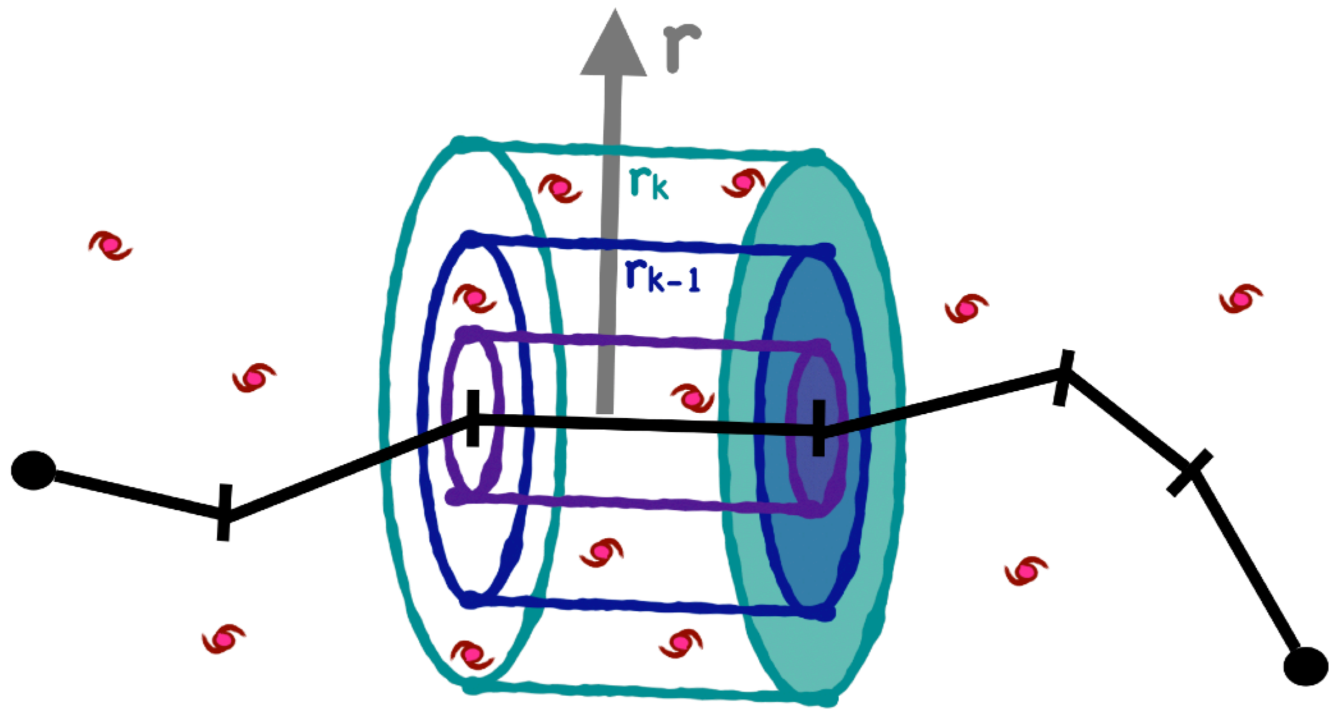

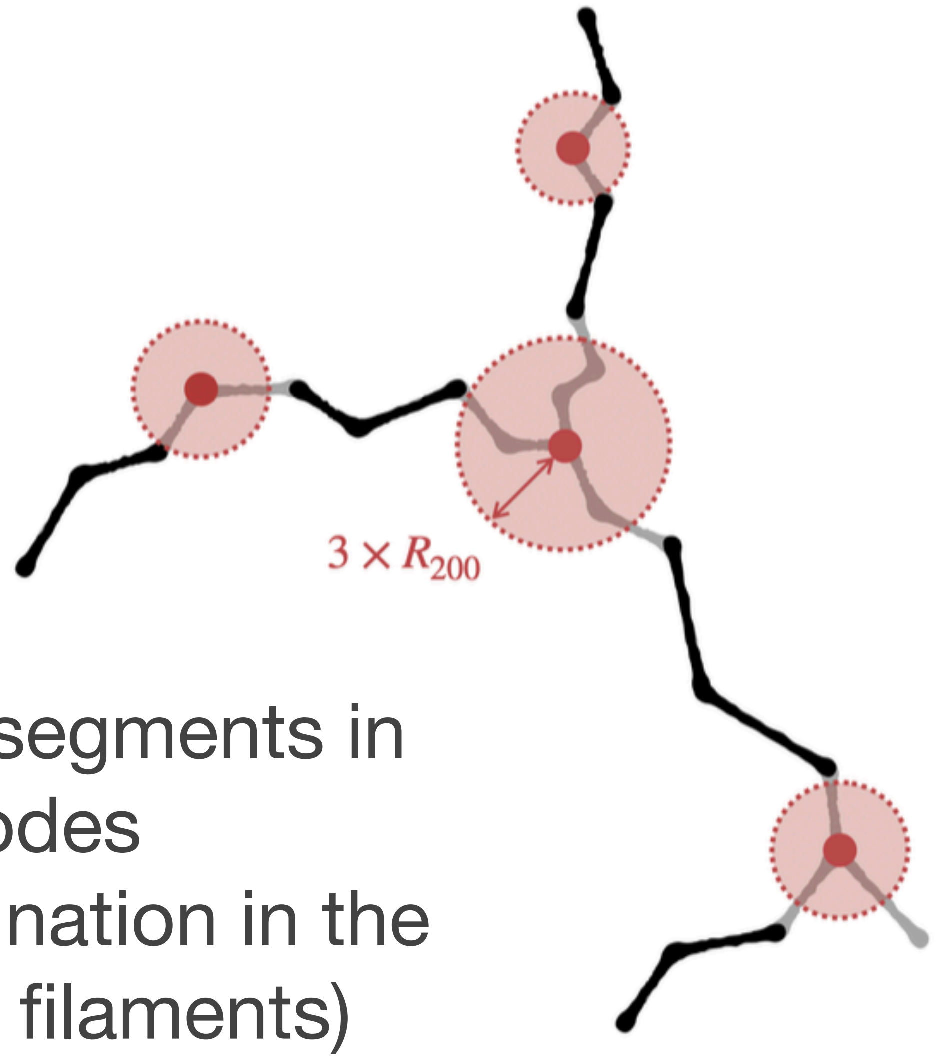

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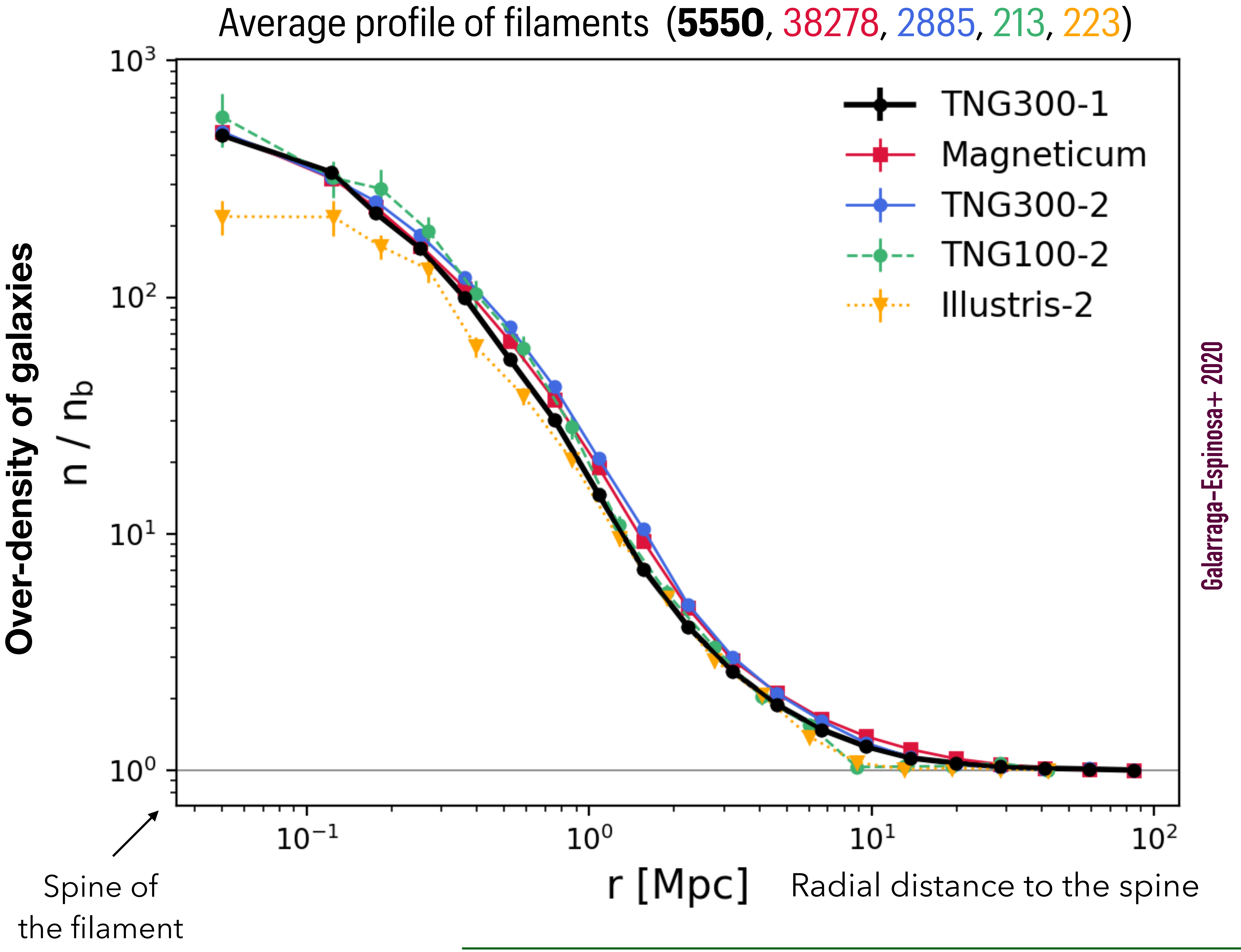

We're mixing all filaments! Maybe some differences (like haloes)?

Possible observables:

- Filament mass
- Density
- Radius, thickness
- Length
- Mass per unit length?
- …

Problem: radius?
Where is the filament stopping?

Recent progress in Wang+ 2024

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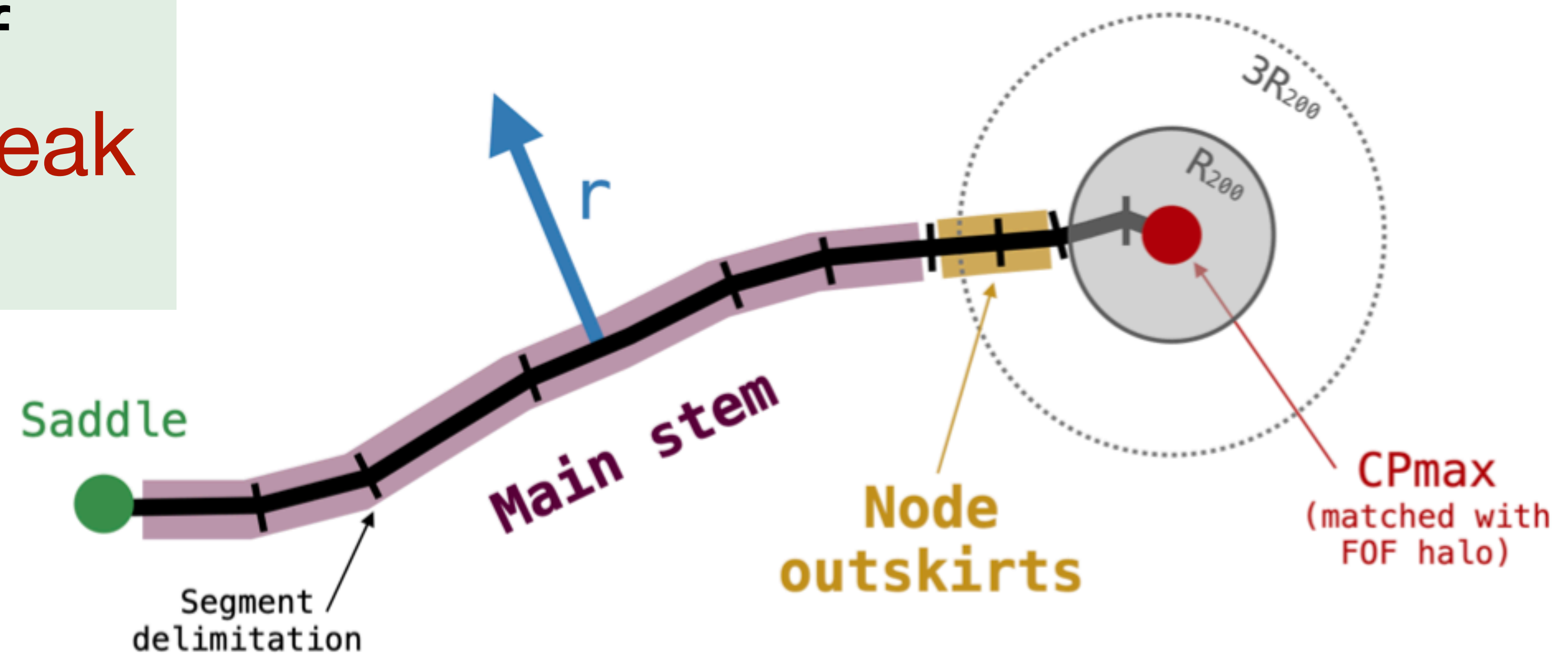
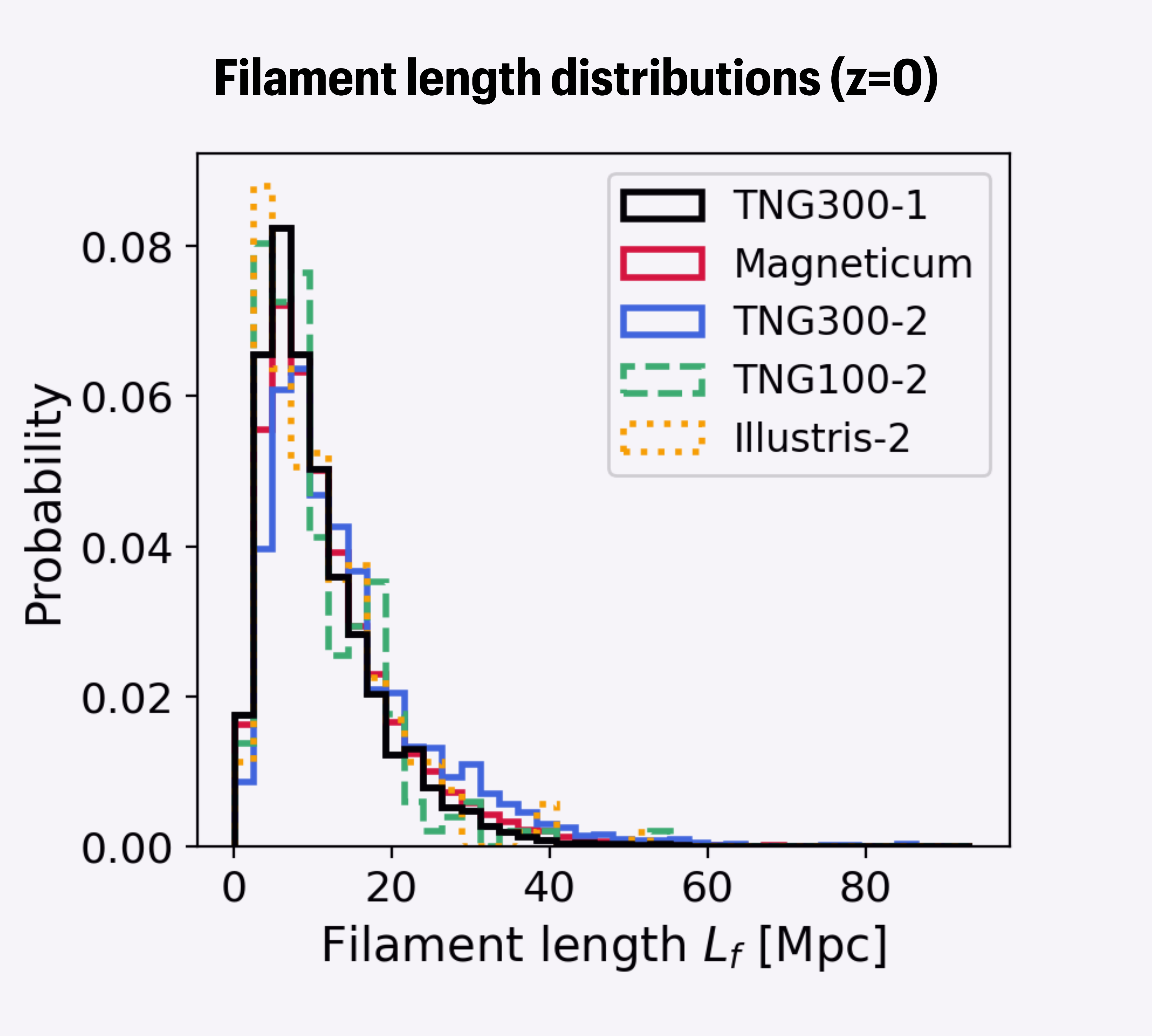
Recent progress in Wang+ 2024

Length is well defined within the DisPerSE framework

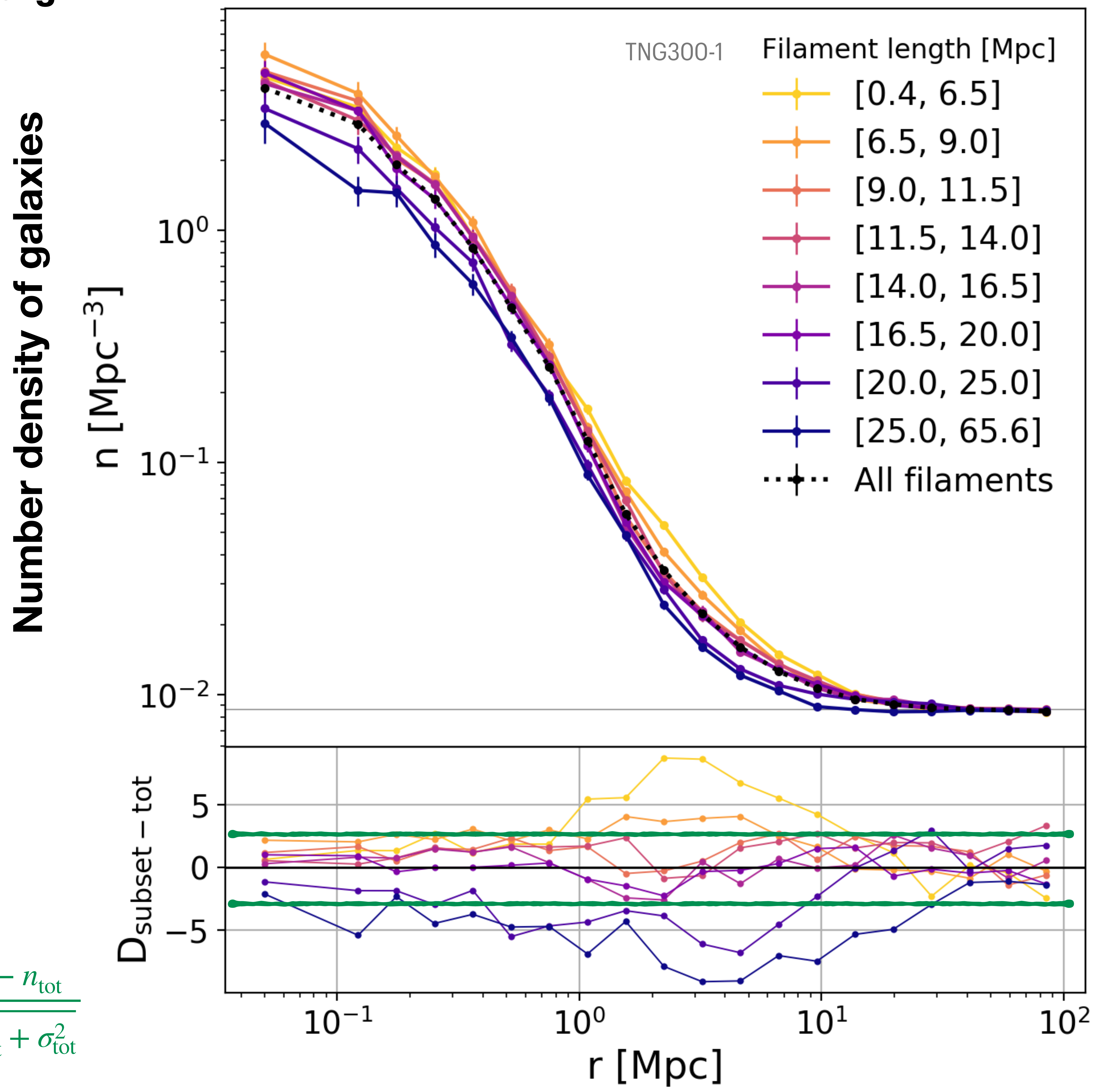
Filament length = sum of segment lengths, from peak to saddle





Variations with filament length?

Profiles by bins of length



$$D_{\text{subset-tot}} = \frac{n_{\text{subset}} - n_{\text{tot}}}{\sqrt{\sigma^2_{\text{subset}} + \sigma^2_{\text{tot}}}}$$

Deviation from the mean profile $> 2\sigma$

Identification of 2 extreme populations

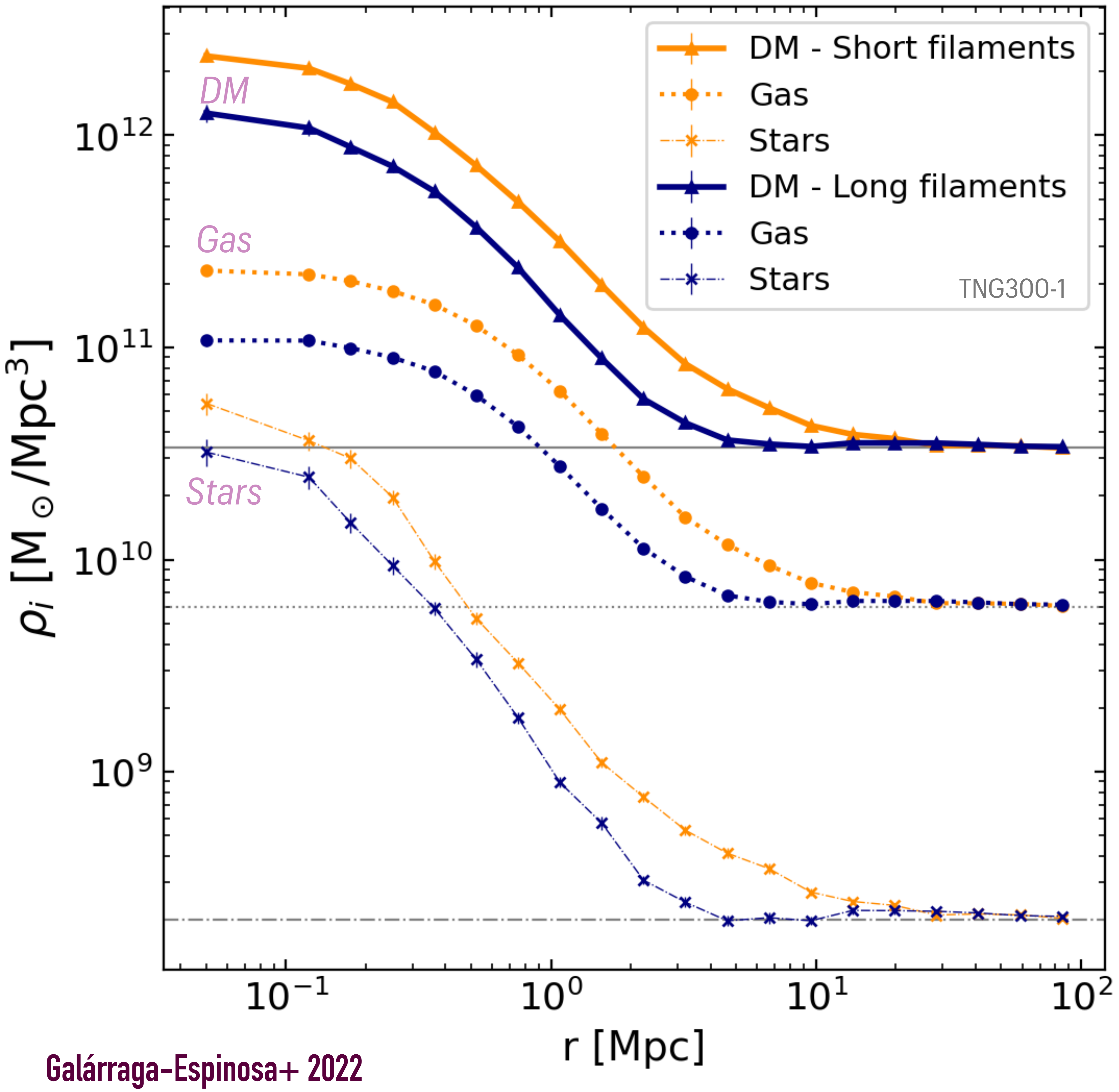
Short: $L_f < 9$ Mpc

Long: $L_f \geq 20$ Mpc

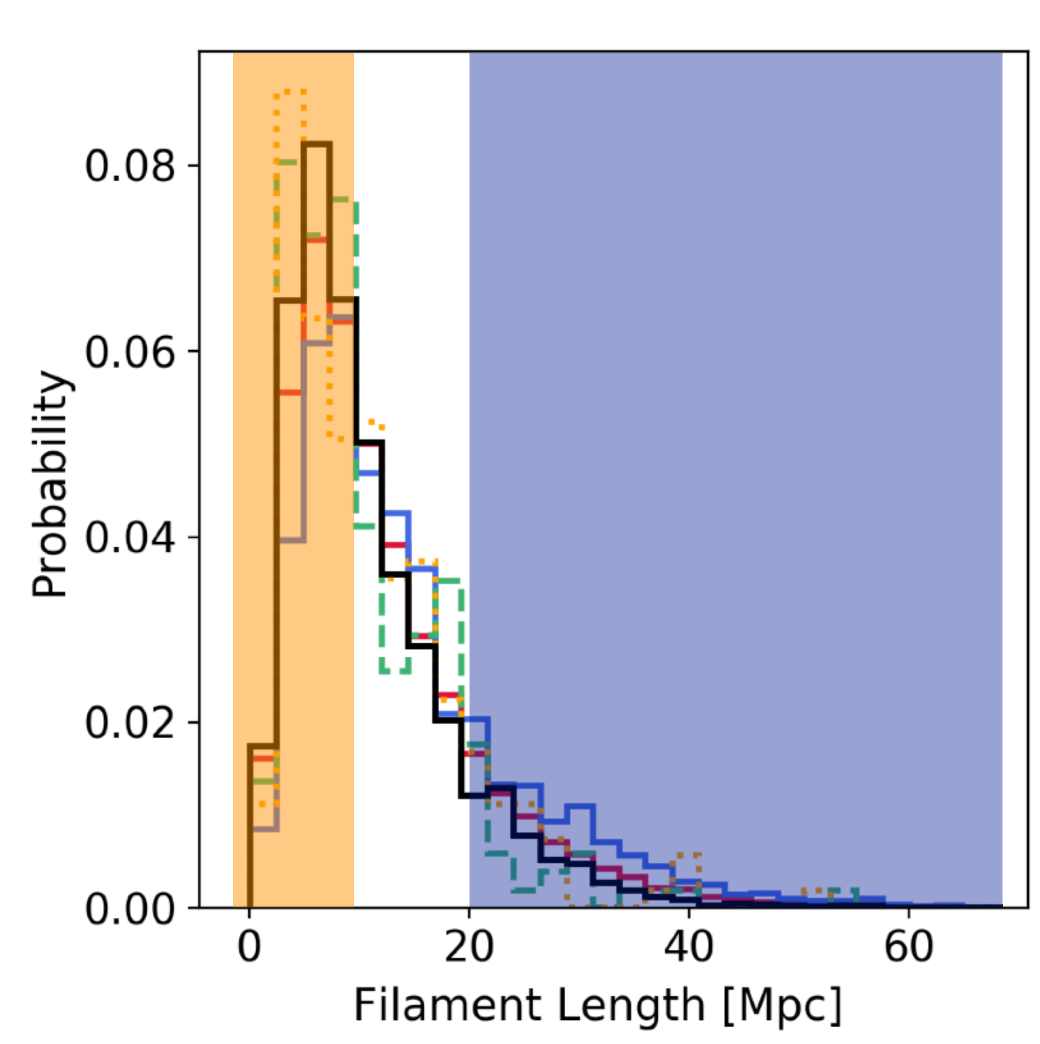
Galarraga-Espinosa+ 2020

Exploring the extremes

DM, **gas**, and **stars** mass densities



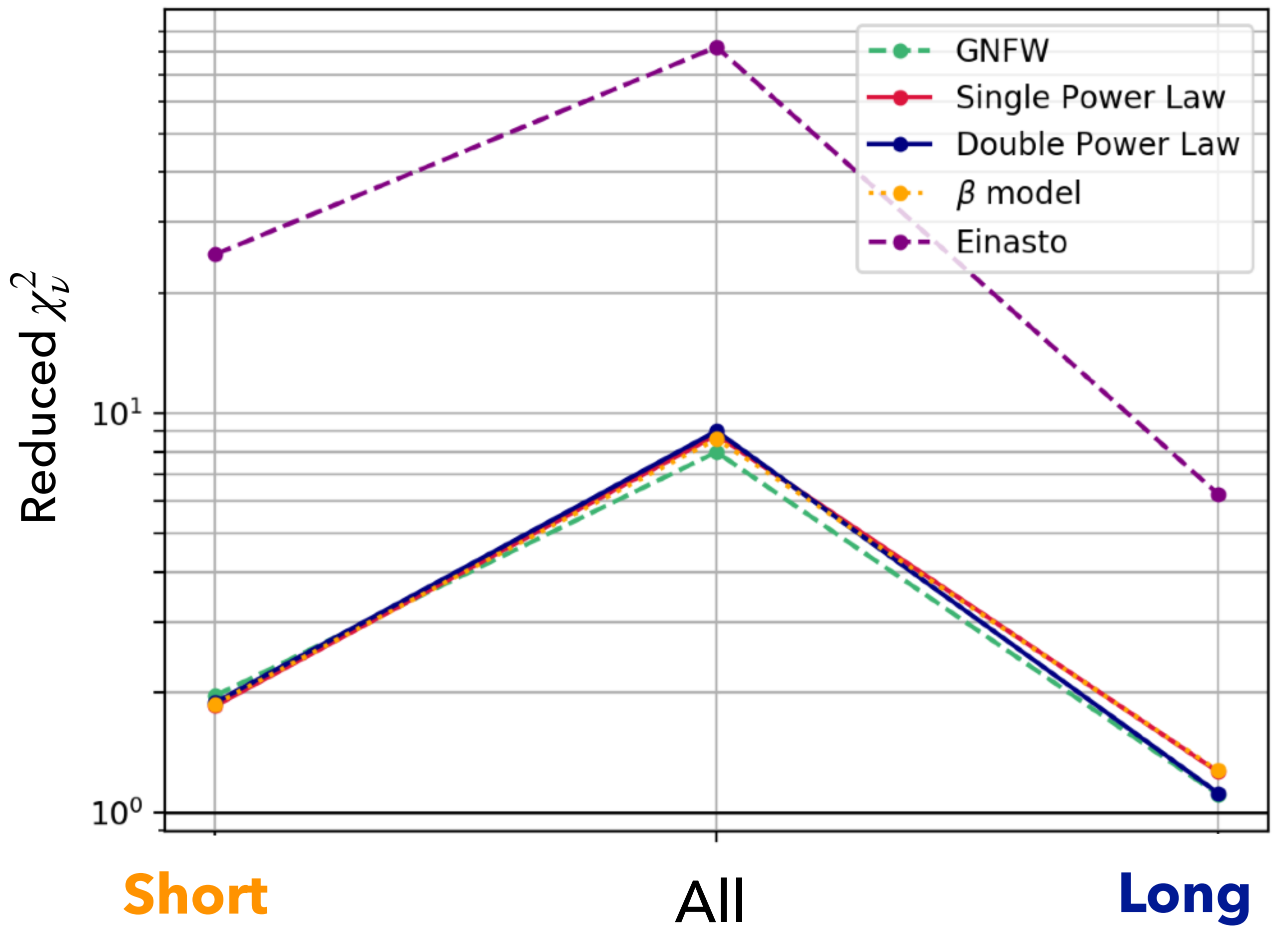
Galárraga-Espinosa+ 2022



+ Kolmogorov-Smirnov (KS) statistical tests
—> 2 different populations

+ Profile modelling with empirical functions
—> better fit results when populations are separated

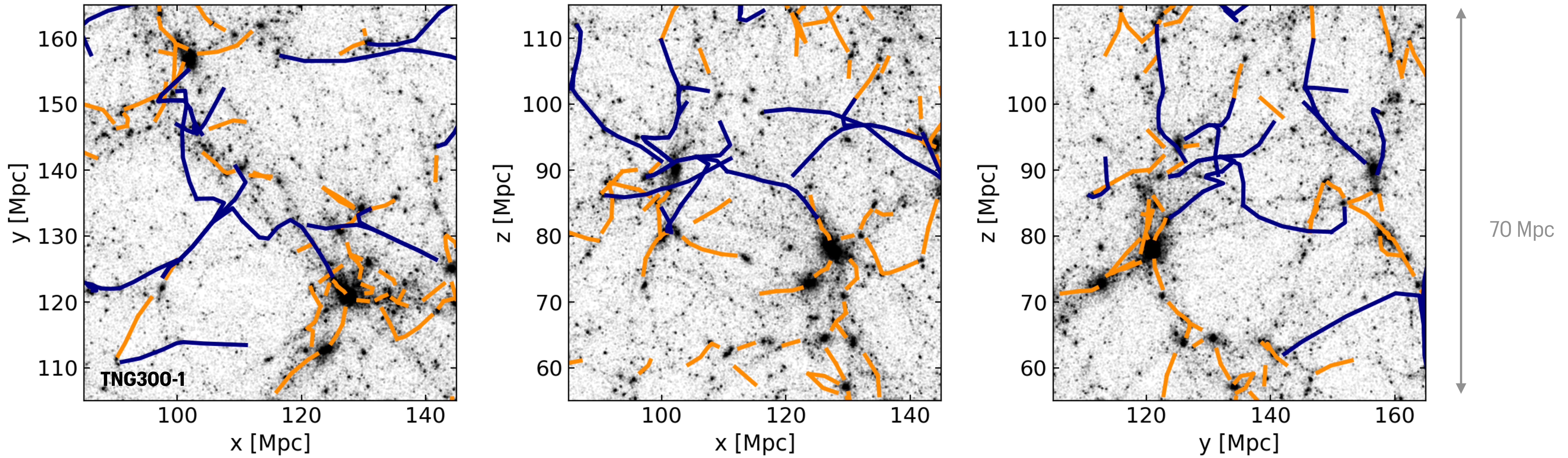
Galarraga-Espinosa+ 2020



Can we physically identify the two populations in the Cosmic Web?

Short $L_f < 9$ Mpc
Long $L_f \geq 20$ Mpc

- Integrating profiles —> Short filaments are **denser** than long.
- Mass of the nodes —> Short filaments are **connected to more massive** nodes than long.



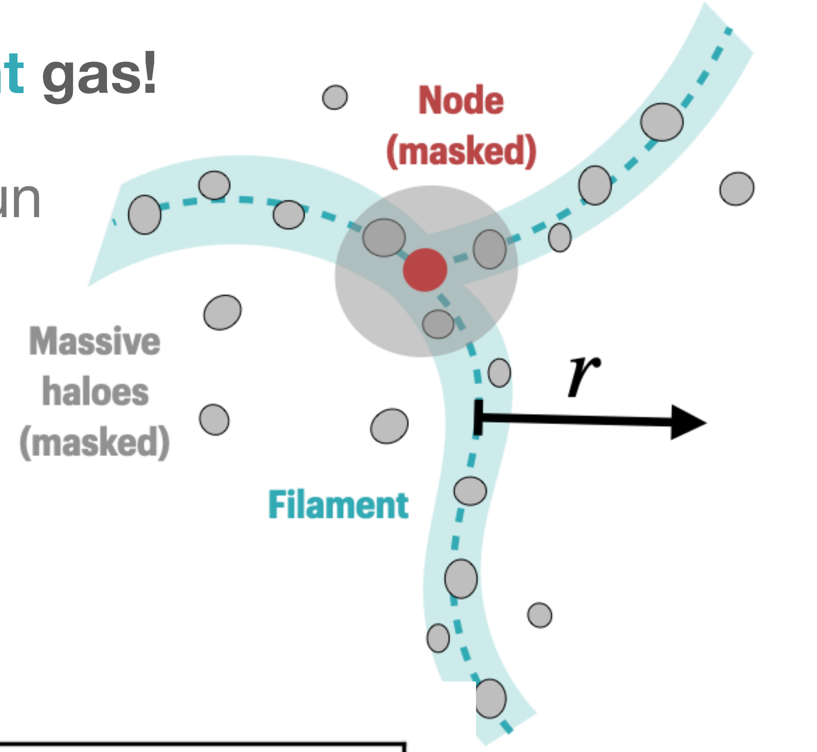
Different environments:
Short : trace more over-dense regions, Long : trace less dense regions

Galárraga-Espinosa+ 2020, 2022

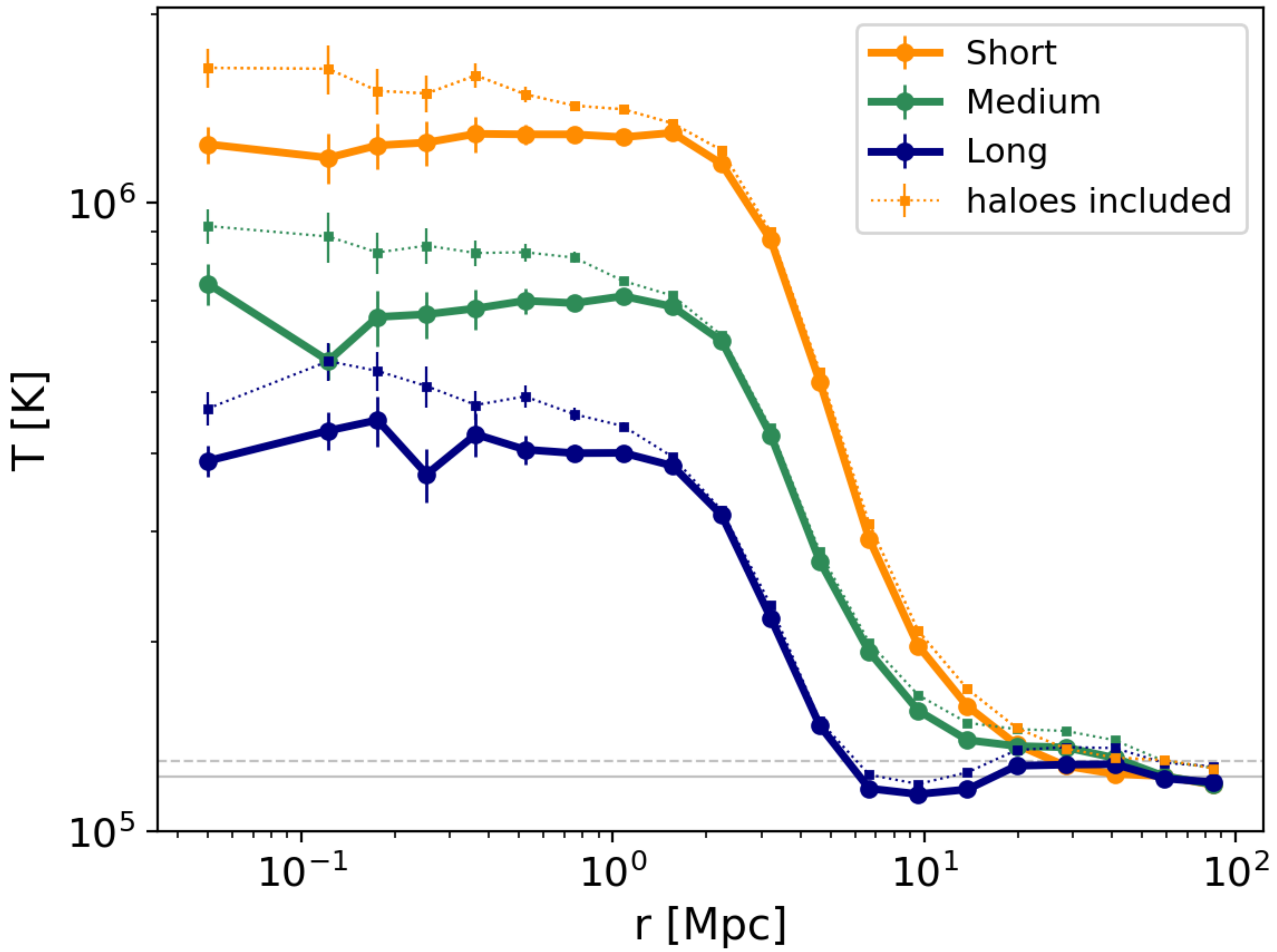
Gas properties at z=0

Focus only on inter-filament gas!

Masked: Mh = 1e12 Msun



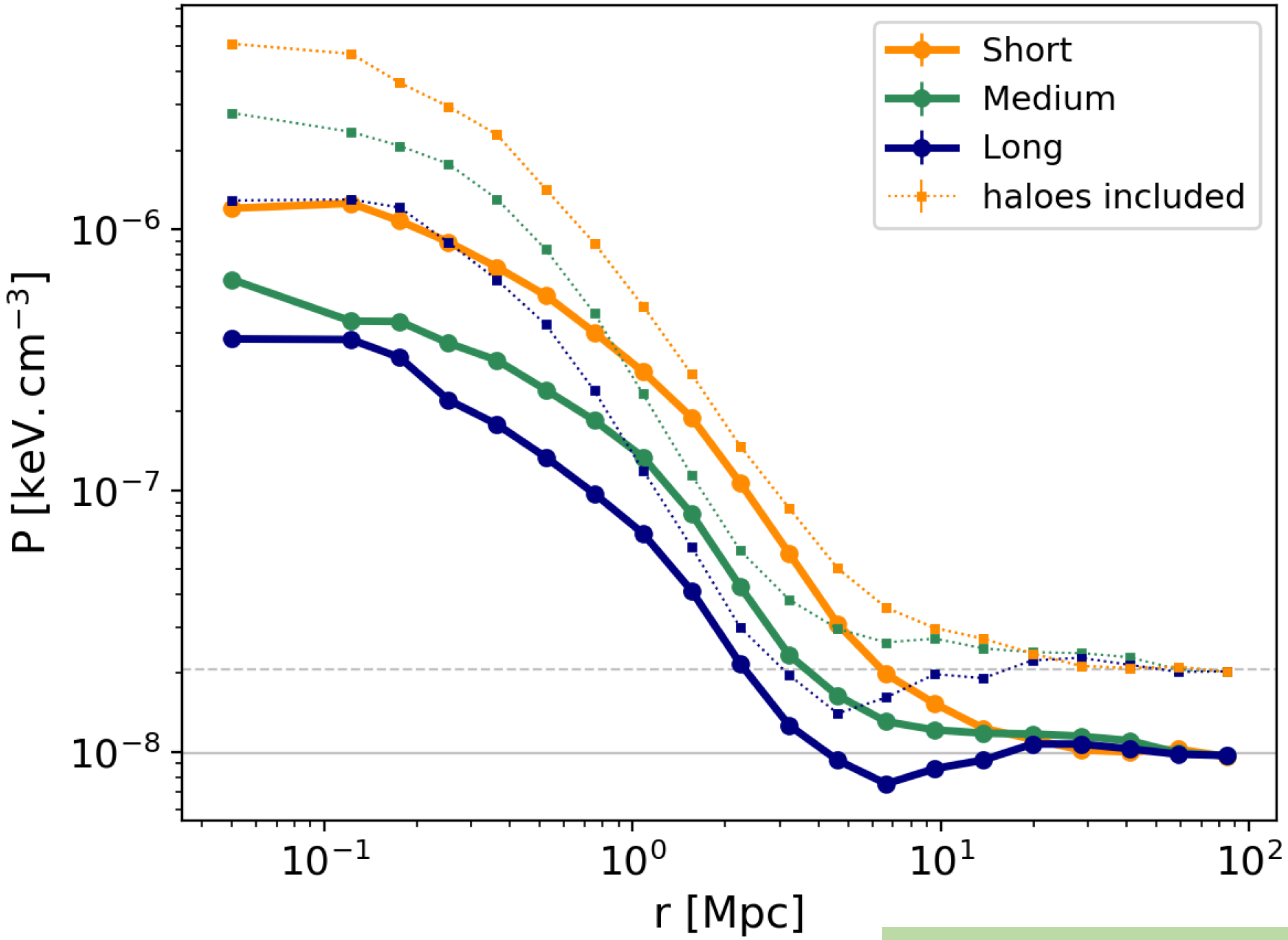
Mean radial **temperature** profiles



$$T_{core} = 4 - 13 \times 10^5 \, K$$

Galarraga-Espinosa+ 2021

Mean radial **pressure** profiles

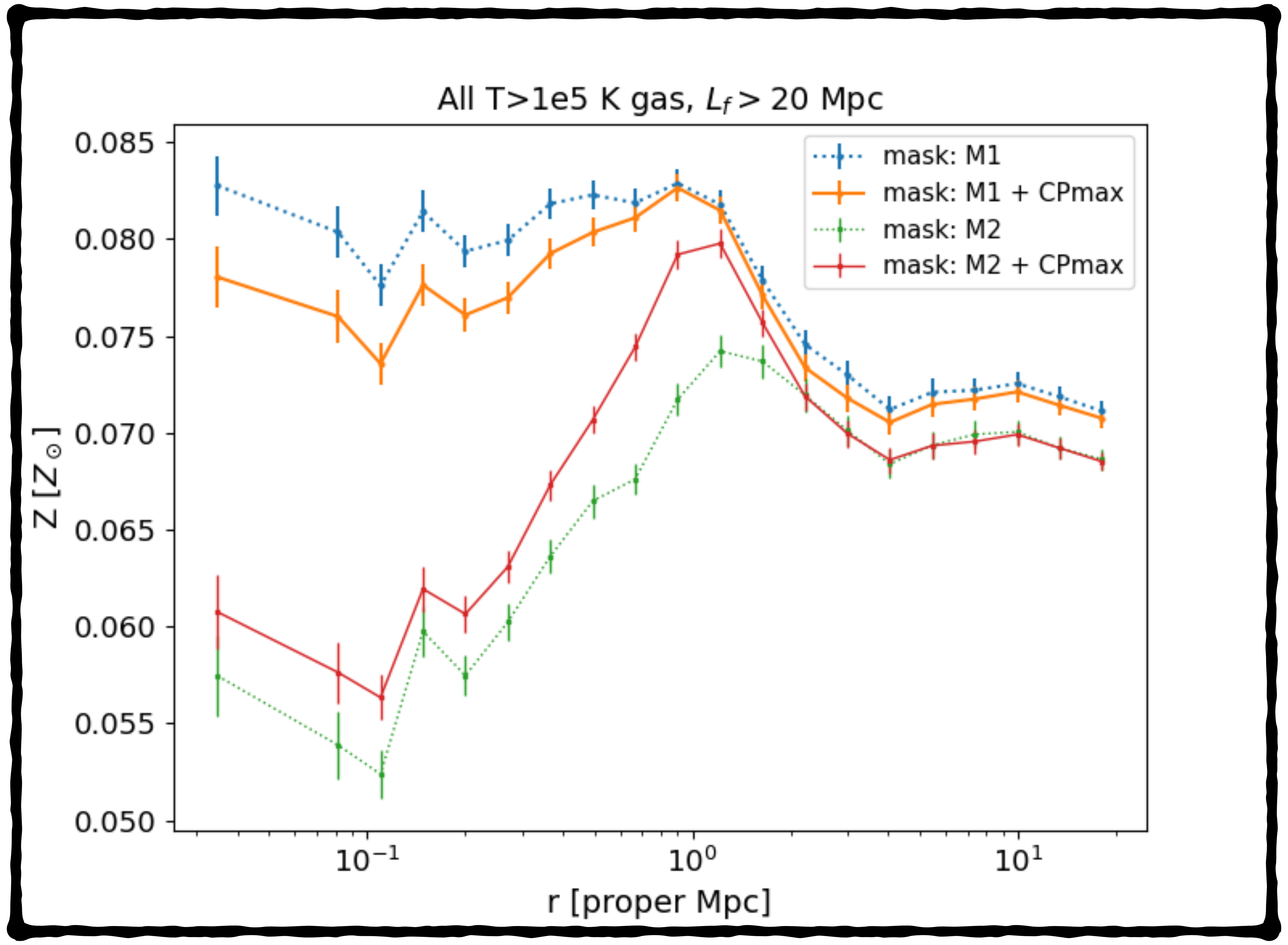


$$P_{core} = 4 - 12 \times 10^{-7} \, keV \, . \, cm^{-3}$$

—> Derived **SZ filament emission**, agreement with observational results (*Tanimura+ 2020a*, Planck data)

Metallicity profiles

(Simulation: TNG300-1)

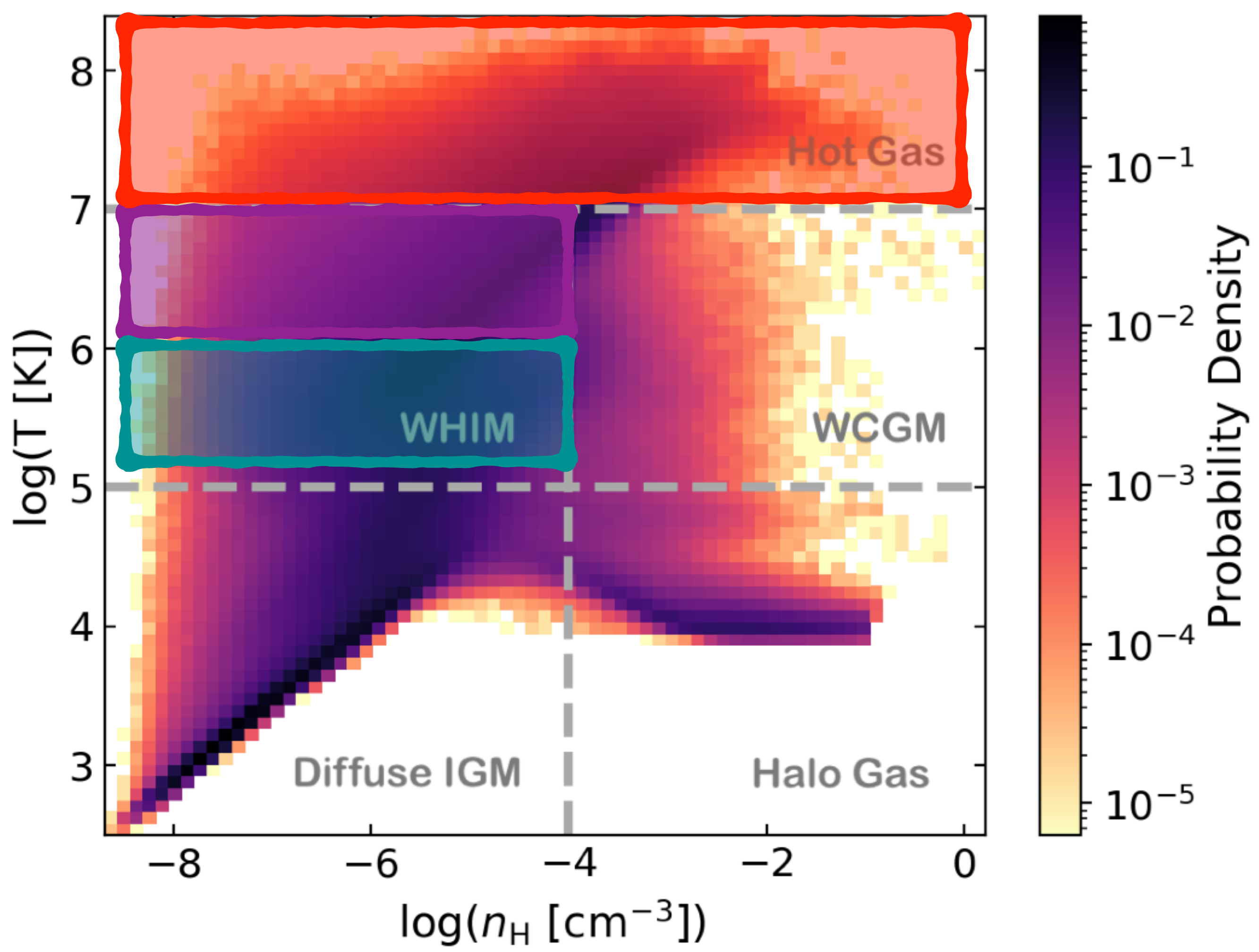


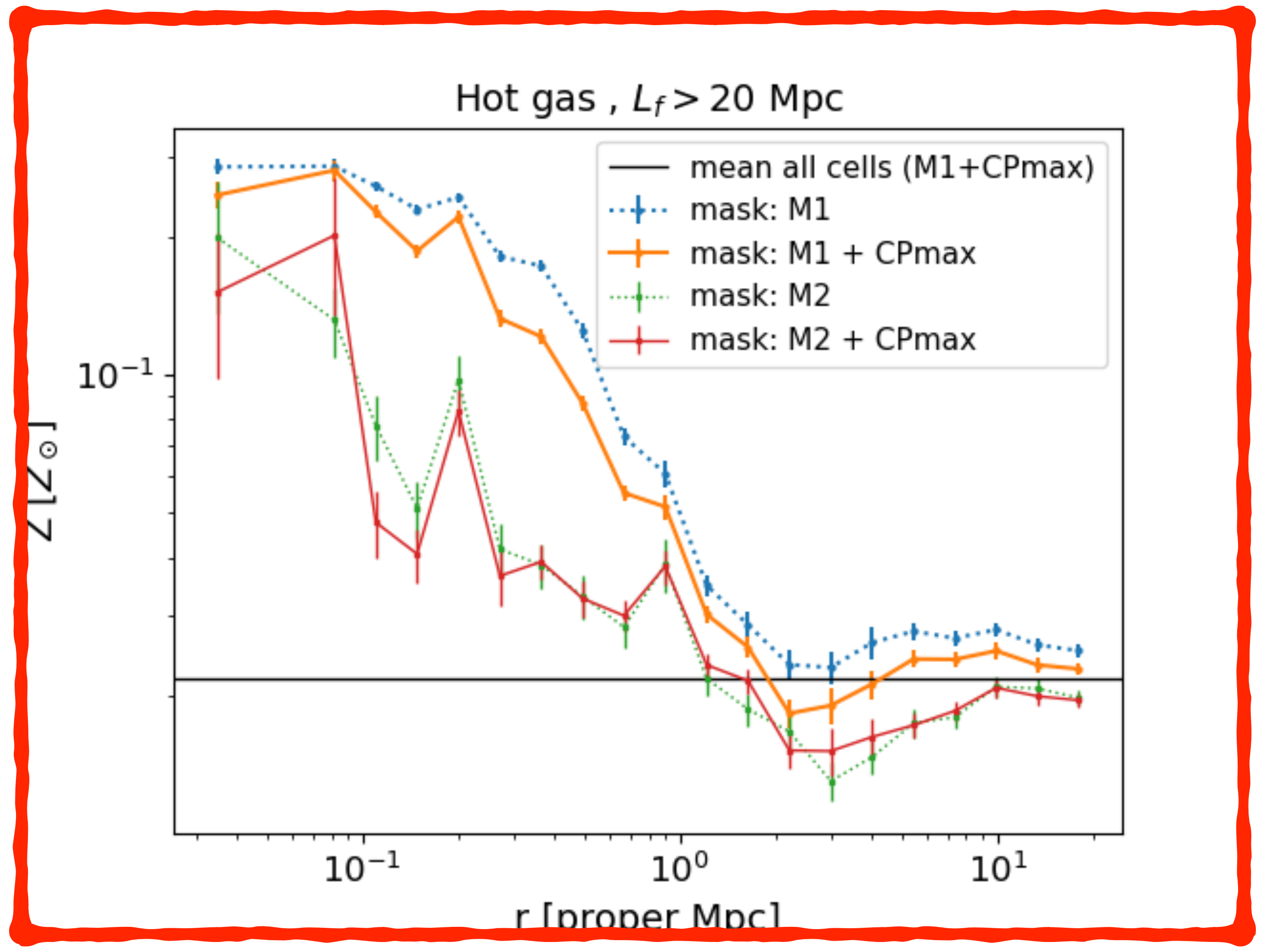
Progressive masking:

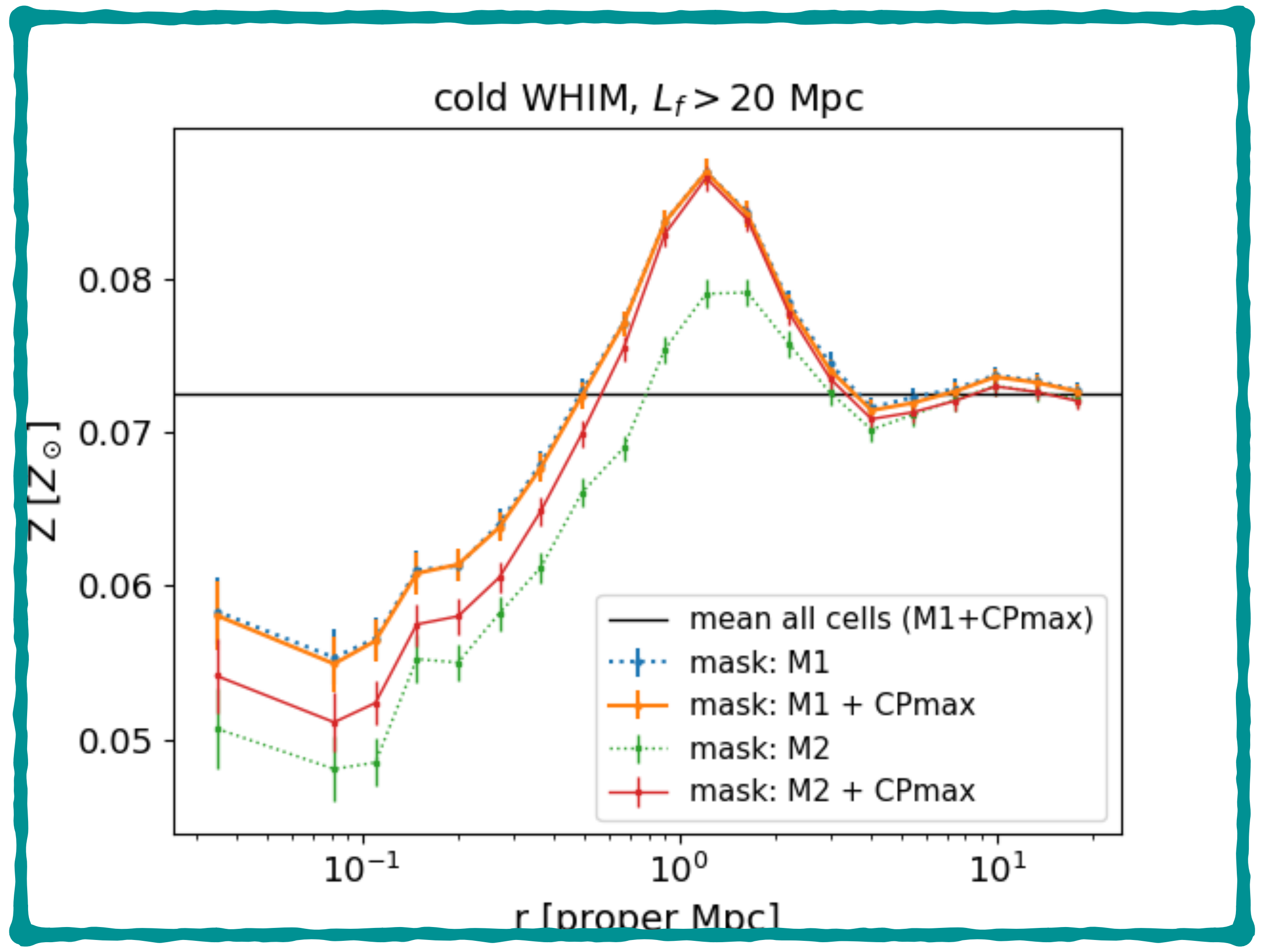
M1 (light) : $M_{500c} \geq 3 \times 10^{13}\, M_\odot$

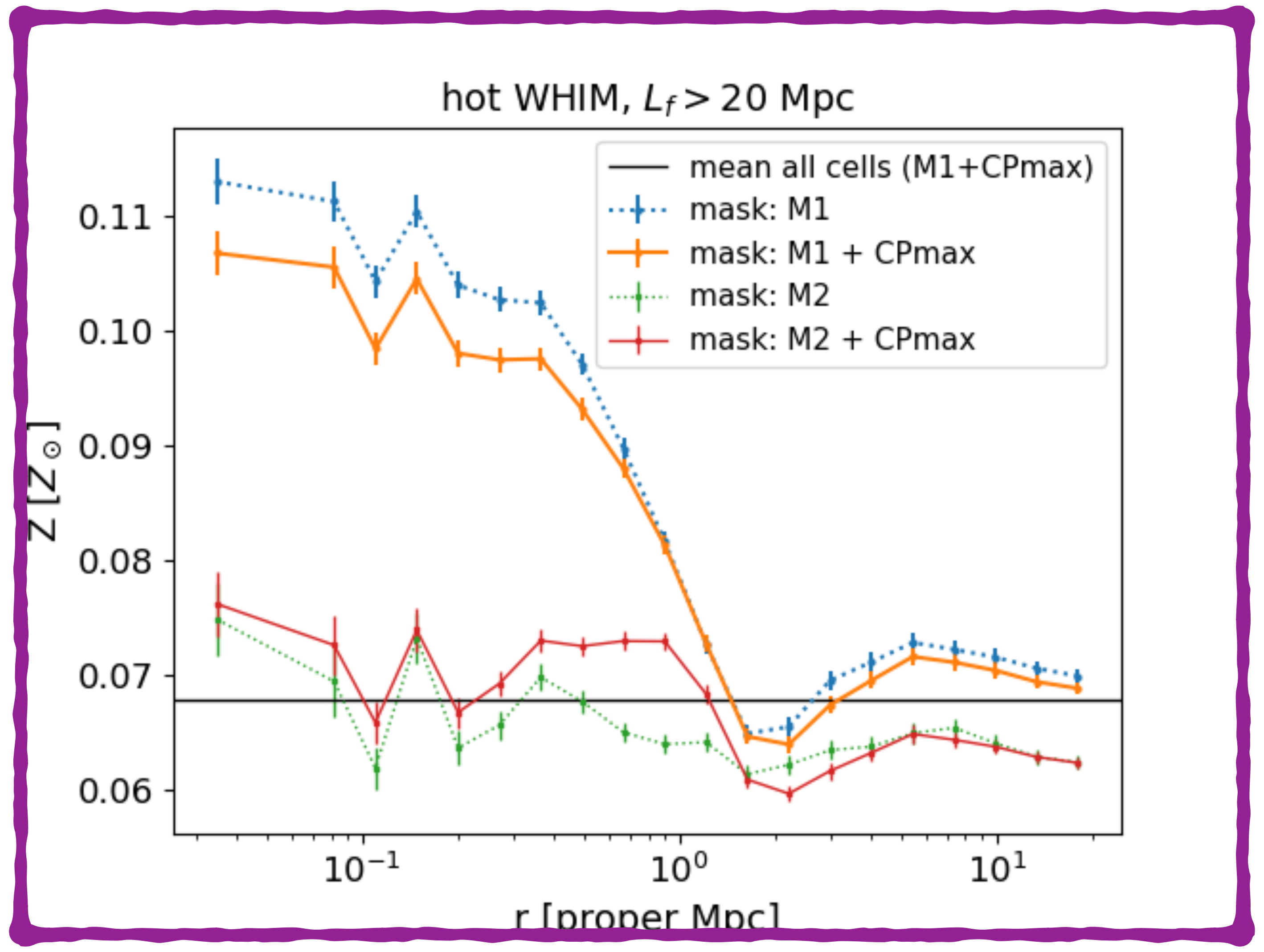
M2 (strong) : $M_{500c} \geq 10^{12}\, M_\odot$

Gas phase separation





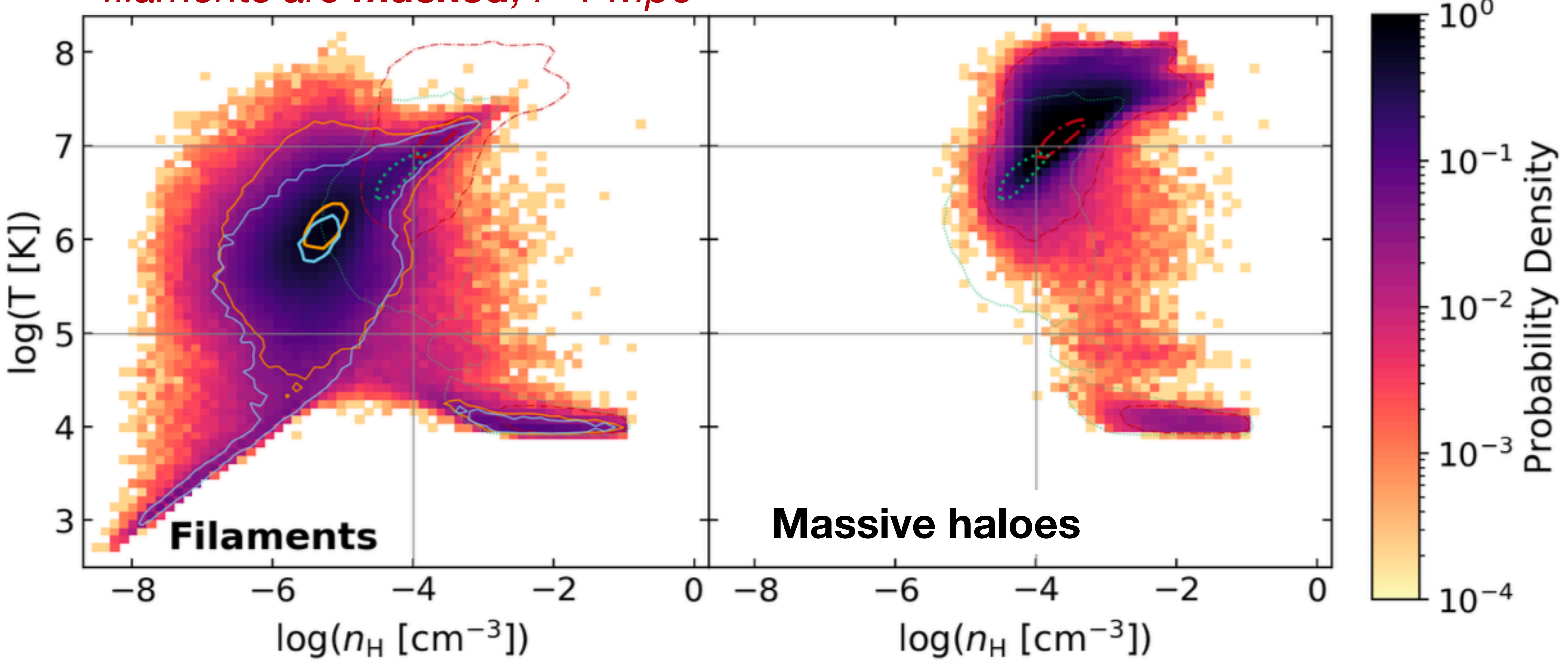




Filaments vs Galaxy clusters

Gas content

__Important:__ haloes inside filaments are __masked__, r=1 Mpc



warm and diffuse (WHIM)

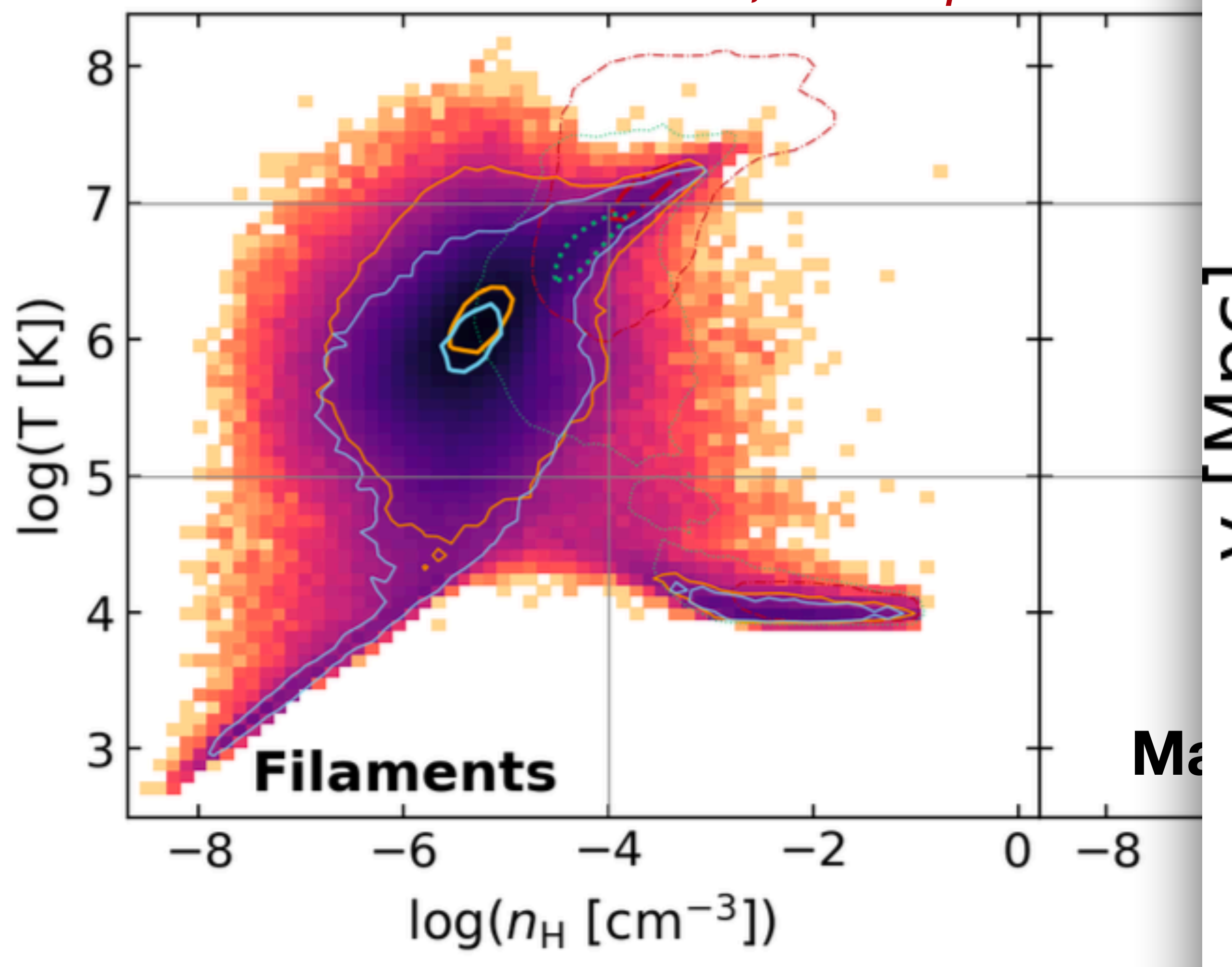
hot (easier to detect, e.g. X-ray)

Galarraga-Espinosa+ 2021

Fi

Gas cont

Important: haloes inside filaments are **masked**, r=1 Mpc



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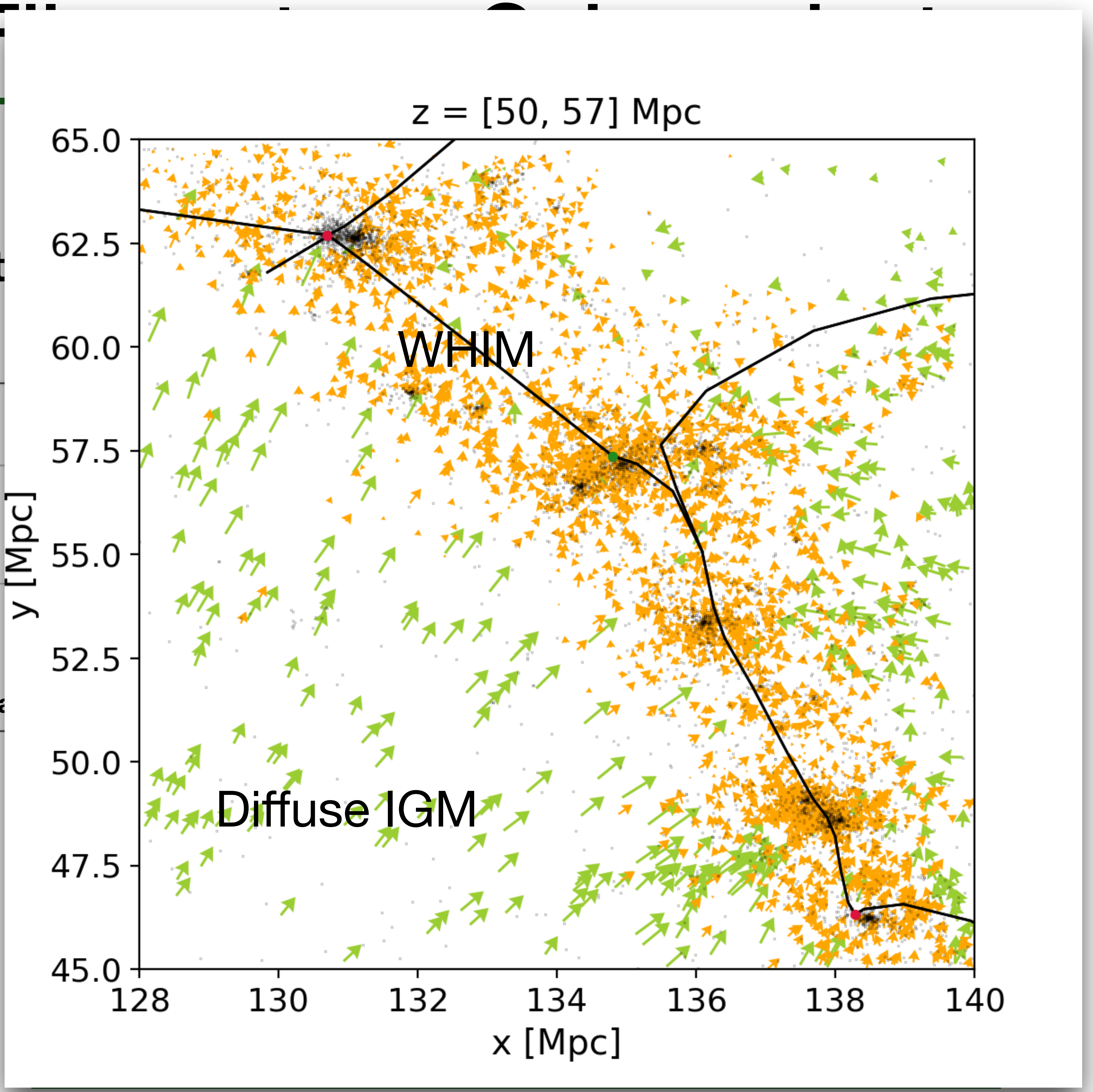
Galarraga-Espinosa+ 2021



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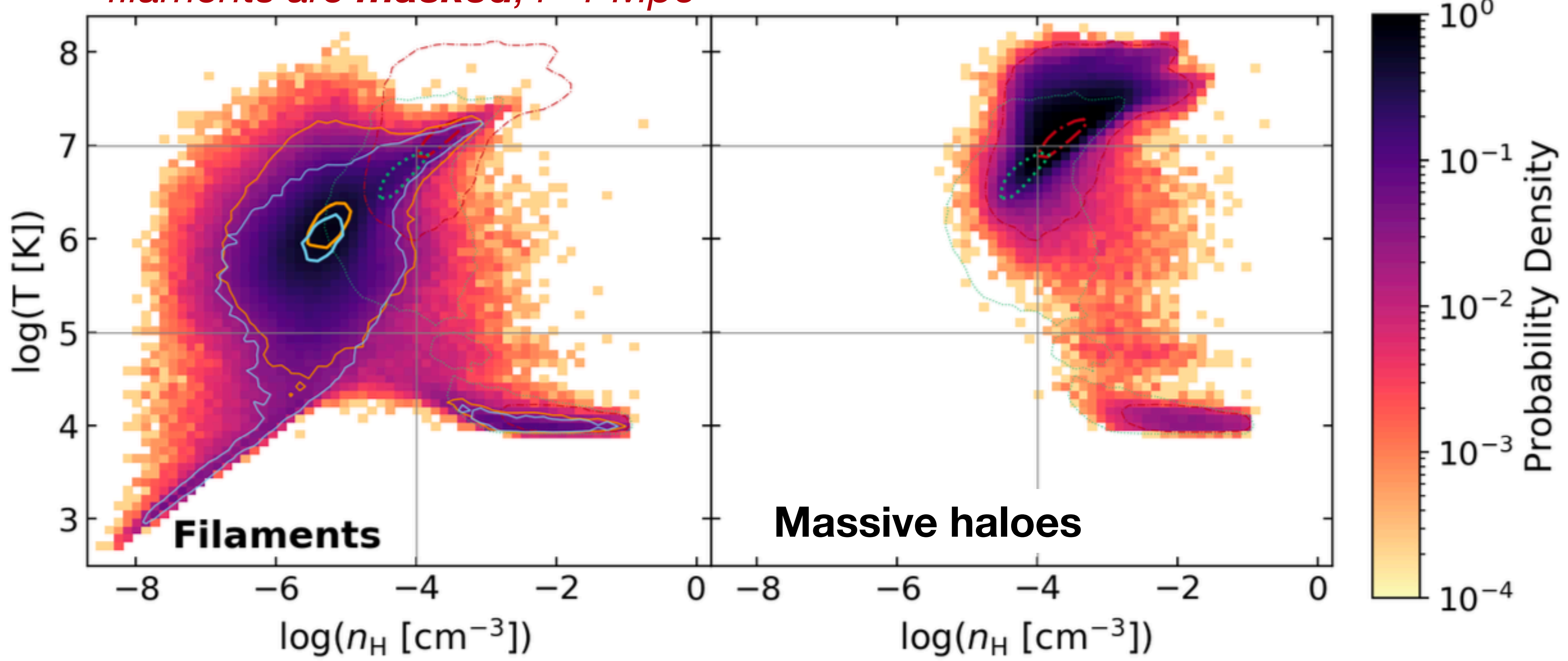

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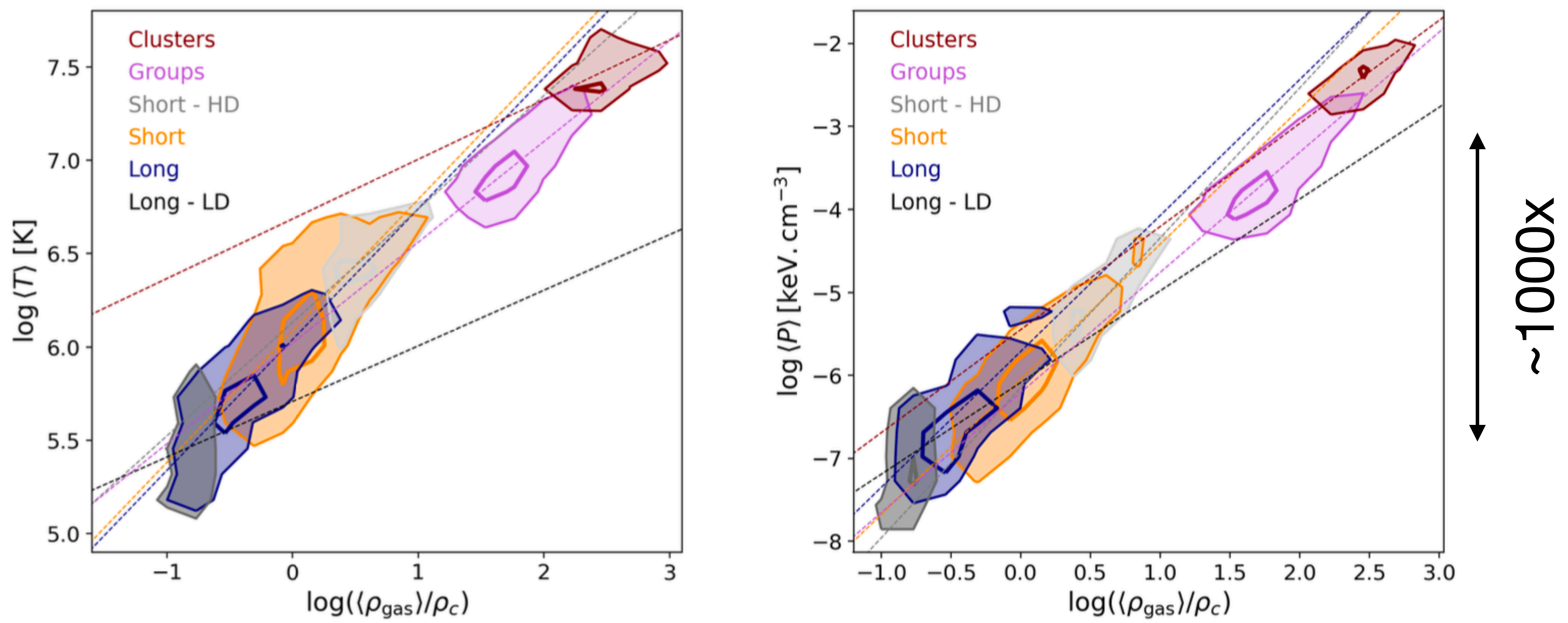
Galarraga-Espinosa+ 2021

Scaling relations

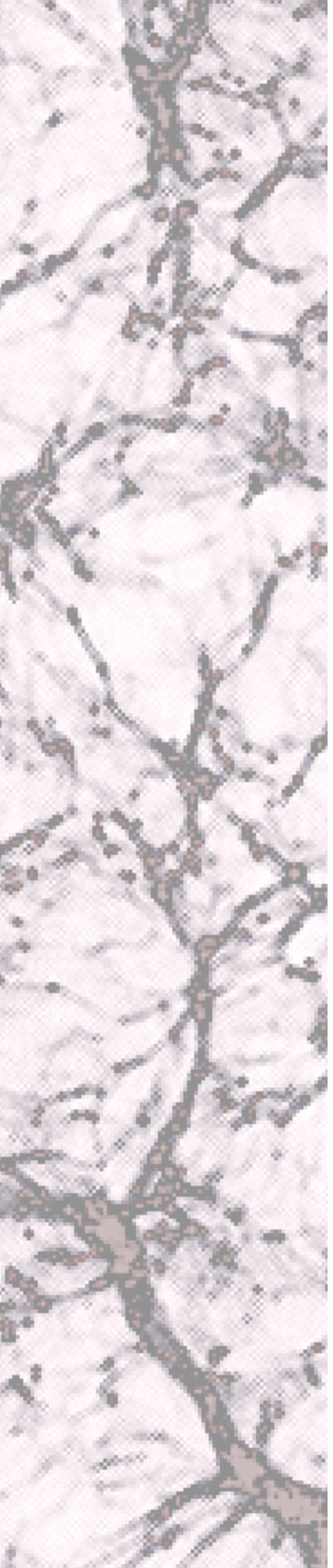


Galarraga-Espinosa+ 2022

Hierarchy of the different large-scale cosmic structures

$M_{200} > 10^{14.5}\ \mathrm{M_\odot/h}$

$M_{200} = 10^{14} - 10^{14.5}\ \mathrm{M_\odot/h}$



Digging deeper...

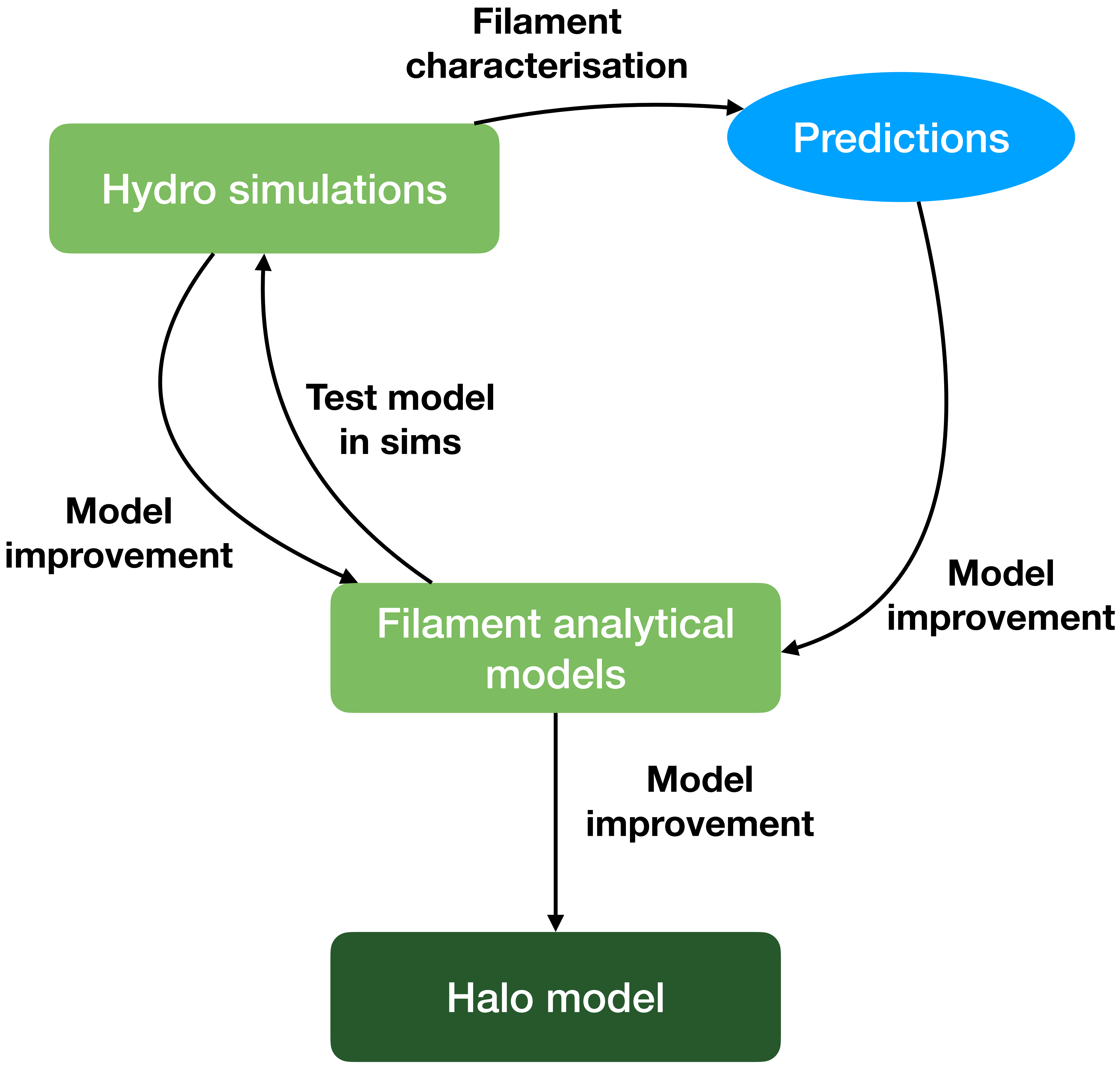
Goals

- **Understanding cosmic filaments**
  what are their fundamental properties?
  what is the impact on halo properties?

- **Transferring this understanding to improve halo modelling**

In collaboration with Daisuke Nagai, Nir Mandelker, Isabel Medlock and the Baryon Pasting Collaboration

How?



Digging deeper...

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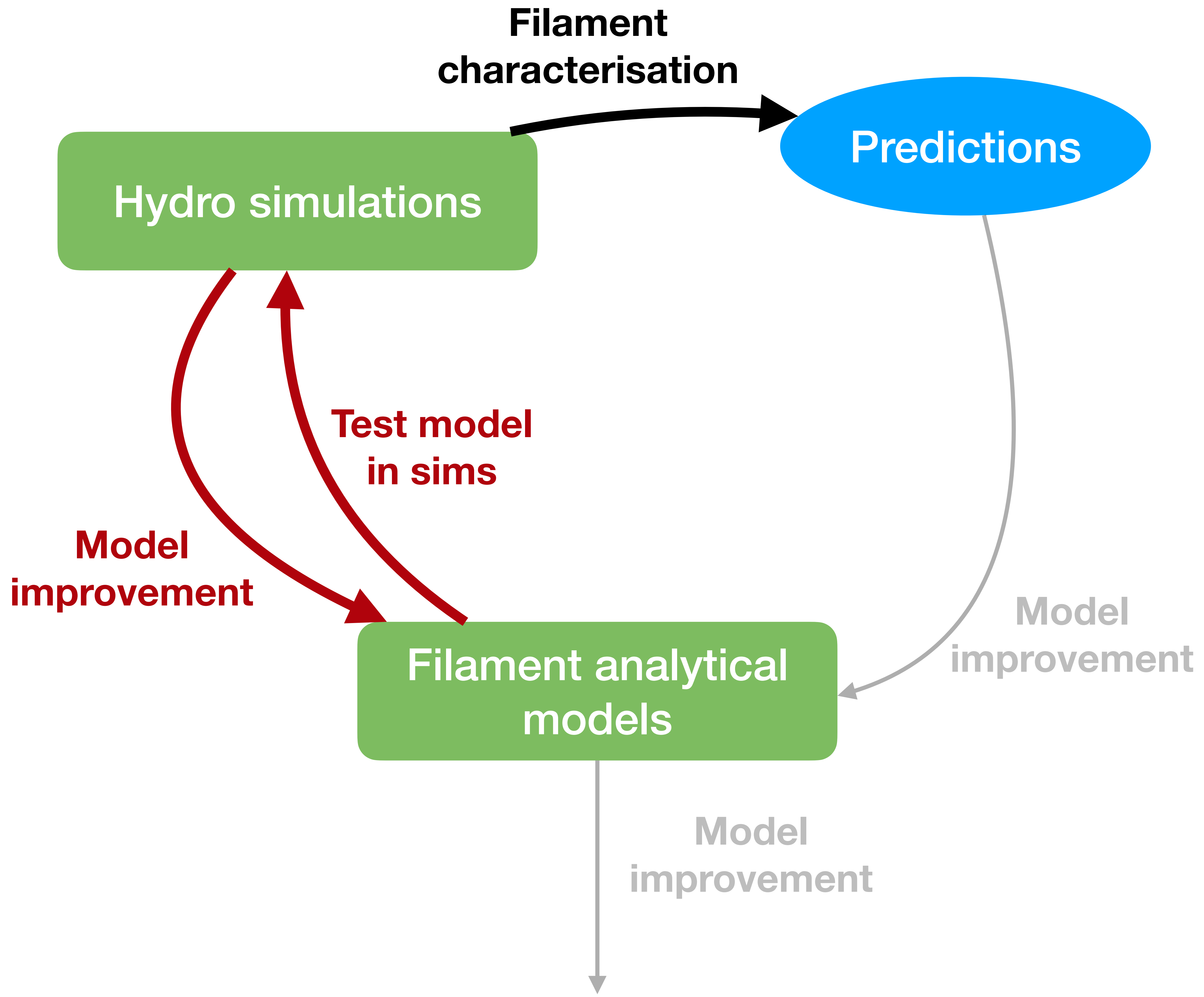

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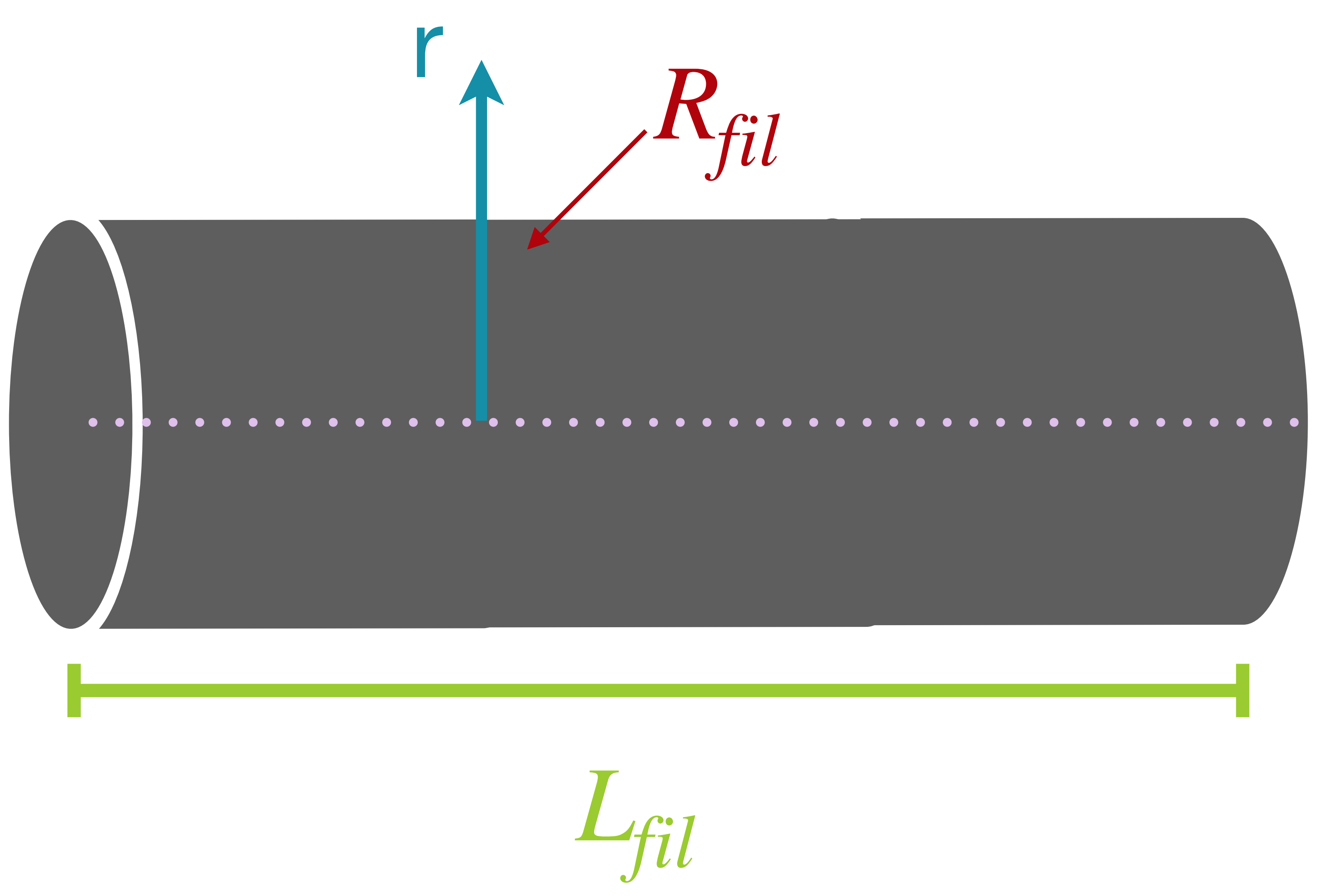
What is the fundamental property of filaments?

Mass per unit length

The 3D profiles

$$\Lambda_{fil} = \frac{M(r < R_{fil})}{L_{fil}} = \pi \, R_{fil}^2 \, \rho(r < R_{fil})$$



Problem: to compute it, we need a radius…

Option 1: fixed density threshold
(like R_200 for haloes)

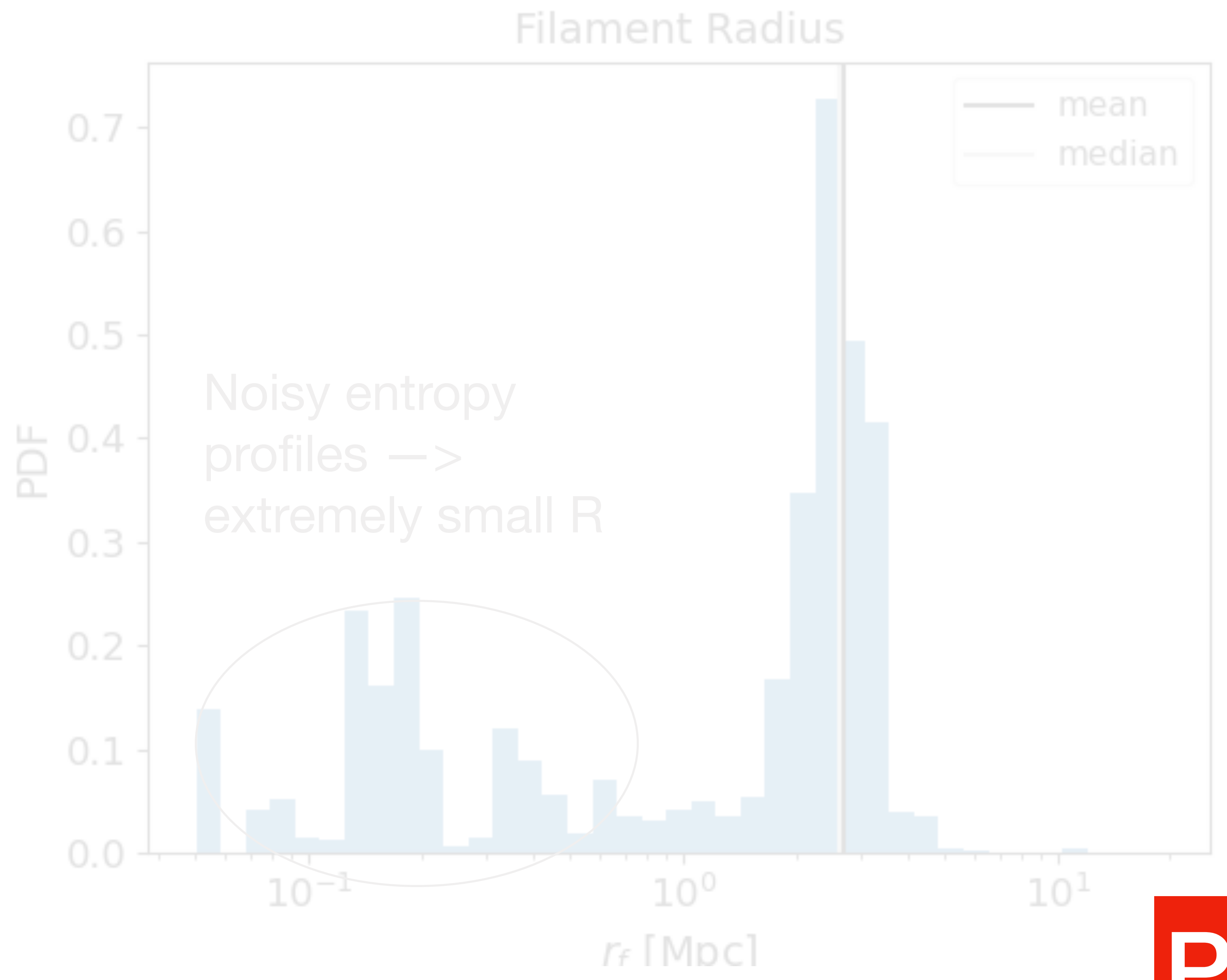
Option 2: physically motivated

- Gas properties: entropy profiles
- DM properties: “splashback radius”
- …

Work in progress!

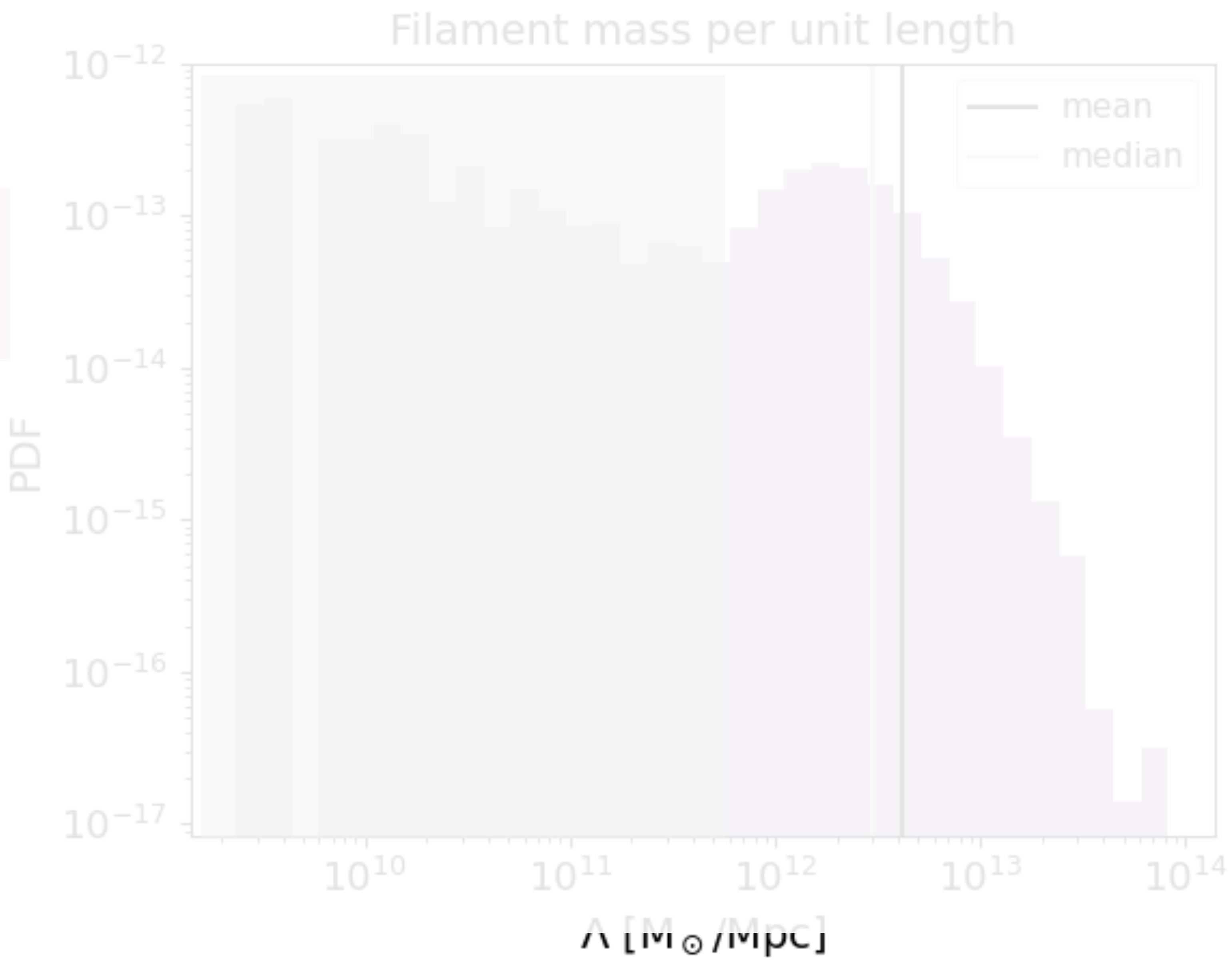
1

From entropy profiles



2

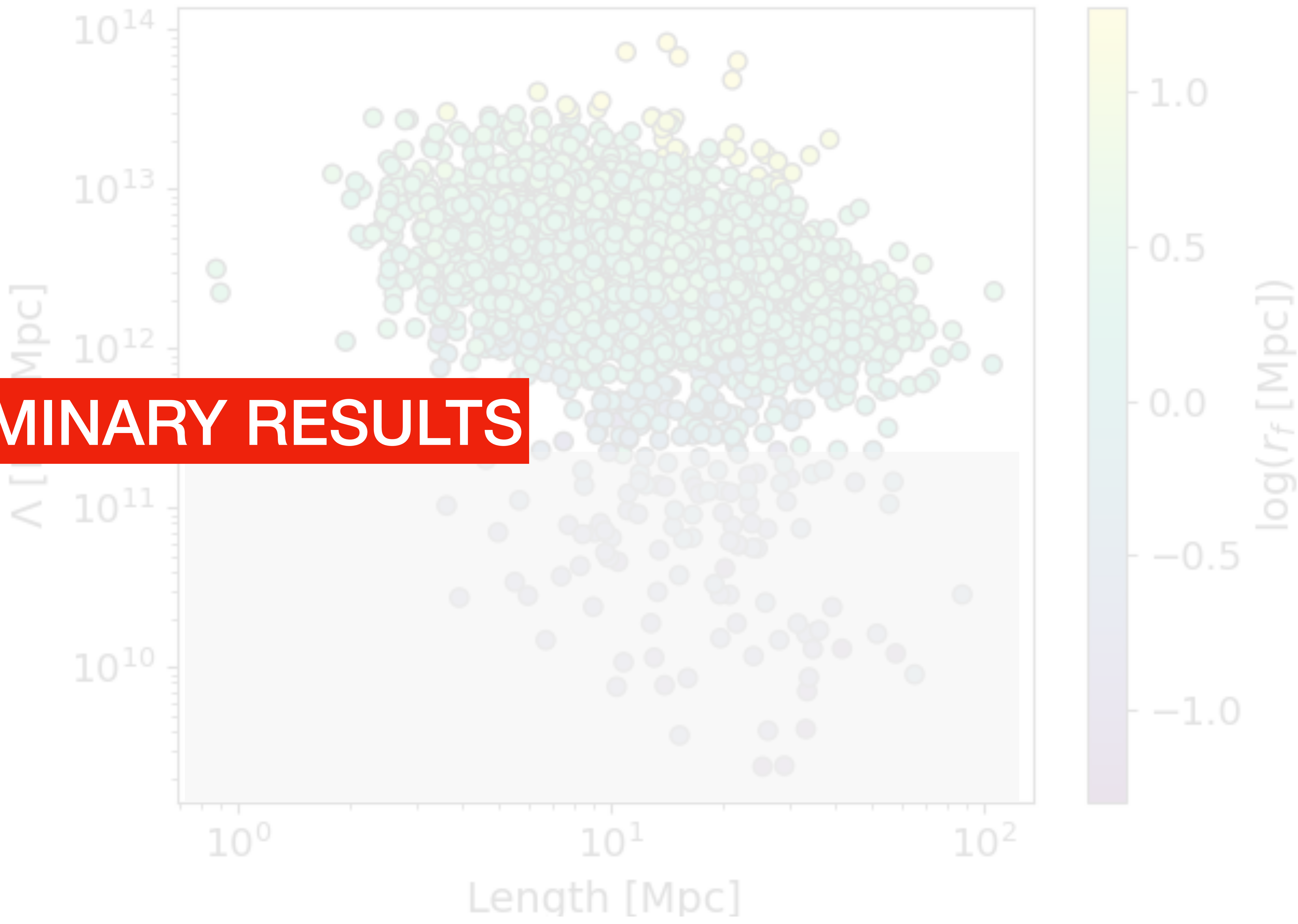
$$\Lambda_{fil} = \frac{M(r < R_{fil})}{L_{fil}}$$



3

Filaments in the fundamental plane

PRELIMINARY RESULTS



There seems to be a main sequence!!!

Comparison with analytical model: Pressure profiles

z=0

Work in progress!

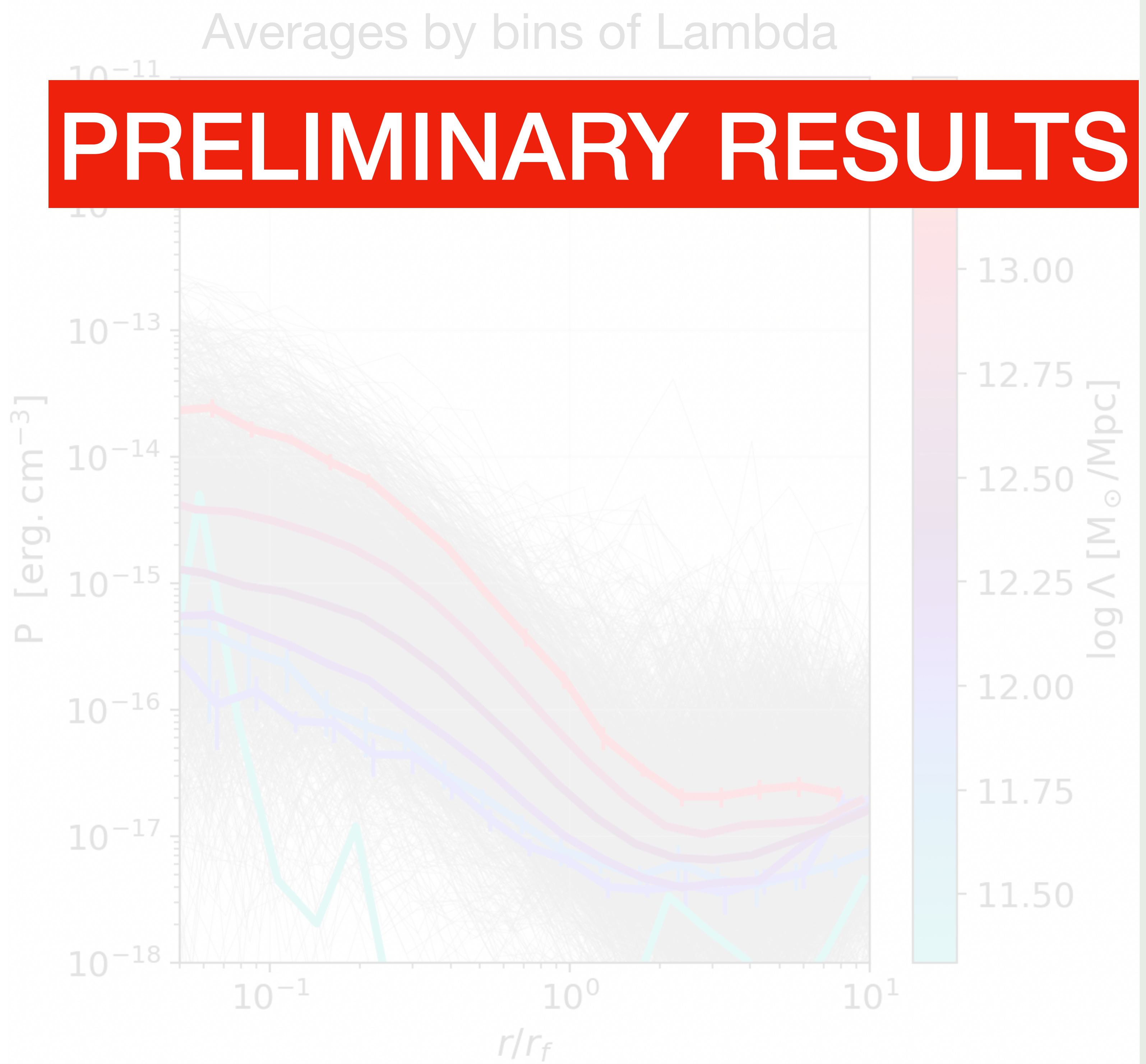
Filaments selection

- Straight filaments (wiggle<1.2)
- Lengths > 2 Mpc
- R_fil = 1-5 Mpc

Other details:

- masking gas in clusters and in topological nodes

Measurements in simulations



Analytical model predictions

Aung, Mandelker, Nagai et al. 2019

What is the picture at higher z?

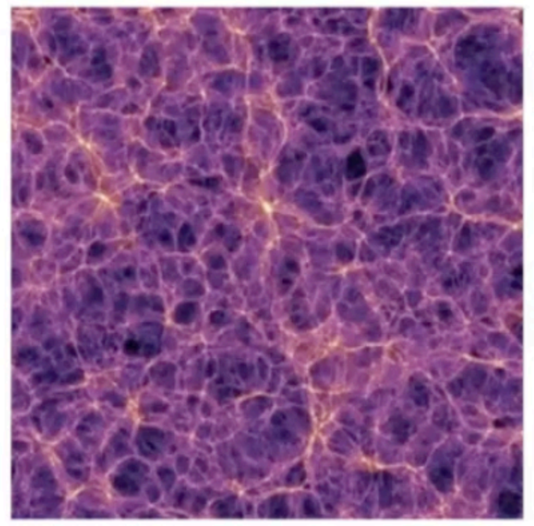
What is the picture at higher z?

IllustrisTNG

Pillepich+ 2018; Nelson+ 2019

\+

Millennium



Springel+ 2005

→

MTNG

full physics,
with lightcone,
X-ray, SZ-maps, ...

Volume ~$(740\ \mathrm{cMpc})^3$
~15x bigger than TNG300

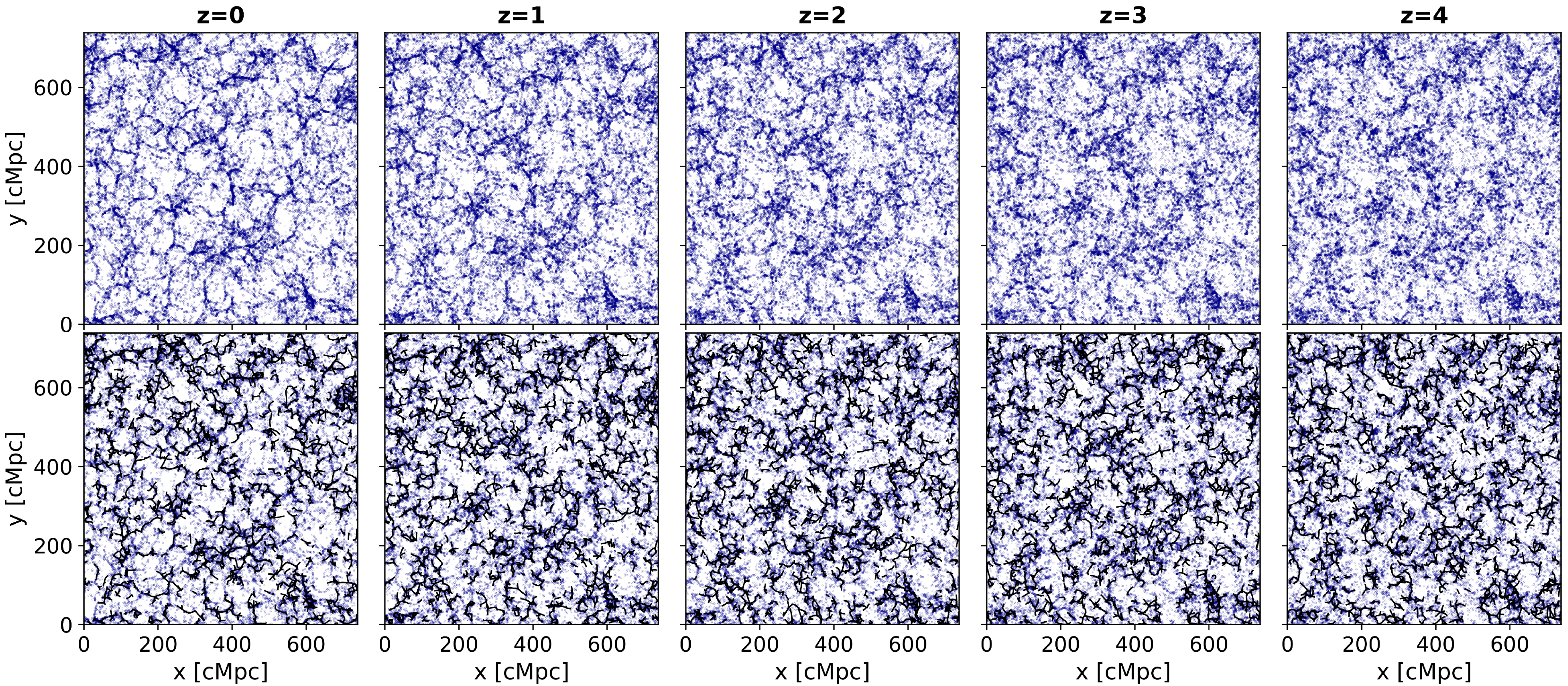
$m_{\mathrm{DM}} = 1.12 \times 10^8\ \mathrm{M}_{\odot}/h$
8x better than Millennium

Introductory papers: Hernández-Aguayo+ 2023, Pakmor+ 2023

Filaments across time

> 110 000 filaments at each snapshot!

(15 cMpc thick slices)



Work at **fixed density of tracers**! (~fixed resolution)
Ensures detection of filaments **at the same scales**

For Sebastiano

Galárraga-Espinosa+ 2024

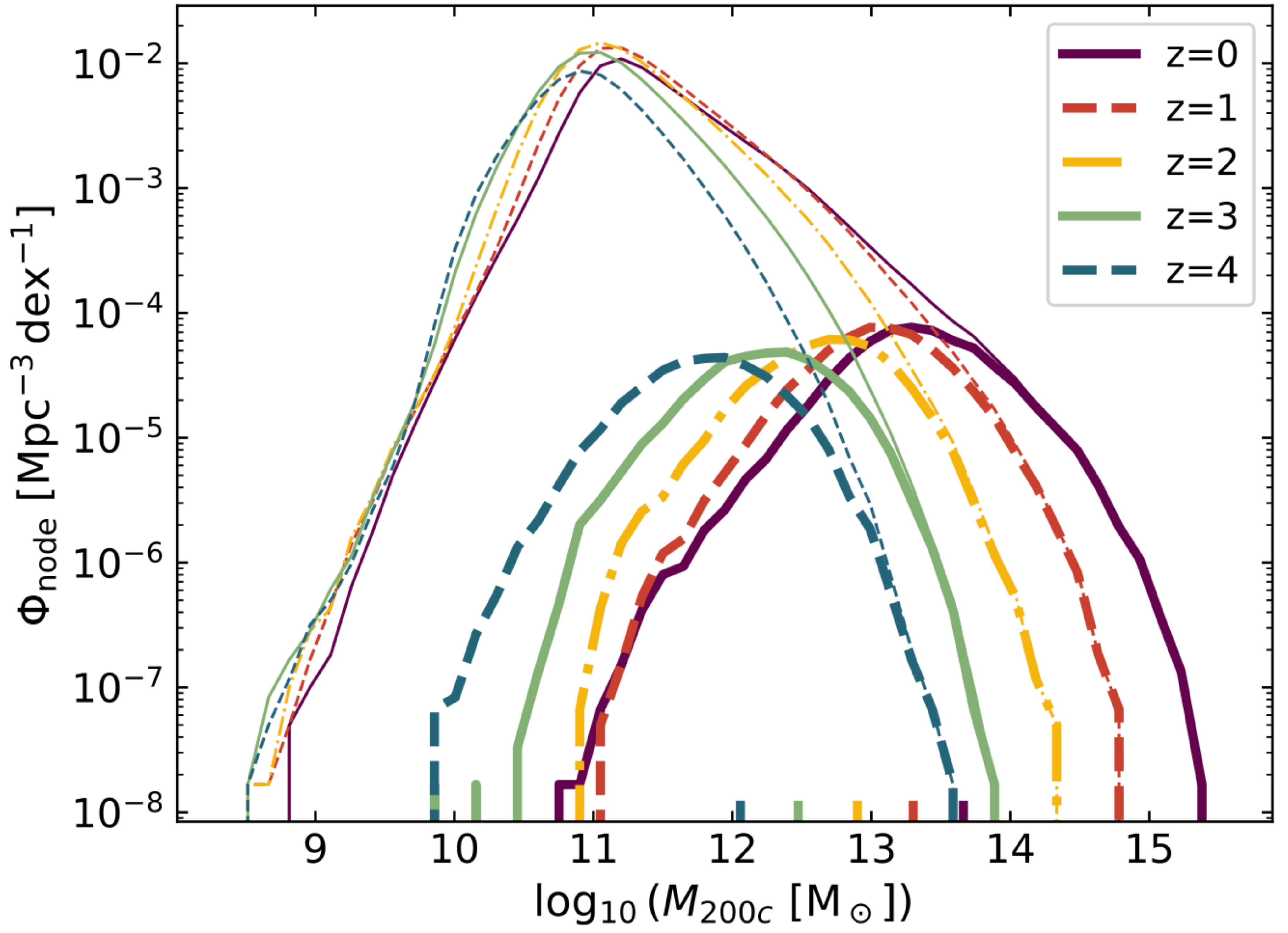
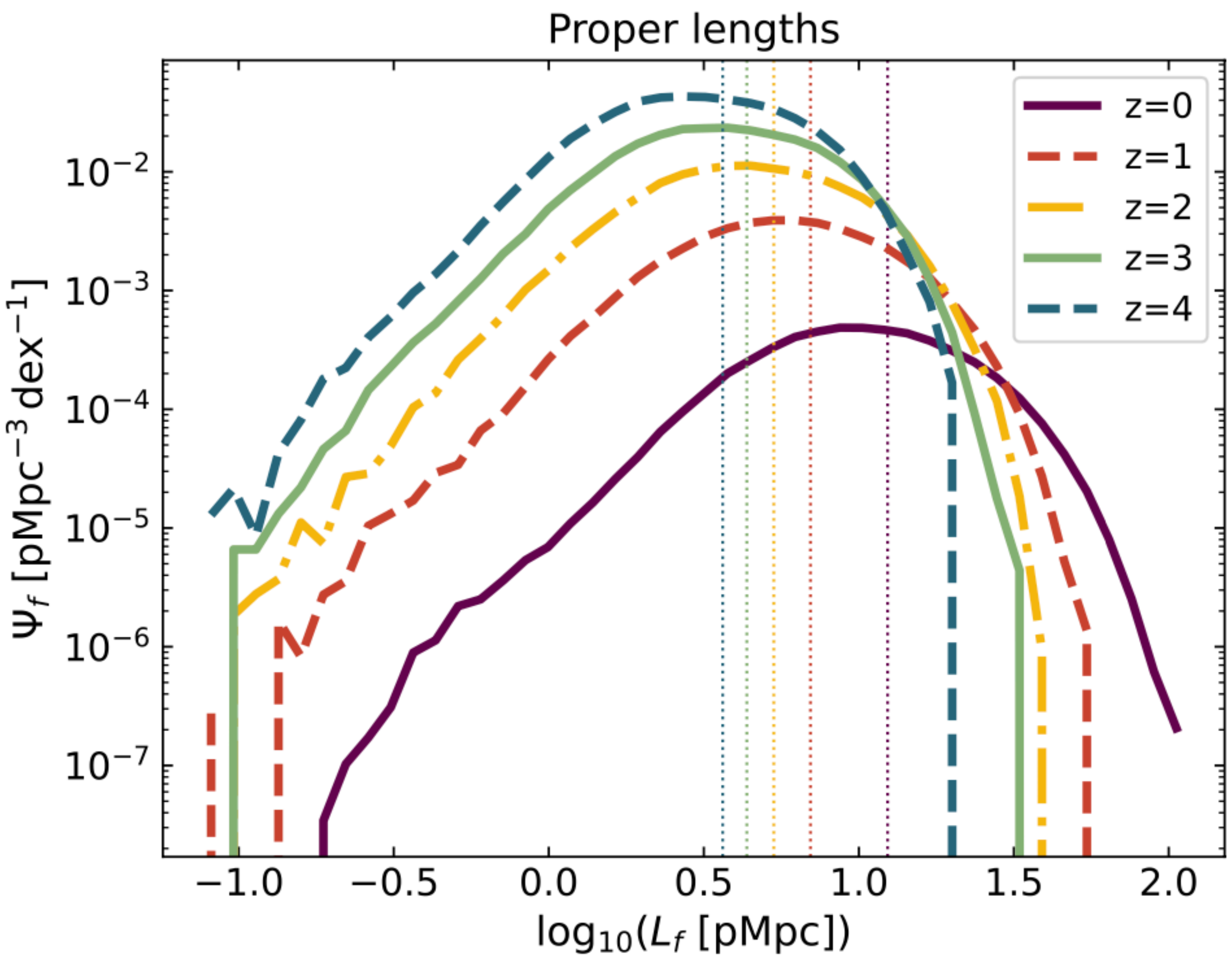


Fig. 5. Mass function of the nodes connected to the filaments at different redshifts (thick curves). The vertical marks show the mean masses, which are $\log_{10}(\bar{M}_{200c}/M_\odot)$ = 13.66, 13.30, 12.90, 12.47, and 12.06, respectively, from z = 0 to 4. For comparison, the thin curves give the mass functions of all the FoF haloes of the MTNG simulation with a stellar mass content of at least 10^8 $M_\odot$.

Filament length functions



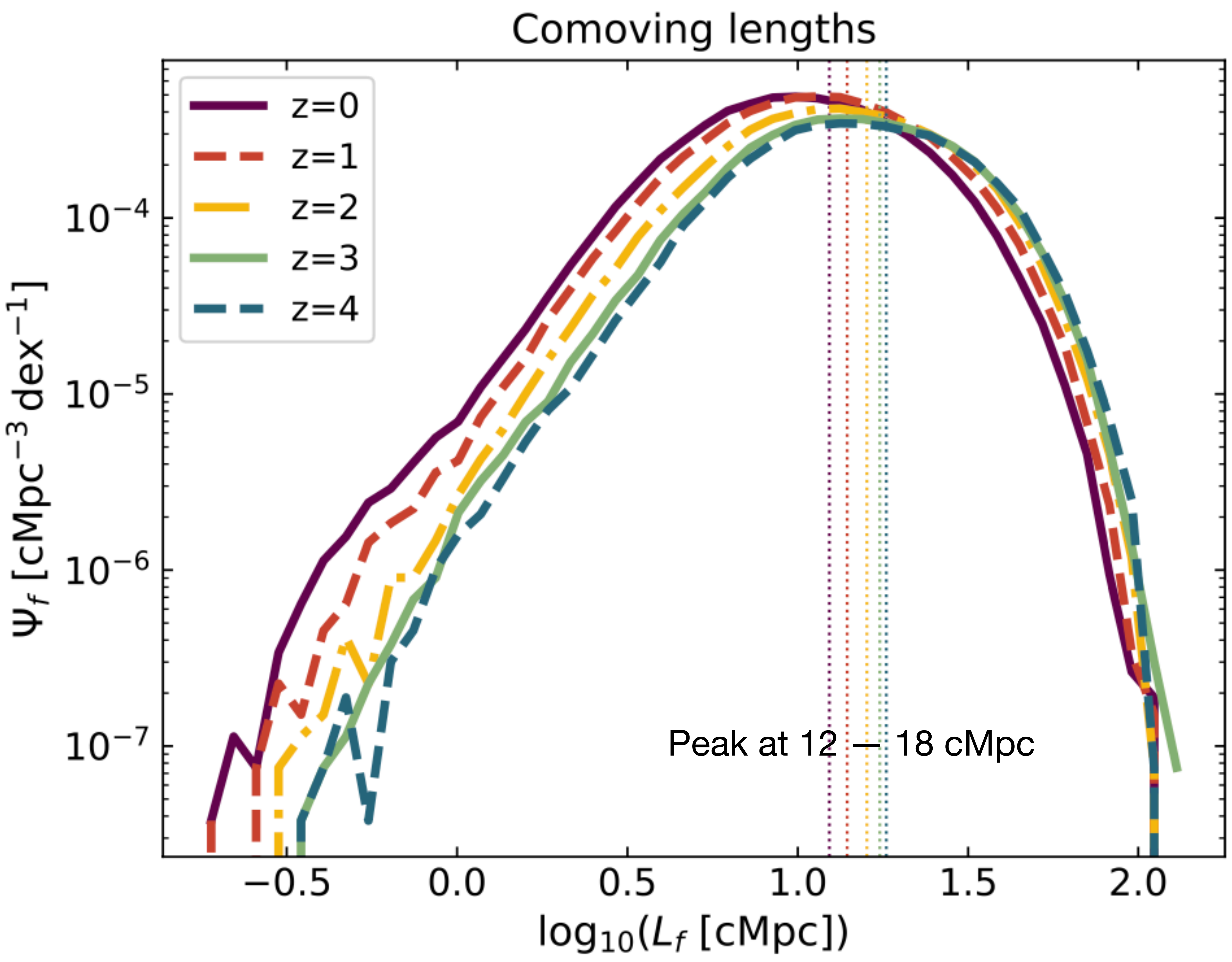
The cosmic web expands (tied to the Hubble flow)
—> **proper** lengths of cosmic filament increase

	$z = 0$	$z = 1$	$z = 1.99$	$z = 3$	$z = 4$
L_{min} [pMpc]	0.20	0.09	0.10	0.09	0.08
L_{max} [pMpc]	115.06	59.02	36.41	34.97	21.00
L_{mean} [pMpc]	12.38	6.98	5.32	4.35	3.64
L_{median} [pMpc]	9.83	5.61	4.25	3.52	2.94

Galárraga-Espinosa+ 2024

Filament length functions

Factoring out the expansion of the Universe:



Little evolution!

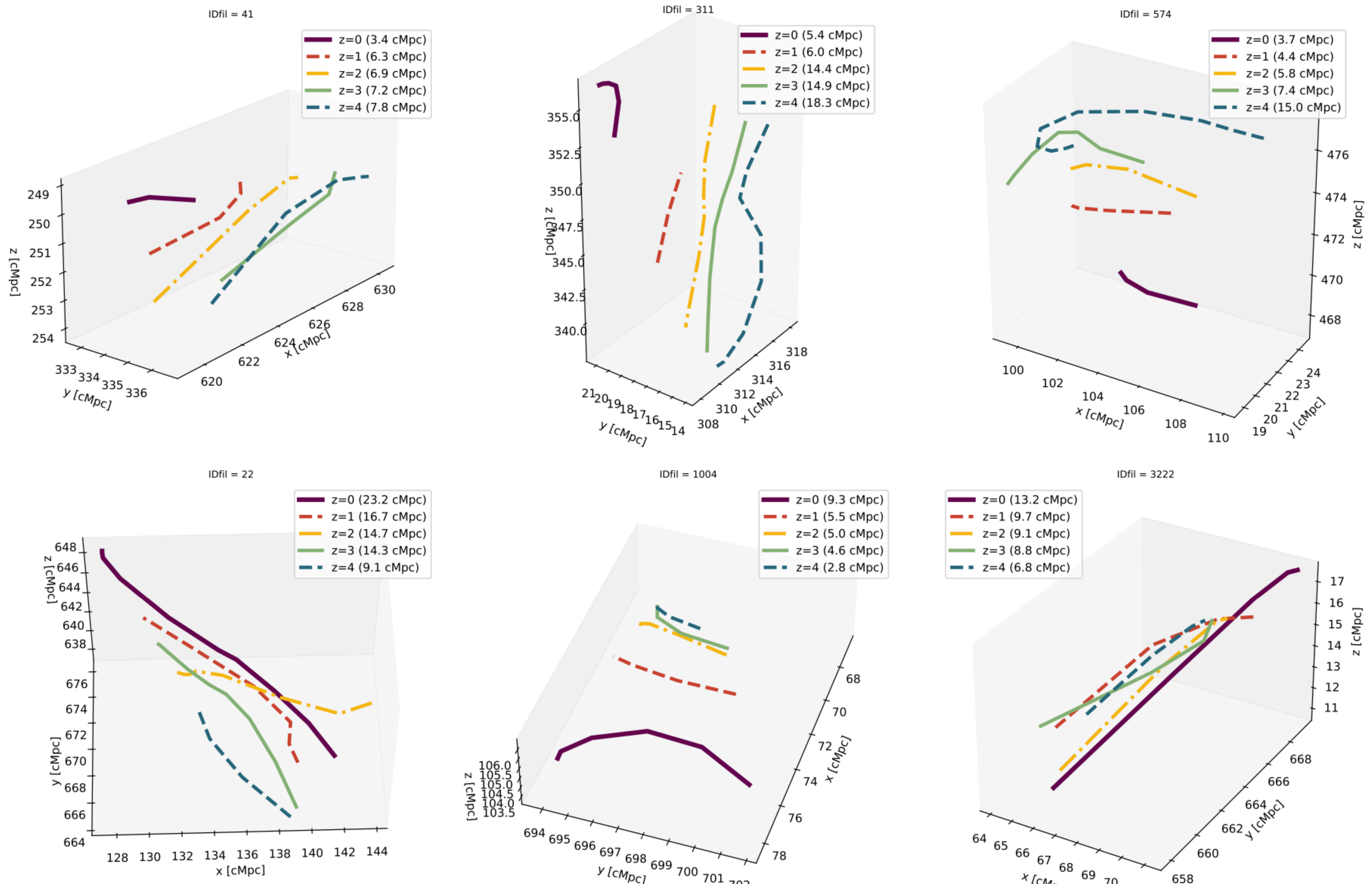
The comoving filament length function is **stable**

Galárraga-Espinosa+ 2024

What about the evolution of individual filaments?

—> Matching positions of peaks and saddles across time

We associate filaments across snapshots —> track the “same” filament



Drift because of gravitational tides

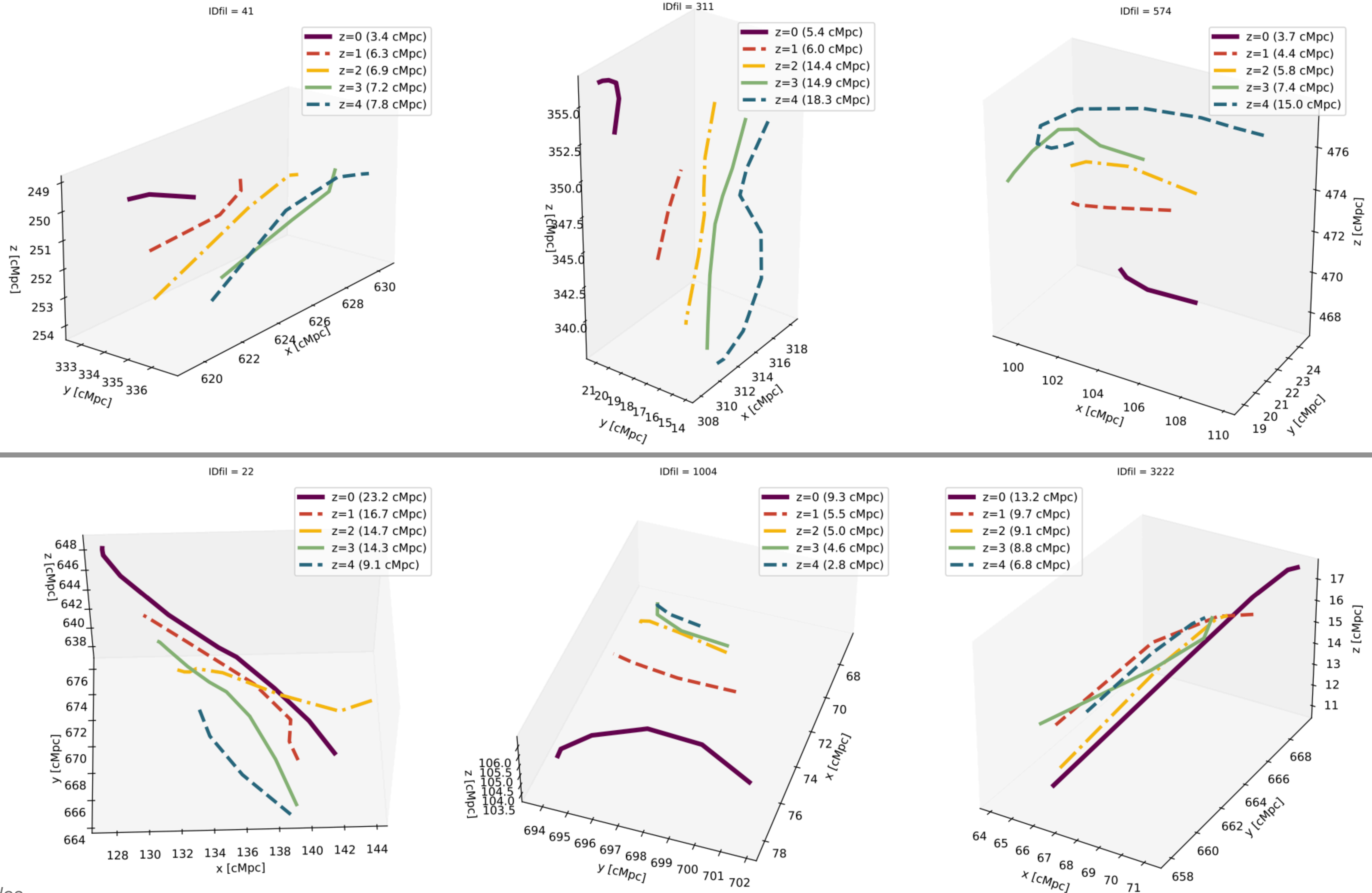
What about the evolution of individual filaments?

—> Matching positions of peaks and saddles across time

We associate filaments across snapshots —> track the "same" filament

Contraction

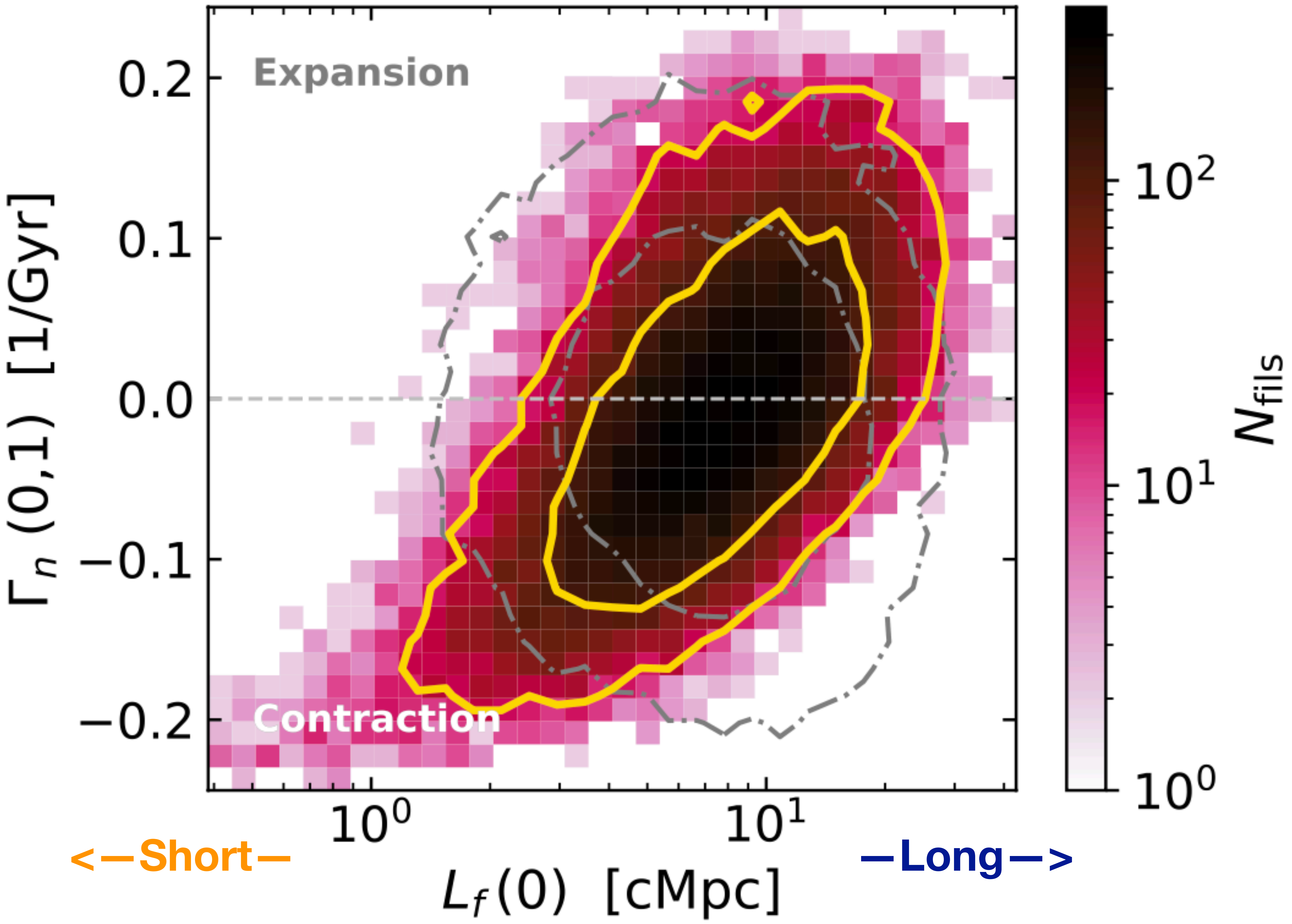
Expansion



Drift because of gravitational tides

Growth rates and length

Example from z=0 to 1



<−Short− −Long−>

Galarraga-Espinosa+ 2024

Normalised filament growth rates, for each filament-progenitor pair:

$$\Gamma_n = \frac{\Delta L}{\Delta t} \times \frac{1}{\text{mean}\, L}$$

Filament expansion/ contraction depends on filament length

- **Long filaments preferentially expand**
- **Short filaments contract**

Evolution: Gravity vs DE dominated? Potential to learn about cosmology?

Filaments are sensitive to cosmological parameters

First exploration using QUIJOTE simulations (High resolution)

Work in progress!
(Ínc. Luisa Lucie-Smith)

Analysis of:

- Fiducial cosmology: 100 realisations (cosmic variance)
- Latin Hypercube: 2000 (different cosmologies)

Examples:

Part II
Filaments in the CGM

Circum-galactic medium

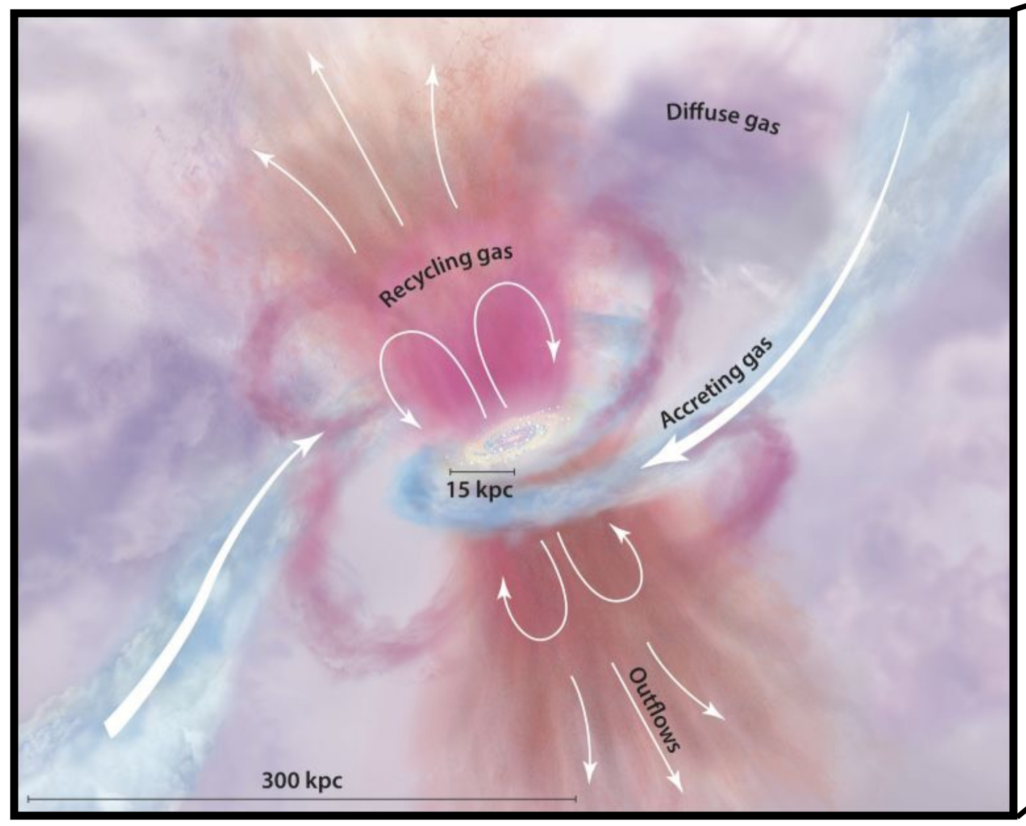
Galaxy evolution: a multi-scale problem

- **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!

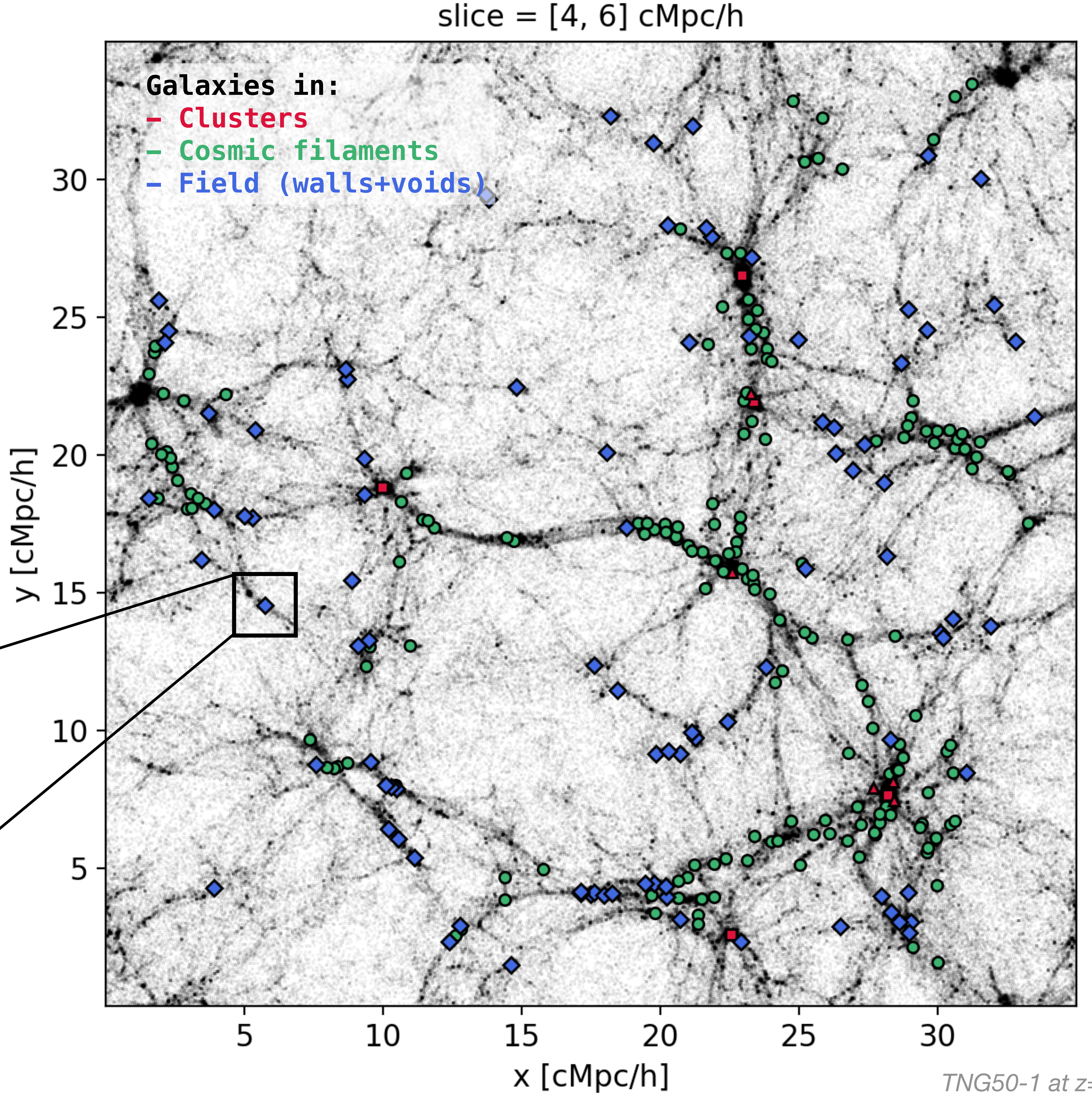
- **We need to** look at accretion and availability of **cold gas**

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

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



TNG50-1 at z=2

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) <u>Central galaxies</u> from TNG50-1

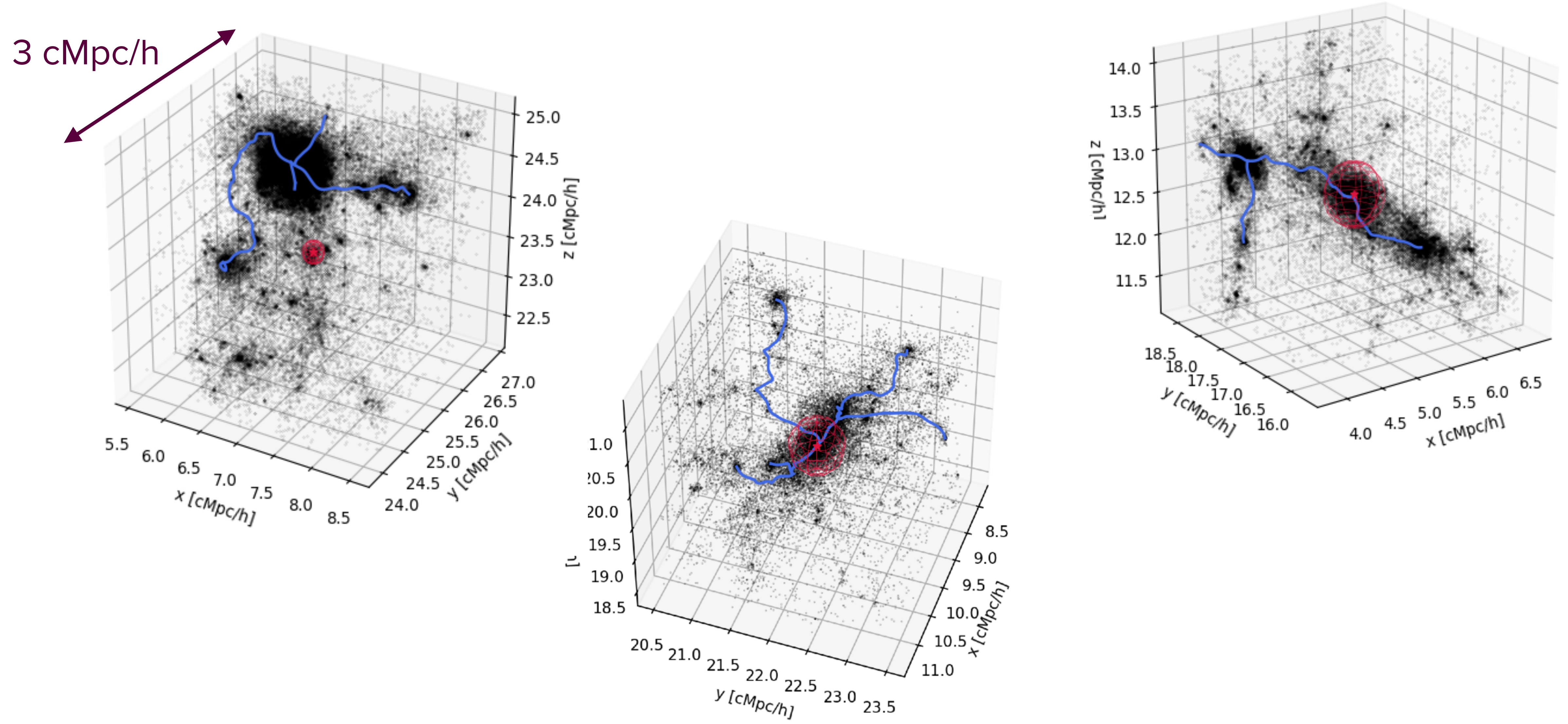
- $M_* \geq 10^8\,\mathrm{M}_\odot/h$
- At **<u>z=2</u>** (peak of SF activity)
- Select **only star-forming**

—> **2942 centrals**

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

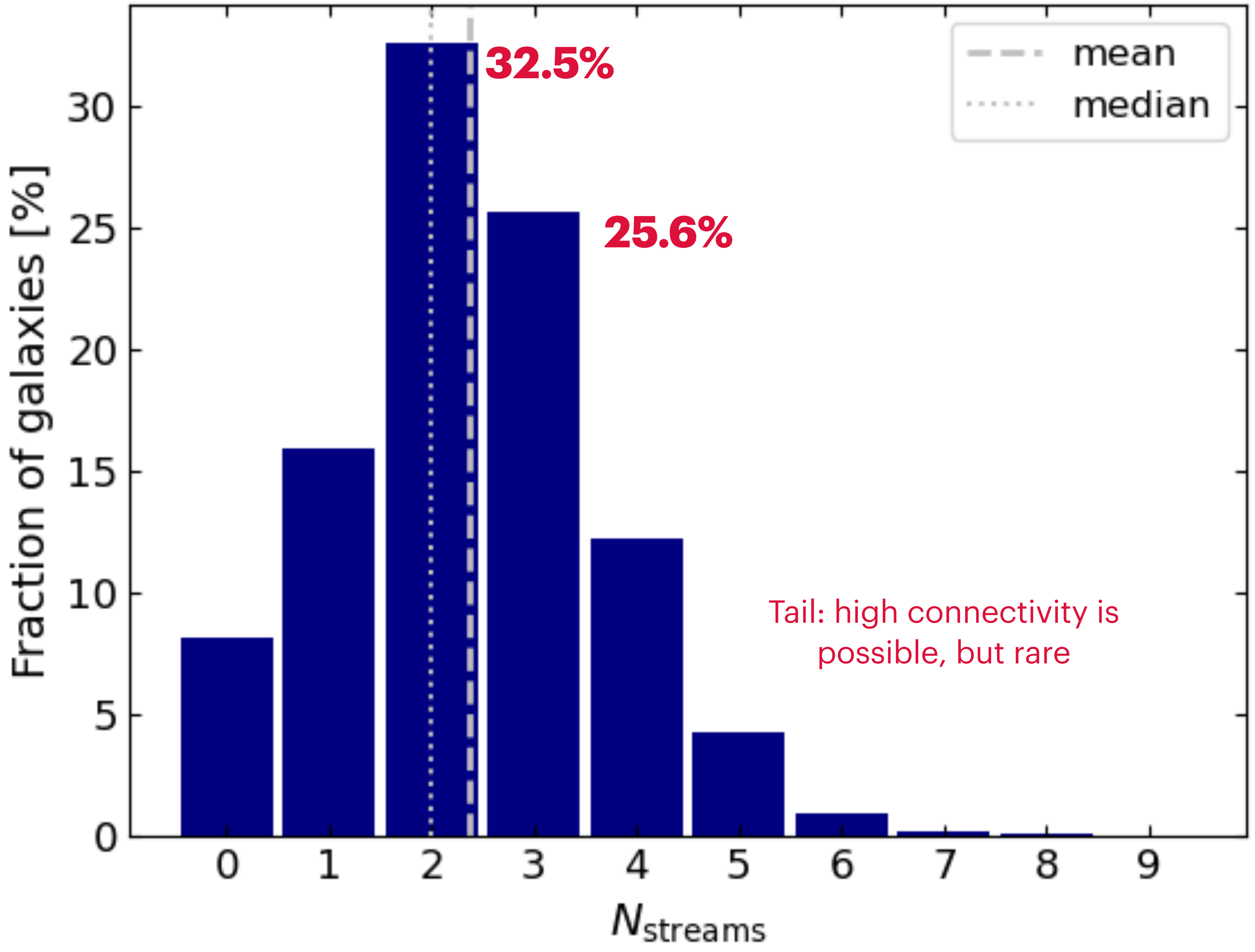
—> Goal: detect the local potential wells

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



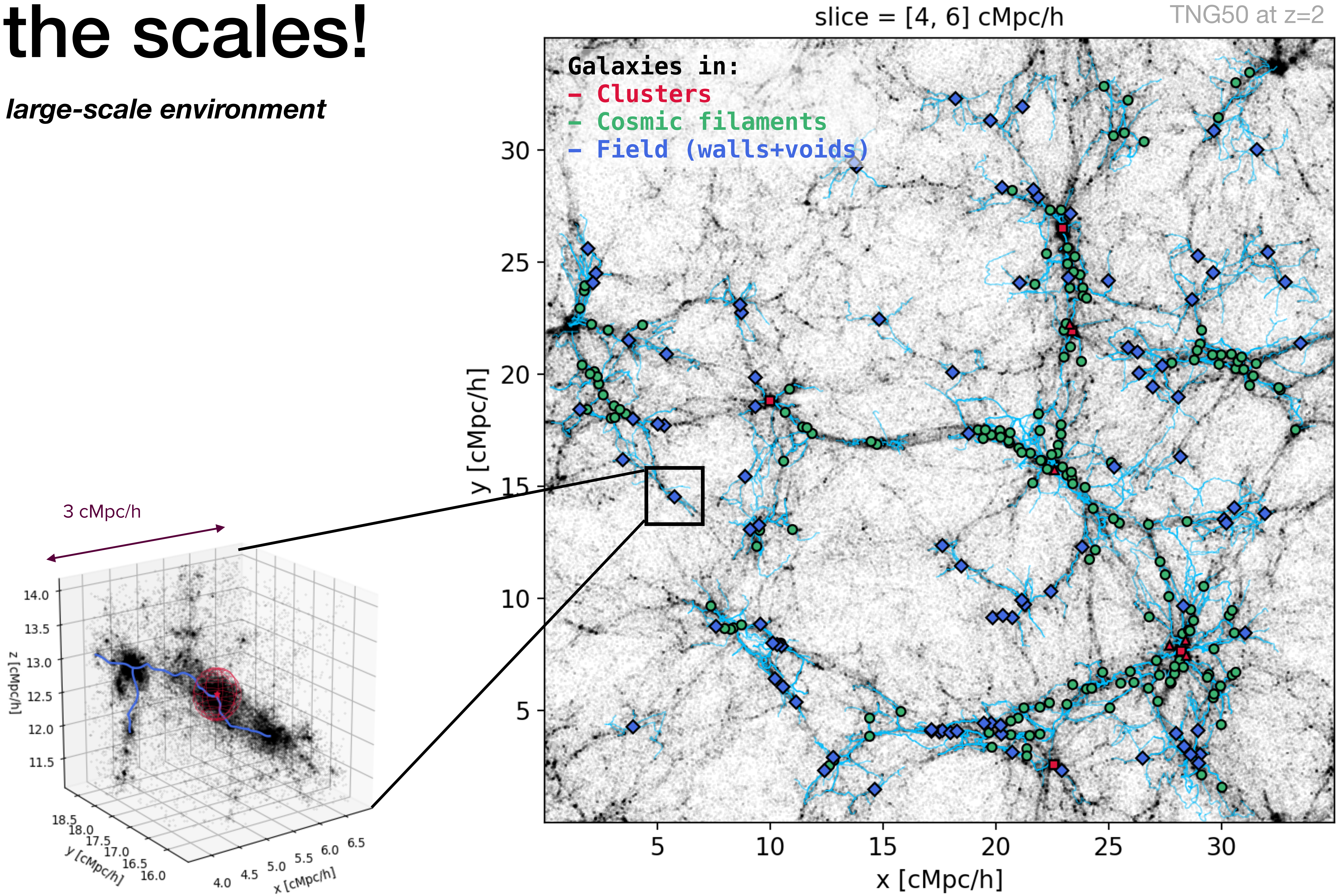
3) The observable: Galaxy connectivity

= Number of streams intersecting Rvir



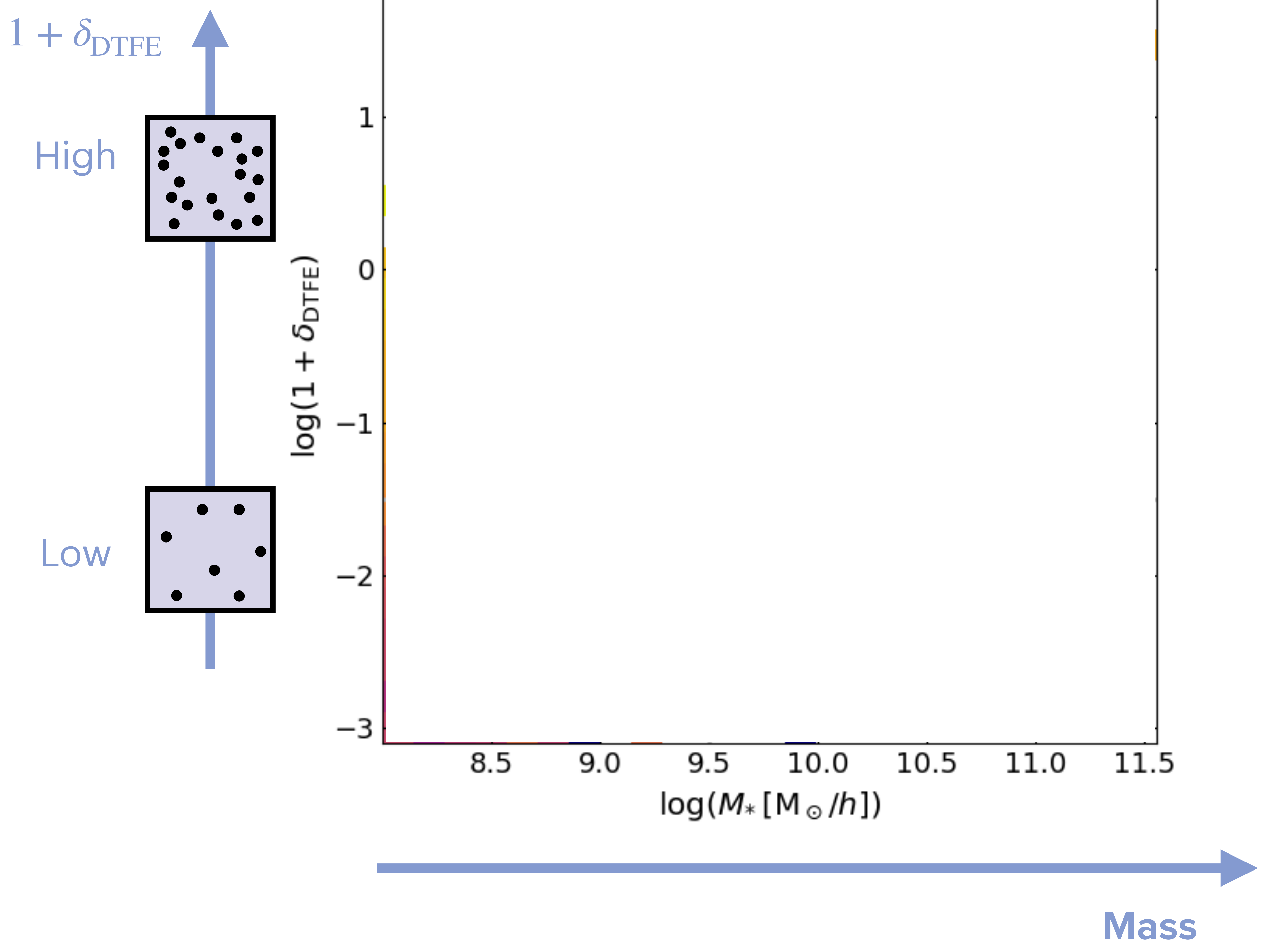
Mind the scales!

Local web vs large-scale environment



Connectivity : any secondary dependences?

Mean connectivity in the mass-overdensity plane



Connectivity : any secondary dependences?

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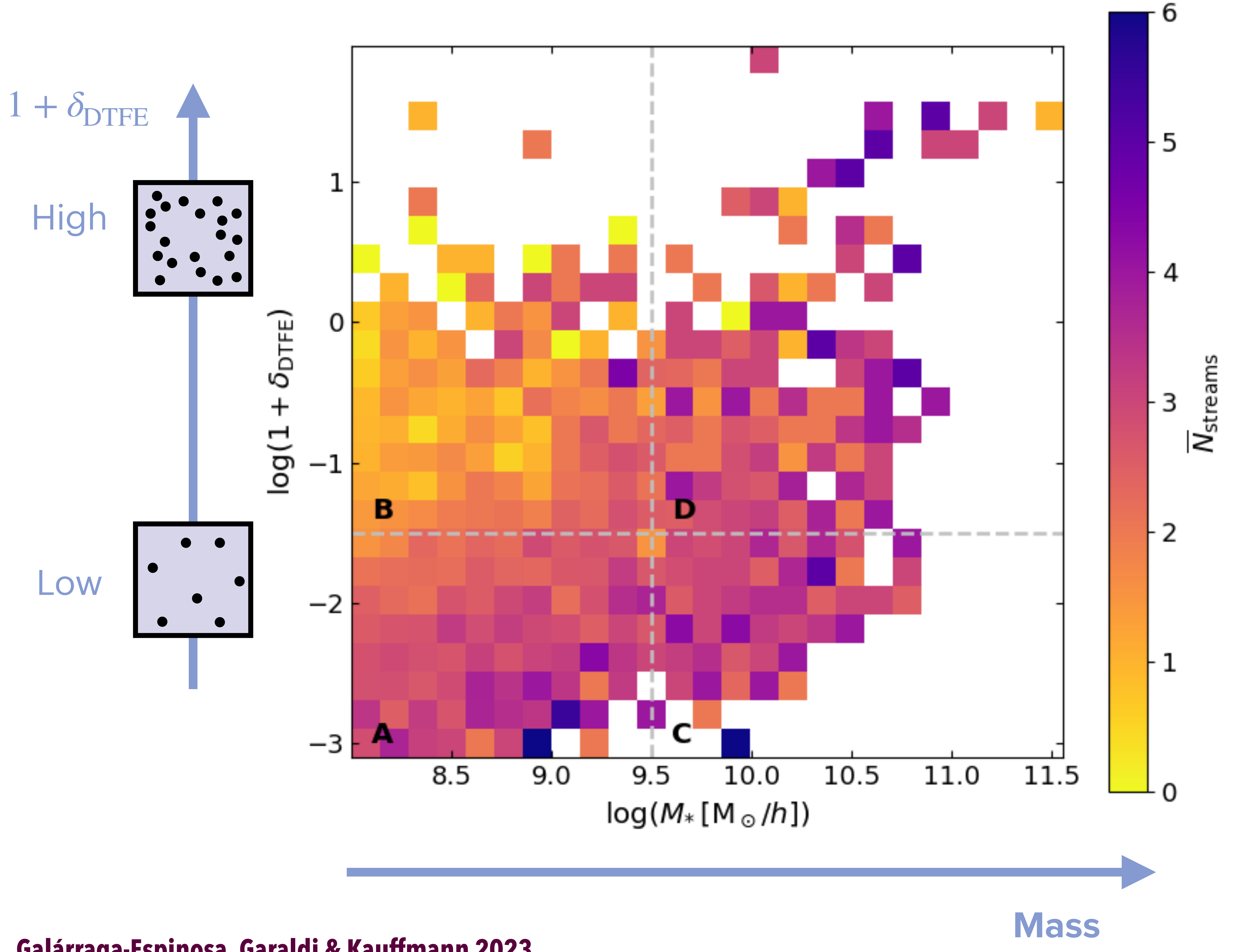
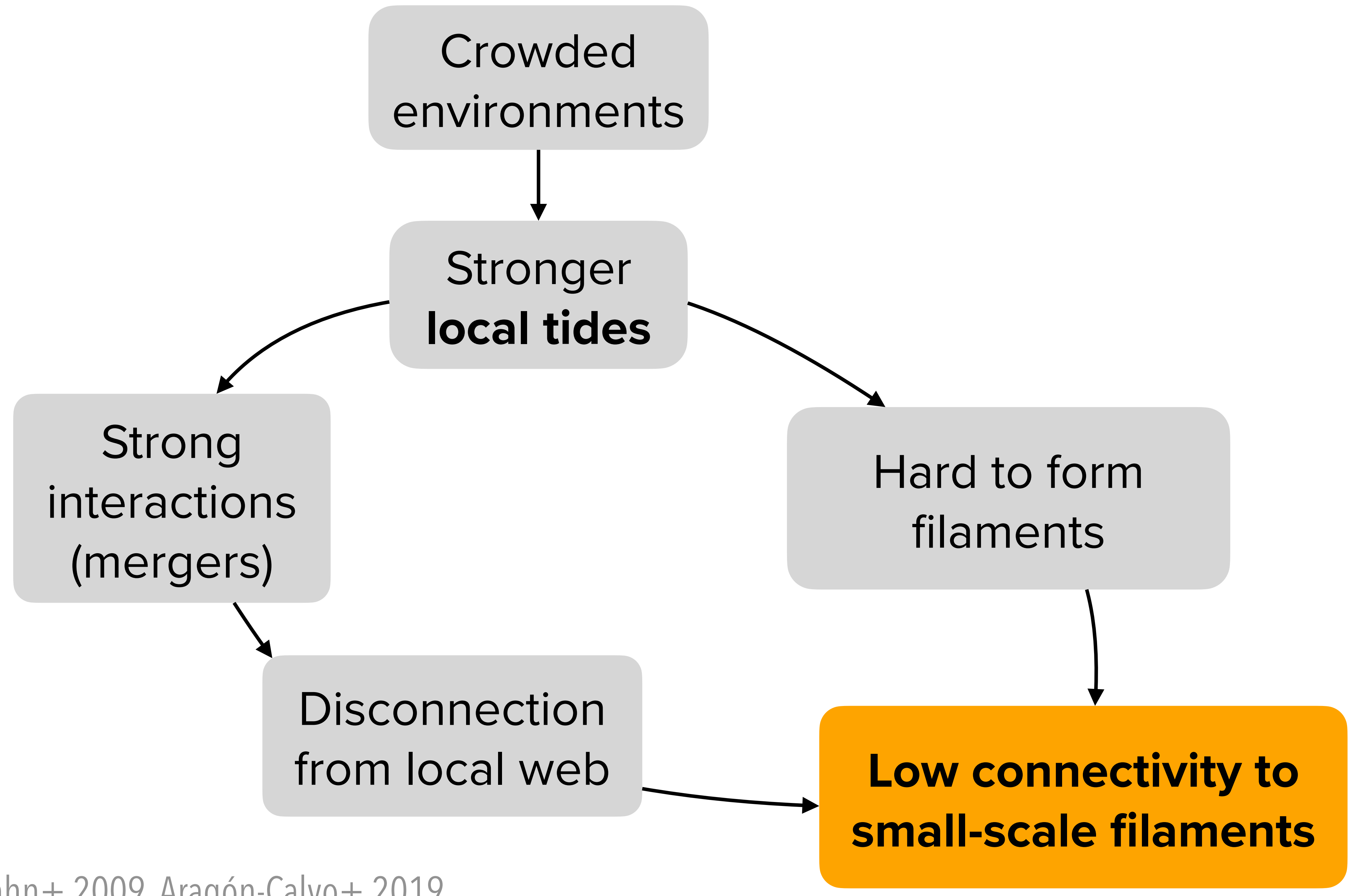


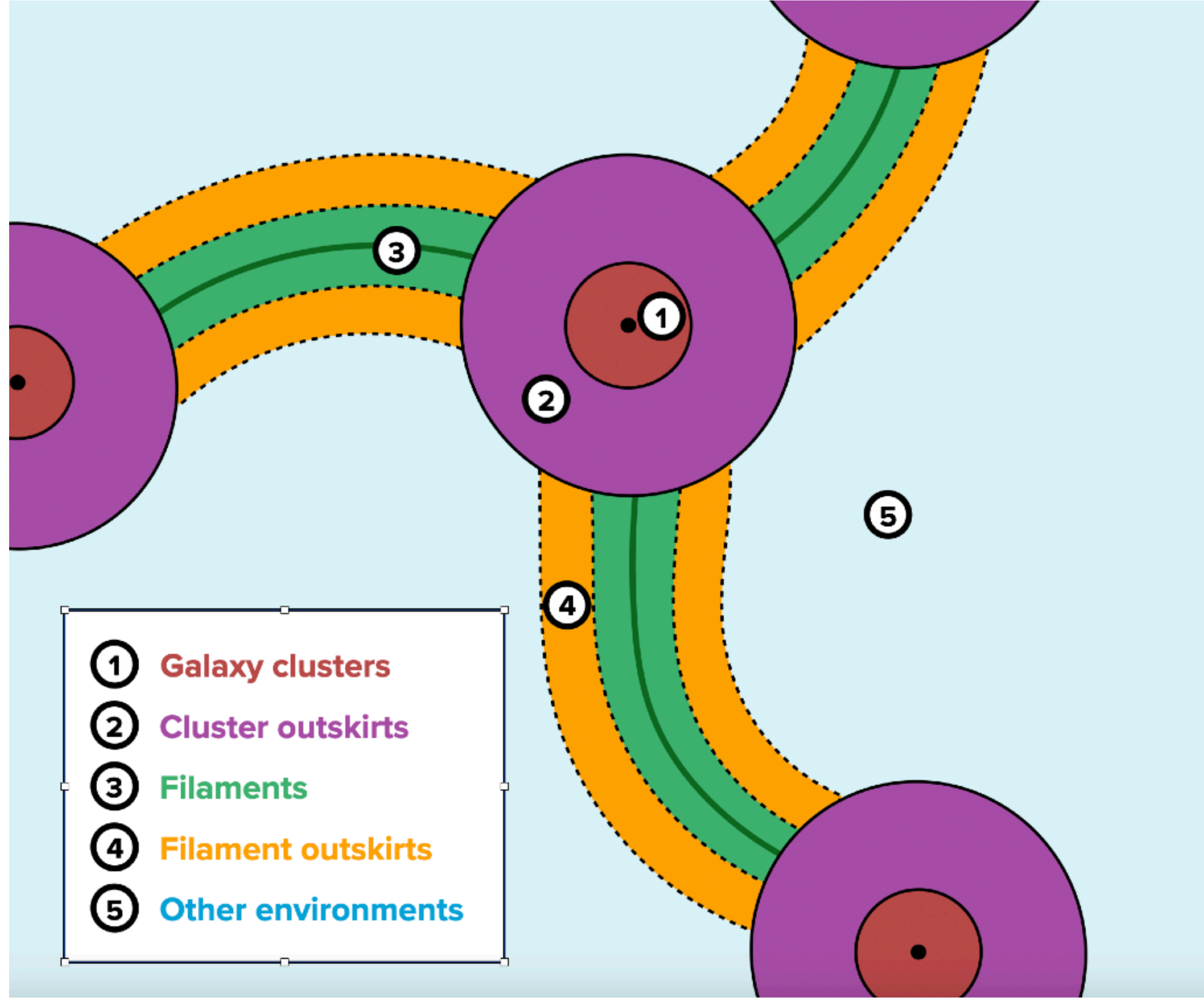
Galárraga-Espinosa, Garaldi & Kauffmann 2023

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!**

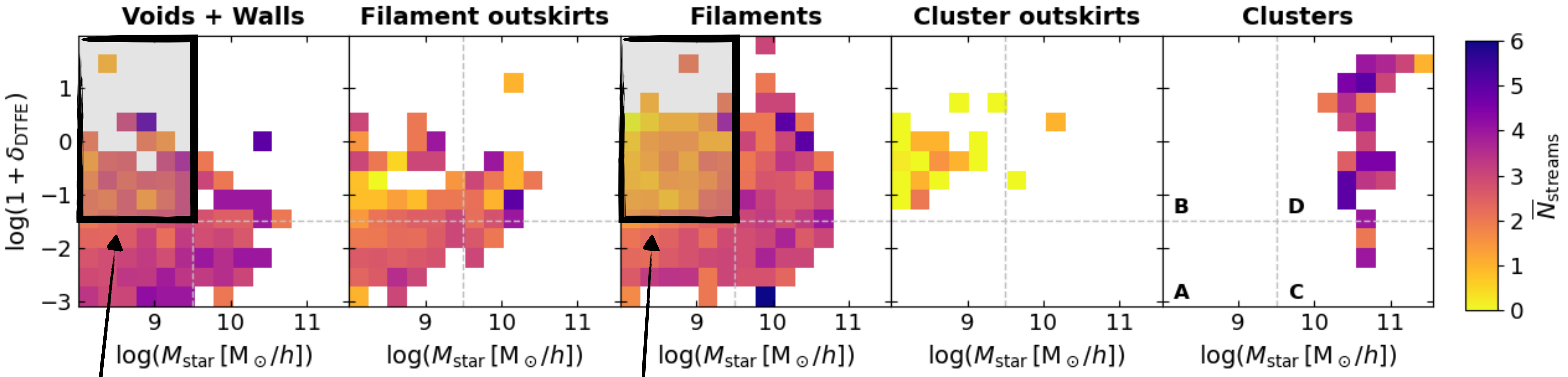


Hahn+ 2009, Aragón-Calvo+ 2019

Variations with large-scale environment?



Connectivity of galaxies in different cosmic web environments



mean = 2.34 ± 0.09

mean = 1.43 ± 0.05

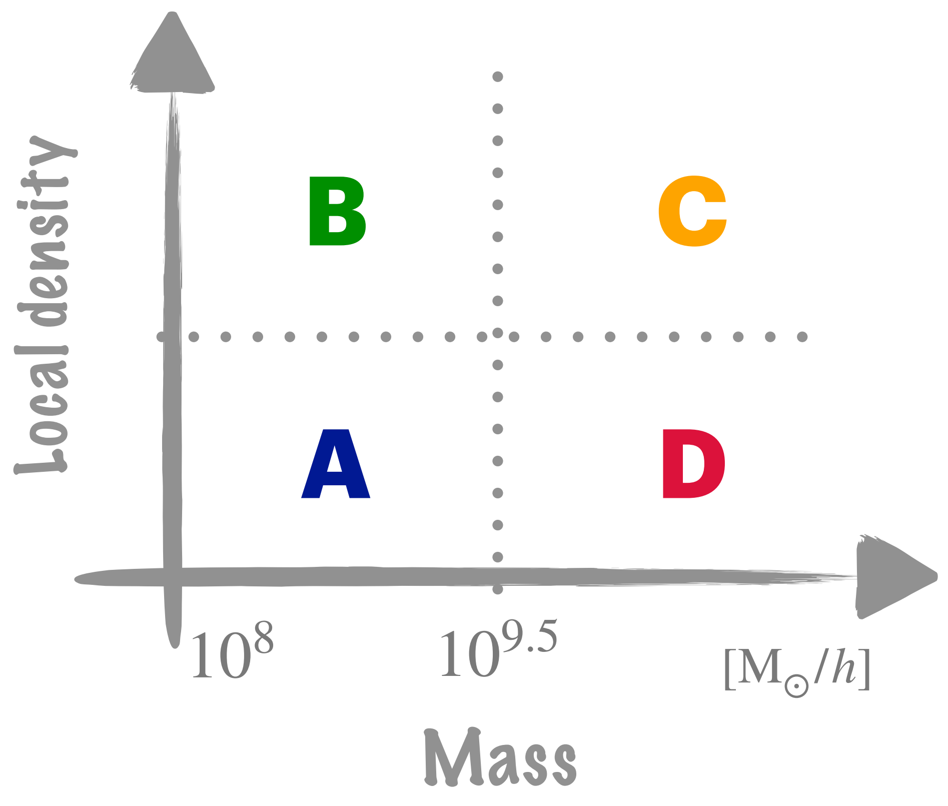
=> ***8.48σ difference***

Variations due to effects of cosmic tides

(different strengths in different locations in the Cosmic Web)

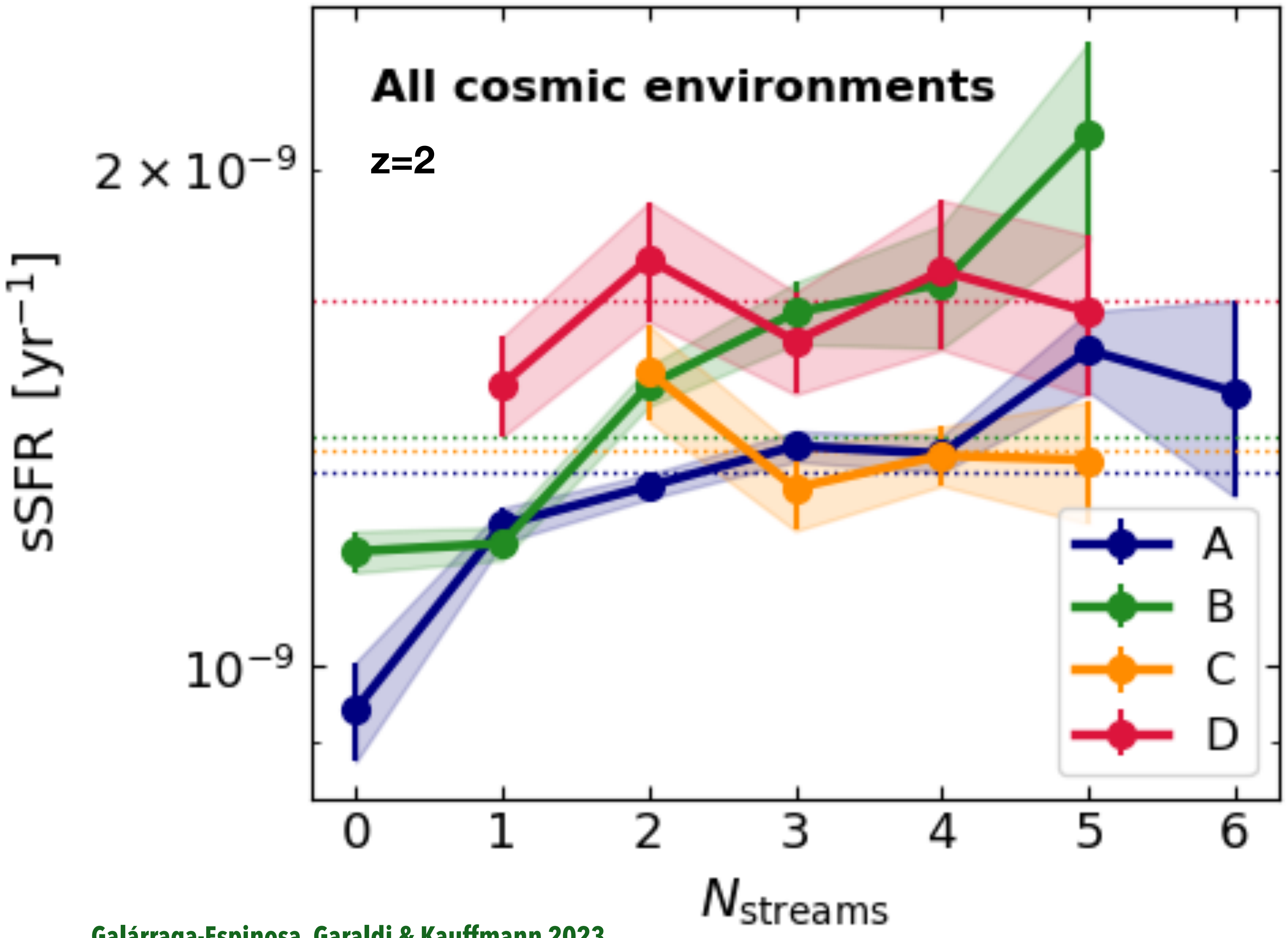
Borzyszkowski+ 2017; Musso+ 2018; Paranjape+ 2018; Kraljic+ 2020; Kuchner+ 2020, Jhee+ 2022:…

Galárraga-Espinosa, Garaldi & Kauffmann 2023



Relation with SFR

Mean sSFR vs connectivity



Galárraga-Espinosa, Garaldi & Kauffmann 2023

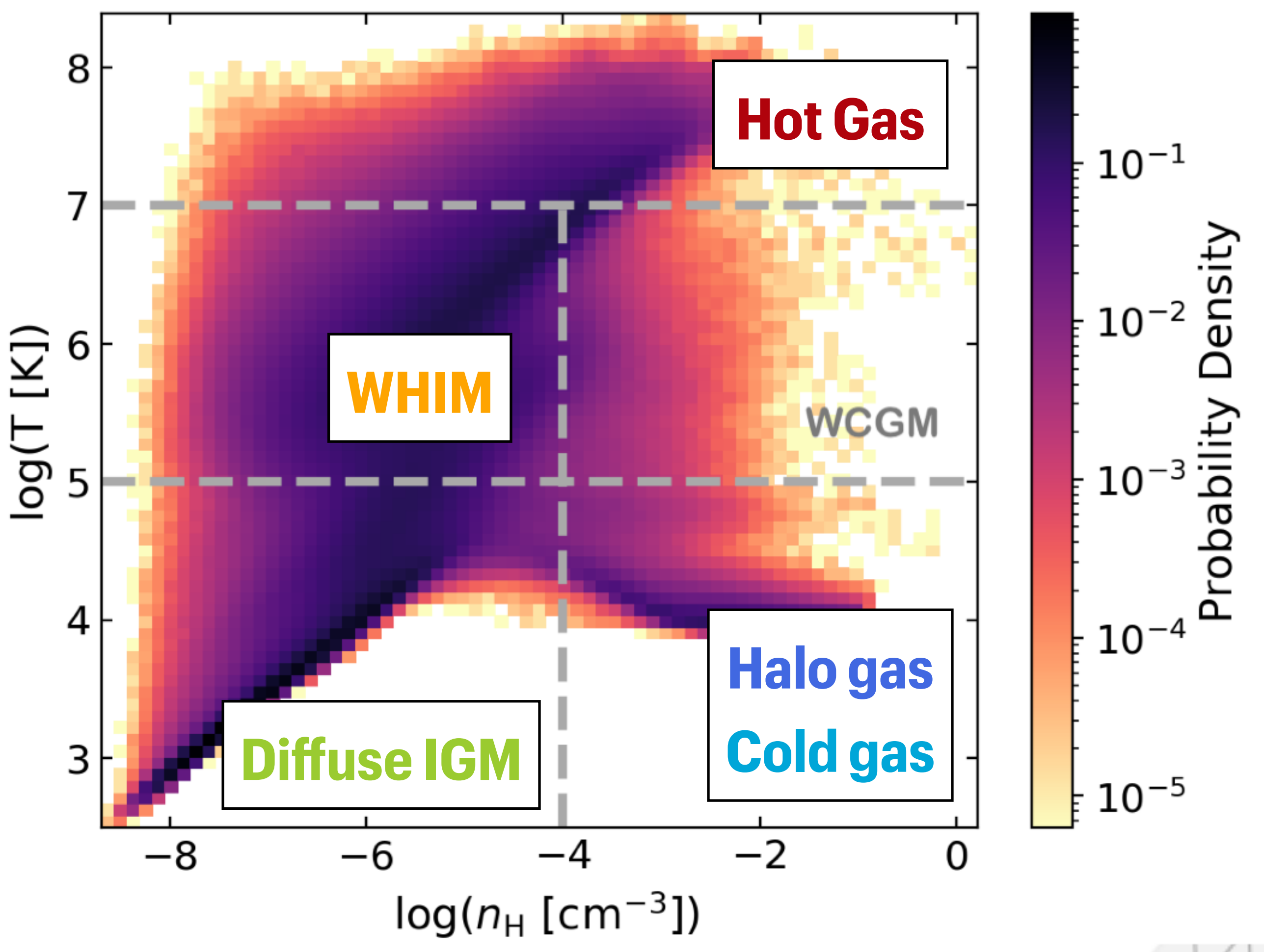
1) sSFR significantly boosted for <u>low mass</u> galaxies (A: 5.84σ, B: 5.92σ)

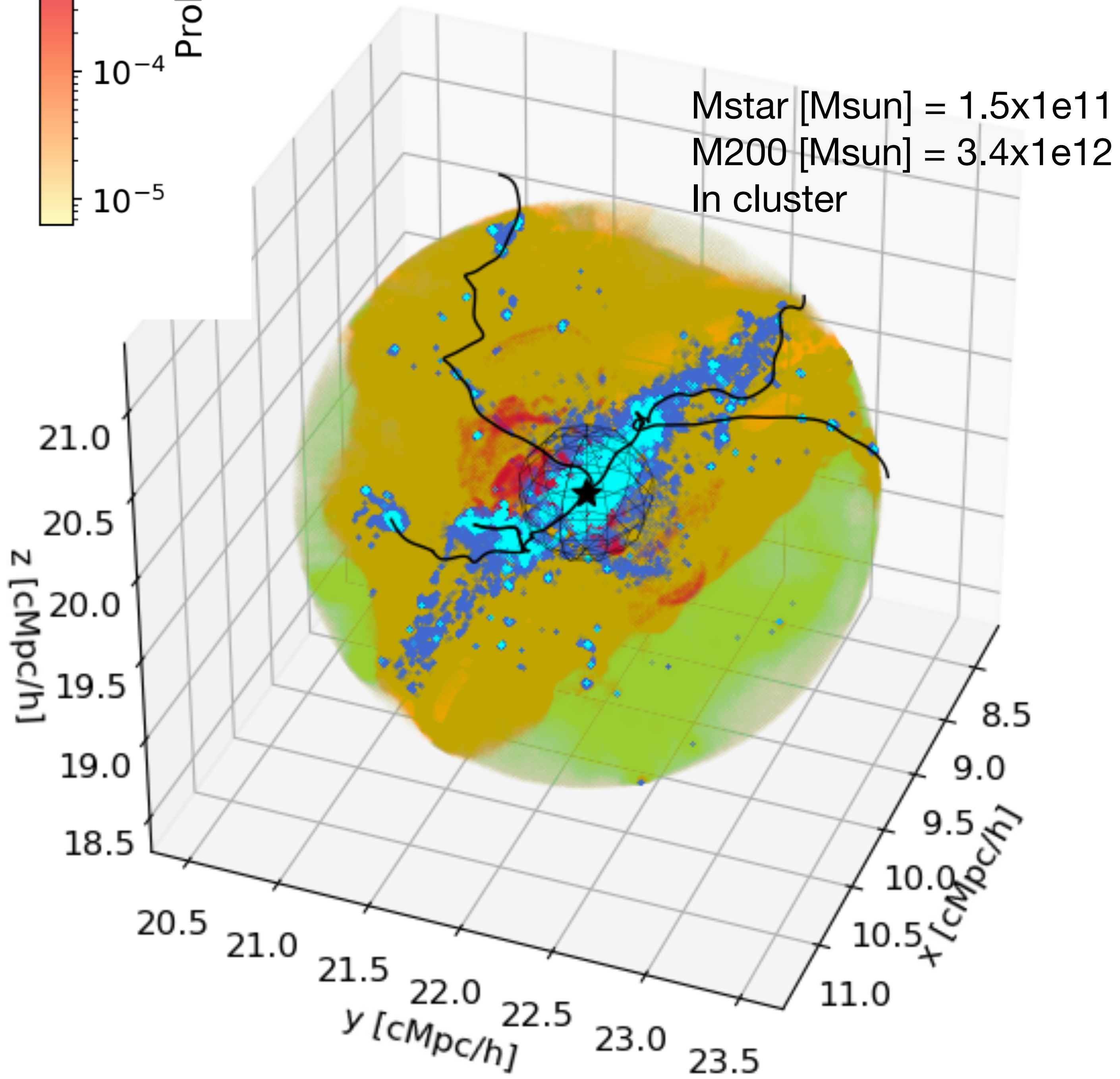
larger number of streams
=> more accretion of cold material (anisotropic accretion)
=> boost galaxy star-formation

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)**





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

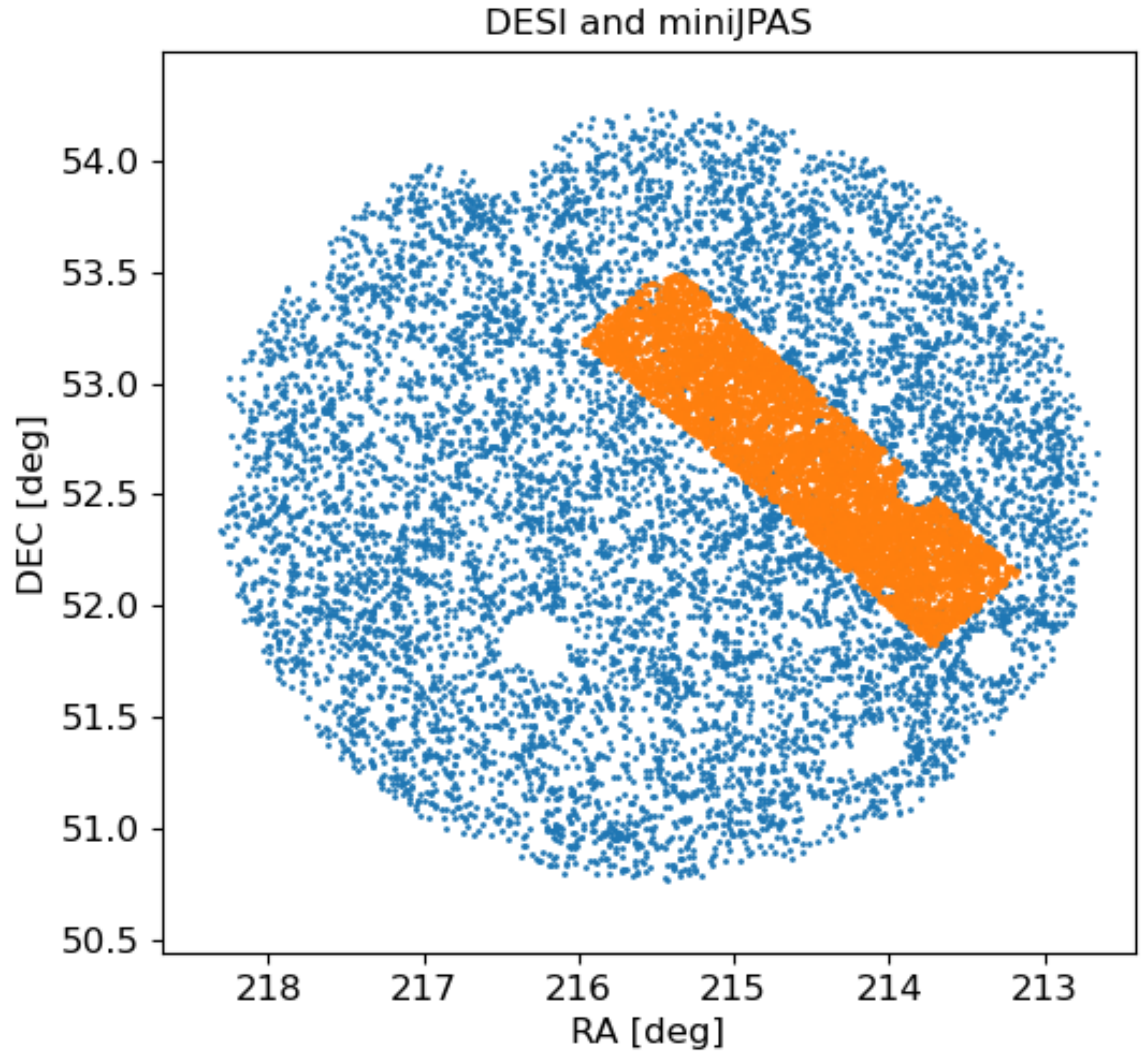
Can we observe this?

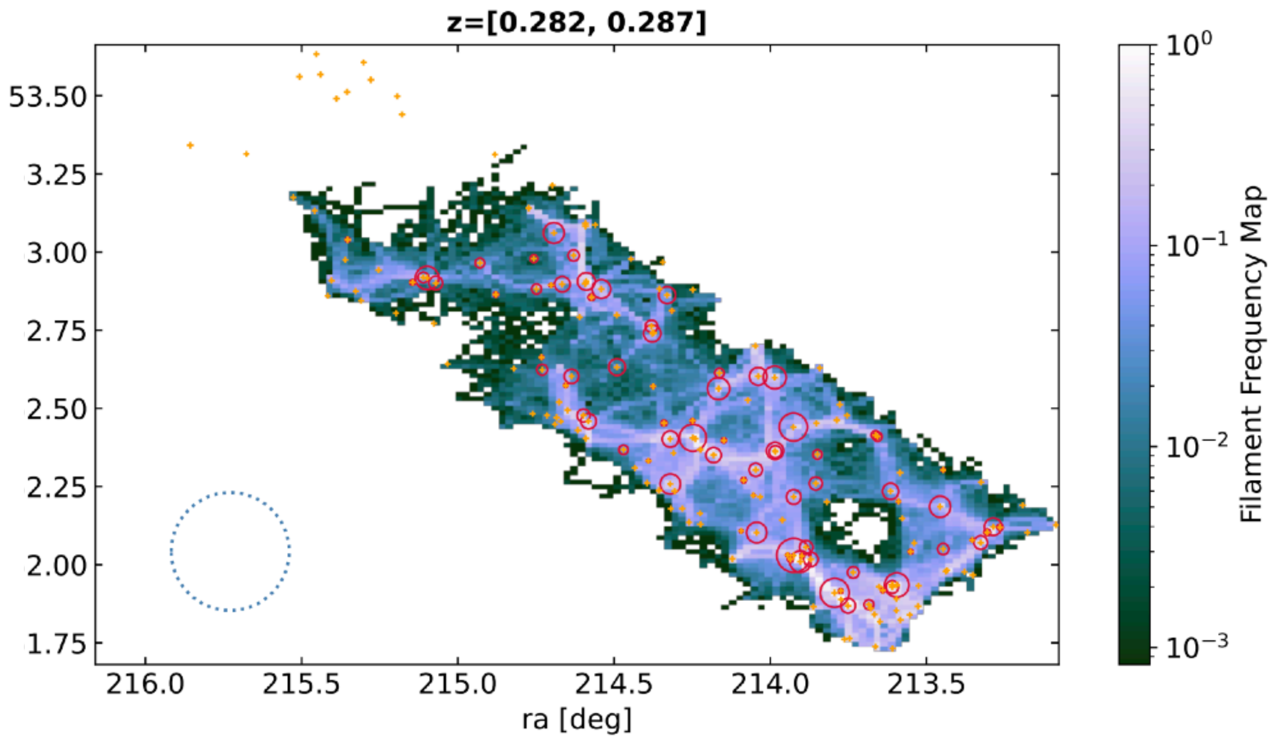
Galarraga-Espinosa et al. 2025 (submitted)

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]

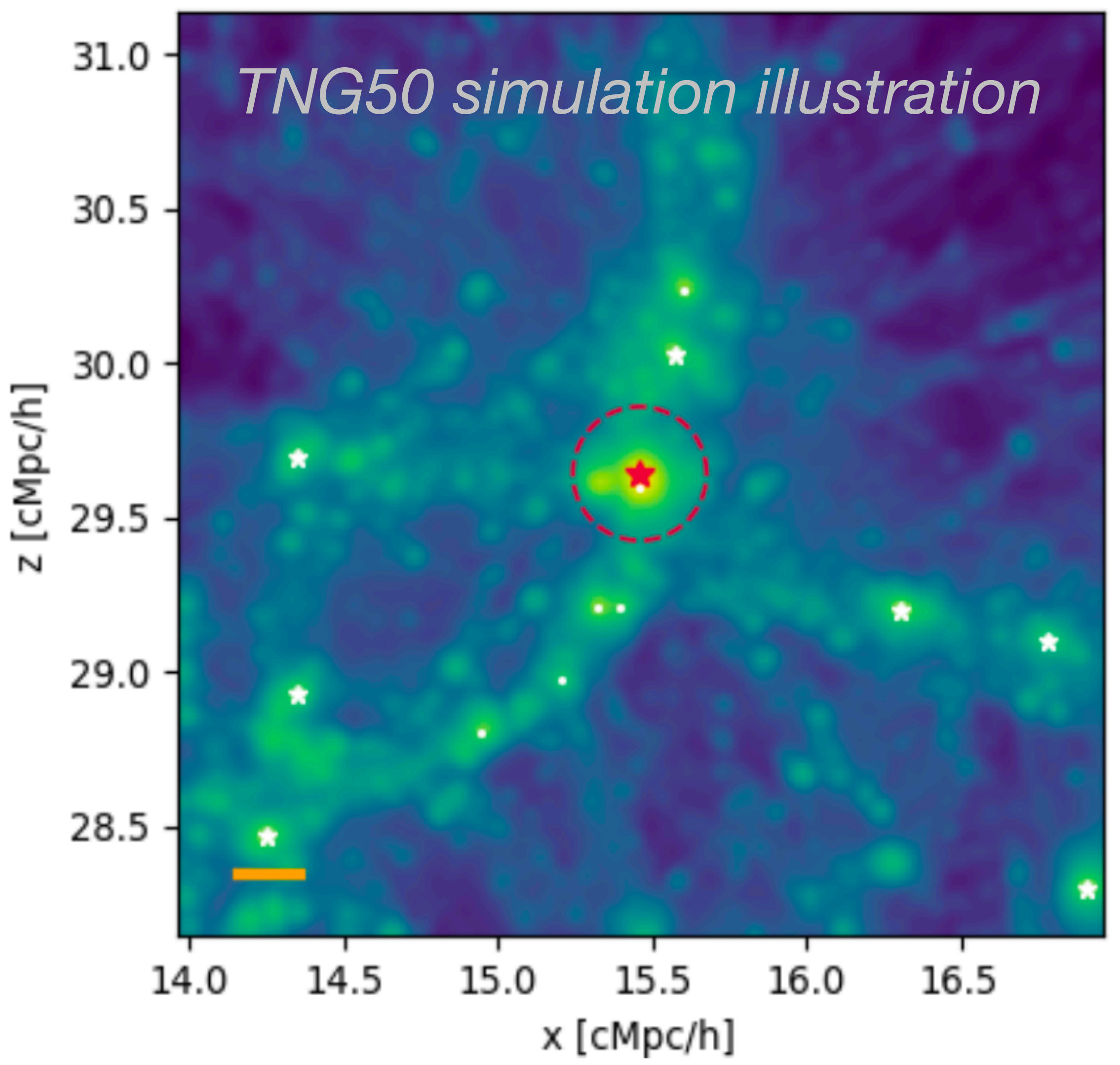
z<1





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

Idea: tracing the streams using galaxies



We need:

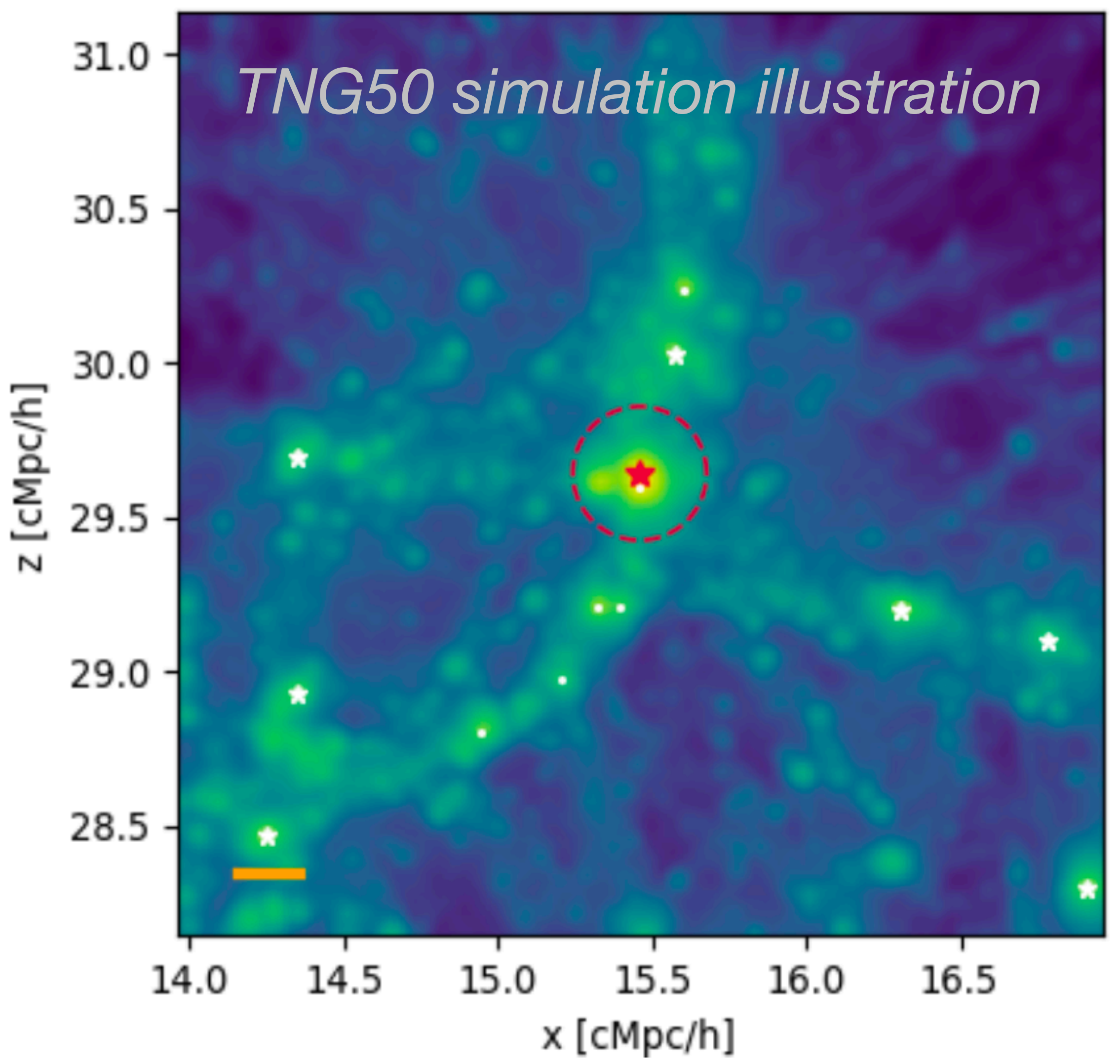
—> high number density of tracers!

—> faint sensitivities!

—> good redshift accuracy

Idea: tracing the streams using galaxies

Galarraga-Espinosa et al. 2025 (submitted)



We need:

—> high number density of tracers!

—> faint sensitivities!

—> good redshift accuracy

Good dataset =

JPAS survey (Bonoli+ 2021)'*spectrophotometric*' survey (56 ultra-narrow bands)

- Low resolution spectrum for each pixel on the sky
- No target selection, no fiber collision
- **Higher sampling** density and **fainter** objects wrt typical spectroscopic surveys.

+

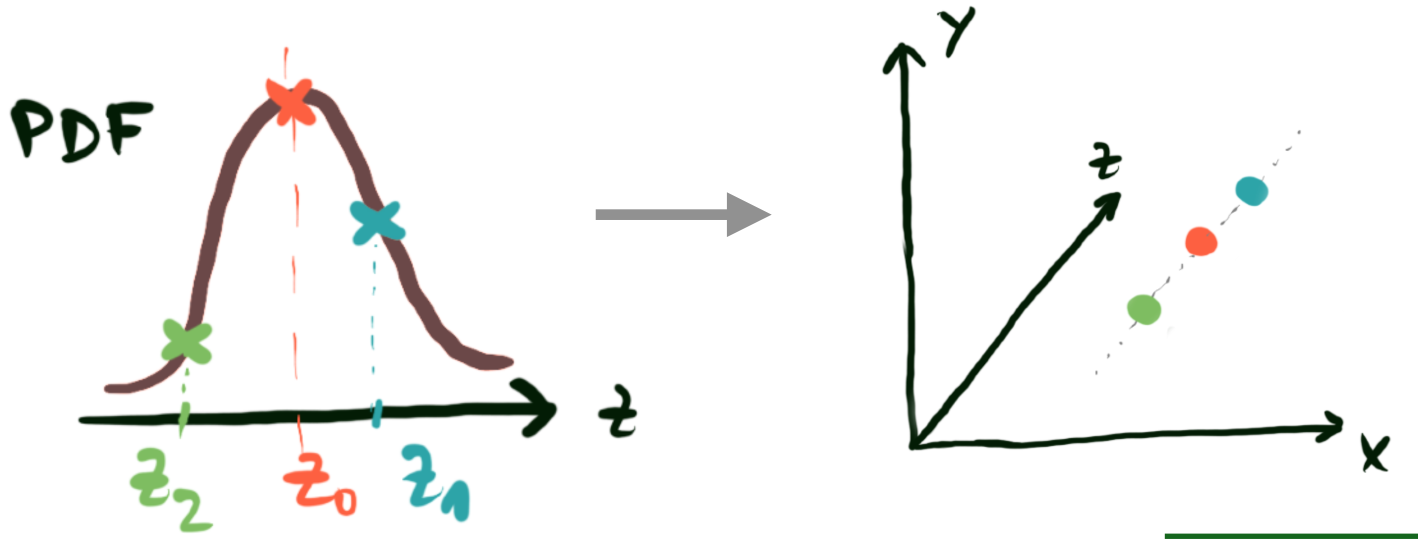
Boost the photo-z accuracy for some galaxies

DESI Bright Galaxy Survey (BGS) (Hahn+ 2022)

- Public VAC from early data release
- **Spectroscopic** redshifts (precision!)
- Only bright and massive objects

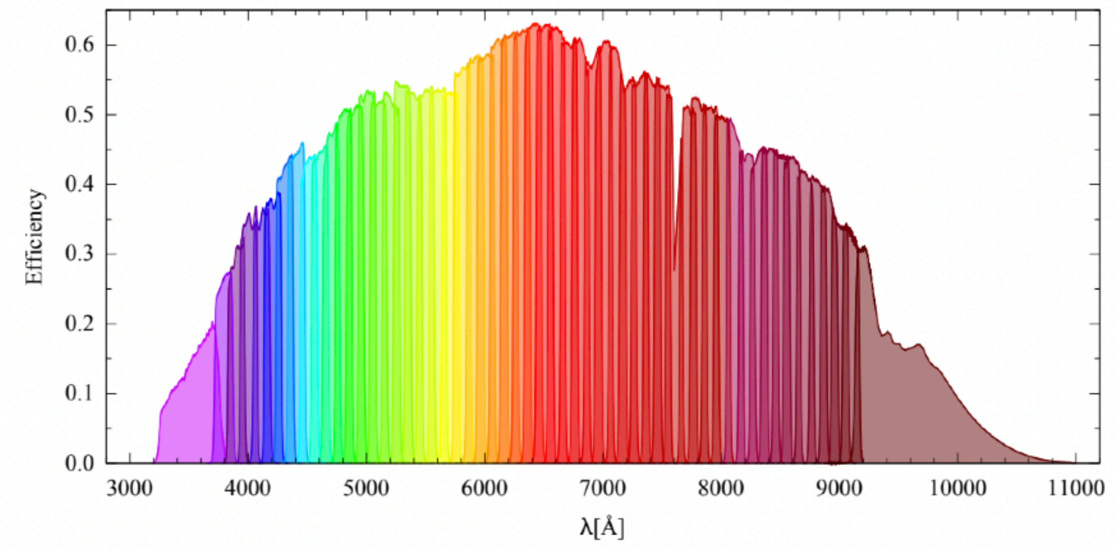
+

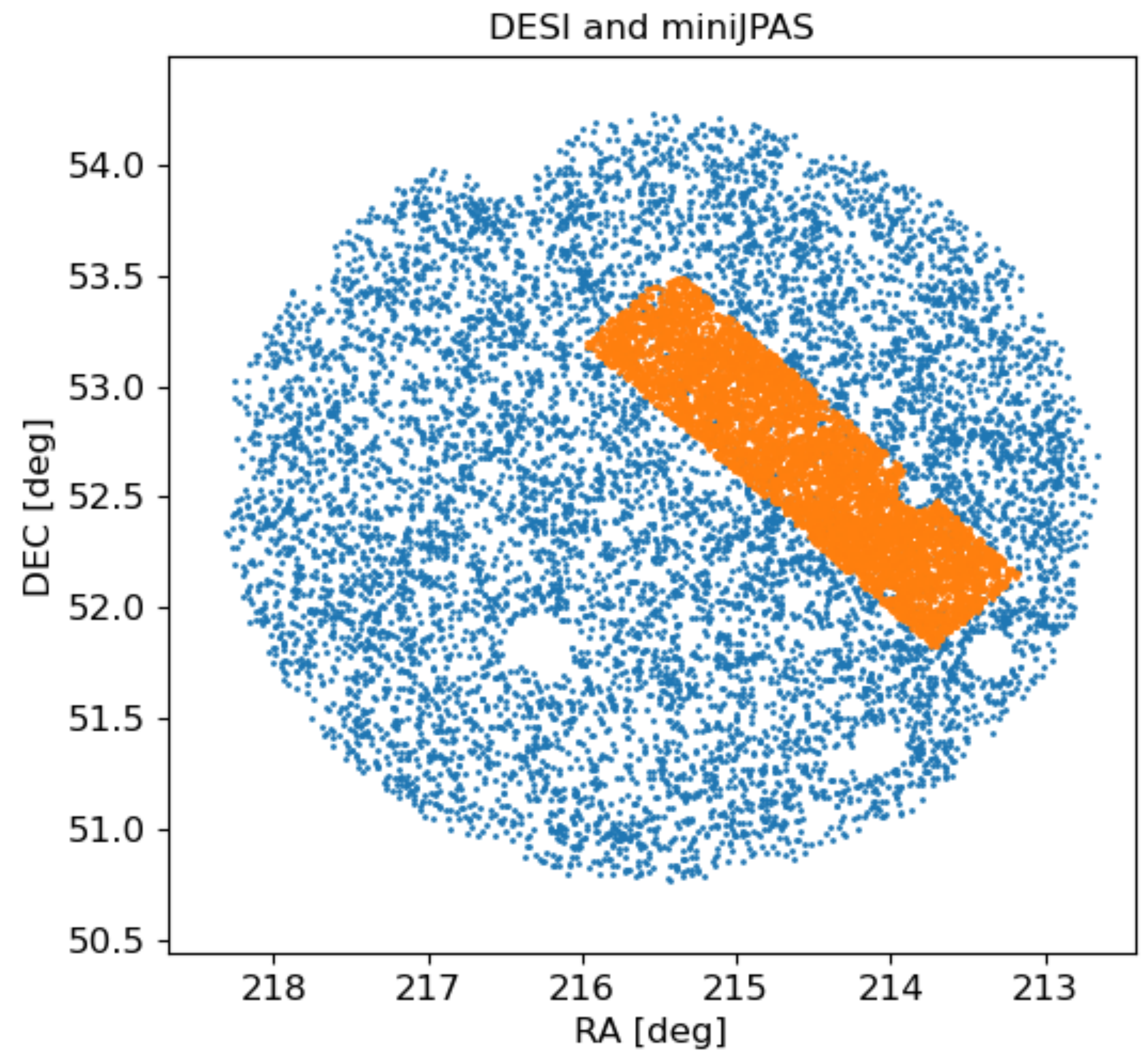
Method: **probabilistic filament detection**



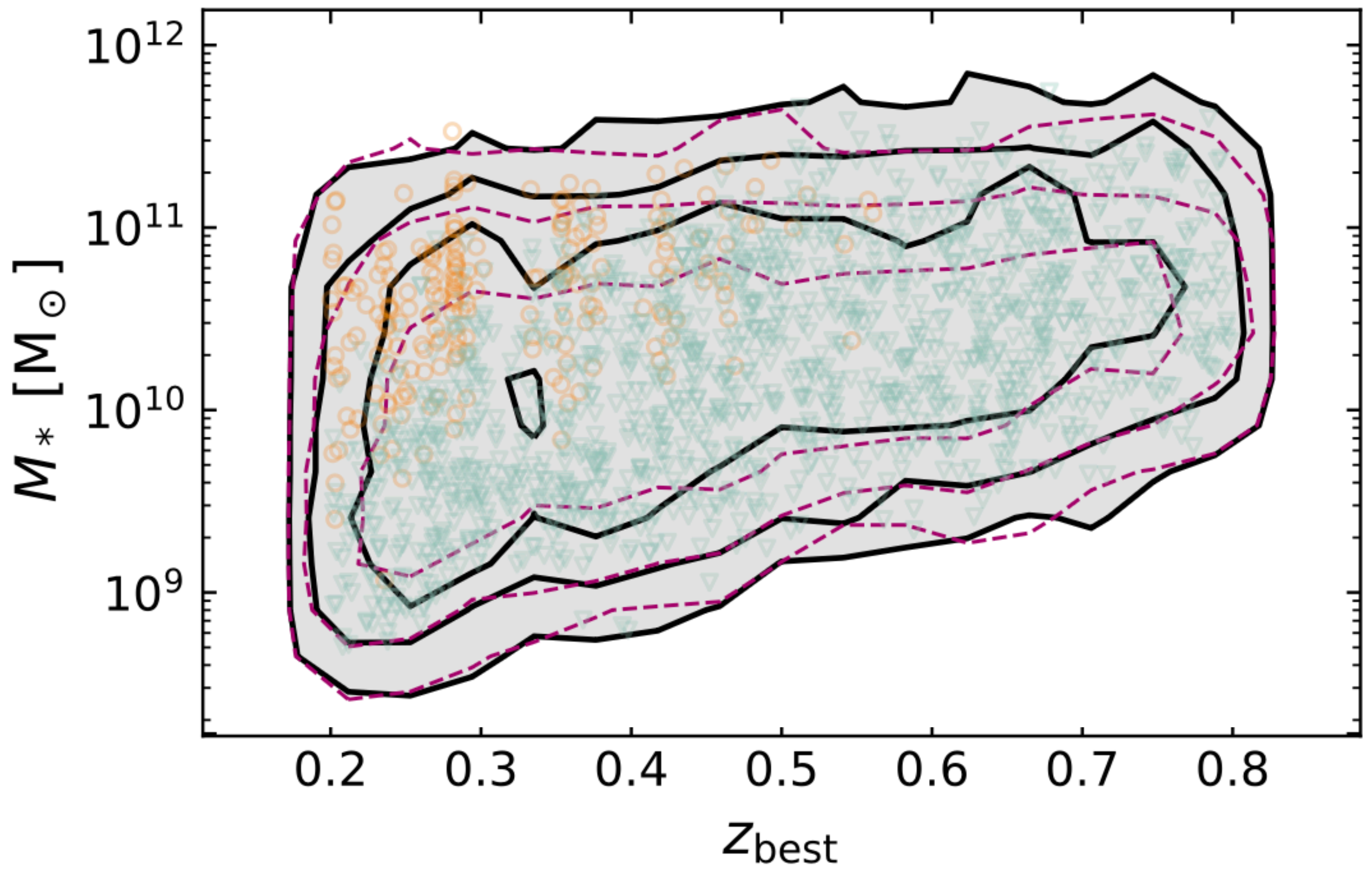
200 Monte-Carlo realisations of galaxy distributions by sampling under the PDF(z) + find filaments in each random realisation

JPAS bands (56)



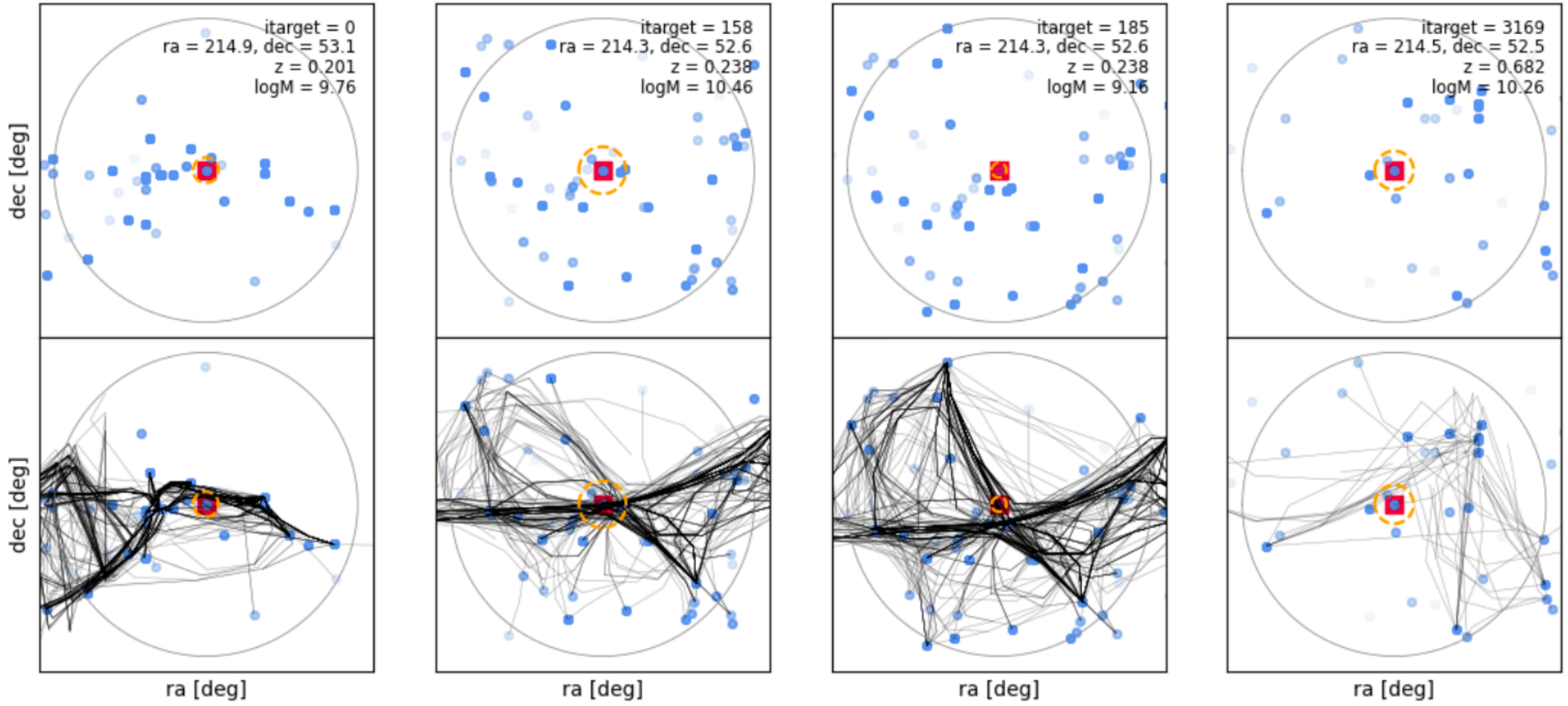


Revealing the web around galaxies



JPAS+DESI catalogue:

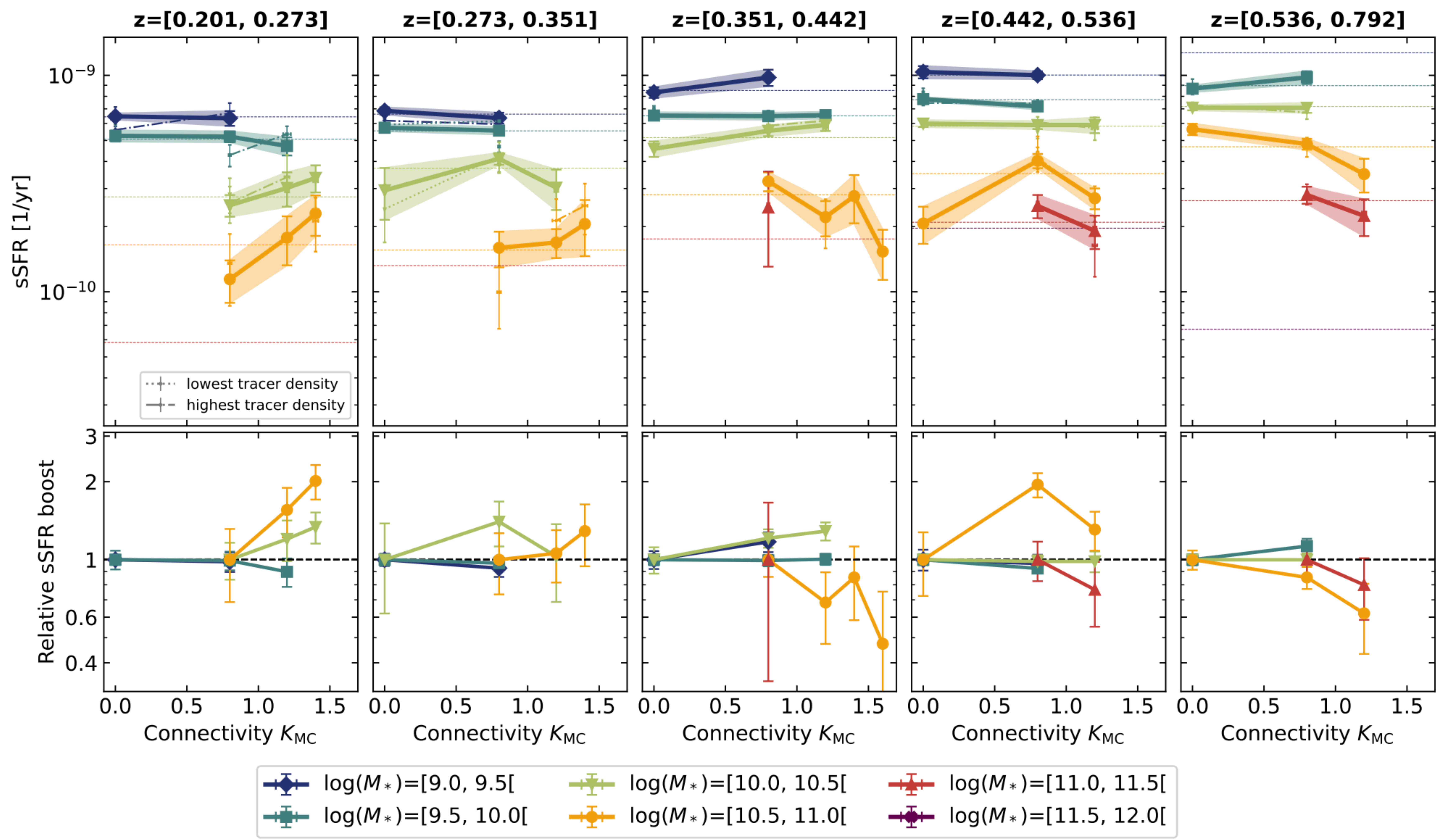
- z=[0.2, 0.8]
- Target galaxies: Mstar > 1e9 Msun
- Tracer galaxies: all galaxies in the 3 pMpc environments



+ Validation using mocks!
(Built using lightcone + random forest classifier + z_err modelling)

Galarraga-Espinosa et al. 2025 (submitted)

Impact on galaxy sSFR?



MW-mass galaxies:

- sSFR boosted with higher K (>2x)
- Higher connectivity —> more channels for gas inflows

Higher masses:

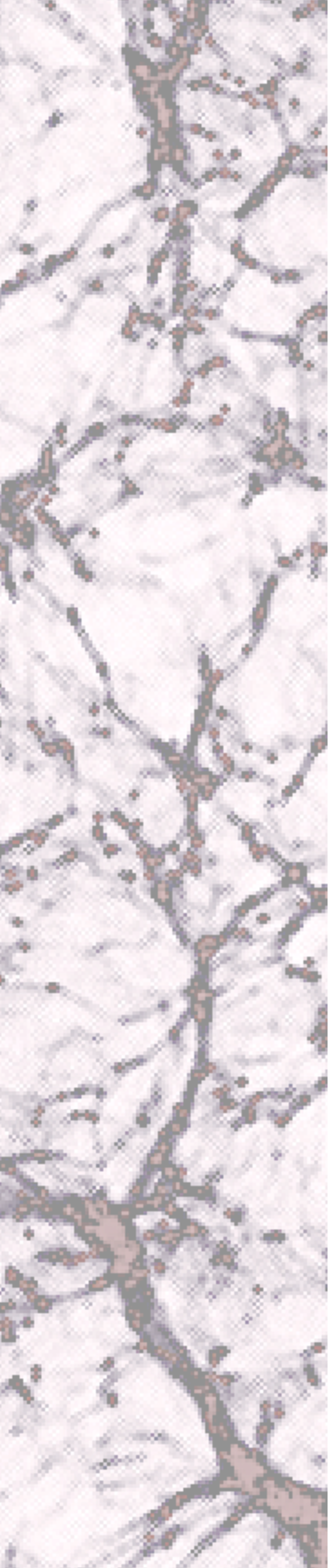
- BCG mass scale
- Cluster physics probably dominate the SF activity, independent from K.
- Connection to warm, large-scale filaments? (not helpful for SF)

Lowest masses:

- Caution: galaxy bias *(Kaiser 1984)* makes it hard to accurately trace the local density

Galarraga-Espinosa et al. 2025 (submitted)

Conclusions



Part I: cosmic filaments are not all the same

Different populations in:

- Distribution of galaxies
- Densities of matter
- Location in the cosmic web
- Gas properties (T, P, n_e, Z)
- Distribution of gas phases (hot, WHIM, diffuse, …)
- Differences detected up to z=4

Short	Long
Puffy	Thin
Denser	**Less dense**
Higher T and P	**Lower T and P**
Tracers of **over-dense regions**	Tracers of **less-dense regions**
Correspond to **bridges of matter** between over-dense structures	Correspond to the **cosmic filaments** (i.e. those at the intersection between cosmic walls)
Tend to **contract**	Tend to **expand**

Galárraga-Espinosa+ 2020, 2021, 2022, 2024

Main collaborators: Nabila Aghanim (IAS-France), Mathieu Langer (IAS-France), Céline Gouin (IAP-France), Volker Springel, Simon White, (MPA-Germany), Corentin Cadiou (Lund University), Hideki Tanimura (ex IPMU-Tokyo), Daisuke Nagai (Yale), Nir Mandelker, Isabel Medlock (Yale)

A lot of work theoretical work in progress:

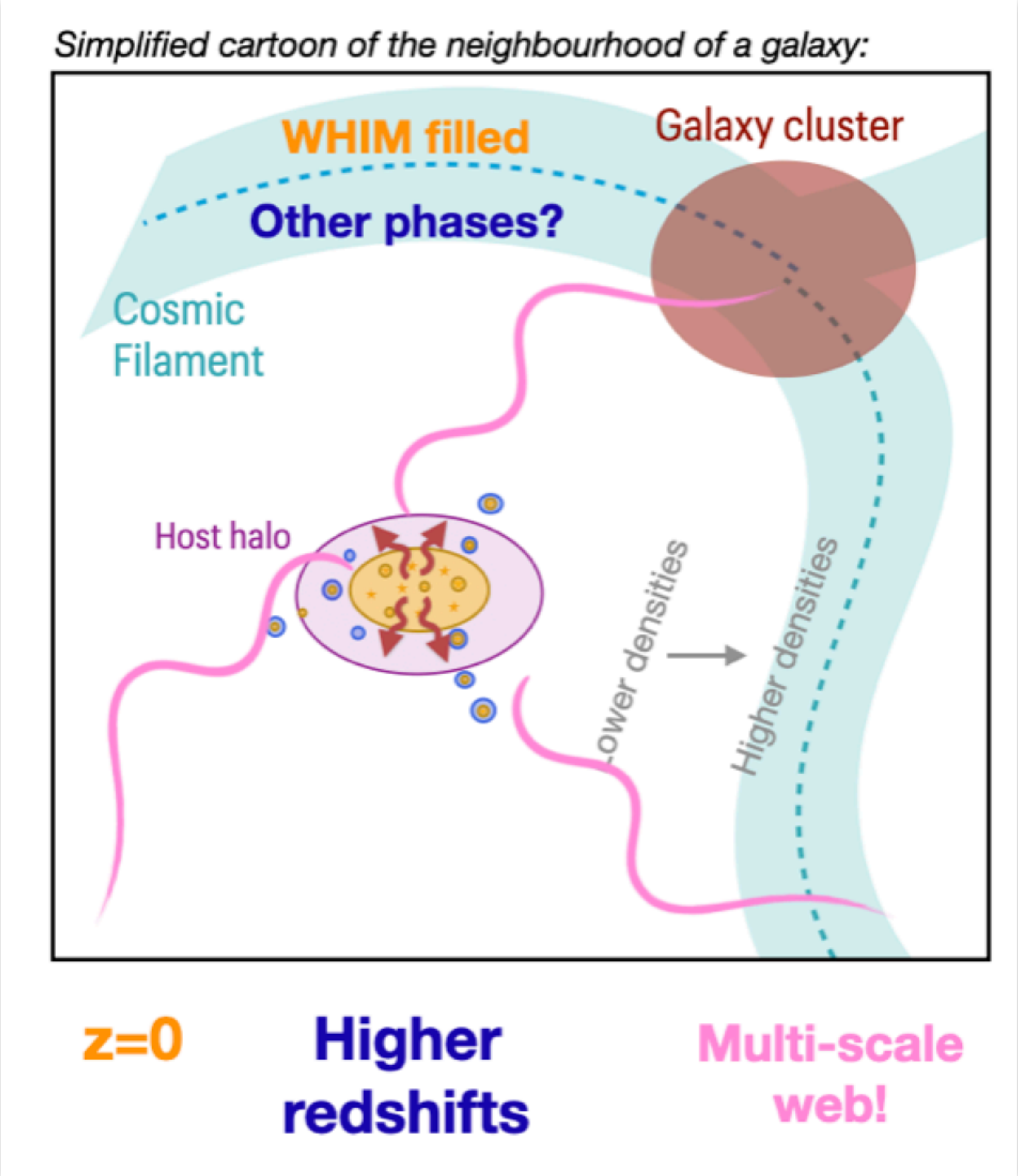
- Filament characterisation: from fundamental theory, to analytical modelling, to observables.
- Which observables for spectroscopic surveys (PFS, DESI, …)?
- Filament properties & statistics: how to best use them as a cosmological probe?

Part II: galaxies in the multi-scale web

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
  - 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

Daniela Galárraga-Espinosa, Kavli-IPMU 33