Berkeley
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MAX PLANCK INSTITUTE
FOR ASTROPHYSICS

Filaments
from the large-scale structure to the CGM

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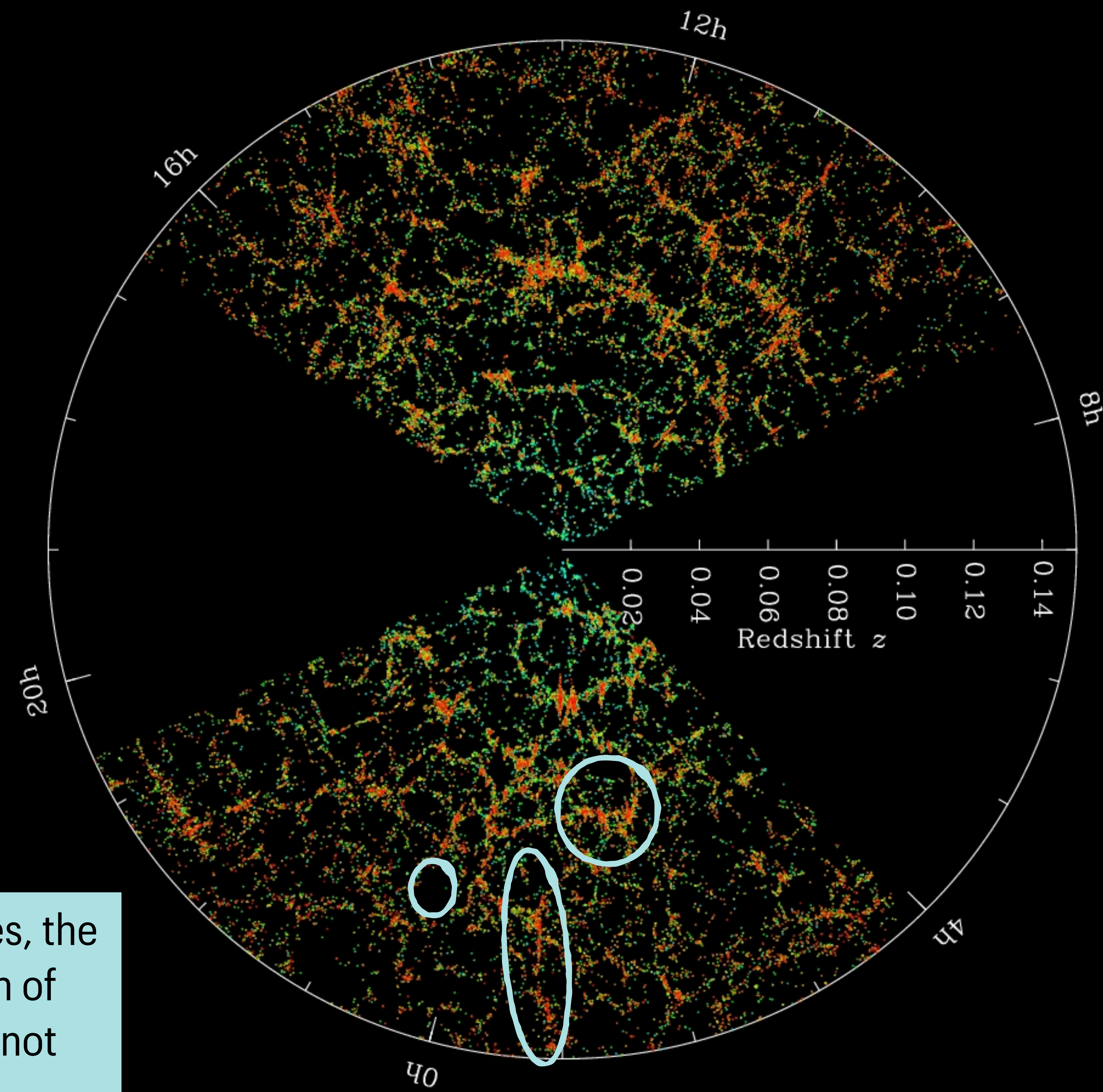
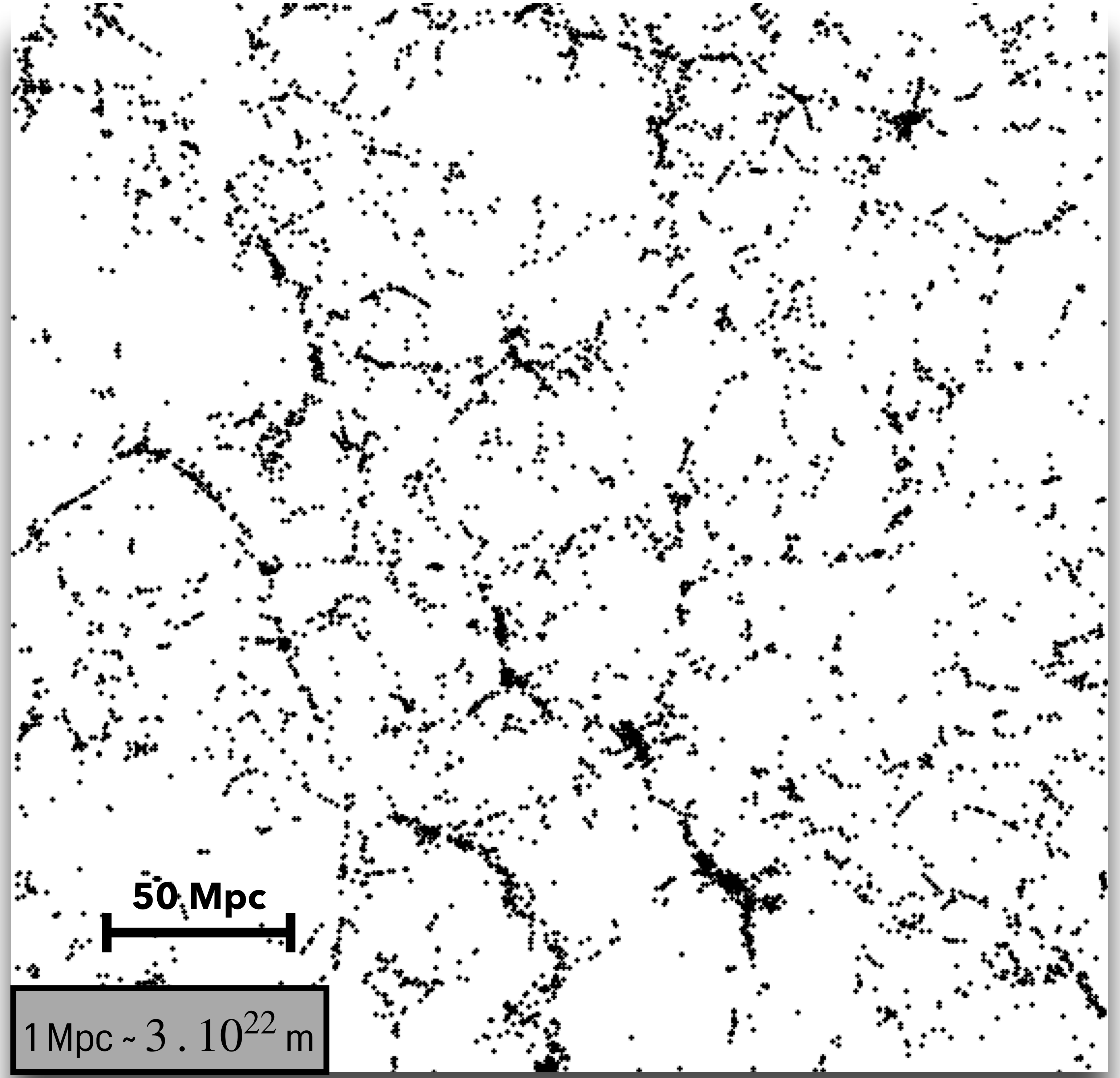


At large scales, the distribution of galaxies is not uniform

Credit: M. Blanton and the Sloan Digital Sky Survey.

The Cosmic Web

As reproduced by the IllustrisTNG (Nelson+ 2019, Pillepich+ 2019) numerical **simulation**:



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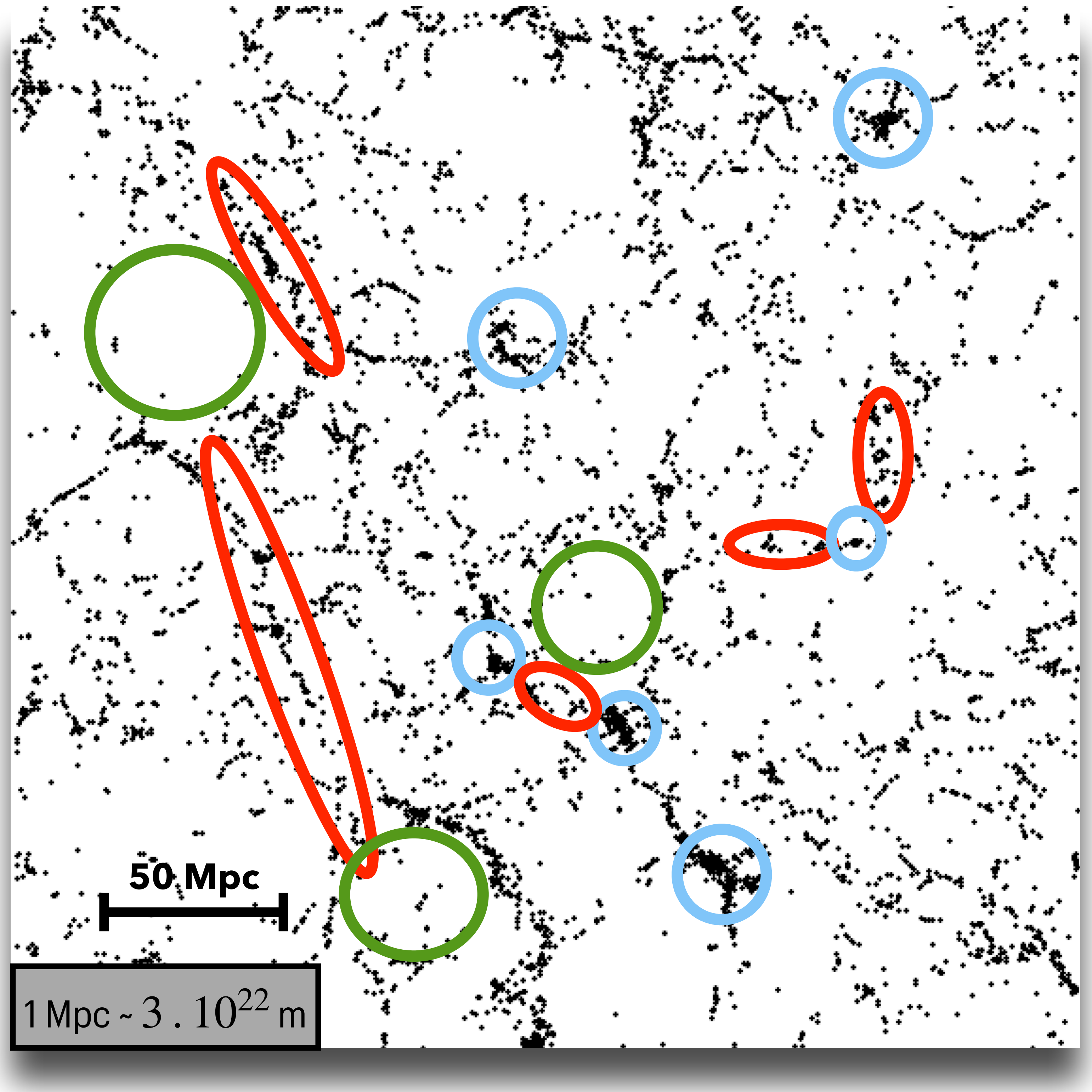
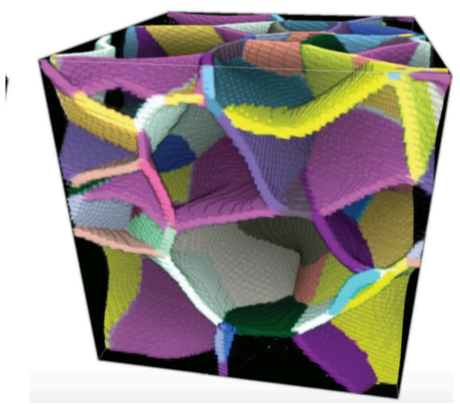




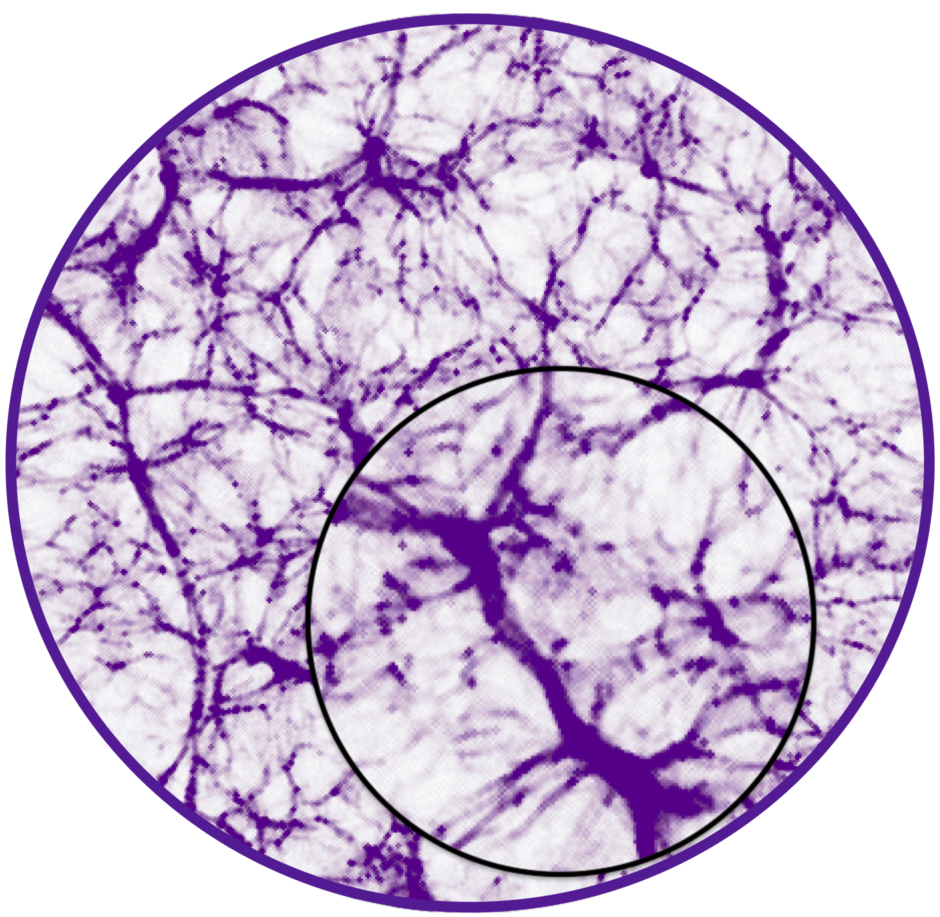
Sousbie 2011

The Components of the Cosmic Web

According to the Λ-CDM model:

Dark Matter

Forms the cosmic skeleton

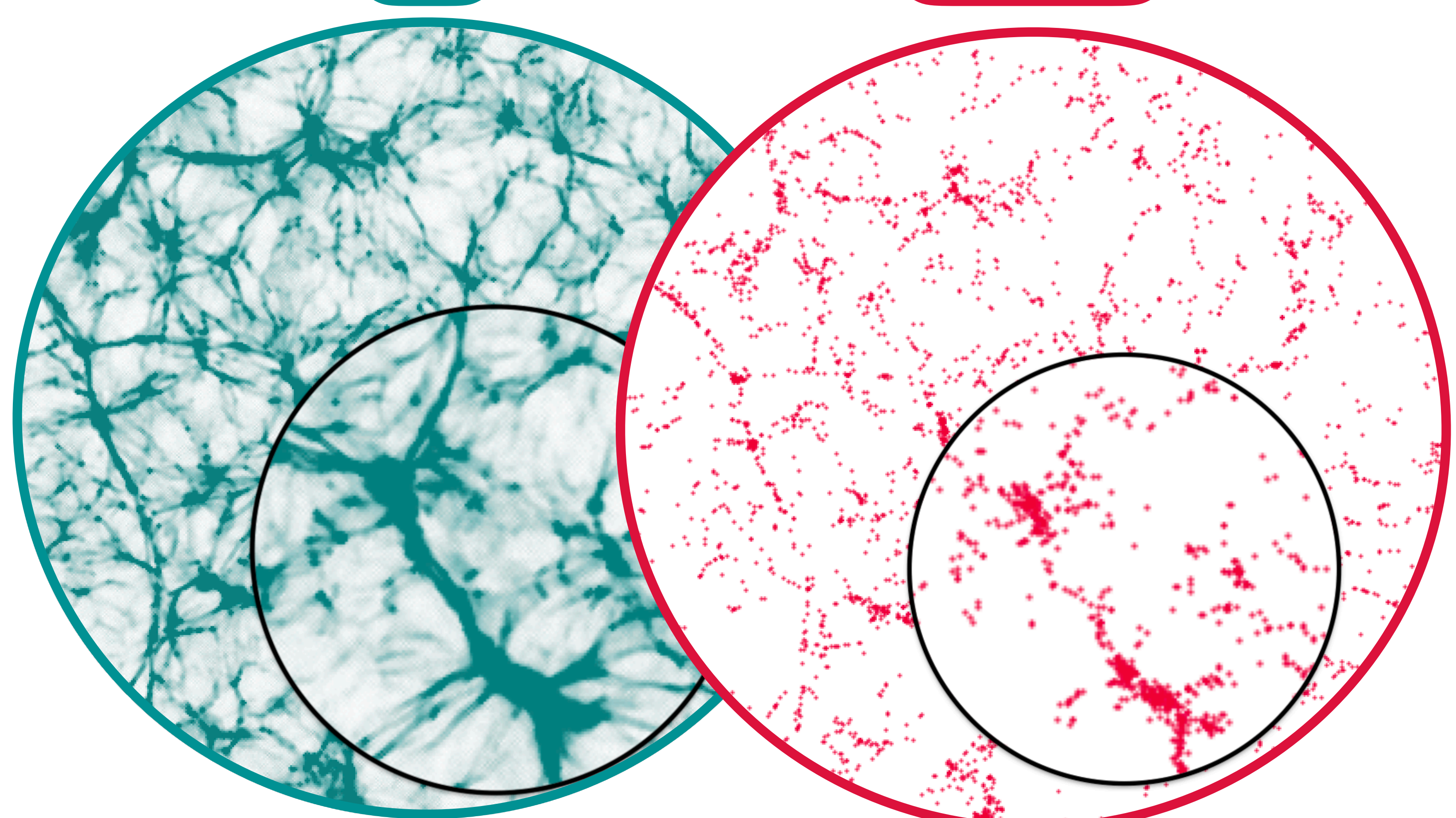


Baryons

Follow the DM skeleton

Gas

Galaxies



Biased tracers of the matter distribution

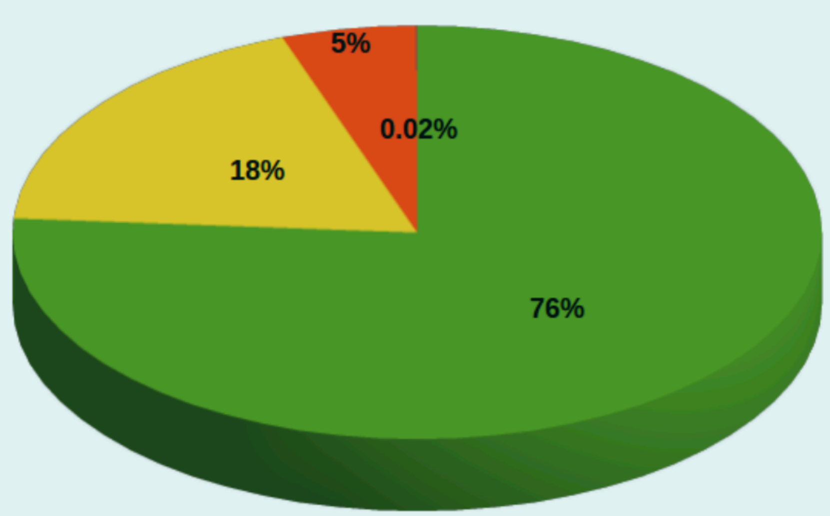
Data from TNG300-1 simulation

Matter in the Cosmic Web

Studies in numerical simulations:

At z=0:

Volume fraction



Ganeshaiah Veena+ 2019

Filaments occupy **only 5%** of the total cosmic volume

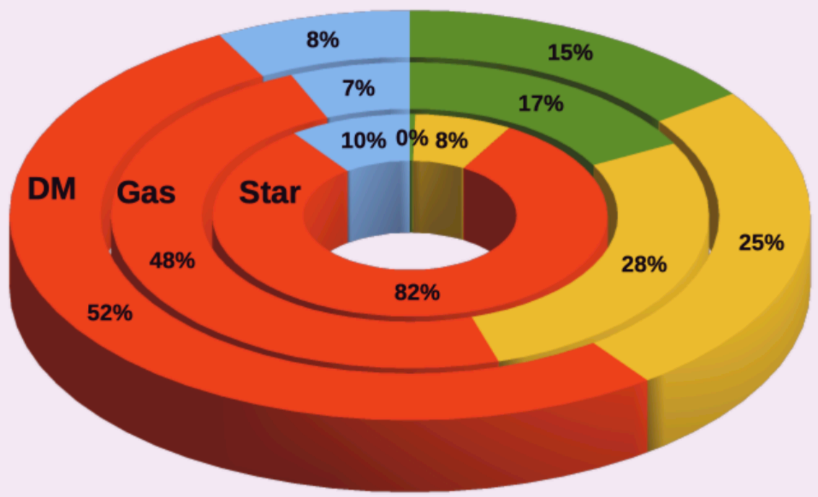
Nodes

Filaments

Walls

Voids

Mass fraction



Ganeshaiah Veena+ 2019

~ 50% of the mass of the Universe is today contained in cosmic **filaments**

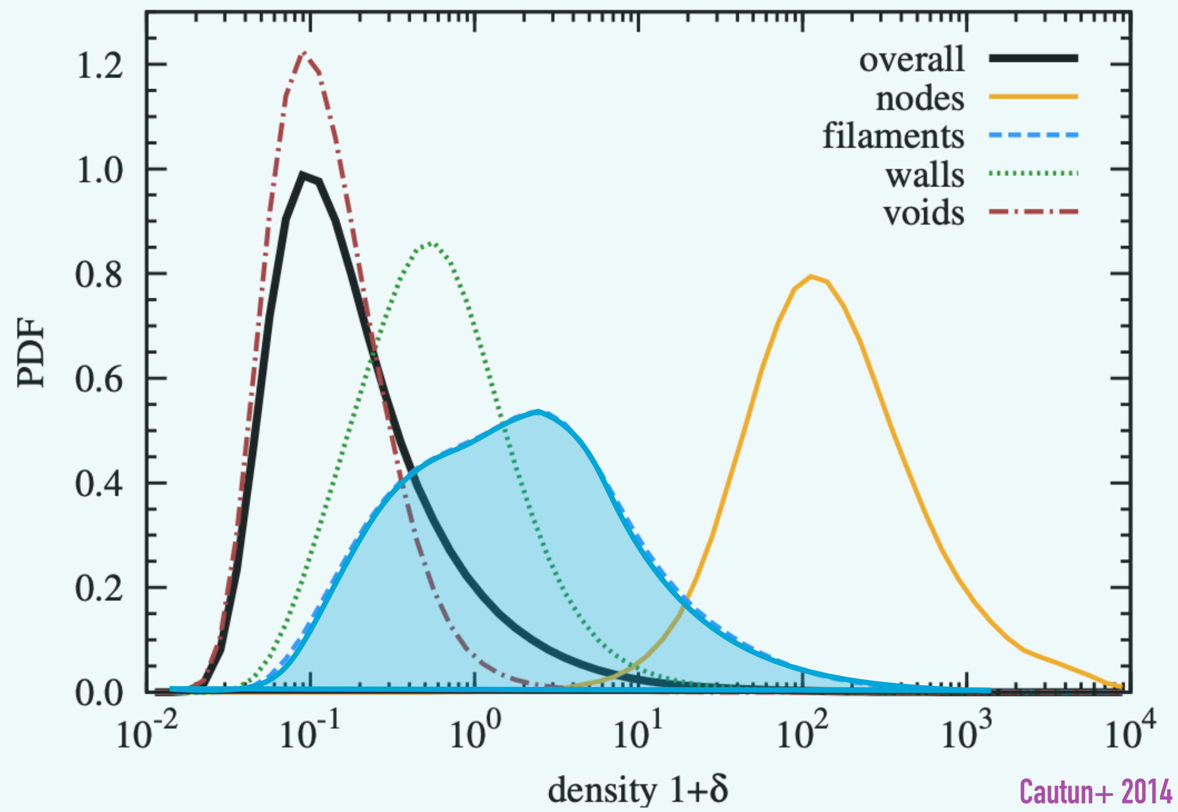
The study of matter at the largest scales is inevitably tied to that of filaments

Matter in the Cosmic Web

Studies in numerical simulations:

At z=0:

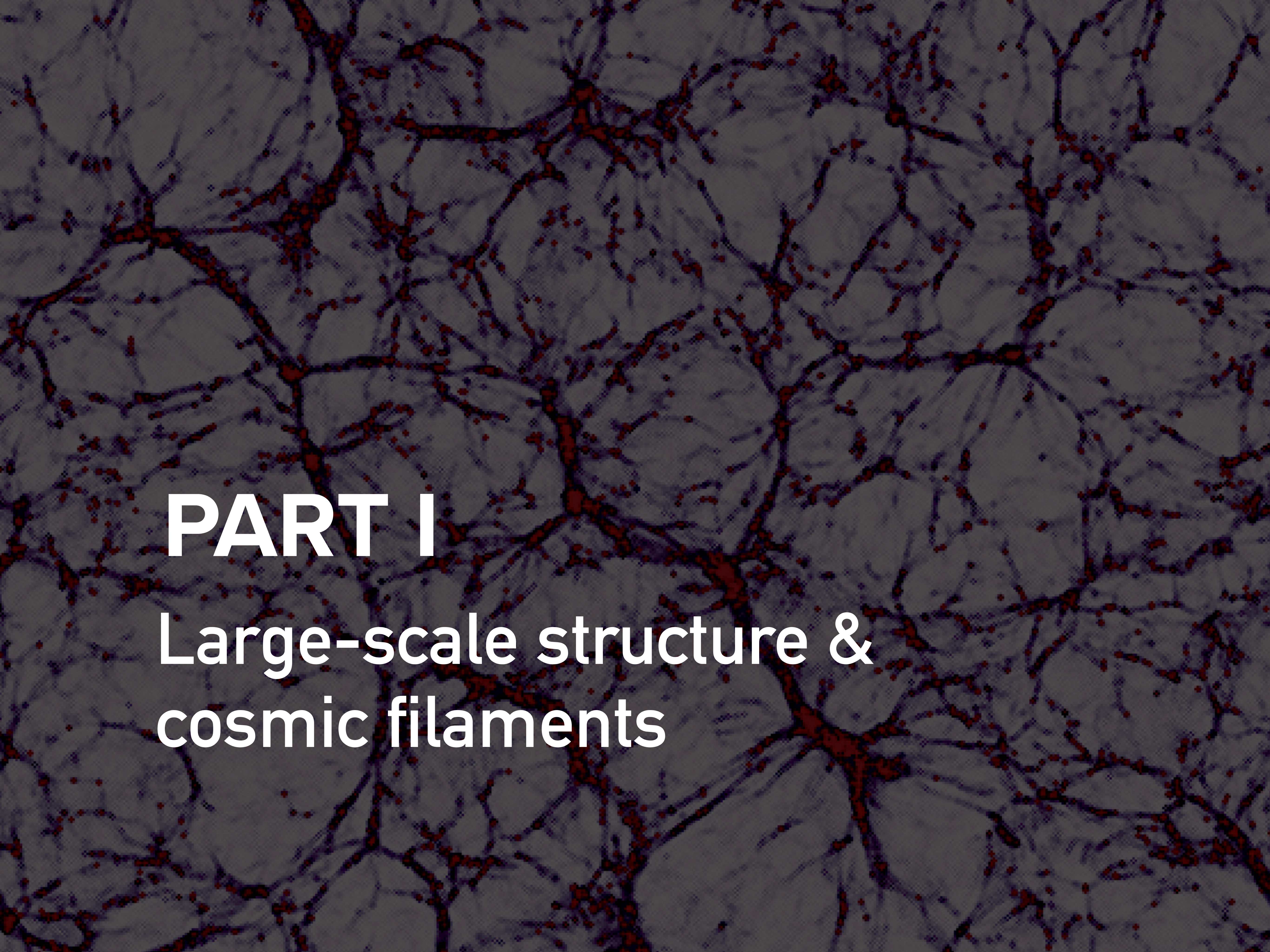
Density distribution



Huge diversity of filaments
(spanning 5 orders of magnitude in density!)

➡ **Are all filaments the same type of structure?**

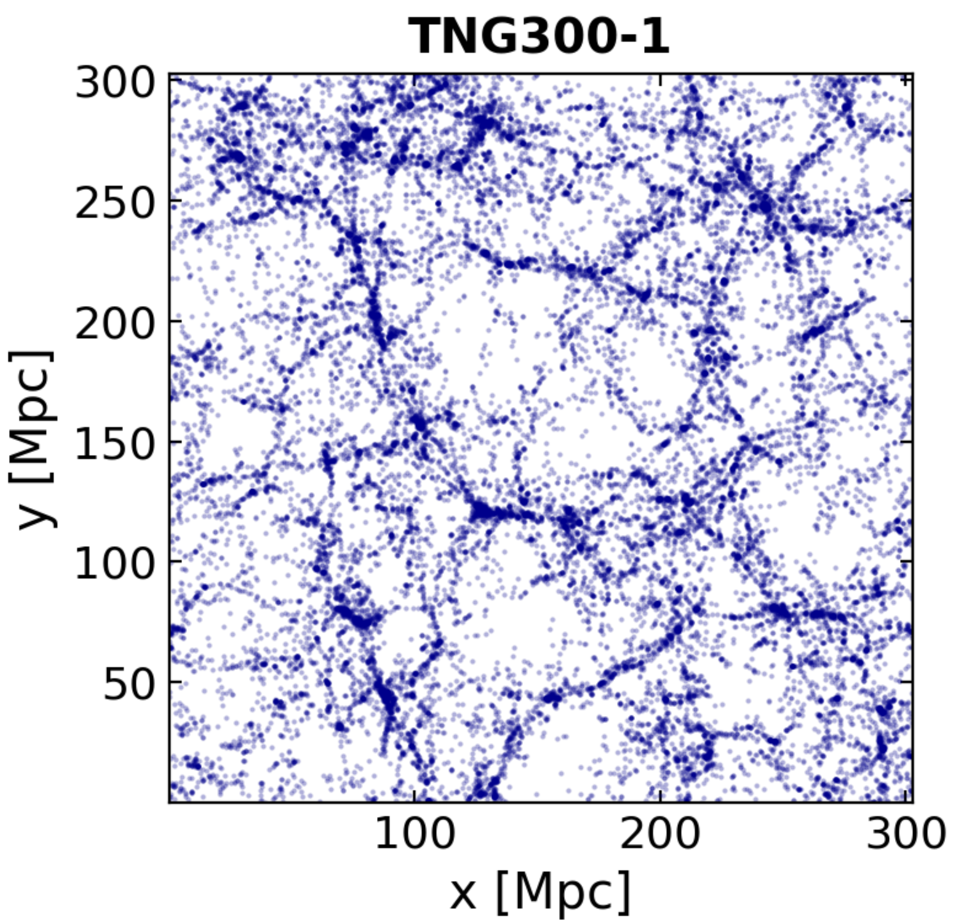
➡ **What are the imprints on the properties of matter? (e.g. gas observables)**



PART I

Large-scale structure & cosmic filaments

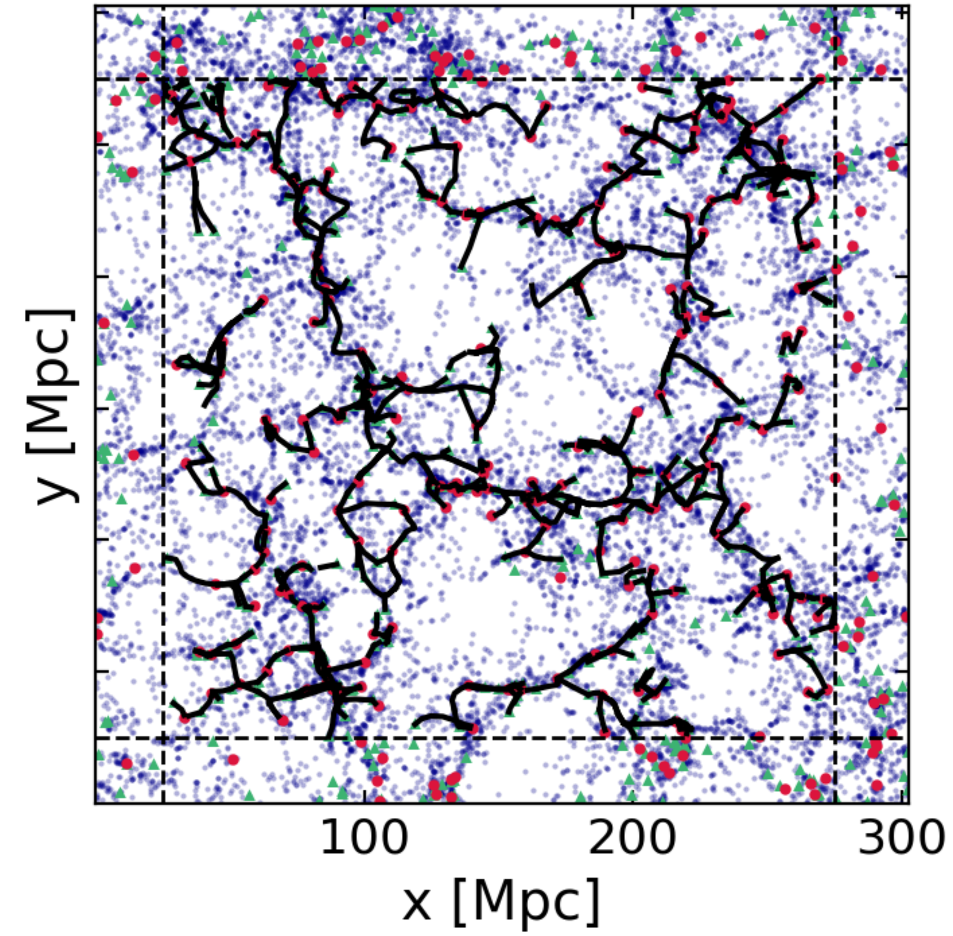
Detecting cosmic filaments



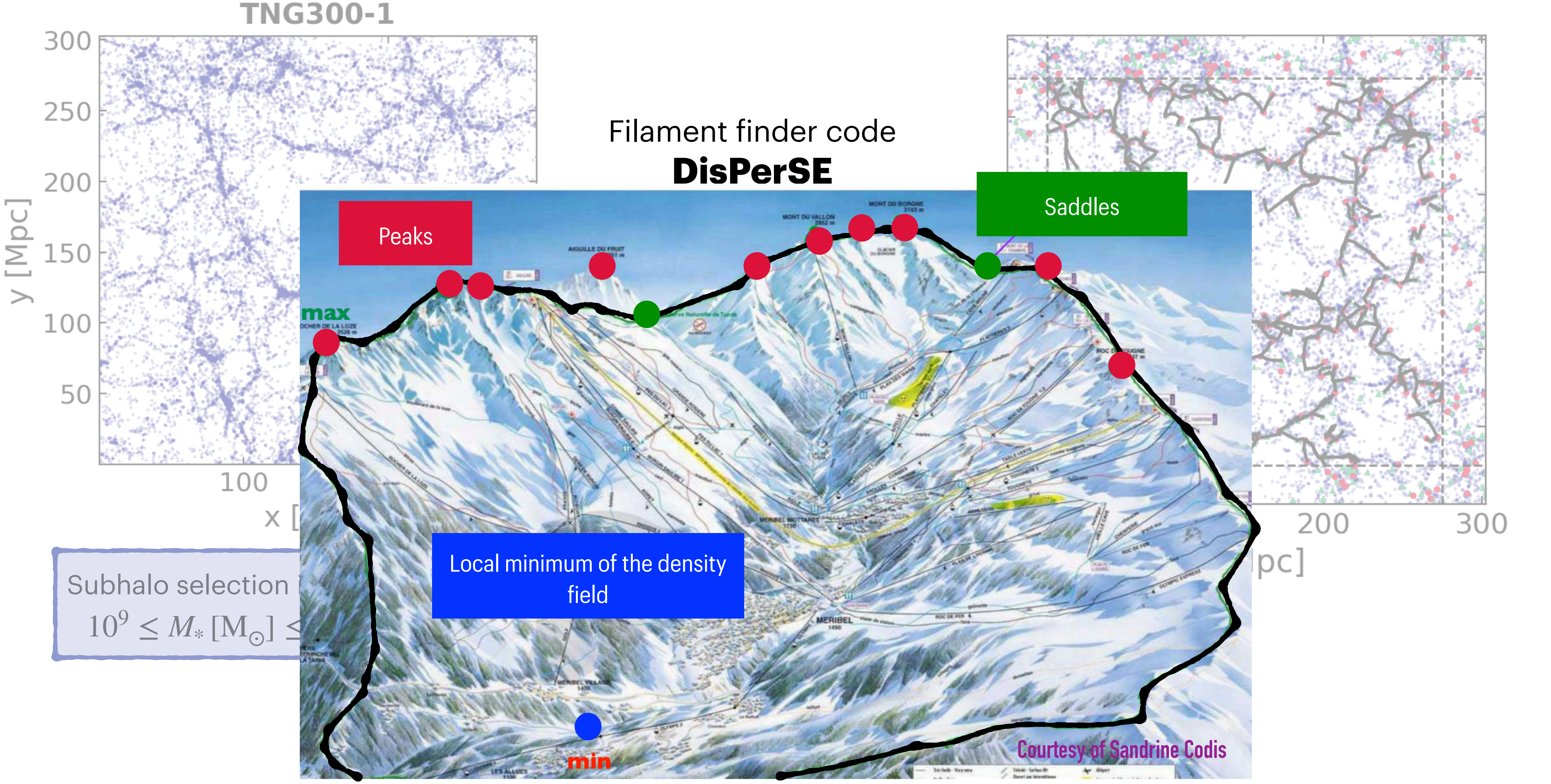
Subhalo selection in mass
$10^9 \leq M_* \, [\mathrm{M}_\odot] \leq 10^{12}$

Filament finder code
DisPerSE

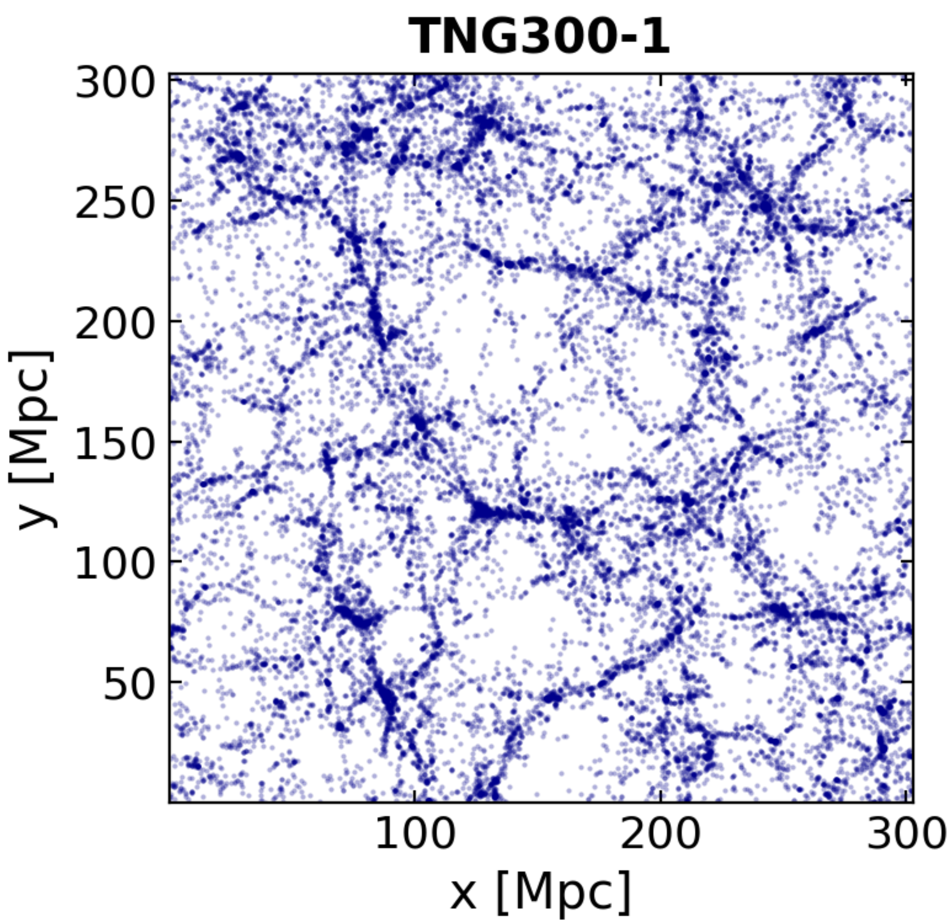
(Sousbie+ 2011, Sousbie 2011)



Detecting cosmic filaments



Detecting cosmic filaments



Filament finder code
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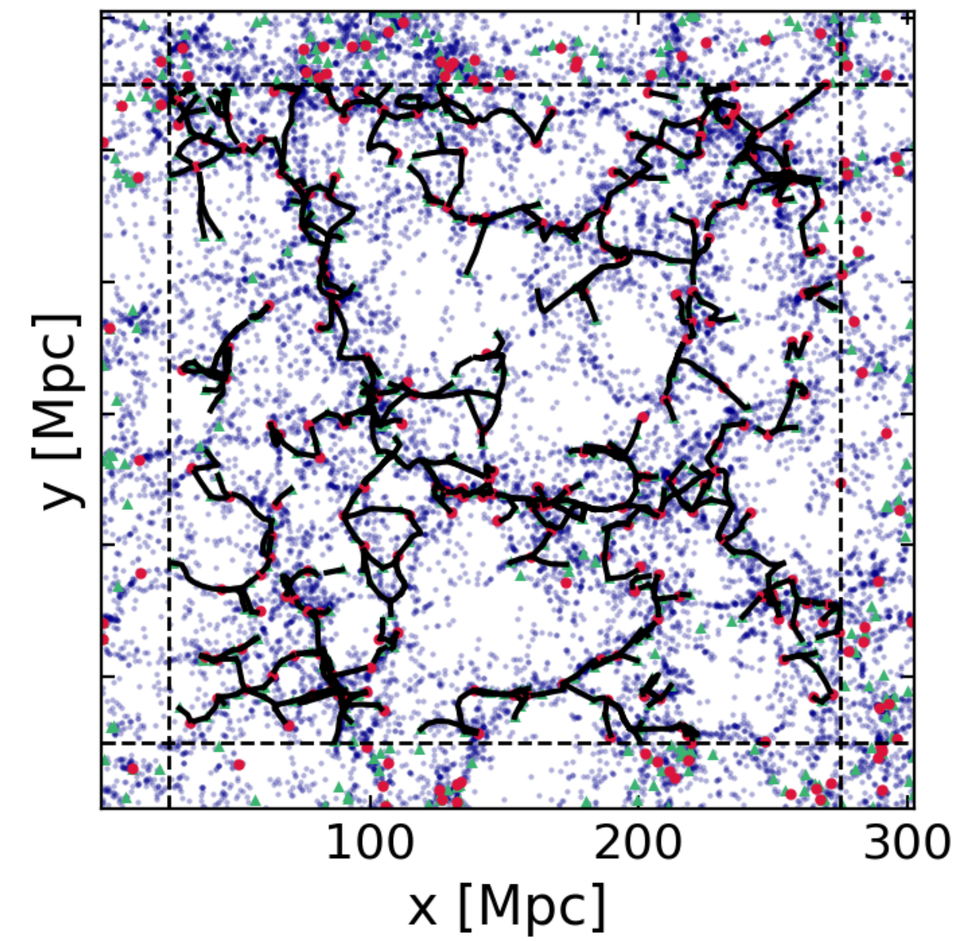
(Sousbie+ 2011, Sousbie 2011)



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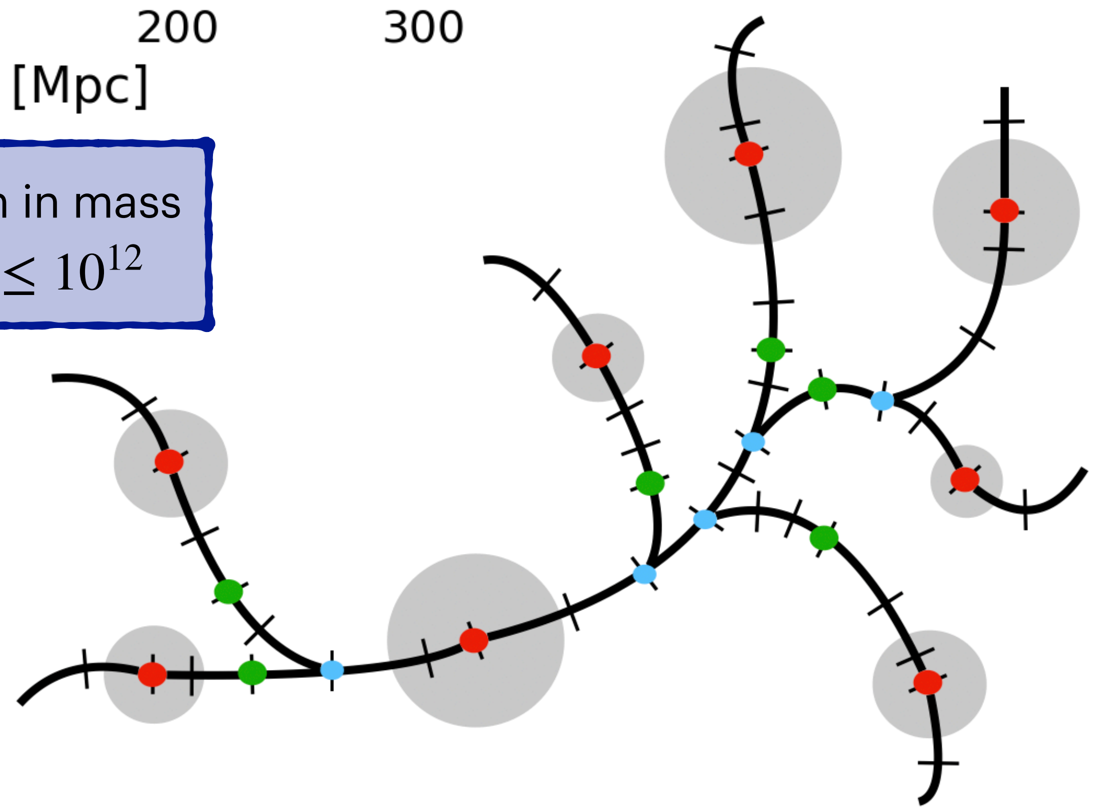


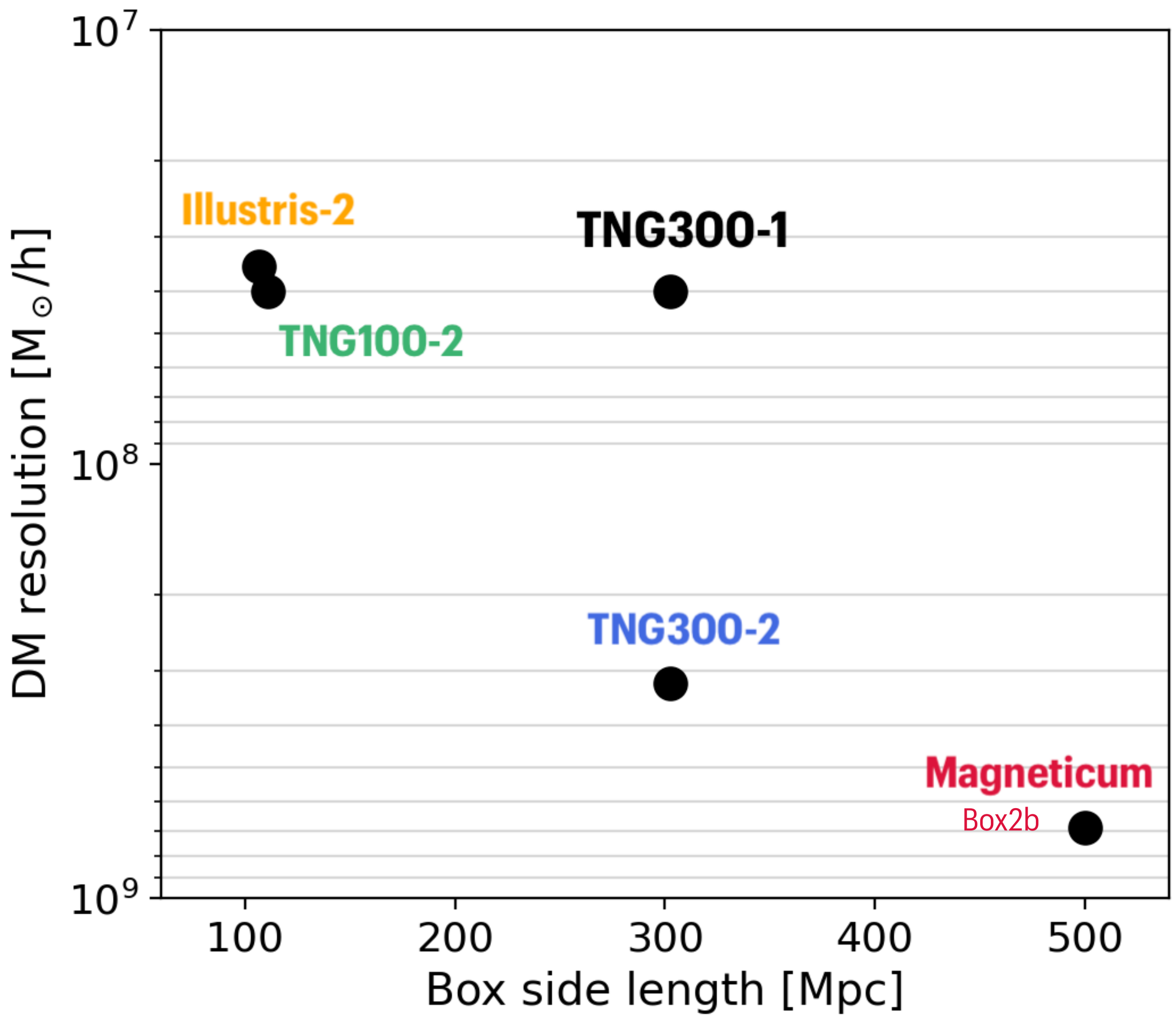
Filaments = sets of segments connecting **maximum density** critical points (CPmax) to **saddles**

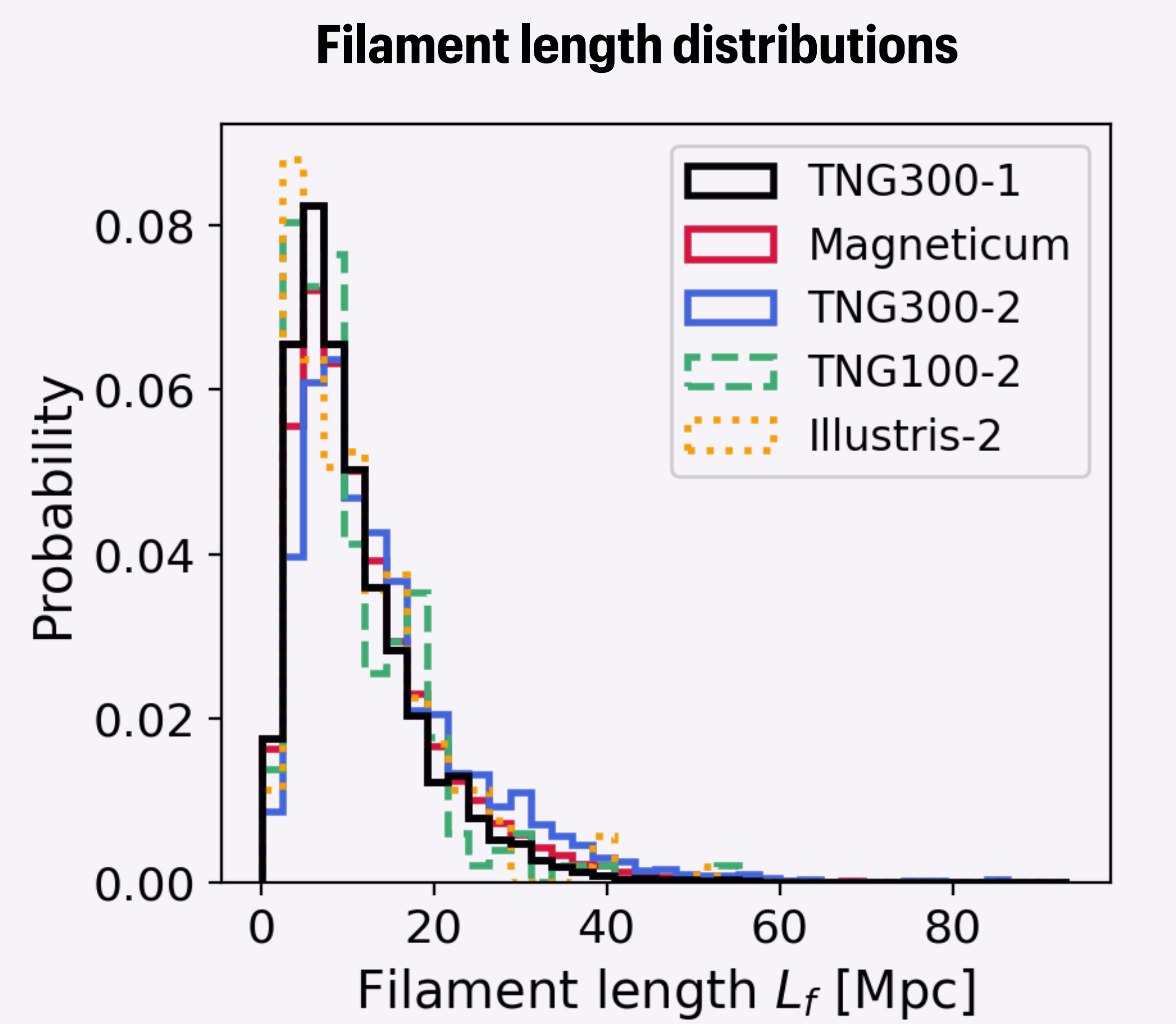
Galarraga-Espinosa+ 2020

Filament catalogues

Analysis of five different publicly available simulations at z=0:

- **TNG300-1** Nelson+ 2019, Pillepich+ 2019
- TNG300-2
- TNG100-2
- Illustris-2 Genel+2014, Vogelsberger+ 2014b, Sijacki+ 2015
- Magneticum (Box2b) Hirschmann+ 2014, Dolag+ 2015, Ragagnin+ 2017





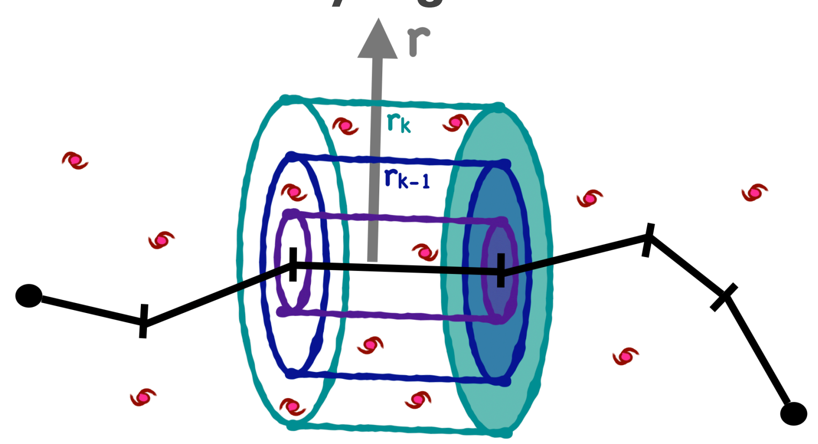
Galarraga-Espinosa+ 2020

Galaxy distribution around filaments

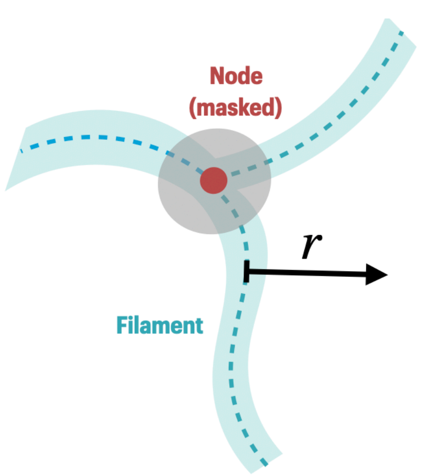
Galarraga-Espinosa+ 2020

Method:

Number density of galaxies

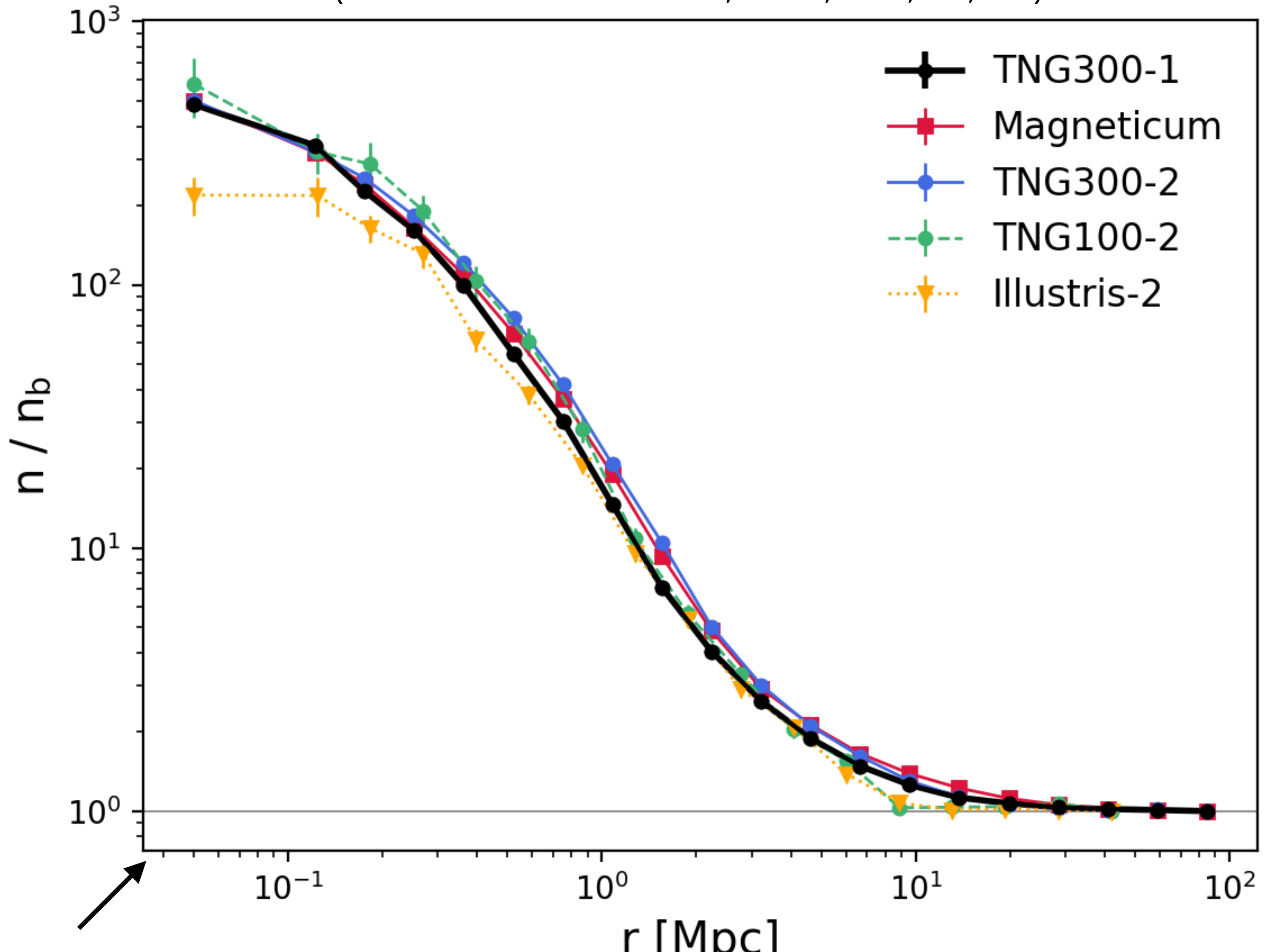


Remove segments in nodes
(= contamination in the study of filaments)



Number density of galaxies

Average profiles
(Number of filaments = **5550**, 38278, 2885, 213, 223)

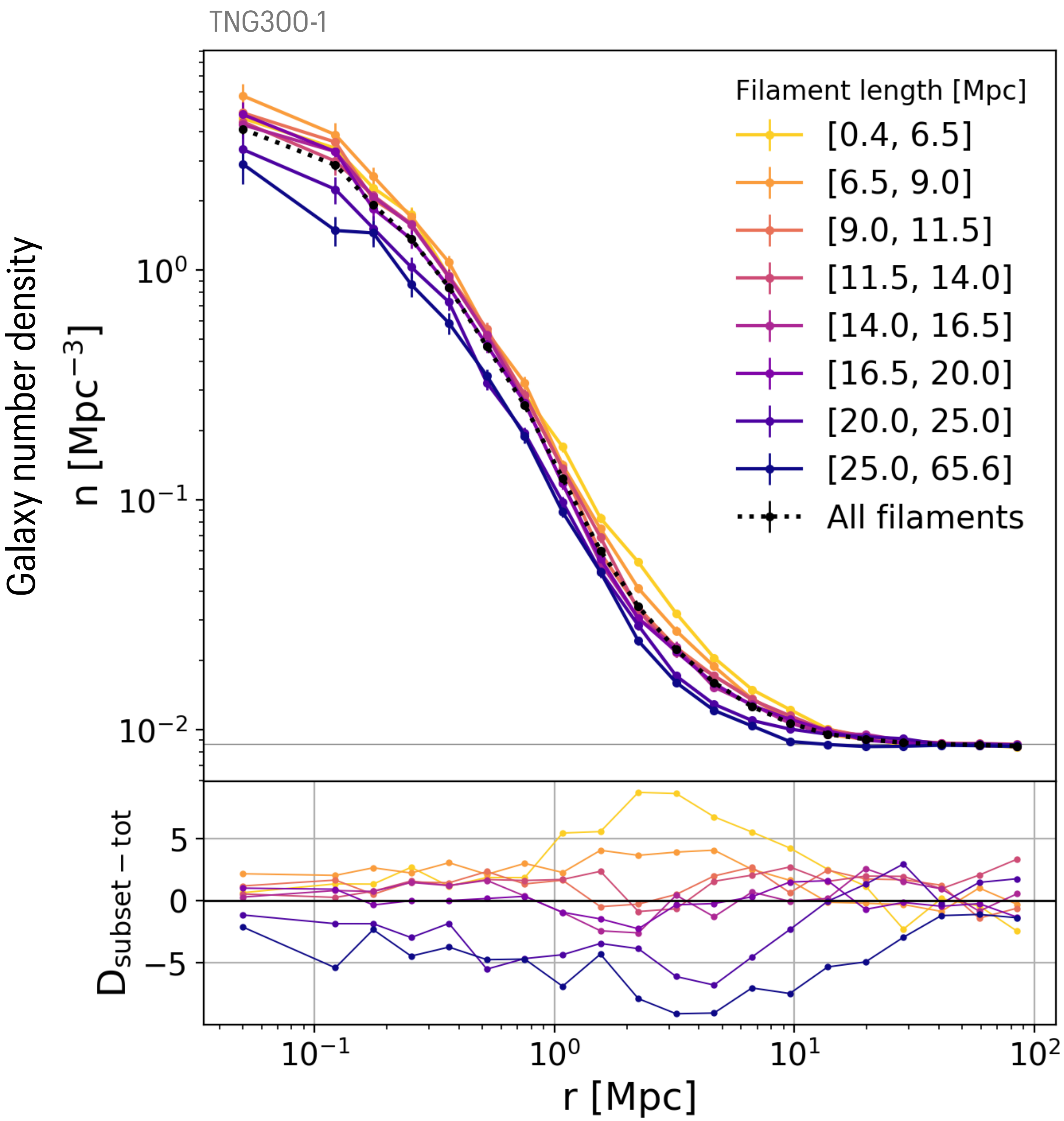


Spine of the filament

Radial distance to the spine

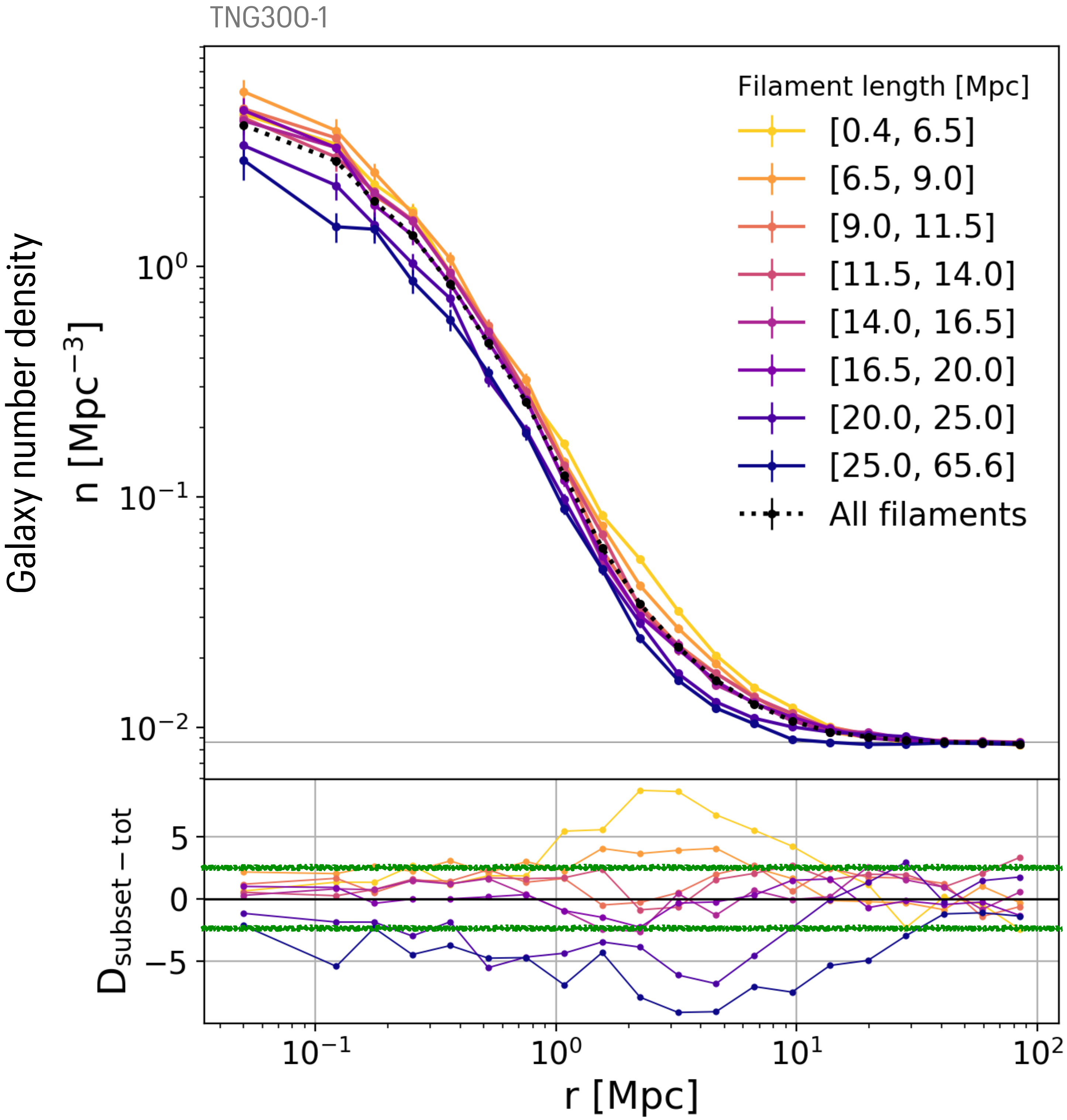
+ Fit with different models (GNFW, beta, Einasto, simple and double power law)

Radial density profiles: variations with filament length



Galarraga-Espinosa+ 2020

Radial density profiles: variations with filament 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 $> 2\sigma$

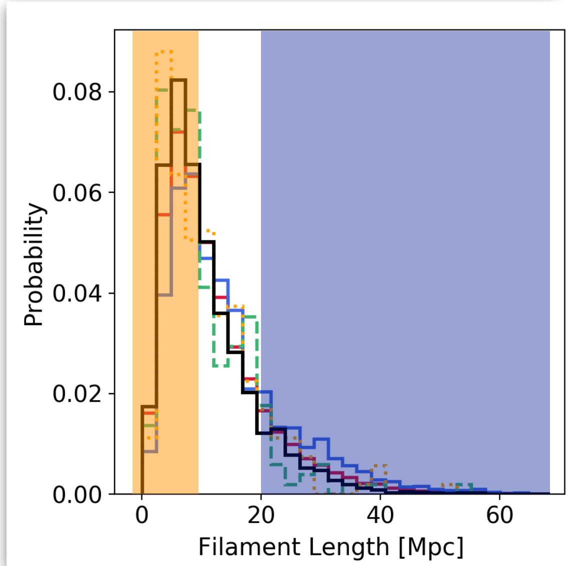
Identification of 2 extreme populations

Short: $L_f < 9$ Mpc

Long: $L_f \geq 20$ Mpc

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

Galarraga-Espinosa+ 2020



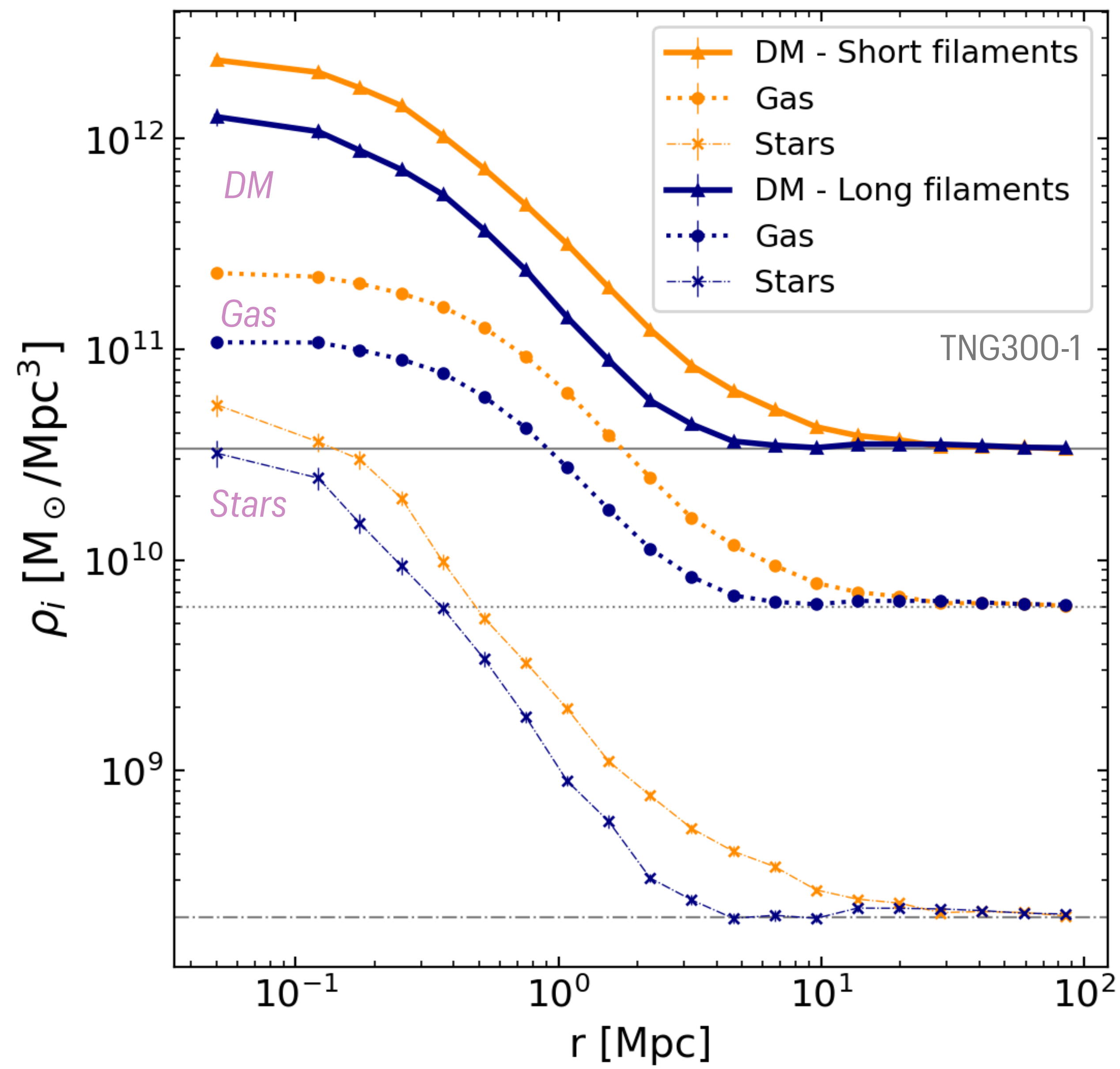
Exploring the extremes

(TNG300-1 simulation)

Short: $L_f < 9$ Mpc

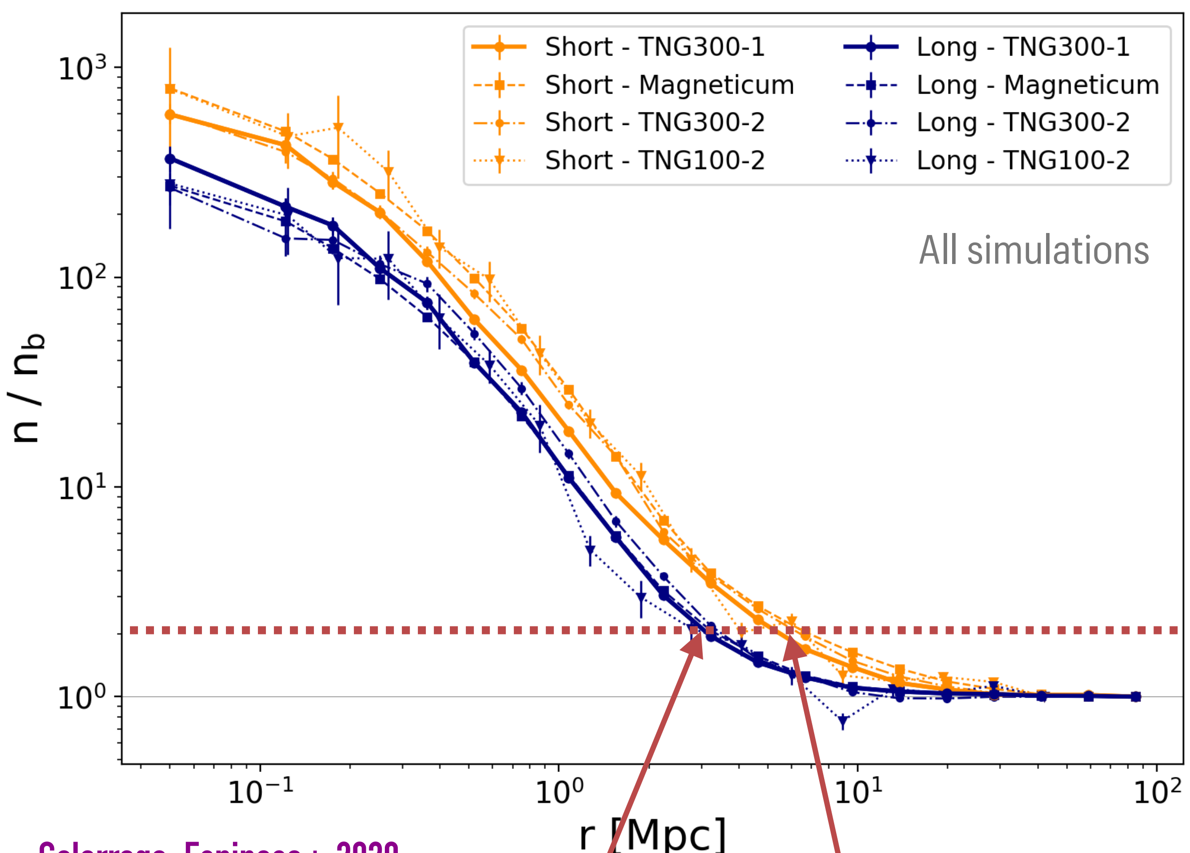
Long: $L_f \geq 20$ Mpc

DM, **gas**, and **stellar** mass densities



Galárraga-Espinosa+ 2022

Galaxy number density



Galarraga-Espinosa+ 2020

$r_2^{\rm L} \sim 3$ Mpc $\quad r_2^{\rm S} \sim 5$ Mpc

Short and **puffy**, **Long** and **thin**

Densities in **short** are **~3x higher** than in **long**

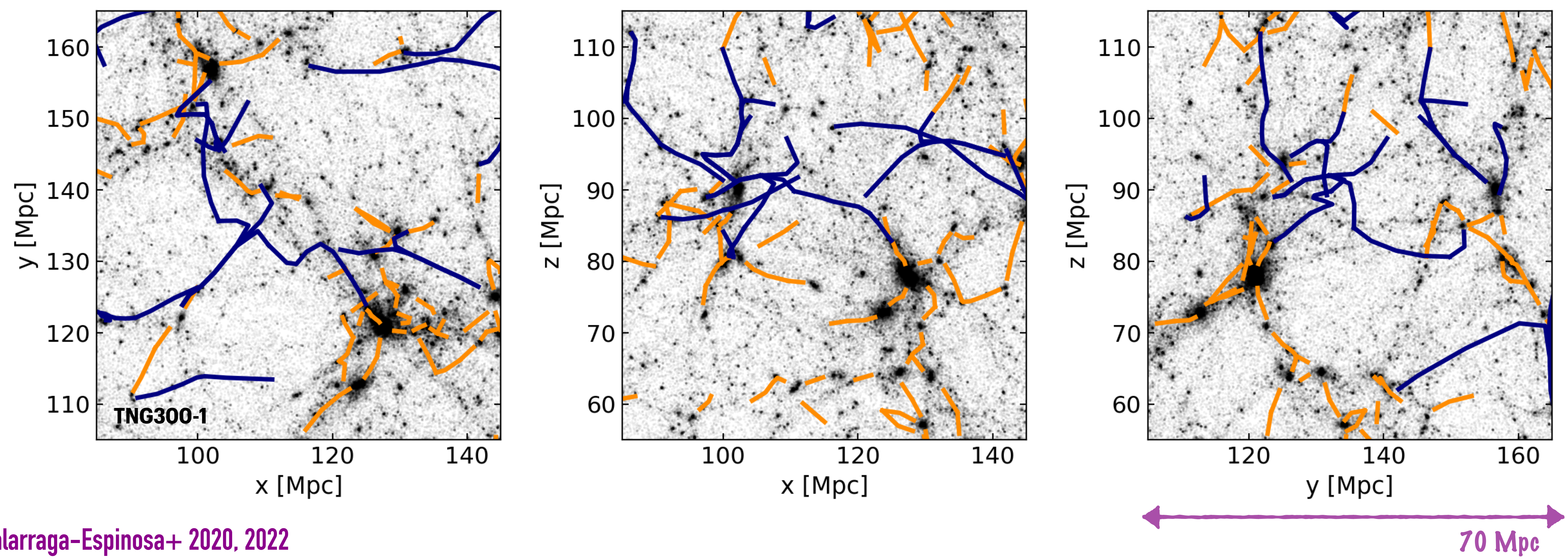
Different Environments

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

- Excess of density (integrated quantity)
  —> Short filaments are **denser** than long.
- Mass of the node connected to the filaments
  —> Short filaments are **connected to more massive** nodes than long.

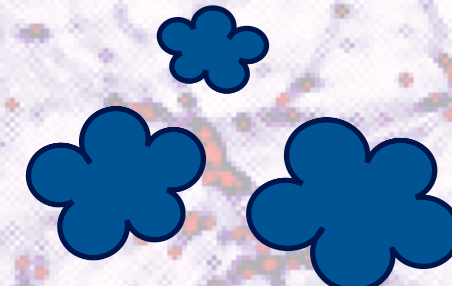
Short $L_f < 9$ Mpc
Long $L_f \geq 20$ Mpc

Different environments in the Cosmic Web:
Short : trace more over-dense regions, Long : trace less dense regions



Galarraga-Espinosa+ 2020, 2022

What about gas properties?

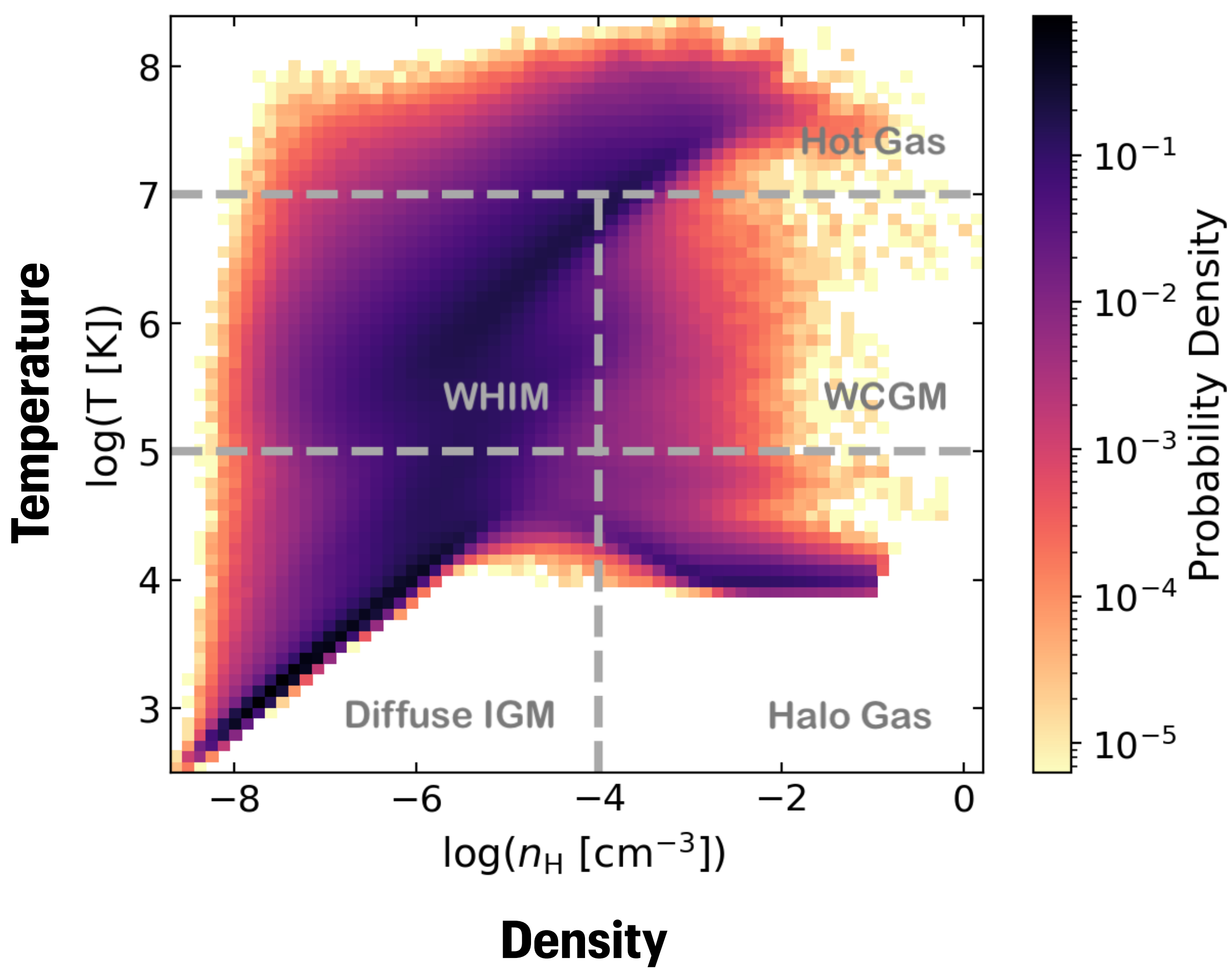


NOT ALL GAS IS THE SAME

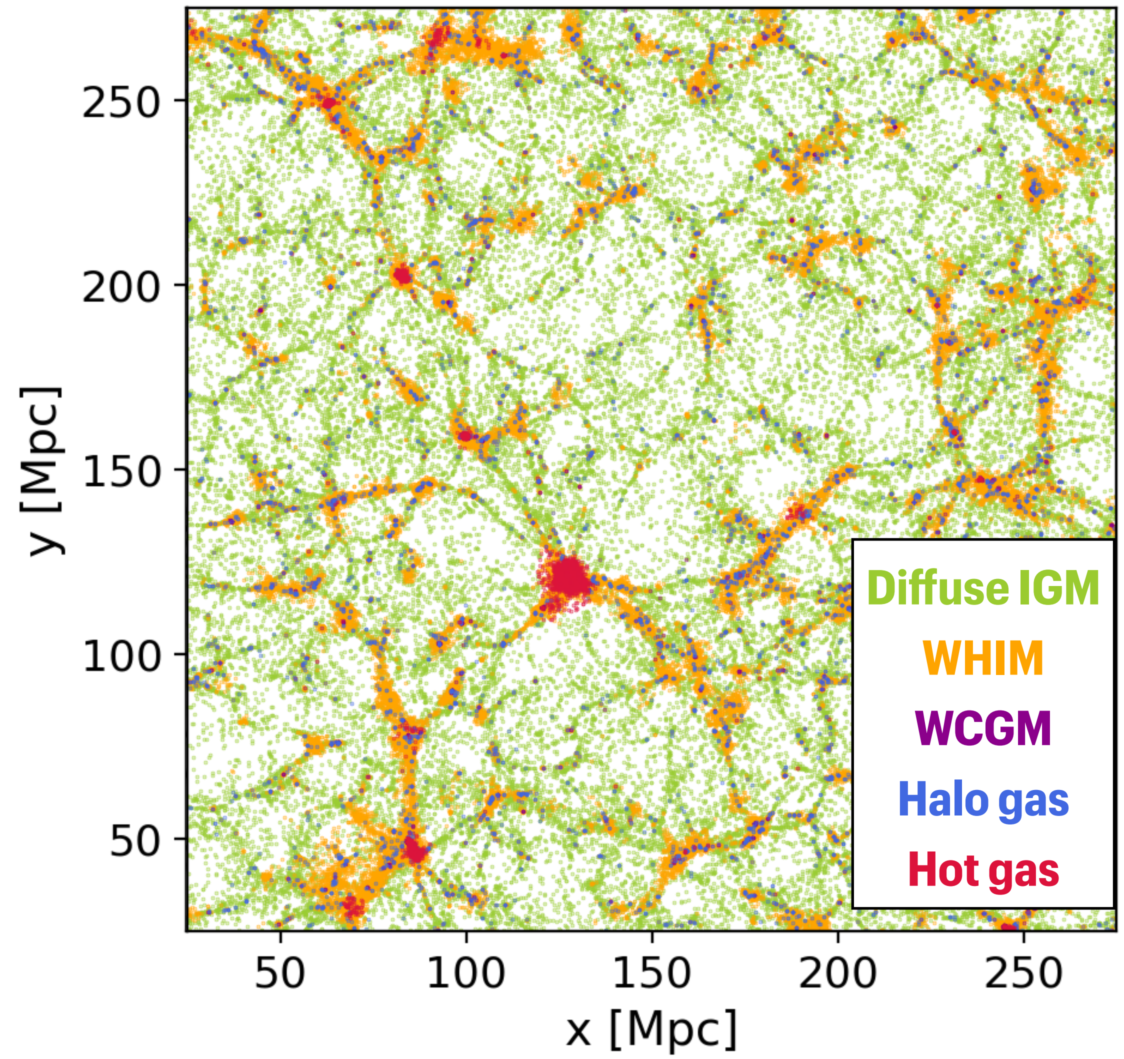
Accretion, ejection, Heating, and cooling → Gas is pushed into different physical states, or **phases**

Separation of gas in different phases, following Martizzi+ 2019

Phase-space diagram

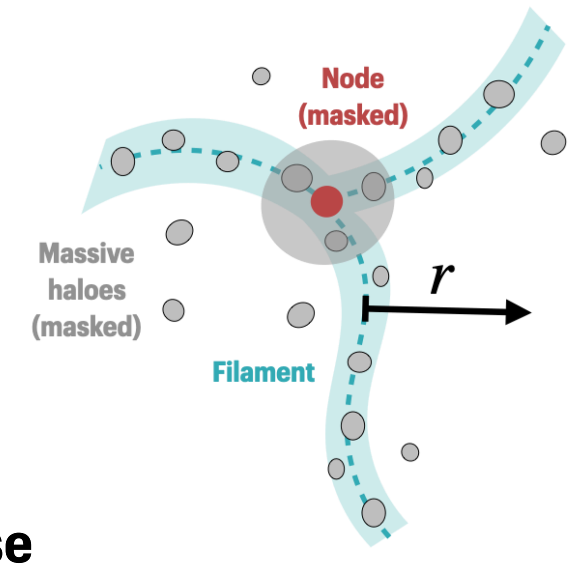


Location of phases in the Cosmic Web

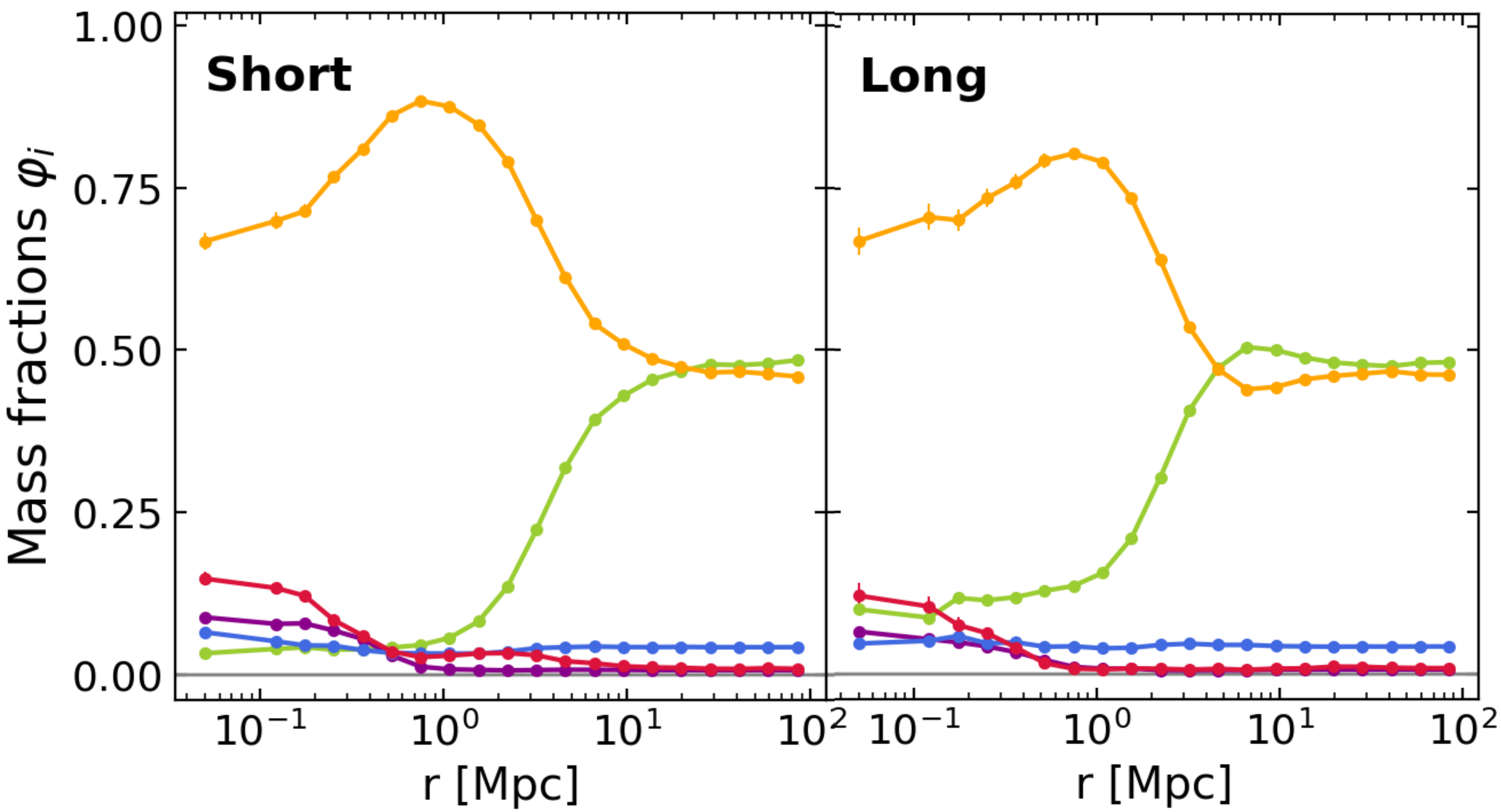


How are the phases distributed around filaments?

Focus only on inter-filament gas!
- ✓ Remove gas in nodes ($3\,R_{200}$)
- ✓ Remove gas in massive haloes $M_{\rm tot} > 10^{12}\,\rm M_\odot$ ($3\,R_{200}$)



Radial profiles of mass fraction of each gas phase



$$\varphi_i(r) = \frac{\rho_{{\rm gas},i}(r)}{\rho_{\rm gas,tot}(r)}$$

Diffuse IGM
WHIM
WCGM
Halo gas
Hot gas

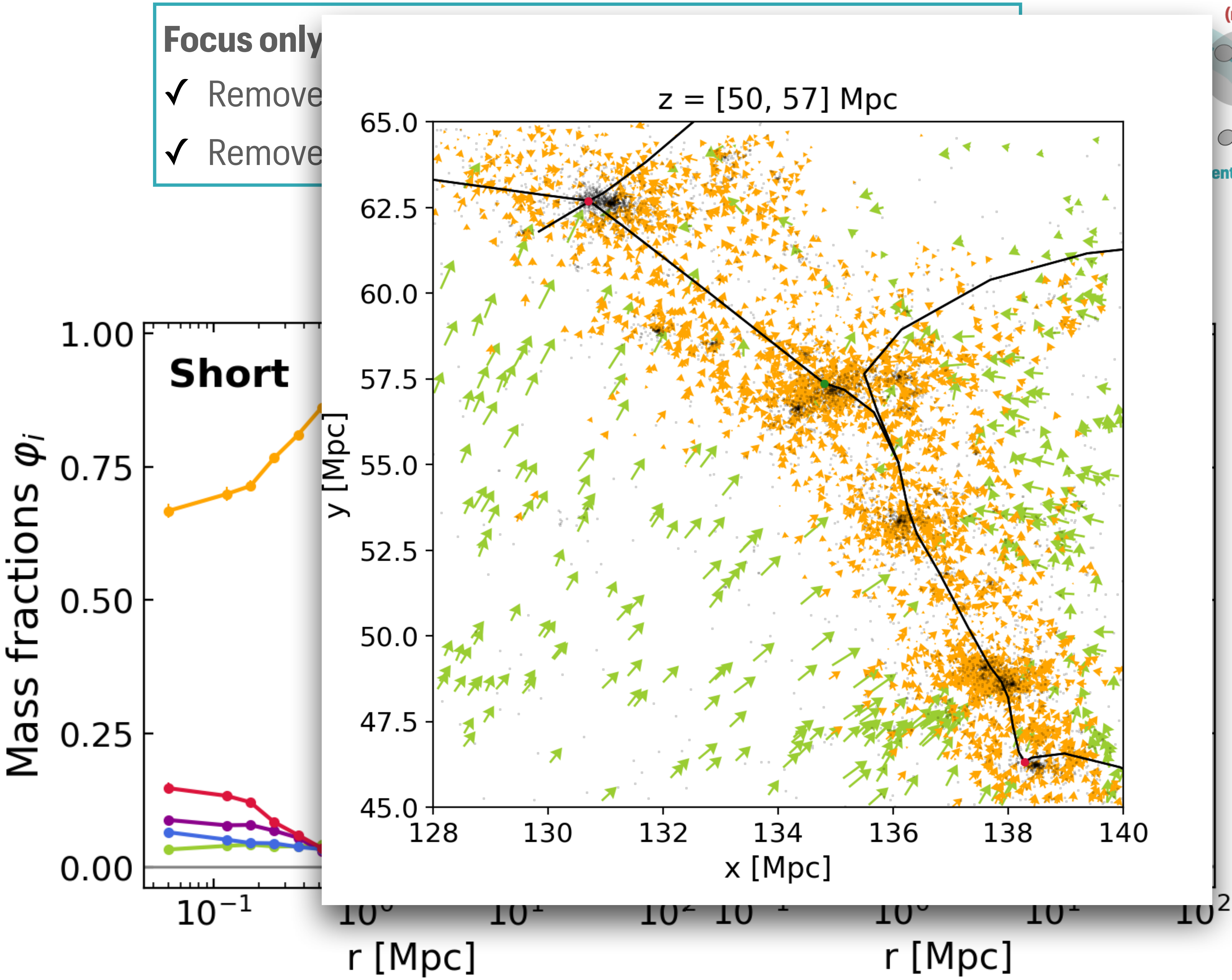
Galarraga-Espinosa+ 2021

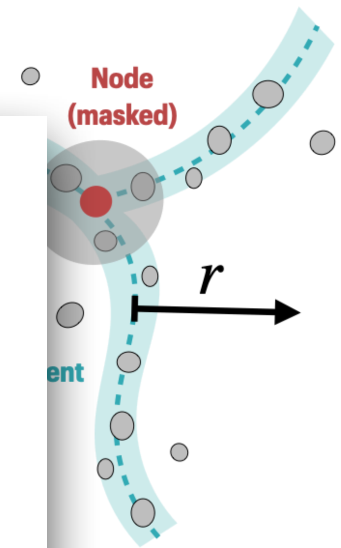
How are the phases distributed around filaments?

Focus only

✓ Remove

✓ Remove





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WHIM

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Galarraga-Espinosa+ 2021

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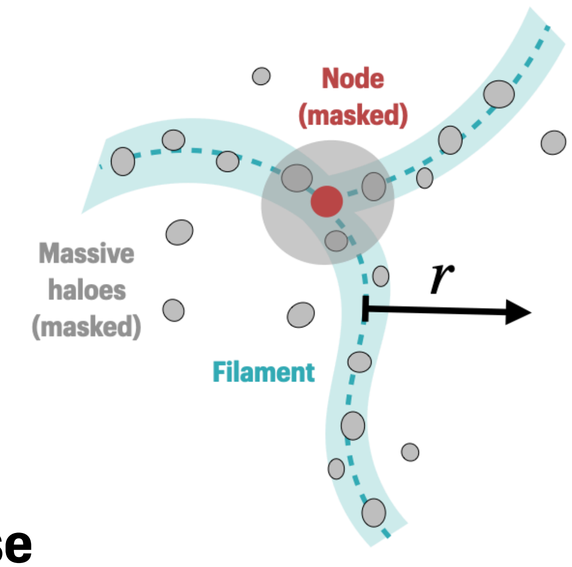
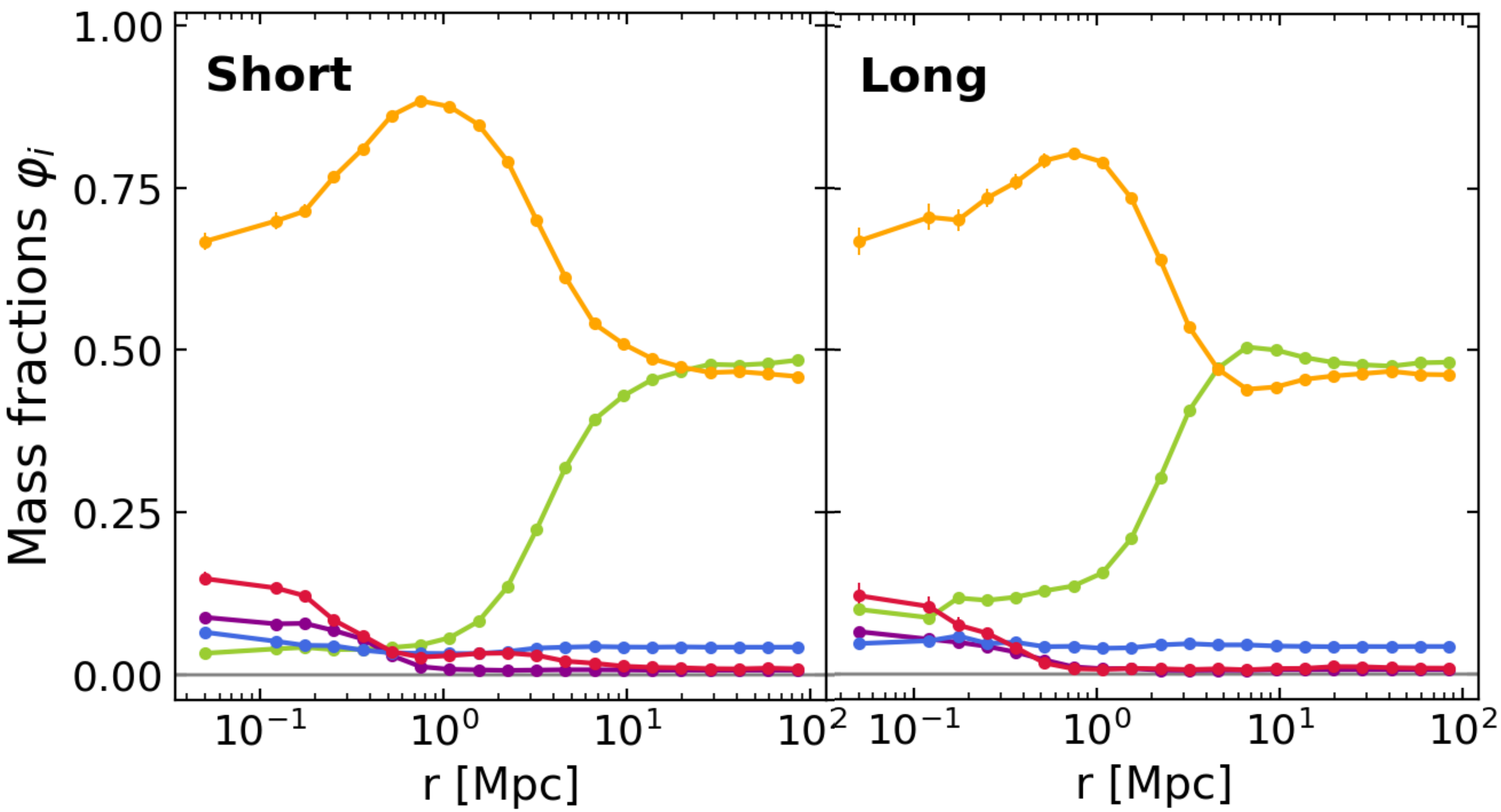


Radial profiles of mass fraction of each gas phase



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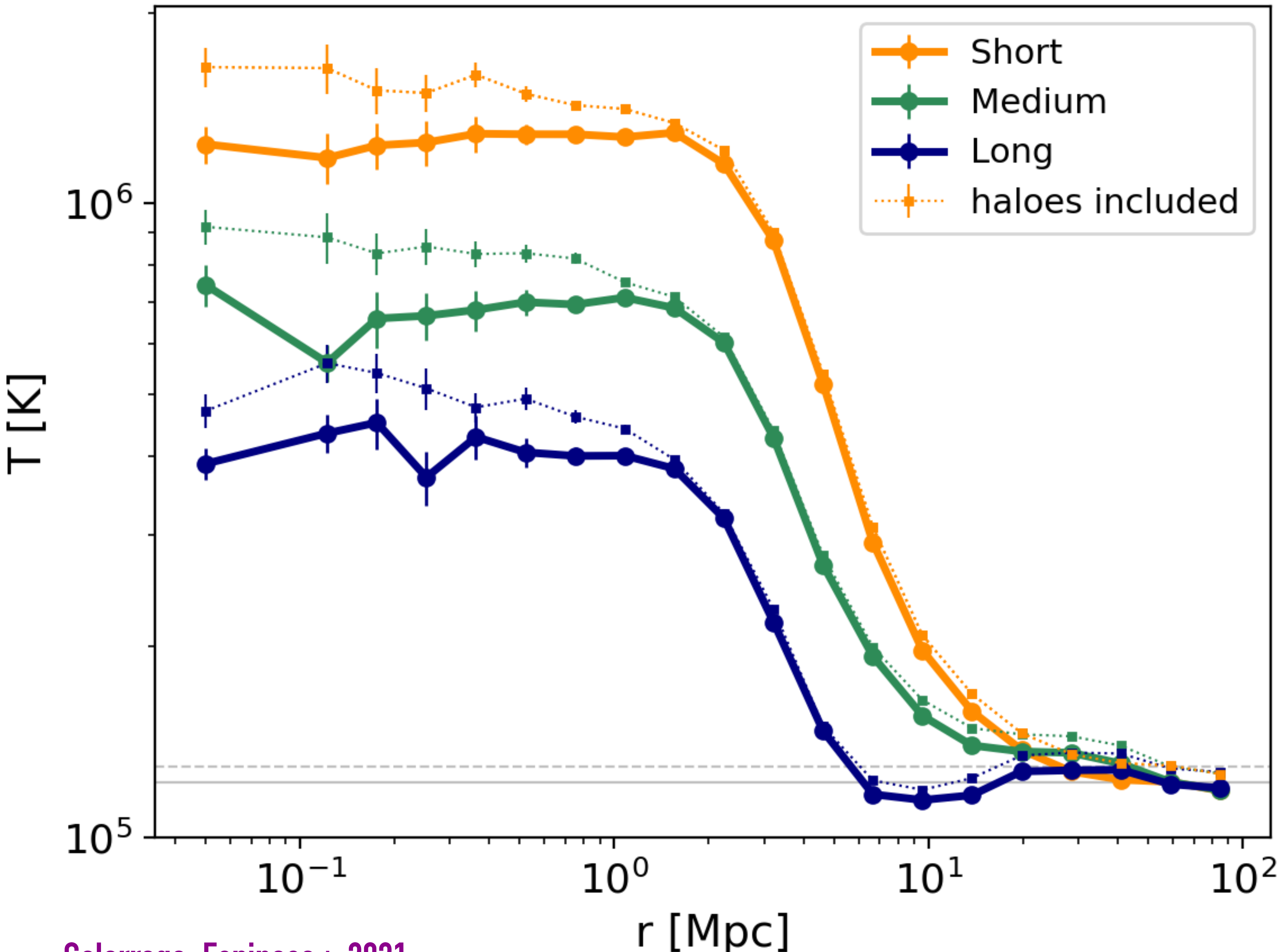
Diffuse IGM
WHIM
WCGM
Halo gas
Hot gas

Galarraga-Espinosa+ 2021

Gas Temperature

Mean radial temperature profiles



Galarraga-Espinosa+ 2021

- Different profiles for different populations of filaments

Short filaments are ~3 times hotter than long

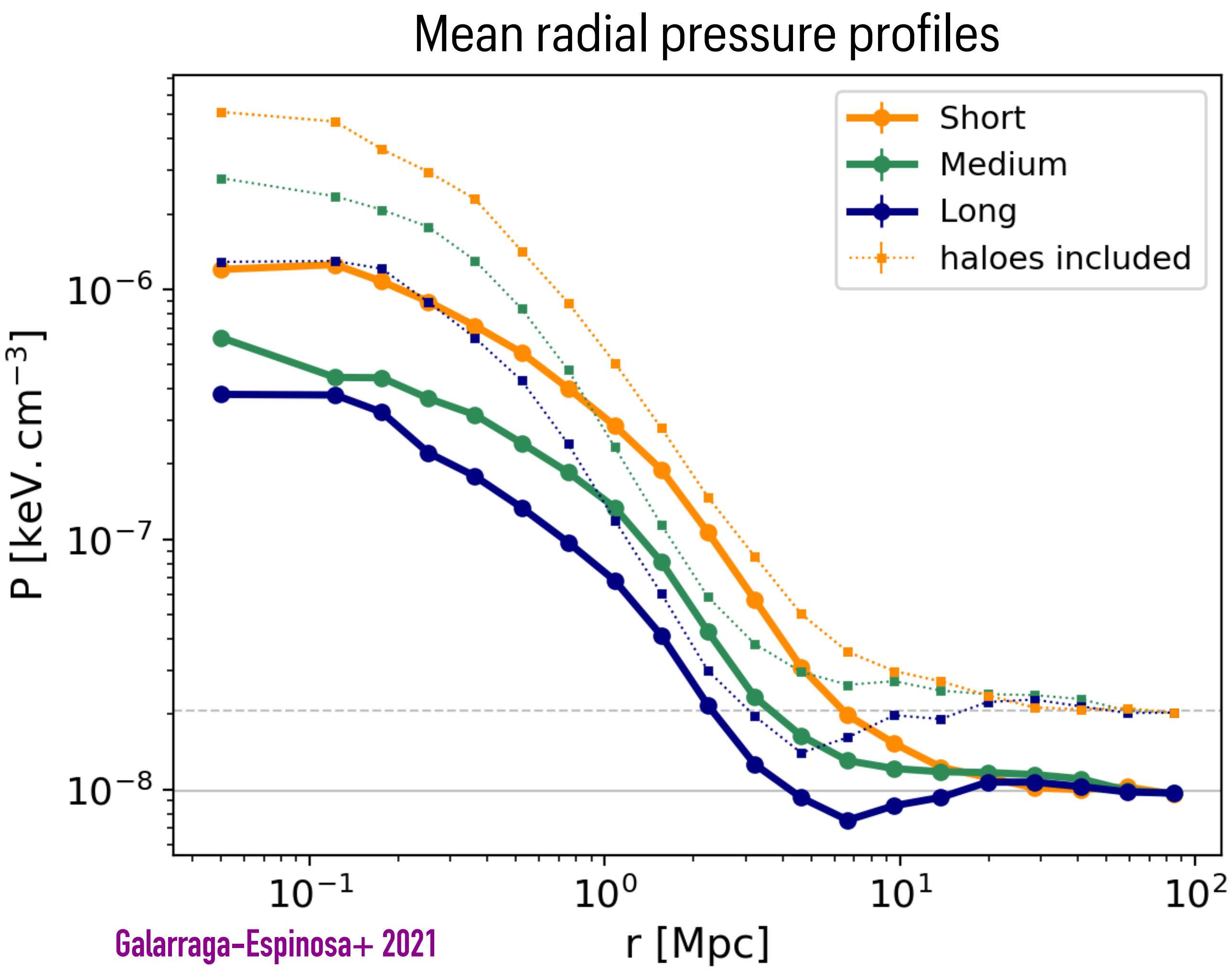
- All filaments: **isothermal** core up to r ~ 1.5 Mpc

In agreement with
Klar & Mücket 2012
Gheller & Vazza 2019
Tuominen+ 2020
Ramsøy+ 2021 (smaller scale filaments)

Average temperature of filaments:

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

Gas Pressure



Galarraga-Espinosa+ 2021

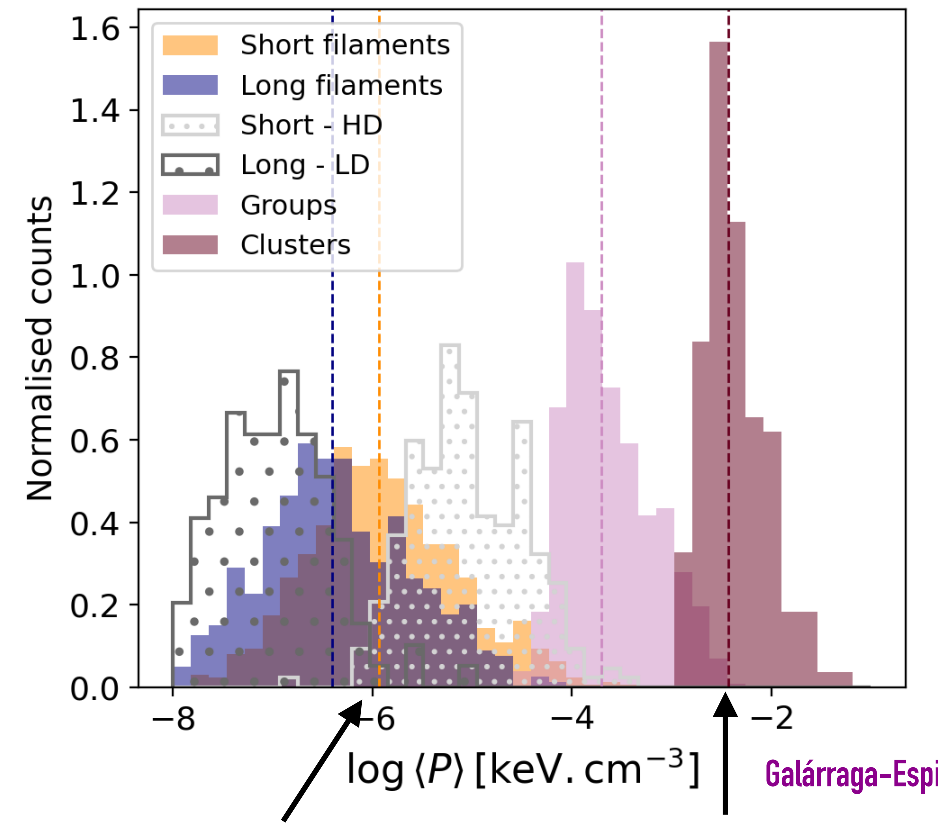
Average pressure of filaments:

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

Pressure values are ~3 times higher in short filaments than in long

Comparison with clusters

Pressure distribution:



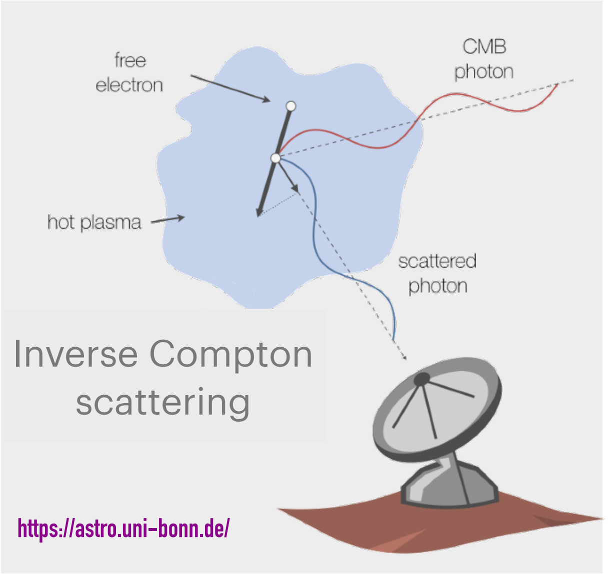
Galárraga-Espinosa+ 2022

Short and long filaments

Clusters

Pressure in cores of **filaments** is **~1000** times **lower** than in cores of **clusters**

Observing cosmic filaments with the Sunyaev-Zel'dovich (SZ) effect

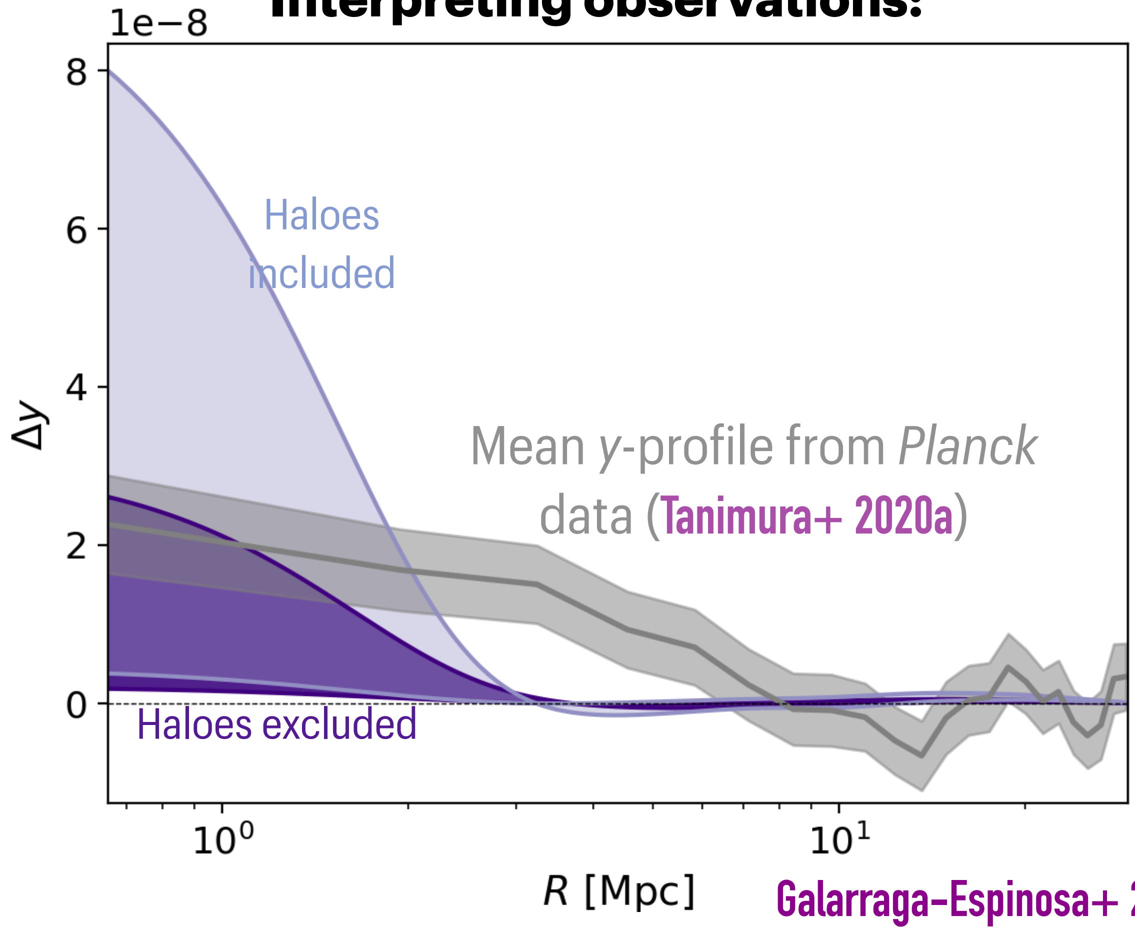


y-Compton parameter
OBSERVABLE

Pressure profiles

$$y = \frac{\sigma_T}{m_e c^2} \int P_e \, dl$$

Interpreting observations:

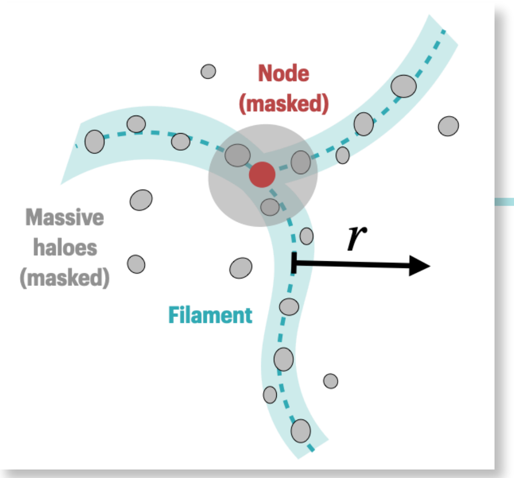


Galarraga-Espinosa+ 2021

Estimation of minimum and maximum SZ signal from cosmic filaments:

- Only inter-filament gas:

$$y_{\rm core} = 0.5 - 4.1 \times 10^{-8}$$



- Including haloes (~ **3x**)

$$y_{\rm core} = 0.1 - 1.5 \times 10^{-7}$$

—> Observed SZ signal mostly due to inter-filament (diffuse) gas!

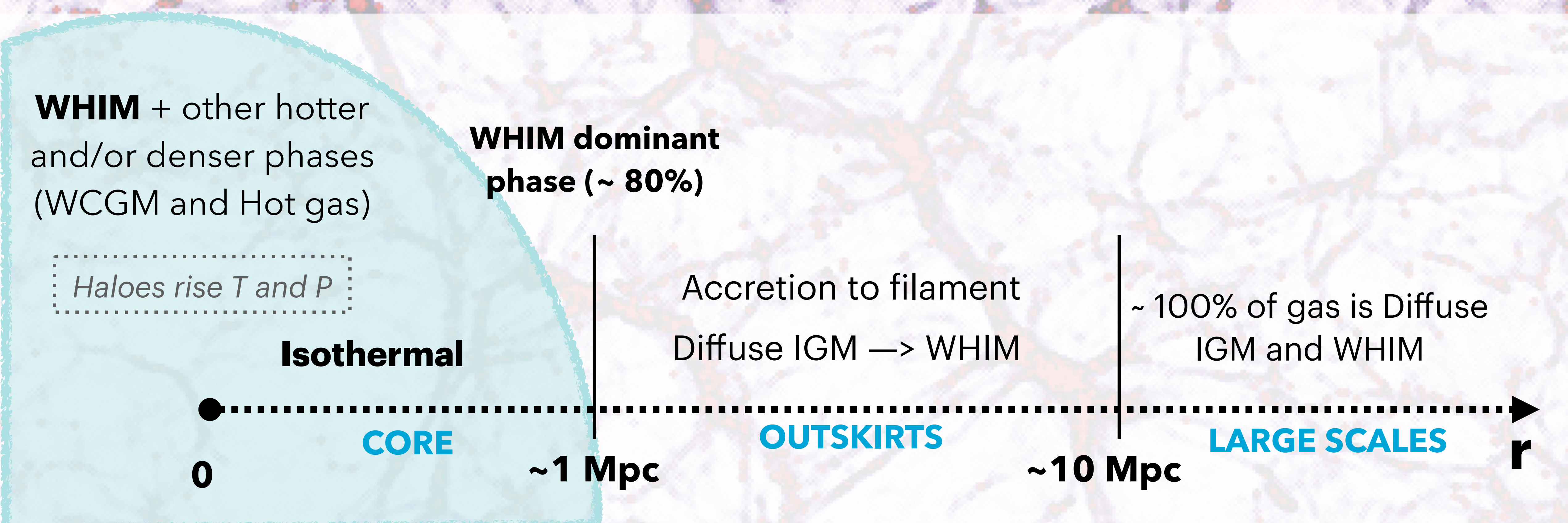
Relevant in the search for missing baryons!

Recap

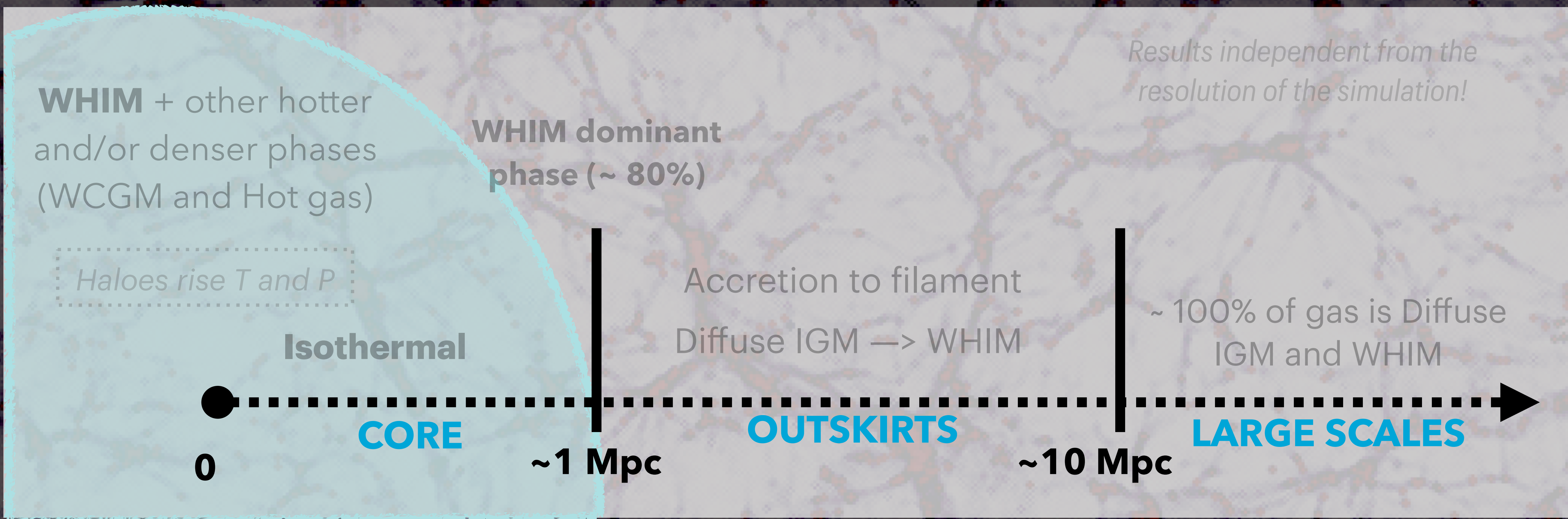
Two populations in:

- Distribution of galaxies
- Densities of matter
- Distribution of gas phases
- Gas properties

Short	Long
Short and puffy	Long and thin
Trace **denser** environments	Trace **less dense** environments
Hotter	**Cooler**
Higher pressure	**Lower pressure**



Three regimes:



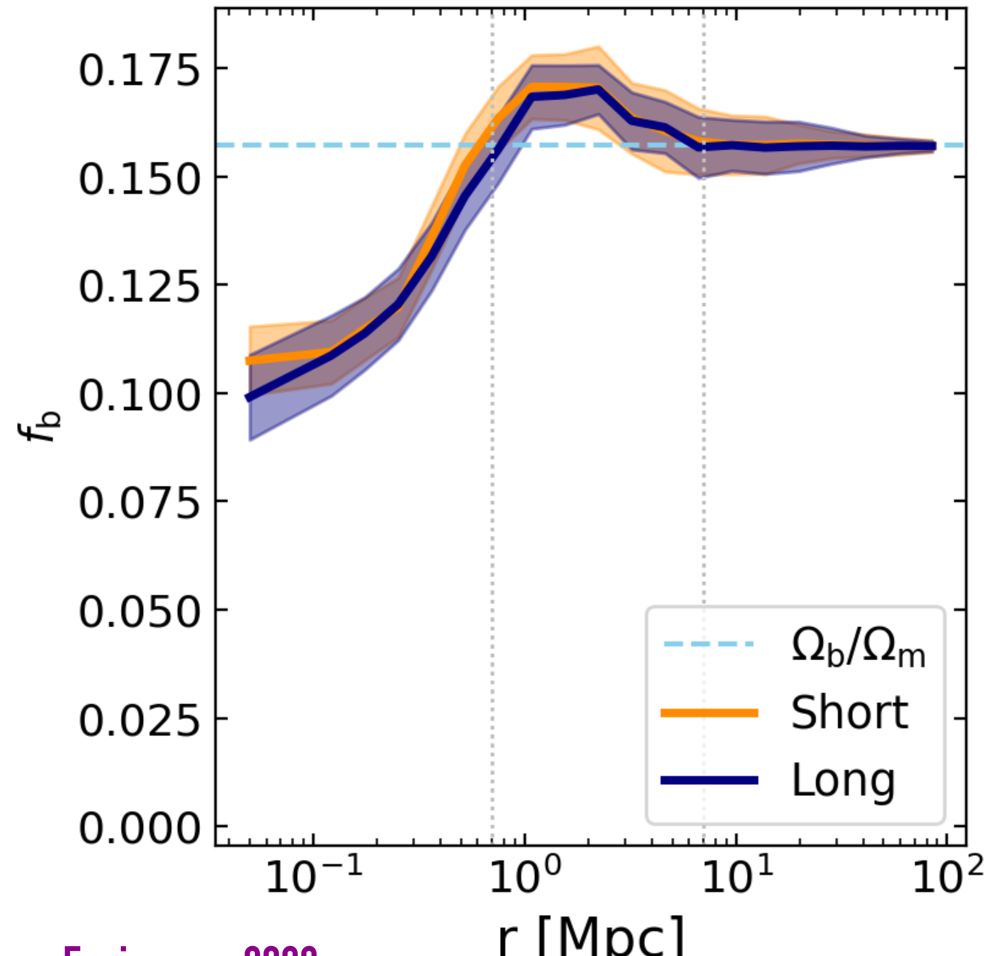
Does gravity explain it all?
What are the driving processes?

——> Ideal observable: the **baryon fraction** of filaments

Baryon fraction of Cosmic filaments

Aim: exploring the relative distribution of matter components

$$f_b(r) \equiv \frac{\rho_{gas}(r) + \rho_*(r)}{\rho_{DM}(r) + \rho_{gas}(r) + \rho_*(r)}$$

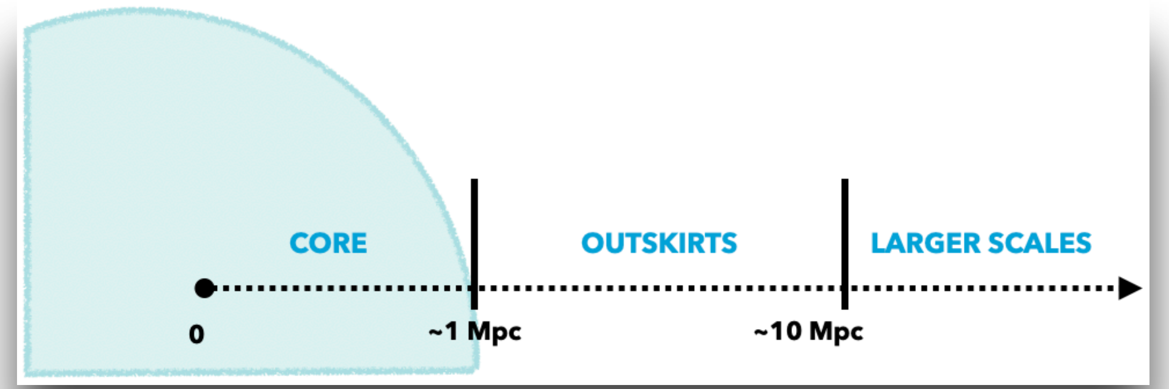


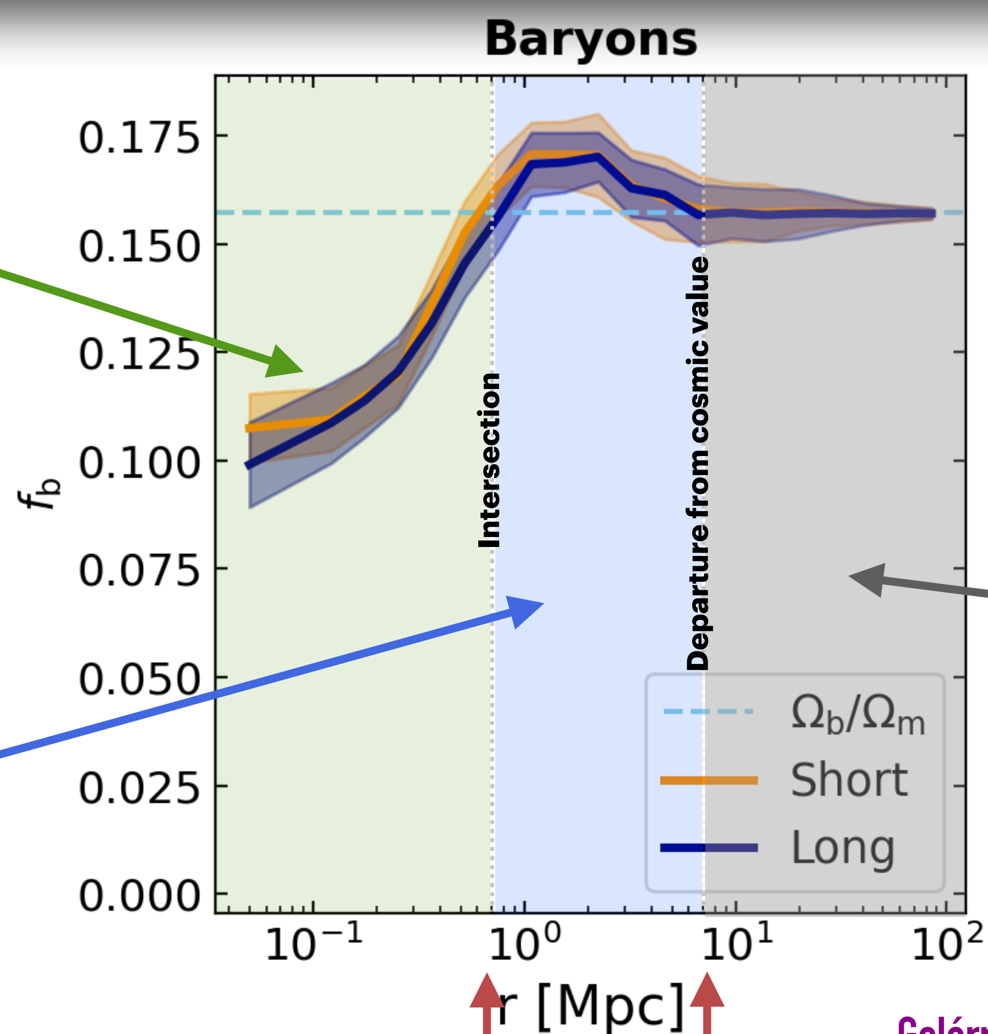
$f_{cosmic} = \Omega_b/\Omega_m = 0.157$

Planck Collaboration+ 2016

Galárraga-Espinosa+ 2022

Baryon fraction of Cosmic filaments





1. Baryon depletion

2. Excess of baryons

$f_{\rm cosmic} = \Omega_{\rm b}/\Omega_{\rm m} = 0.157$

Planck Collaboration+ 2016

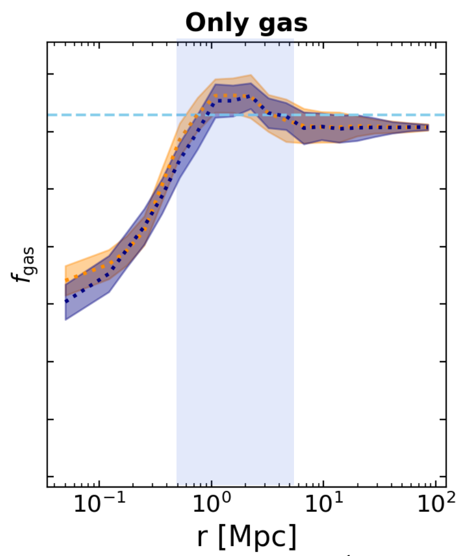
3. Follow the cosmic value

Matter simply falls into filament potential wells (gravity)

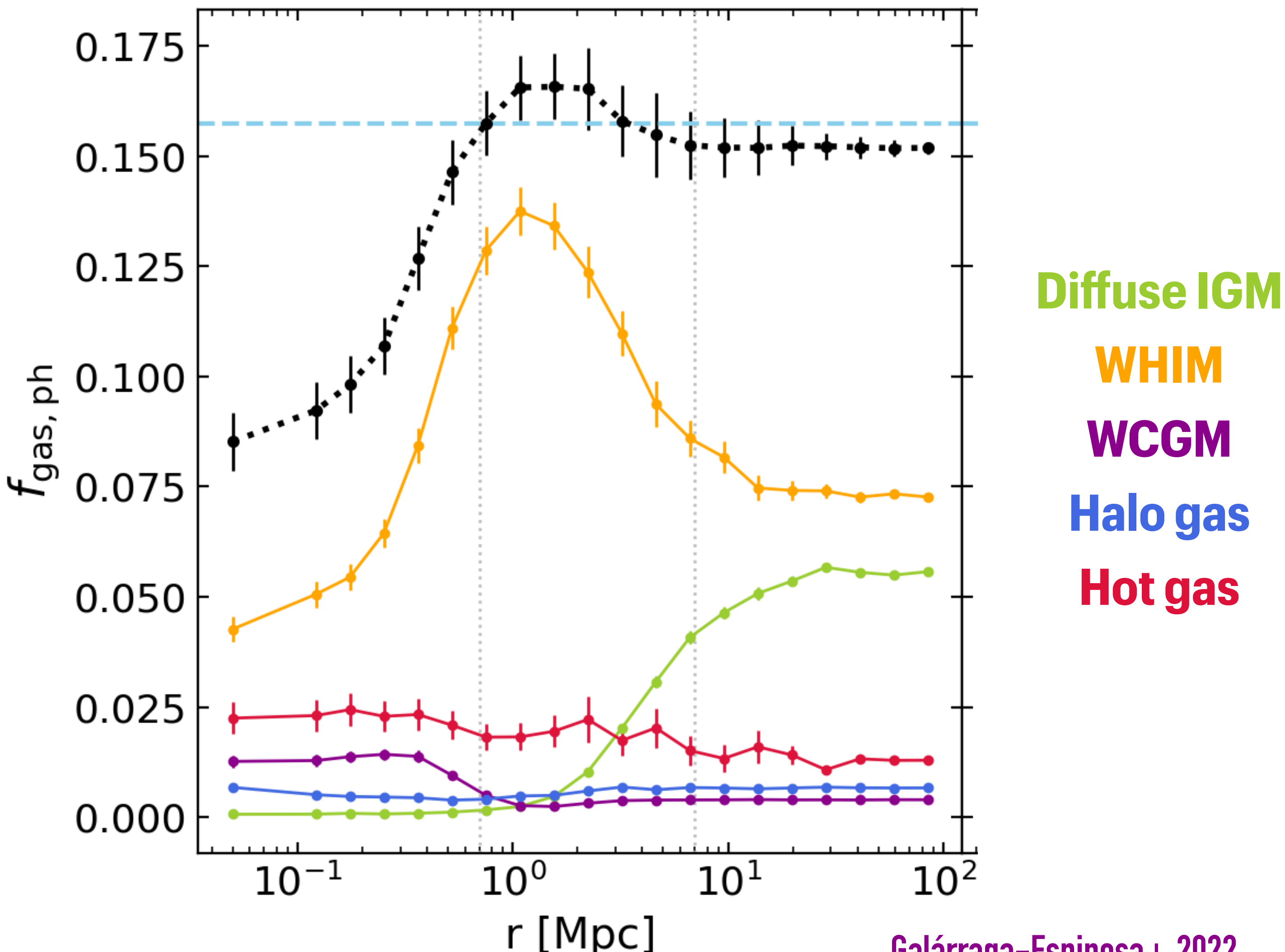
$r_{\rm int} \sim 0.7\,{\rm Mpc}$ $r_{\rm ext} \sim 7\,{\rm Mpc}$

Galárraga-Espinosa+ 2022

Baryon excess at filament outskirts



Disentangle contribution of the different gas phases

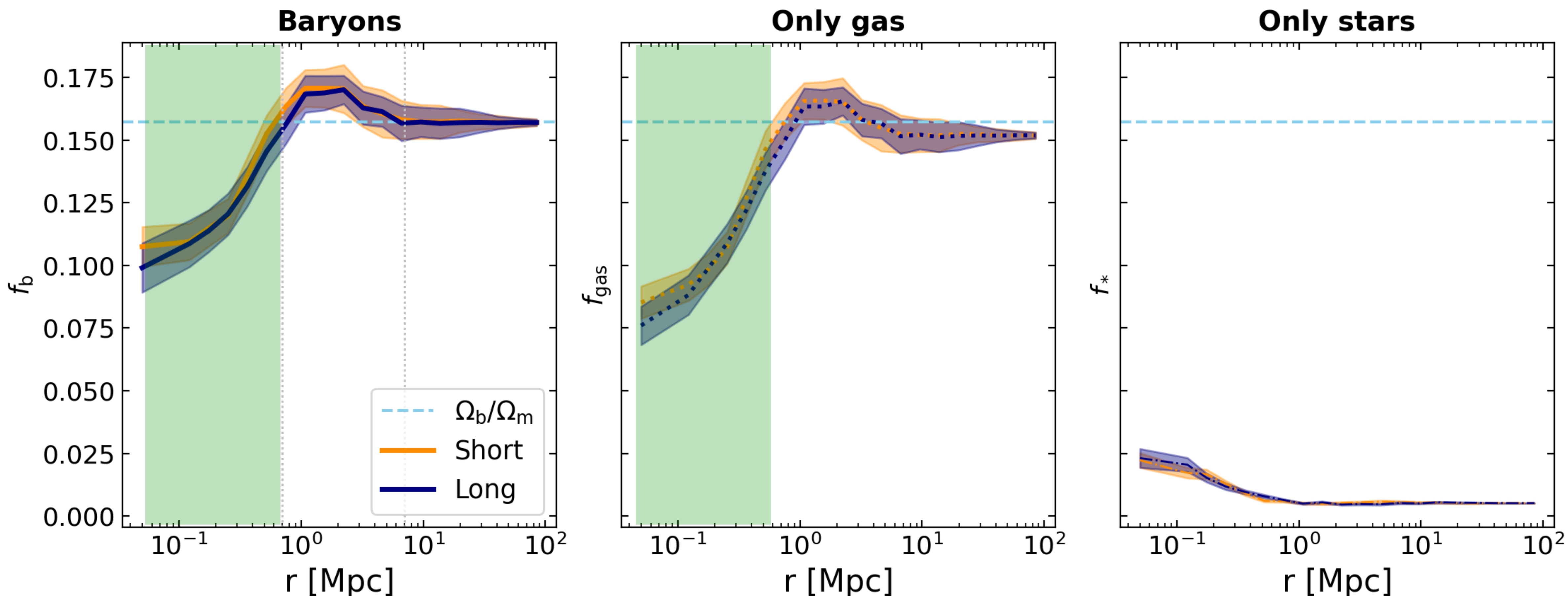


Galárraga-Espinosa+ 2022

- Excess corresponds to **WHIM** gas
- Accretion of gas towards the cores (gravitational attraction)
  —> Diffuse gas is shock-heated and converted into **WHIM**

In agreement with the studies of gas properties!

Baryon **depletion** at filament cores



Galárraga-Espinosa+ 2022

Need mechanism capable of ejecting gas away from filament cores →

Feedback by AGNs?

Modification of the distribution of baryons up to several Mpc away from the sources (e.g. Chisari et al. 2018, in Horizon-AGN)

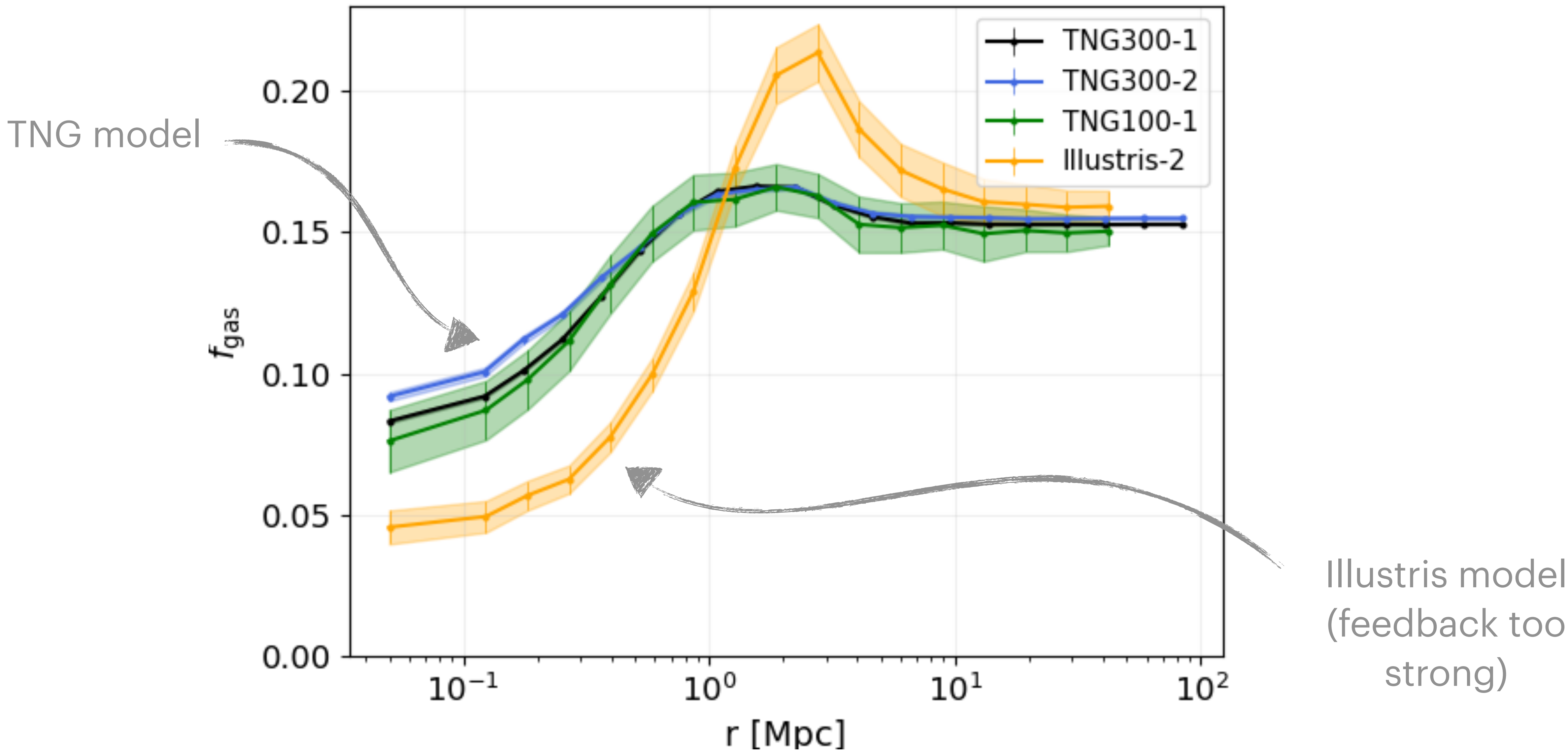
—> compare injected <u>kinetic</u> energy vs <u>potential</u> energy

pushing vs *pulling* of gas

AGNs can be powerful enough to deplete cosmic filaments cores!

Impact of baryonic model…

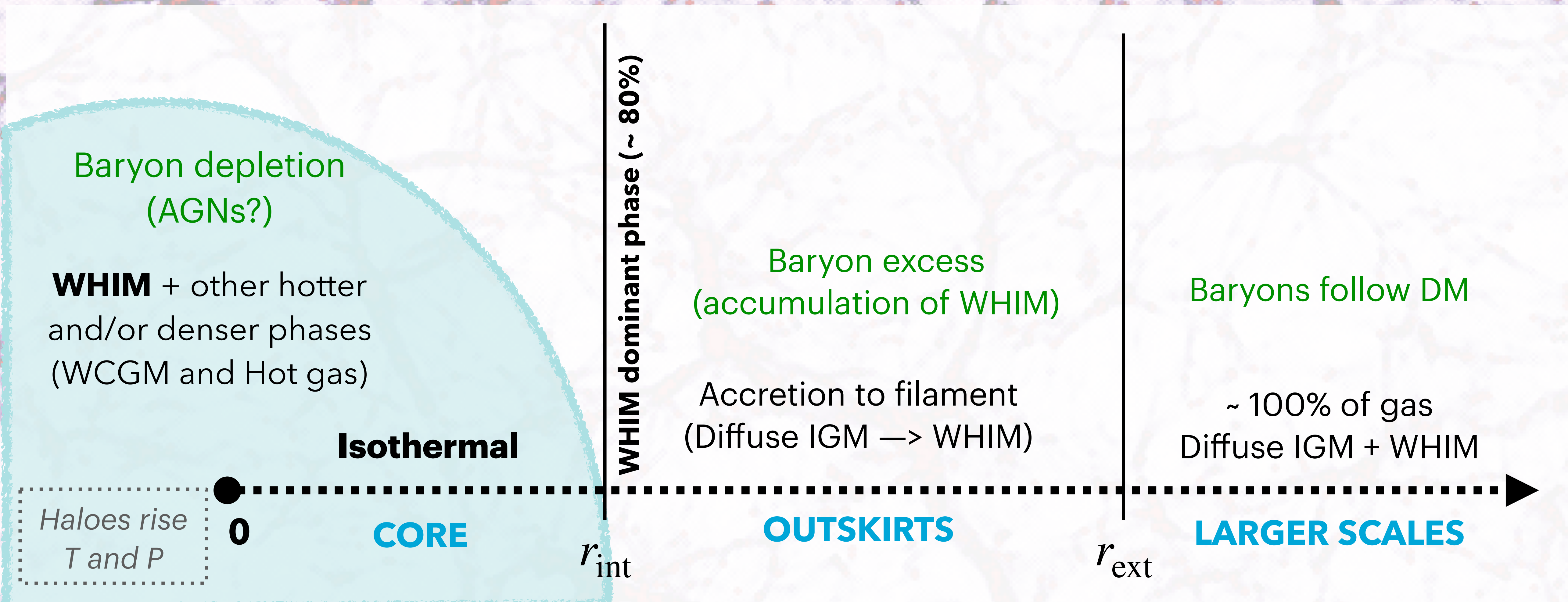
Results in simulation with (too) strong feedback model:



Internal processes in galaxies (such as feedback) have a strong impact on the matter distribution & properties in cosmic filaments

CONCLUSIONS: COSMIC FILAMENTS

A more complete picture of cosmic filaments at z=0



Galárraga-Espinosa+ 2020, 2021, 2022

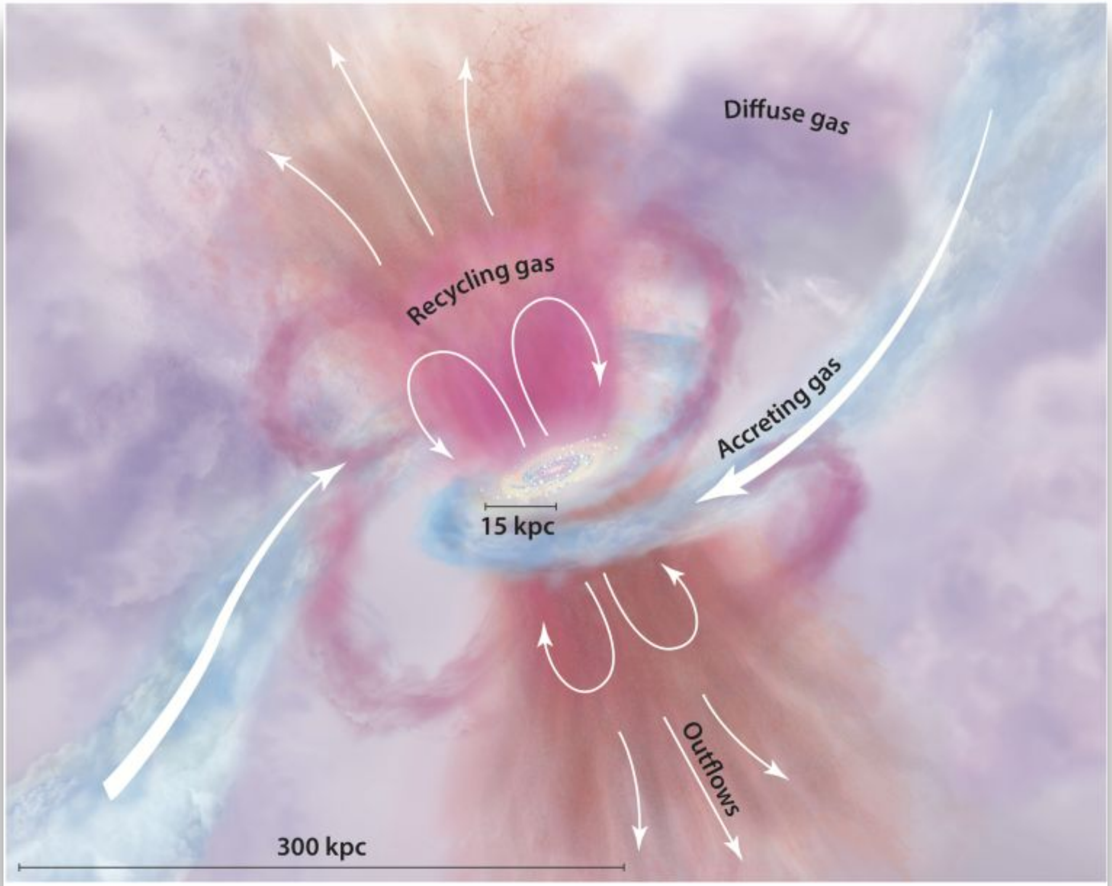
….Currently working on picture at higher z, using MTNG

PART II

From the large-scale structure to the CGM

Filaments at different scales

Circum-galactic medium (CGM)



Tumlinson+ 2017

Cold and dense gas via
small-scale filaments (*streams*)

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

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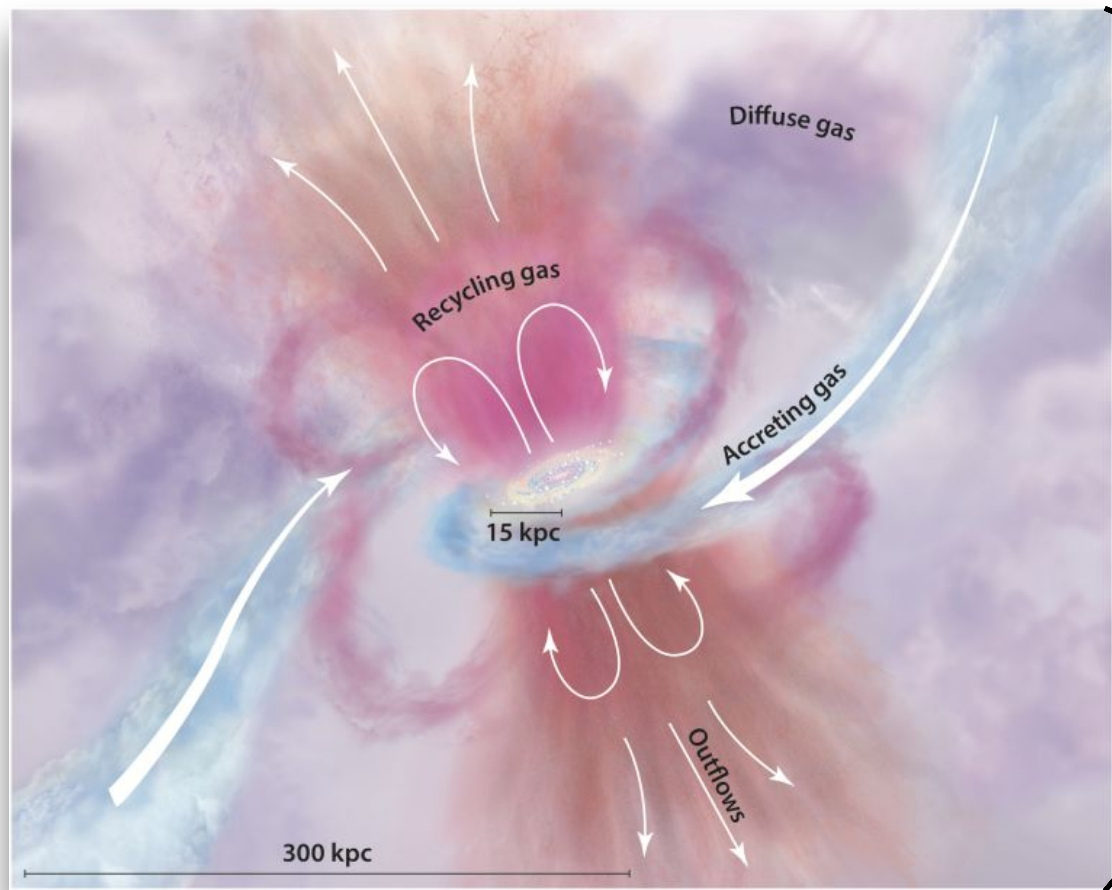
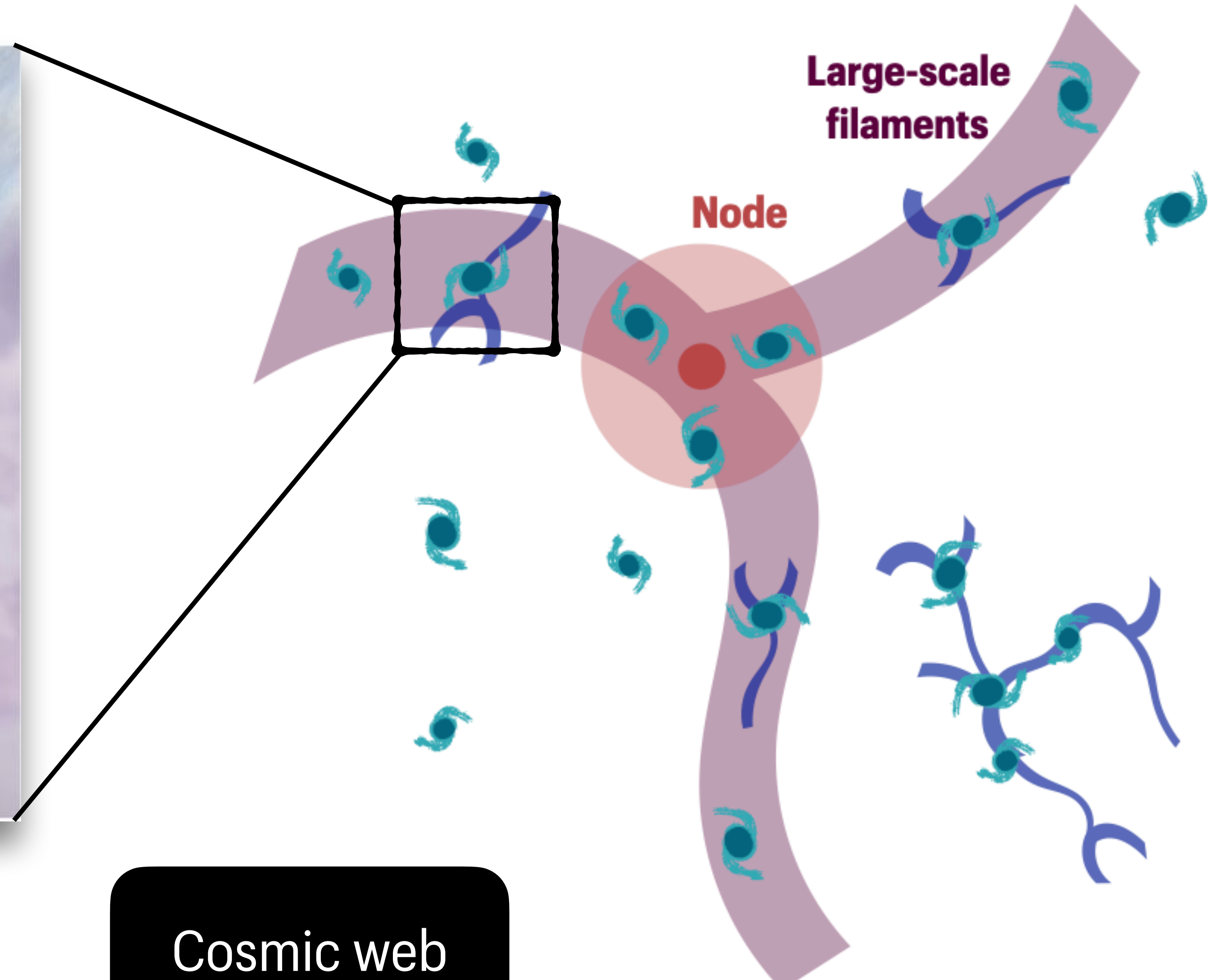


Tumlinson+ 2017



Cosmic web environment

Cold and dense gas via
small-scale filaments (*streams*)

Birnboim & Dekel 2003; Kereš+ 2005; Ocvirk+ 2008; Dekel+ 2009; Pichon+ 2011; Faucher-Giguère & Kereš 2011; Faucher-Giguère+ 2011; Danovich+ 2012; Ramsøy+ 2021, …
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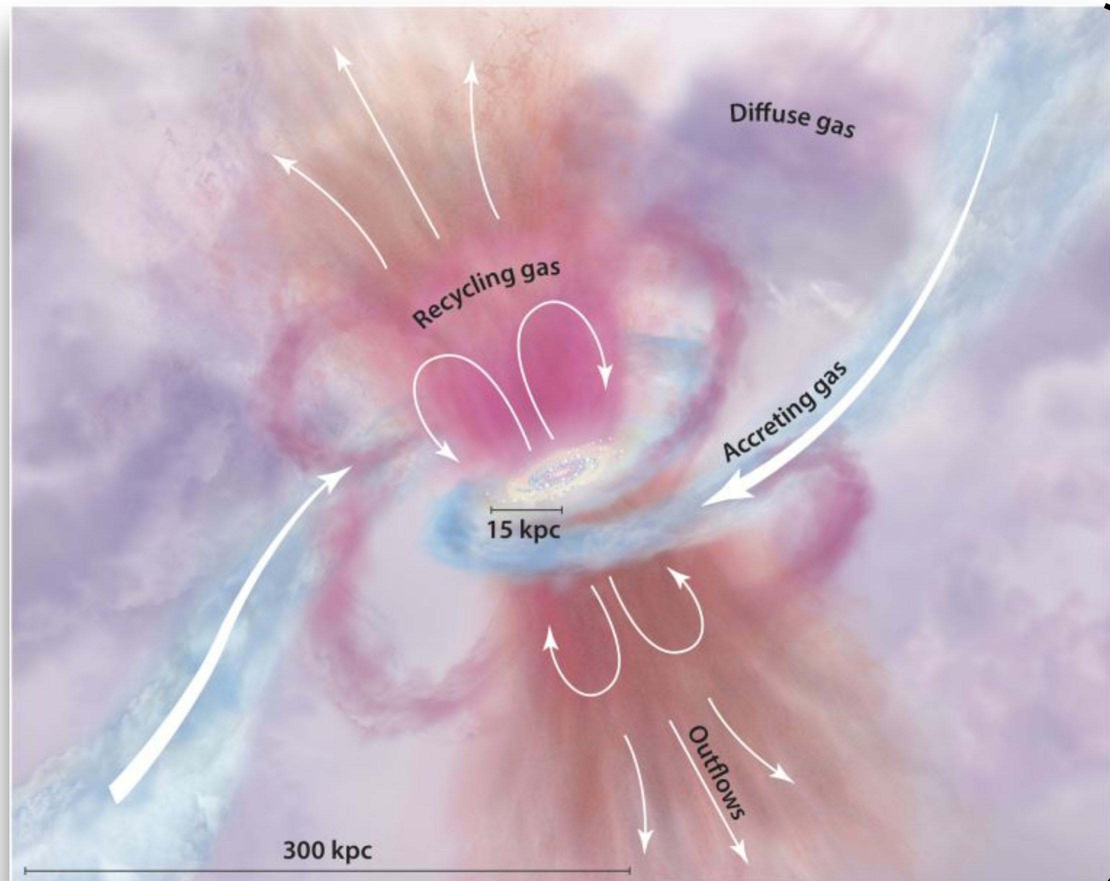
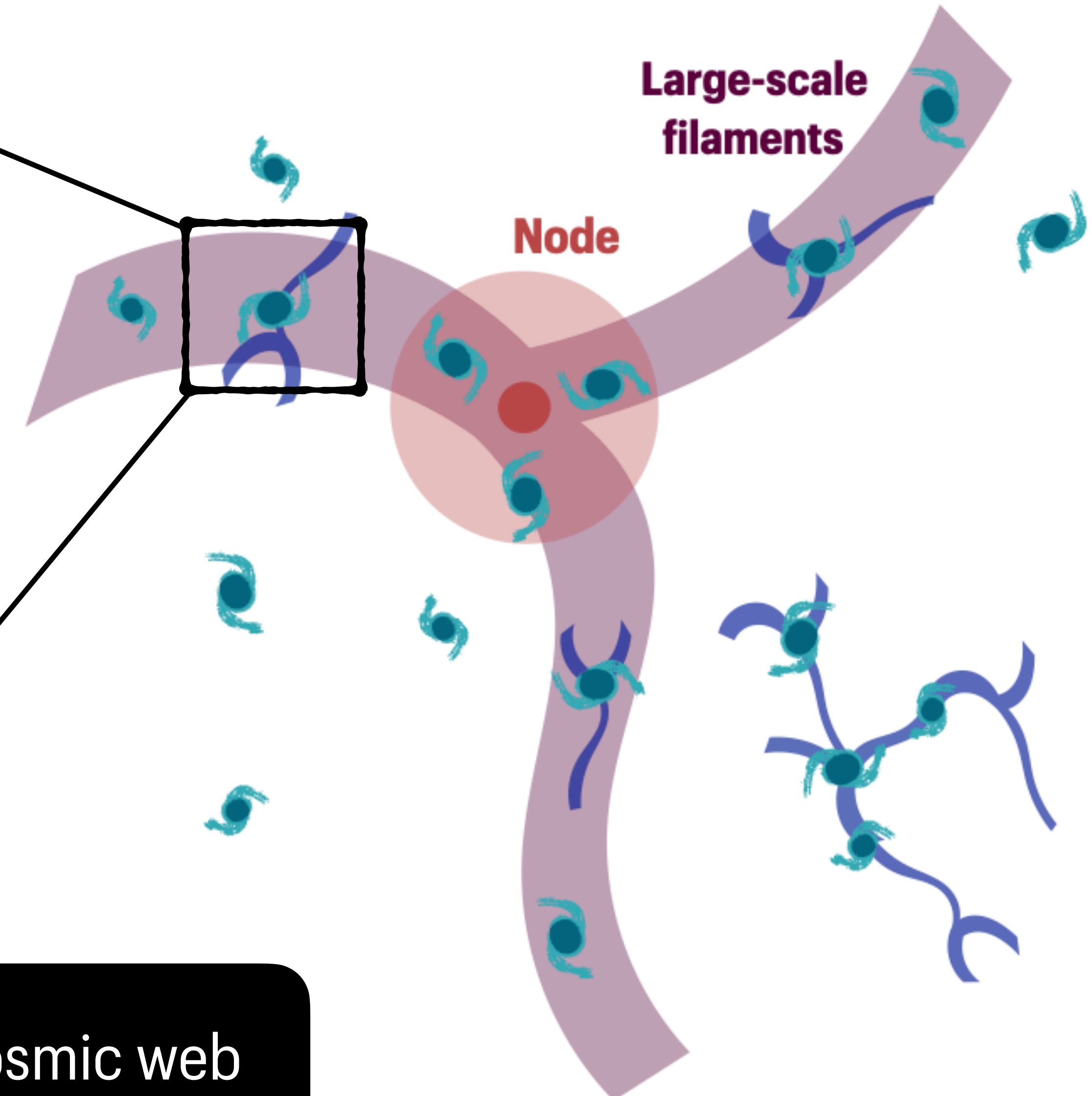


Tumlinson+ 2017



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Bauermeister+ 2010, Prescott+2015, Zabl+2019

Galaxy **star formation**, **quenching**

Finding the streams

Galarraga-Espinosa+ 2023

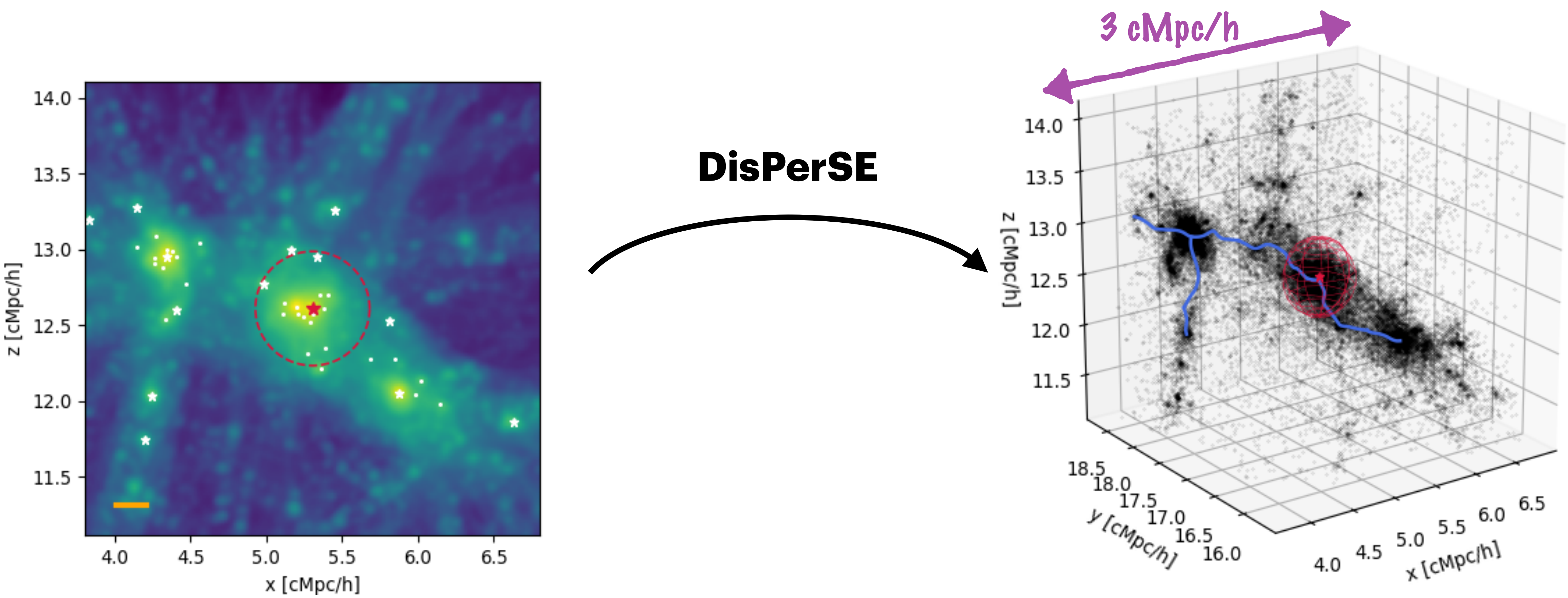
- TNG50-1 simulation
- z=2 (peak of star-formation activity)

Galaxies

- Only centrals
- Mass selection: $M_* \geq 10^8\,\mathrm{M}_\odot/h$
- **2942 galaxies**

Streams

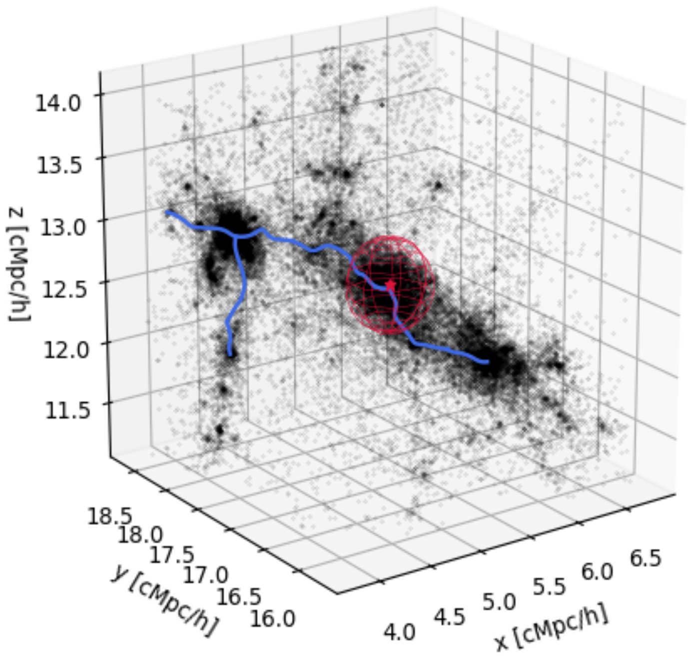
- DisPerSE to dark matter density grid
- Sub-boxes of 3 cMpc/h side length
- Grid resolution = 0.02 cMpc/h

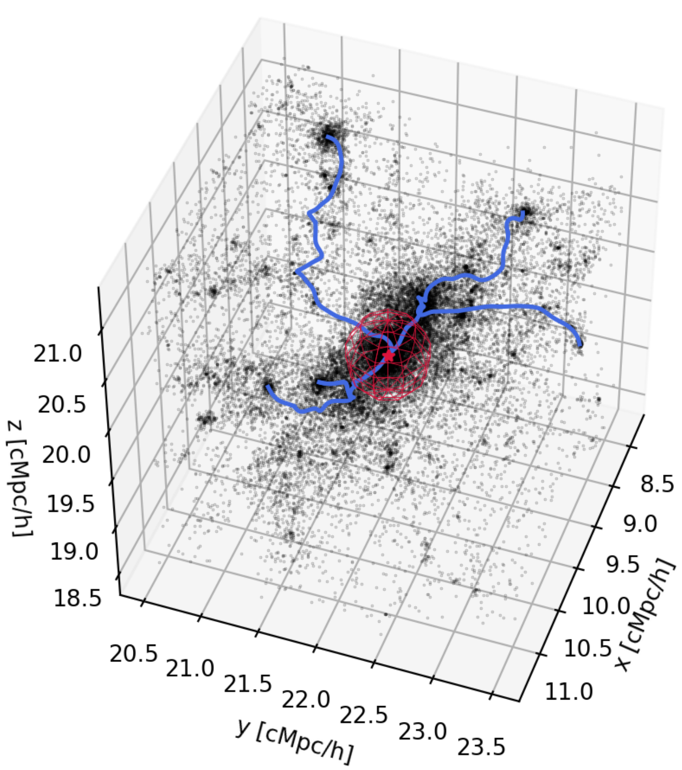


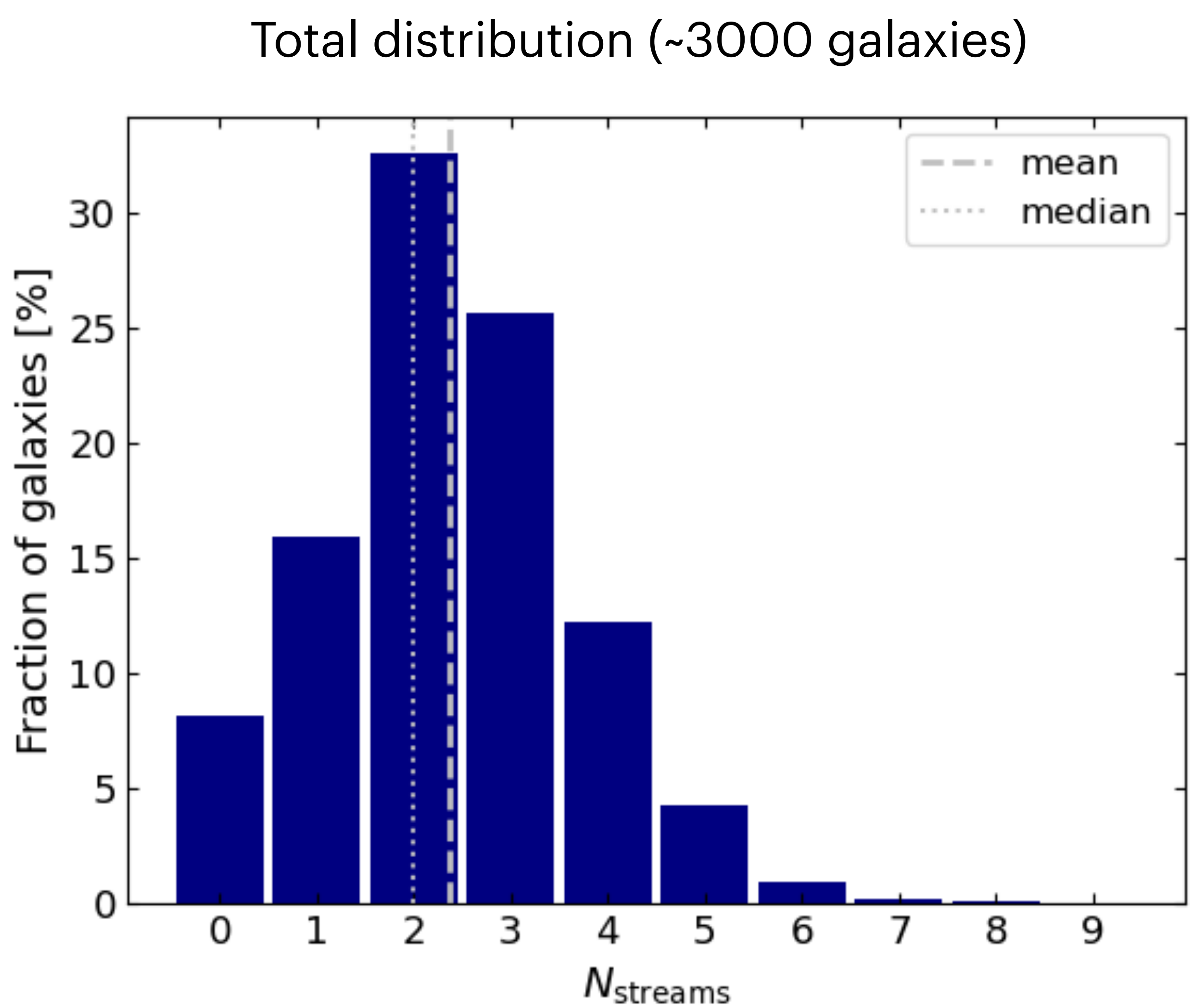
1 galaxy = 1 set of small-scale filaments

GALAXY CONNECTIVITY

Number of streams that cross the virial radius of the host halo.





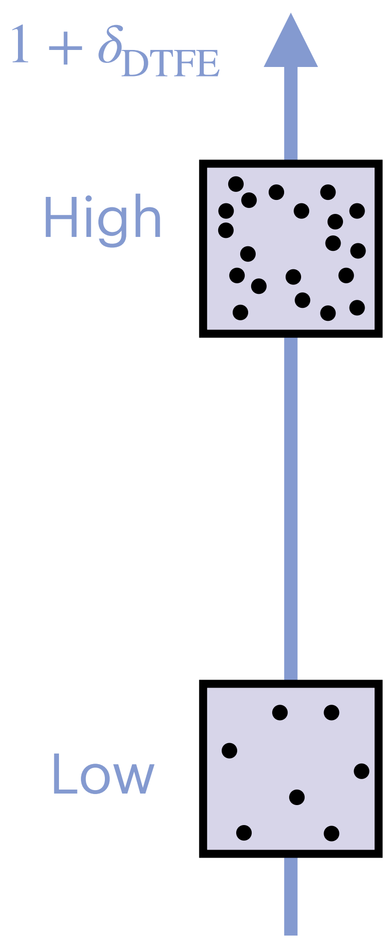


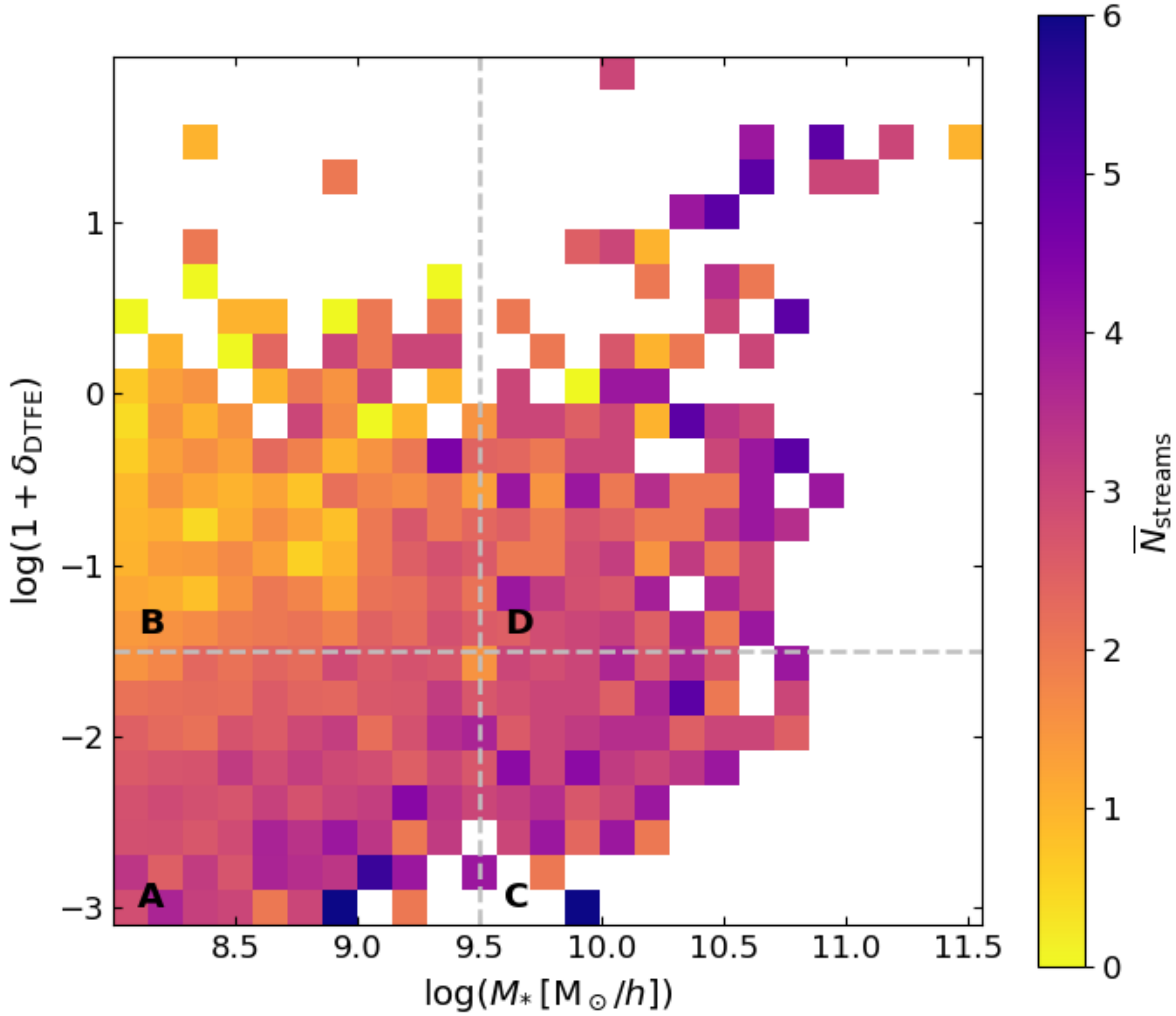
Galarraga-Espinosa+ 2023

GALAXY CONNECTIVITY

Number of streams that cross the virial radius of the host halo.

Connectivity in the mass-overdensity plane





- Trends with **mass**: similar to studies of *galaxy clusters*

  Aragón-Calvo+ 2010, Codis+2018, Darragh-Ford+ 2019, Sarron+ 2019, Malavasi+ 2020, Kraljic+ 2020, Gouin+ 2021

- Trends with **local density** for low mass galaxies

  Stronger *local* tides =>

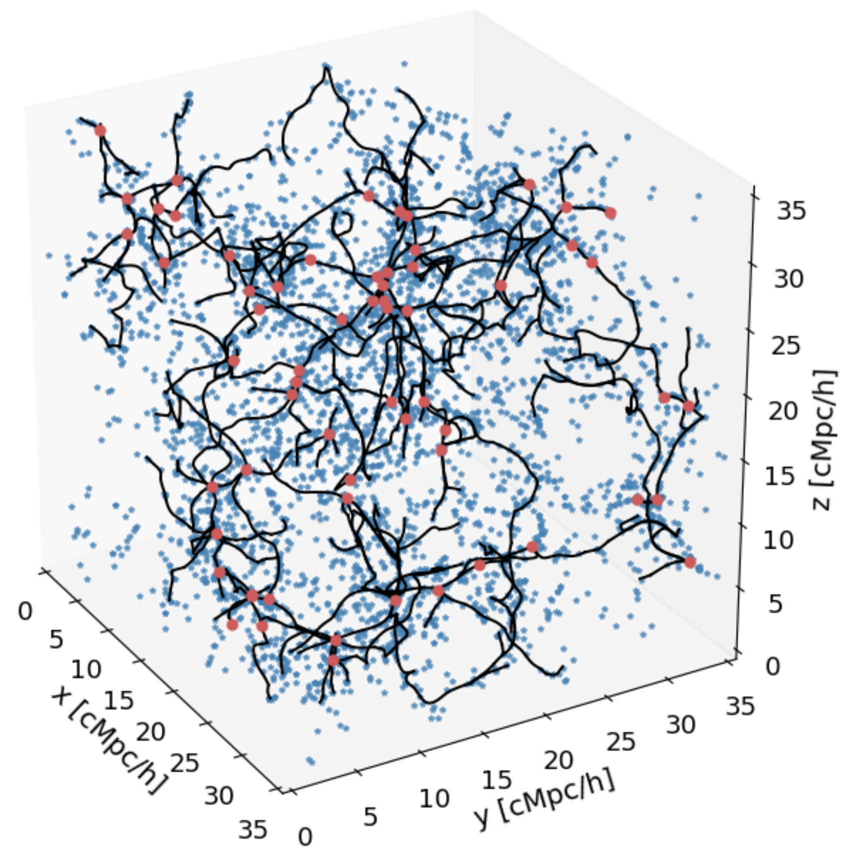
  disconnection from the local web

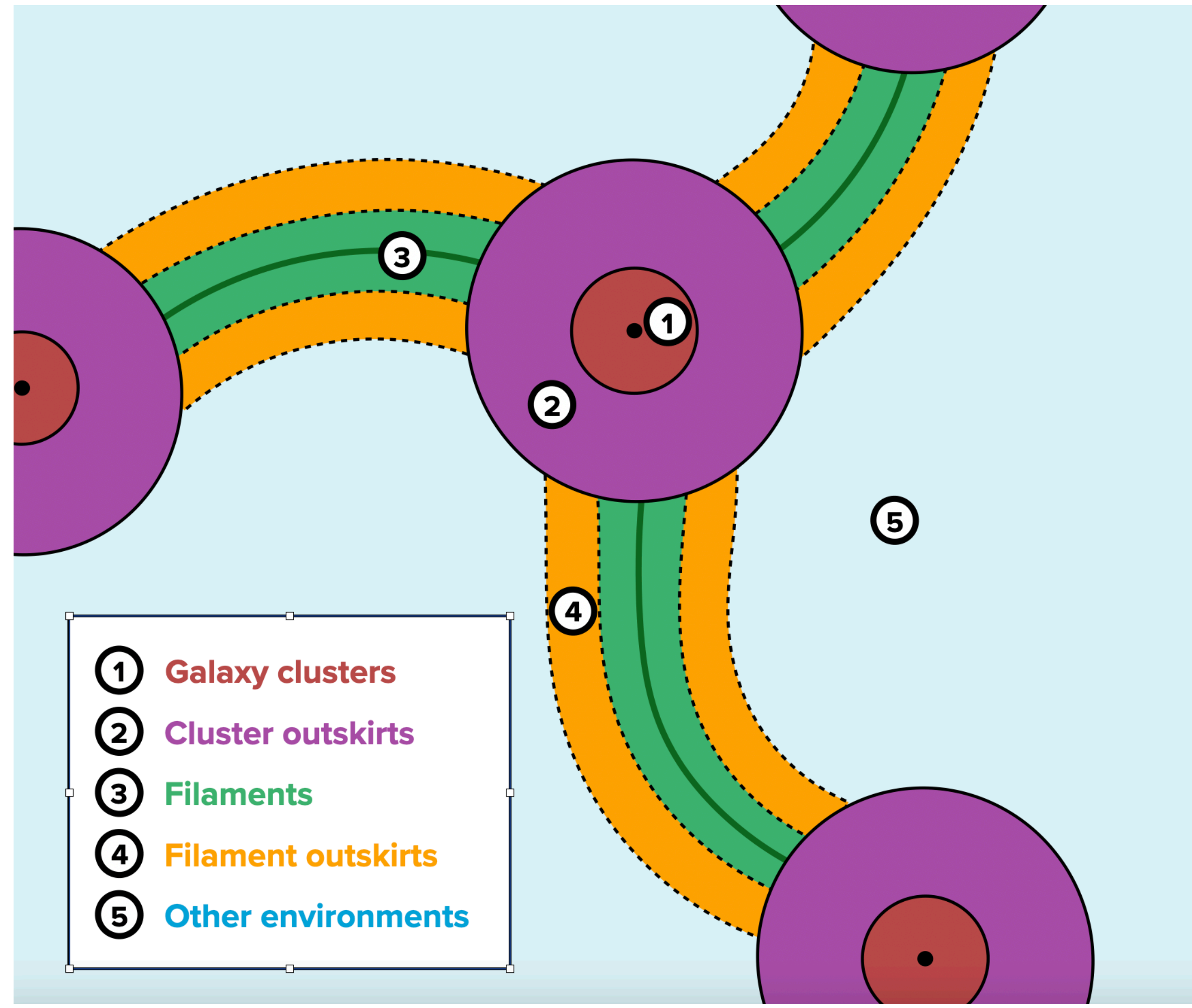
  Hahn+ 2009, Aragón-Calvo+ 2019

Galarraga-Espinosa+ 2023

Galaxies in the Large-Scale Environment

Cosmic skeleton detected from DM density, using DisPerSE on the full TNG50-1 box





	Total
All cosmic environments	2942
Voids + Walls	1211
Filament outskirts	454
Filaments	1213
Cluster outskirts	28
Galaxy Clusters	36

Definition

The rest

1 - 2 cMpc/h from filament axis

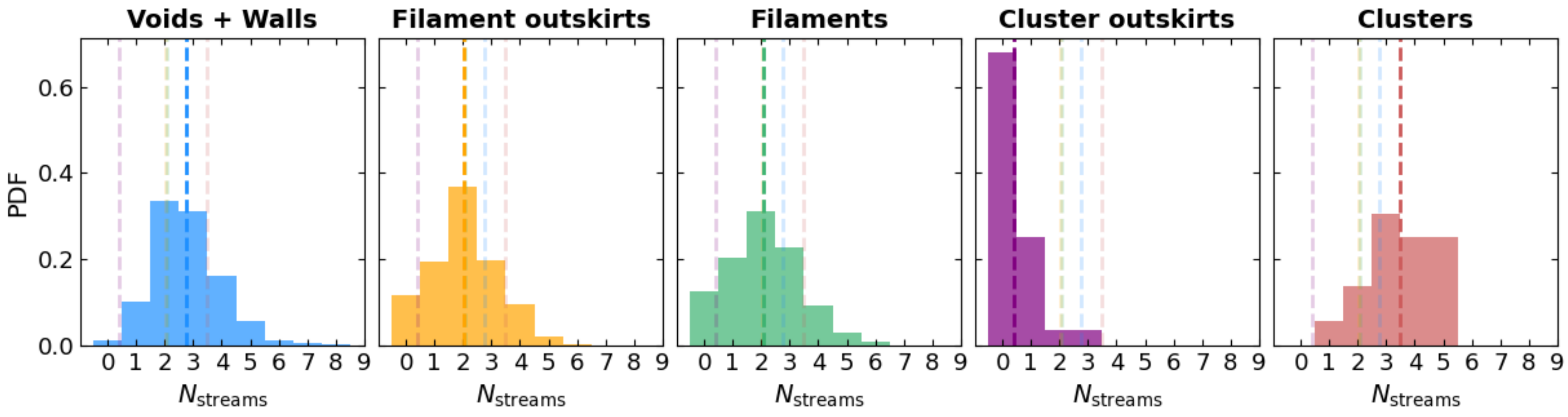
1 cMpc/h from filament axis

Within 1 - 3 R_{200}

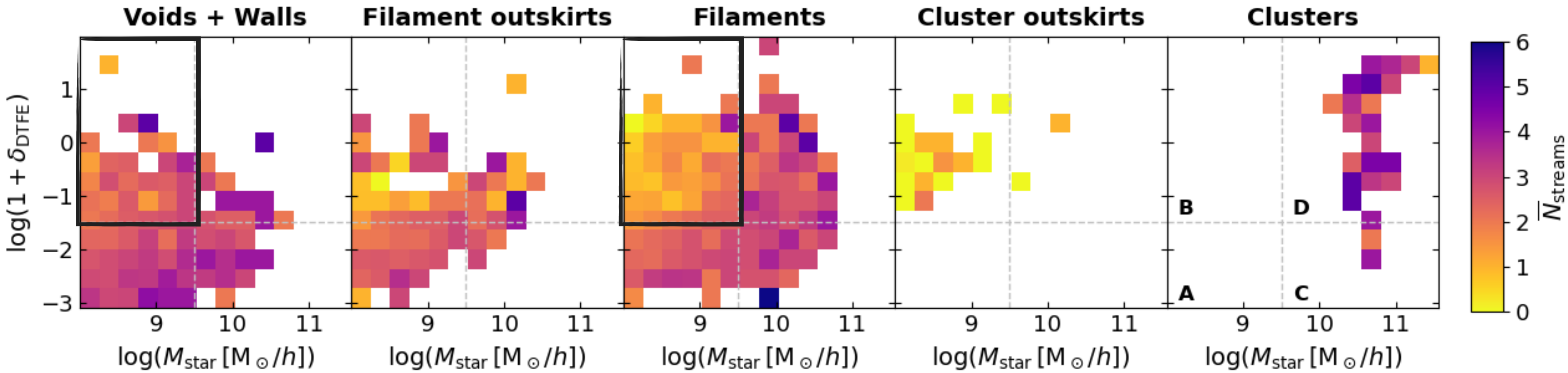
Haloes $M > 10^{12}$ $\mathrm{M}_{\odot}/h$, within R_{200}

Galaxy connectivity in different cosmic environments

Galarraga-Espinosa+ 2023



Different distributions!
Connectivity depends on location of galaxy in the cosmic web

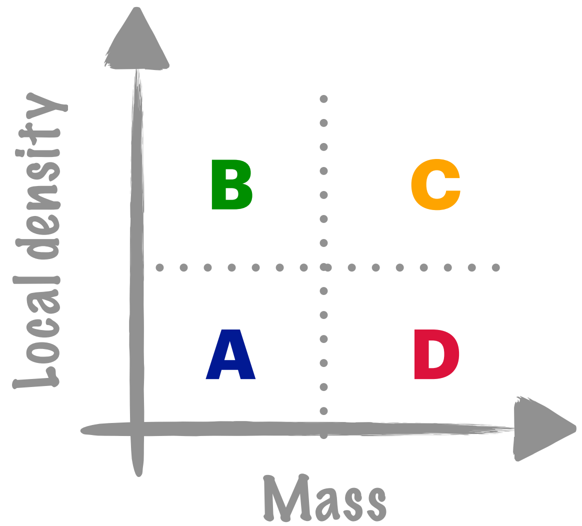


Example: in zone B
Mean = 2.34 ± 0.09 in **voids+walls**
Mean = 1.43 ± 0.05 in **filaments**
—> **8.48σ difference**

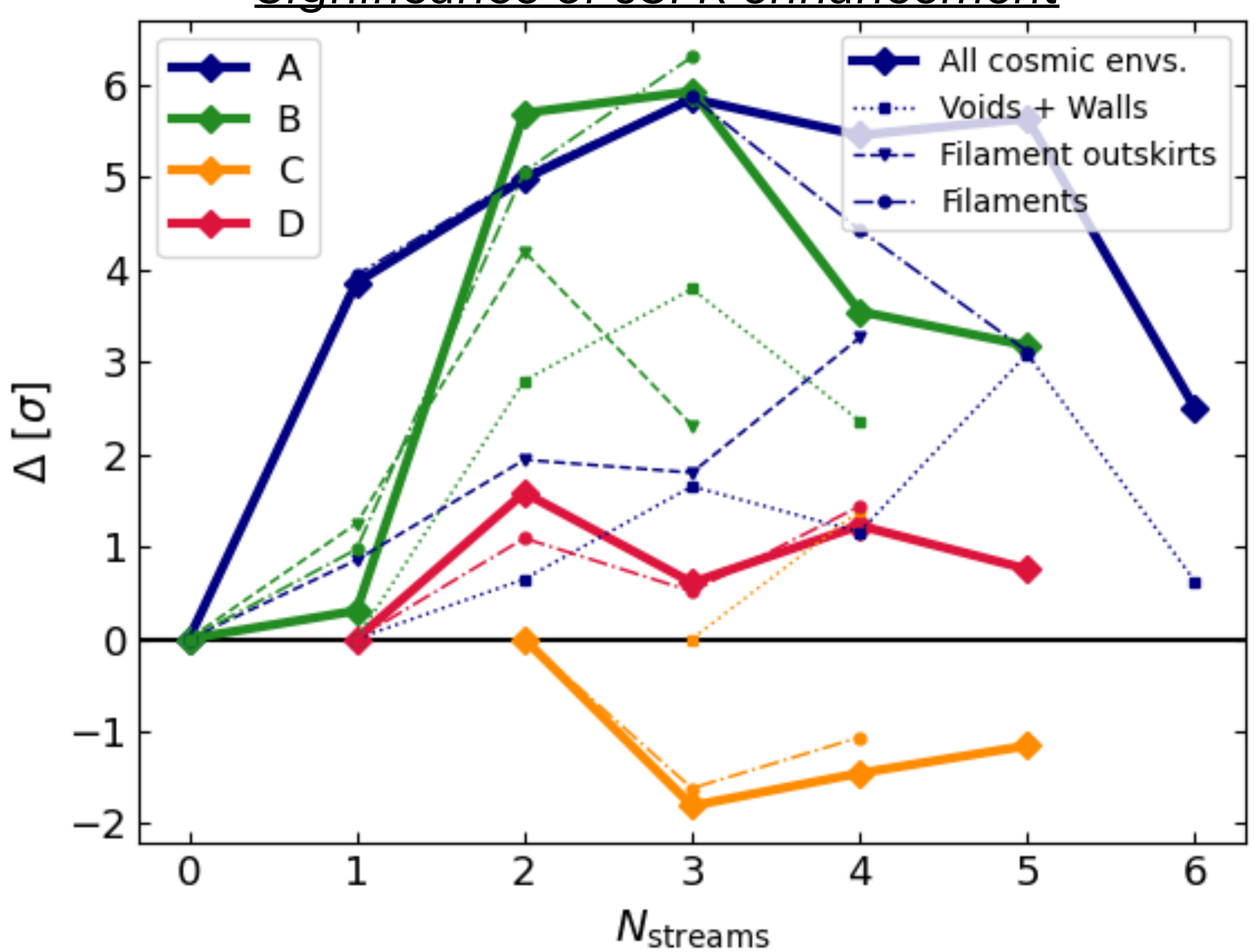
Explained by different strengths of the cosmic tidal flow
Musso+ 2018; Paranjape+ 2018; Kraljic+ 2019, Jhee+ 2022

In agreement with Borzyszkowski+ 2017; Romano-Díaz+ 2017, Garaldi+ 2018

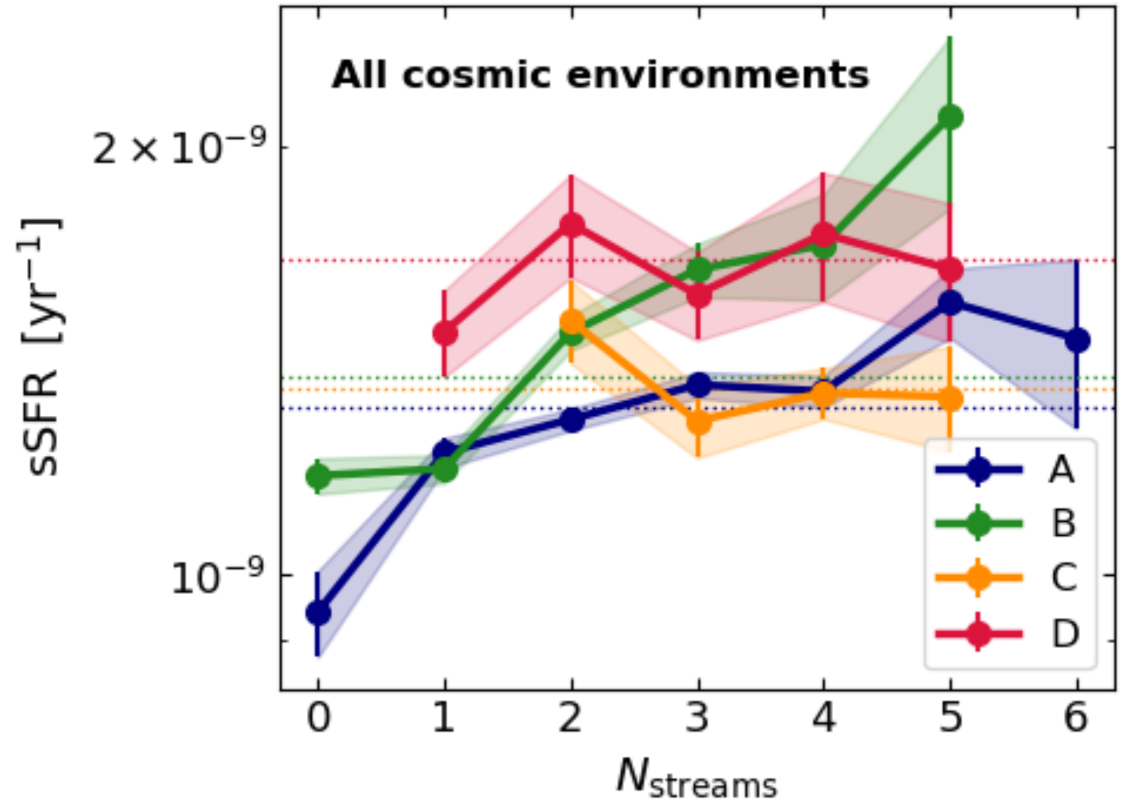
IMPACT ON STAR FORMATION



Significance of sSFR enhancement



Mean sSFR vs connectivity



sSFR significantly boosted for low mass galaxies (A -> 5.84σ, B -> 5.92σ)

larger number of streams

=> more accretion of cold material

=> boost galaxy star-formation

Maximal enhancement (6.30σ) for low mass galaxies in <u>cosmic filaments</u>

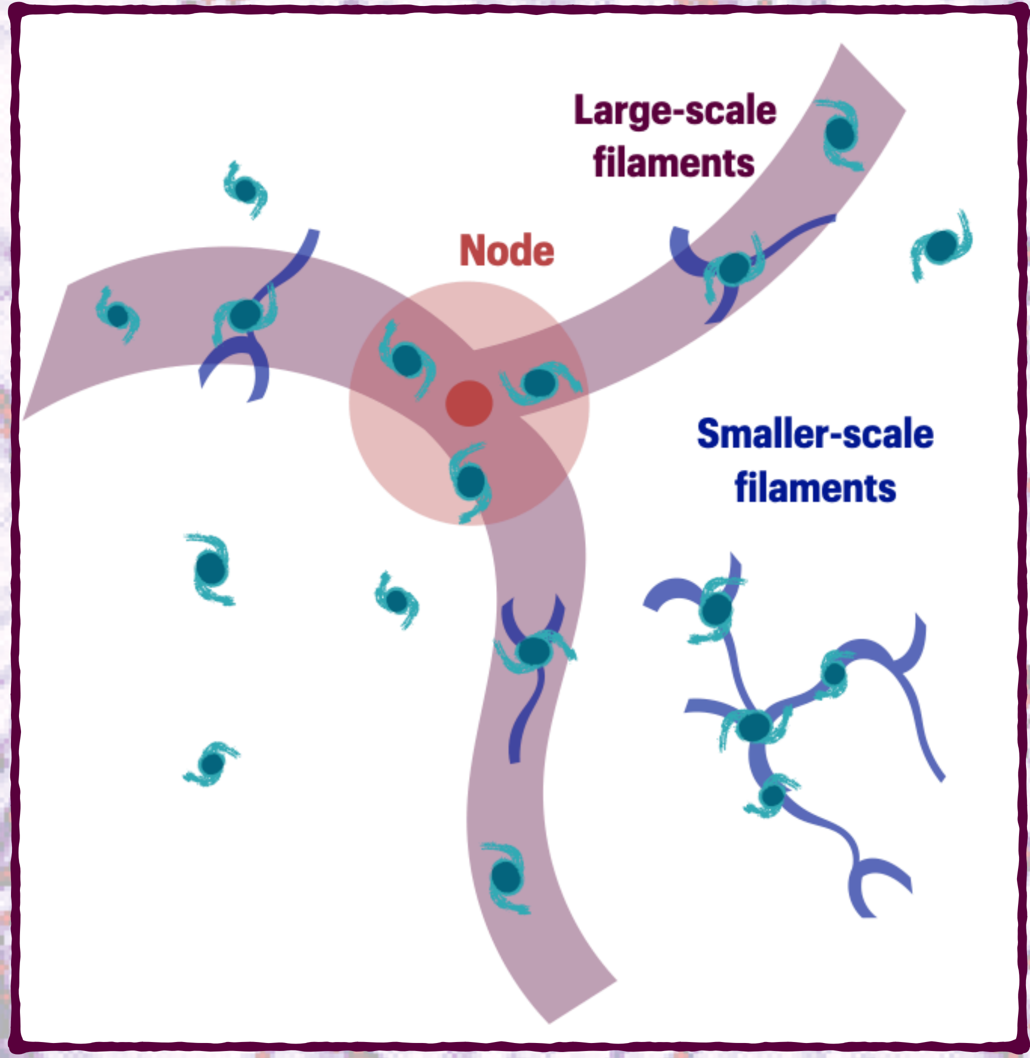
(importance of matter reservoirs!)

Galarraga-Espinosa+ 2023

CONCLUSIONS: GALAXIES IN THEIR MULTI-SCALE ENVIRONMENT

- **At fixed mass and local density (z=2):**
  - **Galaxy connectivity** depends on location in **cosmic web** structures
  - Low mass galaxies: **connectivity enhances the sSFR** (~6σ)!
- Cosmic filaments are rich environments to study galaxy evolution
  - Different populations of galaxies co-exist
  - Less extreme than clusters
  - Diversity in gas density and temperature (see first part of the talk)

Galárraga-Espinosa+ 2023



FUTURE PERSPECTIVES:

- Matter transport via DM streams? Gas properties?
- What fraction of gas accreted via the streams vs isotropic accretion?
- Picture from z=2 to z=0?

+ Currently working on detection of the streams in observations (J-PAS, Bonoli+2021)

THANK YOU FOR YOUR ATTENTION!

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