MAX PLANCK INSTITUTE
FOR ASTROPHYSICS

KITP Cosmic Web Workshop
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Filaments

from the large-scale structure to the CGM

Daniela Galárraga-Espinosa

Postdoc Fellow
@ Max-Planck-Institute for Astrophysics (MPA-Garching)

Main collaborators: Nabila Aghanim (IAS-France), Mathieu Langer (IAS-France), Guinevere Kauffmann (MPA-Germany), Enrico Garaldi (MPA-Germany), Hideki Tanimura (IPMU-Japan)

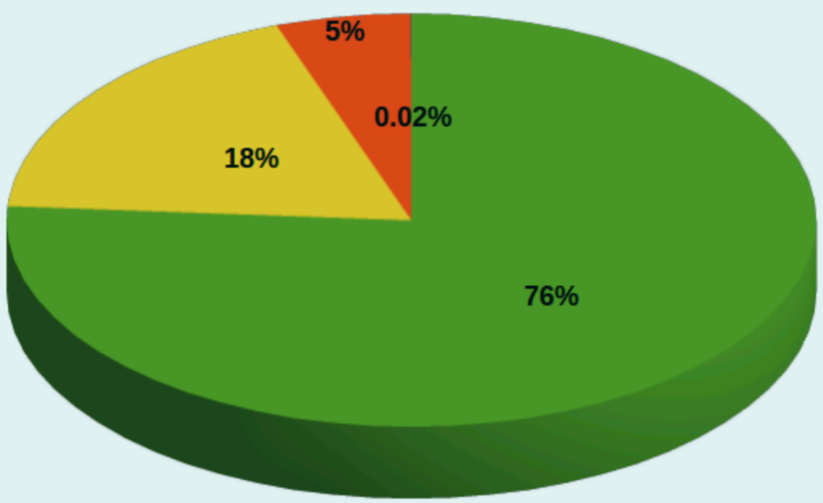
danigaes@mpa-garching.mpg.de

Matter in the Cosmic Web

Several studies based on numerical simulations:

At z=0:

Volume fraction



Ganeshaiah Veena+ 2019

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

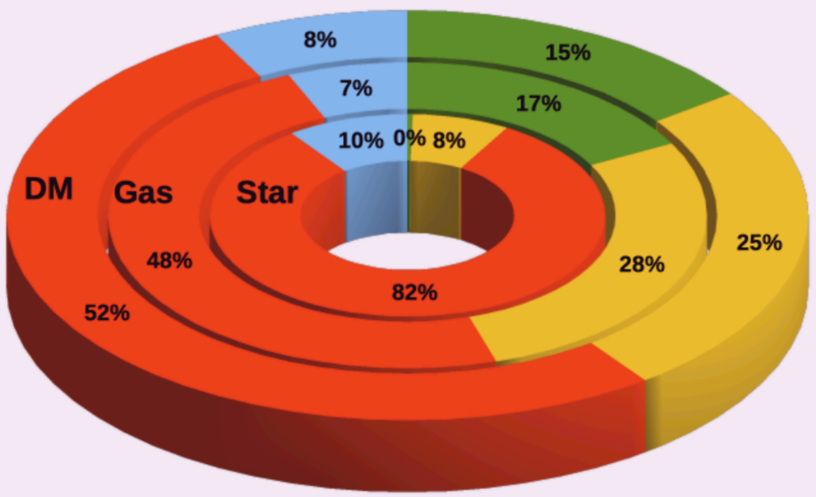
Nodes

Filaments

Walls

Voids

Mass fraction



Ganeshaiah Veena+ 2019

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

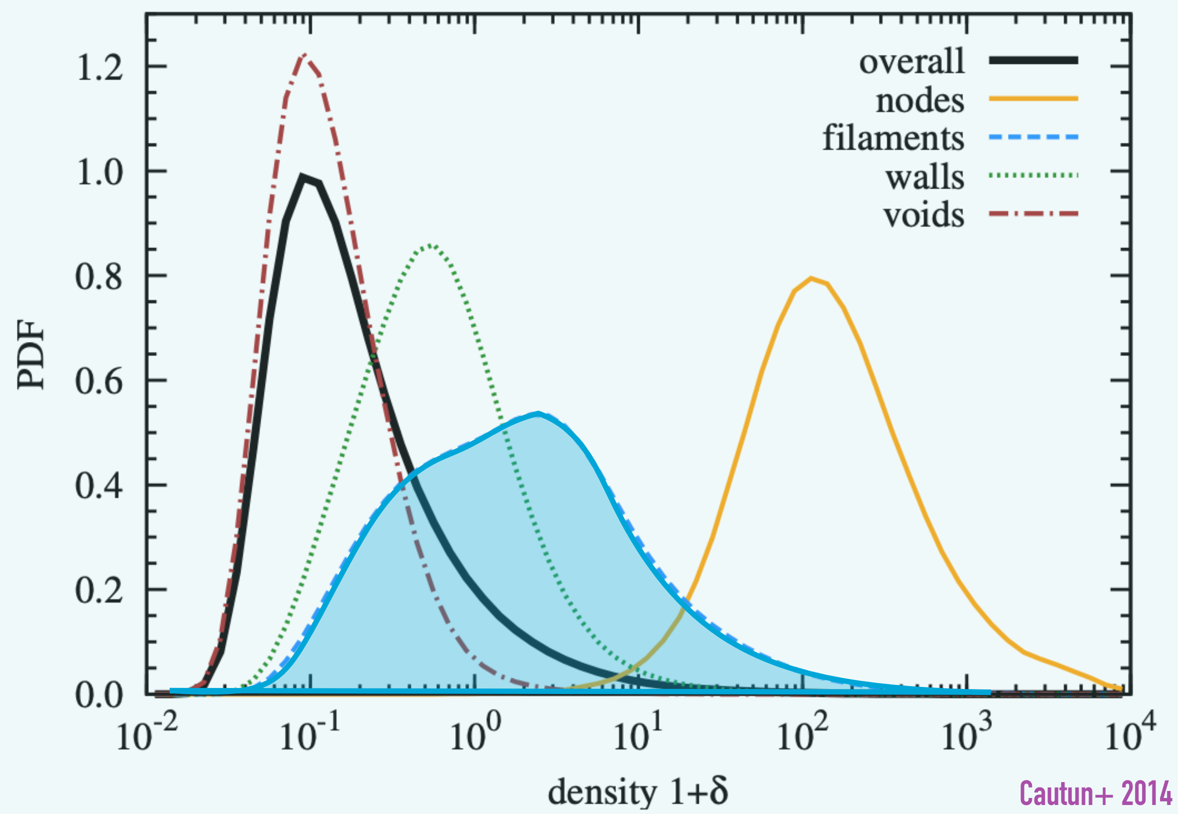
The study of matter at the largest scales is inevitably tied to that of filaments

Matter in the Cosmic Web

Several studies based on numerical simulations:

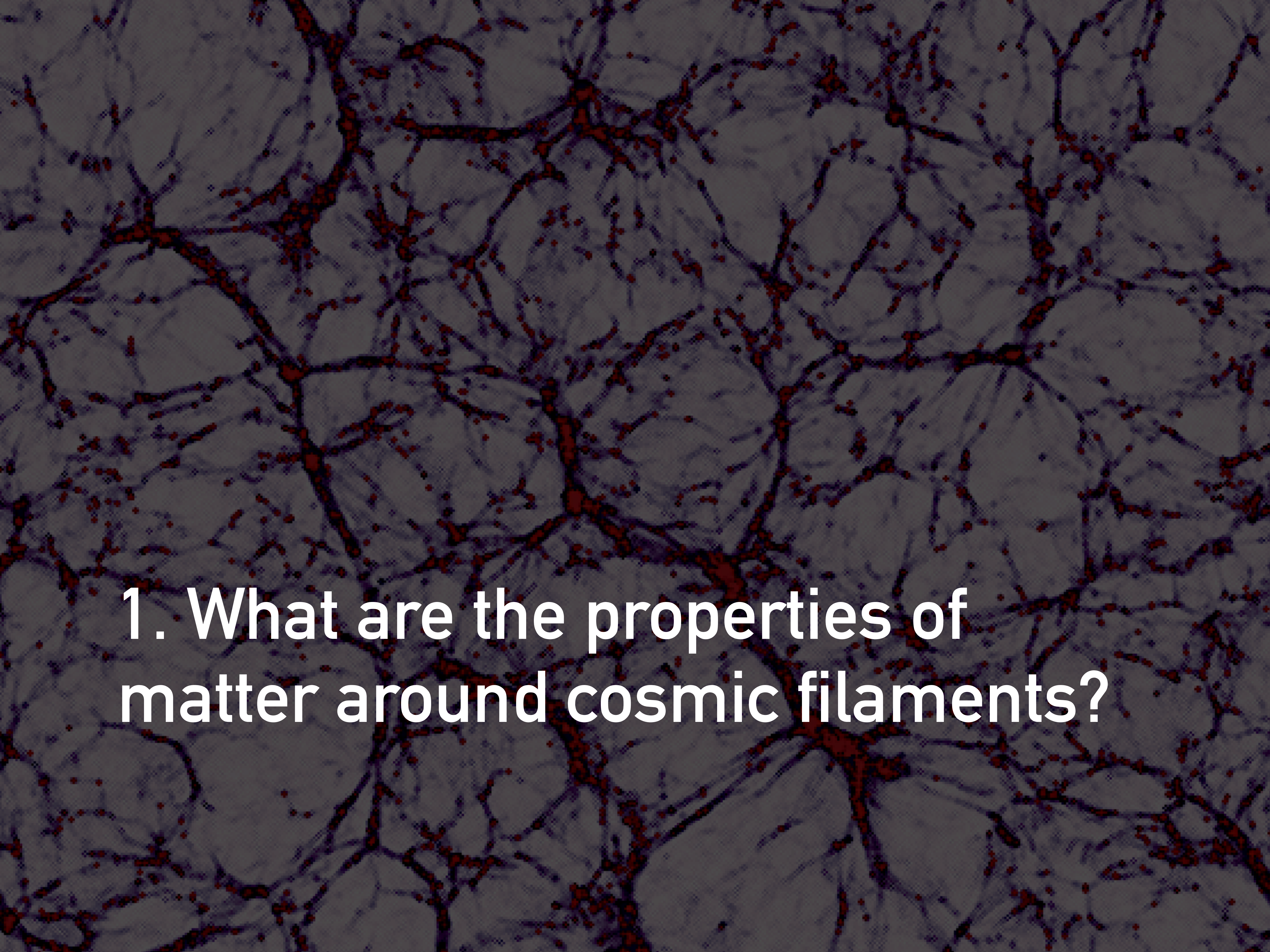
At z=0:

Density distribution



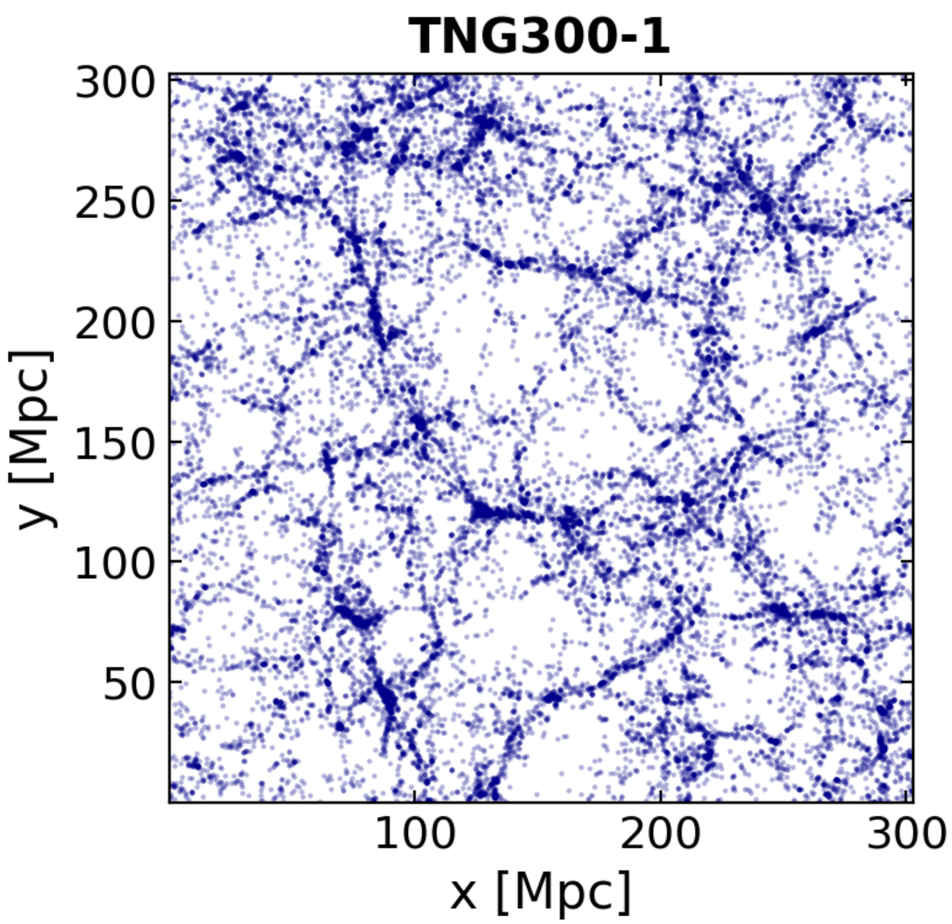
Huge diversity of filaments
(spanning 5 orders of magnitude in density!)

Diversity —> Imprints on the properties of matter?



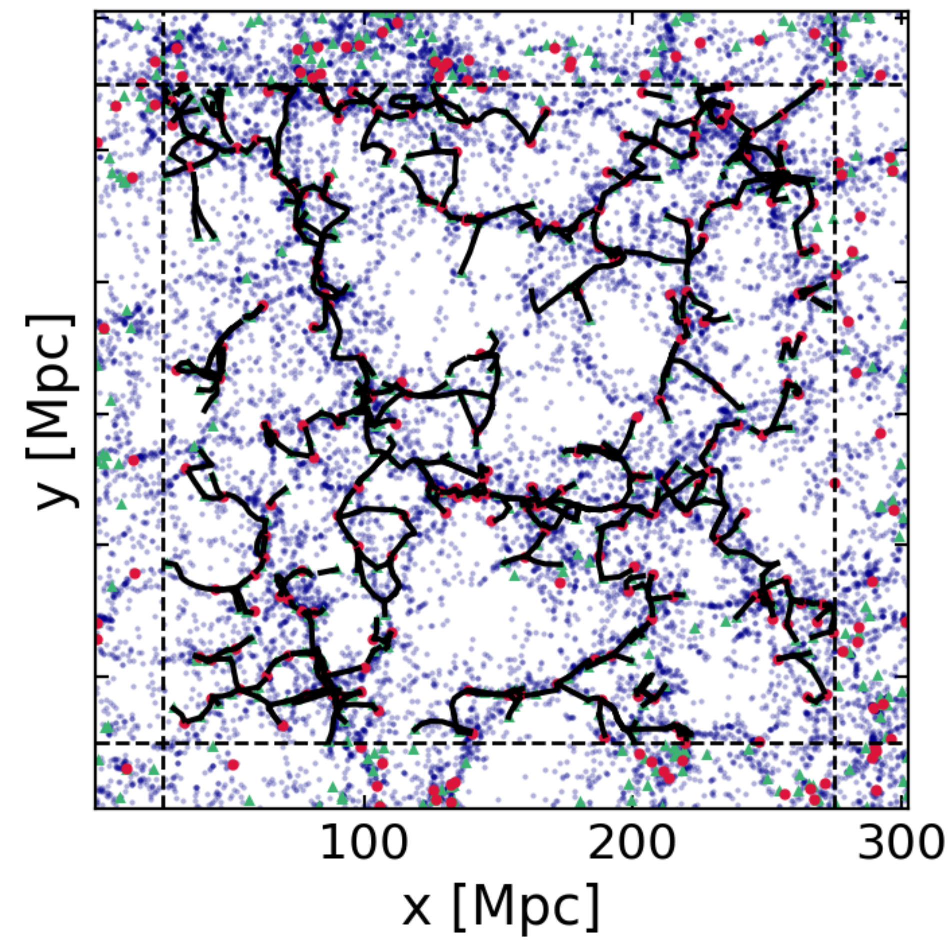
1. What are the properties of matter around cosmic filaments?

Detecting the cosmic filaments

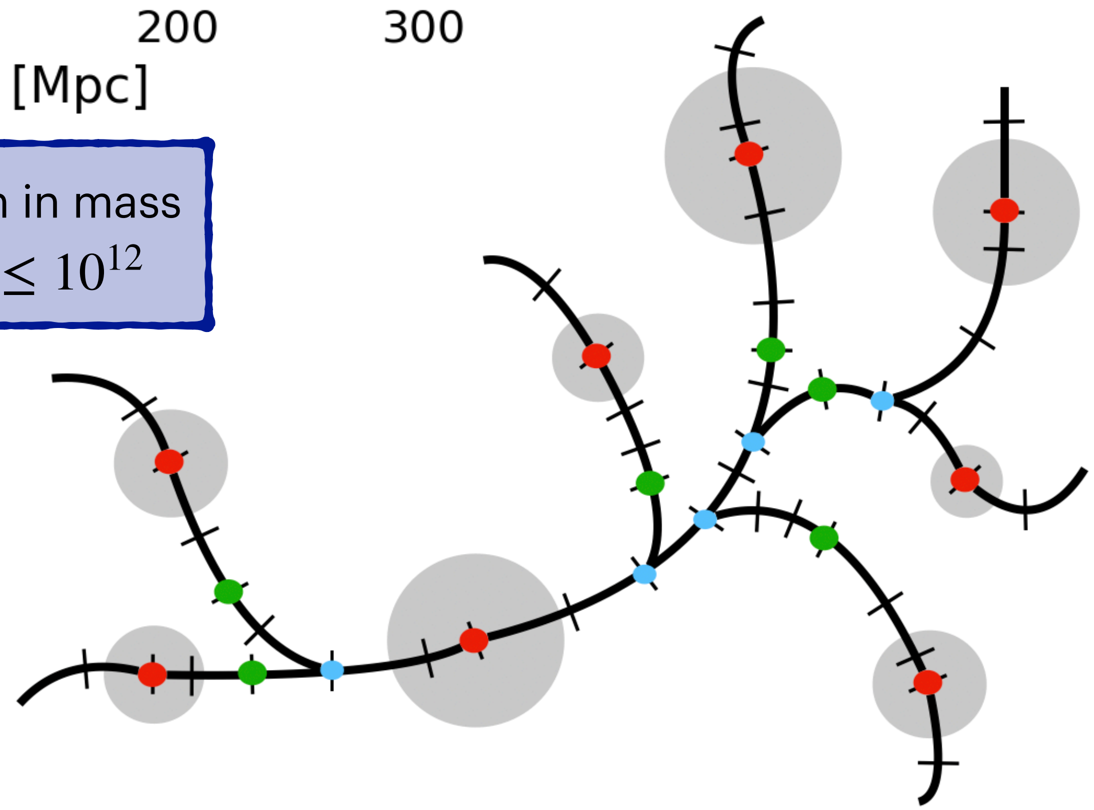


Filament finder code
DisPerSE

(Sousbie+ 2011, Sousbie 2011)



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



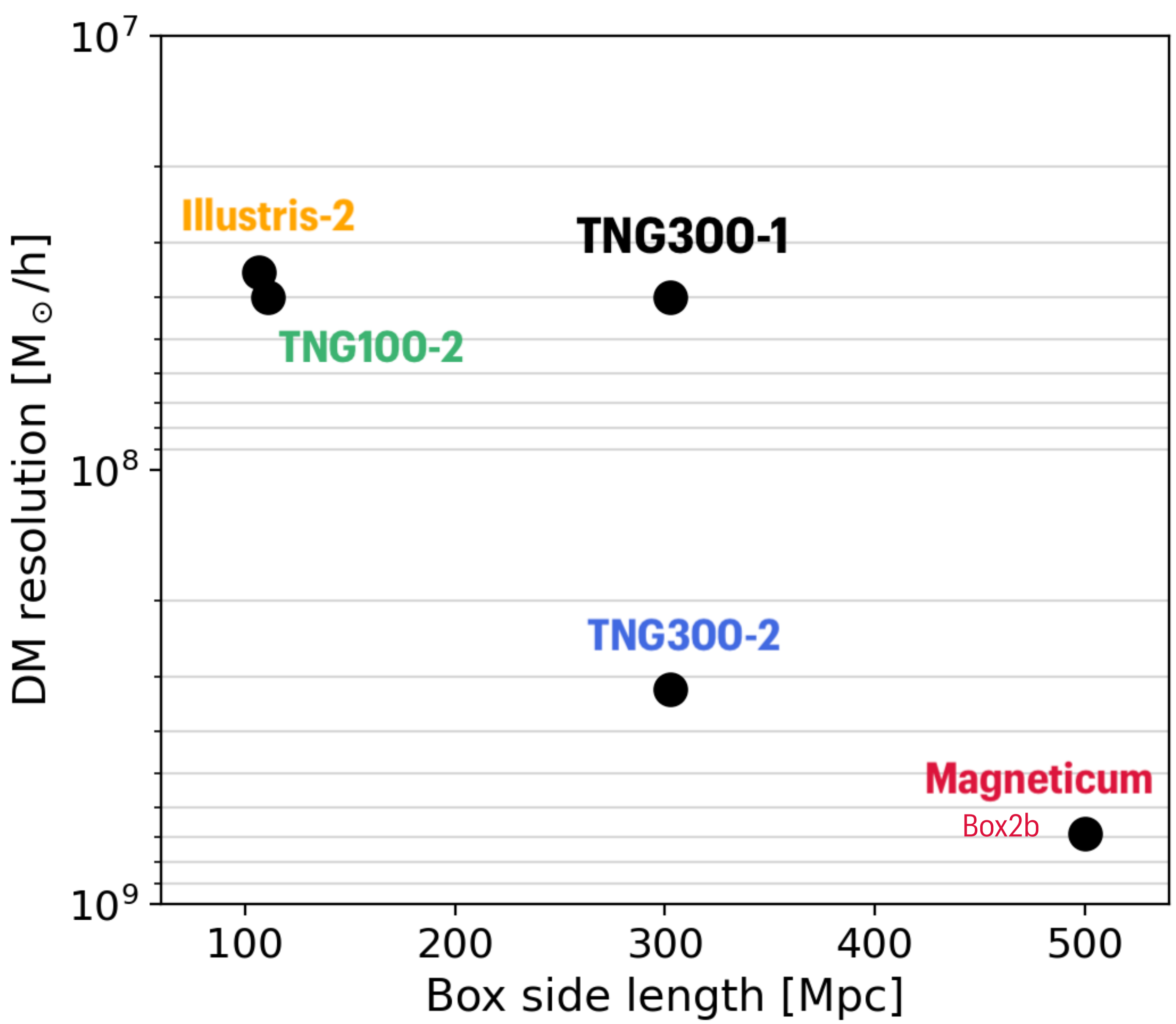
Filaments = sets of segments connecting **maximum density** critical points (CPmax) to **saddles**

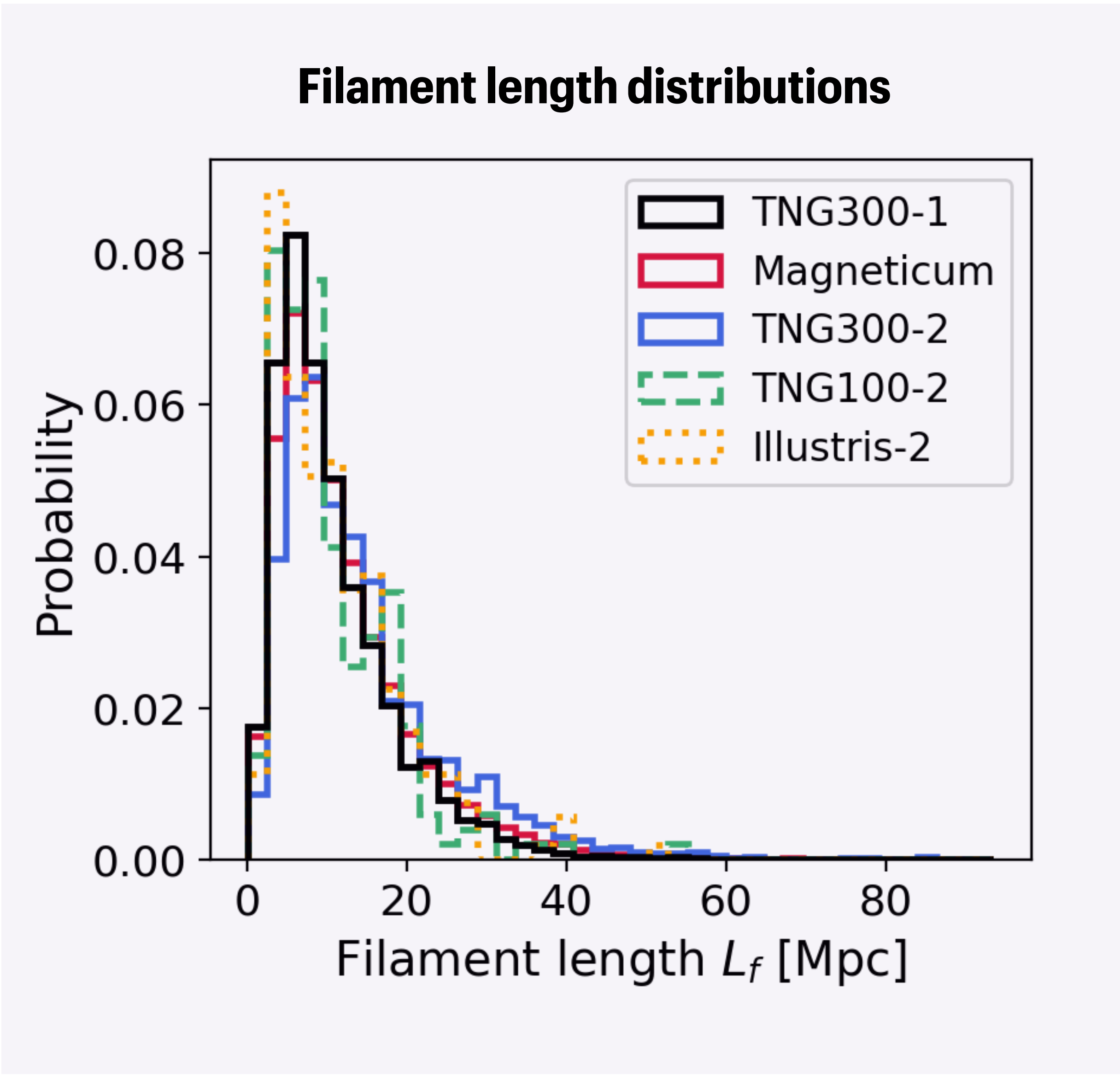
Galarraga-Espinosa+ 2020

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

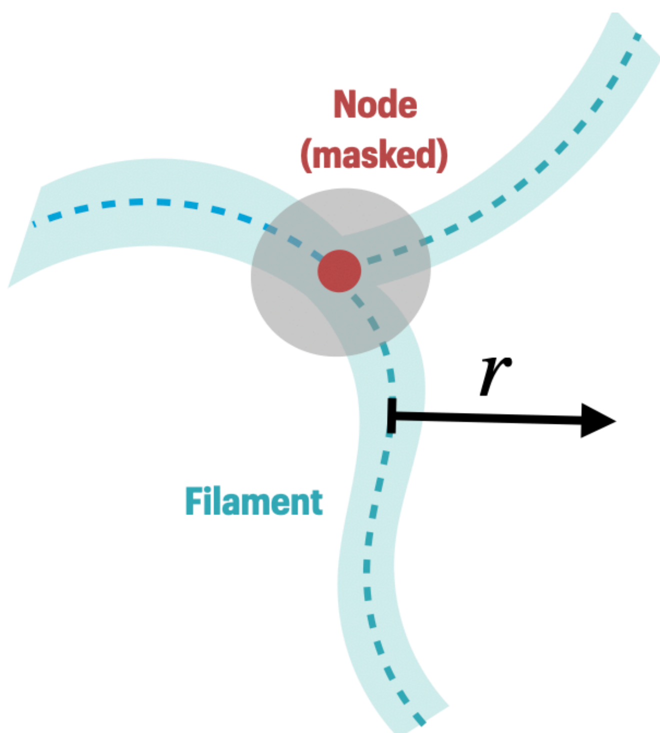




Galarraga-Espinosa+ 2020

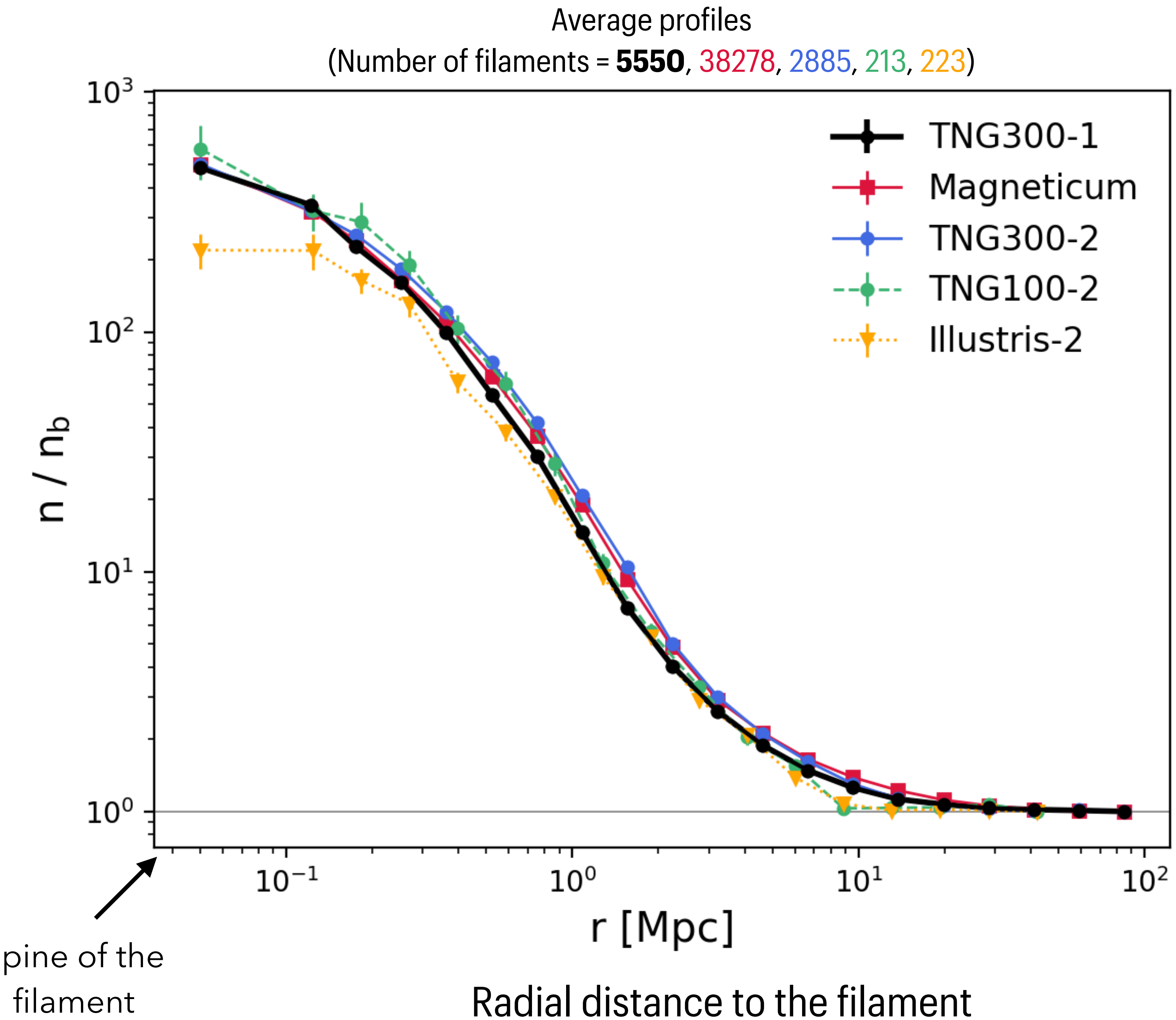
Galaxy distribution around filaments

Galarraga-Espinosa+ 2020



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

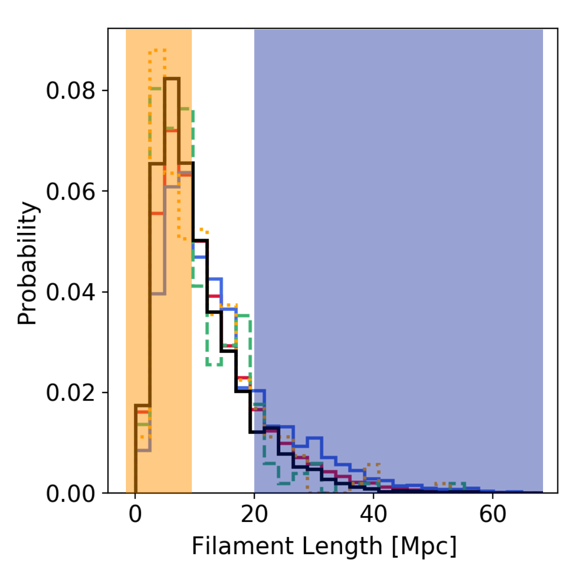
Number density of galaxies



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

Exploring the extremes

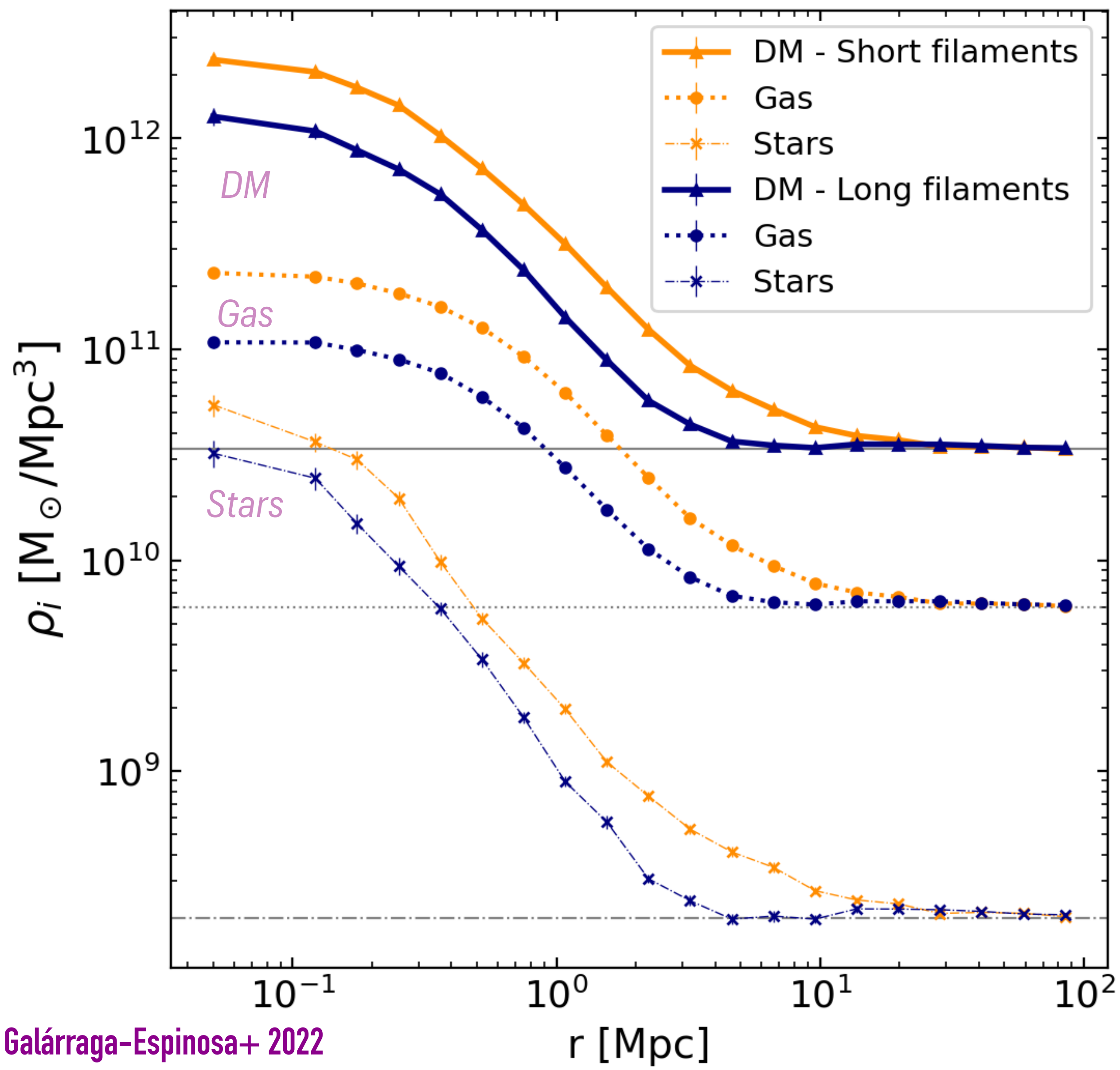
(TNG300-1 simulation)



Short: $L_f < 9$ Mpc

Long: $L_f \geq 20$ Mpc

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



Galárraga-Espinosa+ 2022

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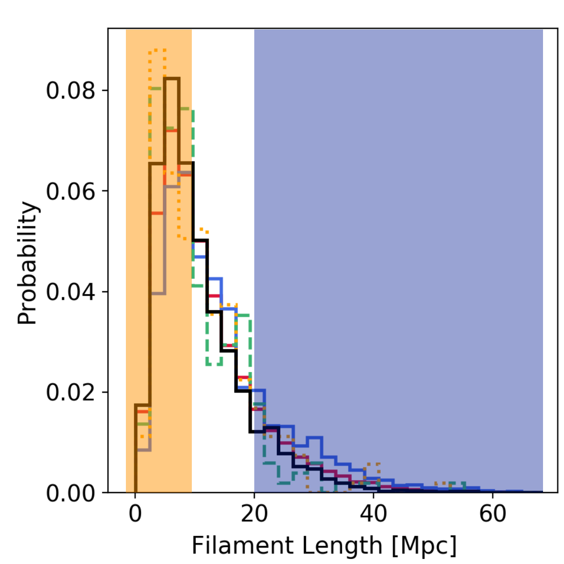

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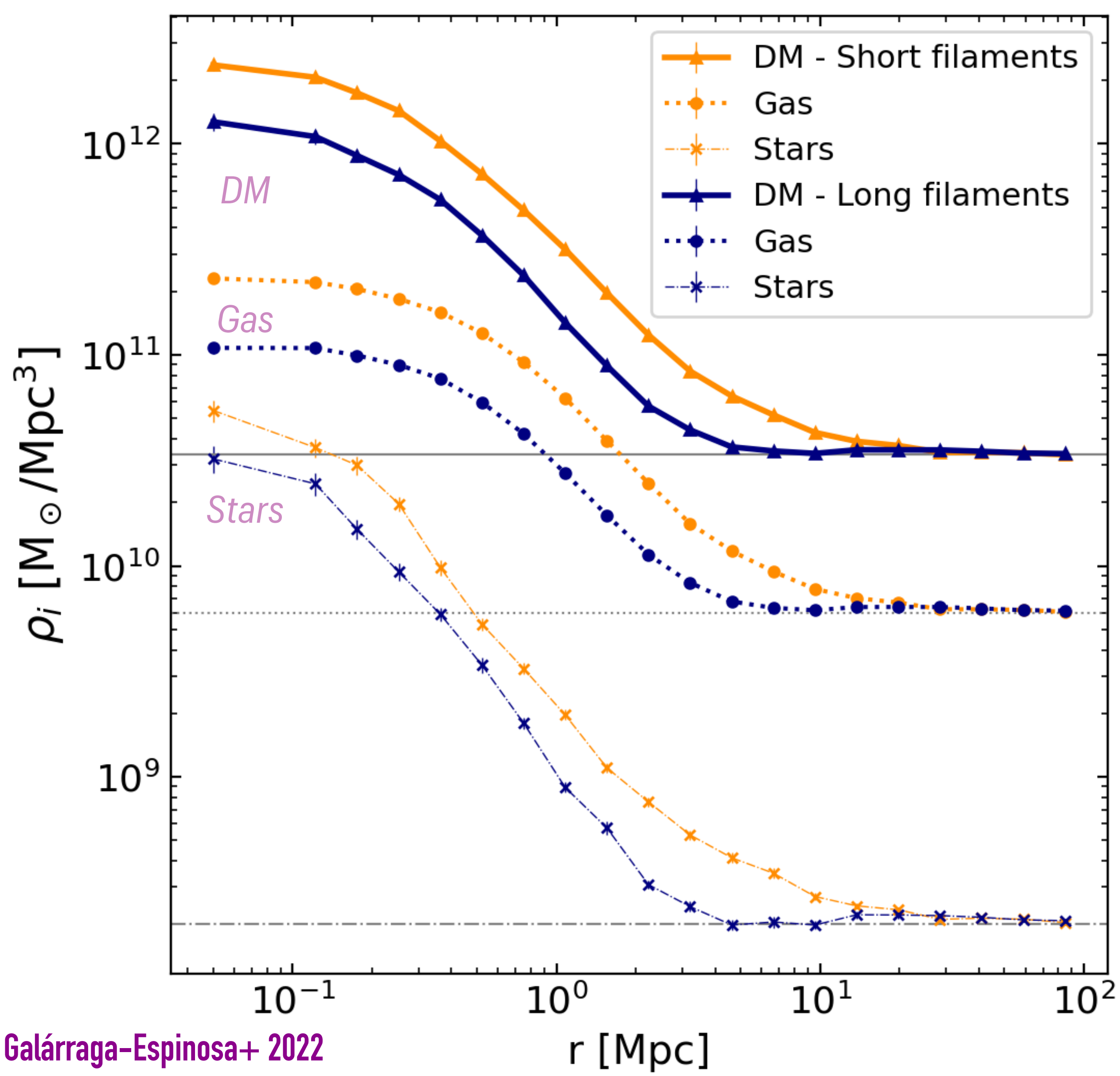
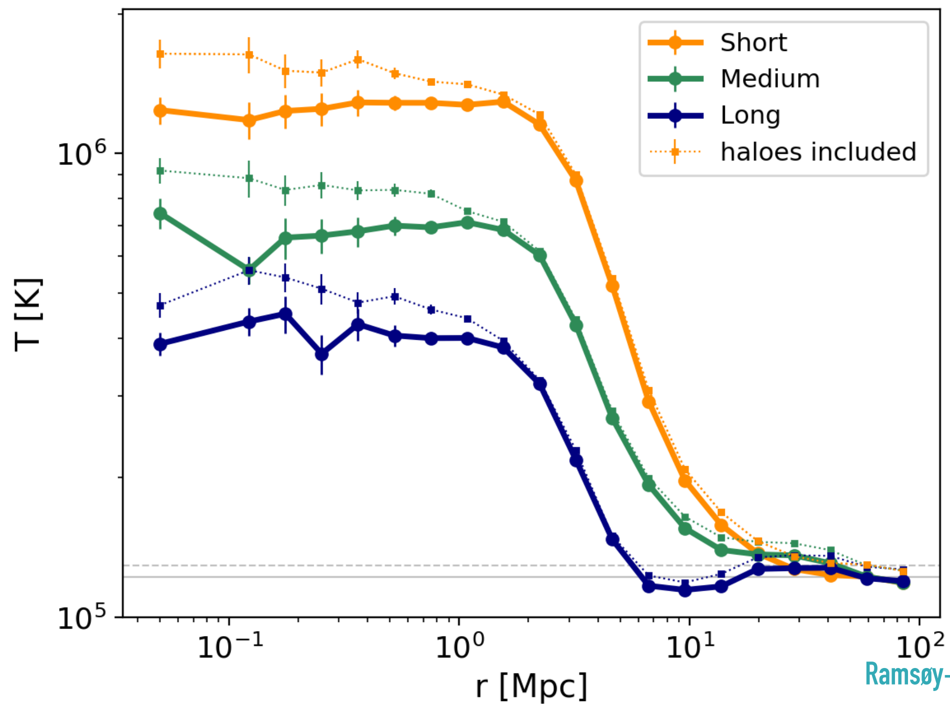


Galárraga-Espinosa+ 2022

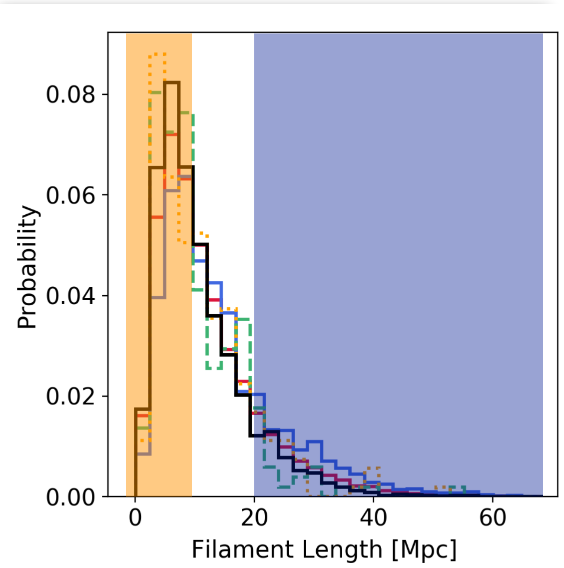
Average gas **temperature** profiles



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

Galarraga-Espinosa+ 2021

Exploring the extremes



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(TNG300-1 simulation)

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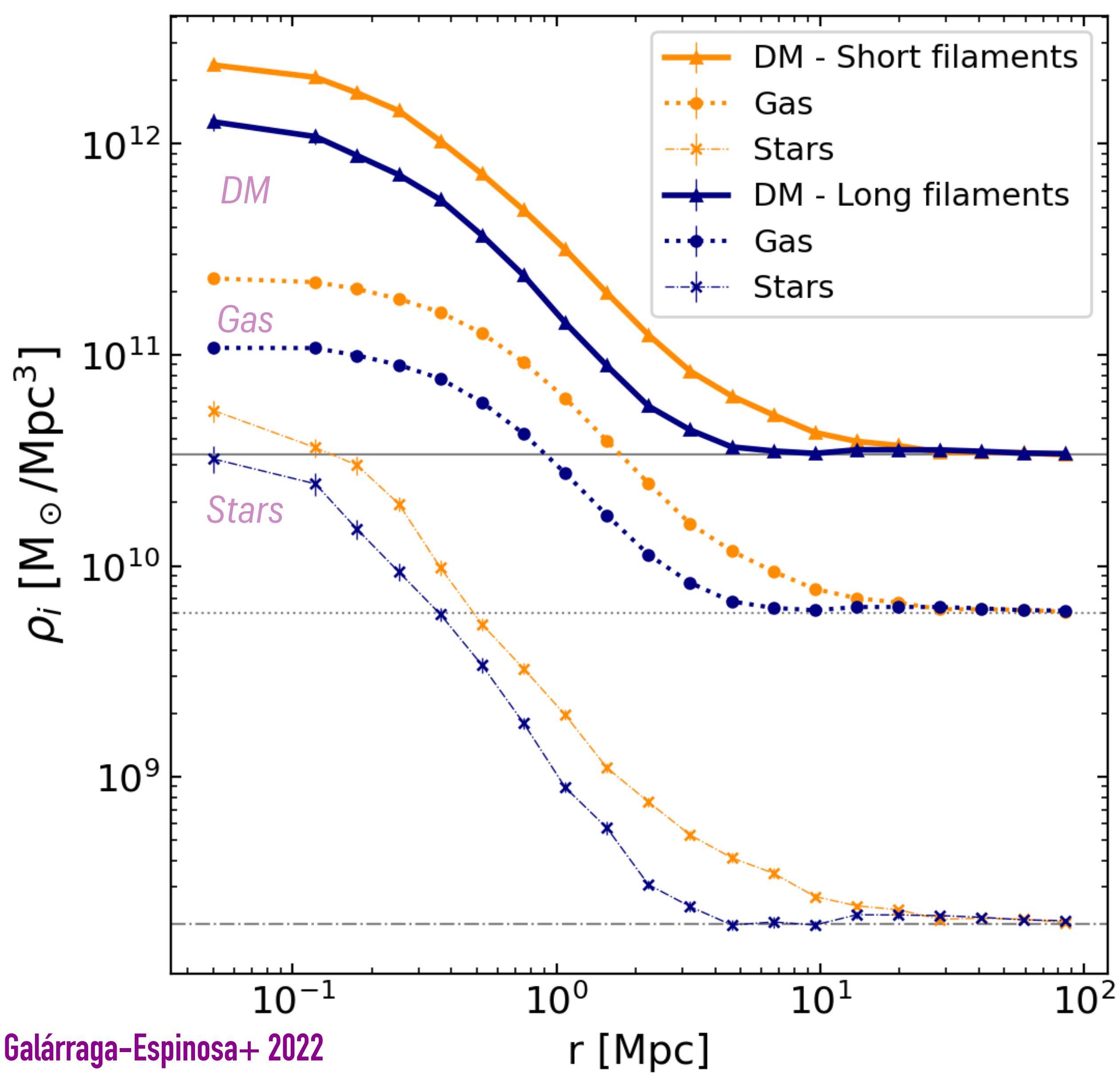

Galárraga-Espinosa+ 2022

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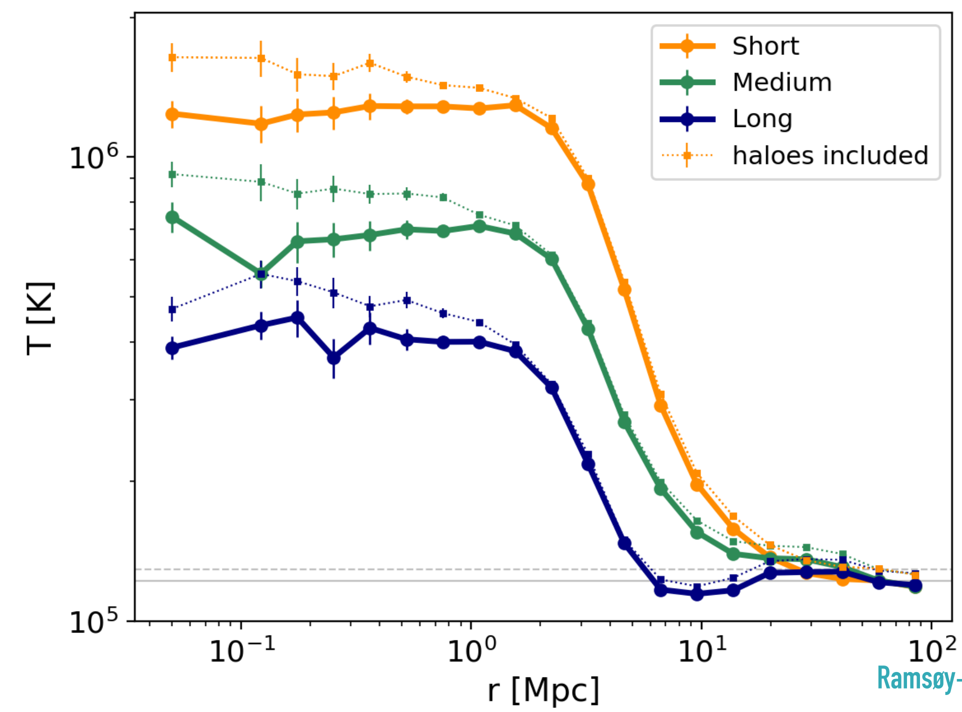

In agreement with
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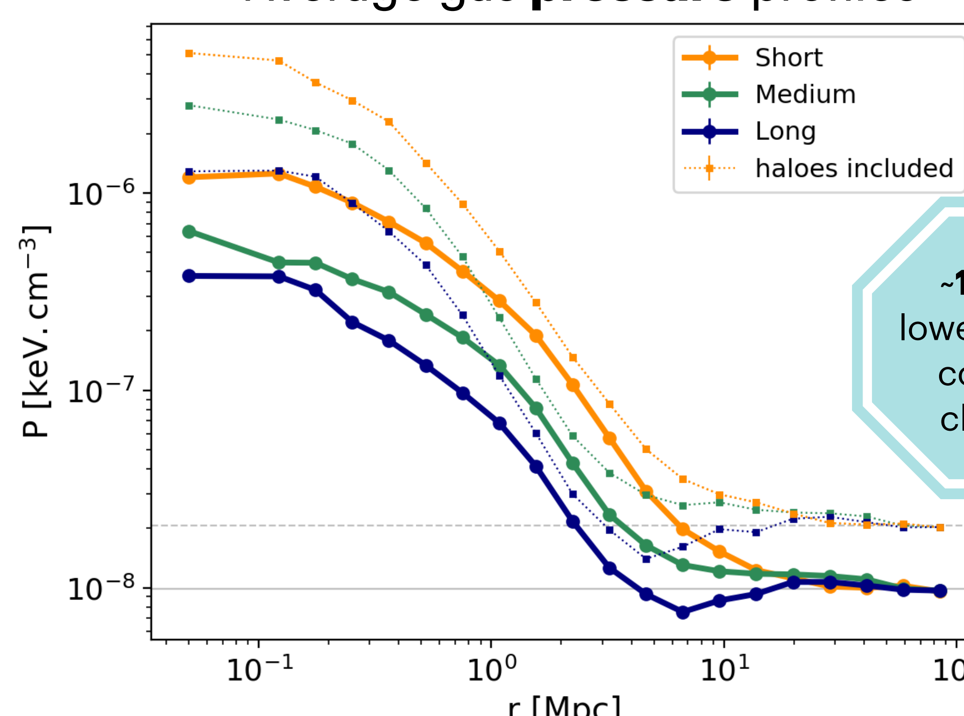
Tuominen+ 2020
Ramsøy+ 2021 (smaller scale filaments)

Average gas **pressure** profiles



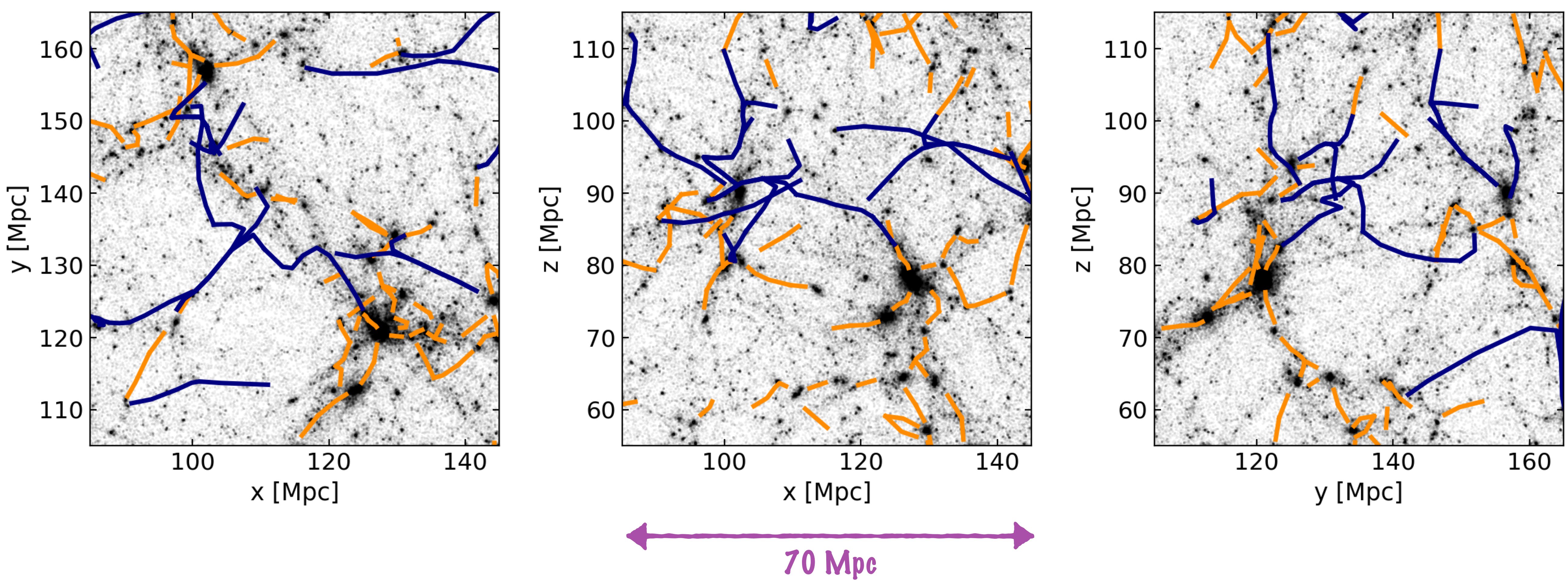
~1000x lower than in cores of clusters

Galarraga-Espinosa+ 2021

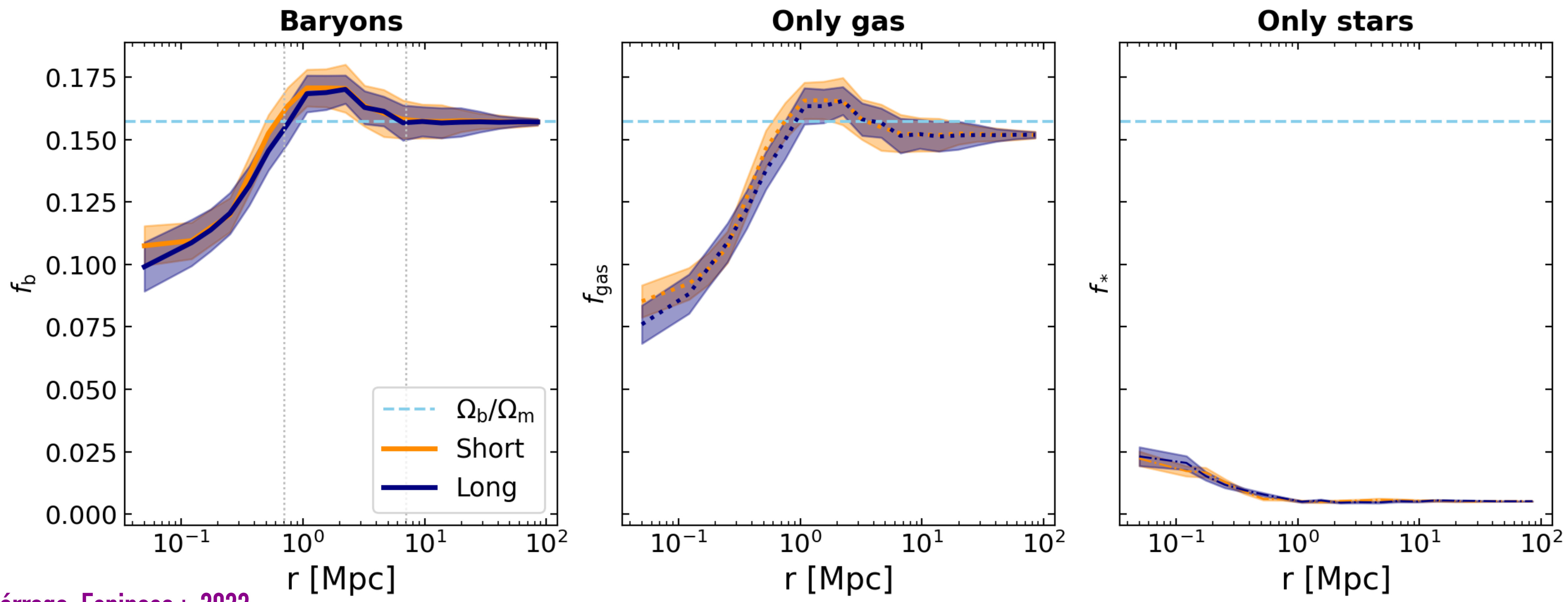
Two extreme populations

(TNG300-1 simulation)

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



Relative distribution of baryons with respect to DM: f_b



Galárraga-Espinosa+ 2022

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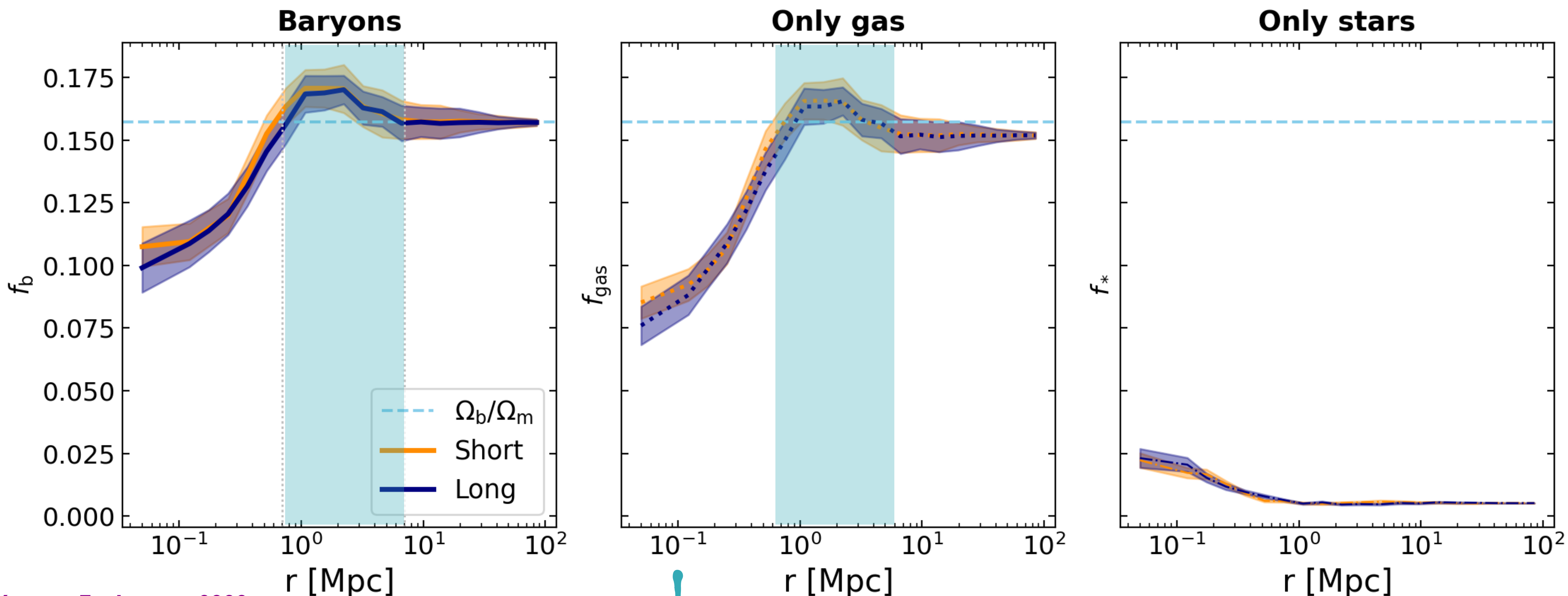
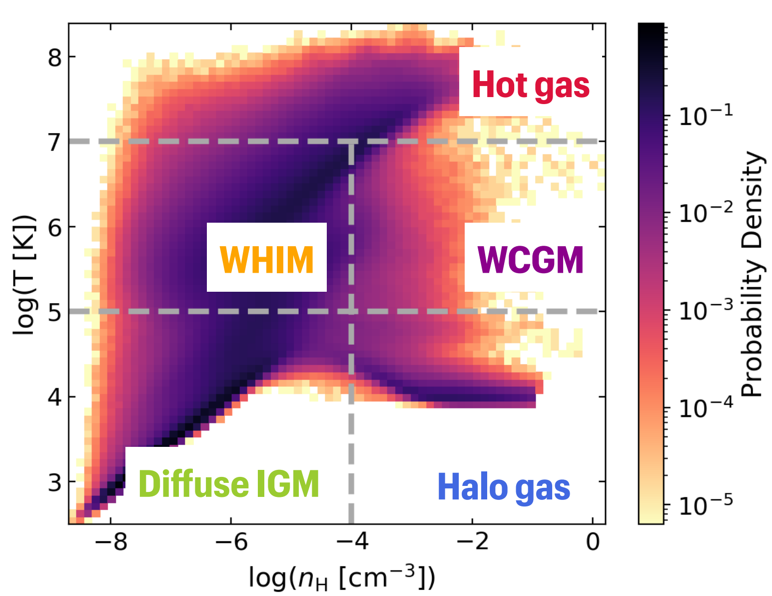
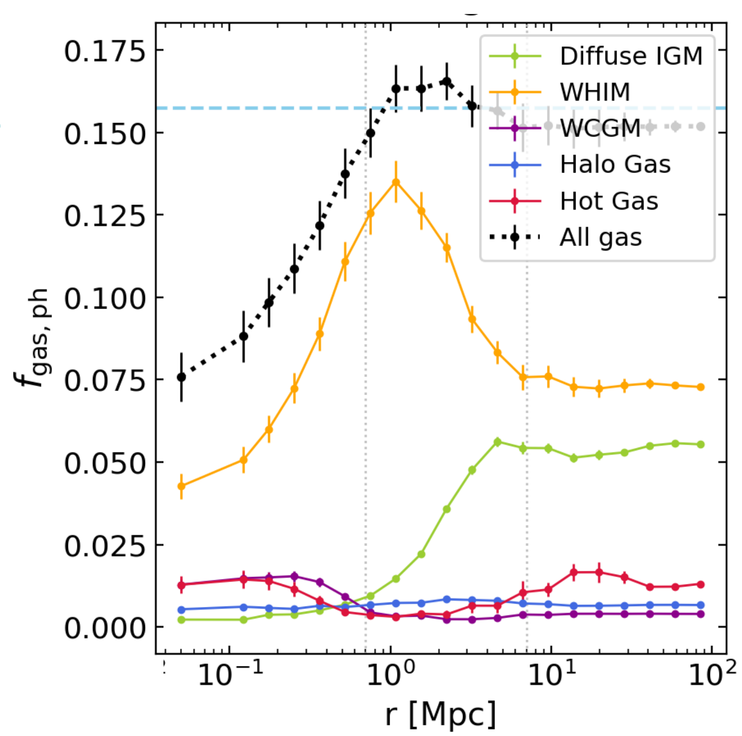


Galárraga-Espinosa+ 2022

Separation of gas in different phases, following Martizzi+ 2019





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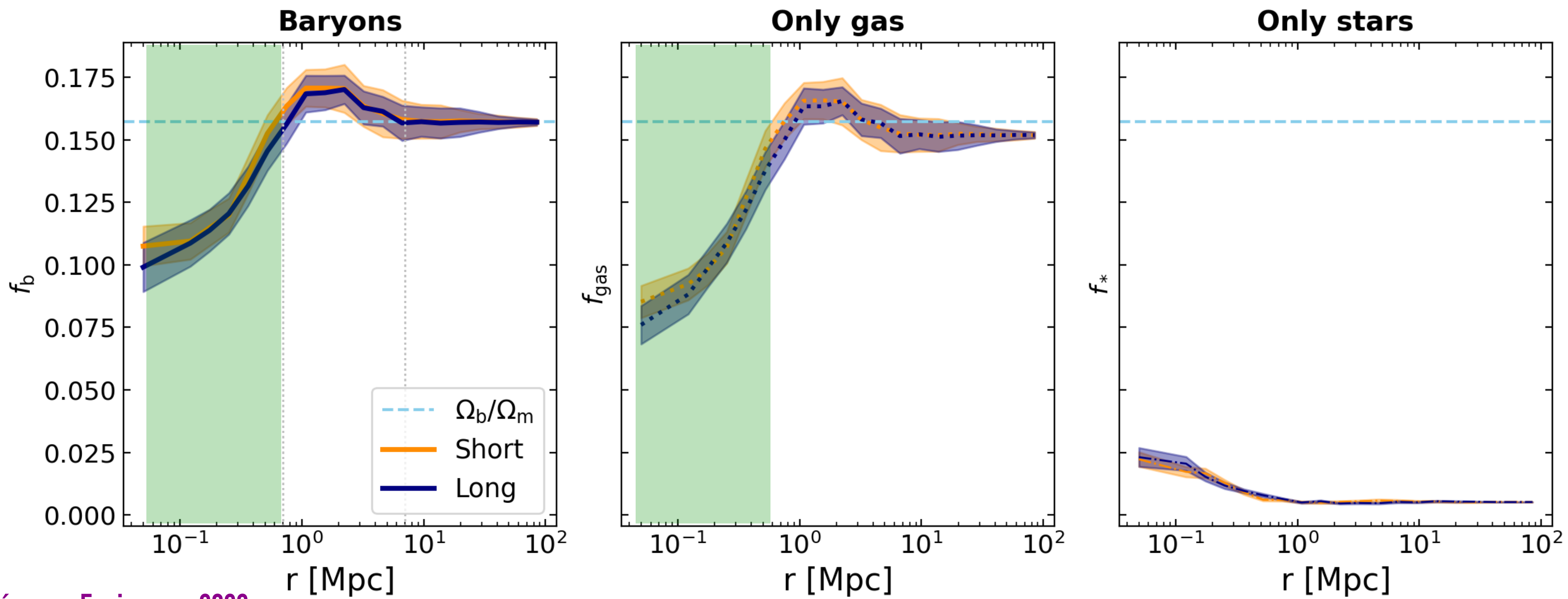


Galárraga-Espinosa+ 2022

Gas depletion at 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)

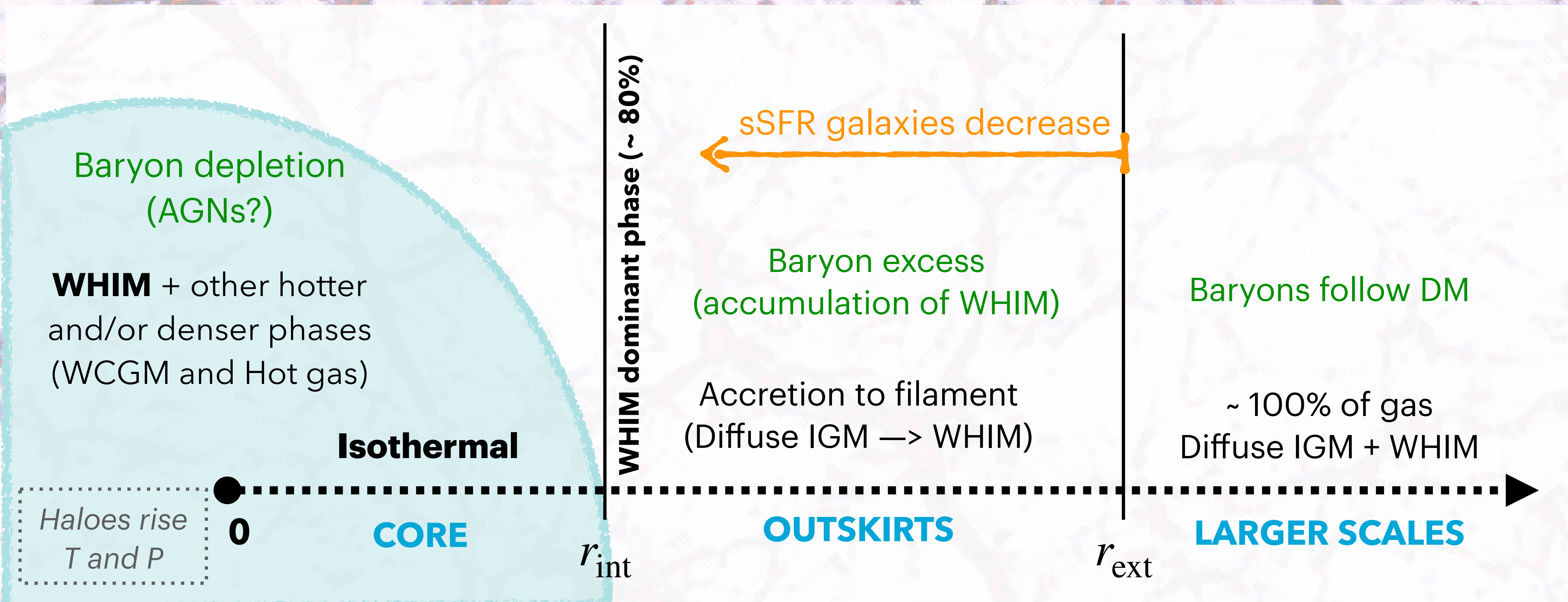
—> compare injected kinetic energy vs potential energy
pushing vs *pulling* of gas

AGNs can be powerful enough to deplete cosmic filaments cores!

But: not all the energy is necessarily transferred to the gas!
(jet orientation & geometry, coupling with the gas, etc.)

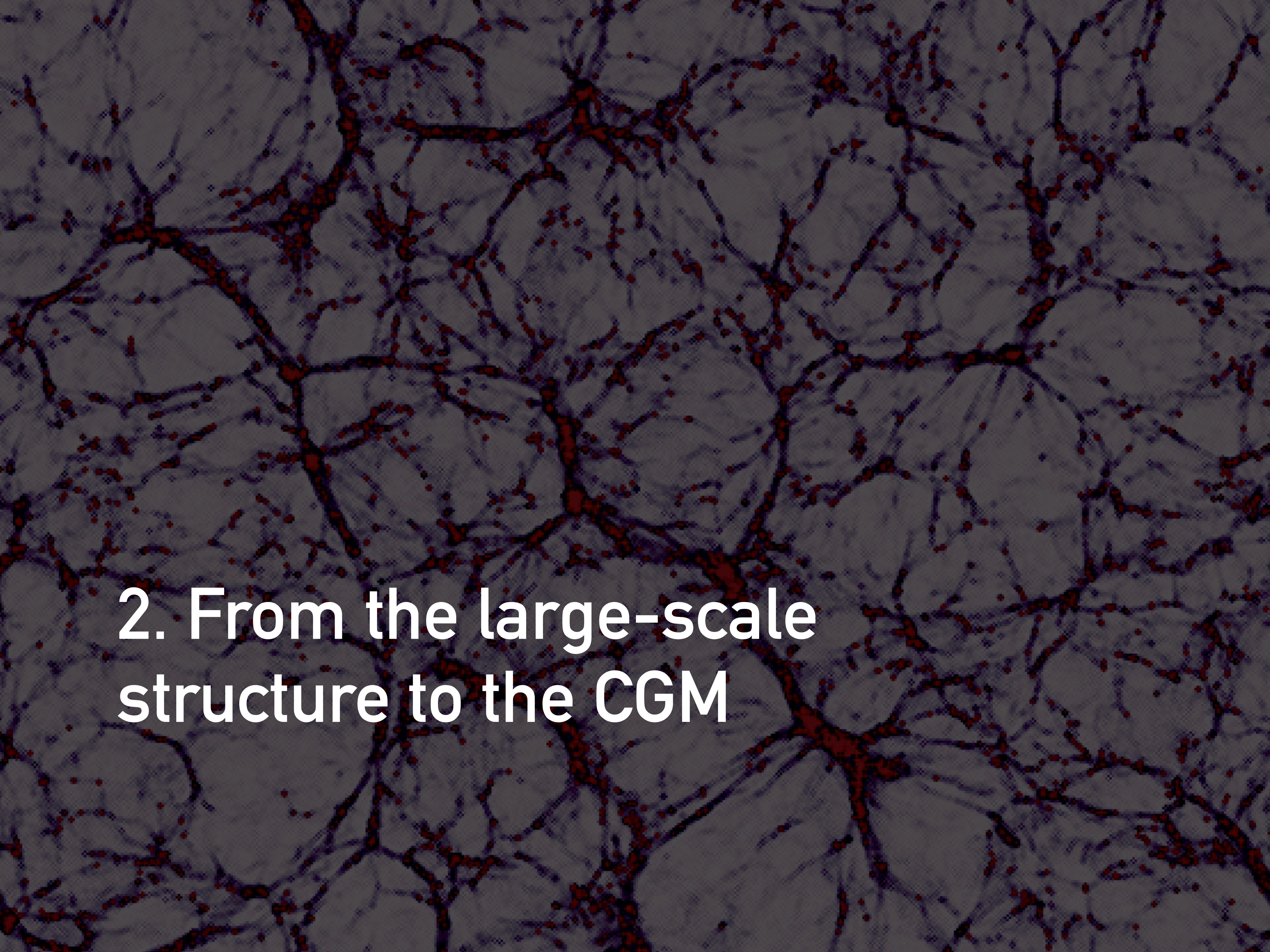
SUMMARY: COSMIC FILAMENTS

A more complete picture of cosmic filaments at z=0



Galárraga-Espinosa+ 2020, 2021, 2022

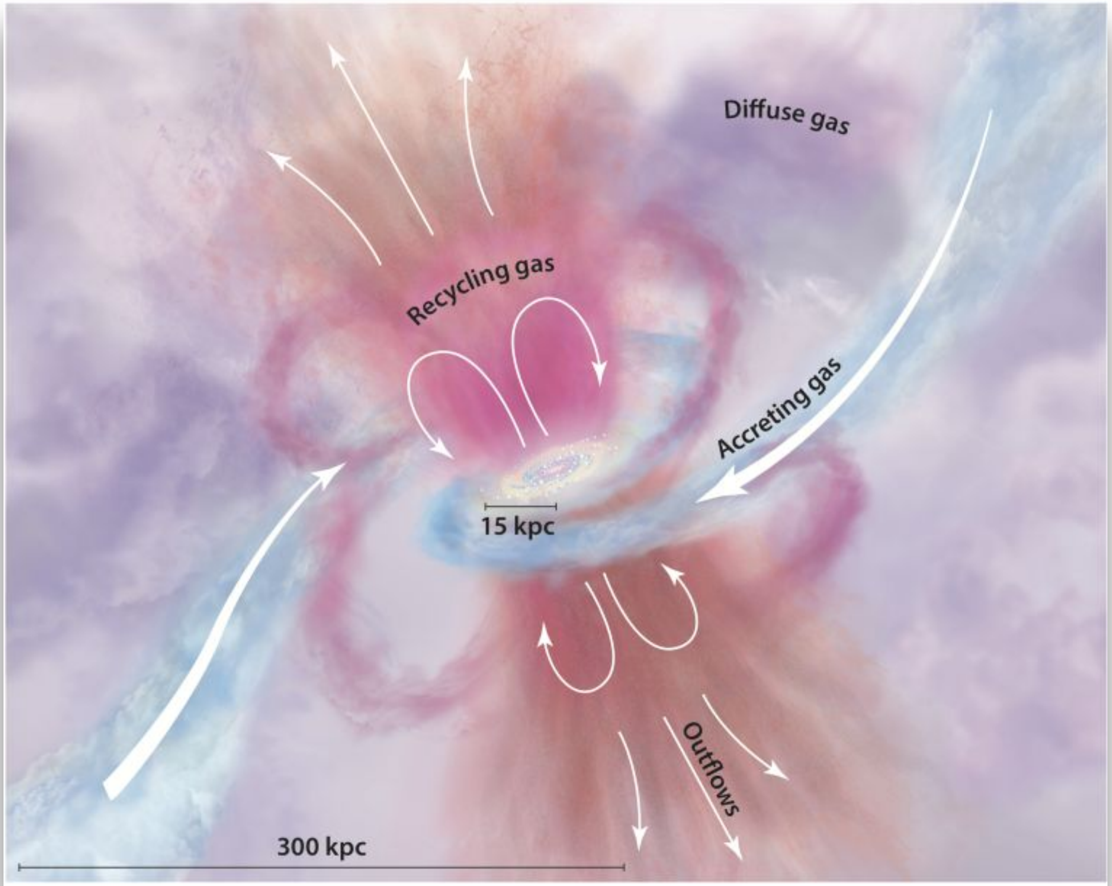
….Currently working on picture at higher z, using MTNG



2. 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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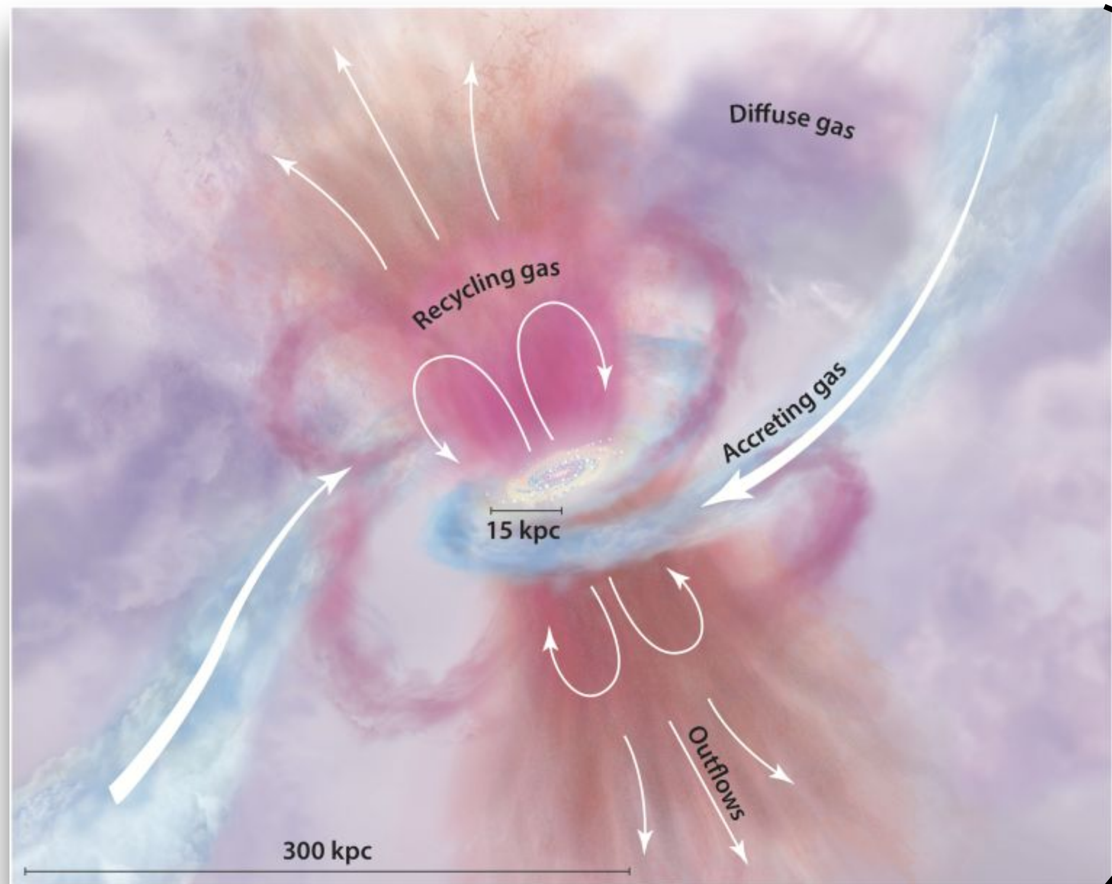
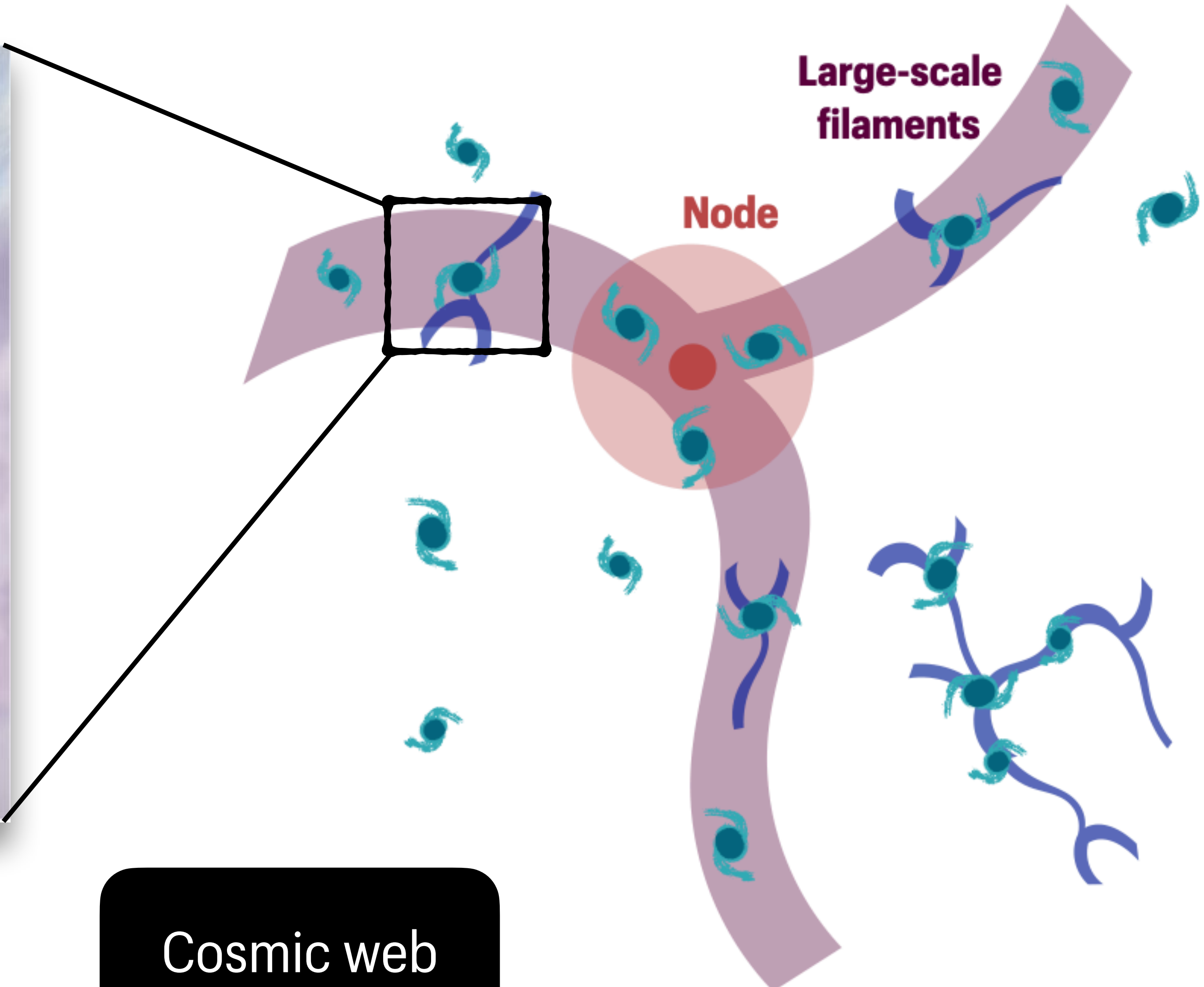


Tumlinson+ 2017



Cosmic web environment

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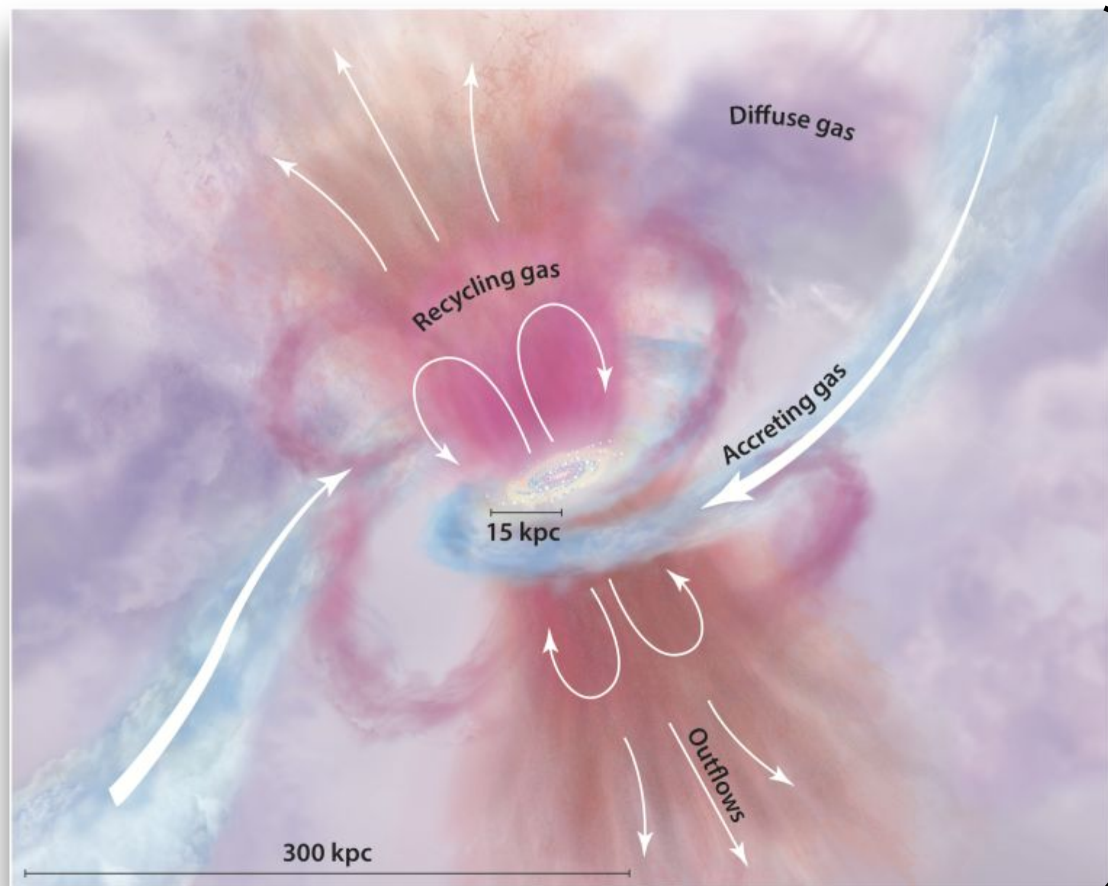

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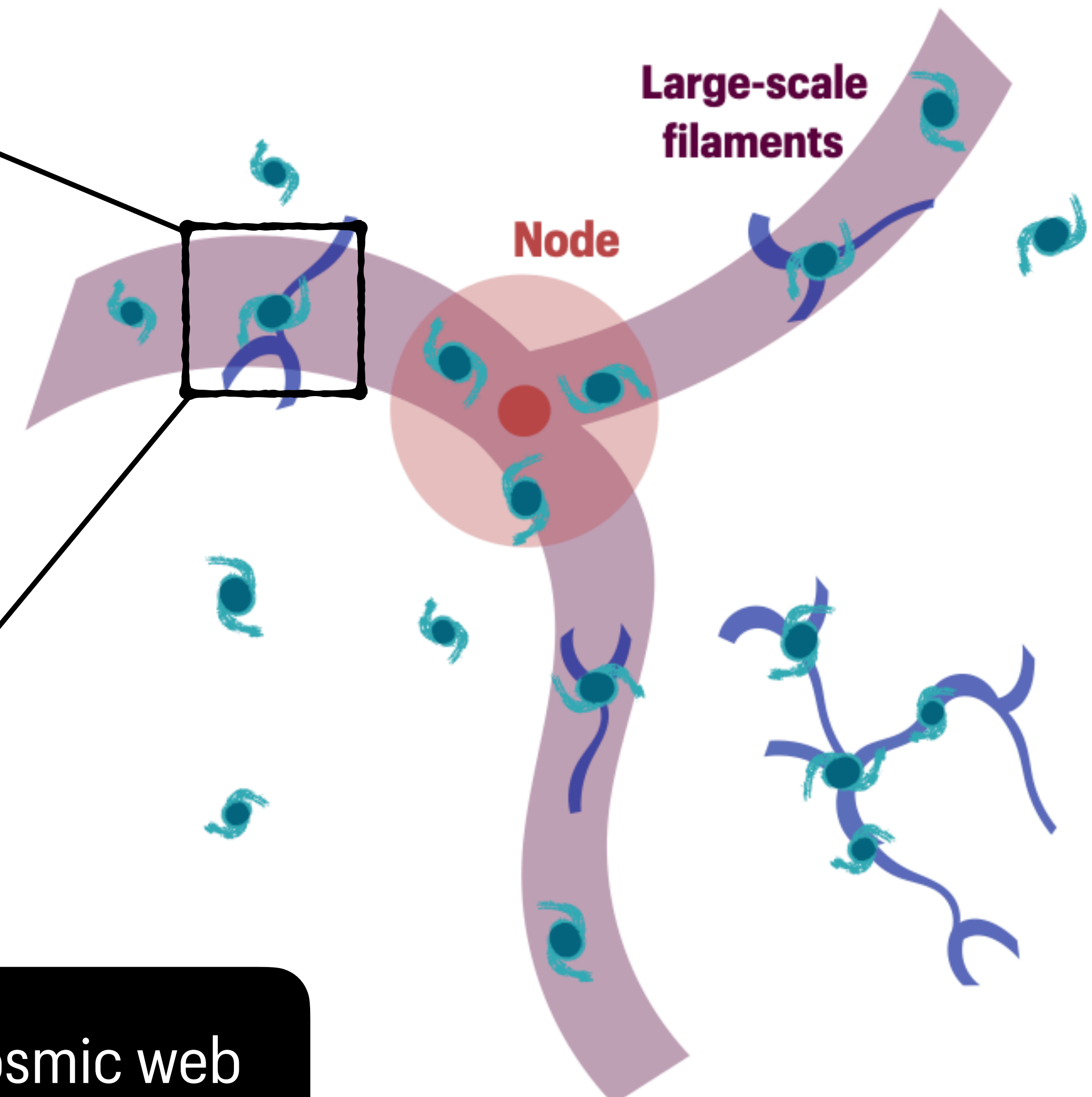

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Bauermeister+ 2010, Prescott+2015, Zabl+2019

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

Finding the streams

Galarraga-Espinosa+ 2023

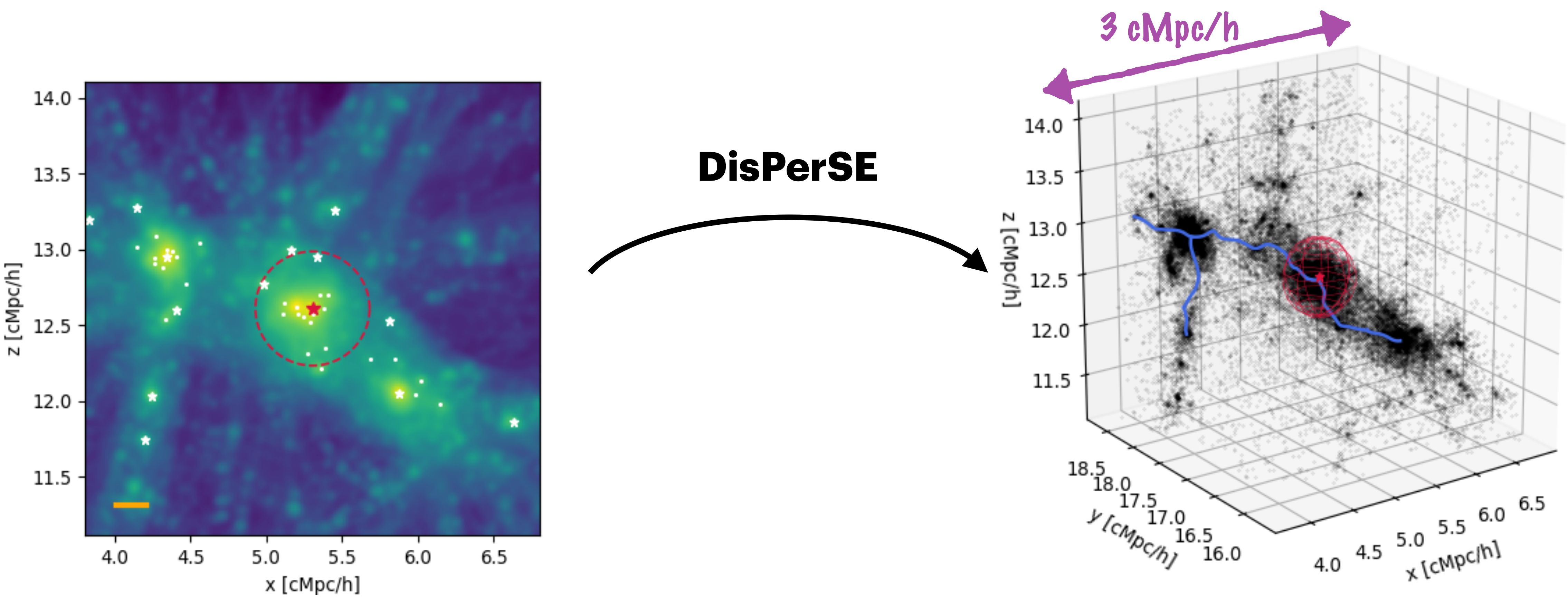
- TNG50-1
- z=2 (peak of star-formation activity)

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

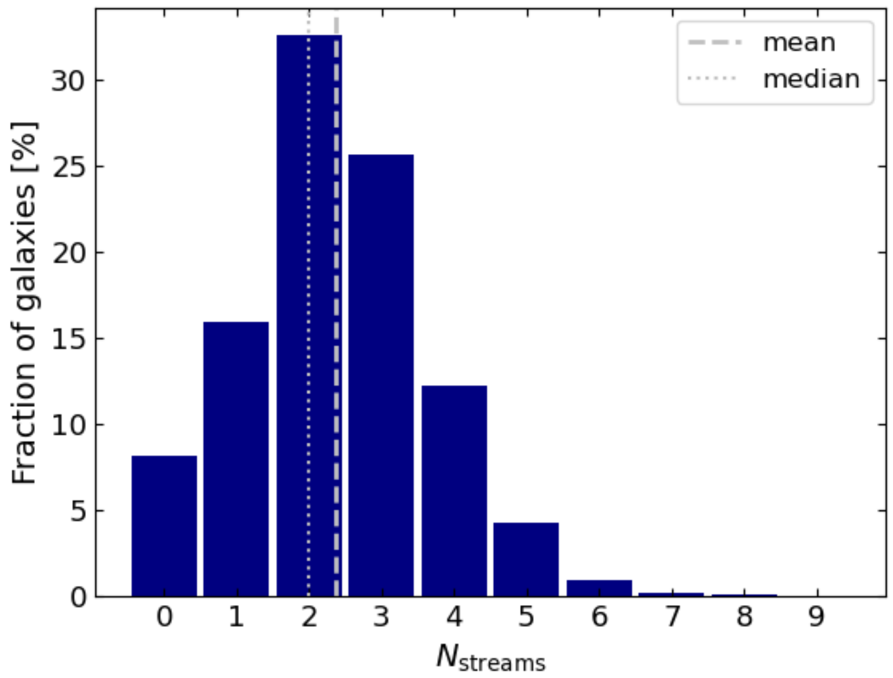


1 galaxy = 1 set of small-scale filaments

Galaxy connectivity

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

Total distribution (~3000 galaxies)



Galarraga-Espinosa+ 2023

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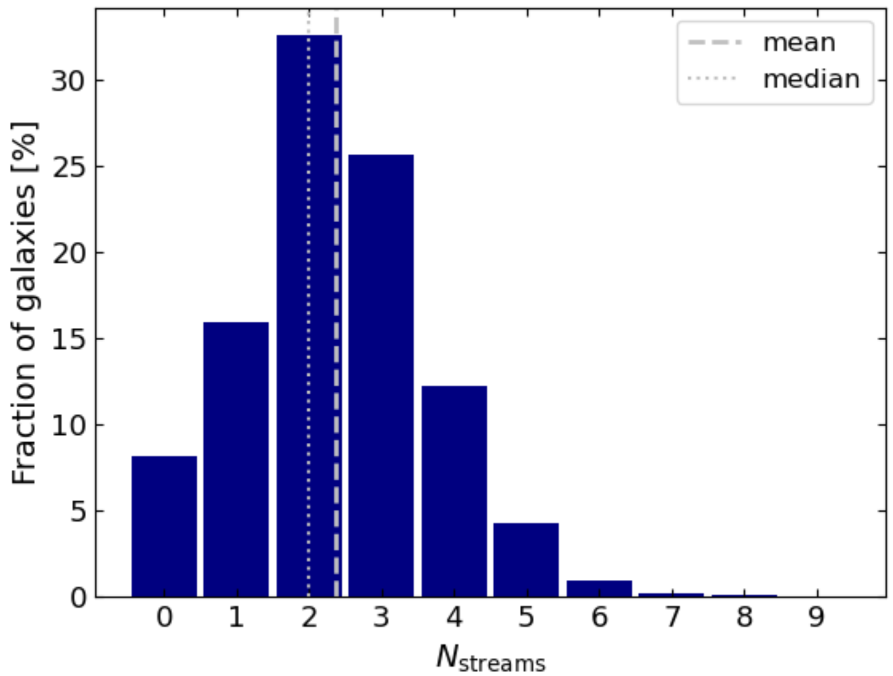
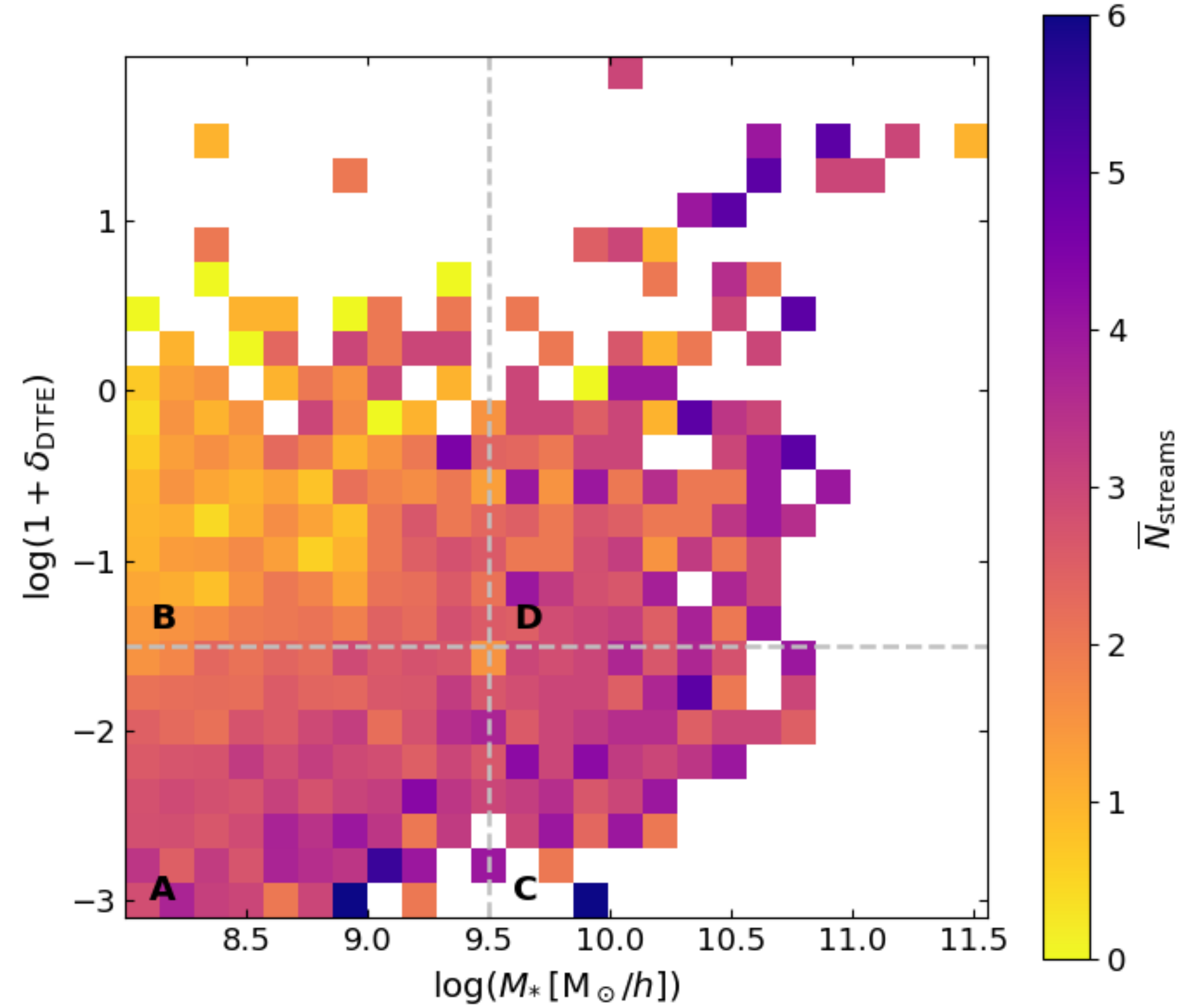


Connectivity in the mass-overdensity plane



- 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

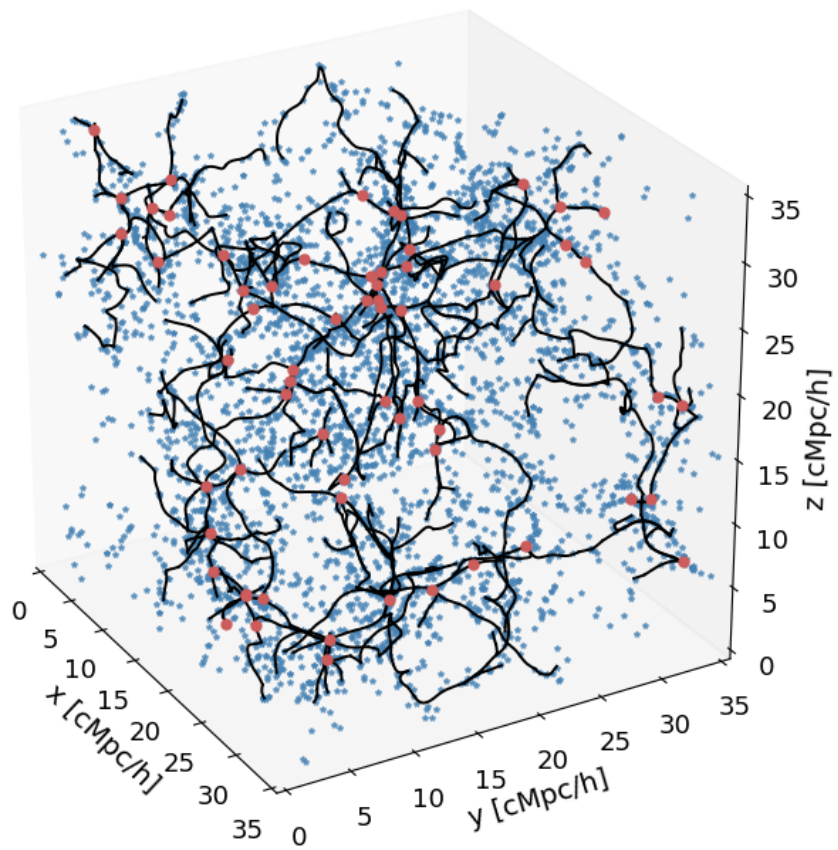
  Stronger *local* tides => disconnection from the local web

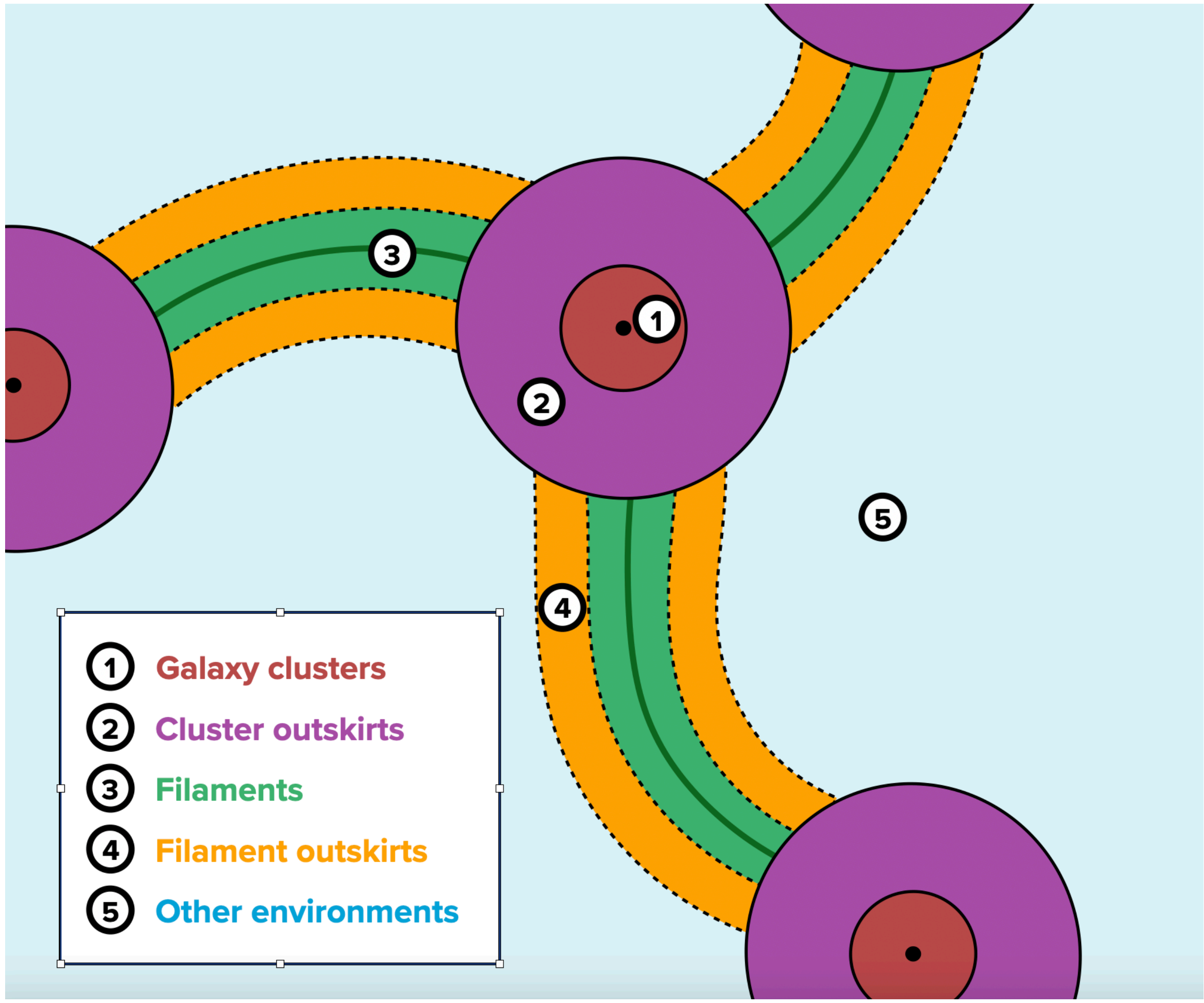
  Hahn+ 2009, Aragón-Calvo+ 2019

Galarraga-Espinosa+ 2023

DEFINING LARGE-SCALE ENVIRONMENTS

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

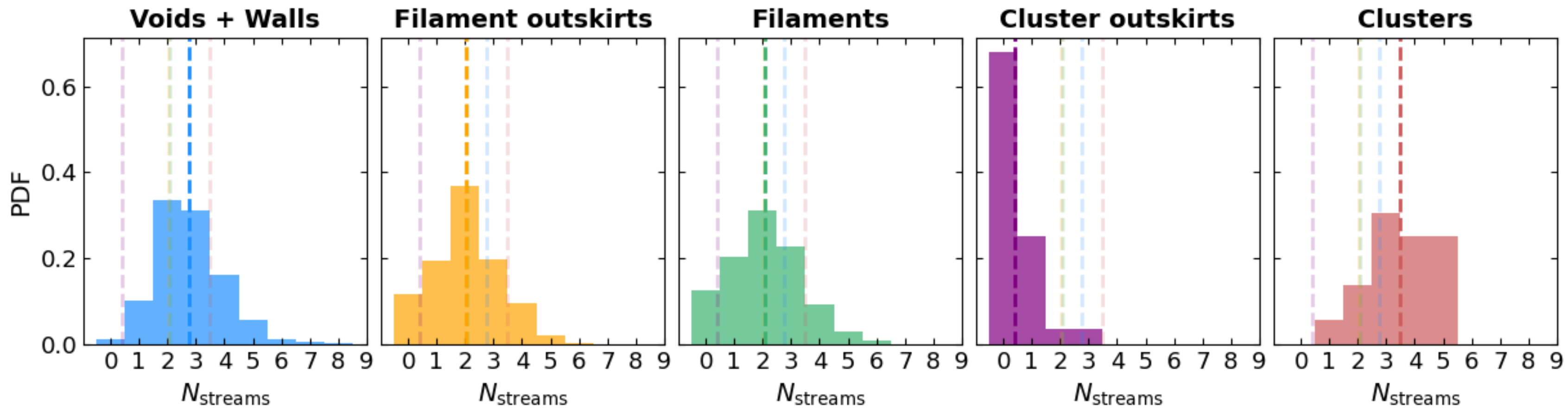
1 cMpc/h from filament axis

Within 1 - 3 R_{200}

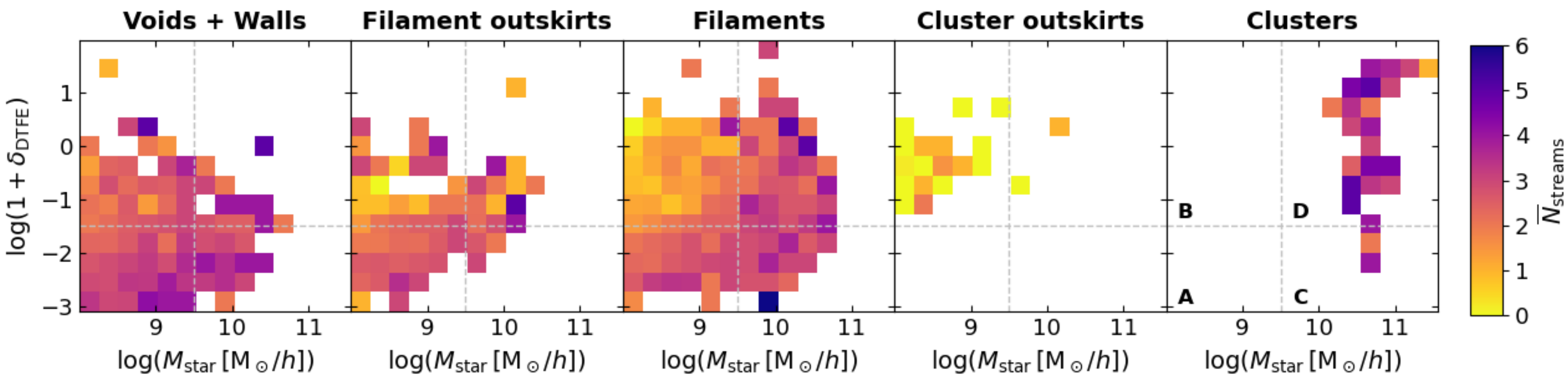
Haloes $M > 10^{12}$ $M_{\odot}/h$, within R_{200}

Connectivity in different cosmic environments

Galarraga-Espinosa+ 2023



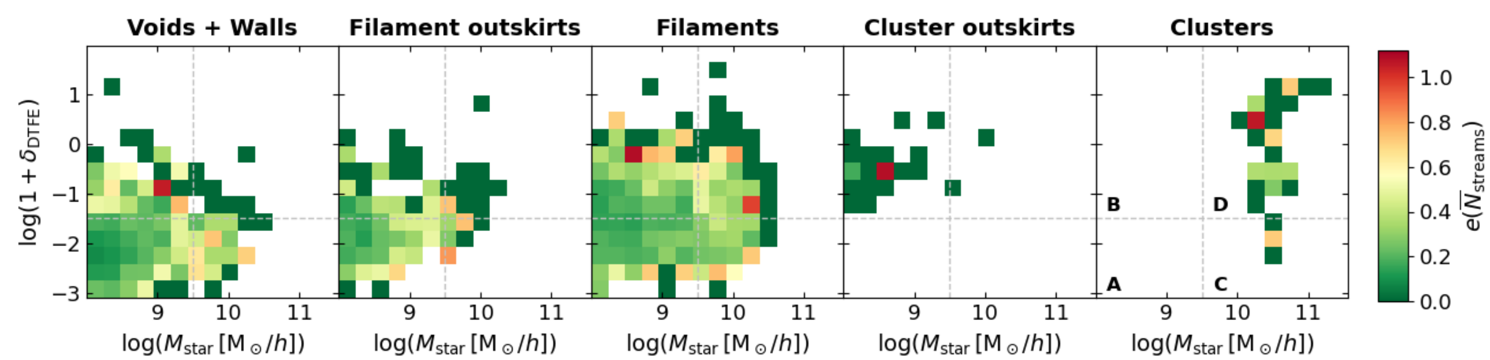
Different distributions!
Connectivity depends on location of galaxy in the cosmic web



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

In **clusters**: trends driven by high masses

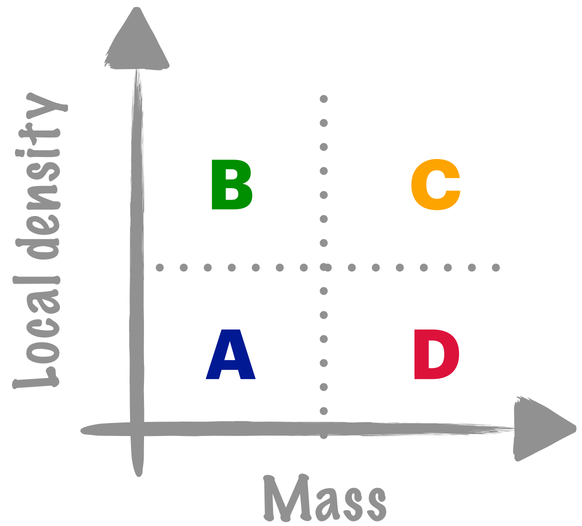
Errors on the mean values:



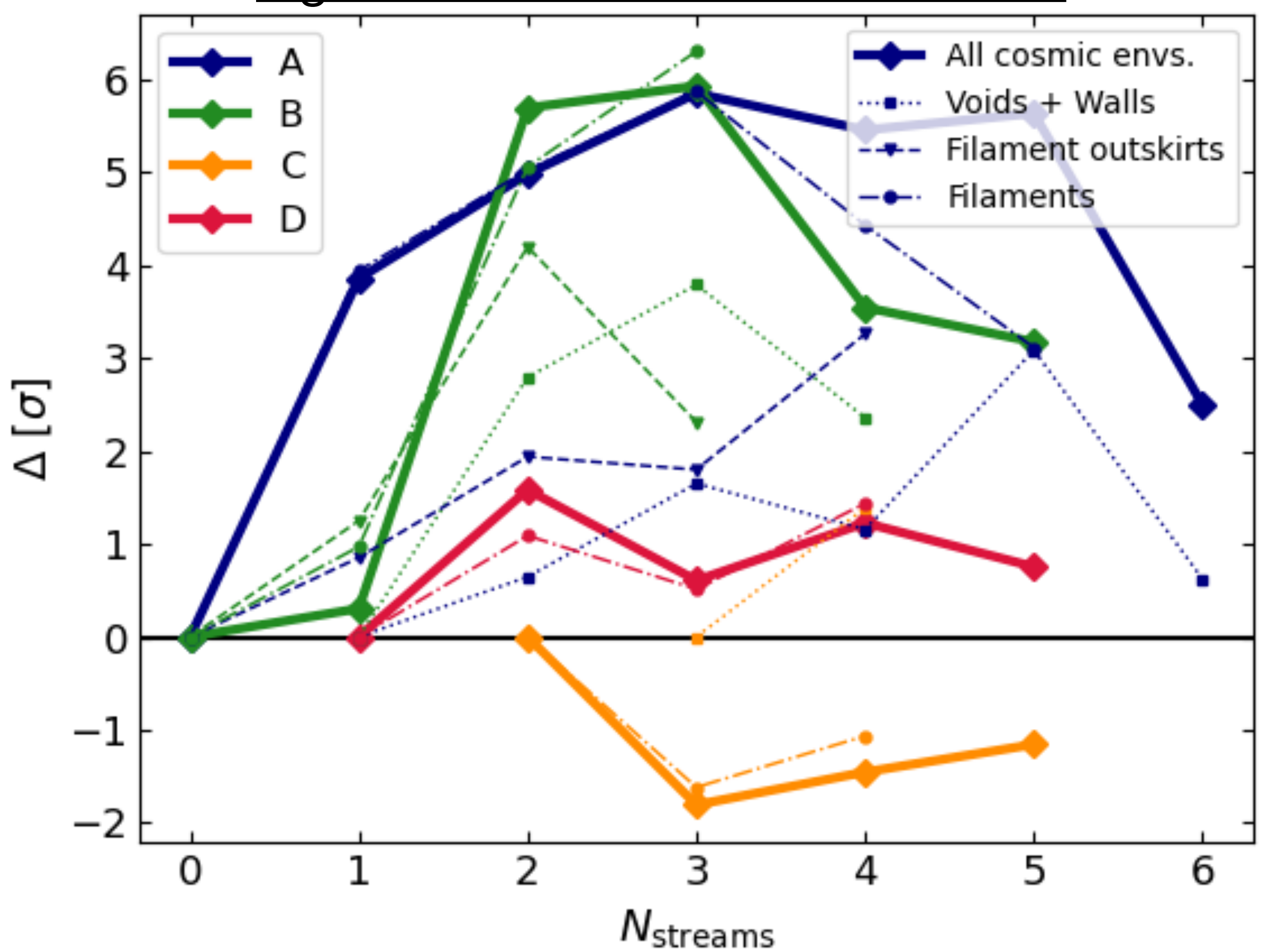
Explained by different strengths of the cosmic tidal flow
Musso+ 2018; Paranjape+ 2018; Kraljic+ 2019, Jhee+ 2022

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

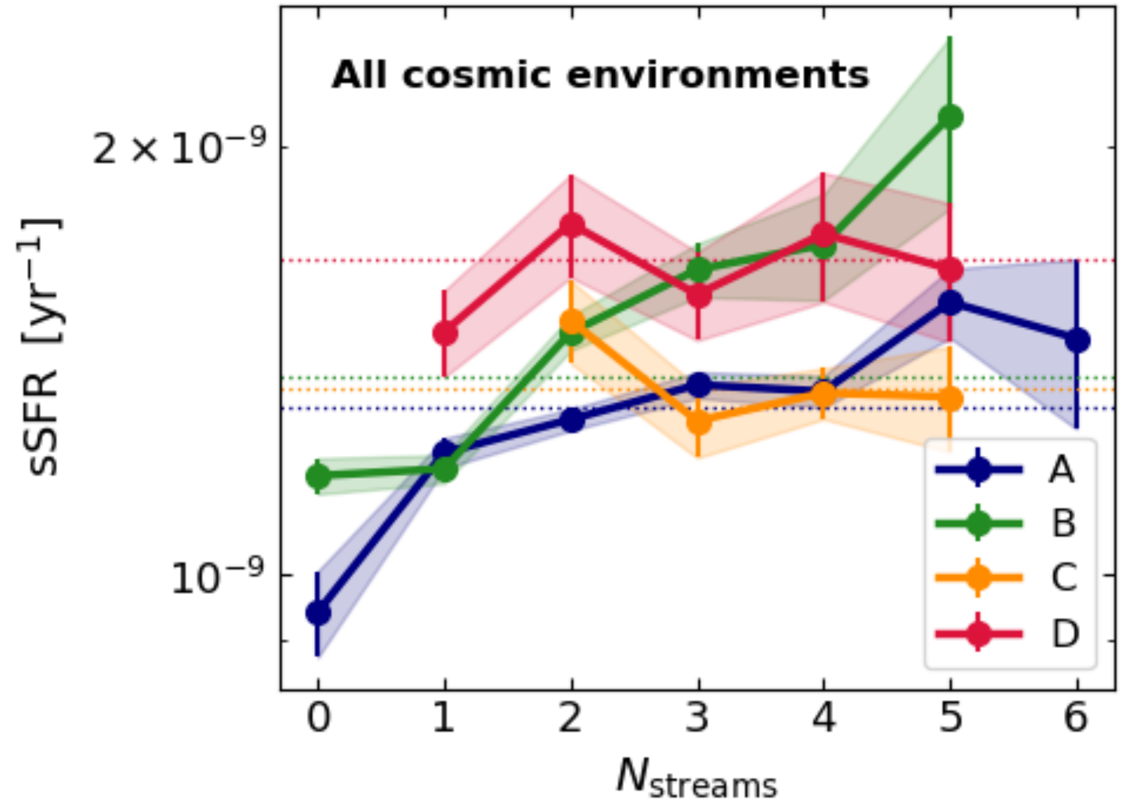
Impact on Star Formation



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)

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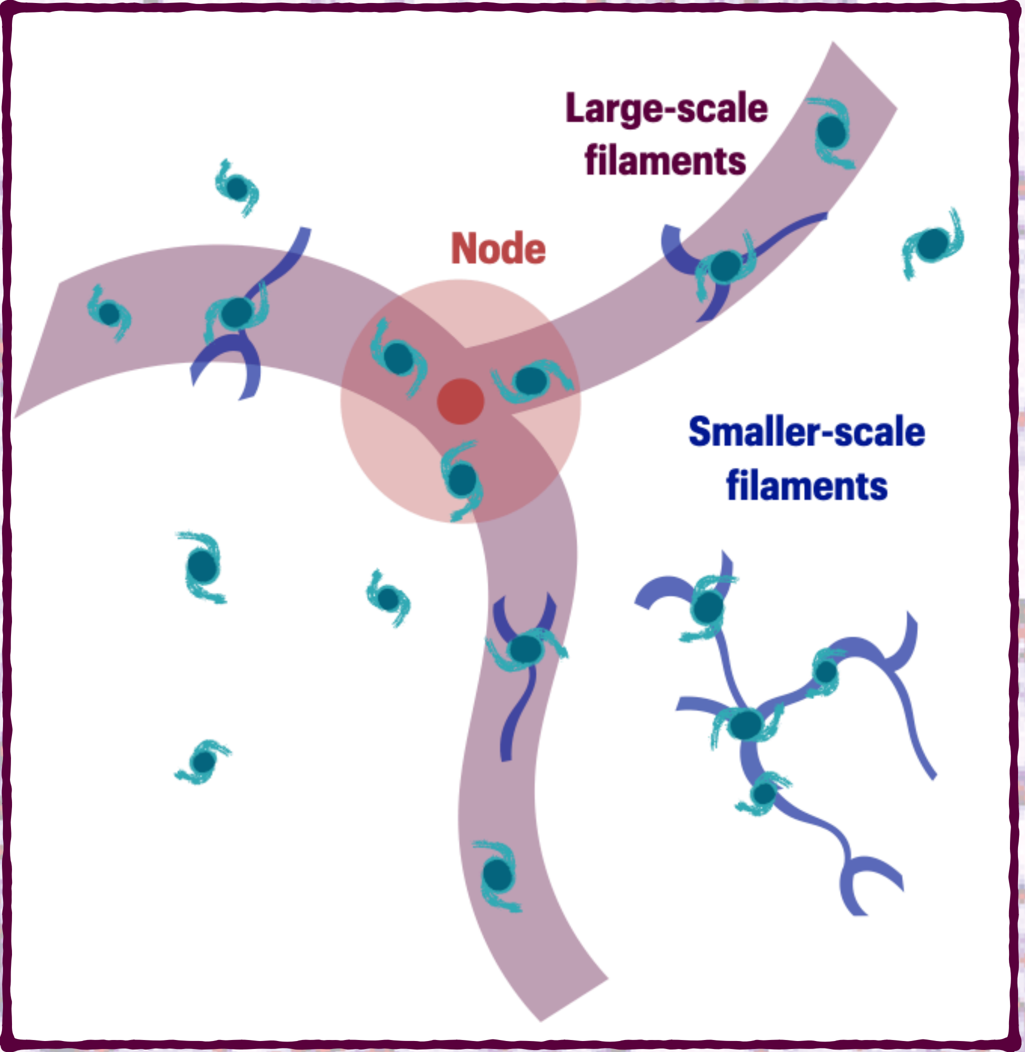

To do:

- 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!