KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

EXCOSM summer school

"Large-scale structure of the Universe: from galaxies to cosmology"

7-11 July 2025 Haapsalu, Estonia

Cosmic Web filaments and their properties

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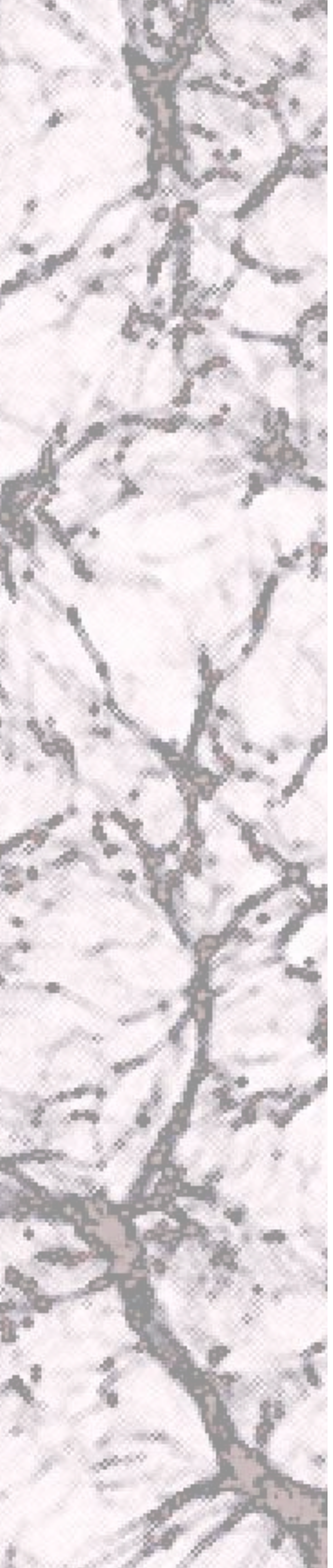


Cosmic Web filaments and their properties

Plan of lecture 1

1) Recap about the cosmic web
2) Motivation: the missing baryon problem
3) Filament gas properties in hydrodynamical simulations
4) Gas in cluster outskirts
5) Observational status of the missing baryon problem

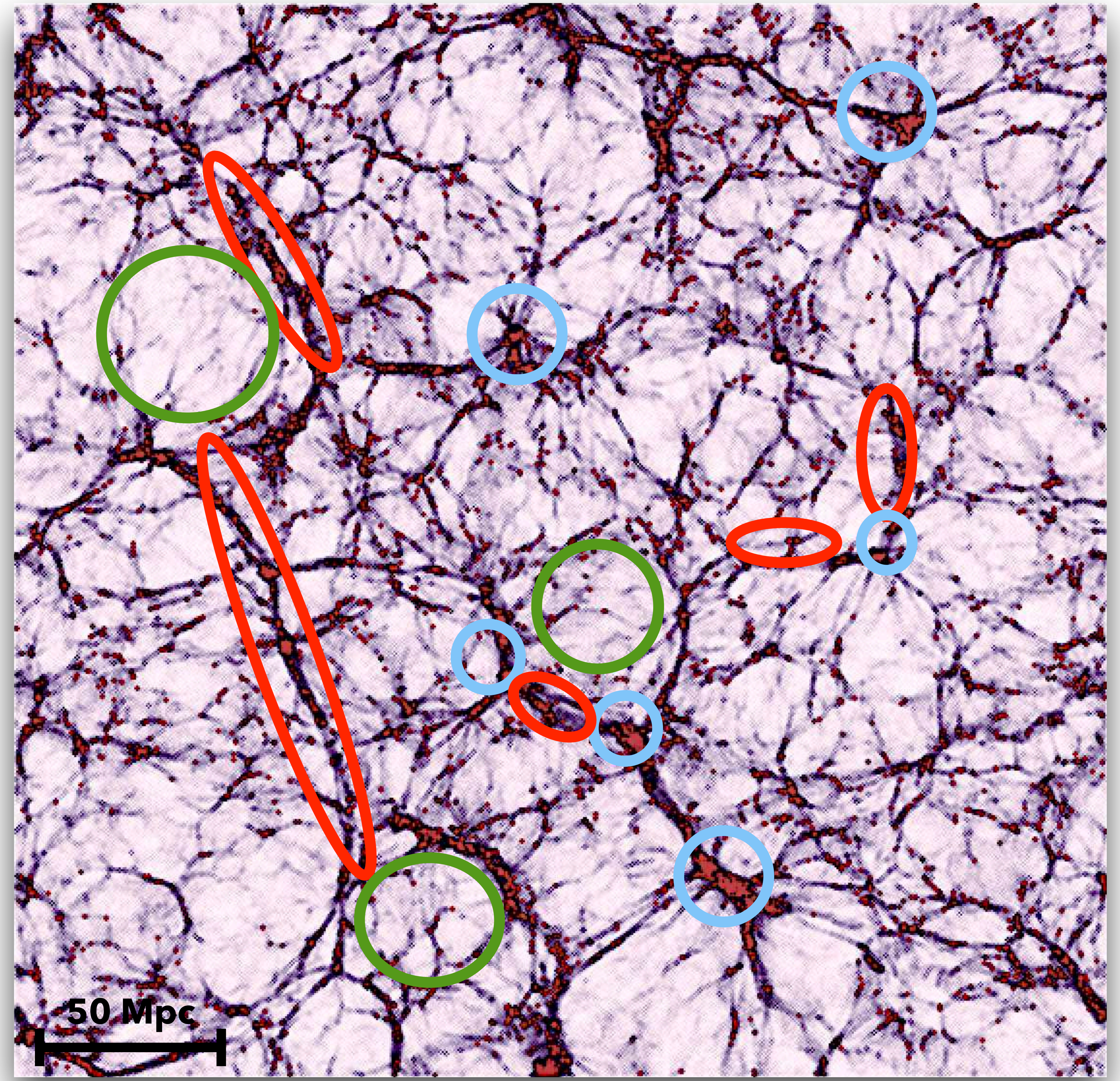
Effect of the multi-scale web filaments on galaxy evolution

Plan of lecture 2

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

Recap from Day 1

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



z=0

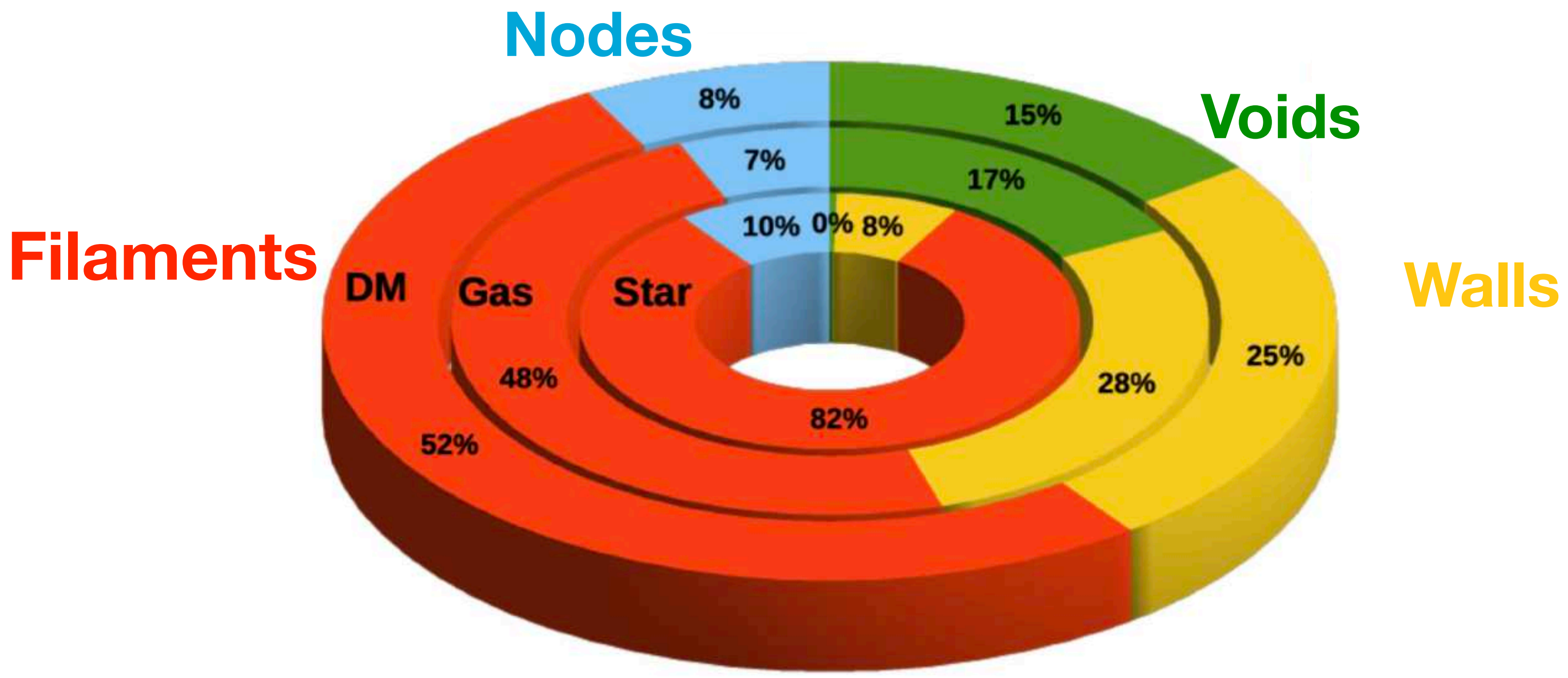
Voids

Walls

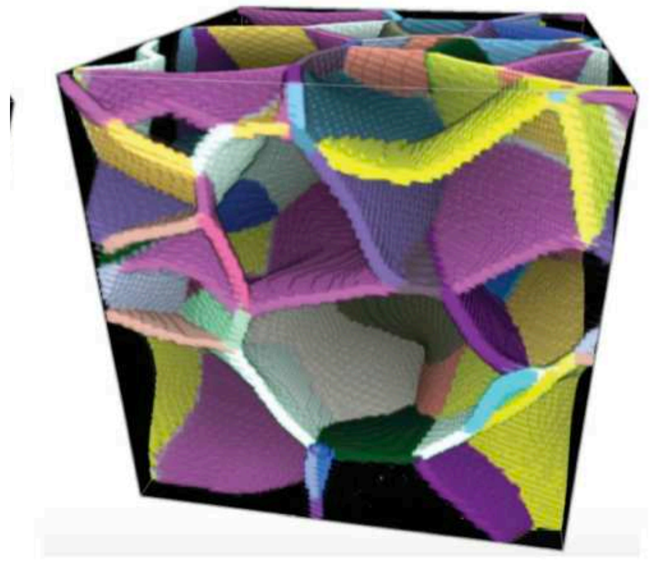
Filaments

Nodes

Matter distribution at large-scales



Ganeshaiah Veena+ 2019



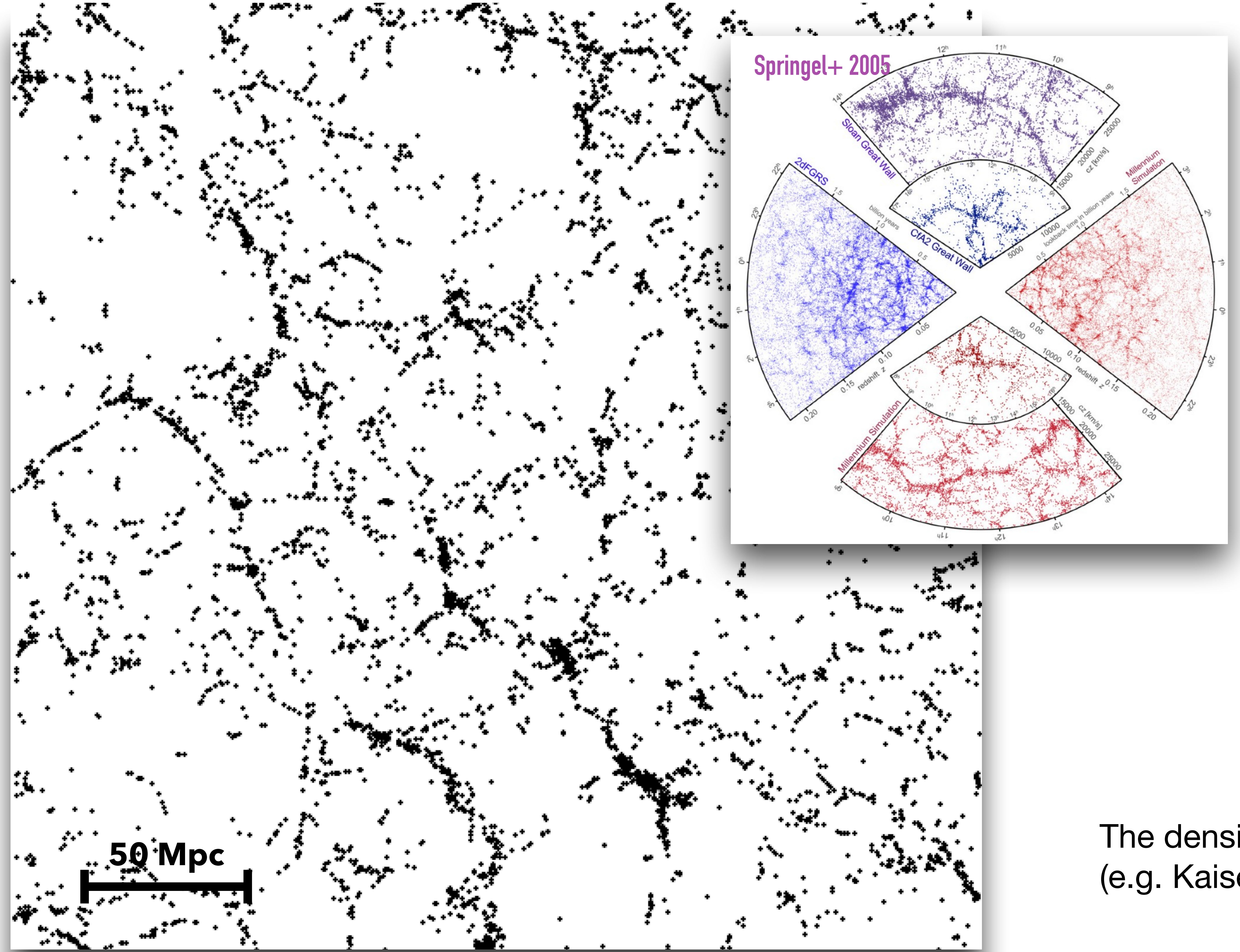
Sousbie 2011

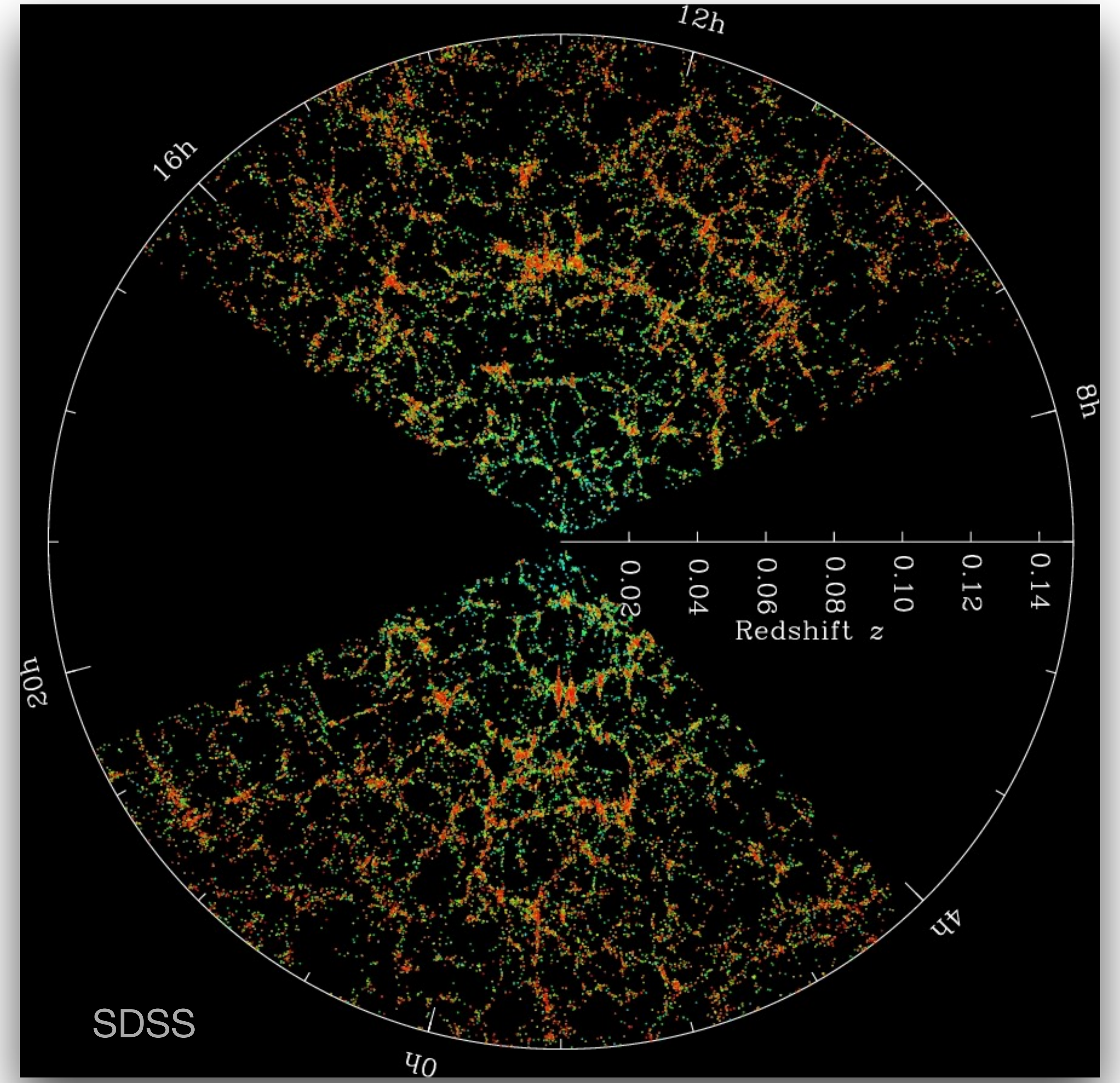
"The Cosmic Web is beautiful"

— Rien

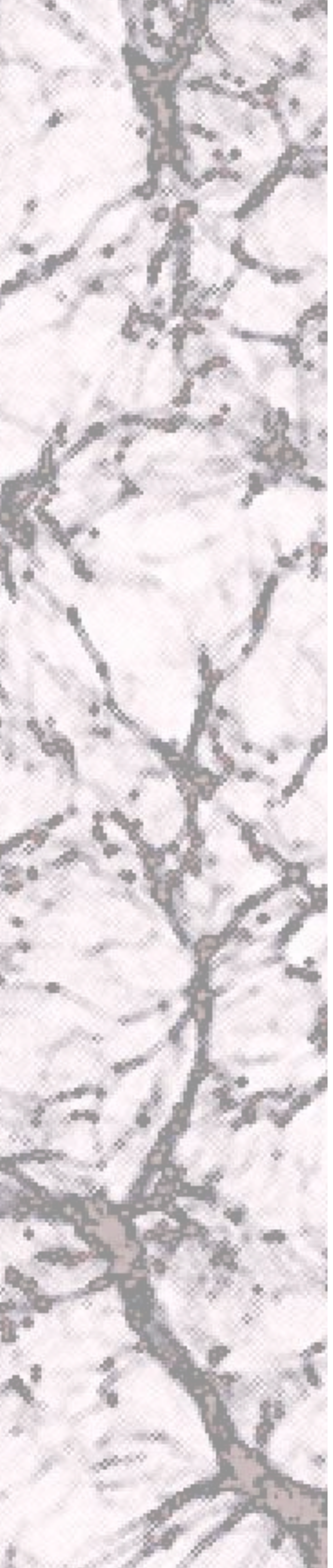
What we observe is different!

Galaxies are biased tracers of the underlying DM density field





The density of galaxies is a non-trivial function of the dark matter density (e.g. Kaiser 1984; Tegmark & Peebles 1998).



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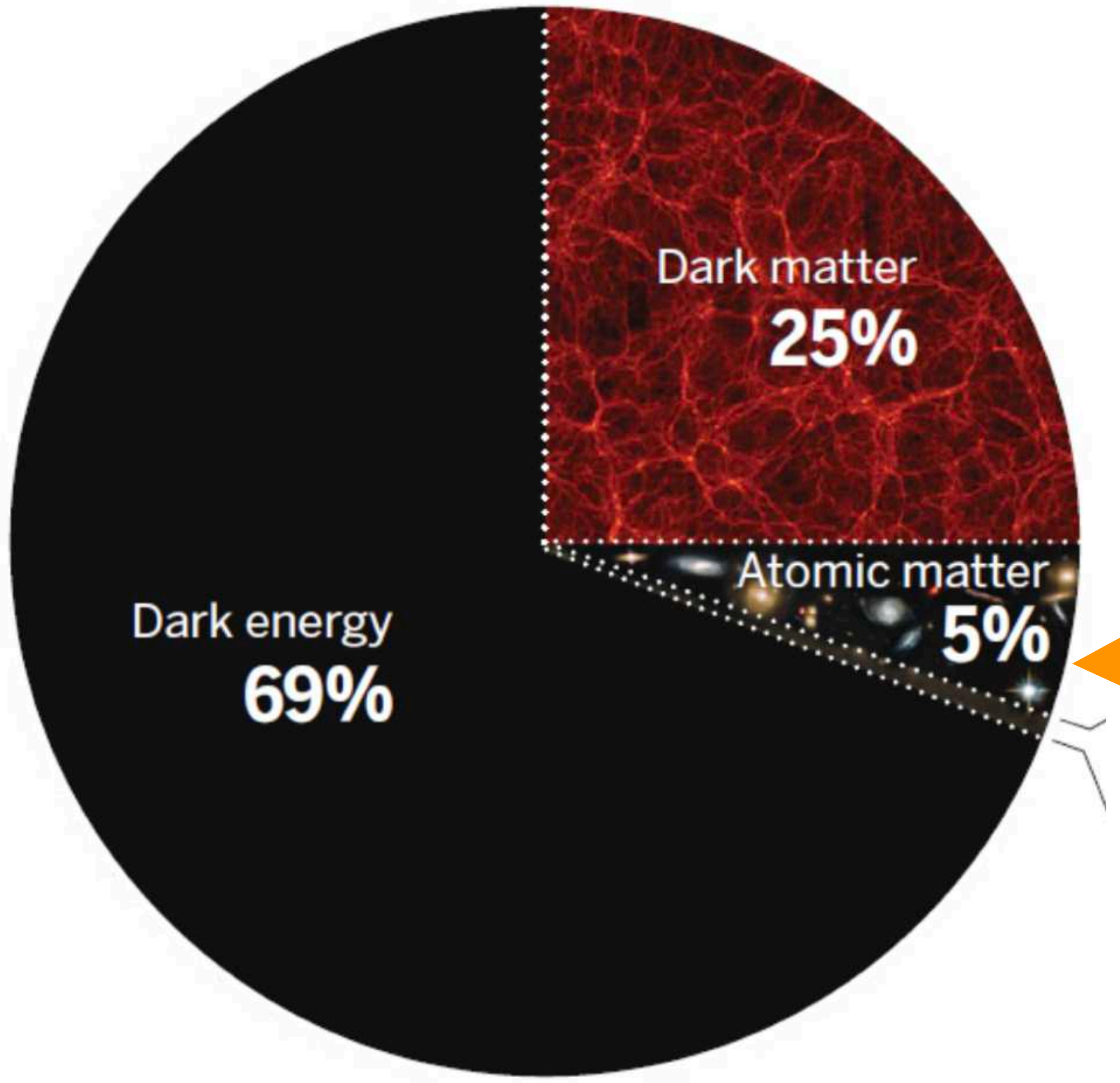
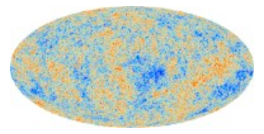
The Missing baryon problem

Components of the Universe, in Lamba CDM:



From CMB studies



Planck collaboration 2018

Fukugita, Hogan, & Peebles 1996, 1998

"The Cosmic Baryon Budget"

There is a baryon deficit in the low-redshift universe relative to the predicted density synthesised in the Big Bang

Cen and Ostriker 1999 ***"Where Are the Baryons?"***

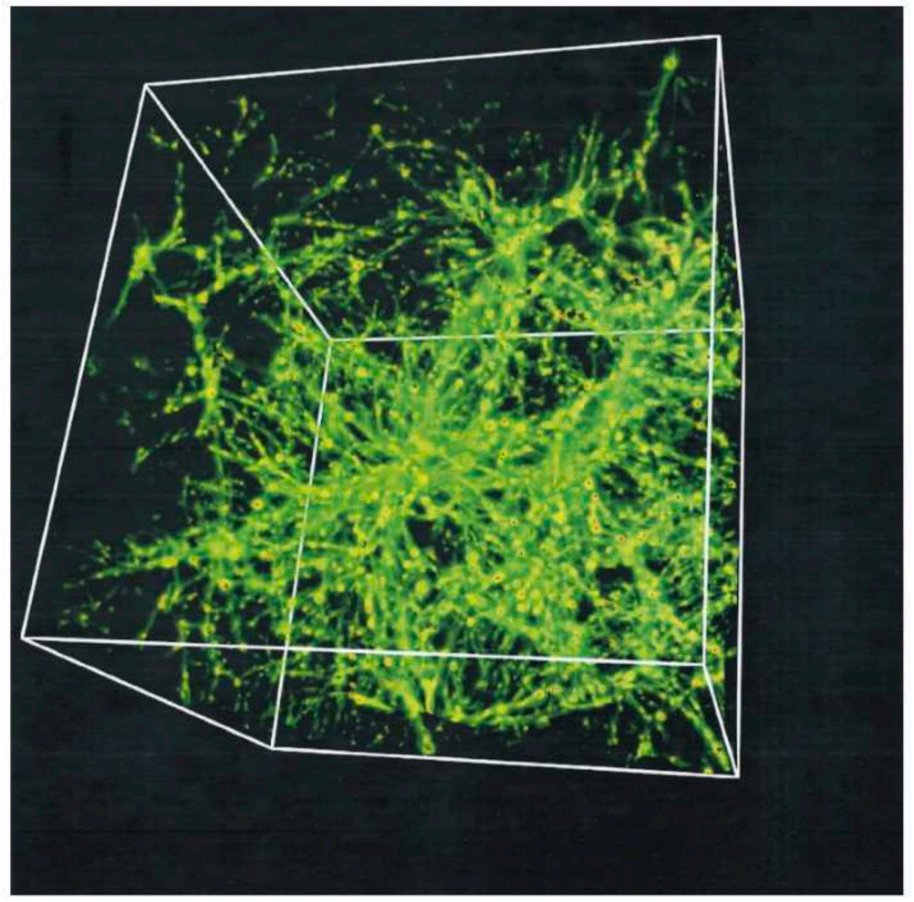


FIG. 3.—Spatial distribution of the warm/hot gas with temperature in the range 10^5–10^7 K at $z = 0$. The green regions have densities about 10 times the mean baryon density of the universe at $z = 0$; the yellow regions have densities about 100 times the mean baryon density, while the small isolated regions with red and saturated dark colors have even higher densities reaching about 1000 times the mean baryon density and are sites for current galaxy formation.

Hydro-simulation —>
Elusive matter is in filaments of the cosmic web

The Cosmic Energy Inventory

In the low redshift universe

Fukugita & Peebles (2004)

TABLE 1

THE COSMIC ENERGY INVENTORY

				Components[a]	Totals[a]
1	dark sector				0.954 ± 0.003
1.1	dark energy			0.72 ± 0.03	
1.2	dark matter			0.23 ± 0.03	
1.3	primeval gravitational waves			$\lesssim 10^{-10}$	
2	primeval thermal remnants				0.0010 ± 0.0005
2.1	electromagnetic radiation			$10^{-4.3\pm0.0}$	
2.2	neutrinos			$10^{-2.9\pm0.1}$	
2.3	prestellar nuclear binding energy			$-10^{-4.1\pm0.0}$	
3	baryon rest mass				0.045 ± 0.003
3.1	warm intergalactic plasma			0.040 ± 0.003	
3.1a	virialized regions of galaxies		0.024 ± 0.005		
3.1b	intergalactic		0.016 ± 0.005		
3.2	intracluster plasma			0.0018 ± 0.0007	
3.3	main sequence stars	spheroids and bulges		0.0015 ± 0.0004	
3.4		disks and irregulars		0.00055 ± 0.00014	
3.5	white dwarfs			0.00036 ± 0.00008	
3.6	neutron stars			0.00005 ± 0.00002	
3.7	black holes			0.00007 ± 0.00002	
3.8	substellar objects			0.00014 ± 0.00007	
3.9	HI + HeI			0.00062 ± 0.00010	
3.10	molecular gas			0.00016 ± 0.00006	
3.11	planets			10^{-6}	
3.12	condensed matter			$10^{-5.6\pm0.3}$	
3.13	sequestered in massive black holes			$10^{-5.4}(1+\epsilon_n)$	
4	primeval gravitational binding energy				$-10^{-6.1\pm0.1}$
4.1	virialized halos of galaxies			$-10^{-7.2}$	
4.2	clusters			$-10^{-6.9}$	
4.3	large-scale structure			$-10^{-6.2}$	
5	binding energy from dissipative gravitational settling				$-10^{-4.9}$
5.1	baryon-dominated parts of galaxies			$-10^{-8.8\pm0.3}$	
5.2	main sequence stars and substellar objects			$-10^{-8.1}$	
5.3	white dwarfs			$-10^{-7.4}$	
5.4	neutron stars			$-10^{-5.2}$	
5.5	stellar mass black holes			$-10^{-4.2}\epsilon_s$	
5.6	galactic nuclei	early type		$-10^{-5.6}\epsilon_n$	
5.7		late type		$-10^{-5.8}\epsilon_n$	
6.	poststellar nuclear binding energy				$-10^{-5.2}$
6.1	main sequence stars and substellar objects			$-10^{-5.8}$	
6.2	diffuse material in galaxies			$-10^{-6.5}$	
6.3	white dwarfs			$-10^{-5.6}$	
6.4	clusters			$-10^{-6.5}$	
6.5	intergalactic			$-10^{-6.2\pm0.5}$	
7	poststellar radiation				$10^{-5.7\pm0.1}$
7.1	resolved radio-microwave			$10^{-10.3\pm0.3}$	
7.2	far infrared			$10^{-6.1}$	
7.3	optical			$10^{-5.8\pm0.2}$	
7.4	X-γ ray			$10^{-7.9\pm0.2}$	
7.5	gravitational radiation	stellar mass binaries		$10^{-9\pm1}$	
7.6		massive black holes		$10^{-7.5\pm0.5}$	
8	stellar neutrinos				$10^{-5.5}$
8.1	nuclear burning			$10^{-6.8}$	
8.2	white dwarf formation			$10^{-7.7}$	
8.3	core collapse			$10^{-5.5}$	
9	cosmic rays and magnetic fields				$10^{-8.3^{+0.6}_{-0.3}}$
10	kinetic energy in the intergalactic medium				$10^{-8.0\pm0.3}$

[a]Based on Hubble parameter $h = 0.7$.

The baryon census in a multiphase Intergalactic medium: 30% of the Baryons may still be missing

Shull, Smith & Danforth (2012)

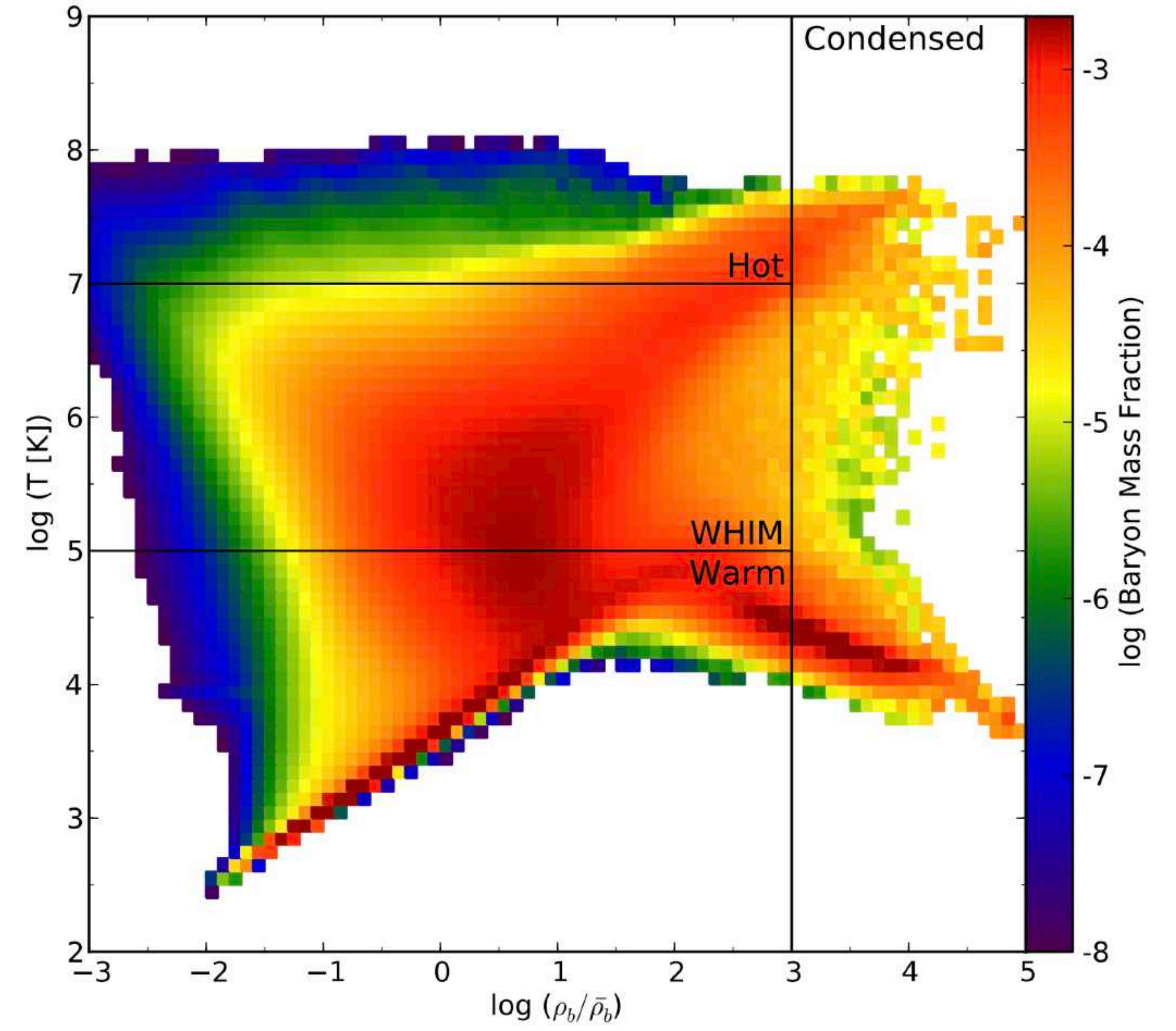


FIG. 1.— Distribution of IGM in temperature T and baryon overdensity $\Delta_b = \rho_b/\bar{\rho}_b$, color-coded by baryon mass fraction. This distribution shows the same thermal phases seen in simulations by other groups and commonly labeled as warm (diffuse photoionized gas), WHIM, and condensed.

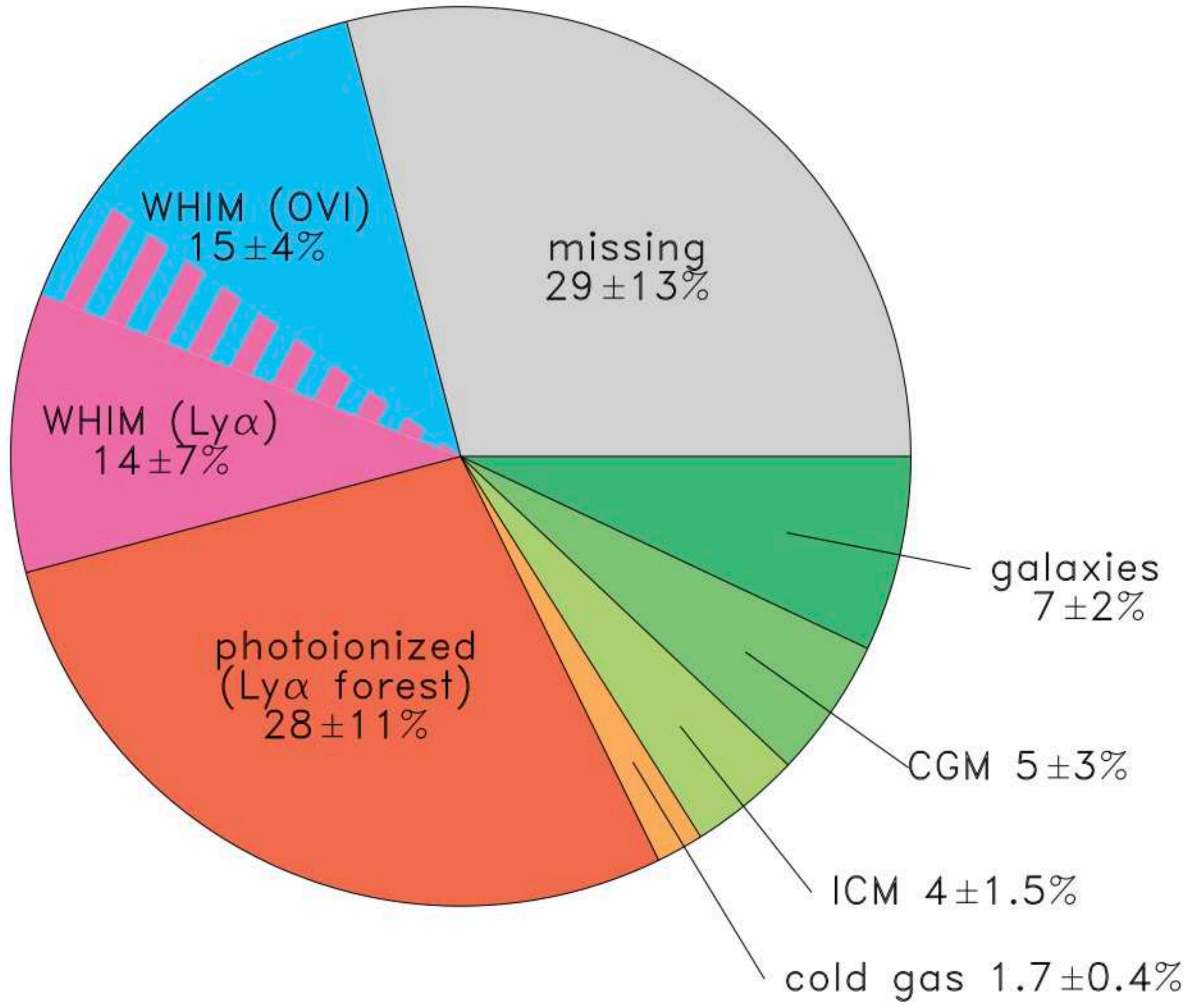


FIG. 9.— Compilation of current observational measurements of the low-redshift baryon census (Section 3.3). Slices of the pie-chart show baryons in collapsed form (galaxies, groups, clusters), in the circumgalactic medium (CGM) and intercluster medium (ICM) and in cold gas (H I and He I). Reservoirs include diffuse photoionized Lyα forest and WHIM traced by O VI and broad Lyα absorbers. Blended colors (BLAs and O VI) have combined total of $25 \pm 8\%$, accounting for double-counting of WHIM at $10^5 - 10^6$ K with detectable metal ions. The collapsed phases (galaxies, CGM, ICM, cold neutral gas) total $18 \pm 4\%$. Formally, $29 \pm 13\%$ of the baryons remain unaccounted for. Our simulations (Figure 2) suggest that an additional 15% reside in X-ray absorbing gas at $T \geq 10^6$ K. Additional baryons may be found in weaker lines of low-column density O VI and Lyα absorbers. Deeper spectroscopic UV and X-ray surveys are needed to resolve this issue.

The unobserved baryons are in the WHIM

(Warm Hot Inter-galactic Medium)

*'It appears that most of the baryonic components are observationally well constrained, **apart from the largest entry, for warm plasma, which still is driven by the need to balance the budget rather than more directly by the observations.**'*

Help! From hydro simulations

EAGLE simulation

5 Mpc thick slice
Galaxies (SDSS-like, Mr<-18.4)

Tuominen+ 2021

Baryon Density

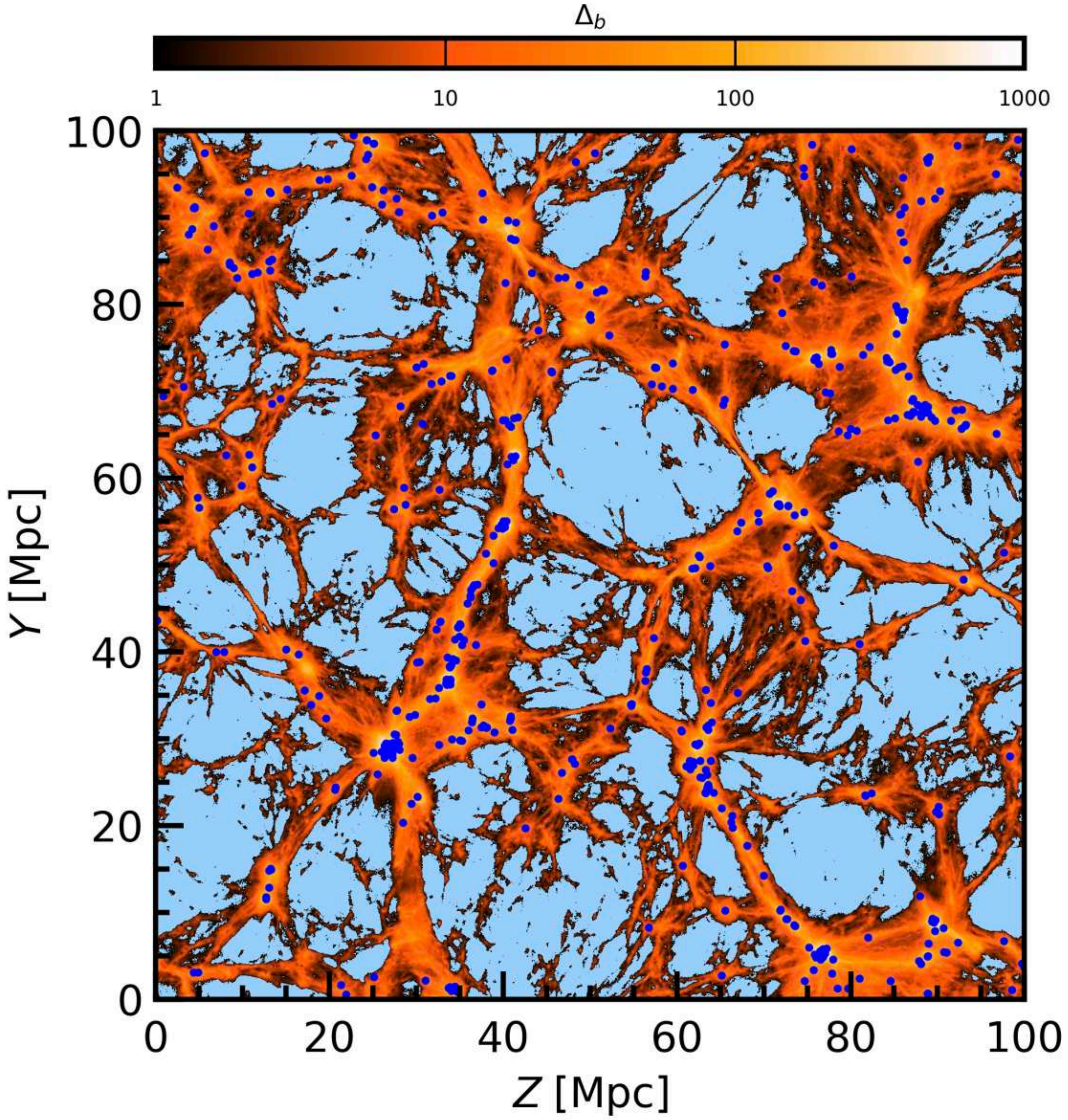


Fig. 1. Projected diffuse baryon density within a representative 5 Mpc slice (colour map) above the mean baryon density and galaxies brighter than M_r = -18.4 (blue dots) in the EAGLE simulation. The light blue colour denotes the regions below the mean baryon density. The density was computed by co-adding the masses of individual gas particles and dividing by the projected volume in each pixel.

Gas Temperature

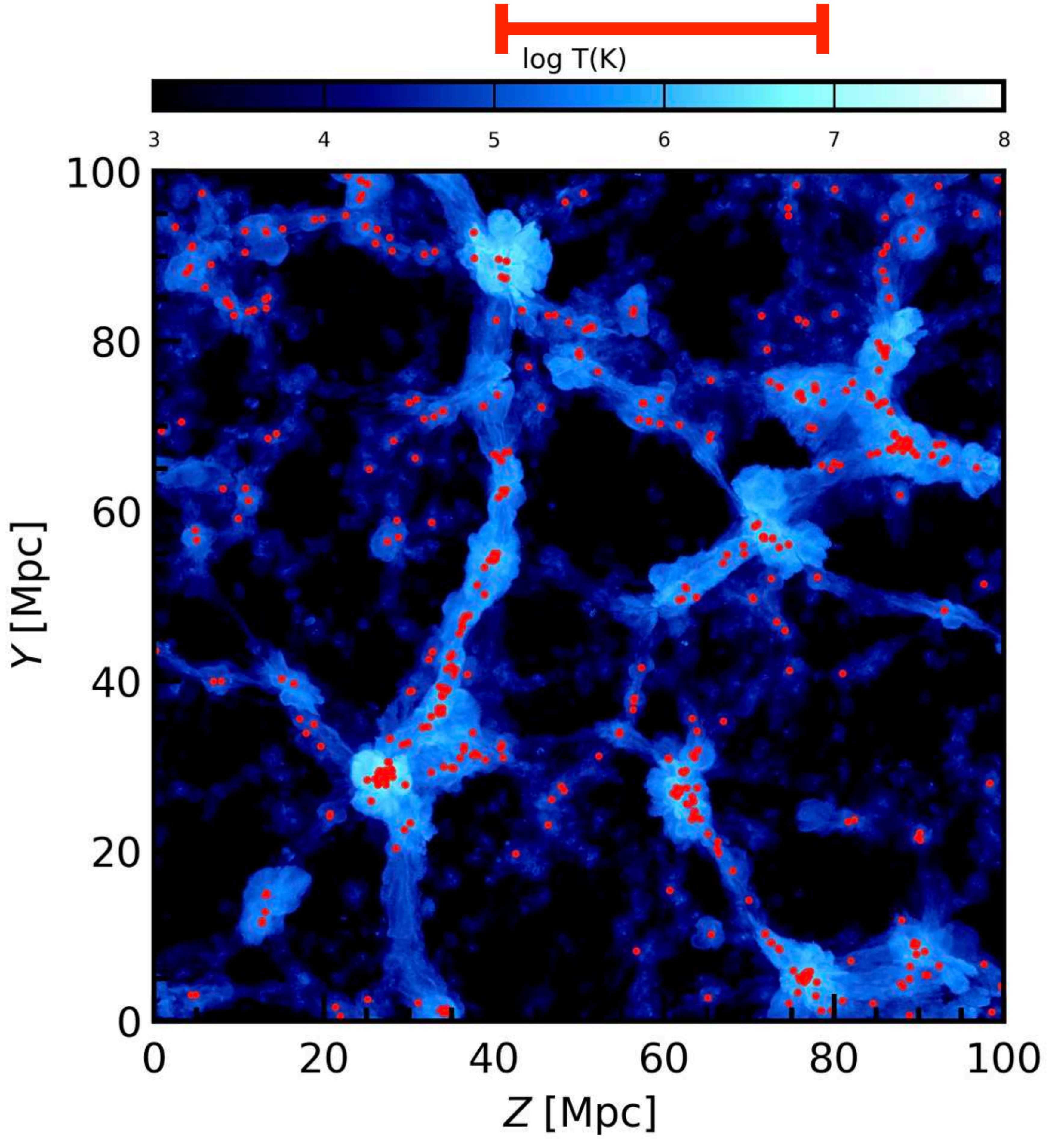


Fig. 5. Mass-weighted mean temperature distribution (in shades of blue) of the intergalactic gas, i.e. gas outside R_{200}, within the same slice as Fig. 1. Red dots denote the location of galaxies brighter than M_r = -18.4.

Yannick M. Bahé and Pascale Jablonka : Filaments in EAGLE and TNG100

EAGLE

IllustrisTNG

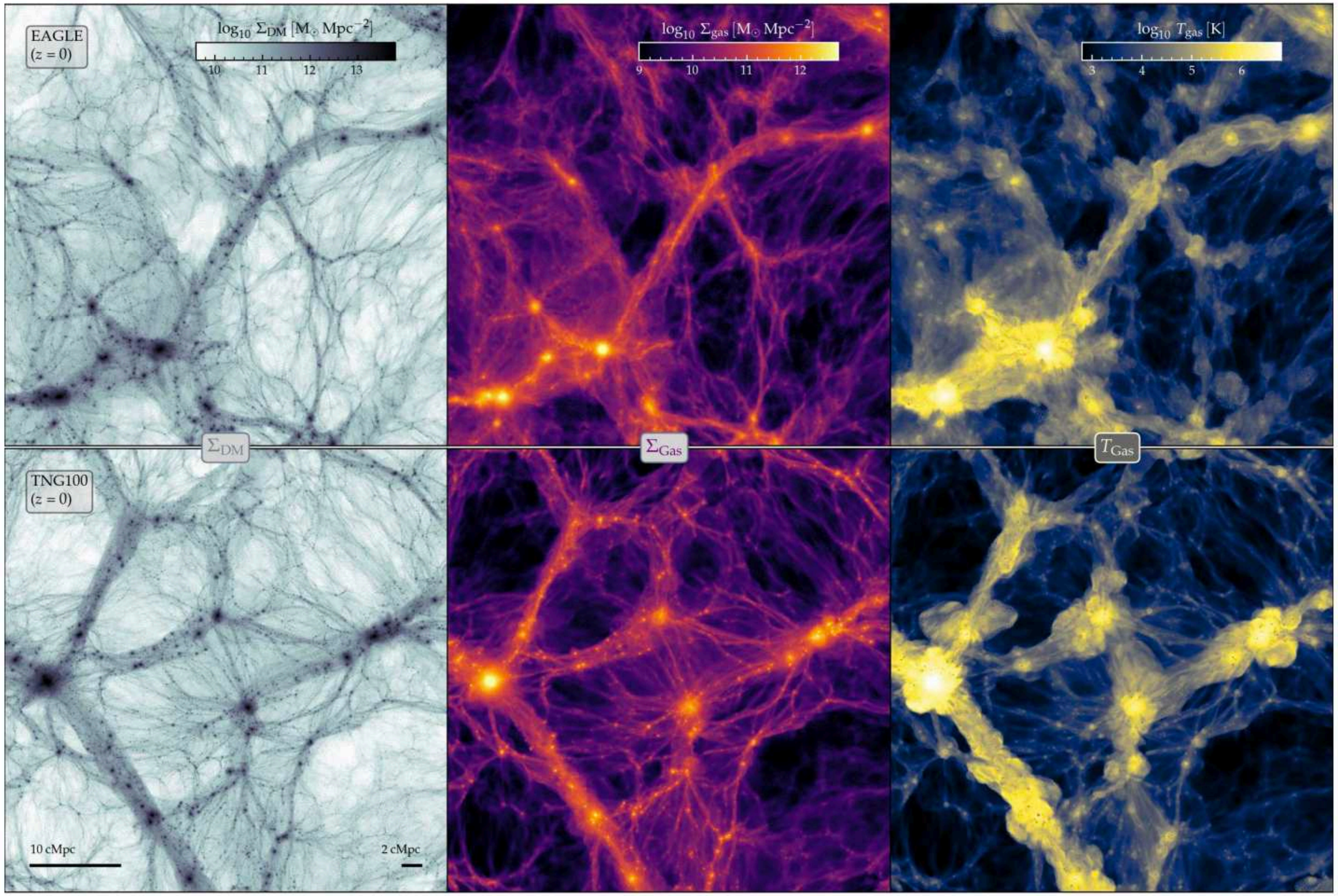
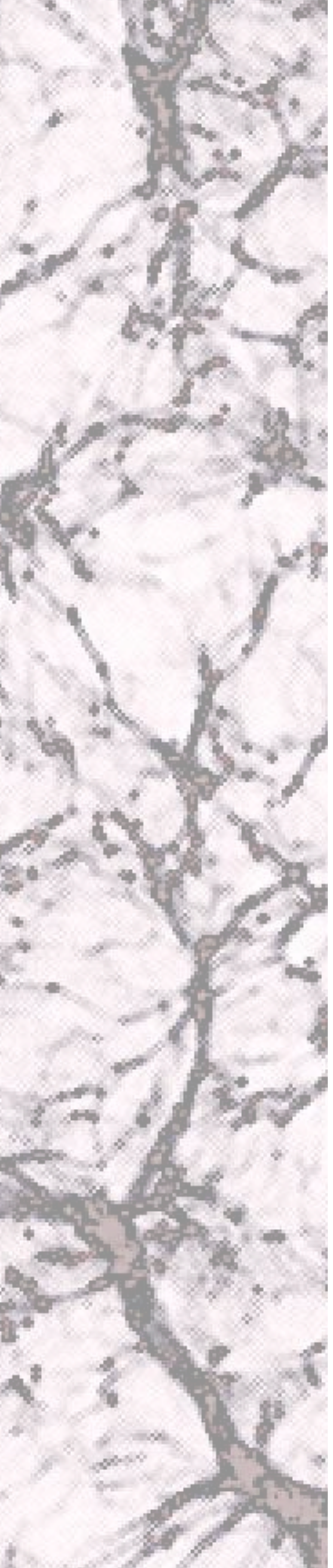


Fig. 15. Structure of the DM and gaseous cosmic web at $z = 0$ in EAGLE (top row) and TNG100 (bottom row). All six panels show a field of view of 50 × 50 Mpc, with a projection depth of 5 Mpc. DM density is shown in the left-hand panels, gas density in the middle, and mass-weighted gas temperature on the right. While the DM structures are near-indistinguishable, there are clear differences between the simulations in both gas density and temperature, as discussed in the text. Particularly noteworthy is the prominence of small gas-rich haloes in TNG that are absent in EAGLE, and the ubiquity of warm gas around filaments in EAGLE.

We need to look at filaments!



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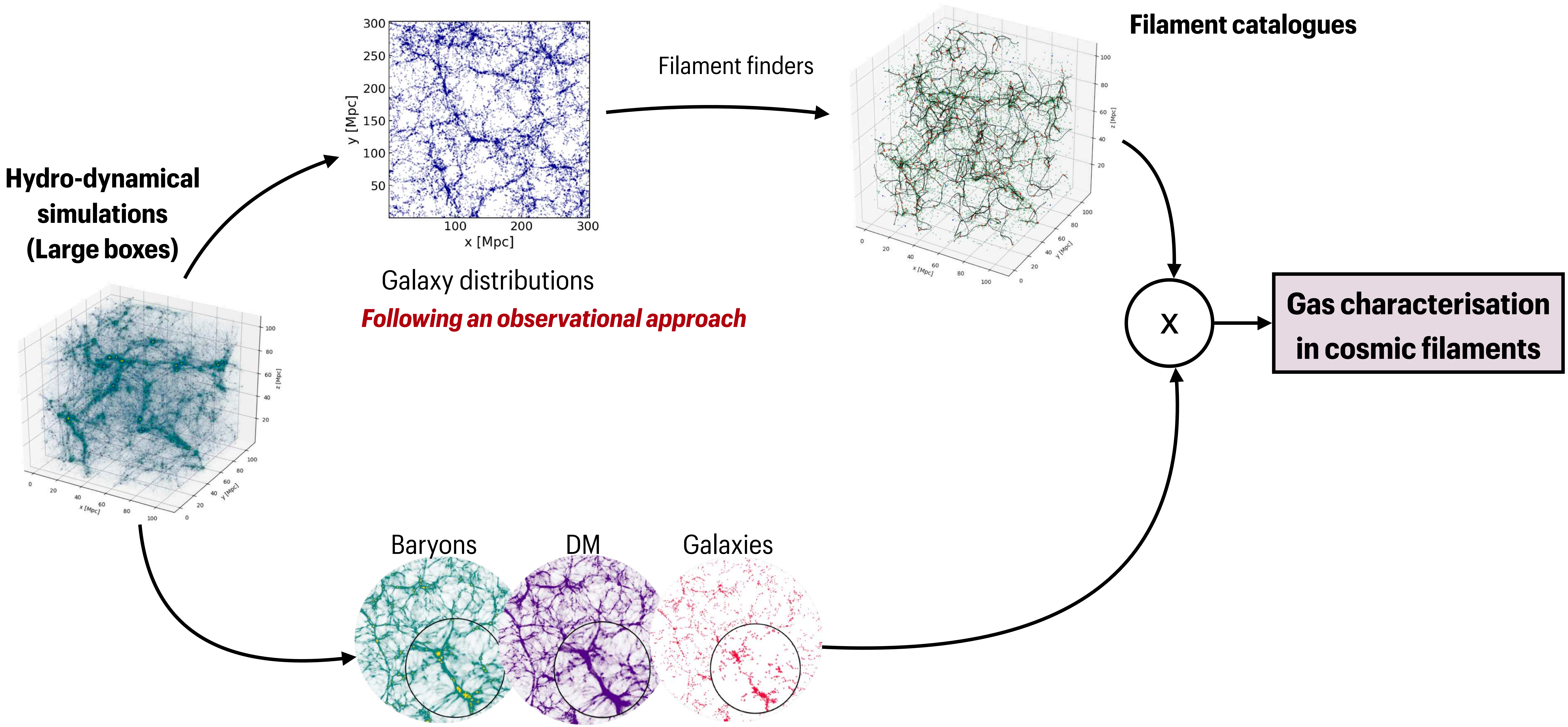
How to get some insight from simulations



Challenge 1: many filament finders!

Different filament finders, different definitions…

1. **Topology-based (DisPerSE, Sousbie+ 2011; Sousbie 2011)**

   Based on Morse theory and persistence diagrams, identifies topological features in the density field (point or).
2. **DM caustics (Origami, Neyrinck 2012)**

   Identifies structures by shell-crossing in the DM phase space (3D Lagrangian dynamics)
3. **Hessian of a field (classification based on eigenvalues of density or potential field):**
   1. MMF (Aragón-Calvo+ 2007, 2010a): Eigenvalue-based filtering to classify web types on multiple scales.
   2. NEXUS / NEXUS+ (Cautun+ 2014): Improved multiscale eigenvalue method applied to density and velocity fields
   3. Pfeifer+ 2022 : eigenvalue-based algorithm used in simulations
4. **Stochastic / statistical methods**

   Bisons (Stoica+ 2007; Tempel+ 2016): treats filaments as random cylinders placed according to a probability field (Markov Chain Monte Carlo)
5. **Graph-based (Pereyra+ 2020): graph of halos.**
6. **Regularised minimum spanning trees (T-rex, Bonnaire+ 2020)**
7. **Machine learning classification tools:**
   1. supervised ML on N-body data to classify web types (Buncher & Carrasco 2019)
   2. convolutional neural networks (CNN, Inoue+ 2022)
   3. deep learning methods (Awad+ 2023)

Each with different inputs:
- Galaxy distributions
- Matter density field
- Velocity field
- Slime mold (pheromones, Hasan+2024)

See comparison projects Libeskind+ 2018 (simulations) and Rost+ 2021 (observations, SDSS)

ChatGPT: summary table

Name	Reference	Input Type	Method	Key Features / Output
DisPerSE	Sousbie 2011	Density field (grid or particles)	Topological (Morse theory)	Persistence-based skeleton of filaments and voids
Slime Mold–based DisPerSE variant	Hasan+ 2023	Point distributions (galaxies, particles)	Bio-inspired growth algorithm with DisPerSE topology	Grows networks mimicking slime mold behaviour, guided by DisPerSE critical points; generates adaptive, continuous networks
ORIGAMI	Neyrinck 2012	Dark matter particles	Dynamical (phase-space caustics)	Shell-crossing detection; assigns web classification per particle
MMF	Aragón-Calvo+2007, 2010a	Density field (grid)	Hessian eigenvalues	Multiscale web classification (voids, sheets, filaments, knots)
NEXUS / NEXUS+	Cautun+2014	Density / velocity fields	Hessian (scale-space filtering)	Classifies cosmic web types via eigenvalues on multiscale smoothed fields
(No name)	Pfeifer+2022	Density field	Hessian-based	Calibrated web classification across cosmologies
Bisous model	Stoica+2007; Tempel+2016	Galaxy catalogue	Statistical (marked point process)	Probabilistic filament detection as cylinder chains; observationally used
(No name)	Pereyra+2020	Galaxy positions	Graph theory	Builds graph structure and extracts filaments via connectivity
T-ReX	Bonnaire+2020	Galaxy catalogue or halos	MST-based	Regularised minimum spanning trees used to define filament skeletons
(No name)	Buncher & Carrasco 2019	Simulated density maps	Machine learning (random forest)	Supervised classification of web types from simulated features
(No name)	Inoue+2022	2D/3D maps	Deep learning (CNNs)	Trained on labelled simulation maps to segment filament structures
(No name)	Awad+2023	Simulation volumes	Deep learning	Identifies filamentary structures using 3D convolutional networks

ChatGPT: strengths and weaknesses of filament finders

Tool	Great for...	Limitations
DisPerSE	Topological robustness, simulations, full 3D maps	Sensitive to noise, hard to tune thresholds
Slime Mold	Realistic network geometry, bio-inspired networks	New, few benchmarks, heuristic tuning
ORIGAMI	Phase-space collapse, theoretical insights	Requires 6D phase-space, no direct obs use
MMF/NEXUS	Full web classification, multiscale fields	Grid-based, smoothing dependent, no jobs use
Bisous	Galaxy catalogues, probabilistic output	Parameter tuning, slow, no dynamics
T-ReX	Fast MST-based networks from galaxies/halos	Geometric only, sensitive to noise
Graph methods	Simple galaxy connectivity	No dynamics, arbitrary linking
ML methods	Flexible, adaptable, learn complex patterns	Data-hungry, less interpretable, hard to trust

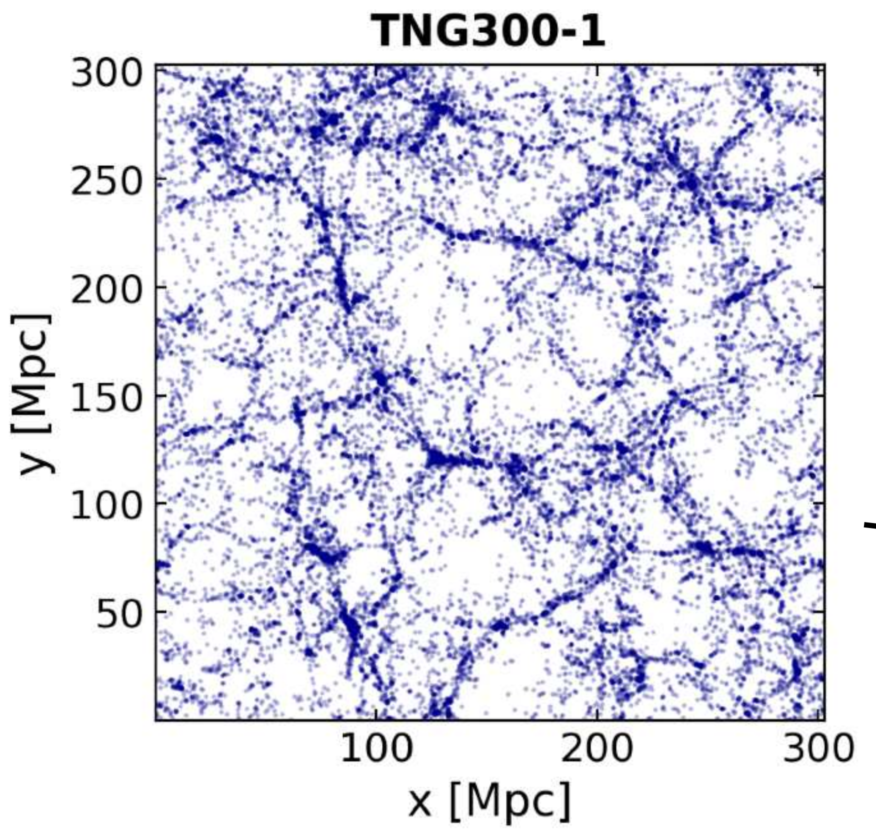
The DisPerSE framework

Publicly available code

Sousbie+ 2011, Sousbie 2011

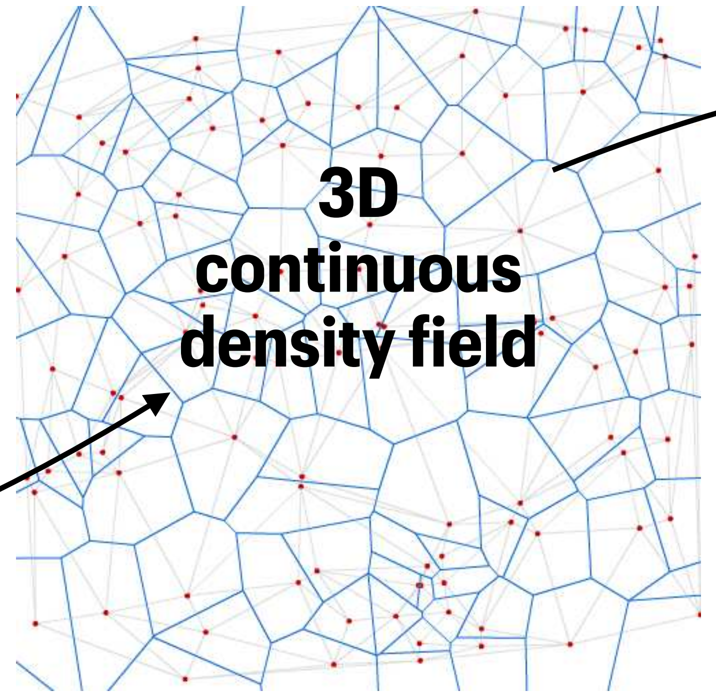
Discrete **Per**sistent **S**tructures **E**xtractor

Distribution of galaxies (discrete)



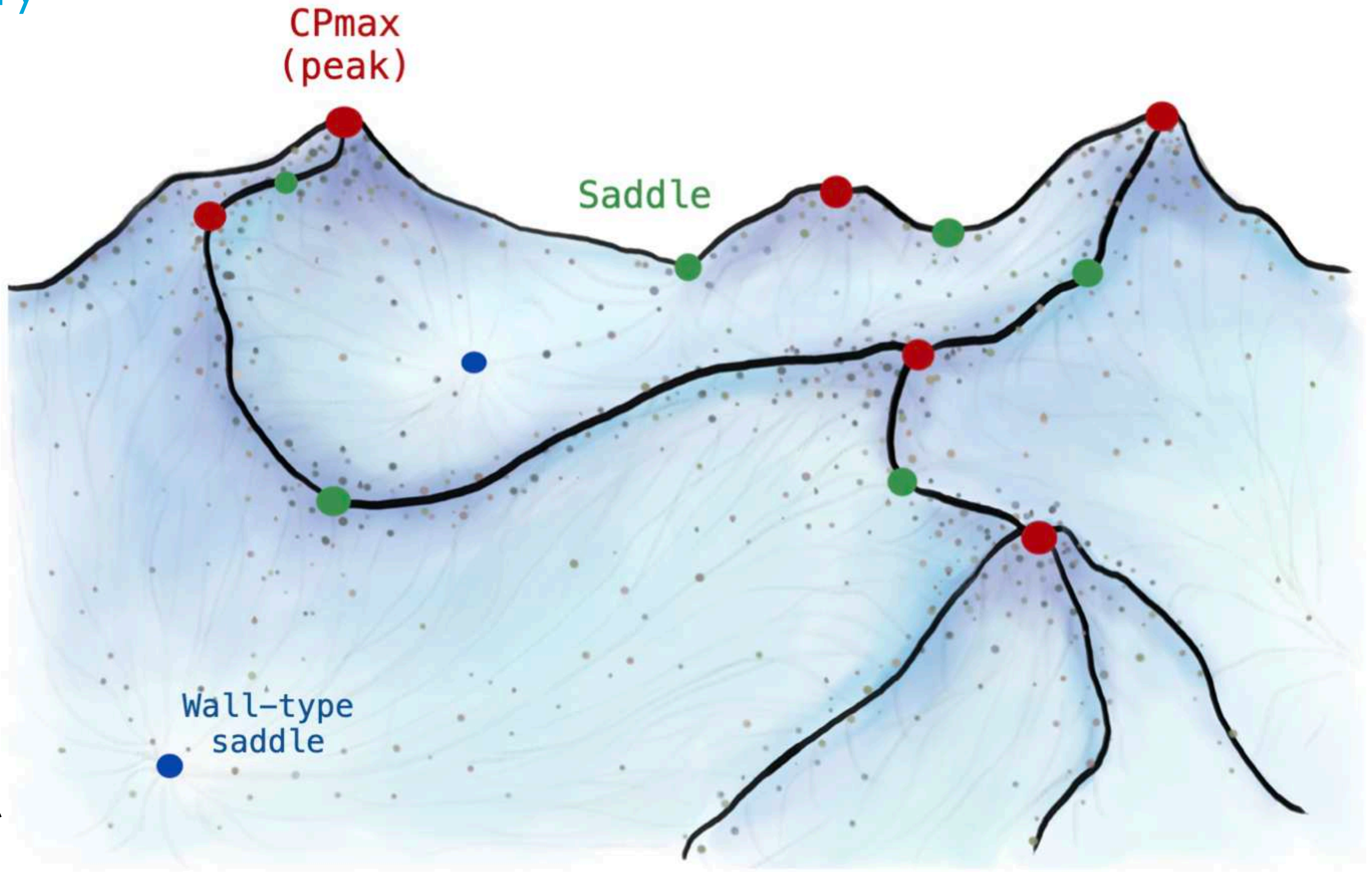
Delaunay tessellation

van de Weygaert & Schaap 2009

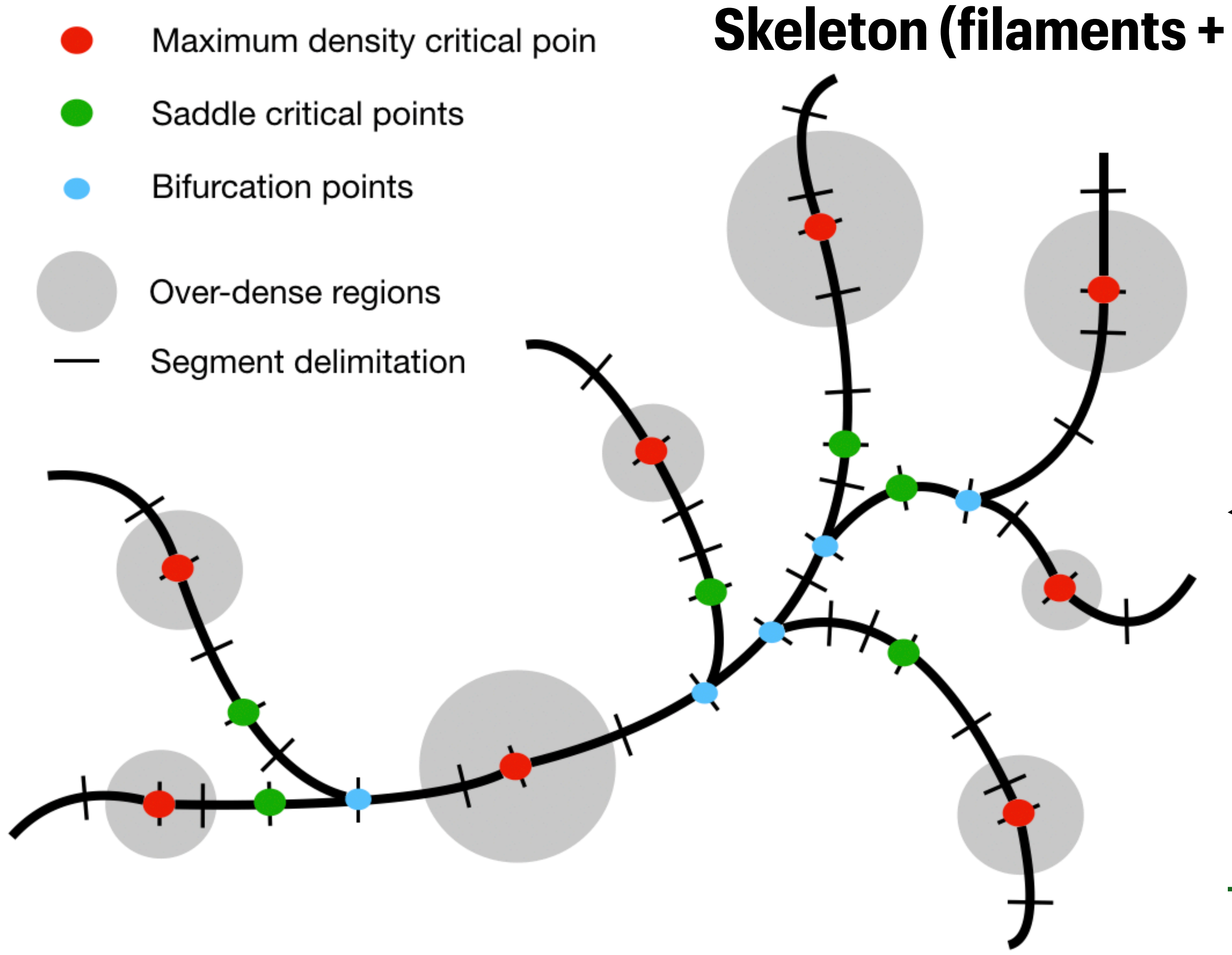


Morse-Smale Complex theory

Extraction of **topological** information



Skeleton (filaments + critical points)



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

Challenge 2: the filament determination depends on the tracer

Zakharova et al 2023

Setup:
- Millennium simulation
- Galaxy properties: semi-analytical models (GAEA)
- 27 cubes, centered on cluster-like haloes
- Extracted DisPerSE filaments in
  - Galaxy distribution (Mstar>1e9 Msun)
  - DM particles distribution
- Also explored:
  - Dependence of different galaxy masses
  - Centrals only vs centrals + satellites

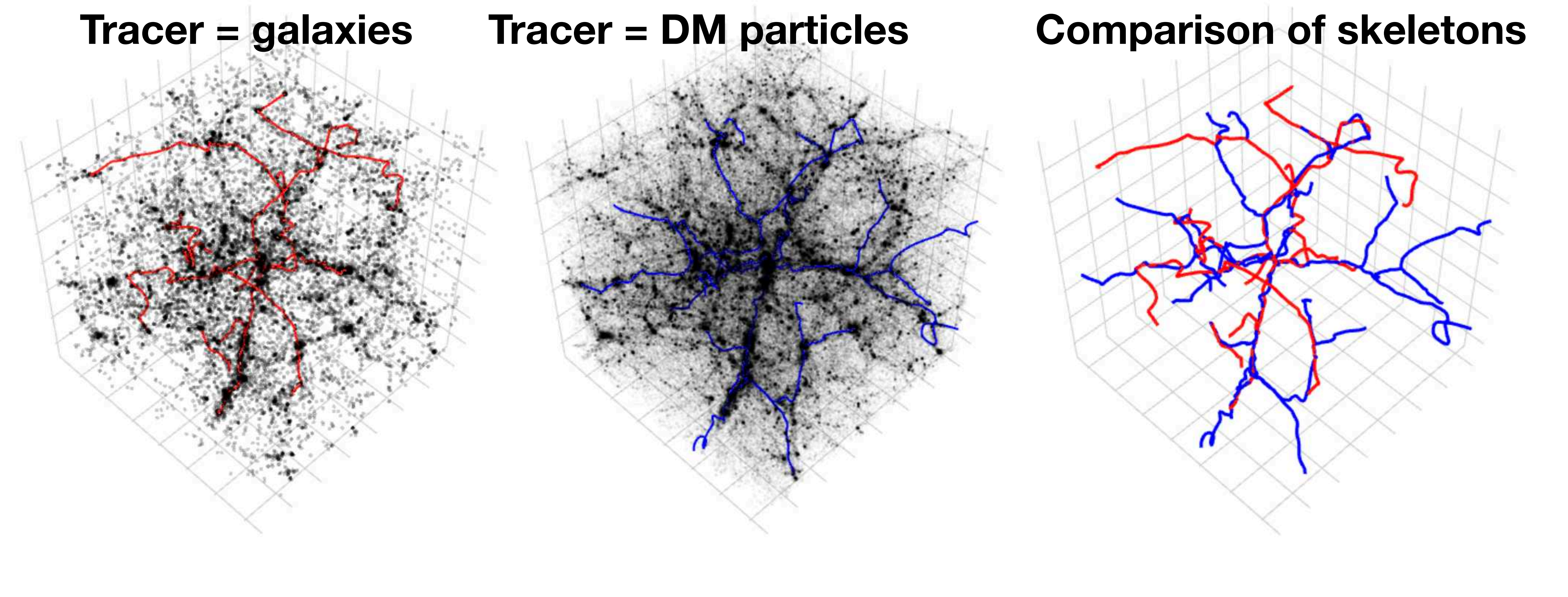


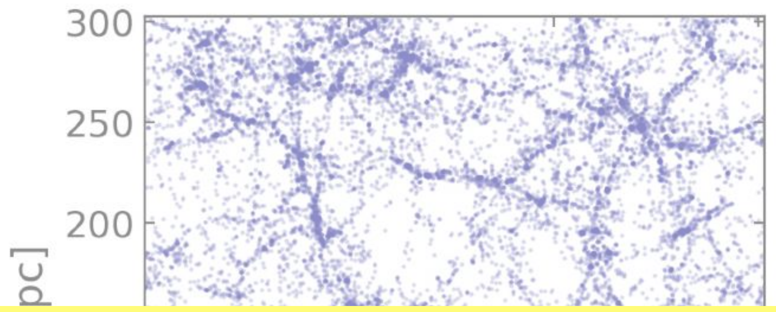
Figure 1. Example of the filamentary structures obtained using DisPerSE. The left panel shows the distribution of all galaxies with $M_* > 10^9 M_\odot$ (black dots) and the filament structure extracted using these galaxies as tracers (red curves). The middle panel shows the distribution of the dark matter particles in the same sub-volume of the Millennium simulation. For the sake of clarity, we only plot 2% of all particles, even though all particles are considered when running DisPerSE. The blue curves show the extracted filaments. The right panel compares the filamentary structures based on galaxies (red) and dark matter (blue). Each cube is 70 Mpc/h on a side.

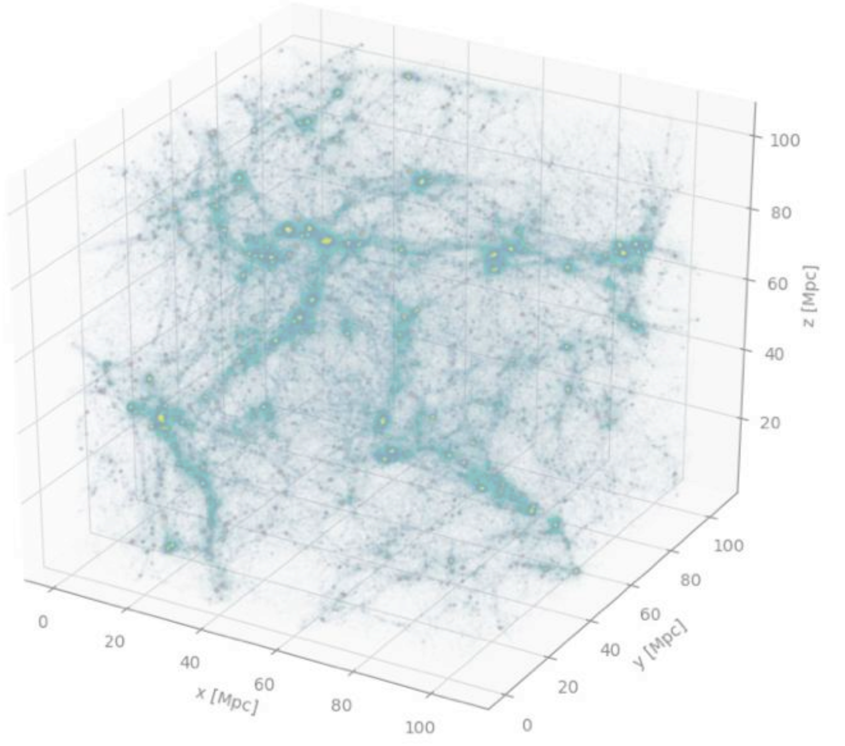
Result:
- *"Regardless of the galaxy stellar mass threshold adopted, about **41%** of the dark matter filaments do not contain enough galaxies to be detected when using galaxies as tracers"*
- **Using galaxies as tracers, only the strongest filaments can be robustly identified.**

Caveats (my personal opinion):
- calibration of Disperse (not done)
- They focus on cluster like regions (observational motivation)
- Disperse in DM particles is crazy. Shot noise levels…!!!

See also: **Laigle et al. 2018**, **Bahé & Jablonka 2025**

How to get some insight from simulations



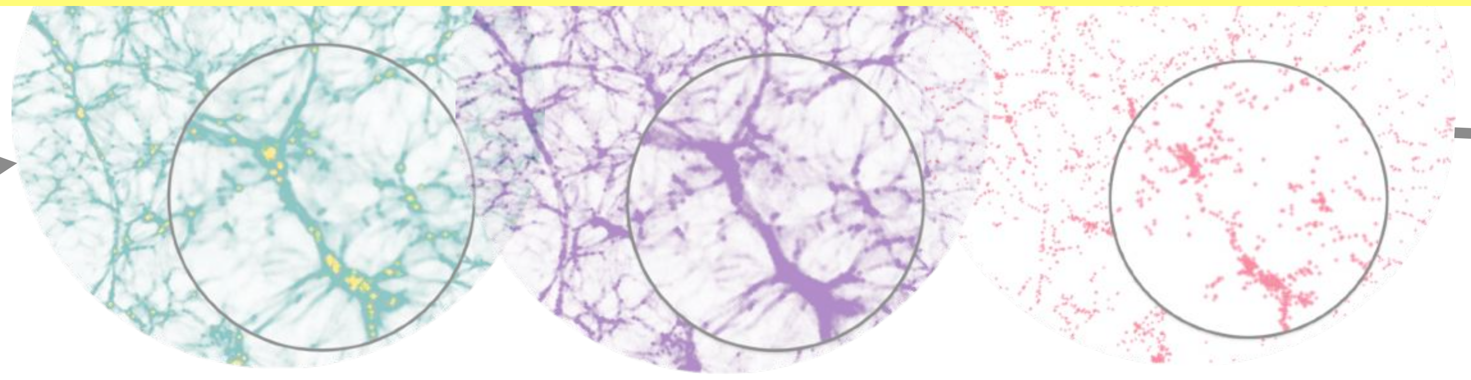


Disclaimer: the following is observation-oriented.

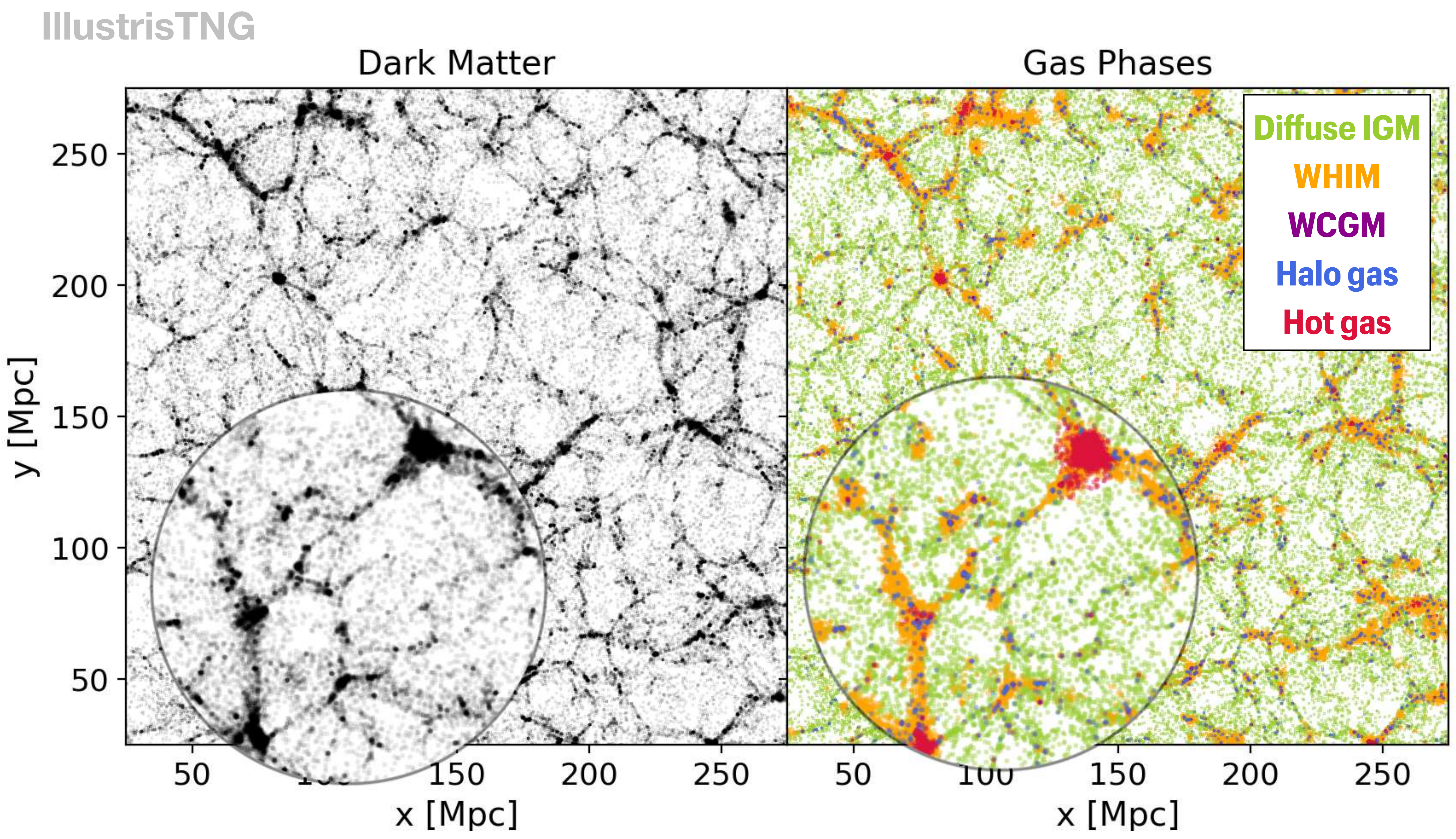
1) We rely on the assumption that the distribution of galaxies reflects well enough that of the dark matter.

2) We know we are sensitive only to the most prominent cosmic web features

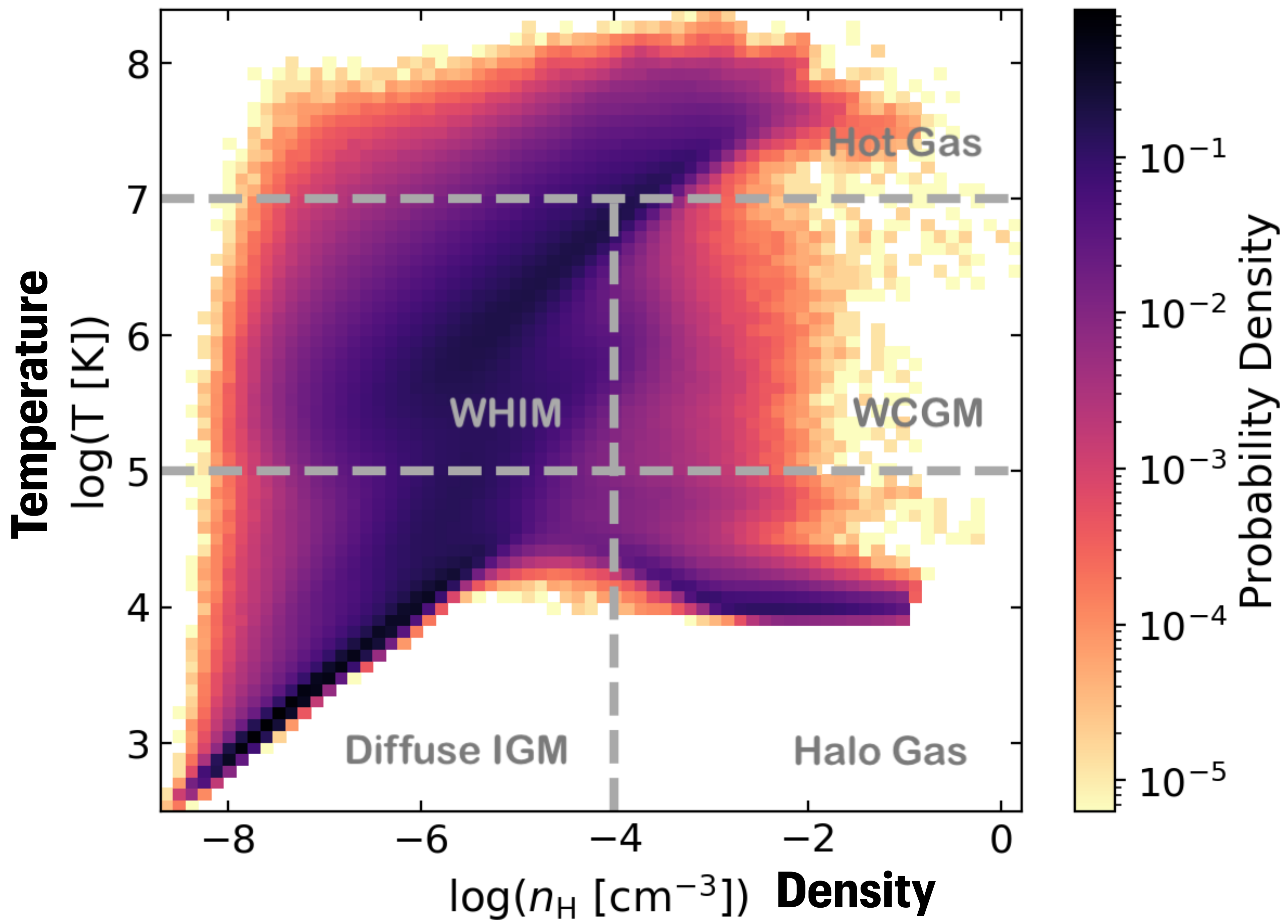
3) The detected (observed) filaments might or might not correspond to the true physical structures (e.g. caustic filaments)



Gas phases



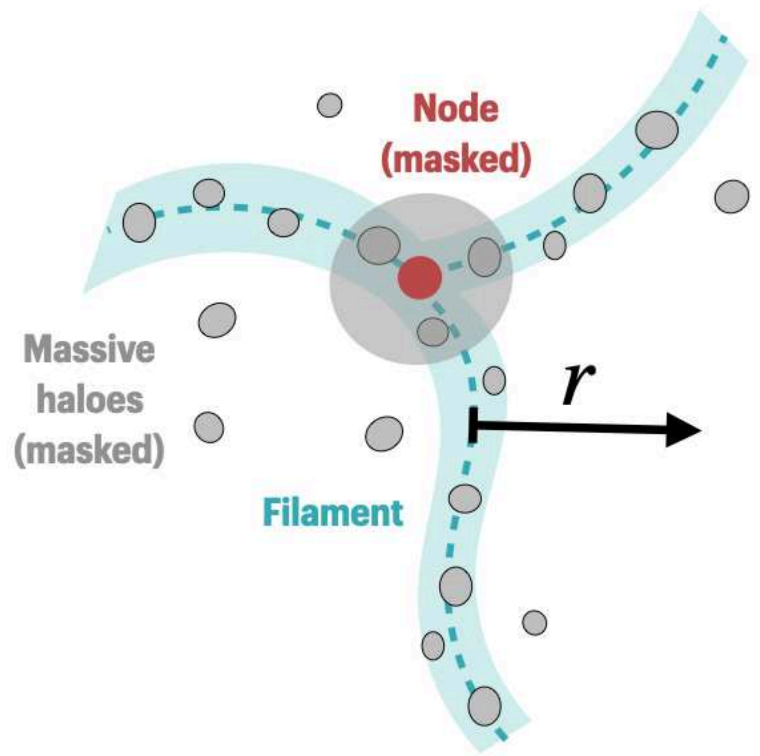
Gas phase separation following Martizzi+ 2019 (TNG300-1)



	Density [cm^{-3}]	Temperature [K]	Comments
Diffuse IGM	$n_H \leq 10^{-4}$	$T \leq 10^5$	Gas in the lowest-density regions of the cosmic web.
WHIM	$n_H \leq 10^{-4}$	$10^5 < T \leq 10^7$	Gas that has been accreted onto cosmic structures and heated by shocks.
WCGM	$n_H > 10^{-4}$	$10^5 < T \leq 10^7$	In the surroundings of galaxies, sensitive to galactic physics.
Halo gas	$n_H > 10^{-4}$	$T \leq 10^5$	In the interstellar medium of galaxies, located inside or near them.
Hot gas	no cut	$T > 10^7$	Shock-heated gas located in the denser regions of the cosmic web.

Galarraga-Espinosa+ 2021

Gas in filament cores



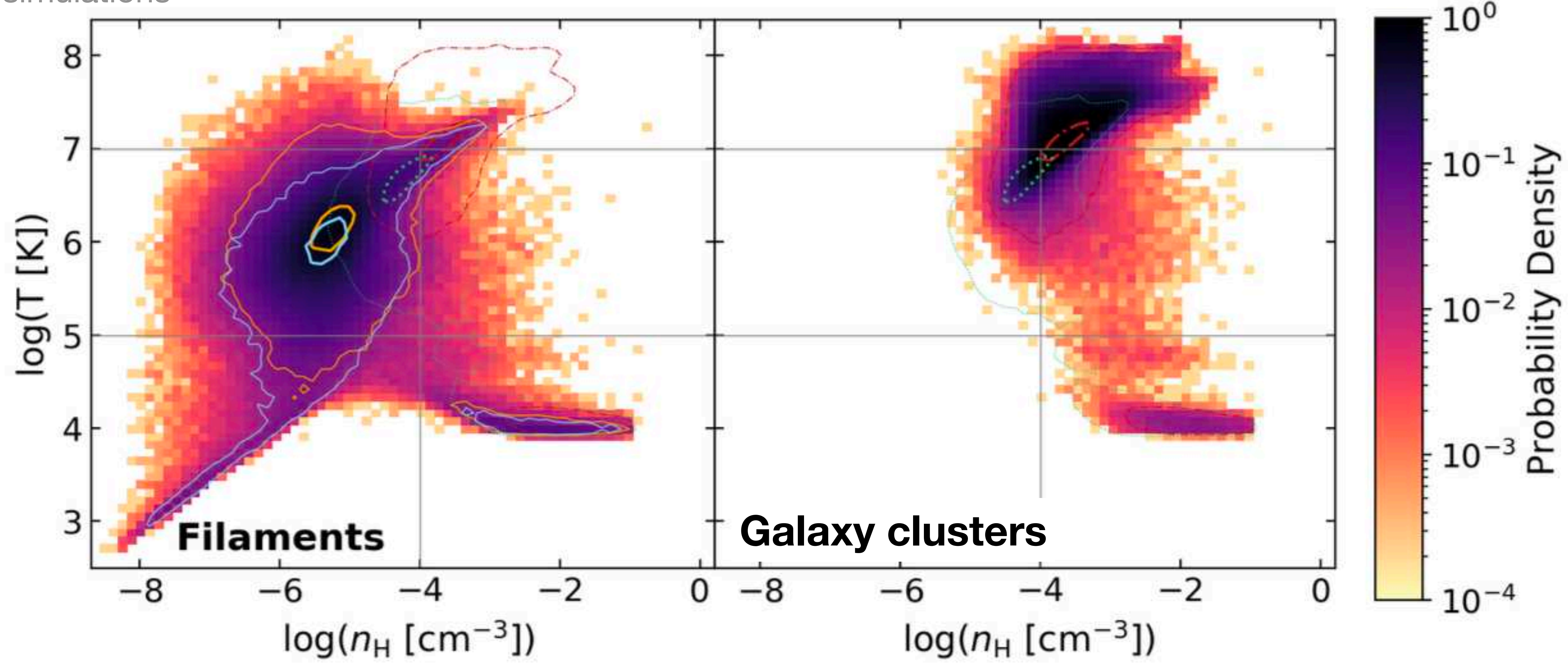
***Important**: gas in massive haloes removed*
—> focus on inter-filament gas

Masked: Mh = 1e12 Msun

Galarraga-Espinosa+ 2021

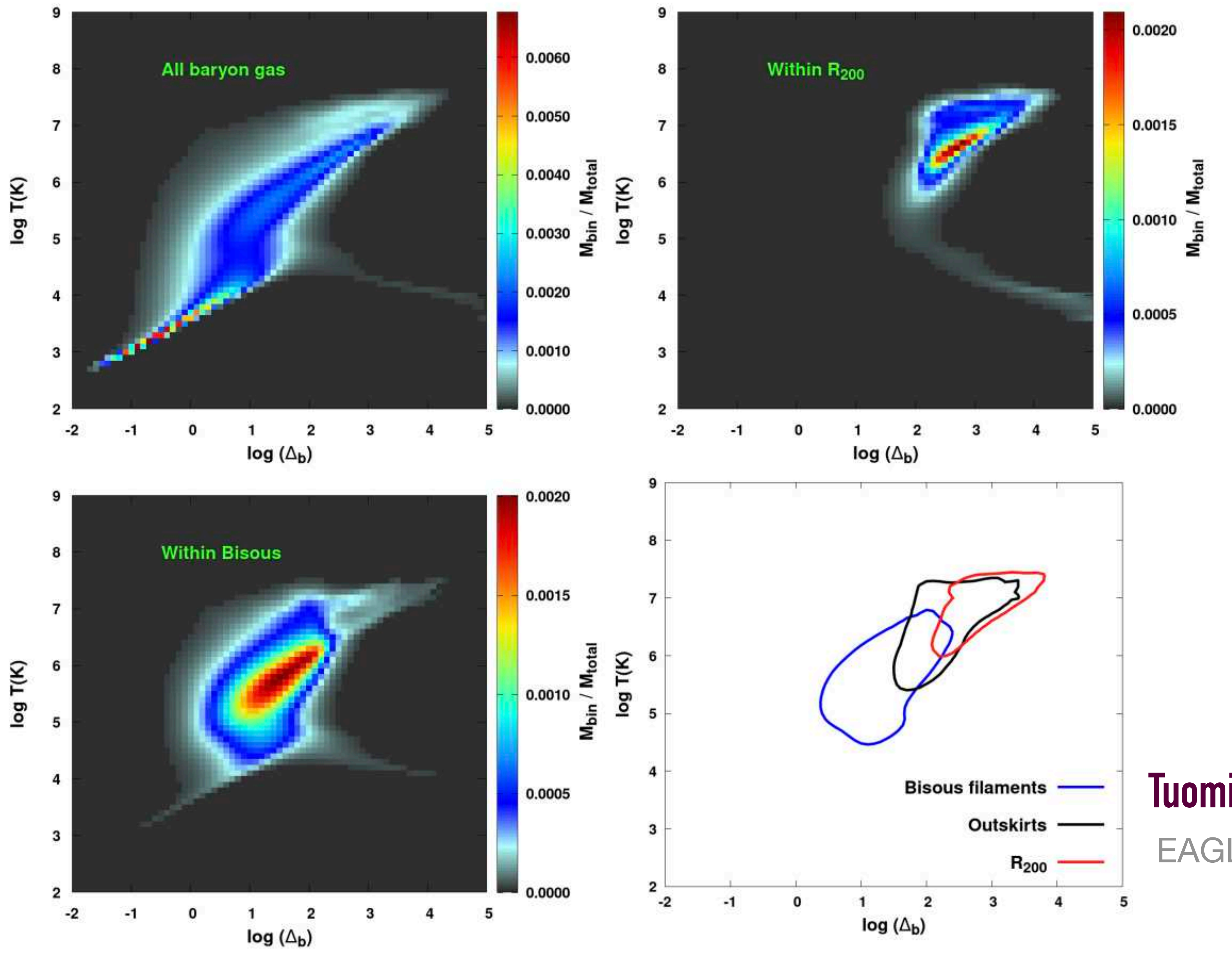
TNG simulations

Gas density-temperature diagram



Gas content

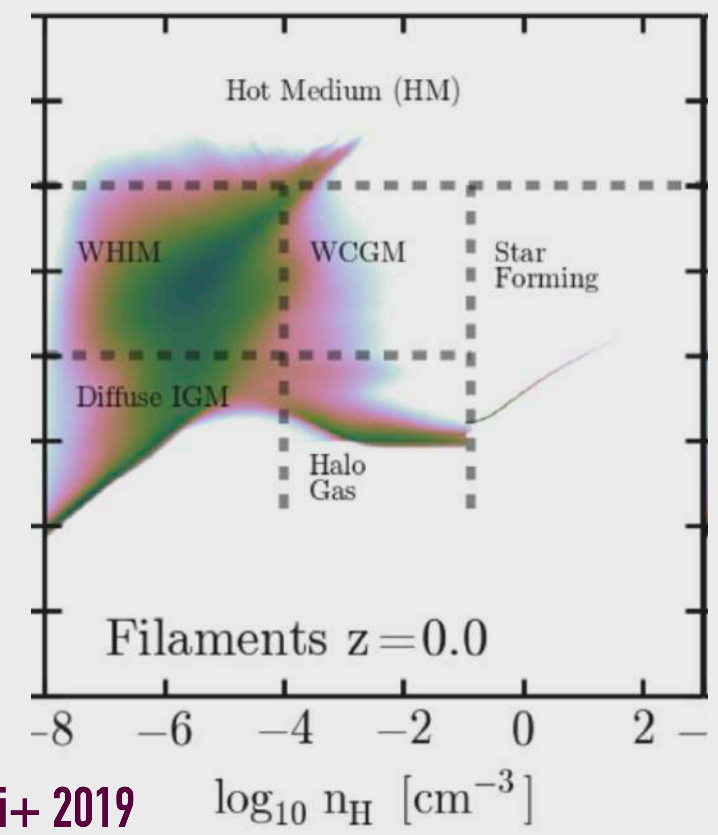
- Filaments: warm and diffuse gas (WHIM)
- Clusters: hot gas (easier to detect, e.g. X-ray)

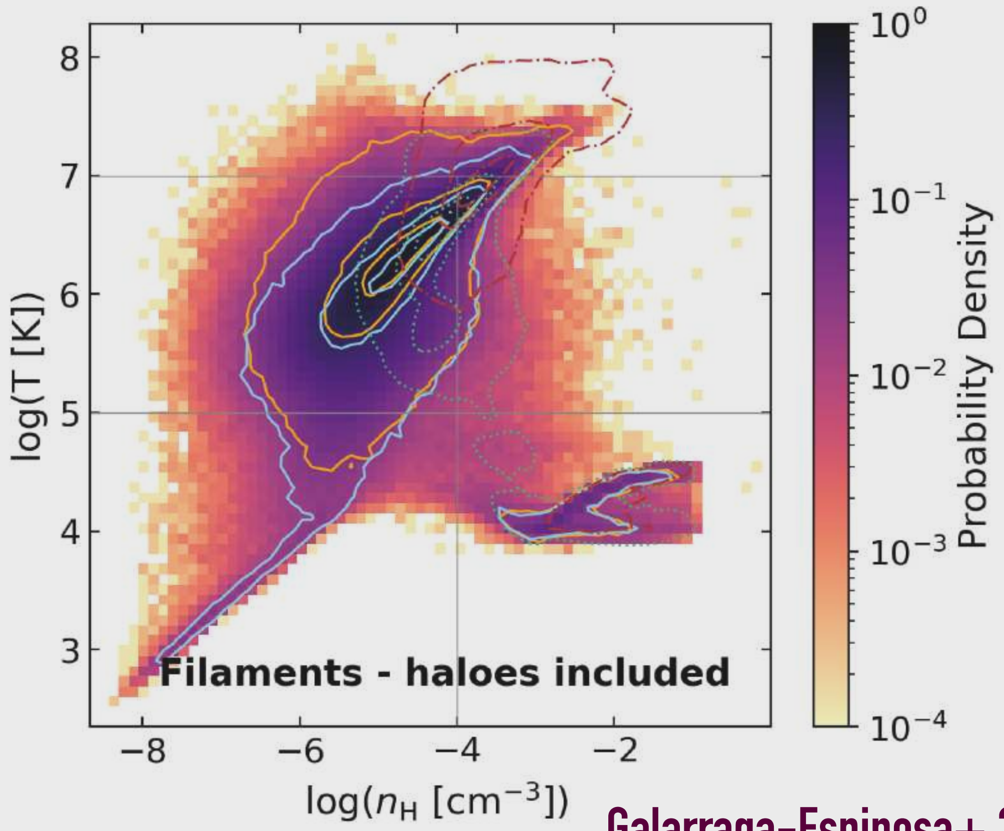


Tuominen+ 2021

EAGLE simulations

When gas in halos is included

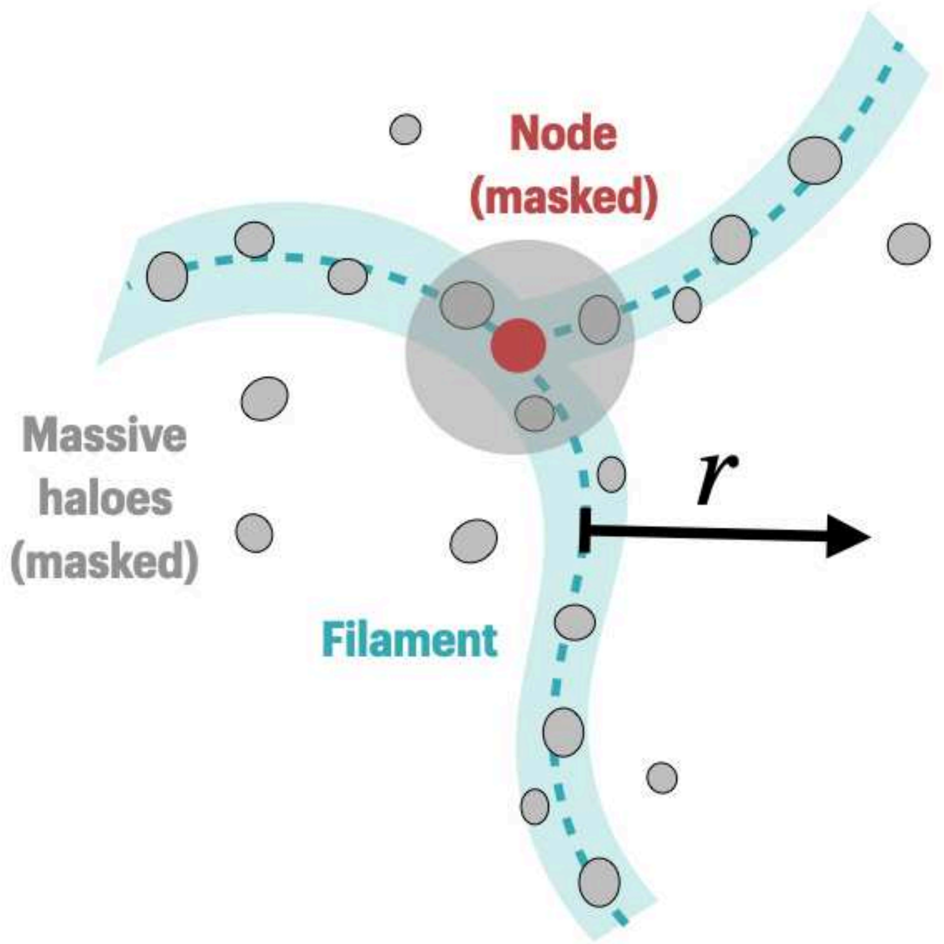




Martizzi+ 2019

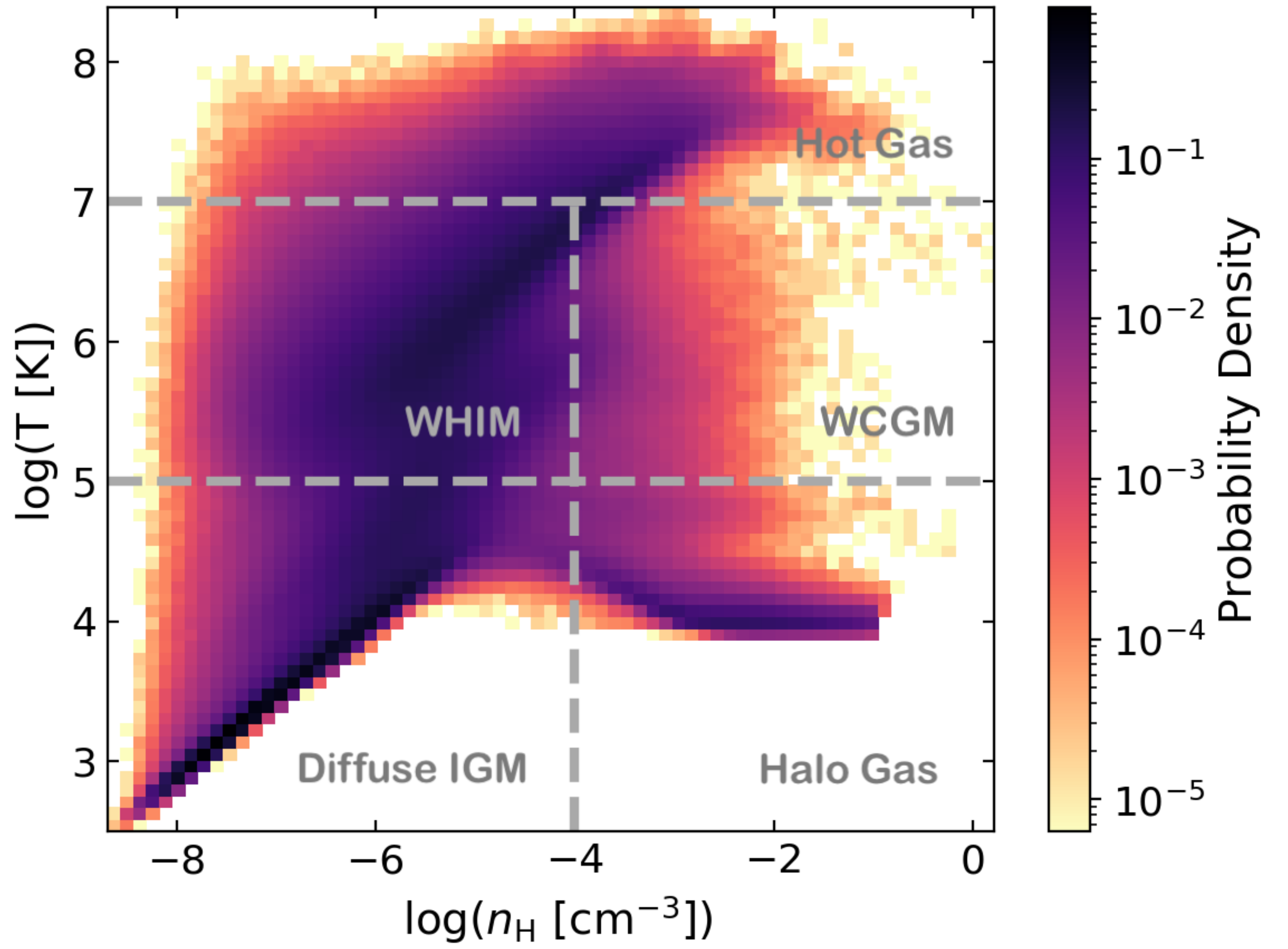
Galarraga-Espinosa+ 2021

Gas further away from the cores



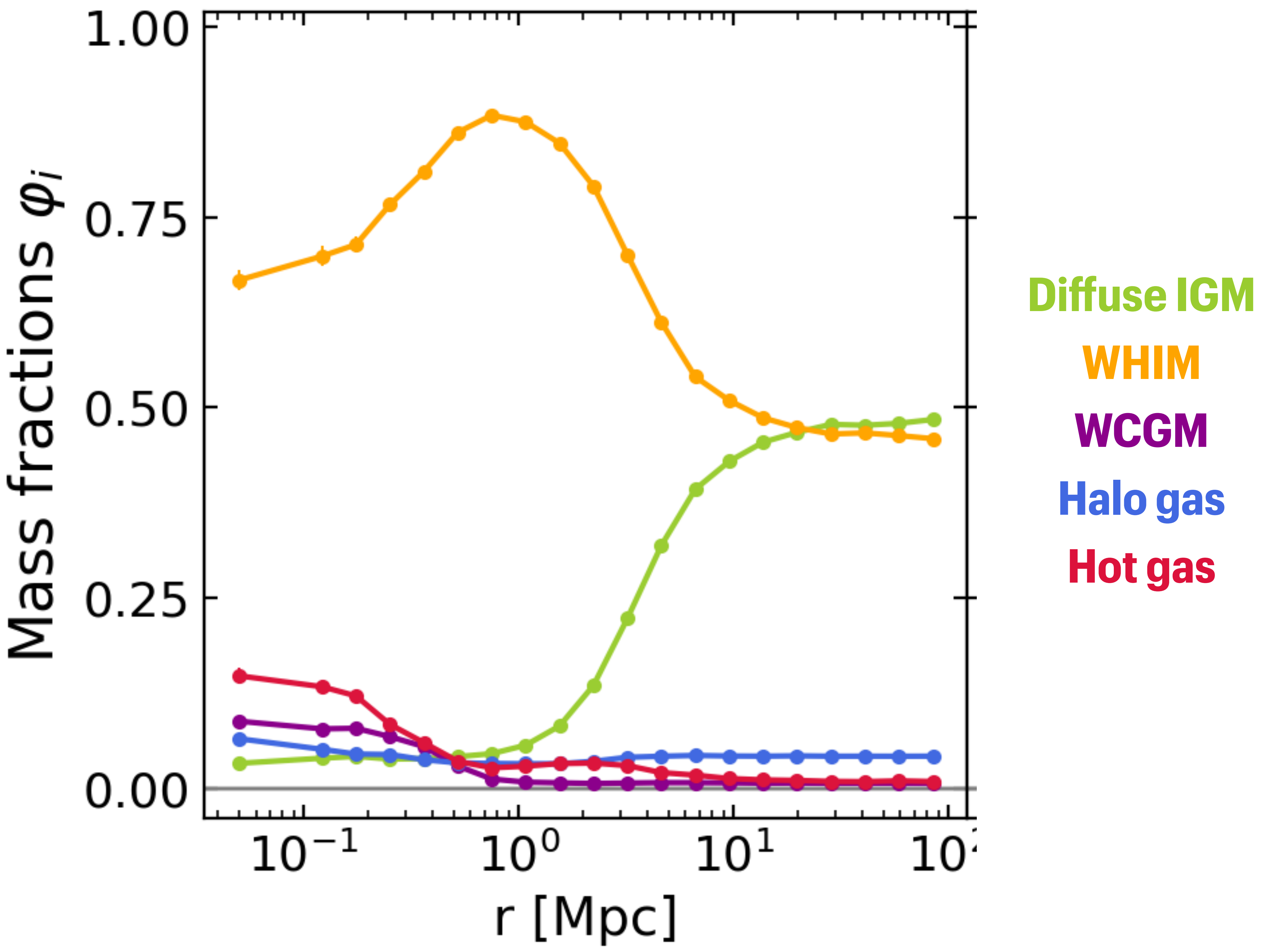
Focus only on inter-filament gas!

- ✓ Remove gas in nodes ($3\,R_{200}$)
- ✓ Remove gas in massive haloes $M_{\rm tot} > 10^{12}\,{\rm M}_\odot$ ($3\,R_{200}$)

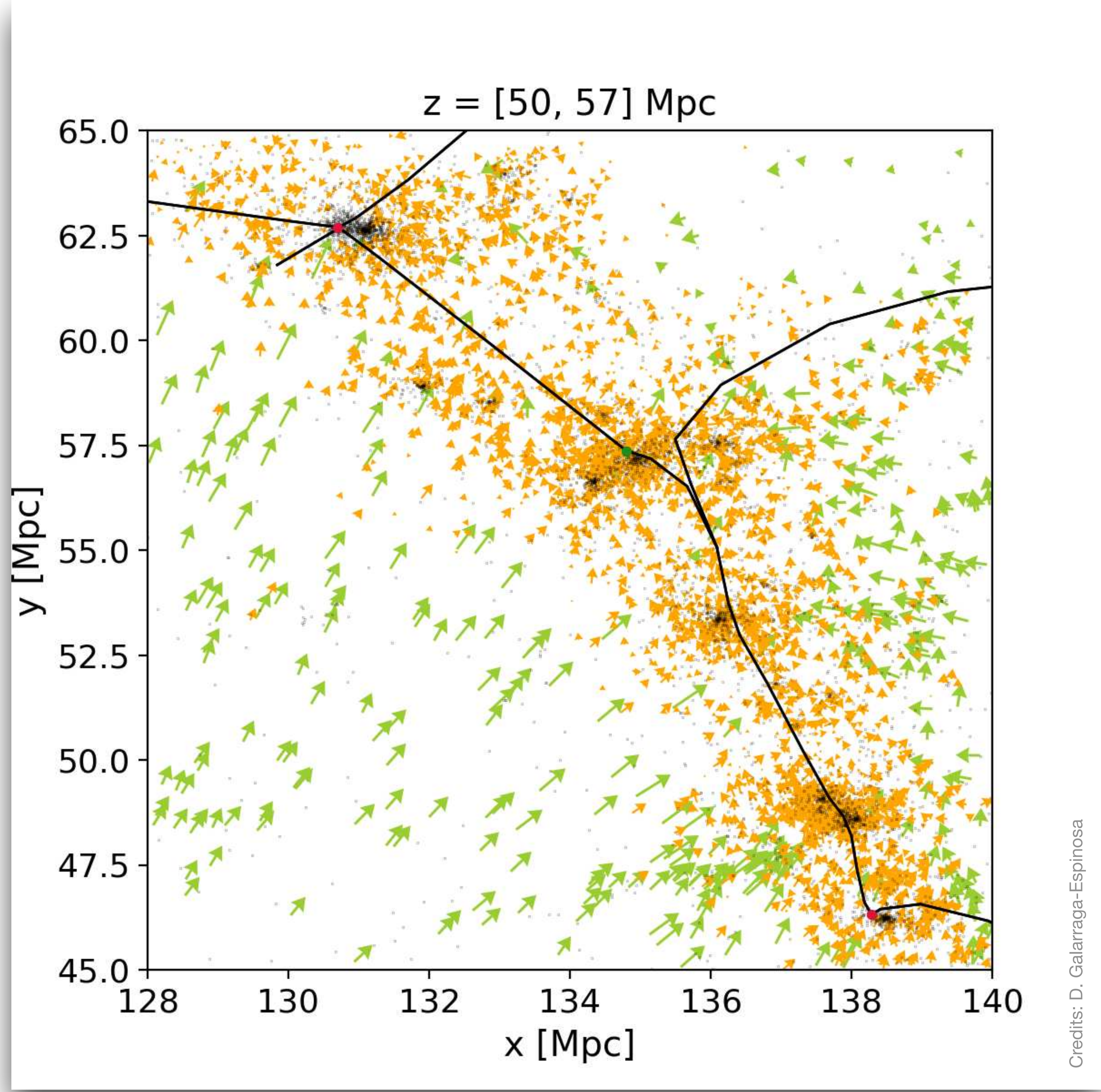


$$\varphi_i(r) = \frac{\rho_{{\rm gas},i}(r)}{\rho_{\rm gas,tot}(r)}$$

Radial profiles of mass fraction of each gas phase



Galarraga-Espinosa+ 2021



Credits: D. Galárraga-Espinosa

Baryon fraction profiles

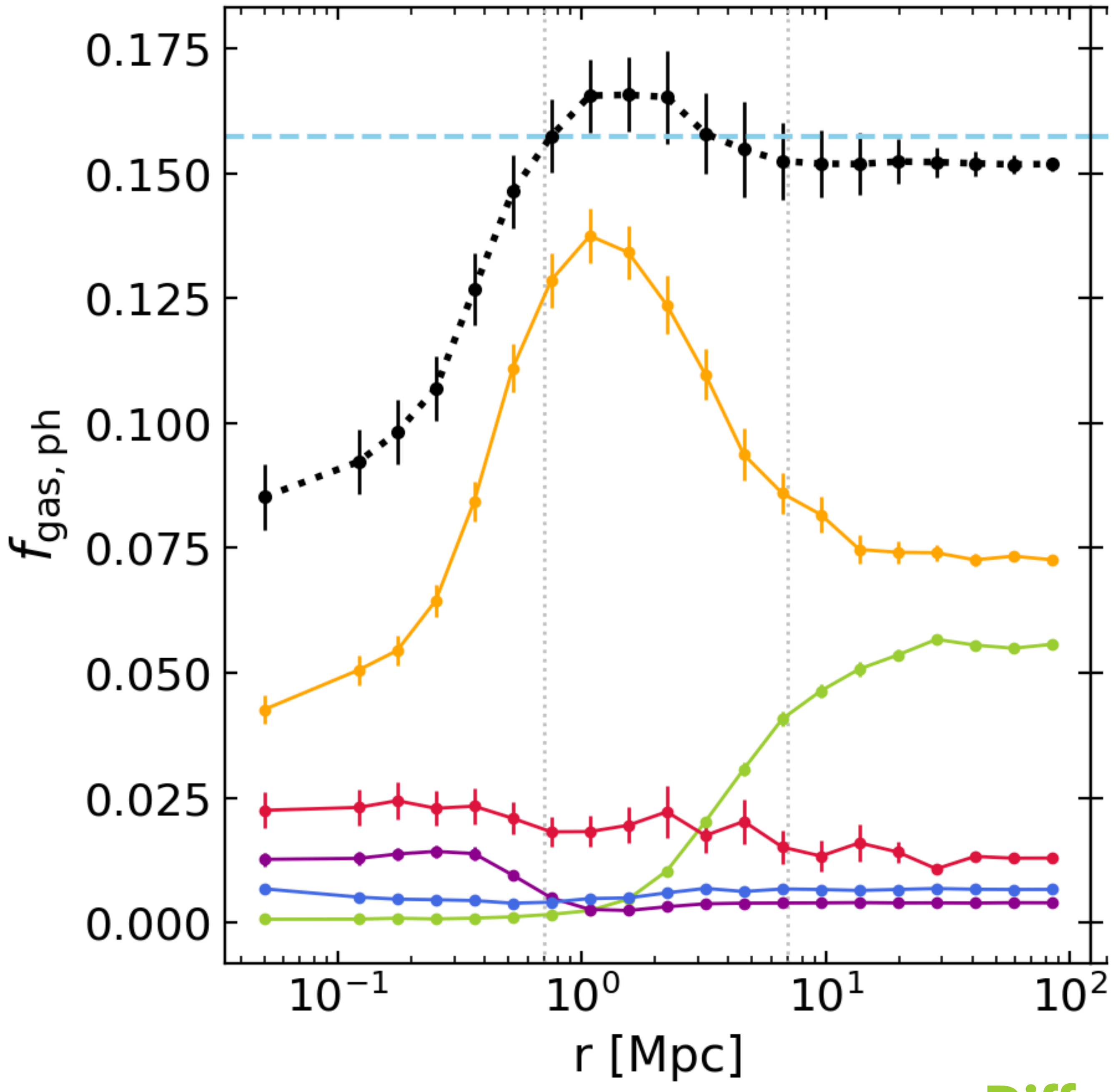
z=0

Relative distributions of baryons, stars, and dark matter around filaments

Galárraga-Espinosa+ 2022

$$f_{\rm b}(r) \equiv \frac{\rho_{\rm gas}(r)+\rho_*(r)}{\rho_{\rm DM}(r)+\rho_{\rm gas}(r)+\rho_*(r)}$$

Fraction of **gas** relative to total matter



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

Planck Collaboration+ 2016

Diffuse IGM

WHIM

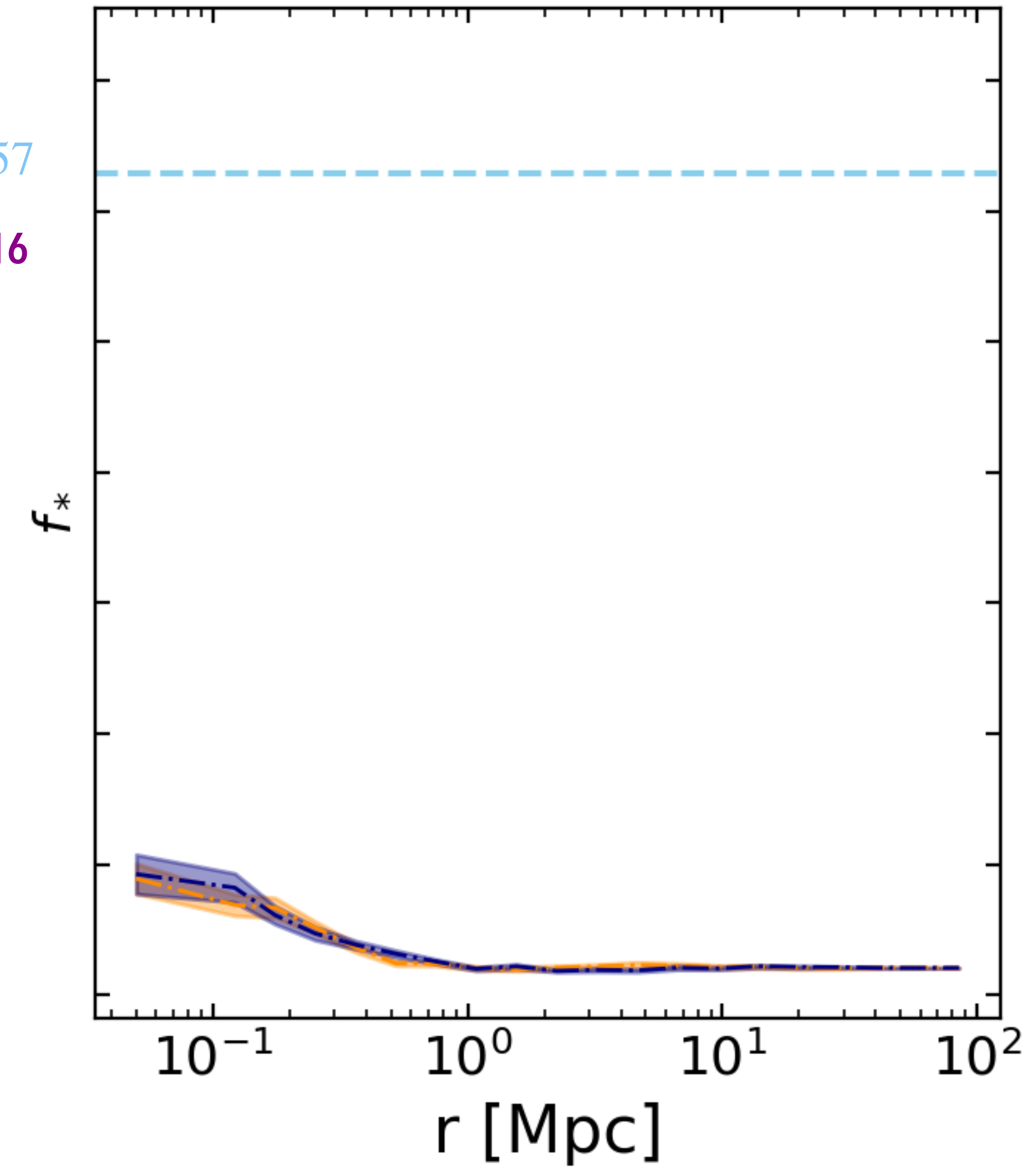
WCGM

Halo gas

Hot gas

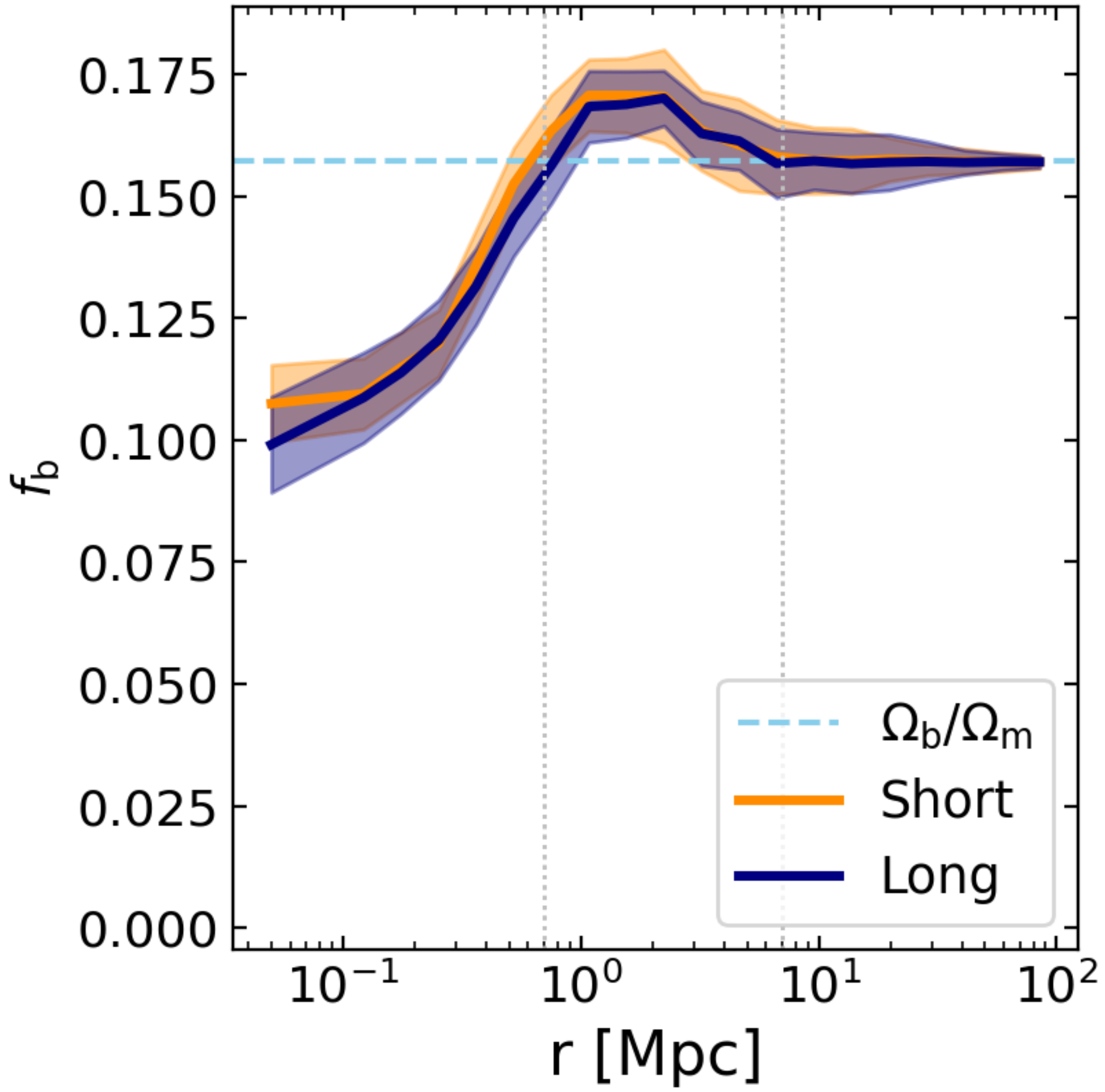
+

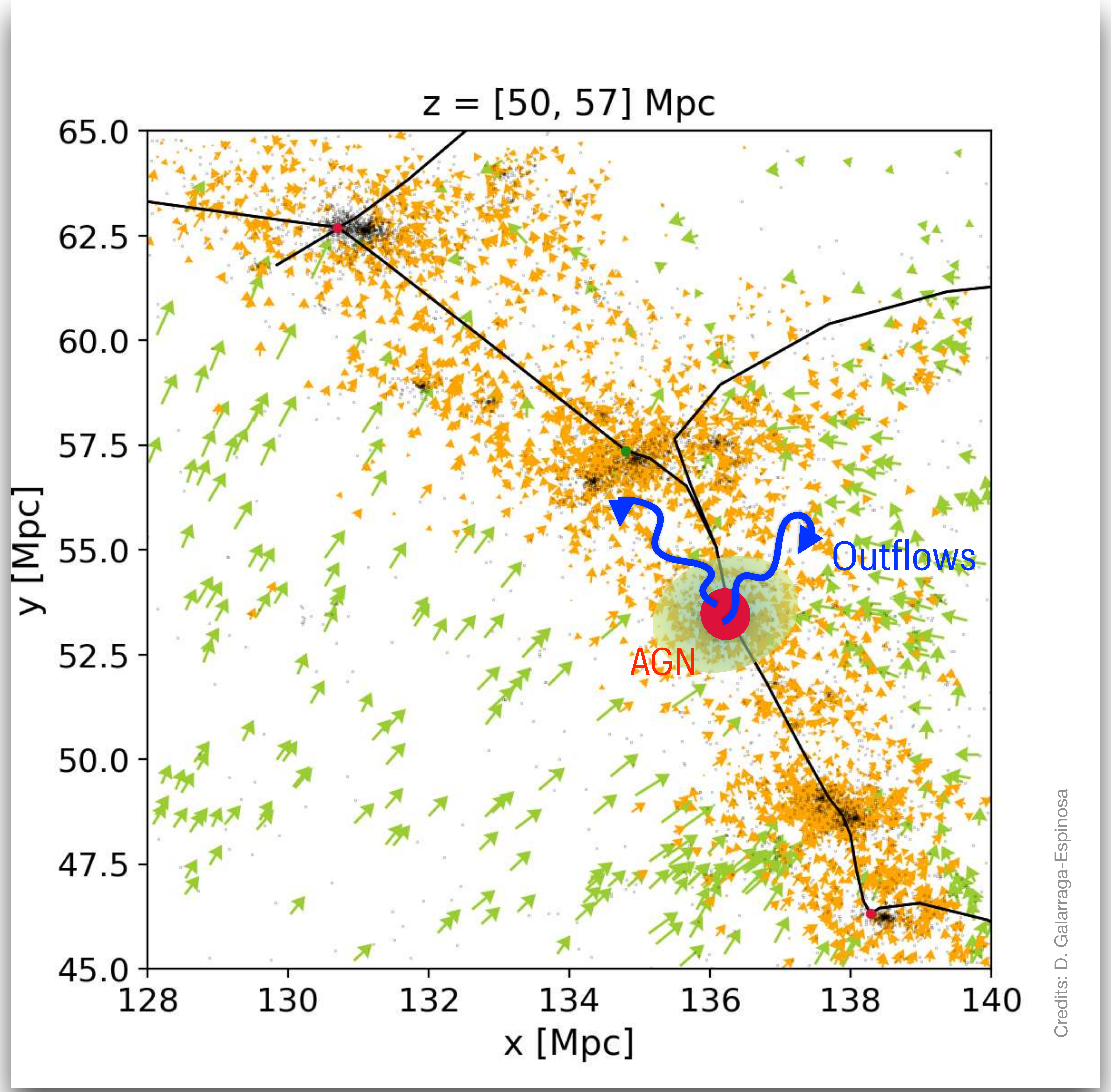
Fraction of **stars** relative to total matter



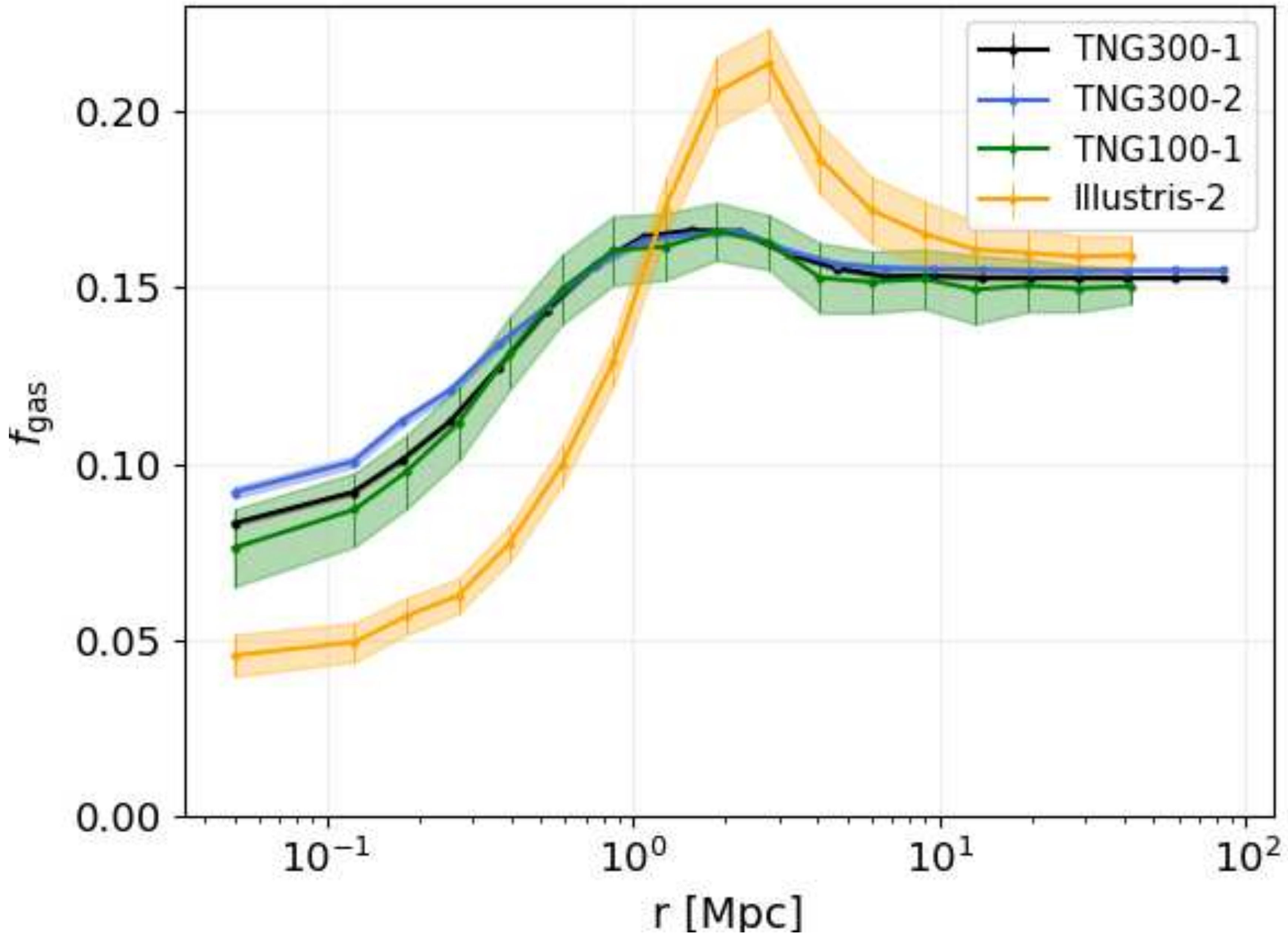
→

Baryon fraction profiles of cosmic filaments



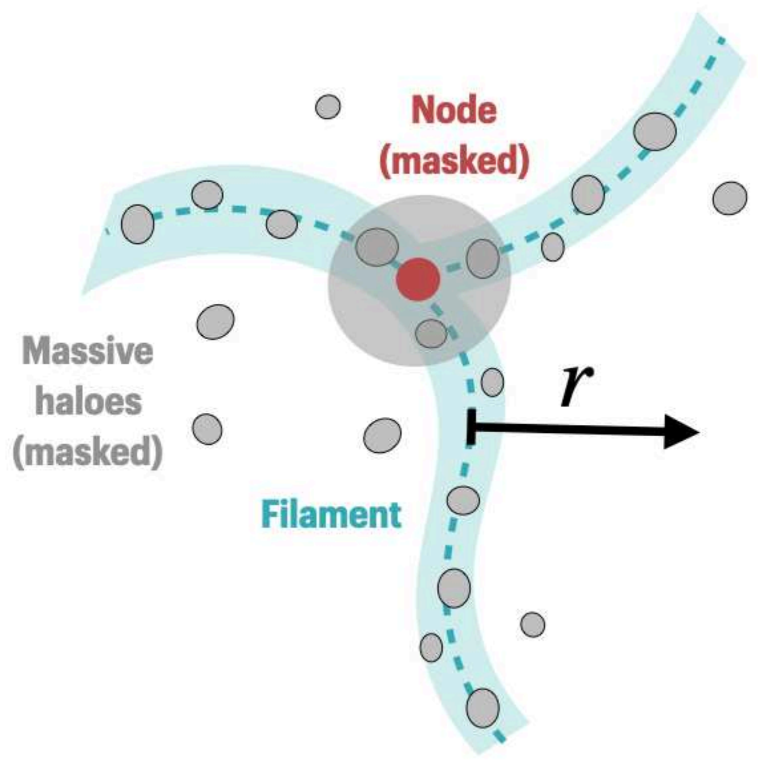


Impact of different baryonic model (stronger feedback)

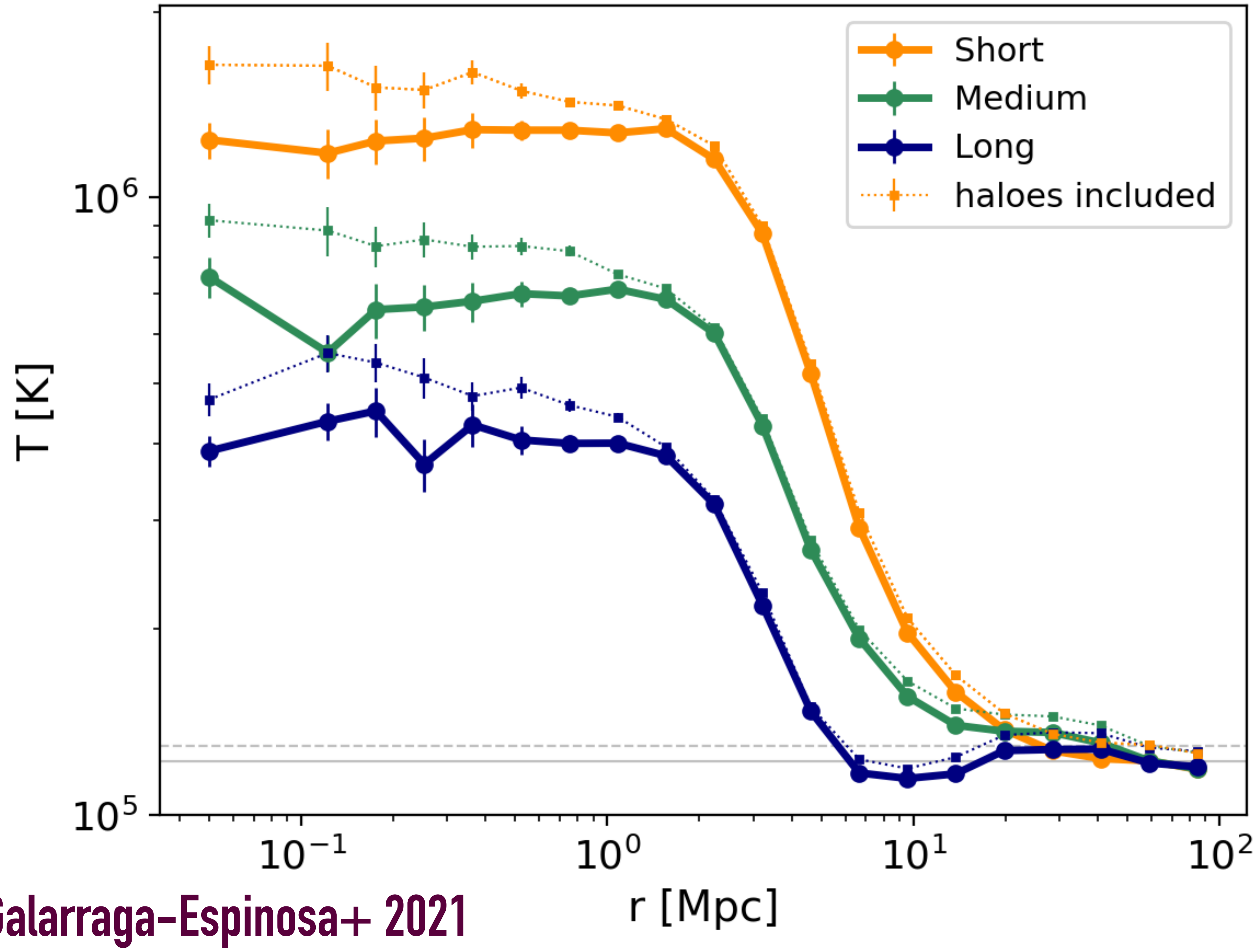


Outflows? (Ejection)
Thermal pressure?

Gas temperature profiles

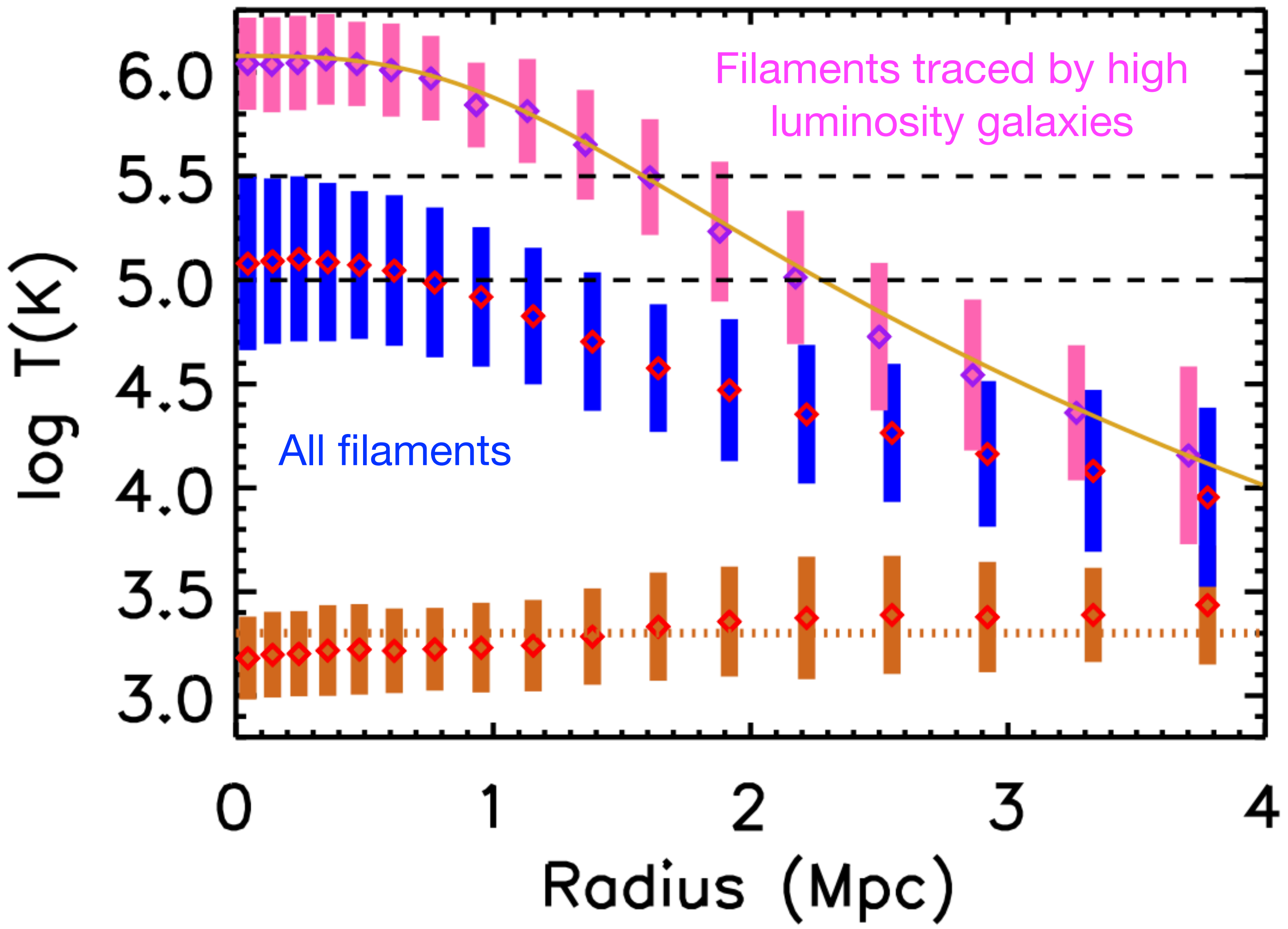


Mean radial **temperature** profiles



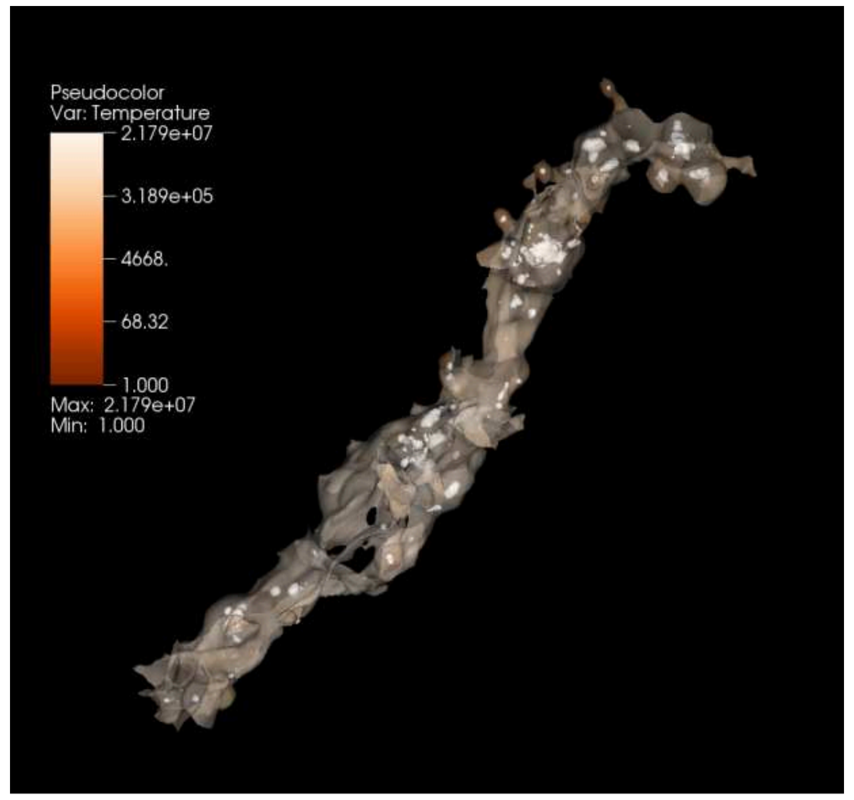
Galarraga-Espinosa+ 2021

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

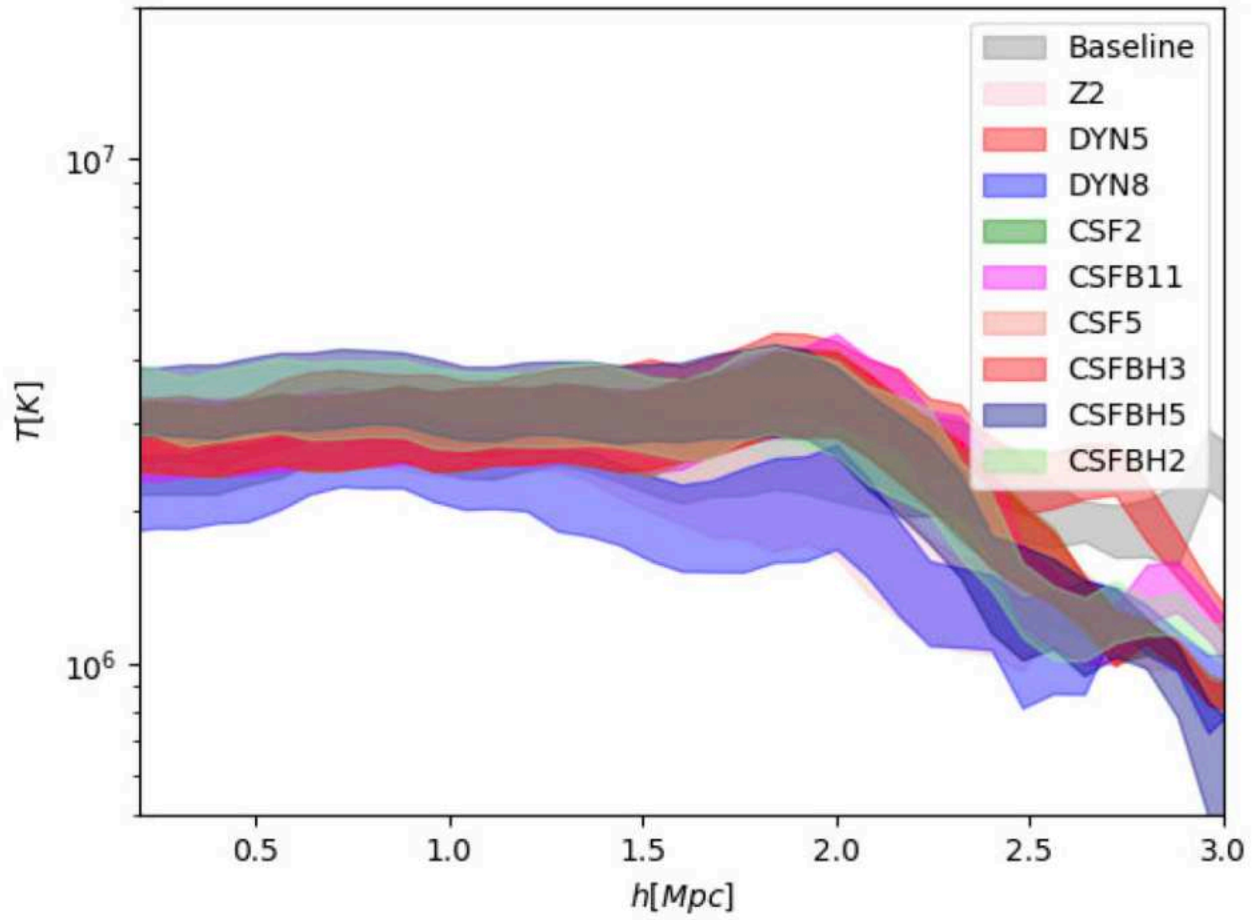


Tuominen+ 2021

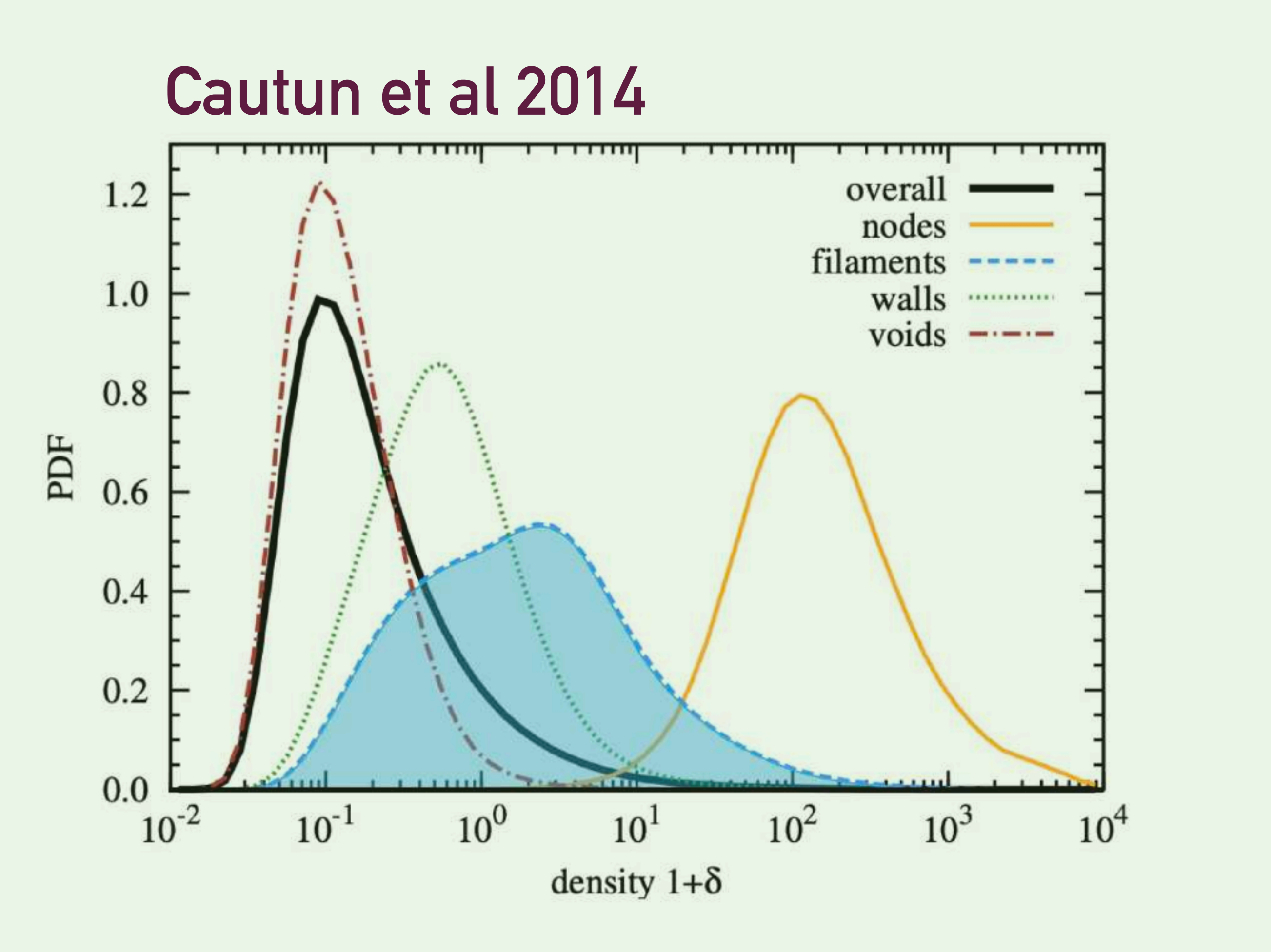
Gheller & Vazza+ 2019



Profiles of ONE filament,
different baryonic models



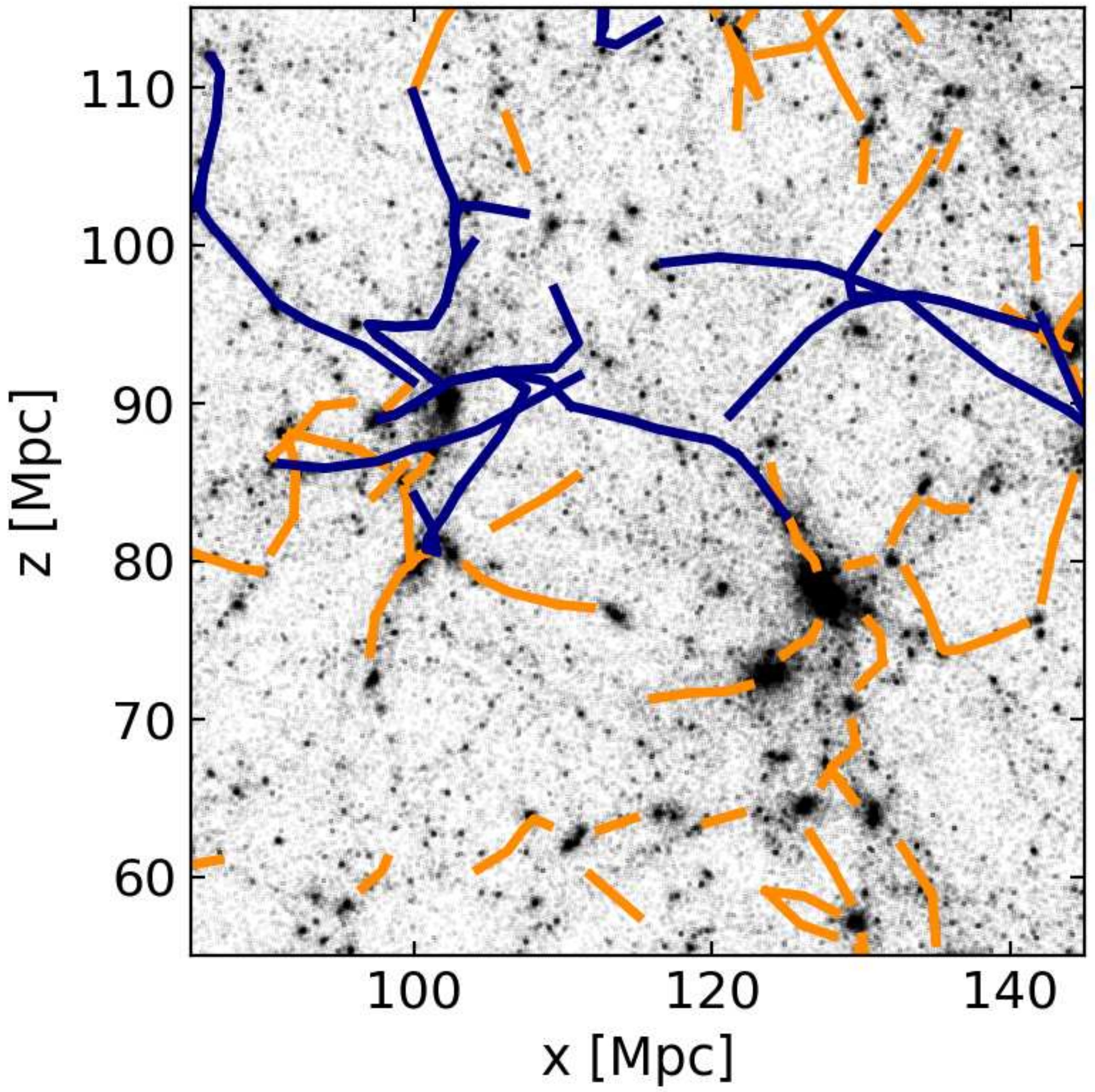
(Hints of filament diversity!)



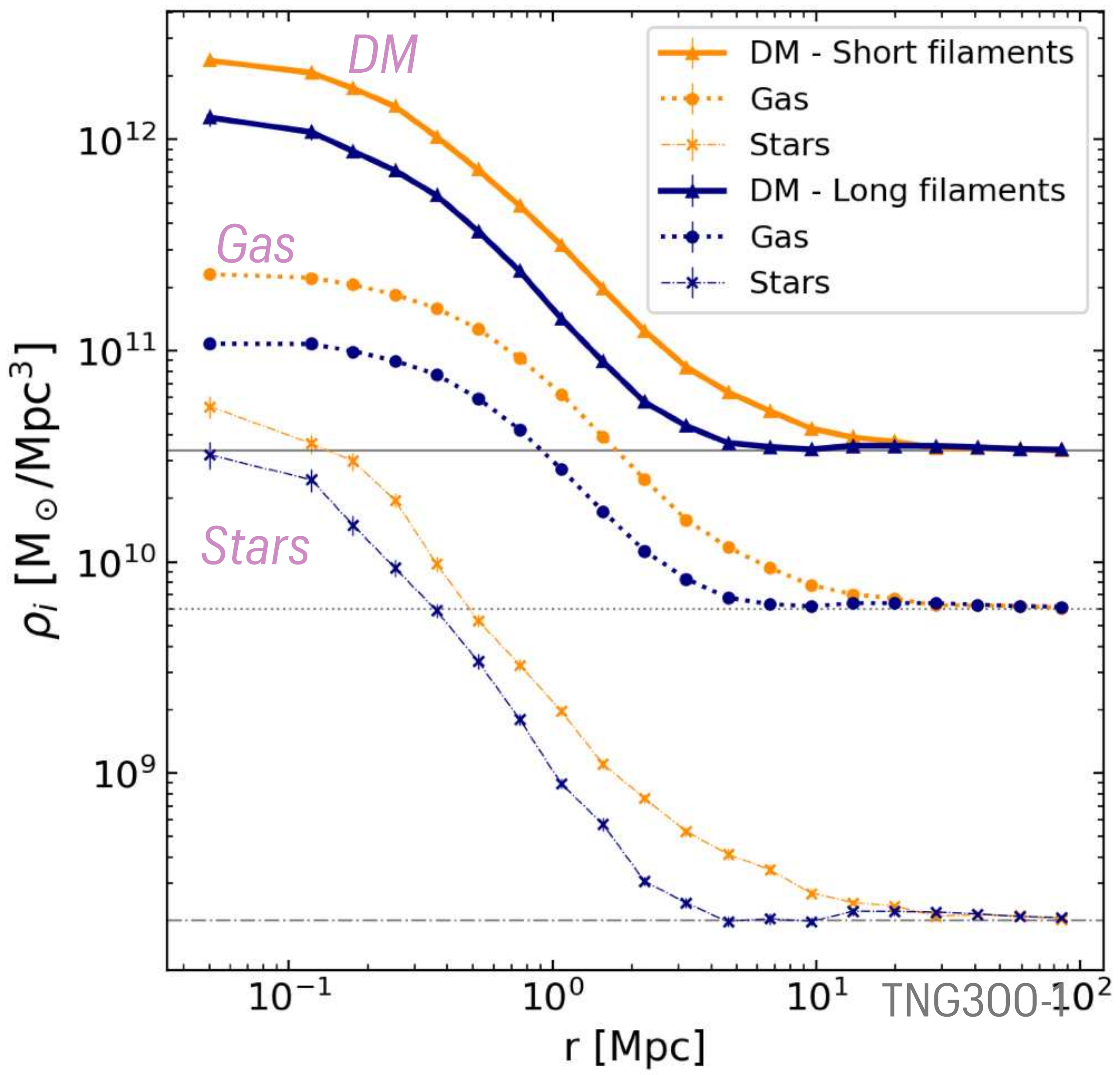
Exploring diversity of filaments using lengths*

Differences 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, …)



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



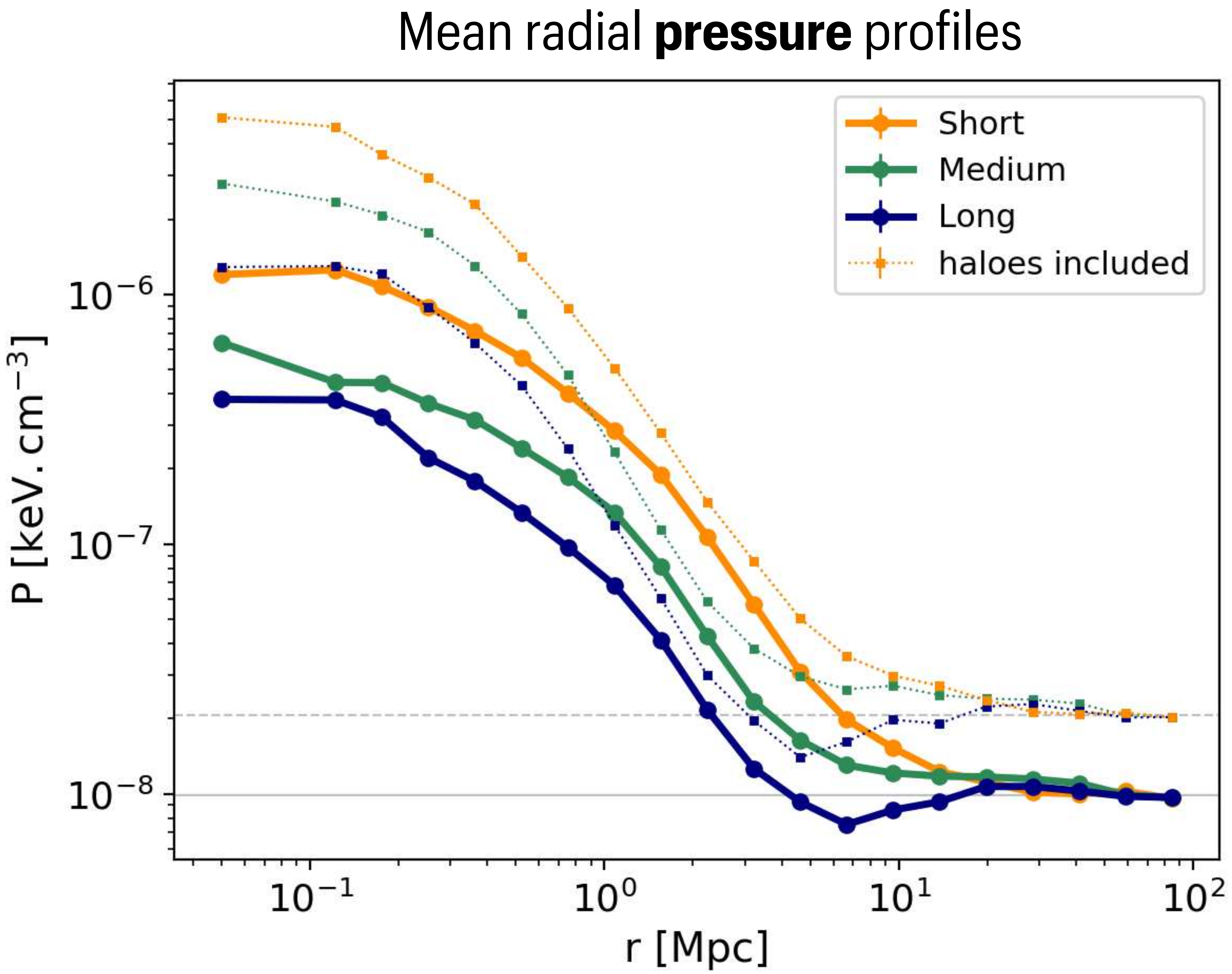
Shortest (<9 Mpc)	Longest (> 20 Mpc)
Puffy	Thin
Denser	**Less dense**
Higher T and P	**Lower T and P**
Tracers of **over-dense regions**	Tracers of **less-dense regions**
Correspond to **bridges of matter** between over-dense structures	Correspond to the **cosmic filaments** (i.e. those at the intersection between cosmic walls)
Tend to **contract**	Tend to **expand**

*length is just one observable, there can be many others (more fundamental)

Galárraga-Espinosa+ 2020, 2021, 2022, 2024

Pressure profiles

Galarraga-Espinosa+ 2021



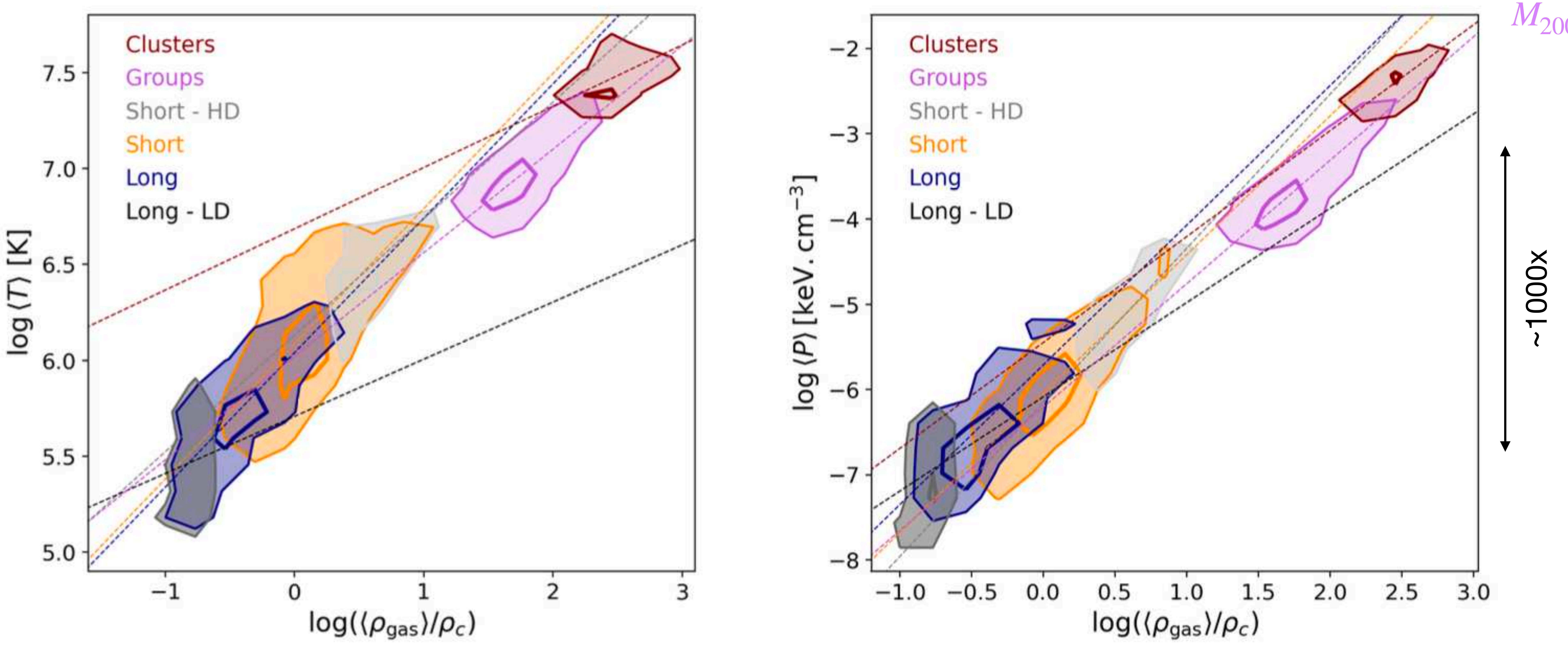
$$P_{core} = 4 - 12 \times 10^{-7}\ \mathrm{keV\,.\,cm^{-3}}$$

(Filaments vs Galaxy clusters)

Scaling relations

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

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



Galarraga-Espinosa+ 2022

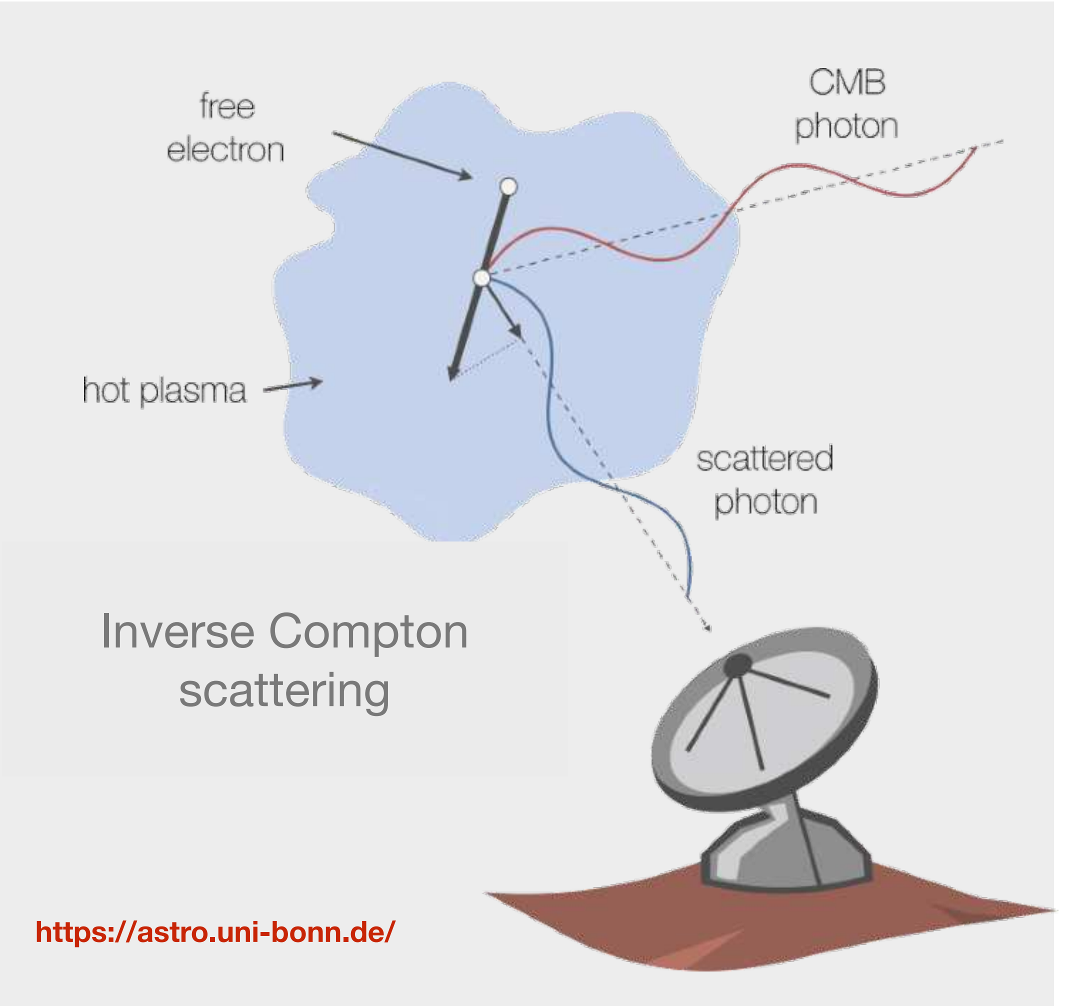
Hierarchy of the different large-scale cosmic structures

Link with observations:
Gas pressure can be directly measured with the thermal SZ effect

y-Compton parameter
OBSERVABLE

Pressure profiles

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

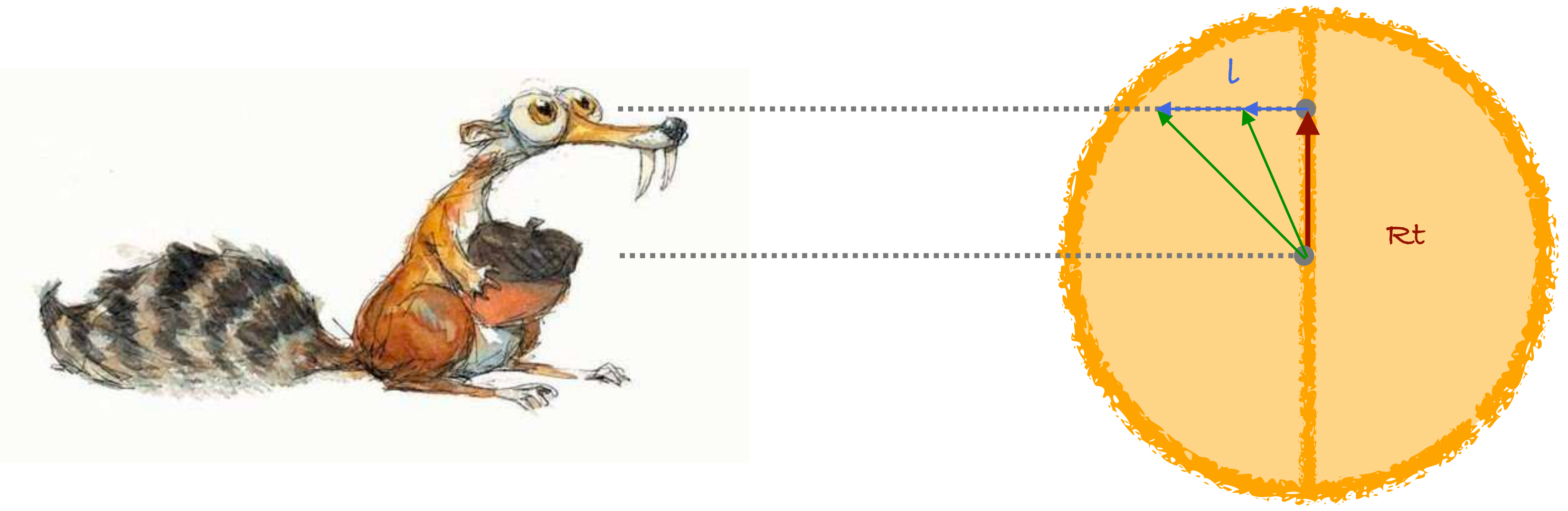


Compute y-profiles in **2 extreme cases**:

Filaments are **perpendicular** to the line of sight

Minimum of signal

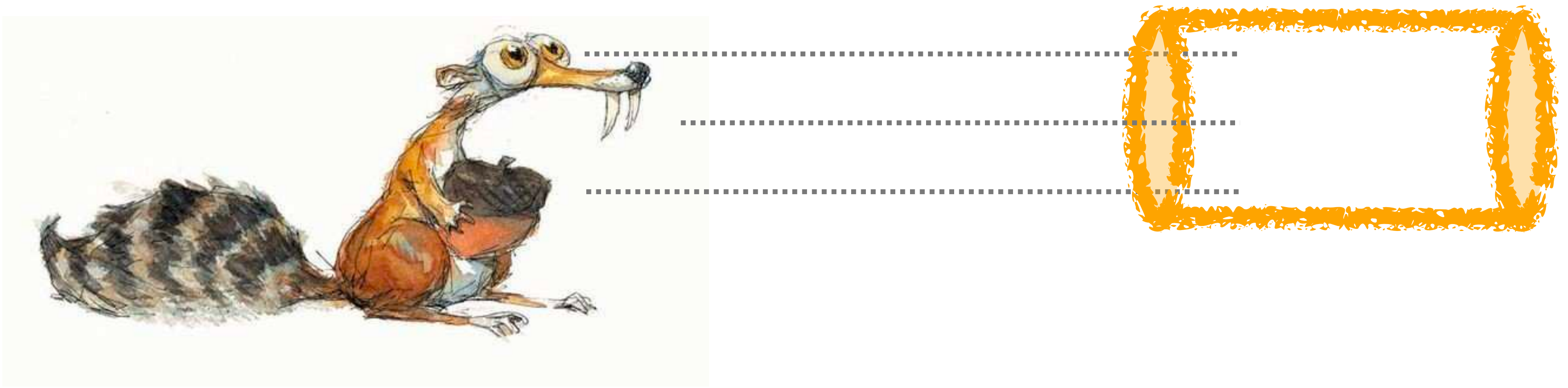
$$y(R_t) = \frac{\sigma_T}{m_e \times c^2} \int 2 \times P(\sqrt{R_t^2 + l^2}) \, dl$$



Filaments are **parallel** to the line of sight

Maximum of signal

$$y(R_t) = \frac{\sigma_T}{m_e \times c^2} P(R_t) \times L_f$$

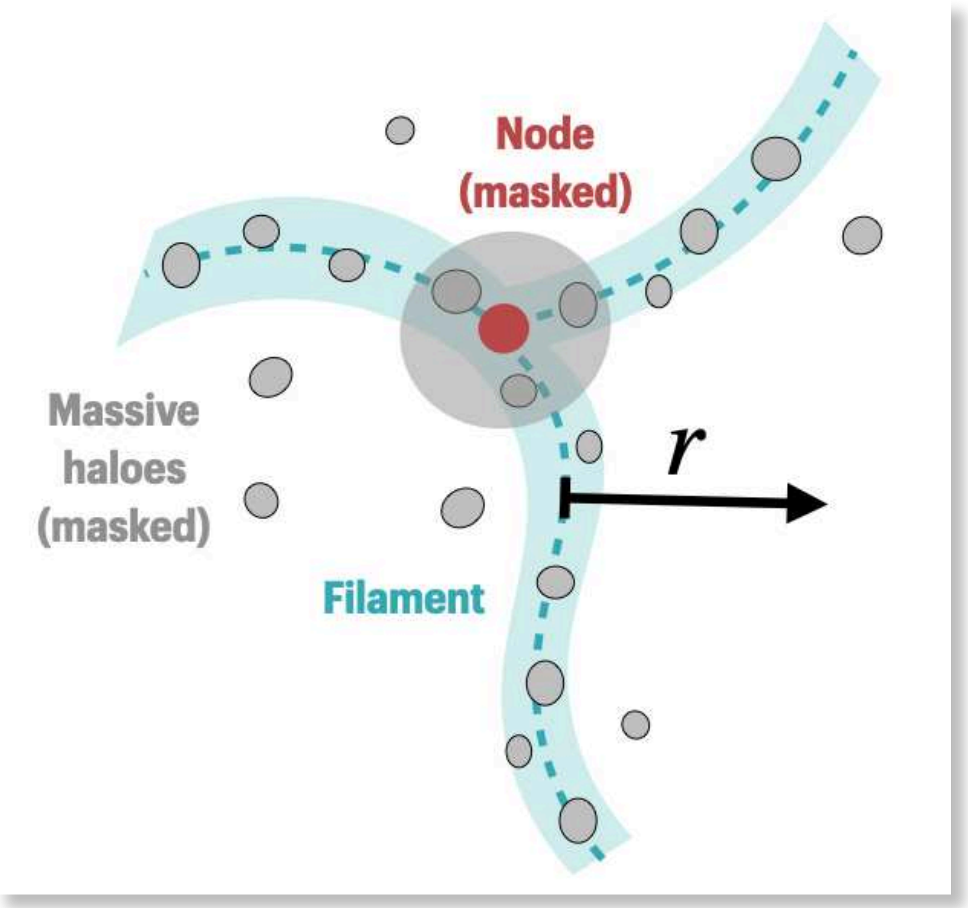


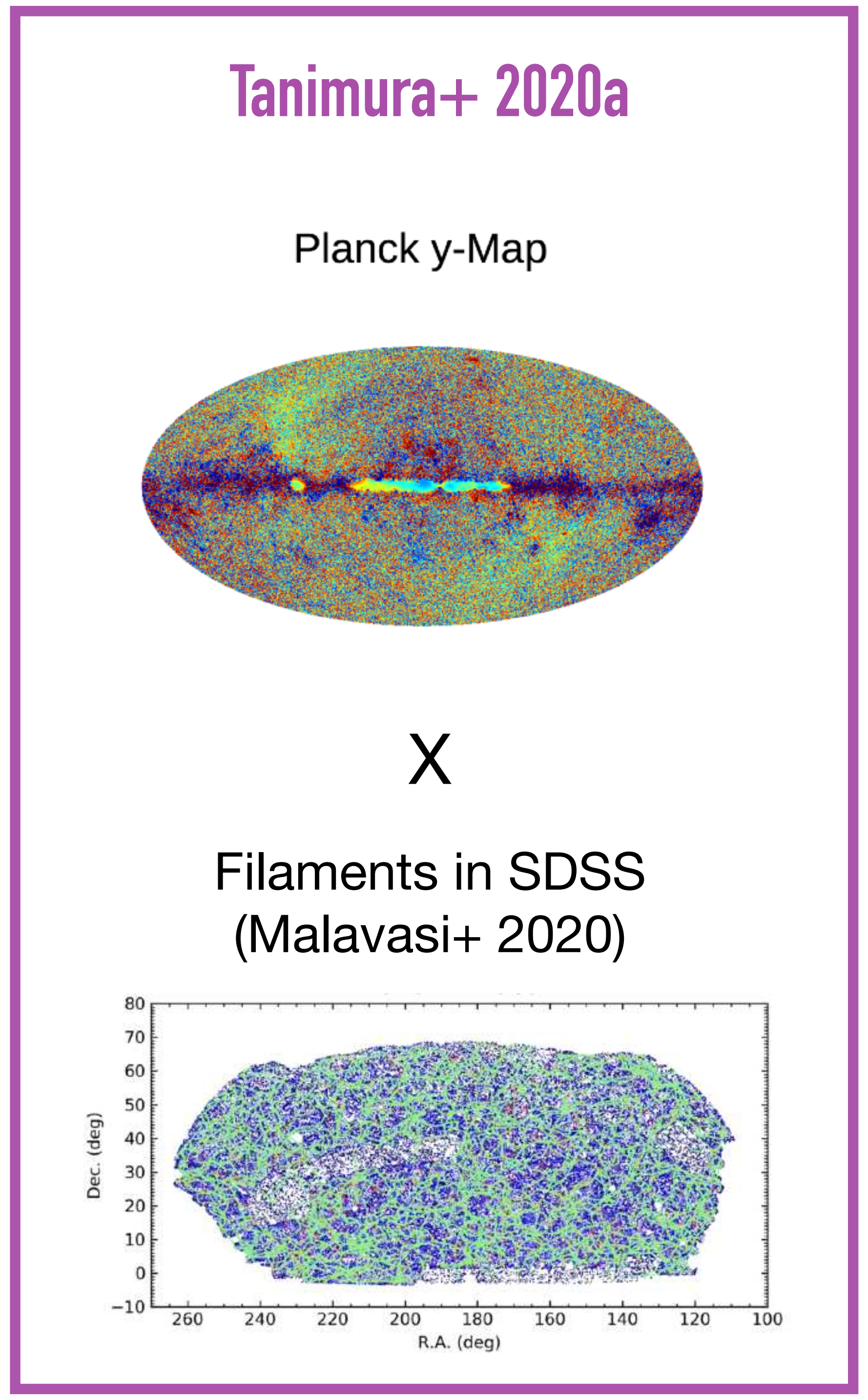
Result: a range of allowed values

Estimation of minimum and maximum SZ signal from cosmic filaments:

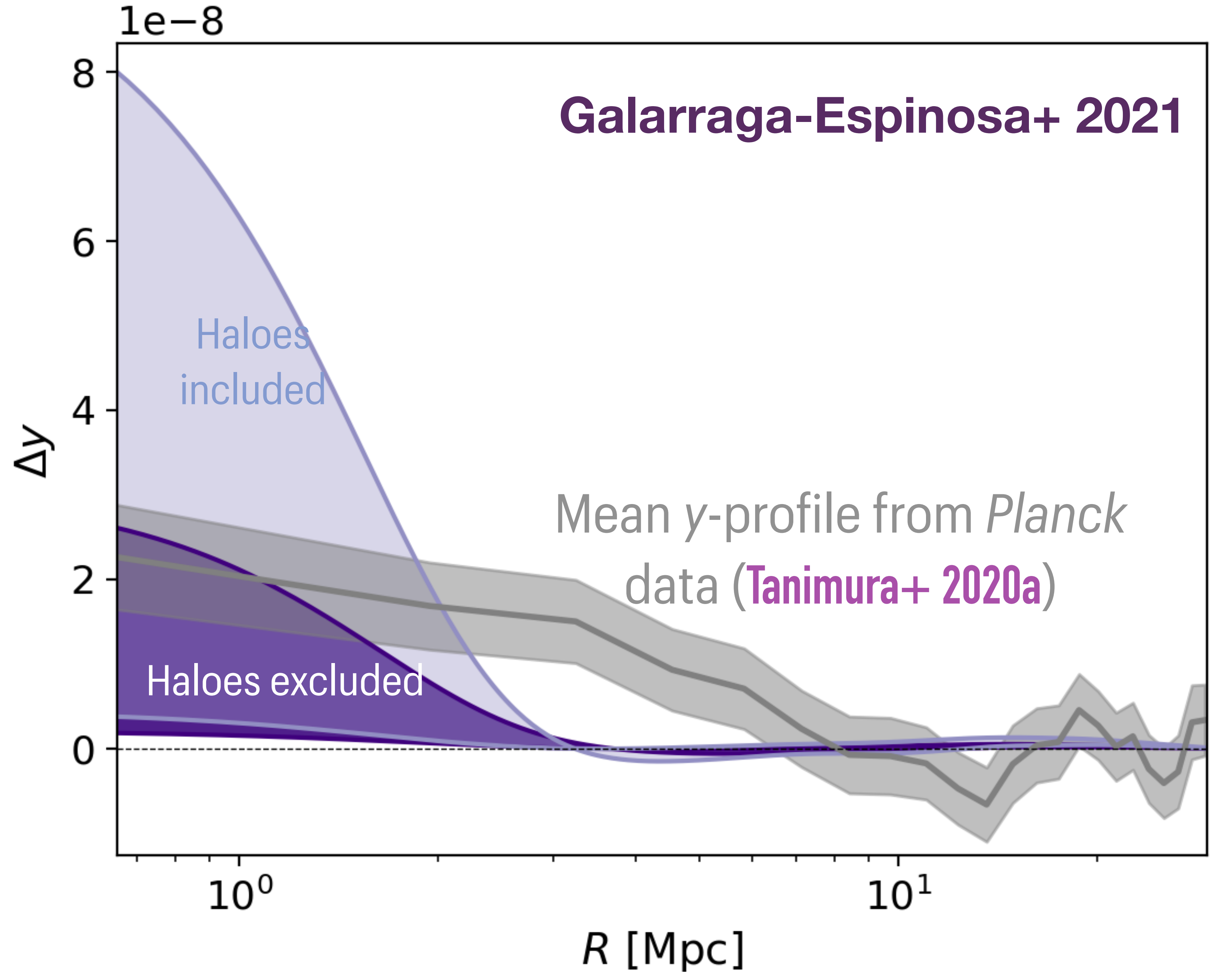
- Only inter-filament gas:
$y_{\rm core} = 0.5 - 4.1 \times 10^{-8}$

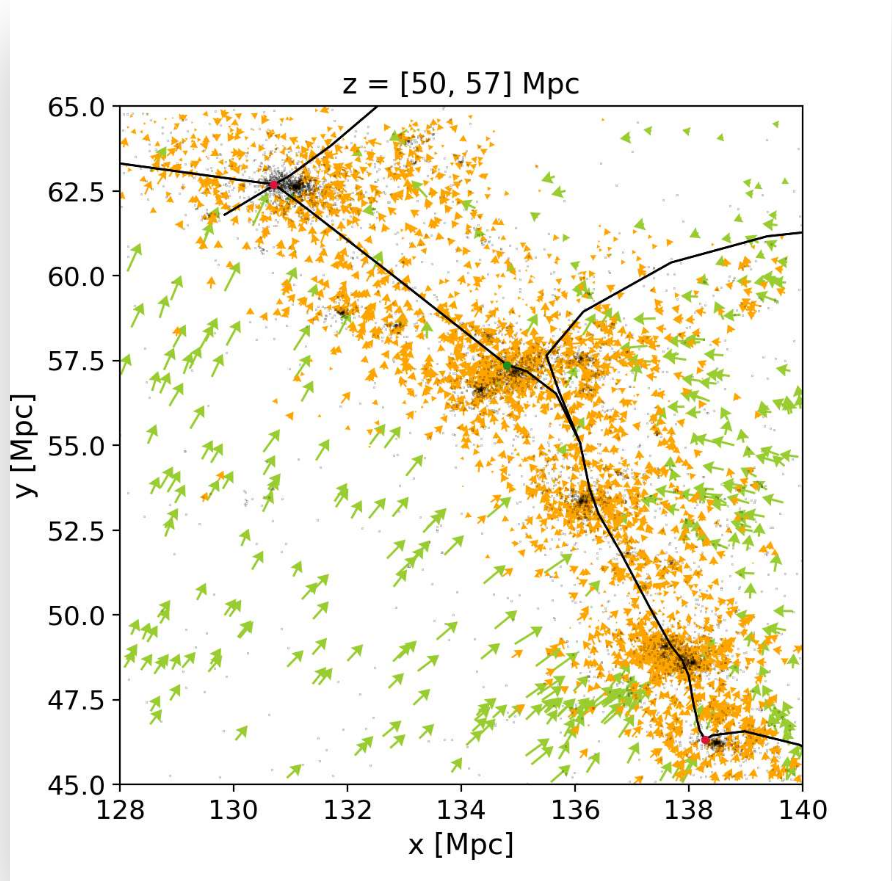
- Including haloes (~ **3x**)
$y_{\rm core} = 0.1 - 1.5 \times 10^{-7}$





Interpreting observations:





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

Gas Metallicity

Ilc et al. 2024

- Dianoga simulations
- Zoom-in around cluster regions
- Focus on filaments in the outskirts of clusters!
- 2 baryonic models: with and without AGN feedback

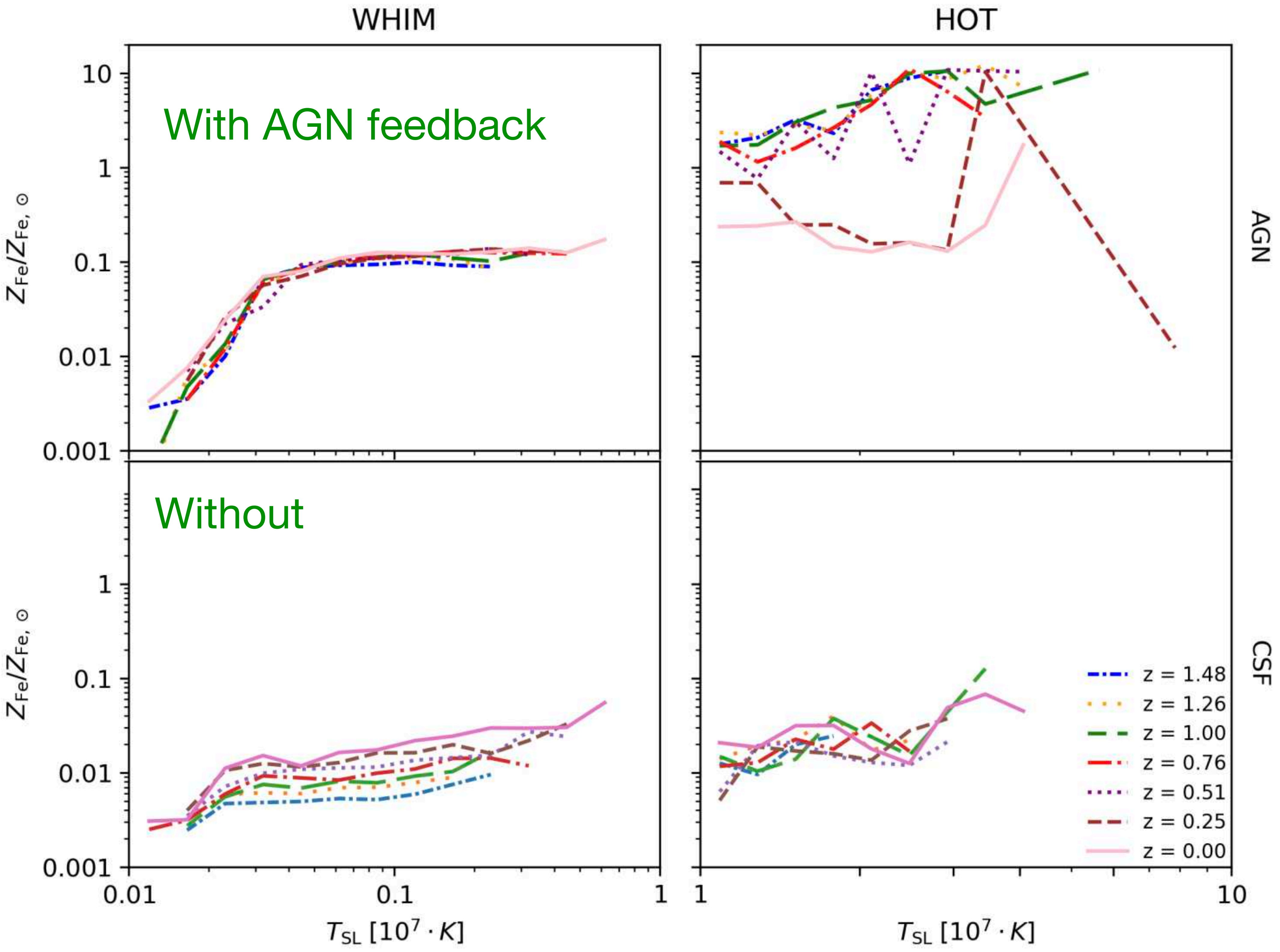
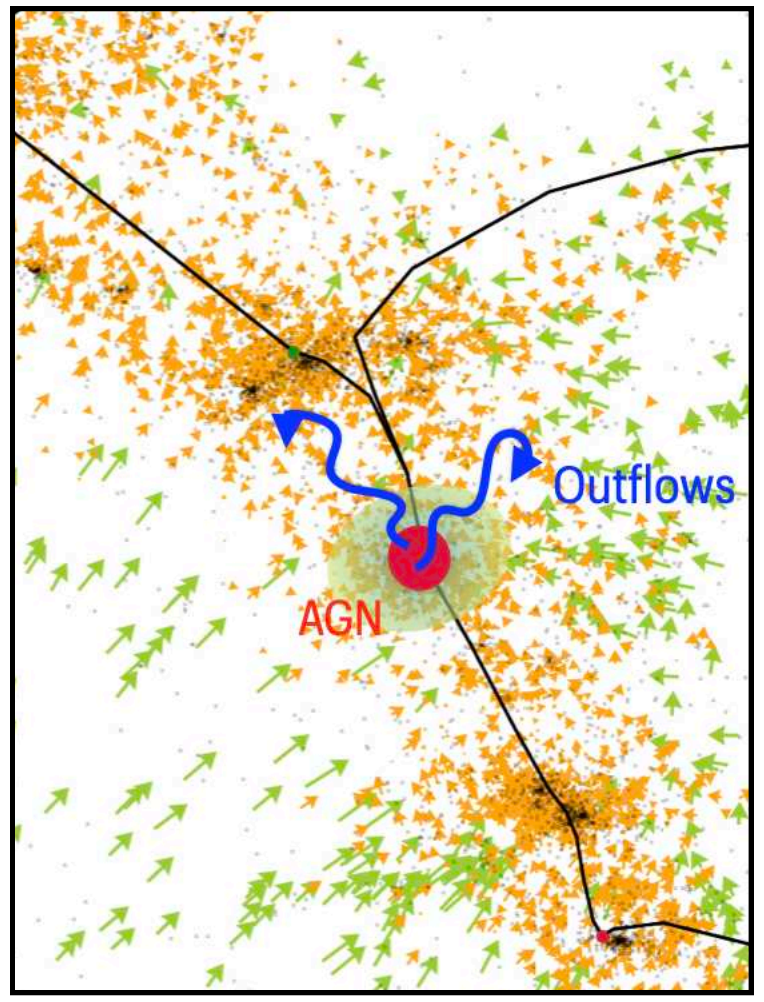


Fig. 12. The median values of metallicity Z_{Fe} as a function of spectroscopic-like temperature T_{SL} for both WHIM and hot gas phase at seven different redshifts. The top panel is for the AGN simulations, and the bottom is for the CSF simulations.



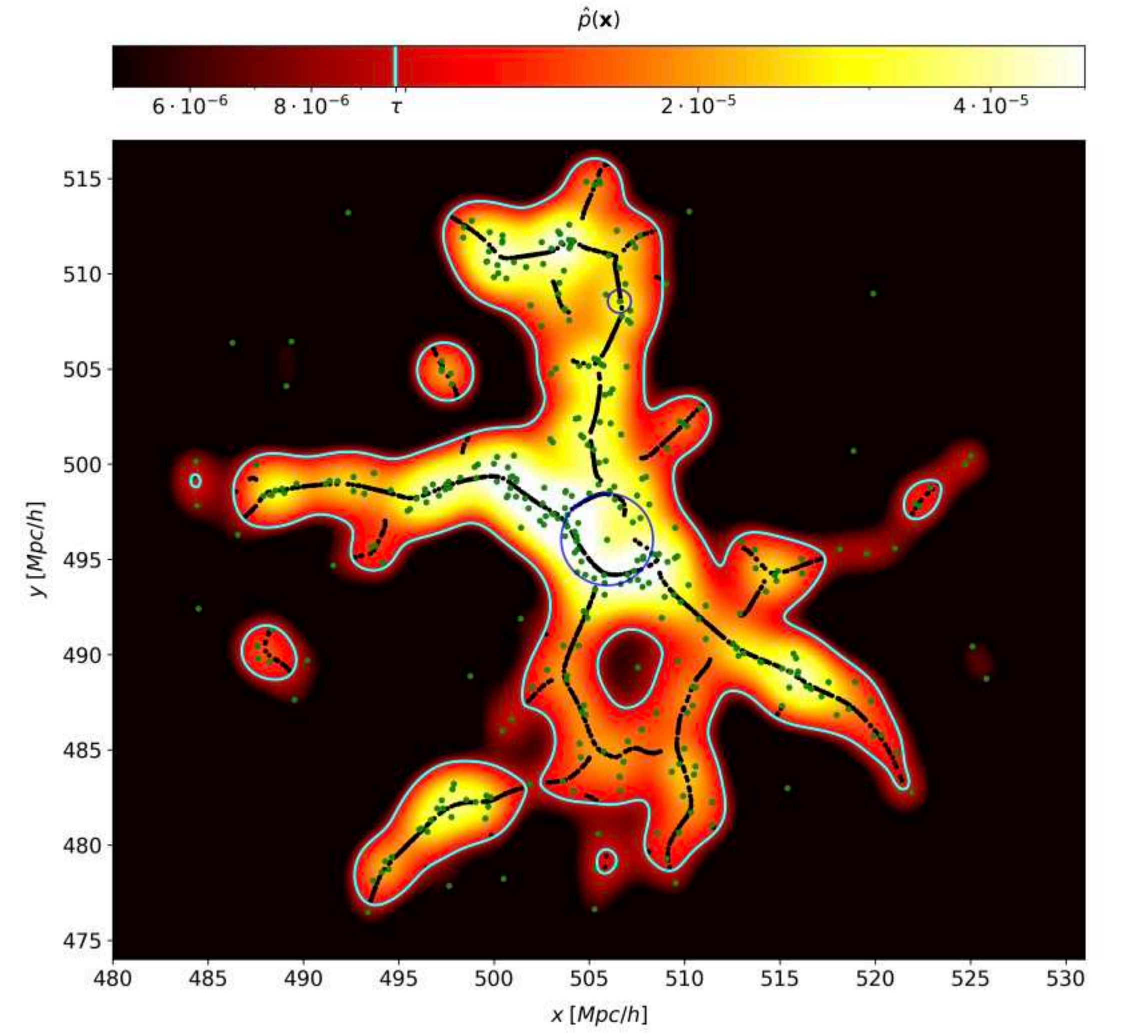


Fig. 1. An example of the final result of the SCMS algorithm in 2D space. Black dots mark the points of the skeleton. Along with the skeleton, the colour-coded kernel density estimator is plotted. Tracers are marked with green points. The contour line is plotted with cyan colour at the threshold τ value. The blue circles represent the virial radius of the two massive clusters ($M_{vir} > 10^{13} M_\odot$ in the 2D space. This skeleton was extracted from a thin slice (~ 1.2 Mpc thick) in region D6 at redshift $z = 0$.

Filament gas is metal enriched (thanks to AGN feedback, redistribution of metals)

Metal rich gas is good for observational prospectives!

…Further hints that small scale physics impacts cosmic web properties

Visual picture

Differences mostly due to feedback effects (supernovae and AGN)

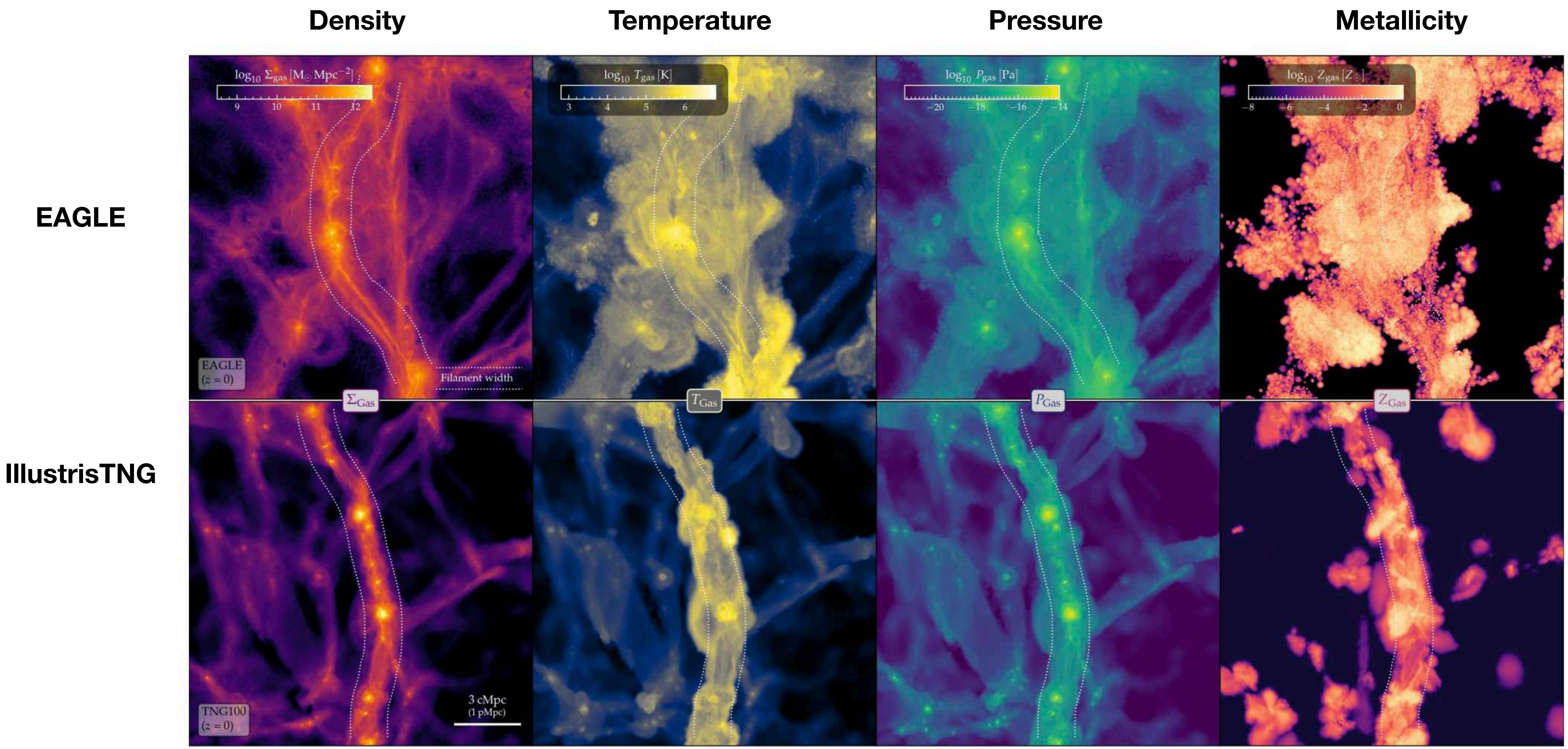
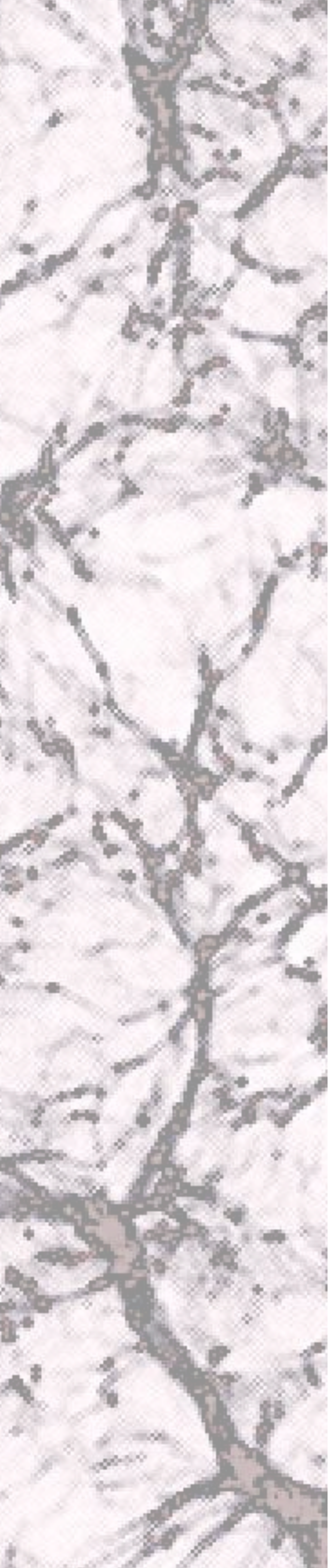


Fig. 17. Detailed view of one representative filament at $z = 0$ in EAGLE (top) and TNG100 (bottom). From left to right, panels show maps of the gas density, temperature, pressure, and metallicity in a $16 \times 16 \times 1$ Mpc slice aligned with the best-fit plane of the filament. White dotted lines trace the edges of each filament as identified from the dark matter. There is abundant structure within the filaments, both along and perpendicular to the spine, with clear differences between the two simulations (see text for details).

Bahé & Jablonka+ 2025 (submitted)



General picture of gas in cosmic filaments

z=0

Gas in filaments

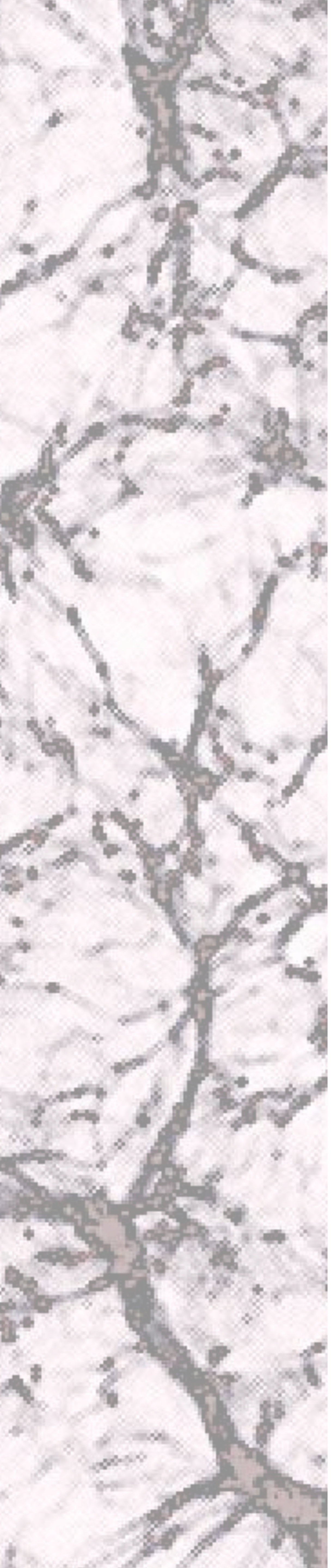
- WHIM dominated (> 80%)
  - Diffuse
  - Warm temperatures
- Metal enriched by astrophysical processes
- Other gas phases also also present (but associated to haloes)

Impact of haloes in filaments:

Including gas associated to haloes: huge impact in observational analysis!
Contamination in the study of the WHIM.

Consensus:

- across different numerical simulations (= models of gas physics)
- Tracers of the web
- filament finders

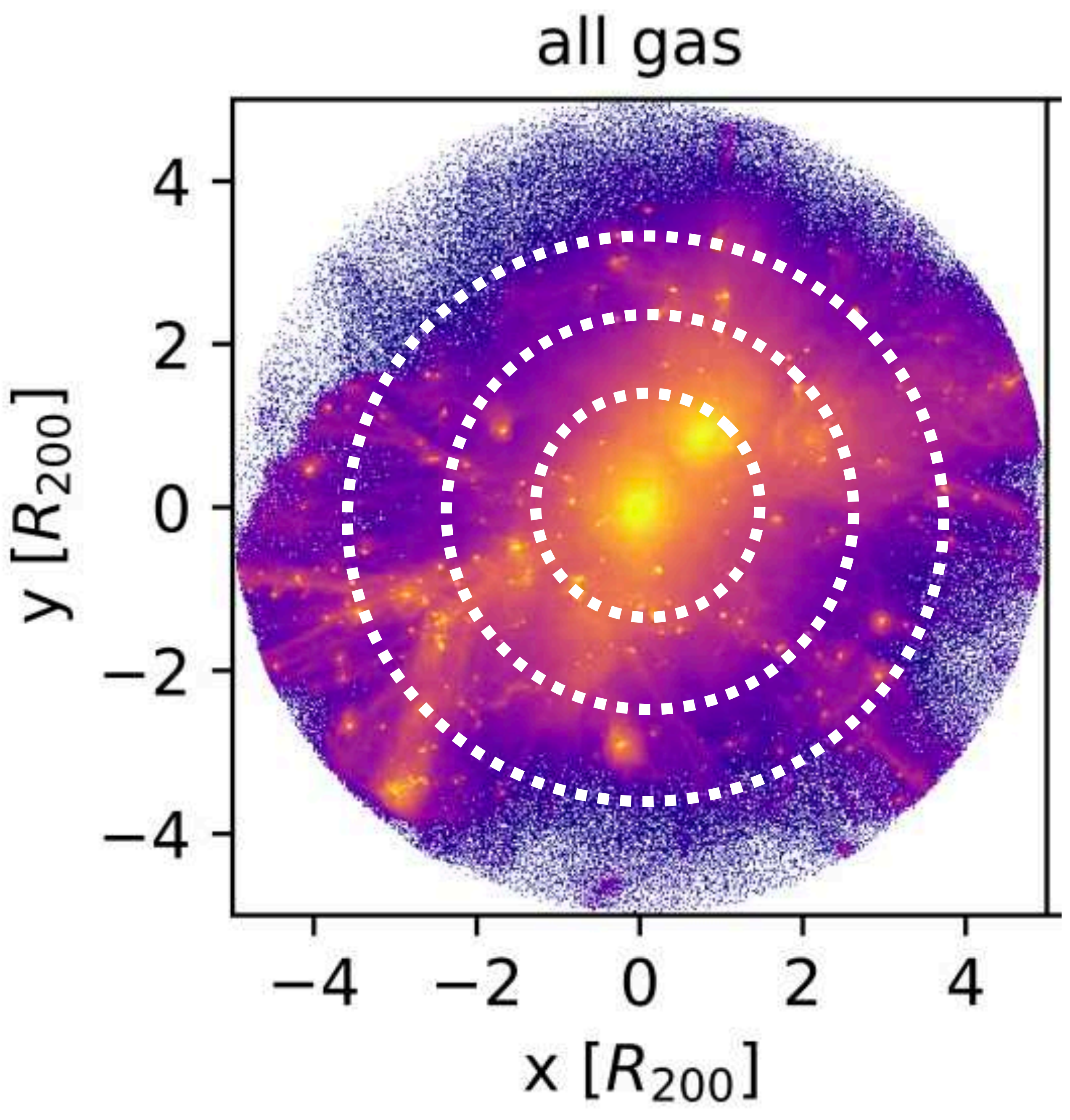


Cosmic Web filaments and their properties

Plan of the lecture

1) Recap about the cosmic web
2) Motivation: the missing baryon problem
3) Filament gas properties in hydrodynamical simulations
4) **Gas in cluster outskirts**
5) Observational status of the missing baryon problem

Outskirts of clusters: interesting regions!



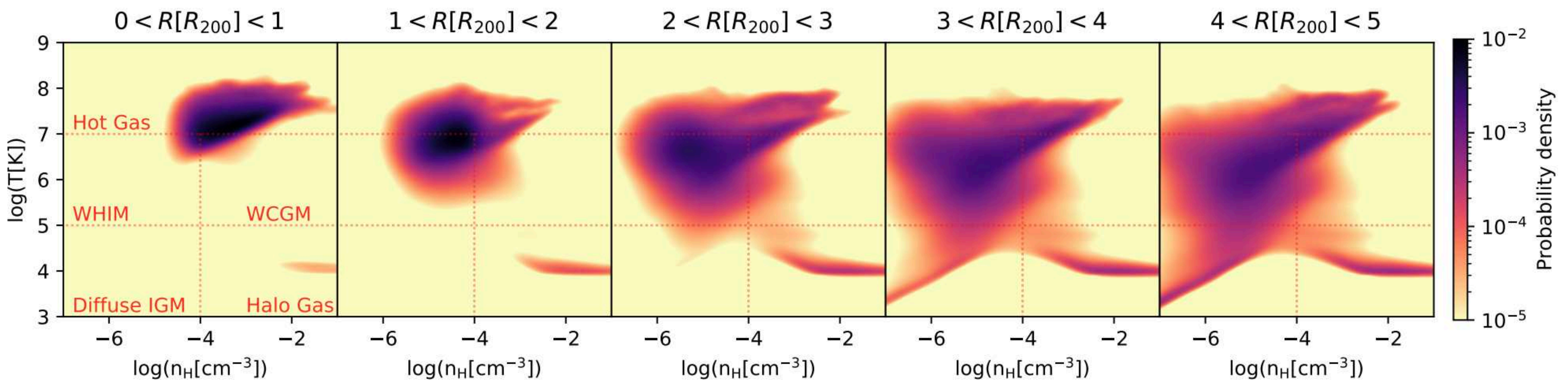
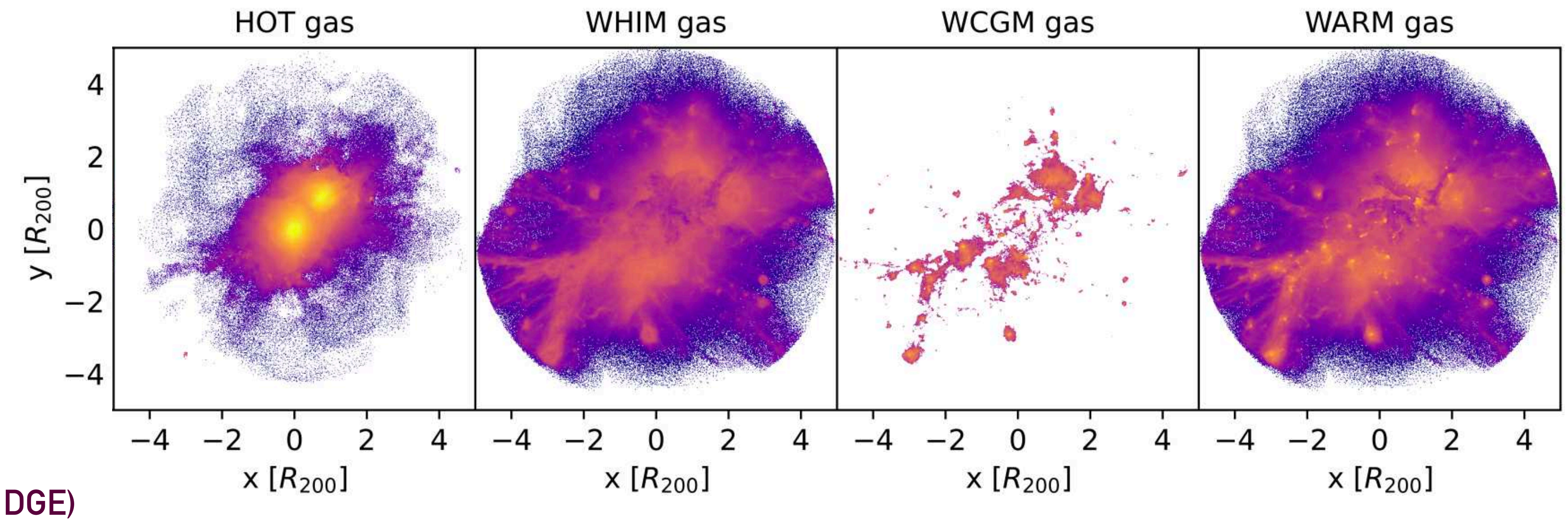


Fig. 1. Stacked temperature-density diagrams for all gas cells around galaxy clusters and groups in IllustrisTNG, considering different radial apertures from cluster central regions $R[R_{200}] < 1$ up to $4 < R[R_{200}] < 5$

Gouin et al. 2022

Spatial distribution of gas phases



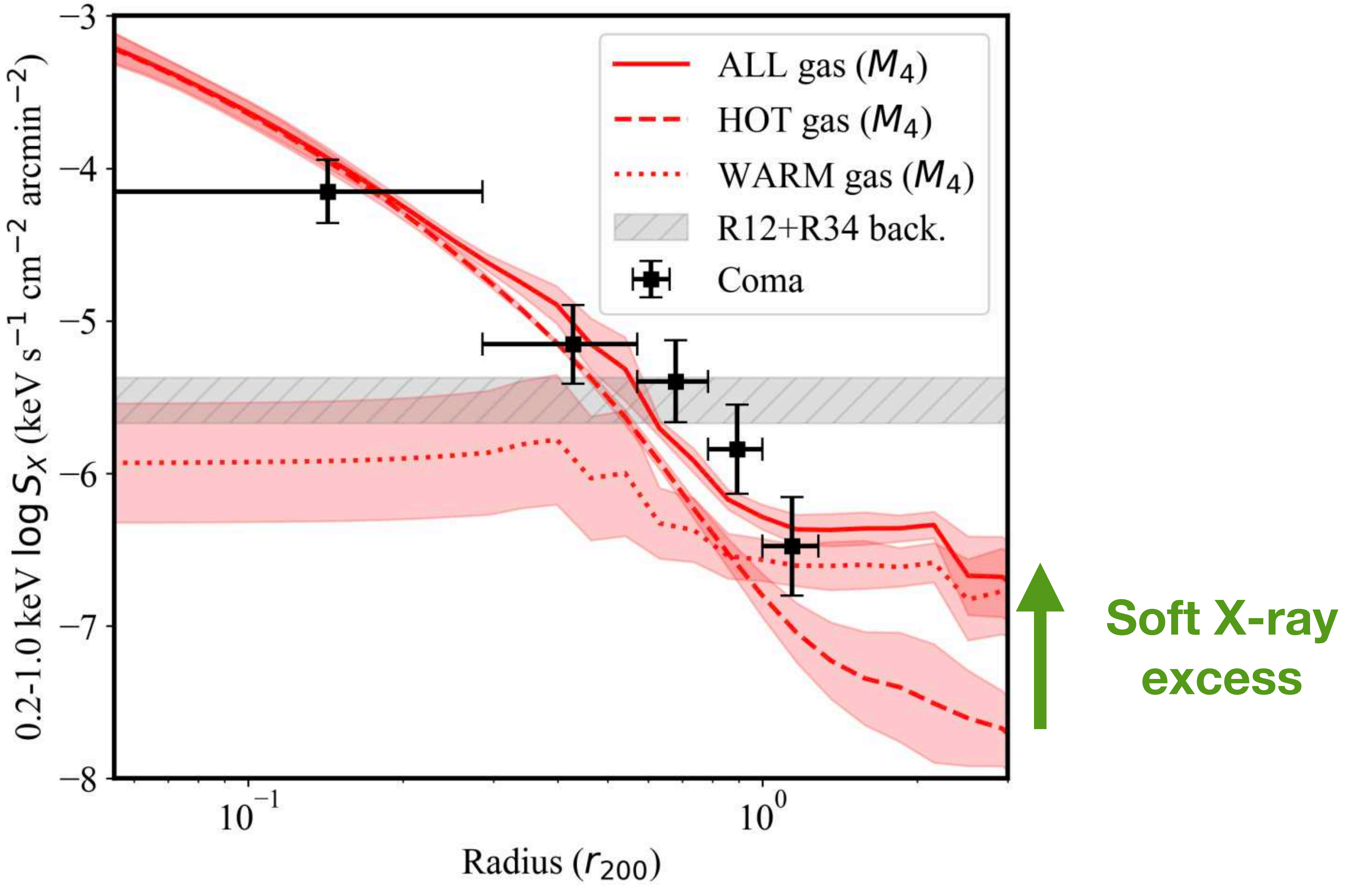
Gouin et al. 2023 (incl. DGE)

Insights into another observational puzzle

Gouin et al. 2025 (submitted, incl. DGE)

- Postprocessing of IllustrisTNG
- Compute surface brightness in soft X-ray band (0.2-1 keV)
- Explore different cluster masses

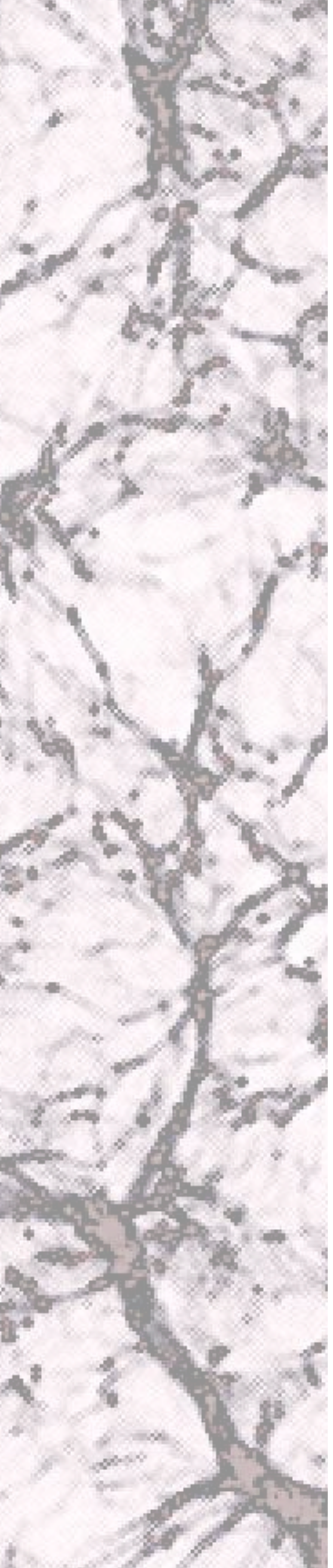
Example for the most massive clusters (M4)



Soft X-ray excess observed by:

- *Lieu et al. 1996*; *Bowyer et al. 1996*, Coma and Virgo clusters (**EUVE**)
- *Bonamente et al. 2001a,b, 2002*: around different clusters (**ROSAT**)
- *Nevalainen et al. 2003; Kaastra et al. 2003; Bonamente et al. 2005* (**XMM–Newton**)
- *Bonamente & Nevalainen 2011* (**Chandra**)

Probably contributing to the missing baryons budget



Cosmic Web filaments and their properties

Plan of the lecture

1) Recap about the cosmic web
2) Motivation: the missing baryon problem
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4) Gas in cluster outskirts
5) **Observational status of the missing baryon problem**

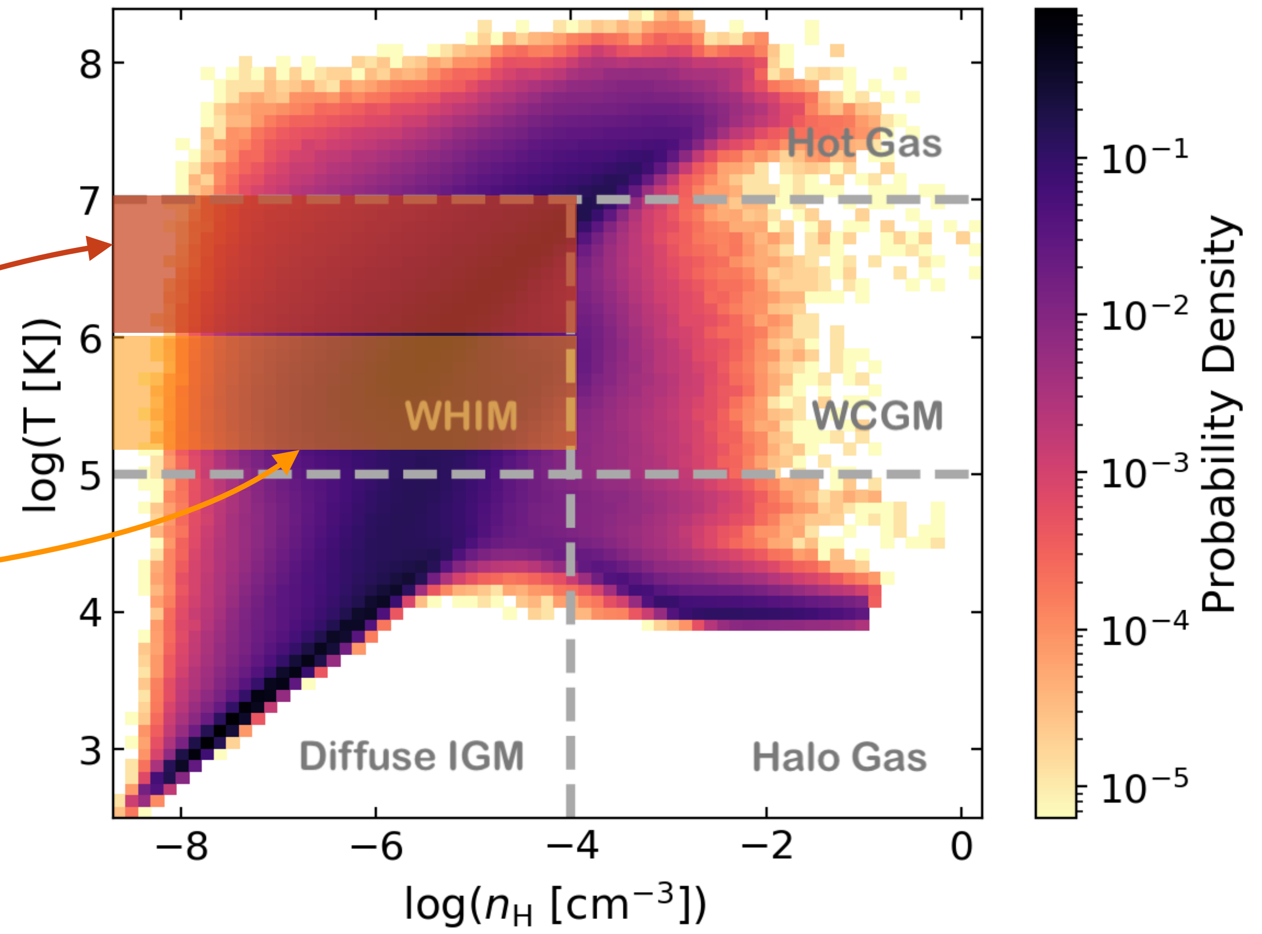
Observational status of the WHIM (in 2025)

Cool WHIM [T = 3*1e5 - 1e6 K] ($T_x \approx$ 0.03–0.1 keV):

Indirectly detected via absorption lines of background quasars and gamma-ray bursts

- -Absorption of Ly-alpha forest, *Penton + 2004*
- -Highly ionised heavy elements (*Nicastro+ 2008, Tejos+ 2016*)
- -OVII absorbers: *Nicastro+ 2018* (large uncertainties!)

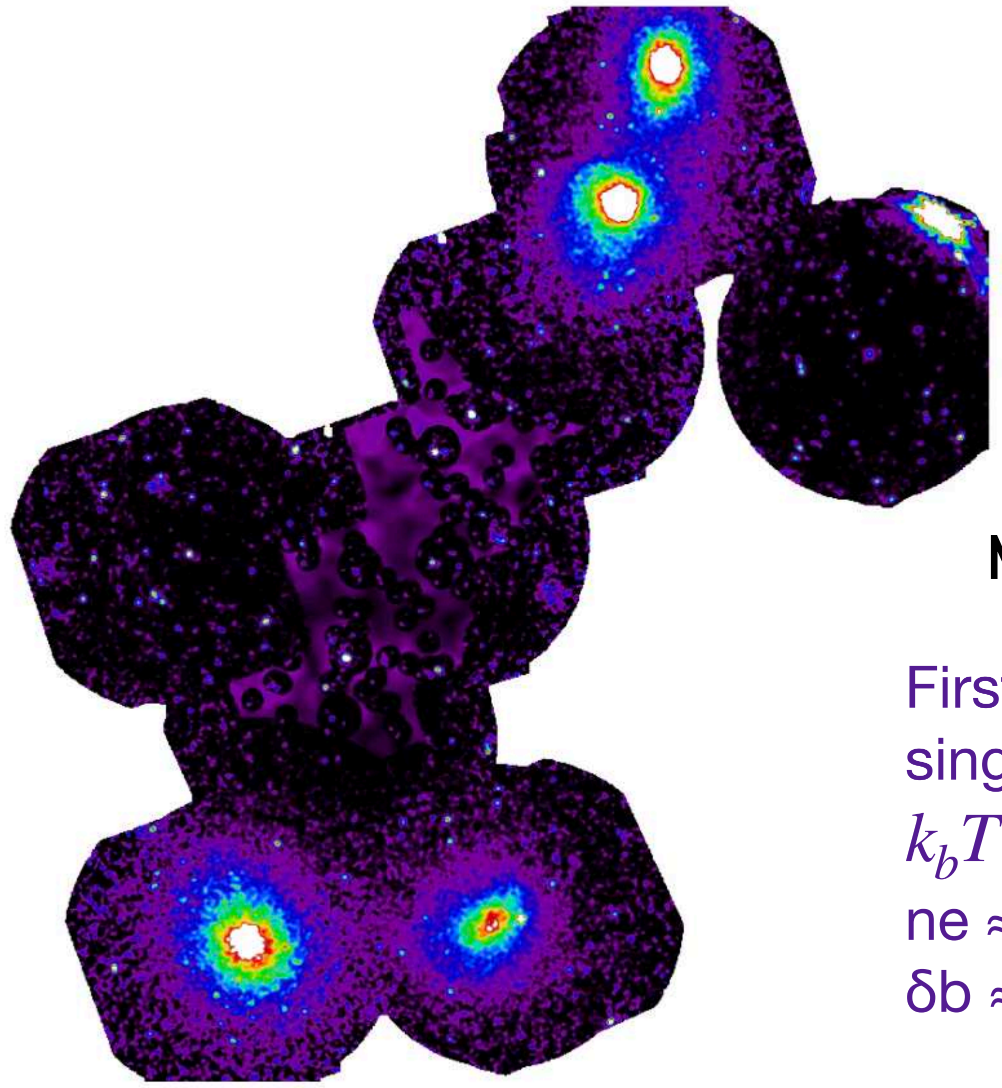
Robustness debated, because rely on quantities inferred from simulations
(e.g. Williams+ 2013, Gatuzz+ 2023)



Hotter WHIM [T = 1e6 - 1e7 K] ($T_x \approx$ 0.1–1 keV):

Expected to be *directly* detectable through **X-ray** emission and thermal **Sunyaev-Zeldovich** (tSZ) effect

- -**Individual detections** in some filaments, cluster outskirts, gas bridges (via excess surface brightness): *Kull & Böhringer+ 1999, Eckert+ 2015, Ursino+ 2015; Bulbul+ 2016; Akamatsu+ 2017; Sugawara+ 2017; Alvarez+ 2018, 2022; Ghirardini+ 2021; Reiprich+ 2021; Dietl+ 2024; Gallo+ 2024; Veronica+ 2024, Migkas+ 2025*
- -**Stacking analyses**:
  - -**X-ray** emission from stacked filaments: *Tanimura+ 2020b, 2022; Zhang+ 2024*
  - -**tSZ** detections in:
    - -Gas bridges: *Bonjean+ 2018, Hincks+ 2022*
    - -Cosmic filaments: *Planck Collaboration 2013; de Graaff+ 2019; Tanimura+ 2020a*



Migkas+ 2025

First constrains for a single filament:
$k_b T \approx$ (0.8–1.1) keV
ne ≈ 10–5 cm–3
δb ≈ (30 – 40)

Fig. A.1: Fully cleaned (as in Fig. 1), CXB-subtracted, combined XMM-Newton-Suzaku mosaic image in the 0.5 – 2 keV band. The Suzaku data were calibrated to the XMM-Newton/MOS count rate. The emission from the cluster outskirts and the AGN residuals was removed from the Suzaku images, thus what is shown here is pure filamentary emission as detected by Suzaku. At the Suzaku's masked areas, the underlying XMM-Newton image is shown instead.

FRB (Fast Radio Bursts) studies:

Recent results confirm that the baryon content matches ΛCDM predictions

Helps resolve the missing baryons problem

Key papers: *Macquart+ 2020; Yang+ 2022, Khrykin+ 2024*