Physical properties of cosmic filaments

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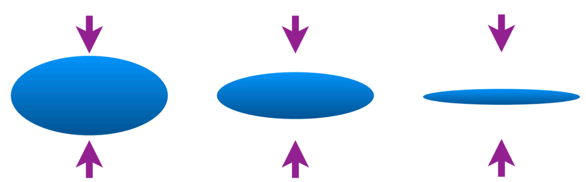
Introduction: Matter in the Universe

According to the Λ-CDM model:

Dark Matter

Baryons

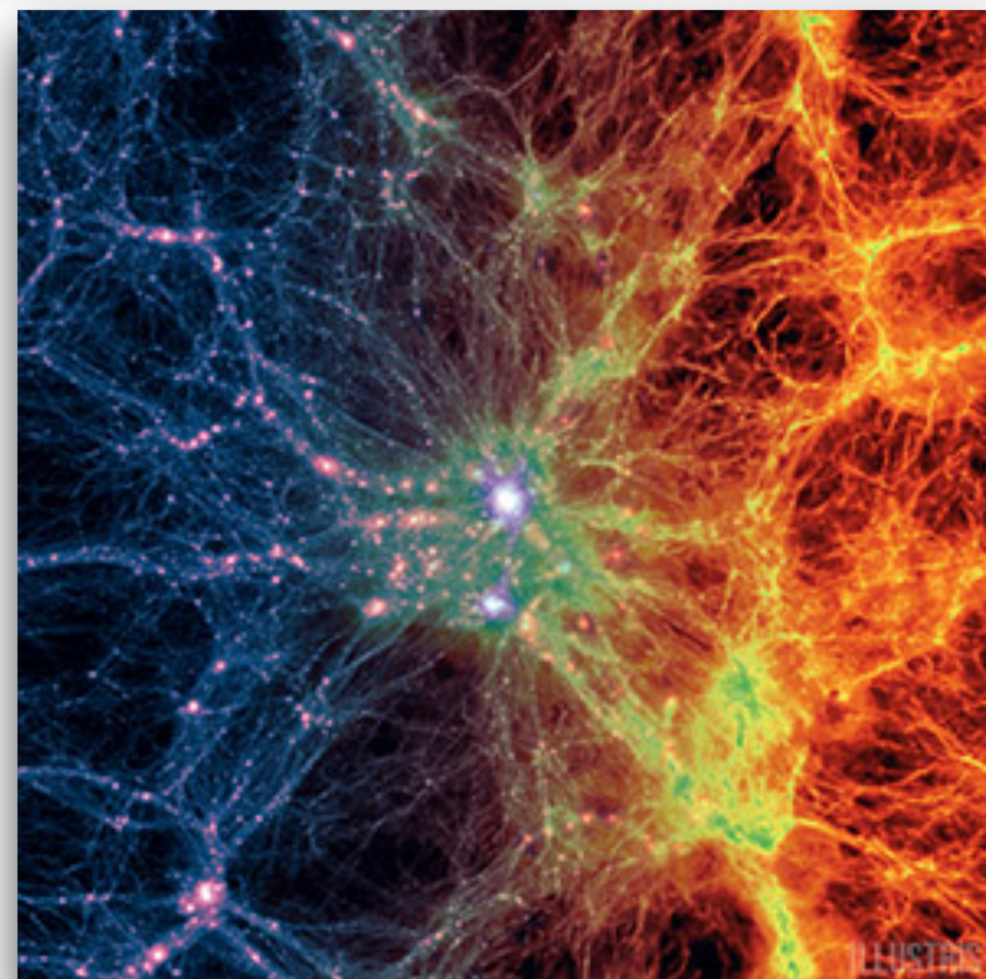
Structure formation by amplification of initial fluctuations and gravitational collapse



Zeldovich+ 1970

Cosmic Web
Multi-scale structure made of nodes, **filaments**, walls, and voids

Bond, Kofman, Pogosyan 1996



IllustrisTNG simulation

Follow the growth of dark matter

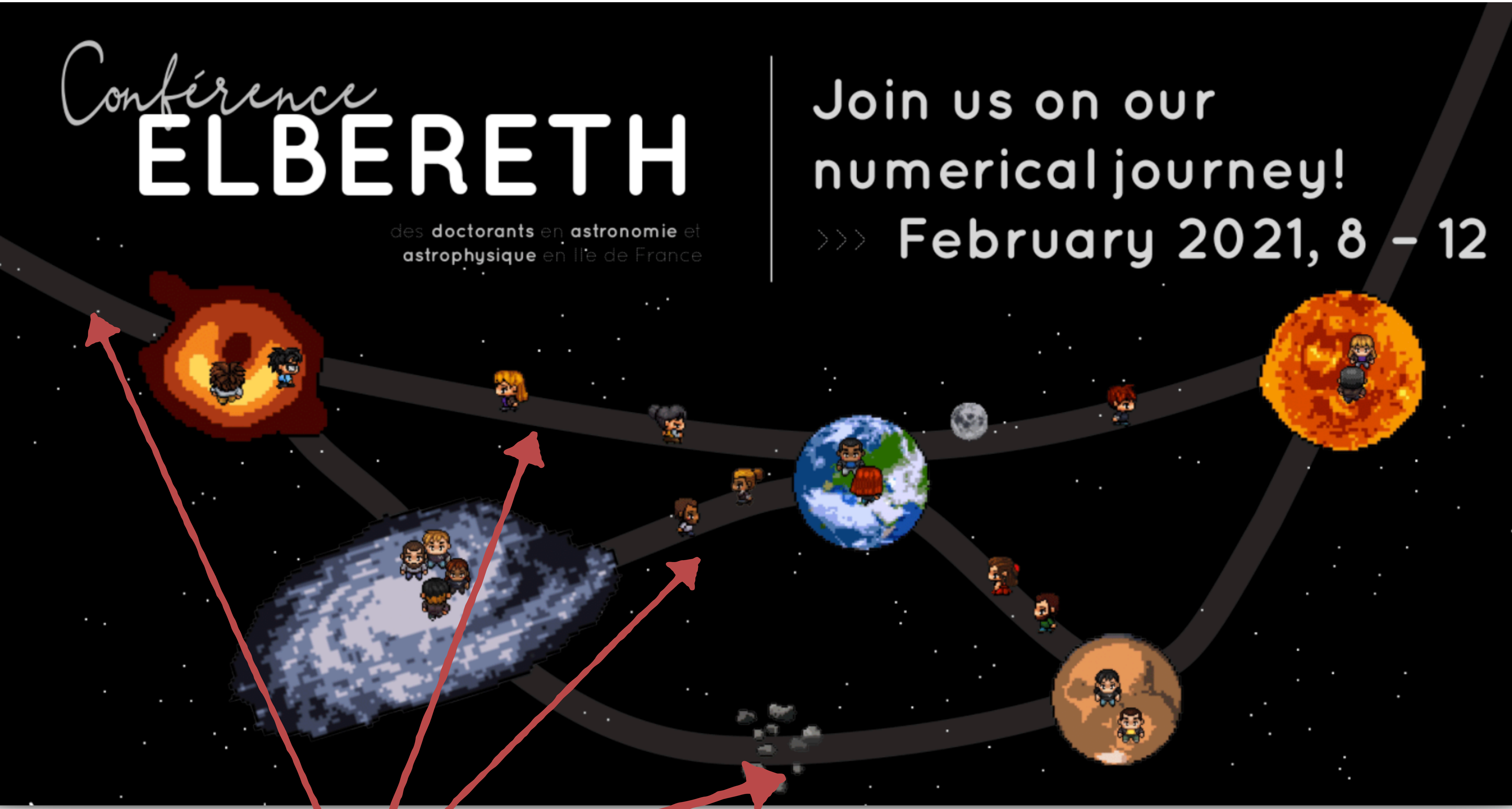
Galaxies

Follow the DM skeleton, with some bias

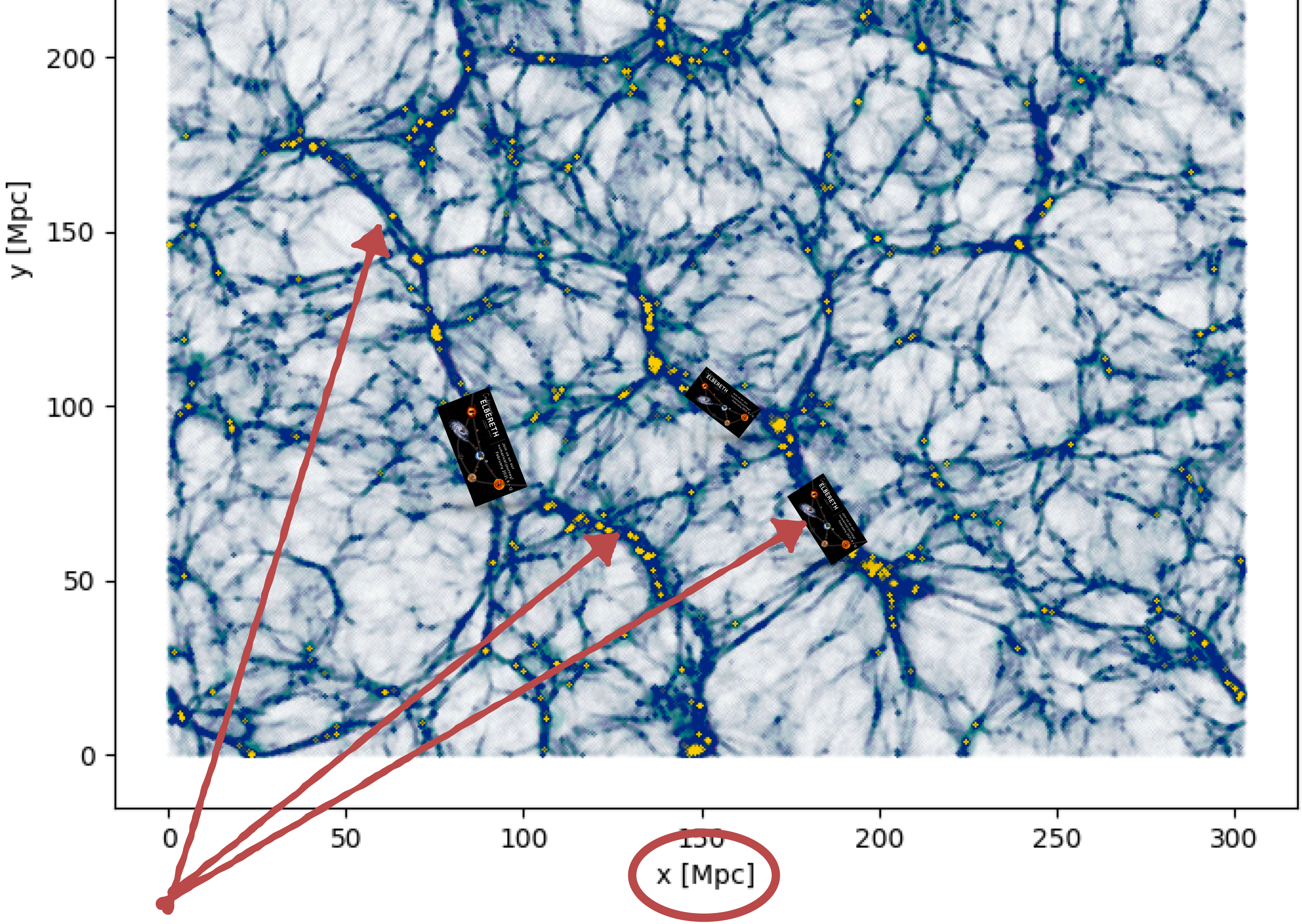
Gas

Mainly in the IGM

But baryons are **collisional**
COMPLEX!


Conférence
ELBERETH
des doctorants en astronomie et
astrophysique en Île de France
Join us on our
numerical journey!
>>> February 2021, 8 - 12

Filaments!



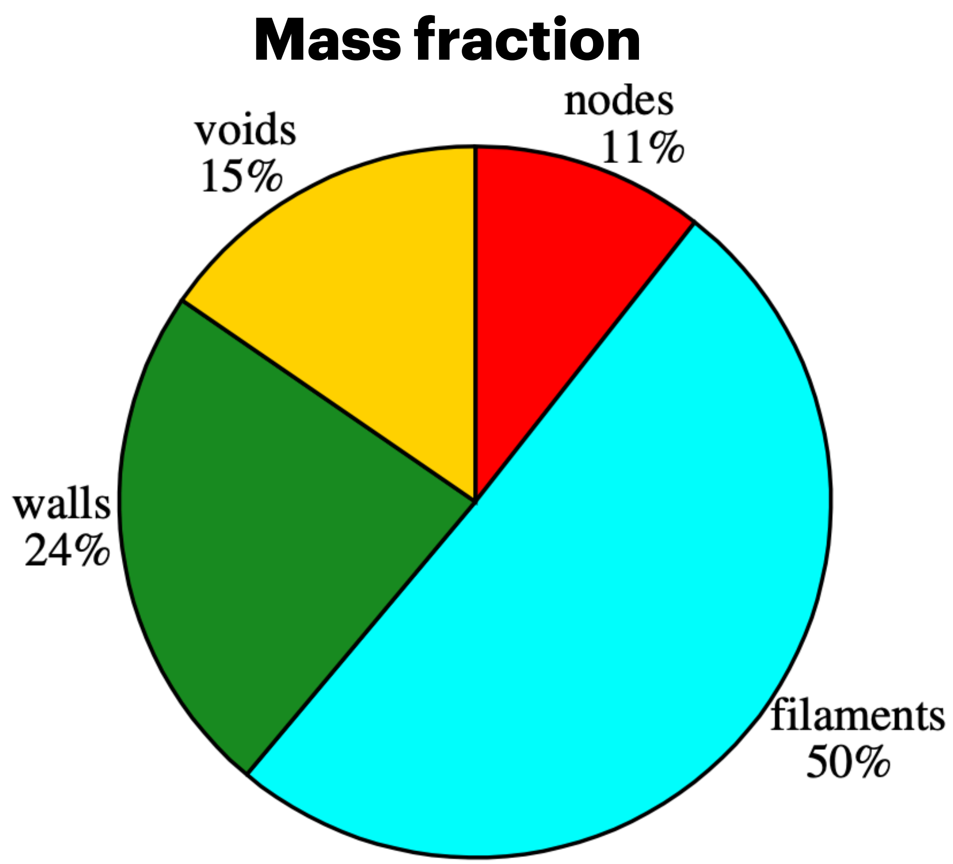
Filaments!

But my studies focus on **COSMIC** filaments (=**Mpc scales**)

INTRODUCTION: COSMIC FILAMENTS

Cautun+ 2014

At z=0 (today)



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

But cosmic filaments are **hard to observe (missing baryon problem!)**,

not well understood...

A global picture is still **lacking**...

We need to **better understand** these structures, that are the **place** of **galaxy evolution!**

Characterisation of cosmic filaments

Focus on two directly observable tracers of matter:

1) From the galaxy distribution

Galarraga-Espinosa+ 2020a

2) From the study of gas

Galarraga-Espinosa+ 2020b

Theory is not well known —> Study in numerical simulations

Focus on the Universe today : **z = 0**

THE SIMULATION DATA

IllustrisTNG

Focus on the Universe today : $z = 0$

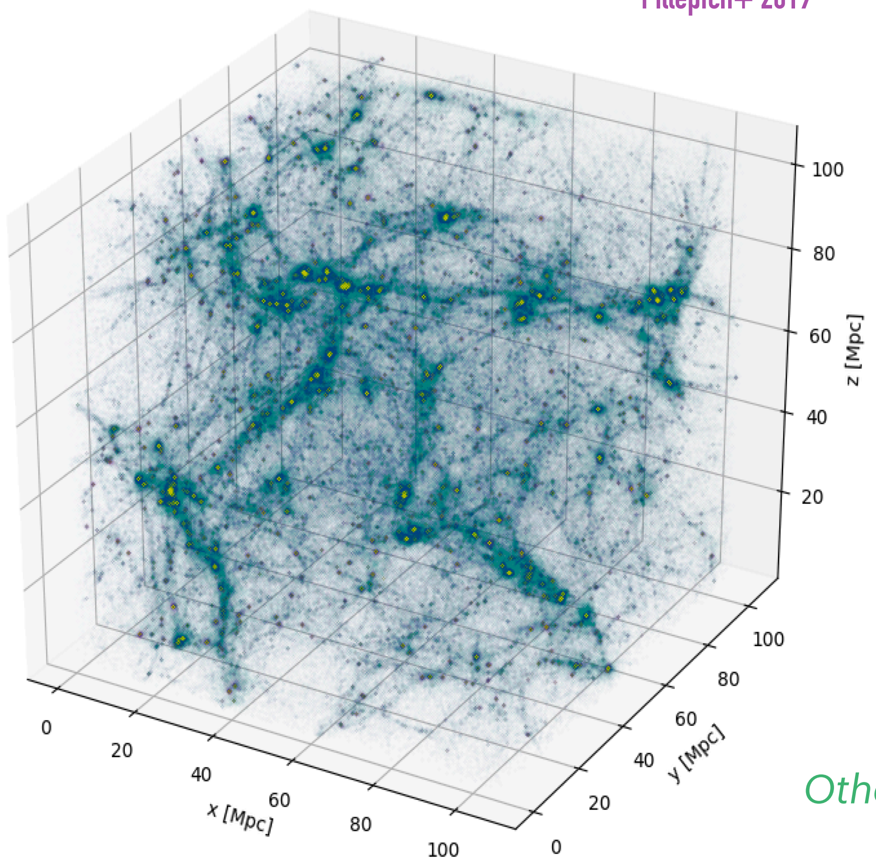
These simulations are publicly available

	TNG300-1	Magneticum	TNG300-2	TNG100-2	Illustris-2
Box size [Mpc^3]	302.6^3	500^3	302.6^3	110.7^3	106.5^3
DM resolution [$M_\odot/h$]	4.0×10^7	6.9×10^8	3.2×10^8	4.0×10^7	3.5×10^7
Density of tracers [Mpc^{-3}]	10.0×10^{-3}	10.1×10^{-3}	5.4×10^{-3}	10.1×10^{-3}	16.9×10^{-3}
Cosmology	*Planck* 2015	WMAP7	*Planck* 2015	*Planck* 2015	WMAP7
Comments	**Reference**	Comparison	Resolution effects	Physical models	Physical models

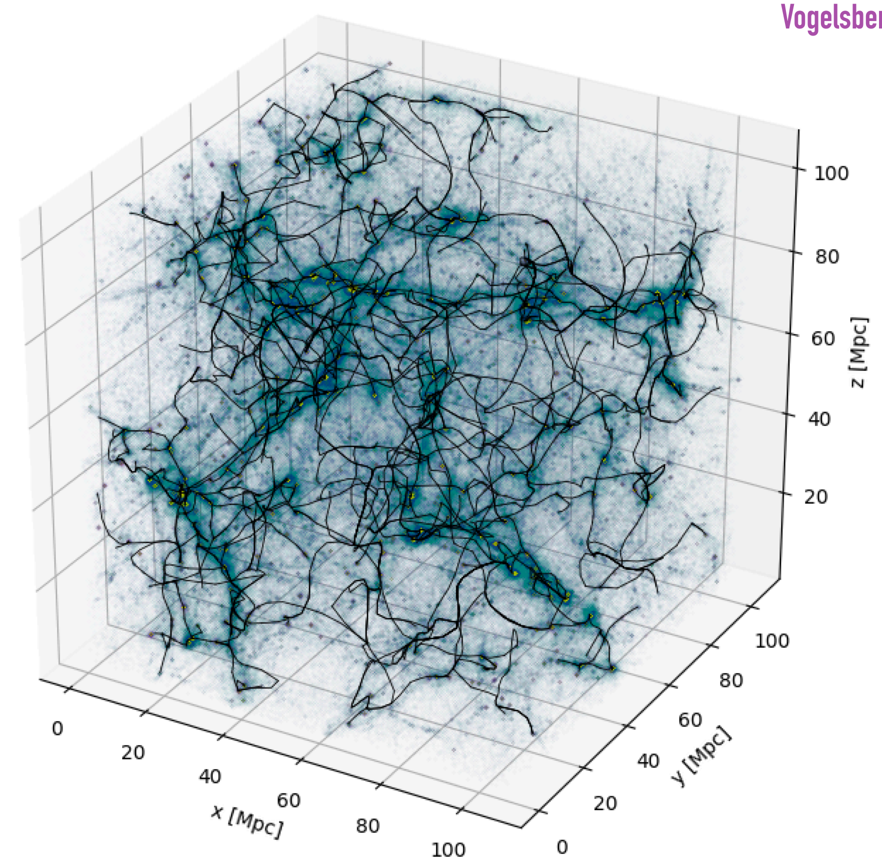
Nelson+ 2019
Pillepich+ 2019

Hirschmann+ 2014
Dolag+ 2015
Ragagnin+ 2017

Genel+2014
Sijacki+2015
Vogelsberger+ 2014b



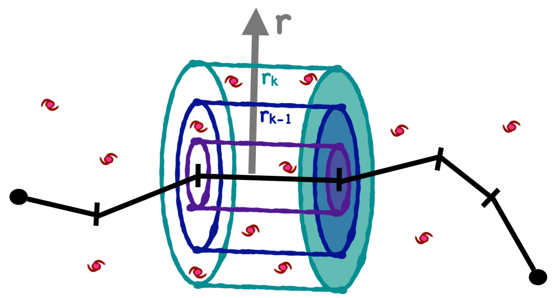
Detection of filaments with **DisPerSE**
(Sousbie+ 2011)



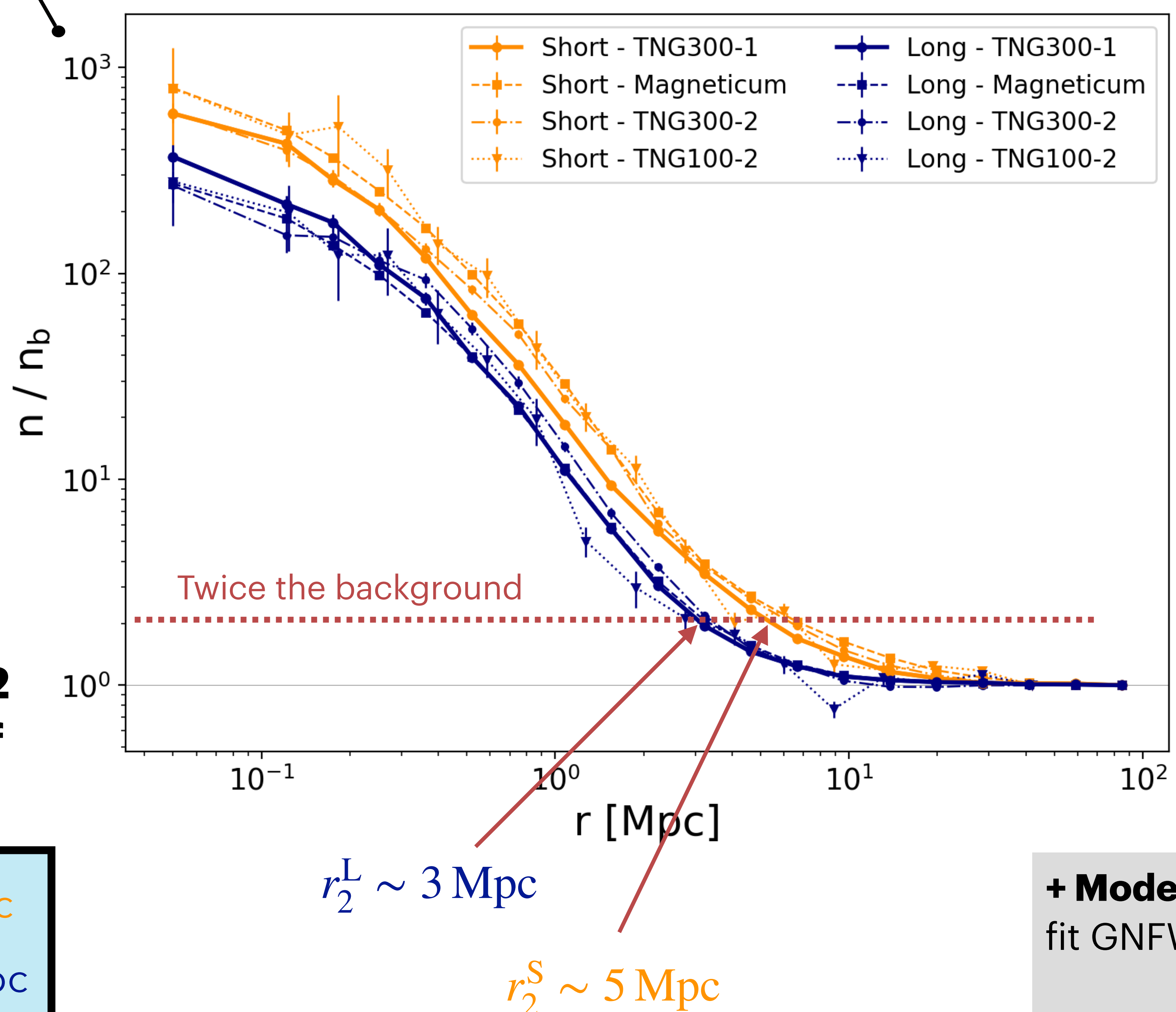
Other detection algorithms: see talk of Tony Bonnaire (tomorrow)

How are Galaxies distributed around Filaments?

Galarraga-Espinosa+ 2020a



Average radial **density profiles** (5550 filaments)



Separation in 2 populations of filaments

Short $L_f < 9$ Mpc

Long $L_f \geq 20$ Mpc

+ Model the density profiles: fit GNFW, Power laws, Einasto and β models

Take Home Message

Galarraga-Espinosa+ 2020a

Galaxies are not distributed in the same way around filaments of different lengths

Short	Long
Short and puffy $r_2 \sim 5\,\mathrm{Mpc}$	Long and thin $r_2 \sim 3\,\mathrm{Mpc}$
Live in **denser** environments, trace over-dense regions	Trace **less-dense** environments
May correspond to **bridges of matter** between over-dense structures (clusters)	May correspond to **cosmic filaments** shaping the large scales of the Cosmic Web
Formation history may be dominated by **gravitational forces of collapse** (matter from the low to high density zones)	**Formation history** may be dominated by **dark energy forces** (cosmic accelerated **expansion** and stretching of the Cosmic Web)

Two populations also predicted by theory (caustics)
Feldbrugge+ 2018

Other studies of galaxies around filaments in simulations:
Kraljic+ 2018, 2019
Ganeshaiah-Veena+ 2018, 2019, 2020

What about gas?

Properties around different populations of filaments?

2) Study of gas around filaments

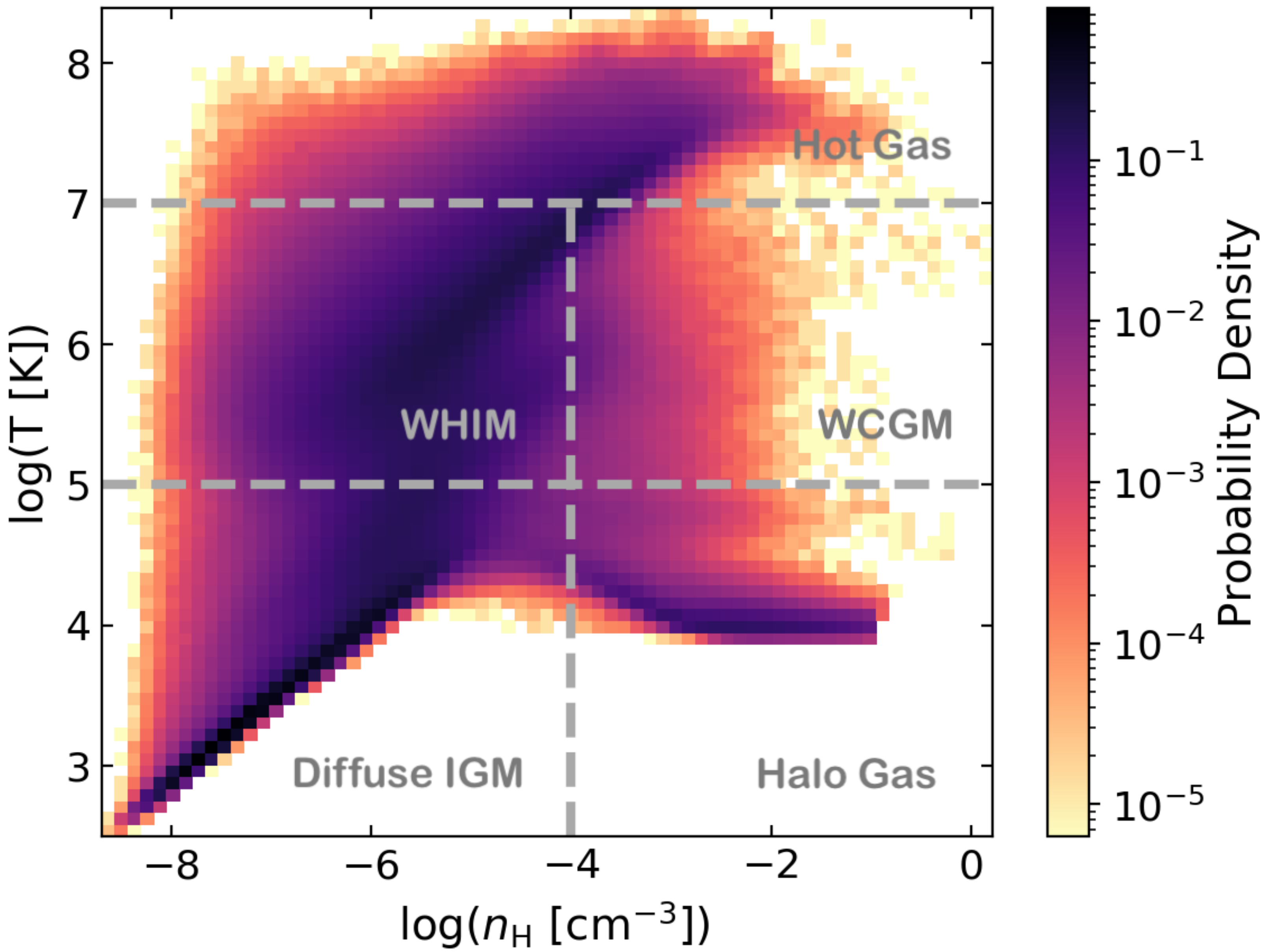
Galarraga-Espinosa+ 2020b

DIFFERENT GAS PHASES

Separation of gas in different phases

Phases as in Martizzi+ 2019

TNG300-1 simulation



Different Gas Phases

Separation of gas in different phases

Phases as in Martizzi+ 2019

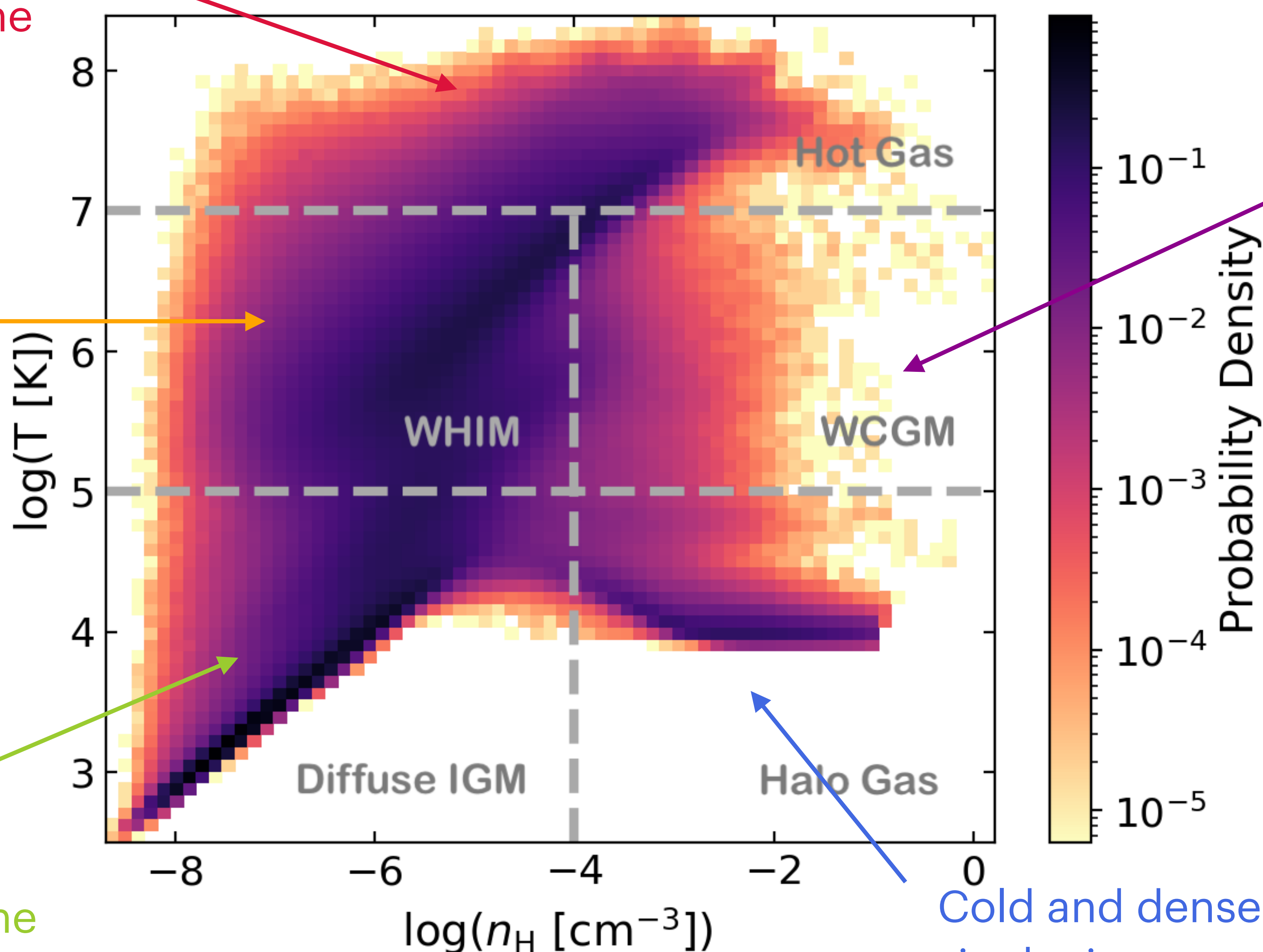
Shock-heated gas, in the denser regions of the Cosmic Web

Accreted onto cosmic structures, heated by shocks

(**WHIM** is HARD to observe!)

Gas in the lowest density regions of the Cosmic Web

TNG300-1 simulation

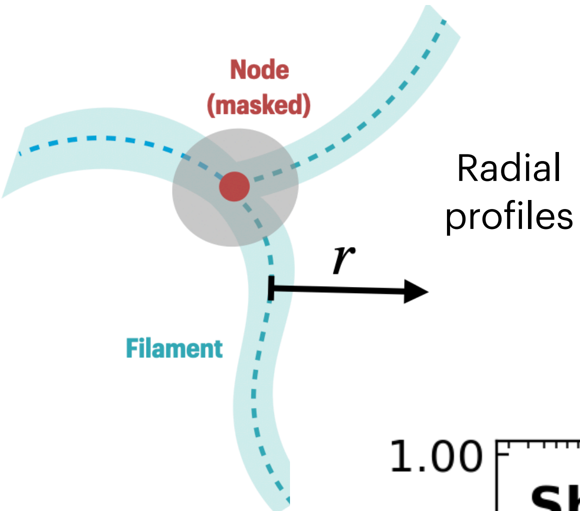


Gas around galaxies

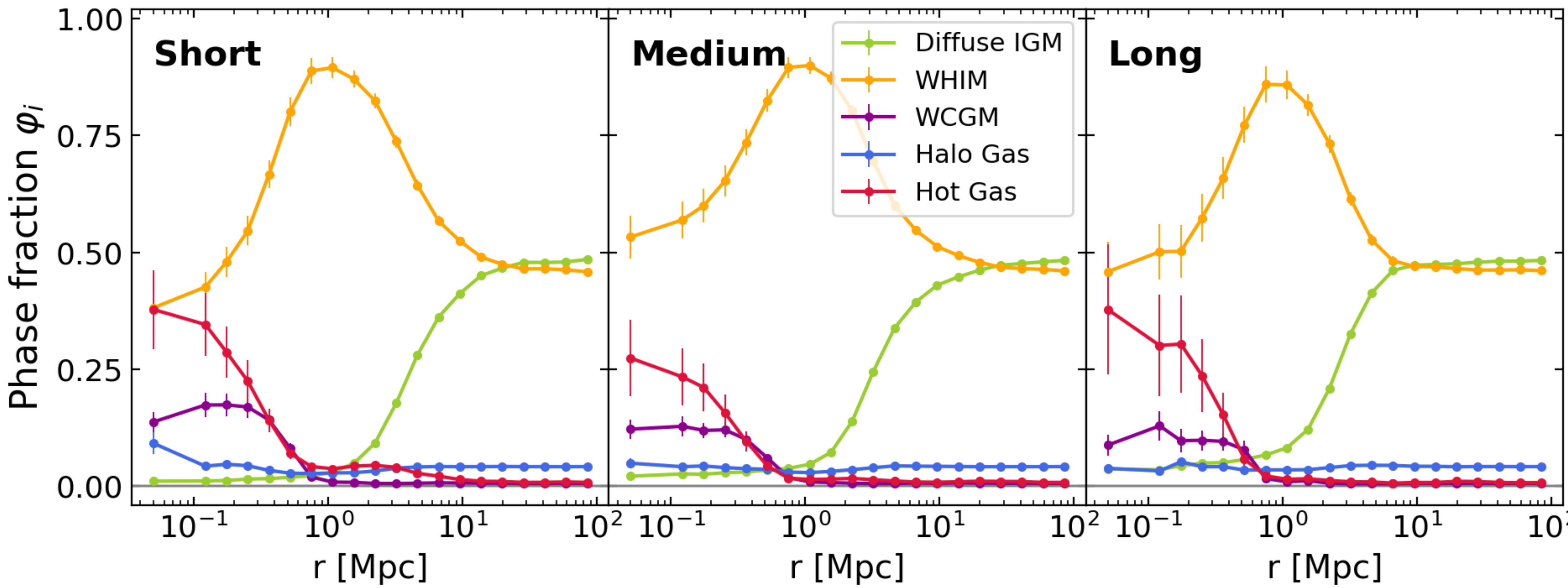
Cold and dense gas in the interstellar medium of galaxies

WHAT IS THE STATE OF GAS AROUND FILAMENTS?

Galarraga-Espinosa+ 2020b



Profiles of phase fraction $\varphi_i(r) = \dfrac{\rho_{\mathrm{gas},i}(r)}{\rho_{\mathrm{gas,tot}}(r)}$

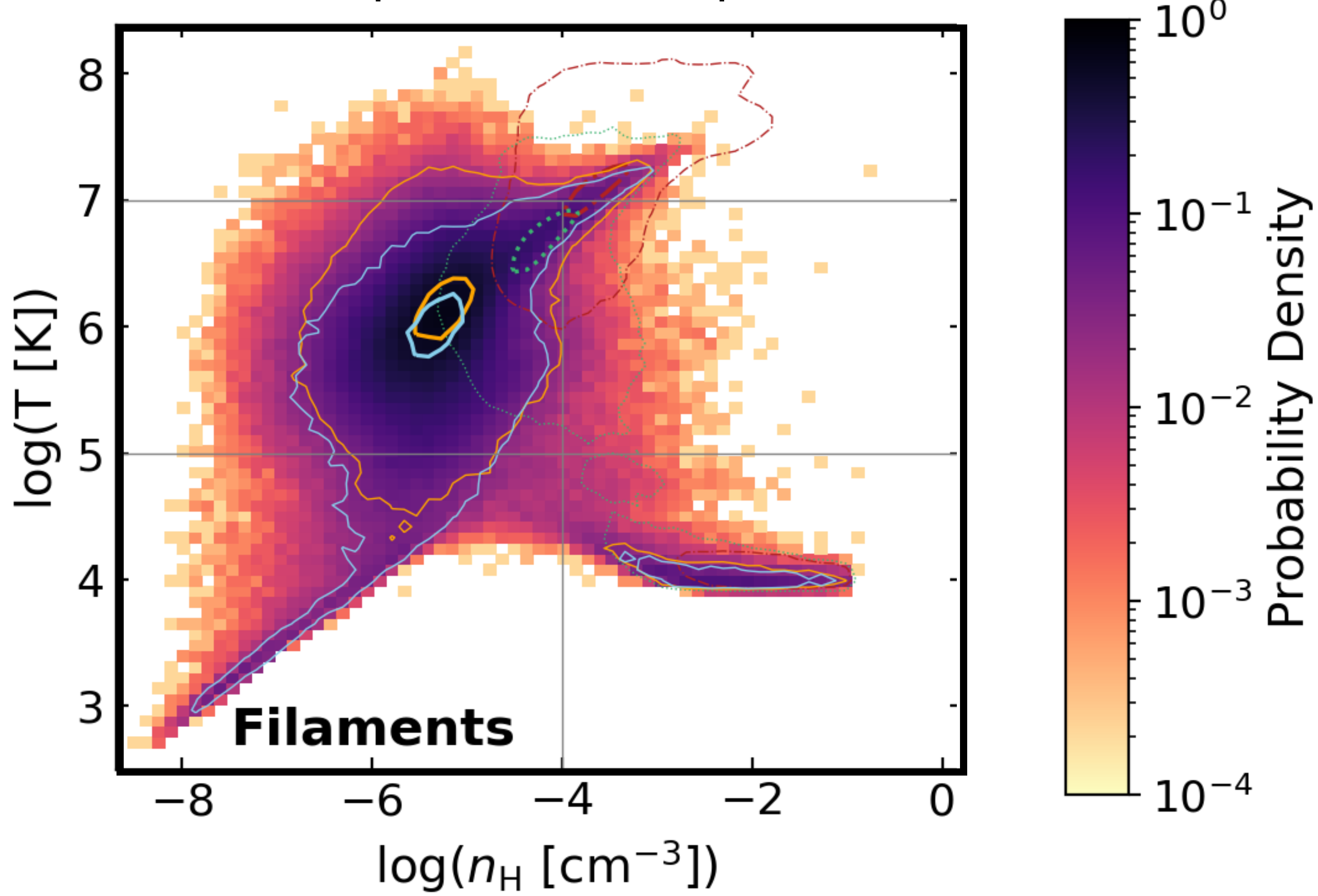


	Density [cm^{-3}]	Temperature [K]	Comments
Diffuse IGM	$n_{\mathrm{H}} \leq 10^{-4}$	$T \leq 10^5$	Gas in the lowest-density regions of the cosmic web.
WHIM	$n_{\mathrm{H}} \leq 10^{-4}$	$10^5 < T \leq 10^7$	Gas that has been accreted onto cosmic structures and heated by shocks.
WCGM	$n_{\mathrm{H}} > 10^{-4}$	$10^5 < T \leq 10^7$	In the surroundings of galaxies, sensitive to galactic physics.
Halo Gas	$n_{\mathrm{H}} > 10^{-4}$	$T \leq 10^5$	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.

What is the state of Gas at Filament cores?

Better understand **filament cores (<1 Mpc)**:

Phase Space of gas in filaments
(at 1 Mpc from the spines)



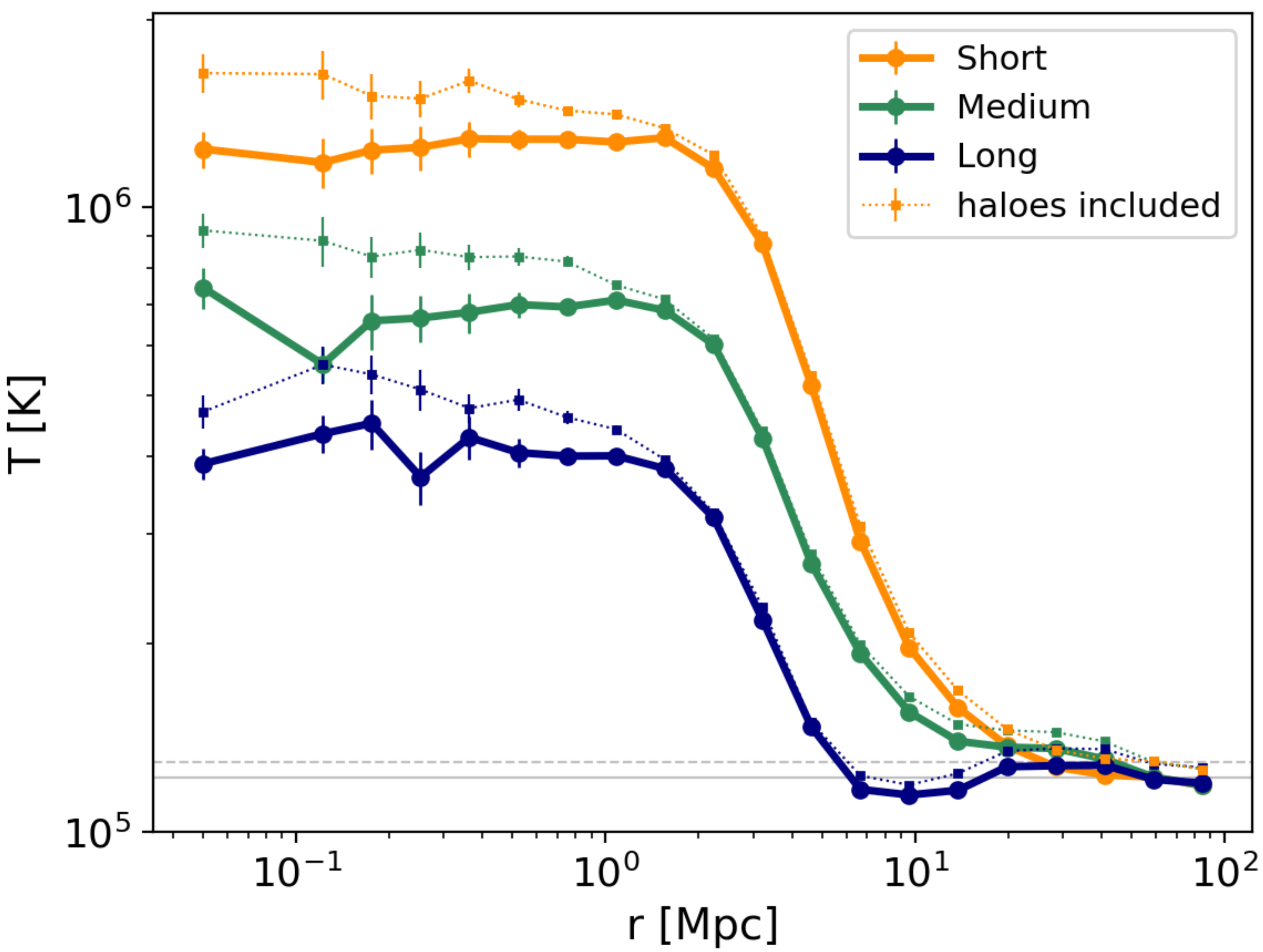
- Different **gas content** in **short** and **long** filaments

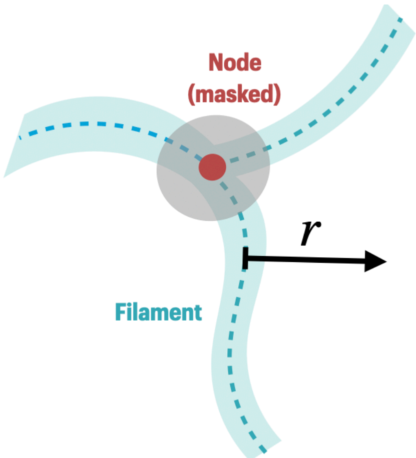
Galarraga-Espinosa+ 2020b

How does the Temperature evolve?

Galarraga-Espinosa+ 2020b

- **Temperature** profiles





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

- **Different** profiles for different types of filaments (short are 3x hotter)
- All filaments: **isothermal** core up to r ~ 1.5 Mpc

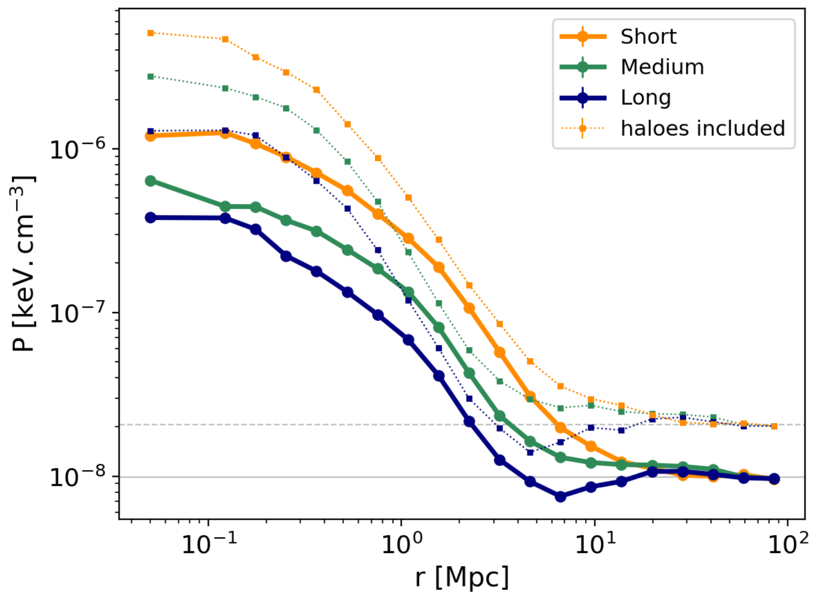
Including haloes
Temperature rises (haloes contain hotter gas)

In agreement with
Klar & Mücket 2012
Gheller & Vazza 2019
Tuominen+ 2020

PRESSURE AND COMPTON *y*-PROFILES

Galarraga-Espinosa+ 2020b

- **Pressure** profiles



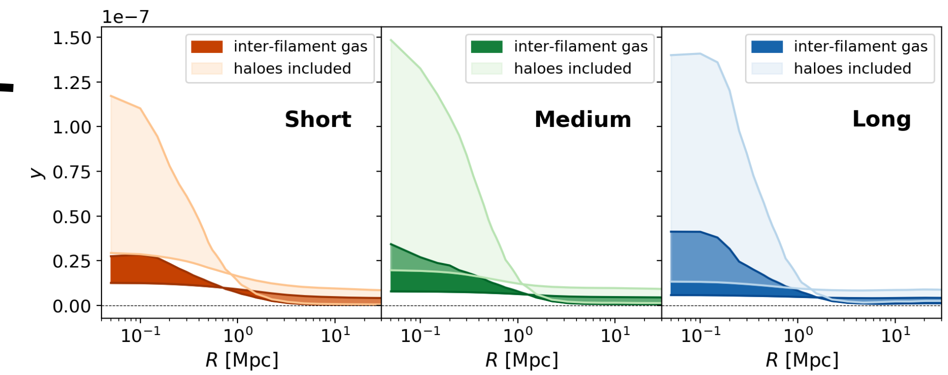
$\mathrm{P_{core}} = 4 - 12 \times 10^{-7}\ \mathrm{keV\,.\,cm^{-3}}$

*~**1000** times lower than cores of clusters!*

OBSERVATION with the Sunyaev-Zel'dovich **(SZ) effect**

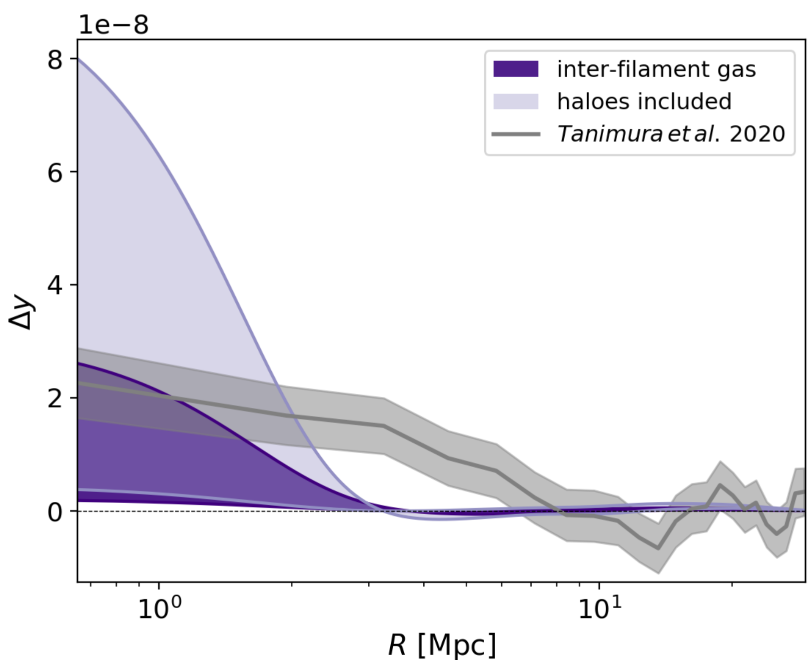
$$y = \frac{\sigma_T}{m_e c^2} \int P_e\, dl$$

Estimation of ***y*-profiles** of filaments



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

(A step towards observation of gas around filaments!)



Comparison with **observations**
(Planck y maps data, SDSS filaments)
Tanimura+ 2020a

Good agreement!

CONCLUSIONS

1. Different populations of filaments at z=0:

- from the **galaxy distribution**
  Galarraga-Espinosa+ 2020a
- from the **gas content & properties**
  Galarraga-Espinosa+ 2020b

Short	Long
Short and puffy $r_2 \sim 5\,\mathrm{Mpc}$	Long and thin $r_2 \sim 3\,\mathrm{Mpc}$
Trace **denser environments**	Trace **less dense environments**
Hotter, **higher pressure** values	**Less hot**, **lower pressure** values

2. Overview of gas properties at different distances from the spine:

WHIM + other hotter and/or denser phases (WCGM and Hot gas)

WHIM dominant phase

Isothermal core

Haloes rise T and P

Accretion to filament

Diffuse IGM —> WHIM

~ 100% of gas is Diffuse IGM and WHIM

CORE

OUTSKIRTS

LARGER SCALES

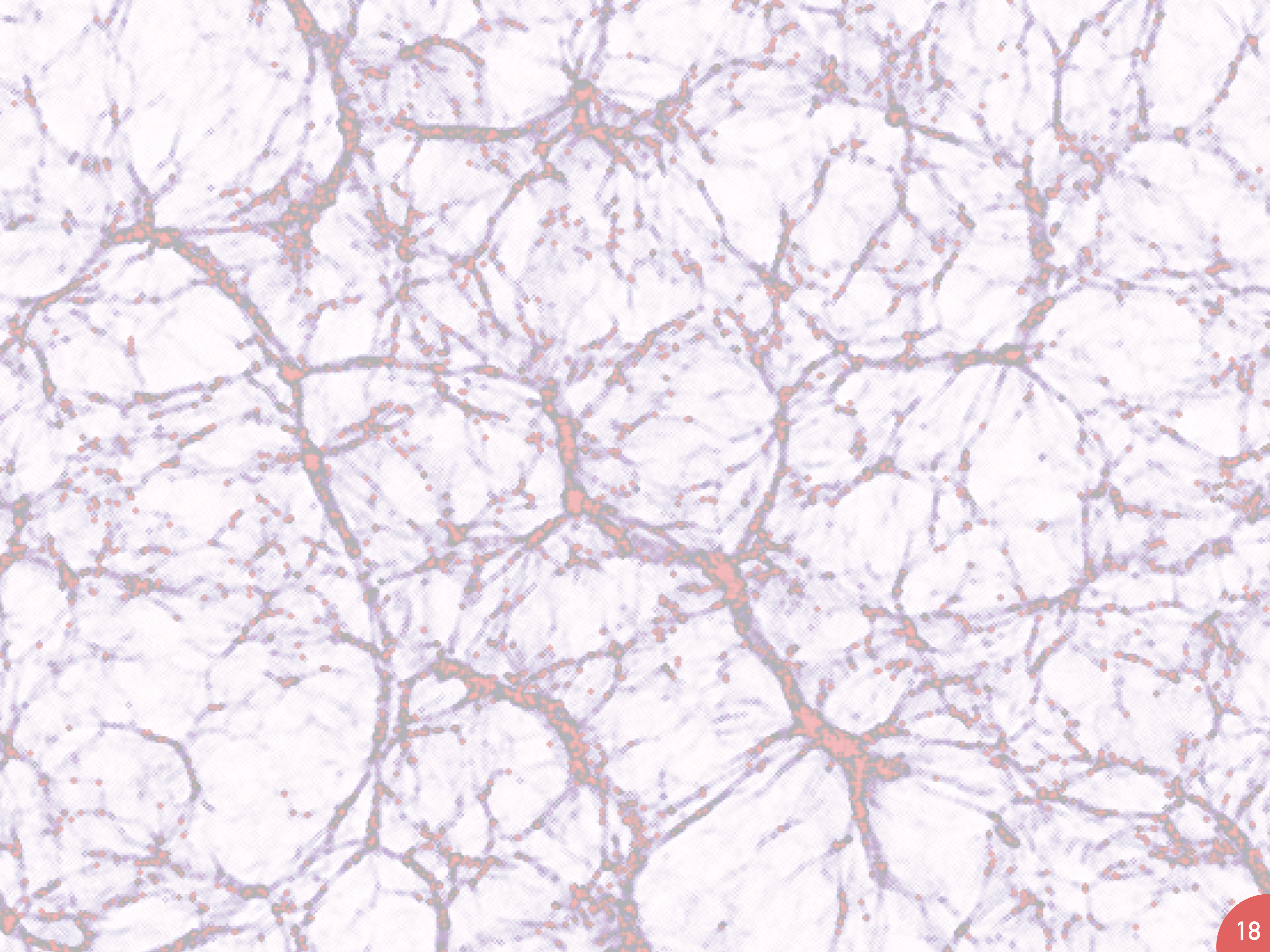
0

1 Mpc

~10 Mpc

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

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



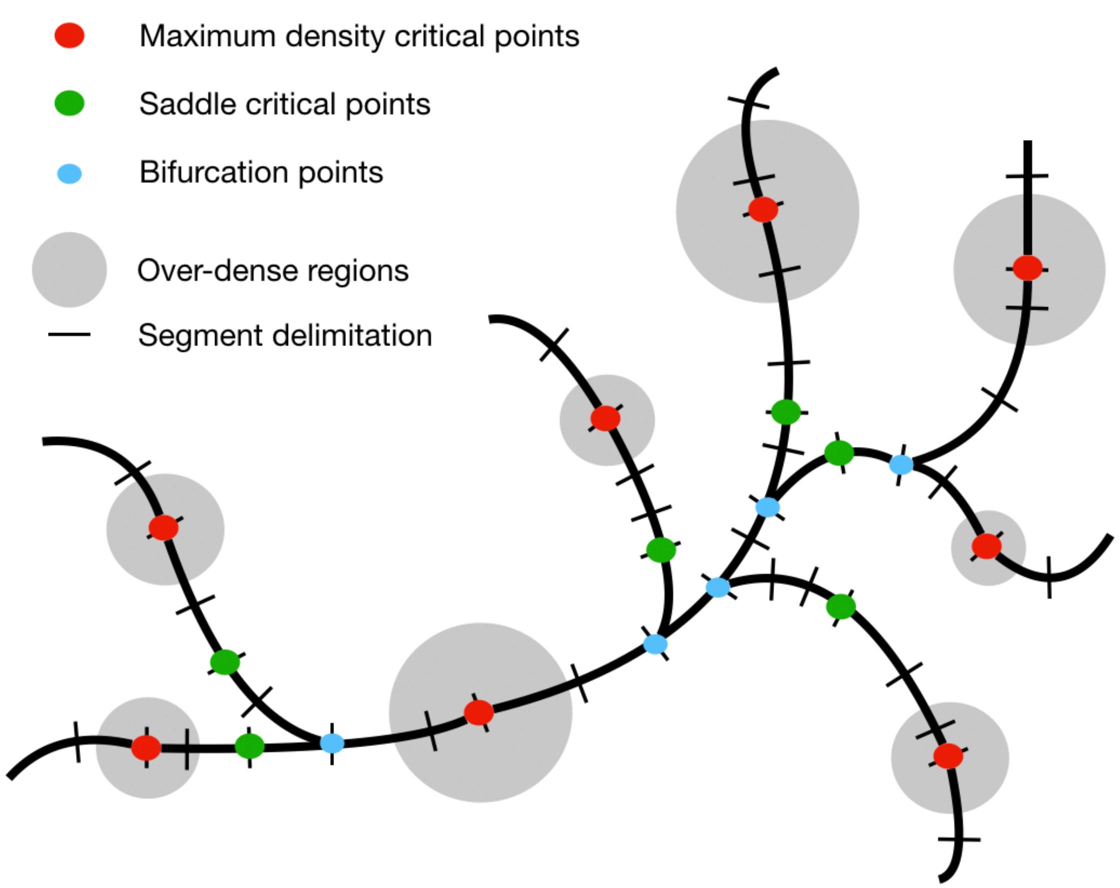
More Slides...

Filament Catalogues

DisPerSE (Sousbie+ 2011)
applied to the galaxy catalogues.

Detection based on the **topology** of the density field

Publicly available code



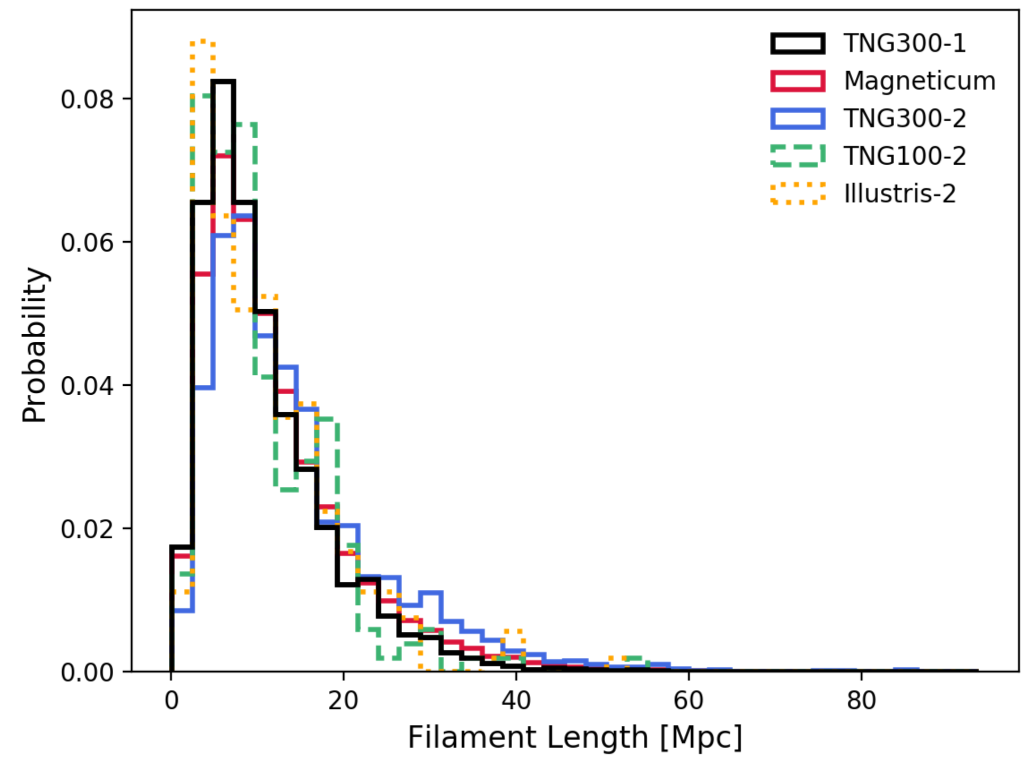
Filaments are sets of segments connecting **maximum density** critical points to **saddles**

Galaxy selection

Cut in stellar mass following **observational** limits

$$\boxed{10^9 \leq M_* \,[\mathrm{M}_\odot] \leq 10^{12}}$$

(Brinchmann+ 2004, Taylor+ 2011)



Other methods also available
(NEXUS+, T-Rex, Bisous, ...)
Cautun+ 2013 Bonnaire+ 2020 Tempel+ 2016

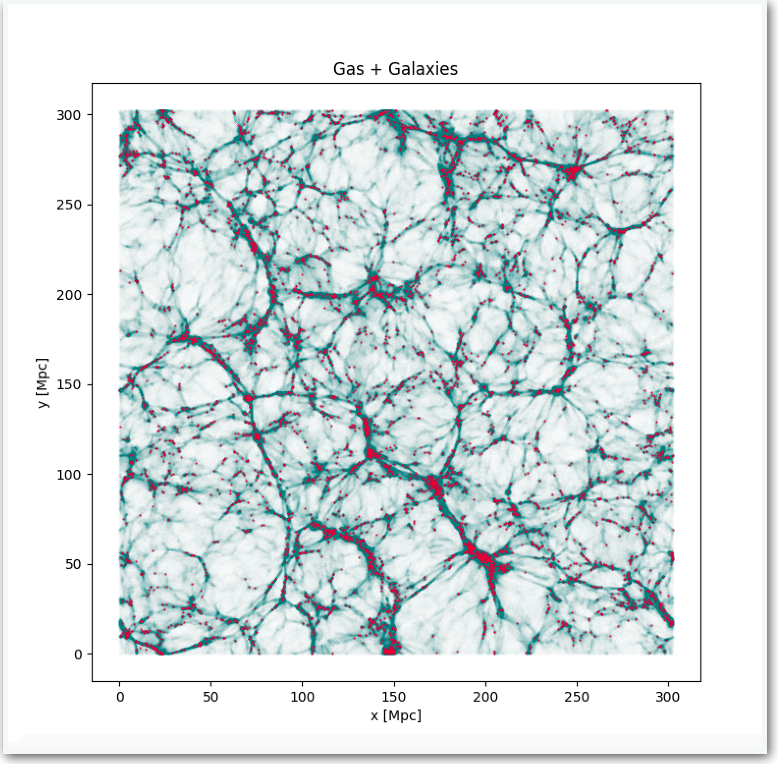
But best choice to trace the **spine**

THE SIMULATION DATA

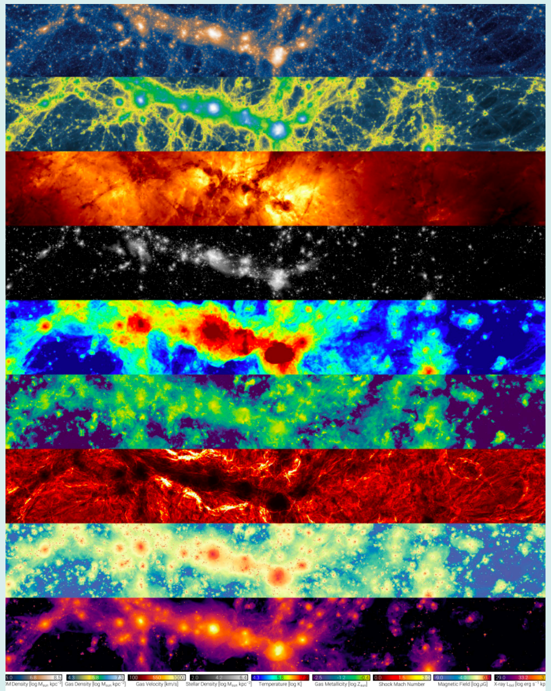
These simulations are publicly available

	TNG300-1
Box size [Mpc^3]	302.6^3
DM resolution [$\mathrm{M}_\odot/h$]	4.0×10^7
Density of tracers [Mpc^{-3}]	10.0×10^{-3}
Cosmology	*Planck* 2015
Comments	**Reference**

Nelson+ 2019
Pillepich+ 2019



Gas and galaxies from **TNG300-1** (slice)



http://www.illustris-project.org

Gas in IllustrisTNG:

- Voronoi **cells** (with different volumes) (refined and de-refined according to mass target of $7.6 \times 10^6\,\mathrm{M}_\odot/h$)
- Baryonic processes (sub-grid): ***"TNG model"***, specifically calibrated on observational data

Pillepich+ 2019

What is the Temperature?

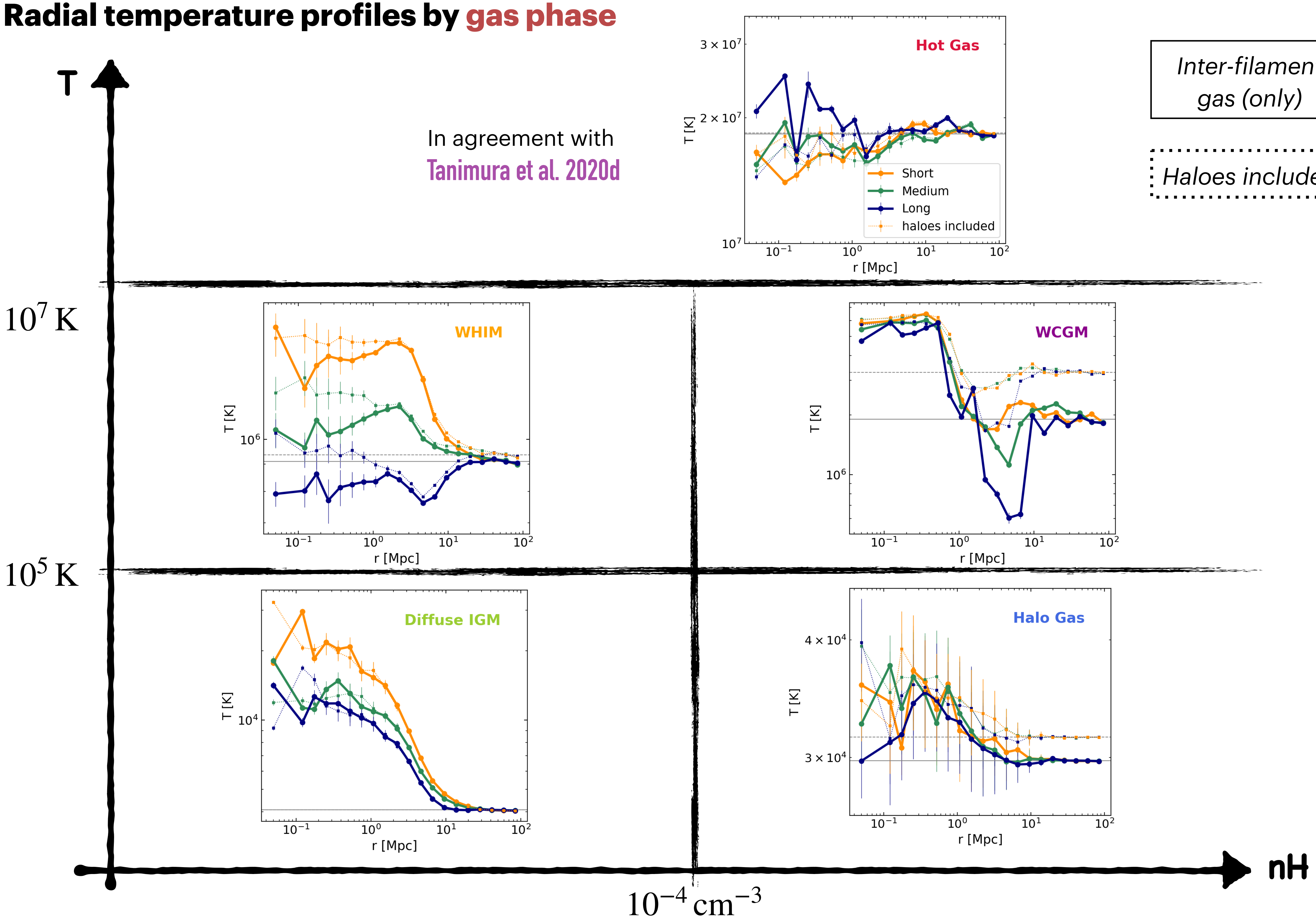
Galarraga-Espinosa+ 2020b

Radial temperature profiles by gas phase

In agreement with Tanimura et al. 2020d

Inter-filament gas (only)

Haloes included

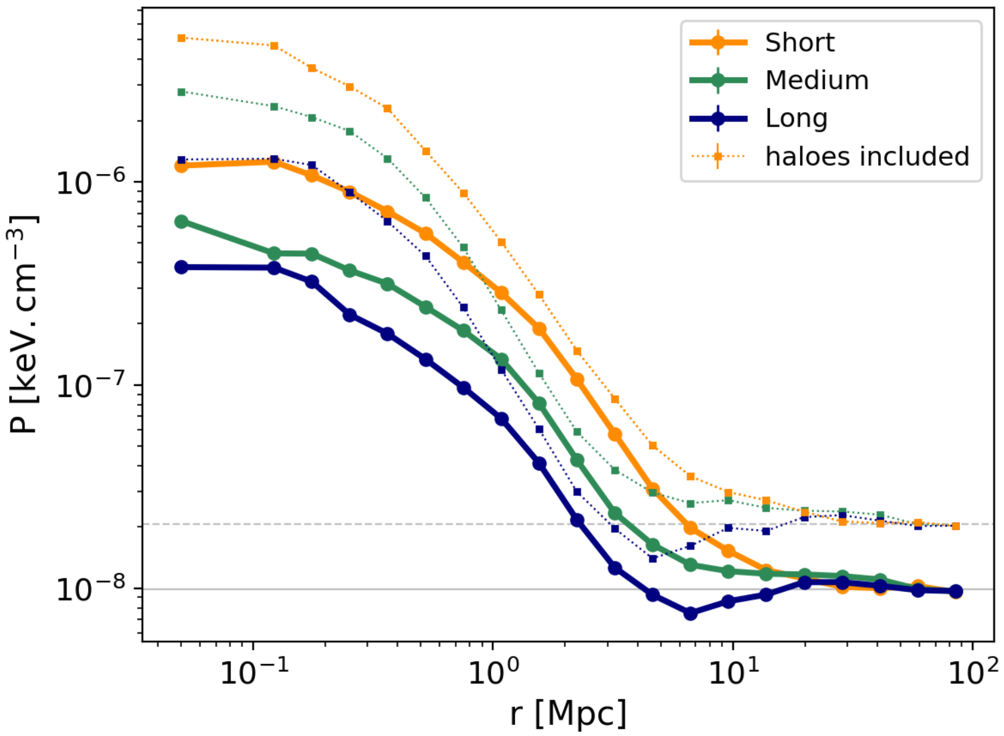


Pressure Profiles

Radial pressure profiles

All gas

Galarraga-Espinosa+ 2020b



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

Comparison with clusters **~1000** times lower

$$P_{clusters} = 1 - 300 \times 10^{-3}\ \mathrm{keV\,.\,cm^{-3}}$$

Arnaud+ 2010

By gas phase