Searching for the hot WHIM

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XCalibur 2019, Winchester, UK

Finding the missing baryons within the filaments of the Cosmic Web with the future high resolution X-ray spectrometers

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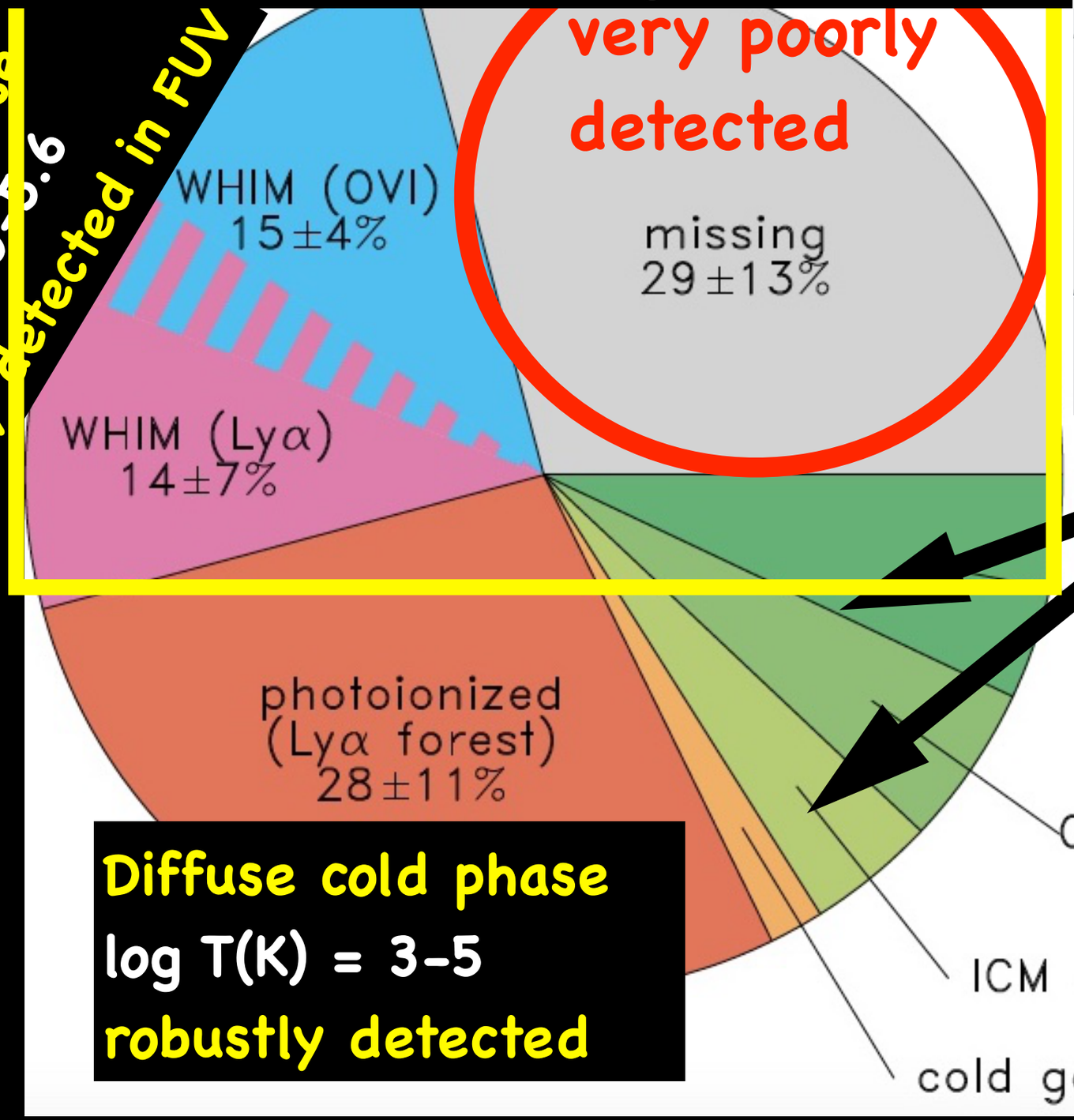
1) Missing baryons?

Circle: Full baryon budget (5% of critical density, well constrained with e.g. Planck)

Shull+12 review of z < 1 baryon component observations



simulations predict lots of hot X-ray baryons

log T(K) = 5.6-7

Highly ionised and low density: easy to miss

This may be the missing baryon component

Need better instrumets to detect it (Arcus, ATHENA)

2) No baryons missing in the simulations

We use EAGLE to understand the whereabouts of the observationally missing baryons

EAGLE: Evolution and Assembly of GaLaxies and their Environments

Schaye et al., 2015, MNRAS, 446, 521

- N-Body Tree-PM smoothed particle hydrodynamics (SPH) code GADGET 3
- Box size 100 Mpc
- Mass resolution: gas 10^6 M_{sol} ; dark matter 10^7 M_{sol}

EAGLE baryon mass distribution

Canonical Warm-Hot Intergalactic Matter (WHIM) range log T(K) = 5-7

Half of the baryons in the WHIM phase

55%

Normalised dm/dT

10^{0}

10^{-1}

10^{-2}

10^{-3}

10^{5}

10^{6}

10^{7}

10^{8}

$T\,[K]$

EAGLE baryon mass distribution

Warm WHIM (log T(K) = 5.0-5.6) not missing: 100s of absorption lines detected

Hottest WHIM (log T(K) = 6.6-7.0) not missing: IGM within r_{200} in clusters and groups, included in the observed baryon budget

FUV

Normalised *dm/dT*

10^{-1}

10^{-2}

10^{-3}

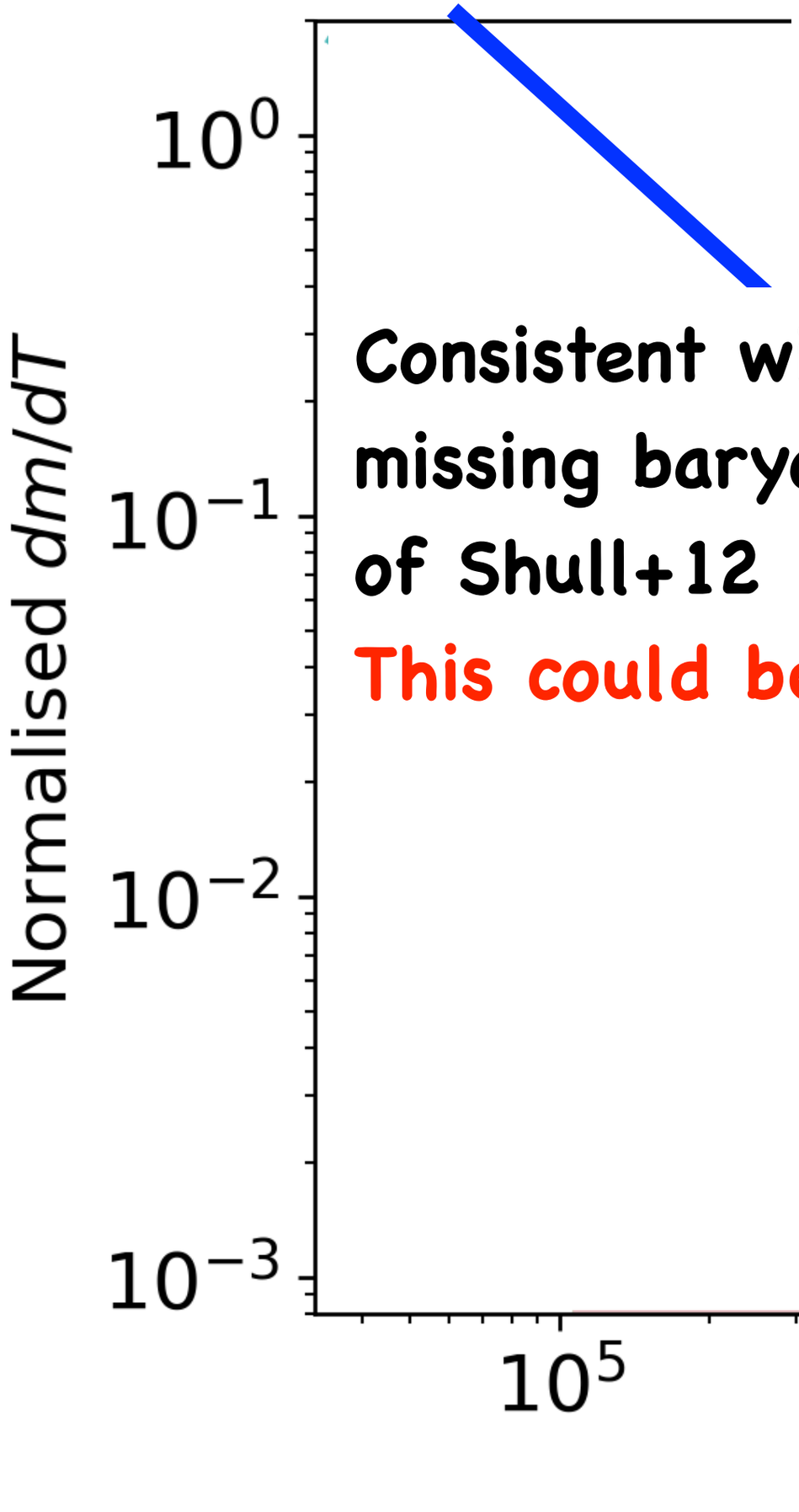
10^{5} 10^{6} 10^{7} 10^{8}

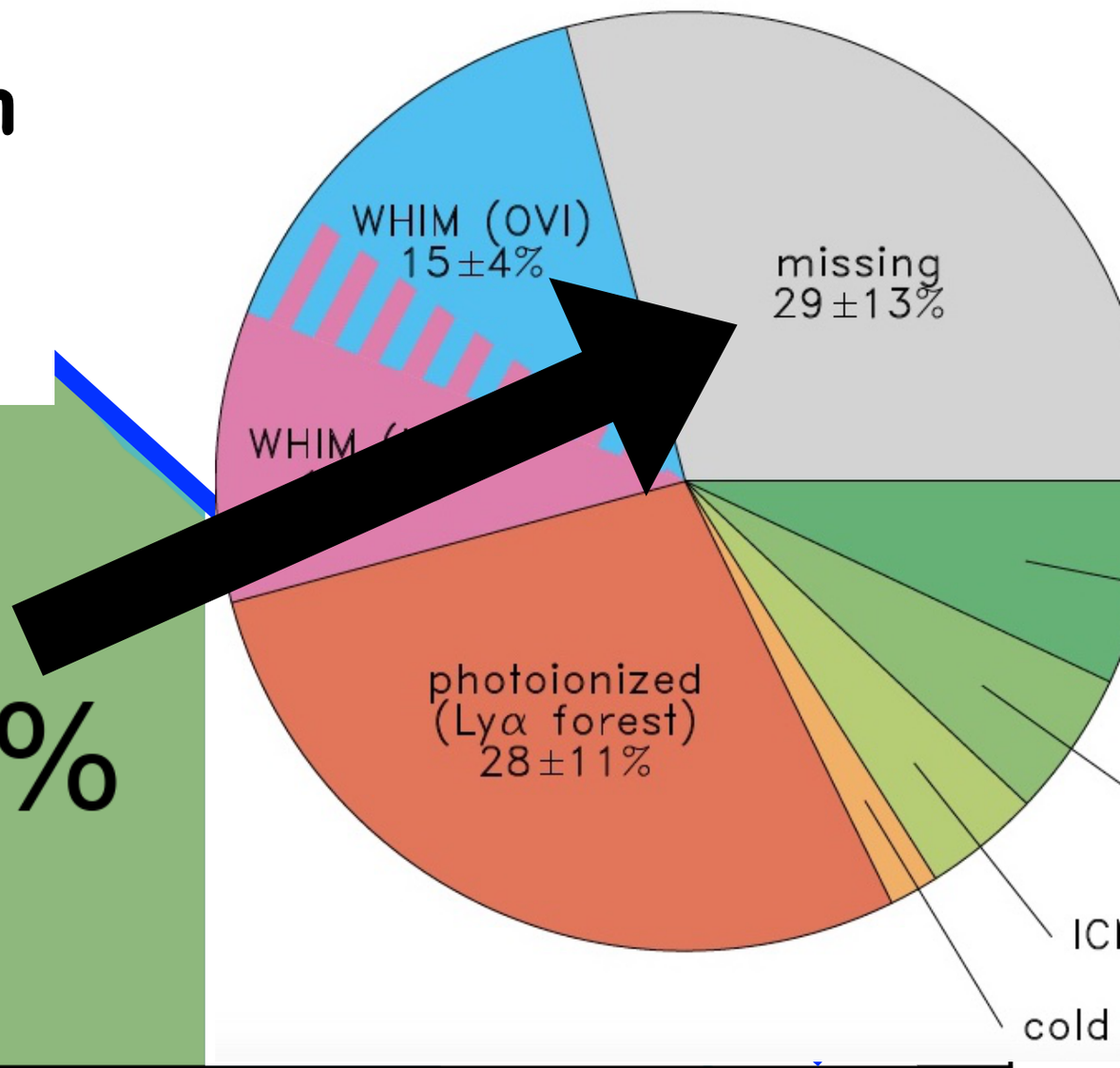
$T\,[K]$

26% of EAGLE baryons are in the "missing" (poorly detectable) range log T(K) = 5.6-6.6

Consistent with the missing baryon fraction of Shull+12

This could be it!

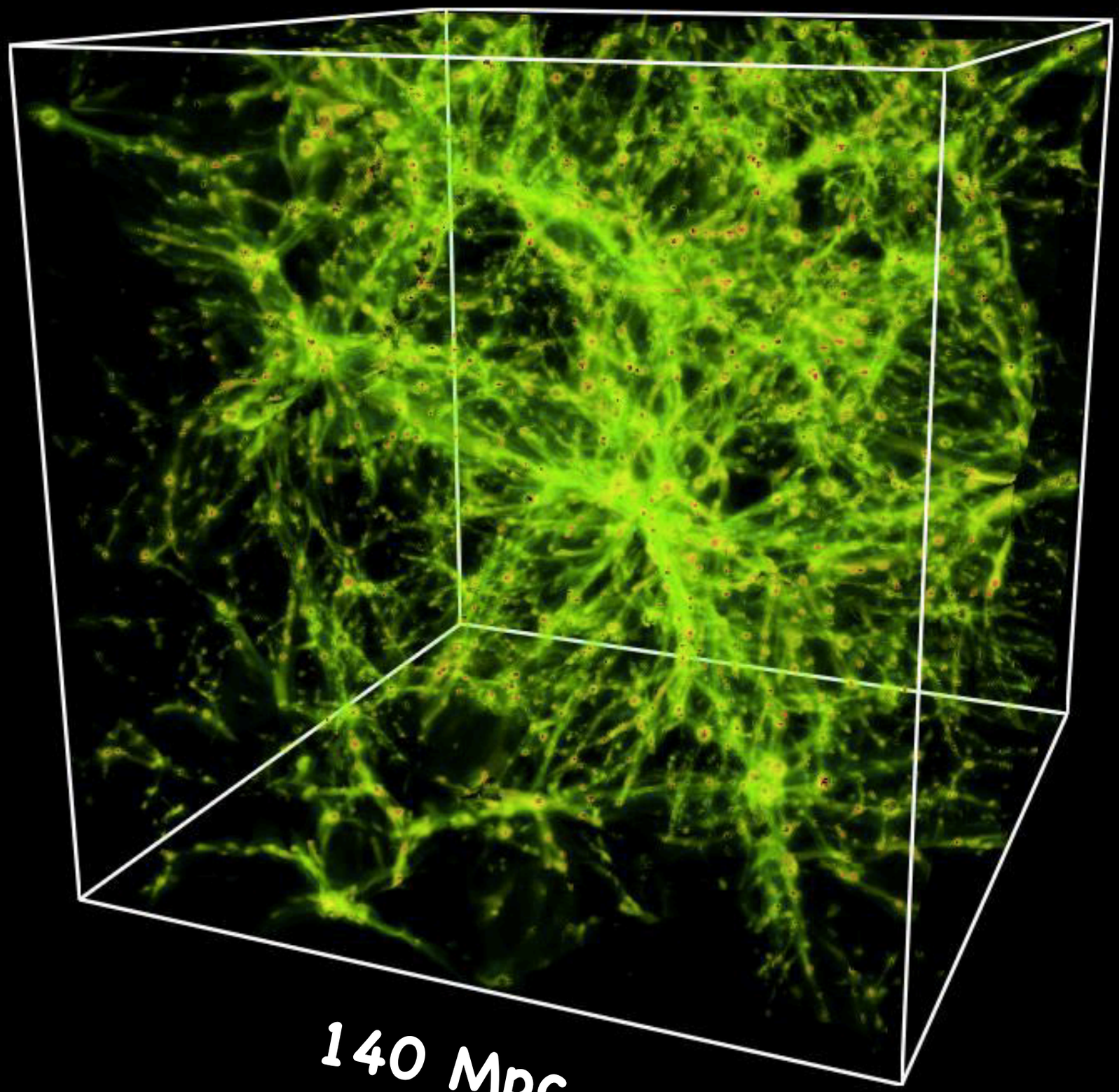




3) Where are the missing baryons i.e. the hot log T(K) = 5.6-6.6 WHIM)?

Simulations and the large scale structure formation theory say: the WHIM is located within the filaments of the Cosmic Web

Cen & Ostriker, 1999, ApJ, 514, 1



140 Mpc

- **CLOSE TO THE … BARYONS ARE …**

- Baryons accrete to … structure (Cosmic W…

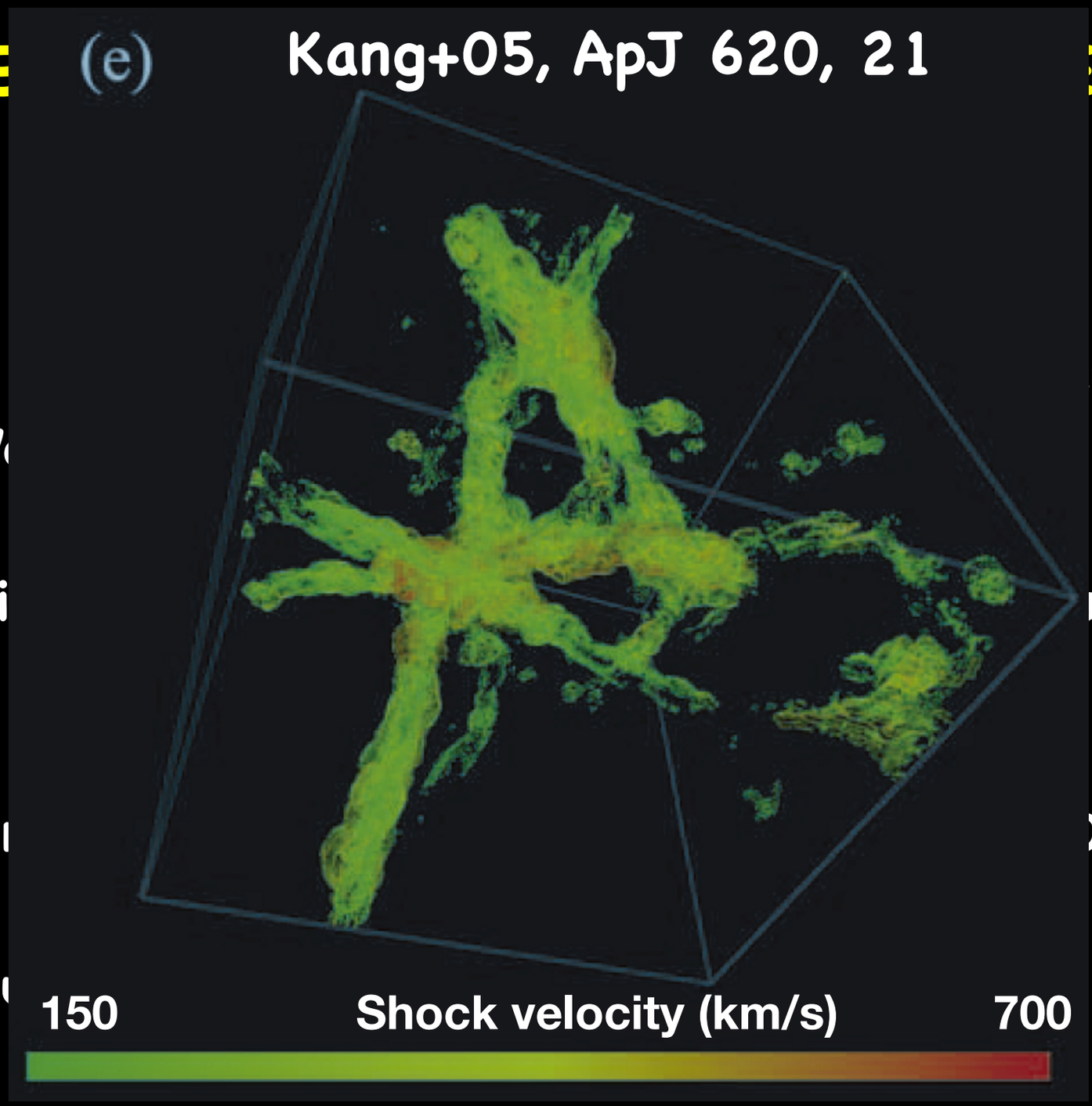
- Closer to the Cosmi… gravity higher

- Electrons accerete … km/s)

- Electrons become s…

- Energy is propagated via shocks

- Heating of baryons up to log T(K) = 7



4) An EAGLE view on the missing baryons

Preliminary stuff from Toni Tuominen's PhD work

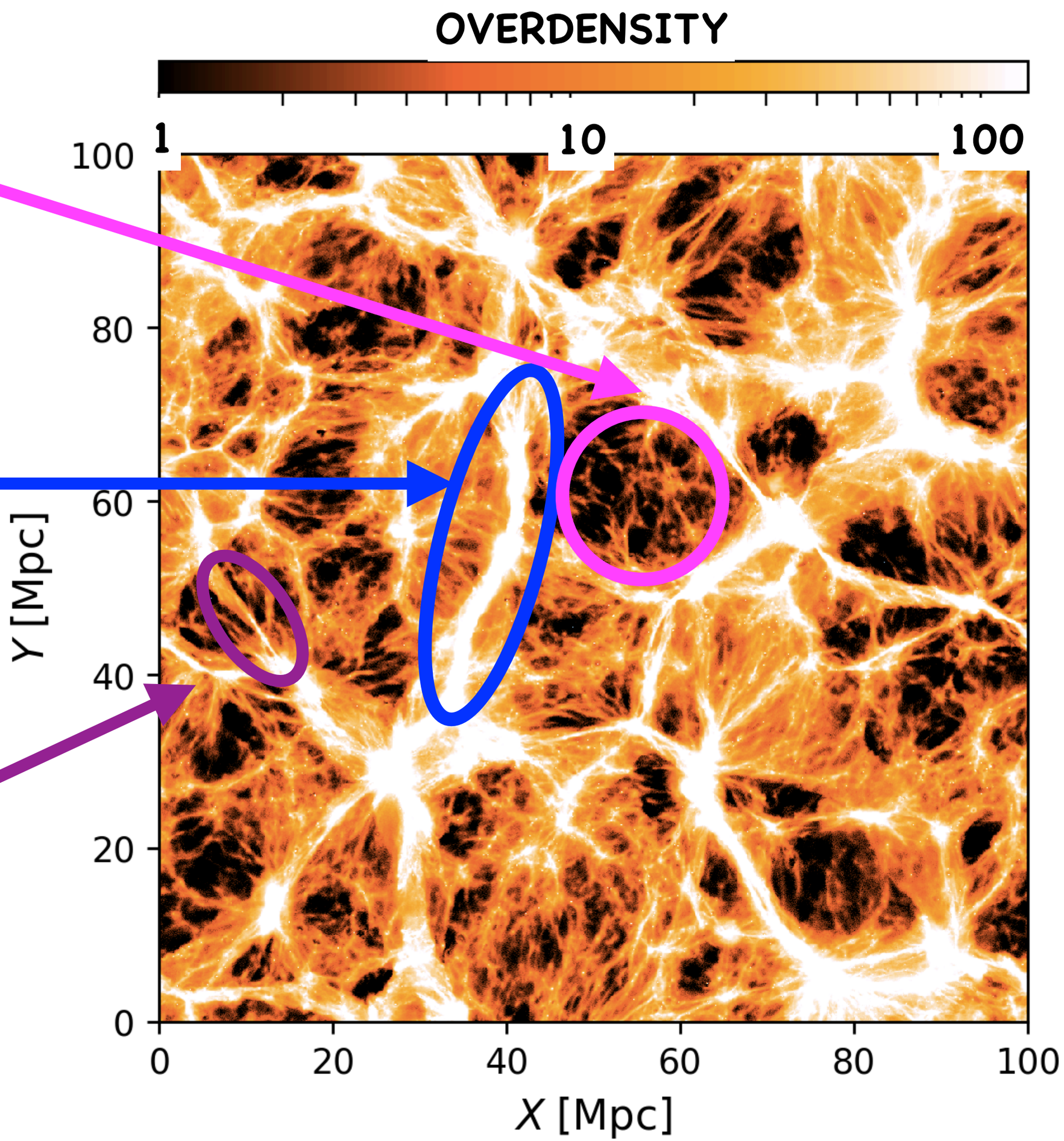
full T range

Voids

Major filaments
10s of Mpc

Minor filaments
1 Mpc

5 Mpc slice



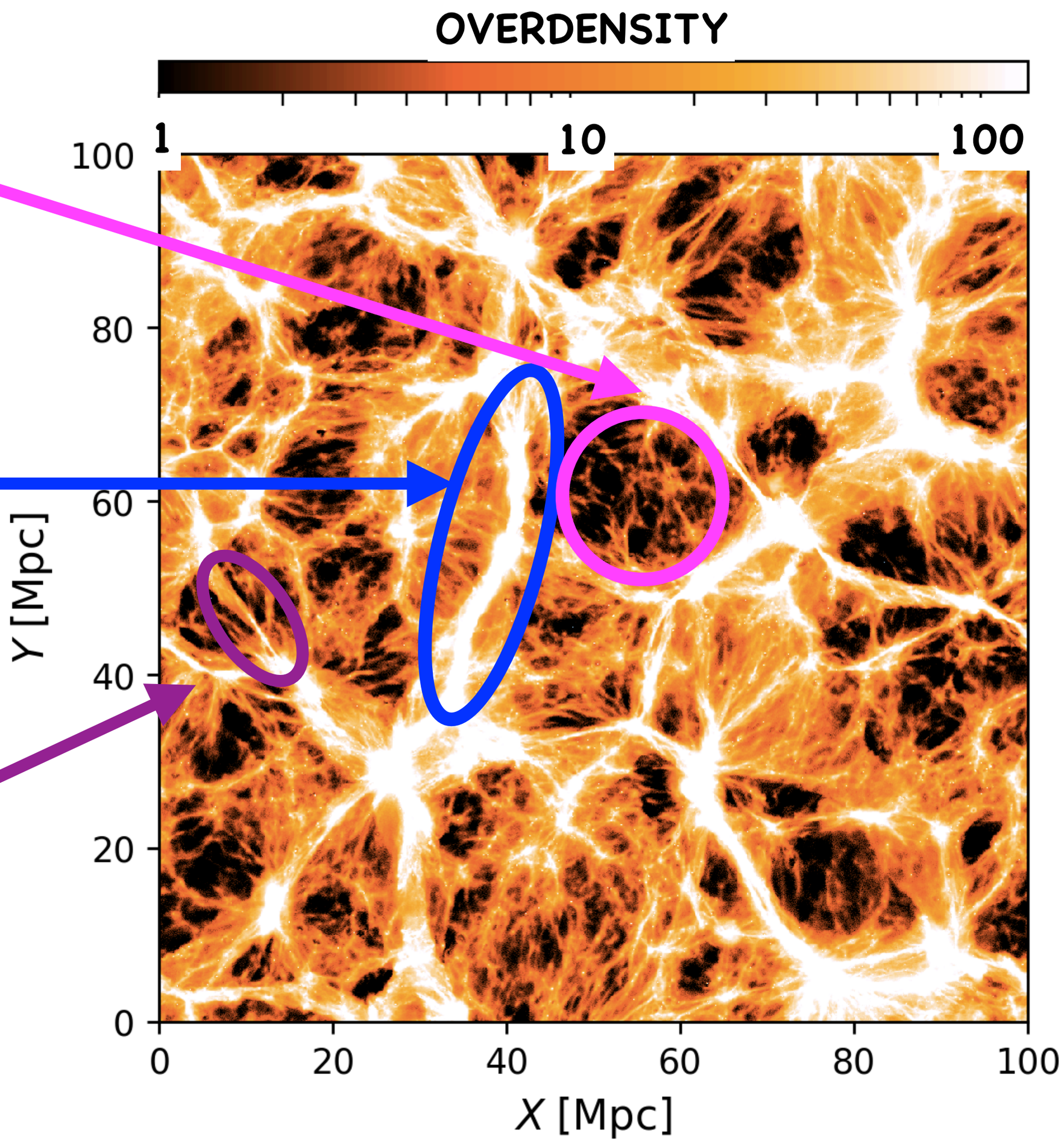
full T range

Voids

Major filaments
10s of Mpc

Minor filaments
1 Mpc

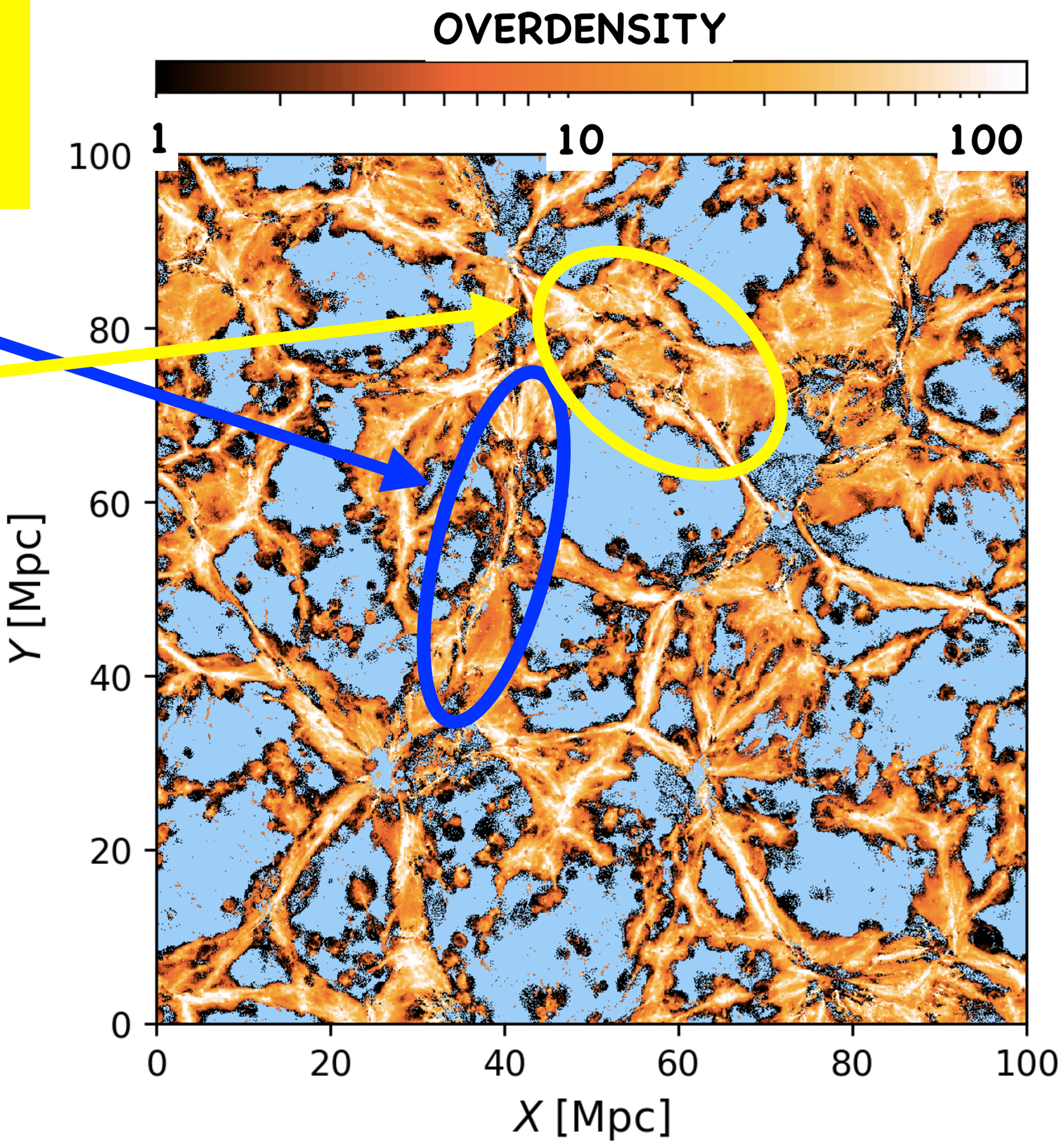
5 Mpc slice



log T = 4-5 cold stuff

Broad filaments and sheets

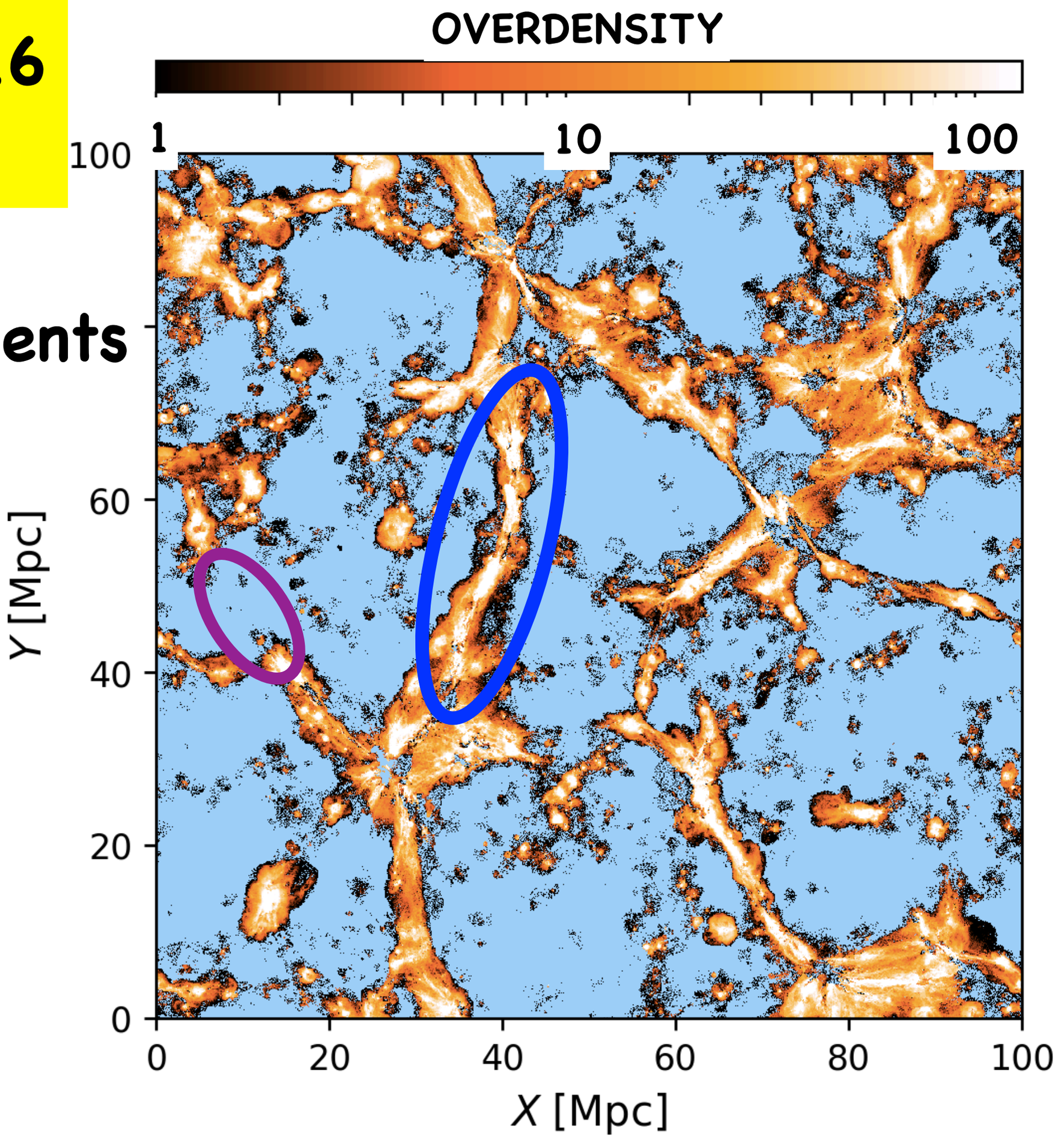
Observed via Ly alpha



log T = 5.0-5.6
warm WHIM

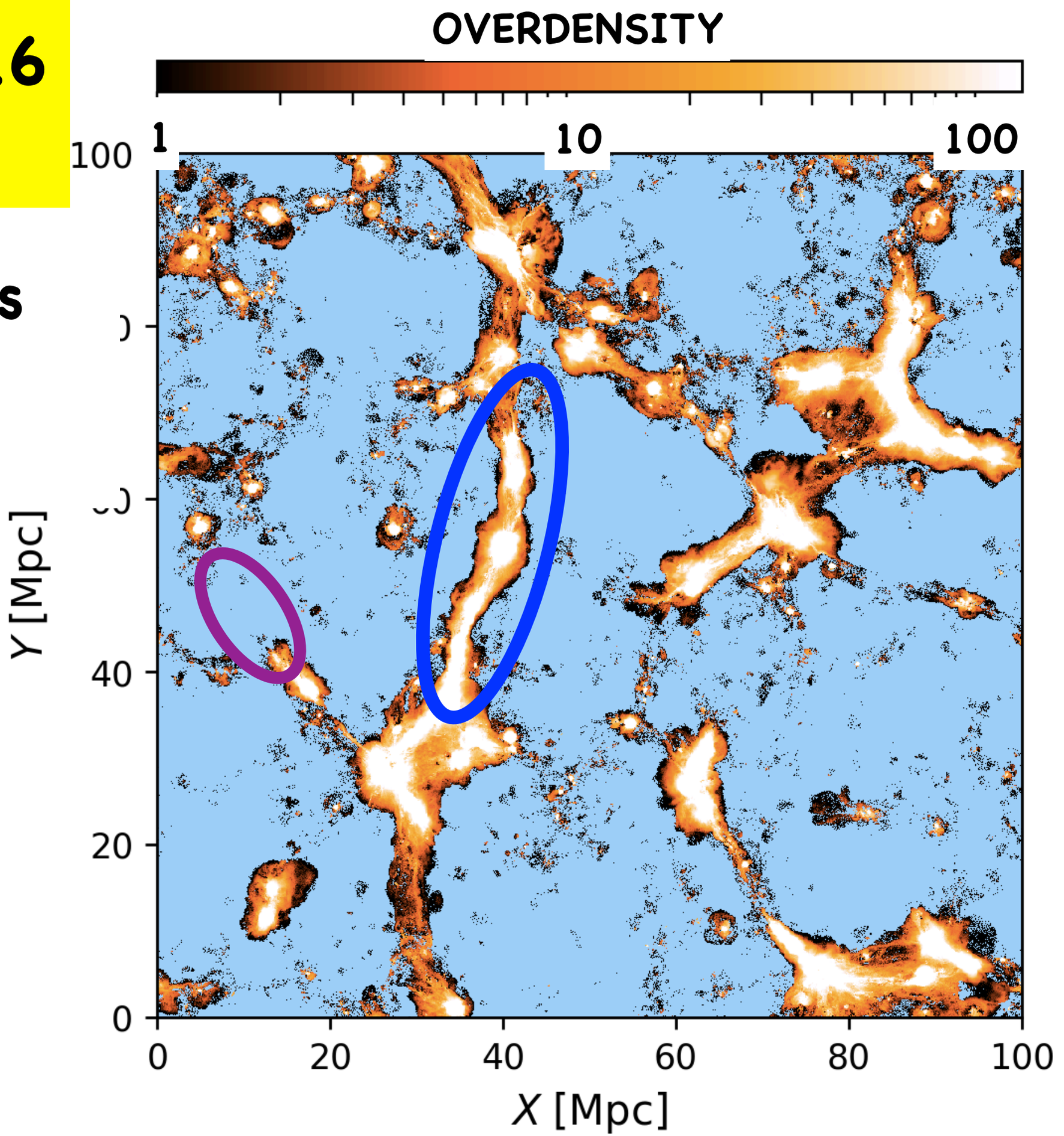
Narrower filaments

Observed via
BLA and OVI



log T = 5.6-6.6 hot WHIM

Most hot baryons condensed into major filaments



log T = 5.6–6.6
hot WHIM

1 Mpc

full T range

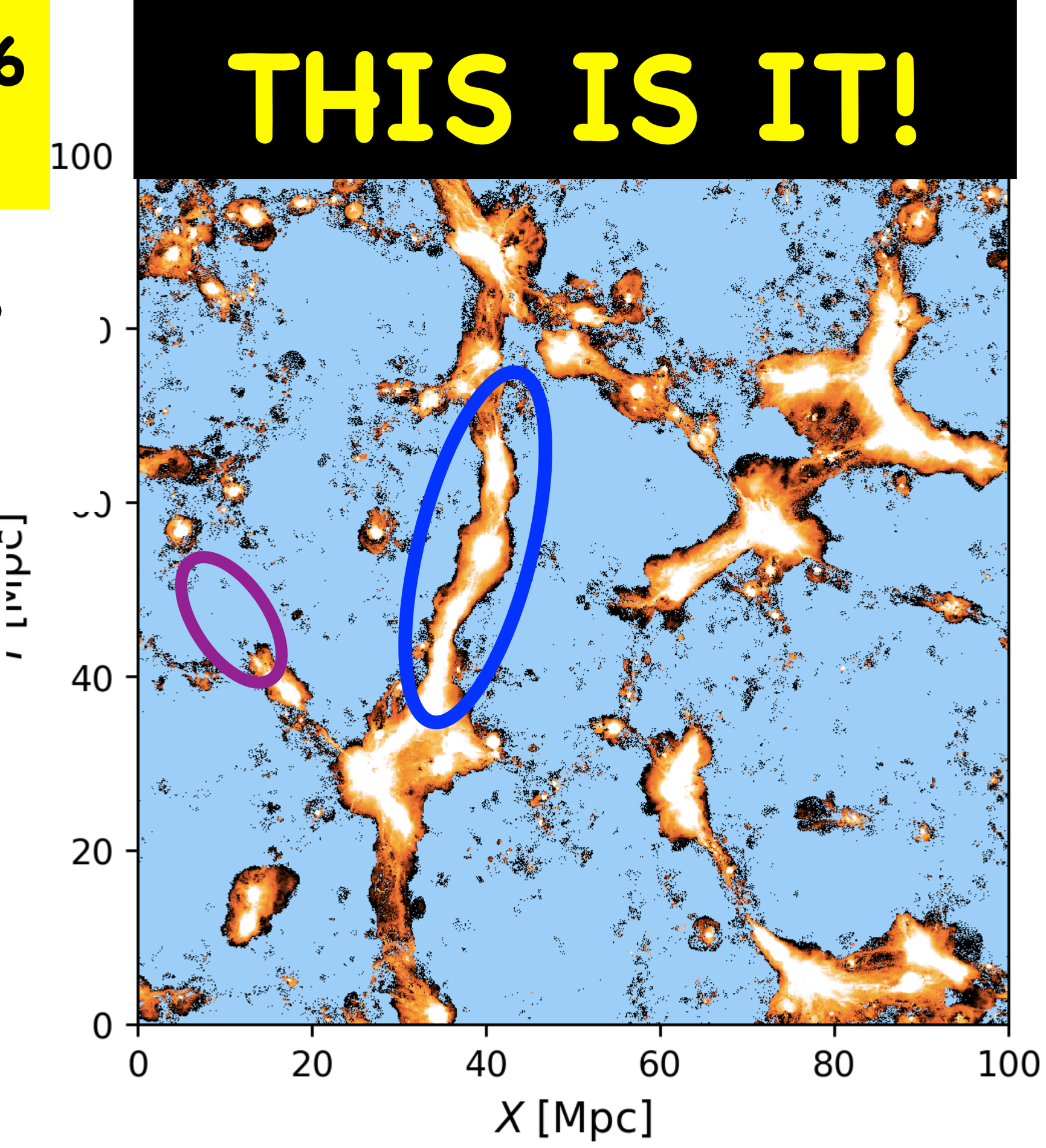
log T = 5.6-6.6 hot WHIM

THIS IS IT!

Most hot baryons condensed into major filaments

Most random lines do not catch it

Currently very poorly detected



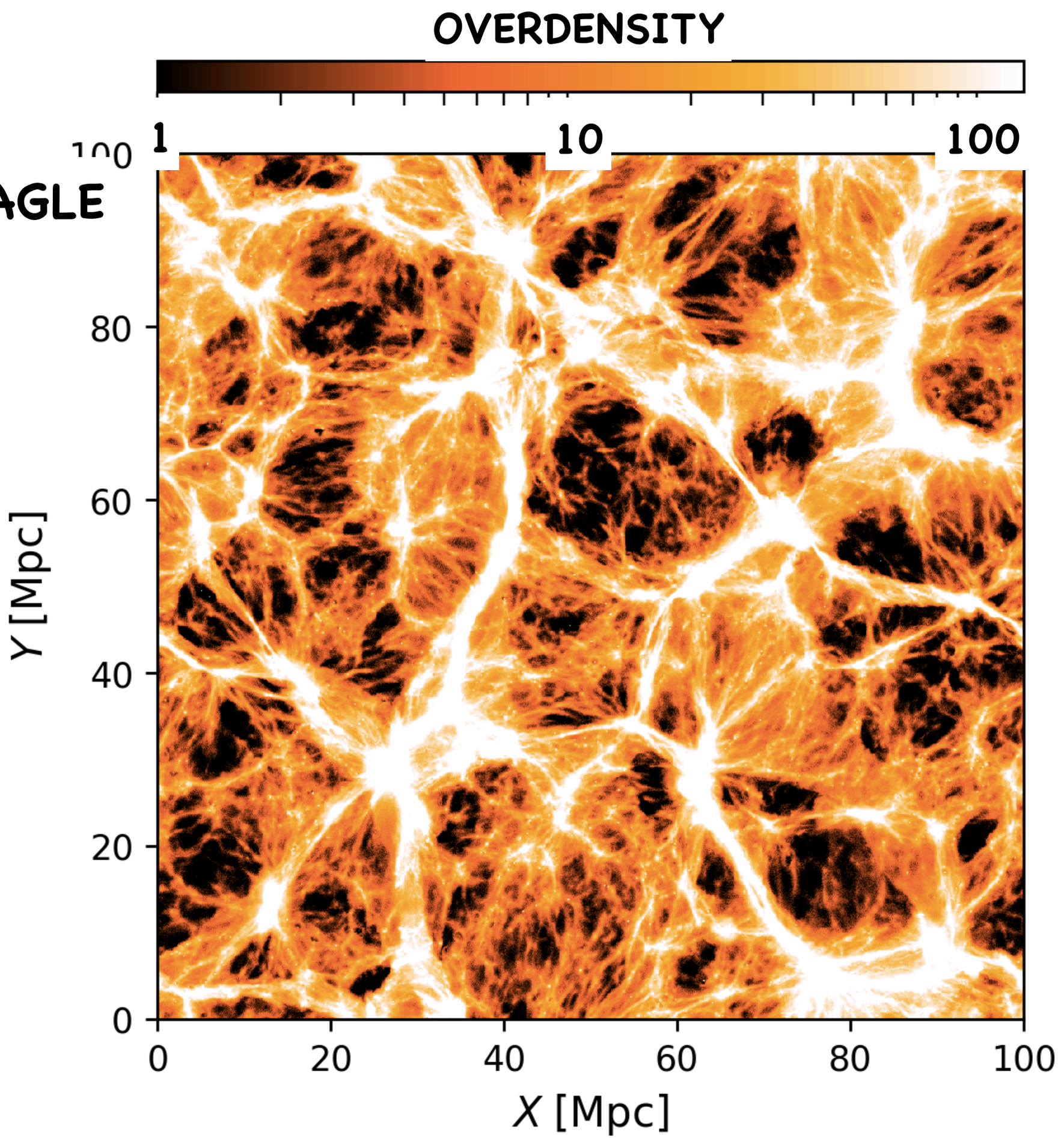
4) How do we find the (poorly observational) hot gas filaments?

Could we use the only very robust observable, the galaxies, to find the hot gas filaments?

full T range

- The baryons in EAGLE simulation

5 Mpc slice



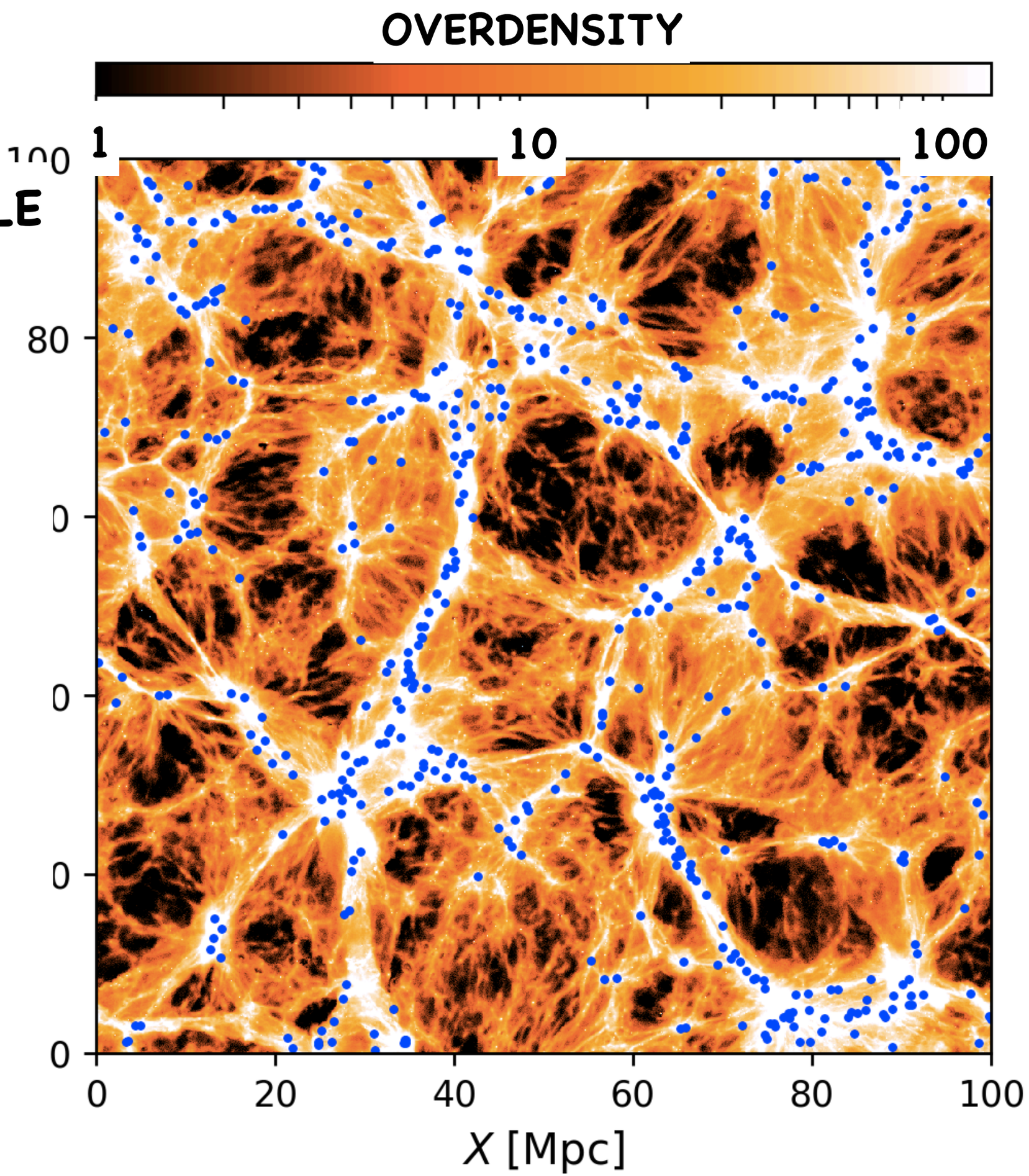
full T range

- The baryons in EAGLE simulation

- Adding the galaxies

- Galaxies follow the dark matter gravity, i.e. galaxies are preferably located along the filament axes (Cosmic Web)

5 Mpc slice



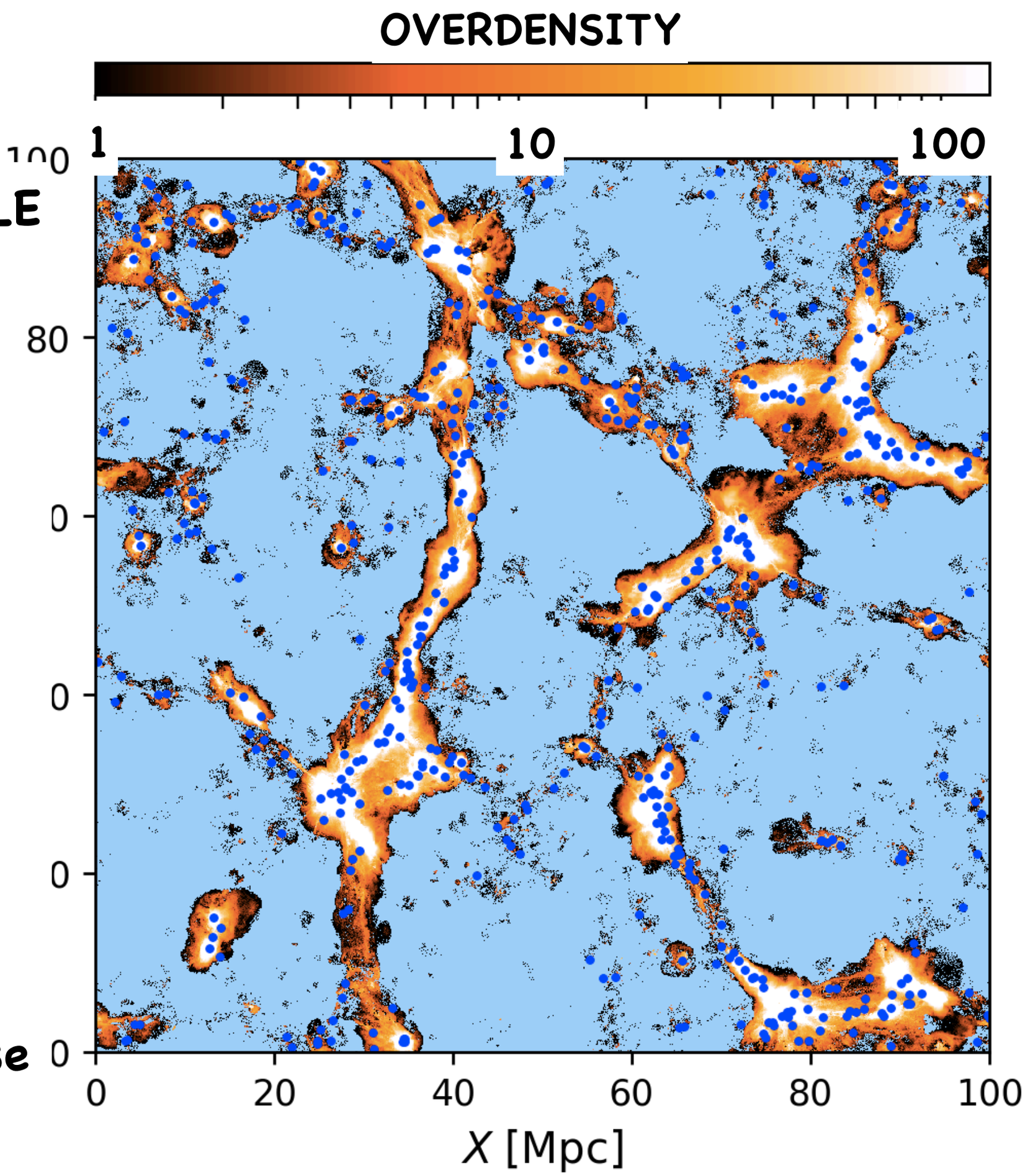
log T = 5.6-6.6

- The baryons in EAGLE simulation

- Adding the galaxies

  - Galaxies follow the dark matter gravity, i.e. galaxies are preferably located along the filament axes (Cosmic Web)

- The hot WHIM is also preferably located close to the filament axes



4) How do we find the (poorly observational) hot gas filaments?

Could we use the only very robust observable, the galaxies, to find the hot gas filaments?

YES!

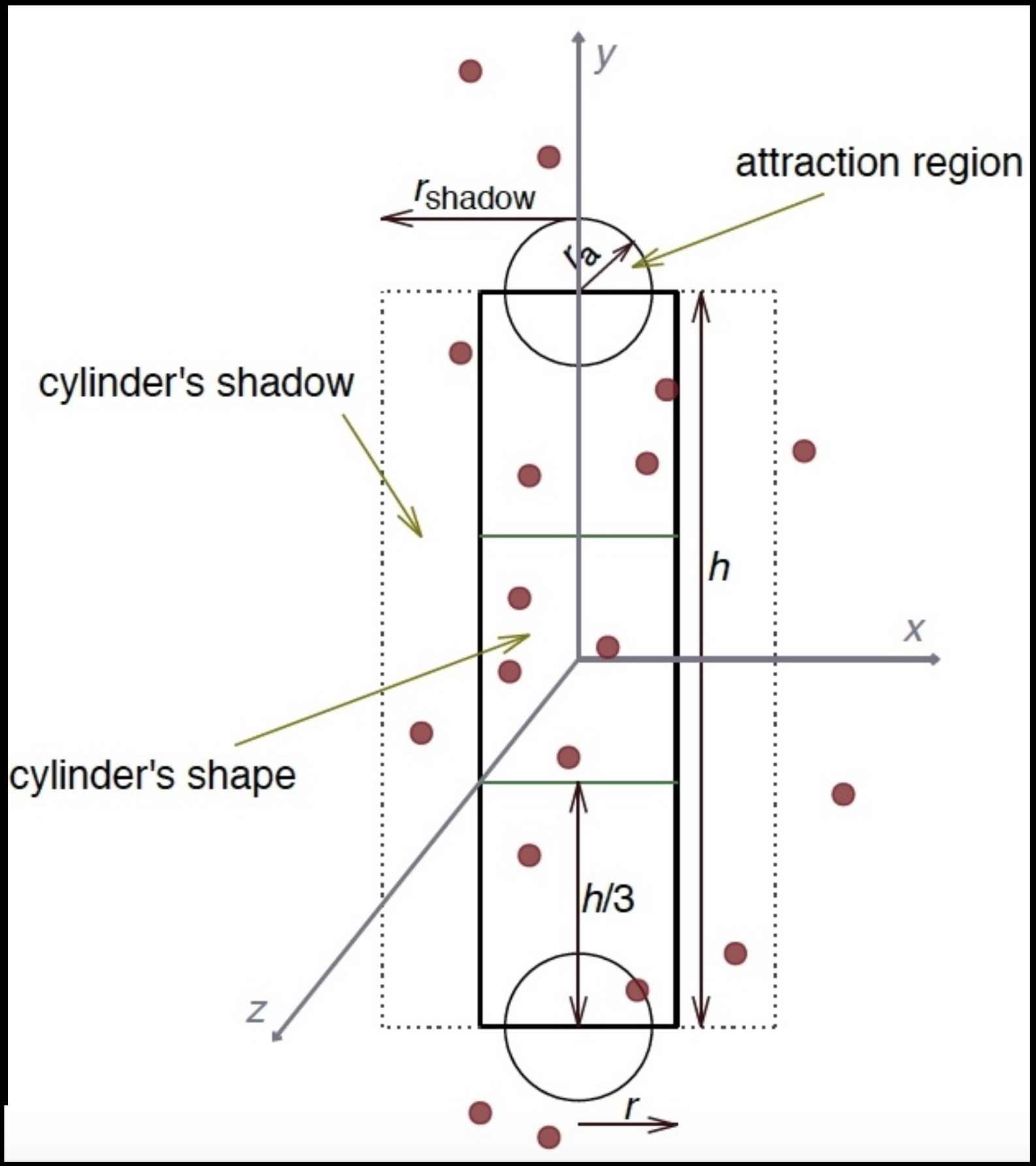
How exactly?

We apply object point process (Bisous process) to construct the filamentary galaxy network

The Bisous model developed with Tartu team over the last decade, refs...

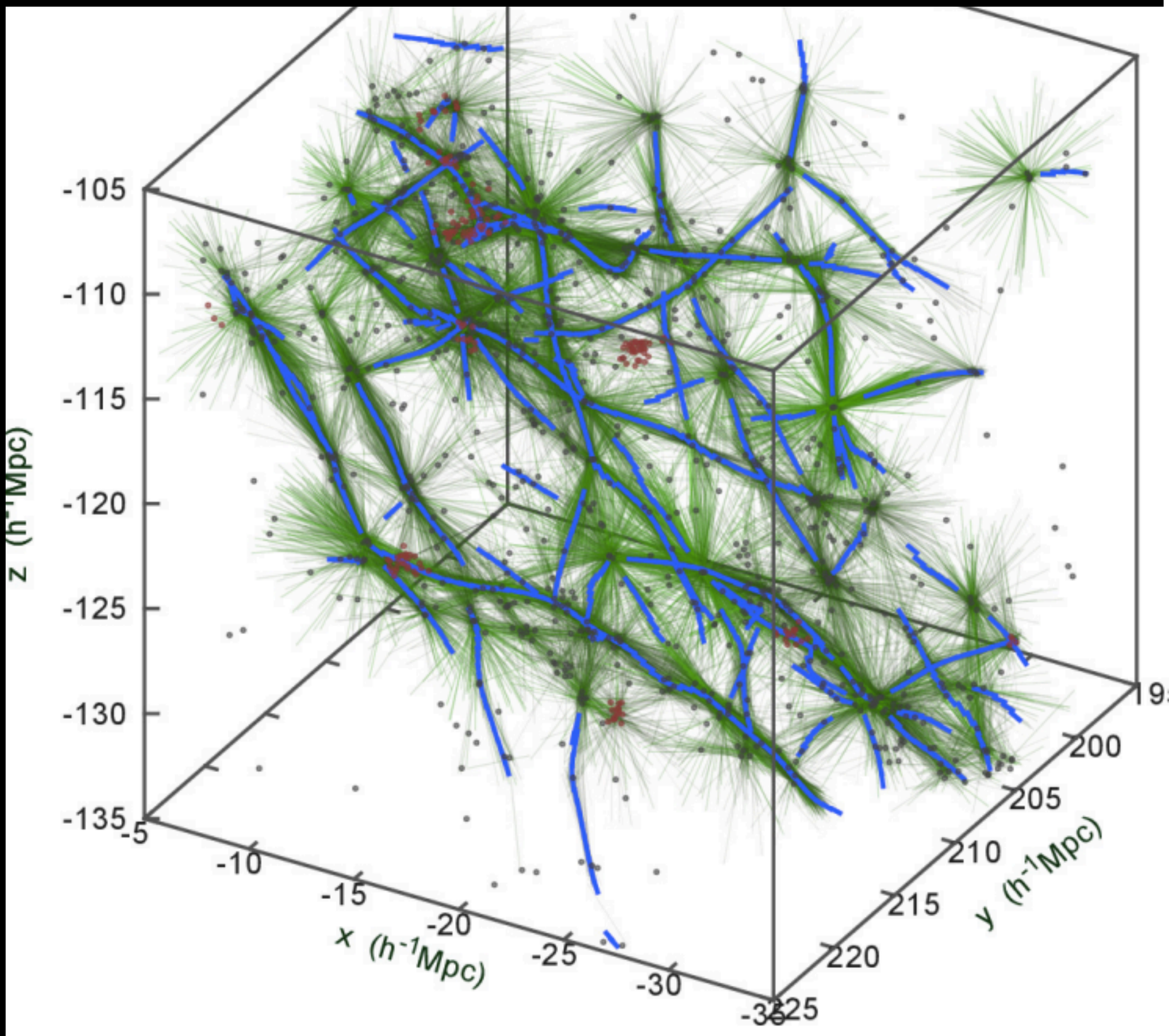
The procedure models the galaxy distribution geometry as connected cylinders

Tempel+16, A&C, 16, 17



Application of Bisous filament finder to SDSS

Tempel et al., MNRAS 2014, 438, 3465



Other applications

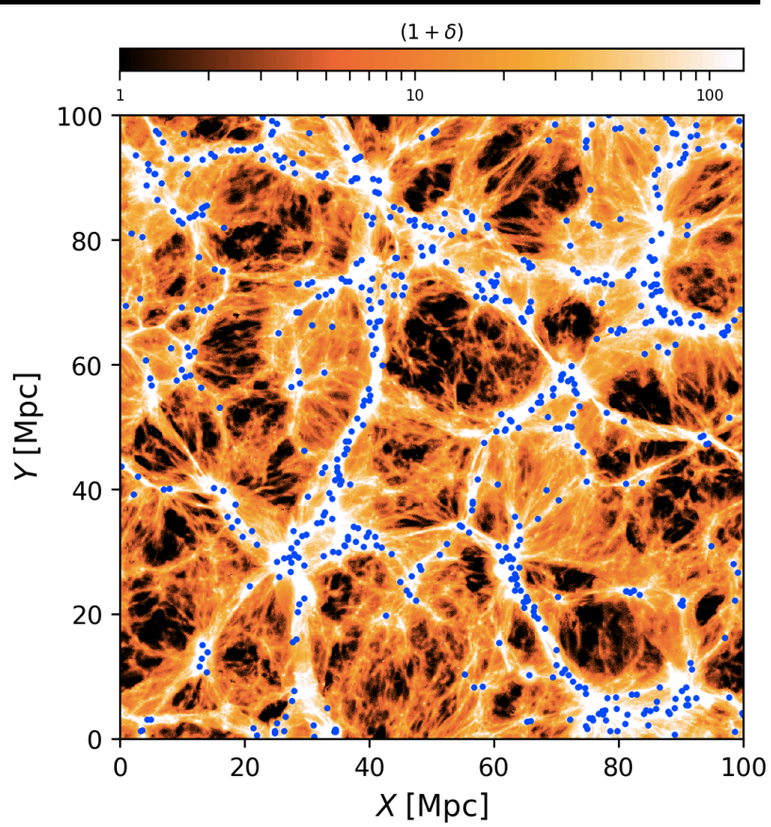
WHIM / missing baryons:

- J. Nevalainen et al., 2015, A&A, 583, 142, "Missing baryons traced by the luminosity density in large-scale WHIM filaments"
- Bonamente et al., 2016, MNRAS, 457, 4236, "A possible Chandra and Hubble Space Telescope detection of extragalactic WHIM towards PG 1116+215"
- Ahoranta, J. et al., 2019, A&A, in press, " Hot WHIM counterparts of FUV Ovi absorbers: The evidence in the line-of-sight towards quasar 3C 273"

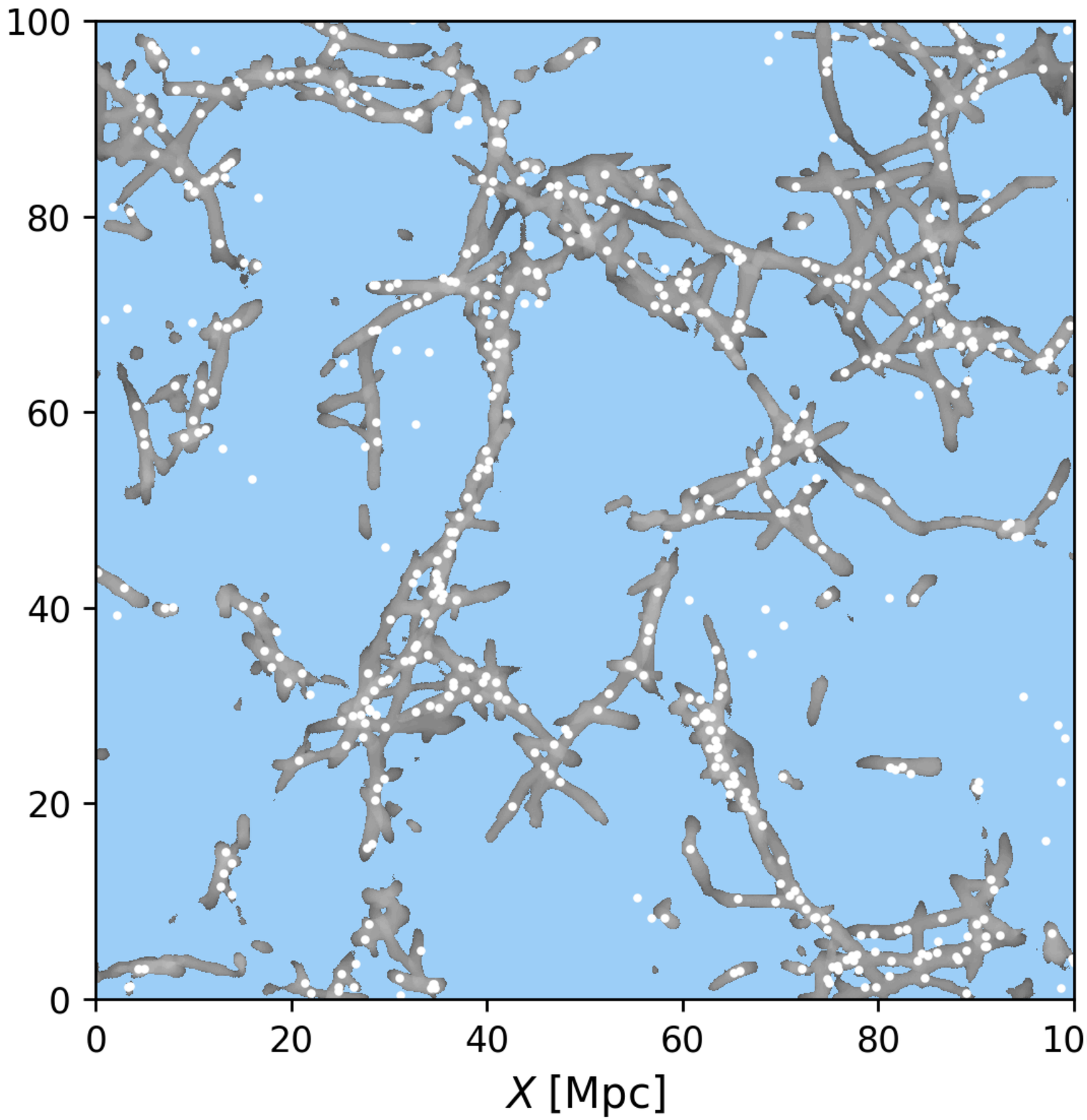
Galaxy properties around filaments / other stuff

- Ganeshaiah Veena et al., 2019, A&A, 725, 130: The Cosmic Ballet II: spin alignment of galaxies and haloes with large-scale filaments in the EAGLE simulation
- Kruuse, M. et al., 2019, A&A, 625, 130, "Photometric redshift galaxies as tracers of thr filamentary network"
- Wang, P., et al., 2018, ApJ, 859, 115, "Alignment between satellite and central galaxies in the SDSS DR7: Dependence on larg scale environment"
- Libesking, N., et al., 2018, MNRAS, 473, 1195, "Tracing the Cosmic Web"
- Kuutma, T., et al., 2017, A&A, 600, 6, "From voids to filamens: environmental transformations of galaxies in the SDSS"
- Poudel, A., 2017, A&A, 597, 86, "The effect of cosmic web filaments on the properties of groups and their central galaxies"

Application of Bisous filament finder to EAGLE



The Bisous method defines filament volume (gray) using the galaxies (spots)

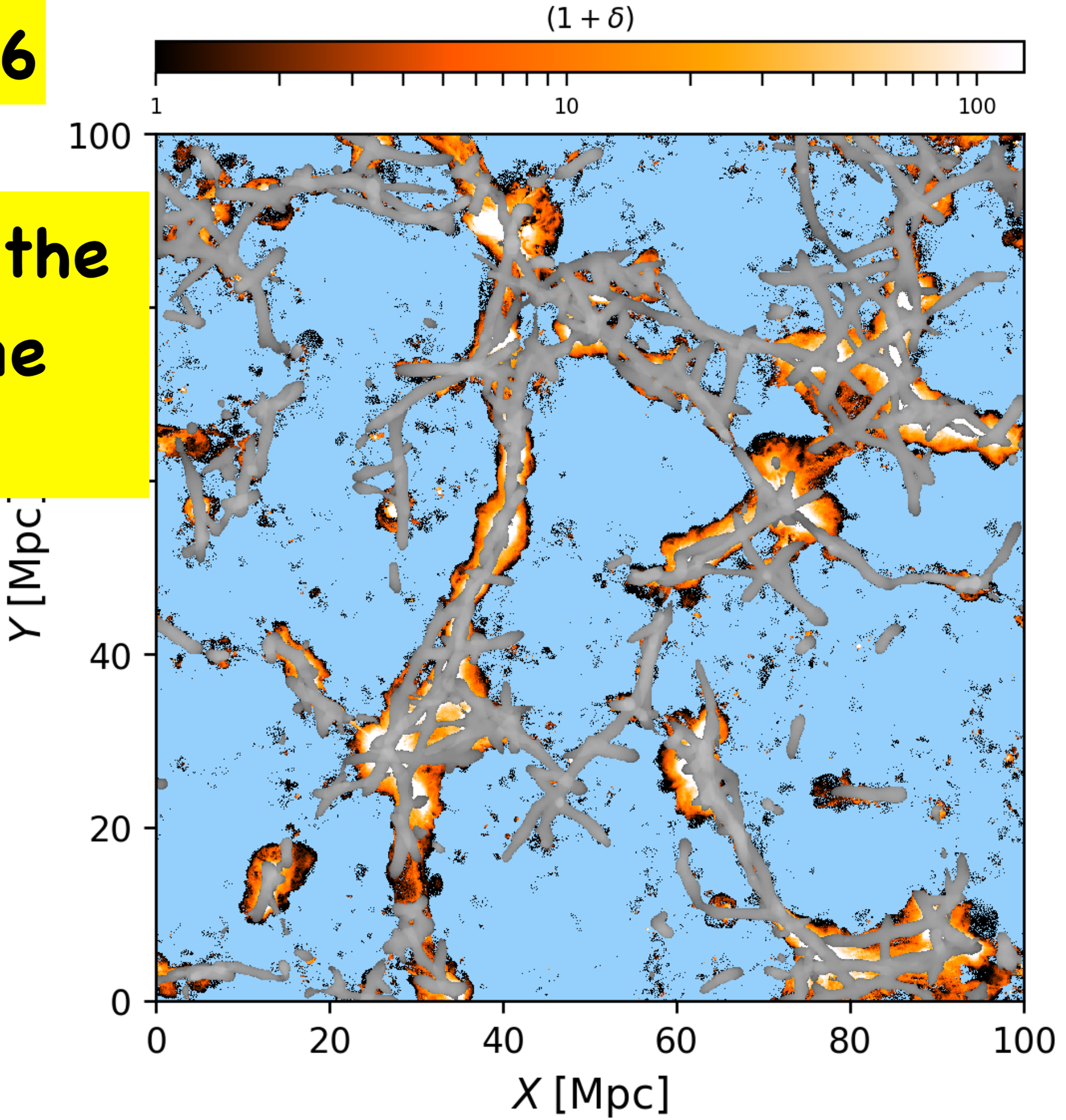


How well do we capture the missing baryons with our filament finder?

Or, what fraction of the missing baryon population is located within the filament volumes?

log T = 5.6-6.6

Filtering with the filament volume map



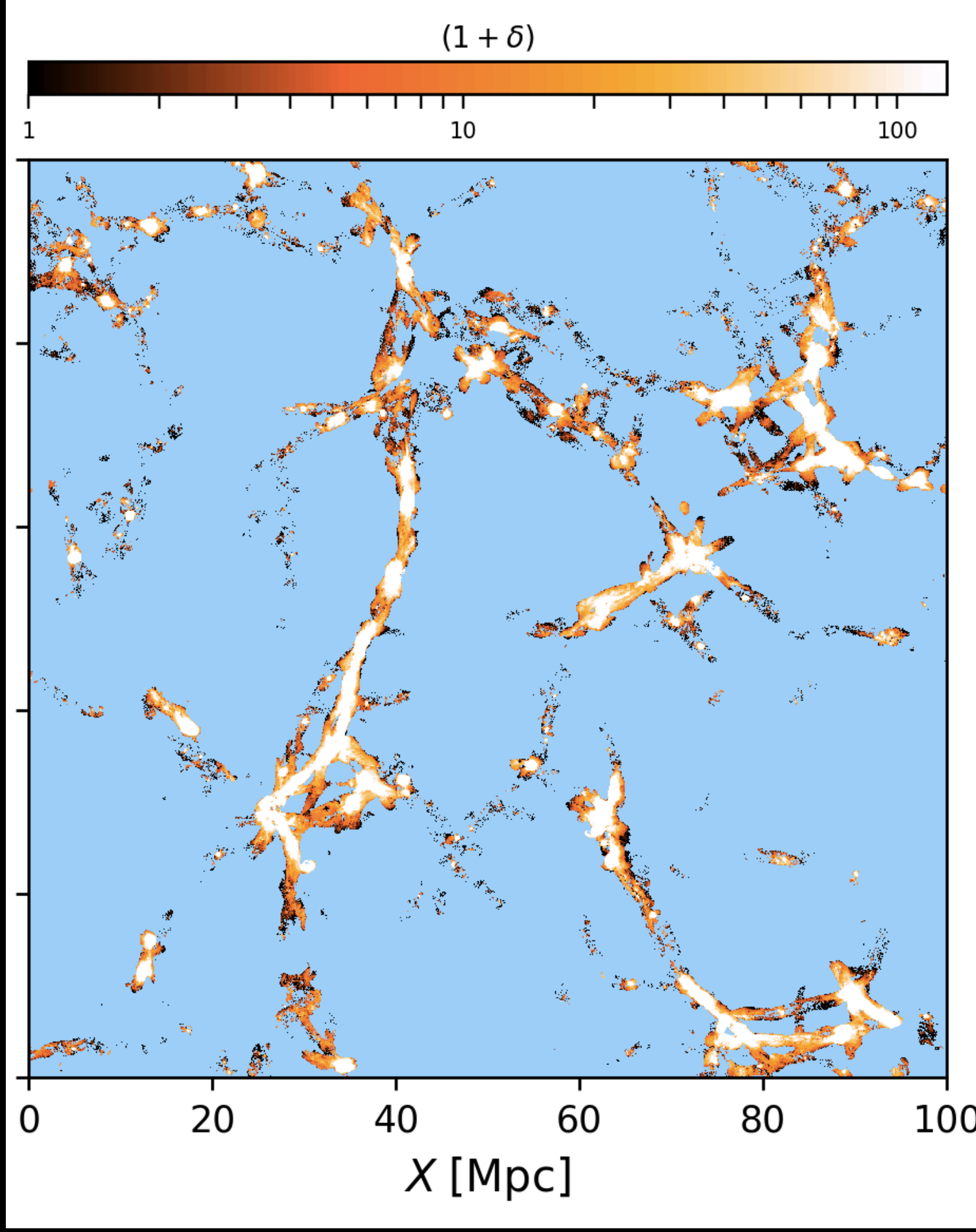
The filament volume contains

70%

of the "missing" baryons in EAGLE

It is a comfortably high number for our method to be promising

We can fine-tune the procedure to catch a higher fraction, TBD



Let's use our missing baryon finder to make finding maps for Arcus and ATHENA for detecting the high metal ions (OVII...)