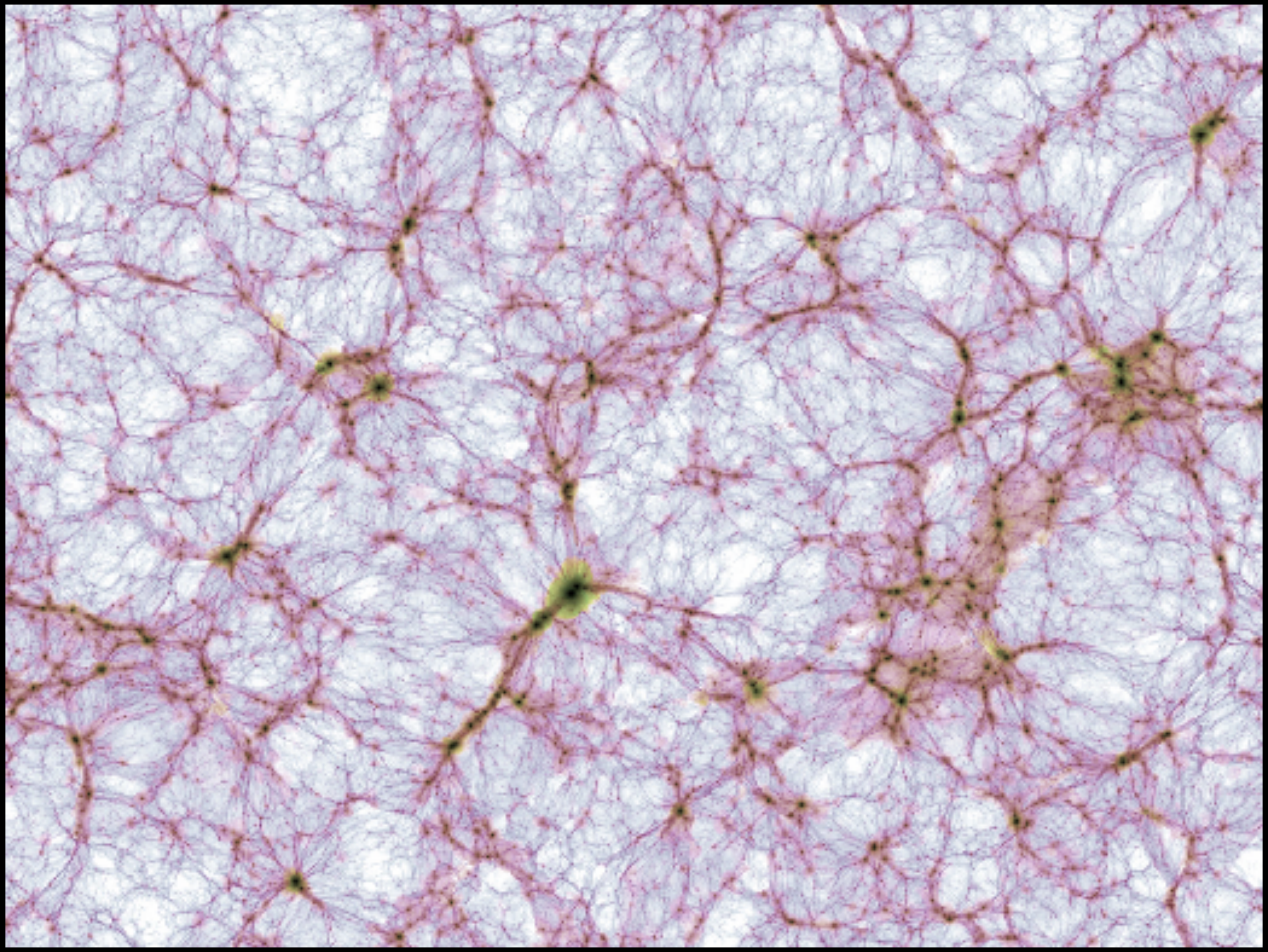

Image Credit: IllustrisTNG Collaboration

Tracing the baryonic cosmic web: predictions from cosmological simulations

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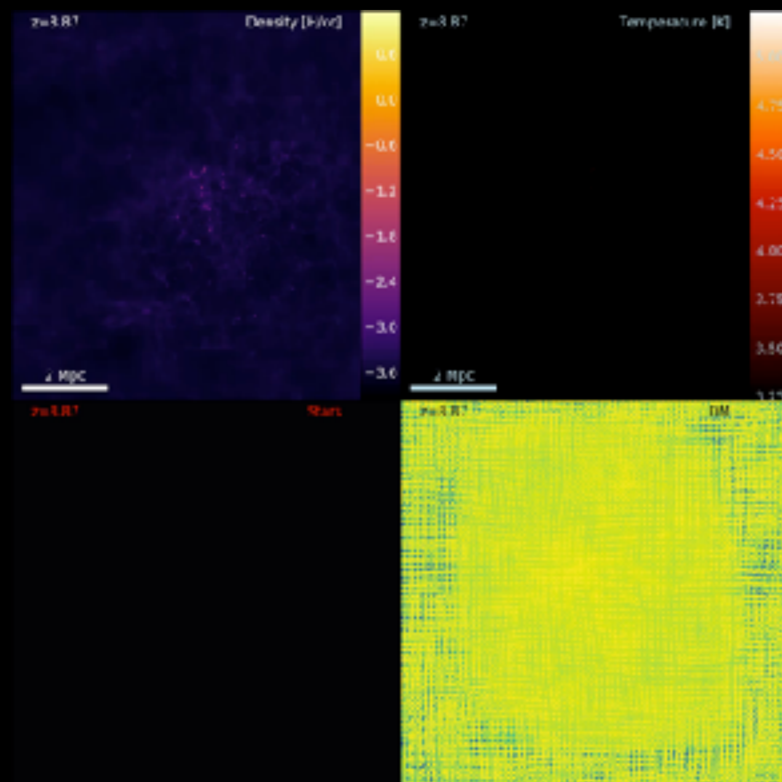
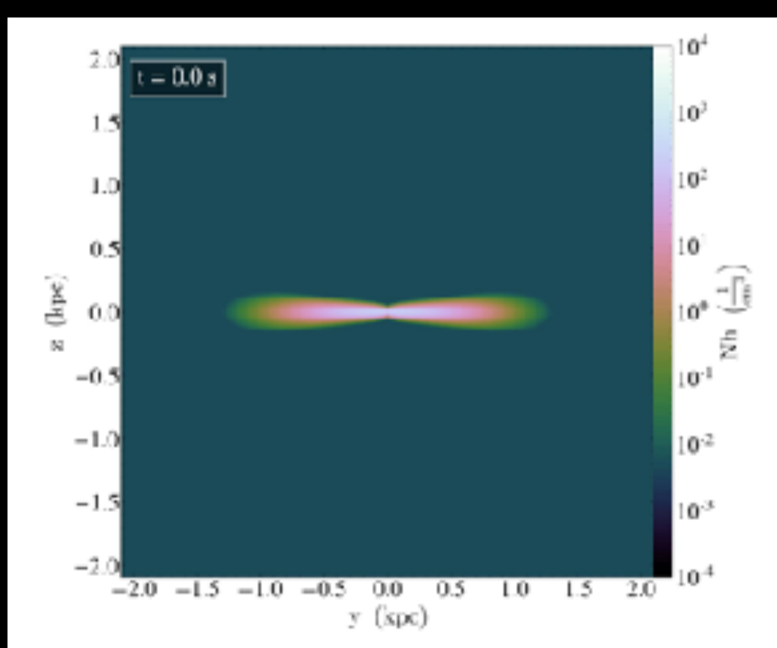
Mark Vogelsberger
Maria Celeste Artale
Markus Haider
Paul Torrey
Federico Marinacci
& the rest of the IllustrisTNG Collaboration

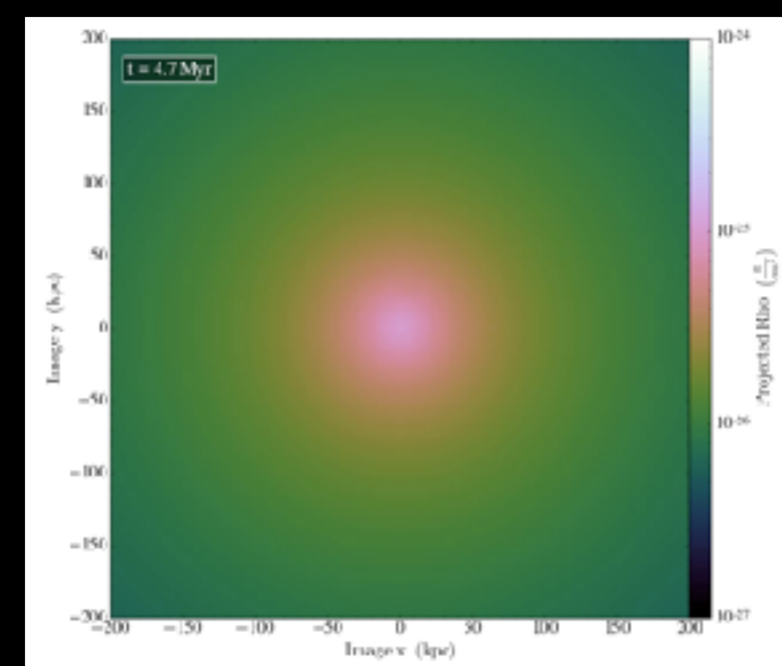
My old love: baryon astrophysics



Cosmological simulations of galaxy clusters with AGN feedback (Martizzi+ 2012a-b, 2013, 2014a-b, 2016)



Simulations of Stellar Feedback (Martizzi+ 2015, 2016, 2019 in prep.)



Simulations of AGN Feedback (Martizzi+ 2013, 2019)

My new love:
the Baryonic Cosmic Web

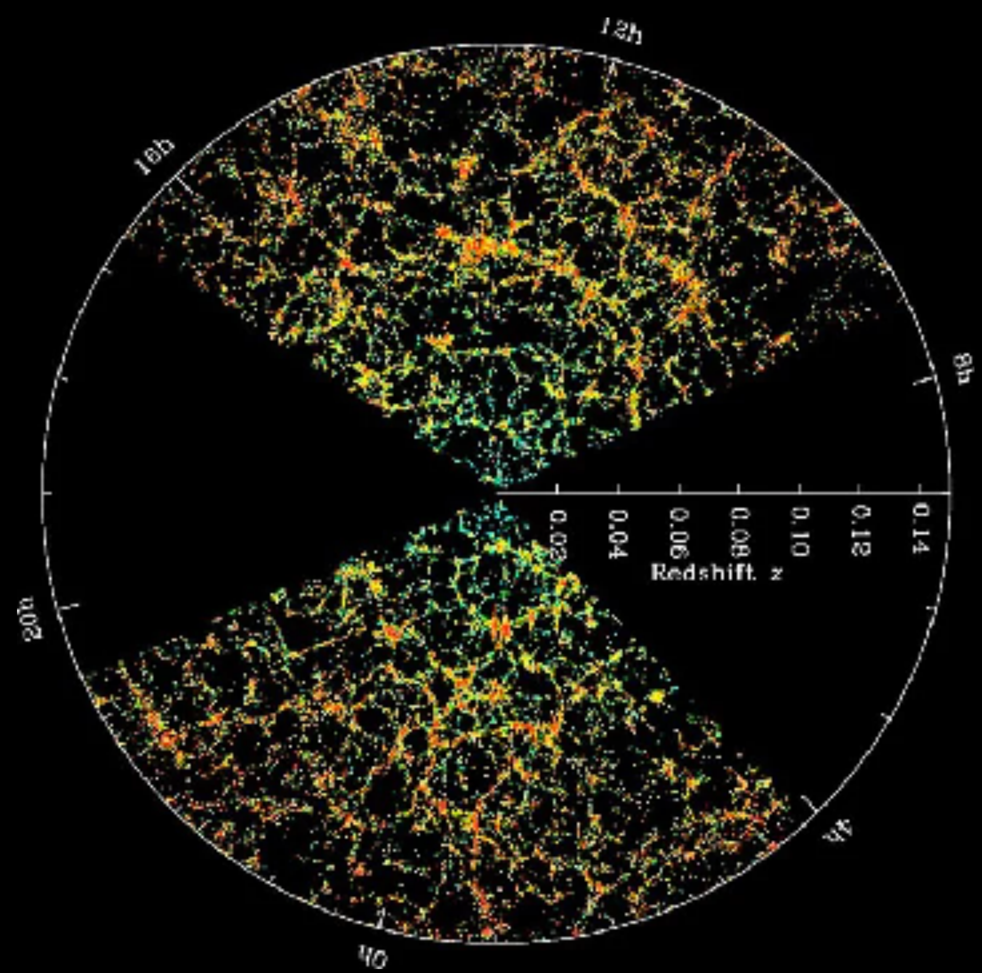


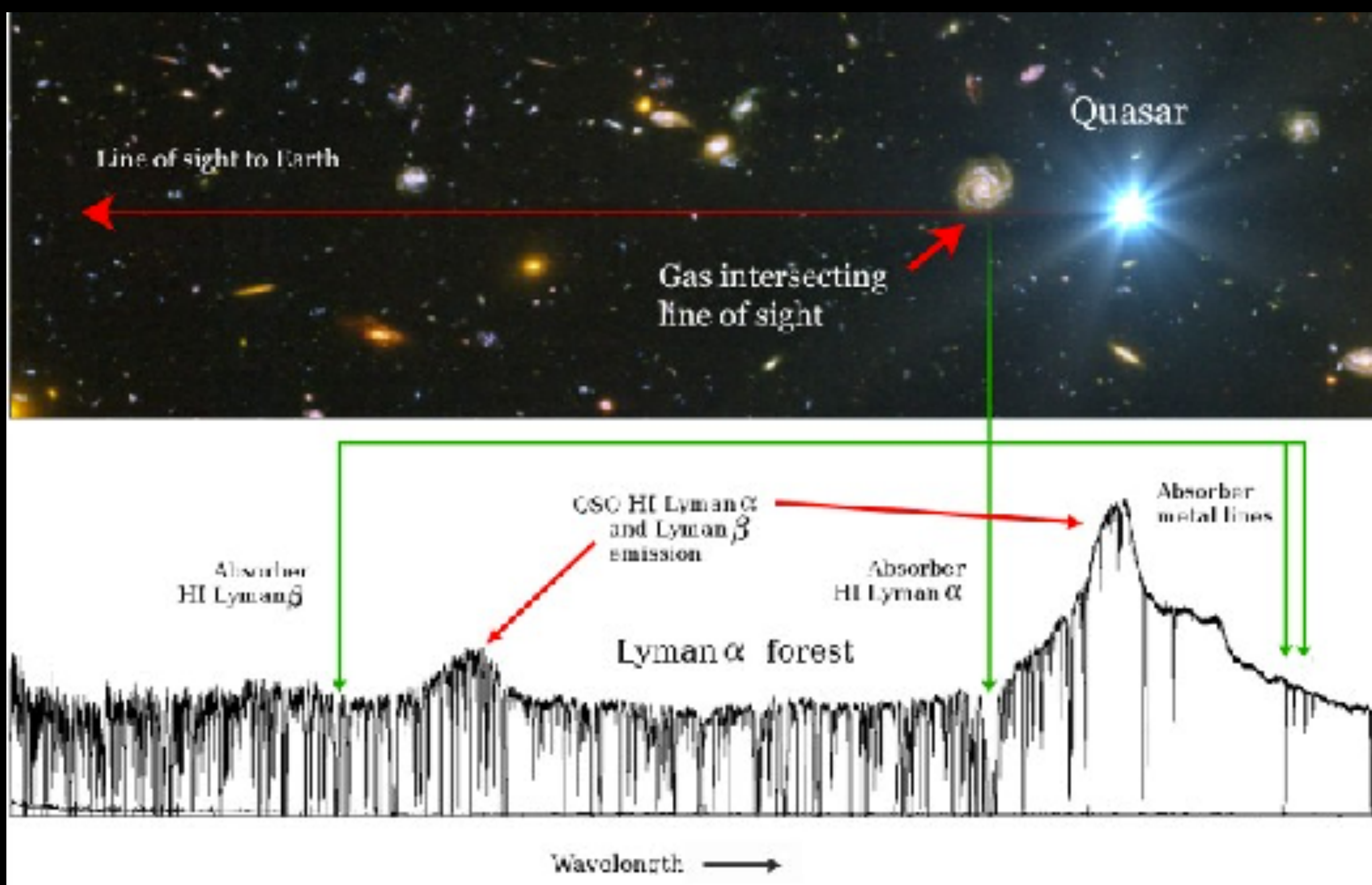
Image Credit: SDSS

Baryonic cosmic structure growth is a multi-physics process.

Multiple galaxy populations and gas phases influenced by:
- Hydrodynamics, e.g. expansion, shocks.
- Radiative processes, e.g. heating, cooling, ionization.
- Gravity and dynamics.
- Location in the Cosmic Web via environment-dependence of the processes above?

Phase 1
The Gaseous Cosmic Web

Studying the Gaseous Cosmic Beacons



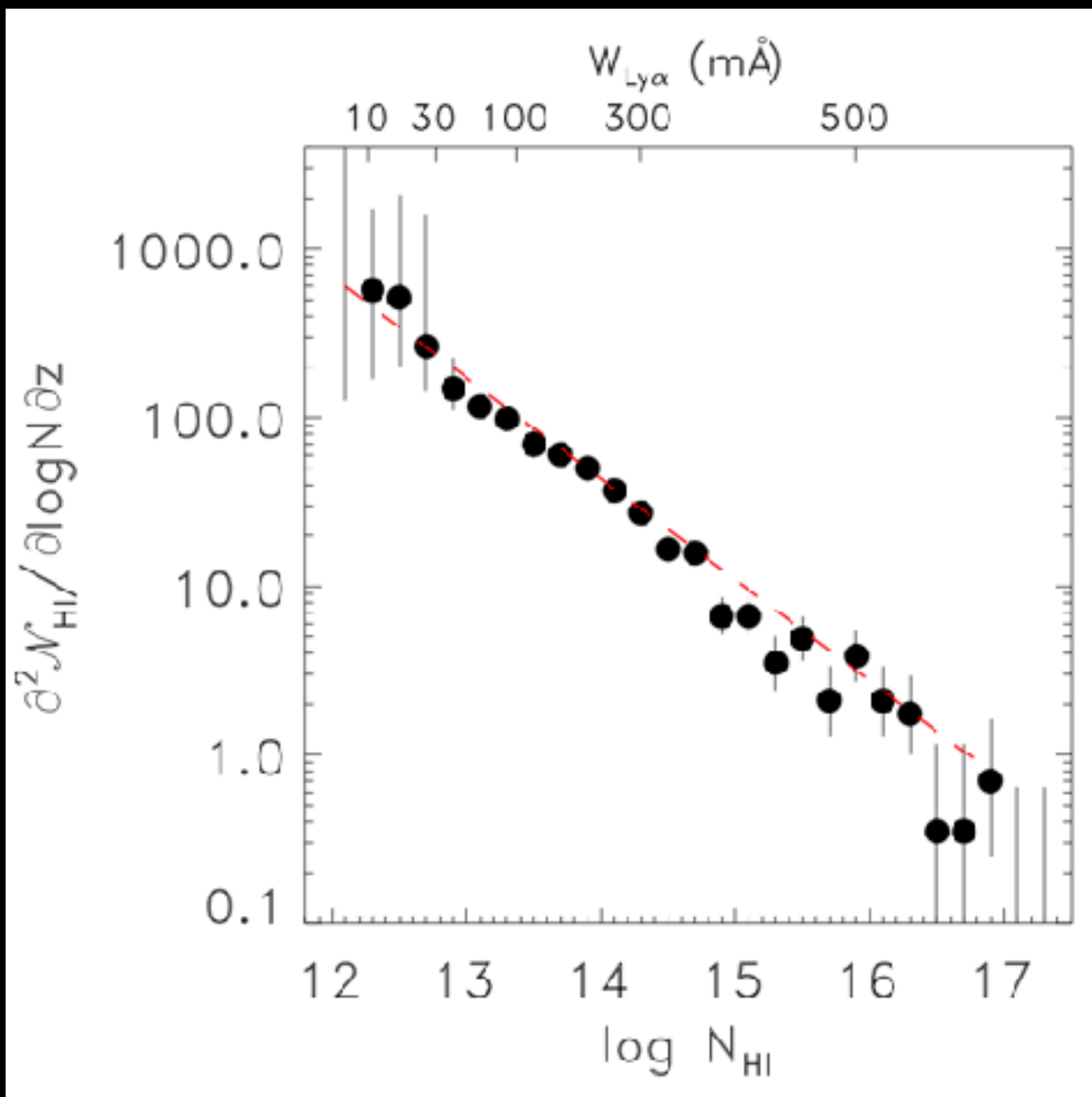
Example: using quasar spectra to detect intervening HI absorbers.

Here comes the "simpleton theorist". For the purpose of this talk:

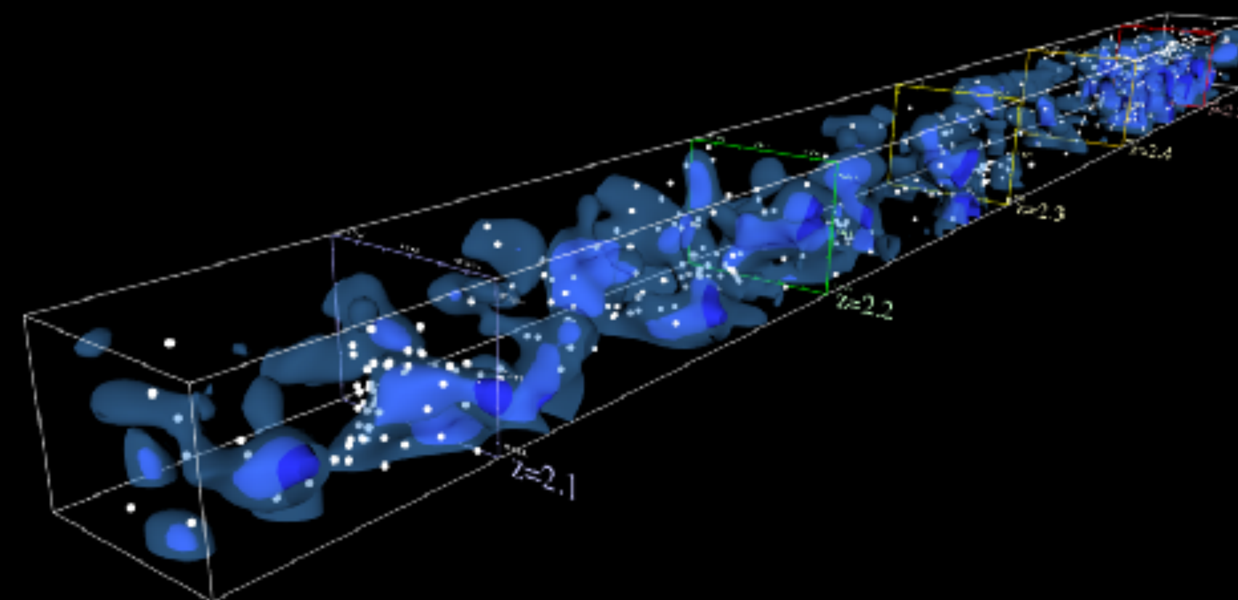
- A Cosmic Beacon is a very luminous, distant object.
- Transient nature is not necessarily required.
- We need to be able to detect them efficiently in a wavelength range of our choice.
- We'd better be able to take their spectra.

I'm not picky. Candidates: Quasars, GRBs, SNe, TDEs…

Example 1:
Ly-α Forest and Tomography

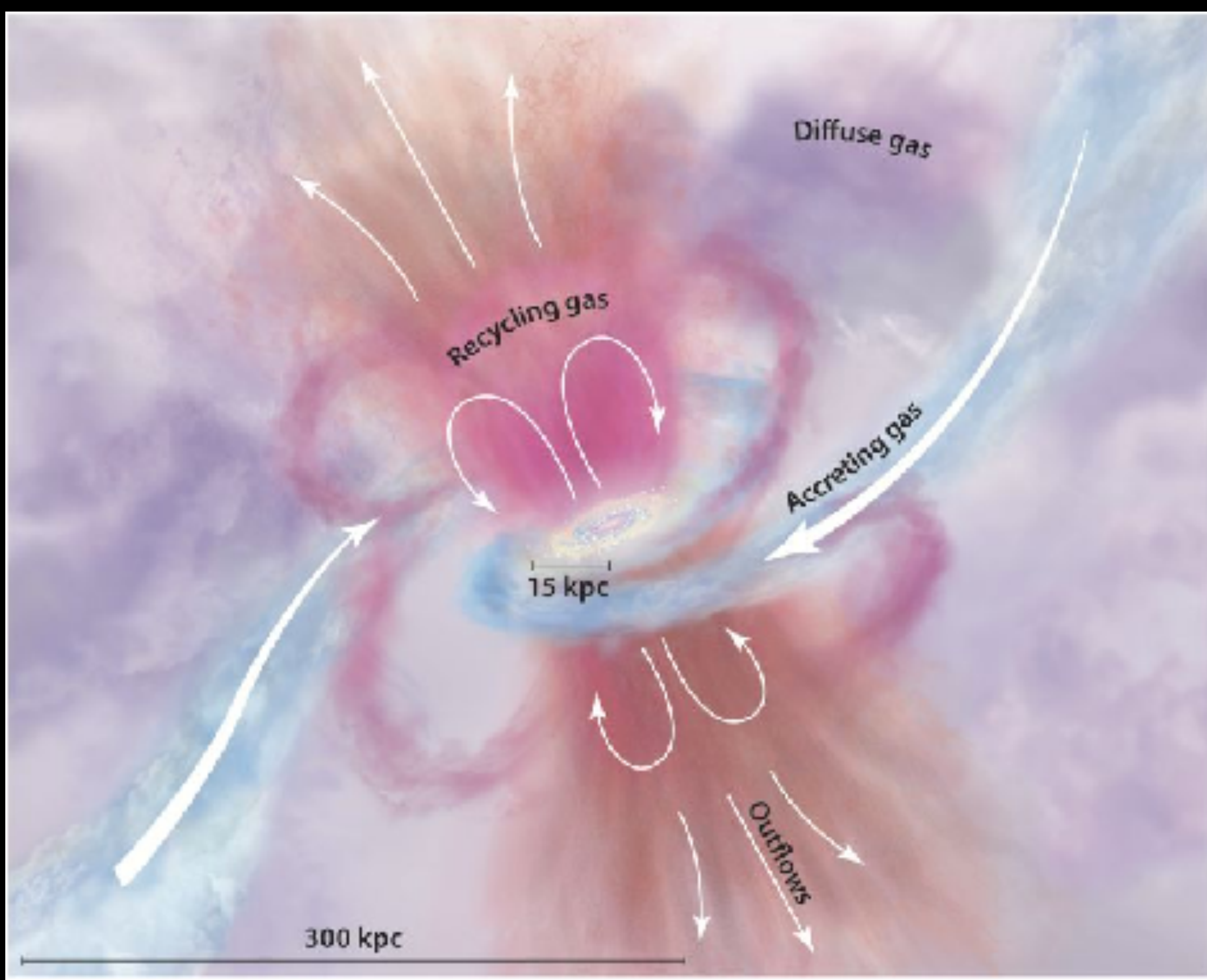


~2250 HI absorbers in HST/COS spectra at z<0.75 (Danforth+ 2016)

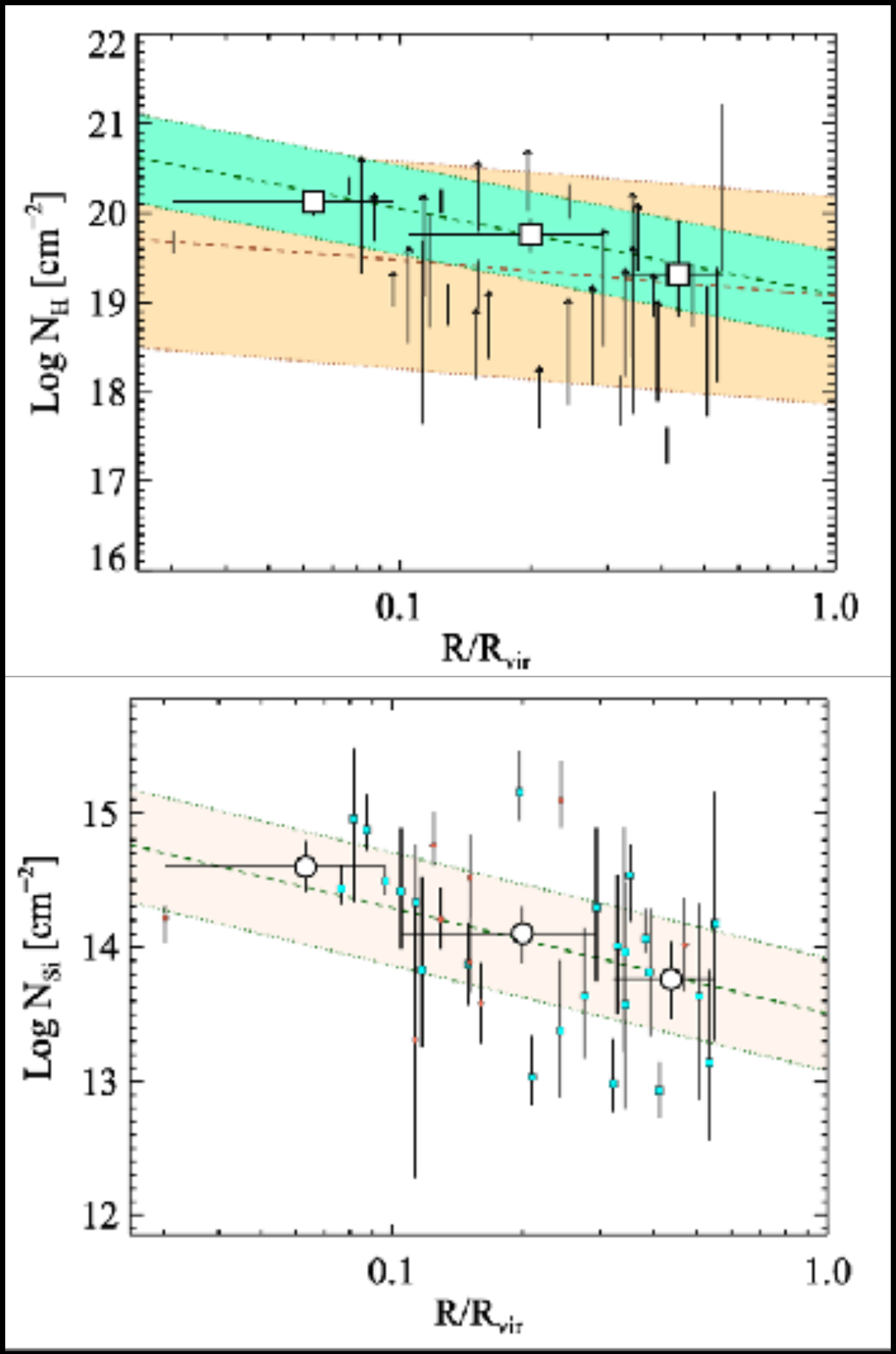


Density field reconstructed using Ly-α absorbers in the spectra of 240 quasars and galaxies (Lee+ 2018, CLAMATO survey)

Example 2: Circumgalactic Medium



Credit: Tumlinson+



Werk+ 2014

Selfish Desires

- See these successes extended to other phases of gas in the Universe at small and large scales.
- See kinematic information added to our knowledge of all gas phases.
- Include topological information on the cosmic web added to the knowledge of all gas phases.
- Make simulation-informed predictions and feasibility studies for future observations of the properties mentioned above.

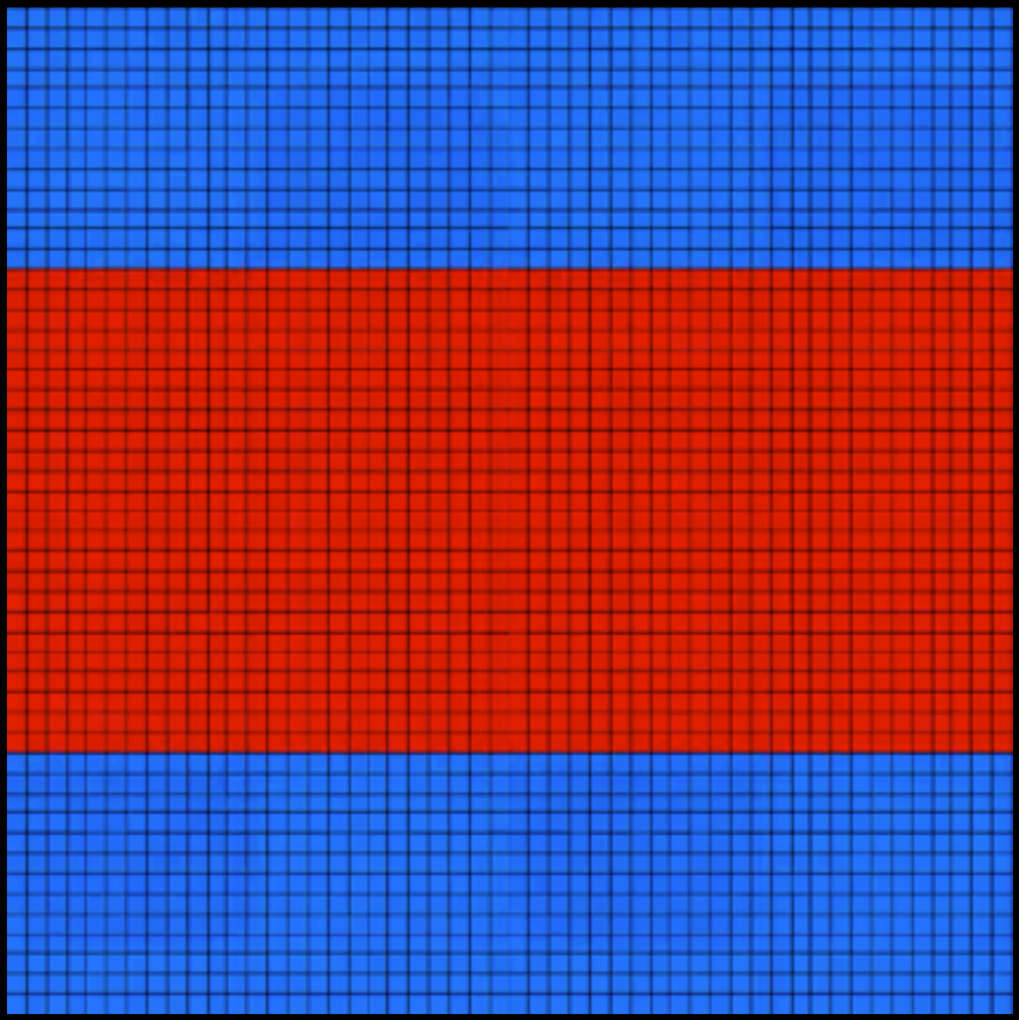
Cosmological Hydrodynamical Simulations

State-of-the-art cosmological simulations (Illustris, EAGLE, Horizon-AGN, MUFASA, etc.):

- Follow dark matter and gas (hydro)dynamics.
- Include radiative cooling.
- Include models for star formation.
- Include models for stellar and AGN feedback.
- Possibly more physics…

Simulations of choice: IllustrisTNG

This is a suite of cosmological hydrodynamical simulations ran with the moving-mesh code AREPO (Springel 2010).



The famous KH instability example

Solver for collisionless dynamics largely derived from the previous code Gadget-3.

The code combines the advantages of Eulerian and Lagrangian hydrodynamic solvers.

Solutions are Galilean-invariant.

Simulations of choice: IllustrisTNG

	Illustris	TNG100	TNG50	TNG300
Overview:				
Specs	L75n1820FP	L75n1820TNG	L35n2160TNG	L205n2500TNG
MHD	no	yes	yes	yes
Cosmology	WMAP7	Planck 2015	Planck 2015	Planck 2015
Box and Resolution:				
Lbox [Mpc]	106.5	110.7	51.7	302.6
# res elements	2 x 1820^3	2 x 1820^3	2 x 2160^3	2 x 2500^3
gas mass in the initial conditions [Msun]	1.26e6	1.39e6	8.47e4	1.1e7
DM mass [Msun]	6.26e6	7.46e6	4.54e5	5.88e7
~EpsilonBaryons [kpc]	0.7	0.7	0.3	1.5

Original Illustris galaxy formation model (Vogelsberger+ 2014)

IllustrisTNG galaxy formation model (Pillepich+ 2018)

Simulations of choice: IllustrisTNG

Notable physical ingredients (Pillepich+2018, Weinberger+2018):

- Ideal MHD included in all runs.
- Star formation assumes Chabrier 2003, IMF.
- Sub-grid model for galactic winds.

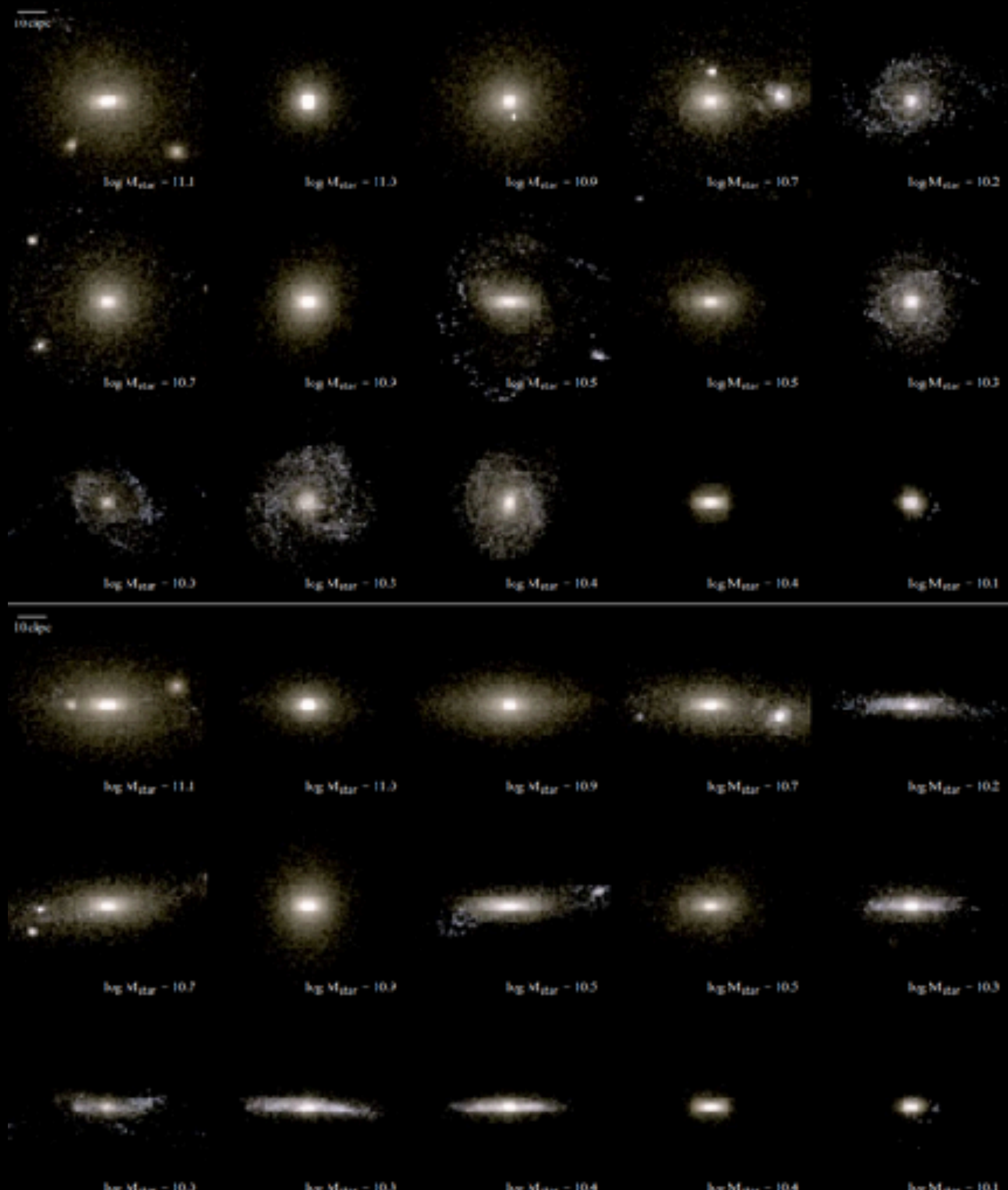
$$v_w = \max\left[\kappa_w \, \sigma_{\rm DM} \left(\frac{H_0}{H(z)}\right)^{1/3}, \, v_{w,\rm min}\right]$$

- Bi-modal AGN feedback model. Quasar mode = thermal injection. Jet mode = kinetic injection.

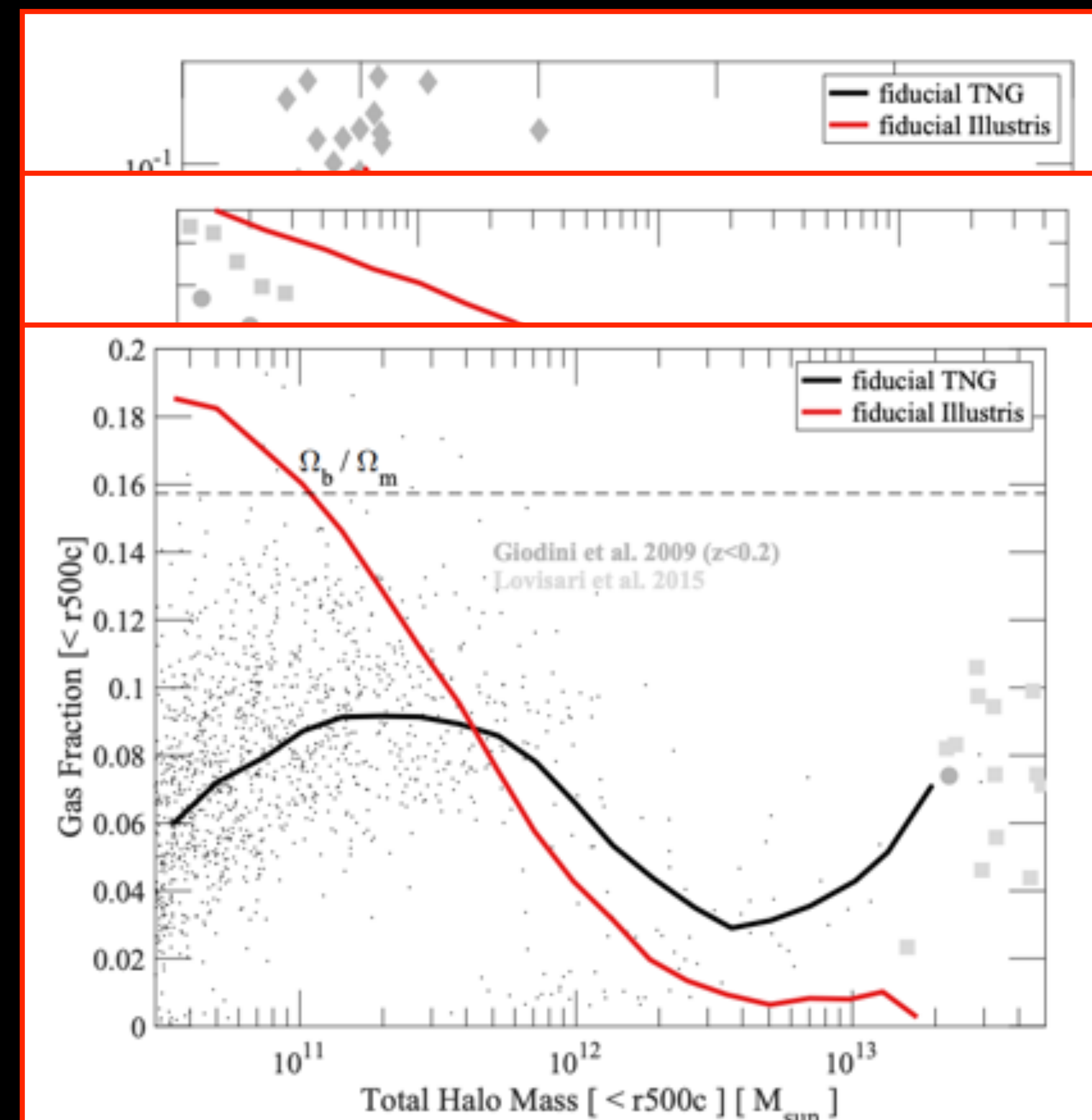
$$\dot{E}_{\rm therm} = 0.02 \dot{M} c^2 \qquad \dot{E}_{\rm kin} = \varepsilon_{f,\rm kin} \dot{M} c^2$$

- Metal advection. Metal yields from SNe type I and II, plus NS-NS mergers (r-process elements).

Simulations of choice: IllustrisTNG

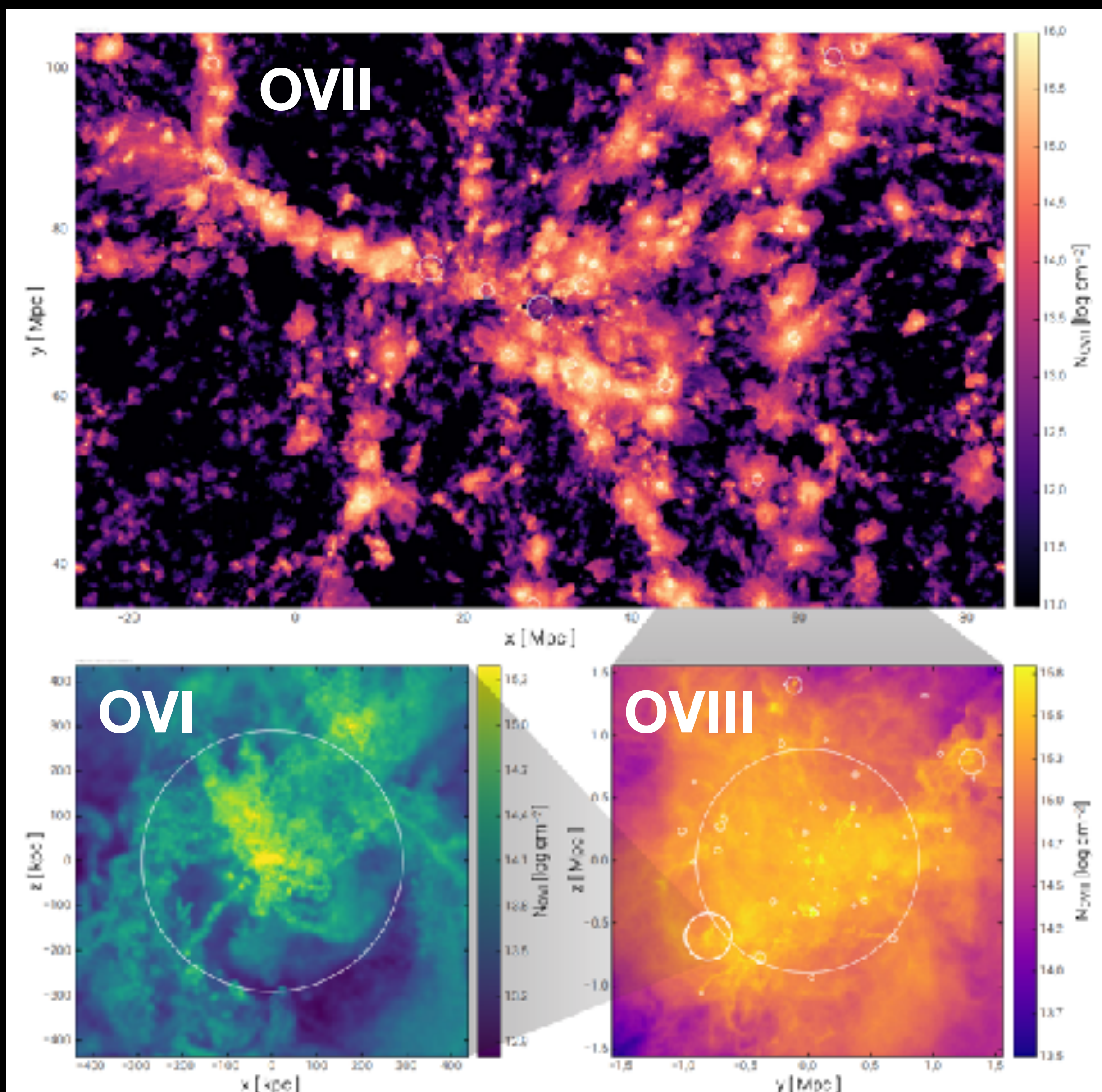


Galaxy Morphologies in TNG100

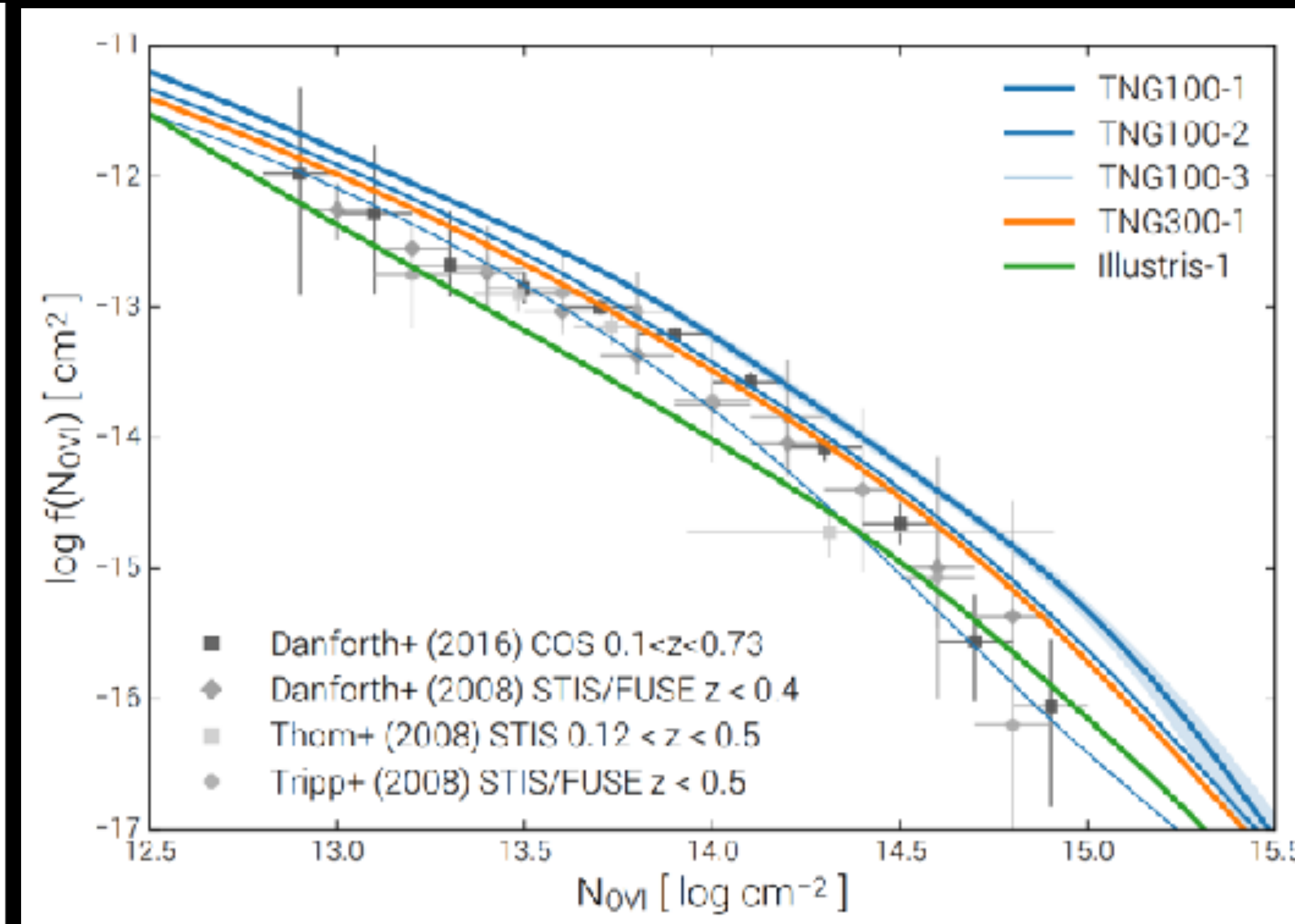


Pillepich+2018

Simulations of choice: IllustrisTNG

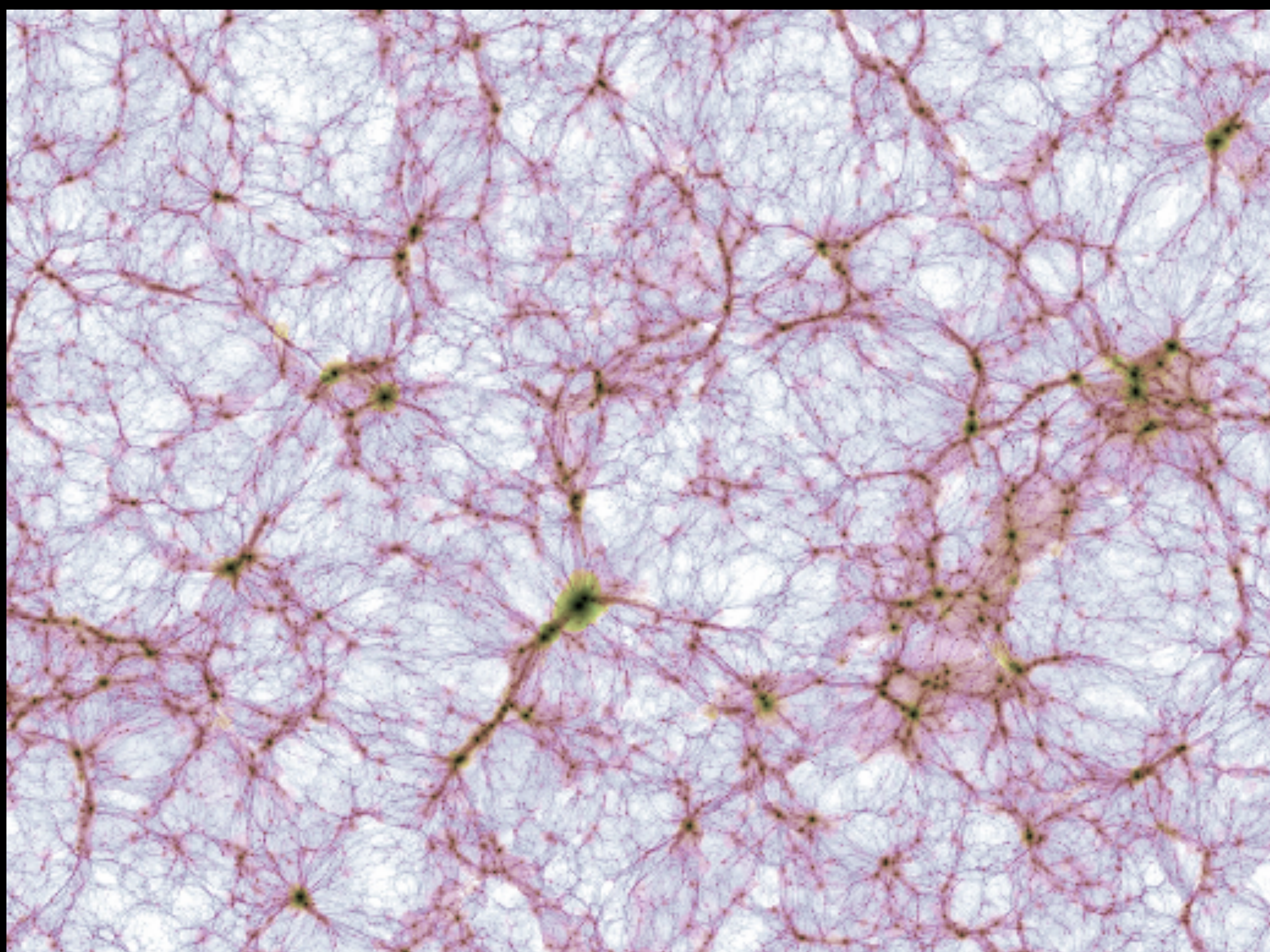


CGM maps in TNG100



Nelson+2018

Baryons in the Cosmic Web of IllustrisTNG



IllustrisTNG - Now public (Nelson+ 2019)
Cosmo-MHD simulation

Goals:

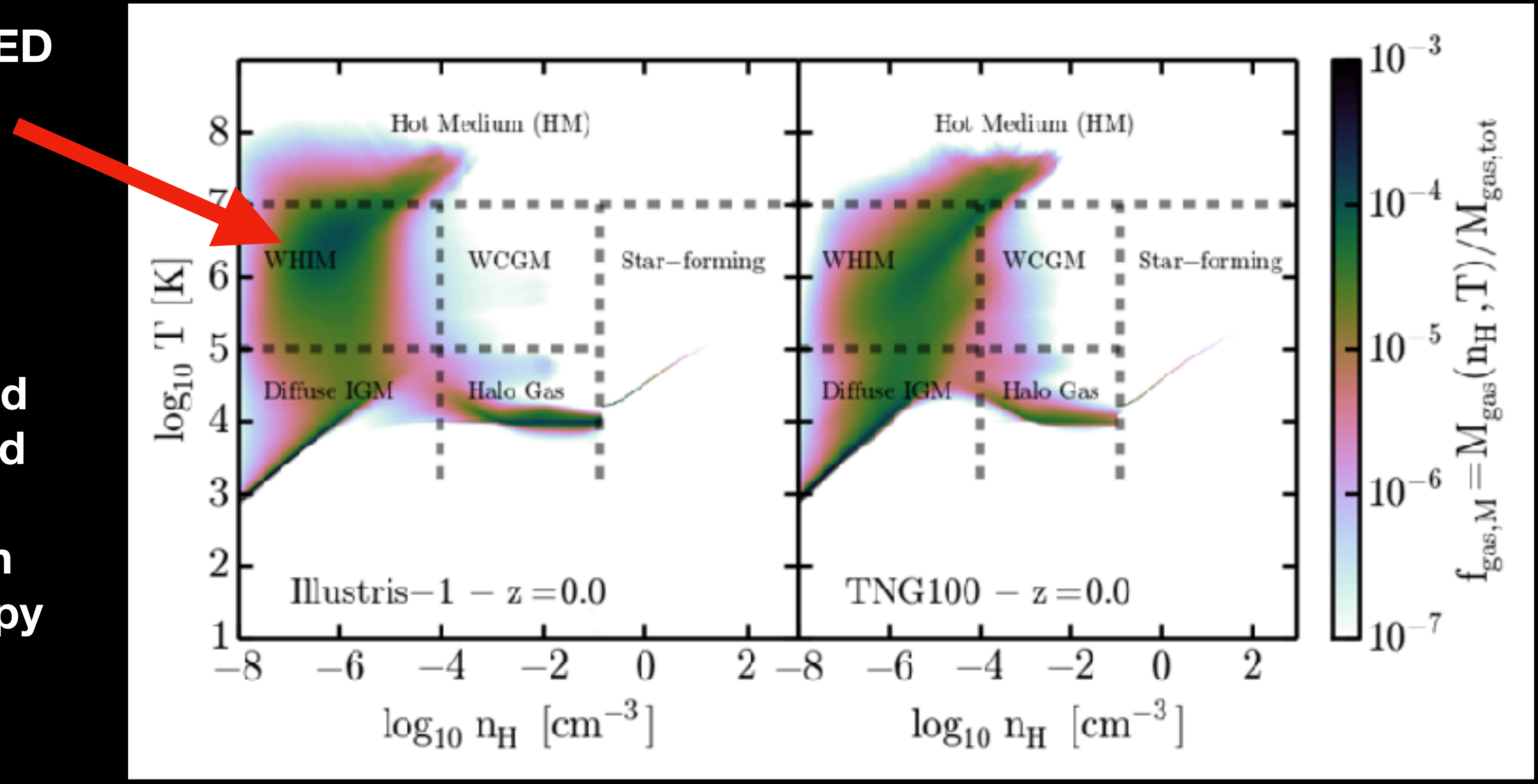
- Explore the connection between the state of baryons and the Large Scale Structure.
- Provide a significant update and generalization to previous theoretical prediction on the “Baryon Census”.
- Provide theoretical predictions for the detection of undetected phases.

Gas Phases in IllustrisTNG

Martizzi+ 2018

WHIM: UNDETECTED PHASE OF THE IGM

WHIM could be detected by X-ray absorption spectroscopy



"Old" Illustris

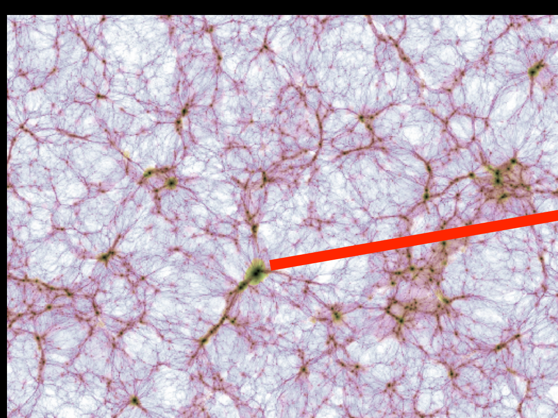
IllustrisTNG

- Where are these phases?
- Is topological information important if we want to find them with Cosmic Beacons?

Let's add info on the Cosmic Web

Martizzi+ 2018

We need a Cosmic Web classification method:



Over-density smoothed on some scale R

$\delta(x,R)$ →

Cosmic Web Class

W = 0 - Knot
W = 1 - Filament
W = 2 - Sheet
W = 3 - Void

I use a classic method developed by Forero-Romero+2009.

Let's add info on the Cosmic Web

Martizzi+ 2018

Forero-Romero+2009 method. In the Zel'dovich approximation the deformation tensor determines whether a particular region will undergo gravitational collapse along a given axis.

Step 1: Measure the deformation tensor.

$$\nabla^2 \phi = 4\pi G \bar{\rho} \delta$$

$$\Psi_{ij}(\mathbf{x}) = \partial_i \partial_j \phi(\mathbf{x})$$

FFT

$$\Psi_{ij,\mathbf{k}} = k_i k_j \phi_{\mathbf{k}}$$

Inverse-FFT

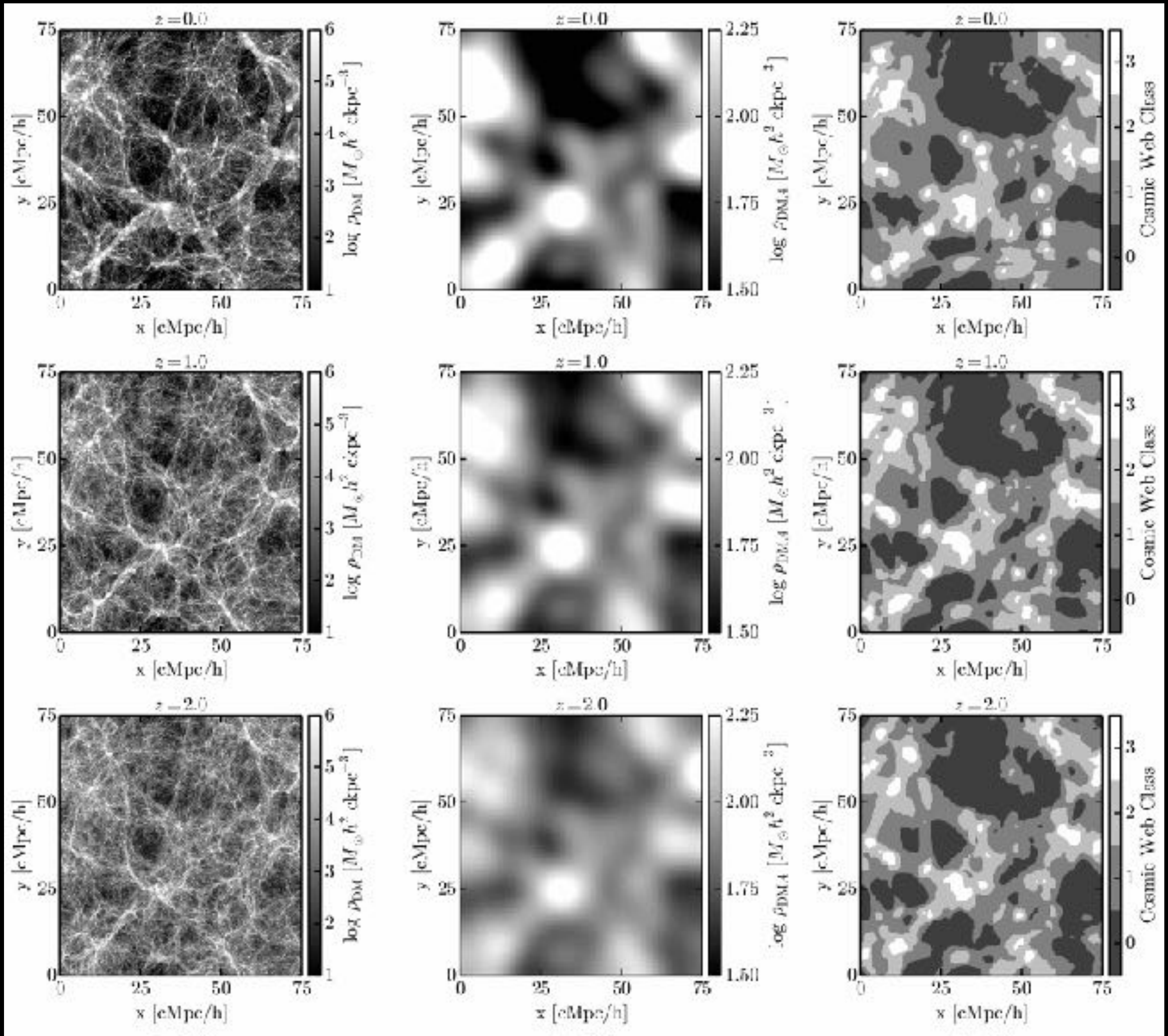
$$\Psi_{ij}(\mathbf{x})$$

Step 2: Diagonalize the deformation tensor.

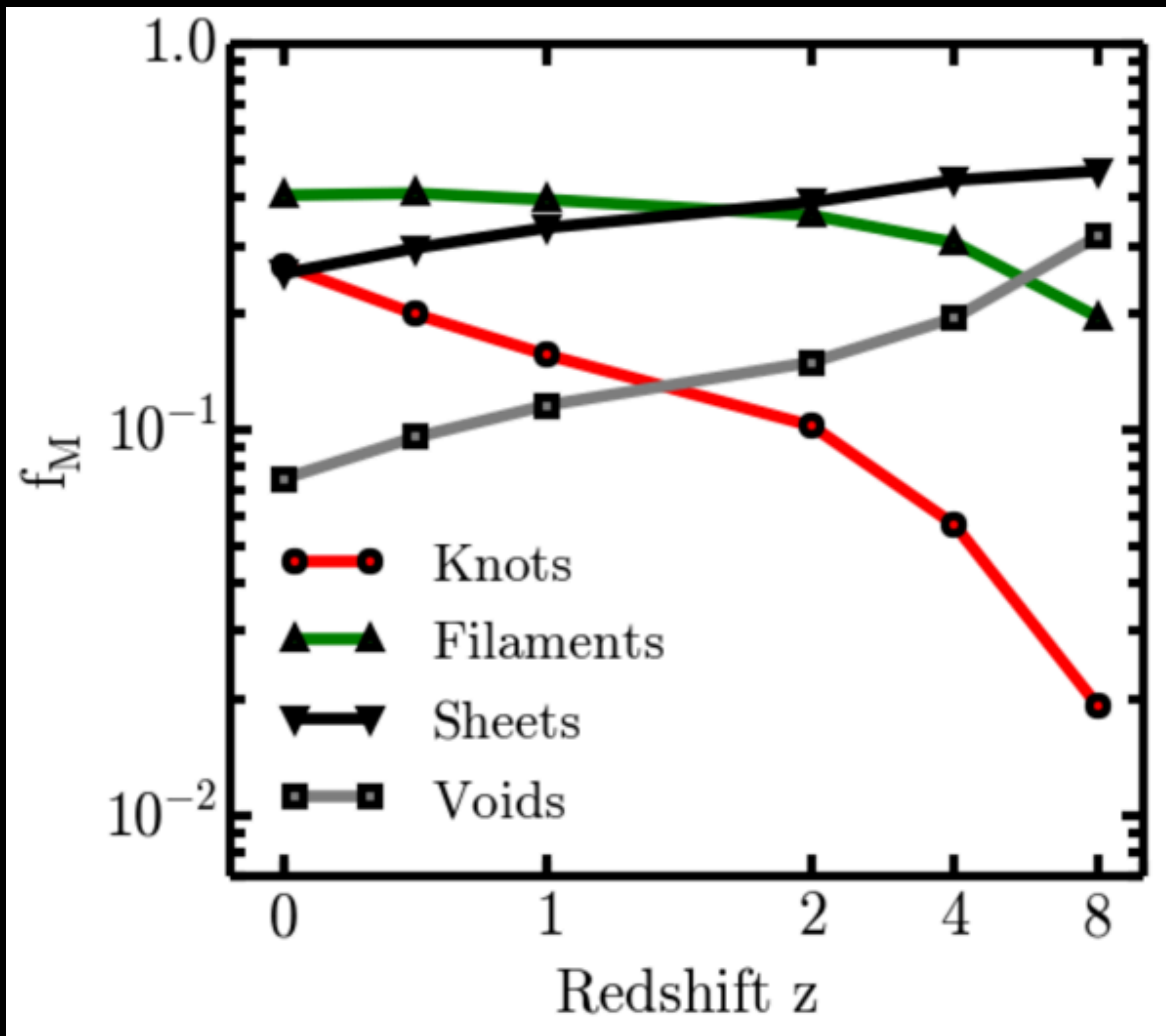
$$\det(\mathbf{\Psi}(\mathbf{x}) - \lambda(\mathbf{x})\mathbf{I}) = 0$$

- 3 principal axes at each location.
- Measure N = number of axes along which the structure collapses (λ>threshold).
- Cosmic Web Class W = (3-N).

Cosmic Web Classification



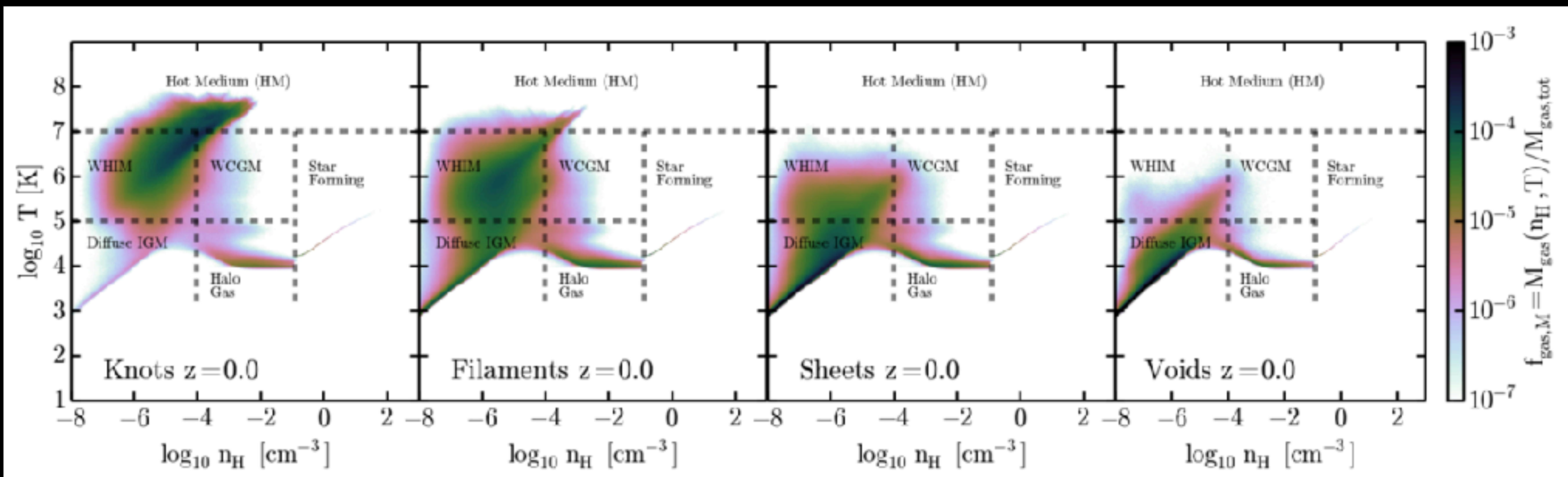
Mass Fraction of Collapsed Structures



IllustrisTNG - TNG100
Martizzi+2018

Cosmic Web Classification performed on a density field smoothed on a scale R = 4 Mpc/h.

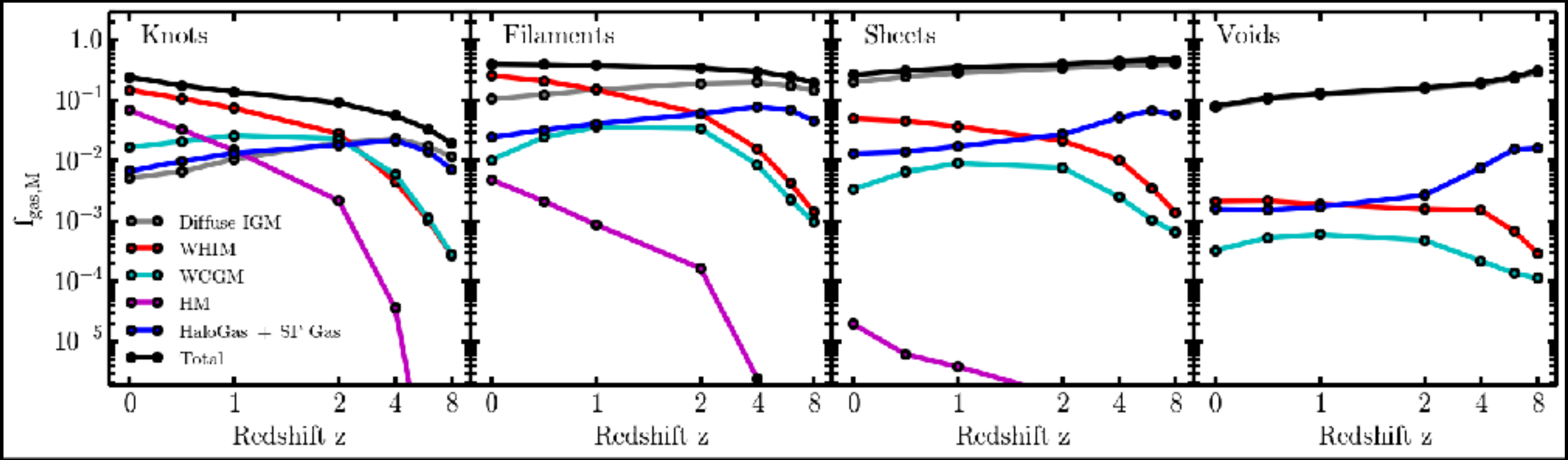
Gas in Knots, Filaments, Sheets and Voids



Knots **Filaments** **Sheets** **Voids**

Multiple gas phases are influenced by the location in the Cosmic Web.

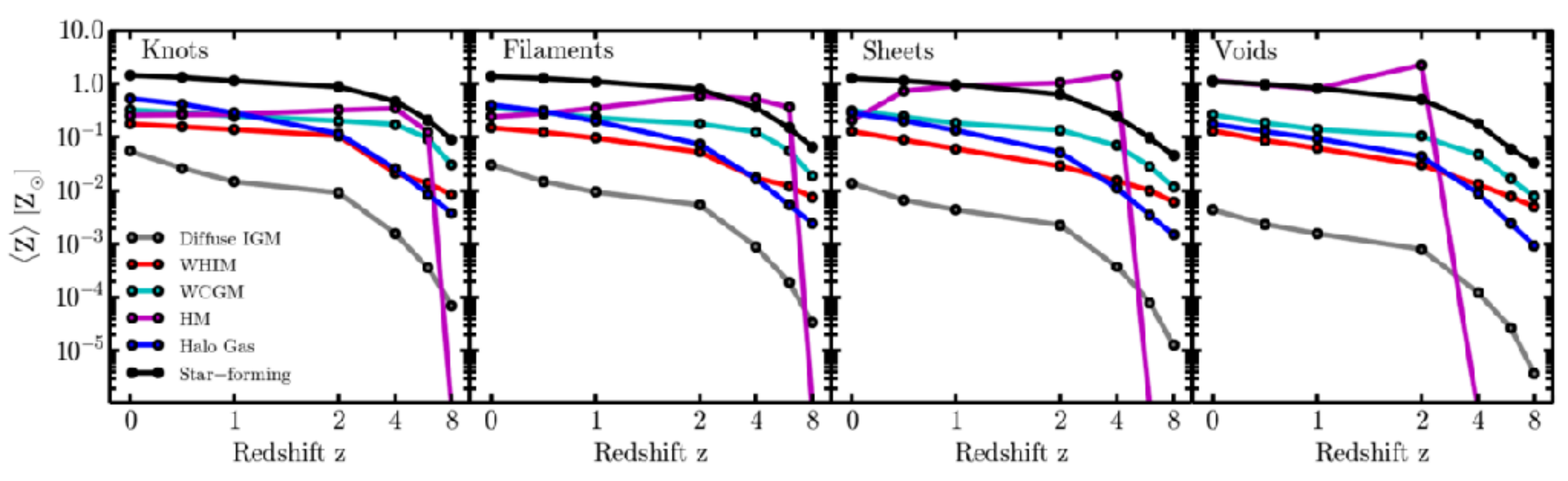
Gas in Knots, Filaments, Sheets and Voids



Study the evolution of gas fractions in different phases.

- **WHIM and Diffuse IGM dominate the budget.**
- **WHIM becomes dominant only at z<1.**
- **Diffuse IGM dominates voids and sheets.**
- **WHIM is prominent only in filaments and knots.**
- **Knots are the only regions with significant Hot Medium.**

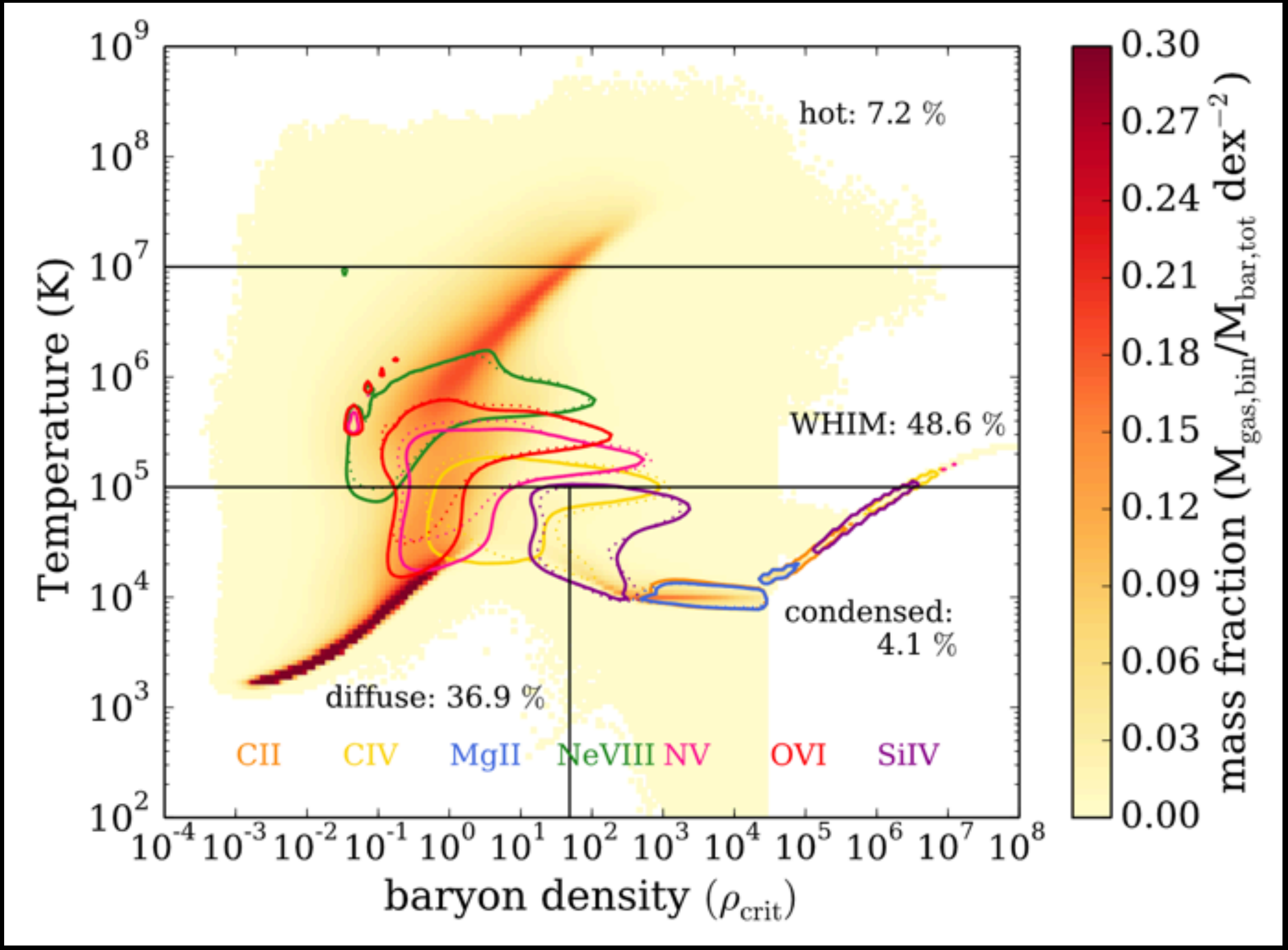
Gas Metallicities



Martizzi+2018

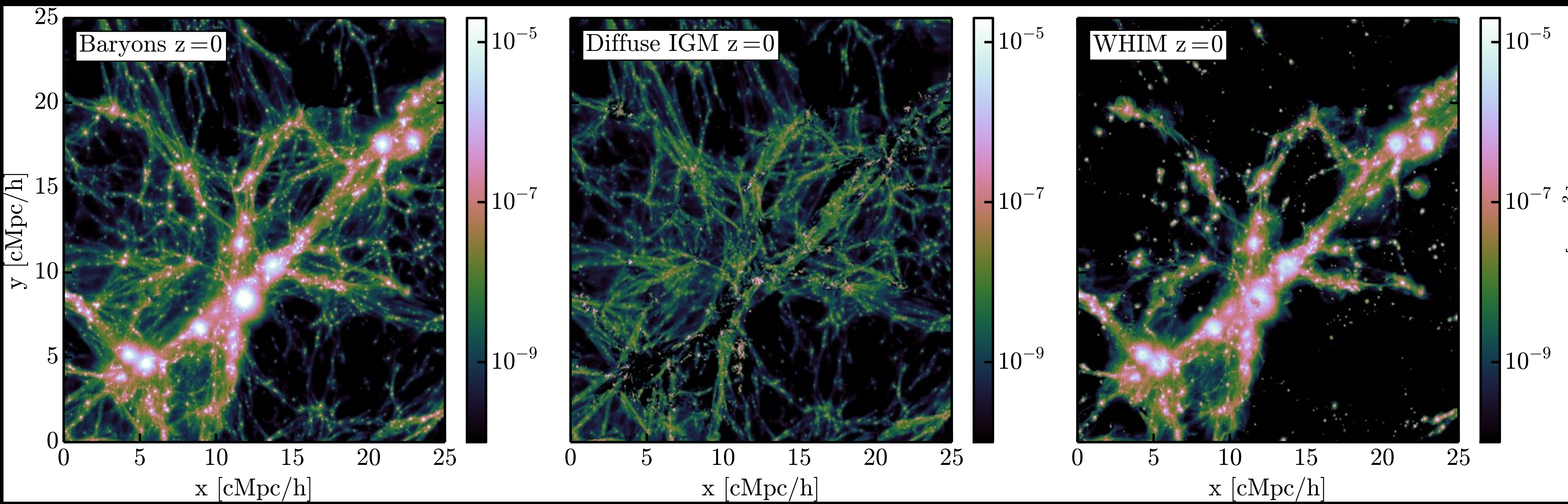
The WHIM is metal rich compared to the Diffuse IGM.

Ionization State



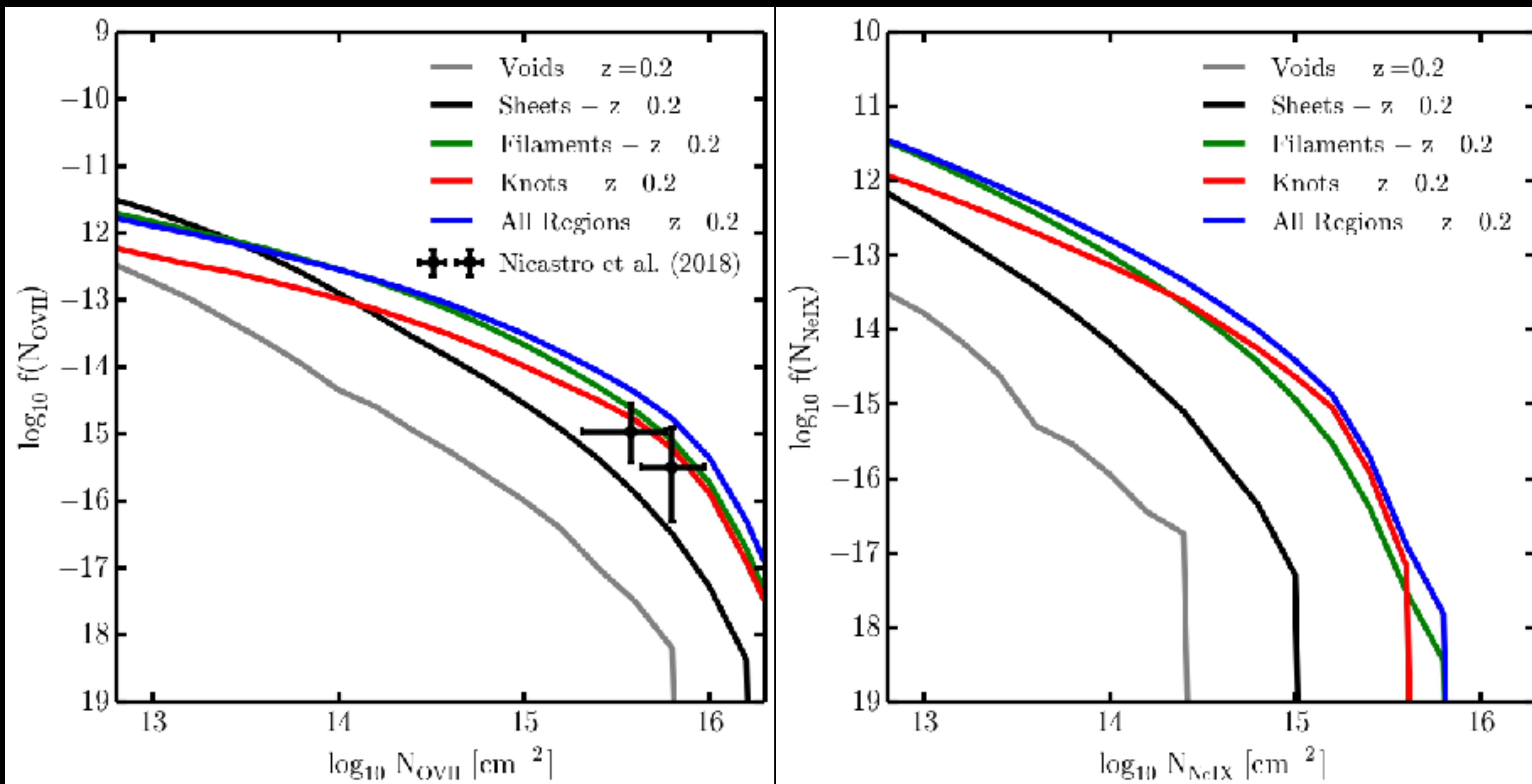
Artale+ (in prep.)

Gas in Knots, Filaments, Sheets and Voids



Diffuse IGM and WHIM populate different regions of the cosmic web.
In fact the WHIM only occupies ~10% of the volume at z=0.
The Diffuse IGM occupies ~89% of the volume at z=0.

Column Densities of “WHIM” Absorbers



WHIM OVII has been recently detected by Nicastro+ 2018. Is it WHIM?

Work so far

- Explore the connection between the state of baryons and the Large Scale Structure. DONE.
- Provide a significant update and generalization to previous theoretical prediction on the “Baryon Census”. DONE.
- Provide theoretical predictions for the detection of undetected phases. FOLLOW-UP WORK.

Athena X-ray Observatory

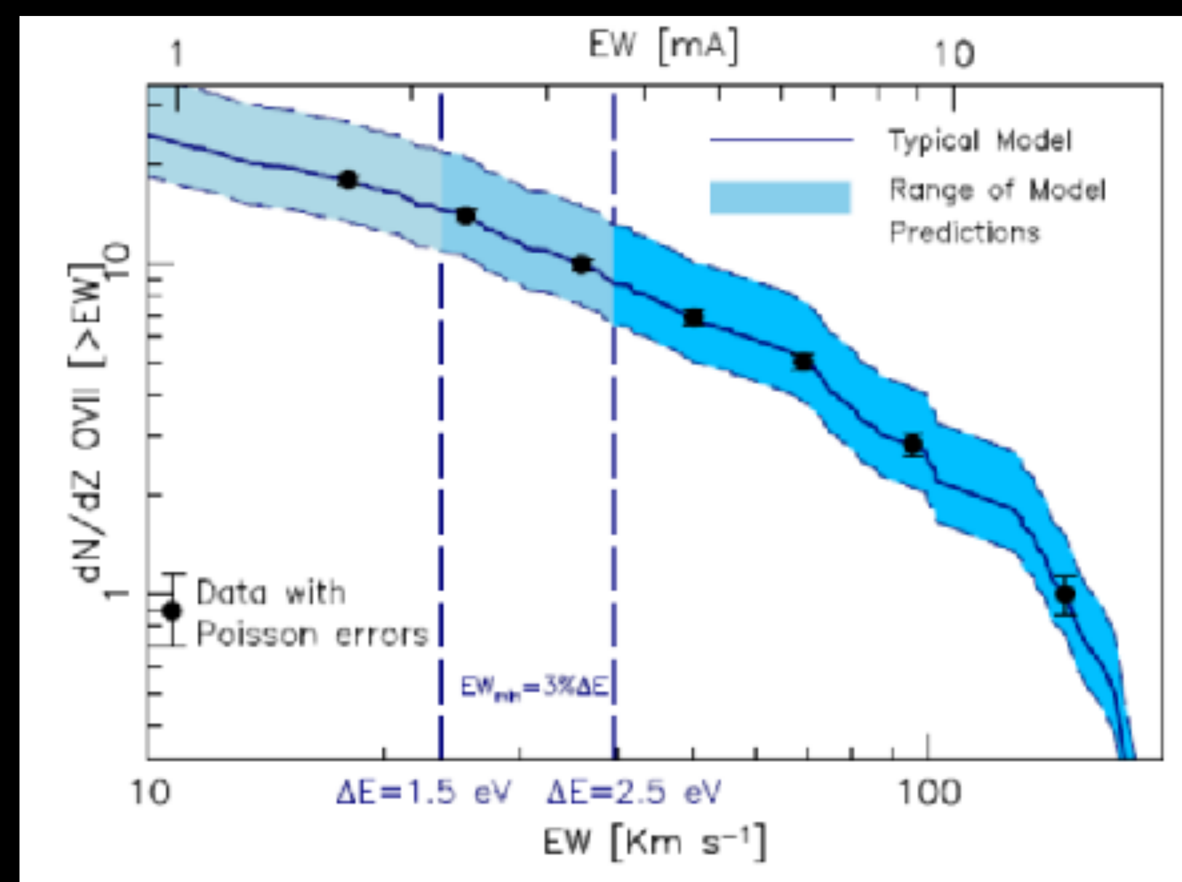
Credit: Athena team

The X-IFU proposed for Athena will have:

- **2.5 eV spectral resolution.**
- **FoV 5 arcmins.**
- **5” pixels.**

Kaastra+ 2013 proposed to observe 25 AGN and 40 GRB afterglows over 5 years.

Still feasible according to updated models and Athena specs?



Synergy Needed with Observers

- Are the specs of future X-ray telescopes sufficient?
- Can a “wide survey of Cosmic Beacons” be designed with these specs?
- Quasars are natural targets to study WHIM absorption…
- What about GRB afterglows? Any future telescope with fast pointing features?
- There is a lot of time before Athena is launched. There is enough time to make proof-of-concept studies and predictions.

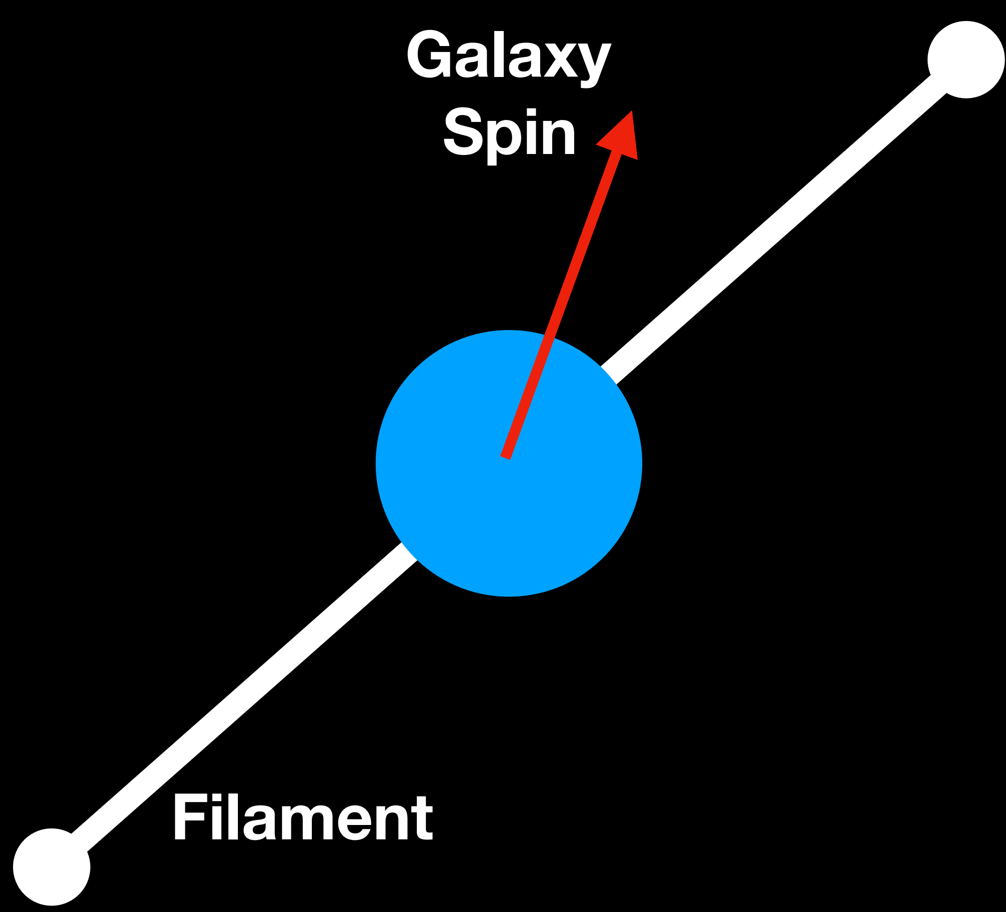
Phase 2
Galaxies in the Cosmic Web
(Very Preliminary)

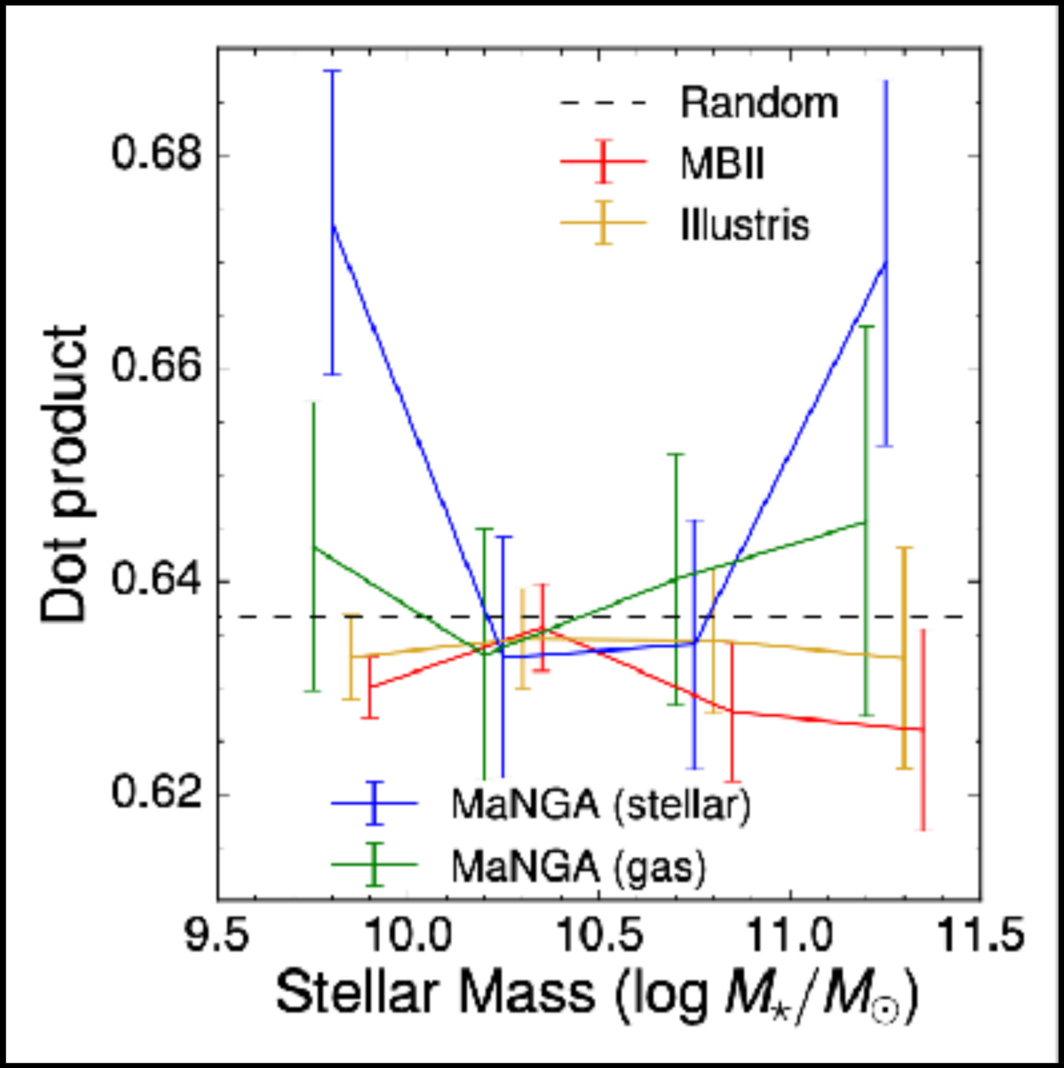
Galaxy Formation

- Hierarchical evolution determined by dark matter halo merger tree.
- Galaxy properties depend on processes internal to dark matter halos. E.g. feedback, secular processes.
- Galaxy properties can be influenced by external processes. E.g. ram-pressure stripping and galaxy harassment in galaxy clusters.
- Does the large scale Cosmic Web morphology leave an imprint on galaxy properties?

Galaxy-Filament Alignments

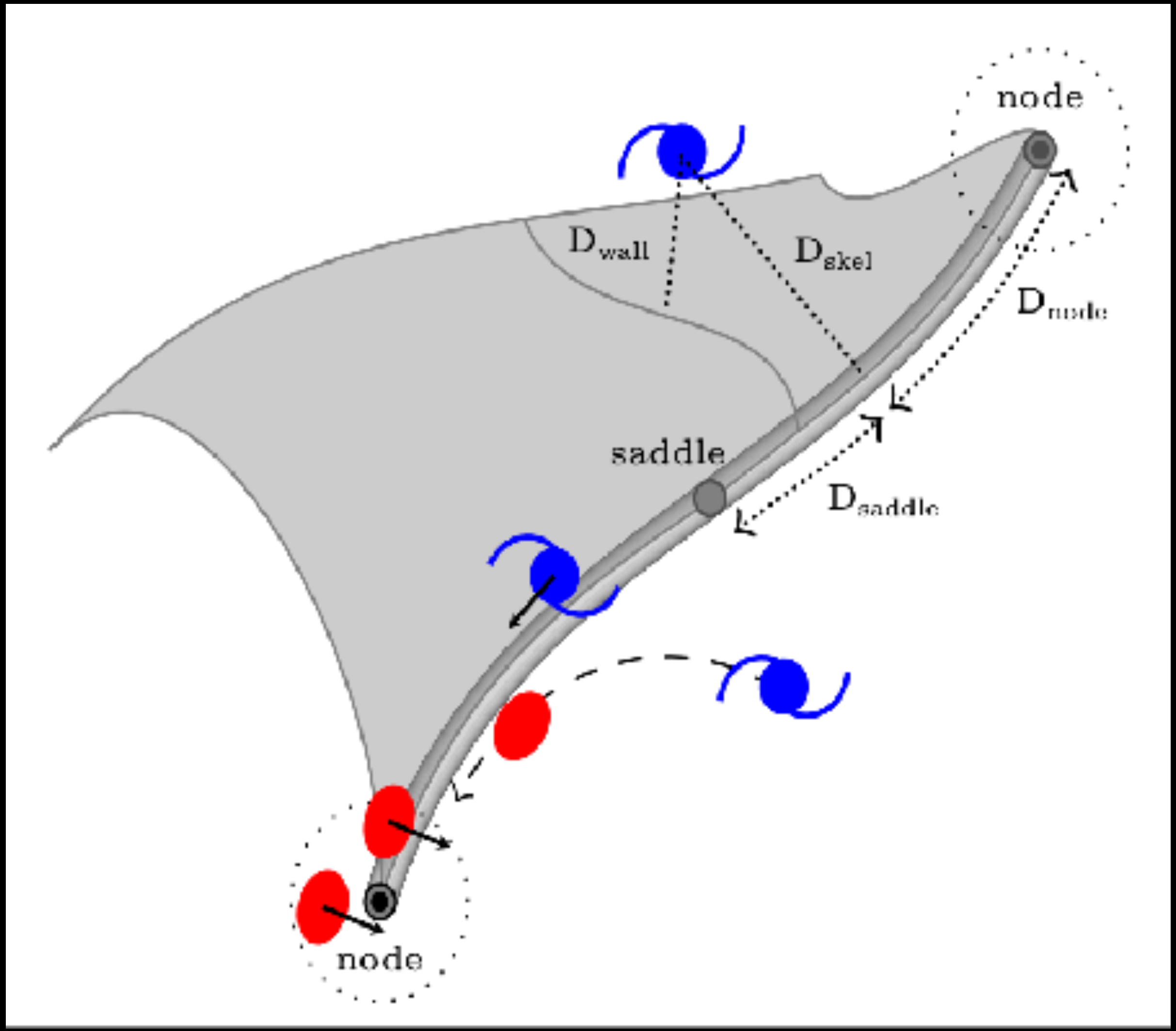
Krolewski+2019: measure alignment between galaxy spins and cosmic filaments using MaNGA galaxies.

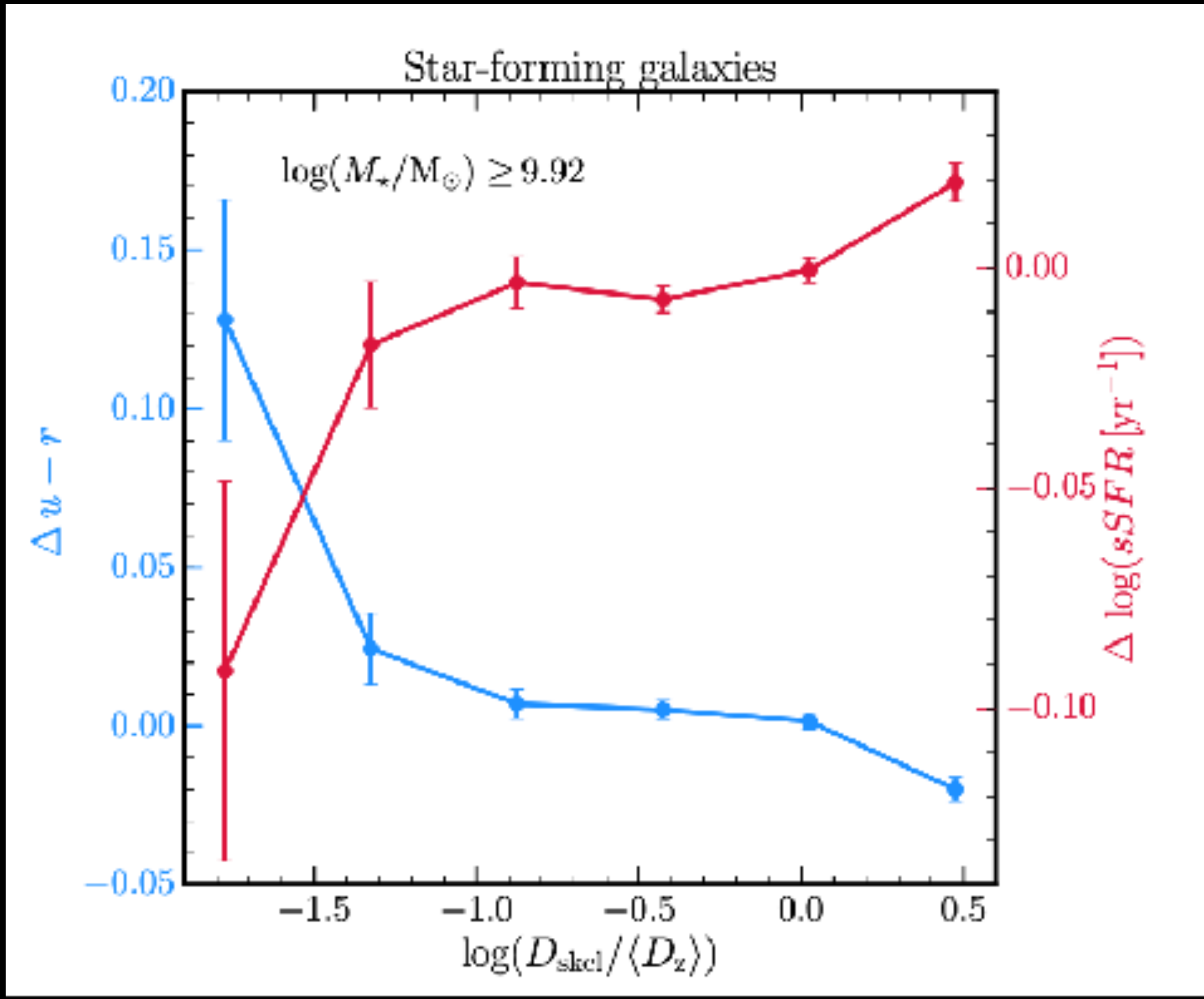




Mass dependent spin alignment?

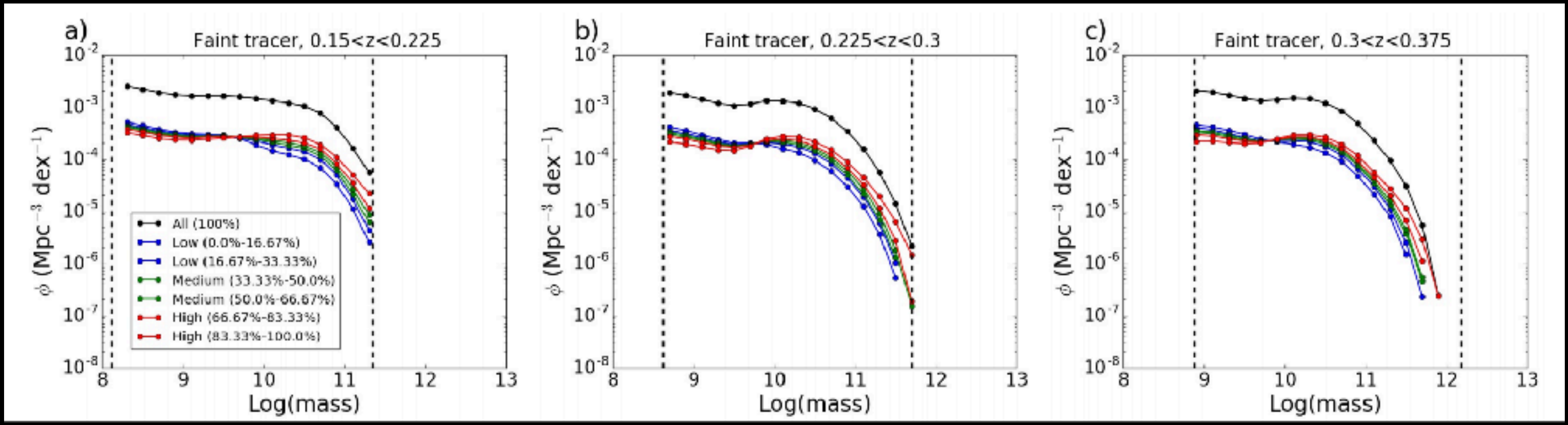
Galaxies vs. Cosmic Web





From Kraljic+2018
Analysis of GAMA galaxies

Stellar mass function vs. Environment



From Etherington+2017
Analysis of DES galaxies

Galaxies vs. Cosmic Web

Get predictions from cosmological hydro simulations (IllustrisTNG).

- Dark Matter Halo Mass = M_dm
- Stellar Mass = M_star
- Galaxy sSFR
- Galaxy Colors
- Formation time z_form
- Large-scale over-density $\delta(R=8\ \mathrm{Mpc}/h)$
- Cosmic Web Class = W

} How do they correlate?

Galaxies vs. Cosmic Web

Get predictions from cosmological hydro simulations (IllustrisTNG).

Dark Matter Halo Mass = M_dm

Stellar Mass = M_star

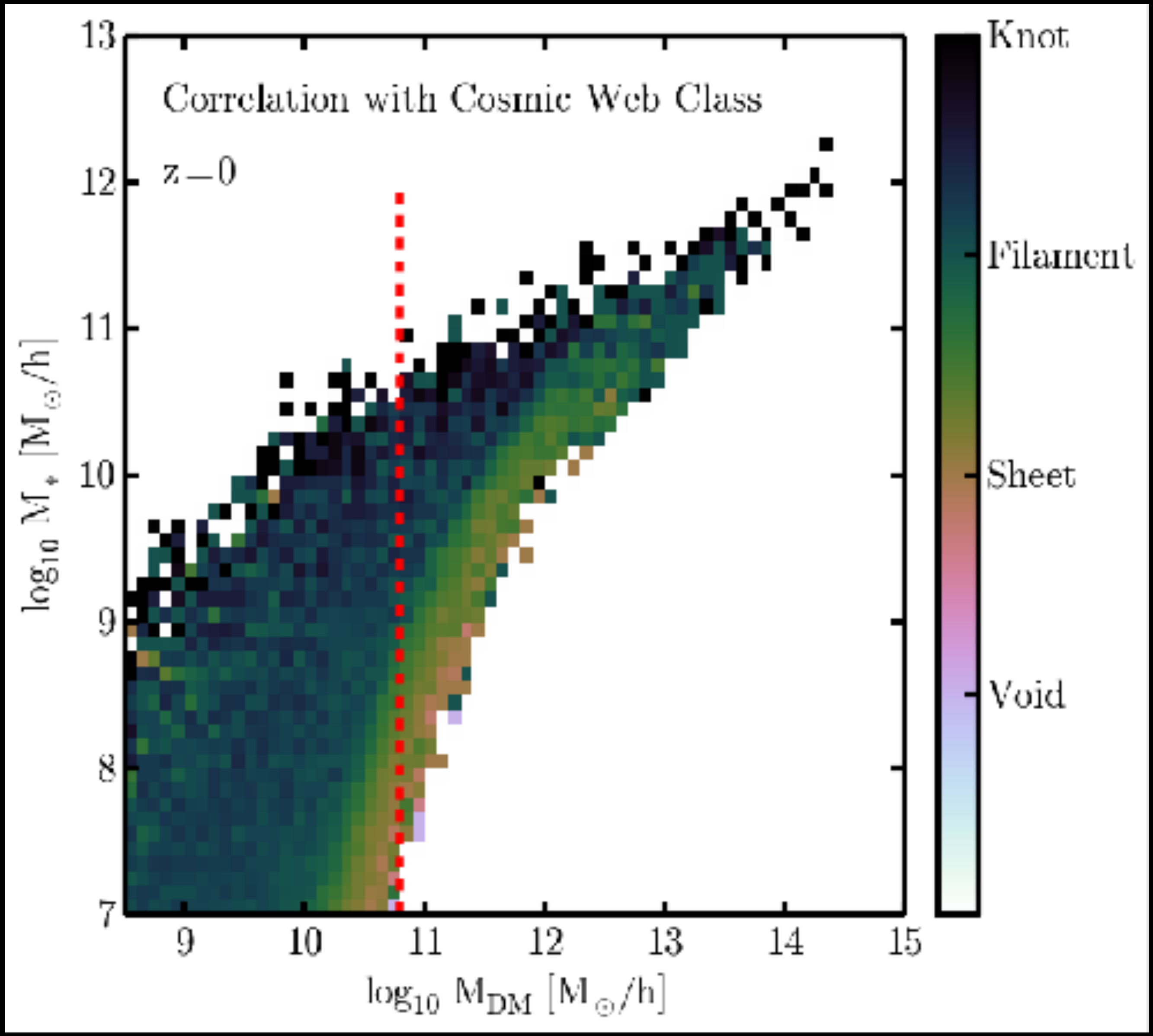
Galaxy sSFR

Galaxy Colors

Formation time z_form

Large-scale over-density δ(R=8 Mpc/h)

Cosmic Web Class = W



Galaxies vs. Cosmic Web

Get predictions from cosmological hydro simulations (IllustrisTNG).

Dark Matter Halo Mass = M_dm

Stellar Mass = M_star

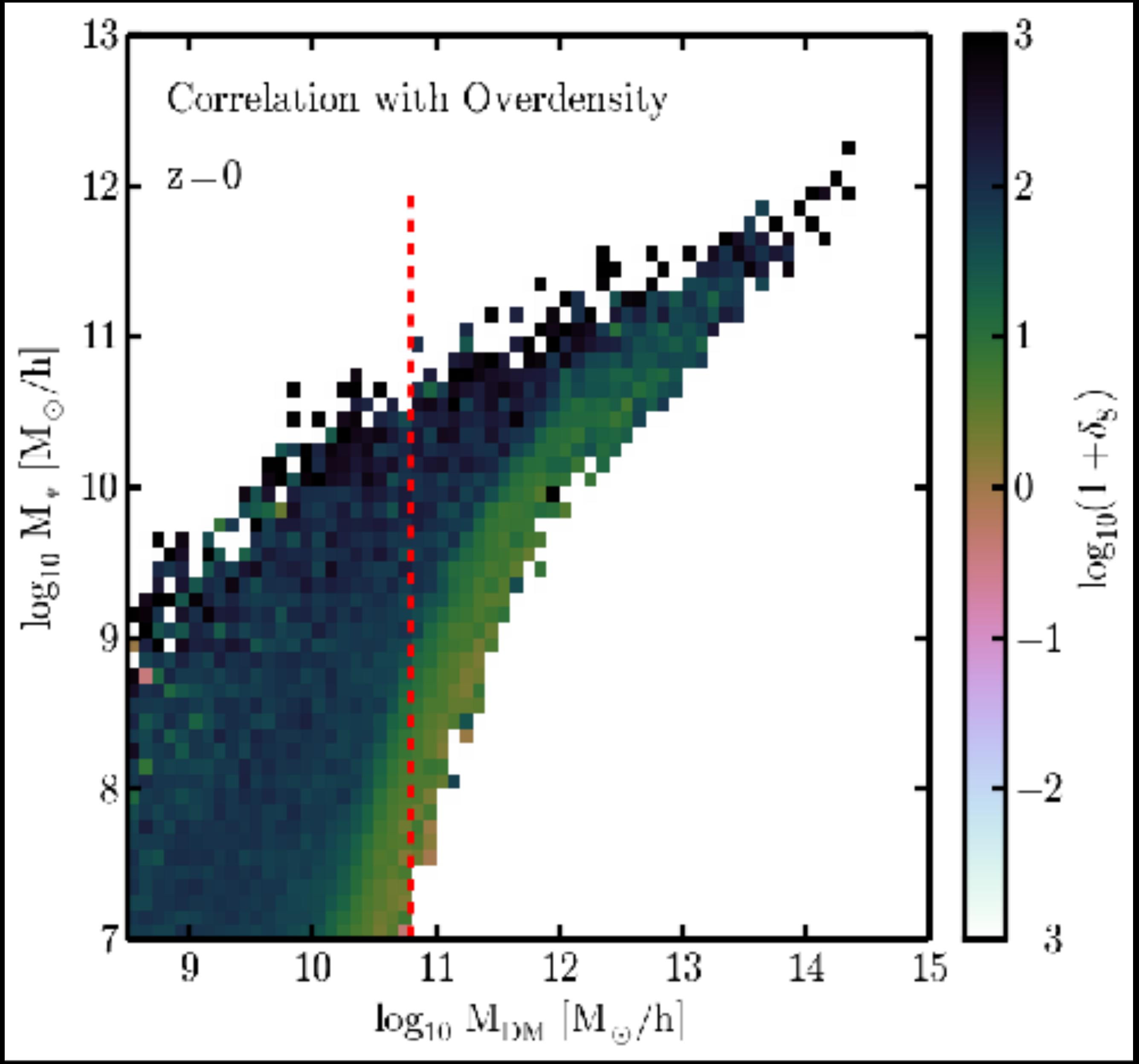
Galaxy sSFR

Galaxy Colors

Formation time z_form

Large-scale over-density δ(R=8 Mpc/h)

Cosmic Web Class = W



Galaxies vs. Cosmic Web

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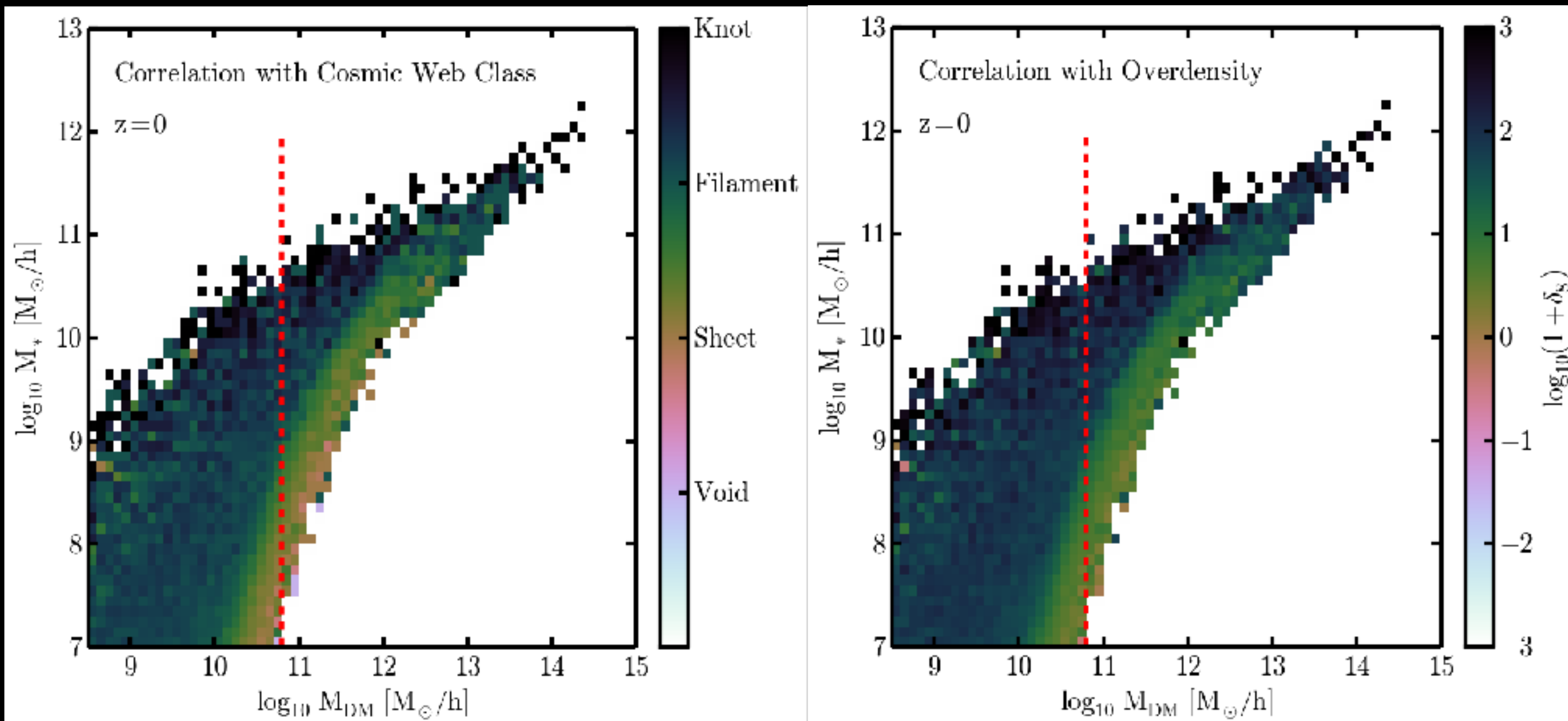
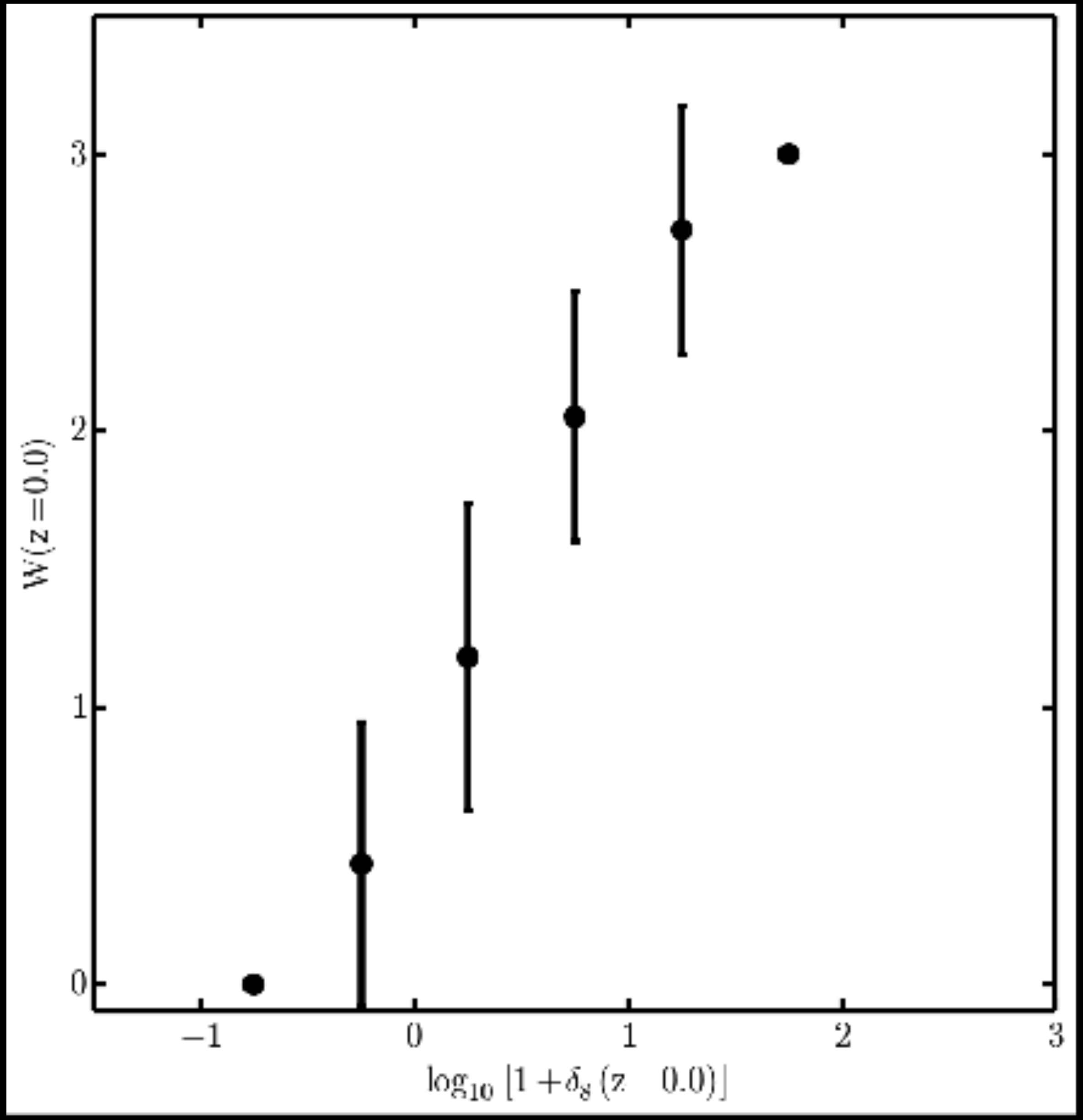


Are the two parameters completely degenerate???

Galaxies vs. Cosmic Web

Get predictions from cosmological hydro simulations (IllustrisTNG).



δ is just the over-density.

W traces the shape of the over-density field.

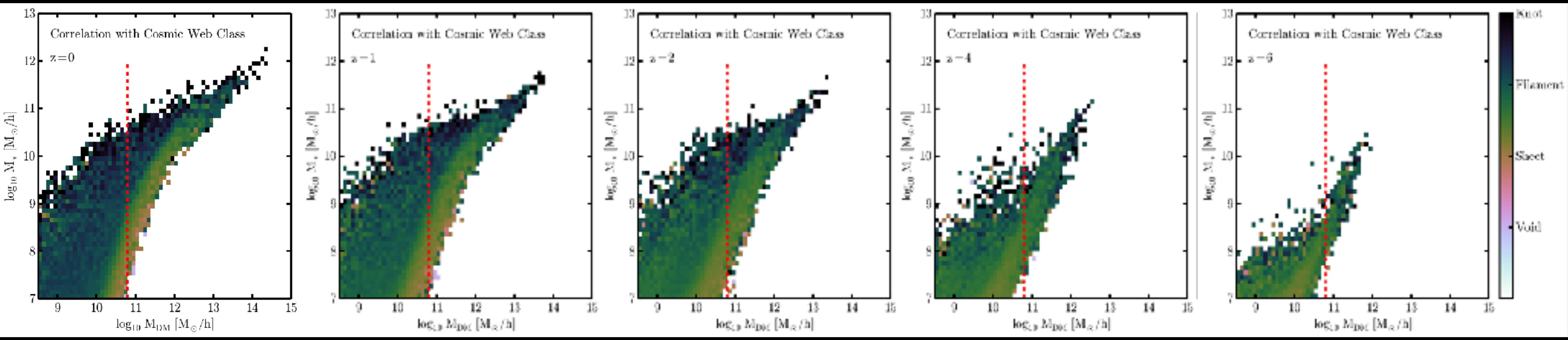
The variables correlated, but with a large scatter.

They are not entirely degenerate.

More on this to be published in Martizzi+ (in prep.).

Galaxies vs. Cosmic Web

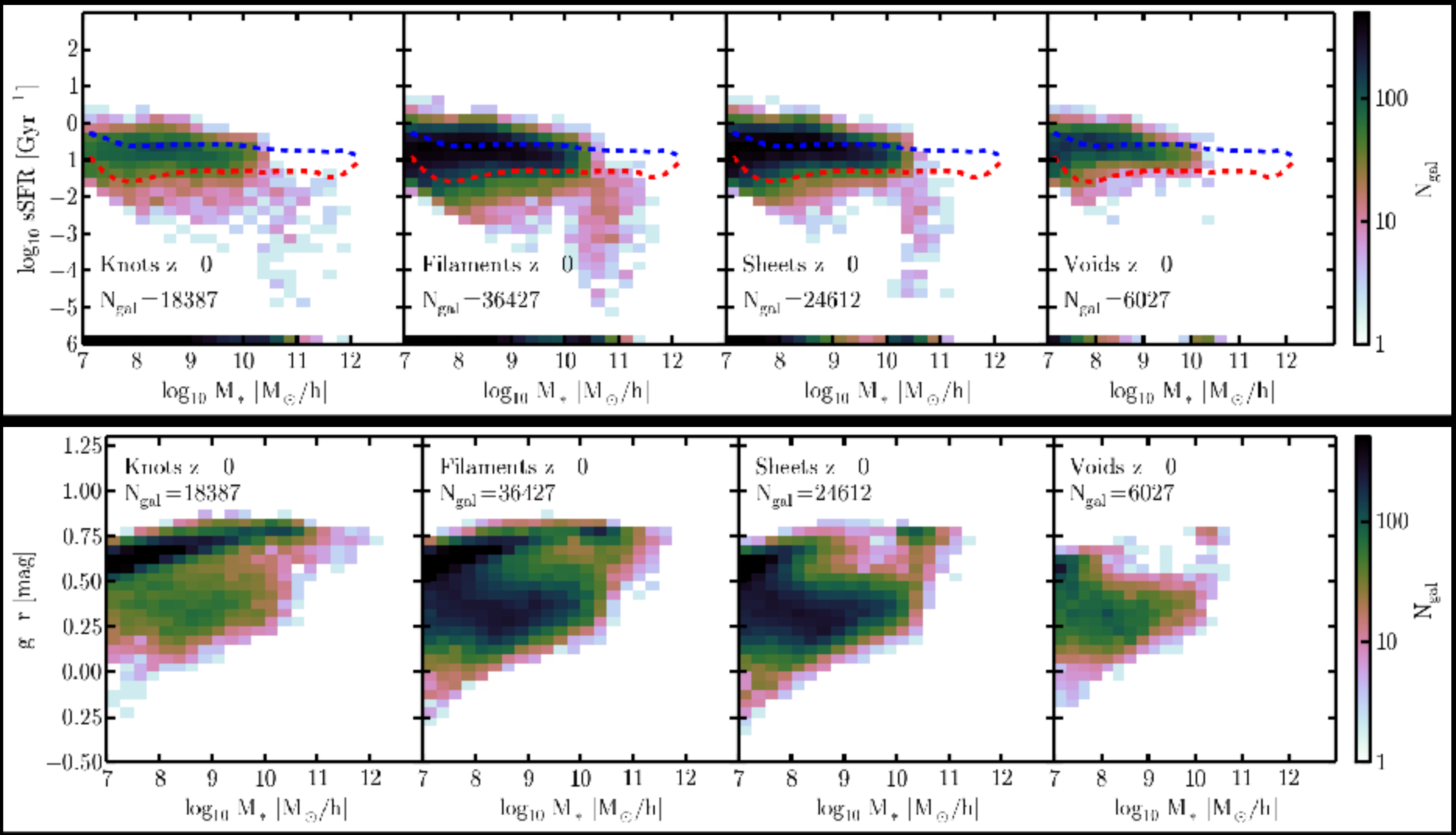
Get predictions from cosmological hydro simulations (IllustrisTNG).



Increasing redshift

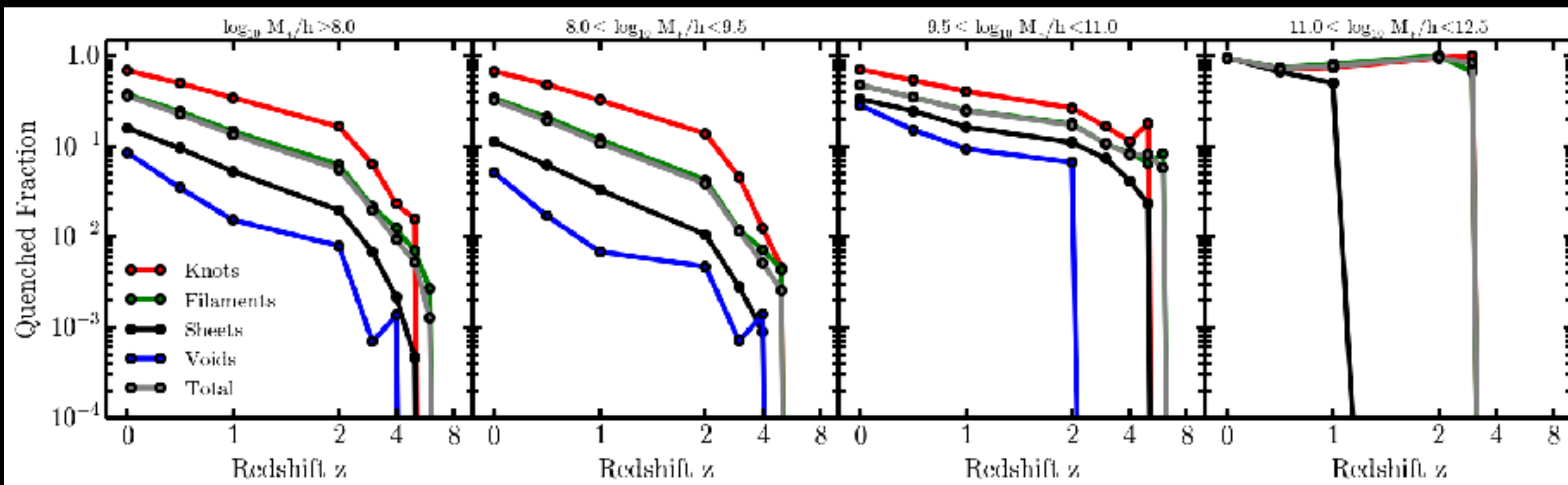
Galaxies vs. Cosmic Web

Get predictions from cosmological hydro simulations (IllustrisTNG).



Galaxies vs. Cosmic Web

Get predictions from cosmological hydro simulations (IllustrisTNG).



Increasing Stellar Mass

All Galaxies

Conclusions

- Current and future galaxy (redshift) surveys allow Cosmic Web reconstruction.
- Cosmological hydrodynamical simulations predict interesting effects that connect galaxy properties to the properties of the large scale Cosmic Web.

Suggestions:

Go to your survey, apply a Cosmic Web Classification method and measure new effects!