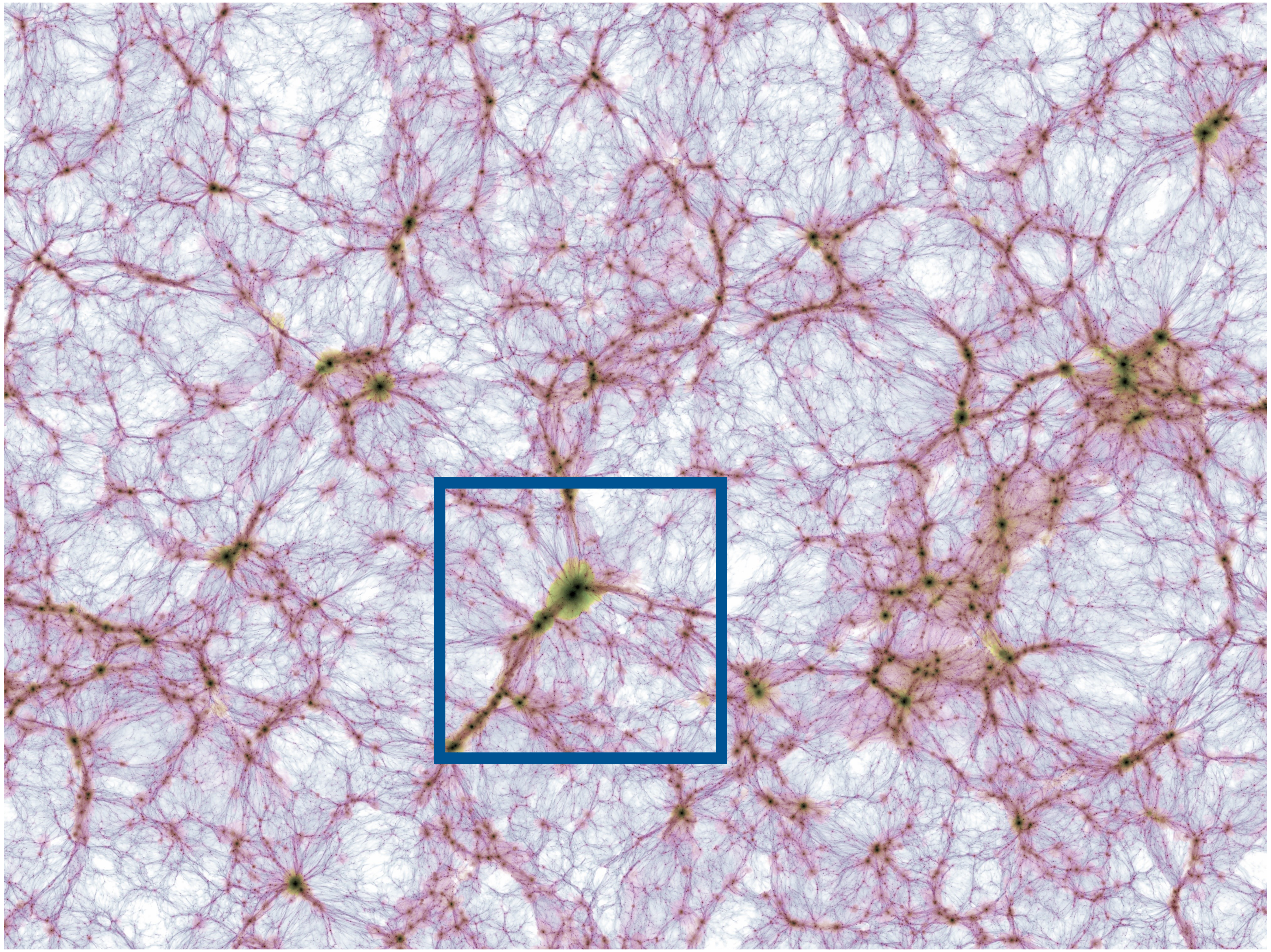
Properties of the cosmic web as detected from galaxy surveys

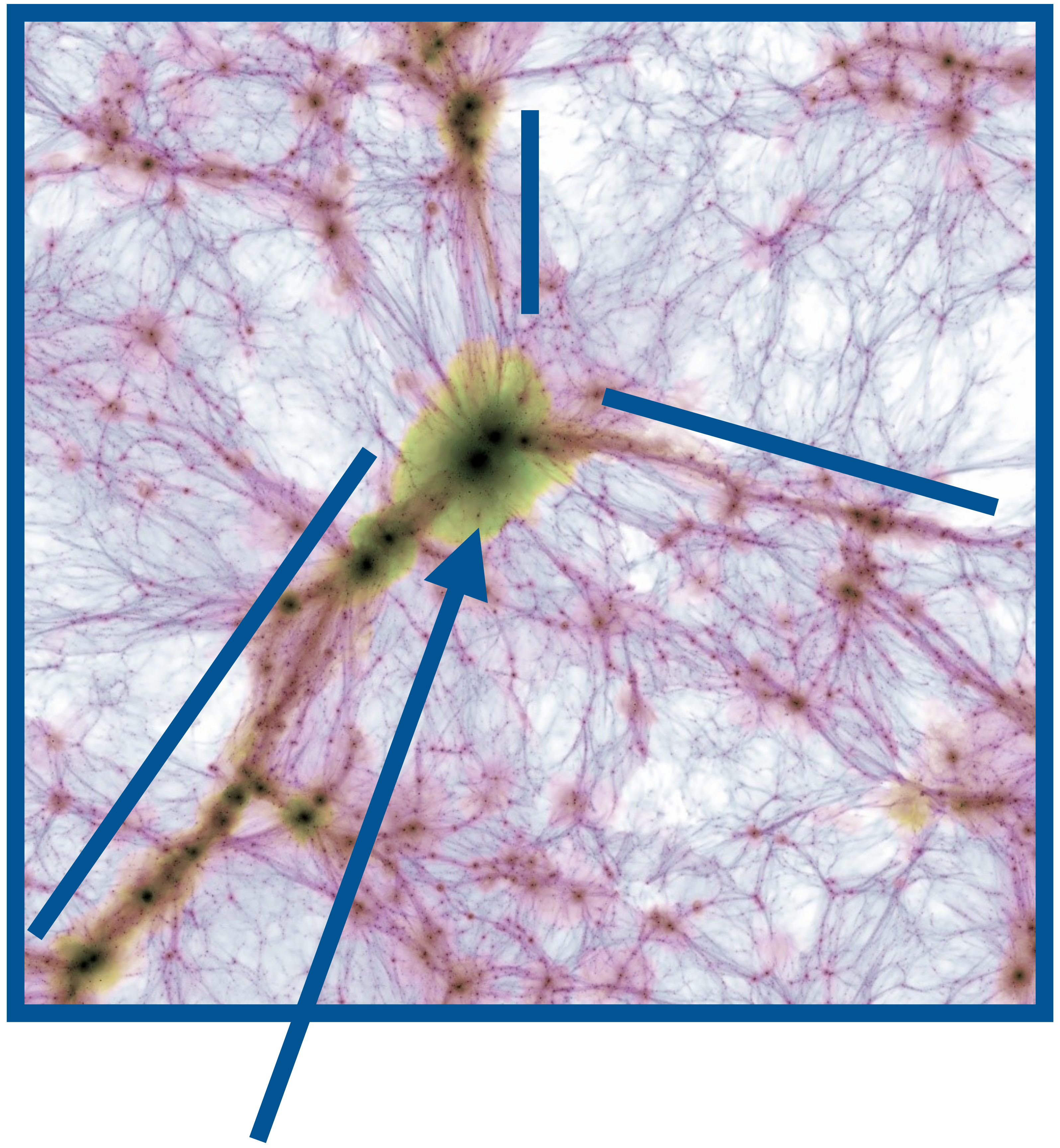
Nicola Malavasi
Marie Skłodowska-Curie Fellow, MPE - Garching

The astrophysics of large-scale structures in the era of eROSITA, Euclid, SPT-3G: the emergence of the cosmic web
IFPU Focus Week - 09/09/2025

The cosmic web

Network of connected structures made of galaxies, dark matter, and gas.
The cosmic web impacts the formation of structures and the formation of galaxies.





Clusters as nodes connected by filaments.

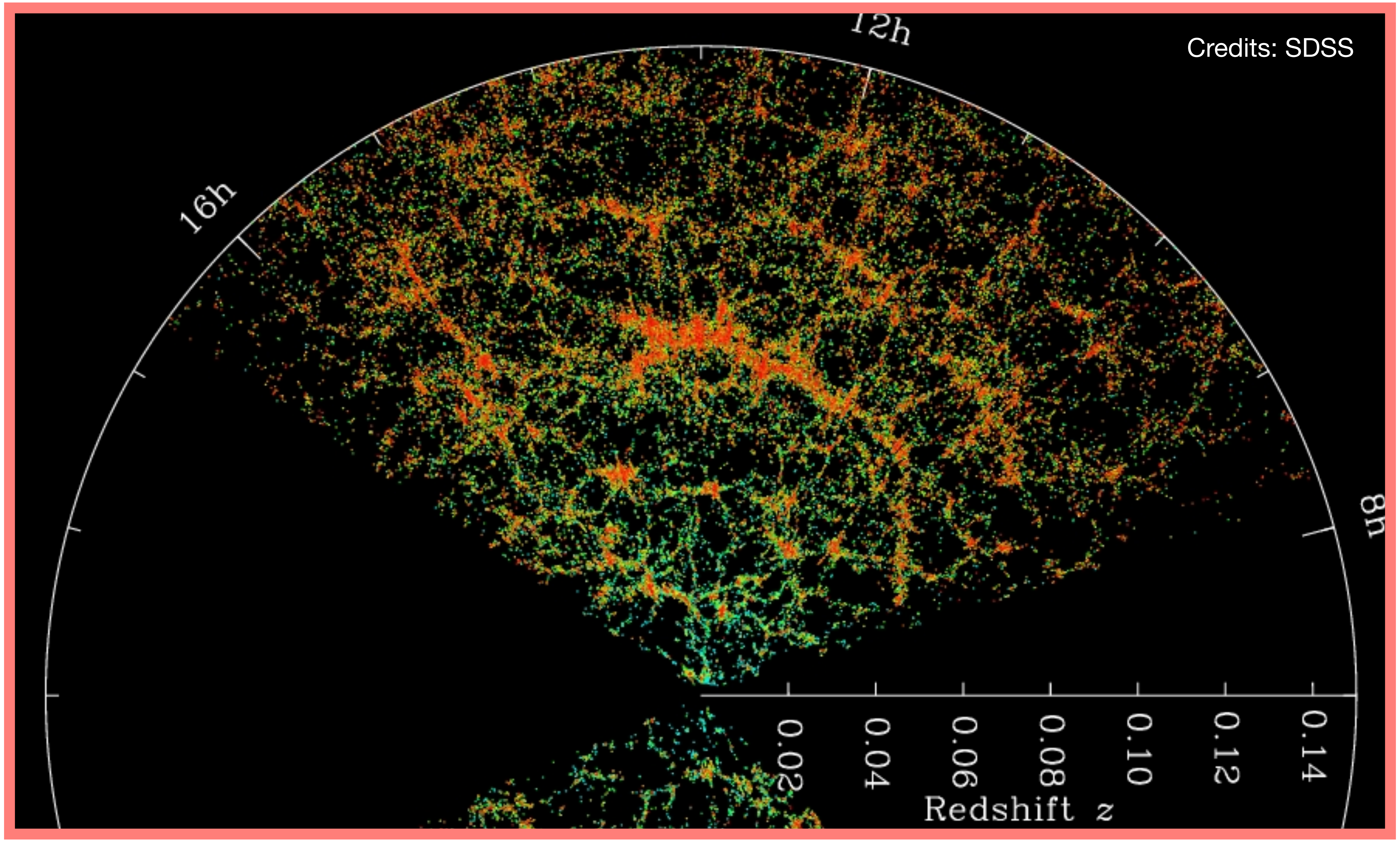
Credits: IllustrisTNG

Aragón-Calvo+10, Cautun+14, Ganeshaiah-Veena+18,19,21, …

Observations
Simulations

Properties of the cosmic web

Multi-structure

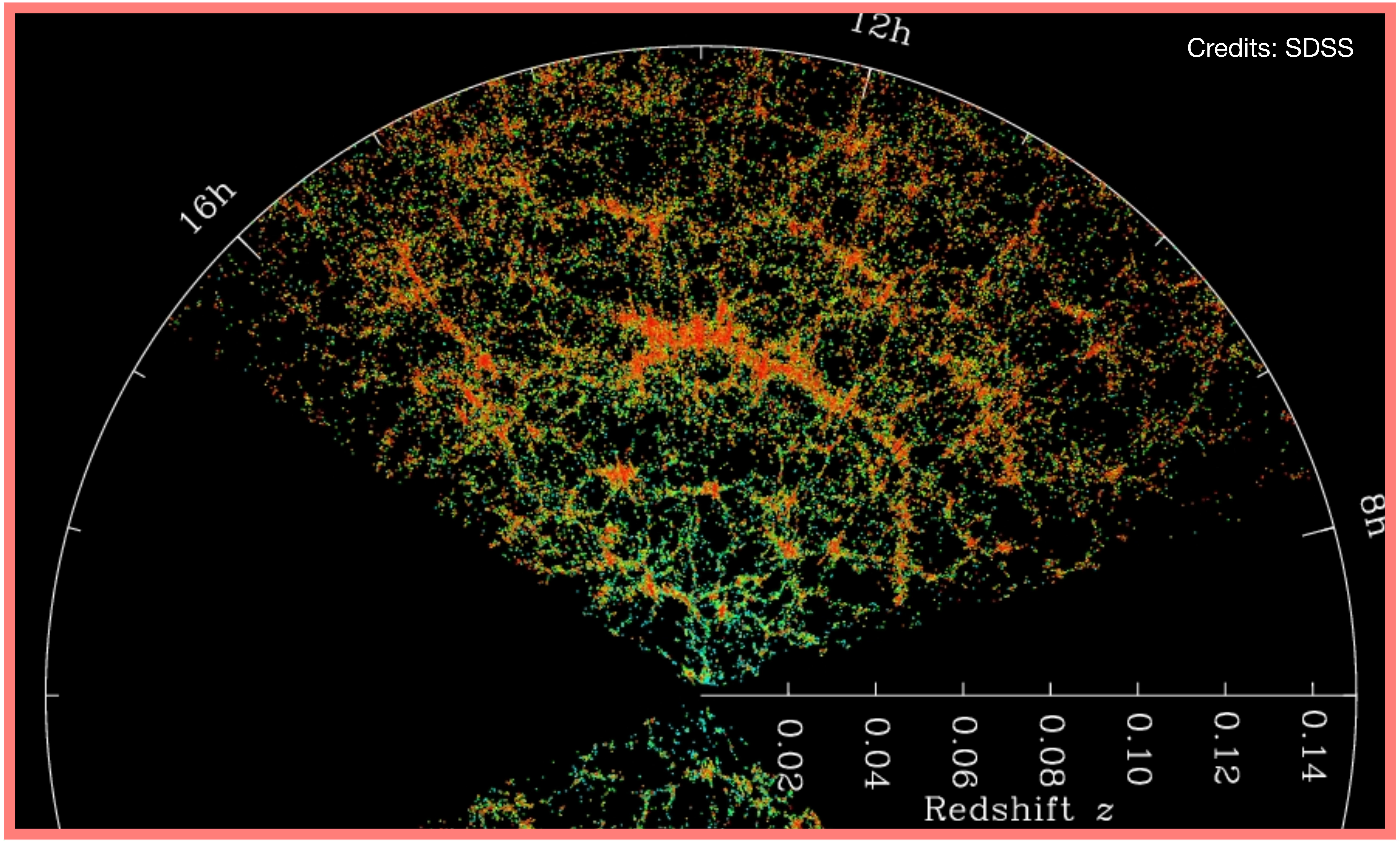


Observations
Simulations

Properties of the cosmic web

Multi-structure

The cosmic web is multi-structure:



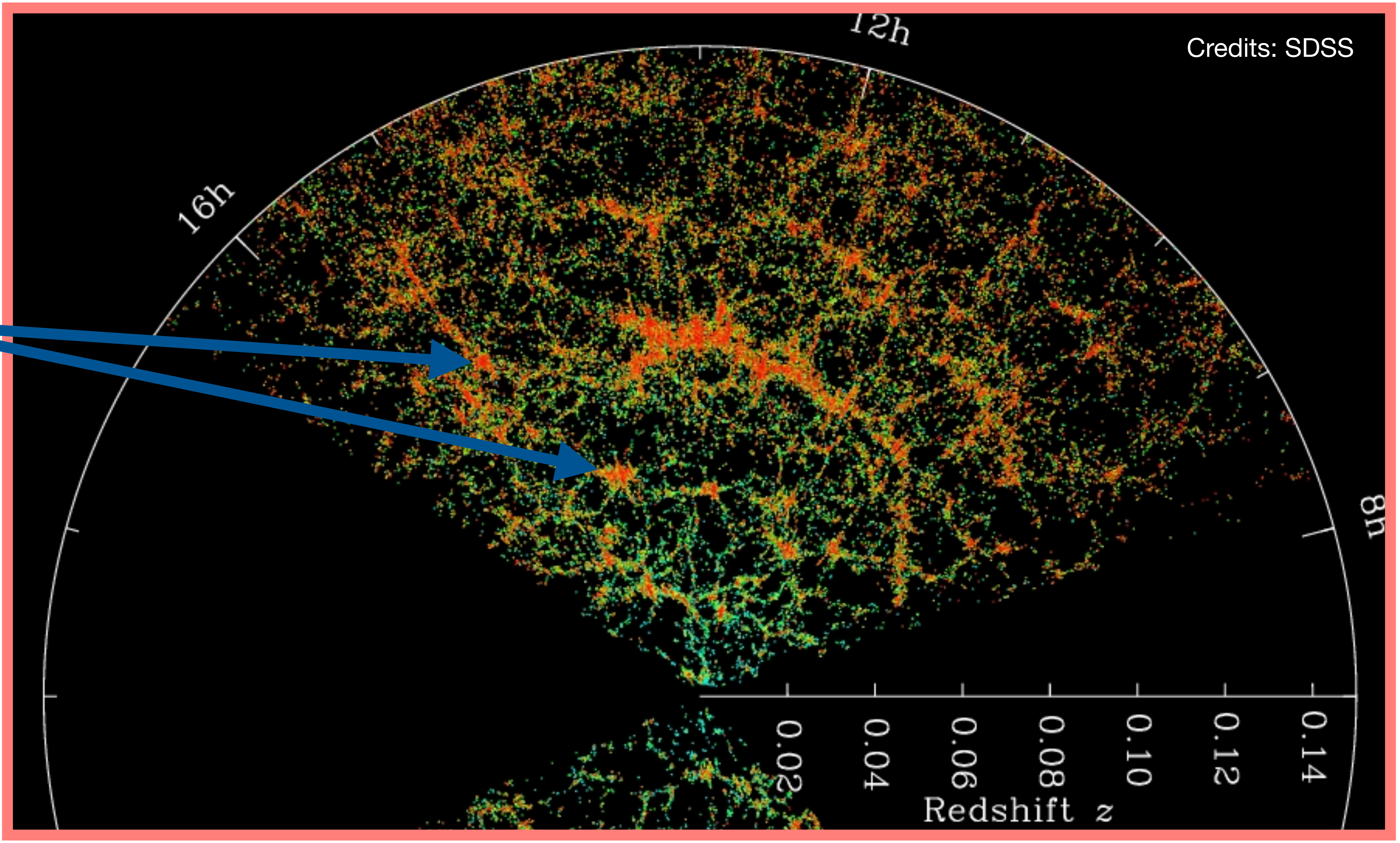
Observations
Simulations

Properties of the cosmic web

Multi-structure

The cosmic web is multi-structure:

- Clusters (~spherical)

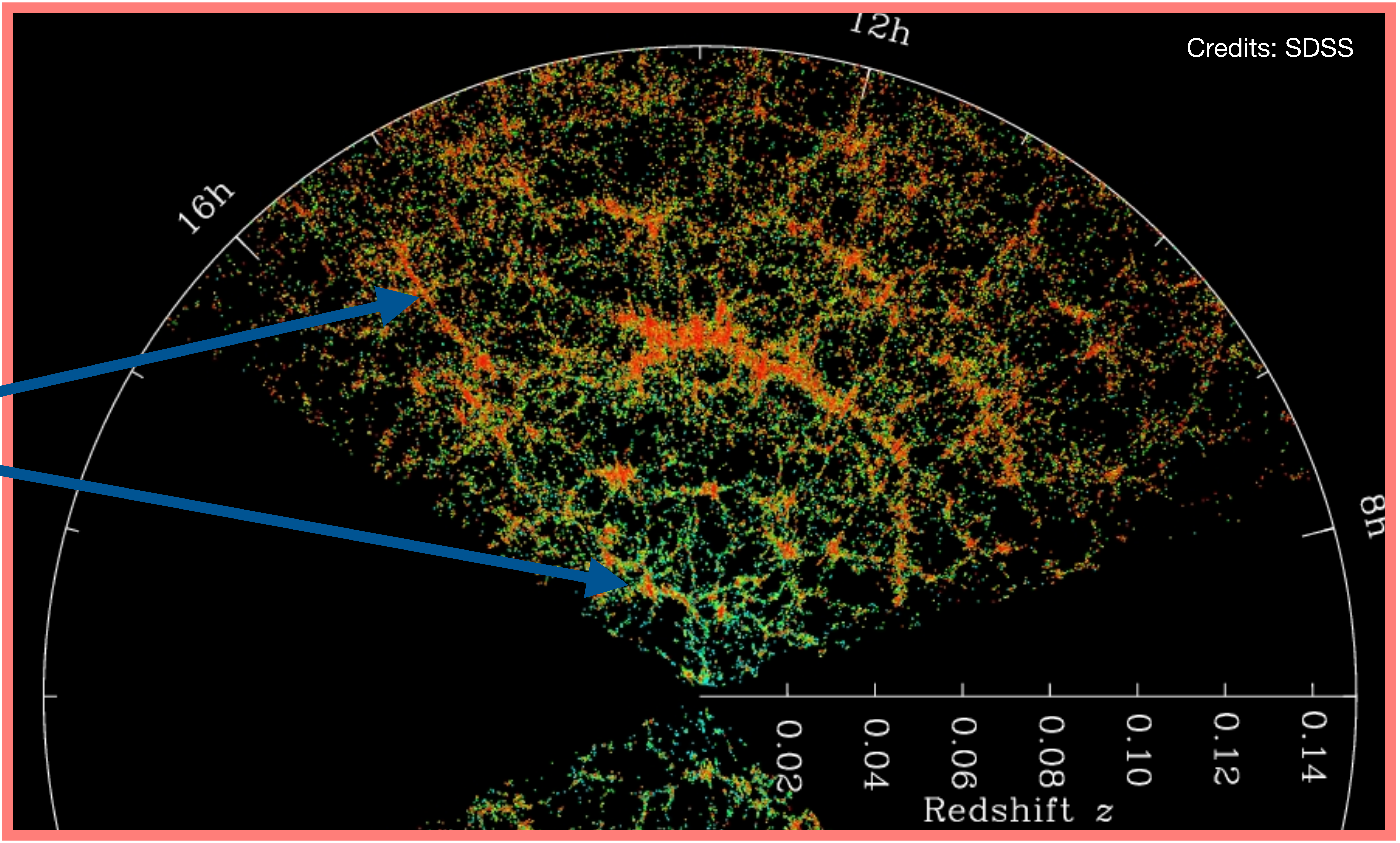


Properties of the cosmic web

Multi-structure

The cosmic web is multi-structure:

- Clusters (~spherical)
- Filaments (linear, anisotropic)



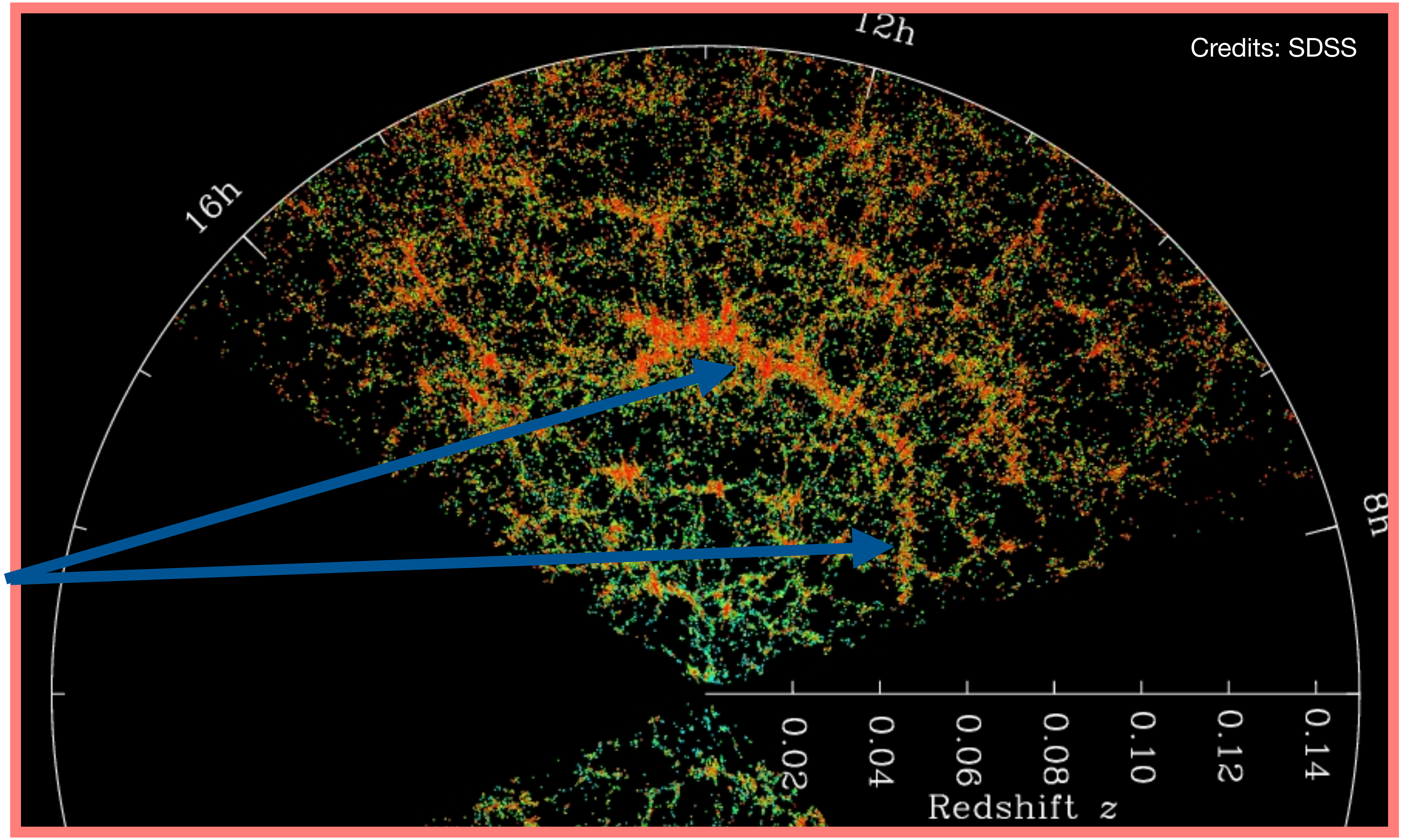
Observations
Simulations

Properties of the cosmic web

Multi-structure

The cosmic web is multi-structure:

- Clusters (~spherical)
- Filaments (linear, anisotropic)
- Walls (planar, anisotropic)



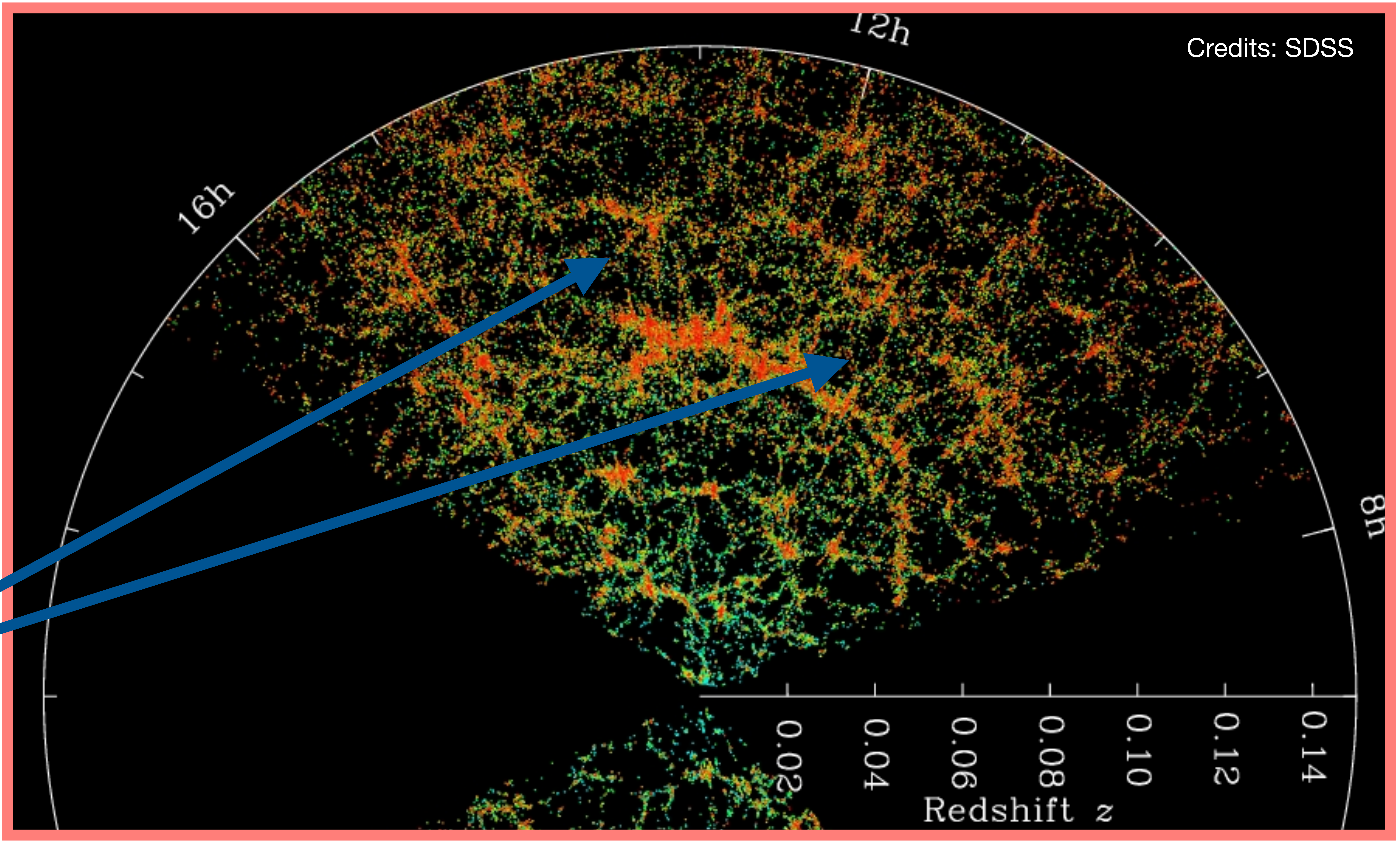
Observations
Simulations

Properties of the cosmic web

Multi-structure

The cosmic web is multi-structure:

- Clusters (~spherical)
- Filaments (linear, anisotropic)
- Walls (planar, anisotropic)
- Voids (~spherical)

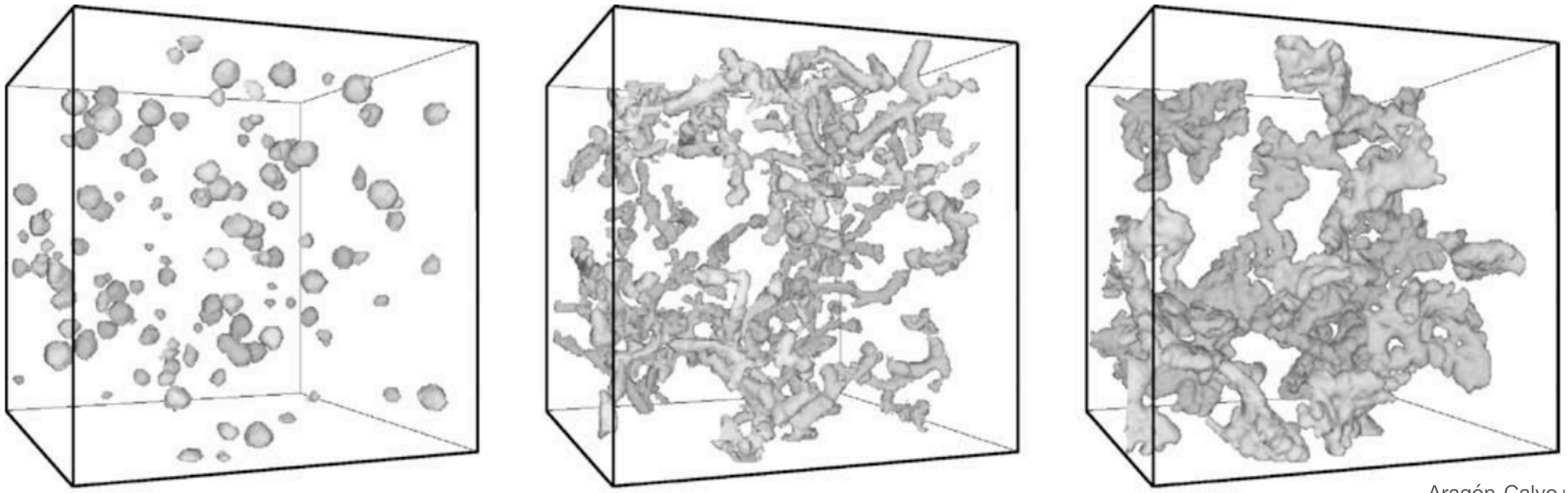


Properties of the cosmic web

Multi-structure

Anisotropy →

Clusters (isotropic) | Filaments (anisotropic) | Walls (anisotropic)

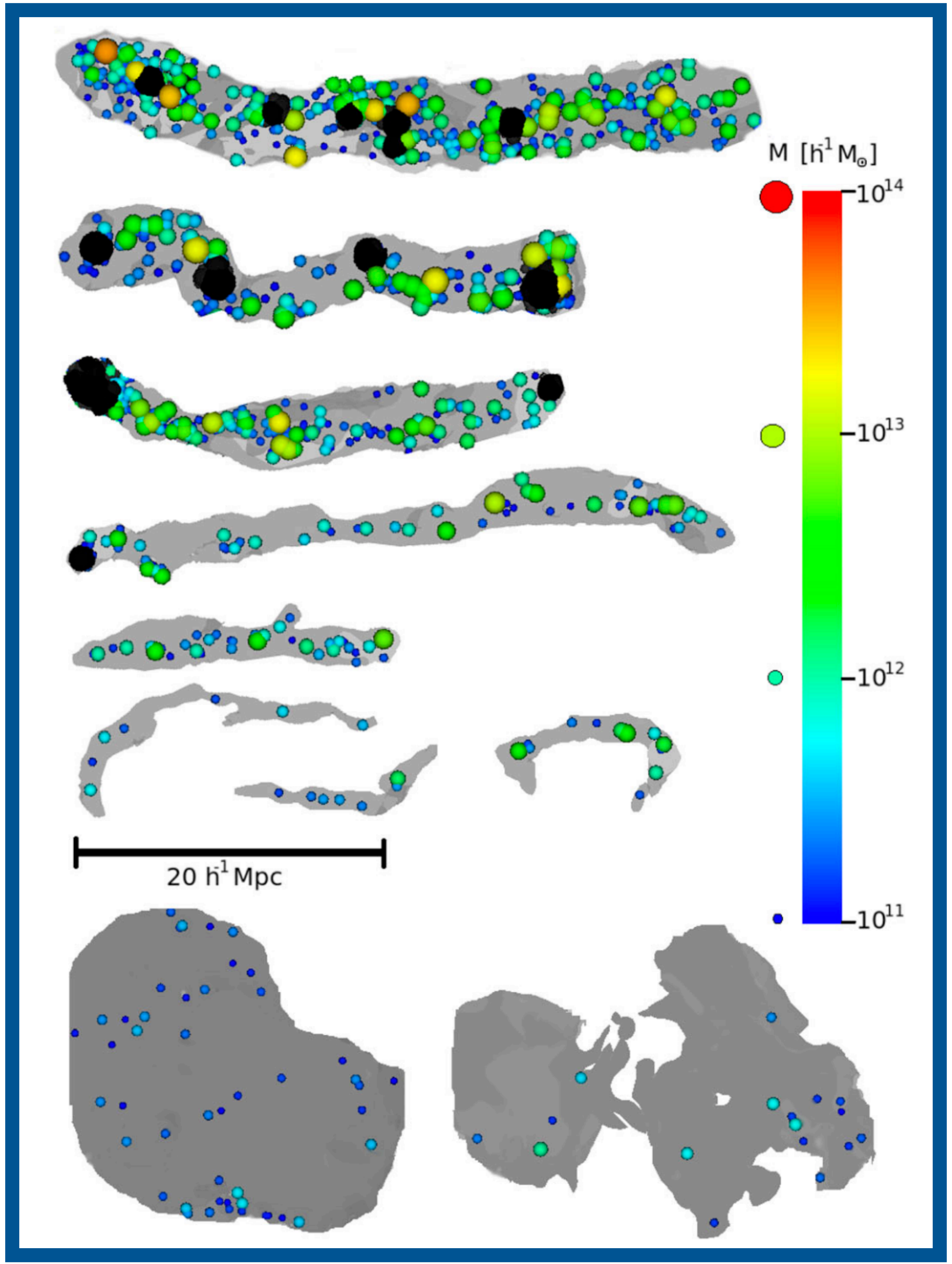


Aragón-Calvo+10

Properties of the cosmic web

Multi-scale

Cautun+14



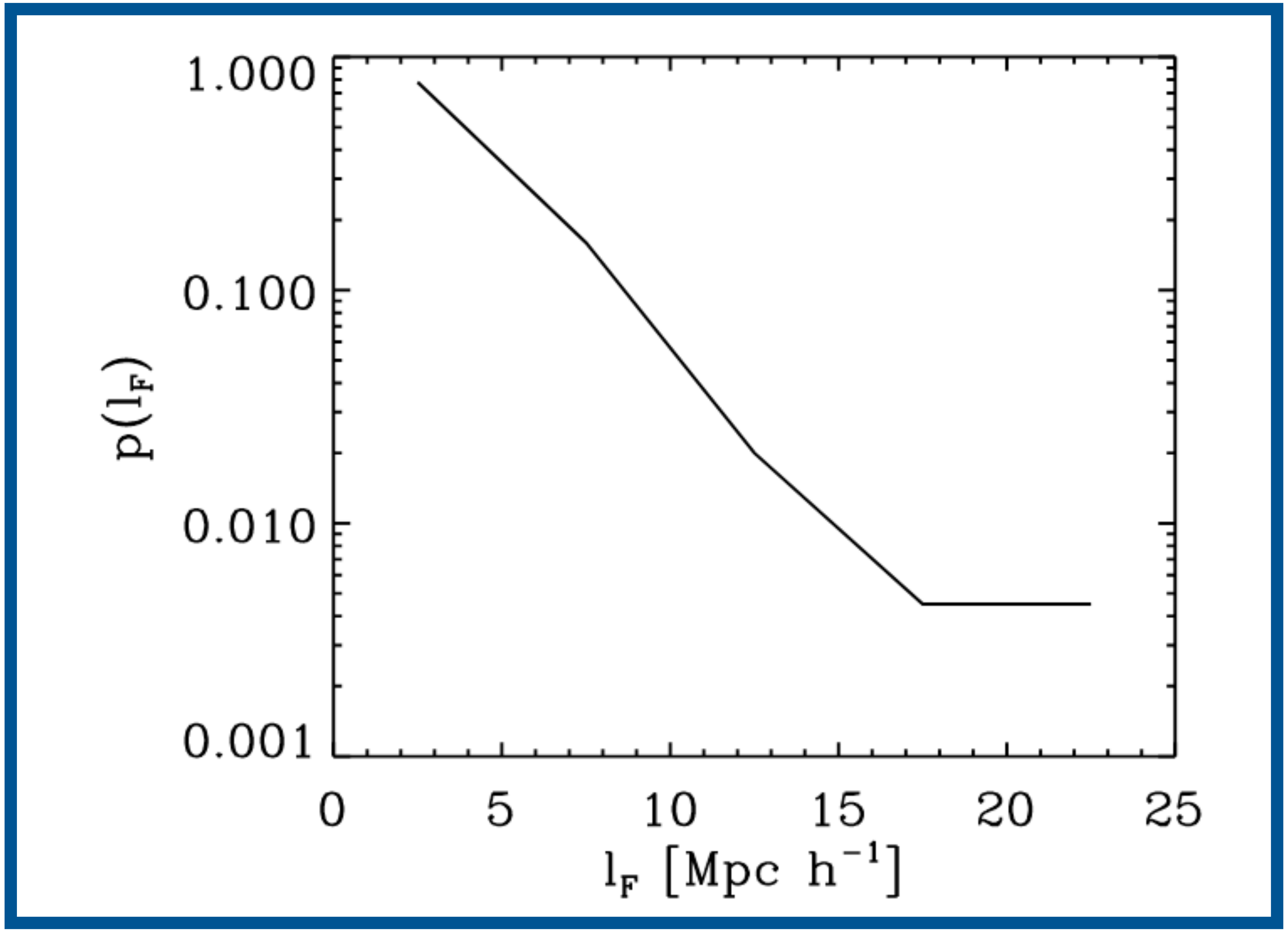
Large distribution of sizes

- Clusters vs groups (nodes vs knots).
- Small filaments vs large filaments (bridges). Galárraga-Espinosa+20, …
- Filament length distribution.
  Aragón-Calvo+10, Malavasi+20, …
- Size distribution for voids.
  Contarini+23, …
- **Very important: density distribution for structures of the cosmic web.**

Properties of the cosmic web

Multi-scale

Aragón-Calvo+10



Large distribution of sizes

- Clusters vs groups (nodes vs knots).
- Small filaments vs large filaments (bridges). Galárraga-Espinosa+20, …
- Filament length distribution.
  Aragón-Calvo+10, Malavasi+20, …
- Size distribution for voids.
  Contarini+23, …
- **Very important: density distribution for structures of the cosmic web.**

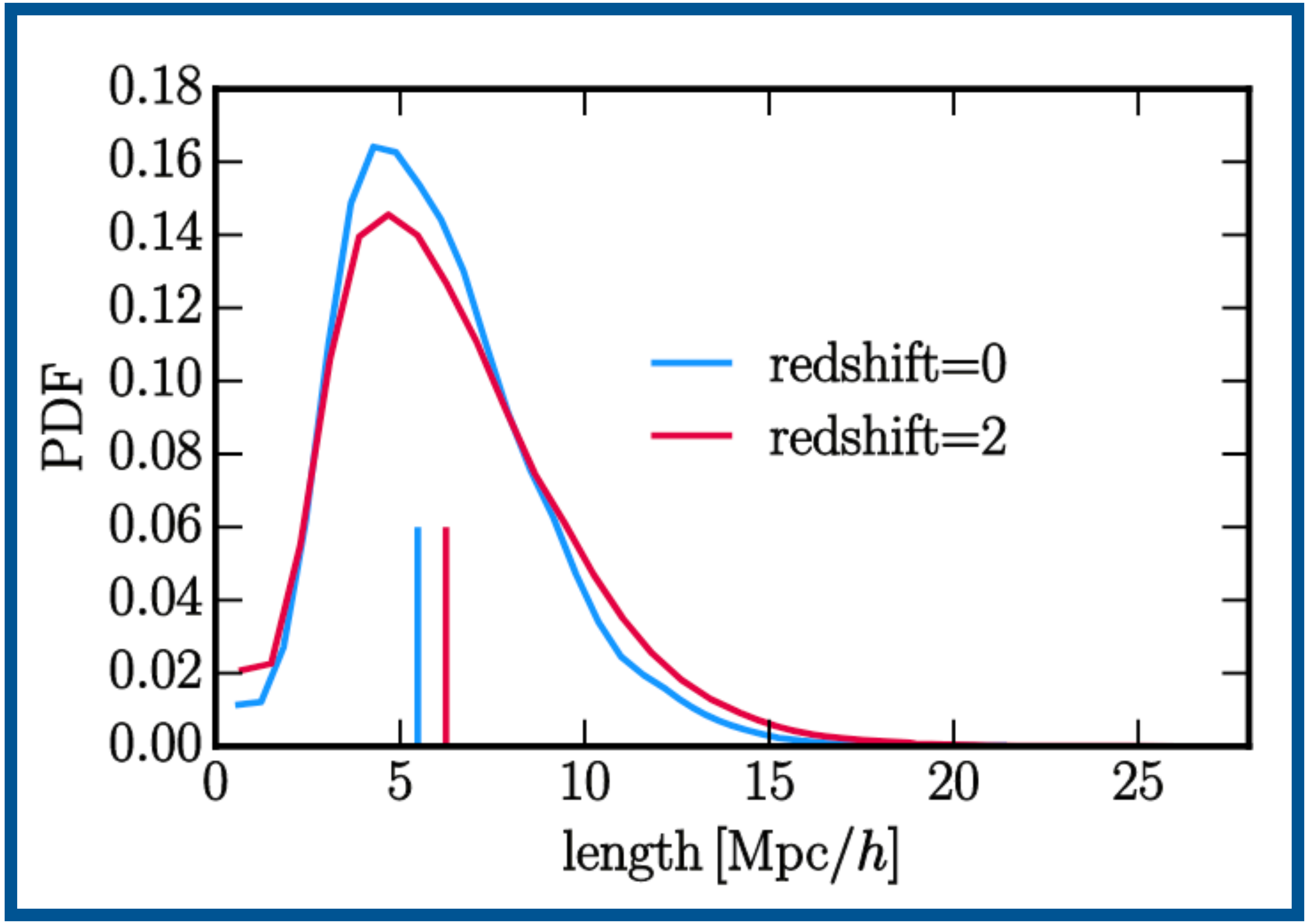
Properties of the cosmic web

Multi-scale

Kraljic+18

Large distribution of sizes

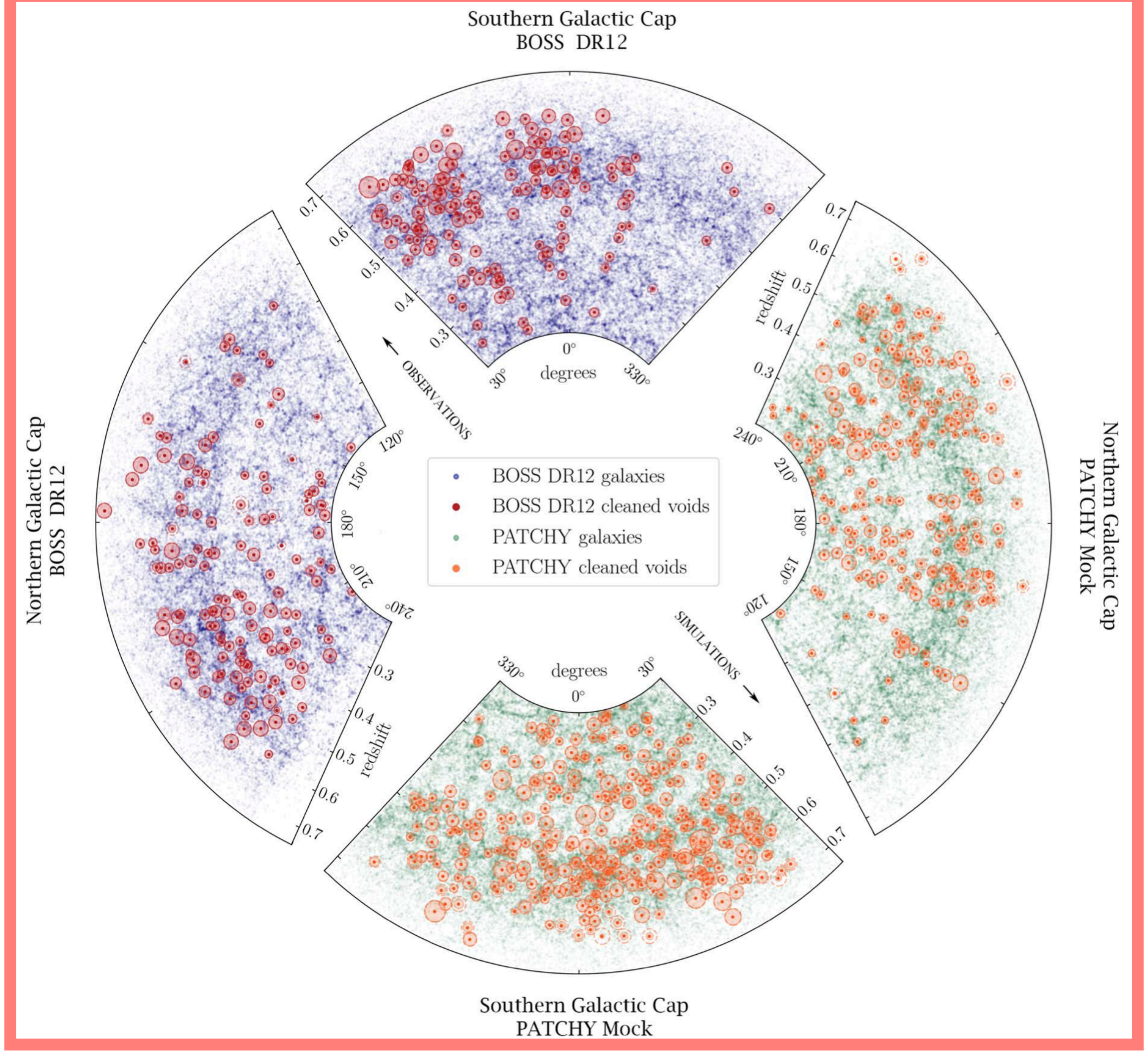
- Clusters vs groups (nodes vs knots).
- Small filaments vs large filaments (bridges). Galárraga-Espinosa+20, …
- Filament length distribution. Aragón-Calvo+10, Malavasi+20, …
- Size distribution for voids. Contarini+23, …
- **Very important: density distribution for structures of the cosmic web.**



Properties of the cosmic web

Multi-scale

Contarini+23



Large distribution of sizes

- Clusters vs groups (nodes vs knots).
- Small filaments vs large filaments (bridges). Galárraga-Espinosa+20, …
- Filament length distribution.
  Aragón-Calvo+10, Malavasi+20, …
- Size distribution for voids.
  Contarini+23, …
- **Very important: density distribution for structures of the cosmic web.**

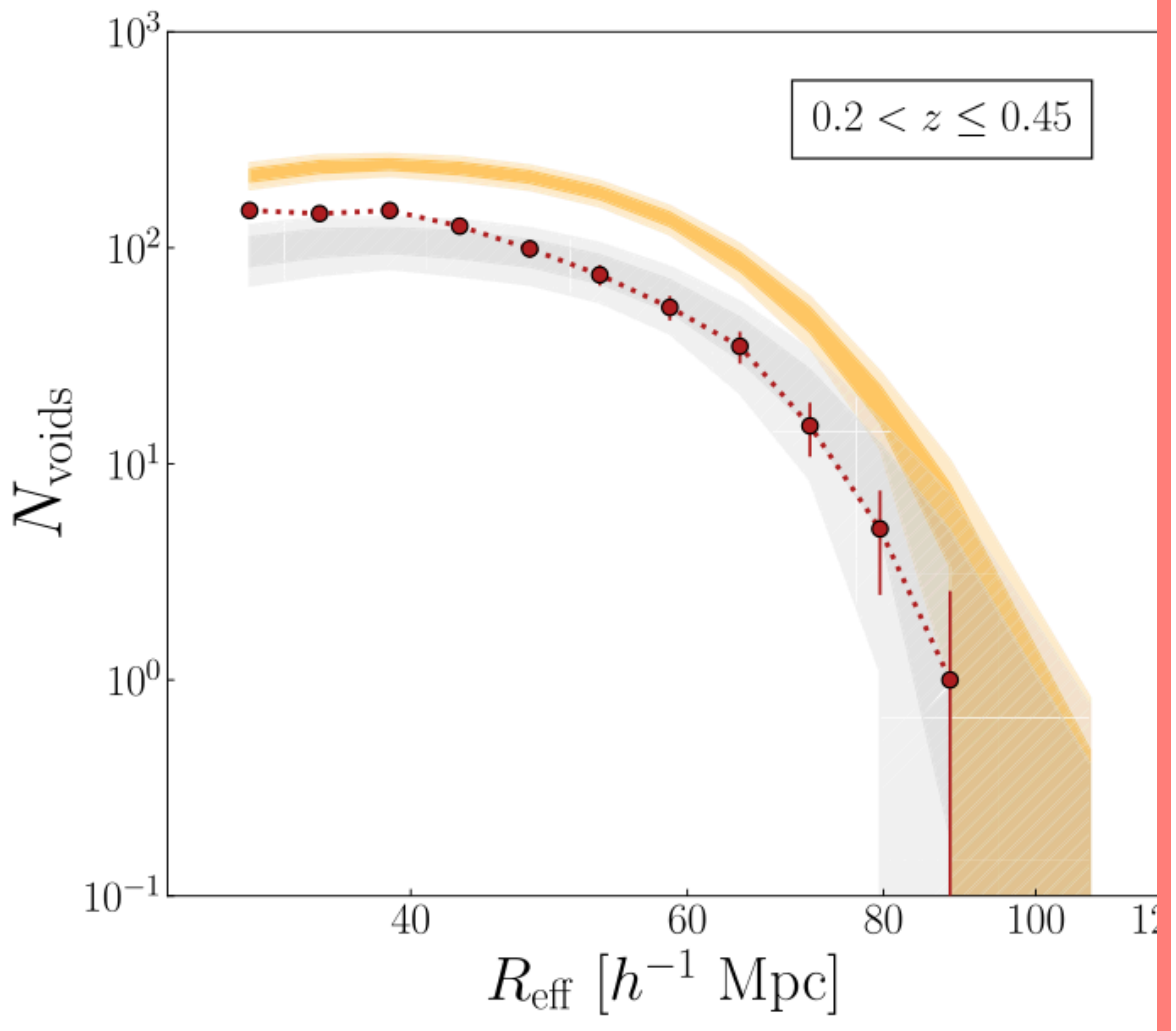
Properties of the cosmic web

Multi-scale

Contarini+23

Large distribution of sizes

- Clusters vs groups (nodes vs knots).
- Small filaments vs large filaments (bridges). Galárraga-Espinosa+20, …
- Filament length distribution.
  Aragón-Calvo+10, Malavasi+20, …
- Size distribution for voids.
  Contarini+23, …
- **Very important: density distribution for structures of the cosmic web.**



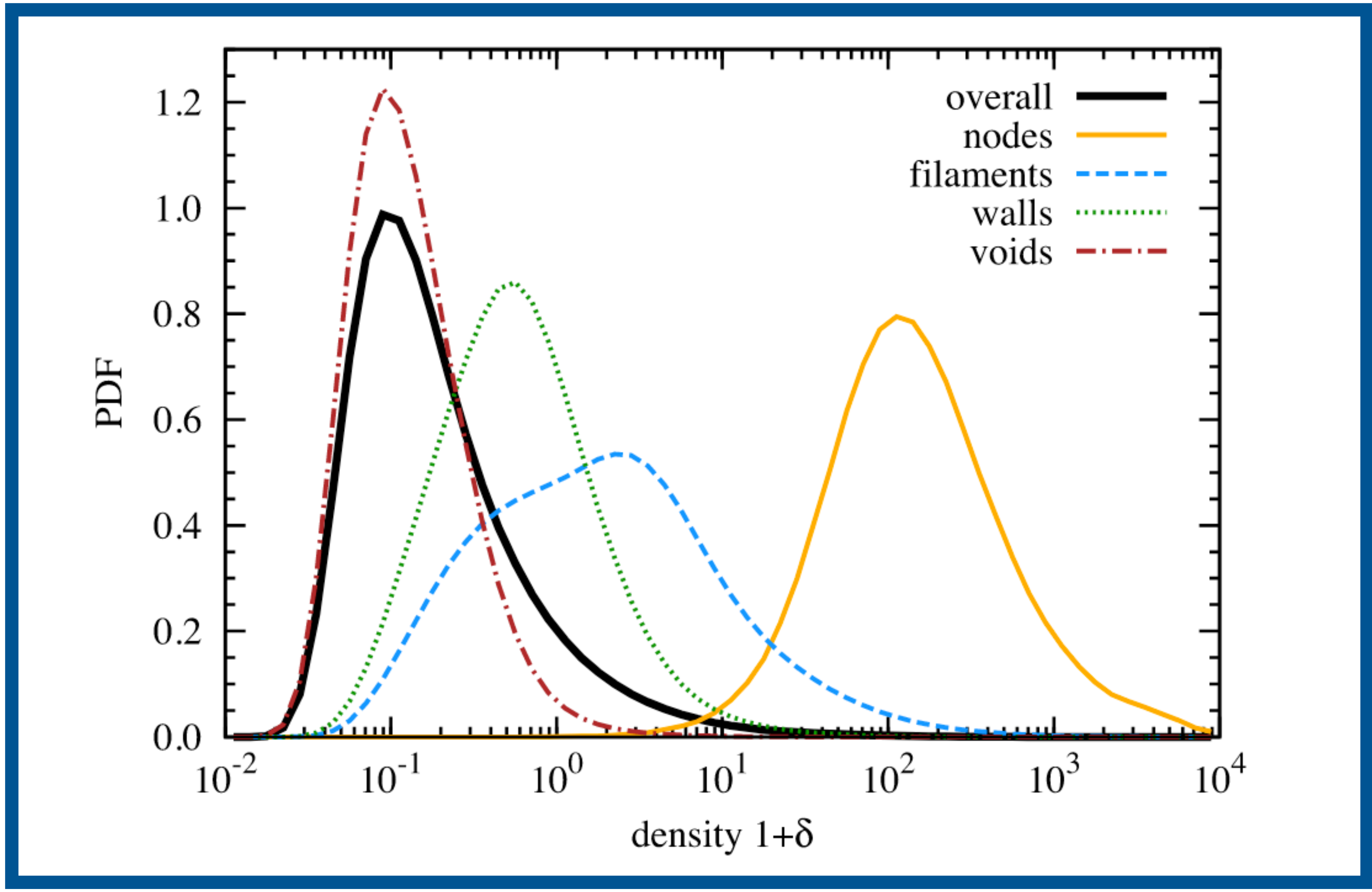
Properties of the cosmic web

Multi-scale

Cautun+14

Large distribution of sizes

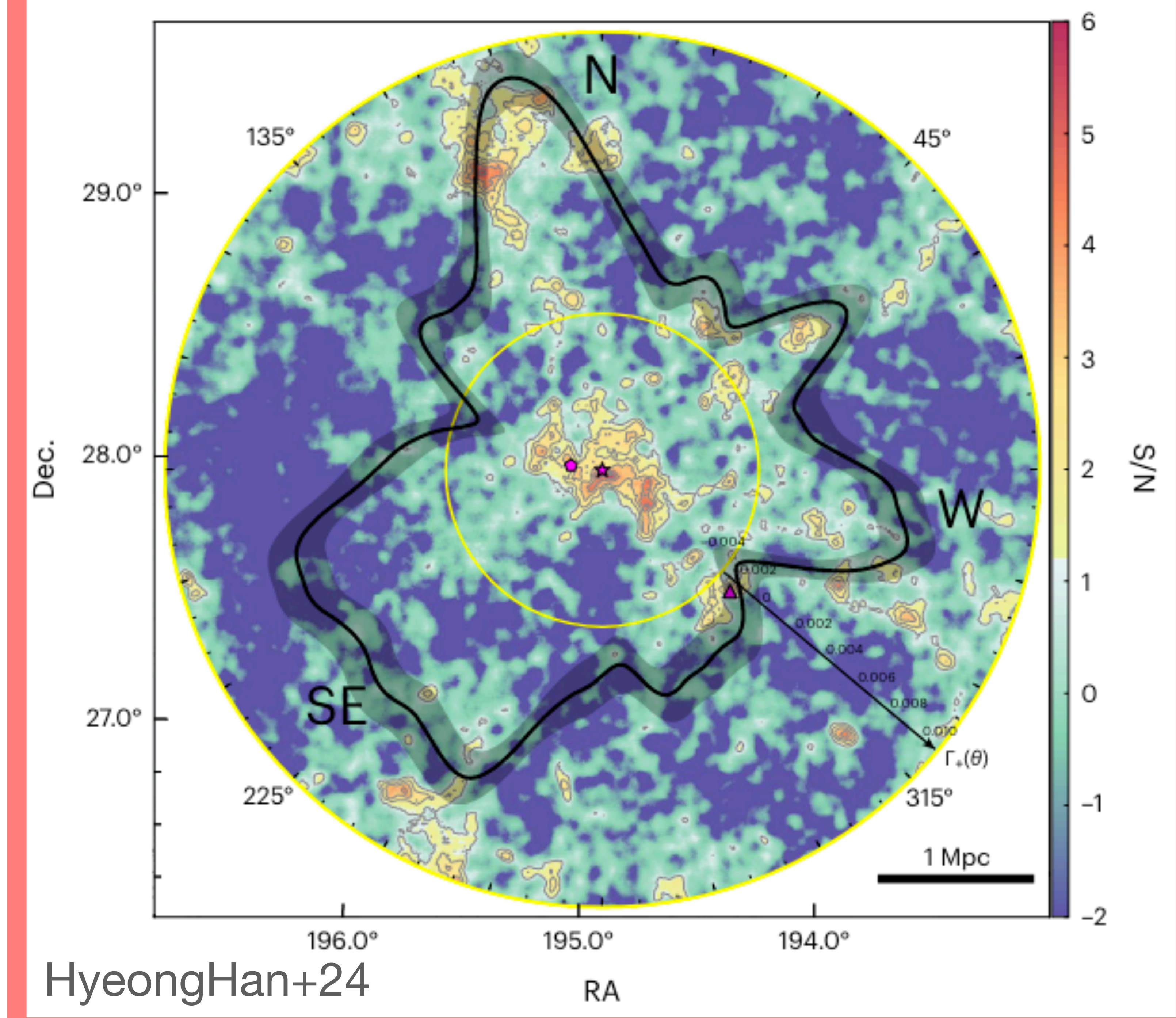
- Clusters vs groups (nodes vs knots).
- Small filaments vs large filaments (bridges). Galárraga-Espinosa+20, …
- Filament length distribution.
  Aragón-Calvo+10, Malavasi+20, …
- Size distribution for voids.
  Contarini+23, …
- **Very important: density distribution for structures of the cosmic web.**



Properties of the cosmic web

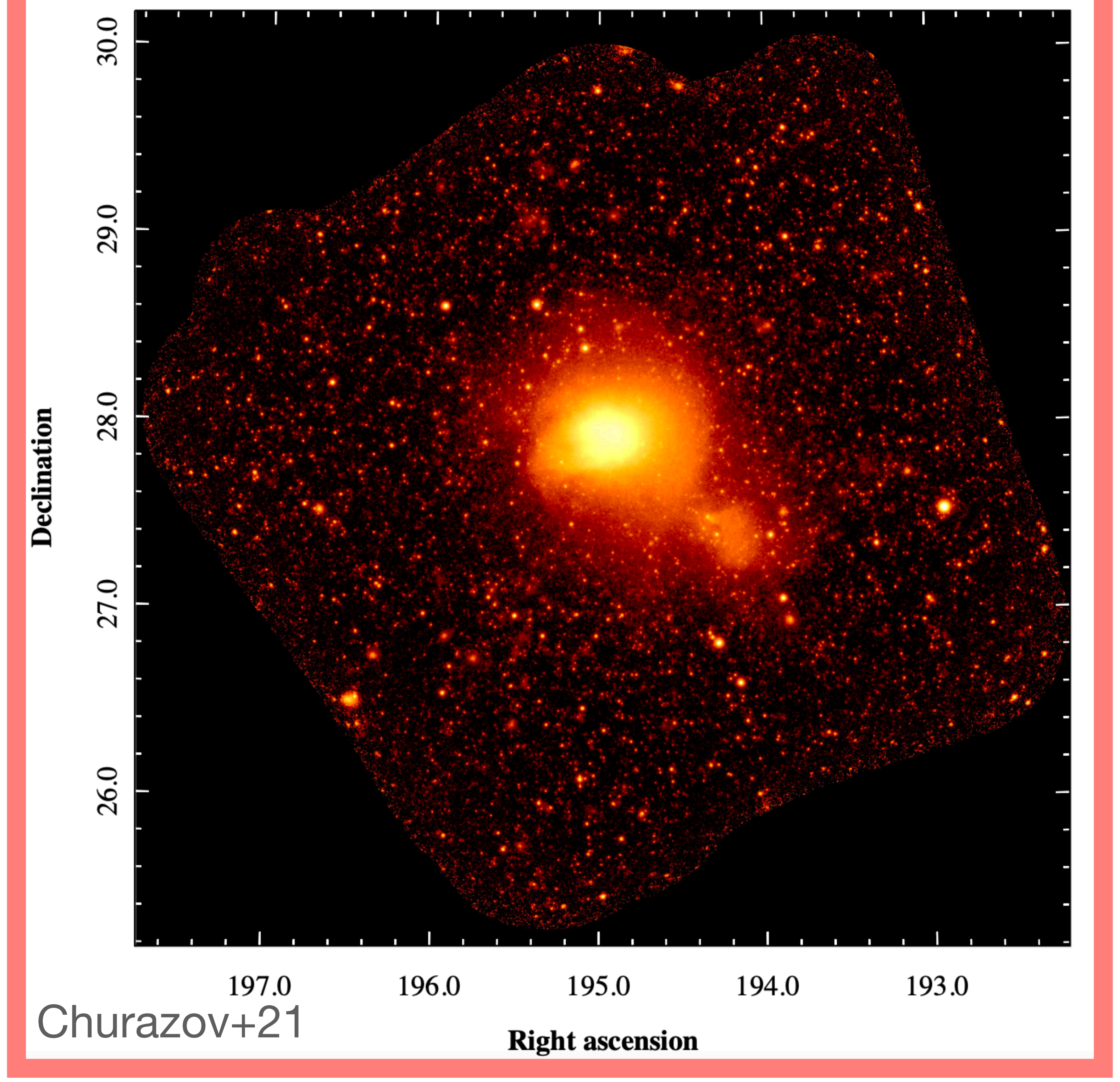
Multi-component

Dark matter



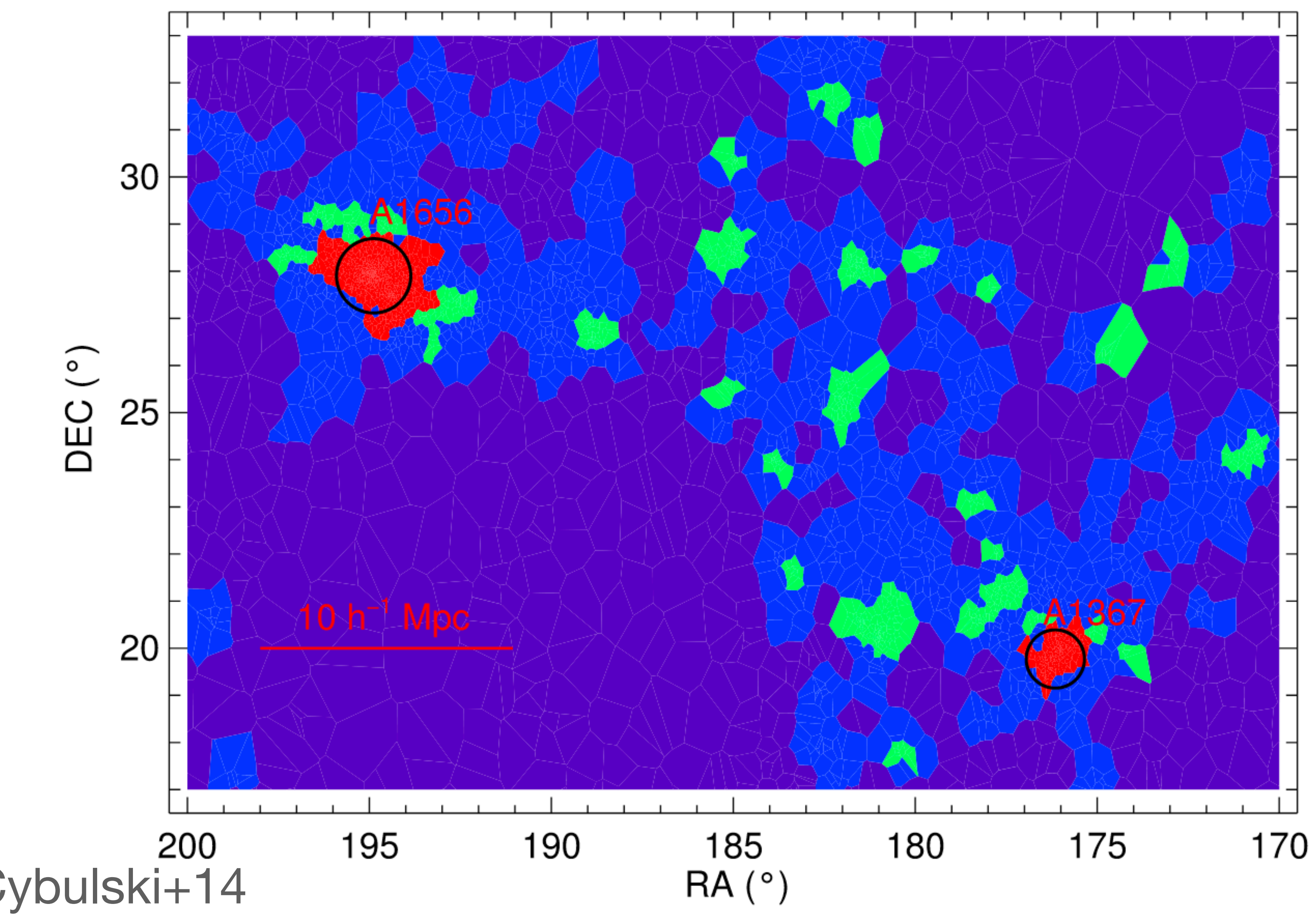
HyeongHan+24

Gas



Churazov+21

Galaxies



Cybulski+14

Properties of the cosmic web

Evolving

Matter departs from voids, flows in walls and filaments to reach clusters.

Credits: IllustrisTNG

Properties of the cosmic web

Evolving

Matter departs from voids, flows in walls and filaments to reach clusters.

Credits: IllustrisTNG

How do we detect the cosmic web?

Two main ingredients:

- **Tracers**
  - Dark Matter (Lensing? Relevant in simulations)
  - Gas (X-ray, SZ, Radio)
  - **Galaxies (Discrete tracer, position is important: redshift!)**
- **Method**
  - Visual identification, density, or surface brightness cut (relevant for diffuse emission)
  - **Algorithm, takes the tracer as input, outputs a catalogue of cosmic web elements**

In the following I will mainly focus on filaments detected from the galaxy distribution. However cluster detection and void detection can also be considered as part of the detection of the cosmic web!

How do we detect the cosmic web?

Using galaxies

Galaxy positions: coordinates and redshift

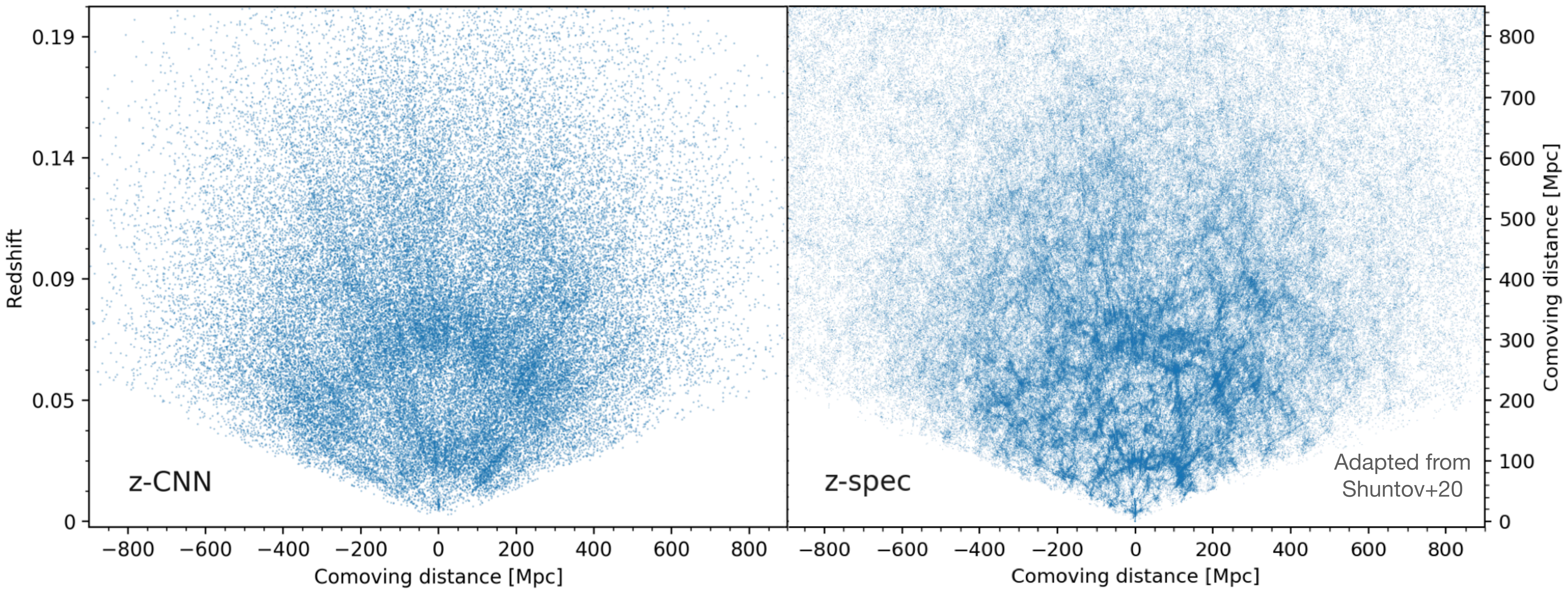
Ideal candidate: redshift survey

- **Redshift precision:** affects galaxy positioning along the line of sight.
- **Contiguous area:** gaps, holes and borders create problems to algorithms. Small fields prevent reconstruction near clusters.
- **Galaxy sampling:** sparse sampling means lower resolution in reconstruction.
- **Type of tracers (bias):** all galaxies above mass/magnitude cut or particular galaxy populations (e.g. quasars, LAEs, red/blue galaxies, …)? Sarron, …, NM et al. to be submitted

Redshift precision

Photometric redshifts: generally permit reconstruction in 2D in redshift slices.

Spectroscopic redshifts: generally permit reconstruction in 3D.

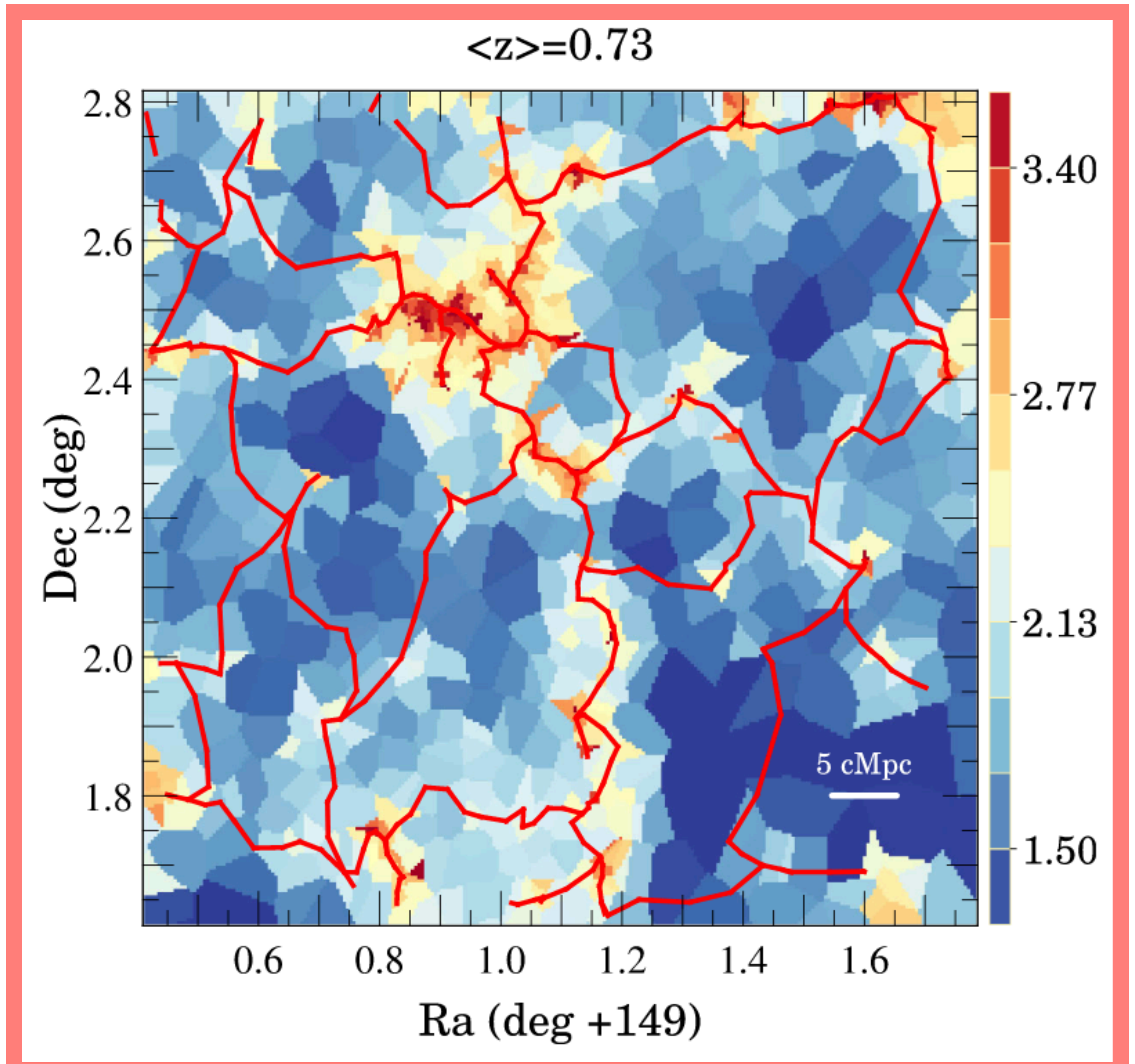


See also: Cooper+05, Malavasi+15, Etherington+15, Cucciati+16, Muldrew+12, Malavasi+25, …

Redshift precision

Photometric redshifts: generally allow to reach higher redshifts on larger areas.

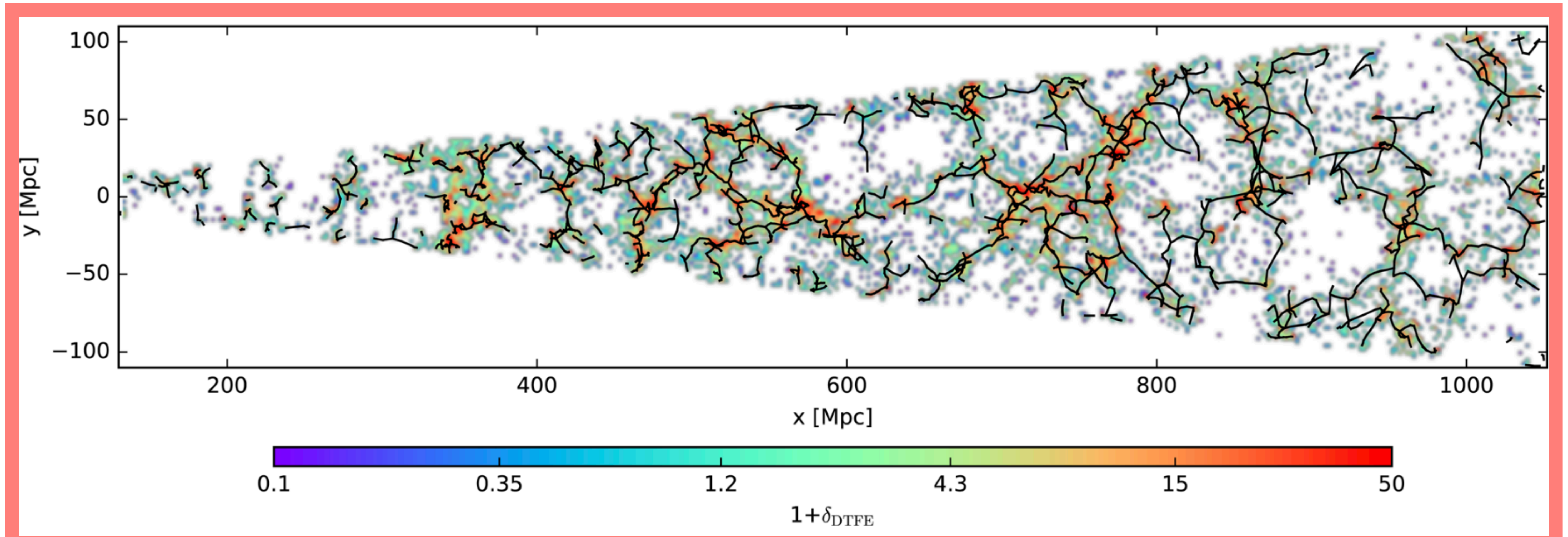
Laigle+18



Cosmic web in COSMOS2015 with photo-z up to z = 0.9.

Spectroscopic redshifts: generally allow to reach only lower redshifts.

Kraljic+18



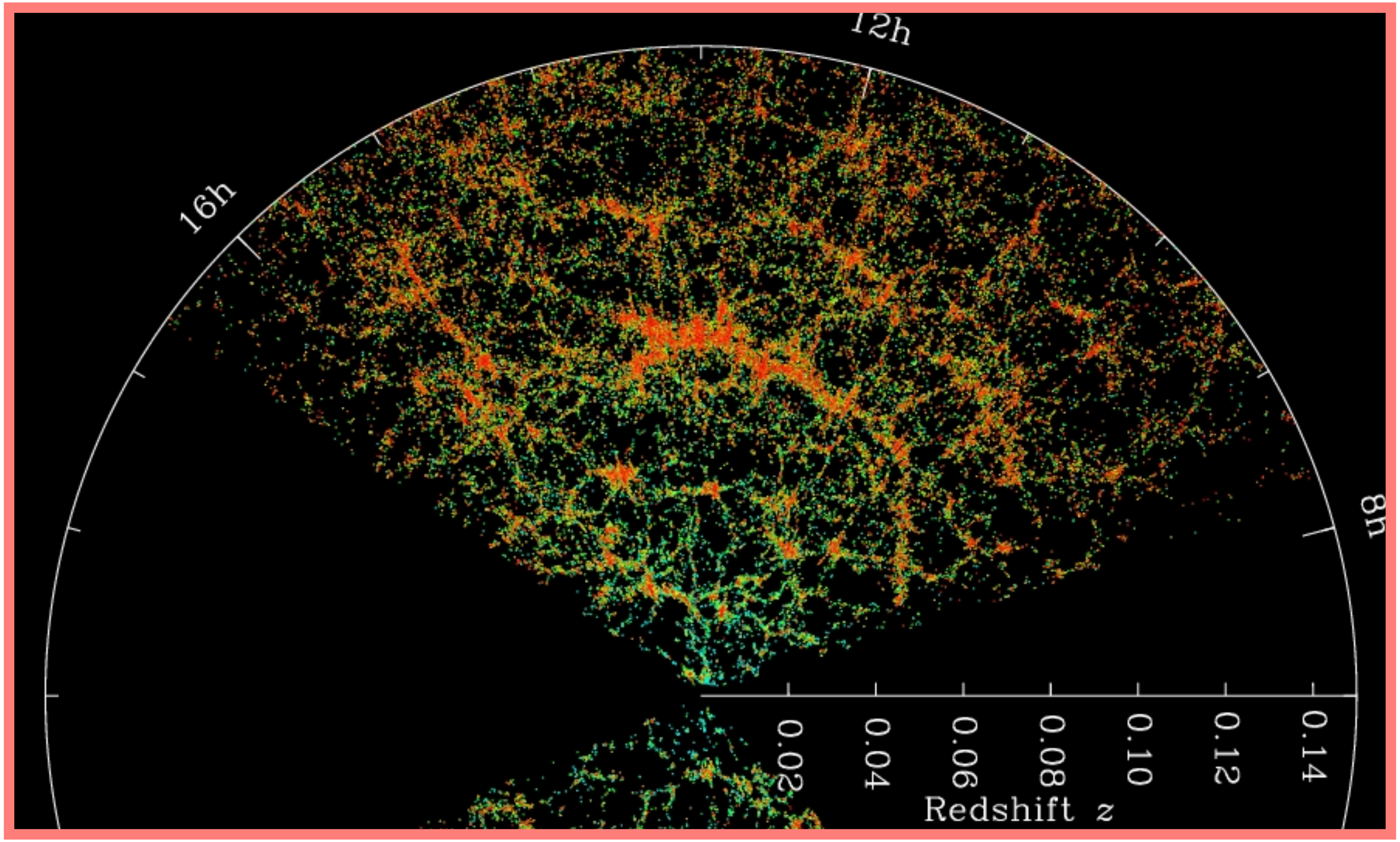
Cosmic web in GAMA up to z = 0.25.

Going beyond the state-of-the-art

Spec-z

In the case of spectroscopic redshifts:

compressing the FoG effect to avoid distortions along the LoS



w/ FoG
w/o FoG
Kraljic+2018
y [Mpc]
x [Mpc]
100
50
0
−50
−100
200
400
600
800
1000
5-7
8-10
11-14
15-19
20-24
25-29
30-54
>=55
number of group members

Going beyond the state-of-the-art

Photo-z

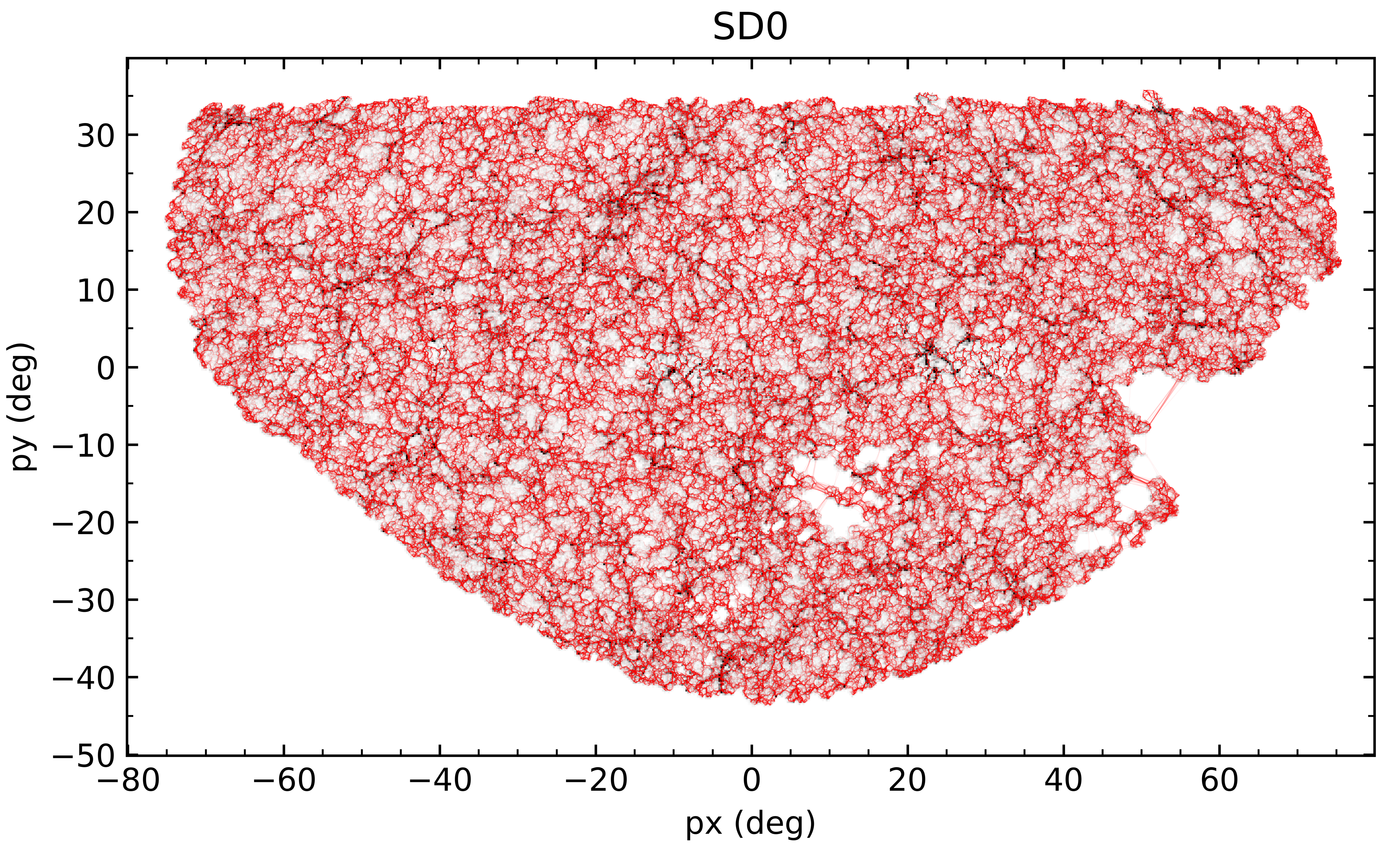
Malavasi et al. to be submitted

z = 0.166

In the case of photometric redshifts:

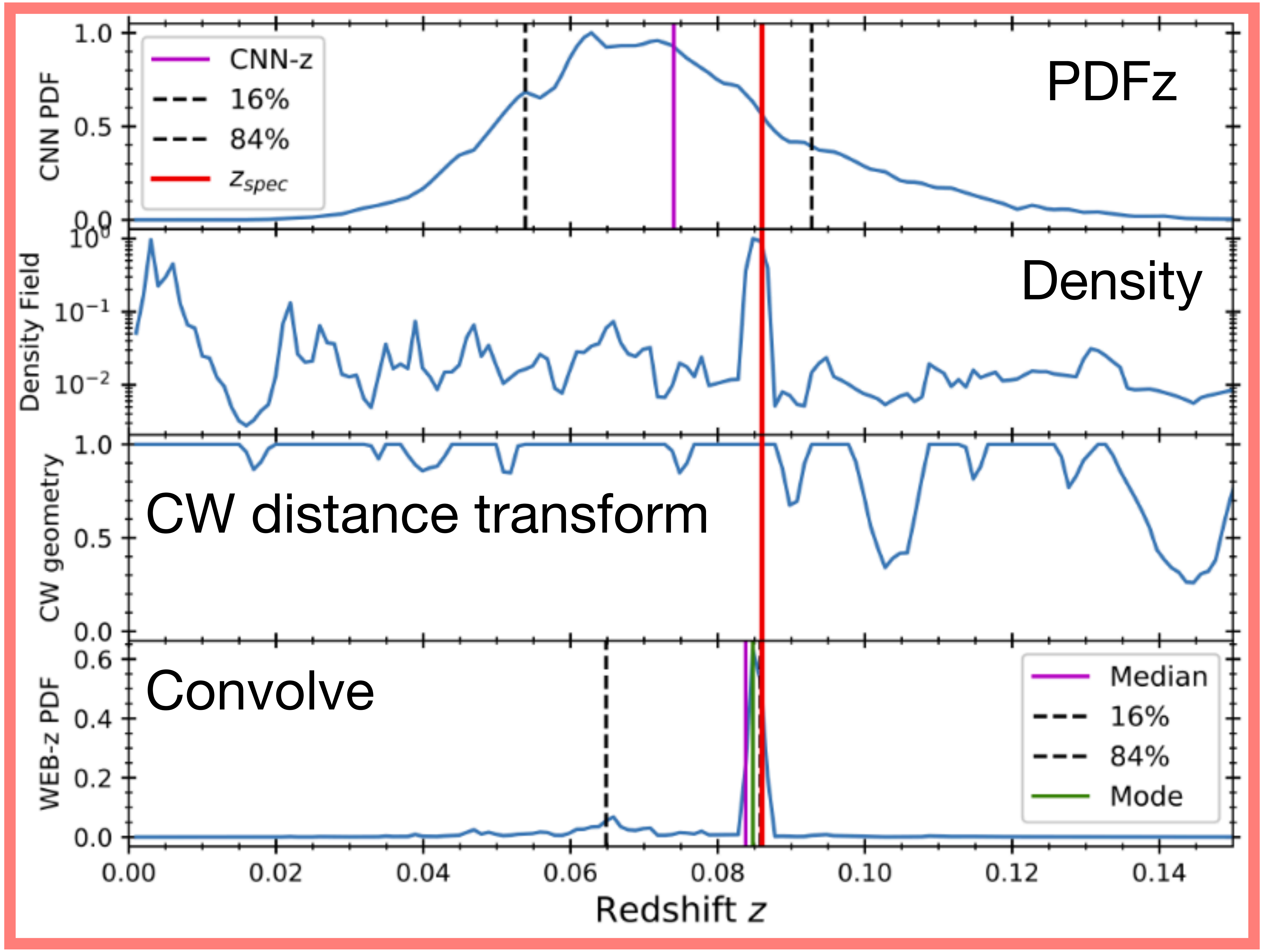
Montecarlo approach: several skeleton extraction with different redshift realizations

Filaments with DisPerSE in the DESI LS with photo-zs.



PhotoWeb: improving photometric redshifts

- Extract the cosmic web on a (spatially) sparsely sampled spec-z sample.
- Convolve with the PDFz of more densely sampled and fainter photo-z sample.
- Obtain greatly improved photo-z with high spatial sampling and faint magnitudes.
- CW from SDSS spec-z, applied to SDSS photo-z: factor > 2 improvement.



Shuntov+20, Aragón-Calvo+15

PhotoWeb: improving photometric redshifts

- Extract the cosmic web on a (spatially) sparsely sampled spec-z sample

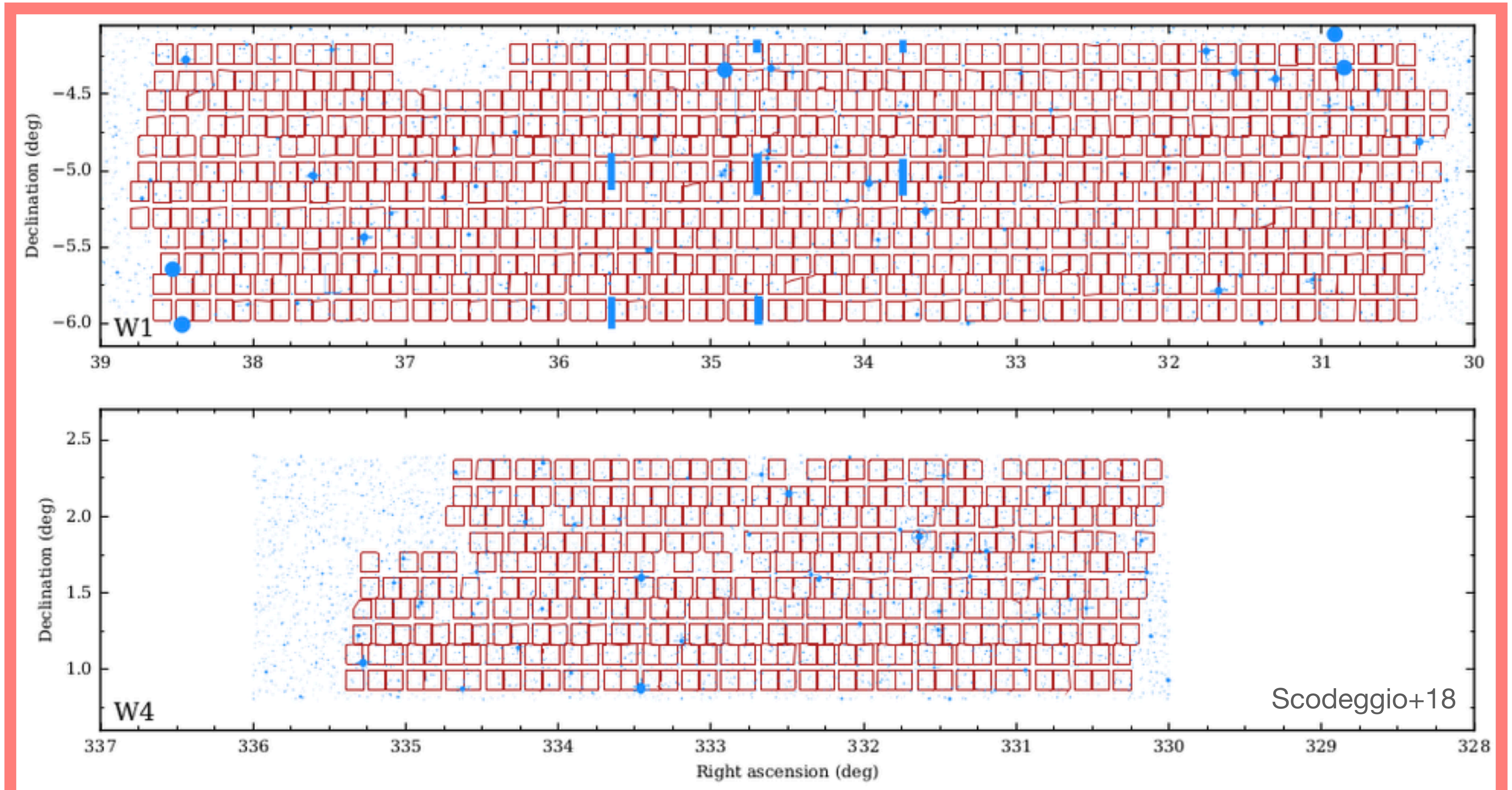
to SDSS photo-z: factor > 2 improvement.

Shuntov+20, Aragón-Calvo+15


z-Web
z-spec
400
600
800
−800
−600
−400
−200
0
200
400
600
800
−800
−600
−40
Comoving distance [Mpc]

Survey contiguous area

- Gaps and holes pose a problem if not properly treated.
- They create artificial low density regions, most of the time internal to the survey.
- Solutions are smoothing, filling or interpolation.
- One notable example: tessellations can interpolate through gaps.

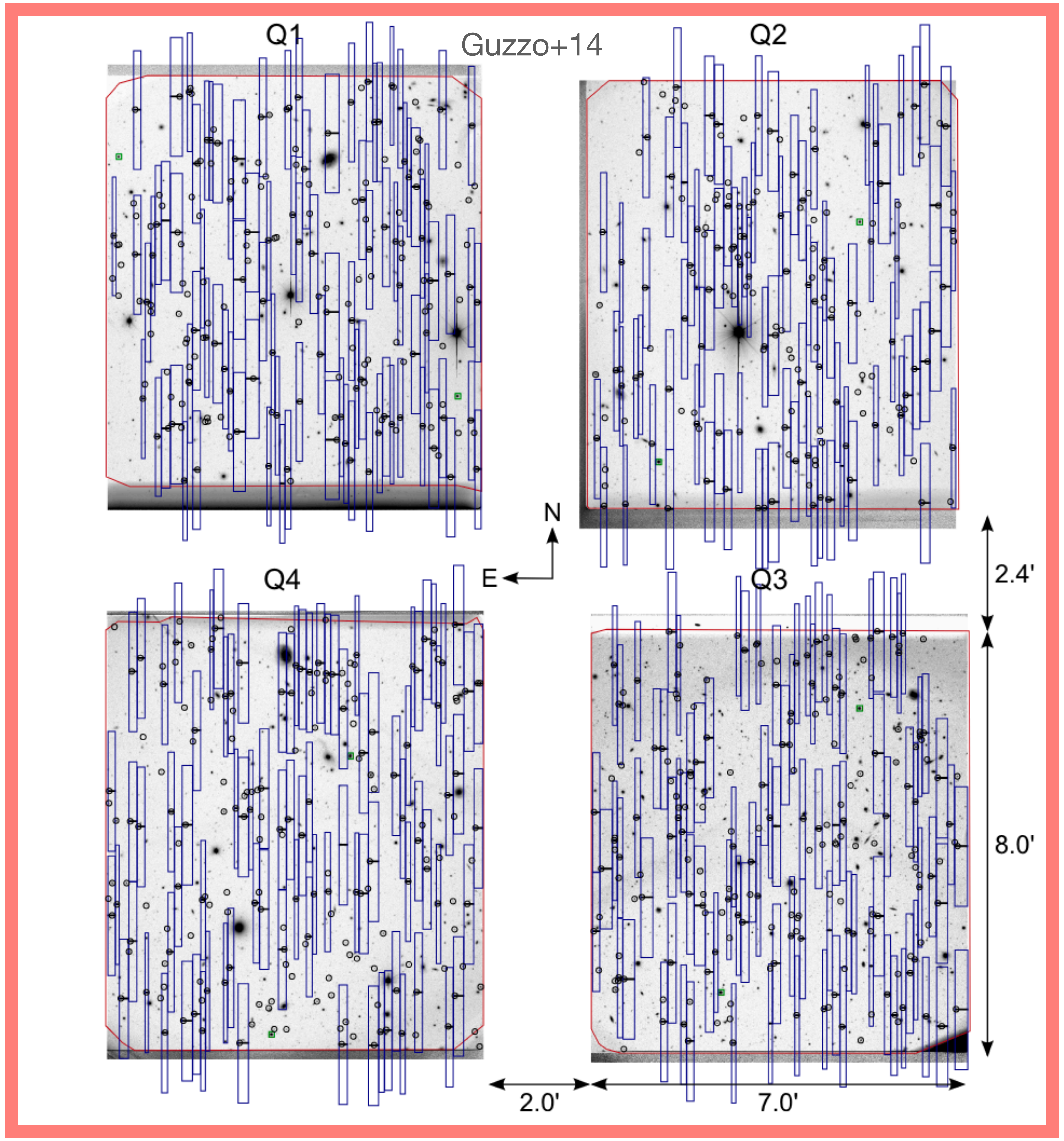


Scodeggio+18

Malavasi+17, Cucciati+14

Survey contiguous area

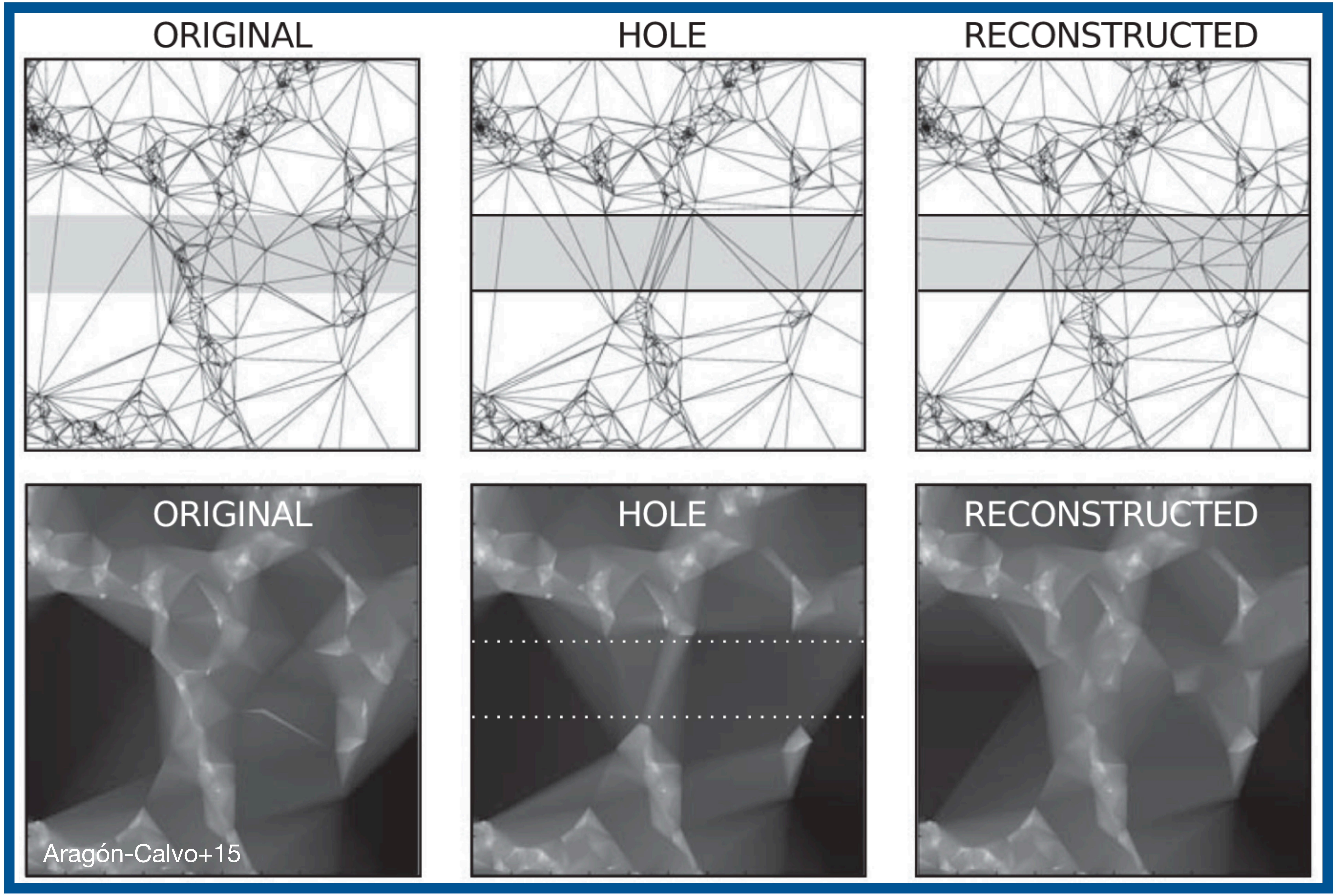
- Gaps and holes pose a problem if not properly treated.
- They create artificial low density regions, most of the time internal to the survey.
- Solutions are smoothing, filling or interpolation.
- One notable example: tessellations can interpolate through gaps.



Malavasi+17, Cucciati+14

Survey contiguous area

- Gaps and holes pose a problem if not properly treated.
- They create artificial low density regions, most of the time internal to the survey.
- Solutions are smoothing, filling or interpolation.
- One notable example: tessellations can interpolate through gaps.



Malavasi+17, Cucciati+14

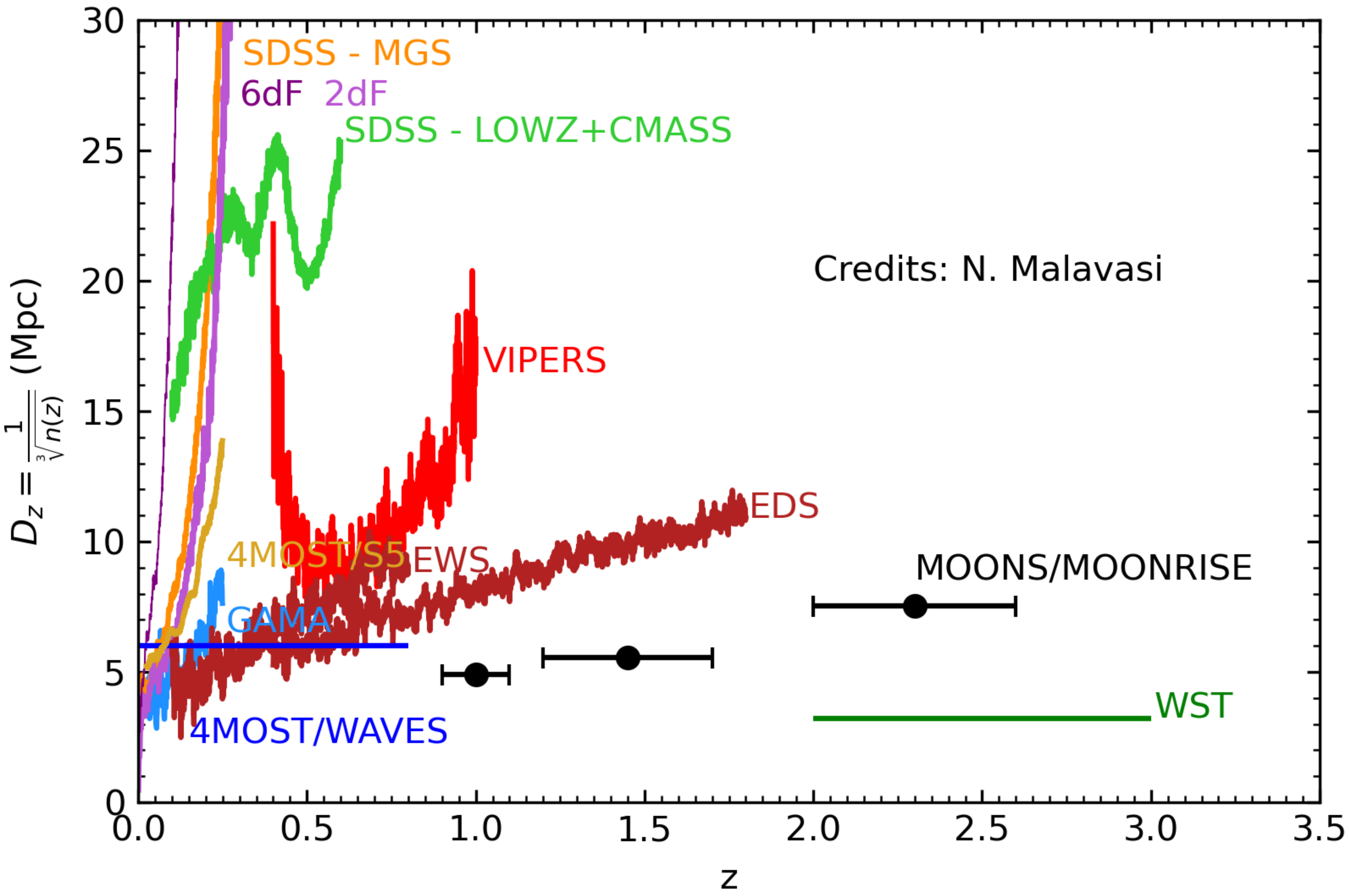
Spatial sampling

Average intergalactic distance.

$$D_z = \frac{1}{\sqrt[3]{n(z)}}$$

Has units of Mpc. Useful quantity to compare surveys among them.

Ideally one wants this function to be as uniform as possible with redshift.



See e.g. Kraljic, …, NM, + in prep.

How to detect the cosmic web?

Density cut?

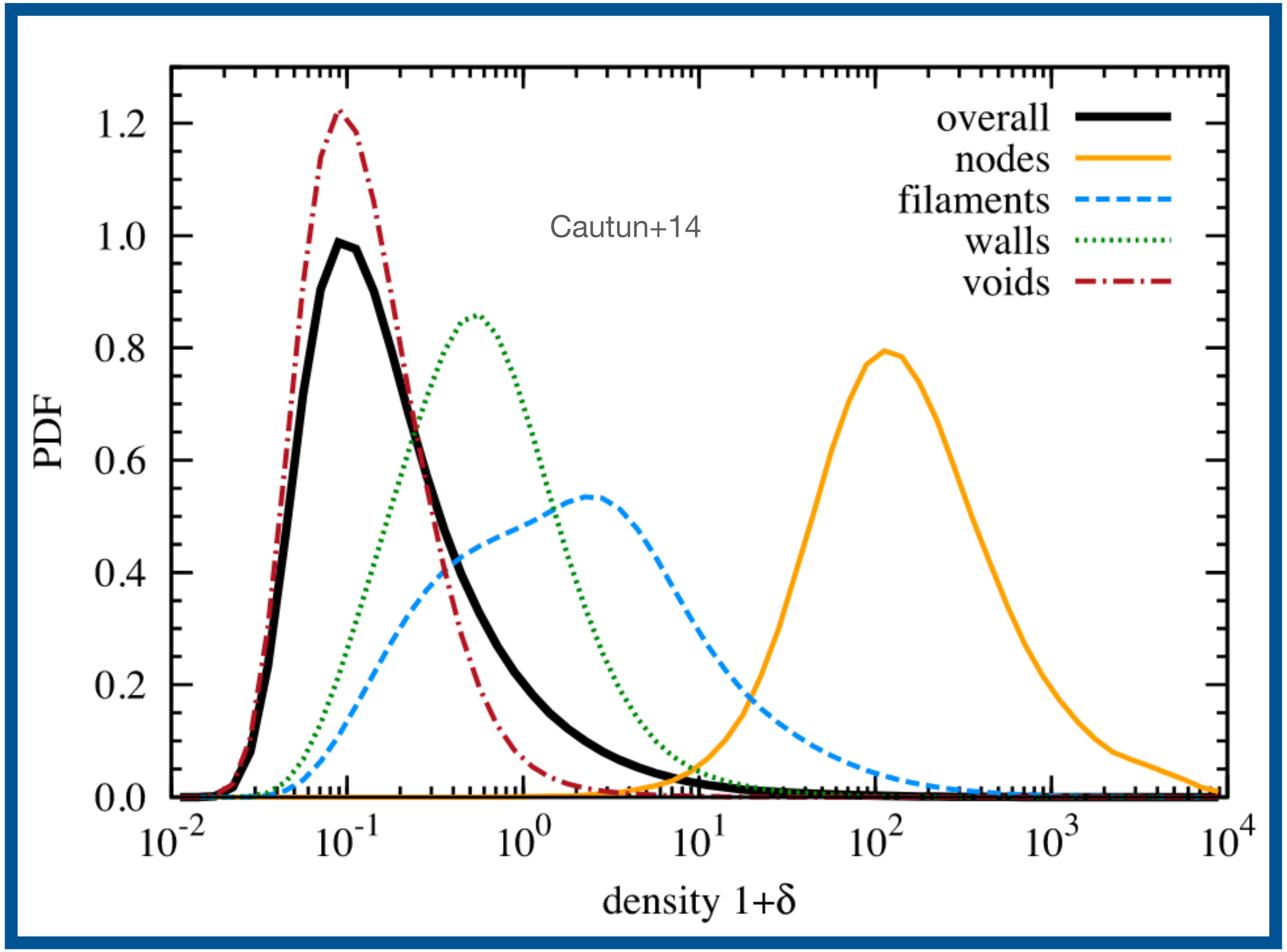
Simplest method to detect the CW: density cut.

Correlation between density and structure type.

Large overlap in density distributions.

From geometrical to topological description.

Analysis of proxies of the tidal field.



Aragón-Calvo+10, Malavasi+20, …

The landscape of available algorithms

Method	Type	Main References
Adapted Minimal Spanning Tree (MST)	Graph & Percolation	Alpaslan et al. (2014a)
Bisous	Stochastic	Tempel et al. (2014, 2016)
FINE	Stochastic	González & Padilla (2010)
Tidal Shear Tensor (T-web)	Hessian	Forero-Romero et al. (2009)
Velocity Shear Tensor (V-web)	Hessian	Hoffman et al. (2012)
CLASSIC	Hessian	Kitaura & Angulo (2012)
NEXUS+	Scale-Space, Hessian	Cautun et al. (2013)
Multiscale Morphology Filter-2 (MMF-2)	Scale-Space, Hessian	Aragón-Calvo et al. (2007a) Aragón-Calvo & Yang (2014)
Spineweb	Topology	Aragón-Calvo et al. (2010c)
DisPerSE	Topology	Sousbie (2011)
ORIGAMI	Phase-Space	Falck et al. (2012); Falck & Neyrinck (2015)
MultiStream Web Analysis (MSWA)	Phase-Space	Ramachandra & Shandarin (2015)

Adapted from Libeskind+18 - up to date to 2018

SCMS (density ridge, Chen et al. 2016, Genovese et al. 2014)

T-Rex (graph theory, Bonnaire et al. 2020),

1-DREAM (machine learning, Awad et al. 2023)

Linking group pairs together (Martínez et al. 2016)

Galaxy alignment (Rong et al. 2016).

List is continuously growing

The landscape of available algorithms

Graph and percolation
CW as connected web.

Hessian
Number of collapsing dimensions.

Phase space
Include velocity information.

Machine Learning
Feature extraction from complex data.

Topology
Gradient of the density field.

Stochastic
Geometrical description.

Based on Libeskind+18

Algorithms applied to surveys

Available samples

- VIPERS + DisPerSE
- SDSS + DisPerSE
- GAMA + MST
- GAMA + Hessian
- COSMOS + DisPerSE
- SDSS + Bisous
- Filaments linking groups of galaxies
- Ridge finders
- Watershed

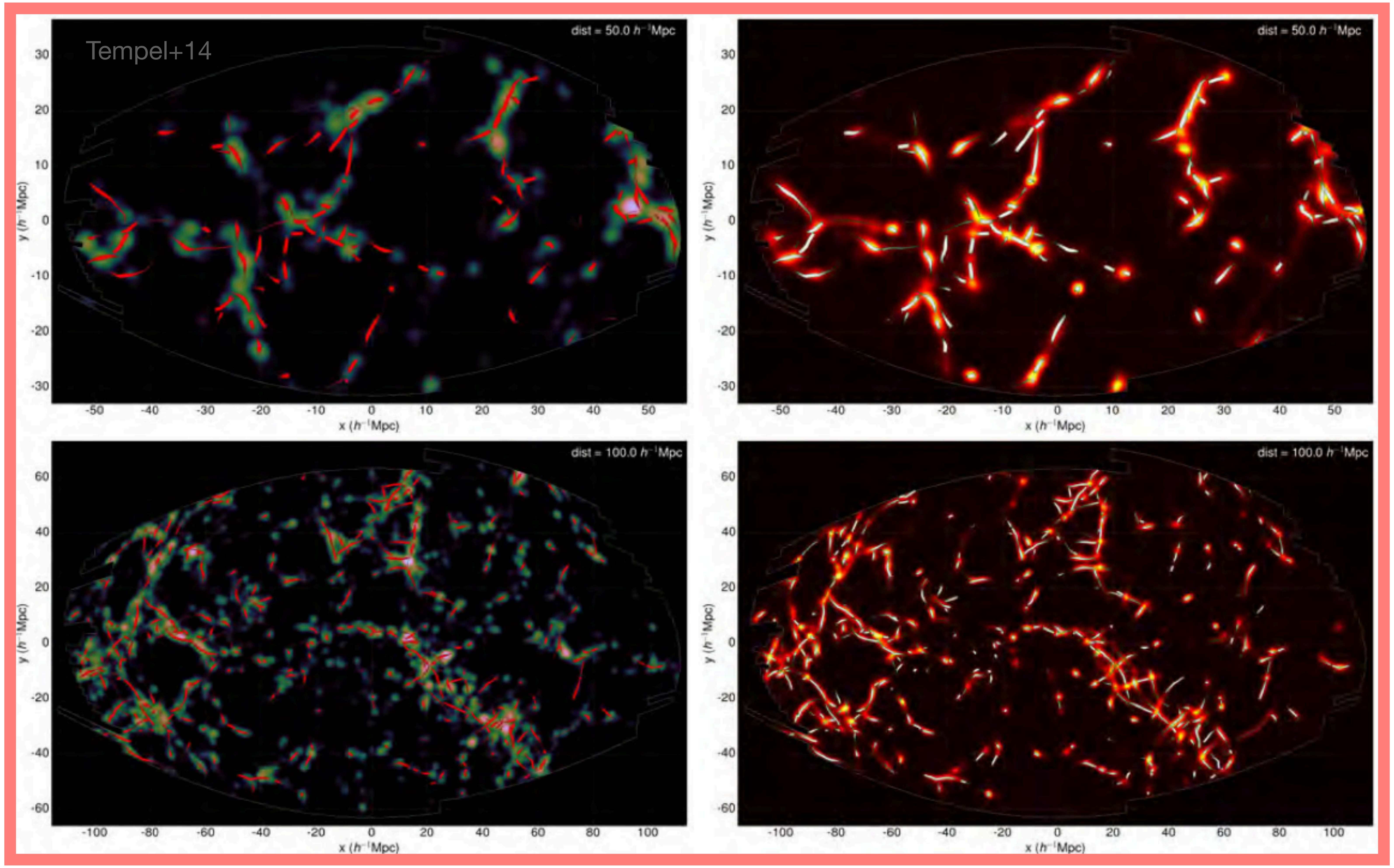
Surveys - VIPERS: Scodeggio+18, SDSS: York+00, GAMA: Driver+09, COSMOS: Scoville+07, Laigle+16

See also: Eardley+15, Sousbie+08,11, Chen+16, Laigle+18, Malavasi+17, Malavasi+20

Algorithms applied to surveys

Available samples

- VIPERS + DisPerSE
- SDSS + DisPerSE
- GAMA + MST
- GAMA + Hessian
- COSMOS + DisPerSE
- SDSS + Bisous
- Filaments linking groups of galaxies
- Ridge finders
- Watershed



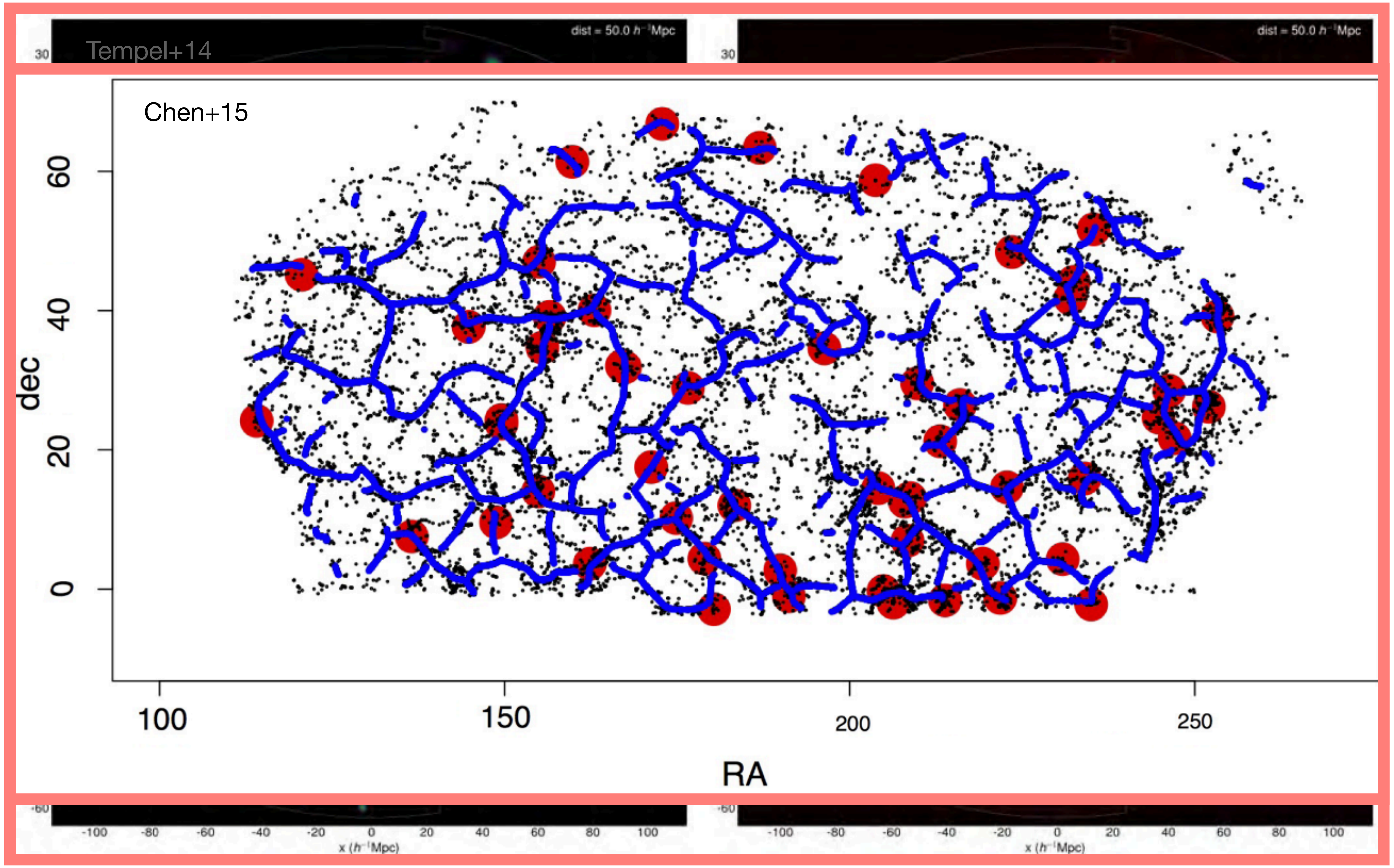
Surveys - VIPERS: Scodeggio+18, SDSS: York+00, GAMA: Driver+09, COSMOS: Scoville+07, Laigle+16

See also: Eardley+15, Sousbie+08,11, Chen+16, Laigle+18, Malavasi+17, Malavasi+20

Algorithms applied to surveys

Available samples

- VIPERS + DisPerSE
- SDSS + DisPerSE
- GAMA + MST
- GAMA + Hessian
- COSMOS + DisPerSE
- SDSS + Bisous
- Filaments linking groups of galaxies
- Ridge finders
- Watershed



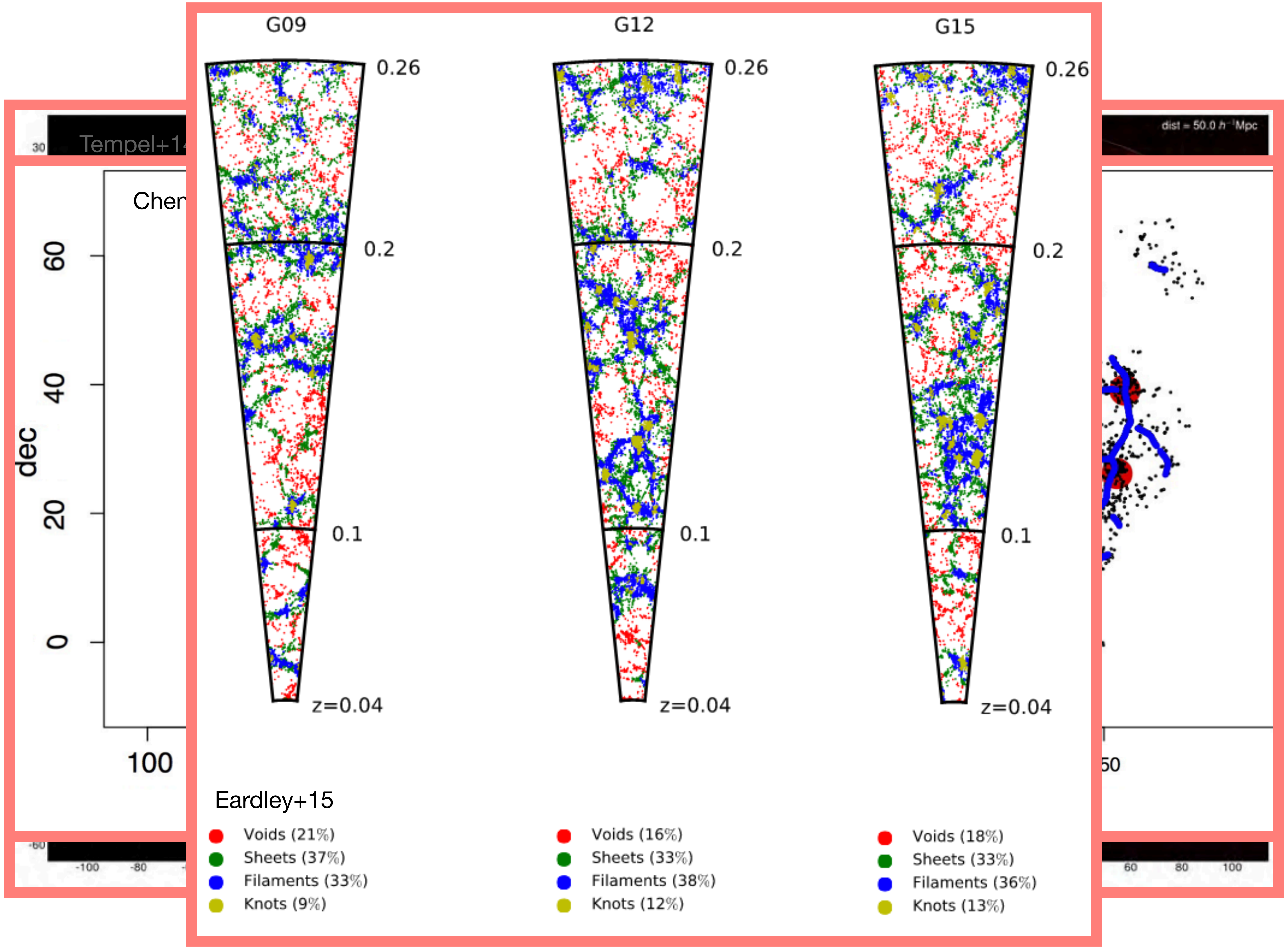
Surveys - VIPERS: Scodeggio+18, SDSS: York+00, GAMA: Driver+09, COSMOS: Scoville+07, Laigle+16

See also: Eardley+15, Sousbie+08,11, Chen+16, Laigle+18, Malavasi+17, Malavasi+20

Algorithms applied to surveys

Available samples

- VIPERS + DisPerSE
- SDSS + DisPerSE
- GAMA + MST
- GAMA + Hessian
- COSMOS + DisPerSE
- SDSS + Bisous
- Filaments linking groups of galaxies
- Ridge finders
- Watershed



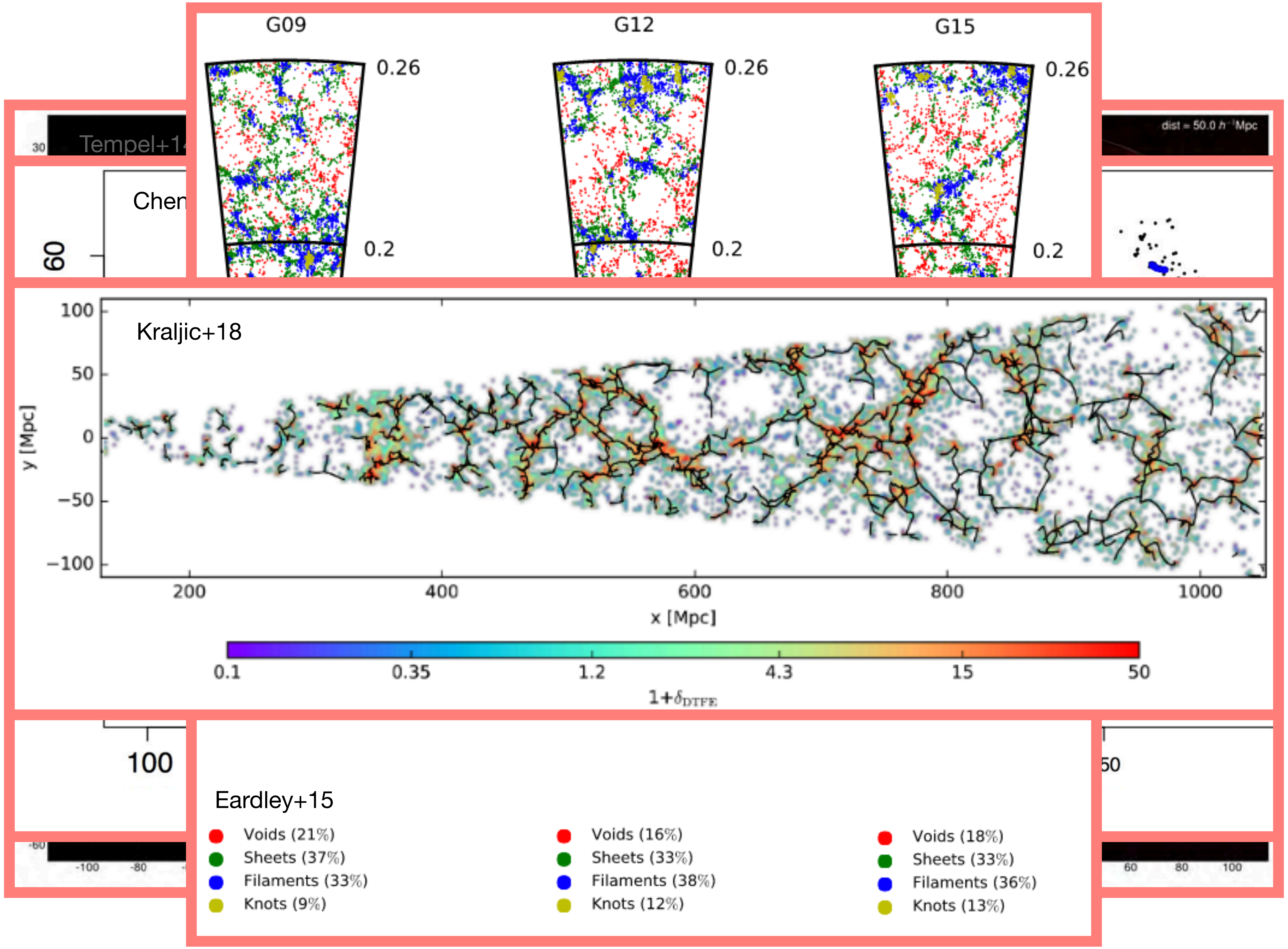
Surveys - VIPERS: Scodeggio+18, SDSS: York+00, GAMA: Driver+09, COSMOS: Scoville+07, Laigle+16

See also: Eardley+15, Sousbie+08,11, Chen+16, Laigle+18, Malavasi+17, Malavasi+20

Algorithms applied to surveys

Available samples

- VIPERS + DisPerSE
- SDSS + DisPerSE
- GAMA + MST
- GAMA + Hessian
- COSMOS + DisPerSE
- SDSS + Bisous
- Filaments linking groups of galaxies
- Ridge finders
- Watershed



Surveys - VIPERS: Scodeggio+18, SDSS: York+00, GAMA: Driver+09, COSMOS: Scoville+07, Laigle+16

See also: Eardley+15, Sousbie+08,11, Chen+16, Laigle+18, Malavasi+17, Malavasi+20

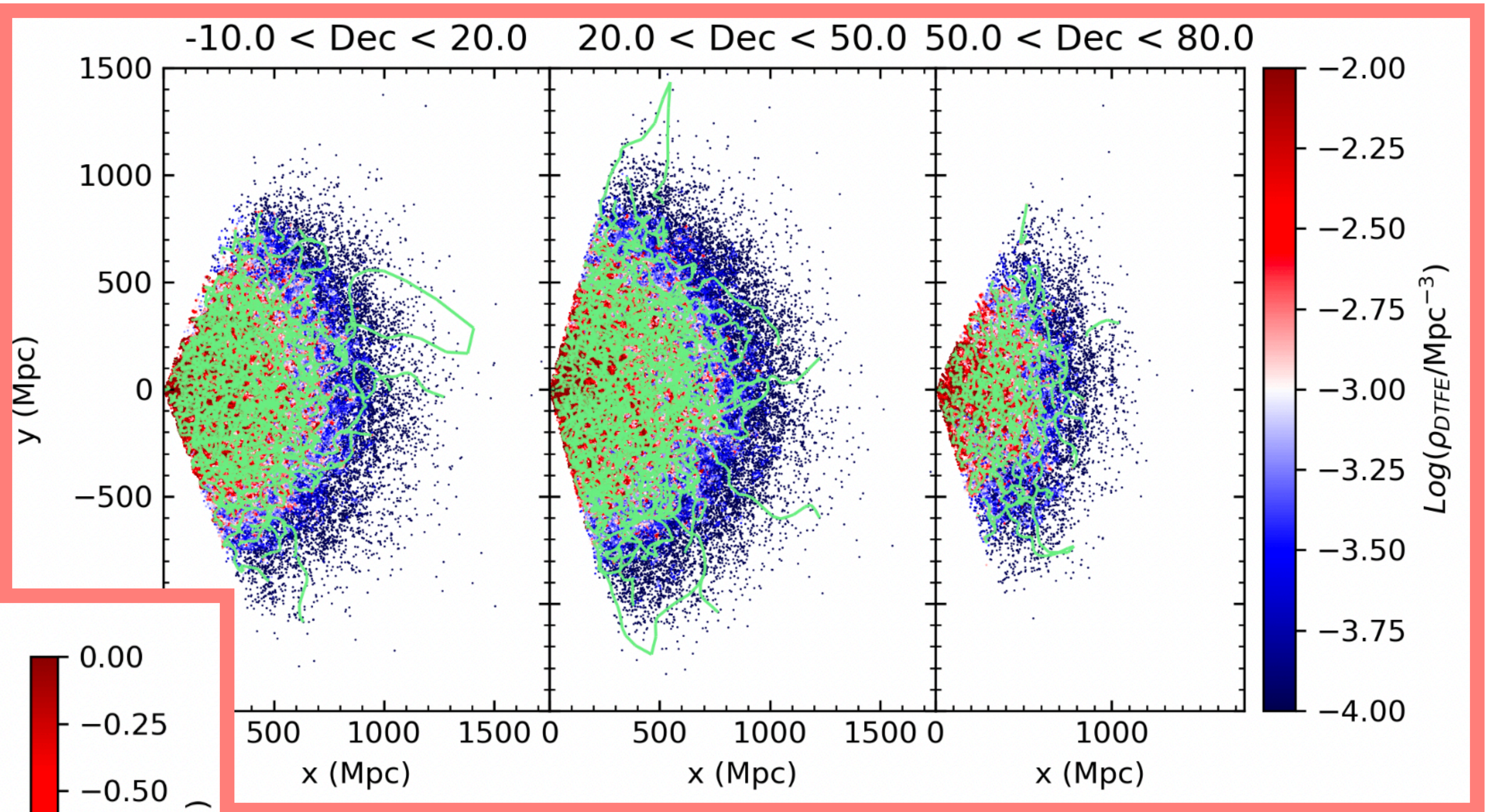
The Cosmic Web in VIPERS

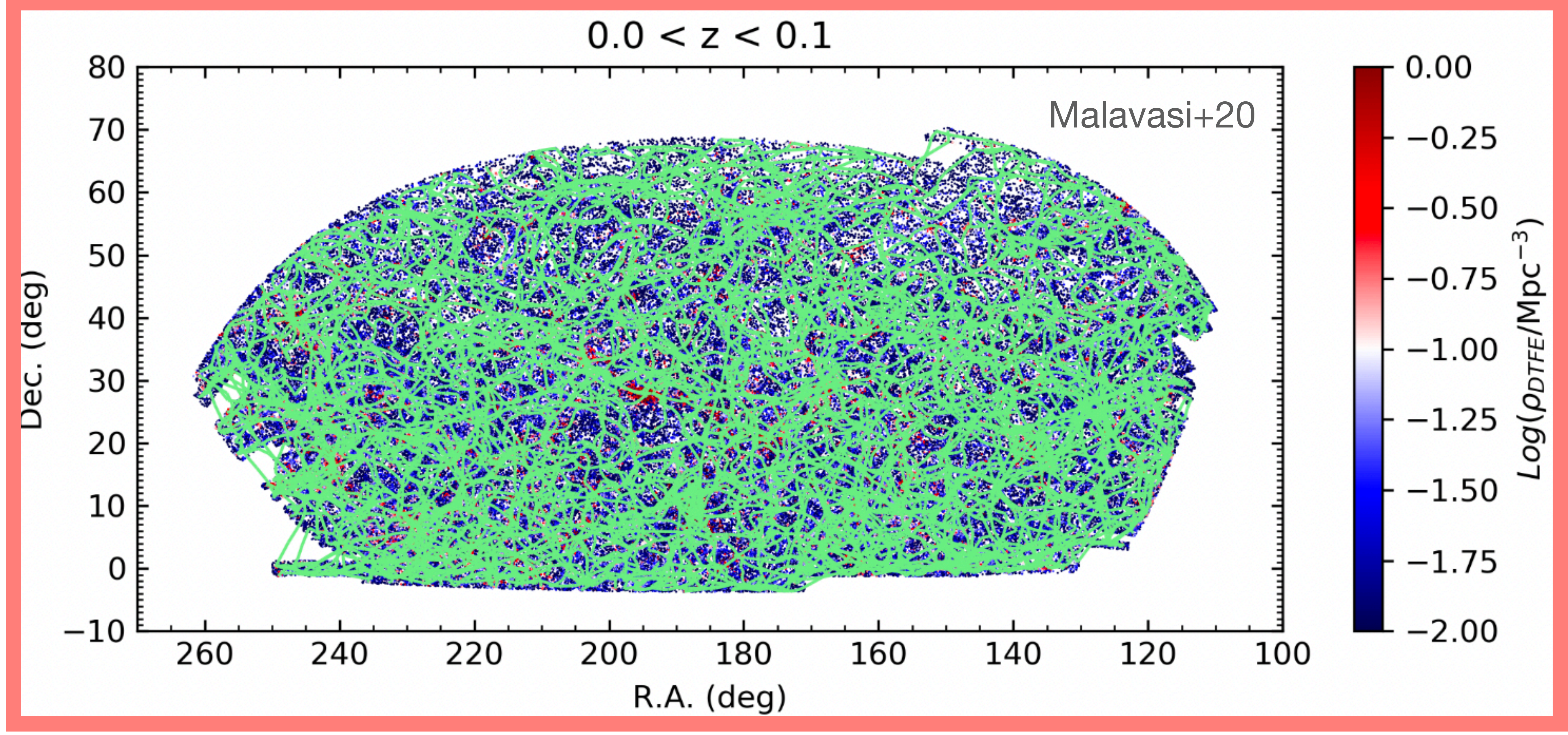
The cosmic web at z ~ 0.7

Catalogue of filaments in the SDSS

We released the catalogue of filaments for use by the community.

Full characterization of properties and systematics.

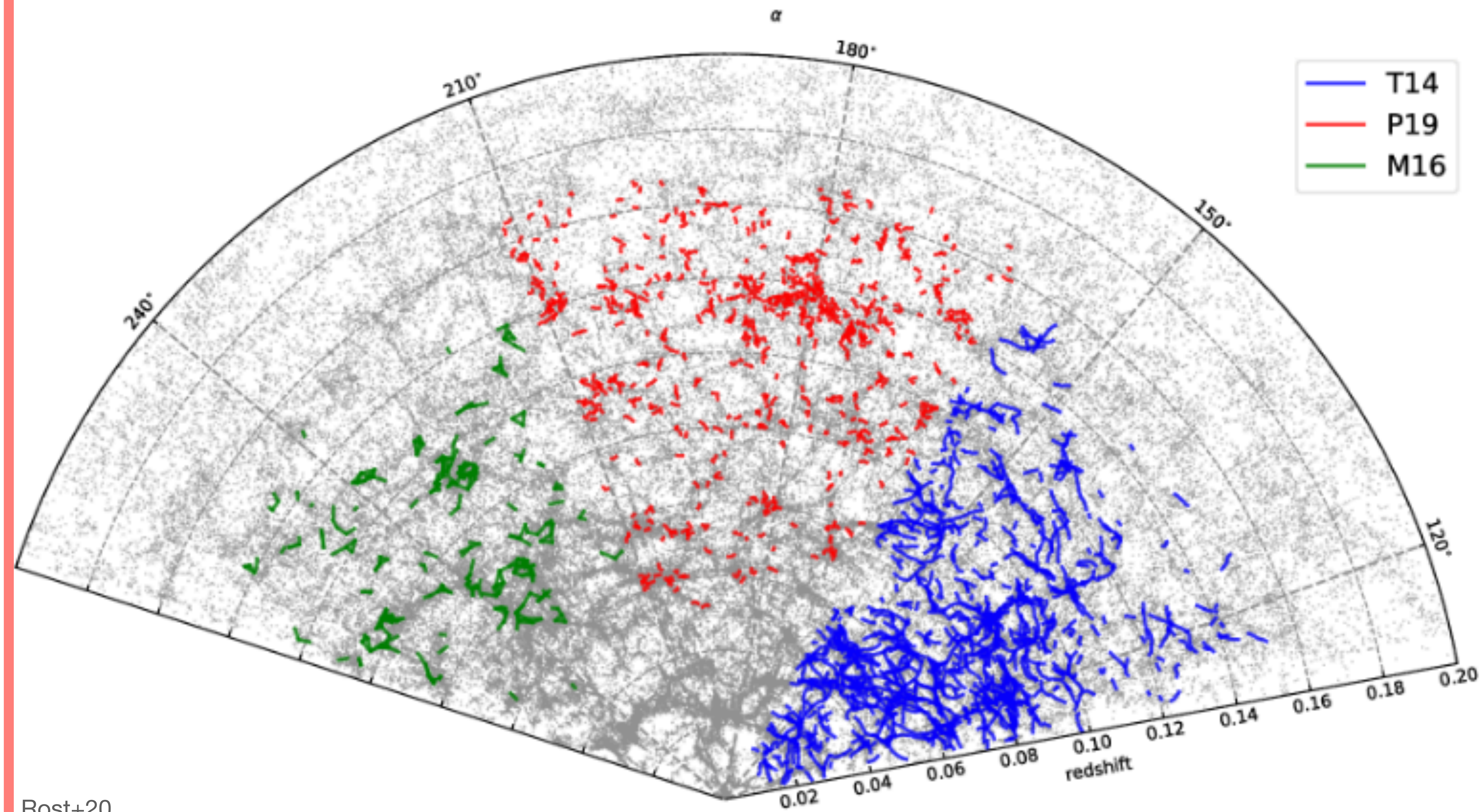




Available for DR7 and DR12.

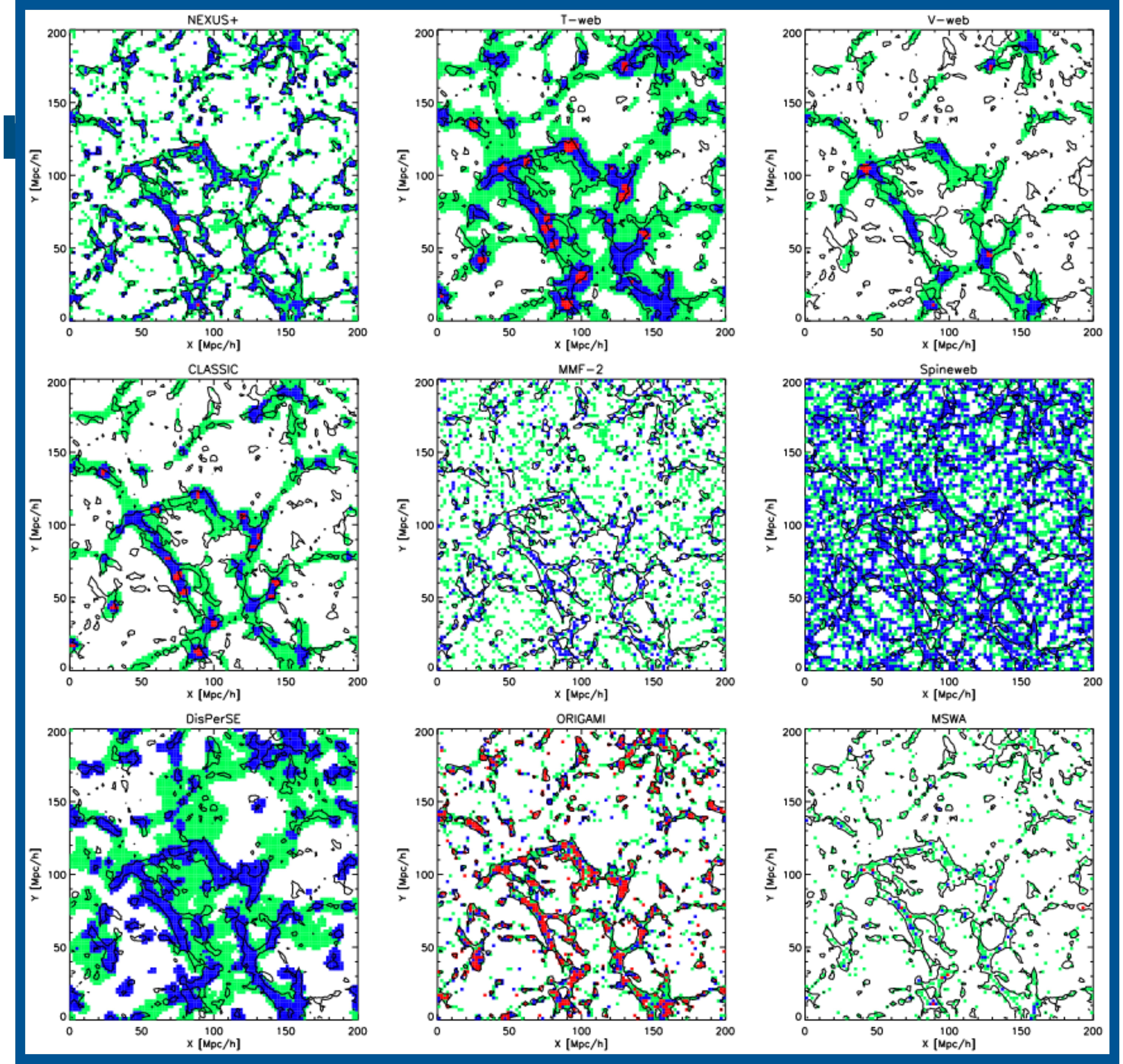
https://l3s.osups.universite-paris-saclay.fr/cosfil.html

Comparing algorithms



Rost+20

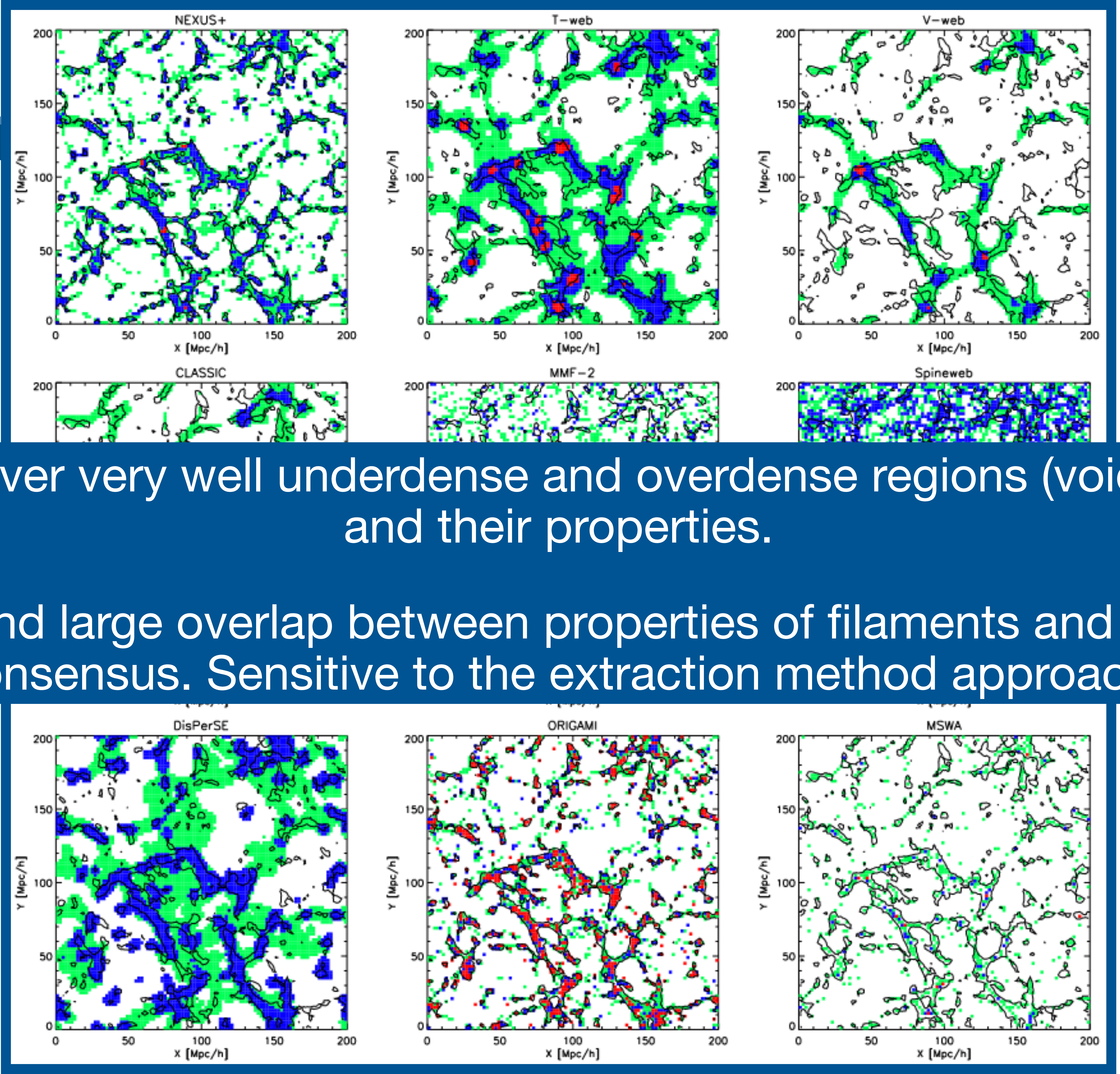
Compar



Libeskind+18

Compar

Libeskind+18



Algorithms recover very well underdense and overdense regions (voids and clusters) and their properties.

Agreement and large overlap between properties of filaments and walls, but no consensus. Sensitive to the extraction method approach.

How to compare skeletons?

Information theory

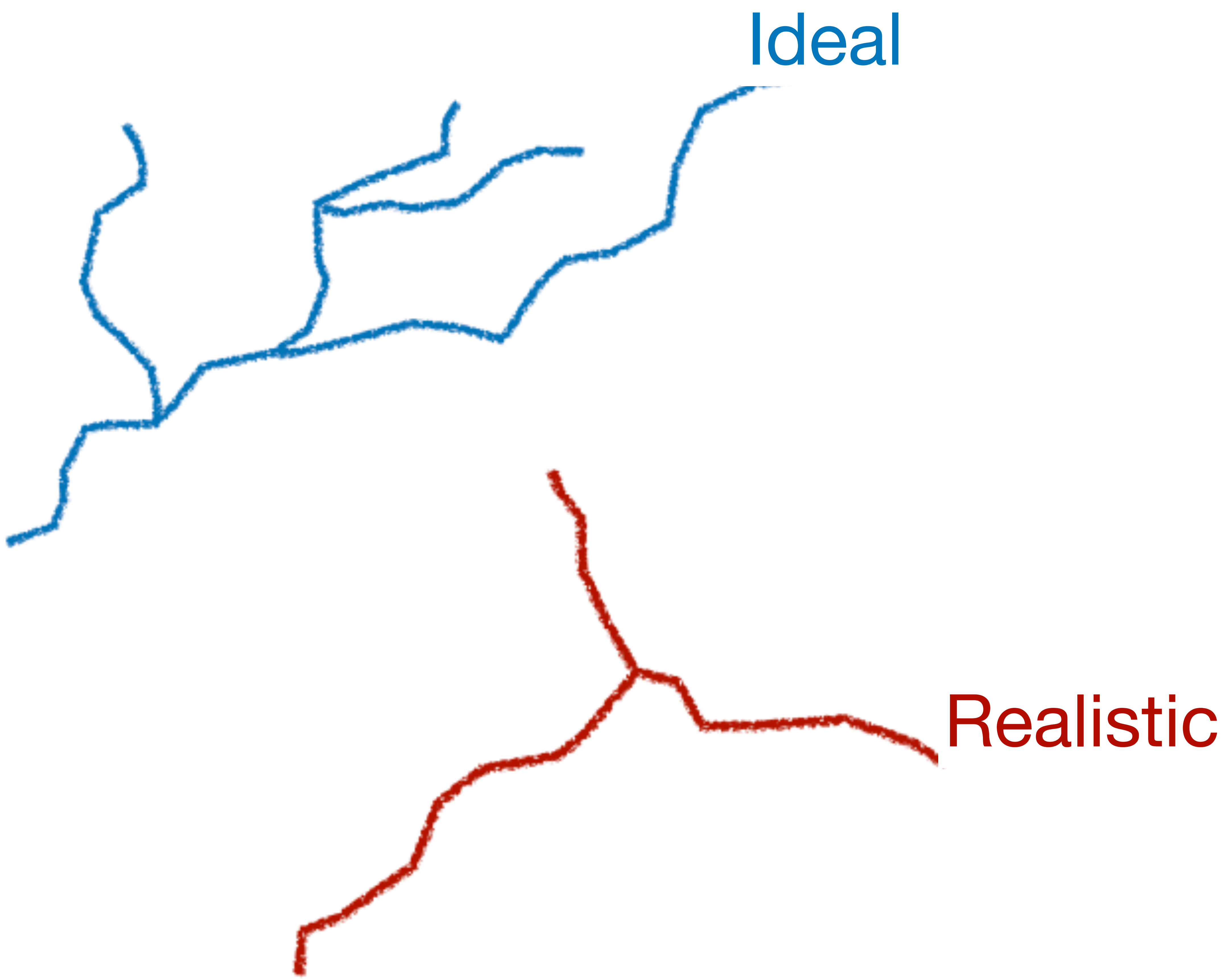
Pseudo-distance/Pseudo-orientation

Machine learning

Jensen-Shannon Divergence, symmetric measurement of disagreement (the higher the JS divergence, the more disagreement).

Pseudo-distances and pseudo-angles

Filament length



Problem of skeleton comparison applied to Euclid Wide.

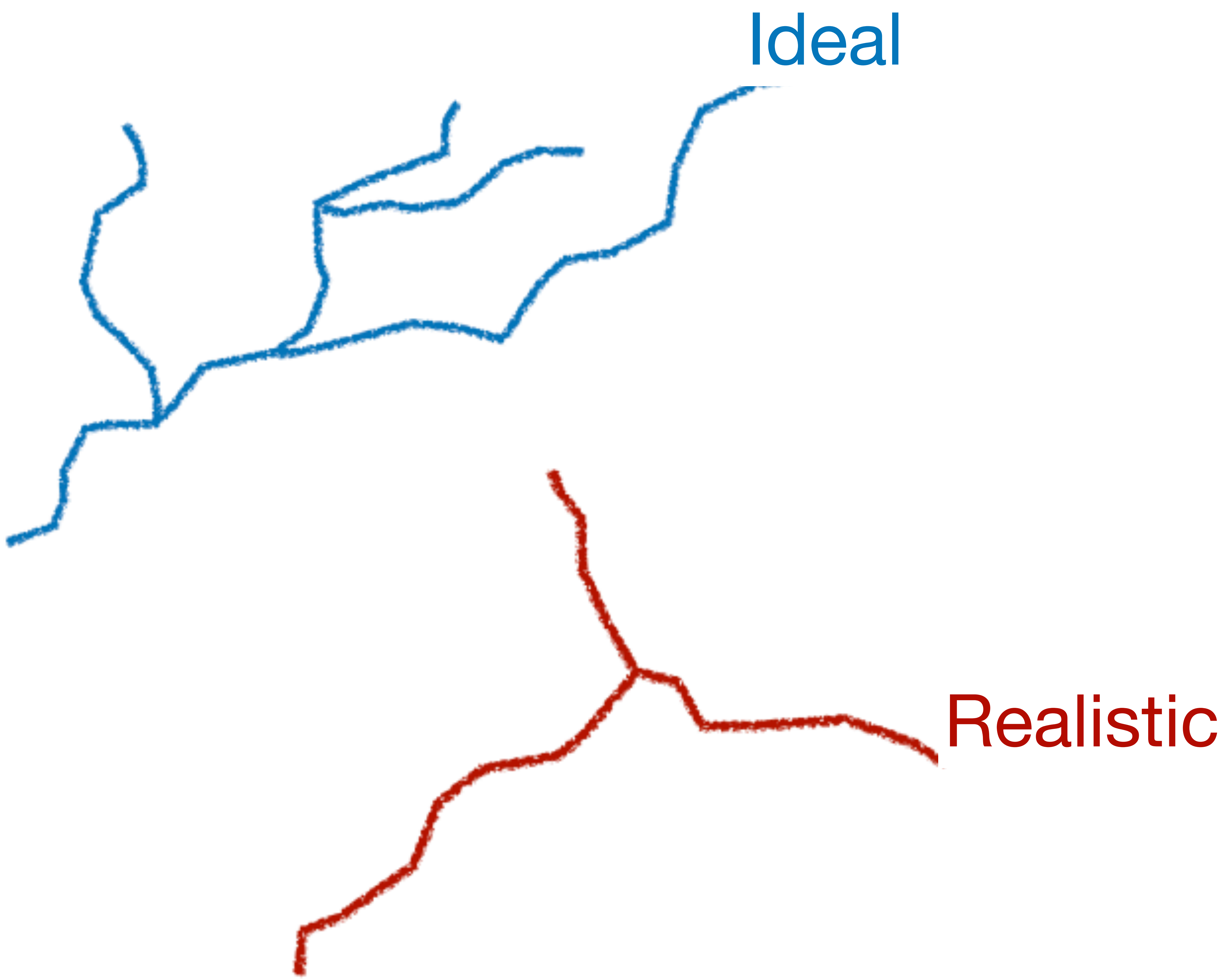
Study skeleton and galaxy properties in relation to the filaments.

Test impact of redshift precision, Euclid-like selection.

Malavasi+25

Pseudo-distances and pseudo-angles

Visual inspection



Problem of skeleton comparison applied to Euclid Wide.

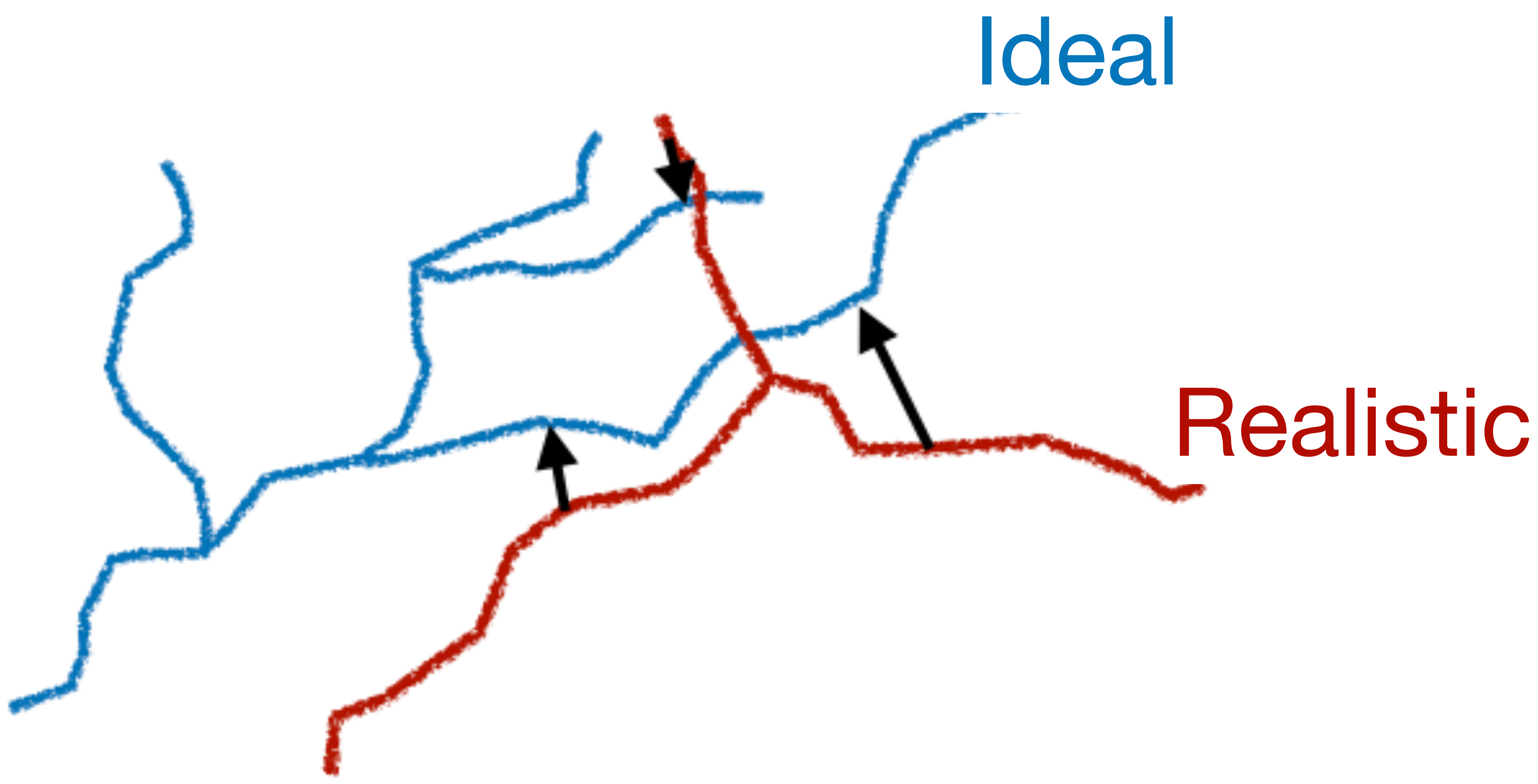
Study skeleton and galaxy properties in relation to the filaments.

Test impact of redshift precision, Euclid-like selection.

Malavasi+25

Pseudo-distances and pseudo-angles

Distances between skeleton segments



Problem of skeleton comparison applied to Euclid Wide.

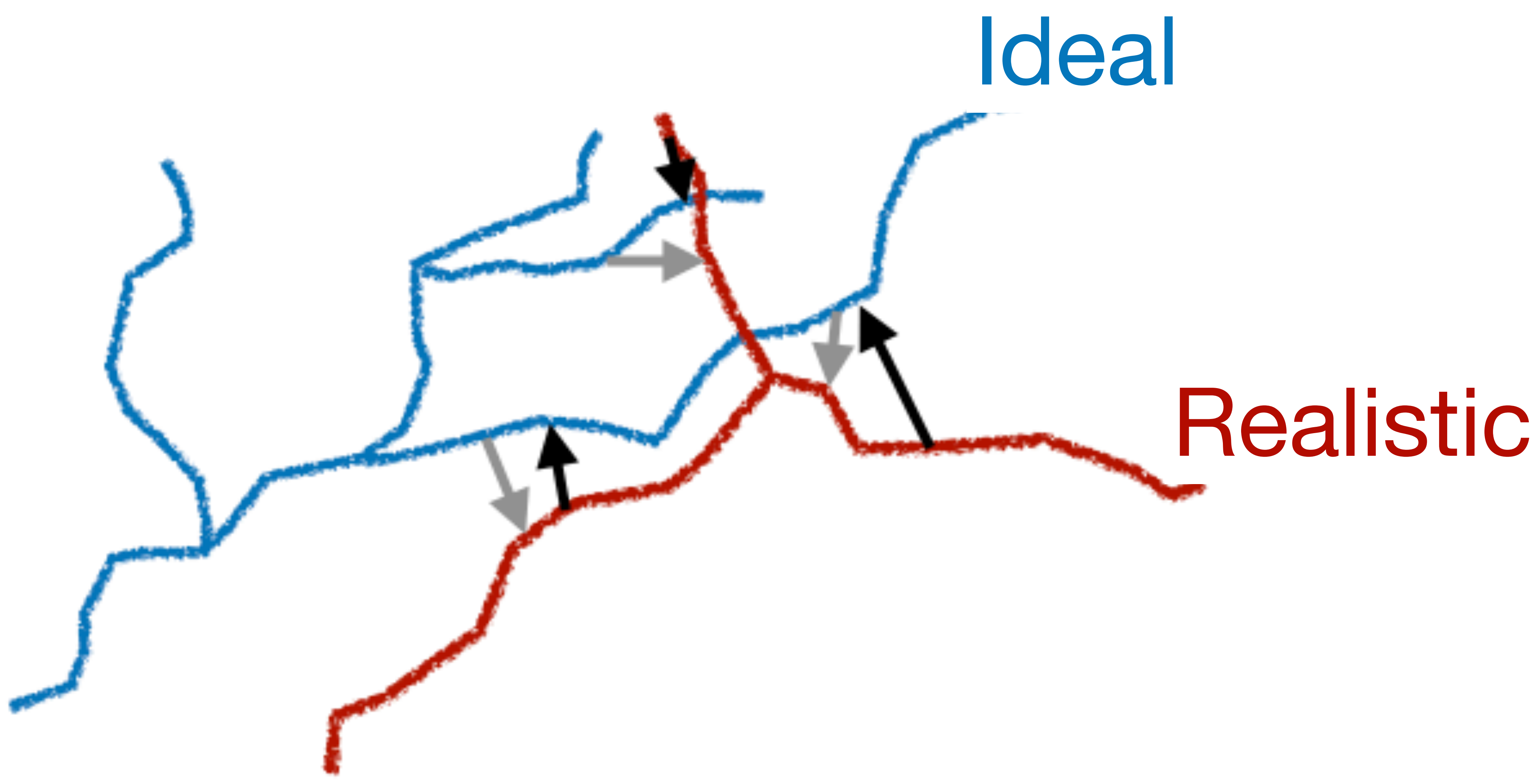
Study skeleton and galaxy properties in relation to the filaments.

Test impact of redshift precision, Euclid-like selection.

Malavasi+25

Pseudo-distances and pseudo-angles

Distances between skeleton segments



Problem of skeleton comparison applied to Euclid Wide.

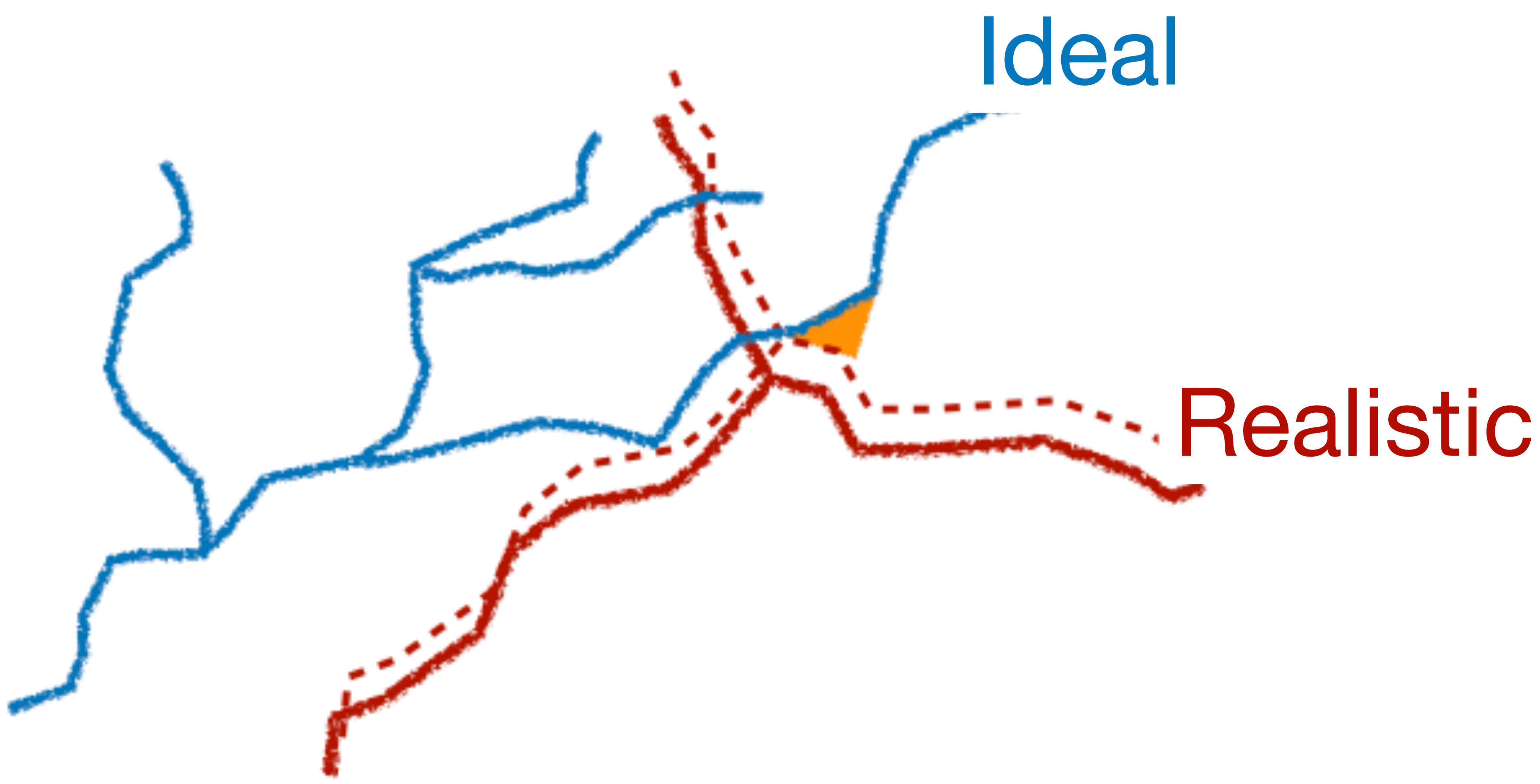
Study skeleton and galaxy properties in relation to the filaments.

Test impact of redshift precision, Euclid-like selection.

Malavasi+25

Pseudo-distances and pseudo-angles

Angles between skeleton segments



Problem of skeleton comparison applied to Euclid Wide.

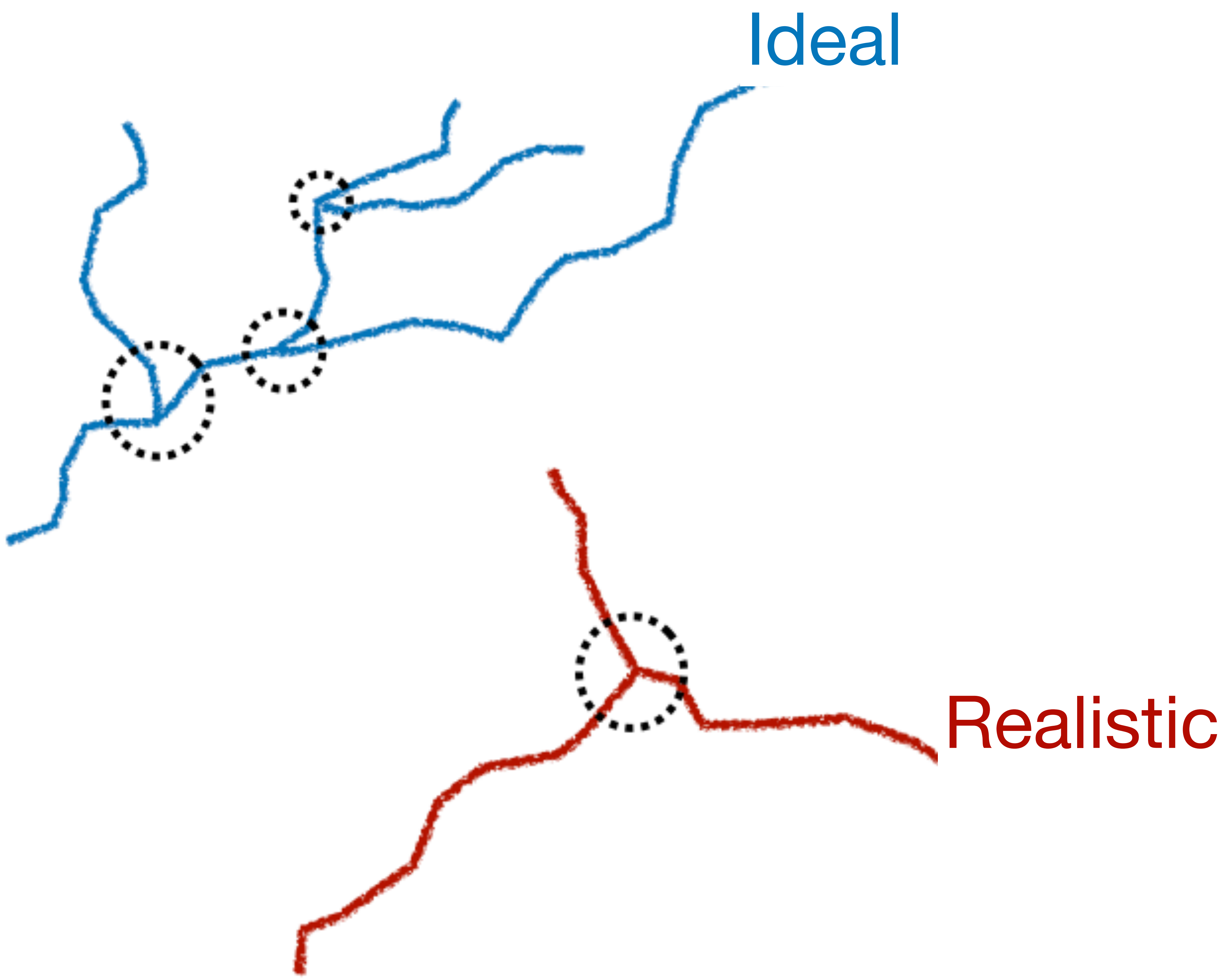
Study skeleton and galaxy properties in relation to the filaments.

Test impact of redshift precision, Euclid-like selection.

Malavasi+25

Pseudo-distances and pseudo-angles

Connectivity-mass relation for nodes



Problem of skeleton comparison applied to Euclid Wide.

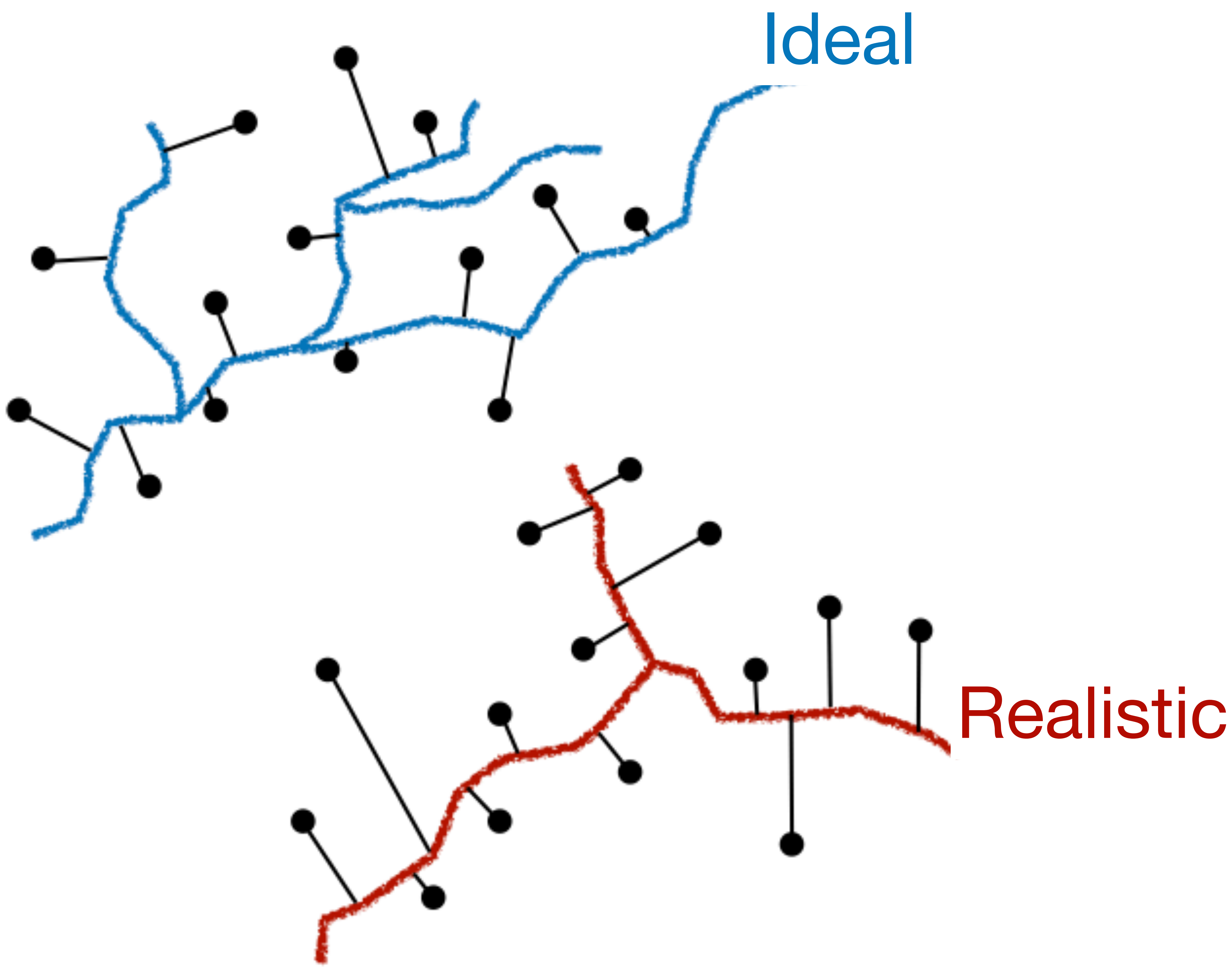
Study skeleton and galaxy properties in relation to the filaments.

Test impact of redshift precision, Euclid-like selection.

Malavasi+25

Pseudo-distances and pseudo-angles

Mass-distance from filament relation for galaxies



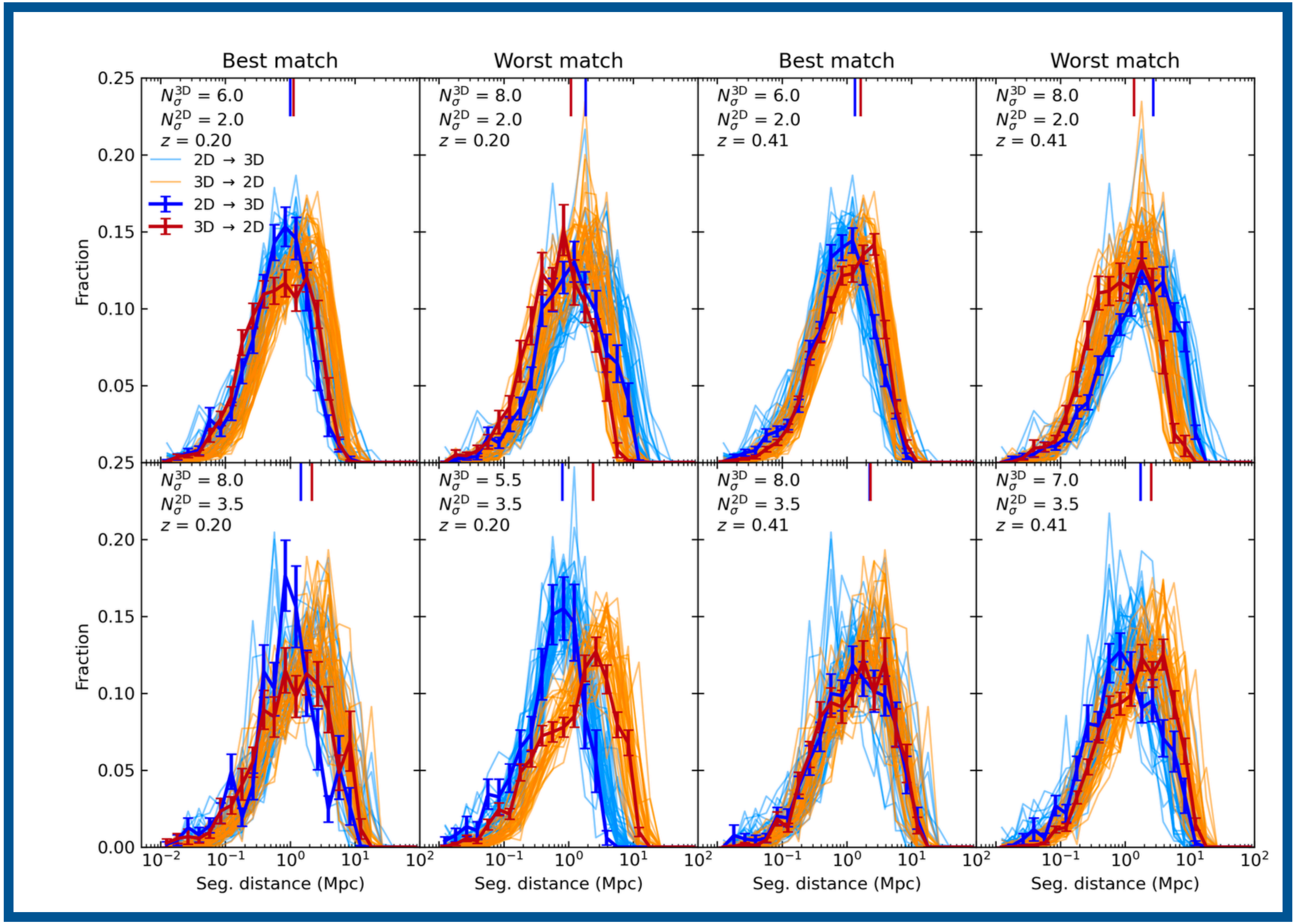
Problem of skeleton comparison applied to Euclid Wide.

Study skeleton and galaxy properties in relation to the filaments.

Test impact of redshift precision, Euclid-like selection.

Malavasi+25

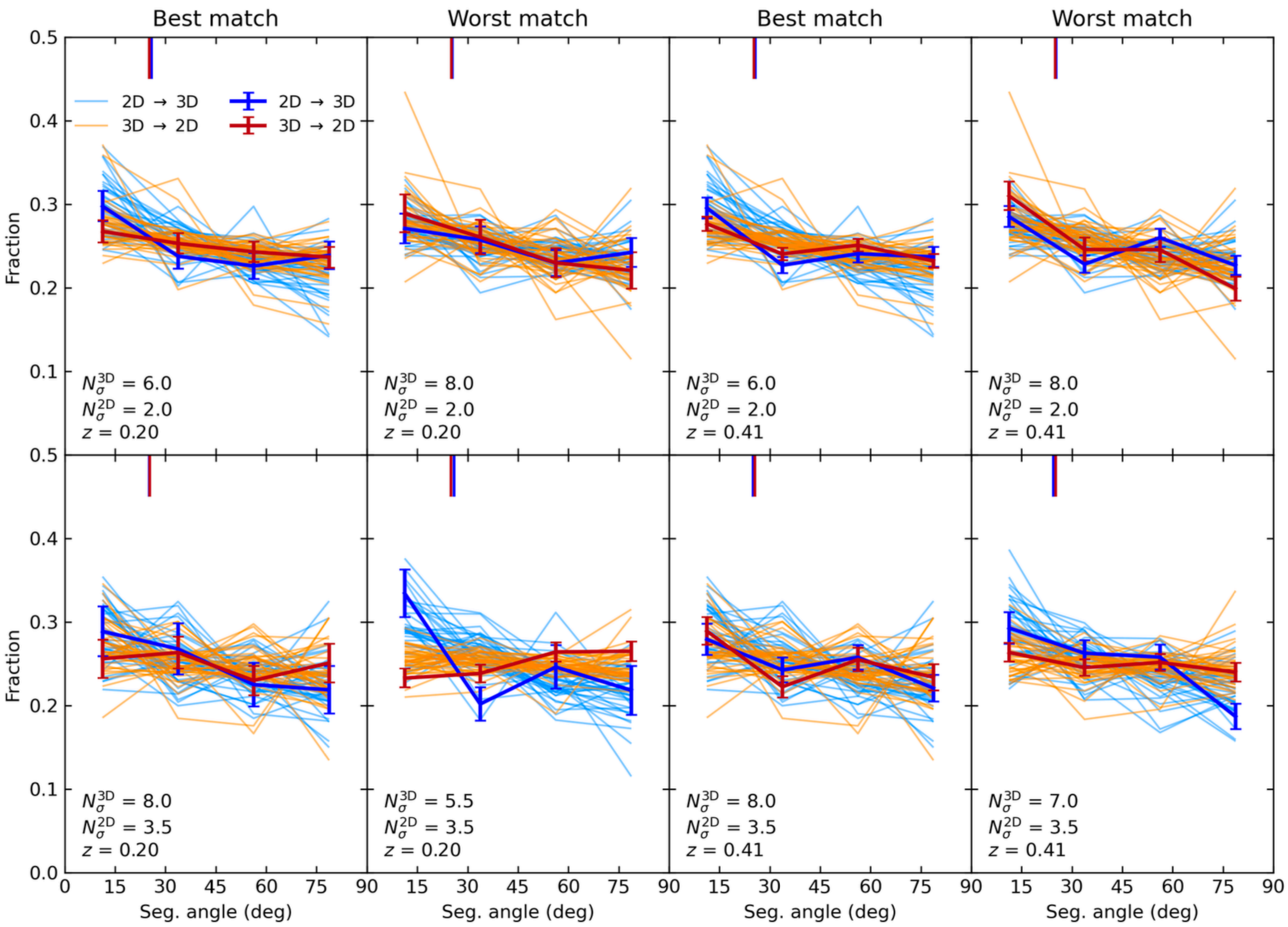
Distributions of pseudo-distances/angles



Problem of skeleton comparison applied to Euclid Wide.

Malavasi+25

Distributions of pseudo-distances/angles



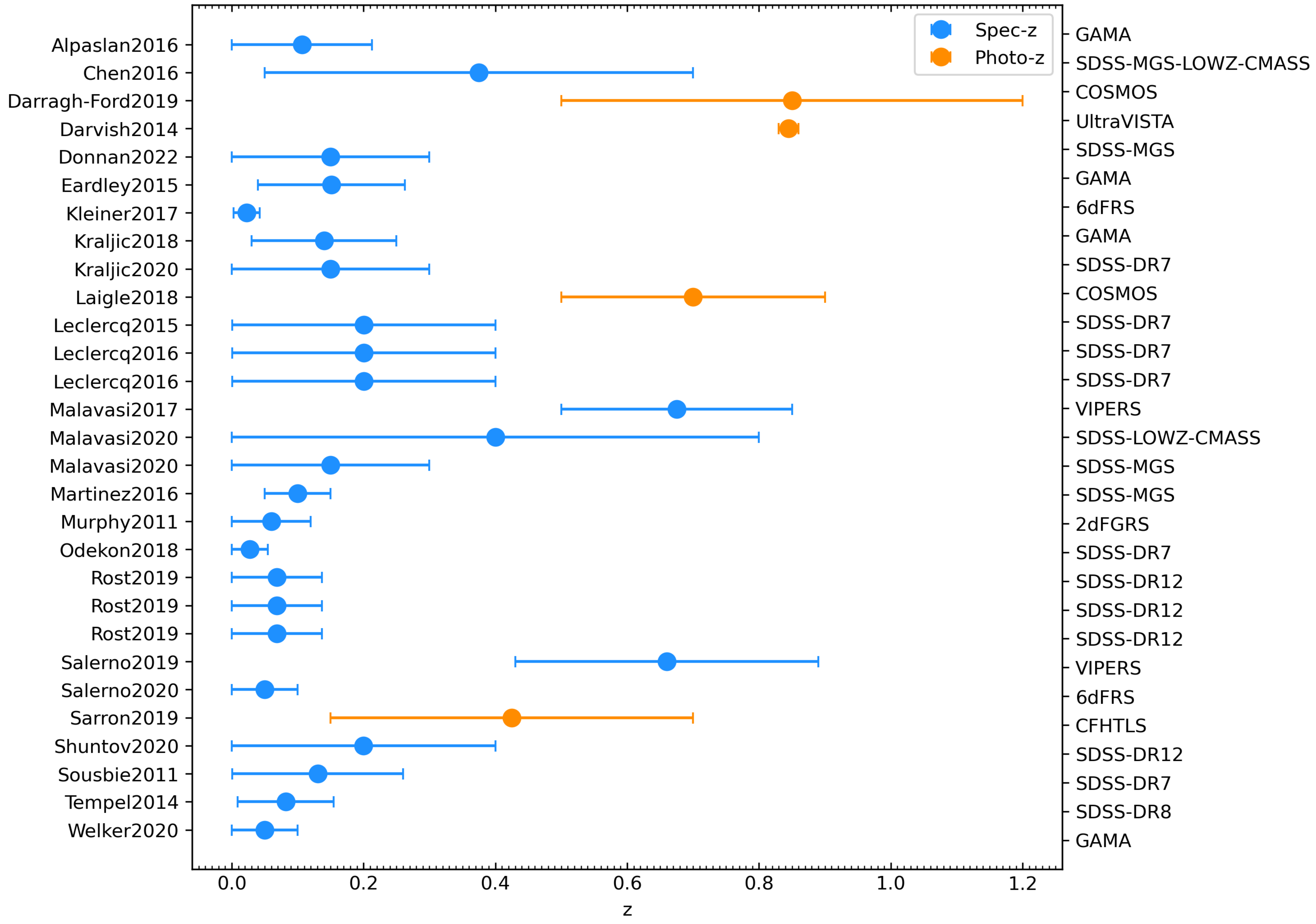
Problem of skeleton comparison applied to Euclid Wide.

Malavasi+25

Open problem:

How to effectively compare two sets of filaments to determine if they are equal or not?

The current landscape of cosmic web detection



What's on this plot:

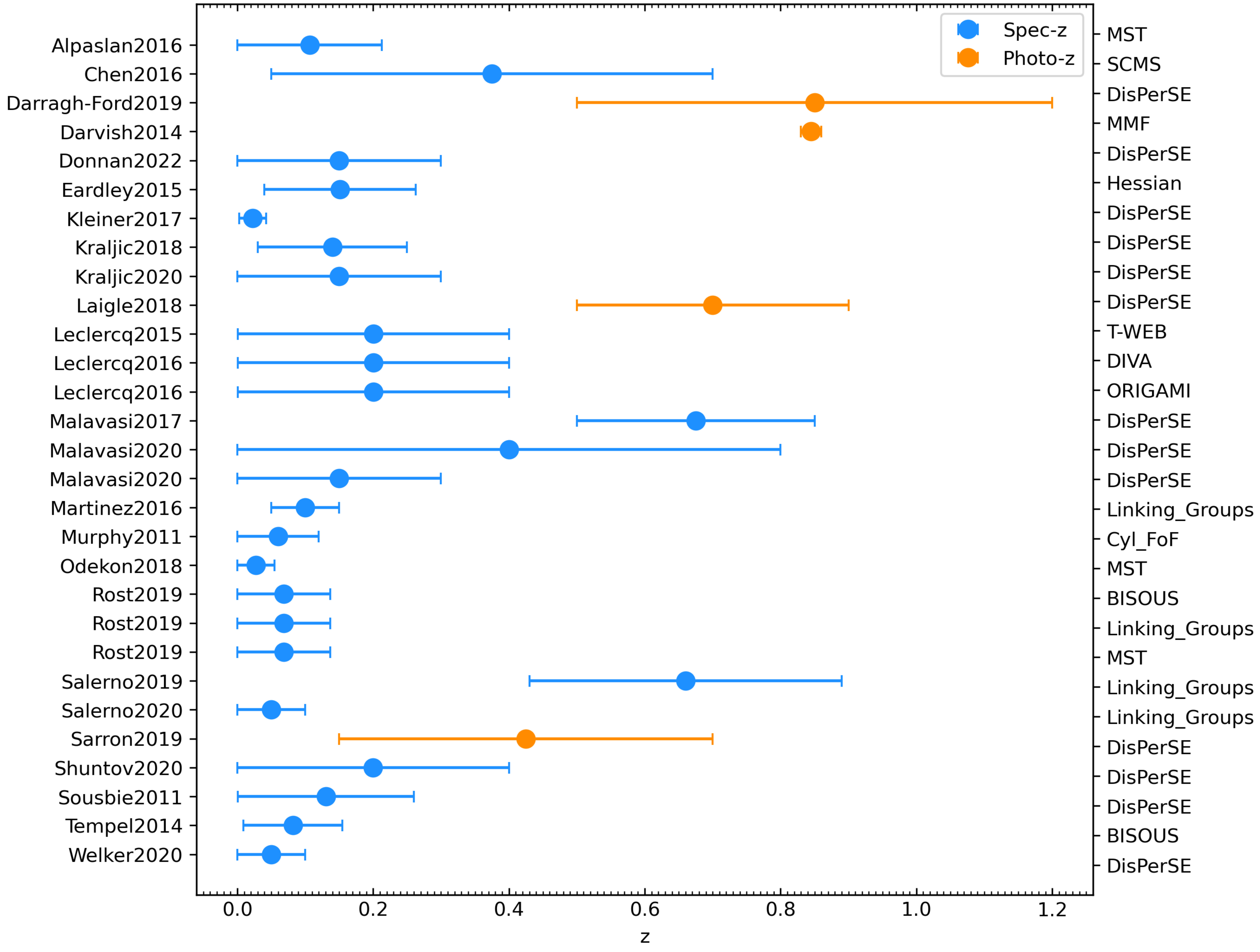
- Code applied to data.

What's NOT on this plot:

- Code applied to simulations.
- Analyses using an existing catalog "as is".
- Future facilities.

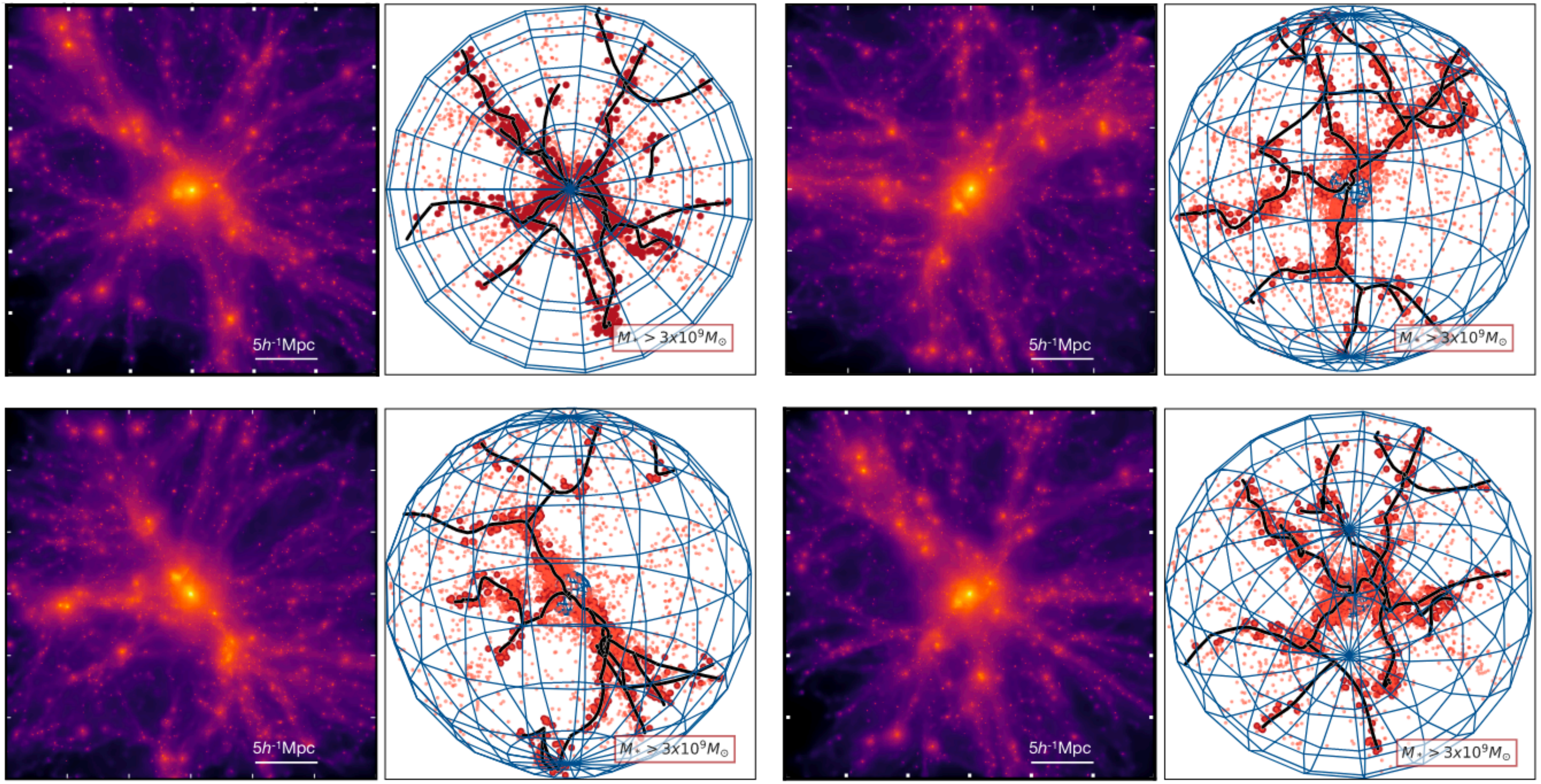
If you think your paper should be here and I did not include it: e-mail me!

The current landscape of cosmic web detection



- Large-area spectroscopic surveys or precise photometric redshift ones.
- Currently CW detection is more or less happening at $z < 1$, independently of the algorithm.
- All algorithm types are used.
- Future facilities needed: big MOS with large FoV.
- Euclid (?), PFS, MOONS, WAVES

Not only on large scales!



Kuchner+20

Recently, strong focus shifted to reconstruction in small regions around clusters!

Better characterization of cluster outskirts

Smaller data sets needed

Synergies with future surveys

Future facilities needed:

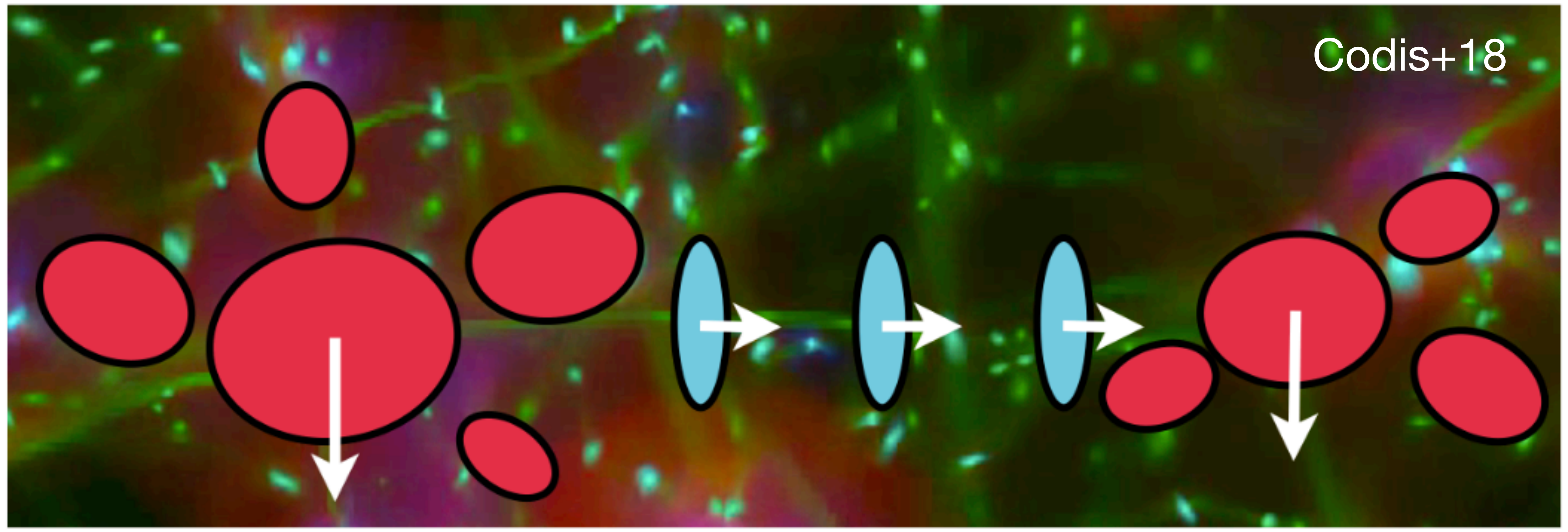
Euclid (?), 4MOST, WEAVE

See also: Cybulski+14, Mahajan+18, Kuchner+21a,b, Cornwell+22,23a,b, Sarron, …, NM, + in prep.

Open problem:

Is the cosmic web detected on small scales similar to what detected using the full survey volume?

Properties of the CW

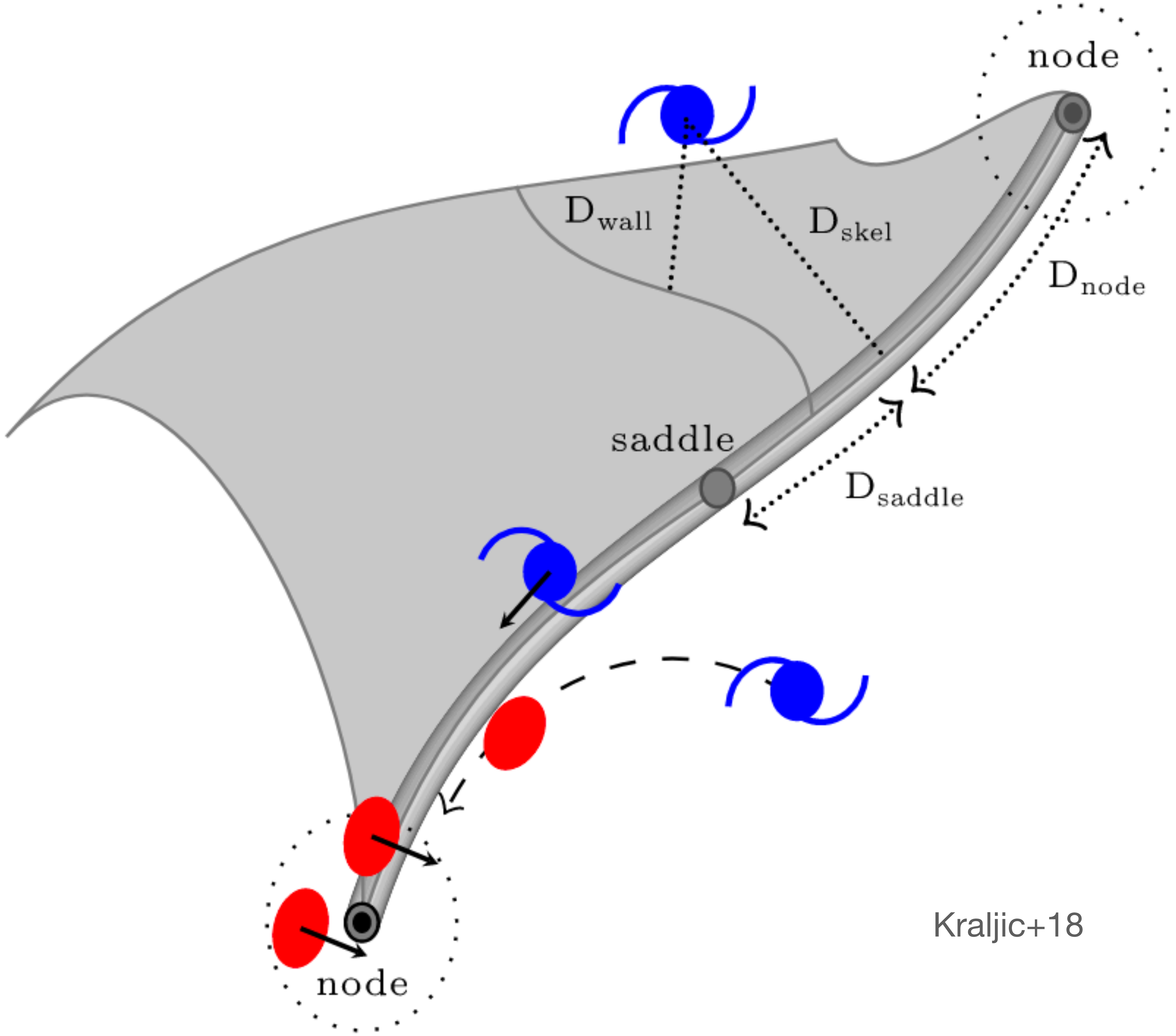


Tracing the CW is tracing the formation of structures:

- **Galaxy formation and evolution:** star-formation quenching in clusters and filaments, spin and shape alignment with filaments. Tempel+13, Alpaslan+16, Chen+17, Malavasi+17-22, Laigle+18, Kraljic+18-20; Rost+20, Salerno+20, Welker+20

- **Cosmology:** number, type, size, and connections of CW structures change with cosmological parameters. Boldrini+24, Mainieri+24

- **Astrophysics of clusters:** matter flows from filaments to clusters. Dekel+09, Martin+16, Bennett+20



Conclusions and open problems

The cosmic web impacts the formation of structures and the formation of galaxies.

We are data-limited in its detection from galaxy surveys. Next generation MOS with big FoVs will solve the issue.

Open problems:

- How to effectively compare two sets of filaments to determine if they are equal or not?
- Is the cosmic web detected on small scales similar to what detected using the full survey volume?