Cosmological simulations: Large-scale structure in the context of multi-scale galaxy evolution

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cnrs

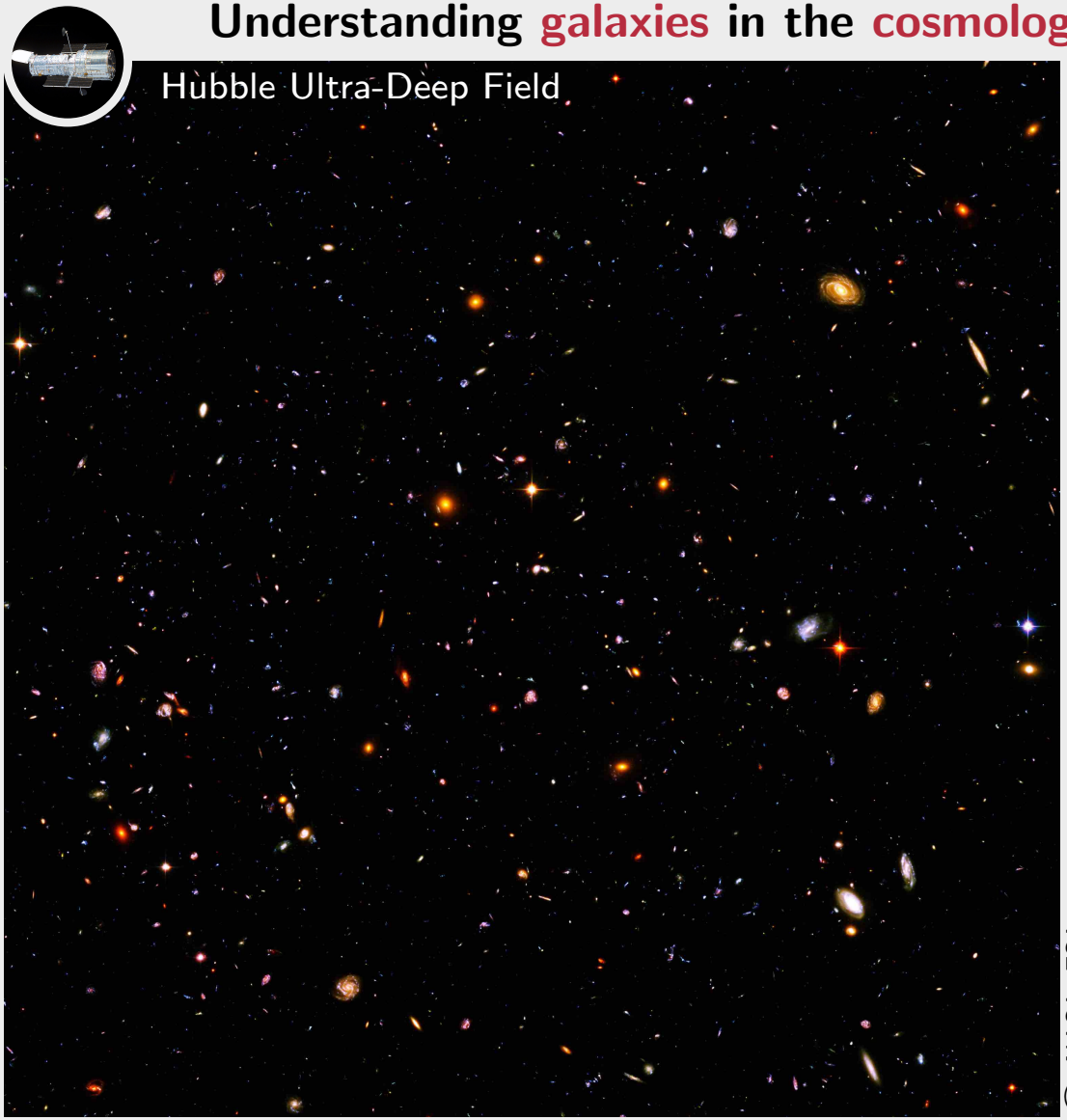
Les Houches 2025 school on Dark Universe, 16 July 2025

Galaxy formation and evolution

Understanding our origins

but also constrain the cosmological model of the Universe

Understanding galaxies in the cosmological context and vice versa



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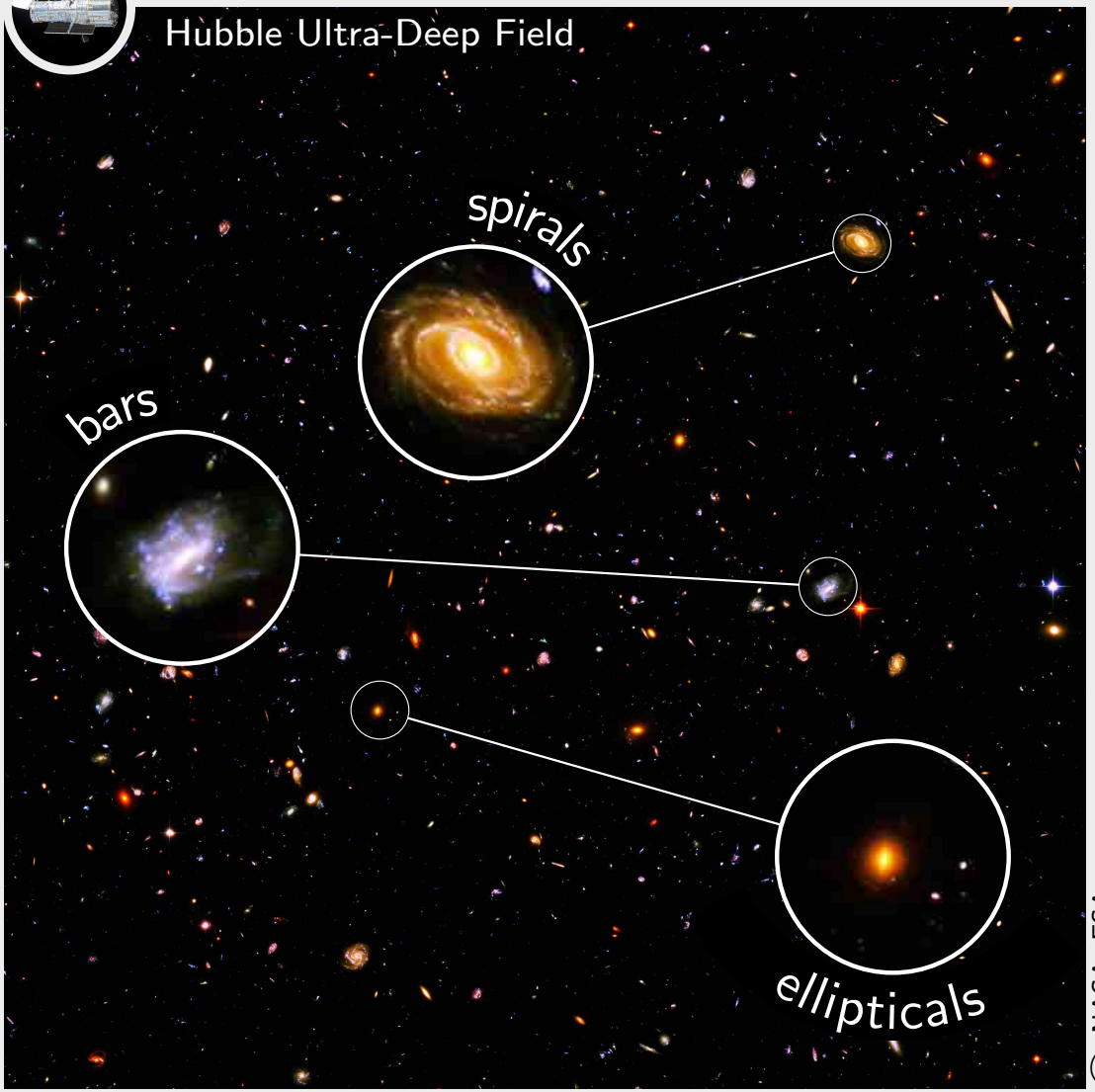

Diversity

Properties:
- stellar mass
- star formation rate
- morphology ...

Correlations:
- mass - star formation rate
- (local) density - mass - color ...

e.g. Hubble 1926, Oemler 1974
Dressler 1980
Strateva et al. 2001

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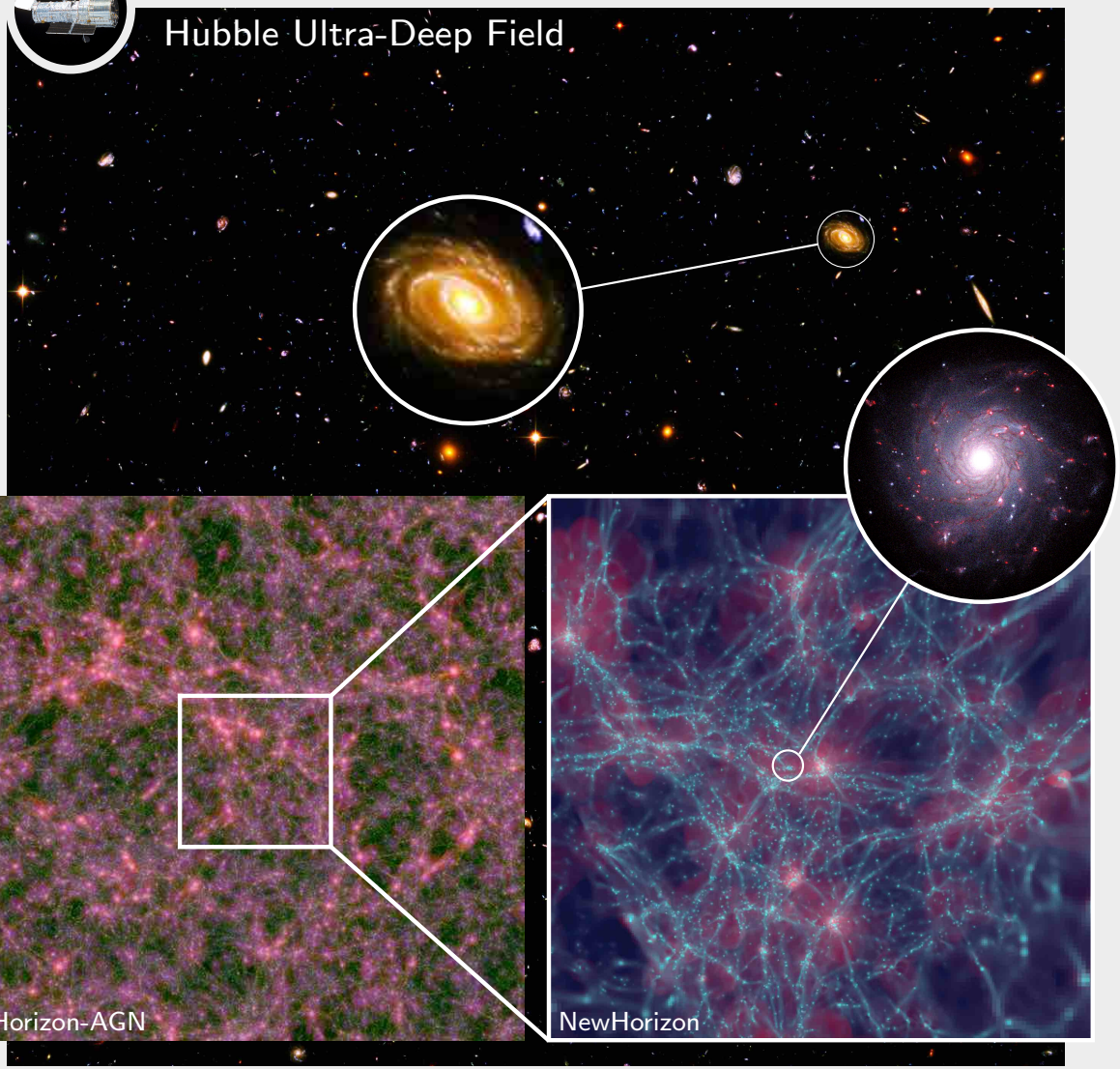

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e.g. Hubble 1926, Oemler 1974
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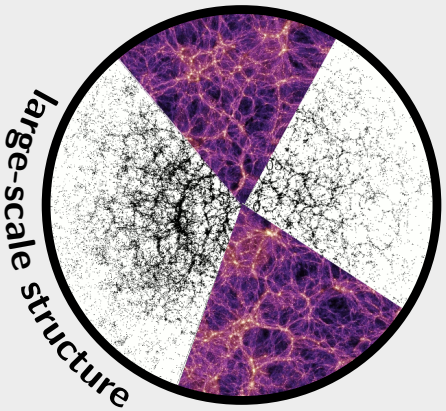
Strategy

Global / Statistics:
- large surveys
  e.g. Euclid, PFS, LSST, DESI
- cosmological simulations
  e.g. Simba, NewHorizon

Local / Detailed analysis:
- resolved surveys
  e.g. Gaia, WEAVE, PHANGS
- modelling
  e.g. idealised simulations

Modelling galaxy formation in a cosmological context

Modelling galaxy formation in a cosmological context



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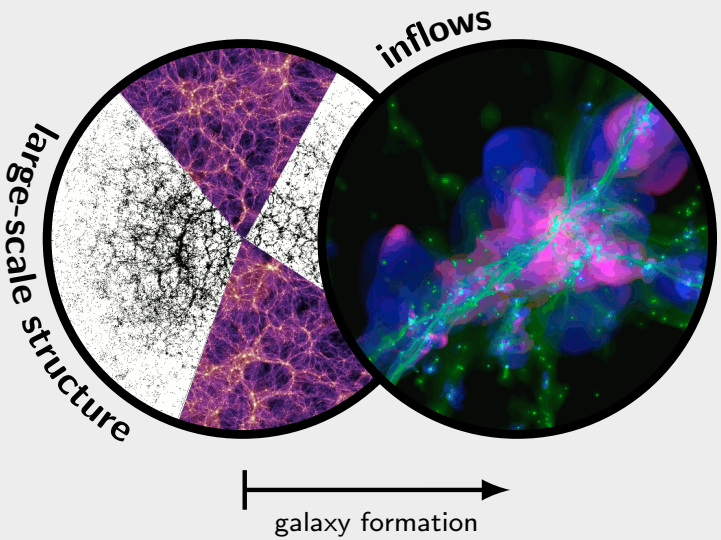

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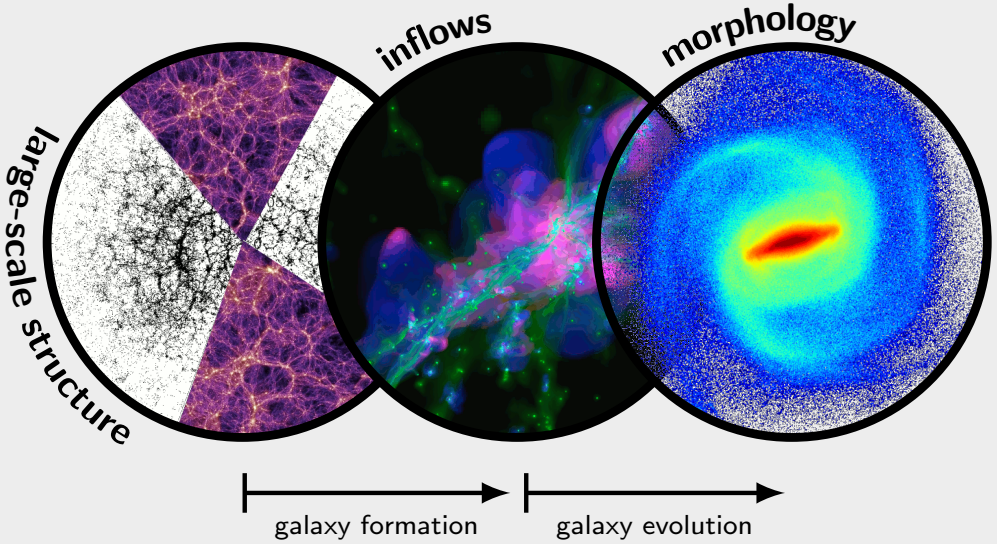

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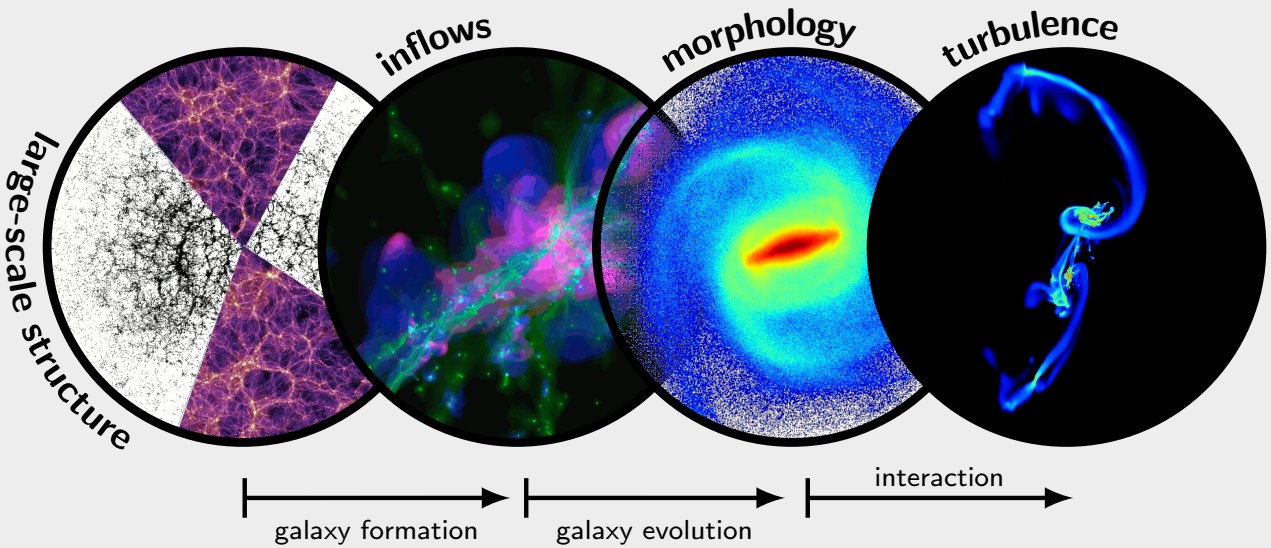

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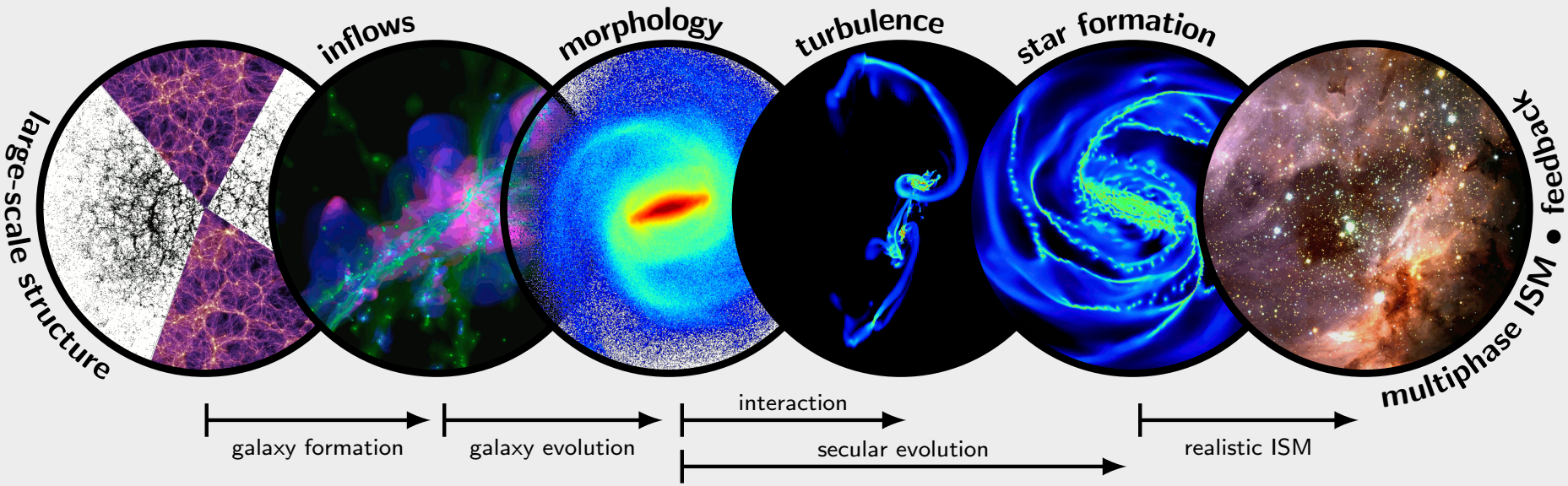

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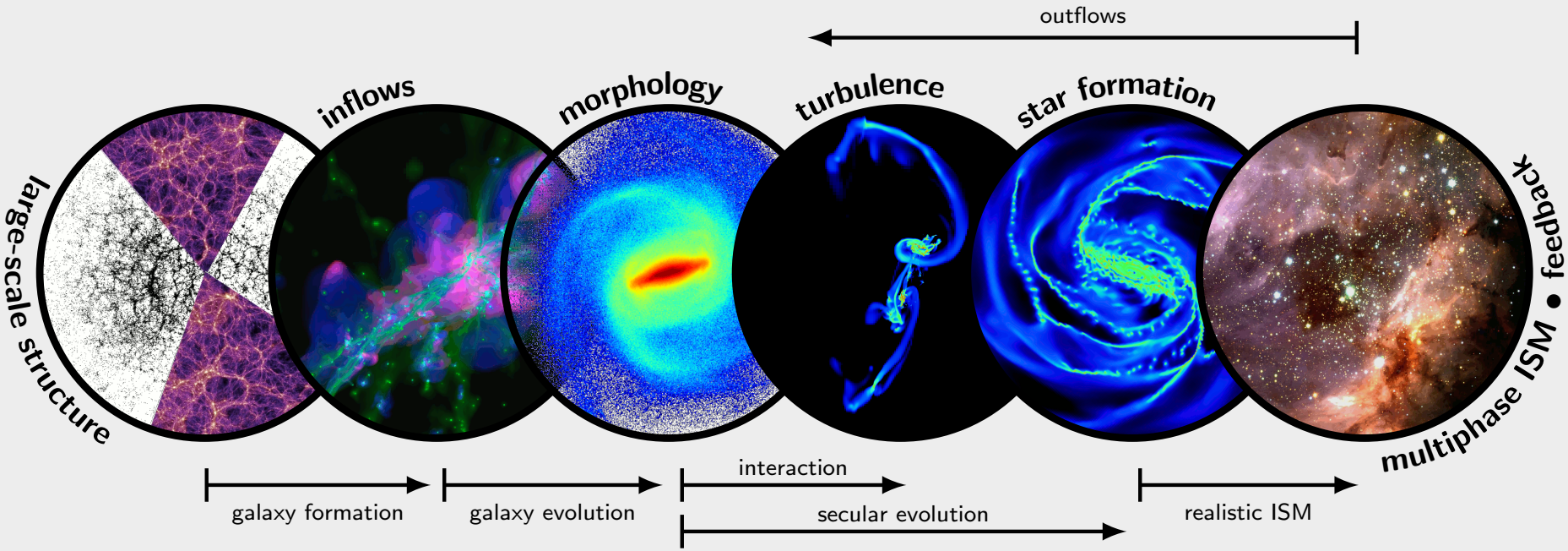

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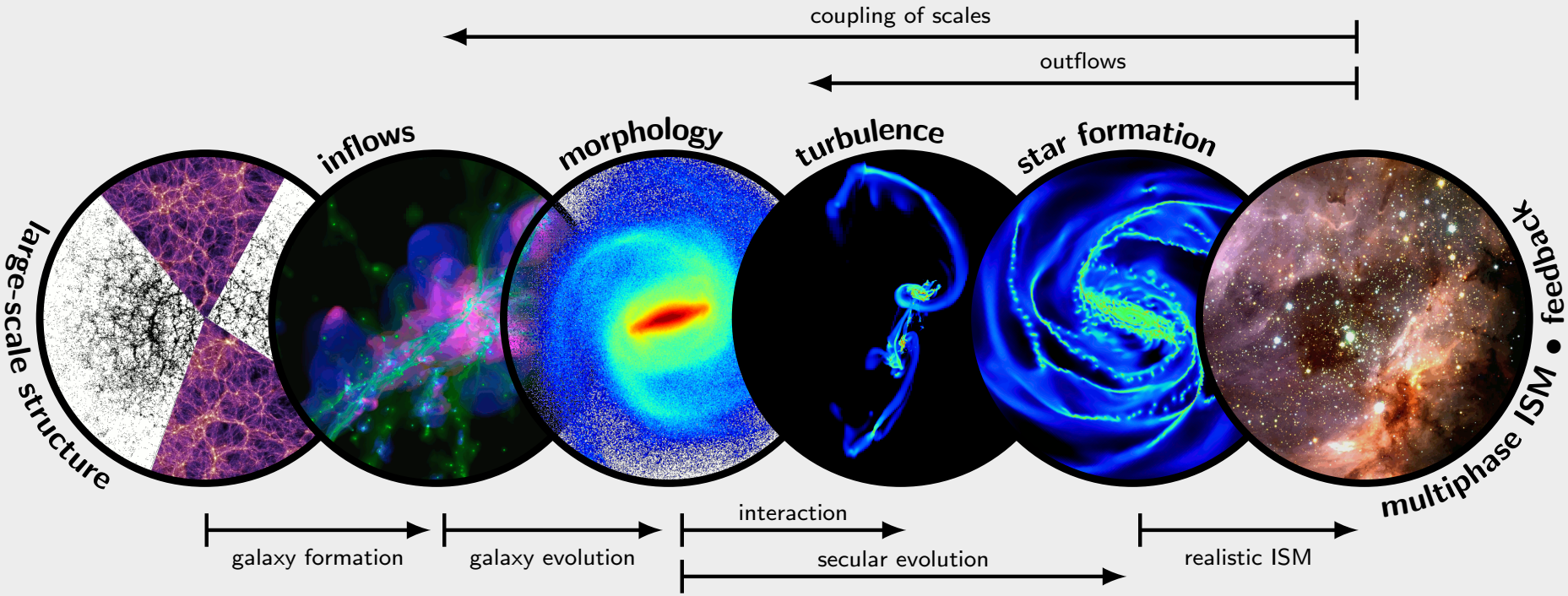
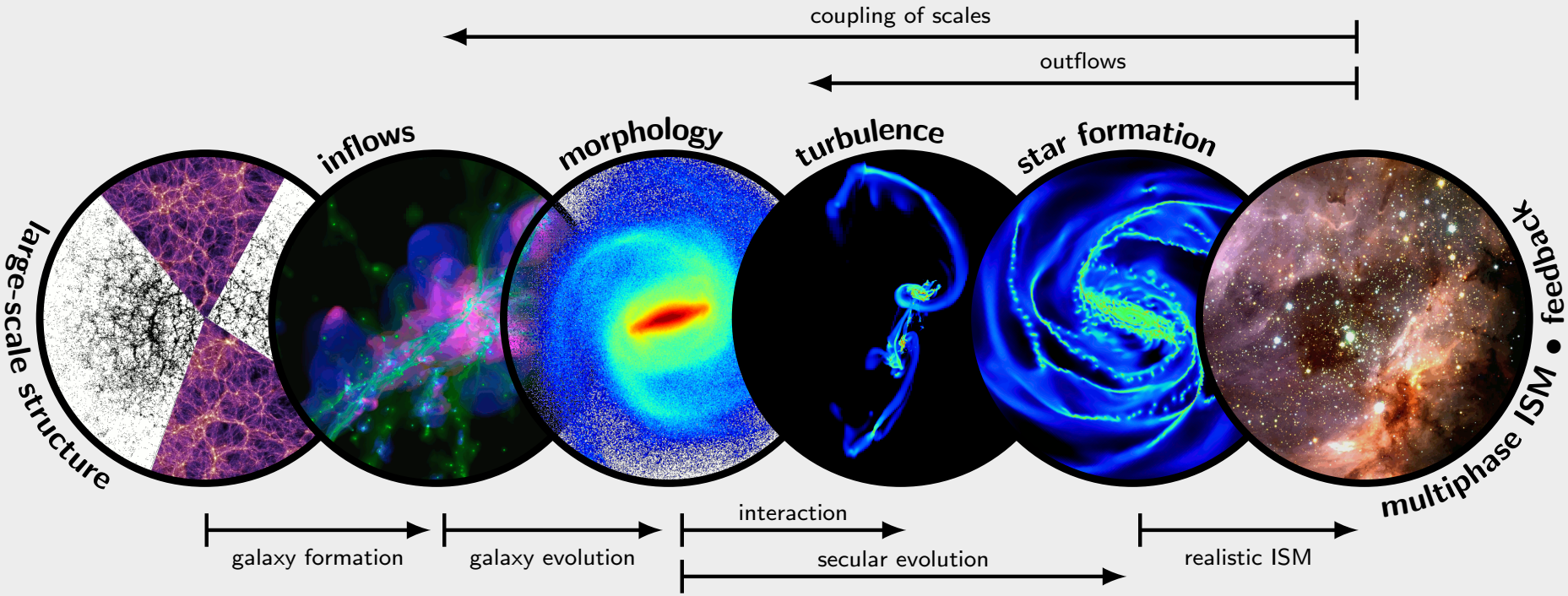


Modelling galaxy formation in a cosmological context: **greatest challenge**
due to vast range of scales and numerous physical processes involved

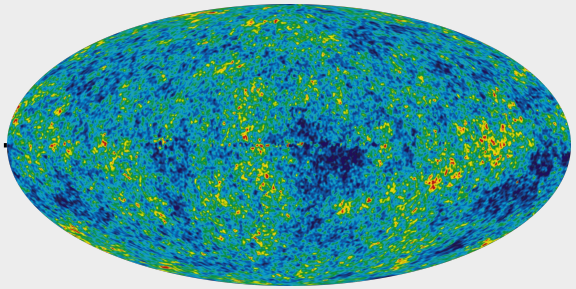


space	$>$ Mpc	10 kpc	$<$ pc
time	$\sim$ 10 Gyr	Gyr	10 Myr
mass		10^{15} $M_\odot$	10^{10} $M_\odot$	$M_\odot$

① initial conditions

Modelling galaxy formation

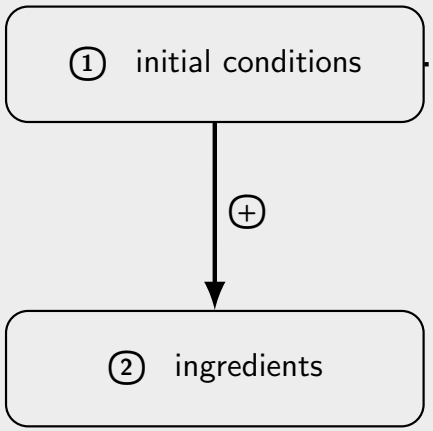
① initial conditions

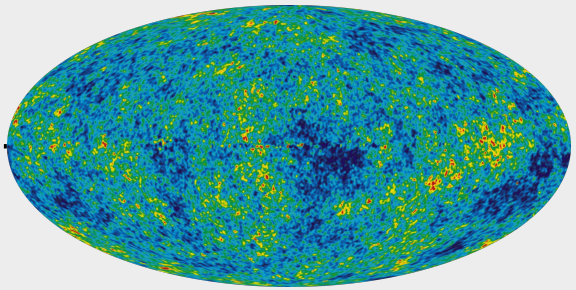


ΛCDM

- CDM paradigm: success on large scales
- simplest (6 parameters only)
- sufficiently accurate

Modelling galaxy formation





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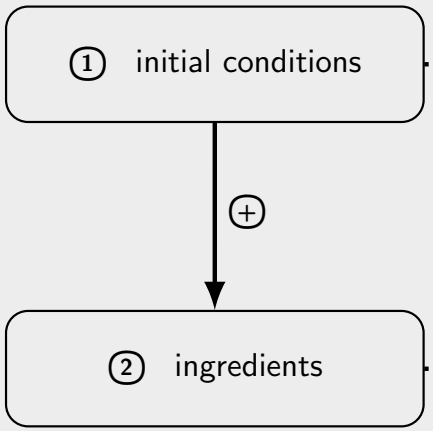

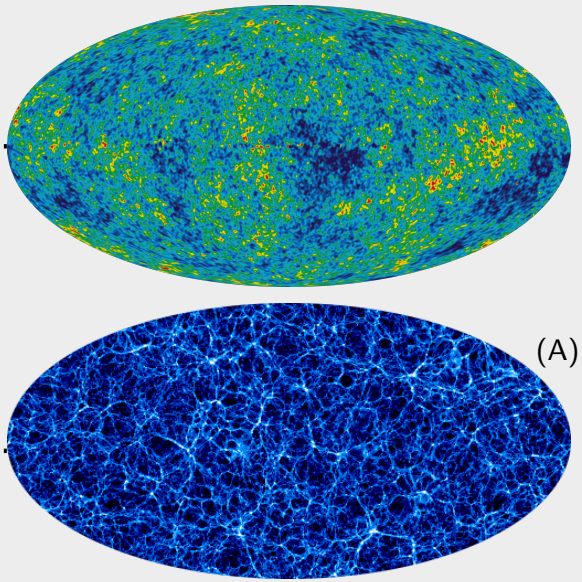

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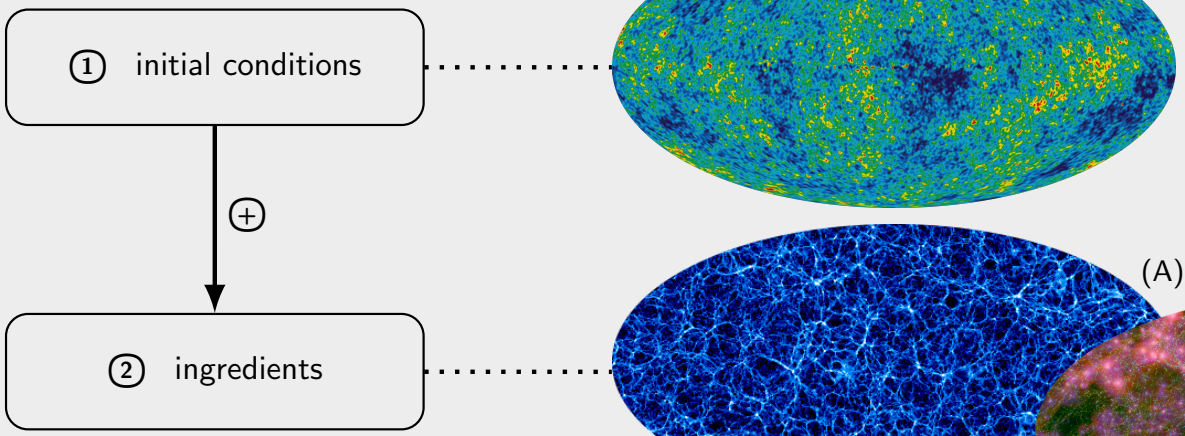

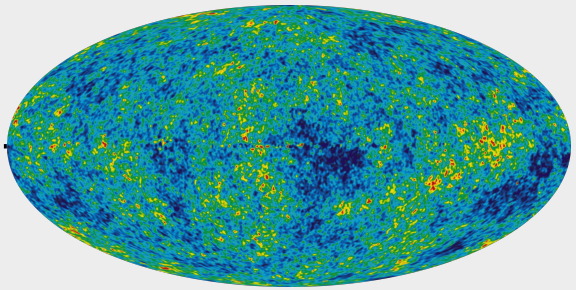

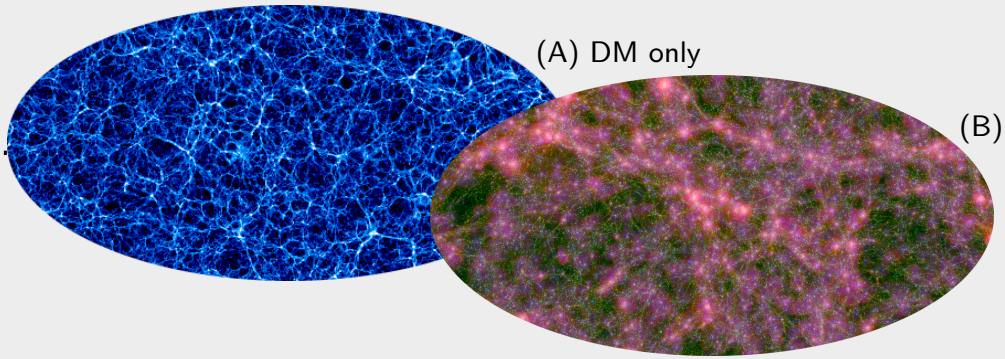

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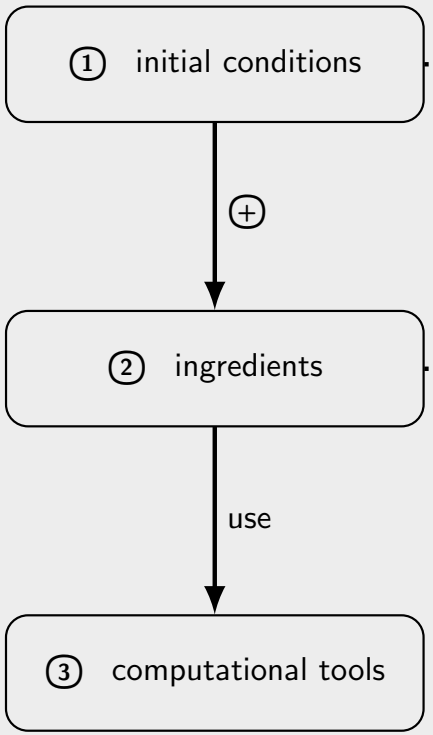

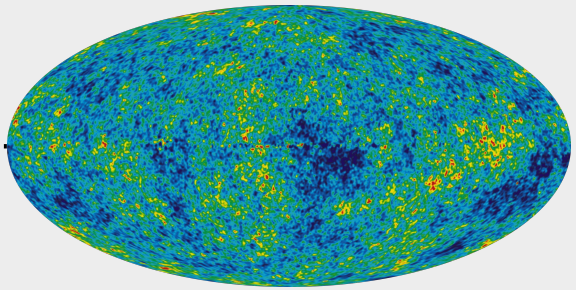

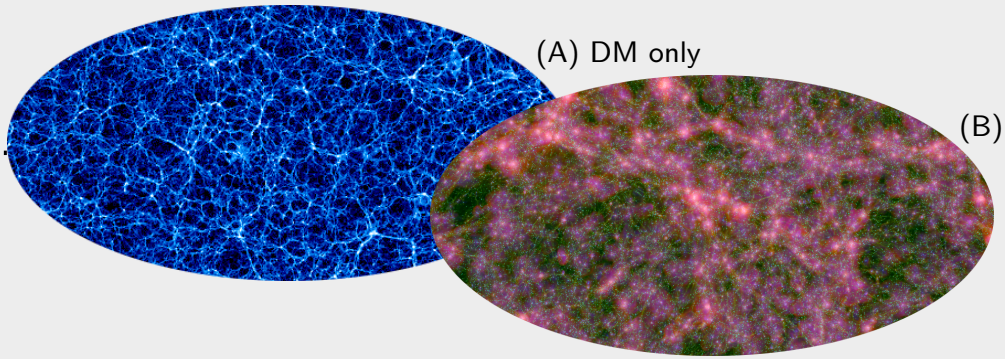

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Modelling galaxy formation

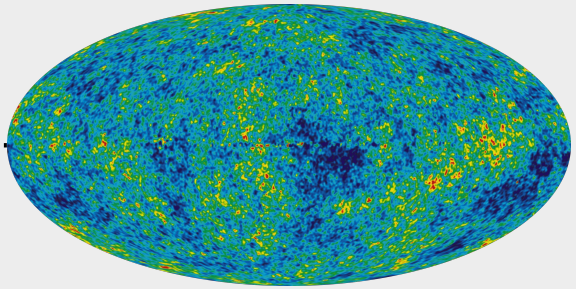
① initial conditions

⊕

② ingredients

use

③ computational tools



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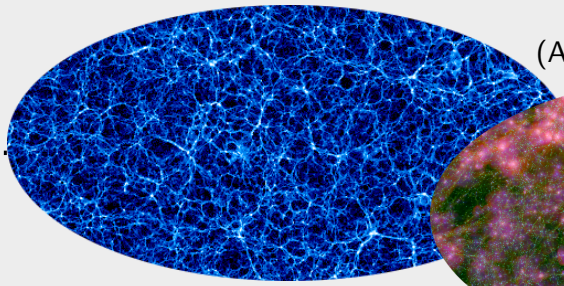

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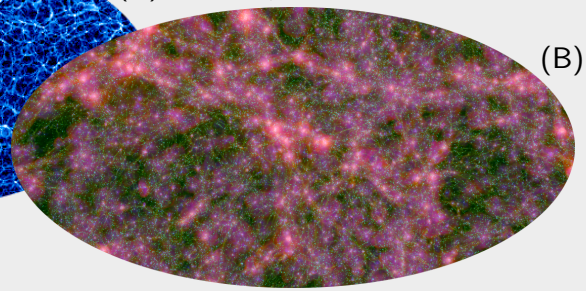

(B) DM & baryons

Methods

- numerical simulations
- SAM
- HOD ...

Modelling galaxy formation

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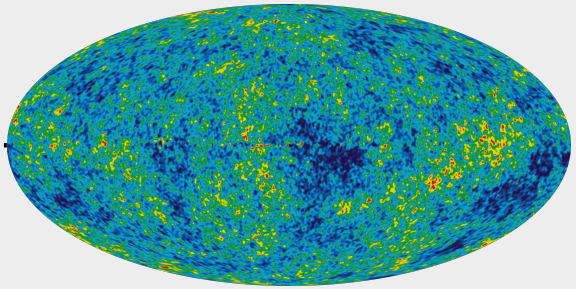

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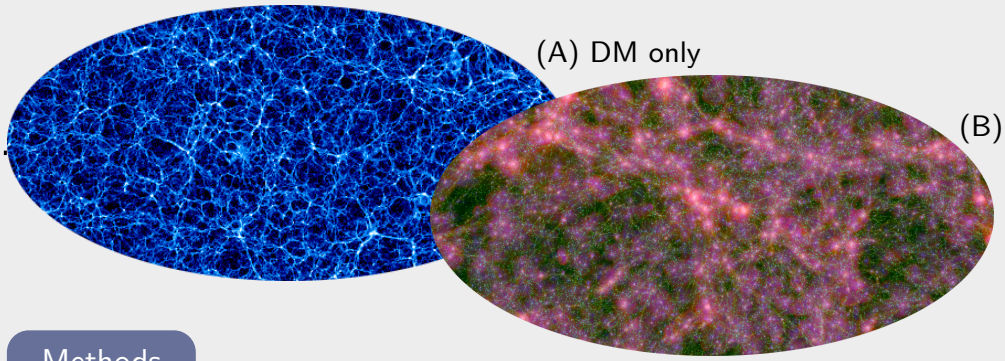

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→ Predictions

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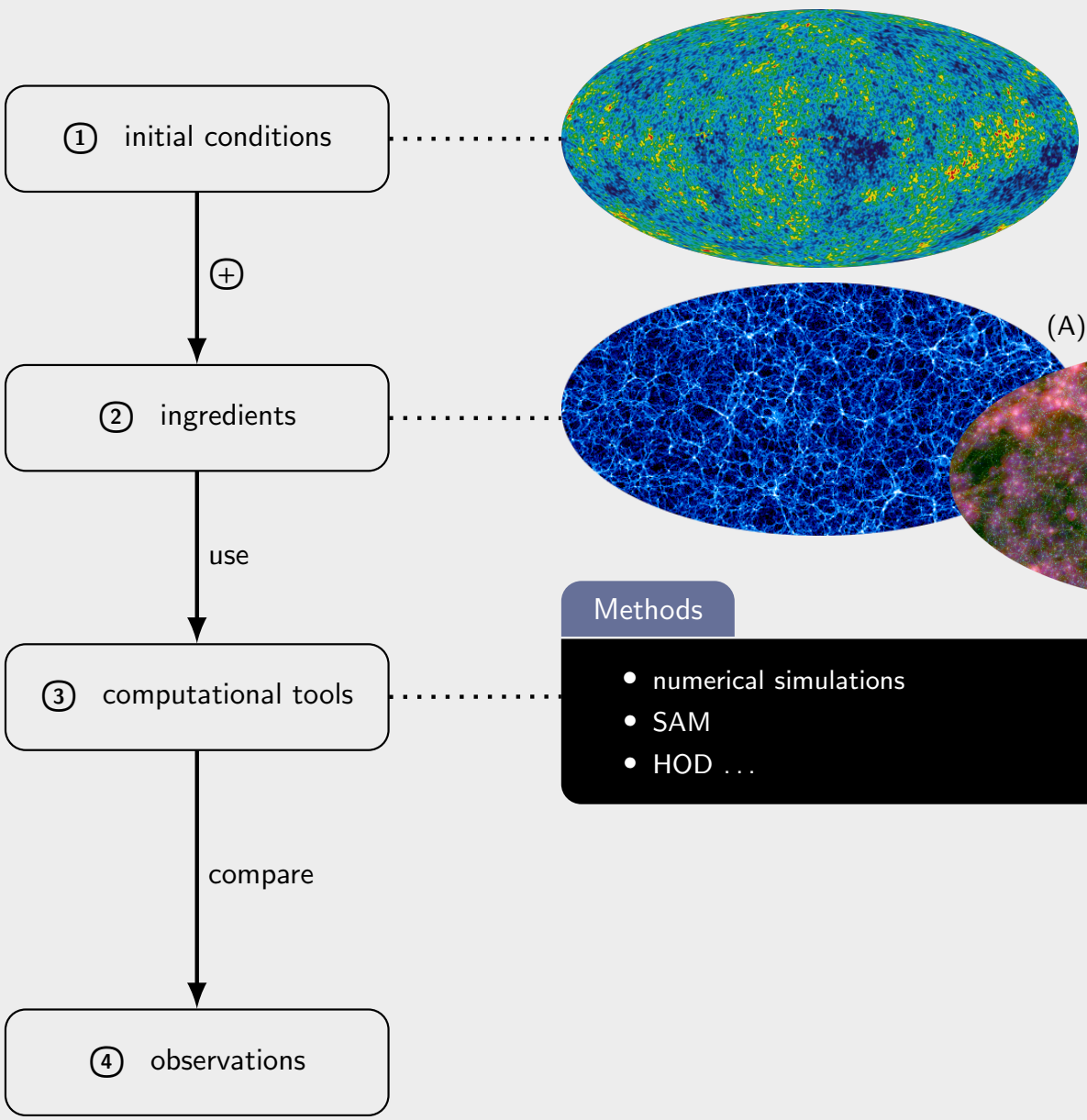

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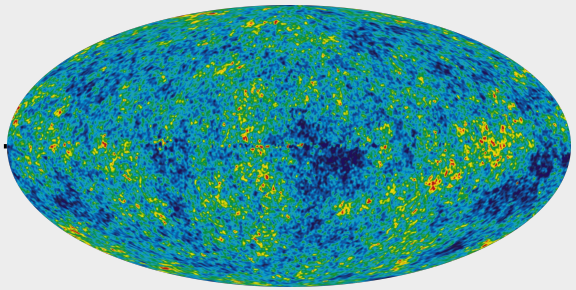

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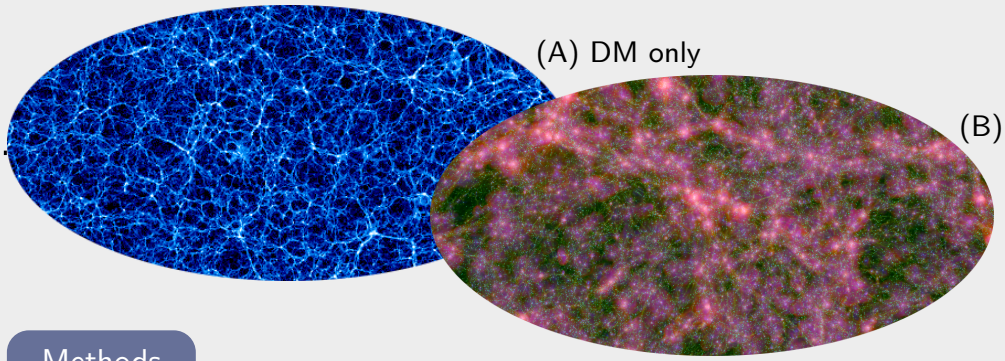

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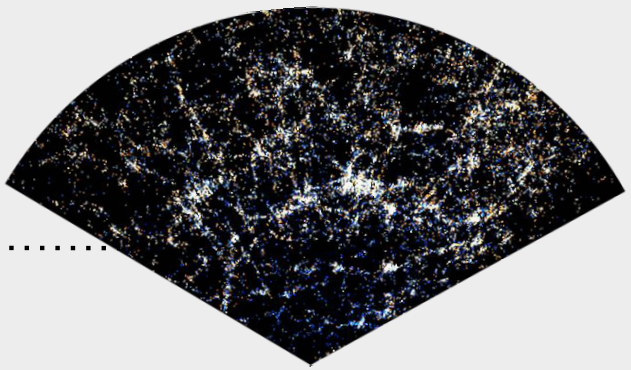

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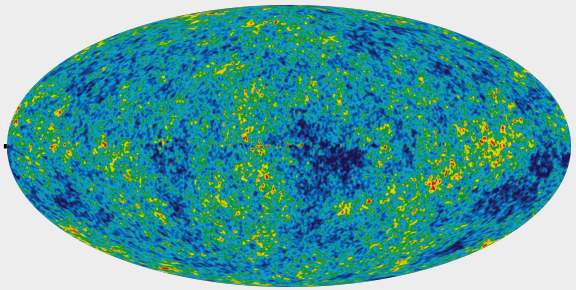

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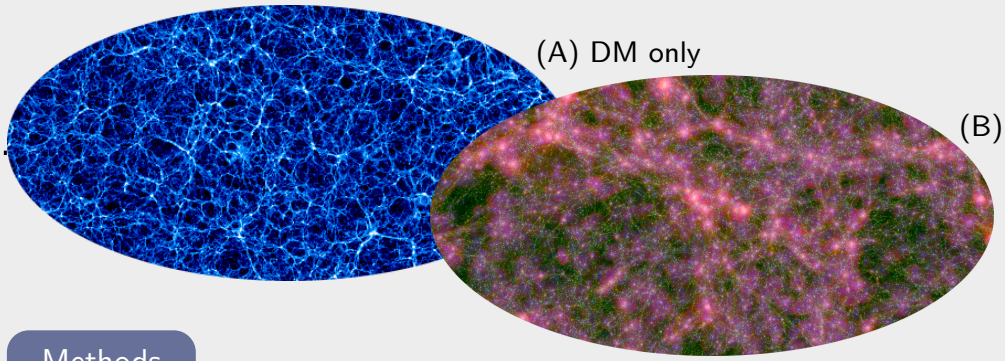

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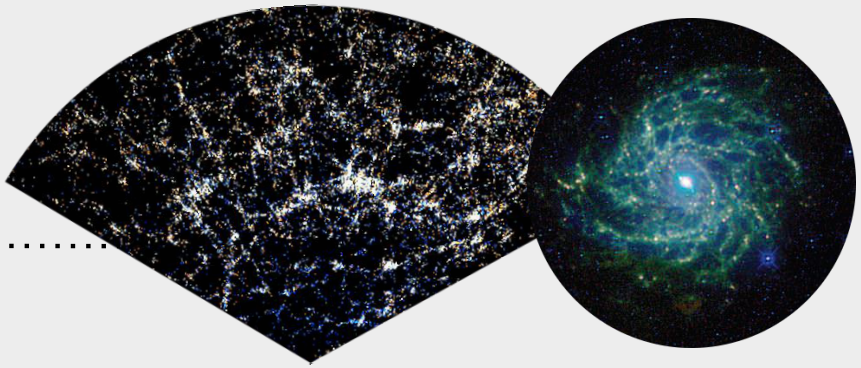

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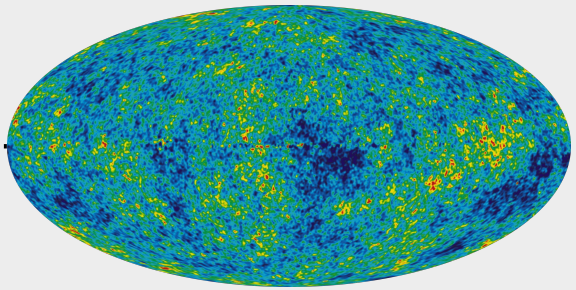

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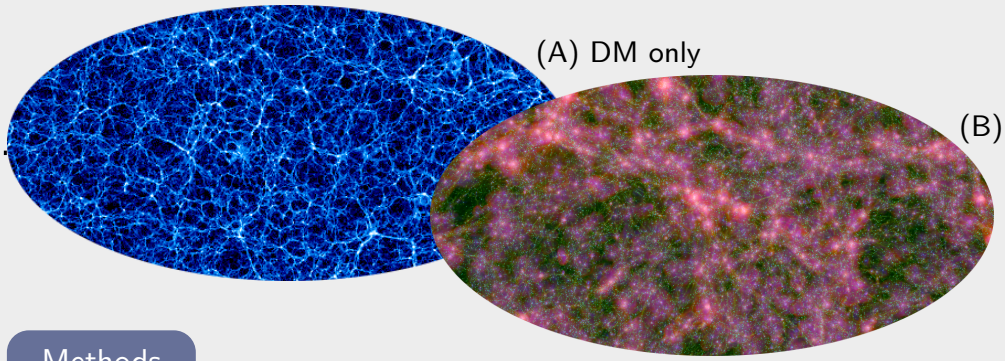

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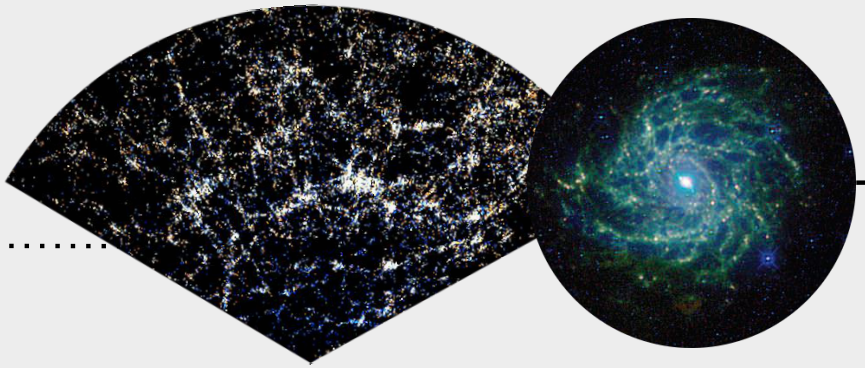

→ Test predictions

Modelling galaxy formation

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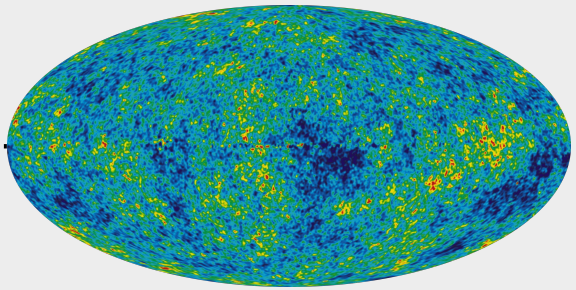

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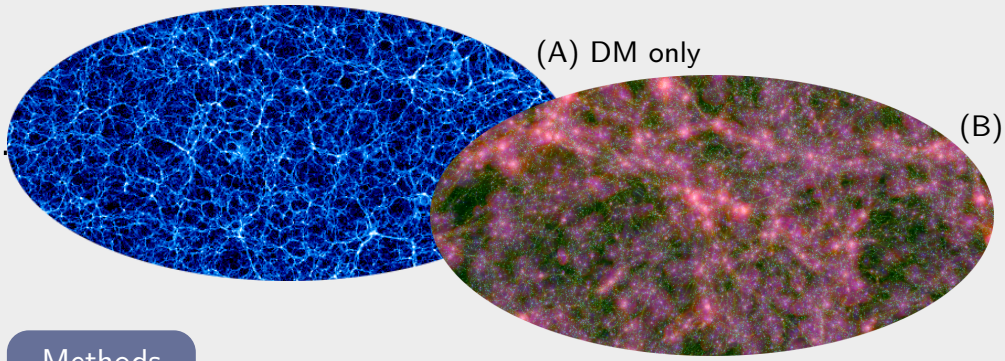

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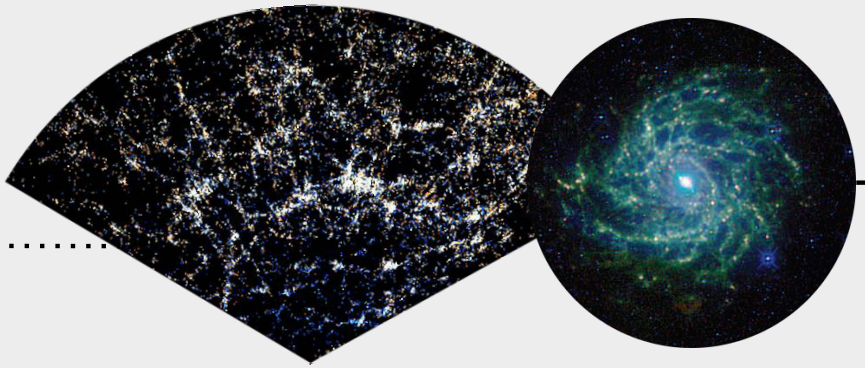
Predictions

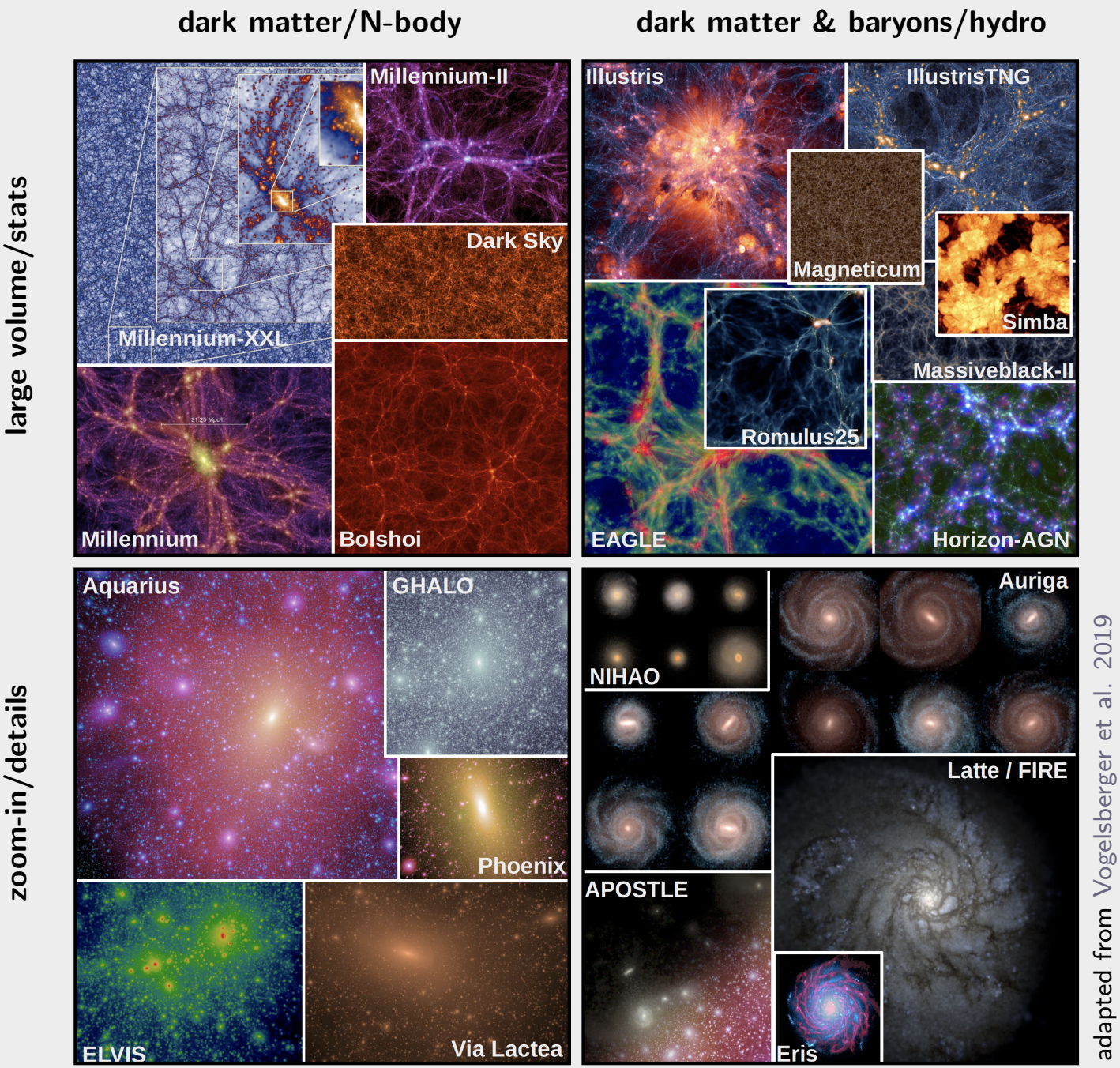
compare



④ observations

Test predictions

Cosmological simulations

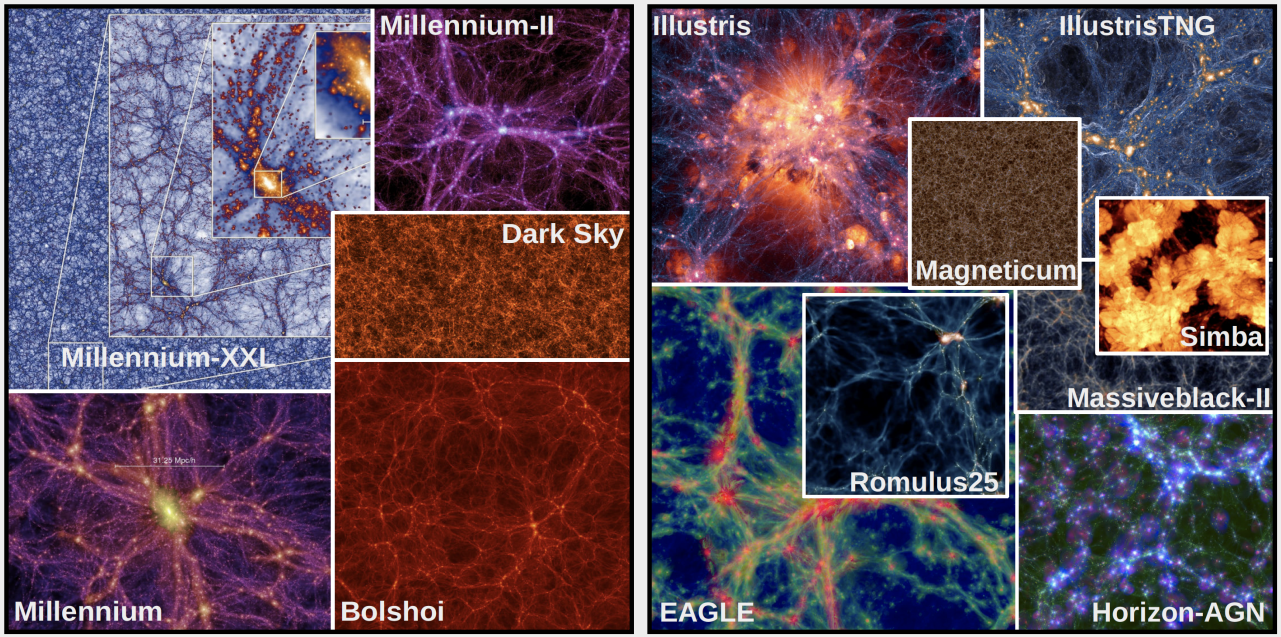


This lecture

dark matter/N-body

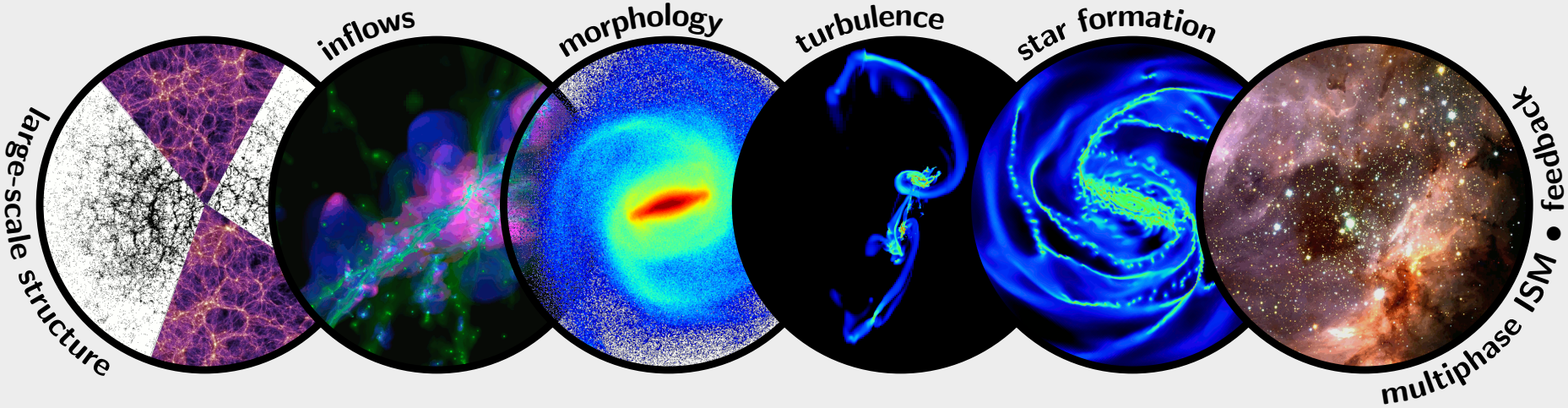
dark matter & baryons/hydro

large volume/stats



adapted from Vogelsberger et al. 2019

Modelling galaxy formation in a cosmological context



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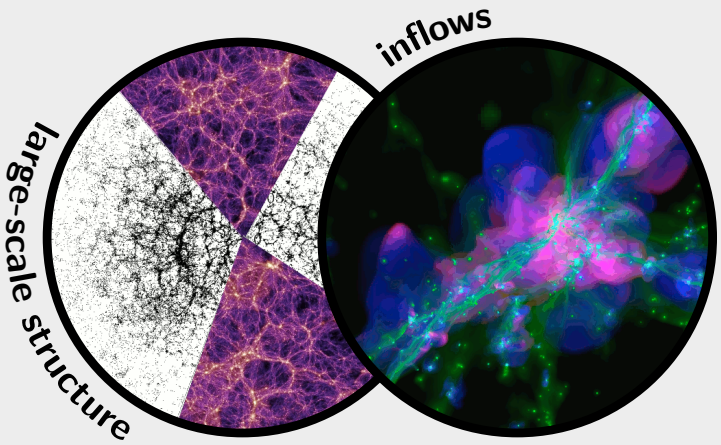


Large-scale structure
impact on galaxies

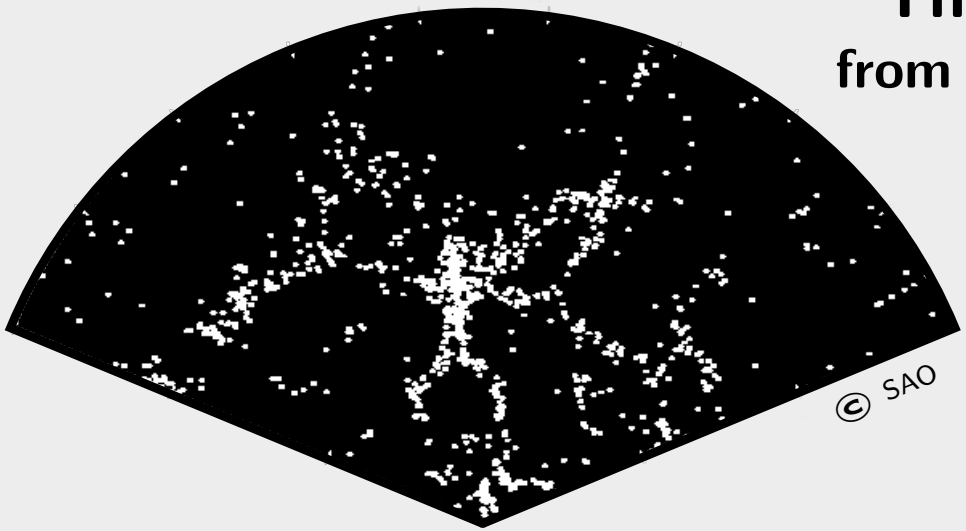
- anisotropy of the cosmic web
- connectivity of the cosmic web
- groups within the cosmic web

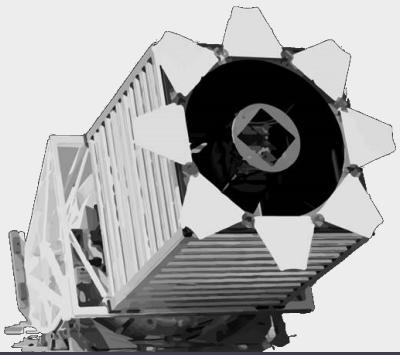
impact of galaxies/cosmology

- morphology of LSS

The Cosmic web
from observations . . .

de Lapparent et al. 1986

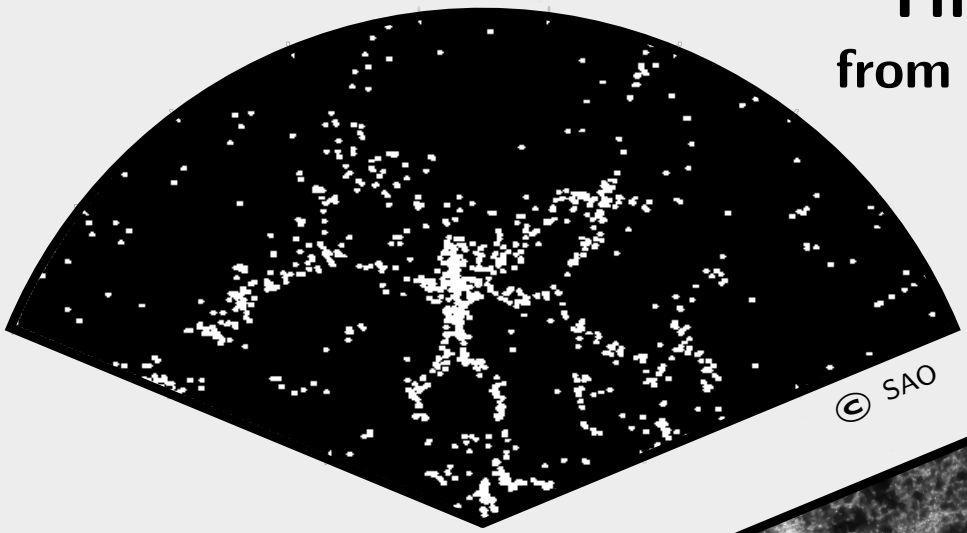


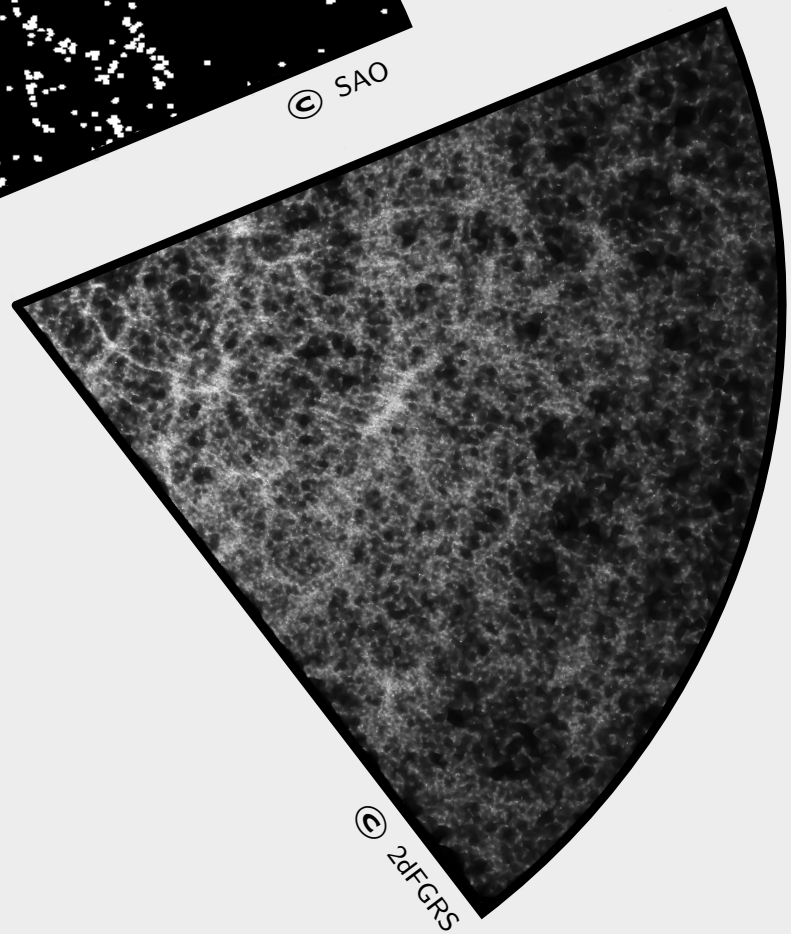


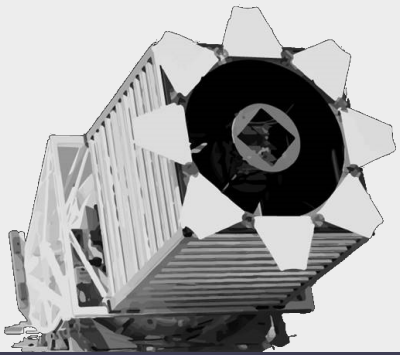
Sloan Foundation Telescope

The Cosmic web
from observations . . .

de Lapparent et al. 1986
Colless et al. 2003







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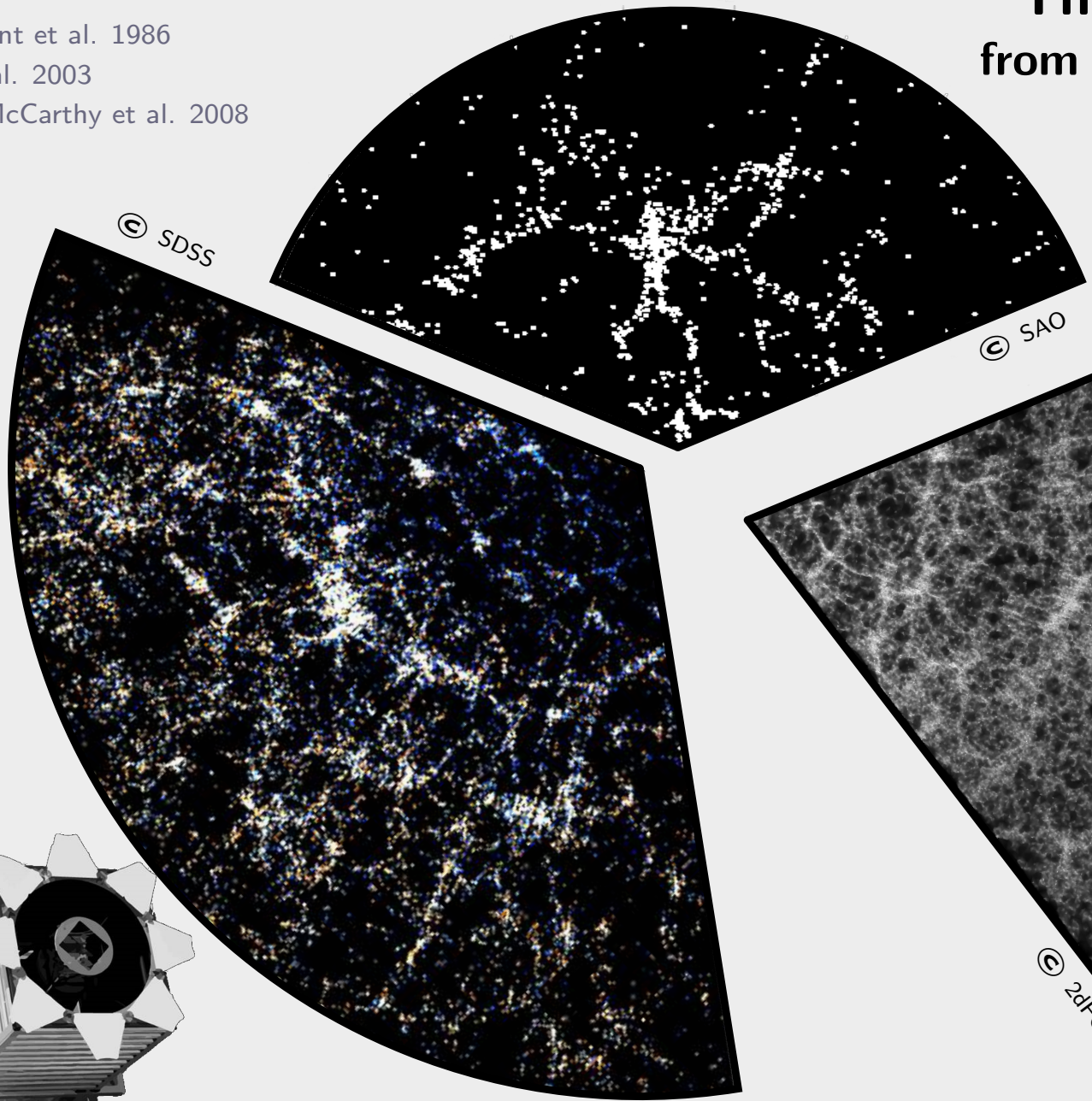

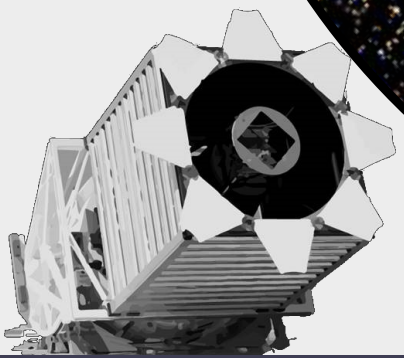

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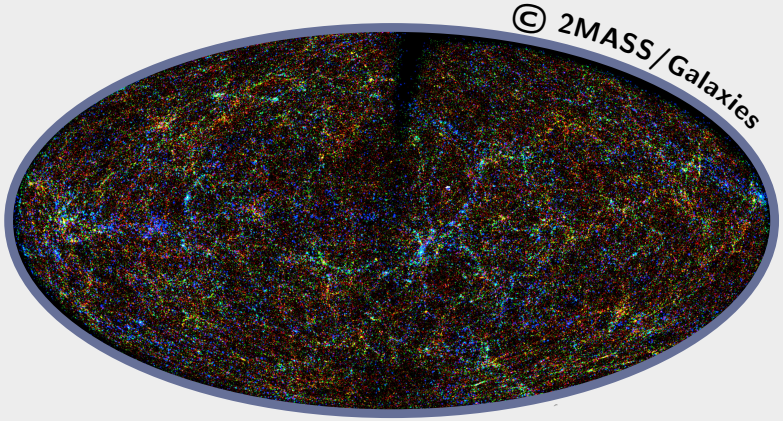
The Cosmic web

. . . to theory



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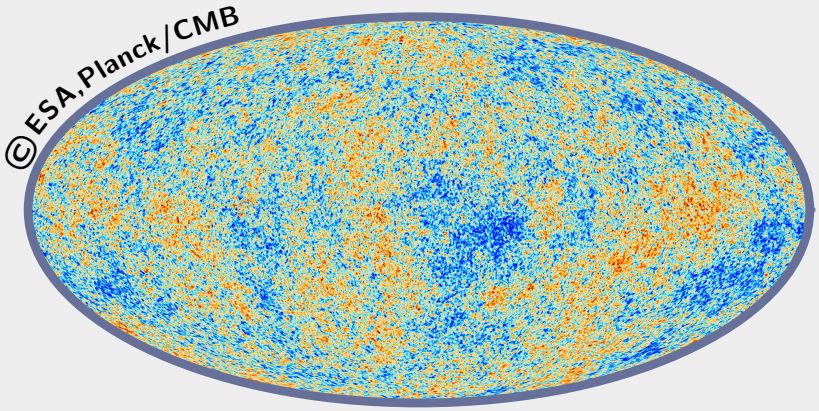
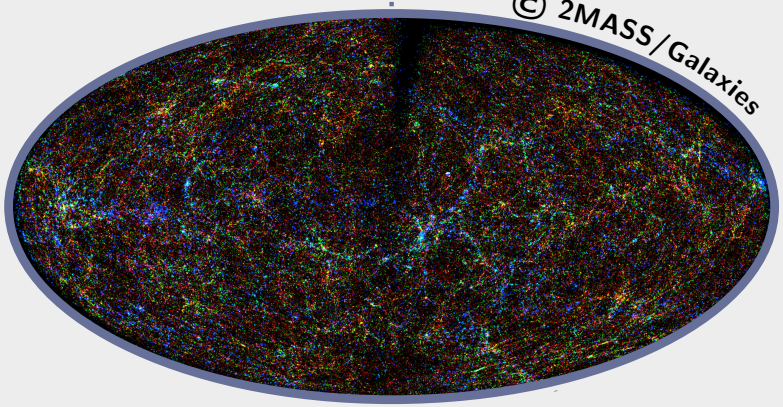
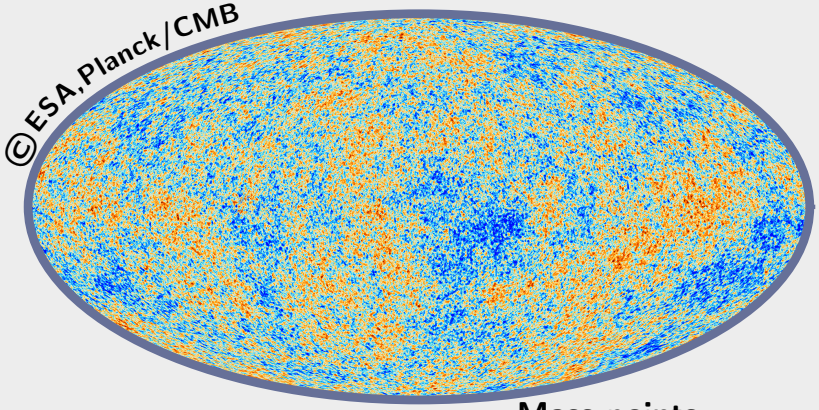


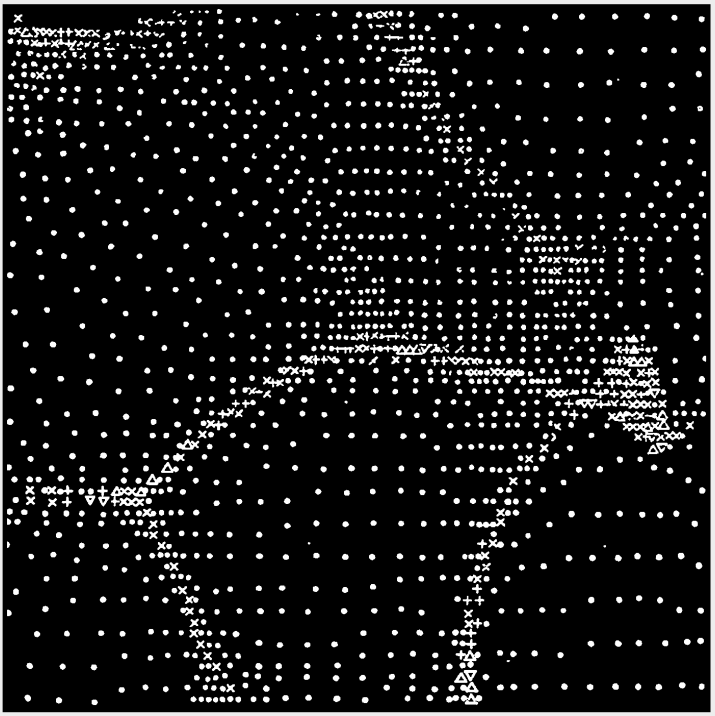




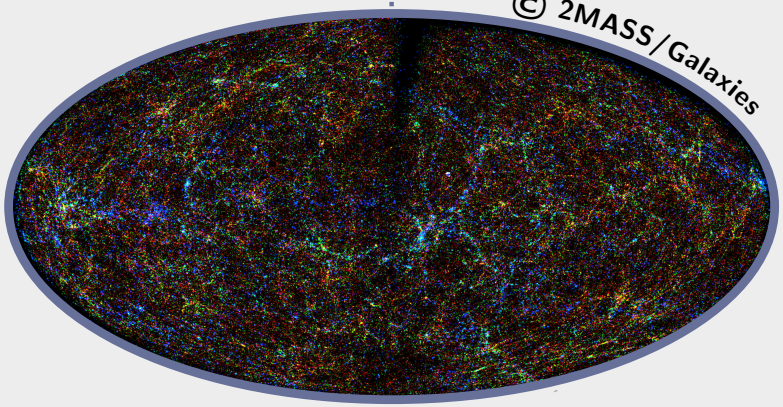
The Cosmic web
. . . to theory

Klypin & Shandarin 1993
Bond, Kofman & Pogosyan 1996

Mass points



Zel'dovich 1970
Doroshkevich & Shandarin 1978



The Cosmic web
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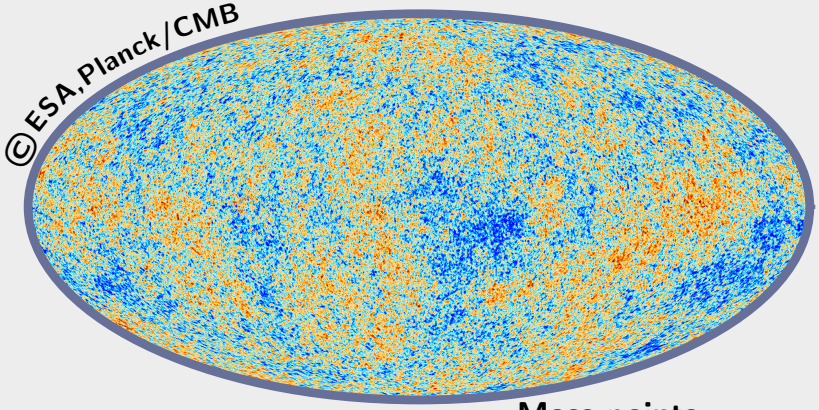

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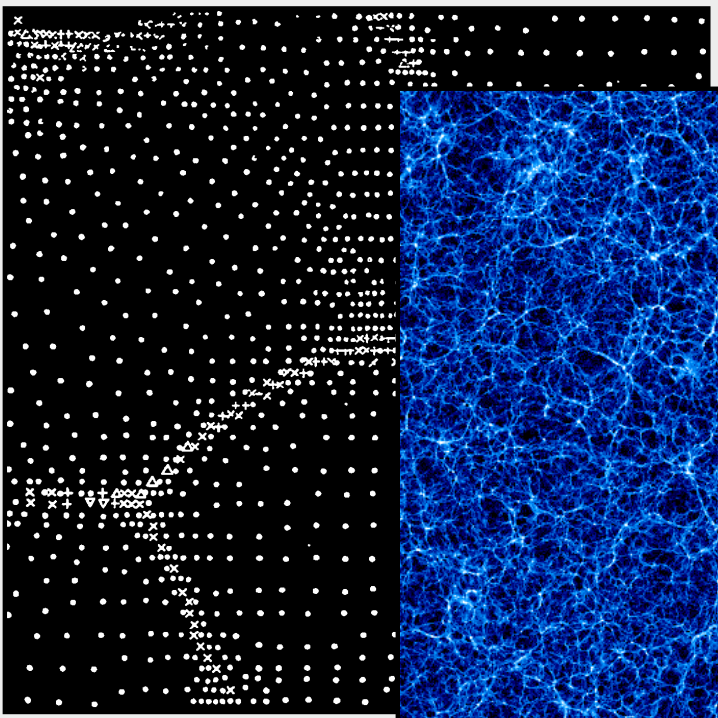

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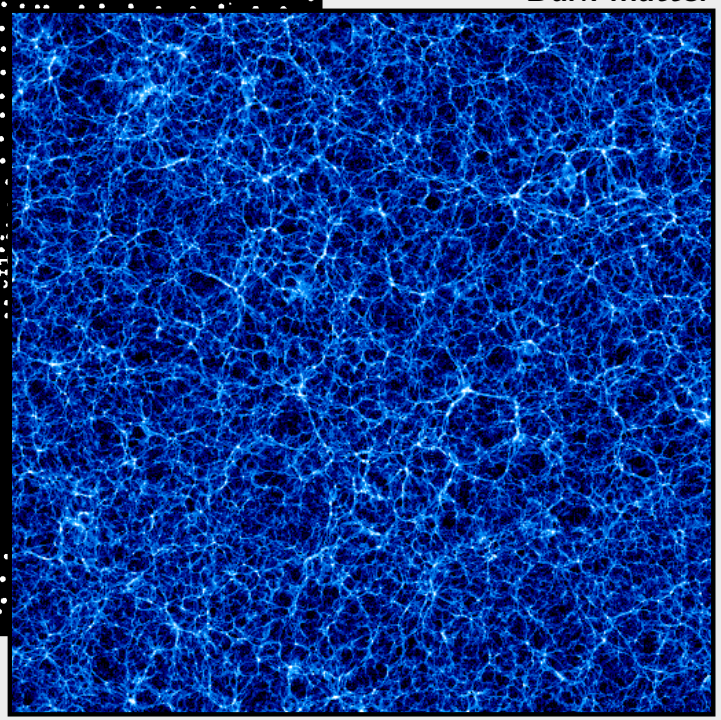
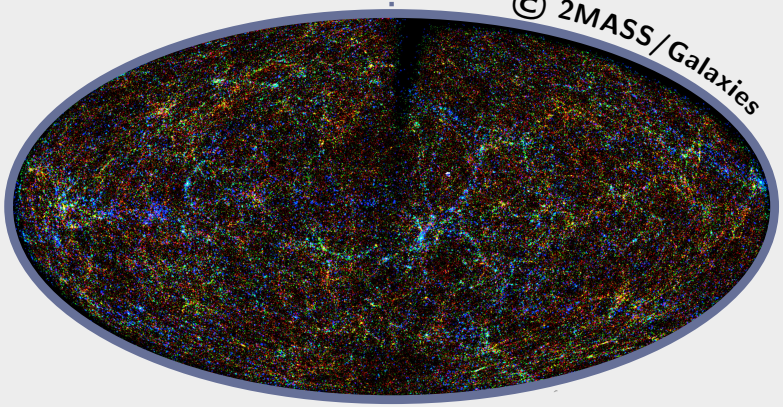


Marenostrum • Yepes et al. 2007



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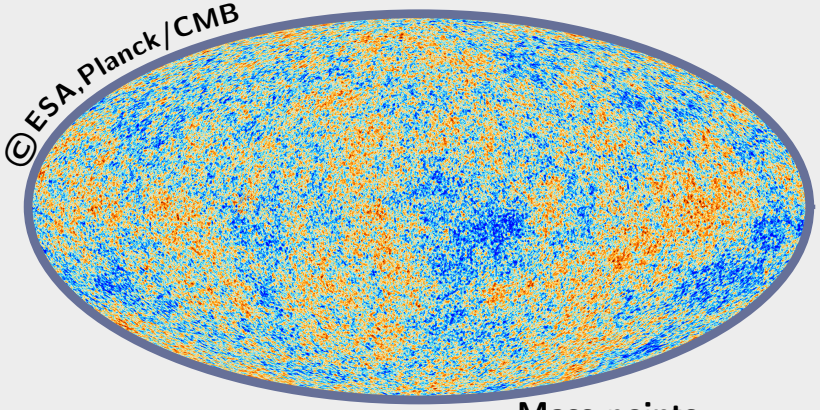

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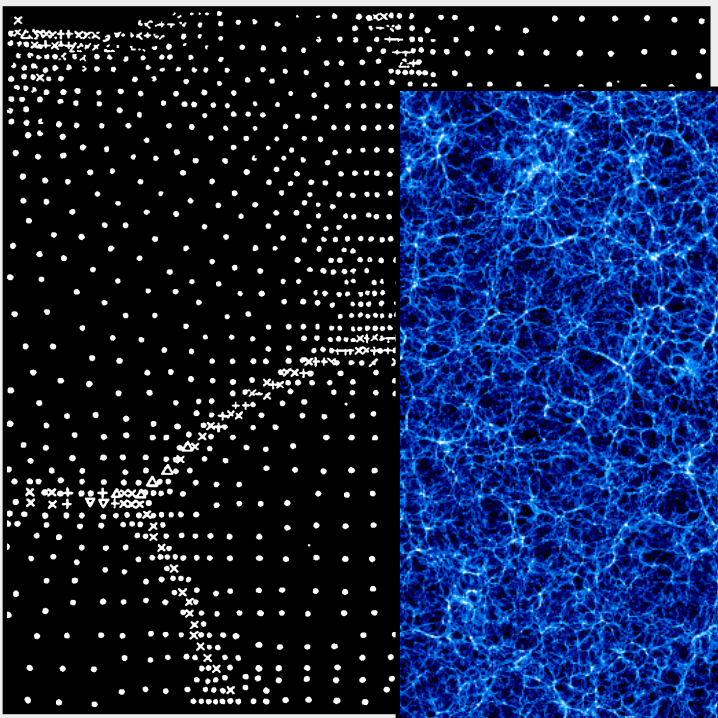

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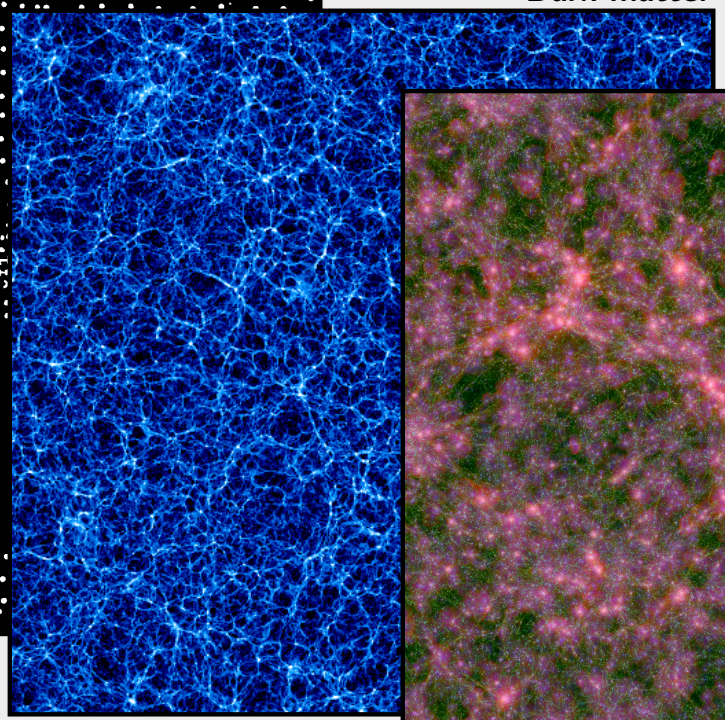
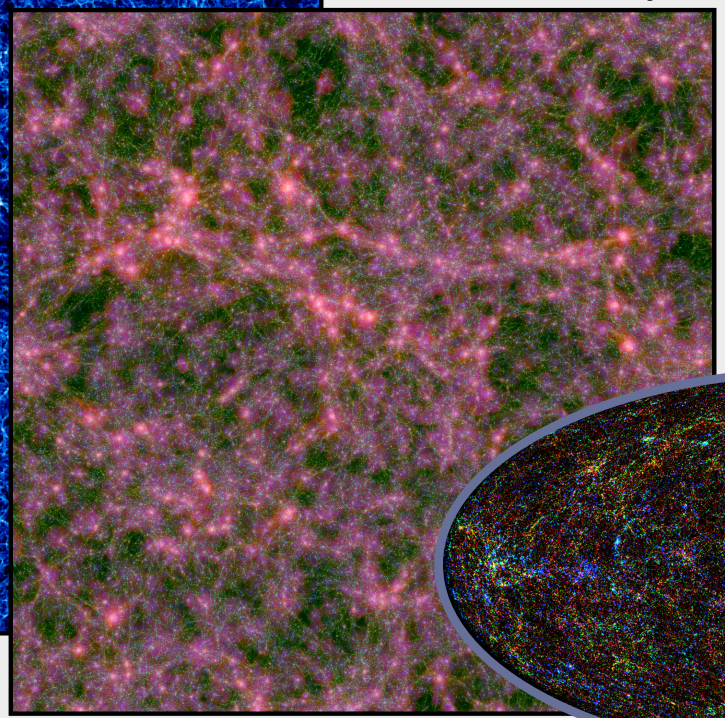
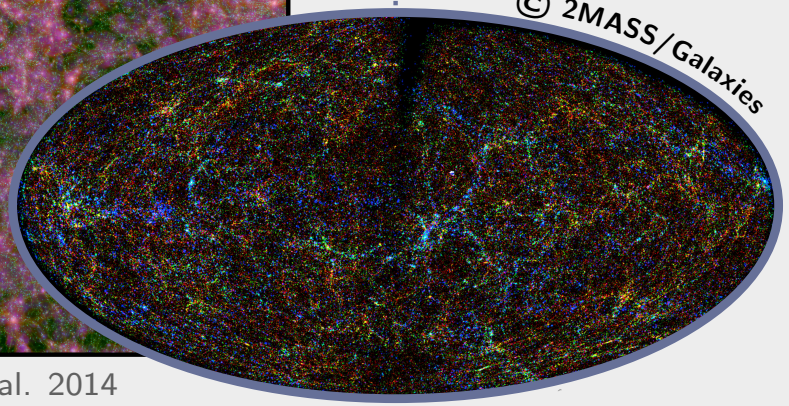


Marenostrum



Horizon-AGN • Dubois et al. 2014



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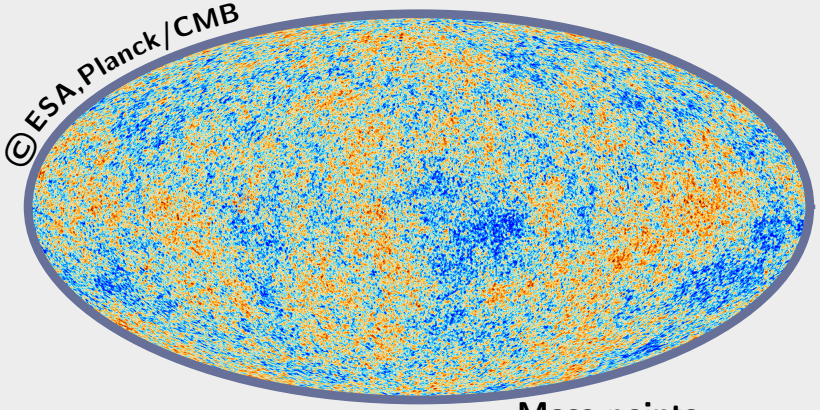

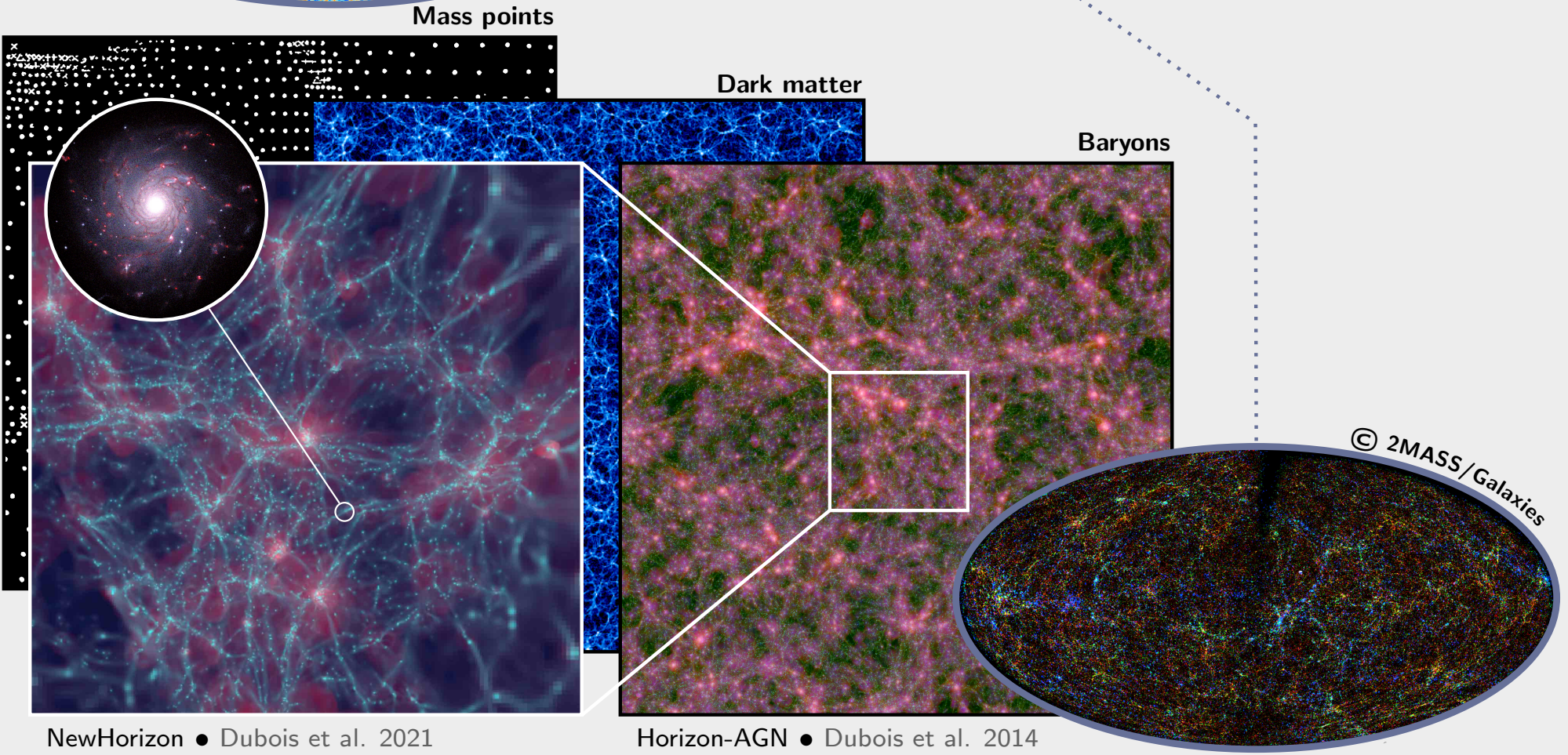

NewHorizon • Dubois et al. 2021

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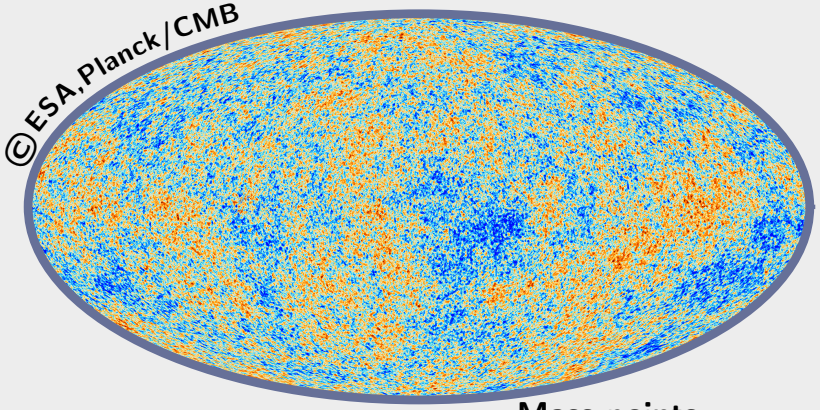


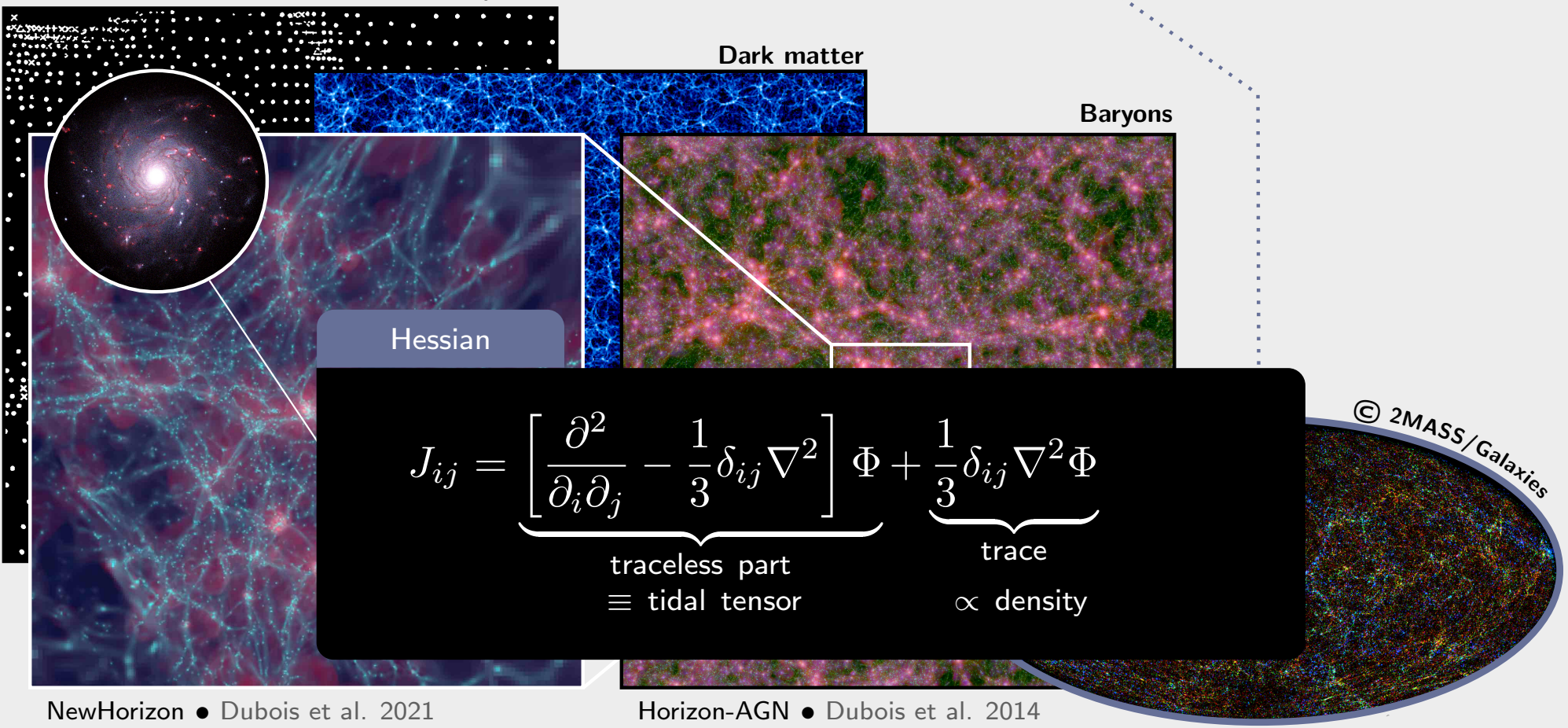
Mass points

Dark matter

Baryons

Hessian

$$J_{ij} = \underbrace{\left[\frac{\partial^2}{\partial_i \partial_j} - \frac{1}{3}\delta_{ij}\nabla^2\right]\Phi}_{\text{traceless part} \equiv \text{tidal tensor}} + \underbrace{\frac{1}{3}\delta_{ij}\nabla^2\Phi}_{\text{trace} \propto \text{density}}$$



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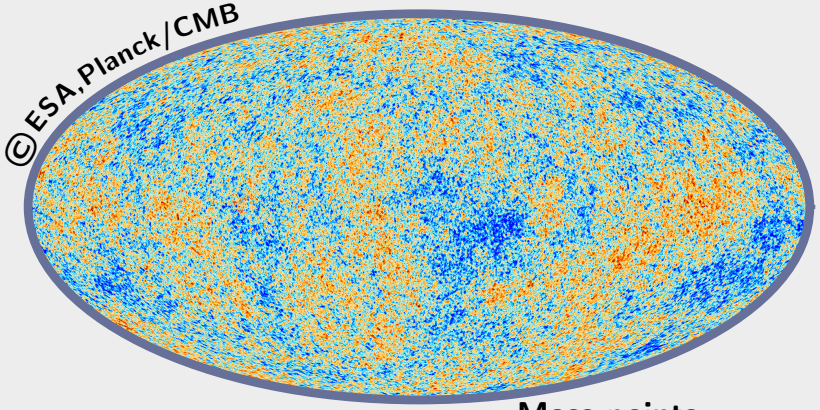

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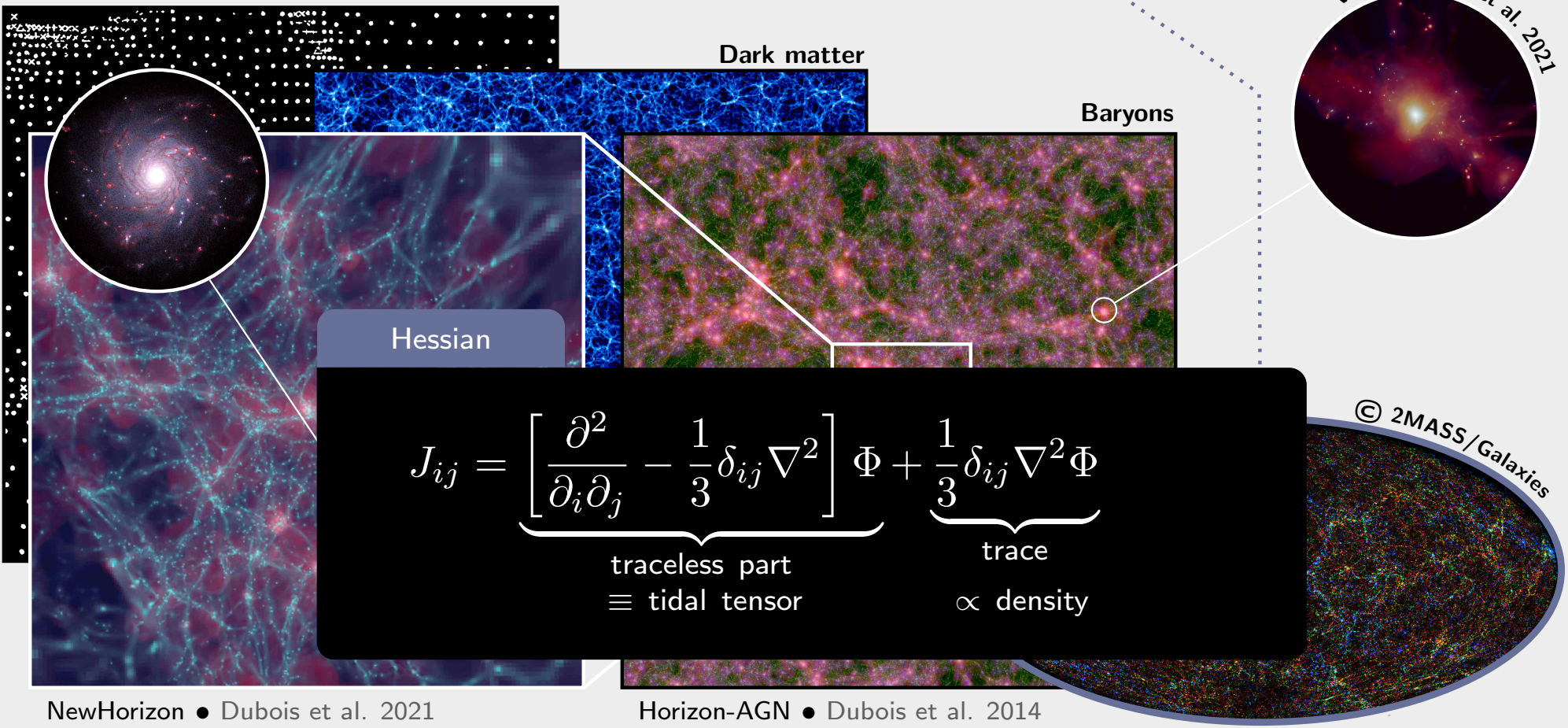

NewHorizon • Dubois et al. 2021

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1 **Scalar properties**

The Cosmic web

The Cosmic web

1 Scalar properties

- **Stellar mass:** more massive galaxies closer to filaments/walls

e.g. Poudel et al. 2016, Kuutma et al. 2017, Malavasi et al. 2017
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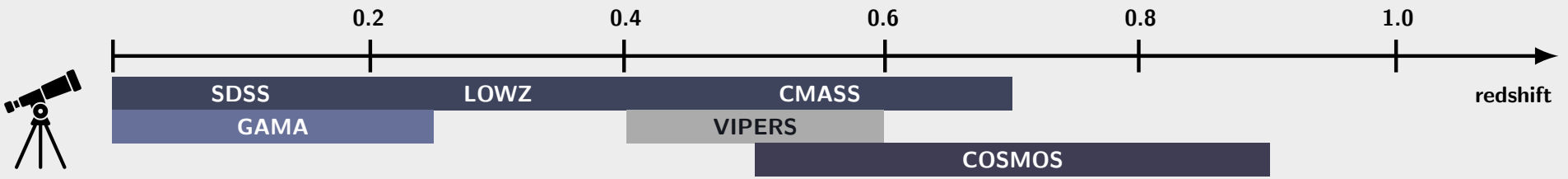

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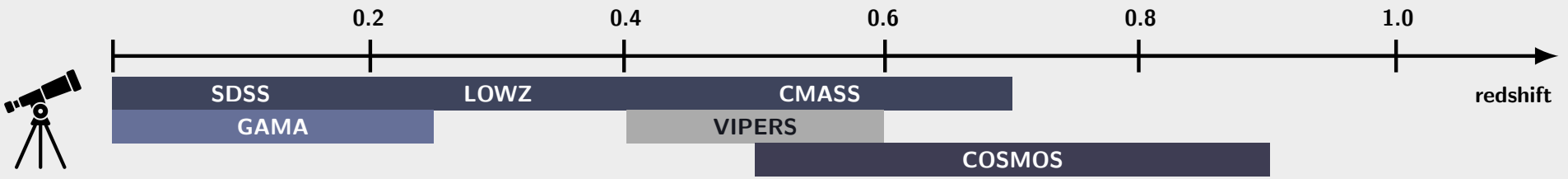

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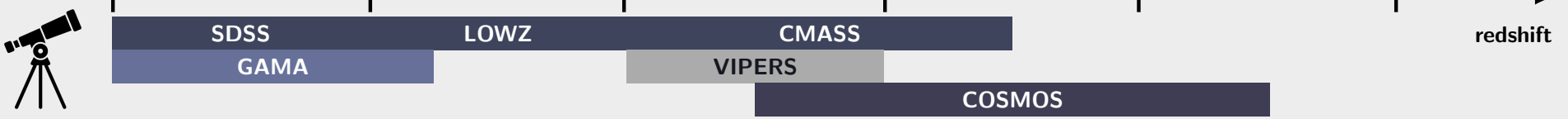
consistent with hydro simulations

Horizon-AGN: Kraljic et al. 2018, Laigle et al. 2018
IllustrisTNG: Hasan et al. 2023
Simba, Eagle, IllustrisTNG: Bulichi, Davé & Kraljic 2024



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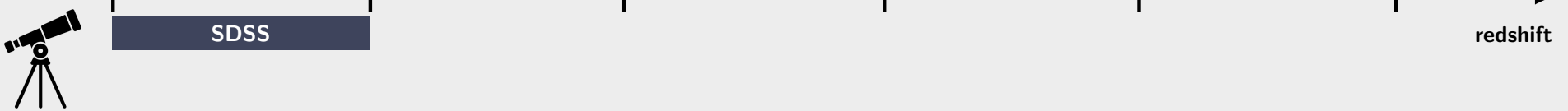
consistent with hydro simulations /filaments

Simba, Eagle, IllustrisTNG: Bulichi, Davé & Kraljic 2024



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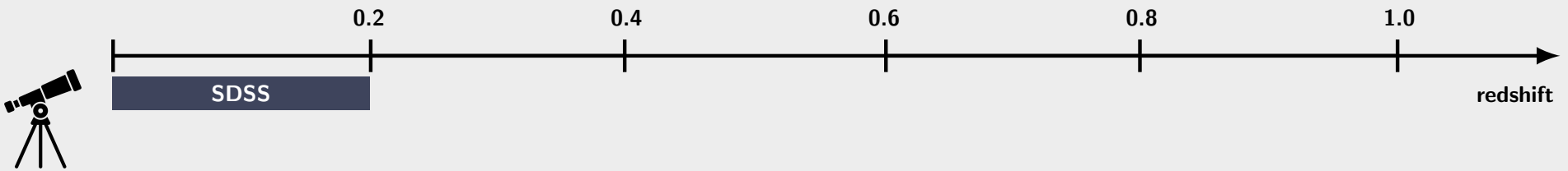
Donnan, Tojeiro & Kraljic 2022



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Donnan, Tojeiro & Kraljic 2022

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IllustrisTNG: Donnan, Tojeiro & Kraljic 2022

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Donnan, Tojeiro & Kraljic 2022

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Welker et al. 2020 (galaxy), Barsanti et al. 2022 (bulge)

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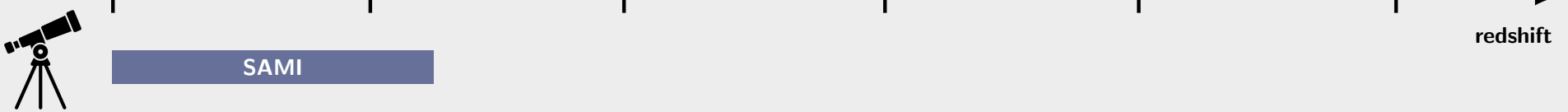
Horizon-AGN: Dubois et al. 2014, Codis et al. 2018
Illustris: Wang et al. 2018



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- **LTGs:** spin $\parallel$ to filaments

Tempel et al. 2013, Kraljic et al. 2021 vs Lee & Erdogu 2007

- **S0s:** spin $\perp$ to filaments

Tempel et al. 2013, Pahwa et al. 2016, Kraljic et al. 2021

3 Connectivity of the cosmic web

The Cosmic web

The Cosmic web

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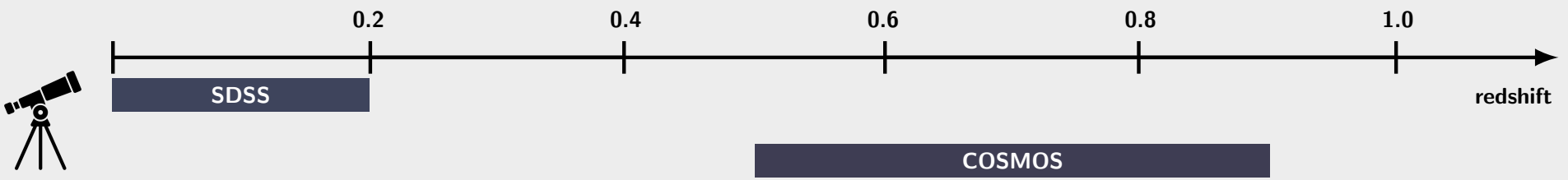

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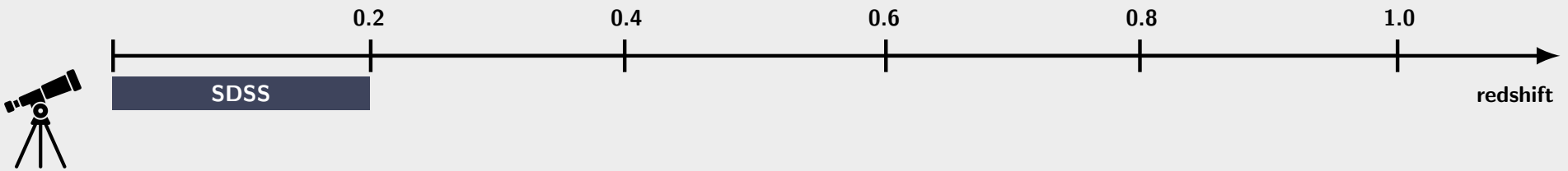
Kraljic et al. 2020b



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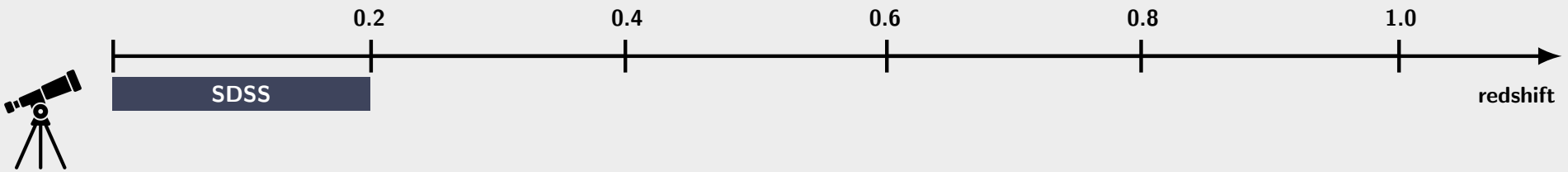

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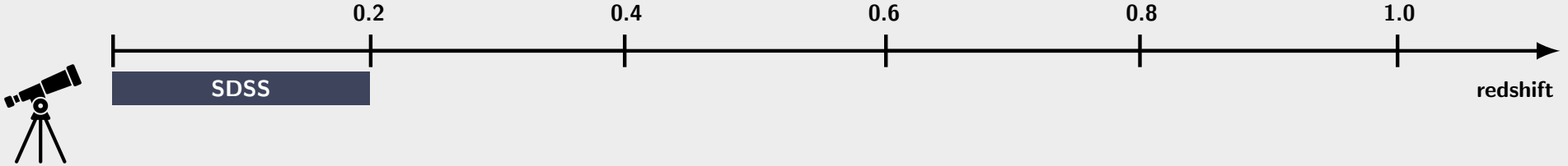
consistent with hydro simulations

Horizon-AGN, Simba: Kraljic et al. 2020b

- At fixed halo mass, galaxies with higher connectivity tend to have
  - higher stellar mass
  - lower sSFR
  - more ellipsoidal morphology



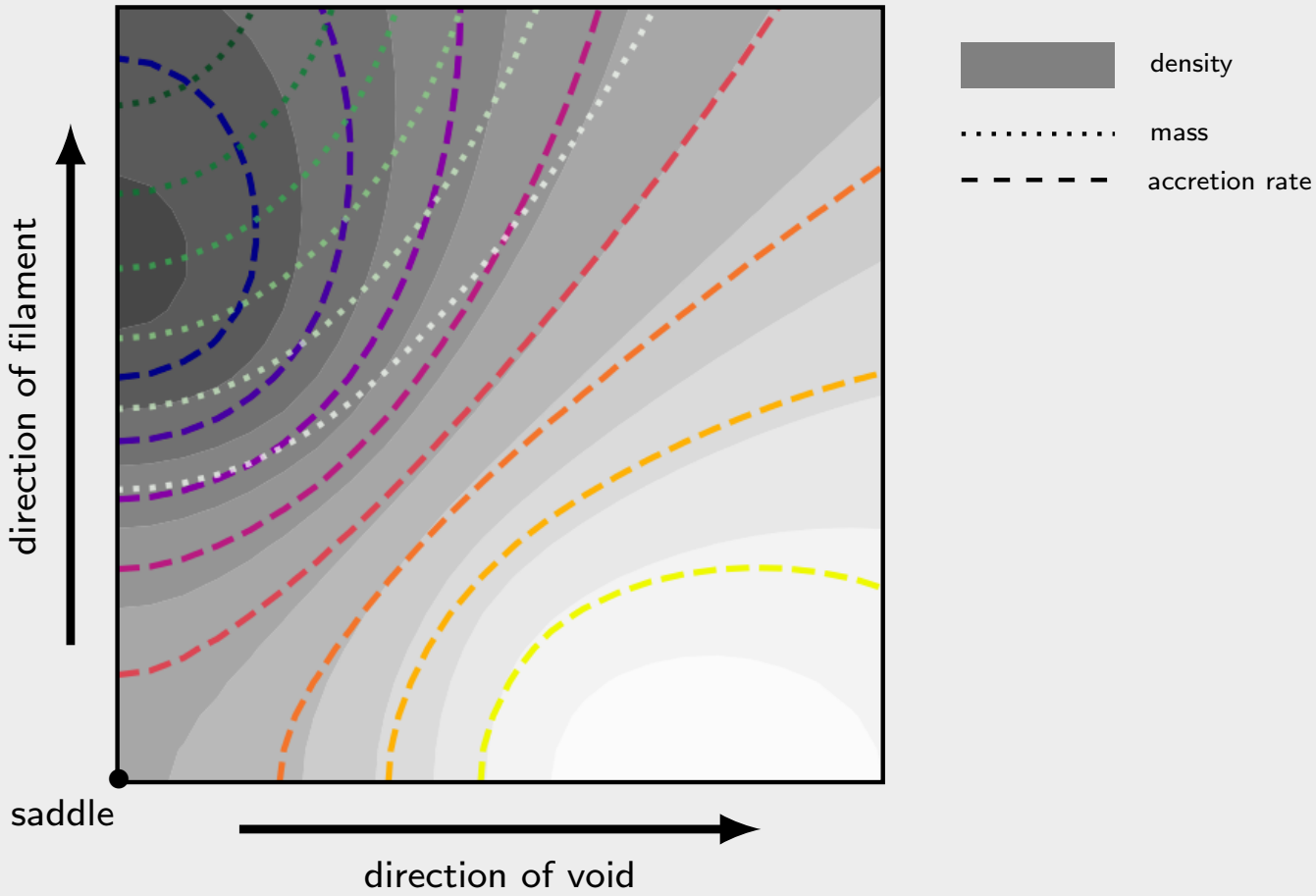
The Cosmic web

I **Large-scale tides: impact on the halo assembly history**

- mass, accretion rate, formation time of halos depend on the geometry of the saddle

Musso et al. 2018

see also e.g. Dalal et al. 2008, Hahn et al. 2009, Borzyszkowski et al. 2017



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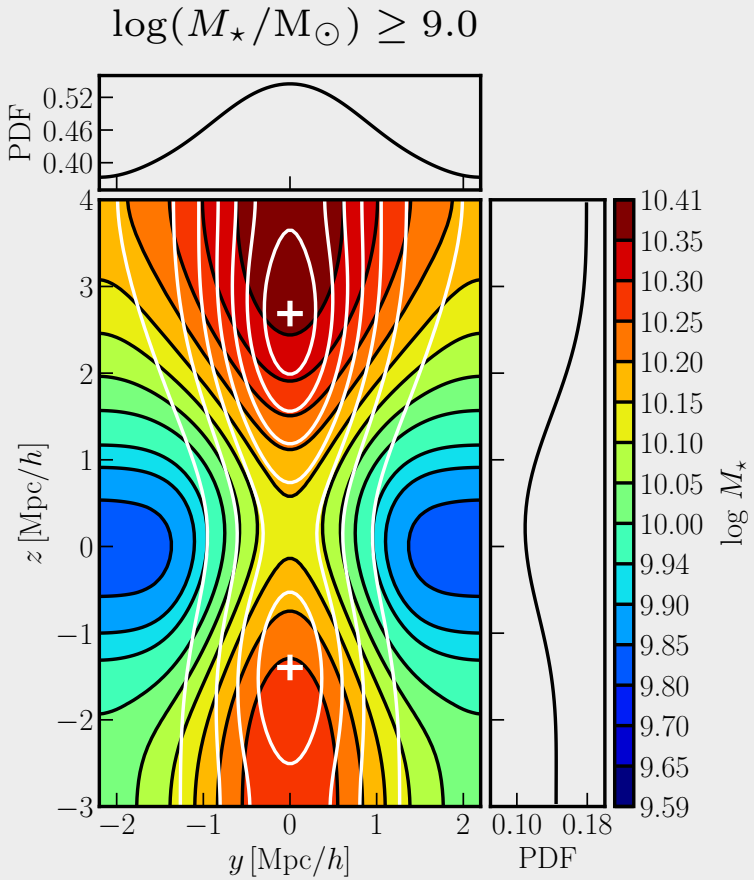

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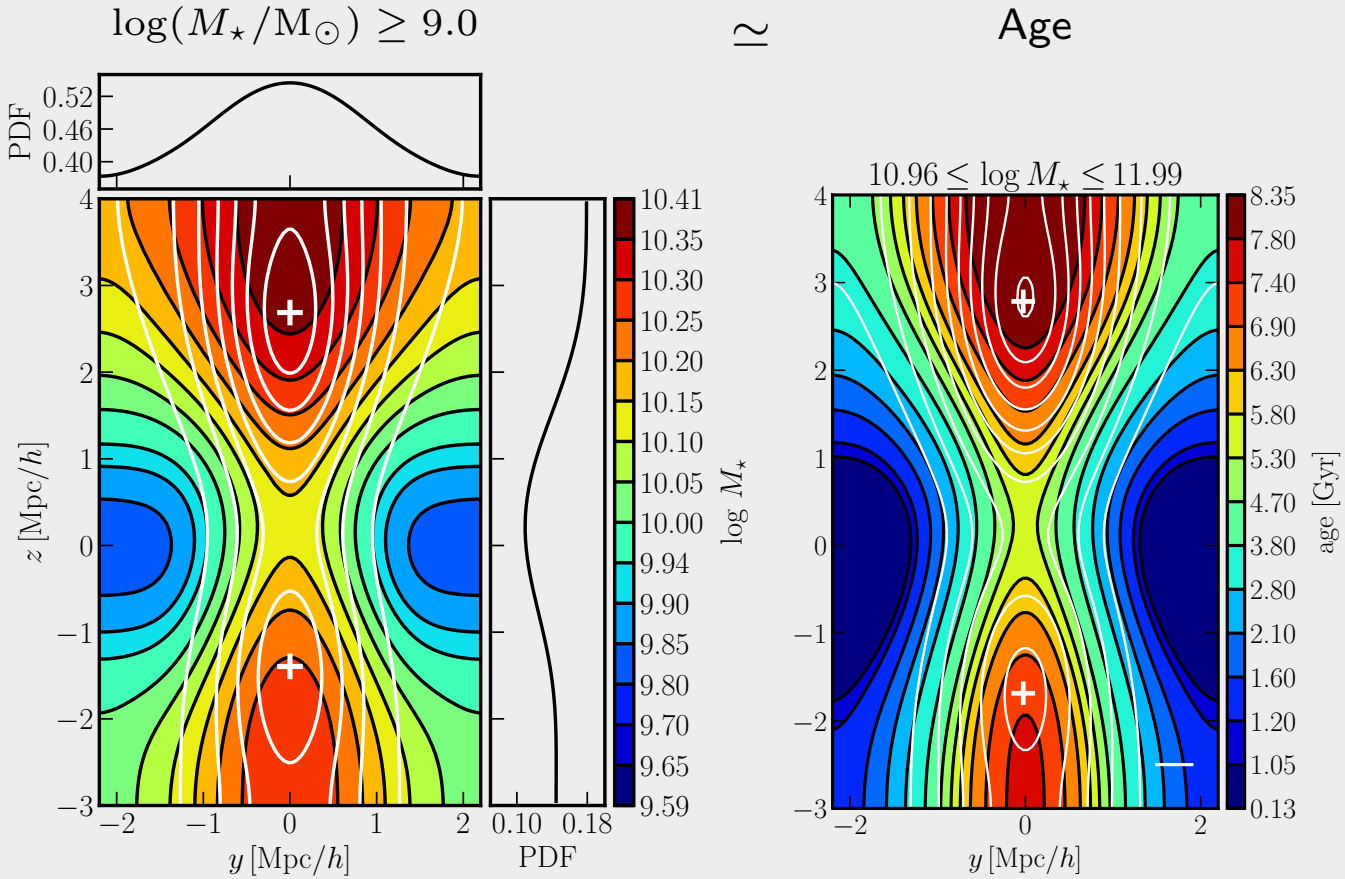

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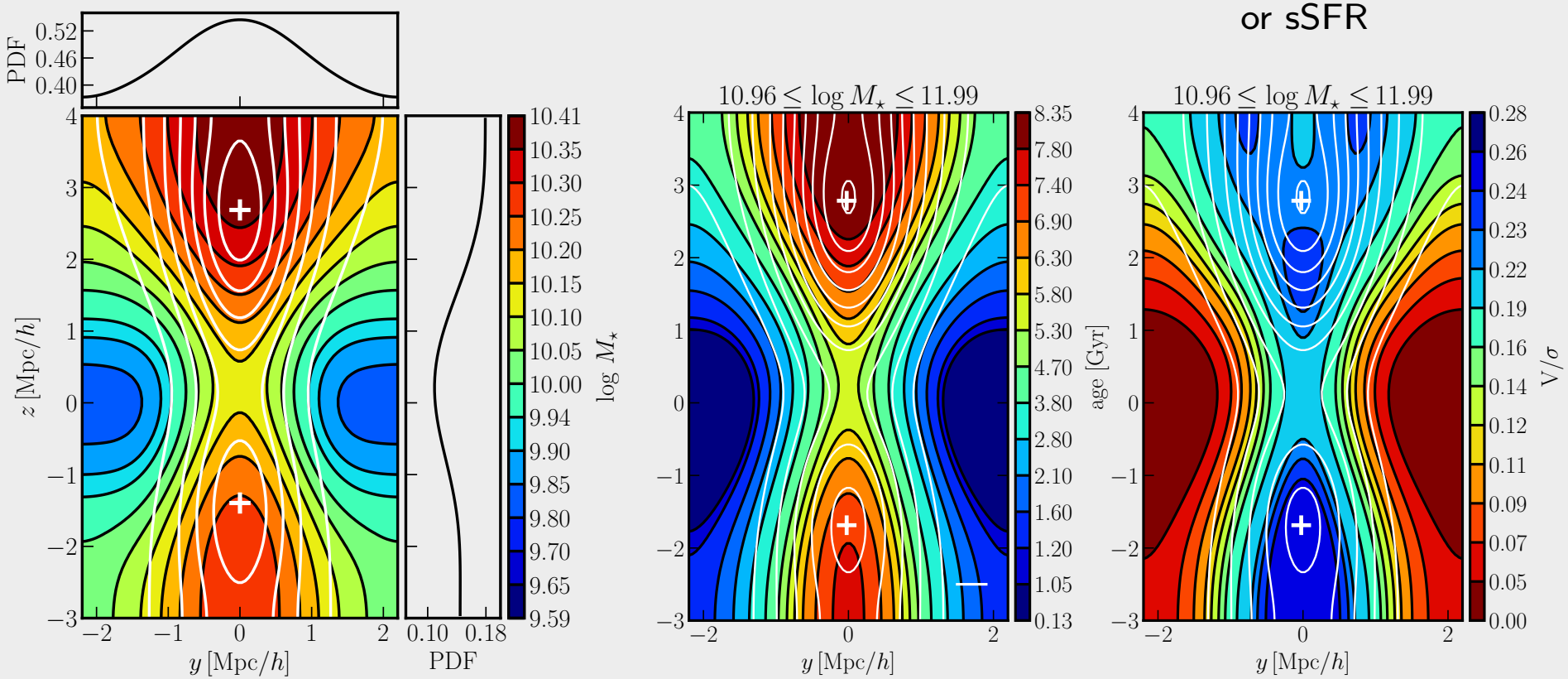
$\log(M_\star/\mathrm{M}_\odot) \geq 9.0$ $\simeq$ Age $\not\simeq$ Morphology or sSFR



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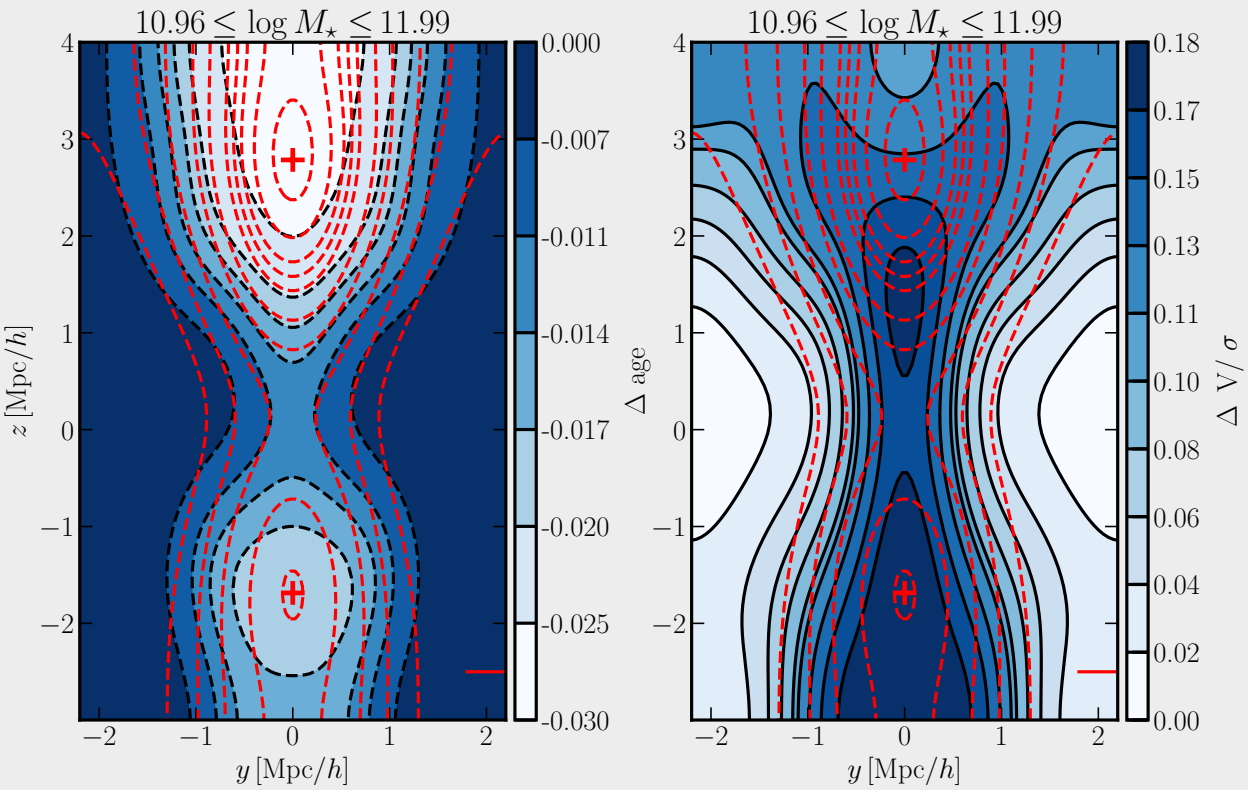
Residuals
at fixed $M_\star$, $M_{\rm halo}$, ρ



Horizon-AGN: Kraljic et al. 2019

The Cosmic web

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Large-scale tides: impact on the halo assembly history

- mass, accretion rate, formation time of halos depend on the geometry of the saddle

Musso et al. 2018

see also e.g. Dalal et al. 2008, Hahn et al. 2009, Borzyszkowski et al. 2017

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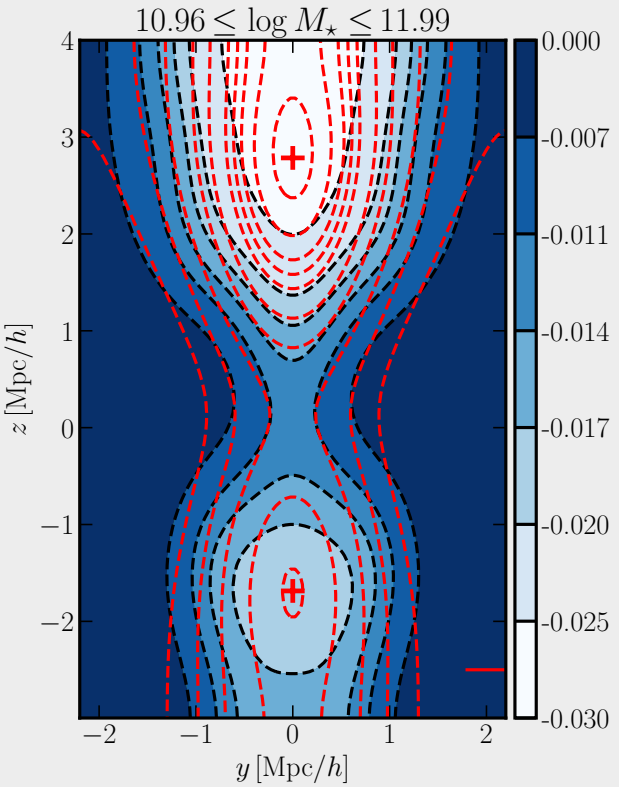
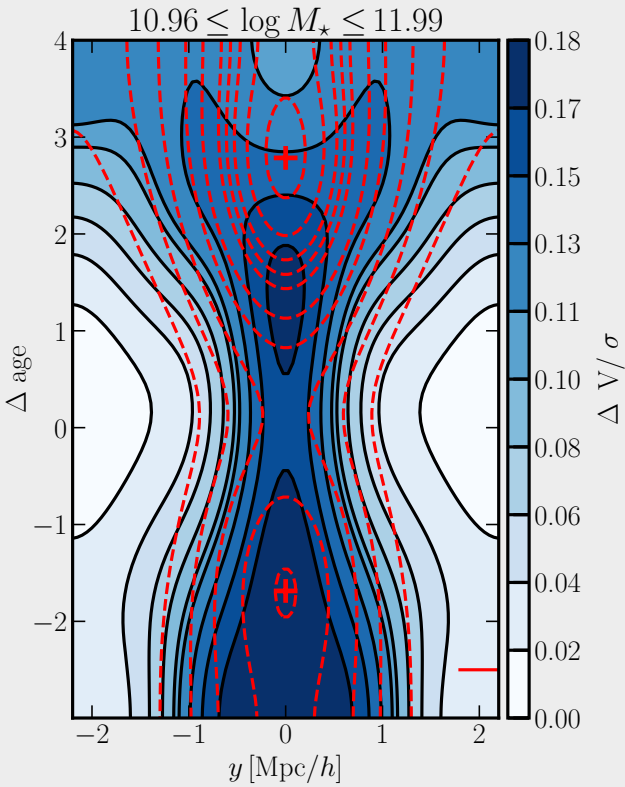
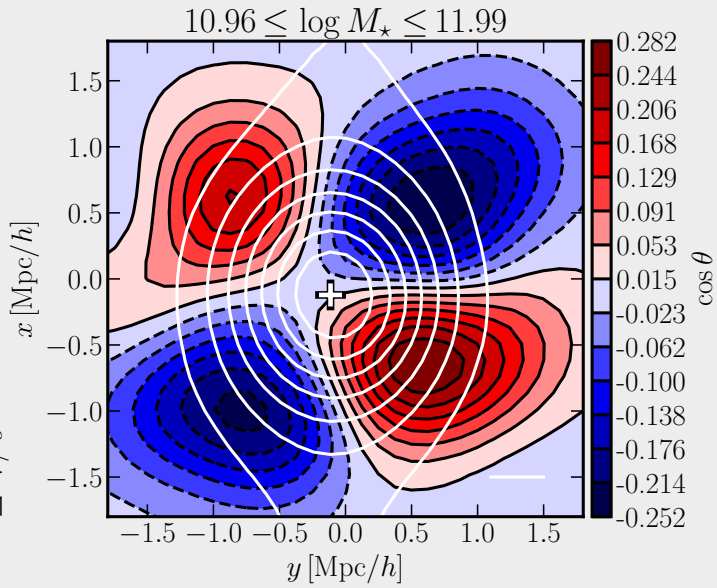
Age



Morphology



spin
also vorticity



see also Pichon et al. 2011
Codis et al. 2015, Laigle et al. 2015
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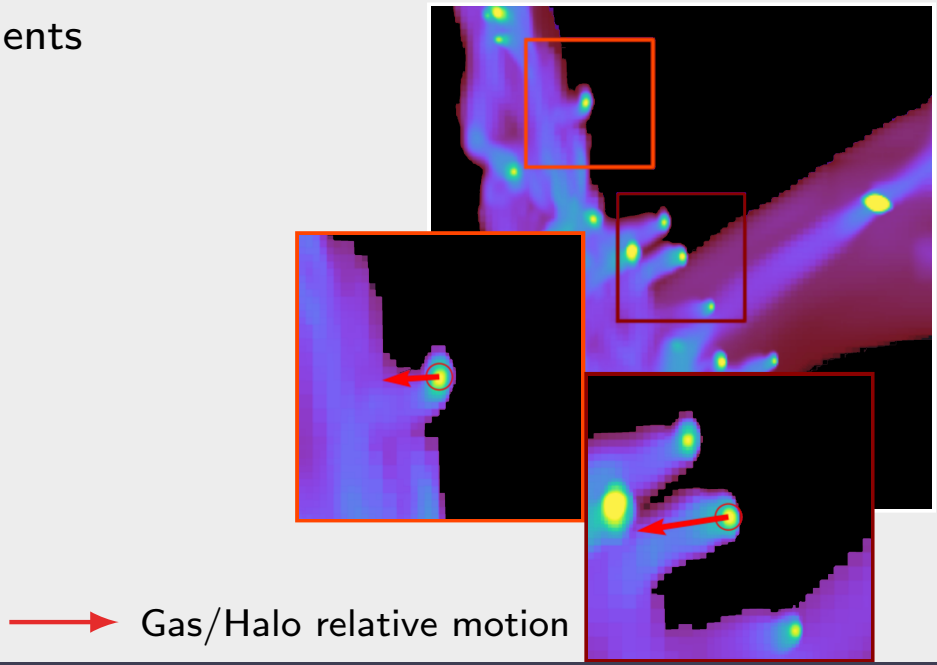
- suppressed accretion of external gas and gas loss via ram pressure after crossing walls and filaments



Thompson, Smith & Kraljic 2023

The Cosmic web

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Bulichi, Davé & Kraljic 2024

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Thompson, Smith & Kraljic 2023

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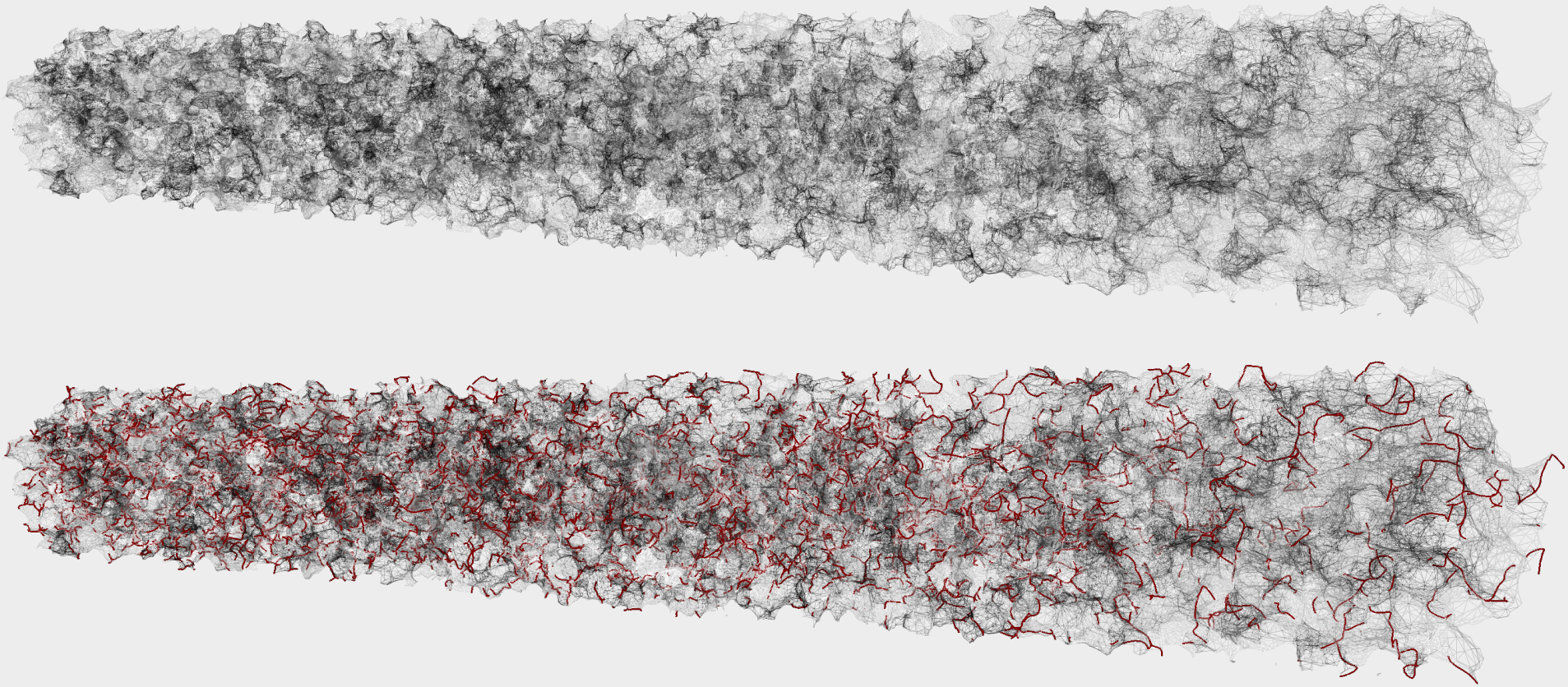
Bulichi, Davé & Kraljic 2024

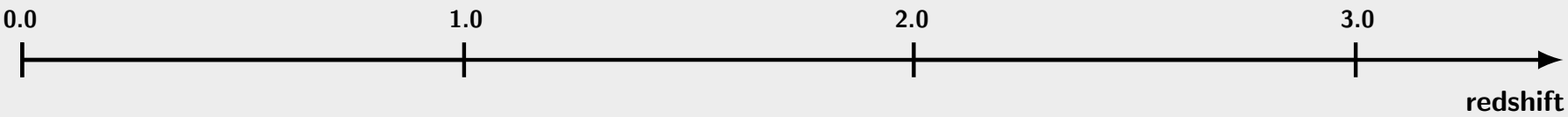
V **The 'cosmic web detachment'**

- detachment of galaxies from filamentary accretion of cold gas at shell-crossing on intergalactic scales

Aragon-Calvo et al. 2019

Cosmic web tracers





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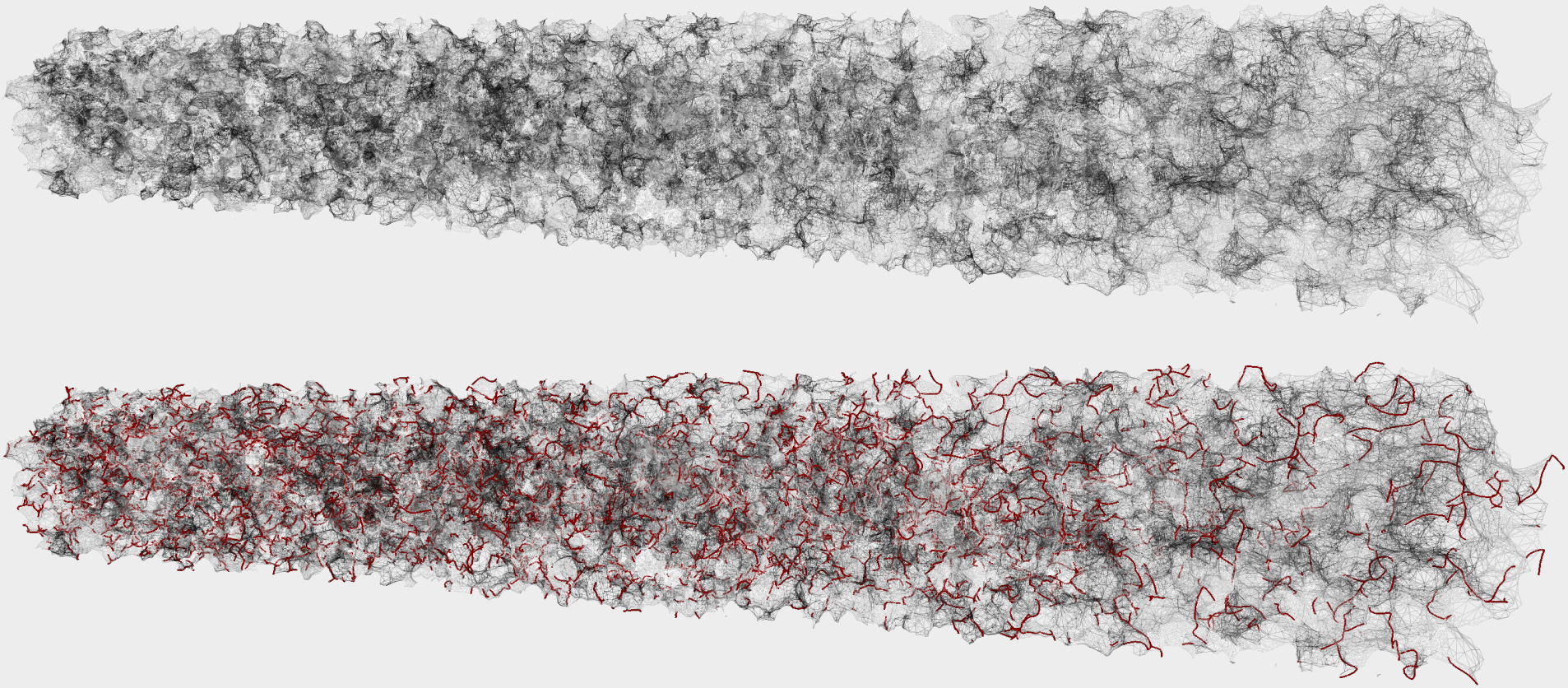

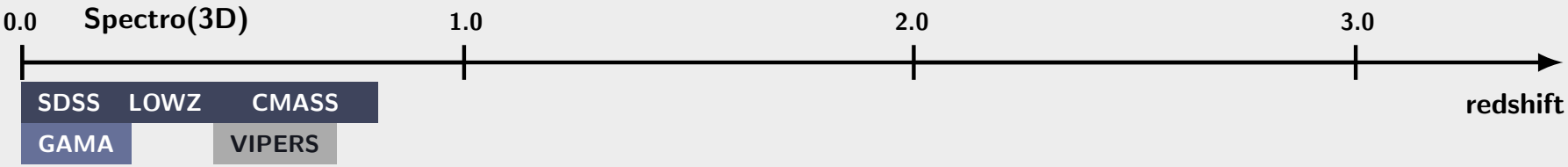

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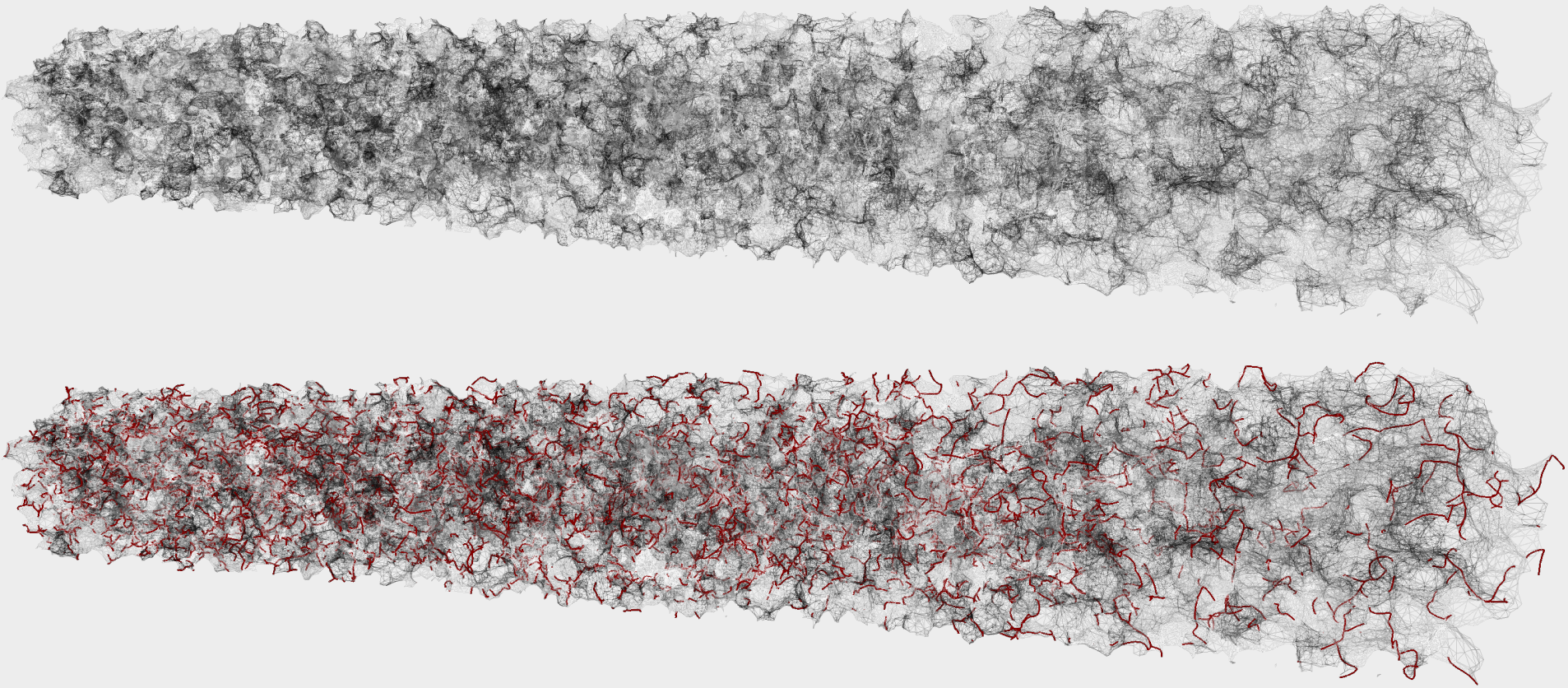

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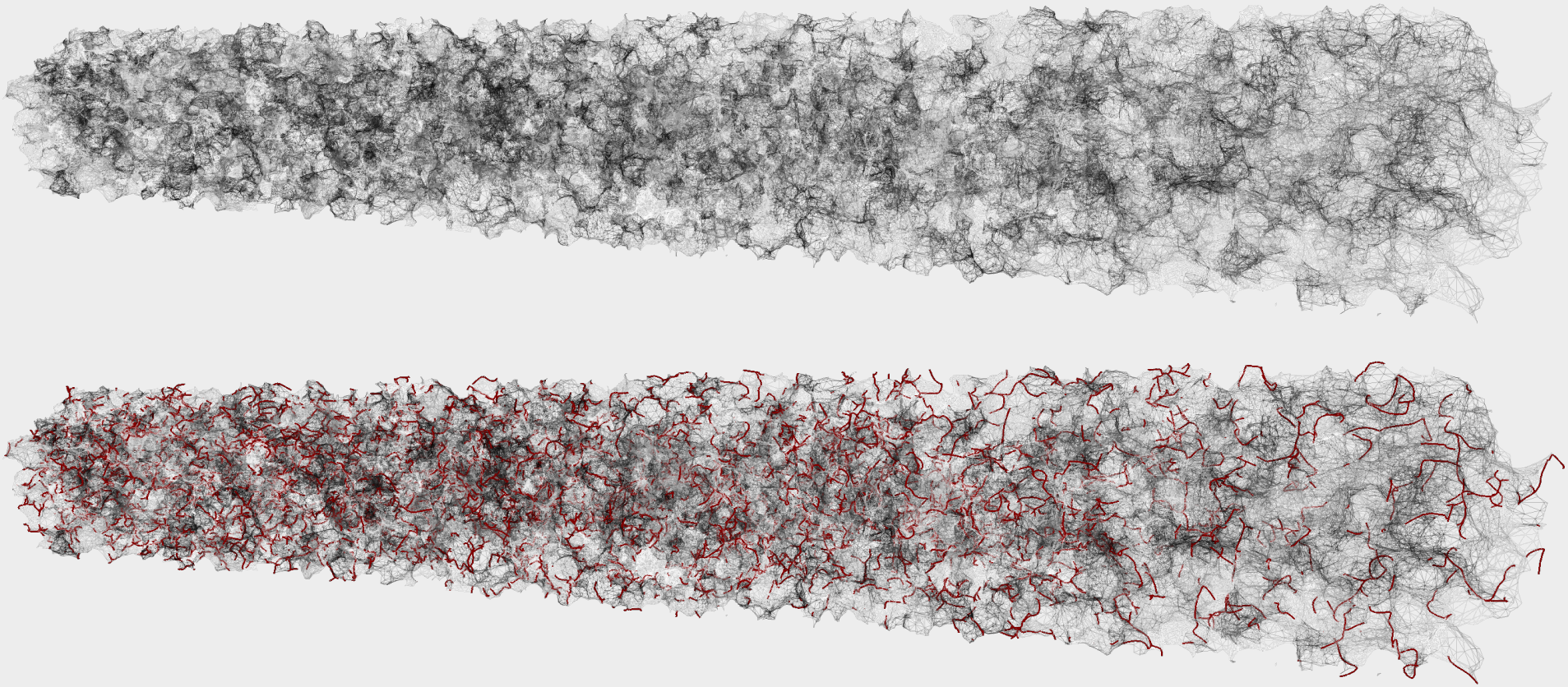

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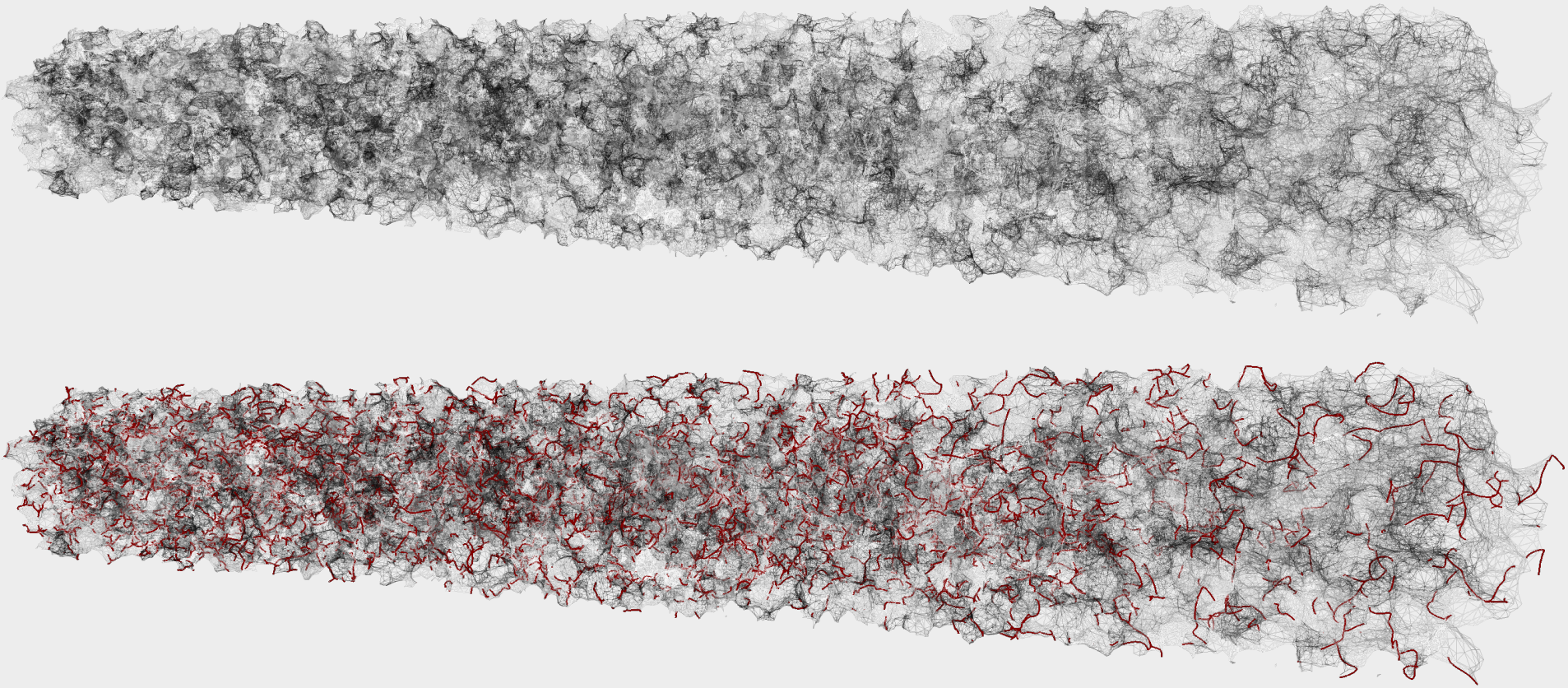
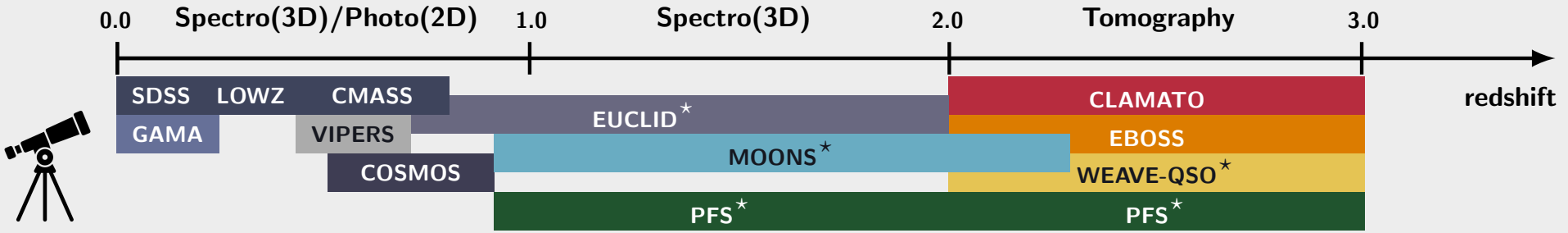
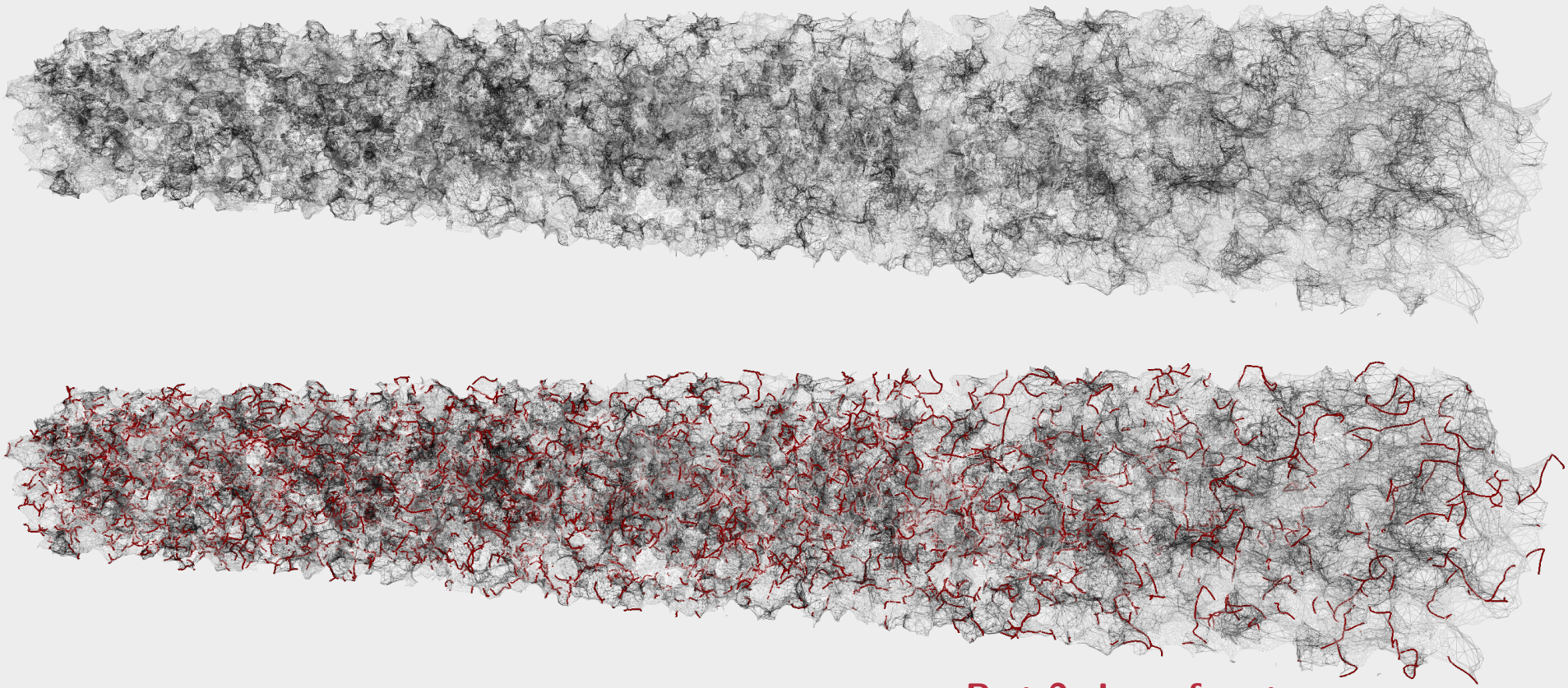
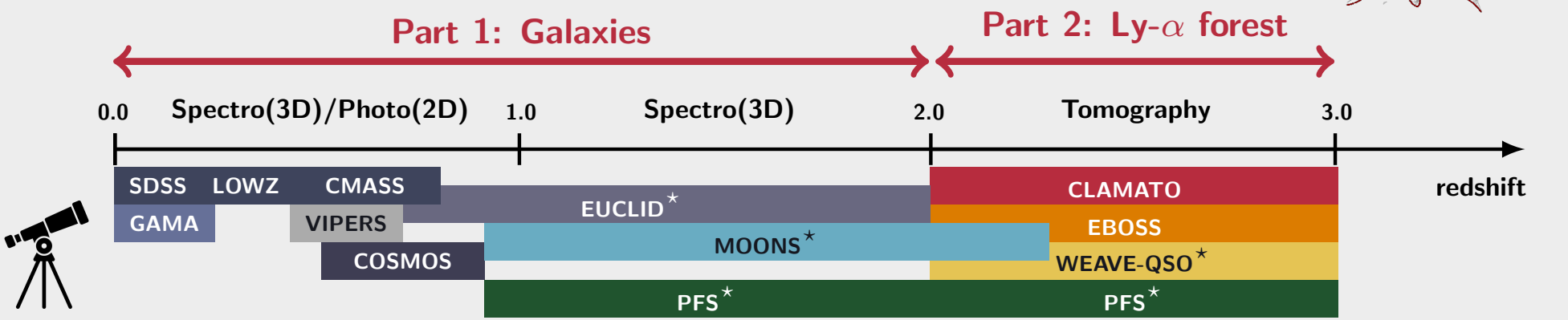




This lecture

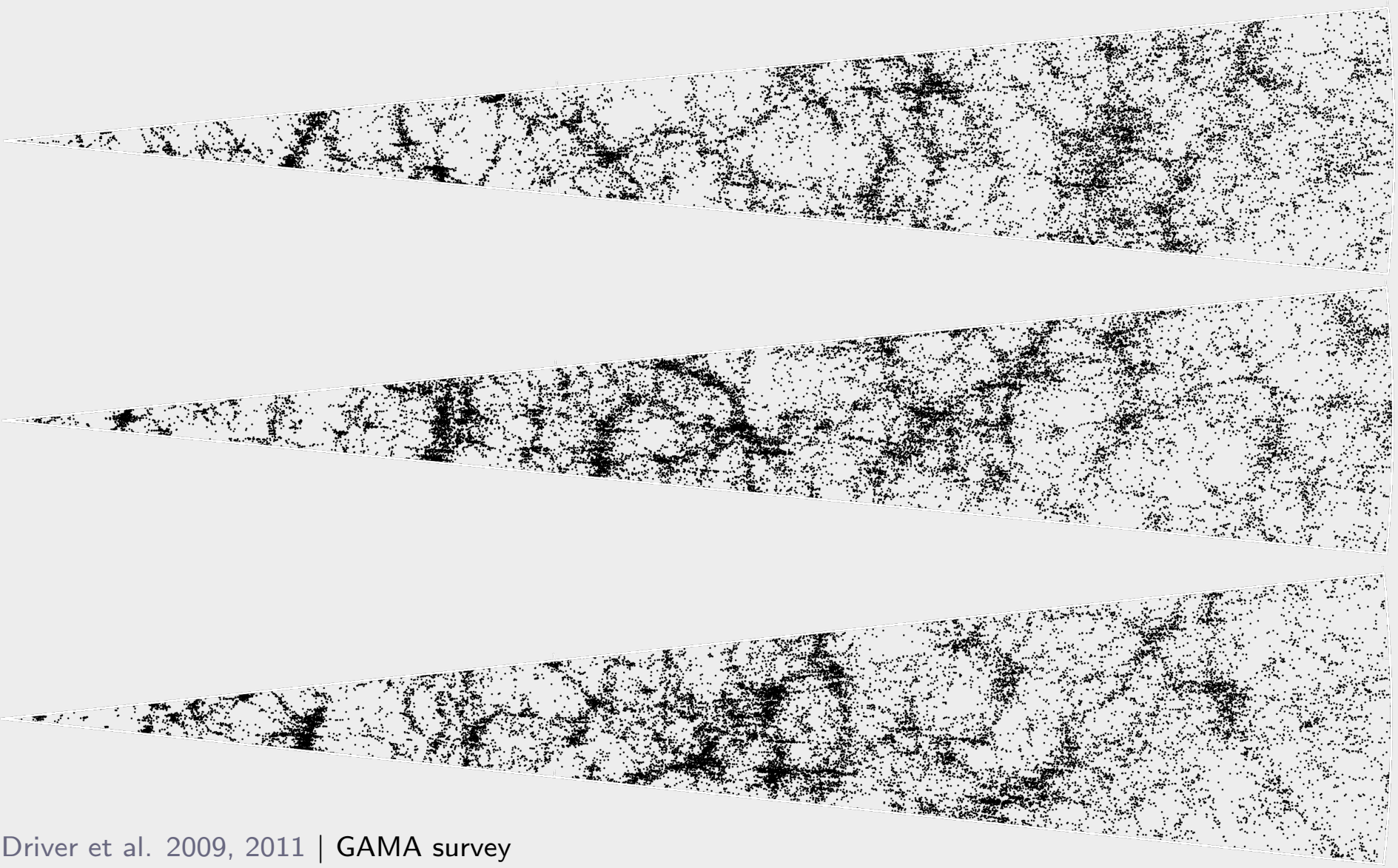
Cosmic web tracers





Galaxy distribution in 3D

redshift space



Driver et al. 2009, 2011 | GAMA survey

Galaxy distribution in 3D

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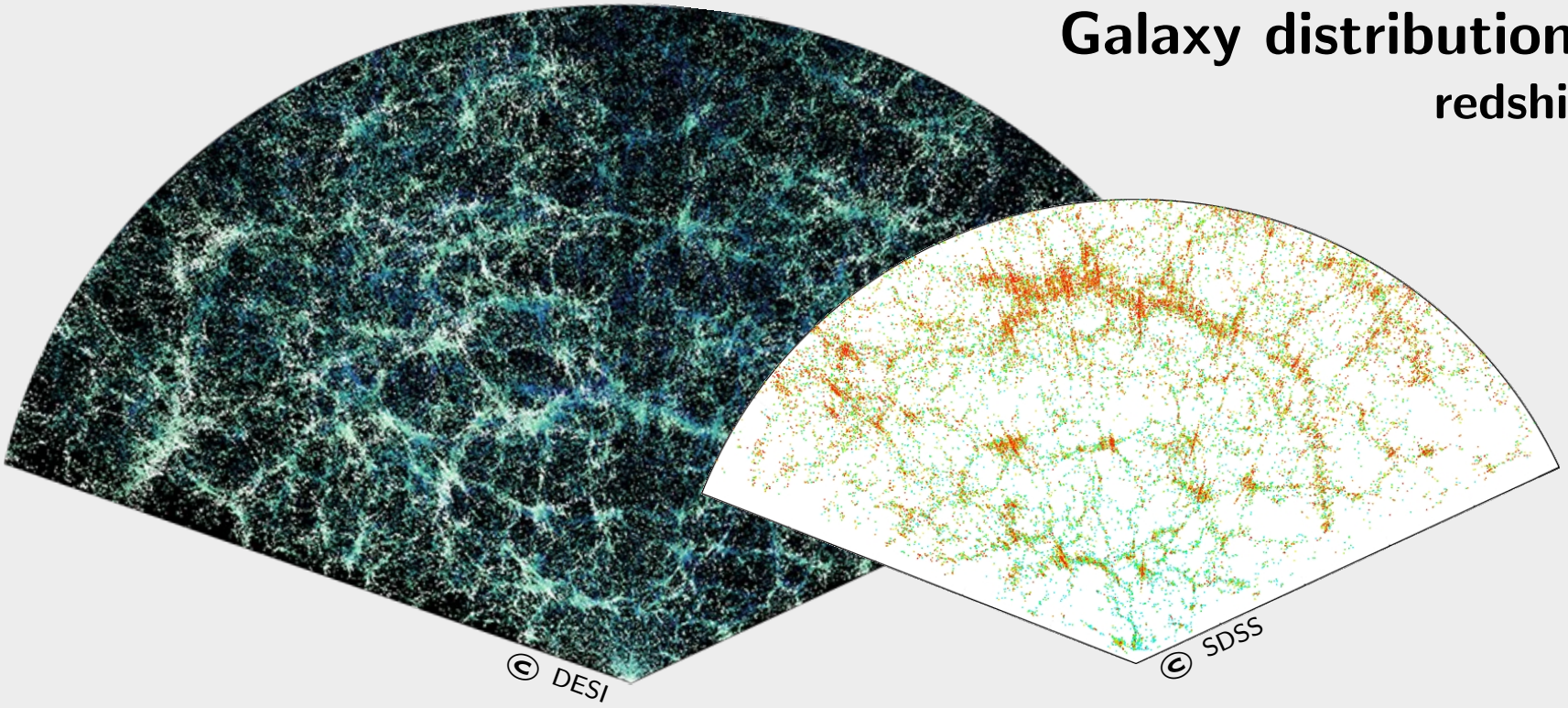

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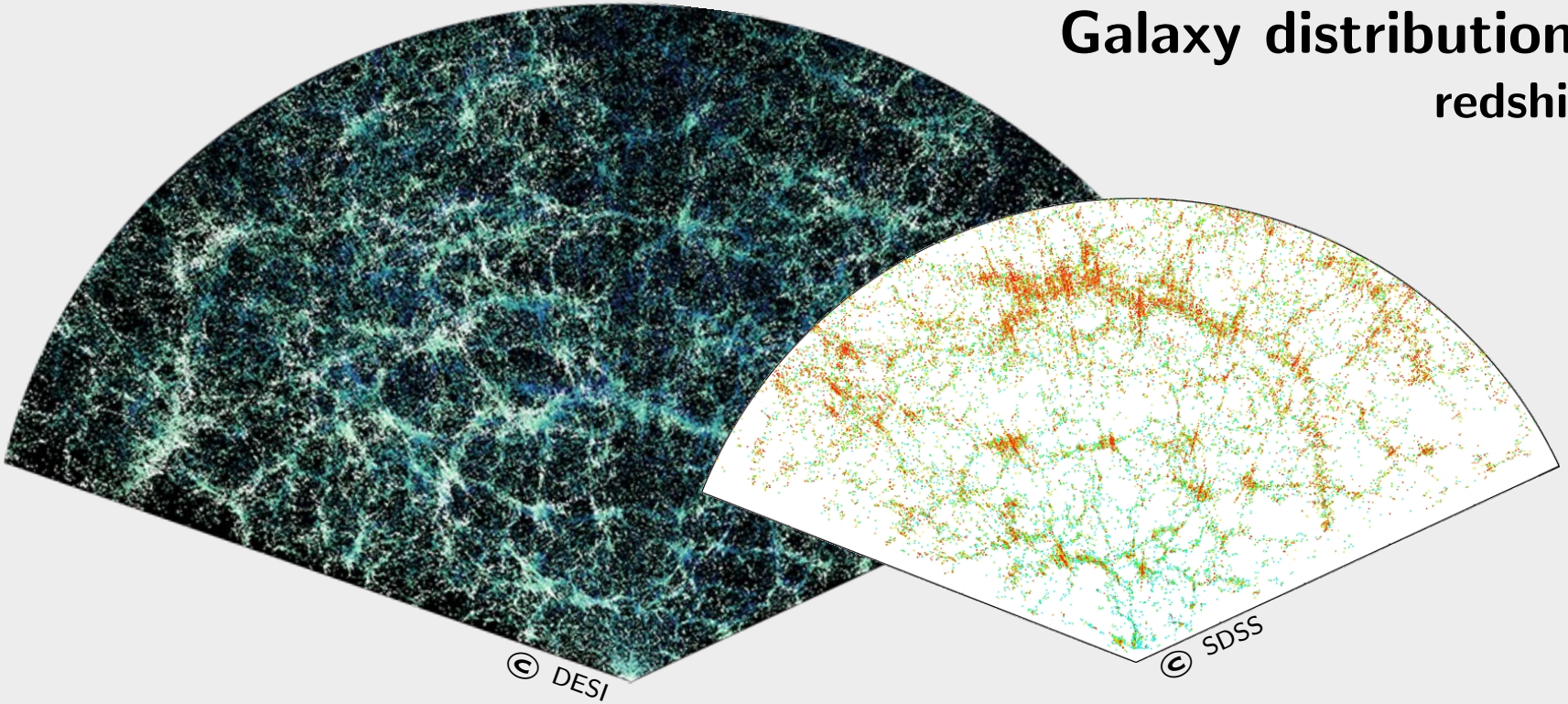
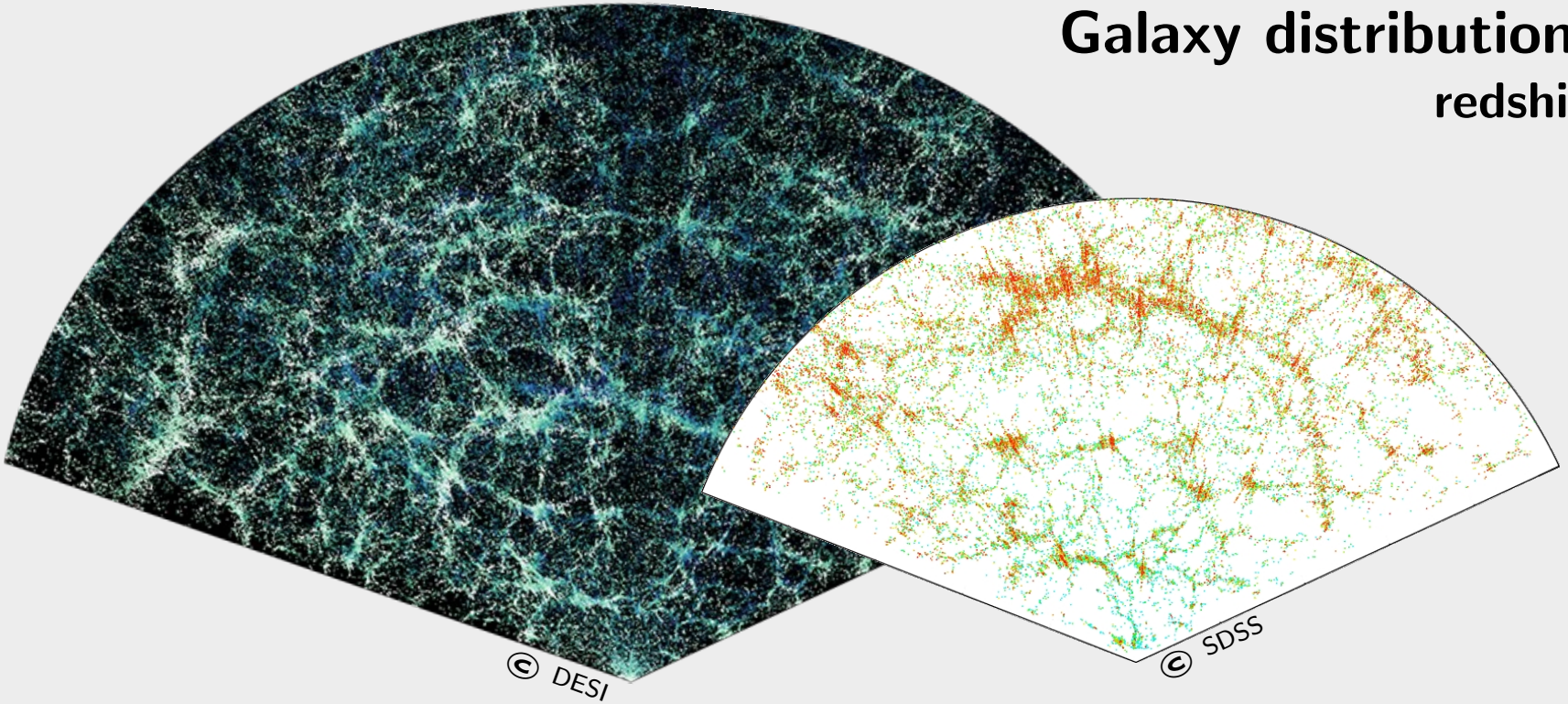


Key issue:

- inhomogeneous universe: real space $\neq$ redshift space

Galaxy distribution in 3D

redshift space



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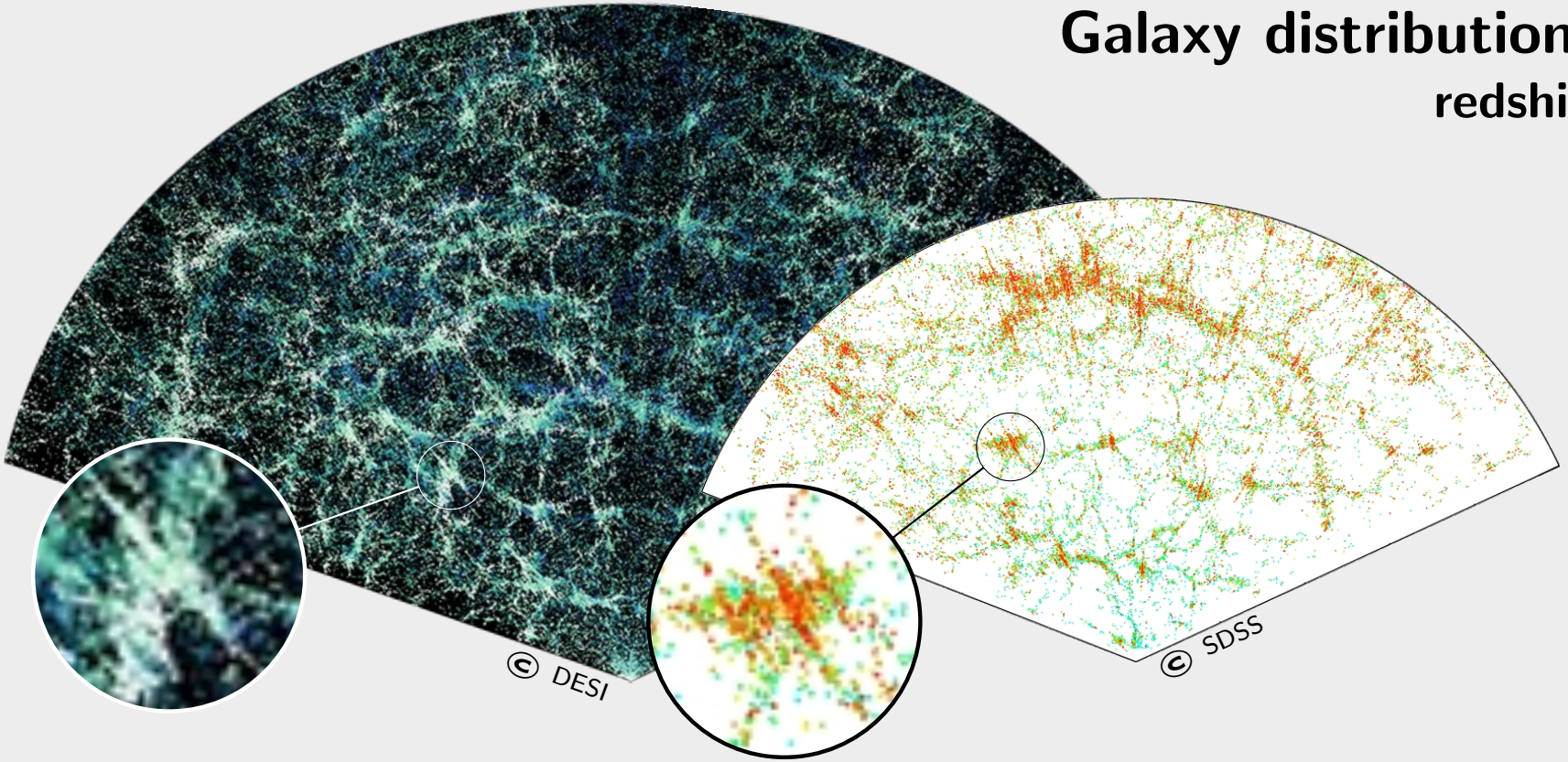

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- inhomogeneous universe: real space $\neq$ redshift space
- distances inferred from observed redshifts $\neq$ comoving distances due to peculiar motions: $r(z_{\rm obs}) \neq r(z_{\rm cosmo})$
- redshift-space distortions: 'Fingers-of-God effect' - small-scale peculiar velocities of galaxies

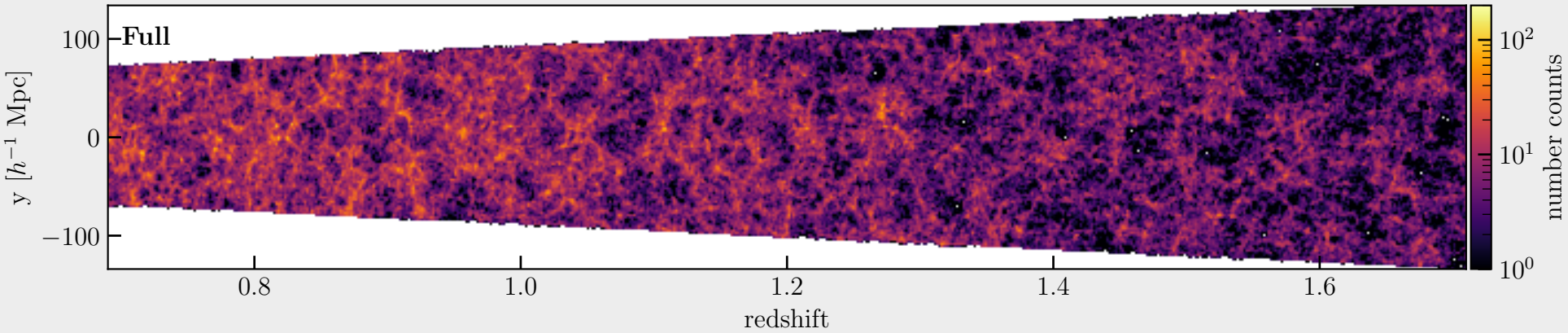
Jackson 1972

'Kaiser effect' - large-scale matter flows

Kaiser 1987

Mock galaxy catalogues

I/ selection function, completeness, . . .



Pearl et al. 2022

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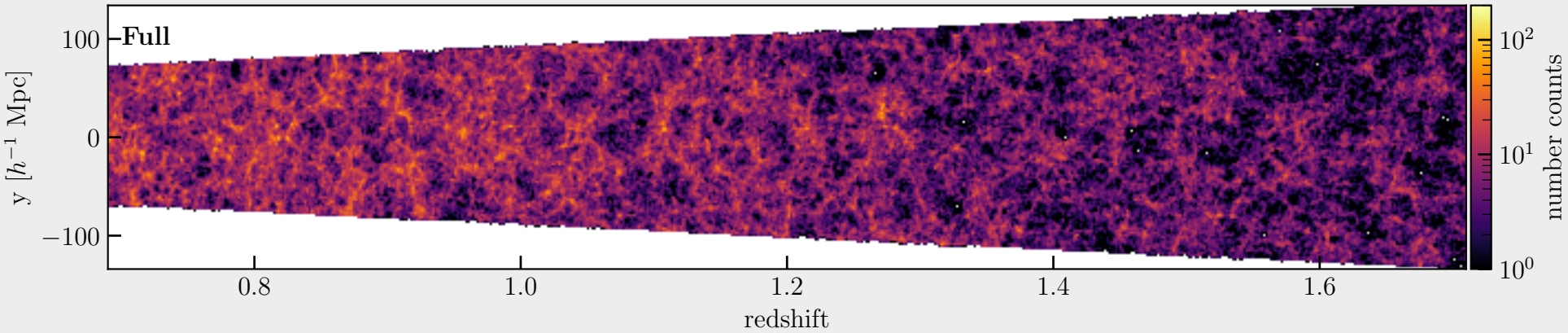

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- DM-only simulation Bolshoi-Planck (Klypin et al. 2016):
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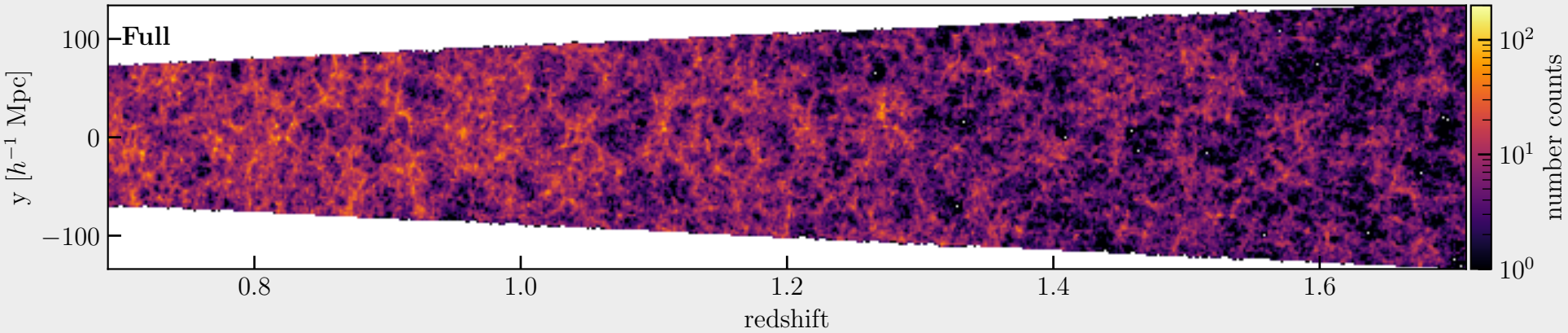

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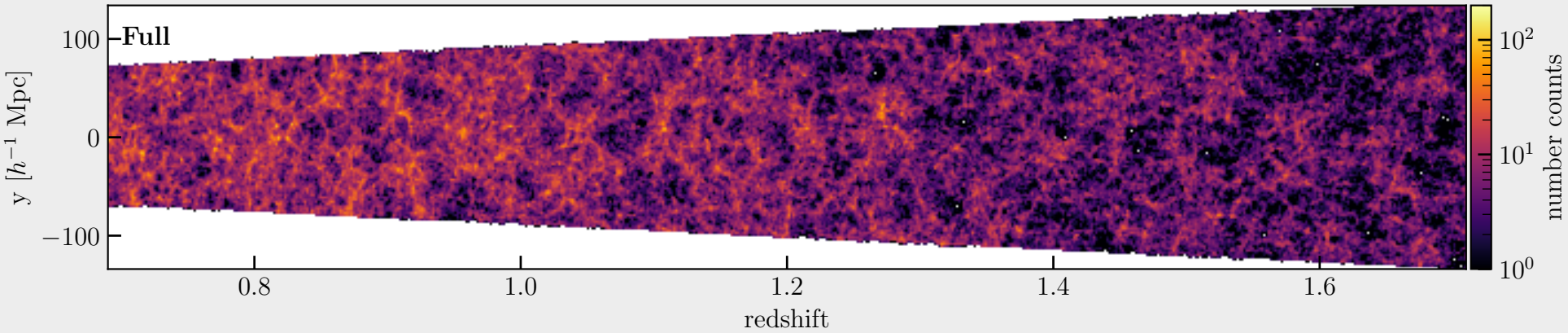

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- procedure CLIMBER (Pearl et al. 2022):
  - mapping from physical to photometric properties informed by observations

Mock galaxy catalogues

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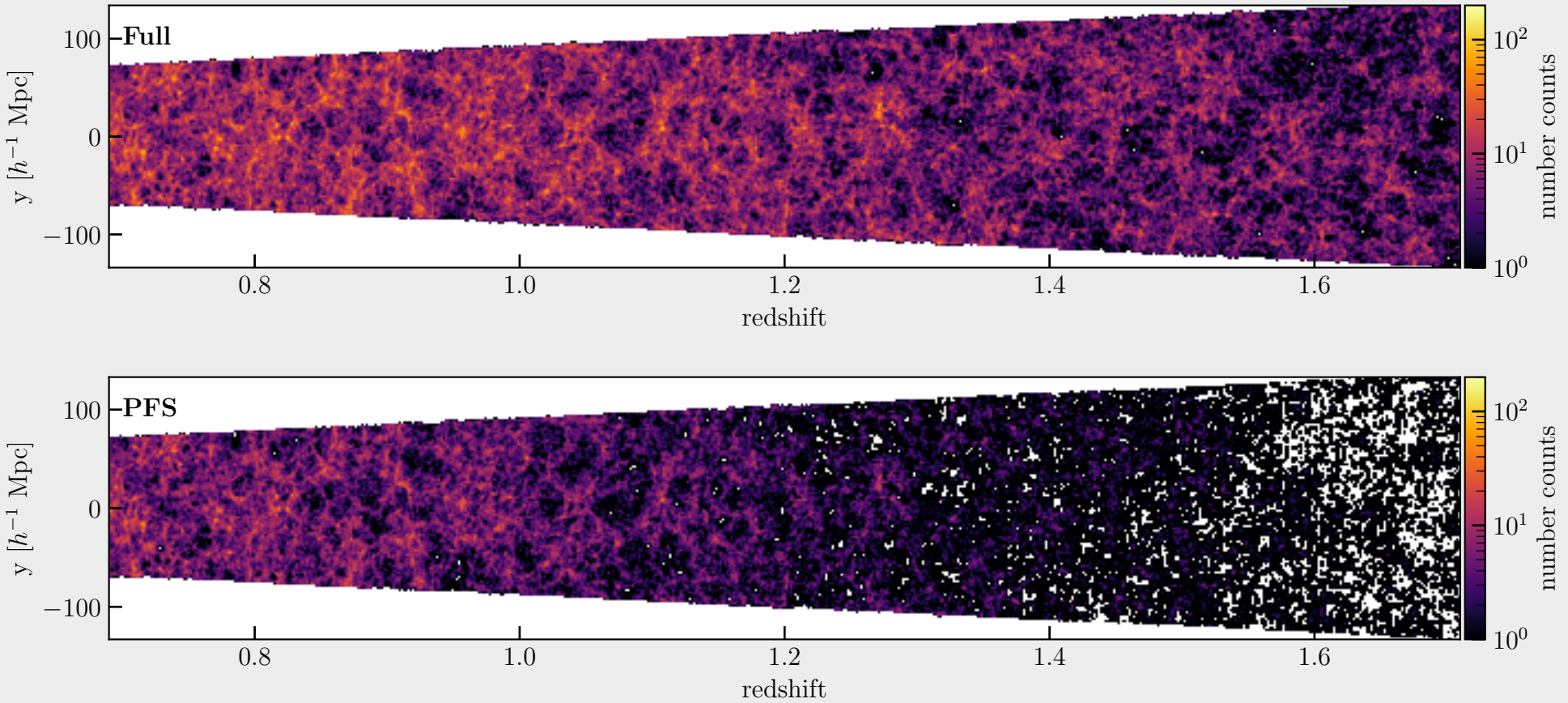
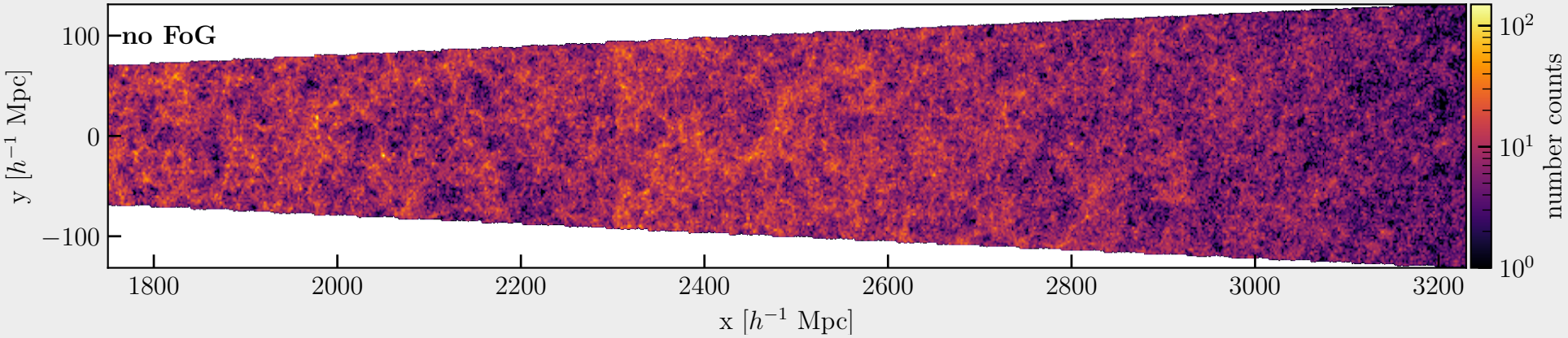


PFS selection: $(z > 0.7 \;\&\; Y < 22.5) \;||\; (z > 1 \;\&\; Y > 22.5 \;\&\; J < 22.8)$

- 90% mass-complete sample of galaxies of all colors to $\sim 3 \times 10^{10}$ $M_\odot$

Mock galaxy catalogues

II/ Redshift-space distortions



Mock galaxy catalogues

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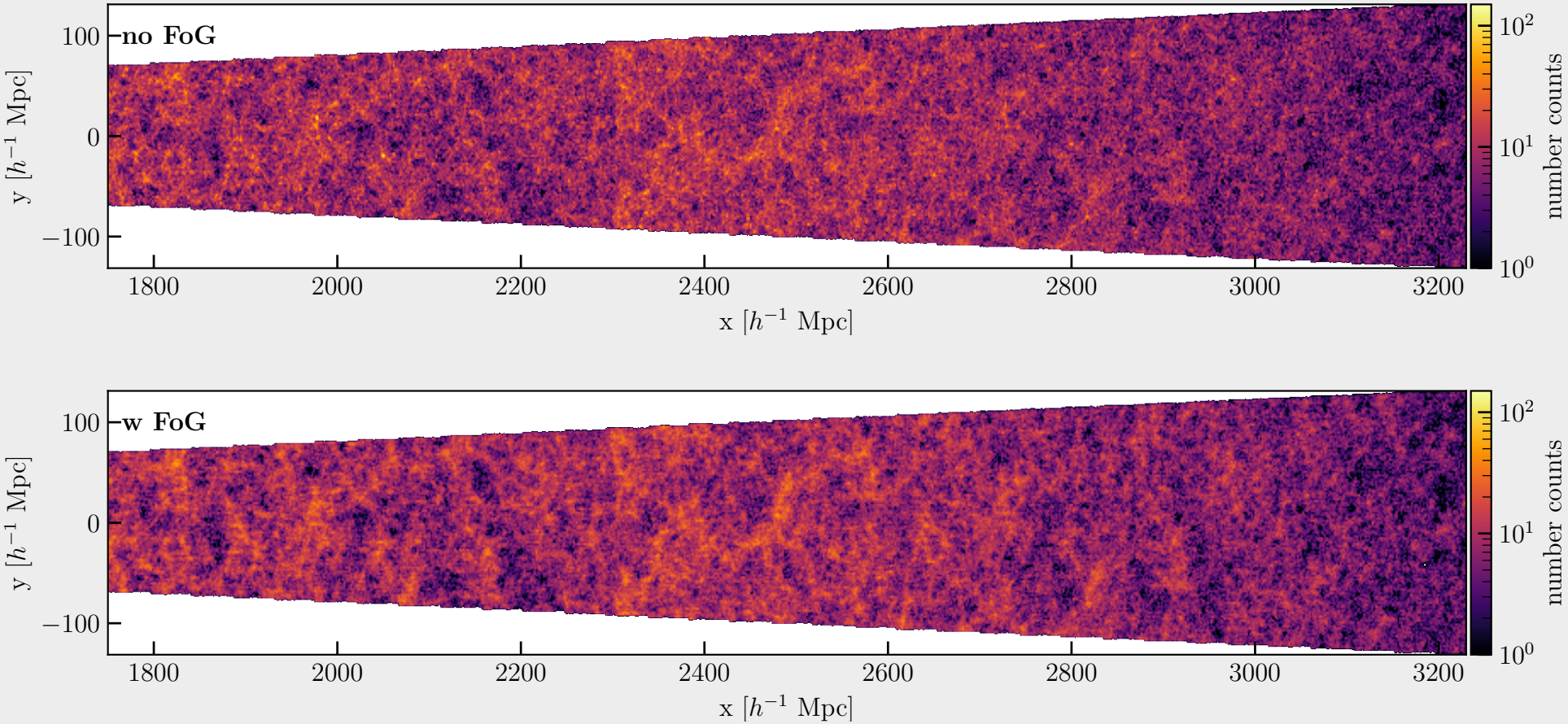
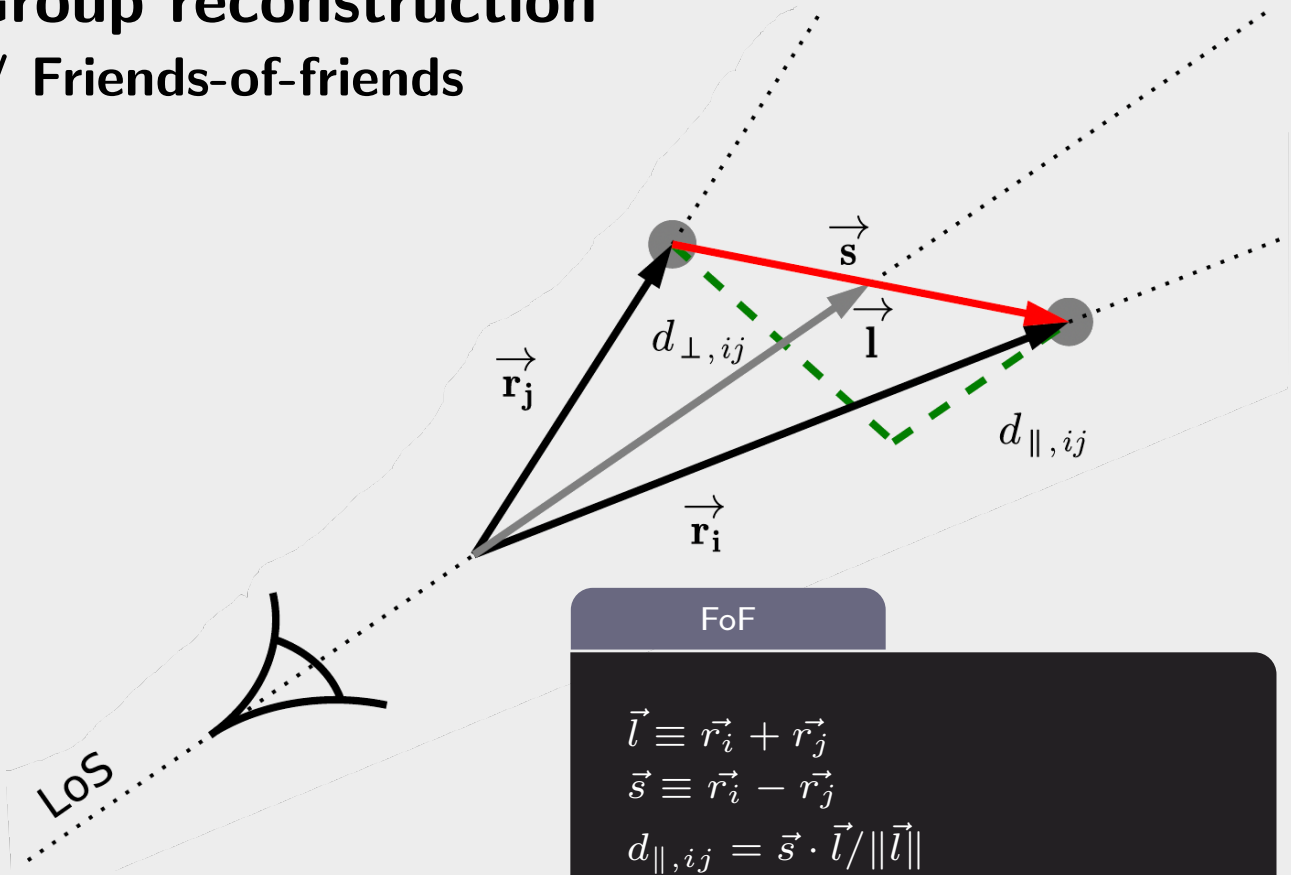


- contribution from peculiar velocity: $1 + z_{\rm pec} = \sqrt{\frac{1+v_{\rm pec}/c}{1-v_{\rm pec}/c}}$

Group reconstruction

I/ Friends-of-friends



FoF

$$\vec{l} \equiv \vec{r_i} + \vec{r_j}$$
$$\vec{s} \equiv \vec{r_i} - \vec{r_j}$$
$$d_{\parallel,ij} = \vec{s} \cdot \vec{l} / \|\vec{l}\|$$
$$d_{\perp,ij} = \sqrt{\vec{s} \cdot \vec{s} - d^2_{\parallel,ij}}$$

Treyer et al. 2018, Kraljic et al. 2018
see also e.g. Huchra &Geller 1982, Knobel et al. 2009
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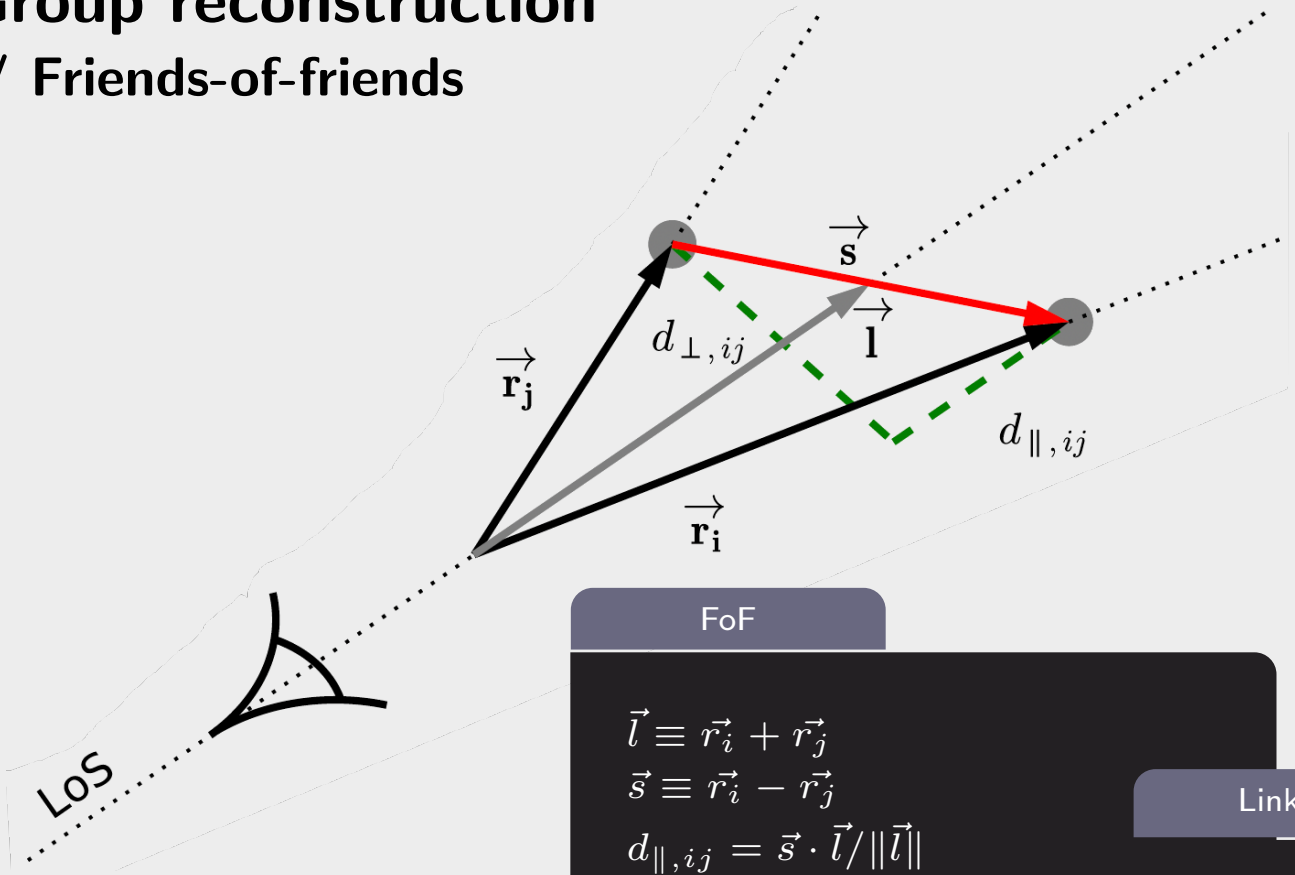

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Linking

$$d_{\perp,ij} < b_\perp \overline{r}_{ij}$$
$$d_{\parallel,ij} < b_\parallel \overline{r}_{ij}$$

$b_\perp$ - projected linking length

$b_\parallel$ - LoS linking length

$$\overline{r}_{ij} = \frac{1}{2}\left(n_i^{-1/3} + n_j^{-1/3}\right)$$

Treyer et al. 2018, Kraljic et al. 2018

see also e.g. Huchra &Geller 1982, Knobel et al. 2009
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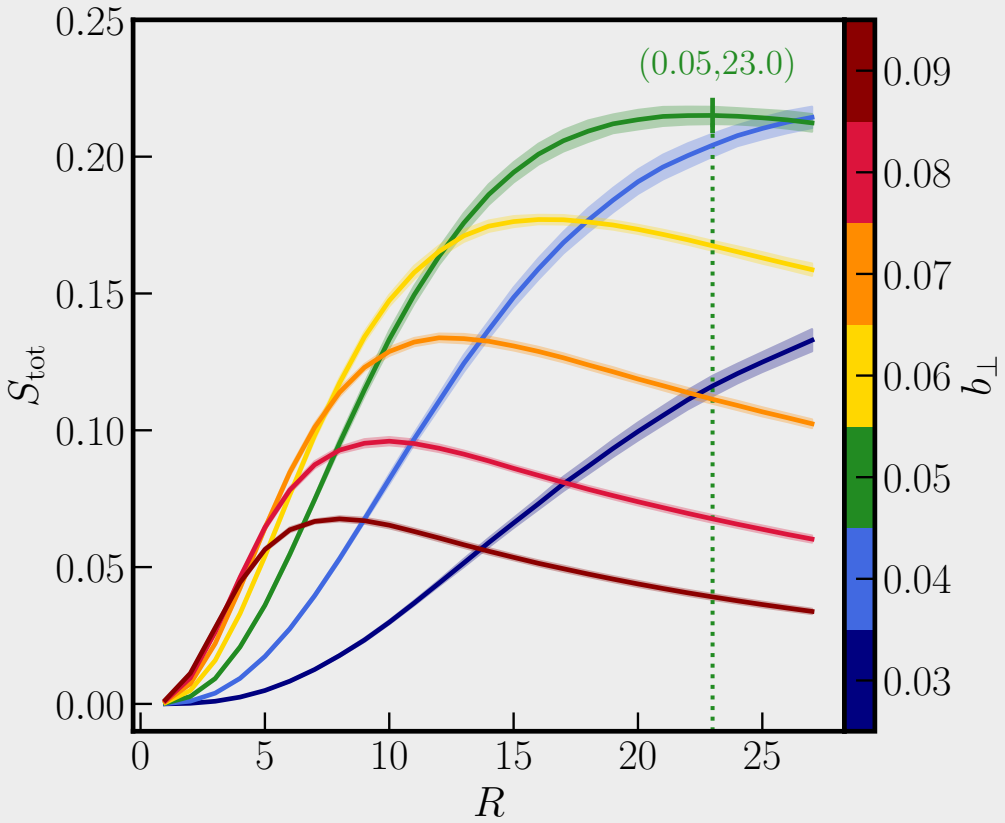
Group reconstruction
II/ Optimisation



Group cost function

$$S_{\rm tot} = Q_{\rm tot} E_{\rm tot}$$

$Q_{\rm tot}$ - global grouping purity

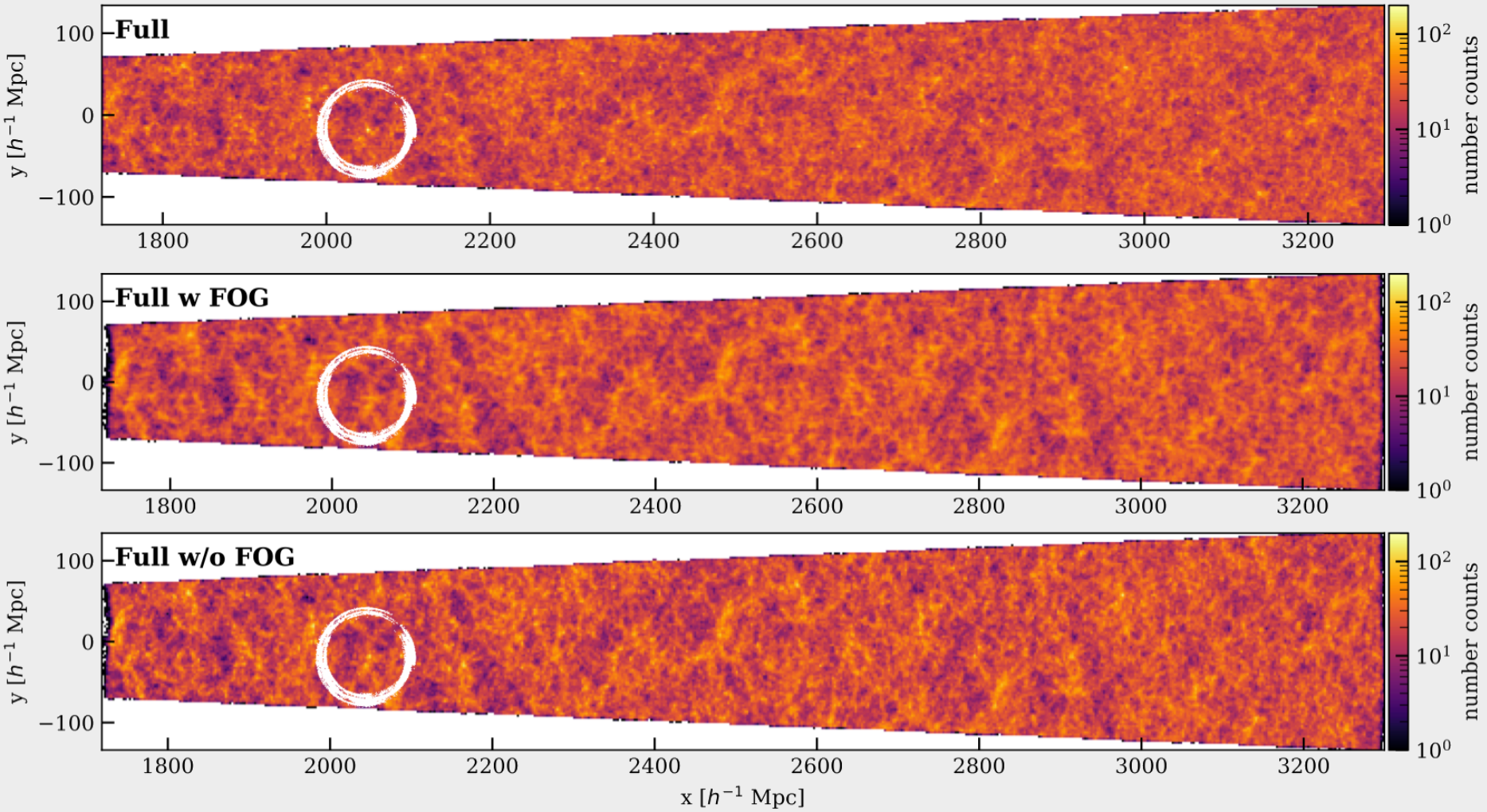
$E_{\rm tot}$ - global grouping completeness

$R = b_\parallel / b_\perp$ - radial expansion factor

Treyer et al. 2018, Kraljic et al. 2018
see also e.g. Robotham et al. 2011

Group reconstruction

III/ Group compression - correction of RSD



- radial compression within groups: $\sigma_\perp = \sigma_\parallel$

Group reconstruction

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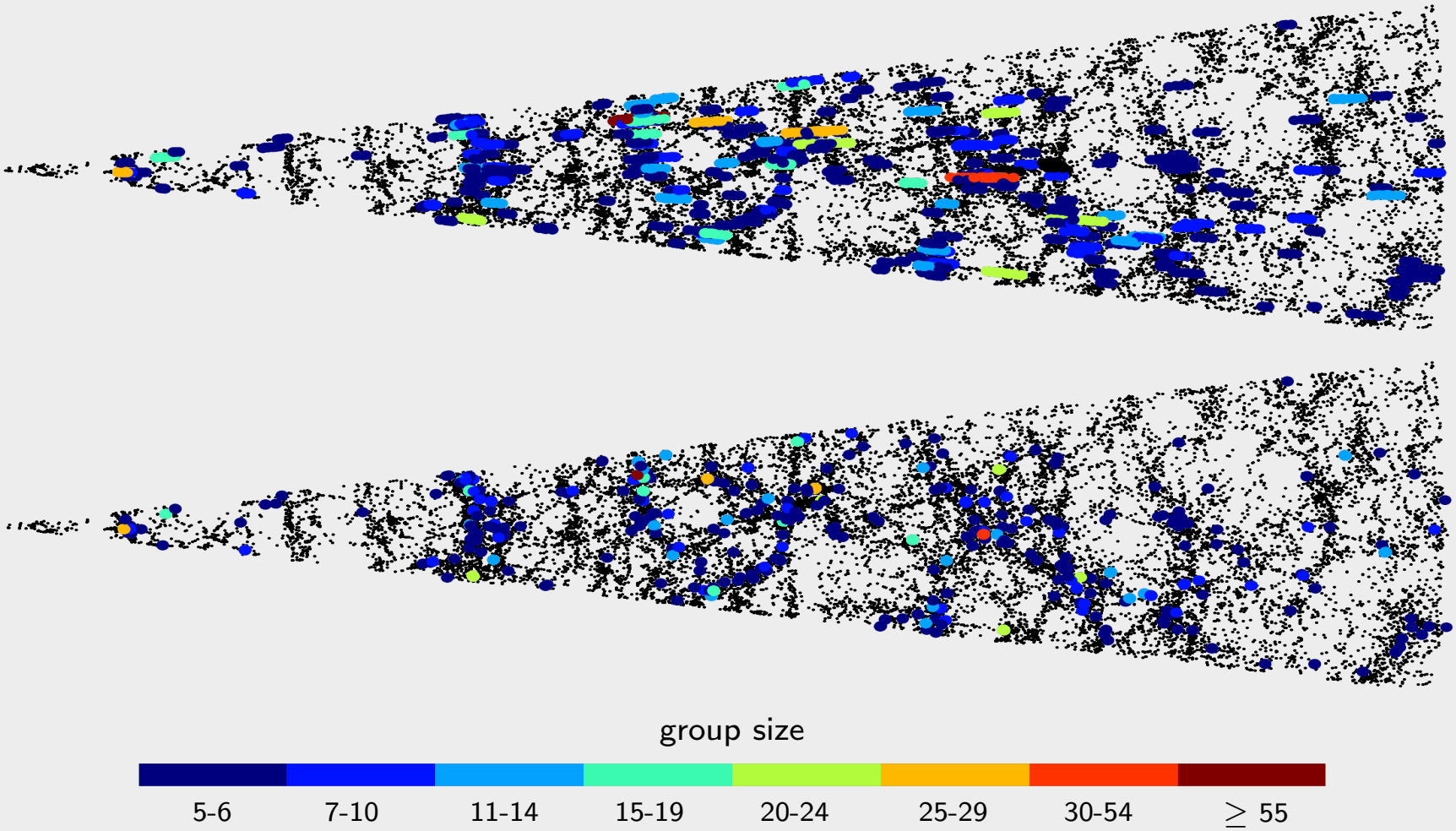
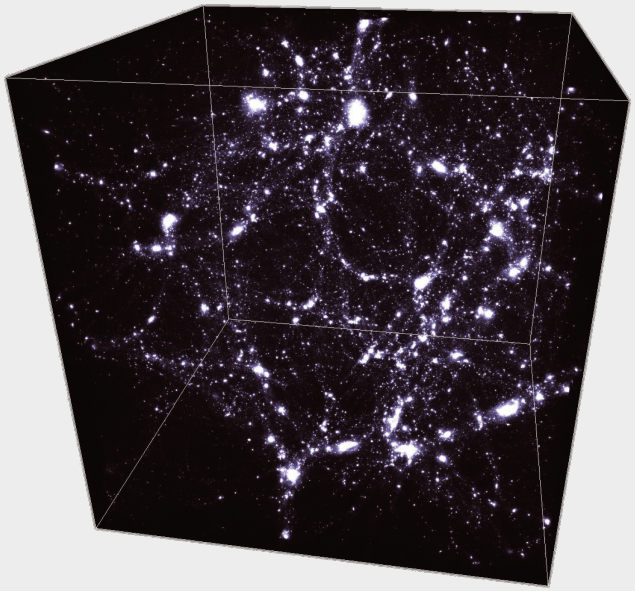


Kraljic et al. 2018 | GAMA

Characterisation of Large-scale structure

Discrete persistent structures extractor (DisPerSE)



Sousbie 2011, Sousbie et al. 2011

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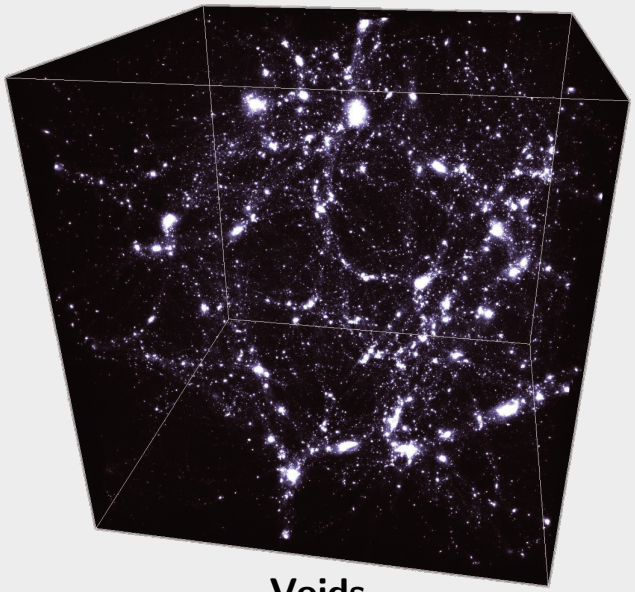
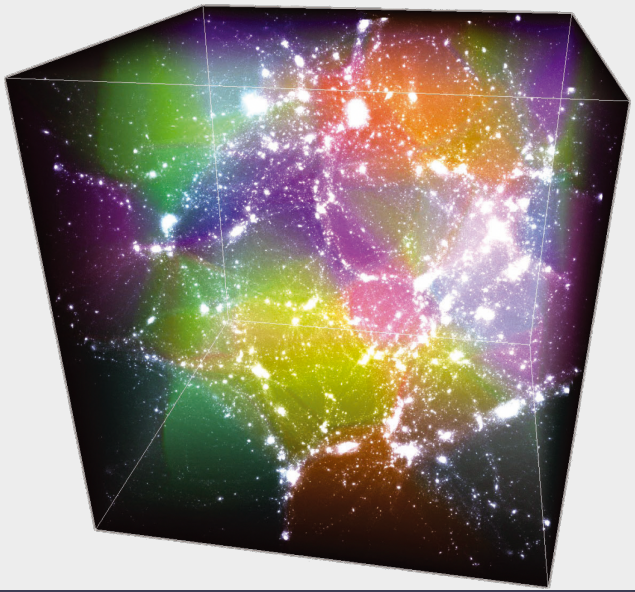
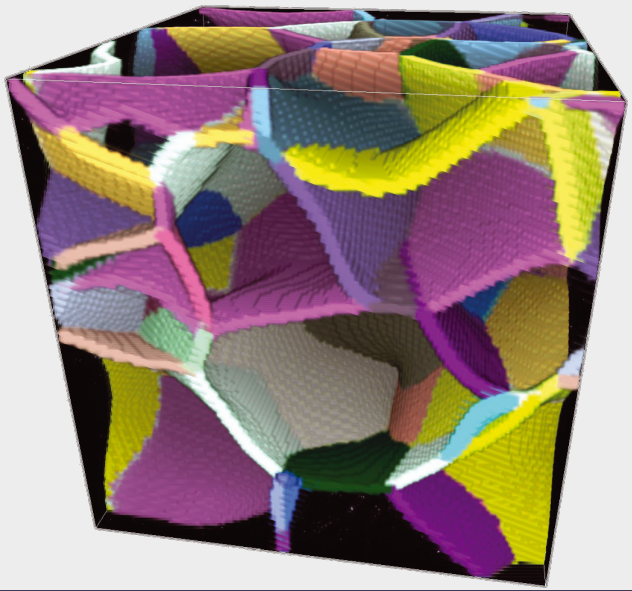


Idea: **Morse theory** (Milnor 1963) $\rightarrow$ global identification of all types of significant structures

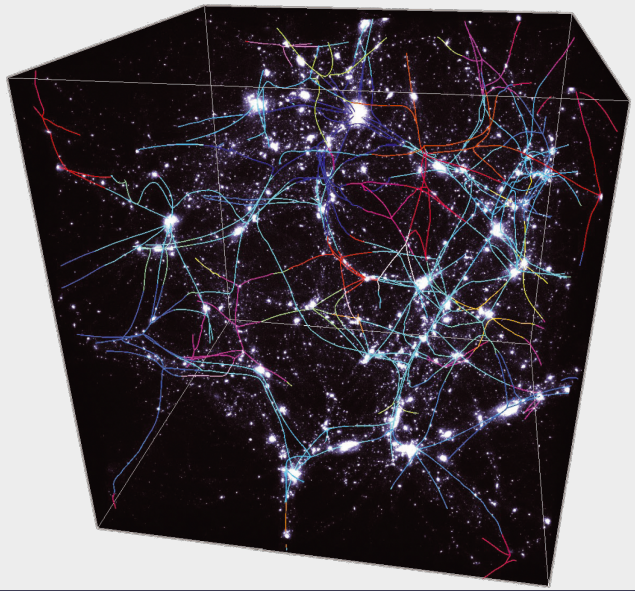
Voids



Walls



Filaments & Nodes



Sousbie 2011, Sousbie et al. 2011

Characterisation of Large-scale structure

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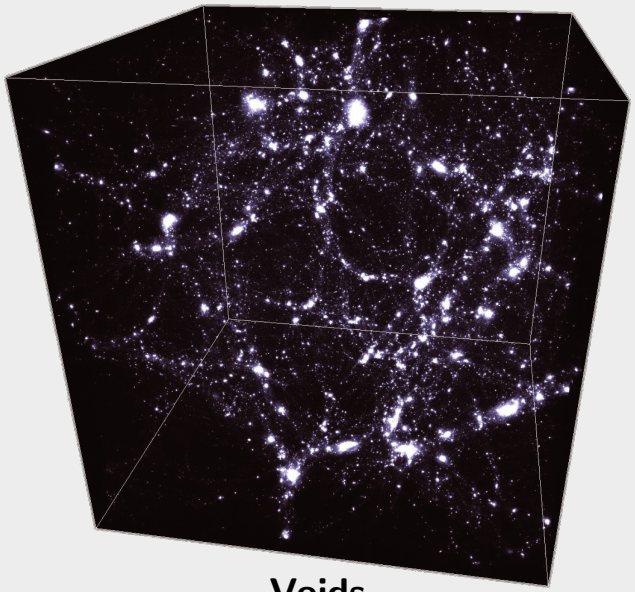
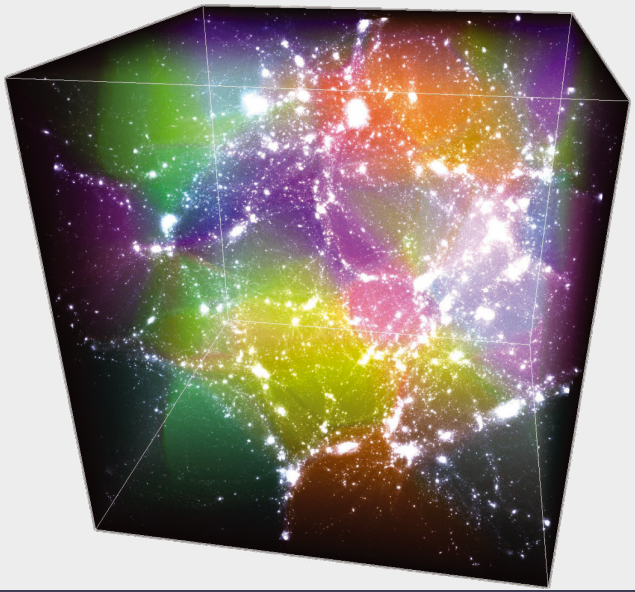


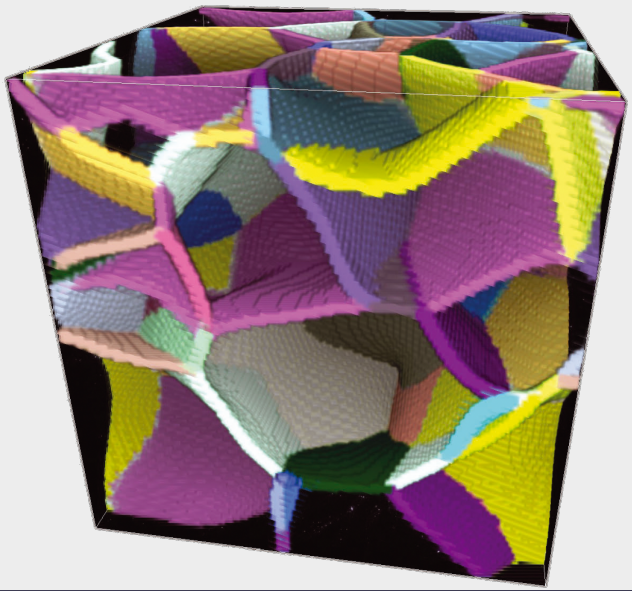
Idea: **Morse theory** (Milnor 1963) $\rightarrow$ global identification of all types of significant structures

Reason: cosmic web features $\rightarrow$ equivalent in the Morse theory

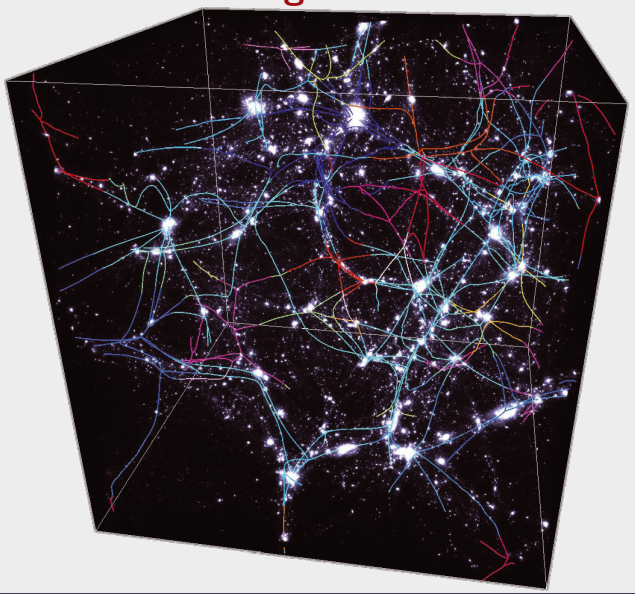
Voids
ascending 3-manifolds



Walls
ascending 2-manifolds



Filaments & Nodes
ascending 1-manifolds & descending 3-manifolds



Sousbie 2011, Sousbie et al. 2011

Characterisation of Large-scale structure

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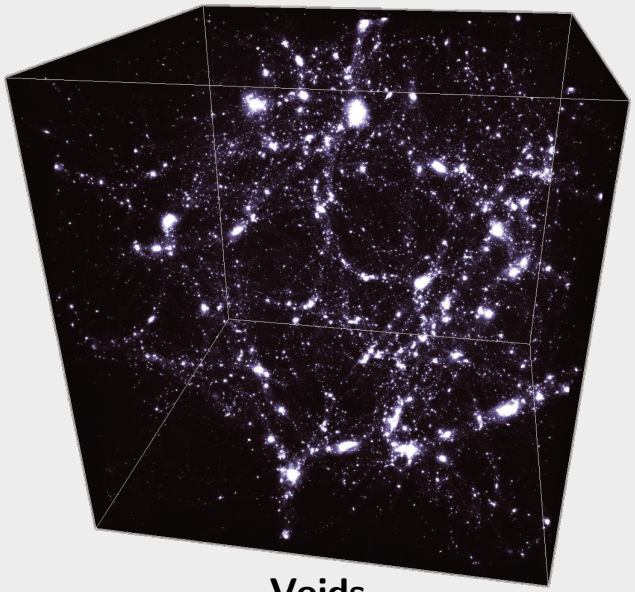
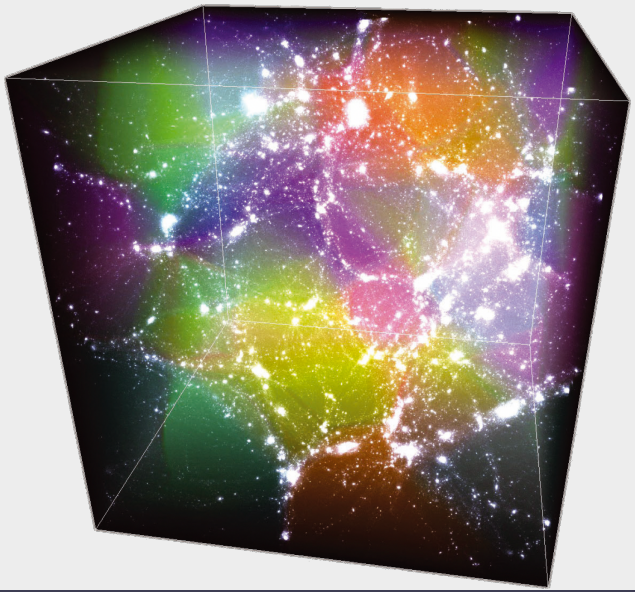


Idea: **Morse theory** (Milnor 1963) → global identification of all types of significant structures

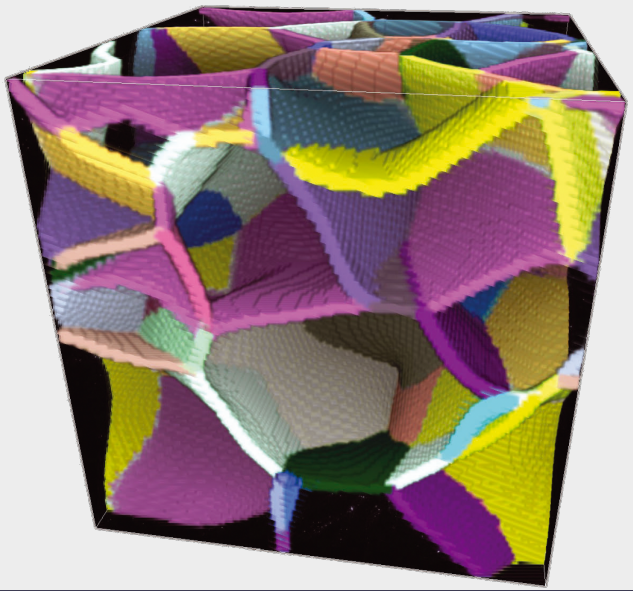
Reason: cosmic web features → equivalent in the Morse theory

Issue: Morse theory → defined for idealised, well-behaved, smooth functions (**Morse functions**)

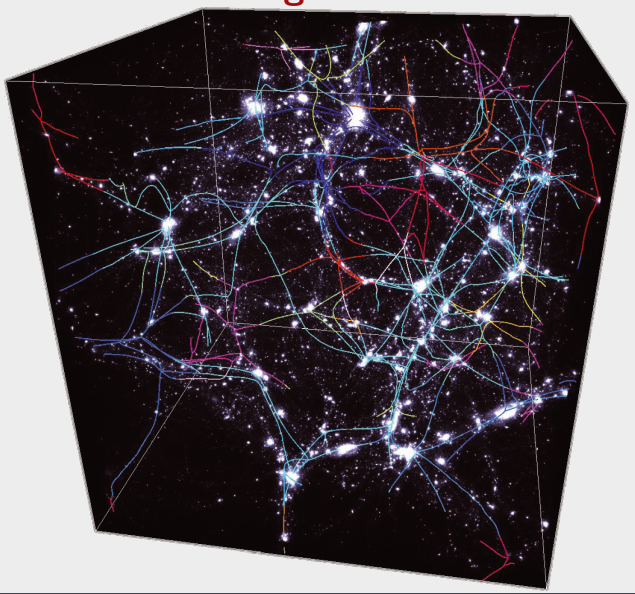
Voids
ascending 3-manifolds



Walls
ascending 2-manifolds



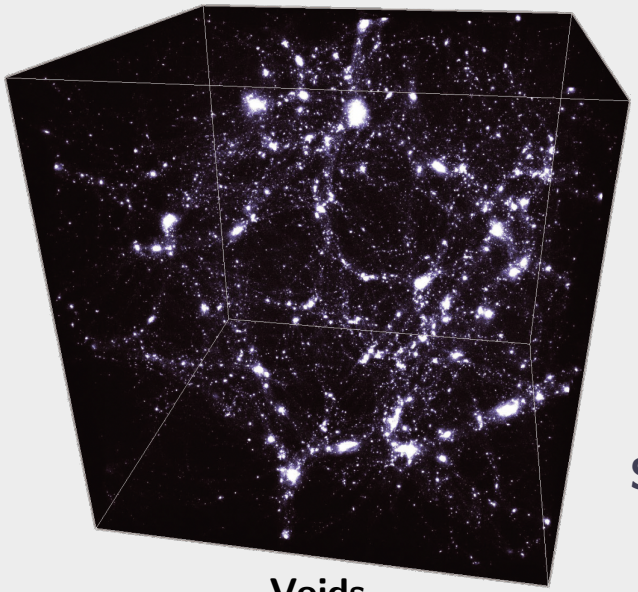
Filaments & Nodes
ascending 1-manifolds & descending 3-manifolds



Sousbie 2011, Sousbie et al. 2011

Characterisation of Large-scale structure

Discrete persistent structures extractor (DisPerSE)



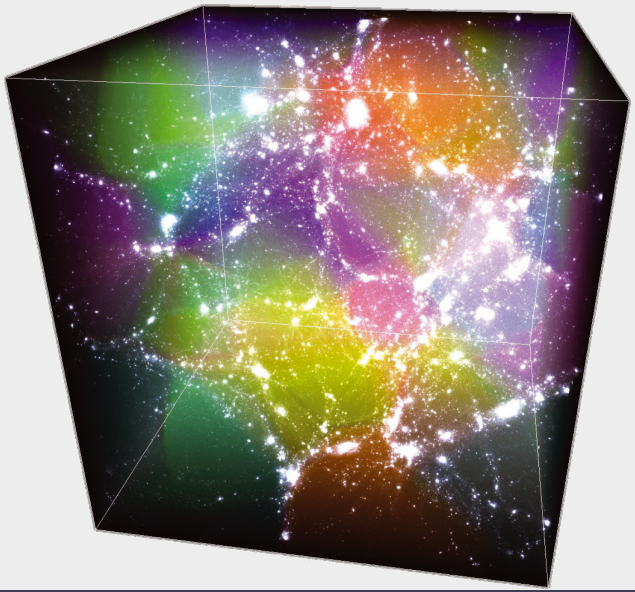
Idea: **Morse theory** (Milnor 1963) → global identification of all types of significant structures

Reason: cosmic web features → equivalent in the Morse theory

Issue: Morse theory → defined for idealised, well-behaved, smooth functions (**Morse functions**)

Solution: DisPerSE → **discrete Morse theory** & **persistence theory**

Voids
ascending 3-manifolds



Walls
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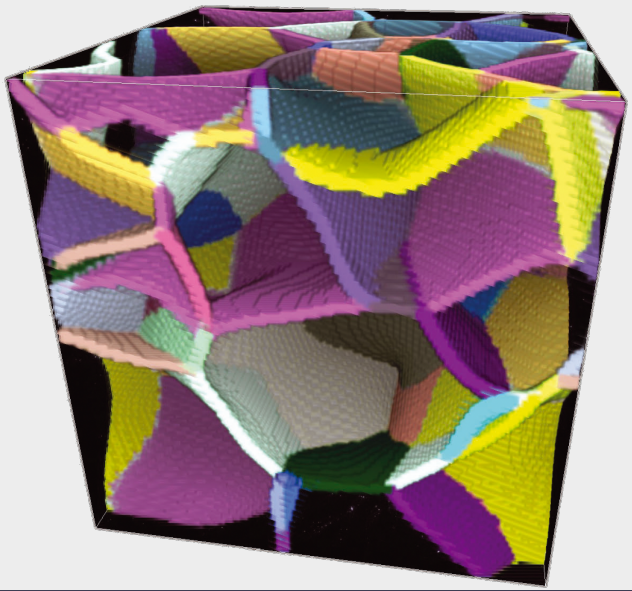

Filaments & Nodes
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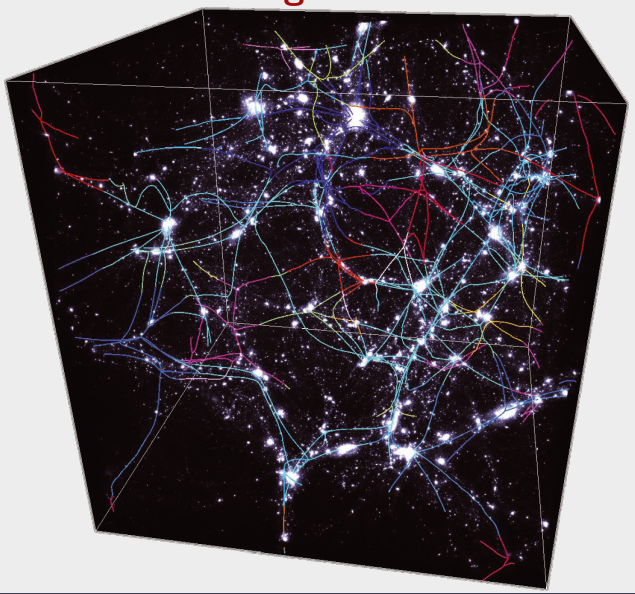

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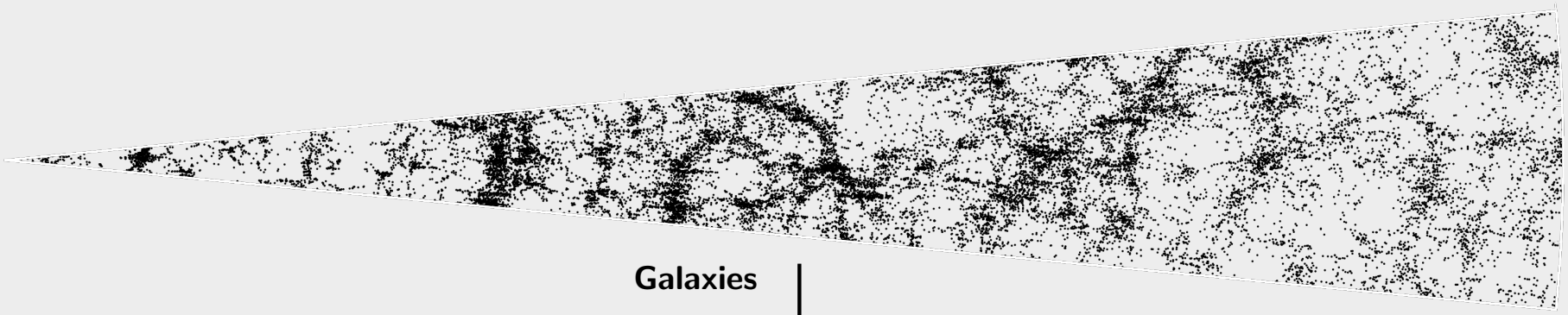
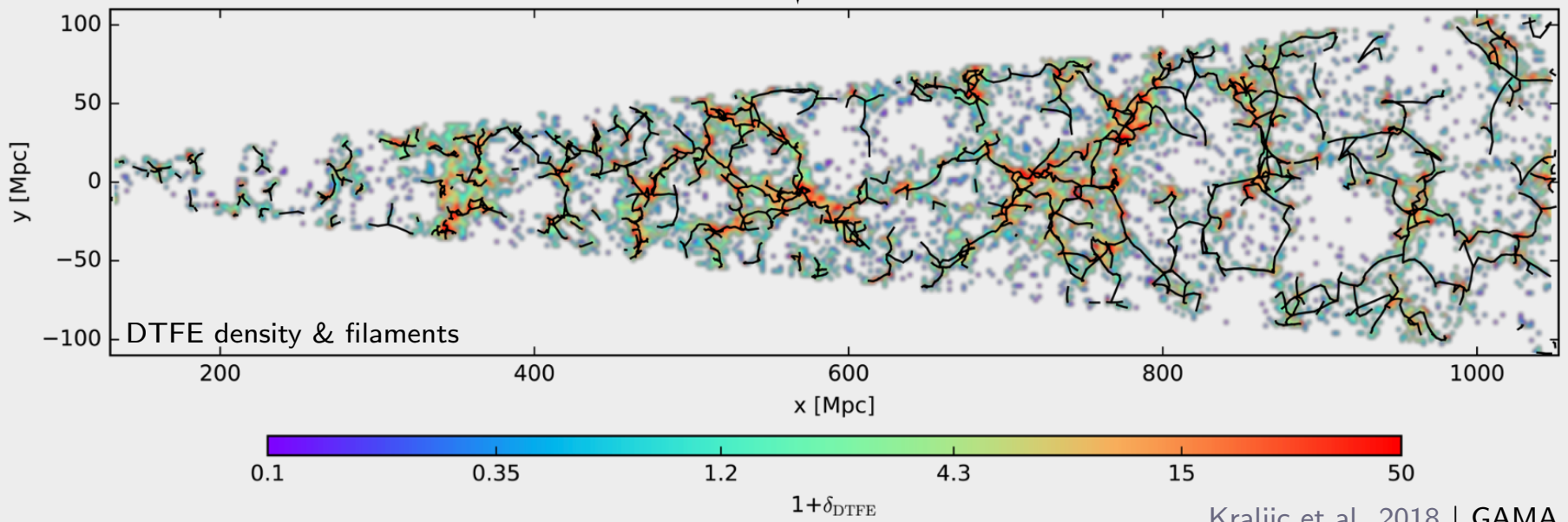


Galaxies

DTFE density

Schaap & van de Weygaert 2000

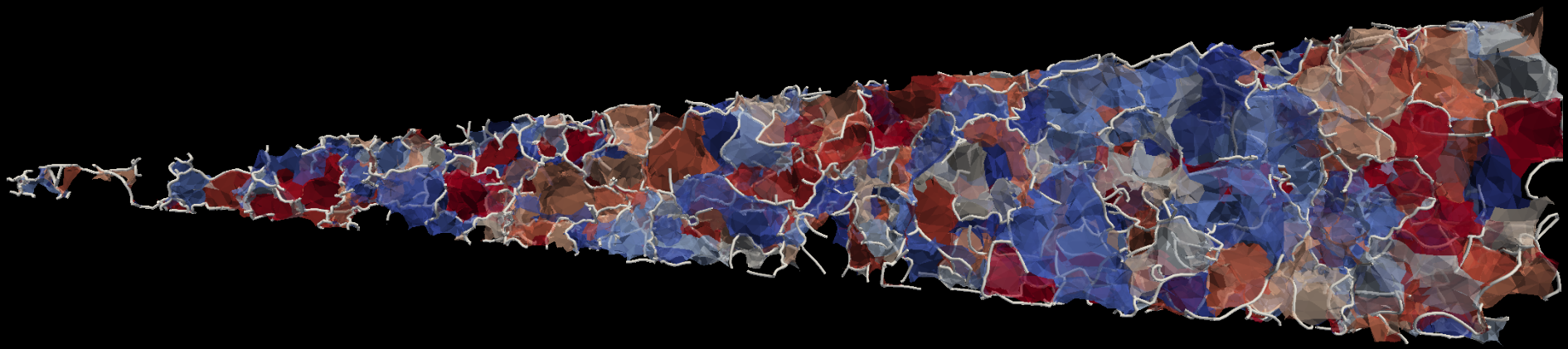
Filaments



Kraljic et al. 2018 | GAMA

The Cosmic web identification

Nodes, filaments, walls, voids



Driver et al. 2009, 2011 | GAMA

Sousbie et al. 2011 | DisPerSE

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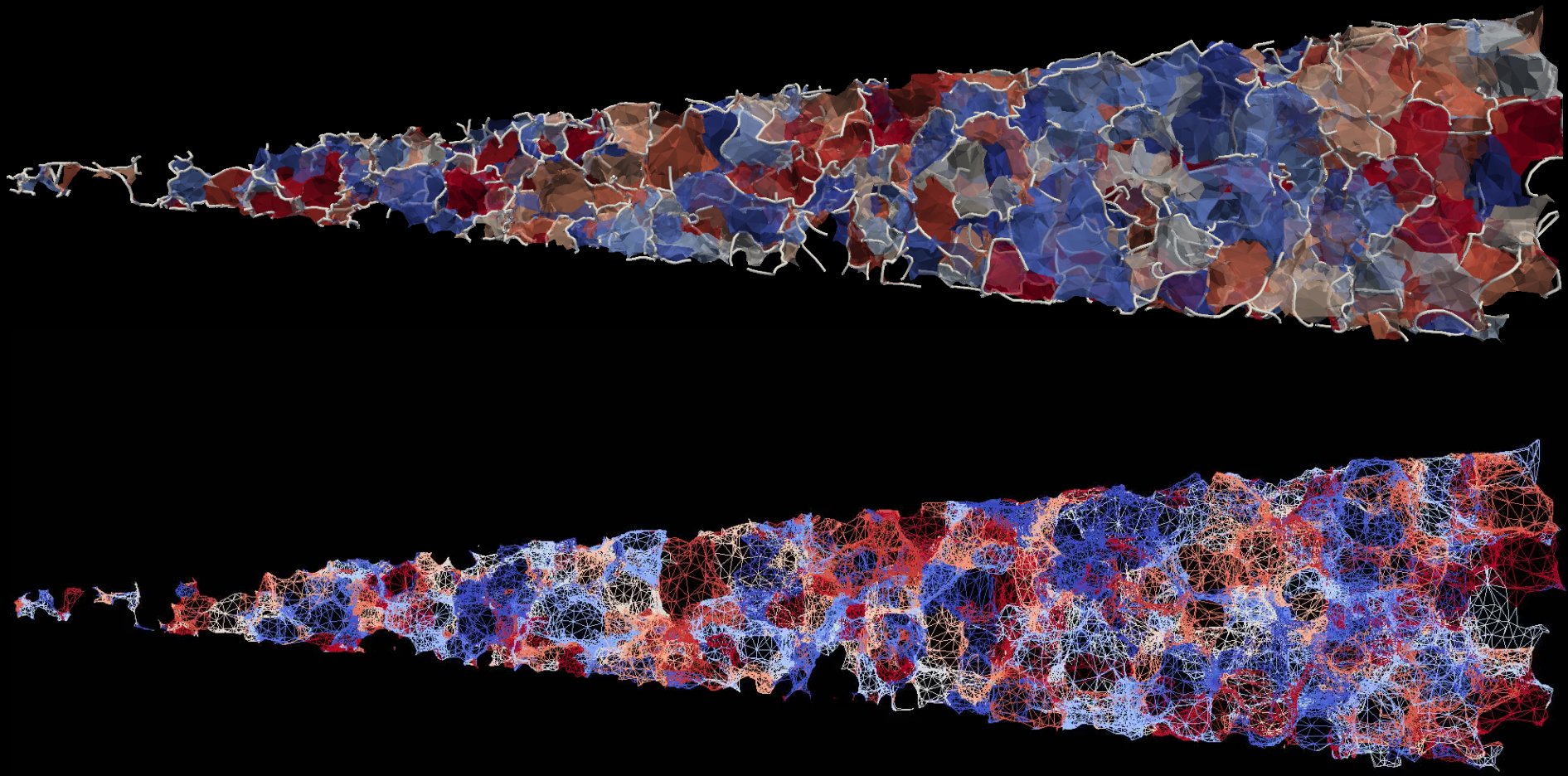
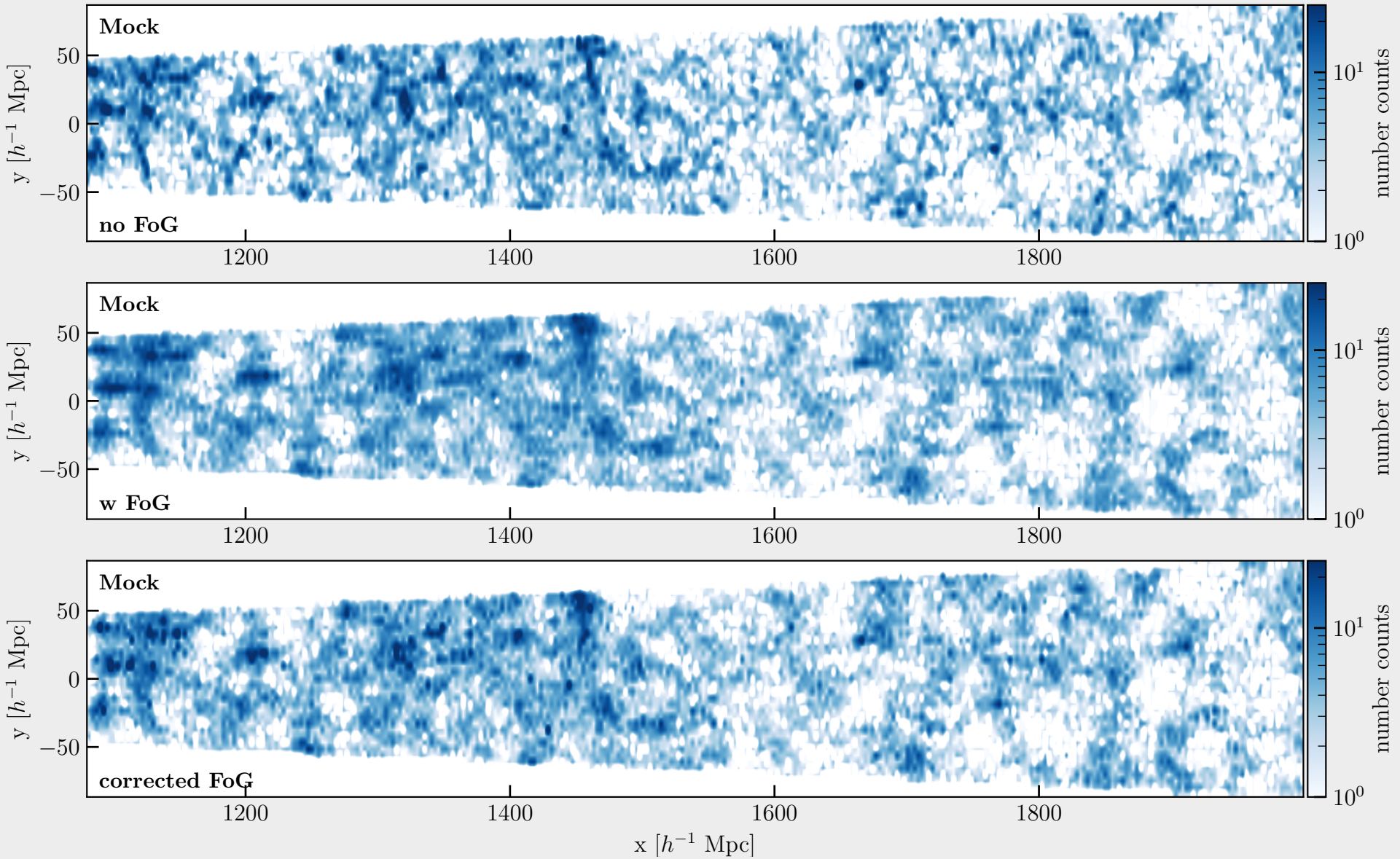


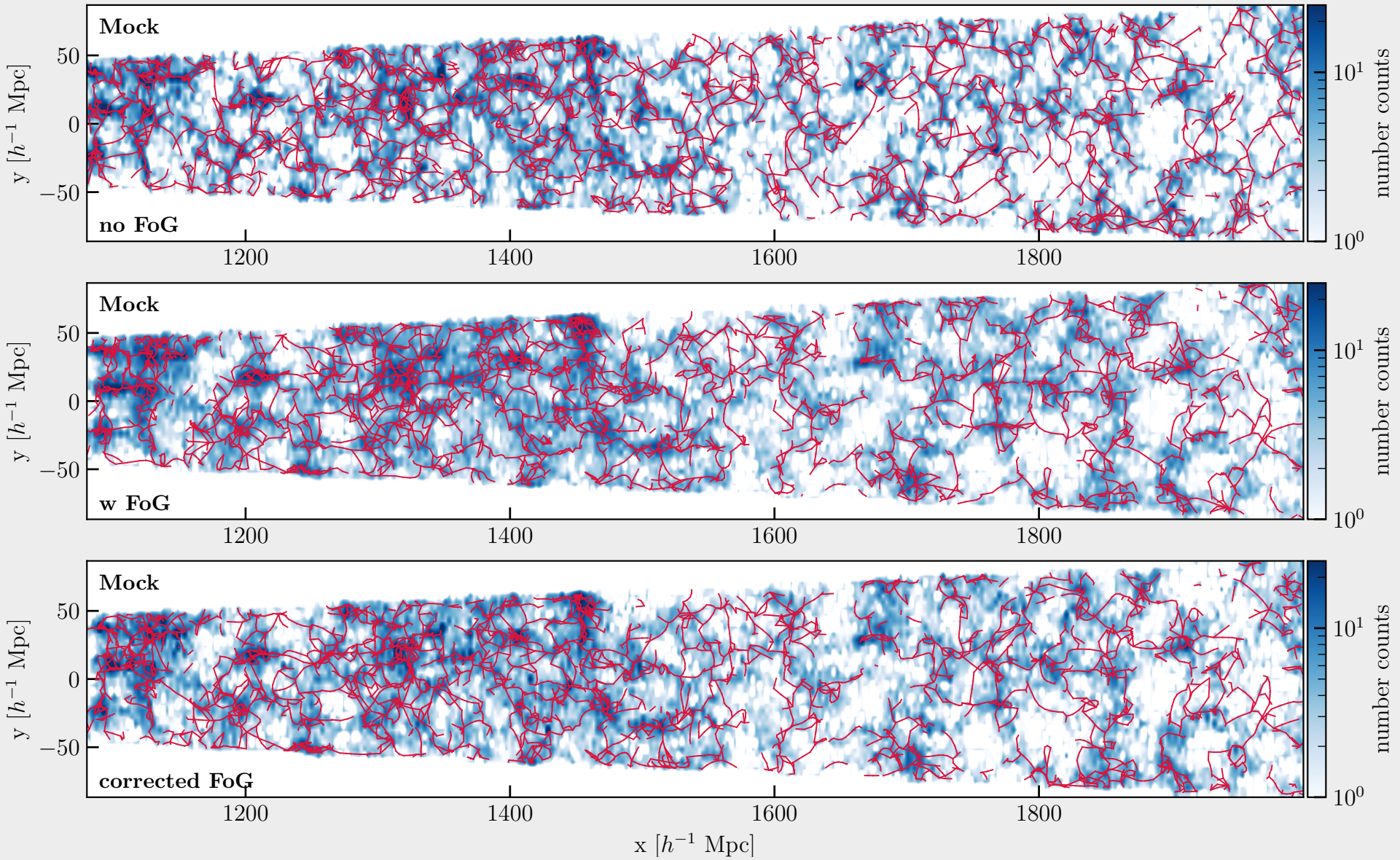
Driver et al. 2009, 2011 | GAMA

Sousbie et al. 2011 | DisPerSE

Reconstructed galaxy density



Reconstructed cosmic web



Cosmic web analysis

I/ Geometrical properties: length of filaments
surface of walls
volume of voids

Cosmic web analysis

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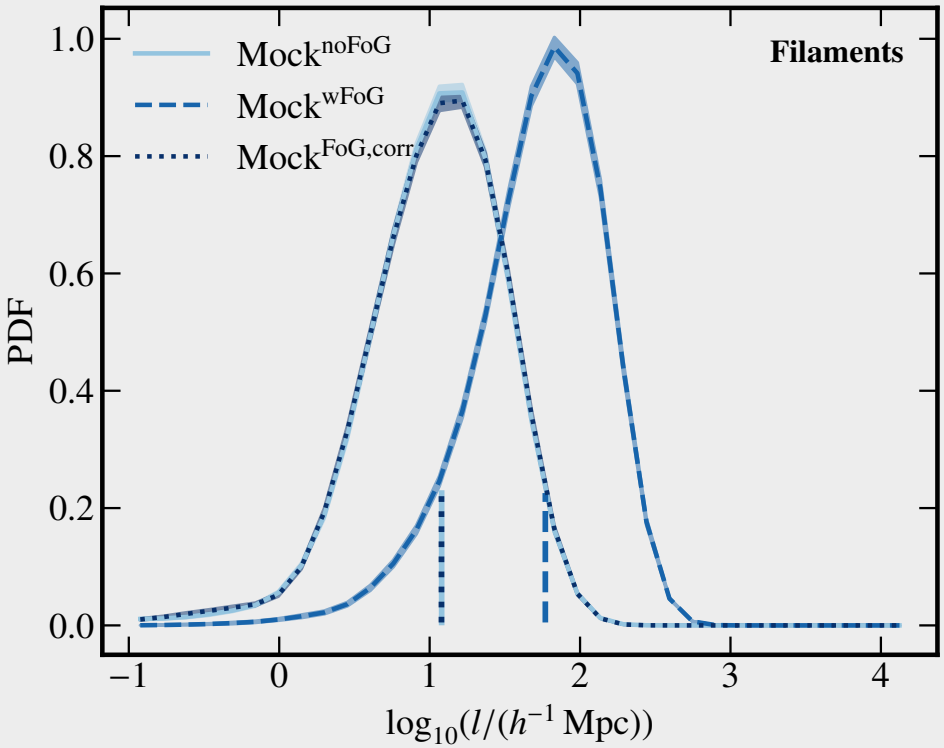

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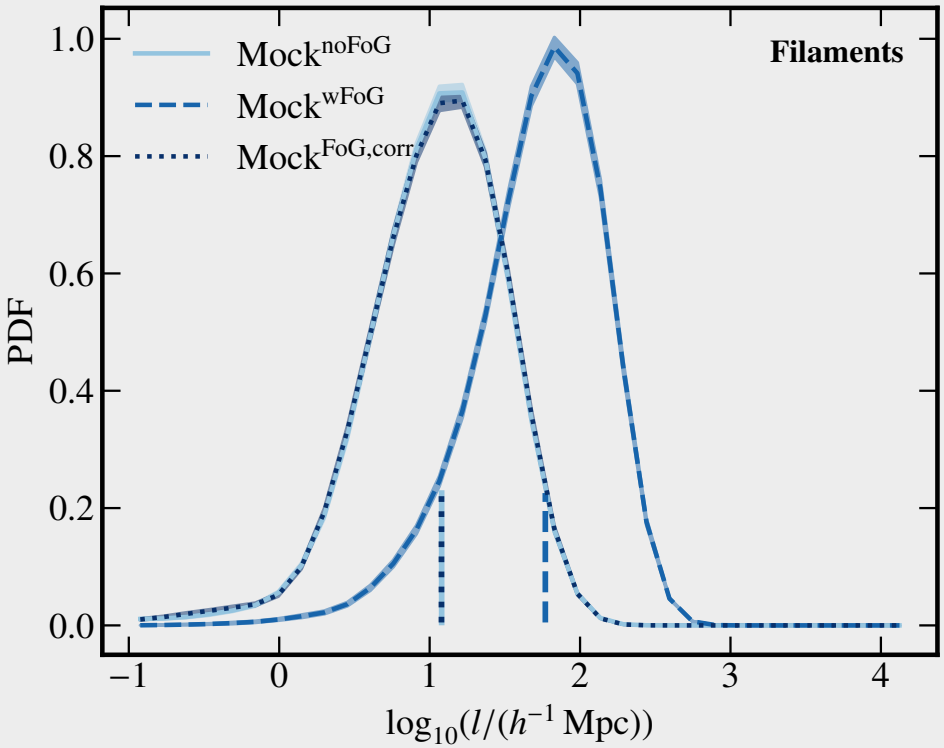
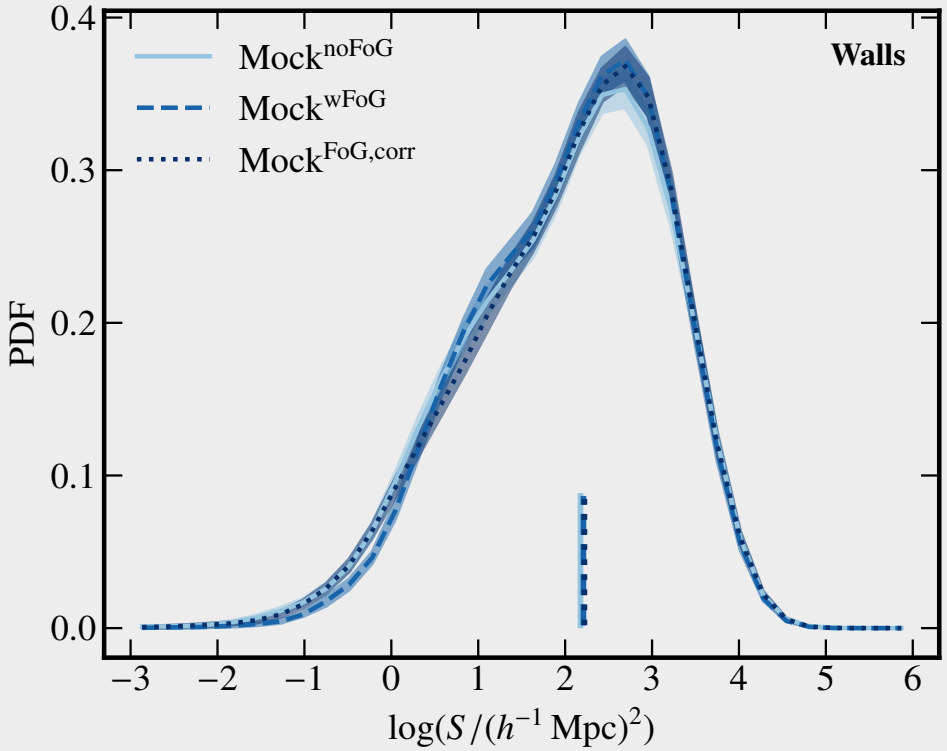
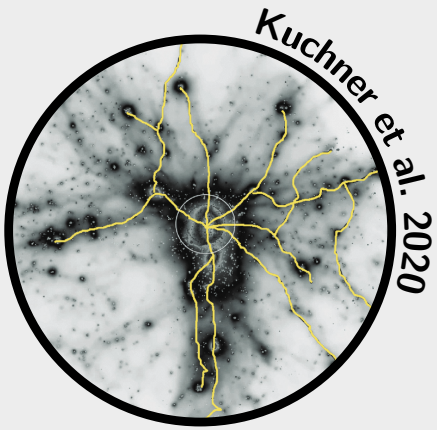




Cosmic web analysis

II/ Topological property: connectivity



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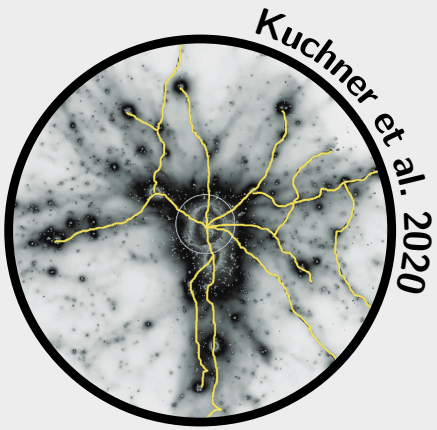

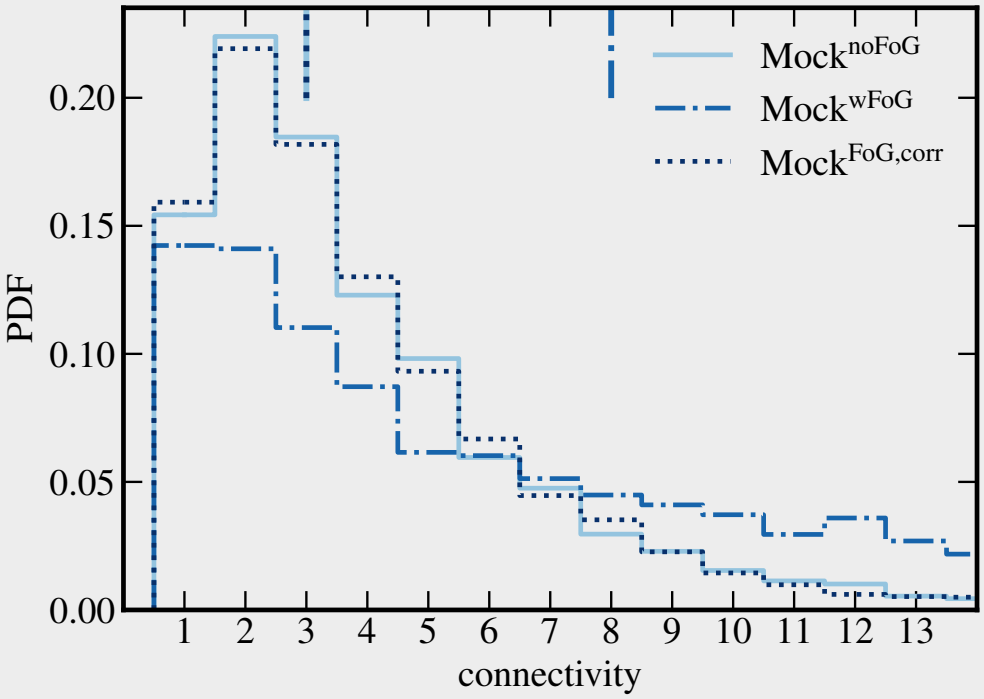

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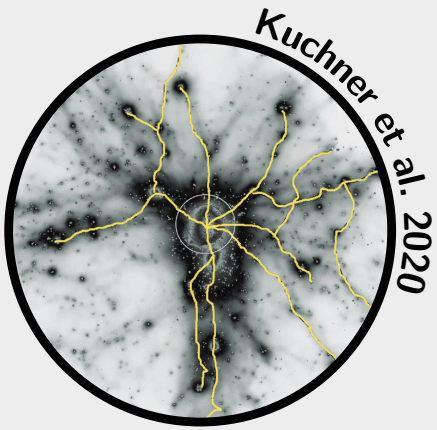
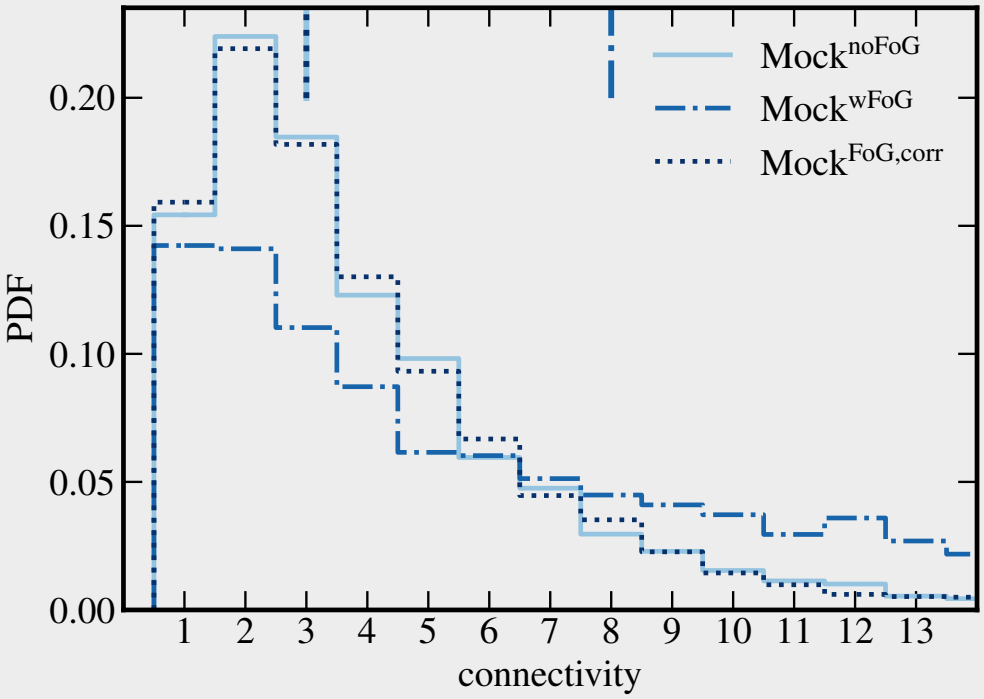
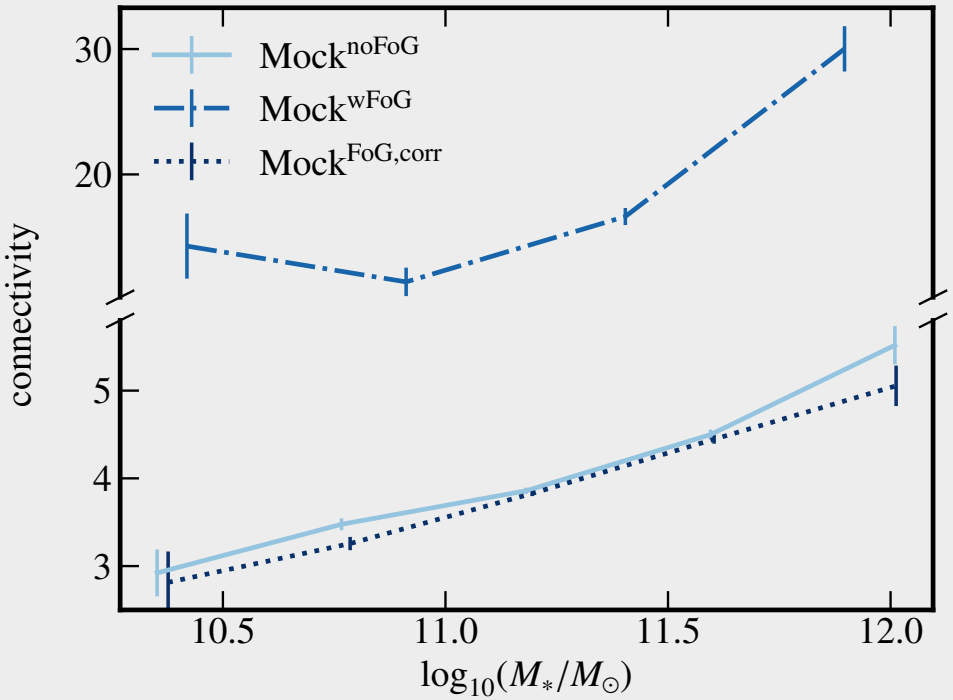
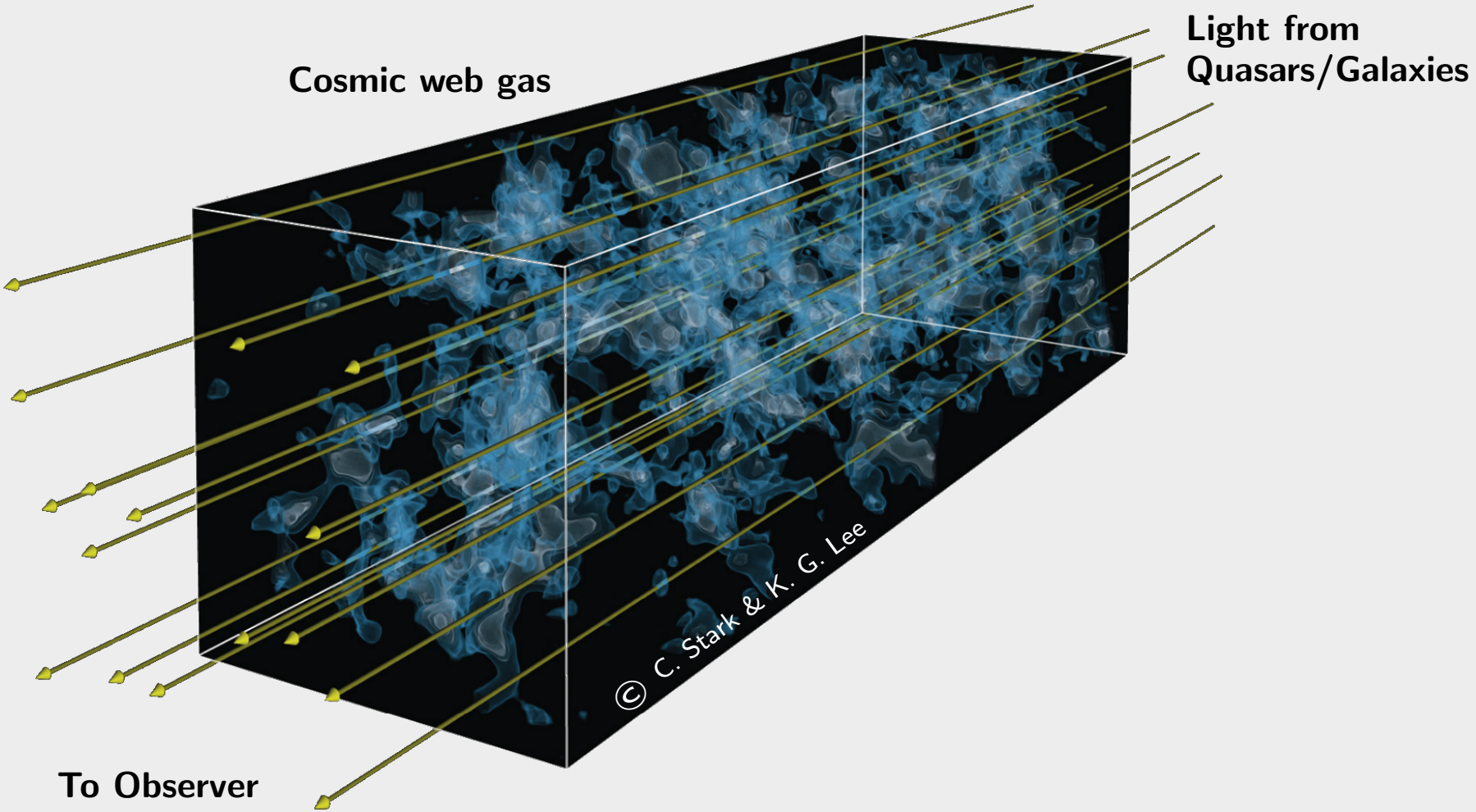






IGM tomography



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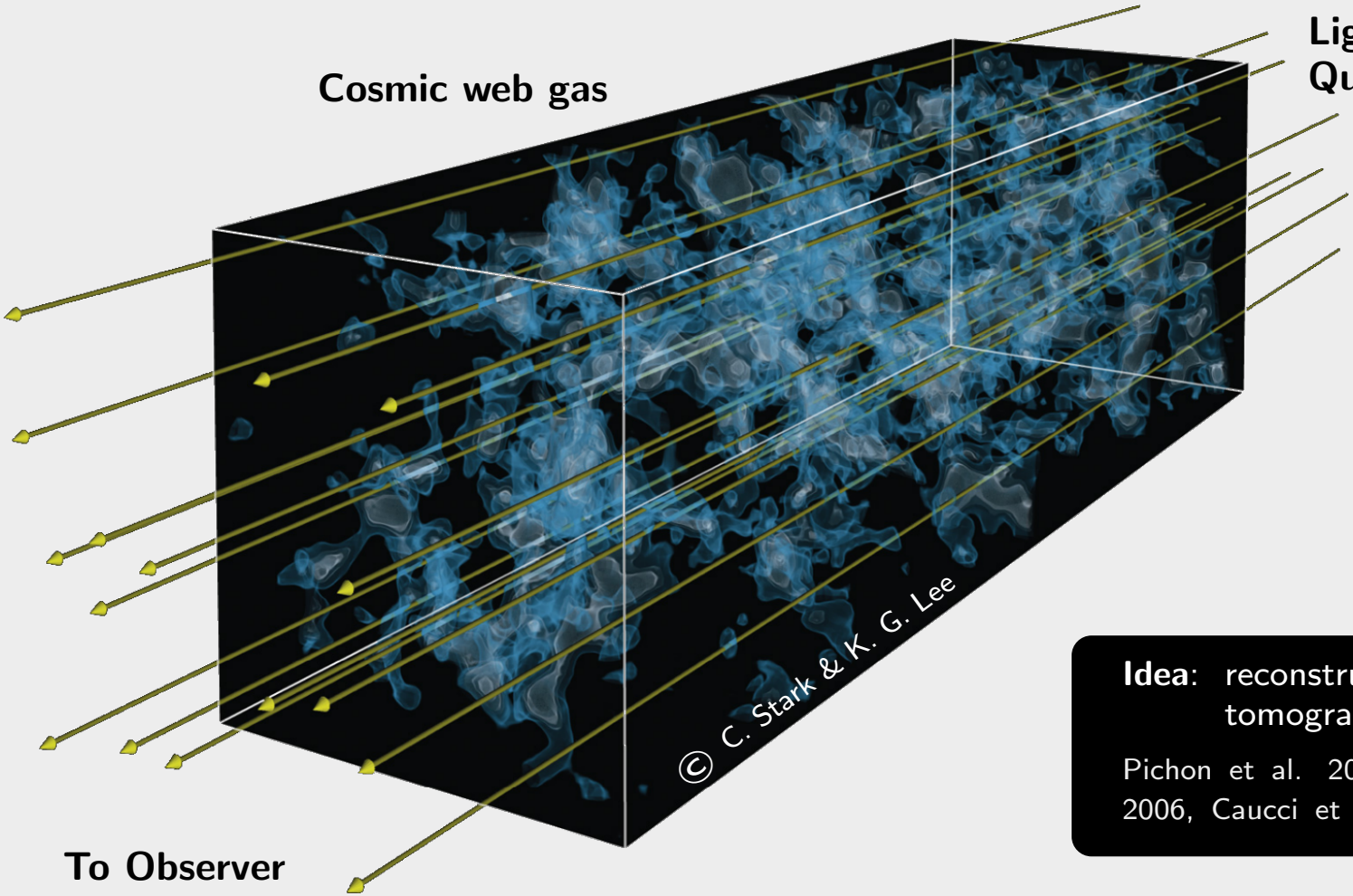
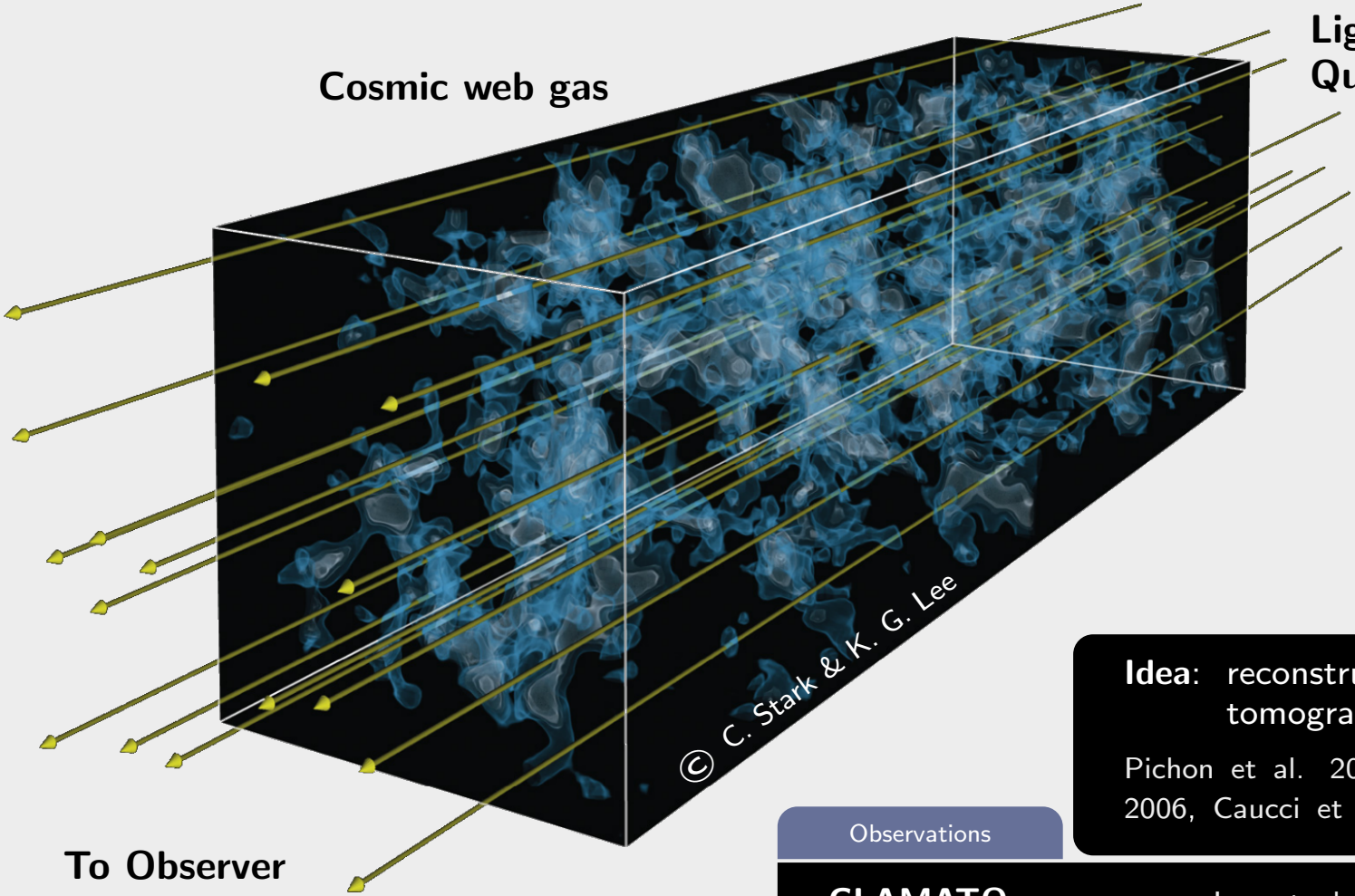


Theory

Idea: reconstruct CW from Ly-α tomography

Pichon et al. 2001, D'Odorico et al. 2006, Caucci et al. 2008 ...

IGM tomography



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Observations

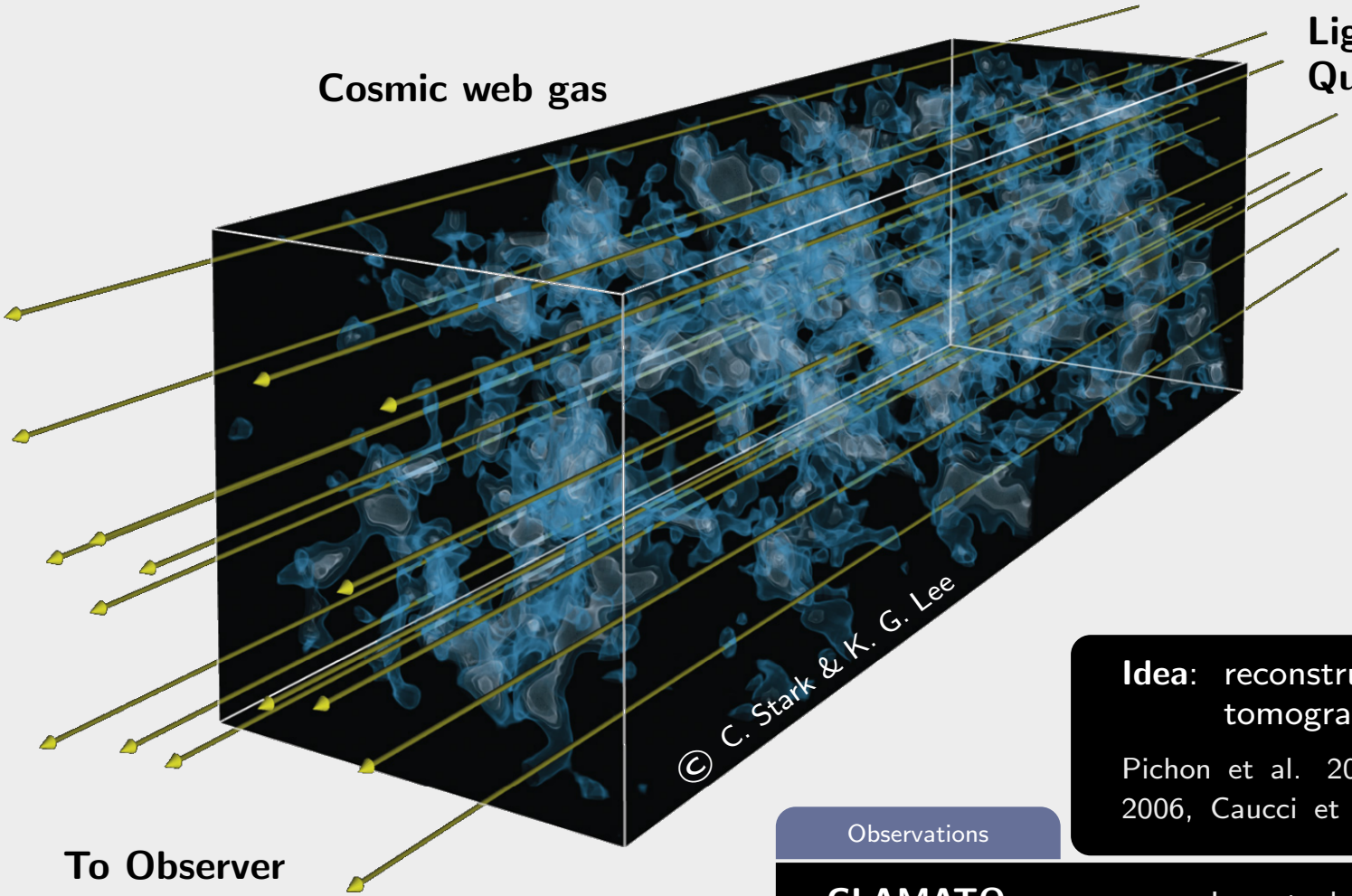
CLAMATO Lee et al. 2018

- $2.05 < z < 2.5$
- $\mathrm{d_{LoS}} = 2.5\,h^{-1}$ Mpc

eBOSS Stripe-82 Ravoux et al. 2020

- $2.1 < z < 3.2$
- $\mathrm{d_{LoS}} = 17.5\,h^{-1}$ Mpc

IGM tomography



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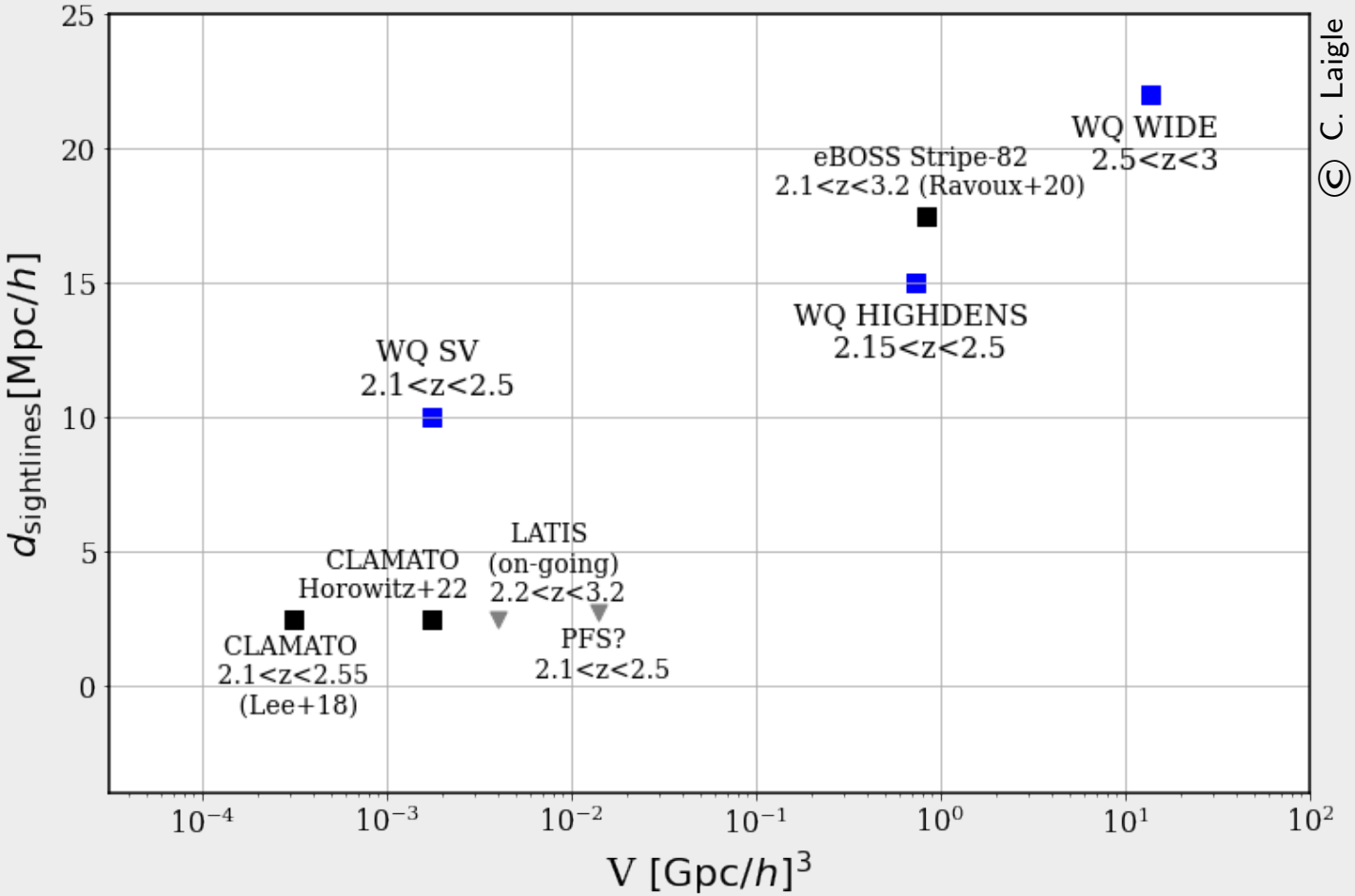
Future surveys

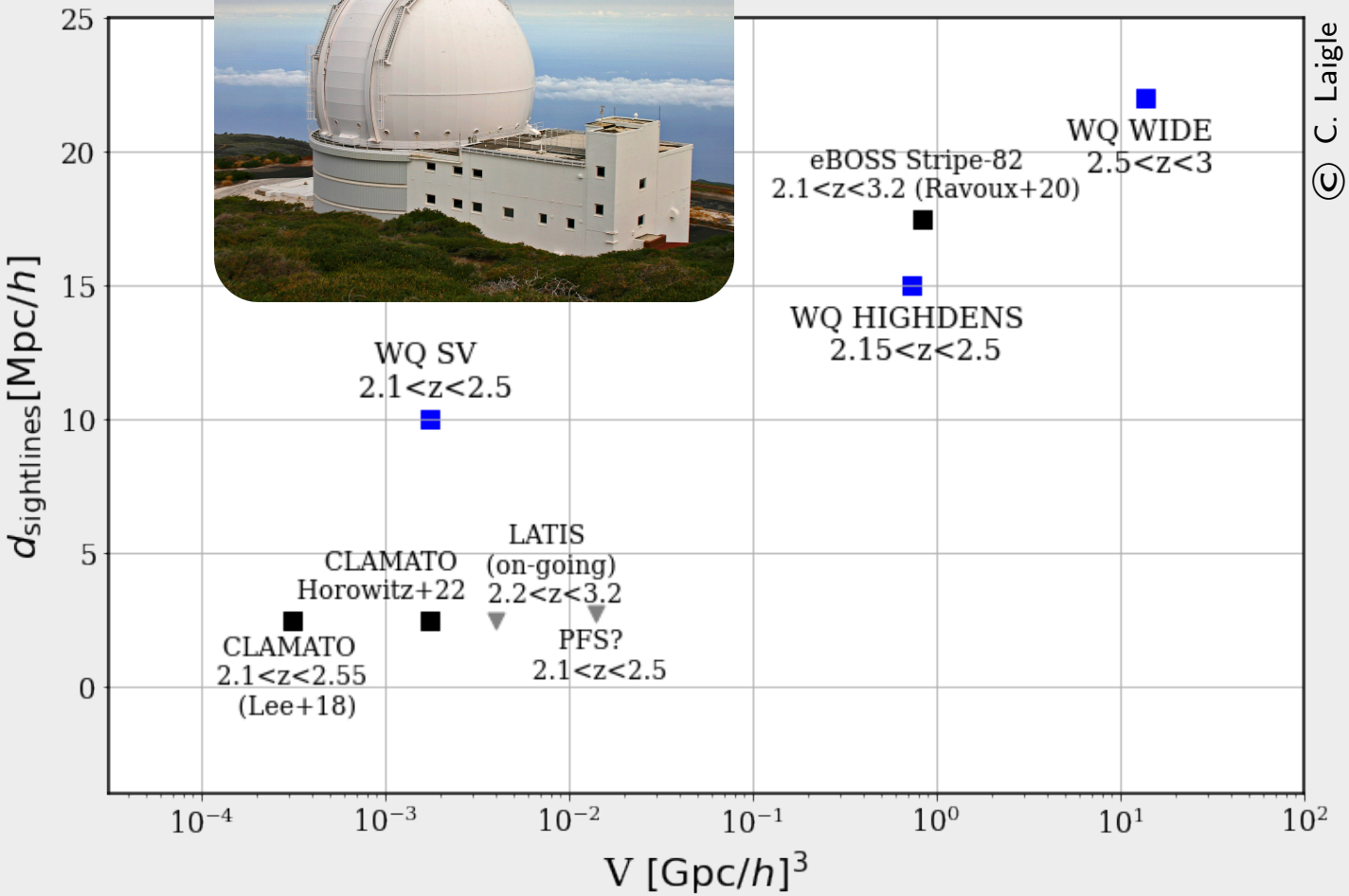
- DESI DESI Collab. 2016
- PFS Takada et al. 2014
- WEAVE-QSO Pieri et al. 2016
- MOSAIC Puech et al. 2018

Surveys

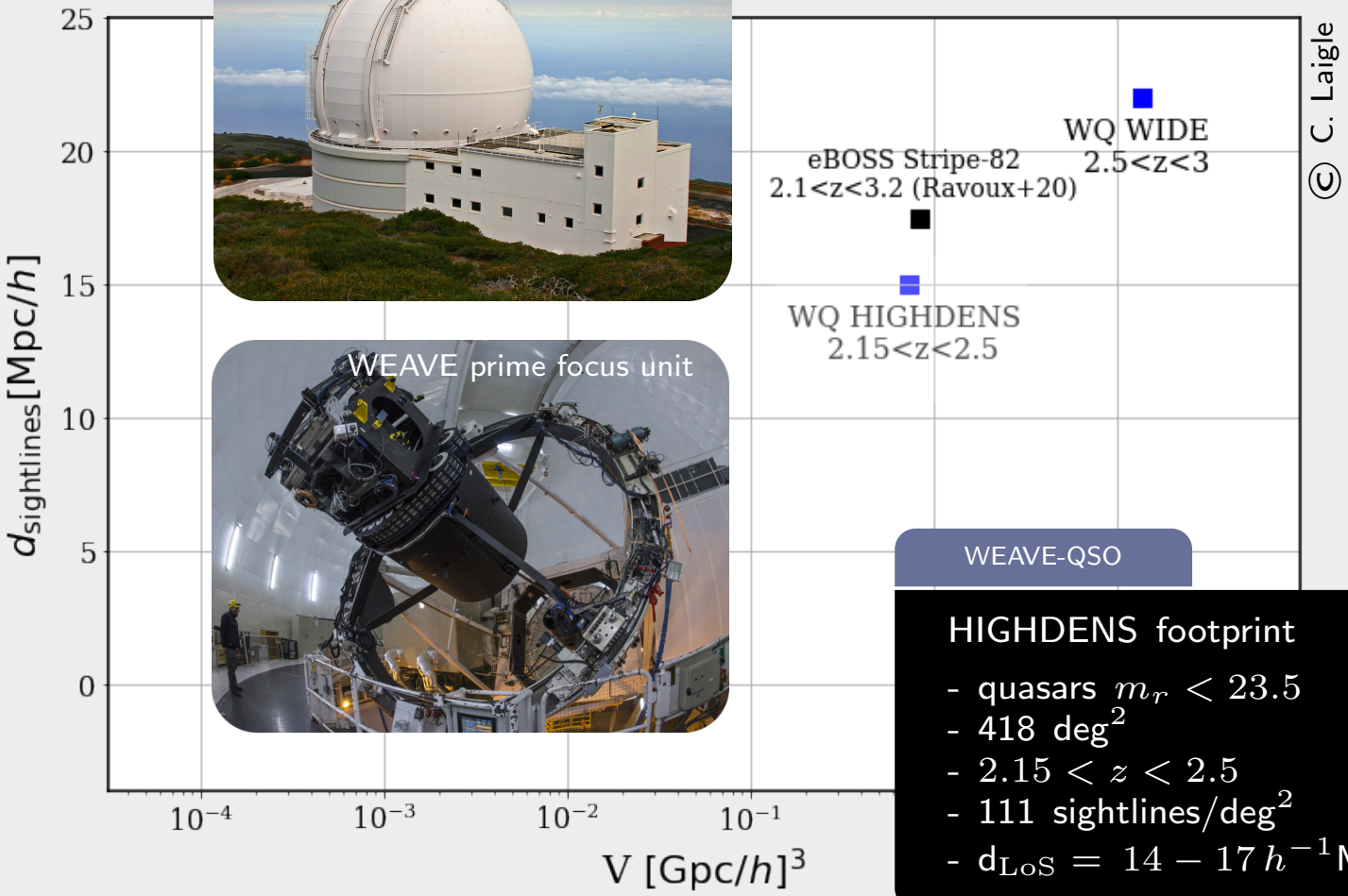

25
20
15
10
5
0
$d_{\text{sightlines}}$[Mpc/h]
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
V [Gpc/h]^3
WQ WIDE
2.5<z<3
eBOSS Stripe-82
2.1<z<3.2 (Ravoux+20)
WQ HIGHDENS
2.15<z<2.5
WQ SV
2.1<z<2.5
LATIS
(on-going)
2.2<z<3.2
CLAMATO
Horowitz+22
PFS?
2.1<z<2.5
CLAMATO
2.1<z<2.55
(Lee+18)
© C. Laigle

Surveys


William Herschel Telescope


WQ WIDE
2.5<z<3
eBOSS Stripe-82
2.1<z<3.2 (Ravoux+20)
WQ HIGHDENS
2.15<z<2.5
WQ SV
2.1<z<2.5
LATIS
(on-going)
2.2<z<3.2
CLAMATO
Horowitz+22
CLAMATO
2.1<z<2.55
(Lee+18)
PFS?
2.1<z<2.5
© C. Laigle
$d_{\mathrm{sightlines}}$[Mpc/h]
V [Gpc/h]^3

Surveys



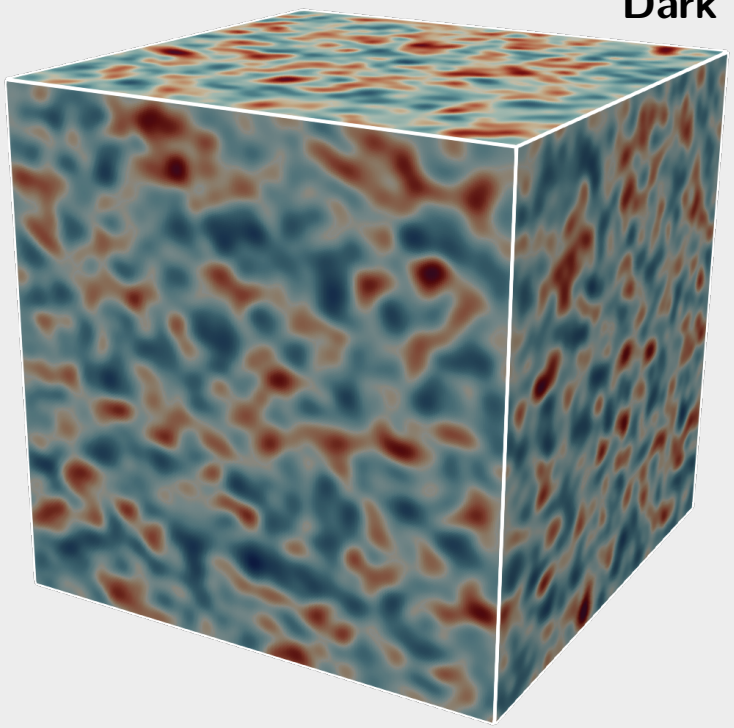
WEAVE-QSO

HIGHDENS footprint

- quasars $m_r < 23.5$
- 418 deg^2
- $2.15 < z < 2.5$
- 111 sightlines/deg^2
- $d_{\text{LoS}} = 14 - 17\,h^{-1}$Mpc

Modelling the Ly-α forest

Dark matter



Mocks

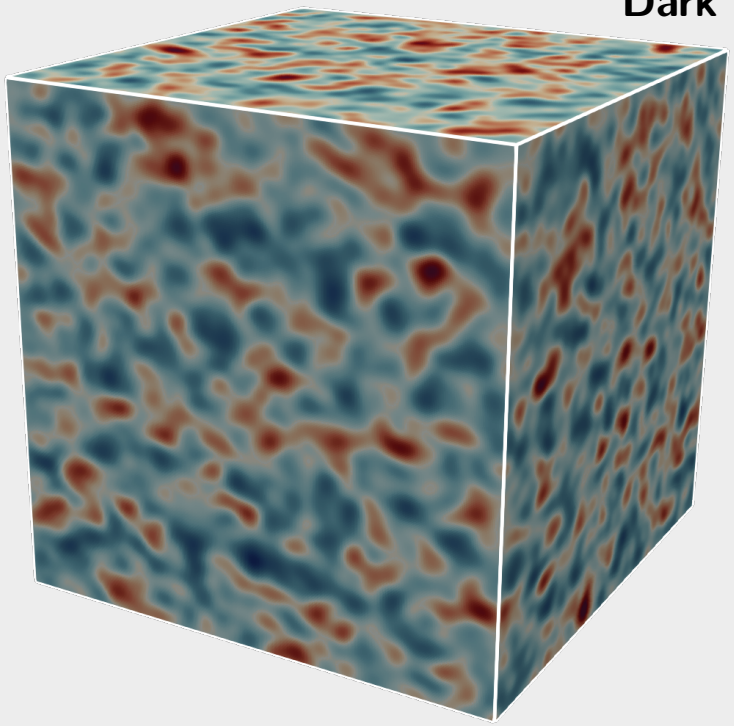
5 ΛCDM N-body simulations GADGET2 Springel 2005

- 1 $(\mathrm{Gpc}\,h^{-1})^3$, 2048^3 DM particles
- $z = 2.5$

Mock data

Modelling the Ly-α forest

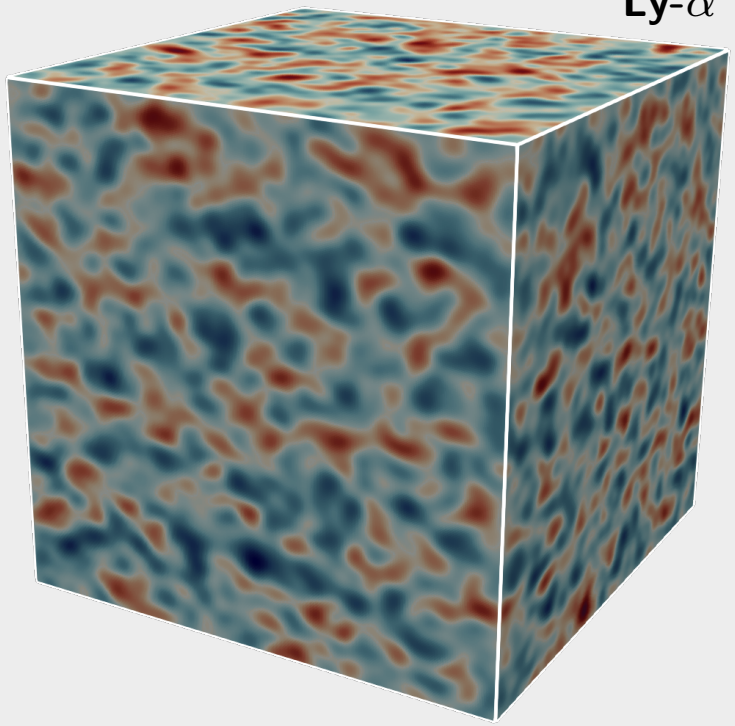
Dark matter



LyMAS

Peirani et al. 2014, 2022

Ly-α



Mocks

5 ΛCDM N-body simulations GADGET2 Springel 2005

- 1 $(\mathrm{Gpc}\,h^{-1})^3$, 2048^3 DM particles
- $z = 2.5$
- Ly-α forest flux synthesised from DM using Horizon-AGN Dubois et al. 2014 with Ly-α Mass Association Scheme LyMAS2 Peirani et al. 2022

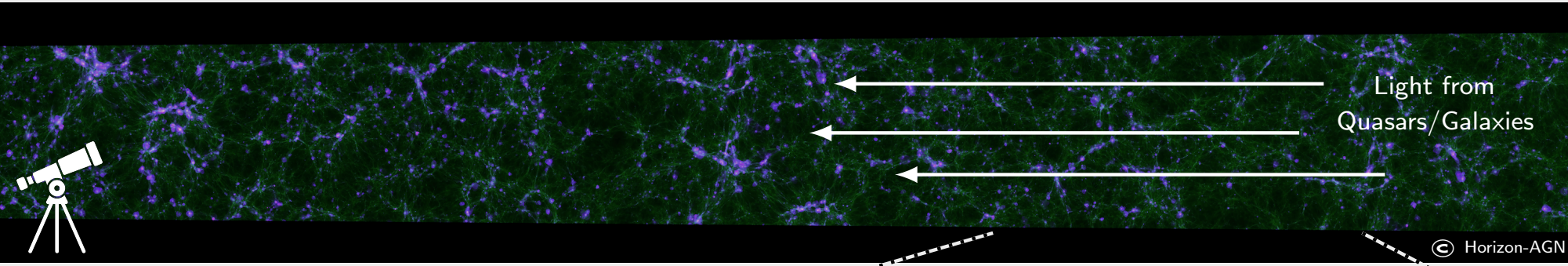
Inversion of the Ly-α forest

Method

Wiener filtering e.g. Pichon et al. 2001, Caucci et al. 2008, Lee et al. 2018

- interpolation between the lines-of-sight
- estimated field: $\mathbf{M} = \mathbf{C}_{\delta 3 d_\delta}(\mathbf{C}_{\delta\delta} + \mathbf{N})^{-1}\mathbf{D}$
- normal covariance matrix prior:

$$\mathbf{C}_{\delta\delta}(x_1, x_2, \mathbf{x}_{1\mathrm{T}}, \mathbf{x}_{2\mathrm{T}}) = \sigma^2_{\delta\delta}\, e^{-\frac{|x_1 - x_2|^2}{2L_x^2}} e^{-\frac{|\mathbf{x}_{1\mathrm{T}} - \mathbf{x}_{2\mathrm{T}}|^2}{2L_\mathrm{T}^2}}$$

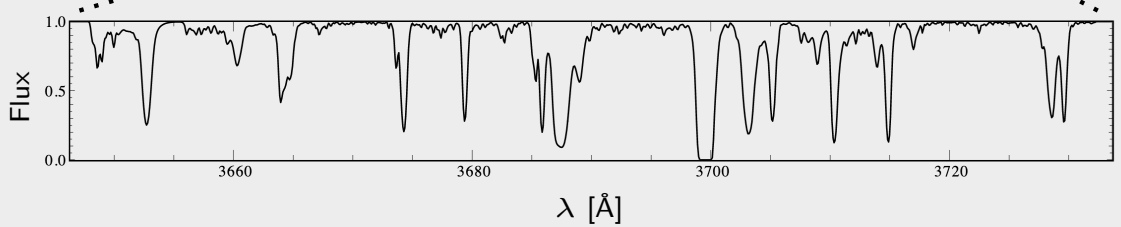


Transmitted flux

$$\mathrm{F}(\nu_0) = \mathrm{e}^{-\tau_\alpha(\nu_0)}$$

traces HI density

$$\tau_\alpha(\nu_0) = \int_0^{x_s} \frac{\sigma_\alpha\, n_{\mathrm{HI}}(x,z)}{1+z}\, dx$$



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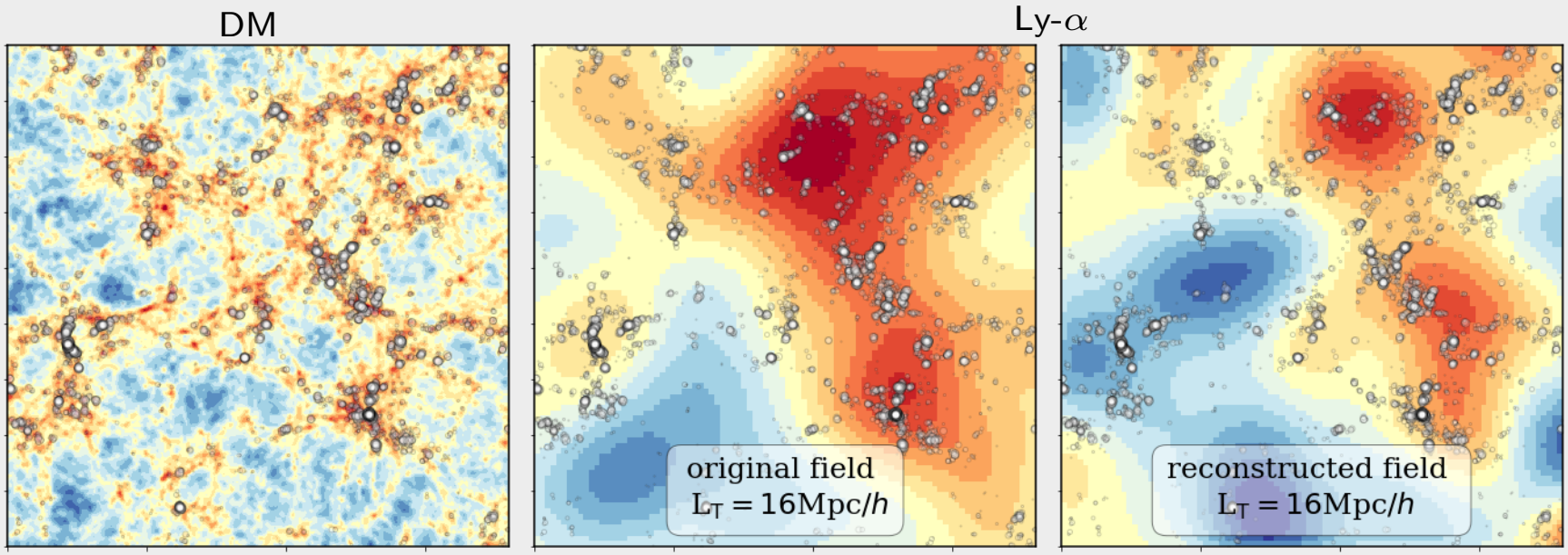
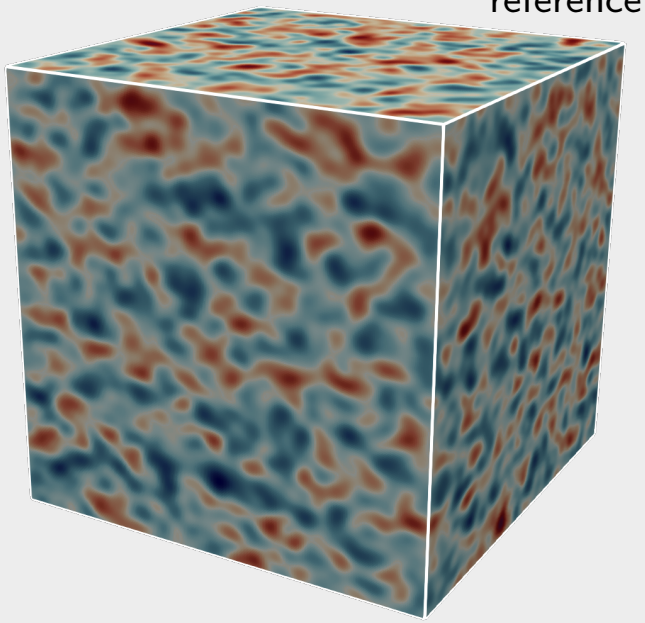
Specific WEAVE-QSO settings:

- $L_x = 2$ Mpc/h, $L_T = 16$ Mpc/h ($\mathrm{N_{QSO}/deg^2}$ from Palanque-Delabrouille et al. 2016)
- smoothing ($\sigma_x = 16$ Mpc/h, $\sigma_T = 2$ Mpc/h) $\Rightarrow$ isotropic field



Adopted configurations

reference Ly-α



Ly-α - reference field

Adopted configurations

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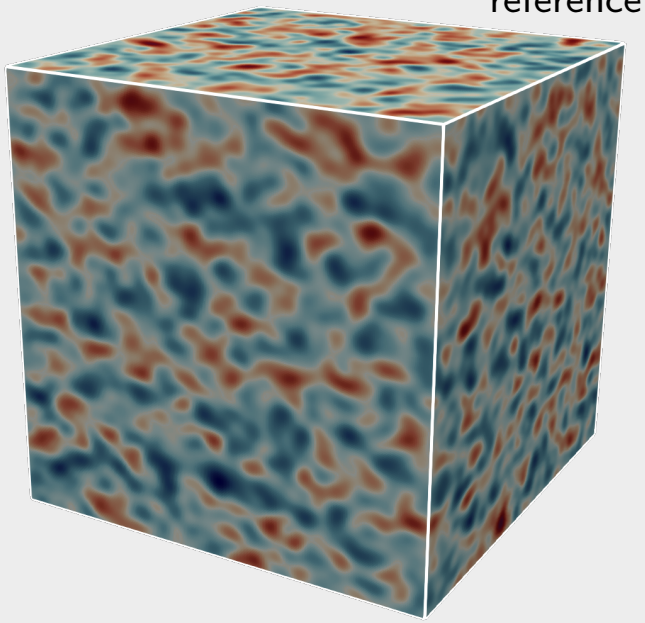
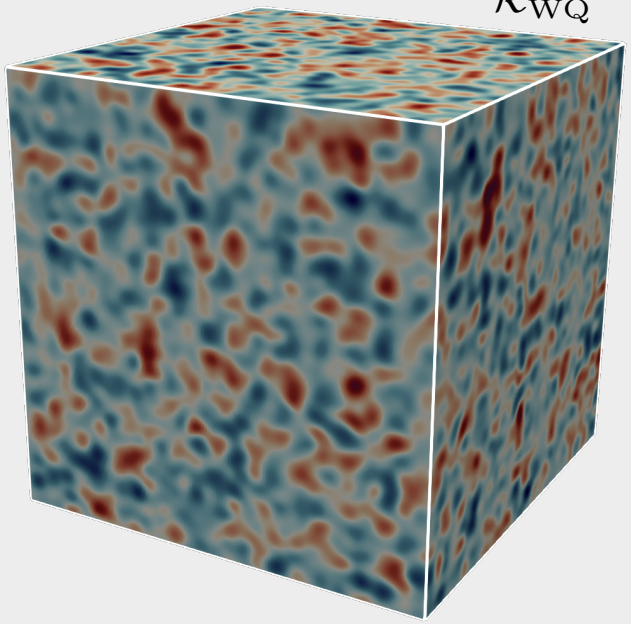


$\mathcal{R}_{\mathrm{WQ}}$

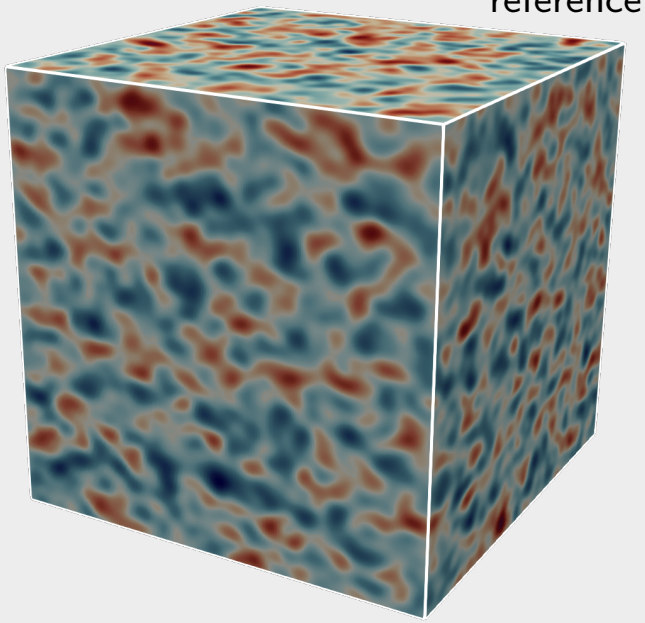


Ly-α - reference field

$\mathcal{R}_{\mathrm{WQ}}$ - random LoS distribution & noise on spectra

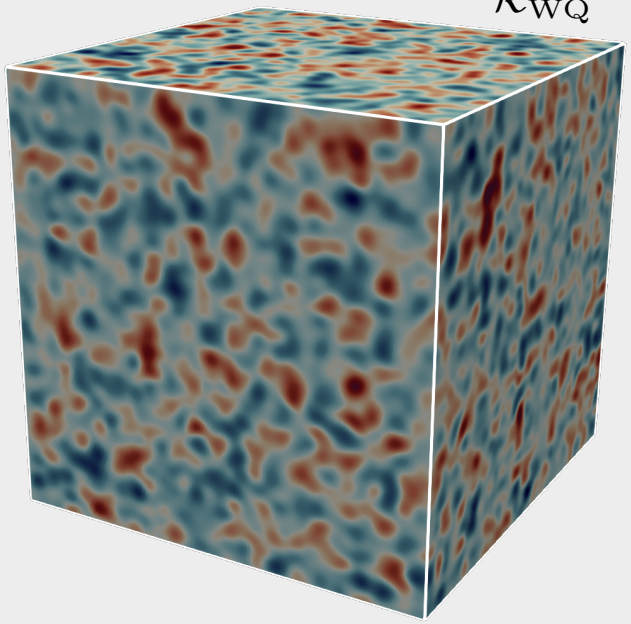
Adopted configurations

reference Ly-α

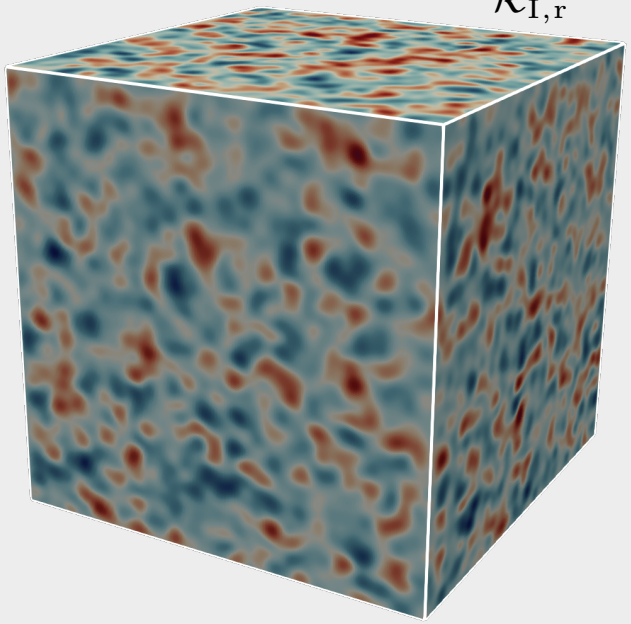


- Ly-α - reference field
- $\mathcal{R}_{\mathrm{WQ}}$ - random LoS distribution & noise on spectra
- $\mathcal{R}_{\mathrm{I,r}}$ - random LoS distribution & no noise

$\mathcal{R}_{\mathrm{WQ}}$

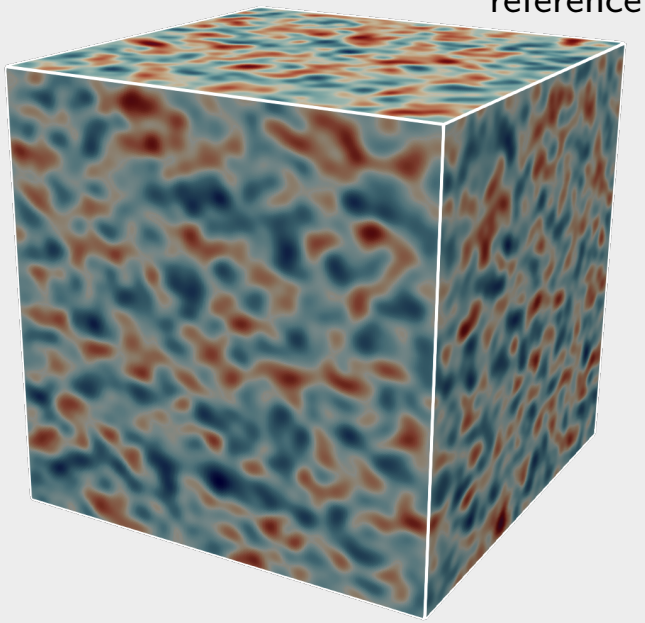


$\mathcal{R}_{\mathrm{I,r}}$



Adopted configurations

reference Ly-α



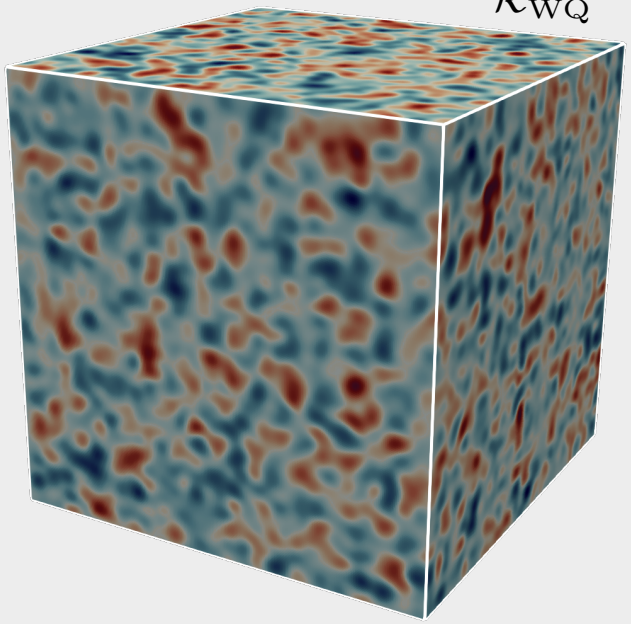
Ly-α - reference field

$\mathcal{R}_{\mathrm{WQ}}$ - random LoS distribution & noise on spectra

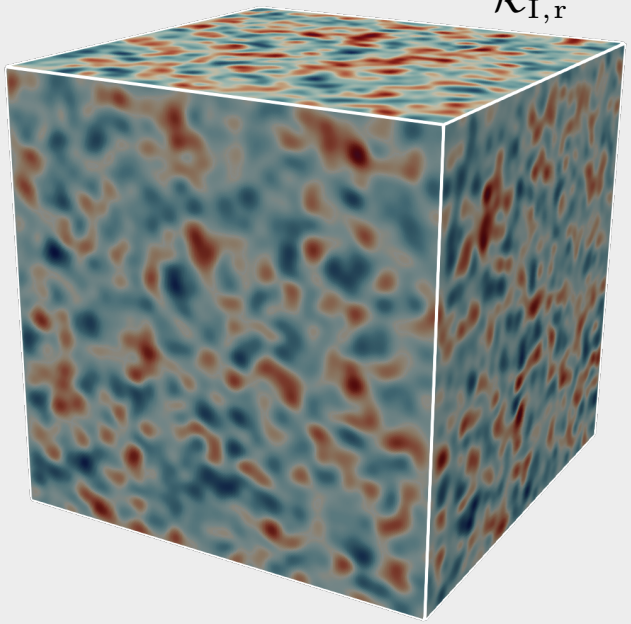
$\mathcal{R}_{\mathrm{I,r}}$ - random LoS distribution & no noise

$\mathcal{R}_{\mathrm{I,U}}$ - uniform LoS distribution & no noise

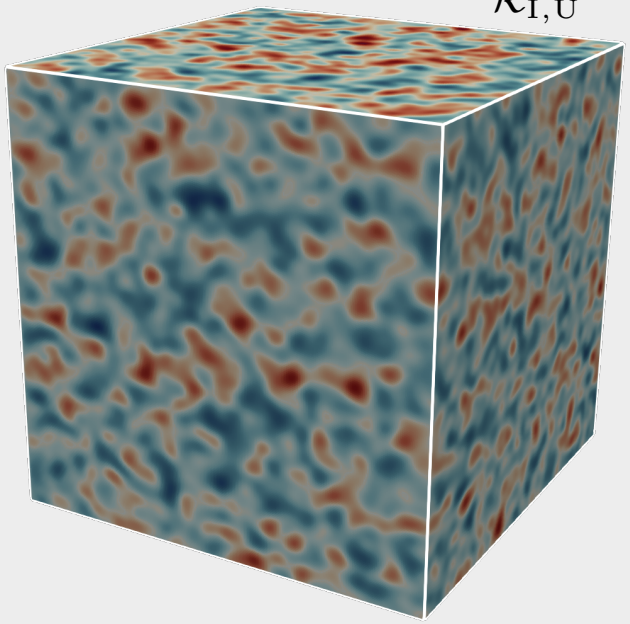
$\mathcal{R}_{\mathrm{WQ}}$



$\mathcal{R}_{\mathrm{I,r}}$

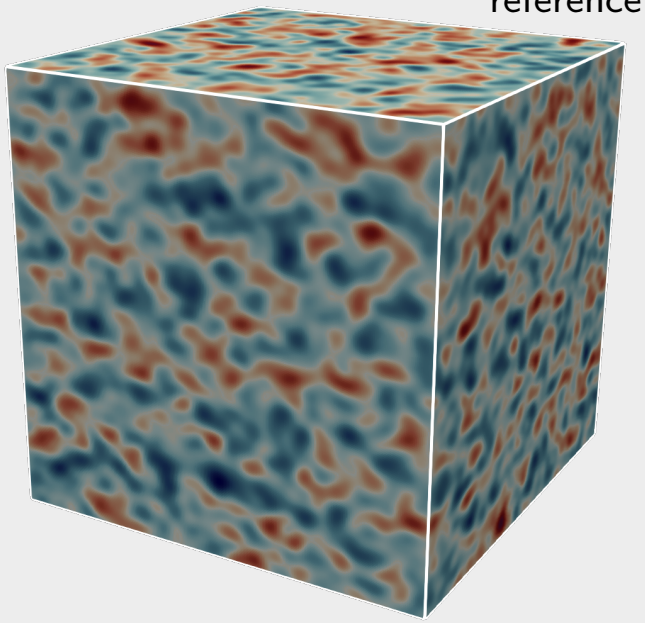


$\mathcal{R}_{\mathrm{I,U}}$



Adopted configurations

reference Ly-α



Ly-α - reference field

$\mathcal{R}_{\rm WQ}$ - random LoS distribution & noise on spectra

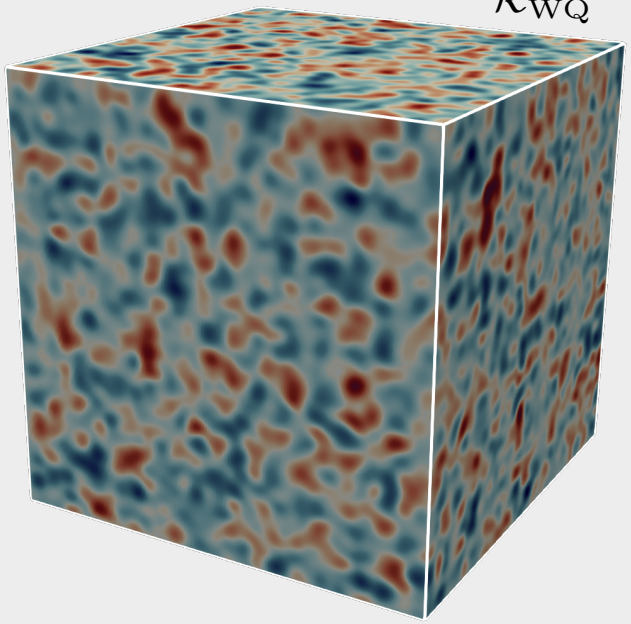
$\mathcal{R}_{\rm I,r}$ - random LoS distribution & no noise

$\mathcal{R}_{\rm I,U}$ - uniform LoS distribution & no noise

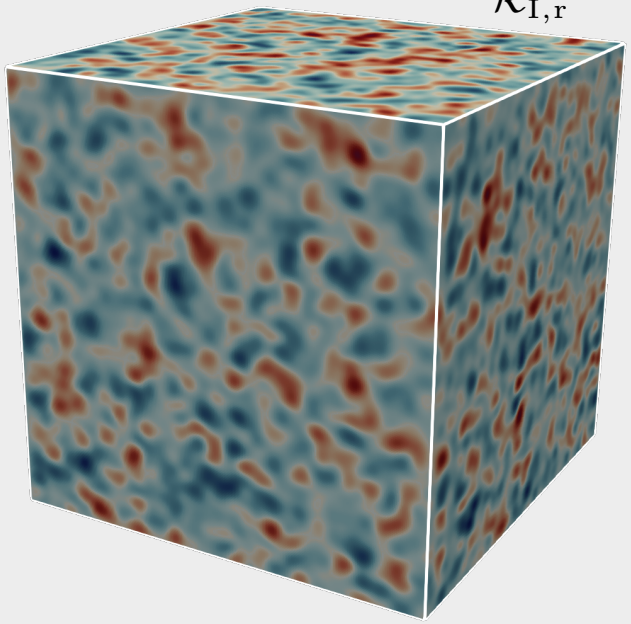
also

$\mathcal{R}_{\rm noise}$ - white Gaussian noise only

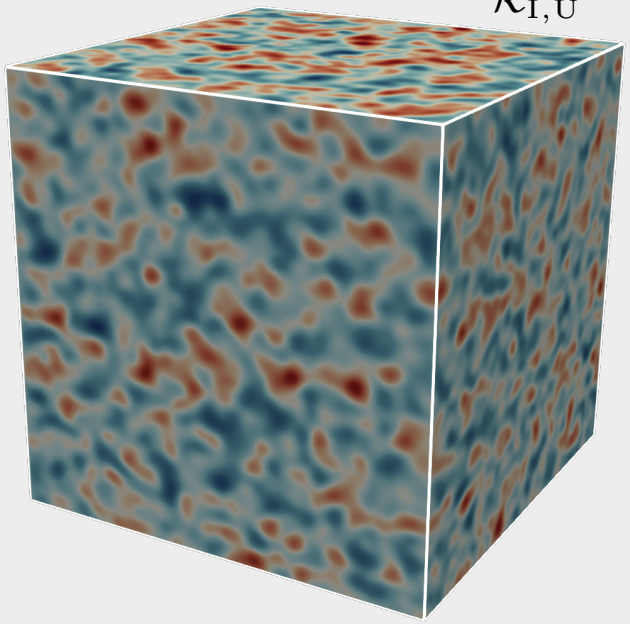
$\mathcal{R}_{\rm WQ}$



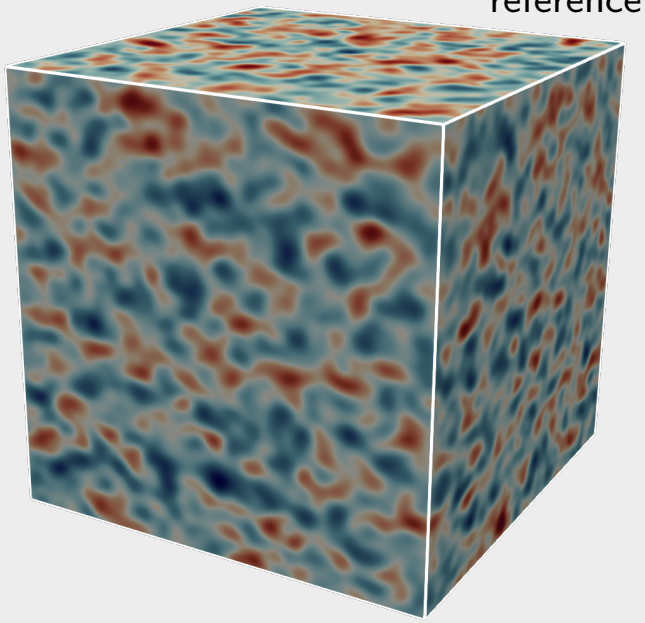
$\mathcal{R}_{\rm I,r}$



$\mathcal{R}_{\rm I,U}$



Adopted configurations



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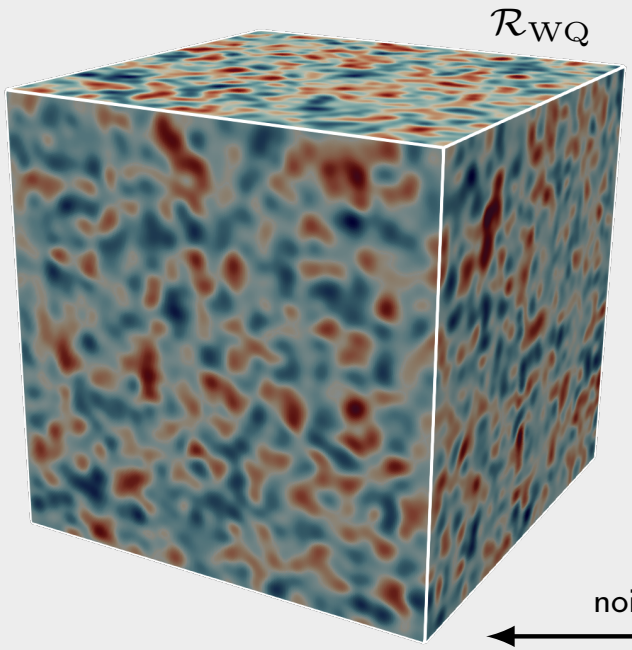
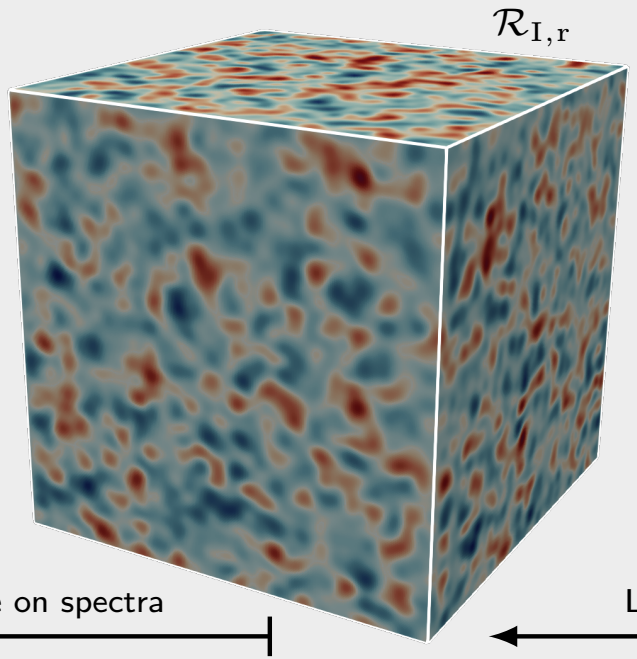
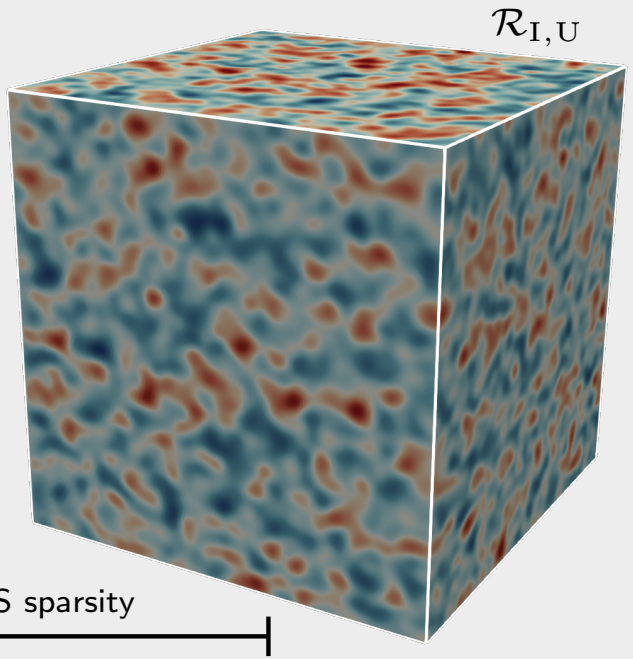
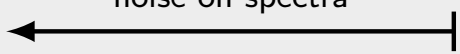
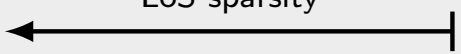




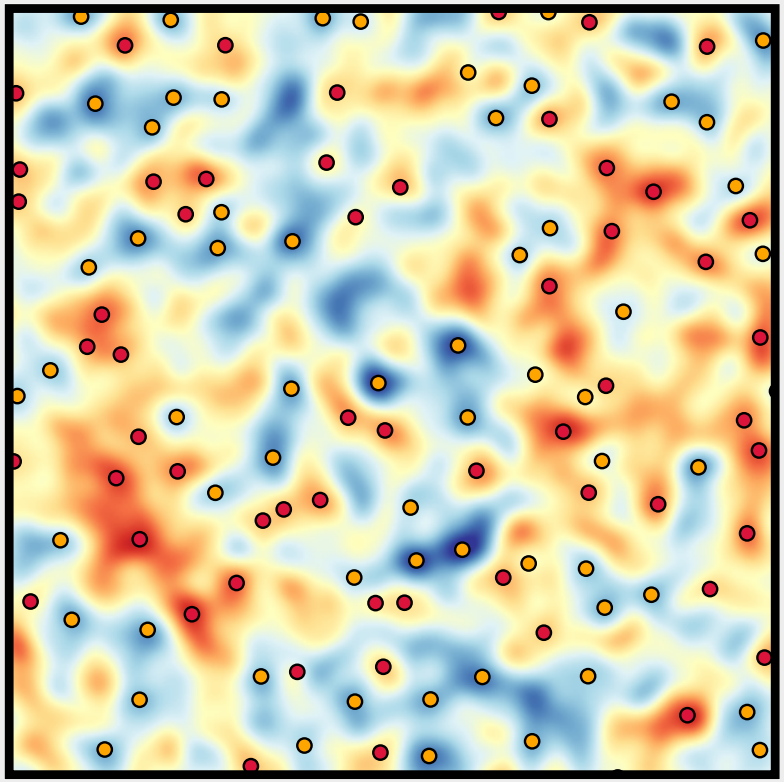






Critical points
Definitions

Peaks & Voids



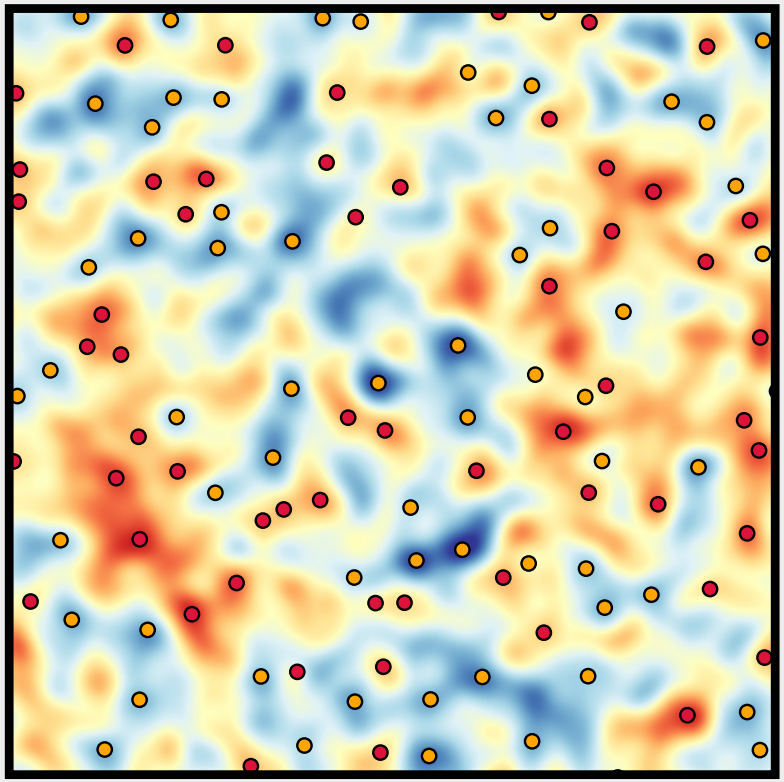
see also Shim et al. 2021 (rarity & redshift dependence)
and Shim et al. 2024 (probing cosmology)

Critical points (signature)

$\mathcal{P}$	-	$(-\ -\ -)$	. . . peaks
$\mathcal{F}$	-	$(-\ -\ +)$	. . . filaments
$\mathcal{W}$	-	$(-\ +\ +)$	. . . walls
$\mathcal{V}$	-	$(+\ +\ +)$	. . . voids

Critical points
Definitions

Peaks & Voids



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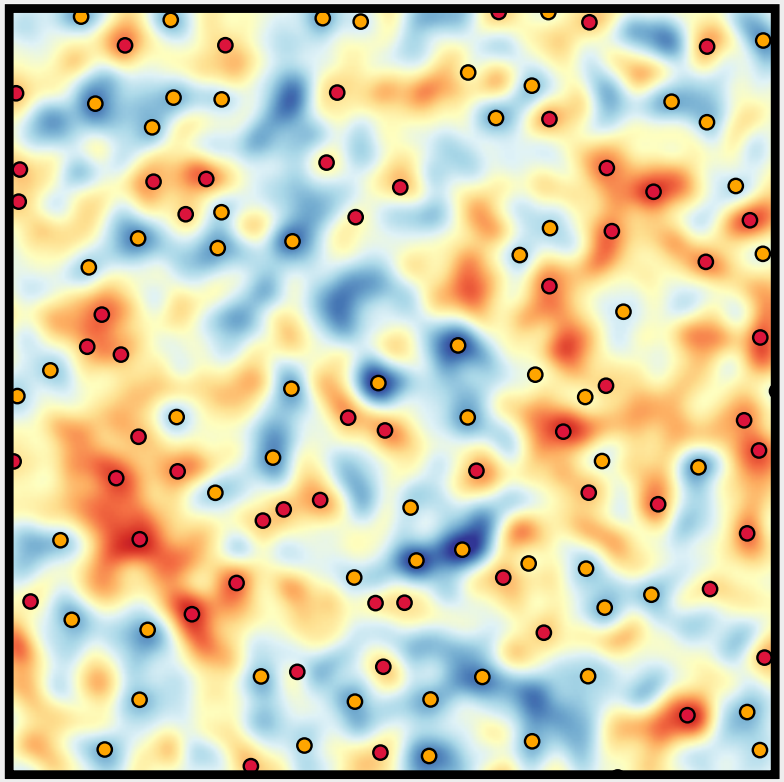
Rarity $\nu \equiv \dfrac{\delta}{\sigma} = \dfrac{\rho/\overline{\rho} - 1}{\sqrt{\langle \delta^2 \rangle}}$

Critical points
Definitions

Peaks & Voids



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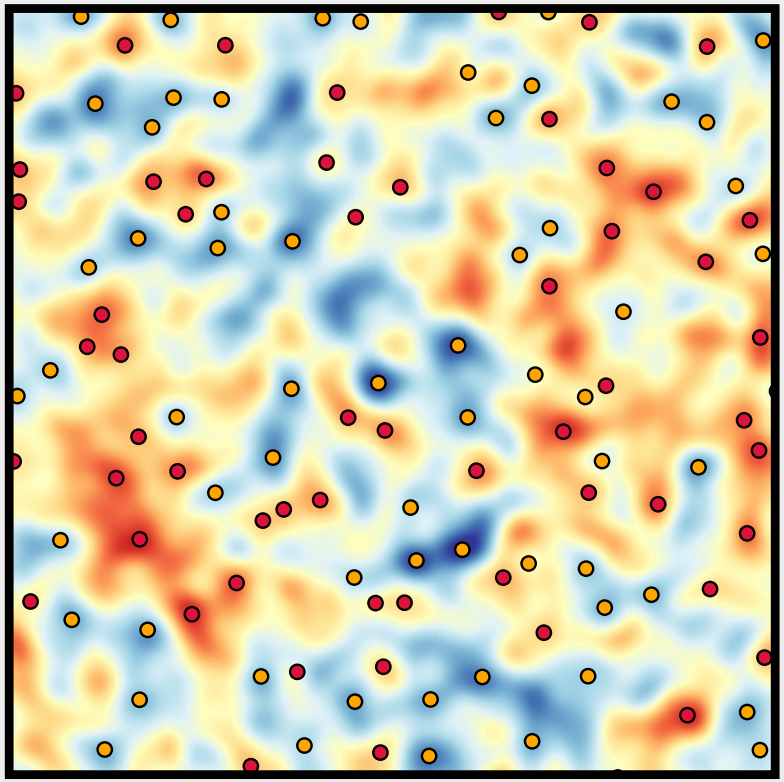
Critical points
Definitions

Peaks & Voids



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$\dfrac{N_{\rm type}(\nu \geq \nu_{\rm type,c})}{N_{\rm type}}$ ... for peaks, filaments

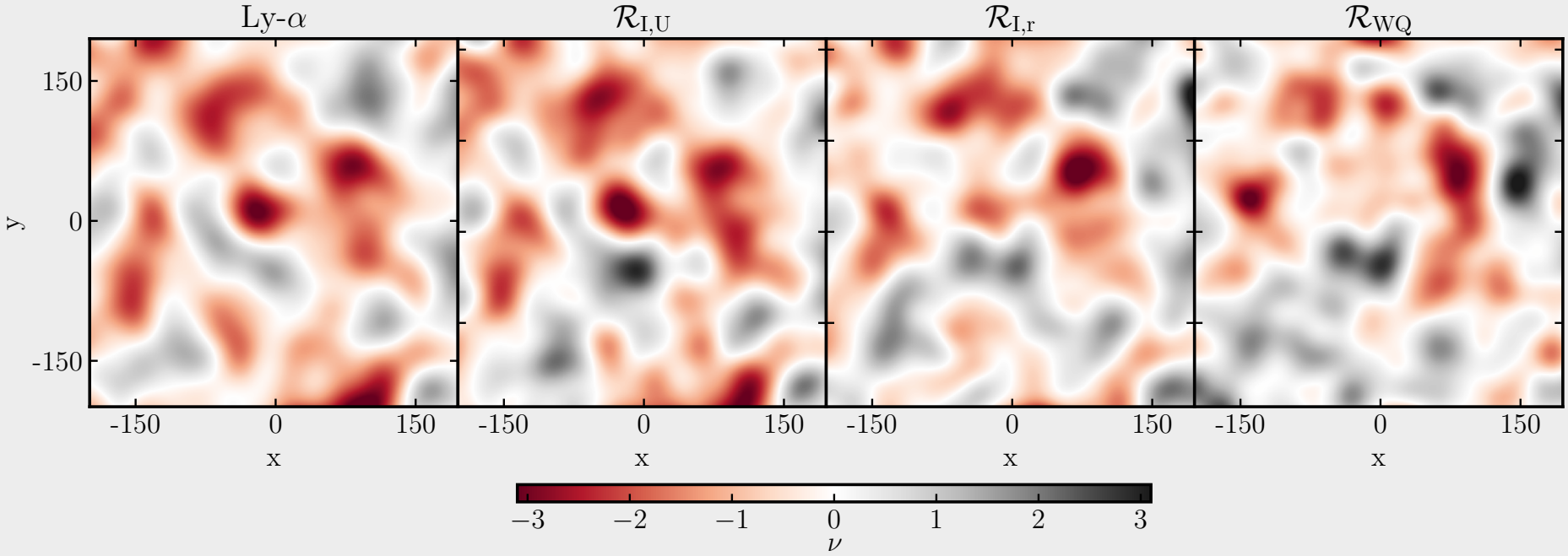
$\dfrac{N_{\rm type}(\nu \leq \nu_{\rm type,c})}{N_{\rm type}}$ ... for walls, voids

Clustering properties

$$1 + \xi_{ij}(r) = \frac{\langle C_i C_j \rangle}{\sqrt{\langle C_i R_j \rangle \langle C_j R_i \rangle}} \sqrt{\frac{N_{R_i} N_{R_j}}{N_{C_i} N_{C_j}}}$$

Davis & Peebles 1983

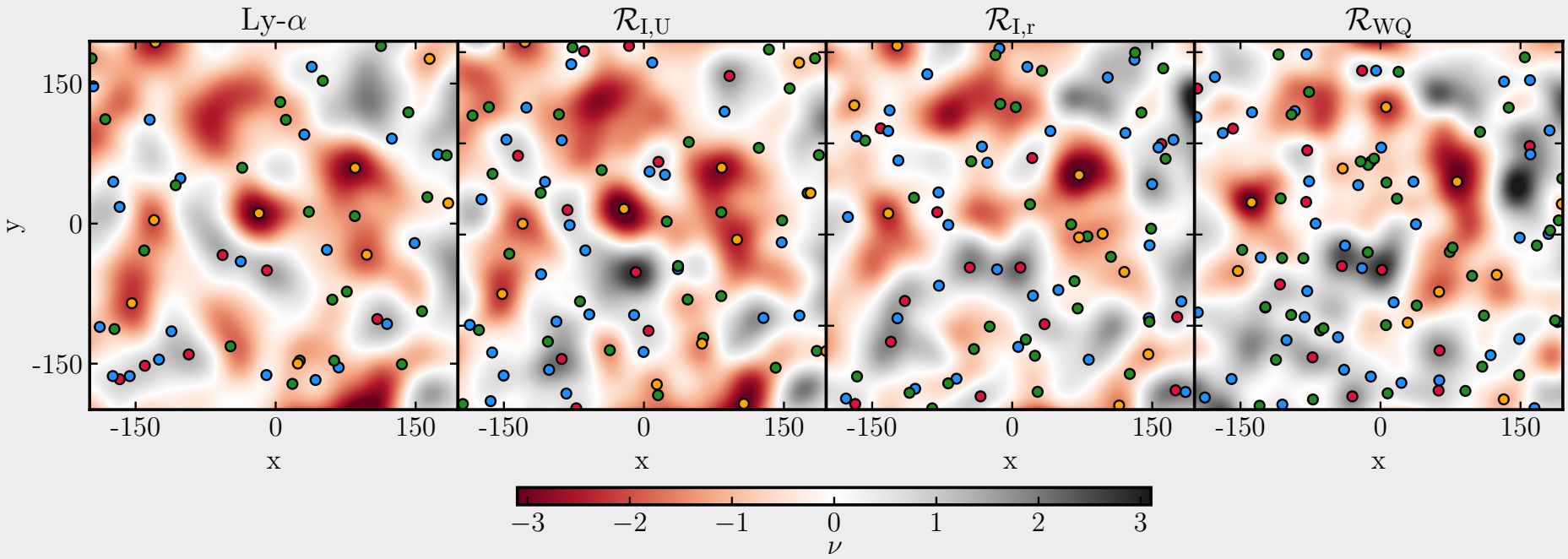
Critical points
Visual inspection



Kraljic et al. 2022

Critical points
Visual inspection

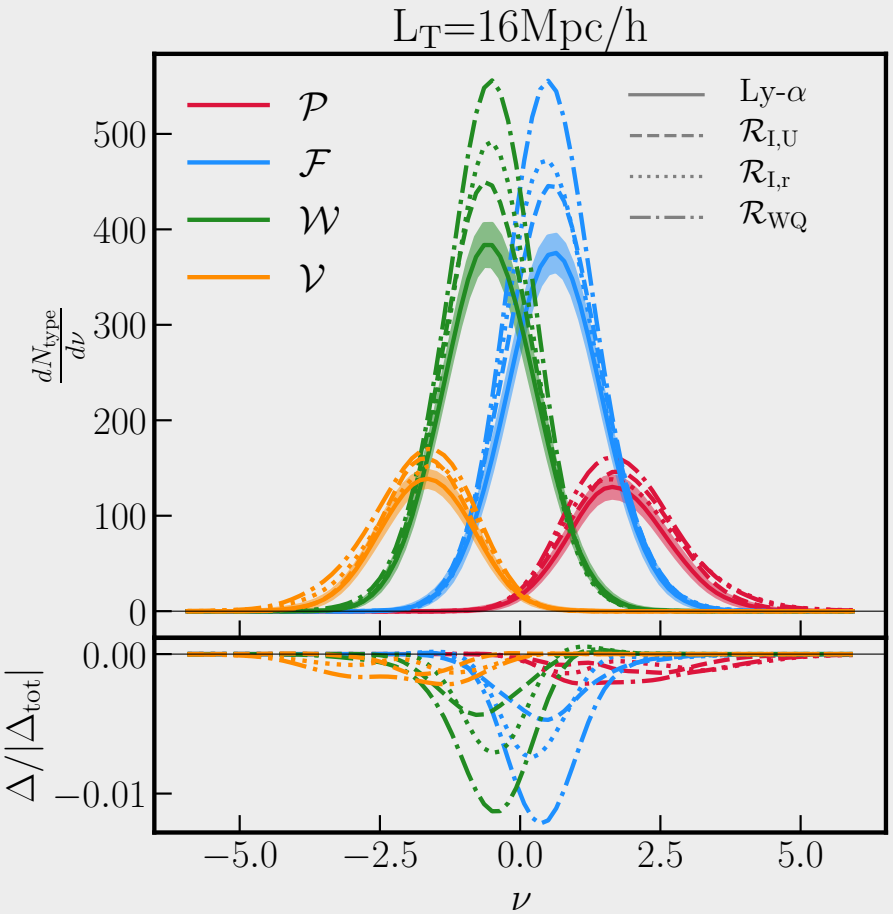
Peaks & Filaments & Walls & Voids



Kraljic et al. 2022

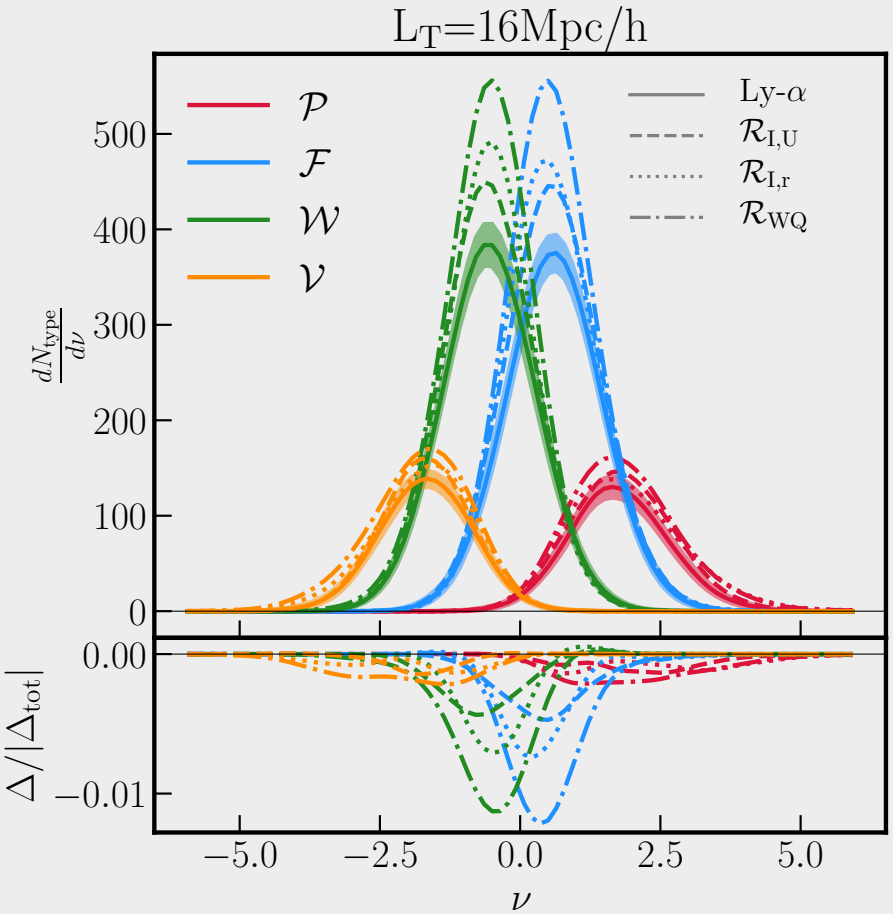
Critical points
1-point function

Absolute number counts



Critical points
1-point function

Absolute number counts



More critical points in reconstructed fields:

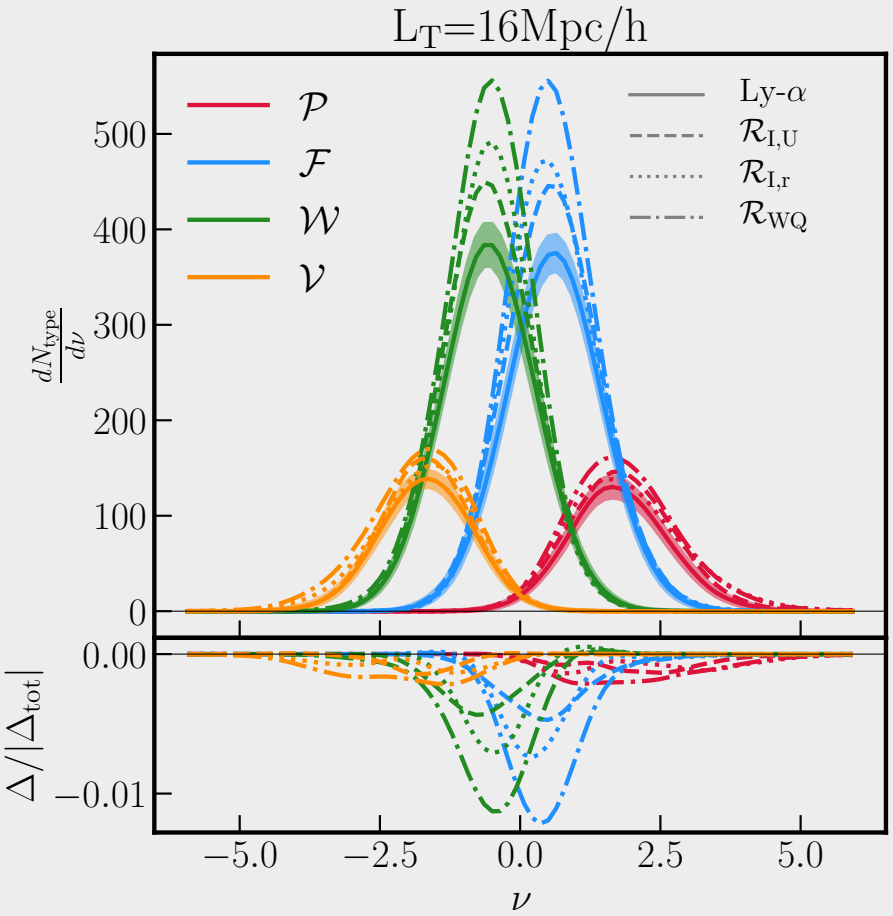
$$N_{\mathcal{R}_{I,U}} \; / \; N_{Ly-\alpha} \sim 1.15$$

$$N_{\mathcal{R}_{I,r}} \; / \; N_{Ly-\alpha} \sim 1.19$$

$$N_{\mathcal{R}_{WQ}} \; / \; N_{Ly-\alpha} \sim 1.35$$

Critical points
1-point function

Absolute number counts



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Preserved (for all fields):

$$\mathcal{F}/\mathcal{P} \; (\mathcal{W}/\mathcal{V}) \sim 3$$

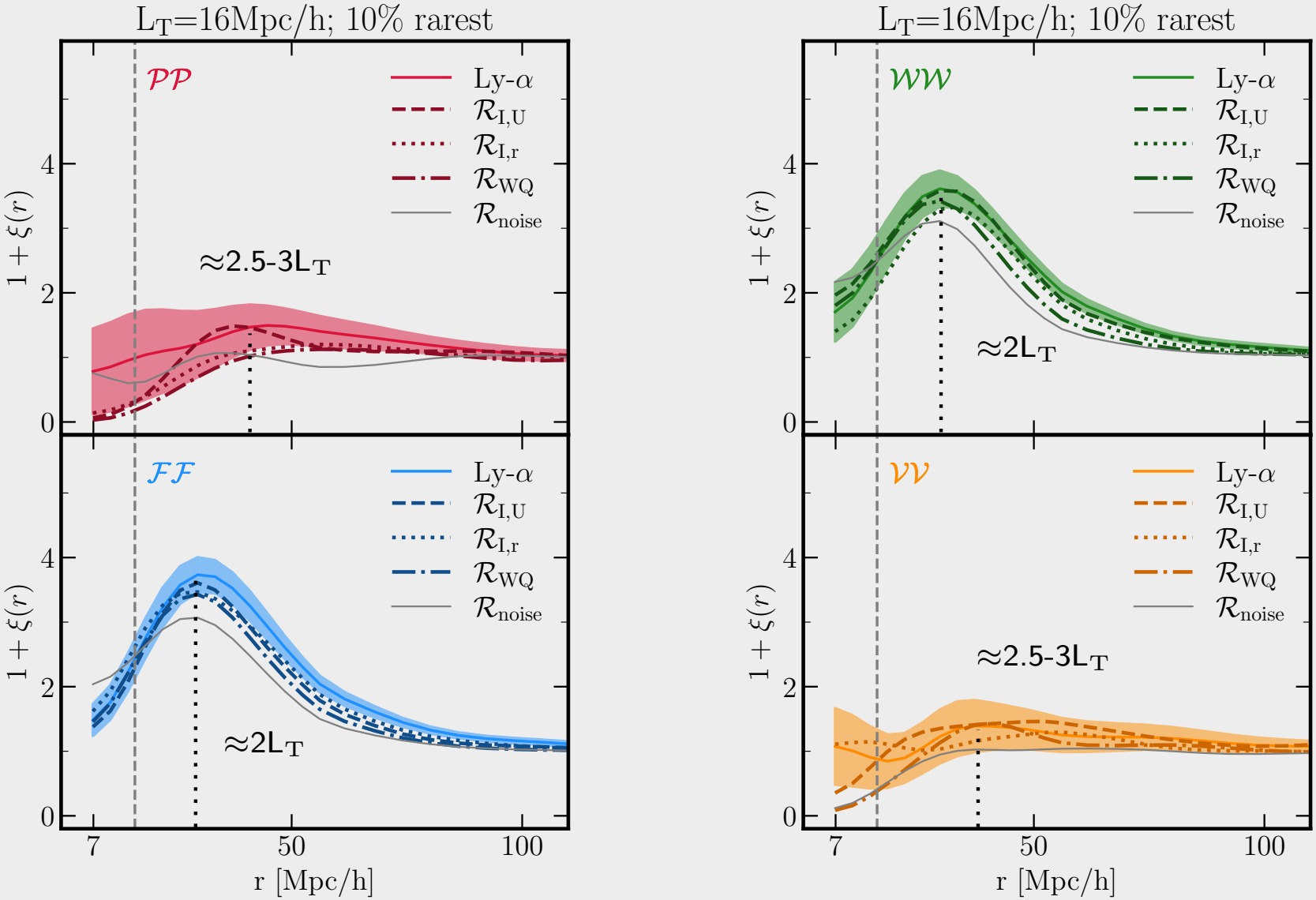
all extrema/all saddles

$$(\mathcal{P}+\mathcal{W})/(\mathcal{F}+\mathcal{V}) \sim 1$$

Quality of the reconstruction

Critical points

2-point function: Auto-correlations



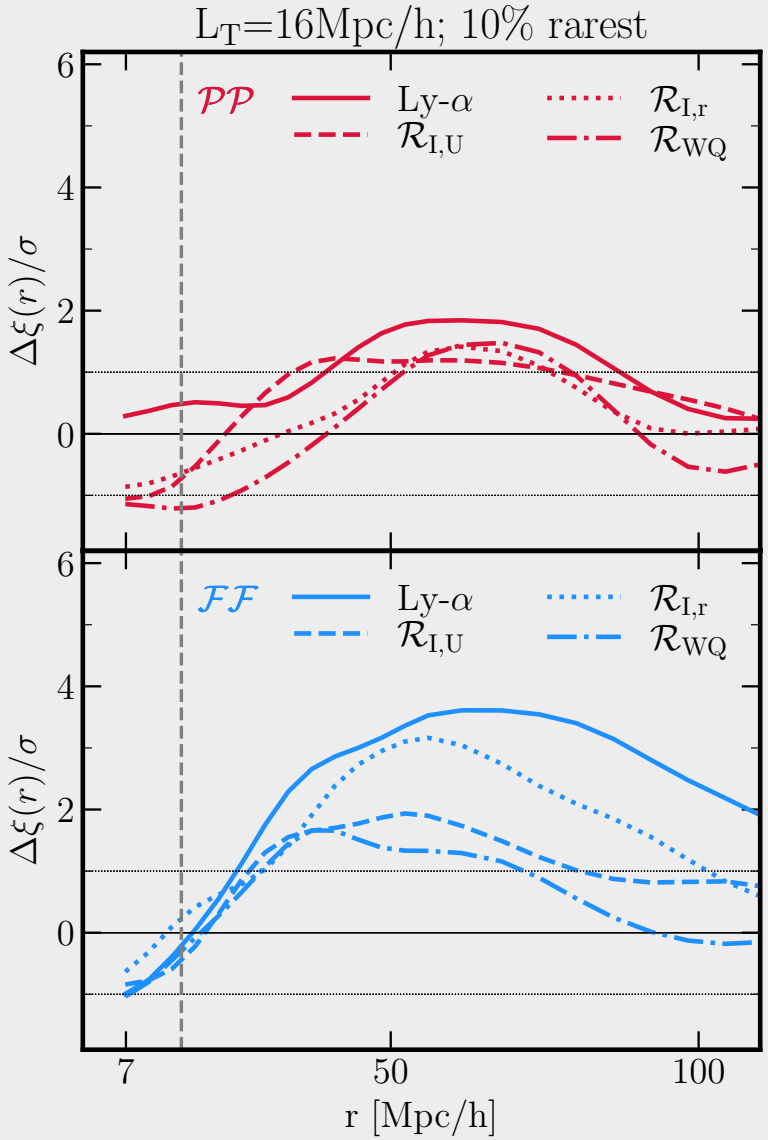
1/ **anti-clustering** at small r; 2/ positive & **maximum**; 3/ **decrease** towards 0 at large r

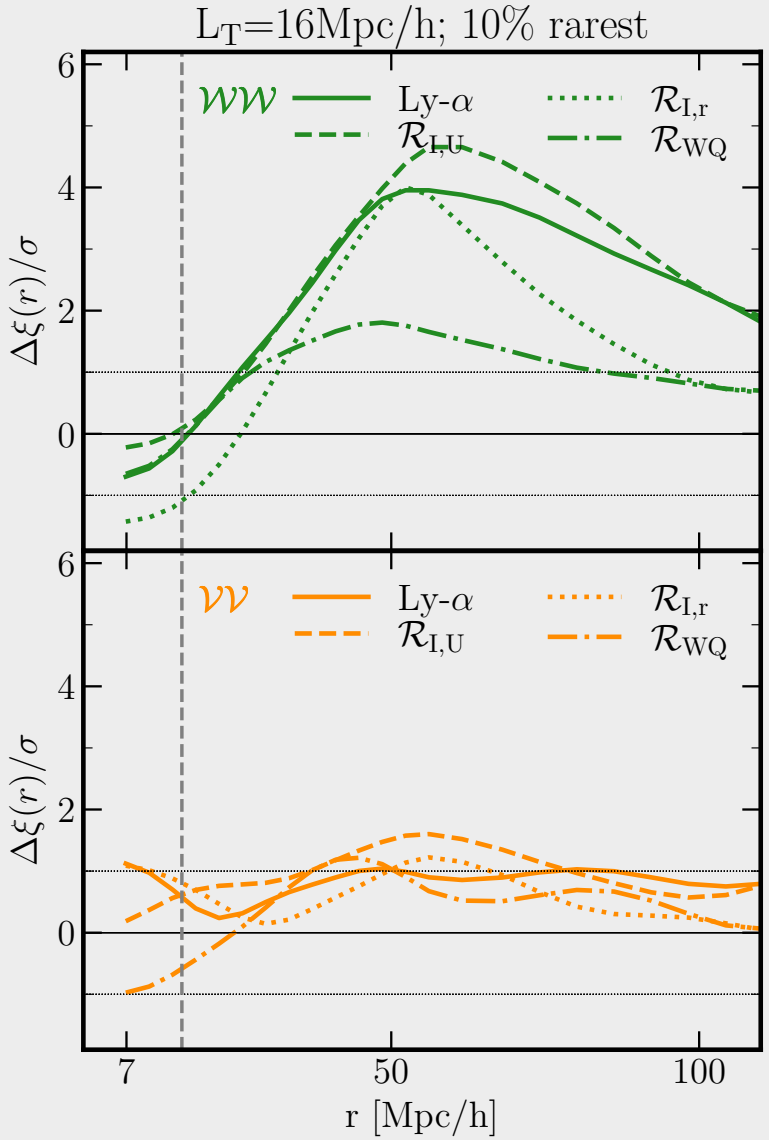
Quality of the reconstruction

Critical points

2-point function: Auto-correlations

Differences w.r.t. the noise-only field



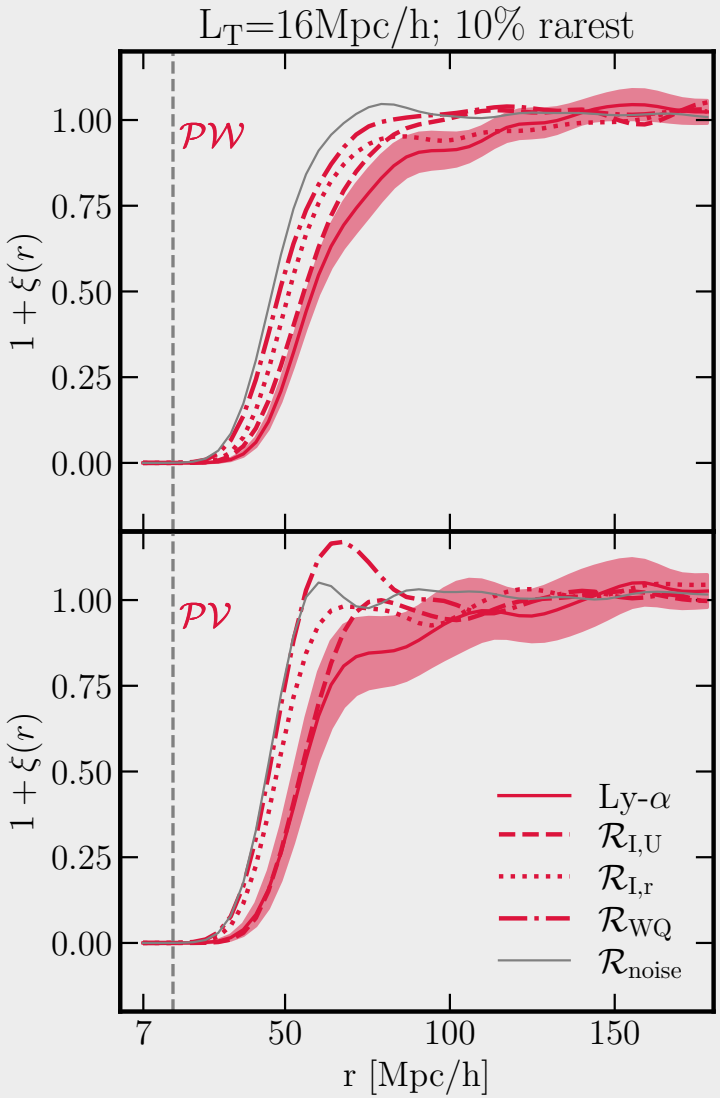


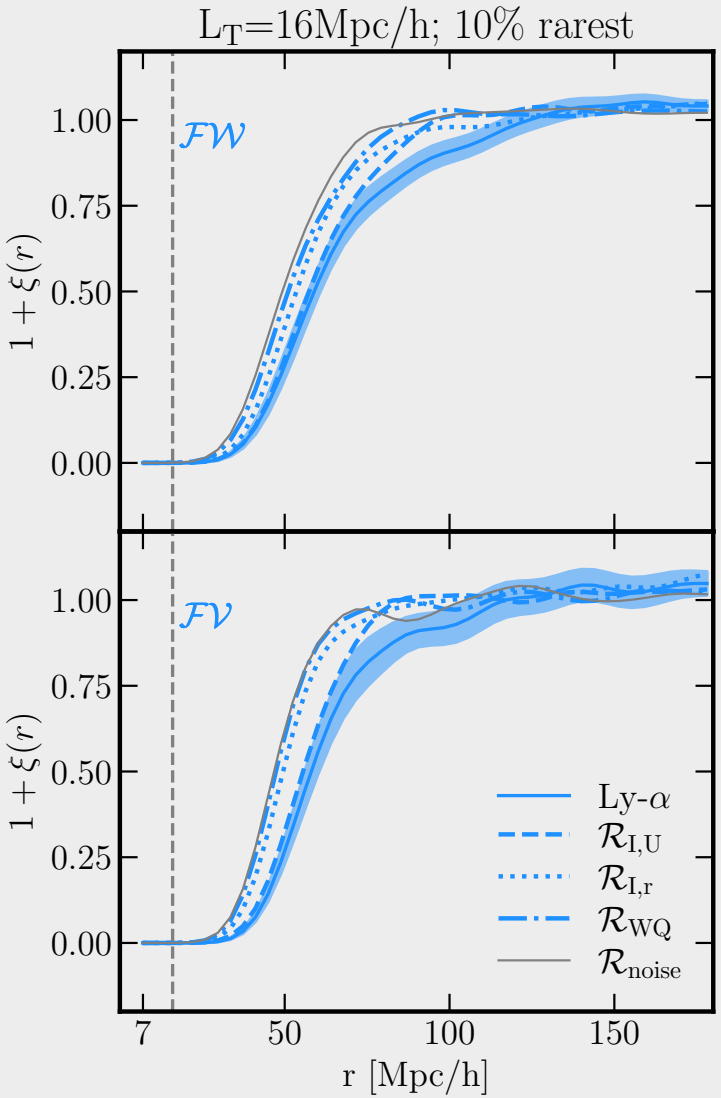
Quality of the reconstruction

Critical points

2-point function: Cross-correlations

Over & **under**-dense critical points





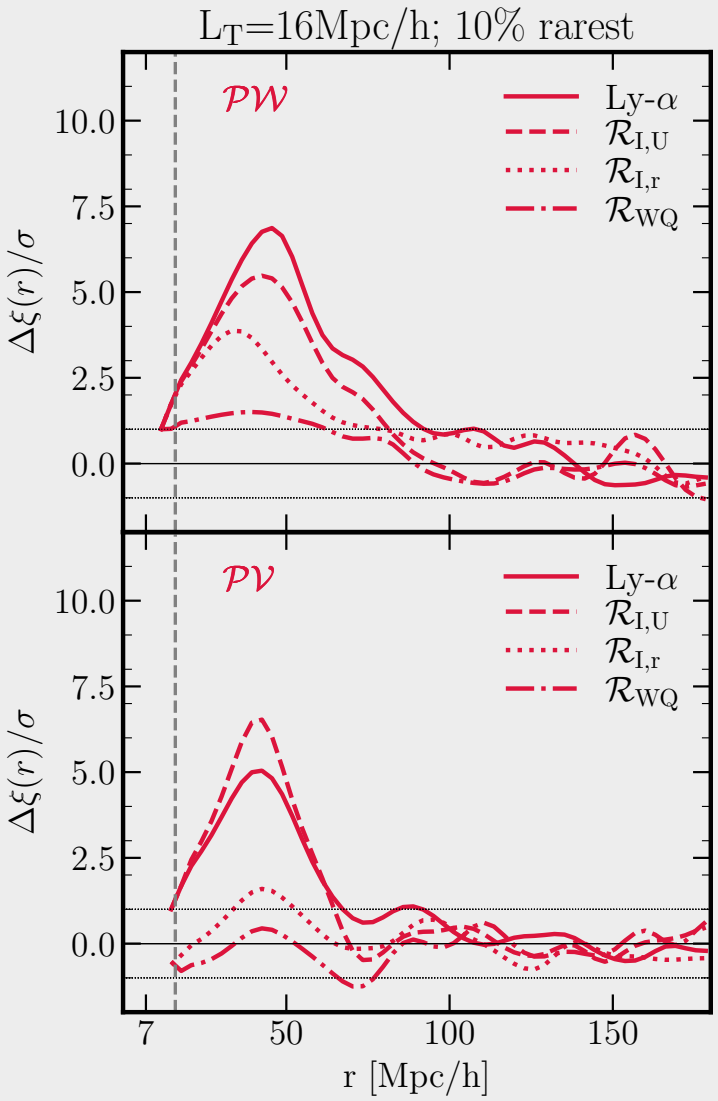
1/ **exclusion zone** at small r; 2/ monotonic increase & **no maximum**; 3/ **anticlustered** at all r

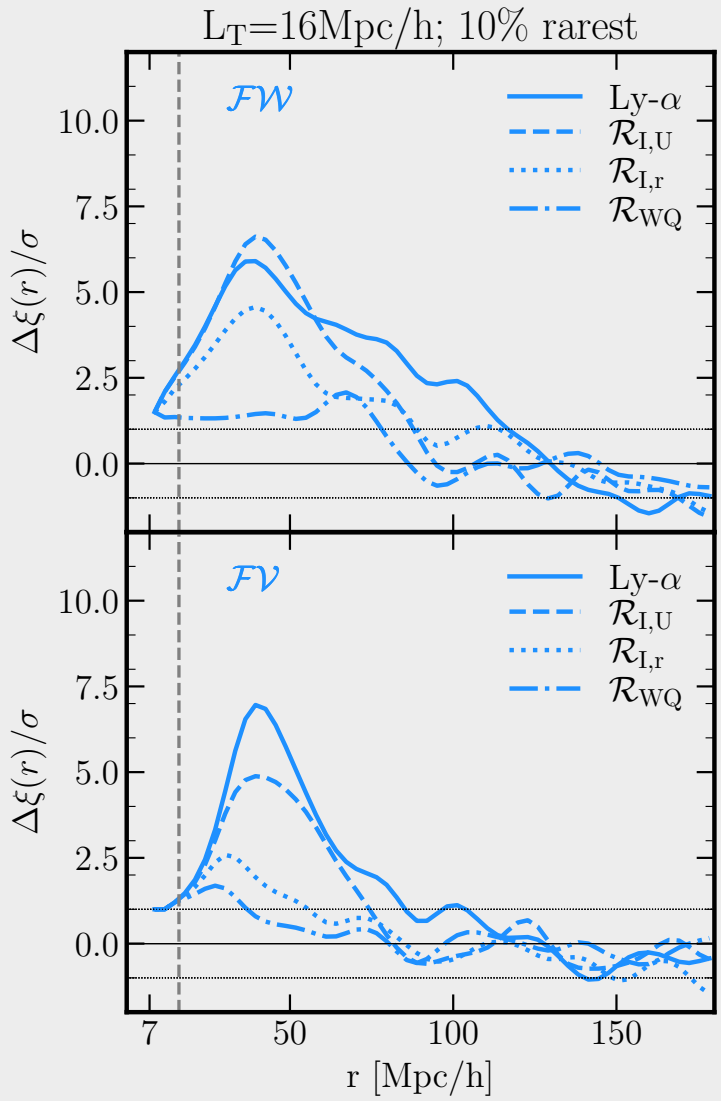
Critical points

2-point function: Cross-correlations

Over & **under**-dense critical points

Differences w.r.t. the noise-only field





Quality of the reconstruction

Critical points

2-point function: Cross-correlations

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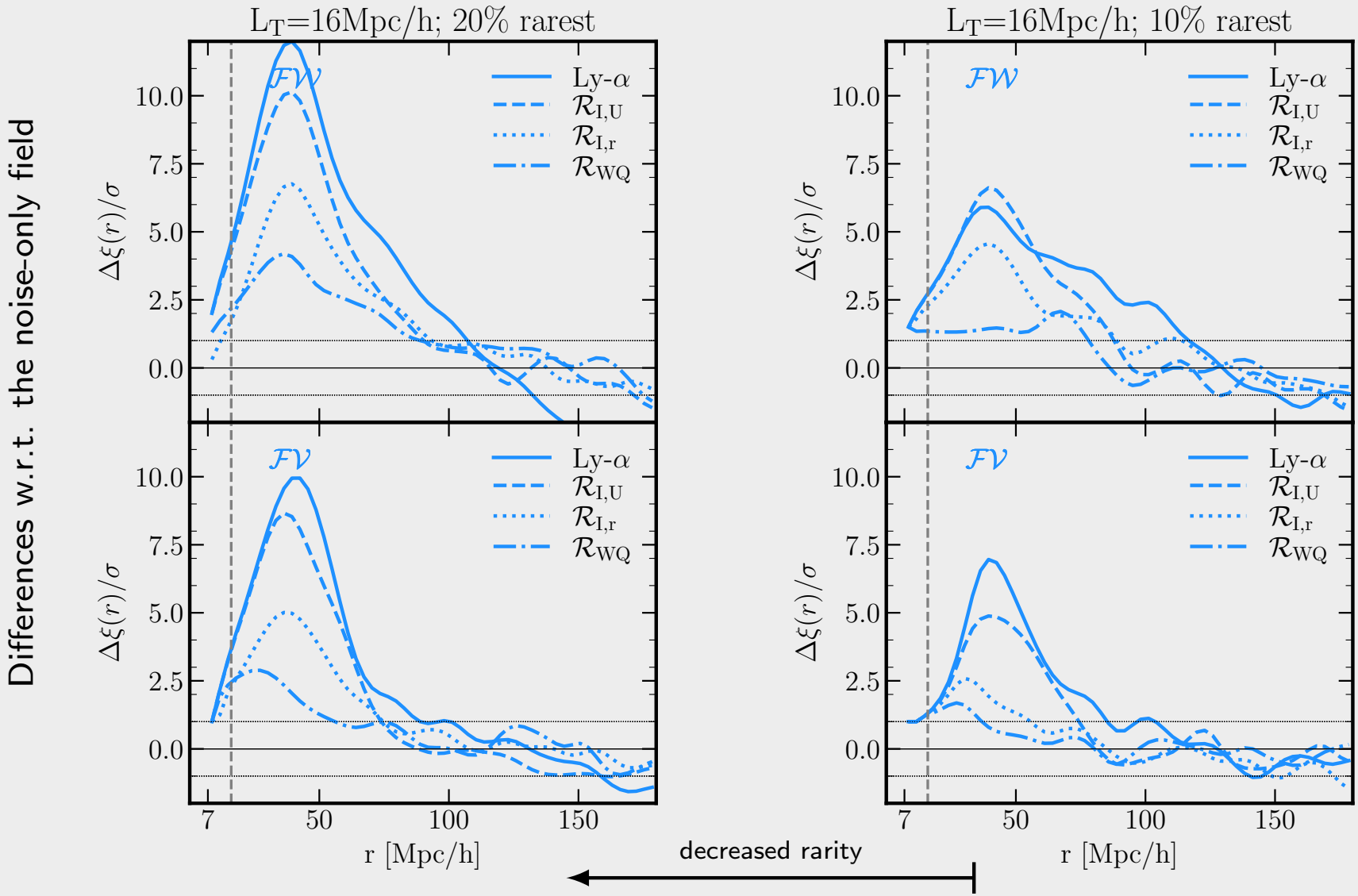


Critical points

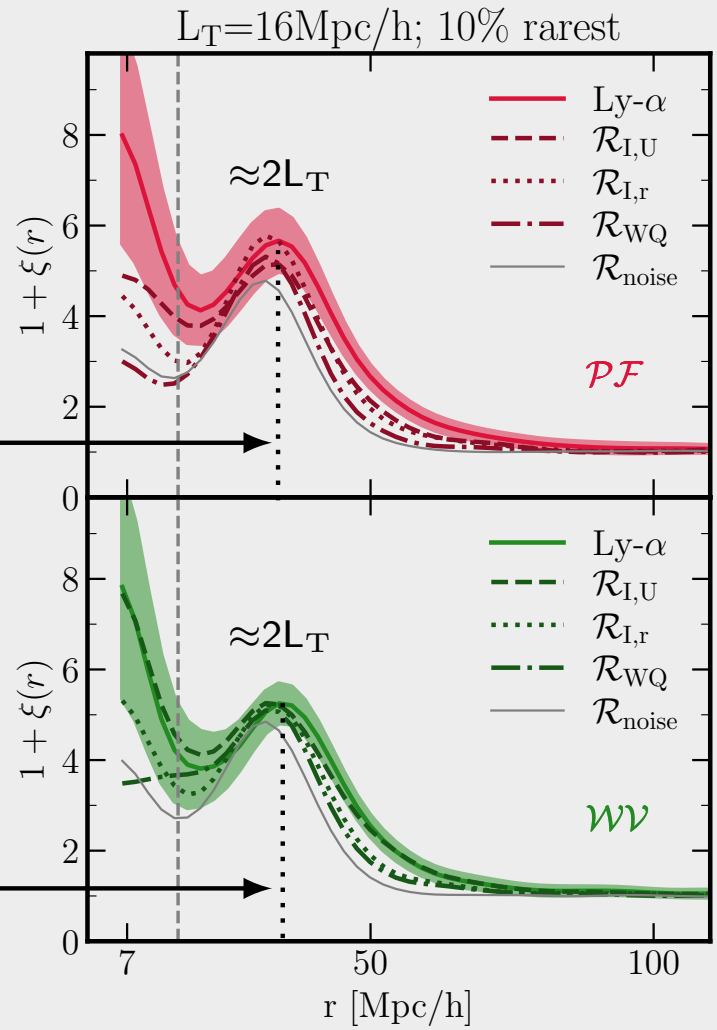
2-point function: Cross-correlations

Same over-density sign critical points

Geometrical properties of the Cosmic web:

typical filament length/2

typical void size/radius



1/ **divergence** at small r; 2/ local **maximum**; 3/ **decrease** toward 0 at large r

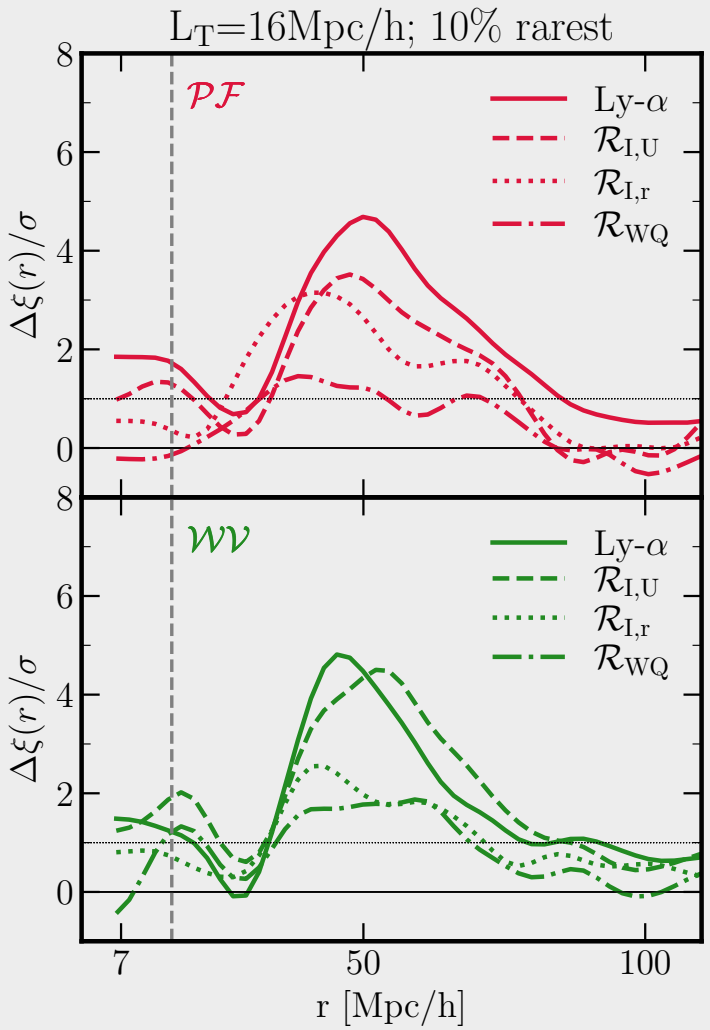
Quality of the reconstruction

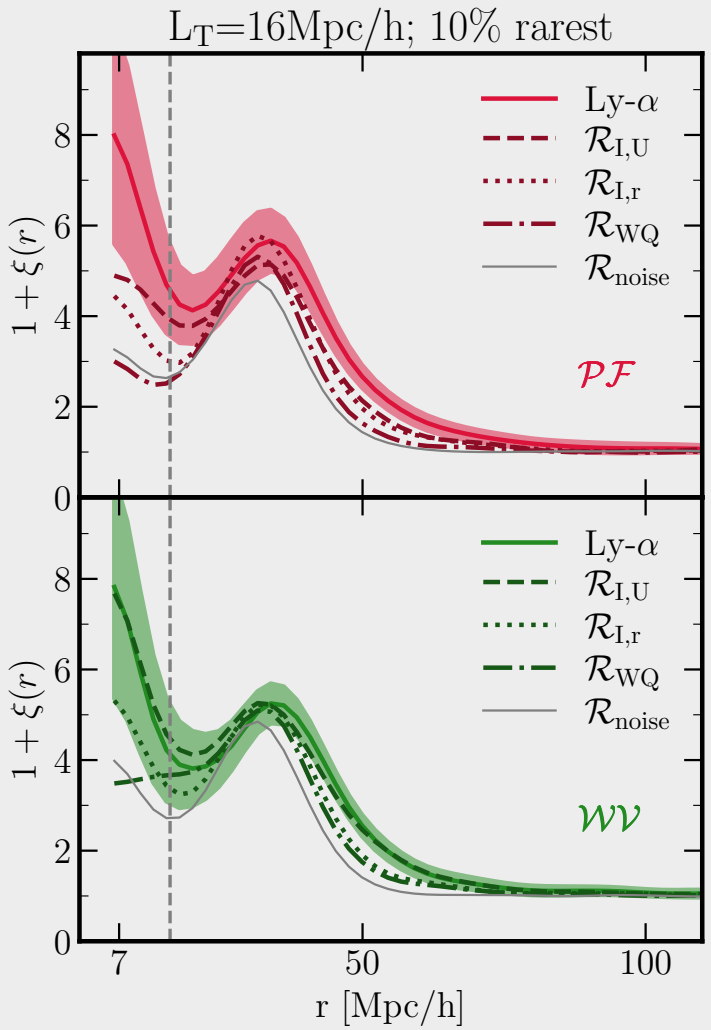
Critical points

2-point function: Cross-correlations

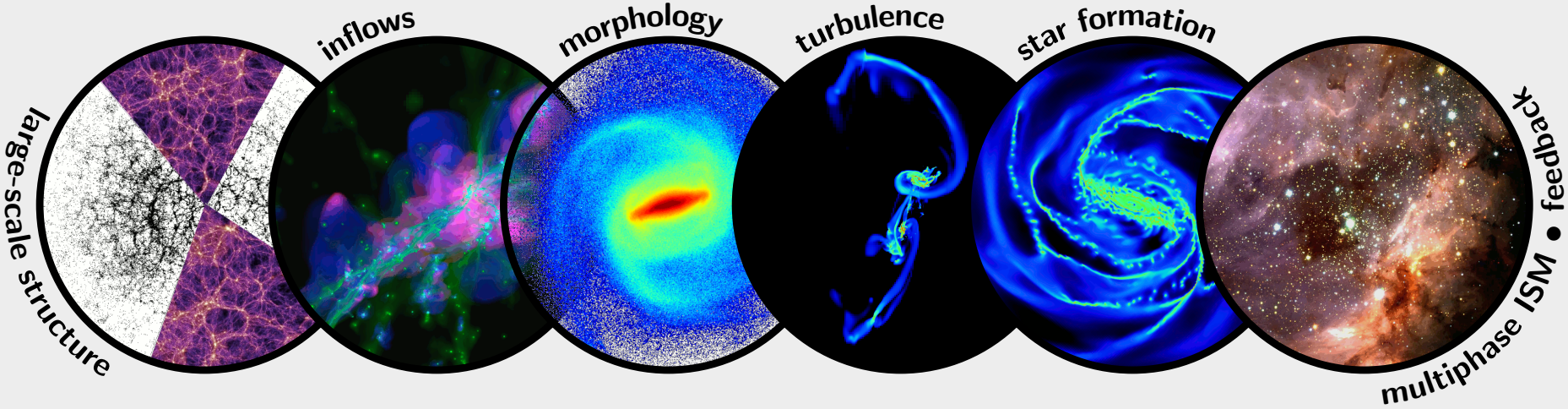
Same over-density sign critical points

Differences w.r.t. the noise-only field

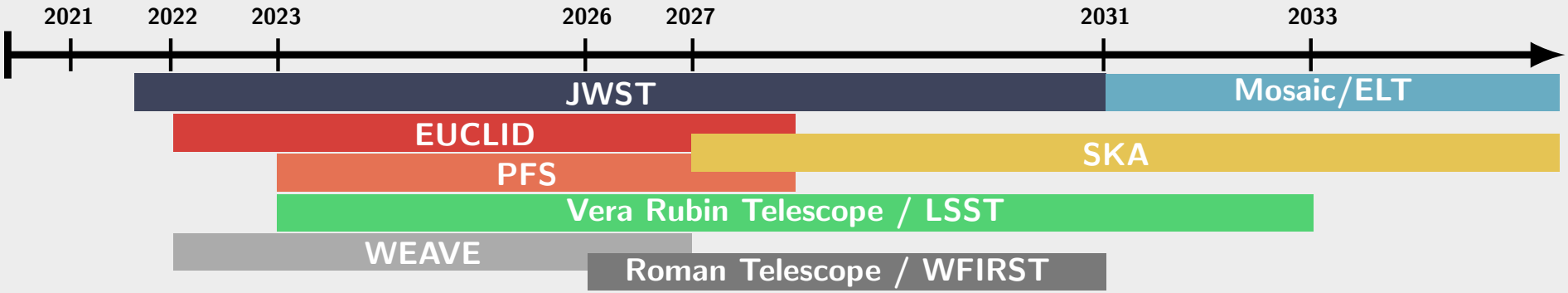




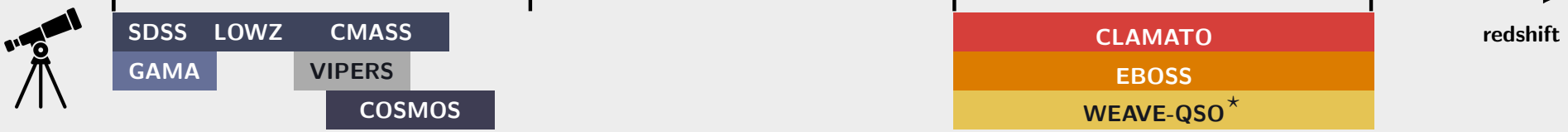
Understanding galaxy evolution as a full multi-scale baryon cycle



The full picture of structure formation can only be revealed by studying its physics over a broad range of scales over the next decade

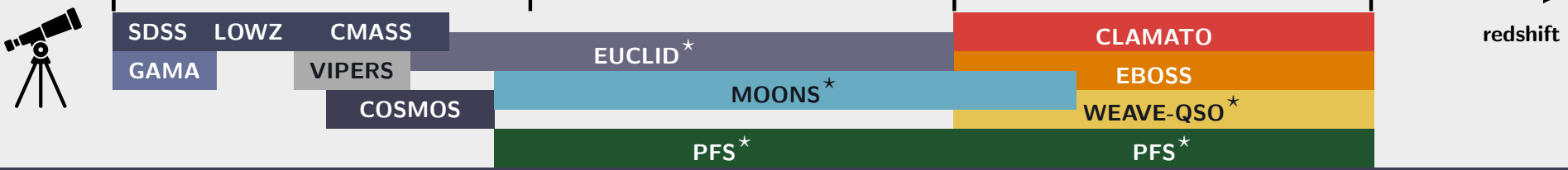


The Multi-scale Universe



Tojeiro & Kraljic 2025

The Multi-scale Universe



Tojeiro & Kraljic 2025

The Multi-scale Universe