Untangling the Cosmic Web

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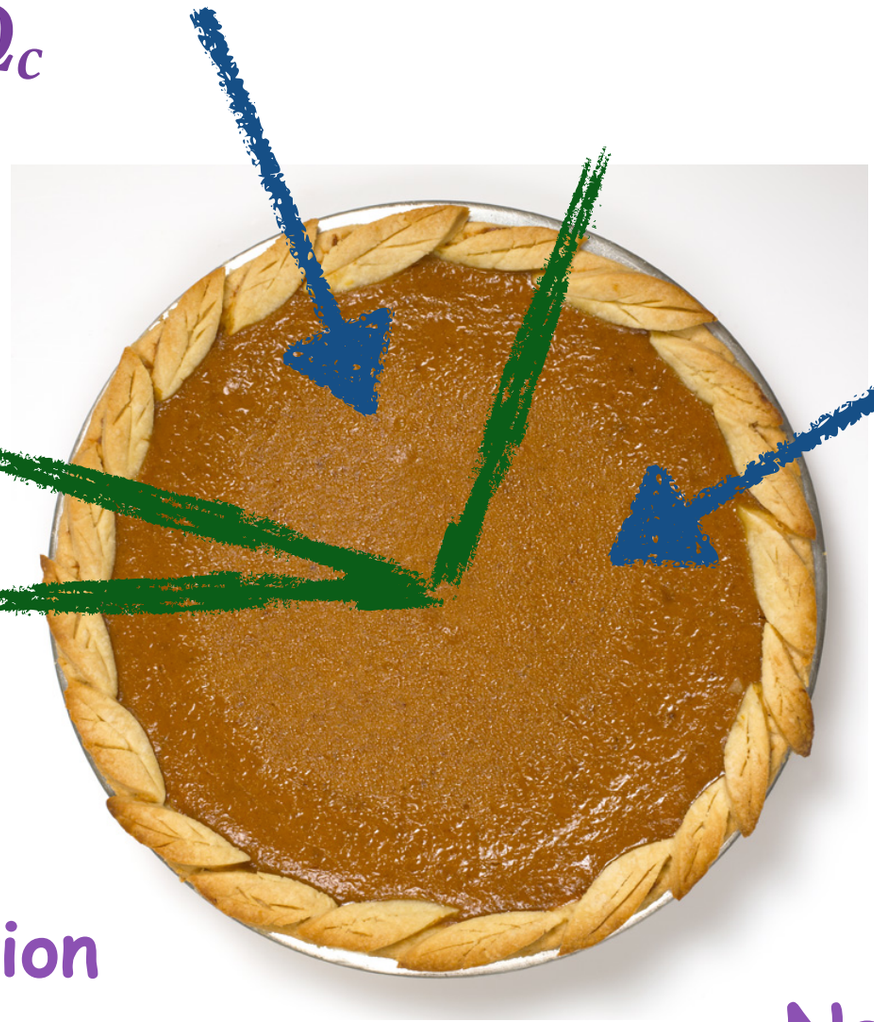
(in collaboration with Oliver Hahn, Ravi Sheth, ***Sujatha Ramakrishnan****, Shadab Alam,* ***Bhaskar Arya****)*

Standard Model of Cosmology

Matter
(cold, dark)
Ω_c

Energy
(dark, constant)
Ω_Λ

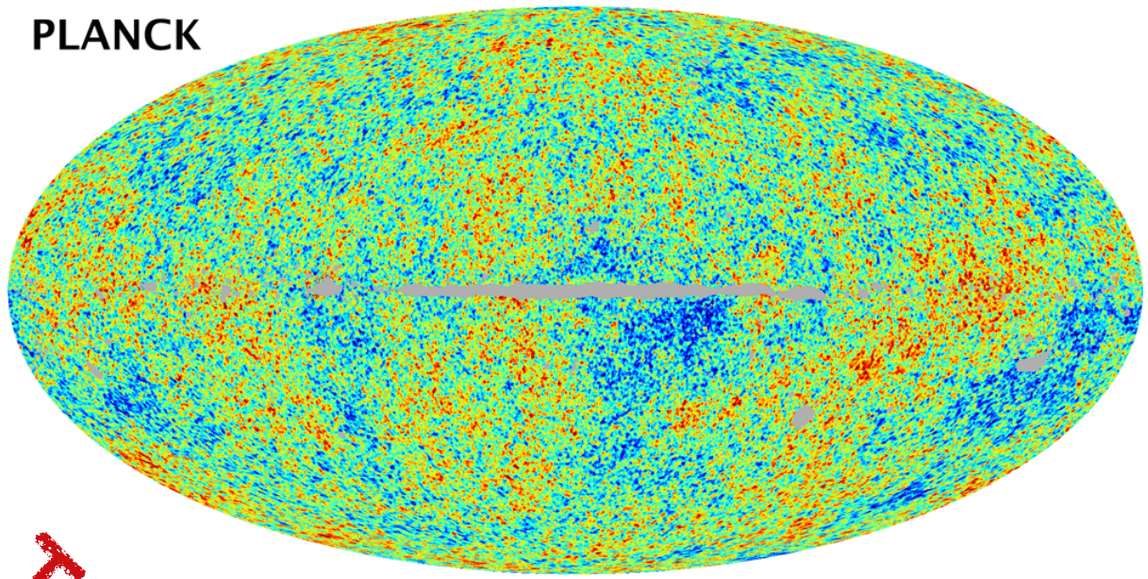


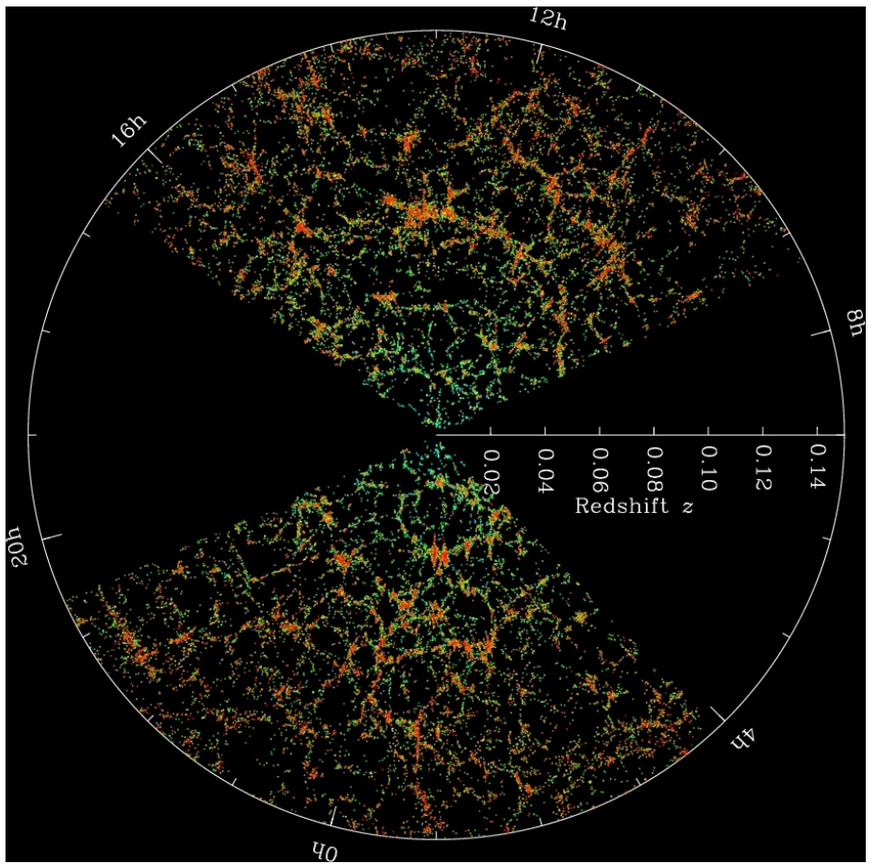
Baryons
Ω_b

Garnish with radiation
Ω_r

Neutrinos to taste
Ω_ν

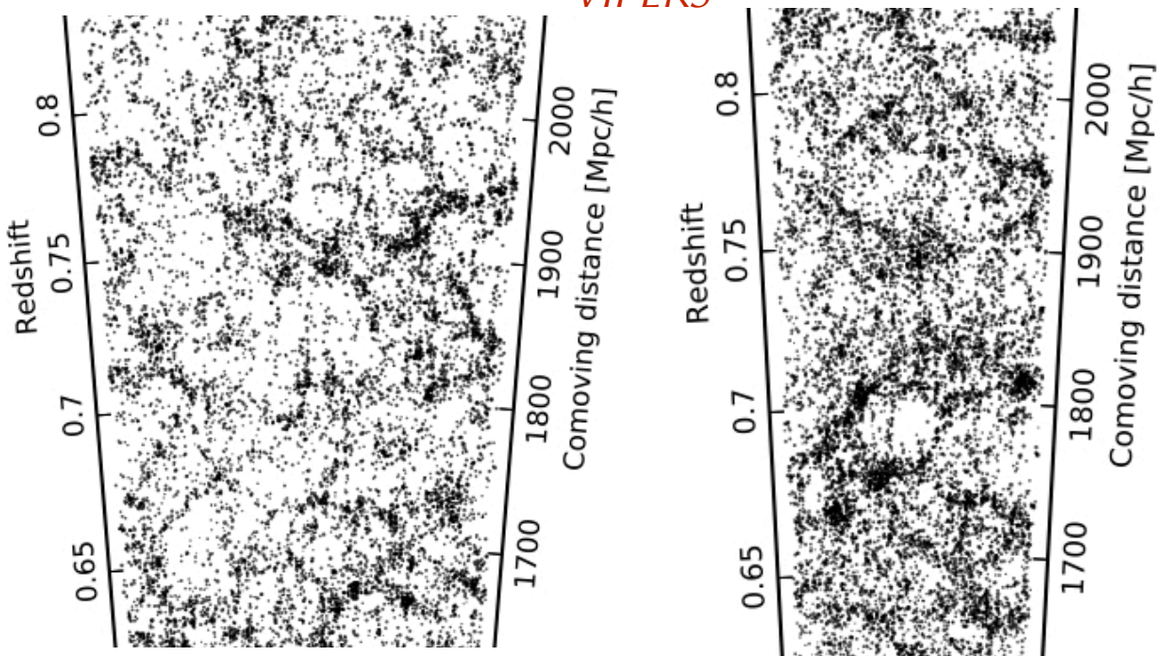
Growth of Structure





Sloan Digital Sky Survey

VIPERS



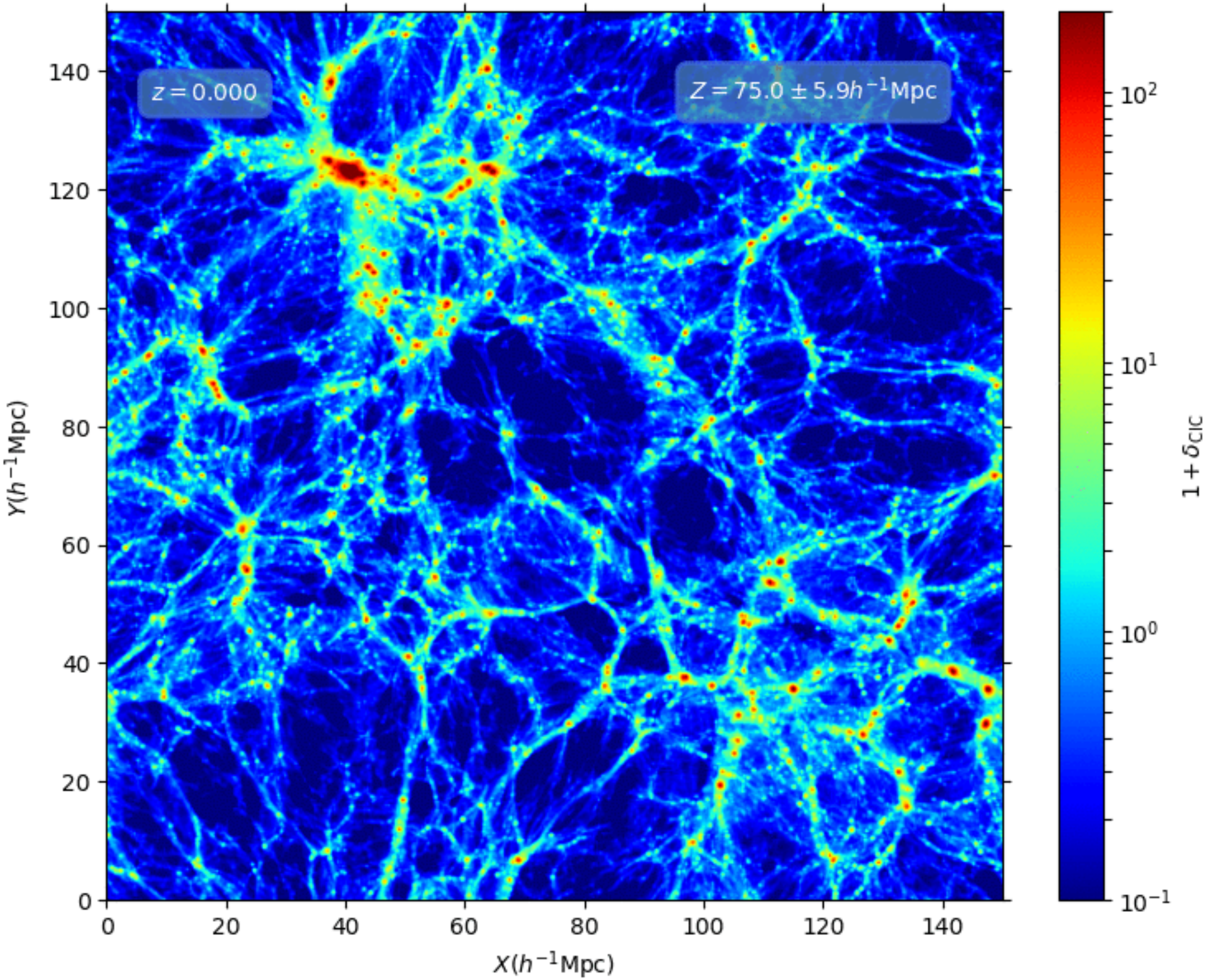
Matter density

Growth of Structure

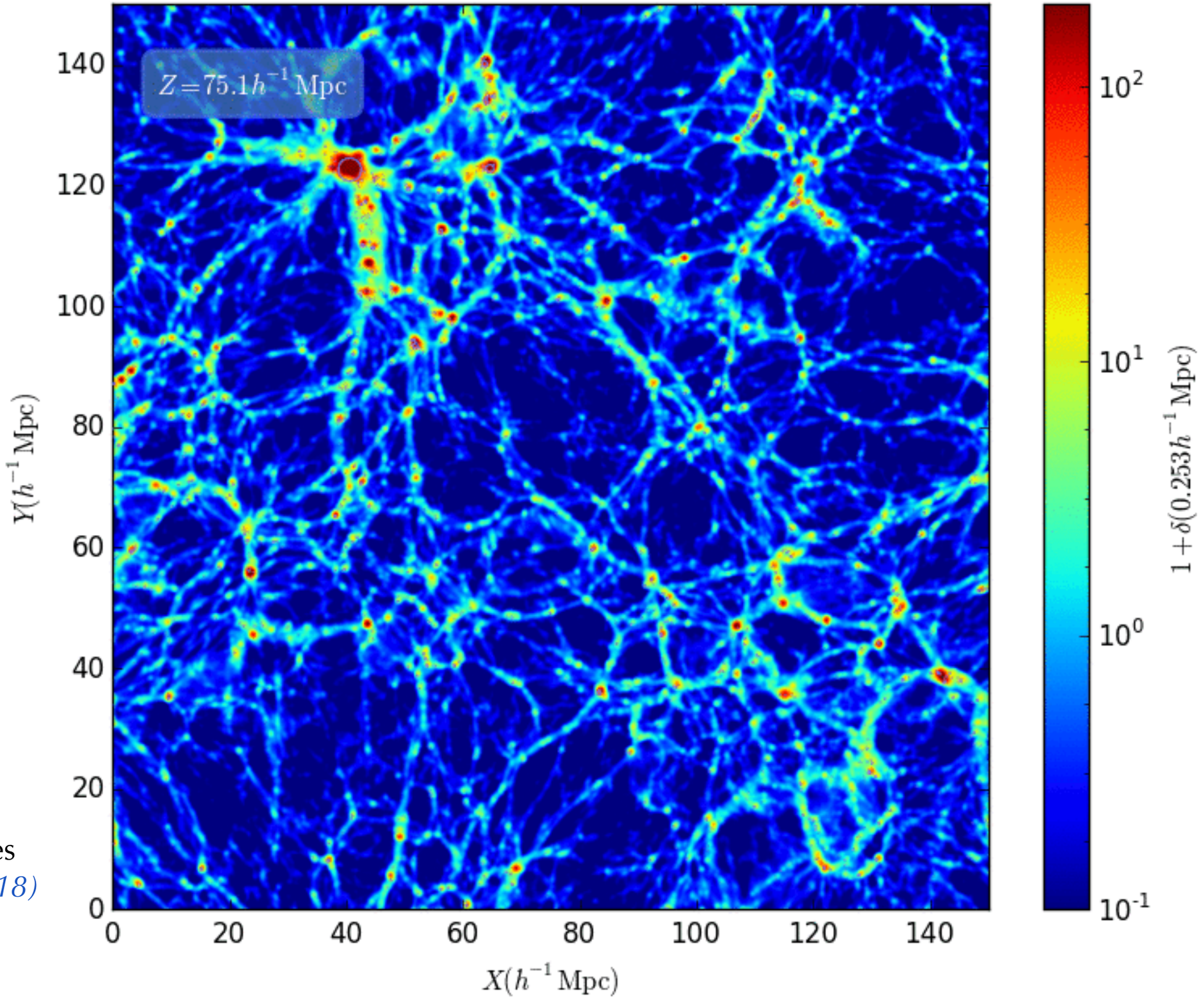
Standard ΛCDM cosmology.

Collisionless cold dark matter.

Newtonian self-gravity.



Dark Cosmic Web

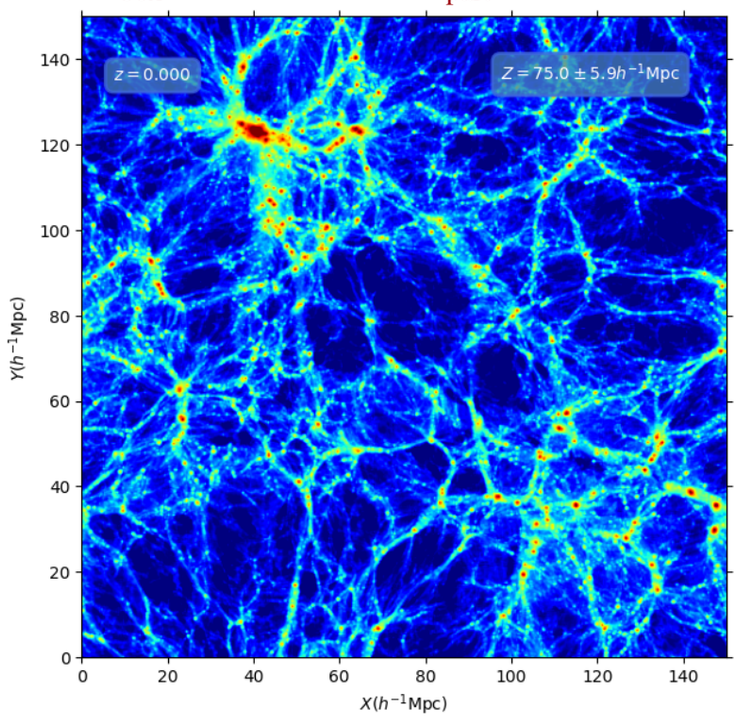


``razor-thin'' slices
(c.f. Stücker+ 2018)

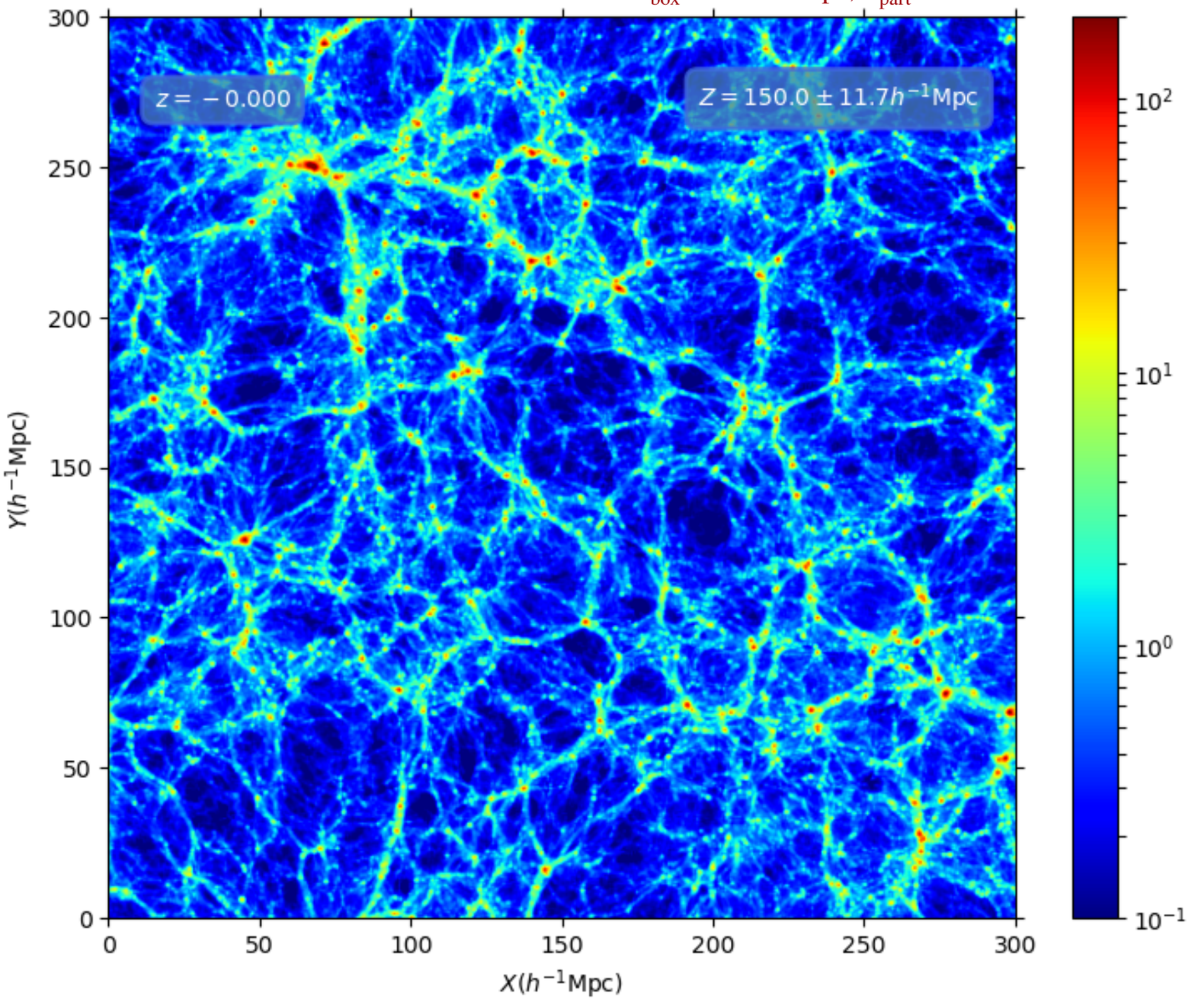
Cosmological Information

Self-similarity

$L_{\rm box} = 150h^{-1}{\rm Mpc}, N_{\rm part} = 1024^3$



$L_{\rm box} = 300h^{-1}{\rm Mpc}, N_{\rm part} = 1024^3$



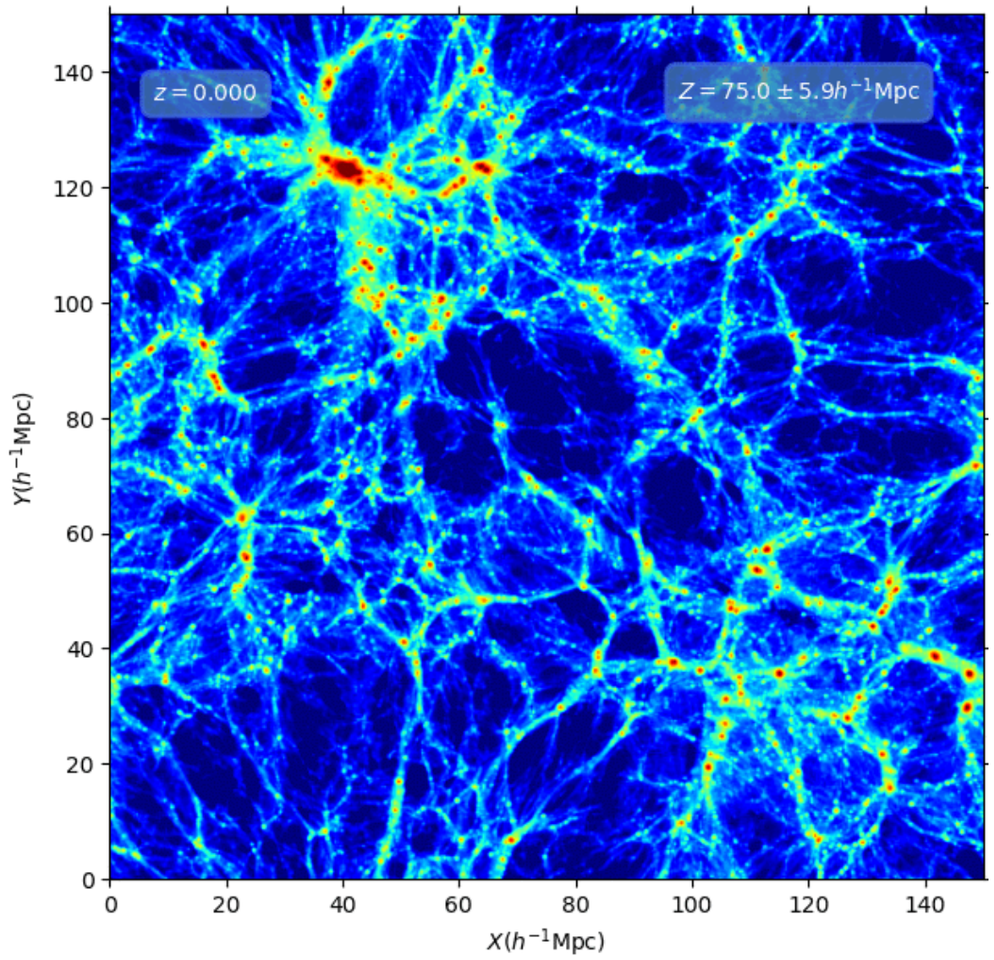
WMAP7

$\Omega_{\rm m} = 0.276, h = 0.7, \sigma_8 = 0.8$

Cosmological Information

Self-similarity

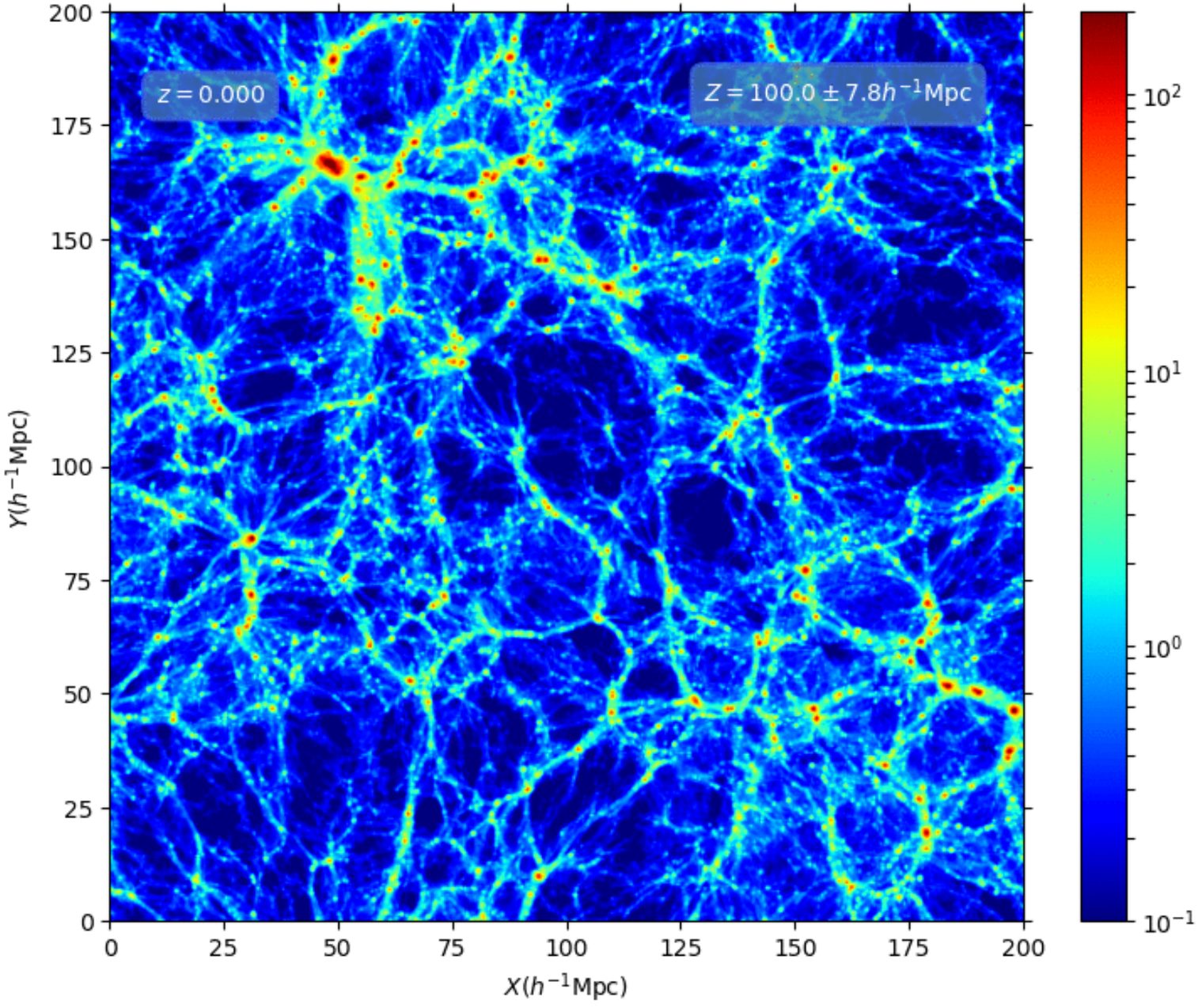
WMAP7



$\Omega_{\rm m} = 0.276, h = 0.7, \sigma_8 = 0.811$

$L_{\rm box} = 150h^{-1}{\rm Mpc}, N_{\rm part} = 1024^3$

P18

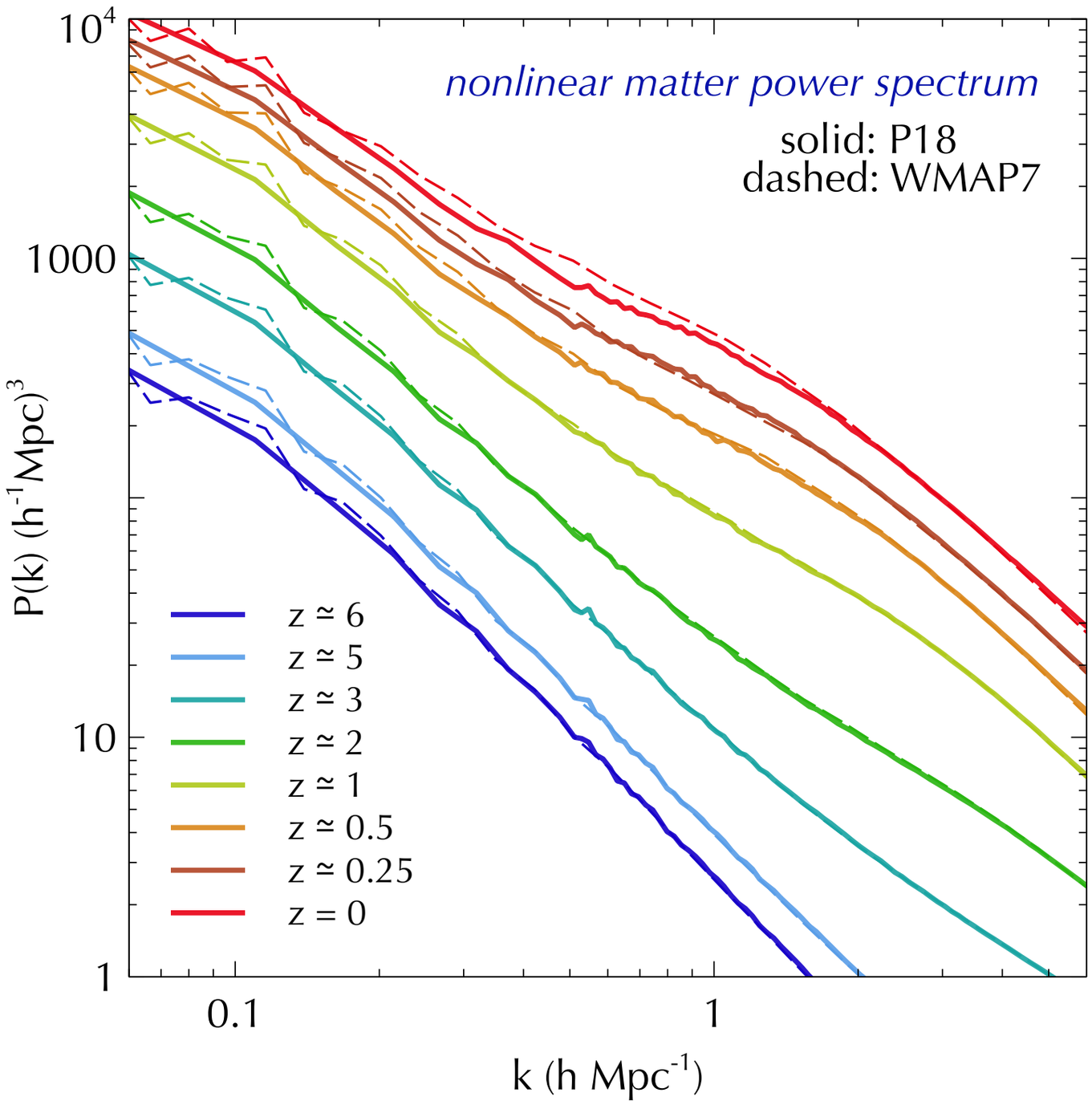


$\Omega_{\rm m} = 0.306, h = 0.678, \sigma_8 = 0.815$

$L_{\rm box} = 200h^{-1}{\rm Mpc}, N_{\rm part} = 1024^3$

Cosmological Information

Self-similarity



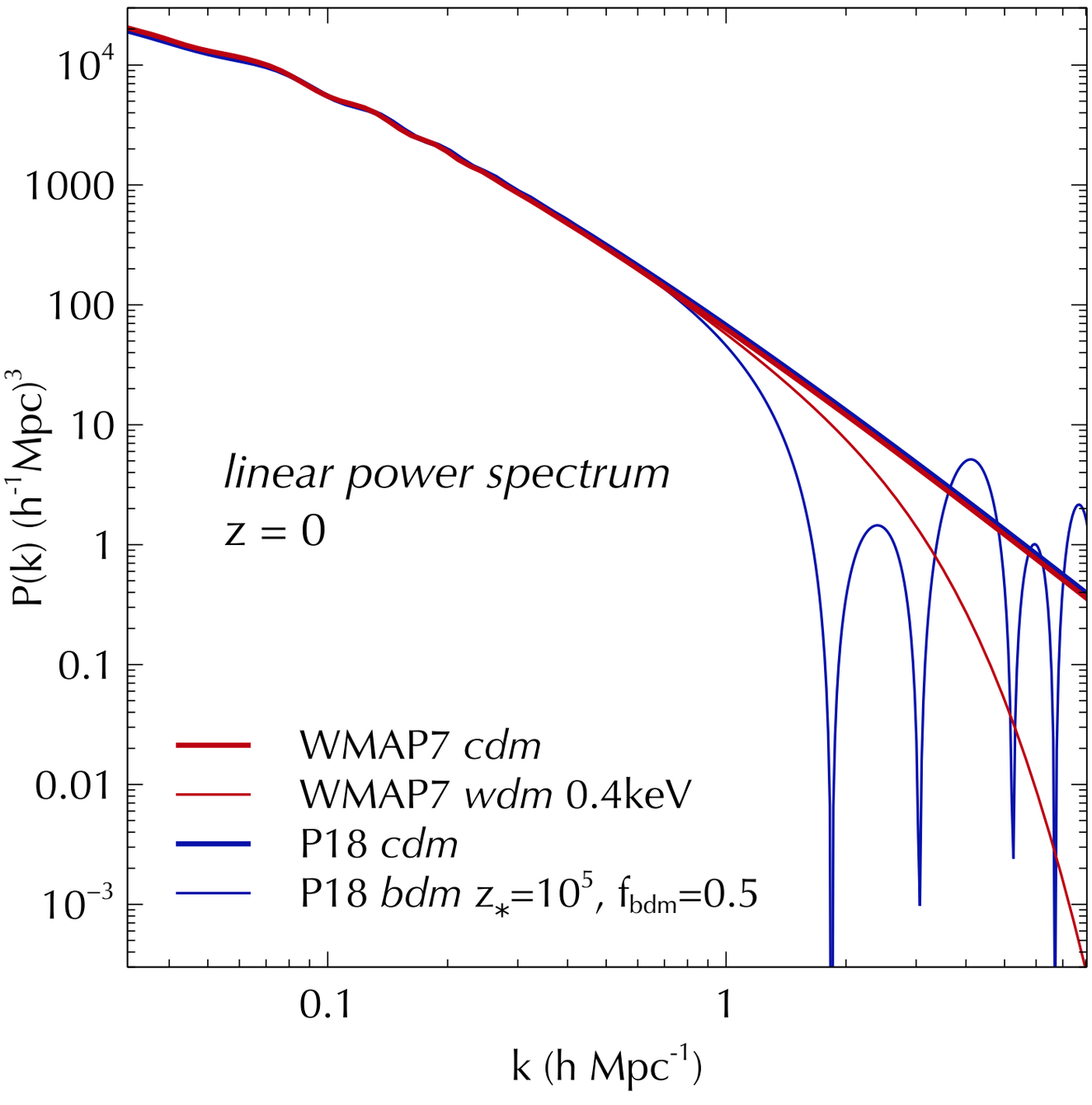
$$\delta(\mathbf{x}) = \rho(\mathbf{x})/\bar{\rho} - 1$$

$$\delta(\mathbf{k}) = \mathrm{FT}\left[\delta(\mathbf{x})\right]$$

$$P(k) \sim \langle \, | \, \delta(\mathbf{k}) \, |^2 \, \rangle$$

Cosmological Information

Dark matter physics



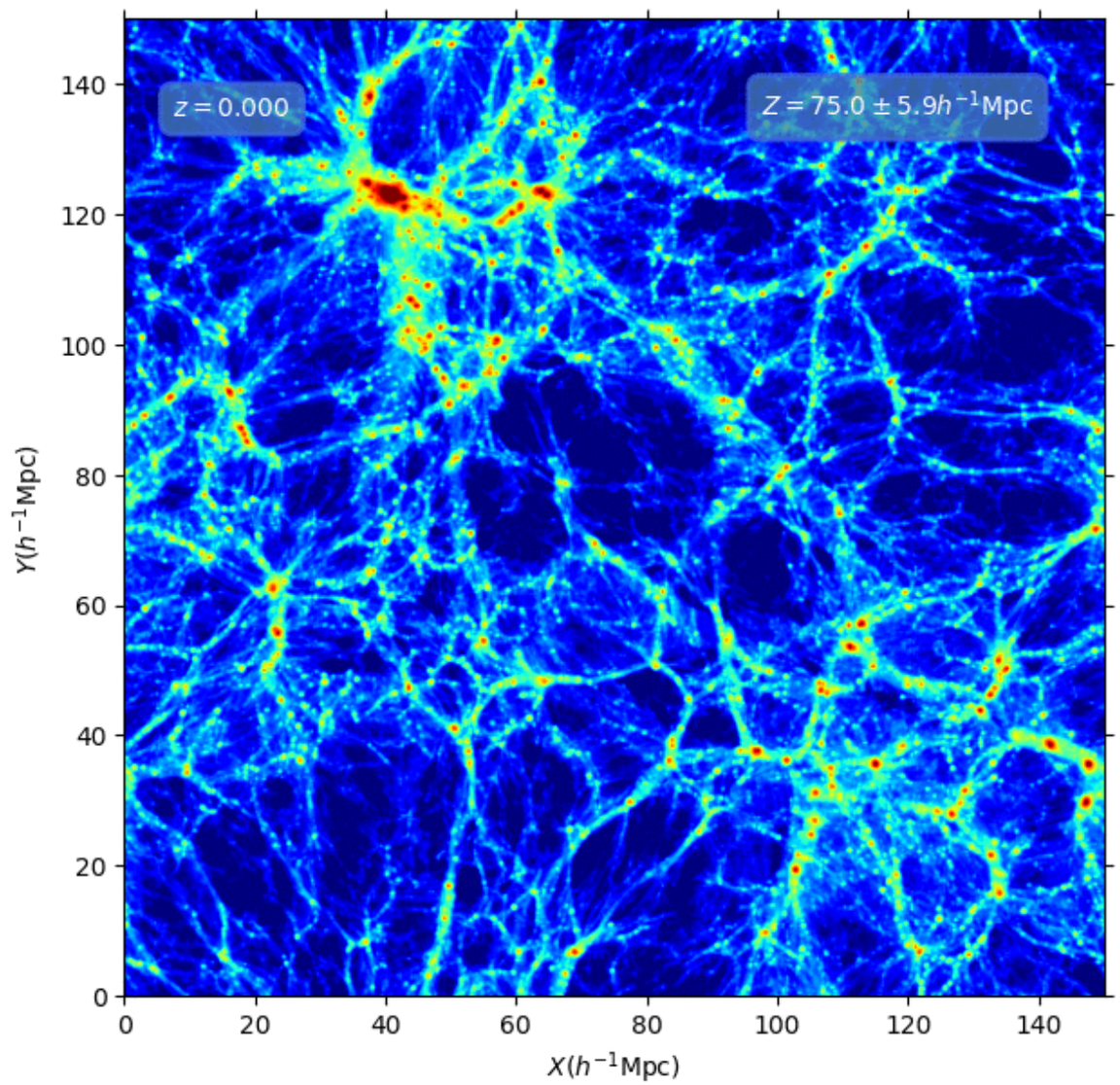
wdm → **warm** dark matter
(Bode+ 2001, Viel+ 2005, Schneider+ 2012)

bdm → **ballistic** dark matter
(Das+ 2019; see also Cyr-Racine+ 2016, Vogelsberger+ 2016)

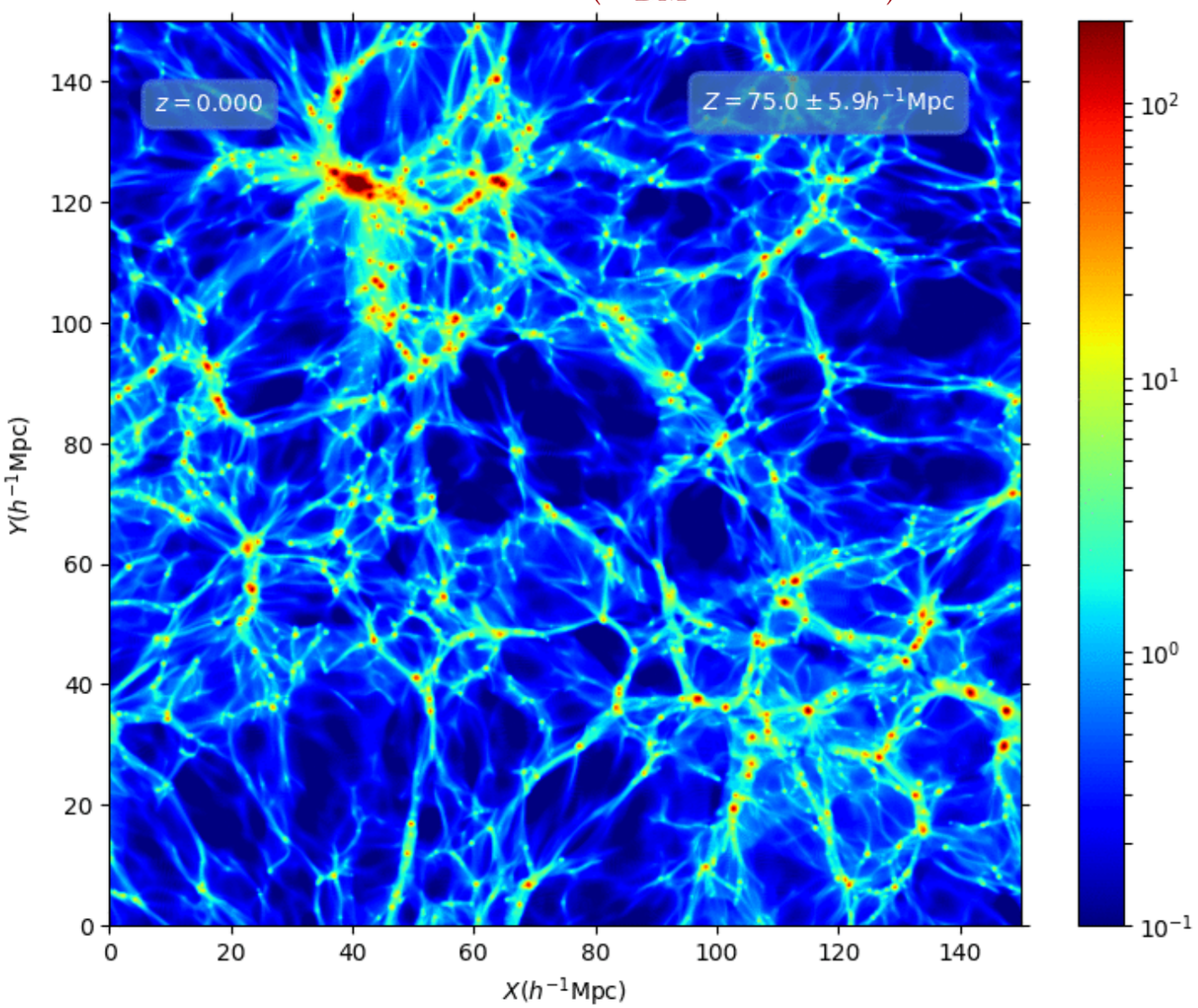
Cosmological Information

Dark matter physics

cold DM



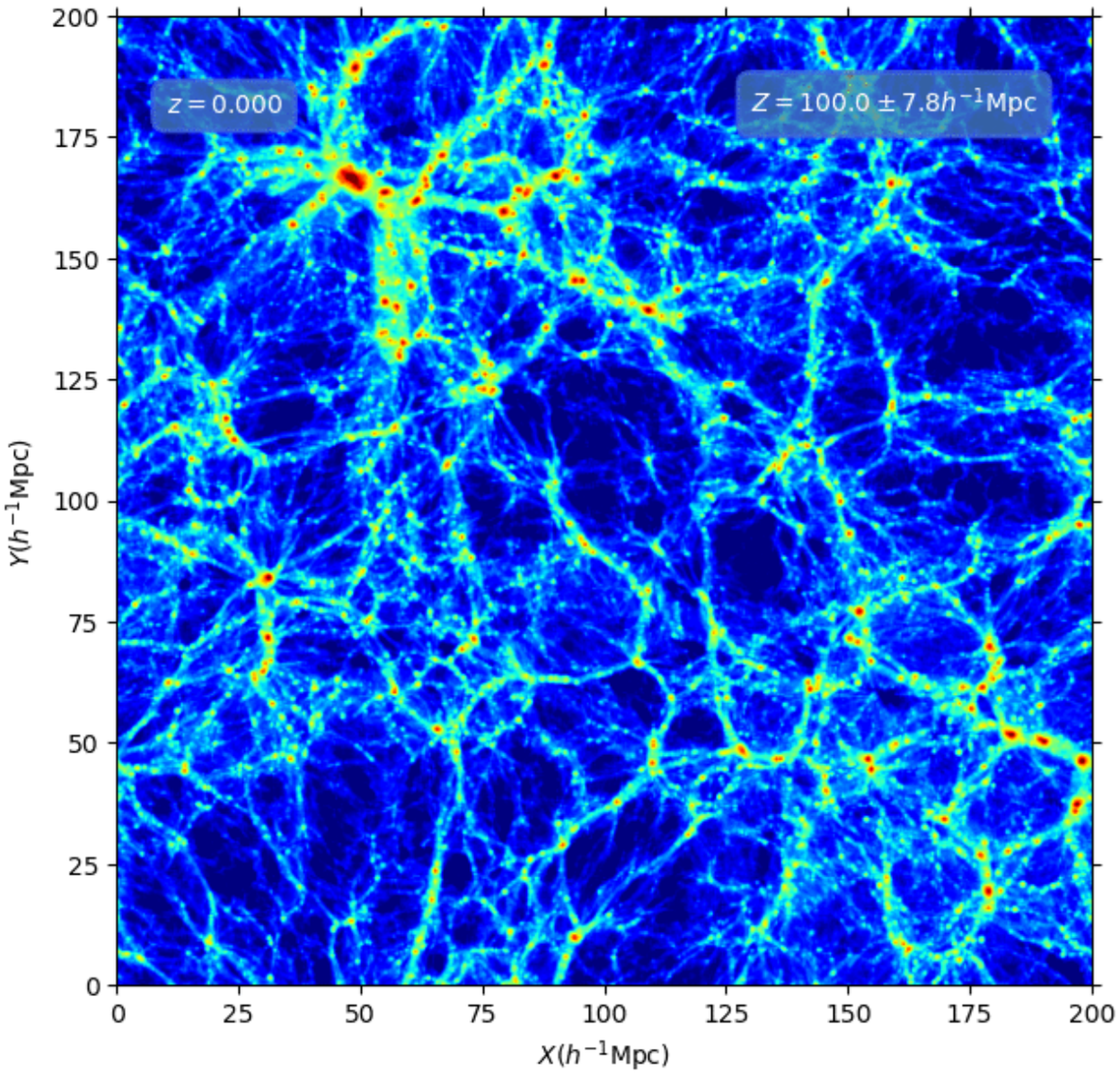
warm DM $\left(m_{\rm DM} = 0.4\,{\rm keV}\right)$



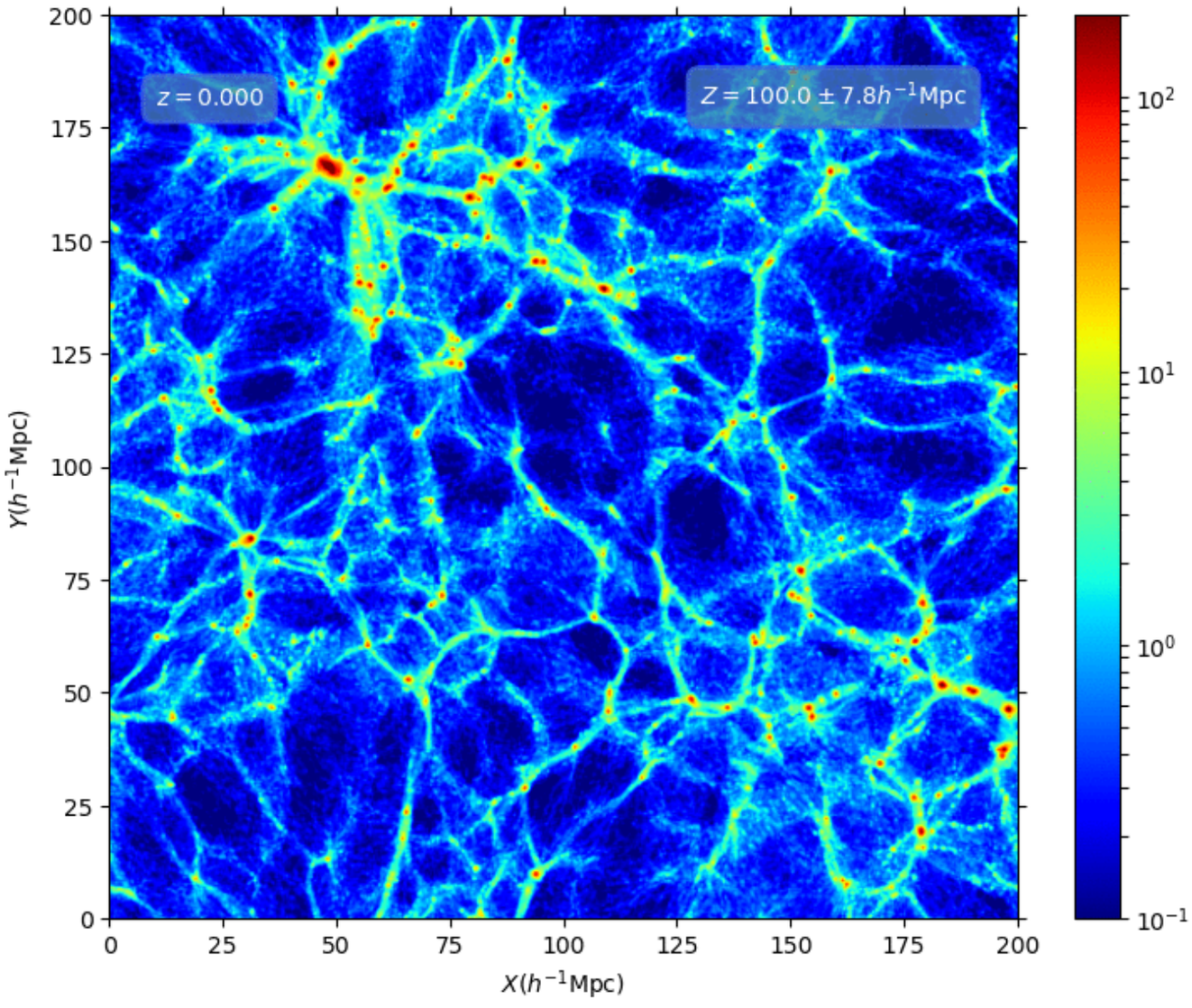
Cosmological Information

Dark matter physics

cold DM

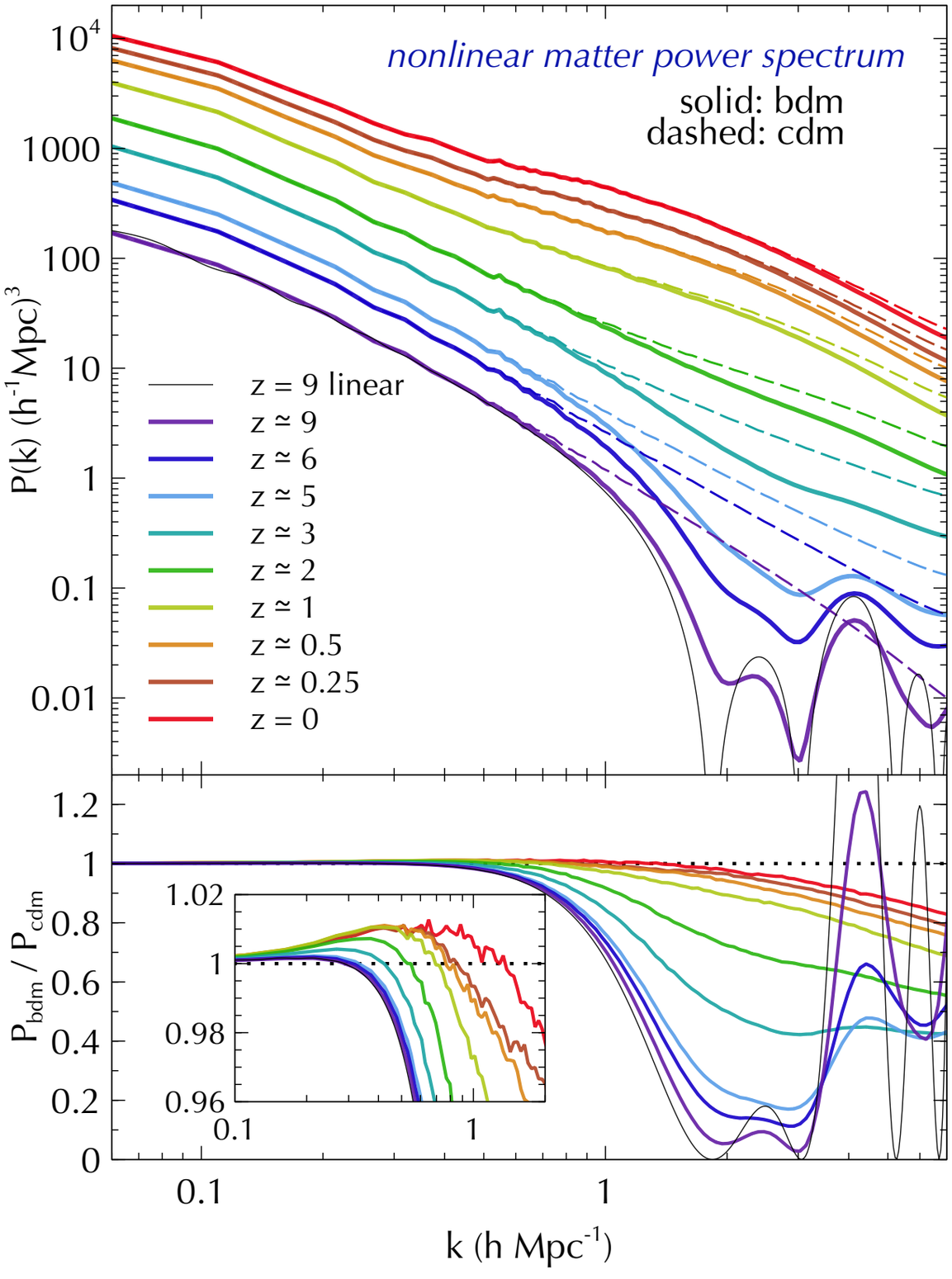


ballistic DM $(z_* = 10^5, f_{\rm bdm} = 0.5)$



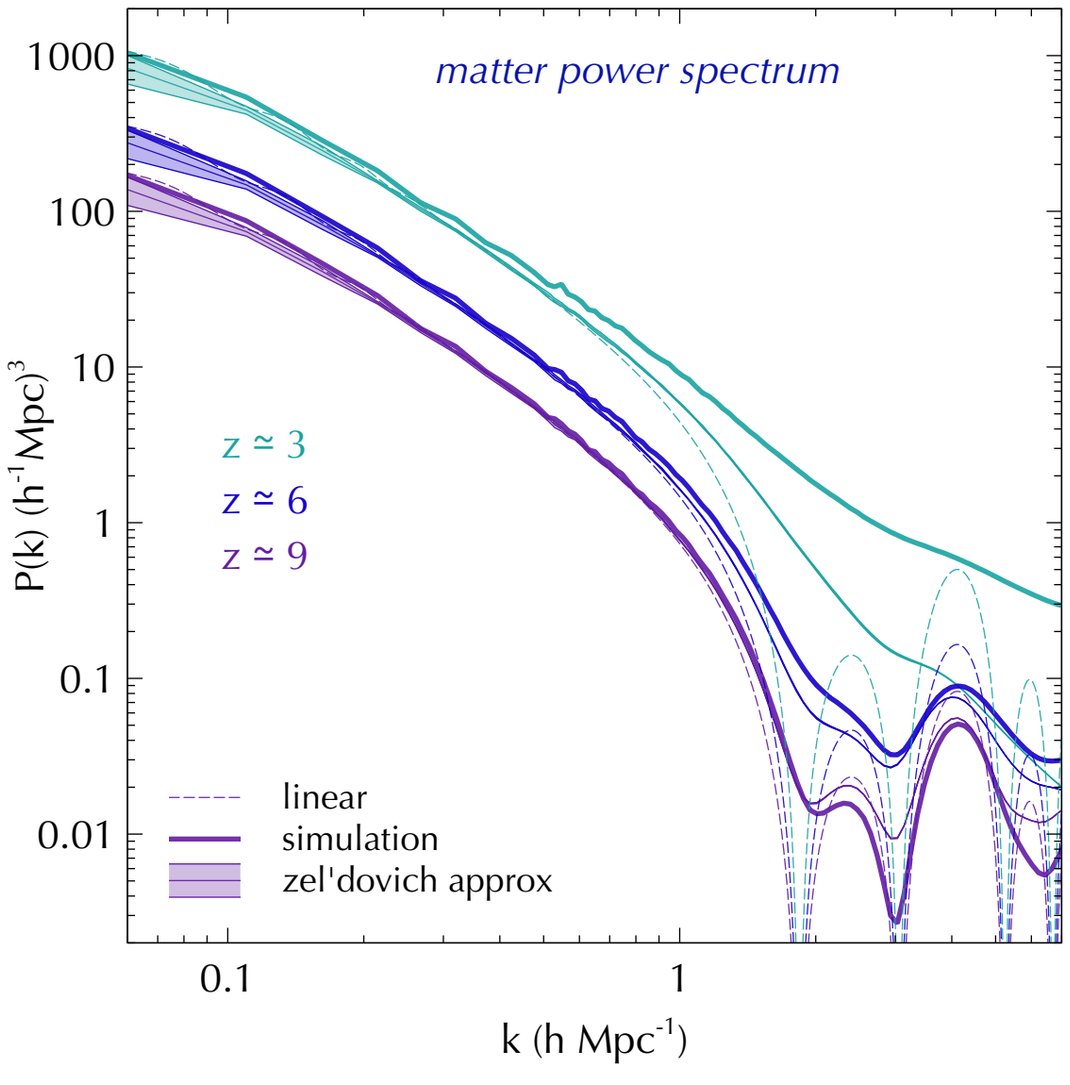
Cosmological Information

Dark matter physics



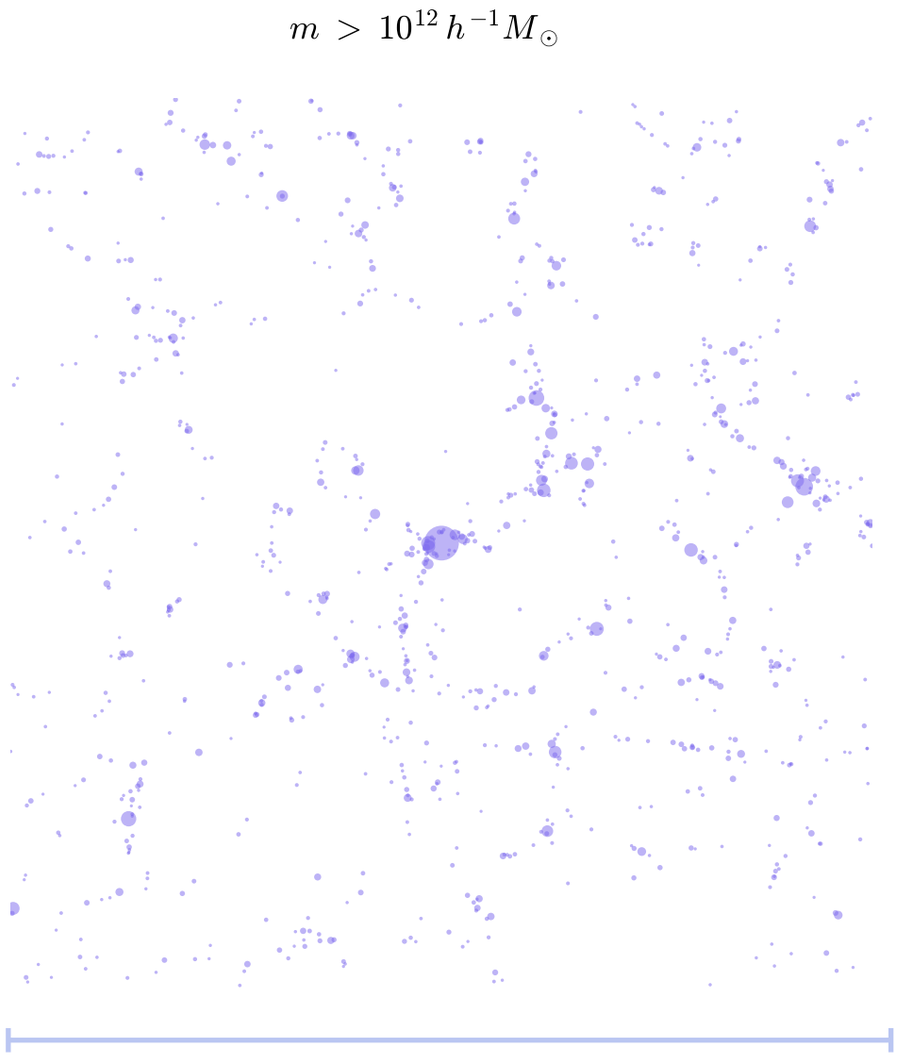
- Small scales rapidly deviate from linear growth
- Simple non-linear models capture early growth

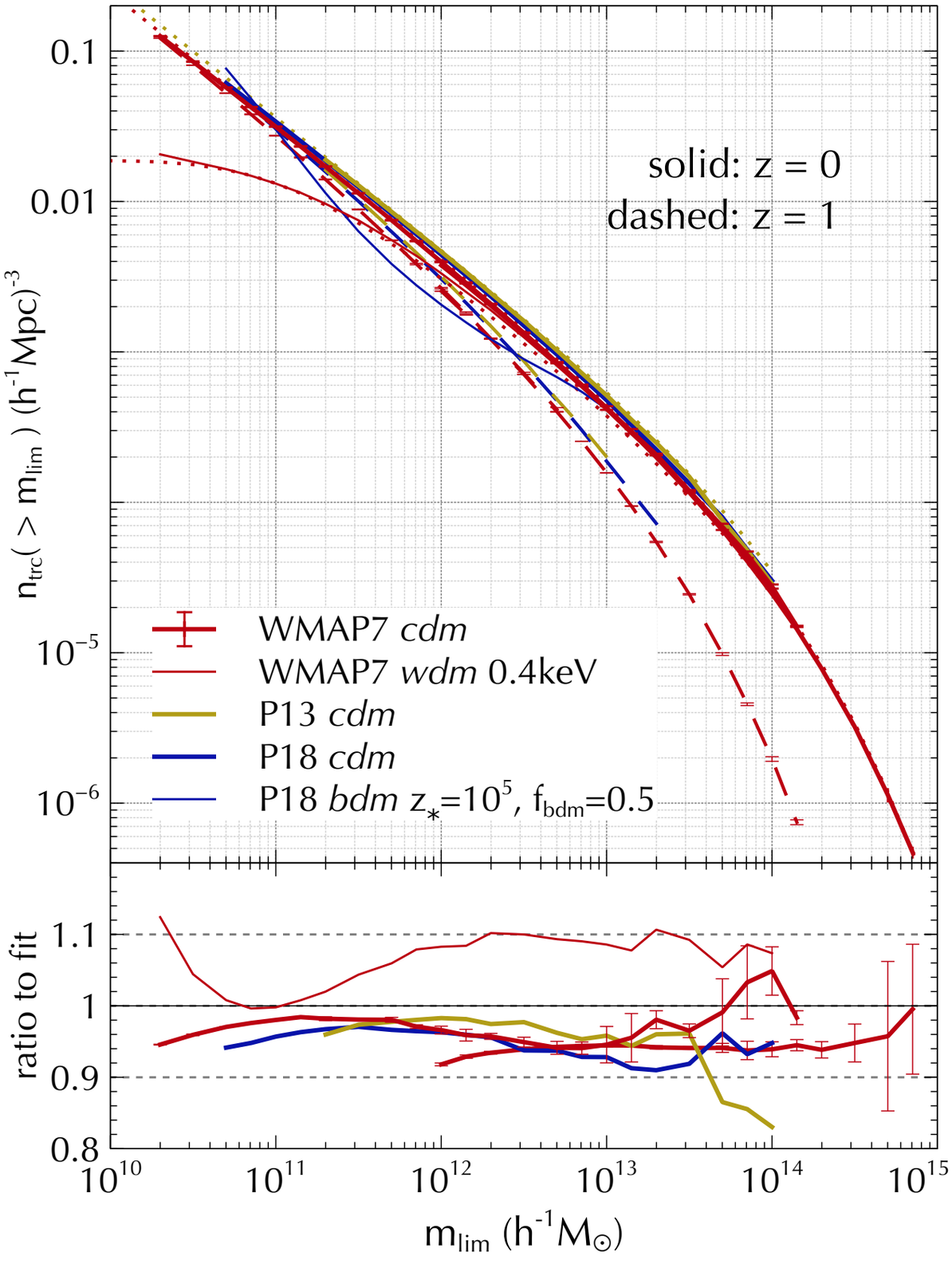
*(**Arya**+ in progress)*



Tracers of matter

Dark Haloes as Cosmic Tracers

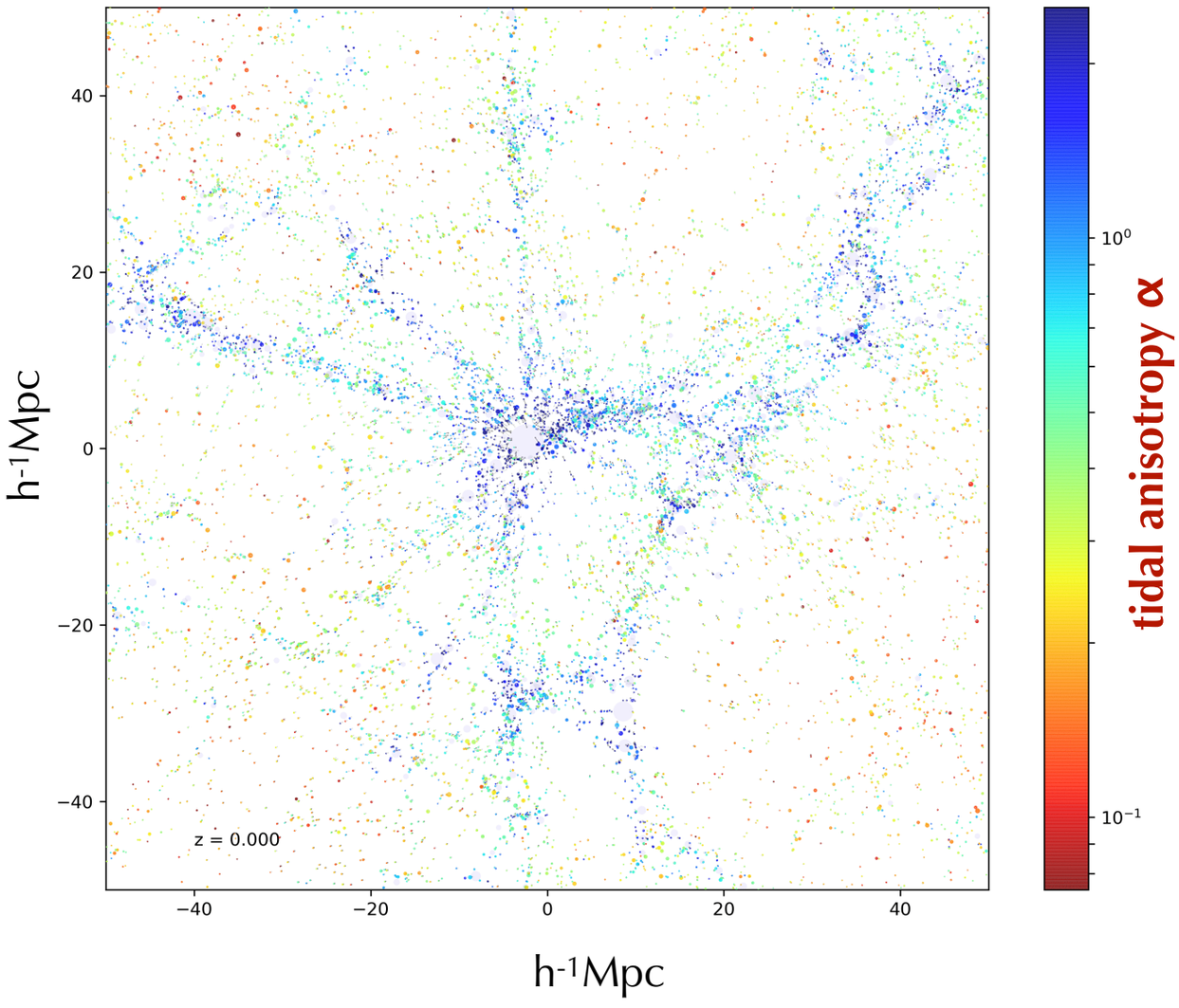




Environment of Cosmic Tracers

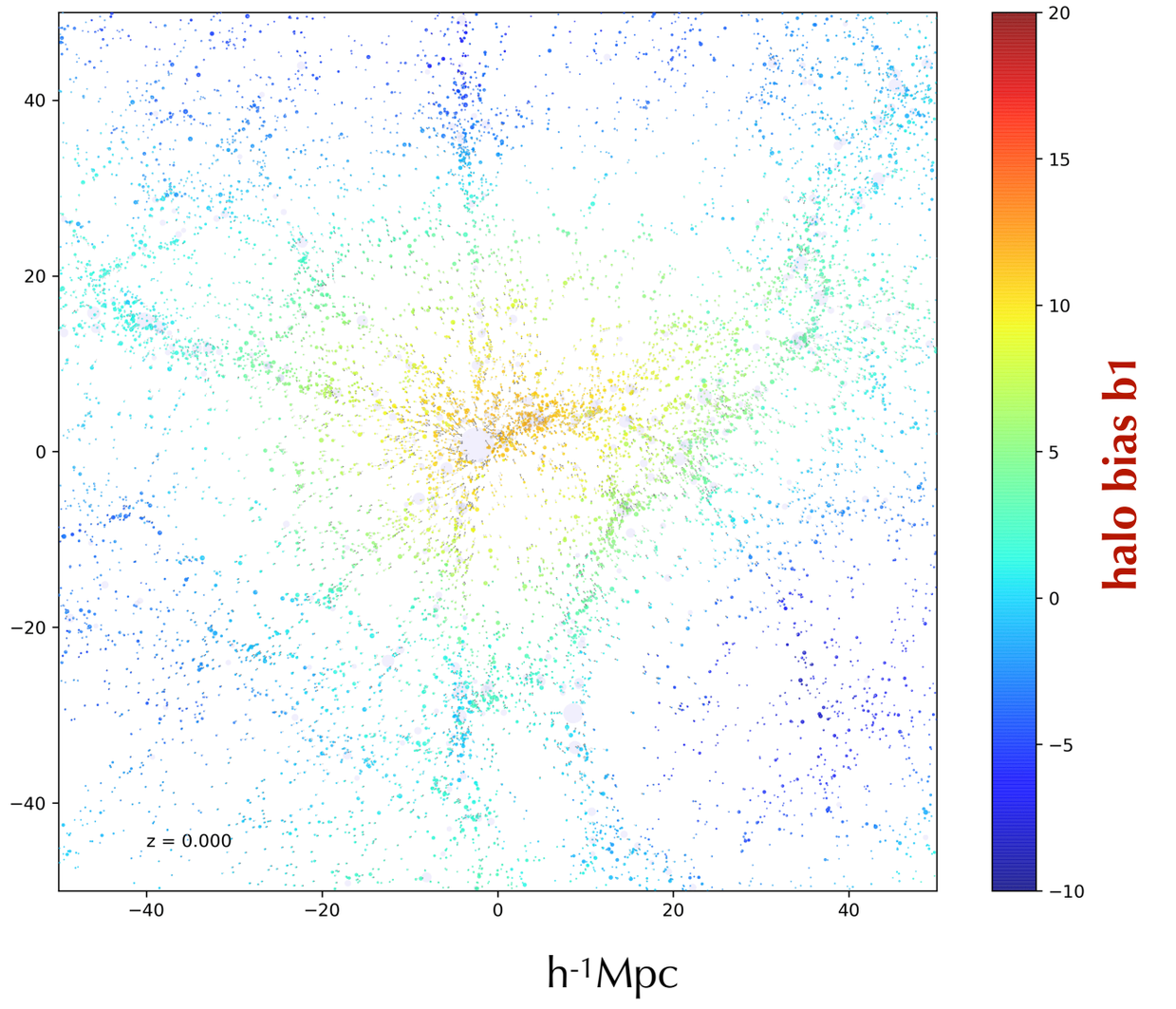
Local tidal field & large-scale density

(***AP***, Hahn & Sheth 1706.09906)



$\alpha \sim$ anisotropy of local tidal field

(defined at few x halo size)



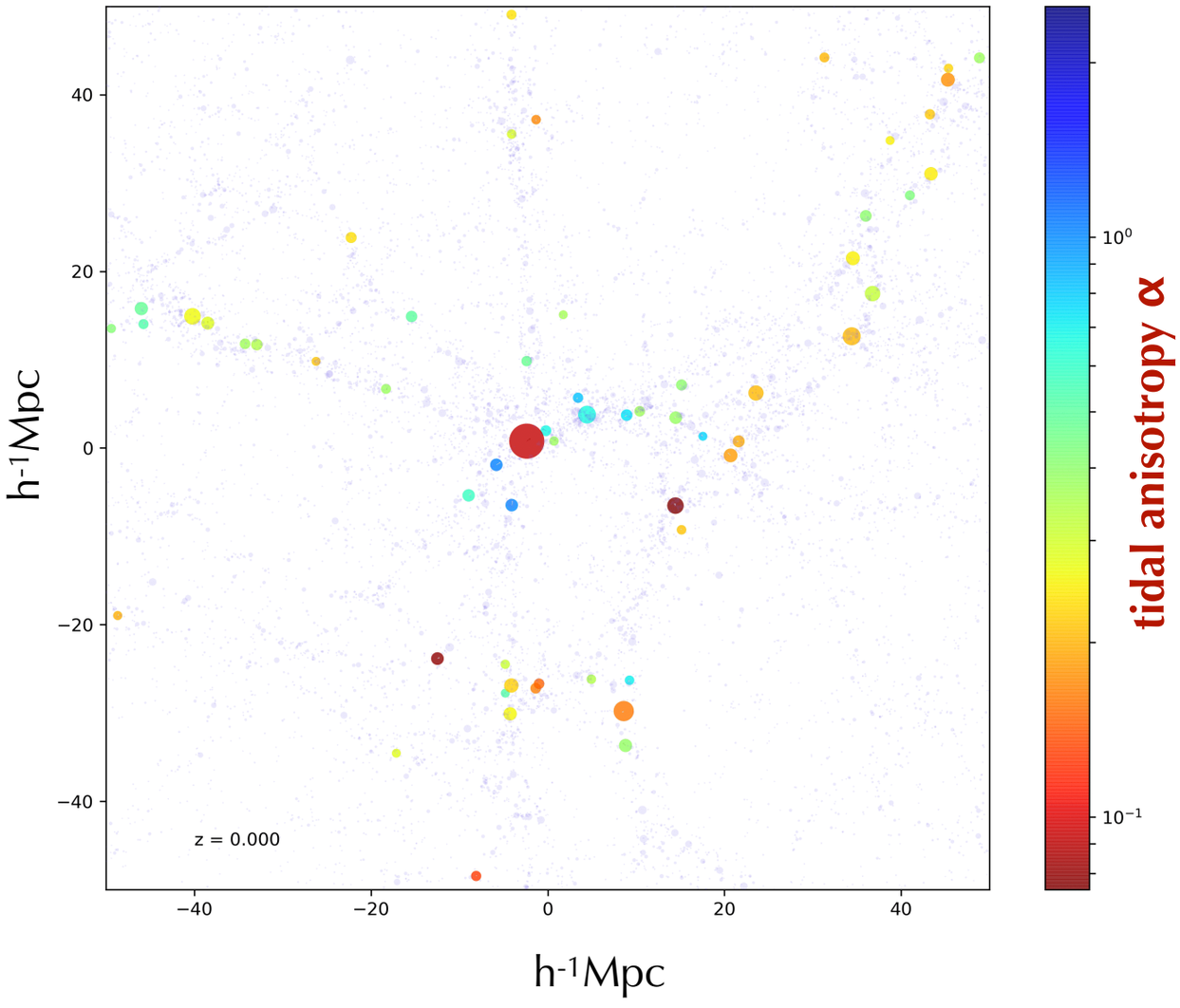
$b_1 \sim$ large-scale halo-centric density

(defined at $\gtrsim 30h^{-1}\mathrm{Mpc}$*)*

Environment of Cosmic Tracers

Local tidal field & large-scale density

(***AP***, Hahn & Sheth 1706.09906)



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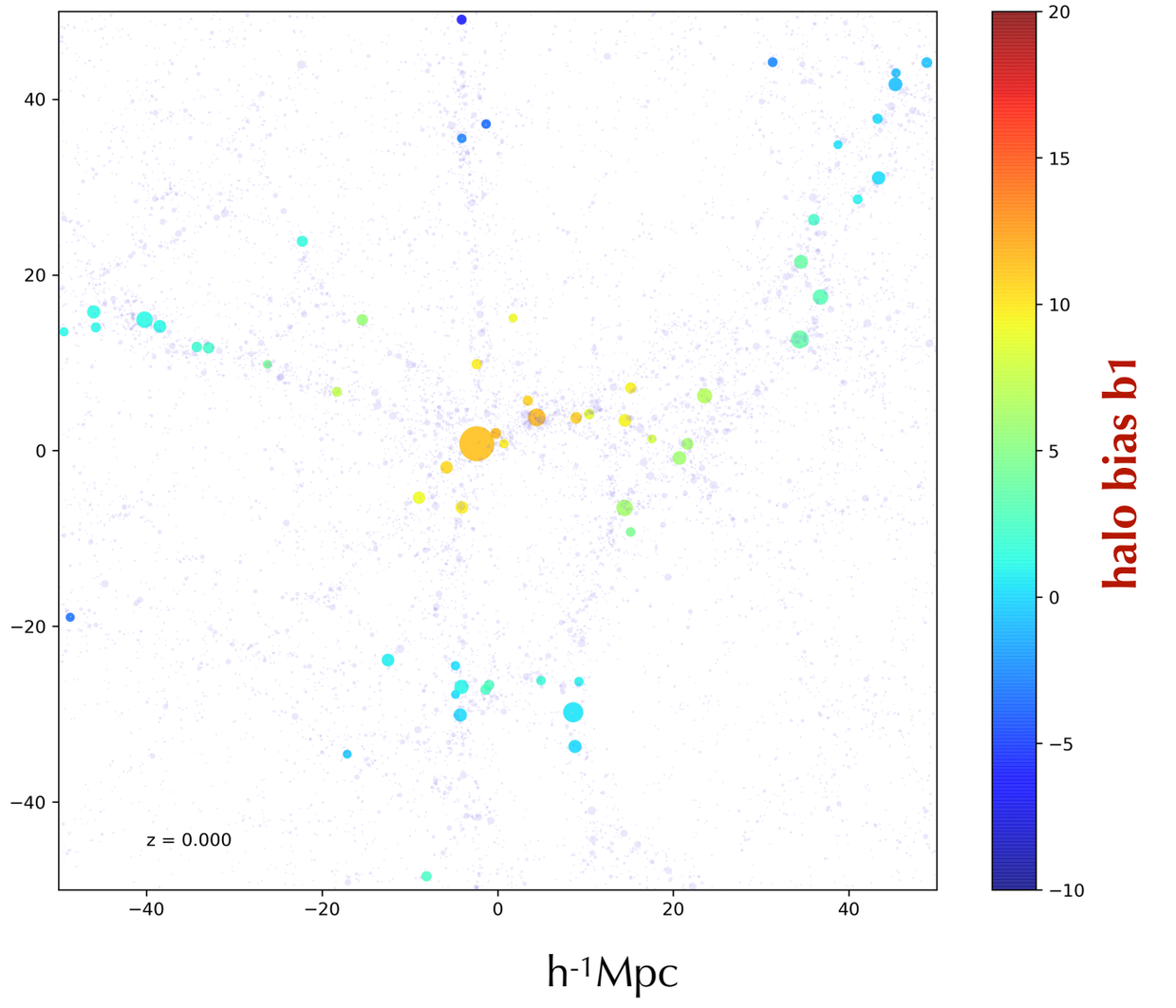

$b_1 \sim$ large-scale halo-centric density

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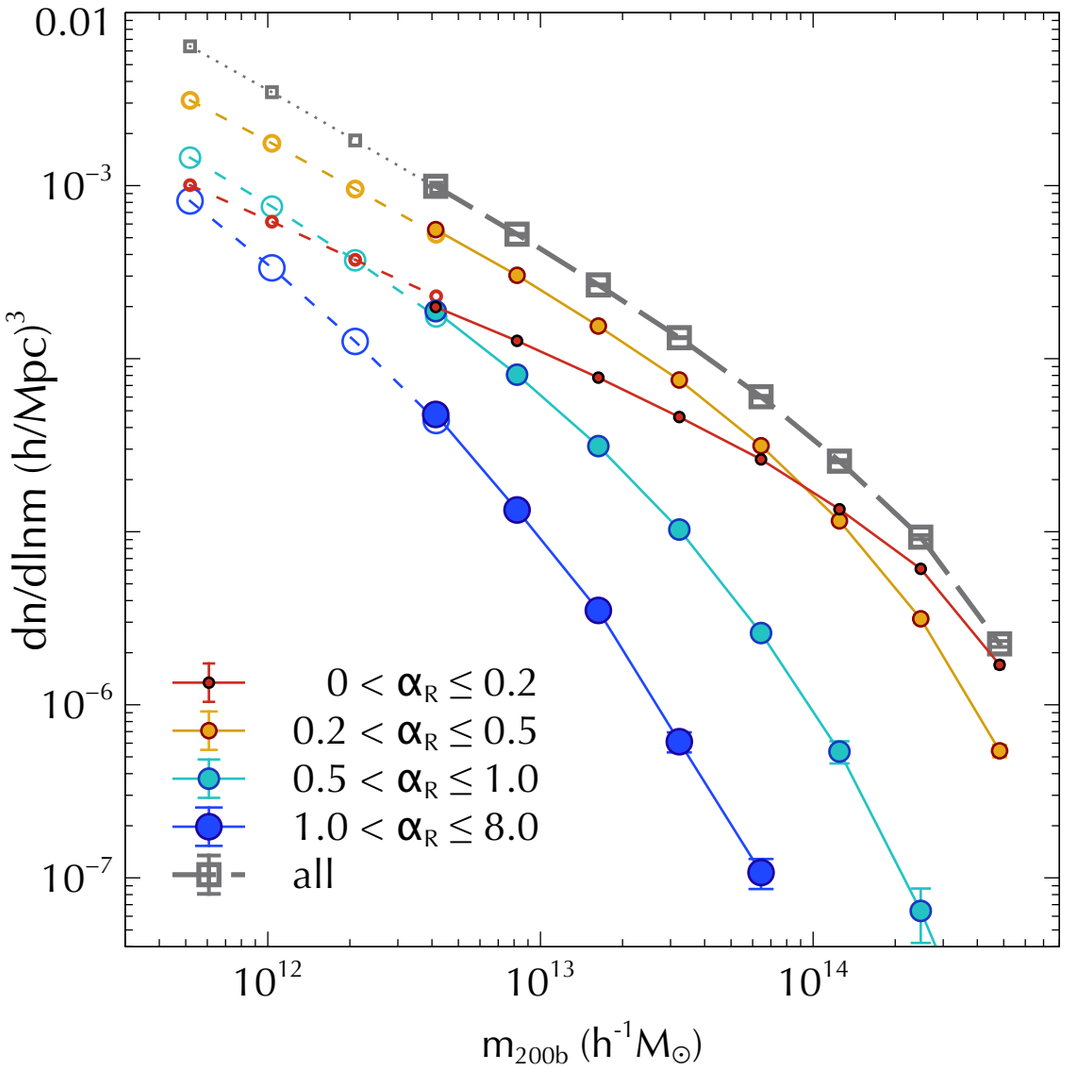
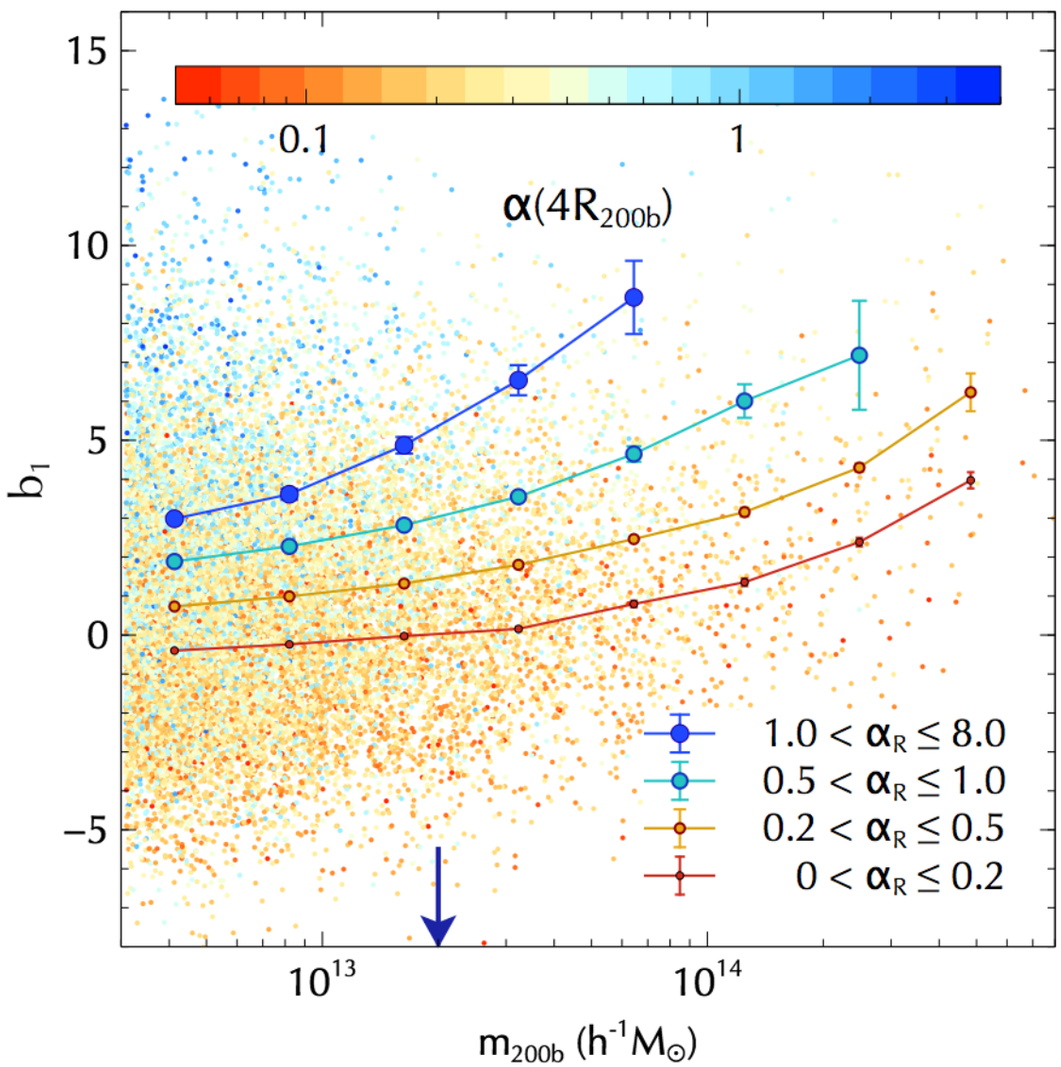
Environment of Cosmic Tracers

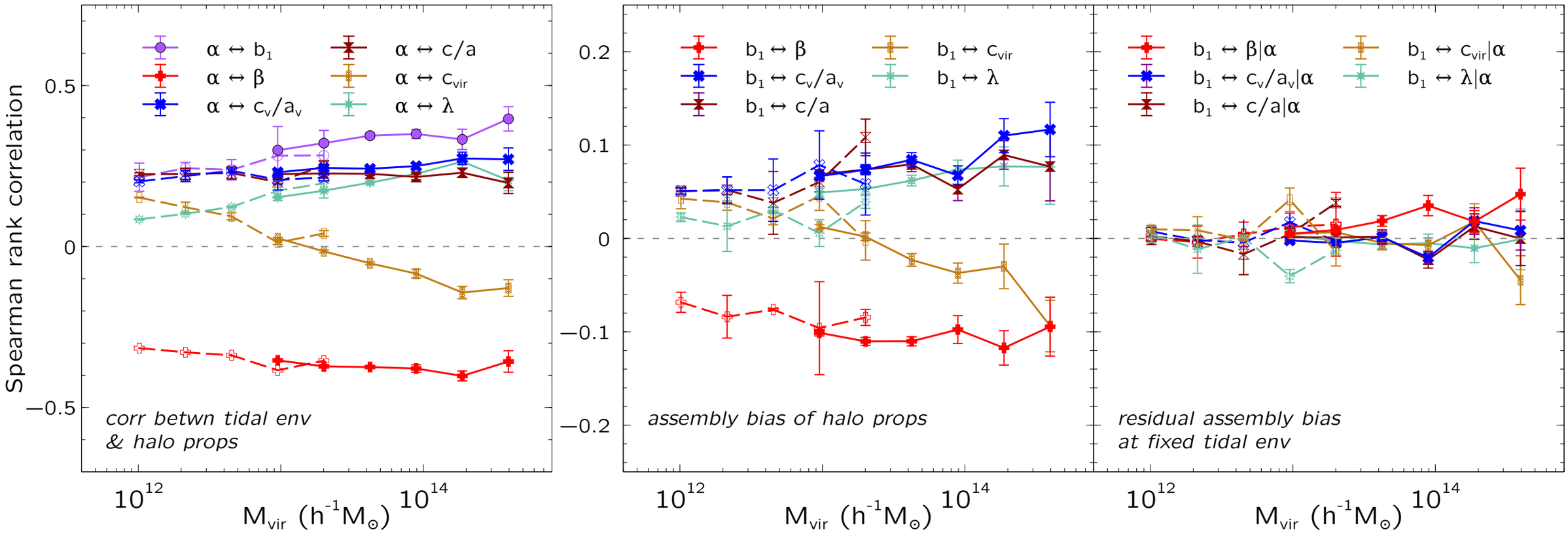
Local tidal anisotropy & large-scale bias





*(**AP**, Hahn & Sheth 1706.09906)*

Tidal Anisotropy Explains Assembly Bias



$\beta \sim$ anisotropy of halo velocity dispersion
$c_v/a_v \sim$ asphericity of halo velocity ellipsoid
$c/a \sim$ asphericity of halo shape
$c_{\rm vir} \sim$ concentration of halo density profile
$\lambda \sim$ halo angular momentum

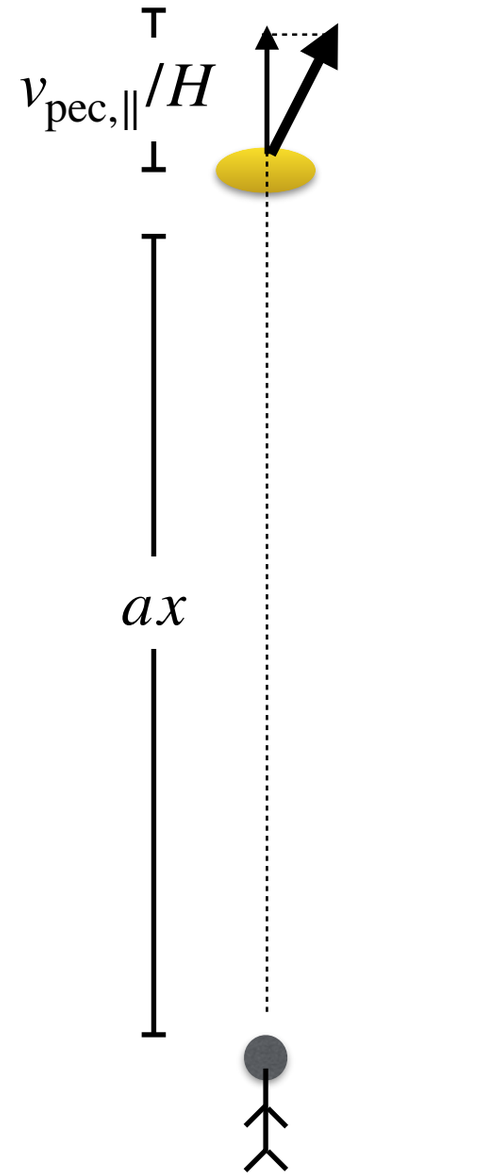
*(**Ramakrishnan**+ 1903.02007)*

Cosmology with the Cosmic Web

Cosmic Web as Cosmic Probe

Galaxy Clusters

Redshift-Space Distortions



$$cz_{\mathrm{obs}} = Hax + v_{\mathrm{pec},\parallel}$$

Lyman-α Forest
Weak Lensing
Voids
...

- *All probes use biased tracers of dark matter.*
- *Tracer ↔ DM mapping is nuisance for cosmology, key variable for galaxy + IGM evolution studies.*

Baryonic Acoustic Oscillations

Sound horizon at last scattering

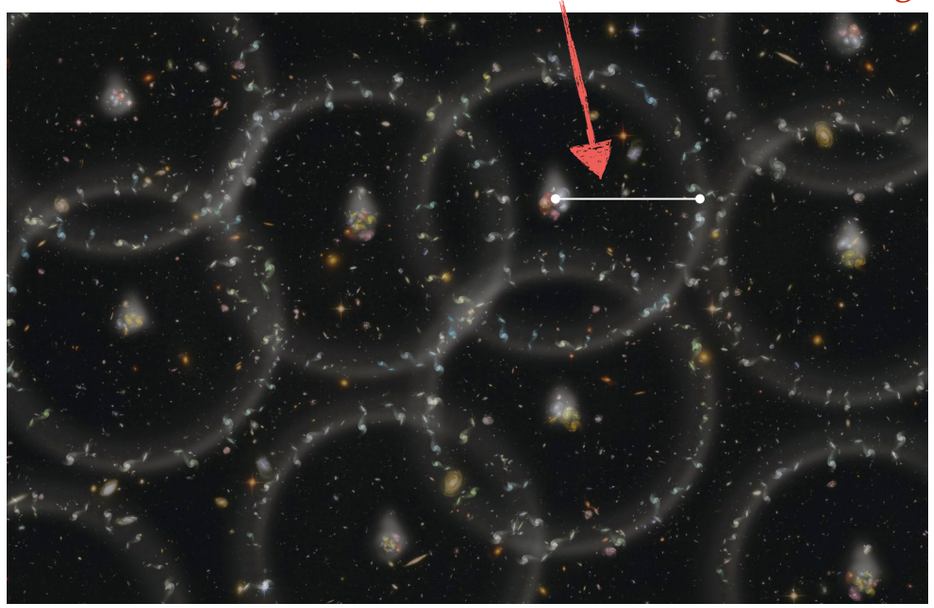
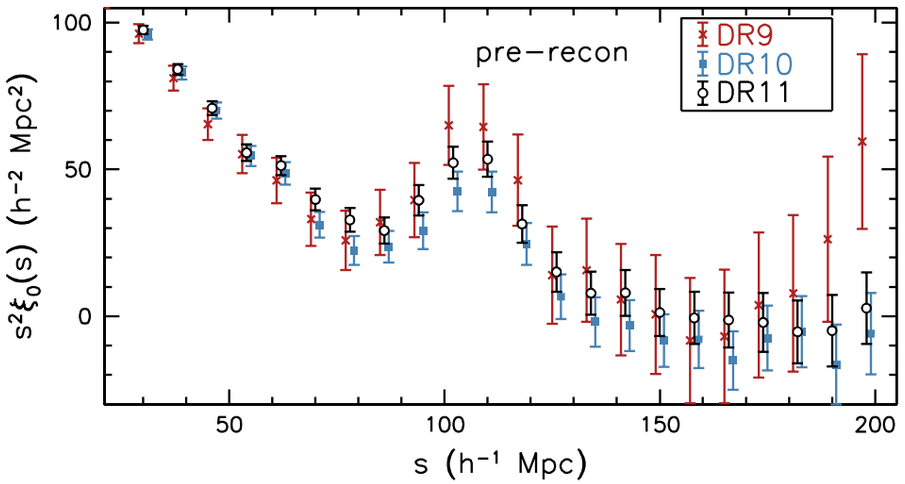
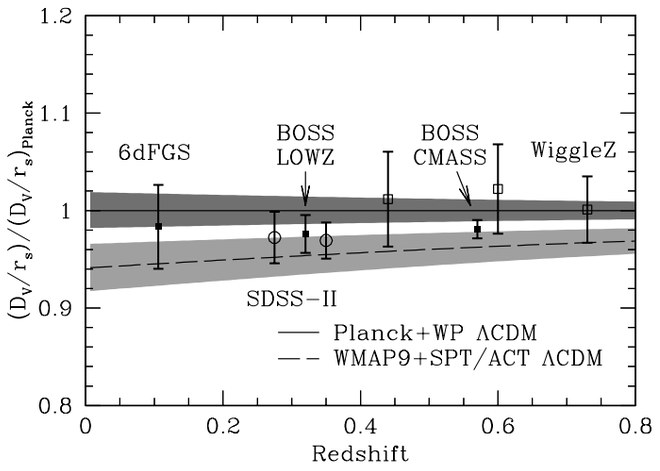


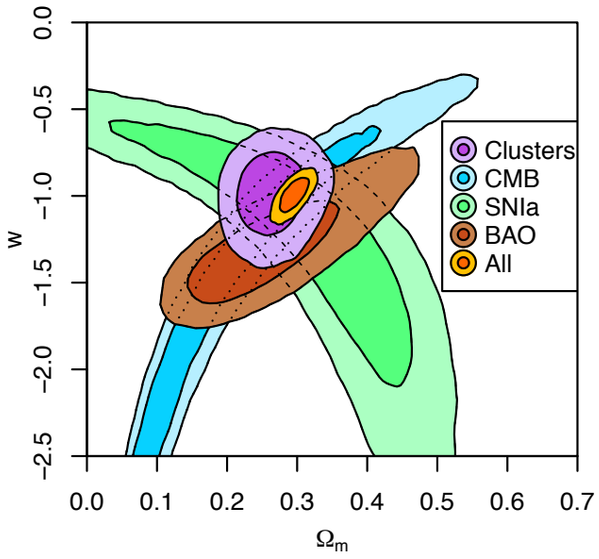
image courtesy: Brookhaven National Lab

Cosmic Web as Cosmic Probe

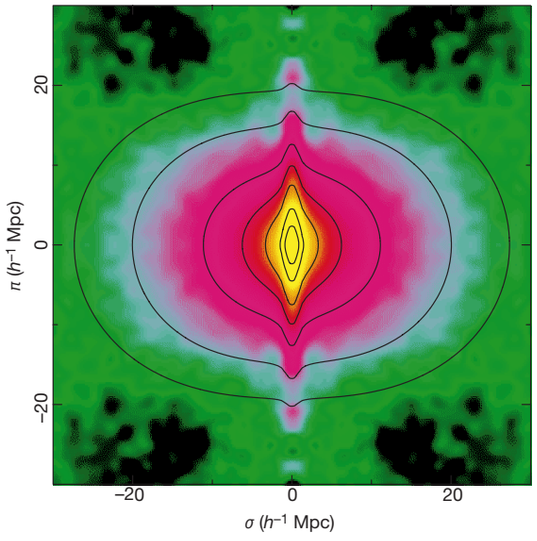


BOSS CMASS (z = 0.55) *(Anderson+ 2013)*

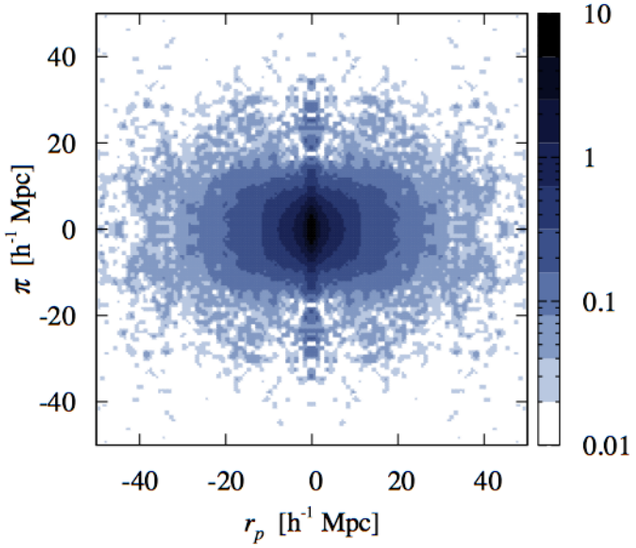




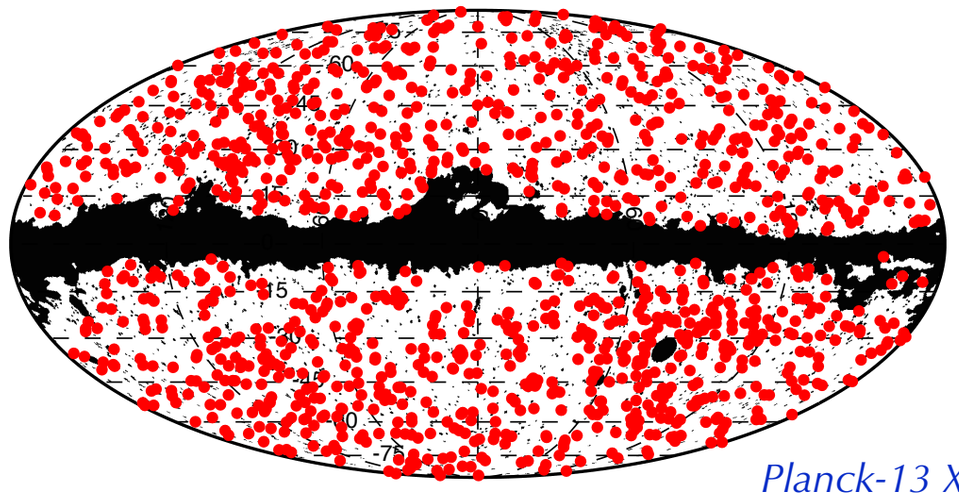
Mantz+ (2014)



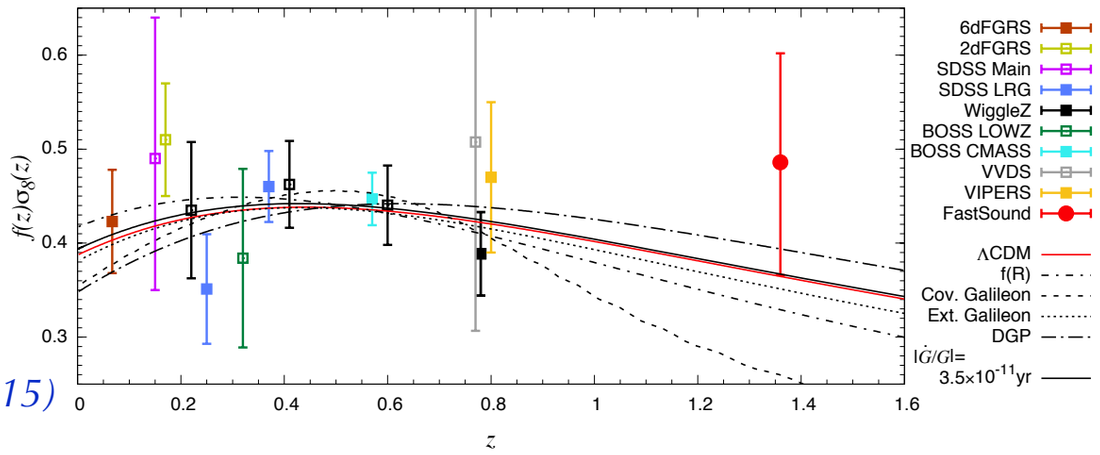
Peacock+, **Nature**, *(2001) [2dfGRS]*



de la Torre et al. (2013) [VIPERS]



Planck-13 XXIX (2014)

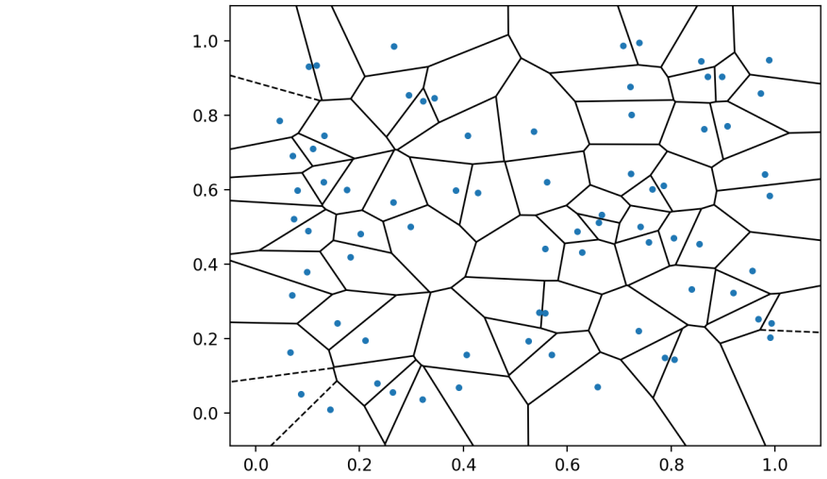


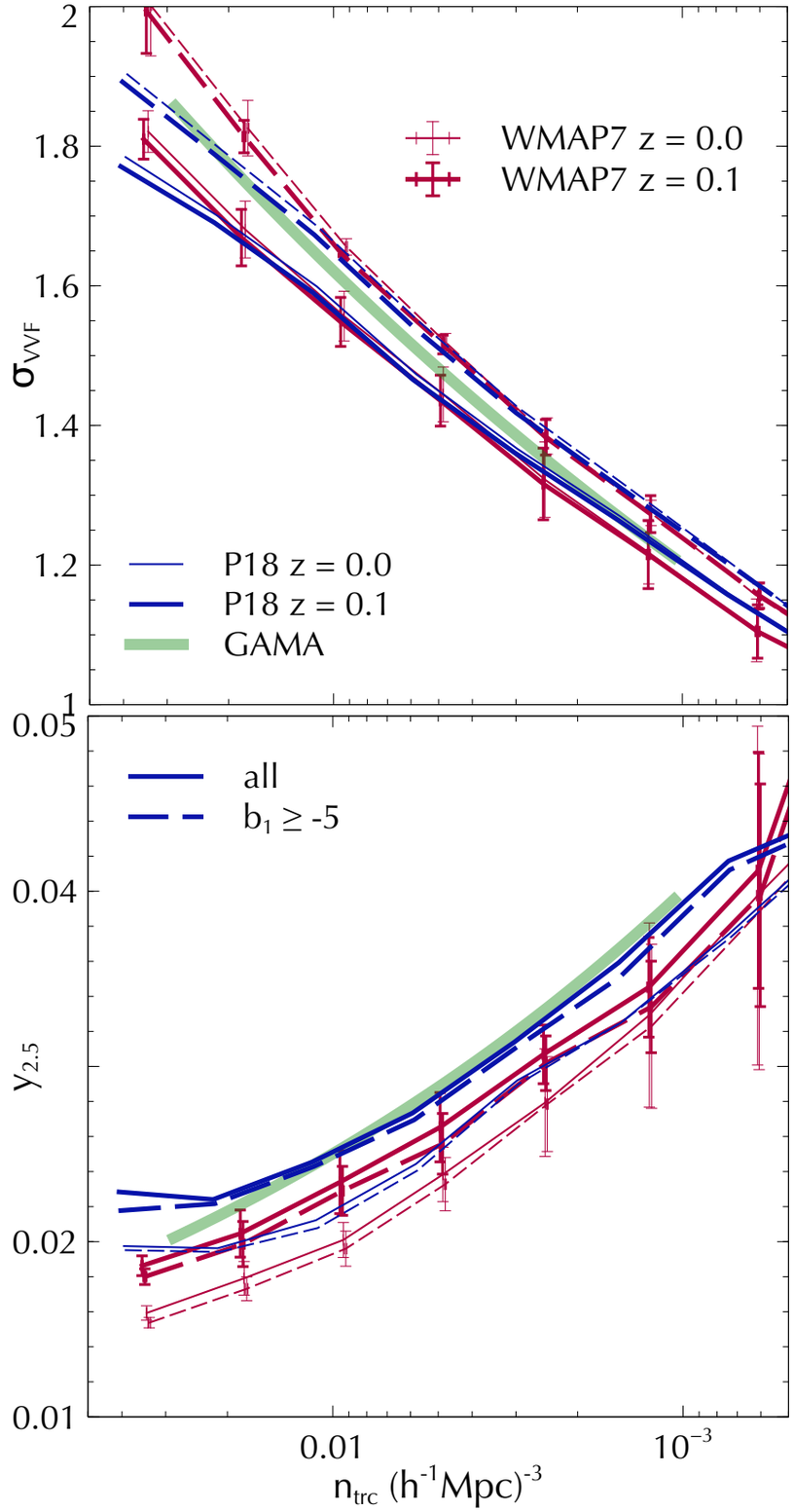
Okumura et al. (2015)

Voronoi Volume Function

A new probe of cosmology and galaxy evolution

(***AP*** *& Alam 2001.08760)*





Conclusions

★ Cosmic web evolution is a rich source of multi-scale, non-linear cosmological information

★ Probed by biased tracers, whose properties must be understood for cosmological use

★ Voronoi volume function: probes both cosmology and galaxy evolution.