Thermal Sunyaev Zeldovich Power Spectrum: Analytical Model and Measures in Simulations

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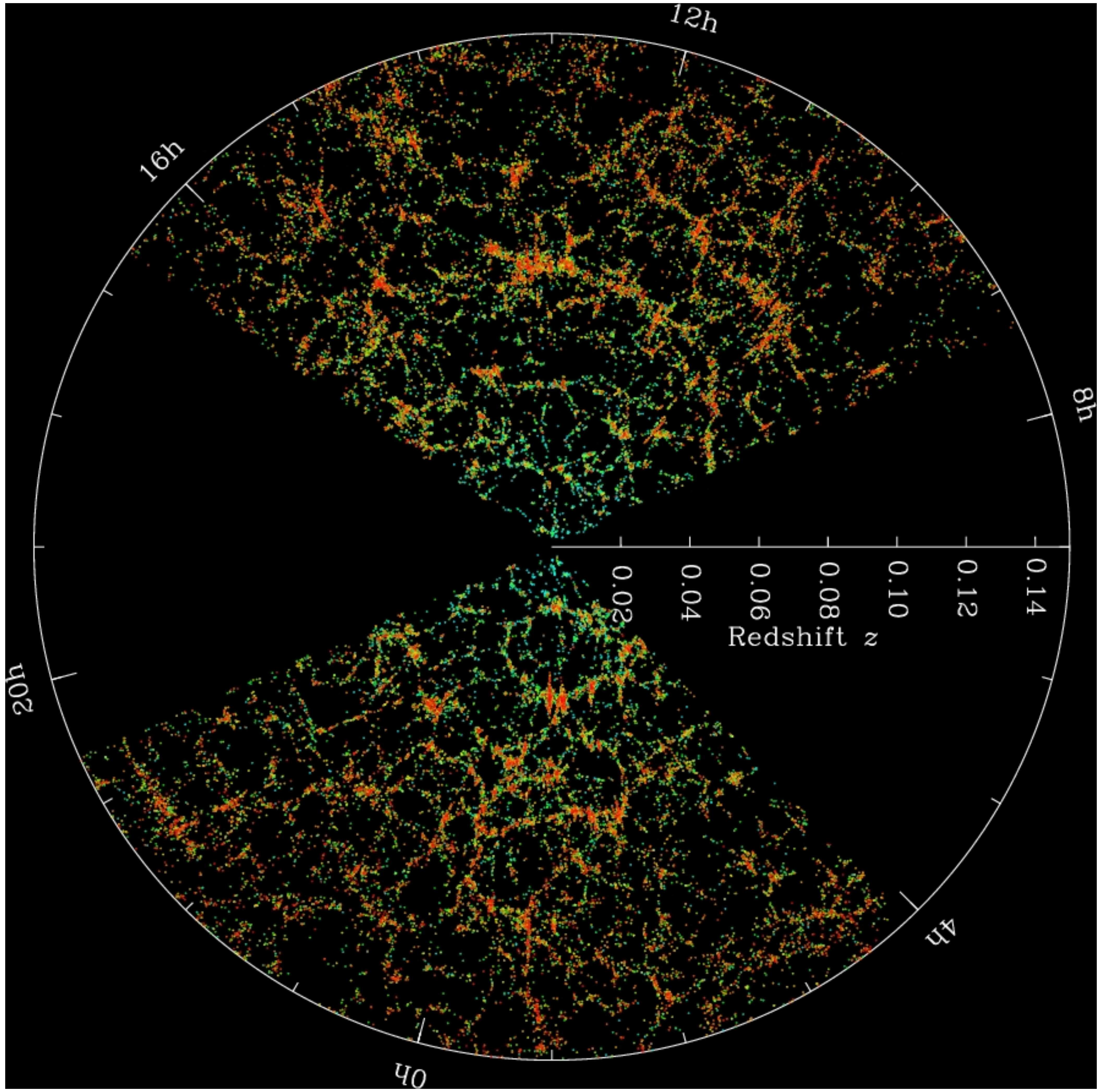
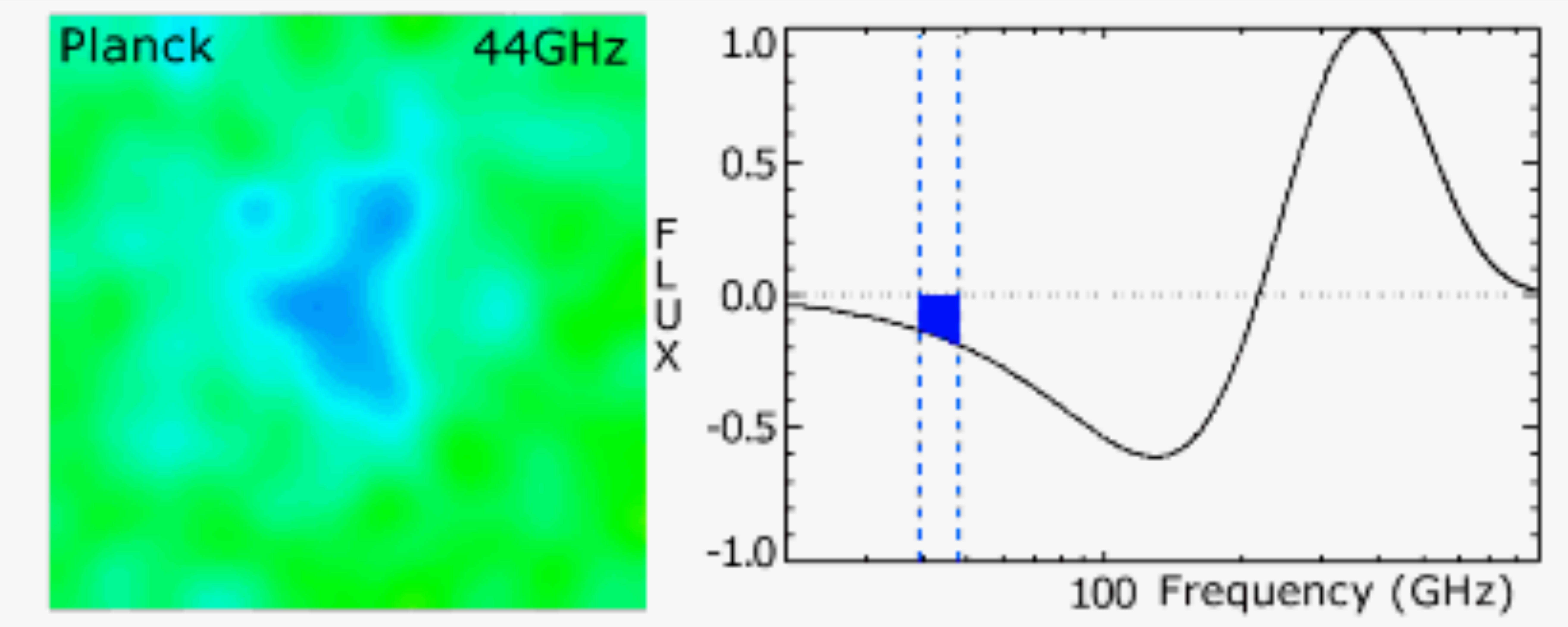
Cosmological probe

- Understand properties of the dark energy → **study the LSS**
- Expansion vs gravity
- Observation: distribution of DM
- Weak lensing, photometric catalog, CMB lensing
- Add **secondary effect** as thermal Sunyaev Zel'dovich effect and use cross correlation → reduce uncertainties



Electromagnetic spectrum

- tSZ produces a **distortion** of the CMB power spectrum
- Amplitude depend on the frequency

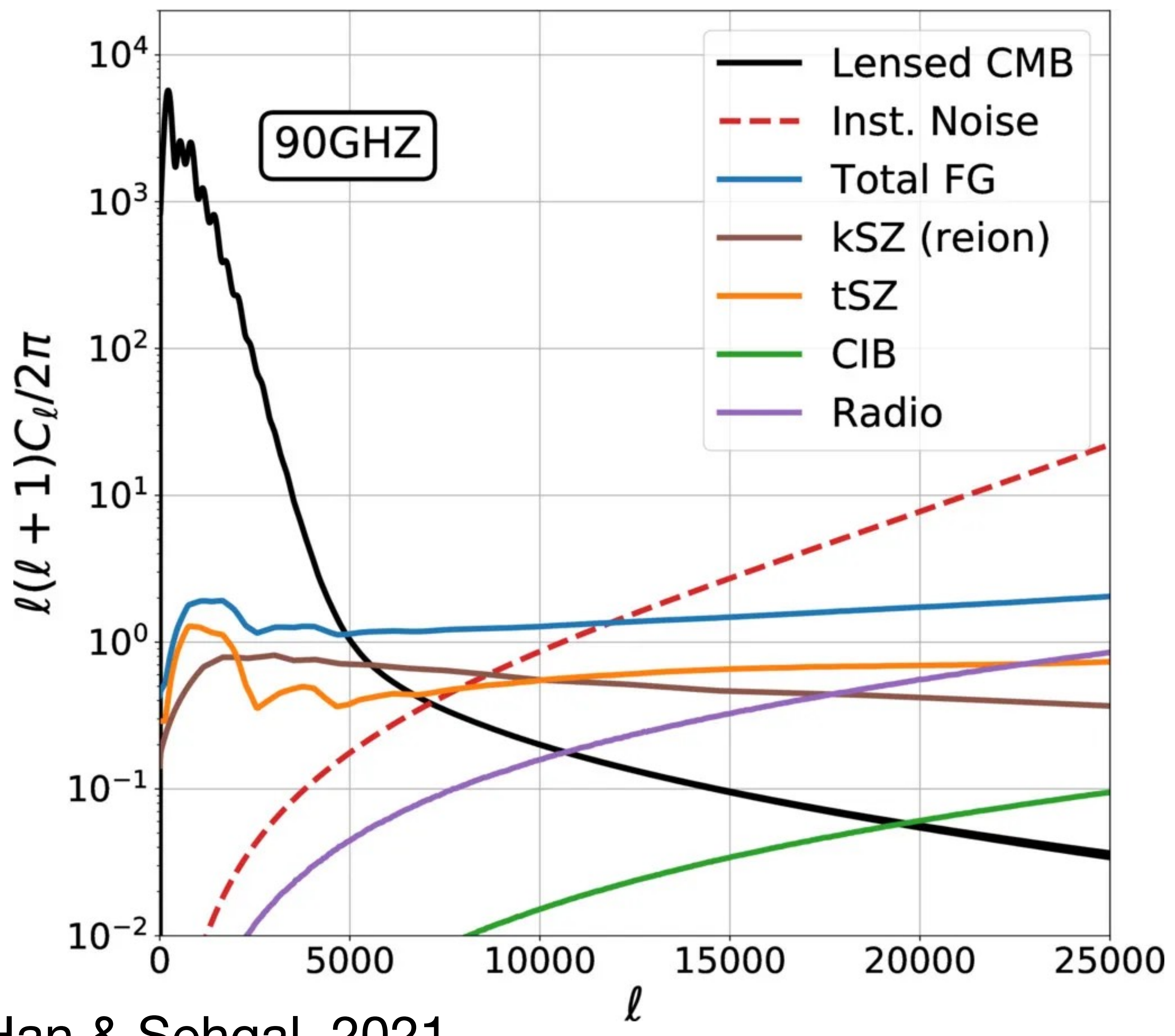


ESA/Planck collaboration

tSZ observation

- Observation of the **full sky** with, eg, Planck
- tSZ if a **foreground**

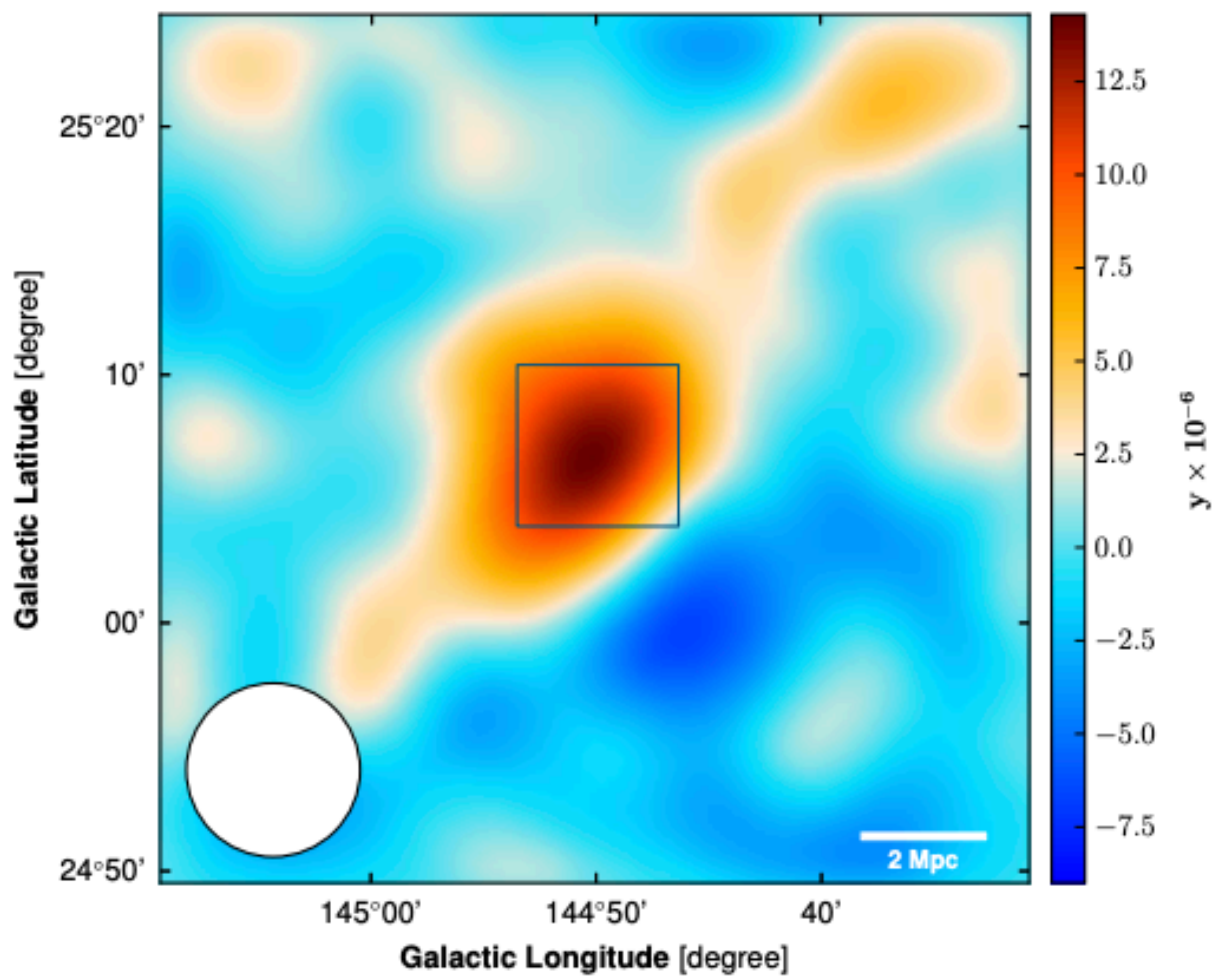
Expected power spectra for a CMB-HD survey



Han & Sehgal, 2021

- Observation of **haloes** with, eg, NIKA-2
- Target halos to measure their pressure along the line of sight

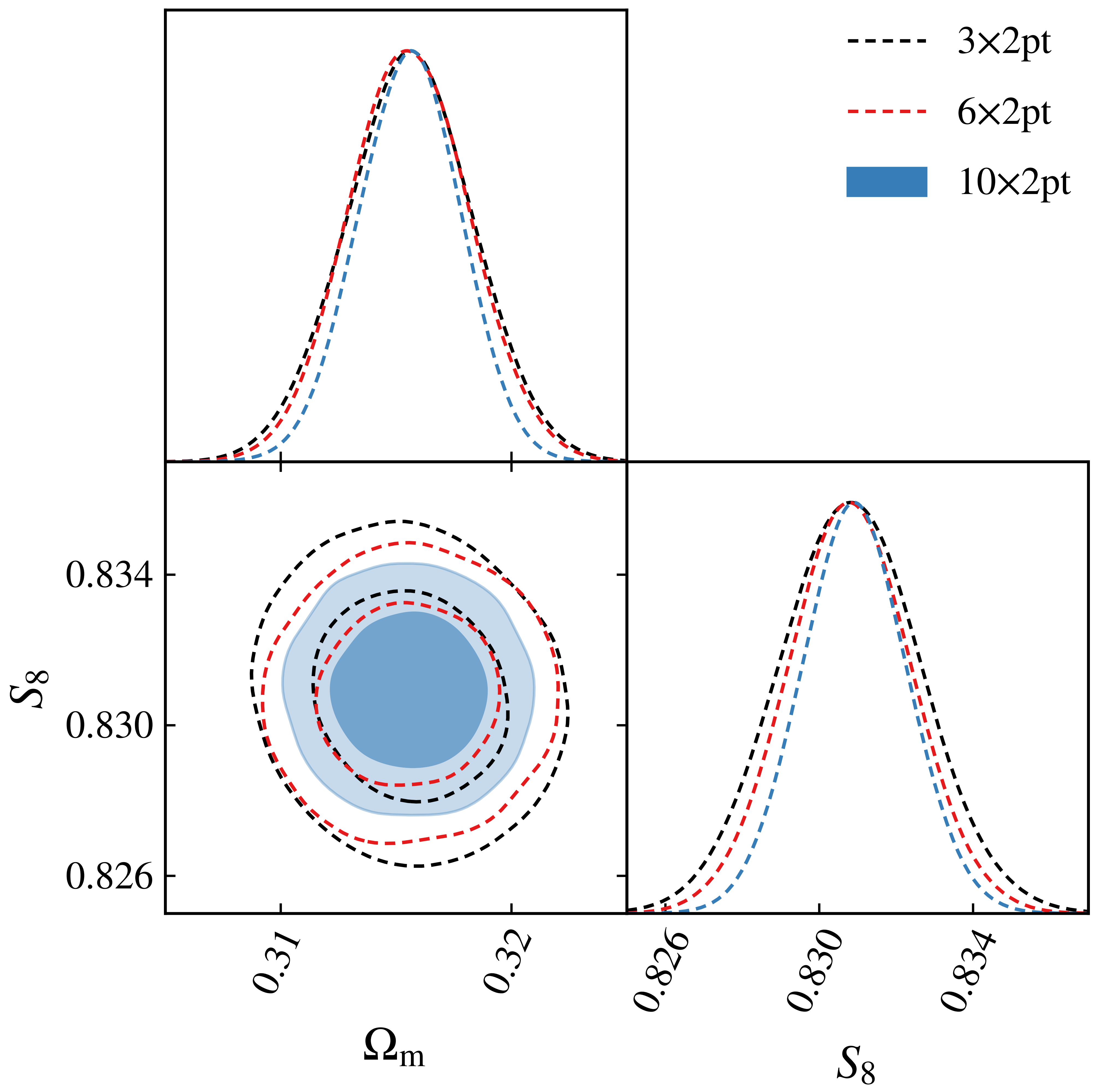
$y \times 10^{-6}$



10x2pt

- Prepare **cross correlation analysis**, extend 3x2pt to first 10x2pt: Weak lensing, CMB lensing, Galaxy survey, tSZ
- Break degeneracies in cosmological parameters or bias

Forecast LSST Y6 x SO Y5

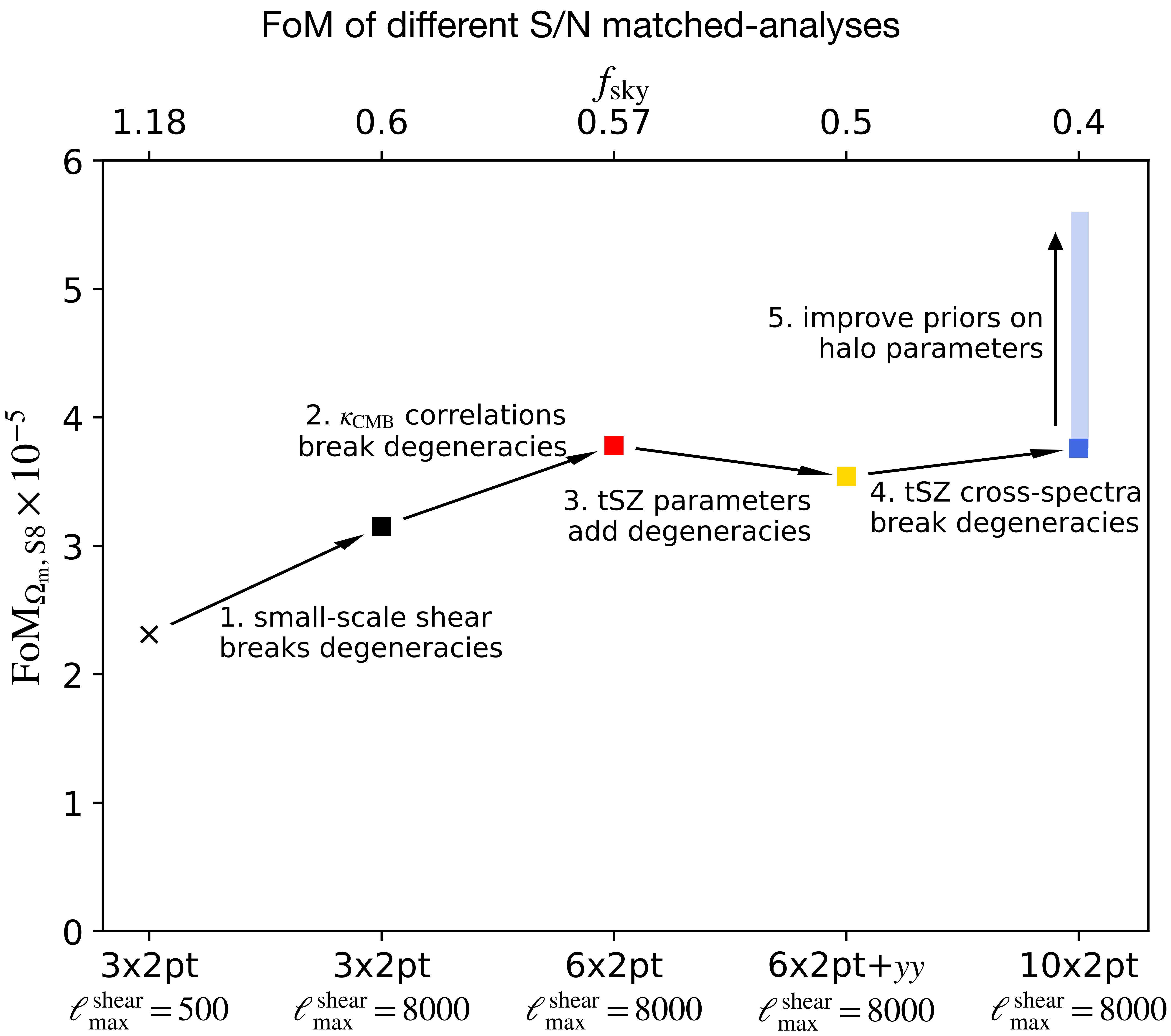


Fang et al., accepted by MNRAS
arXiv: 2308.01856

10x2pt

- To increase the constrain: need to **improve priors on halo parameters**
- $\epsilon_1, \epsilon_2, \Gamma$: parameters that impact the more the prediction by the halo model

$\Rightarrow$ Have a **robust tSZ halo model**



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Simulations comparison

Simulation	Size	Resolution	DM particles	Code used	k_{max}
Horizon AGN & Horizon no-AGN	$100h^{-1}$Mpc	$8 \times 10^{7} M_{\odot}$	1024^3	RAMSES	~30 hMpc^{-1}
Horizon 896hMpc	$896h^{-1}$Mpc	$6 \times 10^{10} M_{\odot}$	1024^3	RAMSES	~3 hMpc^{-1}
Magneticum	$896h^{-1}$Mpc	$2 \times 10^{10} M_{\odot}$	1512^3	GADGET	~5 hMpc^{-1}
Bahamas	$400h^{-1}$Mpc	$5.5 \times 10^{9} M_{\odot}$ $1.14 \times 10^{9} M_{\odot}$	1024^3	GADGET	~7 hMpc^{-1}

\+ different subgrids physics

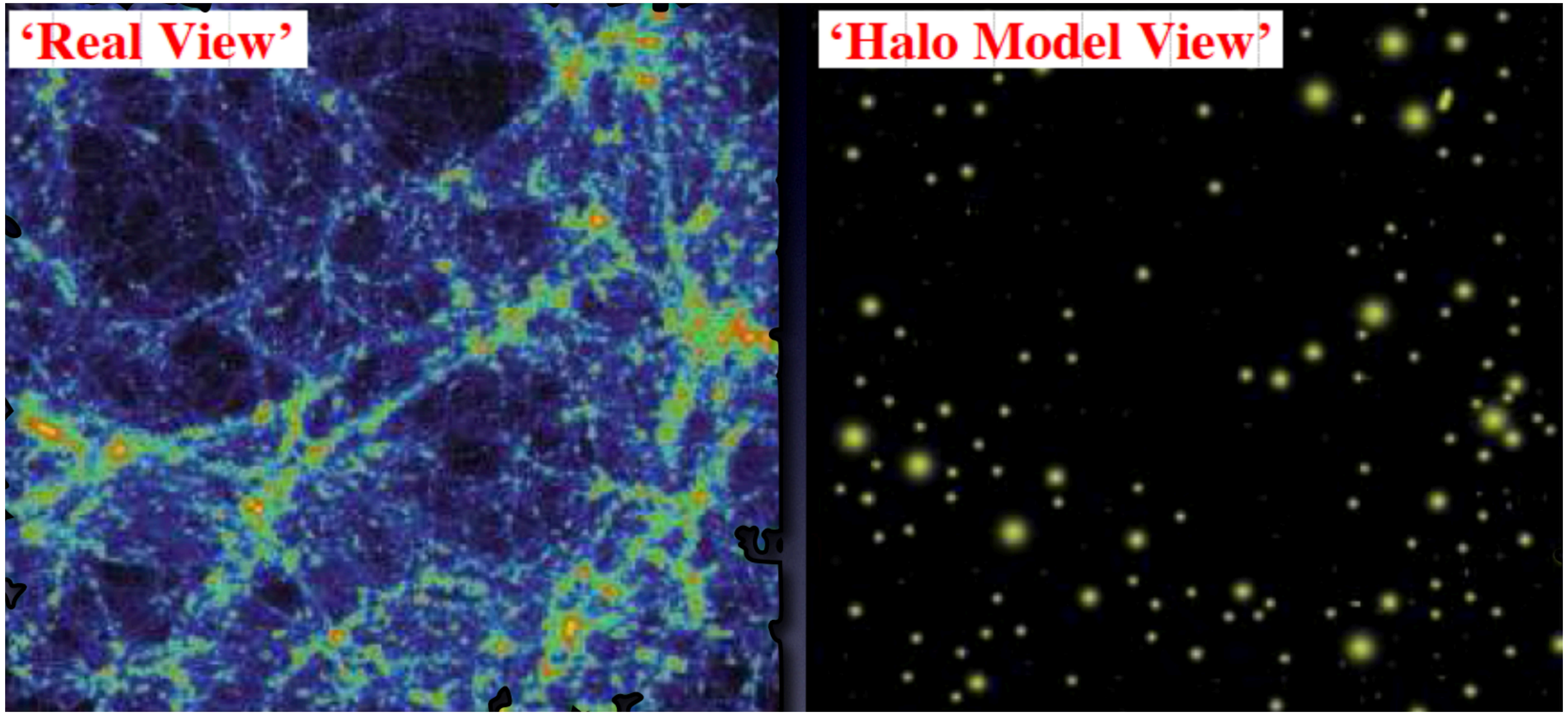
Used for HMcode: fitted for k between 0.015 and 7 hMpc^{-1}

Analytical prediction with HMcode

A. Mead et al., 2015 & A. Mead et al., 2021

- Fortran code: compute power spectrum and cross correlation
- Can be use for matter, pressure, DM, CIB,…
- Hypothesis on **profiles** and **other ingredients**
- Use an **halomodel**
- Power spectrum:
  - **1-halo term**: 2 points in the same halo → FT of the profile
  - **2-halo term**: 2 points in 2 halos
- Calibrated to match power spectrum of **BAHAMAS**

Halo model



© http://www.astro.yale.edu/vdbosch/astro610_lecture13.pdf

- Analytical model: all the matter is partitioned over spherical haloes

- Ingredients:
    - **Halo mass function** $n(M)$: distribution of haloes in a mass range
    - **Halo bias function** $b(M)$: how haloes cluster relative to matter
    - **Halo density profiles**

Halo model - power spectrum

$$P(k) = P^{1h}(k) + P^{2h}(k)$$

$$P^{1h}_{uv}(k) = \int_0^\infty W_u(M,k) W_v(M,k) n(M) dM$$

$$P^{2h}_{uv}(k) = P_{lin}(k) \prod_{i=u,v} \left[\int_0^\infty b(M) W_i(M,k) n(M) dM \right]$$

- FT of the field $u(r), v(r)$ we want to correlate
- Halo mass function
- Linear halo bias
- Linear matter power spectrum

Halo model - Electronic pressure profile

$$P_e(M,r) = \frac{\rho_{bnd}(M,r)}{m_p \mu_e} k_B T_g(M,r)$$

$$\rho_{bnd}(M,r) \propto \left[\frac{ln(1+r/r_s)}{r/r_s}\right]^{1/(\Gamma-1)}$$

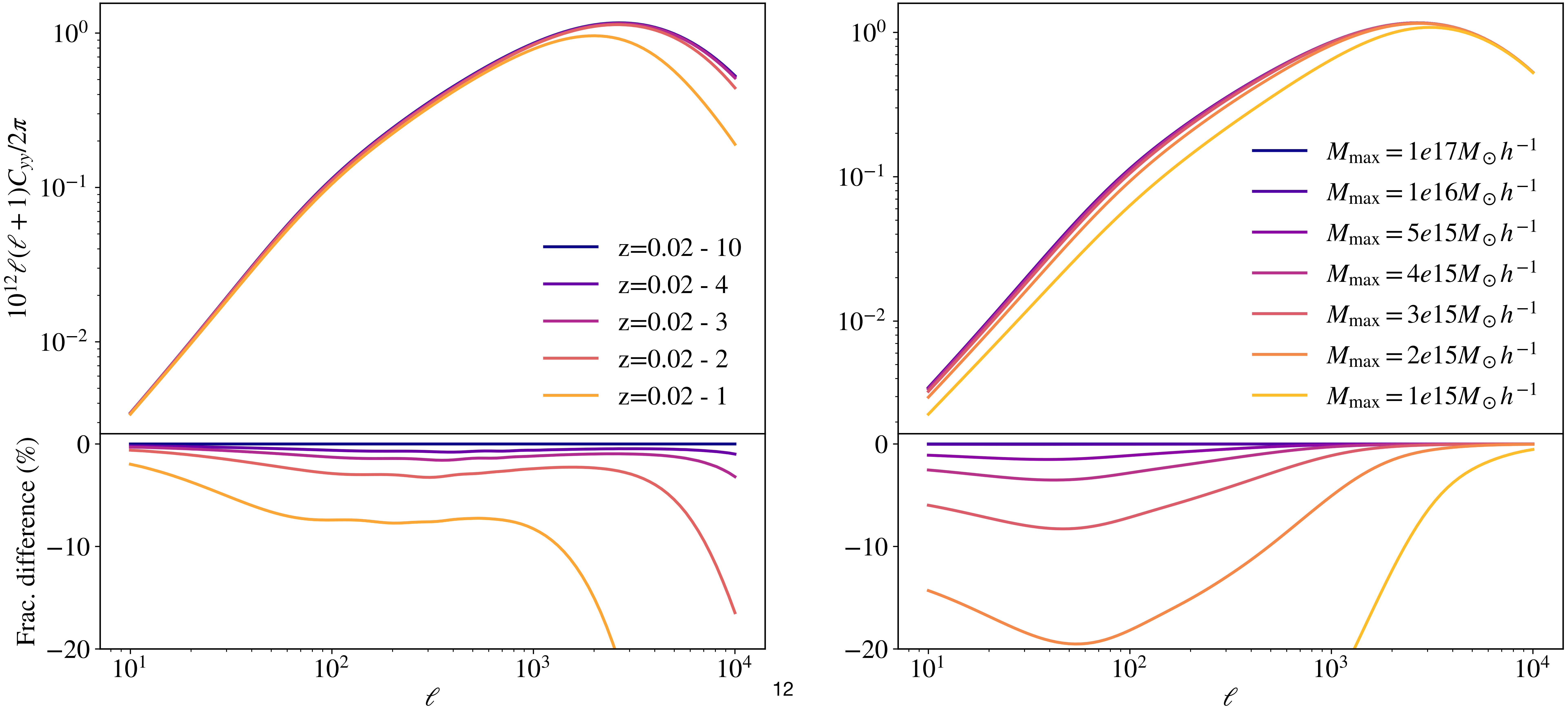
$$T_g(M,r) = T_v(M)\frac{ln(1+r/r_s)}{r/r_s}$$

- Density profile → Komatsu & Seljak (2001)
- Gas temperature depend on virial temperature
- Radius parameter r_s, $c = r_v/r_s$
- Polytropic index Γ

Angular power spectrum prediction

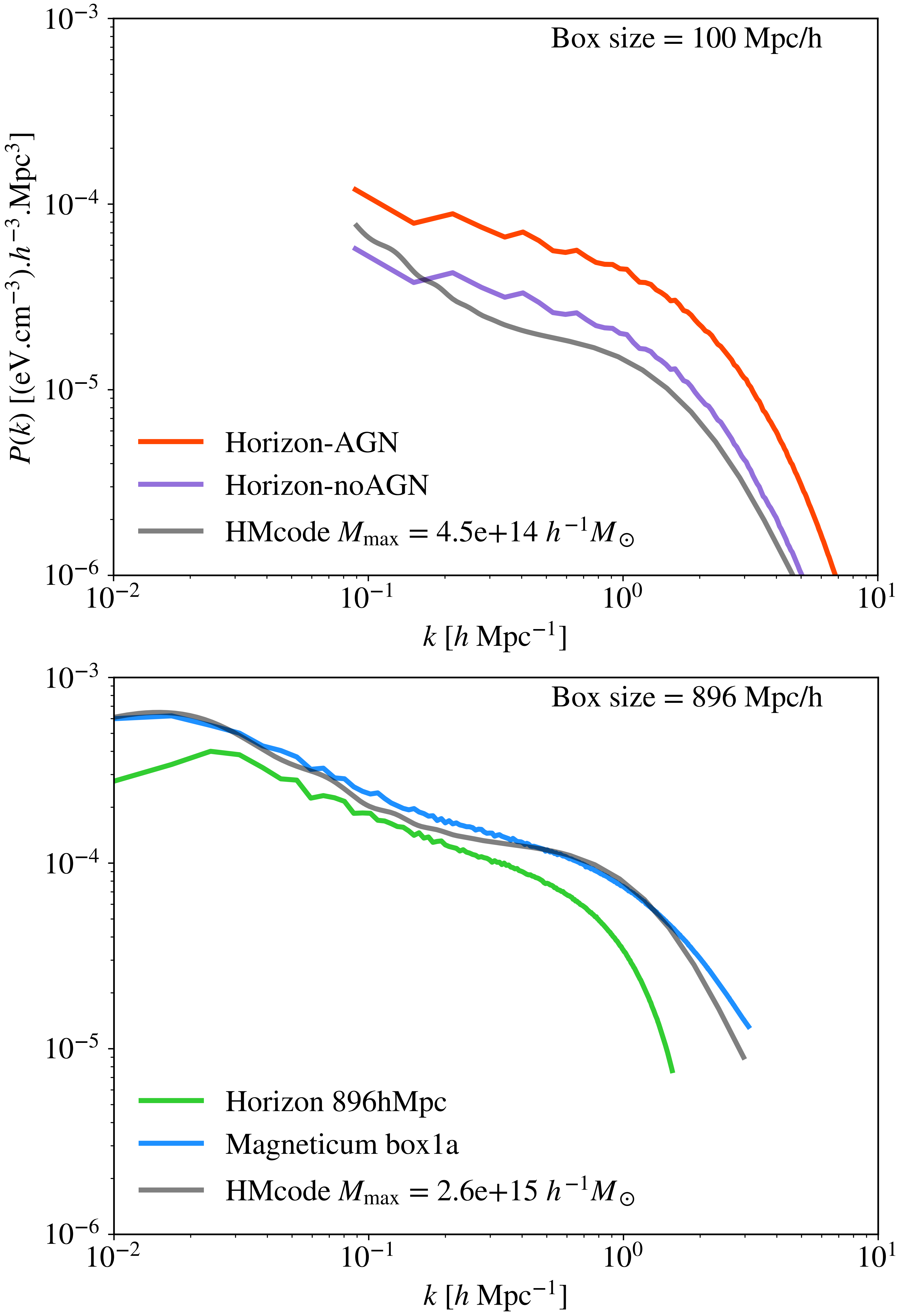
- Need to go **up to z=3-4** to have more than 95% of the signal

  & **up to** $M_{\rm max} = 4e15\, M_\odot\, h^{-1}$ to have more than 95% of the signal



Pressure power spectrum

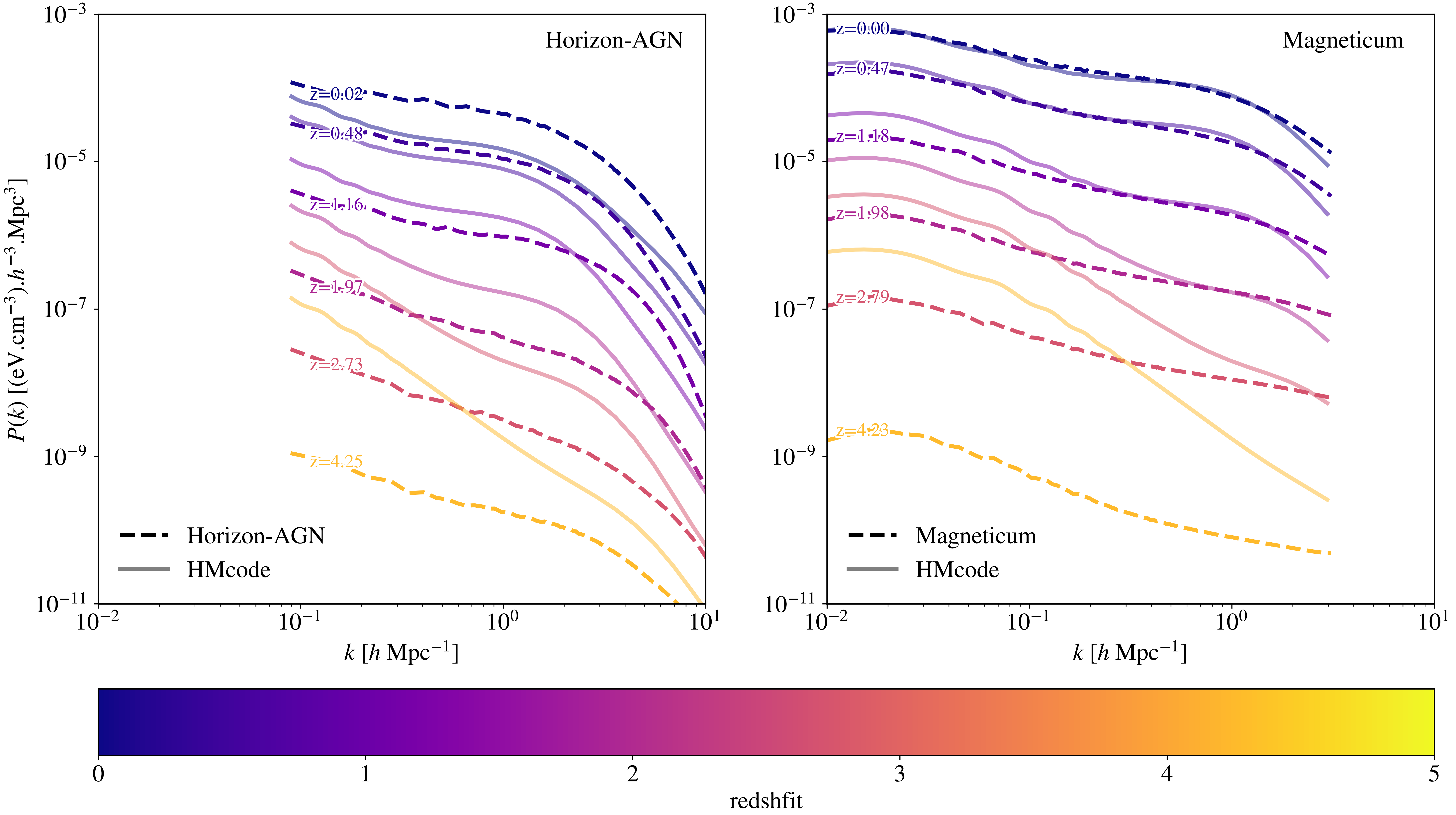
- z = 0
- **HAGN and H-noAGN**: excess of power
- **896hMpc**: lack of power
- **Magneticum**: ~ agreement
- What happen at the **halo scale** is dominant
- Choice of the ingredients of the model
- Choice of the maximum mass in HMcode



Aycoberry, et. al, in prep

Pressure power spectrum evolution with z

- Higher z: far from theory
- But how it propagates to the angular power spectrum?



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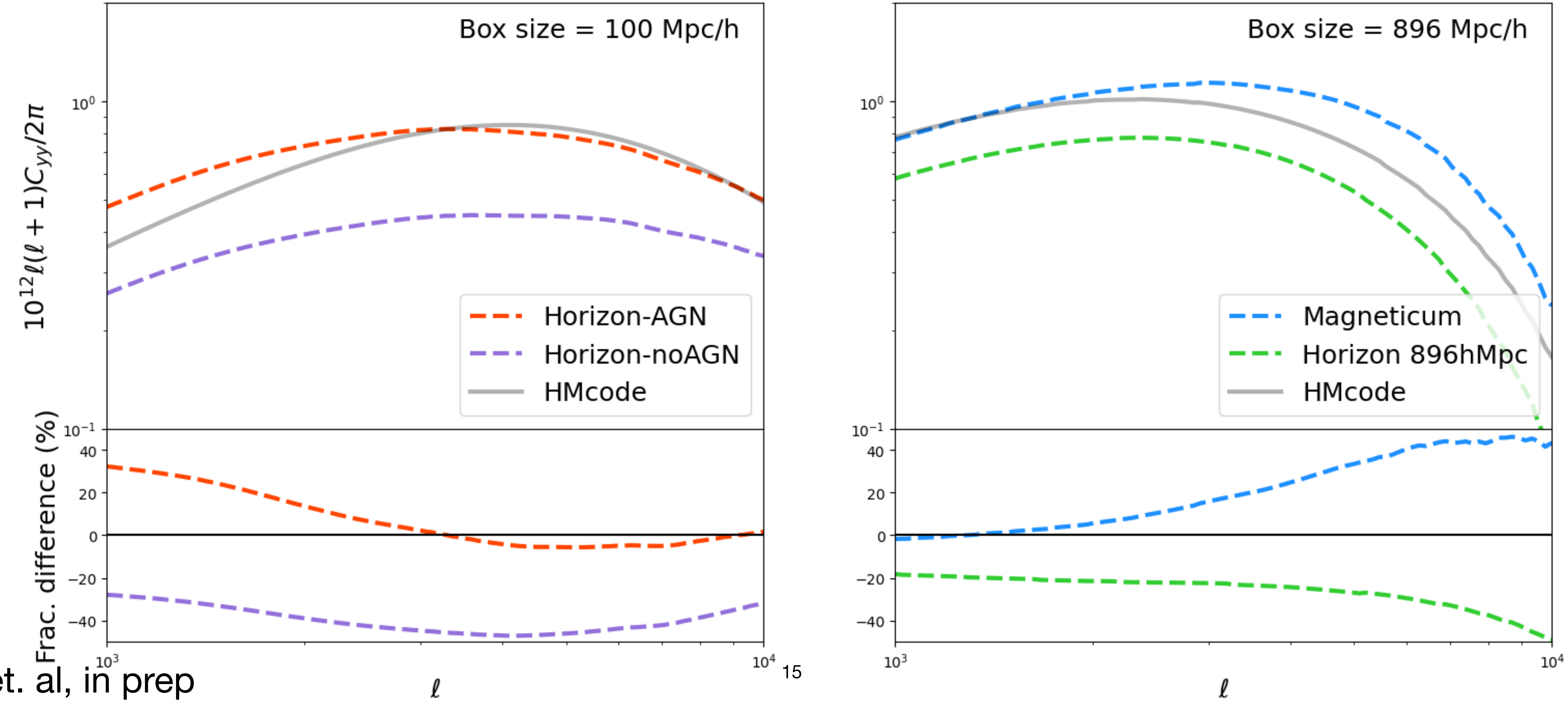
Angular power spectrum prediction

- Integrated between **z = 0.02 and z = 4**
- **HAGN** in good agreement, discrepancy compensate
- Missing power in H-noAGN and Horizon 896hMpc, excess in Magneticum



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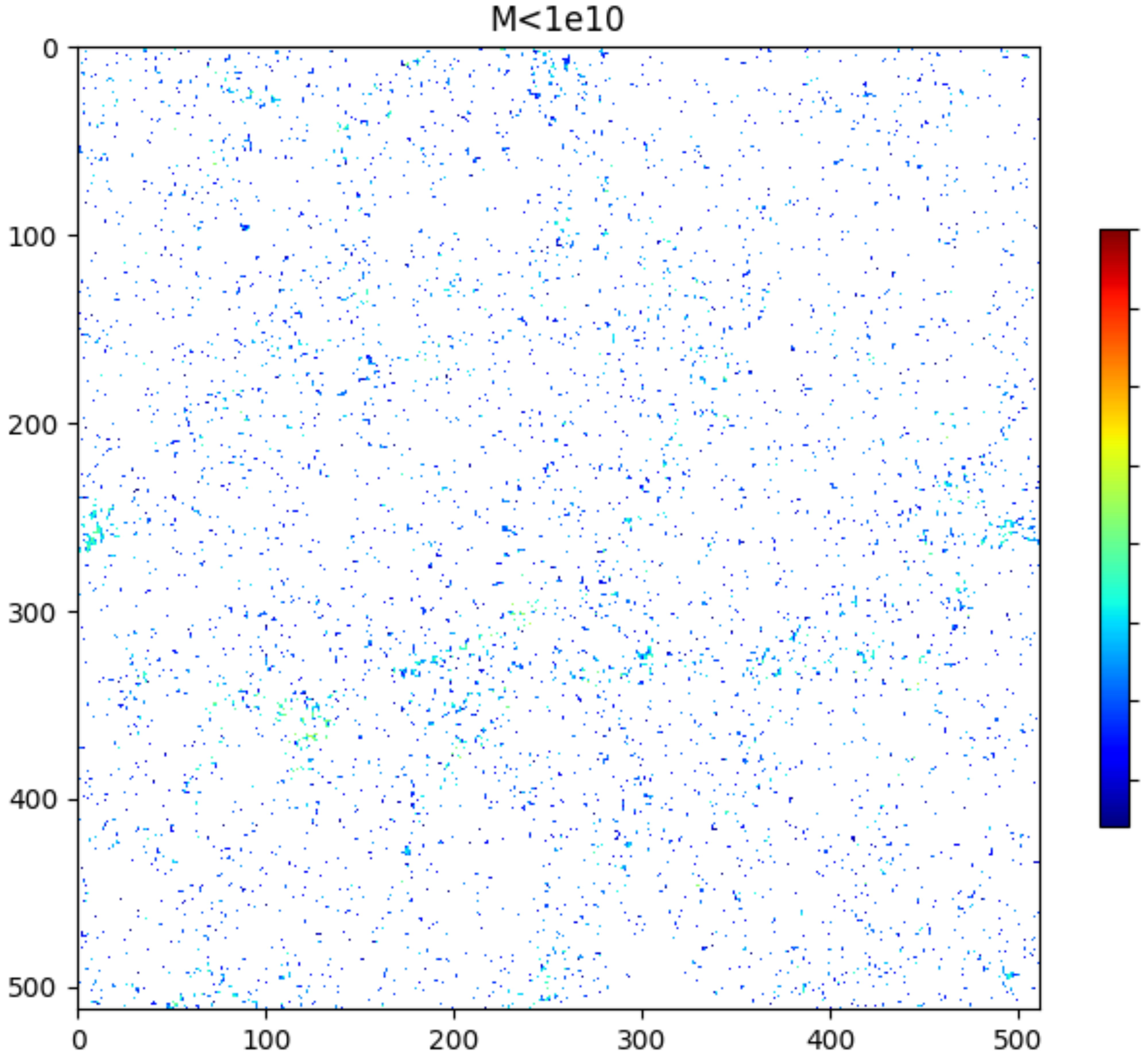
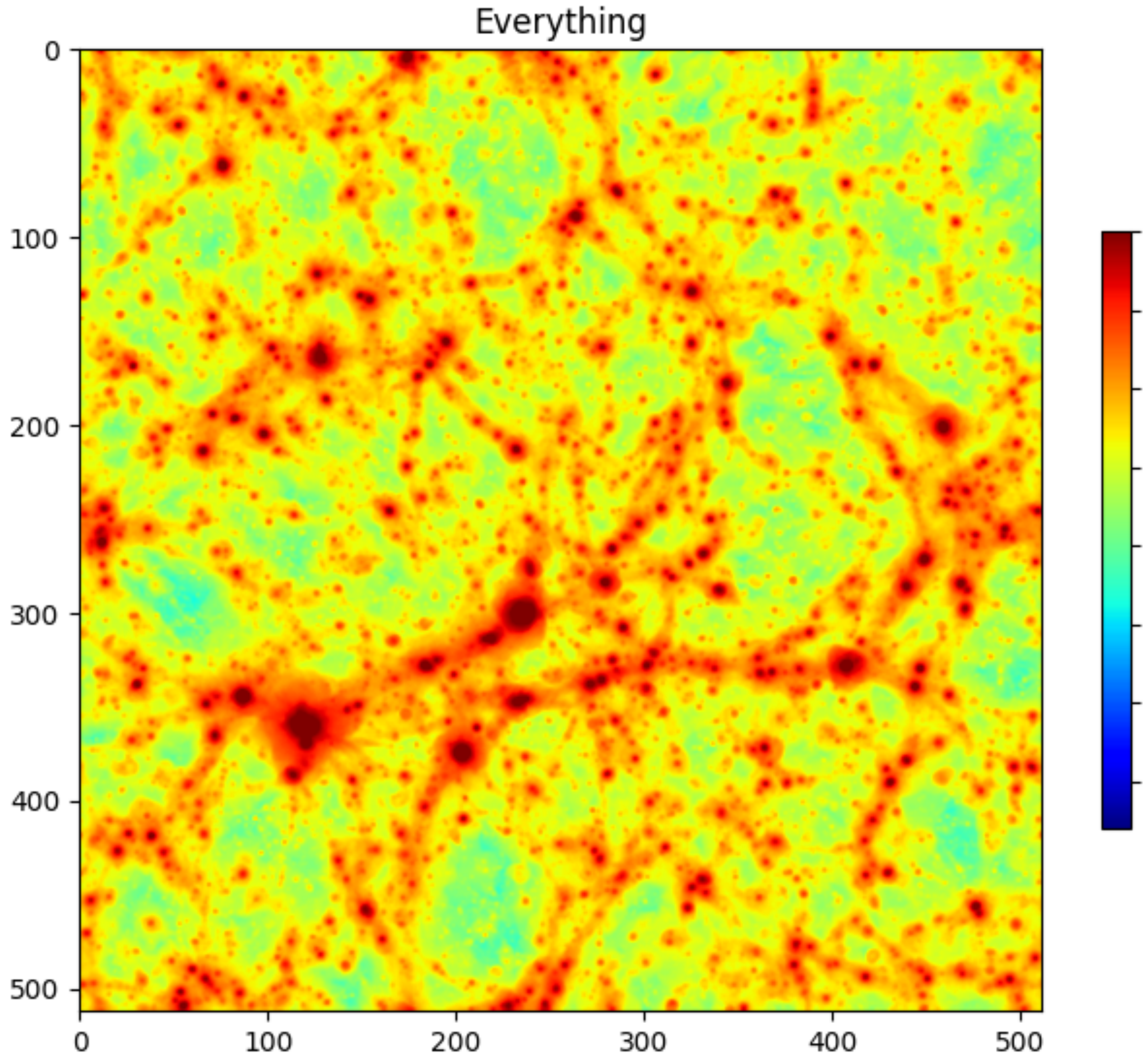
Which mass are important?





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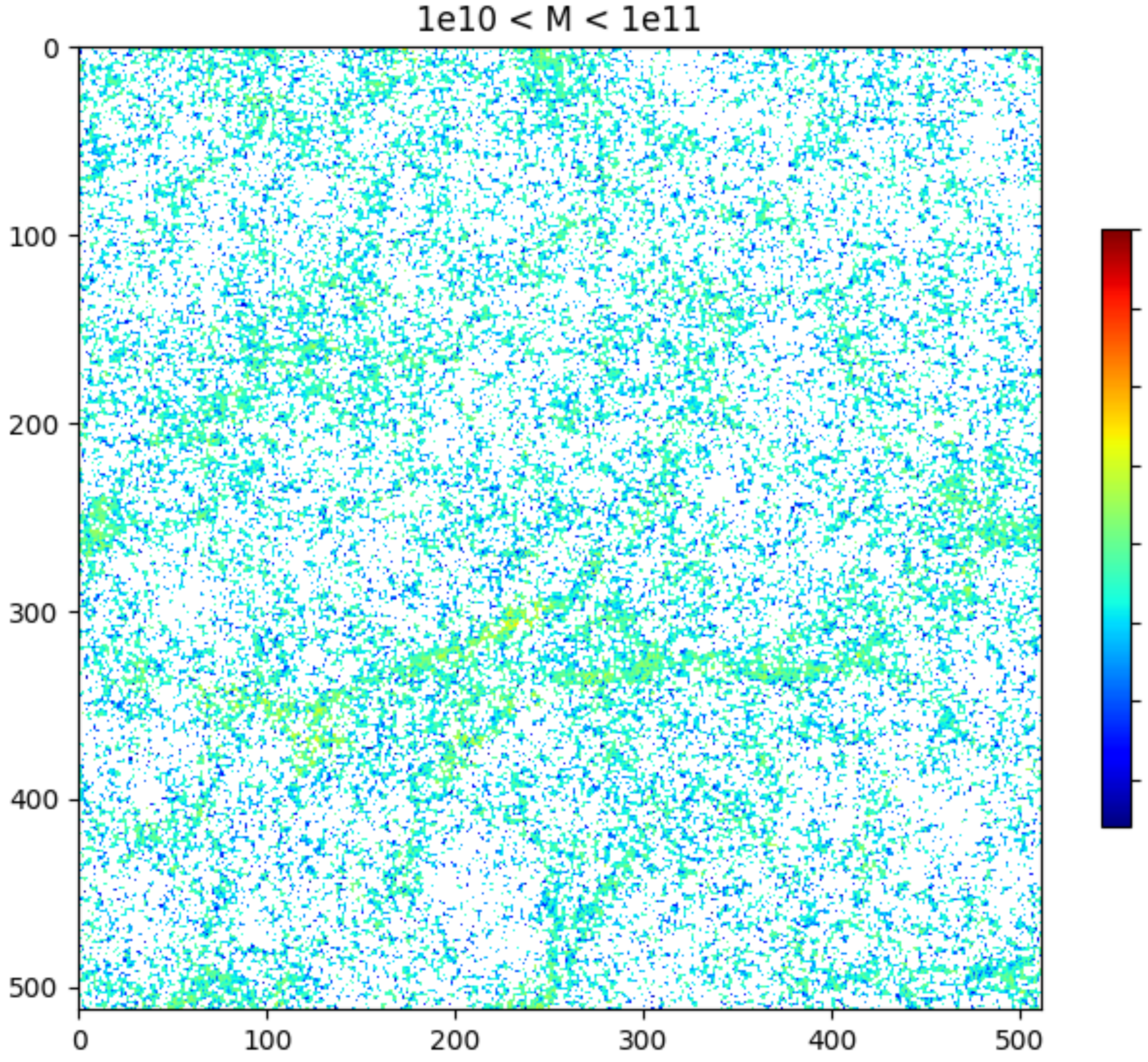

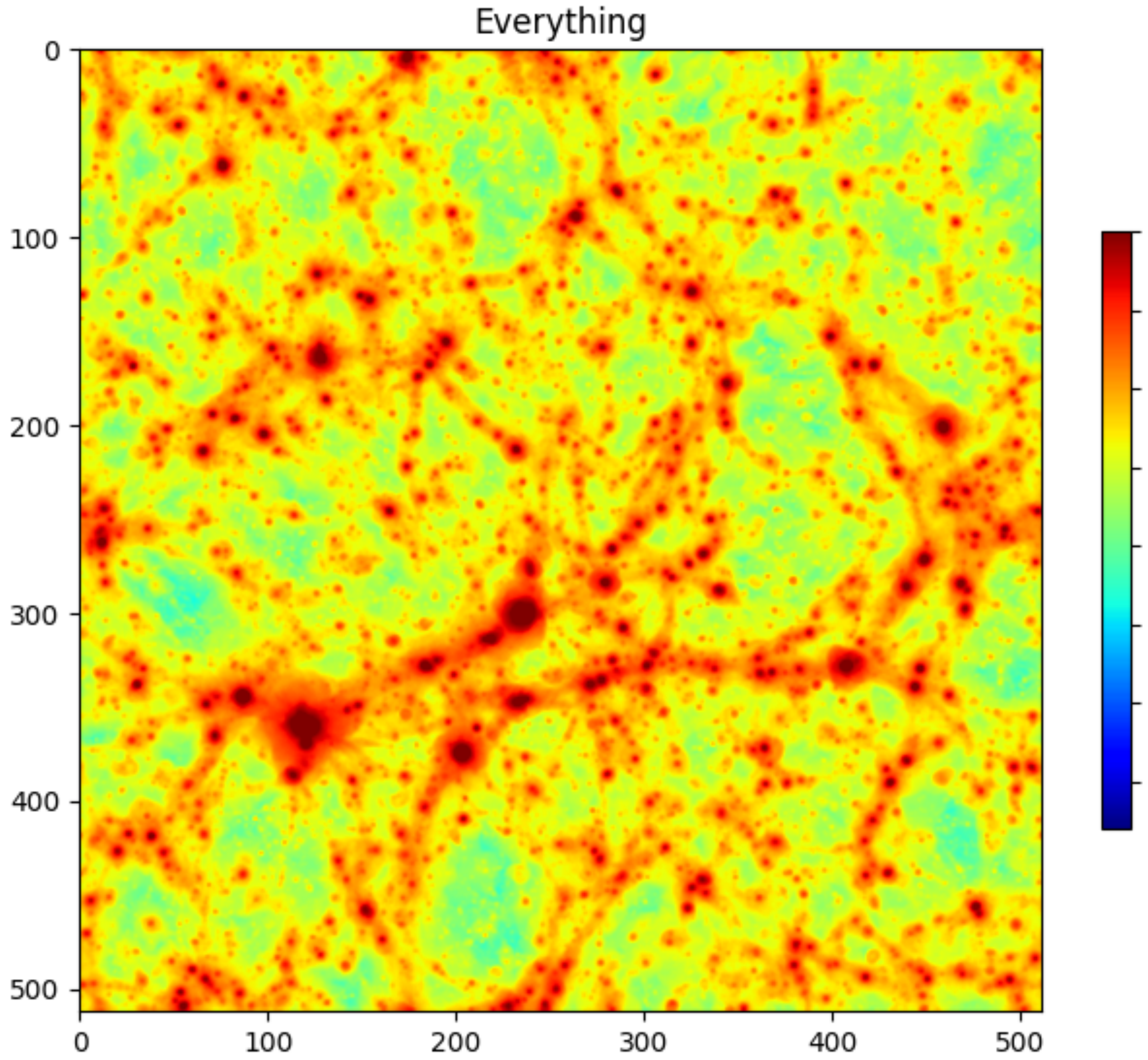

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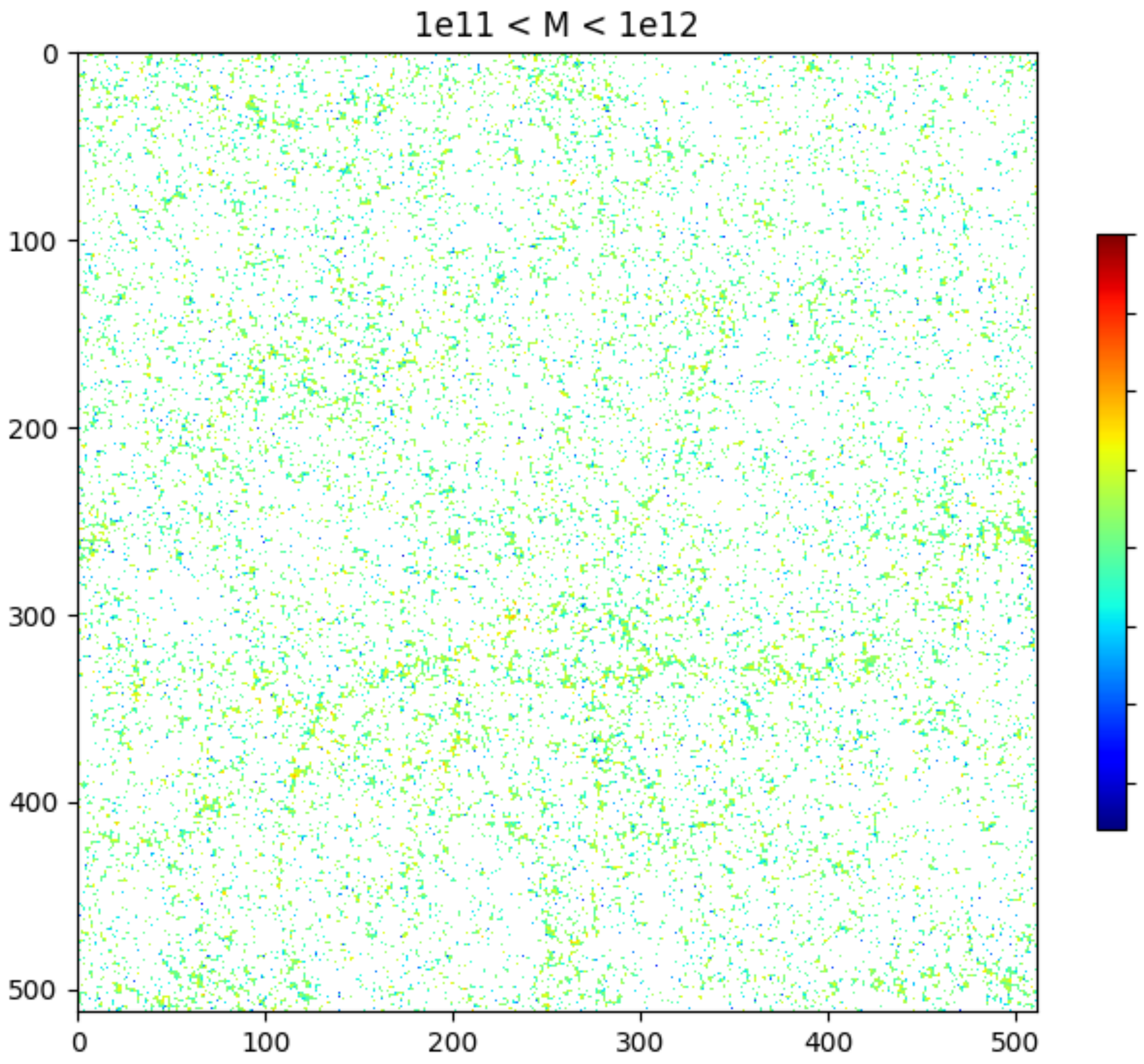

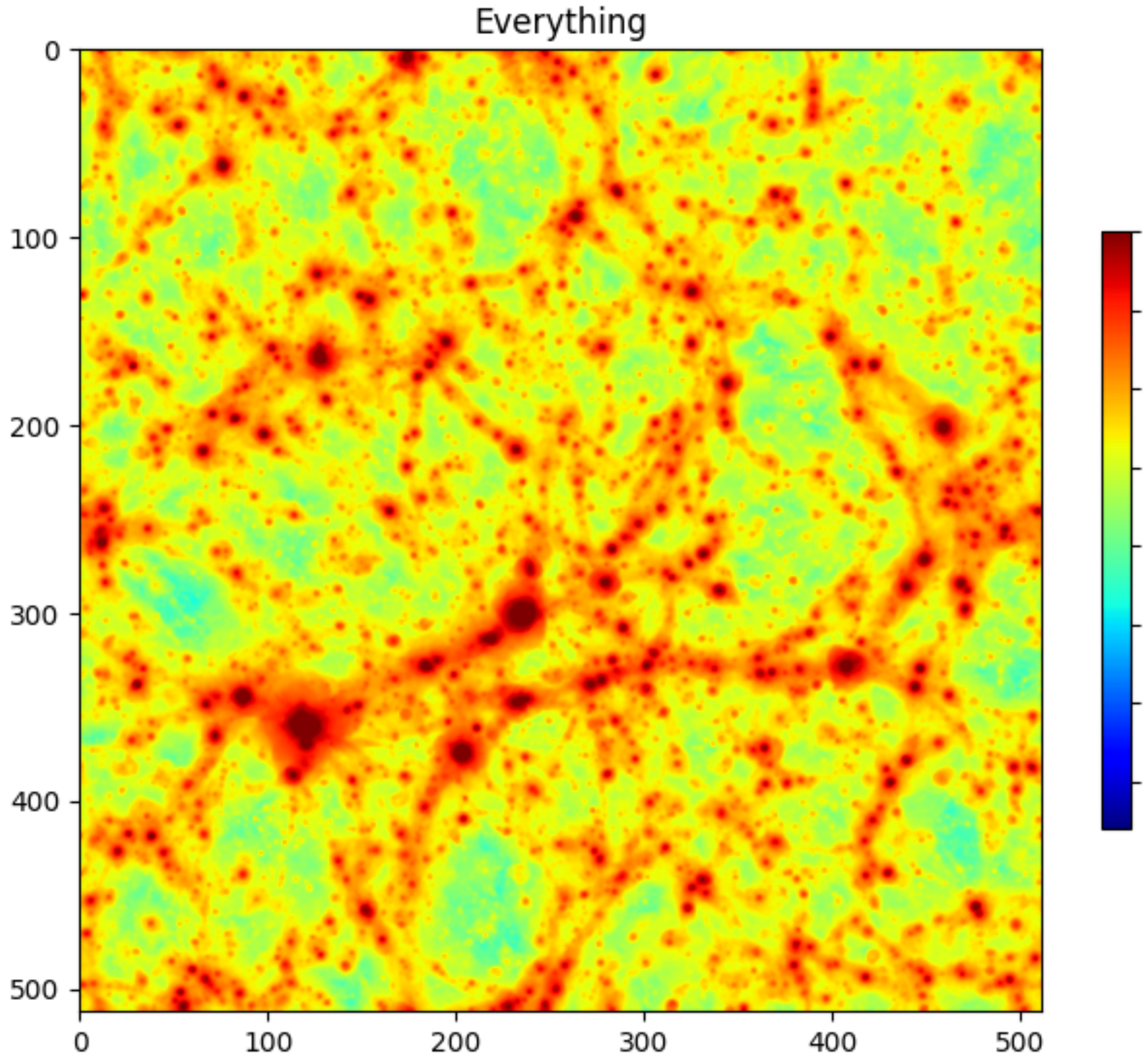

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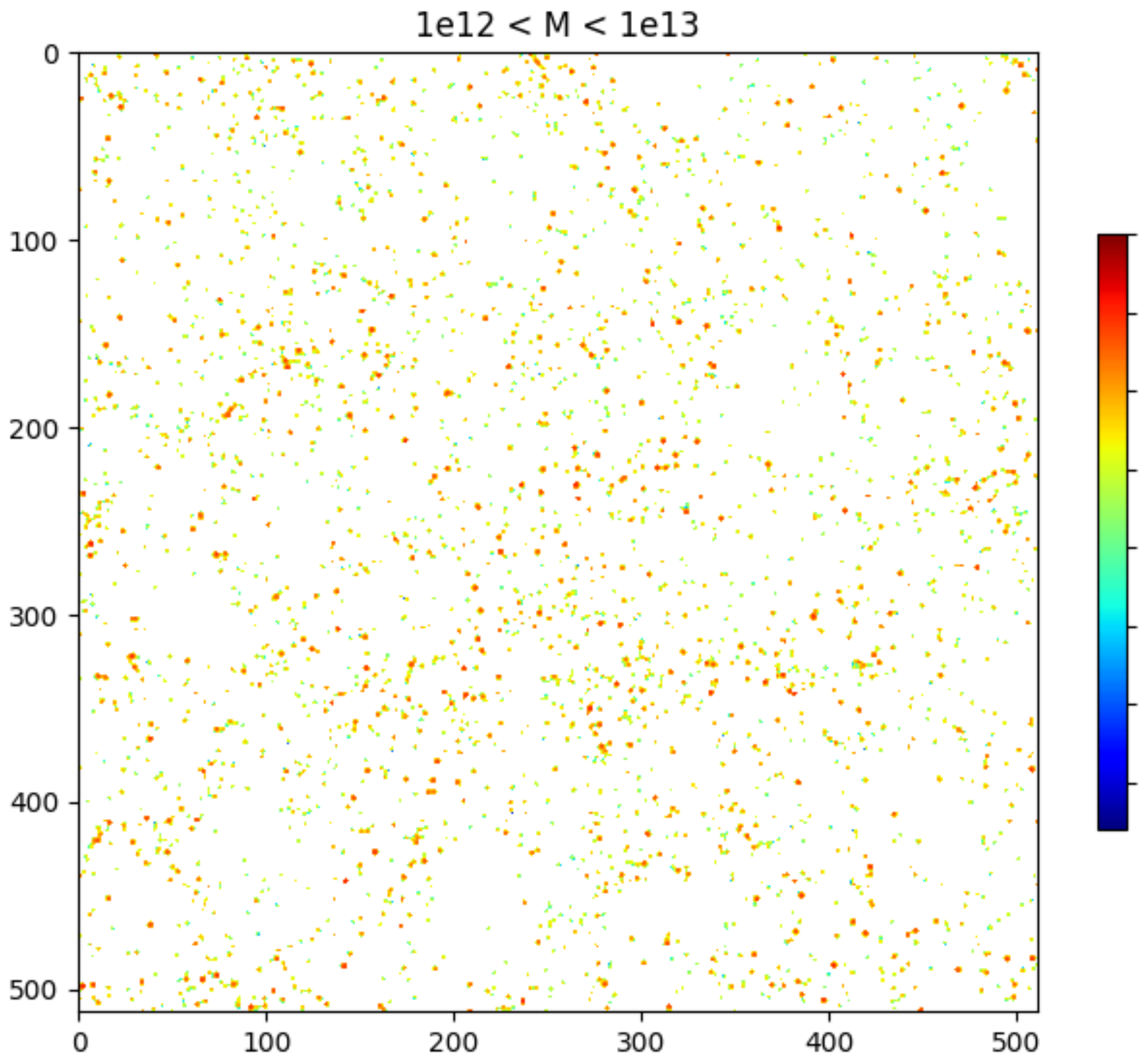

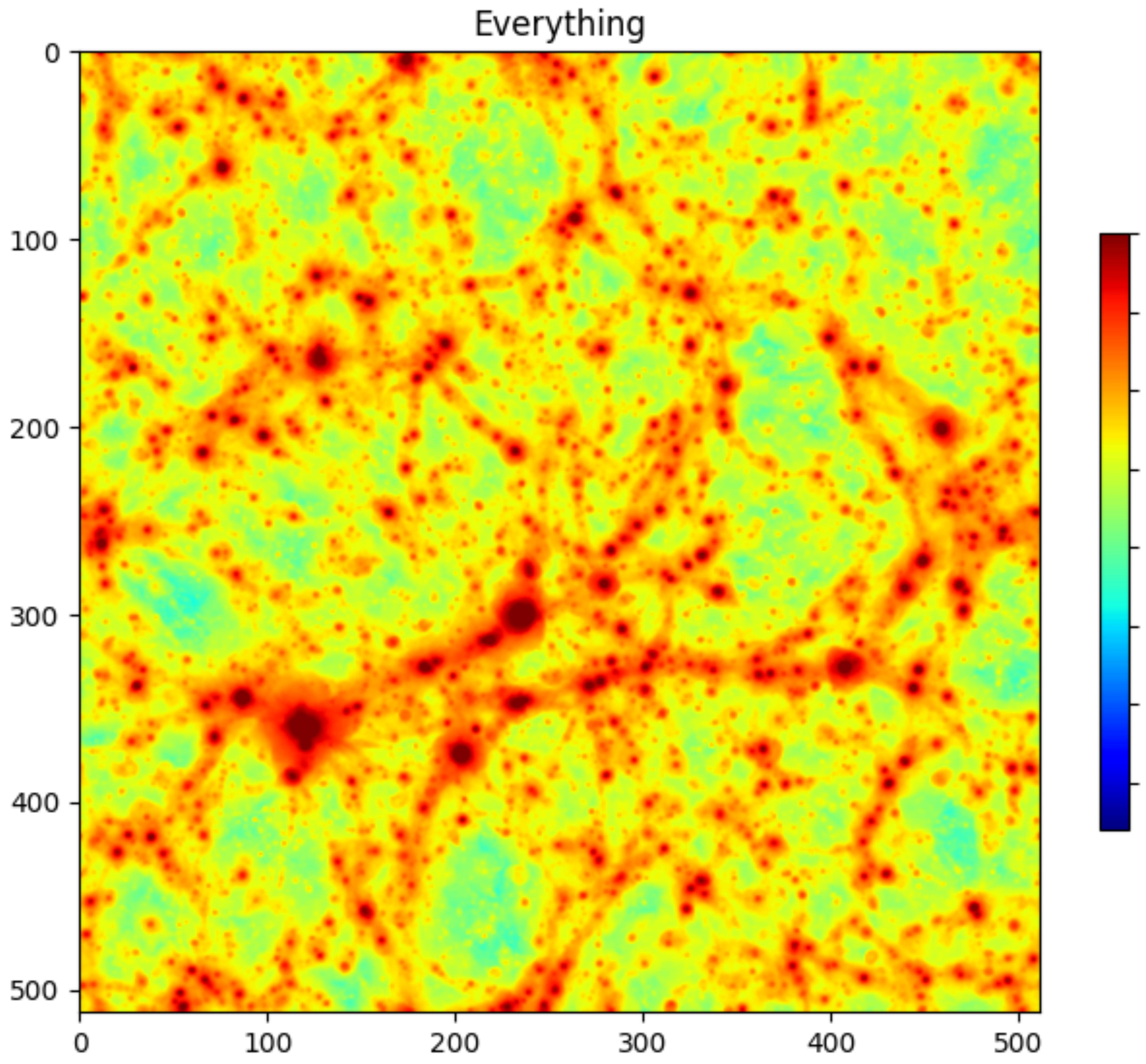

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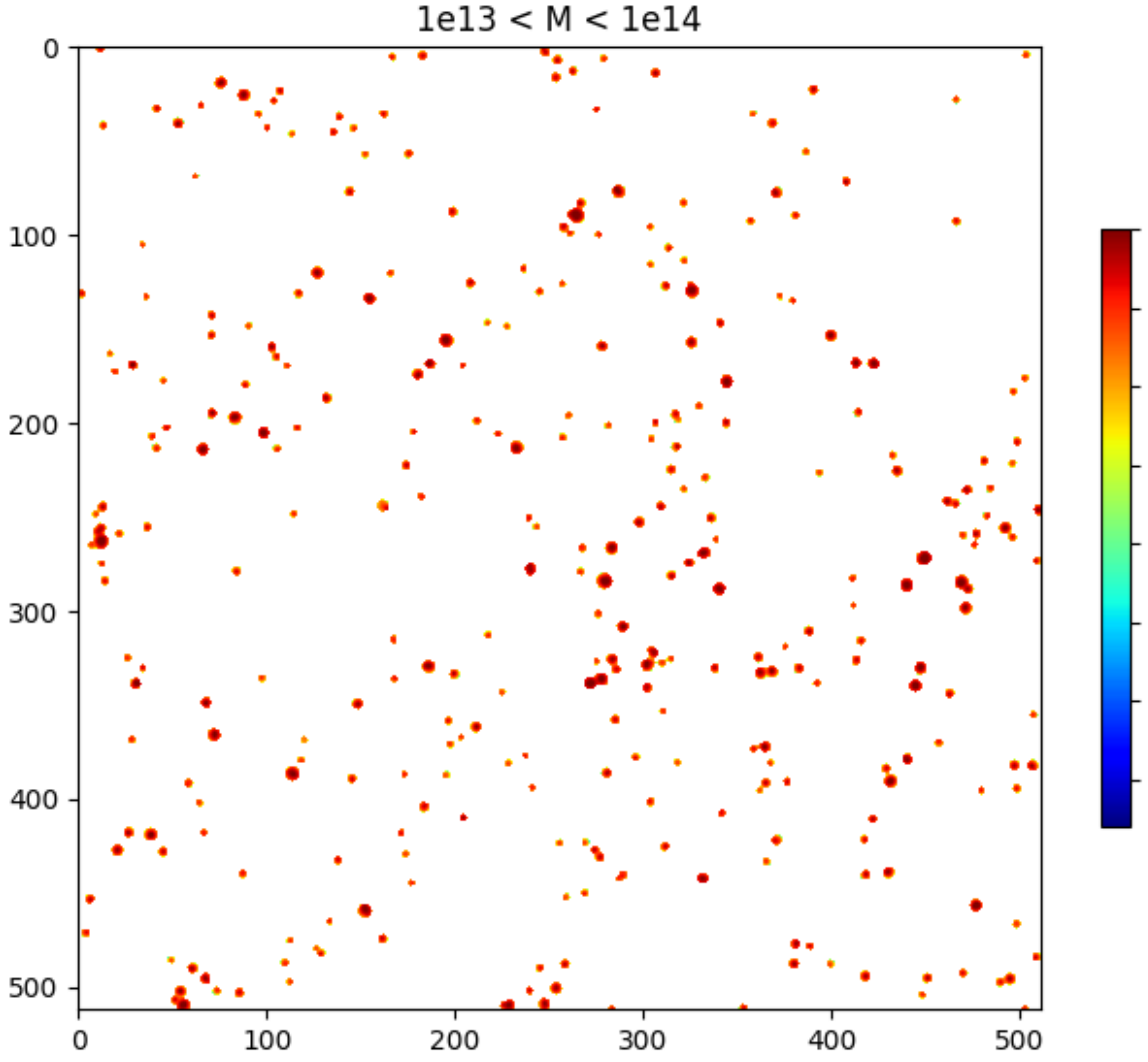

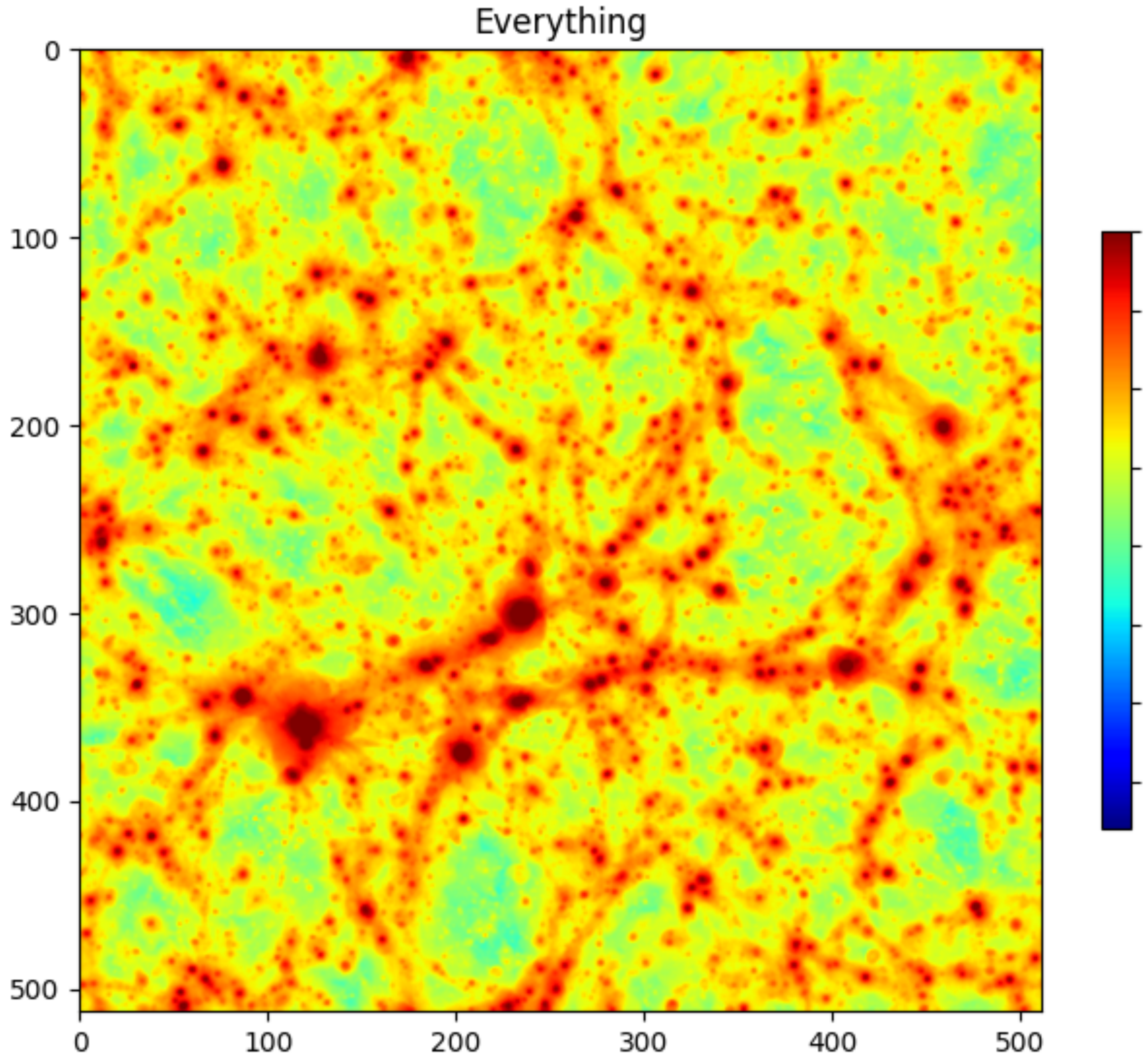

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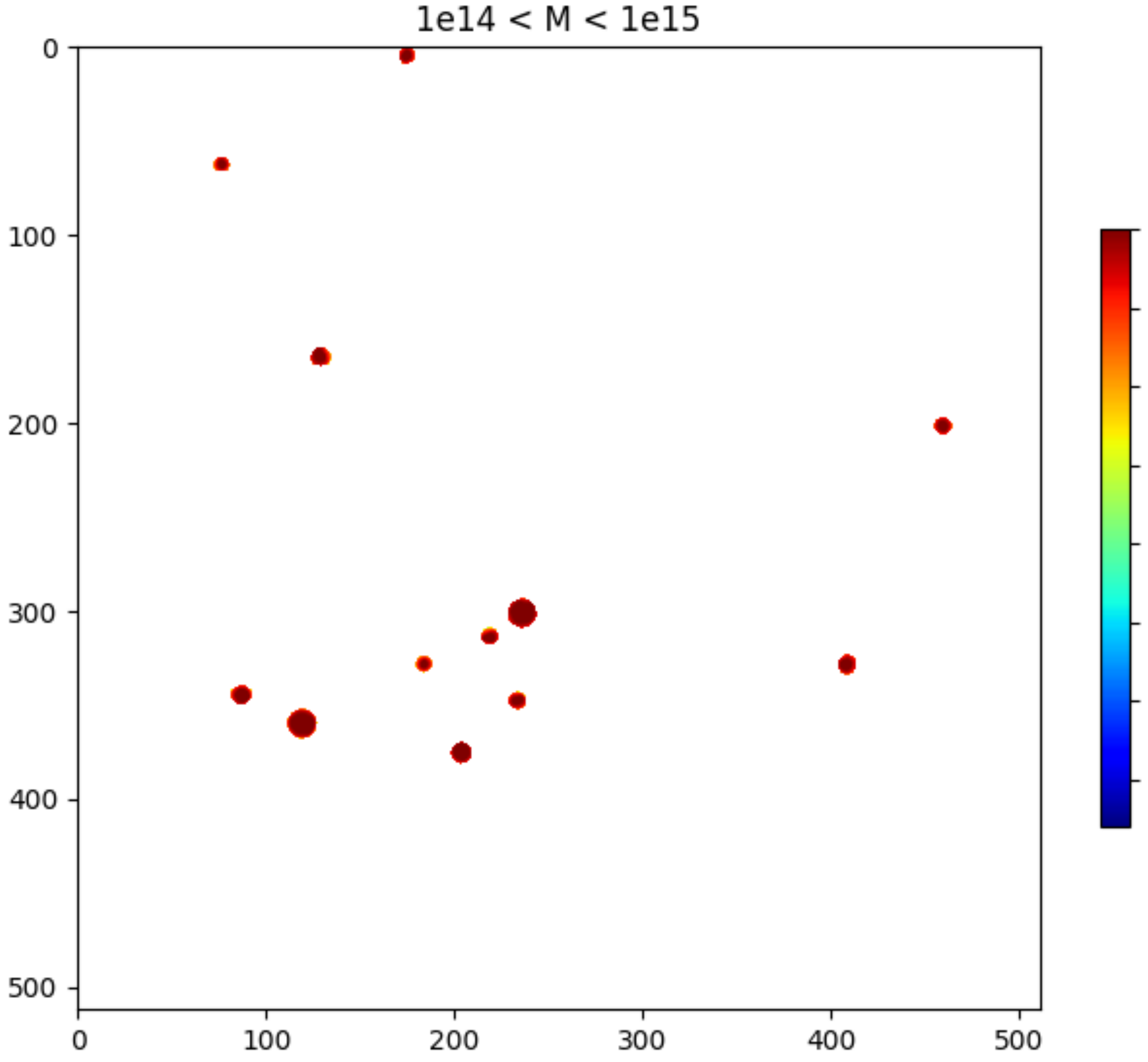
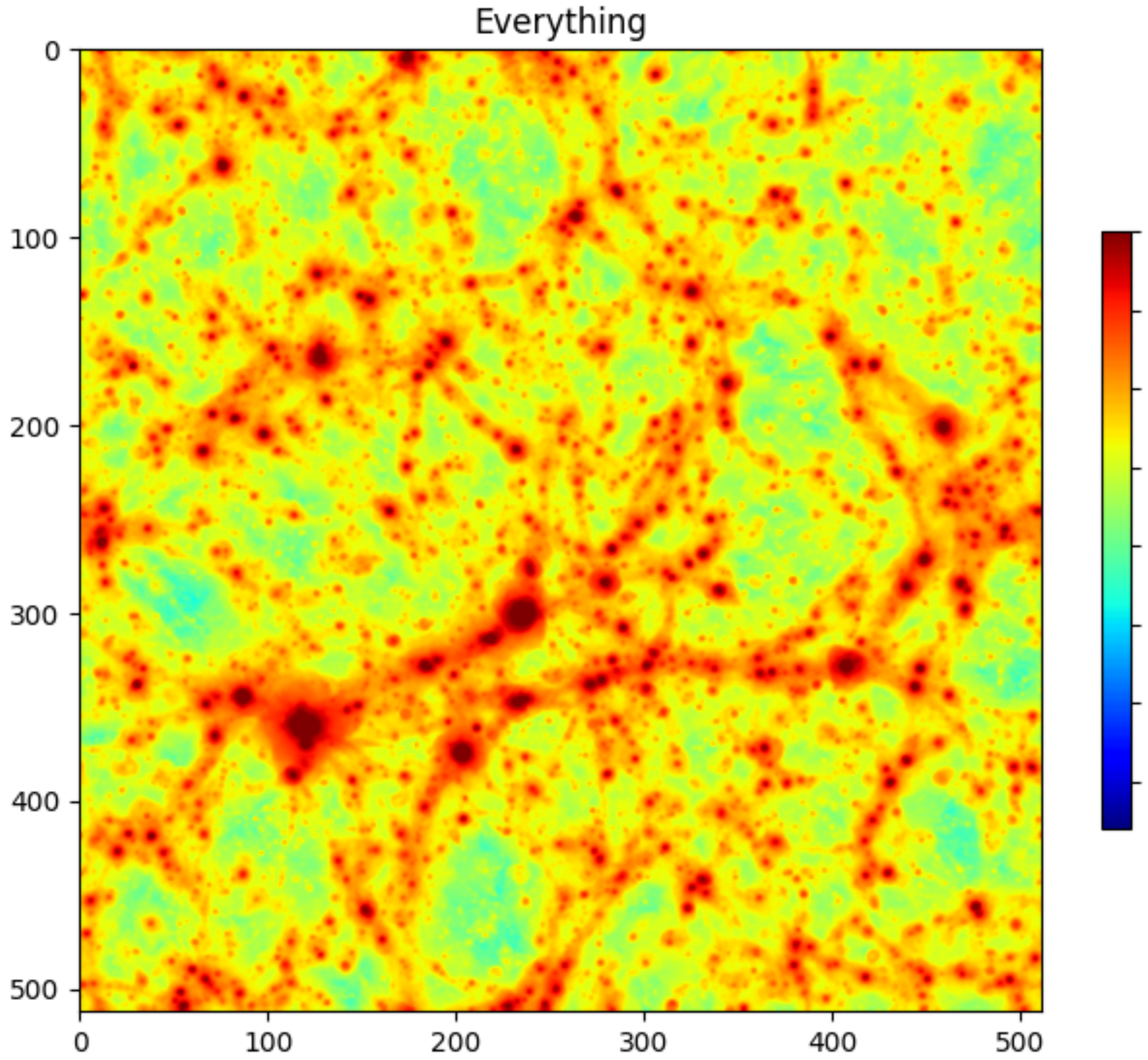
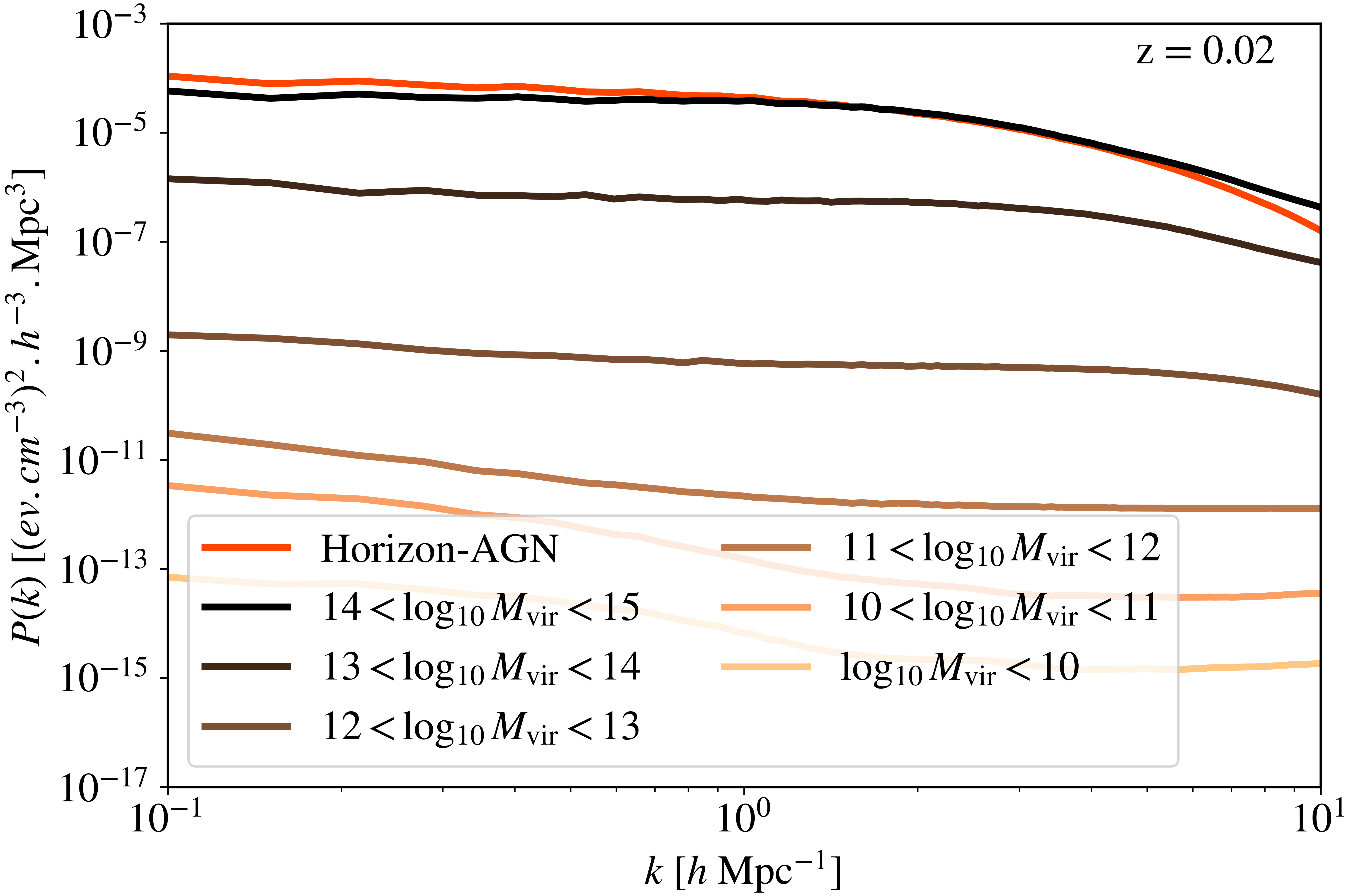




Pressure power spectrum within 1Rvir of a mass bin

- **More massive halos** reproduce almost the total power spectrum

- Same trend for the other simulations, and other z



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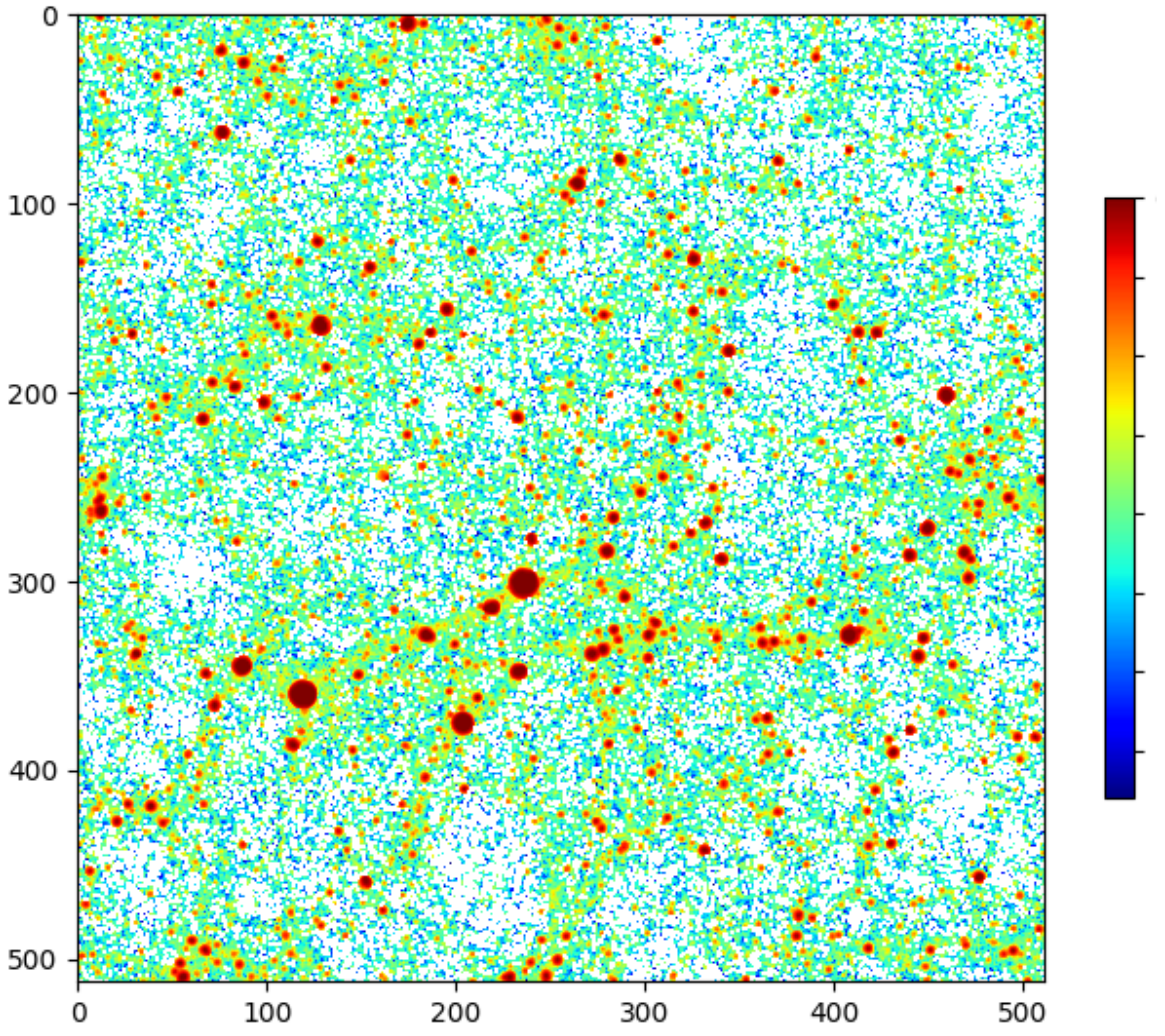
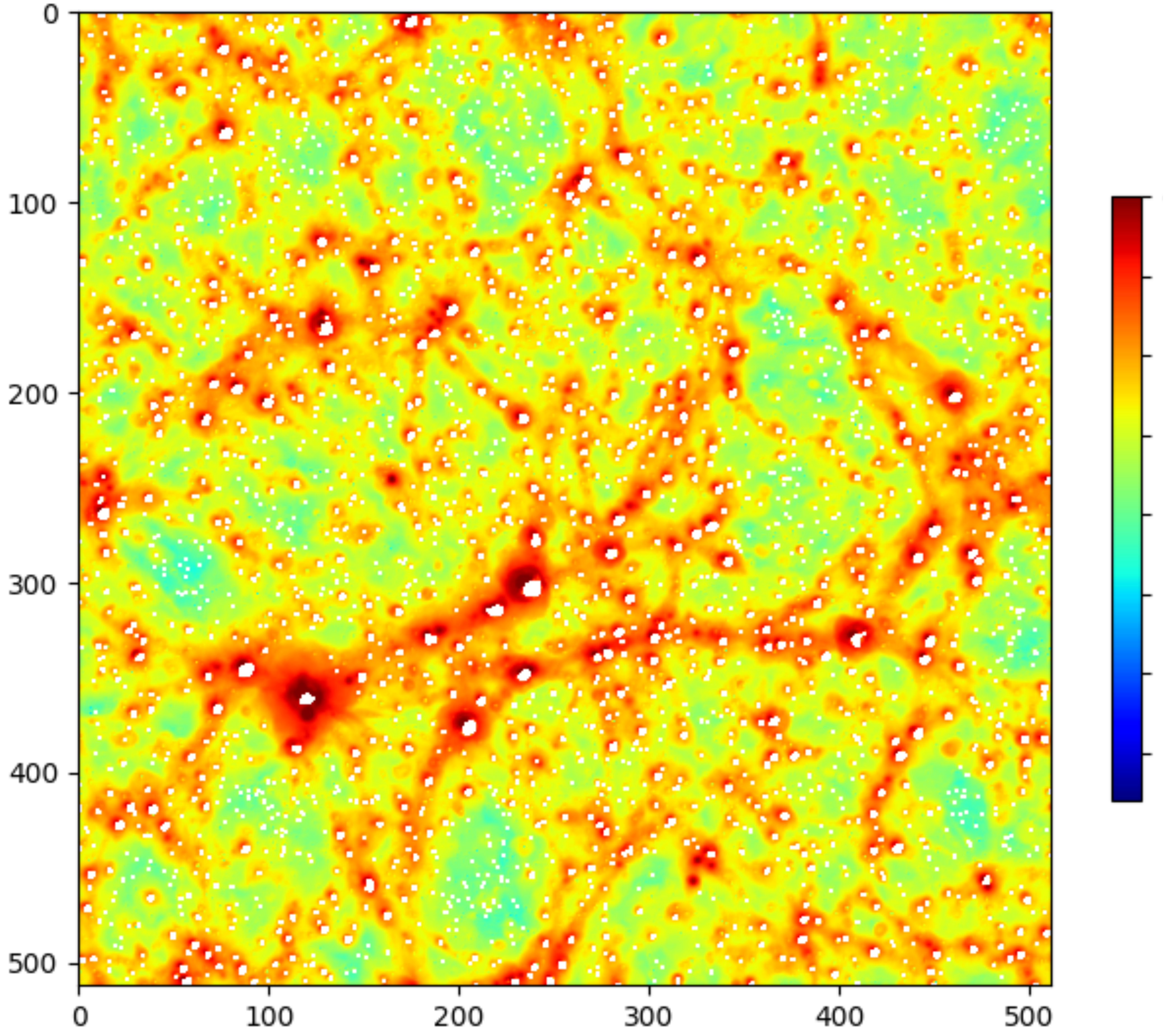
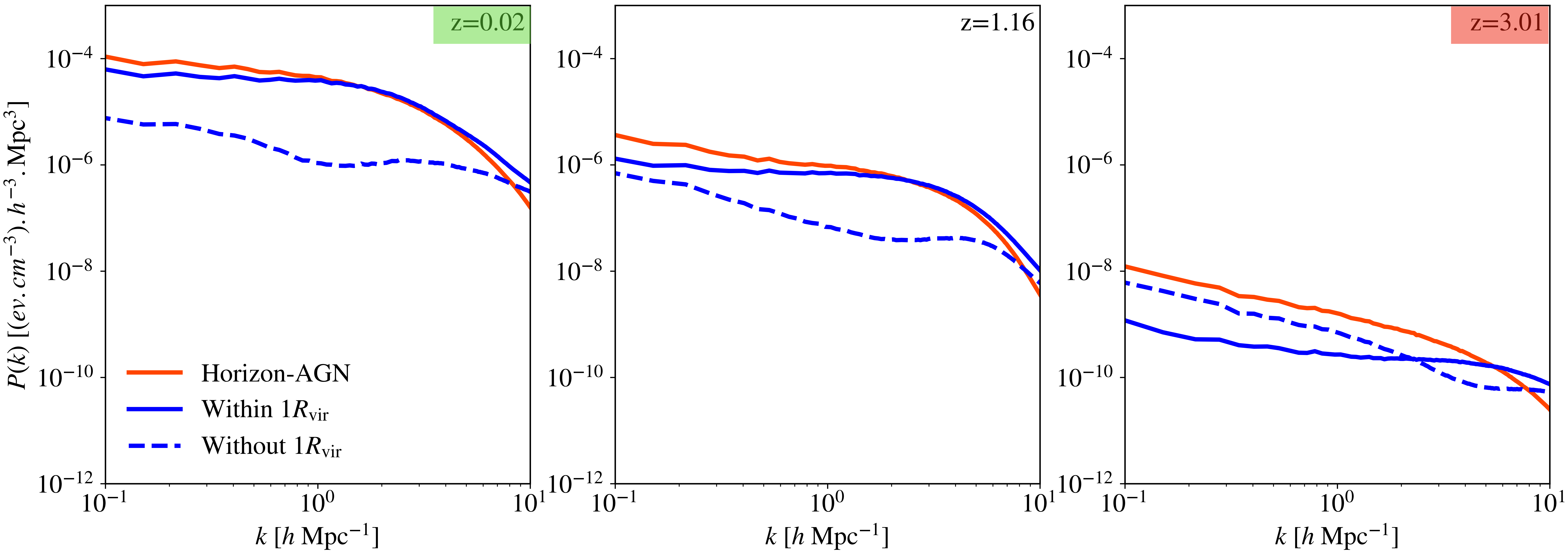
How well the halo model is working?





Pressure power spectrum within 1 Rvir



- Low z: halo model quite ok
- High z: halo model no more valid: more power come from outside the halos

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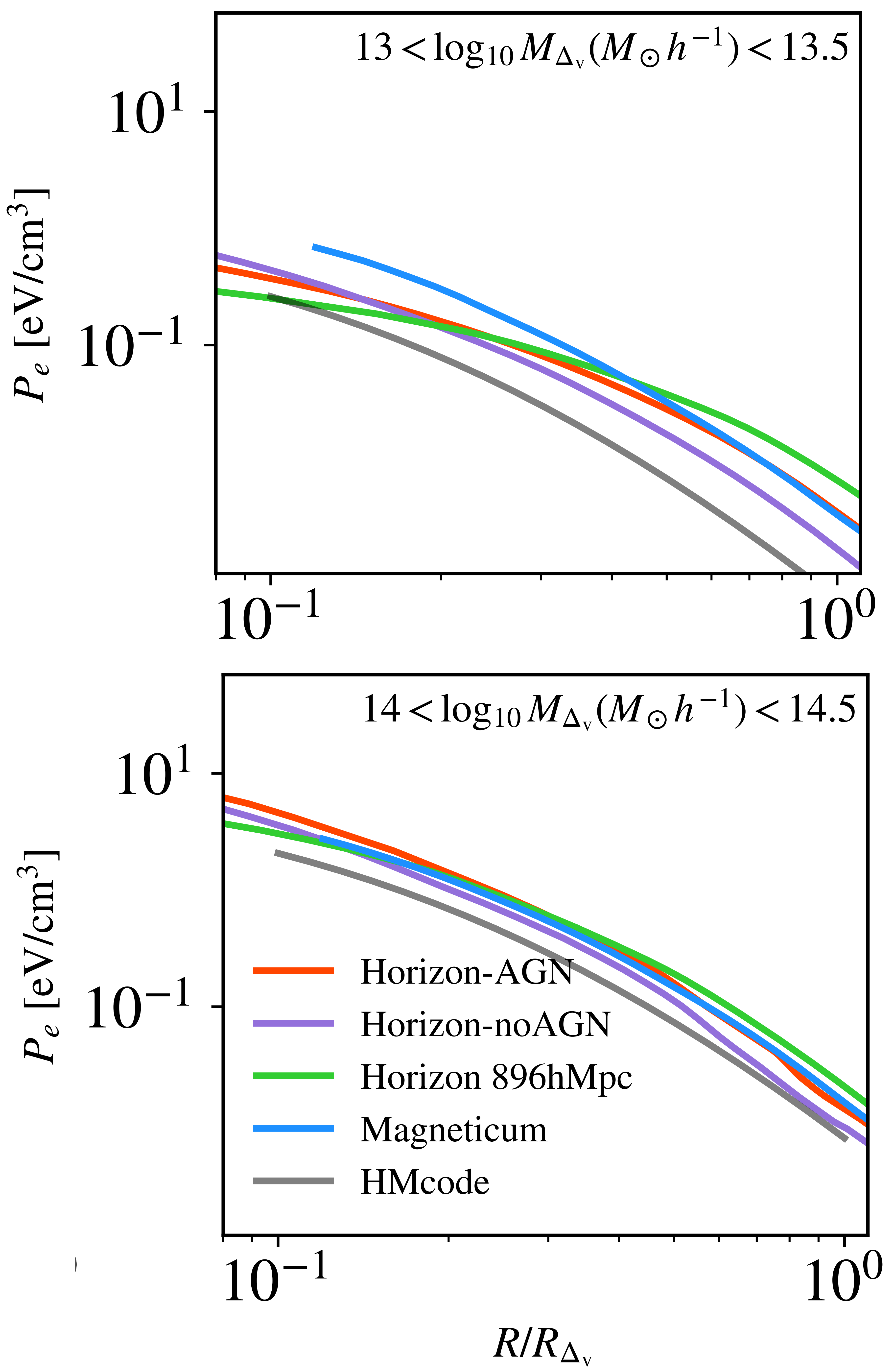
Choice in the model

- HMcode reproduce Bahamas using a halo model
- Use **pressure, temperature and other profiles**
- Need to test the robustness of these profiles
- Parameters are fit through the fitting of the power spectrum

Parameter	Default value	Equation	Physical meaning
ϵ_1	0	34	Halo concentration modification for gas-poor haloes
ϵ_2	0	34	Halo concentration modification for gas-rich haloes
M_0	$10^{14}\,h^{-1}\mathrm{M}_\odot$	25	Halo mass below which haloes have lost more than half of their initial gas content
β	0.6	25	Low-mass power-law slope of halo bound gas fraction
Γ	1.17	35	Polytropic index for the equation of state of gas that is bound in haloes
A_*	0.03	27	Peak fraction of halo mass that is in stars
M_*	$10^{12.5}\,h^{-1}\mathrm{M}_\odot$	27	Halo mass of peak star-formation efficiency
σ_*	1.2	27	Logarithmic width of star-formation efficiency distribution
η	−0.3	29	Power-law index for central–satellite galaxy split
α	1	39	Ratio of halo temperature to that of virial equilibrium
T_w	$10^{6.5}$ K	below 40	Temperature of the warm-hot intergalactic medium

Pressure profiles

- **More pressure** in the simulations, particularly HAGN
- Different profiles → can explain the difference in power spectrum
- Here z=0 but same trend with z
- Future: fit the free parameters at the profile level, use an other analytical prediction



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Conclusion & perspectives

- **Choice of the models** are important:
    - Mass distribution
    - Equation of the profiles
- Investigate more the **profiles** and the impact of these choices in the power spectrum
- Use different codes, emulators & simulations for comparison
- Test the impact of changing the **cosmology** and **equation of state of dark energy**

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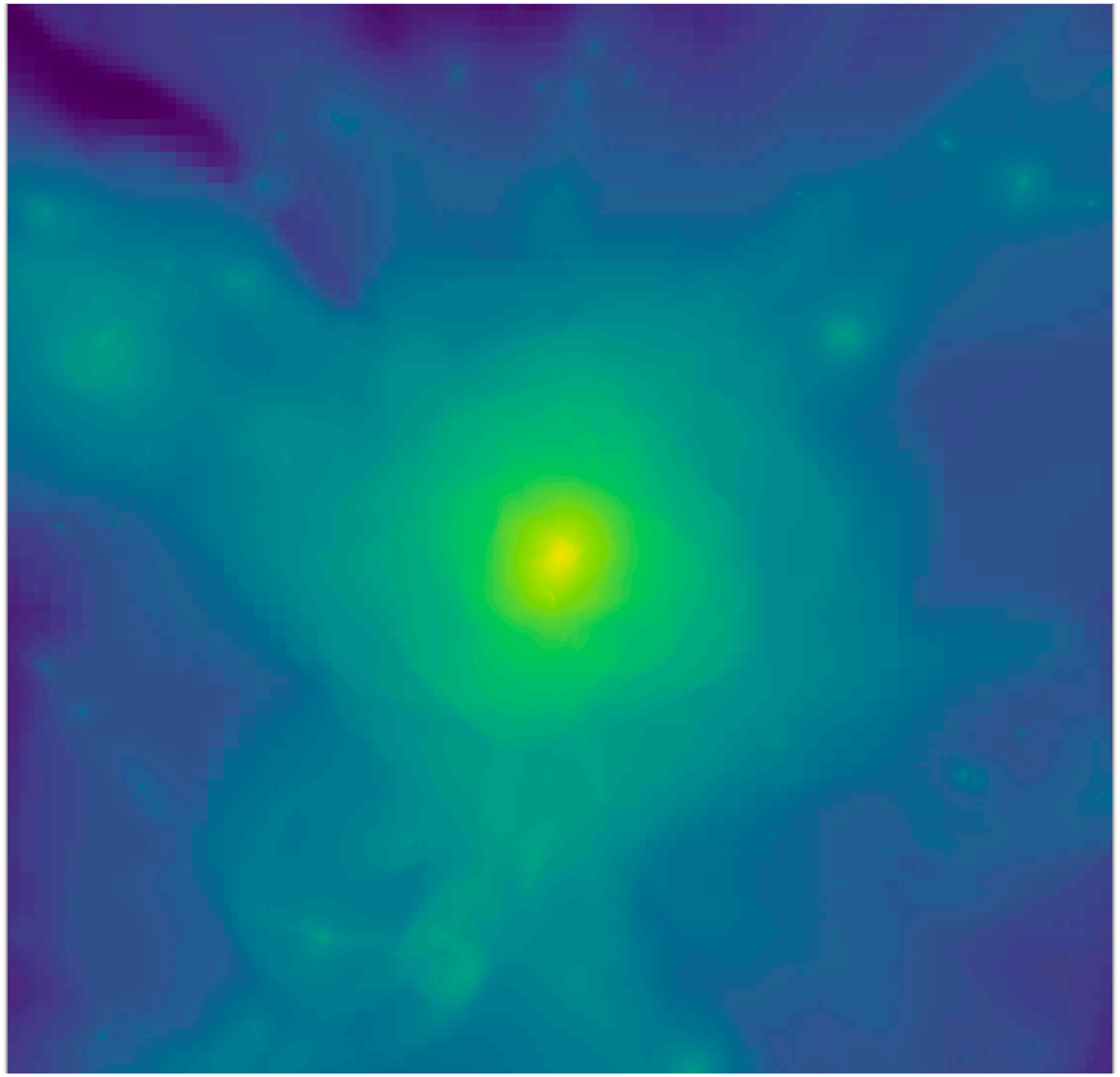
Backup

Simulation Horizon-AGN

Y. Dubois, C. Pichon & J. Devriendt



- Cosmological hydrodynamical simulation
- $100h^{-1}$Mpc comoving volume
- 1024^3 DM particles
  $\rightarrow M_{DM,res} = 8 \times 10^7 M_\odot$
- ΛCDM cosmology, compatible with WMAP-7
  $\Omega_m = 0.272, \Omega_\Lambda = 0.728, \sigma_8 = 0.81, \Omega_b = 0.045$
  $H_0 = 70.4$km/s/Mpc, $n_s = 0.967$
- Adaptive mesh refinement code RAMSES (R. Teyssier, 2002): Eulerian
- Gas dynamics, gas cooling and heating, star formation, feedback from stars, six chemical species (O, Fe, C, N, Mg, Si), and AGN feedback

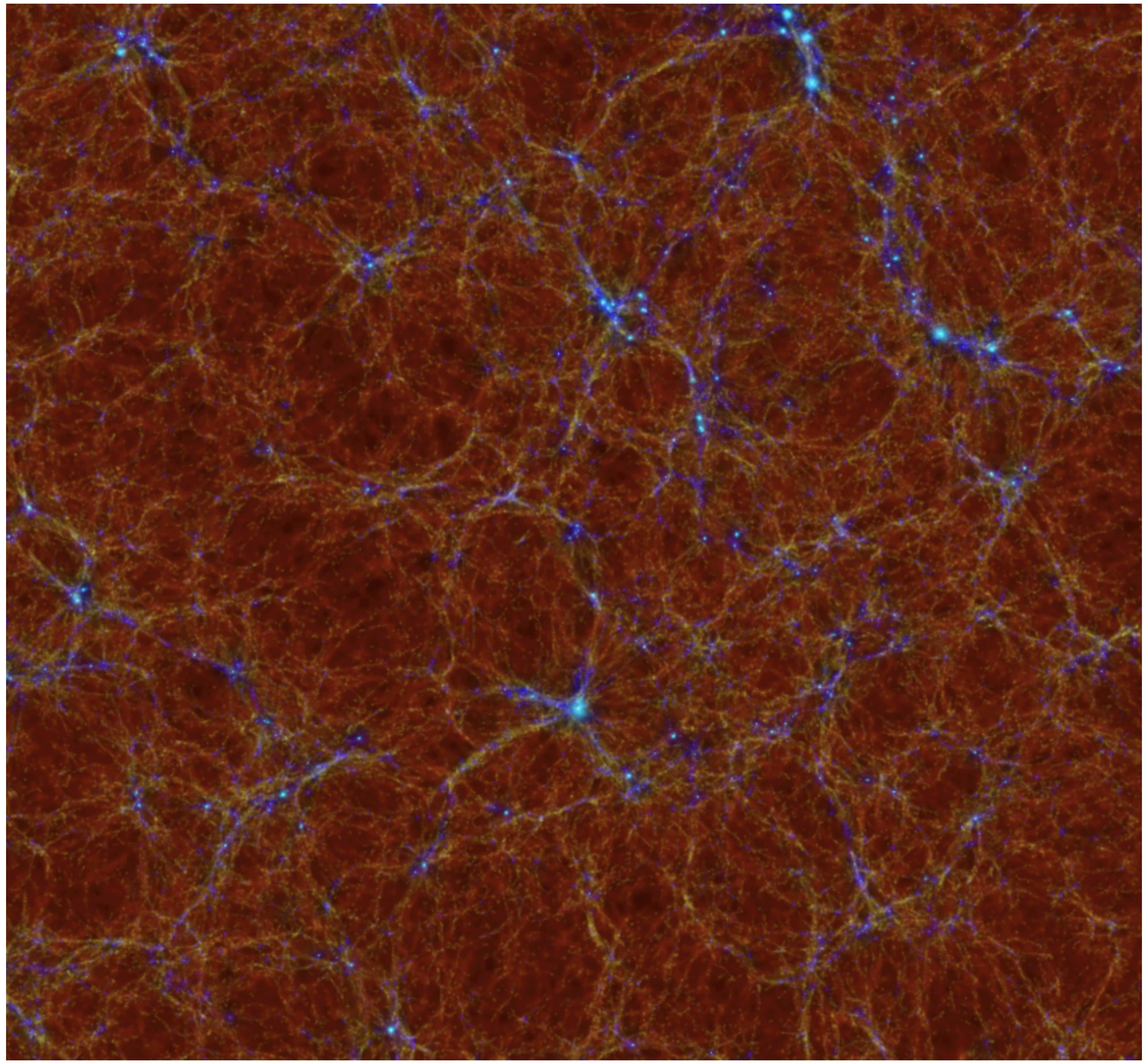
Simulation Horizon 896hMpc

Y. Dubois

- Cosmological hydrodynamical simulation
- $896h^{-1}$Mpc comoving volume
- 1024^3 DM particles $\rightarrow M_{DM,res} = 6 \times 10^{10} M_\odot$
- ΛCDM cosmology, compatible with WMAP-7
  $\Omega_m = 0.272, \Omega_\Lambda = 0.728, \sigma_8 = 0.81, \Omega_b = 0.045$
  $H_0 = 70.4$km/s/Mpc, $n_s = 0.967$
- Adaptive mesh refinement code RAMSES (R. Teyssier, 2002): Eulerian
- Gas cooling and heating, no galactic physics

Magneticum simulations

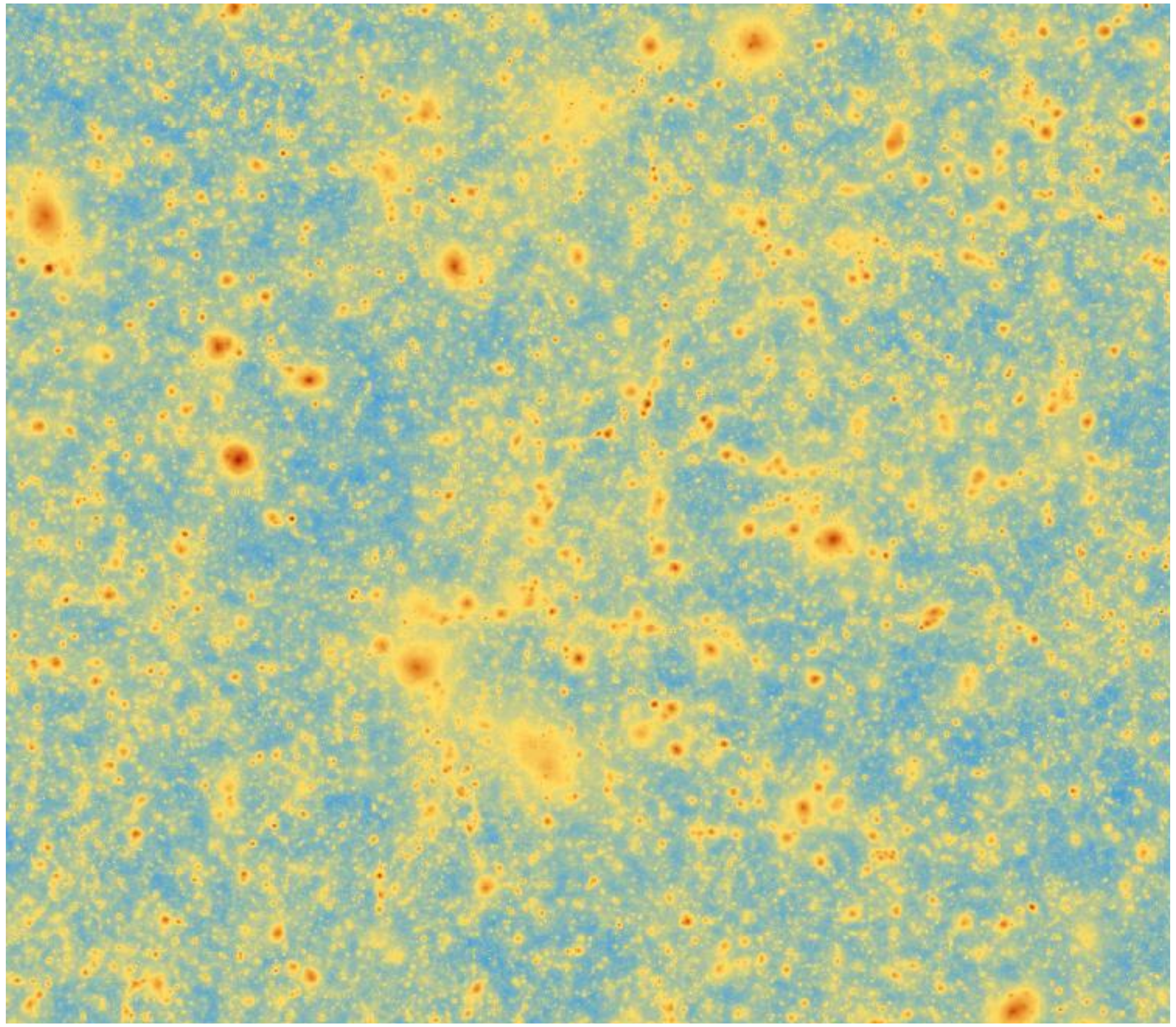
M. Hirschamnn et al.



- Cosmological hydrodynamical simulation
- $18 - 2688h^{-1}$Mpc comoving volume
  we use $896h^{-1}$Mpc
- Box of $896h^{-1}$Mpc:
  1512^3 DM particles $\rightarrow M_{DM,res} = 2 \times 10^{10} M_{\odot}$
- 15 cosmology including WMAP-7
- Use GADGET (V. Springel): Lagrangian
  and higher order SPH Kernels
- Cooling, star formation, winds, metals, stellar population and chemical enrichment, black holes and AGN feedback, thermal conduction, magnetic fields (passive)

Bahamas simulation

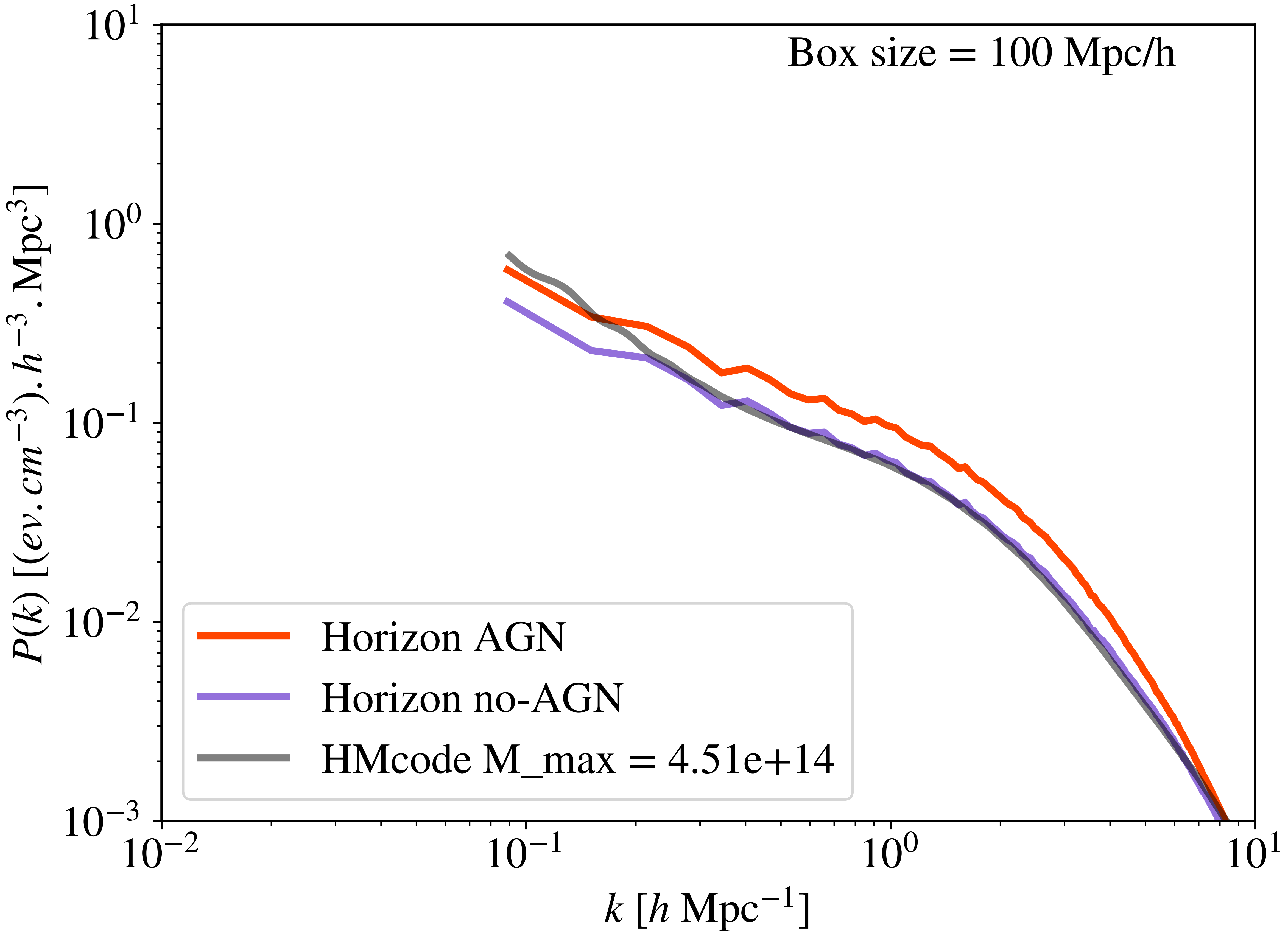
I. McCarthy et al.

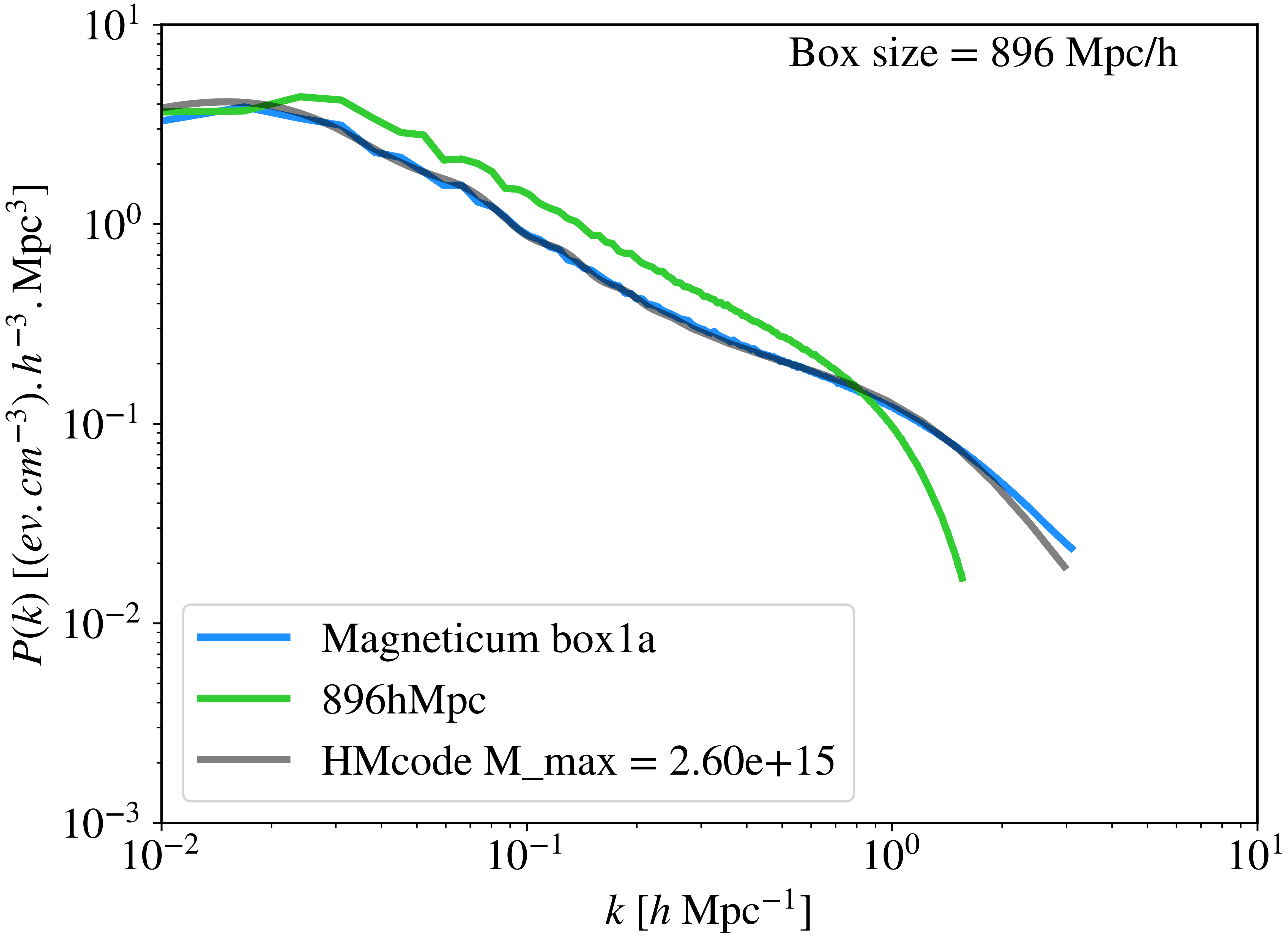


- Follow cosmo-OWLS
- Cosmological hydrodynamical simulation
- $400h^{-1}$Mpc comoving volume
- 1024^3 DM particles
  $\rightarrow M_{DM,res} = 5.5 \times 10^9 M_\odot$ for WMAP-9
  $\rightarrow M_{DM,res} = 1.14 \times 10^9 M_\odot$ for Planck 2013
- WMAP-9 cosmology
  $\Omega_m = 0.2793, \Omega_\Lambda = 0.7207, \sigma_8 = 0.821, \Omega_b = 0.0463, H_0 = 70.0$km/s/Mpc, $n_s = 0.972$
- And Planck 2013 cosmology
  $\Omega_m = 0.3175, \Omega_\Lambda = 0.6825, \sigma_8 = 0.834, \Omega_b = 0.0490, H_0 = 67.11$km/s/Mpc, $n_s = 0.9624$
- Use Gadget
- Radiative cooling and heating, star formation, stellar evolution, 11 chemical species (H, He, C, N, O, Ne, Mg, Si, S, Ca, Fe), feedback from star formation and AGN, accretion of SMBHs, BH formation

z = 0

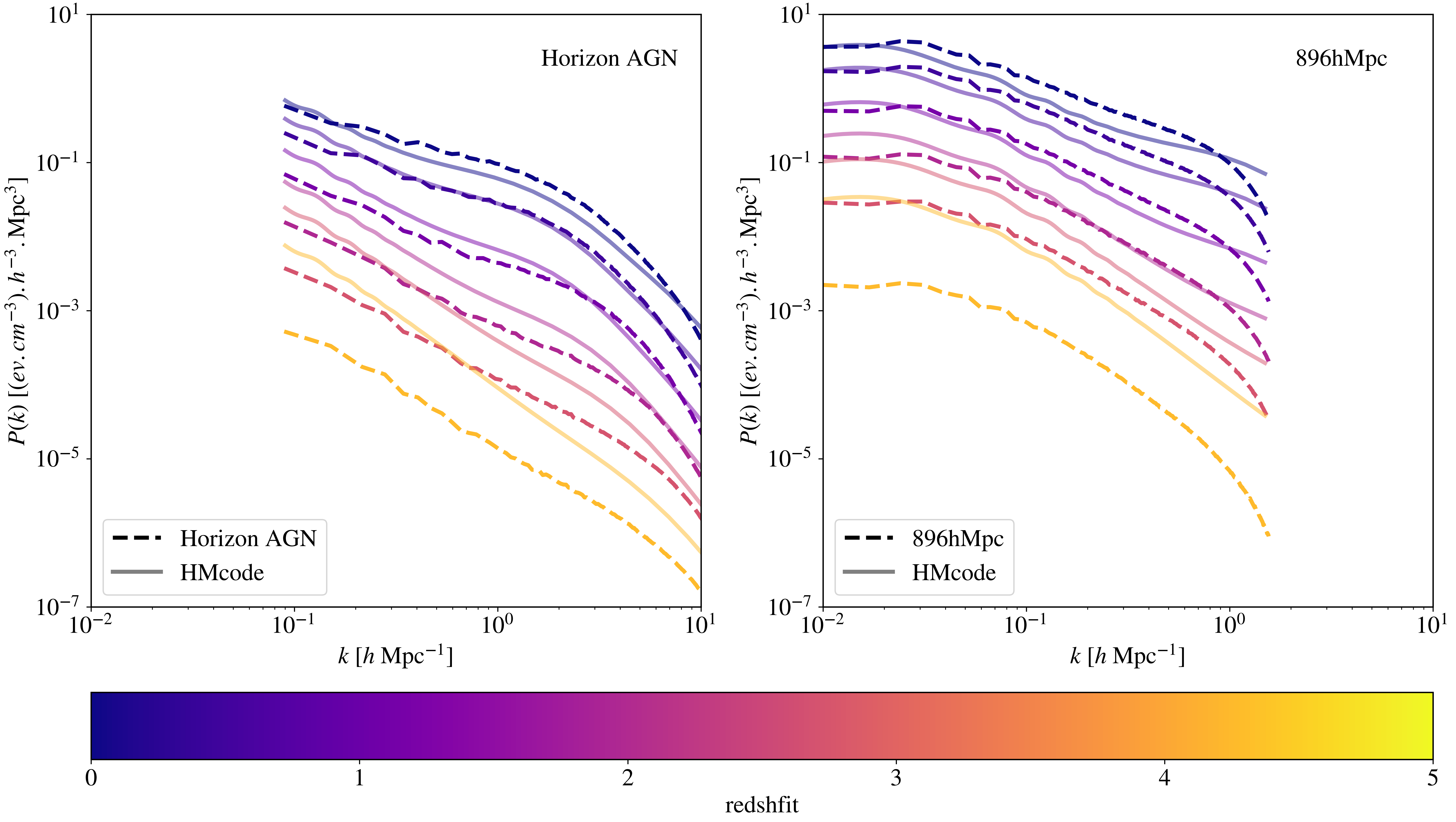
Pressure x matter power spectrum



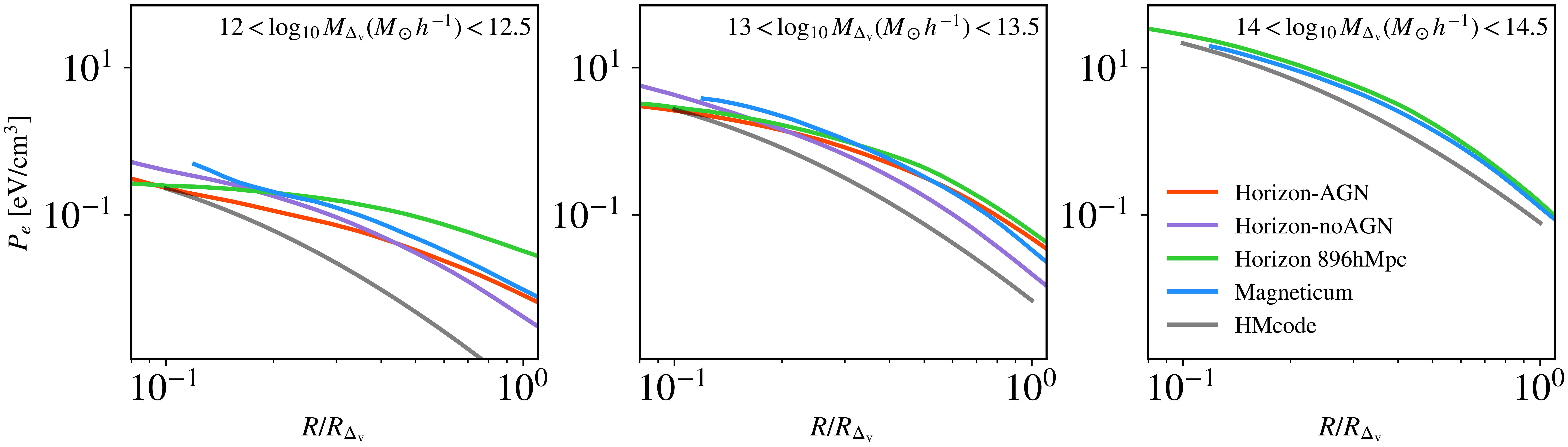


Pressure x matter power spectrum evolution with z

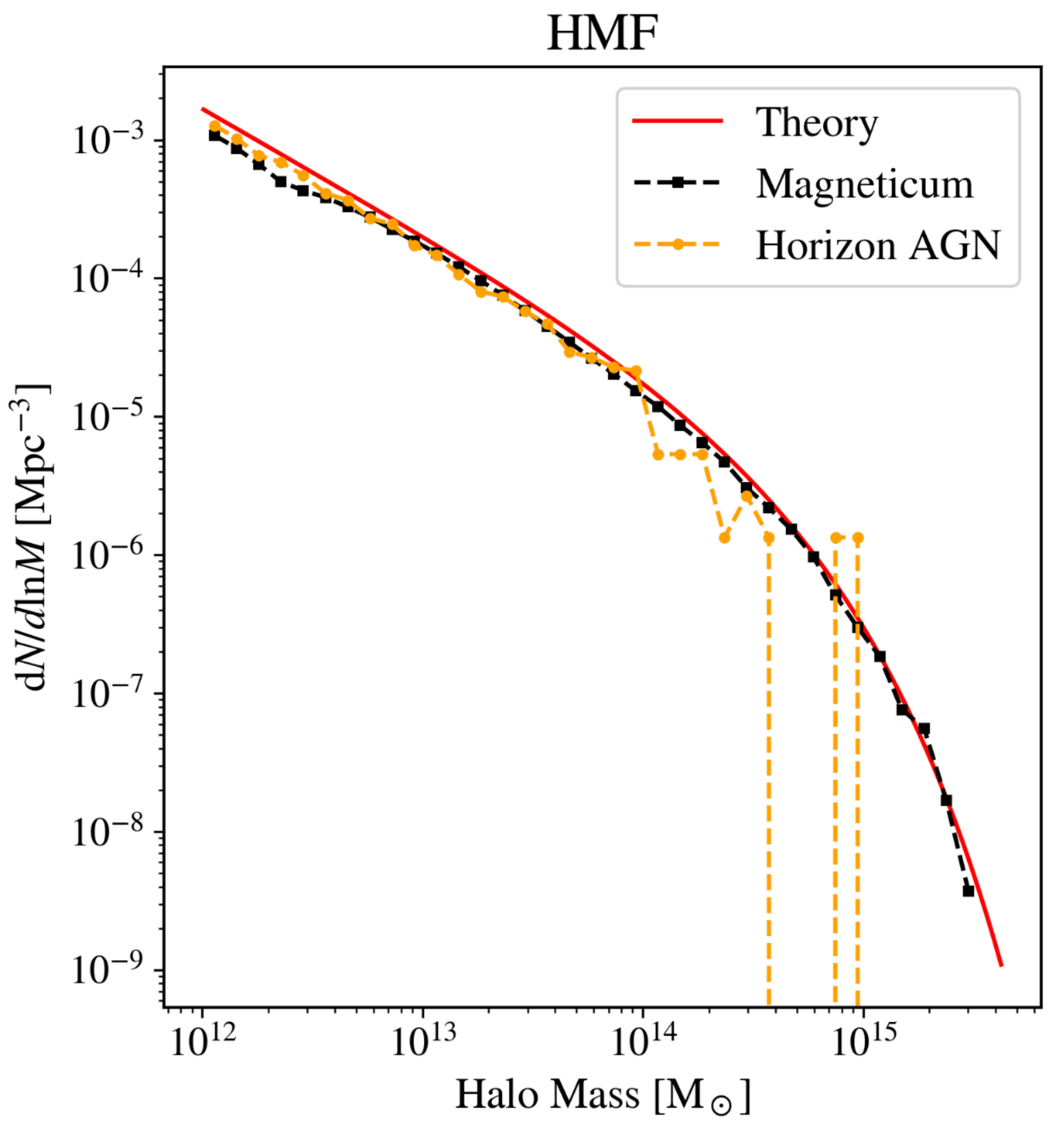
- Higer z: far from theory
- Behavior between the pressure x pressure and matter x pressure
- HMcode calibrated on these spectra

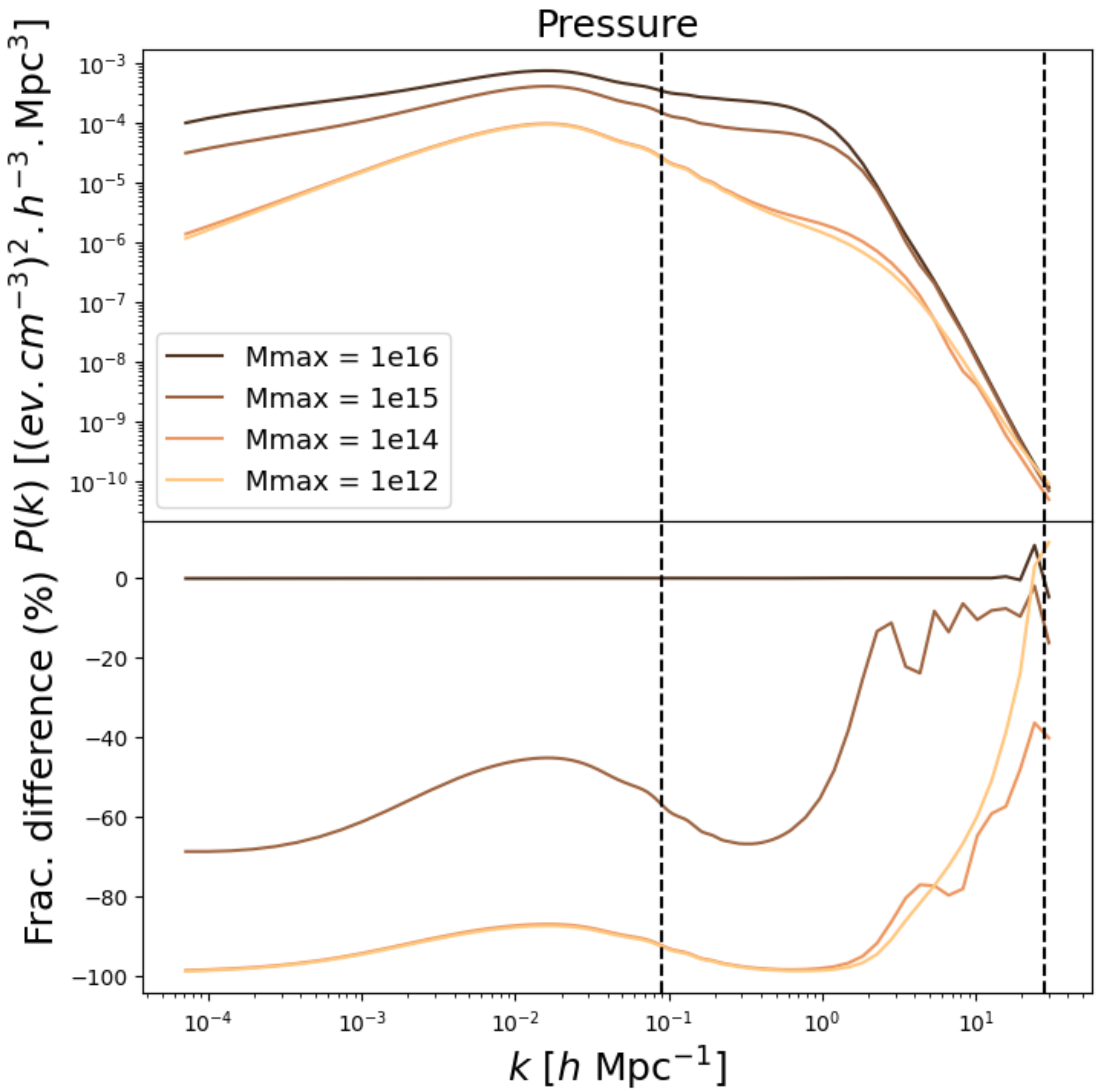


Pressure profile at z=1.18



Mass dependance of the pressure power spectrum





- Choice of maximal mass impact a lot the power spectrum
- What happen at the halo scale become more and more important

z = 0

Mass function

- Dimensionless mass function: $g(\nu)d\nu = \frac{M}{\bar{\rho}}n(M)dM$
- With $\nu = \delta_c/\sigma(M)$ with δ_c: critical linear density threshold for halo collapse and $\sigma(M)$: variance in the linear matter field
- Mass function - **Sheth & Tormen (1999)**: $g(\nu)d\nu = A\left[1 + \frac{1}{(q\nu^2)^p}\right]e^{-q\nu^2/2}d\nu$

  with $p = 0.3$, $q = 0.707$ and $A \sim 0.216$

Halo bias

- $$b(\nu) = 1 + \frac{1}{\delta_c}\left[q\nu^2 - 1 + \frac{2p}{1 + (q\nu^2)^p}\right]$$

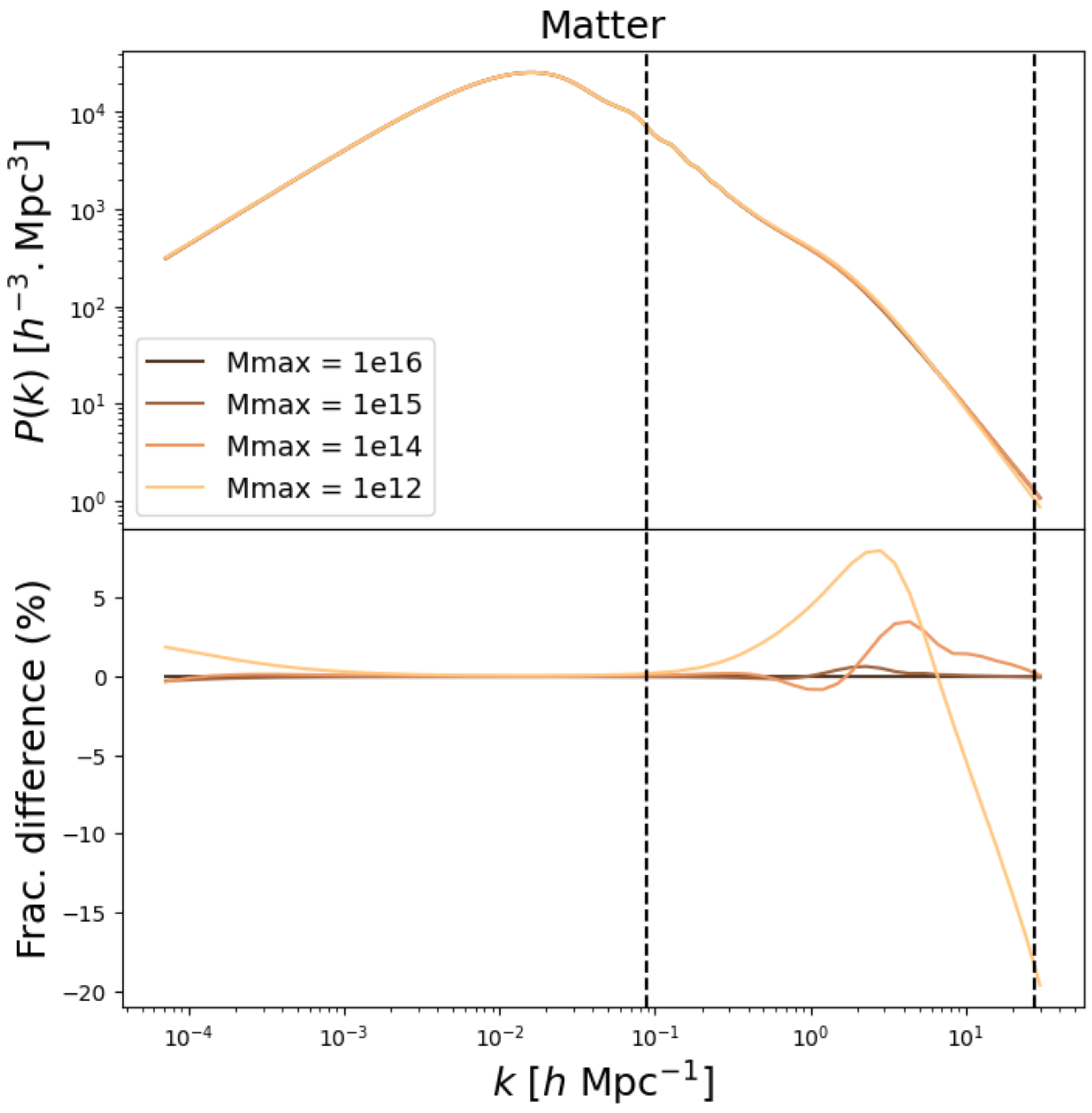
  with $p = 0.3$ and $q = 0.707$

Electronic pressure

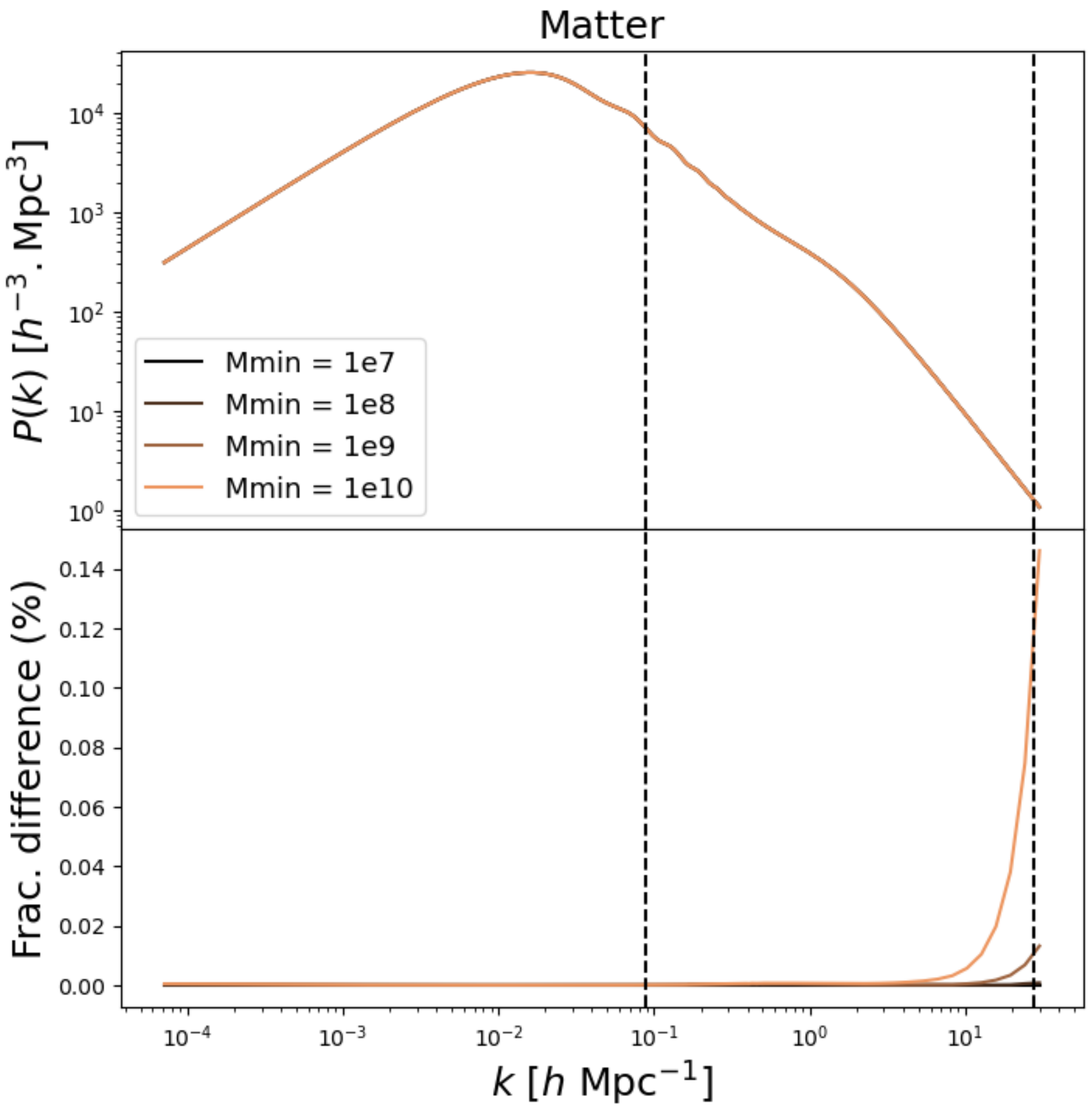
- HAGN give the gas pressure: $P_g = P_{ion} + P_{electron} = \dfrac{\rho k_B T_i}{\mu_i m_p} + \dfrac{\rho k_B T_e}{\mu_e m_p}$
- Local equilibrium: $T_i = Te = Tg \Rightarrow P_g = \dfrac{\rho k_B T}{m_p}\left(\dfrac{1}{\mu_i} + \dfrac{1}{\mu_e}\right) = \dfrac{\rho k_B T}{m_p}\left(\dfrac{1}{\mu_g}\right)$
- $\dfrac{P_e}{P_g} = \dfrac{\mu_g}{\mu_e} \sim 0.492$
- $\mu_i = 1.136, \mu_e = 1.219, \mu_g = 0.6$ for fully ionized gas

Mass dependance of the matter power spectrum

Cut high masses



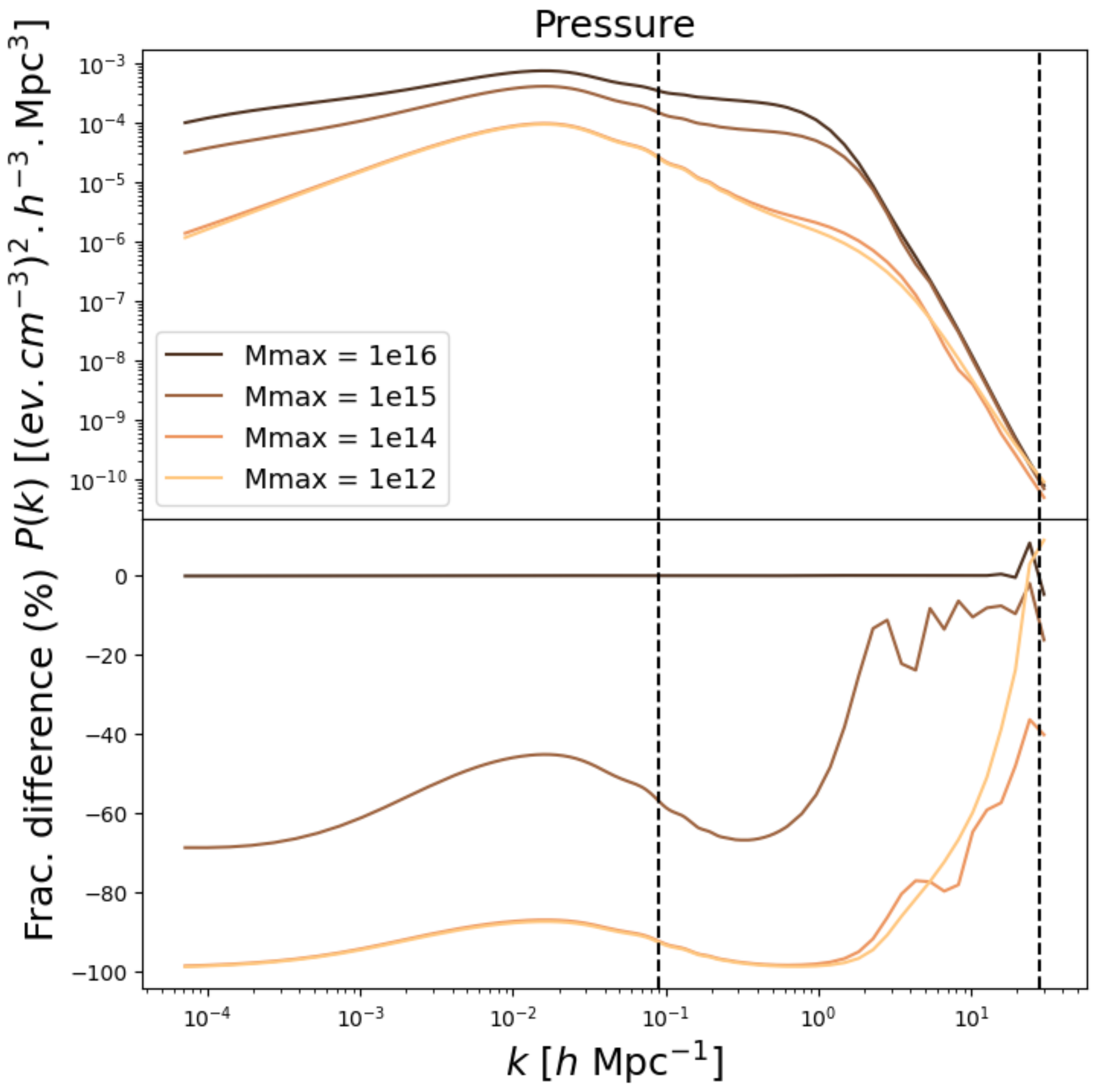
Cut low masses



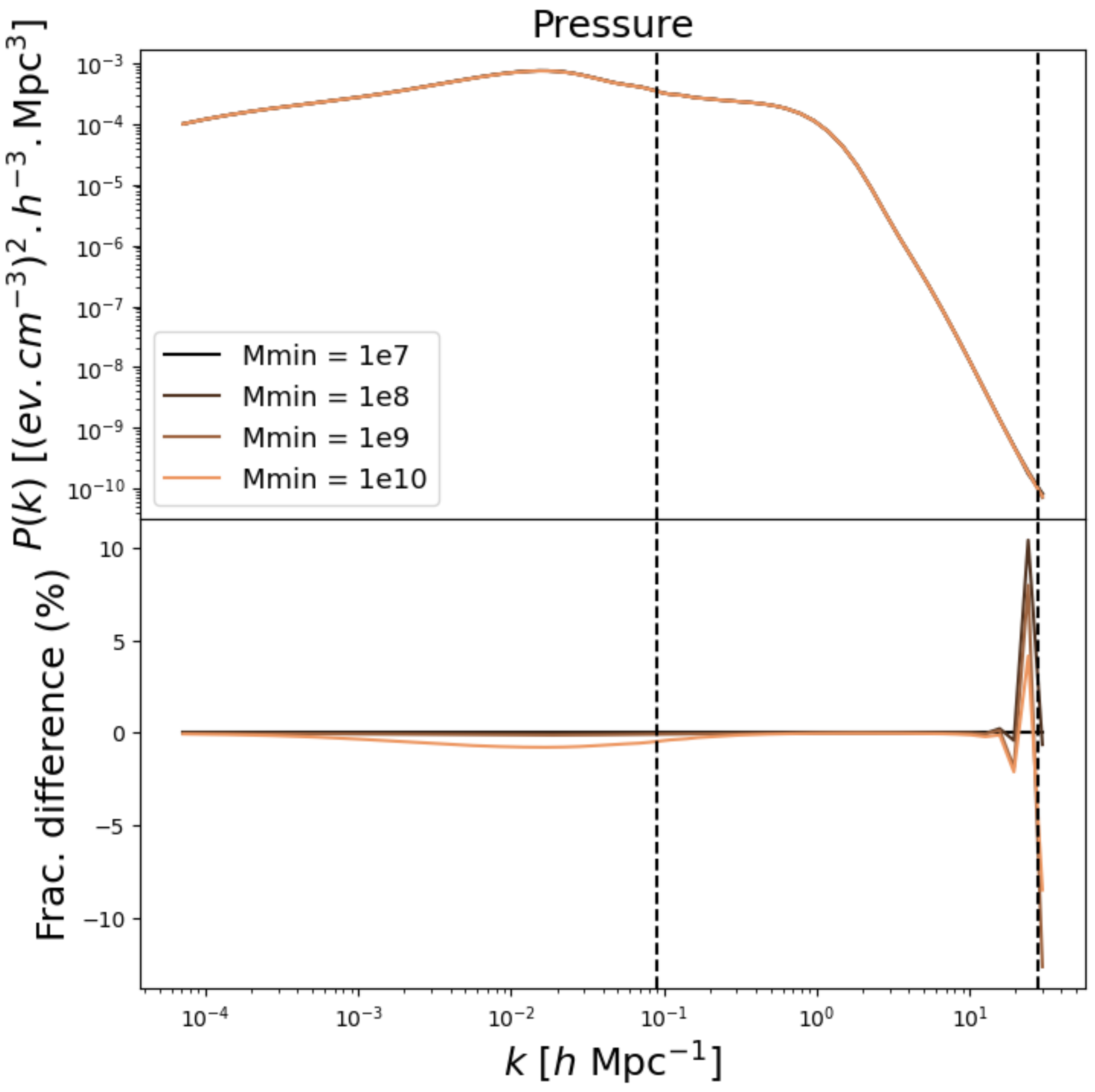
z = 0

Mass dependance of the pressure power spectrum

Cut high masses



Cut low masses



z = 0

Mass dependance of the pressure power spectrum

- z = 0
- Choice if the highest mass really important
- 1-halo dominant → what happens at halo scale