Higher signal from Lower densities

Elena Massara

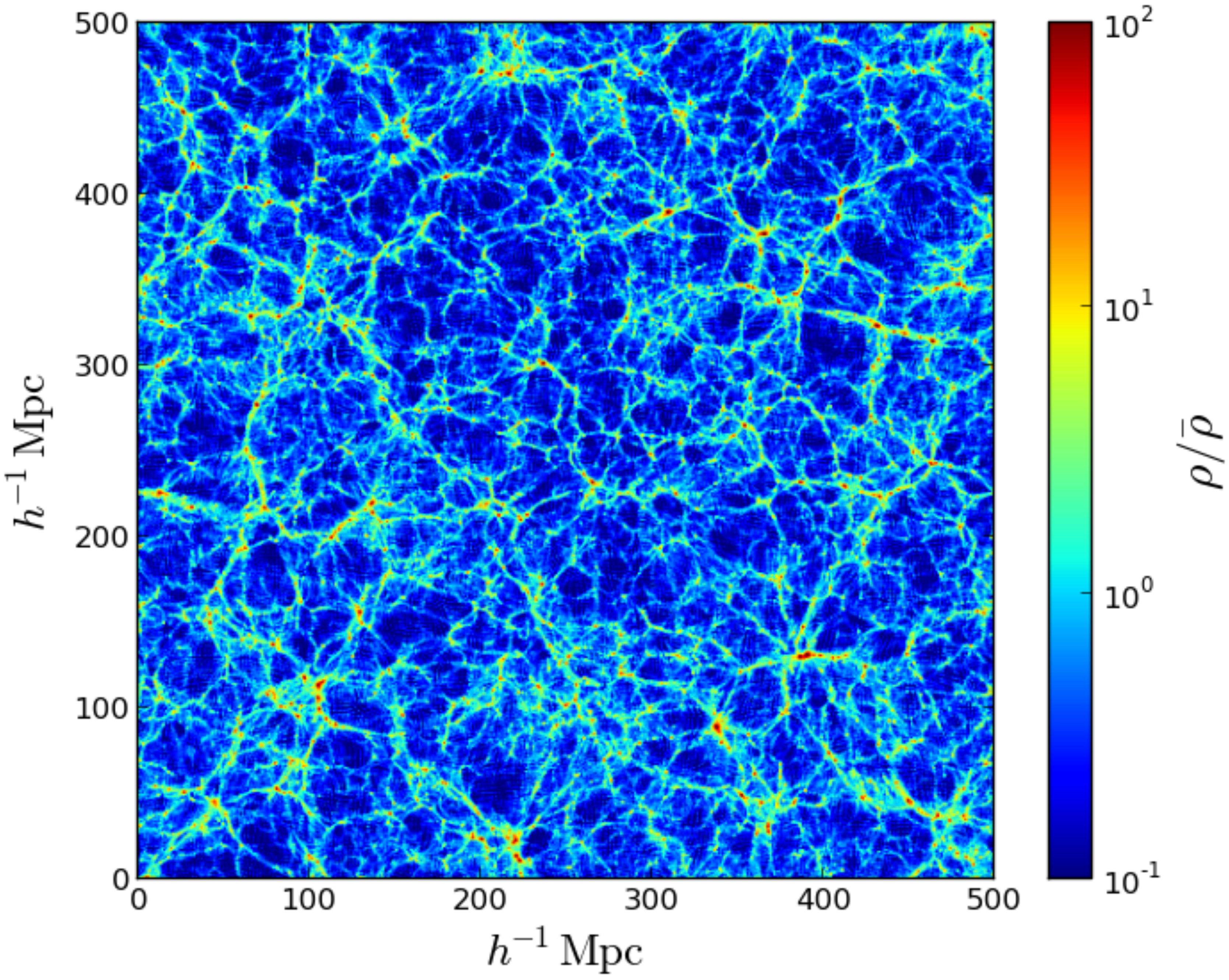
Collaborators: F. Villaescusa-Navarro (Princeton), S. Ho (CCA,Princeton,Carnegie Mellon), N. Dalal (Perimeter), D. Spergel (CCA,Princeton)

UNIVERSITY OF WATERLOO | WATERLOO CENTRE FOR ASTROPHYSICS

OUTLINE

- Introduction
- Reasons why low density regions are of interest when studying cosmology
- Marked power spectrum:
    - Definition
    - Fisher analysis
    - Results and their interpretation
- Conclusion

THE LARGE SCALE STRUCTURE



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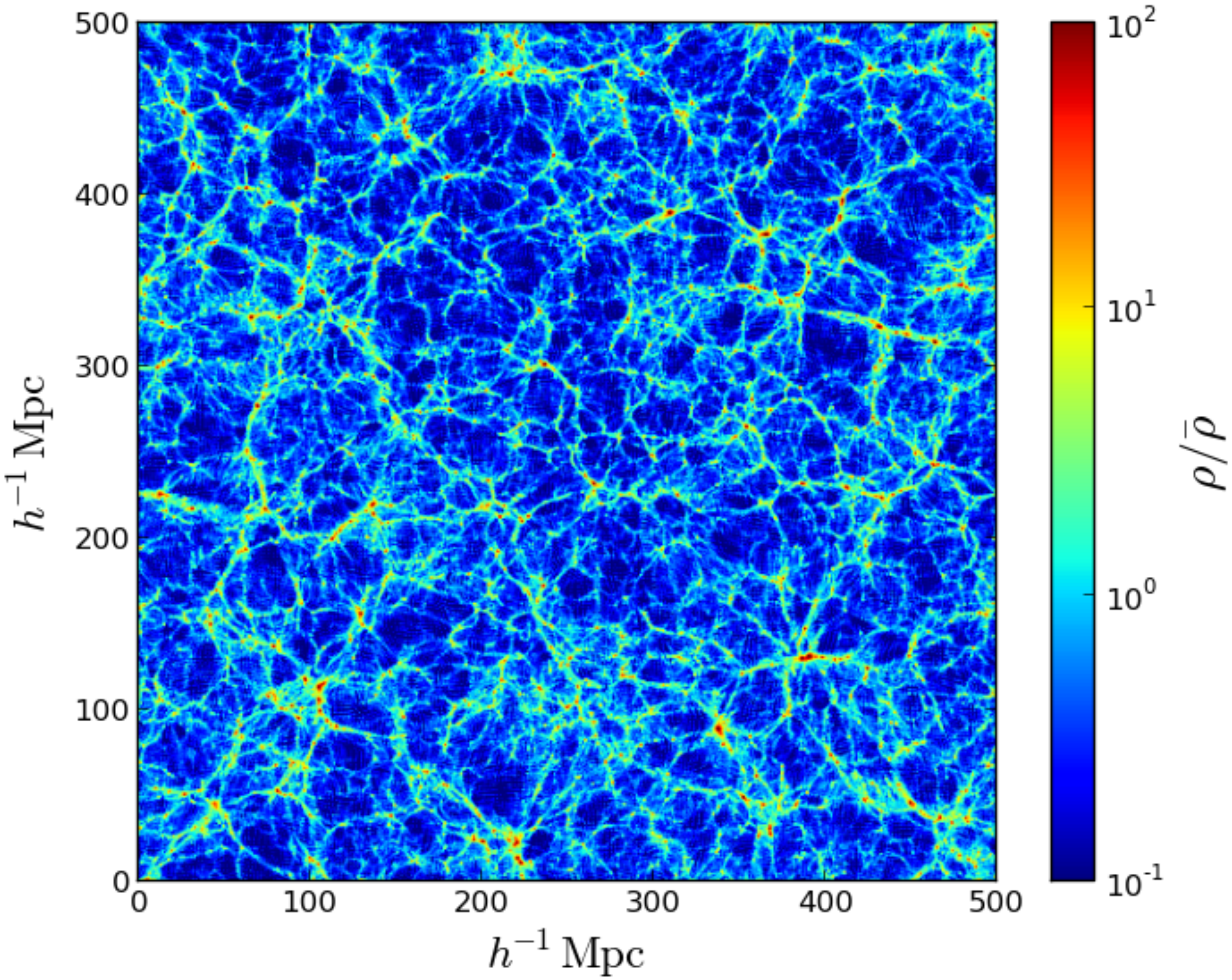

The distribution of matter in the Universe is sensitive to:

- properties of dark matter
- nature of dark energy
- neutrinos' masses
- initial condition of the Universe

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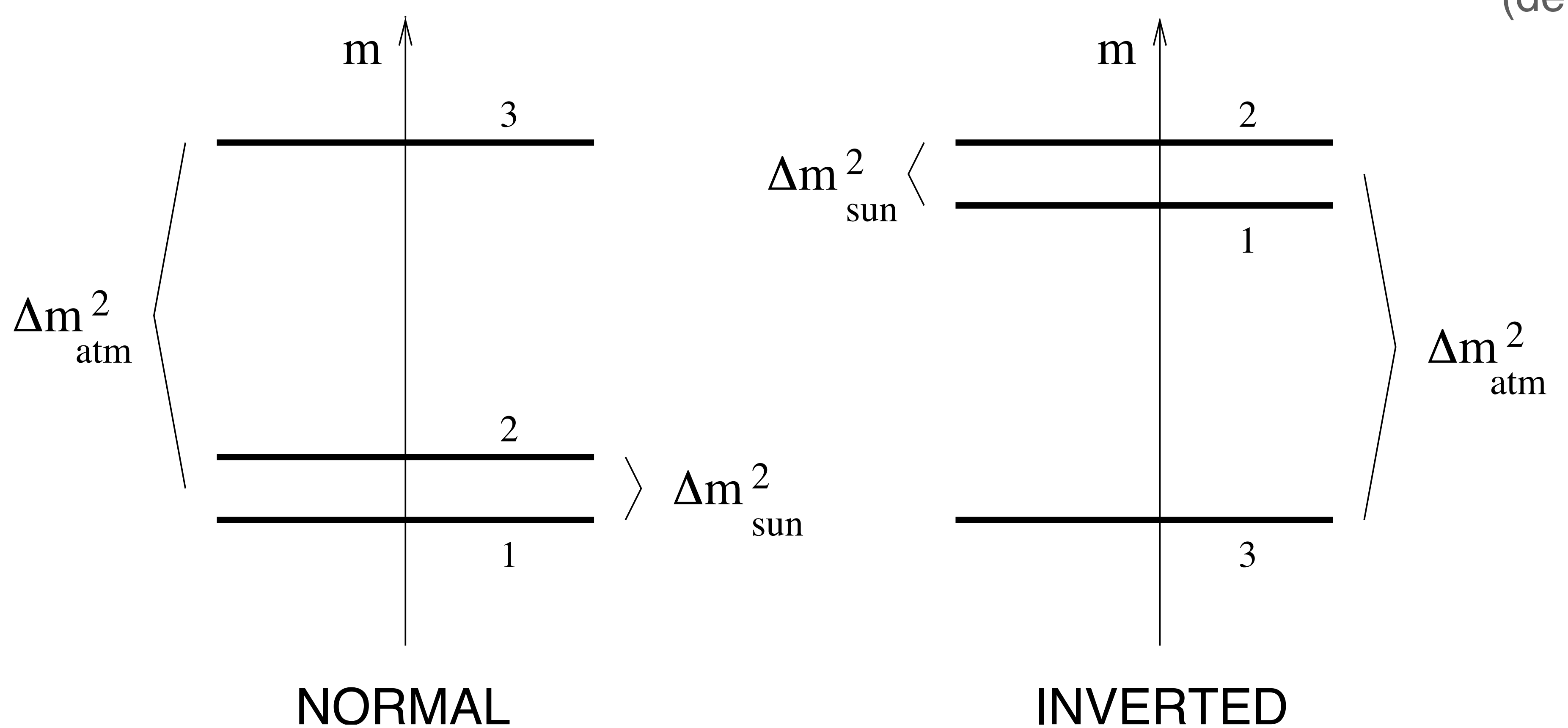

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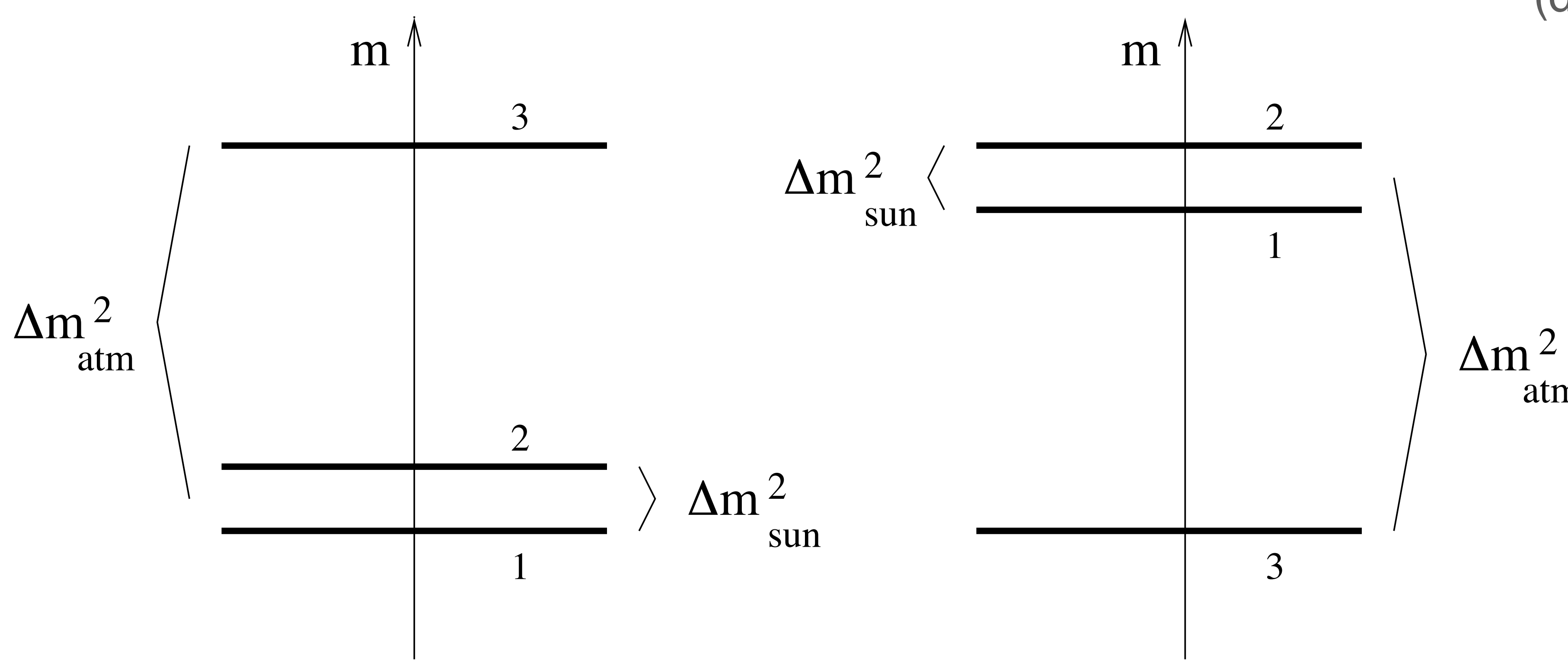

$M_\nu \geq 0.06 eV$ NORMAL

INVERTED $M_\nu \geq 0.1 eV$

$$M_\nu = \Sigma m_i$$

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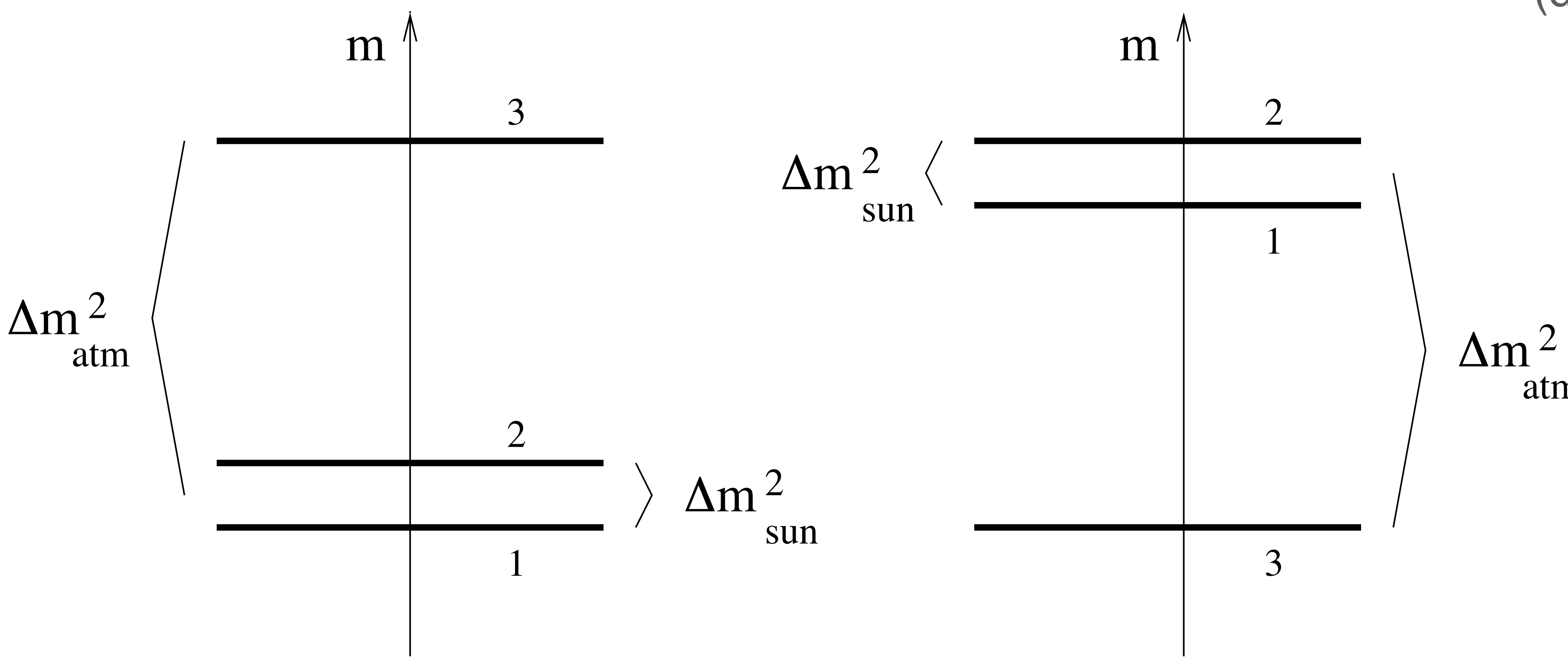

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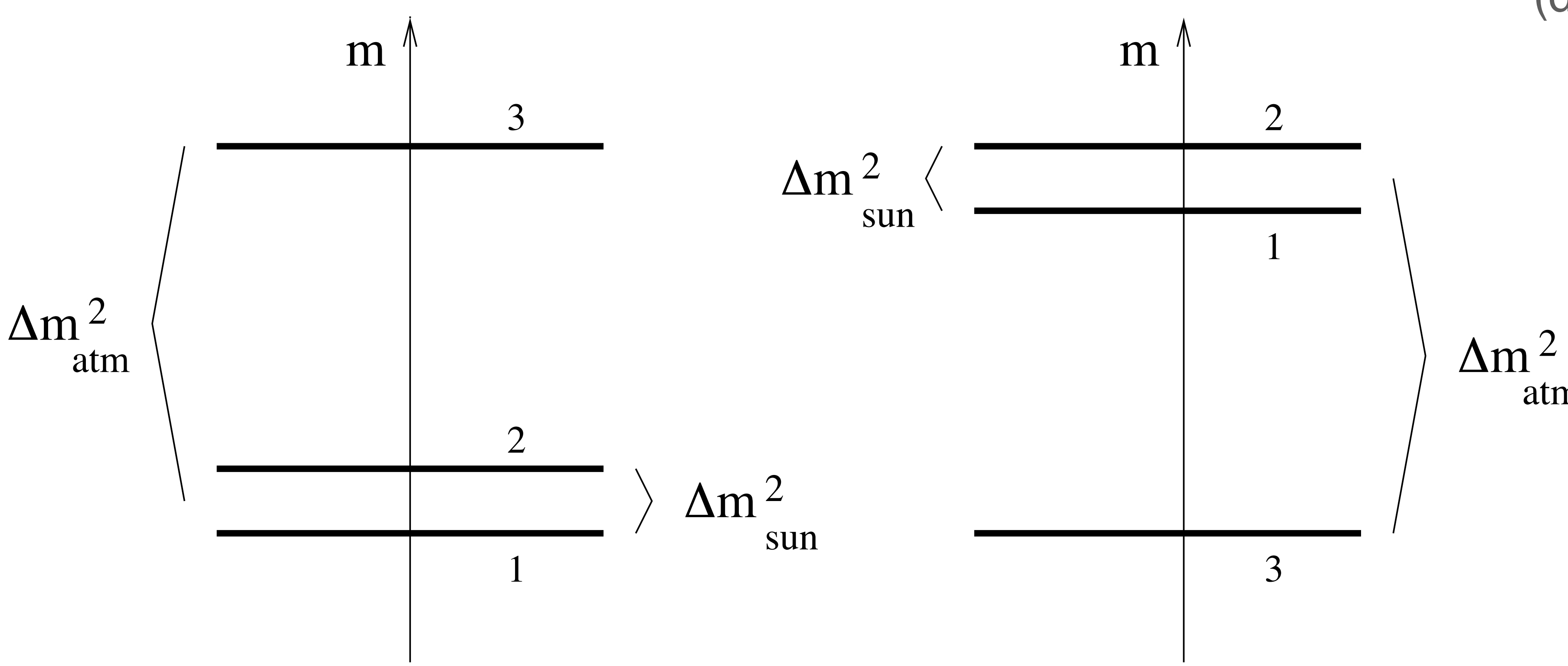

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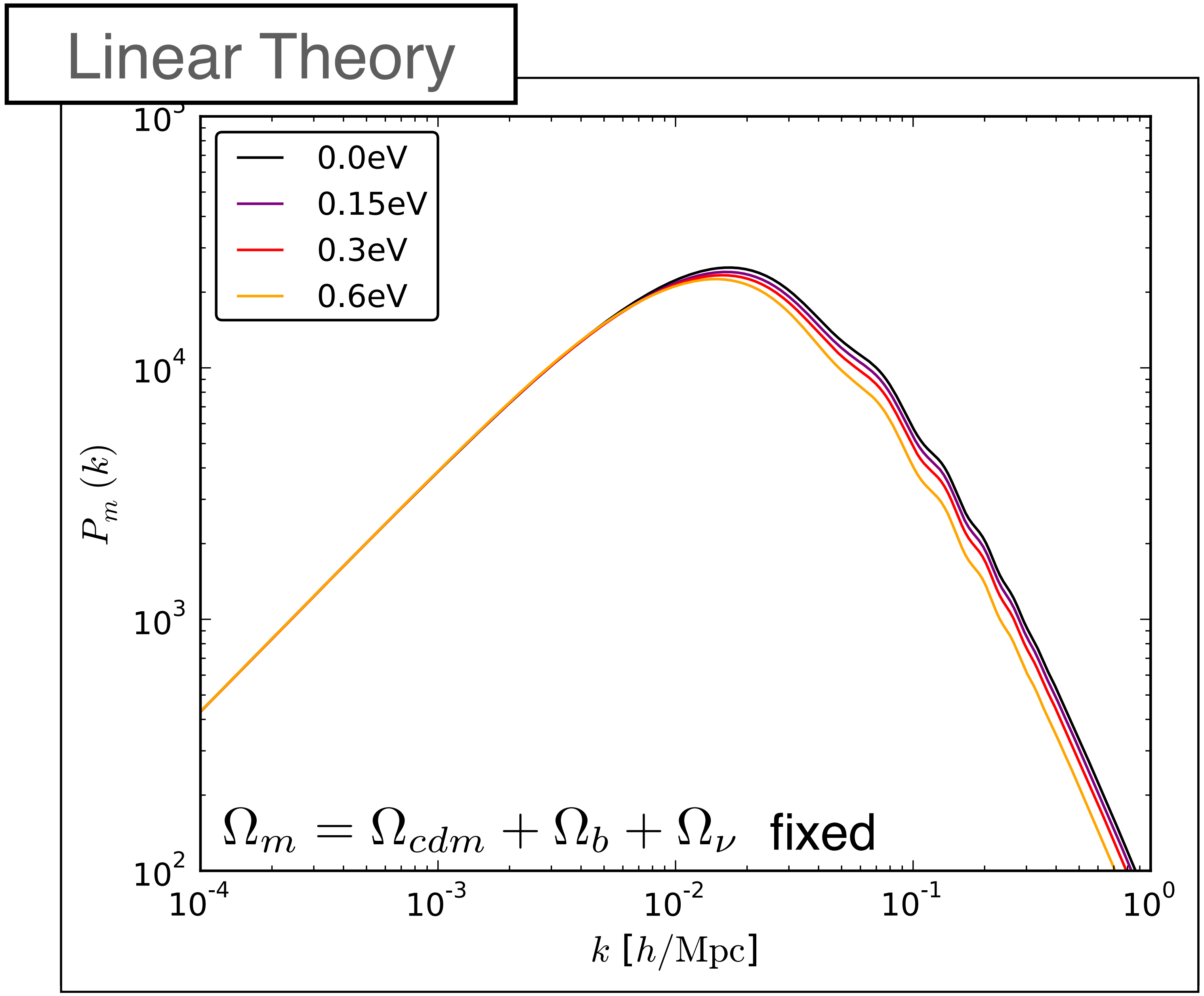
$$0.06 eV < M_\nu < 0.12 eV$$

LINEAR ORDER

Neutrino masses have two effects at linear order:

1) delaying the matter-radiation equality
2) slowing down the growth of matter perturbations

LINEAR ORDER



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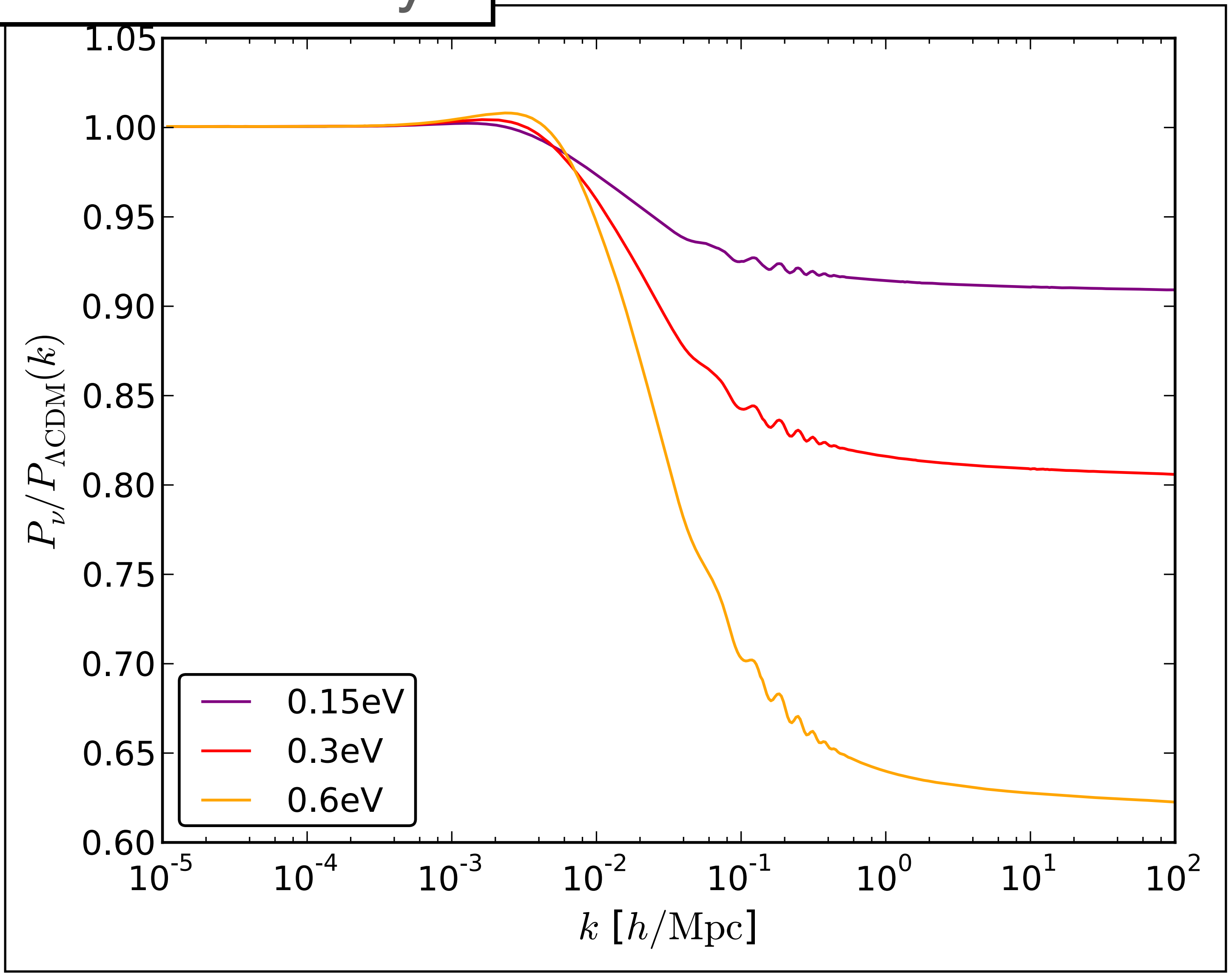
⇓

SUPPRESSION of the linear matter power spectrum at intermediate/ small scales

LINEAR ORDER

Linear Theory



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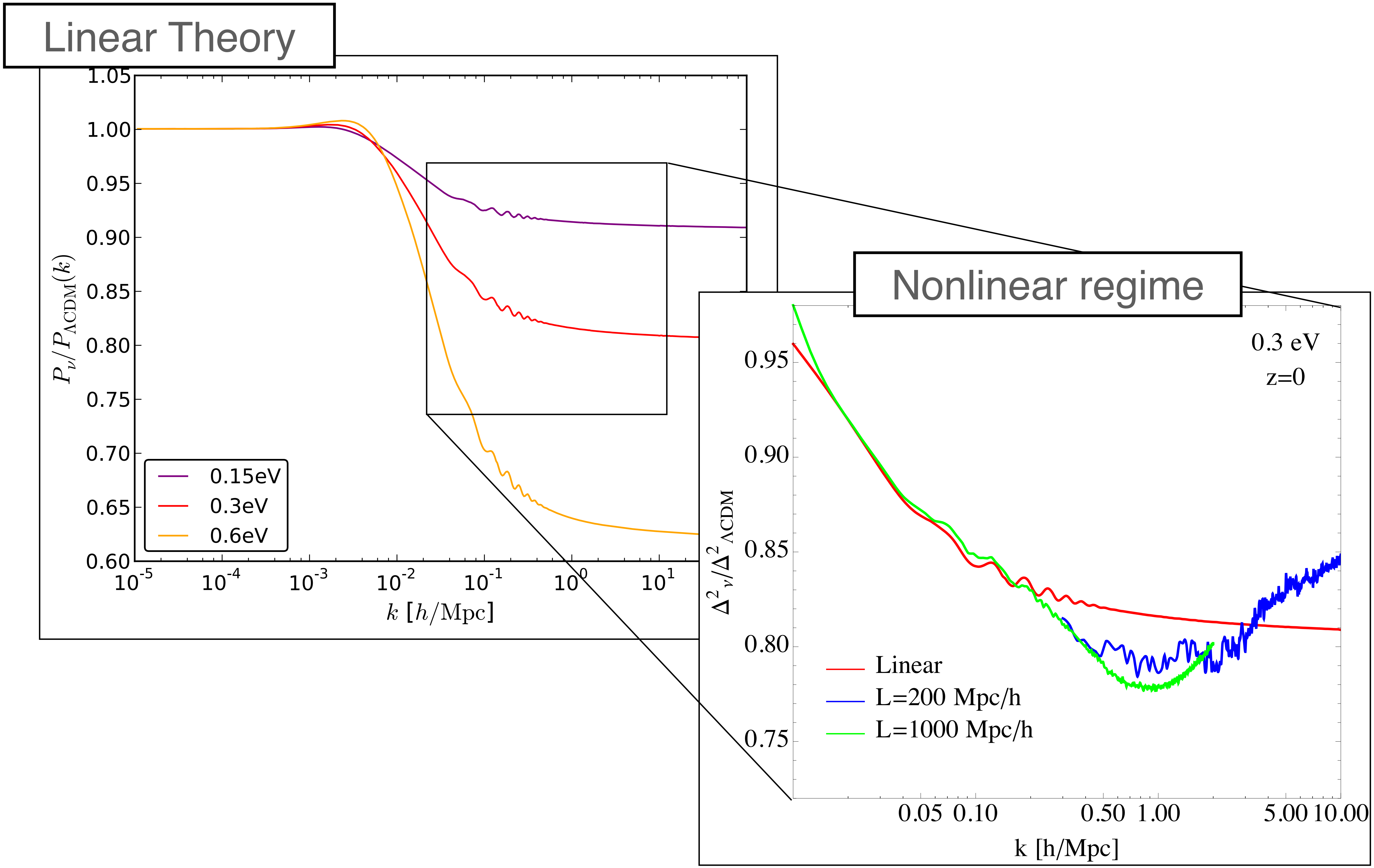
LINEAR & NONLINEAR

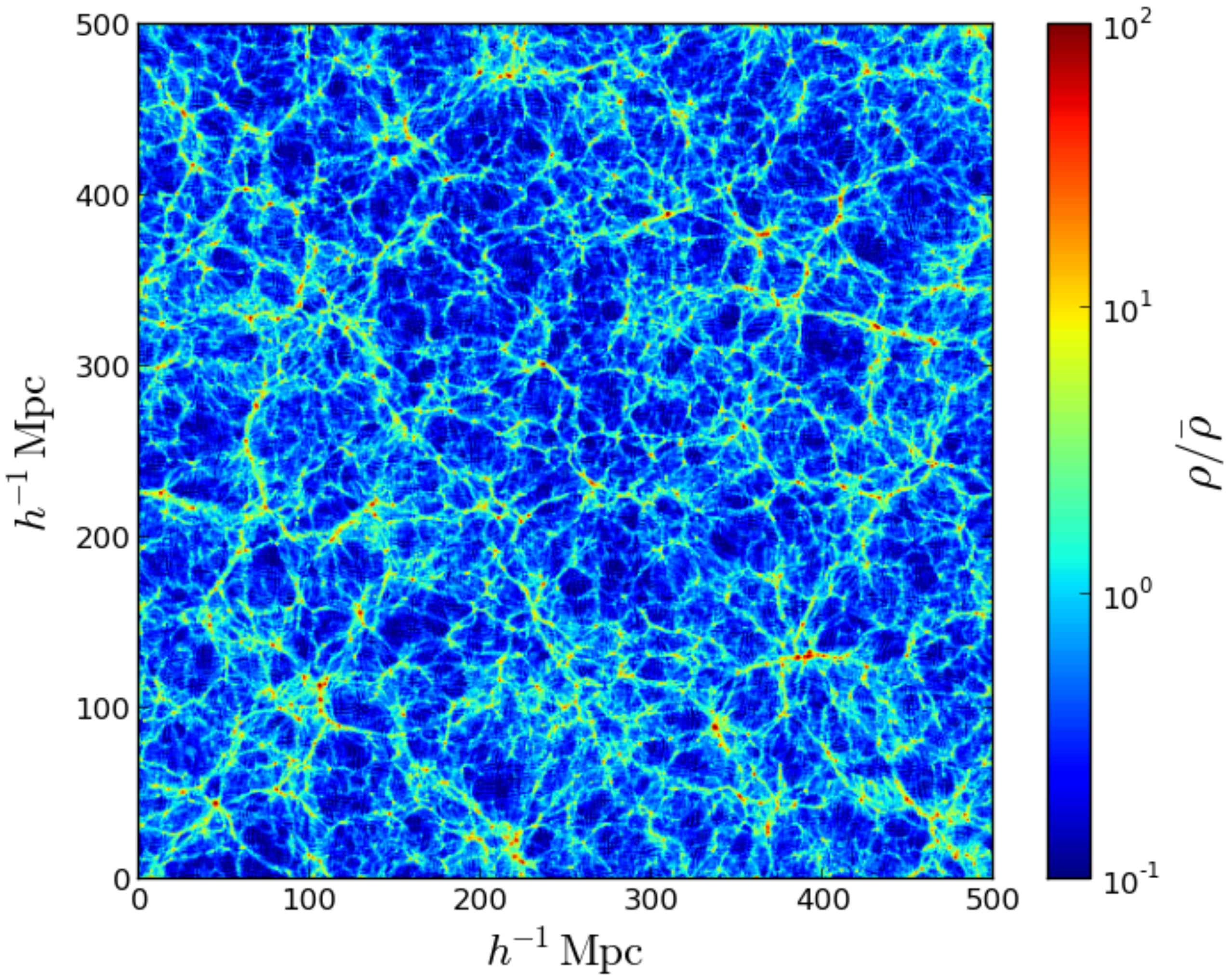


VOIDS

EM, Villaescusa-Navarro, Viel, Sutter, 2015

- Neutrinos: diffuse component

CDM density field



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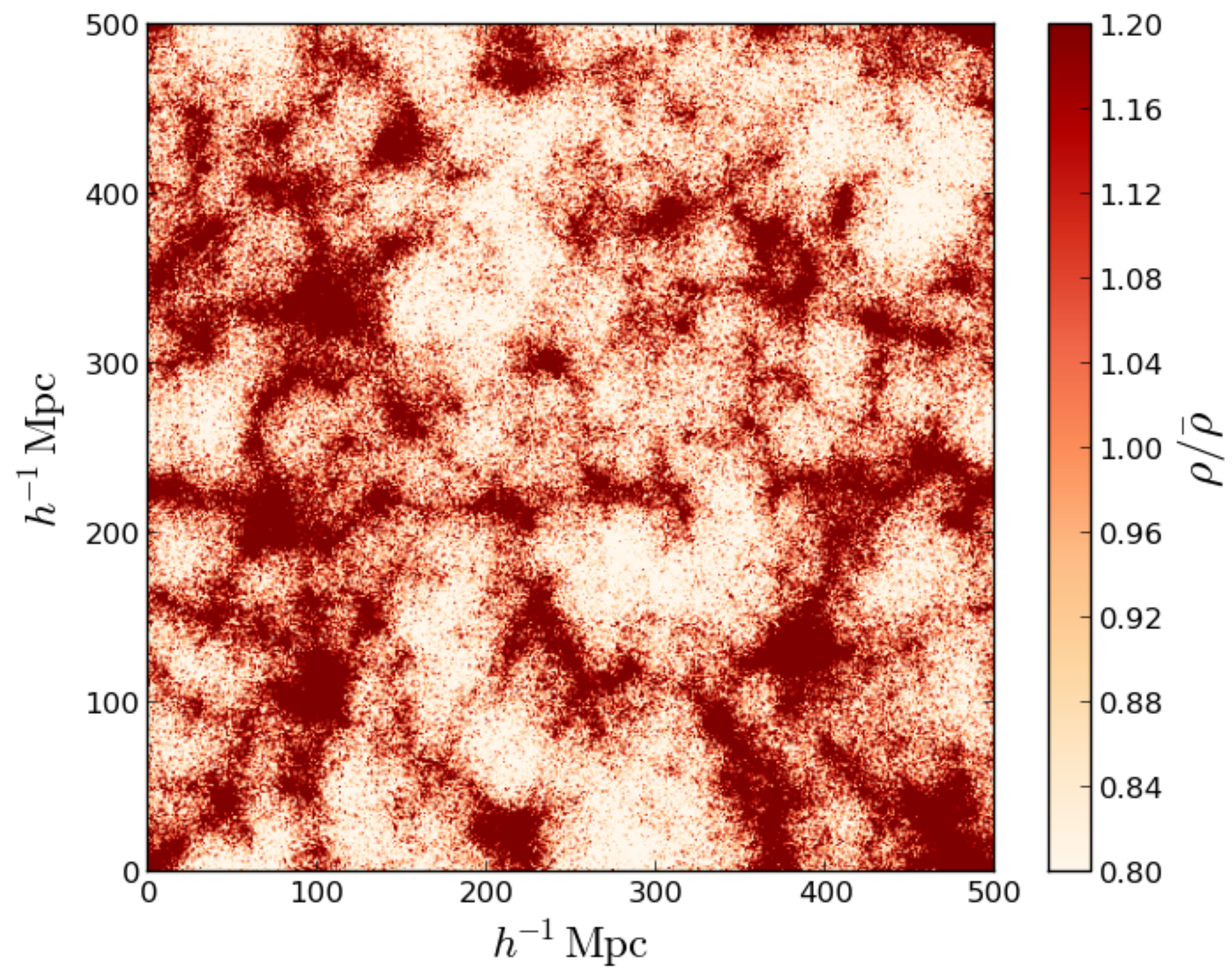

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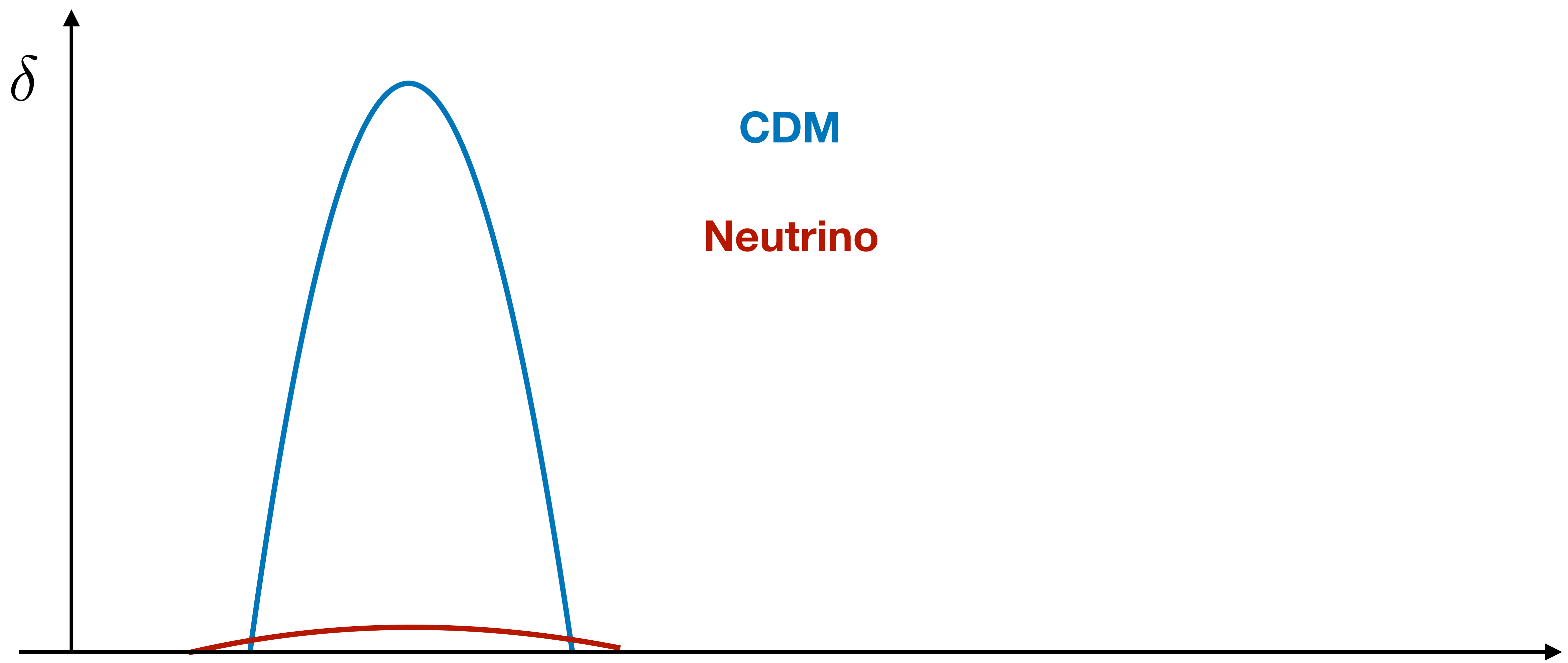

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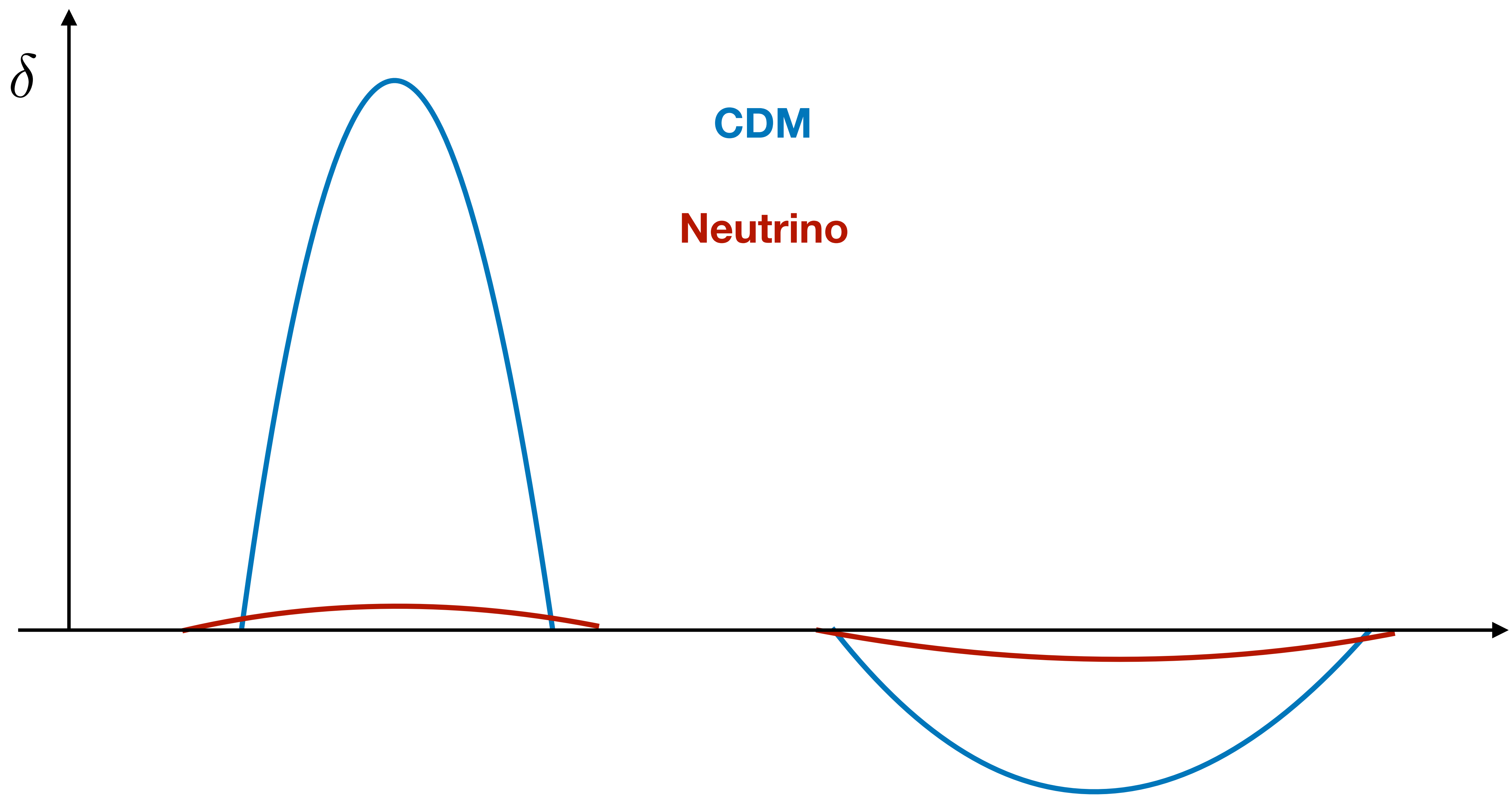

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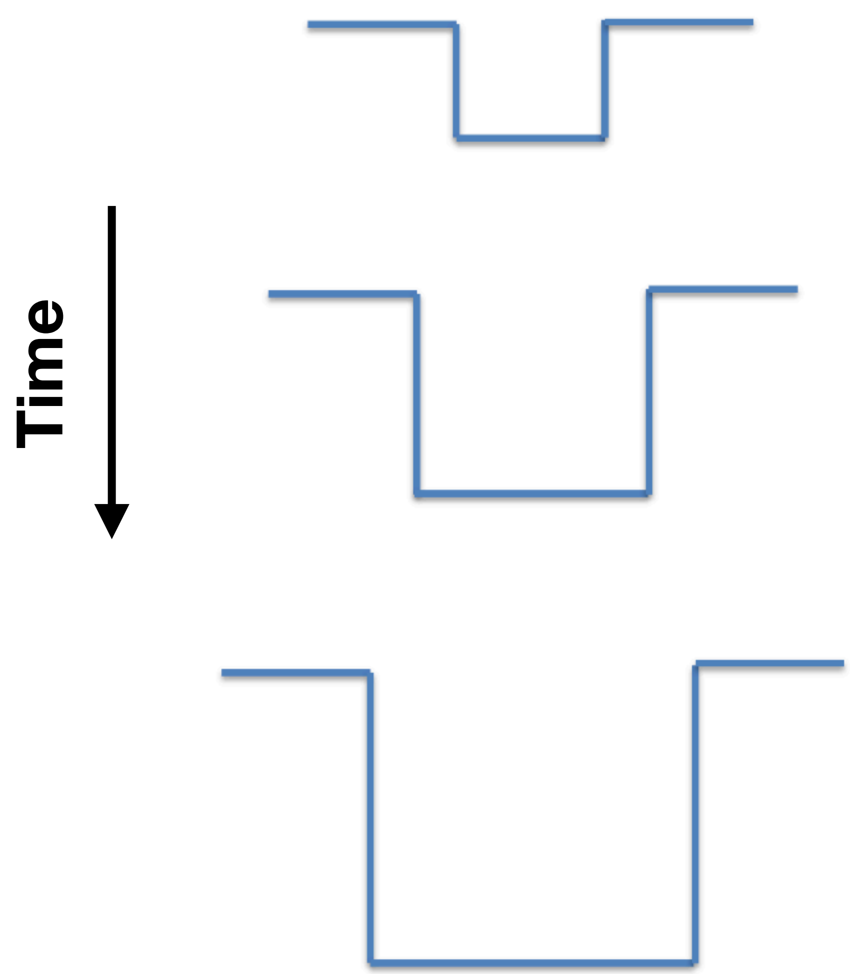

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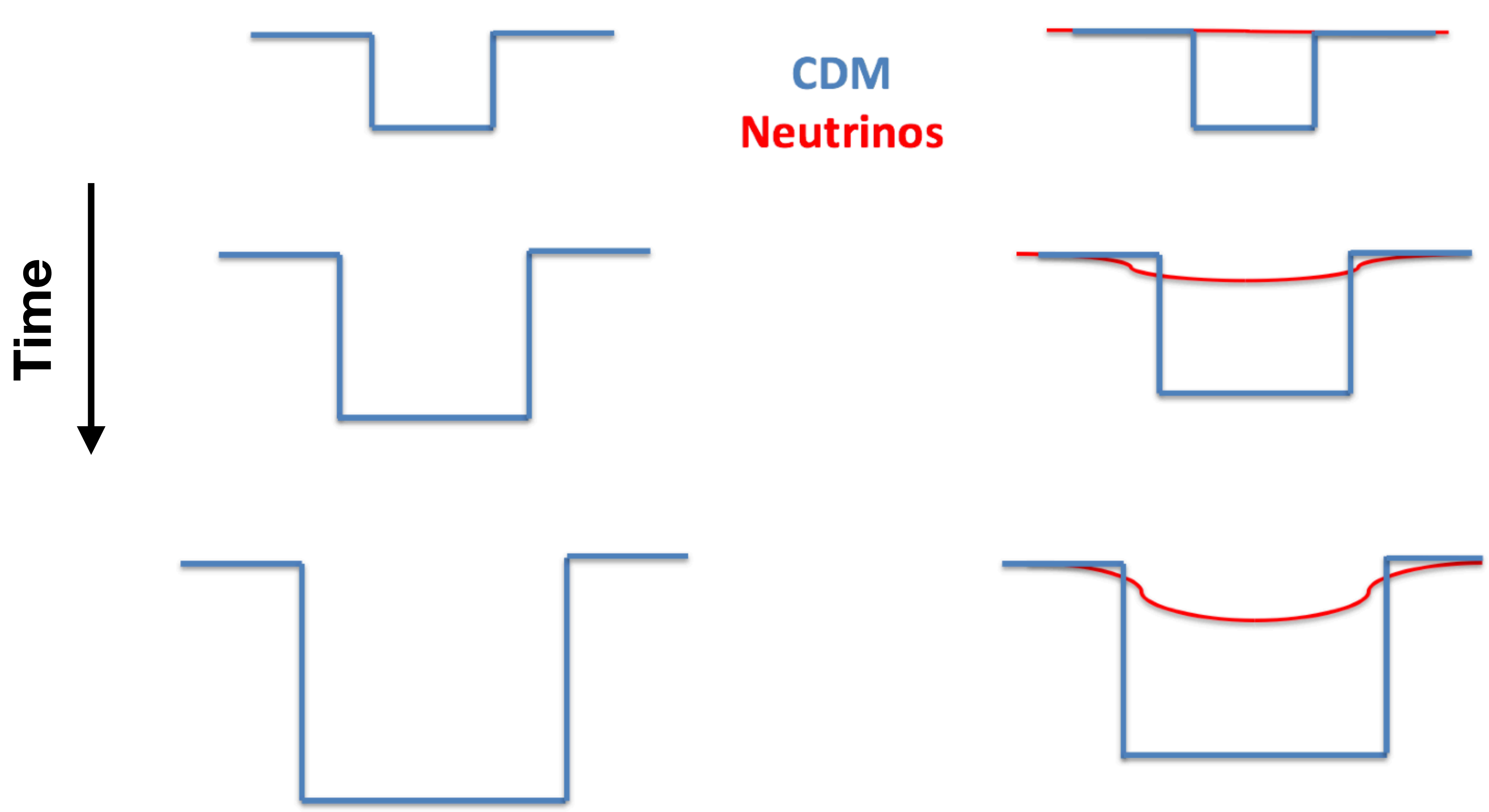

VOID SIZE FUNCTION

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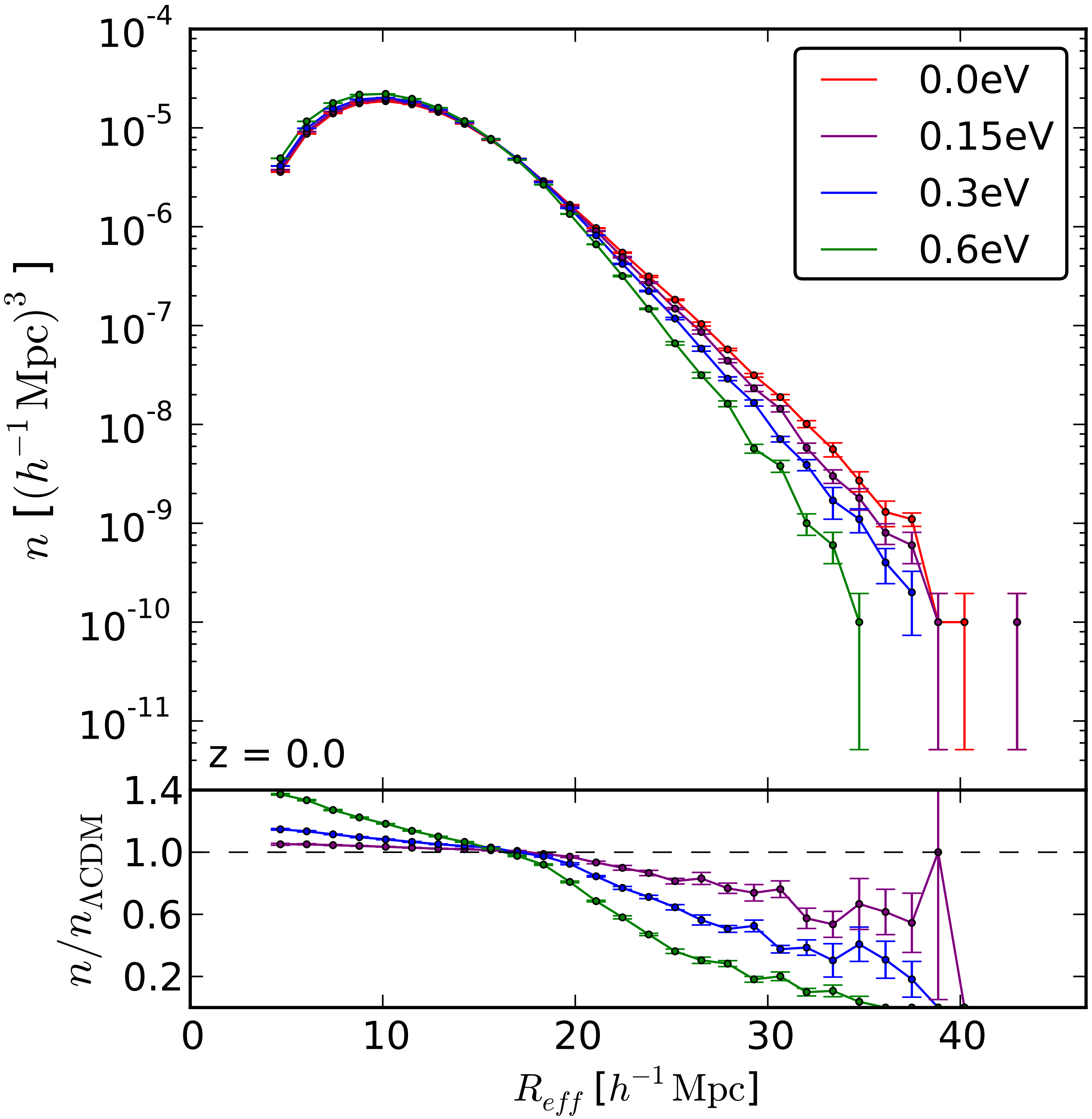

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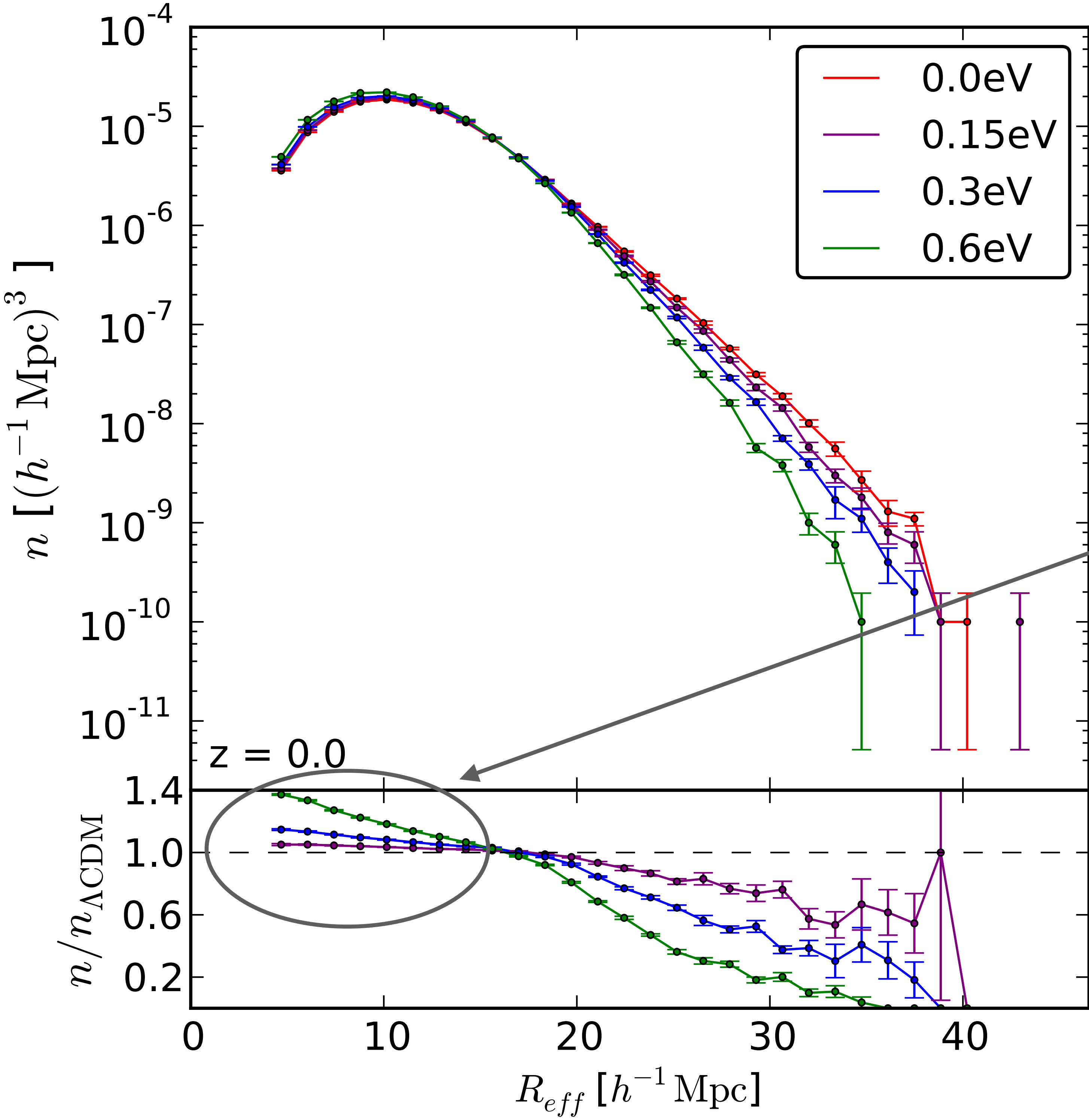

In <u>massive neutrino</u> cosmologies there are

- more small voids

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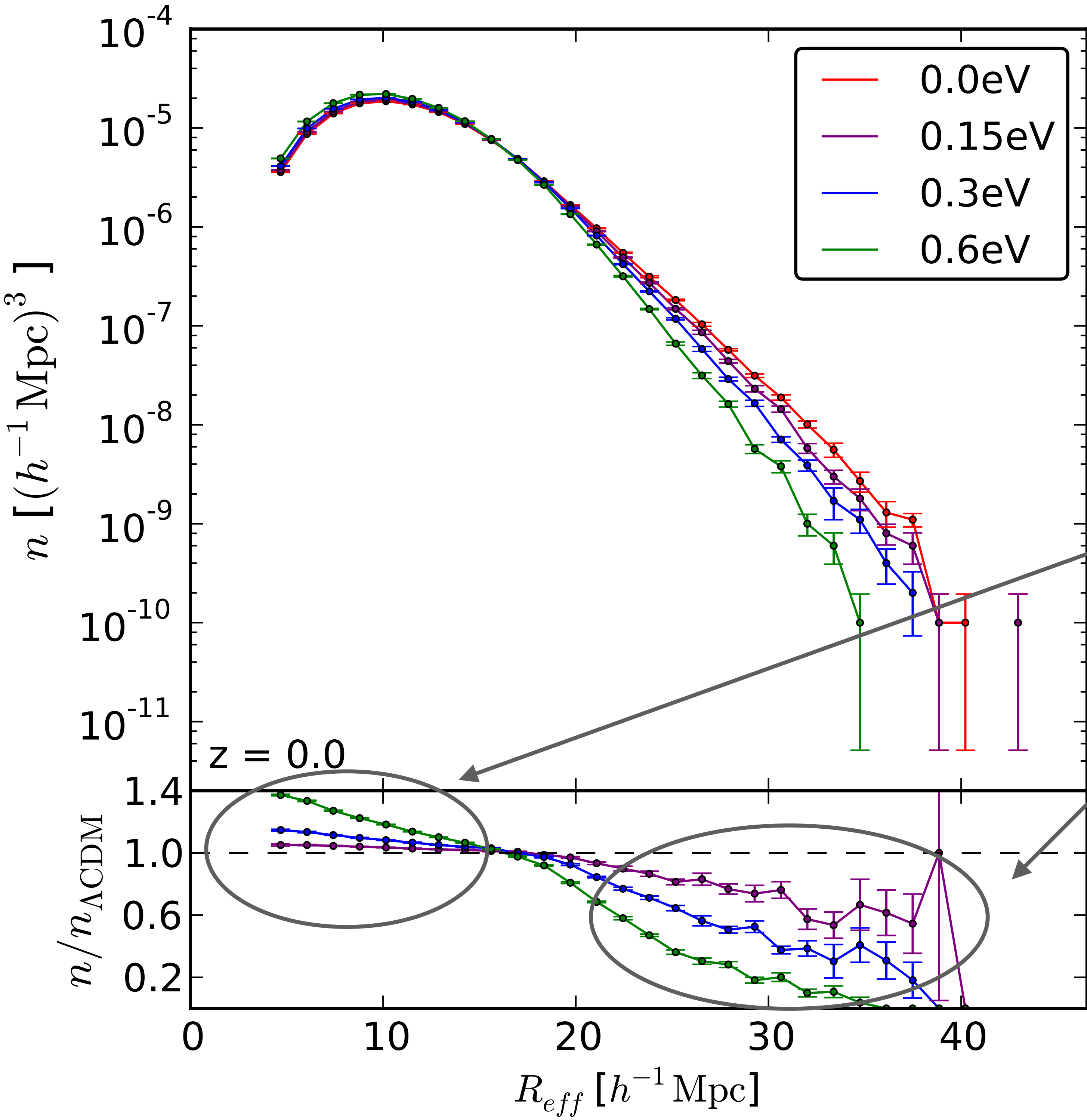
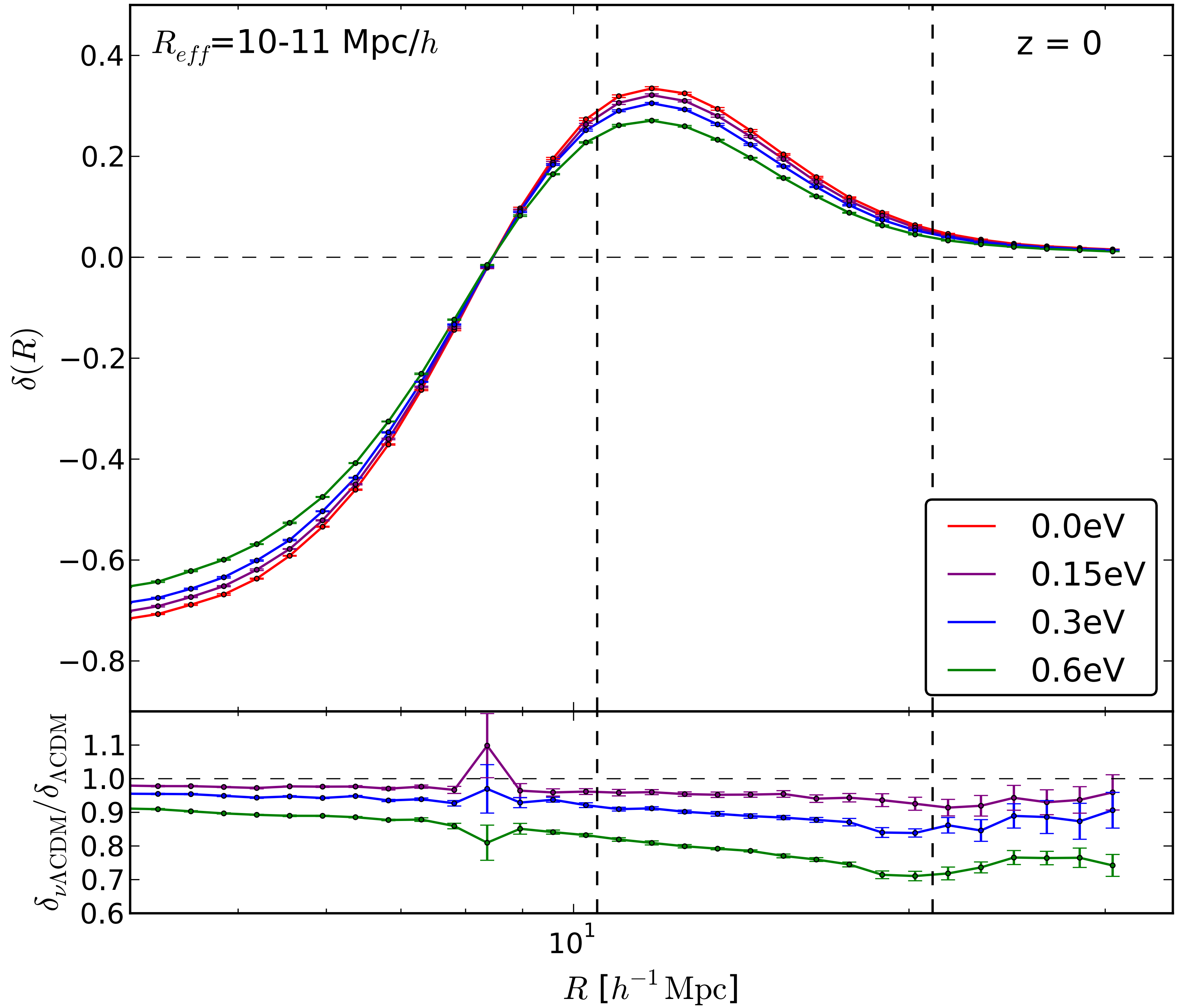


In massive neutrino cosmologies there are

- more small voids
- fewer big voids

MATTER PROFILE around VOIDS

EM, Villaescusa-Navarro, Viel, Sutter, 2015



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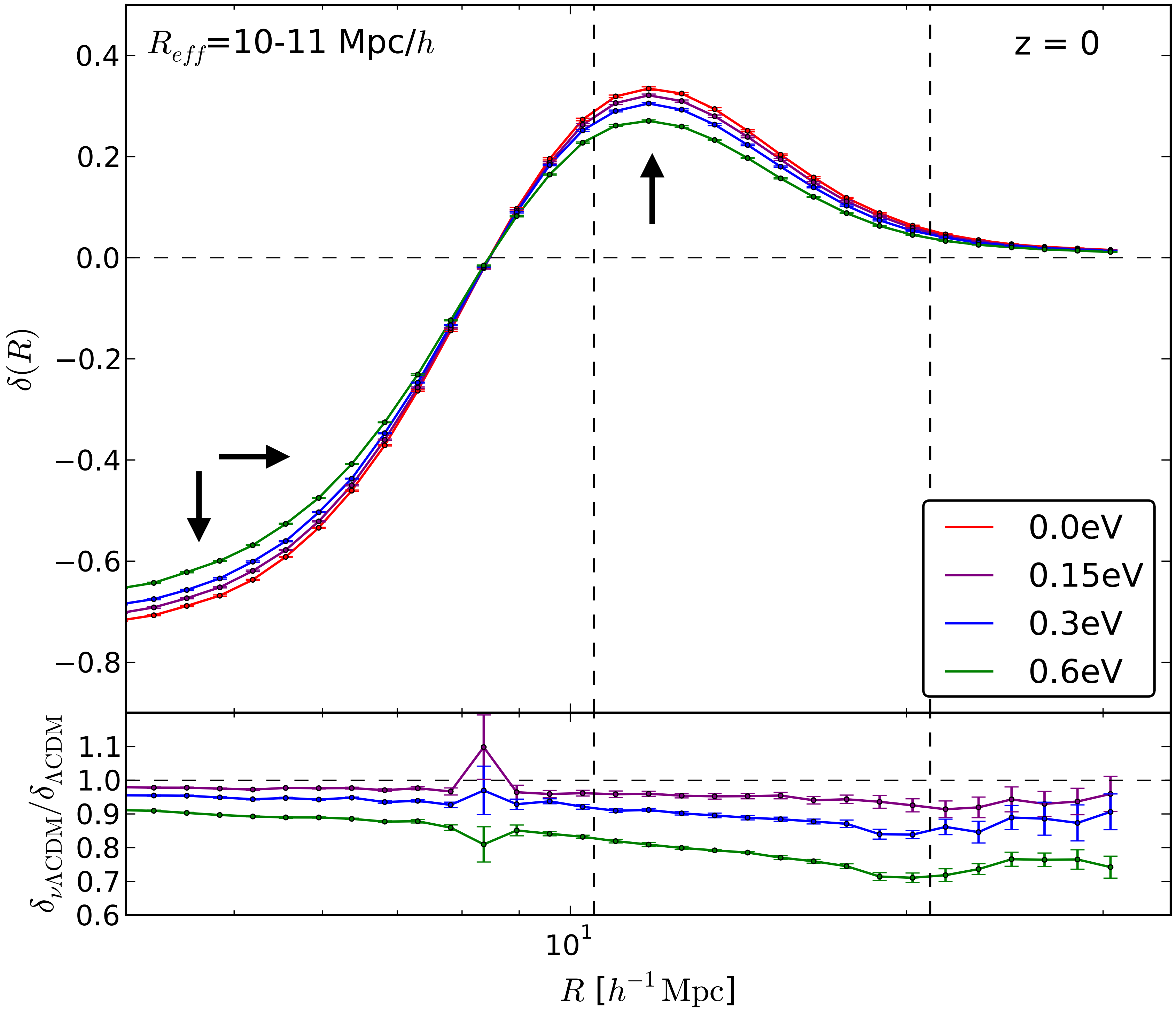
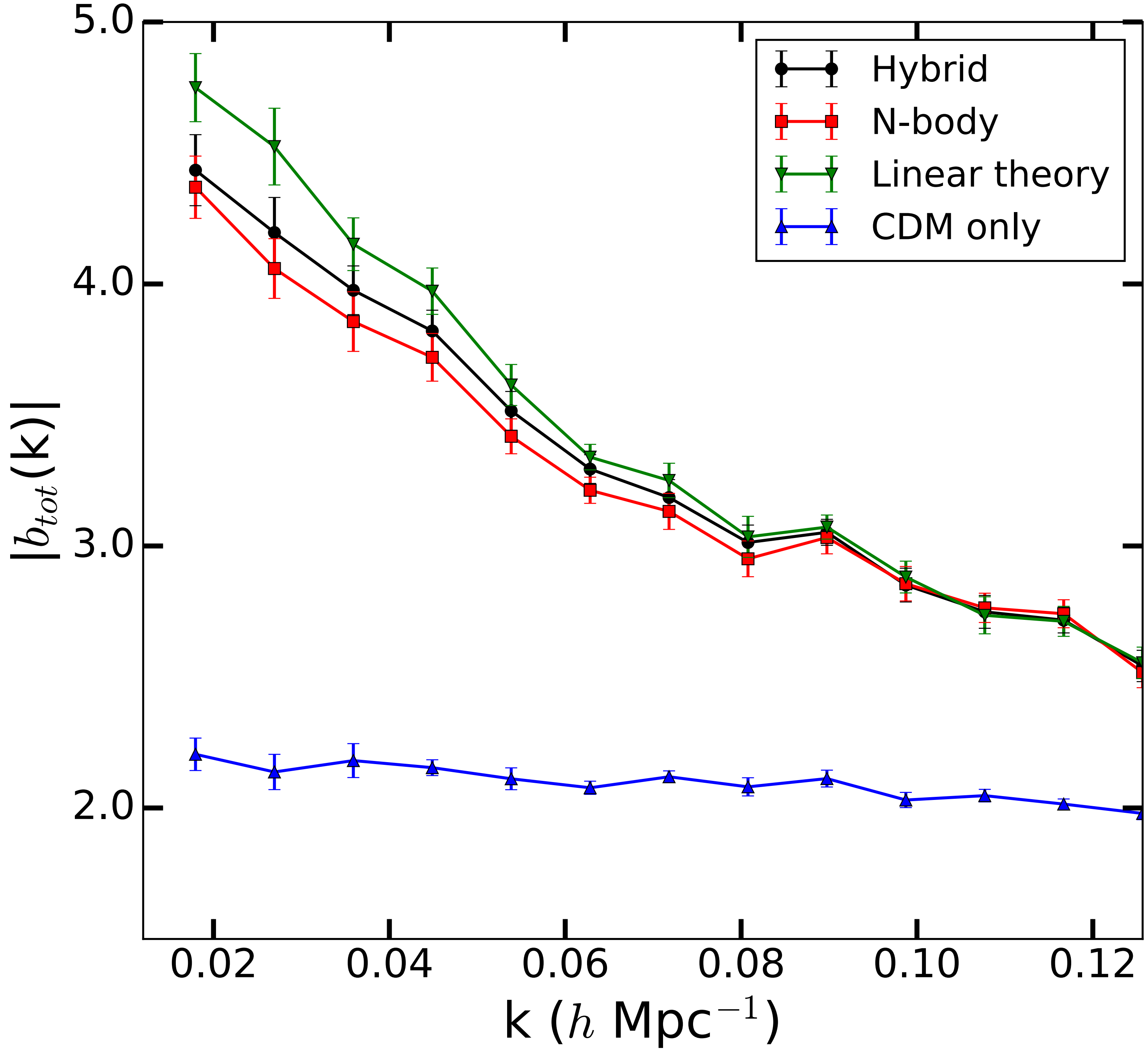


Voids in massive neutrino cosmology are less evolved

VOID BIAS

Banerjee and Dalal, 2016



$$\delta_{\rm void}(k) = b_{\rm tot}(k)\delta_{\rm tot}(k)$$

COSMOLOGY with VOIDS

Voids are good laboratories to study cosmology because

- They are sensitive to diffuse components such as
  - neutrinos
  - dark energy
- They have low densities, thus screening mechanism are inefficient and they are favored place where to study modification of gravity
- They have not undergone virialization, thus they are expected to retain most of their initial cosmological information

LOW DENSITY REGIONS

Low density regions are good probe to study cosmology

Should we build observables related
to low density regions/voids?

Void Size Function,
void-matter cross-correlation, …

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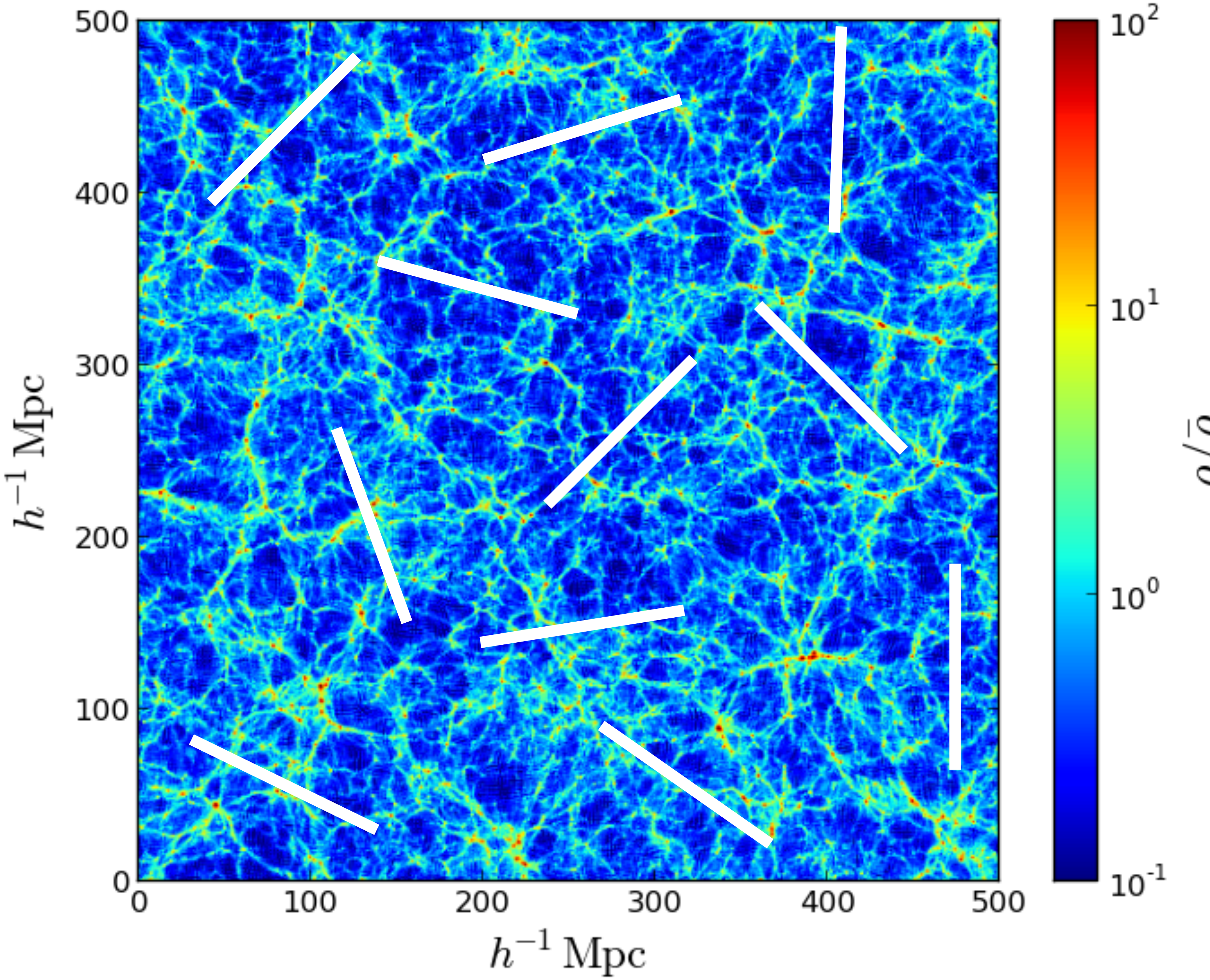
How much do correlation functions/ power spectra depend on low density regions?

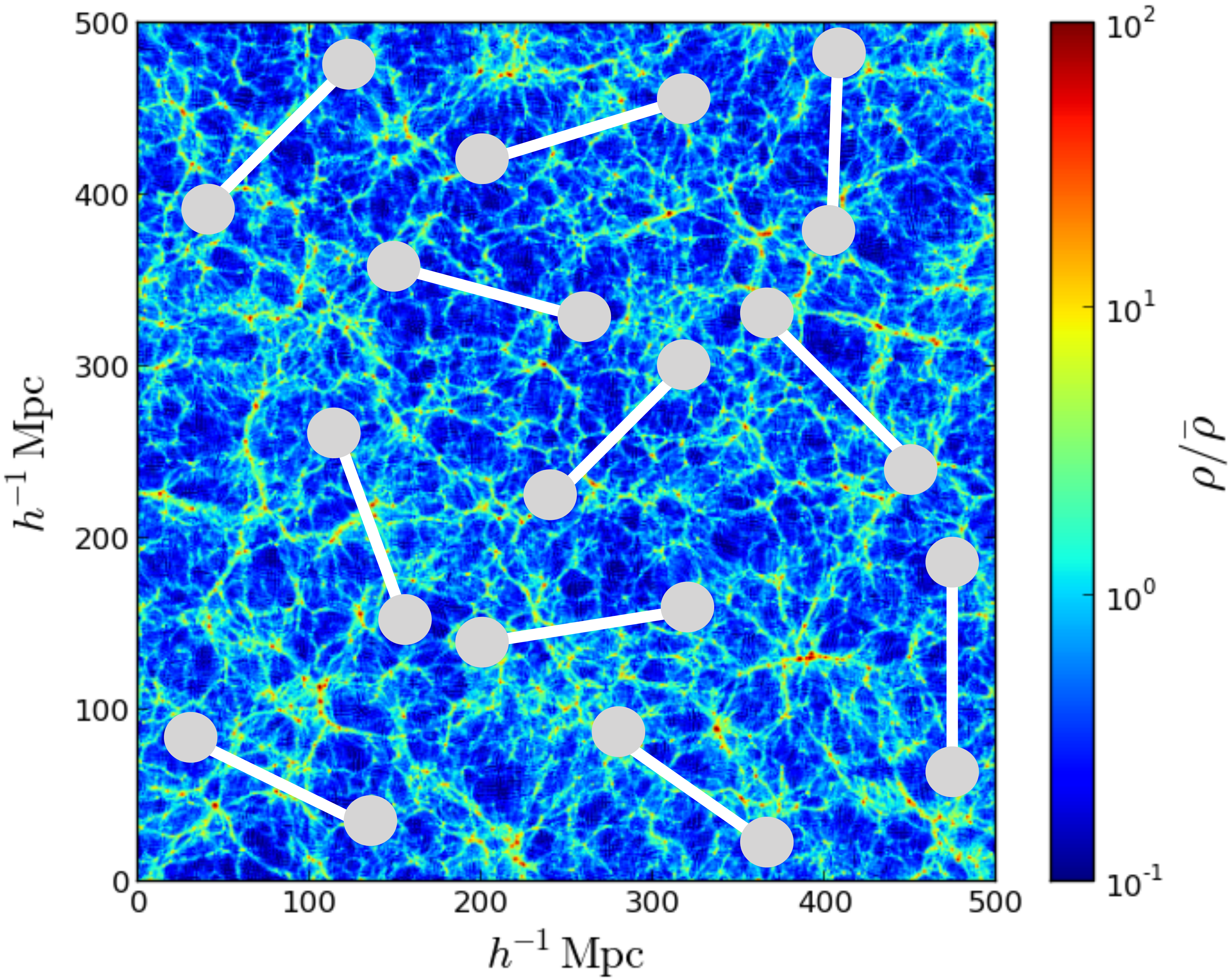
CORRELATION FUNCTION

$$1 + \xi(r) = \frac{V}{N^2} \sum_{i,j=1}^{N} \delta(|\vec{x_i} - \vec{x_j}| - r)$$



MARKED CORRELATION FUNCTION

$$1 + M(r,\phi) = \frac{V}{N^2} \sum_{i,j=1}^{N} \frac{\delta(|\vec{x_i} - \vec{x_j}| - r)\, m(\vec{x_i},\phi)\, m(\vec{x_j},\phi)}{\bar{m}^2}$$



We need m to up-weight low density regions and down-weight high density regions

m must depend on the local density around each point

MARKED CORRELATION FUNCTION

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$$\boxed{m(\vec{x}, \phi = R, p, \delta_s) = \left[\frac{1 + \delta_s}{1 + \delta_s + \delta_R(\vec{x})} \right]^p}$$

(M. White 2016)

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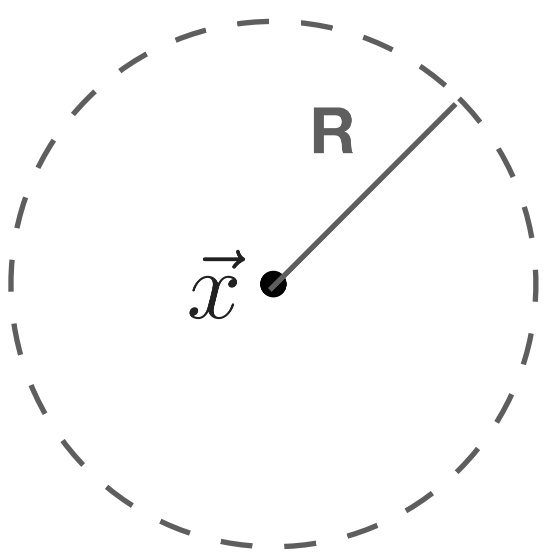

$$\delta_R(\vec{x}) = \frac{1}{V_R}\int_{V_R} d^3y\, \delta(\vec{y})$$

MARKED CORRELATION FUNCTION

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$$m(\vec{x}, \phi = R, p, \delta_s \to 0) \to \left[\frac{\bar{\rho}}{\rho_R(\vec{x})}\right]^p$$

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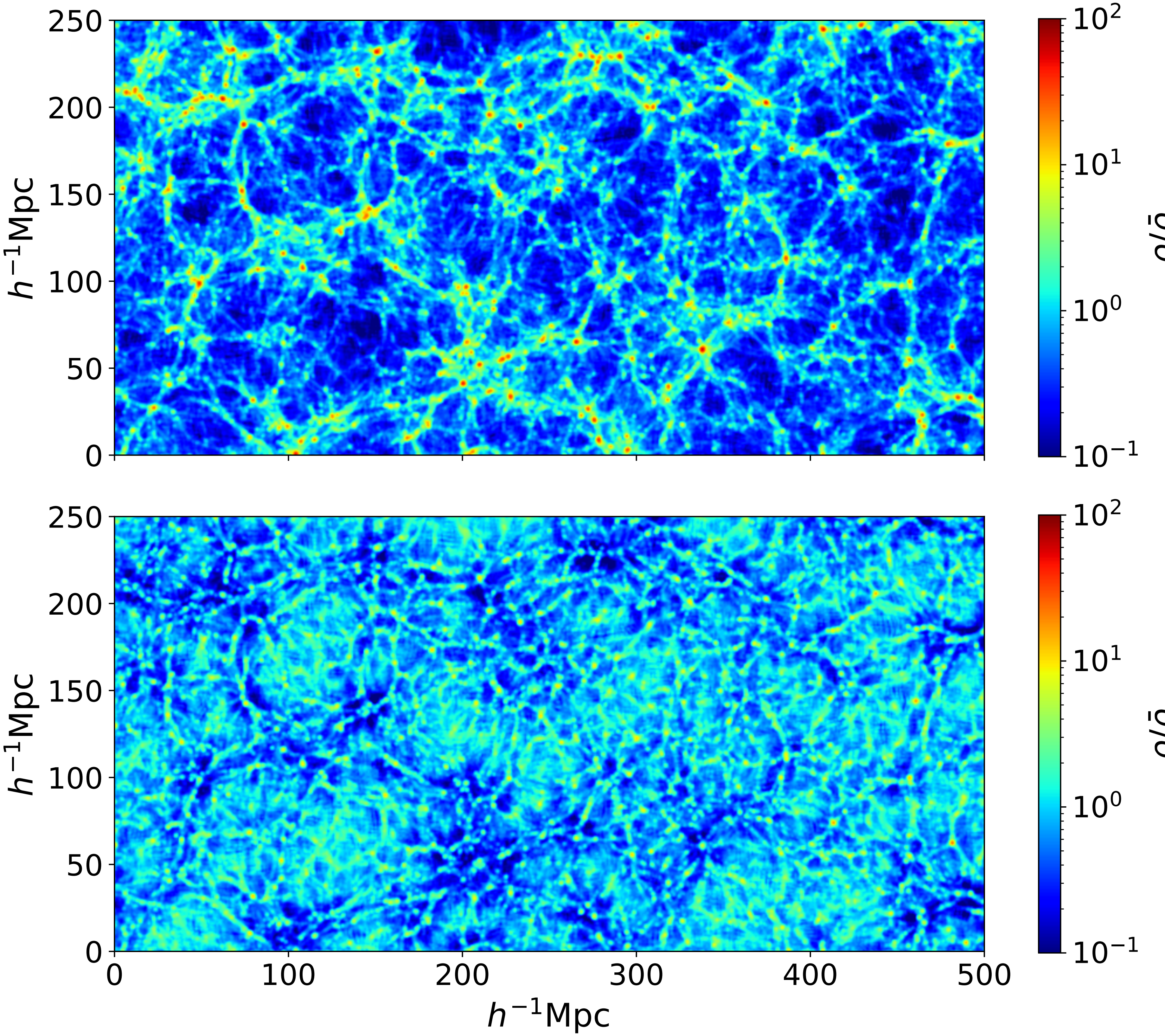
$p > 0$ Weight more particles/galaxies in **UNDER**-densities

$p < 0$ Weight more particles/galaxies in **OVER**-densities

MARKED DENSITY FIELD

EM et al. 2020



Density field

Marked density field with p>0

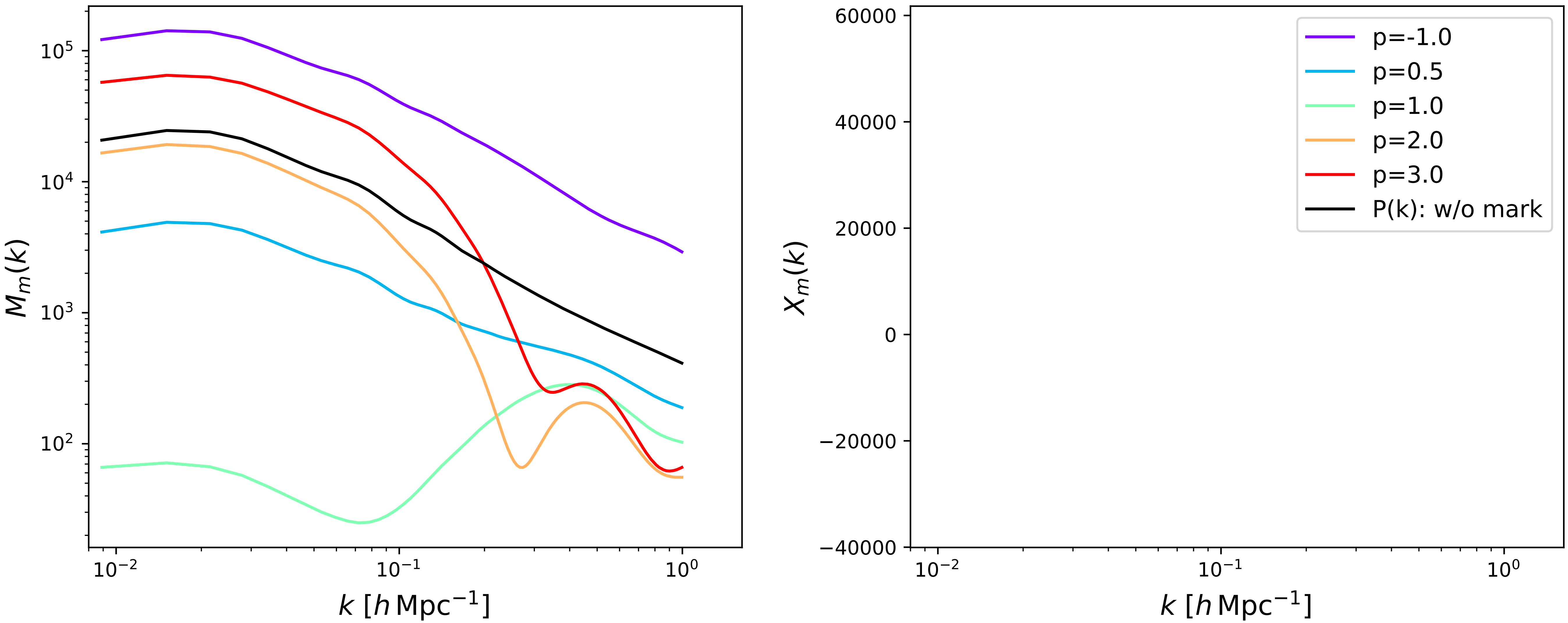
MARKED POWER SPECTRUM

EM et al. 2020

M(k) with R = 10 Mpc/h, δ_s = 0.0

Marked power spectrum

Marked-standard density cross-power spectrum



On large scales, an effective bias can describe the difference between standard and marked power spectra

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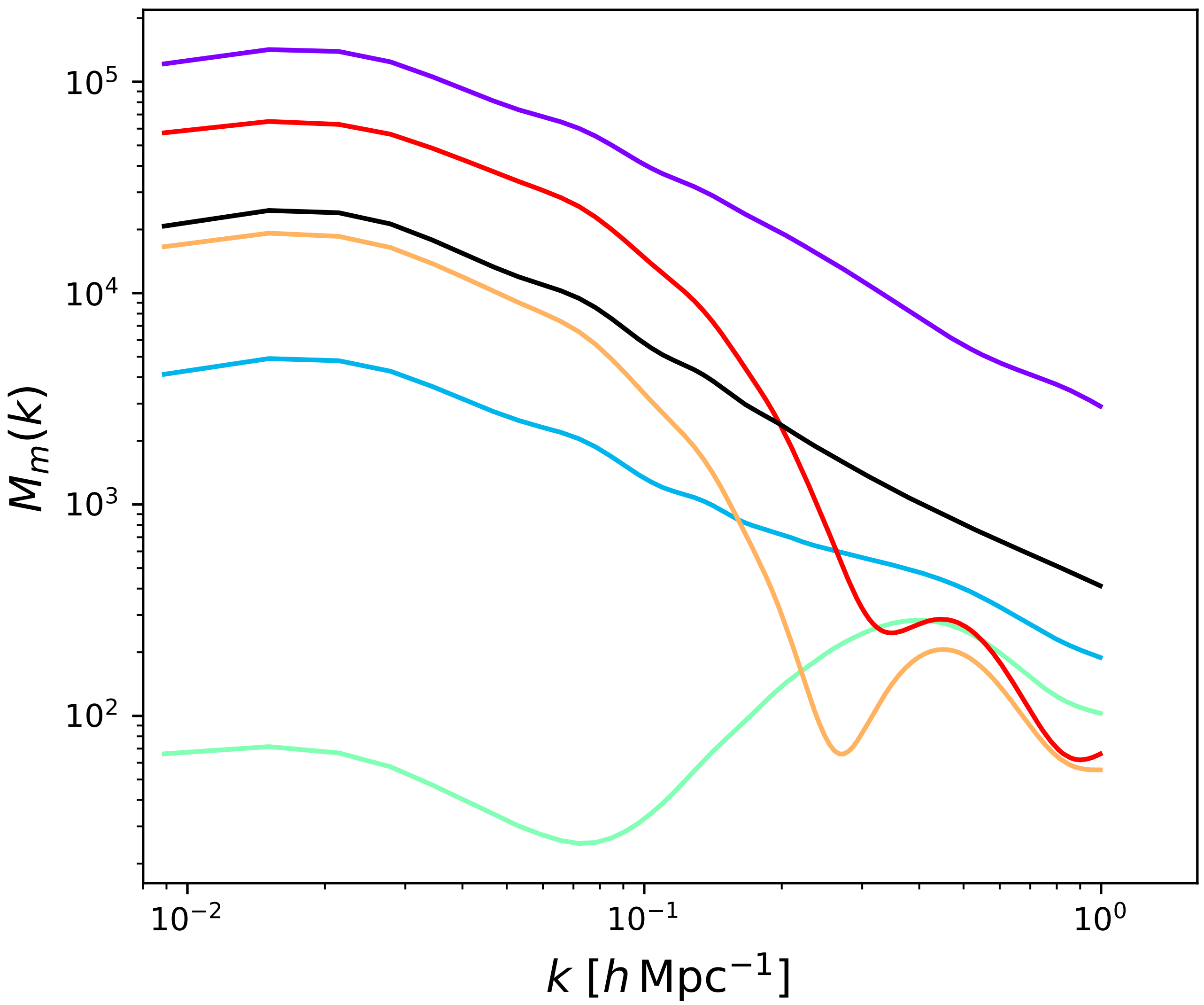
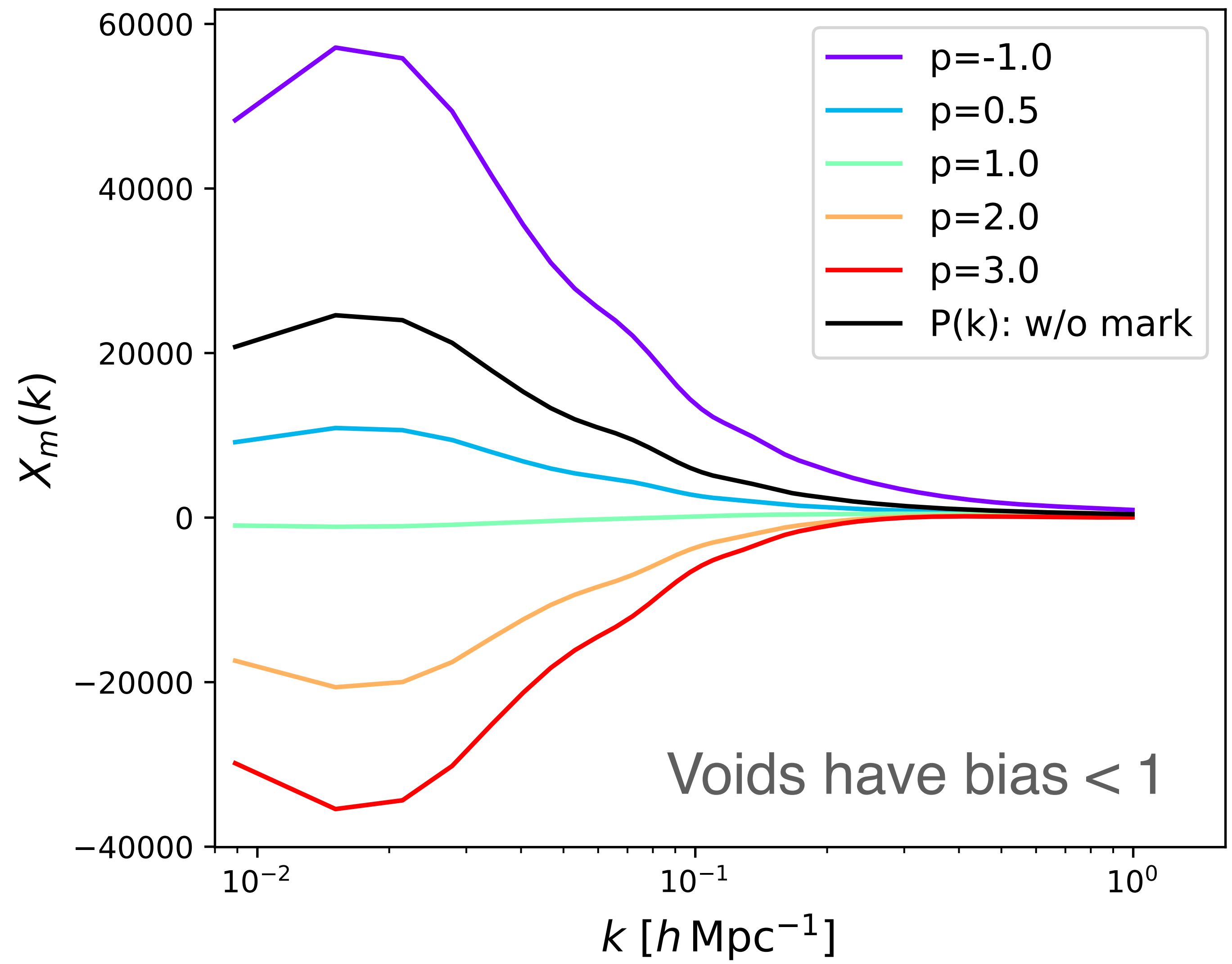


Marked-standard density cross-power spectrum



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INFORMATION CONTENT IN MARKED POWER SPECTRA

FISHER ANALYSIS

Cosmological parameters: $\vec{\theta} = \{\Omega_m, \Omega_b, h, n_s, \sigma_8, M_\nu\}$

Data vector (observables): $\vec{d} = \{P(k_1), P(k_2), .., P(k_n)\}$

Error on each parameter:

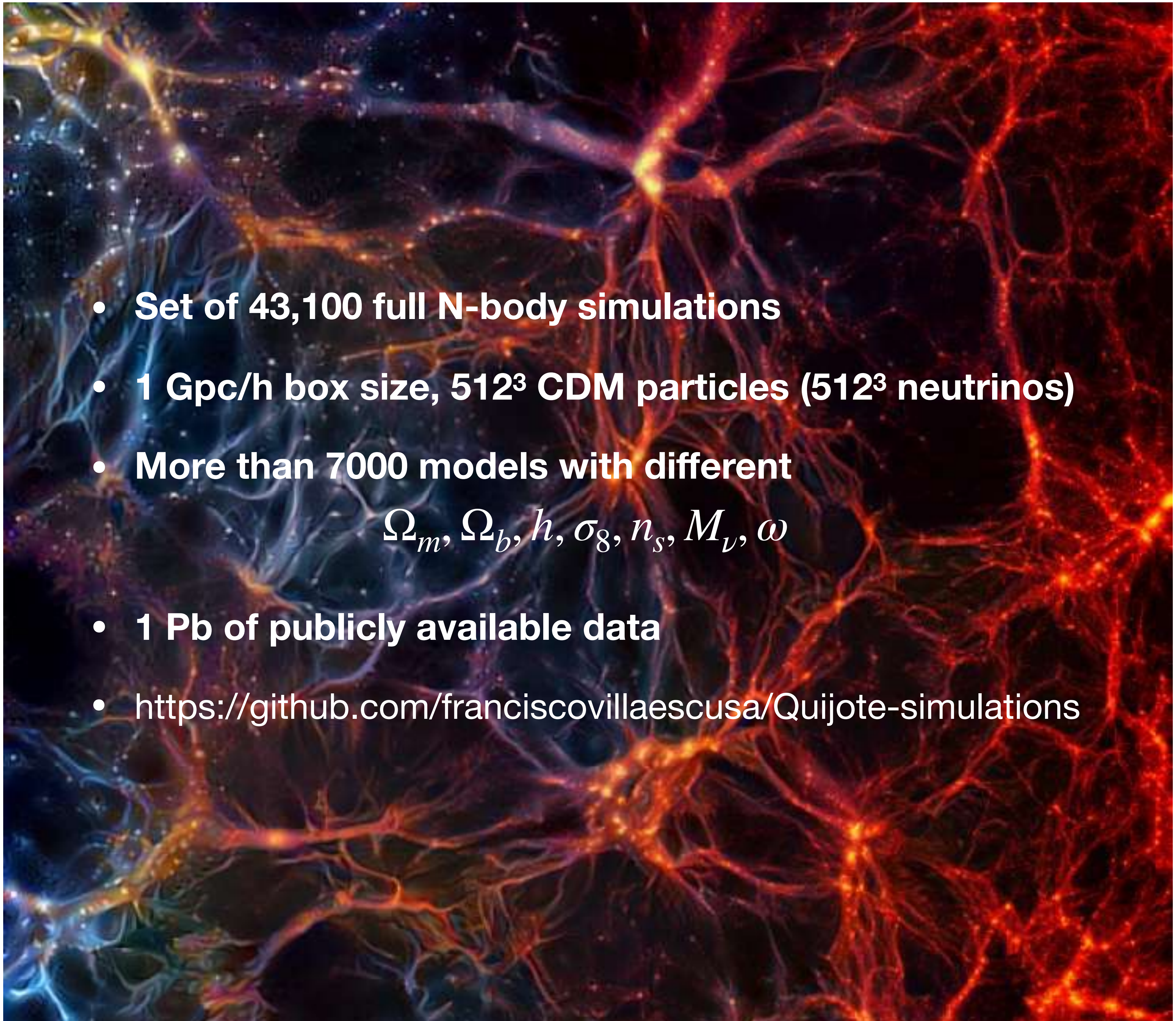
$$\sigma(\theta_\alpha) \leq \sqrt{(F^{-1})_{\alpha\alpha}}$$

Fisher matrix:

$$F_{\alpha,\beta} = \frac{\partial \vec{d}}{\partial \theta_\alpha} C^{-1} \frac{\partial \vec{d}}{\partial \theta_\beta}$$

QUIJOTE SIMULATIONS

Villaescusa-Navarro, Hanh, **EM** et al 2019



- **Set of 43,100 full N-body simulations**
- **1 Gpc/h box size, 512^3 CDM particles (512^3 neutrinos)**
- **More than 7000 models with different**

$$\Omega_m, \Omega_b, h, \sigma_8, n_s, M_\nu, \omega$$

- **1 Pb of publicly available data**
- https://github.com/franciscovillaescusa/Quijote-simulations

QUIJOTE SIMULATIONS

Villaescusa-Navarro, Hanh, **EM** et al 2019

Name	$\Omega_{\rm m}$	$\Omega_{\rm b}$	h	$n_{\rm s}$	σ_8	M_ν(eV)	w	realizations	simulations	ICs	$N_c^{1/3}$	$N_\nu^{1/3}$
Fid	0.3175	0.049	0.6711	0.9624	0.834	0	-1	15000 500 500 1000 100	standard standard paired fixed standard standard	2LPT Zeldovich 2LPT 2LPT 2LPT	512 512 512 256 1024	0 0 0 0 0
$\Omega_{\rm m}^+$	0.3275	0.049	0.6711	0.9624	0.834	0	-1	500 500	standard paired fixed	2LPT	512	0
$\Omega_{\rm m}^-$	0.3075	0.049	0.6711	0.9624	0.834	0	-1	500 500	standard paired fixed	2LPT	512	0
$\Omega_{\rm b}^{++}$	0.3175	0.051	0.6711	0.9624	0.834	0	-1	500 500	standard paired fixed	2LPT	512	0
$\Omega_{\rm b}^+$	0.3175	0.050	0.6711	0.9624	0.834	0	-1	500	paired fixed	2LPT	512	0
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$\Omega_{\rm b}^{--}$	0.3175	0.047	0.6711	0.9624	0.834	0	-1	500 500	standard paired fixed	2LPT	512	0
h^+	0.3175	0.049	0.6911	0.9624	0.834	0	-1	500 500	standard paired fixed	2LPT	512	0
h^-	0.3175	0.049	0.6511	0.9624	0.834	0	-1	500 500	standard paired fixed	2LPT	512	0
$n_{\rm s}^+$	0.3175	0.049	0.6711	0.9824	0.834	0	-1	500 500	standard paired fixed	2LPT	512	0
$n_{\rm s}^+$	0.3175	0.049	0.6711	0.9424	0.834	0	-1	500 500	standard paired fixed	2LPT	512	0
σ_8^+	0.3175	0.049	0.6711	0.9624	0.849	0	-1	500 500	standard paired fixed	2LPT	512	0
σ_8^-	0.3175	0.049	0.6711	0.9624	0.819	0	-1	500 500	standard paired fixed	2LPT	512	0
M_ν^{+++}	0.3175	0.049	0.6711	0.9624	0.834	0.4	-1	500 500	standard paired fixed	Zeldovich	512	512
M_ν^{++}	0.3175	0.049	0.6711	0.9624	0.834	0.2	-1	500 500	standard paired fixed	Zeldovich	512	512
M_ν^+	0.3175	0.049	0.6711	0.9624	0.834	0.1	-1	500 500	standard paired fixed	Zeldovich	512	512

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Villaescusa-Navarro, Hanh, **EM** et al 2019

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Ω_m^+	0.3275	0.049	0.6711	0.9624	0.834	0	-1	500 500	standard paired fixed	2LPT	512	0
Ω_m^-	0.3075	0.049	0.6711	0.9624	0.834	0	-1	500 500	standard paired fixed	2LPT	512	0
Ω_b^{++}	0.3175	0.051	0.6711	0.9624	0.834	0	-1	500 500	standard paired fixed	2LPT	512	0
Ω_b^+	0.3175	0.050	0.6711	0.9624	0.834	0	-1	500	paired fixed	2LPT	512	0
Ω_b^-	0.3175	0.048	0.6711	0.9624	0.834	0	-1	500	paired fixed	2LPT	512	0
Ω_b^{--}	0.3175	0.047	0.6711	0.9624	0.834	0	-1	500 500	standard paired fixed	2LPT	512	0
h^+	0.3175	0.049	0.6911	0.9624	0.834	0	-1	500 500	standard paired fixed	2LPT	512	0
h^-	0.3175	0.049	0.6511	0.9624	0.834	0	-1	500 500	standard paired fixed	2LPT	512	0
n_s^+	0.3175	0.049	0.6711	0.9824	0.834	0	-1	500 500	standard paired fixed	2LPT	512	0
n_s^+	0.3175	0.049	0.6711	0.9424	0.834	0	-1	500 500	standard paired fixed	2LPT	512	0
σ_8^+	0.3175	0.049	0.6711	0.9624	0.849	0	-1	500 500	standard paired fixed	2LPT	512	0
σ_8^-	0.3175	0.049	0.6711	0.9624	0.819	0	-1	500 500	standard paired fixed	2LPT	512	0
M_ν^{+++}	0.3175	0.049	0.6711	0.9624	0.834	0.4	-1	500 500	standard paired fixed	Zeldovich	512	512
M_ν^{++}	0.3175	0.049	0.6711	0.9624	0.834	0.2	-1	500 500	standard paired fixed	Zeldovich	512	512
M_ν^+	0.3175	0.049	0.6711	0.9624	0.834	0.1	-1	500 500	standard paired fixed	Zeldovich	512	512

QUIJOTE SIMULATIONS

Villaescusa-Navarro, Hanh, **EM** et al 2019

Name	Ω_m	Ω_b	h	n_s	σ_8	M_ν(eV)	w	realizations	simulations	ICs	$N_c^{1/3}$	$N_\nu^{1/3}$
Fid	0.3175	0.049	0.6711	0.9624	0.834	0	-1	15000 500 500 1000 100	standard standard paired fixed standard standard	2LPT Zeldovich 2LPT 2LPT 2LPT	512 512 512 256 1024	0 0 0 0 0
Ω_m^+	0.3275	0.049	0.6711	0.9624	0.834	0	-1	500 500	standard paired fixed	2LPT	512	0
Ω_m^-	0.3075	0.049	0.6711	0.9624	0.834	0	-1	500 500	standard paired fixed	2LPT	512	0
Ω_b^{++}	0.3175	0.051	0.6711	0.9624	0.834	0	-1	500 500	standard paired fixed	2LPT	512	0
Ω_b^+	0.3175	0.050	0.6711	0.9624	0.834	0	-1	500	paired fixed	2LPT	512	0
Ω_b^-	0.3175	0.048	0.6711	0.9624	0.834	0	-1	500	paired fixed	2LPT	512	0
Ω_b^{--}	0.3175	0.047	0.6711	0.9624	0.834	0	-1	500 500	standard paired fixed	2LPT	512	0
h^+	0.3175	0.049	0.6911	0.9624	0.834	0	-1	500 500	standard paired fixed	2LPT	512	0
h^-	0.3175	0.049	0.6511	0.9624	0.834	0	-1	500 500	standard paired fixed	2LPT	512	0
n_s^+	0.3175	0.049	0.6711	0.9824	0.834	0	-1	500 500	standard paired fixed	2LPT	512	0
n_s^+	0.3175	0.049	0.6711	0.9424	0.834	0	-1	500 500	standard paired fixed	2LPT	512	0
σ_8^+	0.3175	0.049	0.6711	0.9624	0.849	0	-1	500 500	standard paired fixed	2LPT	512	0
σ_8^-	0.3175	0.049	0.6711	0.9624	0.819	0	-1	500 500	standard paired fixed	2LPT	512	0
M_ν^{+++}	0.3175	0.049	0.6711	0.9624	0.834	0.4	-1	500 500	standard paired fixed	Zeldovich	512	512
M_ν^{++}	0.3175	0.049	0.6711	0.9624	0.834	0.2	-1	500 500	standard paired fixed	Zeldovich	512	512
M_ν^+	0.3175	0.049	0.6711	0.9624	0.834	0.1	-1	500 500	standard paired fixed	Zeldovich	512	512

MARKED POWER SPECTRA

EM et al. 2020

The Mark

$$m(\vec{x}, \phi = R, p, \delta_s) = \left[\frac{1+\delta_s}{1+\delta_s+\delta_R(\vec{x})}\right]^p$$

Considered values for the mark parameters

R = [5, 10, 15, 20, 30] Mpc/h

p = [-1, 0.5, 1, 2, 3]

δ_s = [0, 0.25, 0.5, 0.75, 1]

125 marked power spectra compute on the matter fields
cdm and m = cdm+neutrinos

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$$m(\vec{x}, \phi = R, p, \delta_s) = \left[\frac{1 + \delta_s}{1 + \delta_s + \delta_R(\vec{x})} \right]^p$$

Considered values for the mark parameters

R = [5, **10**, 15, 20, 30] Mpc/h

p = [-1, 0.5, 1, **2**, 3]

δ_s = [0, **0.25**, 0.5, 0.75, 1]

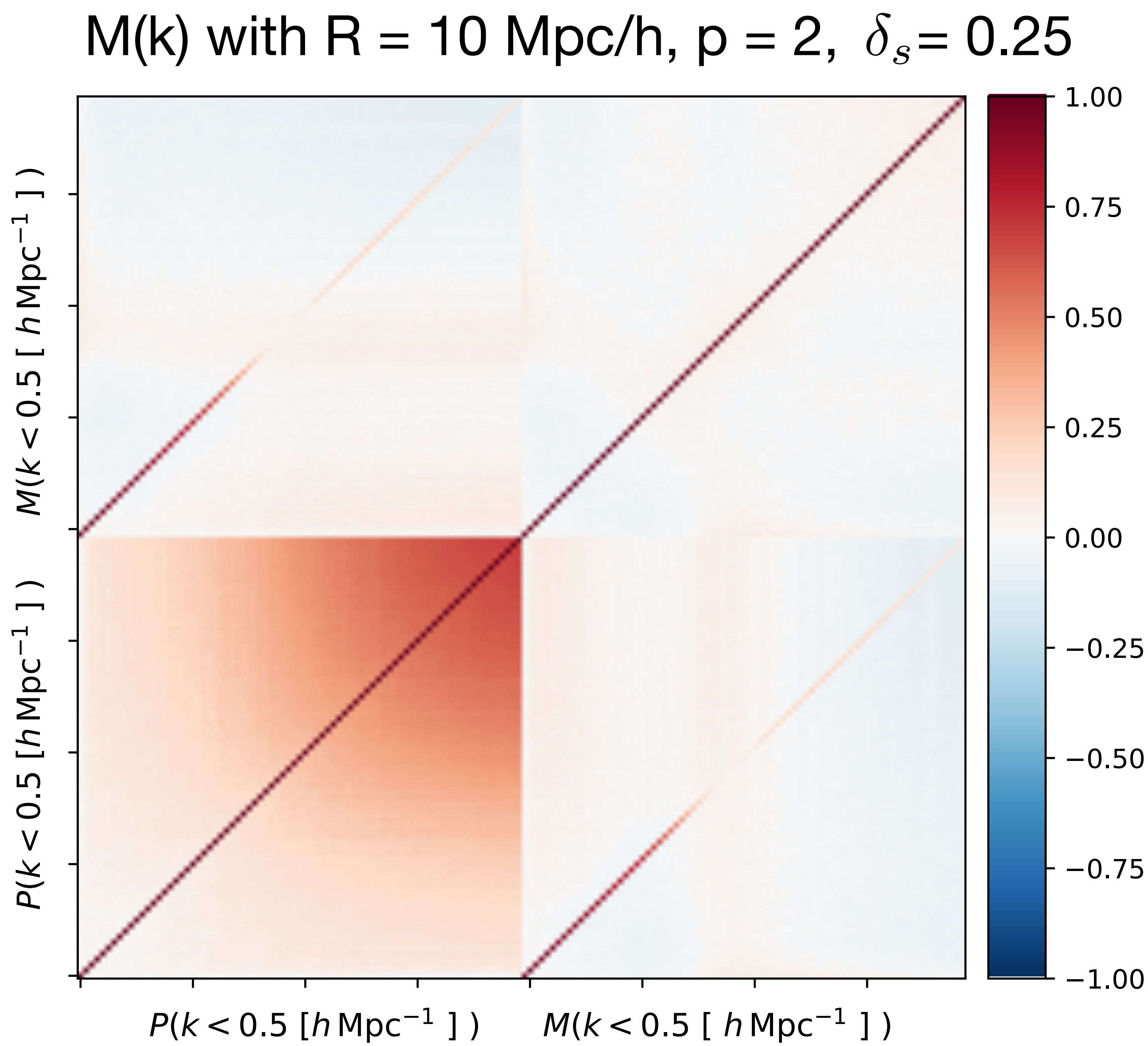
☐ = model giving the tightest constraint on the neutrino masses

125 marked power spectra compute on the matter fields

cdm and m = cdm+neutrinos

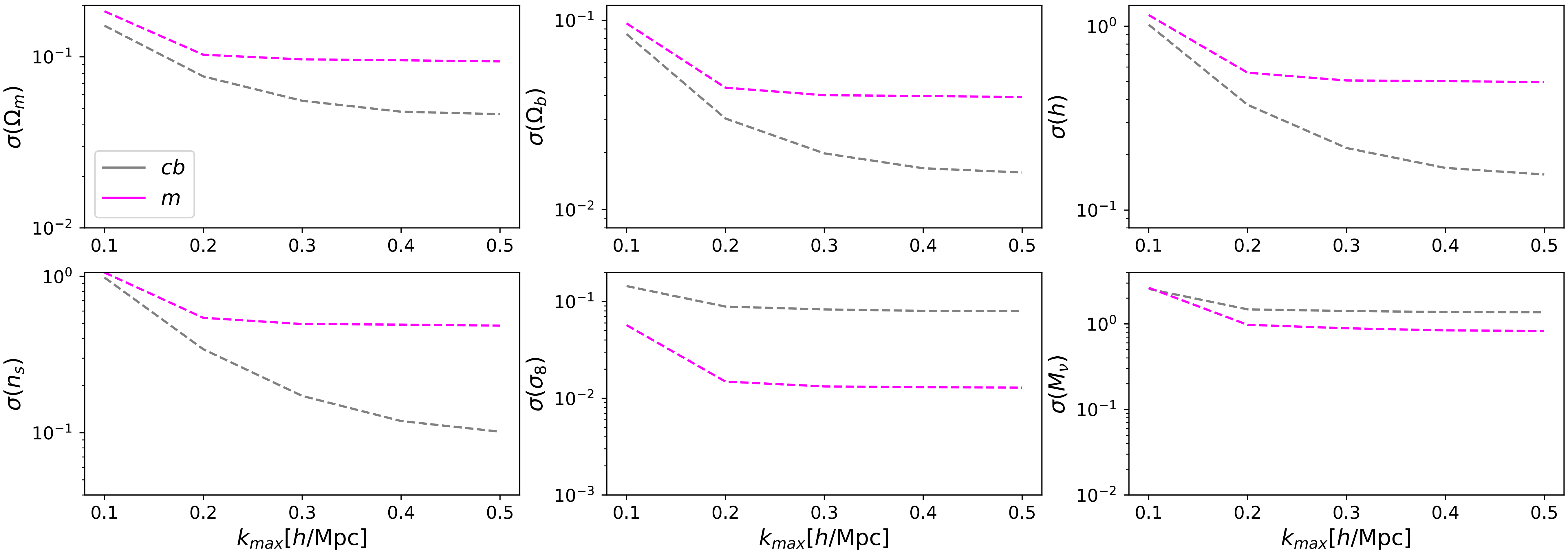
Correlation matrix

EM et al. 2020



Marginalized errors

EM et al. 2020

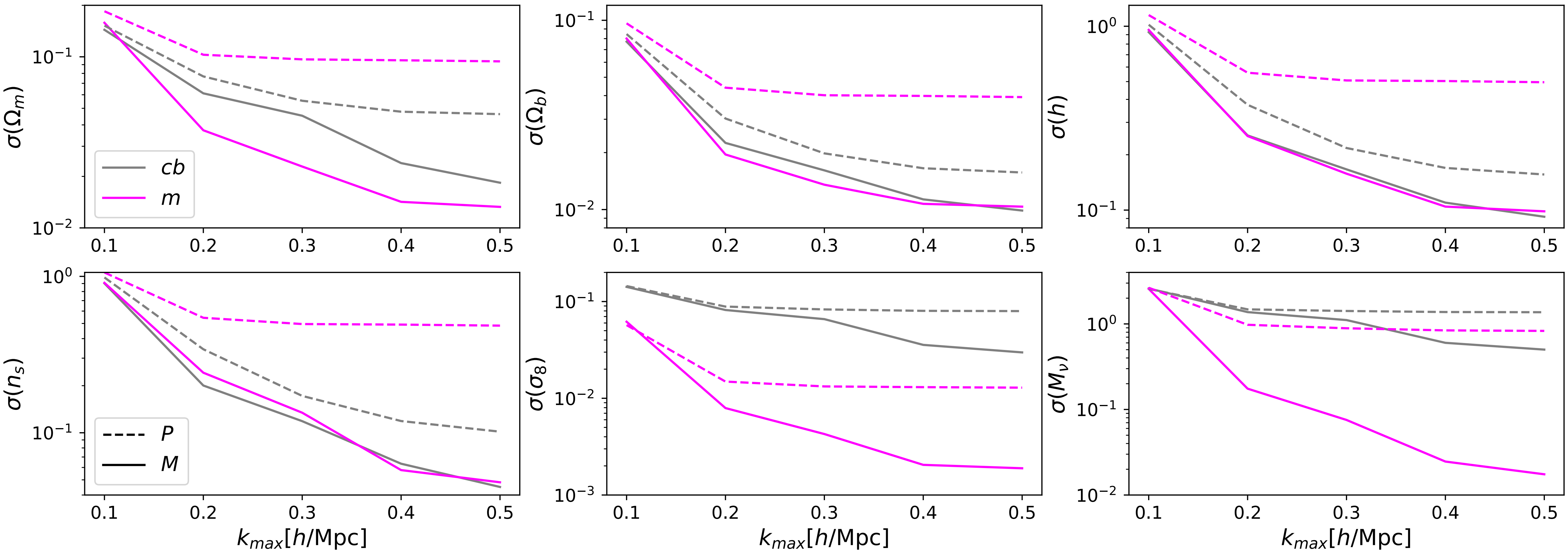


Marginalized errors for k_{max} = 0.5 h/Mpc

Parameter	P_{cb}	M_{cb}	$P_{cb}+M_{cb}$	$M_{cb}+M'_{cb}$	P_m	M_m	P_m+M_m	$M_m+M'_m$
Ω_m	0.046				0.094			
Ω_b	0.016				0.039			
h	0.16				0.50			
n_s	0.10				0.48			
σ_8	0.080				0.013			
M_ν	1.4				0.83			

Marginalized errors

EM et al. 2020

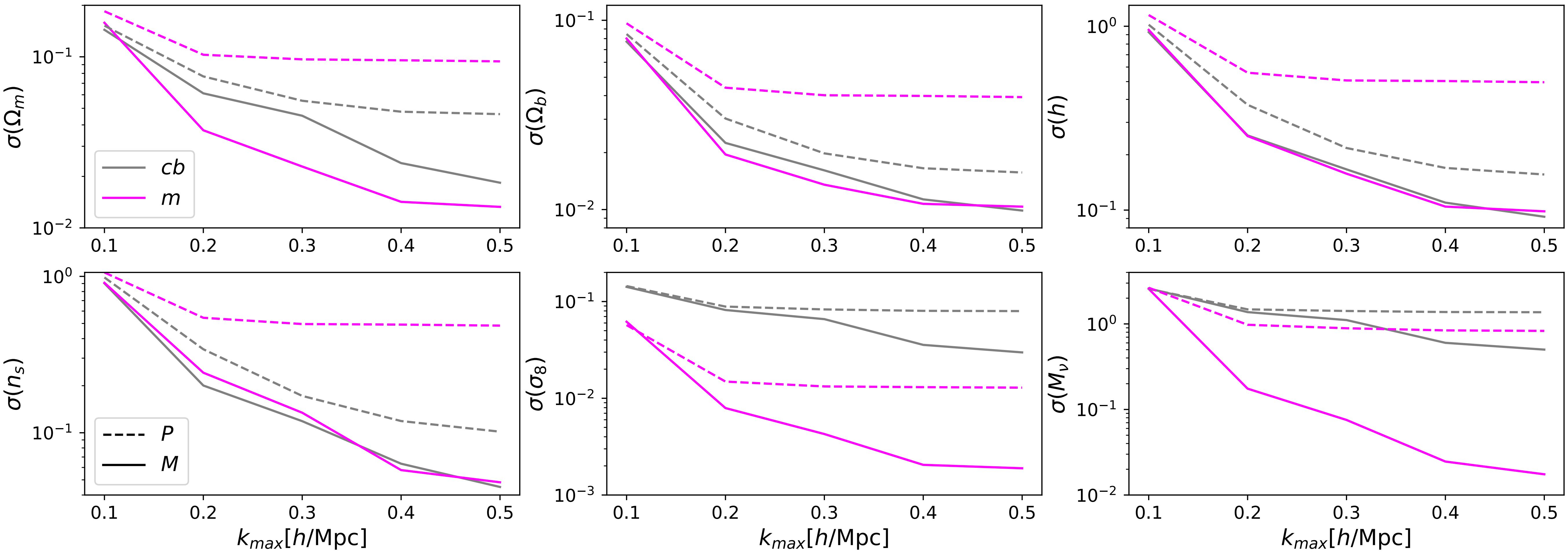


Marginalized errors for k_{max} = 0.5 h/Mpc

Parameter	P_{cb}	M_{cb}	$P_{cb}+M_{cb}$	$M_{cb}+M'_{cb}$	P_m	M_m	P_m+M_m	$M_m+M'_m$
Ω_m	0.046	0.018			0.094	0.013		
Ω_b	0.016	0.0099			0.039	0.010		
h	0.16	0.092			0.50	0.098		
n_s	0.10	0.045			0.48	0.048		
σ_8	0.080	0.030			0.013	0.0019		
M_ν	1.4	0.50			0.83	0.017		

Marginalized errors

EM et al. 2020



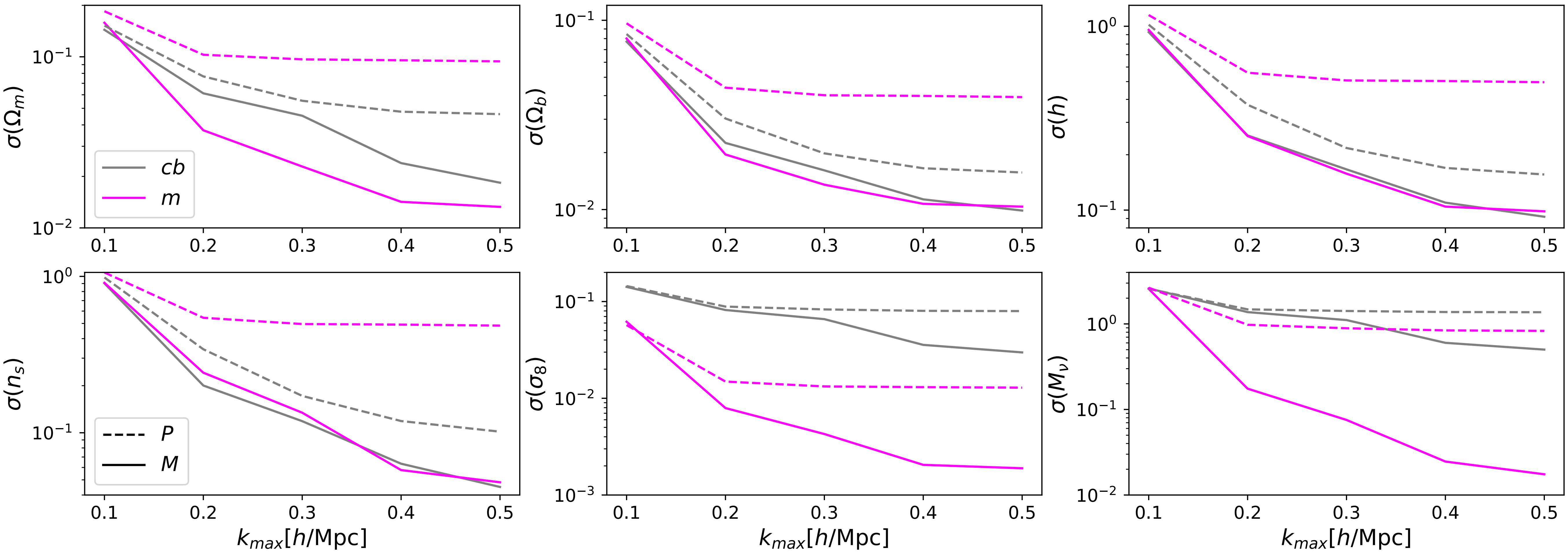
Marginalized errors for k_{max} = 0.5 h/Mpc

Parameter	P_{cb}	M_{cb}	$P_{cb} + M_{cb}$	$M_{cb} + M'_{cb}$	P_m	M_m	$P_m + M_m$	$M_m + M'_m$
Ω_m	0.046	0.018			0.094	0.013		
Ω_b	0.016	0.0099			0.039	0.010		
h	0.16	0.092			0.50	0.098		
n_s	0.10	0.045			0.48	0.048		
σ_8	0.080	0.030			0.013	0.0019		
M_ν	1.4	0.50			0.83	0.017		

3.5 σ detection of the minimum mass using 1 (Gpc/h)^3 volume

Marginalized errors

EM et al. 2020



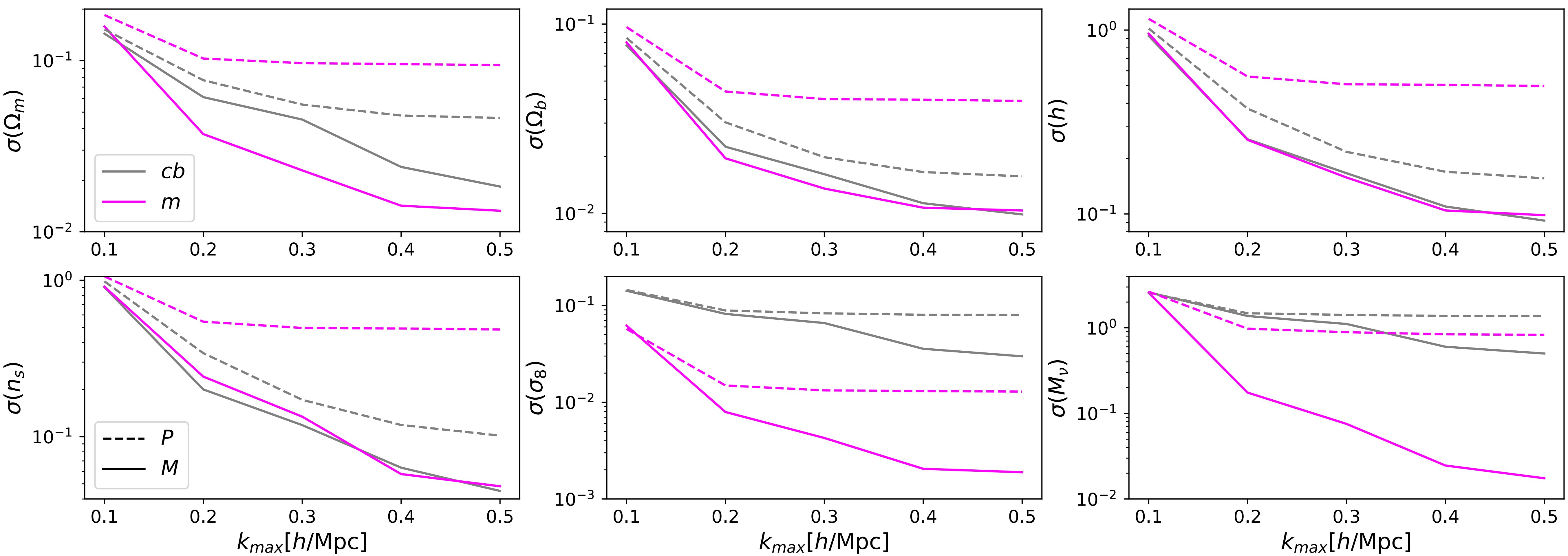
Marginalized errors for k_{max} = 0.5 h/Mpc

Parameter	P_{cb}	M_{cb}	$P_{cb}+M_{cb}$	$M_{cb}+M'_{cb}$	P_m	M_m	P_m+M_m	$M_m+M'_m$
Ω_m	0.046	0.018	0.017		0.094	0.013	0.012	
Ω_b	0.016	0.0099	0.0091		0.039	0.010	0.009	
h	0.16	0.092	0.083		0.50	0.098	0.082	
n_s	0.10	0.045	0.04		0.48	0.048	0.039	
σ_8	0.080	0.030	0.026		0.013	0.0019	0.0015	
M_ν	1.4	0.50	0.44		0.83	0.017	0.014	

4.2 σ detection of the minimum mass using 1 $(\mathrm{Gpc}/h)^3$ volume

Marginalized errors

EM et al. 2020



Marginalized errors for k_{max} = 0.5 h/Mpc

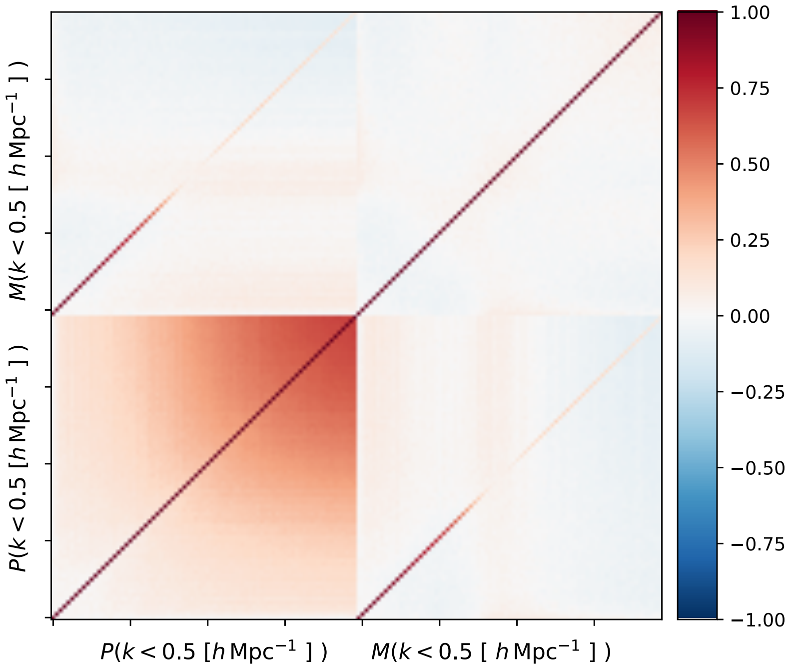
Parameter	P_{cb}	M_{cb}	$P_{cb}+M_{cb}$	$M_{cb}+M'_{cb}$	P_m	M_m	P_m+M_m	$M_m+M'_m$
Ω_m	0.046	0.018	0.017	0.014	0.094	0.013	0.012	0.011
Ω_b	0.016	0.0099	0.0091	0.008	0.039	0.010	0.009	0.008
h	0.16	0.092	0.083	0.068	0.50	0.098	0.082	0.069
n_s	0.10	0.045	0.04	0.029	0.48	0.048	0.039	0.028
σ_8	0.080	0.030	0.026	0.021	0.013	0.0019	0.0015	0.0015
M_ν	1.4	0.50	0.44	0.35	0.83	0.017	0.014	0.01

6 σ detection of the minimum mass using 1 $(\mathrm{Gpc}/h)^3$ volume

THE INFORMATION CONTENT

EM et al. 2020

- The covariance matrix of the considered marked power spectrum M(k) is very diagonal



$$m(\vec{x}, \phi = R, p, \delta_s) = \left[\frac{1+\delta_s}{1+\delta_s+\delta_R(\vec{x})}\right]^p$$

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EM et al. 2020

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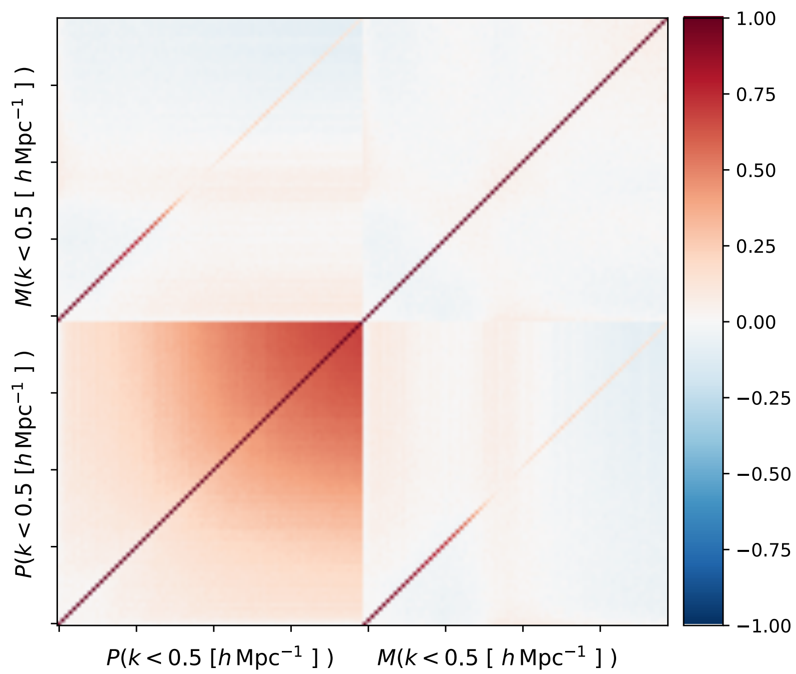

- Marked density field is a nonlinear transformation of the density field
- Other nonlinear transformations, such as the log-transformation, have shown to make the field more Gaussian (Neyrinck et al, 2009, 2010, 2011)

$$m(\vec{x}, \phi = R, p, \delta_s) = \left[\frac{1+\delta_s}{1+\delta_s+\delta_R(\vec{x})}\right]^p$$

THE INFORMATION CONTENT

EM et al. 2020

- The covariance matrix of the considered marked power spectrum M(k) is very diagonal

- The marked power spectrum contains higher order statistics of the density field

$$m(\vec{x}, \phi = R, p, \delta_s) = \left[\frac{1+\delta_s}{1+\delta_s+\delta_R(\vec{x})}\right]^p$$

THE INFORMATION CONTENT

EM et al. 2020

- The covariance matrix of the considered marked power spectrum M(k) is very diagonal

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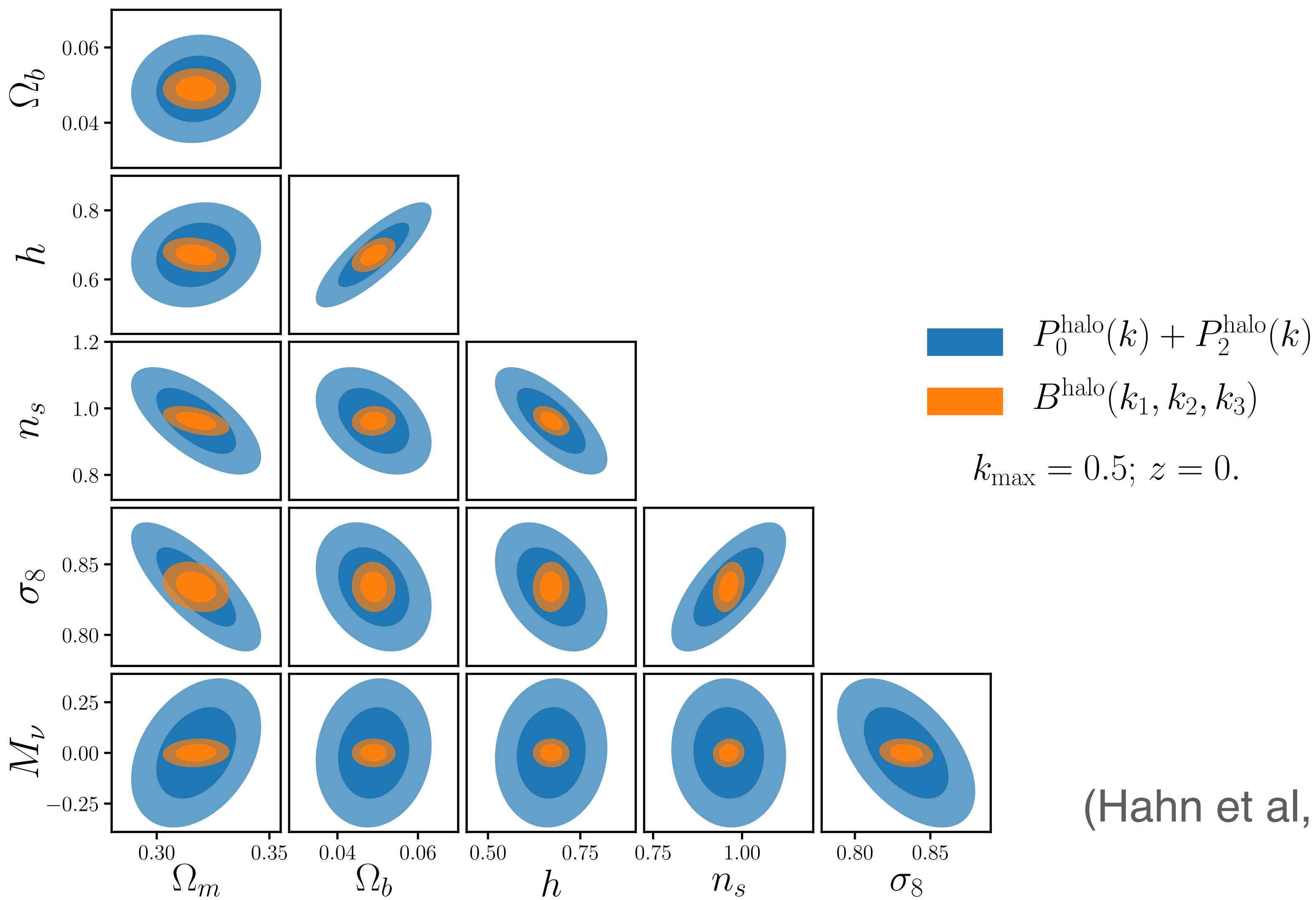

(Hahn et al, 2019)

THE INFORMATION CONTENT

EM et al. 2020

- The covariance matrix of the considered marked power spectrum M(k) is very diagonal
- The marked power spectrum contains higher order statistics of the density field
- The considered marked power spectrum incorporates information from voids

CONCLUSIONS

- We have studied marked power spectra computed on the MATTER density field

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- Marked power spectra on the GALAXY density field will include BIAS and REDSHIFT SPACE DISTORTION, which will degrade the constraints on the sum of the neutrino masses.

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- Marked power spectra on the GALAXY density field will include BIAS and REDSHIFT SPACE DISTORTION, which will degrade the constraints on the sum of the neutrino masses.
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CONCLUSIONS

- We have studied marked power spectra computed on the MATTER density field

- Marked power spectra on the GALAXY density field will include BIAS and REDSHIFT SPACE DISTORTION, which will degrade the constraints on the sum of the neutrino masses.

- Upcoming surveys (DESI, EUCLID, WFIRST) will have larger volumes, that will improve the constraints.

- Mark power spectra are promising and easy-to-compute observables.

THE END