Modelling the Large Scale Structure w and w/o massive neutrinos

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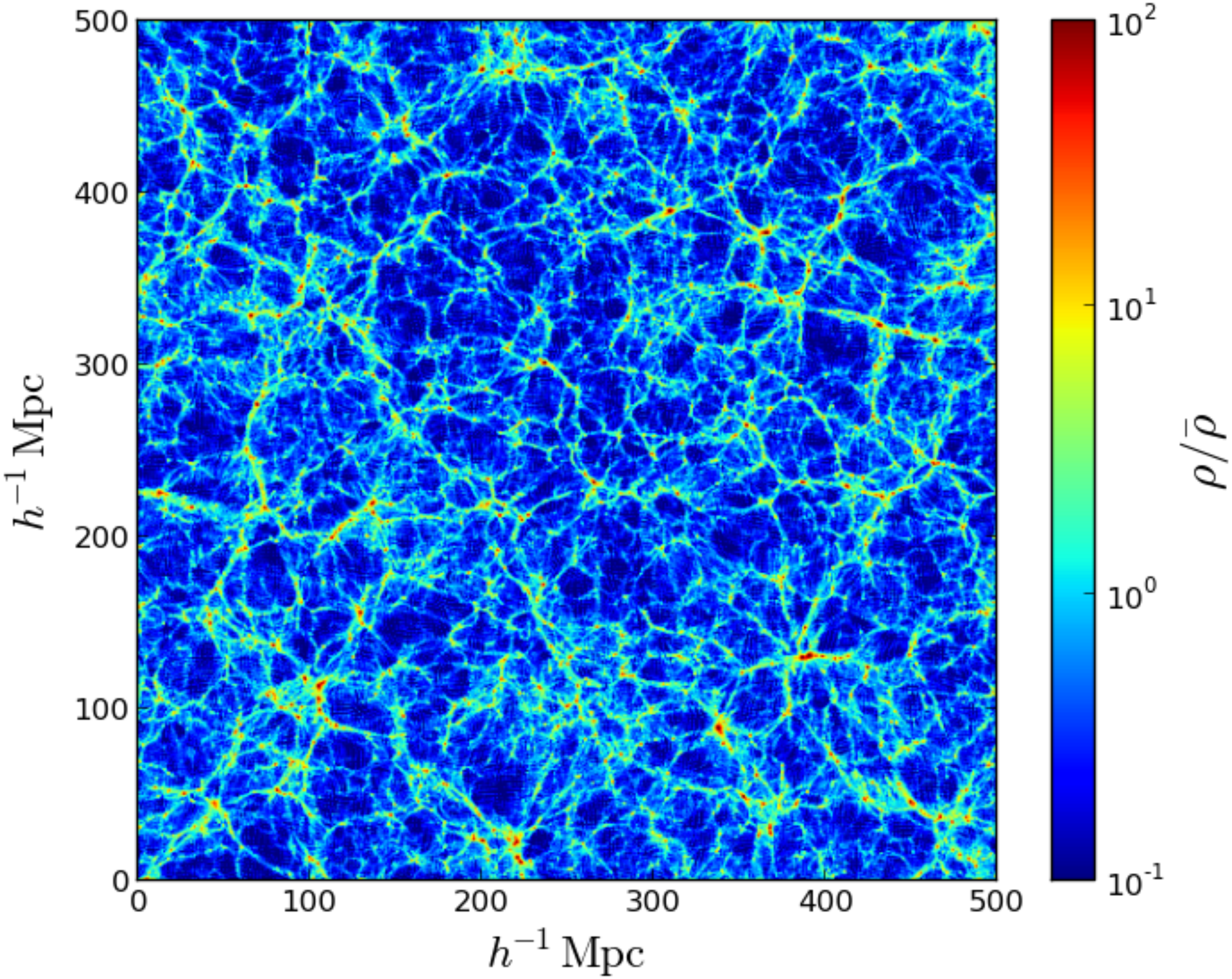
The halo model in a massive neutrino cosmology
(**E.M.**, F. Villaescusa-Navarro, M. Viel - JCAP 1412 (2014) 12, 053)

Voids in massive neutrino cosmologies
(**E.M.**, F. Villaescusa-Navarro, M. Viel, P.M. Sutter - JCAP 1511 (2015) 11, 018)

Density profiles around biased tracers of the cosmic web
(**E.M.**, R. Sheth, P. M. Sutter et al. - in preparation)

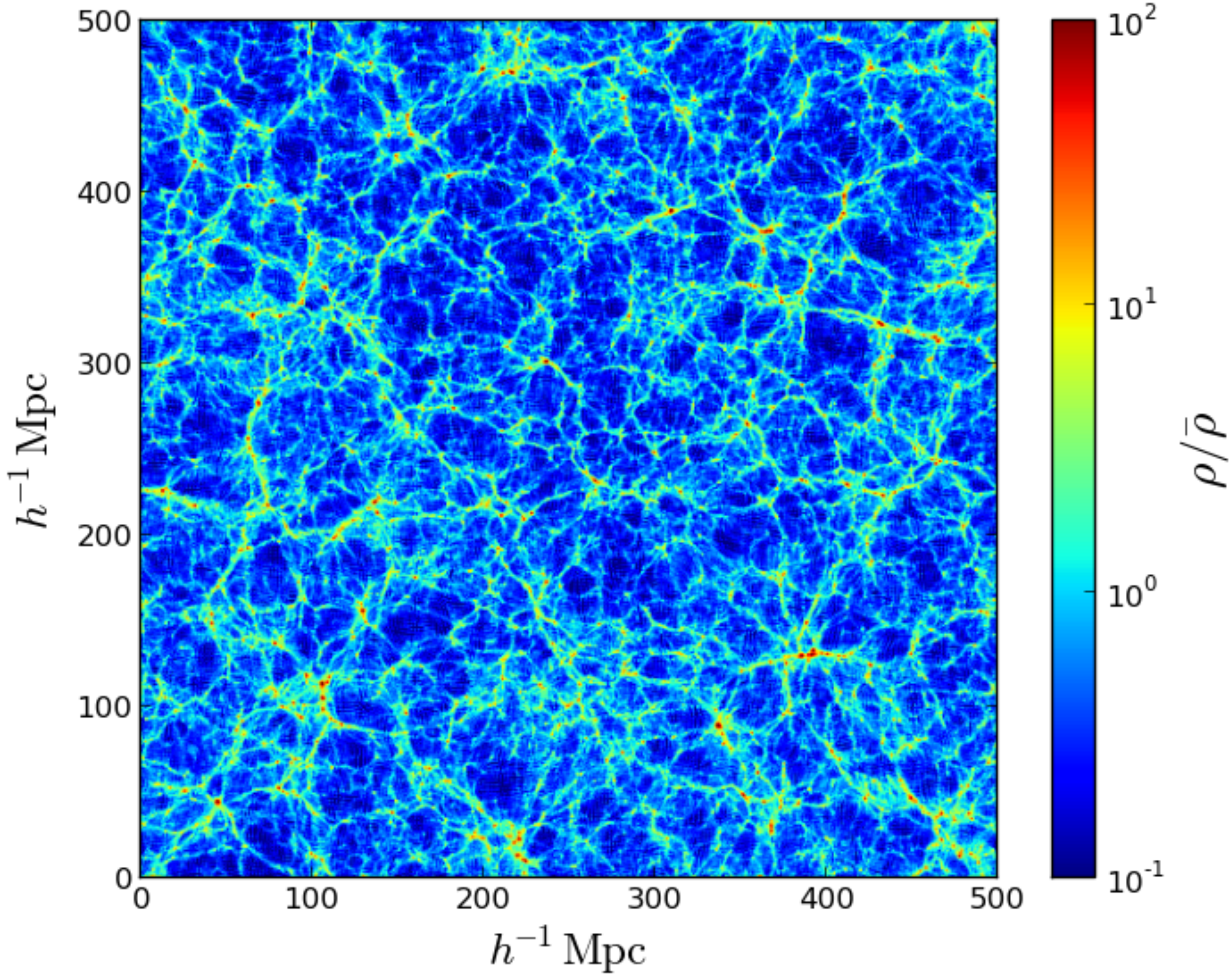
Looking into simulations

LCDM cosmology - CDM particles



Looking into simulations

Massive neutrino cosmology: CDM+neutrino field



Neutrinos in cosmology

- 3 species of active neutrinos
- Neutrinos are massive $\Delta m^2_{21} \sim 10^{-5} eV^2$ (solar neutrinos)

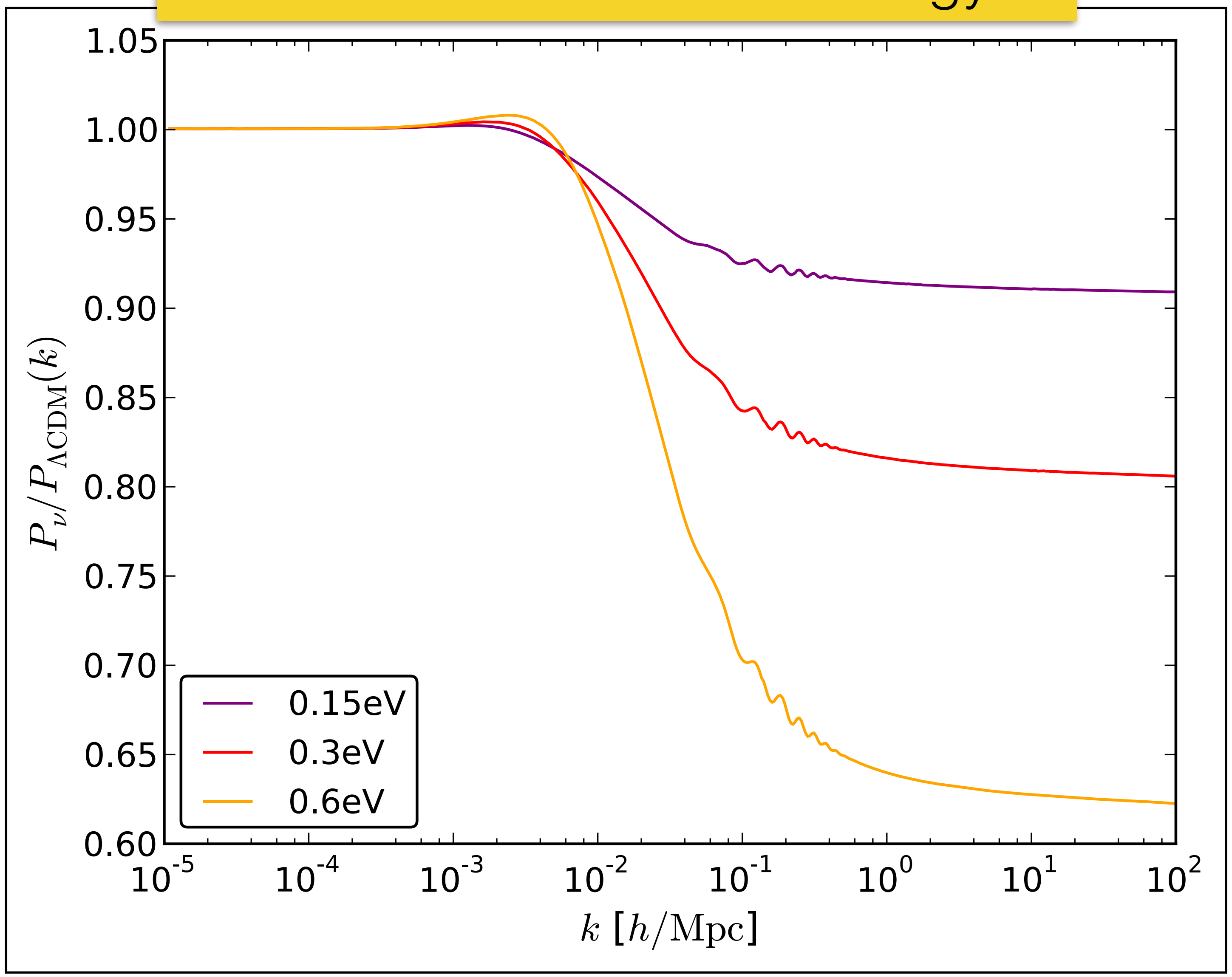
  $|\Delta m^2_{31}| \sim 10^{-3} eV^2$ (atmospheric neutrinos)

  $$\Sigma_i m_i > 0.06\, eV$$

- Cosmology: $\Sigma_i m_i < 0.23\, eV\ (95\% c.l.)$ (Planck 2015)

Neutrinos: linear regime

Ratio between P(k) in massive and massless neutrino cosmology



Neutrino masses have two effects:

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

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

Neutrinos: non-linear regime

- NON-LINEAR MATTER POWER SPECTRUM

  Extension of the halo model to account for the presence of massive neutrinos

- COSMIC VOIDS

  The impact of massive neutrinos on cosmic voids: comprehensive numerical study of statistical properties of voids

  ↓

  A theoretical description of the shape and evolution of void profiles

Modelling the nonlinear matter P(k) in massive neutrino cosmologies

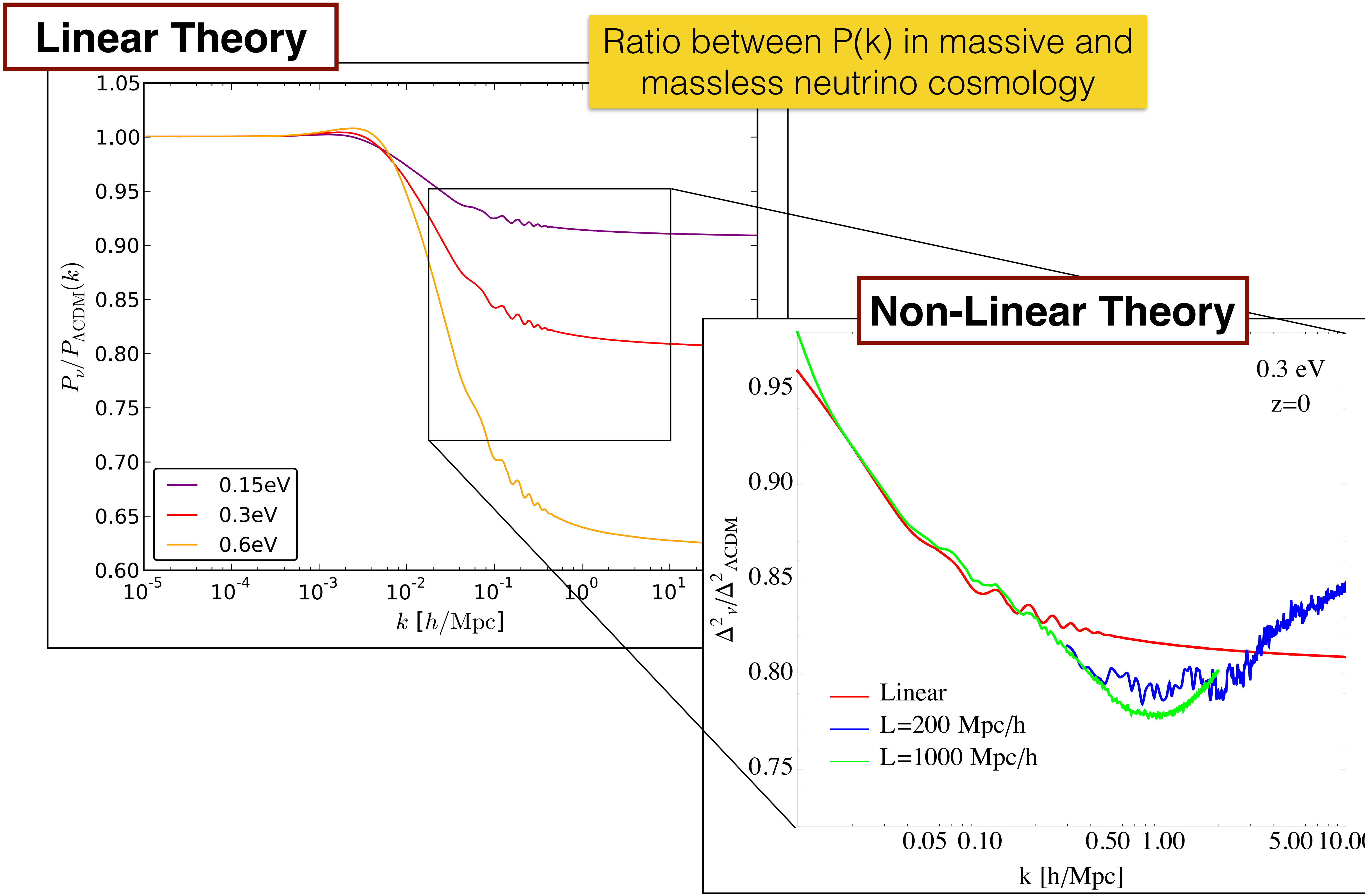
Based on:

The halo model in a massive neutrino cosmology

E.M., F. Villaescusa-Navarro, M. Viel

JCAP 1412 (2014) 12, 053

Neutrinos impact on the P(k)



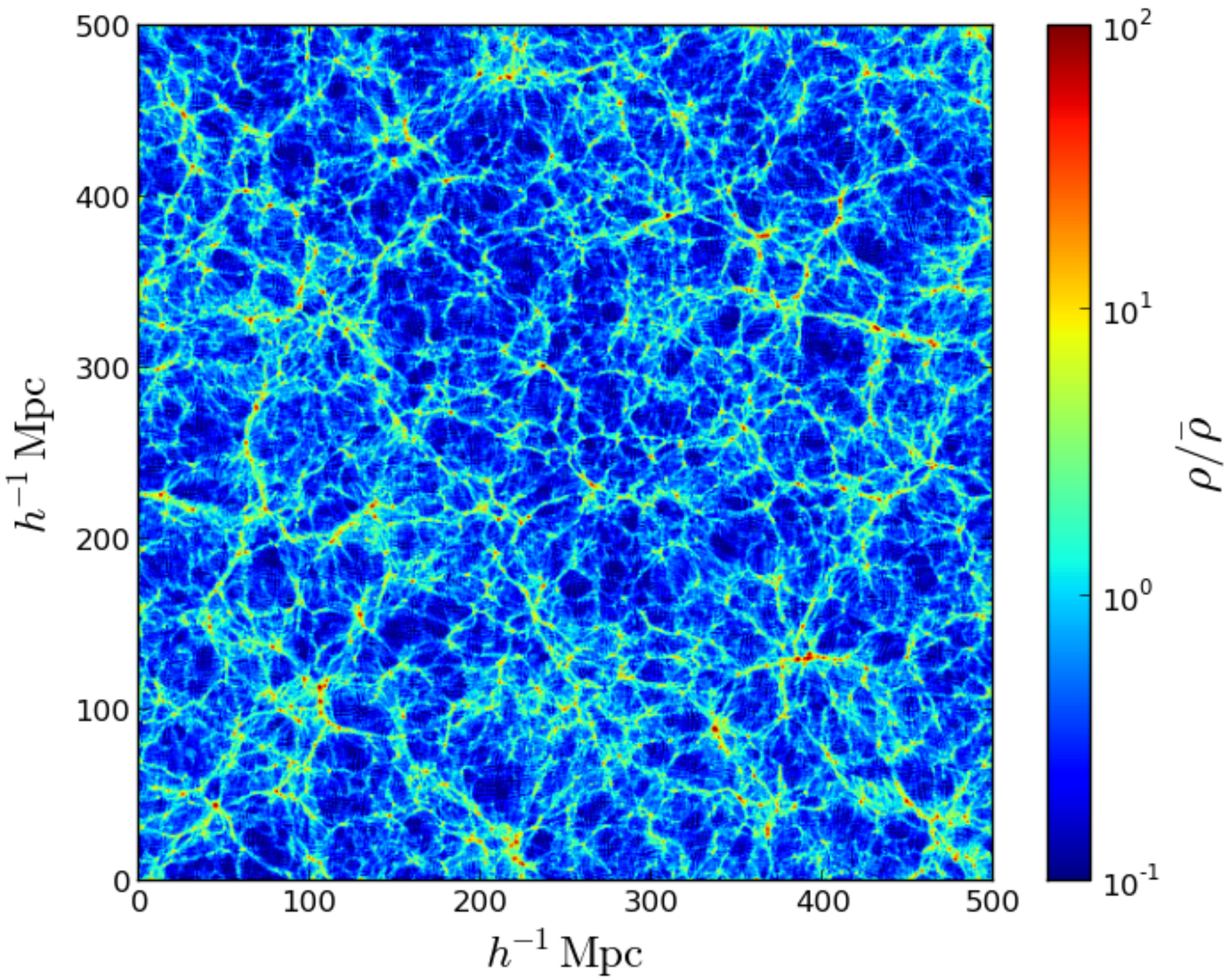
Halo Model

Massive neutrinos case

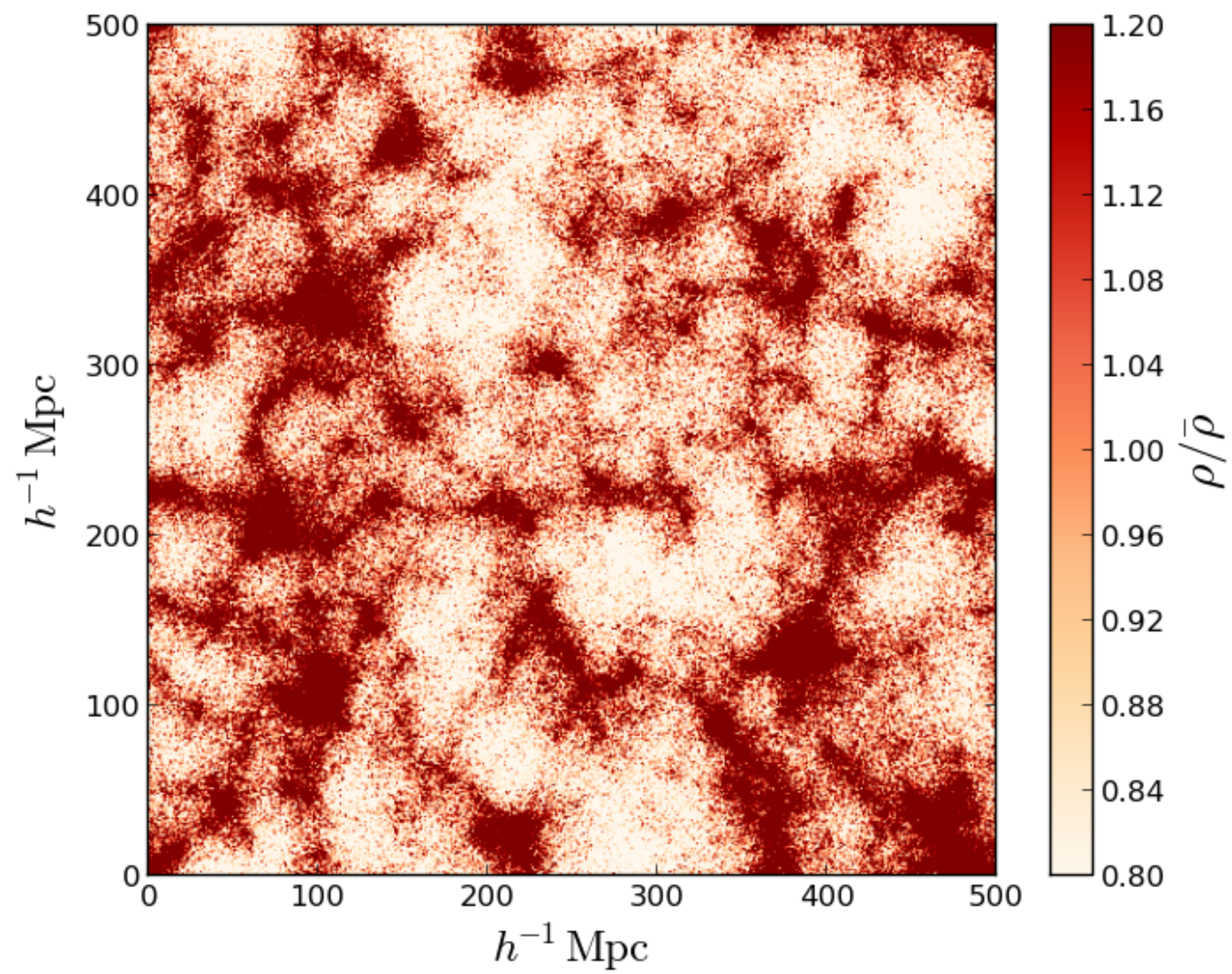
- All **CDM** particles are in halos
- What about **neutrinos**?

N-body simulations

CDM density field



Neutrino density field



Halo Model

Massive neutrinos case

- All **CDM** is in halos

- A **FRACTION of neutrinos** is in halos:

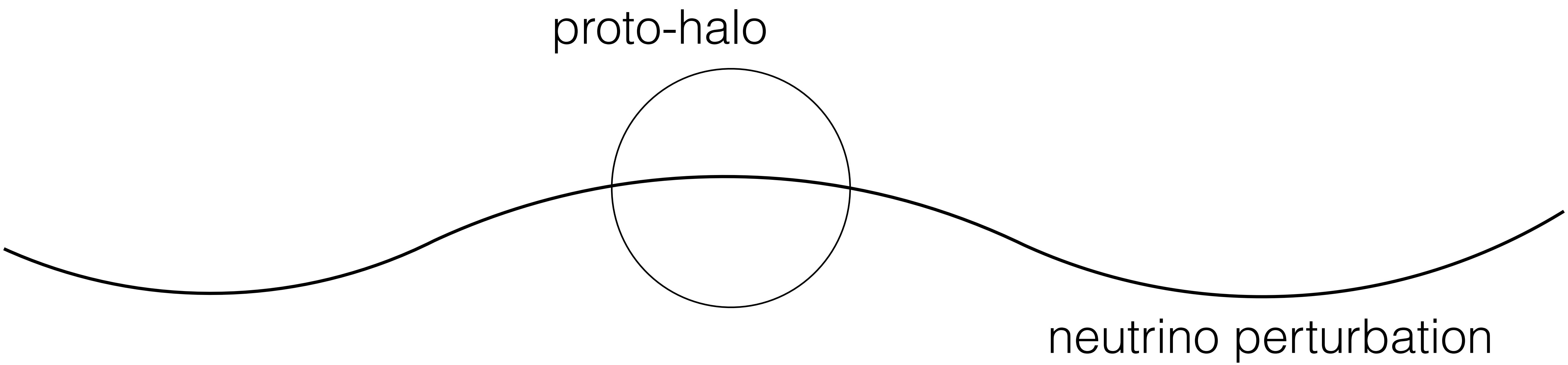
$$\delta_\nu = F_h \delta_\nu^h + (1 - F_h)\delta_\nu^L$$

clustered → described by Halo Model

free-streaming → described by linear theory

$$F_h = \frac{1}{\bar{\rho}_\nu} \int_{M_{\rm cut}}^{\infty} dM_{\rm c}\, n(M_{\rm c}) M_\nu(M_{\rm c})$$

Mass function and halo bias



Neutrino linear perturbations do NOT affect the halo formation

Halo Model

Massive neutrinos case

- All **CDM** is in halos
- A **FRACTION of neutrinos** is in halos:

$$\delta_\nu = F_h \delta_\nu^h + (1 - F_h)\delta_\nu^L$$

- Halo mass function n(M)dM from $P_{\mathbf{CDM}}(k)$
- Halo bias b(M) w.r.t. **CDM** field

} (Castorina et al. 2013)

Halo Model

Massive neutrinos case

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- Halo bias b(M) w.r.t. **CDM** field

} (Castorina et al. 2013)

- Halo profile: **NFW + neutrino profile** (Villaescusa-Navarro et al. 2013)

Results

$$P(k) = \left(\frac{\bar{\rho}_{\mathrm{c}}}{\bar{\rho}}\right)^2 P_{\mathrm{c}}(k) + 2\,\frac{\bar{\rho}_{\mathrm{c}}\bar{\rho}_{\nu}}{\bar{\rho}^2}\,P_{\mathrm{c}\nu}(k) + \left(\frac{\bar{\rho}_{\nu}}{\bar{\rho}}\right)^2 P_{\nu}(k)$$

Cold dark matter-neutrinos

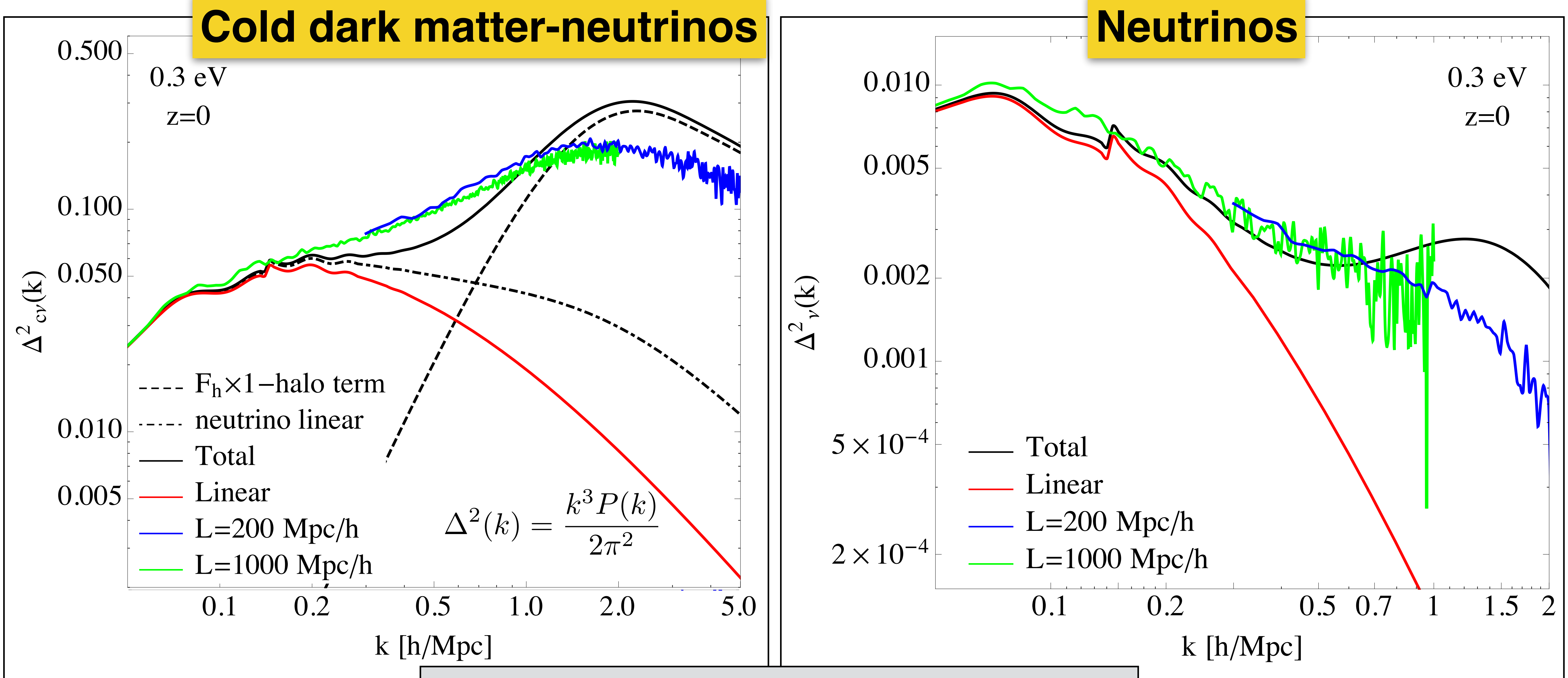
Neutrinos

Results

$$P(k) = \left(\frac{\bar{\rho}_c}{\bar{\rho}}\right)^2 P_c(k) + 2\,\frac{\bar{\rho}_c\bar{\rho}_\nu}{\bar{\rho}^2} P_{c\nu}(k) + \left(\frac{\bar{\rho}_\nu}{\bar{\rho}}\right)^2 P_\nu(k)$$

Cold dark matter-neutrinos

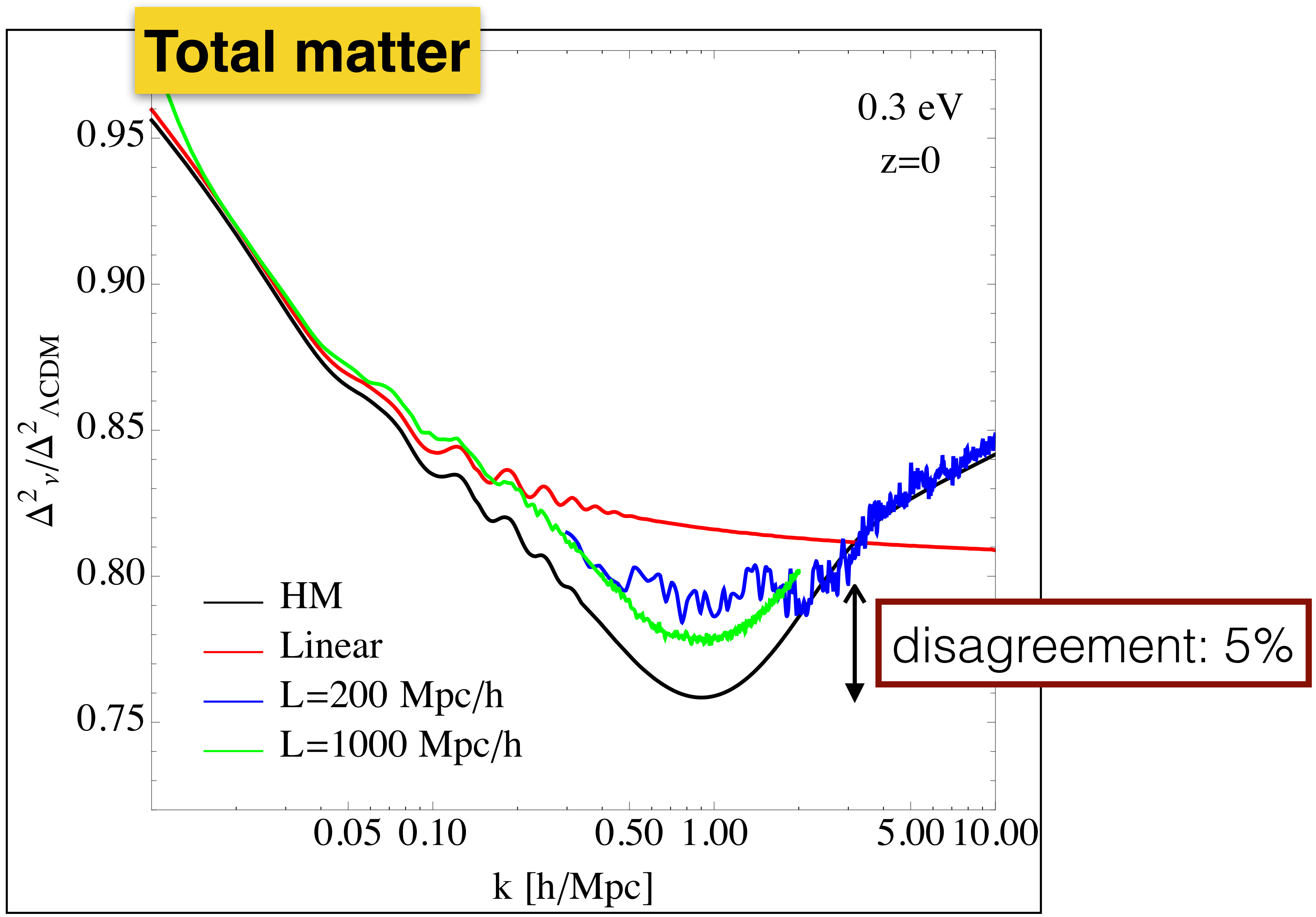
Neutrinos



Neutrinos need to be modelled as clustered + smoothed components

Results

$$\Delta^2_\nu(k)/\Delta^2_{\Lambda\mathrm{CDM}}(k)$$



Neutrinos can just be a smoothed component

Halo Model for galaxy clustering

Halo Occupation Distribution (HOD):

1. The probability distribution p(N|M) of having N galaxies inside a halo of mass M ➞ **3 parameters**

Central galaxy: $$\langle N_c|M\rangle = \begin{cases} 1 & \text{if } M \geq M_{\min} \\ 0 & \text{if } M < M_{\min} \end{cases}$$

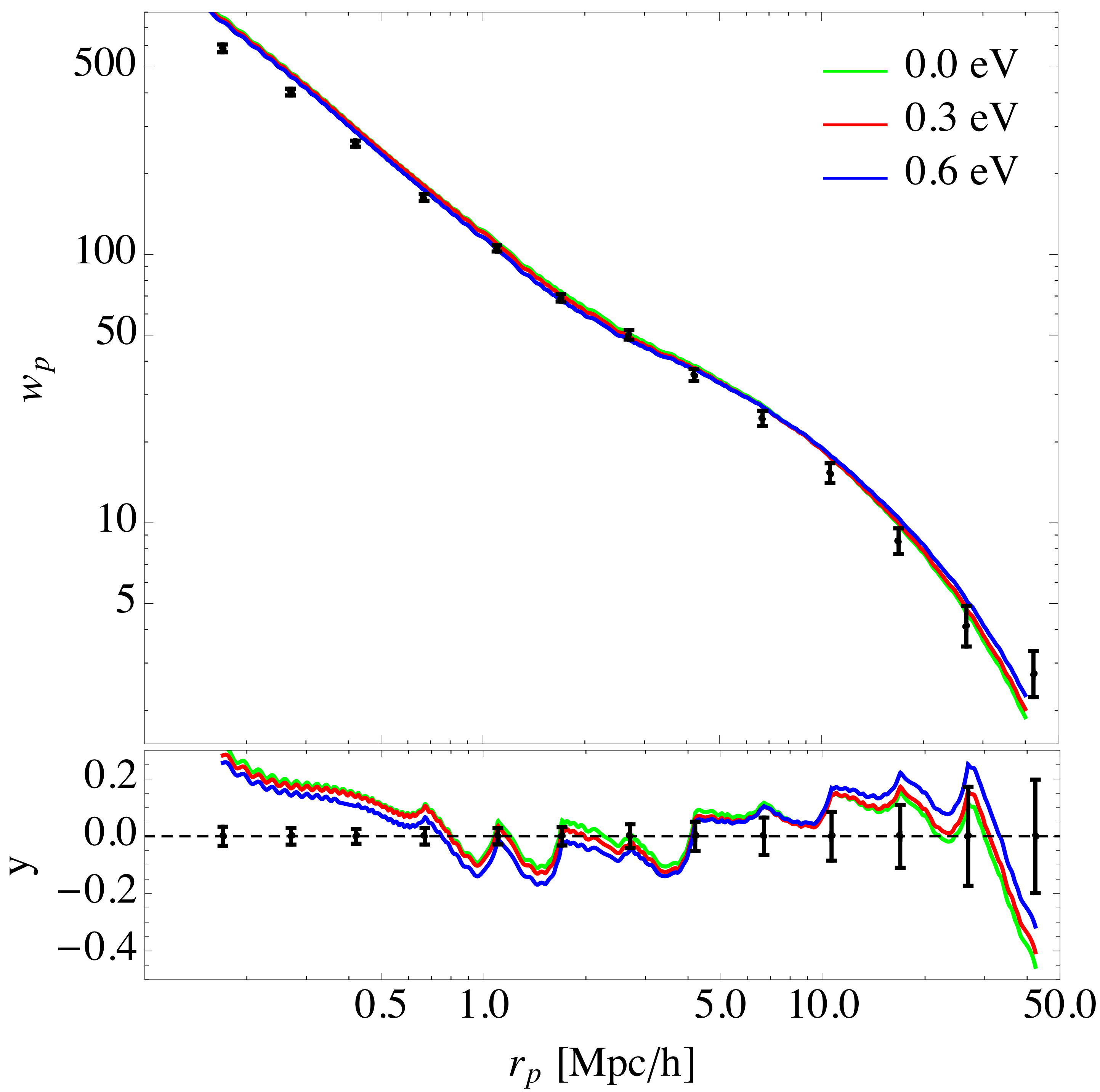
Satellites: $$\langle N_s|M\rangle = \begin{cases} (M/M_1)^\alpha & \text{if } M \geq M_{\min} \\ 0 & \text{if } M < M_{\min}\,. \end{cases}$$

2. The way in which galaxies positions and velocities are related to the underlying matter particles:
   - the central galaxies are at the center of the corresponding halo
   - the distribution and velocity of the satellites follow the ones of cold dark matter particles inside the halo ($b_g = b_v = 1$)

Galaxy correlation function

Predictions using:

- HOD parameters (from simulations) to reproduce clustering of galaxies measured in SDSS II Data Release 7
- The extended version of the Halo Model



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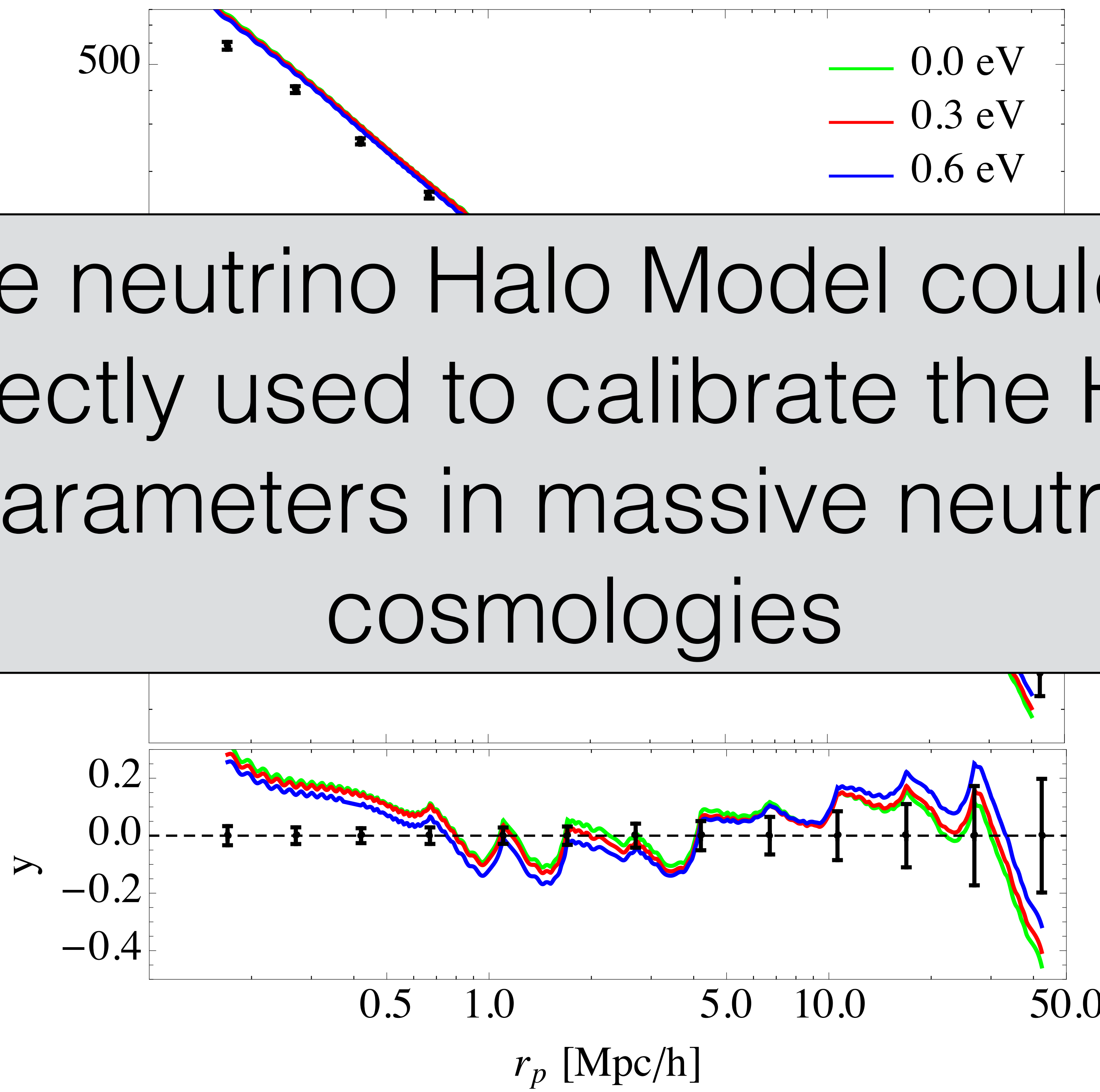


The neutrino Halo Model could be directly used to calibrate the HOD parameters in massive neutrino cosmologies

The impact of massive neutrinos on cosmic voids

Based on:

Voids in massive neutrino cosmologies

E.M., Villaescusa-Navarro, Viel, Sutter

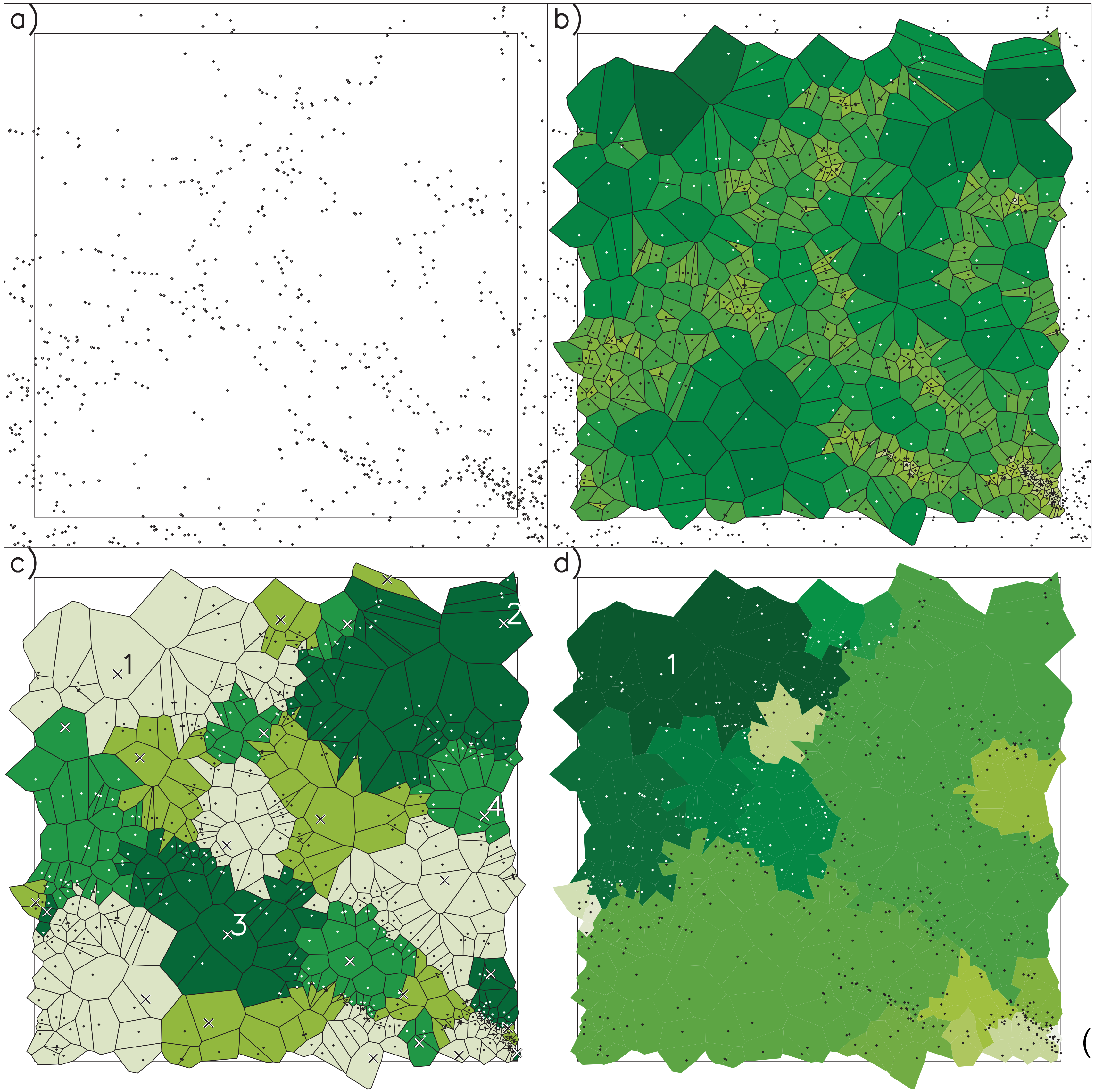
JCAP 1511 (2015) 11, 018

N-body simulations and Void finder

- **Simulations**:
  - CDM particles & neutrino particles
  - low resolution (L = 1 Gpc/h, 256^3 particles) → CDM-voids
  - high resolution (L = 500 Mpc/h, 512^3 particles) → galaxy-voids
  - cosmologies: 0.0 - 0.15 - 0.3 - 0.6 eV
- **Galaxies**: inserted via HOD
- **Void finder**: VIDE - it uses ZOBOV output

(Sutter et al. 2014) (Neyrinck 2008)

ZOBOV - VIDE at work



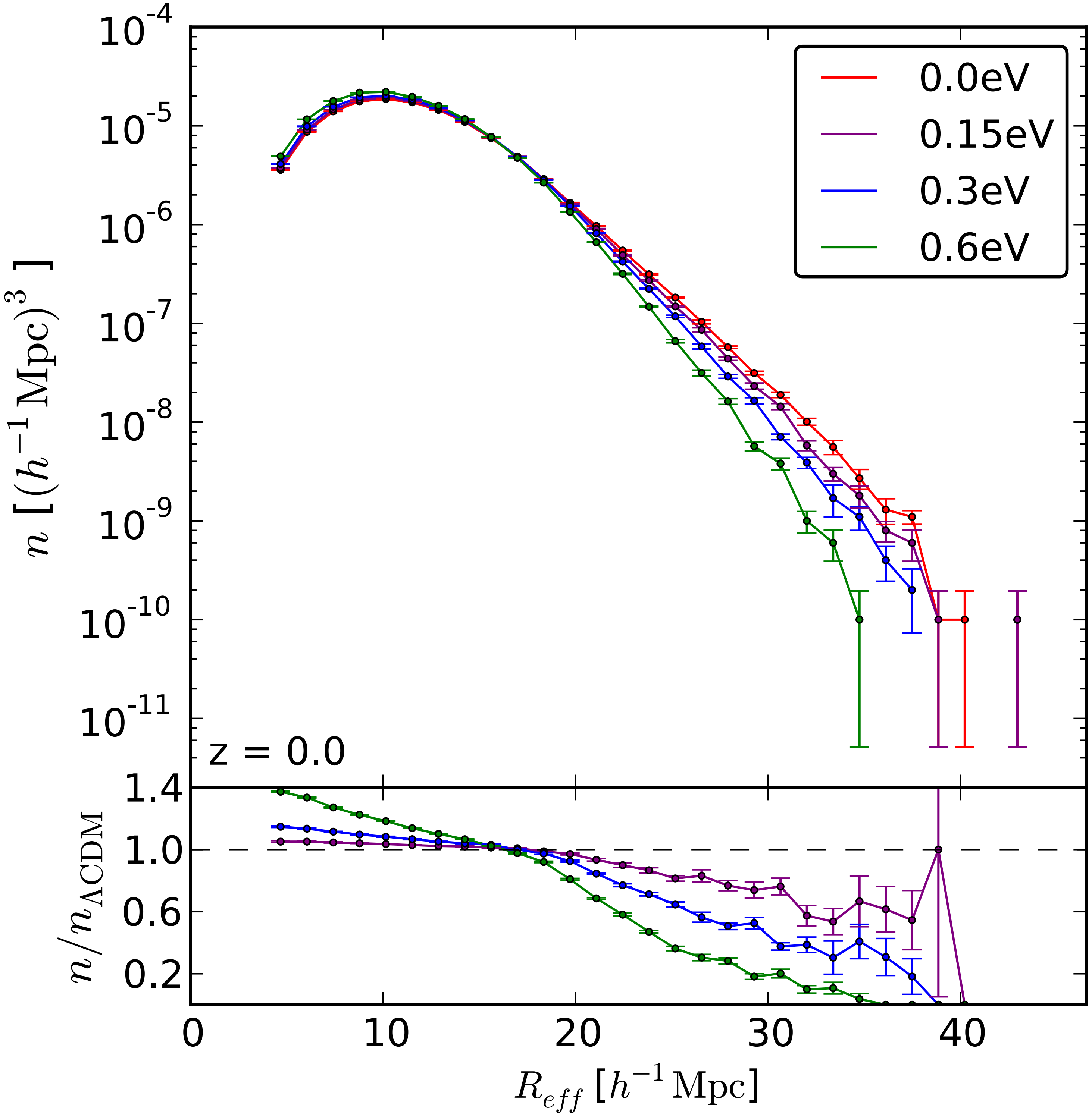
b) Voronoi Tessellation
density field estimator

c) Zoning
merging of Voronoi cells into zones

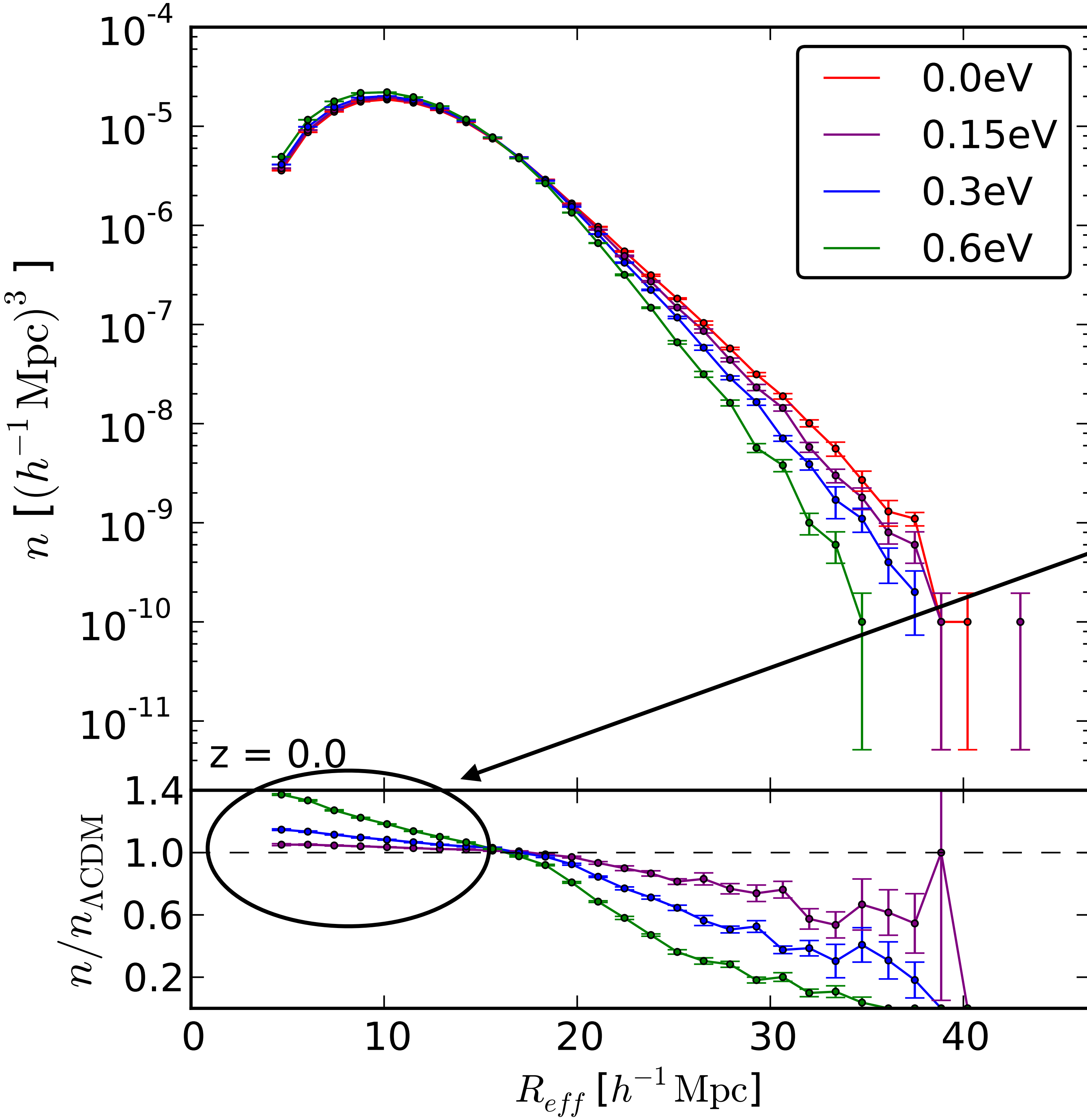
d) Watershed
merging of zones into voids

(Neyrinck 2008)

Number density of voids



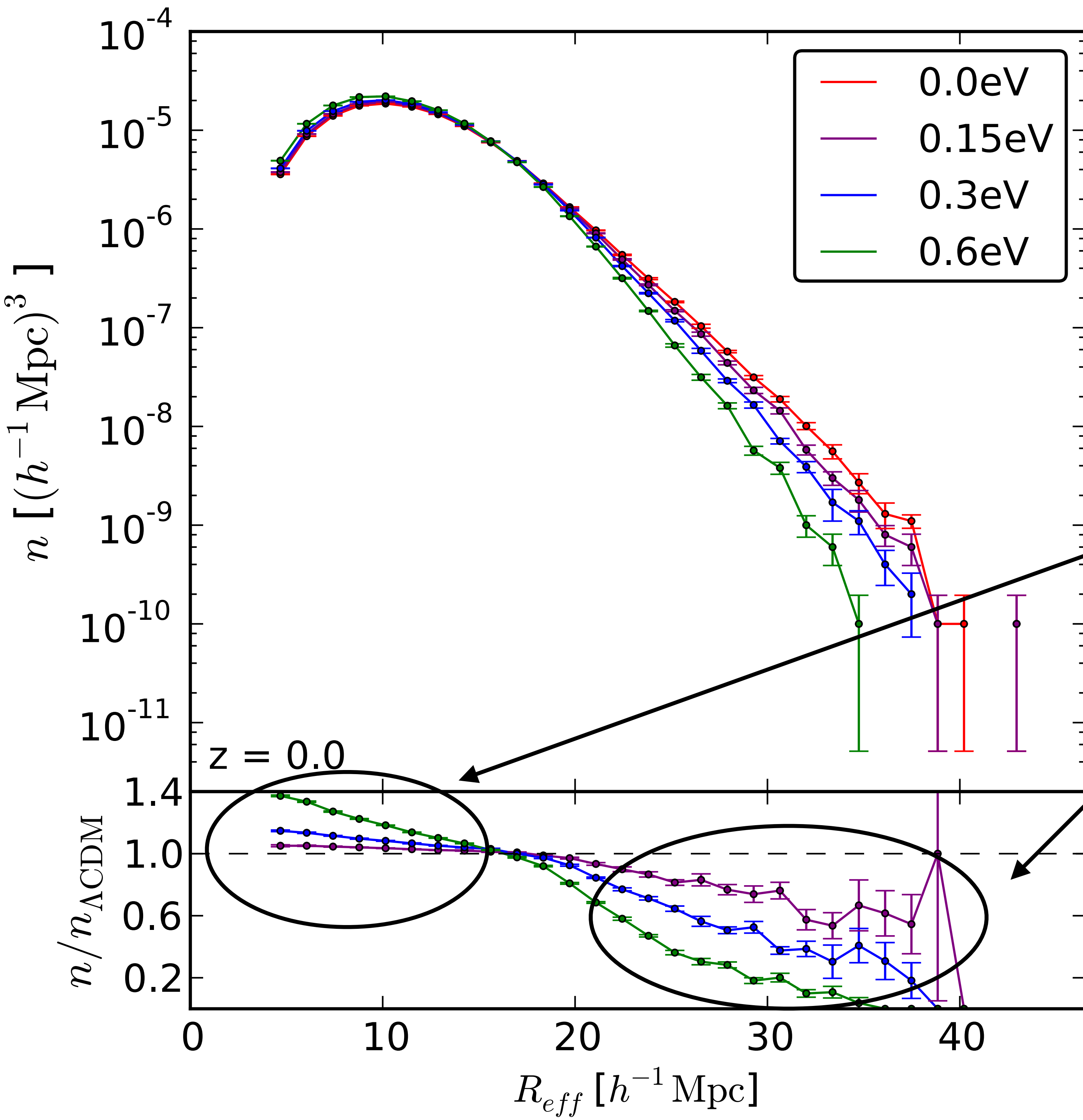
Number density of voids



In massive neutrino cosmologies there are

- more small voids

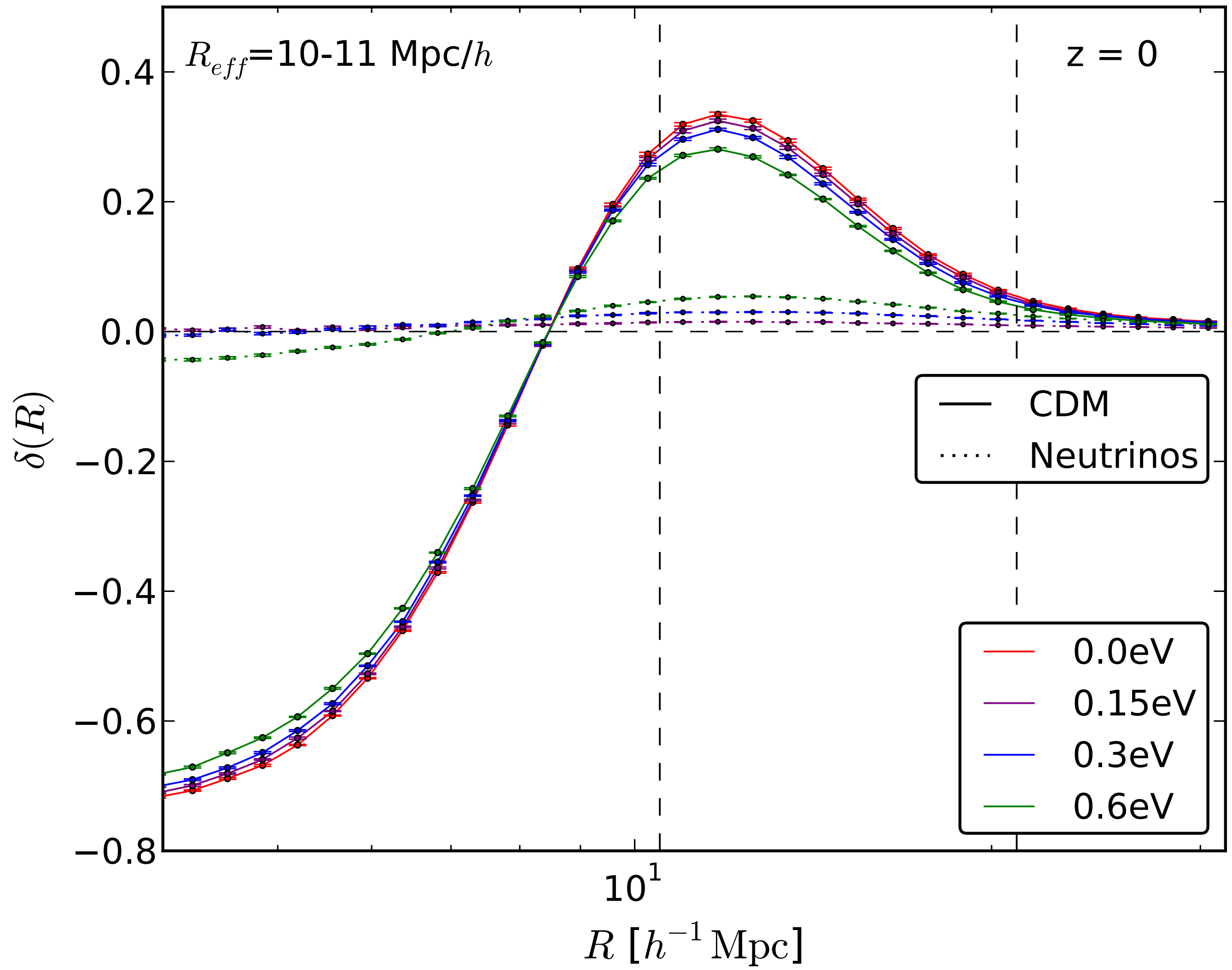
Number density of voids

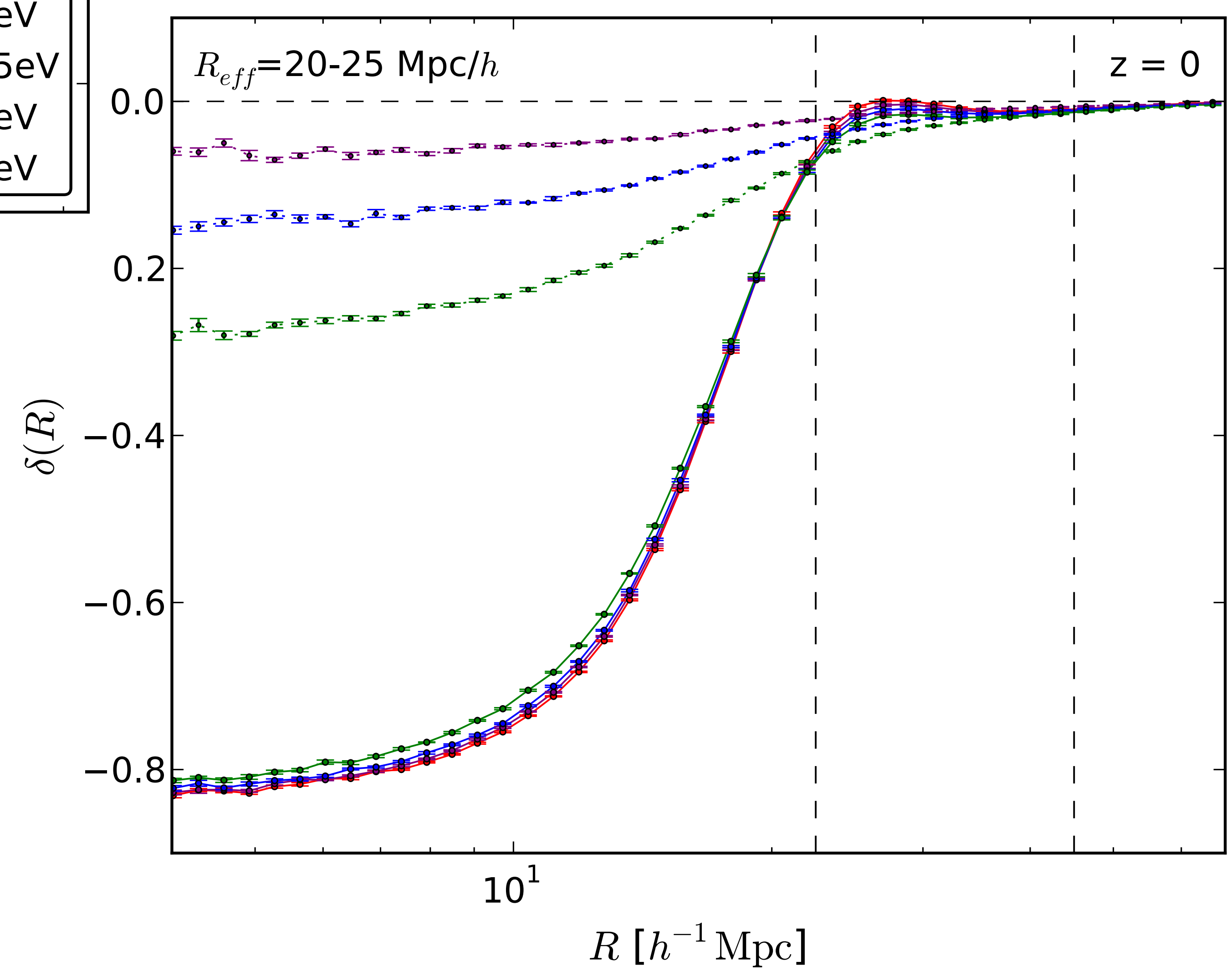


In massive neutrino cosmologies there are

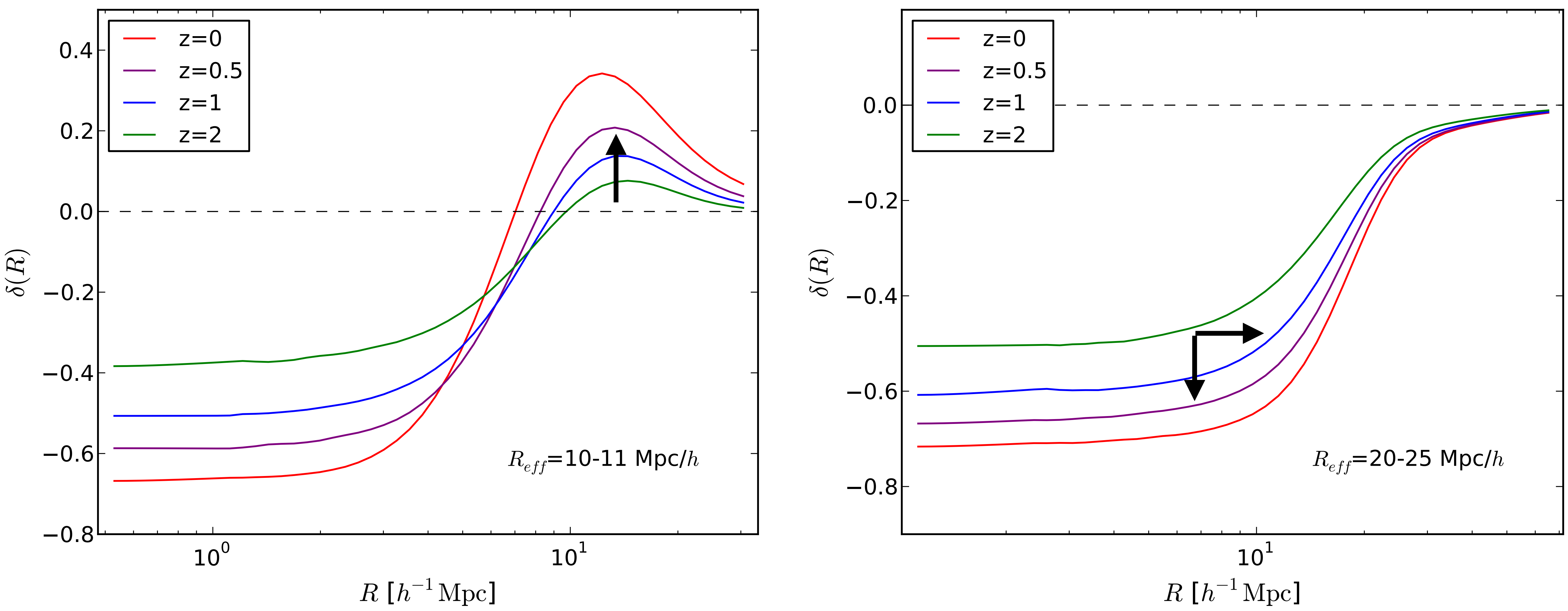
- more small voids
- fewer big voids

CDM / Neutrino profiles

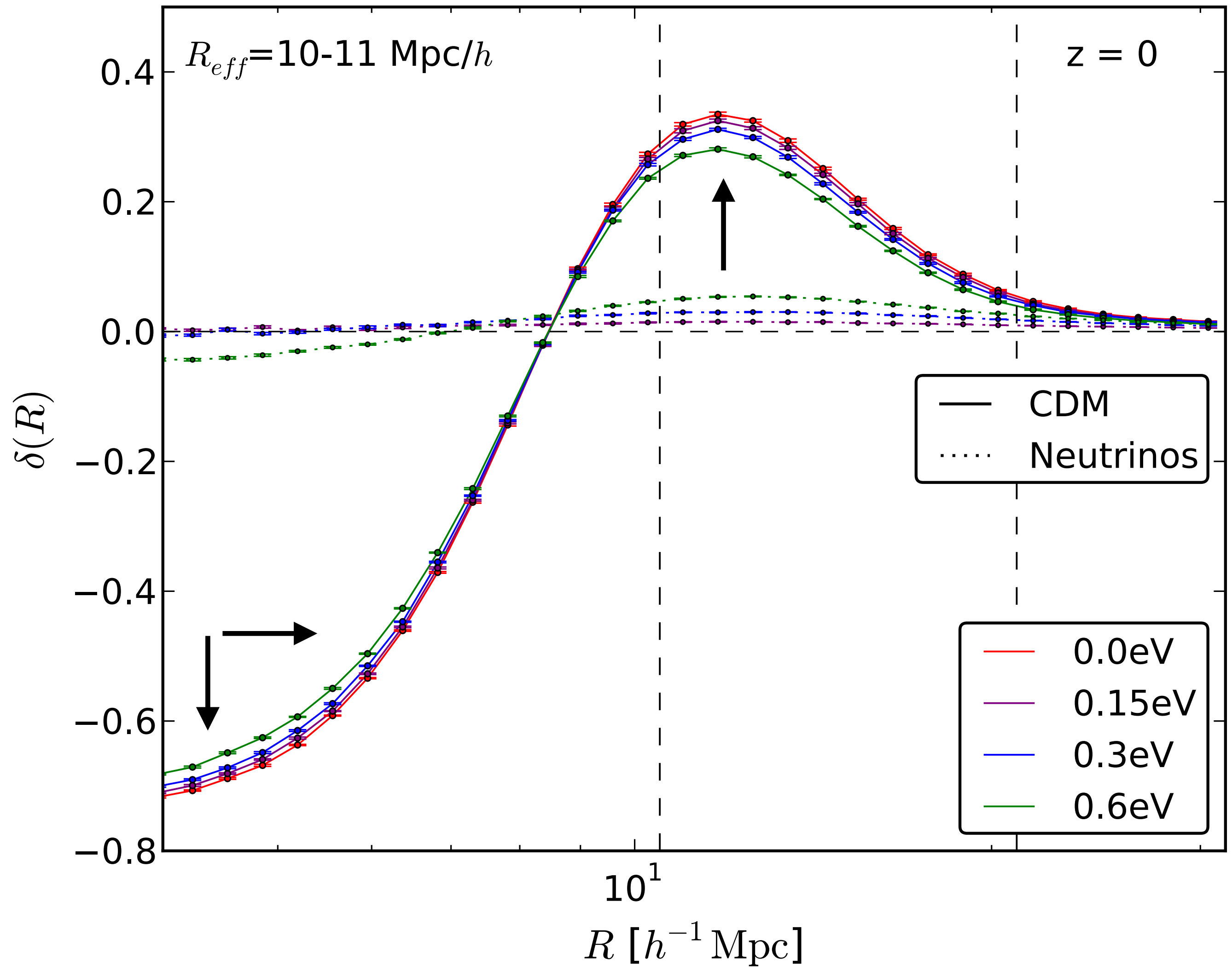




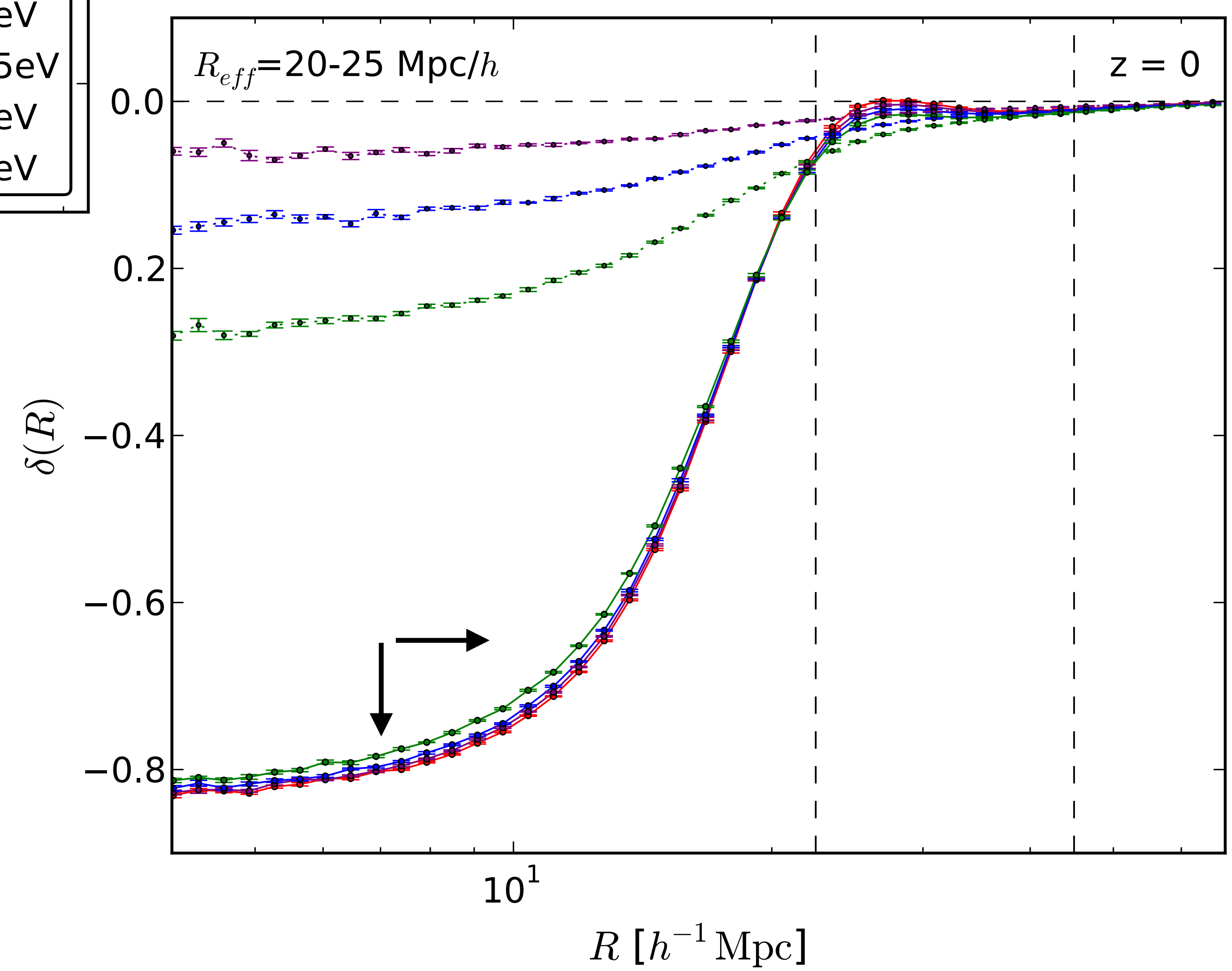
Evolution in time



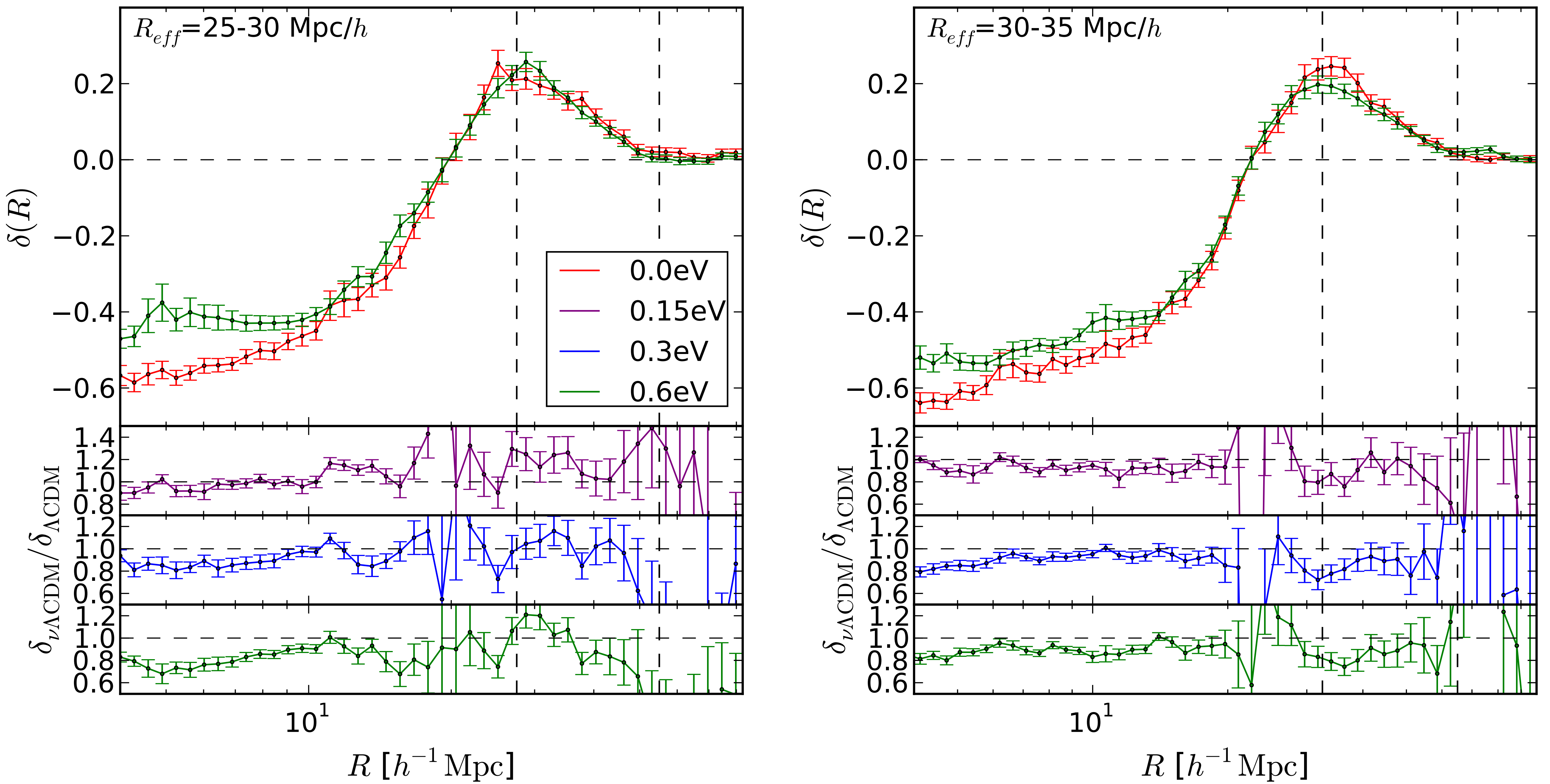
CDM / Neutrino profiles



Voids in massive neutrino cosmology are less evolved

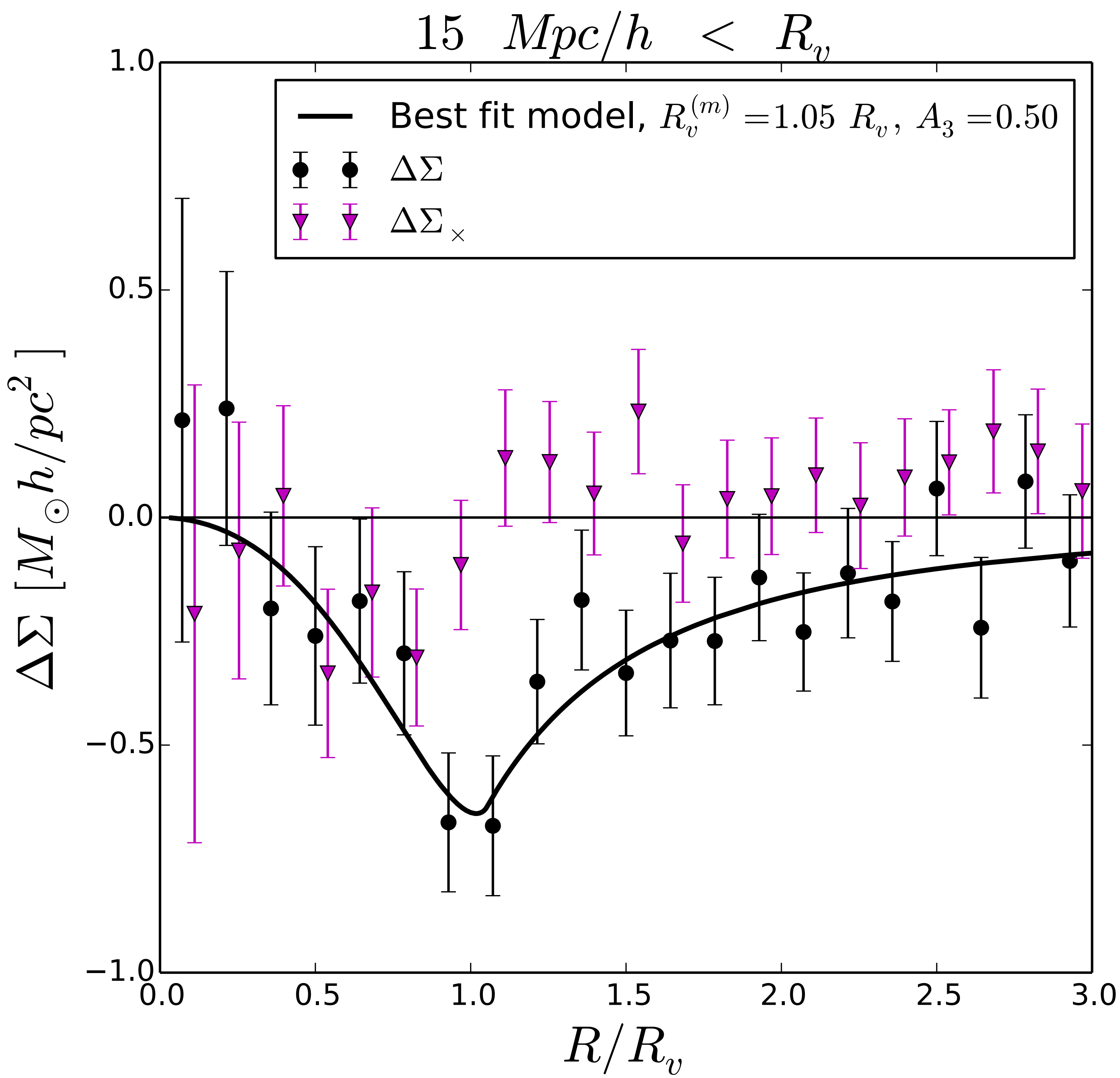


Matter profiles in galaxy voids



Weak-lensing signal could in principle detect different matter profiles around galaxy voids

Weak lensing around voids in SDSS



Clampitt et al. 2014

Model the void profiles from a theoretical point of view

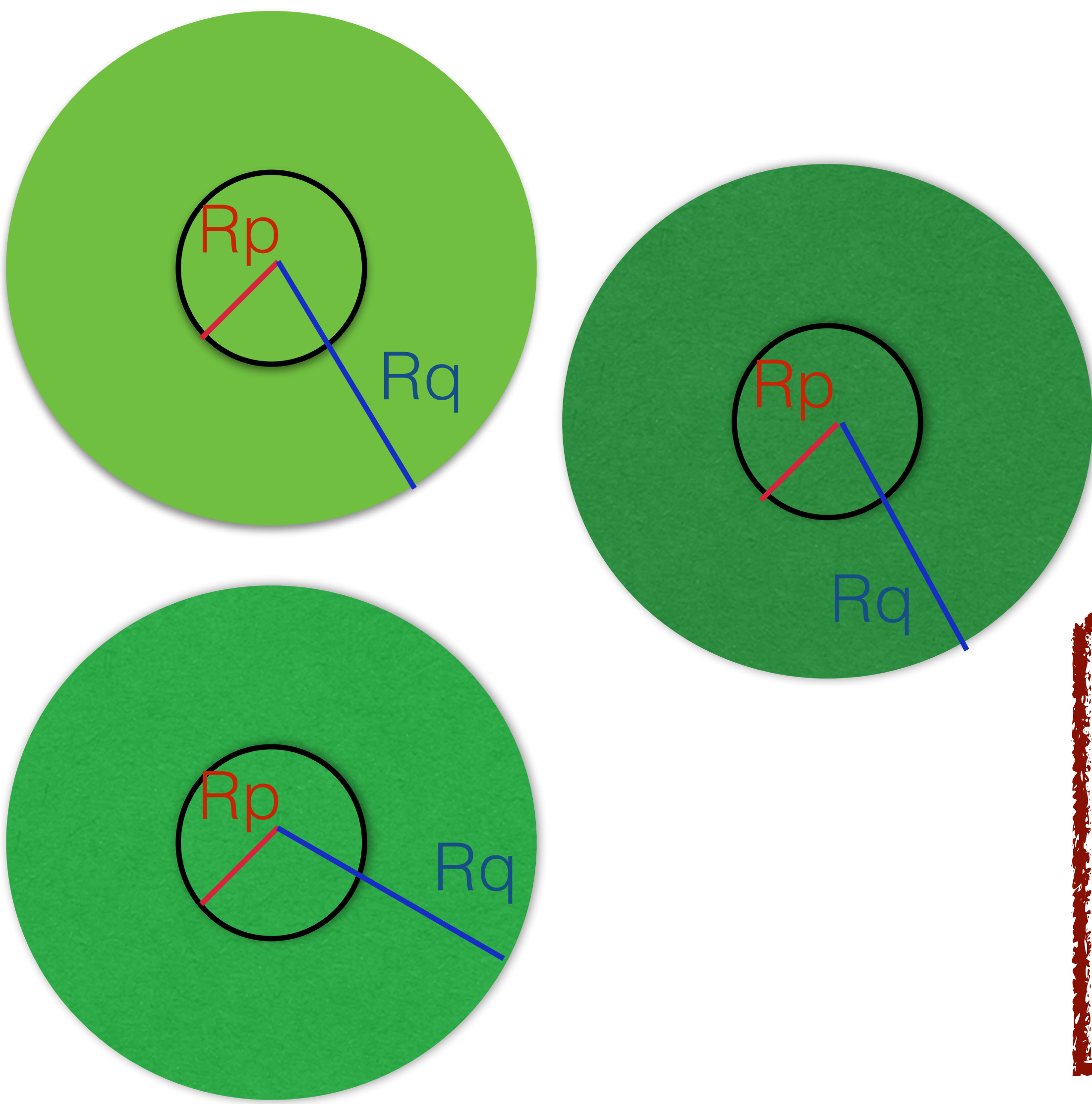
Based on:

Density profiles around biased tracers of the cosmic web

E.M., Ravi Sheth, P. M. Sutter et al.

in preparation

What is an enclosed profile?

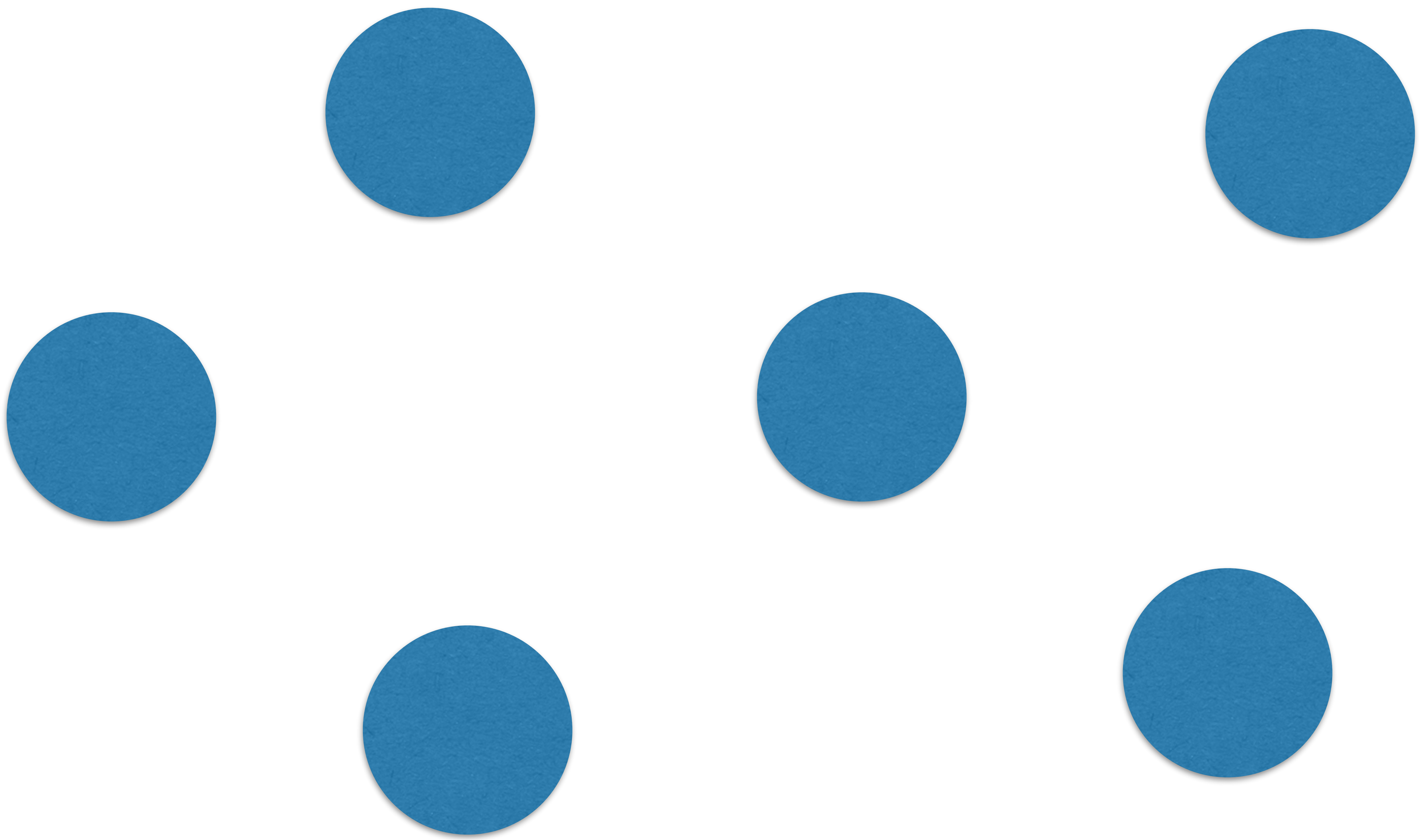


$$\frac{\Sigma_h \Sigma_{m(r_{hm}<R_q)}}{(\Sigma_h)(\Sigma_m)} = 1 + \xi_{hm}(r < R_q)$$

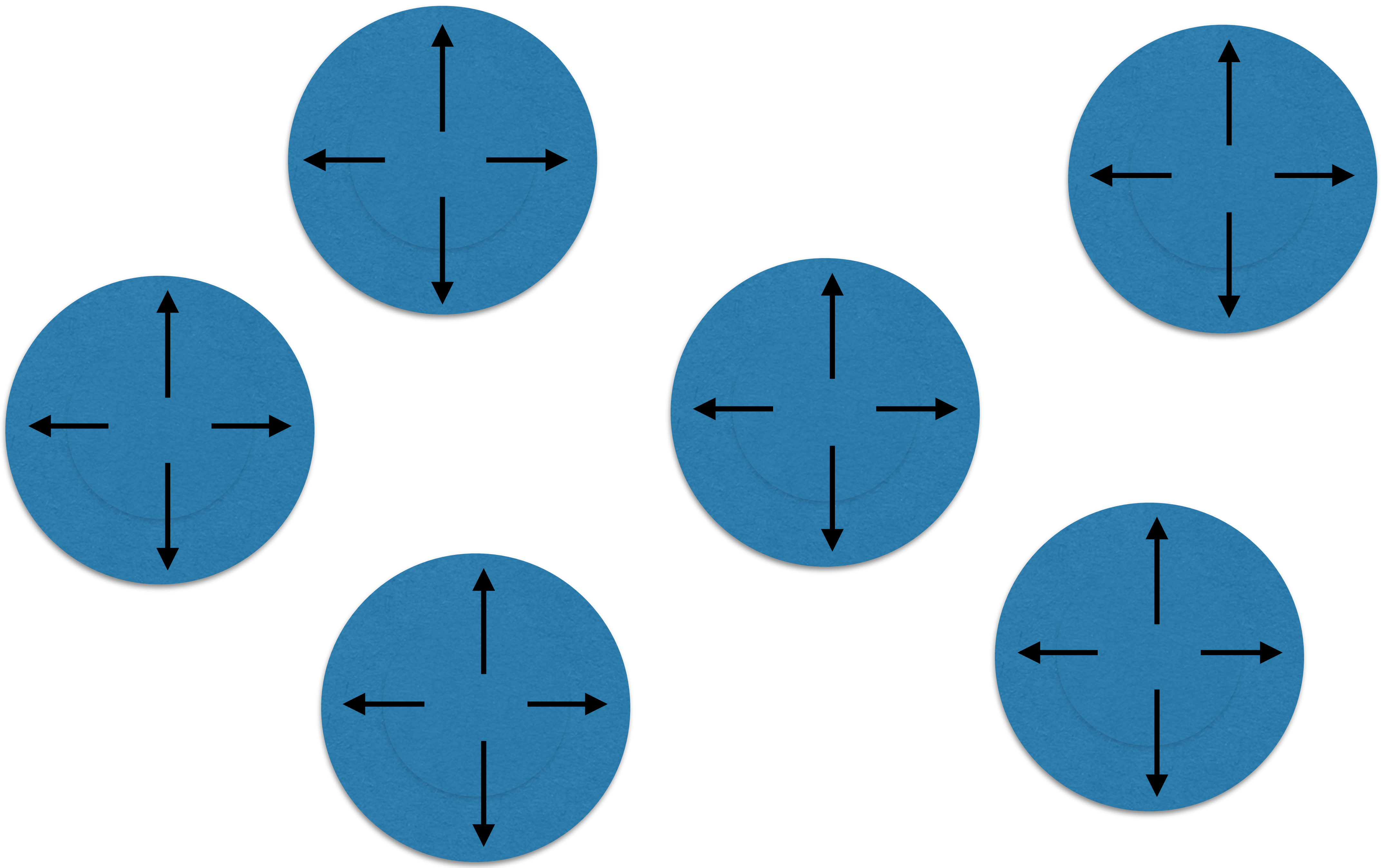
$$\xi_{hm}(r < R_q) = \Delta(r < R_q)$$

The cross-correlation between the patches and the mass is the enclosed mean density profile

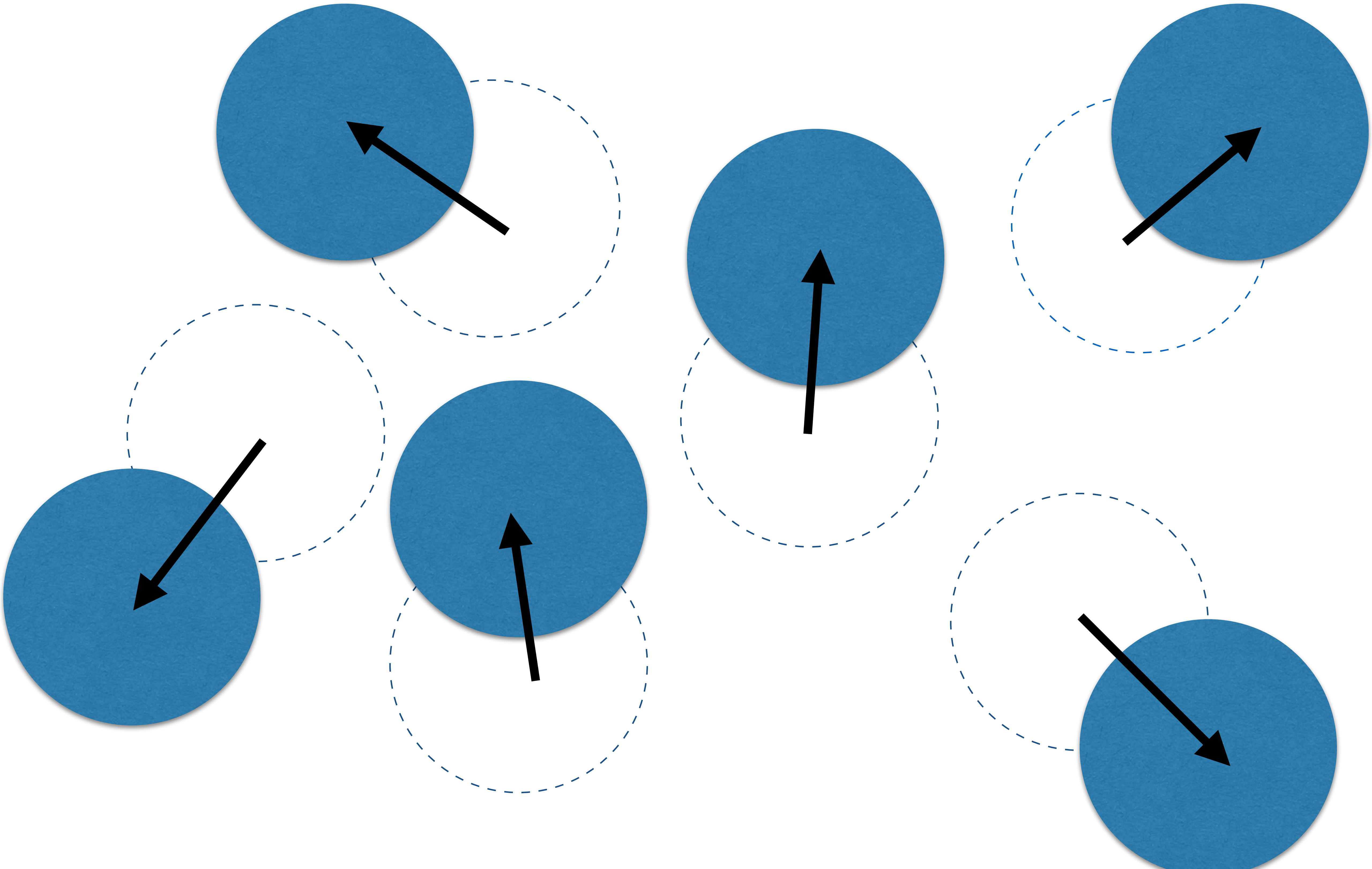
Lagrangian linear field



Eulerian evolved field



Eulerian evolved field



Modelling the evolution

$$\rho_{nl} = \qquad \rho_z \qquad + \qquad \rho_{nl} - \rho_z$$

Modelling the evolution

$$\rho_{nl} = \rho_z + \rho_{nl} - \rho_z$$

Void motion

↓

Zel'dovich approach
(Desjacques el al. 2010)

Modelling the evolution

$$\rho_{nl} = \rho_z + \rho_{nl} - \rho_z$$

Void motion → Zel'dovich approach (Desjacques el al. 2010)

Void expansion → Lagrangian approach

Lagrangian approach

1) Relation between today's tracers and the initial field

EST tells the connection between the bias and the profile around biased tracers in the Lagrangian space (L)

$$\Delta_L(k) = \left(b_{10}^L + b_{01}^L \frac{s_0^{pp}}{s_1^{pp}} k^2 \right) W(kR_p) W(kR_q) P(k)$$

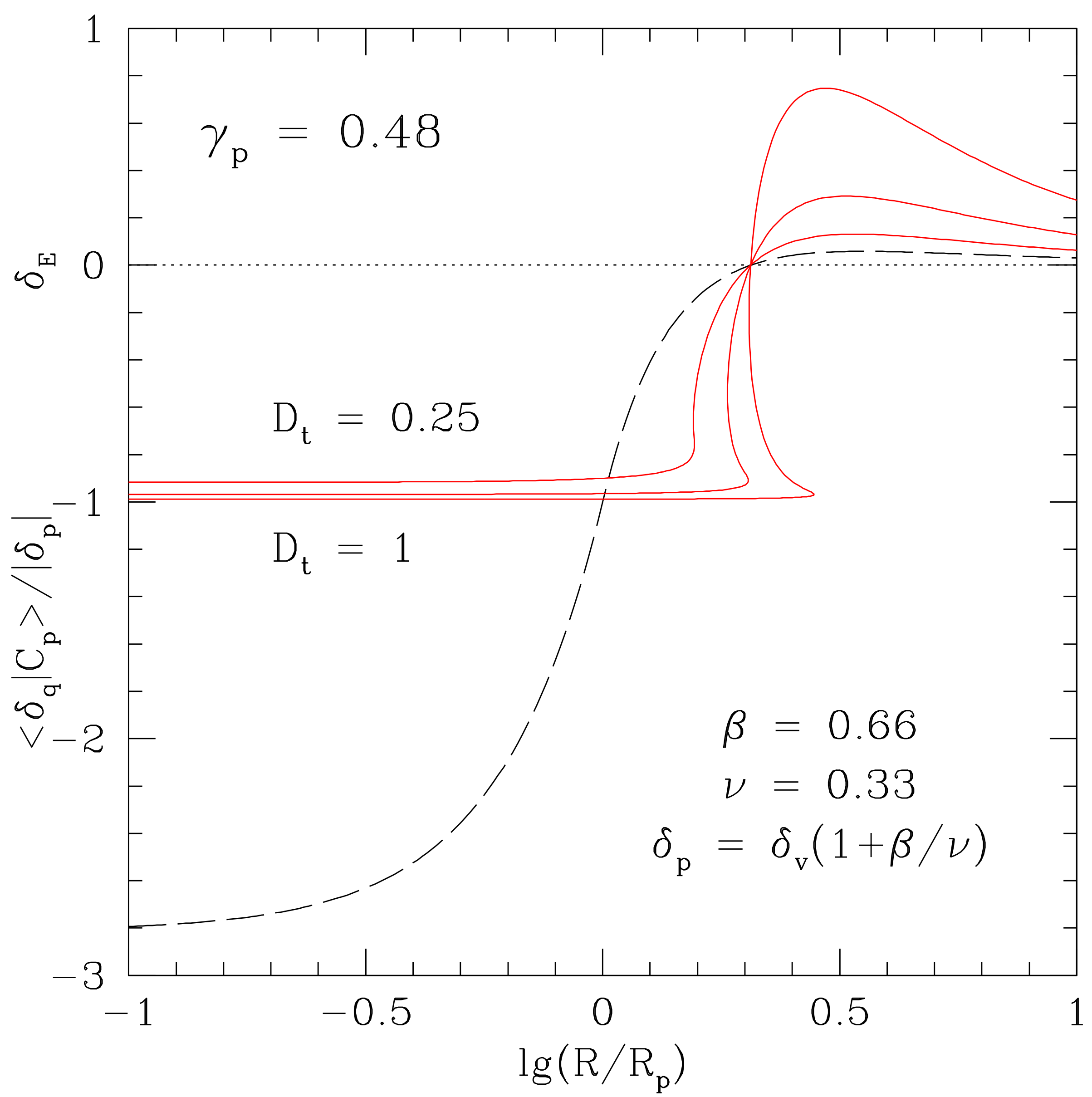
2) Subsequent evolution

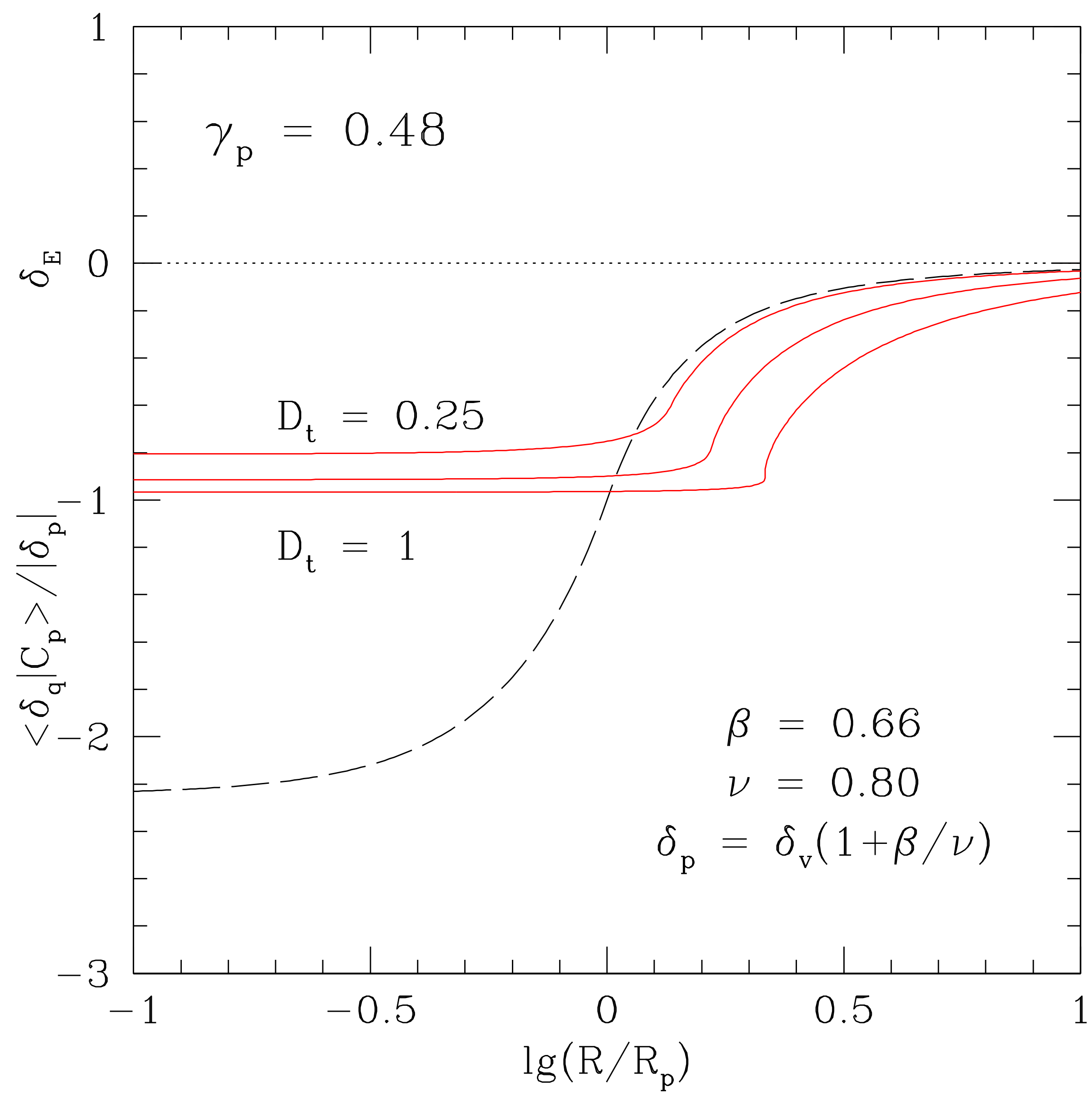
The spherical collapse model map the profile from the Lagrangian (L) to the Eulerian (E) space

$$1 + \Delta_E(< R_E; t) = \left(1 - \frac{D_t \Delta_L(< R_L)}{\delta_c} \right)^{-\delta_c} = \left(\frac{R_L}{R_E(t)} \right)^3$$

Void profiles

$$1 + \Delta_E(< R_E; t) = \left(1 - \frac{D_t \Delta_L(< R_L)}{\delta_c}\right)^{-\delta_c} = \left(\frac{R_L}{R_E(t)}\right)^3$$





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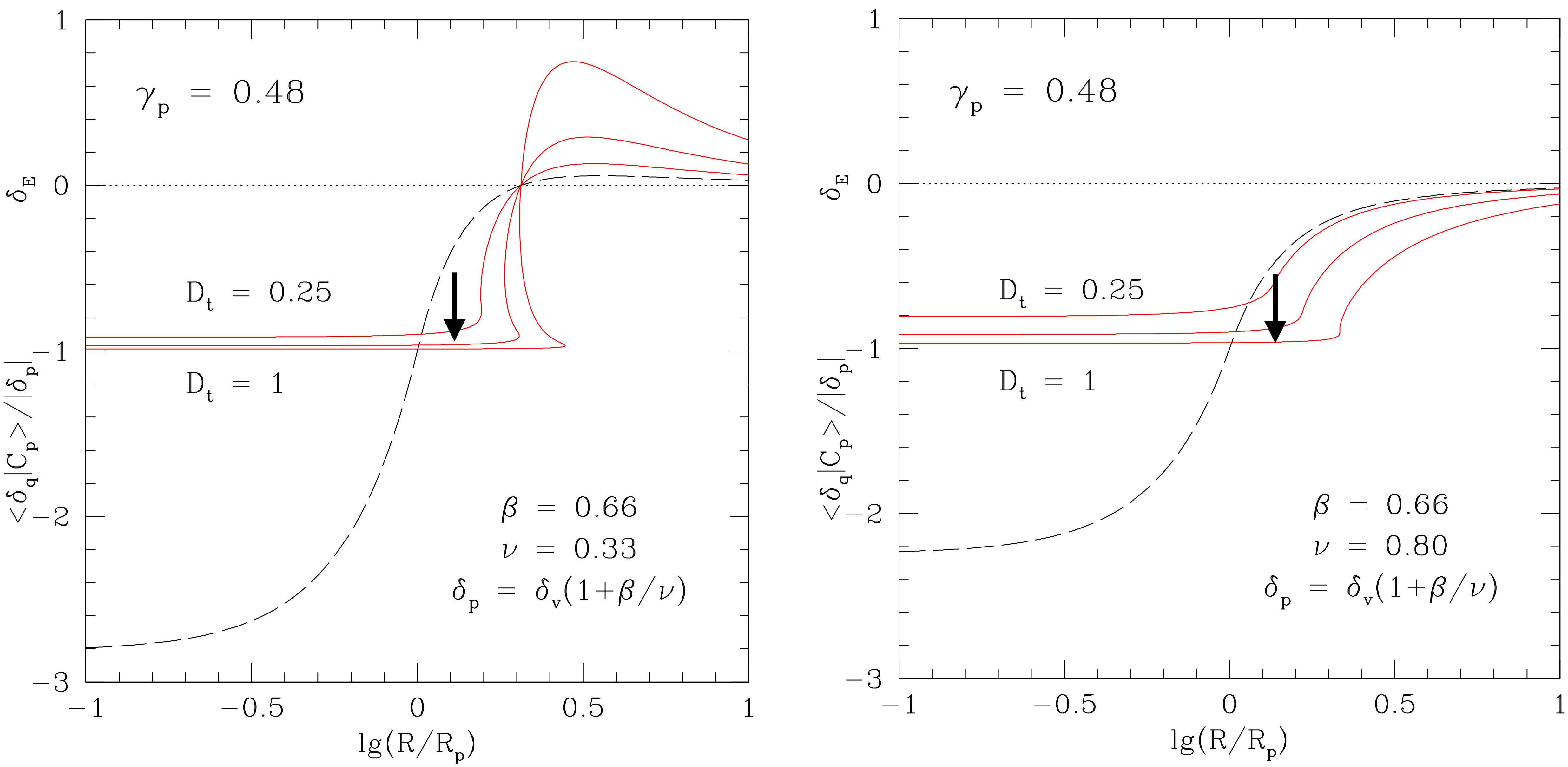

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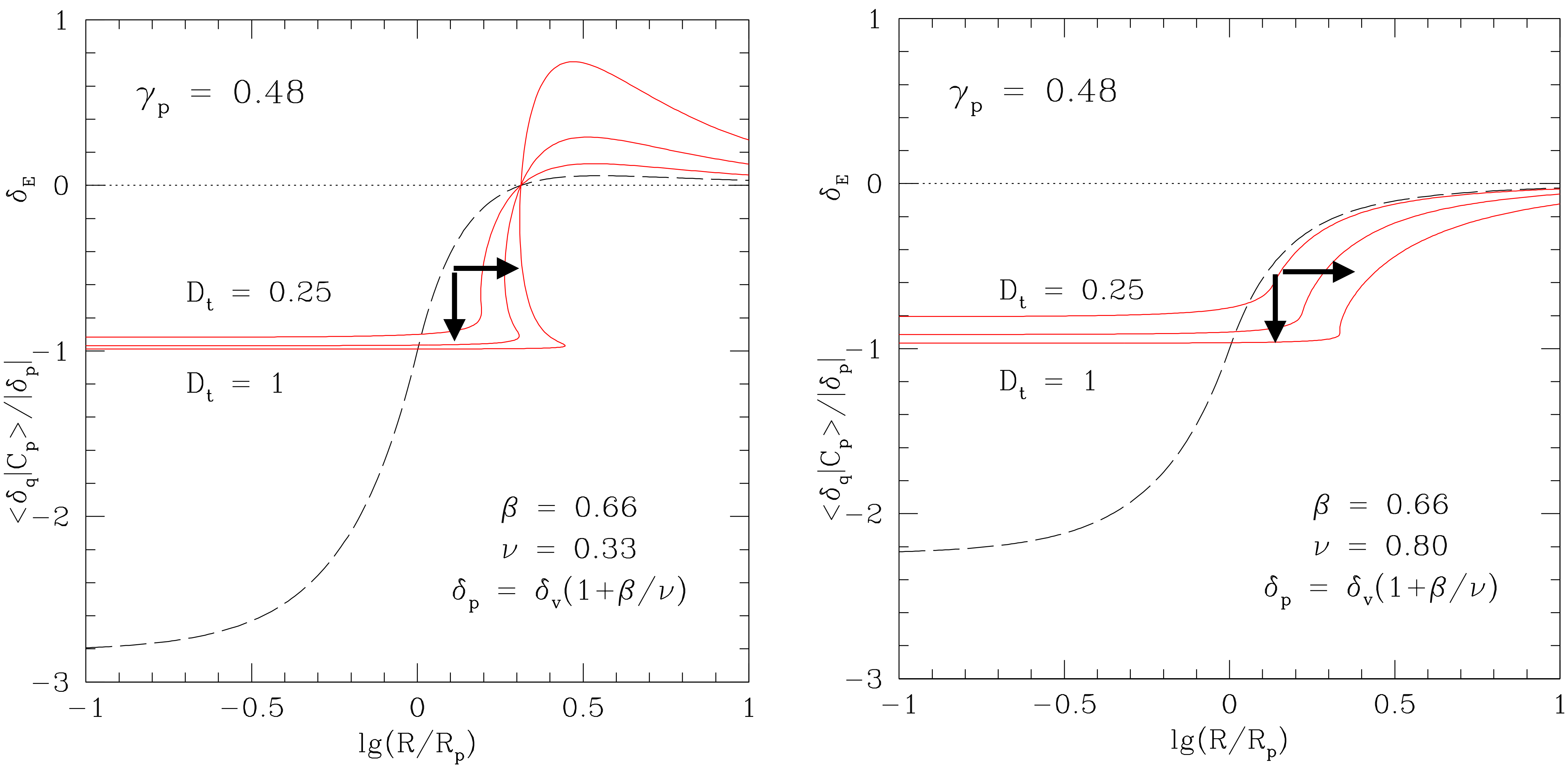

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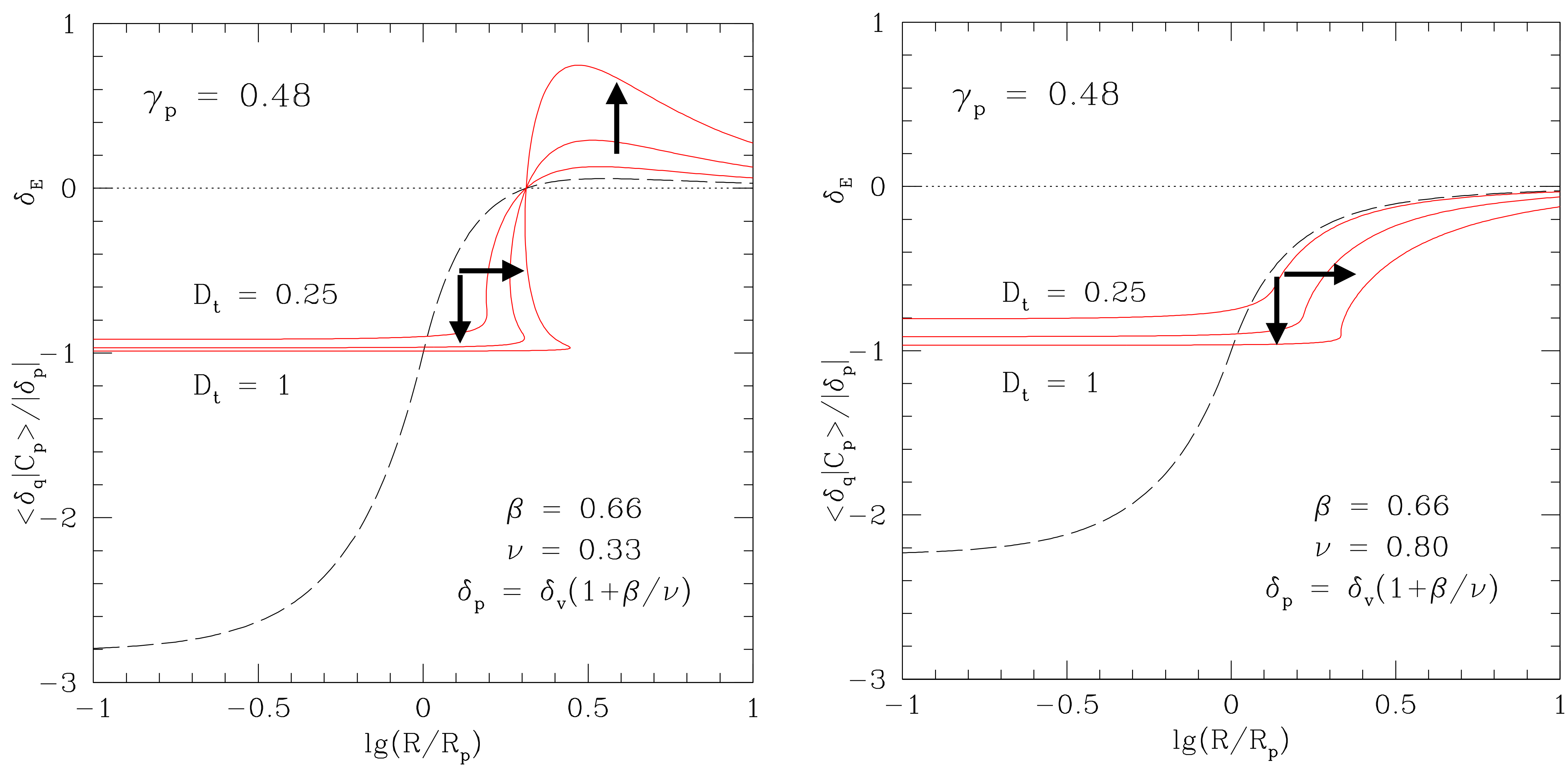

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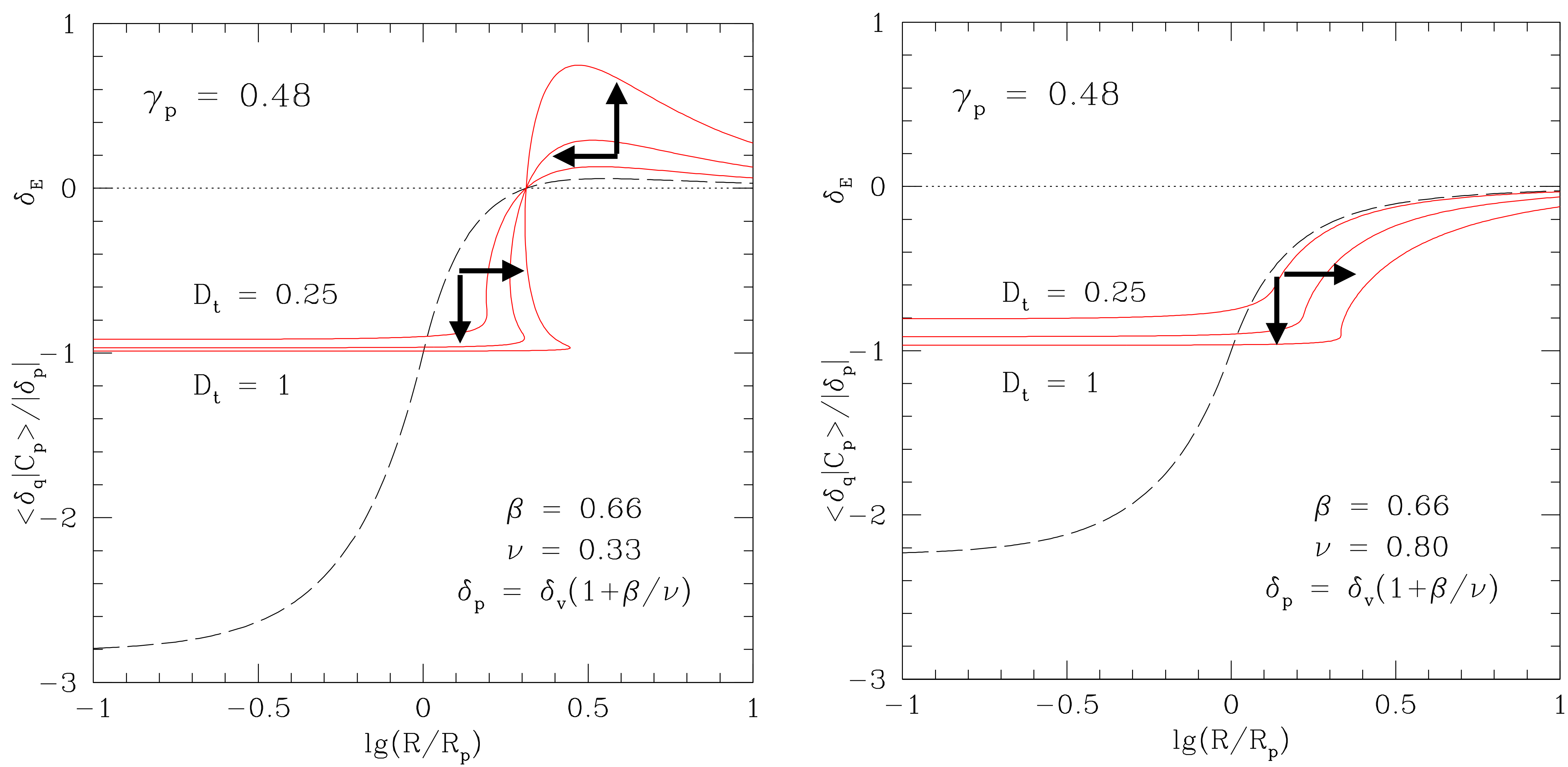
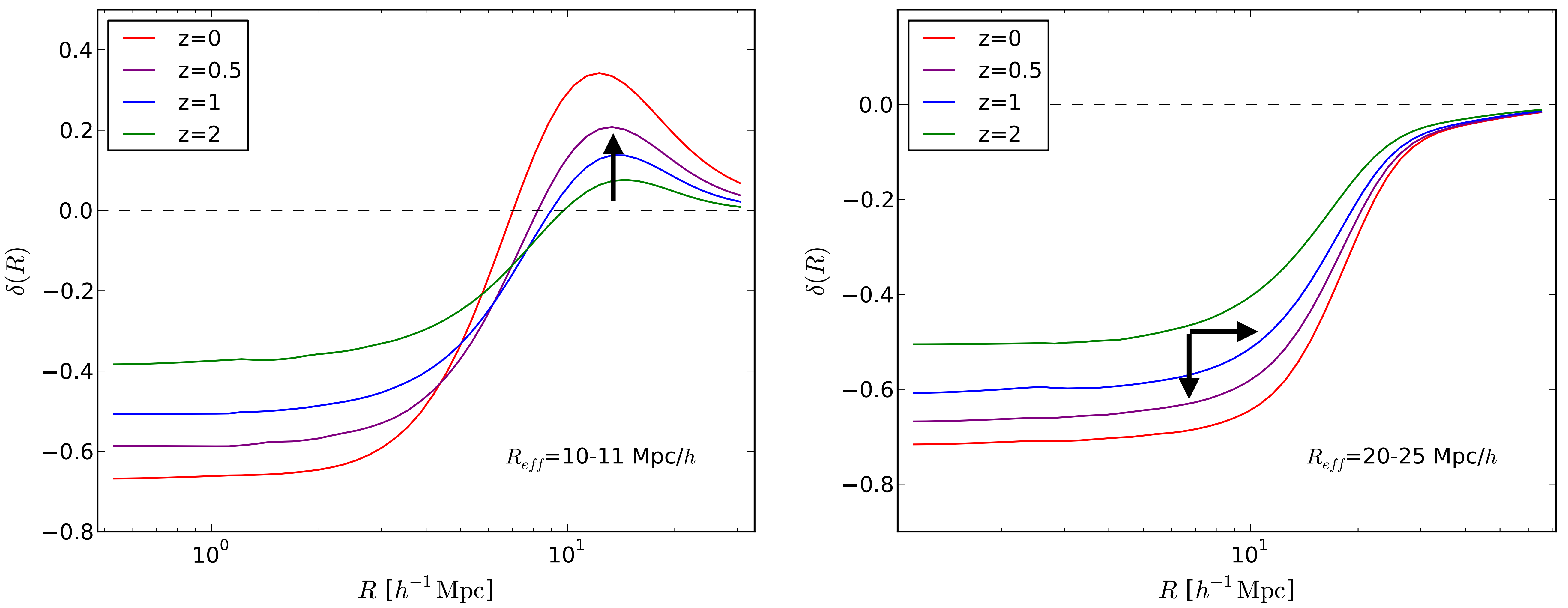


Evolution in time



Zel'dovich approach

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2) Subsequent evolution

The bias evolves from Lagrangian to Eulerian:

$$\Delta_E(k;z) = \frac{D_z}{D_0} \left(\frac{D_z}{D_0} b_v(k) + b_{10}^L + b_{01}^L \frac{s_0^{pp}}{s_1^{pp}} k^2 \right) G(k) W(kR_p) W(kR_q) P(k)$$

$$b_v(k) = 1 - k^2 s_0^{pp} / s_1^{pp}$$

$G(k)$: peak-trough propagator

The void bias evolution

$$P_{vm}(k)/P_{mm}(k) \sim b^E(k)$$

On large scales: $b^E(k,z) = b^L_{10} + D_z/D_0 + [b^L_{01} - D_z/D_0](s_0/s_1)k^2$

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$$b^E_{10} = b^L_{10} + D_z/D_0$$

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$$b^E_{10} = b^L_{10} + D_z/D_0$$

z = 99: $b^E_{10} = b^L_{10}$

z = 0 : $b^E_{10} = b^L_{10} + 1$

SAME EVOLUTION AS THE HALO BIAS

The void bias evolution

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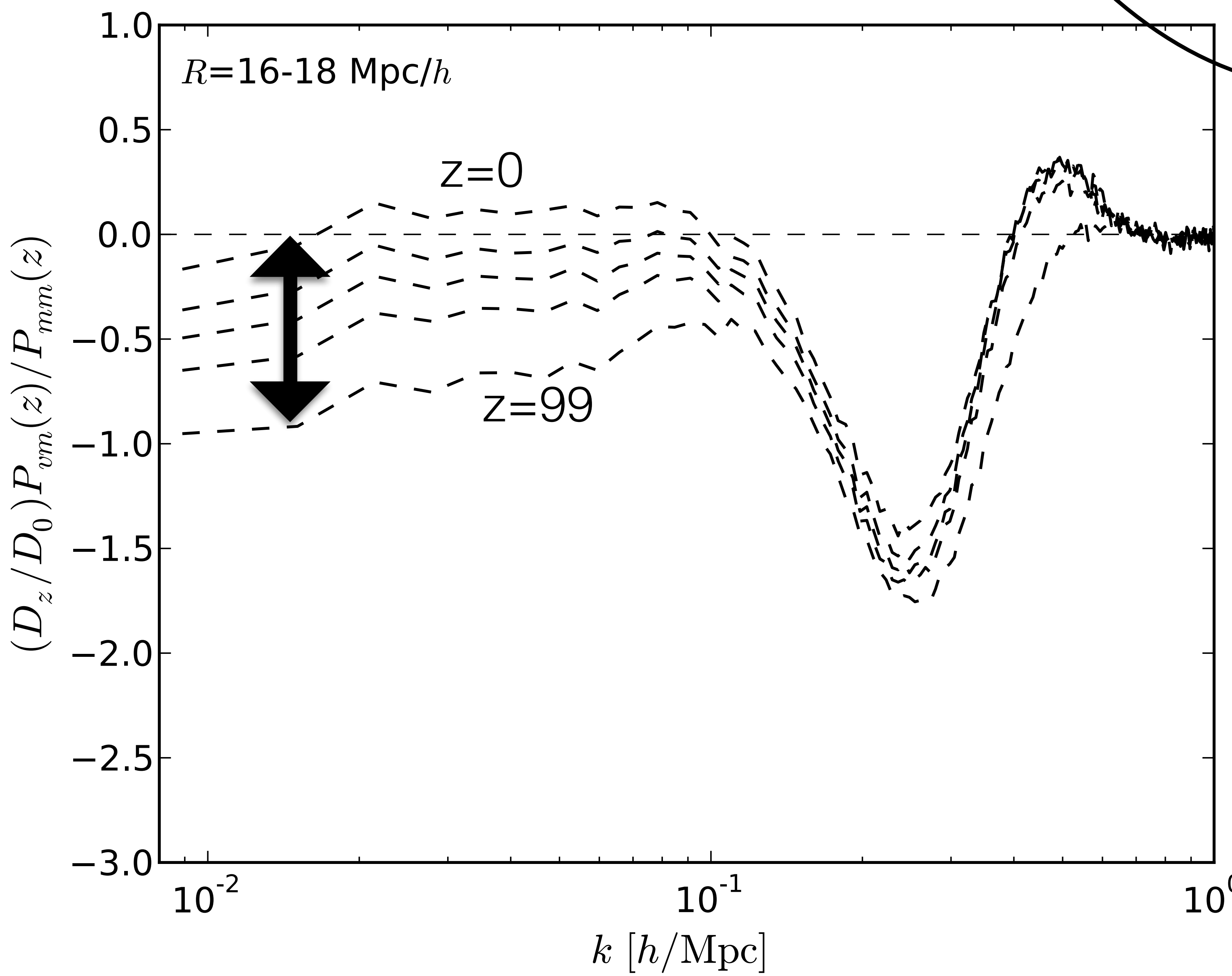

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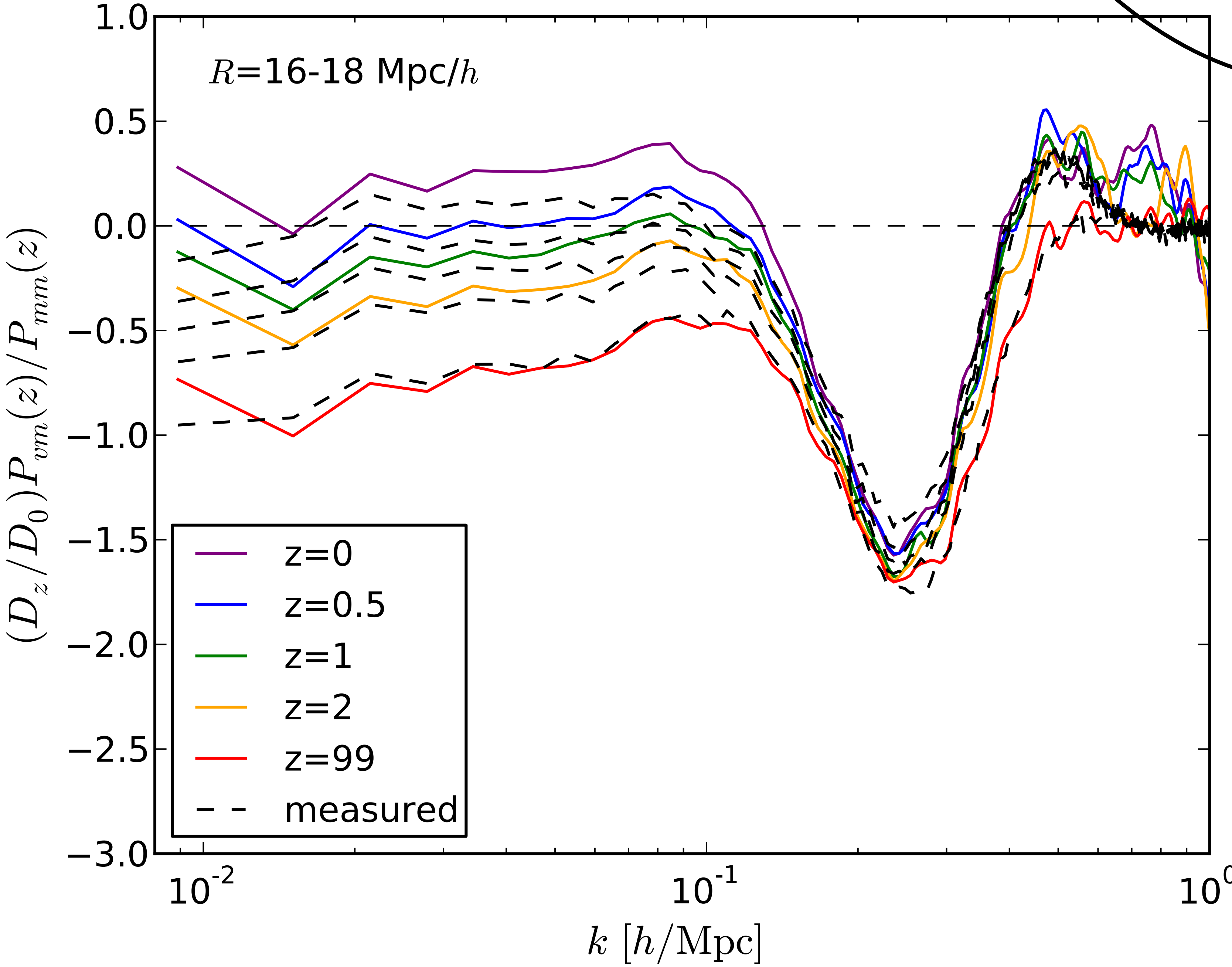

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SAME EVOLUTION AS THE HALO BIAS

The void bias evolution

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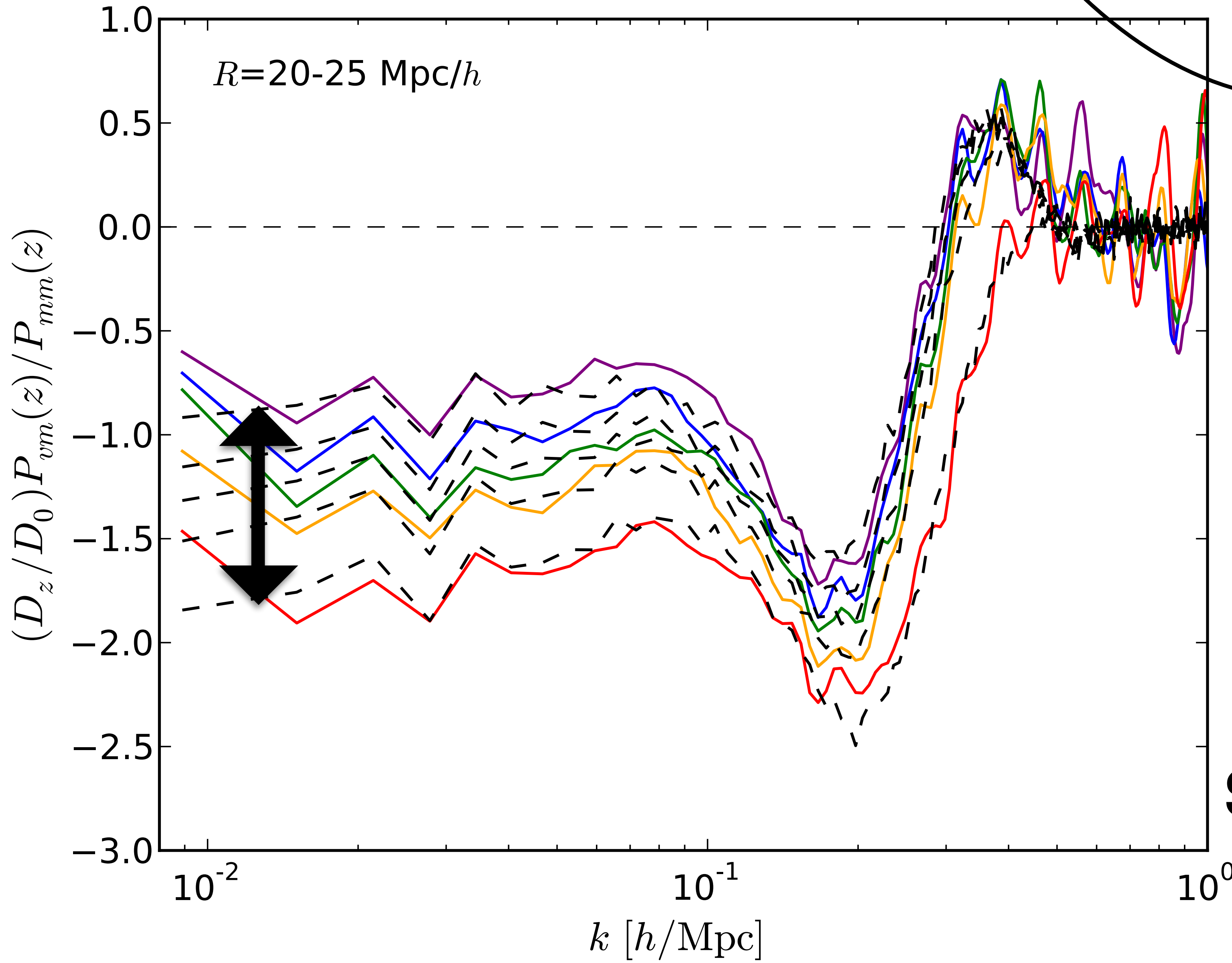

$$b^E_{10} = b^L_{10} + D_z/D_0$$

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z = 0 : $b^E_{10} = b^L_{10} + 1$

SAME EVOLUTION AS THE HALO BIAS

Conclusions

1. We performed an extension of the halo model to include massive neutrinos.
   - The key ingredients are:
     - The neutrino field is the sum of a clustered (subdominant) component and a linear one.
     - CDM is the fundamental field responsible for the clustering of matter.
   - The model is able to reproduce the matter power spectrum from simulations within the 20% level on scale $k < 10$ Mpc/h and the ratio with 2%-5%-10% accuracy for neutrino masses of 0.15-0.3-0.6 eV.
2. Voids in massive neutrino cosmologies:
   - CDM-voids appear to be less evolved, i.e. they are smaller, less empty and with a lower wall at the edge.
   - The total matter density profiles around galaxy-voids show differences that could be in principle detected via weak-lensing.
3. We proposed a theoretical model for the void density profiles:
   - Their evolution is consistent with the results from N-body simulations.
   - The void bias evolves like the halo bias.

CDM prescription

$$n(M_\mathrm{c})dM_\mathrm{c} = \frac{\bar{\rho}_\mathrm{c}}{M_\mathrm{c}} f(\nu_\mathrm{c})d\nu_\mathrm{c}$$

$$\nu_\mathrm{c} = \delta_{sc}^2/\sigma_\mathrm{c}^2$$

$$\sigma_\mathrm{c}^2 \equiv \sigma^2(M_\mathrm{c}) = \int_0^\infty \frac{dk}{2\pi^2} k^2 W^2(kR)\, P_\mathrm{c}^L(k)$$

$$M_\mathrm{c} = \frac{4}{3}\pi\bar{\rho}_\mathrm{c}R^3$$

Total matter power spectrum

$$P(k) = \left(\frac{\bar{\rho}_{\rm c}}{\bar{\rho}}\right)^2 P_{\rm c}(k) + 2\,\frac{\bar{\rho}_{\rm c}\bar{\rho}_\nu}{\bar{\rho}^2}\,P_{{\rm c}\nu}(k) + \left(\frac{\bar{\rho}_\nu}{\bar{\rho}}\right)^2 P_\nu(k)$$

CDM power spectrum

$$\boxed{P_{\rm c}(k) = P_{\rm c}^{1h}(k) + P_{\rm c}^{2h}(k)}$$

$$P_{\rm c}^{1h}(k) = \int_0^\infty d\nu_{\rm c}\, f(\nu_{\rm c})\frac{M_{\rm c}}{\bar{\rho}_{\rm c}}|u_{\rm c}(k|M_{\rm c})|^2\,,$$

$$P_{\rm c}^{2h}(k) = \left[\int_0^\infty d\nu_{\rm c}\, f(\nu_{\rm c})b_{\rm c}(\nu_{\rm c})\,u_{\rm c}(k|M_c)\right]^2 P_{\rm c}^L(k)$$

CDM-neutrino power spectrum

$$\boxed{P_{c\nu}(k) = F_h P^h_{c\nu}(k) + (1 - F_h) P^L_{c\nu}(k)}$$

$$F_h = \frac{1}{\bar{\rho}_\nu} \int_{M_{\rm cut}}^{\infty} dM_{\rm c}\, n(M_{\rm c}) M_\nu(M_{\rm c})$$

$$M_\nu(M_{\rm cut}) = 0.1 \times \frac{4\pi\bar{\rho}_\nu}{3} R_v^3(M_{\rm cut})$$

$$\boxed{P^L_{c\nu}(k) = \sqrt{P_{\rm c}(k) P^L_\nu(k)}}$$

$$\boxed{P^h_{c\nu}(k) = P^{1h}_{c\nu}(k) + P^{2h}_{c\nu}(k)}$$

$$P^{1h}_{c\nu}(k) = \int_{M_{\rm cut}}^{\infty} d\nu_{\rm c}\, f(\nu_{\rm c}) \frac{M_\nu}{F_h \bar{\rho}_\nu}\, u_{\rm c}(k|M_{\rm c})\, u_\nu(k|M_{\rm c})$$

$$P^{2h}_{c\nu}(k) = \int_0^{\infty} d\nu'_{\rm c}\, f(\nu'_{\rm c})\, b(\nu'_{\rm c})\, u_c(k|M'_{\rm c})$$

$$\times \int_{M_{\rm cut}}^{\infty} d\nu''_{\rm c}\, f(\nu''_{\rm c} c)\, b(\nu''_{\rm c})\, \frac{M_\nu}{M''_{\rm c}} \frac{\bar{\rho}_{\rm c}}{F_h \bar{\rho}_\nu}\, u_\nu(k|M''_{\rm c})\, P^L_{\rm c}(k)$$

Neutrino power spectrum

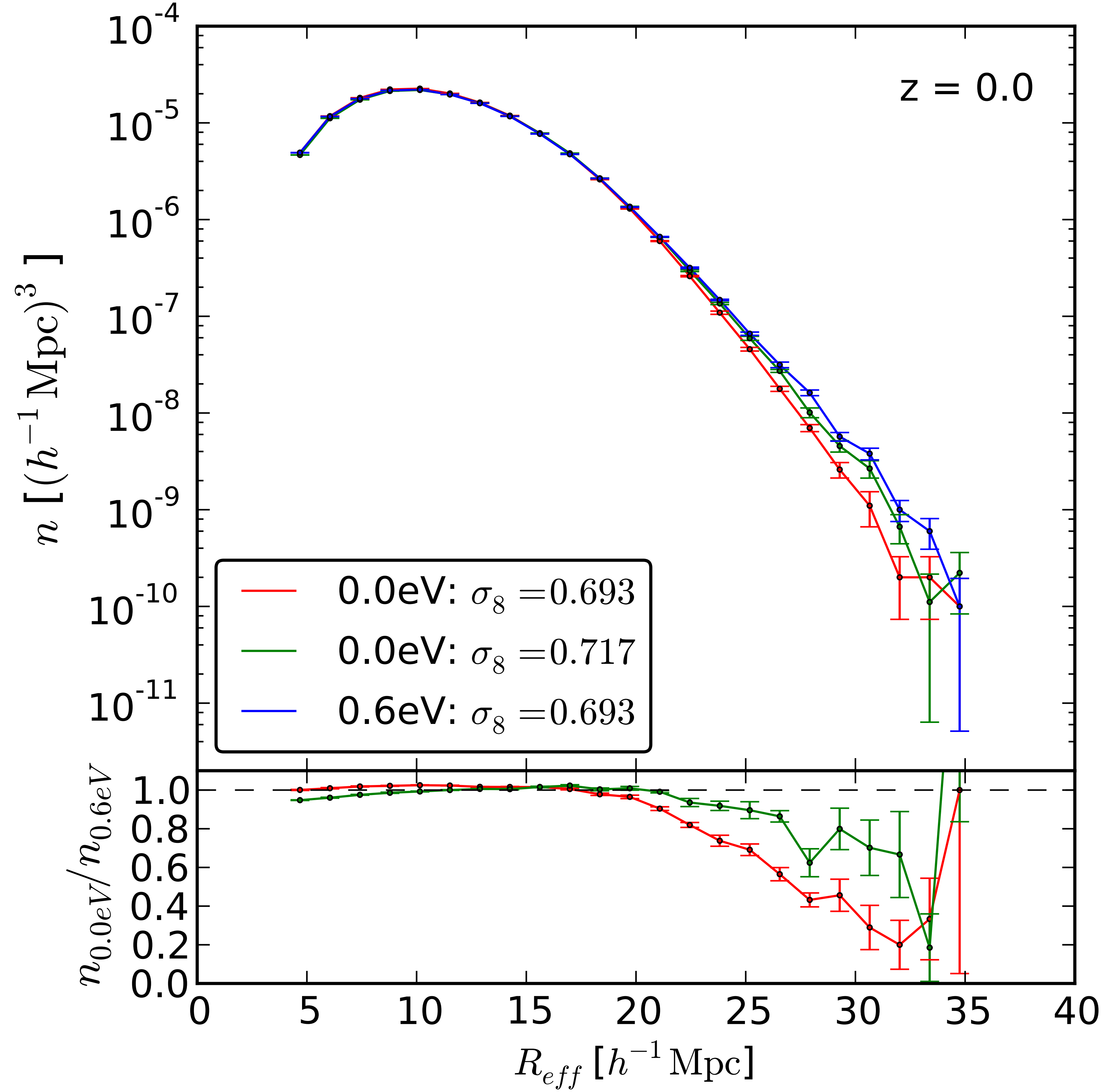
$$\boxed{P_\nu(k) = F_h^2 P_\nu^h(k) + 2F_h(1-F_h)P_\nu^{hL}(k) + (1-F_h)^2 P_\nu^L(k)}$$

$$\boxed{P_\nu^{hL}(k) = \sqrt{P_\nu^h(k) P_\nu^L(k)}}$$

$$\boxed{P_\nu^h(k) = P_\nu^{1h}(k) + P_\nu^{2h}(k)}$$

$$P_\nu^{1h}(k) = \int_{M_{\rm cut}}^{\infty} d\nu_{\rm c}\, f(\nu_{\rm c}) \left(\frac{M_\nu}{F_h \bar{\rho}_\nu}\right)^2 \frac{\bar{\rho}_{\rm c}}{M_{\rm c}} \left|u_\nu(k|M_{\rm c})\right|^2$$

$$P_\nu^{2h}(k) = \left[\int_{M_{\rm cut}}^{\infty} d\nu_{\rm c}\, f(\nu_{\rm c})\, b(\nu_{\rm c})\, \frac{M_\nu}{M_{\rm c}} \frac{\bar{\rho}_{\rm c}}{F_h \bar{\rho}_\nu}\, u_\nu(k|M_{\rm c})\right]^2 P_{\rm c}^L(k)$$



z = 0.0
0.0eV: σ_8 =0.693
0.0eV: σ_8 =0.717
0.6eV: σ_8 =0.693
$n\ [(h^{-1}\,\mathrm{Mpc})^3\ ]$
$n_{0.0eV}/n_{0.6eV}$
$R_{eff}\ [h^{-1}\,\mathrm{Mpc}]$
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
25
30
35
40