The Dark Energy and Massive Neutrino Universe (DEMNUni) campaign

Carmelita Carbone

INAF
ISTITUTO NAZIONALE DI ASTROFISICA
NATIONAL INSTITUTE FOR ASTROPHYSICS
Istituto di Astrofisica Spaziale e Fisica cosmica di Milano

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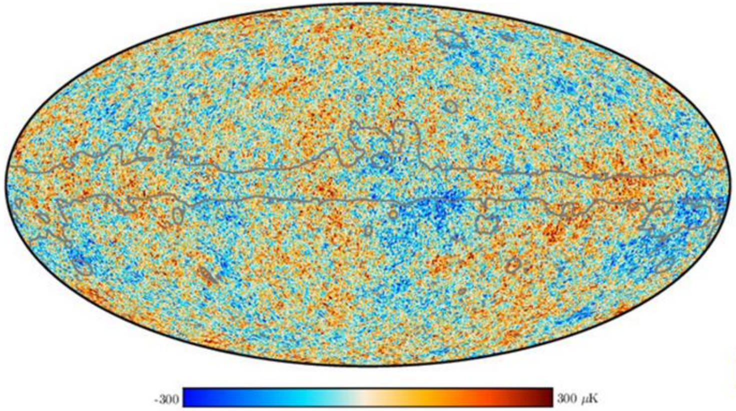
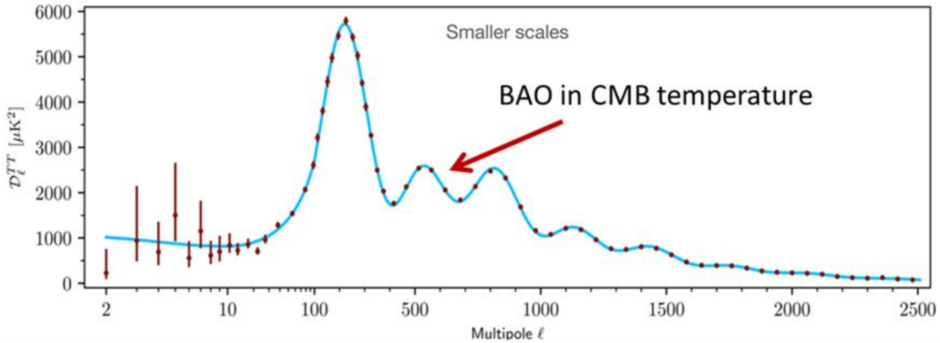
The ΛCDM model from Planck

Planck Collaboration et al (2020):





The best fit model has 6 parameters:

$$\Omega_b h^2 = 0.02237 \quad (0.67\%)$$

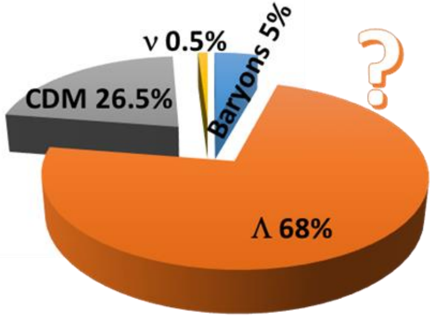
$$\Omega_c h^2 = 0.1200 \quad (1\%)$$

$$\theta_{\mathrm{MC}} = 1.04092 \quad (0.03\%)$$

$$\tau = 0.0544 \quad (13.4\%)$$

$$\ln\left(10^{10} A_s\right) = 3.044 \quad (0.46\%)$$

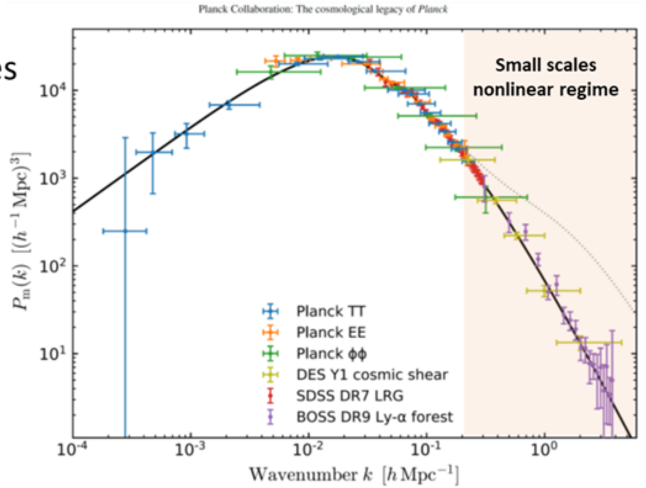
$$n_s = 0.9649 \quad (0.44\%)$$



Why cosmological numerical simulations

- Need to understand structure formation in ΛCDM and beyond- Λ CDM scenarios.

- Linear and perturbative modelling usually not sufficient for cosmological probes at small scales.



- Nonlinear modelling needed to extract useful information to improve cosmological constraints and break degeneracies.

- Need of "universe labs" to study and model new cosmological probes such as cosmic voids and filaments.

- Need to produce many realizations of the universe to compute probe covariances for ongoing and upcoming galaxy surveys (eg Euclid, SKA…), CMB experiments, and GW observatories.

- etc…

N-body simulations with neutrino particles

	CDM	CDM + ν
Power spectrum	$P_m(k)$	$P_{cb}(k)$ $P_\nu(k)$
Growth factor	Scale independent	Scale dependent
Growth rate	Scale independent	Scale dependent
Velocities	Peculiar	Peculiar Peculiar + thermal

Add neutrinos as an extra dark matter particle species with large thermal velocity given by the Fermi-Dirac distribution

DEMNUni simulation campaign: size and resolution

(C. Carbone & collaborators)

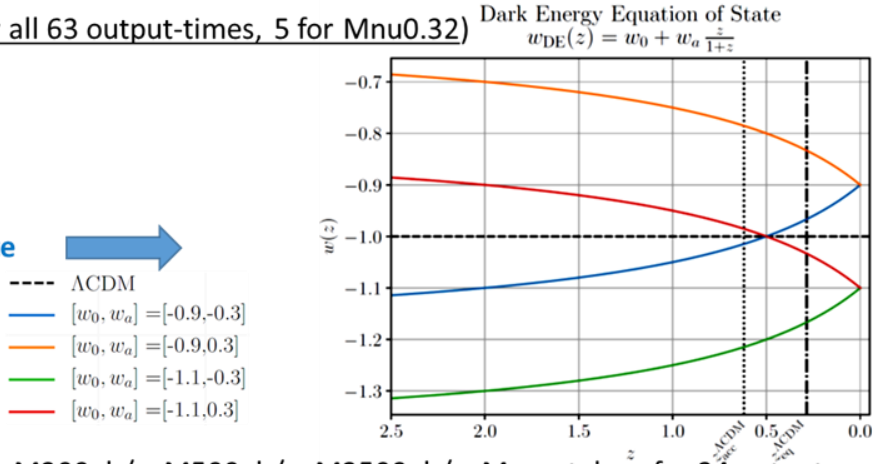
- **16 DEMNUni XL-simulations:**
  $V=(2\ Gpc/h)^3$, $N_{part}= 2 \times 2048^3$ (CDM+ν), $M_{cdm} \cong 8 \times 10^{10}\ M_\odot$

baseline Planck cosmology (according to Euclid SWG-coord meeting 11/06/2013)

\+

- **M_ν=0, 0.16, 0.32, 0.53 eV (w=-1)** (projected density & particle snaps for all 63 output-times, 5 for Mnu0.32)
- **(M_ν, w_0, w_a)=(0-0.16-0.32 eV, -0.9, ±0.3) & (0-0.16-0.32 eV, -1.1, ±0.3)**
  5 snaps per sim, 34 FoF/Sub, M200_b/c, M500_b/c, M2500_b/c, M_{vir}, galaxy-SHAM, catalogues in 0<z<2 (**240TB OF STORED DATA**)

Implemented Dark Energy Equation of State



- **50+50 DEMNUni L-simulations (DEMNUni-Cov):**
  $V=(1\ Gpc/h)^3$, $N_{part}= 2 \times 1024^3$ (CDM+ν), $M_{cdm} \cong 8 \times 10^{10}\ M_\odot$

- **50 sims Planck-LCDM; Mnu=0 eV:** 63 full particle snapshots/sim, FoF/Sub, M200_b/c, M500_b/c, M2500_b/c, M_{vir} catalogs for 34 output-times between z=2 and z=0. Projected densities maps available at all output-times. (**110TB of stored data**)
- **50 sims Planck-LCDM; Mnu=0.16 eV:** 5 full particle snapshots/sim, FoF/Sub, M200_b/c, M500_b/c, M2500_b/c, M_{vir} catalogs for 34 output-times between z=2 and z=0. (**30TB of stored data**)

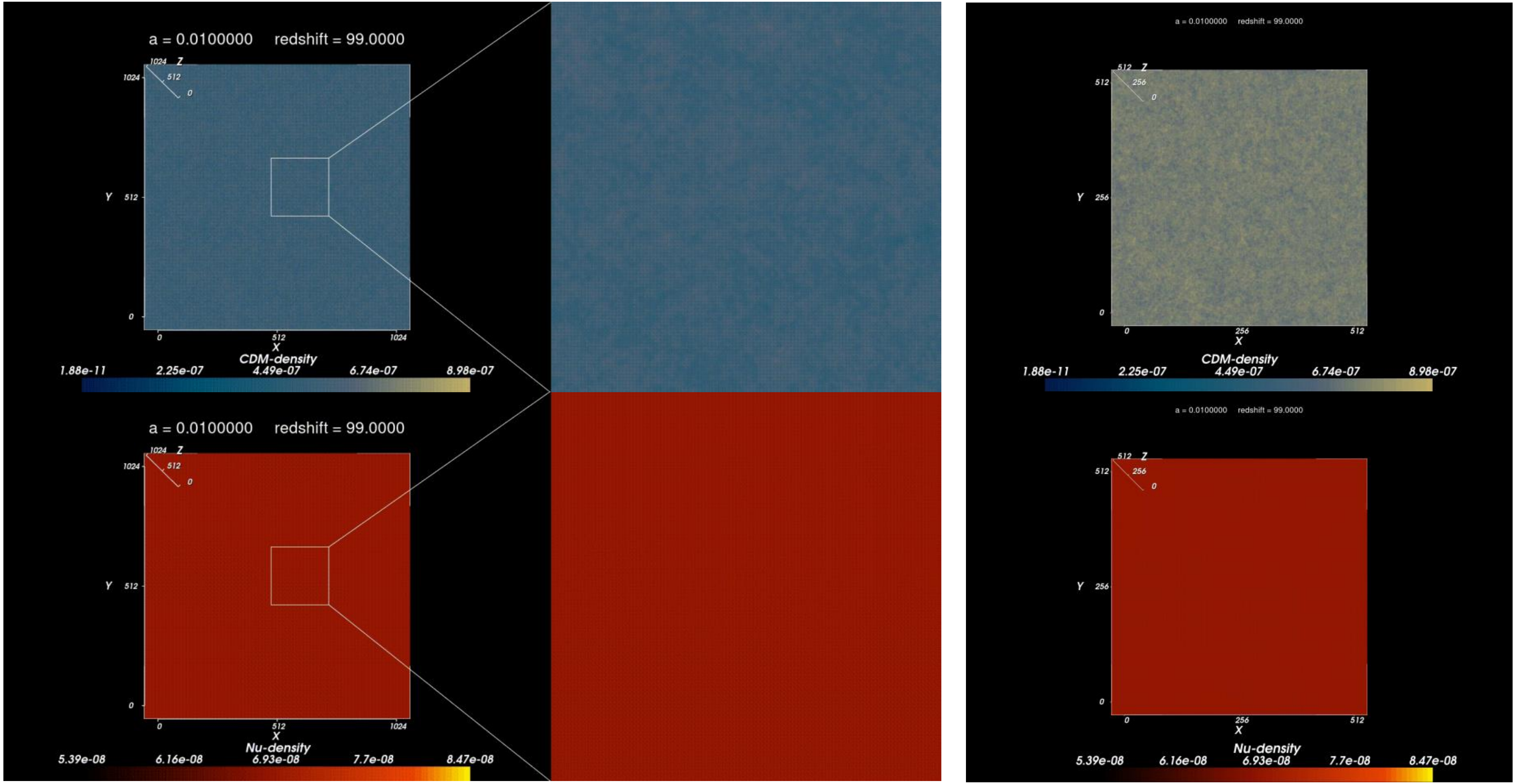
- **DEMNUni M-simulations (DEMNUni-HigRes): $V=(500\ Mpc/h)^3$, $N_{part}= 2 \times 2048^3$ (CDM+ν), $M_{cdm} \cong 1.3 \times 10^9\ M_\odot$**
- **2 sims Planck-LCDM; Mnu=0,0.16,0.32 eV:** (resolution enough for Euclid Halpha galaxies)

DEMNUni allocated HPC resources

- June 2023 PI of the "*Dark Energy and Massive Neutrinos High Resolution Simulations: filling the scale gap for AI-assisted simulations* (HR-DEMNU)" (class-B ISCRA/CINECA call), 2M CPUh on the Tier-1 GALILEO-100 supercomputer at CINECA.
- Oct 2022 PI of the "*Dark Energy and Massive Neutrinos High Resolution Simulations: filling the scale gap for AI-assisted simulations* (DEMN-HR)" (class-A HPC/ICT MoU INAF-CINECA call), 700k CPUh on the Tier-0 MARCONI-100 supercomputer at CINECA.
- Oct 2019 PI of the "*DEMNUni Covariances* III" (class-A HPC/ICT MoU INAF-CINECA call), 2M CPUh on the Tier-0 MARCONI-A1 supercomputer at CINECA.
- Sept 2018 PI of the "*DEMNUni Covariances* II" (class-B ISCRA/CINECA call), 2M CPUh on the Tier-0 MARCONI-A1 supercomputer at CINECA.
- May 2017 PI of the "*DEMNUni Covariances*" (class-A HPC/ICT MoU INAF-CINECA call), 3M CPUh on the Tier-0 MARCONI-A1 supercomputer at CINECA.
- Nov 2015 PI of the "*The Dark-Energy and Massive-Neutrino Universe* II" (class-B ISCRA/CINECA call), 8M CPUh on the Tier-0 IBM/BGQ FERMI supercomputer at CINECA.
- Jan 2012 PI of the "*The Dark-Energy and Massive-Neutrino Universe*" (class-A ISCRA/CINECA call), 5M CPUh on the Tier-0 IBM/BGQ FERMI supercomputer at CINECA.
- 2010 – 2022 PI of 13 small projects for DEMNuni post-processing (class-C ISCRA/CINECA calls), for a total of about 5M CPUh, on Tier-1/Tier-0 supercomputers at CINECA.

For a total of about 26M CPUh
and 400TB of storage among CINECA/INAF/INFN

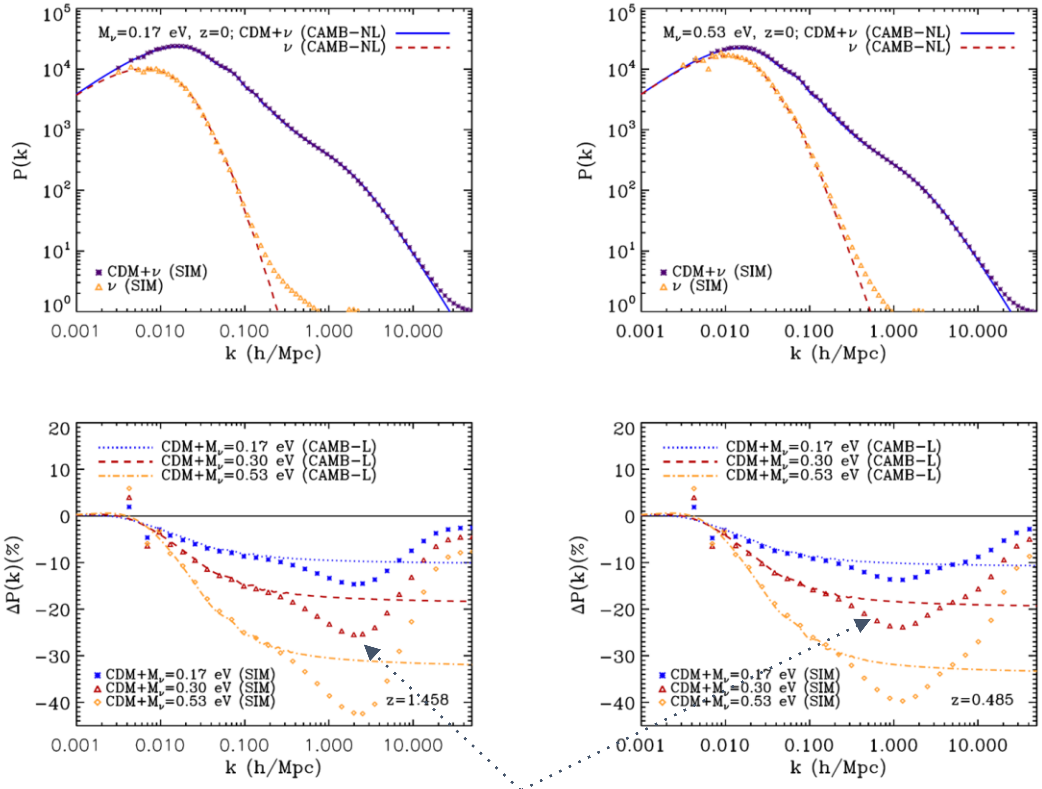
DEMNUni simulations: labs for structure formation in $\nu w_0 w_a$CDM scenarios

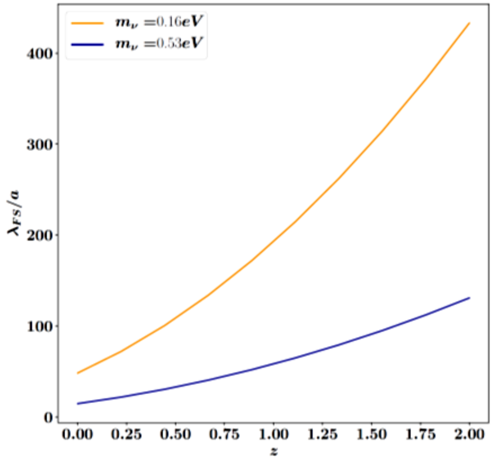


Credits: Tuccari, Tudisco, Sciacca, Vitello

Improving non-linear modelling in the presence of massive neutrinos

CC et al 2016





$$f_\nu = \frac{\Omega_\nu}{\Omega_{CDM} + \Omega_b + \Omega_\nu}$$

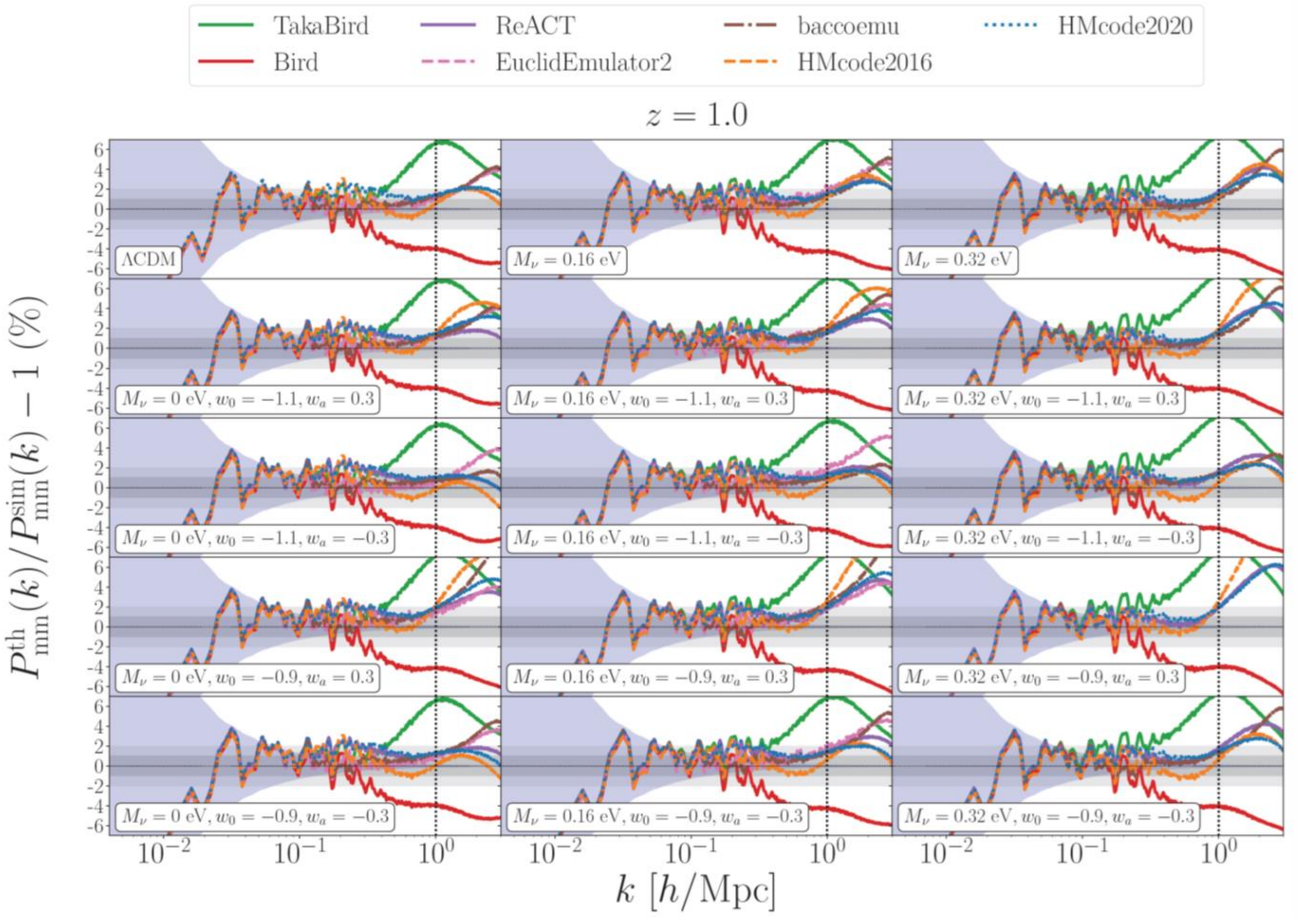
$$\left.\frac{\Delta P}{P}\right|_{max}^{non-linear} \cong -10 f_\nu$$

Hot neutrino velocities, i.e. free streaming neutrinos, suppress structure formation on large scales

$$\lambda_{FS}(m_\nu, z) \sim 8.1 \frac{H_0(1+z)}{H(z)} \left(\frac{1eV}{m_\nu}\right) h^{-1}\mathrm{Mpc}$$

$$k_{fs}(z) = 0.82 H(z)/H_0/(1+z)^2 (m_\nu/1\mathrm{eV}) \; h\mathrm{Mpc}^{-1}$$

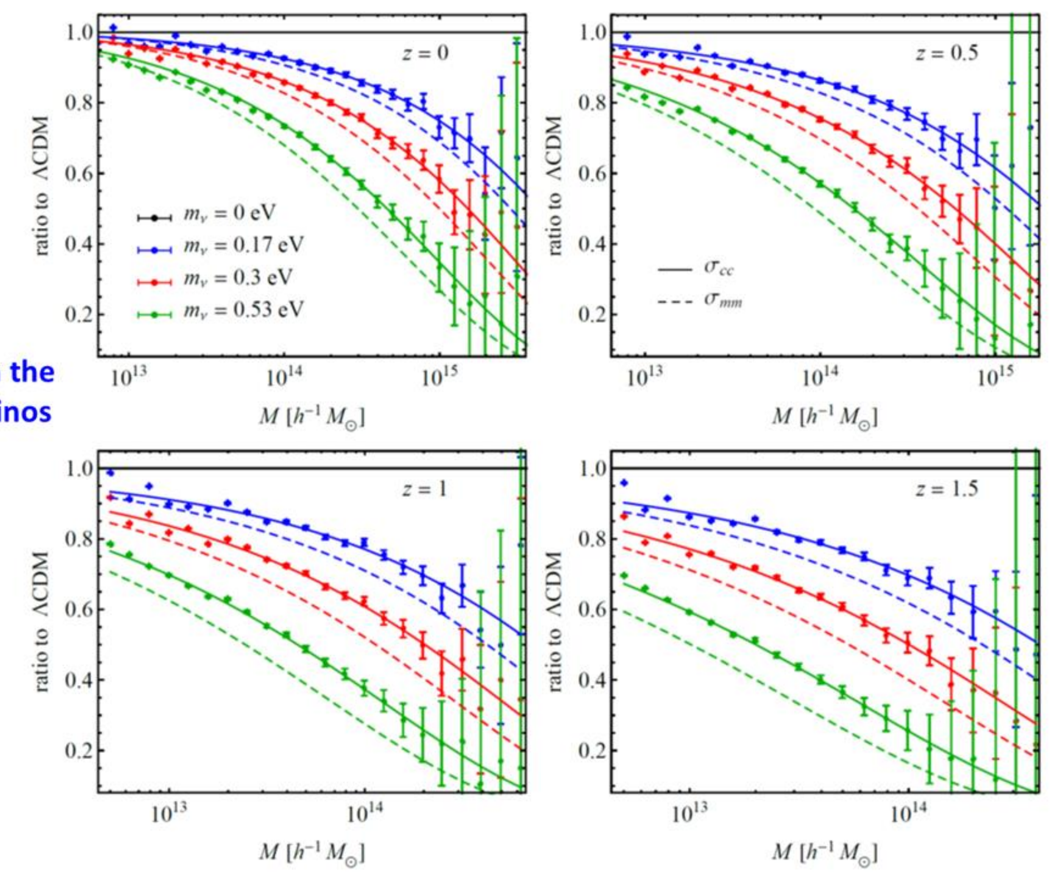
Improving non-linear modelling in the presence of massive neutrinos



Parimbelli, CC et al 2022

Halo Mass Function in the presence of massive neutrinos

Modification of the HMF in the presence of massive neutrinos

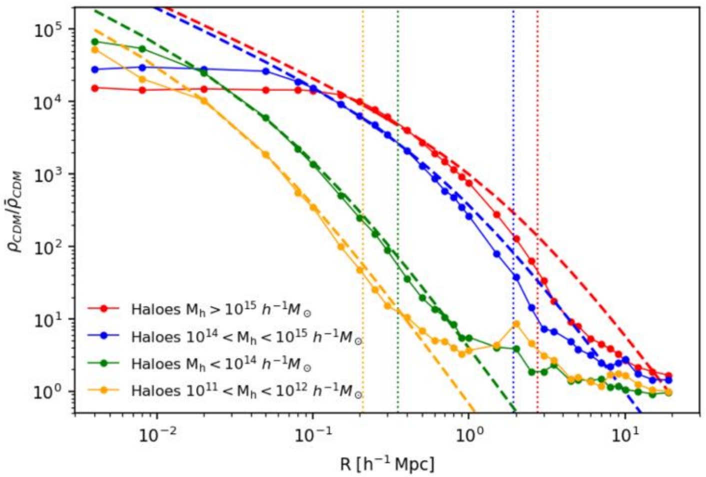


Castorina, CC et al 2015

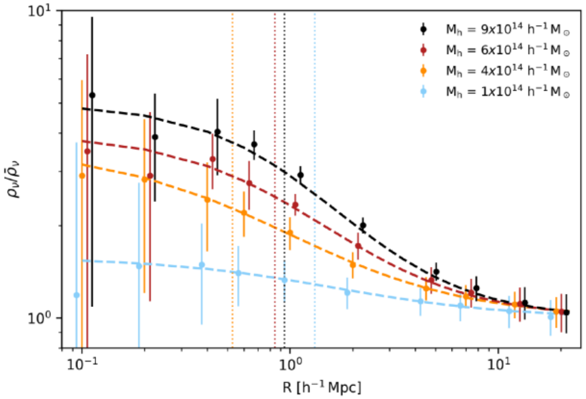
$$\bar{\rho} = \bar{\rho}_c \text{ and } \sigma = \sigma_{cc}$$

$$n(M) = \frac{\bar{\rho}_c}{M} f(\sigma, z) \frac{d \ln \sigma^{-1}}{dM} dM$$

Cold Dark Matter and Neutrinos halo profiles

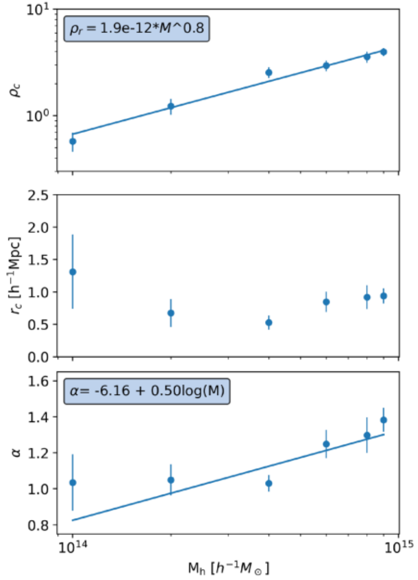


CDM overdensity profiles in haloes with masses M_h in different mass bins. Dashed lines correspond to a NFW density profile fit. Vertical dotted lines set the halo radii R_{200} defined by an overdensity threshold Δ = 200 with respect to the mean background total matter density



Mean neutrino overdensity profiles for $M_h > 10^{14}$ h−1M$_\odot$. The error bars correspond to 1σ dispersion around the calculated mean value of the overdensity at each radius. Fits to formula (dashed lines). Vertical dotted lines set the core radius (r_c parameter) obtained from the fit.

$$\delta_\nu(r) = \frac{\rho_c}{1 + (r/r_c)^\alpha}$$



Hernández-Molinero, CC et al 2024

3D-void size function: similarities and differences with the halo MF

The void size function

$$\frac{\mathrm{d}n}{\mathrm{d}\ln M} = \frac{\rho}{M} f^{v}_{\ln\sigma}(\sigma) \frac{\mathrm{d}\ln\sigma^{-1}}{\mathrm{d}\ln M}$$

The halo mass function

$$\frac{\mathrm{d}n}{\mathrm{d}\ln M} = \frac{\rho}{M} f^{H}_{\ln\sigma}(\sigma) \frac{\mathrm{d}\ln\sigma^{-1}}{\mathrm{d}\ln M}$$

$M \to r$

$$f^{v}_{\ln\sigma} = 2\sum_{j=1}^{\infty} e^{-\frac{j\pi x}{2}} j\pi x^{2} \sin(j\pi\mathcal{D})$$

$$x = \frac{\mathcal{D}}{|\delta_v|}\sigma$$

$\mathcal{D} = \frac{|\delta_v|}{\delta_c + |\delta_v|}$ = *void-and-cloud parameter*

$$\frac{\mathrm{d}n}{\mathrm{d}\ln r} = \frac{f^{v}_{\ln\sigma}(\sigma)}{V(r)} \frac{\mathrm{d}\ln\sigma^{-1}}{\mathrm{d}\ln r_L}\Bigg|_{r_L = r_L(r)}$$

$f^{v}_{\ln\sigma}$ is the fraction of fluctuations that become voids, i.e. probability that a fluctuation of scale R crosses δ_v, the void formation threshold, and have never crossed δ_c, the threshold for collapse, at any scale larger than R (top-hat model)

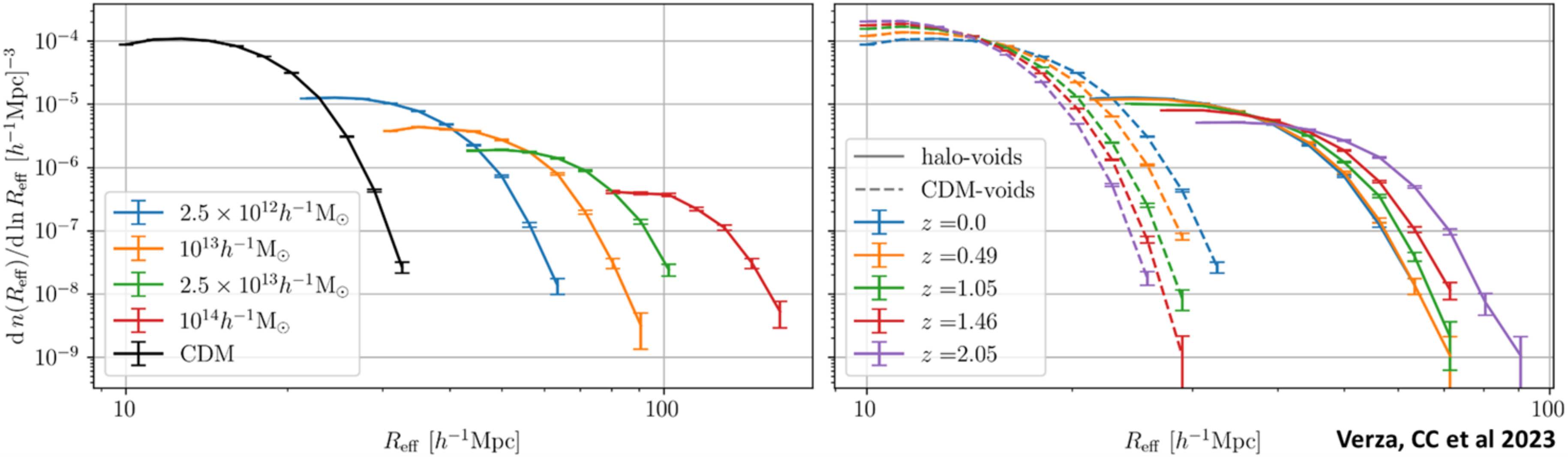
δ_v: ***void formation threshold***

δ_c: ***spherical collapse critical density***

Void size function in DEMNUni simulations: ΛCDM

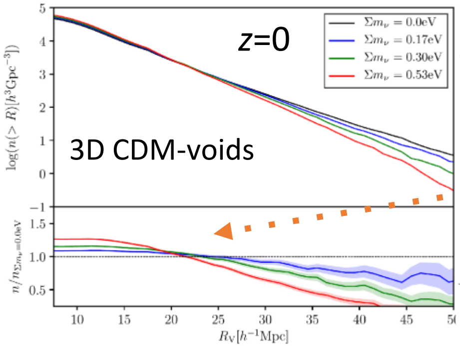
Mean particle separation in h^{-1}Mpc

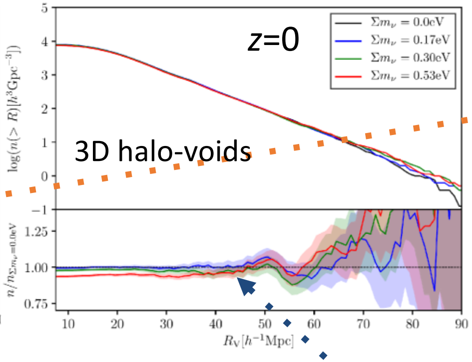
z	CDM	$M_{\min}$ $[h^{-1}M_\odot]$ 2.5×10^{12}	10^{13}	2.5×10^{13}	10^{14}
0	4.0	7.9	12.3	17.3	31.5
0.49	4.0	8.2	13.4	19.8	41.6
1.05	4.0	8.9	15.7	25.5	67.5
1.46	4.0	9.8	18.5	32.5	107.4
2.05	4.0	11.8	25.2	51.3	260.6



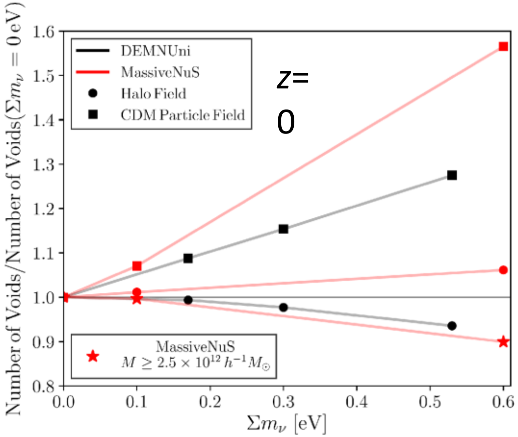
Verza, CC et al 2023

3D-void abundance in DEMNUni: comparison among M_ν cosmologies





In the presence of massive neutrinos, large CDM-voids become less abundant, and small CDM-voids more abundant than in LCDM.

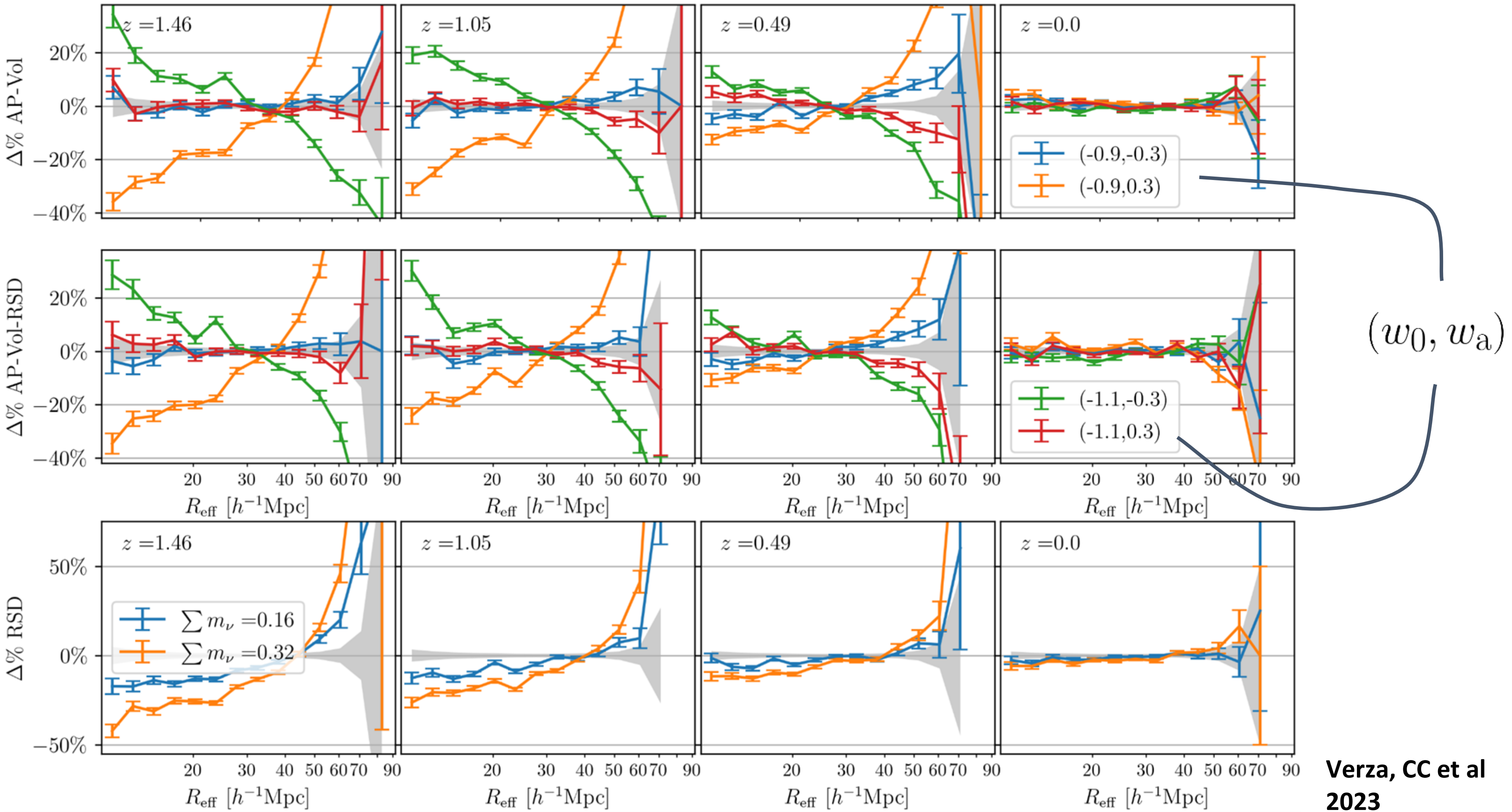


The opposite happens for voids traced by highly biased objects: combination of neutrino impact on HMF and VSF

Kreish et al. 2019

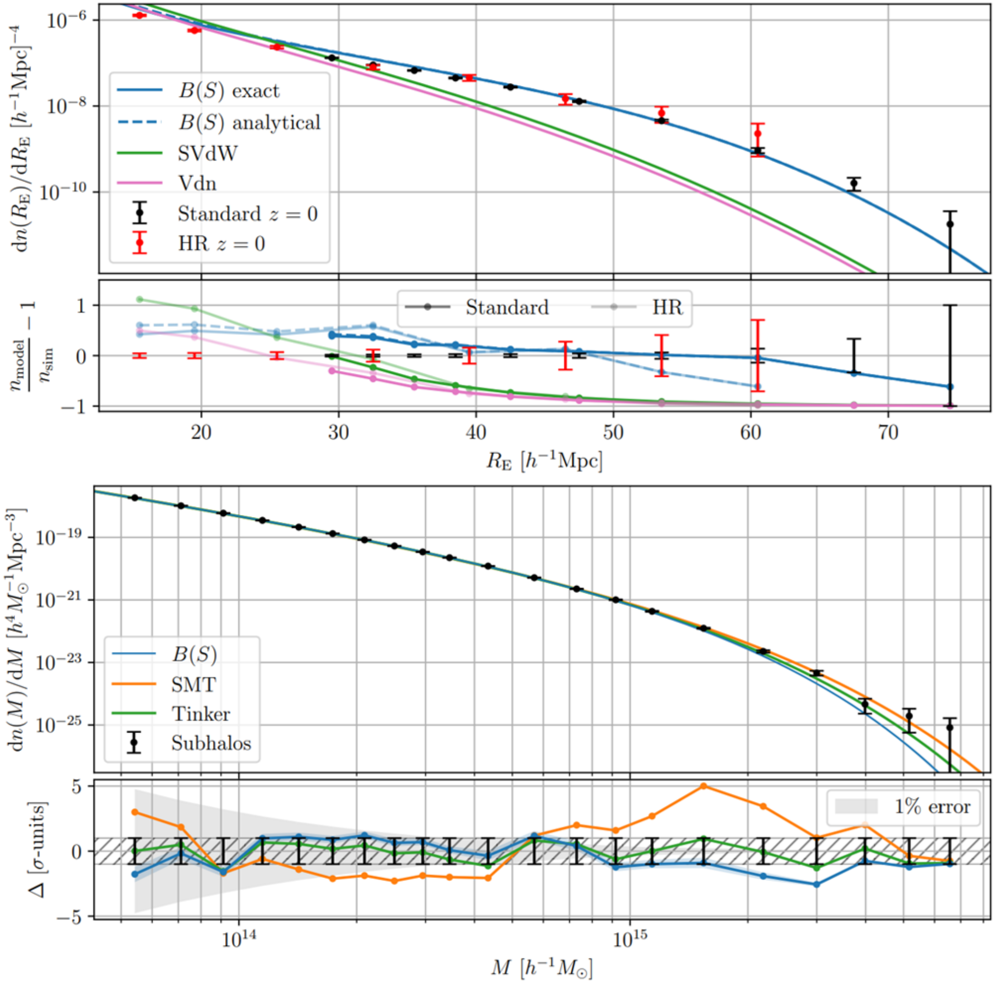
The total number of voids increases with M_ν for CDM-voids and decreases for voids traced by haloes with a high-mass threshold.

Void size function in DEMNUni simulations: sensitivity to DE & M_ν



Verza, CC et al 2023

A new universal multiplicity function: counting both halos and voids



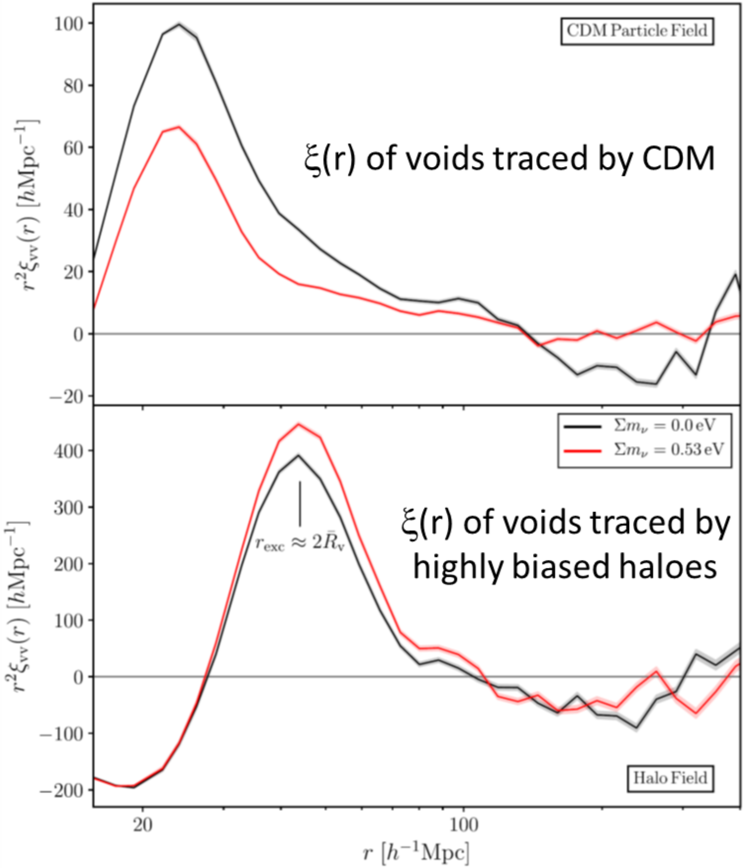
Verza, CC et al 2024

Void-void clustering in DEMNUni: M_ν & tracer bias

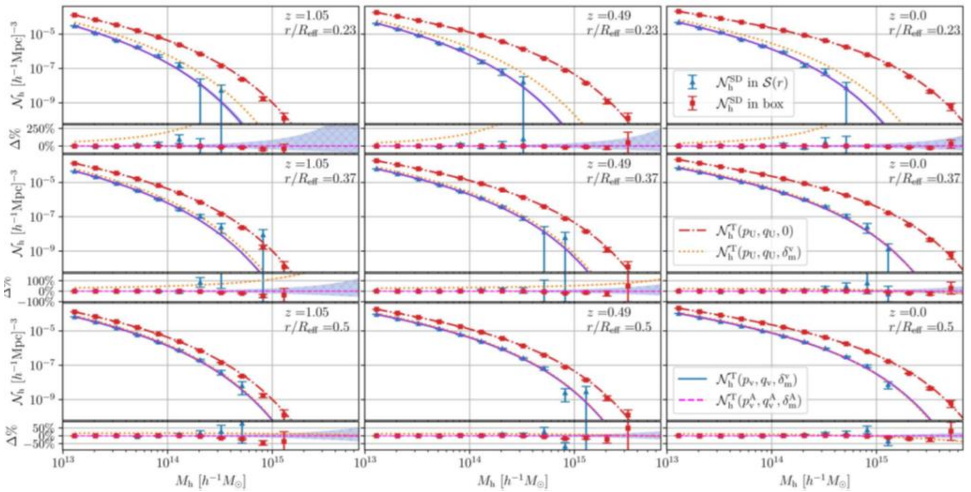
Increasing M_ν decreases void clustering for voids traced by CDM particles, and increases void clustering for voids traced by haloes with large bias

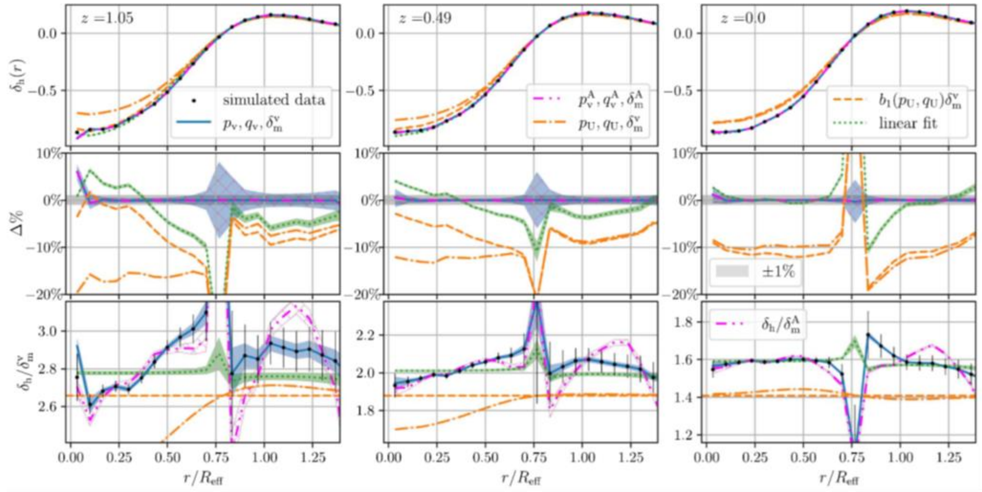
The clustering of particular void populations can be a sensitive probe to the neutrino mass

Kreish et al. 2019



The halo bias within cosmic voids: galaxies in voids evolve differently





$$\frac{\mathrm{d}n_{\mathrm{h}}}{\mathrm{d}M} = [1 + \delta_{\mathrm{lw}}(z)]\,\frac{\bar{\rho}_{\mathrm{m}}}{M} f\,[\tilde{\nu}(z),\, p,\, q]\,\frac{\mathrm{d}\tilde{\nu}(z)}{\mathrm{d}M}. \qquad (4)$$

This quantity is evaluated under the substitutions $\delta_c \rightarrow \delta_c - \delta_{\mathrm{lw}}^{\mathrm{L}}$, $\nu \rightarrow \tilde{\nu} = [\delta_{\mathrm{sc}}(z) - \delta_{\mathrm{lw}}^{\mathrm{L}} D(z=0)/D(z)]/\sigma(M)$, and $\bar{\rho}_{\mathrm{m}} \rightarrow \bar{\rho}_{\mathrm{m}}[1 + \delta_{\mathrm{lw}}(z)]$ in Equation (2). Equation (4) represents the conditional HMF in the limit where the short-wavelength modes forming halos can be considered independent of long-wavelength modes (Sheth & Tormen 1999).

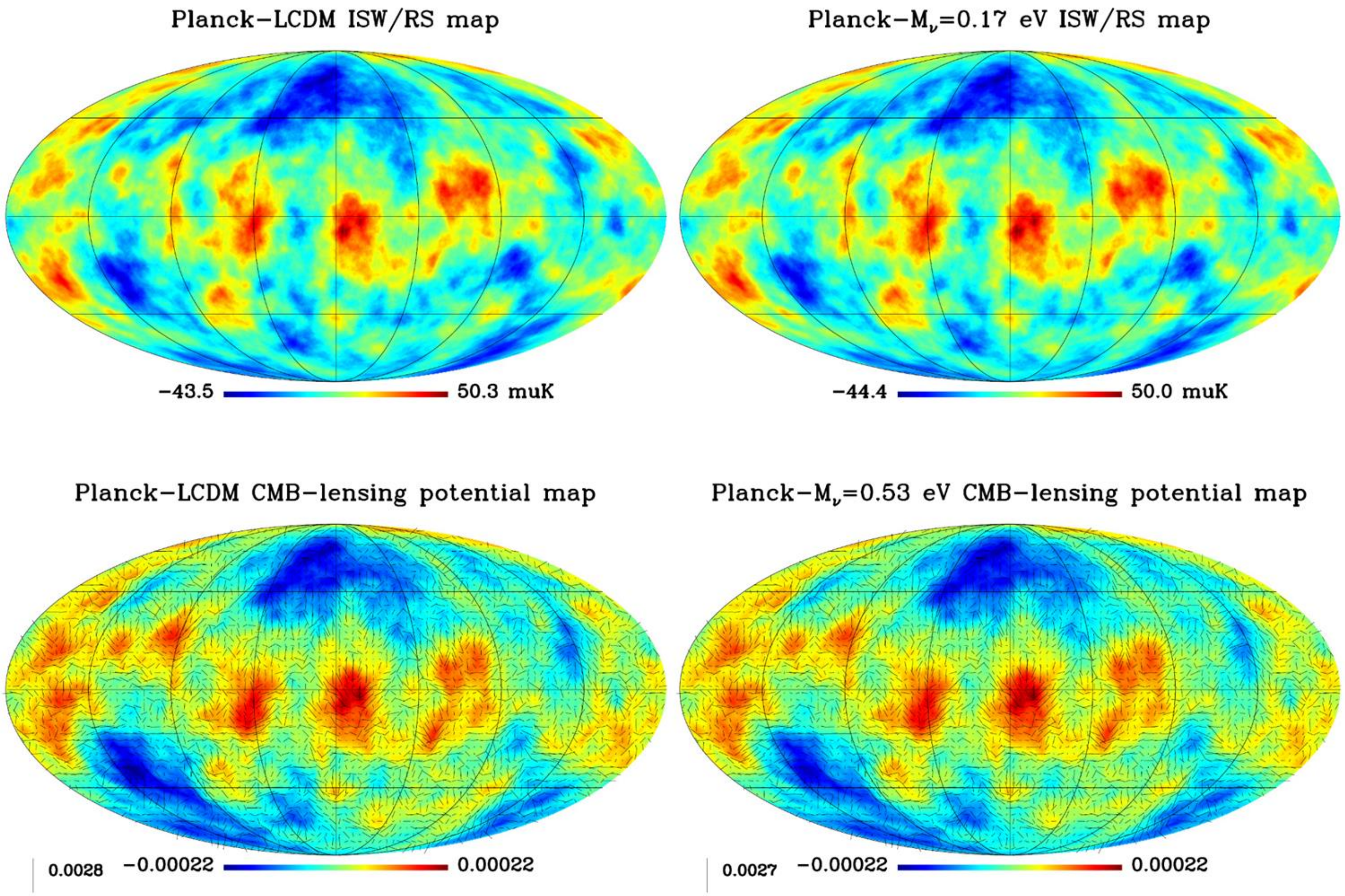
$$\frac{\mathrm{d}n_{\mathrm{h}}}{\mathrm{d}M}(\tilde{\nu},\, p_{\mathrm{v}},\, q_{\mathrm{v}},\, \delta_{\mathrm{m}}^{\mathrm{v}}) = \sqrt{\frac{2}{\pi}}\,\frac{\bar{\rho}_{\mathrm{m}}}{M}(1 + \delta_{\mathrm{m}}^{\mathrm{v}}) \times \left\{ A_{\mathrm{v}}[1 + (q_{\mathrm{v}}\tilde{\nu}^2)^{-p_{\mathrm{v}}}]\,\sqrt{q_{\mathrm{v}}}\,e^{-q_{\mathrm{v}}\tilde{\nu}^2/2}\,\frac{\mathrm{d}\tilde{\nu}}{\mathrm{d}M} \right\} \qquad (6)$$

where $A_{\mathrm{v}} = [1 + \Gamma(1/2 - p_{\mathrm{v}})/(2^{p_{\mathrm{v}}}\sqrt{\pi})]^{-1}$. Here $p_{\mathrm{v}}(r, z)$ and $q_{\mathrm{v}}(r, z)$ effectively account for a possible correlation between the halo and void fields.

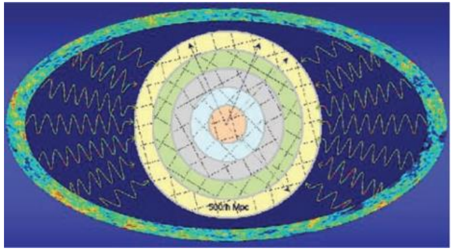
$$\delta_{\mathrm{h}}(r) = \frac{\int_{M_{\mathrm{min}}}^{\infty} \frac{\mathrm{d}n_{\mathrm{h}}}{\mathrm{d}M}[\tilde{\nu},\, p_{\mathrm{v}}(r),\, q_{\mathrm{v}}(r),\, \delta_{\mathrm{m}}^{\mathrm{v}}(r)]\mathrm{d}M}{\int_{M_{\mathrm{min}}}^{\infty} \frac{\mathrm{d}n_{\mathrm{h}}}{\mathrm{d}M}(\nu,\, p_{\mathrm{U}},\, q_{\mathrm{U}},\, 0)\mathrm{d}M} - 1$$

Verza, CC et al ApJL 2022

Weak-Lensing and Integrated Sachs-Wolfe/Rees-Sciama maps



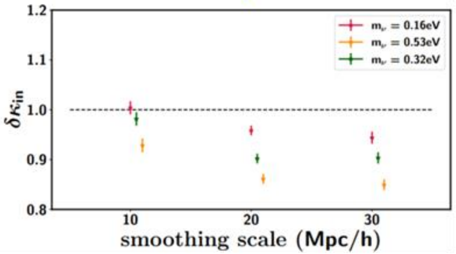
Box stacking technique



CC et al 2016

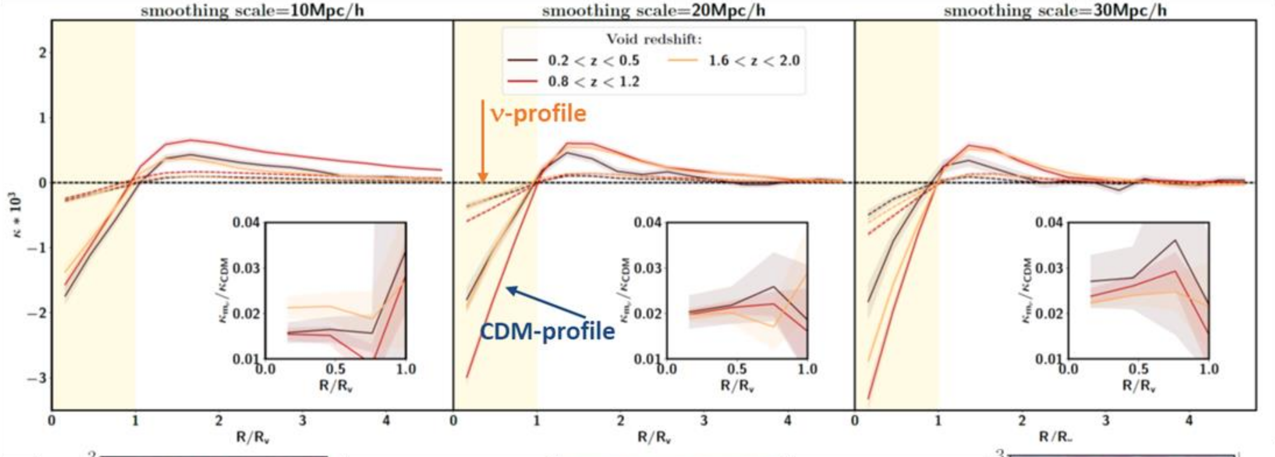
CMB-lensing void profiles in DEMNUni: the M_ν imprint

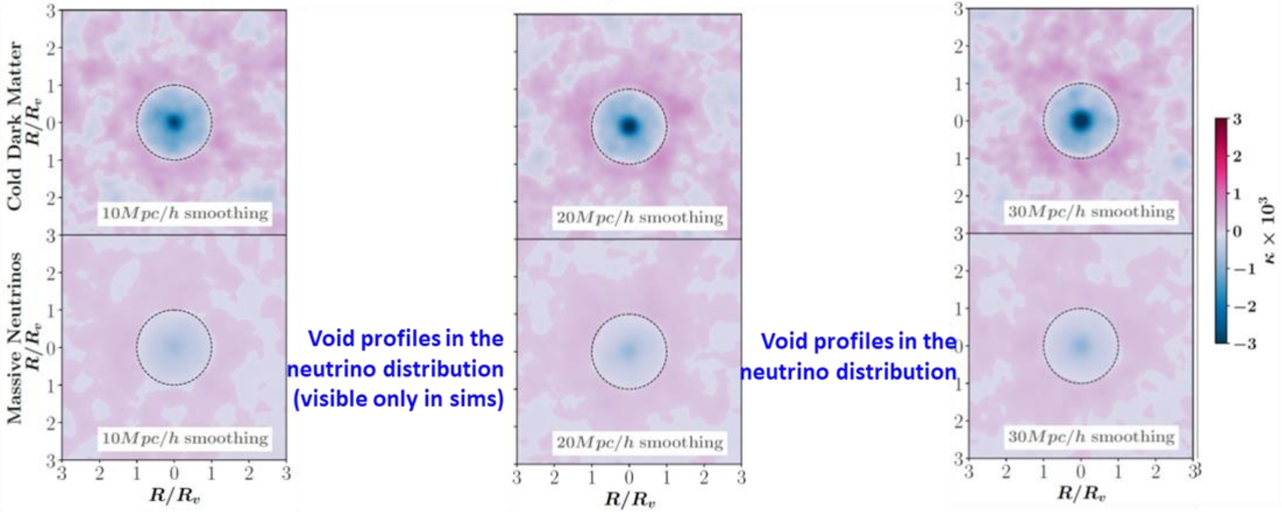
Larger void profiles become shallower with decreasing redshift: neutrinos suppress structure formation



$$\delta\kappa_{in} = \frac{\sum_0^{r<R_v/2} \kappa_{m_\nu=0.16\text{eV},0.32\text{eV},0.53\text{eV}}}{\sum_0^{r<R_v/2} \kappa_{\Lambda\text{CDM}}}$$

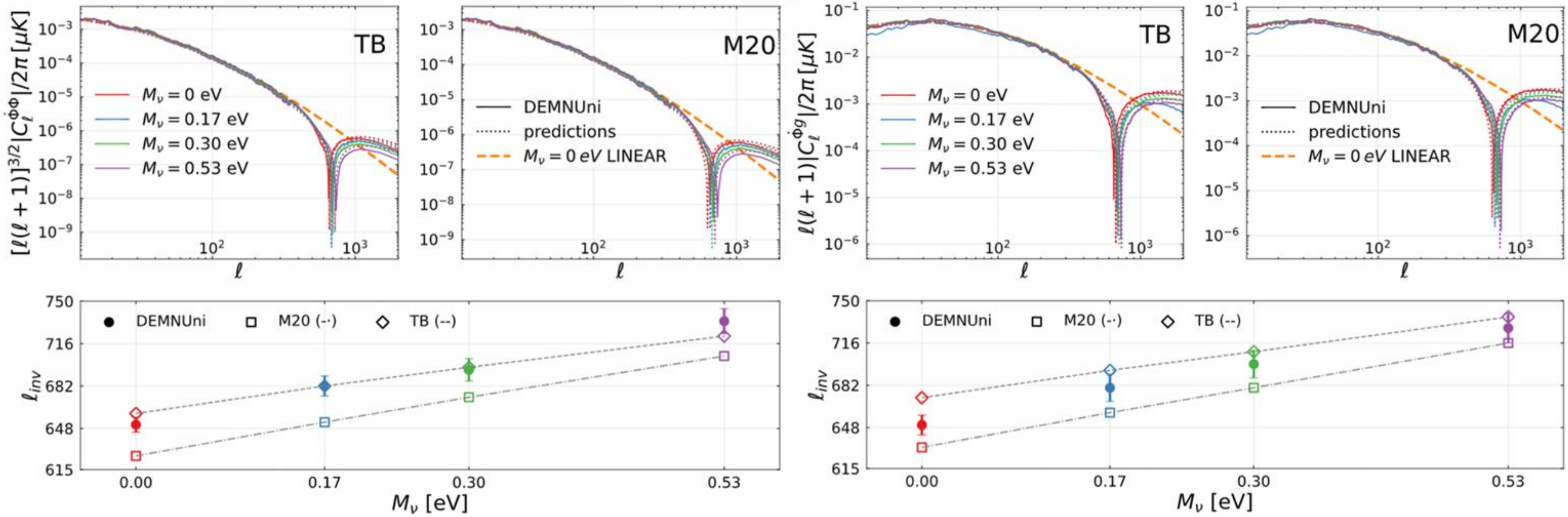
Vielzeuf et al. 2023





ISWRS cross galaxies and CMB-Lensing in M_ν cosmologies

Cuozzo, CC et al. 2024



Thanks to simulations we found the M_ν-dependency of the sign-inversion of the ISWRSxLSS spectra

DEMNUni main scientific results

- First measurements of ISW-RS in the presence of M_ν and dynamical DE
- Improved modelling of matter power spectrum in the presence of M_ν
- First measurement and modelling of matter bispectrum in the presence of M_ν
- Testing matter nonlinear models/emulators against Nbody measurement in the presence of M_ν and dynamical DE
- Improving matter and velocity modelling in the presence of M_ν and dynamical DE
- First measurements of void profiles from the void-CMB_lensing cross correlation in the presence of M_ν and dynamical DE
- First measurements of the cosmic void correlation and void size function in the presence of M_ν and dynamical DE
- Improved modelling of galaxy bias within cosmic voids
- Improved modelling of ISWRS X GC/CMB-L in the presence of massive neutrinos
- Improved multiplicity function for halos and voids
- Improved cosmic neutrino background capture rates

DEMNUni published papers

1. **“Cosmological inference including massive neutrinos from the matter power spectrum: biases induced by uncertainties in the covariance matrix”,** S. Gouyou Beauchamps, P. Baratta, S. Escoffier, W. Gillard, J. Bel, J. Bautista, C. Carbone, arXiv:2306.05988
2. **“COVMOS: a new Monte Carlo approach for galaxy clustering analysis”,** Philippe Baratta, Julien Bel, Sylvain Gouyou Beauchamps, Carmelita Carbone, A&A 673, A1 (2023)
3. “**The effects of massive neutrinos on the linear point of the correlation function**”, G. Parimbelli, S. Anselmi, M. Viel, C. Carbone, F. Villaescusa-Navarro, P. S. Corasaniti, Y. Rasera, R. Sheth, G. D. Starkman, I. Zehavi, JCAP01(2021)009
4. **“DEMNUni: The imprint of massive neutrinos on the cross-correlation between cosmic voids and CMB lensing”,** Pauline Vielzeuf, Matteo Calabrese, Carmelita Carbone, Giulio Fabbian, Carlo Baccigalupi, arXiv:2303.10048
5. **“Cosmic Background Neutrinos Deflected by Gravity: DEMNUni Simulation Analysis”,** Beatriz Hernández-Molinero, Carmelita Carbone, Raul Jimenez, Carlos Peña Garay, arXiv:2301.12430
6. “**Modelling the next-to-leading order matter three-point correlation function using FFTLog**”, M.Guidi, A. Veropalumbo, E. Branchini, A. Eggemeier, C. Carbone, arXiv:2212.07382
7. **“DEMNUni: disentangling dark energy from massive neutrinos with the void size function”,** Giovanni Verza, Carmelita Carbone, Alice Pisani, Alessandro Renzi, arXiv:2212.09740
8. **“DEMNUni: comparing nonlinear power spectra prescriptions in the presence of massive neutrinos and dynamical dark energy”,** G. Parimbelli, C. Carbone, J. Bel, B. Bose, M. Calabrese, E. Carella, M. Zennaro, JCAP11(2022)041
9. “**The halo bias inside cosmic voids**”, Giovanni Verza, Carmelita Carbone, Alessandro Renzi, ApJL 940 L16 (2022)
10. **“The Void Size Function in Dynamical Dark Energy Cosmologies”,** Giovanni Verza, Alice Pisani, Carmelita Carbone, Nico Hamaus, Luigi Guzzo, JCAP12(2019)040
11. **“DEMNUni: cross-correlating the nonlinear ISWRS effect with CMB-lensing and galaxies in the presence of massive neutrinos”,** Viviana Cuozzo, Carmelita Carbone, Matteo Calabrese, Elisabetta Carella, Marina Migliaccio, JCAP04(2024)073
12. “**The bias of cosmic voids in the presence of massive neutrinos**”, Nico Schuster, Nico Hamaus, Alice Pisani, Carmelita Carbone, Christina D. Kreisch, Giorgia Pollina, Jochen Weller, JCAP12(2019)055
13. “**Massive Neutrinos Leave Fingerprints on Cosmic Voids**”, Christina D. Kreisch, Alice Pisani, Carmelita Carbone, Jia Liu, Adam J. Hawken, Elena Massara, David N. Spergel, Benjamin D. Wandelt, *MNRAS*, 488, 4413 (2019)
14. “**Accurate fitting functions for peculiar velocity spectra in standard and massive-neutrino cosmologies**”, Julien Bel, Andrea Pezzotta, Carmelita Carbone, Emiliano Sefusatti, Luigi Guzzo, A&A 622, 8
15. “**DEMNUni: Massive neutrinos and the bispectrum of large scale structures**”, Rossana Ruggeri, Emanuele Castorina, Carmelita Carbone, Emiliano Sefusatti, JCAP03(2018)003
16. “**CMB weak-lensing beyond the Born approximation: a numerical approach**”, Giulio Fabbian, Matteo Calabrese, Carmelita Carbone, JCAP02(2018)050
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24. more coming soon…