"The Dark Energy and Massive Neutrino Universe" cosmological simulations

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DEMNUni simulation sets: size and resolution

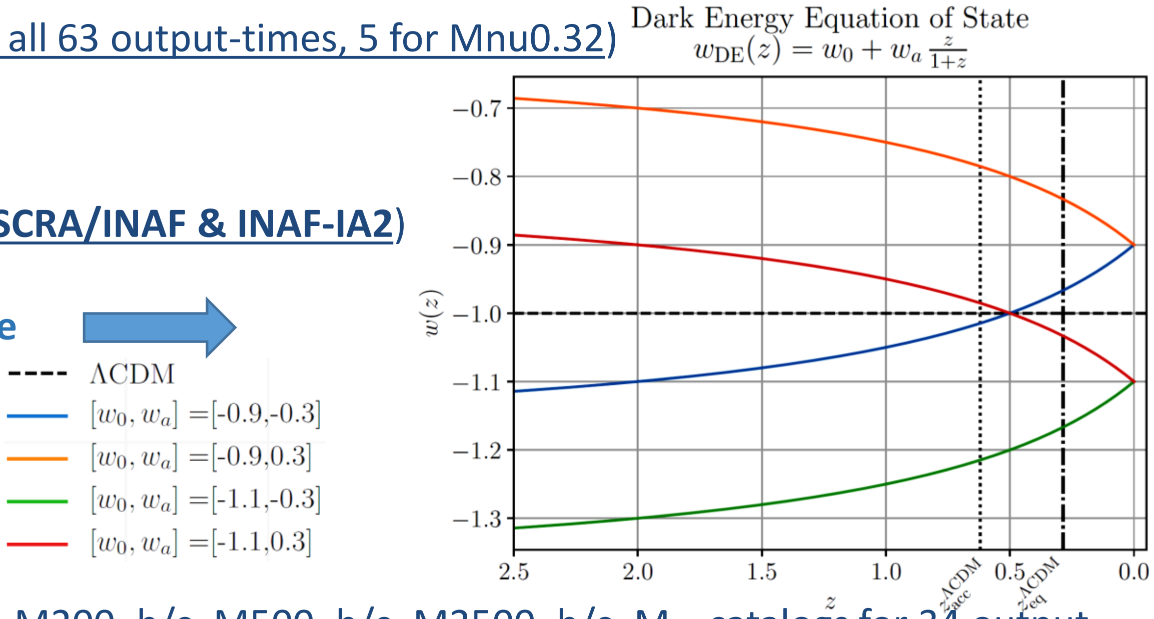
(Carmelita Carbone & about 30 collaborators)

➢ **16 DEMNUni XL-simulations:**
V=(2 Gpc/h)^3, N_{part}= 2 x 2048^3 (CDM+ν), M_{cdm}≅ 8 x 10^{10} M_{sun}

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 @CINECA ISCRA/INAF & INAF-IA2**)

Implemented Dark Energy Equation of State



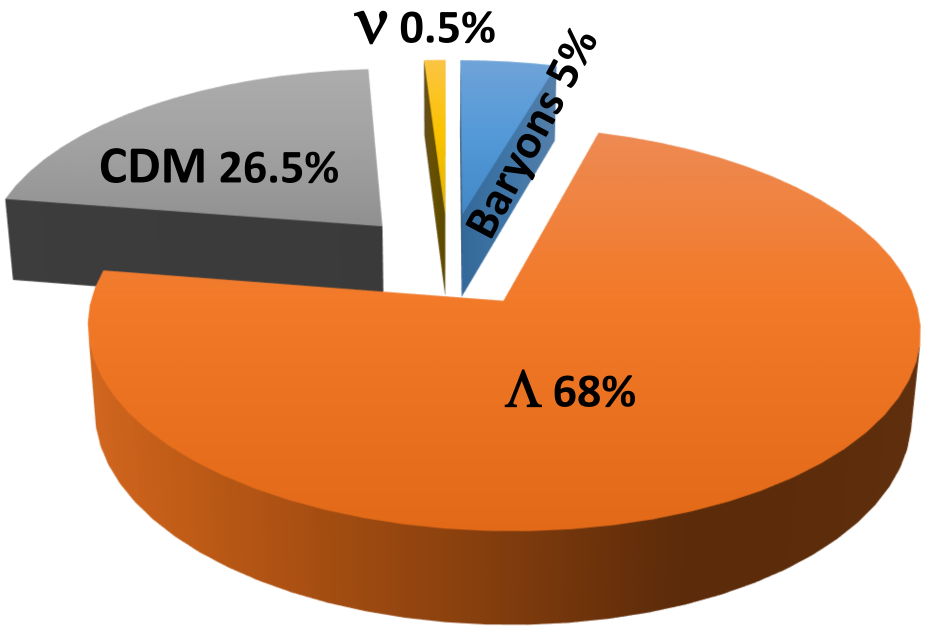
➢ **50+50 DEMNUni L-simulations (DEMNUni-Cov):**
V=(1 Gpc/h)^3, N_{part}= 2 x 1024^3 (CDM+ν), M_{cdm}≅ 8 x 10^{10} M_{sun}

- **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 @INFN-CNAF**)
- **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 @INAF-IA2**)

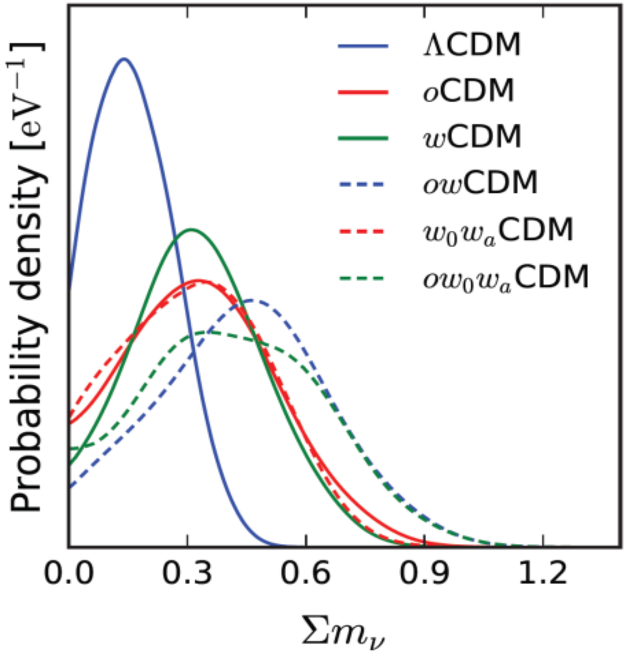
➢ **DEMNUni M-simulations (DEMNUni-HigRes): V=(500 Mpc/h)^3, N_{part}= 2 x 2048^3 (CDM+ν), M_{cdm}≅ 1.3 x 10^9 M_{sun}**
- **15 sims Planck-LCDM; Mnu+(w_0,w_a):** ongoing (resolution enough for Euclid Halpha galaxies)

Neutrino mass & cosmology

Large Scale Structure (LSS) allows us to get constraints on the absolute neutrino mass.



Pellejero-Ibanez et al 2016



<u>Degeneracy</u> with other cosmological parameters as DE parameters: measurements of the 2-point galaxy correlation function provide some information on neutrino mass, but *<u>non-linear modelling</u>* is needed to improve constraints and break degeneracies.

Gadget-III with massive neutrinos

- **Hybrid tree-PM method**: long-range force calculated at low resolution with a particle-mesh scheme, assigning the particles to a regular cubic mesh, using Fourier methods to obtain the corresponding potential, and by numerically differencing the result.
High resolution short-range correction calculated using a tree algorithm. The short-range correction is assembled in real space by collecting contributions from all neighbouring particles.

- **Space-filling fractal**: the Peano-Hilbert curve, to control the domain decomposition associated with parallelisation. The tree decomposition used by the code is independent of the platform, in particular of the number of processors on which it is run.

- **Particle-based M_ν**: Massive neutrinos are incorporated as a separate low-mass collisionless particle species. Neutrino species has significant thermal dispersion, preventing it from clustering on small scales. This allows to avoid following the small-scale evolution of the neutrino component, by ignoring the short-range tree force for the neutrinos and by setting the timestep purely for the dark matter species, effectively relaxing the Courant conditions for the neutrino component. <u>These approximations significantly speed up computation while having a negligible impact on results</u>.

Matteo Viel, Martin G. Haehnelt, Volker Springel 2010

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 applications to Euclid

- KP-CL-3 pre-launch paper-4 “*Halo mass function and bias in non-standard models*” of the Galaxy-Clusters SWG.
- KP-CL-3 pre-launch paper-1 “*Calibration of the halo mass function in $\Lambda(\nu)$ cosmologies*” Castro et al. A&A 671, A100 (2023)
- KP-CMBX-2 pre-launch paper2 “*CMBX Mock Simulations*” in CMBX SWG.
- KP-JC-6 pre-launch paper-3 “*Simulations & non-linearities beyond ΛCDM*” joint Theory and Cosmo-SIM SWGs.
- KP-TH-1 pre-launch paper-6 “*Euclid: Nonlinear spectroscopic clustering in beyond-ΛCDM scenarios with Euclid*”, Theory SWG.
- CMBX-covariances: calibration of FLASK lognormal mocks against DEMNUni-CoV mocks
- Priority models in CoS-SWG WP8: Non-standard models

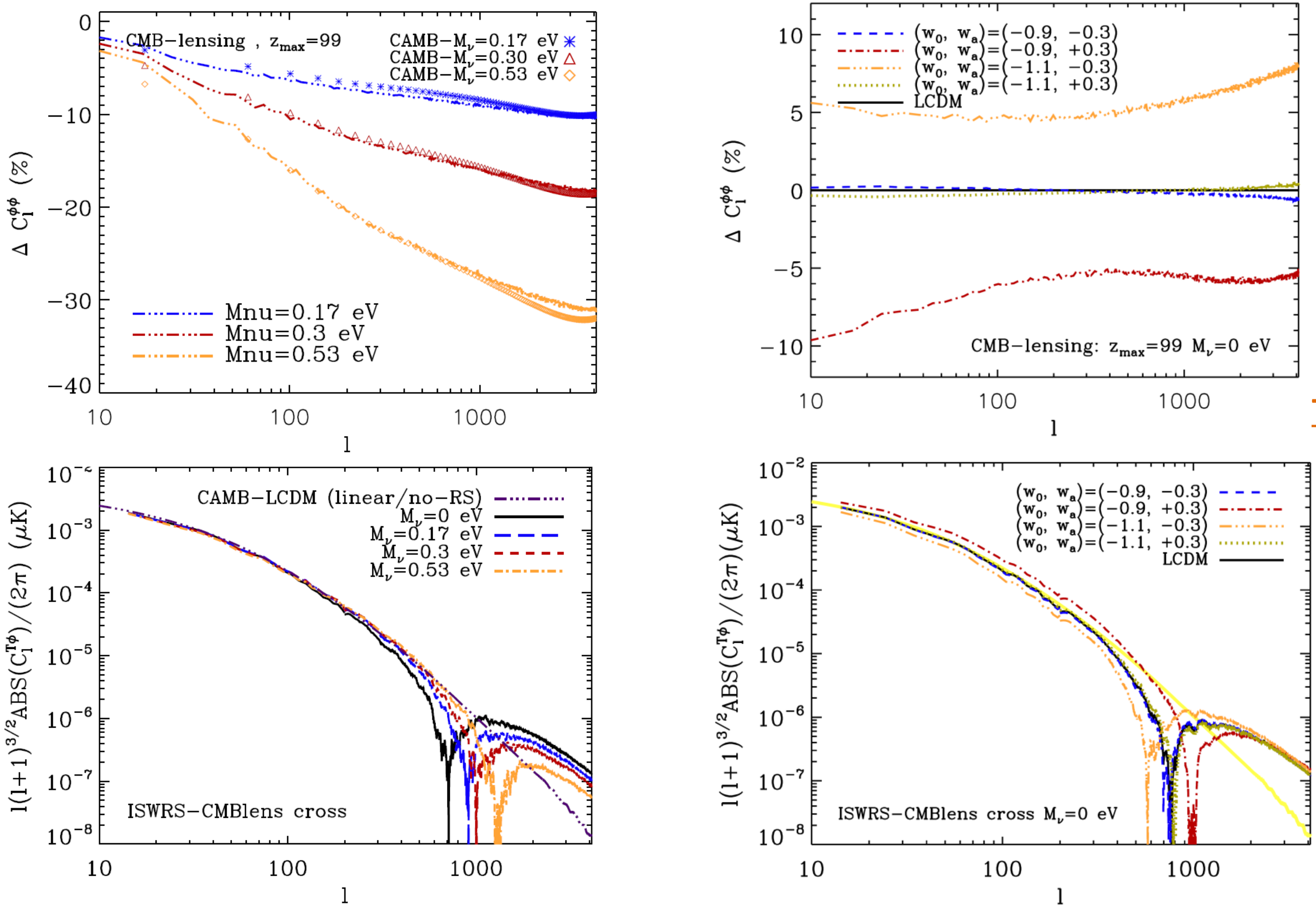
DEMNUni papers

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
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
17. **“Cosmological constraints from galaxy clustering in the presence of massive neutrinos”,** Matteo Zennaro, Julien Bel, Jason Dossett, Carmelita Carbone, Luigi Guzzo, MNRAS, Volume 477, 491 (2018)
18. **“The VIMOS Public Extragalactic Redshift Survey (VIPERS). Exploring the dependence of the three-point correlation function on stellar mass and luminosity at 0.5<z<1.1”,** Moresco et al, A&A 604, A133 (2017)
19. “**DEMNUni: ISW, Rees-Sciama, and weak-lensing in the presence of massive neutrinos**” Carmelita Carbone, Margarita Petkova, Klaus Dolag, JCAP07(2016)034
20. “**The effect of massive neutrinos on the Sunyaev-Zeldovich and X-ray observables of galaxy clusters**”, Roncarelli, Carbone, Moscardini, MNRAS, 447, 1761
21. “**DEMNUni: The clustering of large-scale structures in the presence of massive neutrinos**”, Emanuele Castorina, Carmelita Carbone, Julien Bel, Emiliano Sefusatti, Klaus Dolag, JCAP07(2015)043
22. **More in prep….**

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

CMB-lensing & ISWRS from DEMNUni: (M_ν & DE)



CC et al. 2016

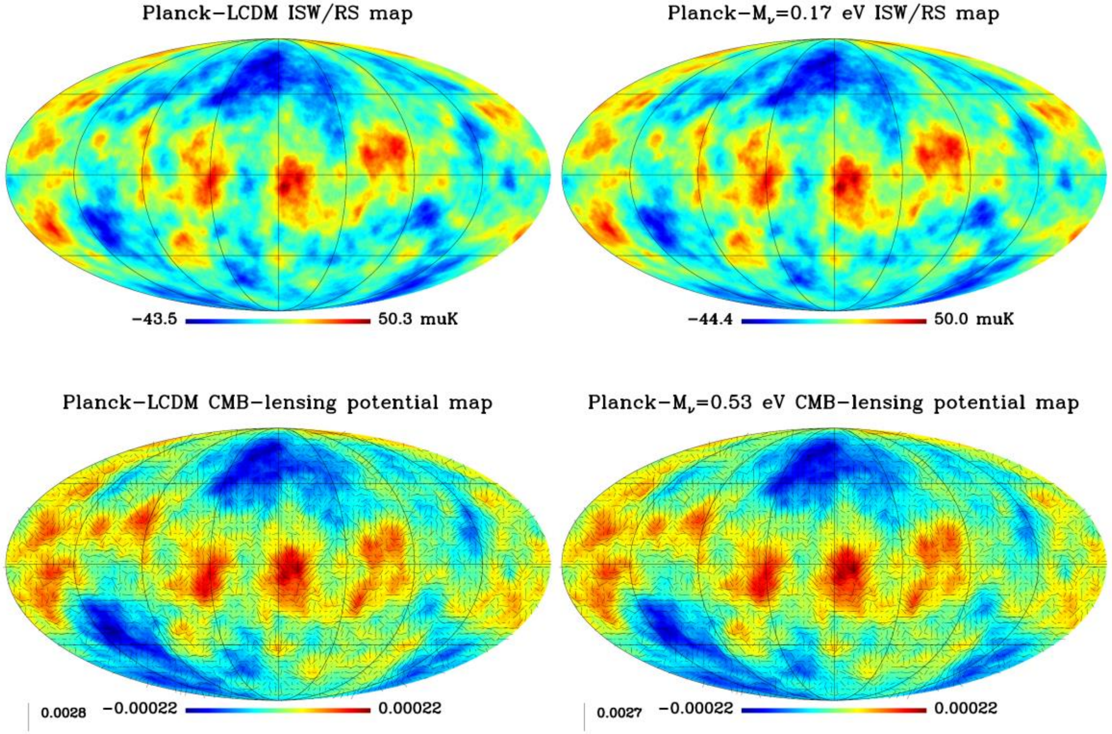
Thanks to the big volume of DEMNUni!!

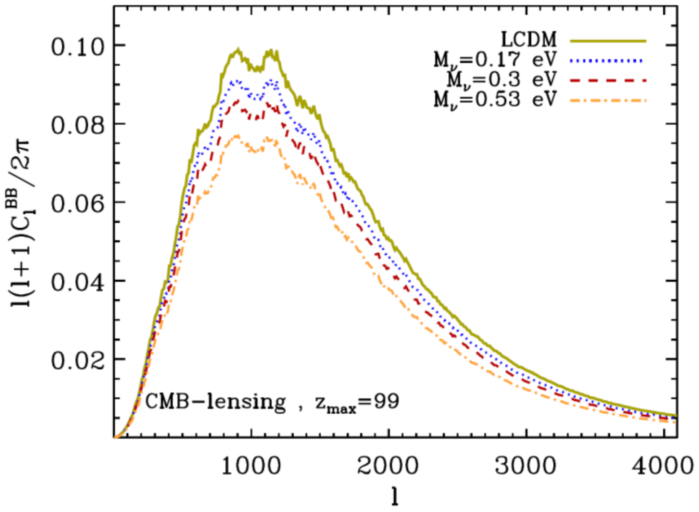
CMB-lensing potential: $\phi(\hat{\mathbf{n}}) \equiv -2\int_0^{r_{\rm LS}} \frac{r_{\rm LS}-r}{r_{\rm LS}\,r}\,\frac{\Phi(r\hat{\mathbf{n}};c\eta_0-r)}{c^2}\,\mathrm{d}r$

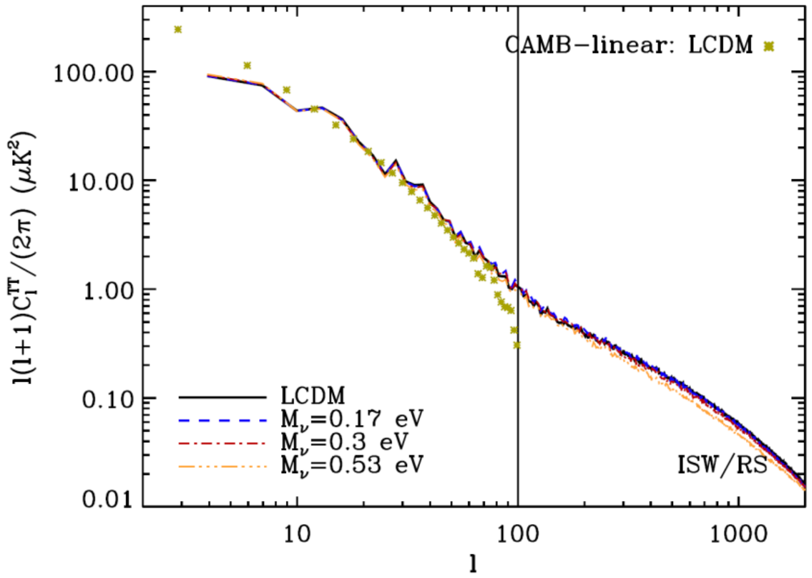
ISW-Rees/Sciama temperature: $\Delta T(\hat{\mathbf{n}}) = \frac{2}{c^3}\bar{T}_0\int_0^{r_{\rm LS}} \dot{\Phi}(r\hat{\mathbf{n}})\,a\,dr$

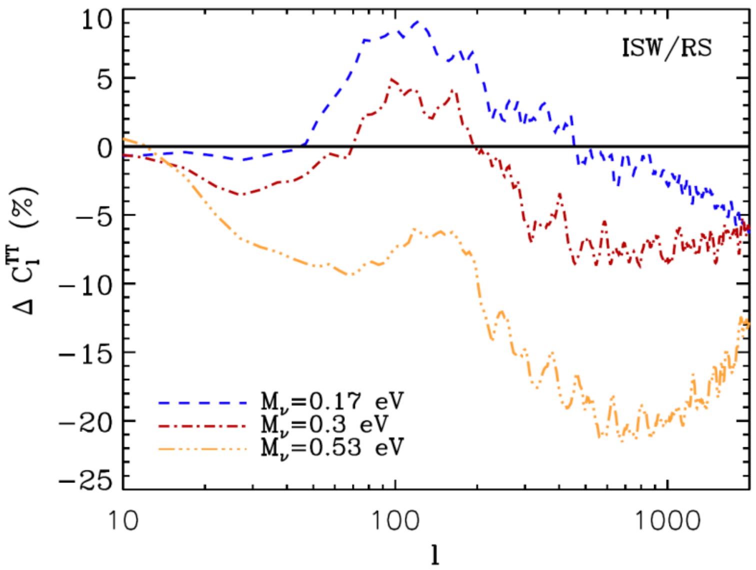
CMB-lensing & ISWRS from DEMNUni: M_ν effects

CC et al. 2016

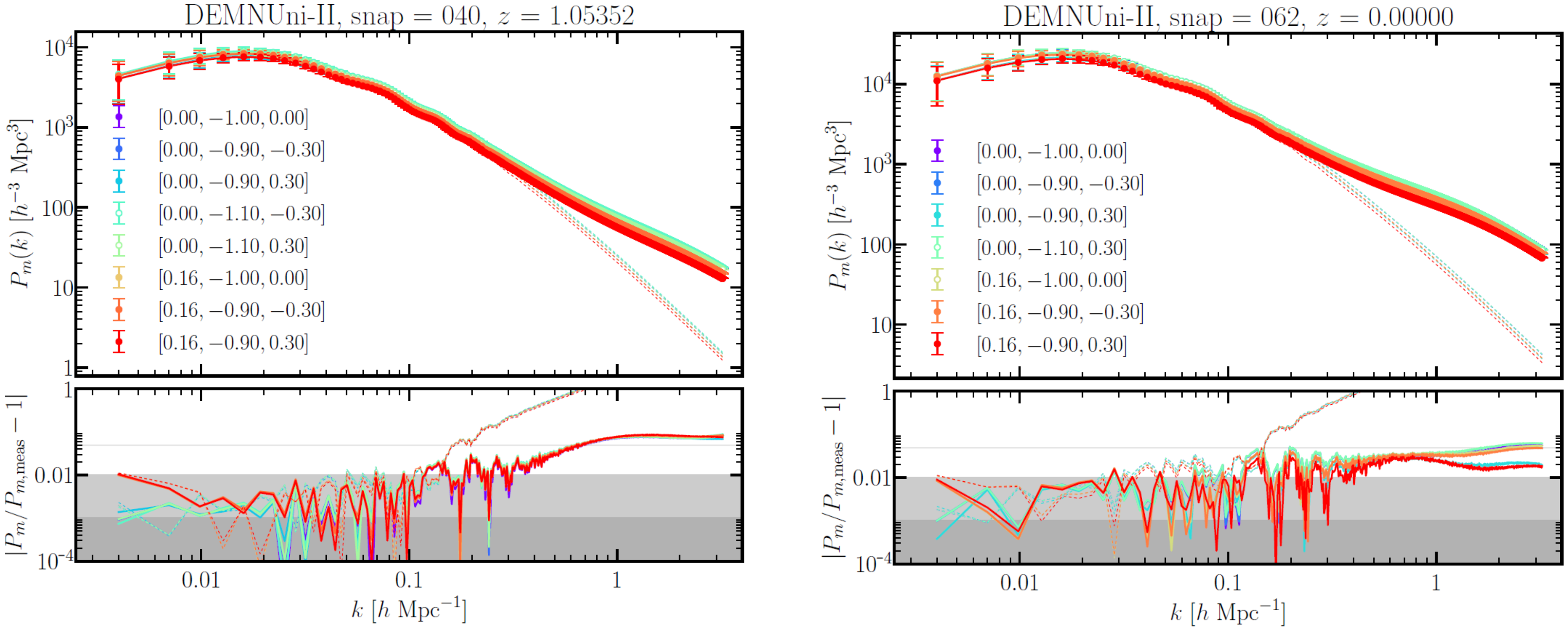








Non linear Pk (M_ν+DE): minimal modifications to Halofit



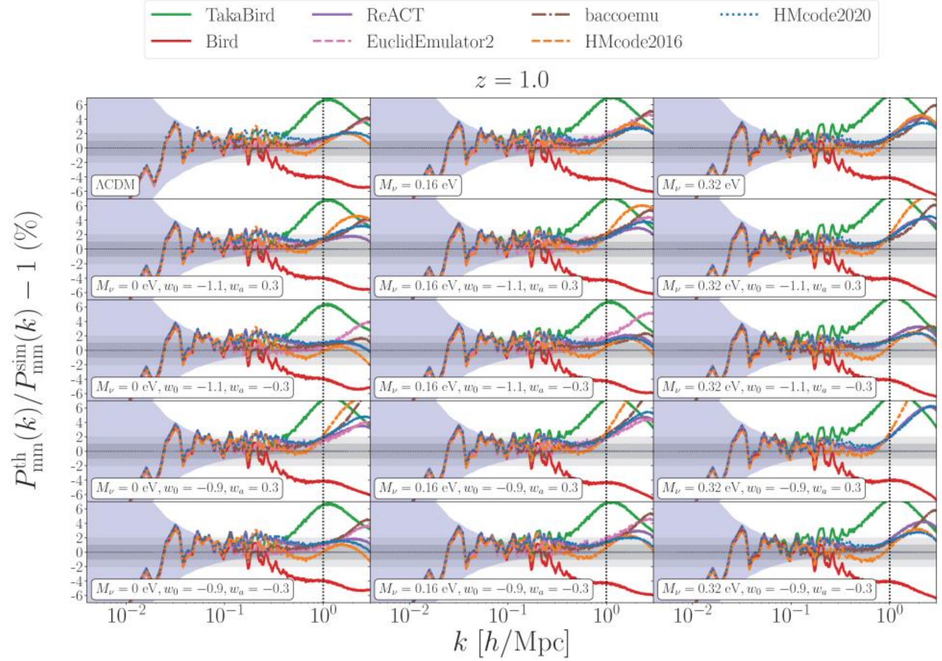
$$P^{HF}_{mm}(k) \equiv (1-f_\nu)^2\, P^{HF}_{cc}(k) + 2\, f_\nu\, (1-f_\nu)\, P^{L}_{c\nu}(k) + f_\nu^2\;P^{L}_{\nu\nu}(k) \qquad P^{HF}_{cc}(k) \,=\, \mathcal{F}_{HF}[P^{L}_{cc}(k)]$$

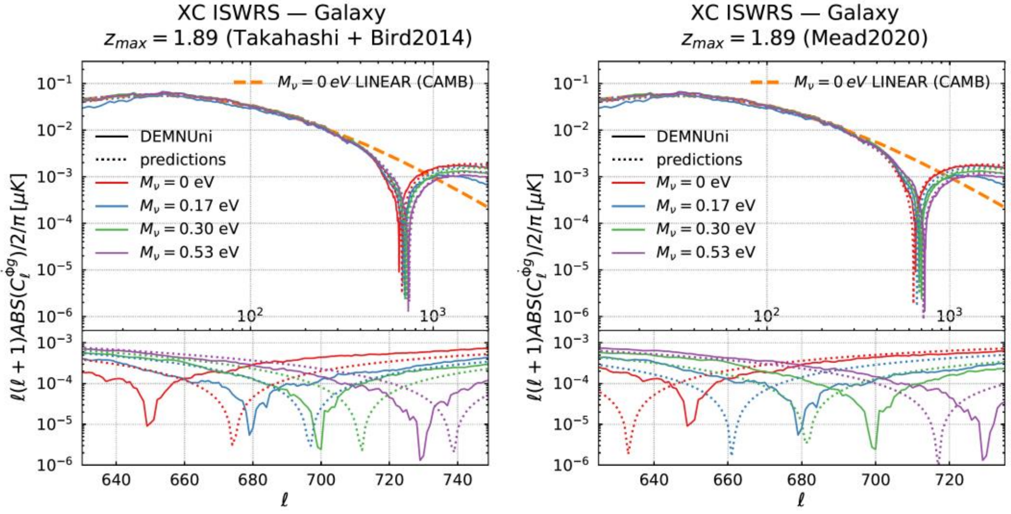
Castorina, CC et al 2015

HALOFIT mapping only for CDM, other contributions are assumed to be linear.
Shaded areas denote regions beyond the accurracy expected from Halofit.

Improving non-linear modelling

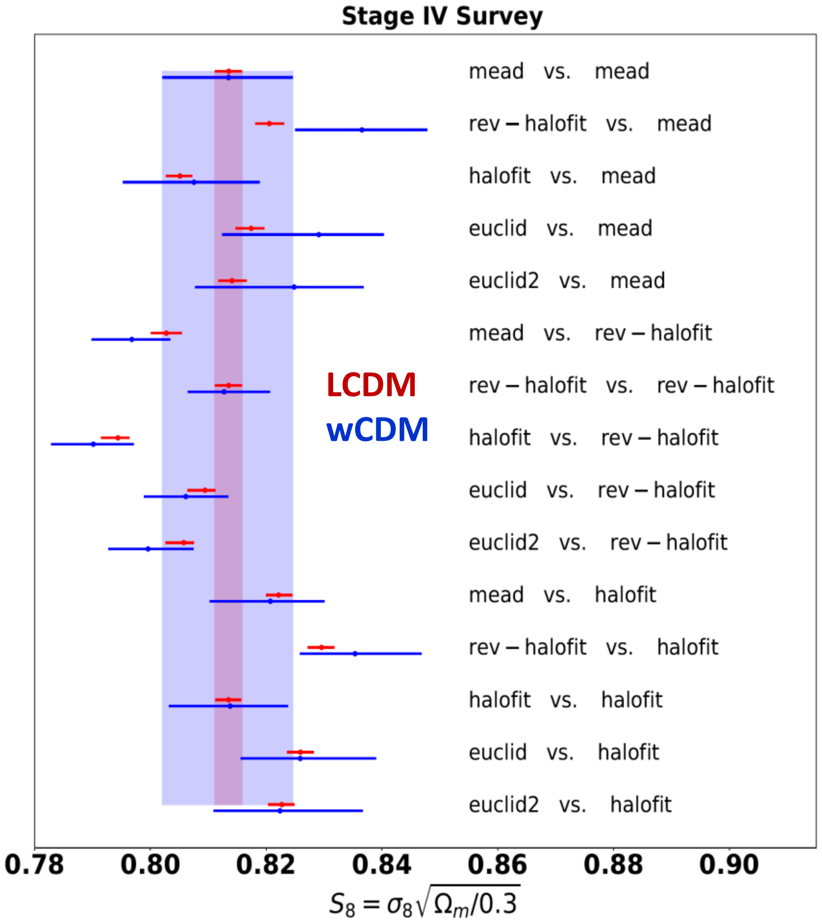
Parimbelli, CC et al 2022





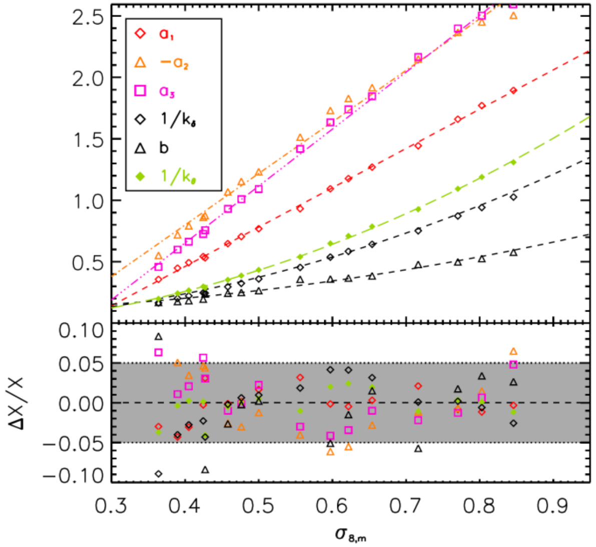
Cuozzo, CC et al in prep

Tan et al. 2023



Weak-lensing alone

Improved modelling for matter velocity spectra (used in VIPERS)



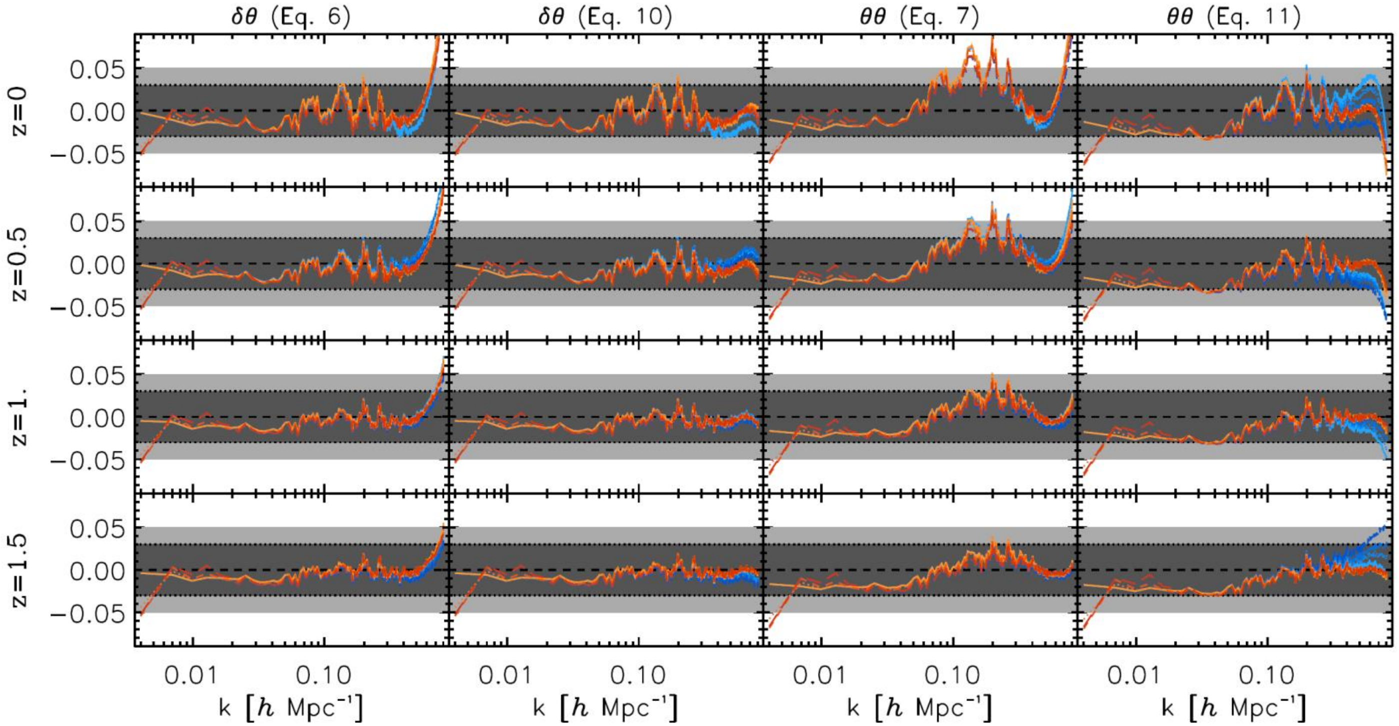
$$
\begin{aligned}
a_1 &= -0.817 + 3.198\sigma_{8,m} \\
a_2 &= 0.877 - 4.191\sigma_{8,m} \\
a_3 &= -1.199 + 4.629\sigma_{8,m} \\
1/k_\delta &= 0.111 + 3.811\sigma_{8,m}^2 \\
b &= 0.091 + 0.702\sigma_{8,m} \\
1/k_\theta &= -0.048 + 1.917\sigma_{8,m}^2
\end{aligned}
$$

Minimising the impact of nuisance parameters on data analysis

Bel, Pezzotta et al. 2019

$P_{\delta\theta}(k) = \left\{(P_{\delta\delta}^{\mathrm{HF}}(k)P_{\theta\theta}^{\mathrm{Lin}}(k)\right\}^{\frac{1}{2}} e^{-\frac{k}{k_\delta}}$

$P_{\theta\theta}(k) = P_{\theta\theta}^{\mathrm{Lin}}(k)e^{-\frac{k}{k_\theta}}$

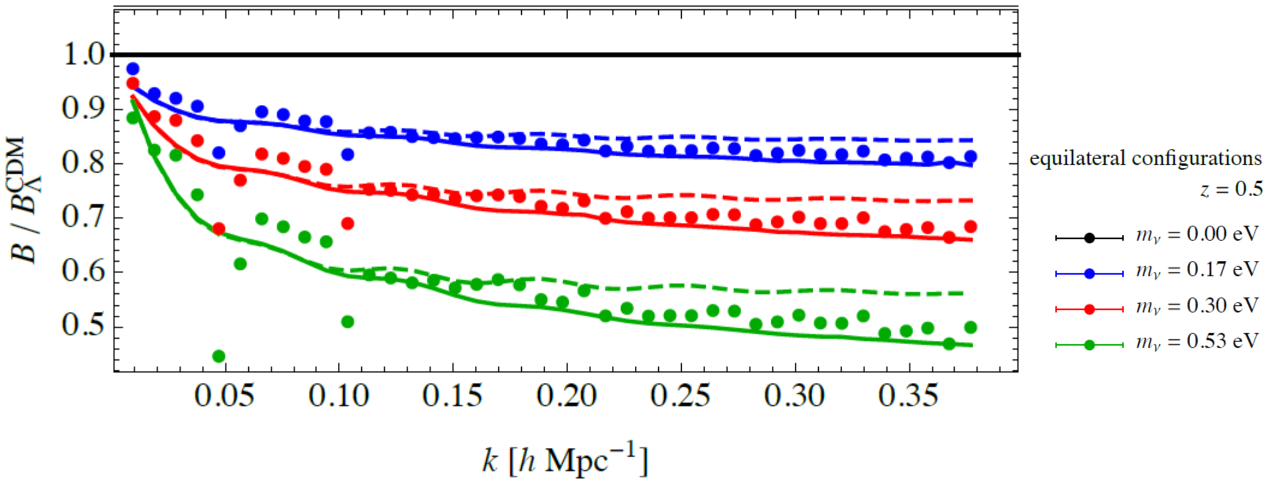


$P_{\delta\theta}(k) = \left\{(P_{\delta\delta}^{\mathrm{HF}}(k)P_{\theta\theta}^{\mathrm{Lin}}(k)\right\}^{\frac{1}{2}} e^{-\frac{k}{k_\delta}-bk^6}$

$P_{\theta\theta}(k) = P_{\theta\theta}^{\mathrm{Lin}}(k)e^{-k(a_1+a_2k+a_3k^2)}$

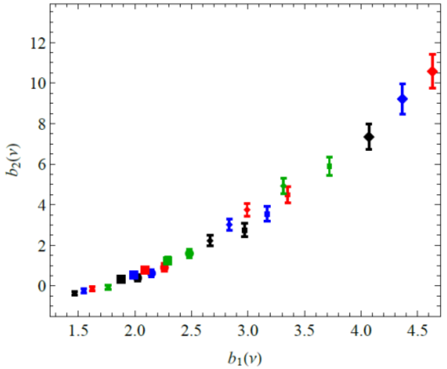
Bispectrum & quadratic bias with massive neutrinos

Ruggeri et al 2018



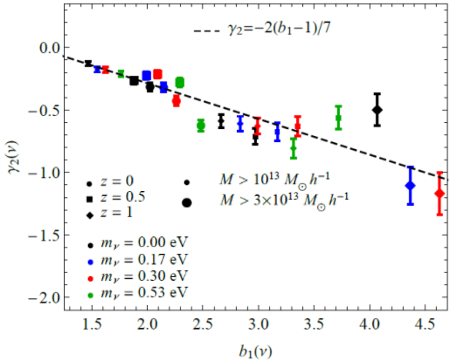
Dashed-lines are tree-level PT, solid 1-loop for cdm

In modelling the total matter bispectrum one needs to evaluate perturbatively at the 1-loop level, and beyond, only B_{ccc}, while the other terms can be trivially computed using tree-level PT predictions.



$$\delta_h = b_1\delta + \frac{b_2}{2}\delta^2 + \gamma_2\mathcal{G}_2 \quad \gamma_2 = \gamma_2^L - \frac{2}{7}(b_1 - 1)$$

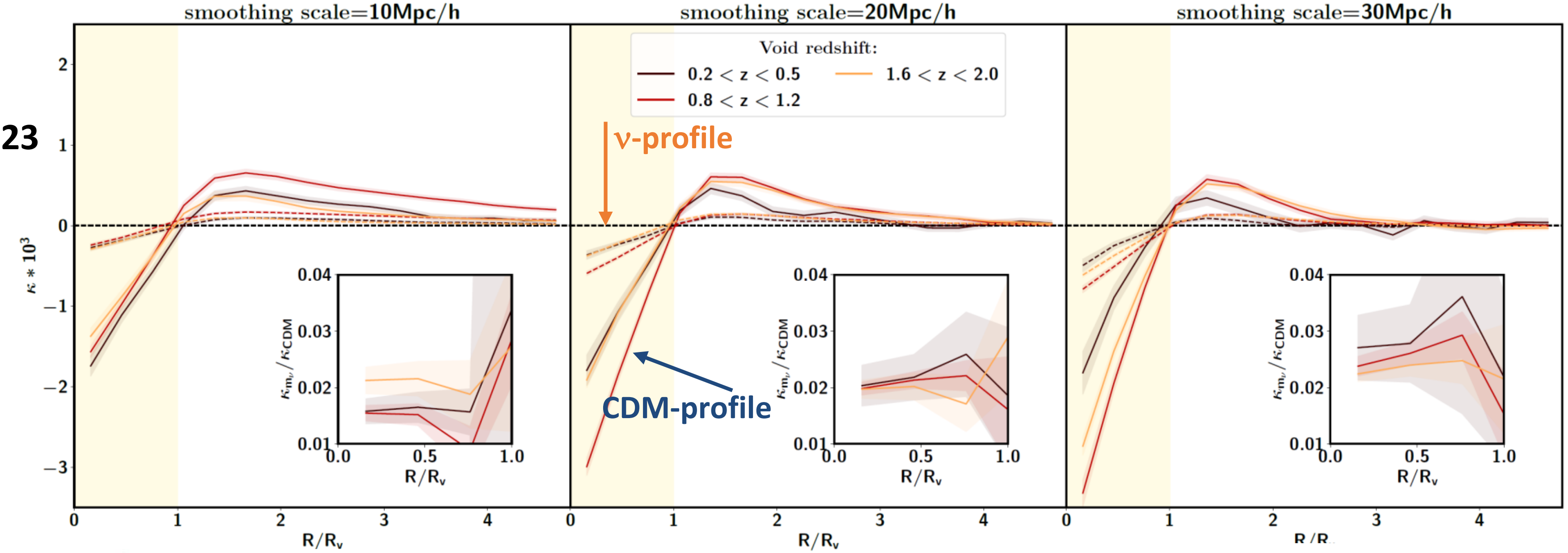
$$B_{hhh}(k_1,k_2,k_3) \equiv \langle\delta_h\delta_h\delta_h\rangle = b_1^3 B(k_1,k_2,k_3) + b_2 b_1^2\Sigma_{123} + 2\gamma_2 b_1^2 K_{123} + 2\ \mathrm{cyc}$$



bias universality wrt z and cosmolgy if ν defined wrt σ_{cc}

CMB-lensing void profiles in DEMNUni: the M_ν imprint

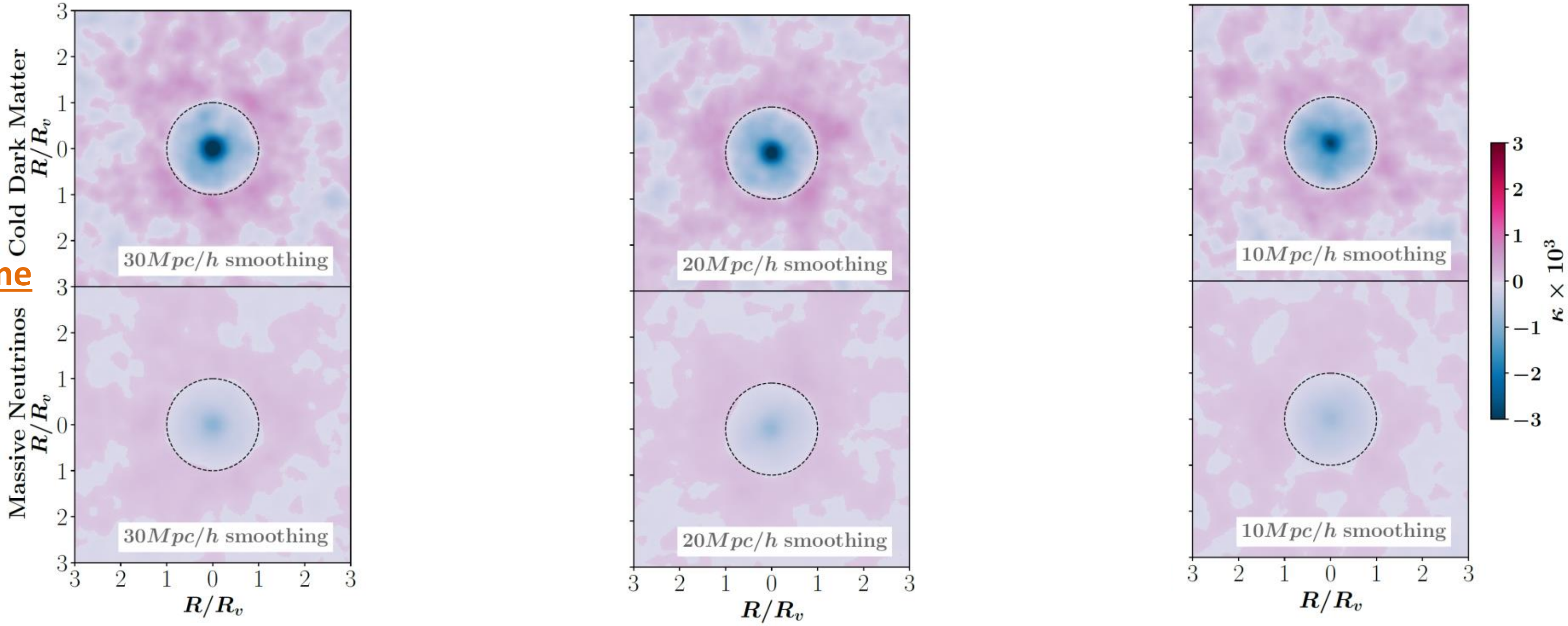
Vielzeuf, CC, et al. 2023



ν-profile

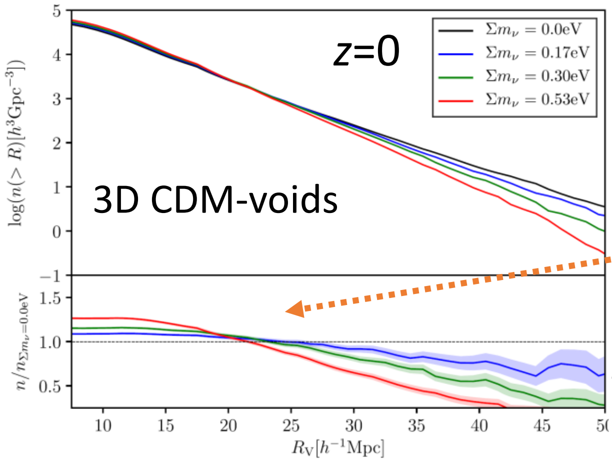
CDM-profile

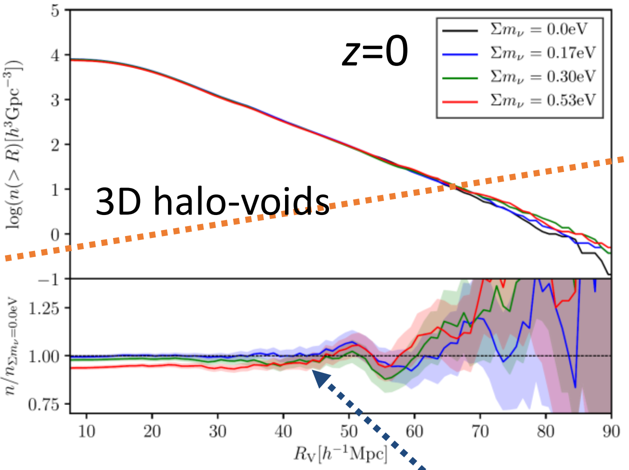
Larger void profiles become shallower with decreasing redshift: neutrinos suppress structure formation



Thanks to the big volume of DEMNUni!!

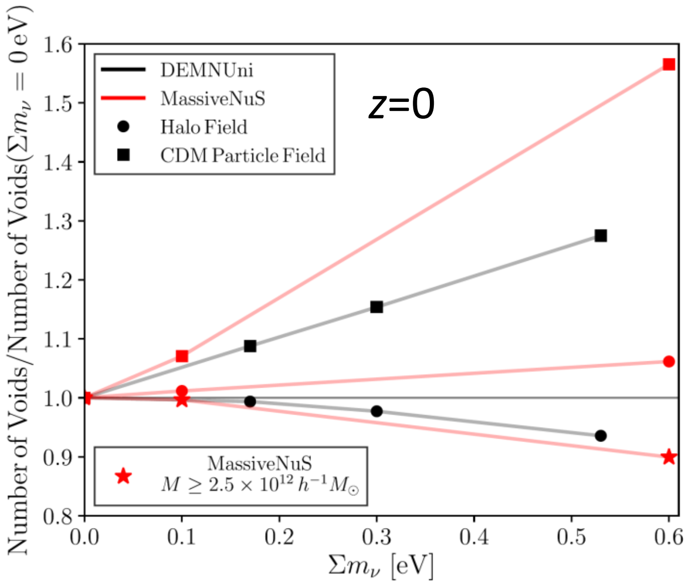
3D-void abundance in DEMNUni: comparison among M_ν cosmologies





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

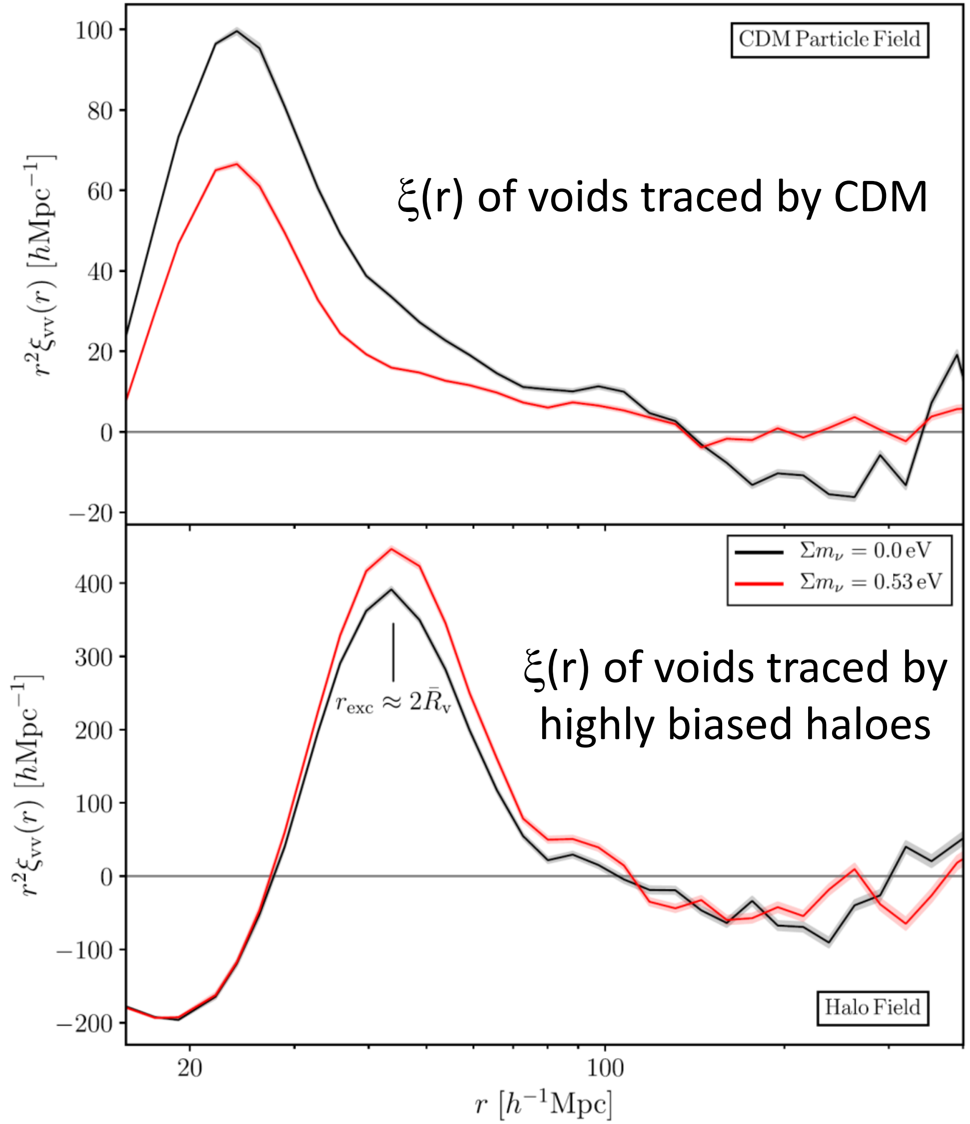
The total number of voids increases with M_ν for CDM-voids and decreases for voids traced by haloes with a high-mass threshold.

Void-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

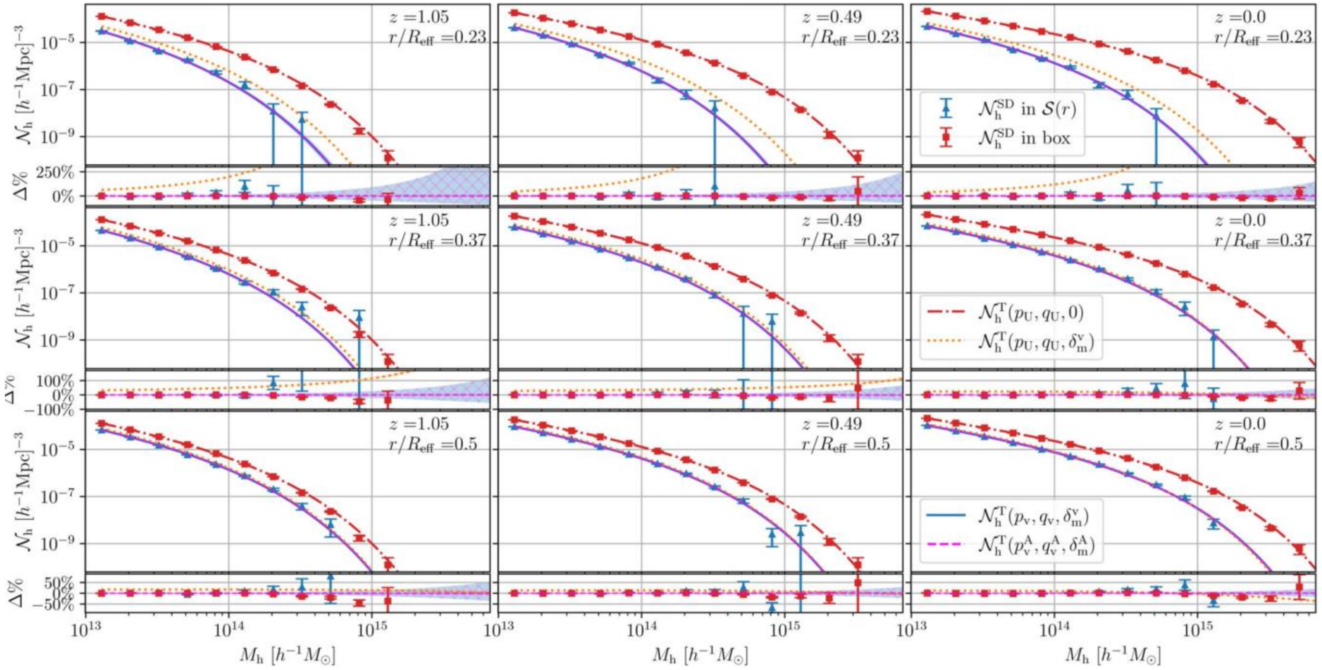
Kreish et al. 2019

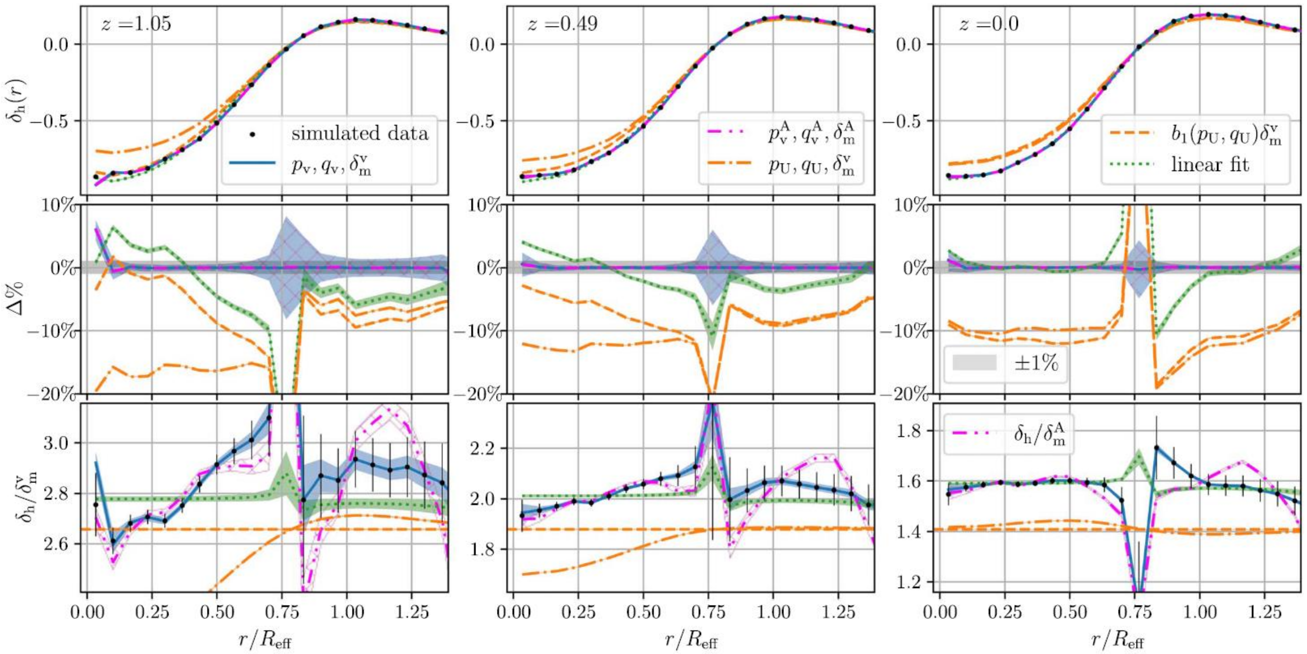


ξ(r) of voids traced by CDM

ξ(r) of voids traced by highly biased haloes

The halo bias within cosmic voids





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

This quantity is evaluated under the substitutions $\delta_\mathrm{c} \rightarrow \delta_\mathrm{c} - \delta_\mathrm{lw}^\mathrm{L}$, $\nu \rightarrow \tilde{\nu} = [\delta_\mathrm{sc}(z) - \delta_\mathrm{lw}^\mathrm{L} D(z=0)/D(z)]/\sigma(M)$, 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).

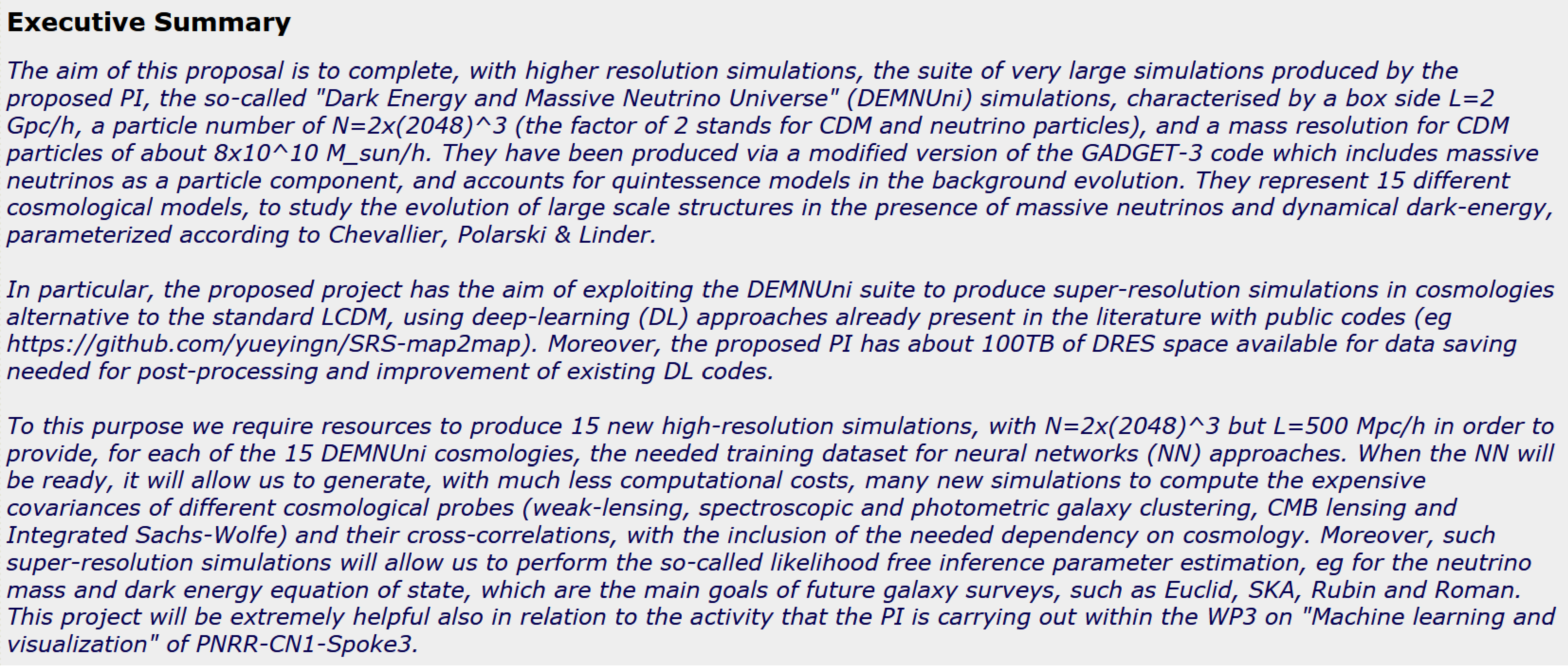
$$\frac{\mathrm{d}n_\mathrm{h}}{\mathrm{d}M}(\tilde{\nu},\, p_\mathrm{v},\, q_\mathrm{v},\, \delta_\mathrm{m}^\mathrm{v}) = \sqrt{\frac{2}{\pi}}\,\frac{\bar{\rho}_\mathrm{m}}{M}(1 + \delta_\mathrm{m}^\mathrm{v}) \times \left\{A_\mathrm{v}[1 + (q_\mathrm{v}\tilde{\nu}^2)^{-p_\mathrm{v}}]\sqrt{q_\mathrm{v}}\,e^{-q_\mathrm{v}\tilde{\nu}^2/2}\frac{\mathrm{d}\tilde{\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

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

Dark Energy and Massive Neutrinos High Resolution Simulations: filling the scale gap for AI-assisted simulations (MoU INAF-CINECA & ISCRA class-B)



Executive Summary

The aim of this proposal is to complete, with higher resolution simulations, the suite of very large simulations produced by the proposed PI, the so-called "Dark Energy and Massive Neutrino Universe" (DEMNUni) simulations, characterised by a box side L=2 Gpc/h, a particle number of N=2x(2048)^3 (the factor of 2 stands for CDM and neutrino particles), and a mass resolution for CDM particles of about 8x10^10 M_sun/h. They have been produced via a modified version of the GADGET-3 code which includes massive neutrinos as a particle component, and accounts for quintessence models in the background evolution. They represent 15 different cosmological models, to study the evolution of large scale structures in the presence of massive neutrinos and dynamical dark-energy, parameterized according to Chevallier, Polarski & Linder.

In particular, the proposed project has the aim of exploiting the DEMNUni suite to produce super-resolution simulations in cosmologies alternative to the standard LCDM, using deep-learning (DL) approaches already present in the literature with public codes (eg https://github.com/yueyingn/SRS-map2map). Moreover, the proposed PI has about 100TB of DRES space available for data saving needed for post-processing and improvement of existing DL codes.

To this purpose we require resources to produce 15 new high-resolution simulations, with N=2x(2048)^3 but L=500 Mpc/h in order to provide, for each of the 15 DEMNUni cosmologies, the needed training dataset for neural networks (NN) approaches. When the NN will be ready, it will allow us to generate, with much less computational costs, many new simulations to compute the expensive covariances of different cosmological probes (weak-lensing, spectroscopic and photometric galaxy clustering, CMB lensing and Integrated Sachs-Wolfe) and their cross-correlations, with the inclusion of the needed dependency on cosmology. Moreover, such super-resolution simulations will allow us to perform the so-called likelihood free inference parameter estimation, eg for the neutrino mass and dark energy equation of state, which are the main goals of future galaxy surveys, such as Euclid, SKA, Rubin and Roman. This project will be extremely helpful also in relation to the activity that the PI is carrying out within the WP3 on "Machine learning and visualization" of PNRR-CN1-Spoke3.

2M CPUh on G100 + 700k CPUh on M100/Leonardo

Conclusions and critical points

- Very large simulations with massive neutrinos and dynamical dark energy with good resolution to study large scale anisotropies (ISW-RS) and cosmic voids
- Not enough resolution to mimic all Euclid galaxies, therefore moving to DEMNUni-HighRes
- Many lab-universes and huge amount of data: long-term storage and open-access needed
- Alternative smart approaches, eg DL, to decreases the needed computational time and storage
- Hopefully PNRR-CN1-Spoke3 will help…