UNIVERSITÀ DEGLI STUDI DI MILANO
DIPARTIMENTO DI FISICA

erc DARK LIGHT

Massive neutrinos and cosmic structure formation: bridging cosmology and particle physics

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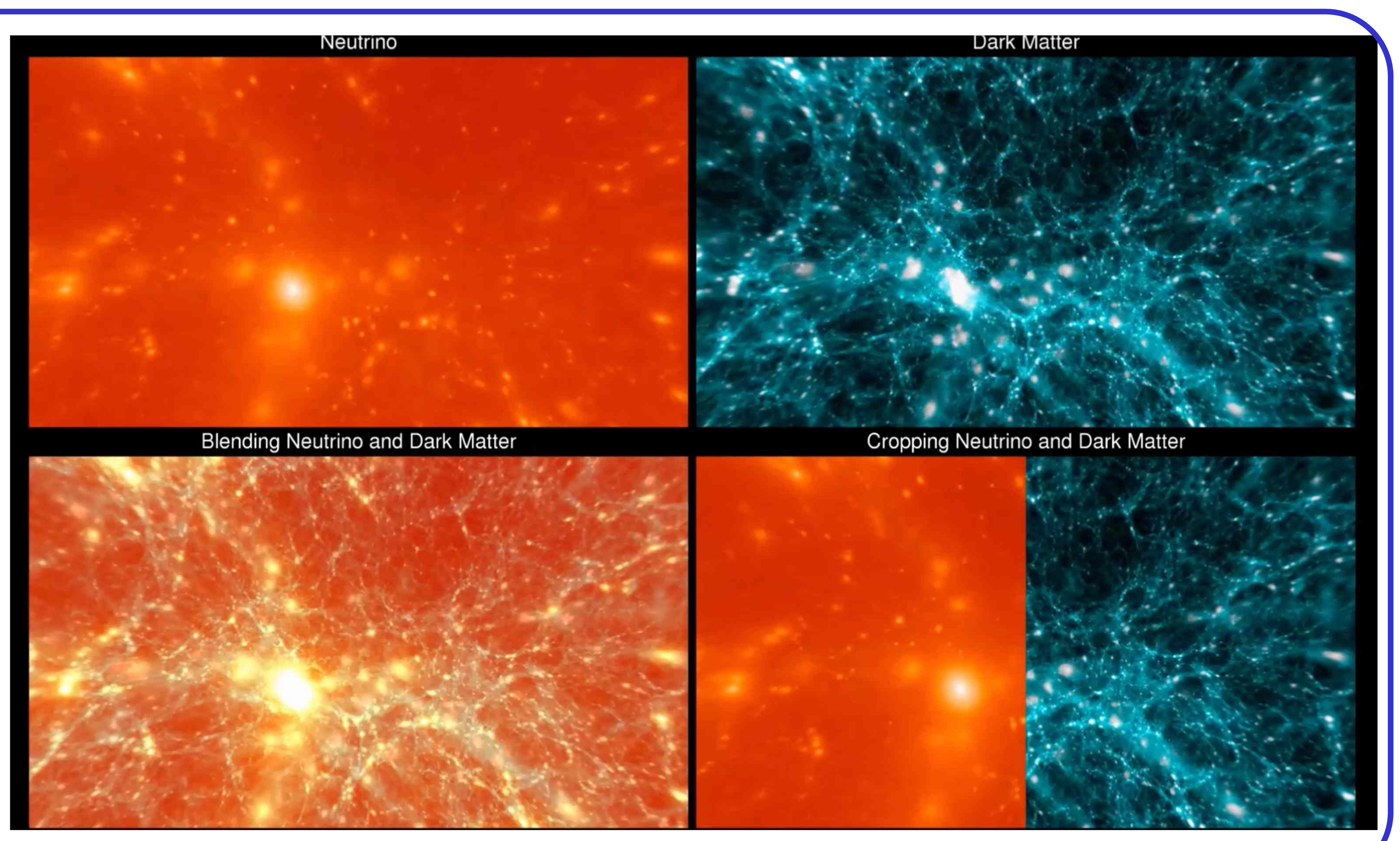
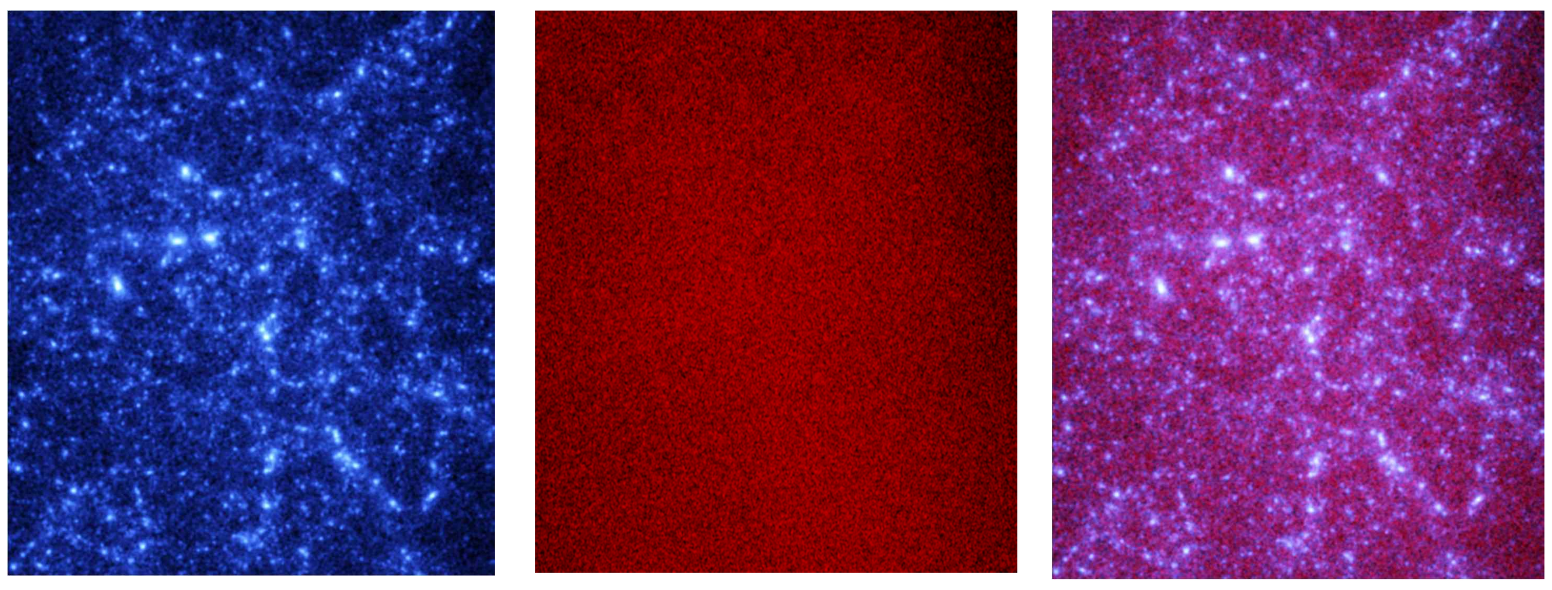
The recent discovery of neutrino flavour oscillations has stimulated a new area of research, devoted to measurements of the neutrino mass not only by means of particle physics experiments, but also via cosmological observations. Massive free-streaming neutrinos have a direct impact on the formation history of cosmic structure. This effect directly probes the sum of neutrino masses, resulting in a suppression of density fluctuations below specific scales. However, such an effect cannot be completely disentangled from that of a dynamical dark energy, undermining the interpretation of observations from future cosmological experiments such as the ESA mission *Euclid*. Non-linear effects can provide more information and help to mitigate such degeneracy. Therefore, non-linear modelling of structure formation in the presence of massive neutrinos and dark energy is needed to improve the accuracy of theoretical predictions, particularly as the precision of the new experiments reaches percent level accuracy. This can only be achieved through numerical gravitational simulations that include both neutrinos and dynamical dark energy, and go beyond the linear approximation, properly accounting for the neutrino contribution during the relativistic and non-relativistic neutrino phases.
Here in Milan we have developed N-body cosmological simulations describing the non-linear gravitational interaction of cold dark matter and massive neutrino particles embedded in a dynamical dark energy background, the largest of this kind. This project is known as the "Dark Energy and Massive Neutrino Universe". Given their large volume and high mass resolution, the DEMN-Universe simulations provide an important contribution to the preparation of future galaxy surveys and CMB probes, which aim at measuring the total neutrino mass and the dark energy equation of state with unprecedented accuracy.



Courtesy of Francisco Villaescusa-Navarro

Neutrino impact on structure formation: galaxy clustering

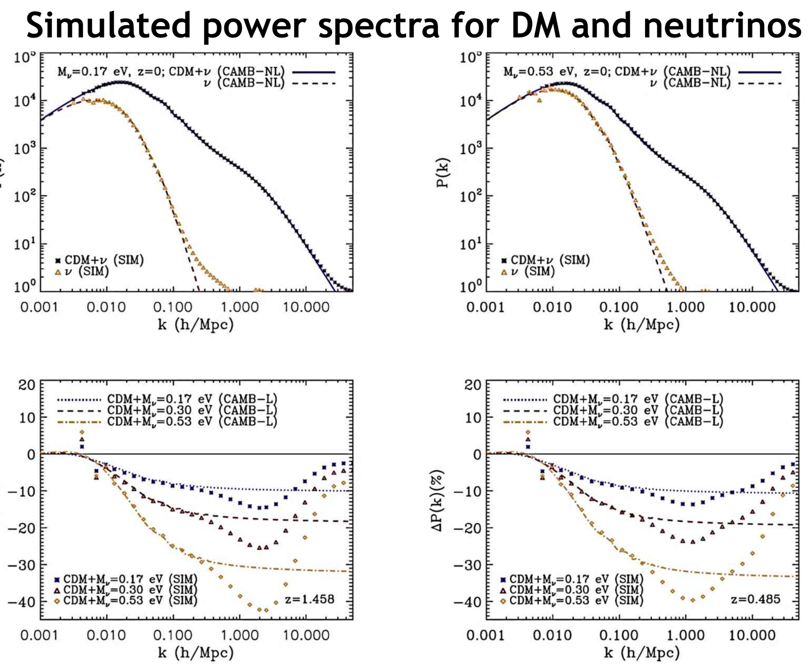
CDM and neutrino clustering from the DEMN-Universe simulations



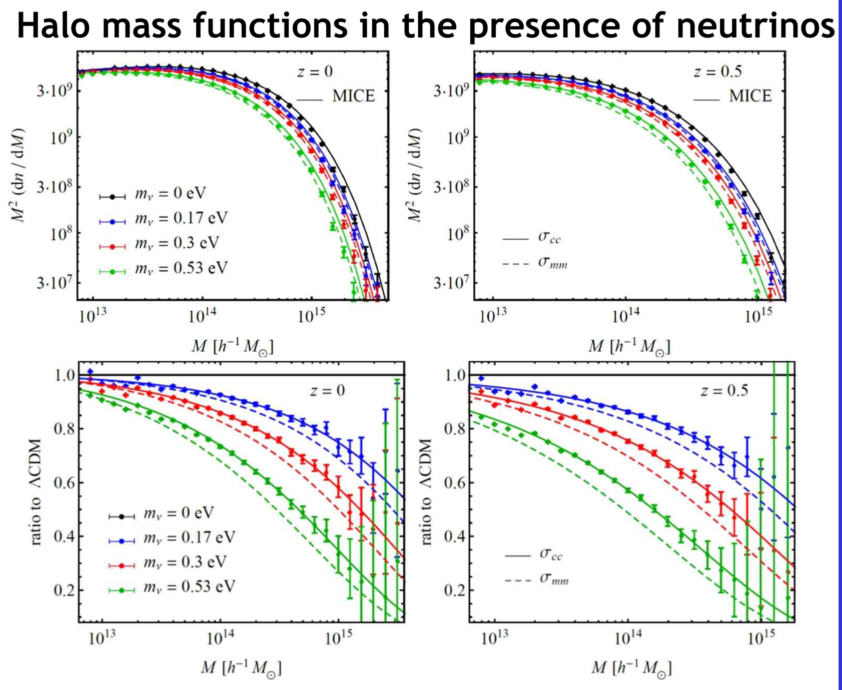
CDM density | ν density | CDM+ν density

An example of the matter density distribution inside a massive cluster with comoving size of about *10* Mpc/*h*, extracted from the DEMN-Universe simulation with total neutrino mass $M_\nu = 0.53$ eV at redshift $z = 0$. The left panel shows the distribution of the Cold Dark Matter (CDM) component alone, the middle panel the massive neutrino distribution, the right panel shows the superposition of the two. Due to their large thermal velocities, neutrinos free stream and their clustering is largely suppressed as compared to the CDM component; therefore they form a smooth and blurred neutrino halo.

Simulated power spectra for DM and neutrinos



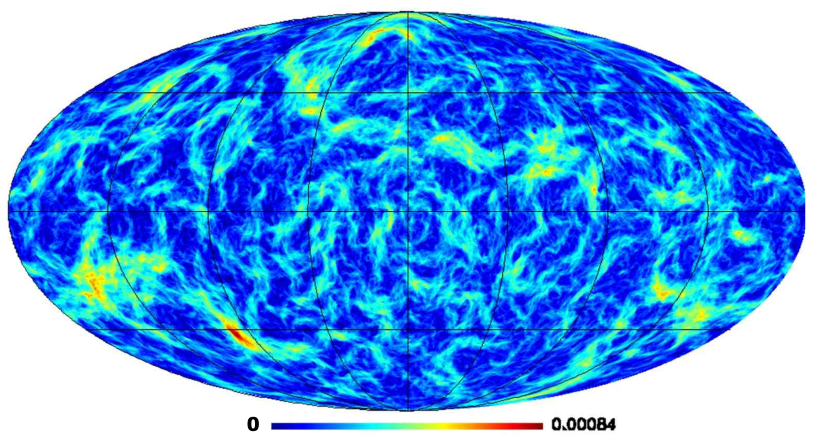
Halo mass functions in the presence of neutrinos



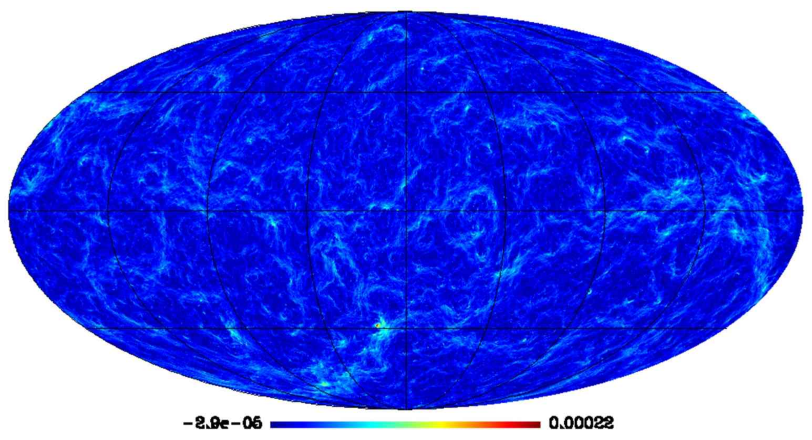
The effect shown above translates into a suppression of the total (CDM+ν) Dark Matter (DM) power spectrum, *P(k)* (left panel), and in a decrease of the halo mass function (right panel), wrt the massless case. The size of these effects increases with the total neutrino mass, M_ν, and can be accurately quantified only via fully non-linear simulations of structure formation accounting for a ν component.

Neutrino impact on structure formation: gravitational lensing

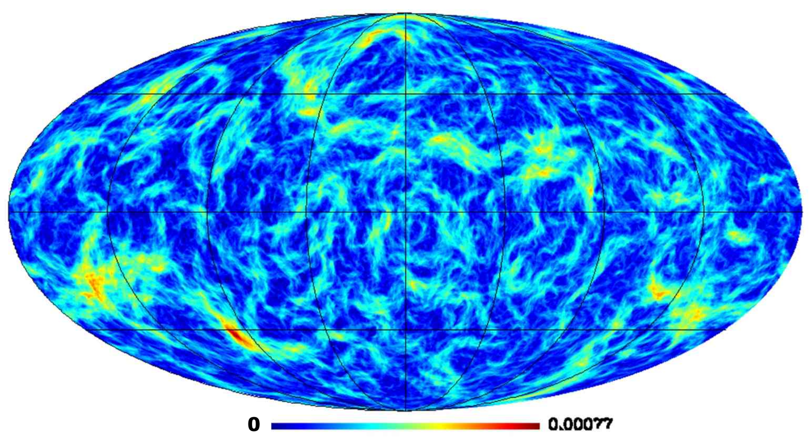
Weak-lensing deflection angle for $M_\nu = 0$ eV



Difference between $M_\nu = 0.53$ eV and $M_\nu = 0$ eV deflection angles



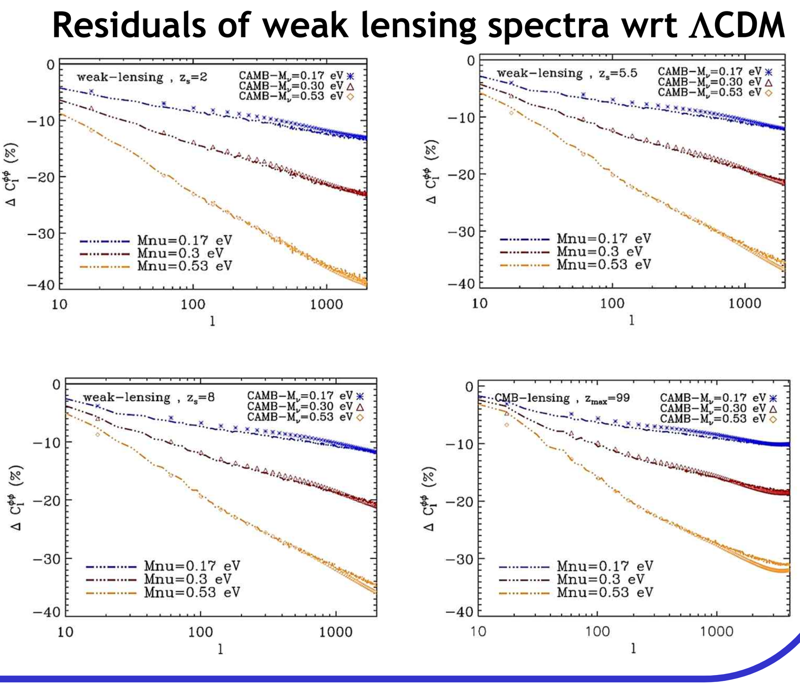
Weak-lensing deflection angle for $M_\nu = 0.53$ eV



All-sky projection of the modulus of the deflection angle produced by the matter distribution which, via its gravitational potential, lenses the light coming from galaxy-sources placed at redshift $z_s = 1$. The top-left panel shows the case of a Universe with a massless neutrino component. The bottom-left panel shows the same distribution for a massive neutrino component with total mass $M_\nu = 0.53$ eV. The right panel shows the difference between the two. As for the clustering case, the suppression of structure formation, due to free-streaming neutrinos, decreases the total lensing effect, by reducing the strength of the gravitational field produced by massive halos, as well as by the total large scale structure distribution of the cosmic web. The above images have been obtained by direct photon ray-tracing across the gravitational potential distribution of the DEMN-Universe simulations.

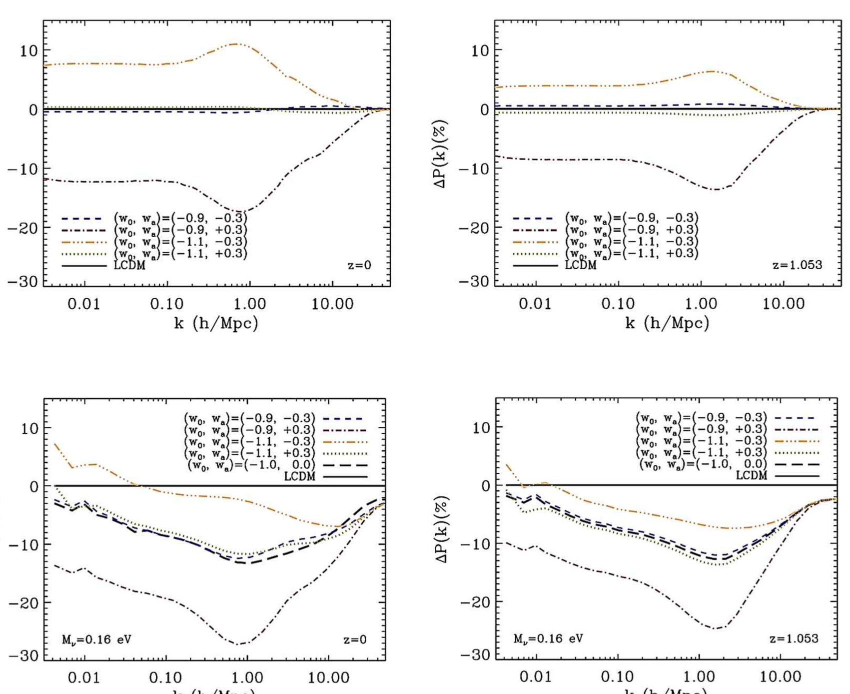
The effect shown above translates into a suppression of the so-called "Cosmic Shear" angular power spectra in the presence of massive neutrinos. The panels show percent residuals of this effect for different neutrino masses, $M_\nu = 0.17, 0.3, 0.53$ eV, and different source redshifts, $z_s = 2,5,8$, together with the case of Cosmic Microwave Background (CMB) photons, lensed by the large scale structure in the Universe. Percent differences are <u>*scale dependent*</u> and increase with M_ν.

Residuals of weak lensing spectra wrt ΛCDM



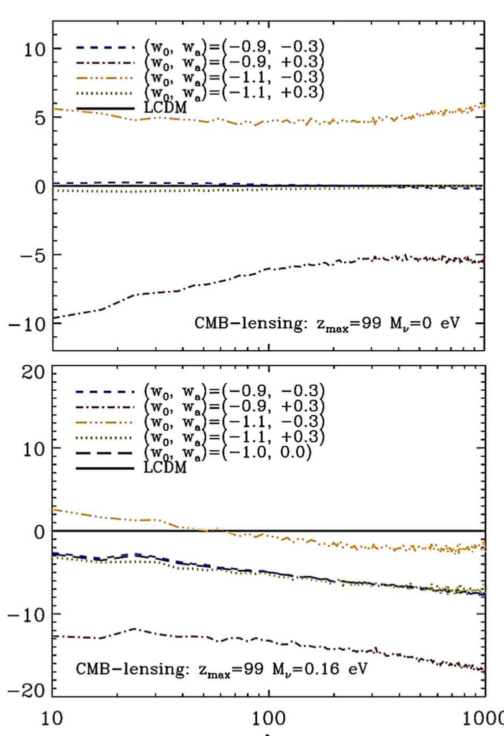
Neutrino and Dark Energy degeneracies

Residuals of matter power spectra wrt ΛCDM



As is well known, the expansion of the Universe is currently accelerating. There exist several hypotheses for the origin of such acceleration, one of these being represented by the presence of a *dynamical* "Dark Energy" (DE), with equation of state characterised by two parameters: w_0 and w_a. Constraints on these parameters, together with measurements of the neutrino mass, represent the primary goal of current and future galaxy surveys and CMB experiments. However, sometimes, the combination of these three parameters can lead to so-called *degeneracies* with the ΛCDM cosmological model, the standard model of cosmology, characterised by massless neutrinos and a *constant* and *uniform* dark energy component, the cosmological constant Λ. The left and right plots show some examples of such degeneracies, extracted from the DEMN-Universe simulations. <u>***Top-left***</u> panels represent percent residuals of total matter power spectra wrt ΛCDM, for the case of massless neutrinos and different values of w_0 and w_a. <u>***Bottom-left***</u> panels represent the same residuals but in the presence of massive neutrinos with total mass M_ν=0.16 eV. The <u>***right***</u> panels represent analogous residuals for the case of CMB-lensing shear power spectra. Note that, in the latter case, the model with $M_\nu=0.16$, $w_0=-1.1$, $w_a=-0.3$, mimics almost perfectly (within 2%) the ΛCDM, as well as the case of massless neutrinos plus a DE component with ($w_0=-0.9$, $w_a=-0.3$) or ($w_0=-1.1$, $w_a=+0.3$).

Residuals of CMB lensing spectra wrt ΛCDM



References: Carbone et al. 2016 (JCAP07(2016)034); Castorina et al. 2015 (JCAP07(2015)043); Zennaro et al. 2017 (Mon Not R Astron Soc (2017) 466 (3): 3244); https://www.researchgate.net/project/DEMN-Universe-DEMNUni