GOING BEYOND COSMOLOGICAL BOUNDS ON NEUTRINO MASSES

DISENTANGLING THE EFFECT OF NEUTRINO MASSES IN COSMO

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CMB and LSS observations are putting the best bounds ever to the sum of neutrino masses. Even more, EUCLID promises to measure it in the following years. Now that cosmology's precision is sufficient for such a discovery, we need to study all possible caveats on the cosmology of neutrino masses.

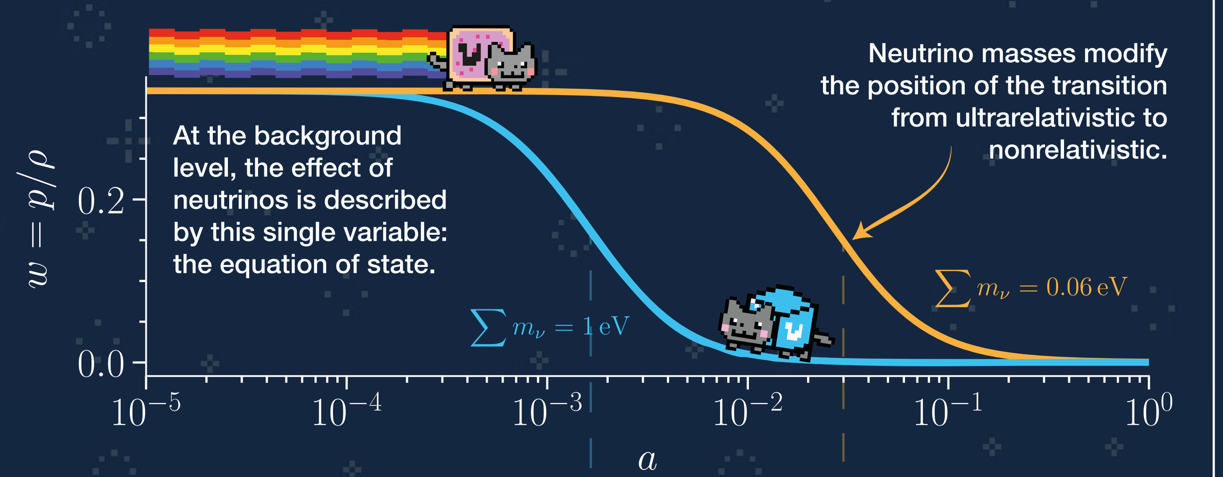
$\sum m_\nu < 0.12\,\mathrm{eV}$

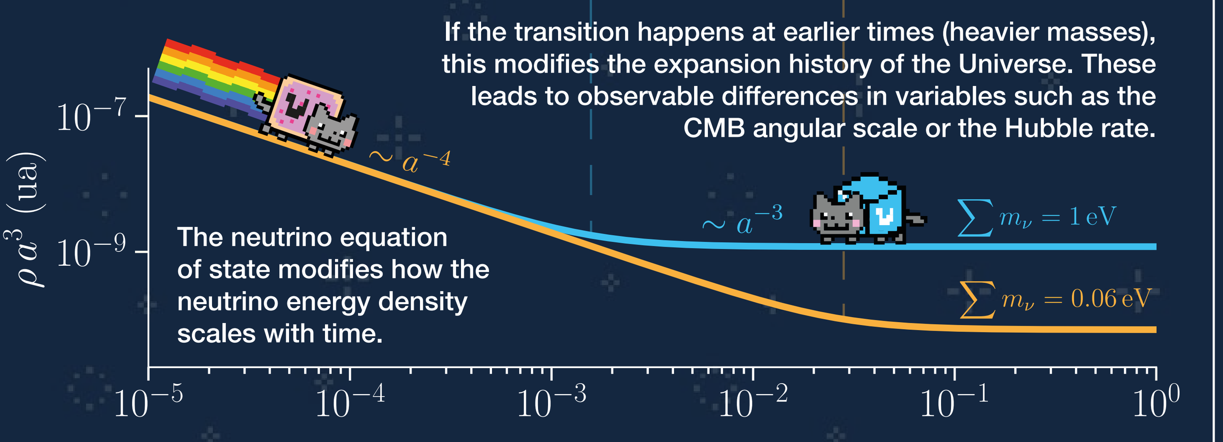
WHAT DOES THIS MEAN?

In particular, these bounds are model-dependent and can be easily relaxed if new physics in the neutrino sector exists. This has already been explored in the context of neutrino long range interactions [1], neutrino decay [2] or non-standard neutrino populations [3]. How can this happen?

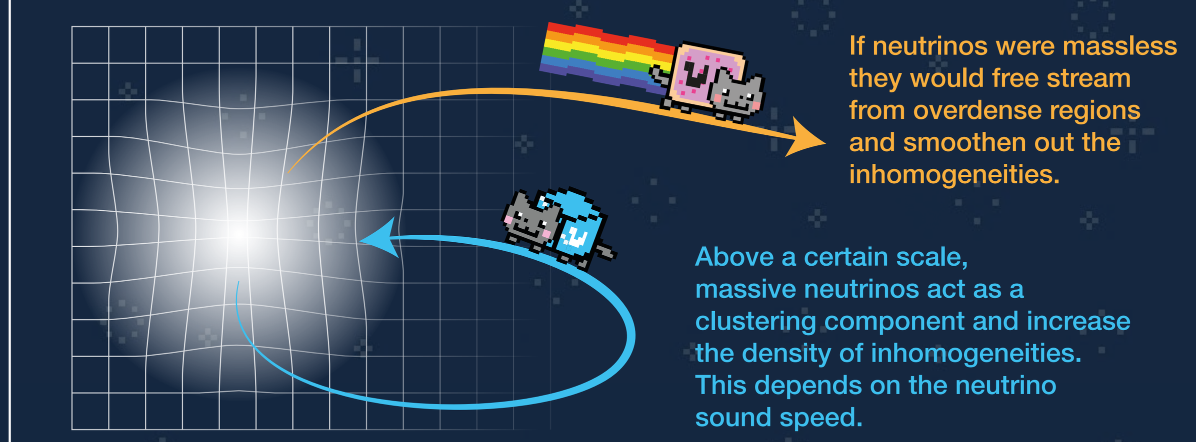
Neutrino masses have an effect on the observable Universe at two different levels:

AT BACKGROUND (HOMOGENEOUS)





AT PERTURBATIONS (INHOMOGENOUS)



Neutrino perturbations are described by four extra variables, the overdensity δ, the velocity θ, the sound speed c_s and the anisotropic stress (or shear) σ. From the continuity equation, they must fulfill two necessary equations:

$$\dot{\delta} = -(1+w)(\theta - 3\dot{\phi}) - 3H\left(c_s^2 - w\right)\delta$$

$$\dot{\theta} = -H(1-3w)\theta - \frac{\dot{w}}{1+w}\theta + \frac{c_s^2}{1+w}k^2\delta - k^2\sigma + k^2\psi$$

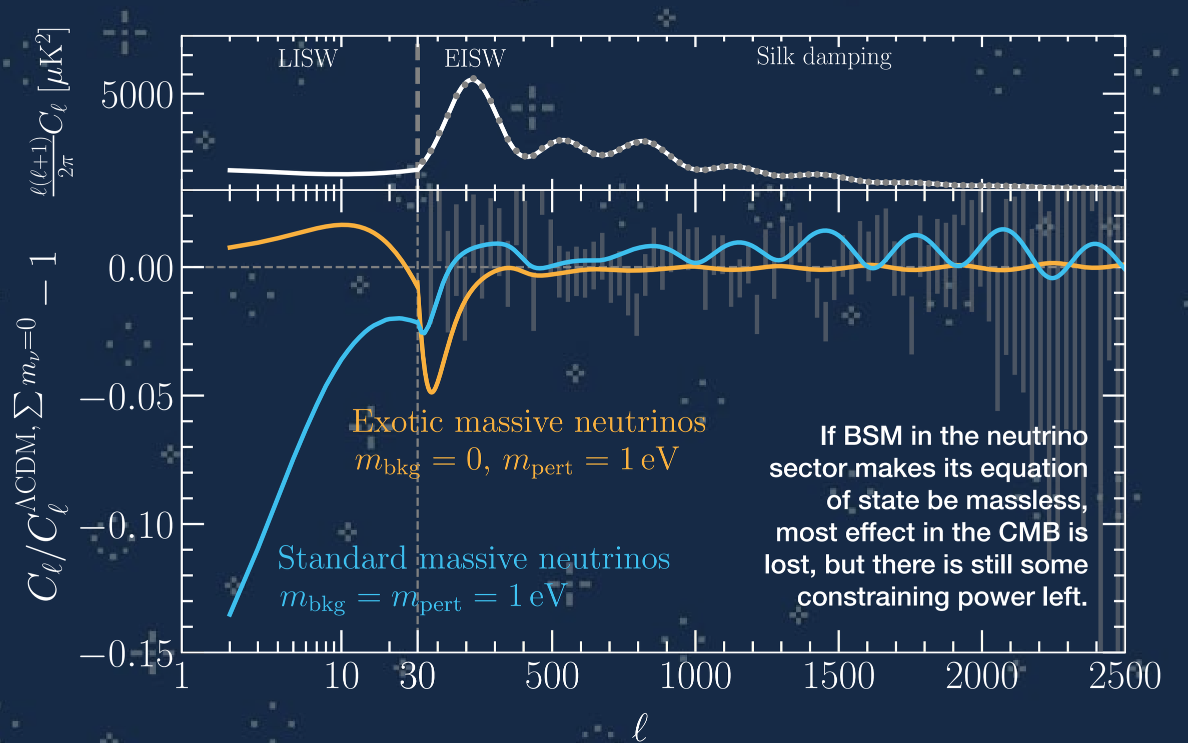
Therefore, there are two free variables. Aside from the equation of state, we can compute the sound speed and the shear if we assume a particular model (e.g. standard massive neutrinos), but in general all these can be independent.

WHAT IF WE TRY TO DISENTANGLE BOTH EFFECTS?

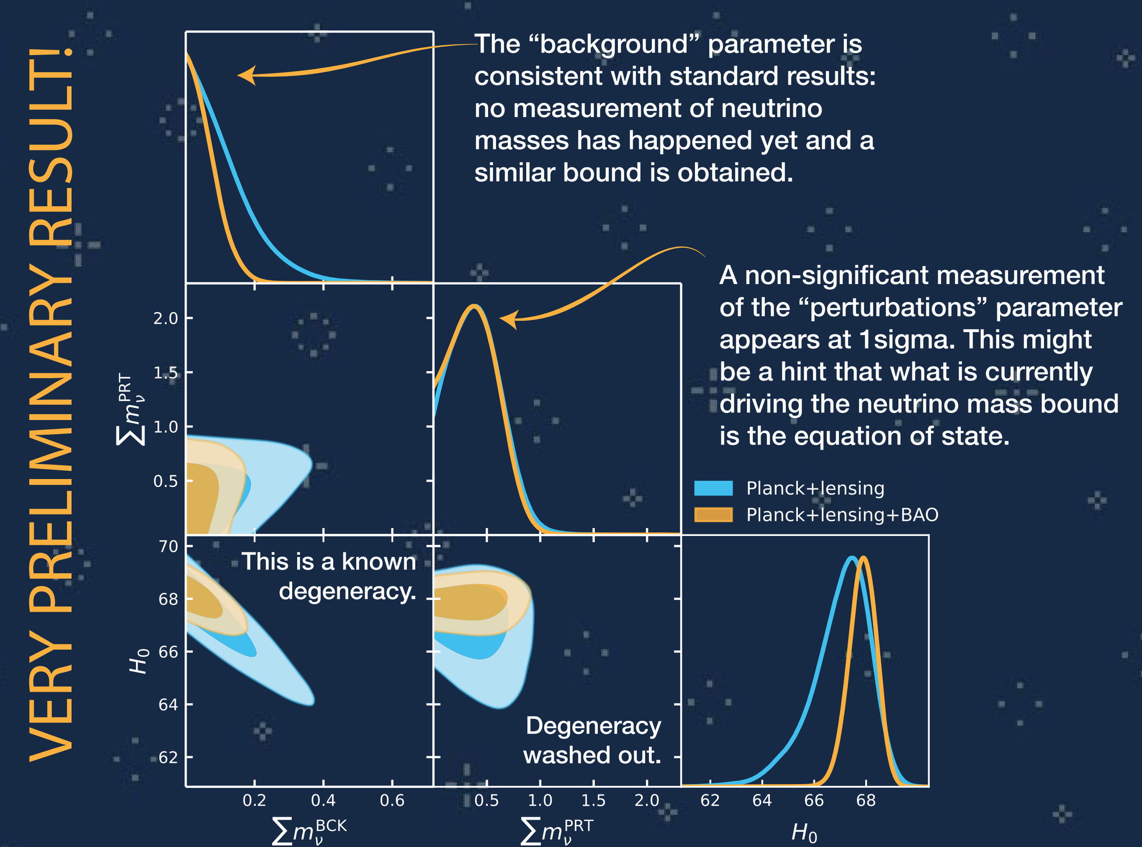
Since mass is not a direct observable, we can work with two different "mass" parameters to describe the variables which are actually observable in cosmo:

$m_{\mathrm{bkg}} \xrightarrow{\text{describes}} w \qquad m_{\mathrm{pert}} \xrightarrow{\text{describes}} c_s^2,\ \sigma$

This framework allows to understand better which effect of neutrino masses are we exactly measuring. Since there are new physics scenarios where these two parameters are different, we will be able to prove the robustness and consistency of the neutrino mass measurement under such scenarios.



Since we are doing cosmology, we can fit both parameters in a triangle plot:



This is preliminary work, but soon will be published to the arXiV together with a public version of CLASS. Since this model independent approach can be adjusted to many BSM models in the neutrino sector, we want this framework to be a useful tool for all cosmology. Hope you want to stay tuned to me and my collaborators. If you want to, keep an eye on my Twitter @tbertolez or my InspireHep profile!

NEUTRINO INTERACTIONS WITH ULTRALIGHT PSEUDOSCALAR DM

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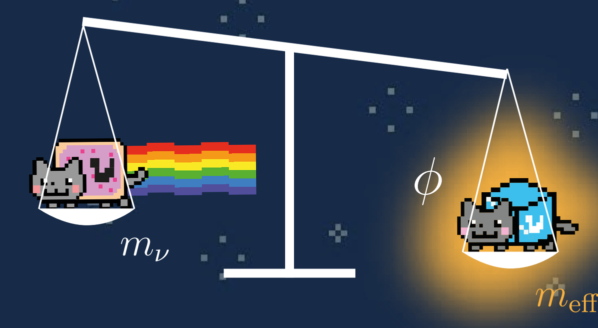
Consider fermions coupled to a pseudoscalar field in an expanding Universe:

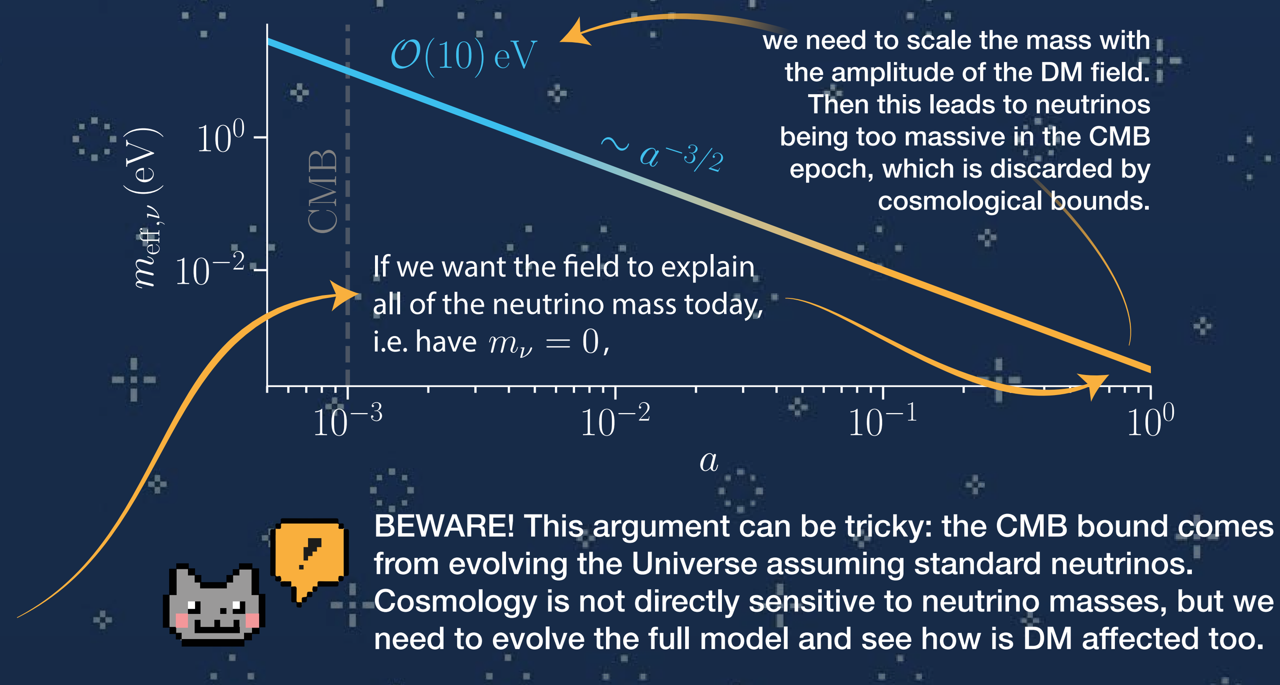
$$\mathcal{S} = \int d^4x\,\sqrt{-g}\left\{-\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - m_\phi^2\phi^2 - g\phi\bar{\psi}i\gamma^5\psi + \bar{\psi}\left[i\not{D} - m_\nu\right]\psi\right\}$$

In such scenario, the neutrino obtains an effective mass in terms of the field, which can also be enhanced by the DM local overdensity.



$$m_{\mathrm{eff},\nu} = \sqrt{m_\nu^2 + g^2\phi^2}$$

Can this pseudoscalar field explain simultaneously dark matter and the origin of neutrino masses? This has already been studied in [4, 5]. The standard answer is NO.

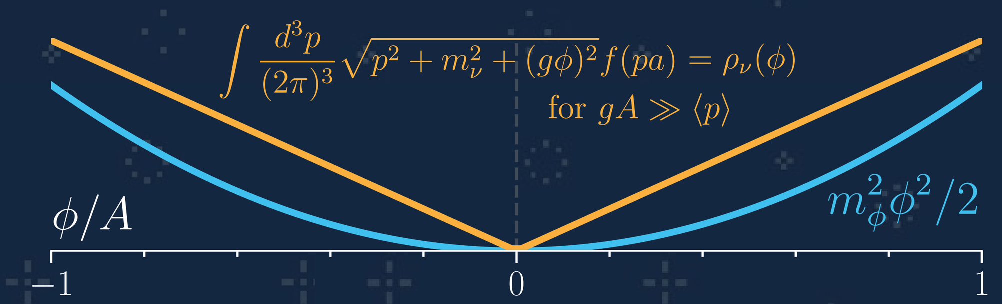


BEWARE! This argument can be tricky: the CMB bound comes from evolving the Universe assuming standard neutrinos. Cosmology is not directly sensitive to neutrino masses, but we need to evolve the full model and see how is DM affected too.

A RIGOROUS COSMOLOGY REQUIRES TO SOLVE THE PSEUDOSCALAR EVOLUTION!

The interaction of a distribution of neutrinos with the pseudoscalar modifies its equation of motion through a new potential term with a different shape:

$$\ddot{\phi} + 3H\dot{\phi} + m_\phi^2\phi = -g^2\phi\int\frac{d^3p}{(2\pi)^3}\frac{1}{\sqrt{p^2 + m_\nu^2 + (g\phi)^2}}f(pa)$$



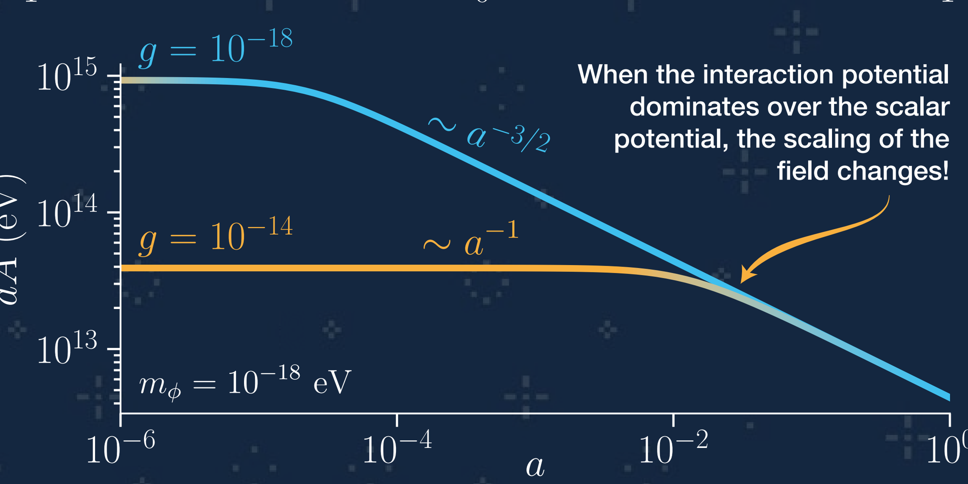
$H \ll m_\phi$
$\tau_H \gg \tau_{m_\phi}$

However, the separation of timescales makes a direct numerical resolution of the cosmological evolution impossible. We need to average out the fast oscillations of the pseudoscalar field.

Instead of solving for the field ϕ, we solve for its oscillation amplitude A. We perform an adiabatic approximation by separating the time variation in its two timescales, and keep the slow one constant. We then find a quantity which is invariant along cosmological evolution:

$$I = a^3\int_0^A\sqrt{\frac{1}{2}m_\phi^2\left(A^2-\phi^2\right) + \left(\rho_\nu(A,a) - \rho_\nu(\phi,a)\right)}\,d\phi = \text{constant.}$$

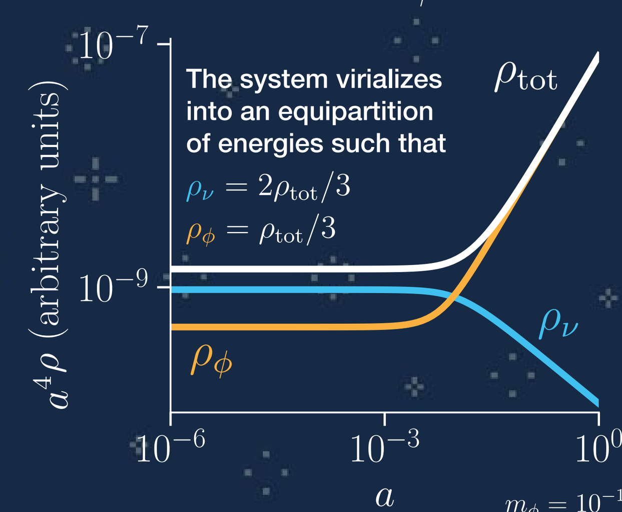
This adiabatic invariant can now be used to compute the field amplitude at any time.

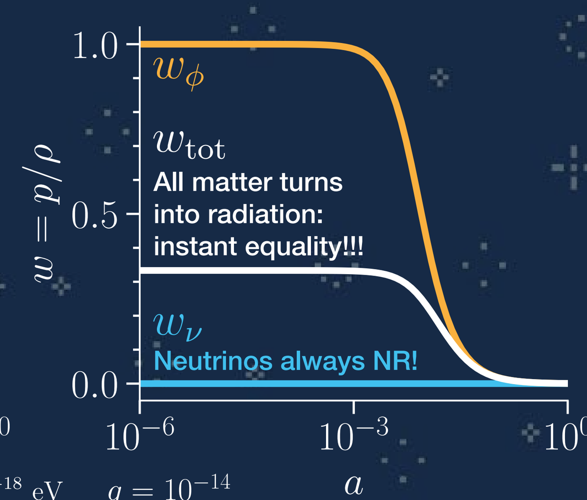


LARGE COUPLING (EXOTIC!) PHENO

In order to compute the cosmological variables of the pseudoscalar-neutrino fluid, we must average over an oscillation of the pseudoscalar field at every time:

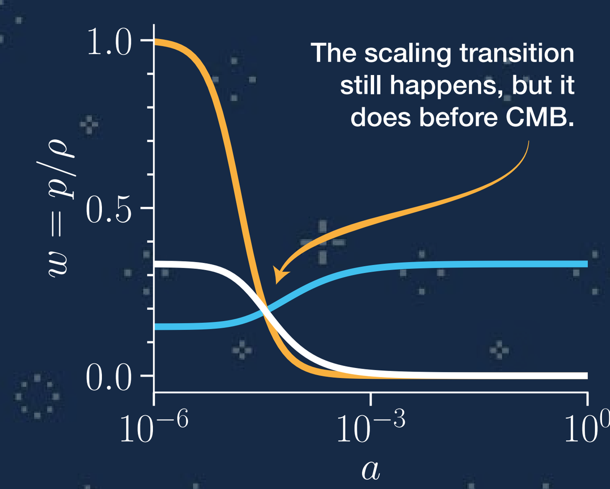
$$\langle\mathcal{O}\rangle = \frac{1}{\tau_A}\oint\frac{\mathcal{O}(\phi,\dot{\phi})}{\dot{\phi}}d\phi \quad \text{with} \quad \dot{\phi} = \sqrt{2[\rho_\nu(A) - \rho_\nu(\phi)] + m_\phi^2(A^2-\phi^2)}, \quad \tau_A = \oint d\phi/\dot{\phi}$$

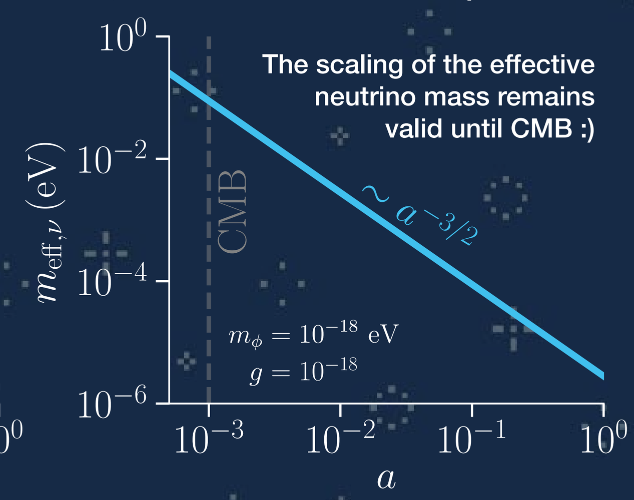




SMALL COUPLING PHENOMENOLOGY

However, existing bounds on neutrino masses are $g\,m_\phi^{-1} = \mathcal{O}(1)\,\mathrm{eV}$. For such values, cosmology is more standard, at least until the CMB epoch.





This is preliminary work, but soon will be published to the arXiV together with a public version of CLASS. Present neutrino-pseudoscalar coupling bounds are likely to be correct, but now should be more trustable. The exotic phenomenology at strong interaction regimes is interesting on its own and deserves attention!

An incomplete list of references:
[1] "Long Range Interactions in Cosmology: Implications for Neutrinos". I. Esteban, J. Salvadó. JCAP 05 (2021) 036.
[2] Archidiacono, Hannestad. JCAP 07 (2014) 046. | Barenboim et al. JCAP 03 (2021) 087| Escudero et al. JHEP 12 (2020) 119...
[3] Farzan, Hannestad. JCAP 02 (2016) 058 | Oldengott et al. JCAP 04 (2019) 049 | Alvey et al. Phys.Rev.D 105 (2022) 6, 063501...
[4] "Neutrino Oscillations as a Probe of Light Scalar Dark Matter". A. Berlin. Phys.Rev.Lett. 117 (2016) 23, 231801.
[5] "Refractive neutrino masses, ultralight dark matter and cosmology". M. Sen, A.Y. Smirnov. JCAP 01 (2024) 040.

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