Accurately Measuring Neutrinos, Massive Light Relics and Axions Using Cosmological Observables

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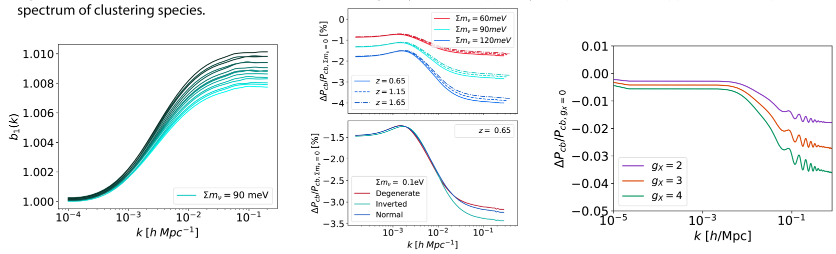
Cosmological data provide a powerful tool in the search for physics beyond the Standard Model. An interesting target are light relics, new degrees of freedom which decoupled from the Standard Model while relativistic. Nearly massless relics contribute to the radiation energy budget, and are commonly searched through variations in the effective number N_{eff} of neutrino species. Additionally, relics with masses on the eV scale (meV-10 eV) become non-relativistic before today, and thus behave as matter instead of radiation. This leaves an imprint in the clustering of the large-scale structure of the universe, as light relics have important streaming motions, mirroring the case of massive neutrinos. Here we forecast how well current and upcoming cosmological surveys can probe light massive relics (LiMRs). We consider minimal extensions to the SM by both fermionic and bosonic relic degrees of freedom. By combining current and upcoming cosmic-microwave-background and large-scale-structure surveys, we forecast the significance at which each LiMR, with different masses and temperatures, can be detected. Similar arguments apply to probing the mass and decay constant of axion-like particles.

Light, but massive, cosmological relics induce a suppression on the matter power spectrum which begins at some characteristic free streaming scale, k_{fs}, and scales with the abundance of the relic. To use galaxies as a probe of the underlying matter power spectrum, we must model the relation between a galaxy overdensity and a matter density through the bias function, $b_1(k, z)$, which depends on both redshift and scale. An abritrary light but massive relic, which neutrinos are an example of, will modify this relationship. Such a relic is defined in terms of its mass and it temperature which we can model with respect to CMB photons and neutrinos.

$$T_X^{(0)} = \left(\frac{g_{*S}^{(0)}}{g_{*S}^{(\mathrm{dec})}}\right)^{1/3} T_\gamma^{(0)} \qquad \Delta N_{\mathrm{eff}} = c_1^\gamma \left(\frac{g_X}{g_\nu}\right)\left(\frac{T_X^{(0)}}{T_\nu^{(0)}}\right)^4$$

$$k_{\mathrm{fs}} = \frac{0.08}{\sqrt{1+z}}\left(\frac{m_X}{0.1\mathrm{eV}}\right)\left(\frac{T_X^{(0)}}{T_\nu^{(0)}}\right)^{-1} h\,\mathrm{Mpc}^{-1} \qquad \Omega_X h^2 = \frac{m_X}{93.14\,\mathrm{eV}}\frac{g_X}{g_\nu}\left(\frac{T_X^{(0)}}{T_\nu^{(0)}}\right)^3$$

Light relics induce a scale-dependent enhancement to the galaxy bias which partially compensates for a suppression to the power spectrum of clustering species.



By modeling the galaxy bias of cosmological relics that are massive, but light, we can improve constraints on the neutrino mass and rule out relic dark matter parameter space with CMB and LSS data. Not modeling relic effects on galaxy bias will skew constraints ≈ 1σ.

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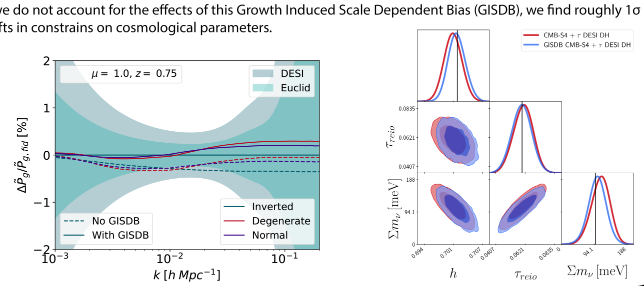
We are then able to relate changes in the galaxy power spectrum and CMB power spectrum to the mass and degrees of freedom of the light relic. After taking into account observations effects including redshift space distortions, the Finger-of-God effect, and the Alcock-Paczynski effect, we can forecast how well upcoming CMB and LSS surveys will be able to constrain different types of light relics. In the case of neutrinos, we find that the gains in discriminatory power are not sufficienct to fully resolve the neutrino hierarchy.

Data		Model			Best-fit parameters			
LSS	CMB	Hierarchy	Nuisance	GISDB	$-2\Delta\log\mathcal{L}$	$\sum m_\nu$ [meV]	τ_{reio}	β_0
DESI	CMB-S4 + τ_{reio}	Degenerate	$\{\beta_0\}$	Yes	0.9	107.6 ± 26.7	5.99e-2 ± 7.20e-3	1.000 ± 1.70e-3
				No	1.1	112.0 ± 26.1	6.07e-2 ± 6.93e-3	1.003 ± 1.73e-3
		Inverted	$\{\beta_0\}$	Yes	0.0	$107.2^{+15.2*}_{-0.42}$	6.16e-2 ± 3.84e-3	1.001 ± 1.63e-3
		Normal	$\{\beta_0\}$	Yes	1.0	99.7 ± 28.6	5.89e-2 ± 6.52e-3	1.000 ± 1.68e-3
	Planck†	Degenerate	$\{\beta_0\}$	Yes	-	±27.44	±8.99e-3	±7.62e-3

If we do not account for the effects of this Growth Induced Scale Dependent Bias (GISDB), we find roughly 1σ shifts in constrains on cosmological parameters.



In the case of generic light relics, we can describe our constraints in terms of the relic mass and either its internal degrees of freedom, g_X, or its temperature. Relics which are relativistic during recombination are generally more constrained by CMB datasets, but we gain information on all relic masses through the bias which allows us to better constrain light relic parameter space than without this information.

$$g(k) = R_L^{\Lambda\mathrm{CDM}}(k) R_L^X(k) R_L^\nu(k)$$

$$R_L^{\Lambda\mathrm{CDM}}(k) = 1 + \Delta_{\Lambda\mathrm{CDM}} \tanh\left(\frac{\alpha k}{k_{\mathrm{eq}}}\right)$$

We show as an example the particular case of a Weyl fermion, highlighting how dataset degeneracies shift with mass and predictions for the next generation datasets.