Snowmass2021 - Letter of Interest

Light but Massive Relics in Cosmology

Thematic Areas: (check all that apply □/■)

■ (CF1) Dark Matter: Particle Like
■ (CF3) Dark Matter: Cosmic Probes
■ (CF7) Cosmic Probes of Fundamental Physics
■ (TF9) Astro-particle physics & cosmology

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Abstract: Many extensions of the Standard Model (SM) of particle physics predict new light degrees of freedom that only couple weakly to the visible sector. While their detection is difficult in accelerators, due to their small couplings, a population of these light relics would leave a striking imprint on cosmological observables. The effect of very light relics, which are relativistic at all times, is fully encapsulated into $\Delta N_{\rm eff}$, the change in the effective number $N_{\rm eff}$ of active neutrinos species. Relics with masses in the eV range $(10^{-3} - 100)$ eV, however, would become non-relativistic before today, and thus would behave as a sub-component of the cosmological dark matter. These Light-but-Massive Relics (LiMRs) freely stream out of gravitational potentials, and thus suppress the formation of cosmic structures. Here we outline the opportunity to search for new physics in the form of LiMRs with upcoming data sets, both of the cosmic microwave background and the large-scale structure, and summarize the challenges that ought to be overcome to claim a detection or rule out their existence.

Background

Cosmological data provide a powerful tool in the search for physics beyond the Standard Model (SM). Numerous extensions of the SM posit the existence of light, feebly interacting particles, including axions and axion-like particles[1–4], dark photons[5–8], and light fermions[9–11]. These are broadly categorized as light relics: new degrees of freedom which decoupled from the SM while relativistic. Consequently, their cosmic abundance was frozen and survived until today. The quintessential example within the SM are neutrinos, but they need not be the only light relics to populate our universe. Explicit exampled of new light relics include a fourth, sterile neutrino, whose existence is suggested by different anomalous experimental results[12–15]; as well as the gravitino, the supersymmetric partner of the graviton[16].

New relics that are sufficiently light will manifest as dark radiation, and can be searched for through their effect on the cosmic microwave background (CMB) anisotropies[17–19] and large-scale structure (LSS) of the cosmos[20;21], typically parametrized by the effective number of neutrino species, $N_{\rm eff}$ (which is 3.045 in the standard cosmological model[22–24]). Massive relics can, on the other hand, become non-relativistic at some point in cosmic history, and behave as dark matter (DM) thereafter. However, their decoupling while relativistic gives these relics significant streaming motion, which sets a scale below which they cannot cluster, thus altering the LSS of our universe. This fact allows cosmological data sets to search for these new degrees of freedom in an increasingly precise way[25;26].

Cosmological data from near-future surveys are expected to provide exquisite measurements of the distribution of matter in our universe. Light but massive relics (LiMRs) that have become non-relativistic before today (with masses $m_X \gtrsim 10^{-3}$ eV), will impact that distribution by behaving as hot DM[25–30]. There is a lower bound on the temperature that any relic that was in thermal equilibrium with the Standard Model should have, $T_X^{(0)} = 0.91$ K. This minimum temperature gives rise to the well-known values of $\Delta N_{\rm eff}$ for each type of relic[31]: 0.027 for scalars (with $g_X = 1$ degrees of freedom), 0.047 for Weyl fermions ($g_X = 2$), 0.054 for massless gauge bosons ($g_X = 2$), and 0.095 for Dirac fermions ($g_X = 4$). In addition, this smallest relic temperature sets a lower bound on the abundance of any massive relic today, which for instance corresponds to 1% of the total DM for a 1-eV mass Weyl relic.

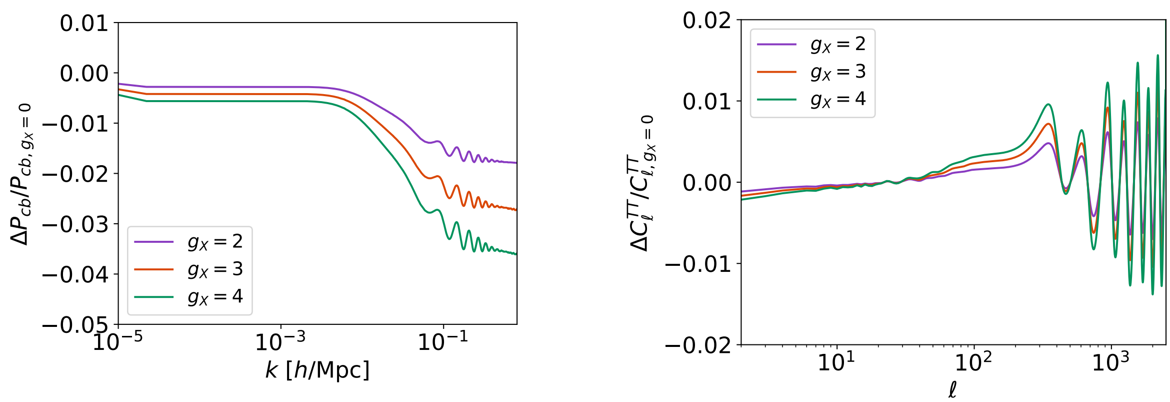

Figure 1: Effect of introducing a fermionic LiMR with degrees of freedom g_X, temperature $T_X = 0.91$ K today and mass $m_X = 0.02$ eV on the CDM+baryon power spectrum (**Left**) and the CMB temperature power spectrum (**Right**), from Deporzio et al. (2020)[32]. Here all cosmological parameters are fixed when introducing the Weyl-fermionic LiMR.

Effects on Cosmology

LiMRs with masses in the eV-scale will become non-relativistic before today. They, therefore, affect the CMB through both their mean energy density (background)[33;34], as well as their perturbations[35;36]. Their additional energy density changes the expansion rate of the universe, which affects the CMB damping tail. Since matter-radiation equality is very well measured through the location of the first acoustic peak, this causes the power spectrum to be suppressed on short-wavelength modes. In addition to this effect, their perturbations cause a change in the amplitude and a shift in the location of the CMB acoustic peaks[19–21]. This is summarized in Fig. 1, where we exemplify the effect of a LiMR on the CMB.

Unlike CDM, which is expected to compose the majority of the matter sector, LiMRs have significant thermal motions, even if non-relativistic, which leaves an imprint in the form of suppressed matter fluctuations, akin to the case of neutrino masses[37–39]. While the mechanism that produces the suppression is the same as for neutrino masses, the free-streaming scale $k_{\rm fs}$ for a LiMR is not fully determined by its mass (or abundance), as their temperature today is unknown. We show the LiMR-induced suppression in the power spectrum $P_{\rm cb}$ of CDM and baryons (as only those form galaxies) in Fig. 1. In all cases the high-k power is more suppressed. Increasing the abundance of the LiMR produces a more marked suppression, while keeping the shape fixed, plus wiggles at the BAO scale, as the LiMR both contributes as radiation at recombination and free streams – like neutrinos – changing the BAO phase[17;20;21;40].

Different upcoming cosmic surveys will, thus, be able to probe relics down to different masses. In particular, the currently running DESI and the upcoming CMB-S4 together will fully cover the parameter space of Dirac fermions, as well a rule out minimal temperature relics with masses above roughly 1 eV, depending on whether they are vectors, Weyl fermions, or scalars.

Of particular interest is the case of the gravitino, where upcoming data would be able to detect its cosmic abundance down to eV masses[32]. This is the benchmark of many models of SUSY breaking[41;42], and a factor of a few better than the best limits currently available[43;44]. Under the assumption that a cosmological gravitino population no longer exchanges entropy after decoupling from the SM bath, we can relate constraints on the mass m_X of the gravitino to bounds on the SUSY breaking scale $\Lambda_{\rm SUSY} \sim \sqrt{m_X M_{\rm Pl}}$[45;46]. These upcoming datasets will, thus, set an upper bound of $\Lambda_{\rm SUSY} \lesssim 50$ TeV, which complements the energy range that can be reached by the next-generation of proposed $\mathcal{O}(100\ \text{TeV})$ particle colliders, showing the promise of cosmological searches for new physics.

Challenges

LiMRs ought to be considered as a contaminant for neutrino-mass measurements with cosmic data sets. This is due to the degeneracy between the LiMR abundance and the neutrino mass, as both produce a power-spectrum suppression. The degradation in the expected errors for the neutrino mass ranges from 10% for heavy relics and futuristic data (DESI+CMB-S4), to nearly 100% for lower masses and current or upcoming data (BOSS/DESI+Planck)[32]. Likewise, marginalizing over the neutrino mass can degrade LiMR constraints by roughly 30%, where this effect is most exaggerated for z-independent bias parameterizations.

In order to obtain robust limits on LiMRs, one aspect that ought to be well understood is their clustering. Massive neutrinos are known to not cluster within typical galaxies[47], and thus it is safe to assume that they fully freely stream. LiMRs, on the other hand, have lower temperature and higher masses than neutrinos, and thus may cluster within galaxies. This fully non-linear effect must be simulated to fully understand it, which requires important computational efforts.

The next-generation of cosmic data will open the possibility of a LiMR detection, or close the eV-mass range window for these relics[32]. Funding of upcoming LSS observatories, such as PUMA[48] or MegaMapper[49], and the CMB-S4[50] and CMB-HD[51] experiments is thus critical for these searches of new physics.

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