Light Relic Targets

Attached is a list of potential targets for $N_{\rm eff}$ within the context of a CMB Stage 4 experiment, using the range $\sigma(N_{\rm eff}) = 0.027 - 0.035$ for guidance. To put the CMB-S4 specific targets, a list of targets from the current sensitivity $\sigma(N_{\rm eff}) = 0.18$ down is included.

I will take 2σ as the basis of comparison with the theoretical targets given that 2σ exclusion is a well agreed upon metric for excluding each of these targets. Standards for a detection or "evidence for" are more complicated especially in a cosmological context. E.g. whether 3σ is sufficient for evidence depends on the robustness of the observable and compatibility with other observations (see current measurement of H_0 for example).

The general context for many of these targets is that a thermal relic will contribute

$$\Delta N_{\rm eff} = g \times \left(\frac{7}{4}\right)\left(\frac{43/7}{g_\star(T_F)}\right)^{4/3} \tag{0.1}$$

For a bunch of particles, $g = n + m \times \frac{7}{4}$ where m and n are integers. In the standard model, when $T_F \gg 100$ GeV, $g_\star = 106.25$ and we get for increasing values of g:

$$\Delta N_{\rm eff} = 0.027, 0.047, 0.054, 0.074, 0.081, 0.094, 0.10, 0.11, \ldots \tag{0.2}$$

In principle, each point defines a target associated to a specific value of g. However, it is hard to quantify the value or reaching specific values of g. E.g. how important is the target $g = 3$ (e.g. three real scalars or a vector and a real scalar) relative to $g = 7/2$ (one Dirac fermion) or $g = 11/4$ (a real scalar and a Majorana fermion) . Nevertheless, $g = 1, 7/4$ and 2 are special as they are the minimal values of g for spin 0, 1/2 and 1 respectively. Certain classes of models to give some guidance as they provide additional motivation for particular values of g associated with the needs of the model. Furthermore, such models may also have more complicated thermal history than freeze-out at very high temperatures and produced difference values of $\Delta N_{\rm eff}$. An incomplete list of possible targets is shown in Figure [**?**]

Fortunately for CMB-S4, the projected sensitivity is in the neighborhood of some of the less ambiguous targets. For $\sigma(N_{\rm eff}) \leq 0.035$ we are reaching targets associated single degrees of freedom with different spins. This is also where we first become sensitive to the minimal case, $g = 1$, that freezes-out before the QCD phase transition. A more focused set of targets for CMB-S4 is shown in Figure **??**.

List of Targets with references

- $\boldsymbol{N_{\rm eff} = 0.24}$ **– Familons:** The Standard model contains an approximate $U(3)^5$ family/flavor symmetry that is broken by the Yukawa couplings (mass matrix). It is natural to consider scenarios where one of these groups is completely broken spontaneously, giving rise to 9 goldstone bosons ($g = 9$). If these goldstones (familons) are in equilibrium with the standard model they contribute $\Delta N_{\rm eff} \geq 9 \times 0.027$ (see for example [**?**]). Observational limits [**?**] on these scenarios allow large ranges of parameters that would be probed by measurements of $N_{\rm eff}$ [**?**].

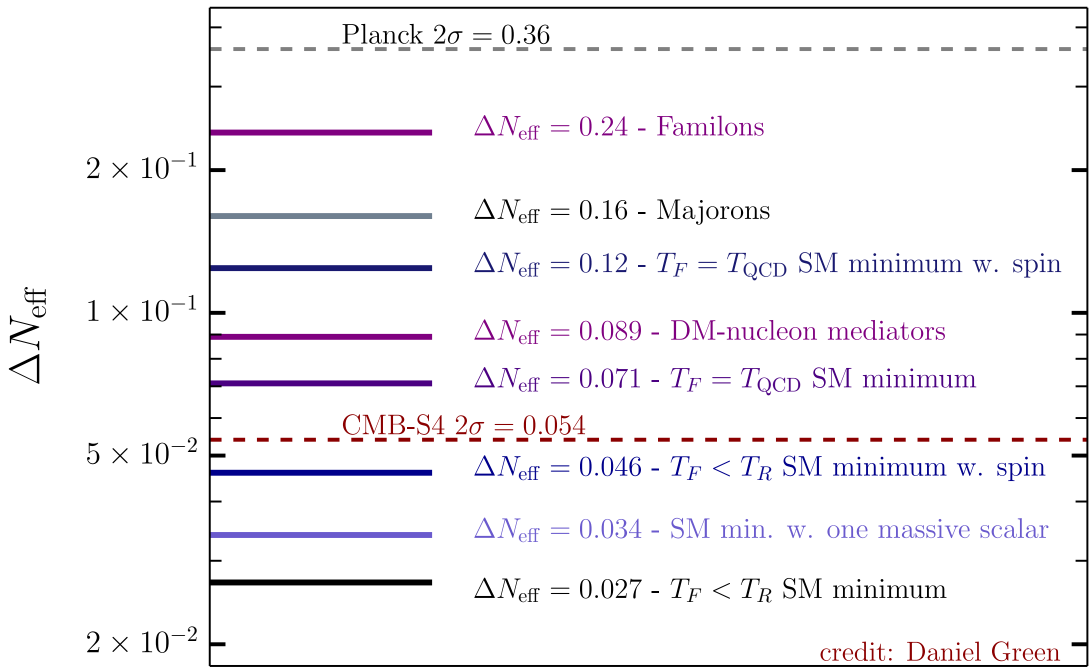

Figure 1: Some interesting targets for $N_{\rm eff}$ that lie below the current Planck $2\sigma = 0.36$ upper limit and the minimum for thermal equilibrium with Standard model of $\Delta N_{\rm eff} = 0.027$. The lines are explained in the text.

- **$N_{\rm eff} = 0.16$ – Majorons:** Similar to familons but coupled only the the neutrinos. Cosmological constraints are up to 7 orders of magnitude stronger than experimental limits [**?**] for some parameter windows. There is a large window that produces $\Delta N_{\rm eff} = 0.16$ that is currently consistent with observations.

- **$N_{\rm eff} = 0.12$ – $T_F = T_{QCD}$ for particles with spin:** Figure **??** shows $\Delta N_{\rm eff}$ as a function of freeze-out temperature T_F. If we take the upper limit on the beginning of the QCD phase transition at 300 MeV, then freeze-out before the QCD phase transition gives $\Delta N_{\rm eff} = 0.071 \times g$. Any particle with spin has $g \geq 7/4$.

- **$N_{\rm eff} = 0.089$ – Mediators of force with nucleons:** Astrophysical constraints leave the possibility of new long rang forces that couple exclusively to nuclei (quarks) with relatively large coupling constants. This case is of particular interest for mediating forces with dark matter (for example). Such a mediator is necessarily in equilibrium above $T_{\rm QCD}$ and will produce $\Delta N_{\rm eff} \geq 0.089$ [**?**].

- **$N_{\rm eff} = 0.071$ – $T_F = T_{QCD}$:** Figure **??** shows $\Delta N_{\rm eff}$ as a function of freeze-out temperature T_F. If we take the upper limit on the beginning of the QCD phase transition at 300 MeV, then freeze-out before the QCD phase transition gives $\Delta N_{\rm eff} = 0.071 \times g$. All particles have $g \geq 1$.

- **$N_{\rm eff} \approx 0.06$ – Light Gravitions:** Current limits on thermalized gravitons require that

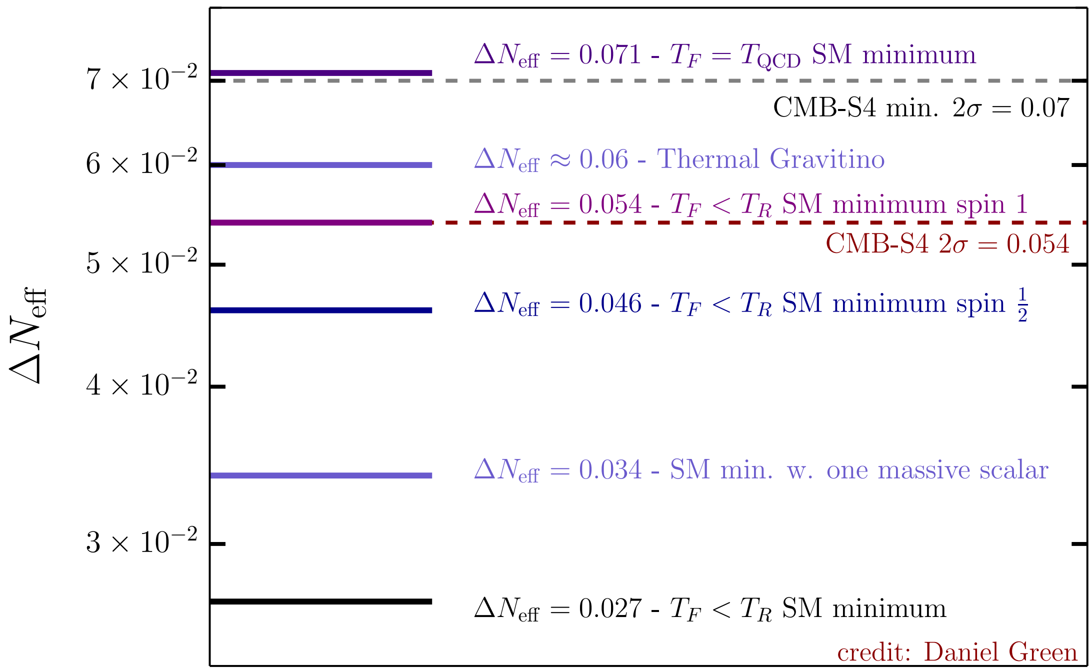

Figure 2: Some interesting targets for $N_{\rm eff}$ that lie near the CMB Stage 4 aspirational and minimum goals of $\sigma(N_{\rm eff}) = 0.027$ and 0.035 respectively.

$m_{3/2} < 4.7$ eV [**?**]. At lower masses, the coupling to the helicity 1/2 components of the gravitino becomes stronger producing a lower freeze-out temperature. We can exclude all light gravitinos if we could probe $\Delta N_{\rm eff} \approx 0.06$ [**?**].

- $\boldsymbol{N_{\rm eff} = 0.027, 0.046, 0.054}$ **– Thermal Relics with** $\boldsymbol{T_F < T_R}$**:** These numbers follow from $\Delta N_{\rm eff} \geq 0.027 \times g$ with $g = 1, 7/4, 2$ for spins 0, 1/2 and 1.

- $\boldsymbol{N_{\rm eff} = 0.034, 0.068}$ **– Thermal Relic with a massive field:** If we have one light field $g = 1$ and one heavy field ($g_h = 1$) with mass m_h that are in equilibrium at $T = m_h$. Suppose that the light field decouples form the standard model at T_F. If the heavy field is (is not) in equilibrium with the light field at freeze-out, the result contribution if $\Delta N_{\rm eff} \geq 0.068$ ($\Delta N_{\rm eff} \geq 0.034$).

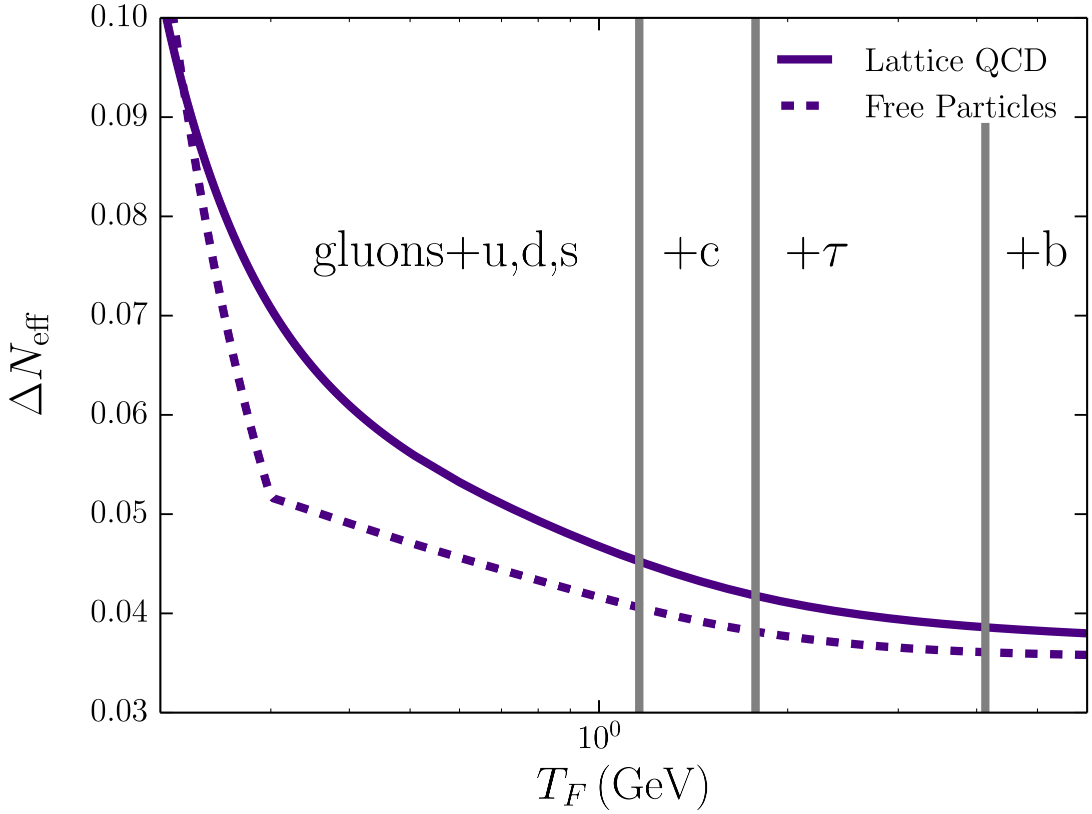

Figure 3: Change to N_{eff} for a single real scalar ($g = 1$) as a function of the freeze-out temperature. The solid line uses lattice calculations [?] of s/T^3 for $T < 1$ GeV to give a more accurate result near the QCD phase transition where treating the quarks and gluons as free particles is not terribly accurate. The dashed line is the result if we assume a gas of free particles. At high temperature both lines asymptote to $\Delta N_{\text{eff}} = 0.027$. The text indicates regions where we would be sensitive to the couplings to specific particles.

References

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