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Variable constants - A theoretical overview

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Abstract. In many theories of unified interactions, there are additional degrees of freedom which may allow for the variation of the fundamental constants of nature. I will review the motivation for such variations, and describe the theoretical relations between variations of gauge and Yukawa couplings.

1. Introduction

The last several years have seen considerable activity in both theoretical and experimental explorations of variable constants. This has been motivated partially by reports of a systematic variation of the fine structure constant in high red shift quasar absorption systems, as well as the emergence of the cosmological concordance model dominated by dark energy. In addition, there have been significant improvements in technical sensitivities, leading to vastly improved limits on the present time variation of α. Here, I will try to motivate the theory behind variable constants as well as discuss briefly the theoretical and experimental constraints on such variations.

It is important to first distinguish which constants can have meaningful variations. At first glance, there would appear to be a long list of potentially non-constant constants beyond the fine-structure constant, α. One could envision variations not only in other gauge and Yukawa coupling constants, but also in the speed of light, c; Newton's constant, G_N; Boltzmann's constant, k_B; Planck's constant, $\hbar$; and Fermi's constant, G_F among many others. Most of these however are not fundamental parameters of the theory, but rather should be considered fundamental units. Variations in the latter (or in any dimensionful quantity) simply reflect a change in our system of units and as such are not unambiguously observable. That is not to say the Universe with a variable speed of light is equivalent to one where the speed of light is fixed, but that any observable difference between these two universes can not be uniquely ascribed to the variation in c. In contrast, variations in dimensionless parameters represent fundamental and observable effects. As such, there is no meaning to statements referring to a measurement of the variation in the speed of light or whether a variation in α is due to a variation in c or $\hbar$. See e.g. Duff et al. (2002); Duff (2002) for a discussion on the number of fundamental units in physics.

Okun (1991) provides a nice example based on the hydrogen atom which illustrates our inability to measure the variation in c despite the physical changes such a variation would inflict. Lowering the value of c would lower the rest mass energy of an electron $E_e = m_e c^2$. When $2E_e$ becomes smaller than the binding energy of the electron to the proton in a hydrogen atom, $E_b = m_e e^4/2\hbar^2$, it becomes energetically favorable for the proton to spontaneously decay to a hydrogen atom

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and a positron. Clearly, this is an observable effect providing evidence that *some* constant of nature has changed. However, the quantity of interest is the ratio $E_b/2E_e = e^4/4\hbar^2c^2 = \alpha^2/4$. Therefore, it is not possible to distinguish which constant among e, $\hbar$, and c is changing.

The notion of time-varying constants goes back at least to Dirac and his large number hypothesis (Dirac 1938a,b). Dirac noticed that the ratio of the electromagnetic interaction between a proton and an electron to their gravitational interaction, $e^2/G_N m_p m_e \sim 10^{40}$, is roughly the same as the ratio of the size of the Universe to the "size" of the electron, $m_e c^3/e^2 H_0 \sim 10^{40}$, where $H_0 \simeq 70$ km s^{-1} Mpc^{-1} is the present-day Hubble parameter. Furthermore, both ratios are roughly the square root of the total number of baryons in the observable Universe, $c^3/m_p G_N H_0 \sim 10^{80}$. Dirac argued that these similarly large ratios could not be coincidence. If they are fundamental and constant, then noting that $H_0 \sim t^{-1}$ is not constant, Dirac proposed a time variation in Newton's constant $G_N \sim t^{-1}$. However, as in the case of Okun's decaying hydrogen atom, the desired result could have been achieved by taking $e^2/m_e \sim t^{1/2}$. The choice simply depends on one's choice of units. Dirac's choice of units fix e, c, and m_e as constants. Of course, the large number hypothesis has been excluded by experiments as the predicted variation of $\dot{G}_N/G_N \sim -10^{-10}$ yr^{-1} is about two orders of magnitude larger than the limits from the Viking landers on Mars which gave $\dot{G}_N/G_N = (2 \pm 4) \times 10^{-12}$ yr^{-1} (Hellings et al. 1983). The limit from big bang nucleosynthesis (see below) is comparable (Yang et al. 1979).

Before going further into the possible theoretical consequences for variations in fundamental constants, it will be useful to discuss how such variations might arise in a fundamental theory. The construction of theories with variable "constants" is straightforward. Consider, for example, a gravitational Lagrangian which contains the term

$$\mathcal{L} \sim \phi R, \qquad (1)$$

where ϕ is some scalar field and R is the Einstein curvature scalar. The gravitational constant is determined if the dynamics of the theory fix the expectation value of the scalar field so that

$$G_N = \frac{1}{16\pi\langle\phi\rangle}. \qquad (2)$$

Similarly a coupling in the Lagrangian of a scalar to the Maxwell term F^2, fixes the fine-strucure constant

$$\mathcal{L} \sim \phi F^2, \qquad \alpha = \frac{1}{16\pi\langle\phi\rangle}. \qquad (3)$$

Gravitational theories of the Jordan-Brans-Dicke type contain the possibility for a time-varying gravitational constant. However, these theories can always be re-expressed such that G_N is fixed and other mass scales in the theory become time dependent (i.e., dependent on the scalar field). For example, the JBD action can be written as

$$S = \int d^4x\,\sqrt{g}\left[\phi R - \frac{\omega}{\phi}\partial_\mu\phi\partial^\mu\phi + \Lambda + \mathcal{L}_m\right], (4)$$

where ω is a number which characterizes the degree of departure from general relativity (GR is recovered as $\omega \to \infty$), Λ is the cosmological constant, and the matter action for electomagnetism and a single massive fermion can be written as

$$\mathcal{L}_m = -\frac{1}{4e^2}F^2 - \overline{\Psi}\,\not{D}\Psi - m\overline{\Psi}\Psi. \qquad (5)$$

Written this way, if the scalar field ϕ evolves, then $G_N \propto 1/\phi$ does as well. In another conformal frame, the JBD action can be rewritten as

$$S = \frac{1}{16\pi G_N}\int d^4x\,\sqrt{g}\Big[\overline{R} -(\omega + \frac{3}{2})\frac{(\partial_\mu\phi)^2}{\phi^2} - \frac{\overline{\Psi}\,\not{D}\Psi}{\phi^{3/2}} - \frac{m\overline{\Psi}\Psi}{\phi^2} -\frac{1}{4e^2}F^2 + \frac{\Lambda}{\phi^2}\Big]. \qquad (6)$$

In this frame, Newton's constant *is* constant, but the fermion mass (after Ψ is rescaled) varies as $\phi^{-1/2}$ and the cosmological constant varies as $1/\phi^2$. The physics described by either of these two actions is identical. The quantity which carries an unambiguous variation is $G_N m^2$ which is proportional to $1/\phi$ in either frame. In this theory, because the Maxwell term is a conformal invariant in four dimensions, the fine-structure constant remains constant.

It is, however, straight forward to consider theories where the fine structure constant is varying. For example,

$$S = \int d^4x \sqrt{g} \left[\frac{1}{2} M_P^2 R - \frac{1}{2} M_*^2 \partial_\mu \phi \partial^\mu \phi \right. \qquad (7)$$
$$\left. - \frac{1}{4} e^{-2\phi} F^2 + \cdots \right],$$

as in the model of Beckenstein (1982). The field dependence of the Maxwell term is often generalized to $-\frac{1}{4} B_F(\phi) F^2$ (see for example Damour & Polyakov (1994); Olive & Pospelov (2002)). As we will see, it will be sufficient to assume only small changes in ϕ relative to its present value and so we can expand

$$B_F = 1 + \zeta_F \phi + \frac{1}{2} \xi_F \phi^2. \qquad (8)$$

With the choice, $\phi(t_0) = 0$,

$$\alpha = \frac{e^2}{4\pi B_F(\phi)} \qquad (9)$$

and

$$\frac{\Delta\alpha}{\alpha} = \zeta_F \phi + \frac{1}{2}(\xi_F - 2\zeta_F^2)\phi^2, \qquad (10)$$

where we have defined $\Delta\alpha/\alpha$ as $(\alpha_0 - \alpha(t))/\alpha_0$ and α_0 is $\alpha(t_0)$, the value of α today.

There are in fact strong constraints which can be placed on ζ_F from the equivalence principle (Olive & Pospelov 2002). The differential acceleration of two elements with different $A_{1,2}$ and $Z_{1,2}$ towards a common attractor can be expressed in terms of ζ_i and (See, e.g. Dicke (1965); Beckenstein (1982)),

$$\frac{\Delta g}{\bar{g}} = 2 \frac{g(A_1, Z_1) - g(A_2, Z_2)}{g(A_1, Z_1) + g(A_2, Z_2)} \qquad (11)$$
$$= \frac{2M_P^2}{M_*^2} f(\zeta_F, \zeta_N, A_i, Z_i, \bar{A}, \bar{Z})$$

where $\bar{Z}$ and $\bar{A}$ represent average Z and A of the common attractor. ζ_N is the analogous coupling of the scalar field to nucleons (if it exists). The analytic expression for f is given in Olive & Pospelov (2002). The best constraints on long-range forces are extracted from $\Delta g/\bar{g}$ measured in experiments that compare the acceleration of light and heavy elements. The differential acceleration of platinum and aluminium is $\leq 2 \times 10^{-12}$ at the 2σ level, and the differential acceleration of the Moon (silica-dominated) and the Earth (iron-dominated) towards the Sun is $\leq 0.92 \times 10^{-12}$ (see e.g., Damour (2001)). Choosing the appropriate values of Z and A and retaining only the hydrogen contribution to the mass of the Sun, we get

$$\frac{2M_P^2}{M_*^2} \left| \zeta_p (\zeta_n - \zeta_p + a\zeta_F) \right| < O(10^{-11}) \qquad (12)$$

where $a \sim 10^{-2}$.

Now, even if in this model, one initially introduces the coupling of ϕ only to F^2, as in the model of Beckenstein (1982) where $B_F(\phi) = \exp(-2\phi)$ or $\zeta_F = -2$, the coupling of ϕ to nucleons appears at higher order and is given by the matrix elements, $\zeta_N = m_N^{-1} \langle N | \frac{\zeta_F}{4} F_{\mu\nu} F^{\mu\nu} | N \rangle \simeq -m_N^{-1} \langle N | \frac{\zeta_F}{2} (E^2 - B^2) | N \rangle$, that determine the contribution of a "photon cloud" to the nucleon mass. Both the naive quark model and dispersion approaches give consistent estimates of these matrix elements (Gasser & Leutwyler 1982). Using the results of Gasser & Leutwyler (1982), presumably valid to 50% accuracy, one finds that $\zeta_p \simeq -0.0007\zeta_F$ and $\zeta_n \simeq 0.00015\zeta_F$. These relations translate into a limit

$$\frac{2M_P^2}{M_*^2} \zeta_F^2 \lesssim 10^{-6} \qquad (13)$$

Thus the simplest version of Beckenstein's model is excluded for $M_* = M_p$.

2. Coupled variations

In unified theories of particle interactions, one general imposes gauge coupling unification at some higher energy scale. At that scale (typically of order 2×10^{16} GeV), all gauge couplings are equal and run to their respective values at low energies (though correct values at low energies also requires supersymmetry). In this case, a change in the fine structure constant would directly imply a change in other gauge couplings (Campbell & Olive 1995). More importantly, variations in the strong gauge coupling will induce variations in the QCD scale Λ_{QCD} as is evident from the low energy expression for Λ when mass thresholds are included

$$\Lambda = \mu \left(\frac{m_c \, m_b \, m_t}{\mu^3} \right)^{2/27} \exp\left(-\frac{2\pi}{9\alpha_s(\mu)} \right). \quad (14)$$

for $\mu > m_t$ up to some unification scale in the standard model (Campbell & Olive 1995; Langanker, Segre, & Strassler 2002; Dent & Fairbairn 2003; Calmet & Fritzsch 2002; Damour, Piazza, & Veneziano 2002).

In addition, it may happen that variations in gauge couplings also induce variations in the Yukawa couplings. This is expected in many string theories where all such couplings are determined by the expectational value of a dilaton and we might expect (Campbell & Olive 1995)

$$\frac{\Delta h}{h} = \frac{1}{2} \frac{\Delta \alpha}{\alpha} \quad (15)$$

where h is a Yukawa coupling and fermion masses are simply proportional to hv where v is the Higgs vacuum expectation value (vev). Variations in Yukawa couplings will also affect variations in Λ_{QCD} so that

$$\frac{\Delta \Lambda}{\Lambda} = R \frac{\Delta \alpha}{\alpha} + \frac{2}{27} \left(3 \frac{\Delta v}{v} + \frac{\Delta h_c}{h_c} + \frac{\Delta h_b}{h_b} + \frac{\Delta h_t}{h_t} \right). \quad (16)$$

Typical values for R are of order 30 in many grand unified theories, but there is considerable model dependence in this coefficient (Dine et al. 2003).

Furthermore, in theories in which the electroweak scale is derived by dimensional transmutation, changes in the Yukawa couplings (particularly the top Yukawa) leads to exponentially large changes in the Higgs vev. In such theories, the Higgs expectation value corresponds to the renormalization point and is given qualitatively by (Campbell & Olive 1995)

$$v \sim M_P \exp(-2\pi c/\alpha_t) \quad (17)$$

where c is a constant of order 1, and $\alpha_t = h_t^2/4\pi$. Thus small changes in h_t will induce large changes in v. For $c \sim h_t \sim 1$,

$$\frac{\Delta v}{v} \sim S \frac{\Delta h}{h} \quad (18)$$

with $S \sim 160$, though there is considerable model dependence in this value as well. For example, in supersymmetric models, S can be related to the sensitivity of the Z gauge boson mass (related to the Higgs vev) to the top Yukakwa, and may take values anywhere from about 80 to 500 Ellis et al. (2002). This dependence gets translated into a variation in all low energy particle masses (Dixit & Sher 1988). In short, once we allow α to vary, virtually all masses and couplings are expected to vary as well, typically much more strongly than the variation induced by the Coulomb interaction alone.

3. Limits on the variations of α

There are a number of important astrophysical and terrestrial constraints on the fine-structure constant that must be respected. The most primordial of the limits comes from big bang nucleosynthesis (BBN) (Kolb, Perry, & Walker 1986; Malaney & Mathews 1993; Scherrer & Spergel 1993; Campbell & Olive 1995; Bergstrom, Iguri, & Rubenstein 1999; Nollett & Lopez 2002; Ichikawa & Kawasaki 2004) which tests for variations back to a cosmological redshift as high as $\sim 10^{10}$.

The theory of big bang nucleosynthesis describes the production of the light elements, D, ^{3}He, ^{4}He, and ^{7}Li, in the early Universe. Its success relies on a fine balance between the overall expansion rate of the Universe and the weak interaction rates which control the relative number of neutrons to protons at the onset of nucleosynthesis. Changes in the expansion rate, which is proportional to $\sqrt{G_N N}$ where N is the number of relativistic particles, or changes in the weak rates, which may result from changes in fundamental parameters, affect the neutron to proton ratio and ultimately the ^{4}He abundance, Y. Thus one can use the concordance between the theory and the observational determination of the light element abundances to constrain new physics (Cyburt et al. 2005). The relation between nucleosynthesis and BBN will be the focus of a separate contribution to these proceedings.

The relatively good agreement between theory and observation for ^{4}He in BBN allows one to set a limit of $|\Delta\alpha/\alpha| \lesssim 0.04$ using $|\Delta Y/Y| \lesssim 4\%$ ($\Delta Y/Y$ scales with $\Delta\alpha/\alpha$). Since this limit is applied over the age of the Universe, we obtain a limit on the rate of change $|\dot{\alpha}/\alpha| \lesssim 3 \times 10^{-12}$ yr^{-1} over the last 13.7 Gyr. In the context of unified or string-inspired theories, this limit is significantly stronger and improves by about two orders of magnitude (Campbell & Olive 1995; Ichikawa & Kawasaki 2002; Müller et al. 2004; Coc et al. 2007; Dent et al. 2007).

One can also derive cosmological bounds based on the microwave background. Changes in the fine-structure constant lead directly to changes in the hydrogen binding energy, E_b. As the Universe expands, its radiation cools to a temperature at which protons and electrons can combine to form neutral hydrogen atoms, allowing the photons to decouple and free stream. Measurements of the microwave background can determine this temperature to reasonably high accuracy (a few percent) (Komatsu et al. 2009). Decoupling occurs when $\eta^{-1}\exp(-E_b/T) \sim 1$, where $\eta \sim 6 \times 10^{-10}$ is the ratio of the number density of baryons (protons and neutrons) to that of photons. Thus, changes in α of at most a few percent can be tolerated over the time scale associated with decoupling (a redshift of $z \sim 1100$) (Nakashima et al. 2008).

Very strong constraints on the variation of α can be obtained from the Oklo natural reactor which operated in Gabon approximately two billion years ago. The site has a rich uranium deposit which is naturally enriched in ^{237}U at the level of about 3.7%. The observed isotopic abundance distribution at Oklo can be related to the cross section for neutron capture on ^{149}Sm (Shlyakhter 1976; Damour & Dyson 1996). The key isotopic ratio is that of ^{149}Sm/^{147}Sm which is 2% at the Oklo site relative to the common terrestrial value of about 90%, indicating strongly that ^{149}Sm was depleted by a thermal neutron source.

The limit on α is based on the resonant neutron capture cross section for

$$^{150}\text{Sm} + n \rightarrow {}^{150}\text{Sm} + \gamma \tag{19}$$

The resonant cross section proceeds through an excited state of ^{150}Sm which happens to lie very close to the Q value

$$E_r = Q - E^* = 0.0973\text{eV} \tag{20}$$

The observed isotopic ratios only allow a small shift of $|\Delta E_r| \sim E_r$ from the present value. This then constrains the possible variations in the energy difference between the excited state of ^{150}Sm and the ground state of ^{149}Sm over the last two billion years. Assuming that the energy difference is due to the α-dependence of the Coulomb energy alone, a limit

$$-0.56 < \Delta\alpha/\alpha \times 10^7 < 0.66 \tag{21}$$

can be obtained (Damour & Dyson 1996; Fujii et al. 2000; Olive et al. 2002; Petrov et al. 2006). However, if all fundamental couplings are allowed to vary interdependently, a much more stringent limit $|\Delta\alpha/\alpha| < (1-5) \times 10^{-10}$ may be obtained (Olive et al. 2002).

Bounds on the variation of the fundamental couplings can also be obtained from our knowledge of the lifetimes of certain long-lived nuclei. In particular, it is possible to use precise meteoritic data to constrain nuclear decay rates back to the time of solar system formation (about 4.6 Gyr ago). Thus, we can derive a constraint on possible variations at a redshift $z \simeq 0.45$ bordering the range (z = 0.5–3.5) over which such variations are claimed to be observed (Murphy, Webb, & Flambaum 2003). The pioneering study on the effect of variations of fundamental constants on radioactive decay lifetimes was performed by Peebles & Dicke (1962) and by Dyson (1972). The isotopes which are most sensitive to changes in α are typically those with the lowest β-decay Q-value, Q_β. The isotope with the smallest Q_β value (2.66 ± 0.02 keV) is ^{187}Re. A precise age of 4.558 Gyr for angrite meteorites can be determined by the ^{207}Pb-^{206}Pb method (Lugmair & Galer 1992). The data on ^{187}Re and ^{187}Os in iron meteorites formed within 5 Myr of the angrite meteorites (Smoliar et al. 1996) then give a limit $-8 \times 10^{-7} < \Delta\alpha/\alpha < 24 \times 10^{-7}$ (Olive et al. 2002; Fujii & Iwamoto 2004; Olive et al. 2004).

Finally, there are a number of present-day laboratory limits on the variability of the fine-struncture constant using atomic clocks. Here, there has been marked improvement in the limit on $\Delta\alpha/\alpha$. The strongest constraint comes from optical frequencies in an Al/Hg ion clock and yields $\dot{\alpha}/\alpha = (1.6 \pm 2.3 10^{-17}$ yr^{-1} (Rosenband et al. 2008).

4. Observations

As there will be several reviews of the observations in these proceedings, I will be very brief here, with the main purpose of drawing together many of the theoretical ideas and limits with the existing observations.

Much of the recent excitement over the prospect that the fundamental constants of nature vary in time has been spurred by the indication that the fine structure constant was smaller at cosmological redshifts $z = 0.5$–3.5 as suggested by observations of quasar absorption systems (Webb et al. 1999; Murphy, Webb, & Flambaum 2003). The statistically significant result of $\Delta\alpha/\alpha = (0.54 \pm 0.12) \times 10^{-5}$, where recall that here, $\Delta\alpha$ is defined as the present value minus its value in the past. This measurement is based on the many-multiplet method which makes use of the α dependence of the relativistic corrections to atomic energy levels. and allows for sensitivities which approach the level of 10^{-6}. This method compares the line shifts of elements which are particularly sensitive to changes in α with those that are not. At relatively low redshift ($z < 1.8$), the method relies on the comparison of Fe lines to Mg lines. At higher redshift, the comparison is mainly between Fe and Si. At all redshifts, other elemental transitions are also included in the analysis.

More recent observations taken at VLT/UVES using the many multiplet method have not been able to duplicate the previous result (Srianand et al. 2004; Chand et al. 2004; Quast et al. 2004). The use of Fe lines in Quast et al. (2004) on a single absorber found $\Delta\alpha/\alpha = (0.05 \pm 0.17) \times 10^{-5}$. However, since the previous result relied on a statistical average of over 100 absorbers, it is not clear that these two results are in contradiction. In Srianand et al. (2004), the use of Mg and Fe lines in a set of 23 systems yielded the result $\Delta\alpha/\alpha = (0.06 \pm 0.06) \times 10^{-5}$ and therefore represents a more significant disagreement and can be used to set very stringent limits on the possible variation in α. The latter analysis has been recently criticized (Murphy et al. 2007) and defended (Srianand et al. 2007).

The result found in Srianand et al. (2004) and in the statistically dominant subsample of 74 out of the 128 low redshift absorbers used in Murphy, Webb, & Flambaum (2003) are sensitive to the assumed isotopic abundance ratio of Mg. In both analyses, a solar ratio of ^{24}Mg:^{25}Mg:^{26}Mg = 79:10:11 was adopted. However, the resulting shift in α is very sensitive to this ratio. Furthermore, it is commonly assumed that the heavy Mg isotopes are absent in low metallicity environments characteristic of QSO absorption systems. Indeed, had the analyses assumed only pure ^{24}Mg is present in the QSO absorbers, a much more significant result would have been obtained. The Keck/Hires data (Murphy, Webb, & Flambaum 2003) would have yielded $\Delta\alpha/\alpha = (0.98 \pm 0.13) \times 10^{-5}$ for the low redshift subsample and $\Delta\alpha/\alpha = (0.36 \pm 0.06) \times 10^{-5}$ for the VLT/UVES data (Srianand et al. 2004).

The sensitivity to the Mg isotopic ratio has led to a new possible interpretation of the many multiplet results (Ashenfelter, et al. 2004; Ashenfelter et al. 2004). The apparent variation in α in the Fe-Mg systems can be explained by the early nucleosynthesis of ^{25,26}Mg. A ratio of (^{25}Mg + ^{26}Mg)/^{24}Mg = 0.62 ± 0.05 (0.30 ± 0.01) is required by the data in Murphy, Webb, & Flambaum (2003) (Srianand et al. (2004)).

In the context of coupled variations, a variation in α would imply a variation in the proton-to-electron mass ratio as well. Naively, one would predict that

$$\frac{\Delta\mu}{\mu} \sim \frac{\Delta\Lambda_{QCD}}{\Lambda_{QCD}} - \frac{\Delta\nu}{\nu} \sim -50\frac{\Delta\alpha}{\alpha} \qquad (22)$$

where $\mu = m_p/m_e$.

Some indications for variations in μ have been reported by Reinhold et al. (2006) based on observations of molecular hydrogen. Though they make it clear that systematic uncertainties are large, they found $\Delta\mu/\mu = (-2.4 \pm 0.6) \times 10^{-5}$. This result was not confirmed in King et al. (2008) who also used molecular hydrogen to derive $\Delta\mu/\mu = (-2.6 \pm 3.0) \times 10^{-6}$, nor in Thompson et al. (2009) who found $\Delta\mu/\mu = (7 \pm 8) \times 10^{-6}$.

5. Conclusions

Variations of fundamental constants are certainly possible within the context of unified theories of particle interactions. Indeed, in the context of string theories, the presence of a dilaton and other moduli fields almost guarantee that at some level gauge and Yukawa coupling constants are dynamical. Whether or not, these fields are fixed at or near the Planck scale (rendering our constants constant over effectively all of the history of the Universe) is unknown. If not, then there is the interesting possibility that the value of these constants varied over cosmological timescales.

While possible, there are many constraints on the variations in α which cover a very wide range of cosmological red shifts. Starting with BBN (at $z \sim 10^{10}$) to the present, the constraints range from modest (order a few percent) to very stringent (such as those from Oklo).

There are also reported and disputed measurements of variations. These will be what make the session and these proceedings particularly interesting.

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