Probing Fundamental "Constants" with Big Bang Nucleosynthesis

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Astrophysical measurements
- Alpha
- $\mu \equiv m_p/m_e$
- Other quantities

Oklo and nuclear physics

Atomic clocks

GUTs, alpha and mu

Spacetime dependence and WEP violation

Cosmology
- BBN
- Unification scenarios

Reviews, previous work:

1. J.-P. Uzan, Rev.Mod.Phys. 75 (2003) 403 [hep-ph/0205340], also astro-ph/0409424
2. Springer Lecture Notes 648 (2004) *"Astrophysics, Clocks and Fundamental Constants"*, ed. Karshenboim and Peik (see astro-ph/0310318)
3. C. M. Müller, G. Schäfer and C. Wetterich, *"Nucleosynthesis and the variation of fundamental couplings"*, astro-ph/0405373
4. TD, *"Composition-dependent forces from varying m_p/m_e"*, hep-ph/0608067

Motivation

Constancy of “constants” (couplings, mass ratios) is an assumption of particle physics
Should be tested!

- Does it make sense?

  Measuring different fundamental constants at different points in spacetime breaks Einstein equivalence principle (Local Position Invariance)

- Generally covariant theories with “varying constants” can easily be constructed

  GR plus scalar field weakly coupled to radiation and matter

- Doing physics with “varying constants”
  1. Look for signals and set limits
  2. Look for related effects (WEP violation)
  3. A nonzero signal can rule out unified theories, test models of quintessence *etc.*

- Important to consider many probes: different z, different environments. . .

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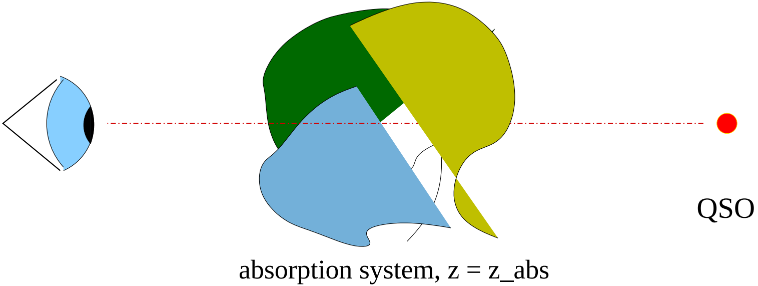
Alpha: measurement methods



$$\omega_z = \omega_0 + q\left[\left(\frac{\alpha_z}{\alpha}\right)^2 - 1\right]$$

"Many-multiplet" method: different species with different q coefficients enhance sensitivity (Murphy et al., astro-ph/0209488)

Latest published result, 143 systems (astro-ph/0310318)

$$\frac{\Delta\alpha}{\alpha} = (-0.57 \pm 0.11) \cdot 10^{-5}, \qquad 0.2 < z_{abs} < 4.2$$

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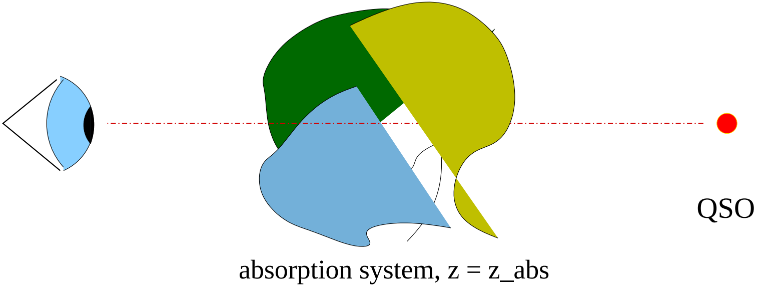

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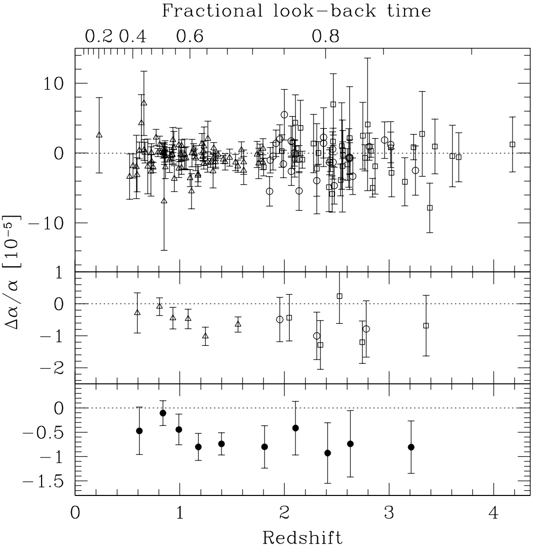
Alpha data



More spectra still being analyzed. . .

Other results on alpha

$$\frac{\Delta\alpha}{\alpha} = (-0.06 \pm 0.06) \cdot 10^{-5},\ 0.4 \leq z \leq 2.3$$ 23 systems, Srianand et al. 2004

$$\frac{\Delta\alpha}{\alpha} = (-0.007 \pm 0.084) \cdot 10^{-5},\ z_{abs} = 1.15$$ Levshakov et al. 2004

Murphy *et al.* criticize error assignments and fitting methods
`astro-ph/0611080, astro-ph/0612407`

Most recently :

$$\frac{\Delta\alpha}{\alpha} = (0.55 \pm 0.25) \cdot 10^{-5},\ z_{abs} = 1.84$$ Levshakov et al. `astro-ph/0703042`

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A new mu?

$$\mu \equiv \frac{m_p}{m_e}$$

Vibro-rotational transitions of molecular hydrogen H_2, different dependences on reduced mass

$$2005: \frac{\Delta\mu}{\mu} = (3.05 \pm 0.75) \cdot 10^{-5} \text{ (A)},\ (1.65 \pm 0.74) \cdot 10^{-5} \text{ (B)}$$ Ivanchik et al.

Two different sets of lab wavelengths!

New lab measurements:

$$\frac{\Delta\mu}{\mu} = (2.4 \pm 0.6) \cdot 10^{-5},\ z_{abs} = 3.02,\ 2.59$$ Reinhold et al. PRL 2006

Recently: NH_3 spectrum constraint on $\Delta\mu/\mu$

$$\frac{\Delta\mu}{\mu} = (0.6 \pm 1.9) \cdot 10^{-6},\ z = 0.685$$ Flambaum and Kozlov, PRL 2007

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Other dimensionless constants

⋆ $y \equiv \alpha^2 g_p$

$(\mu_p = g_p e/4m_p)$

Probe by comparing 21cm H I line and molecular rotation

$$\frac{\Delta y}{y} = (-0.20 \pm 0.44) \cdot 10^{-5}\ (z = 0.247), \qquad (-0.16 \pm 0.54) \cdot 10^{-5}\ (z = 0.685)$$

Murphy et al. 2001

⋆ $x \equiv \alpha^2 g_p \mu^{-1}$

Compare UV heavy element transitions with H I line

$$\frac{\Delta x}{x} = (0.63 \pm 0.99) \cdot 10^{-5},\ 0.23 \leq z_{abs} \leq 2.35$$

Tzanavaris et al. 2006

⋆ $F \equiv g_p \left[\alpha^2 \mu\right]^{1.57}$

Probe by comparing HI and OH lines

$$\frac{\Delta F}{F} = (0.44 \pm 0.36^{\rm stat} \pm 1.0^{\rm sys}) \cdot 10^{-5}\ (z = 0.765)$$

Kanekar et al. 2006

Oklo natural nuclear reactor

2 billion years ago ($z = 0.1$–0.15) naturally enriched uranium in a rock formation with a water moderator. . .

Resulting isotopic ratios in rock samples differ radically from any other terrestrial material

Samarium

Ratio ^{149}Sm/^{147}Sm : normally 0.9, measured at about 0.02 in Oklo sample

Resonant neutron capture

$$^{149}\mathrm{Sm} + n \to {}^{150}\mathrm{Sm} + \gamma$$

Today $E_{r,0} = 97.3$ meV, resonance width $\simeq 60$ meV

Resonance energy arises from $\langle H_c + H_n \rangle$ where $H_c \propto \alpha$

$$\alpha \frac{d}{d\alpha} \langle H_c \rangle \simeq 1\,\text{MeV}$$

Neutron fluence and spectrum: estimate from other isotopes e.g.

$$^{143}\mathrm{Nd}(n, \gamma)^{144}\mathrm{Nd}$$

cross-section has no sharp resonances, depends weakly on α

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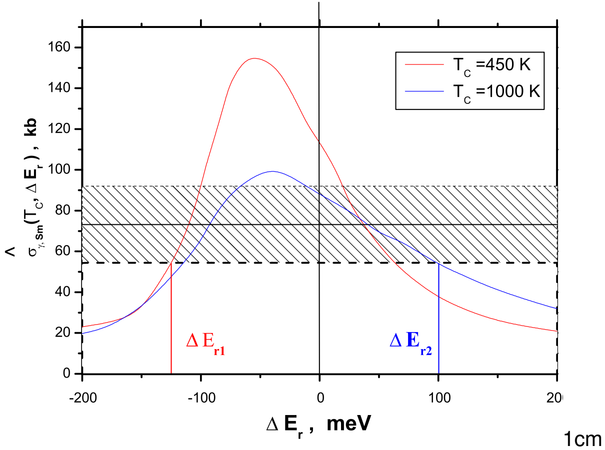
Oklo bound



Recent bound

$$-5.6 \times 10^{-8} < \Delta\alpha/\alpha < 6 \times 10^{-8}, \qquad \dot{\alpha}/\alpha \leq 3.5 \times 10^{-17}\,\mathrm{y}^{-1}$$

Petrov et al. `hep-ph/0506186`, see also Damour & Dyson 1996

Interpreting Oklo, other nuclear physics bounds

Nuclear physics parameters m_n, m_π, ... may also vary!

Can we calculate dependence of $\langle H_n \rangle$ from first principles – QCD, quark masses?

No — in general alpha bound will not hold

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Atomic clocks

Absolute frequency standard: ^{133}Cs ground state hyperfine transition

Measure some other transition in the lab over years ⇒
bound on fundamental "constant" variations (up to variation of $\mu_{\rm Cs}$)

Example

- Atomic hydrogen 1S-2S transition $\nu_H \propto$ Ry
- Mercury electric quadrupole transition $\nu_{\rm Hg} \propto {\rm Ry}\alpha^{-3.2}$
- Caesium hyperfine transition $\nu_{\rm Cs} \propto {\rm Ry}\alpha^2 \frac{\mu_{\rm Cs}}{\mu_{\rm B}} \alpha^{0.8}$

Eliminate $\mu_{\rm Cs}$ to obtain $\dot{\alpha}/\alpha = (-0.9 \pm 2.9) \cdot 10^{-15}\,{\rm y}^{-1}$ Fischer et al. PRL 2004

Update: Peik et al. physics/0611088

$$d\ln\alpha/dt = (-0.26 \pm 0.39) \times 10^{-15}\,{\rm y}^{-1}, \qquad d\ln\mu/dt = (-1.2 \pm 2.2) \times 10^{-15}\,{\rm y}^{-1}$$

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Unification relations between alpha, mu

Unified theories ought to predict low-energy parameters

$$\alpha,\ \sin^2\theta_W,\Lambda_{\rm QCD},\ m_l,\ m_q,\ G_F\ldots$$

$\Rightarrow$ functional relations between α, μ,...

Calmet & Fritszch, Langacker et al., TD & Fairbairn 2001

Example (Varying unified coupling)

GUT scale M_U, unified coupling α_U

$$\frac{\Delta\alpha}{\alpha} \simeq 0.5\frac{\Delta\alpha_U}{\alpha_U}$$

$$\frac{\Lambda_{QCD}}{M} \propto e^{-2\pi/9\alpha_3(M)}\left(\frac{m_c m_b m_t}{M^3}\right)^{2/27} \times \cdots$$

to lowest order:

$$\Delta\ln\frac{m_p}{M_U} \simeq 17\Delta\ln\alpha_U$$

Define $R \equiv \Delta\ln\mu/\Delta\ln\alpha$

$$\Rightarrow R \simeq 34\ ?$$

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Mass generation and thresholds

What about mass generation: how is the hierarchy explained?

$$\frac{\langle\phi\rangle}{M_U}, \; \frac{m_e}{m_t}$$

Both technicolor and hidden sector SUSY-breaking use dynamical scale

$$\frac{\langle\phi\rangle}{M_U} = \exp(2\pi/b_h \alpha_h(M_U)) \times \text{polynomial}$$

if α_h varies with α_U then

$$\Delta \ln \frac{\langle\phi\rangle}{M_U} \simeq 34 \Delta \ln \alpha_U \simeq 68 \Delta \ln \alpha$$

- Variation of m_e
- Threshold effects in running of α_3 and $\alpha_{\rm em}$
- Light quark mass contributions to m_p
- Superpartner thresholds $\tilde{m}$ important in SUSY-GUT

TD, 2003

SUSY-GUT with varying $\tilde{m}$: $R = 4 \pm 5$

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Spacetime dependence of variations

"Spontaneous" violation of LPI: cosmologically varying scalar $\varphi(x^\mu)$

"Constants" are functions of $\langle\varphi\rangle$

General theoretical framework: introduce action

$$\int d^4x\, \mathcal{L}(g_{\mu\nu}, \varphi, \text{matter})$$

Questions:

- Does variation of φ inside virialized systems track cosmological evolution? (Yes! Wetterich 2002, Shaw & Barrow 2005)
- Does the value of φ differ in different environments? (Yes – but not much!)
- Does $\varphi(t)$ vary monotonically or oscillate? (Fujii 2003)
- What drives the variation? (potential $V(\varphi)$, coupling to matter, ...)
- What is the mass of the field?
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WEP

Light scalar coupled to electromagnetic energy mediates composition-dependent force

$$m_{p,n} = m_{N,\mathrm{QCD}} + B_{p,n}\alpha_0(1+\lambda_{em}\varphi) + \cdots$$

φ-mediated force between Earth / Sun and different atoms

- Proton fraction f_p is 0.456 for Cu, 0.385 for U
- Different electromagnetic binding energies B_{nucl}

$\Rightarrow$ differential acceleration

$$\eta \equiv 2\frac{|a_1 - a_2|}{|a_1 + a_2|} \qquad \propto \frac{\lambda^2}{m_N^2} B_{\mathrm{source}}(\Delta f_n B_n + \Delta f_p B_p + \Delta B_{\mathrm{nucl}})$$

Current limit $\eta \lesssim 10^{-13}$ (Eöt-Wash experiments)

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WEP vs. varying "constants"

Phi couplings to e, p/n, α: λ_e, $\lambda_i \pm \lambda_v/2$, λ_{em}

$$\eta \simeq \left(\frac{\lambda_e}{1837} + \frac{\lambda_i - \lambda_v}{2}\right)\left(\left[\frac{\lambda_e}{1837} - \lambda_v\right]\Delta_{12} f_p + \lambda_{em} f_{em} \Delta_{12} \frac{\langle Z^2 A^{-1/3}\rangle}{\langle A \rangle}\right)$$

Variation in $\bar{\phi}$ is ≤ 1 otherwise kinetic energy dominates (Dvali/Zaldarriaga 2001)

Variation of order 10^{-5} in α or $\mu \implies$ some λ must be 10^{-5} or greater

Typically

$$\Delta_{12} f_p \simeq 0.04, \qquad \Delta_{12}(Z^2/A^{2/3}) \simeq -1$$

thus η may be as large as 10^{-12} (λ_v at 10^{-5} level) ...

Elliptical Earth orbit $\rightarrow$ seasonal variation in "constants" (Flambaum, Shaw 2007)

$$\frac{\delta\alpha}{\alpha}_{|\text{seasonal}} = \frac{10^{-9}\eta}{4|\eta_1 - \eta_2|}$$

η_i: sensitivity of mass to α variation, $\eta > 10^{-4}$

clocks require 10^{-18} accuracy or better

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Bounding $\dot{\bar{\varphi}}$

$$\frac{\dot{\bar{\varphi}}}{H} = \sqrt{3\Omega_\varphi(1+w_\varphi)}$$

Cosmological bounds: estimate

$$\dot{\varphi} \leq \dot{\varphi}_{\rm max} \simeq 5 \times 10^{-11}\, y^{-1}$$

η bounds current variations:

$$\eta \geq \frac{K}{c_1^2}\left(\frac{\dot{\alpha}/\alpha}{3.7 \times 10^{-10}\, y^{-1}}\right)^2$$

link between atomic clocks and WEP experiments today: TD, hep-ph/0608067

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Cosmology: CMB & after

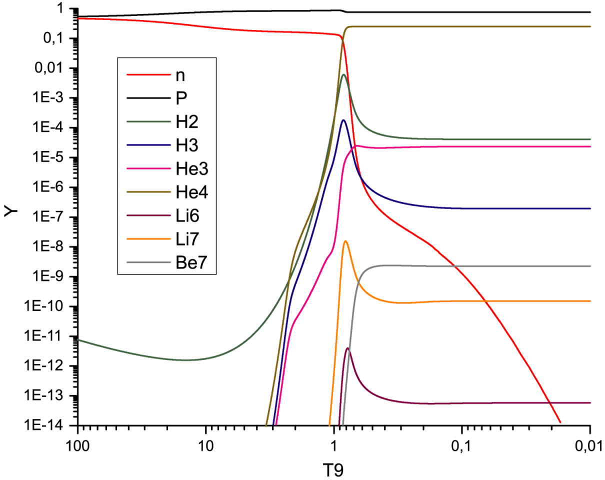
α affects CMB through Thomson scattering, recombination history

$$0.95 < \frac{\alpha_{\rm CMB}}{\alpha_0} < 1.02 \; (1\sigma), \; z \sim 10^3$$ (Martins et al. 2004)

Relatively weak bound, degenerate with variations in other cosmological parameters

Effect of α on 21cm emissions?

BBN: what is it?



$T_9 \equiv T/10^9$ K $\simeq T/0.1$ MeV

BBN motivation

- (Space)time-dependence of φ not known

  Test “constants” at many different redshifts, different astrophysical conditions

  BBN is extremely hot, dense, early compared to any other probe of particle physics

- More than one observable: D, ^{4}He, ^{7}Li, . . . ?

  WMAP determination of baryon density helps to fix one parameter

- Drawbacks: BBN sensitive to many parameters, degeneracy

  Astrophysical abundances have systematic issues

  ”Nuclear physics is unclear physics”

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Cosmology: BBN ($z \sim 10^{10}$)

Simple treatment: All neutrons end up in ^{4}He $\Rightarrow$ Helium abundance

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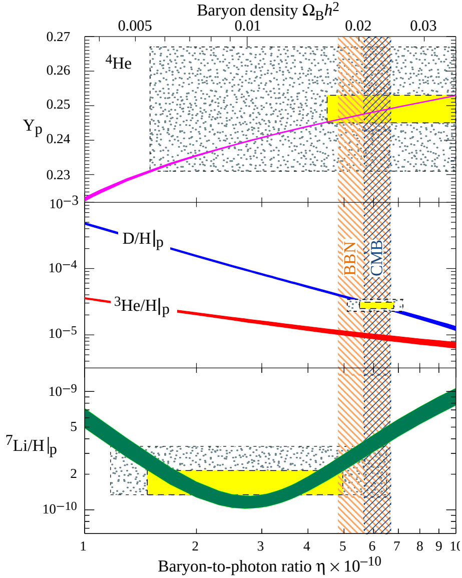
Observation *vs.* theory (Fields and Sarkar, PDG 2006)



Observation vs. theory: the numbers

- ^{4}He
  $Y_p = 0.2472 \pm 0.0012,\ 0.2516 \pm 0.0011$ Izotov et al. 2007
  0.2474 ± 0.0028 Peimbert et al. 2007
  Systematics from astrophysics, atomic physics

  Theory: SBBN with $\eta_{10} = 6.1$ gives $Y_p = 0.2482$ (0.2463 - new τ_n!)

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  Deuterium only destroyed in astrophysical processes
  Few observations, scatter: $\ln$ D/H $= -10.48 \pm 0.09$ O'Meara et al. 2006
  Good agreement with SBBN

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  "Spite plateau" – metal-poor halo stars

  Obs.: $\ln Y_{7\mathrm{Li}} = -22.8 \pm 0.2$ Bonifacio et al. 2007
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  $$\Delta \ln Y_{7\mathrm{Li}} \simeq -1.2 \pm 0.25$$ – factor of 3!

"Lithium problem": questions in stellar astrophysics

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Current project

Use elements other than ^{4}He to constrain more parameters

Problem: Dependence of binding energies and reaction rates ($A > 2$) on QCD

1. Define "nuclear parameters" X_i: inputs to the BBN integration code
   - η
   - G_N
   - α
   - τ_n
   - m_e
   - $Q_N \equiv m_n - m_p$
   - $m_N \equiv (m_n + m_p)/2$
   - Binding energies D, …, ^{7}Be
2. Find leading dependence of abundances on X_i and forward reaction rates
   - Only 8 important reactions
   - ^{4}He insensitive to rates
   - No abundance very sensitive to rates: $\partial \ln Y_a / \partial \ln \langle sigma \rangle \leq 1$
   - Very large dependence of ^{7}Li on binding energies (Q-values)
3. Estimate dependence on "fundamental" parameters G_k

Units defined with $\Lambda_{\rm QCD}$ set to constant

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Results

$\partial \ln Y_a / \partial \ln X_i$	D	^{3}He	^{4}He	^{6}Li	^{7}Li
η	-1.6	-0.57	0.04	-1.5	2.1
G_N	0.94	0.33	0.36	1.4	-0.72
α	2.3	0.79	0	4.6	-8.1
τ_n	0.41	0.15	0.73	1.4	0.43
m_e	-0.16	-0.02	-0.71	-1.1	-0.82
Q_N	0.83	0.31	1.5	2.9	1.0
m_N	3.5	0.11	-0.07	2.0	-12
B_D	-2.8	-2.1	0.68	-6.8	8.8
B_T	-0.22	-1.4	0	-0.20	-2.5
B_3He	-2.1	3.0	0	-3.1	-9.5
B_4He	-0.01	-0.57	0	-59	-56
B_6Li	0	0	0	69	0
B_7Li	0	0	0	0	-6.9
B_7Be	0	0	0	0	81

Table: Dependence of abundances on nuclear parameters

Translating to fundamental parameters

Dependence on electromagnetic and weak interactions: relatively straightforward

Quark mass dependence of $m_{n,p}$ under control (strangeness content?)

Deuteron binding $B_{\rm D}$: systematic treatment in χPT

$$\Delta \ln B_D = (-8 \pm 2) \Delta \ln m_\pi = (-4 \pm 1) \Delta \ln \hat{m}$$

Beane & Savage, Epelbaum et al.

Other binding energies: parameterise pion contribution to B_i as scaling with $(A_i - 1)$ times fudge factors f_i (order 1)

$\partial \ln Y_a / \partial \ln G_k$	D	^{4}He	^{7}Li
$G_{\rm N}$	0.94	0.36	-0.7
α	3.6	1.9	-11
$\langle\phi\rangle$	1.6	2.9	1.7
m_e	0.46	0.40	-0.17
δ_q	-2.9	-5.1	-2.8
$\hat{m}$	$\gtrsim 10$	$\simeq -2.7$	$\gtrsim -60$

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Quark mass dependences via $\delta_q \equiv m_d - m_u$ and binding energies dominate!

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Fundamental parameters related by unification

Write variation of “fundamental” parameters as

$$\Delta \ln G_k = d_k \Delta \bar{\varphi} \equiv \frac{d_k}{d_\alpha} \Delta \ln \alpha$$

vector d_k depends on choice of model

Enforce gauge unification and define γ

$$\frac{\langle \phi \rangle}{M_X} = \text{const.} \left(\frac{\Lambda_c}{M_X} \right)^\gamma$$

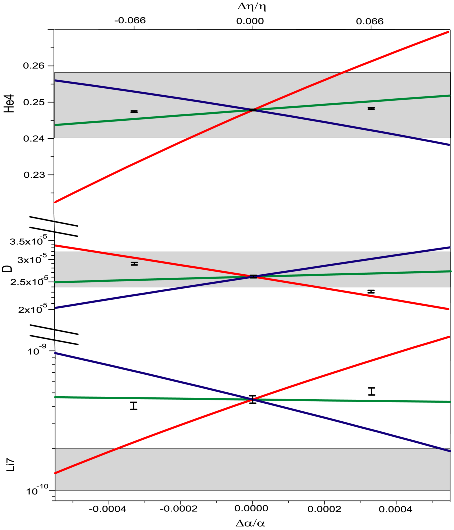
Three scenarios: $\gamma = 0, 1, 1.5$

Neglect variation in M_{P}/M_X and Yukawas

1. $\Delta \ln(G_N, \alpha, \langle \phi \rangle, m_e, \delta_q, \hat{m}) \simeq (64, 1, -32, -32, -32, -32) \Delta \ln \alpha$
2. $\Delta \ln G_k \simeq (78, 1, 0, 0, 0, 0) \Delta \ln \alpha$
3. $\Delta \ln G_k \simeq (87, 1, 22, 22, 22, 22) \Delta \ln \alpha$

Current observational values might (just?) be reconciled

Three unified scenarios



Summary

Many methods exist to investigate EEP and constancy of fundamental "constants":

- ⋆ Astrophysical spectra
- † Nuclear reactions and decays
- ◦ Atomic clocks
- ∗ Cosmology
- • WEP violation

Unlikely source of new physics, but huge implications of any positive result

BBN probes "constants" at earliest time, conditions most different from today

Complex system, observations need to be clarified

We disentangle dependence on nuclear / fundamental parameters and find stringent bounds (percent level)

TD, Stern, Wetterich 0705.0696 [astro-ph]

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