Varying “Constants” in Cosmology and Astrophysics and...

Review and work in progress

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Main references:

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. K.A. Bronnikov and S.A. Kononogov, gr-qc/0604002
4. C.M. Müller, G. Schäfer and C. Wetterich, *"Nucleosynthesis and the variation of fundamental couplings"*, astro-ph/0405373

Motivation

New physics can arise from examining basic assumptions of existing theory . . .

- Space and time a fixed background (Newton)
  $\Rightarrow$ dynamical spacetime (Einstein)
- Vacuum is inert and empty space $\Rightarrow$ Vacuum fluctuates (QFT) and has quantum numbers (Higgs mechanism) and dynamical condensates (QCD)
- Vacuum gravitates (Λ)?
- . . . evolves over time – “cosmon”, quintessence?

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

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. . .

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Prelude: atomic and molecular transitions

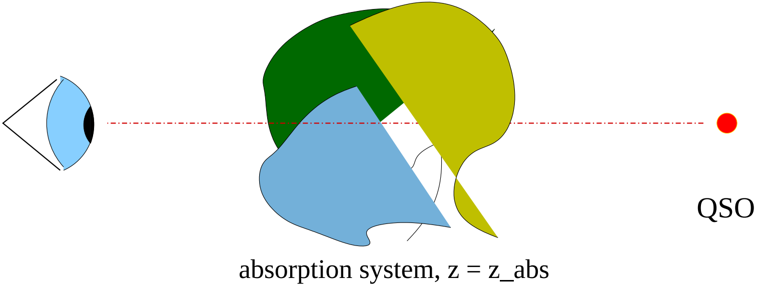
Relative measurements of different transitions provide direct and accurate measurements of dimensionless constants

Transition		Energy scaling
Atomic	Gross structure	Ry
	Fine structure	α^2 Ry
	Hyperfine structure	$\alpha^2(\mu/\mu_B)$ Ry
Molecular	Electronic structure	Ry
	Vibrational structure	$(m_e/m_p)^{1/2}$ Ry
	Rotational structure	(m_e/m_p) Ry
Relativistic corrections		Function of α^2

(from Karshenboim & Peik 2004)

- ⋆ α^2Ry and smaller scales accessible to optical/IR spectroscopy
- ⋆ Vibro/rotational structure may be accessible depending on redshift

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`)

Most recent 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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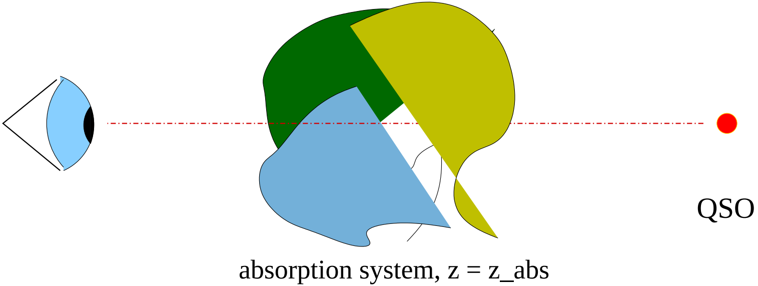

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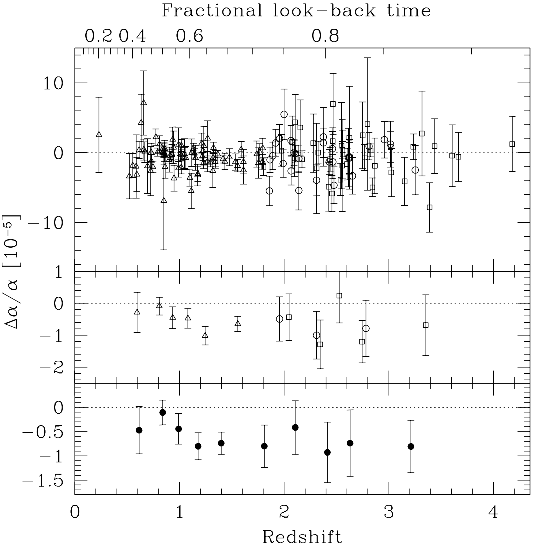
Alpha data



More spectra still being analyzed. . .

Other results on alpha

$$\frac{\Delta\alpha}{\alpha} = (0.15 \pm 0.43) \cdot 10^{-5},\ 1.6 \leq z \leq 2.9$$ Chand et al. 2004

$$\frac{\Delta\alpha}{\alpha} = (0.4 \pm 1.5) \cdot 10^{-6},\ z_{abs} = 1.84,\ 1.15$$ Levshakov et al. 2004

Levshakov et al. (astro-ph/0511765) claim errors below 10^{-6} fora single absorption system – but throw away 2 measurements out of 36 ($> 3\sigma$ out)

Absorption systems are complicated, fitting & analysis methods still under debate.

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A new mu?

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

Method uses vibro-rotational transitions of molecular hydrogen H_2 (Lyman/Werner bands) with different dependences on the reduced mass (Varshalovich 1993, 1995)

$$2002: \frac{\delta\mu}{\mu} = (5.0 \pm 1.8) \cdot 10^{-5},\ z_{abs} = 3.02$$ Ivanchik et al.

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

(A) and (B) use two different sets of laboratory wavelengths.
Difficult to measure in the extreme UV…

With 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

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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

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

Murphy et al. 2001

⋆ $x \equiv \alpha^2 g_p \mu^{-1}$

Compare UV heavy element transitions with H I line

$$\frac{\Delta x}{x} = (1.17 \pm 1.01) \cdot 10^{-5},\ 0.24 \leq z_{abs} \leq 2.04$$

Tzanavaris et al. 2005

If slow cosmological evolution of α and μ is assumed, this is consistent with negative $\Delta \ln \alpha$ and positive $\Delta \ln \mu \ldots$

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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

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

Resonant neutron capture

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

Today $E_{r,0} = 97.3$ meV with a width of $\simeq 60$ 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.

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

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

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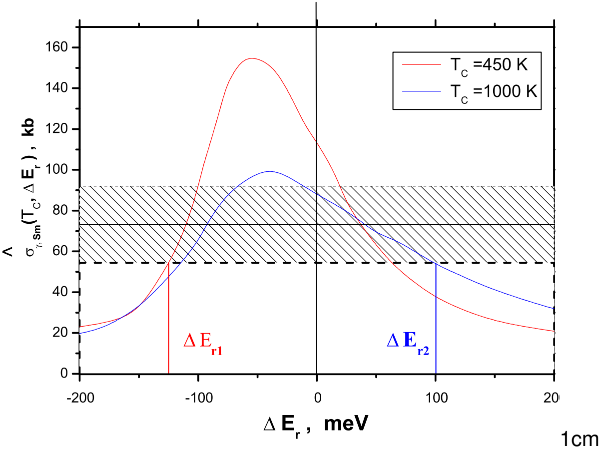
Oklo bound



Most 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

- use phenomenological models *e.g.* Walecka model
- only order-of-magnitude estimates of dependence

$$\Delta \ln \frac{m_\pi}{\Lambda_{\rm QCD}} = 0.5 \Delta \ln \frac{m_q}{\Lambda_{\rm QCD}} \leq 7 \times 10^{-10} \qquad \text{Flambaum \& Shuryak 2002}$$

compare

$$\Delta \ln \frac{m_q}{\Lambda_{\rm QCD}} \leq \text{few} \times 10^{-8} \qquad \text{Olive et al. 2002}$$

Also use beta decays *e.g.* ^{187}Re

$$\Gamma_{187} \propto Q_\beta^3 \propto \alpha^{2\times 10^4}$$

compare with less sensitive U → Pb in meteorites of similar age:

$$-2.4 \times 10^{-6} < \frac{\Delta\alpha}{\alpha} < 0.8 \times 10^{-6}, \; t = 4.6\,\text{Gyr}$$

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Atomic clocks

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

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

Example

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

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

Peik et al. (PRL 2004) use single Yb$^+$ ion to obtain limit

$$\dot{\alpha}/\alpha < 2.0 \times 10^{-15}\,\mathrm{y}^{-1}\ (1\sigma)$$

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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

Explicit violation of Poincaré invariance (LPI) difficult to understand

Replace by “spontaneous” violation: cosmologically varying scalar “Cosmon” $\varphi(x,t)$
Dimensionless “constants” are functions of φ

General theoretical framework: introduce action

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

try to solve for $\varphi(x,t)$

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?
- Does the field have other effects?

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WEP

Light scalar coupled to electromagnetic energy mediates composition-dependent force

$$\mathcal{L} = m_N(\varphi)\bar{N}N + \cdots , \qquad m_{p,n} = m_{\mathrm{N,QCD}} + B_{p,n}(\alpha_0 + \lambda\varphi)$$

Find φ-mediated force between Earth and 1 proton or neutron

Proton fraction f_p is 0.456 for Cu, 0.385 for U $\Rightarrow$ differential acceleration

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

Current limit $\eta \leq 10^{-13}$ (Eöt-Wash experiment)

If $\Delta\varphi$ is the source of $\Delta\alpha$ then $\lambda > 10^{-7} \Rightarrow$

STEP will see a signal ($\eta \geq 10^{-18}$) (Dvali & Zaldarriaga 2001)

In general φ also couples to QCD, fermion masses $\Rightarrow$ Earth's φ field may be 2 orders of magnitude larger (Wetterich 2002)

… MICROSCOPE $\eta \geq 10^{-15}$

Also find direct relations between Ω_φ, w_φ, $\partial_t\alpha \ldots$ today (TD, in preparation)

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Also find direct relations between Ω_φ, w_φ, $\partial_t\alpha \ldots$ today (TD, in preparation)

WEP

Light scalar coupled to electromagnetic energy mediates composition-dependent force

$$\mathcal{L} = m_N(\varphi)\bar{N}N + \cdots, \qquad m_{p,n} = m_{\mathrm{N,QCD}} + B_{p,n}(\alpha_0 + \lambda\varphi)$$

Find φ-mediated force between Earth and 1 proton or neutron

Proton fraction f_p is 0.456 for Cu, 0.385 for U $\Rightarrow$ differential acceleration

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

Current limit $\eta \leq 10^{-13}$ (Eöt-Wash experiment)

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Cosmology: CMB

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)

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

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

$$Y_p = 2\frac{(n/p)_f e^{-t_N/\tau}}{1+(n/p)_f e^{-t_N/\tau}}$$

- $(n/p)_f = e^{-Q/T_f}$: freezeout of weak interactions, compare $\Gamma(n \leftrightarrow p)$ with H
- t_N: "nucleosynthesis time", compare T with deuterium binding energy B_d
- τ: neutron lifetime

Already depends on every fundamental force (electroweak, strong, gravitational)

2. More sophisticated semi-analytic treatment (Müller, Schäfer, Wetterich 2004)

$$\frac{\Delta Y_p}{Y_p} = \sum_i c_i \frac{\Delta X_i}{X_i}$$

for 6 "fundamental parameters" X_i

parameter X_i	M_P	α	$\langle\phi\rangle$	m_e	m_q	Δm
c_i	-0.81	1.9	3.4	0.39	-1.59	-5.36

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BBN: current project

Selected previous work:

- Variation of other abundances (^{4}He, ^{7}Li, D) with α, with numerical code
  Bergström et al. 1999, Nollett & Lopez 2002 $\Rightarrow$ bounds at 2–3% level
- Variation of all light elements (^{4}He, ^{3}He, ^{7}Li, ^{6}Li, D) with α and $\langle\phi\rangle$, semi-analytic approach:
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Ideally: numerical code incorporating dependence on all fundamental parameters (with S. Stern, C. Wetterich)

Dependence of B_d and nuclear reaction rates on m_q is a complex and (in general) unsolved problem!

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

- Astrophysical spectra
- Nuclear reactions and decays
- Atomic clocks
- Cosmology
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