What varying constants and Equivalence Principle violation mean for Dark Energy

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some of own work:

- TD, S. Stern & C. Wetterich, *"Competing bounds on the present-day variation of fundamental constants"*, 0812.4130 (PRD)
- TD, S. Stern & C. Wetterich, *"Time variation of fundamental couplings and dynamical dark energy"*, 0809.4628 (JHEP)
- TD, S. Stern & C. Wetterich, *"Unifying cosmological and recent time variations of fundamental couplings"*, 0808.0702 (PRD)
- TD, *"Eötvös bounds on coupling of fundamental parameters to gravity"*, 0805.0318 (PRL)

Motivation

5σ deviation of fine structure constant α from present value over redshift 0.2–4.2

$$(\Delta\alpha)/\alpha = (-0.57 \pm 0.11) \cdot 10^{-5}$$ Murphy et al. 2001-2003

No conclusive counter-evidence

Nonzero variation ⇒ New cosmic dynamics

- New source of energy-momentum – “dark”?
- Different fundamental “constants” at different points in spacetime breaks Einstein equivalence principle (Local Position Invariance)
- Gravity must be modified
- Weak Equivalence Principle (“universal free fall”) is violated
- Connections between
    1. Recent cosmological time variation ($z \lesssim 0.5$)
    2. Equivalence Principle bounds today
    3. “Dark Energy” parameters: nonzero variation implies $w \neq -1$

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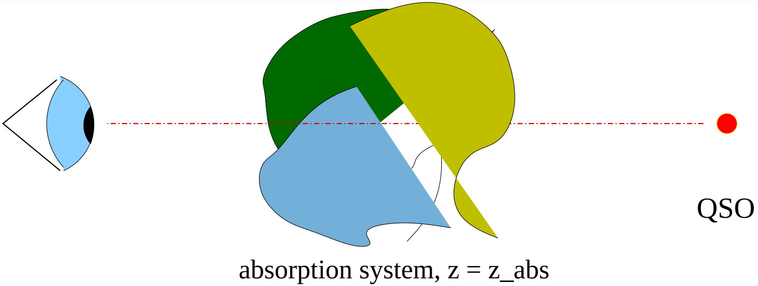
Alpha: measurement methods



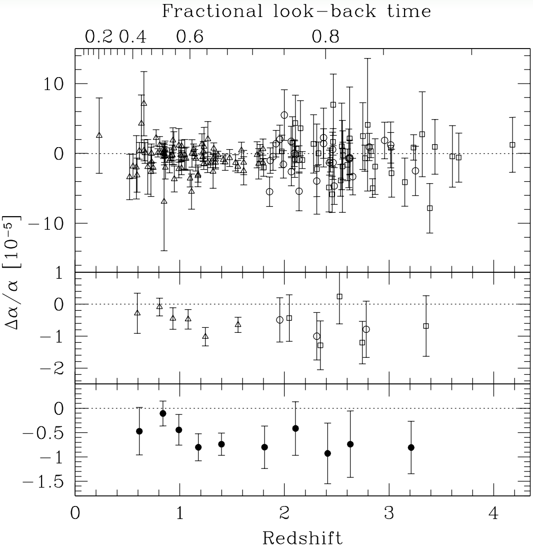
$$\omega_z = \omega_0 + q\left[\left(\frac{\alpha_z}{\alpha}\right)^2 - 1\right]$$

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

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

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

Alpha data



Further VLT/UVES results expected . . .

Laboratory challenges

Atomic clocks bound *present-day* time variation

NIST compares Al/Hg ion transition frequencies

$$\frac{\dot{\alpha}}{\alpha}|_{\rm today} = (-1.6 \pm 2.3) \times 10^{-17}\,\mathrm{y}^{-1}$$ Rosenband et al. Science (2008)

Rules out *linear* time variation for Murphy results

Also stringent bounds for $z \leq 0.5$ from Oklo, meteorites

- More complex or realistic dynamics – “braking”?
- We tried to fit “crossover quintessence” and “growing neutrino” models with variations – 0809.4628
- Spatial variation? . . .

Here we consider slow, (nearly) homogeneous time variation

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Particle physics challenges?

α derived from Standard Model: $\mathcal{O}(20)$ parameters

Unification (GUT) implies *all* gauge couplings should vary

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

sensitive to SU(3) strong coupling Calmet/Fritzsch, Langacker et al. 2001

expect $\Delta \ln \mu \gg \Delta \ln \alpha$ without fine-tuning

Strong observational bounds! eg H_2

$$\frac{\Delta\mu}{\mu} = (2.6 \pm 3.0) \times 10^{-6},\ 2 \leq z \leq 3.5$$ King et al. PRL 2008

Molecular spectra

$$\frac{\Delta\mu}{\mu} = (0.08 \pm 0.47) \times 10^{-6},\ z = 0.89$$ Henkel et al. A&A 2009

NH_3 spectrum constraint

$$\left|\frac{\Delta\mu}{\mu}\right| \leq 1.8 \times 10^{-6}\ (2\sigma),\ z = 0.68$$ Murphy et al. , Science 2008

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Basic theoretical problems

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

Free function $\alpha(\vec{x}, t)$ breaks QFT: variational principle, symmetry, conservation laws

No predictions for anything in Universe, infinite # of DOF

Need new dynamics! α, μ,$\ldots$ are scalar quantities $\Rightarrow$ scalar field φ

- Generally covariant theories with “varying constants”
- GR plus scalar field weakly coupled to radiation and matter – “scalar-tensor”
- Nonzero variation requires non-universal scalar coupling to matter Not equivalent to Brans-Dicke
- (W)EP violation appears as scalar-mediated forces

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Theoretical setup and scalar couplings

Effective action for dimensionless scalar $\varphi \equiv \Phi/M_P$ coupled to matter valid for large distance / long time

$$\mathcal{L} = M_P^2 \left(R + \tfrac{1}{2}(\partial\varphi)^2\right) + M_P^4 V(\varphi) - V_{\varphi m} + \mathcal{L}_{\rm em} + \cdots$$

Electromagnetic action:

$$\mathcal{L}_{\rm em} = -\frac{1}{4}\frac{1}{\alpha(\varphi)} F_{\mu\nu}F^{\mu\nu}$$

Matter coupling action $V_{\varphi m}$ gives mass $m_b(\varphi)$ to particles

Define coupling strength for particle / object, mass M_b:

$$\lambda_b \equiv \frac{d}{d\varphi} \ln \frac{M_b}{M_P}$$

M_b depends on m_p, m_e, m_n, $B_{em} \propto \alpha$, $B_{nuc} \ldots$

Scalar equation of motion & approximations

$\varphi(\vec{x}, t)$ in expanding cosmological background, $H(t) \to$ Hubble rate

$$\ddot{\varphi} + 3H\dot{\varphi} - \vec{\nabla}^2\varphi = -M_P^2 V'(\varphi) - \sum_b \frac{\rho_b}{M_P^2}\lambda_b(\varphi)$$

Can define "Effective potential" due to matter

$$\boxed{V_{\text{eff}} \equiv V(\varphi) + \textstyle\sum_b n_b(\vec{x}, t) m_b(\varphi)}$$

Divide ρ_b and φ into homogeneous average + fluctuations:

$$\bar{\rho}_b(t) + \delta\rho_b(\vec{x}, t), \qquad \bar{\varphi}_b(t) + \delta\varphi_b(\vec{x}, t)$$

- Cosmological evolution: throw away $\vec{\nabla}^2 \Rightarrow$ equation for $\bar{\varphi}$
- Local evolution of light scalar ($M_P^2 V''(\varphi) \ll 1/R^2$, $\lambda_b \ll 1$): Poisson equation

$$\vec{\nabla}^2 \delta\varphi(\vec{x}) \simeq \sum_b \delta\rho_b(\vec{x})\lambda_b(\bar{\varphi})$$

Compare Newtonian potential: $\vec{\nabla}^2 U(\vec{x}) = 4\pi G\rho(\vec{x})$

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Forces from local variations & Eötvös

For light weakly coupled scalars $\delta\varphi(\vec{x})$ behaves like $U(\vec{x})$ near a lump of matter.

A test body M_b will see its mass depend on position:

$$\vec{a} = -\frac{\vec{\nabla}(M_b/M_P)}{M_b} = -\lambda_b \vec{\nabla}\varphi = -2\lambda_b\lambda_s\vec{\nabla}U = 2\lambda_b\lambda_s\vec{g}$$

Acceleration due to φ! “Fifth force” $F_\varphi/F_{\mathrm{Newton}} = 2\lambda_s\lambda_b$.

Bound on *universal* scalar coupling in Solar System: Cassini

$$\lambda^2 \leq 5 \times 10^{-5}$$

Varying couplings or mass ratios $\Rightarrow$ *non-universal couplings* λ_b!

WEP: objects of *different composition* free-fall the same way

Test bodies M_b, M_c

$$\eta \equiv \frac{|a_b - a_c|}{|g|} = 2\lambda_s(\lambda_b - \lambda_c)$$

Bound $\eta = (0.3 \pm 1.8) \times 10^{-13}$ (Schlamminger et al. 2008)

bodies of Be, Ti composition, source is Earth

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Fundamental parameters

We identified 6 dimensionless *fundamental parameters* G_k

1. G_N $(\times\Lambda_c^2)$
2. α
3. $\langle\phi\rangle$ $(/\Lambda_c)$
4. m_e $(/\Lambda_c)$
5. $\delta_q \equiv m_d - m_u$ $(/\Lambda_c)$ – controls n – p mass difference
6. $\hat{m} \equiv \frac{1}{2}(m_d + m_u)$ $(/\Lambda_c)$ – controls m_π, nuclear forces

NB Λ_c is "QCD strong coupling scale"

Dependence of observables on G_k can be estimated

Correlated variations of G_k in unified models

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Fundamental coupling functions

Proportionality assumption:

$$\Delta \ln G_k = d_k \times l(\vec{x}, t) \qquad \simeq d_k \beta_X (\varphi(\vec{x}, t) - \varphi_0)$$

$\beta_X \Rightarrow$ coupling of unified model to φ

$$\frac{d \ln G_k}{d\varphi} \equiv \beta_k = d_k \beta_X$$

Proportionality factors d_k define a “scenario” of variation

Test body couplings $\lambda_b \propto \beta_X$

thus:

$$\eta = 2C[d_k]\beta_X^2 = C'[d_k]\left(\frac{\dot{\alpha}}{\alpha}\right)^2 \dot{\varphi}^{-2}$$

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Scalar mass and kinetic energy

EOM for (homogeneous) scalar

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If $V(\varphi)$ includes mass term $-m^2\Phi^2$ then obtain damped oscillation, $\omega \simeq m/2\pi$

For nontrivial cosmological drift require $m \lesssim H$: very long range

Bound on $\dot{\varphi}$ from kinetic energy (Dvali & Zaldarriaga 2001)

$$T = \frac{1}{2}\dot{\varphi}^2, \qquad V = V(\varphi)$$

thus

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

Expansion history of Universe bounds Ω, w above: estimate

$$\boxed{\dot{\varphi} \leq \dot{\varphi}_{\max} \simeq 3.5 \times 10^{-11}\, y^{-1}}$$

Bounds on η set limits on λ and on present-day / recent variations!

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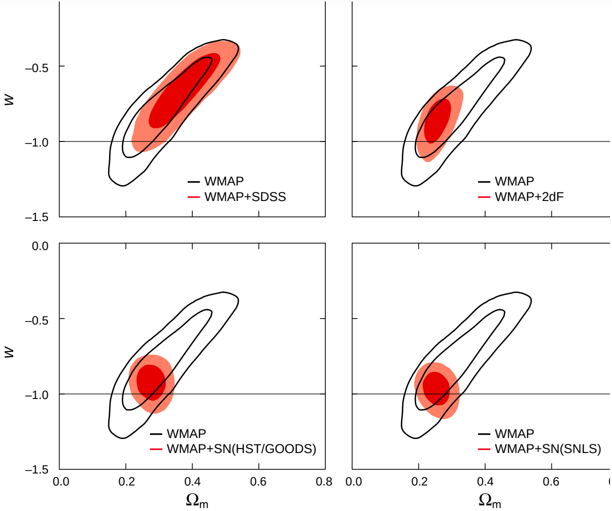
Bound on φ energy density and EOS



Spergel *et al.* 2006

Bounds on recent variation

$$\left|\frac{\dot{\alpha}}{10^{-15}\,\mathrm{y}^{-1}}\right| = \left|\frac{\Omega_\varphi(1+w_\varphi)}{F[d_k]}\right|^{1/2}\left(\frac{\eta}{3.8\times 10^{-12}}\right)^{1/2}$$

F is “unification factor”: relation between α- and mass-variations

Scenario	α only	2	3	4	5, $\tilde{\gamma}=42$	6, $\tilde{\gamma}=70$	6, $\tilde{\gamma}=25$
F (Be-Ti)	$-9.3\,10^{-5}$	95	-9000	-165	-25	-26	41

Bounds come from gravitational effects alone!

		Error on $d\ln X/dt$ $(10^{-15}y^{-1})$				
Scenario	X	Al/Hg	Clocks (μ)	Oklo	^{187}Re	WEP
α only	α	0.023	-	0.033	0.32	6.2
2	α_X	0.027	0.074	0.12	0.015	0.007
2S	α_X	0.044	0.12	0.19	0.026	0.012
3	$\langle\phi\rangle/M_X$	12.4	2.6	54	0.53	0.33
4	$\langle\phi\rangle/M_X$	1.78	6.2	7.7	1.2	0.35
5, $\tilde{\gamma}=42$	α_X	0.024	0.42	0.11	0.069	0.013
6, $\tilde{\gamma}=70$	α_X	0.016	0.30	0.070	0.049	0.008
6, $\tilde{\gamma}=25$	α_X	0.027	0.25	0.12	0.056	0.011

Nonzero variation rules out $w = -1$

If there is a *non-zero* present time variation the scalar must have kinetic energy

$$\Omega_\varphi(1+w_\varphi) \geq 3.8 \times 10^{18} F \left(\frac{\dot{\alpha}/\alpha}{\mathrm{y}^{-1}}\right)^2 \eta_{\max}^{-1}$$

$\eta_{\max}$ is experimental limit

Disproof of pure Λ as “dark energy”

Conclusions and other directions

* Need to know if a slow cosmological time variation of α exists
* Need many probes: different z, different environments
* Purely gravitational effects bound (recent) variations
* Atomic clocks could put bounds on w with nonzero variation

Variation could be due to *environment-dependent* variation (Olive / Pospelov)

probe with entirely different methods – clocks in vacuum chambers . . .

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