# Time variations of constants in cosmology

Jim Rich

SPP-IRFU
CEA-Saclay
91191 Gif-sur-Yvette

james.rich@cea.fr

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# Time variations of constants in cosmology?

arXiv:1412.8160

Investigation of the fundamental constants stability based on the reactor Oklo burn-up analysis (M.S. Onegin)

arXiv:1412.7801

Searching for dark matter and variation of fundamental constants with laser and maser interferometry (Stadnik and Flambaum)

general ref on $\dot{\alpha}$: arXiv:hep-ph/0205340 (J.-P. Uzan)

Outline:

- $\dot{\alpha}$ from laboratory experiments
- $\dot{\alpha}$ from doublets in cosmological spectra
- $\dot{\alpha}$ from ancient nuclear reactors (Oklo)
- Some models of $\dot{\alpha}$

# $\dot{\alpha}$ from laboratory experiments

Standard example: compare two clocks

- Hydrogen maser $\nu \sim h^{-1}\alpha^4(gm_e/m_p)m_ec^2$
- Cavity oscillator of length $L$: $\nu \propto c/L \propto c/a_B = \hbar^{-1}\alpha m_e c^2$
  (interatomic spacings $\propto$ Bohr radius)

Therefore:

$$\frac{\nu_{cavity}}{\nu_{maser}} \propto \alpha^3(m_e/m_p)$$

Frequency ratio is constant in time if $\alpha$ and $m_e/m_p$ are constant.

Present limits with variants of this technique: $\dot{\alpha} < 10^{-17}yr^{-1}$

Illustrates a general prinicple: only variations of dimensionless parameters are meaningful. See physics/0209016 (JR) for amusing examples of this principle.

# technique of 1412.7801: laser interferometry

Interferometer with two arms of lengths $L_1$ and $L_2$, for which the observable is the phase difference $\Delta\Phi = \omega(L_1 - L_2)/c$....

For $L_i \propto a_B$ and $\omega \propto \alpha^2 m_e$, $\Delta\Phi \propto \alpha$.

LIGO precision: $\Delta\Phi \sim 10^{-21}$

sensitive to:

- oscillating $\alpha$
- transient $\alpha$ due to passage of topological defects
- gradiants of $\alpha$ (cosmo-doublets $\Rightarrow \dot{\alpha} \sim 10^{-19} yr^{-1}$ from movement of Earth through solar system)

# cosmological spectral doublets

Atomic lines and fine structure splitting:

$$\lambda \propto \hbar c/\alpha^2 m_e c^2 \qquad\qquad \Delta\lambda_{fs} \propto \hbar c/\alpha^4 m_e c^2$$

Cosmological expansion conserves $\Delta\lambda/\lambda$ so

$$\frac{\Delta\lambda_{obs}}{\langle\lambda\rangle_{obs}} \sim \alpha^2(t_{emission})$$

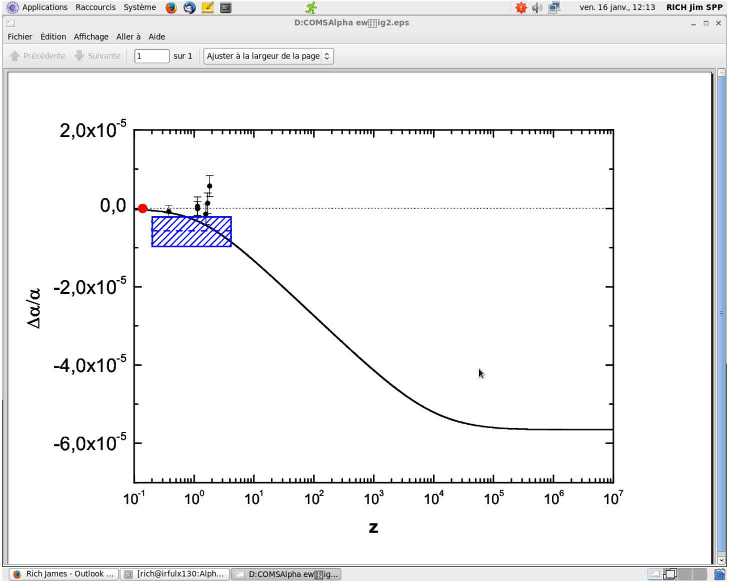
# Bahcall and Schmidt (1967)

Abstract:
The fine structure constant at red shifts $\Delta\lambda/\lambda \sim 0.2$, corresponding to an epoch around two billion years ago, has been determined using the wavelengths of a pair of O III emission lines measured in the spectra of five radio galaxies. We find
$\alpha(z = 0.2)/\alpha(lab) = 1.001 \pm 0.002$ probable error.

present limites: $\Delta\alpha/\alpha <\sim 10^{-5}$

observed "$\alpha$ dipole" would imply spatial gradiant of $\alpha$ that could be tested with technique of 1412.7801

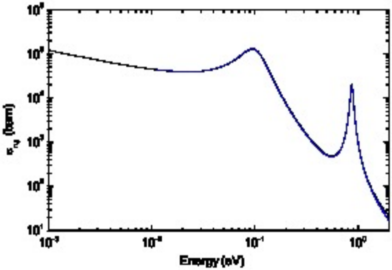
# $\Delta\alpha$ vs. redshift (arXiv:1412:8160)



# Oklo (Gabon) prehistoric reactor

Oklo uranium sample has

- depleted $^{235}U \Rightarrow$ thermal neutrons inducing fission $\sim 2 \times 10^9$years ago.
- depleted $^{149}Sm$ (thermal neutron capture resonance for $n^{149}Sm \rightarrow \gamma^{150}Sm$




Capture resonance corresponds to a state of $^{150}Sm \sim 0.1eV + 8MeV$ above ground state. Apparently it was still in the thermal region $2 \times 10^9$ years ago [Shlyakhter, 1976].

# Oklo analysis in arXiv:1010.6299

The lutetium isotope ratio at the end of burn up is sensitive to the ground state $^{176}$Lu yield in the absorption of neutron by $^{175}$Lu nuclei. This yield have rather high uncertainty: $0.283 \pm 0.056$ with $1\sigma$ error. We have investigated the dependence of the $^{176}\mathrm{Lu}/^{175}\mathrm{Lu}$ ratio at the end of burn-up on this yield...... As a result the core temperature determined from the lutetium isotope ratio is in the range $364\,\mathrm{K} < T < 525\,\mathrm{K}$ at 99% C.L.
The values of the $^{149}$Sm cross section (as it follows from Table 7) are in the range 62.6 kb to 74.0 kb. Following the dependence of the $^{149}$Sm cross section on a resonance shift.....we conclude that the resonance shift should be in the range

$$-11.3\,\mathrm{meV} < \Delta E_r < 0.8\,\mathrm{meV},$$

to satisfy the experimental condition.

# Oklo analysis in arXiv:1010.6299 (cont.)

Constraints for the shift of the $^{149}$Sm resonance obtained in the previous section can be converted into the limits for the variation of the fine structure constant $\alpha$ (see [Petrov:2005])

$$\frac{\Delta\alpha}{\alpha} = \frac{\Delta E_r}{M} \tag{1}$$

where: $M$ is estimated in [Damour&Dyson,1996] as -$(1.1 \pm 0.1)$MeV. Using this value of $M$ we obtain constraints for the variation of the fine structure constant

$$-0.7 \cdot 10^{-9} \leq \frac{\Delta\alpha}{\alpha} \leq 1.0 \cdot 10^{-8} \tag{2}$$

during the past $2 \cdot 10^9$ years.

# model of 1412.8160 (astro-ph/0107512)

BSBM theory [Sandvik,Barrow,Maguiljo] is the extension of the Bekenstein theory to include dynamics of the gravitational field. Total action of this theory has a form:

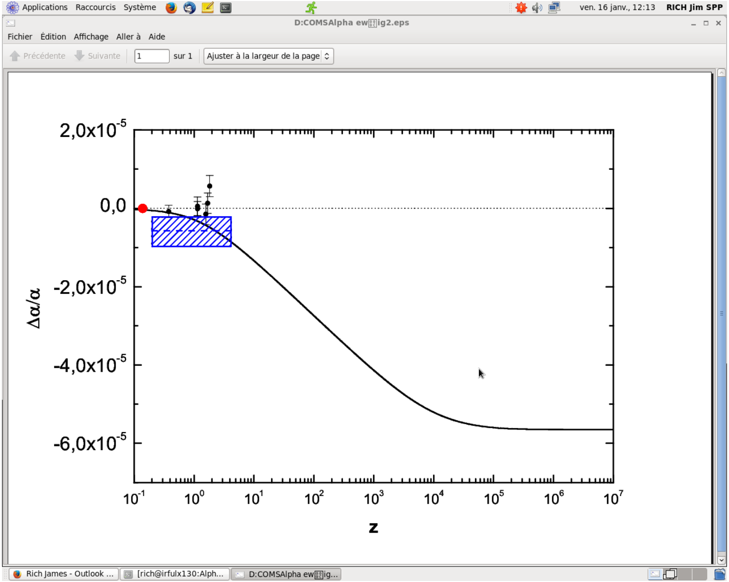
$$S = \int d^4x\sqrt{-g}(L_g + L_{mat} + L_\psi + e^{-2\psi}L_{em}) \qquad (3)$$

where $L_\psi = -\frac{\omega}{2}\partial_\mu\psi\partial^\mu\psi$ and $L_{em} = -\frac{1}{4}f_{\mu\nu}f^{\mu\nu}$. A parameter $\omega$ here is definite as $\omega = \frac{\hbar c}{l^2}$ where dimensional parameter $l$ is having sense of characteristic length. Fine structure constant expressed via $\psi$ with the equation: $\alpha = \frac{e_0^2}{\hbar c}e^{2\psi}$. Varying $\psi$ we get the following equation:

$$\Box\psi = \frac{2}{\omega}e^{-2\psi}L_{em}. \qquad (4)$$

For pure radiation $L_{em} = (E^2 - B^2)/2 = 0$, so $\psi$ remains constant during radiation domination epoch. Only in matter domination epoch changes in $\alpha$ take place.

# $\Delta\alpha$ vs. redshift (arXiv:1412:8160)



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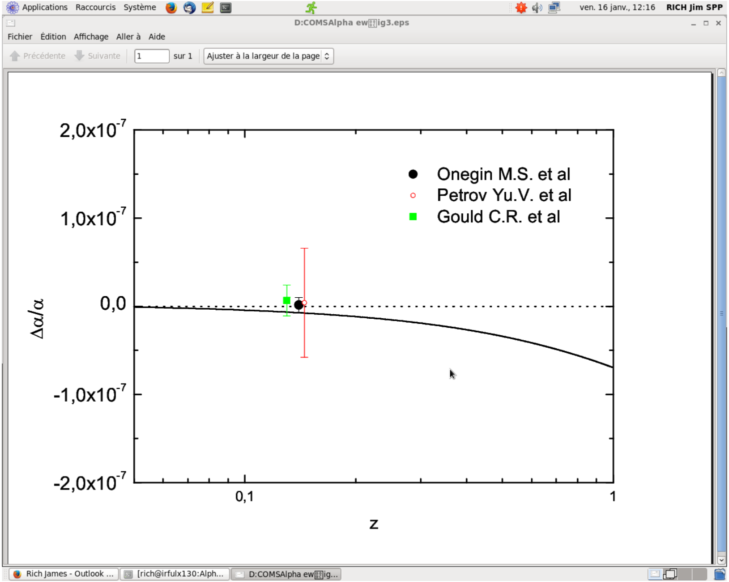

# model 1 of 1412.7801: scalar field $\eta$

$$\mathcal{L}_{\text{int}}^{f} = -\sum_{f=e,p,n} \eta_0 \cos(m_\eta c^2 t/\hbar) \frac{m_f c^2}{\Lambda_f} \bar{f} f, \tag{5}$$

where $f$ is the fermion Dirac field and $\bar{f} = f^\dagger \gamma^0$, and to the electromagnetic field:

$$\mathcal{L}_{\text{int}}^{\gamma} = \frac{\eta_0 \cos(m_\eta c^2 t/\hbar)}{4\Lambda_\gamma} F_{\mu\nu} F^{\mu\nu}, \tag{6}$$

$\Lambda > 10^9 GeV$ from lab and astro observations.

$$m_f \to m_f \left[ 1 + \frac{\eta_0 \cos(m_\eta c^2 t/\hbar)}{\Lambda_f} \right], \tag{7}$$

$$\alpha \to \frac{\alpha}{1 - \eta_0 \cos(m_\eta c^2 t/\hbar)/\Lambda_\gamma} \simeq \alpha \left[ 1 + \frac{\eta_0 \cos(m_\eta c^2 t/\hbar)}{\Lambda_\gamma} \right]. \tag{8}$$

# model 2 of 1412.7801: scalar topological defects

Another possible DM candidate is topological defect DM, which is a stable non-tr ivial form of DM that consists of light DM fields and is stabilised by a self-in teraction potential [Vilenkin1985]. These objects may have various dimensio nalities: 0D (monopoles), 1D (strings) or 2D (domain walls). The transverse size of a topological defect depends on the mass of the particle comprising the defe ct, $d \sim \hbar/m_\phi c$, which may be large (macroscopic or galactic) for a sufficiently light DM particle.

The light DM particle comprising a topological d efect can be either a scalar, pseudoscalar or vector particle. Recent proposals for pseudoscalar-type defect searches include using a global network of magnetom eters to search for correlated transient spin precession effects [GNOME2013] and electric dipole moments [Stadnik2014] that arise from the coup ling of the scalar field derivative to the fermion axial vector currents.

# 1412.7801 (cont.)

Recent proposals for scalar-type defect searches include using a global network of atomic clocks [Derevianko2014], and Earth rotation and pulsar timing [Stadnik2014], to search for transient-in-time alterations of the system freq uencies due to transient-in-time variation of the fundamental constants that ari se from the couplings of the scalar field to the fermion and photon fields. The best current sensitivities for transient-in-time variations of the fundamental c onstants on the time scale of $t \sim 1 - 100$ s with terrestrial experiments ar e offered by atomic clocks, with an optical/optical clock combination [Hinkley2013,Bloom2014] sensitive to variations in $\alpha$: $\delta\alpha/\alpha \sim 10^{-15} - 10^{-16}$ and a hyperfine/optical clock combination [Jefferts2013] to variations in the electron-to-proton mass ratio $m_e/m_p$: $\delta(m_e/m_p)/(m_e/m_p) \sim 10^{-13} - 10^{-14}$.