New tests of variability of the speed of light.

Mariusz P. Dąbrowski

Institute of Physics, University of Szczecin, Poland;
National Center for Nuclear Research, Otwock, Poland;
Copernicus Center for Interdisciplinary Studies, Kraków, Poland

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Plan:

- 1. Main frameworks of varying constants theories.
- 2. Benefits and problems of varying c theories.
- 3. Redshift drift test of varying c models.
- 4. Measuring c with baryon acoustic oscillations (BAO).
- 5. Conclusions.

Collaborators:

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1. Main frameworks of varying constants theories.

Long story of varying constants theories:

H. Weyl (1919): electron radius/its gravitational radius $\sim 10^{40}$

A. Eddington (1935) discussed:

1. proton-to-electron mass $1/\beta = m_p/m_e \sim 1840$
2. an inverse of fine structure constant $1/\alpha = (hc)/(2\pi e^2) \sim 137$
3. electromagnetic to gravitational force between a proton and an electron $e^2/(4\pi\epsilon_0 G m_e m_p) \sim 10^{40}$
4. introduced “Eddington number” $N_{edd} \sim 10^{80}$

P.A.M. Dirac (1937) interesting remarks about the relations between atomic and cosmological quantities: If $G \propto H(t) = (da/dt)/a$, then $a(t) \propto t^{1/3}$ and $G(t) \propto 1/t$ - fundamental constants must evolve in time.

Conclusion: electromagnetic force is strong compared to gravitational since the universe is “old” i.e. $F_e/F_p \propto (e^2/m_e m_p)t \propto t$!!!

varying gravitational constant G theories

First fully quantitative framework: Brans-Dicke scalar-tensor gravity (1961)

The gravitational constant G is associated with an average gravitational potential (scalar field) ϕ surrounding a given particle:

$< \phi >= GM/(c/H_0) \propto 1/G = 1.35 \times 10^{28} g/cm$. The scalar field gives the strength of gravity

$$G = \frac{1}{16\pi\Phi} \tag{1}$$

With the action

$$S = \int d^4x\sqrt{-g}\left(\Phi R - \frac{\omega}{\Phi}\partial_\mu\Phi\partial^\mu\Phi + \Lambda + L_m\right) \tag{2}$$

it relates to low-energy-effective superstring theory for $\omega = -1$

String coupling constant (running) $g_s = \exp\left(\phi/2\right)$ changes in time with ϕ - the dilaton and $\Phi = \exp\left(-\phi\right)$.

Varying speed of light c (VSL) theories

Attempts: Einstein (1907), Dicke (1957), J.-P. Petit (1988) (Einstein eqs remain same due to fine-tuned change of c and G), Moffat (1992).

Albrecht & Magueijo model (1998) (AM model) (Barrow 1999; Magueijo 2003): Introduce a scalar field

$$c^4 = \psi(x^\mu) \tag{3}$$

and so the action is

$$S = \int d^4x\sqrt{-g}\left[\frac{\psi(R+2\Lambda)}{16\pi G} + L_m + L_\psi\right] \tag{4}$$

AM model breaks Lorentz invariance (relativity principle and light principle) so that there is a preferred frame (cosmological or CMB) in which the field is minimally coupled to gravity. The Riemann tensor is computed in such a frame for a constant $\psi = c^4$ and no additional terms $\partial_\mu\psi$ appear in this frame (though they do in other frames). Einstein eqs remain the same **except** c now varies.

Varying speed of light c (VSL) theories

Magueijo covariant (conformally) and locally invariant model (2000, 2001):

$$\psi = \ln\left(\frac{c}{c_0}\right) \quad \text{or} \quad c = c_0 e^{\psi} , \tag{5}$$

with the action

$$S = \int d^4x\sqrt{-g}\left[\frac{c_0^4 e^{\alpha\psi}(R + 2\Lambda + L_{\psi})}{16\pi G} + e^{\beta\psi}L_m\right] , \tag{6}$$

with

$$L_{\psi} = \kappa(\psi)\nabla_{\mu}\psi\nabla^{\mu}\psi . \tag{7}$$

Further assumption: $\alpha - \beta = 4$.

Interesting subcases:

$\alpha = 4; \beta = 0$ - Brans-Dicke with $\phi_{BD} = e^{4\psi}/G$ and $\kappa(\psi) = 16\omega_{BD}(\phi_{BD})$.

$\alpha = 0; \beta = -4$ - minimal VSL theory.

Varying fine structure constant α theories

Varying fine structure constant α (or charge $e = e_0\epsilon(x^\mu)$ theories (Webb et al. 1999, Sandvik 2002)

$$S = \int d^4x\sqrt{-g}\left(R - \frac{\omega}{2}\partial_\mu\psi\partial^\mu\psi - \frac{1}{4}f_{\mu\nu}f^{\mu\nu}e^{-2\psi} + L_m\right) \quad (8)$$

with $\psi = \ln\epsilon$ and $f_{\mu\nu} = \epsilon F_{\mu\nu}$.
Can be related with the VSL theories due to the definition of the fine structure constant

$$\alpha = \frac{e^2}{\hbar c} \quad \text{i.e.} \quad \alpha(t) = \frac{e^2}{\hbar c(t)} \quad (9)$$

Assume linear expansion $e^\psi = 1 - 8\pi G\zeta(\psi - \psi_0) = 1 - \Delta\alpha/\alpha$ with the constraint on the local equivalence principle violence $\mid \zeta \mid \leq 10^{-3}$. The relation to dark energy is(e.g. Vielzeuf and Martins 2012):

$$\gamma = w + 1 = \frac{(8\pi G\frac{d\psi}{d\ln a})^2}{\Omega_\psi}\;. \quad (10)$$

Varying fine structure constant α theories

The field equations for Friedmann universes are (e.g. Barrow, Kimberly, Magueijo 2004)

$$\begin{aligned} \frac{\dot{a}^2}{a^2} &= \frac{8\pi G}{3}\left(\varrho_r + \varrho_\psi\right) - \frac{kc^2}{a^2}, && (11) \\ \frac{\ddot{a}}{a} &= -\frac{8\pi G}{3}\left(\varrho_r + 2\varrho_\psi\right), && (12) \\ \ddot{\psi} &+ 3\frac{\dot{a}}{a}\dot{\psi} = 0, && (13) \end{aligned}$$

where $\varrho_r \propto a^{-4}$ stands for the density of radiation while

$$\varrho_\psi = \frac{p_\psi}{c^2} = \frac{\sigma}{2}\dot{\psi}^2 \qquad (14)$$

stands for the density of the scalar field ψ (standard with $\sigma = +1$ and phantom with σ = -1) and

$$\alpha = \alpha_0 e^{2\psi}. \qquad (15)$$

2. Benefits and problems of varying c and α theories.

Applying the simplest method one can obtain the generalized Einstein-Friedmann equations generalize in varying speed of light (VSL) theories and varying gravitational constant G theories as (ϱ - mass density; $\varepsilon = \varrho c^2(t)$ - energy density in $Jm^{-3} = Nm^{-2} = kgm^{-1}s^{-2}$)

$$\varrho(t) = \frac{3}{8\pi G(t)}\left(\frac{\dot{a}^2}{a^2} + \frac{kc^2(t)}{a^2}\right), \quad (16)$$

$$p(t) = -\frac{c^2(t)}{8\pi G(t)}\left(2\frac{\ddot{a}}{a} + \frac{\dot{a}^2}{a^2} + \frac{kc^2(t)}{a^2}\right), \quad (17)$$

and the generalized conservation law is obtained from (16) and (17)

$$\dot{\varrho}(t) + 3\frac{\dot{a}}{a}\left(\varrho(t) + \frac{p(t)}{c^2(t)}\right) = -\varrho(t)\frac{\dot{G}(t)}{G(t)} + 3\frac{kc(t)\dot{c}(t)}{4\pi G a^2}. \quad (18)$$

introducing Λ to varying c models

If one adds the Λ-term to the equations (16)-(17), and introduces the vacuum mass density

$$\varrho_\Lambda(t) = \frac{\Lambda c^2(t)}{8\pi G(t)} \qquad (\Lambda = \mathrm{const.}) \tag{19}$$

with

$$p_\Lambda(t) = -\varrho_\Lambda(t)c^2, \tag{20}$$

then one has to replace $\varrho \to \varrho + \varrho_\Lambda$, $p \to p + p_\Lambda$ in (16)-(17) and $\dot{\varrho} \to \dot{\varrho} + \dot{\varrho}_\Lambda$ in (18) to obtain

$$\dot{\varrho} + 3\frac{\dot{a}}{a}\left(\varrho + \frac{p}{c^2(t)}\right) + \varrho\frac{\dot{G}(t)}{G(t)} = \frac{\left(3k - \Lambda a^2\right)}{4\pi G(t)a^2}c(t)\dot{c}(t). \tag{21}$$

which is solved by (for $p = w\rho c^2$, $c(t) = c_0 a^n$, $G(t) = G_0 a^q$, $C =$const.)

$$\varrho(a) = \frac{C}{a^{3(w+1)+q}} + \frac{3c_0^2 n}{4\pi G_0}\left(\frac{k}{2n+3w+1} - \frac{\Lambda}{3}\frac{a^2}{2n+3w+3}\right)a^{2(n-1)-q}.$$

Benefits of varying c models

Solves basic problems of standard cosmology: flatness and horizon.

Flatness: inserting this into Friedmann (16) one gets

$$\frac{\dot{a}^2}{a^2} = \frac{8\pi G_0 C}{3} a^{-3(w+1)} + \frac{k c_0^2 a^{2n-2}(2n-1)}{2n+3w+1} \,, \tag{22}$$

and the density term (with C) will dominate the curvature term at large scale factor if

$$2 \geq 2n + 3(w+1) \tag{23}$$

Horizon: For large scale factor the solution is $a(t) = t^{2/3(w+1)}$ and the proper distance to the horizon reads as

$$d_H = c(t)t = c_0 a^n(t) t = c_0 a_0^n t^{(3w+3+2n)/3(w+1)} \tag{24}$$

and the scale factor grows faster than d_H under the same condition as in (23).

varying c (and G) removing or changing singularities.

Varying constants can **remove or change the nature of singularities** (MPD, Marosek 2013).

Type	Name	t sing.	a(t_s)	$\varrho(t_s)$	p(t_s)	$\dot{p}(t_s)$ etc.	w(t_s)	T	K
0	Big-Bang (BB)	0	0	∞	∞	∞	finite	strong	strong
I	Big-Rip (BR)	t_s	∞	∞	∞	∞	finite	strong	strong
I_l	Little-Rip (LR)	∞	∞	∞	∞	∞	finite	strong	strong
I_p	Pseudo-Rip (PR)	∞	∞	finite	finite	finite	finite	weak	weak
II	Sudden Future (SFS)	t_s	a_s	ϱ_s	∞	∞	finite	weak	weak
II_g	Gen. Sudden Future (GSFS)	t_s	a_s	ϱ_s	p_s	∞	finite	weak	weak
III	Finite Scale Factor (FSFS)	t_s	a_s	∞	∞	∞	finite	weak	strong
IV	Big-Separation (BS)	t_s	a_s	0	0	∞	∞	weak	weak
V	w-singularity (w)	t_s	a_s	0	0	0	∞	weak	weak

varying c (and G) removing or changing singularities.

Some of these can be regularized (removed by variable constants):

- In order to regularize an SFS or an FSF singularity by varying $c(t)$, the **light should slow and eventually stop propagating** at a singularity. (cf. loop quantum cosmology (LQC): anti-newtonian limit $c = c_0\sqrt{1 - \varrho/\varrho_c} \to 0$ for $\varrho \to \varrho_c$ with ϱ_c being the critical density (Cailettau et al. 2012). The low-energy limit $\varrho \ll \varrho_0$ gives the standard limit $c \to c_0$.)
- To regularize an SFS, FSF by varying gravitational constant $G(t)$ - **the strength of gravity has to become infinite** at an initial (curvature) singularity. Effectively, a new singularity - **of strong coupling** for a physical field such as $G \propto 1/\Phi$ appears. Such problems were already dealt with in superstring and brane cosmology where both the curvature singularity and a strong coupling singularity show up (choice of coupling, quantum corrections).

Problems of varying c models

Main problem: to obtain the field equations out of any action (cf. also quantum cosmology)?

Equations (16)-(18) have just been obtained in a special frame - the one in which c is a constant and does not lead to any extra boundary terms (apart from standard ones). Einstein equations were simply generalized:

$$G_{\mu\nu} - g_{\mu\nu}\Lambda = \frac{8\pi G}{\psi} T_{\mu\nu} \tag{25}$$

while the action (4) varied in a standard way leads to different field equations

$$G_{\mu\nu} - g_{\mu\nu}\Lambda = \frac{8\pi G}{\psi} T_{\mu\nu} - \frac{1}{\psi}\psi_{;\nu;\mu} + \frac{1}{\psi}\Box\psi. \tag{26}$$

The application of Bianchi identity to (25) gives a conservation equation with dynamical ψ

$$T^{\mu\nu}_{;\mu} = -T^{\mu\nu}\psi_{;\mu} \tag{27}$$

Problems of varying c quantum cosmology

If ψ was supposed to be a dynamical matter field, then one could get the evolution equation using the Lagrangian

$$L_\psi = -\frac{\omega}{16\pi G\psi}\dot{\psi}^2, \tag{28}$$

but working only in a preferred frame and with ψ not coupled to $\sqrt{-g}$.
Treating $\psi = c^4$ as constant in a preferred frame also requires special treatment of the boundary terms in c-varying quantum cosmology. As mentioned, we vary the action in the special frame where c is constant which means that we drop c-induced boundary terms, but recover the time dependence of c again to proceed towards WdW equation (V_3 is a 3-volume)

$$L = \frac{3V_3 c^3(x^0)}{8\pi G(x^0)}\left(ka - a_{,0}^2\, a - \frac{\Lambda}{3}a^3 - \frac{8\pi G(x^0)}{3c^2}\varrho a^3\right) \tag{29}$$

Benefits of varying α cosmology

Since one does not brake Lorentz invariance in varying fine structure constant α theories, then there are no such problems in these models - the standard variational principle applies and the dynamical equation for the scalar field is given!

According to the definition, any variability of c (e, $\hbar$) is related to the variability of α:

$$\frac{\Delta\alpha}{\alpha} = -\frac{\Delta c}{c}. \tag{30}$$

The best constraints on $\Delta\alpha$ are: Oklo natural nuclear reactor:

$\Delta\alpha/\alpha = (0.15 \pm 1.05) \cdot 10^{-7}$ at z = 0.14

VLT/UVES quasars: $\Delta\alpha/\alpha = (0.15 \pm 0.43) \cdot 10^{-5}$ at 1.59 < z < 2.92

SDSS quasars: $\Delta\alpha/\alpha = (1.2 \pm 0.7) \cdot 10^{-4}$ at 0.16 < z < 0.8 .

More bounds on variation of α.

By Webb et al. (PRL 107, 191101 (2011)) (α-dipole $R.A.17.4 \pm 0.9h$, $\delta = -58 \pm 9$: Keck ($\Delta\alpha < 0$) and VLT) as well as other specific measurements of α given in the table below (in parts per million):

Object	z	$\Delta\alpha/\alpha$	Spectrograph	Ref.
HE0515−4414	1.15	-0.1 ± 1.8	UVES	Molaro et al. (2008)
HE0515−4414	1.15	0.5 ± 2.4	HARPS/UVES	Chand et al. (2006)
HE0001−2340	1.58	-1.5 ± 2.6	UVES	Agafonowa et al. (2011)
HE2217−2818	1.69	1.3 ± 2.6	UVES–LP	Molaro et al. (2013)
Q1101−264	1.84	5.7 ± 2.7	UVES	Molaro et al. (2008)

UVES - Ultraviolet and Visual Echelle Telescope

HARPS - High Accuracy Radial velocity Planet Searcher

LP - Large Program measurement

Strongest – atomic clock Rosenband bound at $z = 0$

Rosenband (2008) measurement gives the following bound at $z = 0$

$$\left(\frac{\dot{\alpha}}{\alpha}\right)_0 = (-1.6 \pm 2.3) \times 10^{-17}\mathrm{yr}^{-1}\,. \tag{31}$$

which can be transformed onto the bound for the scalar field coupling ξ:

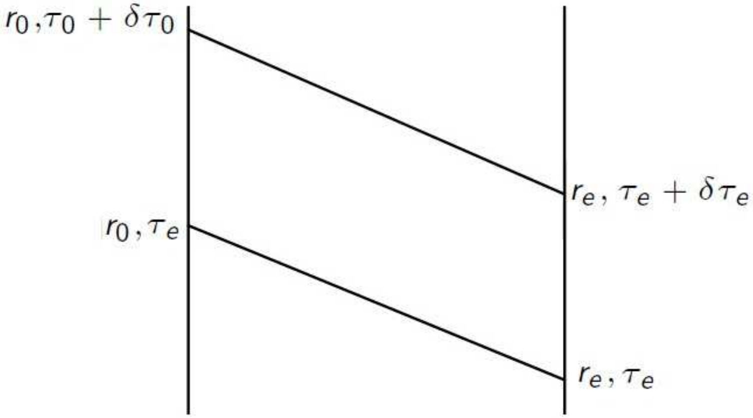
$$\left|\frac{\dot{\alpha}}{\alpha}\right|_0 = |\xi| H_0 \sqrt{3\Omega_{\Phi 0} \mid 1 + w_{\Phi 0} \mid}\,, \tag{32}$$

which translates for $H_0 = (67.4 \pm 1.4)\,\mathrm{km.s}^{-1}\mathrm{Mpc}^{-1}$ Planck value) into the conservative (3σ) bound

$$|\xi| \sqrt{3\Omega_{\Phi 0} \mid 1 + w_{\Phi 0} \mid} < 10^{-6}. \tag{33}$$

3. Redshift drift test of varying c models.

Redshift drift (Sandage 1962, Loeb 1998) - the idea is to collect data from two light cones separated by 10-20 years to look for a change in redshift of a source as a function of time.



There is a relation between the times of emission of light by the source τ_e and $\tau_e + \Delta\tau_e$ and times of their observation at τ_o and $\tau_o + \Delta\tau_o$:

$$\int_{\tau_e}^{\tau_o} \frac{d\tau}{a(\tau)} = \int_{\tau_e+\Delta\tau_e}^{\tau_o+\Delta\tau_o} \frac{d\tau}{a(\tau)} , \tag{34}$$

which for small $\Delta\tau_e$ and $\Delta\tau_o$ reads as $\frac{\Delta\tau_e}{a(\tau_e)} = \frac{\Delta\tau_o}{a(\tau_o)}$.

Redshift drift test.

The redshift drift is defined as ($\tau \to t$ here)

$$\Delta z = z_e - z_0 = \frac{a(t_0 + \Delta t_0)}{a(t_e + \Delta t_e)} - \frac{a(t_0)}{a(t_e)} \,, \qquad (35)$$

which can be expanded in series and to first order in Δt as

$$\Delta z = \frac{a(t_0) + \dot{a}(t_0)\Delta t_0}{a(t_e) + \dot{a}(t_e)\Delta t_e} - \frac{a(t_0)}{a(t_e)} \approx \frac{a(t_0)}{a(t_e)} \left[\frac{\dot{a}(t_0)}{a(t_0)}\Delta t_0 - \frac{\dot{a}(t_e)}{a(t_e)}\Delta t_e \right] \,. \qquad (36)$$

Using above relations we have

$$\Delta z = \Delta t_0 \left[H_0(1+z) - H(t(z)) \right] = (1+z)\frac{\Delta v}{c} \,, \qquad (37)$$

where Δv is the velocity shift and $H(t(z))$ is given in a standard way.

Redshift drift in varying c theory.

In VSL theory the relation (34) generalizes into

$$\int_{t_e}^{t_o} \frac{c(t)dt}{a(t)} = \int_{t_e+\Delta t_e}^{t_o+\Delta t_o} \frac{c(t)dt}{a(t)} \ , \tag{38}$$

which for small Δt_e and Δt_o transforms into

$$\frac{c(t_e)\Delta t_e}{a(t_e)} = \frac{c(t_0)\Delta t_o}{a(t_o)} \ . \tag{39}$$

The definition of redshift in VSL theories remains the same as in standard Einstein relativity and reads as (Barrow, Magueijo 1999)

$$1 + z = \frac{a(t_0)}{a(t_e)} \ . \tag{40}$$

Redshift drift - varying c

Using (39) we have

$$\Delta z = \Delta t_0 \left[H_0(1+z) - H(t_e)\frac{c(t_0)}{c(t_e)} \right] \quad , \tag{41}$$

which after applying the ansatz

$$c(t) = c_0 a^n(t) \tag{42}$$

gives

$$\frac{\Delta z}{\Delta t_0} = \frac{\Delta z}{\Delta t_0}(z,n) = H_0(1+z) - H(z)(1+z)^n \quad . \tag{43}$$

Redshift drift - varying c

In the limit $n \to 0$ the formula (43) reduces to (37) for standard Friedmann universe. Bearing in mind definitions Ω's, and assuming $K = 0$ we have

$$H^2(z) = H_0^2 \left[\Omega_{m0}(1+z)^3 + \Omega_\Lambda\right] \tag{44}$$

and so (43) gives

$$\begin{aligned} \frac{\Delta z}{\Delta t_0} &= H_0 \left[1 + z - (1+z)^n \sqrt{\Omega_{m0}(1+z)^3 + \Omega_\Lambda}\right] \\ &= H_0 \left[1 + z - \sqrt{\Omega_{m0}(1+z)^{3+2n} + \Omega_\Lambda (1+z)^{2n}}\right] \end{aligned} \tag{45}$$

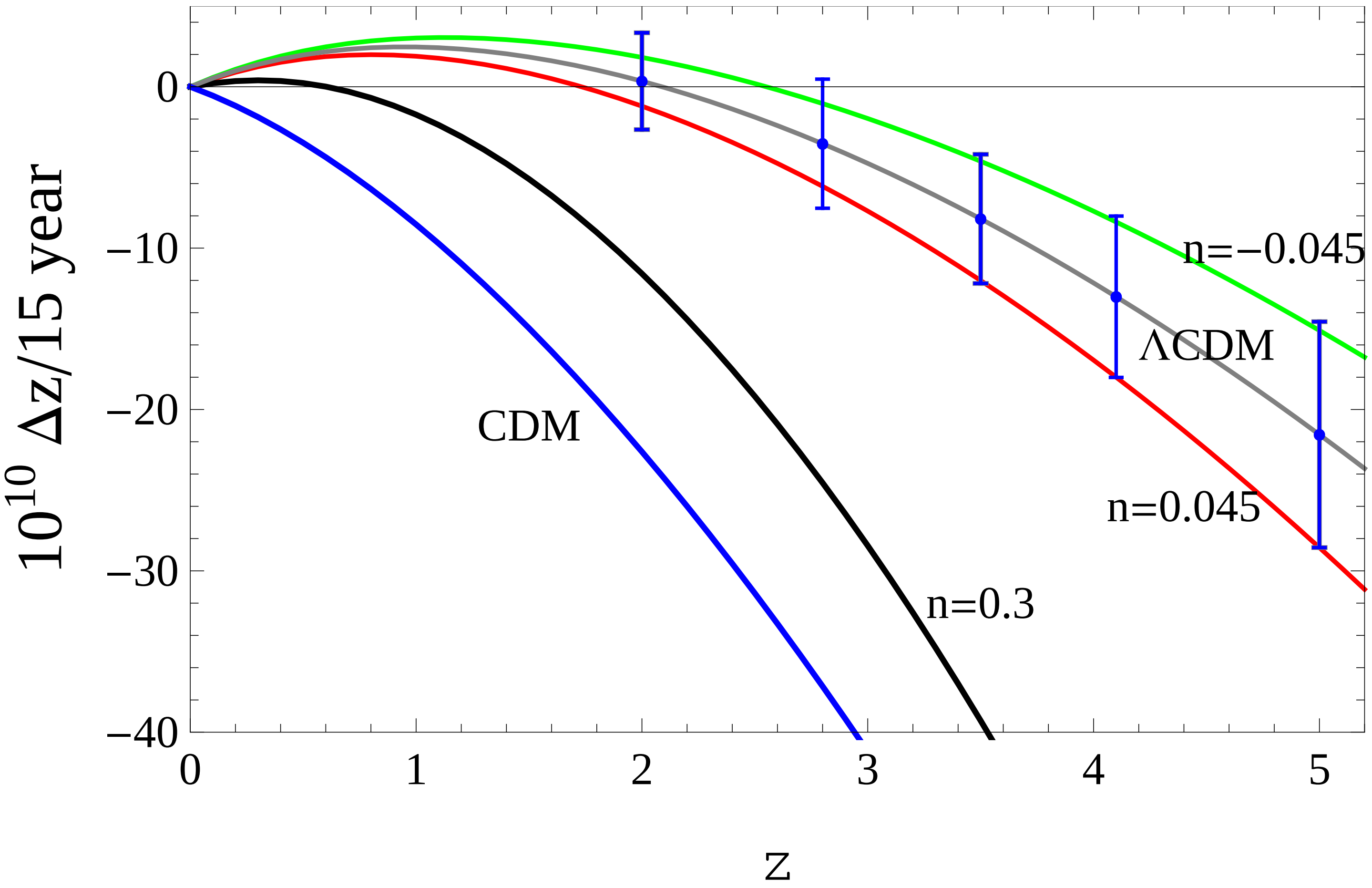
which can further be rewritten to define new redshift function

$$\tilde{H}(z) \equiv (1+z)^n H(z) = H_0 \sqrt{\sum_{i=1}^{i=k} \Omega_{wi} (1+z)^{3(w_{eff}+1)}} \,, \tag{46}$$

where $w_{eff} = w_i + \frac{2}{3} n$.

Redshift drift test - varying c

The VSL redshift drift effect for 15 year period of observations.



Redshift drift test - varying c

- If $n < 0$ (c decreases) then dust matter becomes little negative pressure matter and the cosmological constant became phantom. Both components can mimic dark energy.
- If $n > 0$ then (growing $c(t)$) VSL model becomes more like Cold Dark Matter (CDM) model.
- Theoretical error bars are taken from Quercellini et al. 2012 and presumably show that for $|n| < 0.045$ – **one cannot distinguish between VSL models and ΛCDM models**.
- In other words, by measuring redshift drift, **bounds on the variability of c will be given**.

redshift drift - future experiments

- European Extremely Large Telescope (EELT) (with its spectrograph CODEX (COsmic Dynamics EXperiment))
- Thirty Meter Telescope (TMT), the Giant Magellan Telescope (GMT)
- Problems to measure Lyman-α lines of the number of quasars for $z < 1.7$ from the ground.
- gravitational wave interferometers DECIGO/BBO (DECi-hertz Interferometer Gravitational Wave Observatory/Big Bang Observer). Detection even at $z \sim 0.2$.

4. Measuring c with baryon acoustic oscillations (BAO)

Speed of light c appears in many observational quantities.
Among them in the angular diameter distance

$$D_A = \frac{D_L}{(1+z)^2} = \frac{a_0}{1+z}\int_{t_1}^{t_2}\frac{c(t)dt}{a(t)} \tag{47}$$

where D_L is the luminosity distance, a_0 present value of the scale factor (normalized to $a_0 = 1$ later), and we have taken the spatial curvature $k = 0$ (otherwise there would be $\sin$ or $\sinh$ in front of the integral). Using the definition of redshift and the dimensionless parameters Ω_i we have

$$D_A = \frac{1}{1+z}\int_0^z \frac{c(z)dz}{H(z)}, \tag{48}$$

where

$$H(z) = \sqrt{\Omega_{r0}(1+z)^4 + \Omega_{m0}(1+z)^3 + \Omega_\Lambda}. \tag{49}$$

Angular diameter distance maximum.

Due to the expansion of the universe, there is a maximum of the distance at

$$D_A(z_m) = \frac{c(z_m)}{H(z_m)}. \tag{50}$$

which can be obtained by simple differentiating (48) with respect to z:

$$\frac{\partial D_A}{\partial z} = -\frac{1}{(1+z)^2}\int_0^z \frac{c(z)dz}{H(z)} + \frac{1}{1+z}\frac{c(z)}{H(z)} = 0 \tag{51}$$

In a flat $k = 0$ cold dark matter CDM model

$$z_m = 1.25 \quad \text{and} \quad D_A \approx 1230 \ \ \text{Mpc} \tag{52}$$

For standard ΛCDM model of our interest:

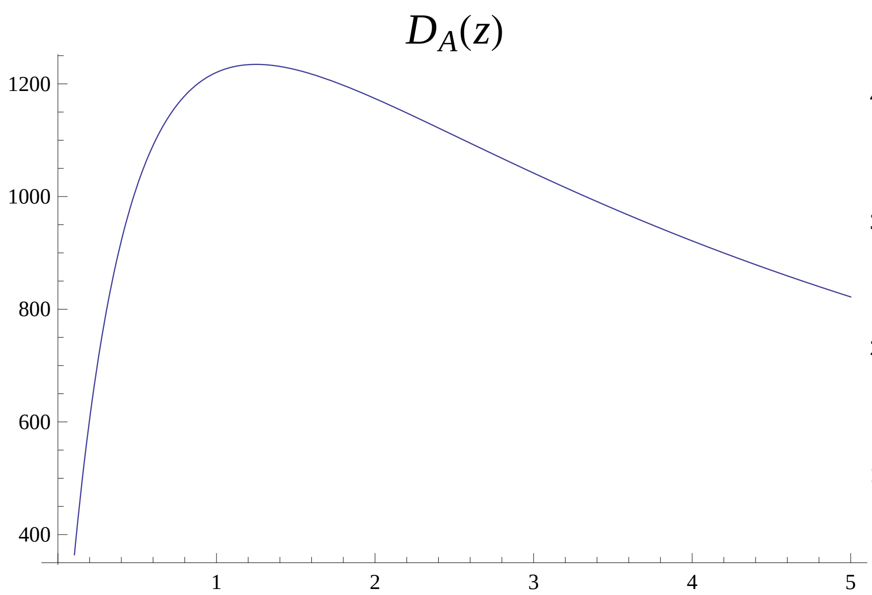
$$1.4 < z_m < 1.8. \tag{53}$$

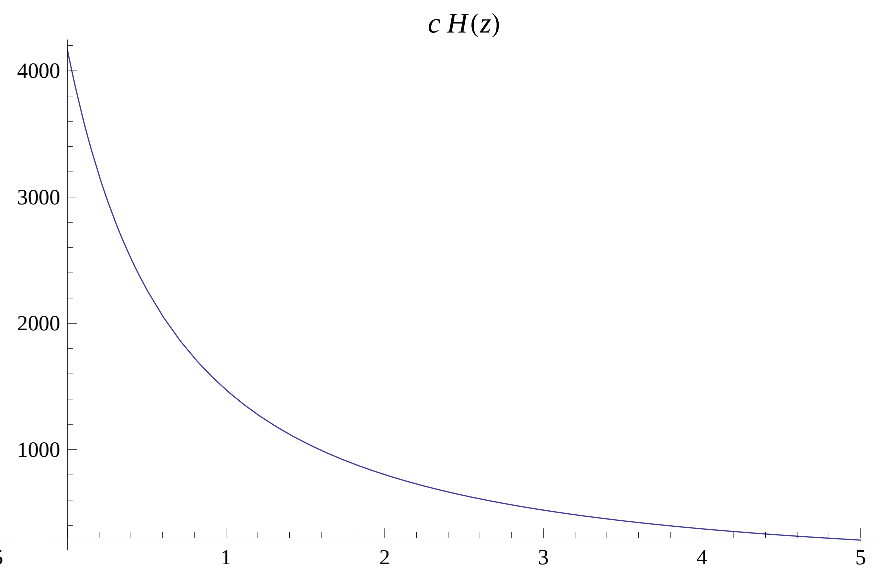
D_A versus $H(z)$

The point: The product of D_A and H gives **exactly** the speed of light c at maximum (the curves intersect at z_m):

$$D_A(z_m)H(z_m) = c_0 \equiv 299792.458 \ \ \mathrm{kms}^{-1} \tag{54}$$

if we believe it is constant! (defined officially www.bipm.org; a relative error 10^{-9} by Evenson et al. 1972)





Measuring z_m

Measuring z_m problematic if one uses D_A only (large plateau around z_m makes it difficult to avoid errors from small sample of data – besides, one has binned data, observational errors, and instrinsic dispersion).

However, one can appeal to an independent measurement of $c_0/H(z)$ which is the radial (line-of-sight) mode of the baryon acoustic oscillations surveys (BAO) for which $D_A(z)$ is the tangential mode (e.g. Nesseris et al. 2006). In other words, we have both tangential and horizontal modes as

$$y_t = \frac{D_A}{r_s} \qquad y_r = \frac{c}{Hr_s}, \tag{55}$$

where

$$r_s = \int_{z_{dec}}^{\infty} \frac{cc_s(z)dz}{H(z)} \tag{56}$$

is the sound horizon size at decoupling and c_s the speed of sound.

Baryon acoustic oscillations.

From BOSS DR11 CMASS (Samushia et al. 2014)

$$\frac{D_V}{r_s(z_d)} = 13.85 \pm 0.17 \quad \text{at} \quad \bar{z} = 0.57, \tag{57}$$

where the volume-averaged distance is

$$D_V = \left[(1+z)^2 cz \frac{D_A^2}{H} \right]^{\frac{1}{3}}, \tag{58}$$

while from BOSS DR11 LOWZ (Tojeiro et al. 2014)

$$D_V = (1264 \pm 25) \left(\frac{r_s(z_d)}{r_{s,fid}(z_d)} \right) \quad \text{at} \quad \bar{z} = 0.32. \tag{59}$$

The method to measure c.

(Salzano, MPD, Lazkoz 2015)

- Measure independently $D_A(z)$ and $H(z)$.
- Calculate z_m.
- The product $D_A(z_m)H(z_m) = c(z_m)$.
- But $c(z_m)$ may not be equal to c_0, so that we can measure $\Delta c = c(z_m) - c_0$.
- This would determine possible variability of c.

The scenarios.

Take background ΛCDM model with an ansatz (Magueijo 2003)

$$c(a) \propto c_0 \left(1 + \frac{a}{a_c}\right)^n \tag{60}$$

where a_c is the scale factor at the transition epoch from some $c(a) \neq c_0$ (at early times) to $c(a) \to c_0$ (at late times to now).

Three scenarios (Salzano, MPD, Lazkoz 2015):

1) standard case $c = c_0$;

2) $a_c = 0.005$, $n = -0.01 \to \Delta c/c \approx 1\%$ at $z \propto 1.5$;

3) $a_c = 0.005$, $n = -0.001 \to \Delta c/c \approx 0.1\%$ at $z \propto 1.5$.

The results.

Based on 10^3 Euclid project (Laureijs et al. 0912.0914) mock data simulations (Font-Ribeira et al. 2014):

1) $z_m = 1.592^{+0.043}_{-0.039}$ (fiducial model input $z_m = 1.596$) and $c/c_0 = 1 \pm 0.009$

2) $z_m = 1.528^{+0.038}_{-0.036}$ (fiducial $z_m = 1.532$) and $c(z_m)/c_0 = 1.00925 \pm 0.00831$

and

$$< c(z_m)/c_0 - 1\sigma_{c(z_m)/c_0} >= 1.00094^{+0.00014}_{-0.00033} \qquad (61)$$

so that **a detection by Euclid of 1% variation at 1σ-level will be possible**.

3) $z_m = 1.584^{+0.042}_{-0.039}$ (fiducial $z_m = 1.589$) and $c(z_m)/c_0 = 1.00095 \pm 0.00852$

and

$$< c(z_m)/c_0 - 1\sigma_{c(z_m)/c_0} >= 0.99243^{+0.00016}_{-0.00013} \qquad (62)$$

so that **a detection by Euclid of 1% variation at 1σ-level will not be possible**.

Perspectives.

- Euclid will have $1/10$ of the errors of the current missions like WiggleZ Dark Energy Survey (e.g. Blake et al. 2011, 2012).
- Other missions which will be competitive to Euclid and useful for our task will be:
- Dark Energy Spectroscopic Instrument (DESI) (Levi et al. 1308.0847)
- Square Kilometer Array (SKA) (Bull et al. 1405.1452)
- Wide-Field Infrared Survey Telescope (WFIRST) (Spergel et al. 1305.5425) (esp. having largest sensitivity at potential z_m region i.e. $1.5 < z < 1.6$).

5. Conclusions

- Varying constants theories (and especially varying c and α) have their advantages as well as problems. The firmest seems to be varying G theories.
- The advantages of varying c theories are: solution of the flatness and horizon problems; singularity problem.
- Violation of Lorentz invariance in c-varying theories leads to a choice of a preferred frame and a drop of standard variational principle.
- α-varying theories have better formulation - variability of α is related to variability of c.
- New tests to check variability of c in future telescope/space missions have been proposed.

Results and conclusions contd.

- 1. Redshift drift test which give clear prediction for redshift drift effect which can potentially be measured by future telescopes (E-ELT, TMT, GMT, DECIGO/BBO).
- 2. Baryon acoustic oscillations test to independently measure the radial D_A and tangential mode c/H of the volume distance at the angular diameter distance maximum z_m.
- In simple terms we have a "cosmic" measurement of the speed of light c with D_A giving the dimension of length being a "cosmic ruler" and $1/H$ giving the dimension of time being a "cosmic clock" i.e.

$$c = \frac{D_A}{\left(\frac{1}{H}\right)}. \tag{63}$$

- We have proven that 1% variability of c can be tested at 1σ level by EUCLID mission. Likely that they can be tested in DESI, SKA, WFIRST.