[My] changing perspectives on Changing Couplings

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Thanks to my collaborators: D. Budker, V. Flambaum, D. Jackson Kimball, M. Ledbetter, S. Pustelny, K Olive, others

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Outline of the talk

1. Introduction. Change of couplings in space and time. Simplest models: Bekenstein model + variants; Dark photon model.
2. Why a particle theorist cannot take this subject very seriously: problems with technical naturallness.
3. If we abandon technical naturalness, there is plenty of other interesting effects one can look for:

- Density dependence. Tests of spectra in the Lab and in our galaxy in search of chameleon-type dependence. Test of depth-dependence of coupling constants.
- Connection to Dark Matter: renormalization of the couplings in the central region of the galaxy.
- Cosmological/astrophysical defects. [Running through walls, telephone poles etc] search for domain walls, strings, monopoles, DM clumps as **transient signals in clocks, magnetometers** etc.

4. Conclusions

[Vague] motivations

1. Existence of dark energy is an established experimental fact, now with the seal of approval by Nobel committee.
2. It may not be a simple cosmological constant Λ, but an ultra-soft dynamical field ϕ that can evolve in time/space
3. Possible coupling of ϕ to normal matter may manifest itself in a number of "strange" phenomena: Lorentz violation; spin-0 fifth force; breakdown of equivalence principle; change of couplings in space and time, etc. Search for these strange phenomena can be viewed as a search for new IR degrees of freedom.
4. There are **endless** experimental possibilities for astrophysical and laboratory tests of e.g. $\Delta\alpha$ or $\Delta(m_e/m_p)$. Recent progress in precision is enormous. This progress is, in my opinion, main driving force behind the continuation of this program.

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) + \bar{\psi}(\partial_\mu\gamma^\mu - m_e)\psi$$
$$-\phi\frac{m_e}{M_s}\bar{\psi}\psi - \phi\frac{m_e}{M_p}\bar{\psi}i\gamma_5\psi$$

If ϕ is light, i.e. quintessence-like field, then there is a preferred frame where $\partial_\mu\phi = (\partial_t\phi, 0, 0, 0)$, that quite generically coincides with the frame of CMB. $\partial_t\phi$ is limited by $(\rho_{d.e.}(1+w))^{1/2}$. There are several consequences of the $\phi - \psi$ interaction Lagrangian:

1. Particle mass depends on time: $m_{eff}(t) = m_e(1 + \phi/M_s)$
2. There is an additional Zeeman-like splitting from $H_{int} = M_p^{-1}\vec{S}\cdot\nabla\phi$. If the spin moves with velocity v over the CMB frame, then $\nabla\phi = \vec{v}\dot{\phi}$.

3. Spin-gravity coupling will appear as "environmental effect": massive over-density will create grad ϕ, that follows $\mathbf{g}_{grav}$ that will couple to the spin. Zeeman-like effect w.r.t. the vertical direction, direction to the Sun etc. (Lambert, Flambaum, MP). Simple Lagrangians can encompass both changing couplings (Flambaum, Peik, Berengut, deNijs) and Lorentz violation (Lehnert, Mueller, Ruiz Cembranos, Heil).

Models: extra U(1) with changing Higgs vev

Consider Okun-Holdom model of an extra U(1) (Marciano's talk), kinetically mixed with hypercharge [dark/hidden/secluded/A' photon model].

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}V_{\mu\nu}F^{\mu\nu} + |D_\mu\phi|^2 - V(\phi),$$

= *theory of new massive photon, weakly mixed with normal EM field.*

If you probe physics at momentum scale q << m_V=e*vev, vector is massive and $\alpha = \alpha_0$. However, if you measure it at q >> m_V, you have to include mixing and $\alpha_{eff} = \alpha_0/(1-\kappa^2)$. If vev changes in time, the dividing line changes and one could perceive this as changing coupling.

Need very small mass of Higgs'. E.g. imagine a Nielsen-Olesen-Abrikosov string/vortex in this theory. In the middle, the symmetry is restored m_V=0, and $\alpha = \alpha_{eff}$, while outside $\alpha = \alpha_0$. Going through such a vertex will look like an effect of "changing couplings".

Bekenstein model of $\alpha(t)$

$$L = L_{SM} + \frac{M_*^2}{2}\left(\partial_\mu \varphi\right)^2 - \frac{\varsigma_F}{4}\varphi\, F_{\mu\nu}F_{\mu\nu}$$

$$\varphi - \text{dependence of } \alpha: \quad \alpha_{\text{eff}} = \alpha/(1+\varsigma_F \varphi)$$

Cosmological evolution equation :

$$\partial_\mu \partial^\mu \varphi = \frac{\varsigma_F}{M_*^2}\left\langle \frac{1}{4} F_{\mu\nu}F_{\mu\nu} \right\rangle$$

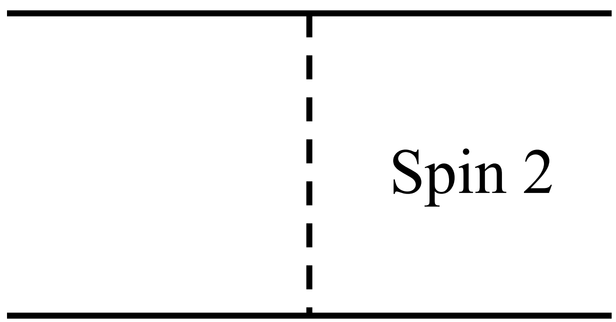
Important consequences:

- No evolution between ~ 5 eV < T < 0.5 MeV
- Linear evolution with ln (z) during matter domination:

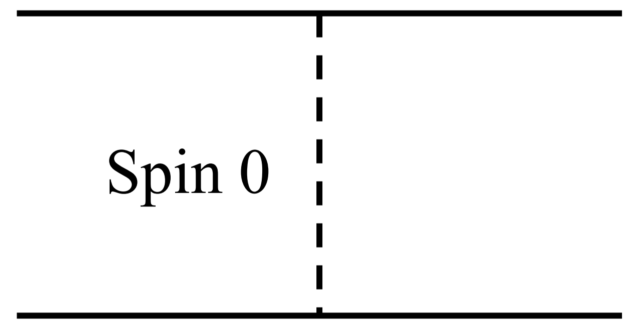
$\Delta\, \alpha/\alpha \sim \ln(1+z)\ \zeta_F^{\,2} M_{\mathrm{Pl}}^{\,2}/M^2_{\,*} \times \Omega_b \times \Delta_{\mathrm{EM}}$

$\Delta_{\mathrm{EM}} \sim$ few 10^{-4} is the EM fraction of proton mass

Bekenstein model is constrained by gravity tests



Universal force, G_N



Non-universal force;

$$\Delta G_N \sim \zeta_F^2 \Delta_{EM}^2 / M_*^2$$

The absence of non-universal force is checked with accuracy better than 10^{-13}. Therefore one can conclude that

$$(\alpha(\text{then})-\alpha(\text{now}))_{max}/\alpha \sim + \text{few} \times 10^{-10}$$

and Bekenstein model cannot give $O(10^{-5})$ shift. One has to "drive" phi evolution by its own potential, $V(\phi)$. The problem is of course that this potential does not follow from anywhere, and worse, is receiving huge quantum corrections that one has to "kill" by hand.

Modified Bekenstein-type model

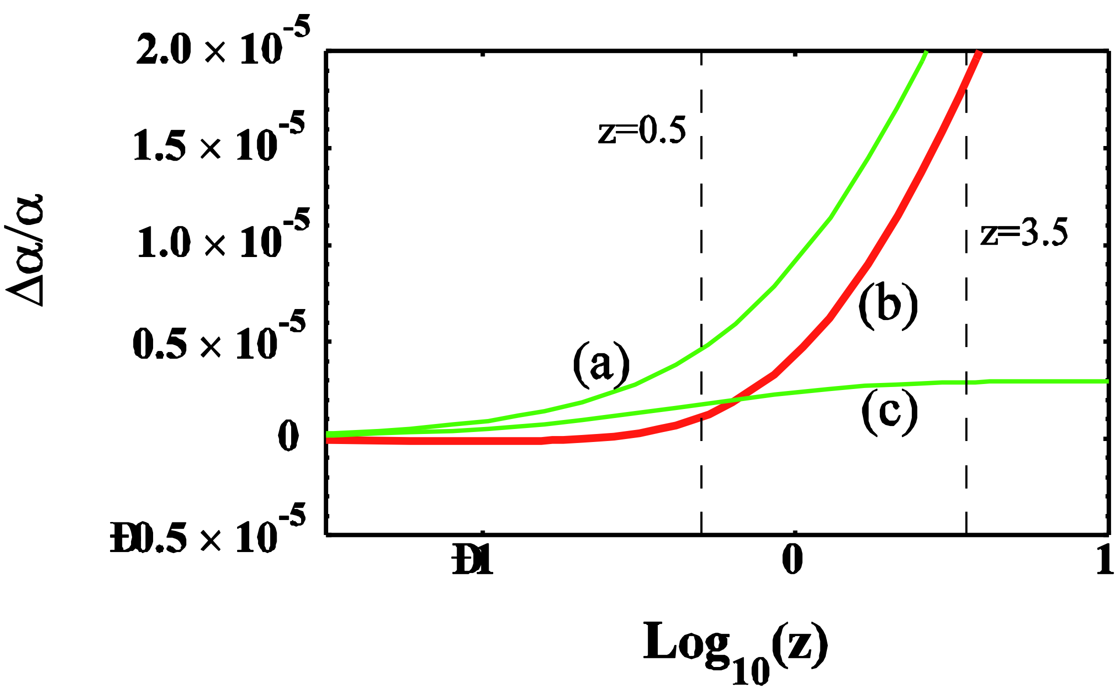
1. Drive the scalar field by coupling to Dark Matter:

$$\phi F_{\mu\nu} F_{\mu\nu} \rightarrow \phi (F_{\mu\nu} F_{\mu\nu} + \bar{\chi} \not\partial \chi)$$

2. Make it move by adding $V(\phi)$ and choosing $\zeta_F M_*^{-1} \sim 10^{-5} M_{pl}$

Predictivity is partially or totally lost:

(K. Olive, MP, 2001)



$\zeta_F = 10^{-5}$ a: $\zeta_m=1$; $\zeta_\Lambda=0$

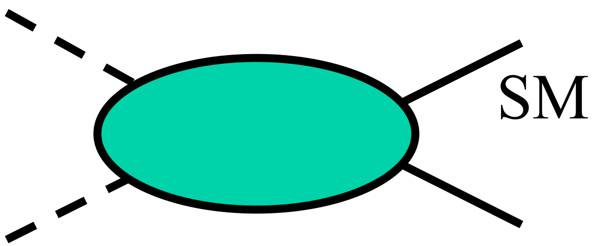
b: $\zeta_m=1$; $\zeta_\Lambda=-2$

c: $\zeta_m=0$; $\zeta_\Lambda=1$

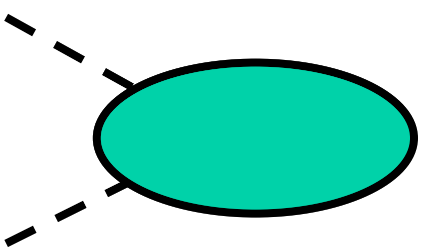
It is remarkable that clock precision is now at similar or better level for $d\alpha/dt$

Changing α models are unnatural SM

Bekenstein's model and spin-offs are *technically unnatural:*



These loops are OK for any cutoff



These loops are a disaster:

$m_\phi \sim \Lambda_{UV}^2/M_* \sim 10^{-20}$ GeV or more

But to have cosmological evolution

now one should have $m_\phi \sim 10^{-42}$ GeV

Cosmological constant problem gets worse than before

Couplings changing on cosmic time = goodbye technical naturalness

Any tree level potential

$V^{tree}(\phi) = c^{tree}{}_0 + c^{tree}{}_1\phi + c^{tree}{}_2\phi^2 + \ldots.$

Would have to have coefficients $c^t{}_i$ very small to keep evolution *slow*. Loops generate *larger* corrections

$V^{loop}(\phi) = c^{loop}{}_0 + c^{loop}{}_1\phi + c^{loop}{}_2\phi^2 + \ldots.$

so that $c^{loop}{}_i >> c^{tree}{}_i$, One has to start with large and opposite tree-vs-loop coefficients $c^{loop}{}_i = - c^{tree}{}_i$ to ensure tight cancellation for several terms in the series… Very unnatural! *Do not expect any change of couplings in time.* [NB: Same pessimistic argument does not apply to interactions protected by shift symmetry: ϕ FFdual, for example]

*** On the other hand, one could argue that theory track record with naturalness is very poor. No success with Λ. No success [so far] with new TeV scale physics. Why not accept limited predictivity and search for variations in alpha, m_e/m_p etc anyways… ***

If we abandon technical naturalness, the landscape of new physics effects expands

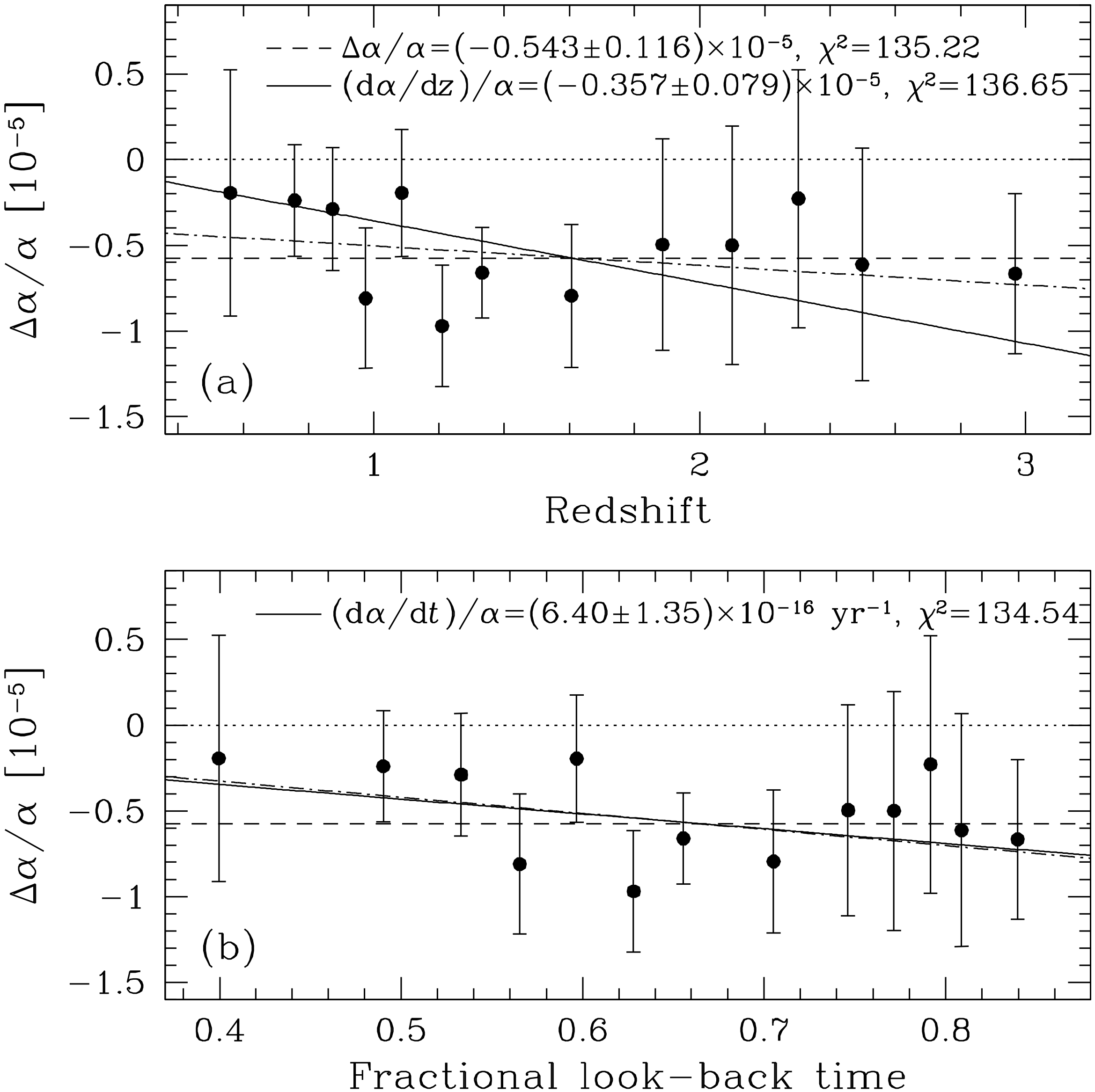
1. Change of couplings that has smooth time evolution + a component that follows gravitational potential (everyone does this)

2. Change of couplings that depends on density – chameleon type models. *New tests in our galaxy; tests in the lab; and underground/ underwater.*

3. Dark matter induced change of couplings – look at the very center of the galaxy.

4. Search for *short-time fluctuations* of couplings and of "LV" coefficients caused by crossing of domain walls, fuzzy strings, monopoles, dark matter clumps etc.

Is it Δ α or dα/dt ? (Murphy et al. 2003)



Could be a signature of separate domains in α

Density-dependent couplings (Olive, MP)

- **Main Idea:**

1. Make Nordtvedt-Polyakov-Damour model (also called chameleon from closely related model by Khoury-Weltman) much stronger coupled than gravity:

   $L = (\partial\phi)^2/2 - (\phi-\phi_0)^2 O_{SM}/TeV^2 - \phi^2 m_0^2/2$

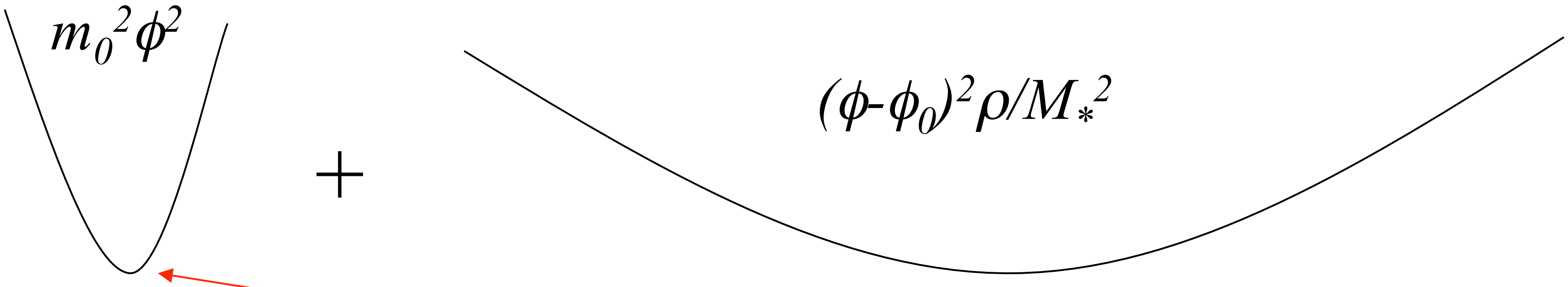
Average O_{SM} (e.g. $m_q\psi\psi$ or $G_{\mu\nu}^2$ or $F_{\mu\nu}^2$) scales like ρ_{matter}

In-medium effective mass of ϕ can be large (no constraints from eq. principle)

2. *In vacuo* position of ϕ can be different, if vacuum (bare) mass is much larger than $m_\phi(\rho_{cosm})$
3. Coupling constants can take different values depending where measured, at low or high ρ_{matter}.

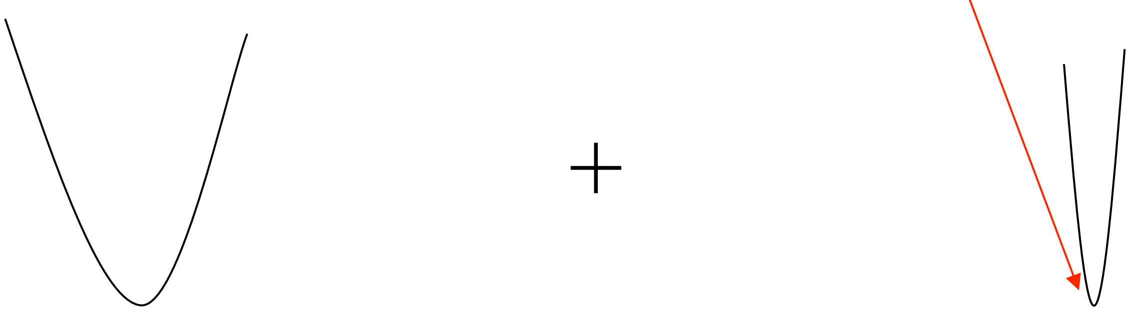
Illustration

- Low density environments



- High density environments

Minimum shifts, range shrinks



Lagrangian of the model

$$L = L_{SM} + \frac{M_*^2}{2}\left(\partial_\mu \varphi\right)^2 - \sum \frac{\xi_O}{2}(\varphi - \varphi_m)^2 O_{SM} - V(\varphi)$$

Effective potential

$$V_{\rm eff} \approx V(\varphi) + \frac{(\varphi - \varphi_m)^2 \rho}{2} \approx \Lambda_0 + \Lambda_2 \frac{\varphi^2}{2} + \frac{(\varphi - \varphi_m)^2 \rho}{2}$$

For an infinite extent medium the minimum is determined as

$$\varphi_{\min} = \varphi_m \frac{\rho}{\rho + \Lambda_2}, \quad m_{\rm eff}^2 = \frac{\rho + \Lambda_2}{M_*^2},$$

while masses and Newton constant receive corrections

$$m_{N\rm eff} = m_N \left(1 + \varphi_m^2 \frac{\Lambda_2^2}{2(\rho + \Lambda_2)^2}\right)$$

$$U(r) = -G_N \frac{m_N^2}{r}\left(1 + \exp(-r m_{\rm eff}) \frac{2M_{\rm Pl}^2}{M_*^2} \frac{\varphi_m^2 \Lambda_2^2}{(\rho + \Lambda_2)^2}\right)$$

In-medium range of the force

$$\lambda_{\rm eff} = m_{\rm eff}^{-1} = \left(\frac{\rho + \Lambda_2}{M_*^2}\right)^{-1/2} = 7\times10^{-3}\,{\rm cm}\ \frac{M_*}{\rm TeV}\left(\frac{10^{24}\,{\rm GeV/cm^3}}{\rho}\right)^{1/2},$$

For large (terrestrial type) densities and TeV-scale couplings, the range of the force falls under a mm

Moreover, coupling of ϕ to matter is quadratic, and gravitational constraints are relaxed.

Environmental Dependence: $\alpha(\rho)$ and $m(\rho)$

Masses and coupling constants depend on ambient matter density. Assuming the hierarchy of densities, $\rho_d >> \Lambda_2 >> \rho_r$, we get

$$\frac{m_{Nr} - m_{Nd}}{m_N} \approx \frac{\varphi_m^2}{2}; \qquad \frac{\alpha_r - \alpha_d}{\alpha} \approx -\xi_F \frac{\varphi_m^2}{2}$$

Variants: models with spontaneous breaking

$$L = L_{SM} + \frac{M_*^2}{2}\left(\partial_\mu \varphi\right)^2 - \sum \frac{\xi_O}{2}\varphi^2 O_{SM} - V(\varphi)$$

Effective potential

$$V_{\text{eff}} \approx V(\varphi) + \frac{\varphi^2 \rho}{2} \approx \Lambda_0 + (p\Lambda_2 + q\rho)\frac{\varphi^2}{2} + \frac{\varphi^4 \Lambda_4}{4}$$

where p and q are +1 or -1.

$$p = \text{-}1,\ q = 1 \Rightarrow \begin{cases} \left\langle \varphi^2 \right\rangle = 0 \quad \text{for} \quad \rho > \Lambda_2 \\ \left\langle \varphi^2 \right\rangle = \Lambda_4^{-1}(\Lambda_2 - \rho) \quad \text{for} \quad \rho < \Lambda_2 \end{cases}$$

Broken phase in low density environments and unbroken phase in high density environments (very natural).

Consequence : No linear couplings on Earth, and so no strong constraints!!!

Possibility for new tests inside our Galaxy

- $\alpha(\rho)$; $m_e/m_p(\rho)$ idea can be tested by measuring $\alpha(\rho_{ISM})$
- There is no specific benefits for going after high z.
- Tests within our Galaxy can be done in emission molecular clouds and use very high quality lines
- Such tests were performed in 2008 (Kozlov, Levshakov, Molaro) → indication on nonzero $\Delta m_e/m_p \sim 10^{-7}$
- Latest tests may be not confirming it (Molaro, 2012, private communication).

Recreating $\alpha(\rho_{\mathrm{cosmo}})$ in the Lab

Having clocks in vacuum chamber and outside may allow to measure the environmental shifts in frequency

For a spherical evacuated chamber of radius R, we have

$$\frac{\alpha(r=R)-\alpha(r=0)}{\alpha} \approx \frac{\xi_F \varphi_m^2}{2} \begin{cases} \dfrac{\Lambda_2^2 R^4}{36 M_*^4} & \text{for} \quad R/\lambda_{vac} << 1 \\ 1 & \text{for} \quad R/\lambda_{vac} >> 1, \end{cases}$$

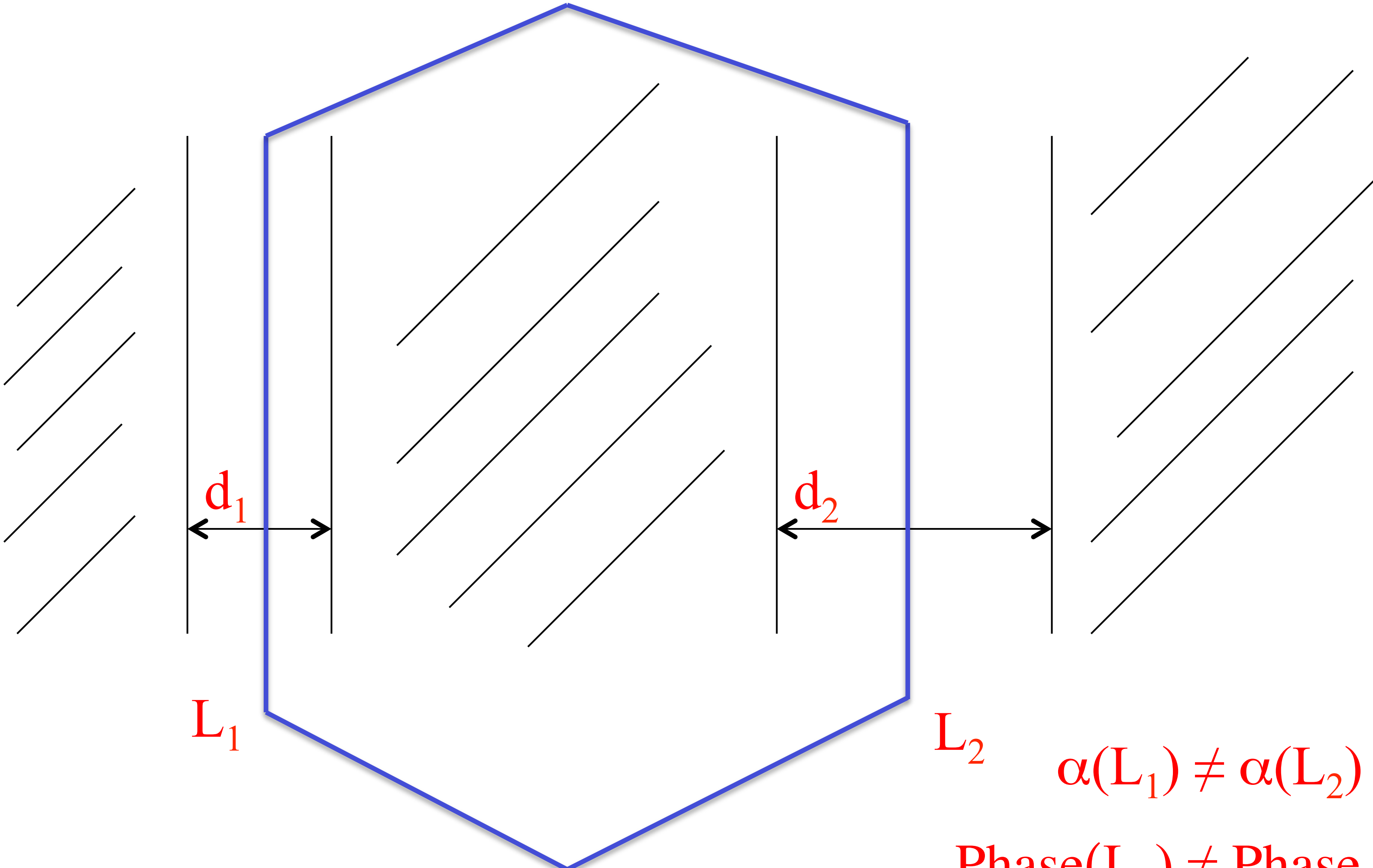
which after substituting for gravitational constraints takes the following form

$$\frac{\alpha(r=R)-\alpha(r=0)}{\alpha} \approx \frac{\xi_F \times \mathrm{TeV}^2}{M_*^2} \begin{cases} 10^{-16} (R/1\mathrm{m})^4 & \text{for} \quad R/\lambda_{vac} << 1 \\ 10^{-15} & \text{for} \quad R/\lambda_{vac} >> 1, \end{cases}$$

Can be searched for using precision methods of atomic physics

Concept of possible test

Sending atoms through high-quality vacuum gaps of different width one can test α(path) with means of atomic interferometry.



$\alpha(L_1) \neq \alpha(L_2)$

Phase(L_1) $\neq$ Phase (L_2)

Even more speculative: "Modified" c, modified couplings at great depth (originally motivated by OPERA c_ν)

(Flambaum, MP) Consider the following background

$$h_{00} = h_{0i} = 0; \quad h_{ii} = -\epsilon \times \mathrm{diag}(1,1,1)$$

with *e* zero on the surface and > 10^{-5} deep underground. Consider QED with identical modification to the limiting speed of *Φ* and *γ*

$$\mathcal{L}_{\rm QED} = -\frac{1}{4}F_{\mu\nu}^2 + |(\partial_\mu + igA_\mu)\Phi|^2 - m^2|\Phi|^2$$

$$\mathcal{L}_\epsilon = h_{\mu\nu}\left(-F_{\mu\alpha}F_{\nu\alpha} + 2[(\partial_\mu + igA_\mu)\Phi]^*(\partial_\nu + igA_\nu)\Phi\right) - \frac{1}{3}h_{\mu\mu}\left(\delta_1(|D_\mu\Phi|^2 - m^2|\Phi|^2) - \delta_2\frac{1}{4}F_{\mu\nu}^2\right).$$

Which is

$$\mathcal{L}_{{\rm QED}+\epsilon} = \mathcal{L}_{\rm int} + (|\partial_0\Phi|^2 - m^2|\Phi|^2)(1+\epsilon\delta_1) - |\partial_i\Phi|^2(1+\epsilon(2+\delta_1)) + \frac{1}{2}\mathbf{E}^2(1+\epsilon(2-\delta_2)) - \frac{1}{2}\mathbf{B}^2(1+\epsilon(4-\delta_2)),$$

Modification of c leads to modification of α

Simple filed redefinitions lead to

$$\mathcal{L}_{\mathrm{QED}+\epsilon} = -\frac{1}{4}F_{\mu\nu}^2 - m^2|\Phi|^2$$
$$+|(\partial_\mu + ig(1-\frac{\epsilon}{2}(3-\delta_2))A_\mu)\Phi|^2.$$

Same QED but $\alpha_{\mathrm{eff}} = \alpha(1-\epsilon\times(3-\delta_2)).$

Unless δ_2=3 (coupling to $T_{\mu\nu}$ like GR), the couplings are different and clock frequencies are different underground/underwater, clocks are "nonuniversal" etc. Even if ε couples to the $T_{\mu\nu}$, effect appears in ε^2 order, unless *e*-modification replicates nonlinear terms in GR.

Conclusion: you cannot "modify" c_ν, and not c_e and c_γ – Then you should expect abnormal $O(\varepsilon)$ and/or $O(\varepsilon^2)$ deviations of clock frequencies. You can try testing this model *without* using neutrinos.

It makes sense testing clocks deep underground/underwater

There has been a concerted effort of testing GR in space. Here we propose to have $O(10^{-10})$ (~ 3 order of magnitude larger than GR effects) tests done deep underground/underwater.

1. Take two types of stable emitters with different dependence on alpha, (e.g. based on Cs and Rb) lower them *as deep as you can*. Compare signals.

2. Synchronize two clocks of the same type, lower one, keep for awhile, bring back, compare.

Possible locations: e.g. Snolab, LNGS, IceCube, - up to 2.5 km depth.

Deepest commercial mines: South Africa – up to 4 km.

Deep oceanic trenches: up to 11 km. (Incidentally the same depth as the maximum of the OPERA beam trajectory). Deep boreholes.

Couplings following dark matter distribution

Make Polyakov-Damour model (also called chameleon from closely related model by Khoury-Weltman) much stronger coupled than gravity:

$$L = (\partial\phi)^2/2 - \phi^2 O_{SM}/M_*^2 - \phi^2 m_0^2/2 \quad \text{(canonically normalized)}$$

Average O_{SM} (e.g. $m_q\psi\psi$ or $G_{\mu\nu}^2$ or $F_{\mu\nu}^2$) scales like $\rho_{\text{baryonic matter}}$

In-medium and in-vacuum minima for ϕ coincide.

However, if initially ϕ is displaced from the minimum, there will be oscillations of scalar field around the minimum that can serve as dark matter (not unlike axion DM picture)

On average, $\langle\phi^2\rangle \sim$ DM density / m_0^2, which leads to

1. Couplings follow DM profile, rather than grav. potential.
2. Significant difference $O(10^{-6})$ of the coupling constants between our patch of the galaxy and the central region if e.g. $m_0 \sim 10^{-10}$ eV; $M_* \sim$ TeV.
3. Try to test couplings in the vicinity of Sgr A*

How do you know if you ran through a wall?

MP, Pustelny, Ledbetter, Jackson Kimball, Gawlik, Budker.

- Many models of "New Physics" predict stable topological defects (domain walls, strings, monopoles). Physicists tend to discuss small size of these objects, e.g. $1/M_{GUT}$ across. But the spatial extent could be much larger, if a theory admits light excitations.

- If such objects are "scattered" in our galaxy, their velocity in the Solar system rest frame ~ 10^{-3} c, and the overall energy density must satisfy, $\rho_{\text{Domain walls}} < \rho_{\text{Dark Matter}}$

- Crucially, if such a defect passes through the Earth, how would you know?

You need a time-synchronized network of sensitive probes that can detect the event in different locations. Domain walls will be an especially suitable "target".

Signal of axion-like domain wall

Consider a very light complex scalar field with Z_N symmetry:

$$\mathcal{L}_\phi = |\partial_\mu \phi|^2 - V(\phi); \quad V(\phi) = \frac{\lambda}{S_0^{2N-4}} \left| 2^{N/2}\phi^N - S_0^N \right|^2$$

Theory admits several distinct vacua, $\phi = 2^{-1/2} S \exp(ia/S_0)$

$$S = S_0; \;\; a = S_0 \times \left\{ 0; \; 2\pi \times \frac{1}{N}; \; 2\pi \times \frac{2}{N}; \dots \; 2\pi \times \frac{N-1}{N} \right\}$$

Reducing to the one variable, we have the Lagrangian

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 - V_0 \sin^2\left(\frac{Na}{2S_0}\right)$$

that admits domain wall solutions

$$a(z) = \frac{4S_0}{N} \times \arctan\left[\exp(m_a z)\right]; \quad \frac{da}{dz} = \frac{2S_0 m_a}{N \cosh(m_a z)}$$

If on top of that *a*-field has the axion-type couplings, $f_i^{-1} \partial_\mu a \bar{\psi}_i \gamma_\mu \gamma_5 \psi_i$

there will be a magnetic-type force on the spin inside the wall,

$$H_{\rm int} = \sum_{i=e,n,p} 2 f_i^{-1} \nabla a \cdot \mathbf{s}_i$$

Maximum size of the signal

L –typical size of the domain [distance between walls]. We treat it as a free parameter. Energy density constraint gives

$$\rho_{\rm DW} \le \rho_{\rm DM} \Longrightarrow \frac{S_0}{N} \le 0.4\ {\rm TeV} \times \left[\frac{L}{10^{-2}\ {\rm ly}} \times \frac{\rm neV}{m_a}\right]^{1/2}$$

$$\Delta t \simeq \frac{d}{v_\perp} = \frac{2}{m_a v_\perp} = 1.3\,{\rm ms} \times \frac{\rm neV}{m_a} \times \frac{10^{-3}}{v_\perp/c}$$

Transient effect can be seen as the influence on the spin,

$$H_{\rm int} = \frac{\mathbf{F}\cdot\nabla a}{F f_{\rm eff}};\ \ f_{\rm eff}^{-1}({\rm Cs}) = \frac{1}{f_e} - \frac{7}{9 f_p};\ \ f_{\rm eff}^{-1}({\rm He}) = \frac{1}{f_n};$$

$$\Delta E = \frac{4 S_0 m_a}{N f_{\rm eff}} \simeq 10^{-15}\,{\rm eV} \times \frac{m_a}{\rm neV} \times \frac{10^9\ {\rm GeV}}{f_{\rm eff}} \times \frac{S_0/N}{0.4\,{\rm TeV}}$$

Axion-type coupling is normalized on astrophysical bounds. If we introduce an effective magnetic field, we discover that

$$B_{\rm eff}^{\rm max} \simeq \frac{m_a}{\rm neV} \times \frac{10^9\ {\rm GeV}}{f_{\rm eff}} \times \frac{S_0/N}{0.4\,{\rm TeV}} \times \left\{ \begin{array}{c} 10^{-11}\,{\rm T}\ \ ({\rm Cs}) \\ 10^{-8}\,{\rm T}\ \ ({\rm He}) \end{array} \right.$$

Network of Magnetometers

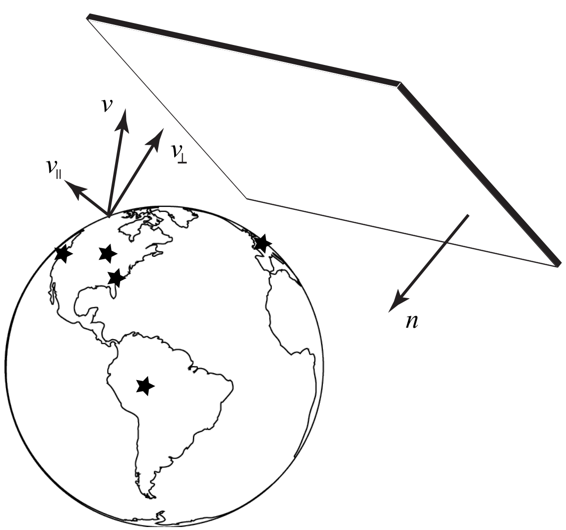
- For alkali magnetometers, the signal is

$$\mathcal{S} \simeq \frac{0.4\,\mathrm{pT}}{\sqrt{\mathrm{Hz}}} \times \frac{10^9\,\mathrm{GeV}}{f_{\mathrm{eff}}} \times \frac{S_0/N}{0.4\,\mathrm{TeV}} \times \left[\frac{m_a}{\mathrm{neV}}\frac{10^{-3}}{v_\perp/c}\right]^{1/2}$$
$$\leq \frac{0.4\,\mathrm{pT}}{\sqrt{\mathrm{Hz}}} \times \frac{10^9\,\mathrm{GeV}}{f_{\mathrm{eff}}} \times \left[\frac{L}{10^{-2}\ \mathrm{ly}}\frac{10^{-3}}{v_\perp/c}\right]^{1/2},$$

- For nuclear spin magnetometers, the tipping angle is

$$\Delta\theta = \frac{4\pi S_0}{v_\perp N f_{\mathrm{eff}}} \simeq 5\times10^{-3}\,\mathrm{rad}\times\frac{10^9\,\mathrm{GeV}}{f_{\mathrm{eff}}}\times\frac{10^{-3}}{v_\perp/c}\times\frac{S_0/N}{0.4\,\mathrm{TeV}}$$

- It is easy to see that one would need >5 stations. 4 events would determine the geometry, and make predictions for the 5th, 6th etc…



Transient effects

- This was one example of transient effects – among many others.
- One can search for other transient effects, e.g. such as short time variations of α and other constants. While e.g. clocks have their best sensitivity when averaged over relatively long time intervals, the sensitivity to shorter times can also be achieved with larger $\Delta f/f$.
- So far, all efforts were directed towards detecting bursts of gravitational waves [e.g. LIGO], but one can definitely look for more exotic transient effects with new [cheaper] techniques.

Conclusions

1. Models of "changing couplings" [and LV] are easy to write down. Models with "changing couplings" suffer from severe tuning problem = loss of predictivity. From a conservative point of view, their change in time on cosmic scales would be a miracle.

2. From more liberal perspective not just $\alpha(t)$ but other models are worth looking for:

- High-precision tests of $\alpha(\rho)$ in a laboratory, and within our Galaxy are possible and quite warranted. How about testing couplings at great depths?
- Models of $\alpha \sim \rho_{\text{Dark Matter}}$ can be tested by studying SgrA*.
- Search of transient effects [short-time fluctuation of couplings/LV parameters] can be looked for with network of sensitive magnetometers and clocks.