Variation of $\alpha$ from a Dark Matter Force

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• There are good reasons to look for new physics:
  • Dark matter (DM) not explained in Standard Model (SM)
  • Neutrino masses ($\lesssim 0.1$ eV) and mixing require new states
    - Right-handed neutrinos, . . .
  • Theoretic or conceptual hints
    - Why is gravity so weak?
    - . . .

• In this talk:
  • DM as a new sector with its own forces
  • Long range scalar force acting on DM and unstable SM states
    - Challenging to probe (no macroscopic population of unstable states)
    - We focus on the muon
    - For concreteness, DM mass of $\sim 1$ GeV
  • Prediction: variations of $\alpha$ in space and time
Some previous work with long range DM forces: Frieman, Gradwohl, Phys. Rev. Lett. 67, 2926 (1991); Gradwohl, Frieman, Astrophys. J. 398, 407 (1992); Dolgov, Phys. Rept. 320, 1 (1999); Farrar, Peebles, Astrophys. J. 604, 1 (2004); Gubser and P. J. E. Peebles, Phys. Rev. D70, 123511 (2004); Phys. Rev. D70, 123510 (2004); Nusser, Gubser, and P. J. E. Peebles, Phys. Rev. D71, 083505 (2005); Kesden and M. Kamionkowski, Phys. Rev. D74, 083007 (2006); Phys. Rev. Lett. 97, 131303 (2006); Farrar, Rosen, Phys. Rev. Lett. 98, 171302 (2007)
Scalar $\phi$, mass $m_\phi^{-1} \sim 100$ kpc coupled to DM $X$ and the muon

- $m_\phi \sim 10^{-28}$ eV

- Yukawa couplings to DM and muons:

\[
\mathcal{L}_i = -g_X \phi \bar{X} X - g_\mu \phi \bar{\mu} \mu
\]

\[
\mathcal{L}_m = -m_X \bar{X} X - m_\mu \bar{\mu} \mu - \frac{1}{2} m_\phi^2 \phi^2 \quad \text{(in vacuo)}
\]

- Equation of motion: $(\square + m_\phi^2) \phi = -g_X \bar{X} X = -g_X n_X \langle \sqrt{1 - v^2} \rangle \text{sgn}(\phi)$

- $v$ velocity of $X$

- Uniform, static, sufficiently large DM population: $\square \phi \approx 0$

\[
\Rightarrow \quad \phi \approx -\frac{g_X n_X}{m_\phi^2}
\]

Formalism adapted from, e.g., S. Gubser and Peebles, Phys. Rev. D70, 123511 (2004)
• Assuming galactic range for $\phi$, we consider $g_X \lesssim m_X/M_P$

• Sub-gravitational $g_X$ to avoid conflict with DM dynamics on large scales

• Coupling to muon constrained by loop-induced $e, p$ couplings

$g_p \sim \frac{\alpha^2}{(4\pi)^2} \frac{m_\mu}{m_p} g_\mu \quad (g_e \propto m_e/m_\mu)$

• Tests of Equivalence Principle: $|g_{p(e)}| \lesssim 10^{-24}(25) \Rightarrow |g_\mu| \lesssim 10^{-17}$

Schlamminger et al., 2007; MICROSCOPE mission, 2017
Variation of $\alpha$

H.D., Giardino, 1804.01098

- Challenge for discovery if $g_X$ and $g_\mu$ near gravitational strength
- No macroscopic population of $\mu$ available

- However, background $\phi$ sourced by DM $\rightarrow \Delta m_\mu = g_\mu \phi$

- Imprint on fine structure constant $\alpha$ (threshold effect)

$$\frac{\Delta \alpha}{\alpha} = \frac{2\alpha}{3\pi} \ln(1 + \frac{\Delta m_\mu}{m_\mu})$$

Similar considerations in different frameworks: Chacko, Grojean, Perelstein, 2002; Dent, 2003
\[ R = 20 \text{ kpc}, \ r_c = 10 \text{ kpc} \]
\[ \rho(r = 8.5 \text{ kpc}) = 0.3 \text{ GeV/cm}^3 \]

\[ \rho_{\text{NFW}} = \frac{\rho_n}{(r/R)(1+r/R)^2} \]
\[ \rho_{\text{Burkert}} = \frac{\rho_b}{(1+r/r_c)(1+(r/r_c)^2)} \]

- \( \Delta \alpha = 1/100 \text{ kpc}^{-1} \), \( g_\mu = -2 \times 10^{-18} \) and \( g_X = 5 \times 10^{-20} \), \( r \) distance from center of the Galaxy in kpc. Blue solid line NFW, red dashed line Burkert profile.

- Solve for \( \phi \) with \( \partial_r \phi|_{r=0} = \phi(\infty) = 0 \); \( \Delta \alpha \equiv \alpha - \alpha_{\text{vac}} \)

- Oklo natural reactor bounds: \( \frac{\Delta \alpha}{\alpha} \lesssim 10^{-8} - 10^{-7} \) (2 billion years ago)
  - Allows \( \mathcal{O}(1) \) change in Milky Way DM content

- Bounds from other galaxies less constraining: \( \frac{\Delta \alpha}{\alpha} \lesssim 10^{-6} \)
- $\Delta m_\mu$ effect grows with $n_X (\sim T^3)$ until horizon size $< 1/m_\phi$

$$
\rho \sim -g_X n_X d^2_{\text{hor}} \propto \begin{cases} 
\text{constant matter-dominated} & \frac{1}{T} \\
\text{radiation-dominated} & (d_{\text{hor}} \sim 1/H)
\end{cases}
$$

- Planck collaboration (2015): $(\alpha_{\text{CMB}} - \alpha_{\text{present}})/\alpha_{\text{present}} = (-3.6 \pm 3.7) \times 10^{-3}$

\[\frac{\Delta \alpha}{\alpha} = 0.000\]

- $\Delta \alpha/\alpha$, with $m_\phi = 1/300 \text{ kpc}^{-1}, g_\mu = 10^{-18}$ and $g_X = 2 \times 10^{-21}$, as a function of the temperature ($T$) of the Universe in eV.

- $g_X \lesssim 10^{-19}$ or else $\Delta m_X/m_X \gtrsim 1\%$, conflict with CMB data

- If Planck result holds: $g_\mu \gtrsim 10^{-19} \Rightarrow g_p \gtrsim 10^{-26}$ (2-loop effect)

$\therefore$ Violations of Equivalence Principle not far from present bounds
Concluding Remarks

A long range DM force can lead to interesting possibilities

- We focused on a scalar mediator

Variations of $\alpha$:

- Gravitational level scalar coupling to DM, unstable SM states: challenge to detect

- Focus on muons: DM can source scalar potential to yield $\Delta m_\mu$

- $\Delta m_\mu \rightarrow \Delta \alpha/\alpha$ (threshold effect)

- Modest Planck hint for $\Delta \alpha/\alpha \sim 10^{-3}$ can be accommodated

- Could imply detectable Equivalence Principle violation

- Discovery of an ultra light scalar: significant implications for physics on long and short distance scales