Constraining Ultralight Scalar Dark Matter with Quadratic Couplings from Big Bang Nucleosynthesis

arXiv:2211.09826

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Spectrum of Dark Matter candidates

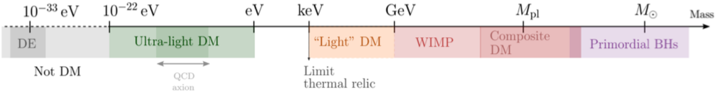
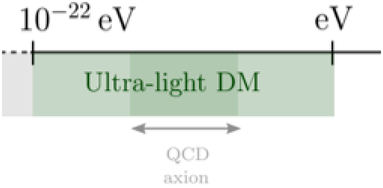


Figure 1: Dark matter candidates range in mass over 90 orders of magnitude! Image from arXiv:2005.03254v2

Ultralight Dark Matter(ULDM)



- Dark matter below an eV is call Ultralight dark matter(ULDM)
- Due to its large number densities (in phase space) Ultralight Dark Matter behaves like a classical field
- The light end of ULDM is fuzzy dark matter that can help with the core-cusp problem

ULDM With Linear Couplings

A possible way to couple to the Standard Model

$$\frac{\phi}{\ } O_{\mathrm{SM}}$$

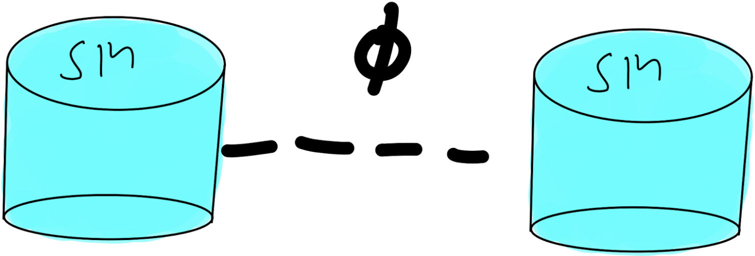


Figure 2: ϕ mediates a long range force. $V(r) \ / \ e^{-m_\phi r}/r$

ULDM With Quadratic Couplings

$$L \quad \frac{\phi^2}{\quad 2} O_{SM}$$

- Photons: $L \quad \frac{1}{16} \frac{2}{2} F \quad F$
- Gluons: $L \quad \frac{3}{2g_3} \frac{2}{2} \mathrm{tr}(G \quad G \quad)$
- Electrons: $L \quad m_e \frac{2}{2} ee$
- Light Quarks: $L \quad = \quad m_q \frac{2}{2} qq$

Varying Fundamental Constants

In the presence of a non-zero ϕ field values the value of fundamental constants shift.

- Photons: $L \quad \frac{1}{16}\frac{{}^2}{{}^2}F \quad F \quad =) \quad \frac{}{} = \frac{{}^2}{{}^2}$
- Gluons: $L \quad \frac{3}{2g_3}\frac{{}^2}{{}^2}\mathrm{tr}(G \quad G \quad) =) \quad \frac{\mathrm{QCD}}{\mathrm{QCD}} = \frac{{}^2}{{}^2}$
- Fermions: $L \quad m\frac{{}^2}{{}^2}ff =) \quad \frac{m}{m} = \frac{{}^2}{{}^2}$

Varying Fundamental Constants and Big Bang Nucleosynthesis

- Increasing the electron mass lowers the amount of phase space available for the reactions $n + (e^+ \text{ or } \nu) \rightarrow p + (\nu \text{ or } e^-)$ and neutron decay. This increases the abundance of neutrons during BBN, increasing the amount of Helium-4 produced.
- Increasing the quark masses increases the neutron proton mass difference. This decreases the equilibrium abundance of neutrons in the early universe and increases the phase space available for neutron decay. Leading to fewer neutrons available for BBN and less Helium-4 production.

Varying Fundamental Constants and Big Bang Nucleosynthesis

- Increasing the α deceases the neutron proton mass difference leading to more Helium-4.
- Increasing $_{QCD}$ deceases the neutron proton mass difference and the increasing the deuterium binding energy. The larger deuterium binding energy leads to BBN to happen earlier increasing the amount of Helium-4 produced.

Dark Matter Evolution

A homogeneous scalar field obeys

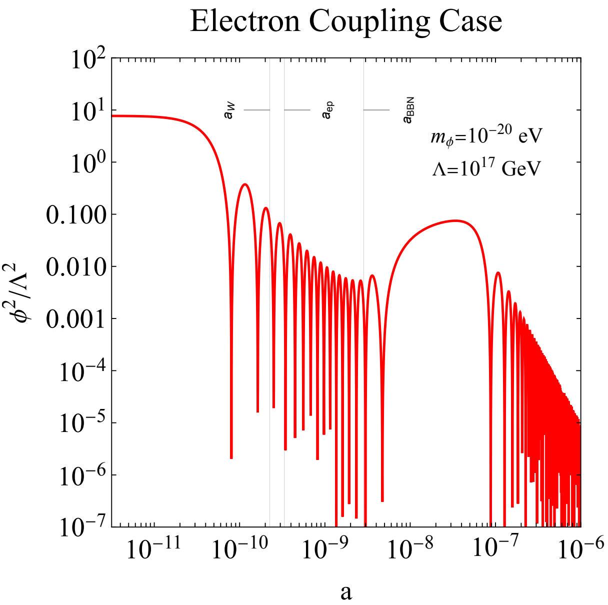
$$\ddot{\phi} + 3H\dot{\phi} + (m^2 + m_I^2)\phi = 0\,,$$

where m is the scalar mass and m_I is the mass induced by interactions with the Standard Model bath. There are three regimes

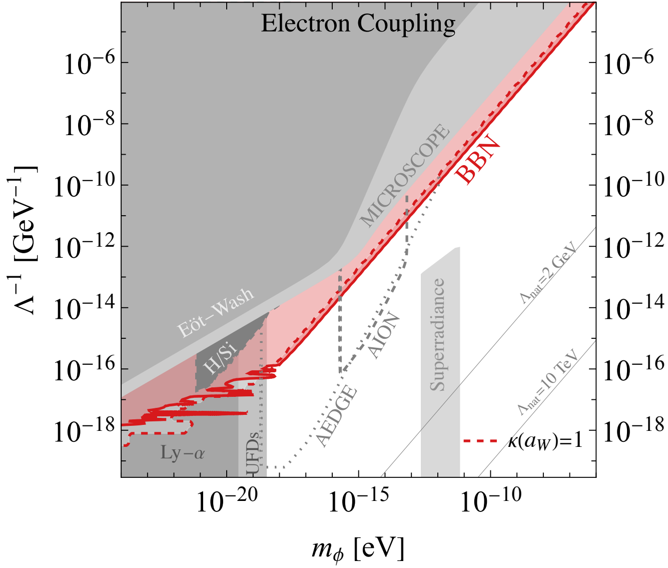
- Hubble friction domination(H): When $H^2 \quad m^2, m_I^2$
- Bare mass domination(B): When $m^2 \quad H^2, m_I^2$
- Induced mass domination(I): When $m_I^2 \quad H^2, m^2$

During Hubble friction dominated it is frozen. During bare mass or induced mass domination the field is rapidly oscillatory and the amplitude is $\propto a^{3/2}(m^2 + m_I^2)^{1/4}$

Example Evolution

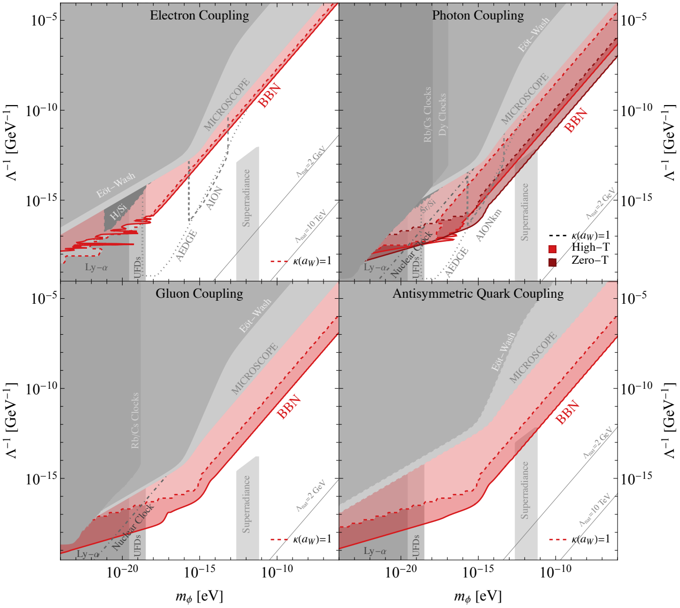


Results



Electron Coupling
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
Λ^{-1} [GeV^{-1}]
10^{-20}
10^{-15}
10^{-10}
m_ϕ [eV]
MICROSCOPE
BBN
Eöt–Wash
H/Si
AION
AEDGE
Superradiance
UFDs
Ly$-\alpha$
Λ_{nat}=2 GeV
Λ_{nat}=10 TeV
$\kappa(a_W)$=1

Results


Electron Coupling
Photon Coupling
Gluon Coupling
Antisymmetric Quark Coupling
Eöt−Wash
MICROSCOPE
BBN
H/Si
AION
AEDGE
Superradiance
UFDs
Ly−α
Rb/Cs Clocks
Dy Clocks
Sr/Si
Nuclear Clock
AIONkm
Λ_{nat}=2 GeV
Λ_{nat}=10 TeV
$\kappa(a_W)$=1
High−T
Zero−T
10^{-5}
10^{-10}
10^{-15}
10^{-20}
Λ^{-1} [GeV^{-1}]
m_ϕ [eV]

Conclusions

- ULDM can lead to "varying fundamental constants"
- Varying fundamental constants modify BBN and lets us put constraints on ULDM
- Back-reaction from the SM can modify the evolution of the dark matter leading to nontrivial behavior.

Thank You!