BBN Constraints on Universally Coupled Ultralight Dark Matter

Philip Sørensen

Centre for Cosmology and Particle Physics Phenomenology

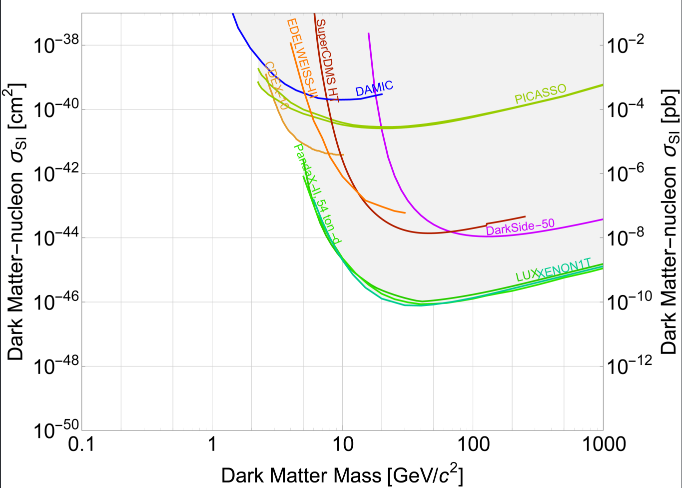
University of Southern Denmark

CP³ Origins

Cosmology & Particle Physics

Dark Matter

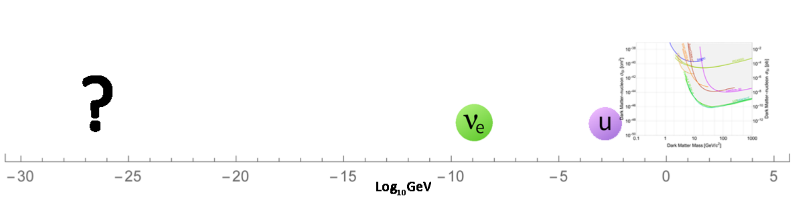
The land of the WIMPs



Plotted using the WIMP Data Plotter: cdms.berkeley.edu/limitplots/mm/WIMP_limit_plotter.html

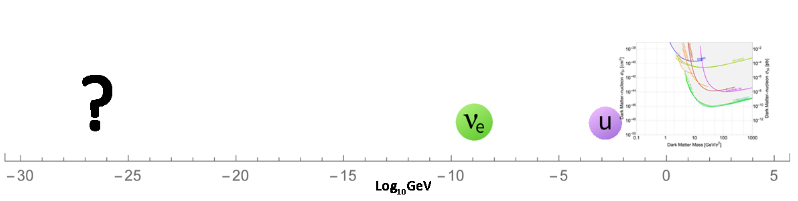
Dark Matter

Ultralight DM: Outside the realm of direct detection



Dark Matter

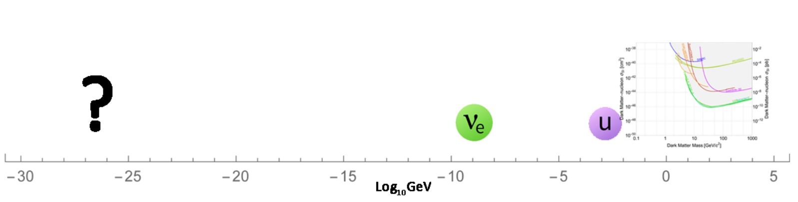
Ultralight DM: Outside the realm of direct detection



- We need new constraints!

Dark Matter

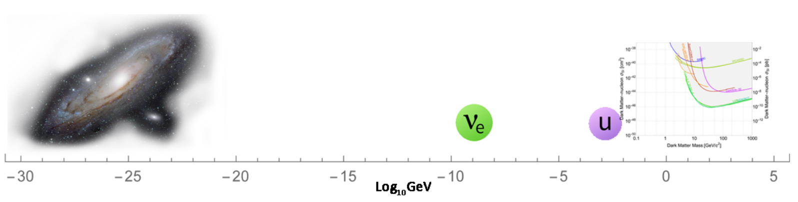
Ultralight DM: Outside the realm of direct detection



- We need new constraints!
- Ultra light = Ultra large: Fuzzy Dark Matter

Dark Matter

Ultralight DM: Outside the realm of direct detection



- We need new constraints!
- Ultra light = Ultra large: Fuzzy Dark Matter

Constructing the Model

A universally coupled scalar field

Constructing the Model

A universally coupled scalar field

Step 1: Add a scalar field

$$\mathscr{L}_{phi} = \sqrt{-g}\left[\frac{1}{2}\left(\nabla_\mu \phi\right)^2 - m_\phi^2 \phi^2\right]$$

Constructing the Model

A universally coupled scalar field

Step 1: Add a scalar field

$$\mathscr{L}_{phi} = \sqrt{-g}\left[\frac{1}{2}\left(\nabla_\mu \phi\right)^2 - m_\phi^2 \phi^2\right]$$

Step 2: Add interaction through modified gravity (perturbed metric)

$$\sqrt{-g}\mathscr{L}_{SM}[g^{\mu\nu}] \to \sqrt{-|g^{\mu\nu}(1-2\alpha)|}\mathscr{L}_{SM}[g^{\mu\nu}(1-2\alpha)]$$

In our model: $\alpha = \pm\phi^2/\Lambda^2$

Effective mass

For Standard Model particels

Massive particles interact:

$$\mathscr{L}_{int} = \mp \frac{\phi^2}{\Lambda^2} m_f \bar{f} f \pm \frac{\phi^2}{\Lambda^2} m_v^2 v^2$$

Here $f =$ any fermion and $v = w, z$. The corresponding diagram:

Effective mass

For Standard Model particels

Interactions can be absorbed into effective masses!

$$m_{f/V} \to m_{f/V} \left(1 + \frac{\phi^2}{\Lambda^2} \right)$$

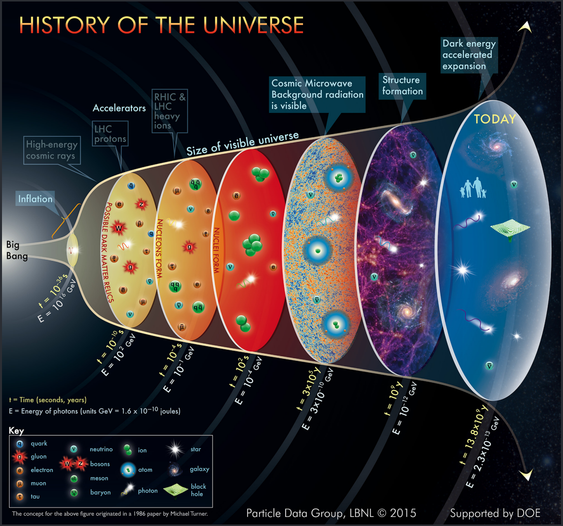
Effective mass

For Standard Model particels

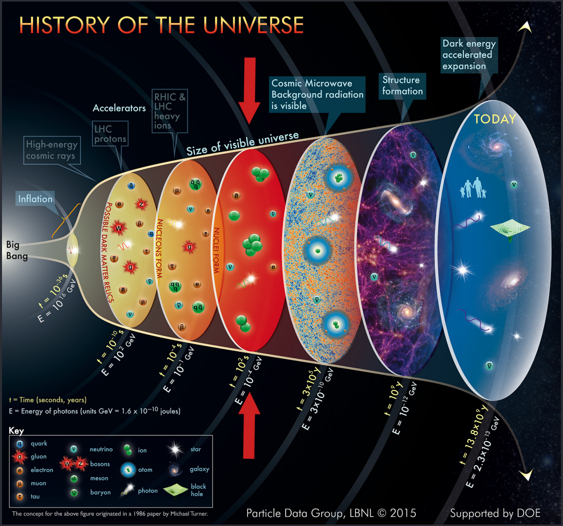
Interactions can be absorbed into effective masses!

$$m_{f/V} \to m_{f/V}\left(1 + \frac{\phi^2}{\Lambda^2}\right)$$

Big Bang Nucleosynthesis



Big Bang Nucleosynthesis



Big Bang Nucleosynthesis

A short recap - BBN in 2 lines

Big Bang Nucleosynthesis

A short recap - BBN in 2 lines

Neutron-proton ratio frozen in at $\approx 0.8\, MeV$

$$\frac{n}{p} = e^{-\frac{m_n - m_p}{T_F(m_W, m_Z)}}$$

Big Bang Nucleosynthesis

A short recap - BBN in 2 lines

Neutron-proton ratio frozen in at $\approx 0.8\ MeV$

$$\frac{n}{p} = e^{-\frac{m_n - m_p}{T_F(m_W, m_Z)}}$$

Nearly all neutrinos ends up in $He^4 \implies$ Constraint on n/p

Big Bang Nucleosynthesis

A short recap - BBN in 2 lines

Neutron-proton ratio frozen in at $\approx 0.8\ MeV$

$$\frac{n}{p} = e^{-\frac{m_n - m_p}{T_F(m_W, m_Z)}}$$

Nearly all neutrinos ends up in He^4 $\implies$ Constraint on n/p

$$\frac{\Delta\left[(m_n - m_p)/T_F\right]}{(m_n - m_p)/T_F} = -\frac{1}{3}\frac{\phi_{BBN}^2 - \phi_0^2}{\Lambda^2} = 0.0033 \pm 0.0085$$

Big Bang Nucleosynthesis

A short recap - BBN in 2 lines

Neutron-proton ratio frozen in at $\approx 0.8\ MeV$

$$\frac{n}{p} = e^{-\frac{m_n - m_p}{T_F(m_W, m_Z)}}$$

Nearly all neutrinos ends up in $He^4 \implies$ Constraint on n/p

$$\frac{\Delta\left[(m_n - m_p)/T_F\right]}{(m_n - m_p)/T_F} = -\frac{1}{3}\frac{\phi^2_{BBN} - \phi^2_0}{\Lambda^2} = 0.0033 \pm 0.0085$$

Change in $\phi \implies$ Change in $m_{f/V} \implies$ Change in BBN!

Effective masses

For Dark Matter particles

The DM scalar also acquires new mass:

$$m_\phi^2 \to m_\phi^2 + 2\Lambda^{-2}\rho_f + 2\Lambda^{-2}\rho_{w/z}$$

Effective masses

For Dark Matter particles

The DM scalar also acquires new mass:

$$m_\phi^2 \rightarrow m_\phi^2 + 2\Lambda^{-2}\rho_f + 2\Lambda^{-2}\rho_{w/z}$$

Important points:

- Changes constraints
- Not previously studied
- Main point of my project

The Plan

My project in a nutshell

Solve the evolution of DM field ϕ

inducing modified mass

$\Downarrow$

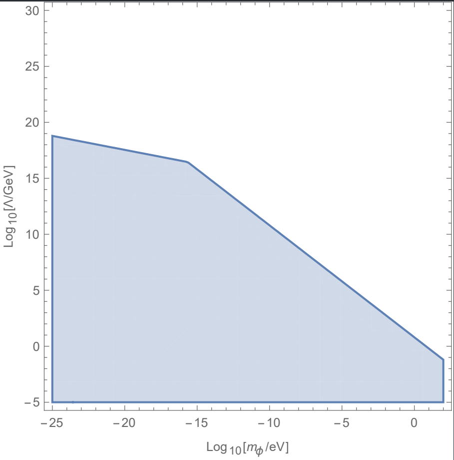
Compute how Dark Matter modify BBN

$\Downarrow$

Harvest the constraints and rejoice

Constraints

Phase space constrained by BBN



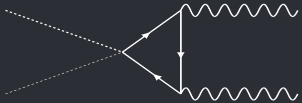
Future

To-do list:

- Include e^+/e^- pairs to prior annihilation

$$e^+e^- \longrightarrow 2\gamma \quad (\ 0.5\ \text{MeV})$$

- Photon coupling through loop effects



- Extend analysis to heavier elements (numerical code)

The End

Thanks to my supervisor Sergey Sibiryakov and Tien-Tien Yu who has helped me solve many of my problems.

Backup slides!

- The Einstein and Jordan Frames
- How I actually did the stuff
  - Solving the Equations of Motion
  - Phase evolution
  - Evolution of ϕ

Backup slides

The Einstein and Jordan Frames

Einstein frame: Regular gravity + interacting field

$$\sqrt{-g}\mathscr{L}_{GR/\phi}[g^{\mu\nu}] + \sqrt{-|g^{\mu\nu}(1-2\alpha)|}\mathscr{L}_{SM}[g^{\mu\nu}(1-2\alpha)]$$

$$\Uparrow \quad g^{\mu\nu} \to g^{\mu\nu}(1\pm 2\alpha) \quad \Downarrow$$

Jordan frame: Modified gravity + non-interacting field

$$\sqrt{-|g^{\mu\nu}(1+2\alpha)}\mathscr{L}_{GR/\phi}[g^{\mu\nu}(1+2\alpha)] + \sqrt{-g}\mathscr{L}_{SM}[g^{\mu\nu}]$$

Equations of Motion

How does ϕ behave?

Satisfies the usual Klein Gordon eq.

$$(\nabla^2 + m_{eff}^2)\phi = 0$$

With modified mass

$$m_{eff}^2 = m_\phi^2 + 2\Lambda^{-2}\rho_f + 2\Lambda^{-2}\rho_{w/z}$$

Solving the EOM

A tale of three phases

The EOM in an expanding universe:

$$\ddot{\phi} + 3H\dot{\phi} + 2\Lambda^{-2}\rho_b\phi + m_\phi^2\phi = 0$$

Drop subdominant mass term and peel of *a* dependence:

	RD	MD
Λ	$a^{-3/4}$	$a^{-15/16}$
m_ϕ	$a^{-3/2}$	$a^{-3/2}$
H	a^0	a^0

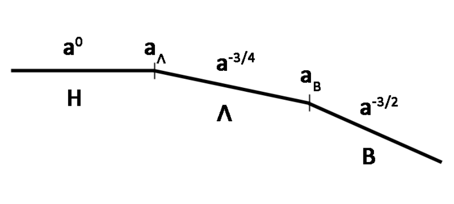
Both subdominant to Hubble friction $\longrightarrow$ Non-oscillating constant

Evolution of ϕ

From today to BBN

Known transition history: Evolution is easy

Example: $H \rightarrow \Lambda \rightarrow B$

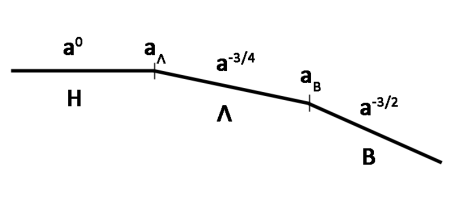


Evolution of ϕ

From today to BBN

Known transition history: Evolution is easy

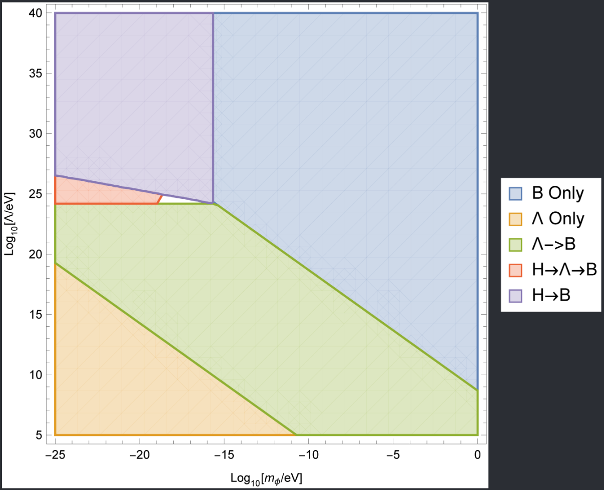
Example: $H \rightarrow \Lambda \rightarrow B$



$$\phi_{BBN} = \left(\frac{a_\Lambda}{a_B}\right)^{-3/4} a_B^{-3/2} \phi_0$$

Evolution of the phases

Phase transitions



Evolution of ϕ

From today to BBN

All histories must end as B: $H \longrightarrow \Lambda$ and H-only are excluded.

Remaining possibilities:

B only

$$\phi_{BBN} = a_{BBN}^{-3/2}\phi_0$$

$\Lambda \longrightarrow B$

$$\phi_{BBN} = \left(\frac{a_{BBN}}{a_B}\right)^{-3/4} a_B^{-3/2}\phi_0$$

$H \longrightarrow B$

$$\phi_{BBN} = a_B^{-3/2}\phi_0$$

$H \longrightarrow \Lambda \longrightarrow B$

$$\phi_{BBN} = \left(\frac{a_\Lambda}{a_B}\right)^{-3/4} a_B^{-3/2}\phi_0$$