The Influence of Dark Energy on the Expansion Rate of the Universe and its Effects on Dark Matter Relic Abundance

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Based on:

B. Dutta, E. Jimenez and I. Zavala. arXiv:1612.05553

Outline

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Standard Cosmology

- Time evolution of DM is described by the Boltzmann equation.

$$\frac{dn}{dt} + 3H_{GR}n = \langle\sigma v\rangle \left(n^2 - n_{eq}^2\right)$$

- Abundance, $Y \equiv \frac{n}{s}$

$$\frac{x}{Y_{eq}}\frac{dY}{dx} = -\frac{\Gamma}{H_{GR}}\left(\left(\frac{Y}{Y_{eq}}\right)^2 - 1\right) .$$

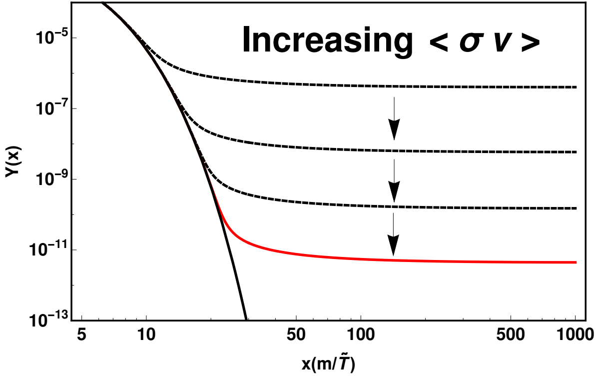
  where $\Gamma \equiv n\langle\sigma v\rangle = Ys\langle\sigma v\rangle$ and $x = m/T$.
- Expansion rate in radiation dominated era, $H_{GR} \sim T^2 \sim 1/x^2$.

Dark Matter Relic Abundance.

Thermal evolution

Evolution is governed by the factor $\frac{\Gamma}{H_{GR}}$.

- $\Gamma \gg H_{GR} \rightarrow Y \sim Y_{eq}$
- $\Gamma \ll H_{GR} \rightarrow Y \sim Y_{\infty}$



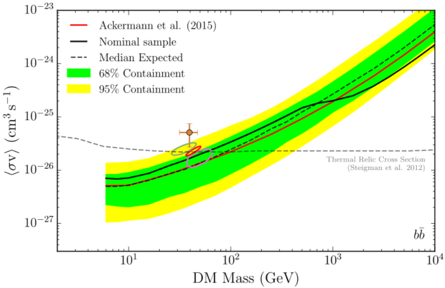
DM Content

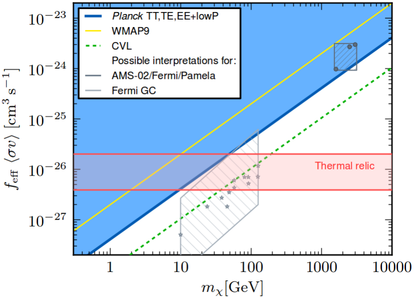
$$\Omega_{DM} = \frac{\rho_0}{\rho_c} = \frac{m s_0 Y_{\infty}}{\rho_c} \approx 0.27$$

$\langle \sigma v \rangle$

$2.1 \times 10^{-26} cm^3/s$

Fermi-LAT[1] and Planck[2] experiments have been exploring upper bounds.





[1] arXiv: 1611.03184

[2] arXiv: 1502.015889

The Problem That We Study

- Is there any non-standard cosmology that predicts different annihilation cross-section for thermal DM?
- Scalar-Tensor Theories are good candidates before big-bang nucleosynthesis.

Previous works

- Catena et al. 2004, Phys. Rev D70. arXiv:0403614
- Catena et al. 2010, Phys. Rev D81. arXiv:0912.4421
- Meeham and Whittingham. 2015, JCAP. arXiv:1508.05174

Outline

Two frames of references connected by $\tilde{g}_{\mu\nu} = C(\phi) g_{\mu\nu} + D(\phi)\partial_\mu \phi \partial_\nu \phi$

Jordan Frame, $\tilde{g}_{\mu\nu}$

- Scalar field couples through the gravitational sector.
- As an example, the action for $D = 0$ is given by,

$$S_{tot} = \frac{1}{2\kappa_{GR}^2}\int d^4x\sqrt{-\tilde{g}}\left[\frac{1}{C}\tilde{R} - \tilde{g}^{\mu\nu} Z(\phi)\partial_\mu\phi\partial_\nu\phi - 2U(\phi)\right] + S_{Mat}\left(\tilde{g}_{\mu\nu}, \Psi_m\right) .$$

- By construction, observables such as mass, length and time take their standard interpretation.

$$\frac{\tilde{x}}{\tilde{Y}_{eq}}\frac{d\tilde{Y}}{d\tilde{x}} = -\frac{\tilde{\Gamma}}{\tilde{H}}\left(\left(\frac{\tilde{Y}}{\tilde{Y}_{eq}}\right)^2 - 1\right)$$

Einstein Frame, $g_{\mu\nu}$

- Scalar field couples through the matter sector.

$$S = \frac{1}{2\kappa^2}\int d^4x\sqrt{-g}\,R - \int d^4x\sqrt{-g}\left[\frac{1}{2}(\partial\phi)^2 + V(\phi)\right] + S_{Mat}\left(C(\phi)g_{\mu\nu} + D(\phi)\partial_\mu\phi\partial_\nu\phi, \Psi_m\right) .$$

- Physical quantities measured in this frame are spacetime dependent.
- $R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \kappa^2\left(T^{\phi}_{\mu\nu} + T_{\mu\nu}\right)$

FRW metric $g_{\mu\nu}$,

$$ds^2 = -dt^2 + a(t)^2 dx_i dx^i .$$

Einstein and scalar field equations become

$$H^2 = \frac{\kappa^2}{3}\left[\rho_\phi + \rho\right] ,$$

$$\dot{H} + H^2 = -\frac{\kappa^2}{6}\left[\rho_\phi + 3p_\phi + \rho + 3p\right] ,$$

$$\ddot{\phi} + 3H\dot{\phi} + V_{,\phi} + Q_0 = 0 .$$

where $H = \frac{\dot{a}}{a}$.

Conformal Scenario

Take $D = 0$

To solve, replace $\frac{d}{dt}$ with $\frac{d}{dN}$, where $N = \ln a/a_0$. Also, $\varphi = \kappa\,\phi$ and during the radiation dominated era, $V = 0$.

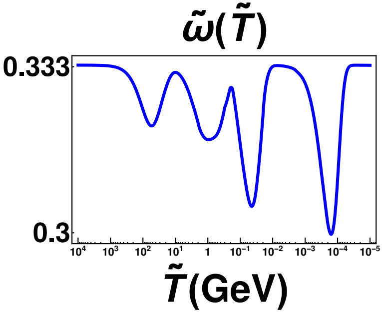
$$H' = -H\left[\frac{3B}{2}(1+\omega) + \frac{\varphi'^2}{2}\right],$$

$$\varphi'' + 3\,\varphi' + \frac{H'}{H}\varphi' + \frac{3B}{1+\lambda}\alpha(\varphi)(1-3\,\omega) = 0.$$

where $B = 1 - \varphi'^2/6$, $\omega = \frac{p}{\rho}$ and $\alpha(\varphi) = \frac{d}{d\varphi}\ln C^{1/2}$.

Conformal Scenario

Equation of State



$\tilde{p} = \tilde{\omega}\tilde{\rho}$

- Radiation domination, $\tilde{\omega} \approx 1/3$.
- Matter domination, $\tilde{\omega} = 0$.
- Dark Energy domination, $\tilde{\omega} = -1$.

Parameter Constraints

Solar system tests of gravity impose constraints[3].

- $\alpha_0^2 \lesssim 10^{-5}$
- $\alpha_0' = d\alpha/d\varphi|_{\varphi_0} \gtrsim -4.5.$
- $\frac{\tilde{H}}{H_{GR}}$ order 1 before the onset of BBN.

[3] arXiv: 0009034. 0103036

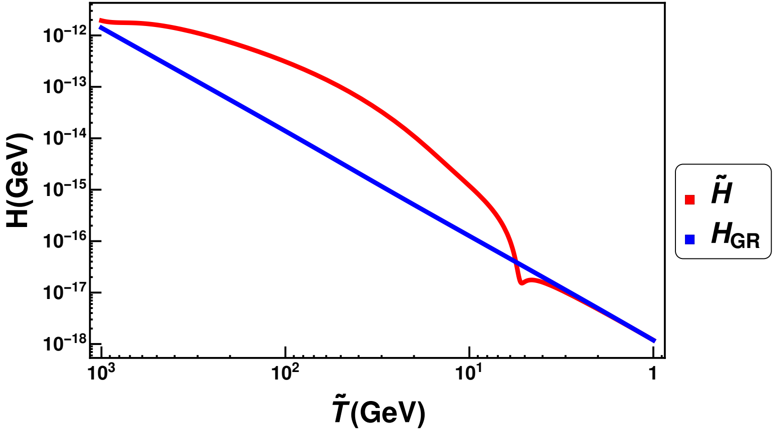
With the solution for the scalar field we find $\tilde{H}$ as follows,

Expansion Rate in the Jordan Frame

$$\tilde{H} = \frac{C^{1/2}(\varphi)}{C^{1/2}(\varphi_0)} \frac{1}{(1-\alpha(\varphi)\varphi')\sqrt{1-\frac{(\varphi')^2}{6(1-\alpha(\varphi)\varphi')^2}}} \frac{1}{\sqrt{1+\alpha^2(\varphi_0)}} H_{GR}$$

where $'$ denotes derivative w.r.t $\tilde{N} = \ln \tilde{a}/\tilde{a}_0$

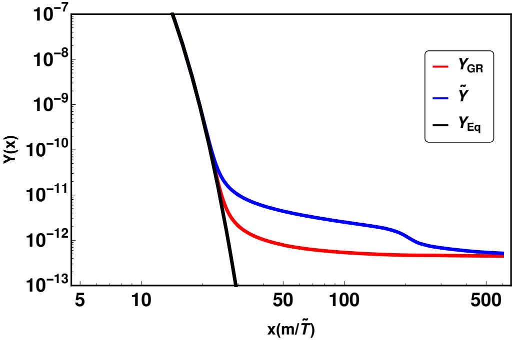
In the plot[4] below $C(\varphi) = (1 + 0.1\, e^{-8\,\varphi})^2$ and $(\varphi_0, \varphi_0') = (0.2, -0.99)$



[4] arXiv: 1612.05553

The Boltzmann equation becomes

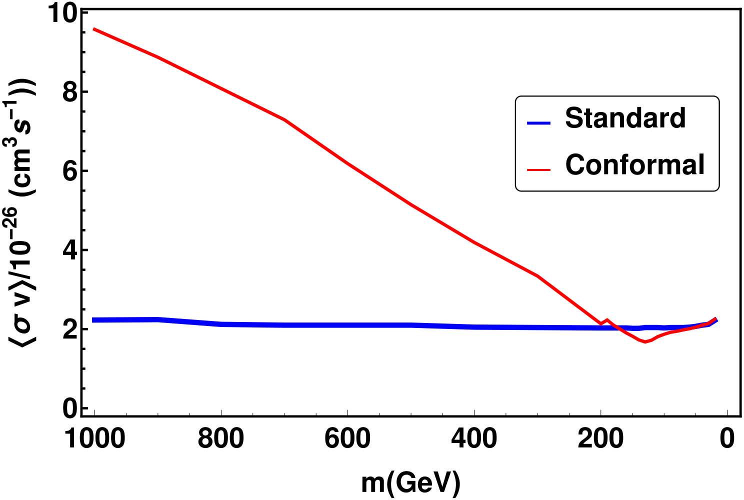
$$\frac{\tilde{x}}{\tilde{Y}_{eq}}\frac{d\tilde{Y}}{d\tilde{x}} = -\frac{\tilde{\Gamma}}{\tilde{H}}\left(\left(\frac{\tilde{Y}}{\tilde{Y}_{eq}}\right)^2 - 1\right).$$



Example for a mass 1000 GeV (arXiv: 1612.05553).

Conformal Scenario

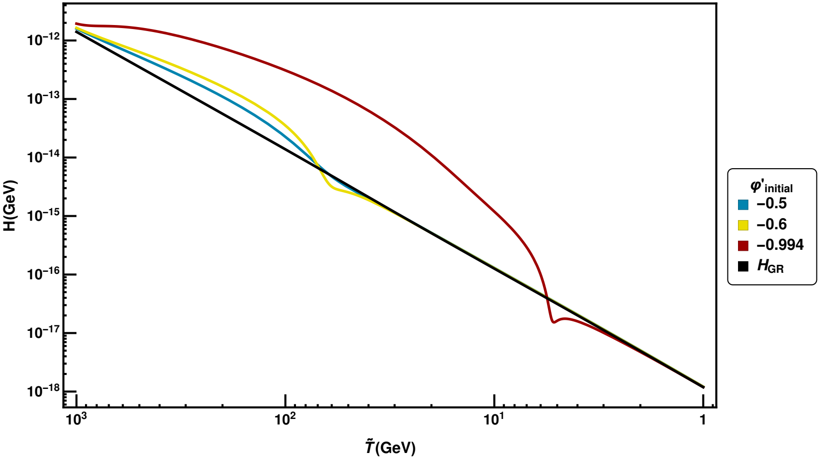
Dark Matter Annihilation Cross Section



arXiv: 1612.05553

Conformal Scenario

More Boundary Conditions

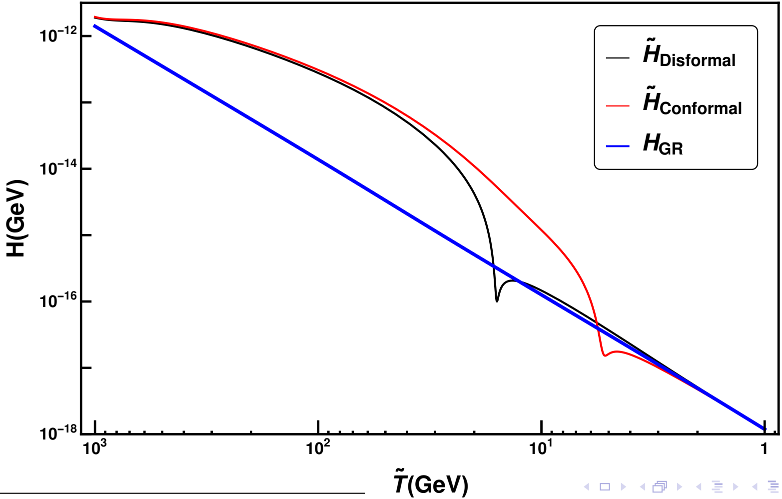


arXiv: 1612.05553

Disformal Scenario

Expansion Rate

In the plot[5] below $C(\varphi) = (1 + 0.1\, e^{-8\,\varphi})^2$, $D(\varphi) = D_0\, \varphi^2$ with $D_0 = -4.9 \times 10^{-14}$ and $(\varphi_0, \varphi_0') = (0.2, -0.99)$.



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Conclusions

- In conformal scenario, expansion rate enhancement up to a factor of 200.
- We have found DM annihilation cross-section larger and smaller than the one predicted by standard cosmology, consistent with the experimental bounds impose by Plack.
- In disformal scenario, we found solutions for boundary conditions that don't give solutions in the conformal scenario.
- DM relic abundance can be used a probe to the predictions of ST.