Conformal Scalar-Tensor Theories and Dark Matter

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Based on:

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

Outline

Standard Cosmology

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

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

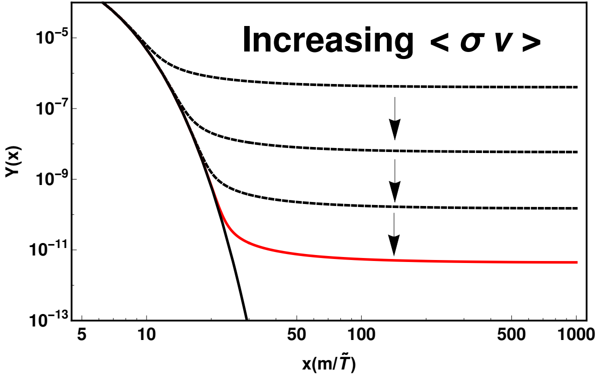
where $\Gamma \equiv n\langle\sigma v\rangle = Ys\langle\sigma v\rangle$ and $x = m/T$.

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

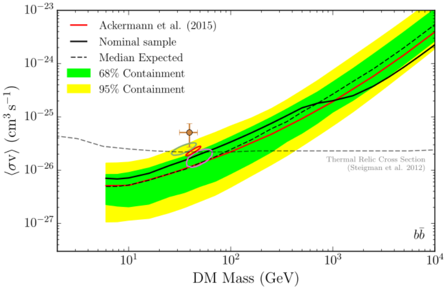
$$\Omega_{DM} = \frac{\rho_0}{\rho_c} = \frac{m s_0 Y_\infty}{\rho_c} \approx 0.27$$

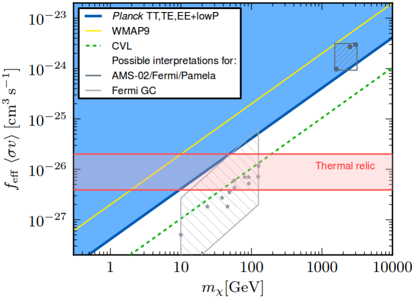
$\langle \sigma v \rangle$

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

Experimental bounds

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

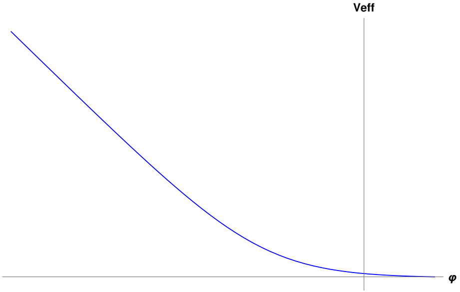
- Catena et al. 2004, Phys. Rev D70. arXiv:0403614
- Catena et al. 2010, Phys. Rev D81. arXiv:0912.4421
- Meeham and Whittingham. 2015, JCAP. arXiv:1508.05174

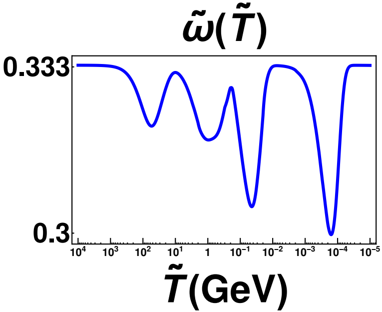
Conformal Scenario

Evolution of scalar field is dictated by,

$$\frac{2}{3B}\varphi'' + (1-\tilde{\omega})\,\varphi' + 2(1-3\,\tilde{\omega})\alpha(\varphi) = 0.$$

where $N = \ln a/a_0$, $B = 1 - \varphi'^2/6$, $\alpha(\varphi) = \frac{d \ln C^{1/2}}{d\varphi}$, $\omega = \frac{p}{\rho}$.





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

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

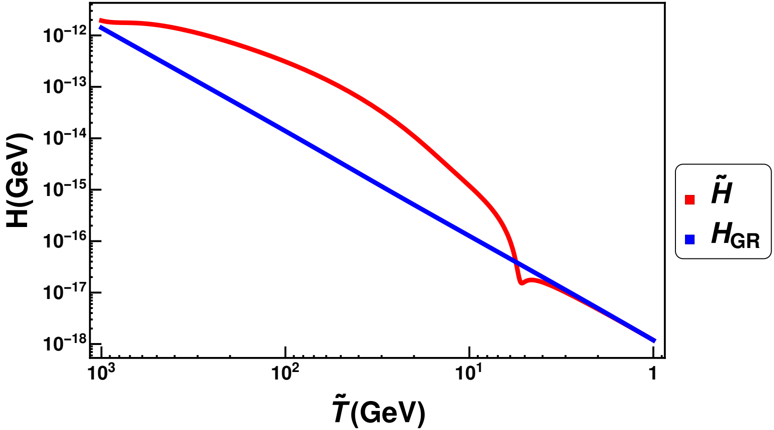
Parameter Constraints

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

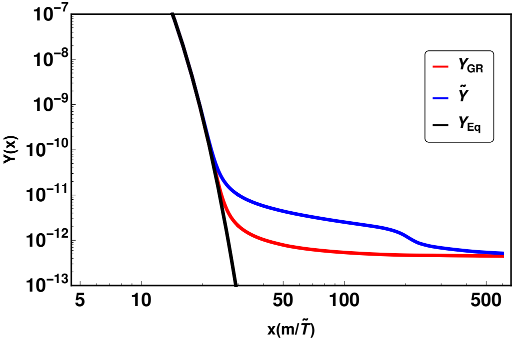
In the plot[4] below $C(\varphi) = (1 + 0.1\, e^{-8\,\varphi})^2$ and $(\varphi_0, \varphi_0') = (0.2, -0.99)$



[4] arXiv: 1612.05553

The Boltzmann equation becomes

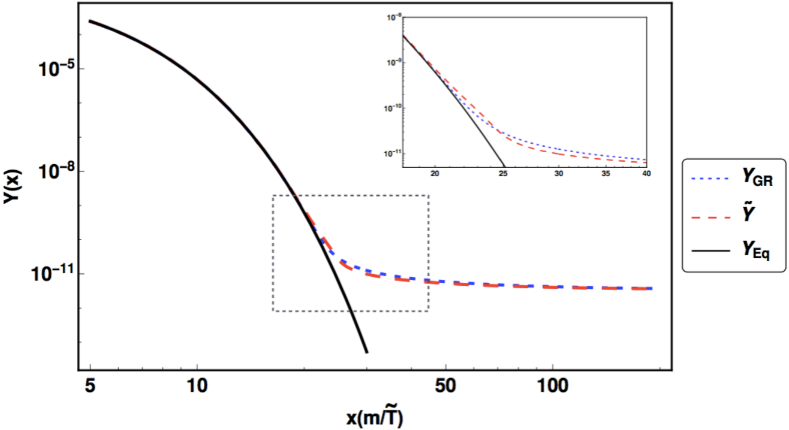
$$\frac{\tilde{x}}{\tilde{Y}_{eq}}\frac{d\tilde{Y}}{d\tilde{x}} = -\frac{\tilde{\Gamma}}{\tilde{H}}\left(\left(\frac{\tilde{Y}}{\tilde{Y}_{eq}}\right)^2 - 1\right).$$



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

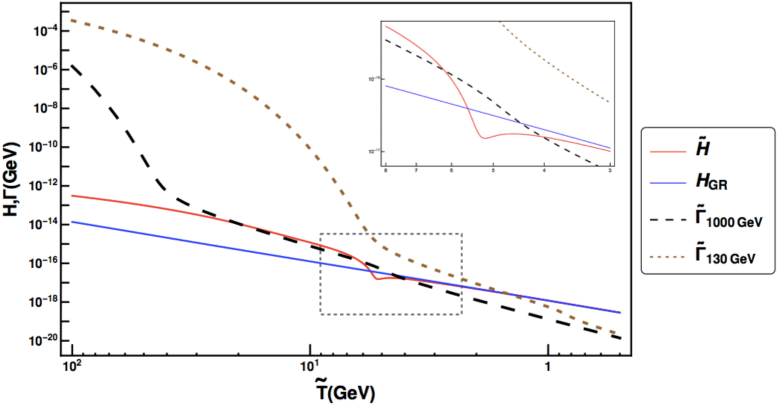
Conformal Scenario

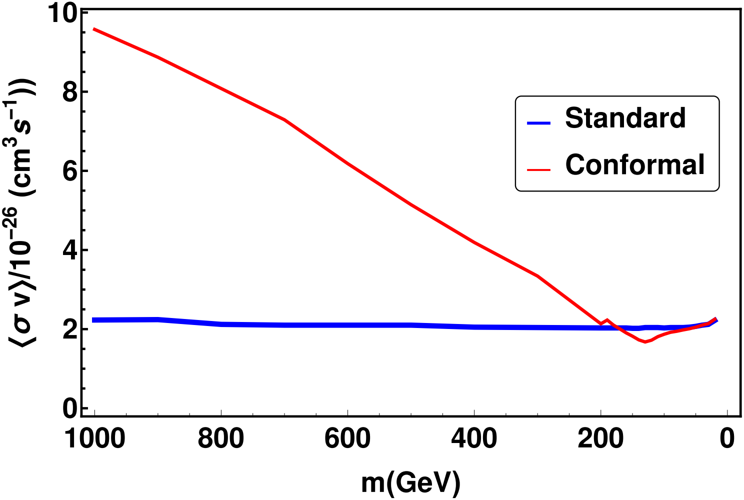
Relic Abundance for 130 GeV



Conformal Scenario

Comparing $\tilde{\Gamma}$ and $\tilde{H}$





arXiv: 1612.05553

Conclusions

- ST present a atractor mechanism to standard cosmology prior to BBN.
- DM annihilation cross-section larger and smaller than the one predicted by standard cosmology, consistent with the experimental bounds.
- Significant variation in the evolution of abundance for high masses (Presented example for 1000 GeV)

Scalar-Tensor Theories of Gravity

Frames of reference

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

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 $\tilde{N} = \ln \tilde{a}/\tilde{a}_0$