Matter Relics in Disformal Scalar-Tensor Theories

(Towards a post-inflationary string cosmology)

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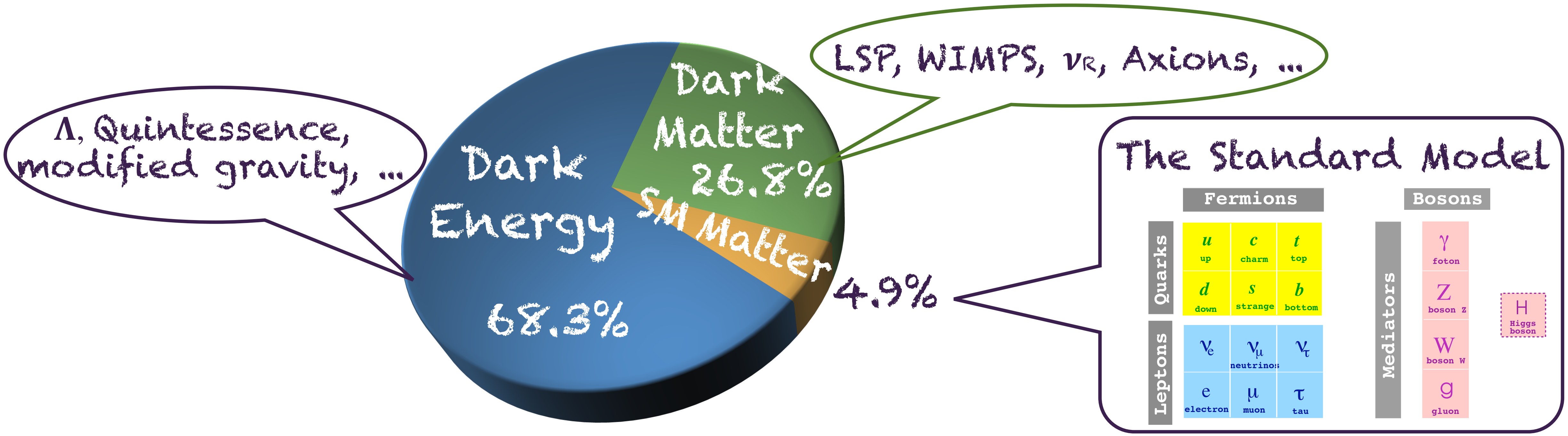
Mitchell Workshop on Collider and Dark Matter Physics 2017

bassed on 1612.05553 + work in progress
w/Bhaskar Dutta, Esteban Jimenez

The ΛCDM model of cosmology

The ΛCDM model, supplemented with inflation is in very good agreement with current observations



Ordinary Matter: *~5% of density content!*

Dark Matter: non-luminous weakly interacting particles (axions, wimps, neutrinos, LSP, etc).

Dark Energy: permeates the universe uniformly causing the accelerated expansion of the universe (Λ, modified gravity, quintessence).

Pre-BBN Cosmological Evolution

- While ΛCDM strongly supported by current data, physics from reheating till just before BBN $(T \sim MeV)$, remains relatively unconstrained.

- During this period, universe may have gone through a *non-standard* period of expansion, compatible with BBN

- In the context of the thermal relic scenario, if such modification happens during DM decoupling, DM freeze-out may be modified with measurable consequences for the thermal relic DM abundances and cross-sections:
  - particle freeze-out may be accelerated (or delayed) and the relic abundance enhanced (or suppressed)

[Kamionkowski, Turner, '90; Salati, '03; Rosati, '03; Profumo, Ullio, '03; Catena et al. '04]

Thermal Relic Scenario

What is the origin and nature of dark matter?

The favourite framework for origin of dark matter is the *thermal relic scenario:*

- During thermal equilibrium $\chi\bar{\chi} \leftrightarrow f\bar{f} \quad (\Gamma_\chi \gtrsim H)$

$$n_\chi^{eq} \sim e^{-m_\chi/T}$$

the longer the DM (anti) particles remain in equilibrium the lower their number densities are at freeze- out. Thus species with larger interaction cross sections which maintain thermal contact longer,

- As universe cools and expands, interactions become less frequent and decay rate drops $\chi\bar{\chi} \leftrightarrow f\bar{f} \quad (\Gamma_\chi \lesssim H)$

- At this point number density freezes-out, and we are left with with a relic of DM particles

freeze out with diminished abundances. Thermal relic WIMPS are excellent DM candidates as their weak scale cross section $\sigma \sim G^2_F m^2_\chi$ gives the correct order of magnitude for $\Omega_{DM} h^2$ for a standard radiation-dominated early universe. However, if the universe experiences a non-standard expansion law during the epoch of dark matter decoupling, freeze-out may be accelerated and the relic abundance enhanced

The longer the DM particles remain in equilibrium, the lower their density will be at freeze-out and vice-versa

Thermal Relic Scenario

In this scenario, a DM candidate with a weak scale interaction cross-section, freezes out with an abundance that matches the presently observed value for the DM density

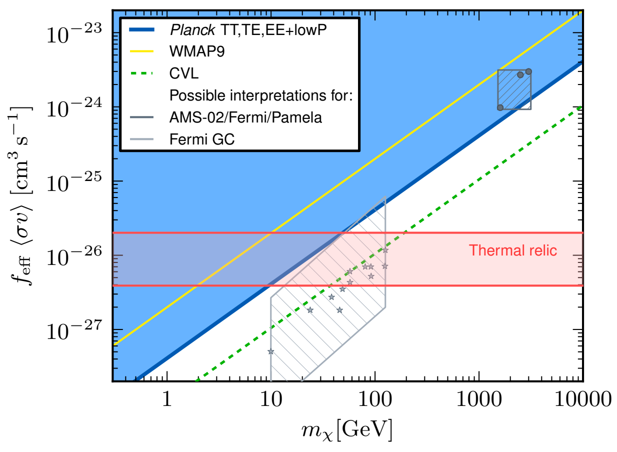
$$\Omega_{DM} = 0.1188 \pm 0.0010 h^{-2}$$

$(h = 0.6774 \pm 0.0046)$

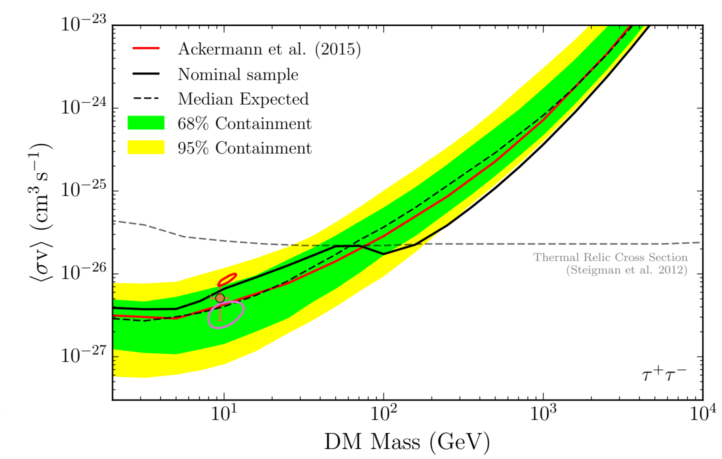
$(H = 100h\,\mathrm{km/s/Mpc})$

Observations indicate that annihilation cross-sections can be smaller than the thermal average value for lower dark matter masses ($\lesssim$100 GeV)

Whereas an annihilation cross-section larger than the thermal average value can still be allowed for larger DM masses

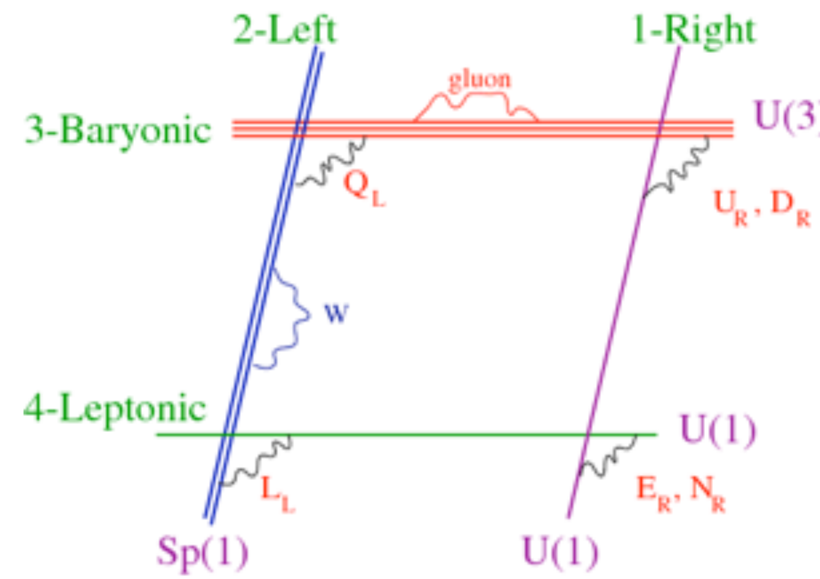


[Planck, '15]
[DES, Fermi-LAT, '16]



String Theory Origin of DM?

- String theory models of particle physics (D-branes, heterotic, M-theory) offers a plethora of potential DM candidates (SUSY partners, axions, hidden sector mater, etc)



- But hard to make a distinction between stringy and field theory LSP, e.g.

- Can we find alternative ways, even if indirect, to test string theory predictions in terms of their dark matter candidates?

Plan

- Conformal and Disformally coupled matter: a phenomenological approach
- Modified expansion rate: conformal case
- Effects on relic abundance
- Turning on Disformal factor
- Towards a D-brane picture

[See Esteban Jimenez's talk]

Conformal&Disformally Coupled Matter

- Consider the following action:

$$S = S_{EH} + S_\phi + S_m$$
$$= \frac{1}{2\kappa^2}\int d^4x\sqrt{-g}\, R - \int d^4x\sqrt{-g}\left[\frac{1}{2}(\partial\phi)^2 + V(\phi)\right] - \int d^4x\sqrt{-\tilde{g}}\, \mathcal{L}_M(\tilde{g}_{\mu\nu})$$

where matter is coupled to

$$\tilde{g}_{\mu\nu} = C(\phi)g_{\mu\nu} + D(\phi)\partial_\mu\phi\partial_\nu\phi$$

$C(\phi)$ *conformal transformation (preserves angles)*

$D(\phi)$ *disformal transformation (distorts angles)*

[Bekenstein, '92]

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Impact on Early Evolution

- Departures from standard cosmology will arise due to the different expansion rate, $\tilde{H}$, determined by scalar evolution

  $\Longrightarrow$ impact in DM relic abundances

[Kamionkowski, Turner, '90]
[Salati, '03; Rosati, '03]
[Profumo, Ullio, '03]

- First study of conformally coupled DM/Quintessence model was considered by Catena et al. Lahanas et al in non-critical string theory models

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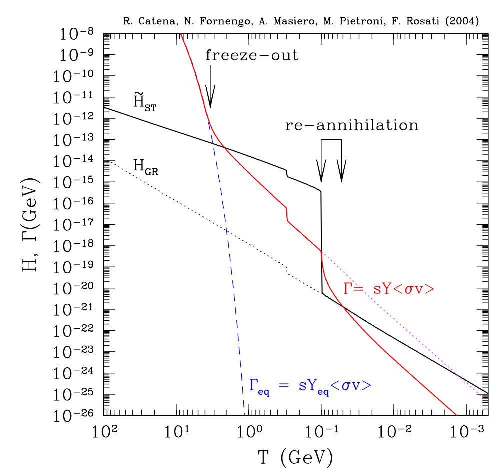
[Lahanas et al. '06]

- A first estimate of modification of the relic abundance of WIMP's due to change in expansion rate at the time of CDM freeze-out



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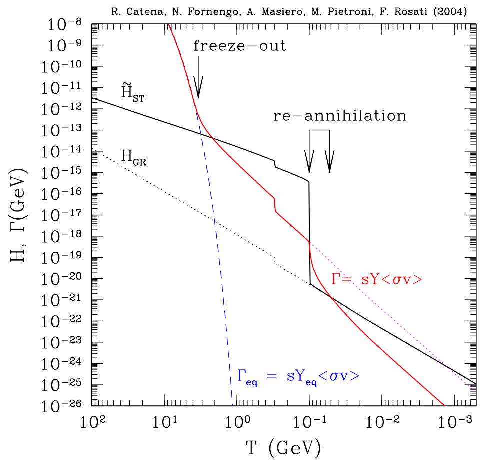

- What are the generic predictions for conformal coupling?
- How is cross-section modified (enhanced/diminished)?
- What is the effect of a disformal coupling?

Modified Expansion rate

In FRW background, evolution equations in Einstein frame (with respect to $g_{\mu\nu}$) 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 $$Q_0 = \rho\left[\frac{D}{C}\ddot{\phi} + \frac{D}{C}\dot{\phi}\left(3H + \frac{\dot{\rho}}{\rho}\right) + \left(\frac{D_{,\phi}}{2C} - \frac{D}{C}\frac{C_{,\phi}}{C}\right)\dot{\phi}^2 + \frac{C_{,\phi}}{2\,C}(1 - 3\,\omega)\right]$$

Total energy is conserved $\nabla_\mu\left(T_\phi^{\mu\nu} + T^{\mu\nu}\right) = 0$, but individual conservation equations are modified:

$$\dot{\rho}_\phi + 3H(\rho_\phi + P_\phi) = -Q_0\dot{\phi} ,$$
$$\dot{\rho} + 3H(\rho + P) = Q_0\,\dot{\phi} .$$

Note that in the Jordan/disformal frame, the energy-momentum tensor is conserved, $\nabla_\mu \tilde{T}^{\mu\nu} = 0$

$\Rightarrow \qquad \tilde{\rho} + 3\tilde{H}(\tilde{\rho} + \tilde{P}) = 0$

Modified Expansion rate

We are looking for the modified expansion rate in the *disformal or Jordan frame*, felt by matter $\tilde{g}_{\mu\nu}$, $\tilde{H} \equiv \frac{d\ln\tilde{a}}{d\tilde{\tau}}$,

$$\tilde{H} = \frac{H\gamma}{C^{1/2}}\left(1 + \alpha(\varphi)\varphi'\right) \qquad (\varphi = \kappa\phi)$$

where $' = d/dN$,

$$\gamma^{-2} = 1 - \frac{H^2}{\kappa^2}\frac{D}{C}\varphi'^2,$$

$$\alpha(\varphi) = \frac{d\ln C^{1/2}}{d\varphi},$$

We need to compare this modified rate with the standard GR:

$$H_{GR}^2 = \frac{\kappa_{GR}^2}{3}\tilde{\rho} \qquad \text{where} \qquad \tilde{\rho} = C^{-2}\gamma^{-1}\rho$$

In terms of H and φ, it can be written as

$$\gamma^{-1}H^2 = \frac{\kappa^2}{\kappa_{GR}^2}\frac{C^2(1+\lambda)}{B}H_{GR}^2 \qquad \left(B = 1 - \frac{\varphi'^2}{6}\right)$$

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Deviation from GR can be readily computed from

$$\xi \equiv \frac{\tilde{H}}{H_{GR}}$$

which needs to go to 1 towards the start of BBN

Conformal Case: Scalar Evolution

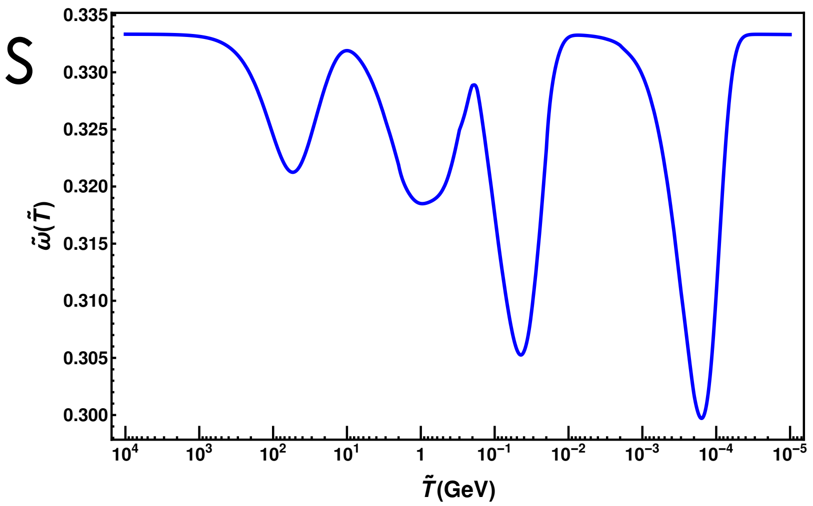
In the conformal case, equations can be reduced to a single master equation for φ, which we solve during radiation and matter era $V(\varphi) \sim 0$

$$\frac{2}{3(1-\varphi'^2/6)}\varphi'' + (1-\tilde{\omega})\,\varphi' + 2(1-3\,\tilde{\omega})\,\alpha(\varphi) = 0,$$

where $\tilde{\omega} = \gamma^2\omega$ is the Jordan frame eos computed from

$$1 - 3\,\tilde{\omega} = \frac{\tilde{\rho} - 3\,\tilde{p}}{\tilde{\rho}} = \sum_A \frac{\tilde{\rho}_A - 3\tilde{p}_A}{\tilde{\rho}} + \frac{\tilde{\rho}_m}{\tilde{\rho}}$$

which takes into account small departures from 1/3 when a species becomes non-relativistic



[See Esteban Jimenez's talk]

Conformal Case: Scalar Evolution

Conformal coupling acts as effective potential for φ

$$\frac{2}{3(1-\varphi'^2/6)}\,\varphi'' + (1-\tilde{\omega})\,\varphi' + 2\underbrace{(1-3\,\tilde{\omega})\,\alpha(\varphi)}_{V_{eff}} = 0,$$

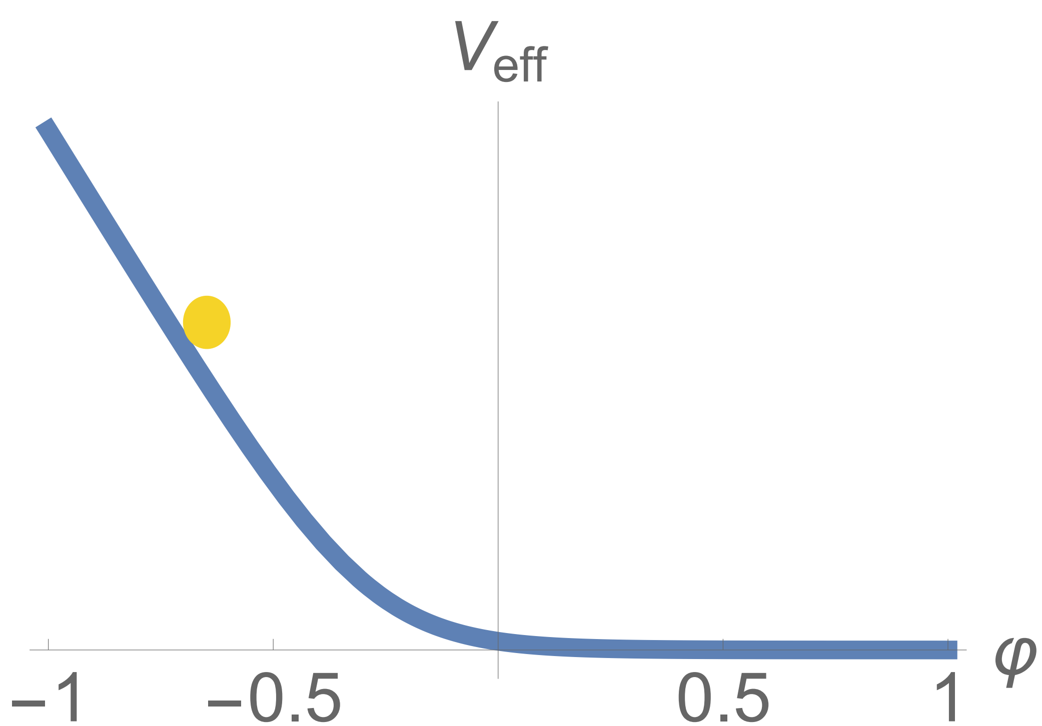
For concreteness we consider

$$C(\varphi) = (1+b\,e^{-\beta\,\varphi})^2$$

$(b = 0.1,\ \ \beta = 8)$

[Catena et al. '04]

$$\Rightarrow \qquad V_{eff} = \ln(1+be^{-\beta\varphi})$$



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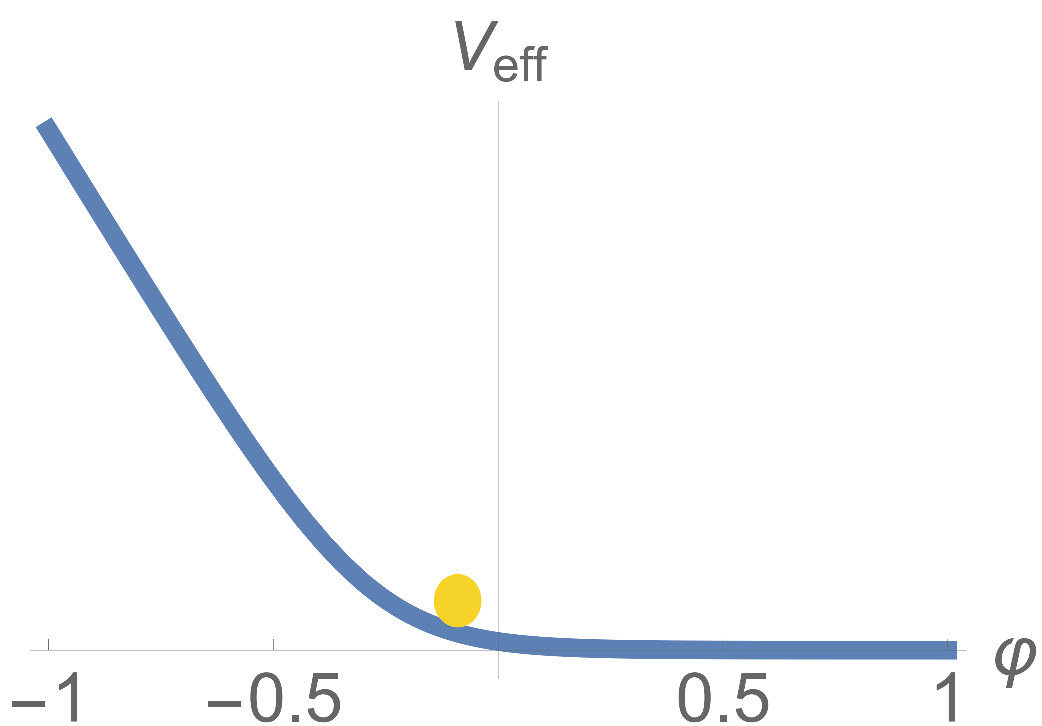

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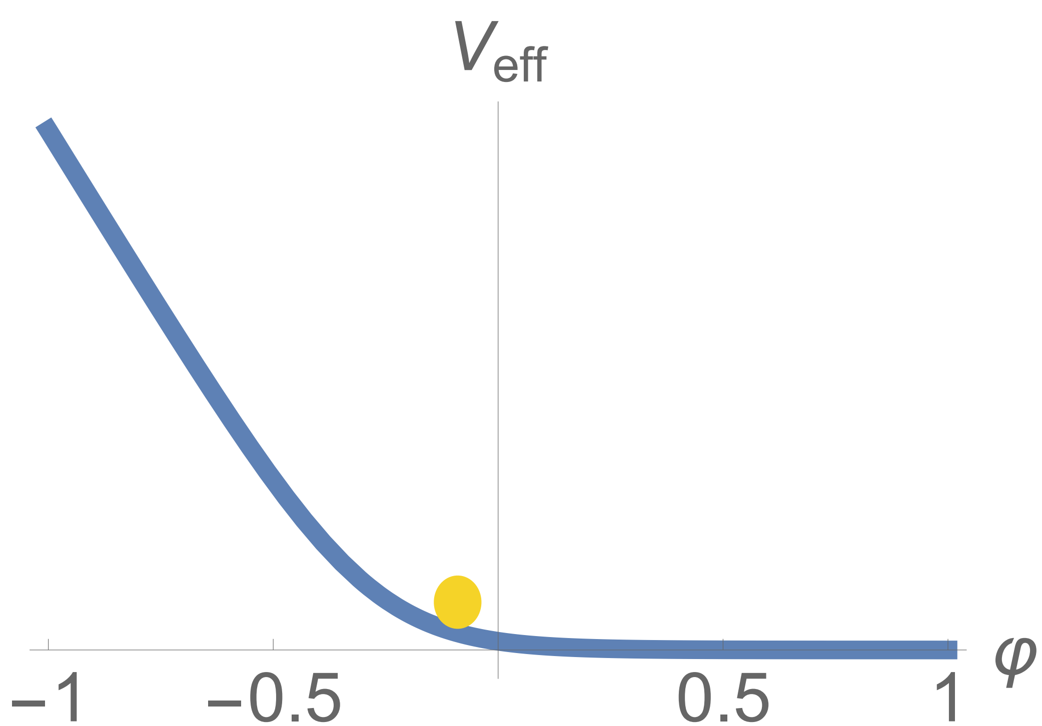

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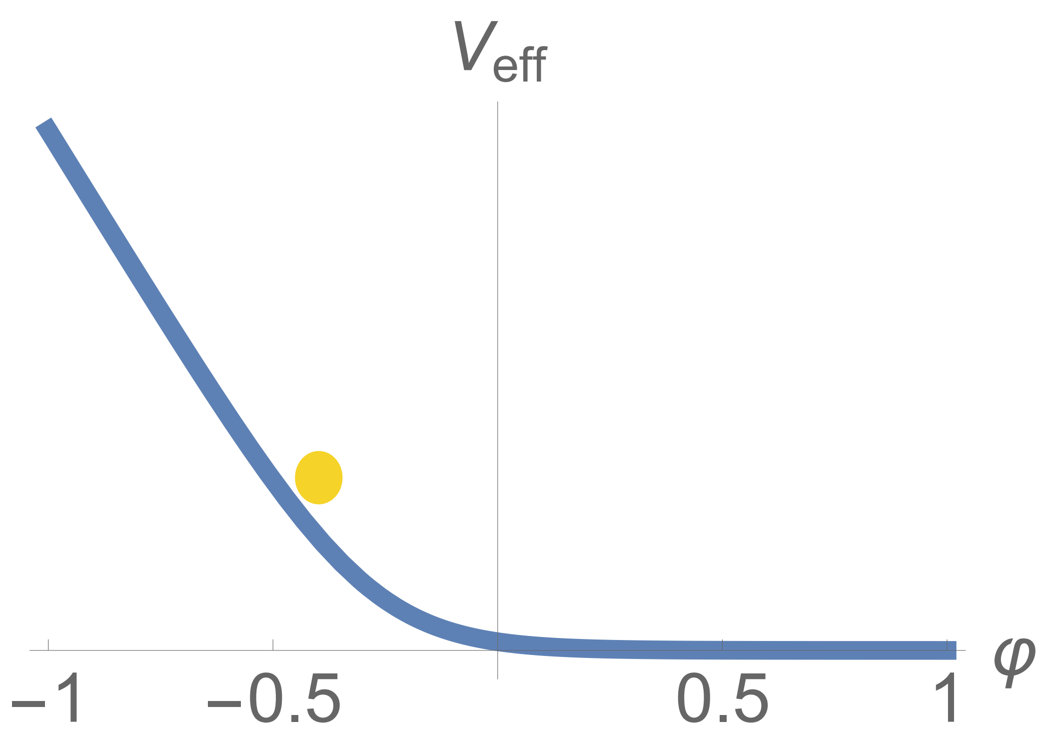

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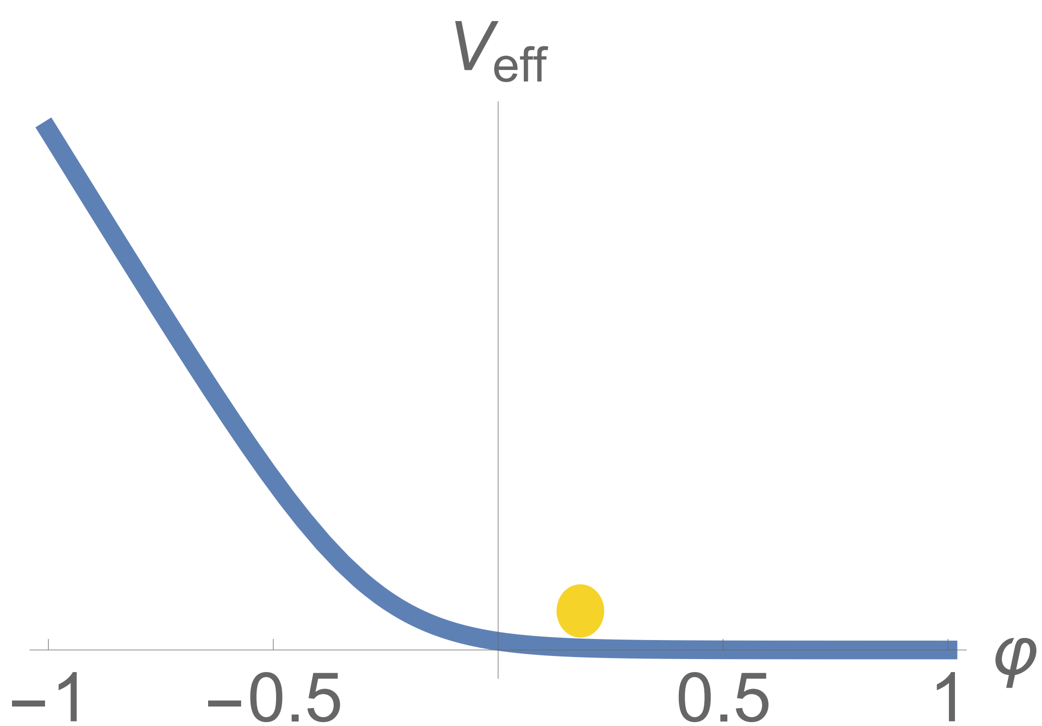
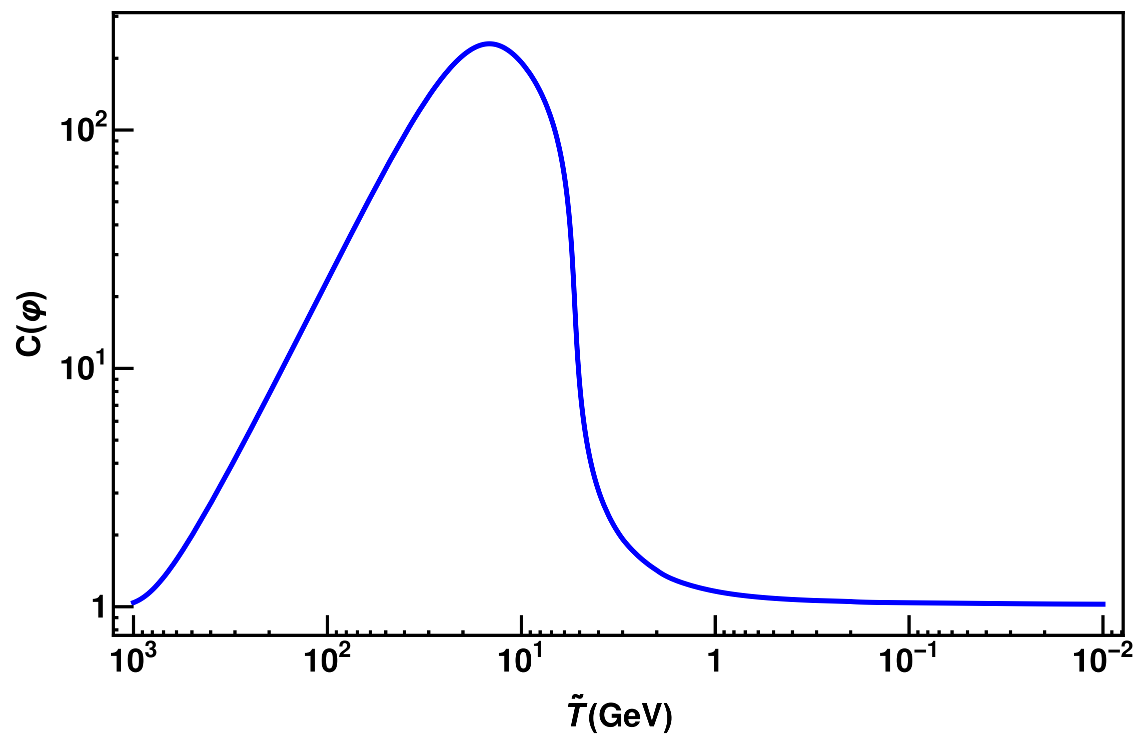


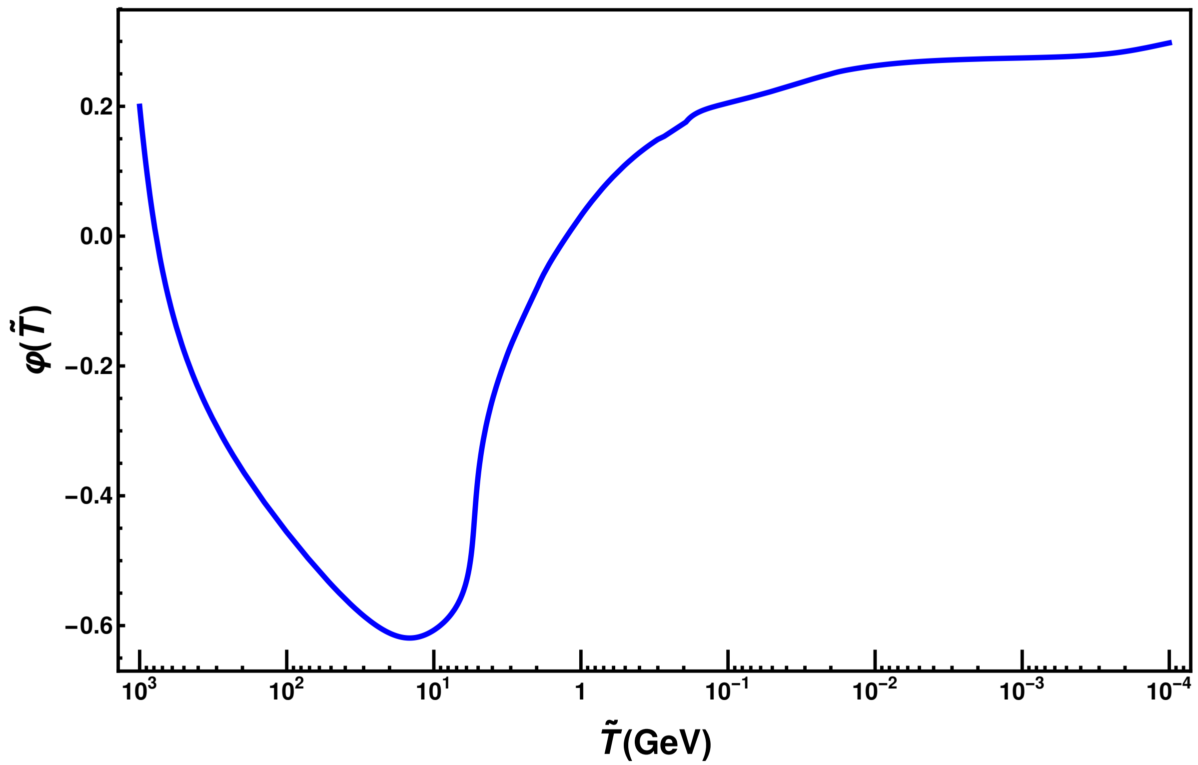
Conformal Case: Scalar Evolution

This second choice of initial conditions gives the most interesting evolution



Conformal factor evolution

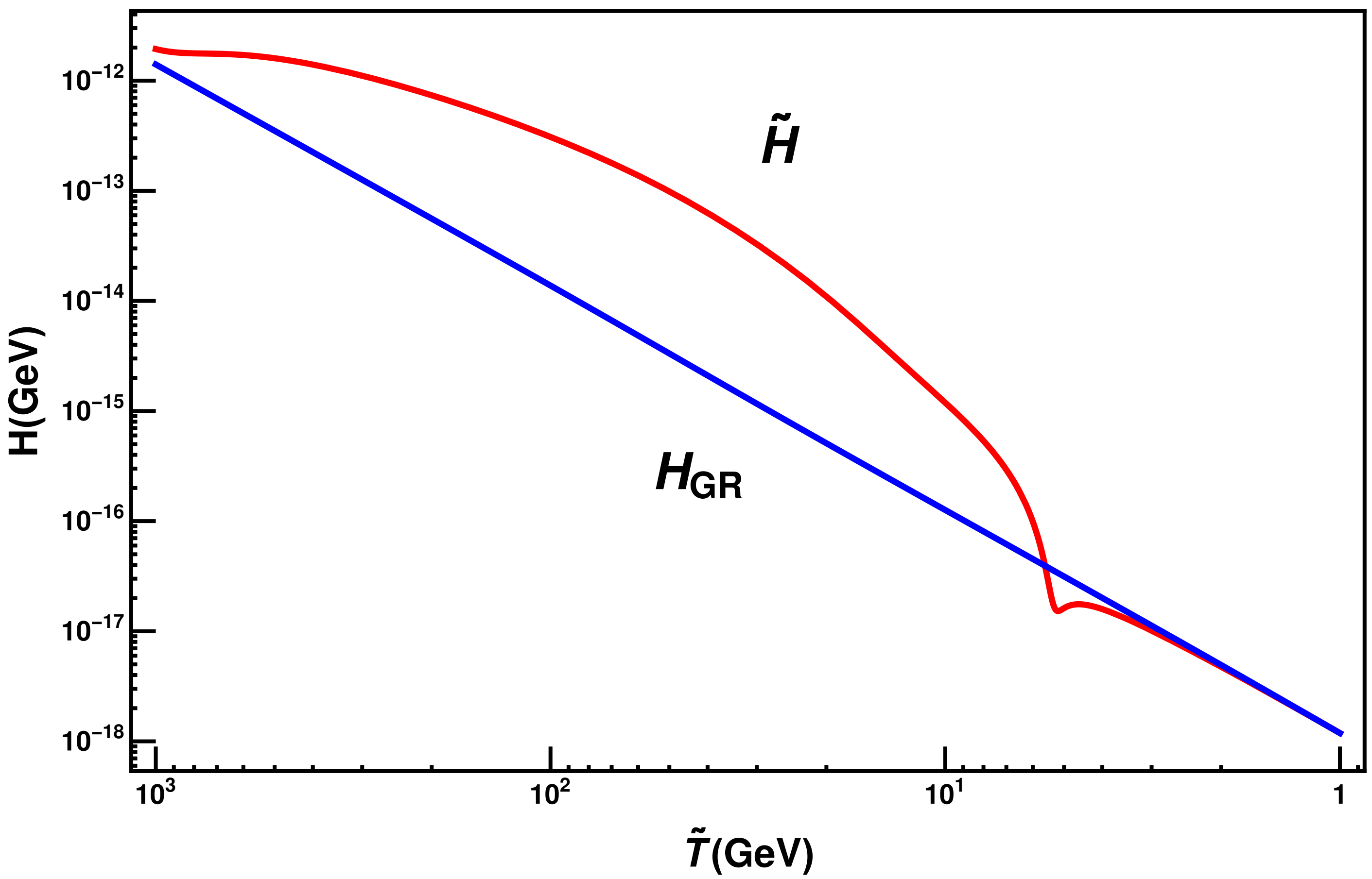
$$(\varphi_0, \varphi_0') = (0.2, -0.994)$$



Scalar field evolution

$$(\varphi_0, \varphi_0') = (0.2, -0.994)$$

Conformal Case: Expansion Rate



Expansion rates comparison

(for initial conditions: $(\varphi_0, \varphi_0') = (0.2, -0.994)$)

$$\tilde{H} = \frac{H\gamma}{C^{1/2}} \left(1 + \alpha(\varphi)\varphi'\right)$$

(we consider only expanding solutions, $(1 + \alpha(\varphi)\varphi') > 0$)

Note that Einstein frame H always decreases (no violation of energy conditions). However, disformal frame H can increase

Notorious notch appears, which gives rise to possibility of re-annihilation effect.

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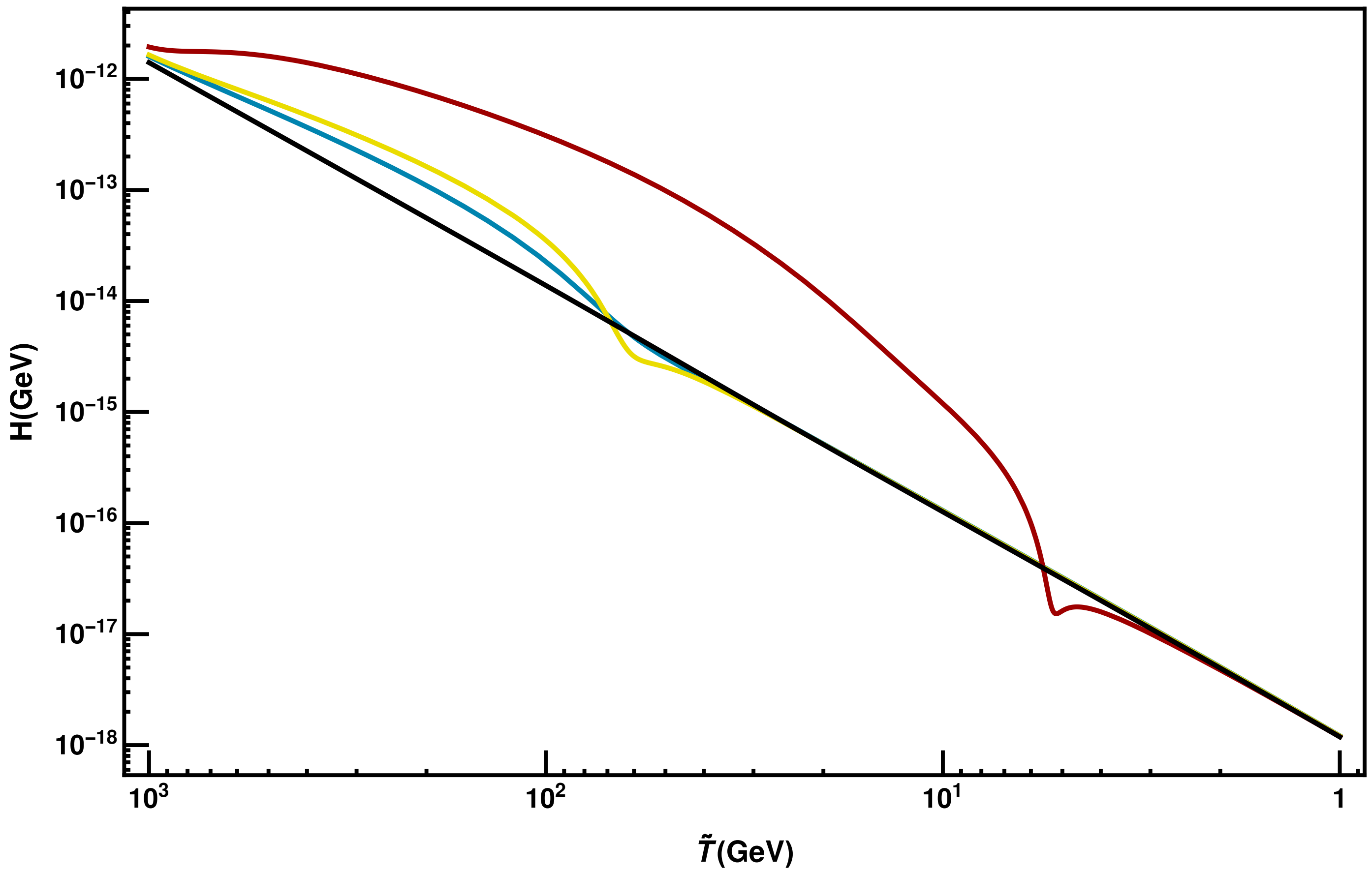

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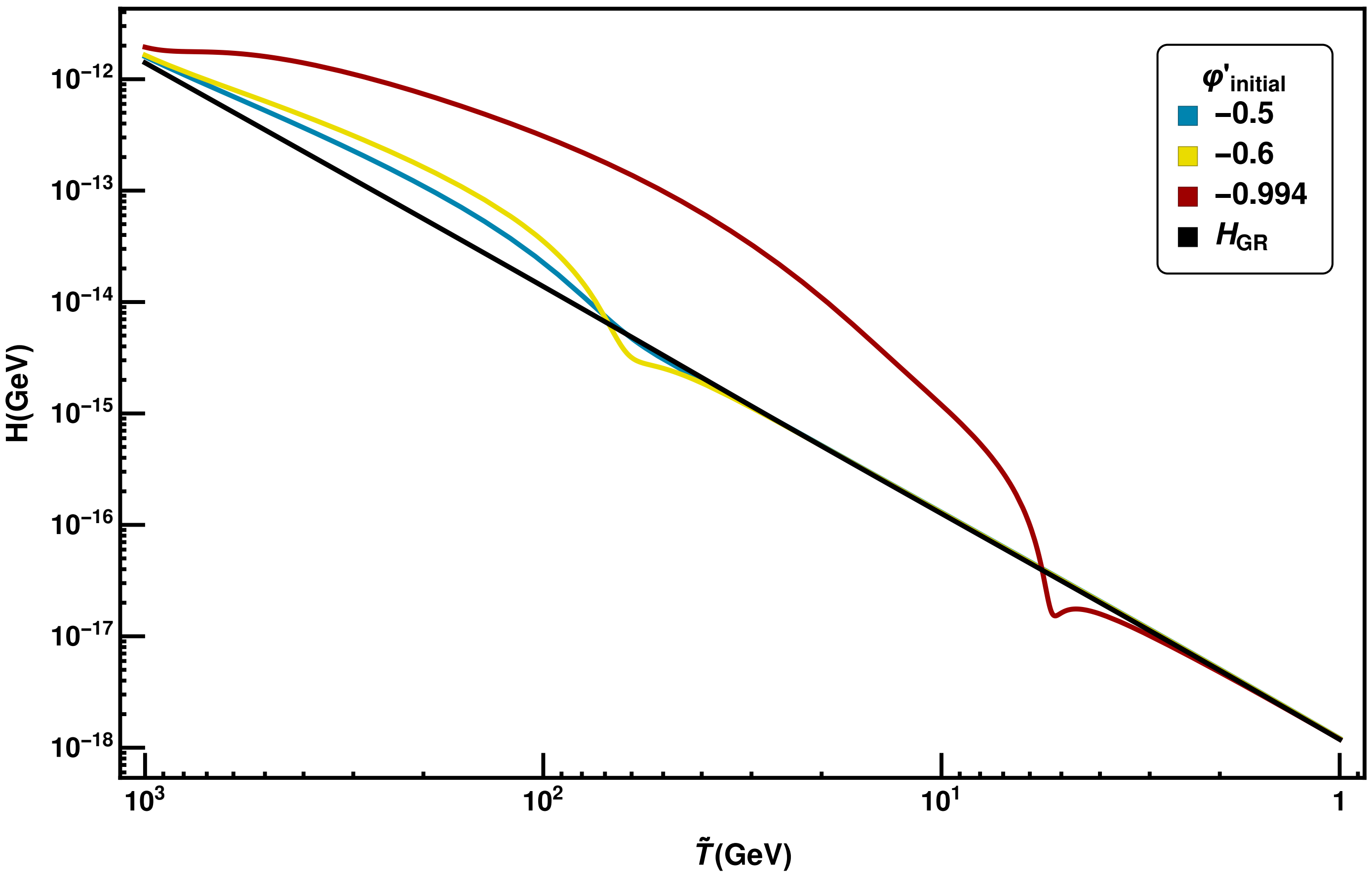

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Effect on DM Relic Abundance

The impact of modified expansion rate on relic abundance for DM particle χ with mass m_χ can now be determined from Boltzmann equation

$$\frac{dn_\chi}{dt} = -3\tilde{H}n_\chi - \langle\sigma v\rangle \left(n_\chi^2 - (n_\chi^{eq})^2\right)$$

which determining the dark matter number density n_χ evolution.

Here $\langle\sigma v\rangle$ is the annihilation cross-section and n_χ^{eq} the equilibrium number density.

Rewriting Boltzmann equation in terms of $x = m_\chi/\tilde{T}$

$Y = \frac{n_\chi}{\tilde{s}}$, $\tilde{s} = \frac{2\pi}{45}g_s(\tilde{T})\tilde{T}^3$

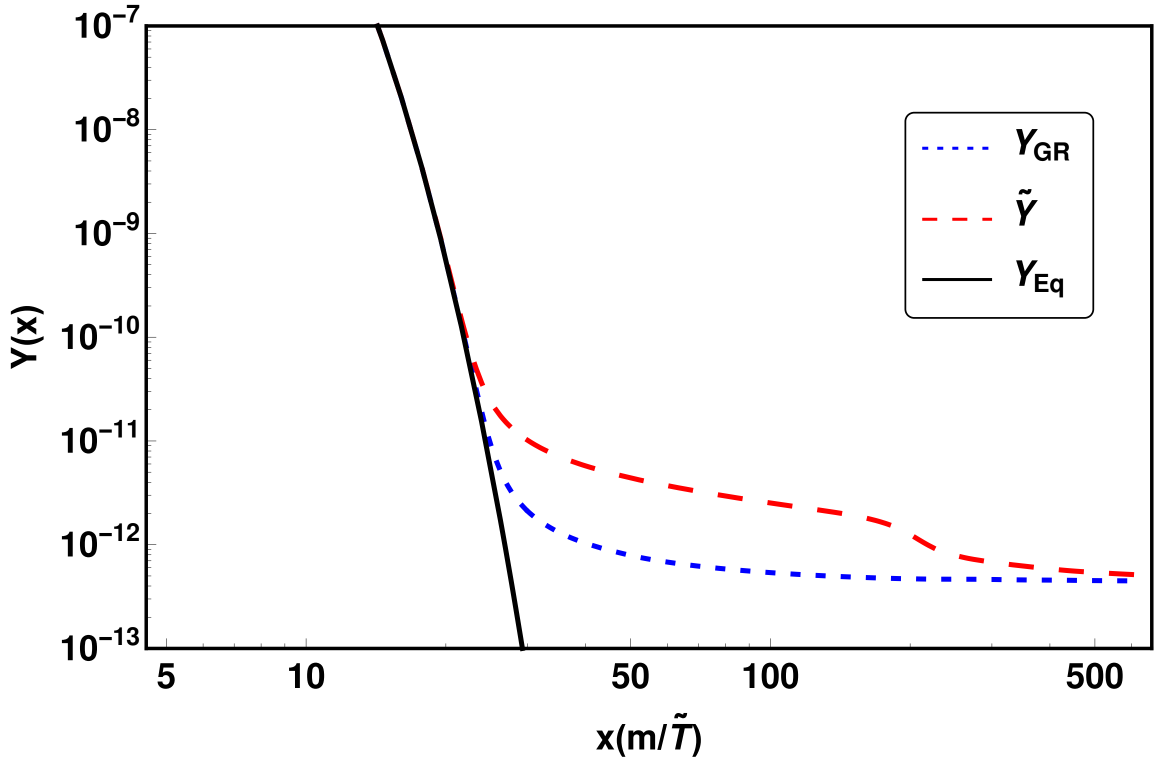
$$\frac{dY}{dx} = -\frac{\tilde{s}\langle\sigma v\rangle}{x\tilde{H}}\left(Y^2 - Y_{eq}^2\right)$$

[See Esteban Jimenez's talk]

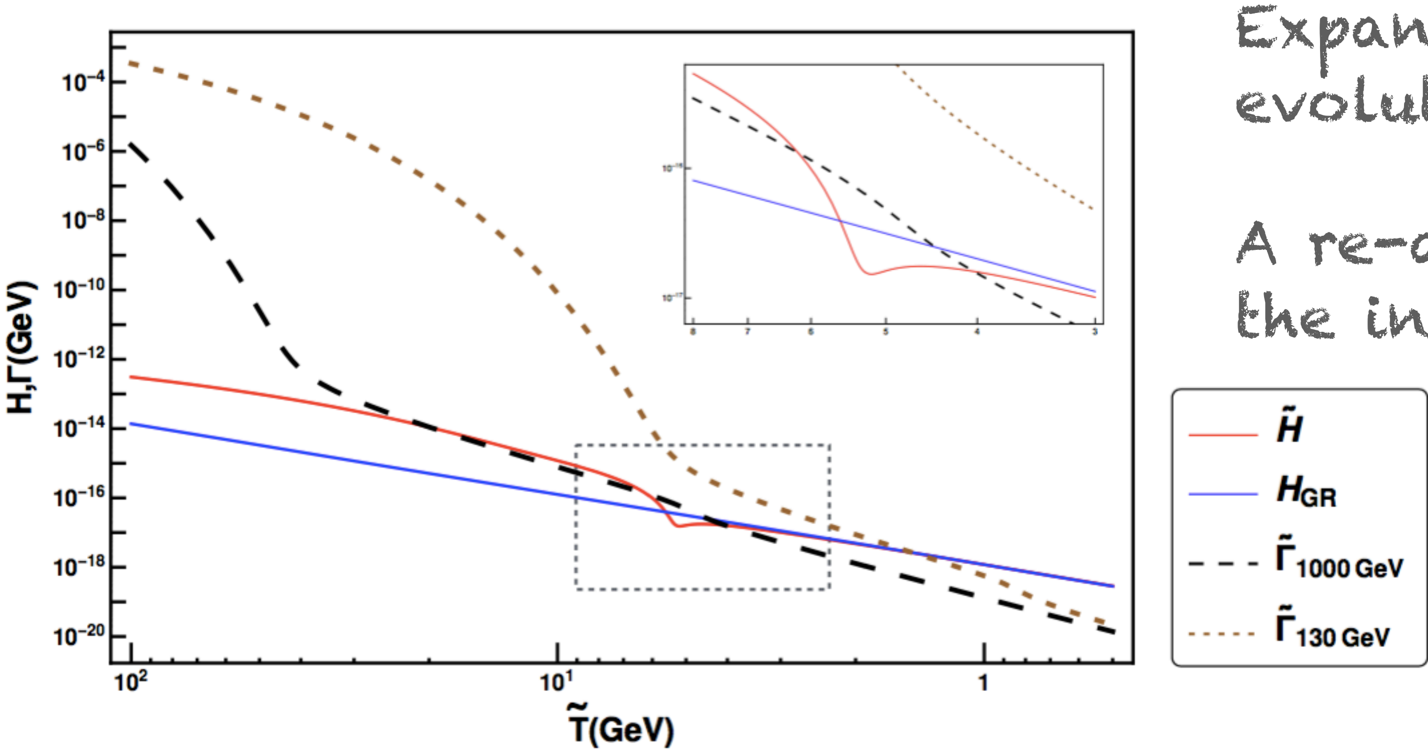
Effect on DM Relic Abundance

Boltzmann equation, gives us the DM relic abundance

[See Esteban Jimenez's talk]



Relic abundance evolution for DM particle with mass $m_\chi = 1000\,\text{GeV}$



Expansion and interaction rates' evolution

A re-annihilation phase occurs for the initial conditions chosen

Disformal Case: Expansion Rate

Turning on the disformal coupling, we need to solve the coupled system of eqs for φ, H

$$\alpha(\varphi) = \frac{d \ln C^{1/2}}{d\varphi},$$
$$\delta(\varphi) = \frac{d \ln D^{1/2}}{d\varphi}.$$

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

$$\varphi''\left[1+\frac{3H^2\gamma^2 B}{\kappa^2}\frac{D}{C}\right] + 3\varphi'\left[1-\tilde{\omega}\frac{3H^2 B}{\kappa^2}\frac{D}{C}\right] + \frac{H'}{H}\varphi'\left[1+\frac{3H^2\gamma^2 B}{\kappa^2}\frac{D}{C}\right]$$
$$+3B\alpha(\varphi)(1-3\tilde{\omega}) + \frac{3H^2\gamma^2 B}{\kappa^2}\frac{D}{C}(\delta(\varphi)-\alpha(\varphi))\varphi'^2 = 0$$

Use same conformal factor plus a small disformal contribution:

$D(\varphi) \; = \; D_0\,\varphi^2$ with $D_0 = -4.9\times 10^{-14}$

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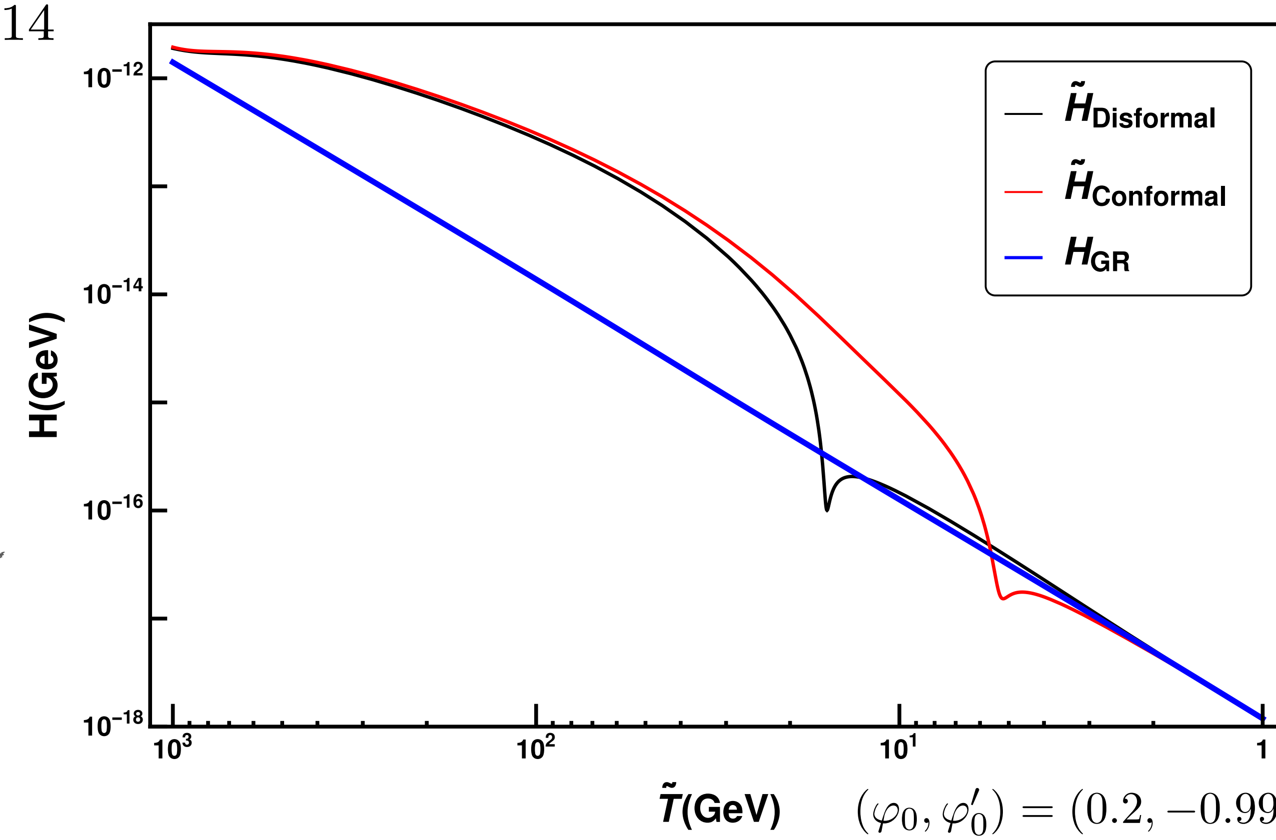
Modified expansion with conformal and disformal functions turned on, for same initial conditions

Shape remains similar, position of notch moves and becomes sharper with a small increase in H



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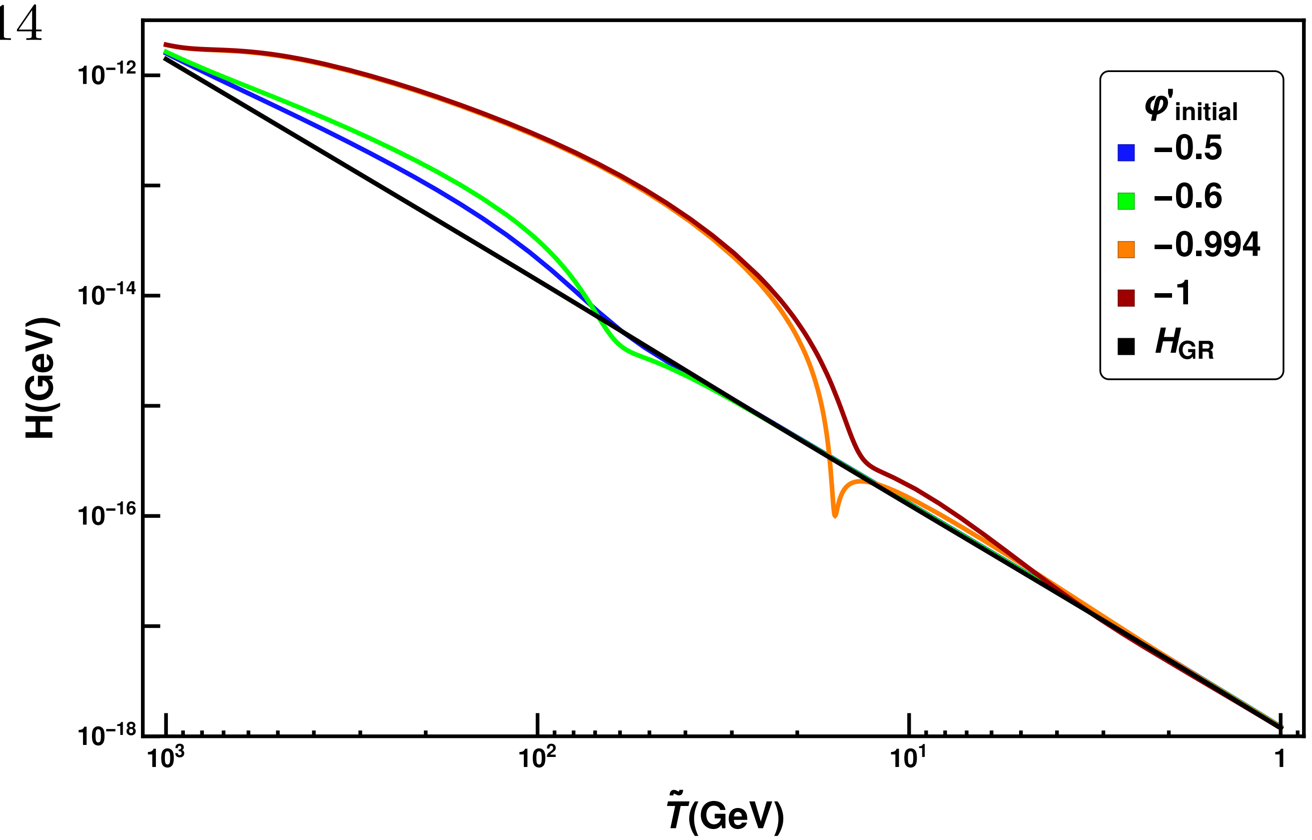

Disformal Case: Expansion Rate

Turning on the disformal coupling, we need to solve the coupled system of eqs for φ, H

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

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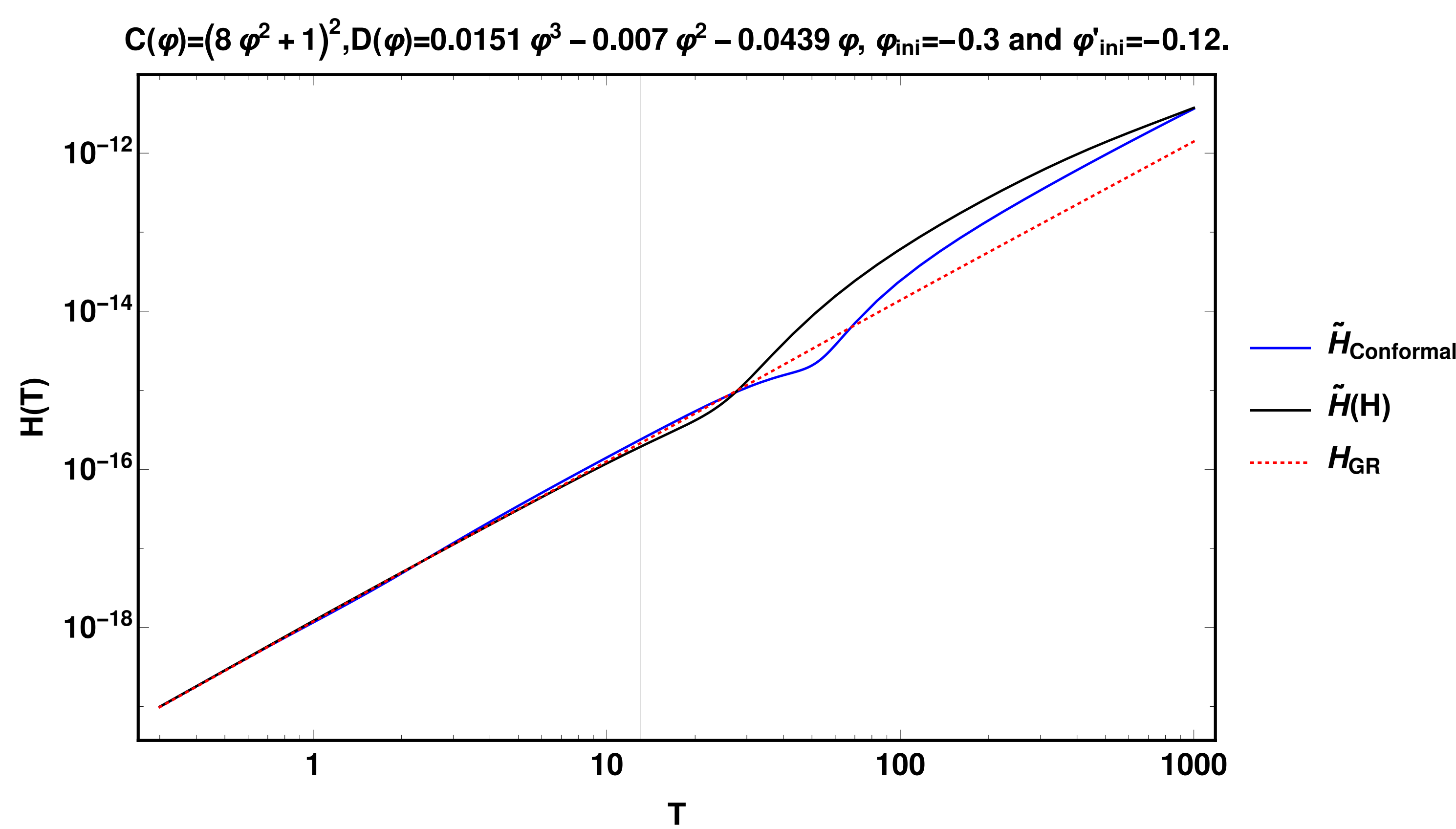
Another example

$$C = (8\varphi^2+1)^2\,,$$

$$D = d_1\varphi^3 + d_2\varphi^2 + d_3\varphi$$



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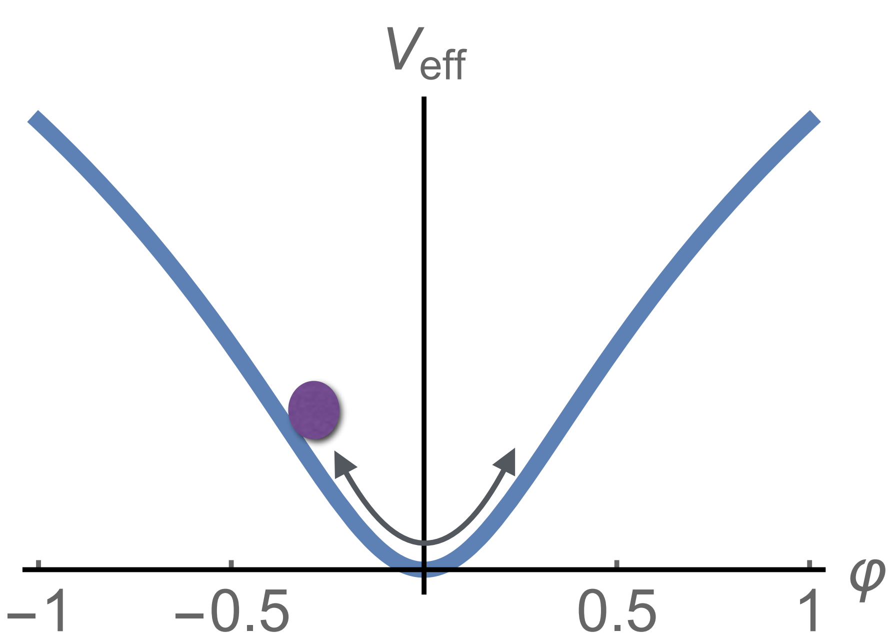

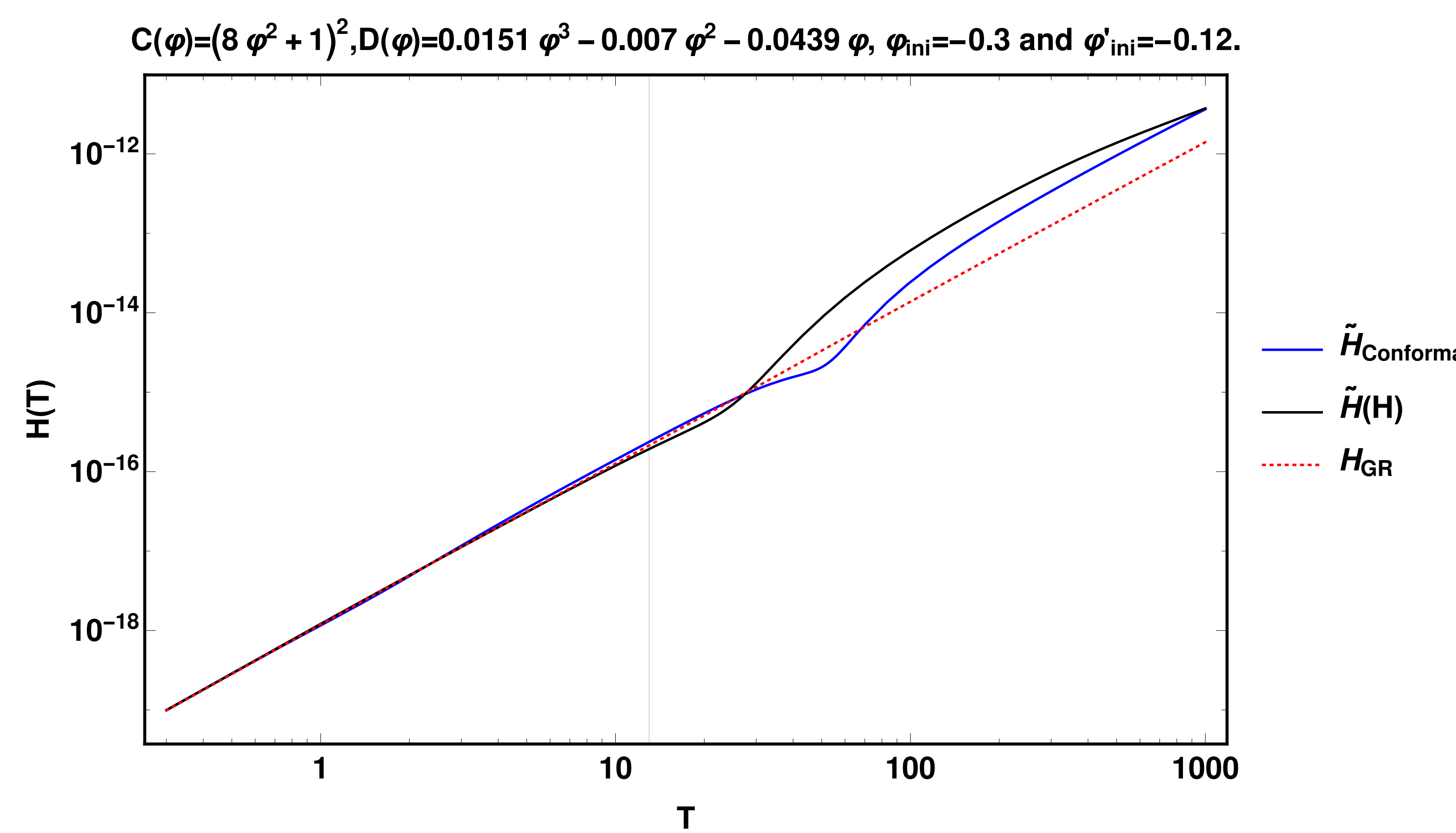

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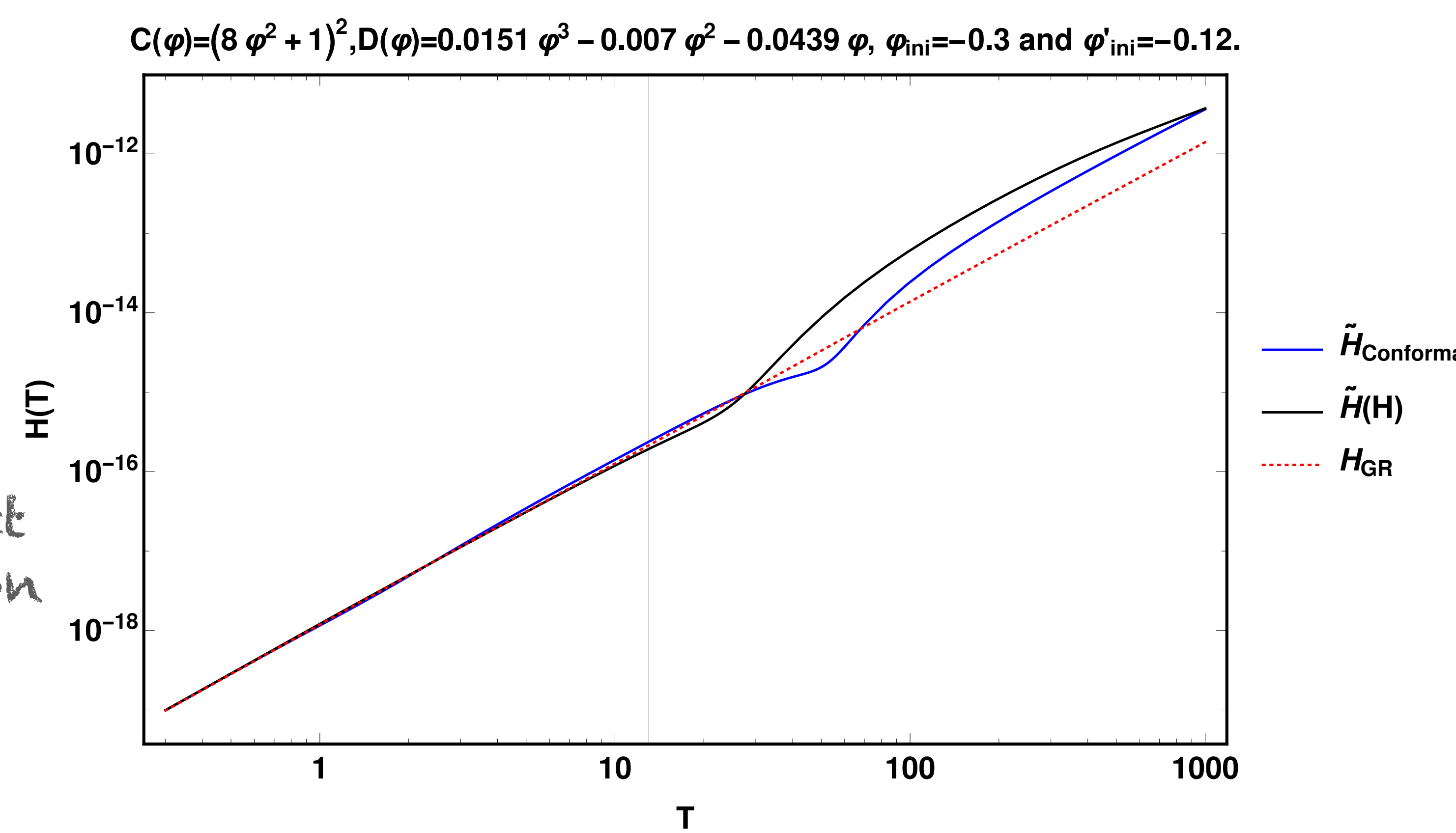
Less dramatic effect, and thus impact on relic abundance and cross-section



THE D-BRANE CASE

Conformal&Disformal couplings arise naturally from D-brane actions. They are dictated by theory and arise as follows:

$$S = S_{EH} + S_\phi + S_m$$

$$S_{EH} = \frac{1}{2\kappa^2}\int d^4x\sqrt{-g}\, R,$$

$$S_\phi = -\int d^4x\sqrt{-g}\left[\frac{b}{2}(\partial\phi)^2 + M^4 C_1^2(\phi)\sqrt{1+\frac{D_1(\phi)}{C_1(\phi)}(\partial\phi)^2} + V(\phi)\right],$$

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D-brane case: $$b = 0,\;\; C_1 = C_2,\;\; D_1 = D_2$$

Accelerating *scaling solutions* in coupled DE/DM models have been found in for monomial potentials.

[Koivisto, Wills, IZ '13]

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WORK IN PROGRESS

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The coupled equations to find the scalar evolution and expansion rates is no modified as

$$H' = -H\left[\frac{3B}{2(1+\lambda)}(1+\omega) + \frac{\varphi'^2 M^4 C D\gamma}{\gamma+1}\right],$$

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Summary

- We investigated modifications to standard relic picture due to non-standard early cosmology evolution in scalar-tensor theories with conformal and disformal couplings to matter

- For suitable initial conditions, interesting non-trivial modifications appear in expansion rate and thus in the relic abundance of DM

- We studied a phenomenological scalar-tensor model, as a warm up to understand D-brane induced conformal/ disformal couplings to matter