D-brane Scalar-Tensor Theories and the Thermal Dark Matter Scenario

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Post-Inflationary String Cosmology
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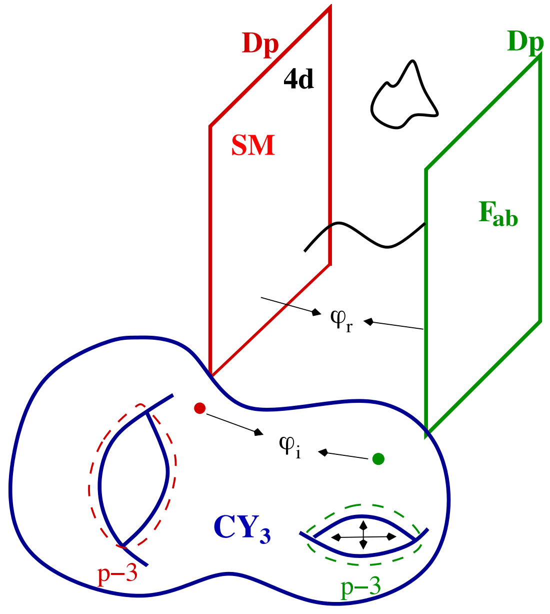
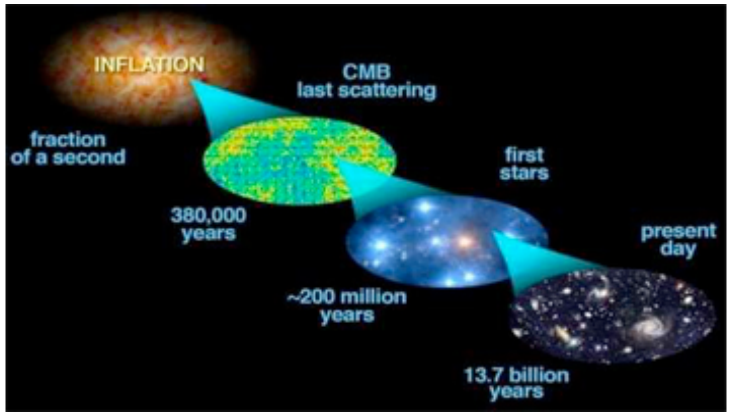
w/Bhaskar Dutta, Esteban Jimenez

String Cosmology

- **String Inflation**
  - Moduli Stabilisation in string inflation
  - Generic predictions in string inflation
  - Global embedding of inflation models
  - Beyond string inflation…



- **Post-String Inflation**
  - Pre- and Re-heating after inflation
  - Dark String Cosmology: DM/DR/DE
  - Late Universe Acceleration: Λ, DE…



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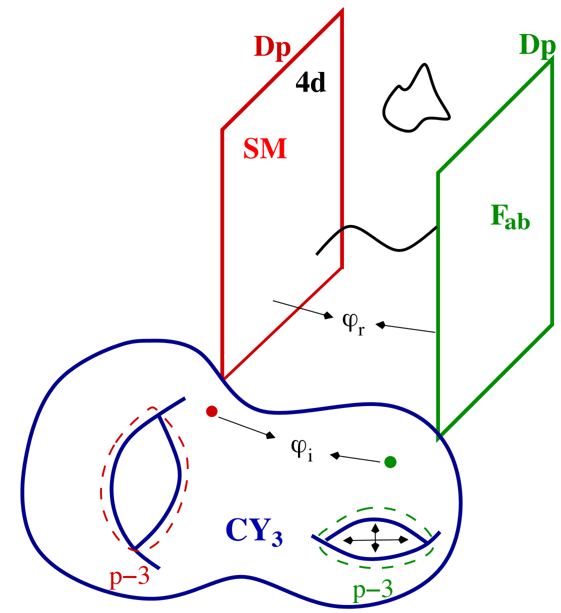

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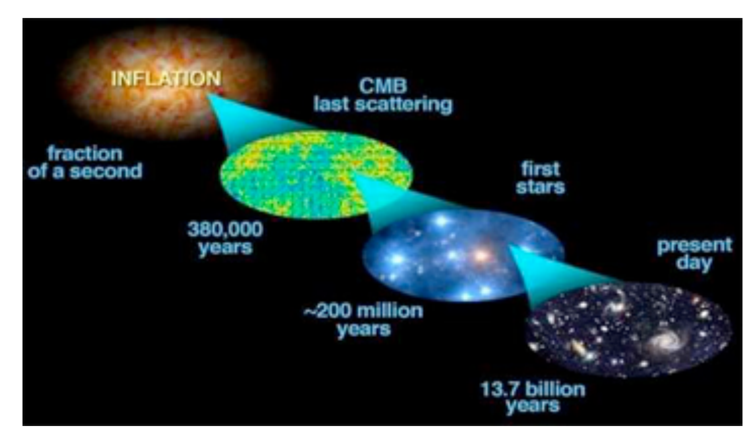
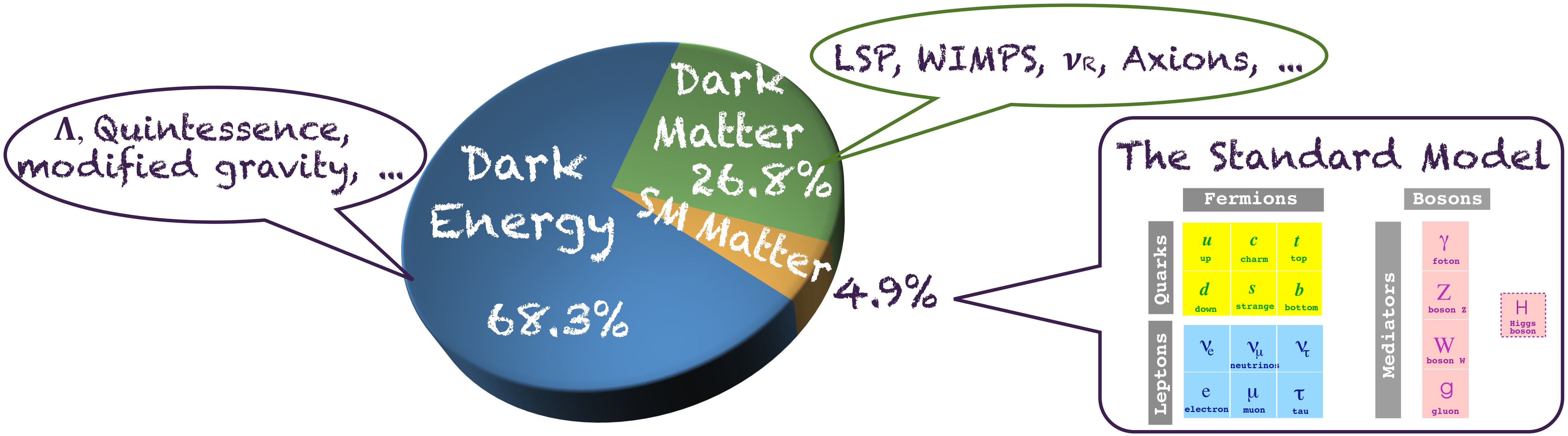


The Cosmic Pie

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, simps neutrinos, LSP, etc).

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

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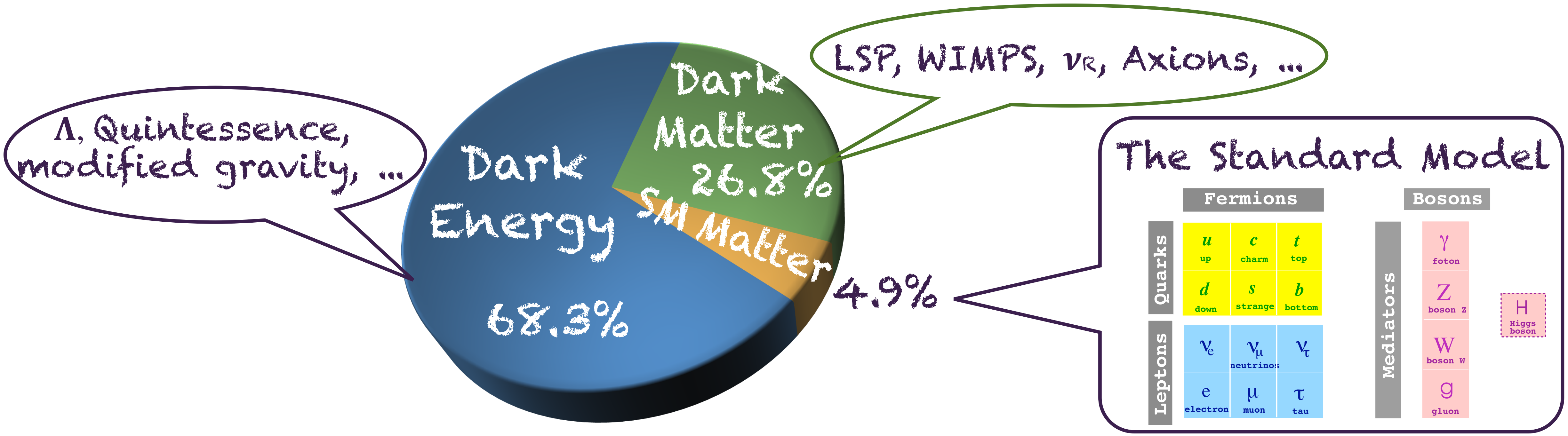

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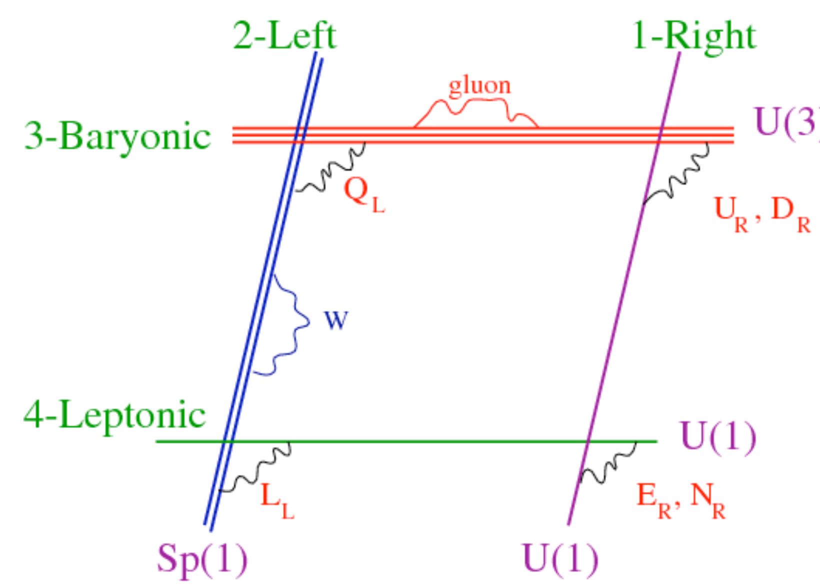
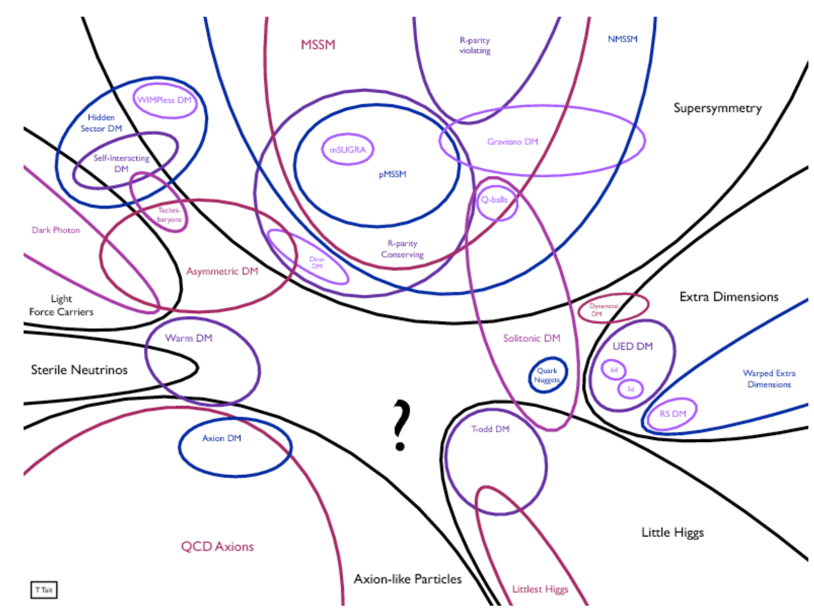
Dark Matter in String Theory

- 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)



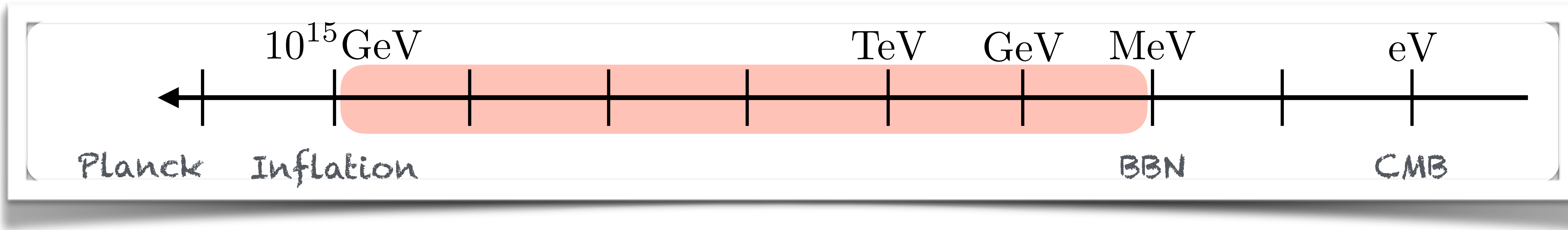
- Can we distinguish between stringy and field theory LSP, e.g.?

- Can we find alternative ways, even if indirect, to test string theory predictions for dark matter?



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, a matter dominated era, etc, compatible with BBN [see Allahverdi's talk]

- If such modification happens during DM decoupling, *DM freeze-out may be modified* with measurable consequences for the thermal relic scenario

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

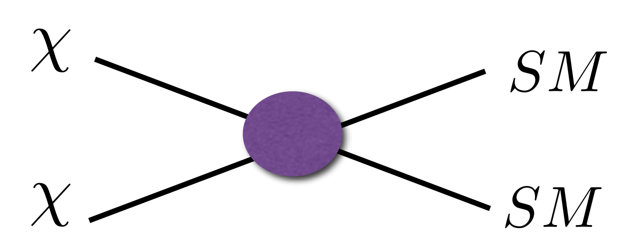
Plan

- The standard thermal relic scenario
- Modified thermal relic scenario:
  D-brane disformal scalar-tensor theories
- Effects on relic abundance and cross section

Thermal Relic Scenario

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

- During thermal equilibrium $(\Gamma_\chi > H)$

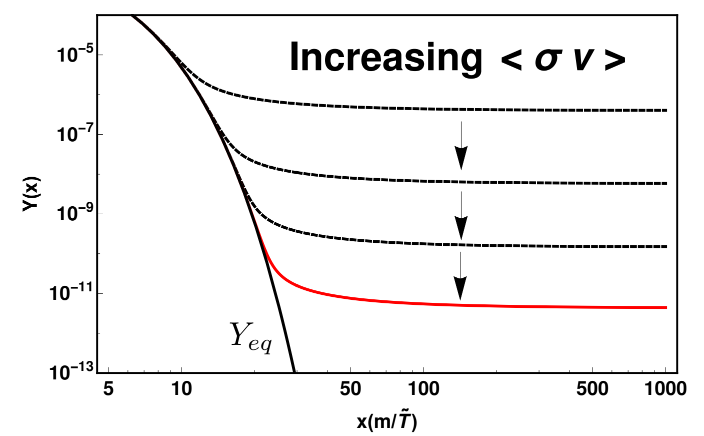


$$\chi\bar{\chi} \leftrightarrows f\bar{f}$$

- As universe cools and expands, interactions become less frequent and decay rate drops $(\Gamma_\chi \lesssim H)$

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

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



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

The Wimp Miracle

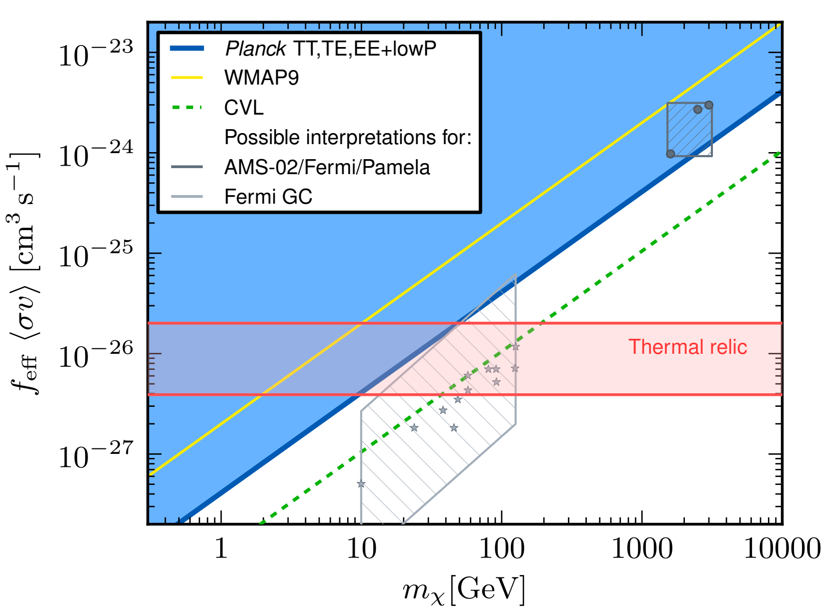
In this scenario, a DM candidate with a weak scale interaction cross-section and $(m \sim 100\,\mathrm{GeV})$ mass, freezes-out with an abundance that matches the presently observed value for the DM density

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

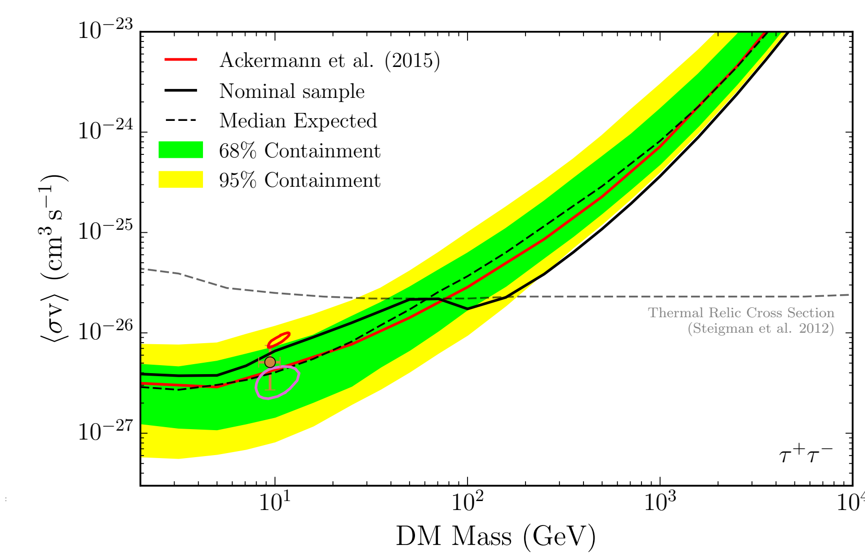
$(h = 0.6774 \pm 0.0046)$

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

However observations indicate that annihilation cross-sections smaller/larger than the thermal average can still be allowed for value for lower/larger dark matter masses



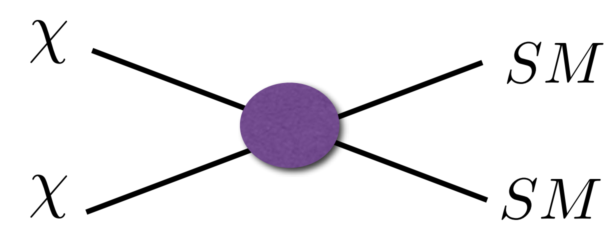
[Planck, '15]
[DES, Fermi-LAT, '16]



The Boltzmann Equation

- The abundance of the present CDM can be computed using the Boltzmann equation

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



LHS RHS

Modifications to the standard picture can arise from modifications from either the LHS or RHS

In this talk, I consider modifications to LHS of Boltzmann equation due to *modification of expansion rate* in *phenomenological and D-brane scalar-tensor theories and its implications*

[Kamionkowski, Turner, '90; Salati, '03; Rosati, '03; Profumo, Ullio, '03; Catena et al. '04, Lahanas et al. '06; ...Meehan, Whittingham '15; D'Eramo, Fernandez, Profumo, '17, ...]

Conformal and Disformal couplings

- In *scalar tensor theories*, besides a conformal relation between two metrics:

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

- Bekenstein deduced the most general relation compatible with general covariance to be of the form:

[Bekenstein, '92]

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

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

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

where C, D satisfy the causality constraint

$$C(\phi) > 0 \text{ and } C(\phi) + 2D(\phi) X > 0, \ (X = \tfrac{1}{2}(\partial\phi)^2)$$

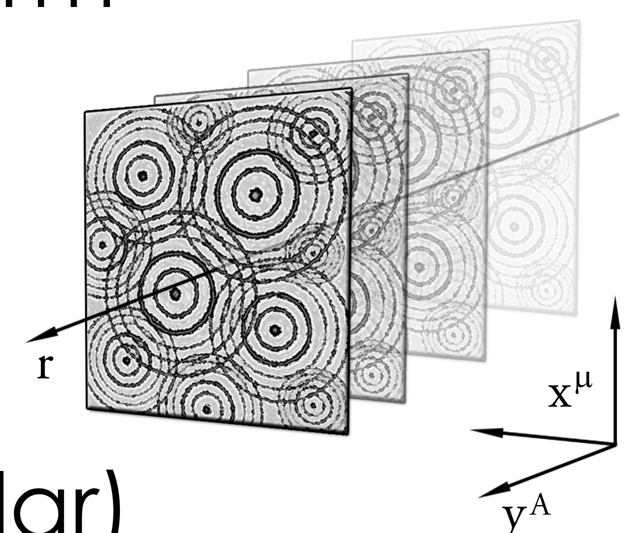
Stringy Scalar-Tensor Theories

- Conformal & Disformal couplings are ubiquitous in scalar-tensor theories arising from string theory ➪ couplings are determined by the theory

- Particularly interesting are scalar-tensor theories arising in D-brane models of cosmology and particle physics:

  Induced metric on the brane takes the form

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

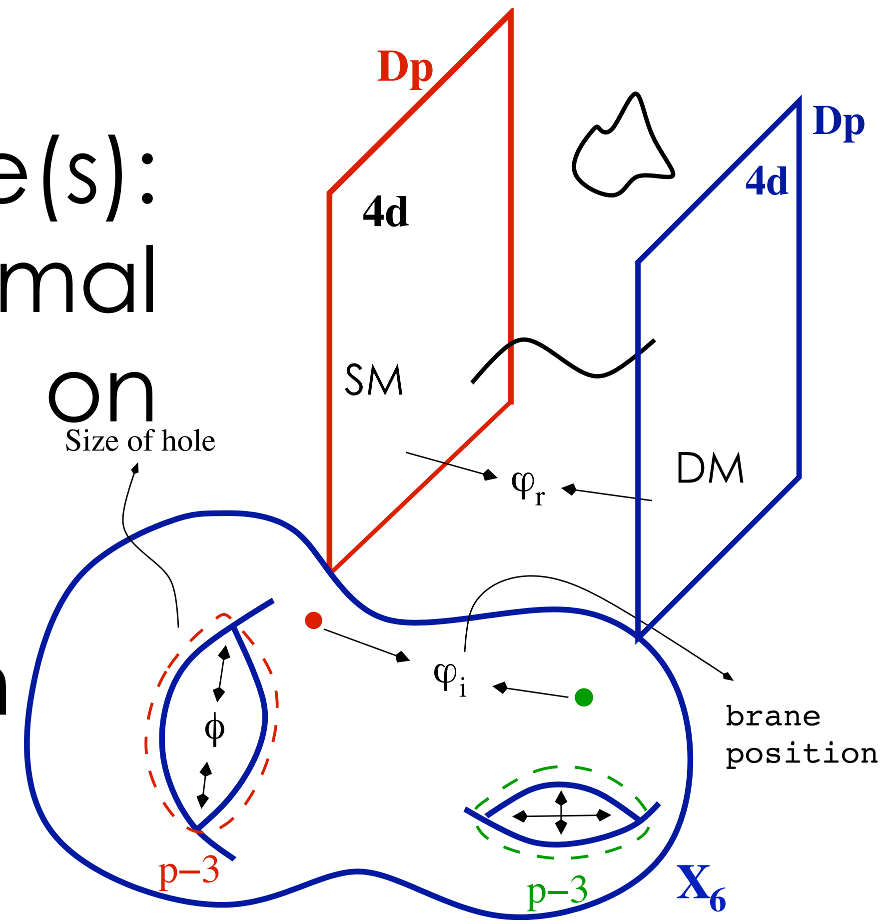


Longitudinal (matter) and transverse (scalar) fluctuations are disformally coupled.

[Dimopoulos, Wills, IZ, '11]
[Koivisto, Wills, IZ '13]

Scalar-tensor from D-branes

- After string inflation & reheating, radiation domination follows.
- Matter lives on a (stack of) D-brane(s): coupled to brane scalar field conformal and disformally via induced metric on brane.



- Coupling described by DBI+CS action

$$S_{DBI} + S_{CS}$$

- In what follows I describe a toy picture of modification of expansion rate and thus thermal relic picture due to D-brane scalar-tensor theory.

[Dutta, Jimenez, IZ, '16-17]

Scalar-tensor from D-branes

- Consider the following action:

$$S = S_{EH} + S_{brane} \,,$$

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

$$S_{brane} = -\int d^4x\sqrt{-g}\left[M^4 C^2(\phi)\sqrt{1+\frac{D(\phi)}{C(\phi)}(\partial\phi)^2} + V(\phi)\right] - \int d^4x\sqrt{-\tilde{g}}\,\mathcal{L}_M(\tilde{g}_{\mu\nu})\,,$$

where matter is coupled to ϕ via

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

$C(\phi)$, $D(\phi)$ dictated by the theory

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compare to the phenomenological case studied in the literature:

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

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

$C(\phi)$, $D(\phi)$ freely chosen in phenomenological models

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$C(\phi)$, $D(\phi)$ dictated by the theory and in a string set-up

$$\kappa^{-2} = M_P^2 = \frac{2\mathcal{V}_6}{2\pi g_s^2\alpha'}, \quad M_s^{-2} = \ell_s^2 = \alpha'(2\pi)^2$$

$$M^4 = M_s^4(2\pi)g_s^{-1}$$

M_s	string scale
g_s	string coupling
$\mathcal{V}_6$	6D volume in string units

Cosmological Equations

In FRW background, evolution equations in Einstein frame (with respect to $g_{\mu\nu}$) become

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

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

$$\ddot{\phi} + 3H\dot{\phi}\gamma^{-2} + \frac{C}{2D}\left(\frac{D_{,\phi}}{D} - \frac{C_{,\phi}}{C} + \gamma^{-2}\left[\frac{5C_{,\phi}}{C} - \frac{D_{,\phi}}{D}\right] - 4\gamma^{-3}\frac{C_{,\phi}}{C}\right) + \frac{1}{M^4 C D \gamma^3}\left(\mathcal{V}_{,\phi} + Q_0\right) = 0 ,$$

where $$Q_0 = \rho\left[\frac{D}{C}\ddot{\phi} + \frac{D}{C}\dot{\phi}\left(3H + \frac{\dot{\rho}}{\rho}\right) + \left(\frac{D_{,\phi}}{2C} - \frac{D}{C}\frac{C_{,\phi}}{C}\right)\dot{\phi}^2 + \frac{C_{,\phi}}{2C}(1 - 3\omega)\right]$$

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

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

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

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

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

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 want to compare this modified rate with the standard GR:

$$H_{GR}^2 = \frac{\kappa_{GR}^2}{3}\,\tilde{\rho}$$

where

$$\tilde{\rho} = C^{-2}\gamma^{-1}\rho$$

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$(\varphi = \kappa\phi)$

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

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

$$\gamma^{-1}H^2 = \frac{\kappa^2}{\kappa_{GR}^2}\frac{C^2}{B}H_{GR}^2$$

(☞ cubic eq for $H(\tilde{\rho},\varphi,\varphi')$)

Deviation from GR can be readily computed from the ratio

$$\xi = \frac{\tilde{H}}{H_{GR}} = \frac{\gamma^{3/2}C^{1/2}(1+\alpha\varphi')}{B^{1/2}}$$

which needs to go to 1 towards the onset of BBN, $\xi \to 1$

Coupled Equations

To find the modified expansion rate, we solve numerically the coupled equations for H and φ ($M^4CD=1$):

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

$$\varphi''\left[1+\frac{3H^2\gamma^{-1}B}{M^4C^2\kappa^2}\right] + 3\,\varphi'\gamma^{-2}\left[1-\frac{3H^2\gamma^{-1}B}{M^4C^2\kappa^2}\tilde{\omega}\right] + \frac{H'}{H}\varphi'\left[1+\frac{3H^2\gamma^{-1}B}{M^4C^2\kappa^2}\right]$$
$$-\frac{6H^2\gamma^{-1}B}{M^4C^2\kappa^2}\,\alpha(\varphi)\varphi'^2 + 3B\gamma^{-3}\alpha(\varphi)(1-3\,\tilde{\omega}) - \frac{2M^4C^2\kappa^2}{H^2}\left[2\gamma^{-3}-3\gamma^{-2}+1\right]\alpha(\varphi) = 0\,.$$

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

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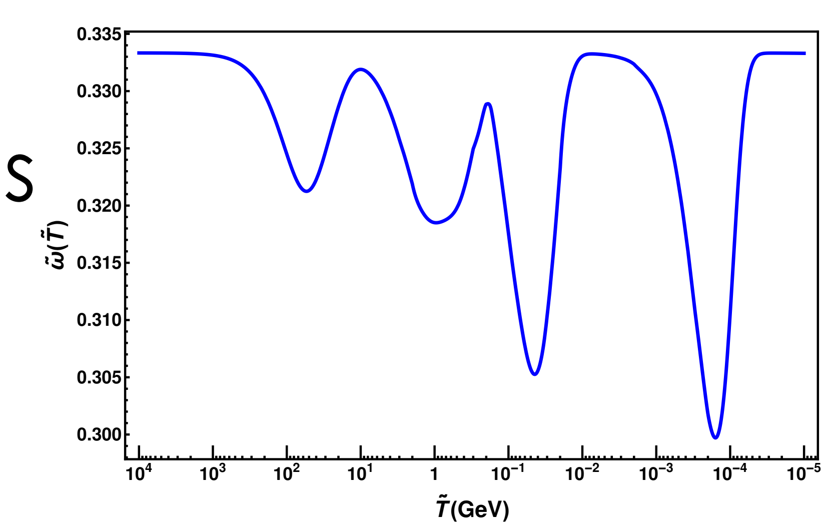
$$\varphi''\left[1 \qquad\qquad\qquad\right] + 3\,\varphi'\gamma^{-2}\left[1 \qquad\qquad\qquad\right] + \frac{H'}{H}\varphi'\left[1 \qquad\qquad\qquad\right]$$

$$+\,3B\gamma^{-3}\alpha(\varphi)(1-3\,\tilde{\omega}) \qquad\qquad = 0\,.$$

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



Pure Disformal (Unwarped) Case

The pure disformal effect is obtained for $C = const.$ ($M^4 C D = 1$)

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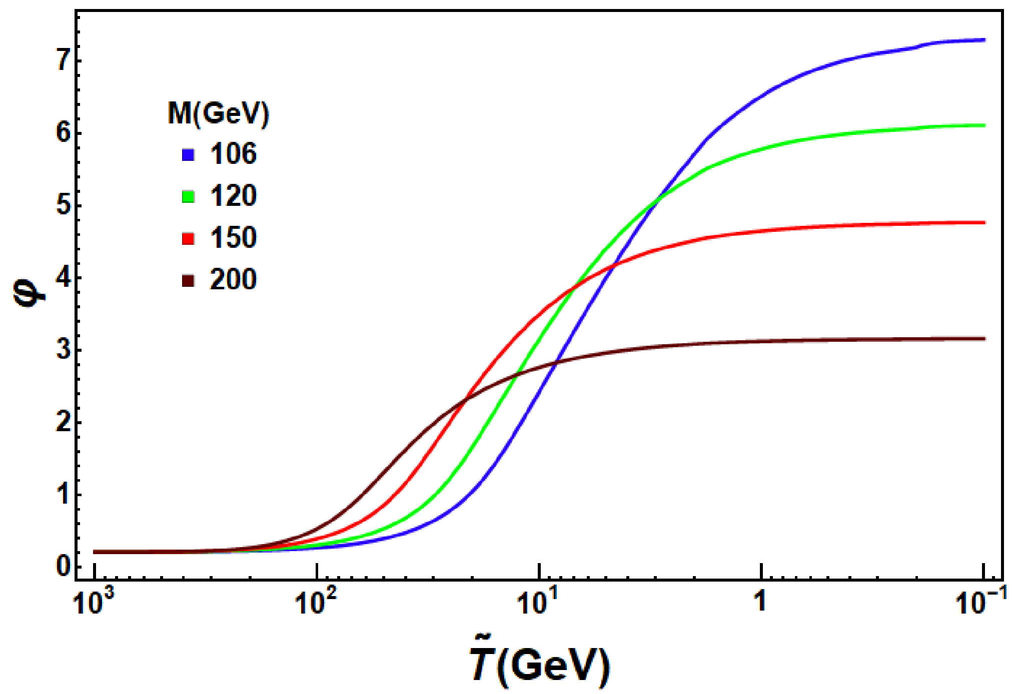
In this case $\xi = \dfrac{\gamma^{3/2}}{B^{1/2}}$ → $\tilde{H} \geq H_{GR}$ $(\gamma \geq 1\,,\ B \geq 1)$

A non-trivial *disformal enhancement* of expansion rate occurs

Disformal Enhancement

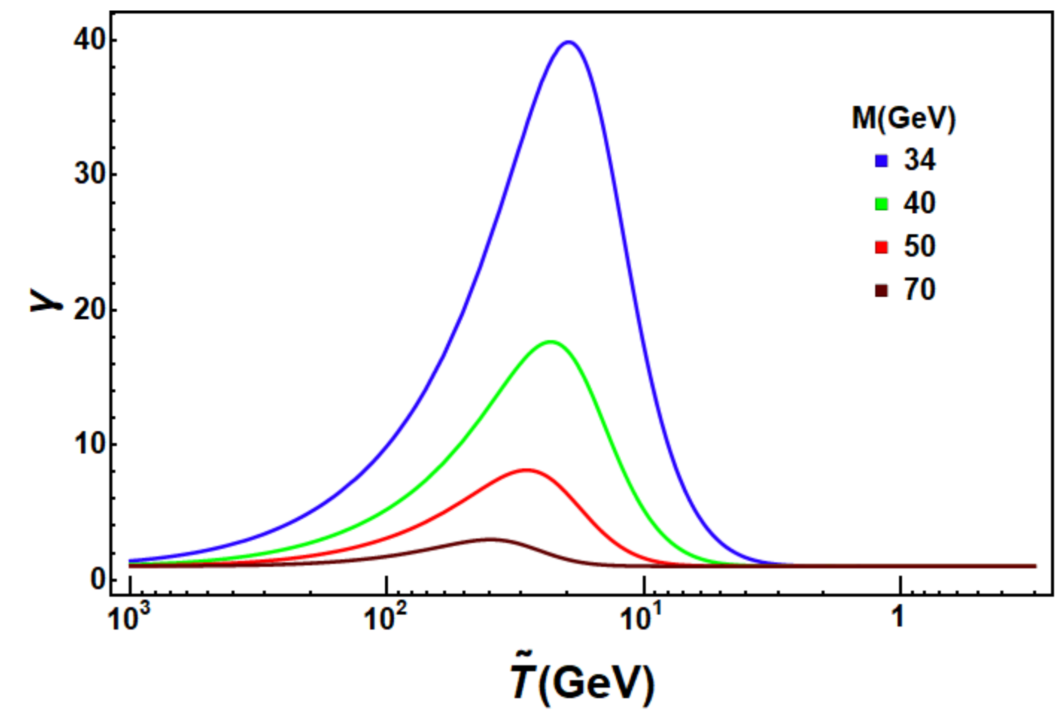
[Dutta, Jimenez, IZ, '16-17]

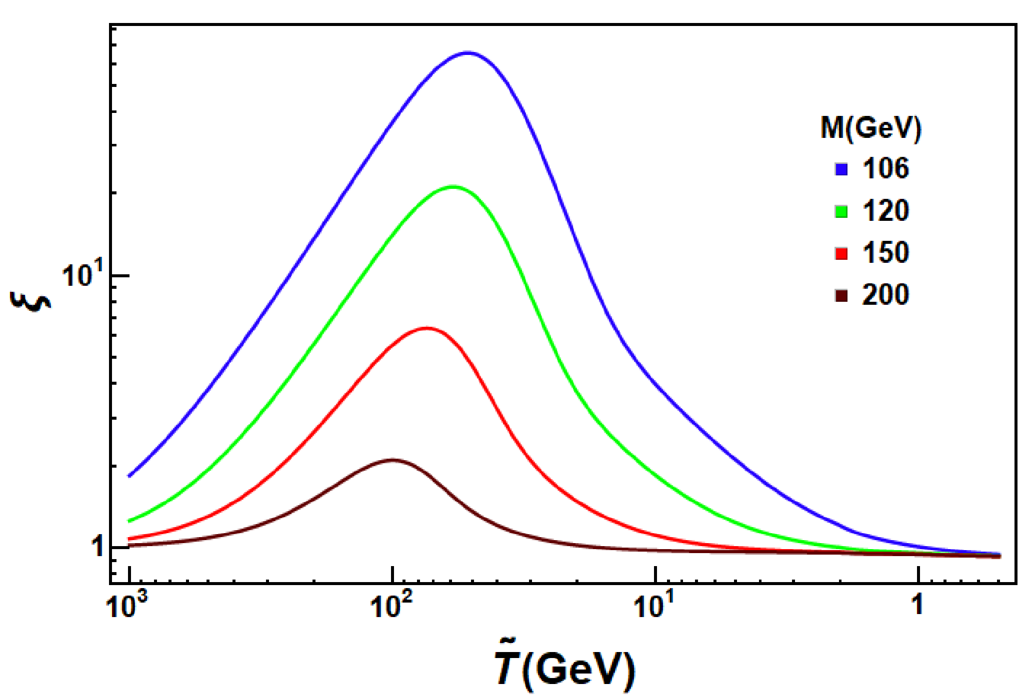
Full numerical solutions:

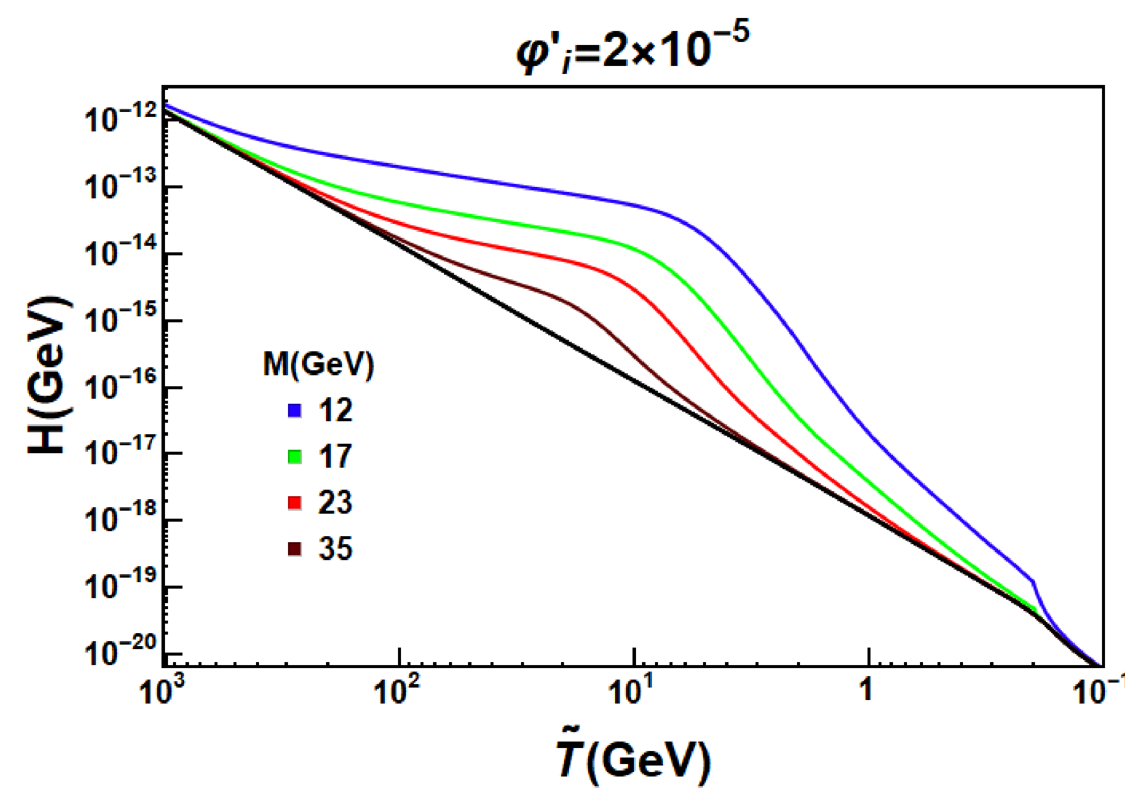


$\varphi_i = 0.2$

$\varphi'_i = 0.002$







Disformal Enhancement

[Dutta, Jimenez, IZ, '16-17]

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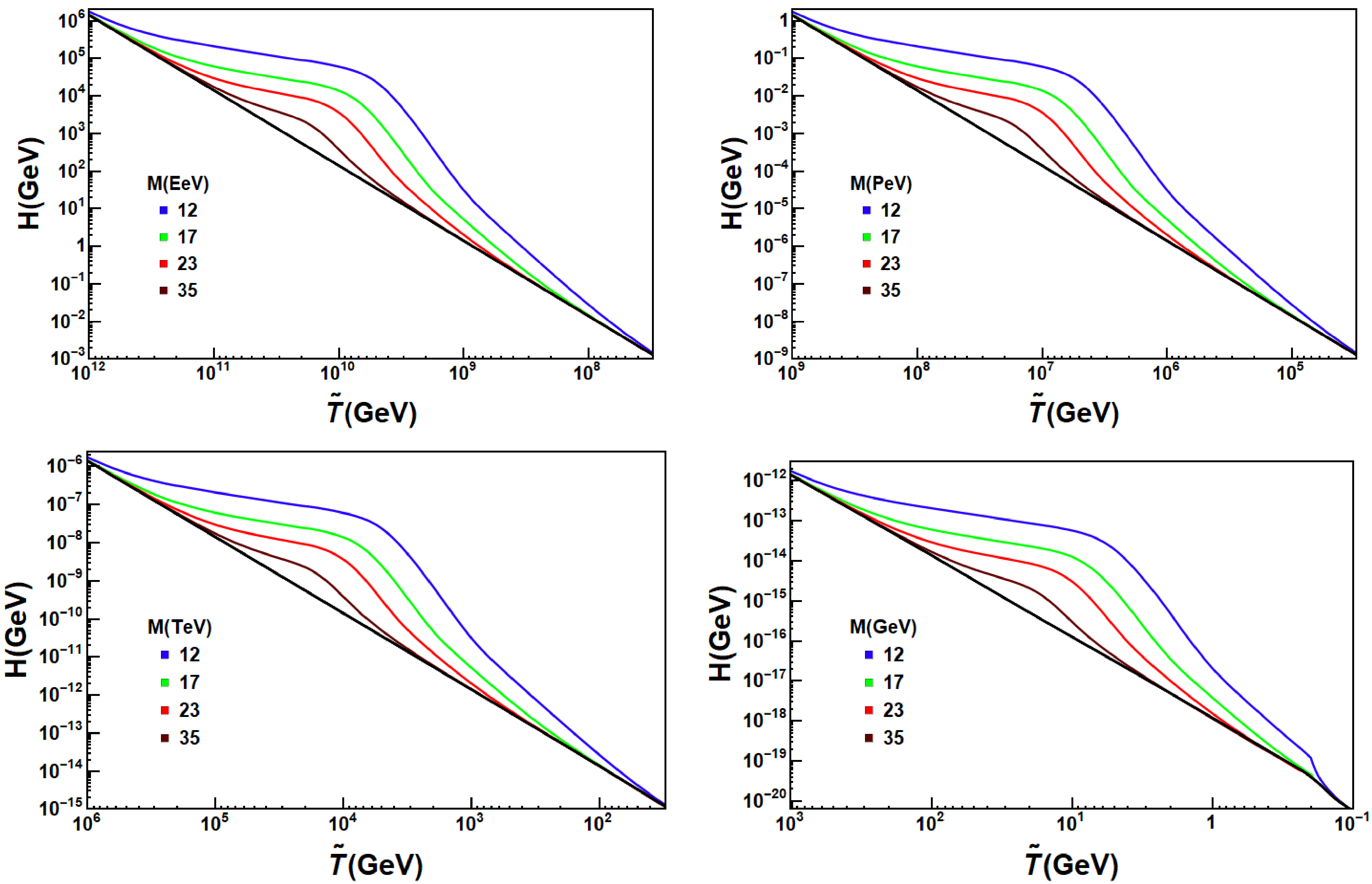


$\varphi_i = 0.2$

$\varphi_i' = 2 \times 10^{-5}$

— H

colour $\tilde{H}$

[Dutta, Jimenez, IZ, '16-17]

Conformal & Disformal Effects

For $C \neq const.$ (warped geometry), there is an interplay of conformal and disformal effects.

$$\varphi'' \left[1 + \frac{3H^2\gamma^{-1}B}{M^4C^2\kappa^2}\right] + 3\,\varphi'\gamma^{-2}\left[1 - \frac{3H^2\gamma^{-1}B}{M^4C^2\kappa^2}\tilde{\omega}\right] + \frac{H'}{H}\varphi'\left[1 + \frac{3H^2\gamma^{-1}B}{M^4C^2\kappa^2}\right]$$

$$-\frac{6H^2\gamma^{-1}B}{M^4C^2\kappa^2}\alpha(\varphi)\varphi'^2 + 3B\gamma^{-3}\underbrace{\alpha(\varphi)(1-3\,\tilde{\omega})}_{} - \frac{2M^4C^2\kappa^2}{H^2}\left[2\gamma^{-3} - 3\gamma^{-2} + 1\right]\alpha(\varphi) = 0\,.$$

$$V_{eff} \sim 3(1 - 3\,\tilde{\omega})\ln C$$

Conformal piece acts as *effective potential* for φ

In this case

$$\xi = \frac{\kappa}{\kappa_{GR}}\frac{C^{1/2}\gamma^{3/2}}{B^{1/2}}\underbrace{\left[1 + \alpha(\varphi)\varphi'\right]}_{}$$

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

The term in parenthesis can become *less than one* ➠ $\xi < 1$

➠ $\tilde{H} < H_{GR}$ ➠ *re-annihilation effect*

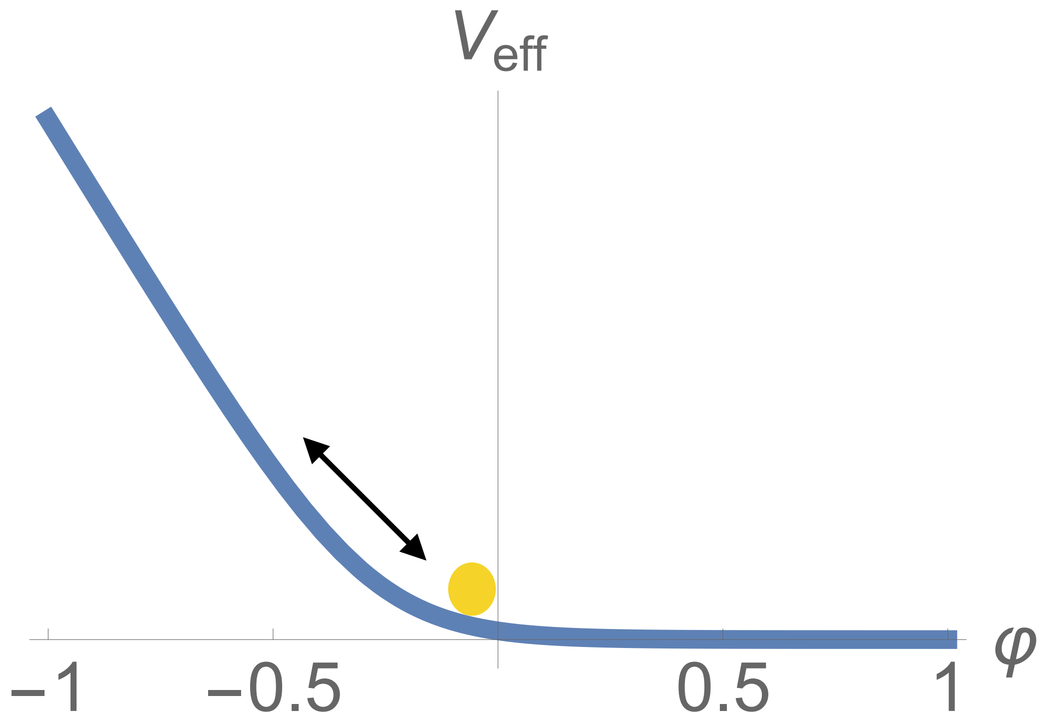
[Catena et al. '04]
[Meehan, Whittingham '15]
[Dutta, Jimenez, IZ, '16-17]

Conformal & Disformal Effects

For concreteness we consider $C(\varphi) = (1 + b\, e^{-\beta\,\varphi})^2 \quad (b = 0.1,\ \beta = 8)$

[Catena et al. '04]

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



This choice of initial conditions gives the most interesting evolution

[Dutta, Jimenez, IZ, '16-17]

Conformal & Disformal Effects

[Dutta, Jimenez, IZ, '16-17]

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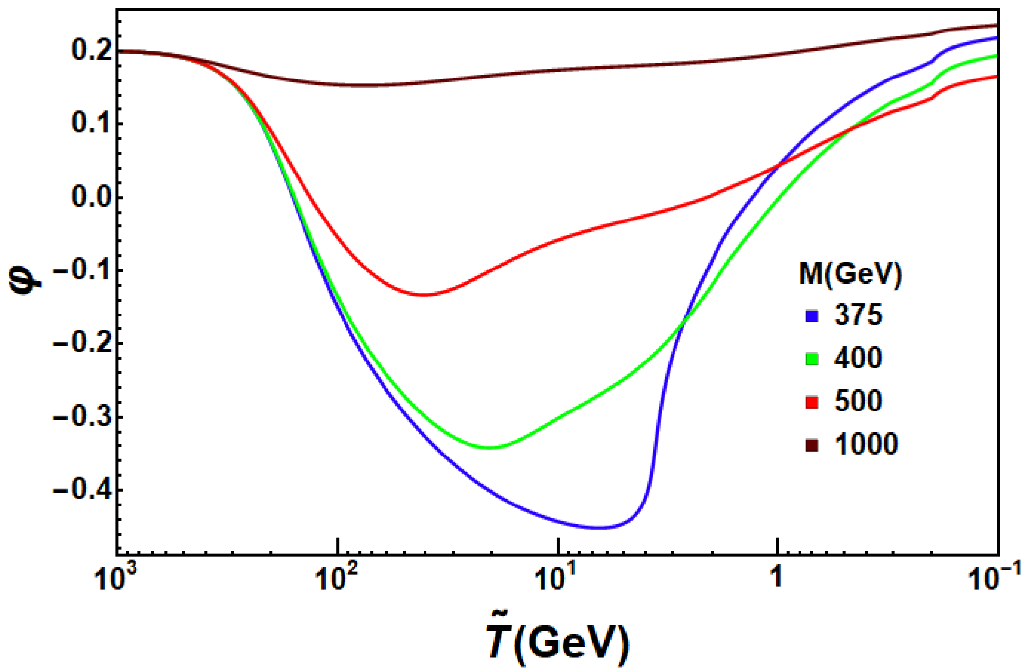
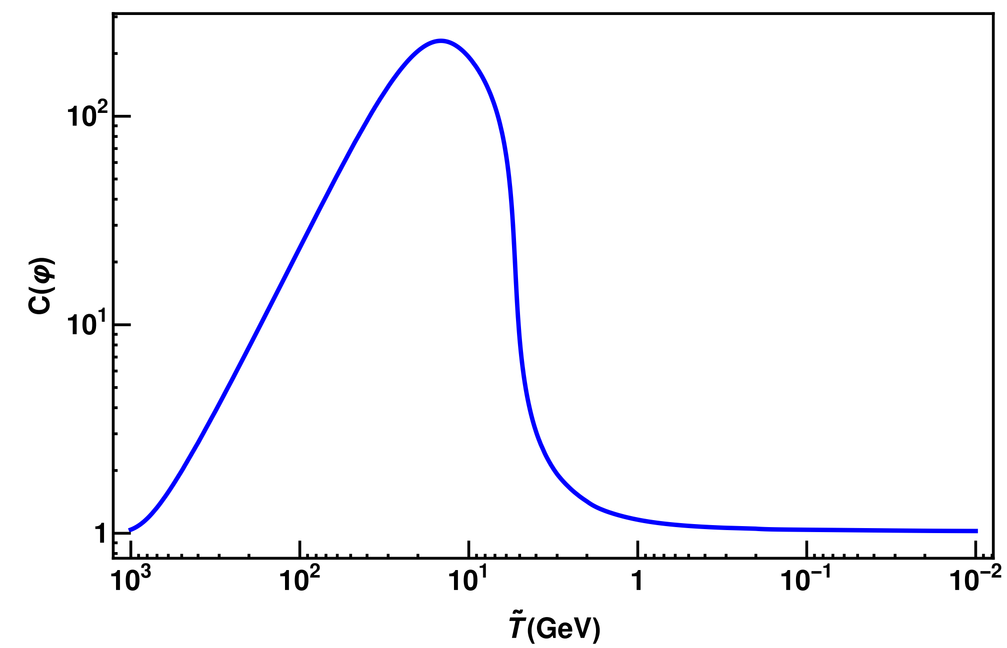
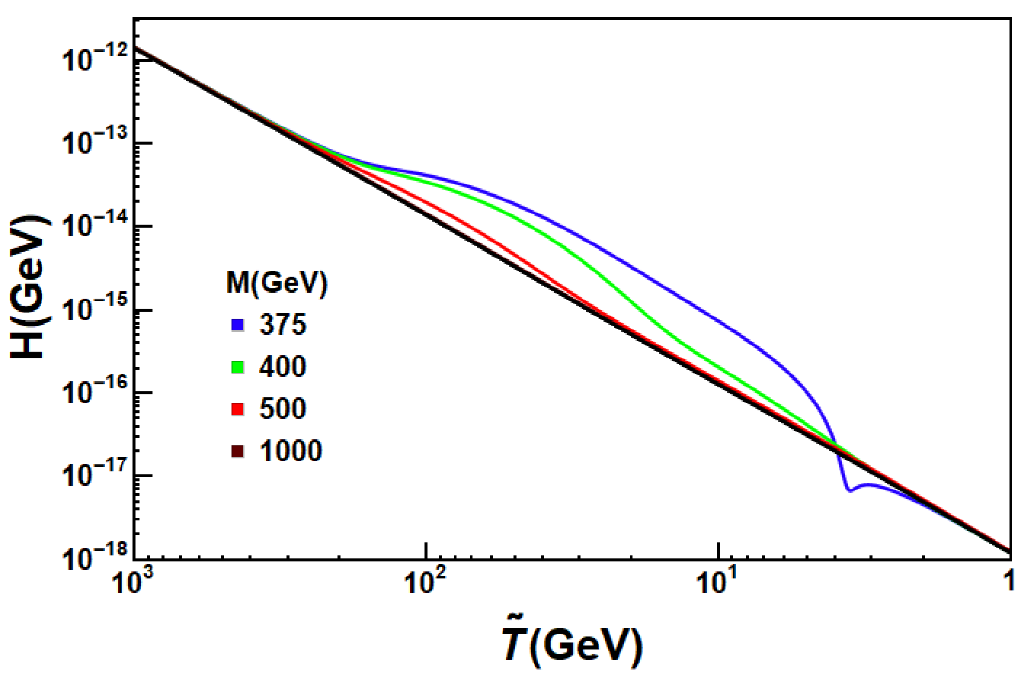
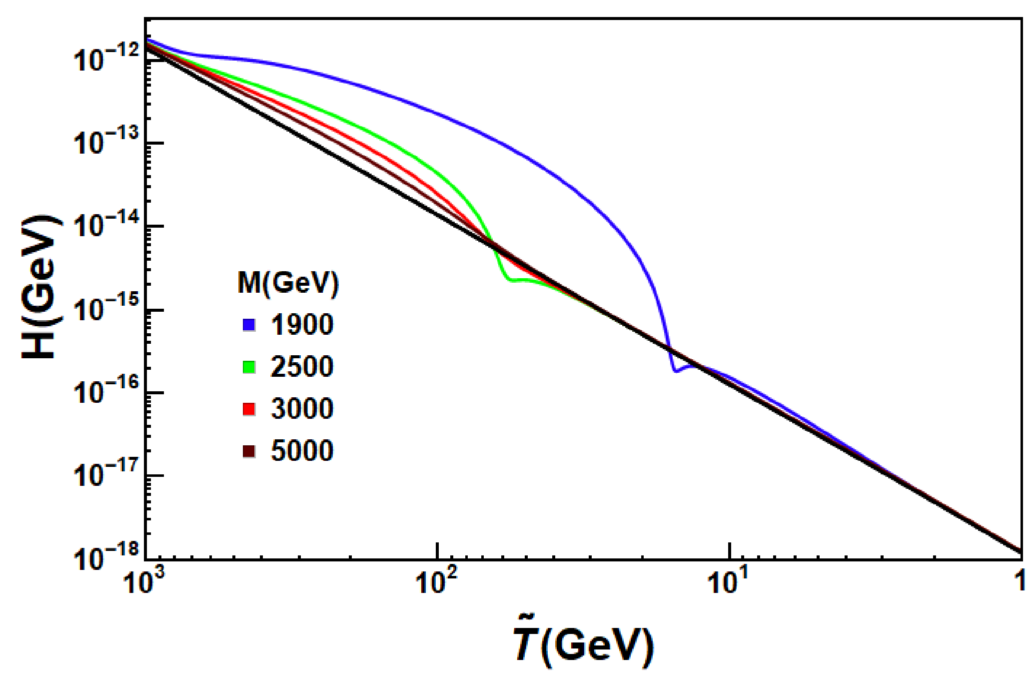


$(\varphi_i, \varphi_i') = (0.2, -0.004)$





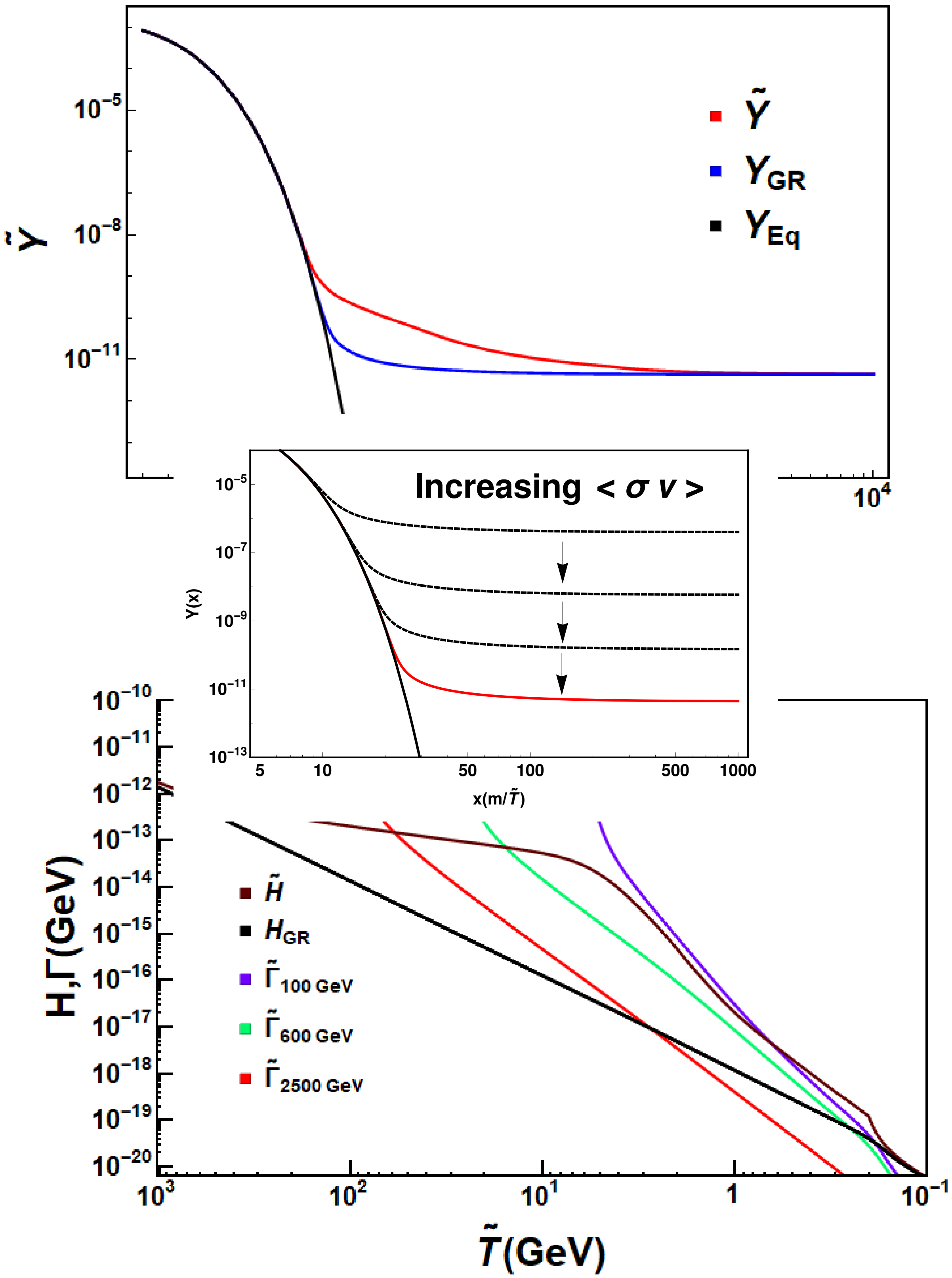
$(\varphi_i, \varphi_i') = (0.2, -0.004)$



$(\varphi_i, \varphi_i') = (0.2, -0.4)$

Disformal Effect on DM Relic Abundance

[Dutta, Jimenez, IZ, '16-17]



Relic abundance evolution is computed from Boltzmann equation

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

$$(Y = n/s,\ x = m/T)$$

Here relic for a DM particle with mass $m_\chi = 100\text{GeV}$

Expansion rate corresponding to M = 12 GeV as function of temperature.

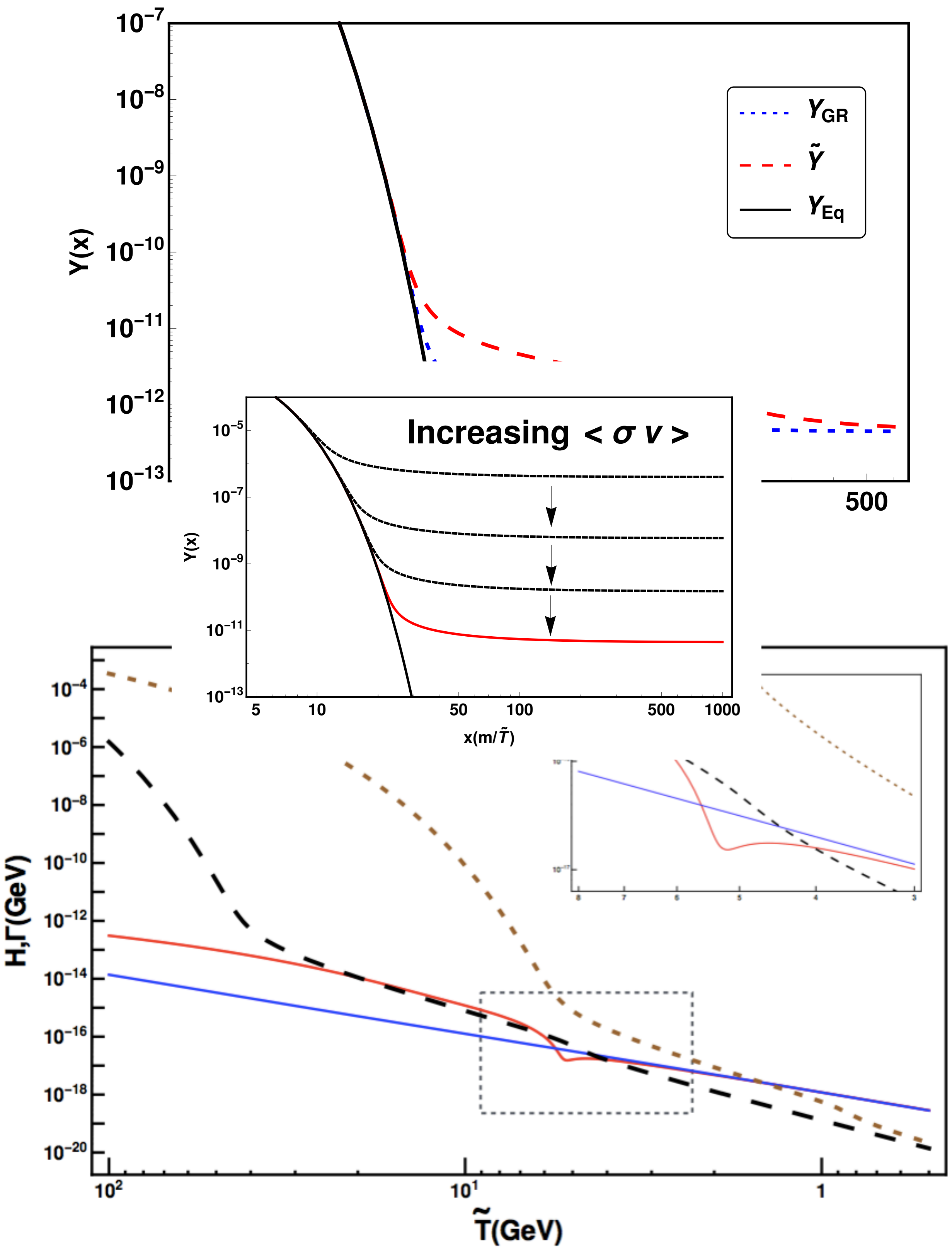
$$\frac{\tilde{x}}{\tilde{Y}}\frac{d\tilde{Y}}{d\tilde{x}} = -\frac{\tilde{\Gamma}}{\tilde{H}}\left(1-\left(\frac{\tilde{Y}_{eq}}{\tilde{Y}}\right)^2\right)$$

$$\left(\tilde{\Gamma} \equiv \tilde{Y}\tilde{s}\langle\sigma v\rangle\right)$$

[Similar behaviour in pheno model (relentless dark matter) recently by D'Eramo, Fernandez, Profumo, '17]

Conformal Re-annihilation Effect

[Dutta, Jimenez, IZ, '16-17]



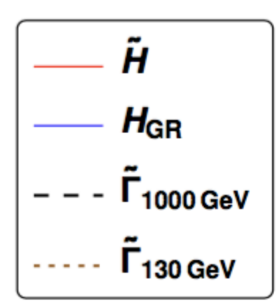
Relic abundance evolution is computed from Boltzmann equation

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

Here relic for a DM particle with mass $m_\chi = 1000\text{GeV}$ for conformal case

Expansion and interaction rates' evolution

A re-annihilation phase occurs for suitable initial conditions



Effect on DM Cross-Section

[Dutta, Jimenez, IZ, '16-17]

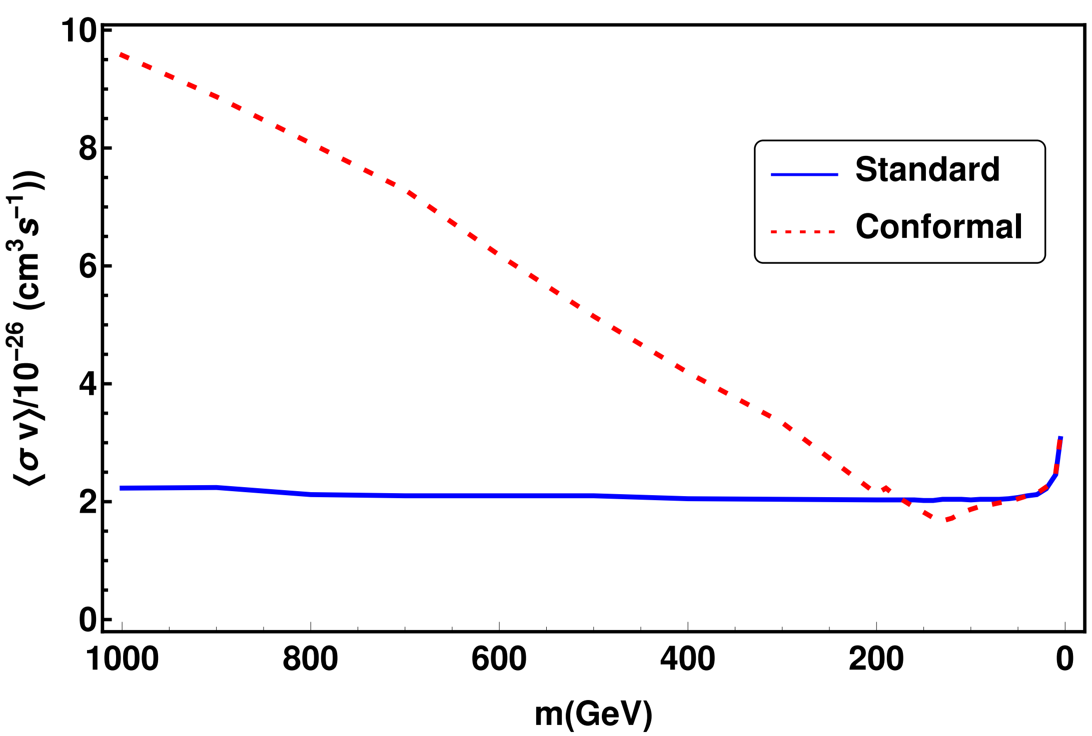
The present dark matter content of the universe is determined by current value of the relic abundance

$$\Omega_{DM} = \frac{m_\chi Y_0 s_0}{\rho_{cr,0}} \qquad (= 0.27)$$

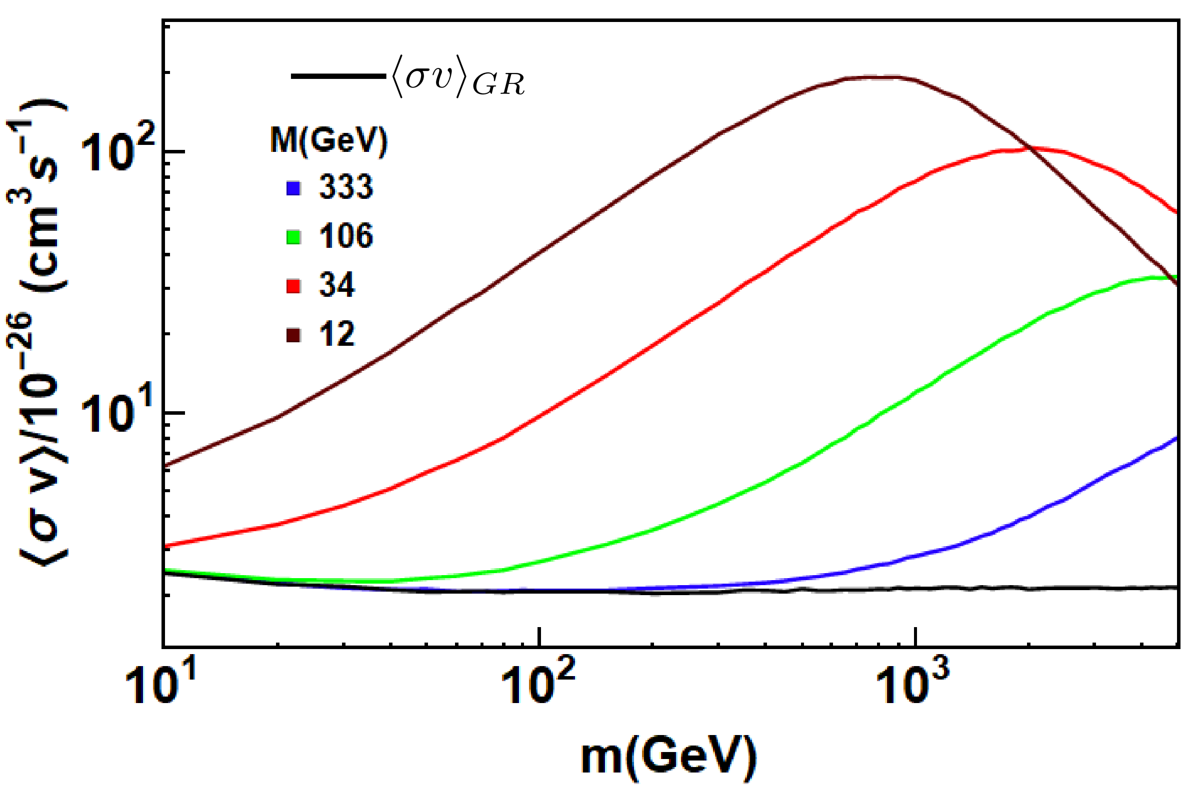
We used this to determine the thermally-averaged annihilation cross section $\langle \sigma v \rangle$ required to match it, and use it to solve the Boltzmann equation

$$\frac{\tilde{x}}{\tilde{Y}} \frac{d\tilde{Y}}{d\tilde{x}} = -\frac{\tilde{\Gamma}}{\tilde{H}} \left(1 - \left(\frac{\tilde{Y}_{eq}}{\tilde{Y}} \right)^2 \right) \qquad \left(\tilde{\Gamma} \equiv \tilde{Y} \tilde{s} \langle \sigma v \rangle \right)$$

The resulting annihilation cross sections are $(\langle \sigma v \rangle_{GR} \sim 2.1 \times 10^{-26} cm^3/s)$



Disformal



Summary

- We studied for the first time modifications to standard thermal relic picture due to non-standard early cosmology evolution in scalar-tensor theories with (D-brane) *conformal and disformal* couplings to matter

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

- The effect of the coupling is to enhance or decrease the expansion rate, with respect to the standard case, thus modifying the standard thermal picture

$$\xi \gtrless 1 \qquad \left(\xi = \frac{\tilde{H}}{H_{GR}} \right)$$

- Dark matter freeze-out occurs at higher temperatures compared to the standard case ➠ reproducing the observed abundance requires significantly larger annihilation rates

Summary

- When conformal term is turned-on, a re-annihilation effect occurs and slightly smaller annihilation rate is needed.

- In the purely disformal case (C=const.), enhancement occurs at different scales, depending on parameter M, affecting different pre-BBN physics

- In a D-brane like set up, the scale M is identified with the string parameters:

$$M^4 = M_s^4 (2\pi) g_s^{-1}$$

thus string scale dictates disformal enhancement scale. For DM production M is very low, implying a very WEAKLY couples, LARGE volume compactification

Outlook

- We considered the simplest case for matter coupling. In a more realistic set-up, we expect a non-universal coupling of matter to the scalar

[Meehan, Whittingham '15]

- Non-standard expansion rate may be relevant for other physical phenomena during the early universe evolution

[Dutta et al. in progress]

- Analysis of different conformal&disformal functions

- Beyond a toy model for a post-string inflationary picture