Dark Energy in String Theory

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Dark Universe Workshop
ICTP-SAIFR, São Paulo, Brazil
October 2019

Dark Energy and Dark Mater in String Theory

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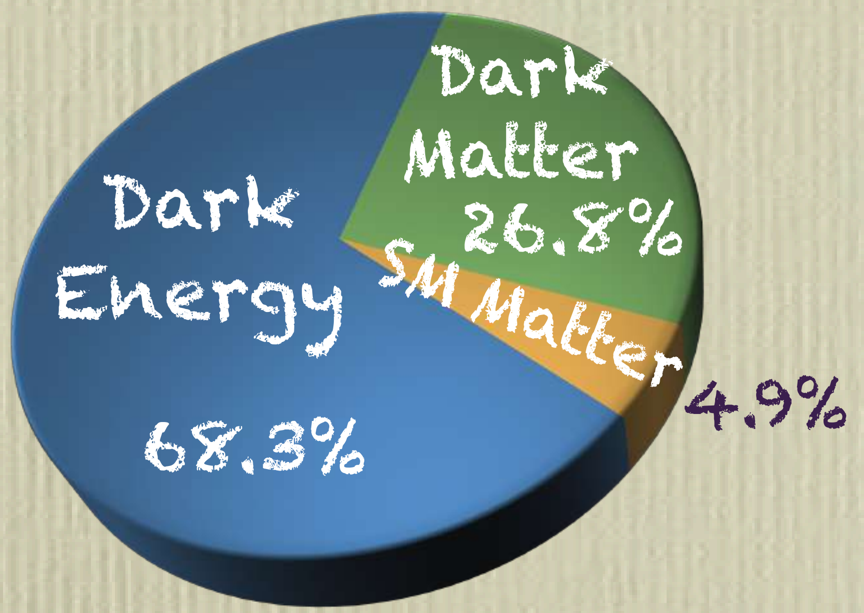
CONCORDANCE ΛCDM MODEL

A phenomenological Standard Model of Cosmology has emerged, in perfect agreement with current observations:

The ΛCDM model (Lambda cold dark matter)



cosmic pie

In this model, the universe contains three major components: *dark energy, Λ, cold dark matter* and ordinary matter.

Complemented with the *inflationary scenario to generate primordial fluctuations that seed large scale structures* we observe today

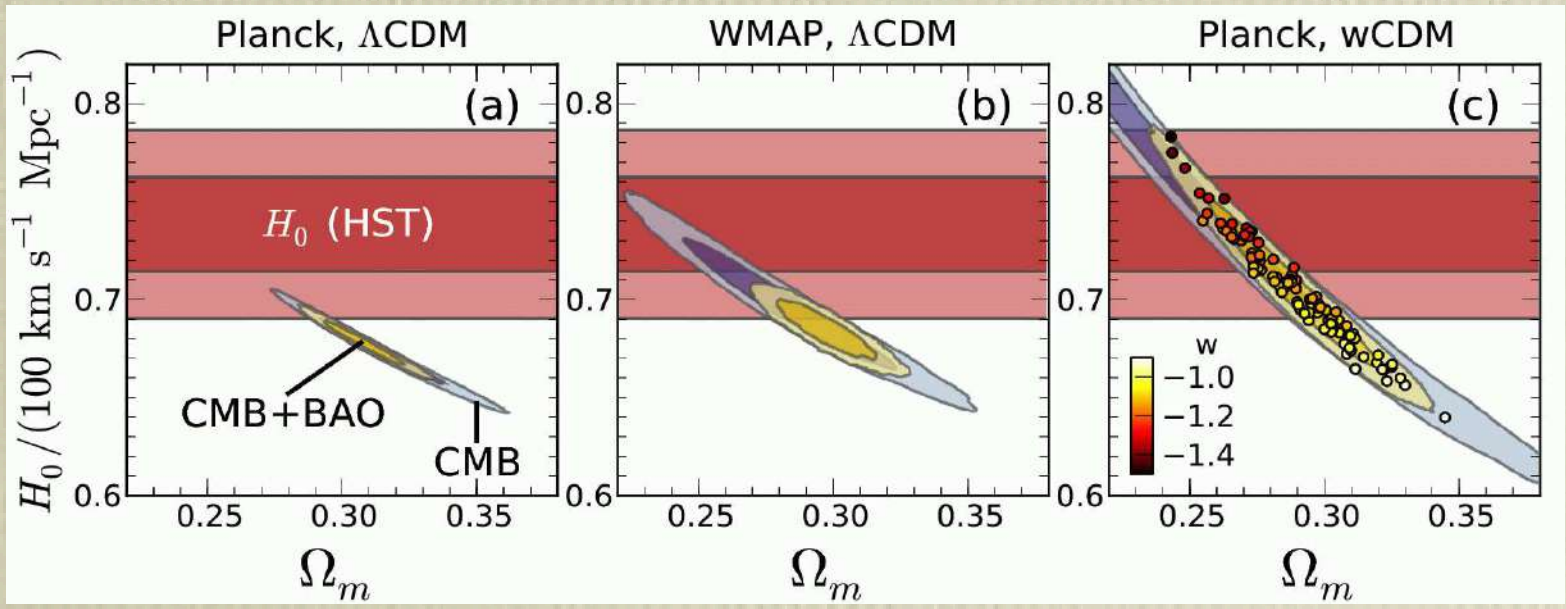
CONCORDANCE ΛCDM MODEL

- Observations consistent with tiny cosmological constant. E.g.

$$\rho_{DE} \sim 7 \times 10^{-121} M_{Pl}^4$$ [Planck]

$$\omega = -1.026 \pm 0.041$$

- Upcoming Dark Energy Surveys will probe ω_{DE}



[Mortonson et al '14]

OBSERVATIONAL HINTS BEYOND ΛCDM?

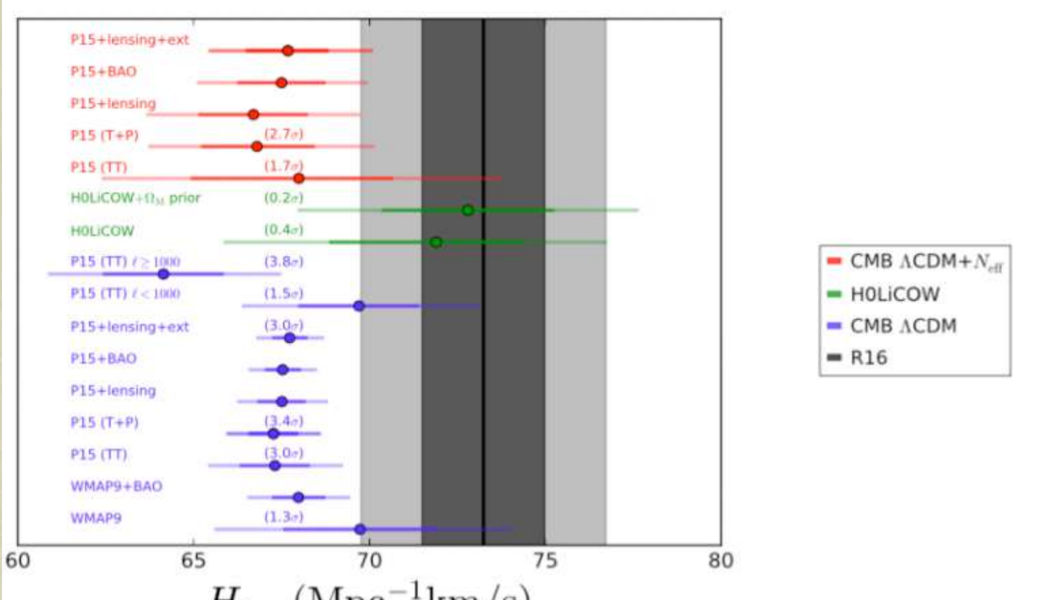
- Hints at physics beyond ΛCDM in H_0 measurements:
  - direct measurement:

$$H_0 = 74.22 \pm 1.84\,\mathrm{km/s/Mpc}$$

  - value inferred from CMB:

$$H_0 = 67.4 \pm 0.5\,\mathrm{km/s/Mpc}$$

giving 4.4σ discrepancy...



[Riess et al. '16]

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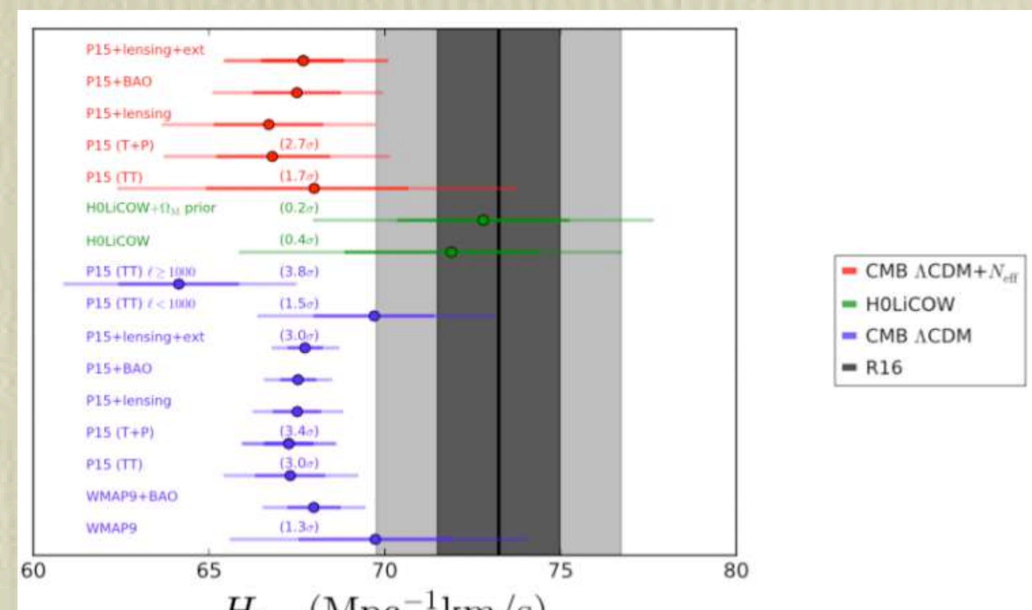

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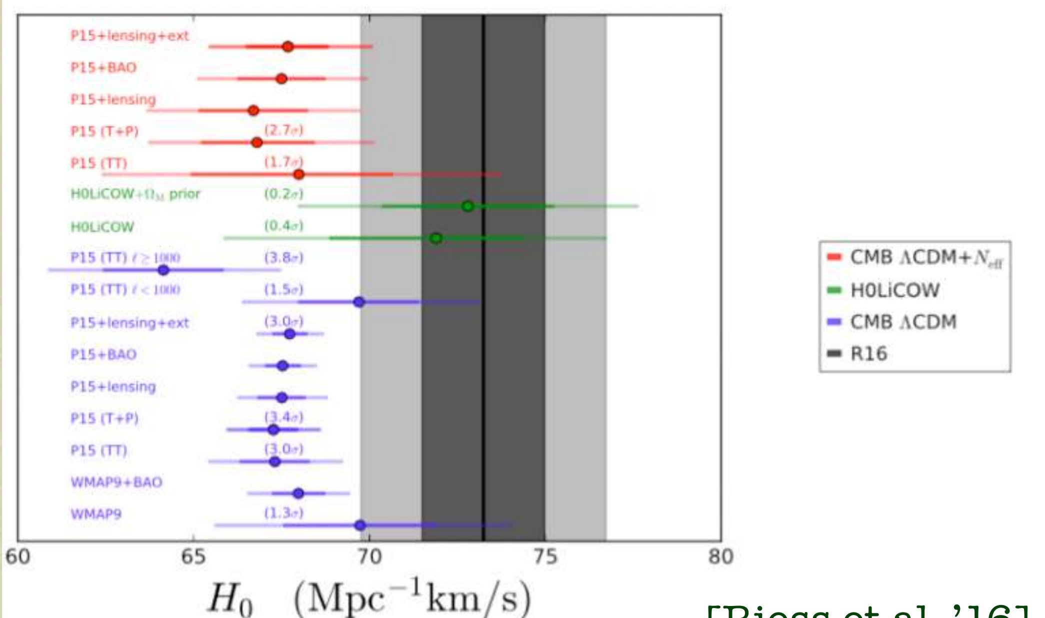

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Physics beyond ΛCDM?

exotic (e.g. phantom) dark energy, dark radiation, dark matter decay, coupled dark matter/dark energy …

DE SITTER AND QUANTUM GRAVITY

- Recent theoretical constraints on low energy effective theories of gravity would suggest that a pure cosmological constant, Λ, cannot be realised in a consistent quantum theory with ultra–violet completion, such as string theory

[Vafa et al. 06-19]

VS

swampland
(no UV completion in QG)

landscape
(have UV completion in QG)

DE SITTER SWAMPLAND CONJECTURE

[Danielsson, Van Riet '18;
Obied, Ooguri, Spodyneiko, Vafa '18;
Garg, Krishnan '18;
Ooguri, Palti, Shiu, Vafa '18]

- The scalar potential in the LEEFT of any consistent quantum gravity must satisfy *either*:

$$\frac{\sqrt{\nabla^i \nabla_i V}}{V} \gtrsim \frac{c}{M_{Pl}} \qquad \text{or} \qquad \frac{\min(\nabla^i \nabla_j V)}{V} \lesssim -\frac{c'}{M_{Pl}^2}$$

for some universal constants c, c' > 0 of order 1.

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- Connections to other conjectures: weak gravity conjecture; distance conjecture, etc.

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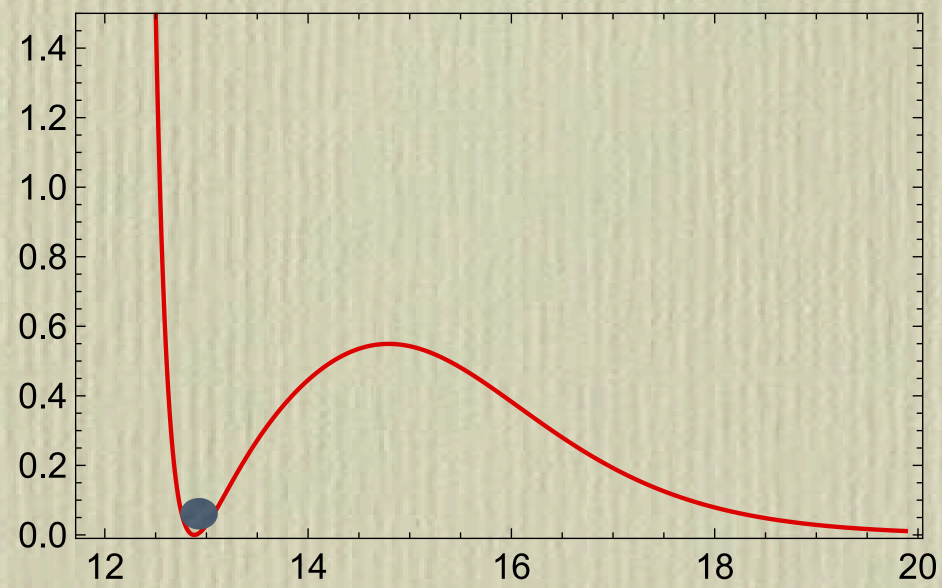
for some universal constants c, c' > 0 of order 1.

- **Rules out metastable dS, allows sufficiently unstable dS**

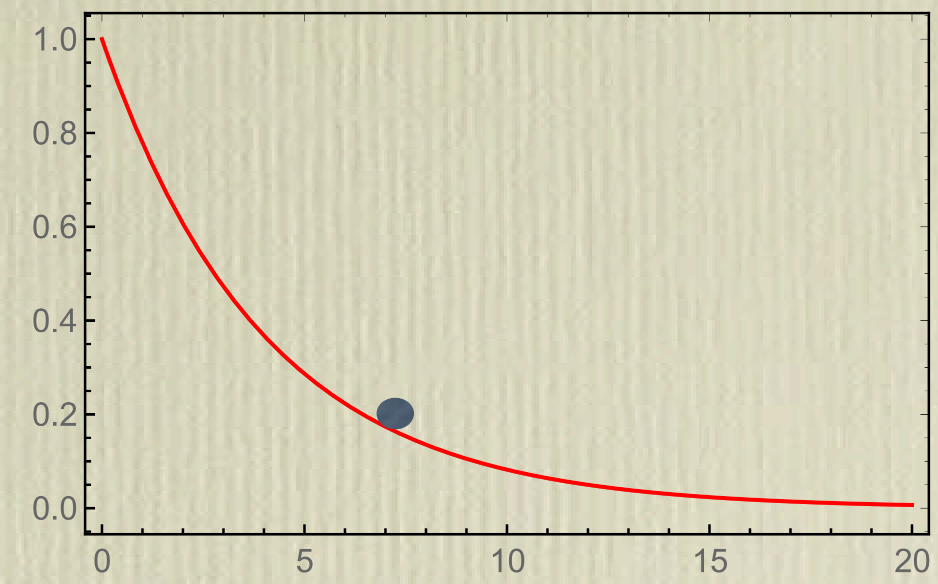
- Connections to other conjectures: weak gravity conjecture; distance conjecture, etc.

IMPLICATIONS FOR DARK ENERGY

- Dark energy may be *quintessence field*:



Cosmological Constant Λ



Dynamical Dark Energy

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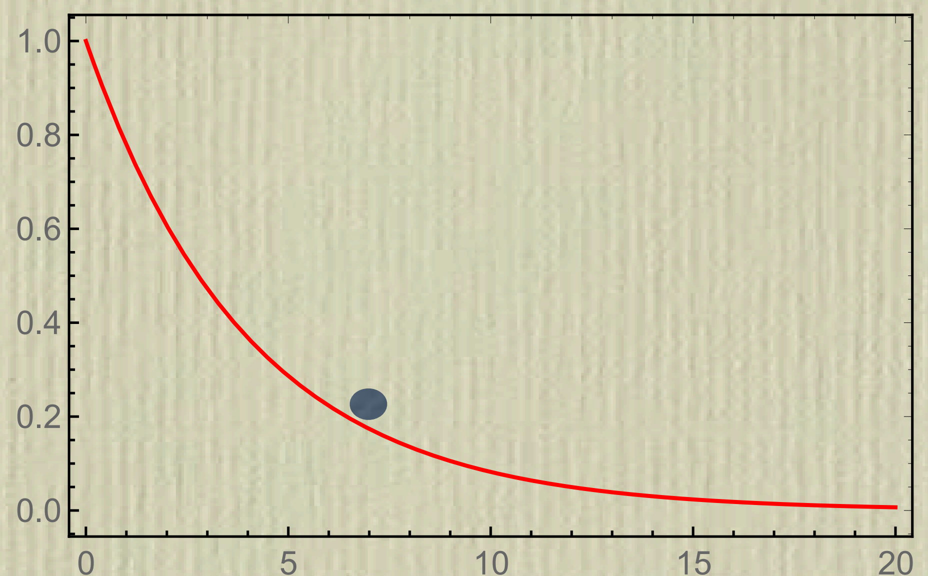

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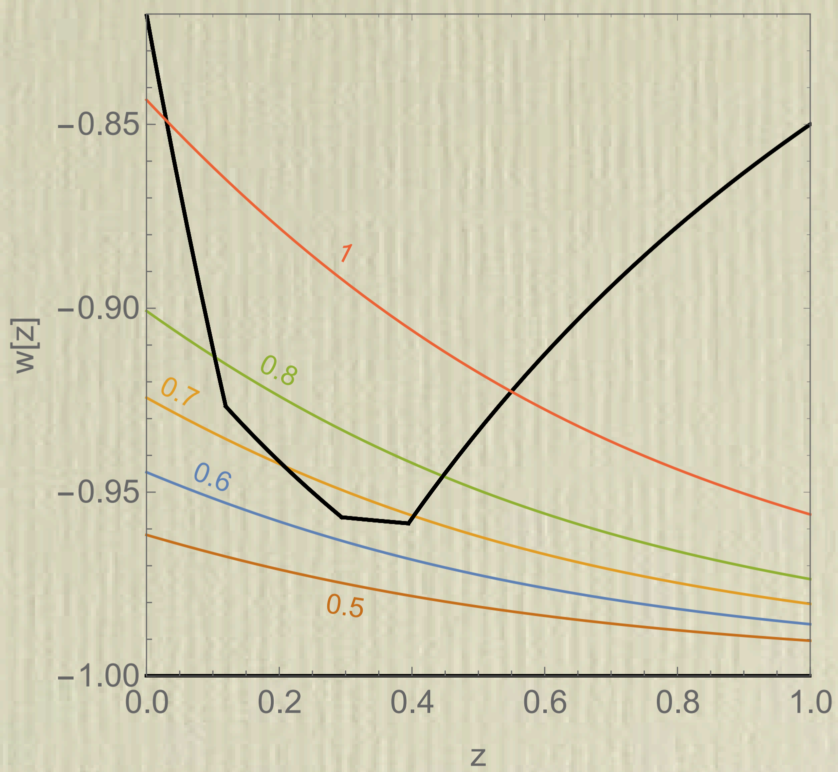

[Agrawal, Obied, Steinhardt, Vafa, '18]

Assuming convex potential, current observations on $\omega(z)$ constrain $c \lesssim 0.6$ in $\frac{\sqrt{\nabla^i \nabla_i V}}{V} \gtrsim \frac{c}{M_{Pl}}$

Relaxing semi-positive definite Hessian, can have $c, c' \sim 1$ and $\omega \sim -1$ by fine-tuning initial conditions.

CONTENTS

- Quintessence in string theory
- Runaway Quintessence from a String Modulus
- Coupled dark energy — dark matter models:
  - early and late time cosmology
- Summary

STRING MODELS OF QUINTESSENCE

- Need a slowly-rolling ultra-light string modulus with:

$$\langle V \rangle \simeq 10^{-120} M_{Pl}^4 \qquad \text{and} \qquad m \lesssim 10^{-32} \mathrm{eV}$$

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Many of the same ingredients and challenges as in dS constructions

- String dilaton or volume modulus lead to fifth forces and varying fundamental constants.
- Local modulus may be sequestered with weaker than Planck SM couplings [Cicoli, Pedro, Tasinato, '12]
- String axion evades 5th forces and can easily be light

$m \sim e^{-\tau} M_{Pl}$ but need $f \gtrsim 3 M_{Pl}$ ... alignment? [Svrcek '06]

[Cicoli et al, '18; Chiang-Murayama, '18; Marsh, '18, Han et al. '18; D'amico et al.'18; Olguín-Trejo et al.'18; Emelin-Tatar, '18; Hertzberg et al. '18; van de Bruck-Thomas, '19; Dimopoulos-Donaldson-Wood, '19, Hardy-Parameswaran, '19...]

QUINTESSENCE FROM A RUNAWAY STRING MODULUS

[Olguín-Trejo, Parameswaran, Tasinato, IZ, '19]

- Consider an early Universe scenario (e.g. inflation) that ends in supersymmetric Minkowski minimum, with most moduli stabilised and heavy in $\mathcal{N} = 1$ supergravity framework:

$$\langle D_i W_{susy} \rangle = 0 \,, \qquad \langle W_{susy} \rangle = 0 \,, \qquad \langle \Phi^i \rangle \quad \text{heavy}$$

where W is the holomorphic superpotential

- Assume a single flat direction (for simplicity): $\Phi = \phi + i\theta$ with ϕ a string coupling constant - saxion - and θ its axion and Kähler potential

$$K = -n \log \left(\Phi + \bar{\Phi} \right)$$

e.g. $n = 3$ for overall volume modulus, $n = 1$ for other volume moduli, complex structure, dilaton, blow-up modulus.

QUINTESSENCE FROM A RUNAWAY STRING MODULUS

[Olguín-Trejo, Parameswaran, Tasinato, IZ, '19]

- Superpotential, W is protected from perturbative corrections to all finite orders by non-renormalisation theorem ☞
  - Axionic shift symmetry ⇒ W cannot depend on θ.
  - Holomorphy ⇒ W cannot depend on ϕ.

  But receives non-perturbative corrections, $W_{np} \propto e^{-\alpha\Phi}$

- On the other hand, the Kähler potential, K, does receive perturbative corrections, but so long as W = 0, these will not lift flat direction.

RUNAWAY STRING MODULUS

- Consider $K = -n \log(\Phi + \bar{\Phi})$ and $W_{np} = A\, e^{-\alpha\Phi}$ at leading order, generated e.g. by worldsheet instantons, gaugino condensation in bulk or brane, Euclidean D-branes, ...
- The parameters $\alpha,\, A$ are model dependent constants.

  E.g. A may be itself exponentially suppressed in heavy moduli vevs, e.g. gaugino condensation with 1-loop threshold corrections:

$$W_{np} = \mu^2 e^{-\alpha f}\,, \quad \text{with} \quad f = \Phi + \sum_j c_j \log(d_j \Phi)$$

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- The parameters $\alpha,\, A$ are model dependent constants.
- The scalar potential $V = e^K \left(|DW|^2 - 3|W|^2\right)$ for the saxion is

$$V = \frac{A^2}{2^n n}\, e^{-2\alpha\phi}\phi^{-n}\left(n^2 + 4\alpha^2\phi^2 + n(4\alpha\phi - 3)\right)$$

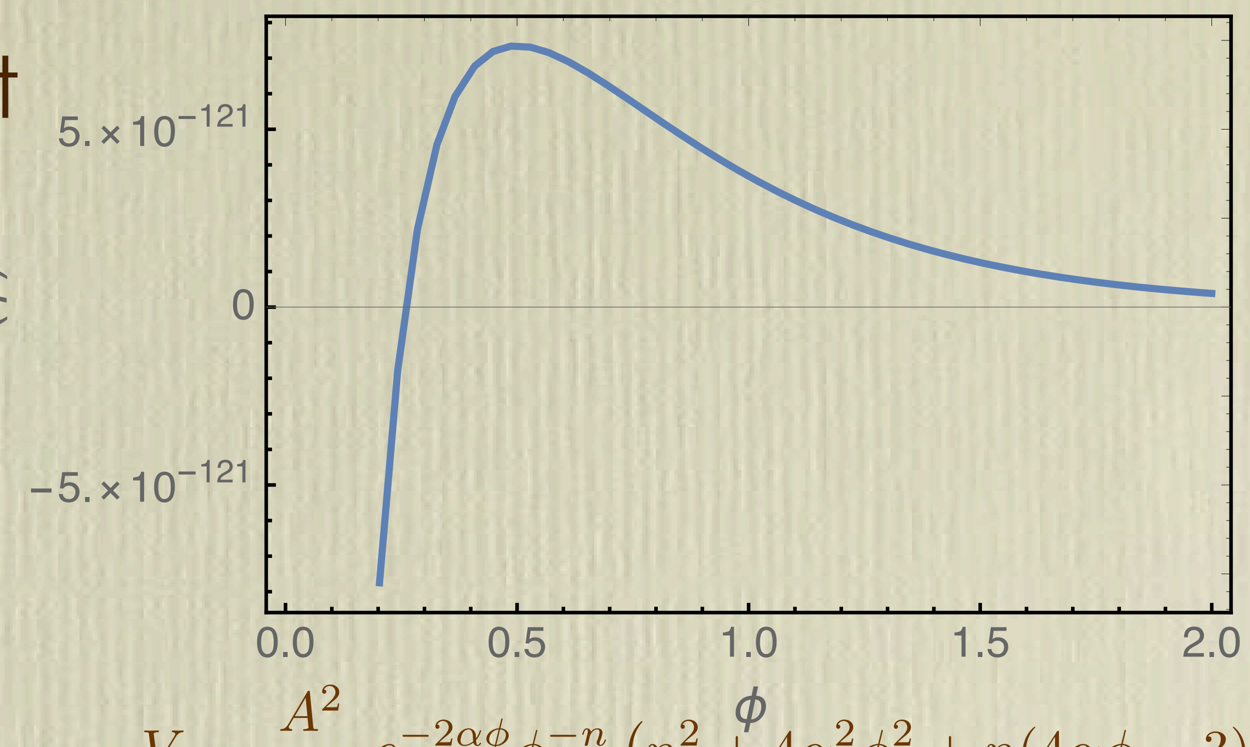
with axion flat direction at leading order

RUNAWAY MODULUS WITH DS MAXIMUM

- If n=1, there is a dS maximum at

$$\phi_{\max} = \frac{1}{\sqrt{2}\alpha},$$

consistent with dS Swampland conjecture.



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- Corrections from K_p and $W_{np_{sub}}$ suppressed for small coupling constant

- Starting from susy Minkowski – well under control

- Giving up dS minimum – no fine tuning of perturbative and non-perturbative corrections against each other

QUINTESSENCE FROM A RUNAWAY MODULUS

- Cosmological equations in an FRW background are:

$$3\left(\frac{\dot{a}}{a}\right)^2 = \frac{1}{4\phi^2}\left(\dot{\phi}^2+\dot{\theta}^2\right) + M_{pl}^{-2}V + 3H_0^2\Omega_M a(t)^{-3} + 3H_0^2\Omega_r a(t)^{-4}$$

$$0 = \ddot{\phi} + 3\frac{\dot{a}}{a}\dot{\phi} + \Gamma^{\phi}_{ab}\dot{\phi}^a\dot{\phi}^b + M_{pl}^{-2}g^{\phi b}\frac{\partial V}{\partial \phi^b}$$

$$0 = \ddot{\theta} + 3\frac{\dot{a}}{a}\dot{\theta} + \Gamma^{\theta}_{ab}\dot{\phi}^a\dot{\phi}^b + M_{pl}^{-2}g^{\theta b}\frac{\partial V}{\partial \phi^b}\,,$$

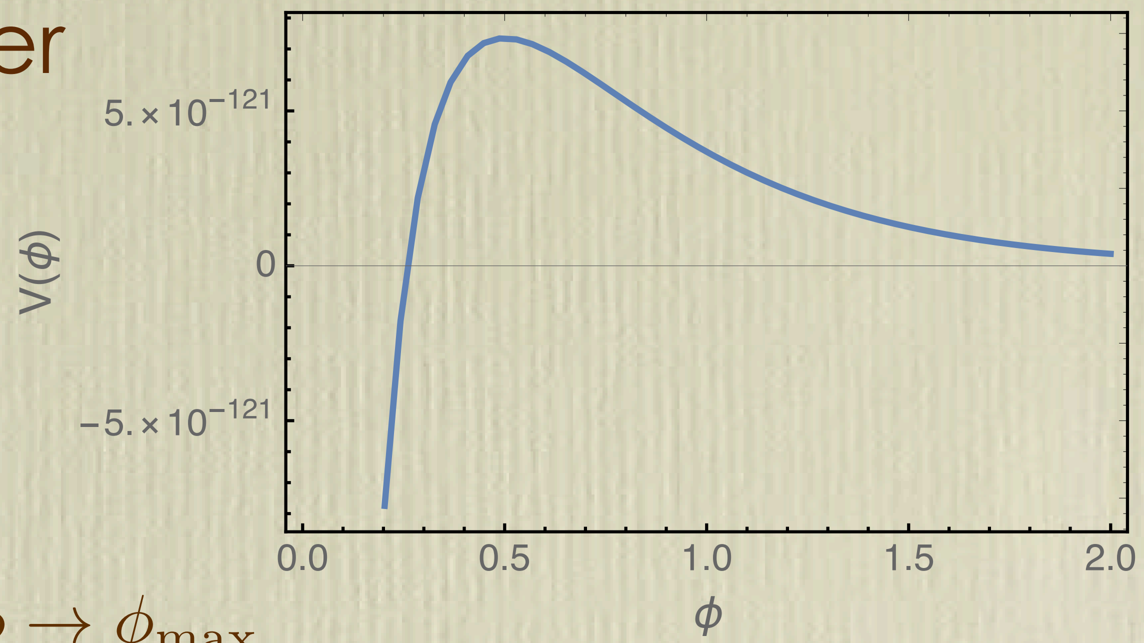
- To source acceleration $\frac{1}{2}\dot{\varphi}_c^2 \ll V$, slow-roll quintessence.

$\left(\varphi_c = M_{Pl}\sqrt{\frac{n}{2}}\log\phi\right)$

that is $$\phi^2\frac{V'(\phi)^2}{9V} \ll M_{Pl}^2 H^2$$

QUINTESSENCE FROM A RUNAWAY MODULUS

- Behaviour of the slow-roll parameter in different regions of the potential:



$$\phi^2 \frac{V'(\phi)^2}{V} \to -\# \frac{A^2}{\phi} \quad \text{as} \quad \phi \to 0$$

$$\phi^2 \frac{V'(\phi)^2}{V} \to \# A^2 e^{-\sqrt{2}} \alpha^3 \left(\phi - \frac{1}{\sqrt{2}\alpha} \right)^2 \quad \text{as} \quad \phi \to \phi_{\max}$$

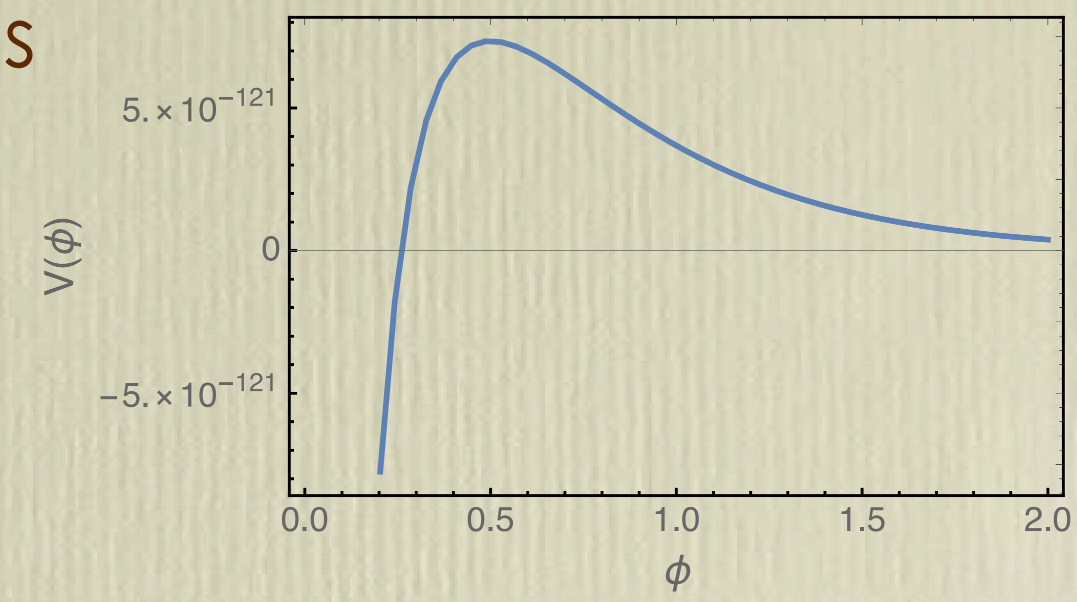
$$\phi^2 \frac{V'(\phi)^2}{V} \to \# A^2 e^{-2\alpha\phi} \alpha^4 \phi^3 \quad \text{as} \quad \phi \to \infty$$

- At hilltop or tail, while H is large, field remains frozen by Hubble friction – sourcing cosmological constant – for most of cosmological history.

- As H decreases, eventually $M_{Pl}^2 H^2 \lesssim \phi^2 V'(\phi_{ini})^2 / V(\phi_{ini})$ and field begins to roll

LATE-TIME QUINTESSENCE ON THE RUNAWAY

- For a quintessence that dominates the energy density: $M_{Pl}^2 H^2 \sim V/3$



$$\epsilon_q = \phi^2 \frac{V'^2}{V^2} \ll 1$$

- At tail $\epsilon_q \to 4\alpha^2\phi^2$ as $\phi \to \infty$ so runaway potential cannot source quintessence at the tail (consistent with dS swampland conjecture, which implies $\epsilon_q \gtrsim 3c^2/M_{Pl}^2$)
- Near the hilltop $\epsilon_q \to \#\alpha^2 \left(\phi - \frac{1}{\sqrt{2}\alpha}\right)^2$ so ϕ remains frozen by

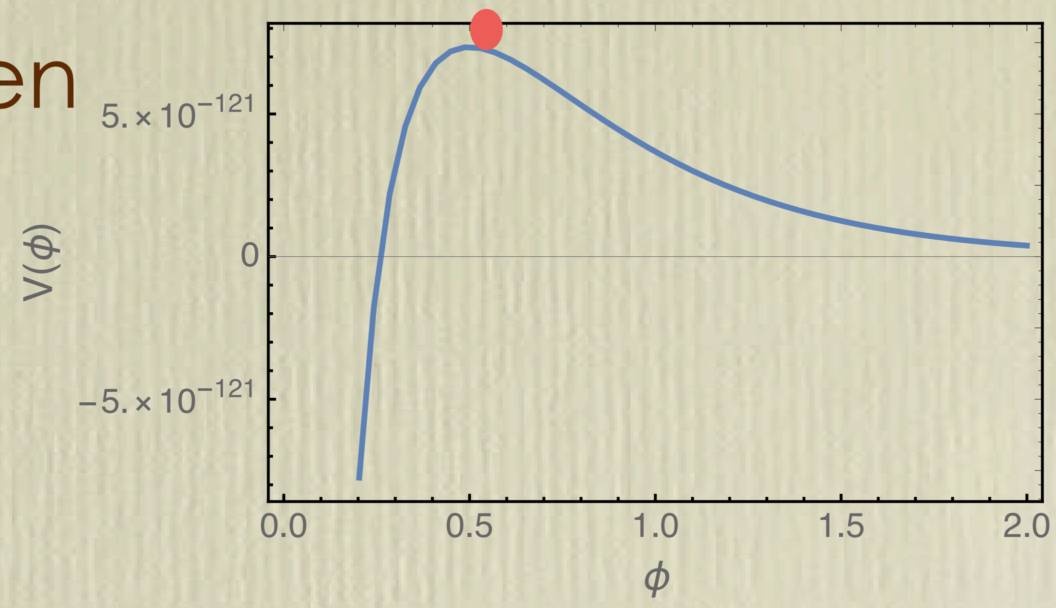
  Hubble friction until $M_{Pl}^2 H^2 \lesssim \epsilon_q(\phi_{ini})$ and then rolls

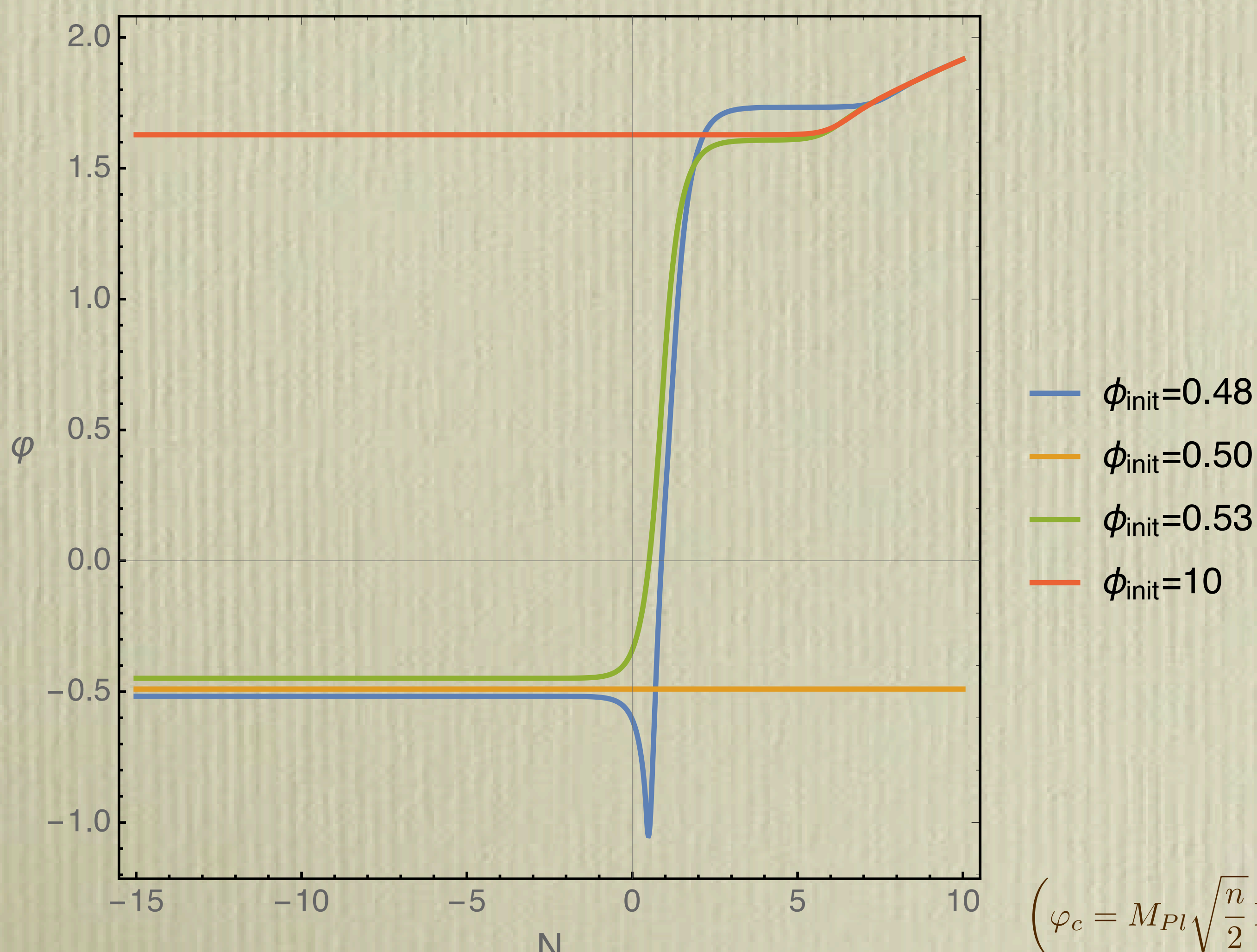
- At dS maximum $\min(\nabla^i\nabla_i V)/V \sim -6.8 M_{Pl}^2$ consistent with dSSC $(\min(\nabla^i\nabla_i V)/V < -c' M_{Pl}^2)$

THAWING QUINTESSENCE FROM RUNAWAY MODULUS

- Near hilltop we have a *viable* frozen or *thawing quintessence* model

- Choosing $A = e^{-138.122}$, $\alpha = \sqrt{2}$,





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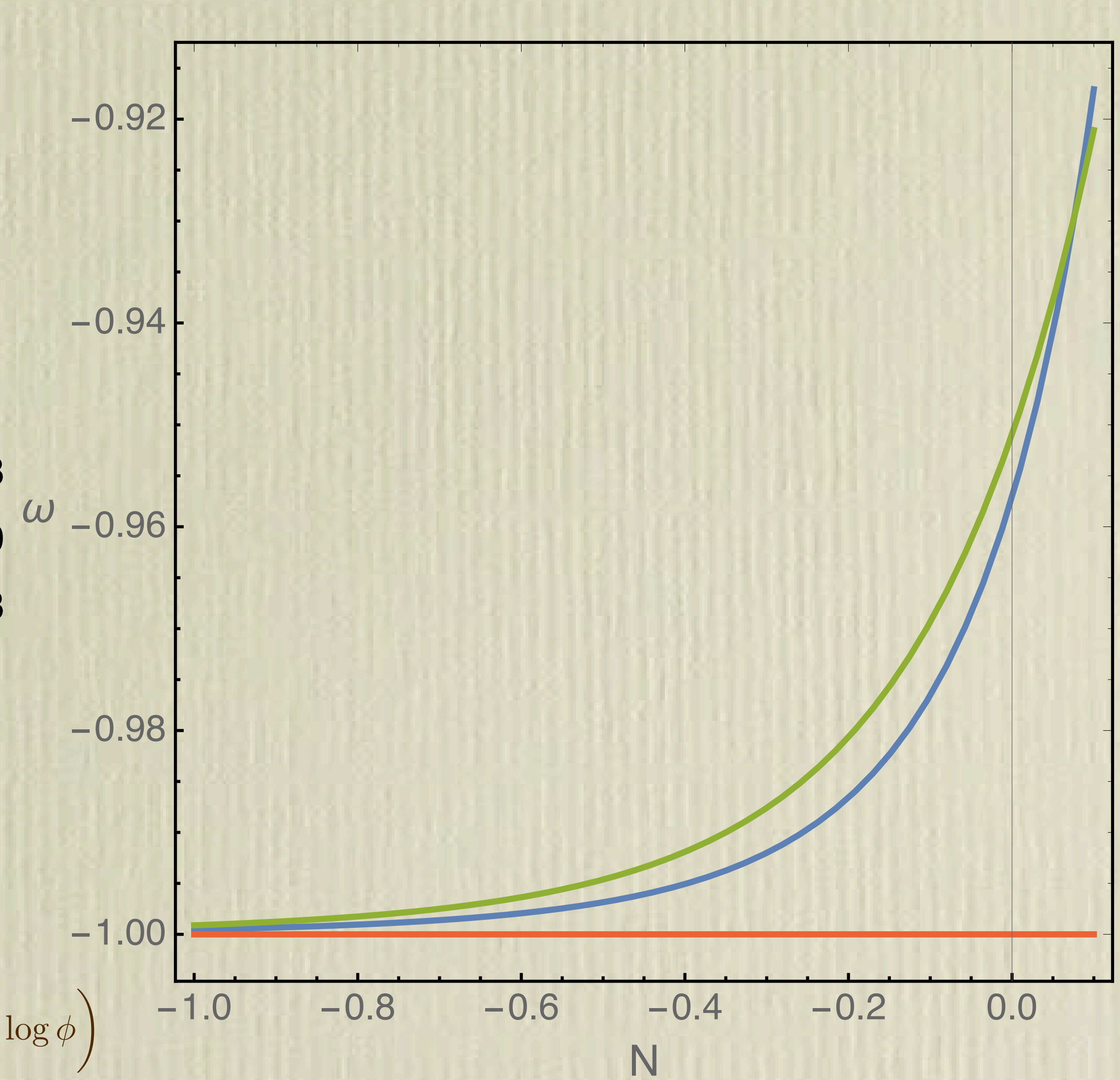

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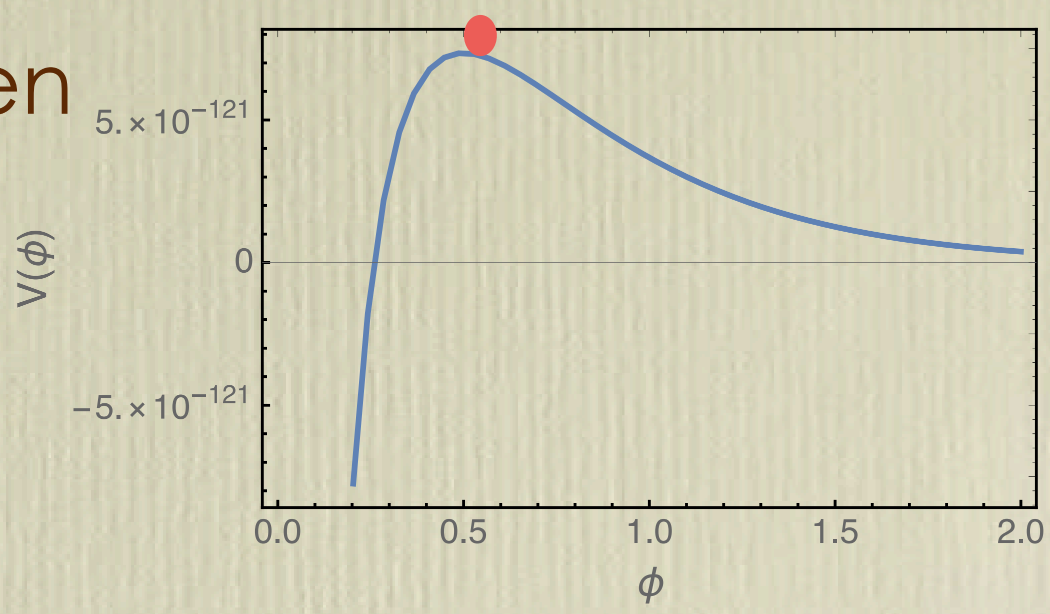

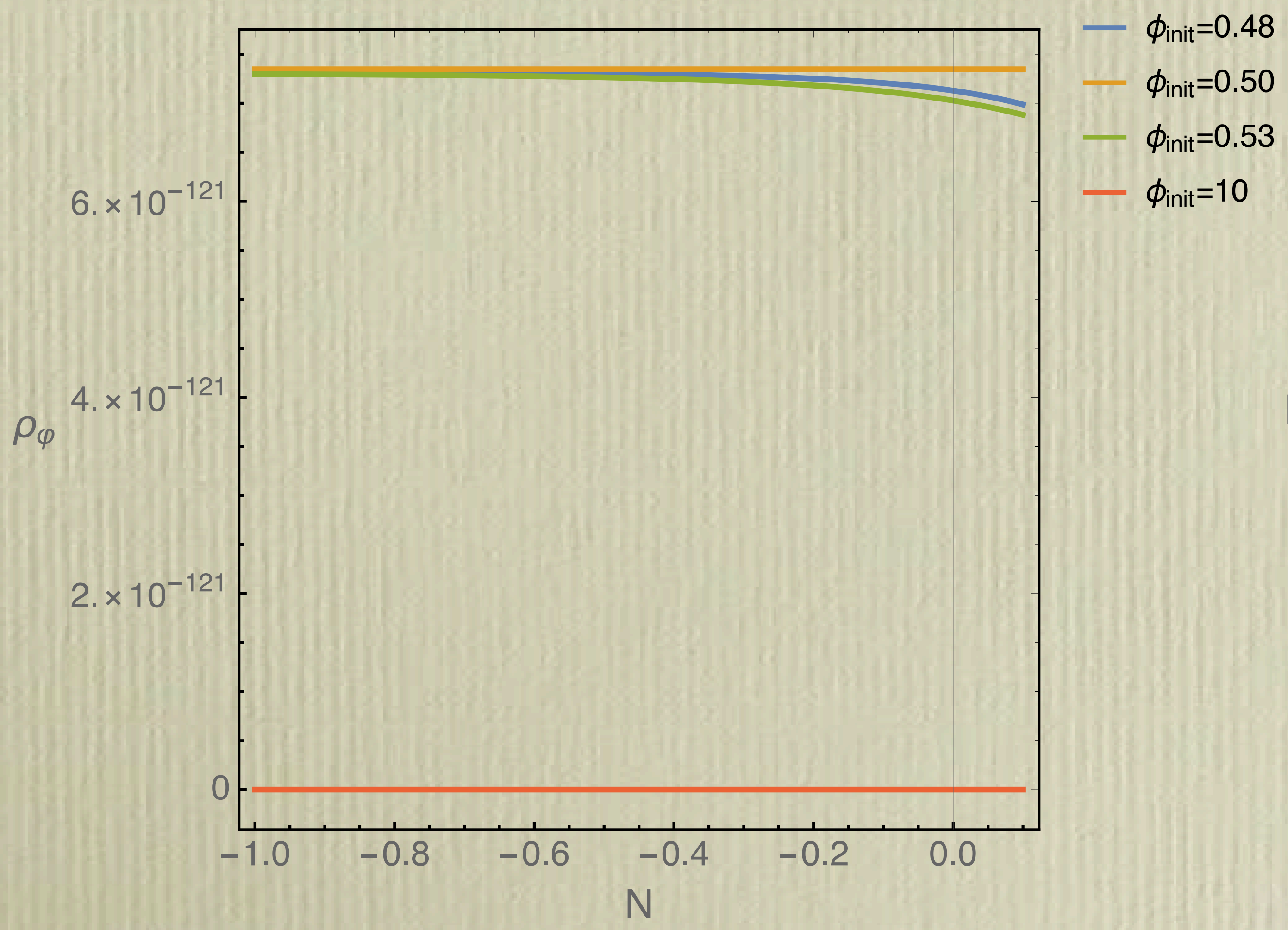

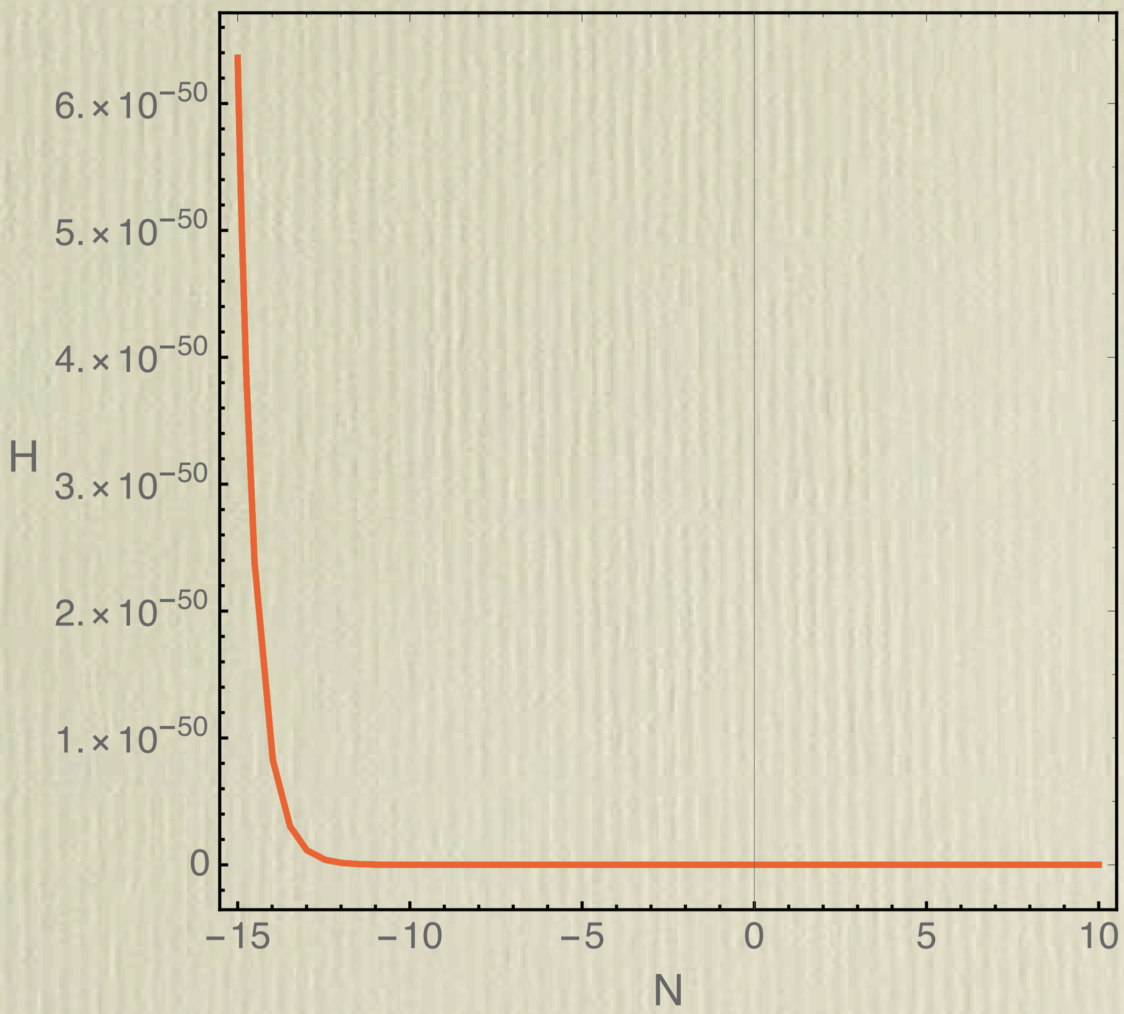

AXION, AXINO, VISIBLE SECTOR

- Axion lifted by subleading corrections $W_{np_{sub}} \Rightarrow$ axion DE with $m_\theta < m_\phi$. E.g. $W_{np_{sub}} = B\, e^{-\beta\phi}$ with $\beta = 2\alpha\,,\ B = -A/20 \Rightarrow \omega = -0.99$

- Axino has light mass $m_{axino} \sim 2\phi^2 e^{K/2} D_\phi D_\phi W$. With params above $m_{axino} \sim 4.2 \times 10^{-33}\mathrm{eV}$ $\Rightarrow$ axino dark radiation

- Relic abundance is model dependent, e.g. via thermal scattering or decays or out of equilibrium decay via lightest stabilised modulus

- So far mild susy breaking by runaway - effect of susy breaking in visible sector must be sequestered, e.g. if modulus describes local feature in string compactification, distant from SM:
$$\Delta m^2 \sim \frac{M_{sb}^4}{M_{Pl}^4} M_{sb}^2 \sim H_0^2$$

- Tree-level decoupling ensures radiative stability, suppression of fifth forces and time variation of fundamental constants…

SUMMARY

- Existence or not of metastable dS vacuum in string theory remains an open question.
- Very few candidates for quintessence in string theory - usually tension with swampland constraints and/or control issues.
- Late time dominating slow-roll quintessence is impossible at runaway tail – no stringy example (and inconsistent with dS conjecture).
- Hilltop in runaway potential can source frozen/thawing quintessence consistently with observations and QG conjectures - and under control! Comes with axion DE and axino DR. BUT need fine-tuned initial conditions... anthropics on a susy Landscape?
- Model dependent questions: susy breaking and vacuum energy in visible sector, fifth forces and time variation of fundamental constants...
- The cosmological constant problem...

COUPLED DARK ENERGY - DARK MATTER MODELS

Puzzle of cosmic coincidence:

Why is the dark energy density of same order (only about two times bigger) as that of matter density in the present cosmological epoch?

- If it is not accidental $\Rightarrow$ an exchange of energy is plausible, and therefore a coupling between dark energy and dark matter.
- Whereas new forces between DE and normal matter are heavily constrained by observations (e.g. in the solar system and gravitational experiments on Earth), this is not the case for DM.
- Resolution of the 'cosmic coincidence' problem implies that dark energy and dark matter follow the same *scaling solution* during a significant period of evolution.

COUPLED DARK ENERGY - DARK MATTER MODELS

- Coupled dark matter - dark energy (scalar field) changes cosmological evolution with interesting implications:
  - Modified thermal dark matter paradigm

    [Kamionkowski, Turner, ’90; Salati, ’03; Rosati, ’03; Profumo, Ullio, ’03, ; Catena et al. ’04 … Meehan, Whittingham ’15, Dutta, Jimenez, IZ, '16-'17, D’Eramo, Fernandez, Profumo, ’17…]
  - Relevant for recent cosmological puzzles: 21cm, H_0

    Costa, Landim, Wang, Abdalla, ’18; Yang, Pan, et al., ’18; Di Valentino, Melchiorri, Mena, Vagnozzi, ’19; Agrawal, Obied, Vafa, ‘19]

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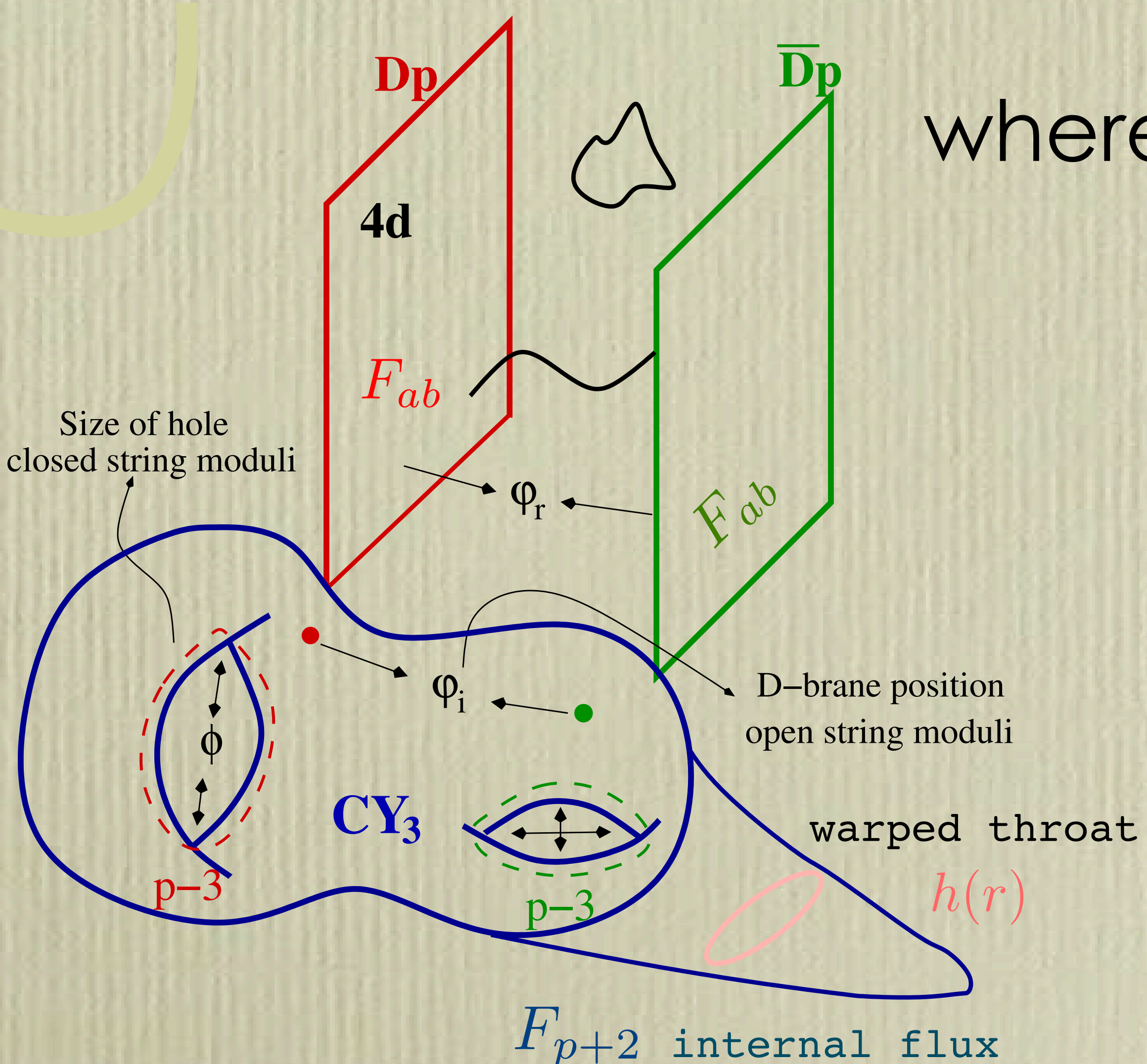
[Dimopoulos, Wills, IZ, ’13; Koivisto, Wills, IZ, ’13; Dutta, Jimenez, IZ, ’16-’17]

D-BRANE SCALAR-TENSOR THEORIES

- In four dimensions, including D-branes, low energy action for scalars, matter and gravity takes the form

$$S = \frac{1}{2\kappa^2}\int d^4x\sqrt{-g}R - \int d^4x\sqrt{-g}\,P(X,\phi) - \int d^4x\sqrt{-\tilde{g}}\,\mathcal{L}_m(\tilde{g}_{\mu\nu})$$

$$M_{10} \to M_4 \times X_6$$



where
$$P(X,\phi) = M^4C^2(\phi)\sqrt{1+2X\frac{D(\phi)}{C(\phi)}} + V(\phi)$$
$$X = \frac{1}{2}(\partial\phi)^2$$
$$\tilde{g}_{\mu\nu} = C(\phi)g_{\mu\nu} + D(\phi)\partial_\mu\phi\partial_\nu\phi \quad \text{(induced metric)}$$

- *non-standard kinetic terms arise* from D-brane DBI action
- *conformal and disformal* coupling between scalar (DE) and matter (DM)

$$ds^2_{10D} = h^{-1/2}(r)\,g_{\mu\nu}dX^\mu dX^\nu + h^{1/2}(r)\;g_{mn}dX^m dX^n$$

D-BRANE SCALAR-TENSOR THEORIES

The induced metric $\tilde{g}_{\mu\nu}$ has the form, which agrees with the most general relation between two metrics compatible with general covariance introduced by Bekenstein [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)

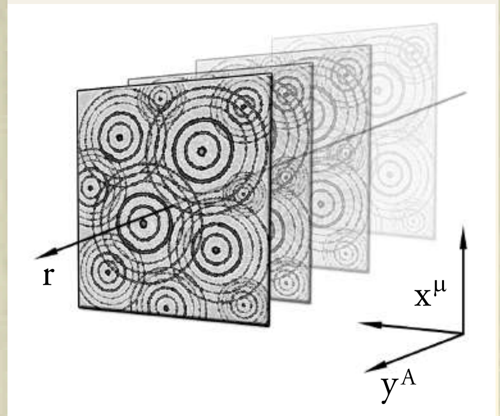
$D(\phi)$ *disformal* transformation (distorts angles)

where C, D satisfy the causality constraint

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

D-BRANE SCALAR-TENSOR THEORIES

Starting action is $S = S_{EH} + S_{brane}$



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

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

$$(M^4CD = 1)$$

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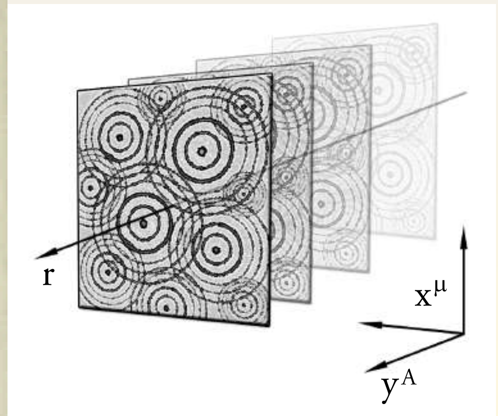

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A natural coupled DM/DE system emerges

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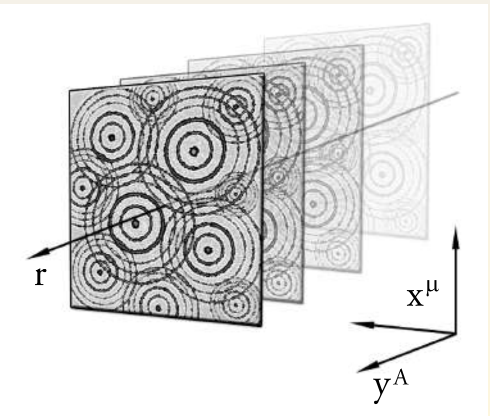

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[Dimopoulos, Wills, IZ, ’13; Koivisto, Wills, IZ, ’13; Dutta, Jimenez, IZ, ’16-’17]

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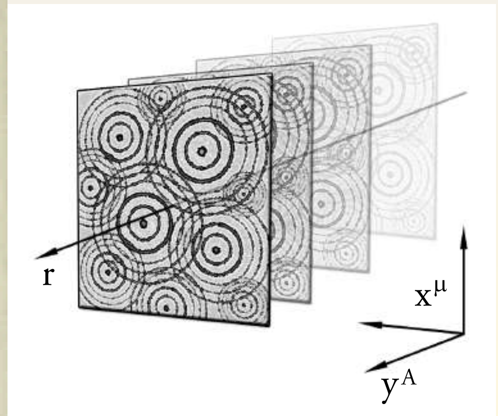

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$$(M^4CD = 1)$$

A natural coupled DM/DE system emerges

[Dimopoulos, Wills, IZ, '13; Koivisto, Wills, IZ, '13; Dutta, Jimenez, IZ, '16-'17]

- Identify the *Dark D-brane* with a moving hidden sector Dbrane (has no or little interaction with SM D-branes)
- Dark D-brane matter can be identified with dark matter (massive fields) or dark radiation (massless fields).
- Brane motion parameterised by brane's position, identified with dark energy (DBI quintessence)
- *Conformal and disformal* couplings can *modify the expansion rate* at different epochs, with interesting cosmological implications

COSMOLOGICAL EVOLUTION

For cosmology, consider evolution in an FRW universe:

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

The evolution equations in *Einstein frame* (with respect to $g_{\mu\nu}$) become

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

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

$$\rho_\phi = \frac{M^4 C D \gamma^2}{\gamma + 1}\dot{\phi}^2 + \mathcal{V}$$

$$P_\phi = \frac{M^4 C D \gamma}{\gamma + 1}\dot{\phi}^2 - \mathcal{V}$$

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

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

COSMOLOGICAL EVOLUTION

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Total energy is conserved $\nabla_\mu\left(T^{\mu\nu}_\phi + T^{\mu\nu}\right) = 0$. 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:

$$\nabla_\mu \tilde{T}^{\mu\nu} = 0$$

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

$$\left(\tilde{\rho} = C^{-2}\gamma^{-1}\rho , \quad \tilde{P} = C^{-2}\gamma P\right)$$

COSMOLOGICAL EVOLUTION

The evolution equations in *Einstein frame* (with respect to $g_{\mu\nu}$) become

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

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

$$\rho_\phi = \frac{M^4 C D \gamma^2}{\gamma + 1}\dot{\phi}^2 + \mathcal{V}$$

$$P_\phi = \frac{M^4 C D \gamma}{\gamma + 1}\dot{\phi}^2 - \mathcal{V}$$

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

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

COSMOLOGICAL EVOLUTION

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Phenomenological models in the literature:

$$\dot{\rho}_{de} + 3H(1+\omega_{de})\rho_{de} = -\mathcal{Q}$$

$$\dot{\rho}_{dm} + 3H\rho_{dm} = \mathcal{Q}$$

where $\mathcal{Q}$ chosen by hand (bottom up)

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

- **LATE TIME UNIVERSE EVOLUTION**

  Accelerating scaling solutions ➠ implications for recent observational puzzles?

- **EARLY UNIVERSE EVOLUTION**

  Modified expansion rate ➠ modified thermal DM, implications for inflation

LATE TIME COSMOLOGY

- Consider an AdS5 throat with a quadratic potential

$$h = \frac{\lambda}{\phi^4}\,, \qquad V = V_0\,\phi^2 \qquad (\Gamma_0 = \lambda V_0)$$

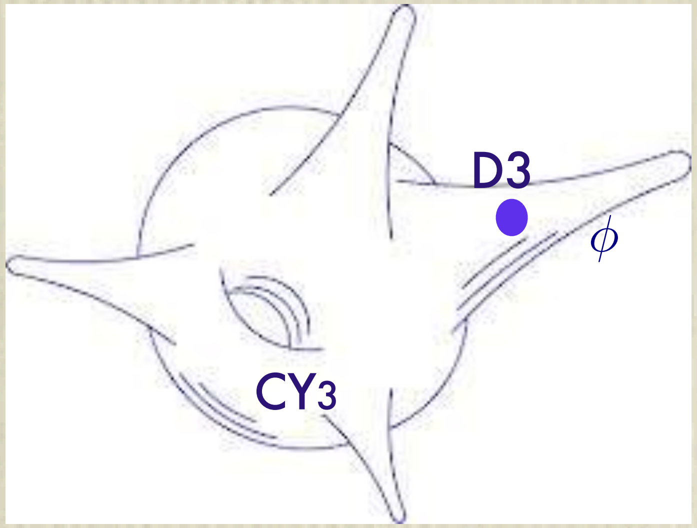
where

$\phi = \sqrt{T_3}\, r$ scalar associated to brane's position

$h(\phi) = h(r)/T_3$ warp factor in terms of the scalar

$C(\phi) = [T_3\, h(\phi)]^{-1/2}$ conformal piece

$D(\phi) = [h(\phi)/T_3]^{1/2}$ disformal piece



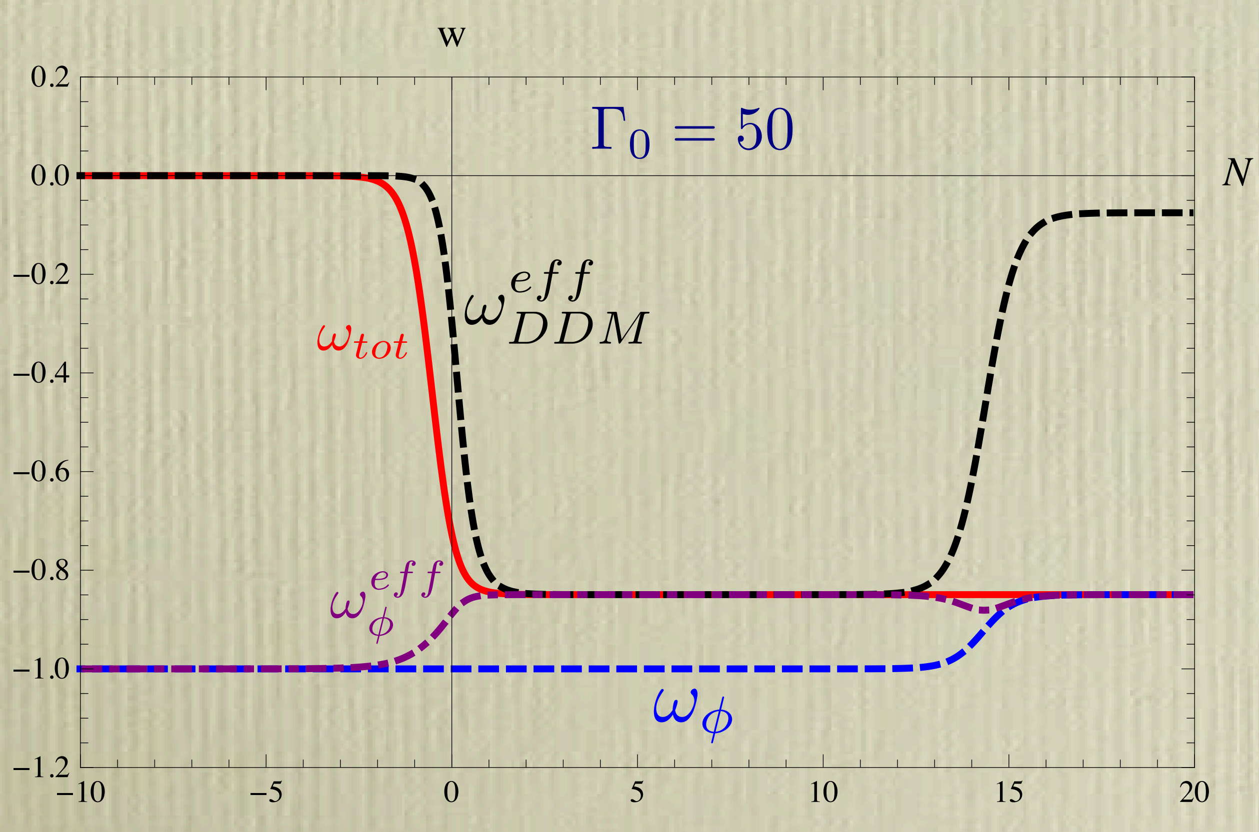
[Koivisto, Wills, IZ, '13]

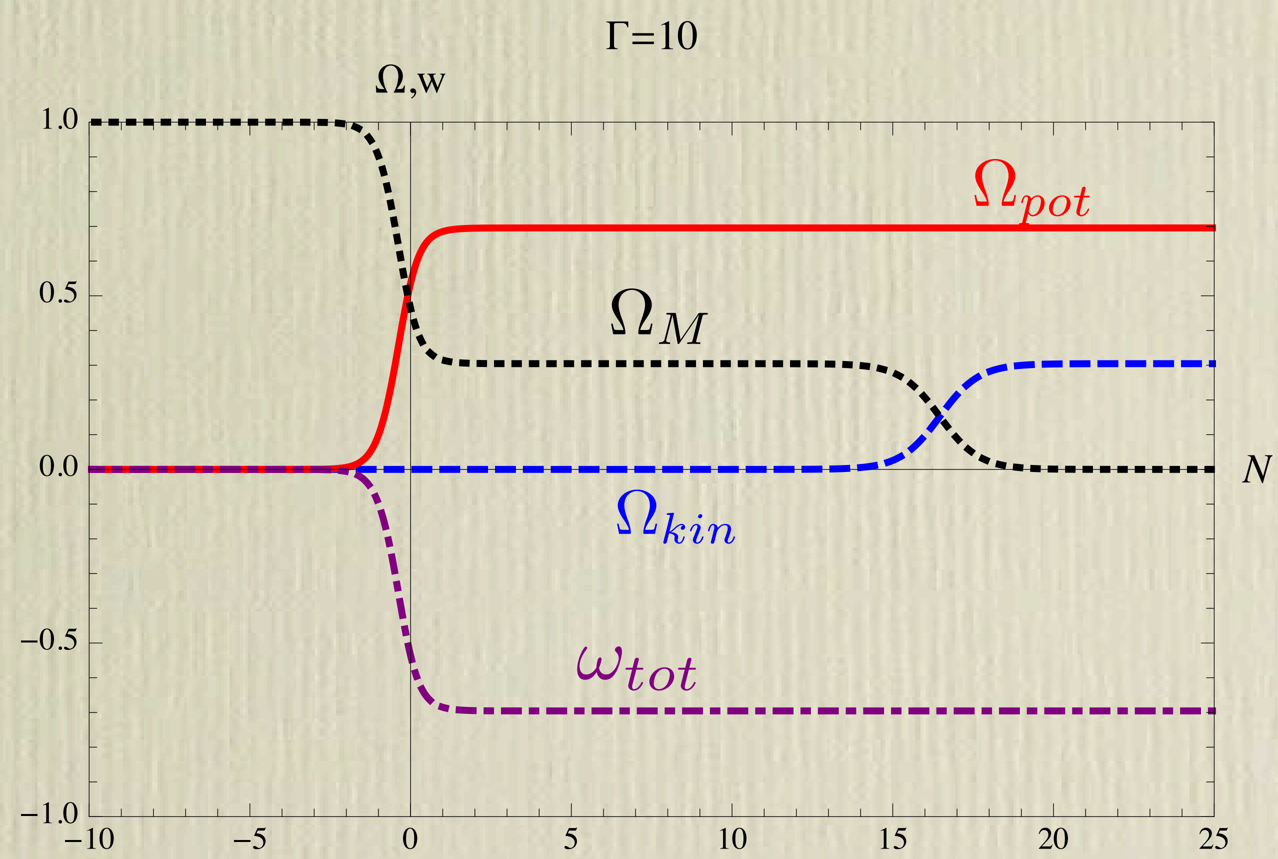
Dynamical system analysis

The resulting fixed points

	Ω_M	Ω_{kin}	Ω_{pot}	ω_{tot}	γ	Stability
Matter Dominated	1	0	0	0	Any	Unstable
Potential Dominated	0	0	1	-1	1	Saddle
Matter Scaling	$\frac{2}{1+\sqrt{1+3\Gamma_0}}$	0	$\frac{-1+\sqrt{1+3\Gamma_0}}{\sqrt{3\Gamma_0}}$	$-\frac{\left(1-\sqrt{1+3\Gamma_0}\right)^2}{3\Gamma_0}$	∞	$\Gamma_0 < 1$ (Saddle)
Kinetic Scaling	0	$\sqrt{\frac{2}{1+\sqrt{1+3\Gamma_0}}}$	$\frac{-1+\sqrt{1+3\Gamma_0}}{\sqrt{3\Gamma_0}}$	$-\frac{\left(1-\sqrt{1+3\Gamma_0}\right)^2}{3\Gamma_0}$	∞	$\Gamma_0 > 1$ (Saddle)

Acceleration requires $\omega < -1/3$ $\quad \Gamma_0 > 1 \quad (\Gamma_0 = \lambda V_0)$





- for h =const. with inverse power law potential (e.g. in LVS, near tip KS)

The resulting fixed points

	Ω_M	Ω_{kin}	Ω_{pot}	ω_{tot}	γ	Stability
Matter Dominated	1	0	0	0	Any	Unstable
Potential Dominated	0	0	1	-1	1	Saddle
Matter Scaling	$\frac{2}{1+\sqrt{1+3\Gamma_0}}$	0	$\frac{-1+\sqrt{1+3\Gamma_0}}{\sqrt{3\Gamma_0}}$	$-\frac{(1-\sqrt{1+3\Gamma_0})^2}{3\Gamma_0}$	∞	Saddle
Kinetic Scaling	0	$\sqrt{\frac{2}{1+\sqrt{1+3\Gamma_0}}}$	$\frac{-1+\sqrt{1+3\Gamma_0}}{\sqrt{3\Gamma_0}}$	$-\frac{(1-\sqrt{1+3\Gamma_0})^2}{3\Gamma_0}$	∞	Attractor

Acceleration requires $\omega < -1/3$ $\quad \Gamma_0 > 1$

System gives a viable coupled quintessence scenario with matter scaling epochs and “easy” acceleration: relaxing coincidence and fine tuning problems of DE.

SUMMARY

- Disformal transformation finds a fundamental origin in terms of D-branes in string theory with clear geometrical origin.

- Coupling among DM and DE cannot be turned off: will always be there unless speed of brane is tuned.

- This system gives a viable *coupled quintessence scenario* with matter scaling epochs and “easy” acceleration: relaxing coincidence and fine tuning problems of DE.

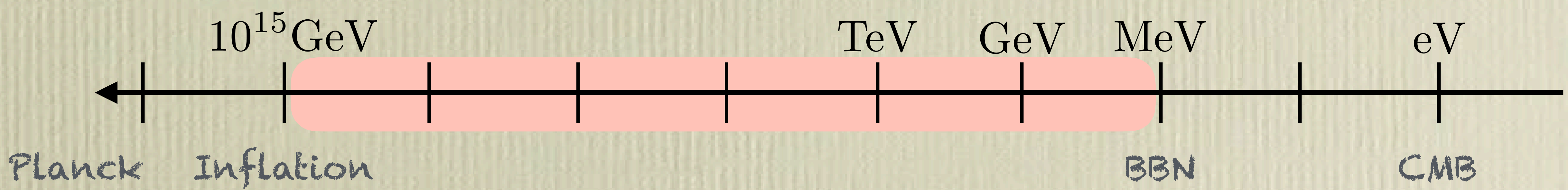
- Can it help with recent cosmological puzzles/hints for new physics beyond ΛCDM?

MODIFIED THERMAL DM SCENARIO

During early universe evolution, non-trivial couplings between dark matter and scalars can modify expansion rate.

If modified expansion occurs 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 ... Meehan, Whittingham ’15, Dutta, Jimenez, IZ, '16-'17, D’Eramo, Fernandez, Profumo, ’17...]



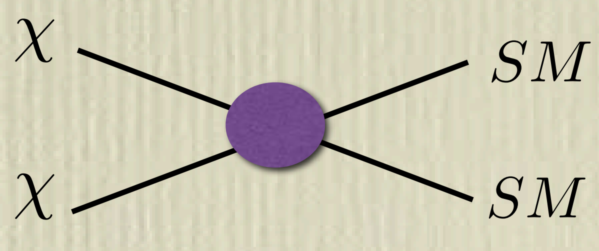
Any modification of the *post-inflationary history* can also have an effect on the range of e-folds relevant for inflation modifying the predictions for the inflationary parameters

[Dai, Kamionkowski, Wang, ’14; Maharana, IZ, ’18]

Modified Thermal DM Scenario

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

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



Modification to LHS of Boltzmann equation due to *modification of expansion rate* in the *scalar-tensor* theories described before will arise.

Modified Expansion rate

The *modified expansion rate* in the *disformal* (or Jordan) *frame*, felt by matter $\tilde{g}_{\mu\nu}$, $\tilde{H} \equiv \frac{d\ln\tilde{a}}{d\tilde{\tau}}$, is given by

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

where $' = d/dN$,

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

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

while the standard GR rate HGR is: $H_{GR}^2 = \dfrac{\kappa_{GR}^2}{3}\,\tilde{\rho}$ $\qquad (\tilde{\rho} = C^{-2}\gamma^{-1}\rho)$

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

Deviations from GR can be readily computed from the ratio

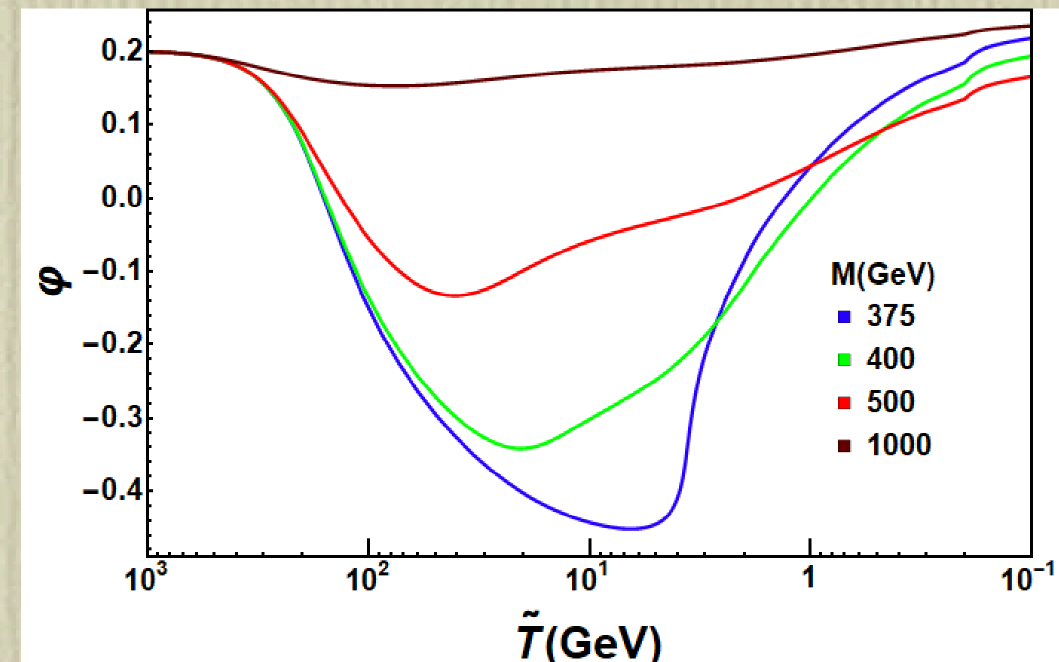
$$\xi = \frac{\tilde{H}}{H_{GR}} = \frac{\gamma^{3/2} C^{1/2} (1 + \alpha\varphi')}{B^{1/2}} \qquad \left(B = 1 - \frac{M^4 C D \gamma^2}{3(\gamma + 1)} \varphi'^2\right)$$

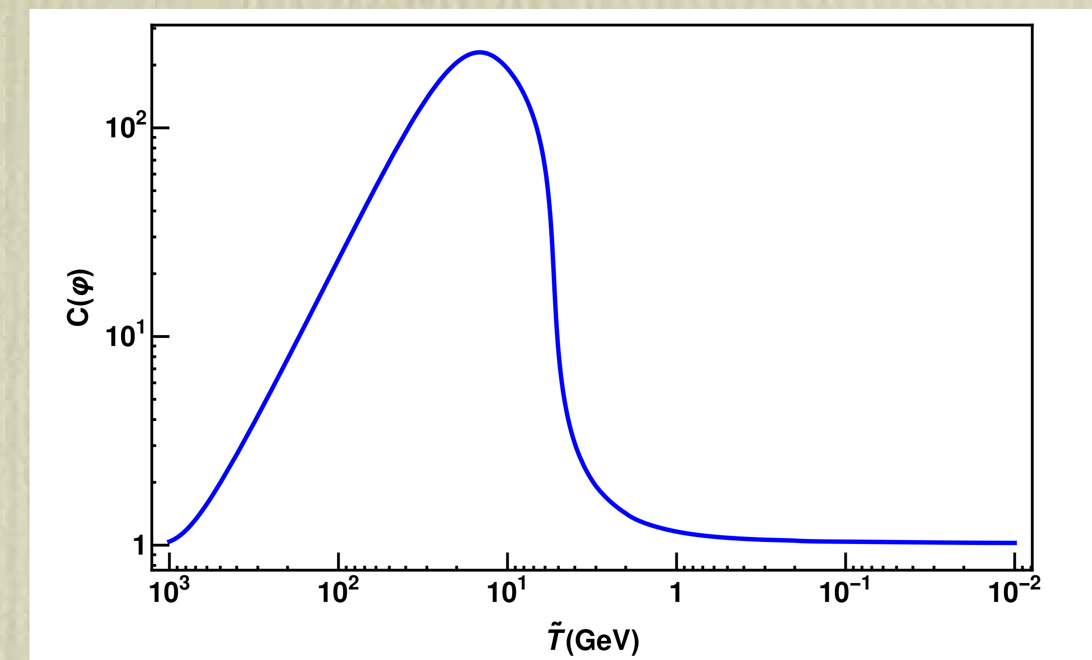
To study post-inflationary modified cosmologies, this parameter should go to one towards the onset of BBN, to avoid spoiling BBN predictions $\xi \to 1$. Similarly, constraints will arise for modifications at different epochs.

Conformal & Disformal Enhancement

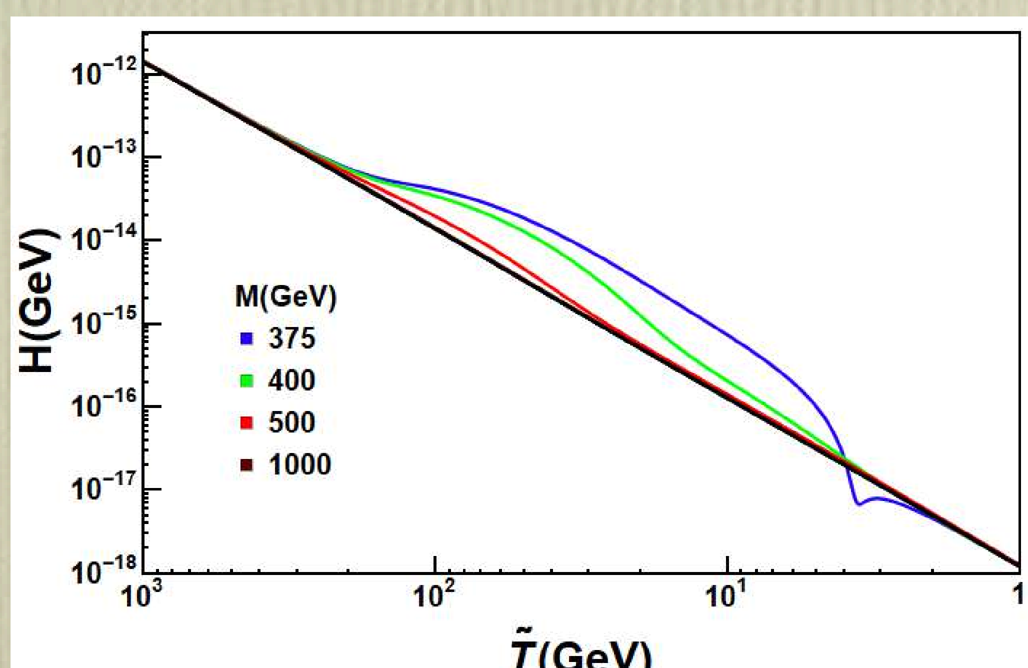
Full numerical solutions:

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





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



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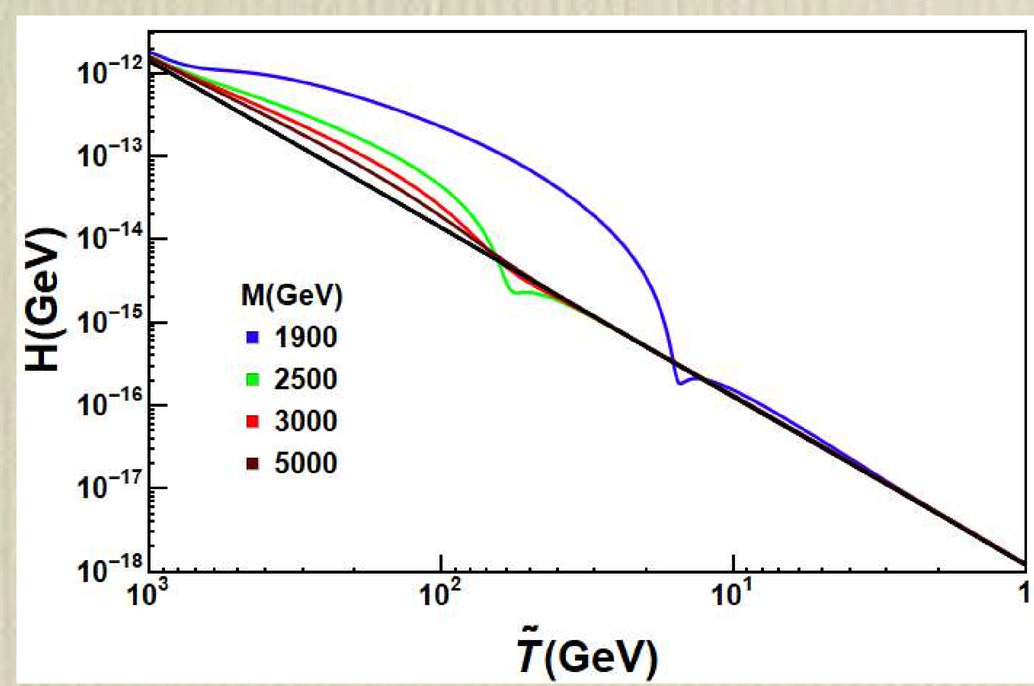
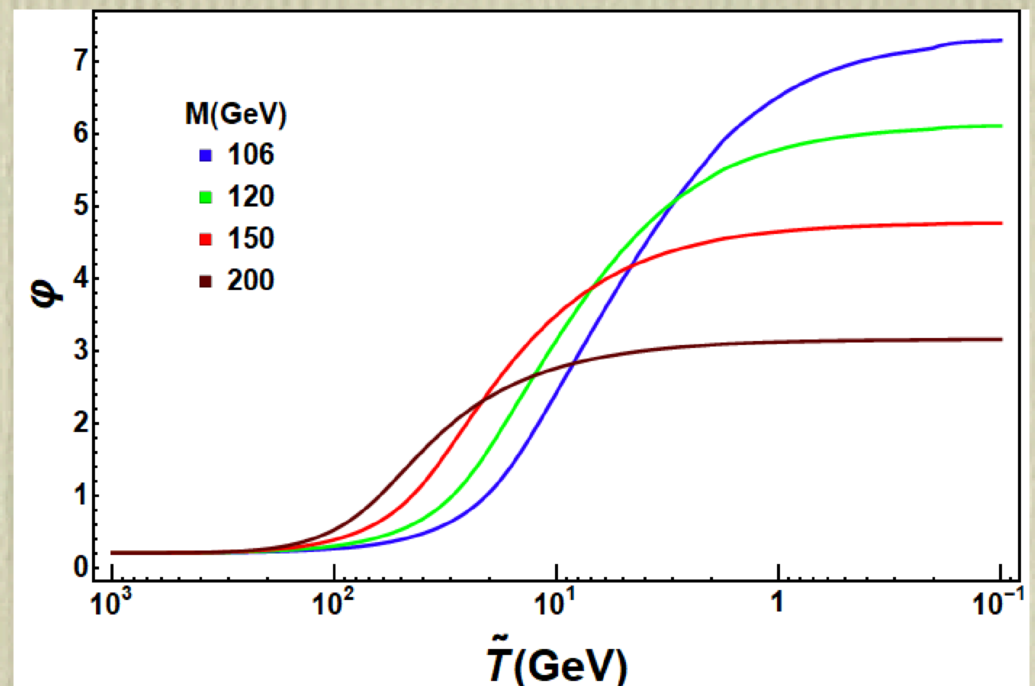


$(\varphi_i, \varphi_i') = (0.2, -0.4)$

Disformal Expansion Rate Enhancement

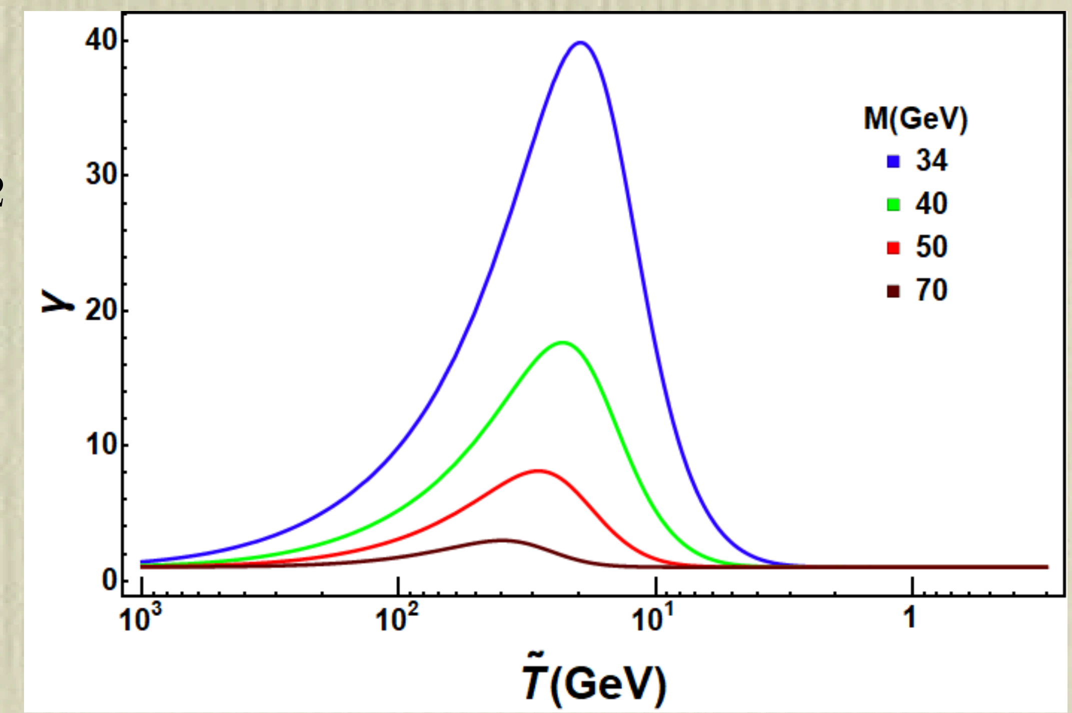
Full numerical solutions:

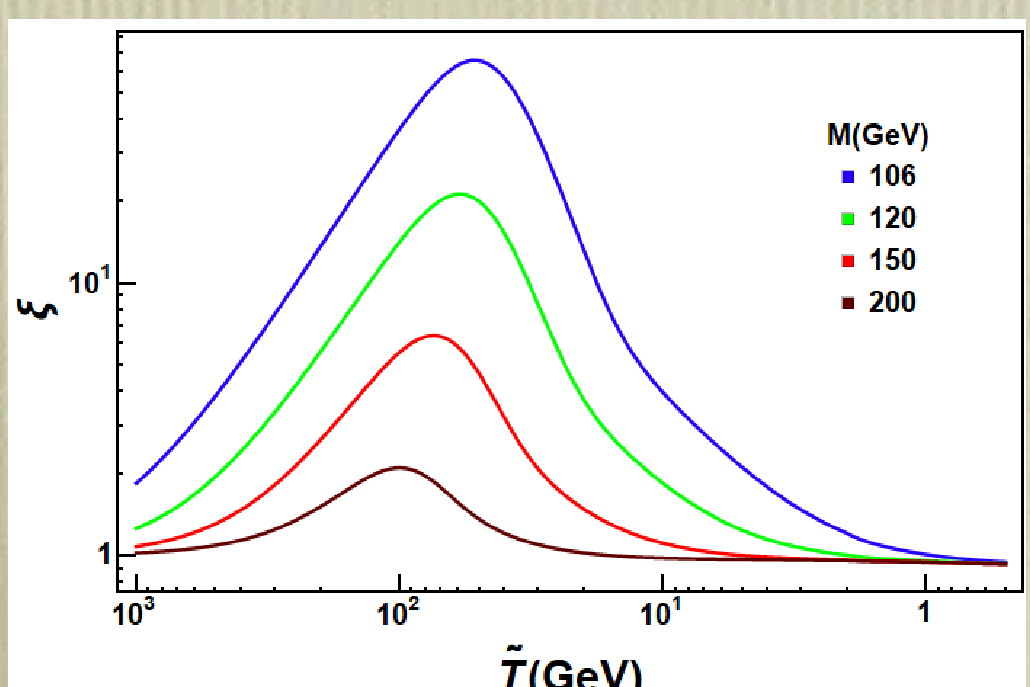
[Dutta, Jimenez, IZ, '16-17]

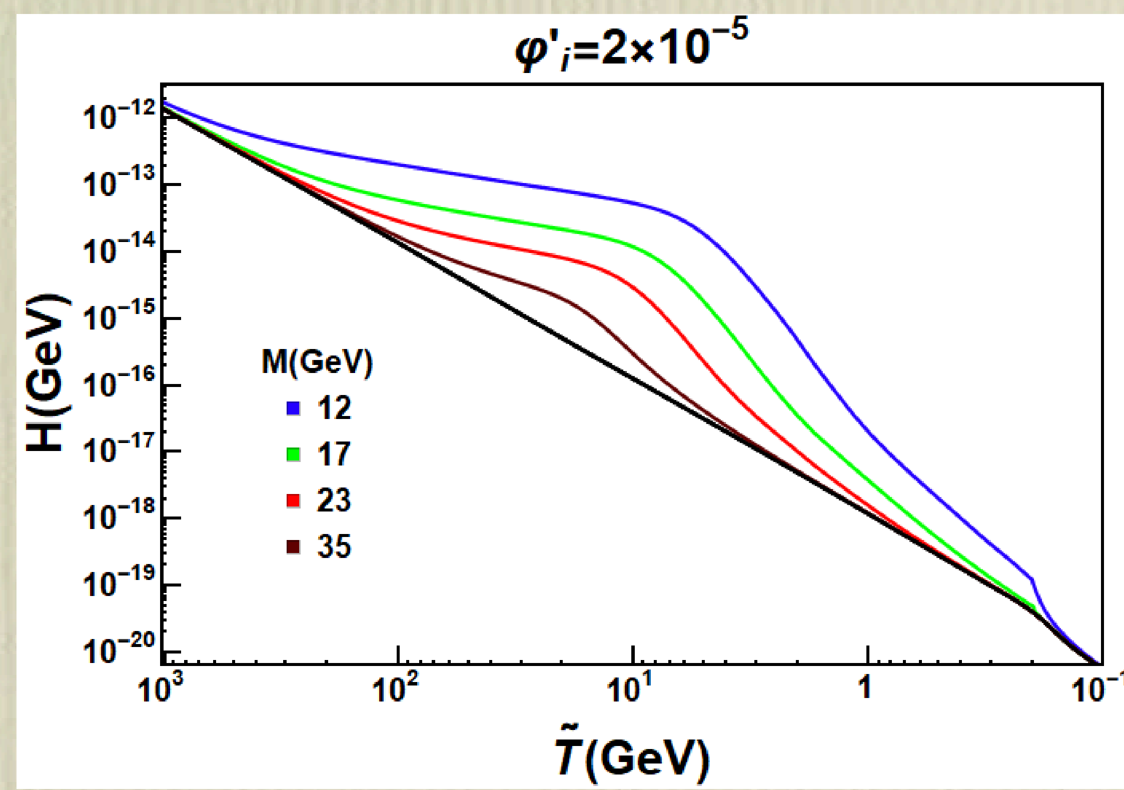


$\varphi_i = 0.2$

$\varphi'_i = 0.002$







Disformal Expansion Rate Enhancement

Full numerical solutions:

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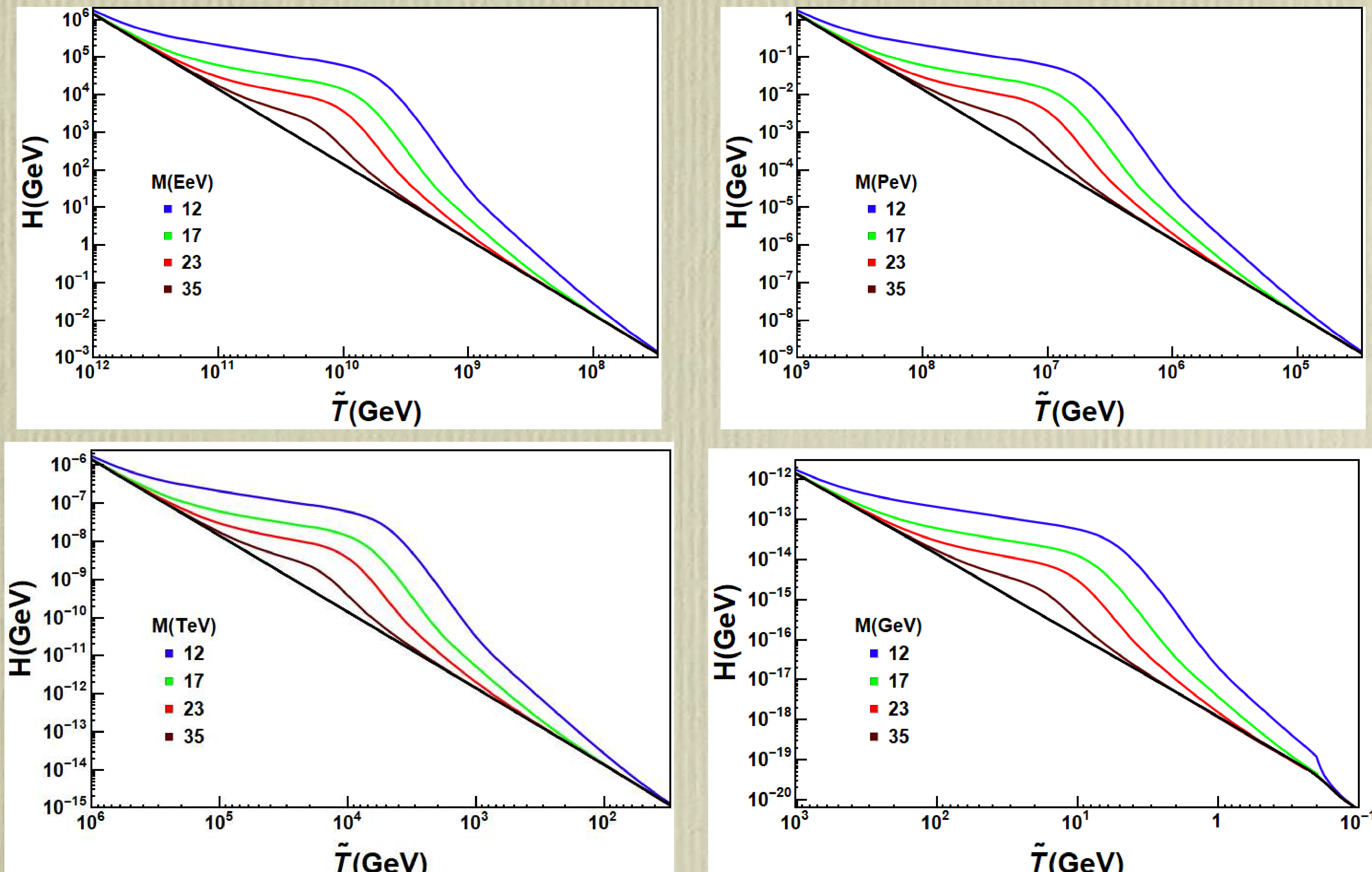


$\varphi_i = 0.2$

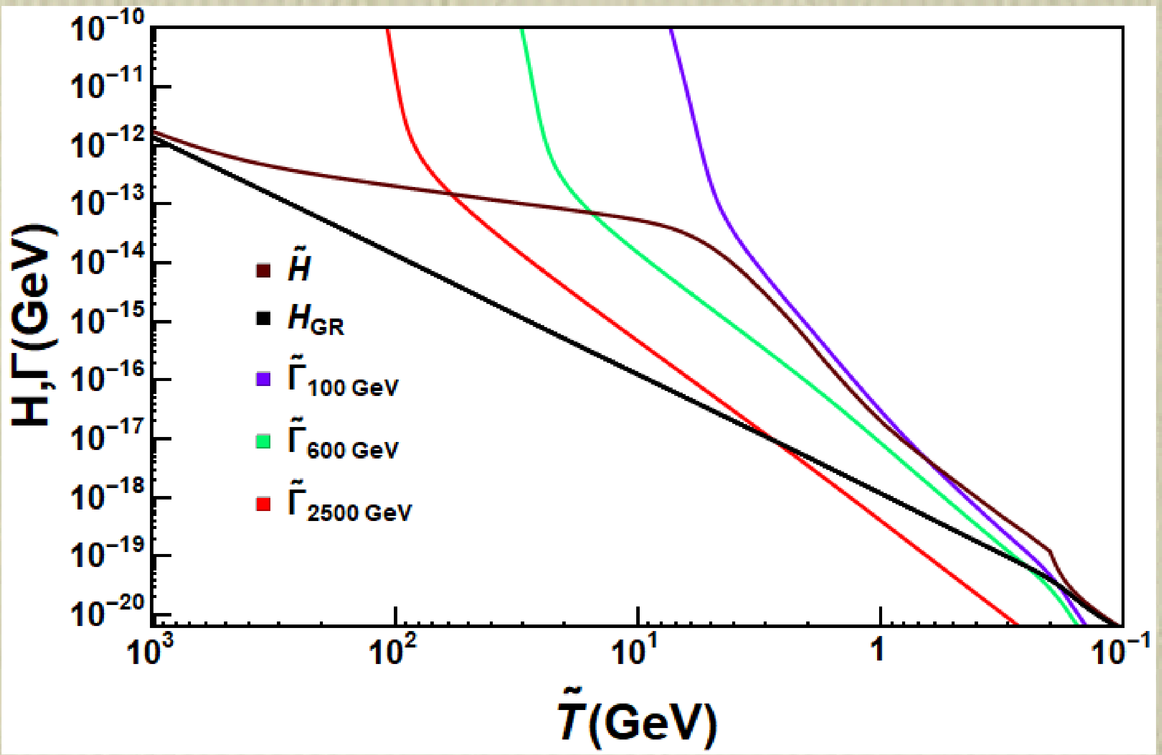
$\varphi_i' = 2 \times 10^{-5}$

— H

colour $\tilde{H}$

Disformal Effect on DM Relic Abundance

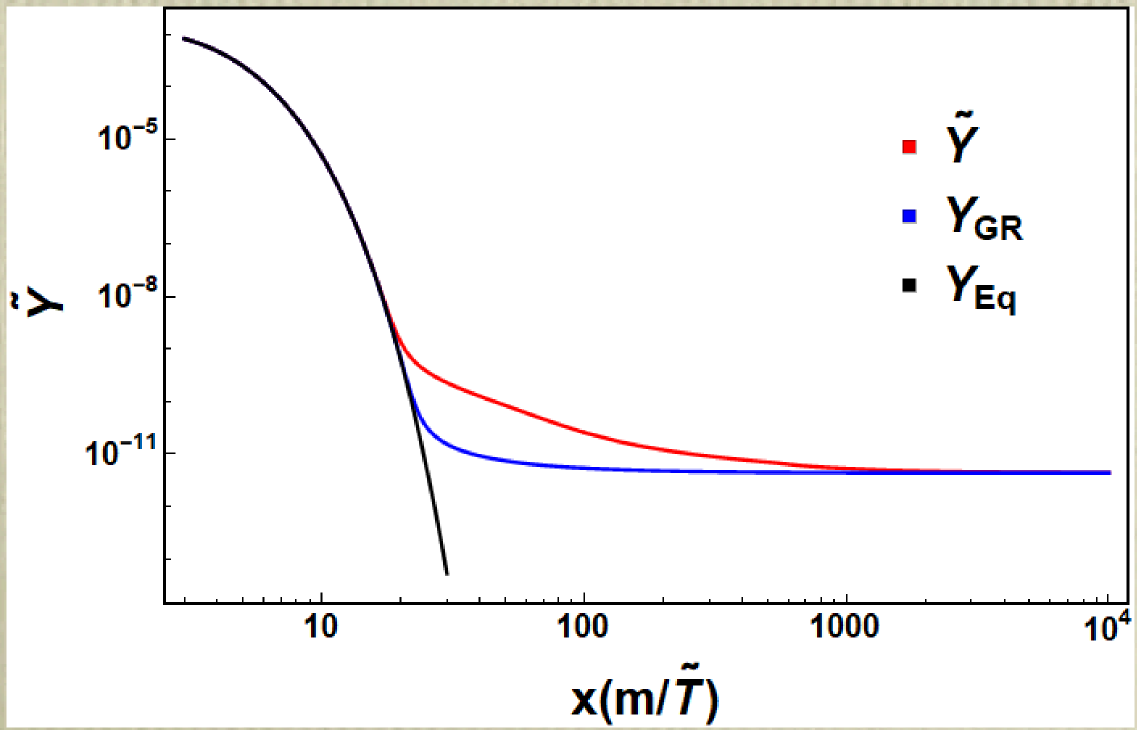
[Dutta, Jimenez, IZ, '16-17]



Expansion and decay rates for M = 12 GeV as function of temperature.

Disformal expansion enhancement implies earlier freeze-out

$(\Gamma_\chi \lesssim H \to \mathrm{freeze-out})$



Relic abundance evolution is computed from Boltzmann equation

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

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

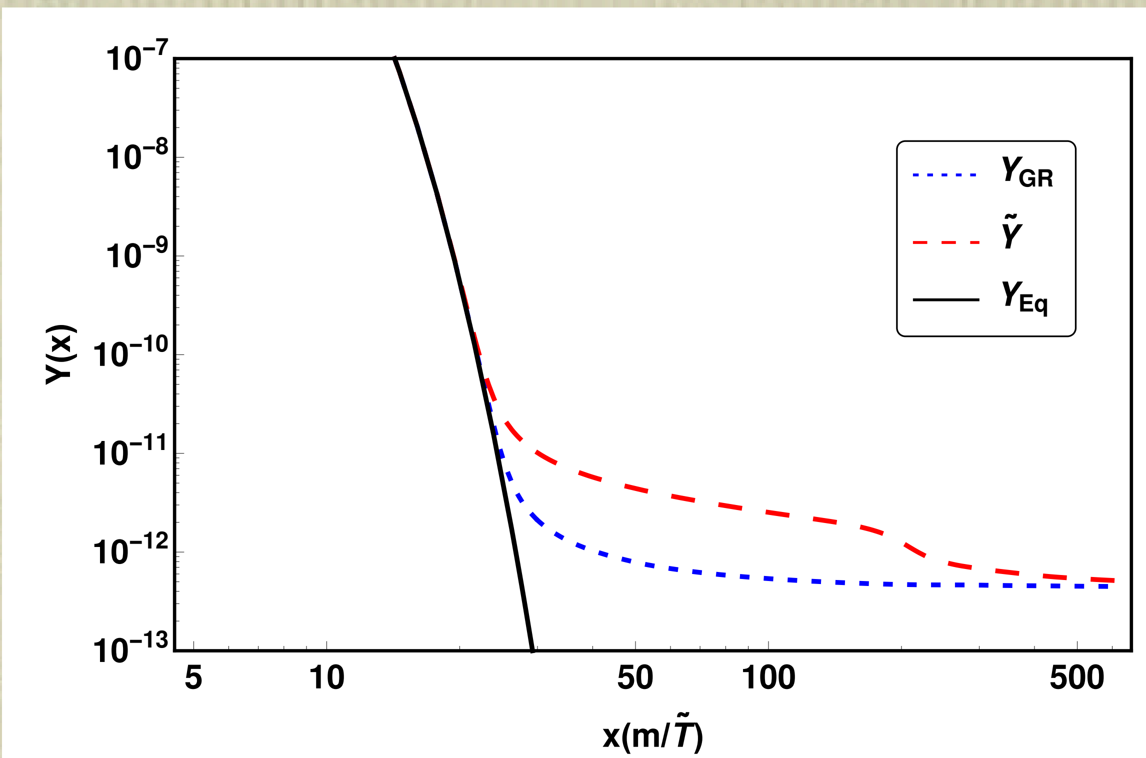
Here relic for a DM particle with mass

$m_\chi = 100\mathrm{GeV}$

[Similar behaviour in phenomenological model: D'Eramo, Fernandez, Profumo, '17]

Conformal Re-annihilation Effect

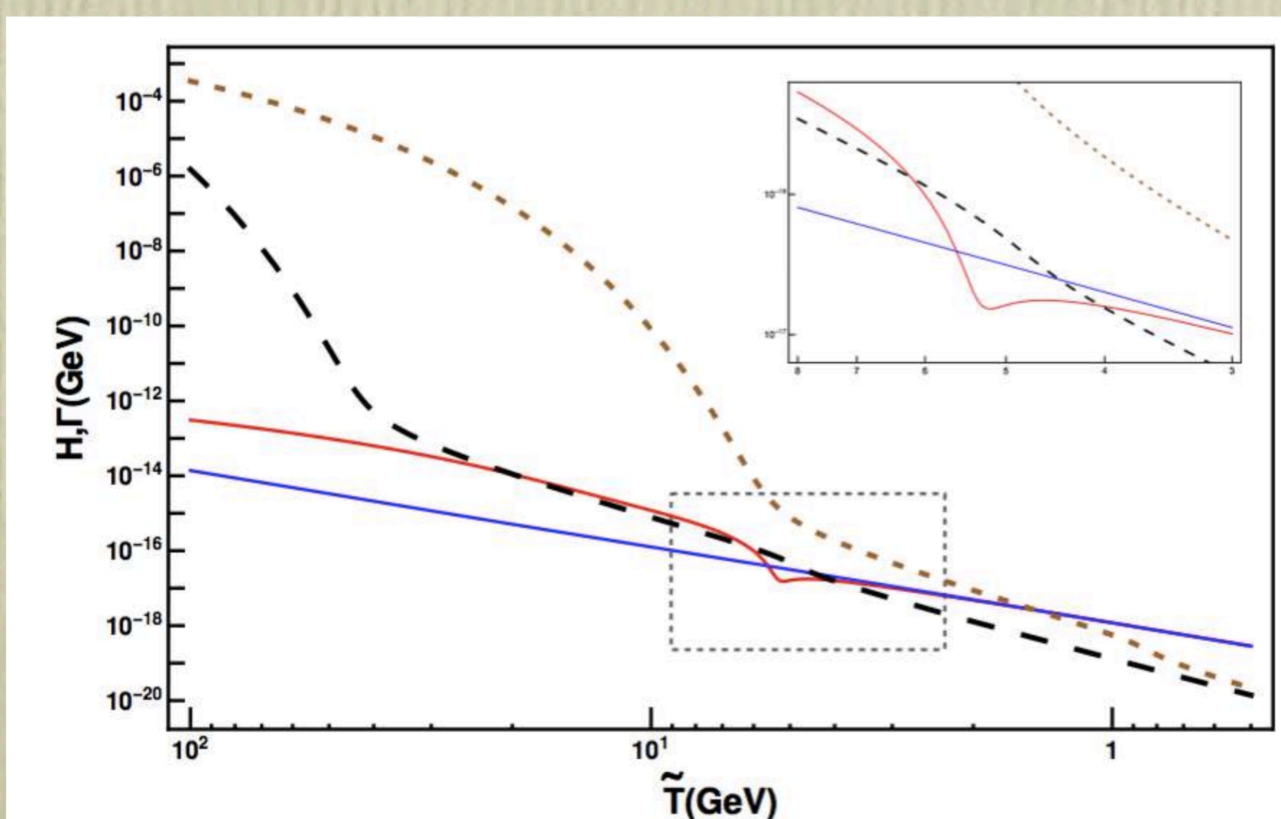
[Dutta, Jimenez, IZ, '16-17]



Relic abundance evolution is computed from Boltzmann equation

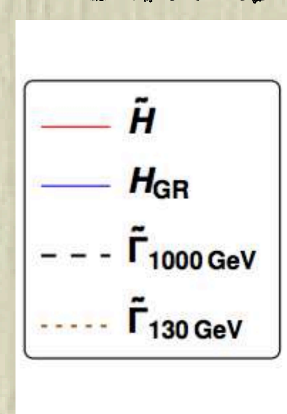
$$\frac{dY}{dx} = -\frac{\tilde{s}\langle\sigma v\rangle}{x\tilde{H}}\left(Y^2 - Y_{eq}^2\right)$$

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

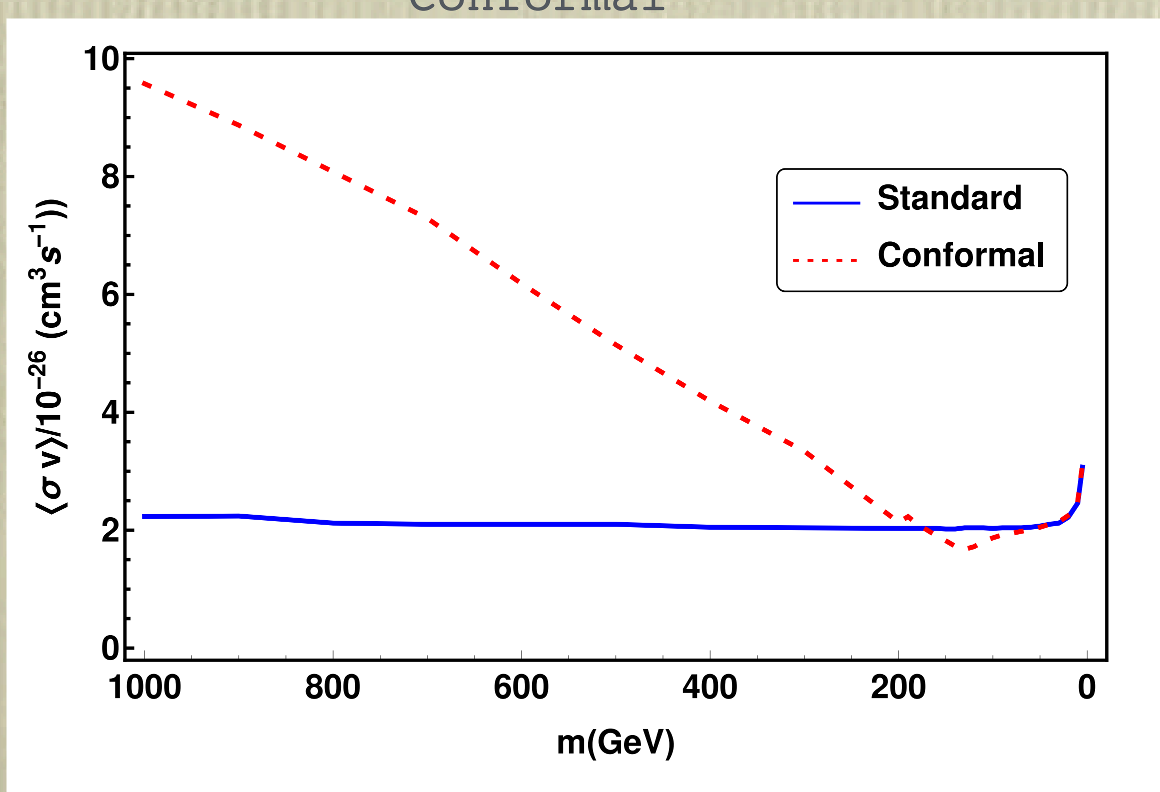
$$\Omega_{DM} = \frac{m_\chi Y_0 s_0}{\rho_{cr,0}} \qquad (= 0.27)$$

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

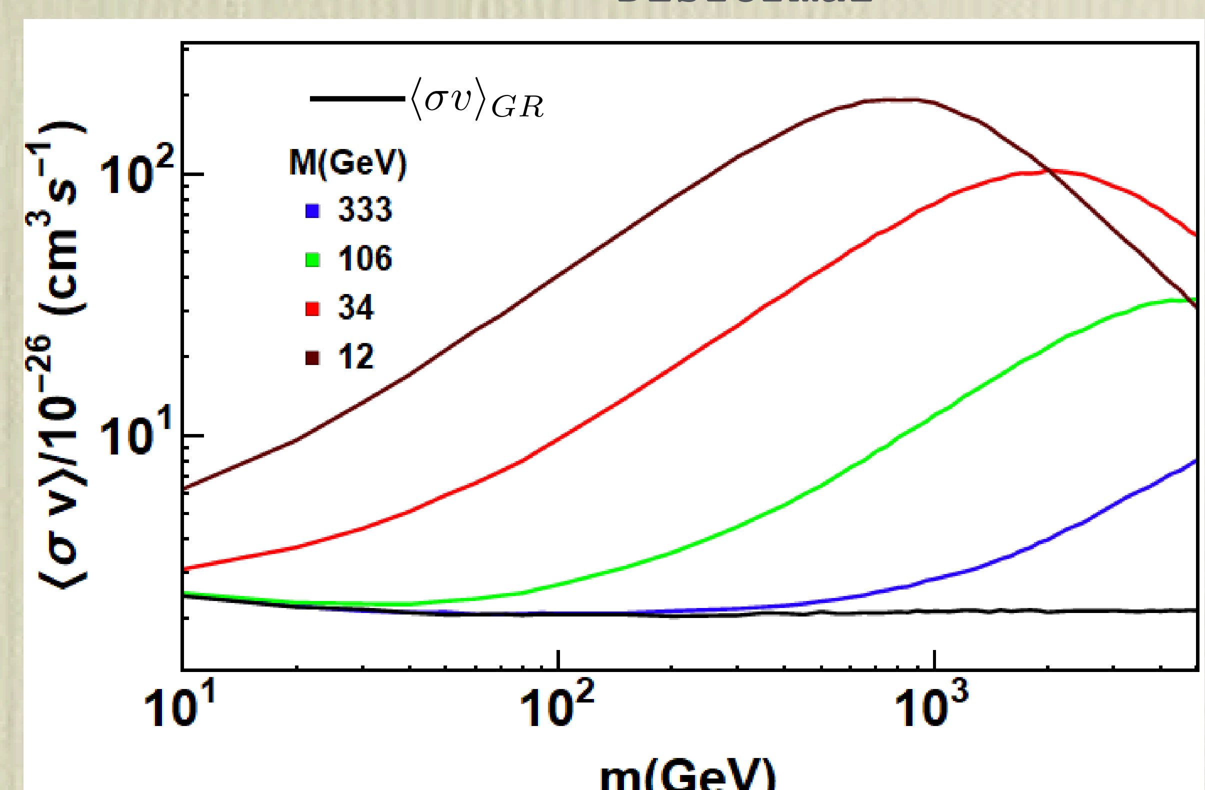
$$\frac{\tilde{x}}{\tilde{Y}}\frac{d\tilde{Y}}{d\tilde{x}} = -\frac{\tilde{\Gamma}}{\tilde{H}}\left(1-\left(\frac{\tilde{Y}_{eq}}{\tilde{Y}}\right)^2\right) \qquad \left(\tilde{\Gamma} \equiv \tilde{Y}\tilde{s}\langle\sigma v\rangle\right)$$

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

Conformal

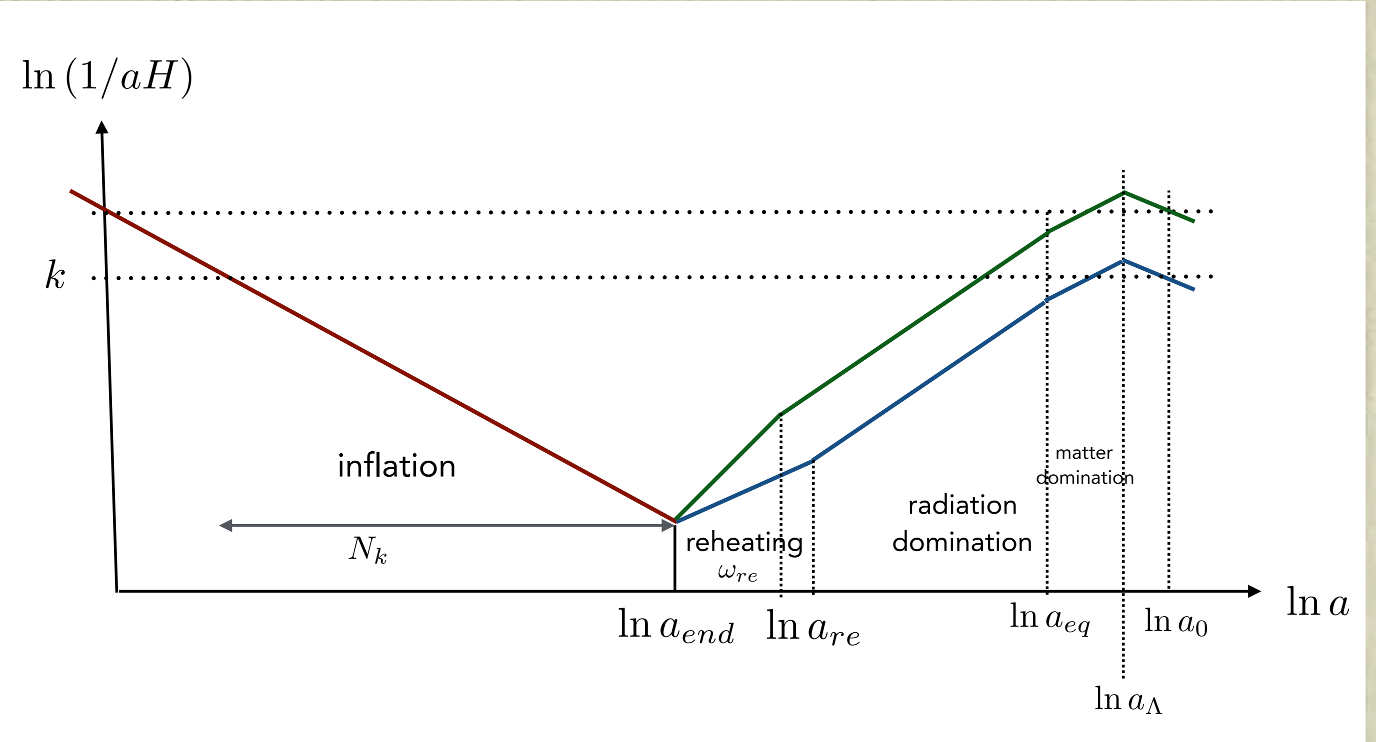


Disformal



Modified Evolution and Inflation

- Given a model of inflation, the cosmological parameters (n_s, r) are determined by the number of e-folds, N_k between horizon exit of the CMB modes and the end of inflation.



- The standard equation that determines N_k is given by

$$N_k \approx 57 + \frac{1}{4}\ln r - \frac{1}{4}(1 - 3w_{\rm re})\, N_{\rm re}\,,$$

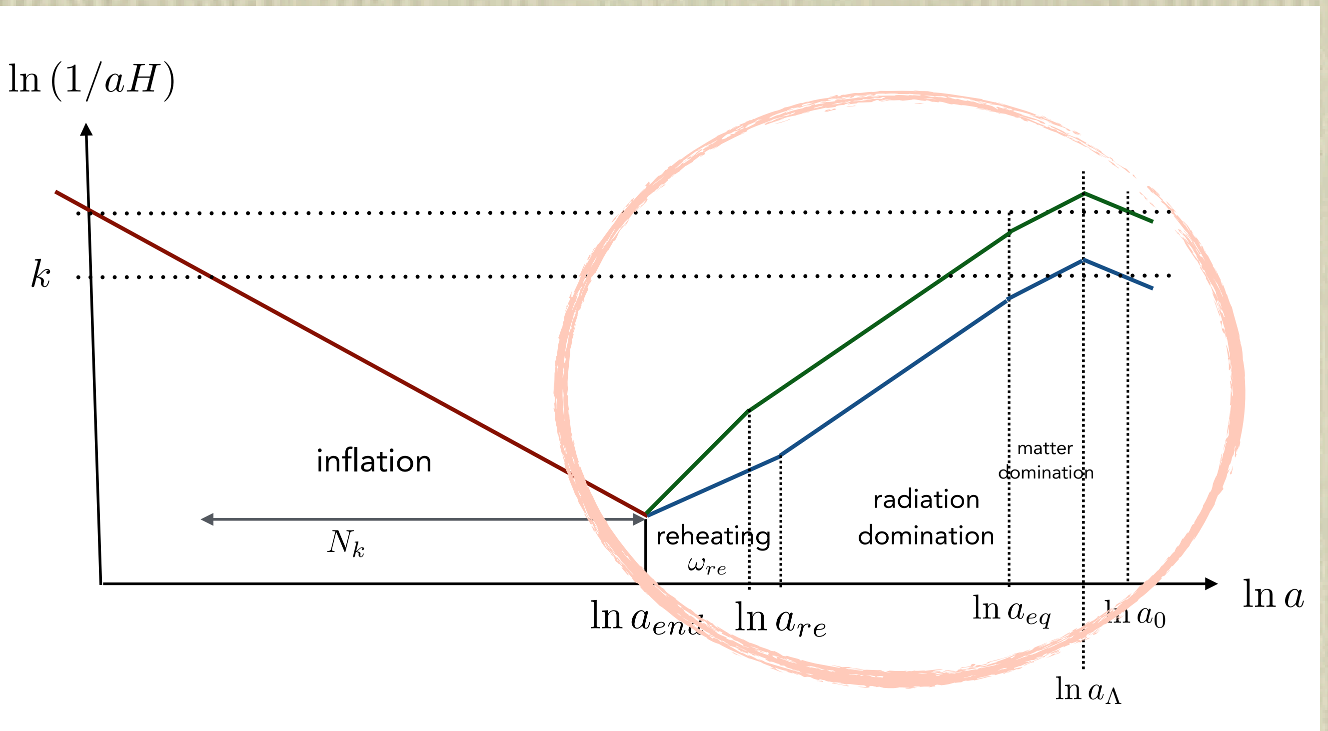
- This assumes a *standard* post-inflationary history associated with the hot big-bang model. In the canonical reheating scenario, $\omega_{\rm re} \simeq 0$. (In more general cases $0 < \omega_{\rm re} < 1/3$)

$$N_k \simeq 60 - 50$$

Modified Evolution and Inflation

- Any modification of the post-inflationary history has an effect on the range of N_k modifying the predictions for (n_s, r).

[Dai, Kamionkowski, Wang, '14]



- The models discussed before in the context of thermal dark matter abundance have a *non-standard cosmological history* prior to BBN.

- How does N_k is modified for these models and what would be the implications for inflationary predictions?

Disformal Coupling and the number of e-folds

[Maharana, IZ, '18]

- For the case of a pure disformal coupling: $C = C_0,\ D = 1/C_0 M^4$
  $(\tilde{g}_{\mu\nu} = C(\phi) g_{\mu\nu} + D(\phi)\partial_\mu \phi \partial_\nu \phi)$

The number of e-folds is modified by δN_k:

$$N_k \simeq N_k^{st} + \delta N_k$$

with

$$\delta N_k = -\frac{1}{8}(1 - 3\tilde{\omega}_{\rm re}) \ln C_{\rm re}$$

For $C_0 < 1$ (e.g. a D-brane at the tip of throat) $\delta N_k > 0$

➟ larger values of N_k compared to standard case.

Disformal Coupling and the number of e-folds

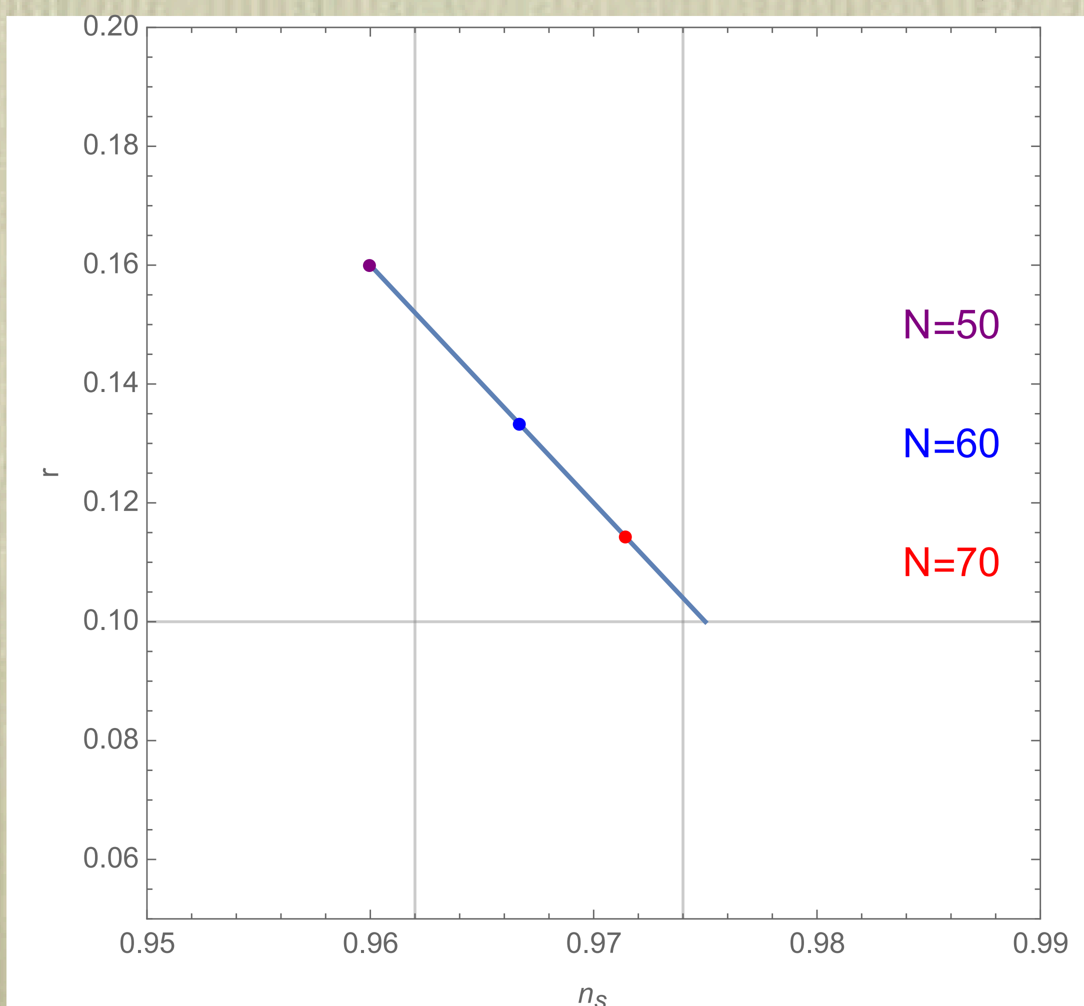
[Maharana, IZ, '18]

For suitable values of C_0, we find $\delta N_k \simeq 15$, implying $(\tilde{\omega}_{\rm re} \sim 0)$

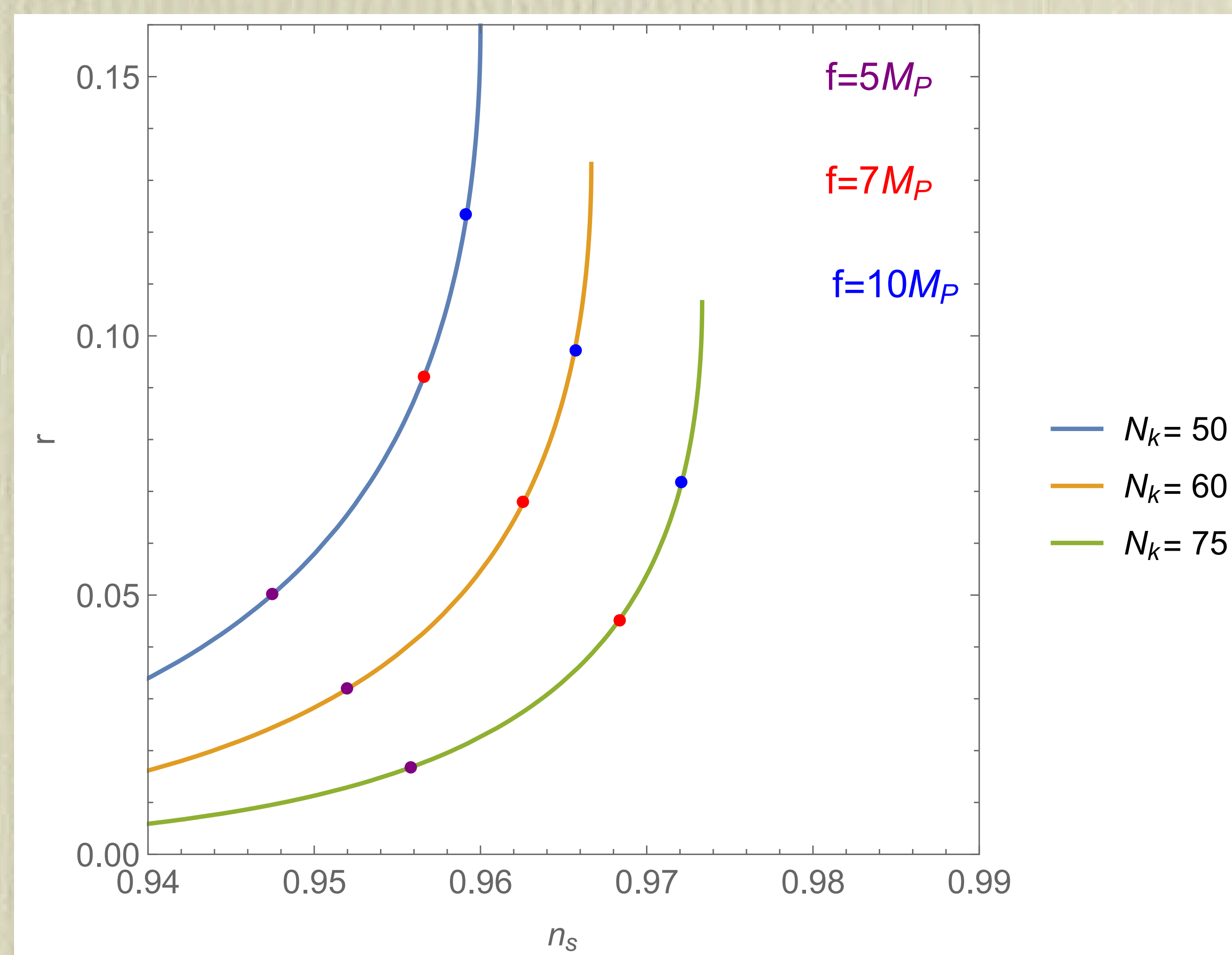
$$N_k \sim (60 - 50) + 15$$

For example, for monomial and natural inflation, this implies

monomial inflation $V \propto \phi^2$



natural inflation $V \propto [1 - \cos(\phi/f)]$



SUMMARY

- Scalar fields are ubiquitous in fundamental theories BSM. These fields can modify the standard cosmological evolution at different epochs, with interesting effects

- Particularly interesting is non-standard evolution in (D-brane) scalar-tensor theories with *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 this coupling is to *enhance or decrease the expansion rate*, with respect to the standard case.

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

SUMMARY

- When non-standard evolution happens during radiation domination, it can modify the standard DM thermal production scenario: freeze-out occurs at higher temperatures ➠ larger annihilation rates.

- Non-standard post-inflationary evolution changes also the inflationary predictions for cosmological parameters

- Non-standard expansion rate may be relevant for other physical phenomena during universe's evolution (21cm, H_0, … ?)