BEYOND ZERO-TEMPERATURE: MODULI FIELDS, THERMAL CORRECTIONS, AND DARK MATTER PRODUCTION

DIEGO GALLEGO MAHECHA

Work in progress... teaser

Dedicado a Dina, su bebé y las 22mil infancias martirizadas en Gaza.

COCO, COSMOLOGÍA EN EN COLOMBIA 2026

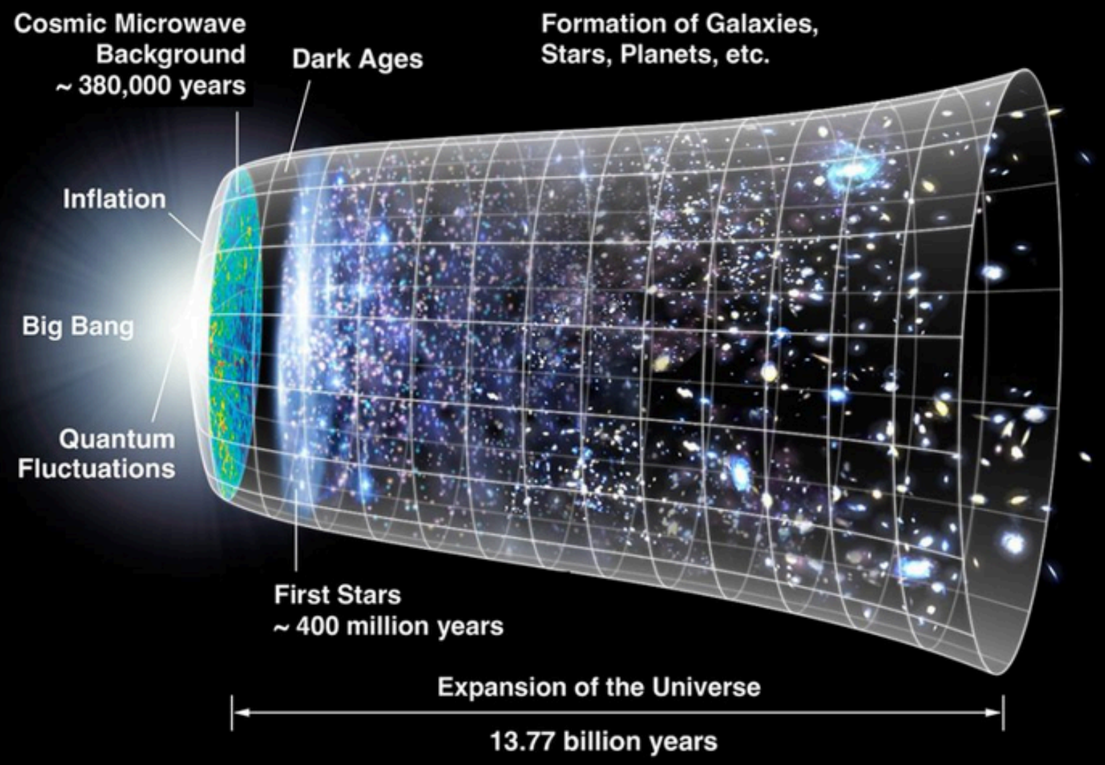
BOGOTÁ, UNIVERSIDAD ECCI NOVIEMBRE 5

WE KNOW A BIG DEAL

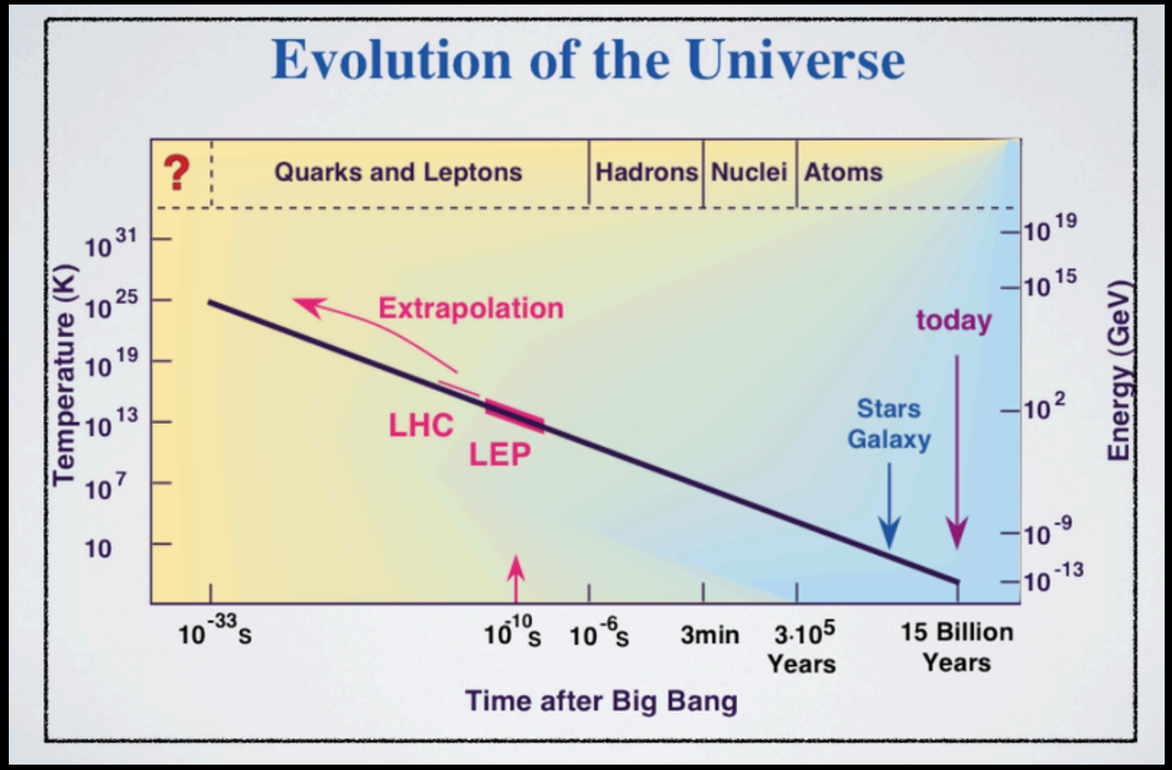
Prety sure of what happened after min. 3

Quite confident of Big Bang Nucleosynthesis (BBN)

As well particles and interactions we deal with up to the TeV scale.



NASA/WMAP Science Team, public domain



D. Marsh 2015

FUTURE IS DARK





Tackling the dark side

knowing the very early cosmology

large and small scales intertwined

Hints from UV constructions

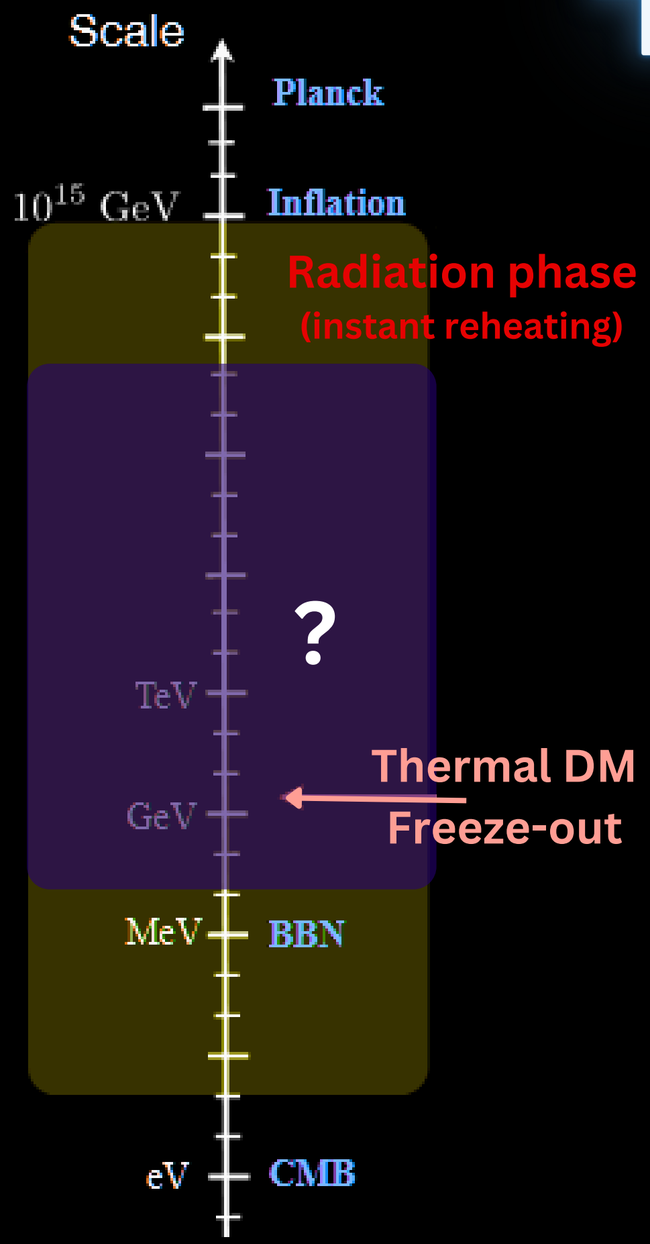
ballpark to start exploring.

Intention

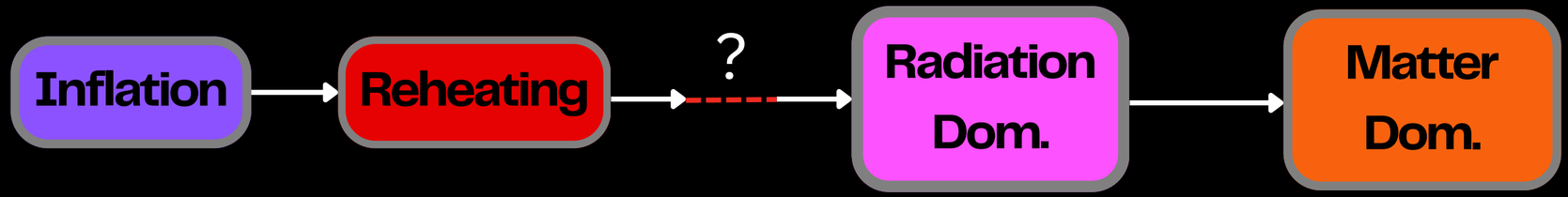
- review some generalities of scalar fields in cosmology.
- motivate the inclution of temperature.
- use a toy model to explore possible implications

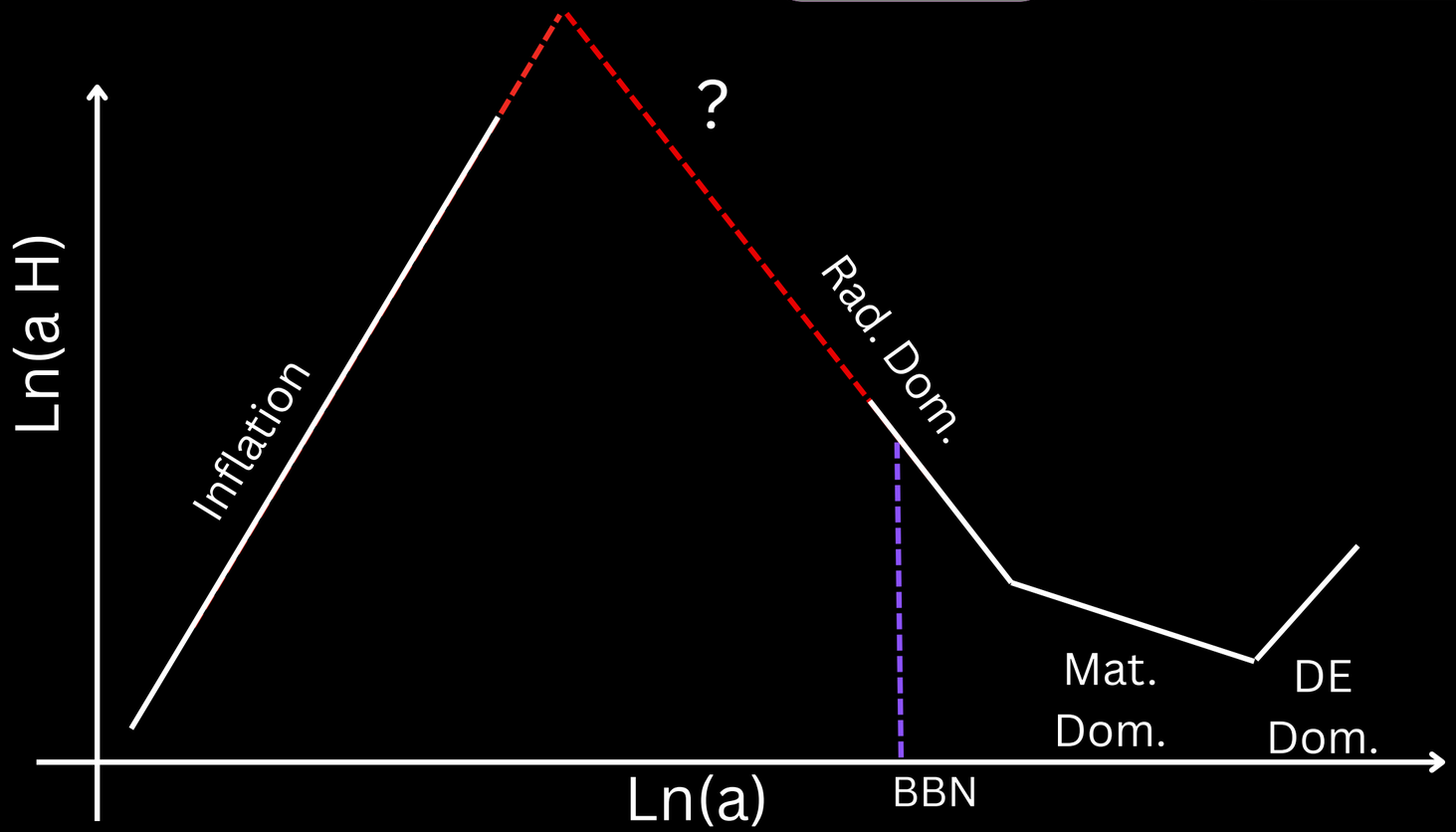
THERMAL HISTORY

Standard history



[Kane-Sinha-Watson '15]





SCALAR FIELDS

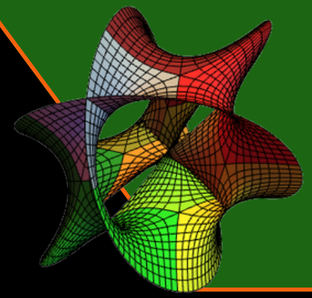
Simplest for going Beyond, e.g.,

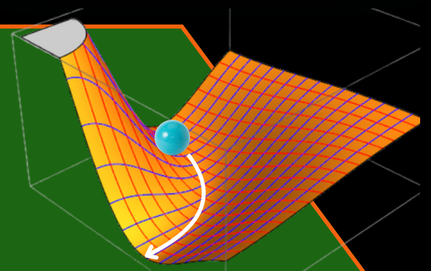
Brans-Dicke gravity Inflation

Quite natural after the Higgs discovery.

Moduli fields

flat directions in SUSY theories





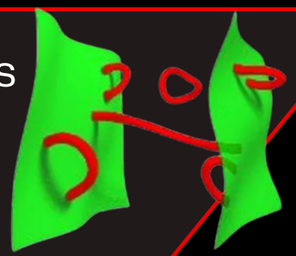
associated to couplings and geometry in string theory.

Gravitational sized interactions $\Gamma \sim \frac{1}{2\pi}\frac{m^3}{M_{\rm P}^2}$

$30\ \mathrm{TeV} \lesssim m$ For decaying before BBN

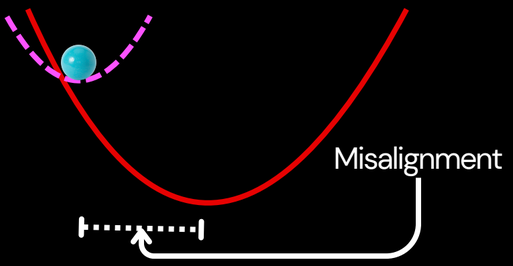
Possible sequestered interactions



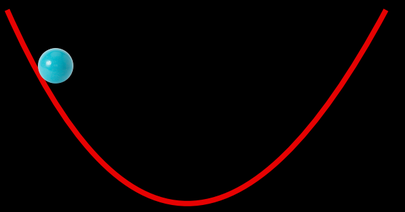


Possible mass hierarchies

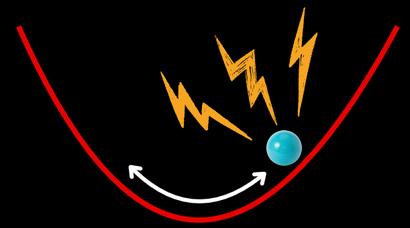
- **Deformed potential during inflation**
- **Initial energy stored**



- **Pinned due to Hubble friction until** $H \sim m$



- **Oscillations around the new “true” minimum**

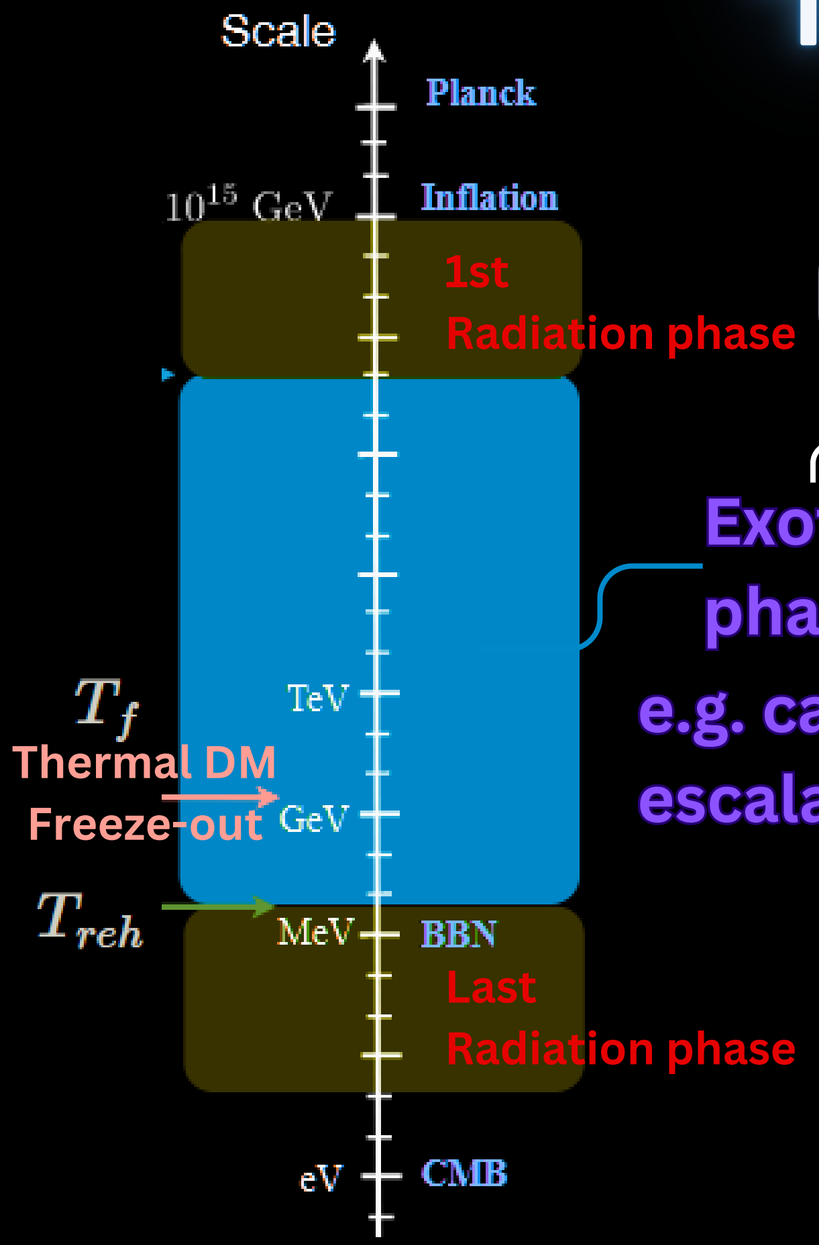


- **Decay, energy release = reheating**

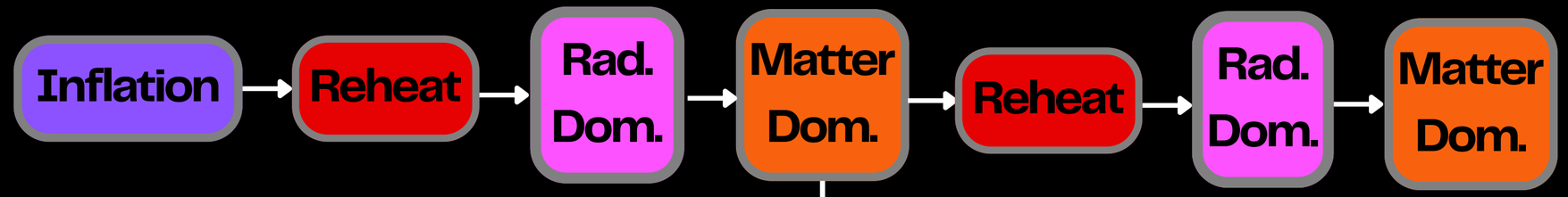
$T \sim \sqrt{M_{\rm P}\Gamma}$

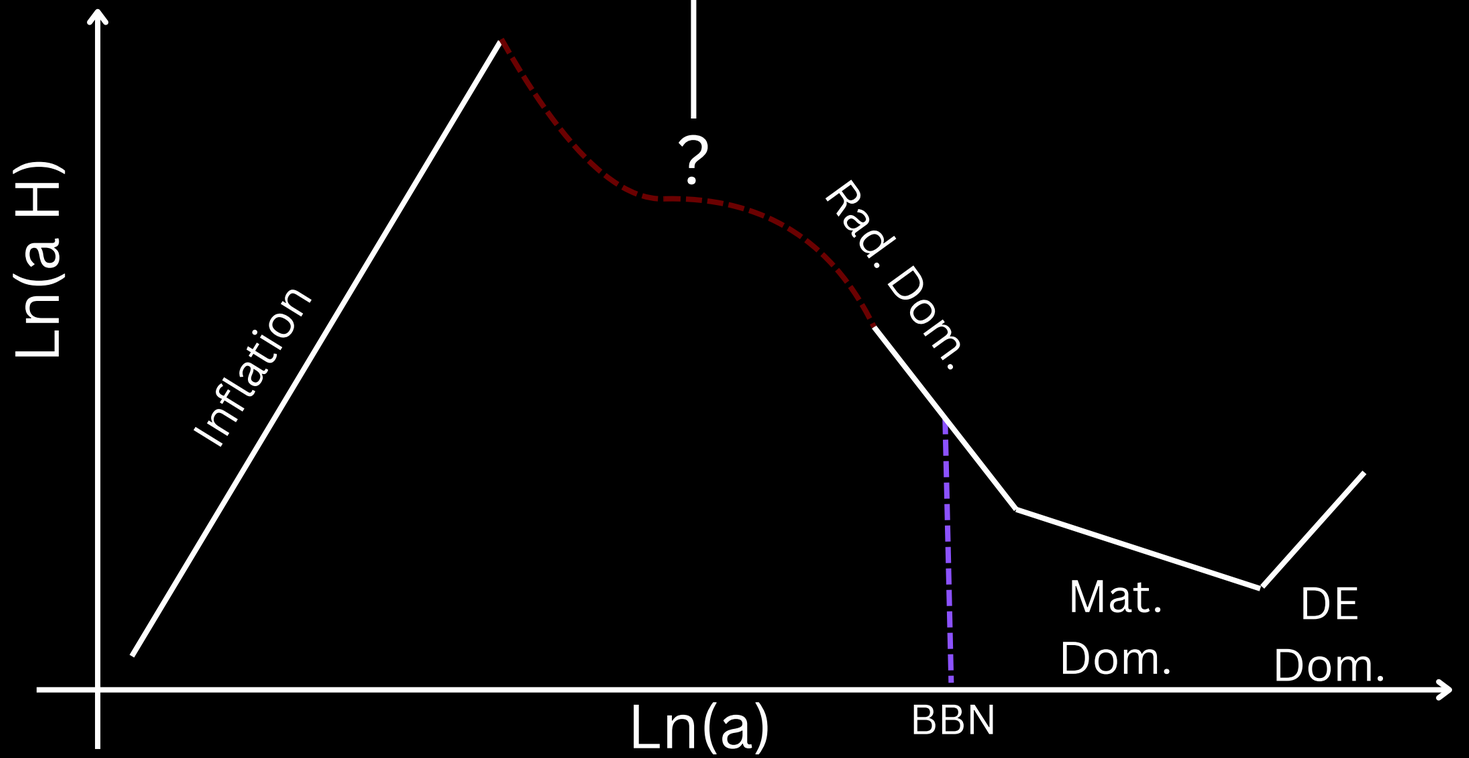
THERMAL HISTORY

Non – standard history



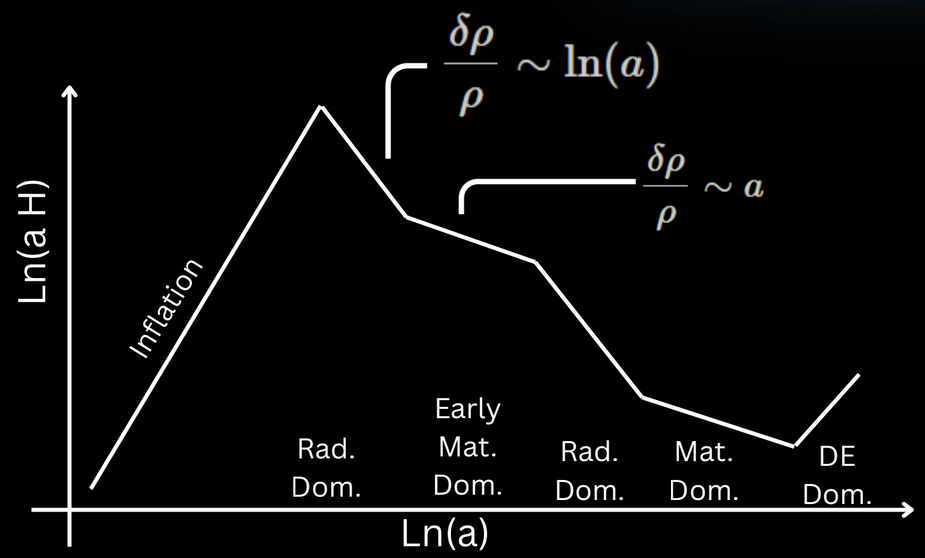
Exotic phases e.g. campos escalares





POSSIBLE EFFECTS

(For a review see [Kane-Sinha-Watson'15] also [Allahverdi et al.'20])



$$\Omega_{DM} \rightarrow \Omega_{DM}\left(\frac{T_{reh}}{T_f}\right)^3$$

$$n_{DM} \sim n_\phi \times Br_{\phi \rightarrow DM}$$

Different expassion history

imprints in the CMB observables — [Liddle-Leach'03,Easther et al. '13 Dutta-Maharana'15, Cicoli et al. '16]

larger matter perturbations, enhanced DM microhalos and PBH production — [Polnarev-Khlopov'85,Erickcek-Sigurdson '11, Fan-Ozsoy-Watson' 14, Erickcek-Sinha- Watson'15,Georg-Sengor-Watson'16]

Dilute relics

entropy injection due to decays dilutes previous relics — [Fornengo-Riotto-Scopel'03,Gelmini et al.'06,Hooper'13, Patwardhan et al.'15,Randall-Scholtz-Unwin'16]

Baryogenesis revisited — [Allahverdi-Dutta- Sinha'10, Kane et al. '11, Allahverdi-Cicoli-Muia'16]

Direct production

non-thermal DM production — [Chung-Kolb-Riotto'99,Giudice-Kolb-Riotto'01,Acharya et al.'08,Allahverdi-Dutta- Sinha'11,Allahverdi et al.'13,Kane et al. 16,Allahverdi-Osiński'19, Bernal et al.'19, Allahverdi et al.'21]

NON-THERMAL PRODUCTION

Microscopic approach

[Albrecht et al.'82, Allahverdi et al.'10]

Klein–Gordon equation with decay in FLRW

Boltzmann equations for radiation and DM

Friedmann equation

$$\ddot{\phi} + 3H\dot{\phi} + \partial_\phi V = -\Gamma\dot{\phi}$$

$$\begin{cases} \dot{\rho}_r + 4H\rho_r = \Gamma(1-Br)\dot{\phi}^2 + \dfrac{\langle\sigma v\rangle}{m_\chi}\left(\rho_\chi^2 - \rho_{\chi,eq}^2\right) \\ \dot{\rho}_\chi + 3H\rho_\chi = \boxed{\Gamma Br\dot{\phi}^2} - \dfrac{\langle\sigma v\rangle}{m_\chi}\left(\rho_\chi^2 - \rho_{\chi,eq}^2\right) \end{cases}$$

$$H^2 = \frac{1}{3}\left(\frac{1}{2}\dot{\phi}^2 + V(\phi) + \rho_r + \rho_\chi\right)$$

Effective approach

[Chung-Kolb-Riotto'99, Giudice-Kolb-Riotto'01, Acharya et al.'08, Allahverdi-Dutta- Sinha'11, Allahverdi et al.'13, Kane et al. 16, Allahverdi-Osiński'19, Allahverdi et al.'21]

- use macroscopic variables

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi) \qquad p_\phi = \frac{1}{2}\dot{\phi}^2 - V(\phi) \qquad w_\phi \equiv \frac{p_\phi}{\rho_\phi} \qquad \rho_\chi = m_\chi n_\chi$$

- assume integration over fast oscillating modes
- use the case of quadratic potential $w_\phi = 0$ [Turner'83]

THERMAL CORRECTIONS

[Kapusta&Gale'07, Weinberg'74, Dolan & Jackiw'74,Binetruy-Gaillard'85a-b]

Effective action

using finite temperature techniques

free gass level usual "Stefan–Boltzmann" $\rho_r \propto T^4$

higher orders reveal dependencies on:

- the couplings
- masses

involved in the thermal bath.

1–loop level

$$F^{(1)} \sim -T^4 + \text{masses}^2 T^2$$

2–loop level

$$F^{(2)} \sim \text{couplings} \times (T^4 + \text{masses}^2 T^2)$$

recall that masses and couplings depend on the moduli

Despite moduli and thermal bath decoupled

Moduli dependencies appear in the masses and couplings

$g(\phi)^2 \propto e^{-\alpha\phi}$ » $F(T,\phi) \sim (1 - re^{\alpha\phi})T^4$

Moduli dynamics

Effects on the moduli stabilization in several string theoretical setups

Constraints and cosmological observables

[Nakayama–Takahashi'09, Mukaida,–Nakayama'13, Hagihara– Hamaguchi–Nakayama'19, Buchmüller et al.'04, Buchmüller et al. '05, Barreiro et al.'08, Anguelova–Calo'08, Anguelova–Calo–Cicoli'09, Papineau'08, Gallego'20]

Thermal corrections in SM and extensions

thermal masses, effective mixing and damping rates for DM production

[Carrinton'92, Guidice'04]

[Baker–Kopp'17, Lello–Boyanovsky–Pisarski'17, Baker–Kopp.'17, Baker et al. '18, Darme et al. '19, Biondini–Ghiglieri'21, Konar–Roshan–Show'22, Abada et al. '23, Biondini '23, Chakrabarty et al. '23, Becker et al.'25]

IDEA

Muduli fields and non-standard cosmologies

Finite temperature effects

Non-thermal DM production

Study the effects of finite temperature in non-thermal producion in non-standard cosmologies

NON-DECAYING SINGLE FIELD IN THERMAL BATH

Corrected equations

$$\ddot{\phi} + 3H\dot{\phi} + \partial_\phi V = -\Gamma\dot{\phi} - \frac{1}{3}\frac{r\alpha e^{-\alpha\phi}}{(1 - re^{-\alpha\phi})}\rho_r$$

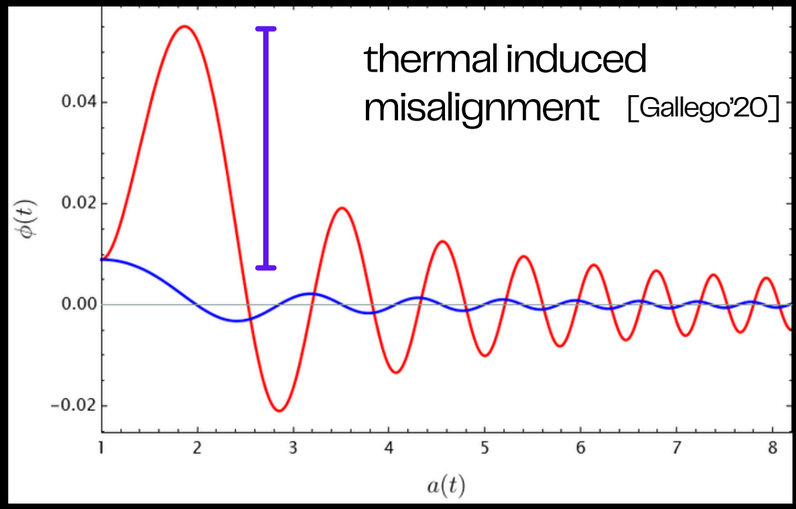
$$\dot{\rho}_r + 4H\rho_r = \Gamma\dot{\phi}^2 + \frac{1}{3}\frac{r\alpha e^{-\alpha\phi}}{(1 - re^{-\alpha\phi})}\dot{\phi}\rho_r$$

m	α	r	$\phi(t_0)$	$\rho_r(t_0)$	Γ
$1/2$	1	$1/7$	$1/50\sqrt{5}$	1	0

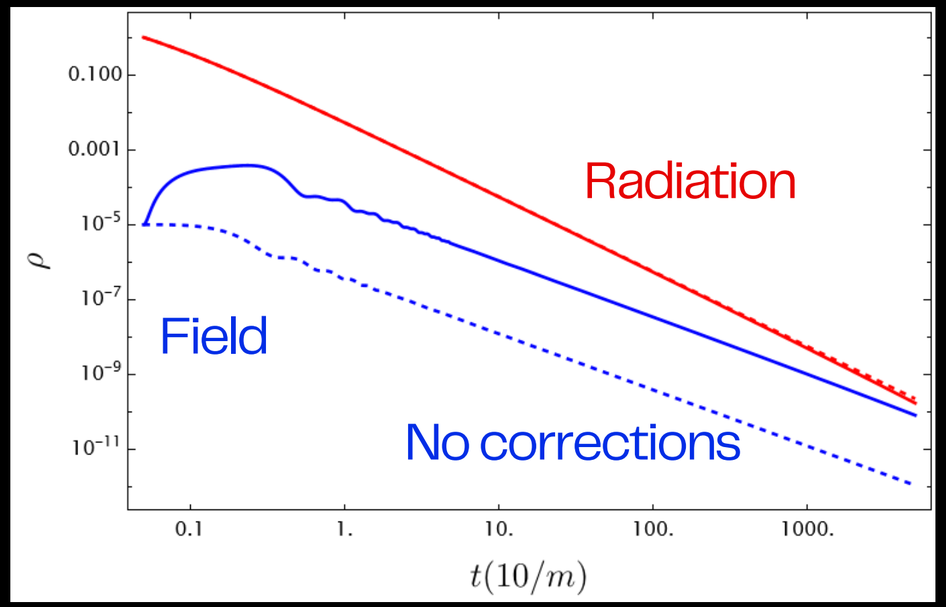
Toy model

$$V = \frac{1}{2}m^2\phi^2$$

Field evolution

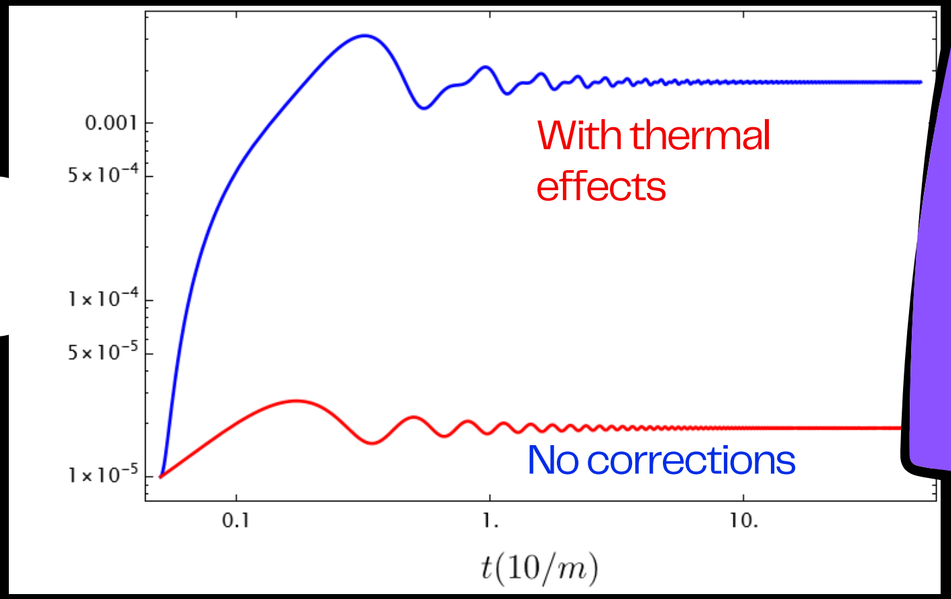


Abundances



Rescaled field energy density

$\rho_\phi a^3$



Larger field contribution
Earlier field domination

SECOND HEAVIER FIELD

Corrected equations

$$\ddot{\phi} + (3H + \Gamma_\phi)\dot{\phi} + \partial_\phi V = \frac{1}{3}\partial_\phi \rho_r$$

$$\ddot{\Phi} + (3H + \Gamma_\Phi)\dot{\Phi} + \partial_\Phi V = 0$$

$$\dot{\rho}_r + 4H\rho_r = \Gamma_\Phi\,(1 - Br_{\Phi\to\chi})\dot{\Phi}^2 + \Gamma_\phi\,(1 - Br_{\phi\to\chi})\dot{\phi}^2 - \frac{1}{3}\partial_\phi \rho_r$$

$$\dot{\rho}_\chi + 3H\rho_\chi = Br_{\Phi\to\chi}\Gamma_\Phi\dot{\Phi}^2 + Br_{\phi\to\chi}\Gamma_\phi\dot{\phi}^2$$

Neglecting thermal production

$$\rho_{sc} = \frac{1}{2}\dot{\phi}^2 + \frac{1}{2}\dot{\Phi}^2 + V(\phi,\Phi)$$

$$H^2 = \frac{1}{3}\left(\frac{1}{2}\dot{\phi}^2 + \frac{1}{2}\dot{\Phi}^2 + V(\phi,\Phi) + m_\chi n + \rho_r\right)$$

Toy model

$$V(\phi,\Phi) = \frac{1}{2}m^2\phi^2 + \frac{1}{2}M^2\Phi^2$$

Parameters

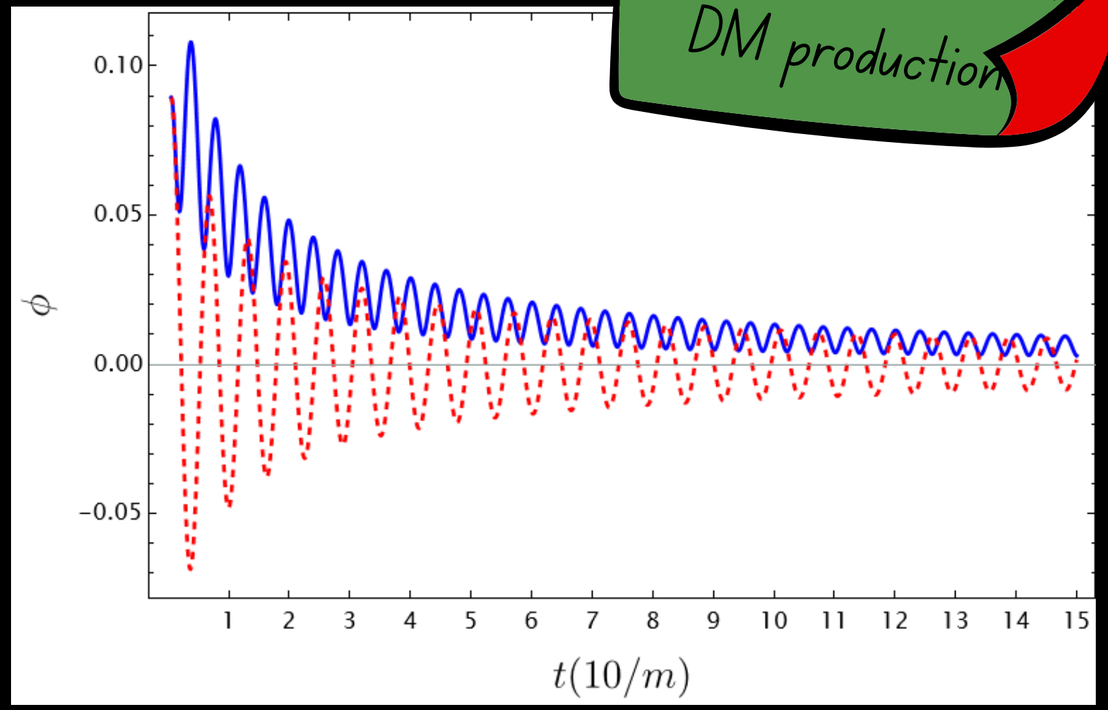
M	$\Phi(t_o)$	m	ϕ_o	r	$\rho_{r,0}$	m_χ
$9/10$	$1/7$	$1/2$	$1/5\sqrt{5}$	1	0	$1/20$

No matter production

Γ_Φ	$Br_{\Phi\to\chi}$	Γ_ϕ	$Br_{\phi\to\chi}$
M^3	0	0	0

Thermal misalignment persists

Thermal kick from reheating
Expected enhanced DM production

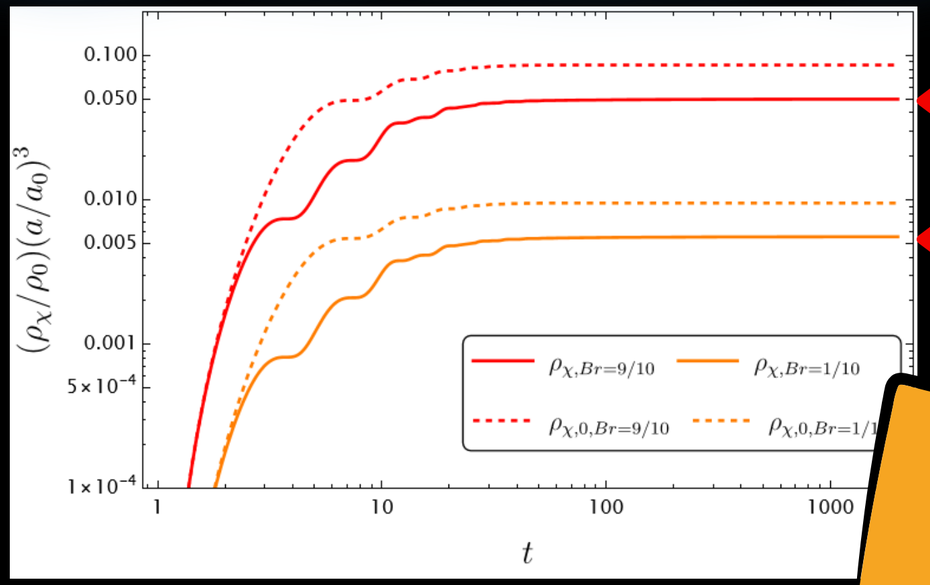


LIGHT FIELD DM NON-THERMAL PRODUCTION

M	$\Phi(t_o)$	m	ϕ_o	r	$\rho_{r,0}$	m_χ
$9/10$	$1/7$	$1/2$	$1/5\sqrt{5}$	1	0	$1/20$

Γ_Φ	$Br_{\Phi\to\chi}$	Γ_ϕ	$Br_{\phi\to\chi}$
M^3	0	m^3	$1/10\ (9/10)$

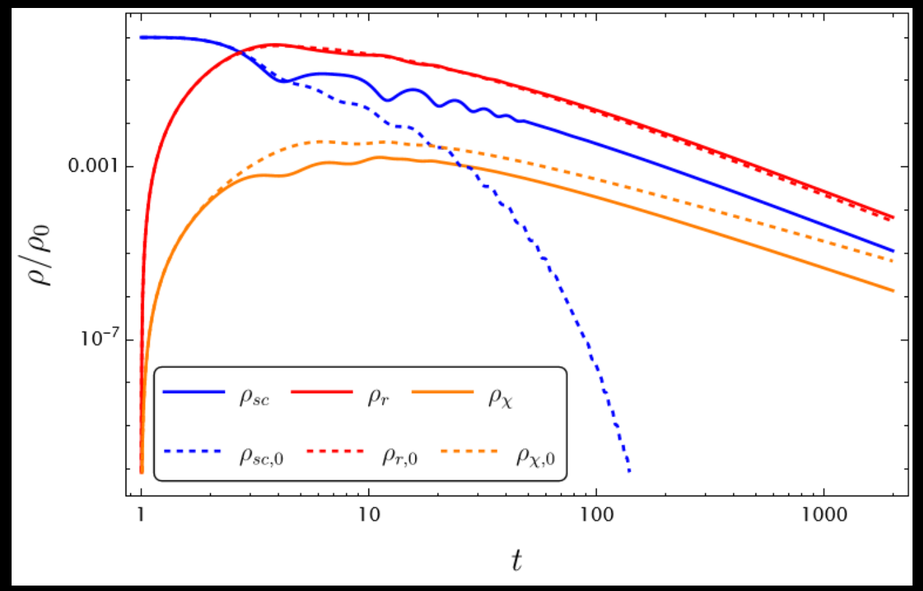
DM relics



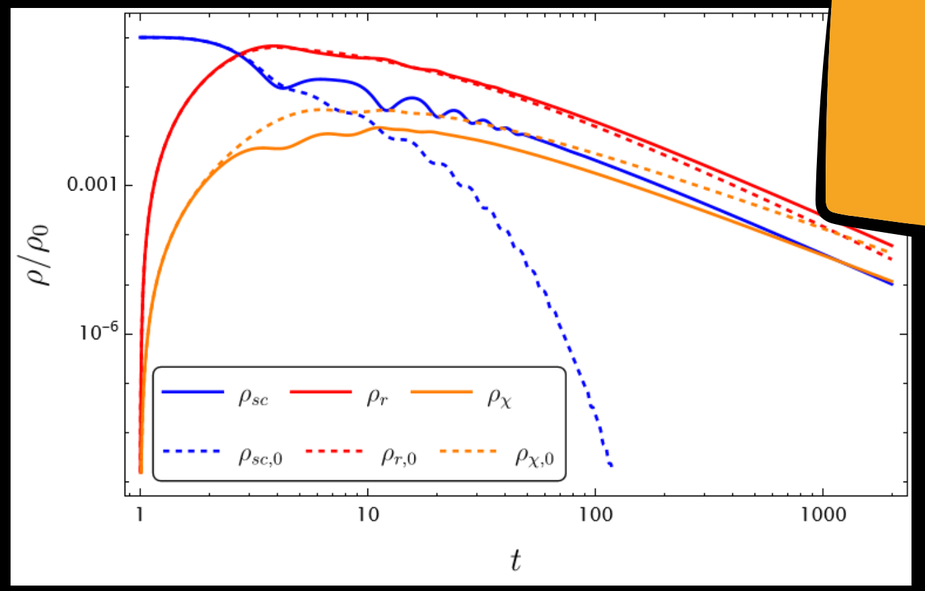
Including thermal effects

DM production is suppressed by finite temperature effects!

Energy abundances Br=1/10



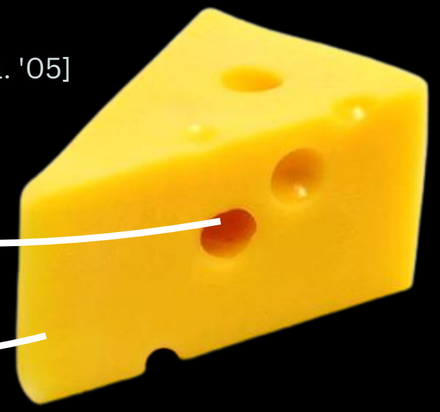
Energy abundances Br=9/10



¿A UV REALIZATION?

Large Volume Scenario from type IIB strings [Balasubramanian et al. '05]

$$V_{mod} = \frac{\zeta}{\mathcal{V}^3} + \frac{\lambda e^{-2x} x^{\beta}}{\mathcal{V}^{2\eta-3}} - \frac{\mu e^{-x} x^{\alpha}}{\mathcal{V}^{\eta}}$$



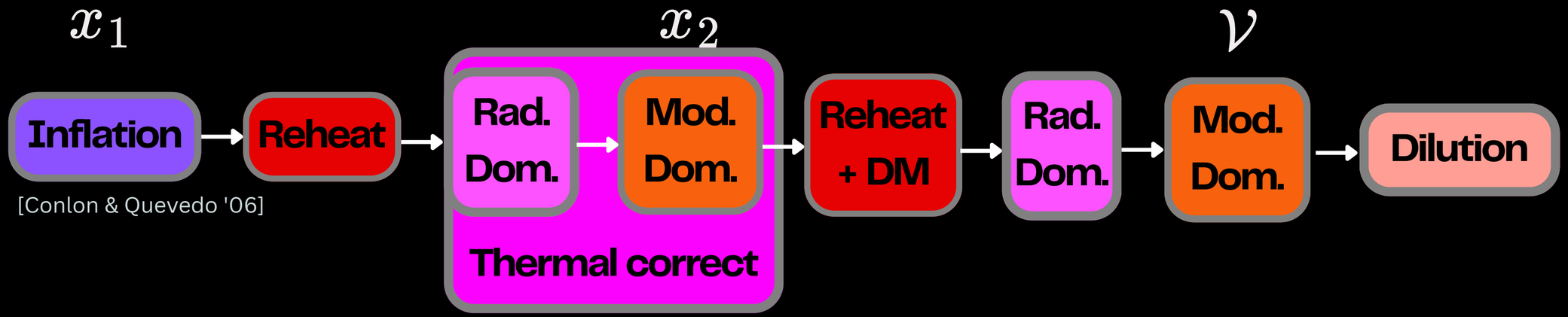
Geometrical moduli asociated to extradimensions

Mass hierarchy $\epsilon \equiv 1/\mathcal{V}$

$$m_x^2 \sim \epsilon^2 M_P^2 \gg m_{\mathcal{V}}^2 \simeq \epsilon m_x^2$$

But $m_\chi \sim \epsilon \gg m_{\mathcal{V}}$ Too light to decay to DM

A scenario with two small moduli and the volume one. $m_{x_1} > m_{x_2} \gg m_{\mathcal{V}}$



[Conlon & Quevedo '06]

SUMMARY

Scalar fields (moduli) are well motivated in UV constructions

A non-standard thermal history is to be expected

DM production is sensitive to the thermal evolution of the universe

Further mechanisms of DM production are to be explored, e.g., branching scenarios

Precise predictions require the inclution of finite temperature effects

Thermal effects change the dynamics of the scalar fields. E.g. increase the field quanta

Contrary to expectations (?) DM production is suppresed

LVS presents a possible set up but further considerations

SUMMARY

Scalar fields (moduli) are well motivated in UV constructions

- Does all this makes any sense?
- How realistic is this toy model?
- How much of this is preserved with theoretical and phenomenological well motivated parameters?
- Non-perturbative effects?
- If this is the case, are the effects within the experimental sensitivity?

Further mechanisms of DM production are to be explored, e.g., branching scenarios

Precise predictions require the inclution of finite temperature effects



THERMAL CORRECTIONS

[Kapusta&Gale'07, Weinberg'74, Dolan & Jackiw'74,Binetruy-Gaillard'85a-b]

Effective action

using finite temperature techniques

free gass level usual "Stefan–Boltzmann" $\rho_r \propto T^4$

higher orders reveal dependencies on:

- the couplings
- masses

involved in the thermal bath.

1–loop level

$$F^{(1)} = -\frac{\pi^2}{90}\left(g_B + \frac{7}{8}g_f\right)T^4 + \frac{1}{24}(\mathrm{Tr}M_b^2 + \mathrm{Tr}M_f^2)T^2$$

2–loop level

$$F^{(2)} = \left(\sum_j f_j(g_i)\right)\left[aT^4 + b(\mathrm{Tr}M_b^2 + \mathrm{Tr}M_f^2)T^2\right]$$

recall that masses and couplings depend on the moduli

Despite moduli and thermal bath decoupled

Moduli dependencies appear in the masses and couplings

$$g(\phi)^2 \propto e^{-\alpha\phi} \;\Rightarrow\; F(T,\phi) = -c_0\left(1 - re^{-\alpha\phi}\right)T^4$$

Moduli dynamics

Effects on the moduli stabilization in several string theoretical setups

Constraints and cosmological observables

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NON-THERMAL PRODUCTION

$$\ddot{\phi} + 3H\dot{\phi} + \partial_\phi V = -\Gamma\dot{\phi}$$

$$\dot{\rho}_r + 4H\rho_r = \Gamma(1-Br)\dot{\phi}^2 + \frac{\langle\sigma v\rangle}{m_\chi}\left(\rho_\chi^2 - \rho_{\chi,eq}^2\right)$$

$$\dot{\rho}_\chi + 3H\rho_\chi = \Gamma Br\dot{\phi}^2 - \frac{\langle\sigma v\rangle}{m_\chi}\left(\rho_\chi^2 - \rho_{\chi,eq}^2\right)$$

$$H^2 = \frac{1}{3}\left(\frac{1}{2}\dot{\phi}^2 + V(\phi) + \rho_r + \rho_\chi\right)$$

Microscopic approach [Albrecht et al.'82,Allahverdi et al.'10]

Klein–Gordon equation with decay in FLRW

Boltzmann equations for radiation and DM

Friedmann equation

Effective approach

[Chung-Kolb-Riotto'99,Giudice-Kolb-Riotto'01,Acharya et al.'08,Allahverdi-Dutta-Sinha'11,Allahverdi et al.'13,Kane et al. 16,Allahverdi-Osiński'19, Allahverdi et al.'21]

- use macroscopic variables

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi) \qquad p_\phi = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

$$w_\phi \equiv \frac{p_\phi}{\rho_\phi} \qquad \rho_\chi = m_\chi n_\chi$$

- assume integration over fast oscillating modes
- use the case of quadratic potential $w_\phi = 0$ [Turner'83]

$$\dot{\rho}_\phi + 3H\rho_\phi = -\Gamma\rho_\phi$$

$$\dot{\rho}_r + 4H\rho_r = \Gamma(1-Br)\rho_\phi + \frac{\langle\sigma v\rangle}{m_\chi}\left(\rho_\chi^2 - \rho_{\chi,eq}^2\right)$$

$$\dot{\rho}_\chi + 3H\rho_\chi = \Gamma Br\rho_\phi - \frac{\langle\sigma v\rangle}{m_\chi}\left(\rho_\chi^2 - \rho_{\chi,eq}^2\right)$$

$$H^2 = \frac{1}{3}\left(\rho_\phi + \rho_r + \rho_\chi\right)$$

DECAYING SINGLE FIELD

Corrected equations

$$\ddot{\phi} + 3H\dot{\phi} + \partial_\phi V = -\Gamma\dot{\phi} - \frac{1}{3}\frac{r\alpha e^{-\alpha\phi}}{(1 - re^{-\alpha\phi})}\rho_r$$

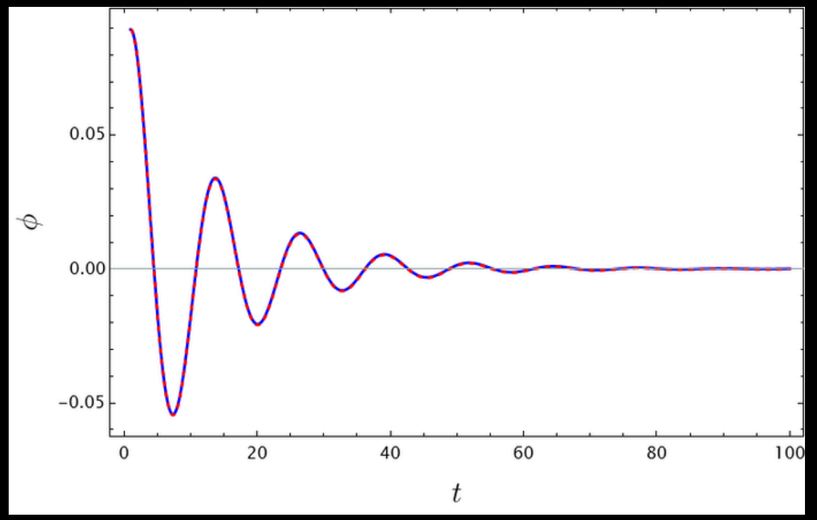
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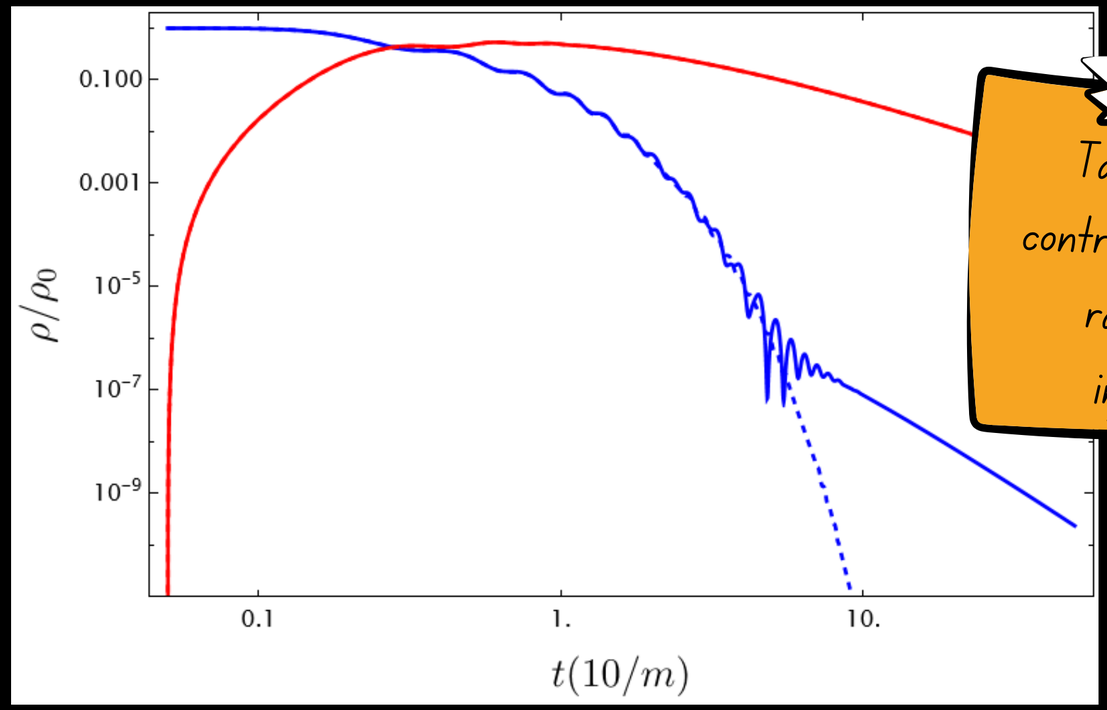
m	α	r	$\phi(t_0)$	$\rho_r(t_0)$	Γ
$1/2$	1	$1/7$	$1/5\sqrt{5}$	0	$1/8$

Toy model

$$V = \frac{1}{2}m^2\phi^2$$

Field evolution





Tail of field contribution from radiation injection

Self induced thermal corrections

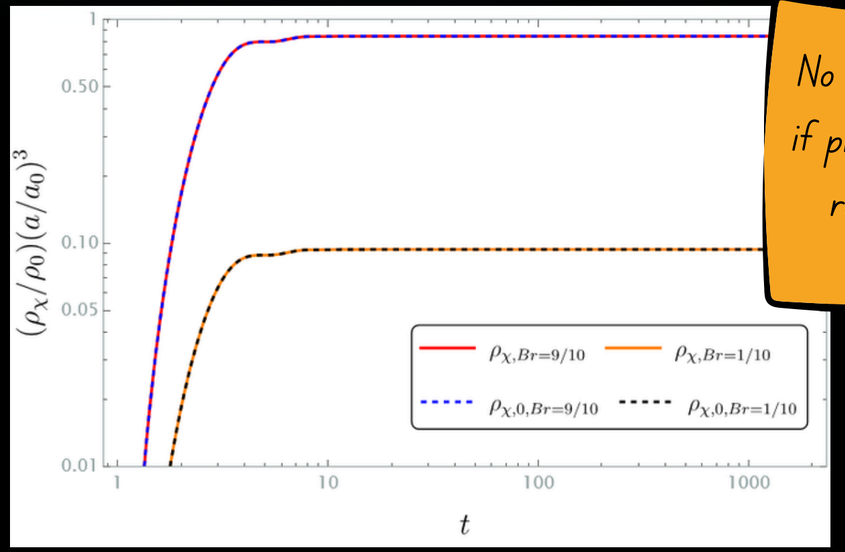
- thermal bath inset by the field decay
- no relevant contributions, but a tail in the field contribution

HEAVY FIELD DM NON-THERMAL PRODUCTION

M	$\Phi(t_o)$	m	ϕ_o	r	$\rho_{r,0}$	m_χ
$9/10$	$1/7$	$1/2$	$1/5\sqrt{5}$	1	0	$1/20$

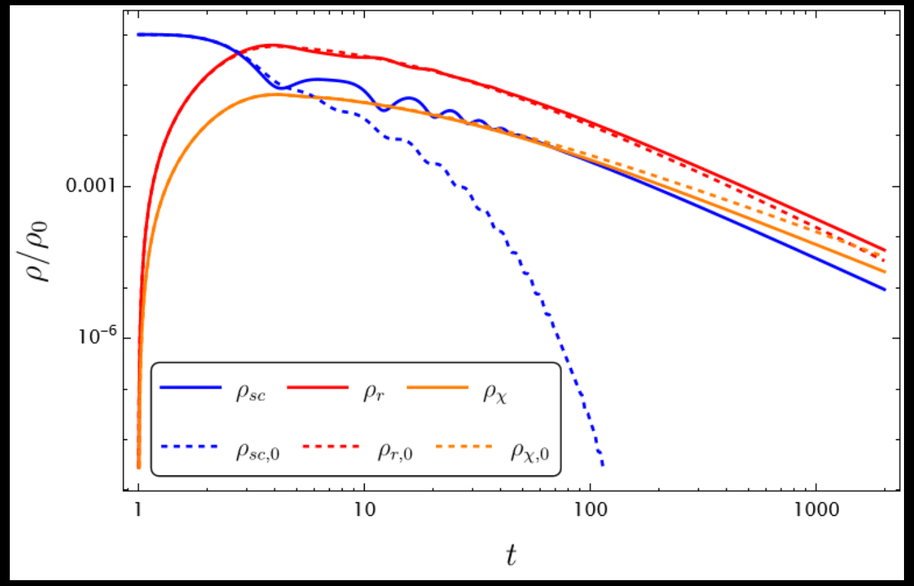
Γ_Φ	$Br_{\Phi\to\chi}$	Γ_ϕ	$Br_{\phi\to\chi}$
M^3	$1/10\ (9/10)$	m^3	0

DM relics

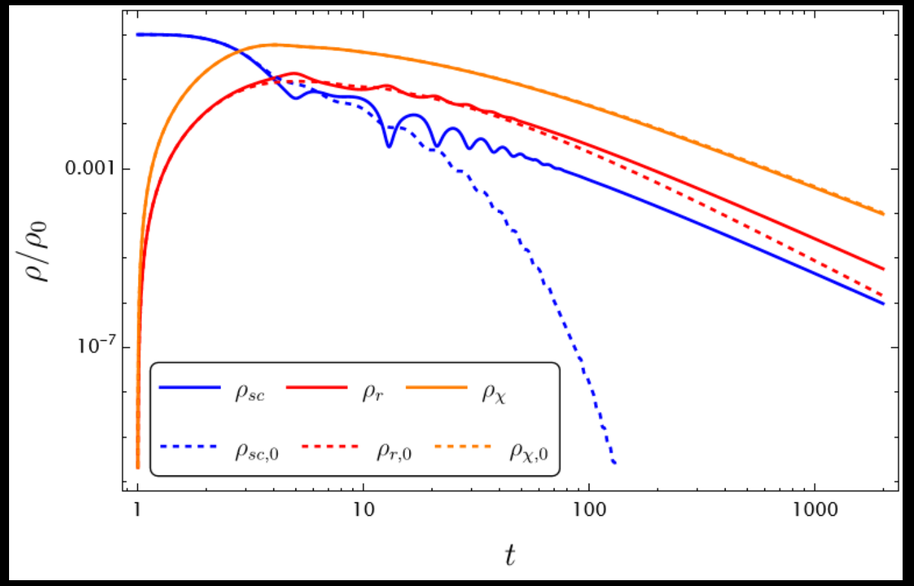


No effects revealed if production by the reheating field decay

Thermal misalignment



Energy abundances



SECOND HEAVIER FIELD

Corrected equations

$$\ddot{\phi} + (3H + \Gamma_\phi)\dot{\phi} + \partial_\phi V = \frac{1}{3}\partial_\phi \rho_r$$

$$\ddot{\Phi} + (3H + \Gamma_\Phi)\dot{\Phi} + \partial_\Phi V = 0$$

$$\dot{\rho}_r + 4H\rho_r = \Gamma_\Phi\,(1 - Br_{\Phi\to\chi})\dot{\Phi}^2 + \Gamma_\phi\,(1 - Br_{\phi\to\chi})\dot{\phi}^2 - \frac{1}{3}\partial_\phi \rho_r$$

$$\dot{\rho}_\chi + 3H\rho_\chi = Br_{\Phi\to\chi}\Gamma_\Phi\dot{\Phi}^2 + Br_{\phi\to\chi}\Gamma_\phi\dot{\phi}^2$$

Neglecting thermal production

$$\rho_{sc} = \frac{1}{2}\dot{\phi}^2 + \frac{1}{2}\dot{\Phi}^2 + V(\phi,\Phi)$$

$$H^2 = \frac{1}{3}\left(\frac{1}{2}\dot{\phi}^2 + \frac{1}{2}\dot{\Phi}^2 + V(\phi,\Phi) + m_\chi n + \rho_r\right)$$

$$V(\phi,\Phi) = \frac{1}{2}m^2\phi^2 + \frac{1}{2}M^2\Phi^2$$

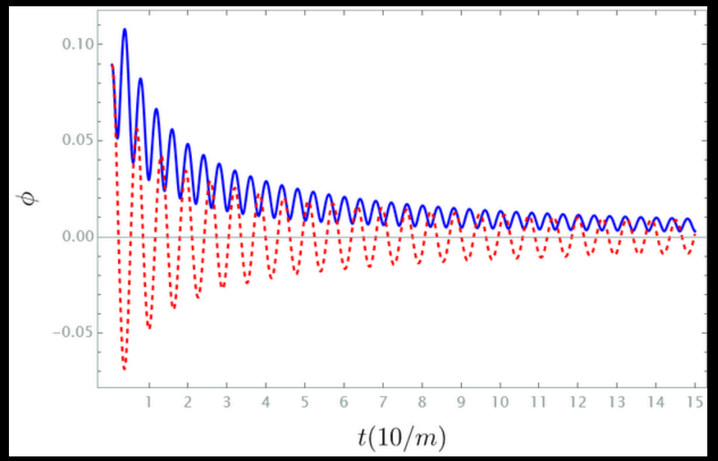
Toy model

M	$\Phi(t_o)$	m	ϕ_o	r	$\rho_{r,0}$	m_χ
$9/10$	$1/7$	$1/2$	$1/5\sqrt{5}$	1	0	$1/20$

No matter production

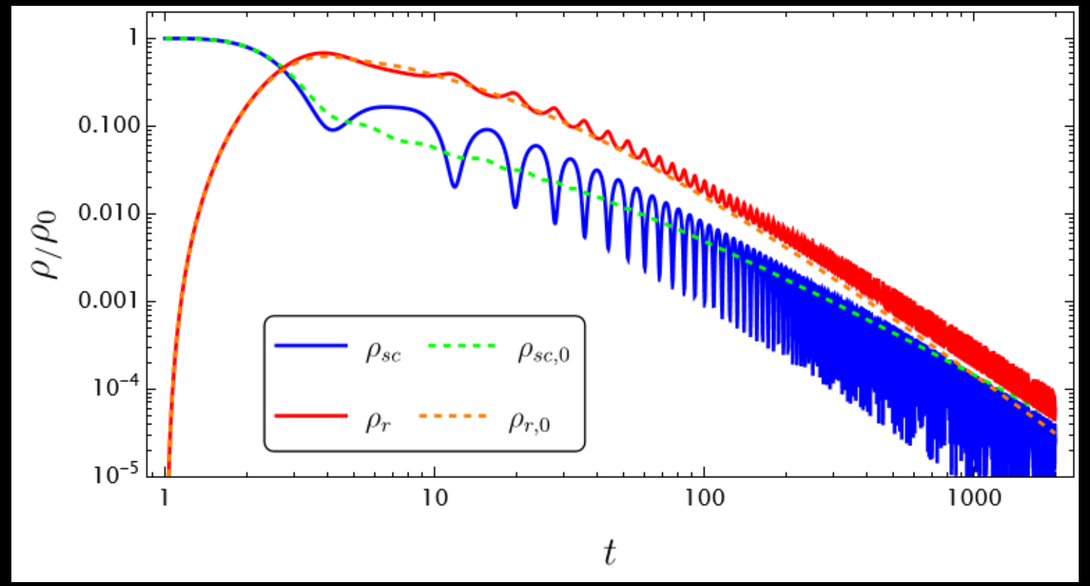
Γ_Φ	$Br_{\Phi\to\chi}$	Γ_ϕ	$Br_{\phi\to\chi}$
M^3	0	0	0

Thermal misalignment



Persistent thermal misalingment

Energy abundances



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