New opportunities for axion dark matter searches in nonstandard cosmological models

arXiv:2107.13588 [hep-ph]

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August 23, 2022

Overview: Axion CDM

Introduction

- Axion
- Misalignment Mechanism
- Phenomenology: $g_{a\gamma\gamma}$

Non Standard Cosmology

- Motivation
- Description
- Misalignment Mechanism
- Phenomenology: $g_{a\gamma\gamma}$

Outlook and Conclusion

Axion $\rightarrow$ solution to the Strong CP Problem.

Peccei-Quinn Mechanism [1].

[1] R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. 38, 1440 (1977)

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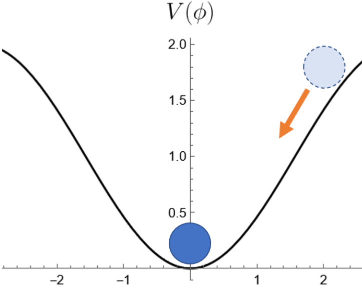
T∼ T_{QCD}: Non perturbative effects of QCD vacuum induce a potential to the axion [2].



[2] S. Weinberg, Phys. Rev. Lett. 40, 223 (1978), F. Wilczek, Phys. Rev. Lett. 40, 279 (1978).

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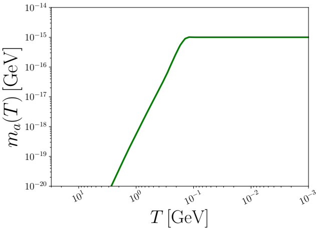
decay constant



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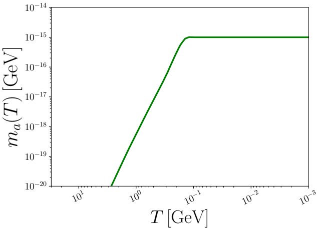

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[3] M.P. Hertzberg, M. Tegmark and F. Wilczek,Phys. Rev. D 78 (2008) 083507 [0807.1726].

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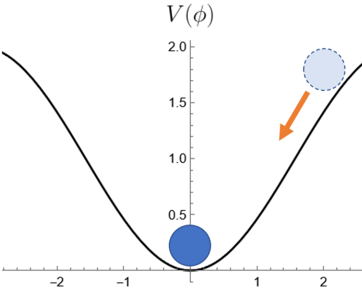

Oscillations of the axion field around the minimum of the potential behave as DM.

Axion production in SC: Misalignment Mechanism

The equation of motion: $\ddot{\theta} + 3H(T)\dot{\theta} + m_a(T)^2 \sin\theta = 0, \qquad \theta = a/f_a$

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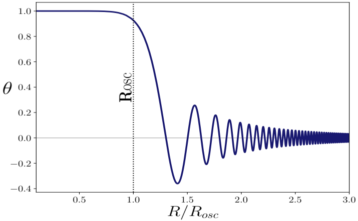

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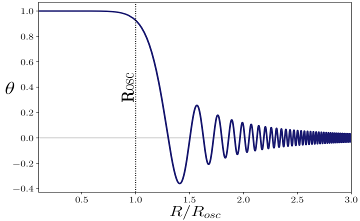

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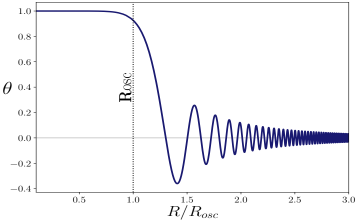

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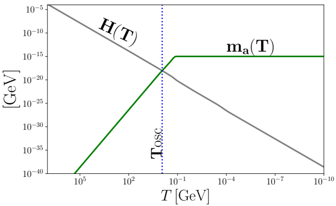

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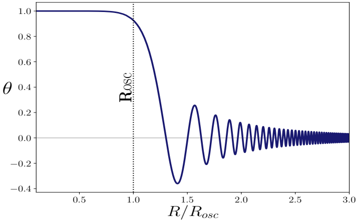

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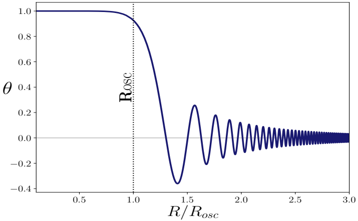

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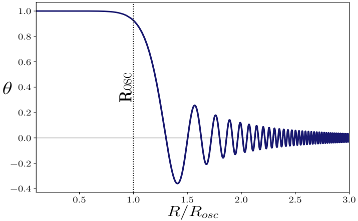

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$$\Omega_a \propto \begin{cases} \theta_i^2\ m_a^{-3/2}, & T \lesssim T_{\rm QCD}, \\ \theta_i^2\ m_a^{-7/6}, & T \gtrsim T_{\rm QCD}. \end{cases}$$

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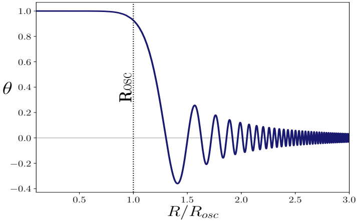

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We want that axions explain the total DM:
$\Omega_a = 0.26$

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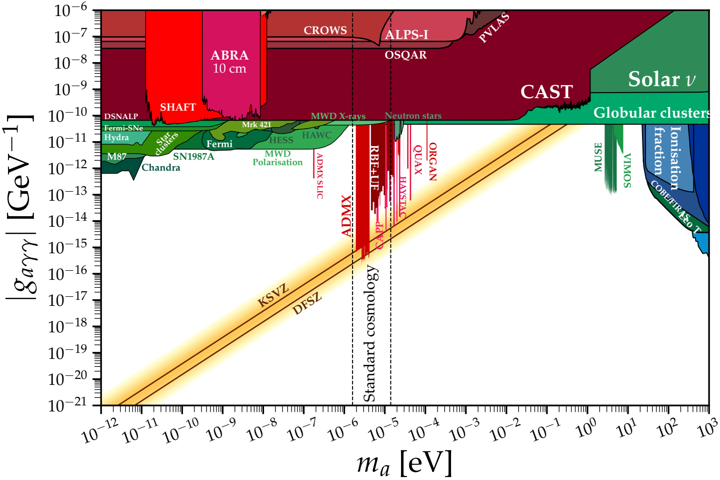

we have used $0.5 \leq \theta_i \leq \pi/\sqrt{3}$. Fig. credits: https://github.com/cajohare/AxionLimits

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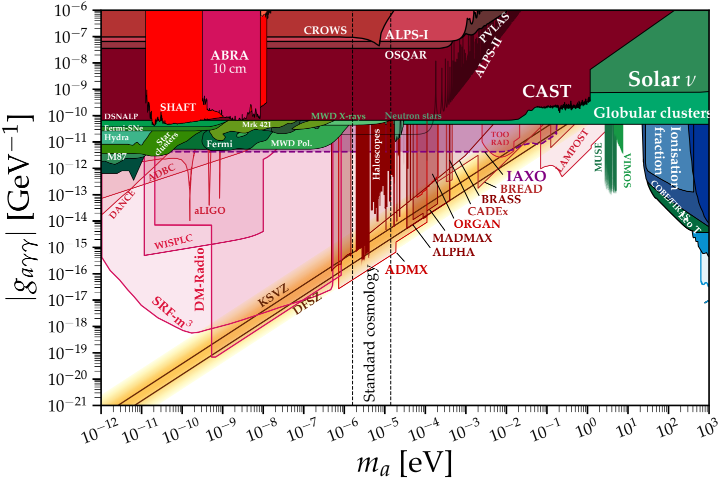

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Proposal: The axion oscillations are developed during a NSC

Objective: Study the effects on the axion abundance

New field ϕ dominates the energy density of the universe,
at $T_{\rm end}$ (prior BBN) ϕ decays into SM degrees of freedom with a decay rate Γ_ϕ.

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Evolution of the energy densities

$$\frac{d\rho_\phi}{dt} + \beta\, H(t)\, \rho_\phi = -\Gamma_\phi \rho_\phi$$
$$\frac{d\rho_{ra}}{dt} + 4H(t)\, \rho_{ra} = \Gamma_\phi\, \rho_\phi$$

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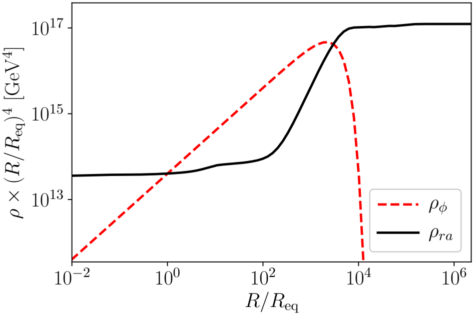

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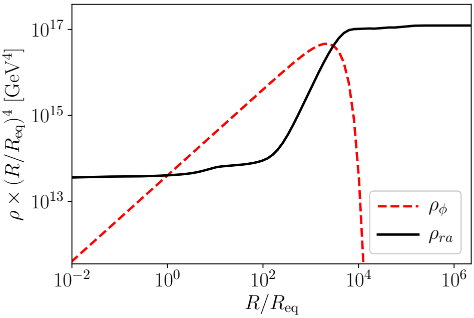

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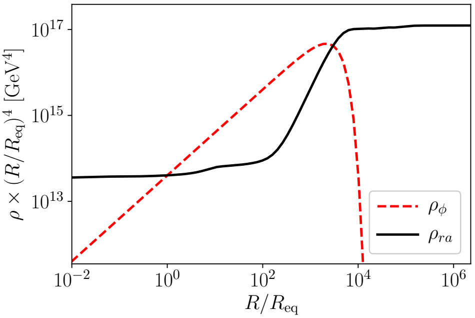

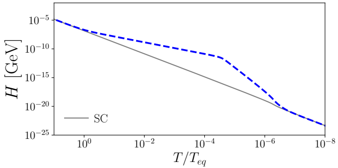

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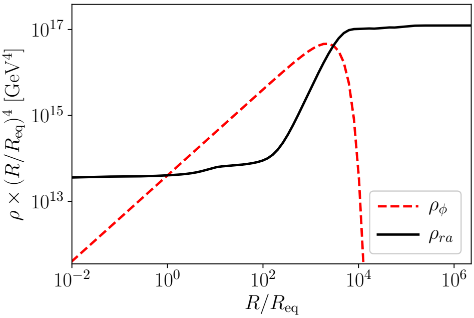

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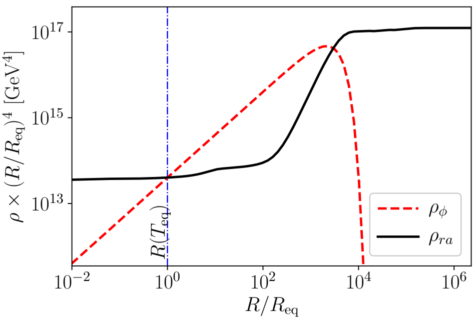

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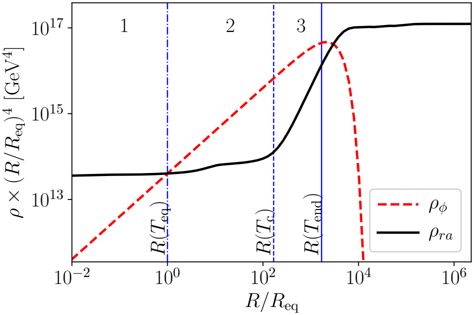

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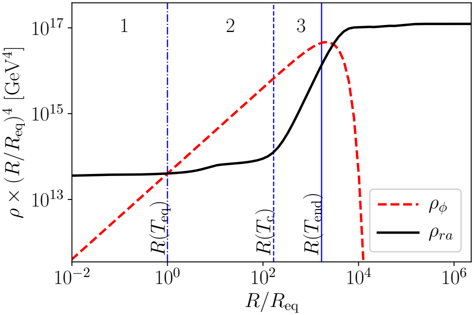

$\beta = 3, \quad T_{eq} = 1\,\text{GeV}, \quad T_{\rm end} = 4\,\text{MeV}$

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NSC parameters: β, T_{eq}, T_{end}.

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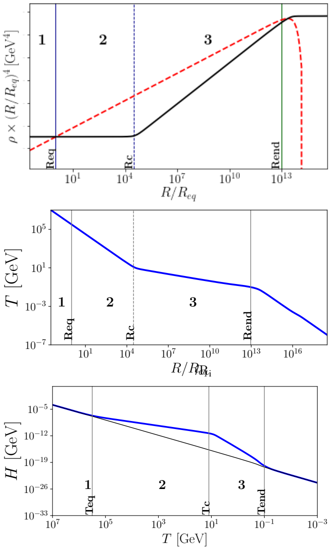

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$R < R_{eq}$

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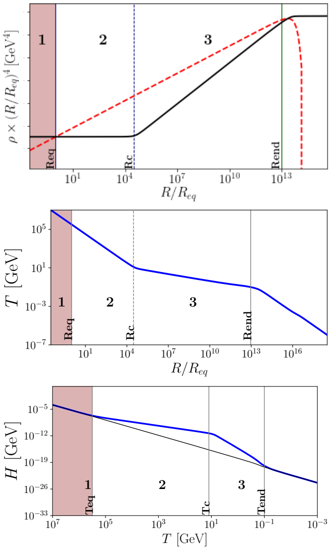

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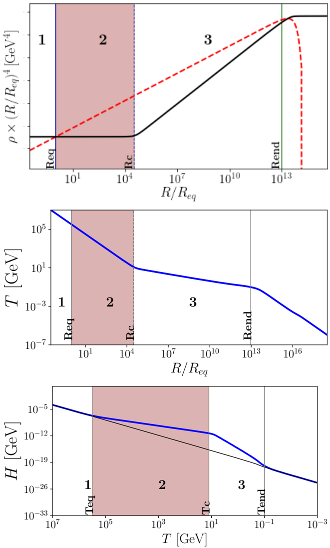
Region 2 $R_{eq}<R<R_c$

- Domination: ϕ $H \propto R^{-\frac{\beta}{2}}$
  faster expansion
- Entropy: conserved $H \propto T^{\frac{\beta}{2}}$
  mild dependency



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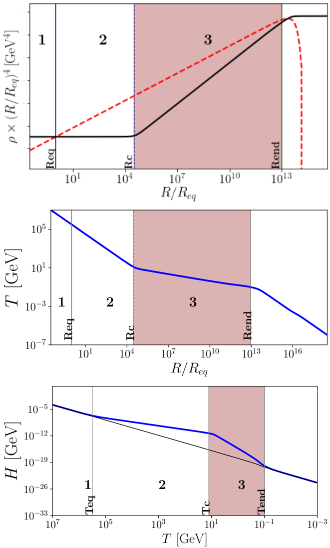
Region 3
$R_c < R < R_{end}$

- Domination: ϕ
but ϕ decays start to affect radiation: $\rho_{ra} \propto R^{-\beta/2}$
- Entropy: not conserved $H \propto T^4$
stronger dependency
H does not depend on β



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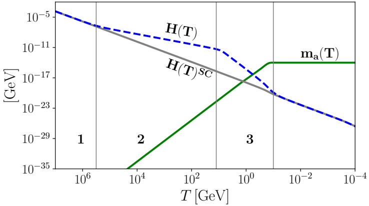
1. Due to $H(T) > H(T)^{SC}$

Oscillations Temperature:

$$H(T_{\rm osc}) = m_a(T_{\rm osc})$$



Axion production in NSC: Misalignment Mechanism

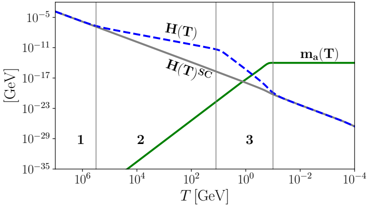
NSC could have 2 effects on the axion production:

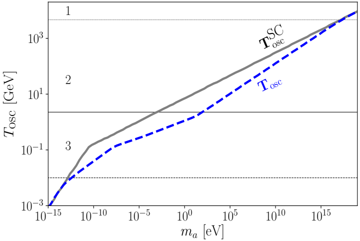
1. Due to $H(T) > H(T)^{SC}$

Oscillations Temperature:

$$H(T_{osc}) = m_a(T_{osc})$$

T_{osc} is lower than in SC
⇒ increase in the axion energy density





Axion production in NSC: Misalignment Mechanism

NSC could have 2 effects on the axion production:

2. For $\beta < 4$: Due to the decay of ϕ, there is a entropy injection[1] to SM.
$\rightarrow$ dilution of the axion energy density.

[1] G.Lazarides, Dilution of cosmological axions by entropy production.Nuclear Physics B346 (1990)

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$$\rho_a(T_0) = \rho_a(T_{osc}) \frac{m_a}{m_a(T_{osc})} \frac{s(T_0)}{s(T_{osc})} \gamma$$

Dilution factor: $\gamma \equiv \frac{S(T_{osc})}{S(T_{end})}, \qquad \gamma \leq 1$

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The dilution factor can be expressed in terms of the NSC parameters depending on which region the axion starts to oscillate.

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- Competition between both effects.
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- Smaller masses than the SC can now account for the whole DM.

NSC with $\beta > 4$:

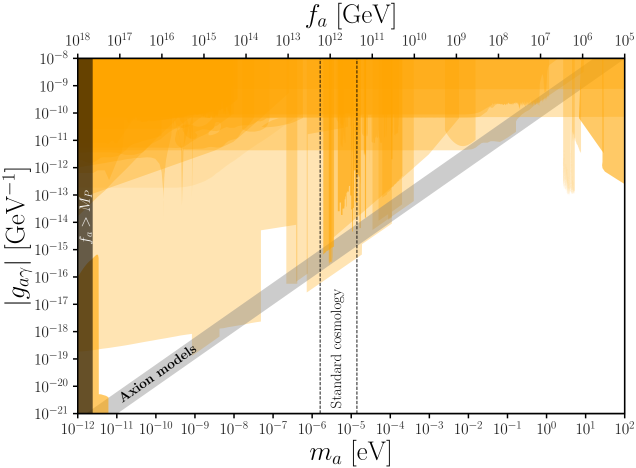
- Since ϕ undergoes redshift faster than radiation, there is not entropy injection.

- Only the first effect appears: lower T_{osc}

- In this case: $\Omega_a^{NSC}(m_a) > \Omega_a^{SC}(m_a)$

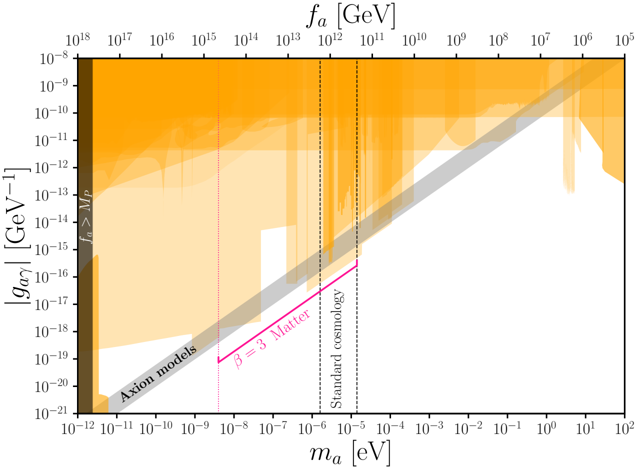
- Higher masses than the SC can now account for the whole DM.

Considering $0.5 \leq \theta_i \leq \pi/\sqrt{3}$



SC: 10^{-6} eV $\lesssim m_a \lesssim 10^{-5}$ eV.

Considering $0.5 \leq \theta_i \leq \pi/\sqrt{3}$ and $T_{end} = 4$ MeV



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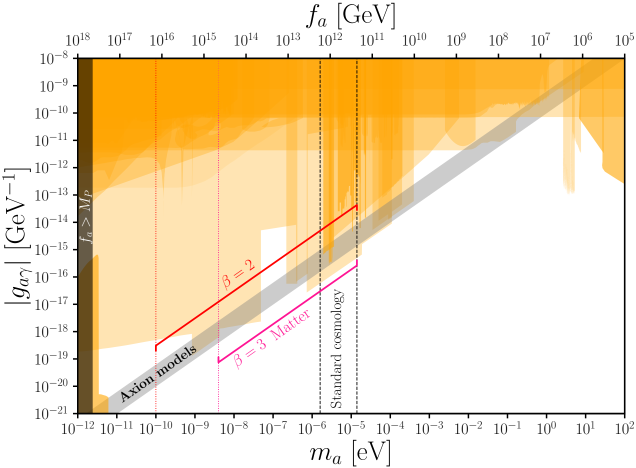

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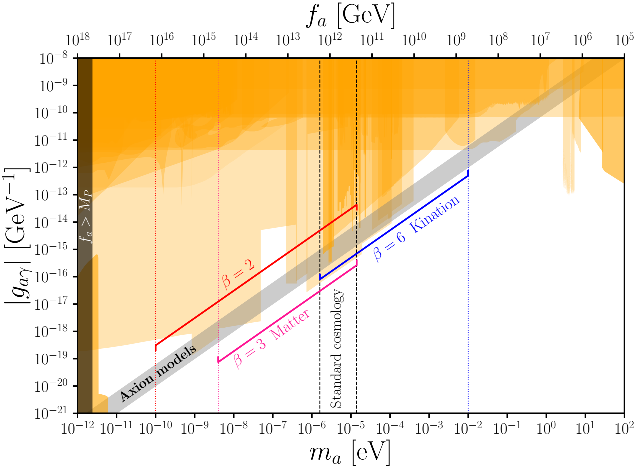

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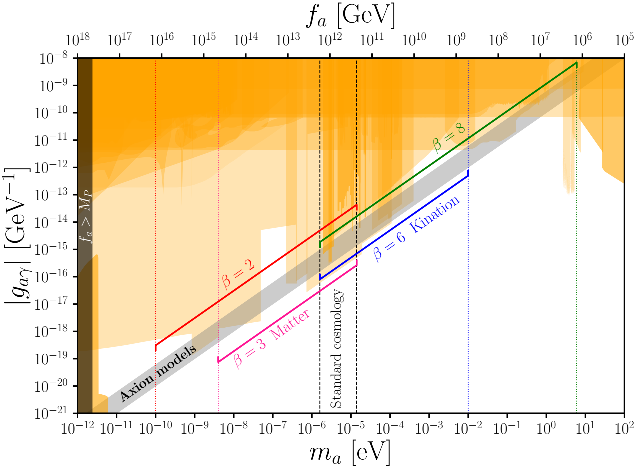

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$\beta = 2$: 10^{-10} eV $\lesssim m_a \lesssim 10^{-5}$ eV

$\beta = 8$: 10^{-6} eV $\lesssim m_a \lesssim 6$ eV.

Outlook and Conclusion

We considered a NSC in the early universe, where a new field starts to dominate the energy density of the universe.

We studied the effects on the universe and we found that the relation between H and T depend on the period of the NSC.

We analyzed the axion production by misalignment mechanism and we found that is possible to obtain two effects that potentially change the axions abundance.

- ⋆ A lower oscillation temperature implies a higher energy density of the axion
- ⋆ The decay of ϕ leads to a dilution of the axion energy density

A smaller β opens the axion window to lower masses

A larger β opens the axion window to higher masses

Case 1

Pre-inflationary PQ symmetry breaking scenario.

$T_{Inf} < f_a$

The Axion field is homogenized over long distances .

θ_i : random

Production mechanisms:

Misaligment Mechanism.

The preferred mass range is $m_a < 5 \times 10^{-6}\,\mathrm{eV}$
anthropic axion window

Caso 2

Post-inflationary PQ symmetry breaking scenario.

$T_{Inf} > f_a$

The axion field takes different values in causally disconnected regions of the universe.

Value[5] : $\bar{\theta}_i^2 = \frac{\pi^2}{3}$

Production mechanisms:

Misaligment Mechanism.
Decay of topological defect.

The preferred mass range is $5 \times 10^{-6}\,\mathrm{eV} < m_a < 10^{-2}\mathrm{eV}$
classic axion window

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[6] M. S. Turner, Cosmic and Local Mass Density of Invisible Axions, Phys.Rev. D33 (1986) 889–896

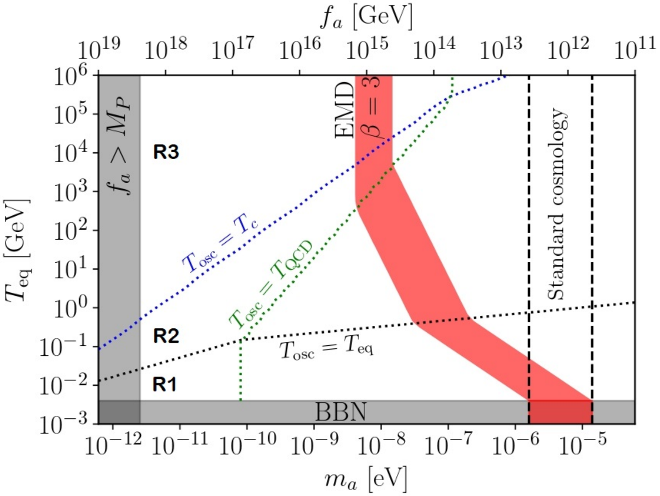
Full expressions for axion relic in NSC

$$\Omega_{\rm std}^{-3/2} \equiv 5 \times 10^{-11} \left(\frac{m_a}{1\,\mathrm{eV}}\right)^{-3/2} \theta_i^2,$$
$$\Omega_{\rm std}^{-7/6} \equiv 2.4 \times 10^{-7} \left(\frac{m_a}{1\,\mathrm{eV}}\right)^{-7/6} \theta_i^2.$$

$$\Omega_{R_1} = \begin{cases} \Omega_{\rm std}^{-3/2} \left(\frac{\beta^2}{4}\right)^{-3/\beta} \left(\frac{T_{\rm end}}{T_{\rm eq}}\right)^{12/\beta-3}, & \text{for } T_{\rm osc} \lesssim T_{\rm QCD} \\ \Omega_{\rm std}^{-7/6} \left(\frac{\beta^2}{4}\right)^{-3/\beta} \left(\frac{T_{\rm end}}{T_{\rm eq}}\right)^{12/\beta-3}, & \text{for } T_{\rm osc} \gtrsim T_{\rm QCD}. \end{cases}$$

$$\Omega_{R_2} \simeq \begin{cases} \Omega_{\rm std}^{-3/2} \left(\frac{T_{\rm end}^2}{m_a M_P}\right)^{\frac{3}{2\beta}(4-\beta)} & \text{for } T_{\rm osc} \lesssim T_{\rm QCD}\,, \\ \Omega_{\rm std}^{-7/6} \left(\frac{\beta^2}{4}\right)^{-3/\beta} \left(\frac{T_{\rm end}}{T_{\rm eq}}\right)^{\frac{3}{\beta}(4-\beta)} \left[\frac{T_{\rm eq}^7}{\left(T_{\rm QCD}^4\, m_a M_P\right)^{7/6}}\right]^{\frac{4-\beta}{\beta+8}} & \text{for } T_{\rm osc} \gtrsim T_{\rm QCD}\,. \end{cases}$$

$$\Omega_{R_3} = \begin{cases} \Omega_{\rm std}^{-3/2} \left(\frac{2}{\beta}\right)^{6/\beta} \left(\frac{T_{\rm end}^2}{m_a M_P}\right)^{\frac{3}{2\beta}(4-\beta)} & \text{for } T_{\rm osc} \lesssim T_{\rm QCD}\,, \\ \Omega_{\rm std}^{-7/6} (8-\beta)^{\frac{\beta+6}{2\beta}} \left(\frac{T_{\rm end}^6}{T_{\rm QCD}^4 m_a M_P}\right)^{3/\beta-2/3} & \text{for } T_{\rm osc} \gtrsim T_{\rm QCD}. \end{cases}$$



Parameter space corresponding to the whole observed DM abundance, for an early matter domination ($\beta = 3$) and $T_{end} = 4$ MeV.