Early-Universe Simulations of the Cosmological Axion

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9/26/2019 GGI Dark Matter Workshop

arXiv:1906:00967 MB, Joshua W Foster, Benjamin R Safdi

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National Energy Research Scientific Computing Center

Axions

• Axions originally introduced to solve the strong CP problem:

$$\mathcal{L} = \theta \frac{1}{16\pi^2} F^a_{\mu\nu} \tilde{F}^{\mu\nu a} \longrightarrow \mathcal{L}_{axion} = (\partial_\mu a)^2 + \frac{(a/f_a + \theta)}{32\pi^2} F\tilde{F}$$

• U(1) PQ symmetry **spontaneously broken** at high scale



Post- vs Pre-inflationary scenario

Two different scenarios can be considered: Breaking the PQ symmetry **before** or **after** inflation

Post- vs Pre-inflationary scenario

Two different scenarios can be considered: Breaking the PQ symmetry **before** or **after** inflation



two free parameters: θ_0 , f_a

one free parameter: f_a inhomogeneous at small scales

after inflation:

 $\rho(\theta_0 = 0.1)$

 $\rho(\theta_0 = \pi/8)$

 $\Omega_{a,0} \sim \langle \theta_0^2 \rangle$

 $\rho(\theta_0 = 1)$

 $\rho(\theta_0 = 0.1)$

 $\rho(\theta_0 = 10^{-3})$

Post- vs Pre-inflationary scenario

Two different scenarios can be considered: Breaking the PQ symmetry before **Focus of this**

talk!

Main goals:

- 1. Obtain axion mass with which correct relic abundance is reached
- 2. Characterise inhomogeneities

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one free parameter: $f_{a_{\perp}}$ mogeneous at small ales









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Early-Universe Simulations of the Axion





time (not to scale)







Facts about Oscillons:

- 1. They are regions with large field values/large energy density
- 2. Their size is given by the axion wavelength ~ inverse $m_a(T)$
- 3. They remain stable as long as $m_a(T)$ is increasing
- 4. Start to dilute once the axion reaches its zero-temperature mass





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time

η=1.10

https://youtu.be/1By1DMq1Epl

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scale)

(not to

time



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After the simulation ends:

1. Analytic evolution to matter-radiation equality 2. Identify over-dense regions $\delta = (\rho - \bar{\rho})/\rho$



Characterising the minihalo spectrum



Inflation

scale)

(not to

time

Important information for: microlensing, pulsar timing surveys, (in)direct detection, ...

Characterising the minihalo spectrum



Inflation

thermal spec.

linear EOM

matter-radiation

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time

alvtid

aD

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Obtaining the relic abundance





Obtaining the relic abundance



Correct relic abundance reached for: $m_a = 25.2 \pm 11.0 \ \mu eV$



Obtaining the relic abundance



Correct relic abundance reached for: $m_a = 25.2 \pm 11.0 \ \mu eV$

linear EOM matter-radiation

 Σ_a

Uncertainties coming from:

31% uncertainty on the relation between abundance and f_a 27% uncertainty from mass growth $m_a(T)$ 15% from violation of scaling regime

~10% others: statistical, fixed degrees of freedom,...





Summary

Assumption: PQ symmetry broken after inflation

We performed simulations through the PQ and QCD phase transition to matter-radiation equality

Identified minihalo mass spectrum Typical mass: 10⁻¹⁴ solar masses



Determined the axion mass that reproduces the correct relic abundance: $m_a = 25.2 \pm 11.0 \ \mu eV$

Furthermore: Simulation data publicly available for further studies: https://zenodo.org/record/2653964 (e.g. gravitational N-body simulations)

Thank you!

Inflation **Sources of Uncertainties on the Axion Mass** thermal spec. simulation MB, Foster, Safdi (1906:00967) PQ transition Klaer and Moore ---- Kawasaki et al. This Work radial @ vev \odot analyti scaling regime? Ω_a 10^{4} **QCD** transition mass growing domain walls 5×10^{14} 10^{15} simulation f_a [GeV] network collapse oscillons form In particular oscillons make it

. impossible to simulate at low breaking scales. Extrapolations needed:

$$\rho_a \propto f_a^{(6+n)/(4+n)}$$

with n=6.68 from lattice simulations

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aD

mass constant

oscillons decay

field linear

linear EOM

matter-radiation

gravity

today

Expected: $\alpha = (n+6)/(n+4) \approx 1.187$ Simulation: $\alpha = 1.24 \pm 0.04$

Leads to 31% uncertainty on axion mass

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scale

(not to

time

today

Leads to 27% uncertainty on axion mass



scale

(not to

time



Scaling regime: 1 string per Hubble volume

We see logarithmic deviations from this assumption similar to *M. Gorghetto & G. Villadoro 2018*!

More on this later!



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Scaling regime: 1 string per Hubble volume

We see logarithmic deviations from this assumption similar to *M. Gorghetto & G. Villadoro 2018*!

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Simple estimate:

Reinterpretation of the volume of the initial state changes string density



Seems to be a small affect. No trend visible.

We estimate a 15% uncertainty related to scaling violation.



What is the reason for this?

Number density not conserved Axion has to still live on the circle





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Inject mode large amplitude mode into field: PQ field + A cos(H x)



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