The cosmological history of axion minihalos

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Axions

- Axions originally introduced to solve the **strong CP problem**:

\[
\mathcal{L} = \theta \frac{1}{16\pi^2} F_{\mu\nu}^a \tilde{F}^{\mu\nu a} \quad \Rightarrow \quad \mathcal{L}_{\text{axion}} = (\partial_\mu a)^2 + \frac{(a/f_a + \theta)}{32\pi^2} F \tilde{F}
\]

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

- **Axion mass** is small (QCD effects),

\[
m_a^2 \approx \frac{m_{\pi}^2 f_{\pi}^2}{f_a^2}
\]

as are its couplings

\[
\text{good cold DM candidate}
\]

CAST Collaboration
What are axion minihalos?
What are axion minihalos?

Galaxy Clusters
What are axion minihalos?
What are axion minihalos?

Dwarf Galaxies
What are axion minihalos?

DM subhalos (ultra-faint)
What are axion minihalos?

![Graph showing the distribution of M dN/dM in Mpc^3 with the y-axis ranging from 10^-12 to 10^2 and the x-axis ranging from 10^8 to 10^16. There are three labeled curves: M-II, Millennium, and MXXL. Z=0 is indicated on the graph.](image)
What are axion minihalos?
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Axion minihalos

The four largest asteroids

Ceres 939 km
Vesta 525 km
Pallas 512 km
Hygiea 434 km
What are axion minihalos?

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The four largest asteroids

Ceres 939 km
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What are axion minihalos?

Axion minihalos

Pallas spread out over our solar system (roughly)
What are axion minihalos?

Facts:

• $10^{-10}$ solar masses heavy
• solar system sized

True within a few orders of magnitude
What are axion minihalos?

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• Requirement: PQ symmetry is broken after inflation! They are formed through axion self-interactions
What are axion minihalos?

Facts:

• $10^{-10}$ solar masses heavy  
• solar system sized  

True within a few orders of magnitude

• Requirement: PQ symmetry is broken after inflation! They are formed through axion self-interactions

• Why should we care about them?
  • Direct detection (are we sitting in a local void?)
  • We can search for them (e.g. through neutron stars)
  • Scenario provides prediction for axion mass
  • Can they host axion stars?
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

\[ V(\Phi, T) = \frac{\lambda}{4} (|\Phi|^2 - f_a^2)^2 \]

Breaking PQ:

- \( \rho(\theta_0 = 0.1) \)
- \( \rho(\theta_0 = 1) \)
- \( \rho(\theta_0 = \pi/8) \)
- \( \rho(\theta_0 = 10^{-3}) \)

Hubble-sized patches
Post- vs Pre-inflationary scenario

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Breaking the PQ symmetry **before** or **after** inflation

**before inflation:**

\[ \Omega_{a,0} \sim \theta_0^2 \]

two free parameters:
\[ \theta_0, f_a \]

**Breaking PQ:**

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Hubble-sized patches
Post- vs Pre-inflationary scenario

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Breaking the PQ symmetry **before** or **after** inflation

**before inflation:**
\[ \Omega_{a,0} \sim \theta_0^2 \]

Two free parameters:
\[ \theta_0, f_a \]

**after inflation:**
\[ \Omega_{a,0} \sim \langle \theta_0^2 \rangle \]

One free parameter: \( f_a \)
Inflation

PQ transition

@ \( T \approx f_a \)

\[
V(\Phi, T) = \frac{\lambda}{4} (|\Phi|^2 - f_a^2)^2
\]

radial mode

axion
$V(\Phi, T) = \frac{\lambda}{4} (|\Phi|^2 - f_\alpha^2)^2$

radial mode

@ $T \approx f_\alpha$

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Solve Equations of Motion on a large 3D grid
(about $10^{11}$ grid sites)
A cosmological history of axion minihalos

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Inflation
thermal spec.
PQ transition
radial @ vev

simulation

\[ V(\Phi, T) = \frac{\lambda}{4} (|\Phi|^2 - f_a^2)^2 \]

@ \( T \approx f_a \)

network of cosmic strings

radial mode

axion

\( \eta = 0.12 \)

K. Saikawa
Inflation
thermal spec.
PQ transition
radial @ vev

\[ V(\Phi, T) = \frac{\lambda}{4} (|\Phi|^2 - f_a^2)^2 \]

@ \( T \approx f_a \)

radial mode
Inflation
thermal spec.
PQ transition
radial @ vev
QCD transition

\begin{equation}
V(\Phi, T) = \frac{\lambda}{4} \left( |\Phi|^2 - f_a^2 \right)^2 \\
+ m_a(T)^2 f_a^2 [1 - \cos \text{Arg}(\Phi)]
\end{equation}

radial mode
axion

@ $T \approx 1$ GeV

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\[ + m_a(T)^2 f_a^2 [1 - \cos \text{Arg}(\Phi)] \]

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Inflation

PQ transition

thermal spec.

radial @ vev

scaling regime

QCD transition

mass growing

domain walls

analytic simulation

time (not to scale)

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\[ V(\Phi, T) = \frac{\lambda}{4} (|\Phi|^2 - f_a^2)^2 + m_a(T)^2 f_a^2 [1 - \cos \text{Arg}(\Phi)] \]

growing axion mass

@ \( T \approx 1 \text{ GeV} \)

domain walls form

radial mode

axion

mass growing
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mass growing
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network collapse

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Evolution of Oscillons

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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https://youtu.be/1By1DMq1EpI
Inflation
thermal spec.
PQ transition
radial @ vev
scaling regime
QCD transition
mass growing
domain walls
network collapse
oscillons form
mass constant
oscillons decay
field linear

oscillons decay

Malte Buschmann (Princeton University) - A cosmological history of axion minihalos

https://youtu.be/1By1DMq1Epl
Malte Buschmann (Princeton University) - A cosmological history of axion minihalos

- Inflation
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NERSC
National Energy Research Scientific Computing Center

η=1.10
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matter-radiation
Obtaining the relic abundance

\[ \Omega_a = \frac{\rho_a}{\rho_c} \]

- Klaer and Moore
- Kawasaki et al.
- This Work

\[ f_a [\text{GeV}] \]

- Oscillons form
- Mass growing
- QCD transition
- PQ transition
- Radial @ vev
- Domain walls
- Network collapse
- Time (not to scale)

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Obtaining the relic abundance

Correct relic abundance reached for:

\[ m_\alpha = 25.2 \pm 11.0 \ \mu\text{eV} \]
Obtaining the relic abundance

Correct relic abundance reached for:

\[ m_a = 25.2 \pm 11.0 \, \mu\text{eV} \]

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, etc.
Sources of Uncertainties on the Axion Mass

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

**Expected:** \( \alpha = (n + 6)/(n + 4) \approx 1.187 \)

**Simulation:** \( \alpha = 1.24 \pm 0.04 \)

*Leads to 31% uncertainty on axion mass*
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

Could be as high as 8.2!

We rerun simulation with 8.2 (in 2D)

**Leads to 27% uncertainty on axion mass**
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Halos collapse further under gravity

MB, Foster, Safdi, Wentzel (work in progress!)

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Halos collapse further under gravity

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Are we sitting in a void?

Experiments like ADMX might not be able to detect a QCD axion in a post-inflationary scenario!

MB, Foster, Safdi, Wentzel (work in progress!)
Radio signals from Neutron Stars

Axions convert to radio photons in magnetic field of neutron star

Large peak in flux when neutron star moves through an axion minihalo!

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oscillons decay

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Halos are tidally disrupted in Milky Way potential

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Characterizing radial profiles and halo mass functions

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- tidal stripping
- today
Radio signals from Neutron Stars

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Summary

- Assumption: PQ symmetry broken after inflation
- We performed simulations through the PQ and QCD phase transition to matter-radiation equality
- N-body simulations until Milky Way forms
- Simulated tidal stripping
- Identified minihalo mass spectrum
  Typical mass: $10^{-18}$ solar masses
- Determined the axion mass that reproduces the correct relic abundance: $m_a = 25.2 \pm 11.0 \mu$eV
- We are most likely sitting in a DM void (bad news for e.g ADMX)
  But: We can look for signals of minihalo - NS collision!
Thank you!