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Axion Dark Matter during reheating

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Based On:

- QCD axion misalignment during reheating [2610.00458]

  (D. B, Debasish Borah, and Nayan Das)

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Do We Need New Physics?

Open Questions:

- **Baryon Asymmetry :** Why is there more matter than antimatter?
- **Small Neutrino Mass :** What is the origin of neutrino masses?
- **Strong CP problem :** QCD permits a CP-violating term: $\mathscr{L}_\theta = \theta \frac{g_s^2}{32\pi^2} G_{\mu\nu}\tilde{G}^{\mu\nu}$

  nEDM Experiments constrain: $|\theta| \lesssim 10^{-10}$

  Question: Why is θ so small?

FOCUS

- **Dark Matter :**

  ✓ Strong gravitational evidence exists across astrophysical and cosmological scales.

  ✓ Electrically neutral, stable on cosmological timescales, and interacts predominantly through gravity.

  ✗ Its particle nature remains unknown.

A new particle beyond the Standard Model is required: **The Axion**

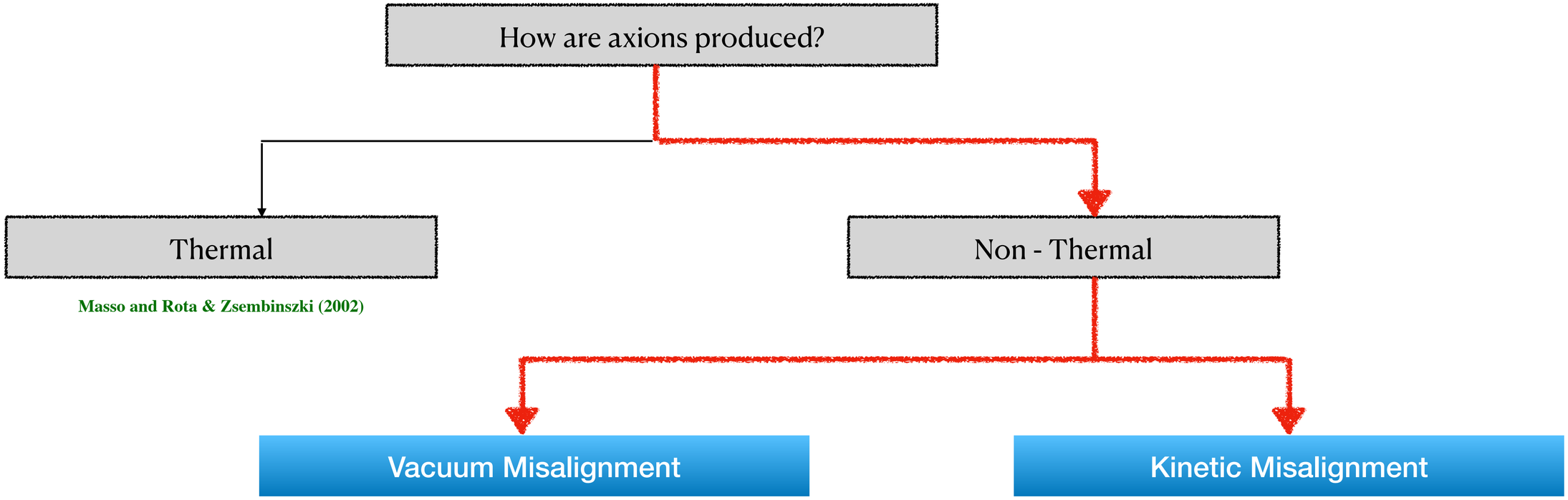
Axion Production Mechanisms

Why Axions?

- Unlike most dark matter candidates, the QCD axion was originally proposed to solve the Strong CP problem
- Later recognized as a compelling dark matter candidate.

Axion : Weakly interacting• Long-lived • Electrically neutral •

Good Dark matter candidate



Masso and Rota & Zsembinszki (2002)

L. F. Abbott, P. Sikivie (1983)
M. Dine, W. Fischler (1983)

Raymond T. Co, Lawrence J. Hall, Keisuke Harigaya (2019)

Cosmology of Axions:

- $\phi_a(x) = f_a\theta(x)$, **where, θ(x): misalignment angle**
- **Evolution equation:** $\ddot{\theta} + 3H\dot{\theta} + m_a^2(T)\sin\theta = 0$
- **Potential:** $V(\theta, T) = m_a^2(T) f_a^2 (1 - \cos\theta)$
- **Mass :** $m_a(T) = \begin{cases} m_a \left(\dfrac{T_{\rm QCD}}{T}\right)^4, & T > T_{\rm QCD}, \\ m_a, & T \le T_{\rm QCD}. \end{cases}$

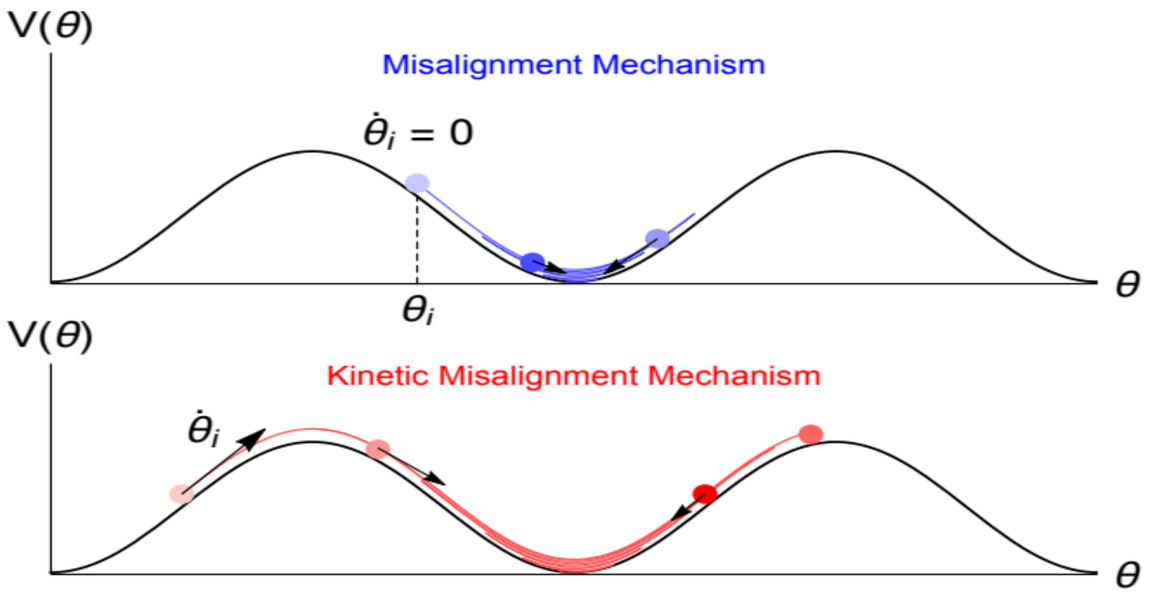


Image adapted from: *R. T. Co, L. J. Hall, and K. Harigaya, Kinetic Misalignment Mechanism [arXiv: 1910.14152]*

Vacuum Misalignment

$\theta_i \in (-\pi, \pi],\ \dot{\theta}_i = 0$

At very high temperatures

- **Hubble Friction:** $3H(T) \gg m_a(T)$
- **Field Remains Frozen**

Universe Cools

$T\downarrow,\ H(T)\downarrow,\ m_a(T)\uparrow$

- $3H(T_{osc}) \approx m_a(T_{osc})$ **Axion starts to oscillate**
- **Cold Dark Matter**

Kinetic Misalignment

$\theta_i \in (-\pi, \pi],\ \dot{\theta}_i \neq 0$

At very high temperatures

At $3H(T') \le m_a(T')$

- Kinetic energy > Potential barrier $\Longrightarrow$ *Field continues rolling across minima*
- **Oscillation Delayed**

T$\downarrow$

At $\dot{\theta}(T_{osc}) \approx 2m_a(T_{osc})$

- Kinetic energy = Height of Potential barrier $\Longrightarrow$ **Axion starts to oscillate**
- **Cold Dark Matter**

Axion Relic Abundance in Standard Cosmology

Radiation-Dominated Universe ★ $H = \frac{1}{2t}$ ★ $S = sa^3 =$ constant

General Prescription:

- **Oscillation condition:**
  - ❋ ***Vacuum Misalignment:*** $3H(T) = m_a(T, f_a) \implies T_{\rm osc} = T_{\rm osc}(f_a)$
  - ❋ ***Kinetic Misalignment:*** $\dot{\theta}(\mathrm{T}) \approx 2\mathrm{m_a}(\mathrm{T}, \mathrm{f_a}) \implies \mathrm{T_{osc}} = \mathrm{T_{osc}}(\mathrm{f_a}, \dot{\theta}_{\rm in})$
- **Energy density at oscillation:** $\rho_a(T_{\rm osc}) = \frac{1}{2}\dot{\phi}_a^{\,2} + V(a, T_{\rm osc})$
- **Number density at oscillation:** $n_a(T_{osc}) = \frac{\rho_a(T_{osc})}{m_a(T_{osc})} = \frac{1}{m_a(T_{\rm osc})}\left(\frac{1}{2}\dot{\theta}^2 f_a^2 + V(a, T_{\rm osc})\right)$
- **Conservation of comoving number density:** $n_a(T) = n_a(T_{\rm osc})\frac{s(T)}{s(T_{\rm osc})}$
- **Present abundance:** $\Omega_a h^2 = \frac{m_a}{\rho_c}\left(\frac{\rho_a(T_{\rm osc})}{m_a(T_{\rm osc})}\frac{s(T_0)}{s(T_{\rm osc})}\right)h^2$

- For $\theta_i = \mathcal{O}(1)$, Observed dark matter abundance typically requires:

  A. **Vacuum Misalignment:** $f_a \approx \mathcal{O}(\,10^{11} - 10^{12}\,)$ GeV.

  B. **Kinetic Misalignment:** $f_a \leq (\,10^{11} - 10^{12}\,)$ GeV. ($\dot{\theta}_i$ vary)

Non - Standard Cosmological History

Was the Universe necessarily radiation dominated immediately after inflation?

- BBN constrains the Universe only for $T \sim \mathcal{O}(\mathrm{MeV})$
- Pre-BBN expansion remains uncertain → Alternative expansion histories are allowed.

This naturally raises the following questions:

- Will the axion relic abundance be modified in a non-standard cosmological history?
- Can it reshape the viable axion parameter space?
- Can the observed dark matter abundance be used to constrain/probe reheating scenarios and the pre-BBN Universe?

Generalized reheating scenario

Inflation

↓

Scalar-field domination:

$V(\phi) \propto \phi^n$

↓

Reheating T_{RH}

↓

Radiation domination

↓

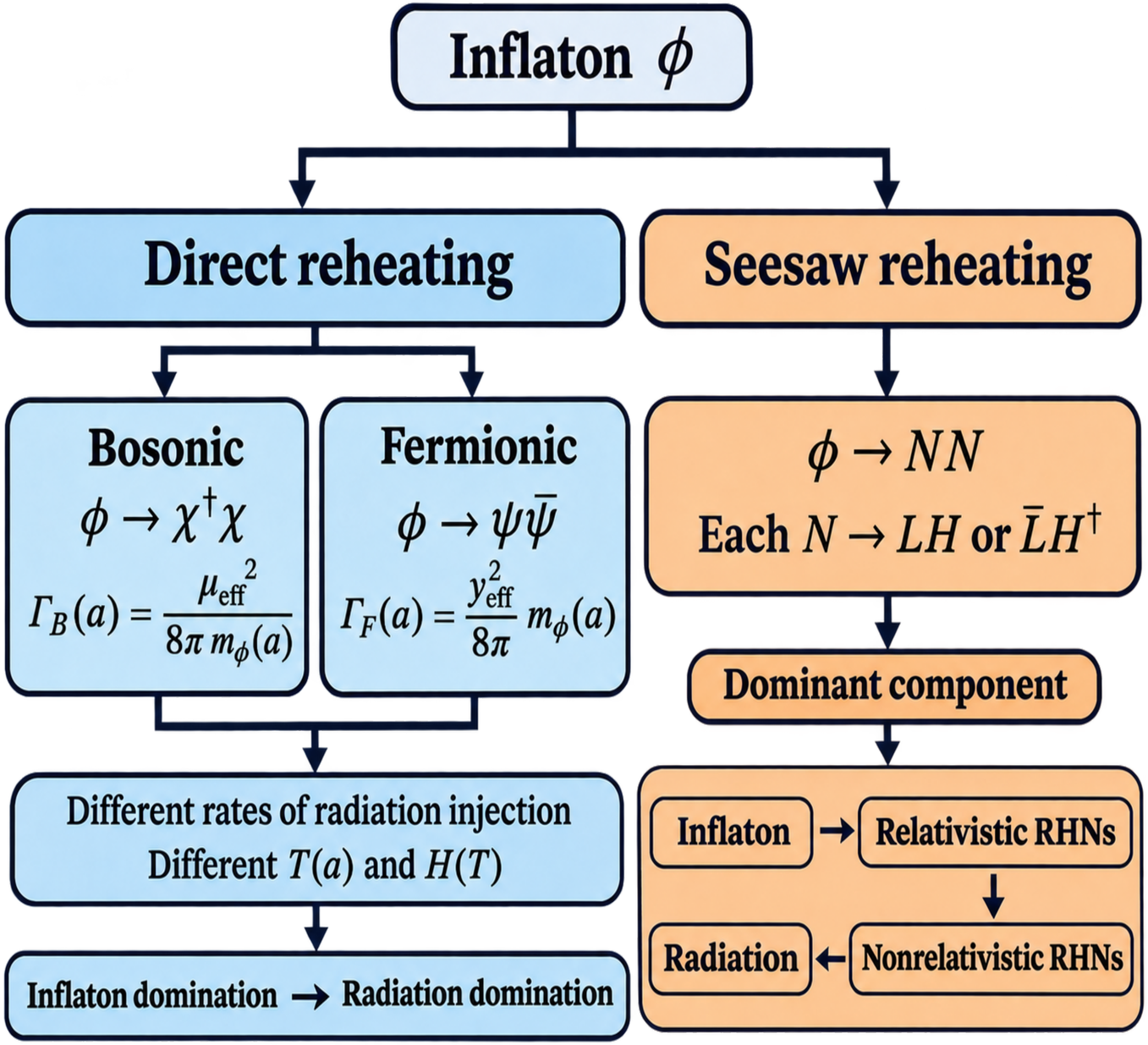
BBN

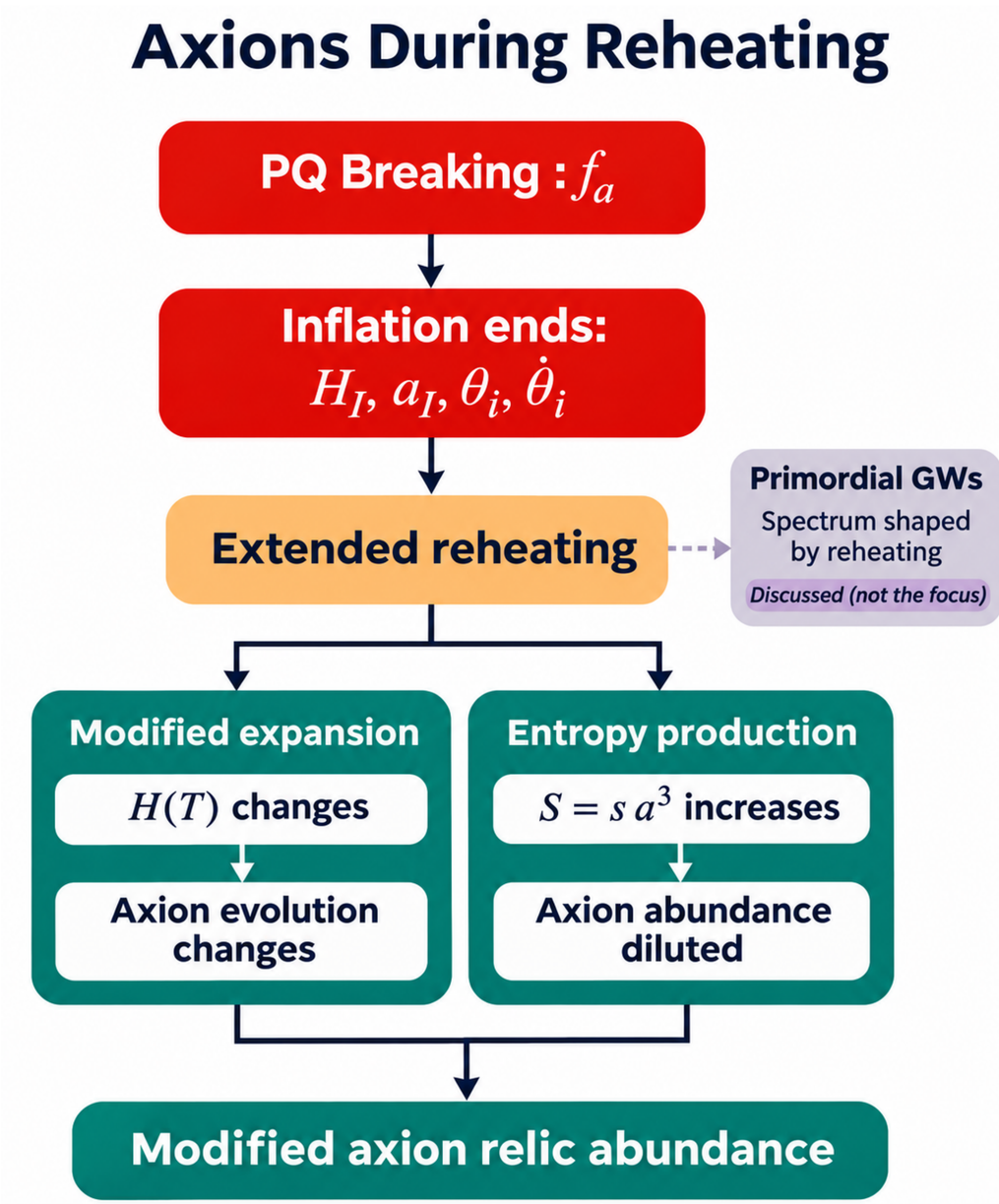
- After inflation, the inflaton oscillates around the minimum of its potential : $V(\phi) \propto \phi^n$
- The energy redshifts as : $\rho_\phi = \rho_{\phi,\mathrm{RH}} \left(\frac{a}{a_{\mathrm{RH}}} \right)^{-6n/(n+2)}$

n	$\omega_\phi = (n-2)/(n+2)$	Expansion History
2	0	Matter-like
4	1/3	Radiation-like
6	1/2	Redshifts faster than radiation
∞	1	Kination

Note: ϕ_a: axion, ϕ: inflaton

Decay Channels and Impact on Axion Dark Matter





Part 1:

Vacuum Misalignment in Non-Standard Cosmology

Impact of Non-Standard Cosmology on Axion Evolution

Evolution equation:

$$\ddot{\theta} + 3H\dot{\theta} + m_a^2(T)\sin\theta = 0$$

- Modified Hubble expansion → delayed $T_{\rm osc}$ → changed initial axion abundance.
- Entropy Production → dilutes the axion relic abundance.
- $$\Omega_a h^2 \;\propto\; \underbrace{\frac{n_a(T_{\rm osc})}{s(T_{\rm osc})}}_{\text{set at onset}} \quad \underbrace{\frac{S(T_{\rm osc})}{S(T_{\rm RH})}}_{\text{dilution during reheating}} \qquad (T_{\rm osc} > T_{\rm RH})$$

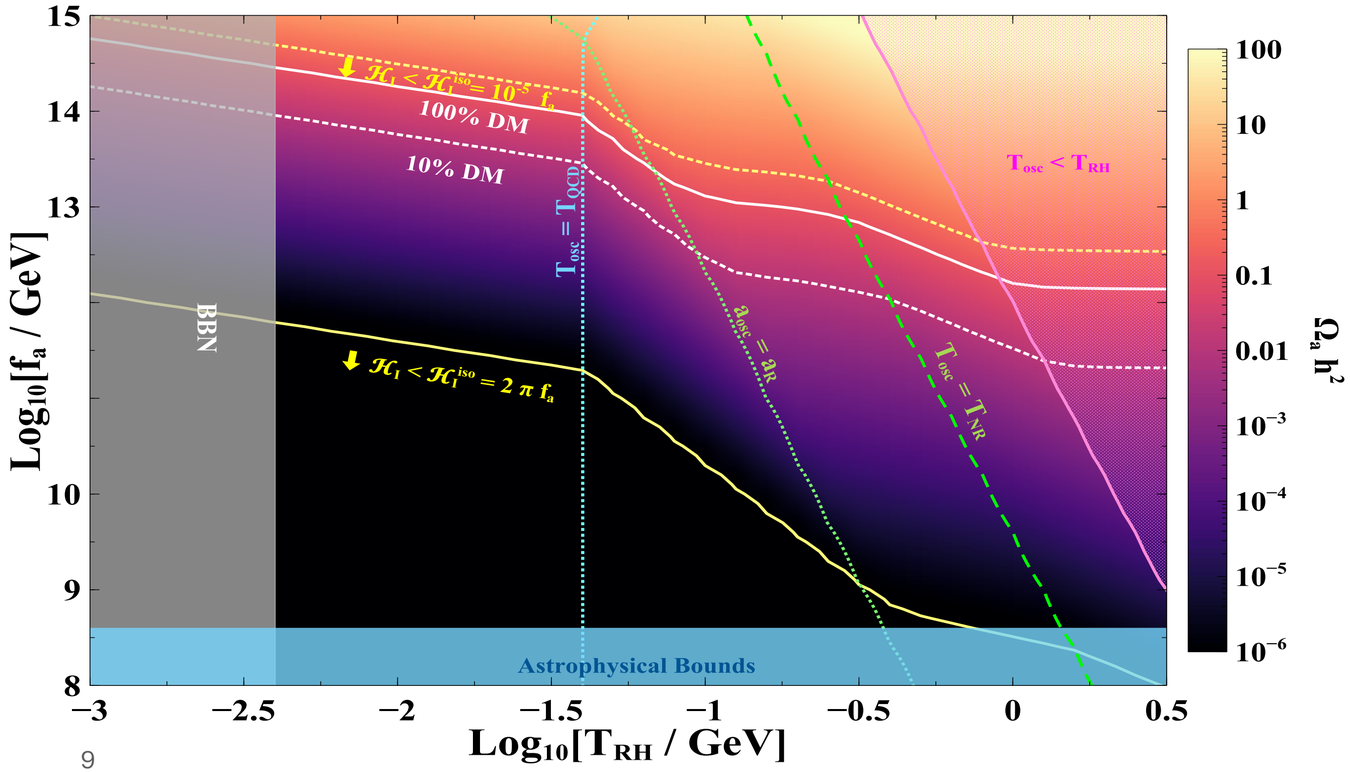
Assumptions and Constraints

- **PQ symmetry broken before inflation** $\Longrightarrow \dfrac{\mathscr{H}_I}{2\pi} < f_a\,.$
- The inflationary scale is bounded by :

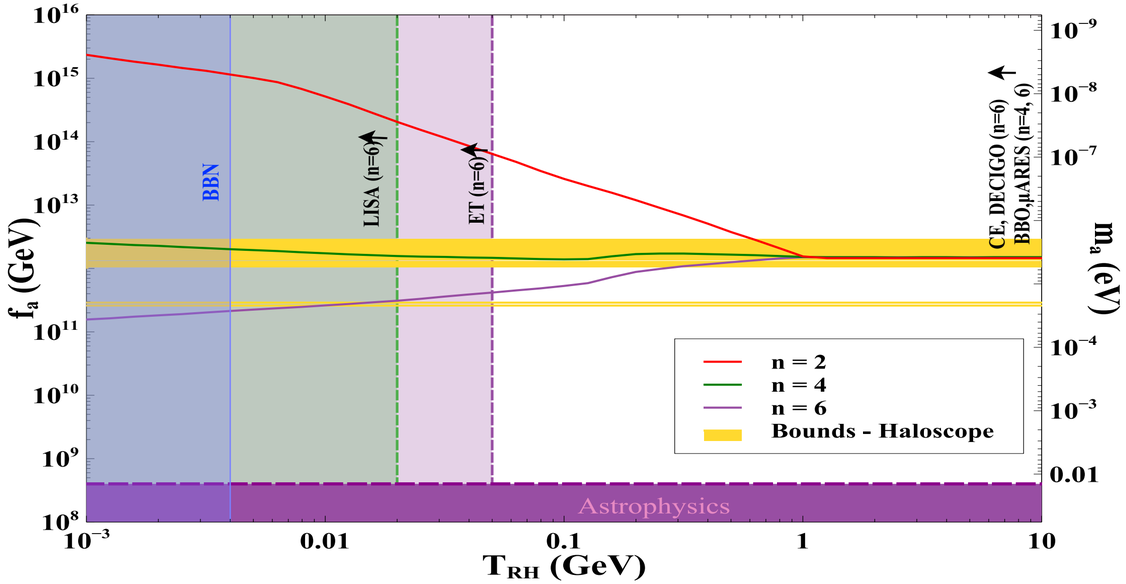
  $\mathscr{H}_I^{\rm max} = \min\left(\mathscr{H}_I^{\rm iso}, 2\pi f_a\right).$
- To avoid thermal restoration of the PQ symmetry **:**

  $T_{\rm max} < f_a$
- $\Omega_a h^2$ independent of the choice of $\mathscr{H}_I$.
- The axion relic abundance depends on the cosmological epoch in which oscillations begin.

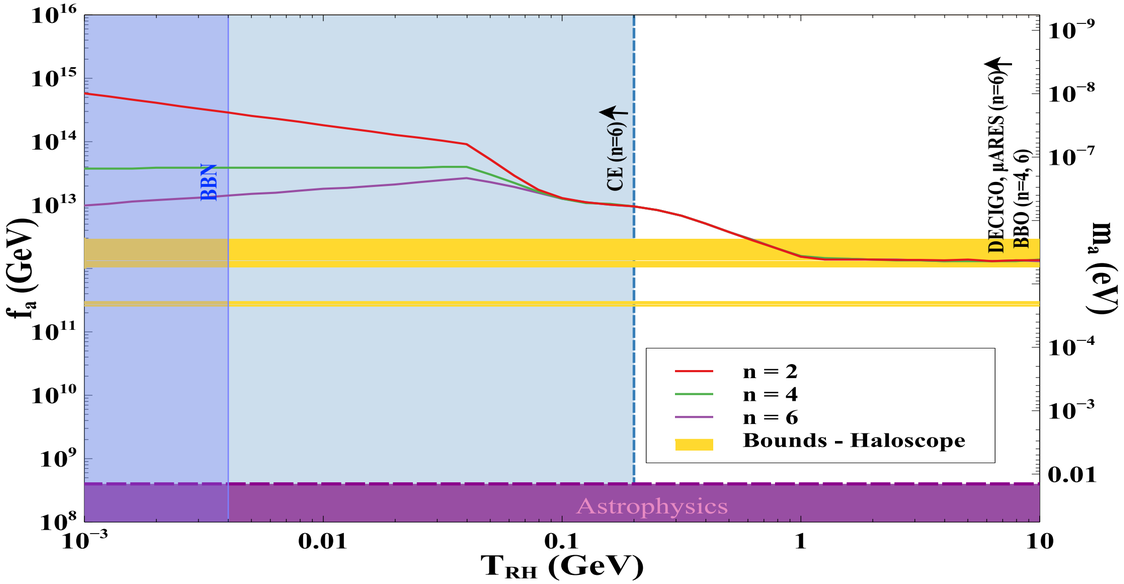
Reheating via RHN: n = 2, $T_{\rm NR} = 2\,T_{\rm RH}, T_{\rm max} = 4\,T_{\rm RH}$ and $\theta_i = 1$



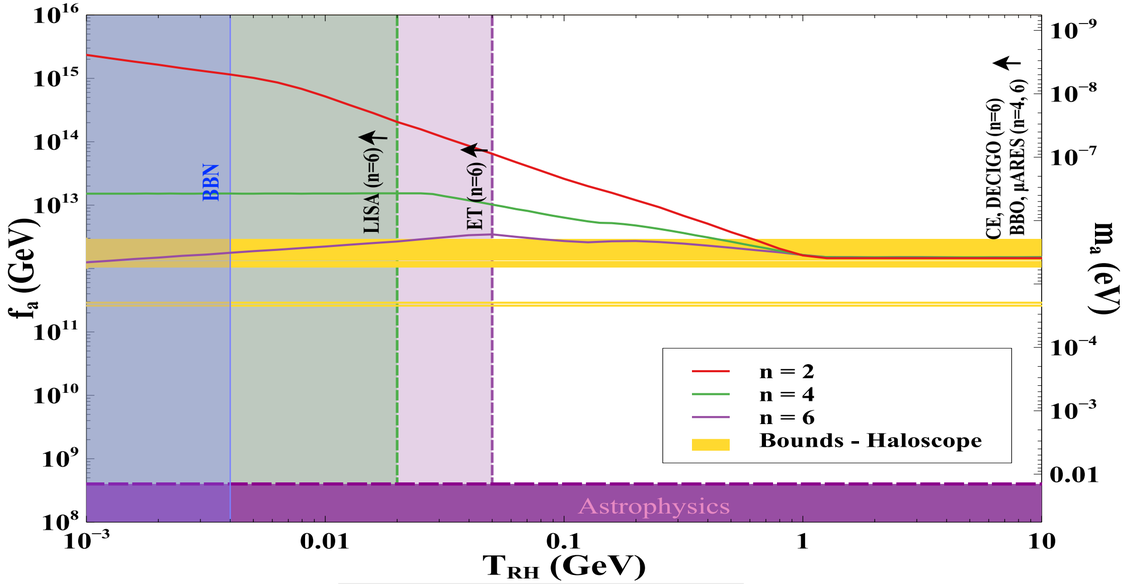
Results: Vacuum Misalignment ($\theta_i = 1$)



Fermionic Decay



Decay via RHN



Bosonic Decay

Results: Vacuum Misalignment

- For n = 2, bosonic and fermionic reheating yield identical relic-abundance predictions.
- For higher n, the preferred f_a depends strongly on the inflaton decay channel and T_{RH}.
- **Existing axion bounds:** A large fraction of the bosonic n=6 region and the entire fermionic (n=4) full-DM contour are excluded.
- **Complementary probes:** Primordial GW sensitivities constrain the reheating history, while axion experiments probe the associated f_a or m_a.

Part 2:

Kinetic Misalignment in Non-Standard Cosmology

Impact of Non-Standard Cosmology on Axion Evolution

Evolution equation: $\ddot{\theta} + 3H\dot{\theta} + m_a^2(T)\sin\theta = 0$

- Modified expansion and temperature evolution: Shift the oscillation temperature $T_{\rm osc}$
- Entropy Production → dilutes the axion relic abundance

Bounds and Constraints

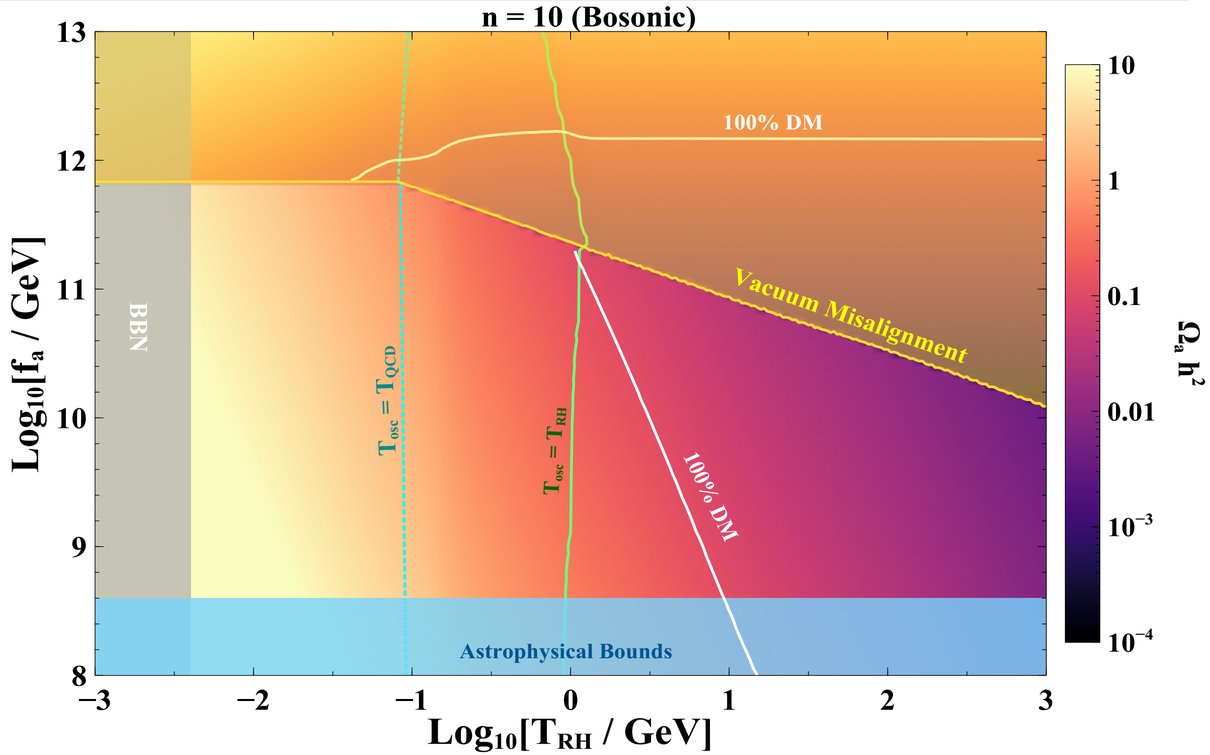
$$\underbrace{\dot{\theta}_{\mathrm{crit},i}}_{\textbf{Enough rotation}} < |\dot{\theta}_i| < \underbrace{\frac{\sqrt{6}\,M_{\rm Pl}H_I}{f_a}}_{\textbf{Energy bound}} \quad \approx 6\times10^{17}\ \textbf{GeV}$$

(For $H_I = 0.1\,f_a$ **)**

Observations: Direct Reheating

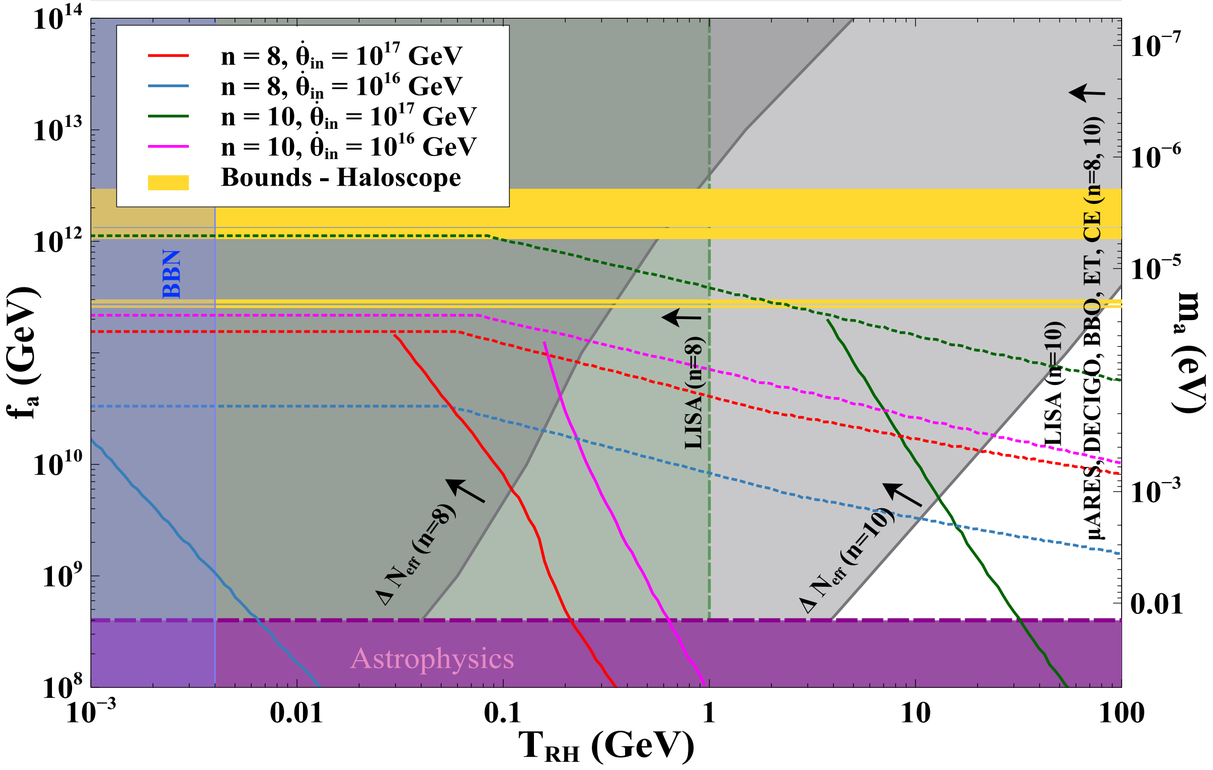
- For n = 2, 4 : $\dot{\theta}_{\rm crit} > 6\times10^{17}$ GeV $\Longrightarrow$ **Disallowed**
- n = 6: **Underabundant.**
- **Larger n:** Viable full-DM solutions can arise, subject to additional constraints.

Bosonic Decay: $\dot{\theta}_i = 5\times10^{16}$ GeV

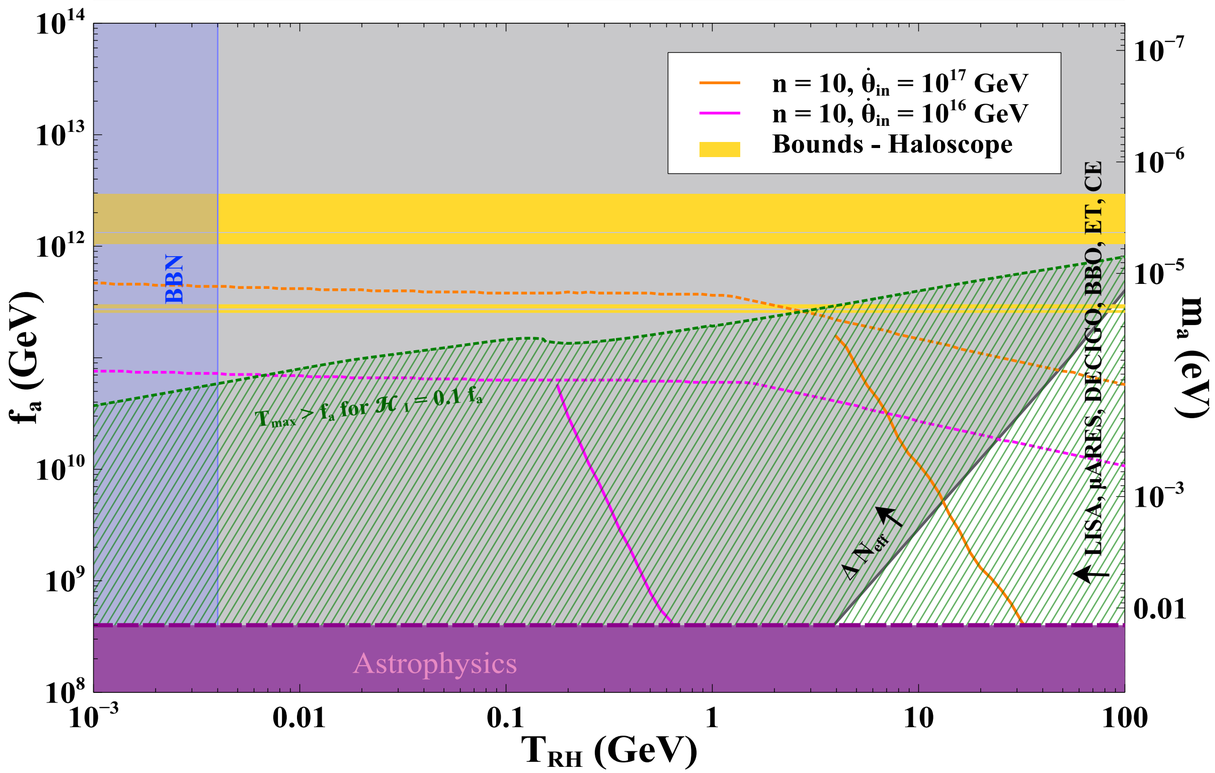


Impact of Non-Standard Cosmology on Axion Relic Abundance

Bosonic Decay



Fermionic Decay



Plot Keys:

- **Green region:** $T_{\max} > f_a$ where thermal restoration of the PQ symmetry may occur.
- Dotted lines: $\dot{\theta}_{crit}$
- **Grey shading** = existing ΔN_{eff} constraint on primordial GWs

Results: $H_I = 0.1 f_a$, $|\dot{\theta}_i| = 10^{16}, 10^{17}$ GeV

- **Bosonic:** n=8,10 allow 100% DM for $|\dot{\theta}_i| = 10^{17}$ GeV.
- **Fermionic:** The displayed n = 10 full-DM curves violate $T_{\max} < f_a$.

Summary

Vacuum Misalignment

- Extended reheating modifies the preferred QCD axion parameter space through changes in the expansion history and entropy production.
- The observed dark matter abundance, together with axion searches, constrains specific inflaton potentials and reheating channels.
- For n=2: larger f_a allows $\mathscr{H}_I$ up to $\sim 10^{10}\,\mathrm{GeV}$, compared with $\sim 10^{7}\,\mathrm{GeV}$ in standard radiation domination.

Kinetic Misalignment

- The initial axion velocity is restricted by the available inflationary energy density, making viable scenarios more constrained.
- Within our benchmark assumptions, higher-power inflaton potentials are favoured; bosonic reheating can remain viable, while the considered fermionic scenarios are strongly constrained.
- RHN-mediated reheating permits viable kinetic misalignment for a sufficiently short RHN-dominated phase.

Outlook:

Axion searches and primordial gravitational-wave observations provide complementary probes of the reheating history.