Spontaneous Leptogenesis with sub-GeV Axion Like Particles

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In Collaboration with **Arghyajit Datta and Arunansu Sil**

Baryon and Lepton Number Violation (BLV 2024)

Outline of the talk

- Introduction to Axion and ALP
- Spontaneous (axionic) Leptogenesis with Weinberg Operator and related issues
- Spontaneous (axionic) Leptogenesis with IHD featuring light ALPs and low reheating temperature
- Conclusion

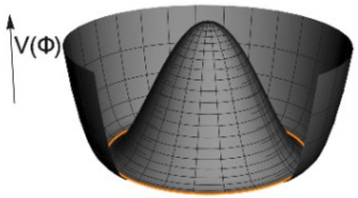
What is Axion (or, Axion-like Particle)?

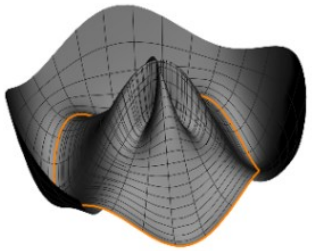
[Peccei, Quinn `77; Weinberg `78; Wilczek `78]

- *Spontaneous breaking* of global axial symmetry $U(1)_{PQ}$

$$\Phi = \frac{\eta(x) + f_\phi}{\sqrt{2}} e^{i\phi(x)/f_\phi}$$

Massless Goldstone Boson, **Axion $\phi(x)$**





- At QCD scale, axial anomaly explicitly breaks $U(1)_{PQ}$

$$m_\phi \approx \Lambda_{\rm QCD}^2 / f_\phi \qquad V_{\rm eff}(\phi) \approx \Lambda_{\rm QCD}^4 \left[1 - \cos\left(\frac{\phi(x)}{f_\phi}\right)\right]$$

Massive **Axion** **(pNGB)**

[Credit: Raffelt, Marsh]

- Originally introduced to solve *the strong CP problem*.

$$\theta \frac{g_s^2}{32\pi^2} G\tilde{G} \rightarrow \underbrace{\left(\theta + \frac{\phi(x)}{f_\phi}\right)}_{\theta_{\rm eff}(x)} \frac{g_s^2}{32\pi^2} G\tilde{G}$$

$\theta_{\rm eff}(x)$ ⇒ **Set to zero by QCD dynamics**

- A more general class of pNGBs: **Axion-like Particles (ALP)**

$$V_{\rm ALP} = m_\phi^2 f_\phi^2 \left(1 - \cos\frac{\phi}{f_\phi}\right)$$

Baryogenesis from CPT violation

- Baryon asymmetry of the Universe: $\eta_B = \frac{n_b - n_{\bar{b}}}{n_\gamma} \approx 6 \times 10^{-10}$

[Sakharov `67]

- Typically, dynamical origin of BAU needs to satisfy **Sakharov's conditions:**

  - B violation
  - C and CP violation
  - Departure from thermal equilibrium

Artefact of CPT symmetry

- **Alternatives** exist, if ***CPT*** breakes spontaneously,

  e.g., interaction of homogeneous ALP with SM fermion in **EFT:**

Shift-symmetric derivative ALP coupling

$$\frac{c}{f_\phi}\partial_\mu \phi j^\mu_X \to \frac{c}{f_\phi}\dot{\phi}(n_X - n_{\bar{X}})$$

$j^\mu_X = \bar{\psi}_X \gamma^\mu \psi_X$: SM Lepton or Quarks or B-L Current

Assumption: Global symmetry breaks before inflation ⇨ Homogeneous ALP, $\phi = \phi(t)$

A non-zero $\dot{\phi}$ causes CPT violation in nature! [CP preserved, T and **CPT** spontaneously broken]

[Cohen, Kaplan `87; Cohen, Kaplan `88]

Spontaneous CPT violation in ALP background

[Li, Wang, Feng, Zhang `02; Kusenko, Schmitz, Yanagida `15; Takahashi, Yamada `16; Bae, Kost, Shin `19; Domcke, Ema, Mukaida, Yamada `20]

Effect of spontaneous CPT violation in ALP background:

- **Shift in energy** for each particle and antiparticle

$$-c\frac{\dot{\phi}}{f_\phi} \qquad c\frac{\dot{\phi}}{f_\phi}$$

Provided, $\dot{\phi} \neq 0$

Interpreted as **effective chemical potential** μ_i , given particles are in **equilibrium**

- An **asymmetry in number density** is generated with this μ_i

$$j^0_X = n^{eq}_X - n^{eq}_{\bar{X}} = \frac{g_X}{(2\pi)^3}\int d^3p\left[\frac{1}{e^{(p-\mu_X)/T}+1} - \frac{1}{e^{(p+\mu_X)/T}+1}\right] \simeq \frac{g_X\mu_X T^2}{6} \qquad [(\mu_X/T)^2 << 1]$$

Spontaneous Leptogenesis (Baryogenesis) for ***X* = leptons (quarks)**

For $\frac{1}{f_\phi}(\partial_\mu\phi)j^\mu_{B-L}$:

$$\mathbf{n^{eq}_{B-L} = (n^{eq}_q - \bar{n}^{eq}_q) - (n^{eq}_\ell - \bar{n}^{eq}_\ell) \simeq \frac{1}{6}\mu_{B-L}T^2}$$

where, $\mu_{B-L} = (2\mu_q + \mu_u + \mu_d)N_f - (2\mu_l + \mu_e)N_f = -\frac{4N_f(1+N_f)}{3+5N_f}\dot{\theta}$

[Evaluated from the inter-relations of different chemical potentials related to interactions in equilibrium]

***B*−*L* asymmetry appears to be developed in equilibrium**

Survival of *B-L* asymmetry with Weinberg operator

- Survival of shift in energy spectra of particles and antiparticles **requires a *B-L* violating** interaction **in thermal equilibrium.**

$$n^{eq}_{B-L} \simeq \frac{1}{6}\mu_{B-L}T^2$$

→ Particles and anti-particles (charged under ***B-L***) equilibrate with **different thermal distributions.**

- Natural choice for ***B-L* violating** operator:

Weinberg operator: $$\mathcal{L}^{\rm H}_{\not{L}} = \frac{1}{2}\kappa_{ij}\frac{(H.\overline{\ell}^C_{L_i})(\ell_{L_j}.H)}{\Lambda}$$

[Weinberg `79]

Constrained by **Neutrino mass,** $m_\nu = \kappa\frac{v^2}{2\Lambda}$

- Interaction rates associated to lepton number violating processes like: $\ell_L\ell_L \leftrightarrow HH, \ell_L H \leftrightarrow \overline{\ell}_L, \overline{H}$

$$\Gamma^{\rm H}_{\not{L}} = 4n^{\rm eq}_\ell\langle\sigma v\rangle \approx \frac{6T^3}{\pi^2}\frac{\sum_i m^2_{\nu_i}}{2\pi v^4}$$

→ **Unique decoupling temprature** followed from $\Gamma^{\rm H}_{\not{L}} \leq \mathcal{H}(= 1.66\sqrt{g_\star}T^2/M_{Pl})$ condition:

$$T^{\rm H}_d \simeq 2\times 10^{13}\ {\rm GeV}$$

Below T^H_d, *B-L* asymmetry n^{eq}_{B-L} gets frozen.

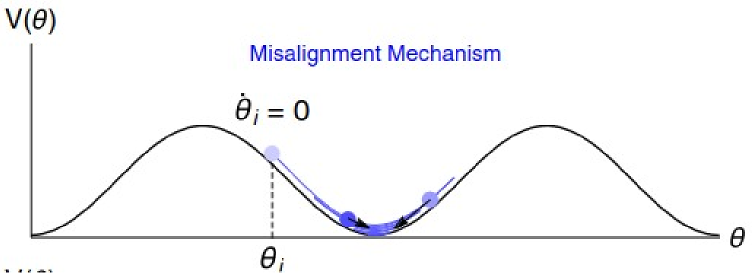
[Ibe, Kaneta `15; Bae, Kost, Shin `19;]

Temperature range of successful sp. leptogenesis with Weinberg operator

- ***B-L* violating** interactions from Weinberg operator remains in **equilibrium** at $T > T_d^H \sim 10^{13}$ GeV
- Occuring in a radiation-dominated Universe: $T < T_{\rm RH}$
- How to **realise** $\dot\phi \neq 0$ at $T > T_d^H$ → connected to **ALP dynamics**

Misalignment Mechanism

$$\ddot a + 3\mathcal{H}\dot a + \frac{\partial V_{\rm ALP}}{\partial a} = 0$$



[Credit: Co, Hall, Harigaya (2019)]

- ALP field is assumed to be stuck at some initial value after inflation at T_{RH} as $\theta_i \equiv \phi_i/f_\phi = \mathcal{O}(1)$
- ALP obtains non-zero velocity at the onset of oscillaton, $3\mathcal{H}(T_{\rm osc}) \simeq m_\phi$

$$T_{\rm osc} \simeq 1.5 \times 10^{13}{\rm GeV}\left(\frac{100}{g_\star(T_{\rm osc})}\right)^{1/4}\left(\frac{m_\phi}{10^9{\rm GeV}}\right)^{1/2}$$

A very restrictive range of high temperature emerges, $T_{\rm RH} > T_{\rm osc} > T_d^{\rm H} \sim 10^{13}$ GeV

Caveats of standard spontaneous leptogenesis

- With Weinberg operator, main obstacle to have a low-scale leptogenesis: $T_d^H \simeq 10^{13}\ \text{GeV}$

  Constrained by light **Neutrino mass,** $m_\nu = \kappa \frac{v^2}{2\Lambda}$

- Presence of heavy ALPs required: $m_\phi \geq 10^9\ \text{GeV}$

- Requires very high reheating temperature.

Our proposal: can we lower the temperature scale of such leptogenesis?

Motivation:

- ✔ Spontaneous leptogenesis with lighter ALPs (**sensitive to experiments**)
- ✔ Reheating temperature can be sufficiently low (consistent with the **lower bound** on T_{RH} > few MeV).

Our scenario: spontaneous leptogenesis with new Weinberg-like operator

- We propose inclusion of an analogous operator **with IHD:**

$$\mathcal{L}^{\Phi}_{\not{L}} = \frac{1}{2}\frac{(\Phi.\bar{\ell}^{C}_{L})(\ell_L.\Phi)}{\Lambda}, \quad \text{with} \quad \Phi = \begin{bmatrix} \Phi^+ \\ \Phi^0 \end{bmatrix}$$

- Associated interaction rate for **B-L violating** interactions

$$\Gamma^{\Phi}_{\not{L}} = \frac{6gT^3}{8\pi^3\Lambda^2}, \quad \text{with } g = 324/23$$

- **disentangled** from **neutrino mass**
- T_d^H remains **unchanged.**

- From $\Gamma^{\Phi}_{\not{L}} = \mathcal{H} \implies T^{\Phi}_{d} \simeq 4 \times 10^6 \text{ GeV} \left(\frac{g_\star}{100}\right)^{1/2} \left(\frac{\Lambda}{10^{12} \text{ GeV}}\right)^2$

IHD assisted interactions stays in thermal equilibrium till a much lower T

ALP dynamics for nonzero $\dot{\theta}$

- Evolution of the ALP field: $\ddot{\phi} + 3\mathcal{H}\dot{\phi} + \frac{\partial V(\phi)}{\partial \phi} = 0, \quad \text{with} \;\; V(\phi) = m_\phi^2 f_\phi^2 (1 - \cos\,\theta)$
- **Starting point**: end of inflation [**Reheating temperature** (instanteneous reheating)]
- **Initial conditions:**

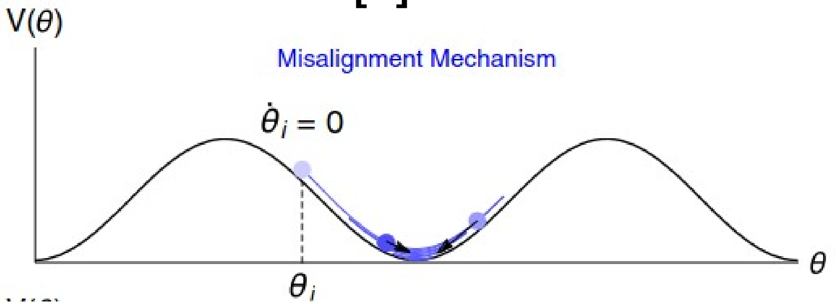
$$[\mathbf{A}]\;\; \theta_i(T = T_{\rm RH}) = 1, \;\; \dot{\theta}_i = 0 \quad \text{(standard misalignment)}$$

[Abbot, Sikivie `83; Dine, Fischler`83; Preskil et. al. `83]

$$[\mathbf{B}]\;\; \theta_i(T = T_{\rm RH}) = 1, \;\; \dot{\theta}_i \neq 0 \quad \text{(kinetic misalignment)}$$

[Co, Harigaya `19; Chang, Cui `19]

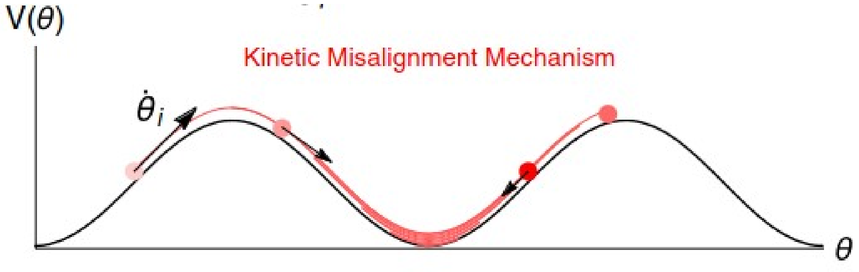
[A]



$T_{\rm RH} > T_{\rm osc} > T_d^\Phi$ is needed

[depends on m_ϕ and Λ]

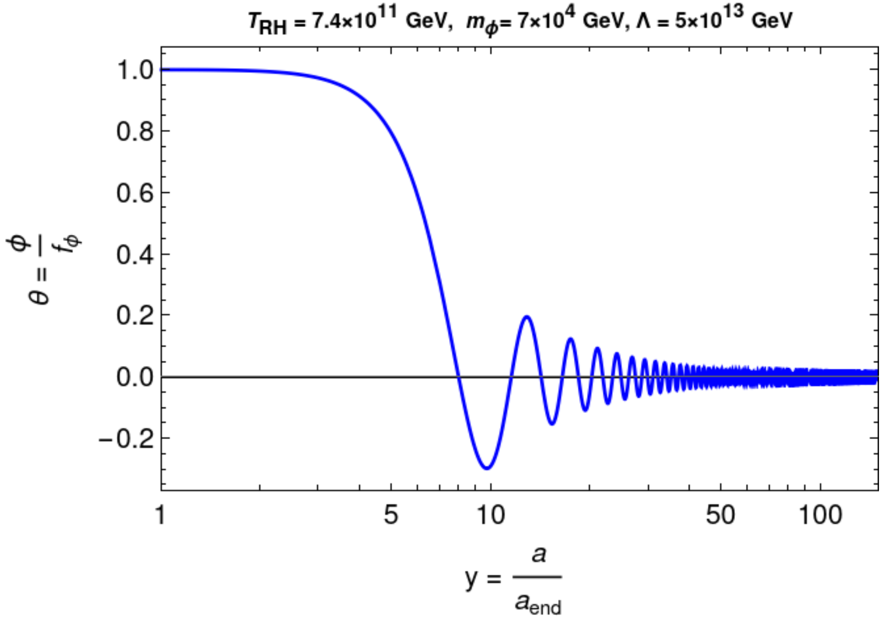
[B]



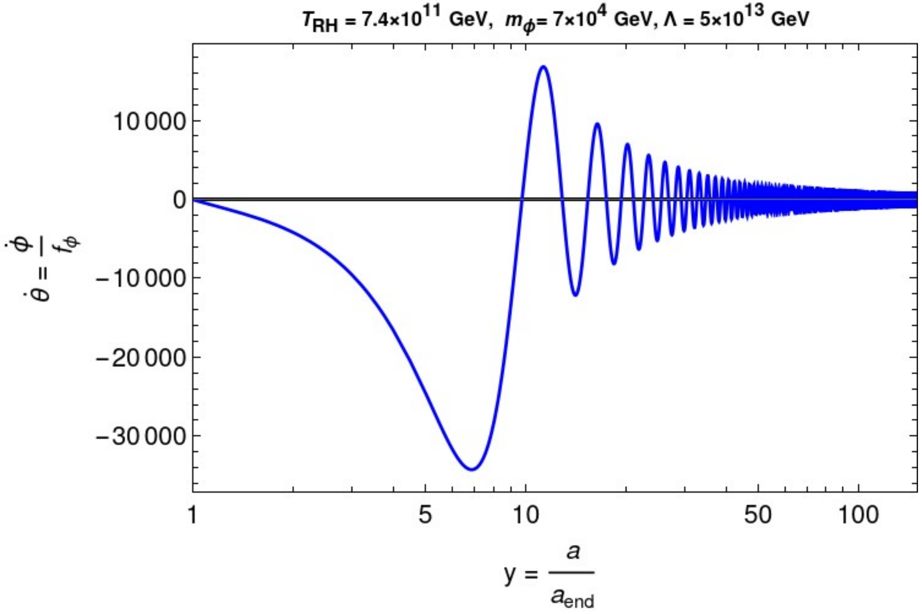
- If ALP has larger initial kinetic energy than the height of ALP potential, ALP field will leap across.
- Oscillation will begin once ALP field gets trapped in a minimum, satisfying $\dot{\theta}(T^\star_{\rm osc}) = 2m_\phi$

[A] Freeze-in Leptogenesis

- Evolution of the ALP field: $\ddot{\phi} + 3\mathcal{H}\dot{\phi} + \frac{\partial V(\phi)}{\partial \phi} = 0$ $\quad [\theta_i = 1,\ \dot{\theta}_i = 0]$



θ evolution since $T = T_{RH}$



$\dot{\theta}$ evolution since $T = T_{RH}$

B-L asymmetry created at $T = T_{\rm osc}$, $\quad n^{\rm eq}_{B-L} \simeq \frac{1}{6}\mu_{B-L}T^2 = -\frac{4}{9}\dot{\theta}T^2$

[A] Freeze-in Leptogenesis (contd...)

- A **precise** estimation of final n_{B-L} results by solving the **Boltzmann equation**

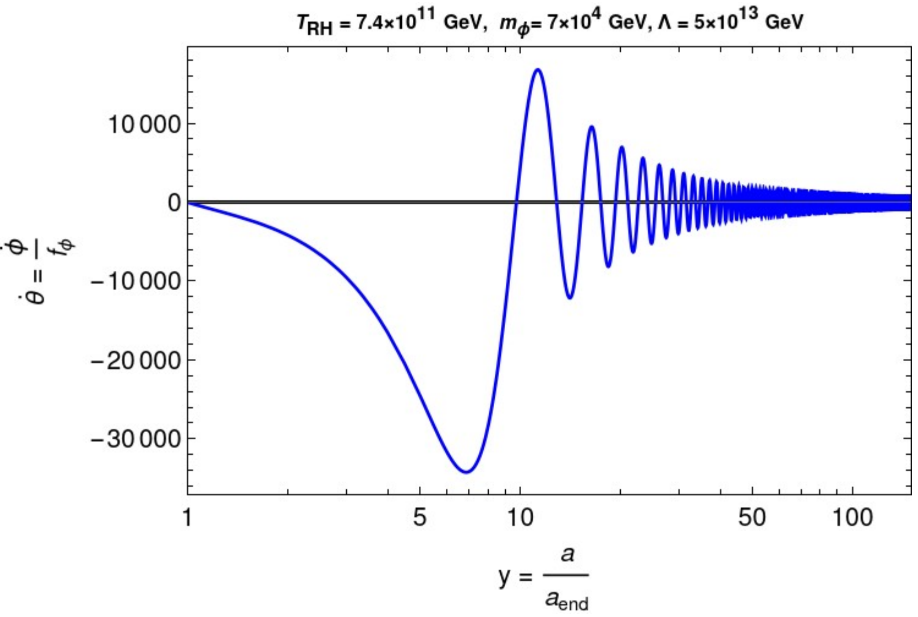
$$n^{\rm eq}_{B-L} = -\frac{4}{9}\dot{\theta}T^2$$

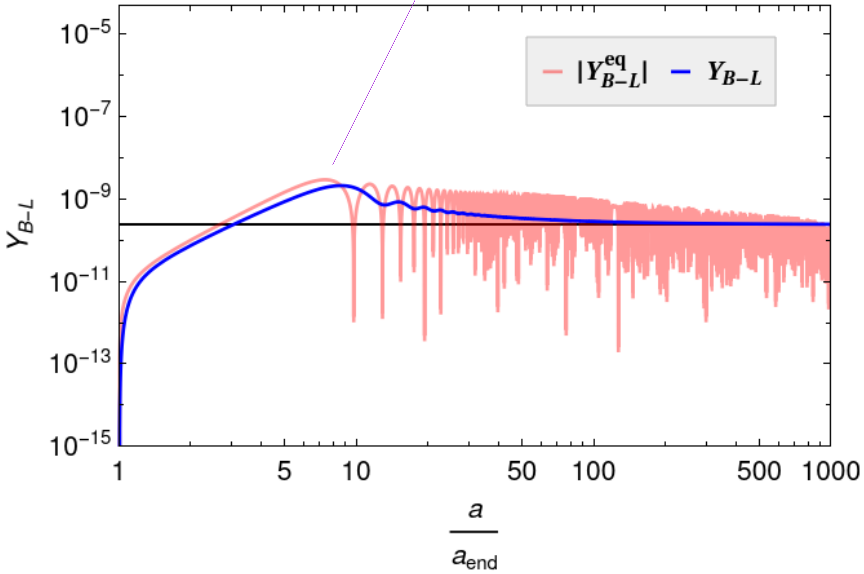
$$\dot{n}_{B-L} + 3\mathcal{H}n_{B-L} = -\Gamma^{\Phi}_{\not{L}}\left(n_{B-L} - n^{\rm eq}_{B-L}\right) \Rightarrow n_B = \frac{28}{79}n_{B-L}$$

$$\Gamma^{\Phi}_{\not{L}} = 6gT^3/8\pi^3\Lambda^2$$

BP	Λ (GeV)	$T_{\rm RH}$ (GeV)	m_ϕ (GeV)	$\dot{\theta}_i$
[A] BP1	1.02×10^{14}	7.4×10^{11}	7×10^{4}	0

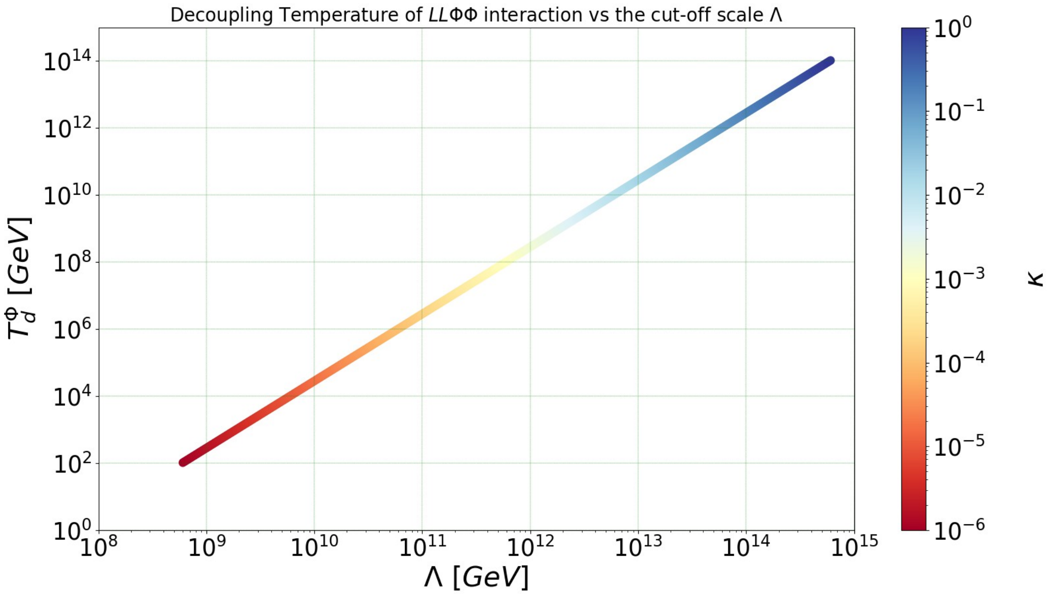
Peak value corresponds to crossing of ALP field across $\theta=0$, attaining maximum velocity





Findings of [A] Freeze-in Leptogenesis

- T_d^Φ can be significantly lowered.
- Still, ALPs with mass $m_\phi \gtrsim 5 \times 10^4$ GeV can reporduce the correct baryon asymmetry.



$$m_\nu = \kappa \frac{v^2}{2\Lambda}$$

Why not for further lower mass?

$$n_{B-L}^{\rm eq} = -\frac{4}{9}\dot{\theta}T^2$$

Requires increase in $\dot{\theta}$ if T_d^Φ is lowered

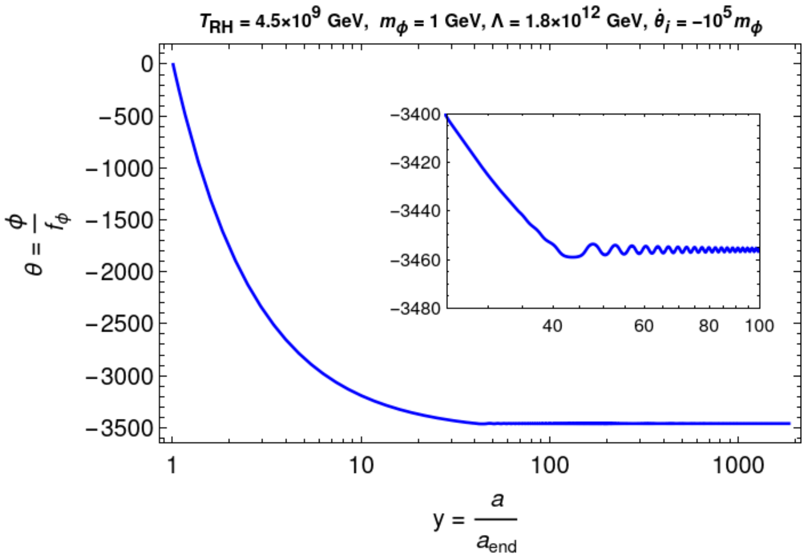
- ALP velocity **can't be made arbitrary large**, being related to ALP mass

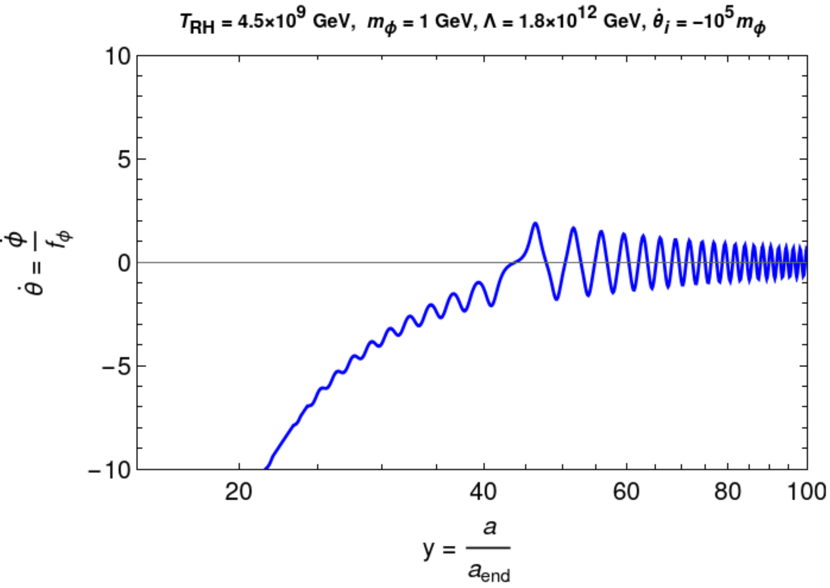
$$\theta(t) \simeq \theta_i\, \Gamma\left(\frac{5}{4}\right)\left(\frac{2}{m_\phi t}\right)^{1/4} J_{1/4}(m_\phi t)$$

$$\dot{\theta} \propto m_\phi^2 \quad \text{(in lowest order)}$$

[B] Freeze-out Leptogenesis

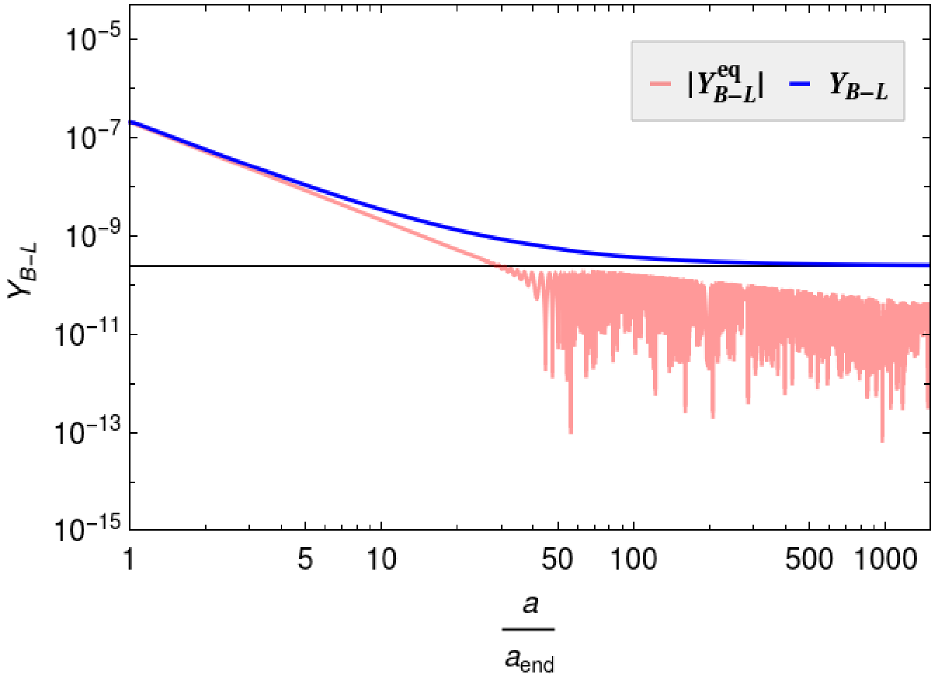
- Evolution of the ALP field: $\ddot{\phi} + 3\mathcal{H}\dot{\phi} + \frac{\partial V(\phi)}{\partial \phi} = 0$ $\quad [\theta_i = 1,\ \dot{\theta}_i \neq 0]$
- A **large initial velocity** can be considered $|\dot{\theta}_i| \lesssim \mathcal{O}(1) T_{\rm RH}^2 / f_\phi$ ⟶ follows from $\dot{\theta}^2 f_\phi^2 / 2 < \rho_R$ at $T = T_{RH}$





- In this case, oscillation starts when $\dot{\theta}(T^\star_{\rm osc}) = 2 m_\phi$
- ALP starts evolving with an existing chemical potential $\Longrightarrow$ $T^\star_{\rm osc} > T_d^\Phi$ is no more needed.
- **Necessary conditions:** $T_{\rm RH} > T_d^\Phi$ **and** $T_{\rm RH} > T^\star_{\rm osc}$

[B] Freeze-out Leptogenesis (contd...)

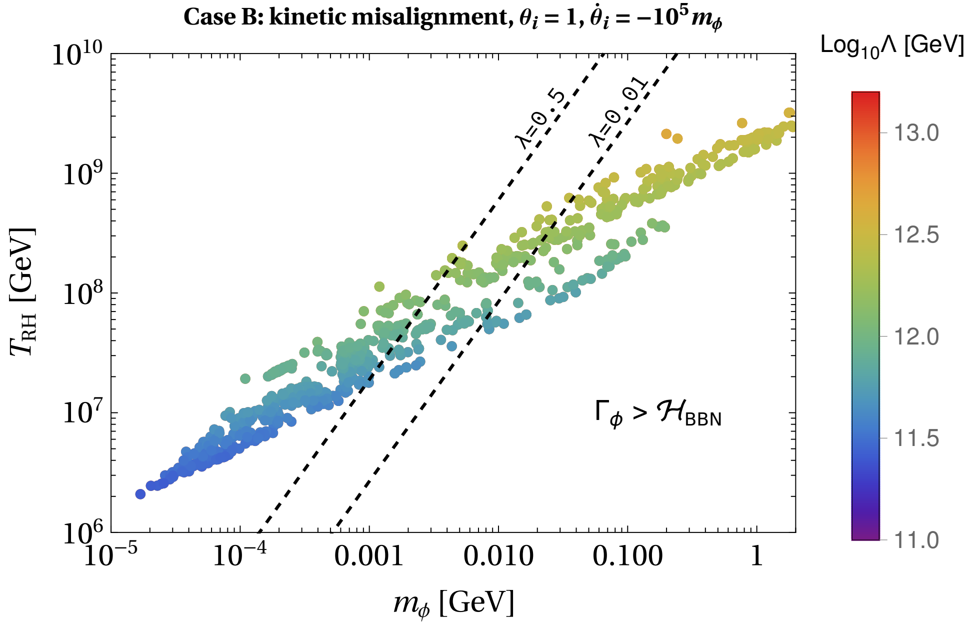


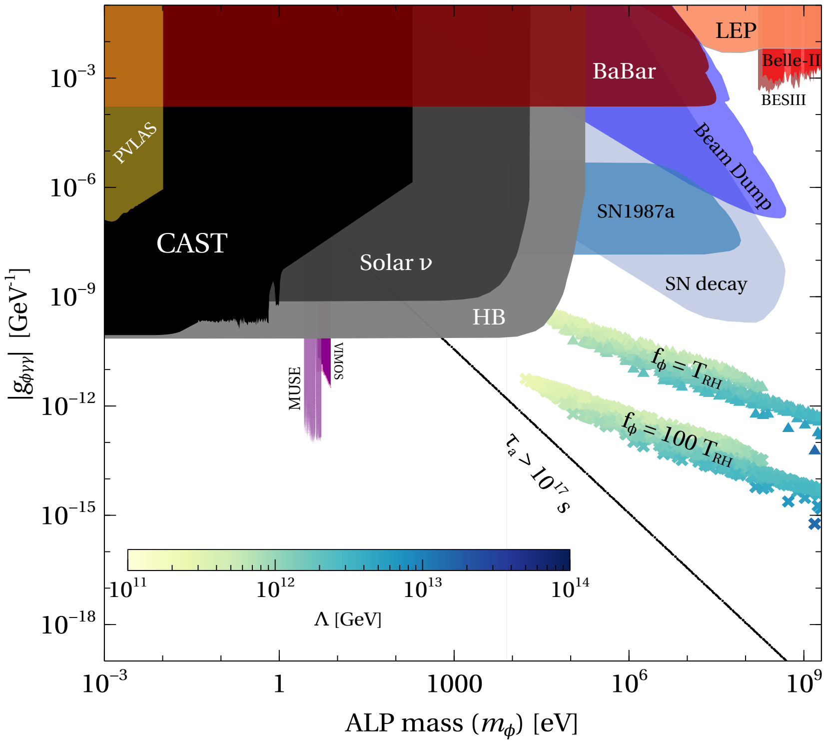
BP	Λ (GeV)	$T_{\rm RH}$ (GeV)	m_ϕ (GeV)	$\dot{\theta}_i$
[B] BP2	5.25×10^{12}	4.5×10^{9}	1	$-10^5 m_\phi$

- Peak value of asymmetry emerges at the beginning due to large initial $\dot{\theta}_i$
- As $T_{\rm RH} < T_d^{\rm H}$, interactions from the Weinberg operator $(\ell_L \ell_L H H)$ does not contribute.
- ***B-L*** asymmetry finally freezes out when $\ell_L \ell_L \Phi\Phi$ interaction decoupled from equilibrium.

[B] Freeze-out Leptogenesis (contd)

- How light the ALP can be?
- How low reheating temperature can be?





- Initial ALP velocity, $\dot{\theta}_i = -10^5 m_\phi$ is considered.
- ALP should decay prior to BBN: $\Gamma_\phi (\simeq \beta m_\phi^3 / f_\phi^2) \gtrsim \mathcal{H}_{BBN}$ $[\beta < \mathcal{O}(1)]$
- $T_{RH} = \alpha f_\phi \;\; [\alpha \leq 1]$ and $\lambda = \beta \alpha^2$

- Sensitive to various **collider** (CMS, CDF, Belle II...) and **beam-dump** (CHARM and MicroBooNE, NA64, FASER...) experiments.

Summary

- ➔ In conclusion, our study presents a *scaled-down* version of **spontaneous leptogenesis** by introducing a new B-L violating operator with an IHD.
- ➔ Apart from avoiding the neutrino mass constraints, it leads to a much smaller decoupling temperature, enabling leptogenesis with a low enough reheating temperature.
- ➔ Here, the asymmetry follows the evolution of ALP velocity, leads to two cases: (a) zero initial velocity: Freeze-in leptogenesis (b) large initial velocity: Freeze-out leptogenesis.
- ➔ Being a reduced-scale situation, our scenario can accommodate much lower ALP masses, even in the experimentally sensitive (e.g. collider and beamdump experiments) sub-GeV regime in the later case (Freeze-out).
- ➔ The IHD adds another benefit of being a compelling dark matter candidate, connecting BAU generation with dark matter within such a minimal and cohesive framework.

Thank you for your attention!

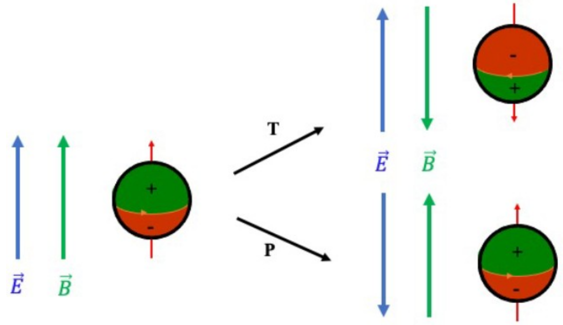
Back-up slides

Strong CP problem

✔ **Motivation: Strong CP Problem**

$$\mathcal{L} \supset \bar{\theta}_{\rm QCD} \frac{g_s^2}{32\pi^2} G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a$$

[Belavin et. al.`75; ‘t Hooft `76; Callan et. al. `76, ...]



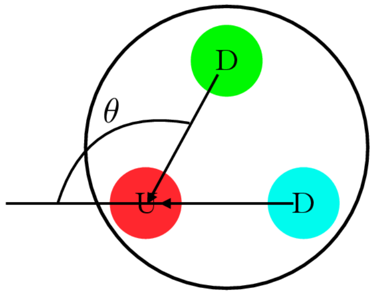
- Violates CP symmetry ($G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a \propto \mathbf{E^a.B^a}$)
- Induces **neutron EDM:** $d_n \sim 10^{-16}\theta$ e cm

$$\theta \equiv \bar{\theta}_{\rm QCD} - \arg\det(M_U M_D)$$

- **Experiment:** $|d_n| < 1.8 \times 10^{-26}$ e cm

$$\theta \lesssim 10^{-10}$$

➡ **Why so small?**



$$d_n \sim \frac{M_U M_D}{M_U + M_D}\frac{1}{m_n^2}\theta e$$

[Hook `18]

More on Axion-like Particle (ALPs)

[Arias et. al. `12; Ringwald `12; PDG `22]

- pseudo-Nambu-Goldstone boson of **PQ-like $U(1)$** symmetry.
- Like QCD axion, ALP Potential can be written as

$$V_{\rm ALP} = m_a^2 f_a^2 \left(1 - \cos\frac{a}{f_a}\right)$$

→ **m_a and f_a are independent**

Generated by ↓ **QCD-like non-perturbative effects or explicit breaking of $U(1)$**

↘ **Provides ALP mass**

- Temperature independent mass, unlike QCD axion.
- Not constrained by strong-CP problem, unlike QCD axion.

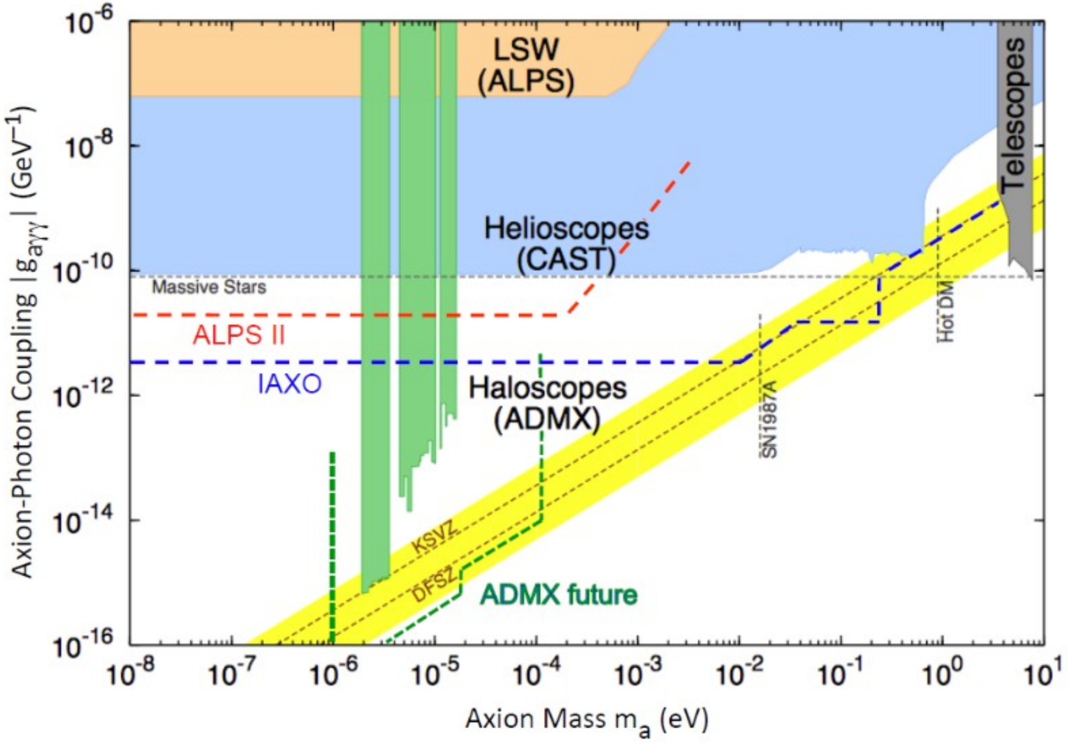
Axion and ALP searches and experiments

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a F \tilde{F} = g_{a\gamma\gamma} \mathbf{E}.\mathbf{B}$$

Axion-Photon transition

[Credit: Ballou `14; Irastorza `22; Battesti `18; Graham et. al ‘16]

- **Light shining through walls (LSW): ALPS II**
- **Haloscopes: ADMX, HAYSTACK, ORGAN ...**
  (For Axion Dark Matter)
- **Helioscope: CAST, IAXO ...**
  (For Solar Axion)



Misalignment mechanism and Axion (ALP) as Dark Matter

- ✔ **Idea: Misalignment mechanism**

[Abbot, Sikivie `83; Dine, Fischler `83; Preskil et. al. `83]

- ➢ Axion e.o.m in FRW background

$$\ddot{a} + 3\mathcal{H}\dot{a} + \frac{\partial V_{\rm ALP}}{\partial a} = 0$$

At $T >> T_{\rm osc}$, $a(t) = a_I$

Oscillation starts when $3\mathcal{H}(T_{\rm osc}) \simeq m_a(T_{\rm osc})$

At $T < T_{\rm osc}$,

$$a = a_I e^{\pm i m_a t} e^{-3\mathcal{H}t/2}$$

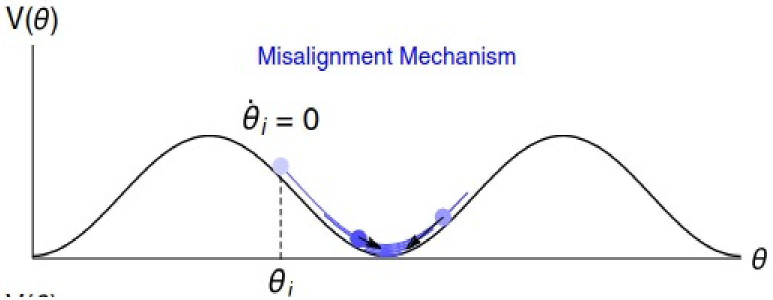
$(\rho_a \propto R^{-3})$ Behaves as **matter**

$$\rho_a(T) = \frac{1}{2} m_a(T_{\rm osc}) m_a(T) f_a^2 \theta_I^2 \left(\frac{R_{\rm osc}}{R}\right)^3$$

Depends on initial *misalignment angle* $\theta_I \equiv a_I/f_a$

- ✔ **Assumption:** pre-inflationary U(1) breaking

[Credit: Co and Harigaya `19]



$$\Omega_a h^2 \sim 0.1 \left(\frac{\theta_I}{\mathcal{O}(1)}\right)^2 \left(\frac{f_a}{10^{12}\ {\rm GeV}}\right)^{7/6}$$

(**for QCD Axion**)

$$\Omega_a h^2 \simeq 0.12 \left(\frac{\theta_I}{\mathcal{O}(1)}\right)^2 \times \left(\frac{m_a}{10^{-9}\ {\rm GeV}}\right)^{\frac{1}{2}} \left(\frac{f_a}{4\times 10^{11}\ {\rm GeV}}\right)^2$$

(**for ALP**)

Axionic solution of Strong CP Problem

[Credit: Quanta Magazine]

- ✔ **Idea:** Promote θ as dynamical field
- ✔ **Prescription:** SM + Global axial $U(1)_{PQ}$ (Peccei-Quinn symmetry)

[Peccei, Quinn `77; Weinberg `78; Wilczek `78]

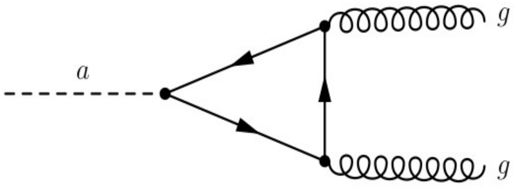
Spontaneously Broken at $T \simeq f_a$

- Axion $\theta \equiv \dfrac{a}{f_a}$ is a massless NGB

$$\Phi = \frac{\eta(x) + f_a}{\sqrt{2}} e^{ia(x)/f_a}$$

Anomalous under QCD at $T \simeq \Lambda_{\rm QCD} \simeq 150 \ {\rm MeV}$

$$\mathcal{L}_a \supset \frac{g_s^2}{32\pi^2} \frac{a}{f_a} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a$$



So, $\theta \dfrac{g_s^2}{32\pi^2} G\tilde{G} \rightarrow \underbrace{\left(\theta + \dfrac{a(x)}{f_a}\right)}_{\theta_{\rm eff}(x)} \dfrac{g_s^2}{32\pi^2} G\tilde{G}$

$\theta_{\rm eff}(x)$ ➡ **Set to zero by QCD dynamics**