7th IBS-ICTP-MultiDark Workshop

Lepto-axiogenesis in minimal KSVZ model

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based on 2109.08605 [JHEP 04 (2022) 116]

with

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Introduction

Axiogenesis = AD baryogenesis + axion

R.T.Co, K.Harigaya, 1910.02080

- Affleck-Dine [AD] baryogenesis
  - baryogenesis from rotational motion in flat direction
  - flat directions exist in supersymmetric [SUSY] SM
- Axion
  - introduced to solve strong CP problem
  - NG mode of global $U(1)_{\mathrm{PQ}}$ symmetry

Axiogenesis ~ AD baryogenesis using axion rotation

- PQ field potential

$$V = V_{\rm PQ} + \frac{P^n}{M_p^{n-4}}$$

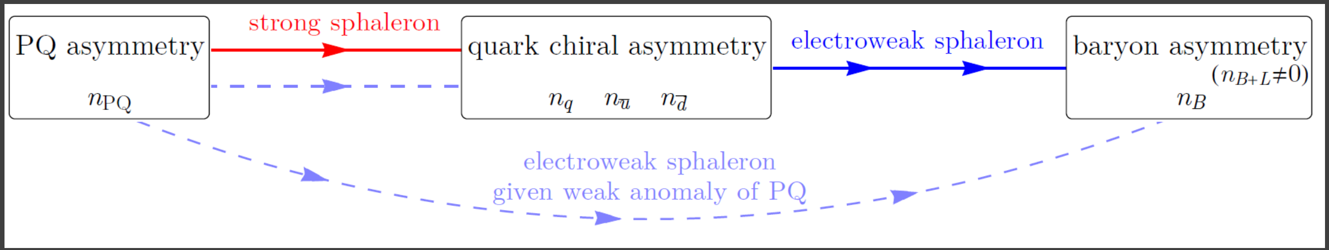
explicit PQ breaking

PQ field: $P = S\, e^{i\theta}/\sqrt{2}$

θ: axion, S: saxion

$V_{\rm PQ}$: $\mathrm{U}(1)_{\rm PQ}$ conserving, develops $\langle P \rangle \simeq f_a \neq 0$

→ "kick" by P^n term induces PQ asymmetry $n_{\rm PQ} = S\dot{\theta}^2 \neq 0$



R.T.Co, K.Harigaya, 1910.02080

→ converted via interactions with fermions (w. B/L number)

c.f. L->B conversion in leptogenesis

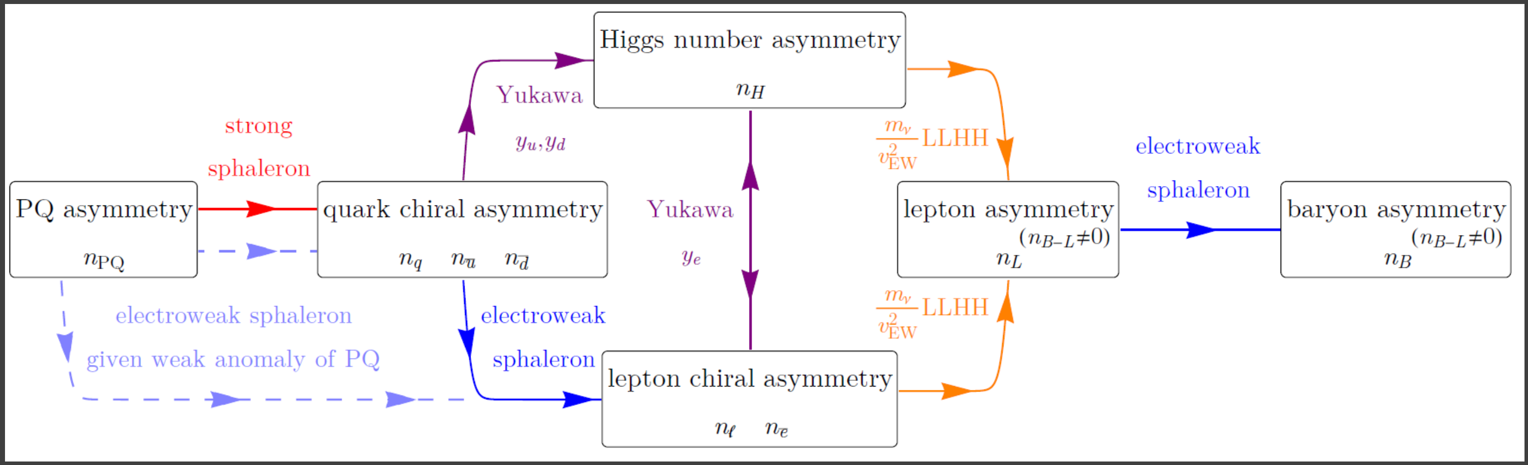
Lepto-Axiogenesis

R.T.Co, N.Fernandez, A. Ghalsasi, L.J.Hall and K.Harigaya, 2006.05687

- Lepton number violation in type-I see-saw

$$M_N NN + y\, LHN \quad \rightarrow \quad \frac{1}{M_N} LHLH\text{: L-violating}$$

conversion via $LHLH$



R.T.Co et.al, 2006.05687

→ successful baryogenesis and axion dark matter [DM]

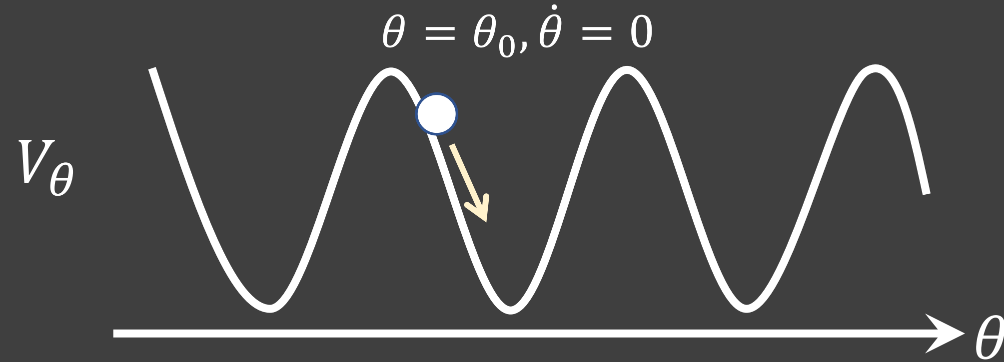
* other L/B violating interactions may also work R.T.Co et.al, 2110.05487

Kinetic misalignment mechanism

$\dot{\theta} \neq 0$ implies axion has velocity

PQ field: $P = S\, e^{i\theta}/\sqrt{2}$

- Misalignment Mechanism [MM]

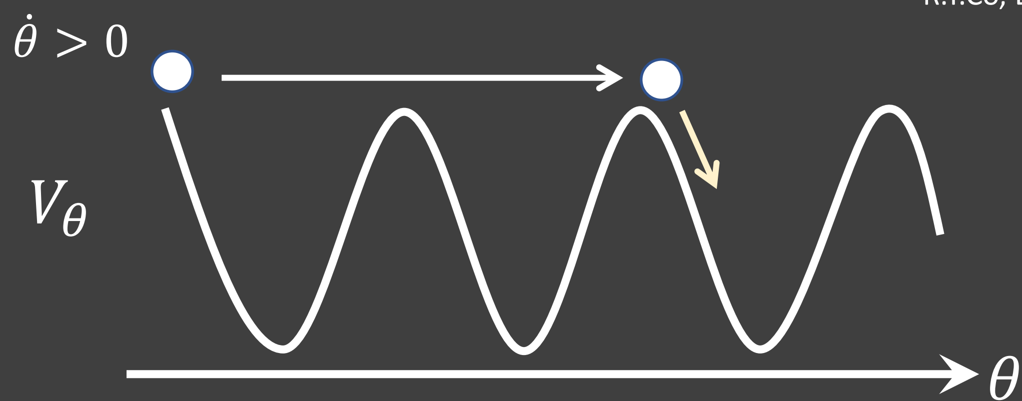


oscillation starts at $H \sim m_\theta$

$f_\theta \sim 10^{12}$ GeV explains DM

- Kinetic Misalignment mech. [KMM]

R.T.Co, L.J.Hall, K.Harigaya, 1910.14152



oscillation starts at $\dot{\theta} \sim m_\theta (> H)$

$f_\theta \sim 10^{8}$ GeV explains DM

Outline

1. Lepto-axiogenesis
2. PQ field dynamics
3. Cosmology
4. Conclusion

Axion motion

PQ field: $P = Se^{i\theta}/\sqrt{2}$

$\dot{\theta}$ maybe important for baryon asymmetry, (axion) DM , GW, …

R.T.Co, D.Dunsky et.al. 2108.09299

- conservation-law based method

R.T.Co, K.Harigaya, 1910.02080 e.t.c.

$$n_{\mathrm{PQ}}(T) = n_{\mathrm{PQ}}(T_i)\frac{a^3}{a_i^3}$$ → estimate dynamics of S and $\dot{\theta}$

- EOM based method : our work

evaluate dynamics by directly solving equation of motion [EOM]

- combination of numerical and analytical calculation
- provide direct/rigorous way to evaluate dynamics

Setup: minimal KSVZ model

- Superpotential

$\Psi, \overline{\Psi}$: KSVZ chiral fields

$$W = y\,P\,\overline{\Psi}\Psi + \lambda\frac{P^n}{n\,M_p^{n-3}} + W_{\mathrm{MSSM+type-I}}$$

$$\rightarrow \quad V = m_P^2\left(\log\frac{|P|^2}{v_P^2} - 1\right)|P|^2 + \frac{\lambda^2|P|^{2n-2}}{M_p^{2n-6}} + \frac{A_P}{M_p^{n-3}}(P^n + h.c.) + V_H + V_{\mathrm{th}}$$

induced by $\mathcal{O}(1)$ Yukawa y

PQ breaking

- $\langle P\rangle = v_P \neq 0$ is realized with only one PQ field
- assume negative Hubble mass term $\quad V_H = -c_H\,H^2|P|^2, c_H > 0$
- there is thermal correction $\quad V_{\mathrm{th}} = a_L\alpha_s^2 T^4 \log\,|P|^2/T^2$ $\quad (m_\Psi = y\langle P\rangle > T)$

Equation of motion

$$\ddot{P} + 3H\dot{P} + \frac{\partial V}{\partial P^*} = 0$$

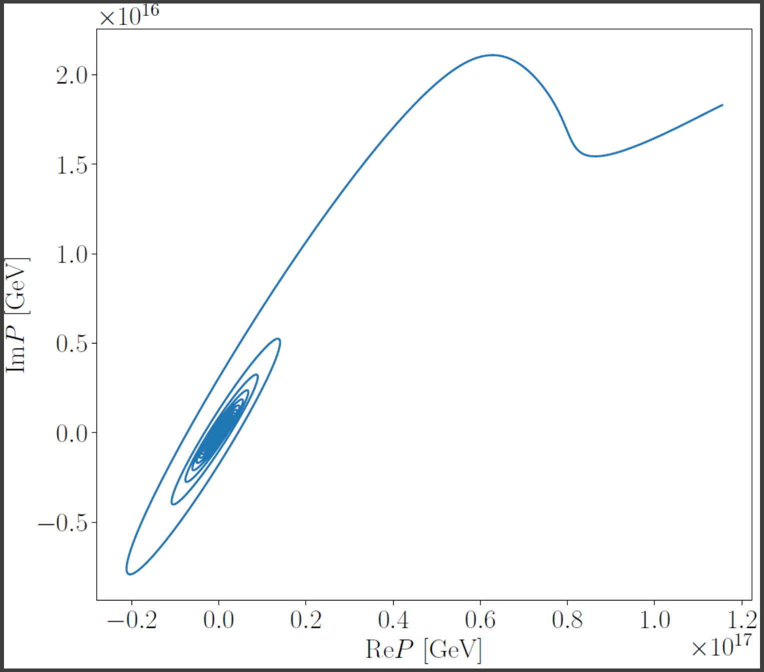
$$\frac{\partial V}{\partial P^*} = \left(m_P^2 \log\frac{|P|^2}{v_P^2} - c_H H^2 + (n-1)\lambda^2 \frac{|P|^{2n-4}}{M_p^{2n-6}} + a_L \alpha_s^2 \frac{T^4}{|P|^2} \right) P + n\frac{A_P}{M_p^{n-3}} P^{*(n-1)}$$

- numerical solution

we can solve this EOM

so what's the problem ?

✓ unsolvable at $H \ll m_P$



Equation of motion

- numerical solution

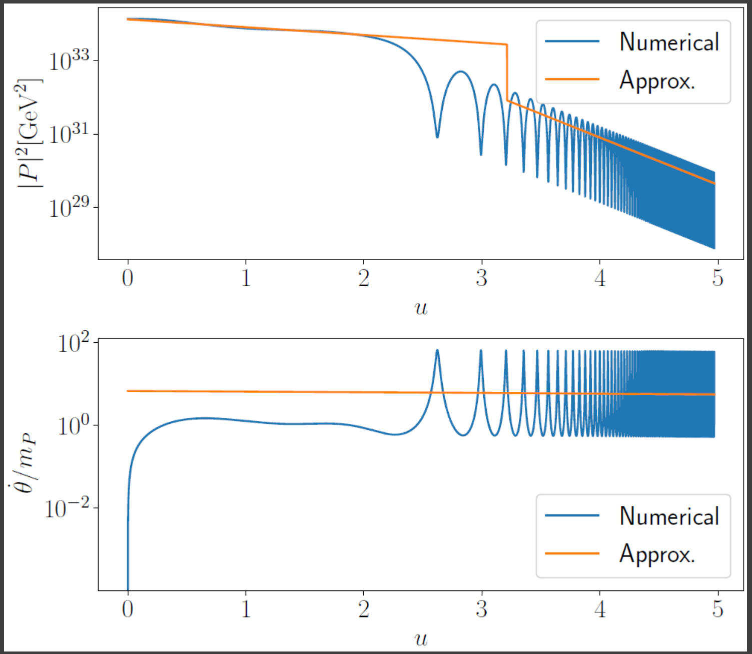
we can solve EOM for $H \gtrsim m_P$

↓

rotation becomes fast for $H \ll m_P$

numerical method is inefficient

$u = \log a/a_i$



we need to know dynamics at later times for baryon and DM density

(unlike usual AD scenario)

EOM at $H \ll m_P$

PQ field: $P = \frac{S}{\sqrt{2}} e^{i\theta}$

higher order terms are small, thermal corrections neglected

radial $\quad \ddot{S} - \dot{\theta}^2 S + 3H\dot{S} + m_P^2\, S\, \log\frac{S^2}{2v_P^2} = -(\Gamma_{\rm g} + \Gamma_a)\, \dot{S}$

angular $\quad \ddot{\theta} + 2\dot{\theta}\dot{S} + 3H\dot{\theta}S = 0$

- Saxion (radial dir.) thermalization
  - saxion is thermalized by gluon scattering and/or decay to axions

$$\Gamma_g = b_g \frac{T^3}{S^2} \qquad \Gamma_a = \frac{m_P^3}{32\pi S^2}$$

  - no thermalization for angular direction due to PQ conservation

c.f. $\quad n_{\rm PQ} = S\dot{\theta}$, so angular EOM $\Leftrightarrow \dot{n}_{\rm PQ} + 3Hn_{\rm PQ} = 0$

Analytic solution

PQ field: $P = \frac{S}{\sqrt{2}} e^{i\theta} = v_P \psi$

EOM $\quad \ddot{\psi} + 3H\dot{\psi} + m_P^2\, \psi \log|\psi|^2 = -\Gamma \frac{\psi}{|\psi|} \frac{d|\psi|}{dt}$

ansatz: $\quad \psi = e^{\Omega}(e^{\Delta/2 + i\, B_+} + e^{-\Delta/2 - iB_-})$ $\qquad \Omega, \Delta, B_\pm$: functions

averaging over rotation: $f \to \langle f \rangle = \frac{1}{2\pi}\int_{-\pi}^{\pi} d\phi\, f(\phi)$ $\qquad \phi = B_+ + B_-$

solution: $\quad \Omega(\mathrm{u}) = \frac{\omega(u)}{4} - \frac{\Delta(\mathrm{u})}{2}$ $\qquad \dot{B}_\pm = m_P \sqrt{\frac{\omega(u)}{2}}$ $\qquad u = \log a/a_i$

$$w(u) = \mathcal{W}\left(C_w^2 \left(\frac{1 + \coth\Delta}{2}\right)^2 \left(\frac{a_i}{a}\right)^6 \right)$$

$\mathcal{W}(z)$: Lambert function
$\mathcal{W} e^{\mathcal{W}} = z$

- $\Delta(u)$ to be determined from energy evolution
- $C_W, \Delta(u_i), B_\pm(u_i)$ are fixed by numerical solution

Implication of solution

$$P \sim v_P e^{\omega/4}\left(e^{iB} + e^{-\Delta - iB}\right)$$

positive rotation negative rotation

$$w(u) = \mathcal{W}\left(C_w^2 \left(\frac{1+\coth\Delta}{2}\right)^2 \left(\frac{a_i}{a}\right)^6\right)$$

$$w(z) \sim \begin{cases} \log z & z > \mathcal{O}(1) \\ z & z < \mathcal{O}(1) \end{cases}$$

- $\langle |P|^2 \rangle$, $\langle \dot{\theta} \rangle$ and $\langle \rho_P \rangle$ a : scale factor

	$\lvert P\rvert \gg v_P$	$\lvert P\rvert \sim v_P$
$\langle \lvert P\rvert^2 \rangle = v_P^2 e^{w/2}\left(1 + e^{-2\Delta}\right)$	$\propto a^{-3}$	$\propto a^{0}$
$\langle \dot{\theta} \rangle = m_P \sqrt{\frac{w}{2}}$	$\propto a^{0}$	$\propto a^{-3}$
$\frac{\langle \rho_P \rangle}{m_P^2 v_P^2} = e^{w/2}\left(1 + e^{-2\Delta}\right)\left(\frac{w}{2} - \tanh\Delta\right) + 1$	$\propto a^{-3}$	$\propto a^{-6}$
	matter	kination
		(circular motion)

Implication of solution

$$P \sim v_P e^{\omega/4}\left(e^{iB} + e^{-\Delta - iB}\right)$$

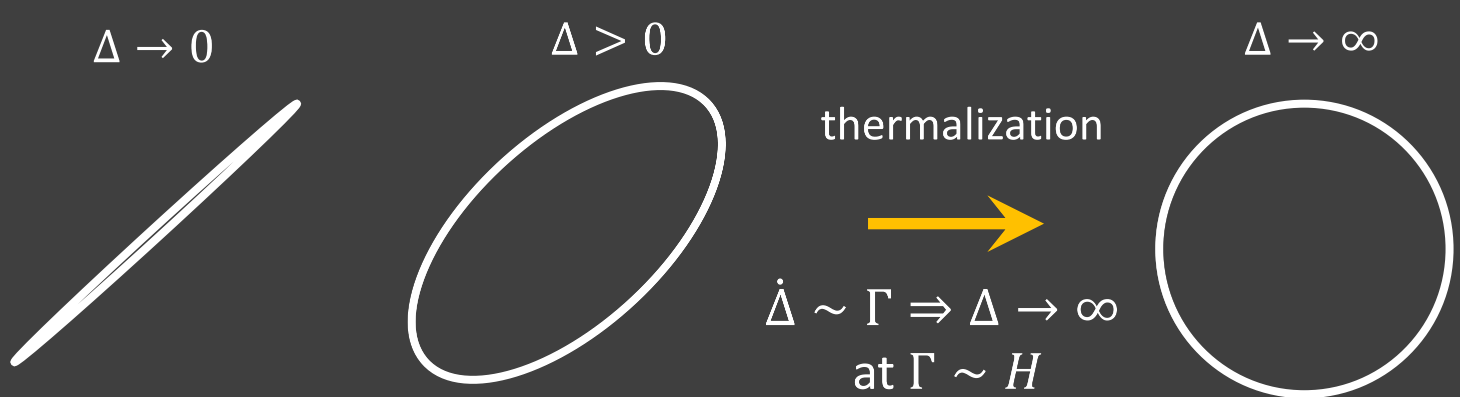
positive rotation   negative rotation

$$w(u) = \mathcal{W}\left(C_w^2 \left(\frac{1+\coth\Delta}{2}\right)^2 \left(\frac{a_i}{a}\right)^6\right)$$

$$w(z) \sim \begin{cases} \log z & z > \mathcal{O}(1) \\ z & z < \mathcal{O}(1) \end{cases}$$

- Δ controls shape of motion

→
- motion is along a line, i.e. oscillation, for $\Delta \to 0$
- motion becomes circular for $\Delta \to \infty$



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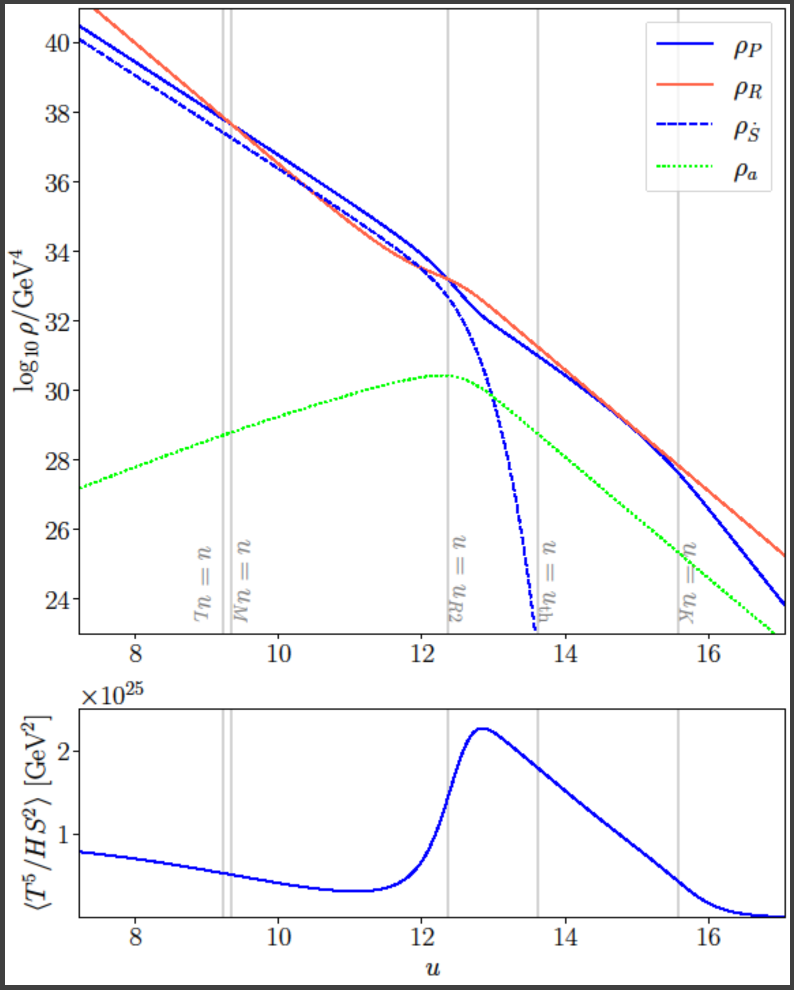
Energy evolution

we assume PQ motion starts after reheating completes

$m_P = A_P = 1\ \mathrm{PeV}, n = 10, T_i = 10^{13}\mathrm{GeV}$



1. radiation domination $\rho_R > \rho_P$
2. PQ energy dominates $\rho_P > \rho_R$
3. saxion is thermalized $\rho_S \to 0$
4. radiation domination $\rho_R \gg \rho_P$

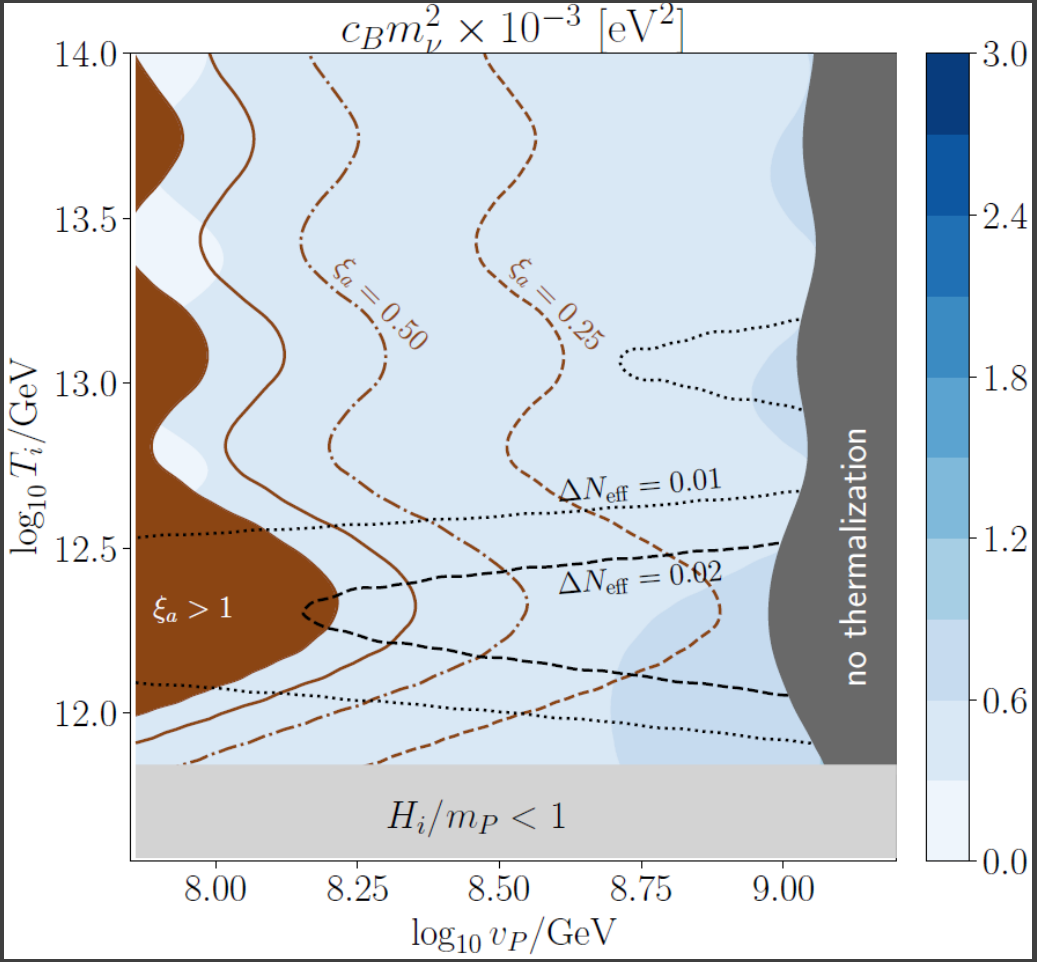
➢ baryon asymmetry

$$n_B \propto n_{\mathrm{PQ}} \int d \log a \, \frac{T^5}{HS^2}$$

generated during thermalization

Baryon asymmetry

values of $c_B m_\nu^2$ to explain baryon asymmetry



T_i: initial temperature

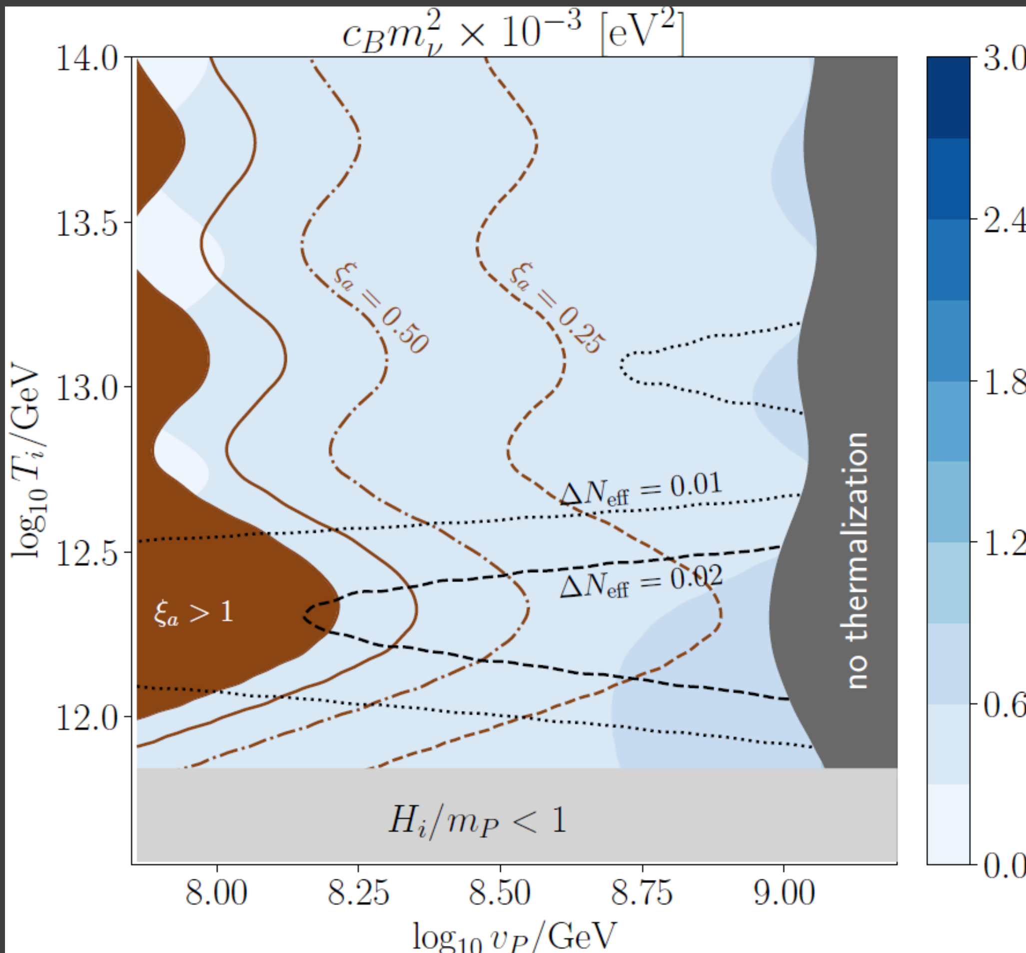
$$M_N^{-1} LHLH \to m_\nu \nu\nu$$

$c_B \sim \mathcal{O}(0.01 - 0.1)$ in MSSM

P.Barnes, R.T.Co et.al. 2208.07878

$$n_B = n_{\mathrm{PQ}} \times \frac{c_B m_\nu^2}{4\pi^3 v_H^4} \int_{u_L}^{u} du \, \frac{T^5}{HS^2}$$

Axion density



T_i: initial temperature

$\xi_a := \Omega_a/\Omega_{\rm DM}^{\rm obs}$

generated by KMM

$v_P \sim 10^8$ GeV gives $\xi_a \sim 1$

DM density

- Axion density

$$\Omega_a h^2 \sim \frac{0.1}{N_{\rm DW}} \times \left(\frac{f_a}{10^8 \mathrm{GeV}}\right)\left(\frac{Y_{\rm PQ}}{3}\right)$$

$$N_{\rm DW} f_a = \sqrt{2} v_P$$

$$Y_{\rm PQ} = n_{\rm PQ}/s \sim 1 - 10$$

small or sizable fraction of DM density

- LSP density

reheat temperature $T_i \sim 10^{12-14}$ GeV in our scenario $m_P < H_i$

- Lightest SUSY Particle [LSP] is produced from gravitino decay
- dilution by PQ field thermalization is $\mathcal{O}(1-10)$
- $m_{\rm LSP} \sim \mathcal{O}(100)$ GeV and $m_{3/2} \sim \mathcal{O}(10^7)$ GeV

c.f. $m_P \sim \mathcal{O}(10^{5-6})$ GeV for baryogenesis

Summary

we demonstrated an axiogenesis scenario by solving EOM

- Analytic solution at $H \ll m_P$

$$P \sim v_P e^{\omega/4}\left(e^{iB} + e^{-\Delta - iB}\right)$$

we found rotation averaged solution of EOM with thermalization

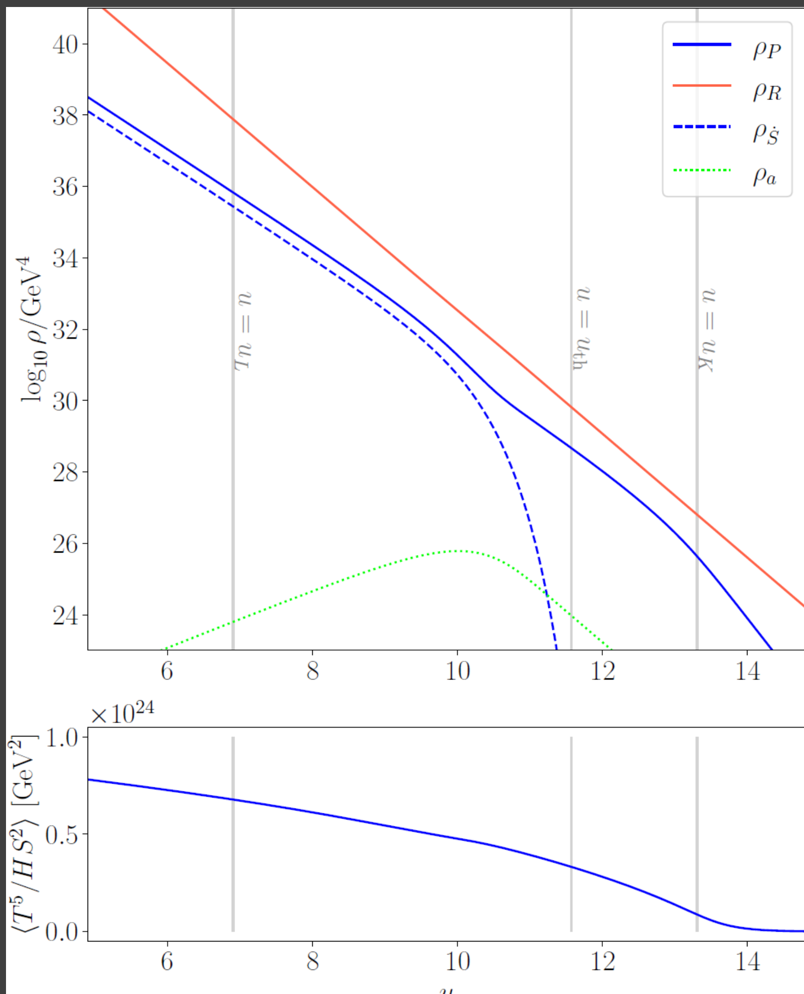
- Lepto-axiogenesis in minimal SUSY KSVZ model

  - PQ field energy may dominate, but is comparable to radiation energy
  - baryon asymmetry can be explained for $v_P \sim 10^{8-9}$ GeV
  - axion density is given by KMM

Backups

Energy evolution for $n = 8$

$m_P = A_P = 0.1\ \mathrm{PeV}, n = 8, T_i = 10^{12}\mathrm{GeV}$

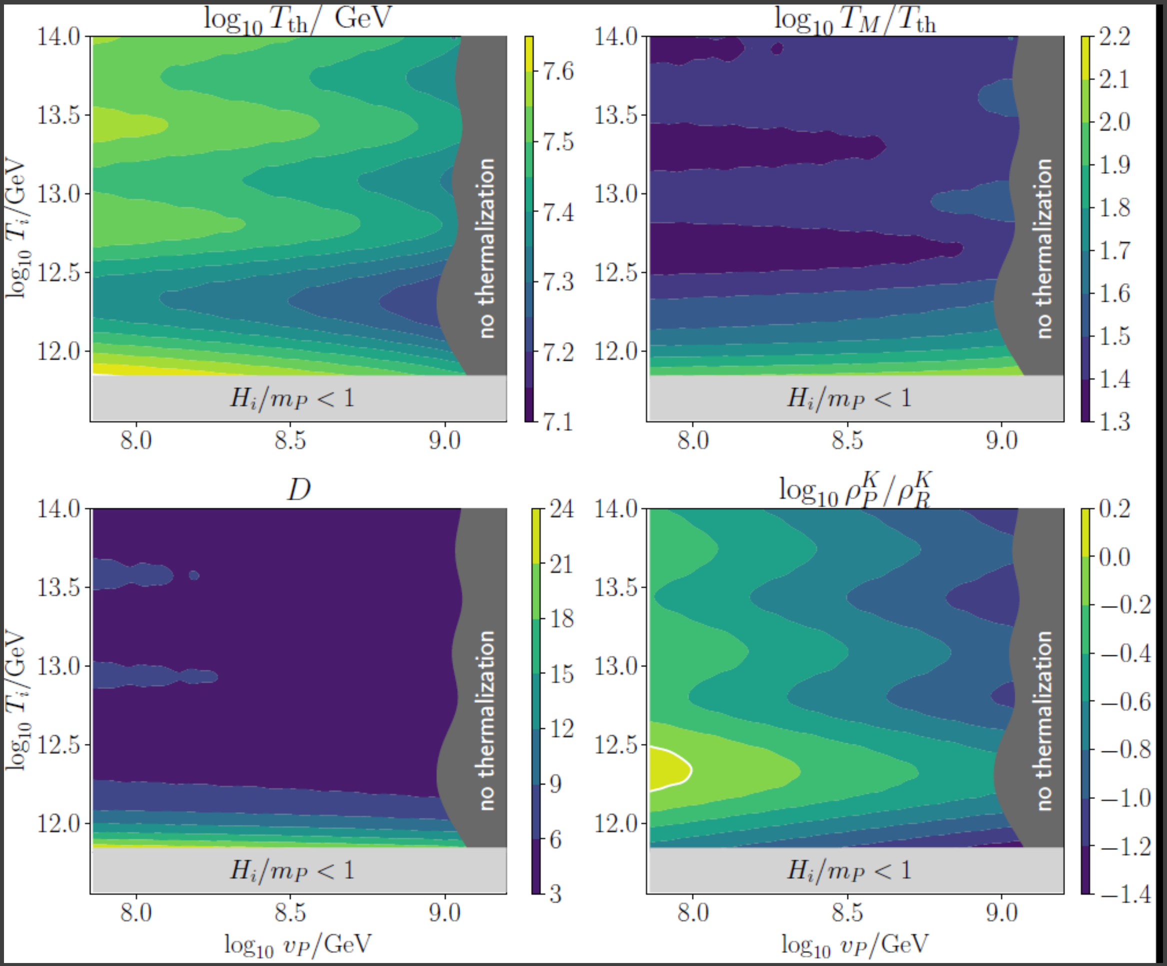


amplitude is smaller than $n = 10$

radiation energy always dominates over PQ energy

baryon asymmetry is generated until PQ field reaches minimum

Temperature, dilution and energy density



$\rho_P \gg \rho_R$ is not realized

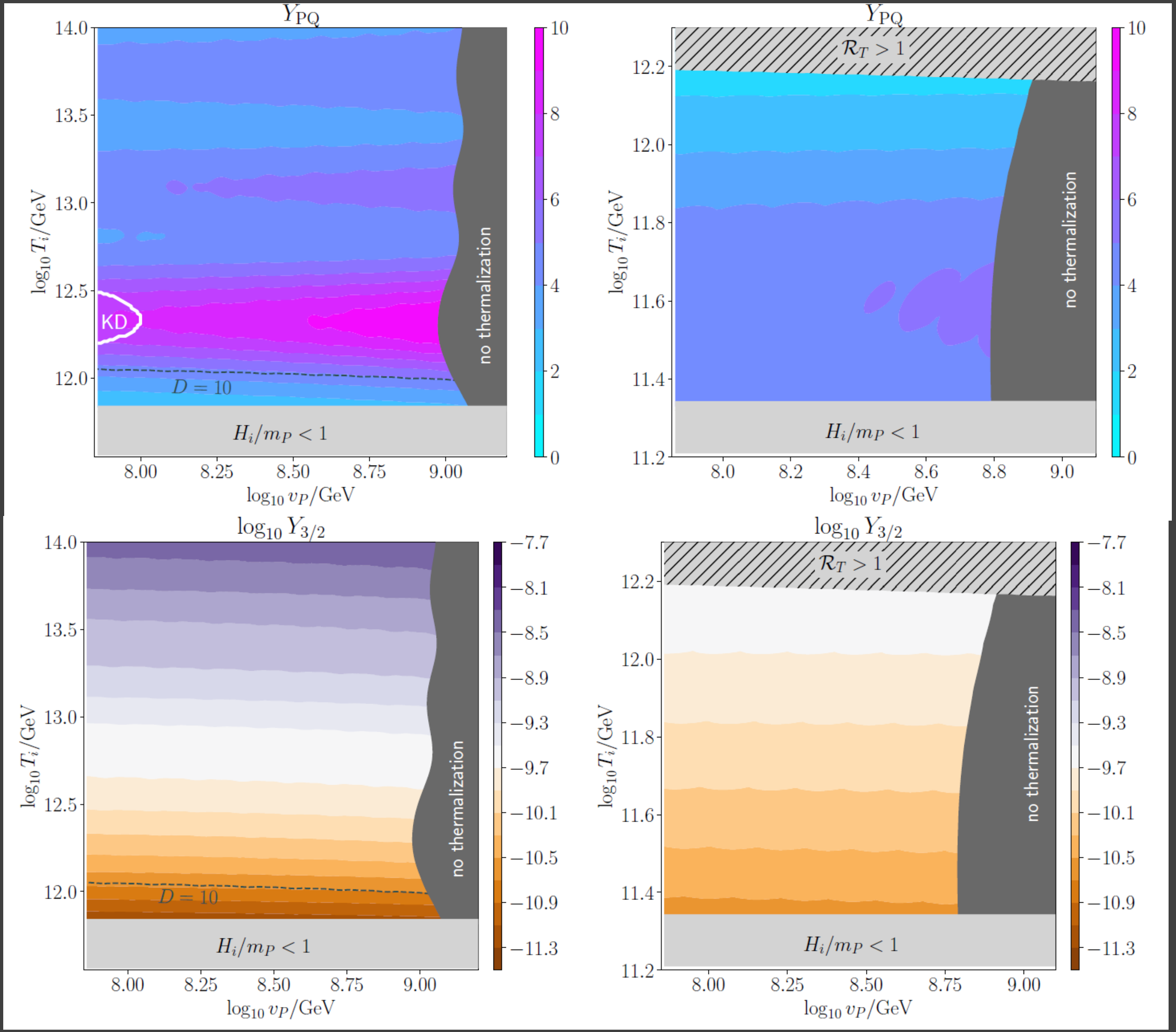
↓

dilution factor is at most $\mathcal{O}(10)$

kination domination happens in the small (yellow) region

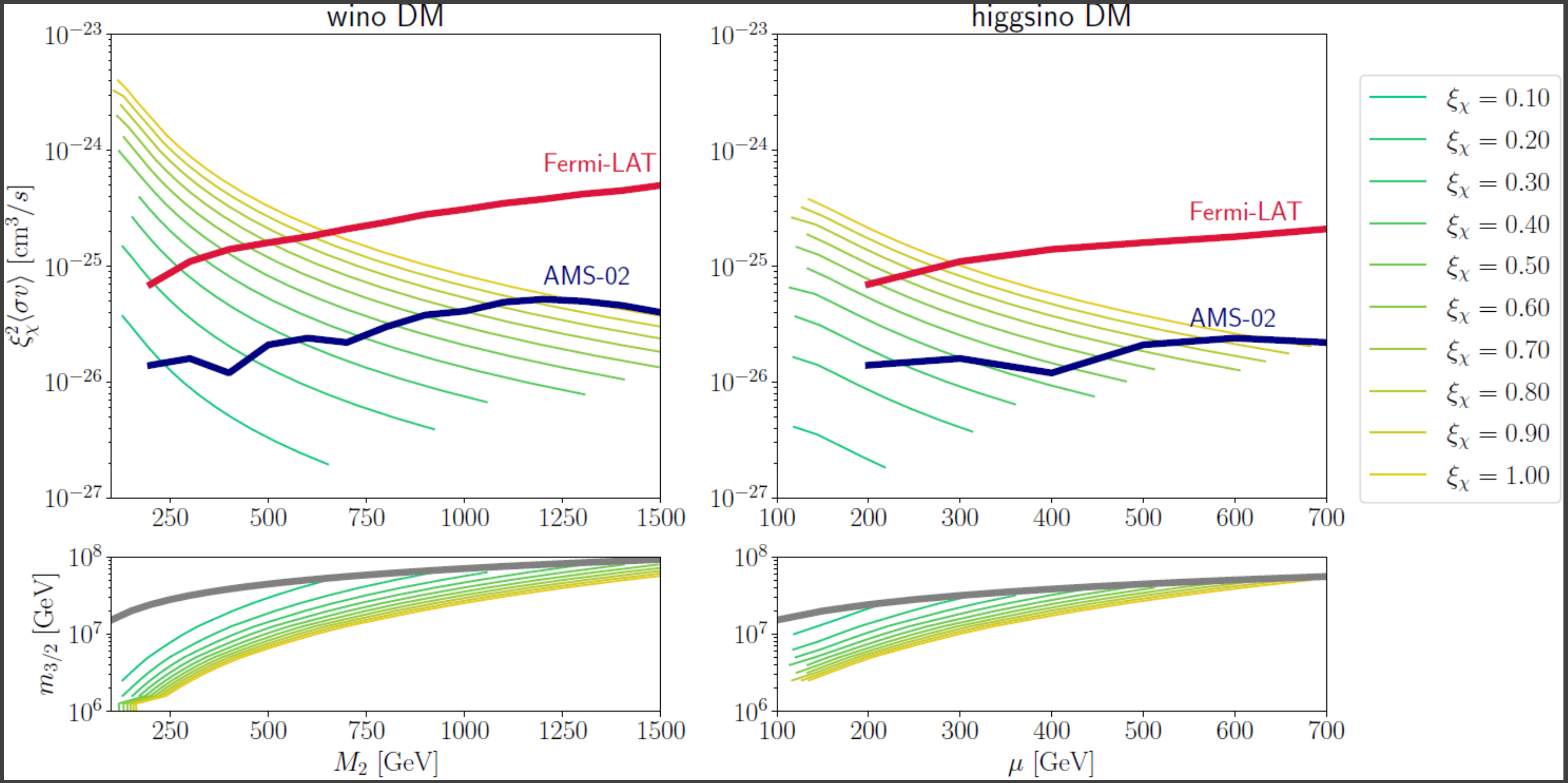
PQ and gravitino yields

$n = 10$ $n = 8$



Indirect detection

$\xi_\chi = \Omega_\chi / \Omega_{\rm DM}$



- $\mathcal{O}(100)$ GeV wino/higgsino explains DM if $m_{3/2} \sim 10^{6-8}$ GeV
- pure wino/higgsino is not excluded if it is enough heavy