Axion-like particles as Cold Dark Matter by the misalignment mechanism with the PQ symmetry unbroken during inflation

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work in progress, in collaboration with prof. Marek Olechowski[†]

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The QCD Axion ($a/f_a \equiv \theta$):

$$V(\theta) = m_a^2 f_a^2 (1 - \cos\theta)\,, \qquad m_a \simeq 6\,\text{eV}\left(\frac{10^6\,\text{GeV}}{f_a}\right), \qquad T \lesssim 1\text{GeV}$$

Axion-Like Particle (ALP):

$$V(\theta) \to U(\theta' \equiv \phi/f_\phi) \propto \Lambda_\phi^4, \qquad m_\phi \sim \Lambda_\phi^2/f_\phi \qquad +1 \text{ free parameter}$$

The Misalignment Mechanism: (homogeneous) initial $\theta_i \neq 0$

$$\ddot{a} + 3H\dot{a} + V'(a) = 0 \quad \Rightarrow \text{Axion starts oscillating at } m \sim 3H \qquad (T_{osc}^{QCD} > 1\text{GeV})$$

$$V \approx \frac{1}{2} m^2 a^2 \quad \Rightarrow \quad a(t) = A(t)\cos(m_a t + \theta_i) \text{ AND } \rho_a \sim A^2 \sim \mathcal{R}^{-3}$$

Axion/ALP condensate $\equiv$ Cold Dark Matter candidate

review in [1510.07633, D. J. E. Marsh]

QCD Axion as CDM:

$$\Omega_a h^2 \sim 2 \times 10^4 \left(\frac{f_a}{10^{16}\ \text{GeV}} \right)^{7/6} \times \theta_i^2$$

$$\Omega_a h^2 = \Omega_{CDM} h^2 = 0.12 \ \Rightarrow \ f_a \simeq 10^{11}\ \text{GeV} \qquad (\text{for } \theta_i \simeq 1)$$

ALP as CDM:

$$\Omega_\phi = \frac{1}{6}(9\Omega_r)^{3/4} \left(\frac{m_\phi}{H_0} \right)^{1/2} \left(\frac{\phi_i}{M_{pl}} \right)^2$$

e.g.:

$$m_\phi = 10^{-12}\text{eV}, \ldots, 10^{-24}\text{eV} \ \Rightarrow \ \phi_i = 10^{14.5}\text{GeV}, \ldots, 10^{17.5}\text{GeV}$$

What is the origin of θ_i? go back to inflationary dynamics of Φ_{PQ}

$$V_{PQ} = \lambda \left(\Phi^\dagger_{PQ}\Phi_{PQ} - \frac{1}{2} f_a^2 \right)^2 \quad + \frac{\alpha}{24} T_{GH}^2 \Phi^\dagger_{PQ}\Phi_{PQ}$$

1. $f_a \gg H_I$ ("PQ broken scenario")

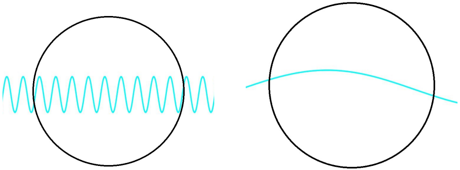
thermal mass due to $T_{GH} = \frac{H_I}{2\pi}$ does NOT restore $U(1)_{PQ}$

Φ_{PQ} quickly attains its vacuum† $|\Phi_{PQ}| = f_a \quad \Rightarrow$ uniform (random) θ_i in our Universe

†[Phys.Rev.D 46 (1992) 532-538, D. H. Lyth, E. D. Stewart]

axion is massless $m_a(T) \to 0$, but light (or massless) fields fluctuate

quantum fluctuations of each mode k that leaves the horizon ($k \lesssim \mathcal{H}$) "freezes"



$\Rightarrow$ random "kicks" to field a averaged over Hubble volumes ("stochastic fluctuations")

$\delta\theta$ grow around θ_i:

$$\langle \delta\theta^2(x) \rangle = \frac{H_I^2}{4\pi^2 \boldsymbol{f_a}^2} \times \Delta N_e \qquad a \equiv f_a \theta$$

the larger f_a the slower $\delta\theta$ dynamics

misalignment $\Rightarrow$ $\delta a \equiv$ isocurvature fluctuations of CDM

strong constraints on the CDM isocurvature power

for the QCD Axion:

$$\Rightarrow H_I < 10^7 \text{GeV} \qquad (\theta_i \simeq 1, f_a \simeq 10^{11} \text{GeV})$$

for an ALP:

$$\Rightarrow H_I \lesssim 10^{10} \text{GeV} \qquad (f_\phi < 10^{17.5} \text{GeV})$$

allowed $\boldsymbol{H_I} \ll 10^{14}$GeV. . .

$$V_{PQ} = \lambda \left(\Phi^\dagger_{PQ}\Phi_{PQ} - \tfrac{1}{2} f_a^2 \right)^2 \quad + \tfrac{\alpha}{24} T_{GH}^2 \Phi^\dagger_{PQ}\Phi_{PQ}$$

2. $f_a \ll H_I$ ("PQ unbroken scenario")

thermal mass due to $T_{GH} = \frac{H_I}{2\pi}$ restores $U(1)_{PQ}$ during inflation

The traditional approach: [review in 1510.07633, D. J. E. Marsh]

- Φ_{PQ} attains 0 (false vacuum) during inflation (NO stochastic fluctuations)
- $U(1)_{PQ}$ is broken later, when $T \sim T_C$

For $T \lesssim T_C$: $\delta\theta \sim O(1) \to$ "white noice" isocurvature power[†]

[†][1903.06194, M. Feix, J. Frank, A. Pargner, R. Reischke, B.M. Schäfer, T. Schwetz]

$\Rightarrow$ the "classical Axion window" for misalignment open:

$$f_a \simeq 10^{11}\text{GeV},\ H_I = 10^{12}\text{GeV}, \ldots, 10^{14}\text{GeV}, \qquad \langle\theta^2\rangle = \pi^2/3$$

strings are formed (disastrous for $\mathcal{C} = N_{DW} > 1$) $+\Omega_a$

$$V_{PQ} = \lambda \left(\Phi^\dagger_{PQ}\Phi_{PQ} - \frac{1}{2} f_a^2\right)^2 \quad + \frac{\alpha}{24} T^2_{GH} \Phi^\dagger_{PQ}\Phi_{PQ}$$

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but Φ_{PQ} **is light at false vacuum**[†]**:** $V''_{PQ}(0) = \alpha H_I^2/48\pi^2 \ll H_I^2$ $\rightarrow \delta\Phi_{PQ}$ emerge

[†] [hep-ph/0606107, M. Beltrán, J. García-Bellido, J. Lesgourgues]

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"The stochastic approach": [A. A. Starobinsky (and J. Yokoyama), 82', 85' (, 94')]

apply "the Langevin equation" to describe evolution of a field $\chi(t, \bar{x})$ coarse-grained over H_I volume $(\bar{x} \in \bar{x}_1, \bar{x}_2, \ldots)$, at each $\bar{x}_i$ accounting for:

- the random quantum "kicks" (uncorrelated in $\bar{x}$)
- the classical evolution (towards the minimum)

$$V_{PQ} = \lambda\left(\Phi_{PQ}^\dagger \Phi_{PQ} - \frac{1}{2} f_a^2\right)^2 \quad + \frac{\alpha}{24} T_{GH}^2 \Phi_{PQ}^\dagger \Phi_{PQ}$$

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- the classical evolution (towards the minimum)

$\rightarrow$ probability distribution $P(t, \chi)$ (satisfies "the Fokker-Planck equation"):

$$(\text{probability of finding } \chi \text{ in } d^n\chi) = P(t, \chi)\, d^n\chi$$

$\Rightarrow$ the stationary solution: $P(\chi) \propto \exp\left(-\frac{8\pi^2}{3H_I^4} V(\chi)\right)$

$$V_{PQ} = \lambda \left(\Phi^\dagger_{PQ}\Phi_{PQ} - \frac{1}{2} f_a^2\right)^2 \quad + \frac{\alpha}{24} T_{GH}^2 \Phi^\dagger_{PQ}\Phi_{PQ}$$

2. $f_a \ll H_I$ ("PQ unbroken scenario")

$P(t, \Phi_{PQ})$ approaches $P(\Phi_{PQ})$ after[1] $\Delta N \simeq 15. \times \left(\frac{1}{\lambda}\right)^{1/2}$ e-folds

$$\lambda \gtrsim 0.05 \;\Rightarrow\; \Delta N < 60$$

$P(\Phi_{PQ})$ reflects $U(1)_{PQ} \Rightarrow$ $\langle \delta\theta^2 \rangle \simeq \pi^2/3$ AND strings are formed[1]

even if $T_{RH} < f_a$, the traditional approach to "PQ unbroken scenario" could still lead to correct results for $\lambda \gtrsim 0.05$ but not for $\lambda \lesssim 0.05$

[1] [Phys.Rev.D 46 (1992) 532-538, D. H. Lyth, E. D. Stewart]

$$V_{PQ} = \lambda \left(\Phi^\dagger_{PQ} \Phi_{PQ} - \tfrac{1}{2} f_a^2 \right)^2 + \tfrac{\alpha}{24} T^2_{GH} \Phi^\dagger_{PQ} \Phi_{PQ}, \qquad \Phi_{PQ} = \tfrac{1}{\sqrt{2}} S \, e^{i\theta}$$

2. $f_a \ll H_I$ ("PQ unbroken scenario")

$\lambda \ll 0.01 \rightarrow$ assume long enough inflation: $P(\Phi_{PQ})$ achieved before last 60 e-folds

typical initial value S_i is predicted by $P(\Phi_{PQ}) \propto \exp\left(-\frac{8\pi^2}{3H_I^4} V(S)\right)$, e.g.:

$$S_i \simeq 0.3 \times \frac{H_I}{\lambda^{1/4}}$$

sometimes very large S_i is necessary and in the corresponding analyses $\lambda \sim 10^{-20}$ are explicitly considered, e.g.:

- "Kinetic Misalignment Mechanism" [1910.14152, R. T. Co, L. J. Hall, K. Harigaya]
- "Parametric Resonance" [1711.10486, 2004.00629, R. T. Co, L. J. Hall, K. Harigaya]

goal: examine the role of radiative corrections to Φ_{PQ} dynamics

Coleman-Weinberg (CW): $\boldsymbol{\lambda(\mu) = 0}$, $\quad g^2 \Phi_{PQ} \bar{Q}_L Q_R + h.c.$

interesting possibility: stability by gravitational interactions (explicit $U(1)_{PQ}$ breaking)

$$V^{(1)} = V_F + \mathcal{O}_5 + \mathcal{O}_6 + \dots \qquad \mathcal{O}_i \sim \frac{1}{M_P^{i-4}} \Phi_{PQ}^{\dagger\, k} \Phi_{PQ}^{l} \quad k \neq l$$

Coleman-Weinberg (CW): $\boldsymbol{\lambda(\mu) = 0}$, $\quad g^2 \Phi_{PQ} \bar{Q}_L Q_R + h.c.$

stability $\Rightarrow V^{(1)} = V_B + V_F$

$$V_B^{(0)} \equiv \frac{1}{2} m_\phi^2 \phi^2 + \lambda_{mix} \phi^2 \Phi_{PQ}^\dagger \Phi_{PQ} = \frac{1}{2} m_\phi^2 \phi^2 + \frac{1}{2} \lambda_{mix} \phi^2 S^2 \quad \left(+ \frac{1}{2} \xi_\phi \mathcal{R} \phi^2 \right)$$

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the "usual" zero-temperature part of the potential in the radiation era:

$$V^{(1)} = \frac{1}{64\pi^2} \left\{ N_\phi \mathcal{M}_\phi^4 \left[\log \left(\frac{\mathcal{M}_\phi^2}{\mu^2} \right) - \frac{3}{2} \right] - N_Q \mathcal{M}_Q^4 \left[\log \left(\frac{\mathcal{M}_Q^2}{\mu^2} \right) - \frac{3}{2} \right] \right\}$$

explicitly

$$V^{(1)} = \frac{1}{64\pi^2} \left\{ N_\phi (m_\phi^2 + \lambda_{mix} S^2)^2 \left[\log \frac{m_\phi^2 + \lambda_{mix} S^2}{\mu^2} - \frac{3}{2} \right] - N_Q (\frac{g^2}{2} S^2)^2 \left[\log \frac{\frac{g^2}{2} S^2}{\mu^2} - \frac{3}{2} \right] \right\}$$

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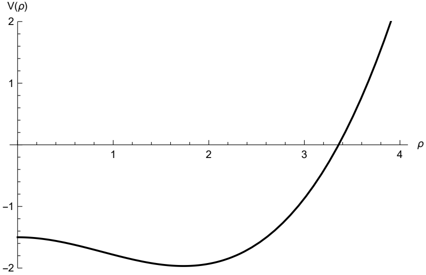

Corrections to "usual" CW in inflationary Universe ($\mathcal{R} = 12H_I^2$ in deSitter)[2]:

$$V^{(1)}(S) = \frac{1}{64\pi^2}\left\{N_\phi \mathcal{M}_\phi^4\left[\log\frac{|\mathcal{M}_\phi|^2}{\mu^2} - \frac{3}{2}\right] - N_Q \mathcal{M}_Q^4\left[\log\frac{|\mathcal{M}_Q|^2}{\mu^2} - \frac{3}{2}\right]\right.$$

$$\left. - N_\phi \frac{1}{15}\boldsymbol{H_I^4}\,\mathbf{log}\,\frac{|\boldsymbol{\mathcal{M}_\phi}|^2}{\boldsymbol{\mu}^2} + N_Q\frac{38}{15}\boldsymbol{H_I^4}\,\mathbf{log}\,\frac{|\boldsymbol{\mathcal{M}_Q}|^2}{\boldsymbol{\mu}^2}\right\}$$

where

$$\mathcal{M}_\phi^2 = m_\phi^2 + \left(\xi_\phi - \frac{1}{6}\right)12\boldsymbol{H_I^2} + \lambda_{mix}S^2$$

$$\mathcal{M}_Q^2 = \boldsymbol{H_I^2} + \frac{g^2}{2}S^2$$

the potential starts becoming somewhat complicated...

[2] [1904.11373, R. J. Hardwick, T. Markkanen, S. Nurmi]

$$\mathcal{M}_\phi^2 = m_\phi^2 + \left(\xi_\phi - \frac{1}{6}\right) 12 H_I^2 + \lambda_{mix} S^2\,, \quad \mathcal{M}_Q^2 = H_I^2 + \frac{g^2}{2} S^2$$

...from now on we will consider a particular (simplified) case:

- $N_\phi = N_Q = 4 \times 3$
- $\lambda_{mix} \equiv \frac{1}{2} g^2 (1+\epsilon)$, $\quad 0 < \epsilon << 1$, $\quad$ ("SUSY" limit)
- $\mathcal{M}_\phi^2 \Big|_{S=0} > \frac{1}{4} H_I^2$ (ϕ does NOT fluctuate)
- assume $\xi_{PQ} H_I^2 S^2$ is negligible

$\Rightarrow$ thermal corrections due to T_{GH} prove negligible

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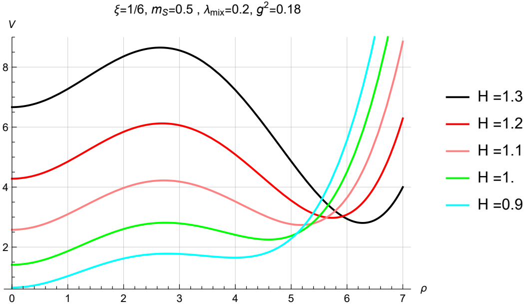
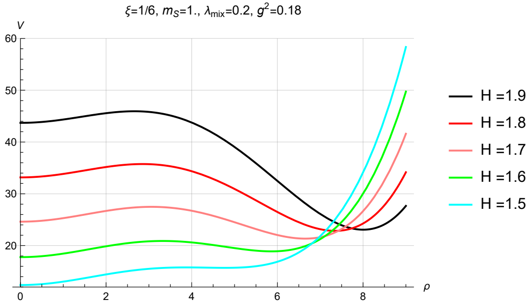
Now, let's expand:

$$V^{(1)} = C_2 \cdot S^2 + C_4 \cdot S^4 + \ldots \quad \Rightarrow C_4 \propto \left(\lambda_{mix}^2 \log \frac{\mathcal{M}_\phi^2 \big|_{S=0}}{\mu^2} - \left(\frac{g^2}{2}\right)^2 \log \frac{H_I^2}{\mu^2} \right)$$

$C_4 < 0$ if H_I is "not too small" $\rightsquigarrow$ **$V^{(1)}$ could have (second) minimum at larger scale**

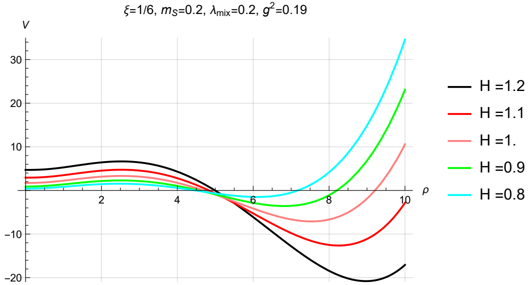


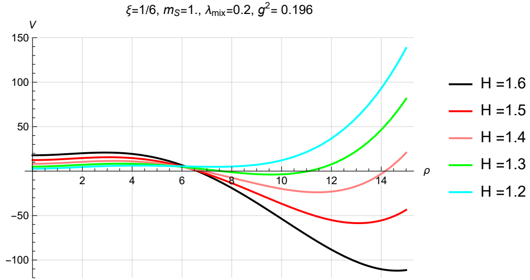


$\Longrightarrow$ for the "not too small" H_I, the $U(1)_{PQ}$ can be restored...

...or even there exists a global minimum S_{min} at larger scale

if H_I is "not too small", the scale S_{min} grows as we approach the "SUSY" limit:





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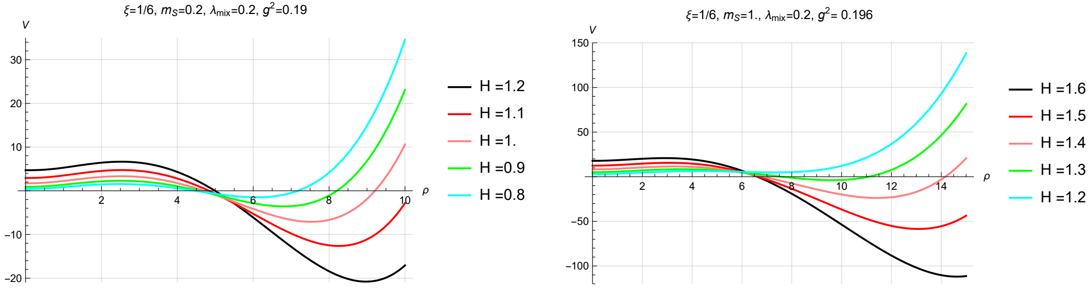

at the global minimum $V'' \ll \frac{9}{4} H_I^2$ so the stochastic dynamics indeed occur;

$$S_{min} \sim \langle S \rangle \qquad (\equiv S_i)$$

Quantitatively:

H_I is "not too small":

$$\langle S\rangle^2 \sim (a\ few) \times 10^{(n-1)} \times \frac{H_I^2}{g^2}, \qquad \lambda_{mix} = \frac{1}{2} g^2 (1 + 10^{-n})$$

H_I "too small":

$$\langle S\rangle^2 \sim (\simeq 1) \times \frac{H_I^2}{g^2}$$

such "SUSY" enhancement of $\langle S\rangle^2$ could be desirable in various non-thermal mechanisms for DM generation

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H_I is "not too small":

[**If δa survive until V(a) is generated, then misalignment is at work and**]

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$$\left[\stackrel{axion\ \ CDM\ \ isocurvature}{\Longrightarrow} \lambda_{mix}, g^2 \lesssim 10^{-5}, \qquad (n = 3) \right]$$

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$$\langle S\rangle^2 \sim (\simeq 1) \times \frac{H_I^2}{g^2}$$

$$\left[\stackrel{axion\ \ CDM\ \ isocurvature}{\Longrightarrow} \lambda_{mix}, g^2 \lesssim 10^{-8} \right]$$

such "SUSY" enhancement of $\langle S\rangle^2$ could be desirable in various non-thermal mechanisms for DM generation

$$\mathcal{M}_\phi^2 = m_\phi^2 + \left(\xi_\phi - \tfrac{1}{6}\right) 12 H_I^2 + \lambda_{mix} S^2\,,\ \ \lambda_{mix} \equiv \tfrac{1}{2} g^2 (1+\epsilon)$$

corrections to $\lambda(\mu) = 0$ are contributions to C_4 in $V^{(1)} = C_2 S^2 + C_4 S^4 + \ldots$
compare:

$$\frac{\lambda(\mu)}{4} S^4 \qquad vs \qquad \frac{3 \times 4}{64\pi^2} \left(\lambda_{mix}^2 \log \frac{\mathcal{M}_\phi^2\Big|_{S=0}}{\mu^2} - \left(\frac{g^2}{2}\right)^2 \log \frac{H_I^2}{\mu^2} \right) S^4$$

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the conclusions on $\langle S \rangle^2$ enchancement and on the upper bound on $\lambda_{mix}, g^2 \sim 10^{-5}$ are unaffected for

$$\lambda(\mu) \lesssim 10^{-12}$$

$\Rightarrow$**much weaker condition than isocurvature constraints based on $\frac{\lambda}{4} S^4$ at tree-level**[†]:

$$\lambda \lesssim 10^{-20}$$

[†] "Introduction to the Theory of the Early Universe Cosmological Perturbations and Inflationary Theory", D. S. Gorbunov, V. A. Rubakov

can δa survive? $\rightarrow$ can S oscillations survive until $U(1)_{PQ}$ breaking?

early onset of S oscillations, e.g.

$$\left(\frac{T_i}{T_{RH}}\right)^4 \sim \frac{5 \cdot 1.66^2}{\pi^3} \frac{\epsilon}{64\pi^2} \frac{5 \times 10^2}{\epsilon_{RH}^2} \left[6 \log \frac{5 \times 10^2 H_I^2}{\mu^2} + 1\right]$$

large thermal mass corrections (symmetry is restored)
$\rightarrow$ S would not resonantly decay to itself: $S \gg \frac{m_S}{\lambda_{mix}}$ not fulfilled
$\rightarrow$ $\dot{m}/m^2 \gg 1$ is not fulfilled...

. . . the broad resonance to massive particles:

$$m_\phi^2 < \omega_S \sqrt{\lambda_{mix}} S$$

even if possible at the beginning, is later blocked (decrease of S and ω_S)

perturbative decay inefficient (small couplings)

thermalization by gluons (or the PQ fermions) is (rather) inefficient[3]

[3] [2004.00629, R. T. Co, L. J. Hall, K. Harigaya]

Summary

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2.

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1. the "traditional" description of Φ_{PQ} dynamics in the "PQ unbroken scenario" ($f_a \ll H_I$) is ofter too simplified, especially if $\lambda <$O(0.01):

   e.g. the field acquires large S_i, if inflation lasts long enough

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2. correct treatment of Φ_{PQ} dynamics in case of super small λ relevant, because such scenarios are often analyzed in the literature, e.g. to generate large S_i

3. to this aim we, first, applied the Coleman-Weinberg approach to $U(1)_{PQ}$ breaking and found enhancement of S_i in the "SUSY" limit if $H_I \sim O(\mu)$;

4. if S oscillation survive until $U(1)_{PQ}$ breaking, then the enhancement translates into $\simeq 10^3$x weaker upper bounds on λ_{mix}, g^2 from CDM isocurvature

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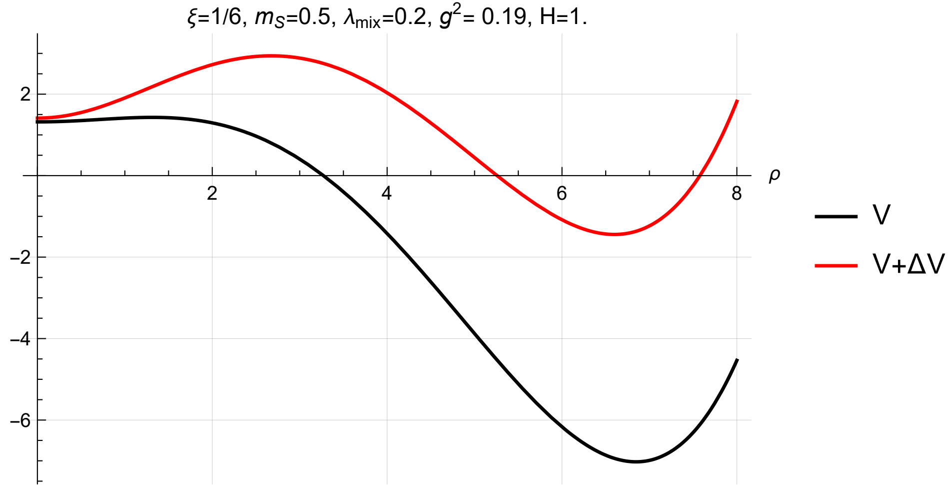
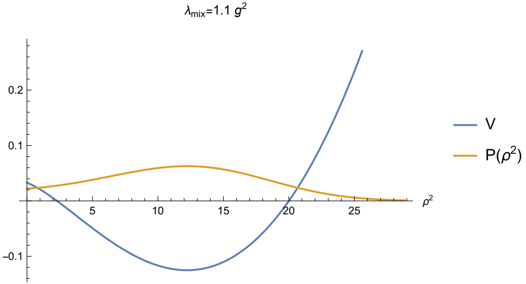
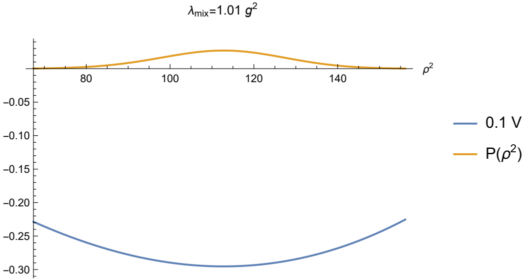
THANK YOU

BACK UP


ξ=1/6, m_S=0.5, λ_{mix}=0.2, g^2= 0.19, H=1.
2
−2
−4
−6
2
4
6
8
ρ
V
V+ΔV

in bulk of parameter space, ρ is light enough to have stochastic dynamics; although, the larger ρ_{min} the deeper the minimum and the more concentrated the distribution is around the global minimum:





$$< \rho >^2 \sim \rho_{min}^2$$