Baryogenesis and dark matter in ALPic Higgs portal

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I. Beyond the SM
- **Standard Model**
  - Successful up to energy scales around TeV
  - But need a more fundamental theory to explain
    - Baryon asymmetry, dark matter, neutrino oscillations, ...
    - Natural EWSB, strong CP problem, flavor structure, unification, cosmic inflation, quantum gravity, ...
- Higgs boson as a window to BSM
  - Higgs mass is sensitive to unknown UV physics

\[ \delta m_H^2 \sim \frac{(\text{cutoff scale})^2}{16 \pi^2} \]

- New physics around TeV
  - Supersymmetry, extra dimension, composite Higgs, ...
  - Solution to other problems of the SM
    e.g. WIMP as dark matter, unification, ...
- **LHC results so far**
  - No clear signals for BSM
  - **SM-like** Higgs boson at 125 GeV

- **Direct and indirect dark matter searches so far**
  - No evidence of WIMPs
• Hints for BSM
  • SM extension by a particle feebly coupled to it?
  • If then, how to resolve the puzzles of the SM?
I. Beyond the SM

Axion-like Particle
- **ALP**
  - Pseudo Nambu-Goldstone boson associated with spontaneously broken U(1)
  - Periodic
    - $\phi \equiv \phi + 2\pi f$
    - Generally, $f = U(1)$ breaking scale
  - Mass and couplings
    - Controlled by perturbative shift symmetry $\phi \rightarrow \phi + \text{constant}$
    - Feebly interacting light particle for large $f$
- **SM extension with an ALP**
  - Perturbative shift symmetry
    - 3 types of interaction

\[
m_\psi e^{ic_1 \frac{\phi}{f}} \bar{\psi} \psi + c_2 \frac{\partial_\mu \phi}{f} \bar{\psi} \gamma^\mu \gamma_5 \psi + \frac{c_3}{16\pi^2} \frac{\phi}{f} F \tilde{F}
\]

- Combinations of \( c_i \) invariant under chiral field redefinitions
- SM extension with an ALP
  - Potential to be probed by cosmological, astrophysical and laboratory observations
    - e.g. anomalous coupling to photons

Jaeckel, Spannowski 2015
Examples

- QCD axion
  - Neutron EDM bound
    \[ d_n \approx 10^{-14} \frac{m_p m_d}{(m_p + m_d) m_n} \bar{\theta} \text{ e·cm} \]
    \[ \bar{\theta} < 10^{-10} \]

  - \( \bar{\theta} \propto \langle \phi \rangle = 0 \) if anomalously coupled to gluons
    \[ \rightarrow \text{natural solution to the strong CP problem} \]
  - Dark matter: misalignment, topological defects
Examples

- Natural inflation
  - Inflation: initial conditions for the Big Bang cosmology
  - Very flat potential from an ALP

\[ V = \Lambda^4 \left( 1 \pm \cos \left( \frac{\phi}{f} \right) \right) \text{ with } f \geq M_{Pl} \]
II. ALPic Higgs portal
- **Higgs portal**
  - New type of ALP interaction

\[ \mu_H^2(\phi/f)|H|^2 \]

- Feeble interaction with the SM via the Higgs field
- Growing interest since 2015
  - ‘cosmological relaxation of the Higgs mass’

Graham, Kaplan, Rajendran 2015
- **Higgs portal**
  - **UV completion with perturbative shift symmetry**
    - Hidden QCD
    - Vector-like lepton doublets $L + L^c$ and singlets $N + N^c$

\[
\Rightarrow M^2 \cos \left( \frac{\phi}{f} \right) |H|^2
\]

anomalous coupling to hidden gluons
→ mixing between $\phi$ and $NN^c$ meson

Effective coupling of $NN^c$ to Higgs due to heavy doublet leptons

KS JEONG @ PNU
Experimental constraints

- ALP-Higgs mixing after EWSB
  - Stringent constraints for ALP at sub-MeV to multi-GeV
    rare K and B meson decays
    beam-dump experiments
- Further constraints
  if anomalously couples to SM gauge bosons
- **Experimental constraints**
  - **ALP-Higgs mixing**

\[ 10^{-9} \leq \sin^2 \theta \leq 3 \times 10^{-7} \]

Flacke, Frugiuele, Fuchs, Gupta, Perez 2016
Choi, Im 2016

\[ \sin^2 \theta \leq \frac{6 \times 10^{-7}}{\text{Br}(\phi \rightarrow \mu^+ \mu^-)} \]
Why ALPic Higgs portal?

- $\phi$ can play an important role in electroweak phase transition!

- New approach to the electroweak hierarchy problem
  - Cosmological relaxation of the Higgs boson mass

- Other roles?
  - First order EWPT for baryogenesis
  - Dark matter

See also, Abel, Gupta, Scholtz 2018
Gupta, Reiness, Spannowsky 2019
II. ALPic Higgs portal

EW scale
Relaxation mechanism

- Cosmological ALP evolution to select the Higgs mass
  \[ V = V_0(\phi) - \mu_H^2(\phi)|H|^2 + V_{\text{br}}(\phi, H) + \cdots \]
  - \( V_0 \): slow-rolling of ALP to scan \( \mu_H^2 \)
  - \( V_{\text{br}} \): barriers formed by EWSB to stop ALP rolling

\[ \mu_H^2 > 0 \Rightarrow \langle h \rangle = 0 \]
\[ \mu_H^2 < 0 \Rightarrow \langle h \rangle \neq 0 \]
Simple model

- Two periodicities with hierarchy, $F \gg f$
  
  - $V_0 = V_0(\phi/F)$ and $V_{br} = V_{br}(\phi/f, H)$

- Barrier potential
  
  - QCD anomaly: $V_{br} \propto h$
    
    c.f. strong CP problem
  
  - Hidden QCD anomaly: $V_{br} \propto h^2$ due to gauge invariance
    
    c.f. coincidence problem
- **Conditions**

  - High enough barriers to stop the ALP

    \[ \frac{F}{f} \sim \frac{(\text{cutoff scale})^4}{\langle V_{br} \rangle} \gg 1 \]

  - **Clockwork mechanism**

    \[ F \sim e^N f \]

    collective rotations of $N$ axions

    Choi, Im 2016
    Kaplan, Rattazzi, 2016
- **Conditions**
  - Evolution dominated by classical rolling
    - Hubble scale $\leq$ GeV during inflation
  - Scanning of $\mu_H^2$ from large positive to negative
    - Large number of $e$-folds

Need progress to construct a viable inflation model and clarify issues related with the barrier potential and low reheating temperature

See e.g. Choi, Kim, Sekiguchi 2016, Evans, Gherghetta, Nagata, Peloso 2017, Son, Ye, You 2018
II. ALPic Higgs Portal

EW phase transition
- EWPT
  - Last period affecting baryon asymmetry
    - Rapid EW sphaleron transition in symmetric phase
      → B+L violation
  - Baryogenesis
    - Nonzero B-L above EW scale: Leptogenesis, Affleck-Dine, ...
    - B+L generation at EW scale and sphaleron decoupling
      → EWBG

Lots of works since 1985
- **EWBG**
  - EW bubbles
  - **Requirements**
    - Strong first-order phase transition to avoid washout
      - PT in SM: Higgs cubic and quartic couplings
        → crossover if $m_h > 75$ GeV
    - Sufficient CP violation beyond SM
Conventional scenarios

- Strong first-order PT
  - e.g. thermal or effective Higgs cubic term, log potential
    - higher dim operator with low cutoff
    - New particles coupled to $H$ or sizable modification of Higgs sector

- Non-local baryogenesis
  - CP violation in front of wall, B violation away from wall

- Probe of EWBG
  - LHC (direct searches) and EDM experiments
    - c.f. ACME II constraint on electron EDM
II. ALPic Higgs Portal

ALP-induced EWPT
- **ALPic Higgs portal**
  - Scalar potential
    - Function of $\phi/f$ due to the periodic nature
      $$V = \lambda|H|^4 + \mu_H^2(\phi/f)|H|^2 + V_0(\phi/f)$$
    - ALP dependent Higgs mass squared
  - ALP can play an important role in EWPT!
- **ALPic Higgs portal**
  
  - Distinctive features
    - Small thermal and quantum corrections to $V$ from ALP interactions for large $f$
    
    $\rightarrow$ Potential $V(h, \phi/f)$ is insensitive to $f$
    
    - $\mu_H^2$ is bounded both from below and above
    - Certain relations between ALP-Higgs couplings
• **ALPic Higgs portal**

  - Scalar potential

    \[ V = \lambda |H|^4 + \left[ \mu^2 - M^2 \cos\left(\frac{\phi}{f} + \alpha\right) \right] |H|^2 - \Lambda^4 \cos\left(\frac{\phi}{f}\right) \]

    - Thermal corrections: \( \Delta V = c_H T^2 |H|^2 \)

  - In terms of 3 positive parameters

    \[ \alpha, \quad \epsilon \equiv \frac{\sqrt{2} \lambda \Lambda^2}{M^2}, \quad r \equiv \frac{\sqrt{2} \Lambda^2}{\sqrt{\lambda} v_0^2} \]

    with \( \lambda \) and \( \mu^2 \) fixed by \( m_h = 125 \text{GeV} \) and \( v_0 = 246 \text{GeV} \)
EWPT

• Amplitude of ALP coherent oscillation

\[ - \frac{\phi_{\text{osc}}}{f} = \frac{\phi_{\text{ini}}}{f} \left( \frac{m_\phi(T_{\text{osc}})}{m_\phi} \right)^{1/2} \left( \frac{T}{T_{\text{osc}}} \right)^{3/2} \]

with \( T_{\text{osc}} \sim \sqrt{m_\phi(T_{\text{osc}})M_{\text{Pl}}} \)

→ negligibly small at PT if Higgs portal is generated much above the weak scale
**EWPT**

- **Phase transition**

  - only a symmetric minimum at \((\phi, h) = (0,0)\)
  - \(\mu_H^2 + c_H T^2 > 0\) in the whole range of \(\phi\)
    because \(\mu_H^2\) is bounded from above and below
  
  - minimum at \((\phi, h) = (0,0)\)
  - \(\mu_H^2 + c_H T^2 < 0\) in a finite range of \(\phi\)

  - another minimum at \(\phi \neq 0\) and \(h \neq 0\)
  - \(\mu_H^2 + c_H T^2 < 0\) in a finite but wider range of \(\phi\)
  - phase transition when EW minimum gets deeper
- **EWPT**
  - Tunneling mainly along the light ALP direction for $f \gg \text{TeV}$
    - Higgs field can be replaced by solving $\partial_h V = 0$
  - Phase transition
    - Two degenerate minima at $T_c$: lower than in the SM
    - Bubble nucleation at $T_n$
    - Barrier disappears at $T_2$
• Approximate scaling behaviors
  - Euclidean action of $O(3)$ symmetric critical bubble

  $$S_3 \propto f^3$$

  \Rightarrow \text{Bubble radius } \propto f, \text{ and } T_n \text{ close to } T_2

  Smooth phase transition, but rapid ALP evolution
  Thick wall for large $f$
- EWPT along ALP direction
  - Case with \( r = 1.2 \)
    - First-order PT in red region (wider at small \( r \))
    - Red region close to blue line
      \( \rightarrow \) EWPT at very low T
    - PT pattern: insensitive to \( f \)
- EWPT along ALP direction
  - Delayed EWPT
    - late-time entropy production to dilute preexisting relics
      \[ \Delta = 10^4 \left( \frac{T_{\text{reh}}}{40\,\text{GeV}} \right)^3 \left( \frac{T_n}{2\,\text{GeV}} \right)^{-3} \]
      temperature after PT
      \[ T_{\text{reh}} = 40\,\text{GeV} \left( \frac{\Delta V^{1/4}}{100\,\text{GeV}} \right) \]
      - Implications for dark matter, e.g. WIMP
III. ALPic Baryogenesis

EW baryogenesis
EWBG

- Strong first-order PT driven by an ALP with
  \[ \mu_H^2 (\phi/f) |H|^2 \]

- New direction in EWBG
  - Free from EDM and LHC constraints for \( f \gg \) TeV
  - ALP searches to reveal the connection between EWPT and baryogenesis
- **EWBG**
  - CP violation for EWBG
    - ALP dependent top quark Yukawa
    - ALP anomalous coupling to EW gauge bosons
  - Conditions for EWBG
    (time for ALP settle-down) $\sim 1/m_\phi$
    $< \text{(time for B generation)} \sim 1/\Gamma_{\text{sph}}$
    $< \text{(duration of PT)} \sim dS_3/dt$
• **Non-local EWBG**  
  
  - CP violation from ALP-dependent top quark mass  
    \[ Y_t = y_t + x_t e^{i\phi/f} \]

  ![Diagram](image)

  - Baryon asymmetry  
    - CP violation \( x_t \), wall width \( L_w \), wall velocity \( v_w \)  
    - Sizable diffusion effect for \( L_w T_n \leq 100 \)  
      \[ \rightarrow \text{upper bound on } f \]
- Non-local EWBG
  - Correct baryon asymmetry for $3 \text{TeV} \leq f \leq 10 \text{TeV}$

ACME II: about 10 times stronger than ACME I
• CP violation from ALP-dependent EW Θ-term

\[ \frac{\phi}{f} W \bar{W} \rightarrow \frac{d\phi}{dt} = \text{chemical potential for Chern-Simons number} \]

• Simultaneous B and CP violations across thick walls

→ B generation through EW anomaly

\[ \frac{dn_B}{dt} = \frac{3}{2} \frac{\Gamma_{\text{sph}}}{T} \frac{d}{dt} f \frac{d\phi}{dt} - \frac{39}{4} \frac{\Gamma_{\text{sph}}}{T^3} n_B \]

↑ sphaleron-induced washout
- Local EWBG

  - ALP evolution after tunneling
    - Strong washout by ALP oscillations with $h(\phi) > v_{\text{cut}} \sim 0.5T_n$
    - Thermal dissipation due to $\phi-h$ mixing
      → reduce the oscillating amplitude

![Graph showing ALP evolution and washout](image.png)
• Correct baryon asymmetry for $10^5 \text{GeV} \leq f \leq 10^7 \text{GeV}$
- How to probe ALP driven EWBG
  - ALP at MeV-GeV (local) or GeV-20GeV (non-local)
    - ALP window without strong theoretical interests so far

ALP-Higgs mixing: rare B-meson decays, beam dump

Anomalous ALP couplings to gauge bosons: optional
IV. ALP Dark Matter

Freeze-in
- **WIMP dark matter**
  - Relic abundance from freeze-out
    \[
    \Omega_\chi \propto \frac{m_\chi}{T_f} \frac{1}{\langle \sigma v \rangle} \text{ with } \langle \sigma v \rangle \sim \frac{\lambda^2}{m_\chi^2}
    \]
    \[\Rightarrow \text{Observed DM density if } \lambda \sim 0.1 \text{ and } m_\chi \sim 100\text{GeV}\]
  - **Well-motivated, natural, experimentally testable, ...**
  - **No signals for new physics at LHC**
    Null results from direct & indirect DM detection searches
  - **May need to go beyond WIMP**
- **Freeze-in DM**
  - Alternative to freeze-out
  - Never in thermal equilibrium: feeble coupled to SM
  - Produced via thermal freeze-in

**Equilibrium yield**

**Freeze-in**

**Freeze-out**

2-2 scattering, decay of thermal particles
- Freeze-in DM
  - Relic abundance assuming negligible initial density
    
    \[ \Omega_\chi \propto m_\chi \frac{\lambda^2}{m} \]
    
    \( m \): mass of thermal particle responsible for production
    
    \( \Rightarrow \) Observed DM abundance if \( \lambda \sim 10^{-12} \) and \( m_\chi \sim 100\text{GeV} \)

  - Need an explanation for \( \lambda \ll 1! \)

Gravitino, axino in SUSY (many works)
Clockwork FIMP, Mohan and Sengupta 2018
- **Higgs portal**  
  - ALP interacting with the SM ONLY via Higgs portal
    \[ V = \lambda |H|^4 + \left( \mu^2 - M^2 \cos \left( \frac{\phi}{f} \right) \right) |H|^2 - \frac{1}{16\pi^2} M^2 \Lambda^2 \cos \left( \frac{\phi}{f} \right) \]
    
    - CP conserving minimum $\phi = 0$ (no ALP-Higgs mixing)
    - Stable due to $Z_2$ symmetry $\phi \to -\phi$
    - Feebly coupled to SM thermal bath for large $f$
    - → Natural framework for freeze-in DM
- **ALP DM**
  - If thermalized, it overcloses the universe in most of parameter space satisfying the bound on DM scattering with nuclei
  - **ALP properties**
    - Mass mainly from closing Higgs loops: \( m_\Phi \approx \frac{1}{4\pi} \frac{M}{f} \Lambda \)
    - Interactions with the SM
      \[
      \frac{\lambda_{h\phi}}{4} h^2 \phi^2 + \frac{\lambda_{h\phi} v}{2} h\phi^2 \text{ with } \lambda_{h\phi} = \left( \frac{M}{f} \right)^2
      \]
    - Never in equilibrium for \( \lambda_{h\phi} < 10^{-7} \)
- **ALP DM**
  - ALP production via freeze-in
    - Higgs decay $h \rightarrow \phi \phi$: dominant if open
    - Higgs annihilation $hh \rightarrow \phi \phi$
  - ALP heavier than MeV for $\Lambda$ above TeV
    - No BBN constraint
  - Coherent oscillations: negligible if $T_{osc} \gg 10^6 \times m_\phi$
ALP DM

- Correct DM density
  
  - Higgs decay
    \[ \lambda_{h\phi} \approx 10^{-10} \times \left(\frac{m_\phi}{3\text{MeV}}\right)^{-\frac{1}{2}} \text{ and } m_\phi \approx 1\text{MeV} \times \left(\frac{\Lambda}{10^3\text{GeV}}\right)^{\frac{4}{5}} \]
  
  - Higgs annihilation
    \[ \lambda_{h\phi} \approx 10^{-11} \text{ and } m_\phi \approx 380\text{GeV} \times \left(\frac{\Lambda}{10^9\text{GeV}}\right) \]
- **UV completion**
  
  - Non-perturbative Higgs portal from hidden QCD

  \[ V_{\text{eff}} \supset -M^2 \cos\left(\frac{\phi}{f}\right)|H|^2 - \frac{1}{16\pi^2} M^2 \Lambda^2 \cos\left(\frac{\phi}{f}\right) - \mu_N \Lambda_c^3 \cos\left(\frac{\phi}{f} + \alpha\right) \]

  ALP-Higgs mixing for \( \alpha \neq 0 \)

  ALP = decaying DM

  Strong constraints from gamma ray observations

  Essig et al 2013
**UV completion**

- **Viable model**
  - supersymmetry + spontaneously broken $U(1)_X$
  - $m_L$ from superpotential, while $\mu_N$ from Kaehler potential

\[
\mu_N = \frac{m_{\text{susy}}}{M_{\text{pl}}} m_L
\]

- **ALP-Higgs mixing**
  - Upper bound on $m_{\text{susy}}$ to make it cosmologically viable
  
  e.g. $m_{\text{susy}} \leq 10\, \text{TeV}$ if Yukawa couplings are order unity
V. Summary
• Axion-like particle
  - Controlled by perturbative shift symmetry
  - Strong CP problem, dark matter, inflation, ...

• ALP coupled to the SM via Higgs portal
  - May give information on the origin of EWSB while explaining
    - electroweak hierarchy: cosmological relaxation
    - matter-antimatter asymmetry: EWBG
    - dark matter: misalignment, freeze-in

Thank you