Higgs portal with an ALP

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- SM extension with an ALP
- Higgs portal
  I. Electroweak hierarchy
  II. Electroweak baryogenesis
  III. Freeze-in dark matter
- Summary

Axion-like Particle

- 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, …

- Extension of the SM with an ALP
  - Pseudo Nambu-Goldstone boson
  - Perturbative shift symmetry $\mathrm{U}(1)_\phi$: $\phi \to \phi$ +(constant)

$$L = L_{\mathrm{SM}} + \frac{1}{2}(\partial\phi)^2 + \frac{\partial_\mu \phi}{f} J^\mu_{\mathrm{SM}} + \frac{1}{32\pi^2}\frac{\phi}{f} F\tilde{F} - \mathrm{V}_{\mathrm{NP}}(\phi/f)$$

where f = $\mathrm{U}(1)_\phi$ breaking scale if linearly realized

  - Light and weakly coupled in the limit of large f

- Extension of the SM with an ALP
  - May address the puzzles of the SM

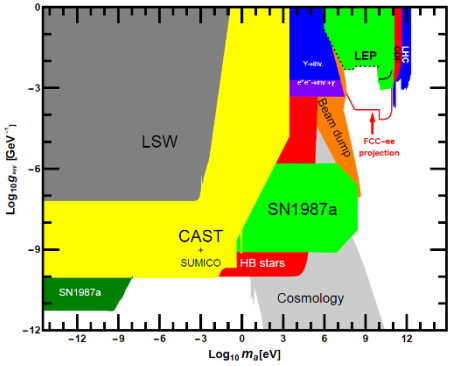
    Talk by Jihn E. Kim
  - Example: QCD axion anomalously coupled to gluons

    - Natural solution to the strong CP problem

    - Candidate for dark matter Talk by Giovanni Villadoro

    (misalignment, topological defects)
  - Potential to be probed by cosmological, astrophysical and laboratory observations

    Talks by Andreas Ringwald
    Asimina Arvanitaki
    David J. E. Marsh
    Maria Baryakhtar
    Pierre Sikivie



Jaeckel, Spannowski 2015

Higgs portal

- Higgs portal
  - ALP interacts with the SM via the Higgs field

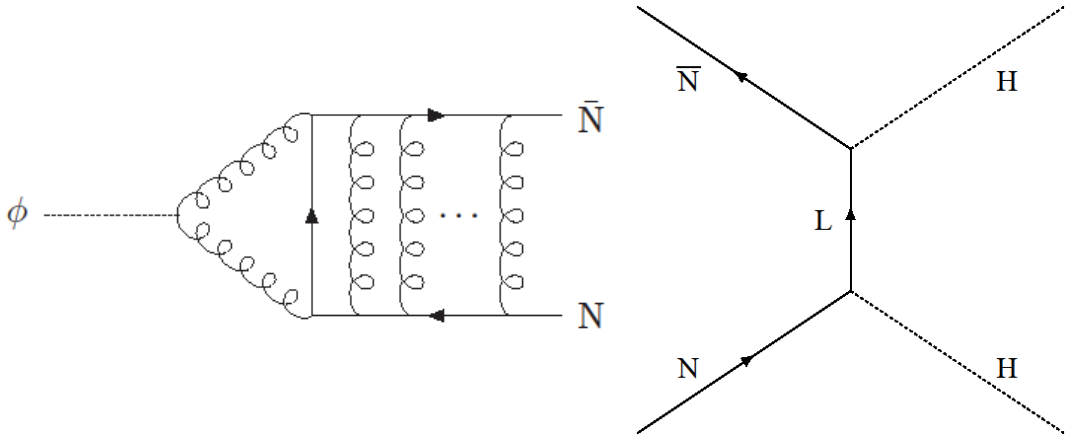
$$V = \lambda|H|^4 + \mu_H^2(\phi/f)|H|^2 + V_0(\phi/f)$$

portal to a hidden sector

  - Interactions: constrained by the periodicity
  - Example: $-M^2 \cos\left(\frac{\phi}{f}\right)|H|^2$

- Higgs portal
  - UV completion: hidden QCD under which $U(1)_\phi$ is anomalous

    → Controllable ALP interactions



$$\Rightarrow -\frac{\Lambda_{\text{hid}}^3}{m_L}\cos\left(\frac{\phi}{f}\right)|H|^2$$

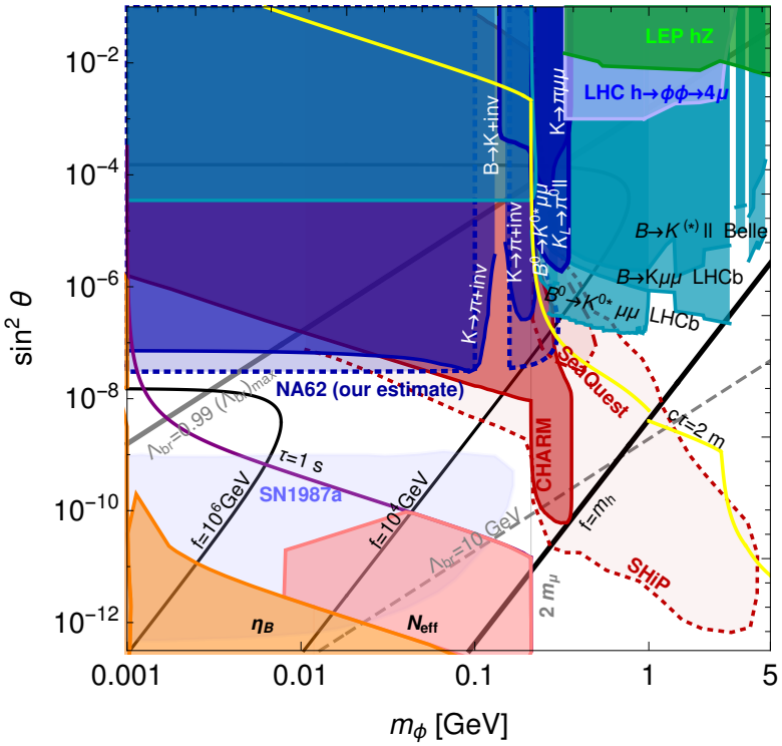
- Higgs portal
  - Difference from the conventional Higgs portal
    - Globally, μ_H^2 is bounded both from above and below
    - Locally, $\sum_n c_n M^2 \left(\frac{\phi}{f}\right)^n |H|^2$ with $|c_n| \leq 1$

      → Certain relations between couplings due to periodicity
  - Electroweak symmetry breaking
    - Mixing between the ALP and Higgs boson
    - Higgs decay $h \to \phi\phi$ if the ALP is light

- Experimental constraints
  - ALP-Higgs mixing

Flacke, Frugiuele, Fuchs, Gupta, Perez 2016

Choi, Im 2016



  - Further constrained if anomalously coupled to gauge bosons

- Why an ALP with Higgs portal?
  - ϕ can play an important role in electroweak phase transition!

    Graham, Kaplan, Rajendran 2015
  - New approach to the electroweak hierarchy problem

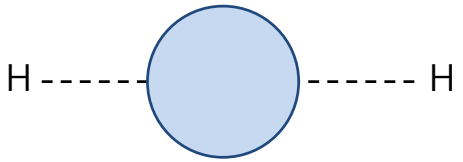
    - Cosmological relaxation of the Higgs boson mass
  - Other roles?

    - First order phase transition?

    - Dark matter?

I. Electroweak hierarchy

- Electroweak hierarchy problem
  - Higgs mass: sensitive to unknown UV physics



$$\delta m_H^2 \sim \frac{\Lambda_{\text{cut}}^2}{16\pi^2}$$

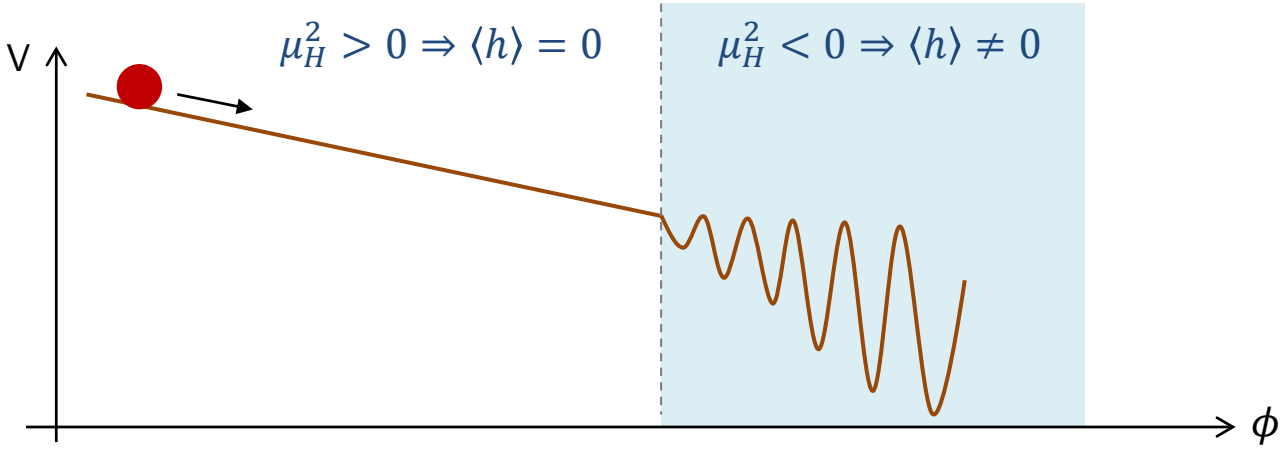
  - Unnatural without new physics around TeV

    - Supersymmetry, extra dimensions, strong dynamics, …

  - LHC experiments

    - No signals for new physics around TeV

- Relaxation mechanism Graham, Kaplan, Rajendran 2015
  - ALP with a Higgs portal: $\mu_H^2(\phi)|H|^2$
  - Cosmological ALP evolution to select the Higgs mass



- ϕ slow-rolls while scanning μ_H^2 from $\Lambda_{\rm cut}^2$ to negative, and stops by barriers formed by EWSB

- Relaxation mechanism
  - Potential

$$V = V_{\text{sliding}}(\phi/f_{\text{eff}}) + \mu_H^2(\phi/f_{\text{eff}})h^2 + V_{\text{barrier}}(\phi/f, h) + \cdots$$

- Sliding: $V_{\text{sliding}} = \Lambda_{\text{cut}}^4 \left(-c_1 \frac{\phi}{f_{\text{eff}}} + c_2 \frac{\phi^2}{f_{\text{eff}}^2} + \cdots \right)$

- Higgs mass-squared: $\mu_H^2(\phi) = \Lambda_{\text{cut}}^2 \left(k_0 - k_1 \frac{\phi}{f_{\text{eff}}} + \cdots \right)$

- Barriers: $V_{\text{barrier}}(\phi, h) = -\mu_{\text{br}}^4(h) \cos\left(\frac{\phi}{f}\right)$

with $f_{\text{eff}} \gg f$

- Conditions
  - High enough barriers to stop the ALP

$\partial_\phi V_0 \sim \partial_\phi V_{\rm barrier}$ at time when $\langle h \rangle \sim v = 174\,\text{GeV}$

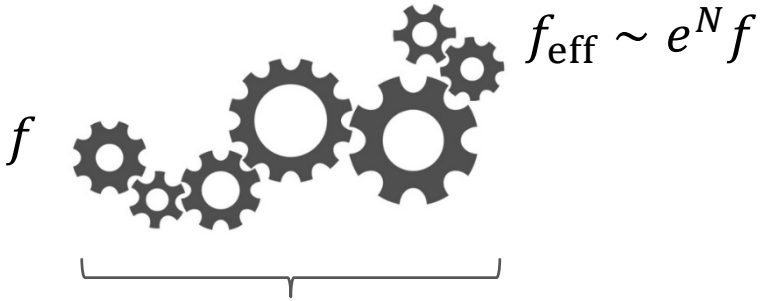
$\Rightarrow$ Large hierarchy between F and f

$$\frac{f_{\rm eff}}{f} \sim \left(\frac{\Lambda_{\rm cut}}{\mu_{\rm br}(h=v)} \right)^4 \gg 1$$

  - Clockwork mechanism

Choi, Im 2016

Kaplan, Rattazzi, 2016



- Conditions
  - Evolution dominated by classical rolling

$$H_{\rm inf} < \left(\partial_\phi V_{\rm sliding}\right)^{1/3} \Rightarrow \text{Hubble scale} \leq \text{GeV during inflation}$$

  - Scanning of μ_H^2 from $\Lambda_{\rm cut}^2$ to negative

$$N_e > \frac{H_{\rm inf}^2}{\partial_\phi V_{\rm sliding}} f_{\rm eff} \Rightarrow \text{Large number of } e\text{-folds}$$

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

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

- Higgs-dependent barrier potential
  - QCD anomaly

$$V_{\text{barrier}}(\phi, h) = -y_u \Lambda_{\text{QCD}}^3 h \cos\left(\frac{\phi}{f}\right)$$

  - Too large strong CP phase due to V_{sliding}
  - Possible solutions

Graham, Kaplan, Rajendran 2015

- Slope of V_{sliding} decreases after inflation
- Slope of V_{barrier} increases after inflation

Nelson, Prescod-Weinstein 2017

- Higgs-dependent barrier potential
  - Hidden QCD anomaly

    - ϕ couples to gauge-invariant operator $|H|^2$

$$V_{\text{barrier}}(\phi, h) = -\Lambda_{\text{hid}}^2 h^2 \cos\left(\frac{\phi}{f}\right)$$

  - Coincidence problem

    - Higgs-independent barriers from closing Higgs loops

  - Possible solutions

    Espinosa, Grojean, Panico, Pomarol, Pujols, Servant 2015

    - Multiple ALPs for double scanning

- Peccei-Quinn relaxation **KSJ**, Shin 1709.10025
  - Scheme to avoid the coincidence and strong CP problems
  - Two ALPs anomalously coupled to QCD

$$V = -y_u \Lambda_{\rm QCD}^3 h \cos\left(\frac{\phi}{f} + \frac{a}{f_a}\right) + V_{\rm sw}(a,\phi) + \cdots$$

  - Switching potential

    - Large mass to a during inflation, but to ϕ after inflation

    $\Rightarrow$ During inflation: ϕ selects the Higgs mass

    After inflation: a selects the strong CP phase

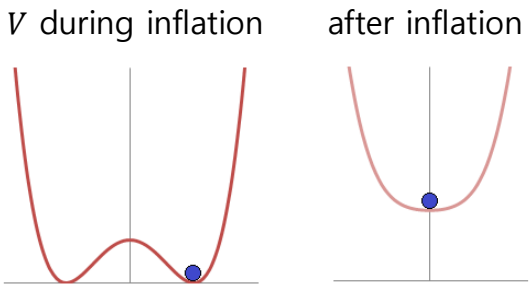
- Peccei-Quinn relaxation
  - Switching potential from two hidden QCDs

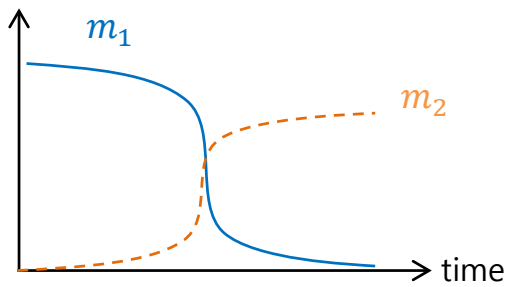
$$V_{\text{switch}} = m_1 \Lambda_1^3 \cos\left(\frac{a}{f_a}\right) + m_2 \Lambda_2^3 \cos\left(\frac{\phi}{f}\right)$$

light hidden quark mass

confinement scale of hidden QCD

  - Hidden quark mass from the VEV of a scalar field with an inflaton-dependent potential



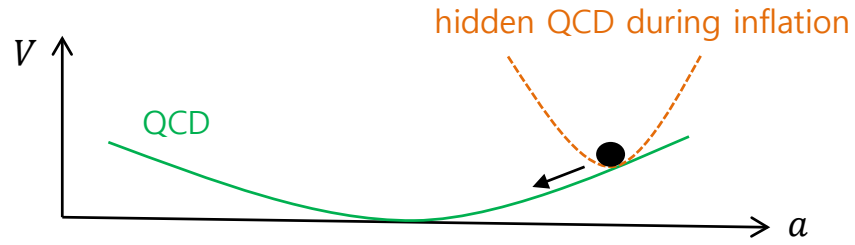


- Peccei-Quinn relaxation

  - Cutoff scale of the Higgs mass $\leq 10^7\,\mathrm{GeV}\left(\frac{f}{10^6\,\mathrm{GeV}}\right)^{-1/6}$
  - Properties of ϕ
    - Heavy as stabilized by hidden QCD after inflation

      → Reheating temperature above the weak scale

    - No mixing with the Higgs boson as $\theta_{\mathrm{QCD}} = \left\langle \frac{a}{f_a} + \frac{\phi}{f} \right\rangle = 0$
  - Dark matter from a



II. Electroweak baryogenesis

- Matter-antimatter asymmetry
  - EWPT: Last period affecting baryon asymmetry

    Rapid EW sphaleron transition in symmetric phase

    → B+L violation (but B-L invariant)
  - Baryogenesis

    - Nonzero B-L above EW scale

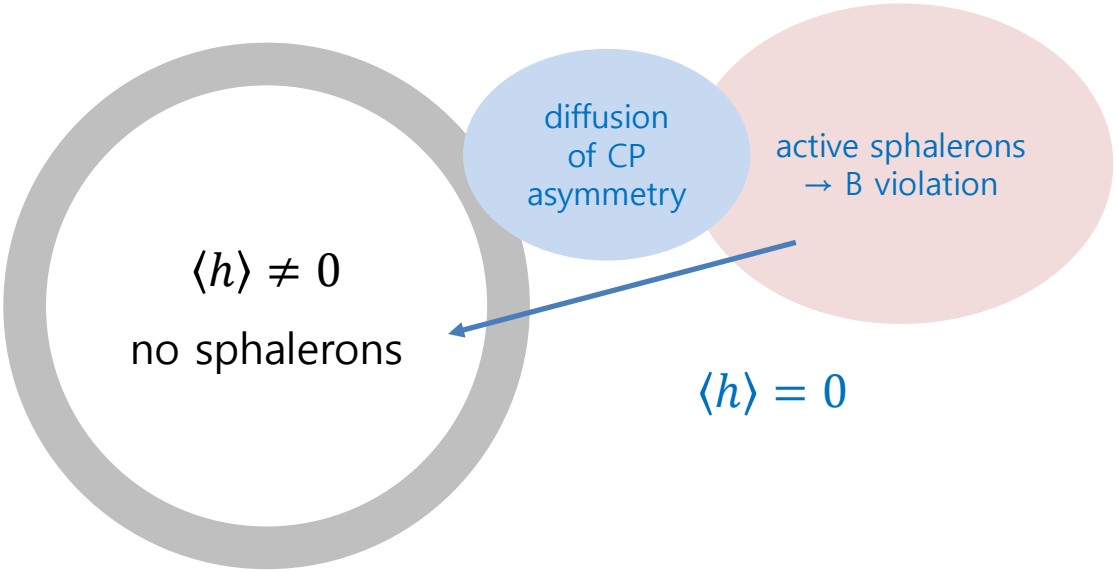
      e.g. Thermal leptogenesis, Affleck-Dine, …

    - 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

      SM: crossover if $m_h > 80$ GeV

    - Sufficient CP violation

      SM: CKM and strong CP phases

    → Need BSM

- 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
  - CP violation

    Large during baryogenesis but small in present

- Non-local baryogenesis

  CP violation in front of wall, B violation away from wall

- LHC (direct searches) and EDM: Probe of EWBG

  c.f. ACME II constraint on electron EDM

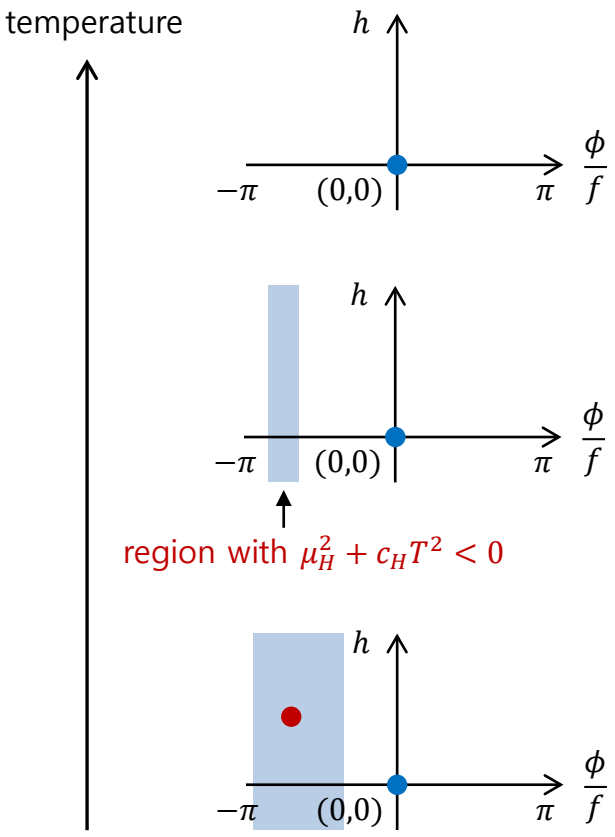
- Higgs portal
  - Potential: $V = \lambda|H|^4 + \mu_H^2(\phi/f)|H|^2 + V_0(\phi/f)$

    with $\mu_H^2 = \mu^2 - M^2\cos\left(\frac{\phi}{f} + \alpha\right)$ and $V_0 = -\Lambda^4\cos\left(\frac{\phi}{f}\right)$

  - For f much above the weak scale
    - Thermal corrections: $\Delta V_{\mathrm{TH}} \simeq c_H T^2|H|^2$
    - V is a function of $\theta \equiv \frac{\phi}{f}$, and is insensitive to f

- EWPT driven by the ALP **KSJ**, Jung, Shin 1806.02591, 1811.03294

  - Phase transition



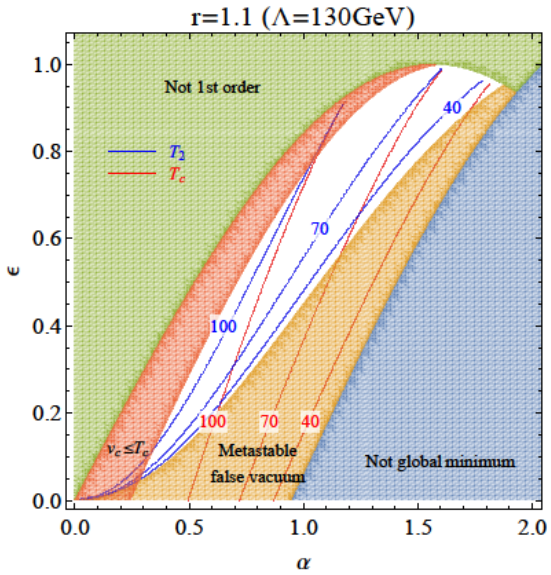
- only a symmetric minimum at $(\phi, h) = (0,0)$
  due to V_0 and thermal Higgs mass
- $\mu_H^2 + c_H T^2 > 0$ in the whole range of ϕ
  because μ_H^2 is bounded from above and below

- minimum at $(\phi, h) = (0,0)$
- $\mu_H^2 + c_H T^2 < 0$ in a finite range of ϕ

- 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 ϕ
- phase transition when EW minimum gets deeper

- EWPT driven by the ALP
  - Tunneling mainly along the ALP direction
  - Approximate scaling behaviors
    - Euclidean action of O(3) symmetric critical bubble: $S_3 \propto f^3$
    - Radius of critical bubble: $R_c \propto f$
  - Phase transition
    - Two degenerate minima at T_c: lower than in the SM
    - Bubble nucleation at T_n
    - Barrier disappears at T_2: close to T_n

- EWPT driven by the ALP
  - Strong first order phase transition: insensitive to f

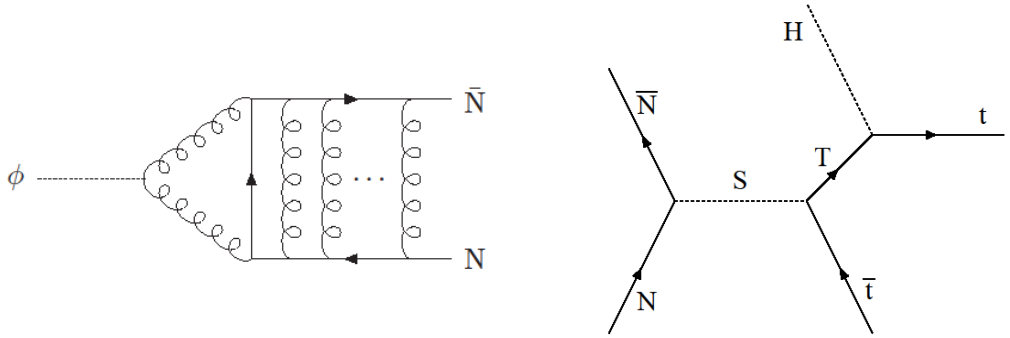


$$\epsilon \equiv \frac{\sqrt{2\lambda}\Lambda^2}{M^2}$$

  - Weak coupling limit with $f \gg$ the weak scale
    - Free from EDM and LHC constraints
    - Instead, probable in ALP searches

- EWBG: non-local baryogenesis **KSJ**, Jung, Shin 1806.02591
  - CP violation from ALP-dependent top quark mass

$$Y_t = y_t + x_t e^{i\phi/f}$$

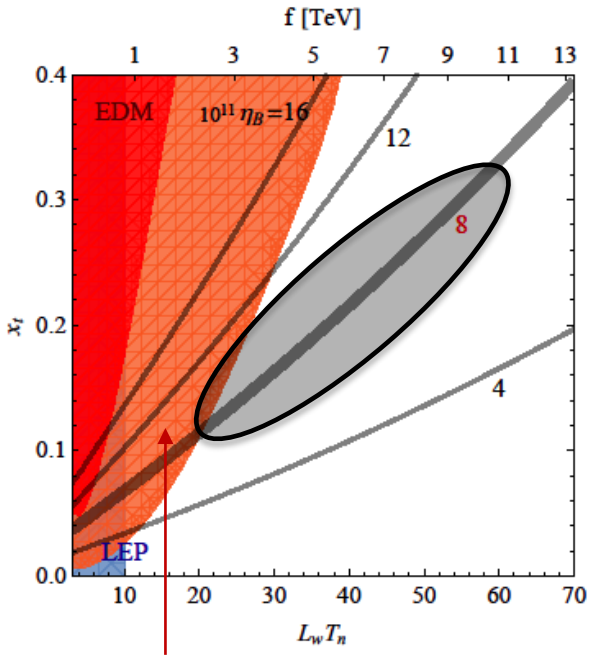


  - Baryon asymmetry

    - depends on CP violation x_t, wall width L_w, wall velocity v_w

    - diffusion effect: sizable for $L_w T_n \leq 100$ → upper bound on f

- EWBG: non-local baryogenesis
  - Correct baryon asymmetry for $3\mathrm{TeV} \leq f \leq 10\mathrm{TeV}$



GeV to 20 GeV ALP

ACME II: about 10 times stronger than ACME I

- EWBG: local baryogenesis **KSJ**, Jung, Shin 1811.03294
  - CP violation from ALP-dependent EW Θ-term

    $\frac{\phi}{f} W\tilde{W} \rightarrow \frac{d\phi}{dt}$ = chemical potential for Chern-Simons number

  - Simultaneous B and CP violations across walls (thick for large f)

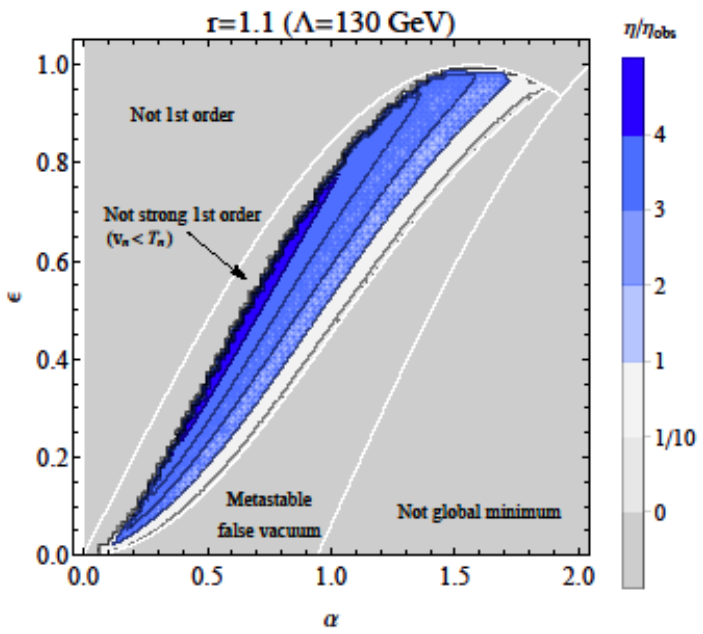
    → B generation through EW anomaly

$$\frac{dn_B}{dt} \approx \boxed{\frac{3}{2}\frac{\Gamma_{\rm sph}}{T}\frac{d}{dt}\frac{\phi}{f}} - \frac{39}{4}\frac{\Gamma_{\rm sph}}{T} n_B$$

sphaleron-induced washout

- EWBG: local baryogenesis
  - ALP evolution after tunneling

    - Thermal dissipation due to ϕ-h mixing: upper bound on f
  - Correct baryon asymmetry for $10^5\mathrm{GeV} \leq f \leq 10^7\mathrm{GeV}$



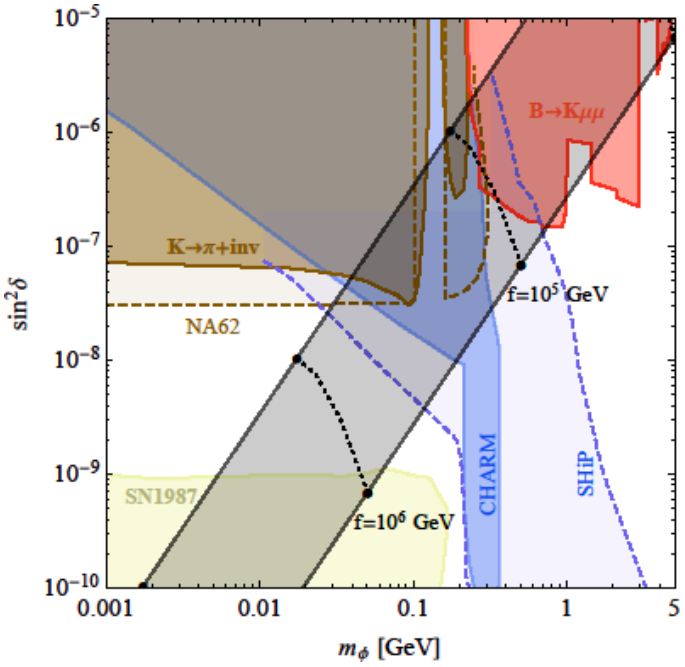
MeV to GeV ALP

$f = 10^6$ GeV

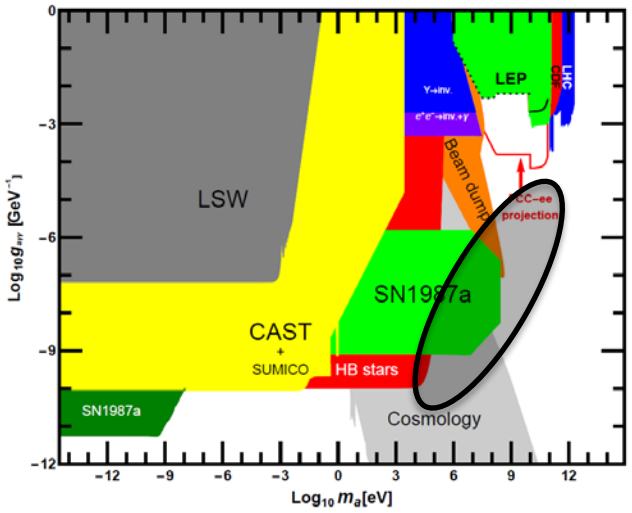
- How to probe the ALP driving EWBG?
  - ALP at MeV-GeV (local) or GeV-20GeV (non-local)

    - ALP window without strong theoretical interests so far

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



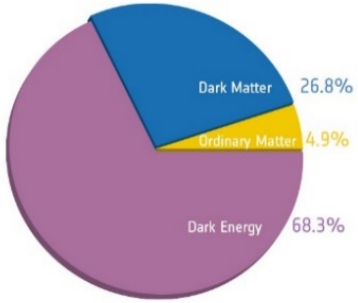
Jaeckel, Spannowski 2015



anomalous ALP couplings to gauge bosons: optional

III. Freeze-in dark matter

- WIMP dark matter



  - Relic abundance from freeze-out

$$\Omega_\chi \propto \frac{m_\chi}{T_f}\frac{1}{\langle\sigma v\rangle} \text{ with } \langle\sigma v\rangle \sim \frac{\lambda^2}{m_\chi^2}$$

$\Rightarrow$ Observed DM density if $\lambda \sim 0.1$ and $m_\chi \sim 100\text{GeV}$

  - Well-motivated, natural, experimentally testable, …
  - No signals for new physics at LHC

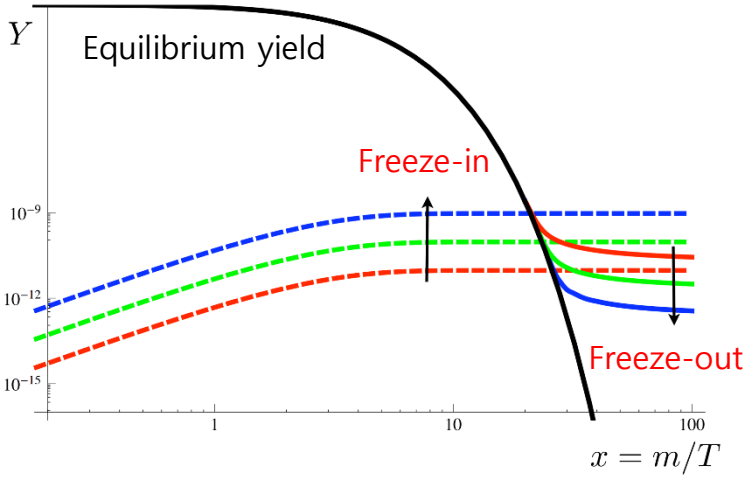
    Null results from direct & indirect DM detection searches

  - May need to go beyond WIMP

- Freeze-in DM

McDonald 2001, Choi, Roszkowski 2005, Petraki, Kusenko 2007
Hall, Jedamzik, March-Russell, West 2009

  - Alternative to freeze-out
  - Never in thermal equilibrium: feeble coupled to SM
  - Produced via thermal freeze-in



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 **KSJ**, Im 1907.xxxxx
  - ALP interacting with the SM ONLY via Higgs portal

$$V = \lambda|H|^4 + \left(\mu^2 - M^2\cos\left(\frac{\phi}{f}\right)\right)|H|^2 - \frac{1}{16\pi^2}M^2\Lambda^2\cos\left(\frac{\phi}{f}\right)$$

closing Higgs loops

  - 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
  - Never in thermal equilibrium for $\lambda_{h\phi} < 10^{-7}$
    - Mass mainly from closing Higgs loops: $m_\phi \simeq \frac{1}{4\pi}\frac{M}{f}\Lambda$
    - Portal coupling: $\frac{\lambda_{h\phi}}{4}h^2\phi^2 + \frac{\lambda_{h\phi}v}{2}h\phi^2$ with $\lambda_{h\phi} = \left(\frac{M}{f}\right)^2$

freeze-in production by $hh \to \phi\phi$

by $h \to \phi\phi$ (dominant if open)

- ALP DM
  - Correct DM density

    - Higgs decay

    $\lambda_{h\phi} \simeq 10^{-10} \times \sqrt{\frac{3\mathrm{MeV}}{m_\phi}}$ and $m_\phi \simeq 1\mathrm{MeV} \times \left(\frac{\Lambda}{10^3\mathrm{GeV}}\right)^{\frac{4}{5}}$

    - Higgs annihilation

    $\lambda_{h\phi} \simeq 10^{-11}$ and $m_\phi \simeq 380\mathrm{GeV} \times \left(\frac{\Lambda}{10^9\mathrm{GeV}}\right)$

  - ALP heavier than MeV for Λ above TeV
  - Coherent oscillations: negligible if $T_{\mathrm{osc}} \gg 10^6 \times m_\phi$

- UV completion: non-perturbative portal
  - Vector-like lepton doublets $L + L^c$ and singlets $N + N^c$ charged under hidden QCD confining at $\Lambda_{\rm hid}$

$$yHLN^c + y'H^+ L^c N + m_L L L^c + \mu_N e^{i\alpha} N N^c + \frac{1}{32\pi^2}\frac{\phi}{f} G_H \tilde{G}_H$$

effective portal coupling

not forbidden by ALP shift symmetry

anomalous coupling

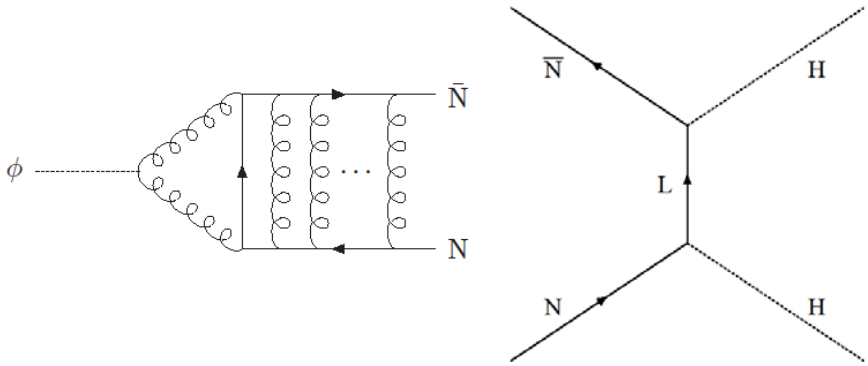
in the basis where all the parameters are real

- UV completion: non-perturbative portal
  - Lepton singlet lighter than the confinement scale

$$V_{\text{eff}} \ni -M^2 \cos\left(\frac{\phi}{f}\right)|H|^2 - \frac{1}{16\pi^2} M^2 \Lambda^2 \cos\left(\frac{\phi}{f}\right) - \mu_N \Lambda_{\text{hid}}^3 \cos\left(\frac{\phi}{f} + \alpha\right)$$

with $M^2 = yy' \frac{\Lambda_{\text{hid}}^3}{m_L}$ and $\Lambda \sim m_L$

should be suppressed:
ALP-Higgs mixing for $\alpha \neq 0$



- UV completion: non-perturbative portal
  - Viable model

    - supersymmetry + spontaneously broken $U(1)_X$

    - m_L from superpotential, while μ_N from Kaehler potential

$$\mu_N = \frac{m_{\rm susy}}{M_{Pl}} m_L$$

  - ALP-Higgs mixing: ALP is a decaying DM

    → Upper bound on $m_{\rm susy}$ to make ALP cosmologically stable

- UV completion: radiative portal

Gupta, Komargodski, Perez, Ubaldi 2015

  - Vector-like lepton doublets $L + L^c$ and singlet N

$$m_L L L^c + y e^{i\phi/f} H L N + y' H^+ L^c N + \frac{1}{2}\mu_s e^{i(\phi/f+\alpha)} NN$$

effective portal coupling

not forbidden by ALP shift symmetry

with small $\mathrm{U}(1)_\phi$ breaking: $\frac{1}{2}\mu_{sb} NN$

in the basis where all the parameters are real

- UV completion: radiative portal
  - ALP potential at loop and proportional to $\mu_{\rm sb}$

$$V_{\rm eff} \ni -M^2 \cos\left(\frac{\phi}{f}\right)|H|^2 - \frac{M^2\Lambda^2}{16\pi^2}\cos\left(\frac{\phi}{f}\right) - \frac{\mu_{\rm sb}\mu_{\rm s}\Lambda^2}{16\pi^2}\cos\left(\frac{\phi}{f}+\alpha\right)$$

with $M^2 = \frac{yy'}{16\pi^2}\mu_{\rm sb}\, m_L \ln\left(\frac{\Lambda^2}{m_L^2}\right)$

should be suppressed if $\alpha \neq 0$

  - Higgs-independent ALP potentials: UV sensitive

- UV completion: radiative portal
  - Viable model

    - supersymmetry + spontaneously broken $U(1)_X$

    - m_L from superpotential, while μ_s from Kaehler potential

$$\mu_s = y\frac{m_{\rm susy}}{M_{Pl}}m_L$$

  - ALP decays due to ALP-Higgs mixing

    - Longevity condition is insensitive to $m_{\rm susy}$

      but constrains M and m_ϕ

Summary

❖ An ALP coupled to the SM via a Higgs portal

- May give information on the origin of EWSB
- May solve the SM puzzles
  - electroweak hierarchy: cosmological relaxation
  - matter-antimatter asymmetry: EW baryogenesis
  - dark matter: freeze-in

Thank you!