Baryogenesis and dark matter in ALPic Higgs portal

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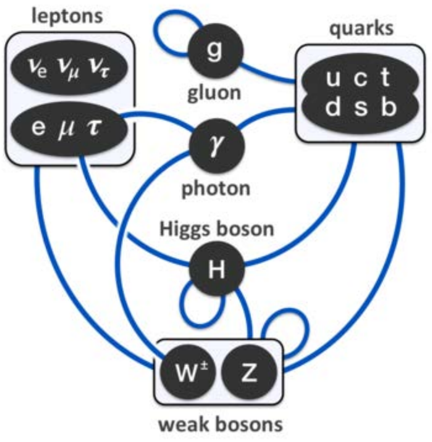
I. Beyond the SM

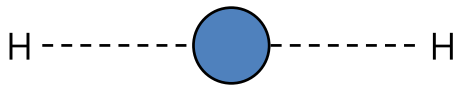
- Standard Model
  - Successful

    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

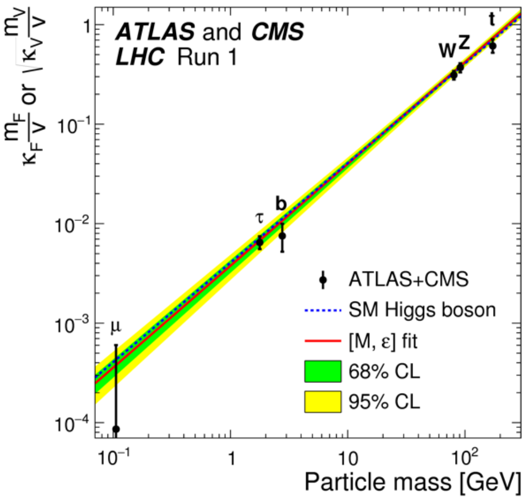


$$\delta m_H^2 \sim \frac{(\text{cutoff scale})^2}{16\,\pi^2}$$

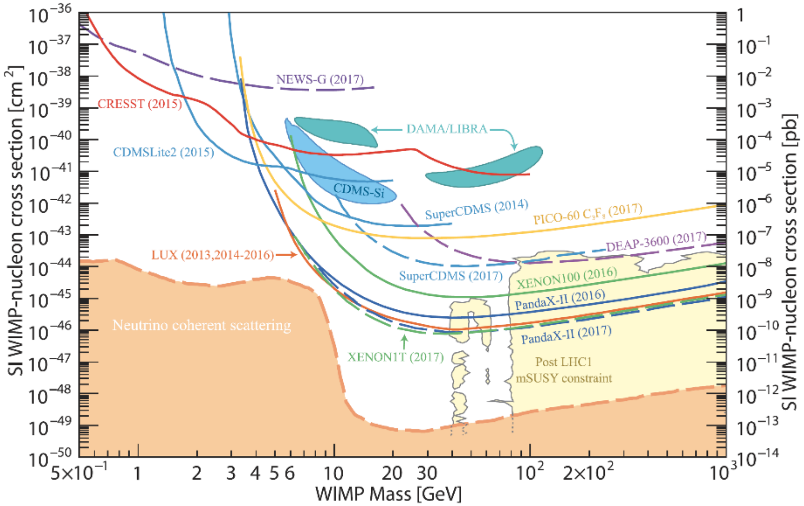
  - New physics around TeV
    - Supersymmetry, extra dimension, composite Higgs, …
    - Solution to other problems of the SM

      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 $\phi \to \phi + \mathrm{constant}$
    - Feebly interacting light particle for large f

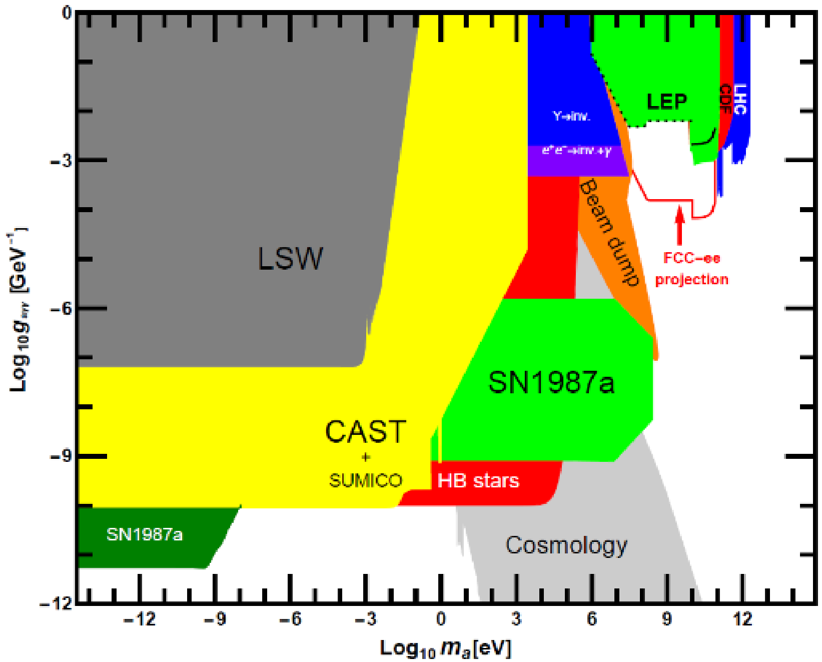
- SM extension with an ALP
  - Perturbative shift symmetry

    - 3 types of interaction

$$m_\psi e^{i c_1 \frac{\phi}{f}} \bar{\psi}\psi + c_2 \frac{\partial_\mu \phi}{f} \bar{\psi}\gamma^\mu \gamma_5 \psi + \frac{c_3}{16\pi^2} \frac{\phi}{f} F\tilde{F}$$

    - Combinations of c_i invariant under chiral field redefinitions

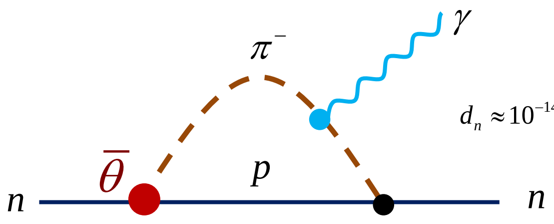
- SM extension with an ALP
  - Potential to be probed by cosmological, astrophysical and laboratory observations
    - e.g. anomalous coupling to photons



Jaeckel, Spannowski 2015

- Examples
  - QCD axion

    - Neutron EDM bound



$$d_n \approx 10^{-14} \frac{m_u m_d}{(m_u + m_d) m_s} \bar{\theta} \; e \cdot cm$$

$$\frac{\bar{\theta}}{32\pi^2} G\tilde{G} \text{ with } \bar{\theta} < 10^{-10}$$

    - $\bar{\theta} \propto \langle \phi \rangle = 0$ if anomalously coupled to gluons

      $\rightarrow$ natural solution to the strong CP problem

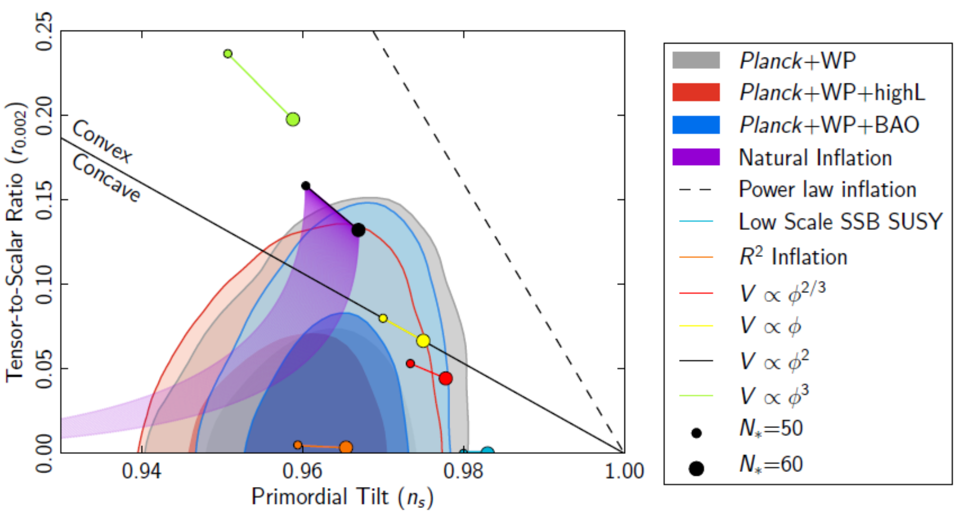
    - Dark matter: misalignment, topological defects

- Examples

Freese, Frieman, Olinto 1990

  - 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

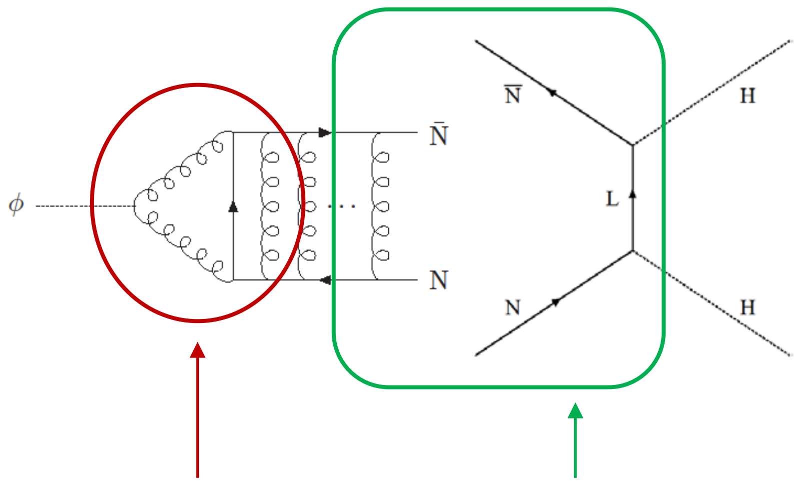
'cosmological relaxation of the Higgs mass'

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 ϕ and NN^c meson

Effective coupling of NN^c to Higgs

due to heavy doublet leptons

- Experimental constraints
  - ALP-Higgs mixing after EWSB

    - Stringent constraints for ALP at sub-MeV to multi-GeV

      rare K and B meson decays

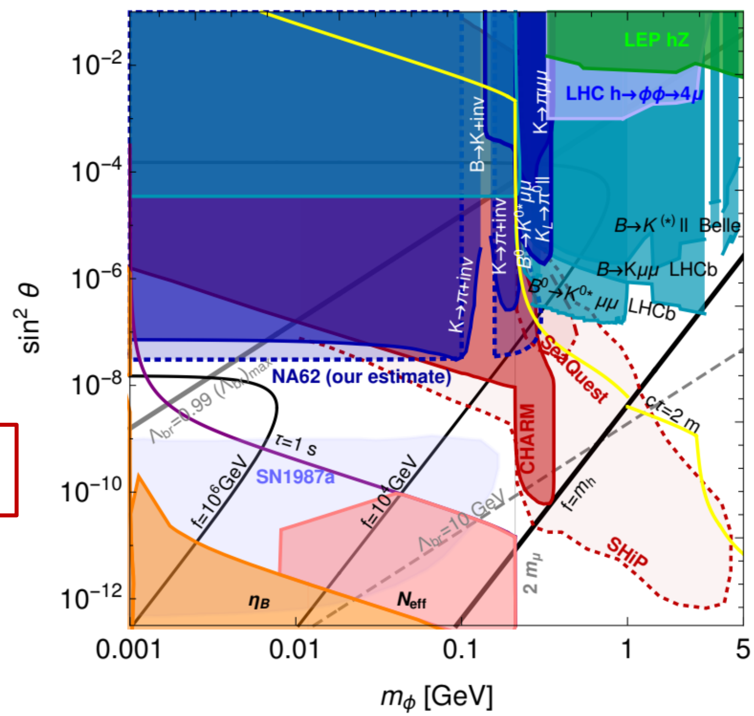
      beam-dump experiments
  - Further constraints

    if anomalously couples to SM gauge bosons

- Experimental constraints
  - ALP-Higgs mixing

Flacke, Frugiuele, Fuchs, Gupta, Perez 2016

Choi, Im 2016



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

$$\sin^2\theta \leq \frac{6 \times 10^{-7}}{\mathrm{Br}(\phi \to \mu^+\mu^-)}$$

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

    Graham, Kaplan, Rajendran 2015
    Lots of works

  - 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

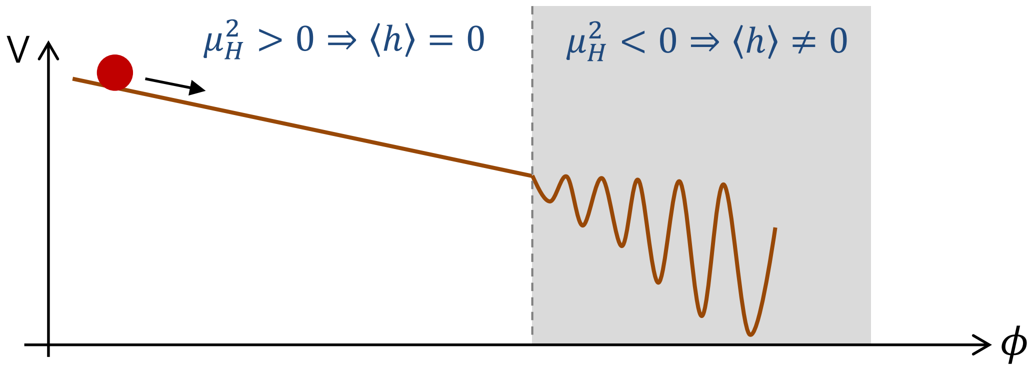
II. ALPic Higgs portal

EW scale

- Relaxation mechanism
  - Cosmological ALP evolution to select the Higgs mass

$$\mathrm{V} = \mathrm{V}_0(\phi) - \mu_H^2(\phi)|H|^2 + V_{\rm br}(\phi, H) + \cdots$$

- V_0: slow-rolling of ALP to scan μ_H^2
- $V_{\rm br}$: barriers formed by EWSB to stop ALP rolling



- Simple model
  - Two periodicities with hierarchy, $F \gg f$

    - $V_0 = V_0(\phi/F)$ and $V_{\rm br} = V_{\rm br}(\phi/f, H)$
  - Barrier potential

    - QCD anomaly: $V_{\rm br} \propto h$

      c.f. strong CP problem

    - Hidden QCD anomaly: $V_{\rm br} \propto h^2$ due to gauge invariance

      c.f. coincidence problem

- Conditions
  - High enough barriers to stop the ALP

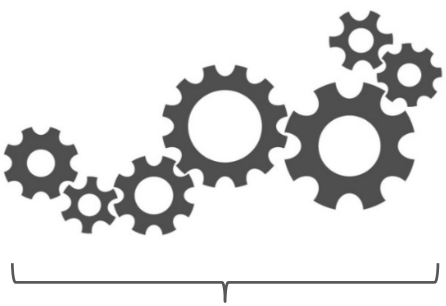
$$\rightarrow \frac{F}{f} \sim \frac{(\text{cutoff scale})^4}{\langle V_{\rm br} \rangle} \gg 1$$

  - Clockwork mechanism

Choi, Im 2016

Kaplan, Rattazzi, 2016

f



$F \sim e^N f$

collective rotations of N axions

- Conditions
  - Evolution dominated by classical rolling

    - Hubble scale ≤ GeV during inflation
  - Scanning of μ_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

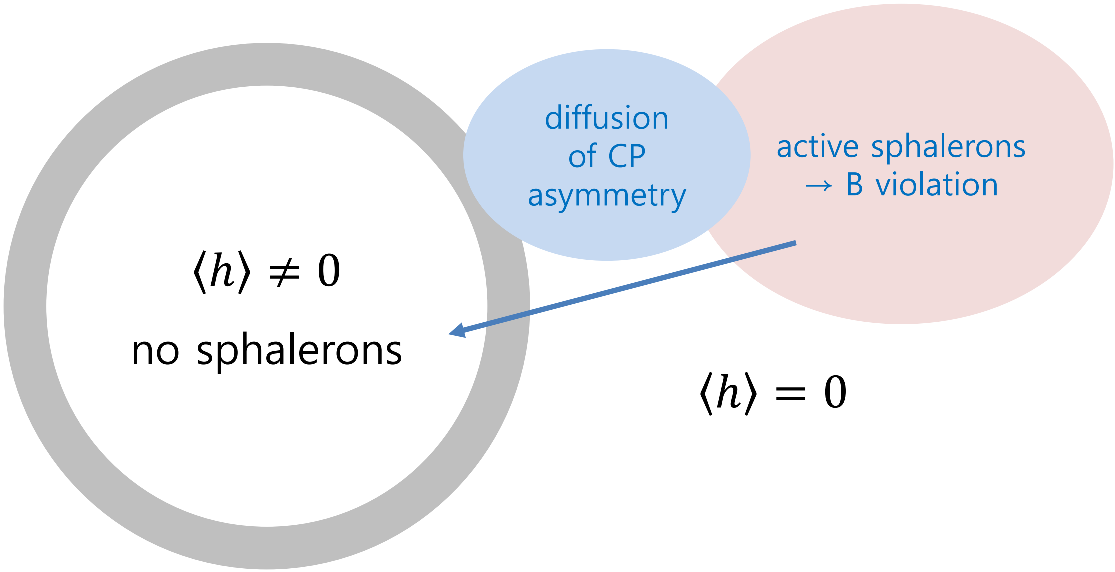
  - Baryogenesis

    - 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 ϕ/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

      → Potential $V(h, \phi/f)$ is insensitive to f

    - μ_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 λ and μ^2 fixed by $m_h = 125\text{GeV}$ and $v_0 = 246\text{GeV}$

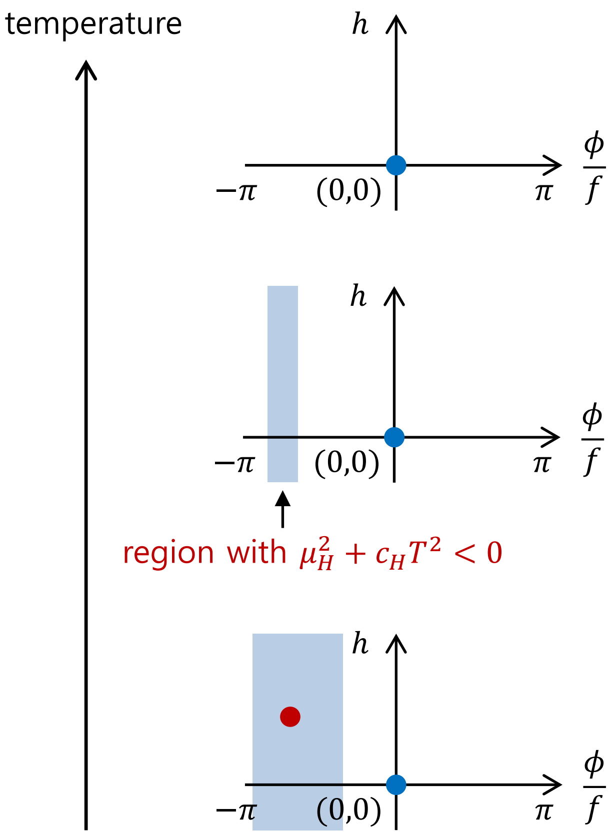
- EWPT
  - Amplitude of ALP coherent oscillation

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

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

    → 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 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
  - Tunneling mainly along the light ALP direction for $f \gg$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

- EWPT
  - Approximate scaling behaviors

    - Euclidean action of O(3) symmetric critical bubble

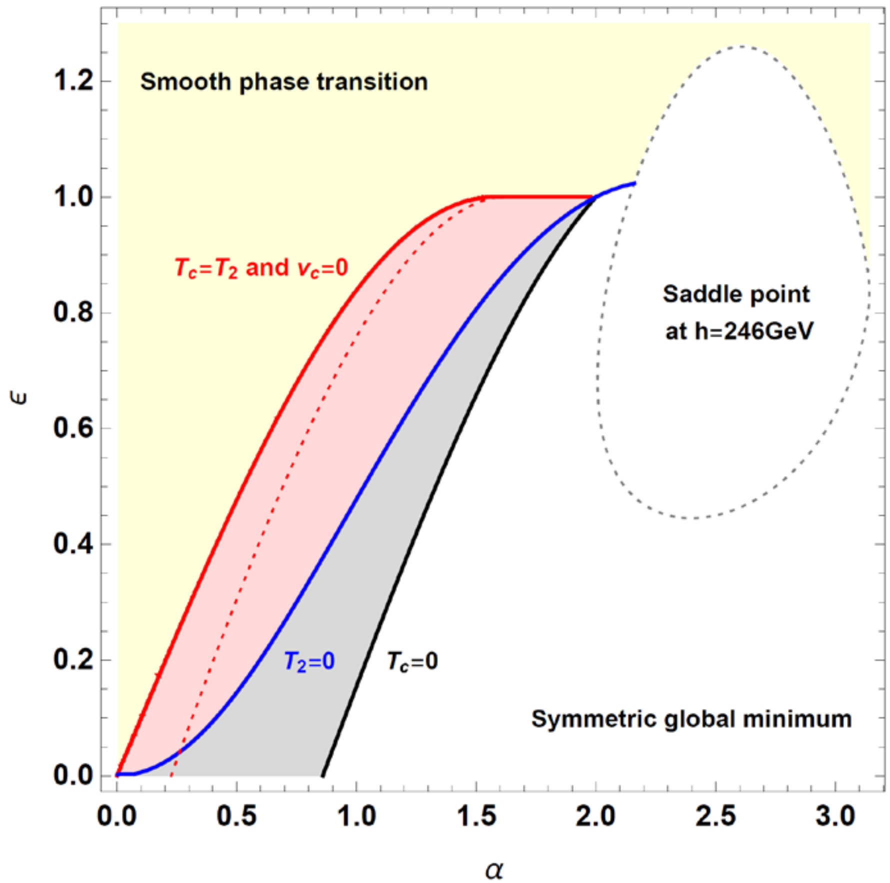
$$S_3 \propto f^3$$

⇒ Bubble radius $\propto f$, and T_n 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 → EWPT at very low T
- PT pattern: insensitive to f

- EWPT along ALP direction
  - Delayed EWPT

    - late-time entropy production to dilute preexisting relics

$$\Delta = 10^4 \left(\frac{T_{\rm reh}}{40{\rm GeV}}\right)^3 \left(\frac{T_n}{2{\rm GeV}}\right)^{-3}$$

temperature after PT

$$T_{reh} = 40{\rm GeV}\left(\frac{\Delta V^{1/4}}{100{\rm GeV}}\right)$$

    - 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

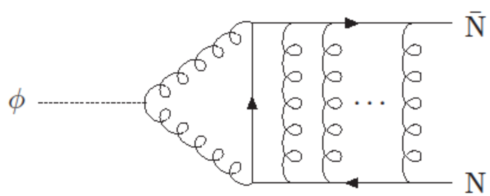
    (time for ALP settle-down) $\sim 1/m_\phi$

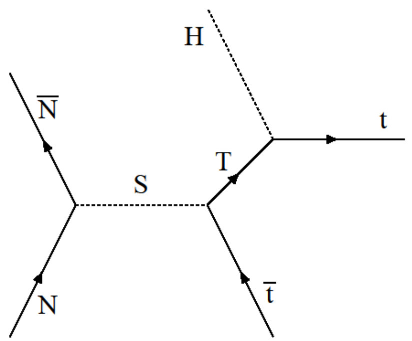
    $<$ (time for B generation) $\sim 1/\Gamma_{\mathrm{sph}}$

    $<$ (duration of PT) $\sim dS_3/dt$

- Non-local EWBG KSJ, Jung, Shin 1806.02591
  - CP violation from ALP-dependent top quark mass

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

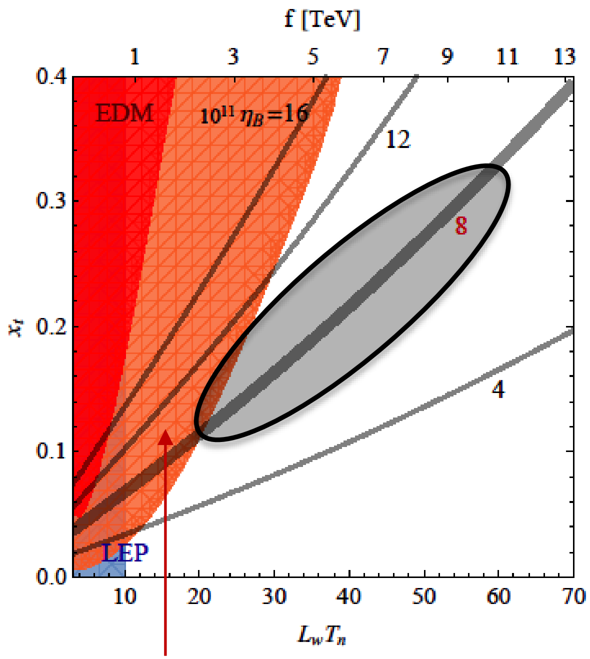




  - Baryon asymmetry
    - CP violation x_t, wall width L_w, wall velocity v_w
    - Sizable diffusion effect for $L_w T_n \leq 100$

      → upper bound on f

- Non-local EWBG
  - 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

- Local EWBG KSJ, Jung, Shin 1811.03294
  - CP violation from ALP-dependent EW Θ-term

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

  - Simultaneous B and CP violations across thick walls

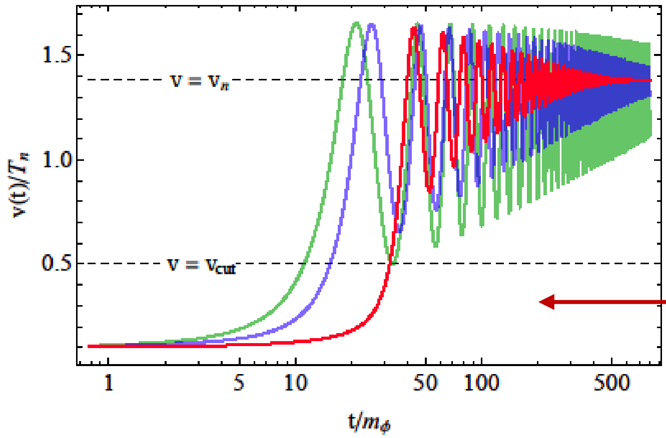
    → B generation through EW anomaly

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

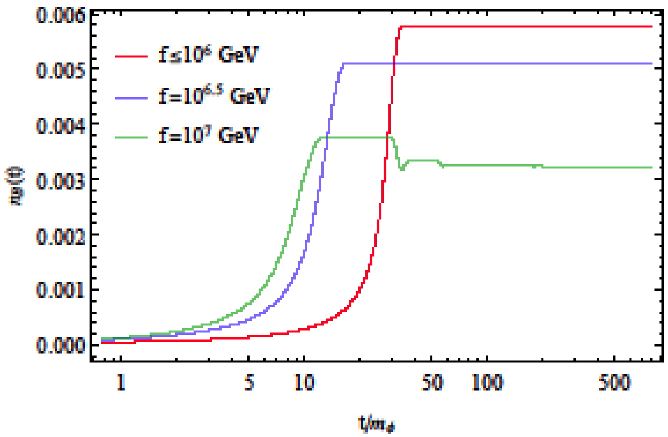
↑ sphaleron-induced washout

- Local EWBG
  - ALP evolution after tunneling

    - Strong washout by ALP oscillations with $h(\phi) > v_{\text{cut}} \sim 0.5T_n$



active sphalerons

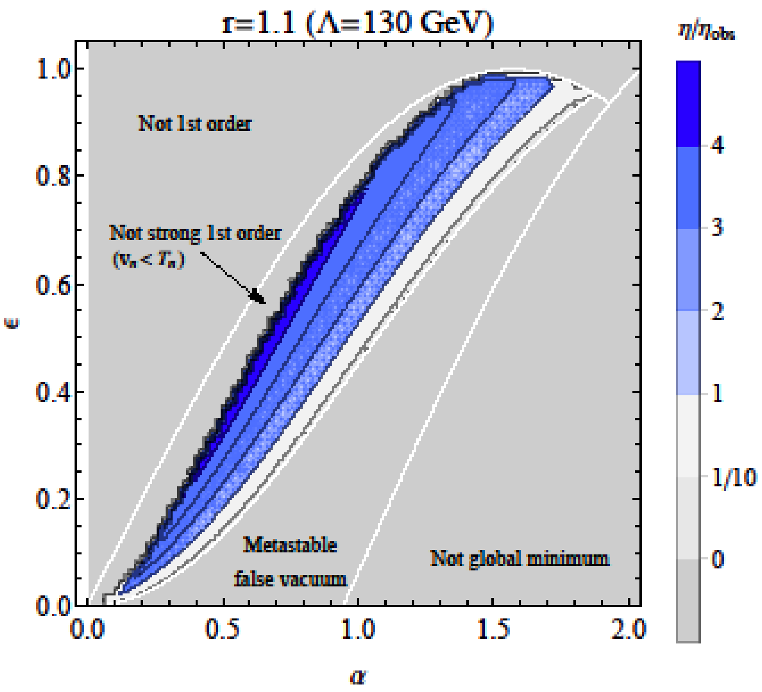


    - Thermal dissipation due to ϕ-h mixing

      → reduce the oscillating amplitude

- Local EWBG
  - Correct baryon asymmetry for $10^5\mathrm{GeV} \le f \le 10^7\mathrm{GeV}$

MeV to GeV ALP

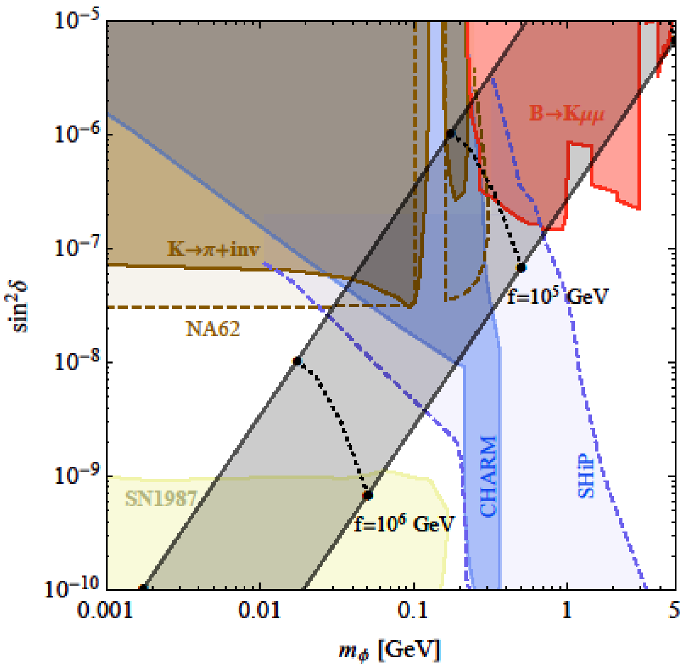


$f = 10^6$ GeV

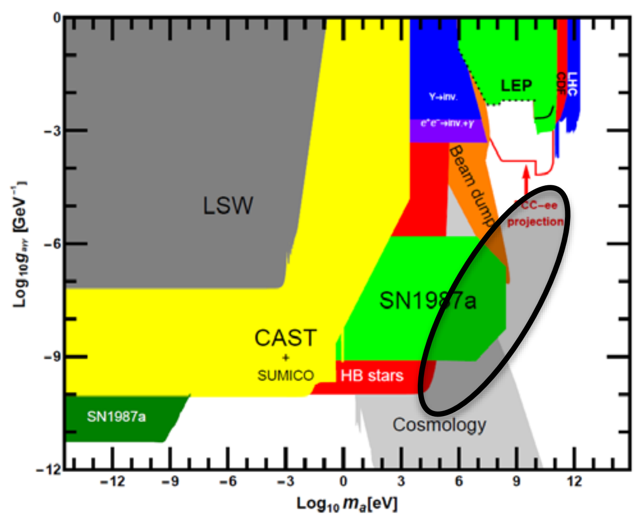
- How to probe ALP driven EWBG
  - ALP at MeV-GeV (local) or GeV-20GeV (non-local)

    \- ALP window without strong theoretical interests so far

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



Jaeckel, Spannowski 2015



anomalous ALP couplings to gauge bosons: optional

IV. ALP Dark Matter

Freeze-in

- WIMP dark matter
  - Relic abundance from freeze-out

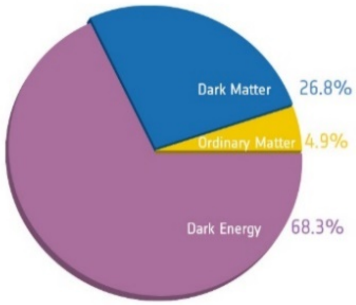
$$\Omega_\chi \propto \frac{m_\chi}{T_f}\frac{1}{\langle\sigma v\rangle} \text{ with } \langle\sigma v\rangle \sim \frac{\lambda^2}{m_\chi^2}$$

$\Rightarrow$ 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

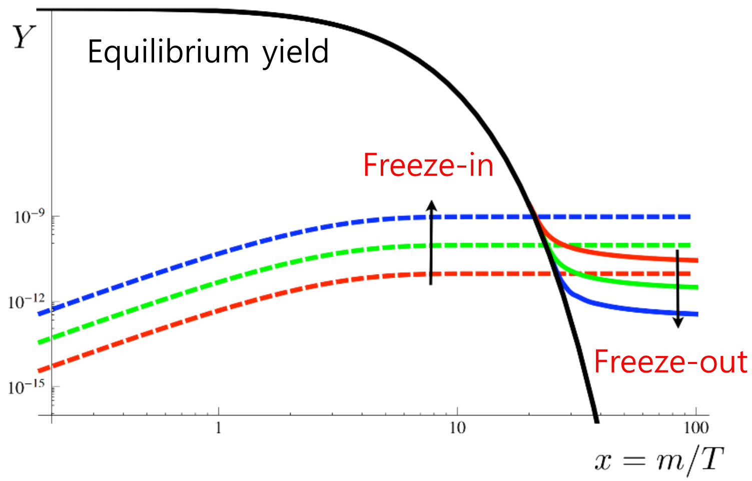
  - May need to go beyond WIMP



- 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 $m_\chi \sim 100\mathrm{GeV}$

  - Need an explanation for $\lambda \ll 1$!

Gravitino, axino in SUSY (many works)

Clockwork FIMP, Mohan and Sengupta 2018

- Higgs portal KSJ, Im 1907.07383
  - 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
  - ALP properties
    - Mass mainly from closing Higgs loops: $m_\phi \simeq \frac{1}{4\pi}\frac{M}{f}\Lambda$
    - 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 $h \to \phi\phi$: dominant if open
    - Higgs annihilation $hh \to \phi\phi$
  - ALP heavier than MeV for Λ above TeV
    - No BBN constraint
  - Coherent oscillations: negligible if $T_{\rm osc} \gg 10^6 \times m_\phi$

- ALP DM
  - Correct DM density

- Higgs decay

$$\lambda_{h\phi} \simeq 10^{-10} \times \left(\frac{m_\phi}{3\mathrm{MeV}}\right)^{-\frac{1}{2}} \text{ and } m_\phi \simeq 1\mathrm{MeV} \times \left(\frac{\Lambda}{10^3\mathrm{GeV}}\right)^{\frac{4}{5}}$$

- Higgs annihilation

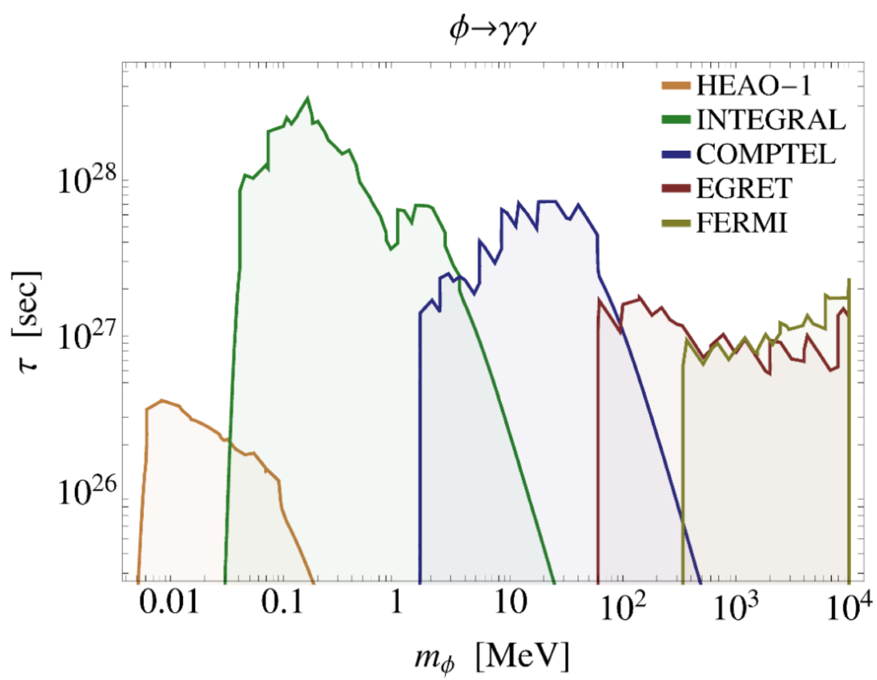
$$\lambda_{h\phi} \simeq 10^{-11} \text{ and } m_\phi \simeq 380\mathrm{GeV} \times \left(\frac{\Lambda}{10^9\mathrm{GeV}}\right)$$

- UV completion
  - Non-perturbative Higgs portal from hidden QCD

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

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 μ_N from Kaehler potential

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

  - ALP-Higgs mixing

    - Upper bound on $m_{\rm susy}$ to make it cosmologically viable

      e.g. $m_{susy} \leq 10$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