Baryogenesis & Dark Matter in Axionic Higgs Portal

Recent and on-going works in collaboration with

Sang Hui Im, Tae Hyun Jung, Sunghoon Jung, Chang Sub Shin, Seodong Shin, Jong-Chul Park

Kwang Sik JEONG

Pusan National University, Korea

APCTP-PH2020 Workshop

14 Nov 2020

I. Introduction

II. Axionic Higgs portal

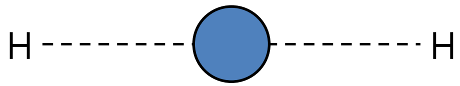
- Axion
- Dark matter
- Baryogenesis

III. Summary

What is physics beyond the SM?

- Before LHC

Models to explain the EW hierarchy problem

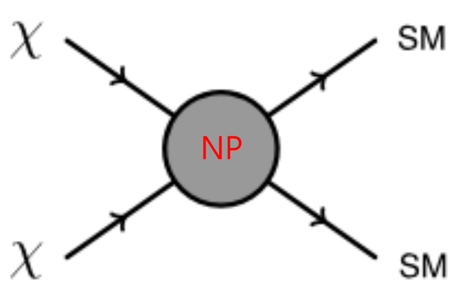


$$\delta m_H^2 \sim \frac{(\text{UV cutoff scale})^2}{16\,\pi^2}$$

→ **TeV** particles with **sizable couplings** to the SM

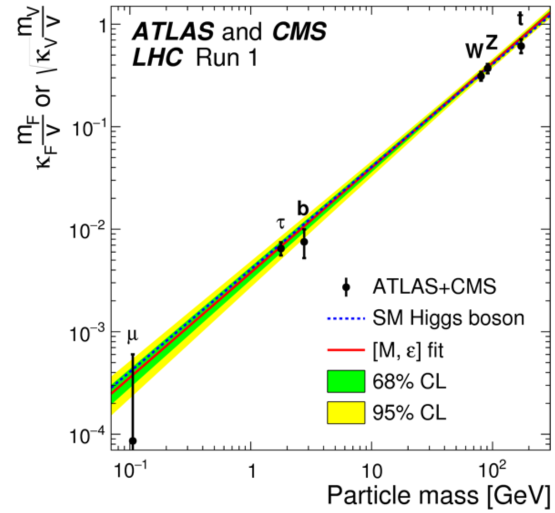
e.g. SUSY, extra dimensions, composite Higgs, …

→ (often) WIMP as cold dark matter



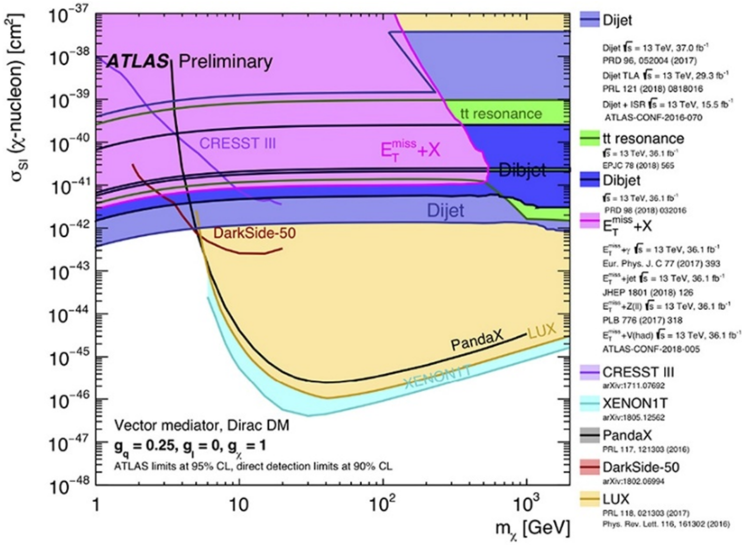
LHC results so far

- No significant deviations from the SM
- No clear signals for BSM



Direct & indirect dark matter searches so far

- No evidence of WIMPs

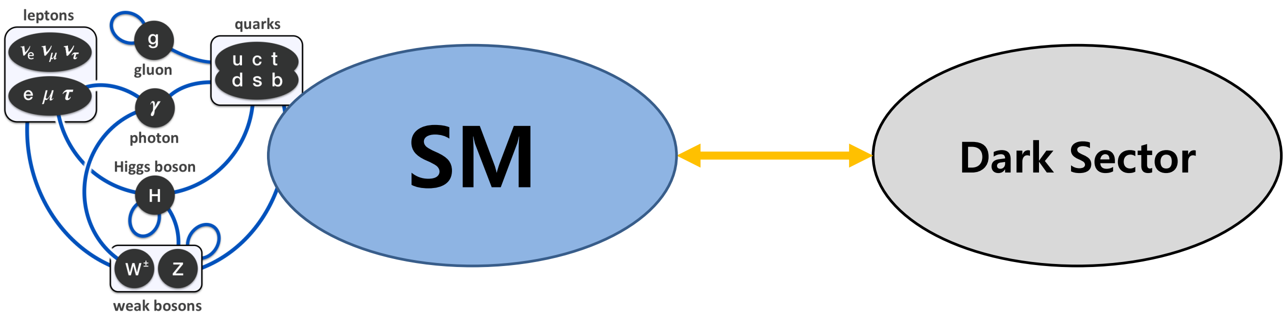


What is physics beyond the SM?

- After LHC

Another viable direction

- New **light** particles **feebly coupled** to the SM



- Cosmologically important

- Solution to the SM problems?

What is physics beyond the SM?

- Portal frameworks

  Interaction between the SM and dark sector

  - Dark Higgs: $\lambda S^2 H^\dagger H$
  - Sterile neutrino: $yLHN$
  - Dark photon: $\epsilon F'_{\mu\nu} B^{\mu\nu}$
  - Axion: $\frac{a}{f} \tilde{F}_{\mu\nu} F^{\mu\nu}$

Axion/Axion-like-particle

- Pseudo Nambu-Goldstone boson of spontaneously broken U(1)

Periodic: $\phi \equiv \phi + 2\pi f$

where axion decay constant $f =$ U(1) breaking scale

Mass and couplings

- Interaction: suppressed by f
- Mass: controlled by shift symmetry, $\phi \to \phi + \text{constant}$

$$m_\phi = \frac{(\text{shift symmetry breaking scale})^2}{f}$$

→ Feebly interacting light particle for large f

Axion portal

- Perturbative shift symmetry, $\phi \to \phi + \text{constant}$

  3 types of interaction

  - Yukawa, derivative, and anomalous coupling

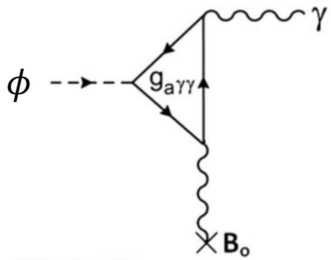
$$m_\psi e^{ic_1\frac{\phi}{f}}\bar{\psi}\psi + c_2\frac{\partial_\mu\phi}{f}\,\bar{\psi}\gamma^\mu\gamma_5\psi + \frac{c_3}{16\pi^2}\frac{\phi}{f}F\tilde{F}$$

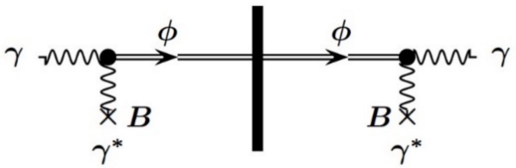
  - Physics: combinations of c_i invariant under chiral field redefinitions

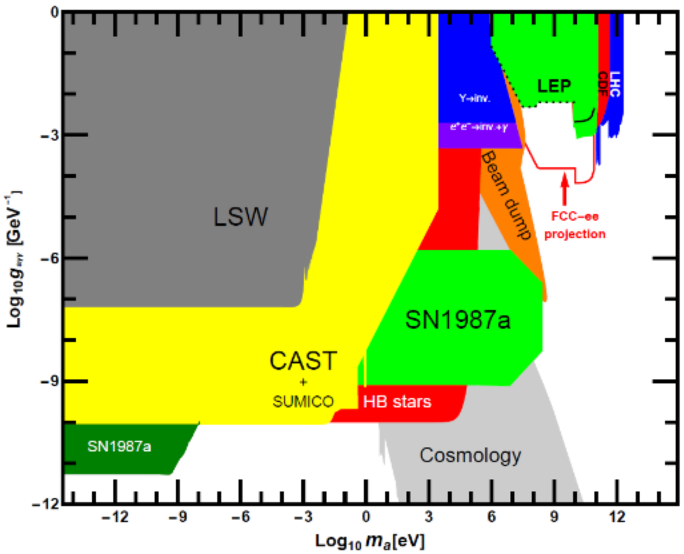
- Potential to be probed by cosmological, astrophysical and laboratory observations

Experiments

- Anomalous coupling to photons
  - Primakoff axion-photon conversion
  - Light-shining-through-walls
  - star cooling
  - …





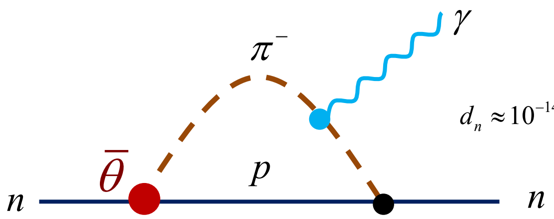


Jaeckel, Spannowski 2015

Examples

- QCD axion for CP conservation in QCD

Neutron EDM bound on $\bar{\theta} G \tilde{G}$



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

Peccei, Quinn 1977

Axion anomalously coupled to gluons

- Natural solution to the strong CP problem: $\bar{\theta} \propto \langle \phi \rangle = 0$
- Dark matter: misalignment, topological defects

Examples

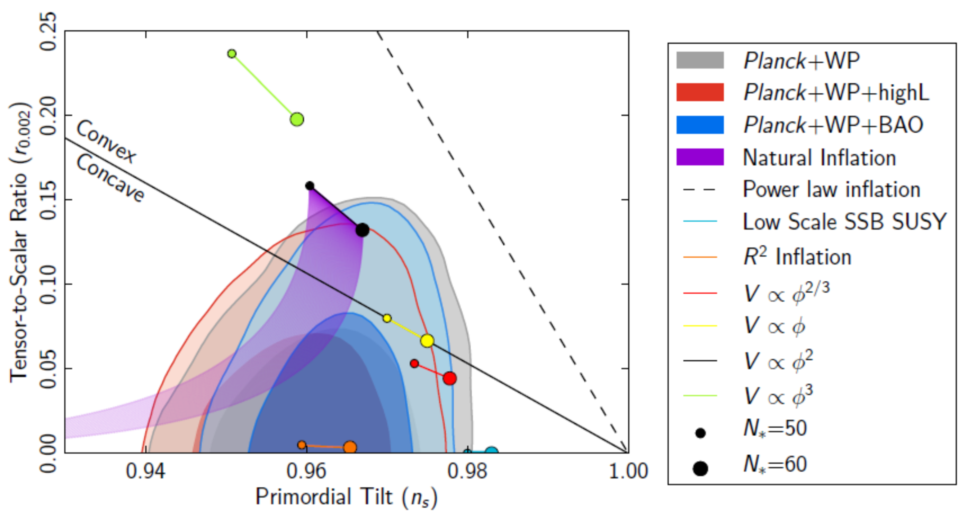
Freese, Frieman, Olinto 1990

- Natural inflation

Inflation: initial conditions for the Big Bang cosmology

Very flat potential from axion

$$V = \Lambda^4 \left(1 - \cos\left(\frac{\phi}{f}\right)\right) \text{ with } f \geq M_{Pl}$$



Portal interaction

- Axion portal ($\phi \equiv \phi + 2\pi f$)

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

- Another type of axion portal coupling

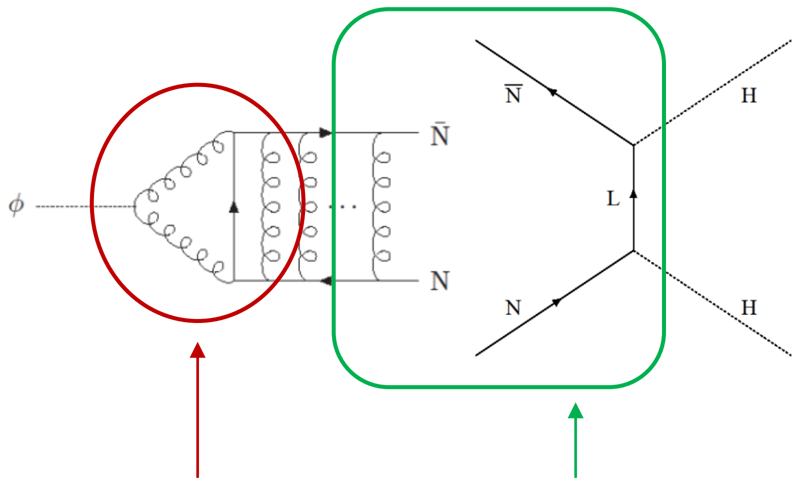
$$M^2\cos\left(\frac{\phi}{f}\right)|H|^2$$

- Feeble interaction with the SM via the Higgs field
- Much interest after *"Cosmological relaxation of the Higgs mass"*

Graham, Kaplan, Rajendran 2015

UV completion

- Model with perturbative shift symmetry
  - Hidden QCD
  - Vector-like lepton doublets $L + L^c$ and singlets $N + N^c$



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

Collider signatures: work in progress
KSJ, Seodong Shin, Jong-Chul Park, Sunghoon Jung

anomalous coupling to hidden gluons
→ mixing between ϕ and NN^c meson

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

Axion properties

- Scalar potential

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

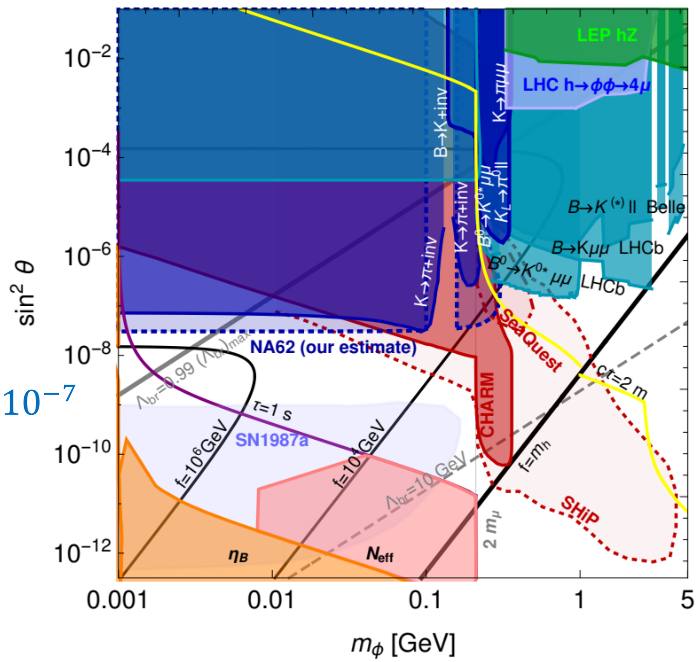
closed Higgs loop: $\Lambda^4 \geq \frac{1}{16\pi^2} M^2 \Lambda_{cut}^2$

- Axion properties depend on $\boldsymbol{f, M, \Lambda, \alpha}$

- Axion evolution is tied to EW symmetry breaking!

Experimental constraints

- Axion-Higgs mixing after EWSB for $\alpha \neq 0$
  - Stringent constraints for axion at sub-MeV to multi-GeV from rare K and B meson decays, and beam-dump experiments
- Further constraints if anomalously couples to SM gauge bosons



$$10^{-9} \leq \sin^2\theta \leq 3\times10^{-7}$$

$$\sin^2\theta \leq \frac{6\times10^{-7}}{\mathrm{Br}(\phi \to \mu^+\mu^-)}$$

Flacke, Frugiuele, Fuchs, Gupta, Perez 2016

Choi, Im 2016

Cosmological roles of axion

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

Axion-driven EW phase transition

for M above the weak scale

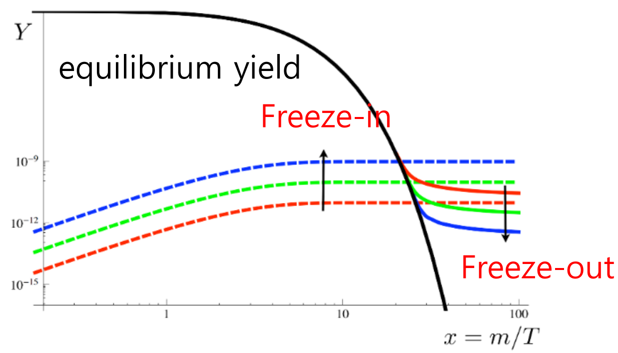
Cosmologically stable axion

for tiny α or huge f

Freeze-in dark matter

- Alternative to WIMP dark matter (freeze-out)
- Never in thermal equilibrium: feebly coupled to SM
  - Produced via thermal freeze-in

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



2-2 scattering, decay of thermal particles

- Relic abundance: $\Omega_\chi \propto \lambda^2 \, m_\chi$
  - 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

Axionic Higgs portal

KSJ, Im 1907.07383

- Coupled to the SM ONLY via Higgs portal

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

closing Higgs loops: $\alpha = 0$

- CP conserving minimum $\phi = 0$

  - No ALP-Higgs mixing

  - Stable axion due to accidental Z_2 symmetry $\phi \to -\phi$

  - Feebly coupled to SM thermal bath for large f

  $\to$ Natural framework for freeze-in DM

Axion dark matter

- Axion properties

  - Mass mainly from closed Higgs loops: $m_\phi \simeq \frac{\Lambda^2}{f}$

  - 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 thermal equilibrium for $\lambda_{h\phi} < 10^{-7}$

- If thermalized, it overcloses the universe in most of parameter space satisfying the bound on DM scattering with nuclei

Axion dark matter

- Freeze-in production via $h \to \phi\phi$ (dominant if open), and $hh \to \phi\phi$
  - Correct dark matter density

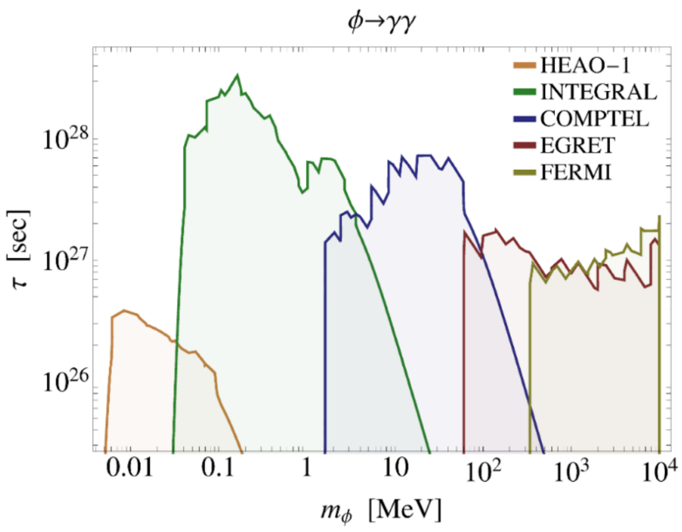
$$\lambda_{h\phi} \simeq 10^{-10} \times \left(\frac{m_\phi}{3\mathrm{MeV}}\right)^{-\frac{1}{2}} \text{ and } m_\phi \simeq 1\mathrm{MeV} \times \left(\frac{\Lambda}{10^3\mathrm{GeV}}\right)^{\frac{4}{5}}$$

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

- Coherent oscillations: negligible if $T_{\mathrm{osc}} \gg 10^6 \times m_\phi$

UV completion

- Non-perturbative Higgs portal via hidden QCD
  - Lepton doublets $L + L^c$ and singlets $N + N^c$
  - Generically, $\alpha \neq 0$
- Severe constraint on the lifetime (α) from gamma ray observations



Essig et al 2013

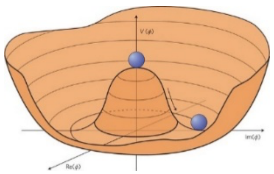
Suppression of $\alpha \neq 0$ effect

by $\frac{m_{susy}}{M_{Pl}}$ if invoked with SUSY

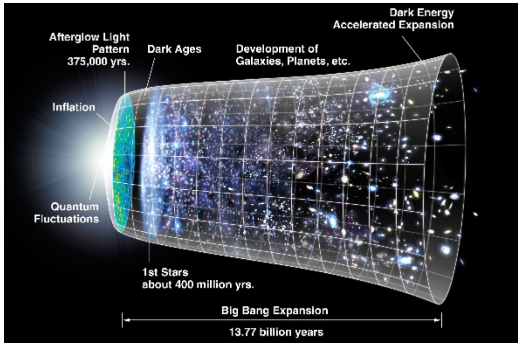
→ SUSY below 10TeV for $y \sim 1$

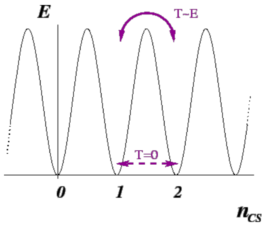
Electroweak phase transition

- Last period affecting baryon asymmetry



B+L violation by rapid EW sphaleron transition in symmetric phase





- Baryogenesis

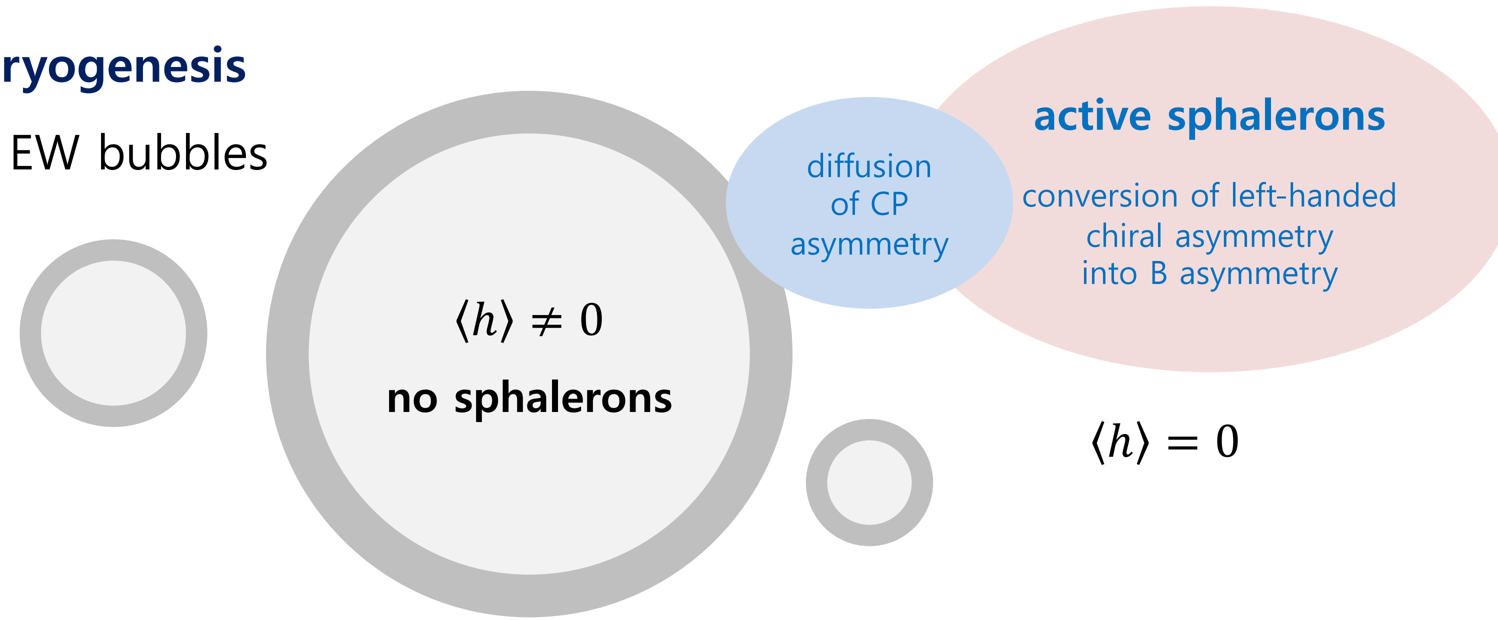
1) Nonzero B-L above EW scale: Leptogenesis, Affleck-Dine, …
2) B+L generation at EW scale and sphaleron decoupling

→ EW baryogenesis

Lots of works since 1985

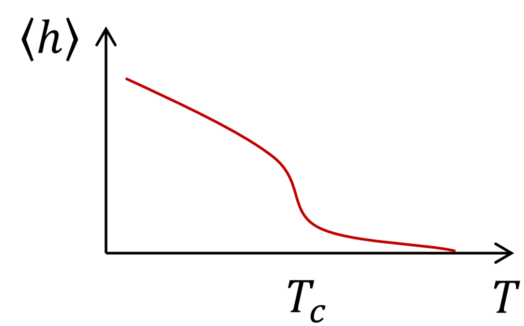
EW baryogenesis

- EW bubbles



- Requirements
  - Strong first-order phase transition to avoid washout

    SM: crossover if $m_h > 75$ GeV
  - Sufficient CP violation beyond SM



Conventional scenarios

- Strong first-order phase transition

  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. severe constraint from electron EDM: $|d_e| < 1.1\times 10^{-29} e\cdot\mathrm{cm}$

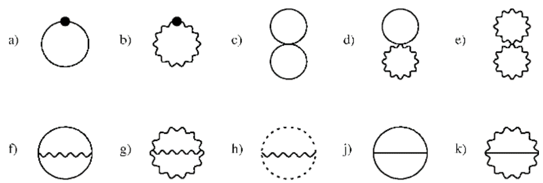
  ACME II 2018

Axionic Higgs portal

- Free energy: $V = V_0$+(thermal effect)

$$V_0 = \lambda|H|^4 + \left[\mu^2 - M^2\cos\left(\frac{\phi}{f}\right)\right]|H|^2 - \Lambda^4\cos\left(\frac{\phi}{f} + \alpha\right)$$

$$\Delta V_{\text{thermal}} = c_H T^2 |H|^2$$



- Free energy in terms of 3 positive parameters

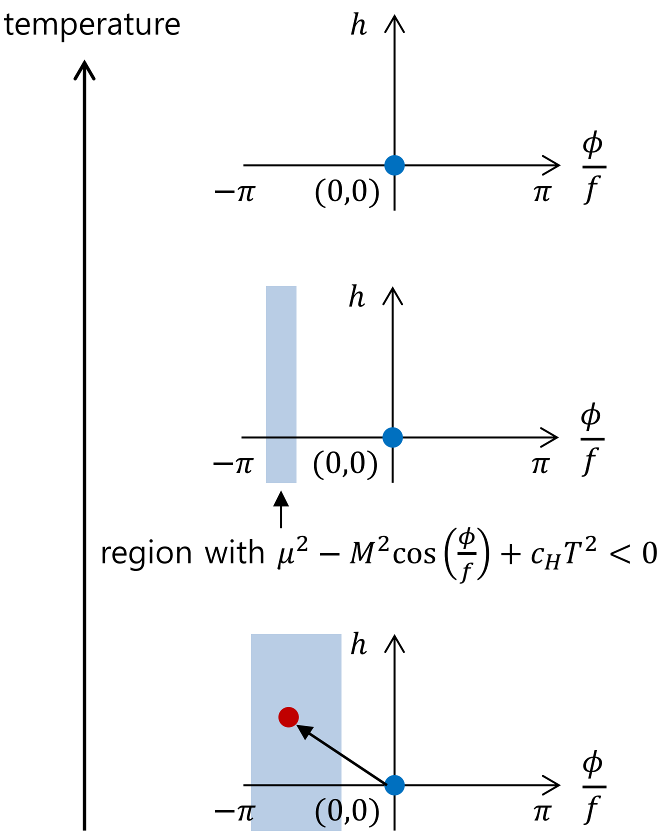
$$\alpha, \quad \epsilon \equiv \frac{\sqrt{\lambda}\Lambda^2}{M^2}, \quad r \equiv \frac{\Lambda^2}{\sqrt{\lambda}v_0^2}$$

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

EWPT in axionic Higgs portal

- For large f, tiny thermal and quantum corrections to V from axion
- Free energy $V = V(h, \phi/f)$: Insensitive to f
- Tunneling mainly along the light axion 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 in axionic Higgs portal



- only a symmetric minimum at $(\phi, h) = (0,0)$

- $\mu^2 - M^2\cos\left(\frac{\phi}{f}\right) + c_H T^2 > 0$ in whole range of ϕ

- minimum at $(\phi, h) = (0,0)$

- $\mu^2 - M^2\cos\left(\frac{\phi}{f}\right) + c_H T^2 < 0$ in finite range of ϕ

- another minimum at $\phi \neq 0$ and $h \neq 0$

- $\mu^2 - M^2\cos\left(\frac{\phi}{f}\right) + c_H T^2 < 0$ in finite but wider range of ϕ

- phase transition when EW minimum gets deeper

Approximate scaling behaviors

- Euclidean action of O(3) symmetric critical bubble

$$S_3 \propto f^3$$

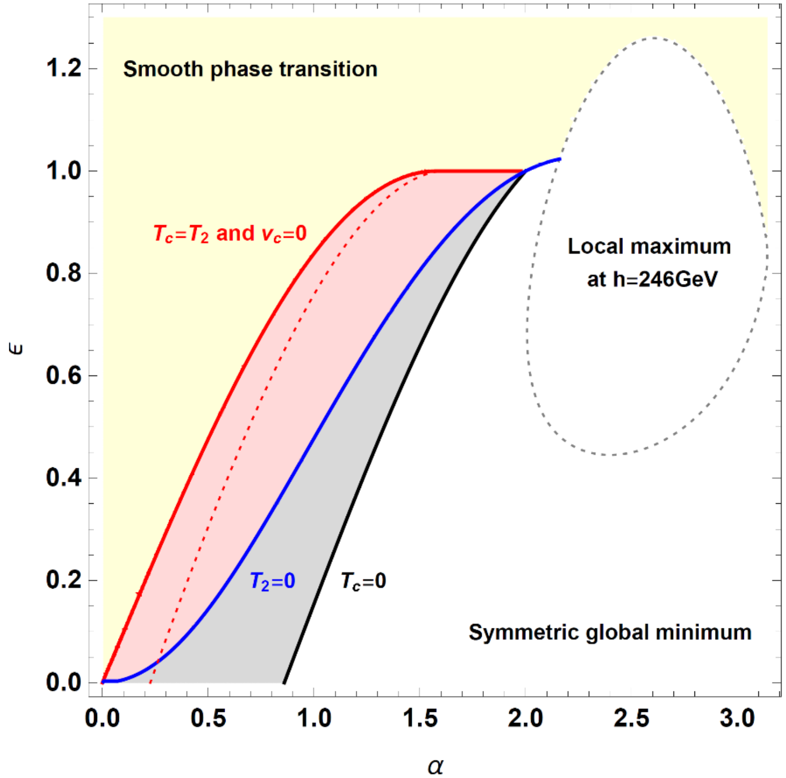
$\Rightarrow$ Bubble radius $\propto f$, and T_n close to T_2

c.f. conventional models: thin wall, T_n close to T_c

- Relatively smooth phase transition (no substantial expansion of bubbles), but rapid ALP evolution

EW phase transition

- Case with $r \equiv \frac{\Lambda^2}{\sqrt{\lambda} v_0^2} = 1.2$



- 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

Implications

- Delayed EW phase transition

  - Late-time entropy production to dilute preexisting relics

    (e.g. dark matter)

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

Temperature after phase transition

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

- Strong first order phase transition

  - EW baryogenesis

Axionic EW baryogenesis

- Strong first order phase transition driven by axion via

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

- New direction in EWBG
  - Free from EDM and LHC constraints for $f \gg$TeV
  - Axion searches to reveal the connection between EW phase transition and baryogenesis

EW baryogenesis

- CP violation depending on the bubble wall profile

1) Axion-dependent top quark Yukawa

$$\left(y_t + x_t e^{i\phi/f}\right) h t_L t_R$$

axion variation along the wall → B number chemical potential

2) Anomalous axion coupling to EW gauge bosons

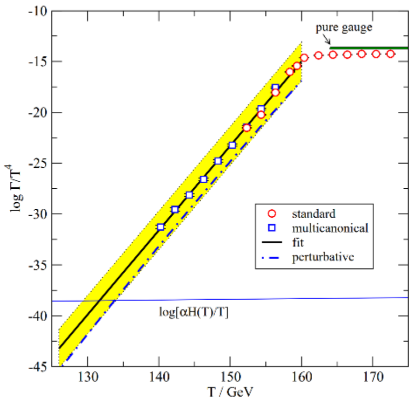
$$\frac{1}{16\pi^2}\frac{\phi}{f} W_{\mu\nu}\widetilde{W}^{\mu\nu}$$

$\frac{d\phi}{dt}$ → B number chemical potential

EW baryogenesis

- Condition for EWBG

time for axion settle-down after tunneling $\dfrac{1}{m_\phi}$ $<$ time for baryon asymmetry generation $\dfrac{1}{\Gamma_{\rm sph}}$ $<$ duration of EW phase transition $\dfrac{dS_3}{dt}$

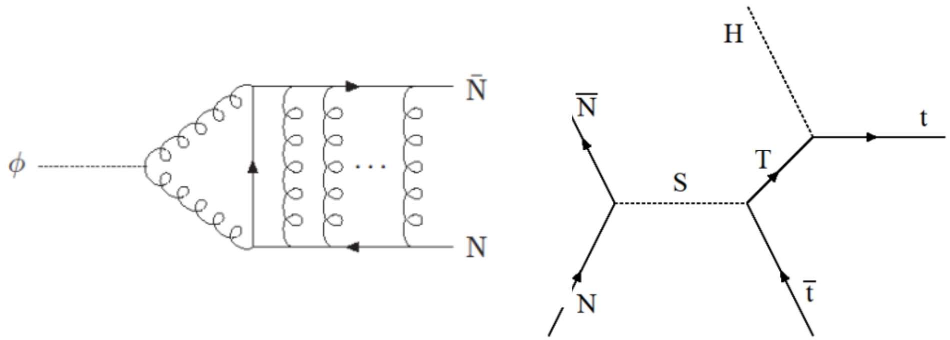


D'Onofrio, Rummukainen, Tranberg 2014

1) Non-local EWBG KSJ, Jung, Shin 1806.02591

- CP violation from axion-dependent top quark mass

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

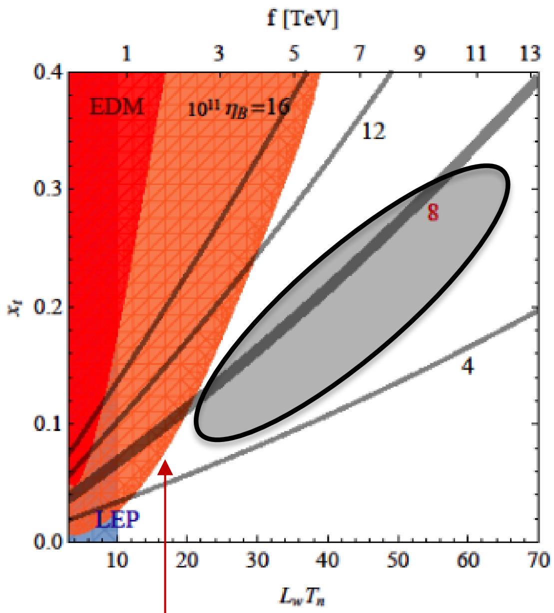


- Baryon asymmetry
  - CP violation x_t, wall width L_w, wall velocity v_w
  - Sizable diffusion effect for $L_w T_n \leq 100 \rightarrow$ upper bound on f

1) Non-local EWBG

- Correct baryon asymmetry for $3\text{TeV} \leq f \leq 10\text{TeV}$

(axion mass: GeV to 20 GeV)



ACME II: about 10 times stronger than ACME I

2) Local EWBG KSJ, Jung, Shin 1811.03294

- CP violation from axion-dependent EW Θ-term

$$\frac{\phi}{f} W\widetilde{W} \rightarrow \frac{d\phi}{dt} = \text{chemical potential for baryon number}$$

- Simultaneous B and CP violations across thick walls

  - B generation through EW anomaly

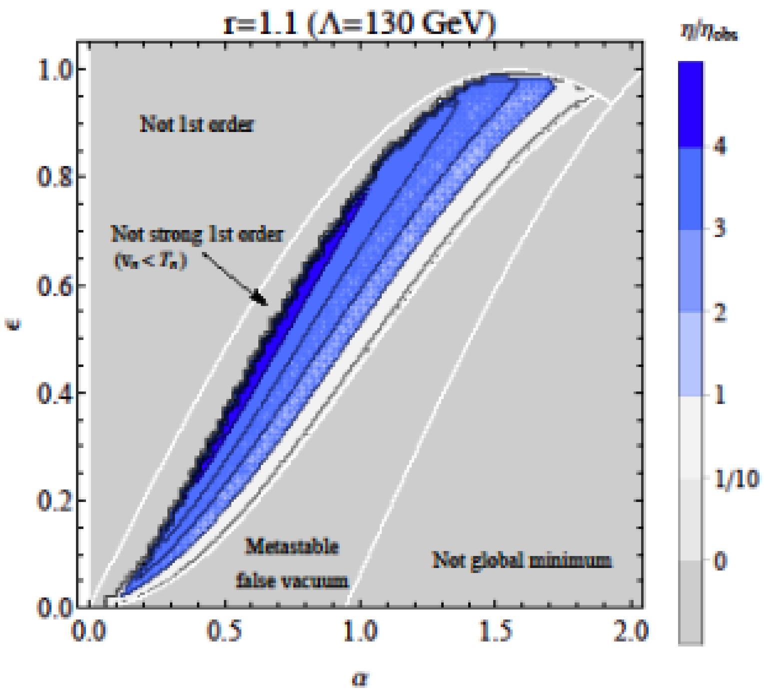
$$\frac{dn_B}{dt} = \frac{3}{2}\frac{\Gamma_{\rm sph}}{T}\frac{d}{dt}\frac{\phi}{f} - \underbrace{\frac{39}{4}\frac{\Gamma_{\rm sph}}{T^3}n_B}_{\text{sphaleron-induced washout}}$$

  - Wash-out: need to suppress axion oscillations quickly via thermal dissipation (axion-Higgs mixing)

2) Local EWBG

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

(axion mass: MeV to GeV)



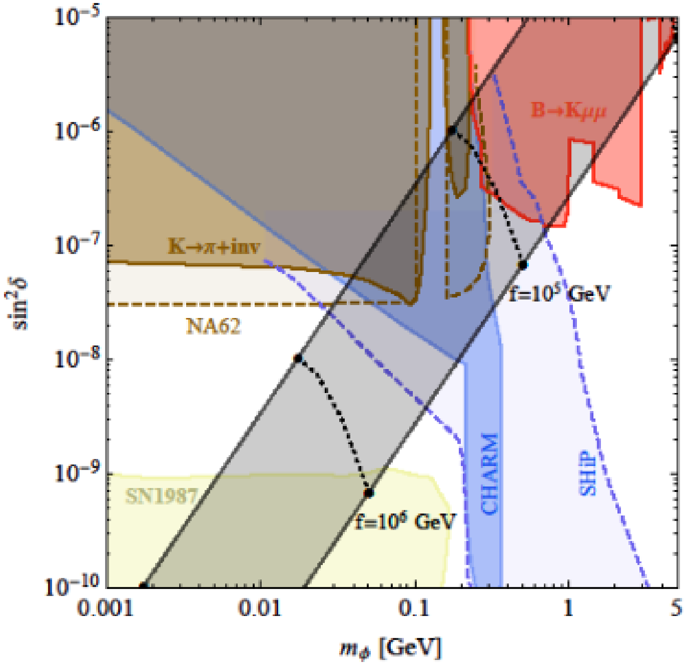
$f = 10^6$ GeV

How to probe axion-driven EWBG

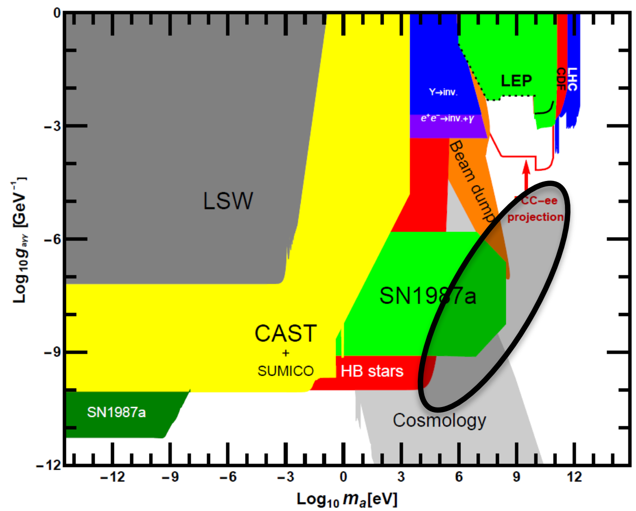
- Axion at MeV-GeV (local) or GeV-20GeV (non-local)

  - window without strong theoretical interests so far

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



Jaeckel, Spannowski 2015



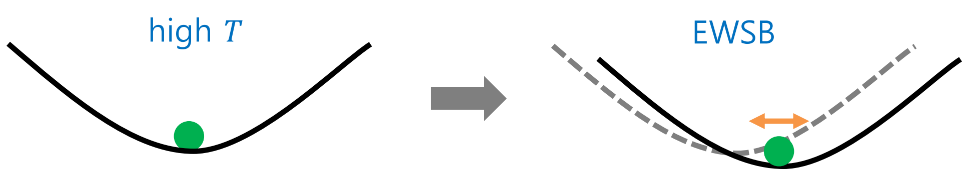
anomalous ALP couplings to gauge bosons

Axionic cogenesis KSJ, Sang Hui Im 2012.xxxxx

- Axionic Higgs portal with $M \ll m_Z$

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

axion evolution is triggered by EW symmetry breaking



- CP violation from anomalous coupling to EW gauge bosons

$$\frac{1}{16\pi^2}\frac{\phi}{f}W_{\mu\nu}\widetilde{W}^{\mu\nu}$$

axion evolution $\frac{d}{dt}\frac{\phi}{f}$: chemical potential of baryon number

Axionic cogenesis

- Spontaneous baryogenesis via slow shift of potential minimum $\frac{\phi}{F}$

  - Correct baryon asymmetry for $F > 10^7 \times f$

  - Clockwork mechanism

f

$F \sim e^N f$

Choi, Im 2016

Kaplan, Rattazzi, 2016

collective rotations of N axions

- Dark matter from axion coherent oscillations

  - Cosmologically stable due to tiny mass

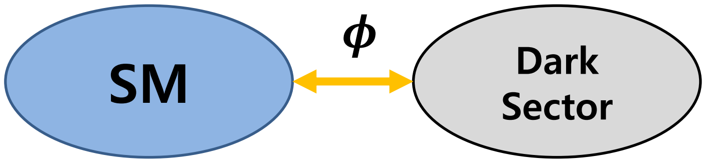
  - Photophobic axion to avoid astrophysical constraints

    ($f < 10^7$GeV for sufficient thermal dissipation)

Axion coupling to dark sector

- Axion-driven EWBG with CP violation from
  - axion-dependent top quark Yukawa
  - anomalous axion coupling to EW gauge bosons

- Dark sector
  - Dark photon dark matter: $\frac{\phi}{f}\tilde{F}'_{\mu\nu}F'^{\mu\nu}$
  - Fermionic dark matter: $m_\chi e^{ic\frac{\phi}{f}}\bar{\chi}\chi$



Any role in dark matter production?

Axion

- Feebly interacting light particle with properties controlled by perturbative shift symmetry
- Strong CP problem, dark matter, inflation, …

Axionic Higgs portal

- Electroweak hierarchy: cosmological relaxation
- Matter-antimatter asymmetry via EW baryogenesis
- Dark matter via freeze-in or misalignment

Thank you