# New physics searches via Axion-like particles

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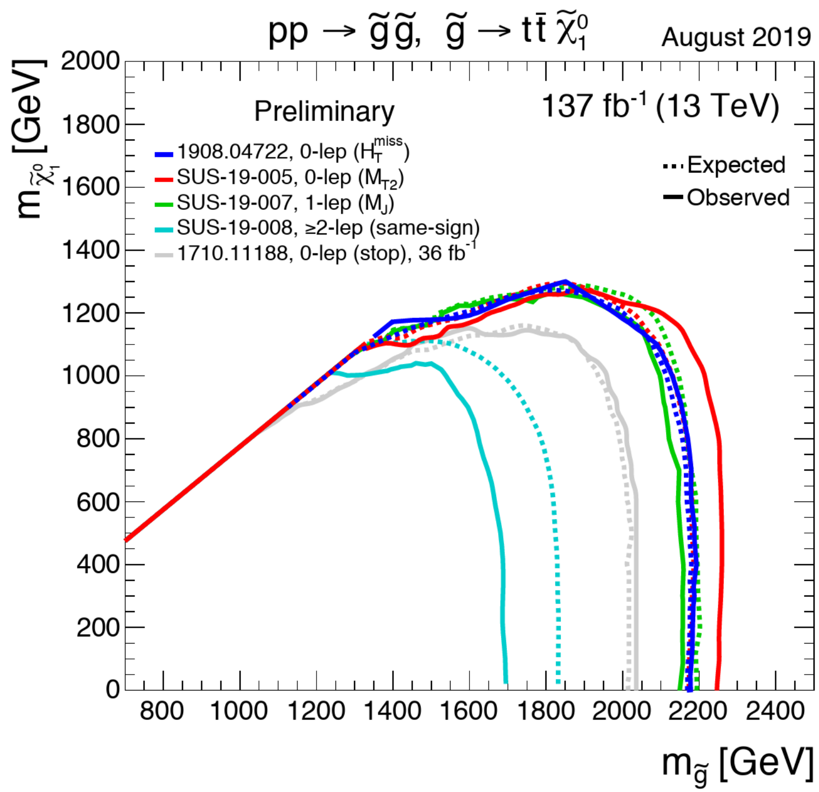
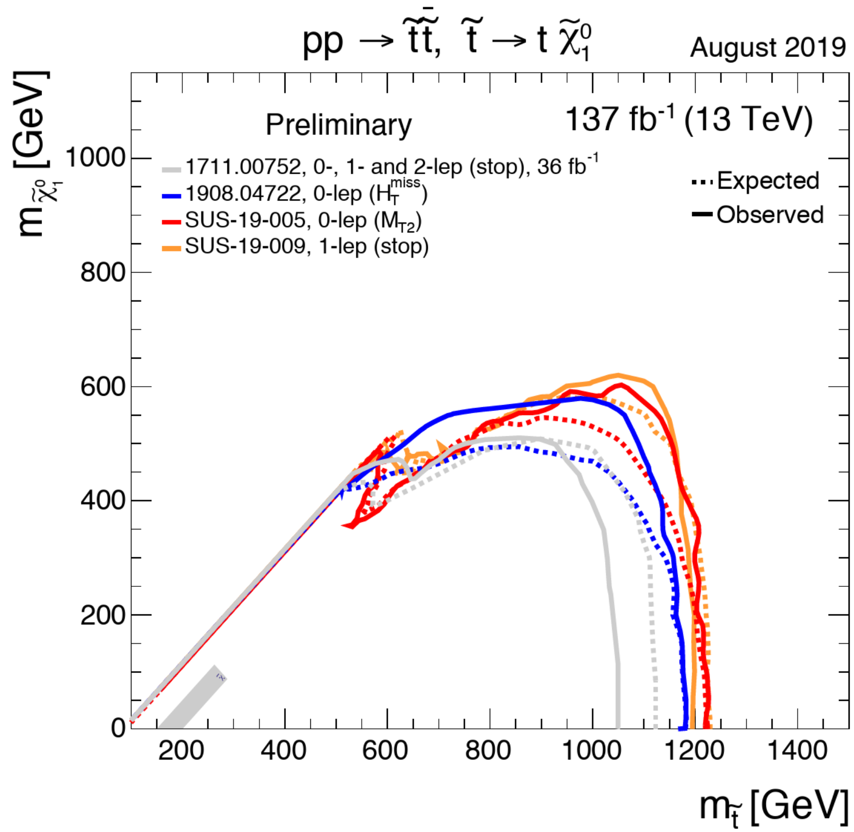
# Outline

- ALPs as a portal to new physics
  : Motivation and structure
- Bottom-up approach : SM problems
- Top-down approach : UV complete theories
- Conclusion

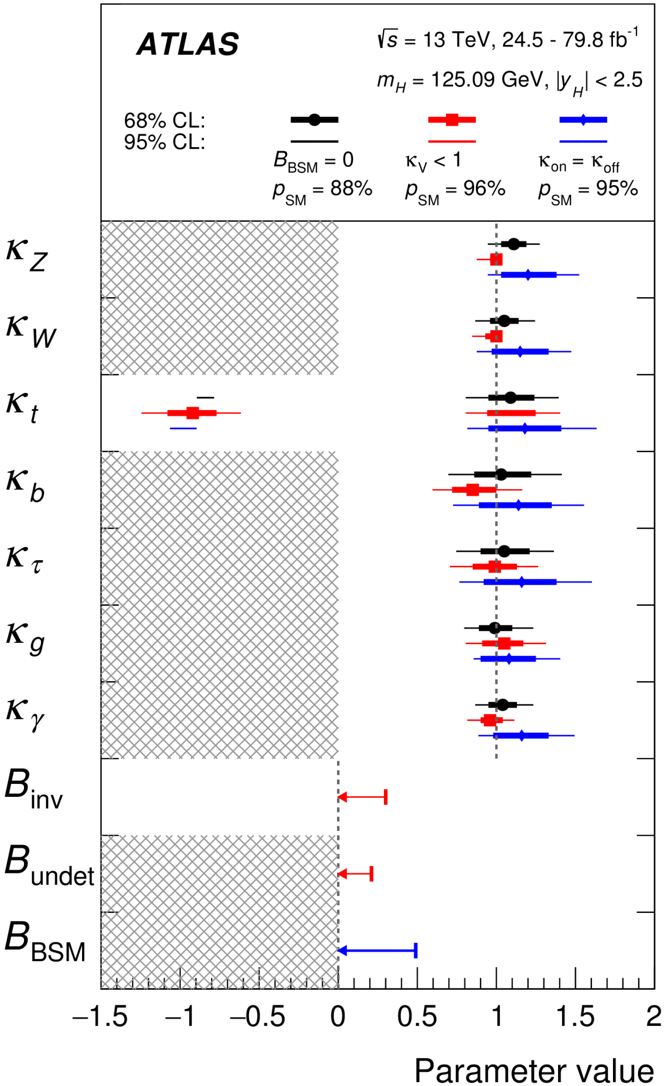
# LHC up to 2019




: New physics scale seems higher than conventional expectation.

# Higgs couplings

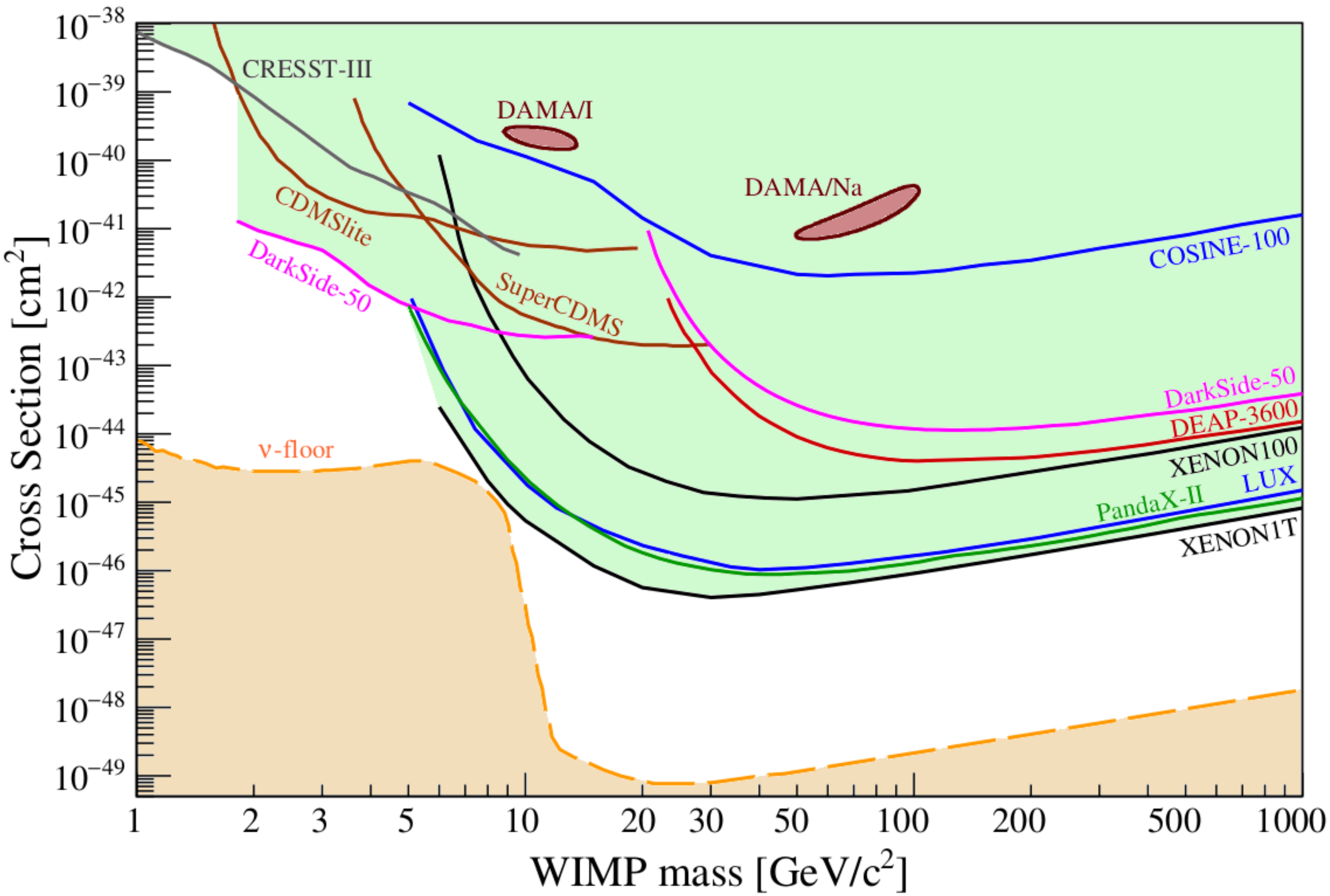



: Good agreement with the SM predictions

: Allow only small mixing with the SM Higgs boson and small radiative corrections to the couplings

# WIMP paradigm being challenged

M. Schumann '19



A new physics sector seems coupled to the SM rather weakly.

A good physics candidate for naturally small couplings while solving the SM problems?

# An example : QCD axion

Solves the strong CP problem of the SM :

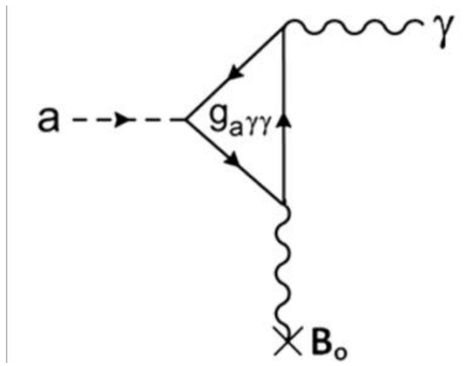
$$\theta_{QCD} < 10^{-10}$$

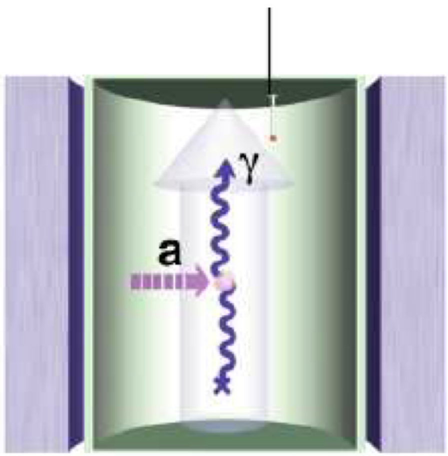
Dark matter problem as well :

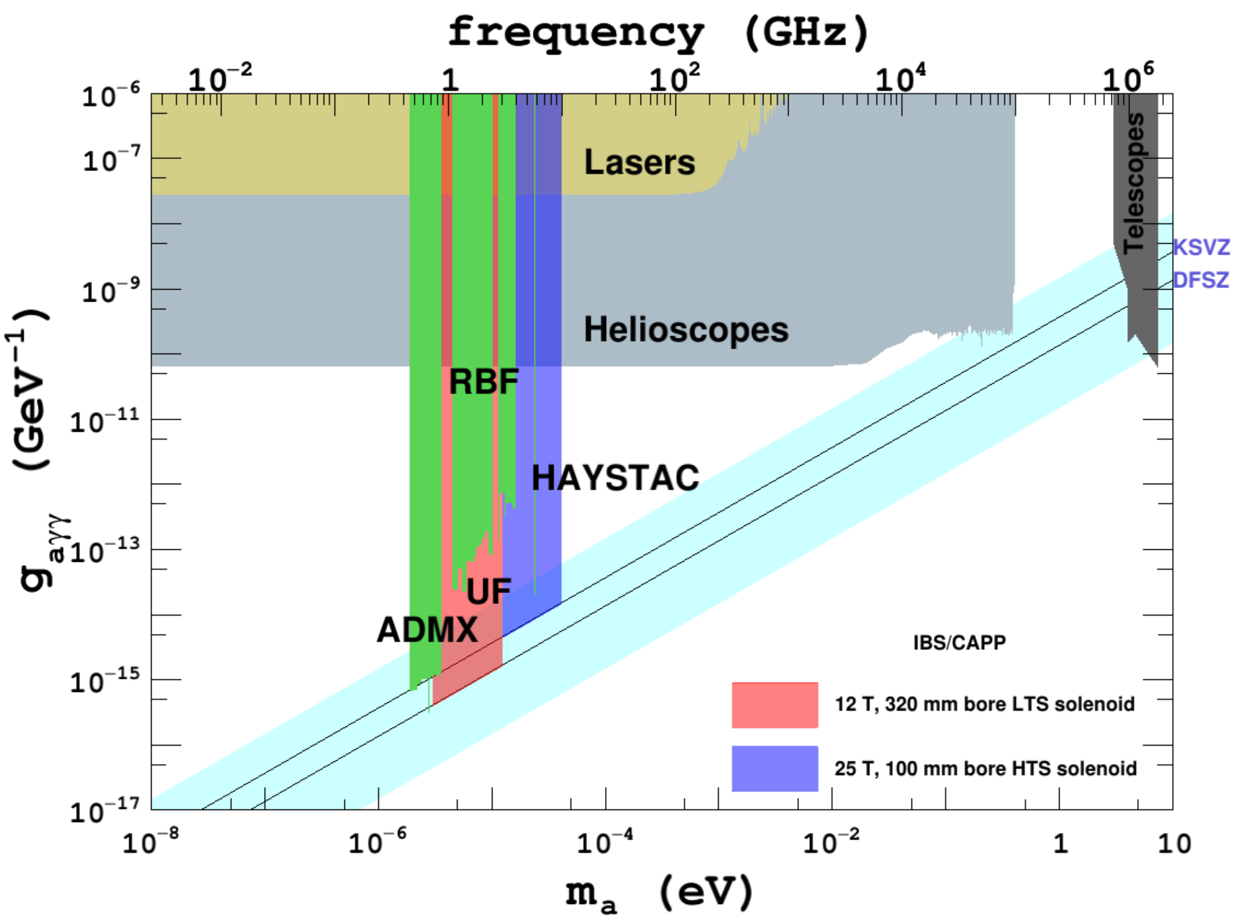
$$f_a \approx 10^9 \ \text{or} \ 10^{12} \ \text{GeV}$$

$$\frac{\partial_\mu a}{f_a}\bar{\psi}\gamma^\mu\psi + \frac{1}{32\pi^2}\frac{a}{f_a}G_{\mu\nu}\widetilde{G}^{\mu\nu}$$ : tiny couplings to the SM

# Still within the experimental reach




with targeted couplings and mass

# Axion-like particle (ALP)

i) Perturbative (approximate) shift symmetry : $a \;\rightarrow\; a + c$

ii) Discrete gauge symmetry : $a \;\rightarrow\; a + 2\pi n f$ ( $\frac{a}{f} = \theta$ ; angle)

$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)^2 + \frac{\partial_\mu a}{f} J^\mu + \frac{1}{32\pi^2}\frac{a}{f} G_{\mu\nu}\widetilde{G}^{\mu\nu}$$

Natural size of ALP couplings is determined by $f$.

# ALP mass

$$\frac{1}{32\pi^2}\frac{a}{f}G_H\widetilde{G}_H \quad \Rightarrow \quad V(a) = \Lambda_{HC}^4 \cos\left(\frac{a}{f}\right)$$

$$m_a = \frac{\Lambda_{HC}^2}{f}$$

$m_a$ and $f$ are free parameters with (technical) naturalness.
What values would we look at experimentally?

# ALP effective interactions to the SM

high energy non-perturbative effect

$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)^2 - V(e^{ia/f}, \psi, H)$$

$$\underbrace{+ \frac{\partial_\mu a}{f}\left(\sum_\psi c_\psi \bar{\psi}\gamma^\mu \psi + c_H H^\dagger i \overleftrightarrow{D}^\mu H\right) + \frac{1}{32\pi^2}\frac{a}{f}\sum_F c_F F_{\mu\nu}\widetilde{F}^{\mu\nu}}_{\text{Perturbative shift symmetry conserving interactions}}$$

Which interactions are we interested in?

# Bottom-up approach

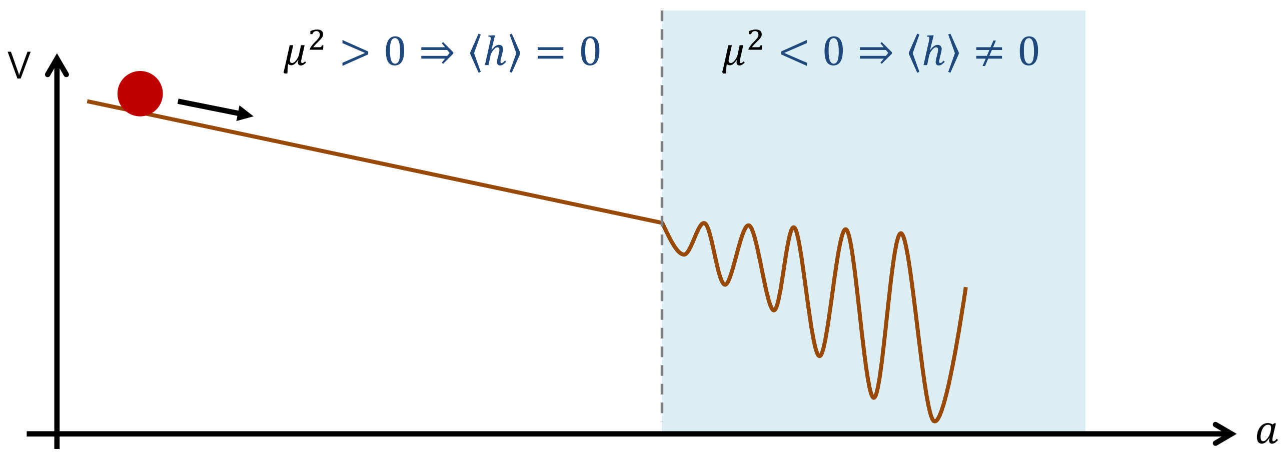
Similarly to the QCD-axion, ALPs may be involved in solving SM problems.

i) Weak scale hierarchy
ii) Dark Matter
iii) Baryogenesis

# Weak scale hierarchy : Relaxion

Graham, Kaplan, Rajendran '15

- Promoting the Higgs mass to a dynamical field (ALP) : $\mu^2(a)|H|^2$
- Cosmological ALP evolution to select the Higgs mass




- $a$ slow-rolls while scanning $\mu^2$ from $\Lambda_{cut}^2$ to negative, and stops by barriers formed by EWSB.

$$\mu^2(a)|H|^2 \ \subset \ V(e^{ia/f}, \psi, H)$$

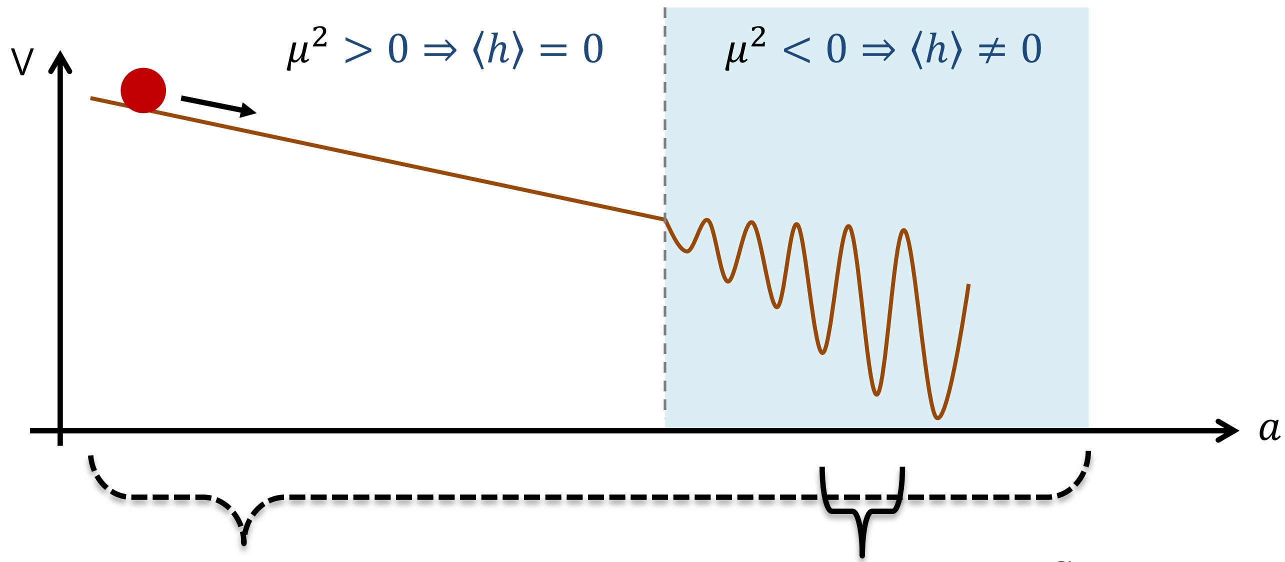
: shift symmetry breaking interaction to the SM

How do we obtain it?

$$\frac{|H|^2}{\Lambda} N_H N_H^c + \frac{1}{32\pi^2}\frac{a}{f} G_H \widetilde{G}_H \quad \Rightarrow \quad \frac{|H|^2}{\Lambda}\Lambda_{HC}^3 \cos\left(\frac{a}{f}\right)$$

high scale confinement

# Trouble : ALP scale hierarchy




Long periodic $\frac{a}{F} G_H \tilde{G}_H$

Short periodic $\frac{a}{f} G_H{}' \tilde{G}_H{}'$

To stop relaxion with the weak scale Higgs VEV

$$\frac{F}{f} \approx \frac{\Lambda_{cut}^4}{v^4} > 10^4$$

Discrete gauge symmetry : $a \rightarrow a + 2\pi n f$

$$\frac{a}{F} G_H \tilde{G}_H + \frac{a}{f} G_H' \tilde{G}_H' \qquad F = f \times \text{integer}$$

## Clockwork scheme

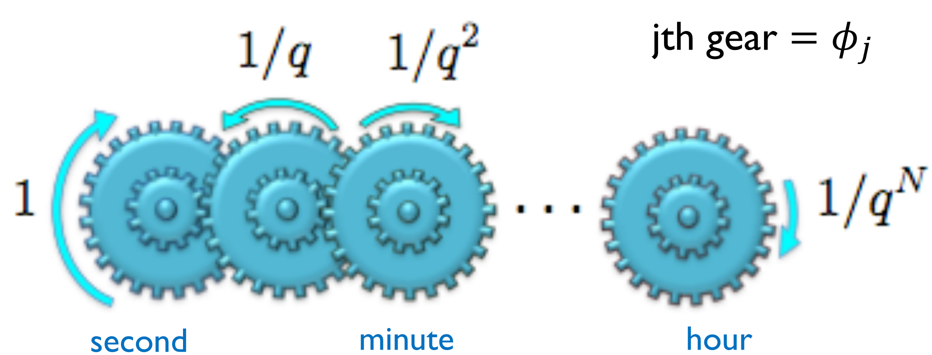
Choi, SHI '15
Kaplan, Rattazzi '15

$$V(\phi_i) = \sum_{i=0}^{N} \frac{1}{2} m_i^2 \left(\phi_i - q\phi_{i+1}\right)^2$$

$$F = f \times q^N$$

$N$ : Number of ALPs

jth gear $= \phi_j$



# Relaxion interactions to the SM

$$M^2|H|^2\cos\left(\frac{a}{f}\right)+c_\gamma\frac{e^2}{16\pi^2}\frac{a}{f}F\widetilde{F}$$

$$\langle a\rangle\sim f$$

**Relaxion-Higgs mixing**

Choi, SHI '16
Flacke, Frugiuele, Fuchs, Gupta, Perez '16

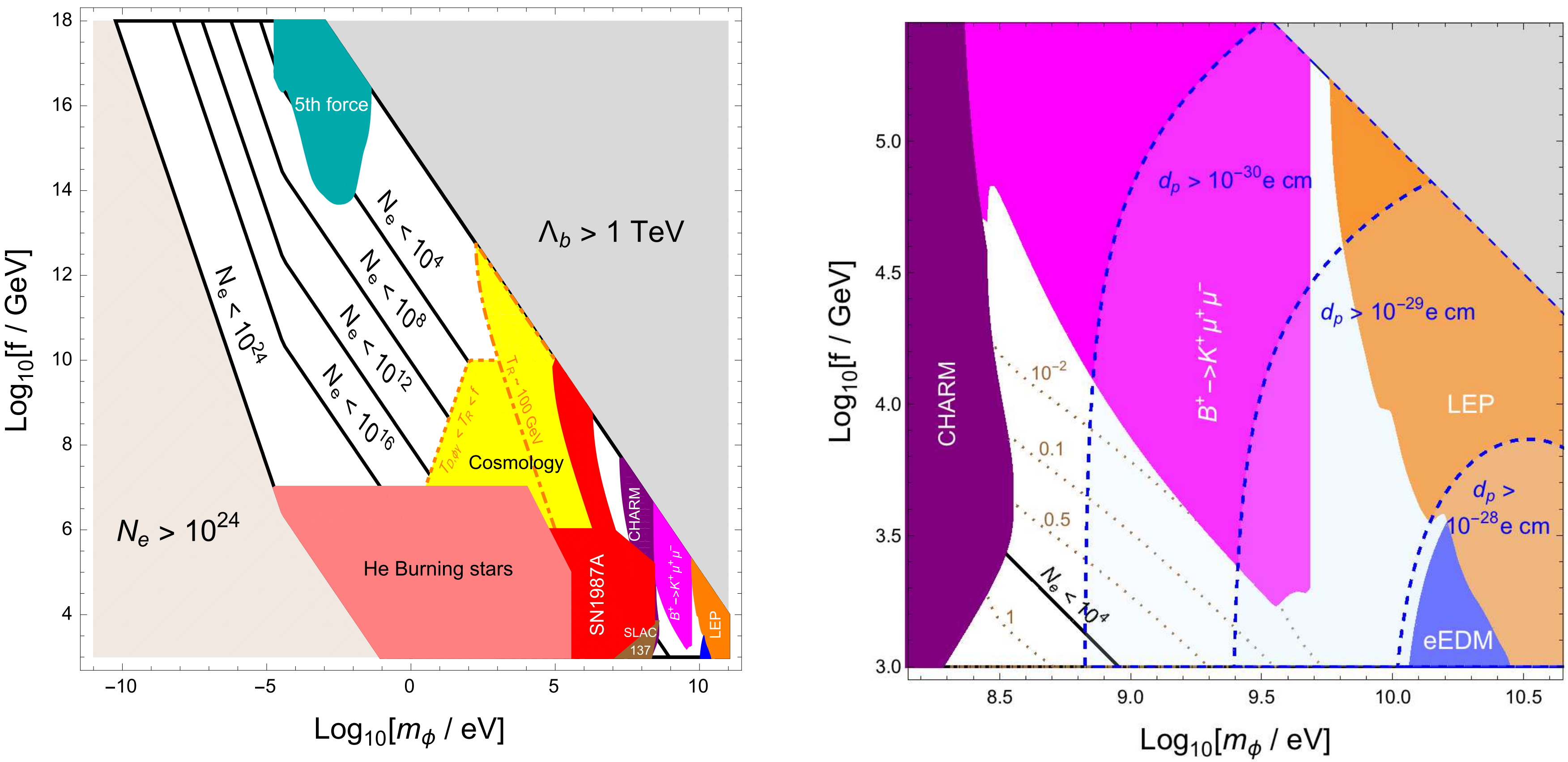
**Relaxion-photon coupling**

Choi, SHI '16

Simultaneous presence of them breaks CP.

# What should we look for?

Choi, SHI ‘16

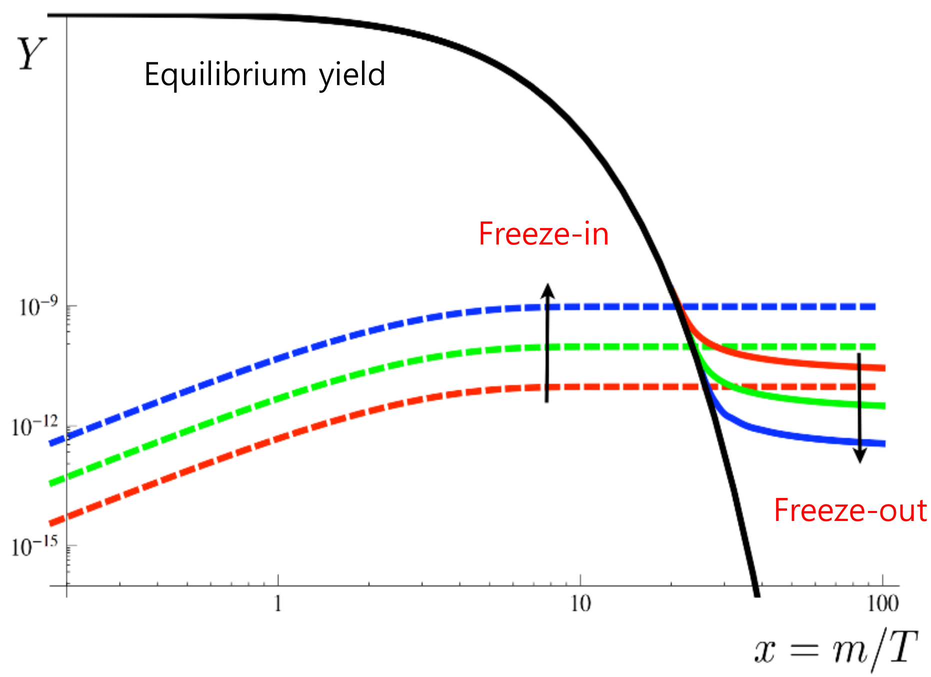


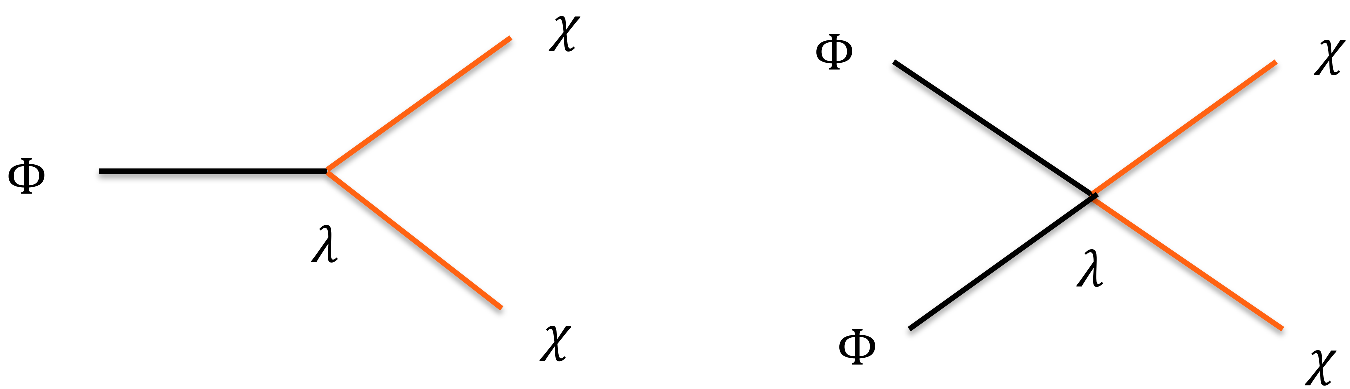

- Beam dump (SHiP), Proton EDM
- HL-LHC, CLIC [Frugiele, Fuchs, Perez, Schlaffer ’18]

# Dark Matter : Freeze-in paradigm

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

- Alternative to freeze-out
- Never in thermal equilibrium: feebly coupled to SM
- Produced via decay or annihilation of particles in thermal bath






$\Phi$ : particle in thermal bath

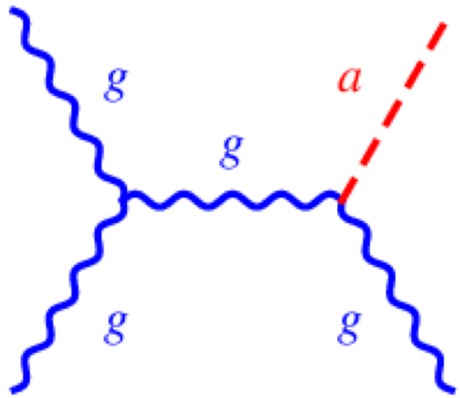
$\chi$ : dark matter

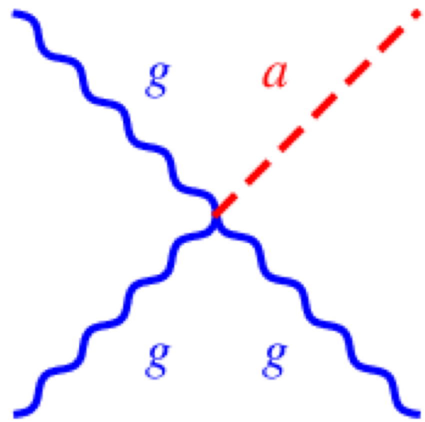
$$\Omega_\chi \propto m_\chi \frac{\lambda^2}{m_\Phi} \quad , \quad \lambda^2$$

- Observed DM abundance if $\lambda \sim 10^{-12}$ for $m_\chi \sim m_\Phi$
- Need an explanation for $\lambda \ll 1$!

# QCD-axion freeze-in production

Graf, Steffen '10
Bae, Choi, SHI '11




$$\frac{a}{f_a} G\widetilde{G} \quad \Rightarrow \quad Y_a \propto \frac{M_{\rm Pl} T_R}{f_a^2}$$

QCD-axion is cosmologically stable due to its small mass (meV~$\mu$eV) but cannot be freeze-in DM because it shall be hot.

# Freeze-in ALP dark matter

SHI, Jeong '19

Cold DM with $m_a > 100$ keV while cosmologically stable

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

Suppose that this is an only operator that breaks ALP shift symmetry.

Radiative correction

$$M^2 \cos\left(\frac{a}{f}\right)|H|^2 + \frac{1}{16\pi^2} M^2 \Lambda_{\rm cut}^2 \cos\left(\frac{a}{f}\right)$$

No phase difference

$$V = -M^2 \cos\left(\frac{a}{f}\right)|H|^2 - \frac{1}{16\pi^2} M^2 \Lambda_{\rm cut}^2 \cos\left(\frac{a}{f}\right)$$

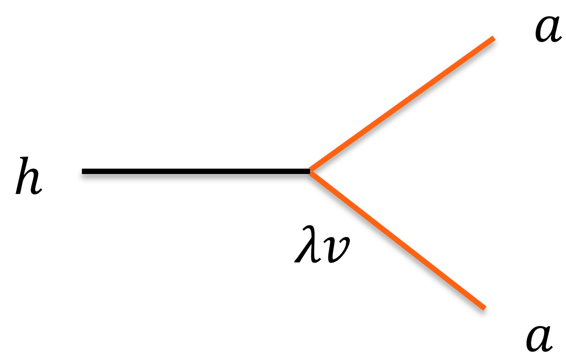
ALP is stabilized at $a = 0$. ⇨ The vacuum preserves $Z_2$ symmetry : $a \to -a$. So ALP does not decay.

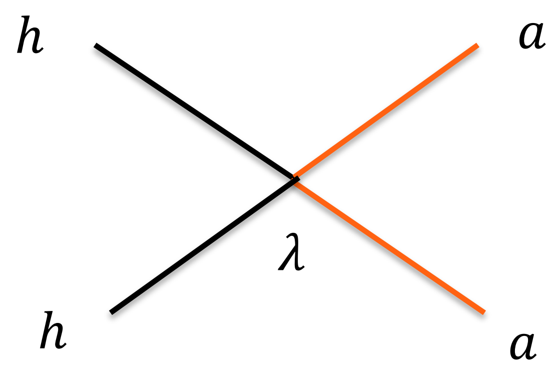
Around the vacuum,

$$V = \frac{1}{2}\lambda |H|^2 a^2 + \frac{1}{2} m_a^2 a^2 + \cdots$$

where $\lambda = \left(\frac{M}{f}\right)^2, \quad m_a \approx \frac{\sqrt{\lambda_{ha}}}{4\pi}\Lambda_{\rm cut}$

: naturally small $\lambda$ while having large enough mass !




Fixing $\lambda$ to obtain the correct relic density,

$$m_a \approx 1\,\mathrm{MeV}\left(\frac{\Lambda_{\mathrm{cut}}}{1\,\mathrm{TeV}}\right)^{4/5}$$

$$f \approx 10^8\,\mathrm{GeV}\left(\frac{M}{1\,\mathrm{TeV}}\right)\left(\frac{\Lambda_{\mathrm{cut}}}{1\,\mathrm{TeV}}\right)^{1/5}$$

# Experimental probe?

Unfortunately very challenging as much as other freeze-in models

$$V = \frac{1}{2}\lambda|H|^2 a^2 + \frac{1}{2}m_a^2 a^2 + \cdots \qquad \lambda < 10^{-10}$$

For a light ALP around MeV, there should be a new degree of freedom around TeV which couples to the Higgs.

$$m_a \approx 1\,\mathrm{MeV}\left(\frac{\Lambda_{\rm cut}}{1\,\mathrm{TeV}}\right)^{4/5}$$

Hidden-color confinement $\Lambda_{cut} = \Lambda_{HC}$

$$M^2 \cos\left(\frac{a}{f}\right)|H|^2 \quad \Longleftarrow \quad \frac{|H|^2}{\Lambda} N_H N_H^c + \frac{1}{32\pi^2}\frac{a}{f} G_H \widetilde{G}_H$$

$$H L_H N_H^c + H^\dagger L_H^c N_H + m_L L_H L_H^c$$

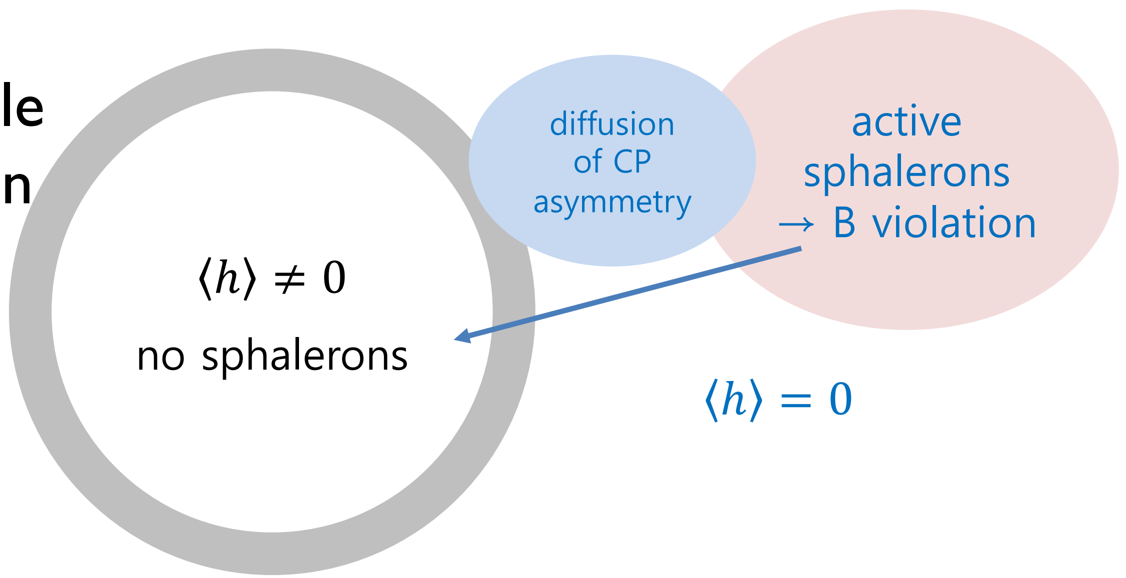
$(\Lambda = m_L)$

Higgs can sizably mix with hidden-color $\eta'$ meson of mass $\Lambda_{cut}$.

# Electroweak Baryogenesis

Appealing framework for experimental testability

EW bubble nucleation

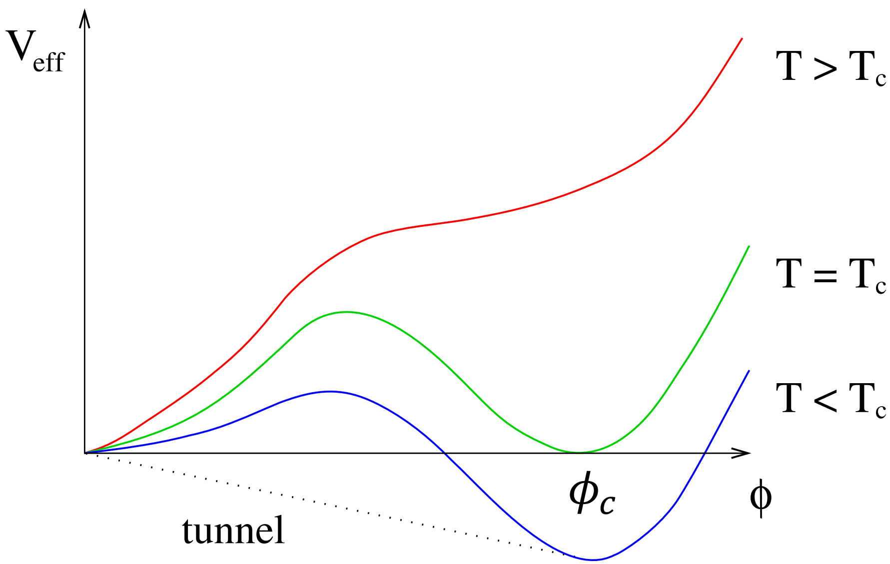



i) B violation : sphalerons ✓
ii) C & CP violation : CKM not enough ✗
iii) Out of equilibrium : strongly first-order EWPT ✗

⇨ NP

## Finite temperature Higgs potential

$$V_{\rm eff}(\phi, T) \simeq D(T^2 - T_0^2)\phi^2 - \boxed{ET\phi^3} + \frac{\bar{\lambda}}{4}\phi^4$$




$$\frac{\phi_{\rm c}}{T_{\rm c}} = \frac{2E}{\bar{\lambda}} > 1$$

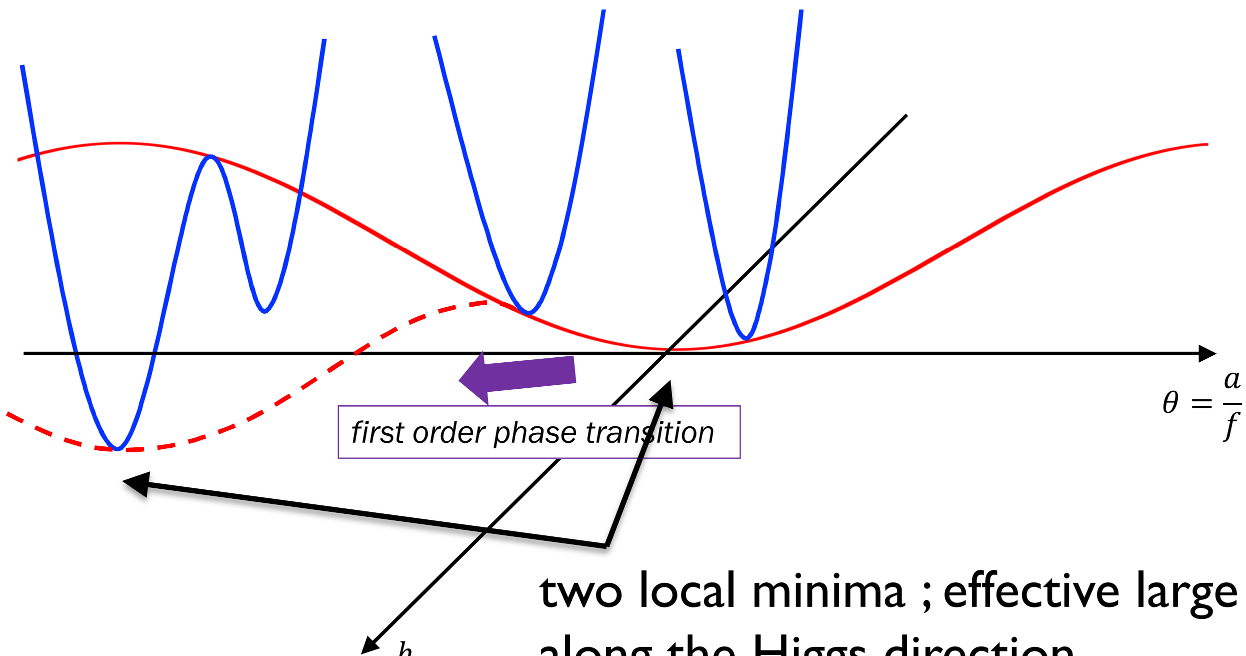
strongly first-order EWPT

- A large cubic term is needed.
- It makes two local minima in the Higgs potential.

# Axionic electroweak baryogenesis

K S Jeong, T H Jung, C S Shin '18

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




two local minima ; effective large cubic term along the Higgs direction

Picture borrowed by C S Shin's talk at CERN

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

The potential only depends on $\theta = \frac{a}{f}$, insensitive to $f$.

→ Weak coupling limit $f \gg \mathrm{v}$.

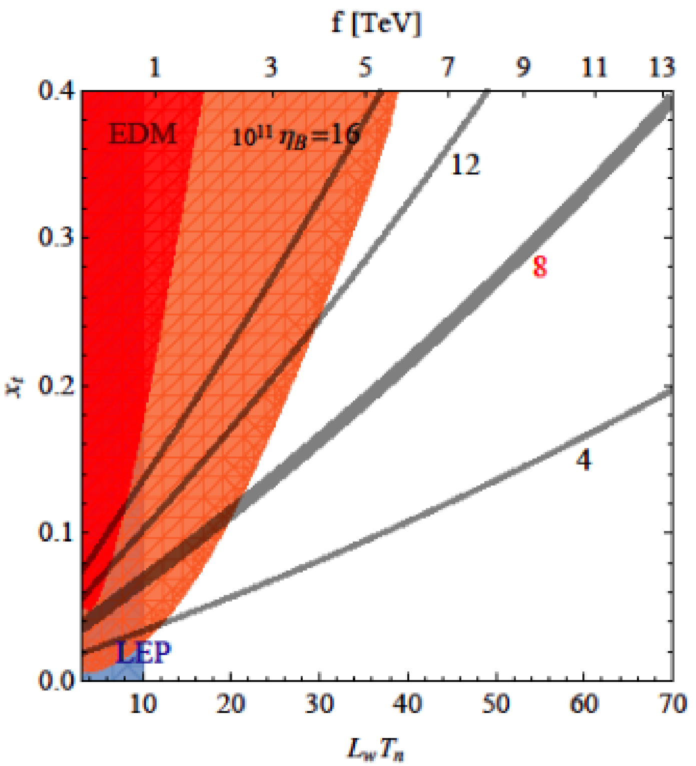
→ Free from EDM and LHC constraints while allowing testability.

CP violation from top Yukawa : $Y_t = y_t + x_t e^{i\phi/f}$

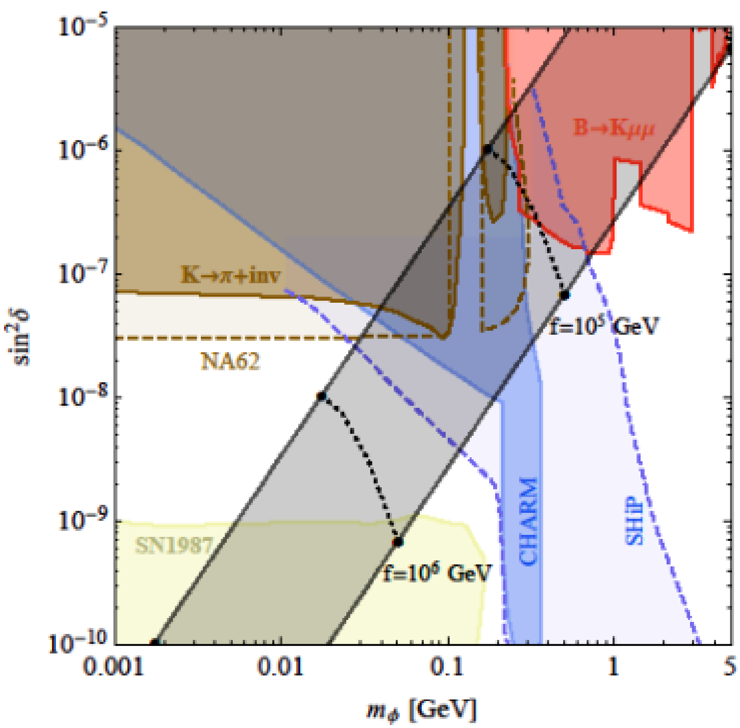
For the correct baryon asymmetry, $3\ \mathrm{TeV} \leq f \leq 10\ \mathrm{TeV}$

$\mathrm{GeV} \leq m_a \leq 20\ \mathrm{GeV}$

Electron EDM




Beam dump



# Spontaneous EWBG with 2nd order EWPT

SHI, K.S. Jeong under progress

$$\theta_{\rm EW} W_L \widetilde{W}_L = \partial_\mu \theta_{\rm EW} J_B^\mu = \underbrace{\dot{\theta}_{\rm EW} \left(n_B - n_{\bar{B}}\right)}$$

$\dot{\theta}_{\rm EW} \neq 0$ : energy preference of baryons over anti-baryons

$$\Rightarrow \quad \underbrace{\frac{dn_B}{dt} \approx \underbrace{\frac{3}{2}\frac{\Gamma_{\rm sph}}{T}}_{\text{B violation}} \underbrace{\dot{\theta}_{\rm EW}}_{\text{C \& CP and Lorentz violation}} - \frac{39}{4}\frac{\Gamma_{\rm sph}}{T^3} n_B}_{\text{B wash-out by sphalerons}}$$

Baryogenesis has to happen just before/during the sphaleron process turns off (i.e. EWPT) to avoid a strong wash-out.

$$V = V_{\rm SM} - \underbrace{M^2}_{M^2 < v^2}|H|^2 \cos\left(\underbrace{\frac{a}{F} + \alpha}_{\theta}\right) - \Lambda_{\rm HC}^4 \cos\left(\frac{a}{F}\right) + \underbrace{\frac{a}{f}}_{\theta_{EW}} W_L \widetilde{W}_L$$

As EWPT happens, $a$ starts to move due to the Higgs VEV dependent potential, while not significantly affecting the SM phase transition structure.

$$\frac{dn_B}{dt} \approx \frac{3}{2}\frac{\Gamma_{\rm sph}}{T}\underbrace{\dot{\theta}_{\rm EW}}_{\dot{\theta}_{\rm EW} = \frac{\dot{a}}{f} = \frac{F}{f}\dot{\theta} \sim \frac{F}{f} \times \text{Hubble}} - \underbrace{\frac{39}{4}\frac{\Gamma_{\rm sph}}{T^3} n_B}_{\text{persistent time scale} \sim \text{Hubble}}$$

For $F \sim f$, the produced baryon asymmetry is negligible.
For the correct baryon asymmetry, $F \sim 10^9 f$ (clockwork)

# Top-down approach

## Origin of defining properties of ALP ?

i) Discrete gauge symmetry : $a \ \rightarrow \ a + 2\pi n f$

$$\Rightarrow \quad \frac{a(x)}{f} = \theta(x)$$ angle variable

$$\Phi(x) = (S(x) + f)e^{i\theta(x)}$$

axial degree of freedom of (elementray or composite) complex scalar field

$$B_2(x) = \frac{1}{2\pi}\omega_i^{(1,1)}\theta^i(x)$$

$$\star H_3(x) = d\theta(x)$$

string theoretic form fields

ii) Perturbative shift symmetry : $a \rightarrow a + c$

; Global $U(1)$ → incompatible with quantum gravity (black hole argument)

→ cannot be a fundamental symmetry

→ To be identified as accidental symmetry from gauge symmetry or discrete symmetry

Example in the SM

: $\mathrm{U}(1)_\mathrm{B}$ and $\mathrm{U}(1)_\mathrm{L}$ accidentally originated from the SM gauge symmetries

ALP physics often requires a very high quality of global U(1).

eg) QCD axion, Freeze-in ALP DM, …

How to obtain it specifically?

## High quality global $U(1)_{PQ}$ : gauge symmetry origin

Fukuda, Ibe, Suzuki, Yanagida '17

Two sequestered sectors interacting with each other only via gauge interactions ($U(1)_A$ and $SU(N)_C$)

Under $U(1)_A$

$\Phi_i \to e^{ic_i\alpha(x)}\Phi_i$

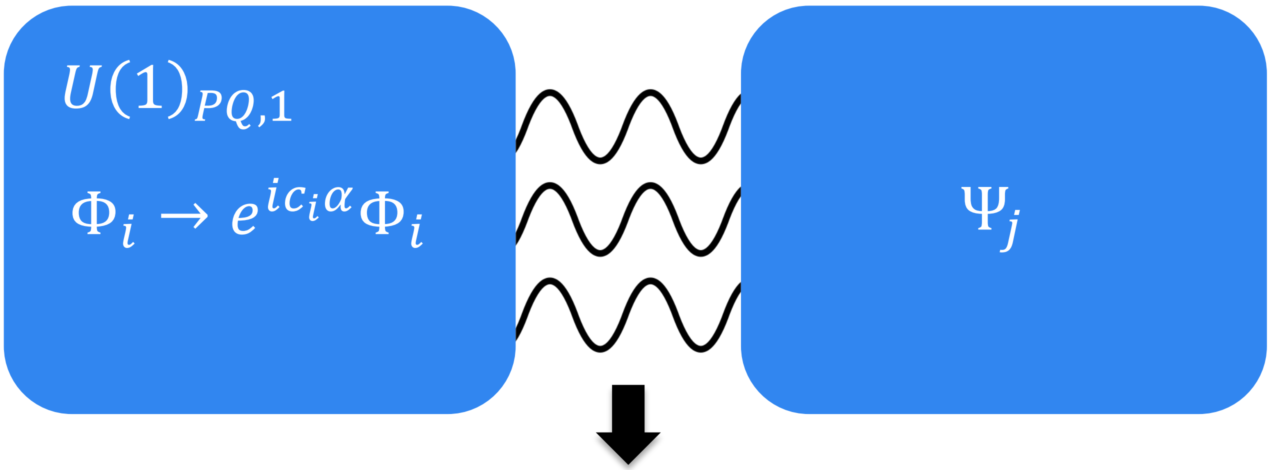
$\Psi_j \to e^{id_j\alpha(x)}\Psi_j$

$$\theta G\tilde{G} \to \Big[\theta + \alpha(x)\underbrace{\Big(\textstyle\sum_i c_i + \sum_j d_j\Big)}_{}\Big]G\tilde{G}$$

0 for $U(1)_A \times [SU(N)_C]^2$ anomaly cancellation

## High quality global $U(1)_{PQ}$ : gauge symmetry origin

We then have two accidental $U(1)_{PQ}$ broken only by anomalies.




$$\theta G\tilde{G} \to [\theta + \underbrace{\alpha \textstyle\sum_i c_i}_{\neq 0}]G\tilde{G}$$

## High quality global $U(1)_{PQ}$ : gauge symmetry origin

We then have two accidental $U(1)_{PQ}$ broken only by anomalies.

$\Phi_i$

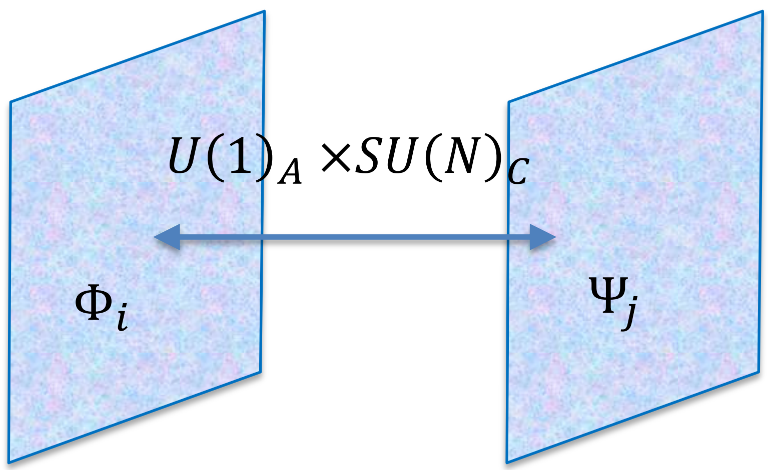
$U(1)_{PQ,2}$

$\Psi_j \to e^{i d_j \beta} \Psi_j$

$$\theta G\tilde{G} \to \Big[\theta + \underbrace{\beta \textstyle\sum_j d_j}_{\neq 0}\Big] G\tilde{G}$$

The previous construction needs a good sequestering of the two sectors. How could it be?

Extra dimensional locality




H C Cheng and D E Kaplan '01
Izawa, Watari , Yanagida '02
…

Implications for bottom-up ALPs? To be studied

## $U(1)_A$ in string theory

Witten '84

Matter sector

$$\Phi_i \to e^{ic_i\alpha(x)}\Phi_i$$

Green-Schwarz modulus

$$a \to a + c_{GS}\,\alpha(x)$$

$$\theta G\tilde{G} \to [\theta + \alpha(x)\underbrace{(\textstyle\sum_i c_i + c_{GS})]}_{}G\tilde{G}$$

0 for $U(1)_A \times [SU(N)_C]^2$ anomaly cancellation

$U(1)_A$ gauge boson mostly gains its mass by eating GS modulus remaining accidental $U(1)_A$ for the matter sector.

Matter sector

$$\Phi_i \to e^{ic_i' \alpha} \Phi_i$$

$$\Downarrow$$

$$\theta G\tilde{G} \to [\theta + \underbrace{\alpha \textstyle\sum_i c_i'}_{\neq 0}] G\tilde{G}$$

In order to preserve supersymmetry, however,

$$D_A = \sum_i q_i^2 |\Phi_i|^2 - \xi_{\rm FI}^2 = 0$$

$U(1)_A$ Fayet-Iliopouls term

$$\xi_{\rm FI} \sim \frac{\alpha_{\rm YM}}{4\pi} M_{\rm Pl}$$ in most of compactifications

$$f \sim \langle \Phi_i \rangle \sim M_{\rm GUT}$$

It seems hard to get a low scale ALP decay constant.

The situation is similar for stringy form field ALPs.

## Low scale ALP decay constant from large internal volume

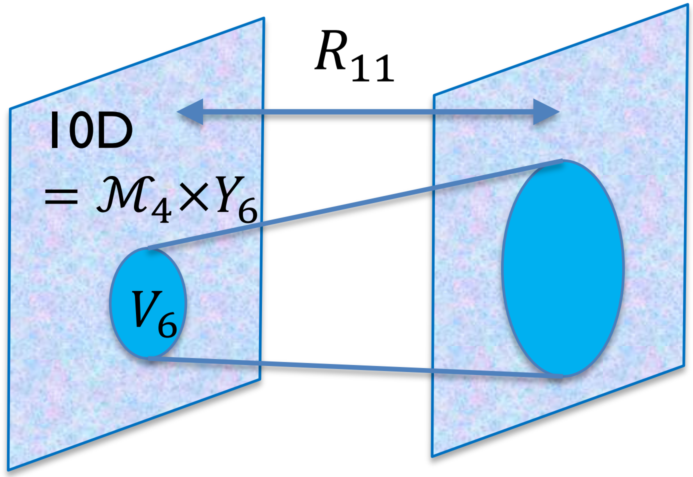
- Large Volume Scenario in Type IIB

Balasubramanian, Berglund, Conlon, Quevedo '05

- Warped large 11D in Heterotic M-theory

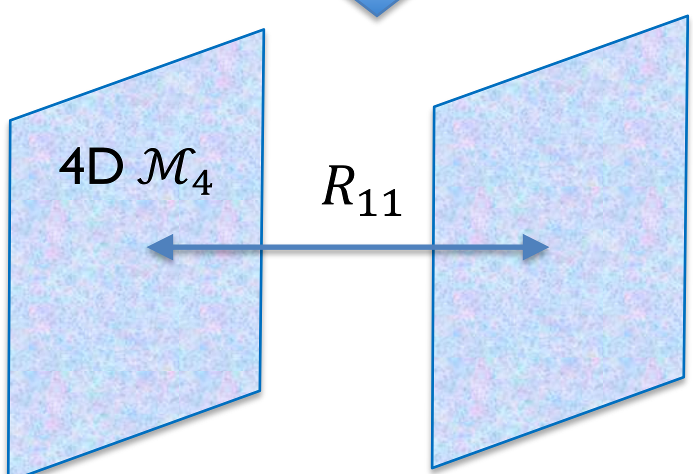
Svrcek, Witten '06
SHI, Nilles, Olechowski '19

# Heterotic M-theory : 5D effective description

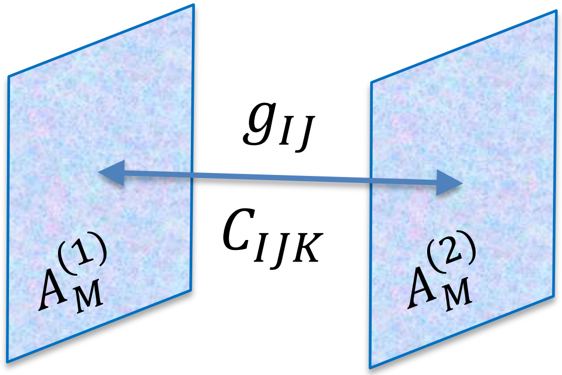



$$R_{11} \gg V_6^{1/6} \sim \frac{1}{M_{11}}$$

$$E < M_{11}$$




Polynomially warped extra dimension




4D axions : $C_{mn11}$ , $C_{\mu\nu 11}$

gauge fixing

$$S_{\sigma-\mathcal{A}_{11}} = -\int d^5x \frac{1}{2}\eta^{\mu\nu}\partial_\mu\phi_L\partial_\nu\phi_L + \frac{1}{2}\eta^{\mu\nu}\partial_\mu\phi_R\partial_\nu\phi_R + e^{2px_{11}}\frac{1}{2}\left[(\partial_{11}\phi_L + m_{\mathcal{A}}\phi_L)^2 + (\partial_{11}\phi_R - m_{\mathcal{A}}\phi_R)^2\right]$$

: two continuum clockwork axions

Choi, SHI, C S Shin '17

zero modes

$$\mathcal{L}_{4\mathrm{D}} = -\frac{1}{2}(\partial_\mu a_1)^2 - \frac{1}{2}(\partial_\mu a_2)^2 - \epsilon_k\partial_\mu a_1\partial^\mu a_2 + \frac{1}{16\pi^2}\left[\frac{a_1}{f_1}\mathrm{tr}F_{(1)}\tilde{F}_{(1)} + \frac{a_2}{f_2}\mathrm{tr}F_{(2)}\tilde{F}_{(2)}\right]$$

: two axions with kinetic mixing

$$\mathcal{L}_{4\mathrm{D}} = -\frac{1}{2}(\partial_\mu a_1)^2 - \frac{1}{2}(\partial_\mu a_2)^2 - \epsilon_k \partial_\mu a_1 \partial^\mu a_2 + \frac{1}{16\pi^2}\left[\frac{a_1}{f_1}\mathrm{tr}F_{(1)}\tilde{F}_{(1)} + \frac{a_2}{f_2}\mathrm{tr}F_{(2)}\tilde{F}_{(2)}\right]$$

Visible sector

$$\epsilon_k \sim \left(\frac{M_{11}}{M_{\mathrm{Pl}}}\right)^5$$

$$f_1 \sim M_{11}$$

$$f_2 \sim M_{11}\sqrt{\frac{M_{11}}{M_{\mathrm{Pl}}}}$$

$M_{11}$ can be lowered up to TeV scale. SHI, Nilles, Olechowski '18

→ Successful QCD axion with $M_{11}$ lying in the axion window

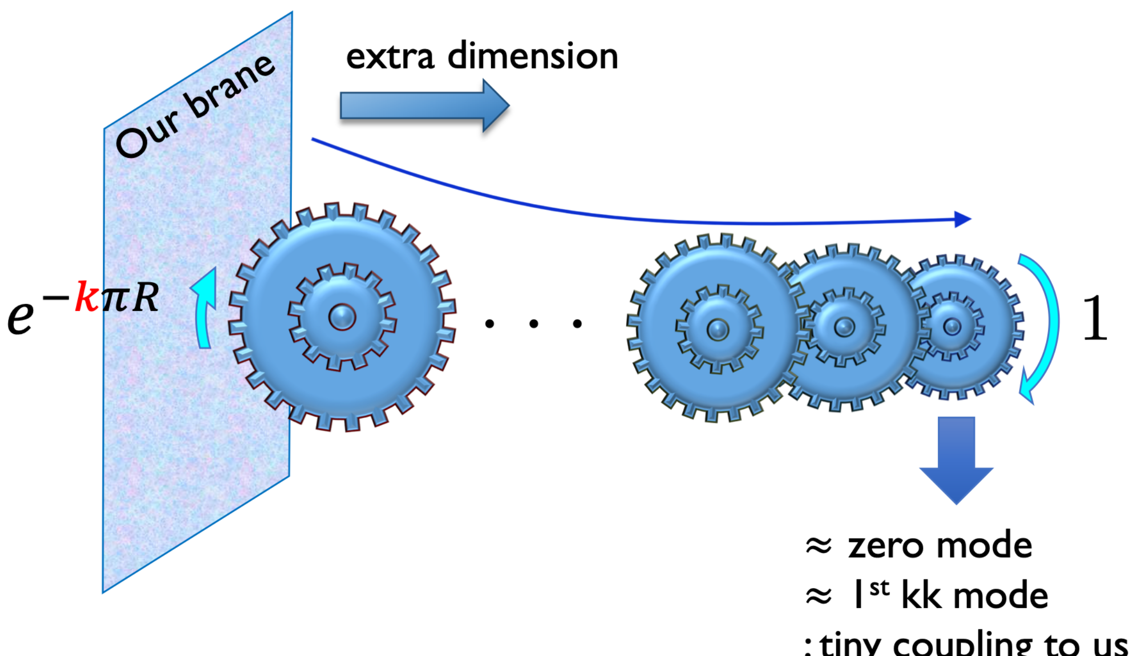
SHI, Nilles, Olechowski '19

# Kaluza-Klein axions as ALPs from heterotic M-theory

SHI, Nilles, Olechowski '19

$$M_n \approx 9\, n\, \mathrm{GeV} \left( \frac{M_{11}}{10^{10}\,\mathrm{GeV}} \right)^{9/4}$$

$$f_{L1}^{(n)} \sim f_{R1}^{(n)} \sim \frac{M_{\mathrm{P}}}{n^{3/10}} > 2.4 \times 10^{15} \mathrm{GeV} \left( \frac{M_{11}}{10^{10}\,\mathrm{GeV}} \right)^{3/8}$$



# Conclusion

- A new physics sector seems to be quite weakly coupled to the SM.
- ALP provides a natural candidate as a weakly coupled portal for a new physics sector to interact with the SM.
- It has good potential to resolve the SM problems having experimental testability.
- From UV perspective, the origin of ALP shift symmetry needs a non-trivial structure in the theories, which may have implications for low energy physics.