Review on Axions in Particle Physics

Kwang Sik JEONG

부산대학교
PUSAN NATIONAL UNIVERSITY

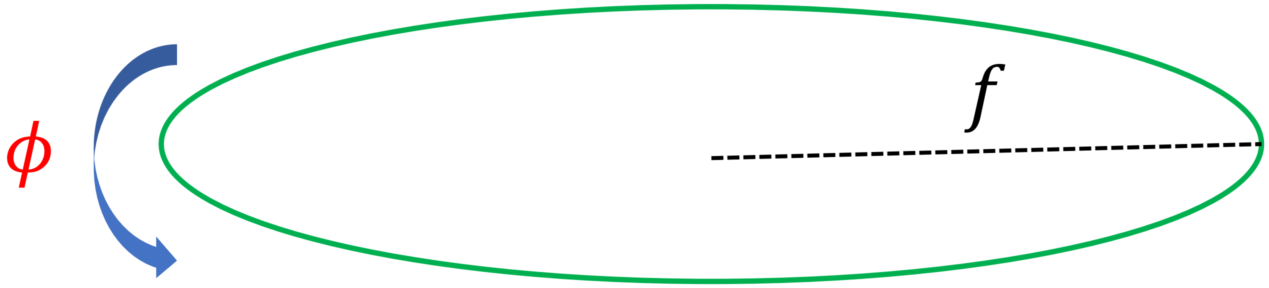
December 1, 2023

Korea University

International Workshop on Multi-probe approach to wavy dark matters

Why Axions?

Axion/ALP = Pseudo Nambu-Goldstone boson of spontaneously broken U(1)



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

- Periodicity: axion decay constant $f =$ U(1) breaking scale
- Shift symmetry: axion interactions suppressed by f
- Mass from shift symmetry breaking: $m_\phi = \frac{(\text{shift symmety breaking scale})^2}{f}$

For large f, axion is a *naturally light* and *feebly interacting* scalar particle!

Why Axions?

Axions can resolve the puzzles of the Standard Model:

Strong CP problem → QCD axion

Dark matter → Axion/Axion-like Particle

Cosmic inflation → Axion/Axion-like Particle

Gauge hierarchy problem → Relaxion

Matter-antimatter asymmetry → Axion/Axion-like Particle

and also other difficulties of the SM

Axion Interactions

Perturbative shift symmetry

3 types of interactions: Yukawa, derivative, and anomalous couplings

$$m_\psi e^{ic_1\frac{\phi}{f}}\bar{\psi}_L\psi_R + \frac{\partial_\mu\phi}{f}\left(c_2\bar{\psi}\,\gamma^\mu\gamma_5\psi + \cdots\right) + \frac{c_3}{32\pi^2}\frac{\phi}{f}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

U(1) current density

perturbative | non-perturbative

Physical quantities should be invariant under chiral field redefinition : $\psi_{L,R} \to e^{\pm i\alpha\frac{\phi}{f}}\psi_{L,R}$

Light and feebly coupled axions with various couplings to the SM

→ Potential to be probed by *cosmological*, *astrophysical*, and *laboratory* observations

Axion Dark Matter

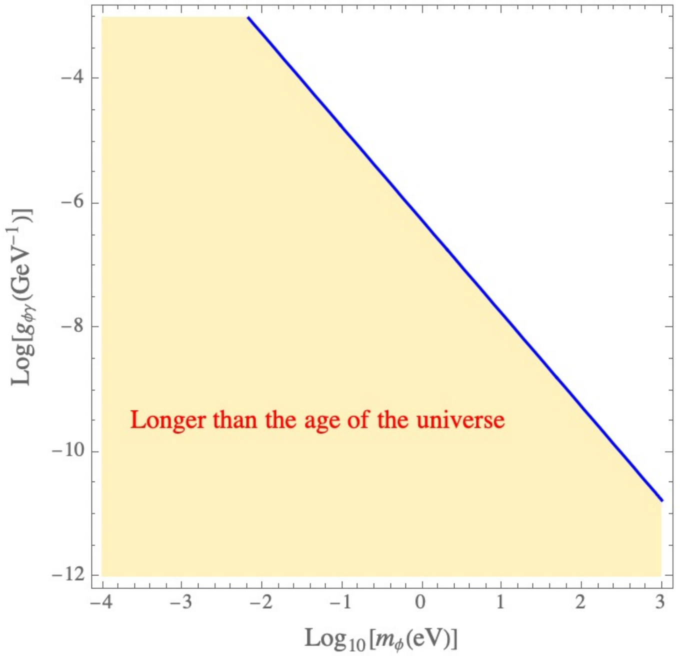
Electromagnetic coupling

$$-\frac{g_{\phi\gamma}}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} = g_{\phi\gamma}\phi\vec{E}\cdot\vec{B} \quad \text{where} \quad g_{\phi\gamma} = \frac{\alpha_{\rm EM}}{2\pi}\frac{c_{\rm EM}}{f}$$

- Axion decay width

$$\Gamma(\phi\to\gamma\gamma) = \frac{g_{\phi\gamma}^2 m_\phi^3}{64\pi}$$

- *Light axions* are compelling candidate for the *dark matter* in our Universe



Axion Dark Matter

Electromagnetic coupling

$$\nabla \cdot \vec{E} = \rho - g_{\phi\gamma}\vec{B}\cdot\nabla\phi$$

$$\nabla \times \vec{B} = \partial_t\vec{E} + \vec{J} + g_{\phi\gamma}(\vec{B}\partial_t\phi - \vec{E}\times\nabla\phi)$$

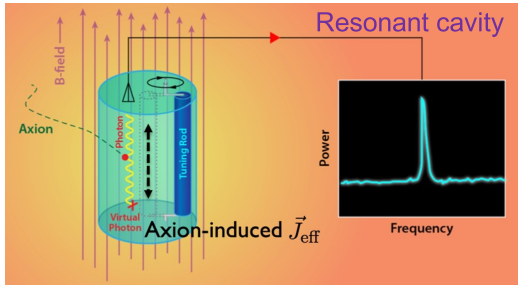
$$\nabla \cdot \vec{B} = 0$$

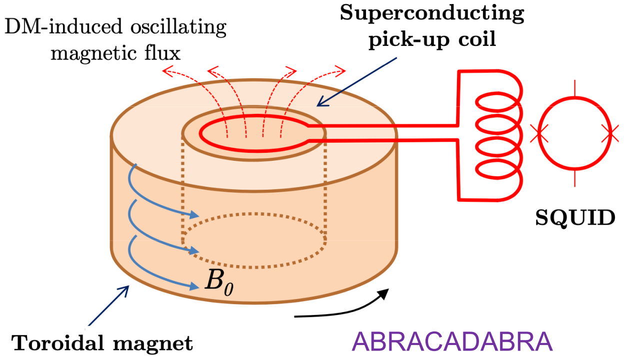
$$\nabla \times \vec{E} = -\partial_t\vec{B}$$

$$-\frac{g_{\phi\gamma}}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} = g_{\phi\gamma}\phi\vec{E}\cdot\vec{B} \quad \text{where} \quad g_{\phi\gamma} = \frac{\alpha_{\mathrm{EM}}}{2\pi}\frac{c_{\mathrm{EM}}}{f}$$

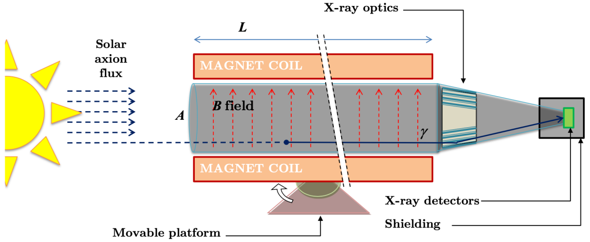
- Axion-induced EM fields due to effective electric charge and current

→ *Photonic probes* for *axion detection*



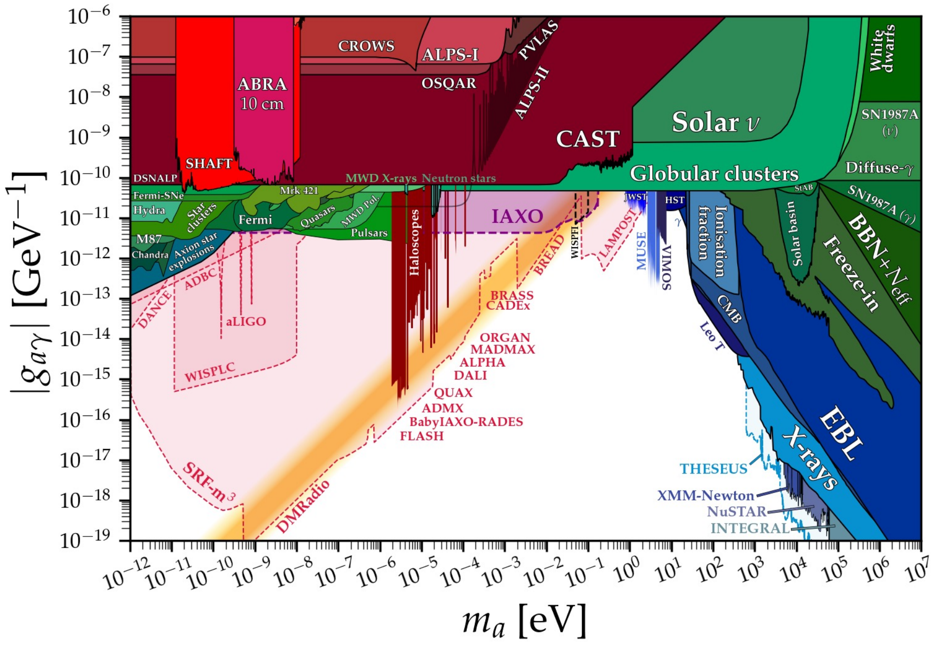


ABRACADABRA



Axion helioscope

https://github.com/cajohare/AxionLimits



Wavy Dark Matter

Axion dark matter

- Macroscopic de Broglie wave length for light axion dark matter

$$\lambda_{\rm dB} = \frac{2\pi}{m_\phi v} \simeq 1.5\,{\rm km}\left(\frac{\mu{\rm eV}}{m_\phi}\right)\left(\frac{250\,{\rm km/s}}{v}\right)$$

where v is the velocity dispersion of the galactic halo

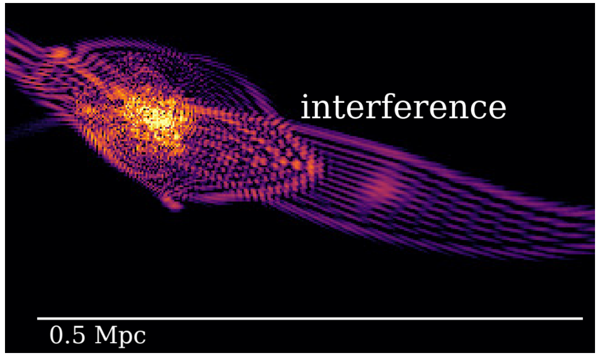
For $\lambda_{\rm dB} \gg$ (average interparticle separation),

halo *axions* behave as a *classical oscillating field* with oscillating amplitude

$$\phi(t) = \frac{\sqrt{2\rho_\phi}}{m_\phi}\cos\left(m_\phi t\right)$$

c.f. Wave turbulence and interference in filaments

Cosmic web formed by gravitational interactions and interference of axion waves



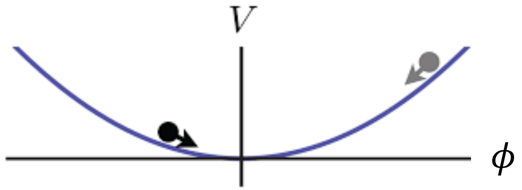
Philp Mocz et al, 2019

Axion Production

Production mechanisms

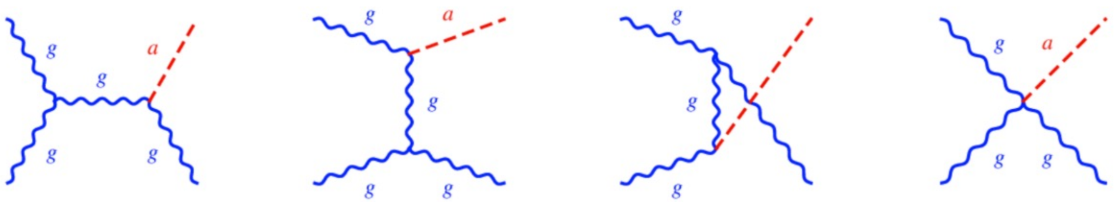
- Misalignment mechanism

Non-relativistic axions from axion coherent oscillations



- Thermal production

Thermal axions if coupled to the SM

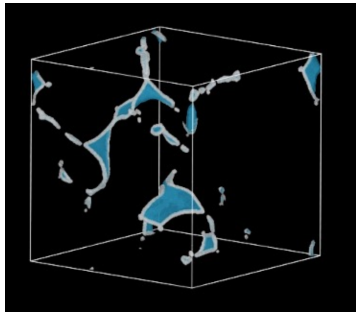


- Decay of heavy particles

Relativistic axions if produced from a particle much heavier than the axion

- Decay of topological defects

Axions from topological defects if symmetry breaking occurs after inflation

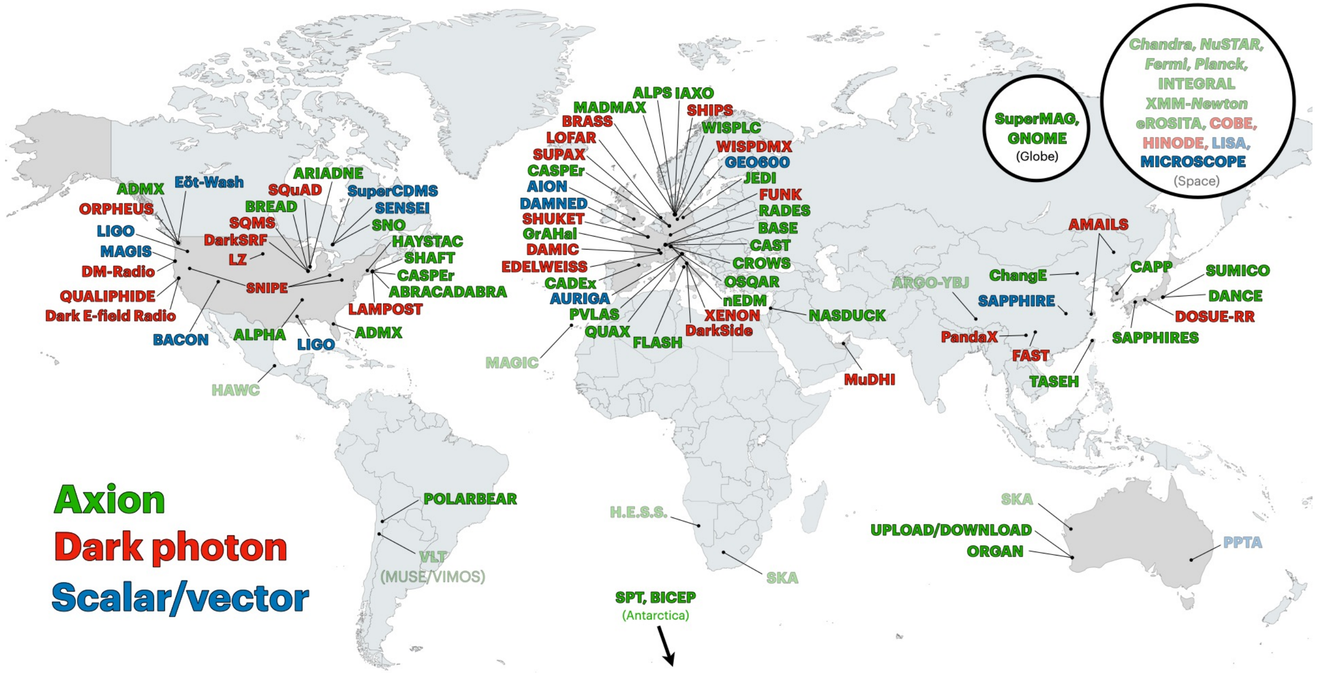


Search for Axion Dark Matter

Experiments

Axion dark matter search requires various experimental approaches

- Huge possible ranges of f and m_ϕ, and 3 types of axion couplings



https://github.com/cajohare/AxionLimits

Axionic Extension

QCD Axion

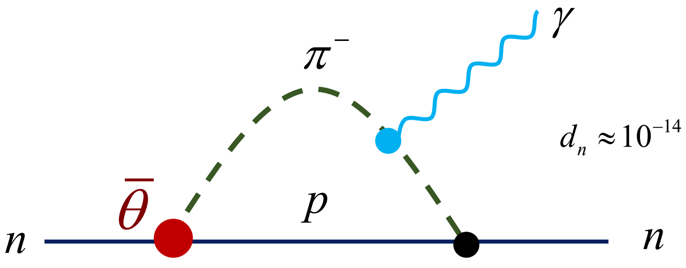
Strong CP Problem

CP violation in the QCD sector

$$\delta_{\mathrm{CKM}} \sim \arg(\det[y_u y_u^+, y_d y_d^+]) \simeq 1.2 \pm 0.3$$

$\bar{\theta} = \theta + \arg(\det[y_u y_d])$ with a topological QCD θ-term given by $\frac{\theta}{32\pi^2} G_{\mu\nu} \tilde{G}^{\mu\nu}$

Constraint from neutron electron dipole moment



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

Bound on the neutron EDM

$$|\bar{\theta}| < 10^{-10}$$

Why so tiny?

QCD Axion

Peccei, Quinn 1977

Peccei-Quinn solution

Promote θ to a scalar field, the QCD axion, associated with $U(1)_{\mathrm{PQ}}$ to cancel $\bar{\theta}$ dynamically

$$\langle\bar{\theta}\rangle = \left\langle \frac{\phi}{f} \right\rangle = 0$$

QCD axion

- Mass: $m_\phi \simeq 6\mu\mathrm{eV}\left(\frac{10^{12}\mathrm{GeV}}{f}\right)$
- Coupled to gluons, and possibly to photon and fermions

$$m_\psi e^{ic_1\frac{\phi}{f}}\bar{\psi}_L\psi_R + \frac{\partial_\mu\phi}{f}\left(c_2\bar{\psi}\,\gamma^\mu\gamma_5\psi + \cdots\right) + \frac{c_3}{32\pi^2}\frac{\phi}{f}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

where $C_i = O(1)$ are model-dependent, e.g. KSVZ, DFSZ

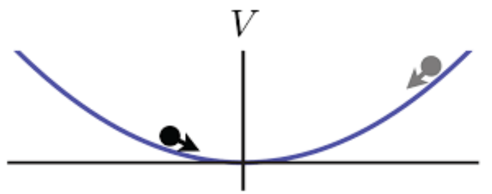
QCD Axion

Appealing dark matter candidate for large f

- Axion relic abundance assuming spontaneous PQ breaking during inflation

$$\Omega_\phi h^2 \simeq 0.18\theta_{\rm ini}^2 \left(\frac{f}{10^{12}\mathrm{GeV}}\right)^{1.19} \left(\frac{\Lambda_{\rm QCD}}{400\mathrm{MeV}}\right)$$

where $\theta_{\rm ini}$ is the axion misalignment angle

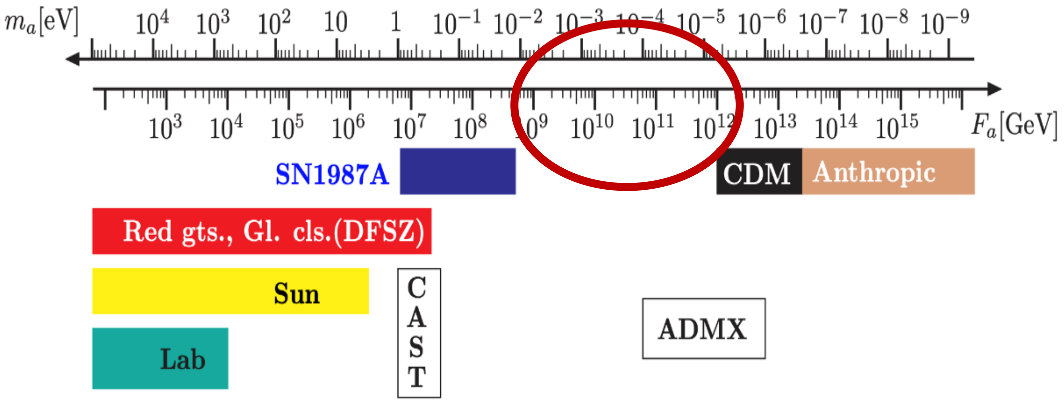


- QCD axion window

$$10^9\mathrm{GeV} \leq f \leq 10^{12}\mathrm{GeV}$$

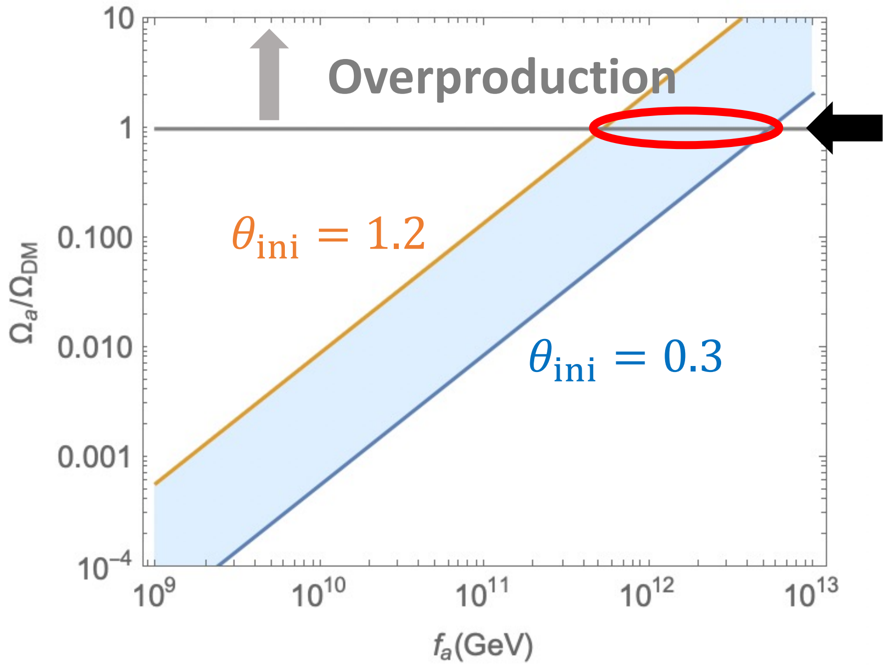
astrophysical bound

To avoid axion overproduction for $\theta_{\rm ini} \sim 1$



Cosmology with QCD Axion

Fraction of axion DM for $0.3 \leq \theta_{\rm ini} \leq 1.2$



Correct dark matter abundance

$\Omega_\phi = \Omega_{\rm DM}$ requires fine-tuning

$\theta_{\rm ini}$ close to the origin

$\rightarrow$ Anthropic argument?

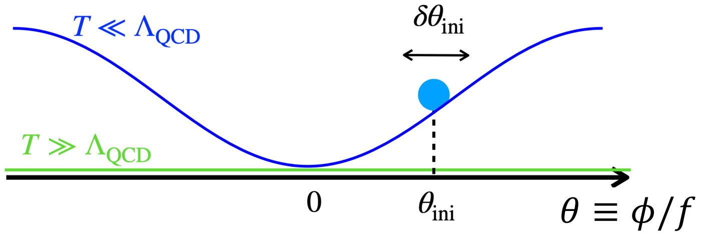
$\Omega_\phi = \Omega_{\rm DM}$ requires fine-tuning

$\theta_{\rm ini}$ close to the potential hilltop (anharmonic effect)

Lyth 1990

Cosmology with QCD Axion

Spontaneous PQ symmetry breaking before or during inflation



→ Axion quantum fluctuations during inflation

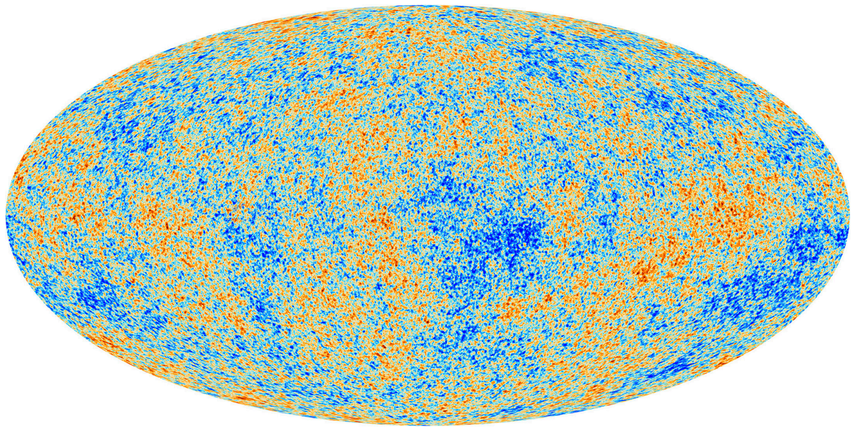
$$\delta\theta_{ini} = \frac{H_{inf}}{2\pi f}$$

- do not affect the total energy density during the primordial inflation
- turn into isocurvature density perturbations at the QCD phase transition

→ Imprint on the CMB radiation

Constraint on the isocurvature power spectrum

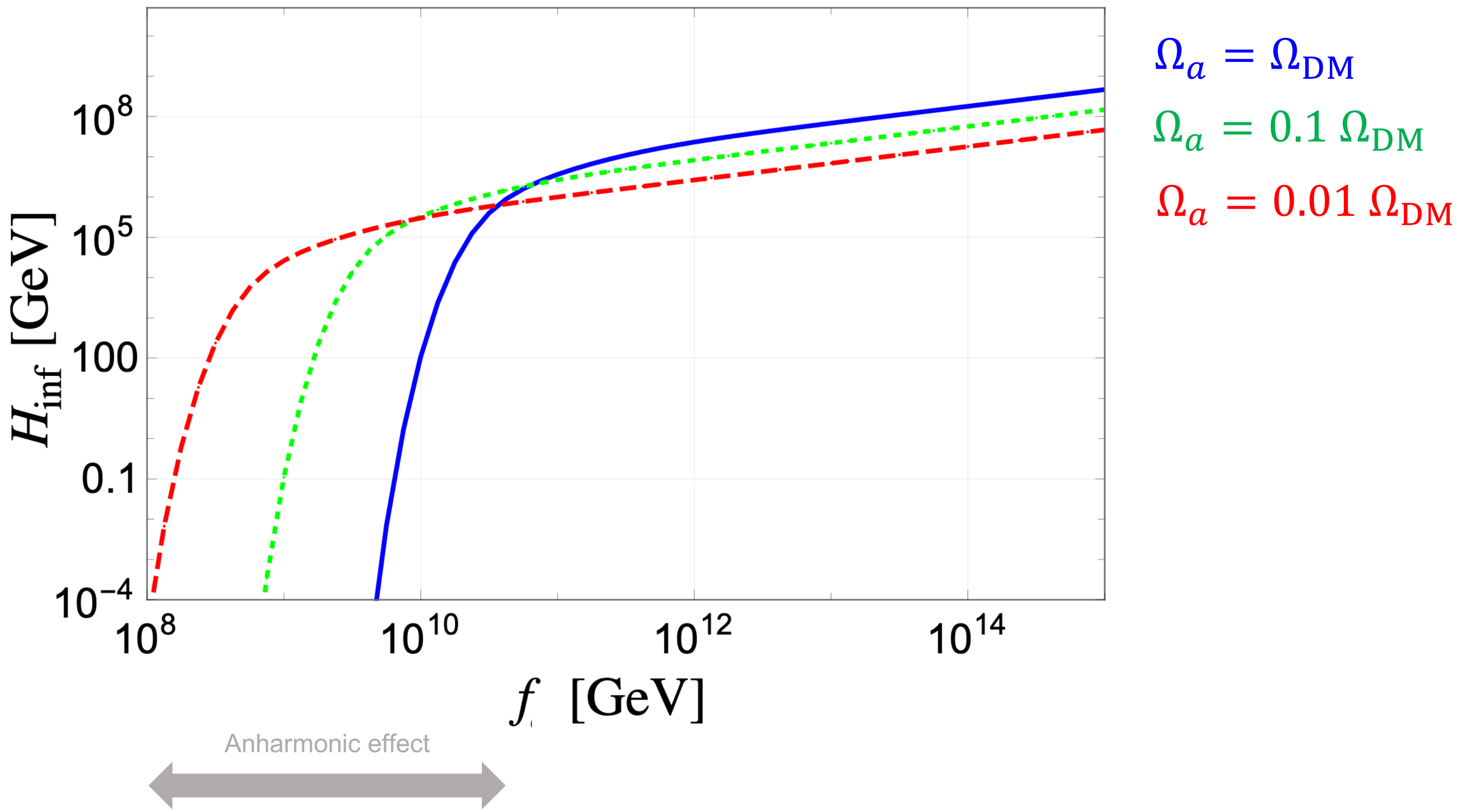
$$\Delta_S^2 \simeq \left(\frac{\Omega_a}{\Omega_{DM}} \frac{\partial \ln \Omega_a}{\partial \theta_{ini}} \frac{H_{inf}}{2\pi f}\right)^2 < 8.3 \times 10^{-11}$$



Planck collaboration

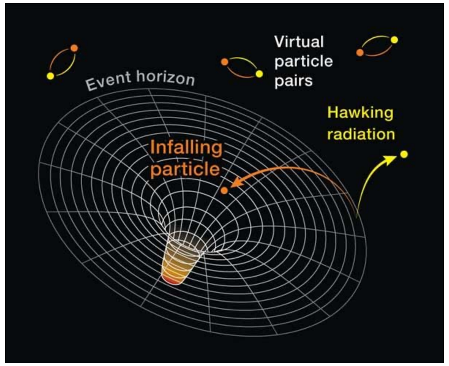
Cosmology with QCD Axion

Isocurvature bound on the inflation scale



Theoretical Issues

Georgi, Hall, Wise 1981, Dine, Seiberg 1986, …
Recently, increased interests



How to protect the PQ symmetry against quantum gravity?

Quantum gravity effects generally break any global symmetry:

Hawking 1975, Abbot, Wise 1989, Coleman, Lee 1990, …

$$\Delta V = \lambda \left(\frac{f}{M_{Pl}} \right)^n f^4 \cos\left(m\frac{\phi}{f} + \alpha \right)$$

for positive integers n and m

→ PQ solution to the strong CP problem is spoiled unless λ or α is highly suppressed

Tiny PQ breaking can be important in cosmology because QCD is asymptotically free

→ Nonzero neutron EDM *Recent work, e.g. Choi, Im, Jodlowski, 2023*

→ Modified evolution of the QCD axion

Higaki, KSJ, Kitajima, Takahashi 2016,

KSJ, Matsukawa, Nakagawa, Takahashi 2022

Theoretical Issues

How to generate an intermediate axion decay constant?

- f is determined by the dynamics stabilizing U(1) breaking scalar field
- QCD axion dark matter requires f below about 10^{12} GeV unless $\theta_{\rm ini}$ is unnaturally tiny

$$f_a \equiv \langle \Phi \rangle \leq 10^{12} \text{ GeV}$$

Any connection to other fundamental scales?

Planck scale, GUT scale, supersymmetry breaking scale, seesaw scale, …

e.g. $f = \sqrt{M_{\rm Pl} m_{\rm SUSY}}$ in SUSY models

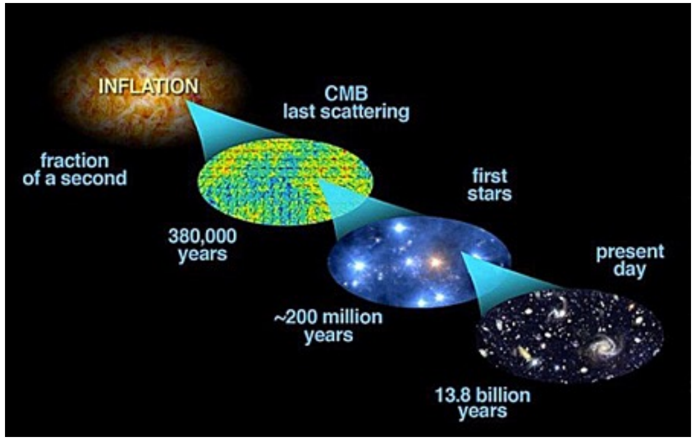
Axionic Extension

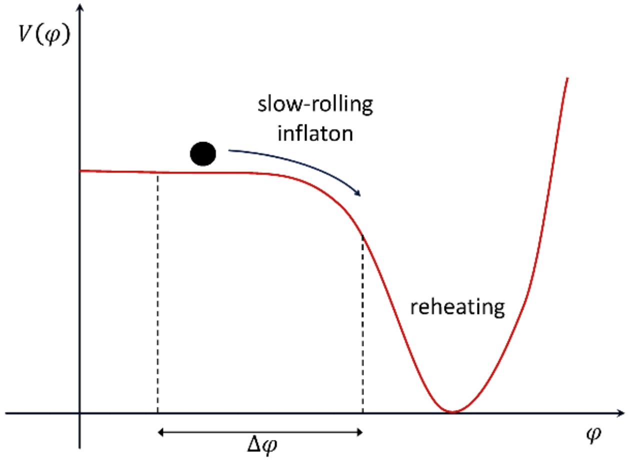
Axion for Inflation

Cosmic Inflation

Essential part of the standard cosmological model

- Initial conditions for the hot big bang universe
- Primordial density perturbations





Exponential expansion via slow-roll inflation: unusually flat potential flat relative to the vacuum energy

Stability against radiative corrections and quantum gravity effects

→ *Axion* is a natural candidate for an *inflaton* (shift symmetry)

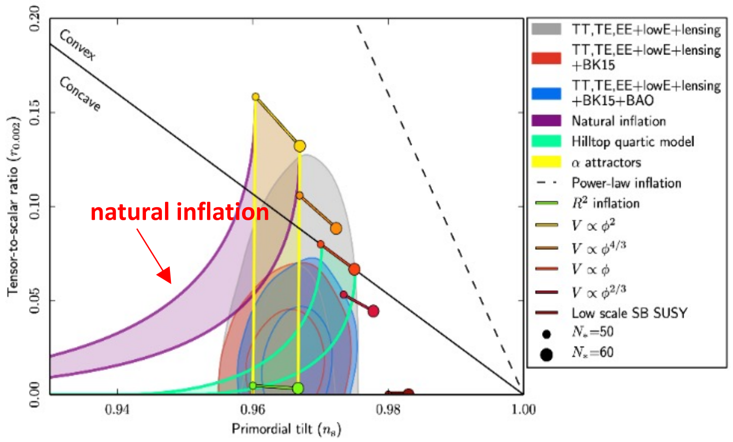
Natural Inflation

Freese, Frieman, Olinto 1990

Minimal setup for axion-driven inflation

$$V = V_0 - M^4 \cos\left(\frac{\phi}{f}\right) \quad \text{with} \quad M^4 = V_0$$

- Marginally consistent with the recent Planck observations on CMB



shape and magnitude of the inflaton potential

$$n_s \approx 1 + 2\frac{V''}{V} - 3\left(\frac{V'}{V}\right)^2$$

$$r = \frac{A_t}{A_s} \approx 8\left(\frac{V'}{V}\right)^2$$

- Trans-Planckian decay constant

  → Quantum gravity, $\left(\frac{f}{M_{\rm Pl}}\right)^n$ with $n > 0$, may spoil the field theoretic description

Axion-driven Inflation

Ross, German 2009, 2010, Gong, KSJ 2021

Models with multiple fields such that the axion potential during inflation is given by

$$V = V_0 - M^4 \cos\left(\frac{\phi}{f}\right) \quad \text{with} \quad \boxed{M^4 \ll V_0}$$

- Compatible with the Planck results if $f \geq 10^6 \times m_\phi$
- sub-Planckian decay constant

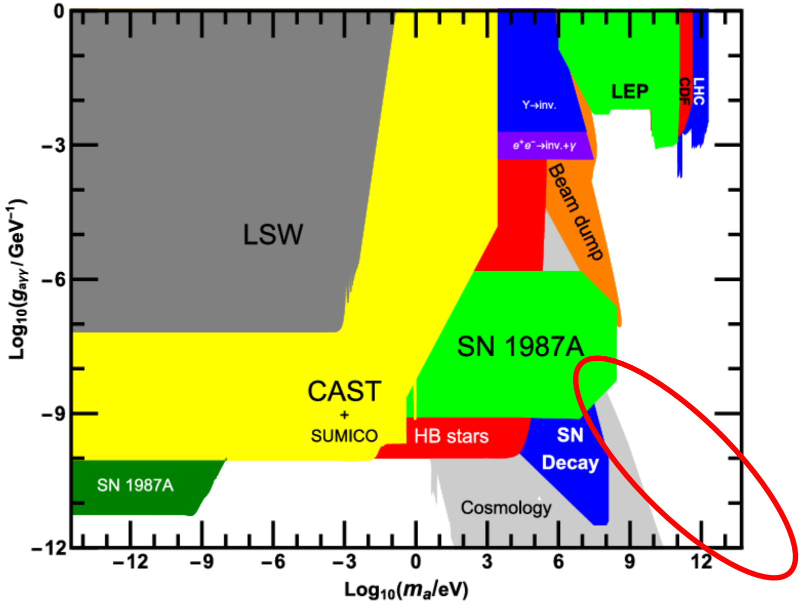
Czerny, Higaki, Takahashi 2014
Gong, KSJ 2021

$$f \sim \sqrt{\frac{M^4}{V_0}} M_{Pl}$$

- Models with axion(=inflaton) as dark matter

Daido, Takahashi, Yin 2017, Gong, KSJ 2021

Jaeckel, Spannowski 2015

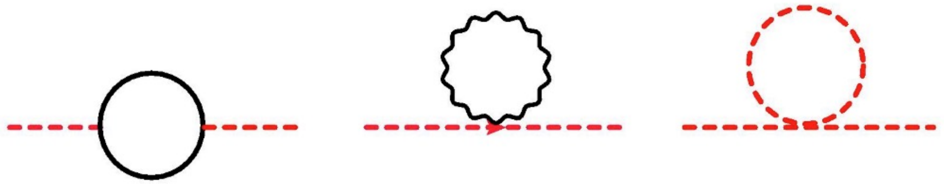


Axionic Extension

Relaxion

Gauge Hierarchy Problem

How to stabilize the weak scale against unknown UV physics?

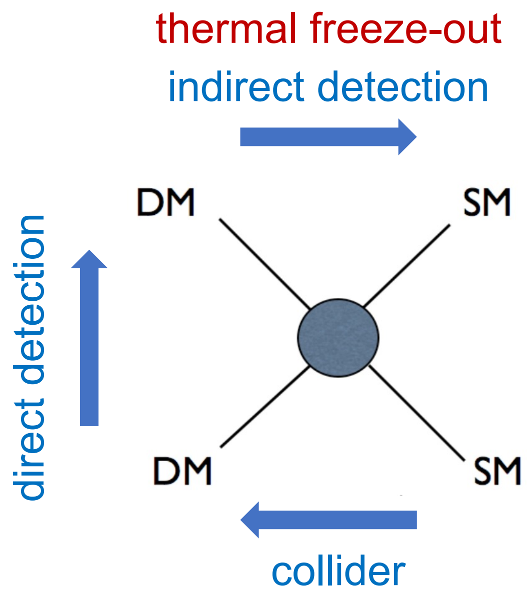


$$\delta m_H^2 \sim \frac{(\text{UV cutoff scale})^2}{16\pi^2}$$

Supersymmetry, extra dim, composite Higgs, and so on

→ TeV particles with sizable couplings to the SM

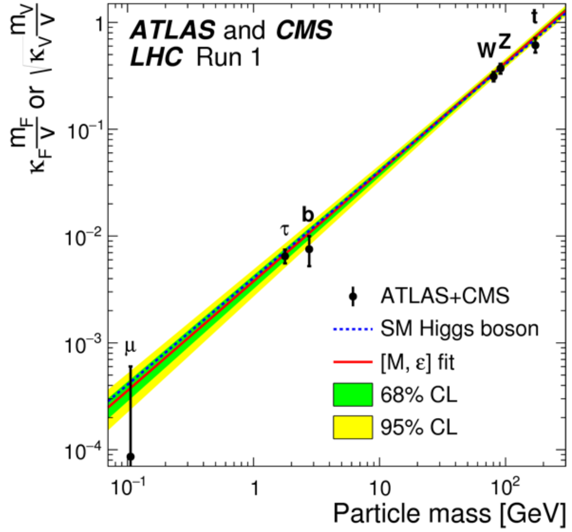
→ Such extensions naturally have WIMP as cold dark matter



Gauge Hierarchy Problem

LHC searches so far

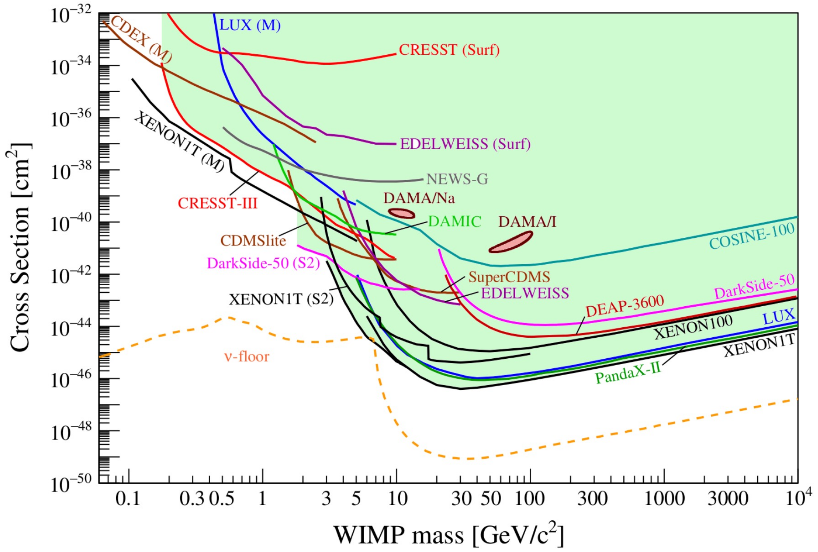
- No significant deviations from the SM
- No clear signals for physics beyond the SM



Direct and indirect dark matter searches so far

- No evidence of WIMPs

APPEC Committee Report

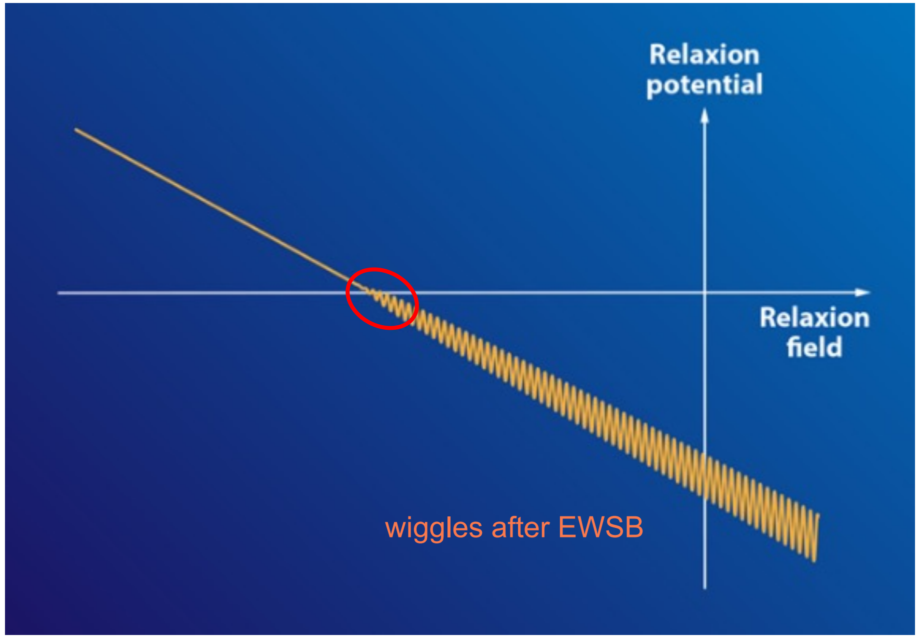


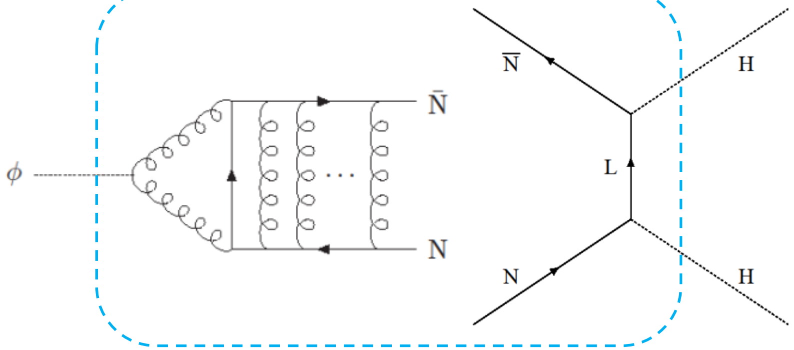
Relaxation Mechanism

Graham, Kaplan, Rajendran 2015

New approach to the gauge hierarchy problem

Cosmological evolution of the *relaxion* to select the Higgs mass: $\mu_H^2(\phi)|H|^2$





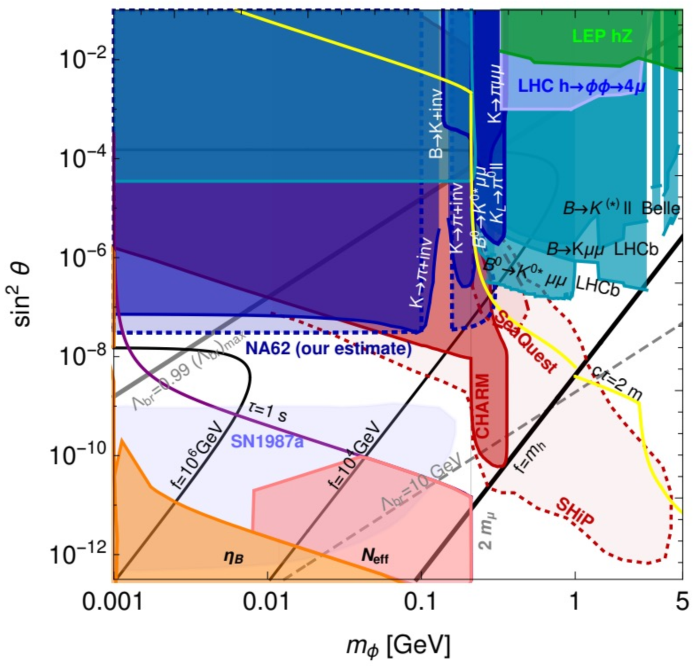
hidden QCD and quarks

Relaxion slow-rolls while *scanning* μ_H^2 from $(\text{cutoff scale})^2$ to negative, and *stops* due to barriers formed by *EWSB*

Relaxion Couplings

Relaxion-Higgs mixing after EWSB

Stringent constraints for relaxion at sub-MeV to multi-GeV from rare K and B meson decays and beam-dump experiments



Flacke, Frugiuele, Fuchs, Gupta, Perez 2016

Choi, Im 2016

Axionic Extension

Axion for Baryogenesis

Baryon Asymmetry

Baryogenesis

Sakharov's condition: B violation, C and CP violation, interactions out of thermal equilibrium

→ In SM, B+L anomaly, CP phases in the fermion sector, EW phase transition (crossover)

→ Not sufficient

B+L violation by EW sphaleron transitions in symmetric phase

→ EW phase transition is the last period affecting baryon asymmetry

Baryogenesis scenarios

- Nonzero B−L above the EW scale: Leptogenesis, Affleck-Dine, …
- B+L generation at EW scale and sphaleron decoupling: EW baryogenesis

  LHC (direct searches) and EDM experiments

  c.f. severe constraint from electron EDM, $|d_e| < 10^{-29} e \cdot \mathrm{cm}$

  ACME II 2018

Axion-driven Baryogenesis

Axion derivative coupling to fermions

$$\frac{\partial_\mu \phi}{f} J^\mu \quad \text{with} \quad J^\mu \equiv \bar{\psi}\gamma^\mu\gamma_5\psi = (\rho, \vec{J})$$

→ *Time derivative of axion*, $d\phi/dt$, serves as a *chemical potential* for the fermion number

Spontaneous baryogenesis

Cohen, Kaplan 1987, and lots of works
Recent review, e.g. Simone, Kobayashi 2016

Axion evolution + B violation much faster than thermalization

KSJ, Jung, Shin 2019, 2020

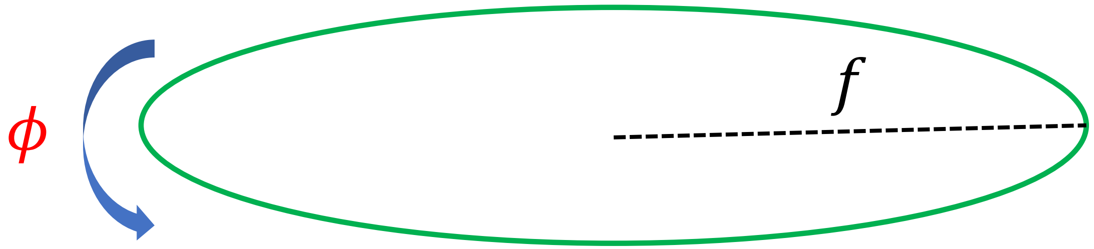
e.g. axion-driven baryogenesis with axion-dependent Higgs mass, $\mu_H^2(\phi)|H|^2$

observed baryon asymmetry for axion with mass, $m_\phi \sim \frac{(\text{weak scale})^2}{f}$

Summary

Why Axions?

Naturally *light* and *feebly interacting* scalar particle due to *shift symmetry*



Why *axions*?

- Appealing candidate for the unknown degrees of freedom: *dark matter*, *inflaton*
- Make the SM more natural by solving the *strong CP problem*, *gauge hierarchy problem*
- Explain the *matter-antimatter asymmetry* of the universe

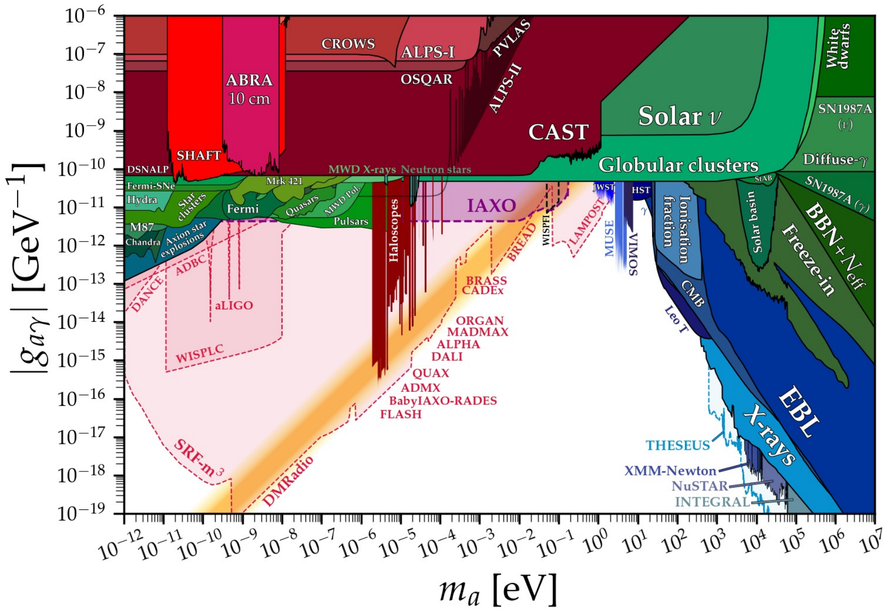
Why Axions?

Theoretically well-motivated axions

→ Strong theoretical support for *axion searches*!

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

→ Many *new experimental techniques* developed to detect axions



Search for axion dark matter

THANK YOU