Beyond the Standard Model

Part II

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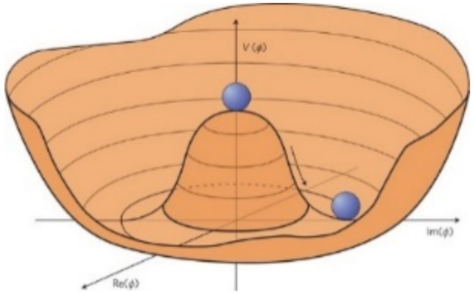
Axion

Feebly Coupled Light Particle

- **Axion** Axion-like Particle (ALP)
  - Pseudo Nambu-Goldstone boson of spontaneously broken U(1)



- Periodic: $\phi \to \phi + 2\pi f$

axion decay constant f = U(1) breaking scale

- Shift symmetry $\phi \to \phi$ +(constant) to control axion mass and couplings
  - Interactions suppressed by f
  - Mass from explicit breaking of the shift symmetry

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

Feebly interacting light particle for large f

2-1. Introduction- Axion

- **Axion Portal**
  - Perturbative shift symmetry $\phi \to \phi$ +(constant)

- 3 types of interaction: Yukawa, derivative and anomalous couplings

$$\underbrace{m_\psi e^{ic_1\frac{\phi}{f}}\bar{\psi}_L\psi_R + \frac{\partial_\mu\phi}{f}\,\underbrace{(c_2\bar{\psi}\,\gamma^\mu\gamma_5\psi + \cdots)}_{\text{U(1) current density}}}_{\text{perturbative}} + \underbrace{\frac{c_3}{32\pi^2}\frac{\phi}{f}F_{\mu\nu}\tilde{F}^{\mu\nu}}_{\text{non-perturbative}}$$

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

- Potential below the QCD confining scale $\Lambda_{\rm QCD}$ in $c_2 = 0$ basis

$$\underbrace{m_q e^{ic_1'\frac{\phi}{f}}\bar{q}_L q_R}_{\text{light quark below }\Lambda_{\rm QCD}} + \frac{c_3'}{32\pi^2}\frac{\phi}{f}G_{\mu\nu}\tilde{G}^{\mu\nu} \to$$

Light degrees of freedom: meson and axion

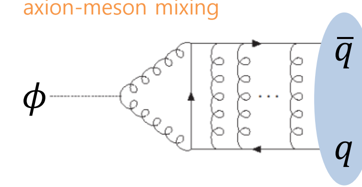
Without instantons

- $\mathrm{U(1)_{PQ}}$ invariant combination: massive
- NG boson combination: massless

$$\to L_{\rm eff} = m_q\Lambda_{\rm QCD}^3\cos\left(n_1\frac{\phi}{f} + n_2\frac{\varphi}{f_\varphi}\right) + \Lambda_{\rm QCD}^4\cos\left(m_1\frac{\phi}{f} + m_2\frac{\varphi}{f_\varphi}\right)$$

meson $\arg\langle qq\rangle$

axion-meson mixing



Integrating out heavy meson for $f_\varphi \ll f$, $V_{\rm eff} = -m_q\Lambda_{\rm QCD}^3\cos\left(\frac{\phi}{f}\right)$

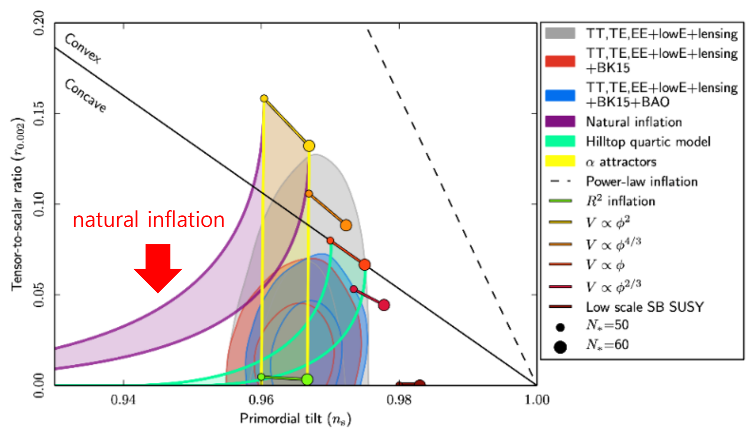
- **Axion Portal**
  - Potential to be probed by cosmological, astrophysical and laboratory observations

- **Examples**
  - QCD axion
    - Anomalous coupling to gluons → Natural solution to strong CP problem
    - Dark matter candidate: cold, warm, or hot
  - Natural inflation
    - Very flat potential from axion

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

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

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



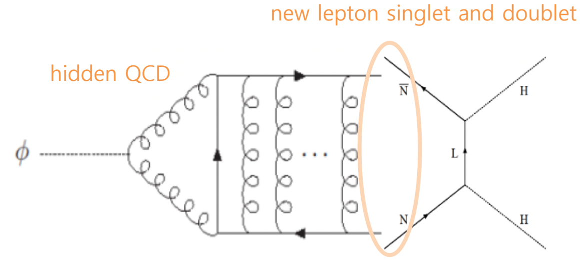
- Examples
  - Relaxion

Cosmological selection of the electroweak scale

- Based on coupling to the Higgs sector

$$\Delta V = -\mu_\phi^2 \cos\left(\frac{\phi}{F}\right) |H|^2$$

$\rightarrow$ Relaxion evolution is tied to EWSB for μ_ϕ above the weak scale

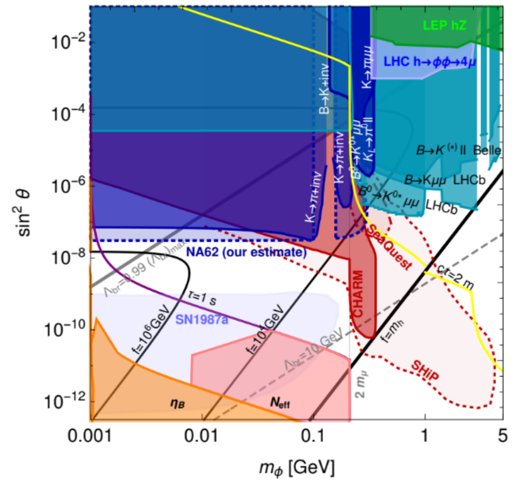


- Relaxion-Higgs mixing after EWSB

For sub-MeV to multi-GeV relaxion,

constraints from rare K and B meson decays

and beam-dump experiments

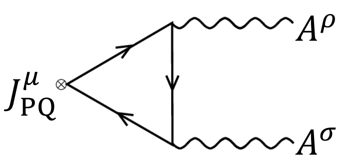


Flacke et al

QCD axion

Solution to the Strong CP problem

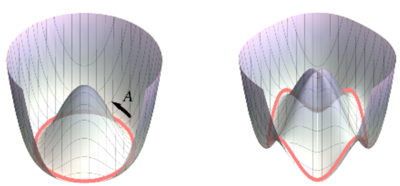
- **Axion Potential**
  - Spontaneously broken PQ symmetry → Axion NG boson
  - Chiral anomalies → non-derivative axion couplings



- QCD anomaly $\frac{N_{\rm DW}}{32\pi^2}\frac{a}{f}G_{\mu\nu}\tilde{G}^{\mu\nu}$ → Solution to strong CP problem

- EM anomaly $\frac{c}{32\pi^2}\frac{a}{f}F_{\mu\nu}\tilde{F}^{\mu\nu}$

Domain-wall number



  - Axion-dependent field redefinition,

light quarks: u, d, s

$$\Delta L = \frac{N_{\rm DW}}{32\pi^2}\frac{a}{f}G_{\mu\nu}\tilde{G}^{\mu\nu} - \bar{q}_L M q_R + (\text{derivative couplings})$$

After QCD condensation, potential for axion and mesons

$$V = -\Lambda_{\rm QCD}^4 \cos\left(N_{\rm DW}\frac{a}{f} + \sum_{i=u,d,s}\frac{\varphi_i}{f_i}\right) - 2\Lambda_{\rm QCD}^3 \sum_{i=u,d,s} m_i \cos\left(\frac{\varphi_i}{f_i}\right)$$

- Breakdown of $\mathrm{U(1)_{PQ}}$ to $Z_{N_{\rm DW}}$

- Mixing between axion and neutral mesons, π, η, η'

- **Axion Potential**
  - Integrating out heavy mesons

$f_\pi \simeq$130MeV, $m_\pi \simeq$135MeV

$$V_{\rm eff} = -f_\pi^2 m_\pi^2 \sqrt{\frac{m_u^2+m_d^2+2m_u m_d \cos\left(N_{\rm DW}\frac{a}{f}\right)}{(m_u+m_d)^2}}\left(1+O\left(\frac{m_{u,d}}{m_s}\right)\right) \simeq -m_u \Lambda_{\rm QCD}^3 \cos\left(N_{\rm DW}\frac{a}{f}\right)$$

- **Axion Properties**
  - Mass: $m_a^2 = \frac{m_u \Lambda_{\rm QCD}^3}{(f/N_{\rm DW})^2}$
  - Couplings
    - axion-gluon → neutron EDM
    - axion-photon: $\Delta L = \frac{1}{4} g_{a\gamma\gamma} F_{\mu\nu}\tilde{F}^{\mu\nu} = g_{a\gamma\gamma}\vec{E}\cdot\vec{B}$
    - axion-fermion: $\Delta L = \frac{c_f}{2f}(\partial_\mu a)\bar{f}\gamma^\mu\gamma_5 f = i g_{aff} a \bar{f}\gamma_5 f + \cdots$

$$g_{a\gamma\gamma} = \frac{e^2}{8\pi^2}\frac{N_{DW}}{f}\left(\frac{E}{N_{DW}} - \frac{2}{3}\frac{4+m_u/m_d}{1+m_u/m_d}\right)$$

EM anomaly   axion-meson mixing

$$g_{aff} = \frac{c_f m_f}{f}$$

  - Axion decay to photons: $\Gamma_{a\to\gamma\gamma} = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi} = 10^{-24}{\rm s}^{-1}\times\left(\frac{m_a}{\rm eV}\right)^5$

- Models
  - KSVZ (hadronic) Axion

    - SM particles: PQ singlets

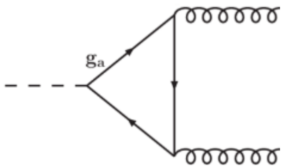
    PQ scalar: spontaneous PQ breaking by $\langle\Phi\rangle \neq 0$

    - Extra quarks with $y\Phi\bar{q}_L q_R$ where $\Phi = \frac{1}{\sqrt{2}}(f + s(x))e^{ia(x)/f}$

    saxion

    axion-photon coupling even if PQ quarks are EM neutral

    axon-SM fermion coupling at loop level



extra quarks

  - DFSZ Axion

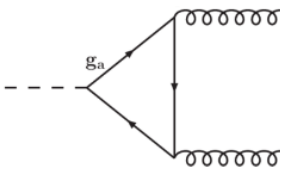
    - Two Higgs doublets charged under $\mathrm{U(1)_{PQ}}$: H_u, H_d

      Potential: $\Delta V = \lambda_H \Phi^2 H_u H_d$

      PQ-invariant Yukawa terms: $H_u Q U^c + H_d Q D^c + H_d L E^c$

    - Domain-wall number = 6

    - Tree-level couplings between axion and SM fermions



SM quarks

- Theoretical Issues
  - Why physics determines f?

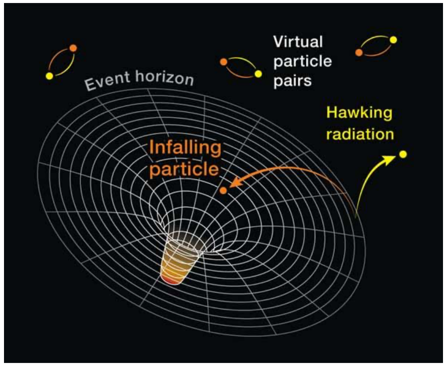
    f =(PQ breaking scale) ← scale of new physics
  - How to protect $\mathrm{U(1)_{PQ}}$ against quantum gravity effects?

    Planck suppressed explicit PQ breaking operators

    e.g. $\Delta V = \sum_{n\geq1} \frac{\Phi^{4+n}}{M_{Pl}^n}$ ← harmful

  c.f. blackholes and wormholes break global symmetries

  Euclidean field configuration in gravity



Hawking temperature

$T = \frac{\hbar c^3}{8\pi G k_B M}$

gauge field outside blackholes and wormholes

PQ symmetry from high energy gauge symmetry?

QCD axion

Cosmology

- Axion Cosmology

Crucially depends on whether $\mathrm{U}(1)_{\mathrm{PQ}}$ is restored during inflation or not

Let $\theta \equiv \frac{a(x)}{f}$

No NG boson yet

- PQ symmetry unbroken during inflation

  - After inflation, θ takes random values in different Hubble patches

    → average initial misalignment angle: $\langle \theta_{ini}^2 \rangle = \frac{\pi^2}{3}$

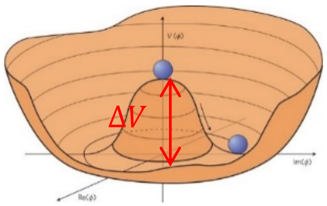
  - sizable density fluctuations when the axion gets massive

    → gravitational bound object

size ~ (Hubble parameter) at QCD phase transition

Issues: Axion mini-clusters e.g. R ~ 10pc for the QCD axion

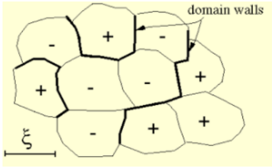
Collapsing to dense axion stars? Stable? …



  - Relics of PQ phase transition

    Topological objects: strings and domain-walls

    → Need $N_{\mathrm{DW}} = 1$ to avoid the cosmological domain-wall problem

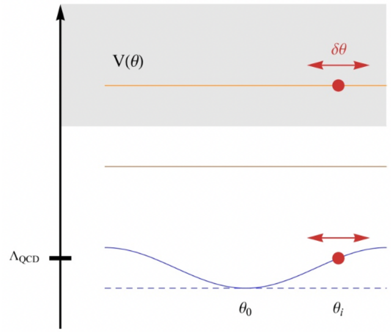


stable domain-walls for $N_{\mathrm{DW}} \geq 2$ overclose the universe

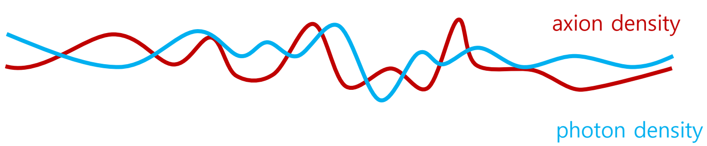
- Axion Cosmology
  - PQ symmetry breaking during inflation no restoration
    - Topological defects are diluted: $N_{\mathrm{DW}} \neq 1$ is allowed
    - After inflation, θ takes the same value in the whole observable universe

effective PQ symmetry restoration if $\delta\theta > \pi$

- Quantum fluctuations during inflation: $\delta\theta = \frac{H_{\mathrm{inf}}}{2\pi f}$



→ Isocurvature density perturbations after QCD phase tr.



Constrained by the observed CMB spectrum adiabatic, Gaussian

$$\left(\frac{\delta T}{T}\right)_{\mathrm{iso}} < 4\times10^{-6}$$

▪ Axion Evolution

- Equation of motion

R: scale factor

$$\ddot{\theta} + 3H\dot{\theta} - \frac{\nabla^2}{R^2}\theta + \frac{\partial V(\theta,T)}{\partial\theta} = 0$$

H: Hubble parameter

Harmonic approximation: $V(\theta,T) \approx \frac{1}{2}m_a^2(T)\theta^2$

Dilute instanton gas approximation

$m_a(T) = m_a(0)\times\left(\frac{\Lambda_{QCD}}{T}\right)^{\frac{11}{6}N_c-2}$ at $T > \Lambda_{QCD}$

c.f. anharmonic effect if the initial position is close to the hilltop

- Fourier modes evolve independently

$\ddot{\theta}_k + 3H\dot{\theta}_k + \omega^2\theta_k = 0$ with $\omega^2 = \frac{k^2}{R^2} + m_a^2(T)$

- $3H > \omega$: Modes outside the horizon

→ Overdamped oscillation: $\theta_k \approx$(constant) over $\delta t \sim 1/H$

- $3H < \omega$: Modes inside the horizon

→ Damped oscillation with frequency ω

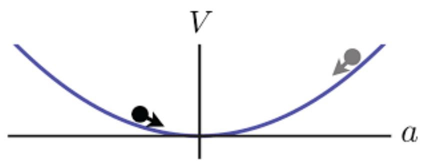
oscillation amplitude decreases with expansion

$H \ll \omega$ → Fast oscillation and slow damping

- Axion Production
  - **Axions from misalignment mechanism**

    - Homogeneous field $\nabla\theta = 0$

    - Adiabatic evolution: Slow change of H, θ, m_a during one oscillation



oscillation temperature: $T_{\rm osc}$

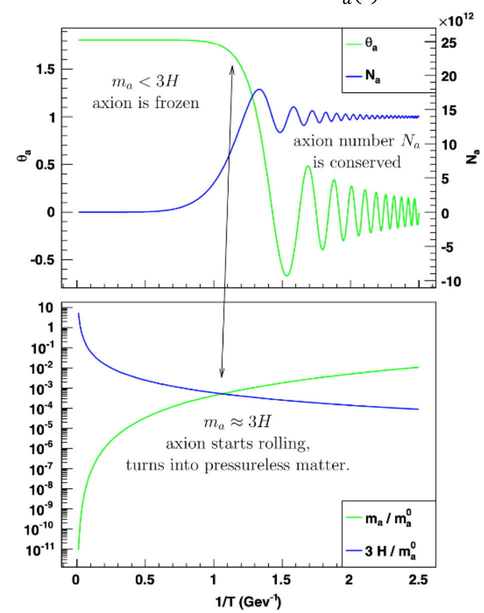
axion starts rolling when $3H(T) \approx m_a(T)$

radiation domination

$H^2(T) = \frac{1}{3M_{Pl}^2}\frac{\pi^2 g_*}{30}T^4$

number density

$n_a = \frac{\langle \rho_a(t) \rangle}{m_a(t)} \propto R^{-3}$



Wantz, Shellard

- Energy density of coherent axion oscillation

initial misalignment angle

$$\langle \rho_a(t) \rangle = c m_a^2(T) f^2 e^{-3Ht} \quad \text{with } c e^{-3Ht}|_{T_{\rm osc}} = \theta_{\rm ini}^2$$

average over one oscillation: $\cos(m_a t)$

scales as R^{-3} like pressure-less non-relativistic particles

→ Axion cold dark matter

Axion Production

- Relic density

$$\rho_a(T_0) = m_a(T_0) n_a(T_{\rm osc}) \left(\frac{R(T_{\rm osc})}{R(T_0)}\right)^3$$

Present universe: $T_0 = 2.4\times10^{-13}$GeV, $H_0 = 1.5\times10^{-42}$GeV

Axion cold dark matter density

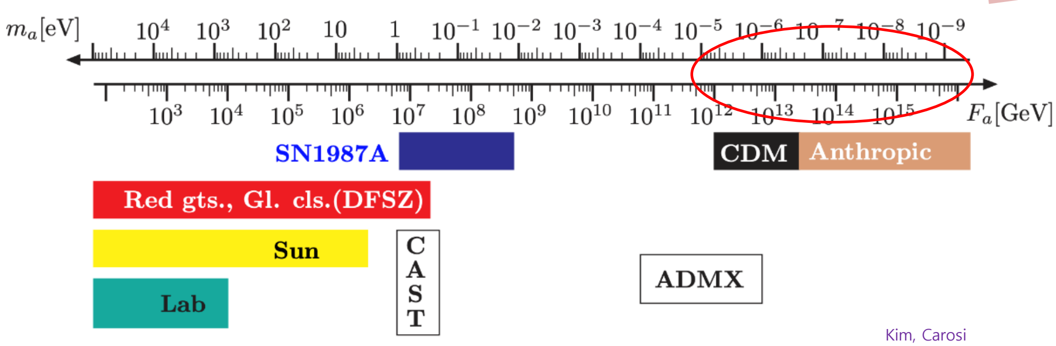
$$\Omega_a h^2 \simeq 0.18\theta_{\rm ini}^2 \left(\frac{f}{10^{12}{\rm GeV}}\right)^{1.19} \left(\frac{\Lambda_{\rm QCD}}{400{\rm MeV}}\right)$$

PQ symmetry breaking after inflation

- $\langle\theta_{\rm ini}^2\rangle = \frac{\pi^2}{3}$ (spatial average)
- anharmonic correction: $\Omega_a \to 2\Omega_a$

PQ broken during inflation

- $\theta_{\rm ini}$: free parameter

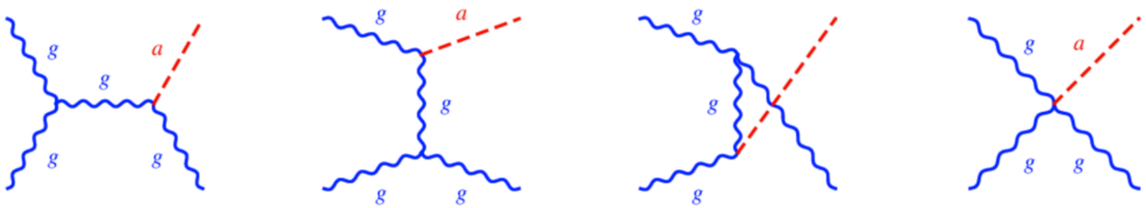


Kim, Carosi

2-2. QCD Axion- Cosmology

- Axion Production
  - **Thermal axion**

    - Produced from quark-gluon plasma



Cross section: $\frac{\alpha_s^3}{8\pi^2}\frac{1}{f^2}$ → Interaction rate $\Gamma \sim 10^{-5}\frac{T^3}{f^2}$

$\Gamma \sim H$

Decoupling temperature: $T_{\rm dec} \sim 10^{11}{\rm GeV}\left(\frac{f}{10^{12}{\rm GeV}}\right)^2$

→ axions are thermalized if $T > T$_dec

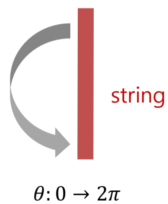
- Hot axion dark matter

From Boltzmann eq: $\Omega_a h^2 \simeq 5\times10^{-9}\left(\frac{f}{10^{12}{\rm GeV}}\right)^{-1}$

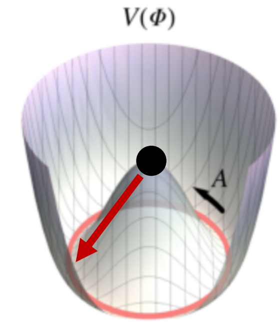
- **Axion Production**
  - **Axions from topological defects**

Case with PQ symmetry breaking after inflation

- PQ phase transition at $t_{\rm PQ}$ → Production of axionic strings



$$\Phi = \frac{f}{\sqrt{2}} e^{i\theta}$$



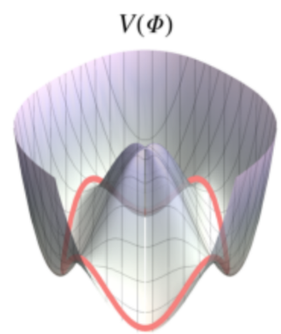
Core width $\sim \frac{1}{f}$ and string tension $\mu_{\rm string} \sim f^2$

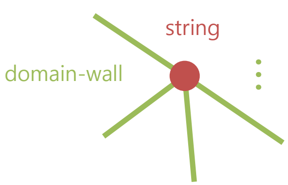
Long range interaction between strings mediated by massless axion field

- QCD phase transition at $t_{\rm QCD}$ → Axion potential

$$V(\theta) \simeq -m_u\, \Lambda_{\rm QCD}^3 \cos(N_{\rm DW}\theta)$$

→ Degenerate $N_{\rm DW}$ vacua along axion direction





$N_{\rm DW}$ domain-walls attached to string

wall tension $\sigma_{\rm wall} \sim m_a f^2$

- Axion Production

For $N_{\rm DW} \geq 2$, domain-walls are stable due to degenerate vacuum structure

→ Overclosure of the universe

Need explicit $Z_{N_{\rm DW}}$ breaking effect to lift the degenerate vacua

- **Axions from topological defects for $N_{\rm DW} = 1$** no cosmological domain-wall problem

  - Disk-like domain-wall bounded by a string

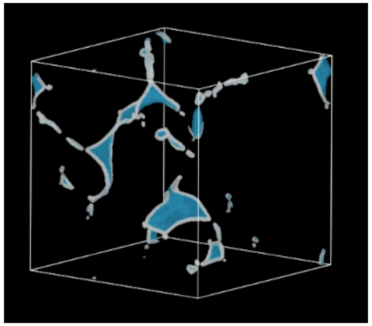
    → Unstable and collapse by wall tension while producing axions

Evolution of strings and walls: simple scaling solution

collapsing time

$$\rho_{\rm string} \sim H^2 \mu_{string} \sim \frac{f^2}{t^2} \quad \text{for } t_{\rm PQ} < t < t_{\rm coll}$$

$$\rho_{\rm wall} \sim H\sigma_{\rm wall} \sim \frac{m_a(t) f}{t} \quad \text{for } t_{\rm QCD} < t < t_{\rm coll}$$



Axion number density from string-wall network dimensional analysis

$$\frac{d}{dt}(R^3 n_a) \sim HR^3 \frac{\rho_{\rm string} + \rho_{\rm wall}}{(\text{typical energy of emitted axion})} \quad \text{until collapsing}$$

Axion Production

Axions from topological defects for $N_{\mathrm{DW}} = 1$

- Most axions are produced near t_{coll}, soon after the moment $m_a(t) \sim\ H(t)$

  → Non-relativistic

- Axion cold dark matter from the string-wall system

$$\Omega_a h^2 = c_a \left(\frac{f}{10^{12}\mathrm{GeV}}\right)^{1.19} \left(\frac{\Lambda_{\mathrm{QCD}}}{400\mathrm{MeV}}\right)$$

with $c_a \simeq$3-6 from numerical simulations

→ $1.7c_a$ times larger than the axion density from misalignment

QCD axion

Axion searches

- Searches for axion/axion-like particle

Axion Interactions

$$\frac{\alpha_s}{8\pi}\frac{a}{f}G\tilde{G} - \frac{g_{a\gamma\gamma}}{4}aF\tilde{F} + \frac{c_f}{2f}(\partial_\mu a)\bar{f}\gamma^\mu\gamma_5 f$$

axion-photon coupling

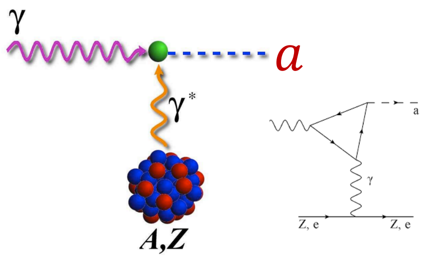
$$g_{a\gamma\gamma}\vec{E}\cdot\vec{B}$$

axion-electron, axion-neutron couplings

$$\frac{i}{2}g_{aee}a\bar{e}\gamma_5 e + \frac{i}{2}g_{aNN}a\bar{N}\gamma_5 N$$

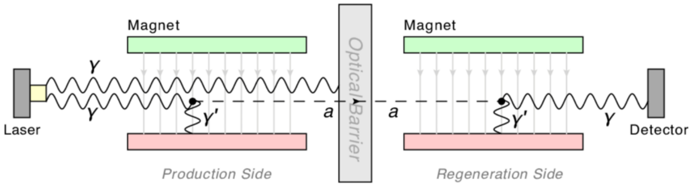
- **Terrestrial**

Experiments based on Primakoff effect



→ Conversion between photon and axion in external EM field

- Light shining through walls: Strong B over long distances



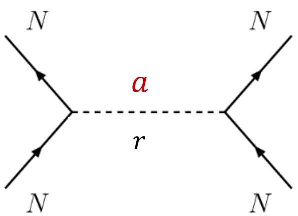
2-3. Axion Searches

- **Terrestrial**
  - Photon polarization

    Linearly polarized light passing through magnetic field

    → Primakoff effect to reduce the parallel component
  - Fifth force

    Spin-dependent forces mediated by axion: axion-neutron coupling



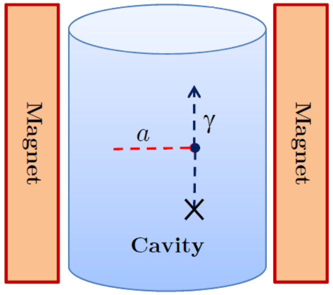
Range: suppressed by $e^{-m_a r}$

- **Celestrial**
  - Direct searches astrophysical source of axions

    Microwave resonant cavity experiments for $m_a = 10^{-6}$- 10^{-4}eV

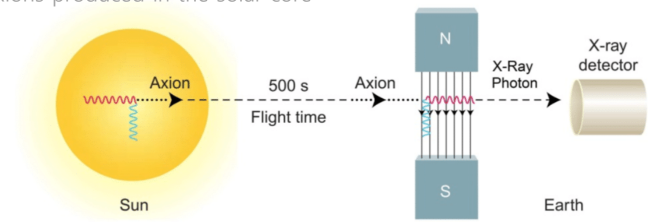
    - Conversion of axions to microwave photons

    Need to tune cavity e.g. $m_a = 10^{-5}$eV → frequency= $\frac{m_a}{\hbar} = 2.4$GHz



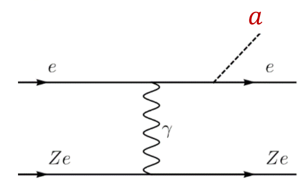
- **Celestrial**
  - Direct searches
    - Axion helioscope for $m_a = 0.1\text{-}1\mathrm{eV}$

axions produced in the solar core



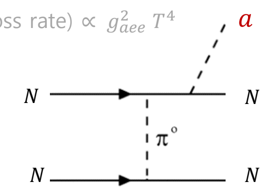
  - Indirect Searches: Stellar energy loss limits
    - White dwarf, red giant: Bremsstrahlung $e + Ze \rightarrow Ze + e + a$

      Primakoff $\gamma + Ze \rightarrow \ Ze + a$

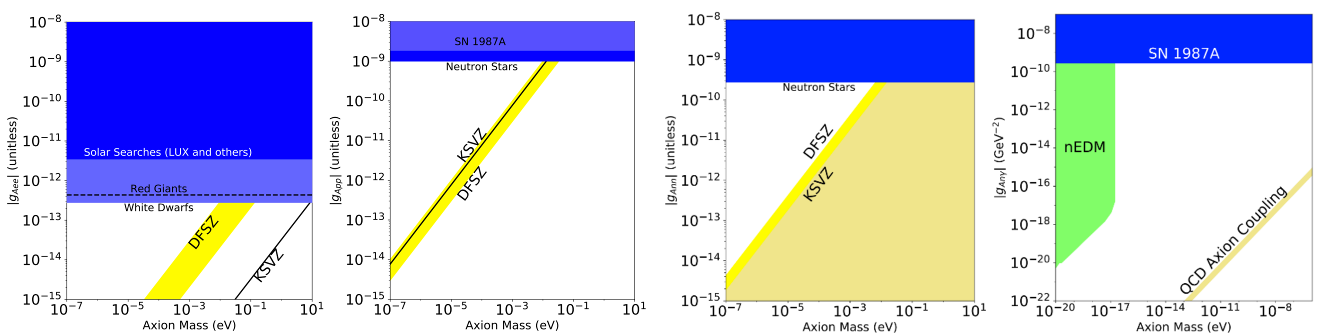


(additional energy loss rate) $\propto\ g_{aee}^2\, T^4$

    - Neutron star, supernovae: Nucleon Bremsstrahlung $N + N \rightarrow N + N + a$



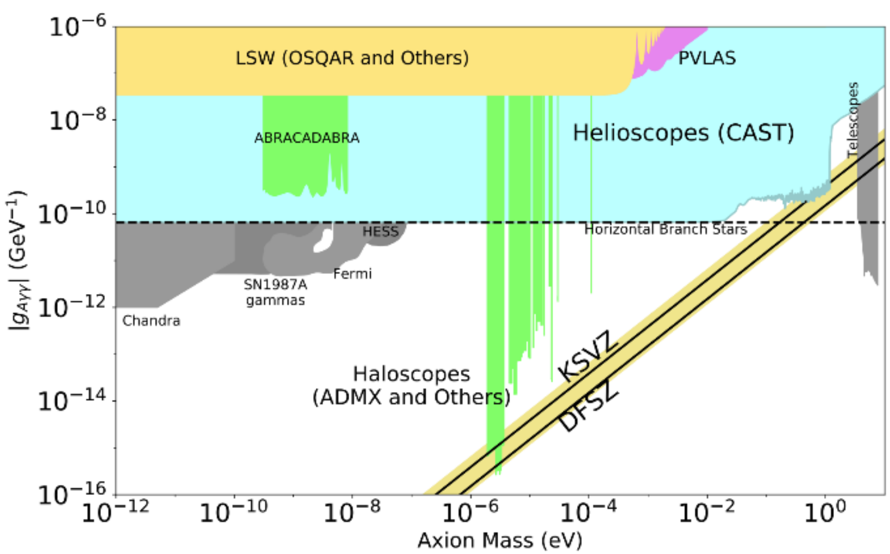
Astrophysical bounds: $f > 10^9\mathrm{GeV}$

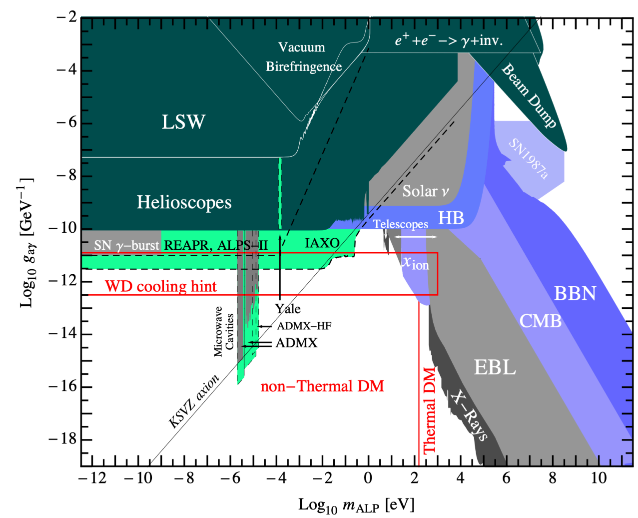


PDG

- **Cosmological**
  - Direct: axion cold dark matter
  - Indirect: hot dark matter, dark radiation, isocurvature density perturbation, gravitational waves, CMB spectral distortion, …

- Constraints on axion





Axion

Summary

2-4. BSM Models

- Two BSM scenarios
  - **Axionic Extension**
    - Light scalar particles feebly coupled to the SM
    - Light scalar from continuous shift symmetry

Natural and interesting candidate for 'very weakly coupled light particle' beyond the SM!

  - **Supersymmetric Extension**
    - Heavy particles above the weak scale with sizable coupling to the SM
    - Supersymmetry to remove the UV sensitivity of scalar fields