秋の学校「理論と観測から迫るダークマターの
正体ととその分布」@ 国立天文台 (Nov. 9-11)

ダークマター・アクシオン

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1. Strong CP problem and axion

- QCD Lagrangian

$$\mathcal{L}_{\text{QCD}} = \mathcal{L}_q - \frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + \frac{g^2\theta}{32\pi^2}F^a_{\mu\nu}\tilde{F}^{a\mu\nu}$$

$F^a_{\mu\nu}$: gluon field strength

$$\tilde{F}^{a\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\lambda\eta}F^a_{\lambda\eta}$$

CP violating term

  - θ : a parameter in QCD
  - T transformation

$$T\left[F^a_{\mu\nu}\tilde{F}^{a\mu\nu}\right]T^{-1} \Rightarrow -\left[F^a_{\mu\nu}\tilde{F}^{a\mu\nu}\right]$$

- Experiment
  - Neutron dipole moment

$$|\theta| < 0.7 \times 10^{-11}$$

  - Why θ is so small? → **Strong CP Problem**
- Solution Peccei-Quinn Mechanism (1977
  - Make θ dynamical variable (field)

Peccei-Quinn mechanism

- Introducing a scalar field a $\Leftarrow$ Axion

$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + \frac{1}{2}\partial_\mu a \partial^\mu a + \frac{g^2}{32\pi^2}\left(\theta - \frac{a}{F_a}\right)F^a_{\mu\nu}\tilde{F}^{a\mu\nu}$$

- Effective potential $V(a)$

Vafa Witten (1984)

$$\exp\left[-\int d^4x\, V(a)\right] = \int \mathcal{D}A_\mu \exp\left[-\int d^4x \left\{\frac{1}{4}F^a_{\mu\nu}F^a_{\mu\nu} + i\frac{g^2}{32\pi^2}\left(\theta - \frac{a}{F_a}\right)F^a_{\mu\nu}\tilde{F}^a_{\mu\nu}\right\}\right]$$

$$\leq \int \mathcal{D}A_\mu \exp\left[-\int d^4x \left\{\frac{1}{4}F^a_{\mu\nu}F^a_{\mu\nu}\right\}\right] = \exp\left[-\int d^4x\, V(a = \theta F_a)\right]$$

→ $V(a) \geq V(a = \theta F_a)$ → CP invariant minimum

$a - F_a\theta \to a$ $\qquad$ $V(a)$ min. at $a = 0$

- This is realized by introducing a complex scalar field Φ (PQ scalar) with coupling to quarks and $U(1)_{PQ}$

- $U(1)_{PQ}$ is is spontaneously broken at some scale η

Axion

- Axion is the Nambu-Goldstone boson associate with $U(1)_{PQ}$ breaking and can be identified with the phase of PQ scalar

$$\Phi = |\Phi| e^{i\theta} = (\eta + \varphi) e^{ia/\eta}$$

- Axion acquires mass through QCD non-perturbative effect

$$m_a \simeq 0.6 \times 10^{-5} \text{eV} \left(\frac{F_a}{10^{12} \text{GeV}} \right)^{-1}$$

$F_a = \eta / N_{\text{DW}}$

N_{DW}: domain wall number

- Axion is a good candidate for dark matter of the universe
- Cosmological evolution of axion (PQ scalar)
  - PQ symmetry breaking after inflation

    Formation of topological defects → Domain wall problem
  - PQ symmetry breaking before inflation

    Isocurvature perturbations → Isocurvature problem

Today’s Talk

- Introduction
- PQ symmetry breaking after inflation
  - Cosmological evolution of axion
  - Comic axion density
- PQ symmetry breaking before inflation
  - Axion in the inflationary universe
  - Suppression of Isocurvature Perturbations
- Axion Search
- Conclusion

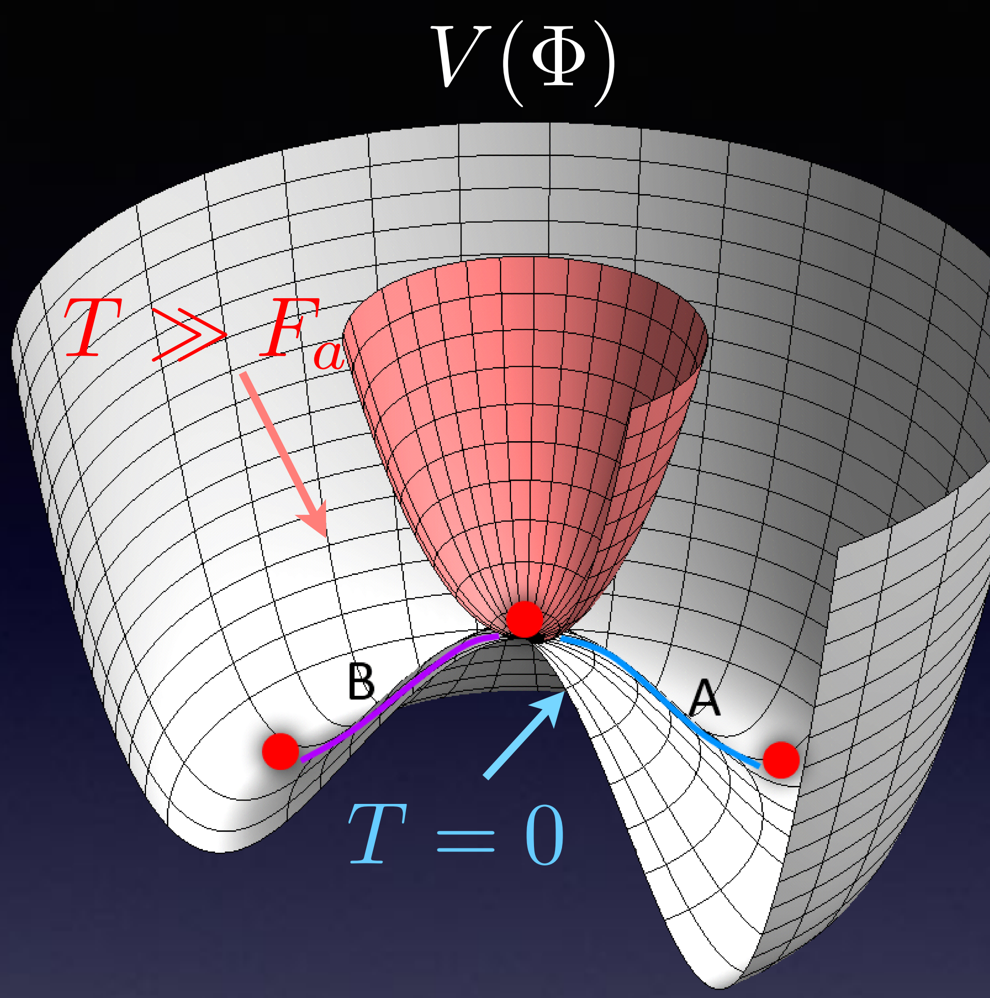
2. Cosmological Evolution of Axion (PQ after inflation)

$T \simeq \eta$

- $U_{PQ}(1)$ symmetry is broken
  - Axion is a phase direction of PQ scalar and massless

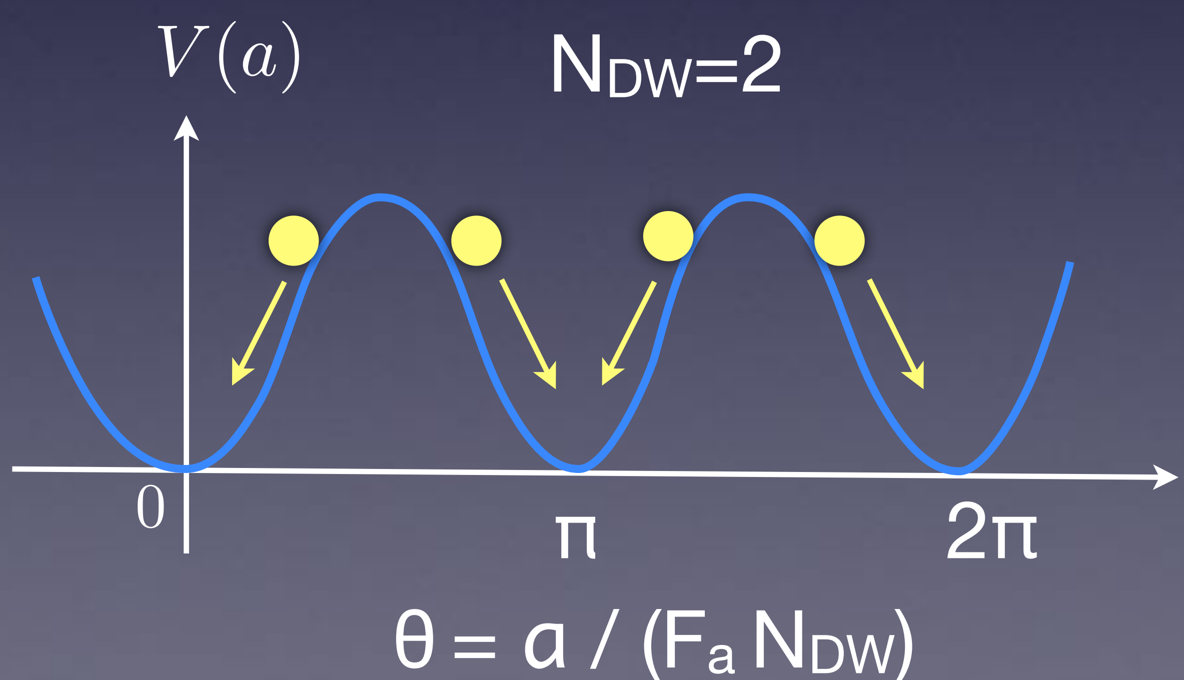
$$\Phi = |\Phi| e^{i\theta} = |\Phi| e^{ia/\eta} \qquad m_a = 0$$

  - Formation of Cosmic Strings



$T \simeq \Lambda_{\rm QCD}$

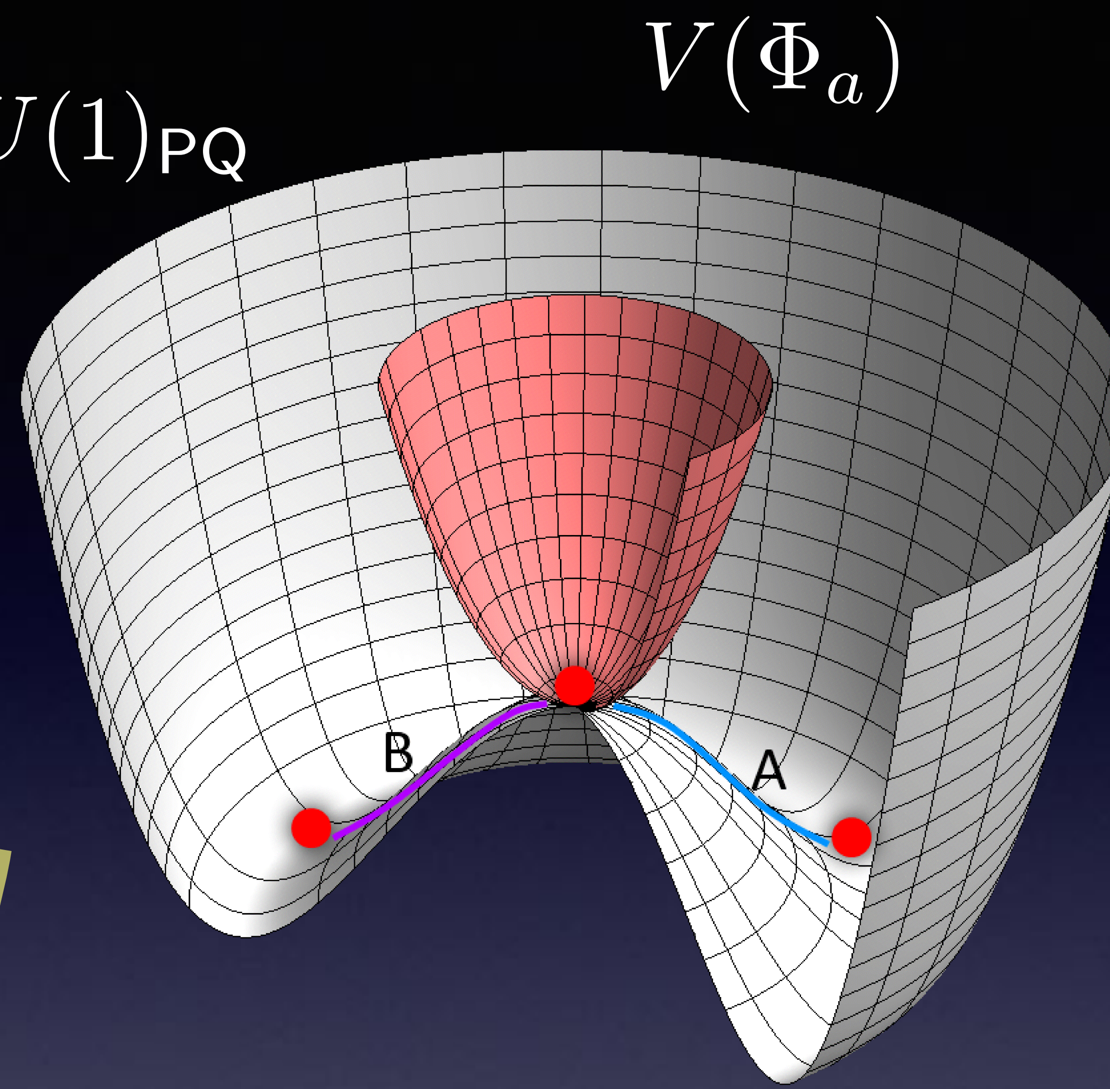
- Axion acquires mass through non-perturbative effect
  - $U_{PQ}(1)$ is broken to $Z_{N_{DW}}$
  - Coherent oscillation
  - Formation of Domain Walls



Cosmic String

- Spontaneous symmetry breaking of $U(1)_{\mathrm{PQ}}$

$$\Phi = |\Phi| e^{i\theta} = |\Phi| e^{ia/\eta}$$

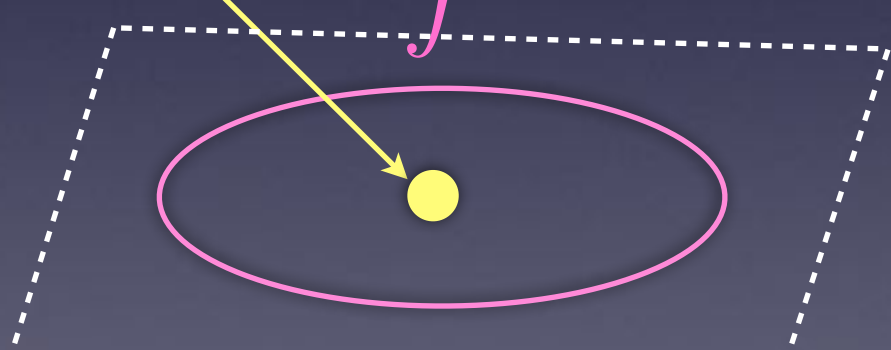


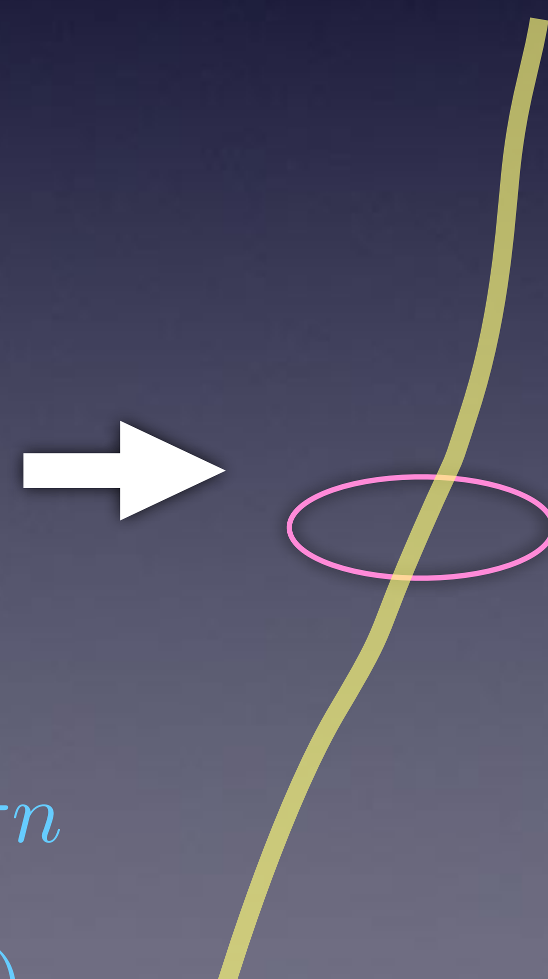
- Formation of Cosmic Strings

θ takes different values at different places in the Universe

$\Phi = 0$

$$\oint d\theta = 2\pi$$





Axionic String

$$\oint \partial_\mu \theta dx^\mu = \oint d\theta = 2\pi n$$

$(n$: integer$)$

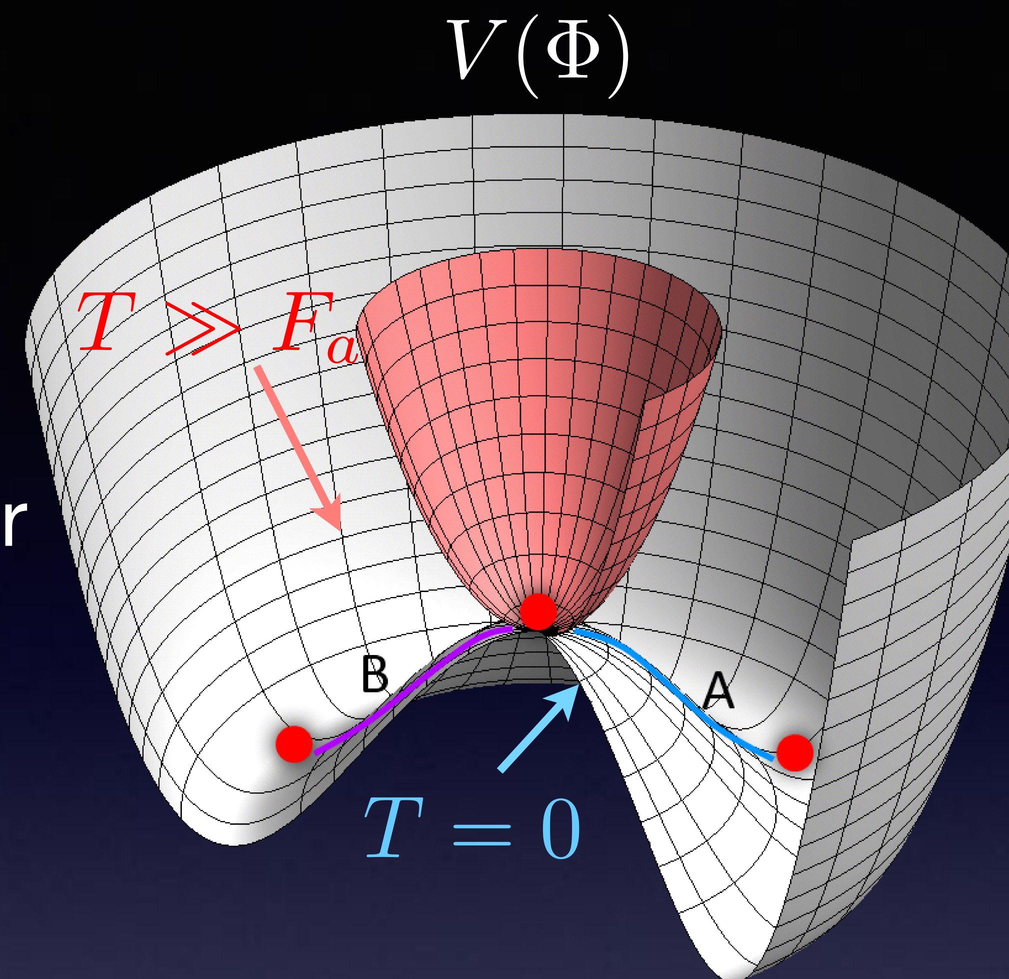
2. Cosmological Evolution of Axion

$T \simeq \eta$

- $U_{PQ}(1)$ symmetry is broken
  - Axion is a phase direction of PQ scalar and massless

$$\Phi = |\Phi| e^{i\theta} = |\Phi| e^{ia/\eta} \qquad m_a = 0$$

  - Formation of Cosmic Strings



$T \simeq \Lambda_{QCD}$

- Axion acquires mass through non-perturbative effect
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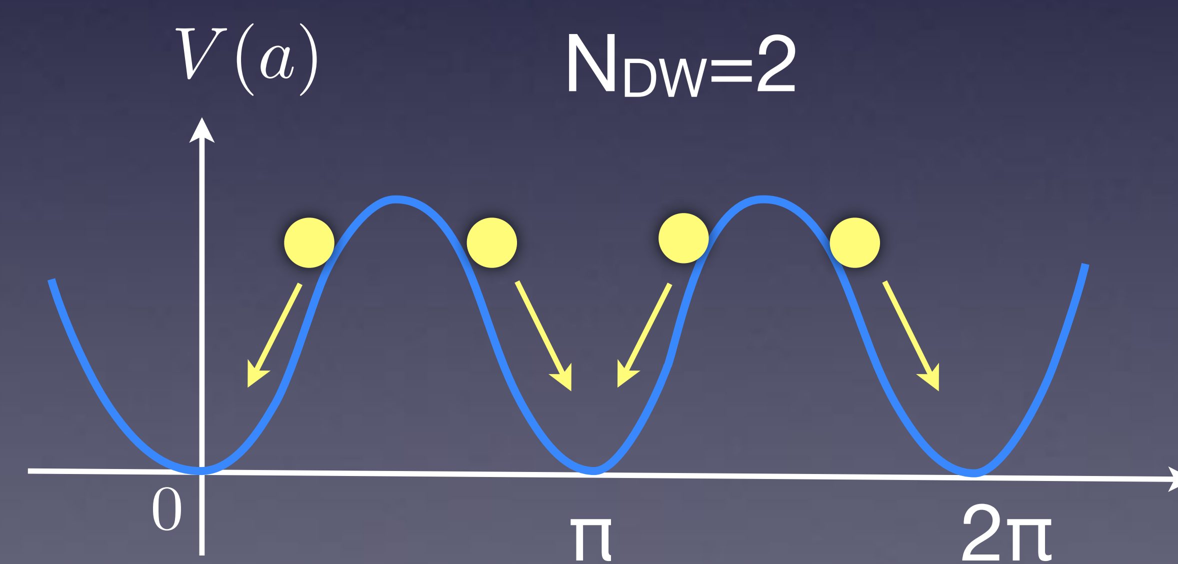
  - Formation of Domain Walls



$\theta = a / (F_a N_{DW})$

$$V(a) = m_a^2 F_a^2 \left[1 - \cos\left(\frac{a}{F_a} \right) \right]$$

Remark

- PQ scale

  - $F_a = \frac{\eta}{N_{\rm DW}}$ $\qquad \eta = N_{\rm DW} F_a$

- PQ phase

  - $\theta = \frac{a}{\eta} = \frac{a}{F_a N_{\rm DW}}$
  - $\theta_a \equiv \frac{a}{F_a} = \frac{N_{\rm DW}\, a}{\eta} = N_{\rm DW}\,\theta$

- Potential

  - $$V(a) = m_a^2 F_a^2 \left[1 - \cos\left(\frac{a}{F_a}\right)\right] = m_a^2 F_a^2 \left[1 - \cos\left(\frac{a N_{\rm DW}}{\eta}\right)\right]$$
    $$= m_a^2 F_a^2 [1 - \cos\theta_a] = m_a^2 F_a^2 [1 - \cos(N_{\rm DW}\,\theta)]$$

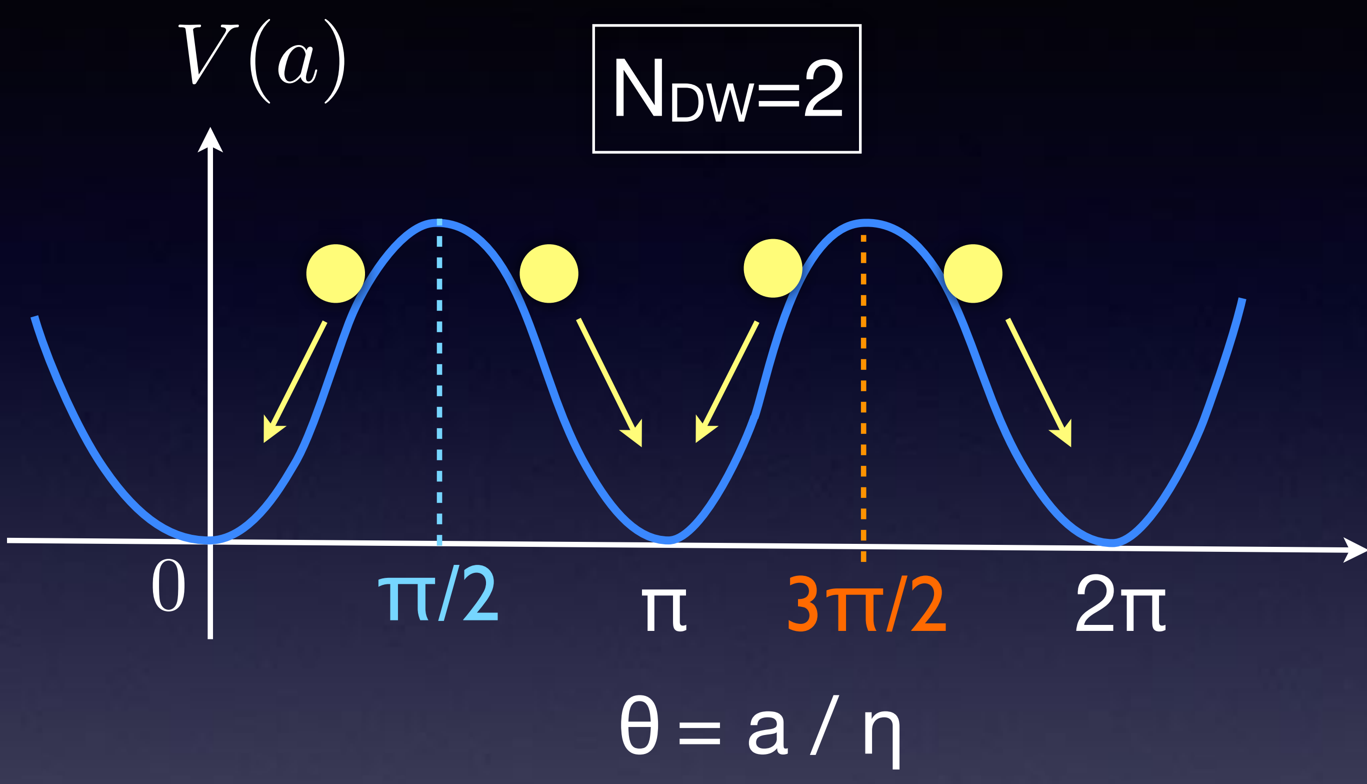
Domain Wall

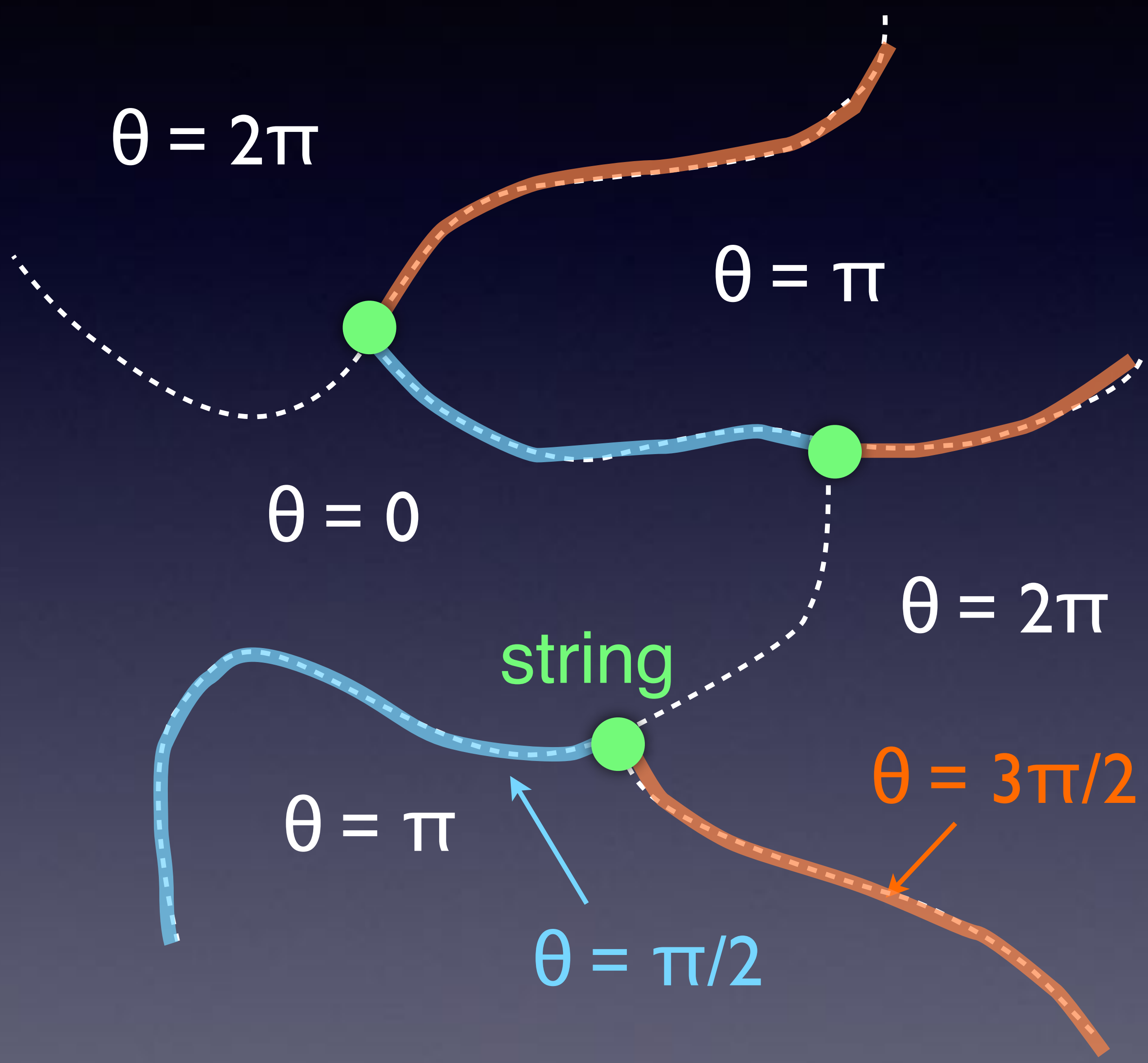
- Formation of Domain Walls (N$_{DW}$: Domain wall number)

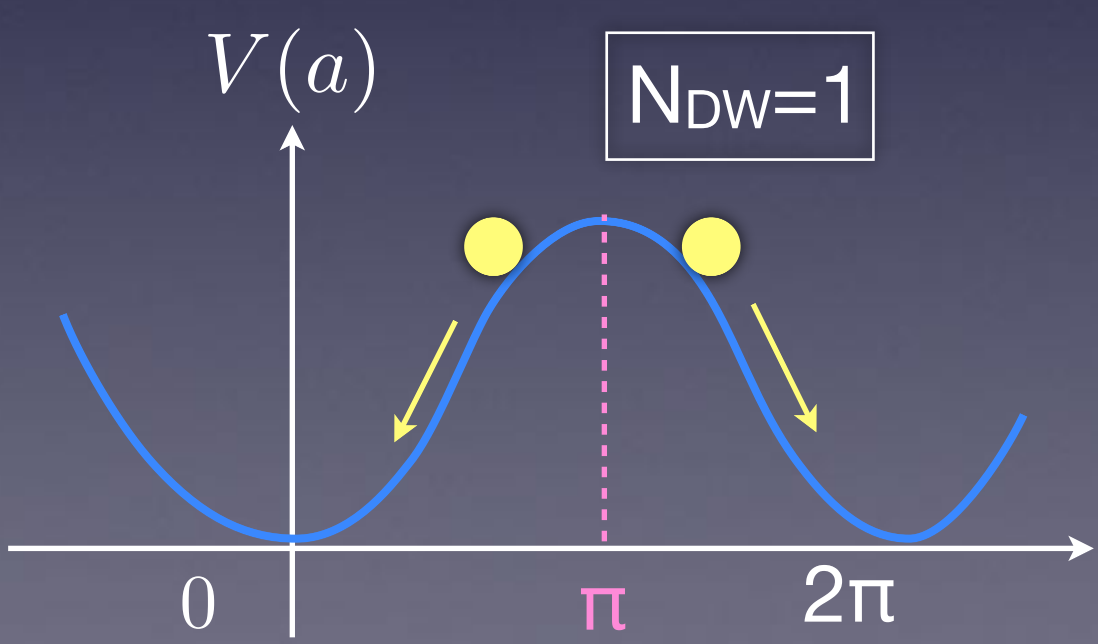
depends on axion models

KSVZ: $N_{\rm DW} = 1$

DFSZ: $N_{\rm DW} = 6$



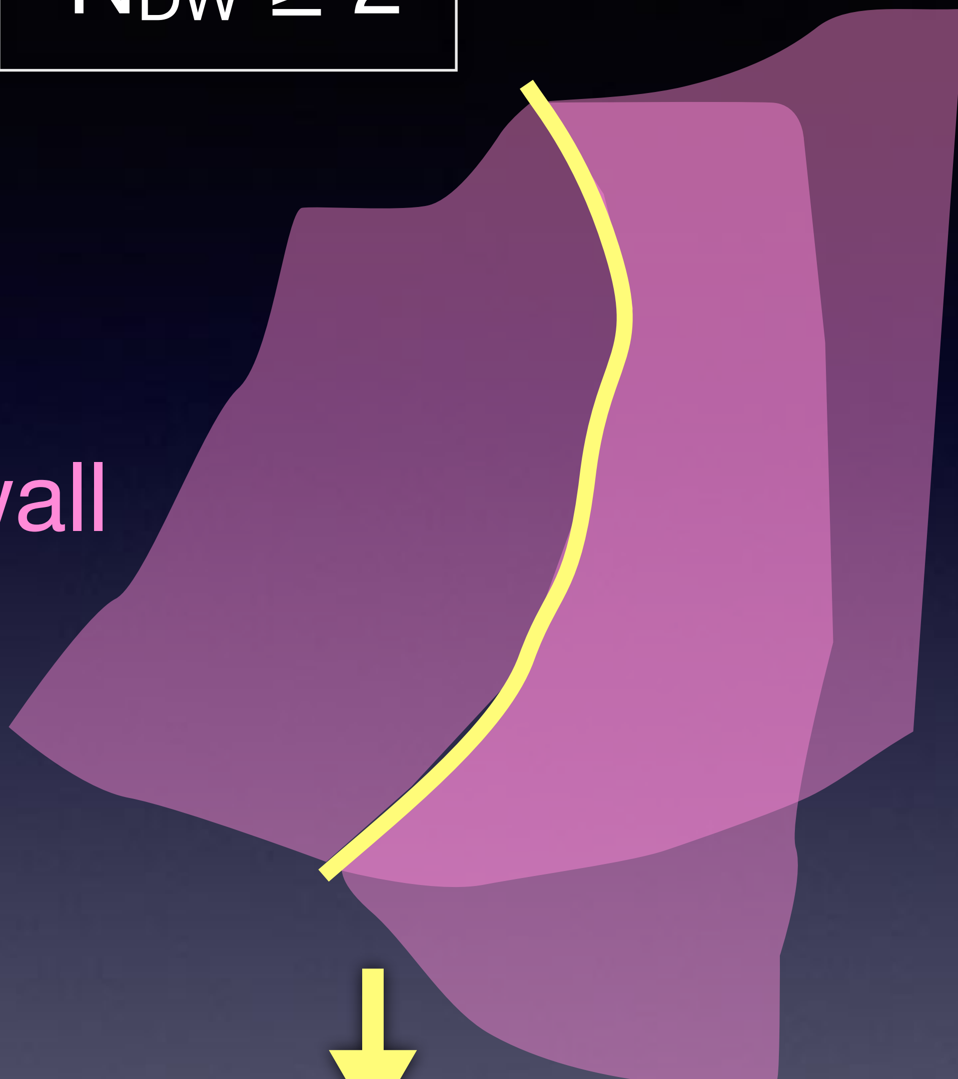




→ Axion Domain Wall

- Domain walls attach to strings

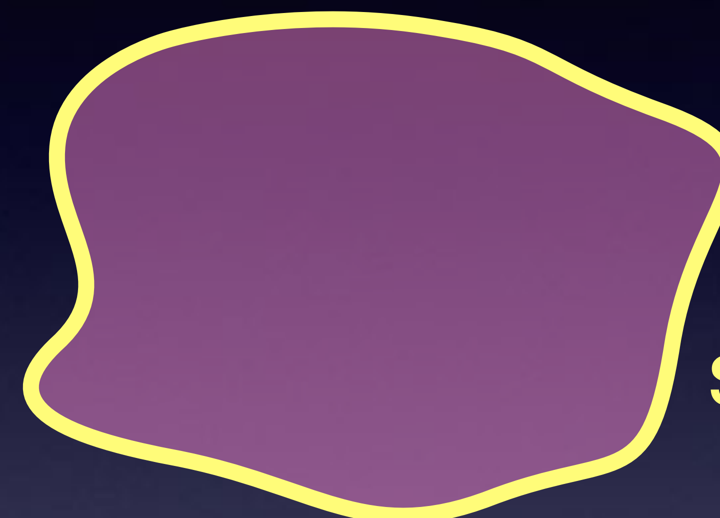
$N_{DW} \geq 2$



Stable and dominate the universe

Domain Wall Problem

$N_{DW}=1$



Collapse

Virenkin Everett (1982)
Barr Choi Kim (1986)

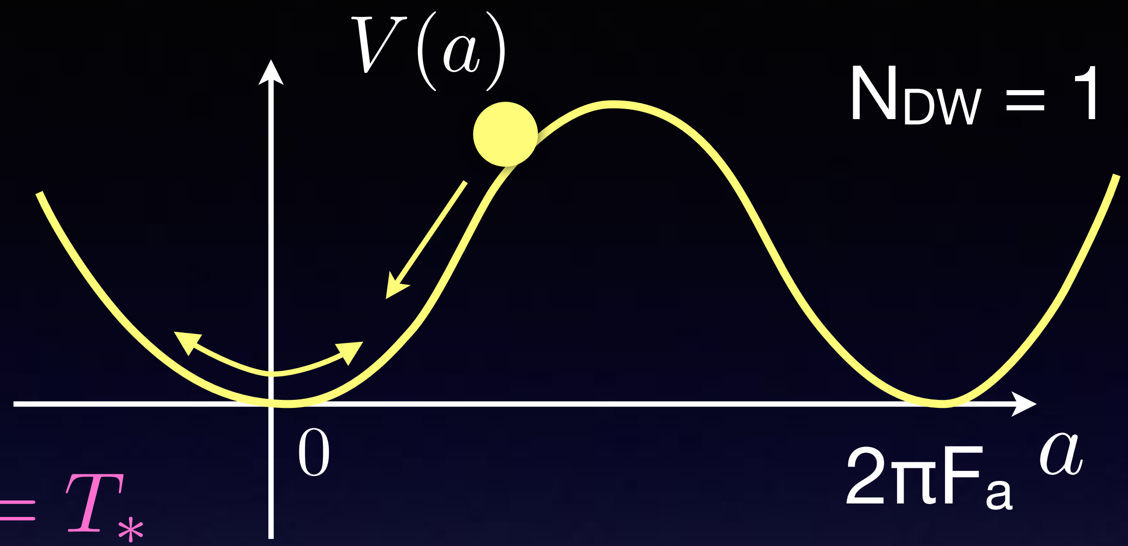
Axion overproduction

3. Cosmic Axion Density

- Three sources for cosmic axion density
  - coherent oscillation
  - axions from strings
  - axions from string-wall networks

3. Cosmic Axion Density

3.1 Coherent axion oscillation



$$H \simeq m_a(T_*)$$

- Axion field starts to oscillate at $T = T_*$
- Coherent oscillation of axion field gives a significant contribution to the cosmic density ($\Omega_{\text{CDM}} h^2 \simeq 0.12$)

$$\Omega_{a,\text{osc}} h^2 \simeq 7 \times 10^{-4} \langle \theta_*^2 \rangle \left(\frac{F_a}{10^{10}\,\text{GeV}} \right)^{1.19}$$

spatial average

$\langle \theta_*^2 \rangle \simeq 6$

$\theta_* = a_*/F_a$: misalighnment angle at T_*

including anharmonic effect

$$\Omega_{a,\text{osc}} h^2 \simeq 0.12 \quad \text{if} \quad F_a \simeq 2 \times 10^{11}\ \text{GeV}$$

3.2 Axions from strings

- Axionic strings are produced when U(1) $_{PQ}$ symmetry is spontaneously broken

- Numerical Simulation

  Hiramatsu, MK, Sekiguchi, Yamaguchi, Yokoyama (2010)
  MK, Saikawa, Sekiguchi (2014)

  - String network obeys scaling solution

$$\rho_{\rm string} = \xi \frac{\mu}{t^2} \quad (\mu \sim \eta^2 \text{ : string tension})$$

$$\xi = 1.0 \pm 0.5$$

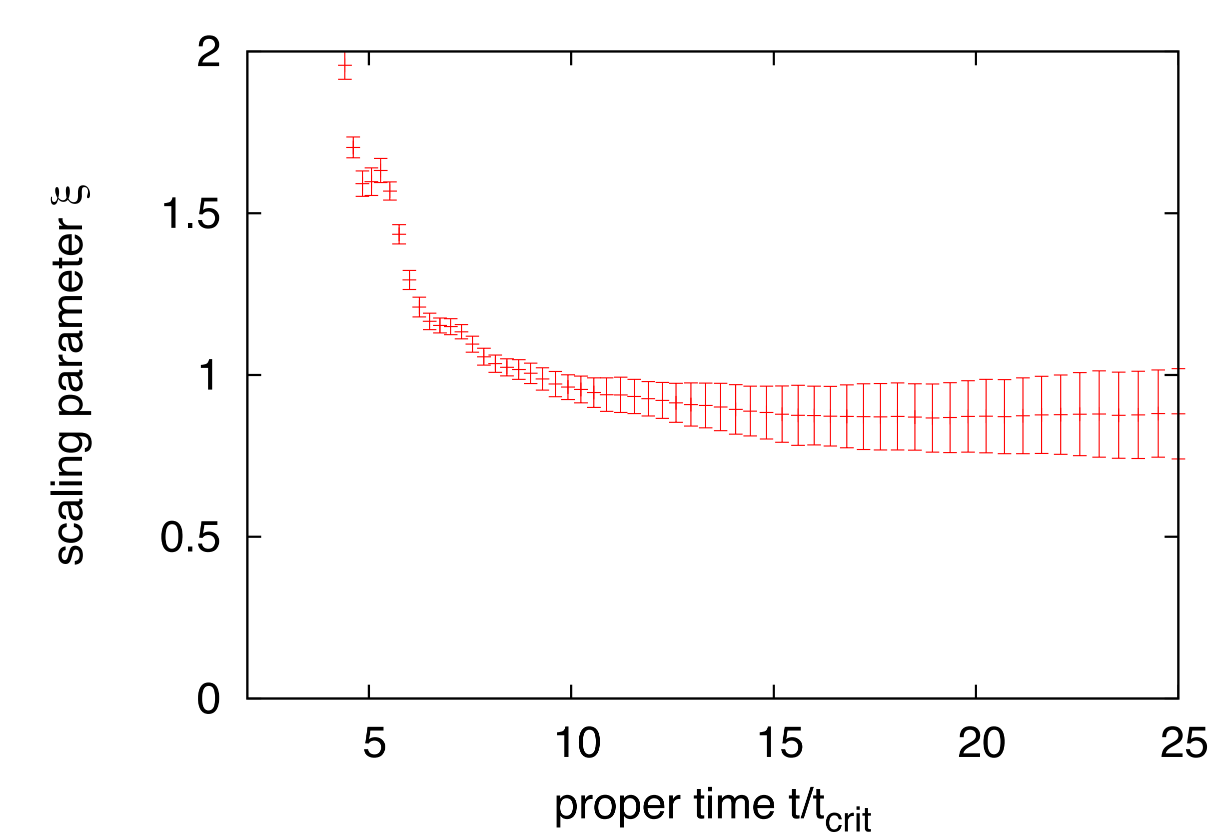
  - Energy Spectrum

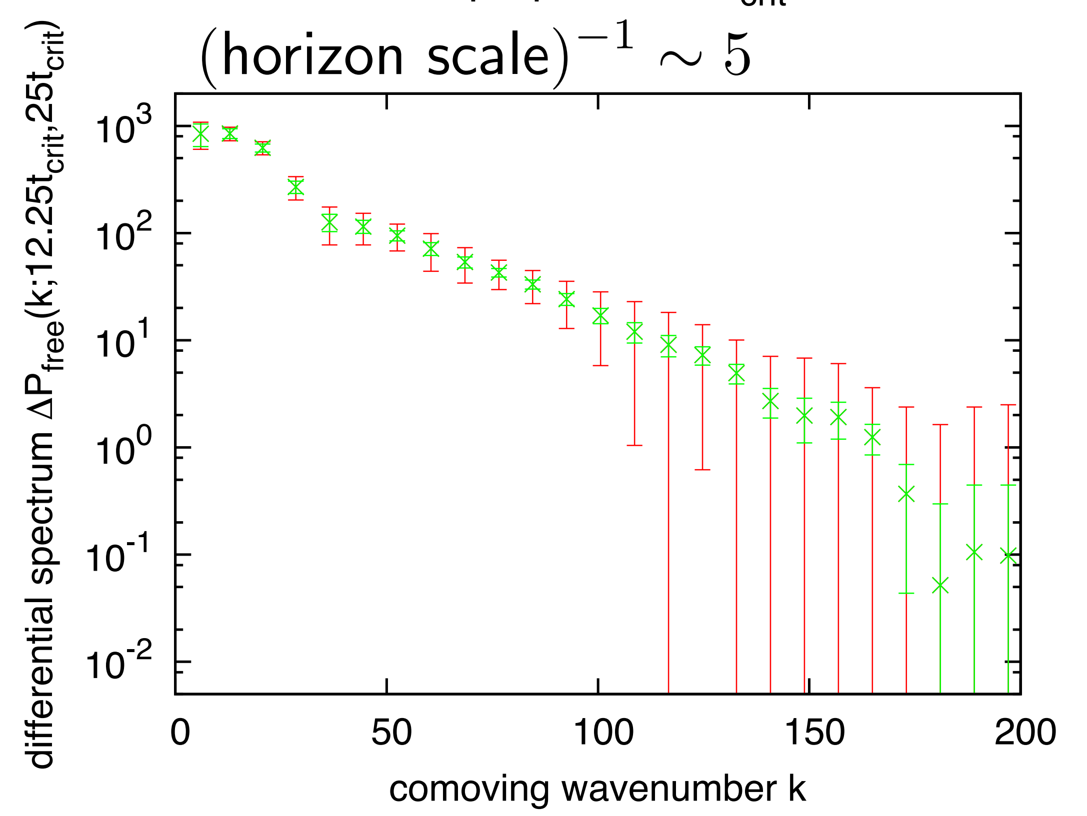
    peaked at k ~ horizon scale

    exponentially suppressed at higher k

  - Mean energy $\bar{\omega}_a = \epsilon \dfrac{2\pi}{t}$

$$\epsilon = 4.02 \pm 0.70$$





Density of Axions from Strings

- Mean energy

$$\bar{\omega}_a = \epsilon \frac{2\pi}{t}$$

$$\boxed{\epsilon = 4.02 \pm 0.70}$$

MK, Saikawa, Sekiguchi (2014)

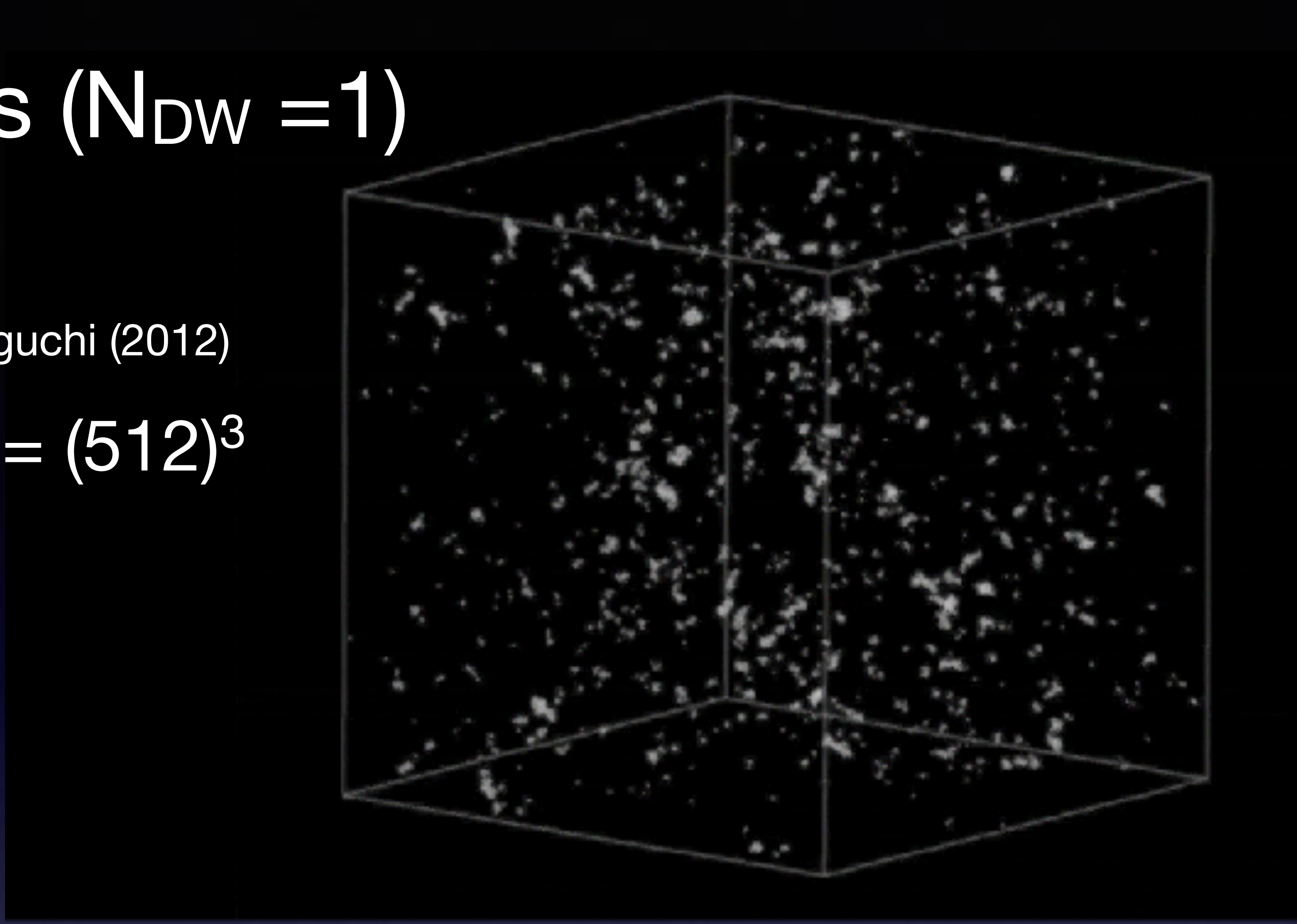
- Cosmic density of produced axion

$$\boxed{\Omega_{a,\mathrm{string}} h^2 = (7.3 \pm 3.9) \times 10^{-3} N_{\mathrm{DW}}^2 \left(\frac{F_a}{10^{10}\mathrm{GeV}} \right)^{1.19}}$$

- Axions from strings gives at least comparable contribution to the cosmic density with those from the coherent oscillation

$$\Omega_{a,\mathrm{osc}} h^2 \simeq 4 \times 10^{-3} \left(\frac{F_a}{10^{10}\mathrm{GeV}} \right)^{1.19}$$

3.3 Axion from Domain Walls ($N_{DW} = 1$)



- Simulation of string-wall network

  Hiramatsu, MK, Saikawa, Sekiguchi (2012)

  - Lattice simulation with N(grid) = $(512)^3$

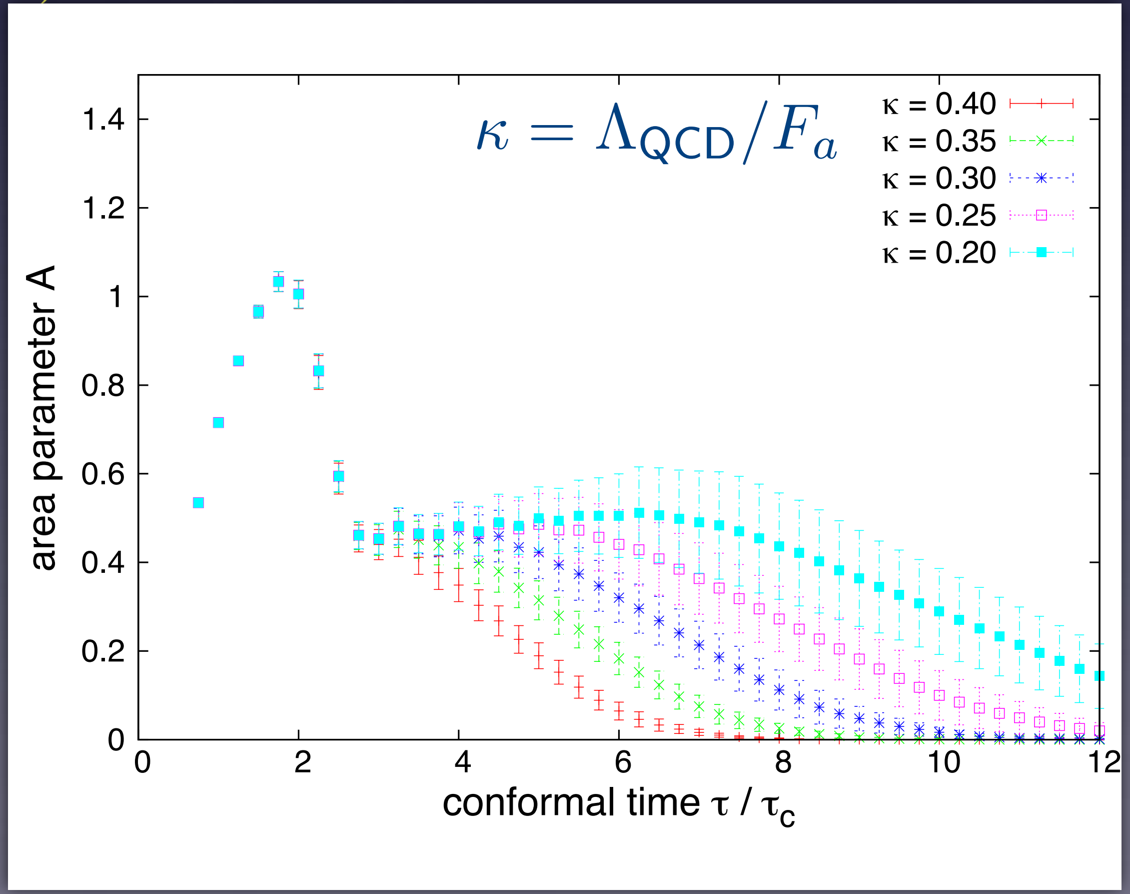
- Strings obey scaling solution

- Walls

$$\rho_{\text{wall}} = \mathcal{A}\frac{\sigma}{t}$$ $(\sigma \sim F_a^2 m_a \ : \ \text{wall tension})$

$\mathcal{A}$: area parameter

$$\mathcal{A} \simeq 0.50 \pm 0.25$$



- Domain wall collapse
  when wall tension exceeds string tension

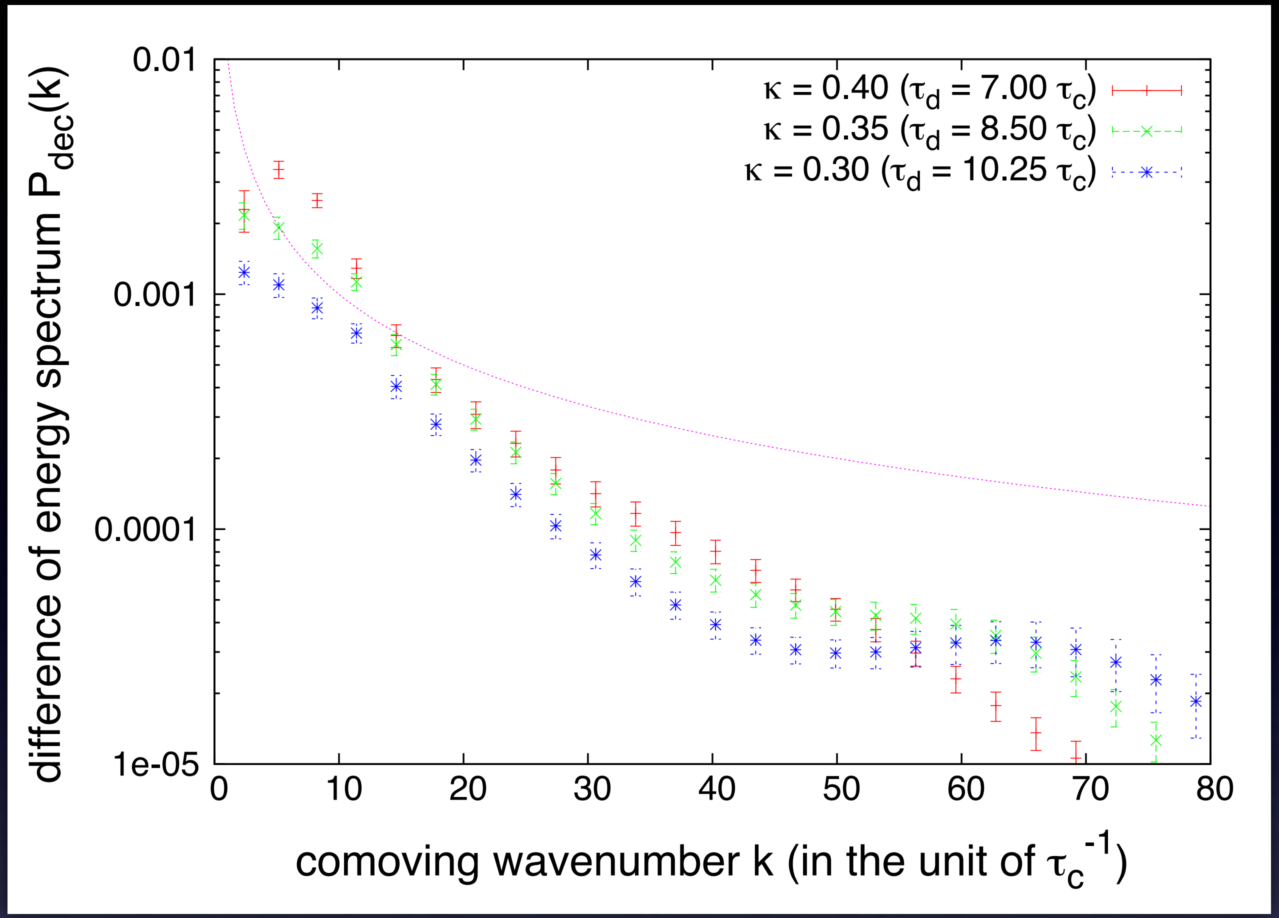
→ Axions from collapsed domain walls

- Energy spectrum of emitted axion
  - Peak at k ~(axion mass)

$$\frac{E_a}{m_a}(t_{\mathrm{decay}}) = \tilde{\epsilon}_w$$

$$\boxed{\tilde{\epsilon}_w = 3.23 \pm 0.18}$$

Hiramatsu, MK, Saikawa, Sekiguchi (2012)

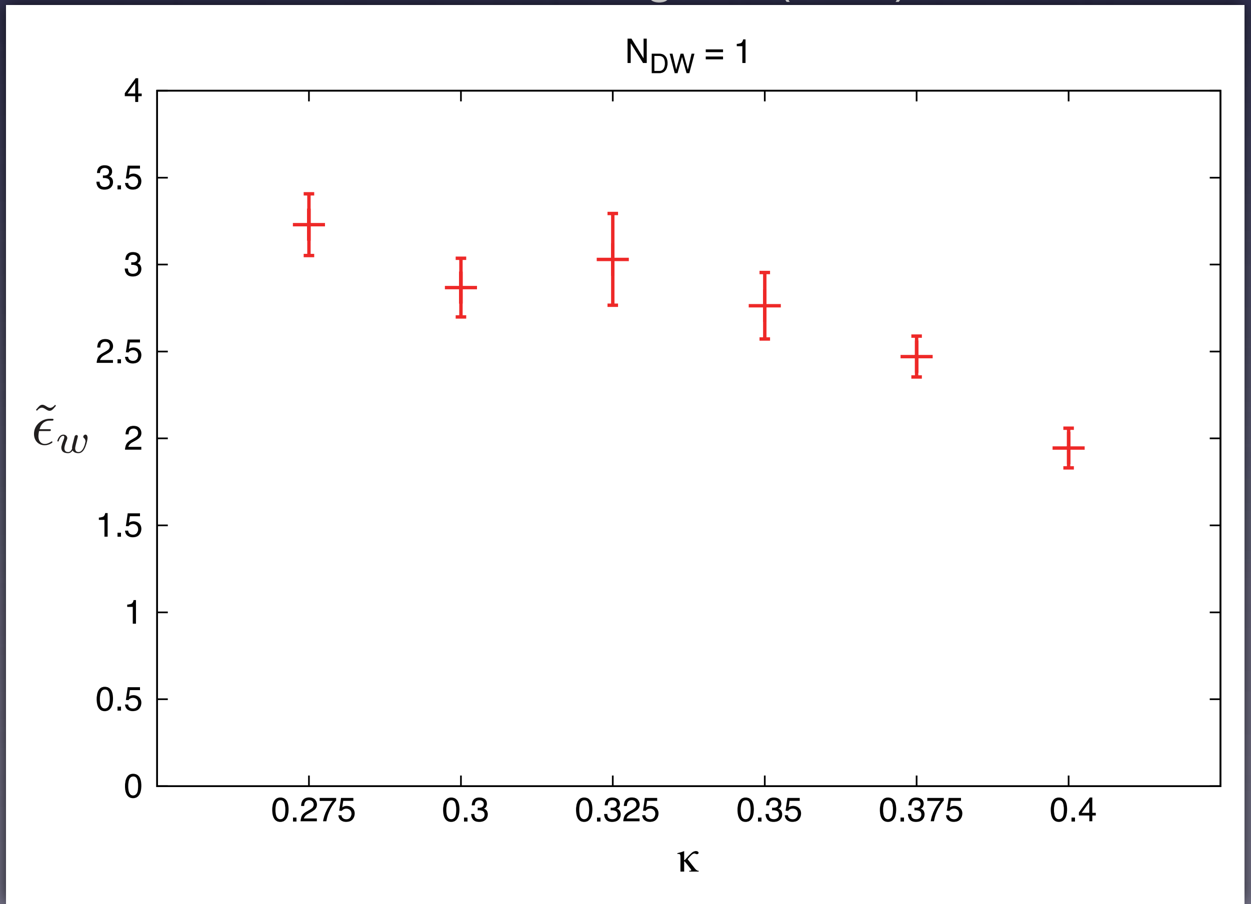


- Axion density from string-wall sys.

$$\boxed{\Omega_{a,\mathrm{wall}} h^2 = (3.7 \pm 1.4) \times 10^{-3} \times \left(\frac{F_a}{10^{10}\,\mathrm{GeV}}\right)^{1.19}}$$

comparable to axion densities from other sources

MK, Saikawa, Sekiguchi (2014)



Cosmic Axion Density (N_{DW} =1)

- Total cosmic axion density

$$\Omega_{a,\mathrm{tot}}h^2 = \Omega_{a,\mathrm{osc}}h^2 + \Omega_{a,\mathrm{strng}}h^2 + \Omega_{a,\mathrm{wall}}h^2$$
$$= (1.6 \pm 0.4) \times 10^{-2} \left(\frac{F_a}{10^{10}\mathrm{GeV}}\right)^{1.19}$$

↔ $\Omega_{\mathrm{CDM}}h^2 \simeq 0.12$

WMAP, Planck

- Constraint on F_a

$$F_a \lesssim (4.6 - 7.2) \times 10^{10}\ \mathrm{GeV}$$
$$m_a \gtrsim (0.8 - 1.3) \times 10^{-4}\ \mathrm{eV}$$

3.4 Axion from Walls ($N_{DW} \geq 2$)

- Wall-string networks are stable and soon dominate the universe

  ➡ Domain Wall Problem

- The problem can be avoided by introducing a "bias" term which explicitly breaks PQ symmetry   Sikivie (1982)

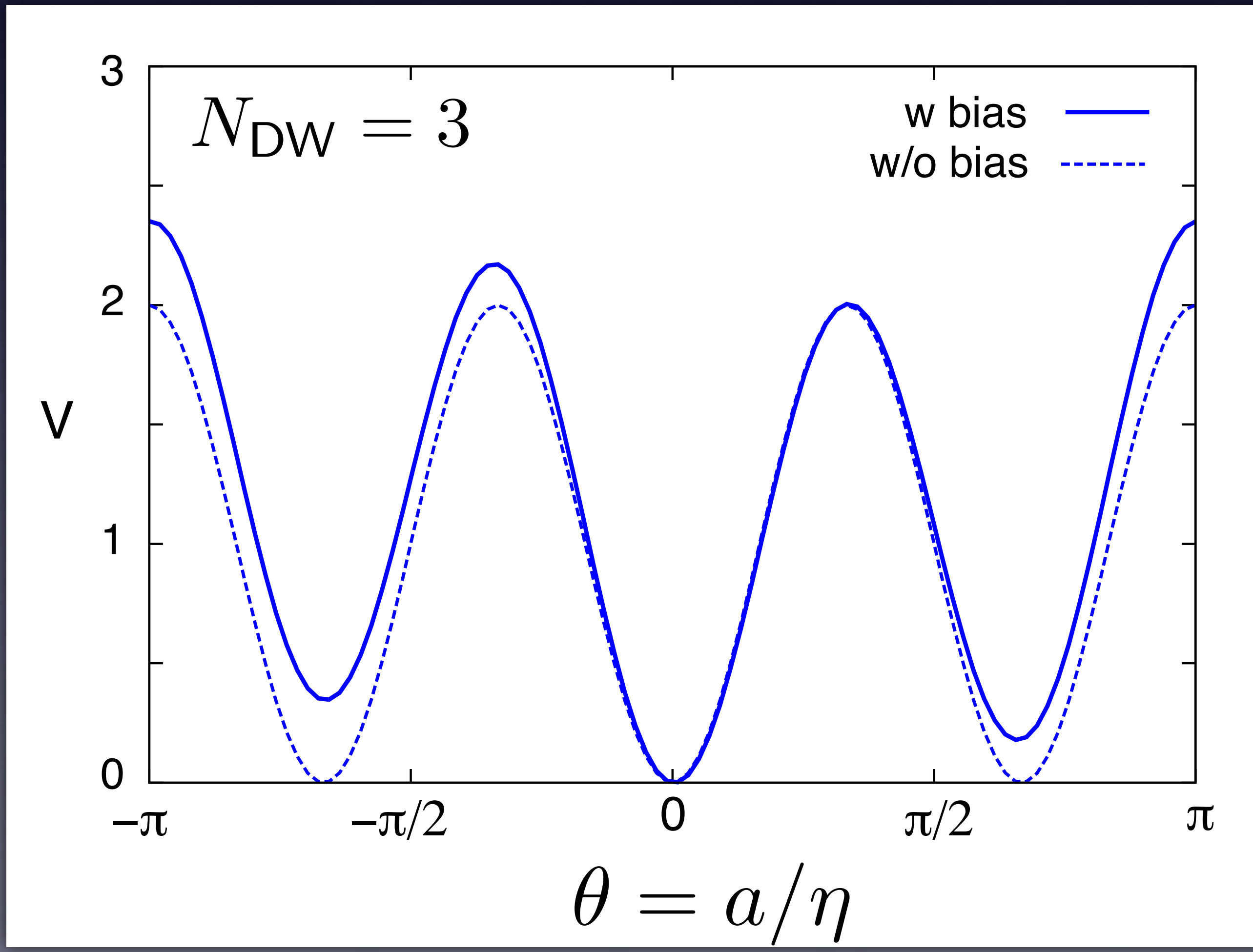
$$V_{\text{bias}} = -\Xi\eta^3\left(\Phi e^{-i\delta} + \text{h.c.}\right)$$

Ξ : bias parameter

δ : phase of bias term

- Bias term lifts degenerated vacua

- Differences of the vacuum energy produce pressure on the walls and eventually annihilate domain walls



- For small bias
  - Long-lived domain walls emit a lot of axions which might exceed the observed matter density

    Large bias is favored

- For large bias
  - Bias term shifts the minimum of the potential and might spoil the original idea of Peccei and Quinn

$$\theta = \frac{2\Xi N_{\rm DW}^3 F_a^2 \sin\delta}{m_a^2 + 2\Xi N_{\rm DW}^2 F_a^2 \cos\delta} < 7 \times 10^{-12}$$

δ : phase of bias term
($\theta = 0$ for $\delta = 0$)

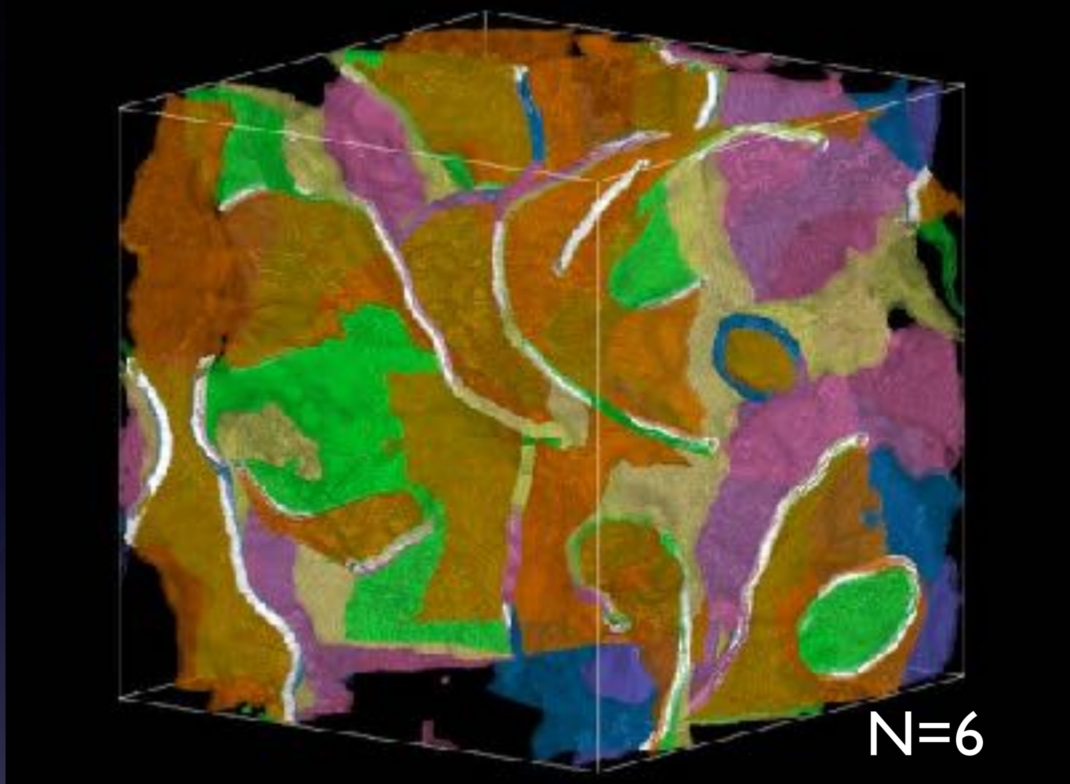
Small bias is favored

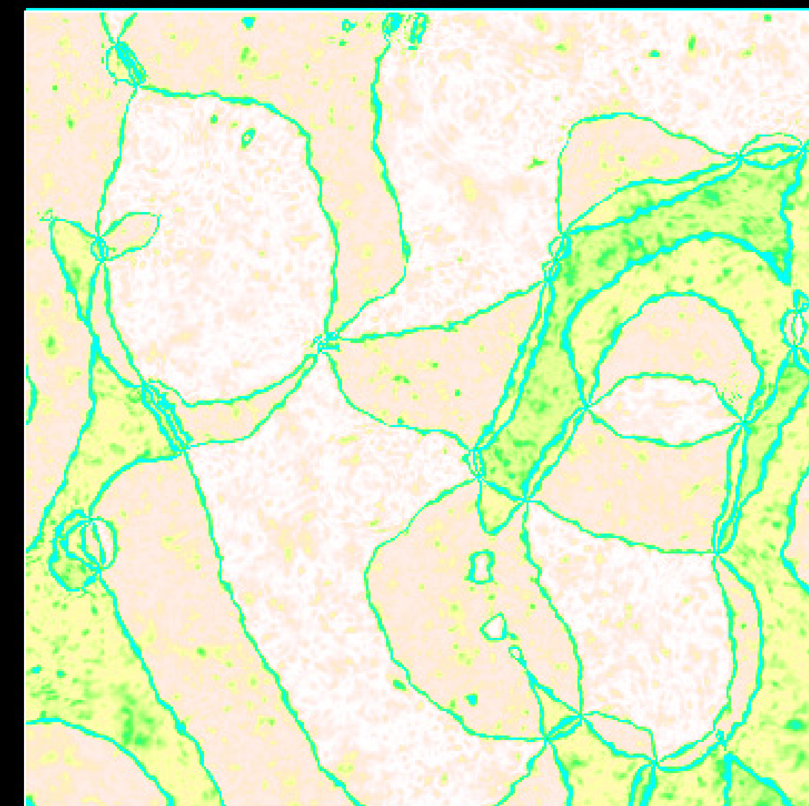
- Search for consistent parameters

Numerical simulations

MK, Saikawa, Sekiguchi (2014)

- 2D and 3D Lattice simulations

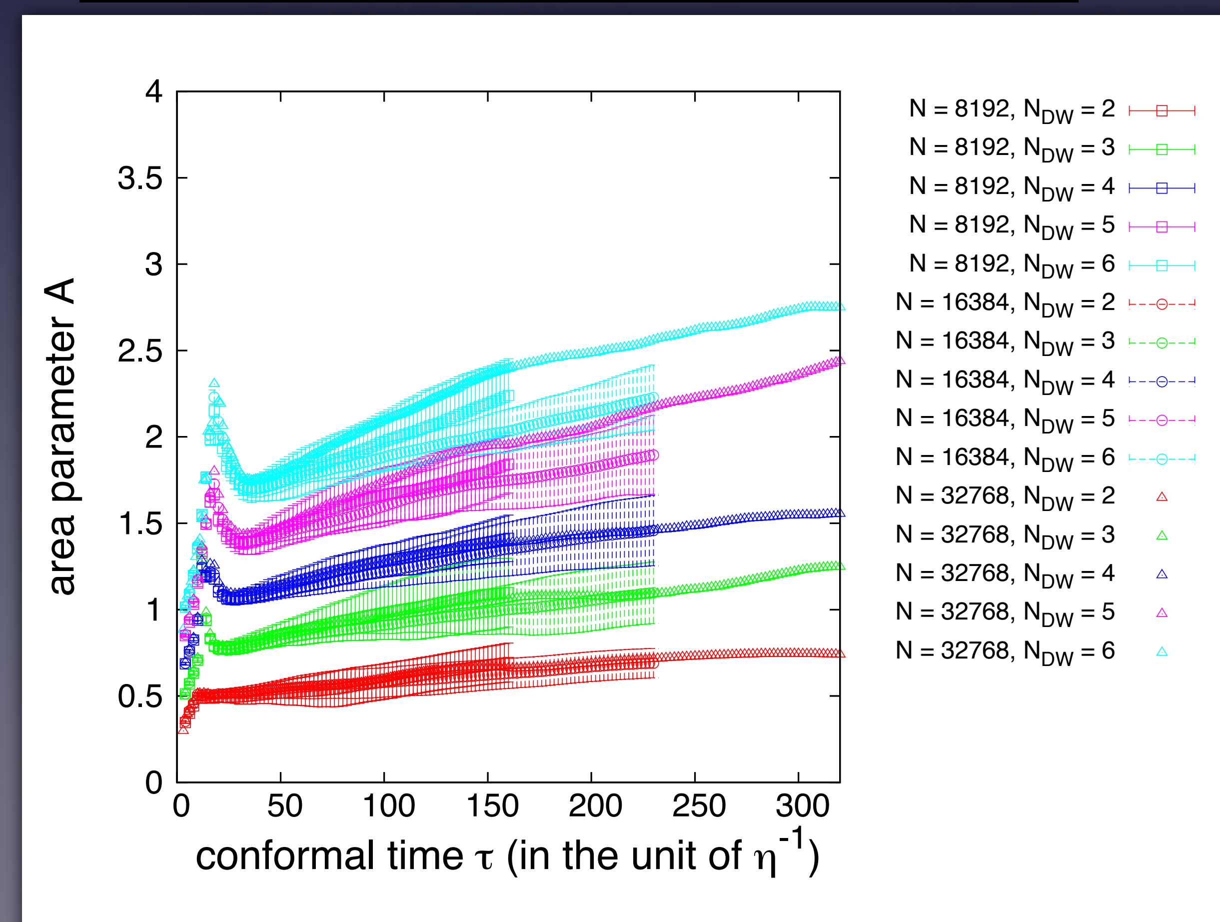




$N_{\rm DW} = 6 \quad \Xi = 6\times 10^{-5}$

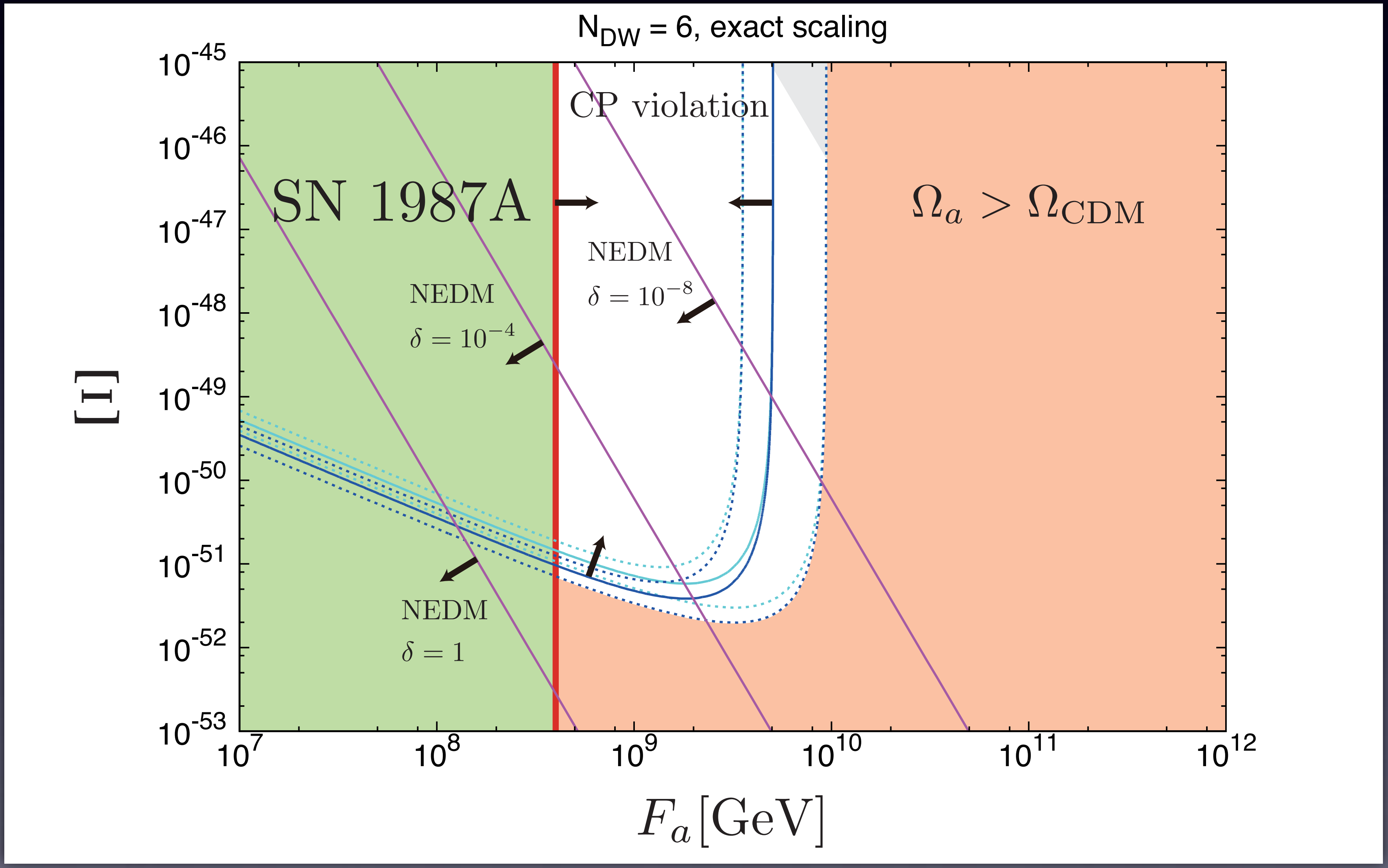
- Area parameter $\rho_{\rm wall} = \mathcal{A}\frac{\sigma}{t}$
  - Area parameters is larger for larger $N_{\rm DW}$

$N_{\rm DW}$	$\mathcal{A}(\tau_f)$ $(N = 16384,\ \tau_f = 230)$
2	0.690 ± 0.085
3	1.10 ± 0.18
4	1.46 ± 0.20
5	1.90 ± 0.23
6	2.23 ± 0.19



Constraints

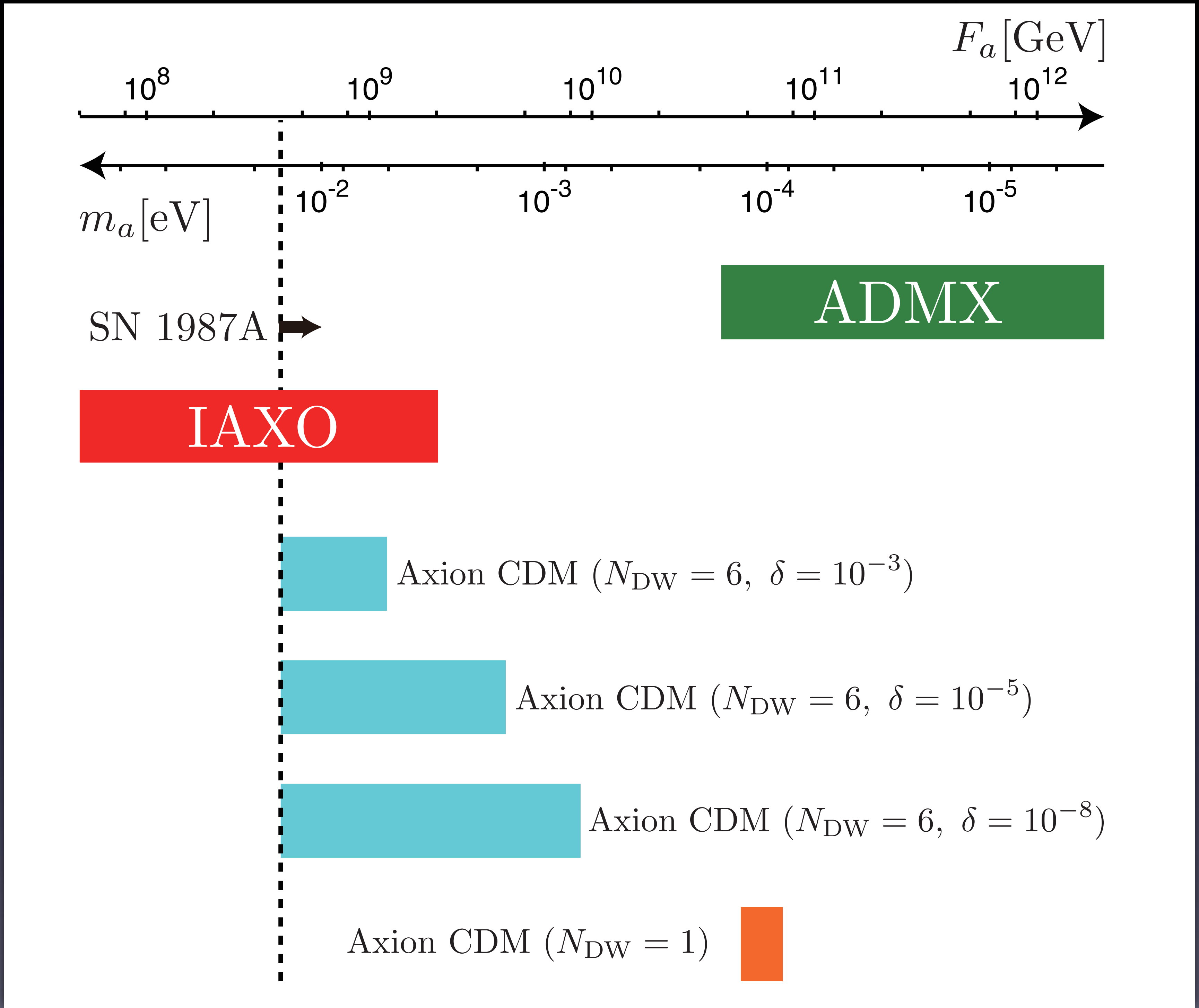
- Axion density $\Omega_{a,\text{wall}} + \Omega_{a,\text{str}} + \Omega_{a,\text{osc}} < \Omega_{\text{dark}}$
- Neutron electric dipole moment (NEDM) $\bar{\theta} < 0.7 \times 10^{-11}$
- Astrophysical constraint (SN1987A) $F_a > 4 \times 10^8$ GeV



MK, Saikawa, Sekiguchi (2014)

- NEDM constraint depends on the phase of bias δ
- For allowed region to exist, δ should be δ < 0.03

3.5 Summary: case of symmetry breaking after inflation



- Axion can be dark matter of the universe for $F_a = 4 \times 10^8$ GeV - 6×10^{10} GeV and can be probed in the next generation experiments

4. Axion in the Inflationary Universe (~~PQ~~ before inflation)

- If PQ symmetry is broken during or before inflation
  - Strings and domain walls are diluted away by inflation

    No domain wall problem

  - Only coherent oscillation gives a significant contribution to the cosmic density

$$\Omega_{a,\mathrm{osc}} \simeq 0.19\ \theta_*^2 \left(\frac{F_a}{10^{12}\mathrm{GeV}} \right)^{1.19}$$

    Inflation makes θ_* the same in the whole observable universe (θ_* is a free parameter)

  - Isocuravture perturbation problem

4.1 Axion Isocurvature Fluctuations

- Axion acquires fluctuations during inflation

$$\delta a = F_a \delta\theta_a \simeq \frac{H_{\rm inf}}{2\pi} \quad \Leftarrow \quad \langle \delta a^2 \rangle = F_a^2 \langle \delta\theta_a^2 \rangle = (H_{\rm inf}/2\pi)^2$$

$$\rho_a \simeq \rho_a(t) + \delta\rho_a(t,\vec{x}) = \frac{1}{2}[a(t) + \delta a(t,\vec{x})]^2 = \frac{1}{2} m_a^2 F_a^2 [\theta_*(t) + \delta\theta_a(t,\vec{x})]^2$$

- Small fluctuation

$$\theta_* > \delta\theta_a \quad \Rightarrow \quad \rho_a \simeq \frac{1}{2} m_a^2 F_a^2 \theta_*^2 \qquad \frac{\delta\rho_a}{\rho_a} \simeq 2\frac{\delta\theta_a}{\theta_*}$$

- Large fluctuation

$$\theta_* < \delta\theta_a \quad \Rightarrow \quad \rho_a \simeq \frac{1}{2} m_a^2 F_a^2 \langle \delta\theta_a^2 \rangle \simeq \frac{1}{2} m_a^2 \frac{H_{\rm inf}^2}{(2\pi)^2}$$

$$\frac{\delta\rho_a}{\rho_a} \simeq \left(\frac{F_a \delta\theta_a}{H_{\rm inf}/2\pi} \right)^2$$

→ Fluctuations determine the density

$$\Omega_a \simeq 0.19 \left(\frac{F_a}{10^{12}\,{\rm GeV}} \right)^{-0.81} \left(\frac{H_{\rm inf}/2\pi}{10^{12}\,{\rm GeV}} \right)^2$$

Lyth (1992)

4.1 Axion Isocurvature Fluctuations

- Axion fluctuations produced during inflation contribute to CDM isocurvature density perturbation

$$S = \frac{\delta\rho_{\rm CDM}}{\rho_{\rm CDM}} - \frac{3\delta\rho_\gamma}{\rho_\gamma} = \frac{\Omega_a}{\Omega_{\rm CDM}}\frac{\delta\rho_a}{\rho_a}$$

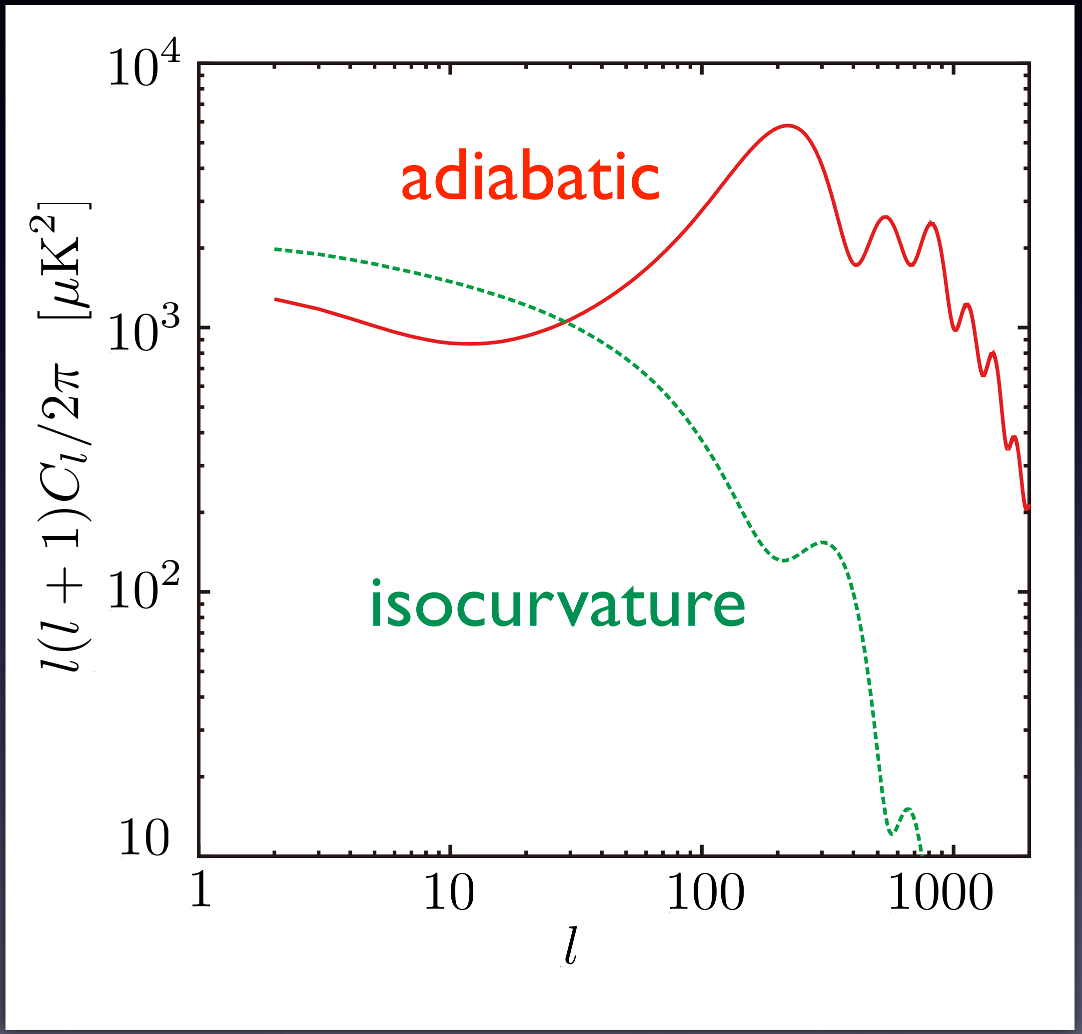
- Isocurvature perturbations lead to CMB angular power spectrum

- Stringent constraint on amplitude of isocurvature perturbation

$$\beta_{\rm iso} = \frac{P_S(k_0)}{P_\zeta(k_0) + P_S(k_0)}$$

$$k_0 = 0.002\ {\rm Mpc}^{-1}$$

CMB angular Power spectrum



- WMAP9

$$\beta_{\rm iso} < 0.047\ (95\%\ {\rm CL})$$

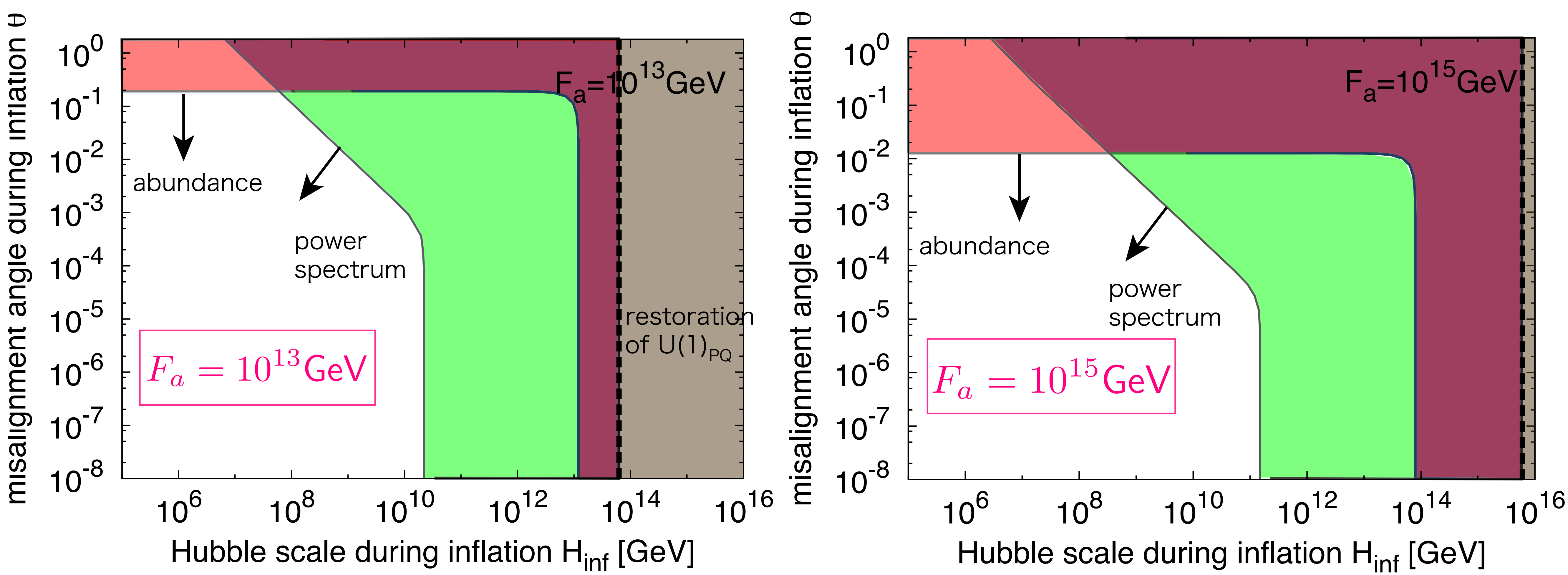
- PLANCK 2015

$$\beta_{\rm iso} < 0.033\ (95\%\ {\rm CL})$$

Axion isocurvature fluctuations

- Stringent constraints from CMB

Hikage, MK, Sekiguchi, T.Takahashi (2012)



Constraint from power spectrum is updated including Planck data

- Only low energy scale inflation models are allowed
  High scale inflation ($H_{inf} > 10^{13}$GeV) inconsistent with axion

- If axion is dark matter

$$H_{\rm inf} < 2.2 \times 10^{7}\,{\rm GeV} \left(\frac{F_a}{10^{12}\,{\rm GeV}}\right)^{0.41}$$

4.2 Suppress Isocurvature Perturbations

- Amplitude of isocurvature perturbations is determined by fluctuations of misalignment angle

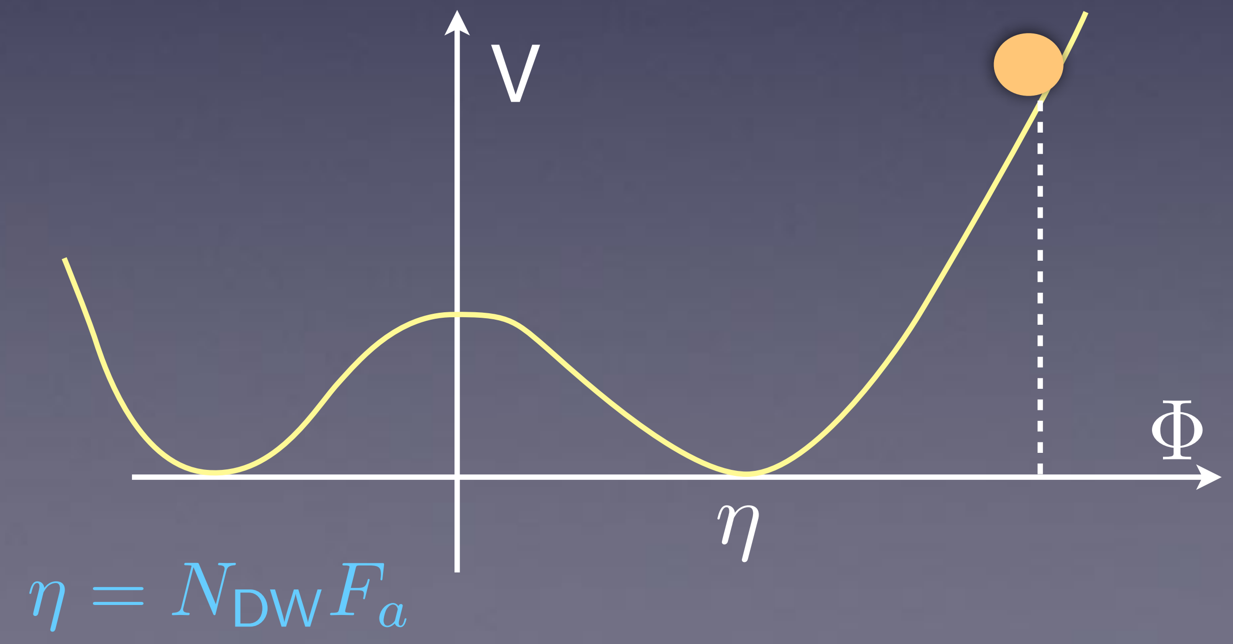
$$\frac{\delta\rho_a}{\rho_a} \simeq 2\frac{\delta\theta_a}{\theta_*}$$

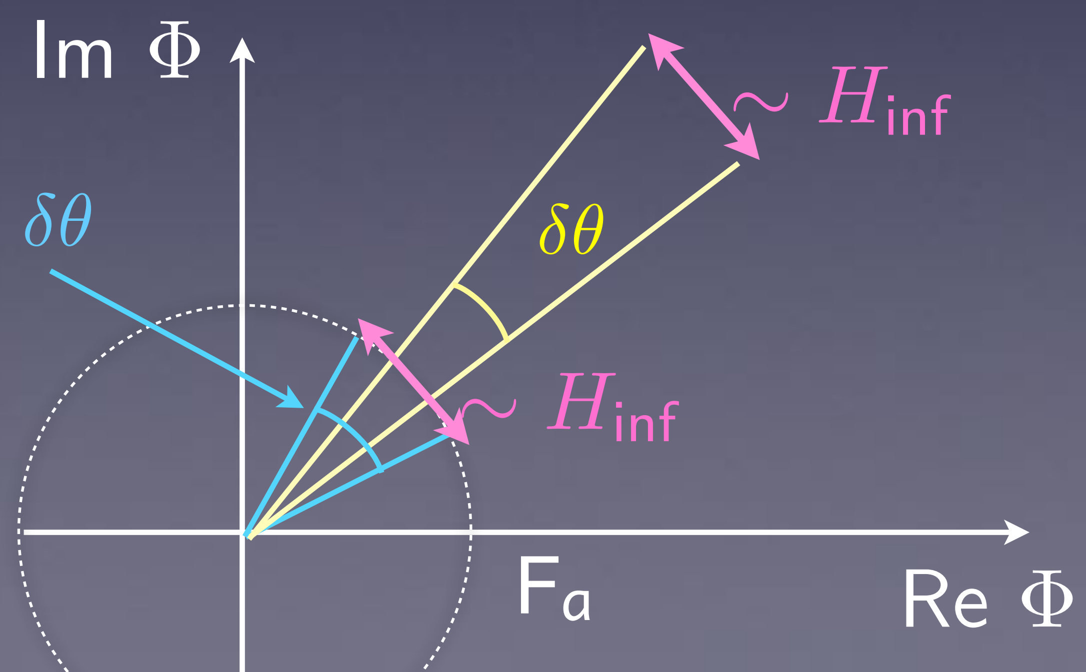
$$\delta\theta_a \simeq \frac{N_{\rm DW}}{\eta}\left(\frac{H_{\rm inf}}{2\pi}\right) = \frac{1}{F_a}\left(\frac{H_{\rm inf}}{2\pi}\right)$$

- If PQ field has a large value during inflation effective PQ scale becomes large

$$\delta\theta_a \simeq \frac{N_{\rm DW}}{|\Phi|}\left(\frac{H_{\rm inf}}{2\pi}\right) \qquad |\Phi| \gg F_a \;\Rightarrow\; \delta\theta_a \searrow$$

suppress isocurvature perturbations Linde (1991)





- However, PQ field oscillates after inflation

➡ Large fluctuations of PQ field through parametric resonance

This leads to non-thermal restoration of U(1)$_{PQ}$ symmetry

$$V_{PQ} \simeq \frac{\lambda}{2}(|\Phi|^2 - \eta^2)^2 + \lambda\langle|\delta\Phi|^2\rangle|\Phi|^2$$

$\langle|\delta\Phi|^2\rangle \gtrsim \eta^2$

↓

symmetry is restore

- Strings and domain walls are produced

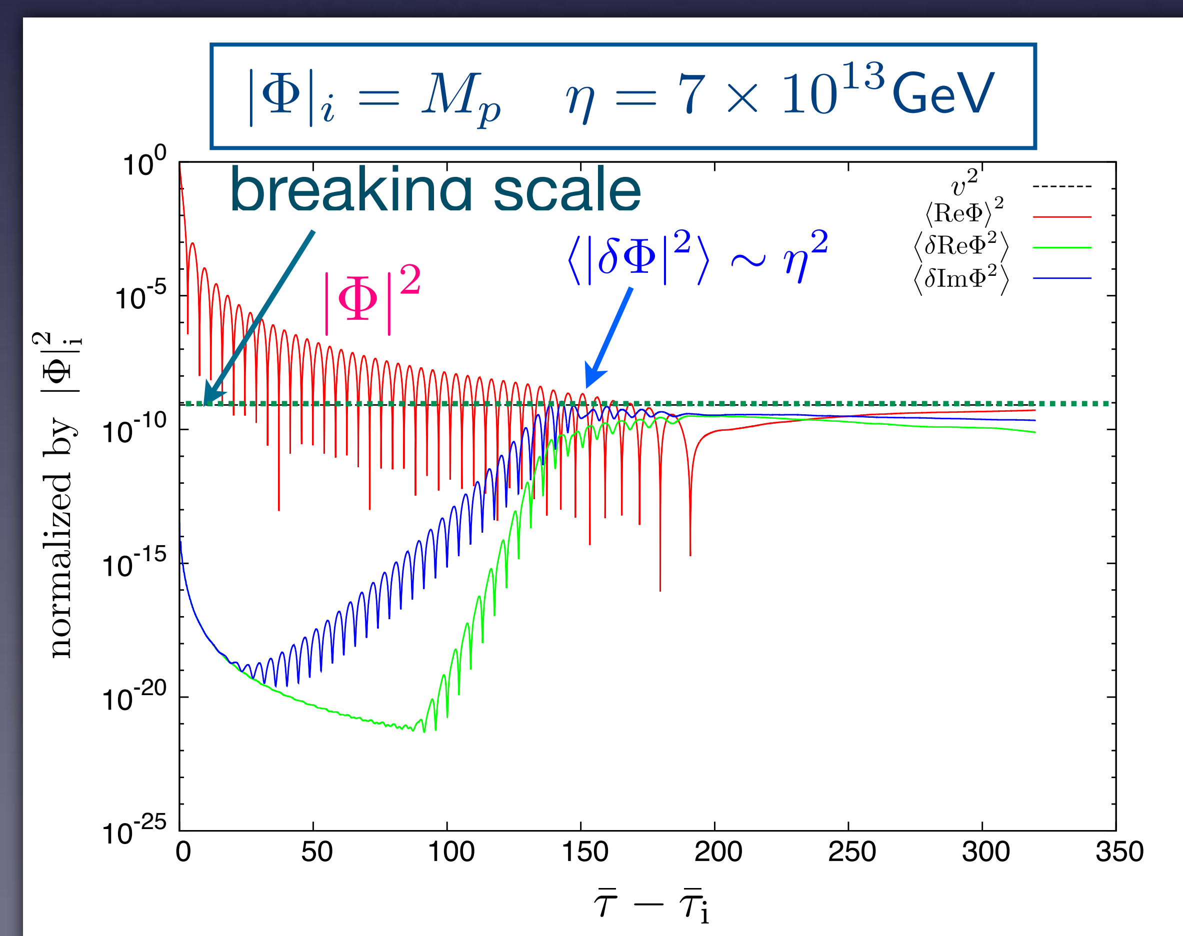
- To avoid defect formation, PQ field must settle down to the minimum before the fluctuations fully develop

MK, Yanagida, Yoshino (2013)

- Lower bound on breaking scale η

➡ $\eta \gtrsim 10^{-4}|\Phi|_i$

Φ_i initial value of PQ field



- If PQ potential is controlled by

$$V_{PQ} \sim |\Phi|^{2n} \quad (n \geq 3)$$

PQ field slowly roll down to the min.

Model without cosmological problems

Moroi, Mukaida, Nakayama, Takimoto (2014)   Harigaya, Ibe, MK, Yanagida (2015)

- Potential

$$V(\Phi) = -m_\Phi^2|\Phi|^2 + \lambda_4^2|\Phi|^4 + \frac{\lambda_6^2}{M_p^2}|\Phi|^6 - \frac{c_H}{3}V_{\rm inf}|\Phi|^2$$

- During inflation

$$\Phi_{\rm inf} = M_P c_H^{1/4}\left(\frac{H_{\rm inf}}{10^{14}{\rm GeV}}\right)^{1/2}\left(\frac{2\times10^{-5}}{\lambda_6}\right)^{1/2}$$

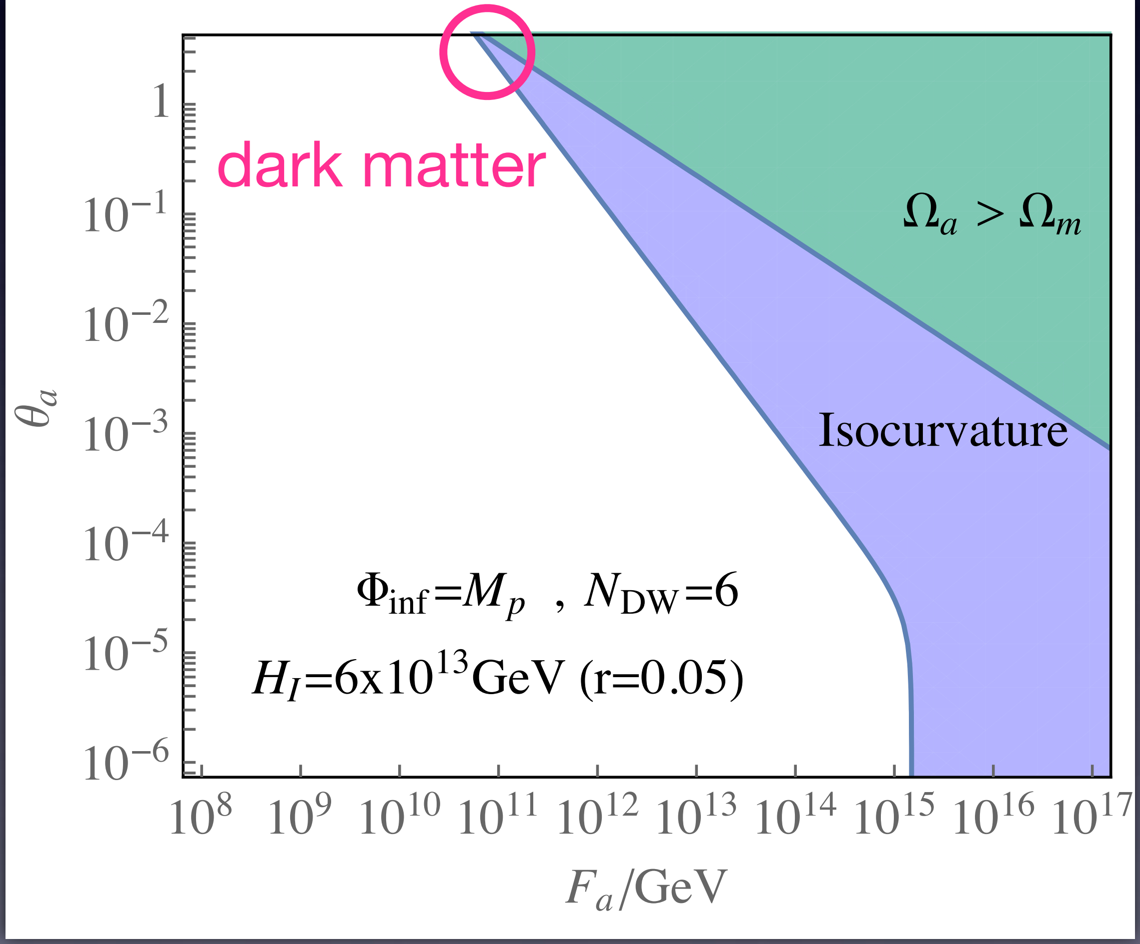
Field value can be as large as Planck

- Oscillation is driven by quartic term at

$$\Phi_{\text{osc-4}} = 10^{16}{\rm GeV}\left(\frac{\lambda_4}{7\times10^{-8}}\right)\left(\frac{2\times10^{-5}}{\lambda_6}\right)$$

- To avoid domain wall problem

$$\Phi_{\text{osc-4}} \lesssim 10^4\eta$$



→ Axion dark matter is consistent high scale inflation with r < 0.05 ($H_{\rm inf} \lesssim 6\times10^{13}$ GeV)

5. Dark matter axion detection

- axion-photon interaction

$$\mathcal{L}_{\text{int}} = -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} = -g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$$

$$g_{a\gamma\gamma} = \frac{\alpha C}{2\pi F_a}$$

$$C \sim \begin{cases} 0.97 & \text{KSVZ} \\ -0.36 & \text{DFSZ} \end{cases}$$

- Maxwell equations
  - $-\frac{\partial}{\partial t}\vec{E} + \vec{\nabla} \times \vec{B} = g_{a\gamma\gamma}\left(\frac{\partial a}{\partial t}\vec{B} + \vec{E} \times \vec{\nabla} a\right)$
  - $-\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times \vec{E}$
  - $\vec{\nabla} \cdot \vec{E} = -g_{a\gamma\gamma}\vec{B} \cdot \vec{\nabla} a$
  - $\vec{\nabla} \cdot \vec{B} = 0$

- Wave equation ($|\nabla a| \ll |\partial a/\partial t|$ $B \simeq$ static)

$$-\frac{\partial^2 \vec{E}}{\partial t^2} + \nabla^2 \vec{E} = g_{a\gamma\gamma} \frac{\partial^2 a}{\partial t^2} \vec{B}$$

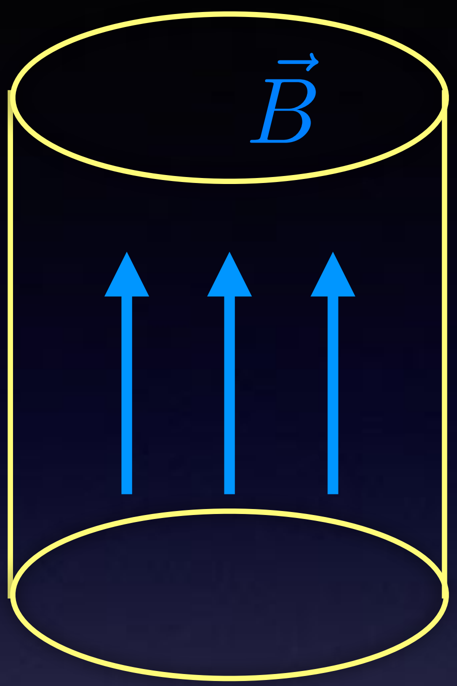
- Axon de Broglie wavelength

$$\lambda \sim \frac{2\pi\hbar}{m_a v} \sim 10\,\text{m}\left(\frac{m_a}{10^{-4}\text{eV}}\right)$$

> detector size

Microwave cavity

Sikivie (1985)



- Electric and magnetic field $\vec{B} = B_0 \vec{z} \quad \vec{E} = E(t,\vec{x})\vec{z}$

$$E(t,\vec{x}) = \frac{1}{\sqrt{2\pi}} \int d\omega e^{-i\omega t} E(\omega,\vec{x})$$

$$E(\omega,\vec{x}) = \sum_j \lambda_j(\omega)\psi_j(\vec{x}) \qquad B_0(\vec{x}) = \sum_j \eta_j \psi_j(\vec{x})$$

$$\nabla^2 \psi_j = -\omega_j^2 \psi_j$$

$$\int \psi_i \psi_j d^3x = V\delta_{ij}$$

- Axion field

$$a(t) = \frac{1}{\sqrt{2\pi}} \int d\omega e^{-i\omega t} a(\omega)$$

Halo axion $\quad m_a < \omega < m_a(1 + O(10^{-6}))$

- Wave equation

$$(\nabla^2 + \omega^2)E(\omega,\vec{x}) = -g_{a\gamma\gamma} B_0 \omega^2 a(\omega)$$

$$\lambda_j(\omega) = -g_{a\gamma\gamma} \frac{\eta_j \omega^2}{\omega^2 - \omega_j^2} a(\omega)$$

$\omega_j \simeq \omega \quad \Rightarrow \quad$ Resonance

axion $\Rightarrow \gamma$

- Time average of energy of j-mode

$$\langle U_j \rangle = \frac{1}{T}\int |E_j(\omega,\vec{x})|^2 d\omega d^3x = g_{a\gamma\gamma}^2\,\eta_j^2\,V\frac{1}{T}\int \frac{|a(\omega)|^2\omega^4}{(\omega^2-\omega_j^2)^2+\omega^4/Q^2}d\omega$$

$$\left[\int dt F(t)^2 = \int d\omega |F(\omega)|^2\right]$$

$\omega_j = m_a \quad Q \ll 10^6$

$$\simeq Q^2\frac{1}{T}\int d\omega |a(\omega)|^2 = Q^2\langle a^2\rangle$$

- Quality factor

$$Q = \frac{\omega_j}{\Delta\omega} \simeq \omega\,\frac{\text{(energy stored)}}{\text{(power loss)}}$$

- Axion-photon conversion rate

$$P = \frac{\omega U_j}{Q} = g_{a\gamma\gamma}^2\,G_j^2\,V\,\langle B_0^2\rangle\,\rho_a\,\frac{Q}{m_a}$$

$$G_j^2 \equiv \eta_j^2/\langle B_0^2\rangle$$

$$\rho_a = m_a^2\langle a^2\rangle$$

- Signal to noise ratio

$$\text{S/N} = \frac{P}{k_B T_S}\sqrt{\frac{t}{b}}$$

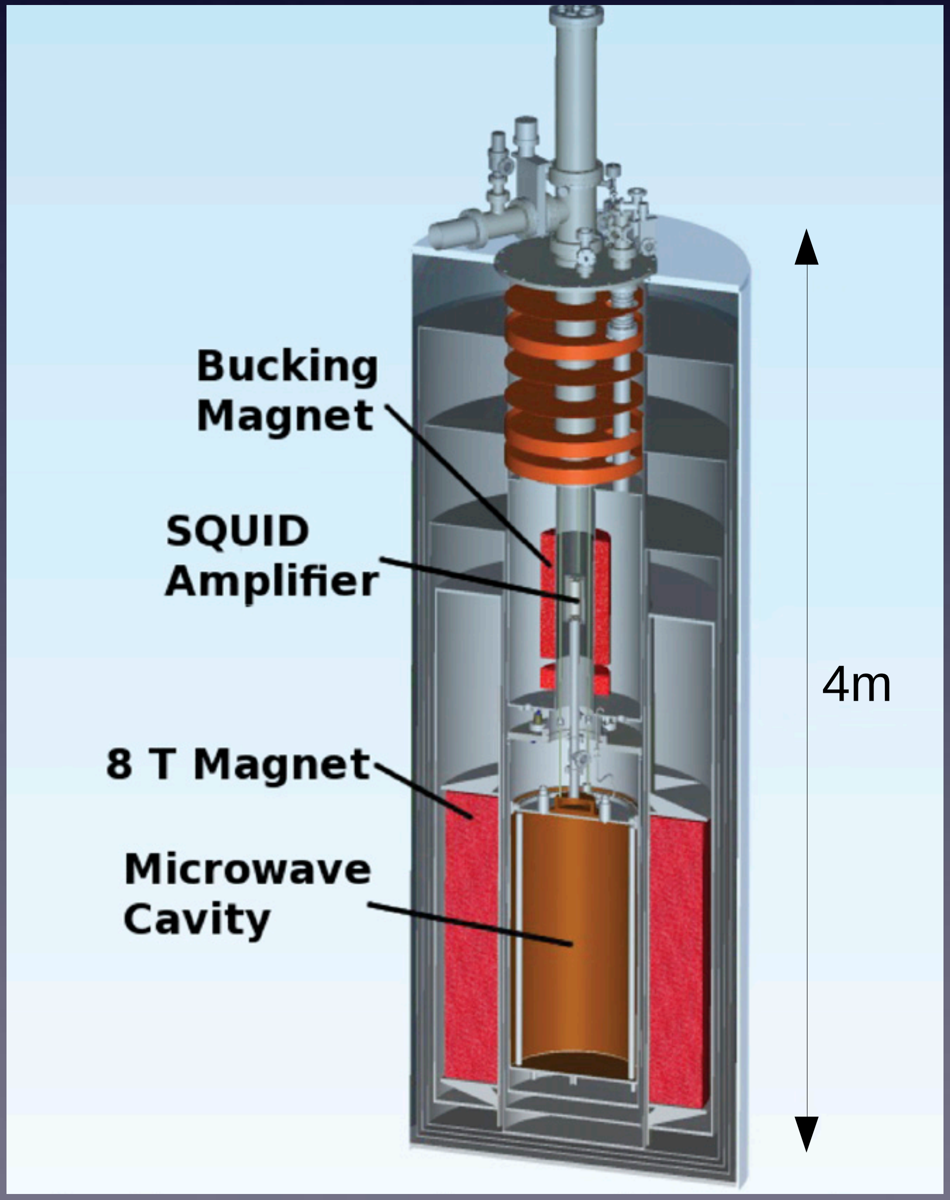
(T_S: sys. noise temp, t: integration time

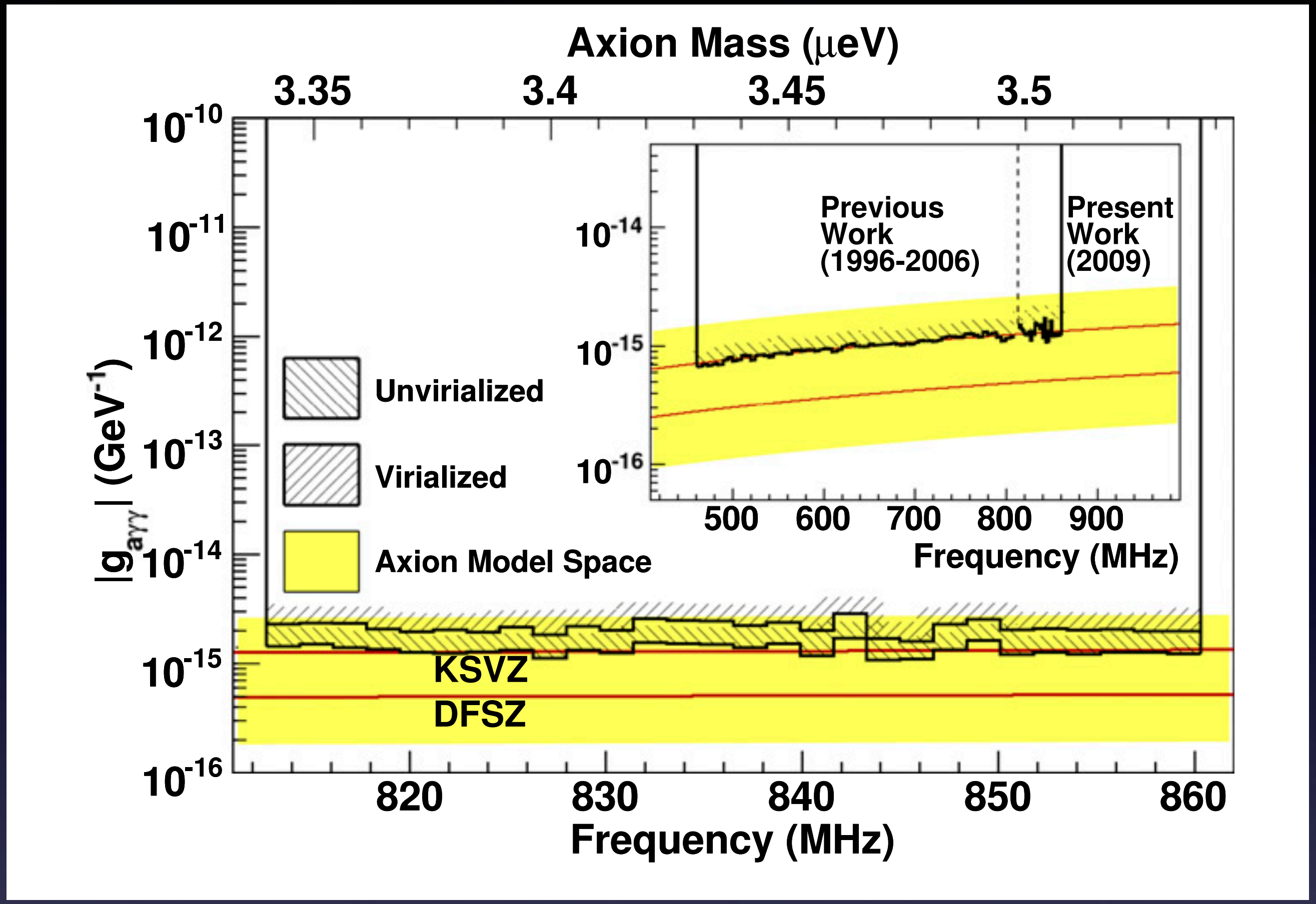
b: bandwidth)

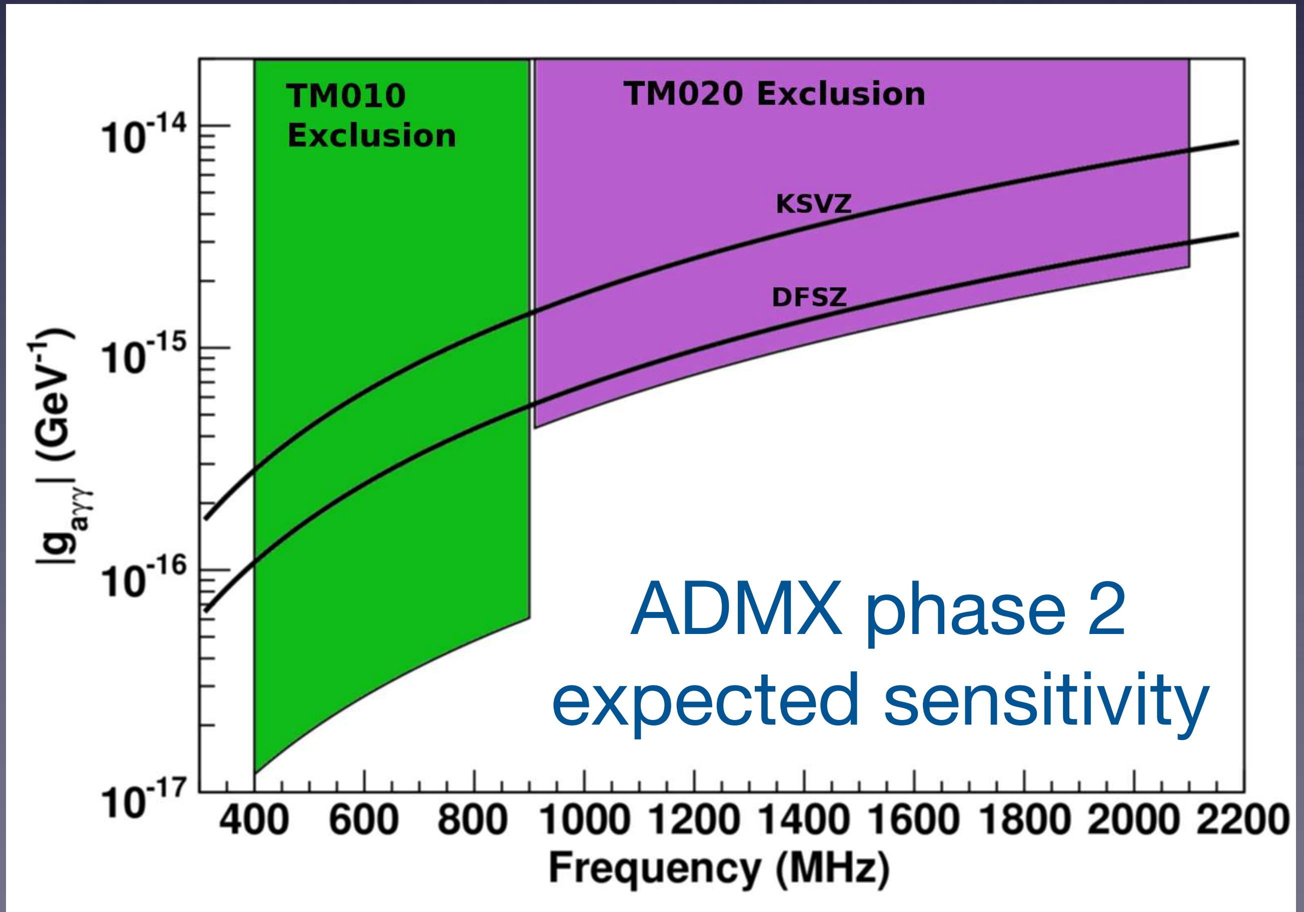
ADMX (Axion Dark-Matter eXperiment)

Asztalos et al (2010)

- 7.6T magnetic field
- cylindrical copper-plated microwave cavity ($Q \sim 10^5$)
- SQUID microwave amplifier
- expected signal ~ 10^{-22} W

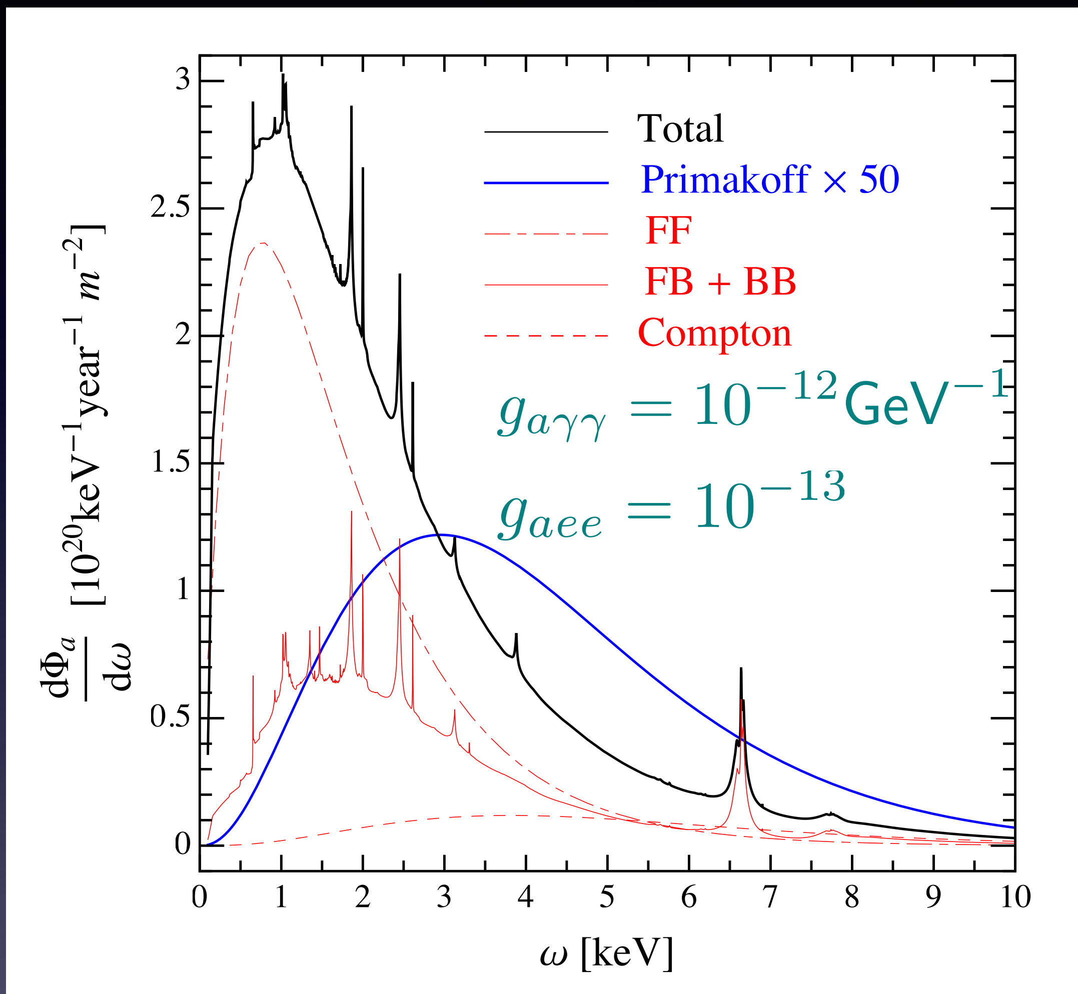




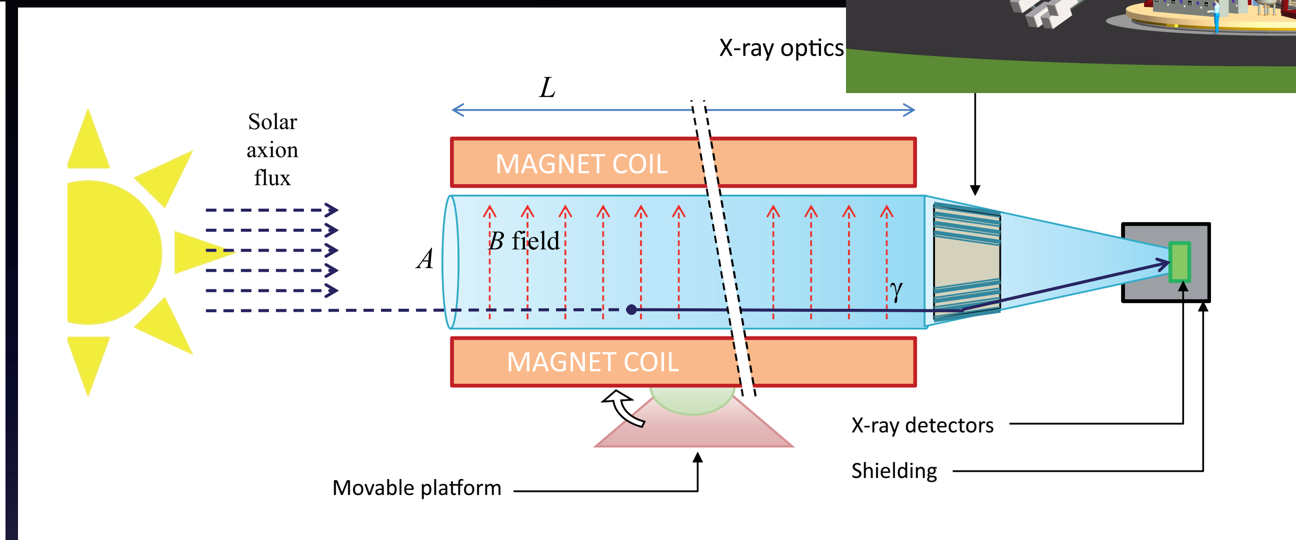


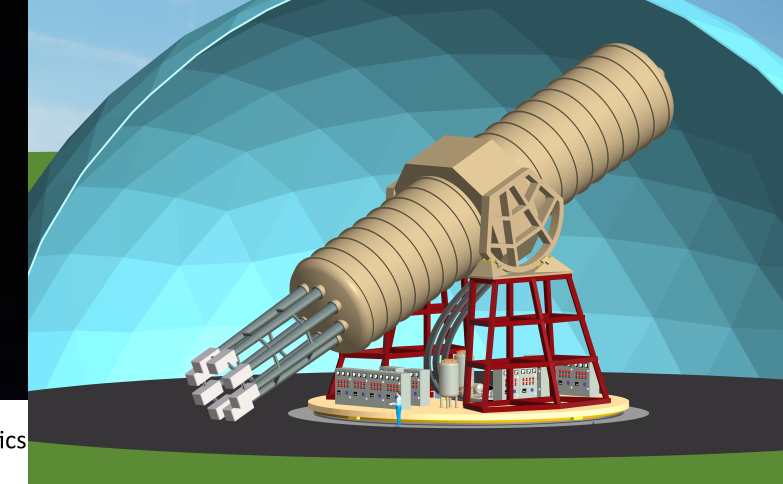
IXAO (International Axion Observatory)

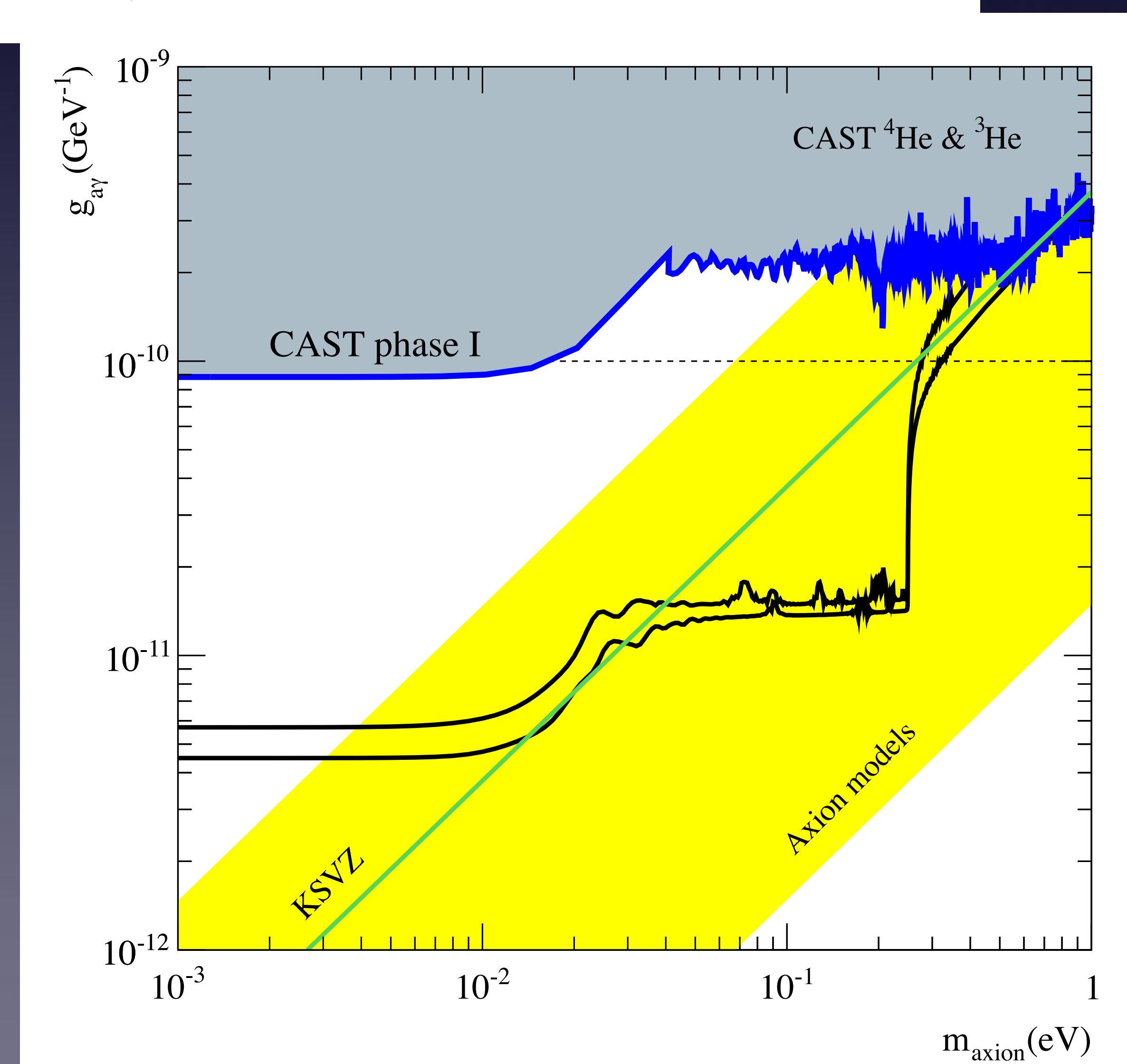
- Solar axion



Redondfo (2013)



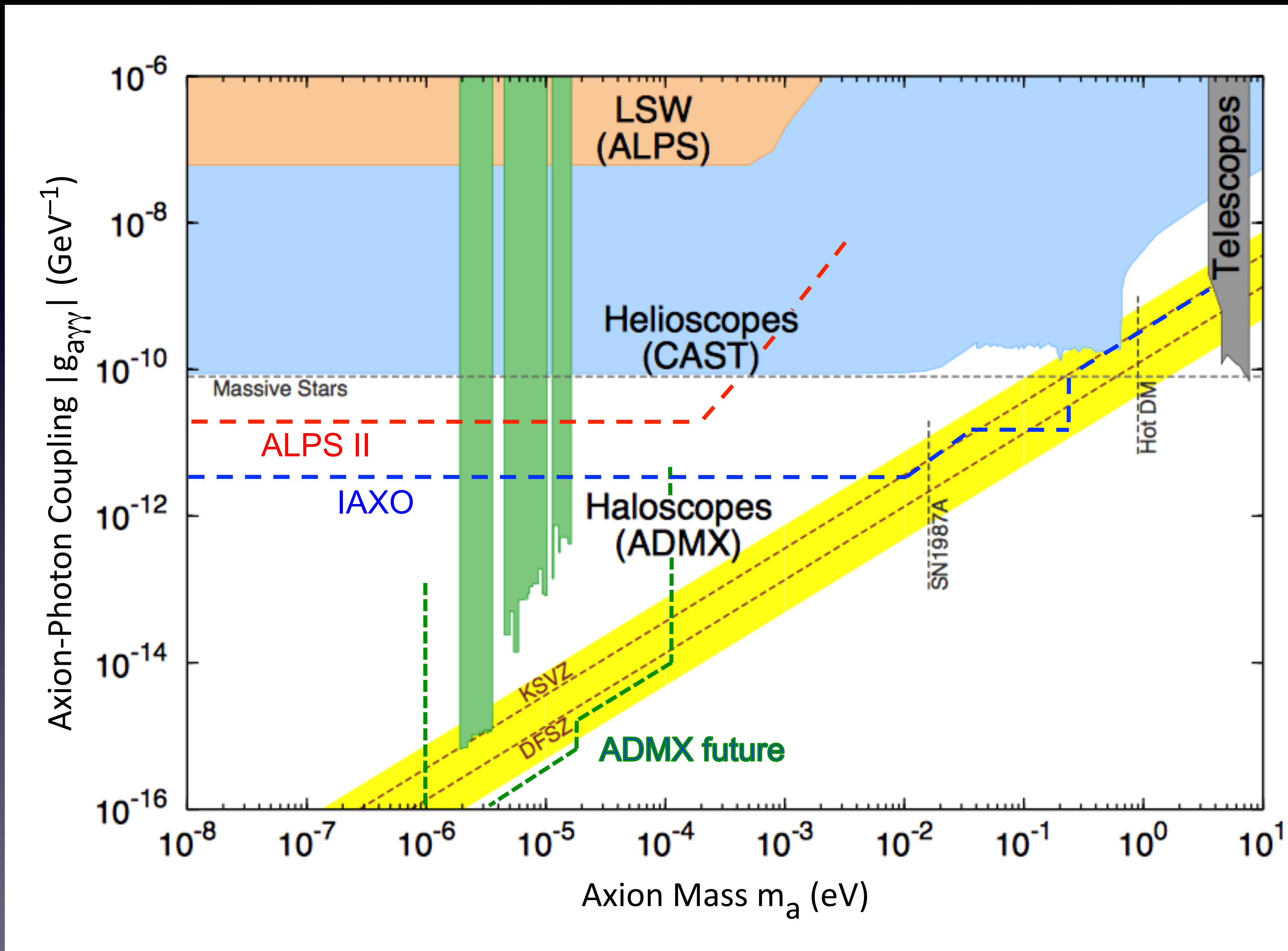




- Axion-photon conversion probability

$$P_{a\gamma} \simeq 2.6 \times 10^{-17} \left(\frac{B}{10\mathrm{T}}\right)^2 \left(\frac{L}{10\mathrm{m}}\right)^2$$

Current limits and future perspectives



Graham et al. (2016)

6. Conclusion

- If PQ symmetry is broken after inflation, topological defects are formed and axions from them give a significant contribution to the CDM density of the universe and axion can be dark matter for $F_a \sim 5X10^{10}$ GeV
- For domain wall number ≥ 2 there exist a serious domain wall problem which can be avoided by introducing a bias term and axon can be dark matter for lower PQ scales ($F_a \sim 3X10^9$ — 10^{10} GeV)
- If PQ symmetry breaks before or during inflation, axion has isocurvature density perturbations which are stringently constrained by CMB observations. As a result only low scale inflation models are allowed.
- Dark matter axion can be detected in future by axion search experiments such as ADMX and IAXO