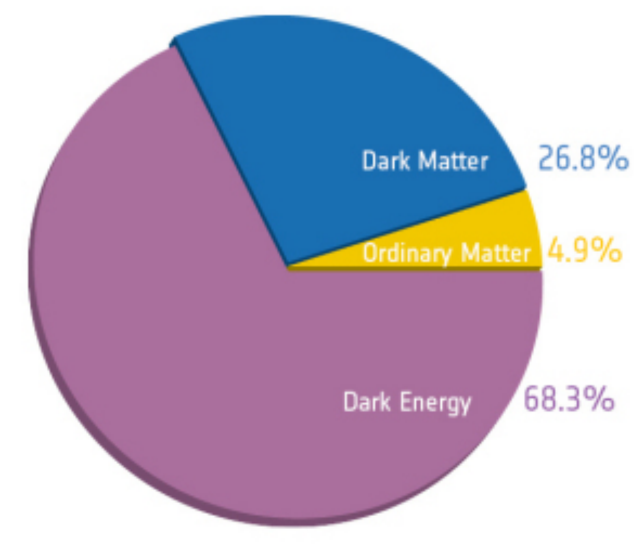
Production and evolution of axion dark matter in the early universe

Ken'ichi Saikawa (DESY)

Based on
T. Hiramatsu, M. Kawasaki, KS, T. Sekiguchi, PRD85, 105020 (2012) [1202.5851]
T. Hiramatsu, M. Kawasaki, KS, T. Sekiguchi, JCAP01, 001 (2013) [1207.3166]
M. Kawasaki, KS, T. Sekiguchi, PRD91, 065014 (2015) [1412.0789]
A. Ringwald, KS, PRD93, 085031 (2016) [1512.06436]

Dark matter

- Recent astrophysical observations imply that about 27% of the total energy of the universe is occupied by unknown matter.
  - Stable in cosmological timescales
  - Collisionless ("invisible")
  - "Cold" (velocity dispersion is sufficiently small at the beginning of structure formation)



Credit: ESA and the Planck Collaboration

- Physics beyond the Standard Model
  - A well motivated candidate: axion and axion-like particles

Peccei-Quinn extension of the standard model

  - Solution to the strong CP problem

Strong CP problem and axion

- Strong CP problem
  - Quantum chromodynamics (QCD) allows a CP violating term:

$$\mathcal{L} \supset \frac{\alpha_s}{8\pi} \theta G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

Physical observable: $\bar{\theta} = \theta + \arg \det M_q$

  - Non-observation of neutron electric dipole moment implies

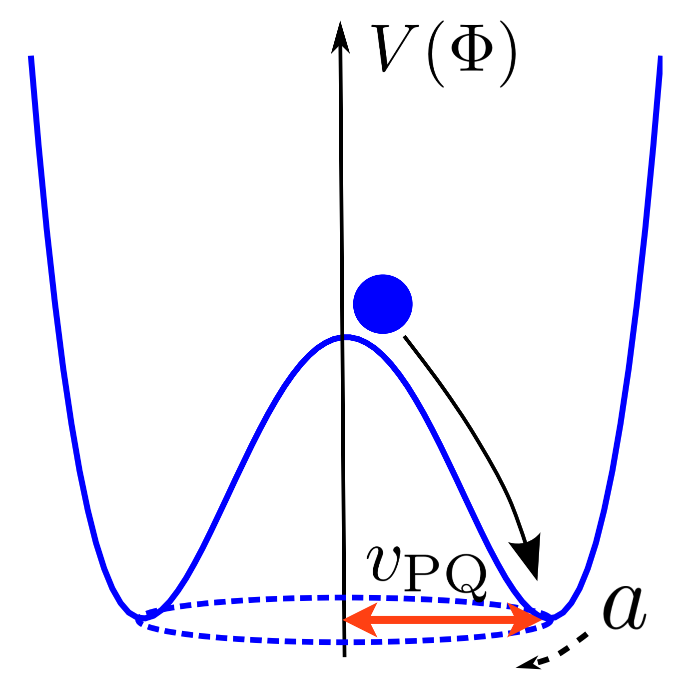
$$|\bar{\theta}| < \mathcal{O}(10^{-11})$$

"Why it is so small ?"

- Peccei-Quinn (PQ) mechanism
  - Take $\bar{\theta}$ as a dynamical variable
    that explains its smallness, i.e. $\bar{\theta} \to \bar{\theta}_{\text{eff}}(x) = a(x)/F_a$
  - Predicts the existence of light particle $a(x)$ = axion .

Axion as a Nambu-Goldstone boson

- Axions can be identified as Nambu-Goldstone bosons arising from breaking of global symmetry. (Peccei-Quinn (PQ) symmetry)

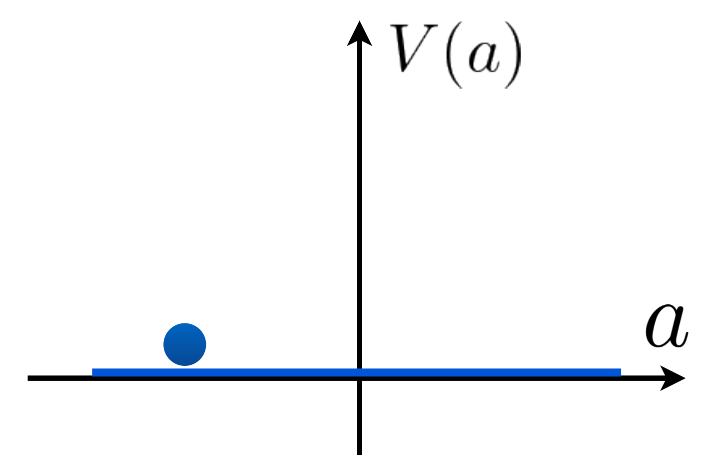


- Hidden scalar field:

$$\Phi(x) = \frac{1}{\sqrt{2}}\left[v_{\rm PQ} + \rho(x)\right] e^{ia(x)/v_{\rm PQ}}$$

Massive modulus, massless phase:

$$m_\rho \sim v_{\rm PQ}, \quad m_a = 0$$



- Interactions with standard model particles are suppressed by a large symmetry breaking scale.

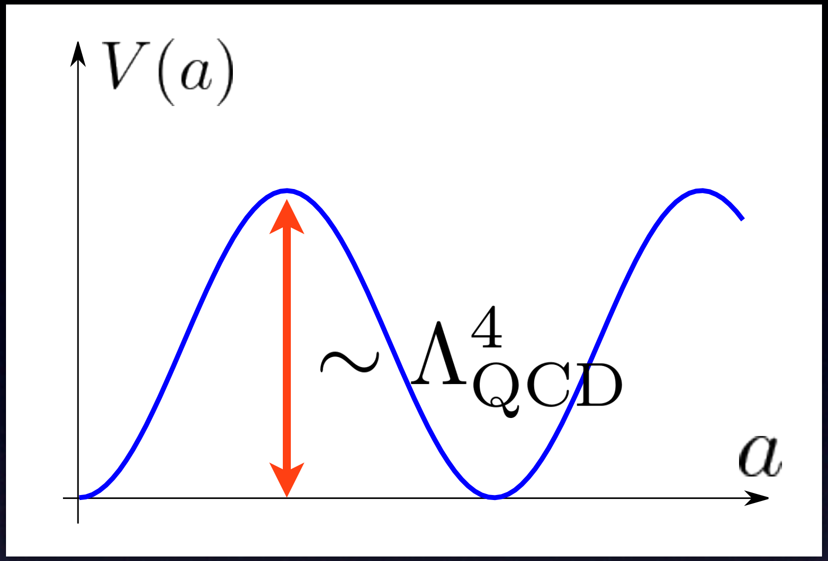
$$v_{\rm PQ} \gg v_{\rm electroweak} \approx \mathcal{O}(100)\,\mathrm{GeV}$$

Properties of axion

- Axions can couple to gluons via

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi}\frac{a}{F_a}G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

$F_a \propto v_{\rm PQ}$: axion decay constant



- Below the QCD scale $\Lambda_{\rm QCD} \sim \mathcal{O}(100\,{\rm MeV})$, topological charge fluctuations in QCD vacuum induce the potential energy:

$$V(a) \sim \Lambda_{\rm QCD}^4\left(1-\cos\frac{a}{F_a}\right)$$

➡ $\langle a\rangle = 0$ at the minimum, solving strong CP problem

- Mass of QCD axions $m_a \sim \Lambda_{\rm QCD}^2/F_a$:

$$m_a = \frac{m_\pi F_\pi}{F_a}\frac{\sqrt{z}}{1+z} \simeq 6\,{\rm meV}\left(\frac{10^9\,{\rm GeV}}{F_a}\right) \qquad z = m_u/m_d = 0.48(3)$$

- Tiny coupling with matter + non-thermal production

→ good candidate of cold dark matter

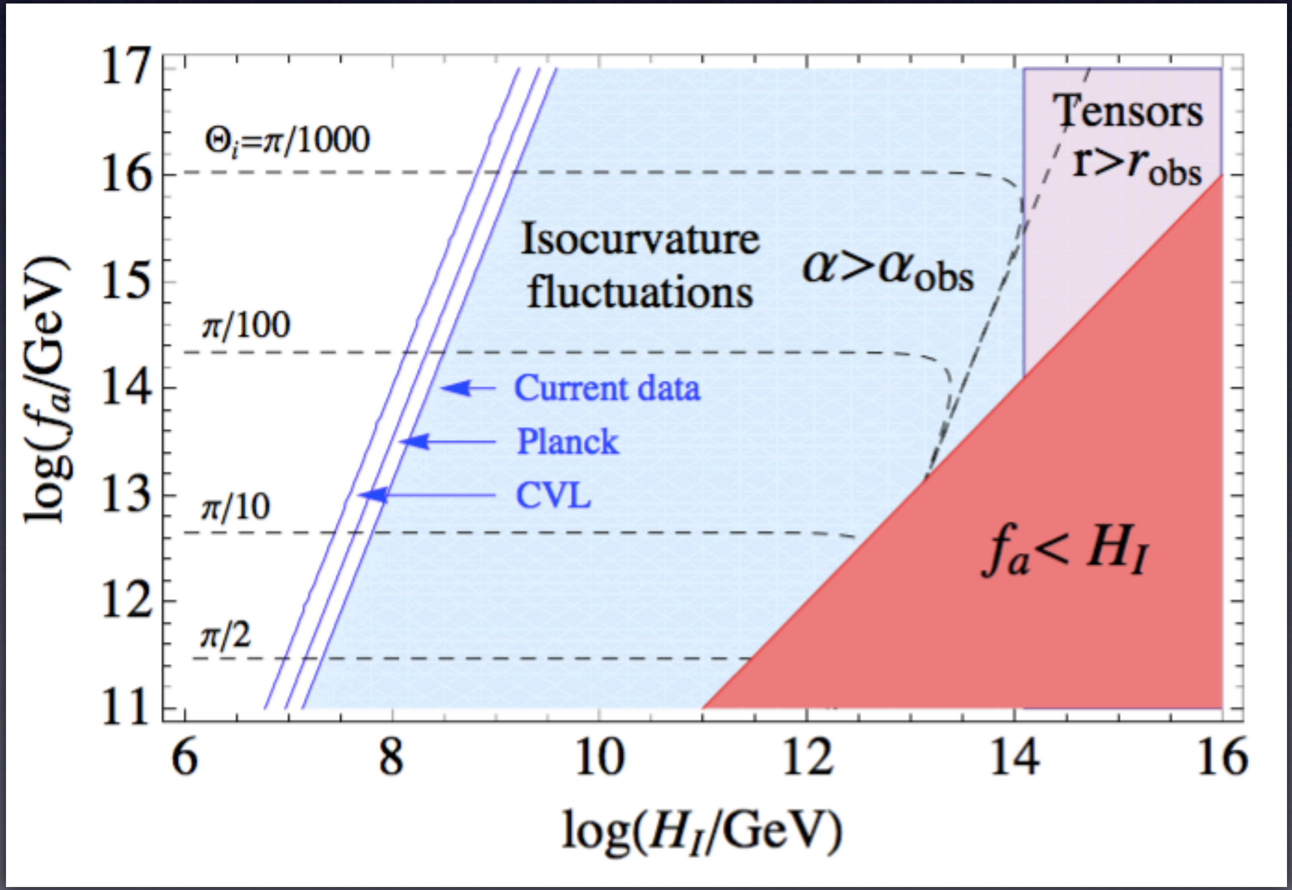
How axions are produced ?

$$\Omega_a = \Omega_a(F_a), \quad m_a \simeq 6\,\mathrm{meV}\left(\frac{10^9\,\mathrm{GeV}}{F_a}\right)$$

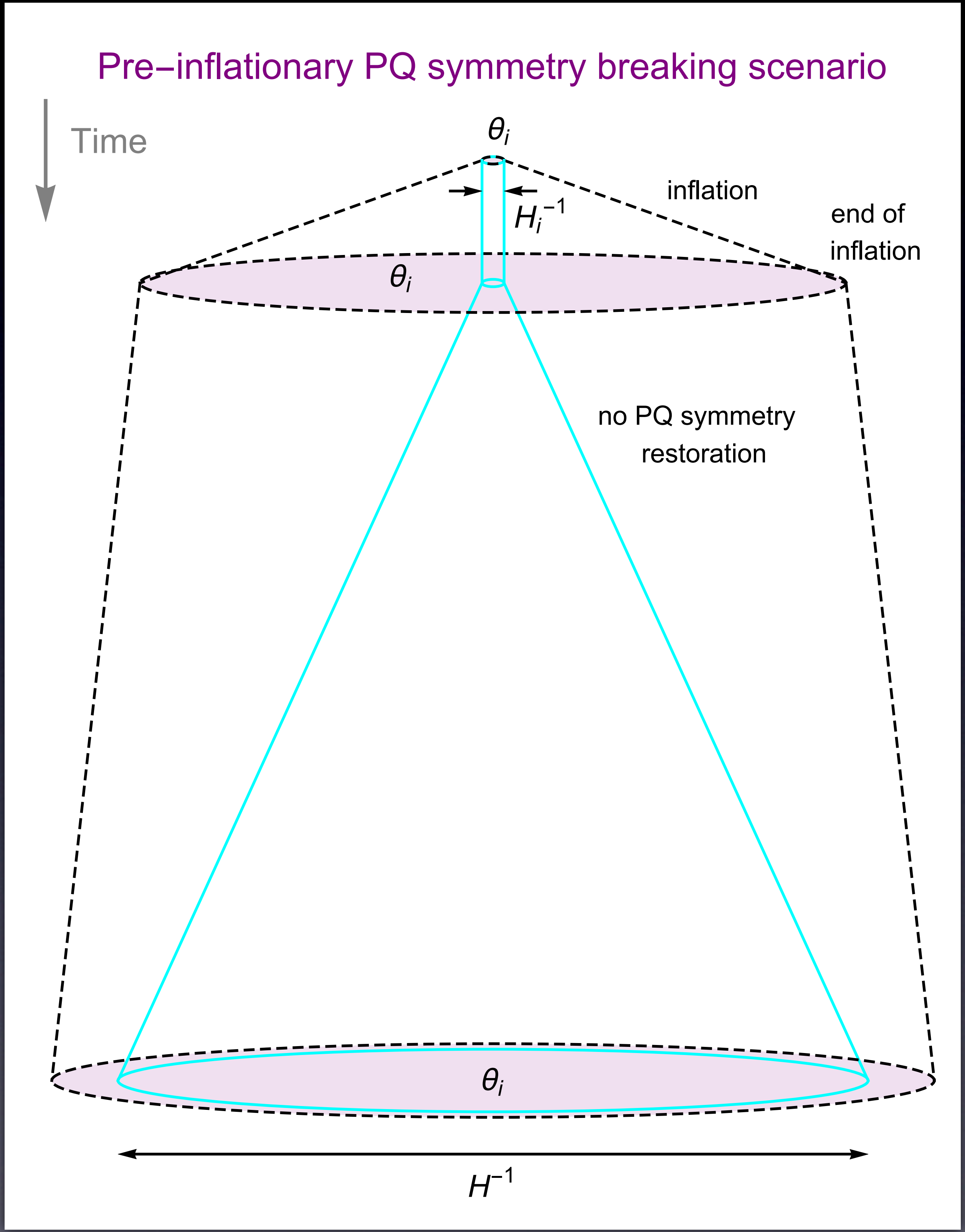
- What is the "typical mass" of the axion (or the "typical value" for the axion decay constant), if axions explain 100% of CDM abundance ?
- Predictions strongly depend on the early history of the universe.
- Two possibilities:
    - PQ symmetry is never restored after inflation
    - PQ symmetry is restored during/after inflation

Pre-inflationary PQ symmetry breaking scenario

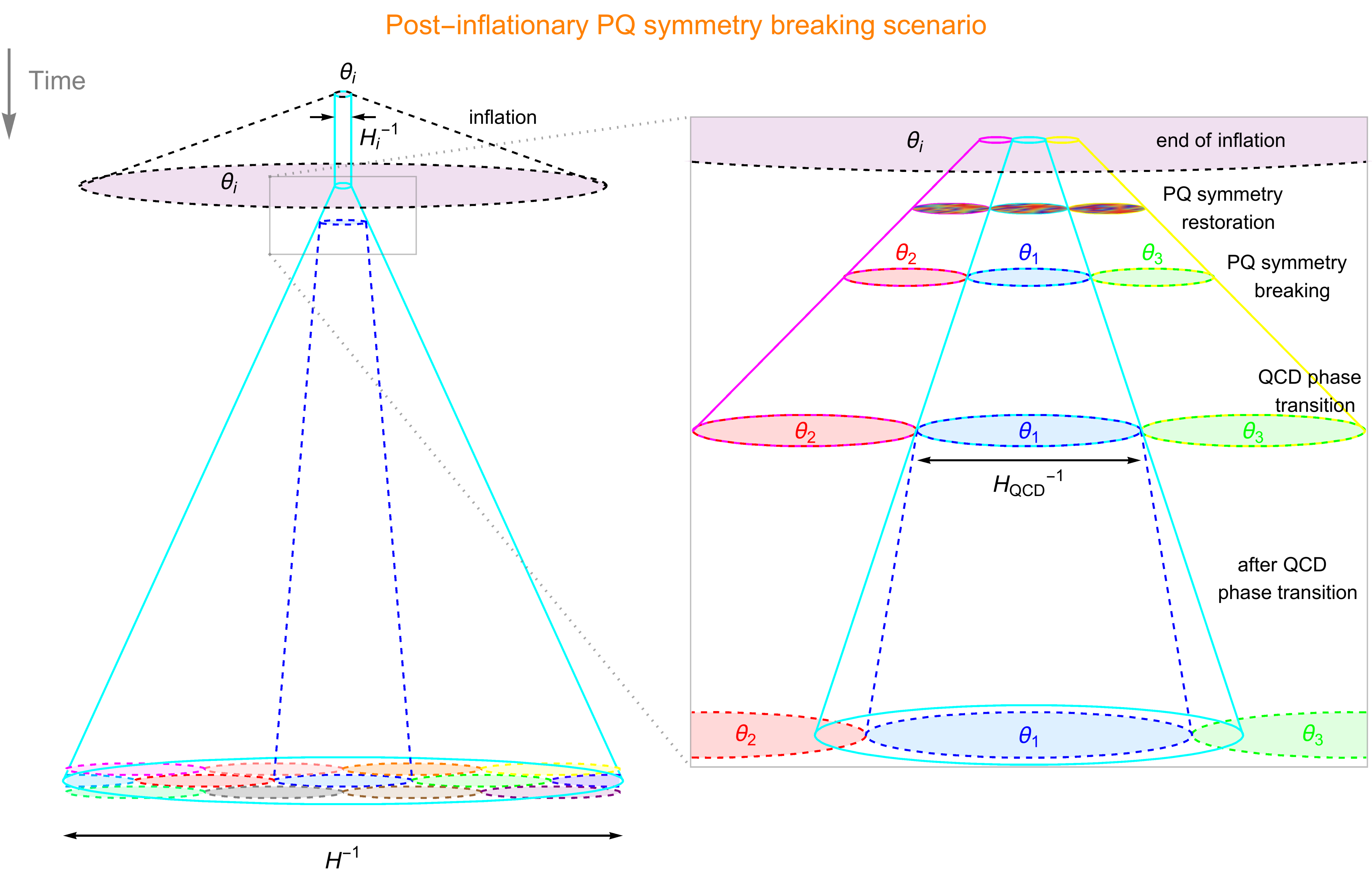
- Relic axion CDM abundance depends on F_a and initial misalignment angle θ_i
- Severe constraints from isocurvature fluctuations if inflationary scale is sufficiently high.



Hamann, Hannestad, Raffelt and Wong (2009)



Post-inflationary PQ symmetry breaking scenario

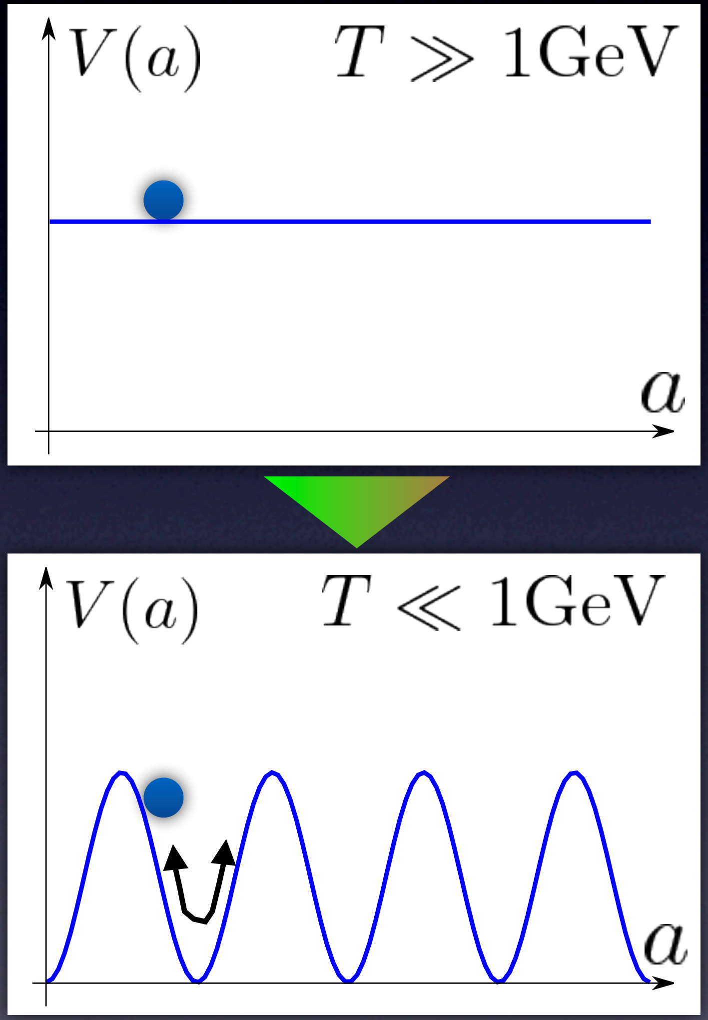


- Present observable universe contains many different patches with different values of θ_i.
- Topological defects (strings and domain walls) are formed.
- Relic axion density should be estimated by summing over all possible field configurations.

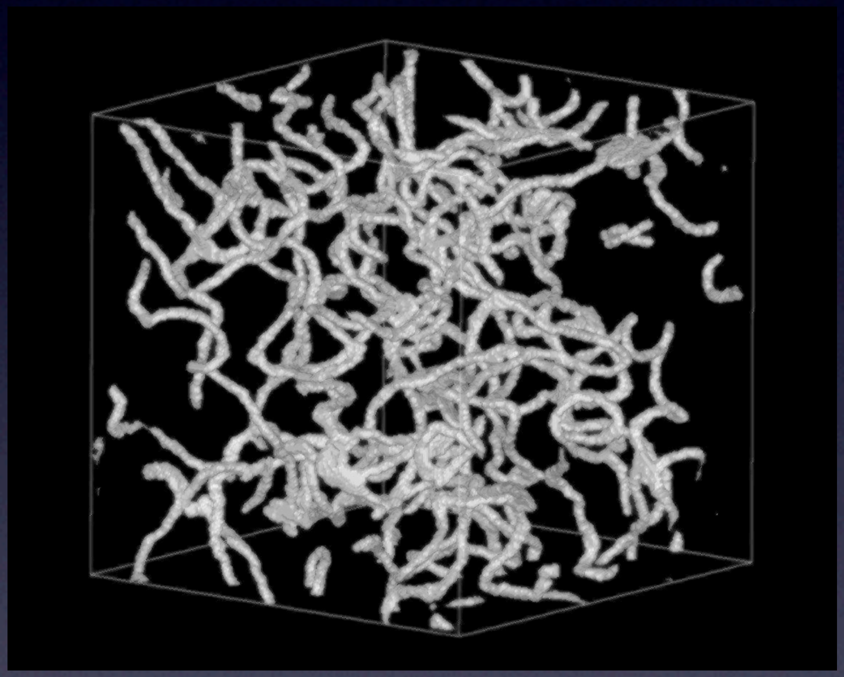
How axions are produced ?

If PQ symmetry is broken after inflation,
there are three contributions:

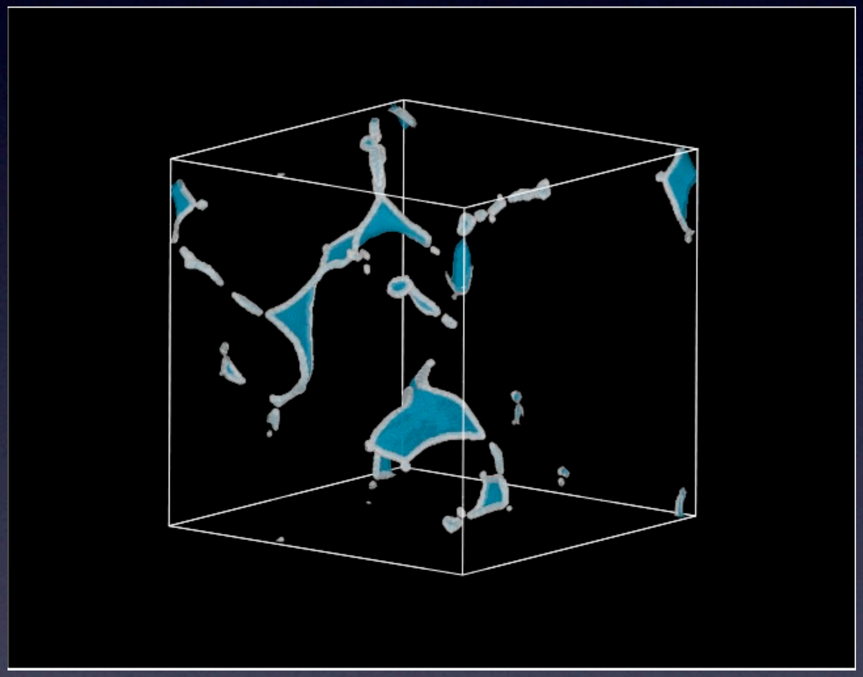
(1) Re-alignment mechanism



(2) Radiation from strings



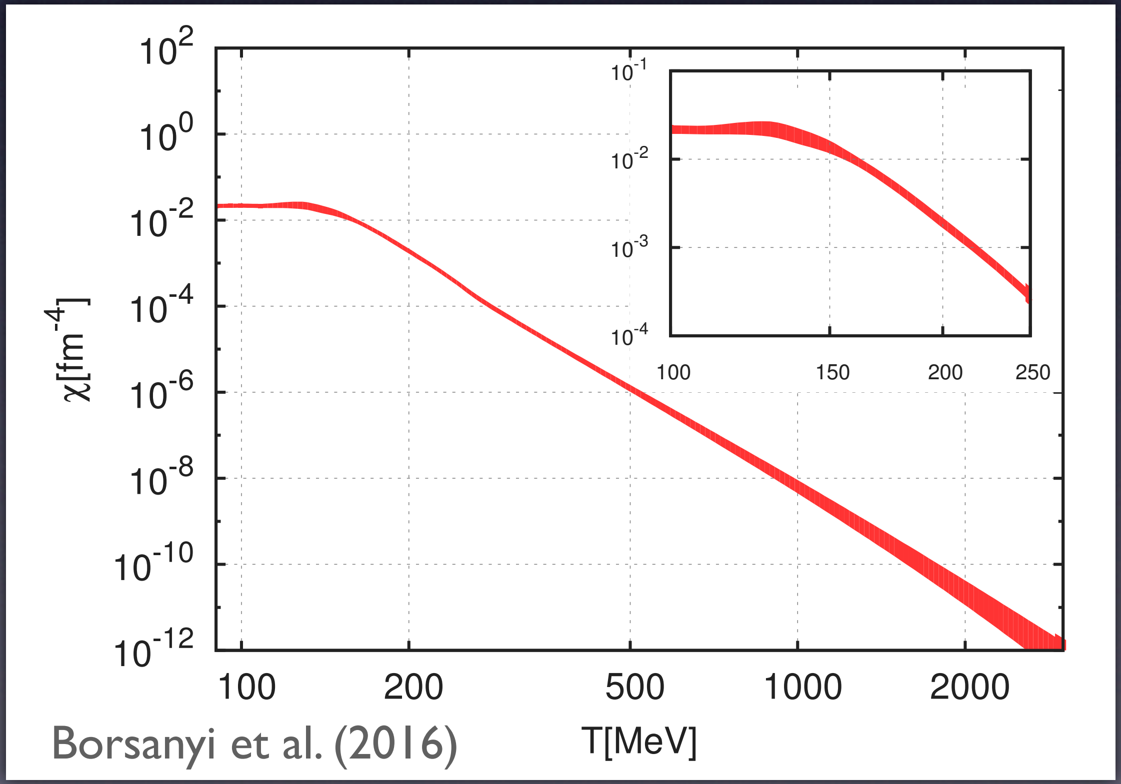
(3) Collapse of string-wall systems



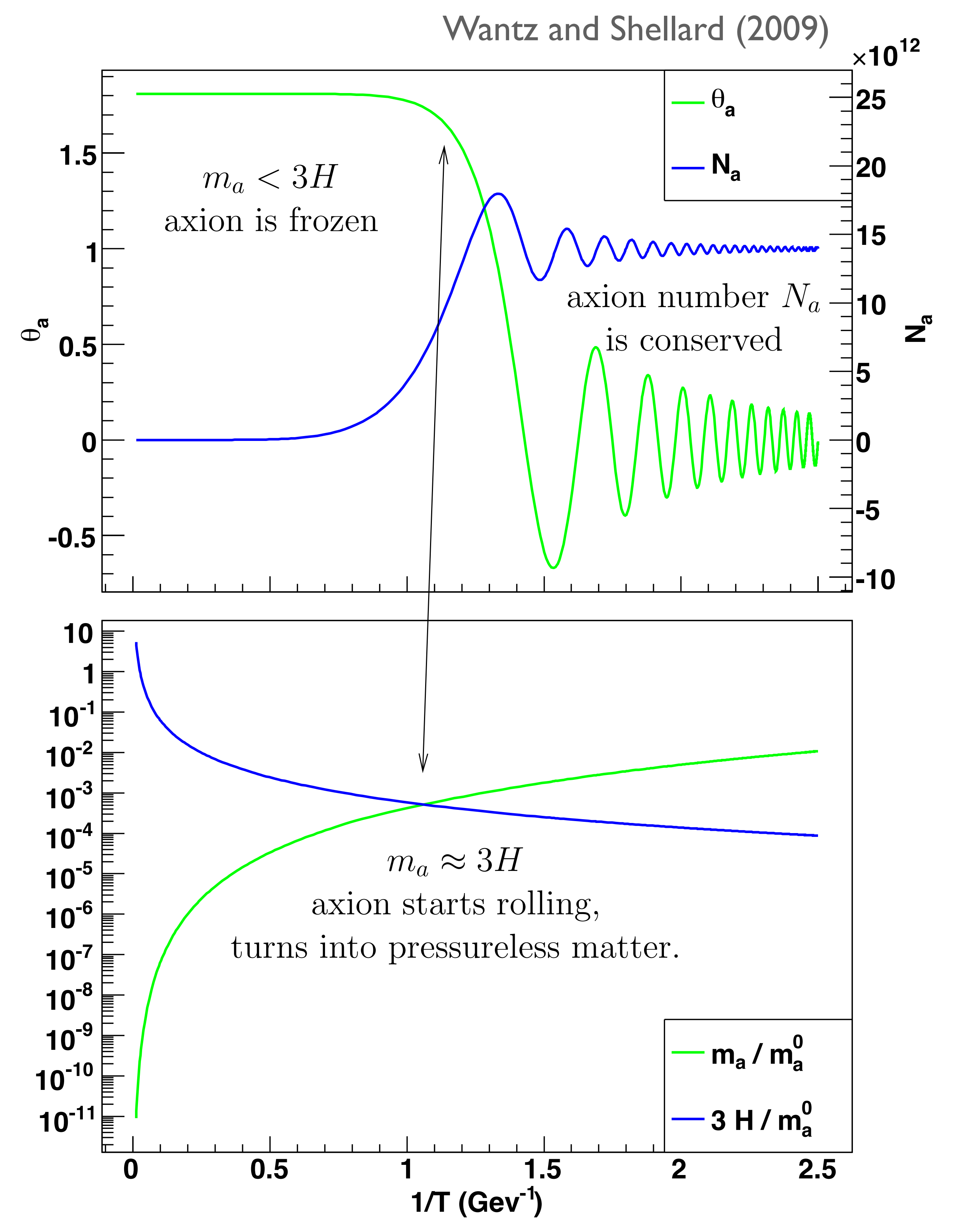
- Total abundance is sum of all these contributions.
- All these effects have to be quantitatively taken into account.

Re-alignment mechanism

- Axion field starts to oscillate at $$m_a(T_{\rm osc}) \approx 3H(T_{\rm osc})$$
- Temperature dependence of axion mass is important. $$m_a(T)F_a = \sqrt{\chi(T)}$$
- Recently, the lattice calculations of χ in full QCD became available.



Borsanyi et al. (2016)



Wantz and Shellard (2009)

Axionic string and axionic domain wall

Peccei-Quinn field (complex scalar field)

$\Phi = |\Phi| e^{ia(x)/v_{\mathrm{PQ}}}$ $a(x)$: axion field

String formation $T \lesssim F_a$

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

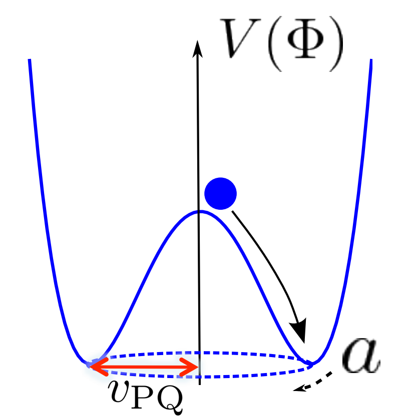
$$V(\Phi) = \lambda \left(|\Phi|^2 - \frac{v_{\mathrm{PQ}}^2}{2} \right)^2$$

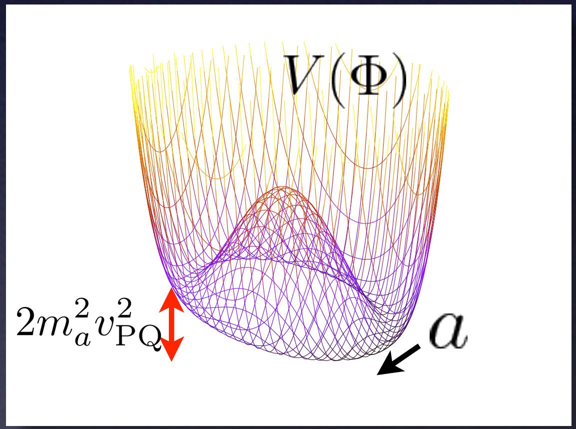
Domain wall formation $T \lesssim 1\mathrm{GeV}$

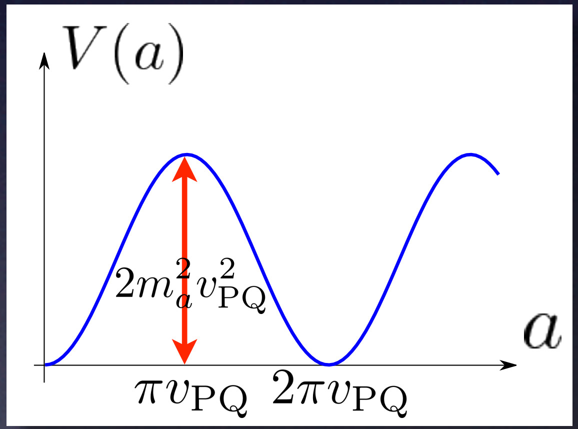
QCD effect

$$V(\Phi) = \lambda \left(|\Phi|^2 - \frac{v_{\mathrm{PQ}}^2}{2} \right)^2 + \boxed{m_a^2 v_{\mathrm{PQ}}^2 (1 - \cos(a/v_{\mathrm{PQ}}))}$$

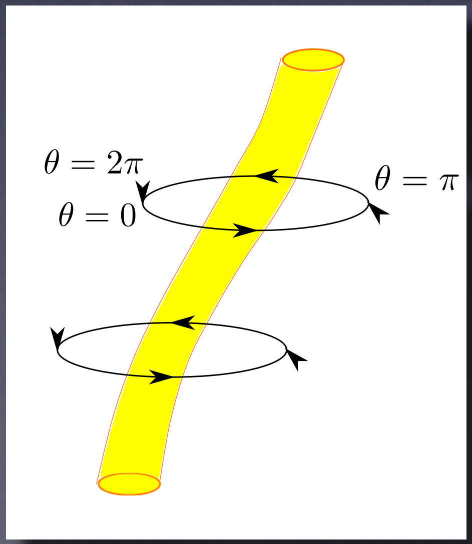
field space

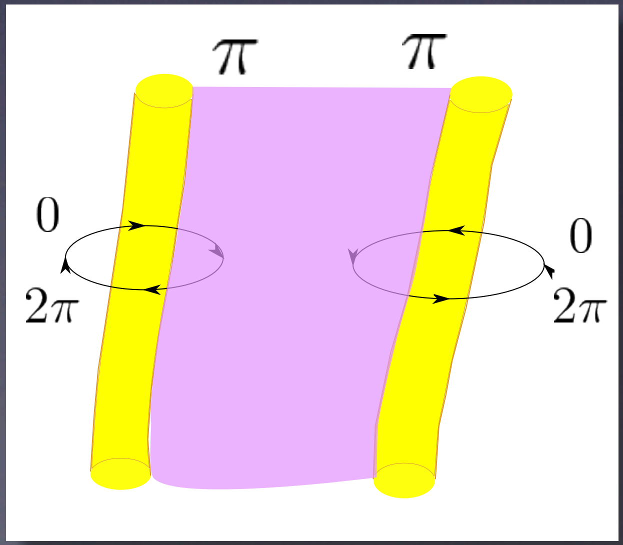






coordinate space





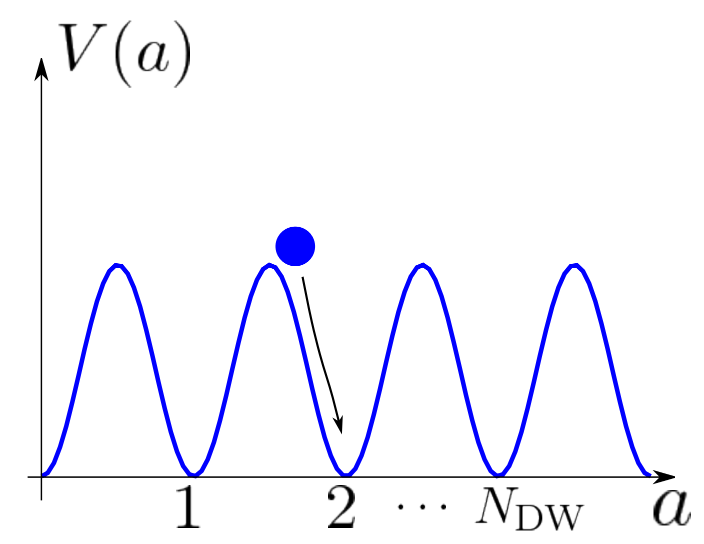
strings attached by domain walls

Domain wall problem

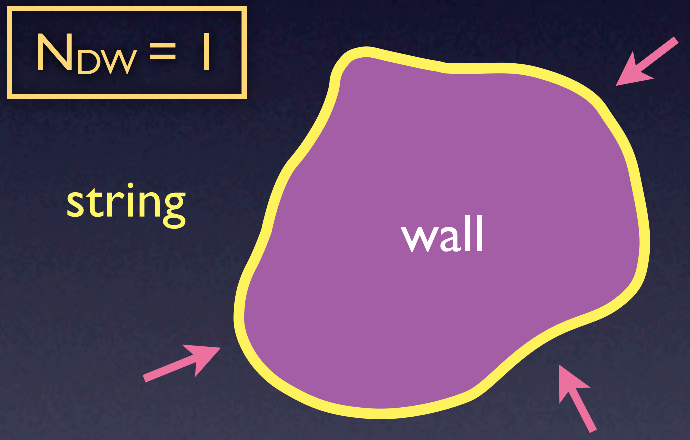
- Domain wall number N_{DW}
  - N_{DW} degenerate vacua

$$\boxed{V(a) = \frac{m_a^2 v_{PQ}^2}{N_{DW}^2}\left(1-\cos\left(N_{DW}\frac{a}{v_{PQ}}\right)\right)}$$

N_{DW} : integer determined by QCD anomaly



- If $N_{DW} = 1$, string-wall systems are unstable.
  - They collapse soon after the formation.



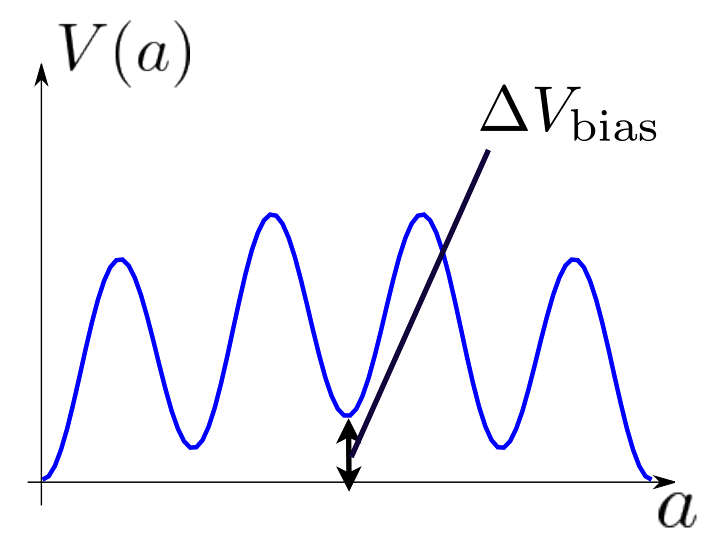
- If $N_{DW} > 1$, string-wall systems are stable.
  - coming to overclose the universe.

Zel'dovich, Kobzarev and Okun (1975)

  - We may avoid this problem by introducing an energy bias (walls become unstable). Sikivie (1982)

$$V(a) = \frac{m_a^2 v_{PQ}^2}{N_{DW}^2}\left(1-\cos\left(\frac{N_{DW}a}{v_{PQ}}\right)\right) + \underline{\Delta V_{\rm bias}}$$

lifts degenerate vacua

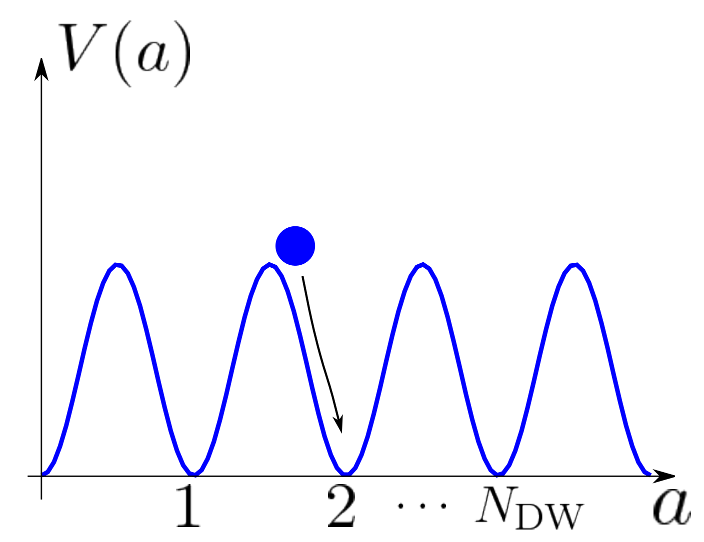


Domain wall problem

- Domain wall number N_{DW}
  - N_{DW} degenerate vacua

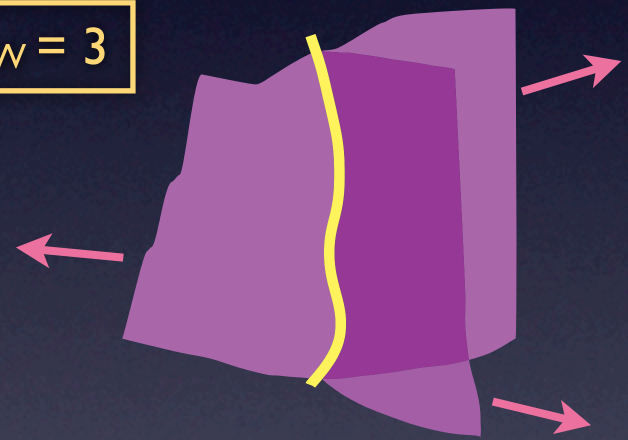
$$\boxed{V(a) = \frac{m_a^2 v_{\rm PQ}^2}{N_{\rm DW}^2}\left(1-\cos\left(N_{\rm DW}\frac{a}{v_{\rm PQ}}\right)\right)}$$

$N_{\rm DW}$: integer determined by QCD anomaly



- If $N_{\rm DW} = 1$, string-wall systems are unstable.
  - They collapse soon after the formation.

$N_{\rm DW} = 3$



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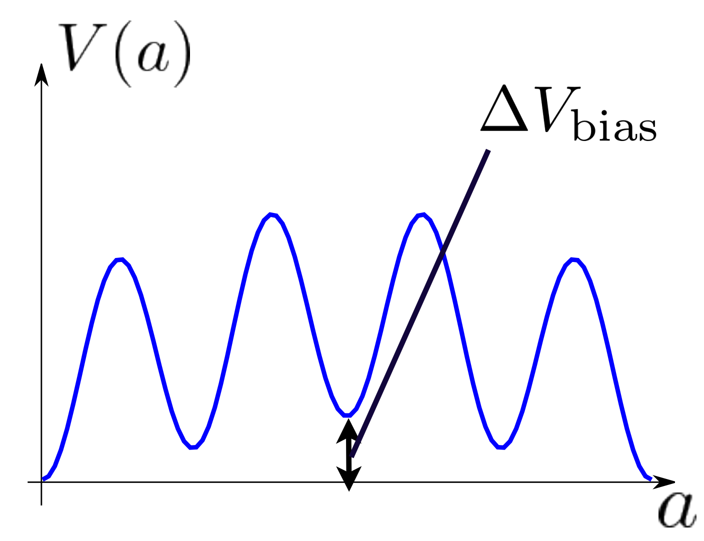
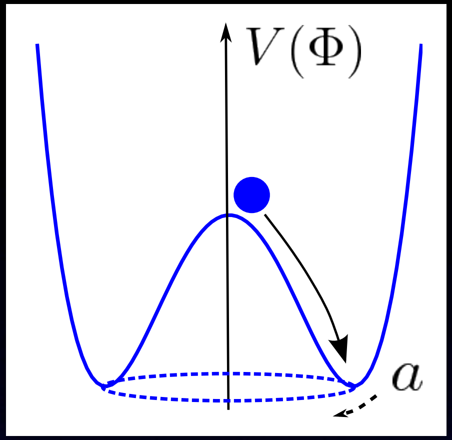
$$V(a) = \frac{m_a^2 v_{\rm PQ}^2}{N_{\rm DW}^2}\left(1-\cos\left(\frac{N_{\rm DW}a}{v_{\rm PQ}}\right)\right) + \underset{\uparrow}{\underline{\Delta V_{\rm bias}}}$$

lifts degenerate vacua



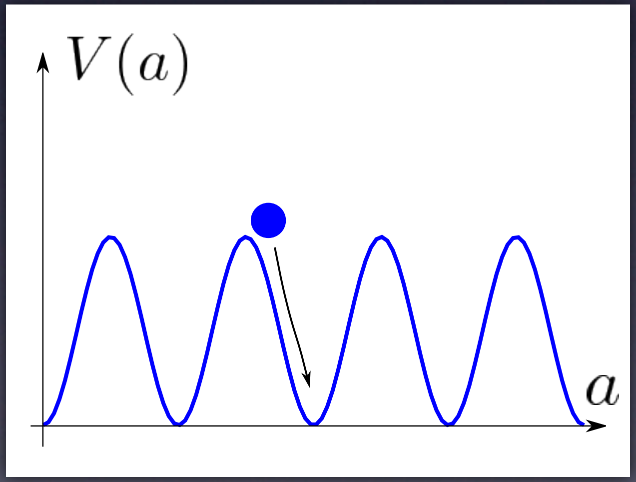
Production of axions in the early universe

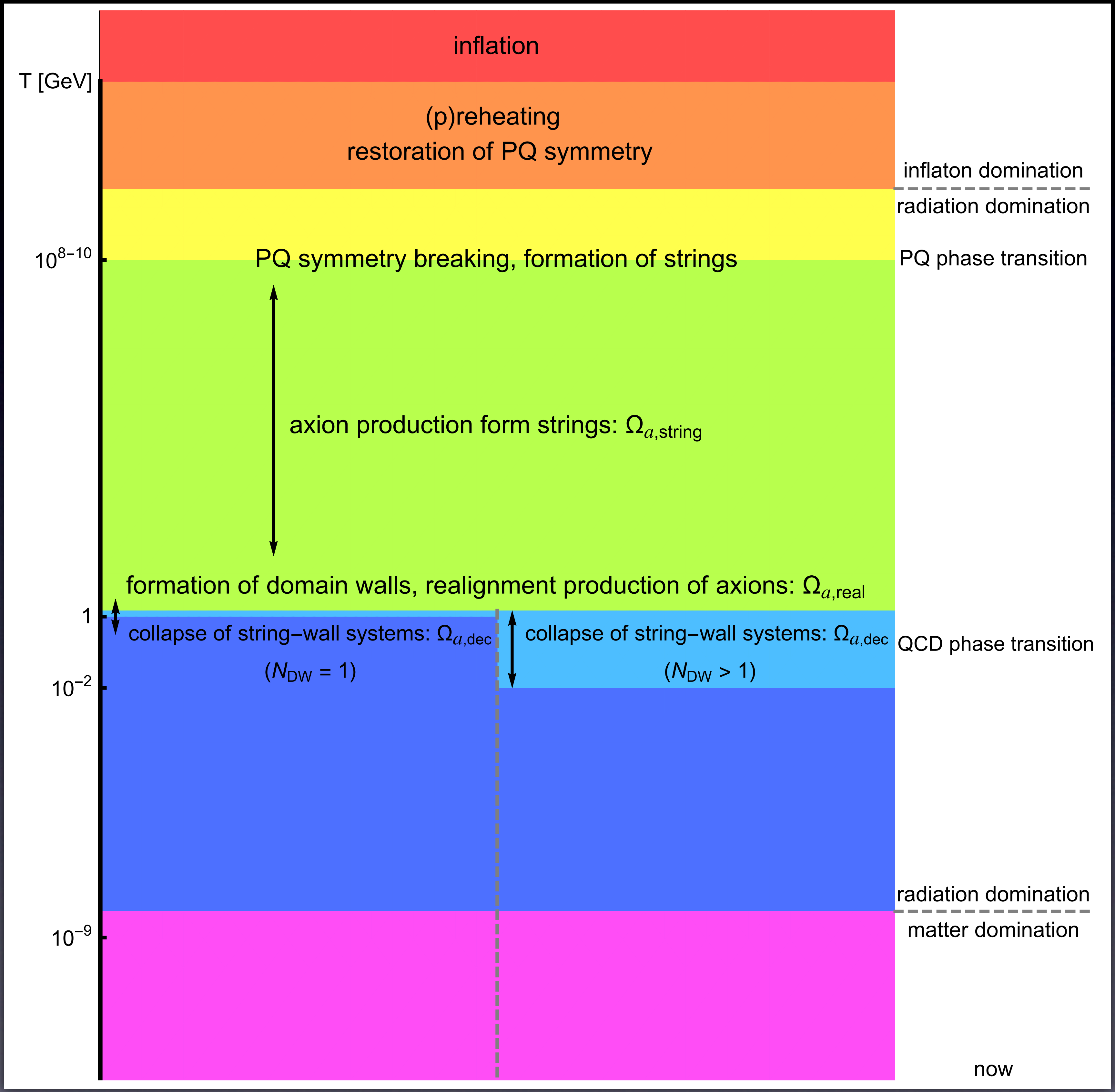
(post-inflationary PQ symmetry breaking scenario)



$$T \lesssim F_a \simeq 10^{8-11}\,\mathrm{GeV}$$

$$T \lesssim 1\,\mathrm{GeV}$$





inflation

(p)reheating
restoration of PQ symmetry

inflaton domination

radiation domination

PQ symmetry breaking, formation of strings

PQ phase transition

axion production form strings: $\Omega_{a,\text{string}}$

formation of domain walls, realignment production of axions: $\Omega_{a,\text{real}}$

collapse of string–wall systems: $\Omega_{a,\text{dec}}$
($N_{\text{DW}} = 1$)

collapse of string–wall systems: $\Omega_{a,\text{dec}}$
($N_{\text{DW}} > 1$)

QCD phase transition

radiation domination

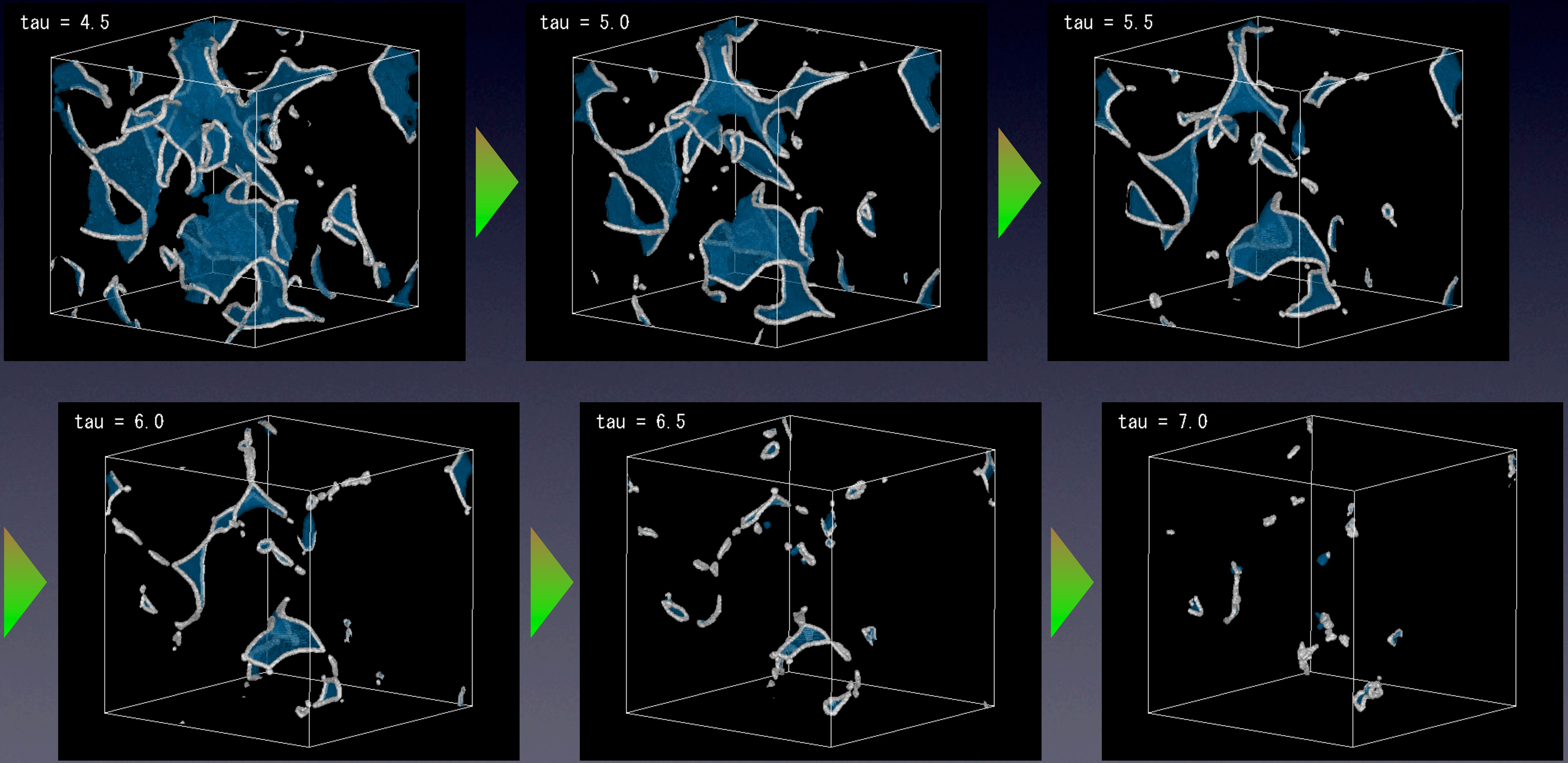
matter domination

now

Numerical simulation : $N_{DW} = 1$

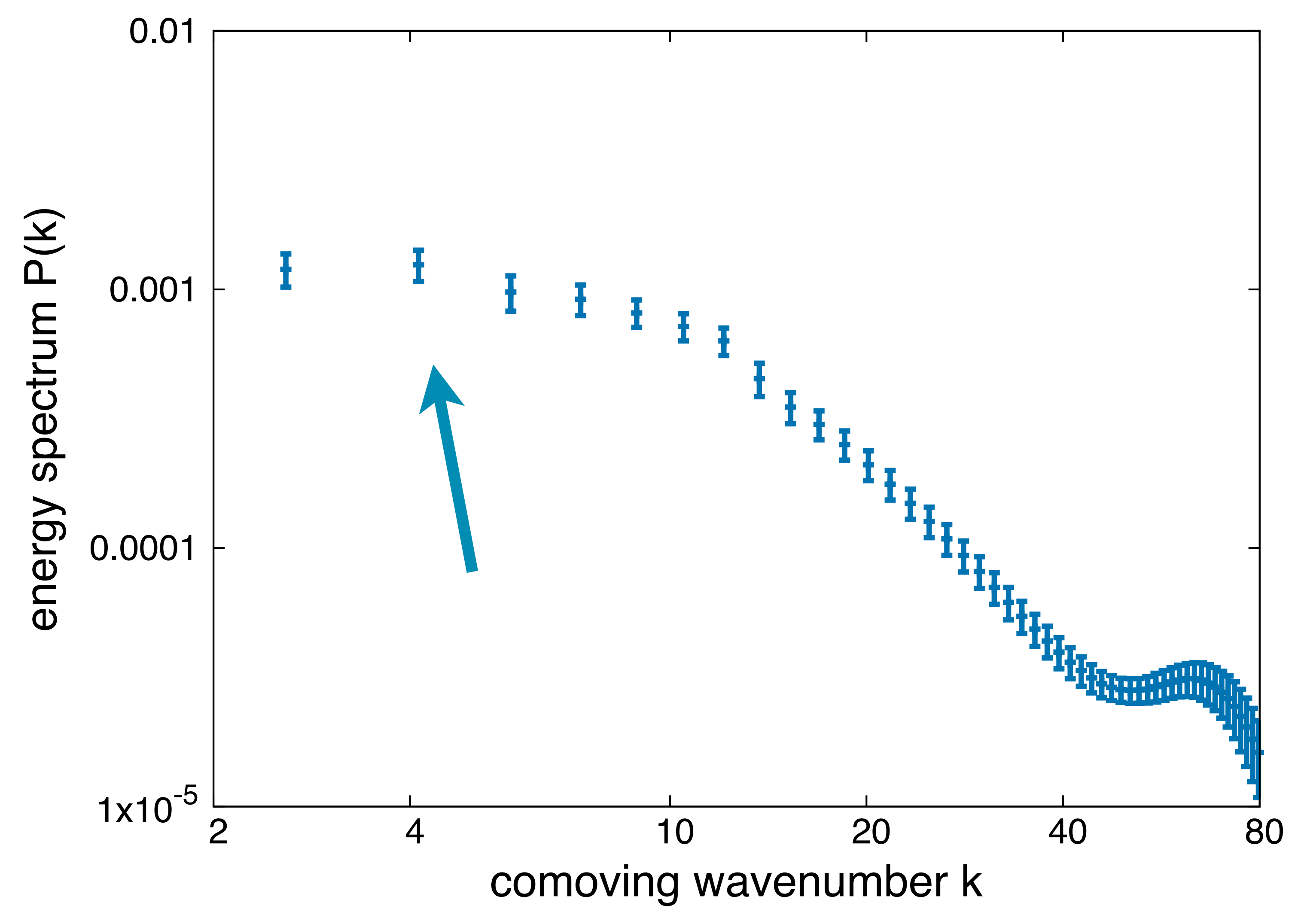
Hiramatsu, Kawasaki, KS and Sekiguchi (2012)

- Solving the classical field equations on lattice
- Number of grids in simulation box: $N^3 = 512^3$



Spectrum of radiated axions

Hiramatsu, Kawasaki, KS and Sekiguchi (2012)
Kawasaki, KS and Sekiguchi (2015)



Mean energy

$$\frac{\langle\omega_a\rangle}{m_a}(t_{\rm decay}) = 3.23 \pm 0.18$$

$$\omega_a = \sqrt{m_a^2 + k^2/R(t)^2}$$

$R(t)$: scale factor of the universe

Contribution to the relic abundance

$$\rho_a(t_{\rm today}) = m_a \frac{\rho_a(t_{\rm decay})}{\langle\omega_a\rangle}\left(\frac{R(t_{\rm decay})}{R(t_{\rm today})}\right)^3$$

$$\rho_a(t_{\rm decay}) \approx \rho_{\rm defects}(t_{\rm decay})$$

Axion dark matter abundance ($N_{DW} = 1$)

- Re-alignment mechanism Borsanyi et al. (2016), Ballesteros, Redondo, Ringwald and Tamarit (2016)

$$\Omega_{a,\mathrm{real}} h^2 \approx (3.8 \pm 0.6) \times 10^{-3} \left(\frac{F_a}{10^{10}\ \mathrm{GeV}} \right)^{1.165}$$

- Production from string-wall systems

$$\Omega_{a,\text{string-wall}} h^2 \approx 1.2^{+0.9}_{-0.7} \times 10^{-2} \left(\frac{F_a}{10^{10}\ \mathrm{GeV}} \right)^{1.165}$$

- Total axion abundance

$$\Omega_{a,\mathrm{tot}} h^2 \approx 1.6^{+1.0}_{-0.7} \times 10^{-2} \left(\frac{F_a}{10^{10}\ \mathrm{GeV}} \right)^{1.165}$$

$$\Omega_{a,\mathrm{tot}} \leq \Omega_{\mathrm{CDM}}$$

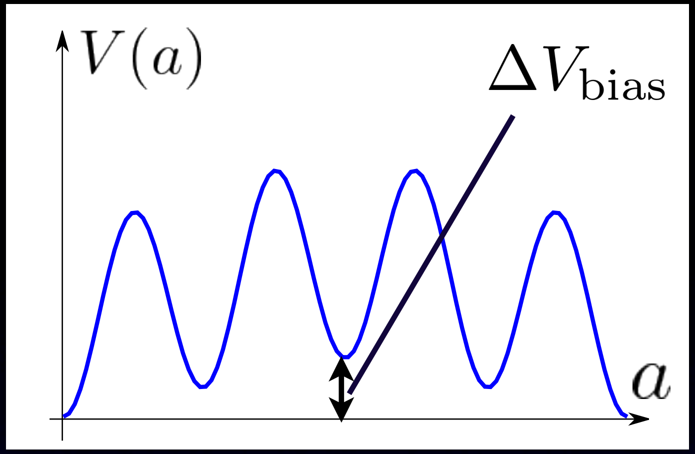
$$\Omega_{\mathrm{CDM}} h^2 \simeq 0.12$$

⇒

$$\boxed{\begin{aligned} F_a &\lesssim (3.8\text{–}9.9) \times 10^{10}\ \mathrm{GeV} \\ m_a &\gtrsim (0.6\text{–}1.5) \times 10^{-4}\ \mathrm{eV} \end{aligned}}$$

- Large uncertainty comes from estimation of the string density in numerical simulations.

Models with N_{DW} > 1: long-lived domain walls



- Domain walls are long-lived and eventually annihilated due to the energy bias.
- Origin of the bias term ?
  - $U(1)_{PQ}$ may not be an exact symmetry: Global symmetry can be spoiled by gravitational effects.

Holman et al. , Kamionkowski and March-Russell,
Barr and Seckel, Ghigna, Lusignoli and Roncadelli, Dine (1992)

  - We can assume that the PQ symmetry is not *ad hoc* but instead an accidental symmetry of an exact discrete Z_N symmetry (with large N).

Choi, Nilles, Ramos-Sanchez and Vaudrevange (2009)

  - Planck-suppressed operators allowed by the Z_N symmetry work as the bias term.

$$\mathcal{L} \supset \frac{g}{M_{\rm Pl}^{N-4}}\Phi^N + {\rm h.c.}$$

$$g = |g|e^{i\Delta}$$

$$\Delta V_{\rm bias}(a) = -2\Xi v_{\rm PQ}^4 \cos\left(N\frac{a}{v_{\rm PQ}} + \Delta_D\right)$$

$$\Xi = \frac{|g|N_{\rm DW}^{N-4}}{(\sqrt{2})^N}\left(\frac{F_a}{M_{\rm Pl}}\right)^{N-4}, \quad \Delta_D = \Delta - N\bar{\theta}$$

Constraints

- CP violation

The higher dimensional operator shifts the minimum of the potential and spoils the original Peccei-Quinn solution to the strong CP problem.

$$\frac{\langle a \rangle}{F_a} \simeq \frac{\frac{N|g|N_{\rm DW}^{N-1}}{(\sqrt{2})^{N-2}} \left(\frac{F_a}{M_{\rm Pl}}\right)^{N-2} M_{\rm Pl}^2 \sin\Delta_D}{m_a^2 + \frac{N^2|g|N_{\rm DW}^{N-2}}{(\sqrt{2})^{N-2}} \left(\frac{F_a}{M_{\rm Pl}}\right)^{N-2} M_{\rm Pl} \cos\Delta_D} < 7 \times 10^{-12}$$

→ Large N is required

- Dark matter abundance

Long-lived domain walls produce too much cold axions.

Hiramatsu, Kawasaki, KS, and Sekiguchi (2013); Kawasaki, KS, and Sekiguchi (2015)

$$\Omega_a h^2 \simeq (3.4\text{–}6.2) \times N_{\rm DW}^{-2} \left(\frac{\Xi}{10^{-52}}\right)^{-1/2} \left(\frac{F_a}{10^9\,{\rm GeV}}\right)^{-1/2} \quad \text{with} \quad \Xi = \frac{|g|N_{\rm DW}^{N-4}}{(\sqrt{2})^N} \left(\frac{F_a}{M_{\rm Pl}}\right)^{N-4}$$

→ Small N is required

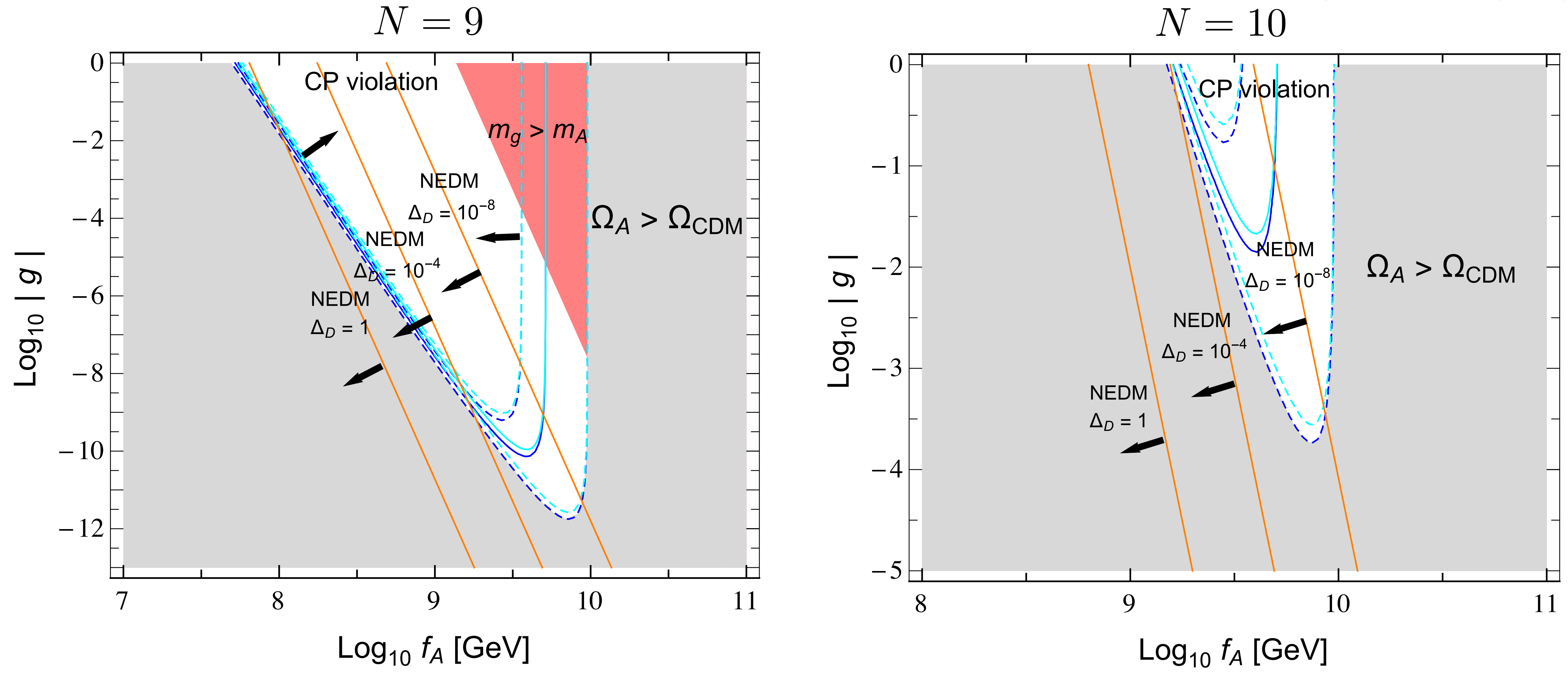
- Constraints on the energy bias (= on the coefficient g)

$$\Delta V_{\rm bias}(a) = -2\Xi v_{\rm PQ}^4 \cos\left(N\frac{a}{v_{\rm PQ}}+\Delta_D\right) \quad \Longleftarrow \quad \mathcal{L}\supset \frac{g}{M_{\rm Pl}^{N-4}}\Phi^N + {\rm h.c.}$$

- Loopholes appear if the order of the discrete symmetry is N = 9 or 10, but some tuning of the phase parameter Δ_D is required.

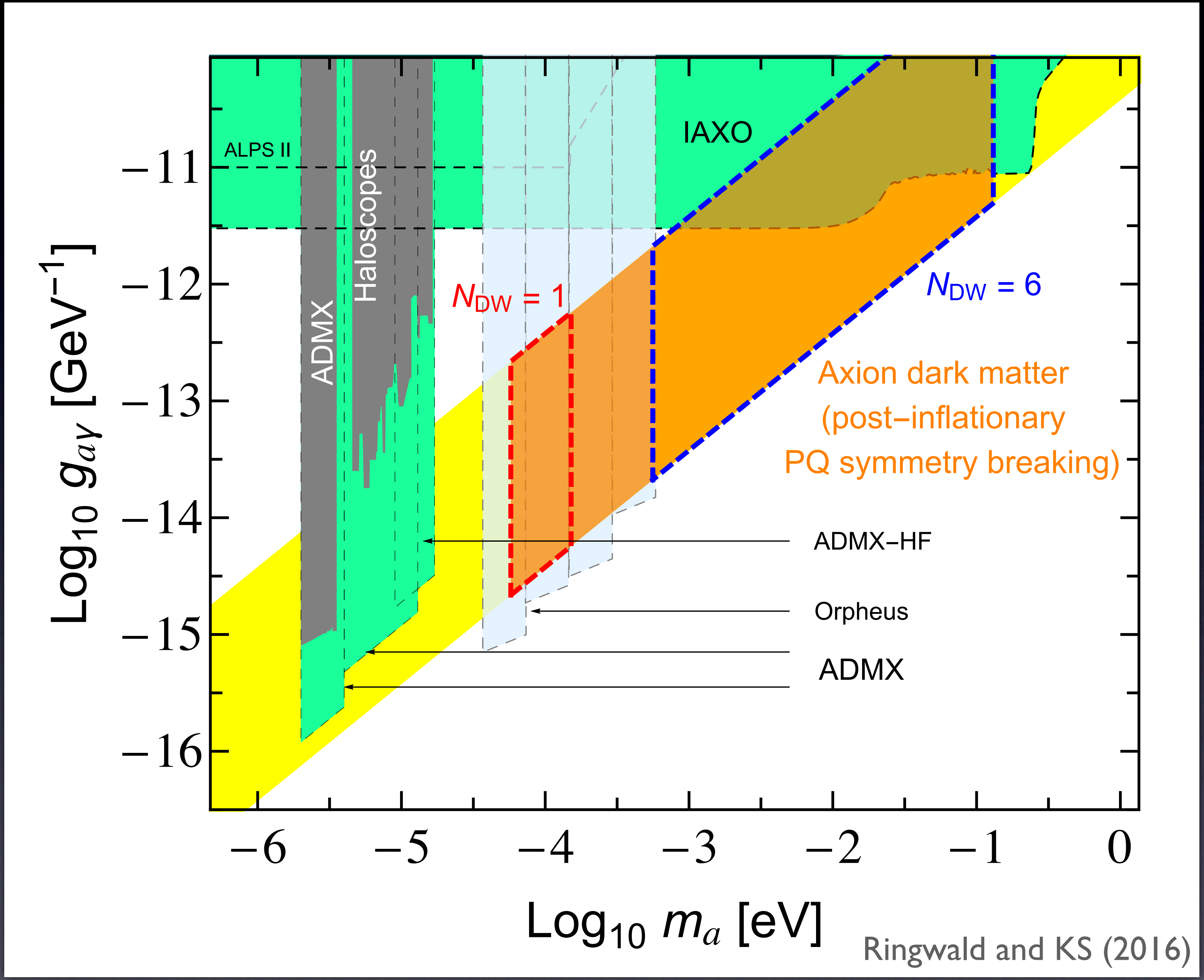
- If we allow such a mild tuning, axions can explain total dark matter abundance in the small F_a range.

Ringwald and KS (2016)



Search for axion dark matter

Search space in photon coupling $g_{a\gamma} \sim \alpha/(2\pi F_a)$ vs. mass m_a



Ringwald and KS (2016)

Mass ranges predicted in the post-inflationary PQ symmetry breaking scenario can be probed by various future experimental studies.

Conclusion

- Predictions for axion dark matter strongly depend on the early history of the universe.
- If the PQ symmetry is broken after inflation, string-wall systems give additional contribution to the CDM abundance.
- Axion can be dominant component of dark matter if

$$F_a \simeq (3.8\text{–}9.9) \times 10^{10}\,\mathrm{GeV}$$

$$m_a \simeq (0.6\text{–}1.5) \times 10^{-4}\,\mathrm{eV}$$

for $N_{DW} = 1$

$$F_a \simeq \mathcal{O}(10^{8}\text{–}10^{10})\,\mathrm{GeV}$$

$$m_a \simeq \mathcal{O}(10^{-4}\text{–}10^{-2})\,\mathrm{eV}$$

for $N_{DW} > 1$

- Mass ranges can be probed in the future experiments.