Axion as a non-WIMP dark matter candidate

Ken'ichi Saikawa (DESY)

Necessary conditions for dark matter candidates: "a ten-point test"

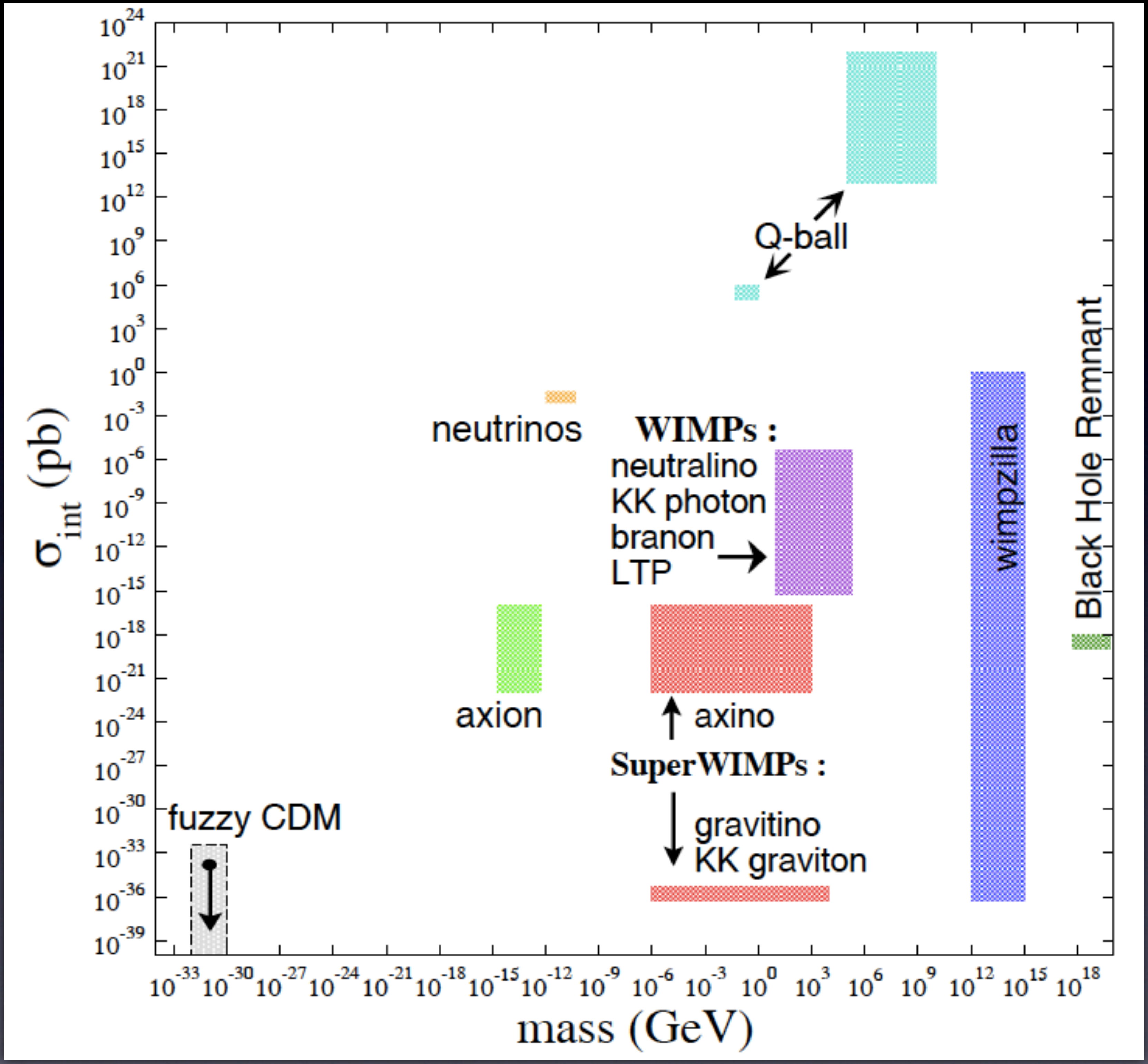
Taoso, Bertone, and Masiero (2008)

A particle can be considered a good DM candidate only if a positive answer can be give to *all* the following points.

(1) Does it match the appropriate relic density?
(2) Is it cold?
(3) Is it neutral?
(4) Is it consistent with BBN?
(5) Does it leave stellar evolution unchanged?
(6) Is it compatible with constraints on self-interactions?
(7) Is it consistent with *direct* DM searches?
(8) Is it compatible with gamma-ray constraints?
(9) Is it compatible with other astrophysical bounds?
(10) Can it be probed experimentally?

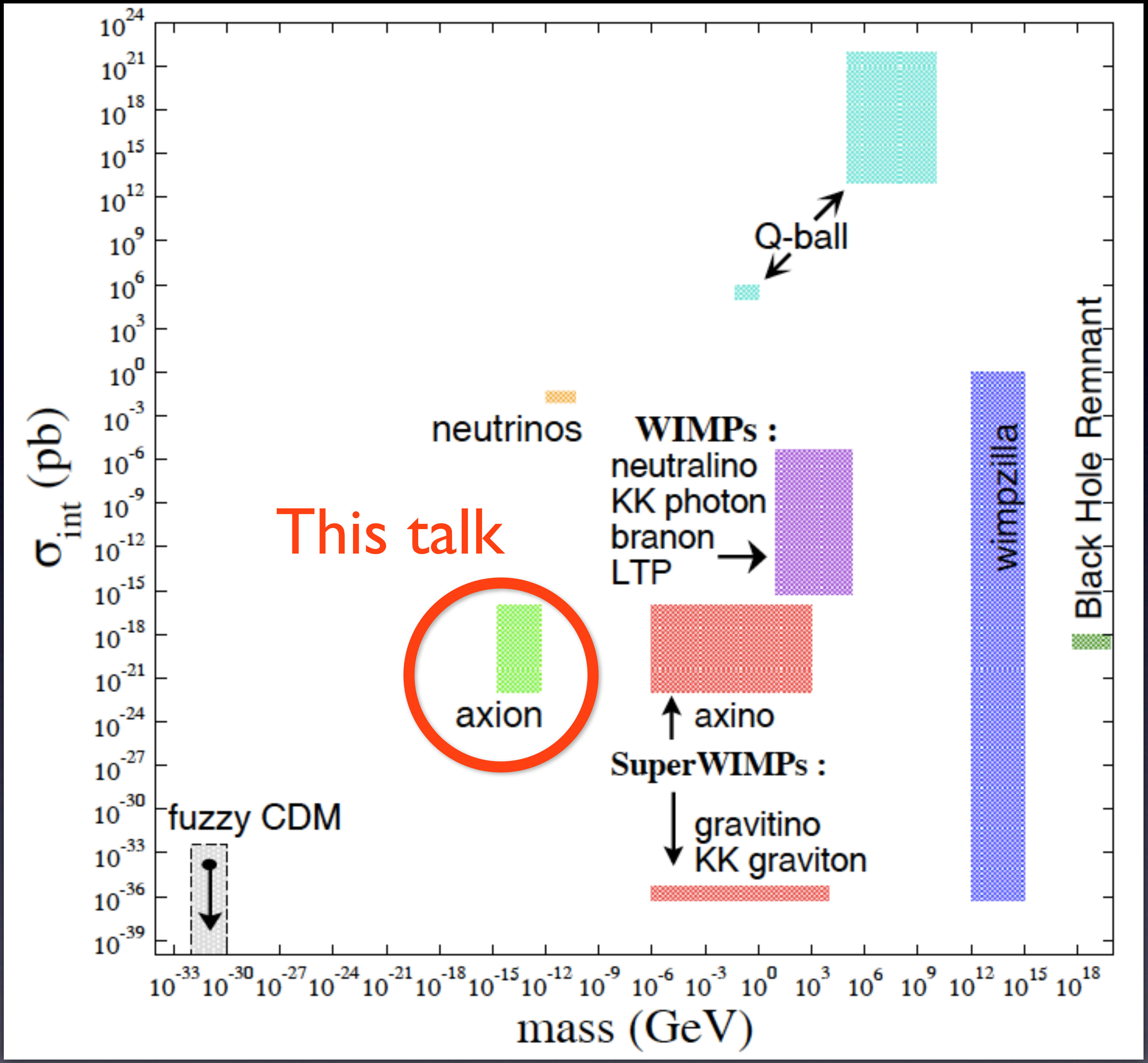
Plenty of room for consideration of non-WIMP candidates.

Zoo of dark matter candidates



from Dark Matter Scientific Assessment Group (DMSAG) report (2007)
https://science.energy.gov/~/media/hep/pdf/files/pdfs/dmsagreportjuly18_2007.pdf

Zoo of dark matter candidates



from Dark Matter Scientific Assessment Group (DMSAG) report (2007)
https://science.energy.gov/~/media/hep/pdf/files/pdfs/dmsagreportjuly18_2007.pdf

QCD axion as dark matter candidate

- Motivated by Pecccei-Quinn mechanism Peccei and Quinn (1977)
  as a solution of the strong CP problem

- Spontaneous breaking of global U(1) Peccei-Quinn symmetry at

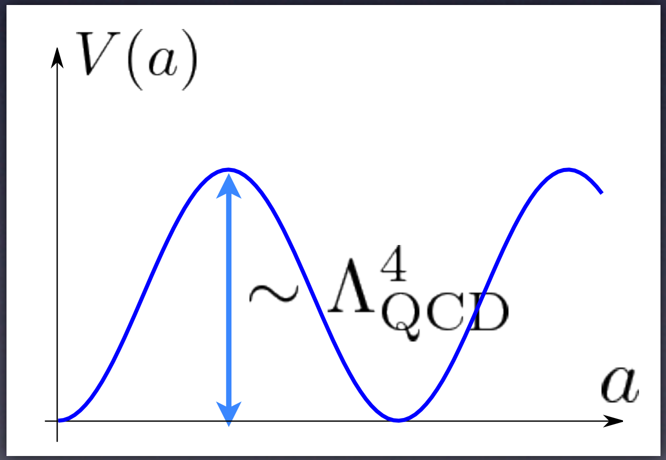
$$F_a \simeq 10^{8-11}\,\mathrm{GeV}$$ "axion decay constant"

  - Nambu-Goldstone theorem
    → emergence of the (massless) particle ≡ axion
    Weinberg(1978), Wilczek(1978)

- Axion has a small mass (QCD effect)
  → pseudo-Nambu-Golstone boson

$$m_a \sim \frac{\Lambda_{\mathrm{QCD}}^2}{F_a} \sim 6\times 10^{-5}\mathrm{eV}\left(\frac{10^{11}\mathrm{GeV}}{F_a}\right)$$

$\Lambda_{\mathrm{QCD}} \simeq \mathcal{O}(100)\mathrm{MeV}$



- Tiny coupling with matter + non-thermal production
  → good candidate of cold dark matter

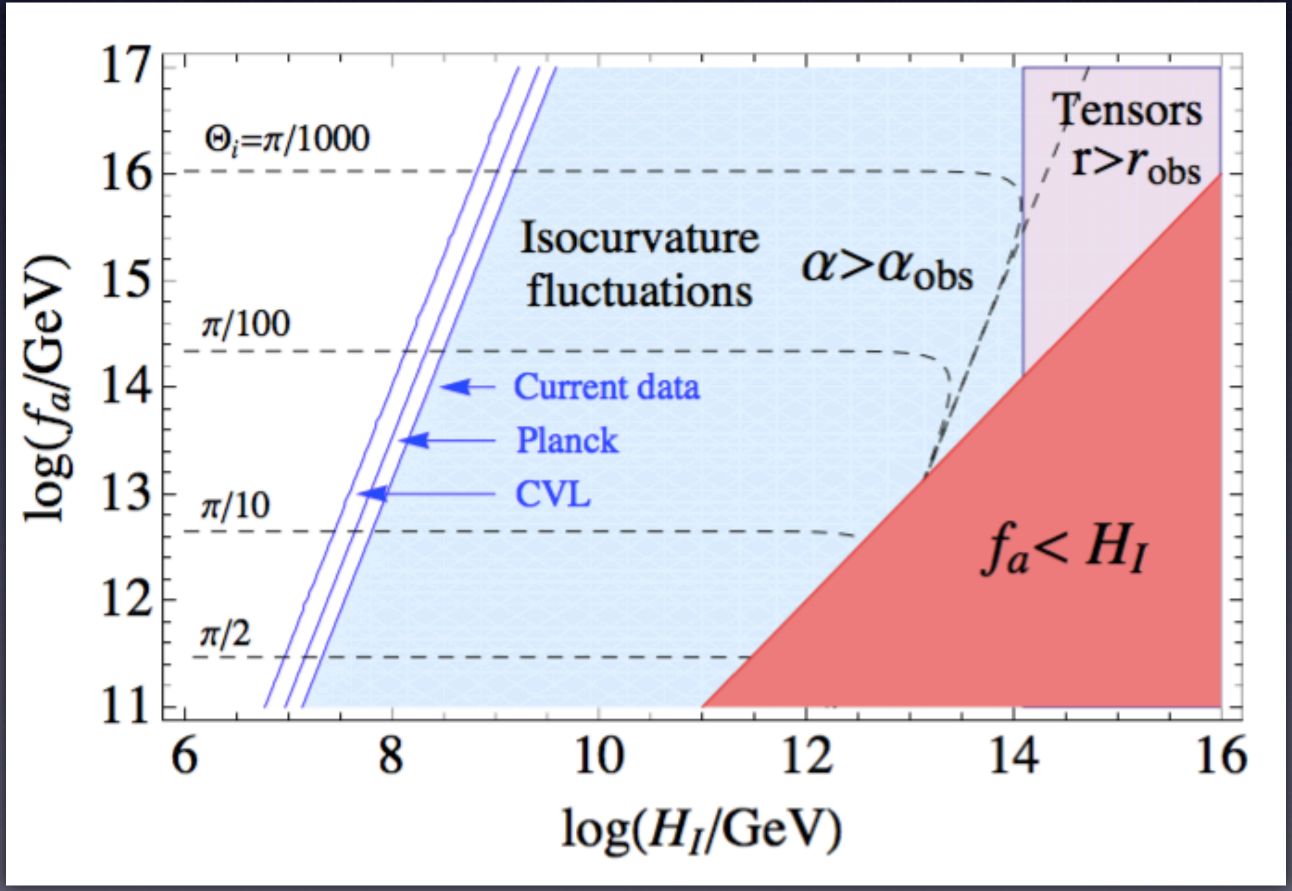
How axions are produced ?

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

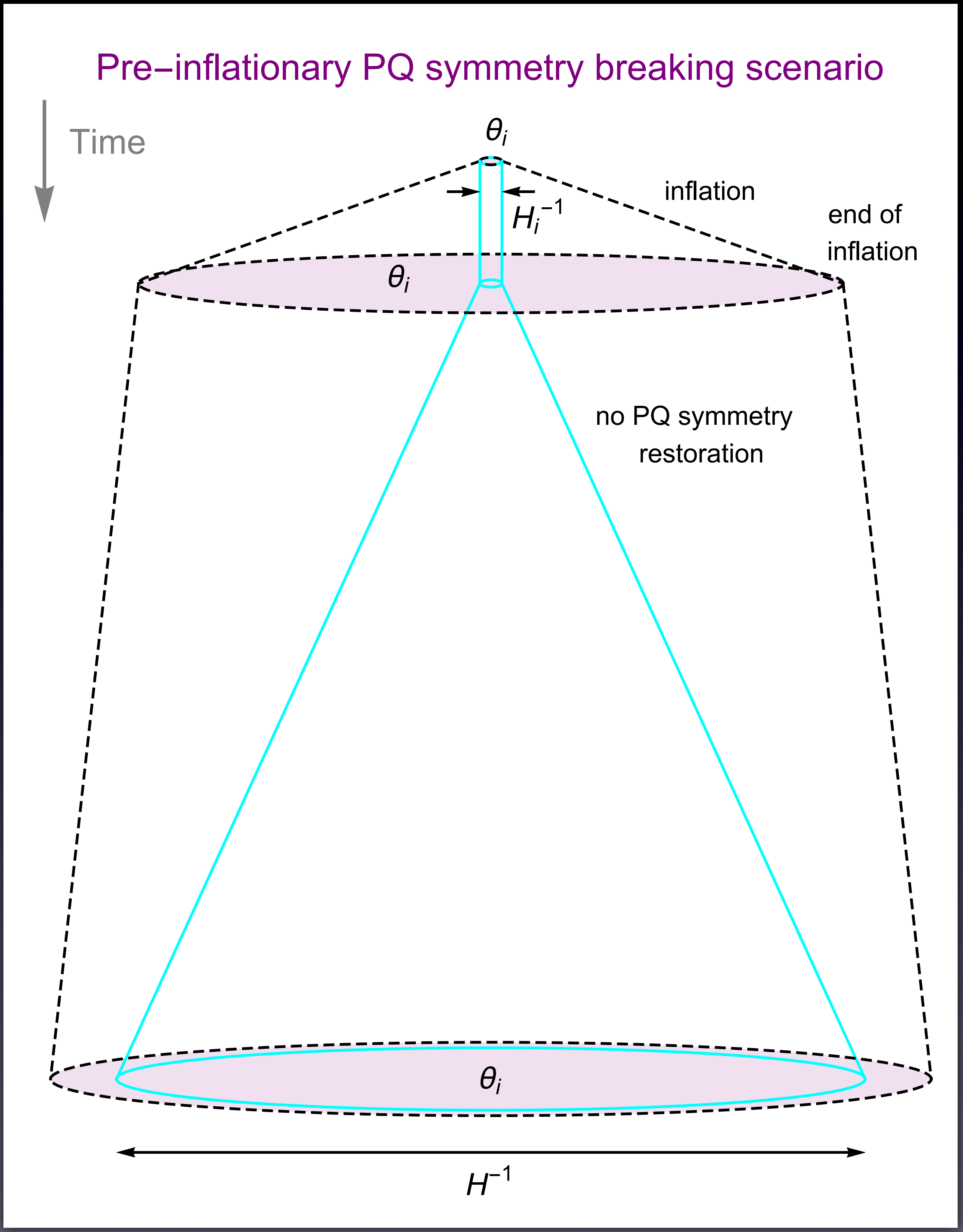
- What is the "typical mass" of the axion (or the "typical value" for the axion decay constant), if axions explain 100% of CDM abundance ?
- Predictions strongly depend on the early history of the universe.
- Two possibilities:
  - PQ symmetry is never restored after inflation
  - PQ symmetry is restored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

Pre-inflationary PQ symmetry breaking scenario

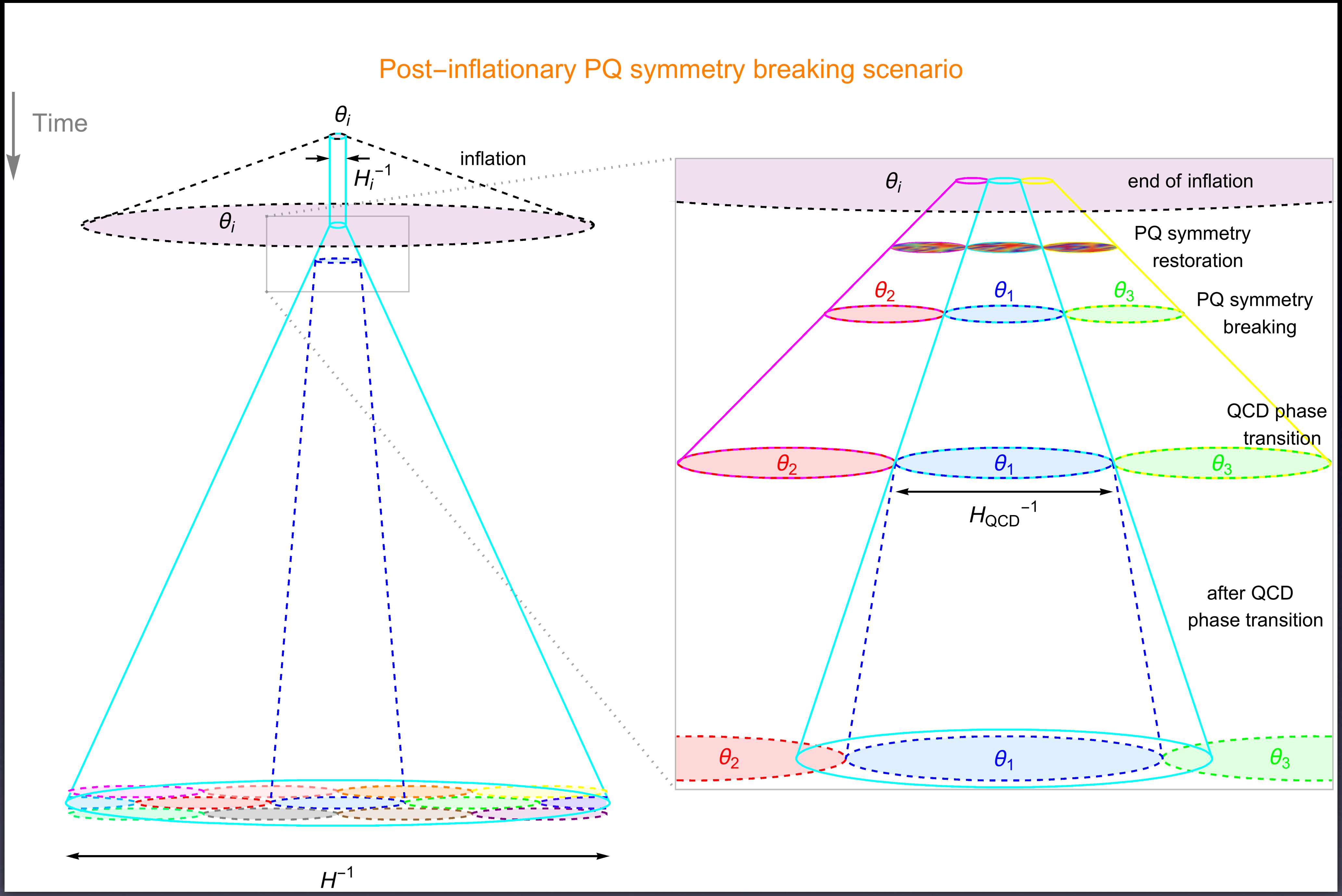
- Relic axion CDM abundance depends on F_a and initial misalignment angle $\theta_i = \langle a \rangle_i / F_a$.
- Severe constraints from isocurvature fluctuations if inflationary scale is sufficiently high.



Hamann, Hannestad, Raffelt and Wong (2009)



Post-inflationary PQ symmetry breaking scenario



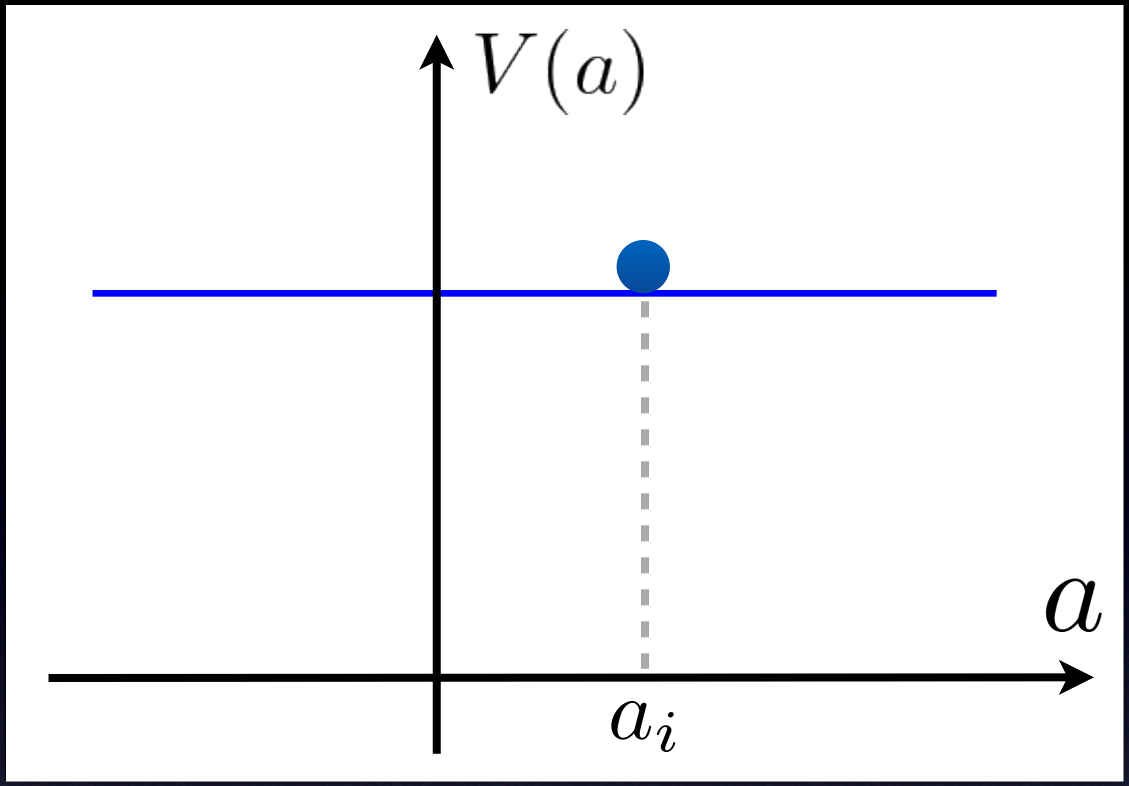
- Present observable universe contains many different patches with different values of θ_i.
- Topological defects (strings and domain walls) are formed.
- Relic axion density should be estimated by summing over all possible field configurations.

Re-alignment mechanism

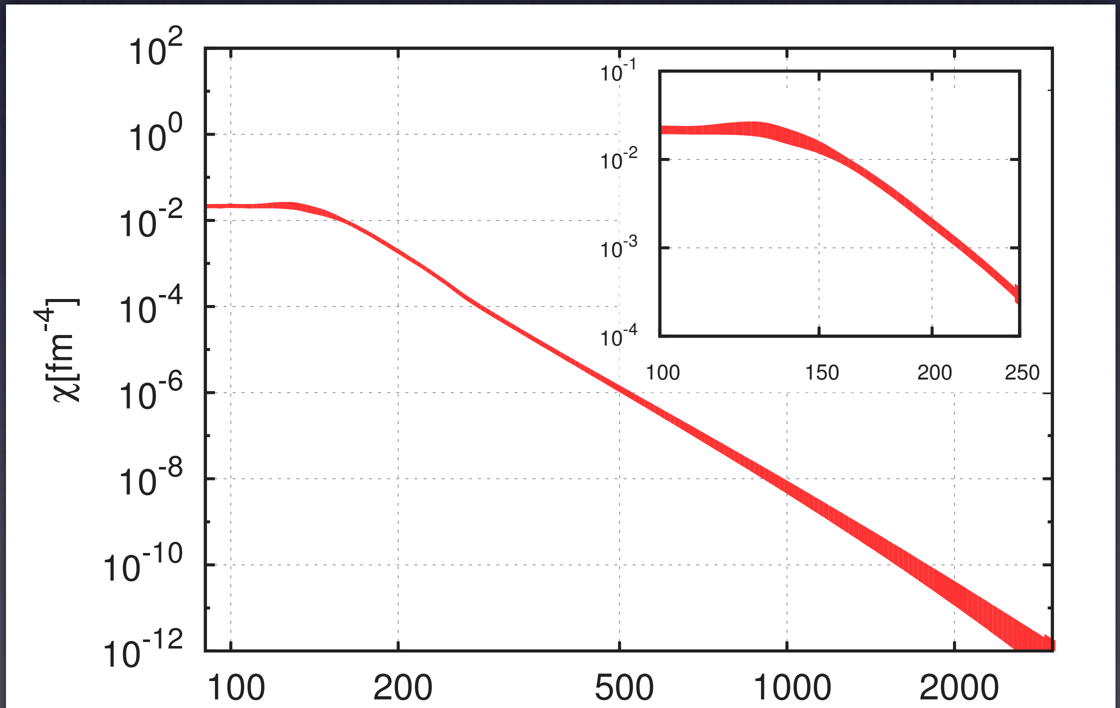
- Axion field starts to oscillate at $m_a(T_{\rm osc}) \approx 3H(T_{\rm osc})$
- Temperature dependence of axion mass is important.

$$m_a(T)F_a = \sqrt{\chi(T)}$$

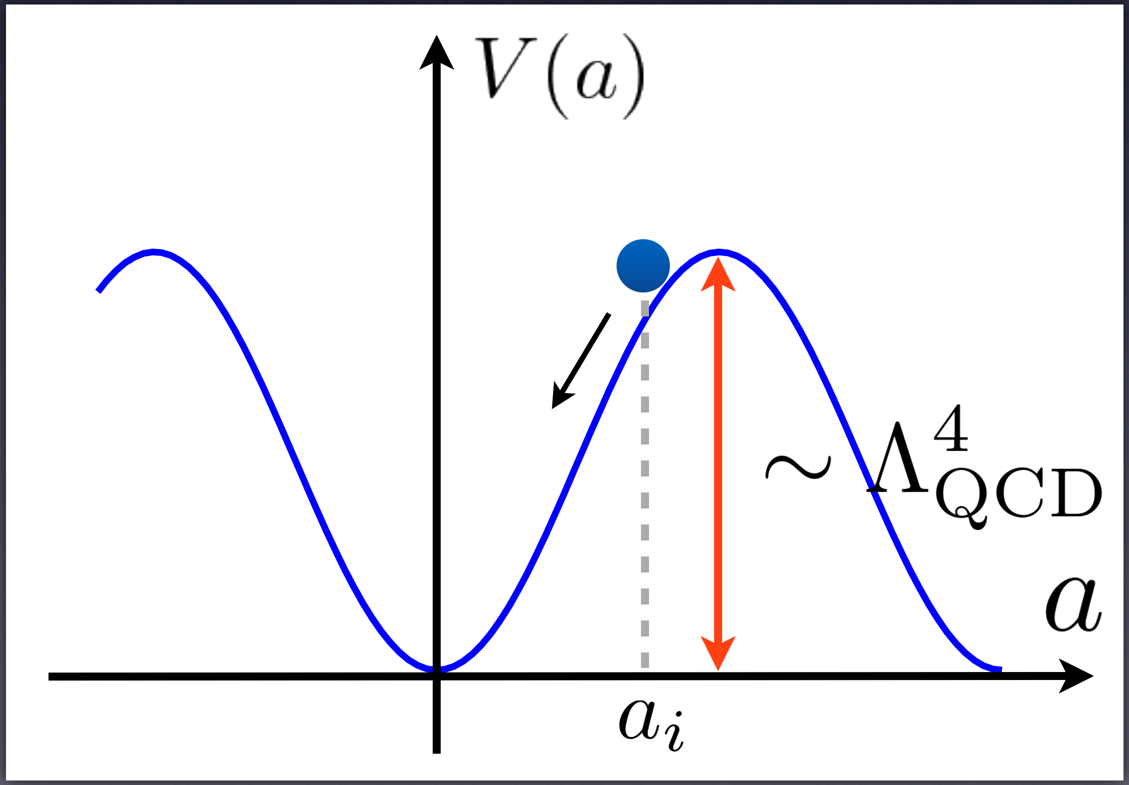
- Recently, the lattice calculations of χ in full QCD became available.



QCD phase transition



Borsanyi et al. (2016)



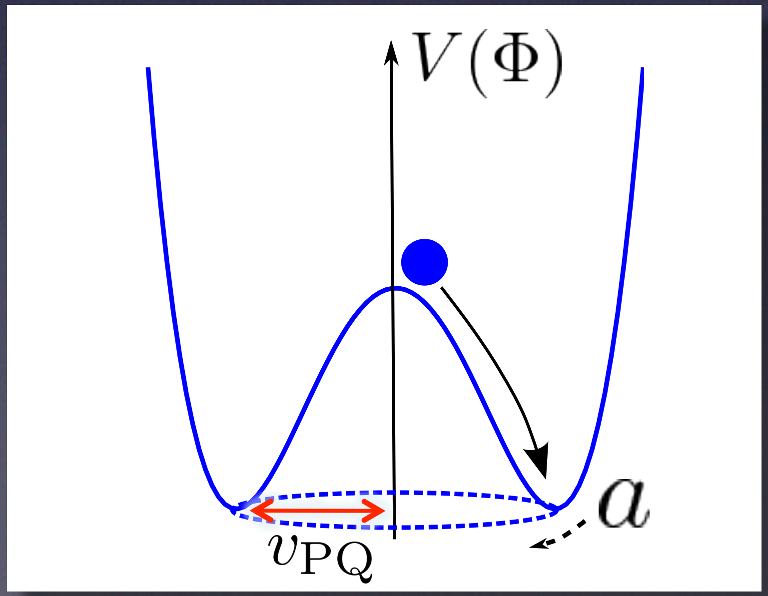
Axionic string

- Peccei-Quinn field (complex scalar field)

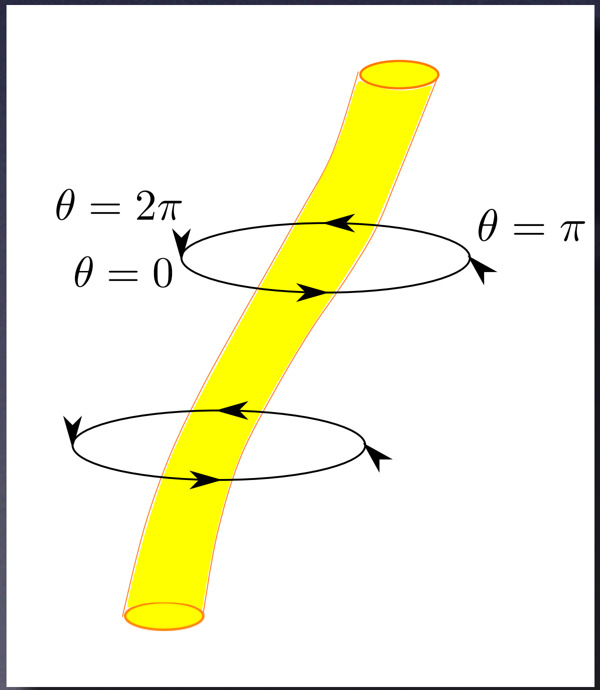
$$\Phi = |\Phi| e^{ia(x)/v_{\rm PQ}} \qquad a(x) \text{ : axion field}$$

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

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



field space

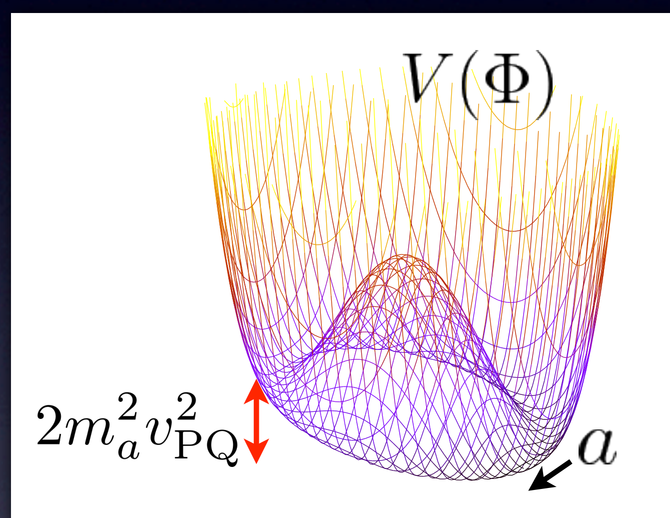


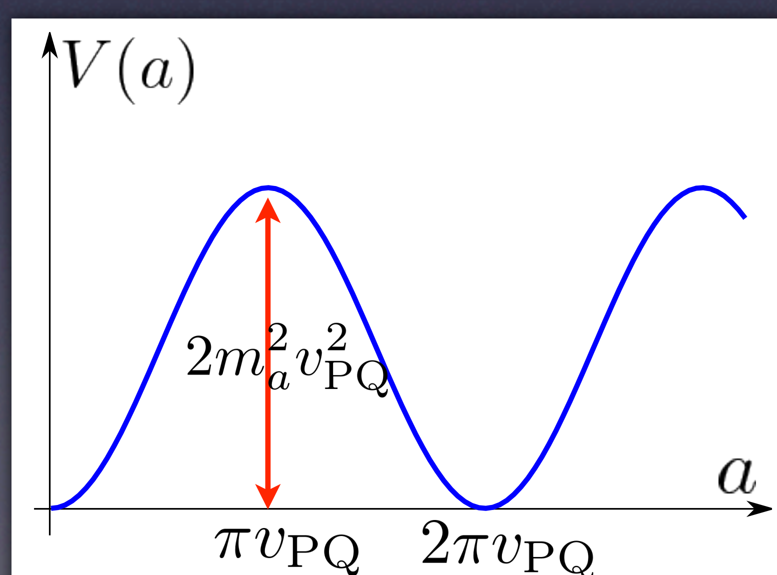
coordinate space

Axionic domain wall

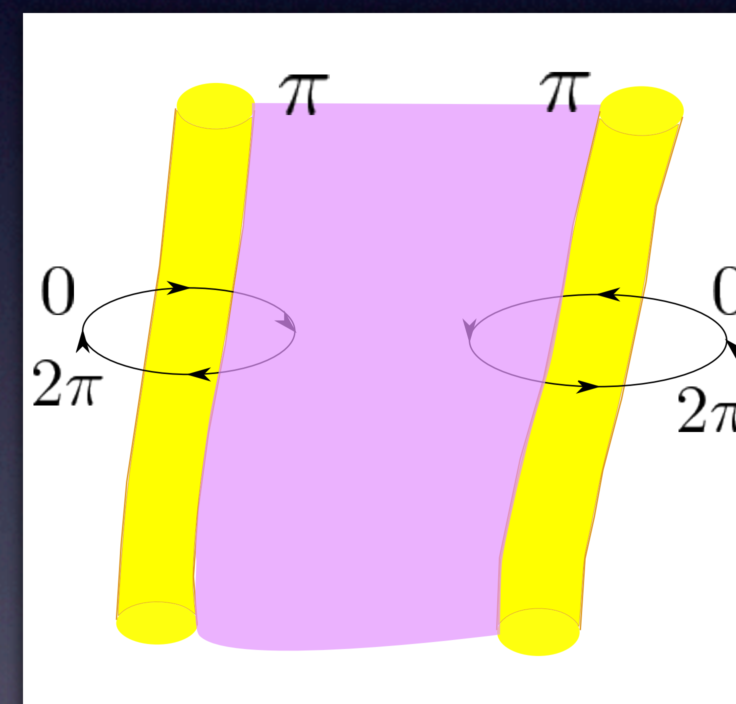
Mass of the axion (QCD effect ; $T \lesssim 1\mathrm{GeV}$)

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





field space



coordinate space

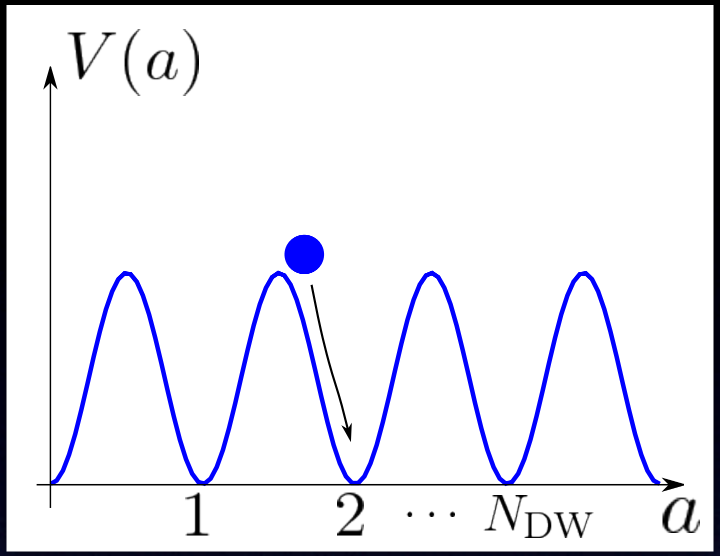
Strings attached by domain walls

Domain wall problem

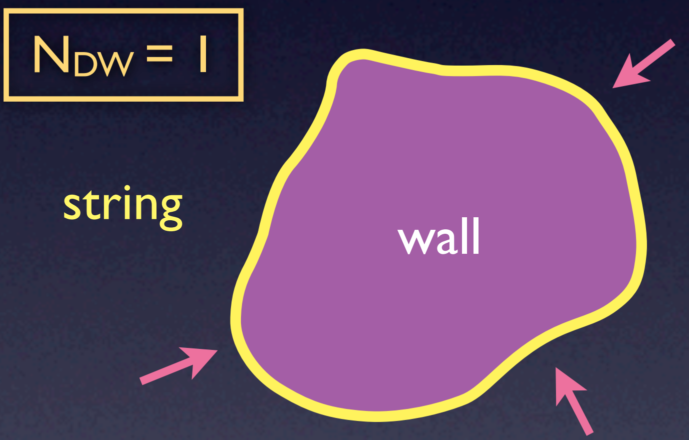
- Domain wall number N_{DW}
  - N_{DW} degenerate vacua

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

N_{DW} : integer determined by QCD anomaly



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



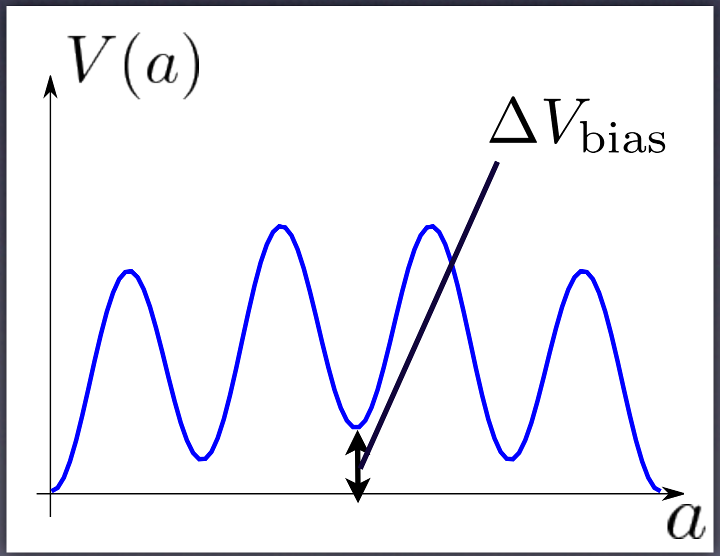
- If $N_{DW} > 1$, string-wall systems are stable.
  - coming to overclose the universe.

Zel'dovich, Kobzarev and Okun (1975)

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

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

lifts degenerate vacua



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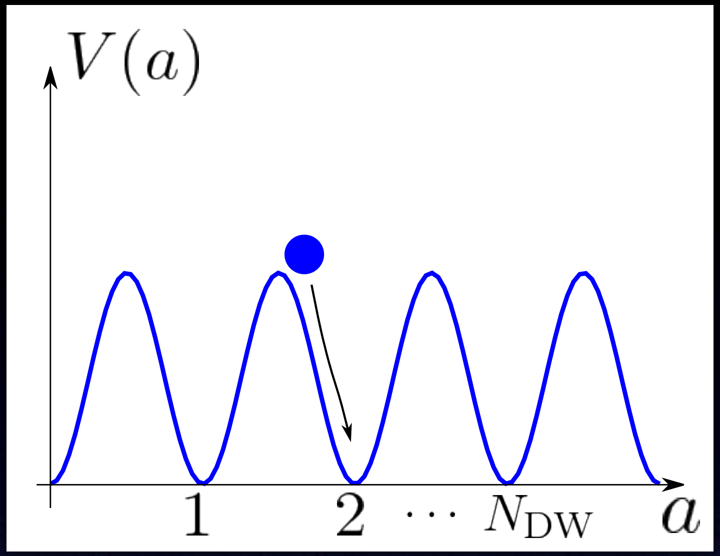

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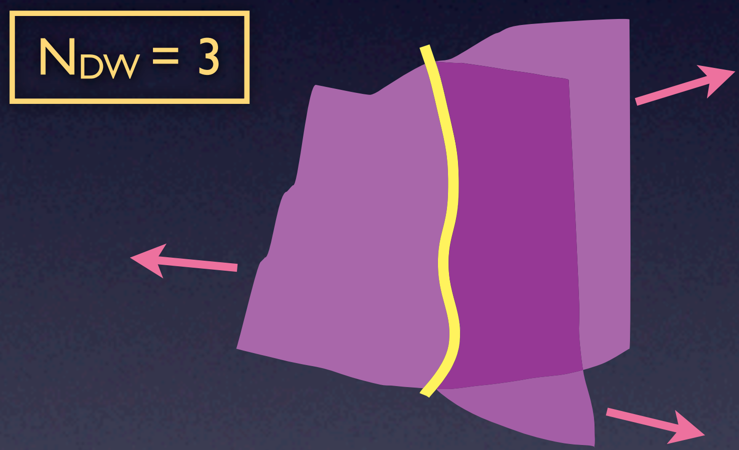

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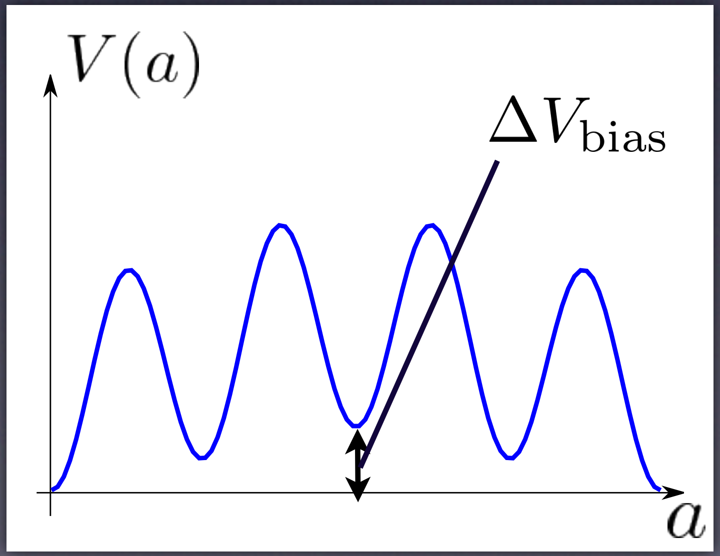
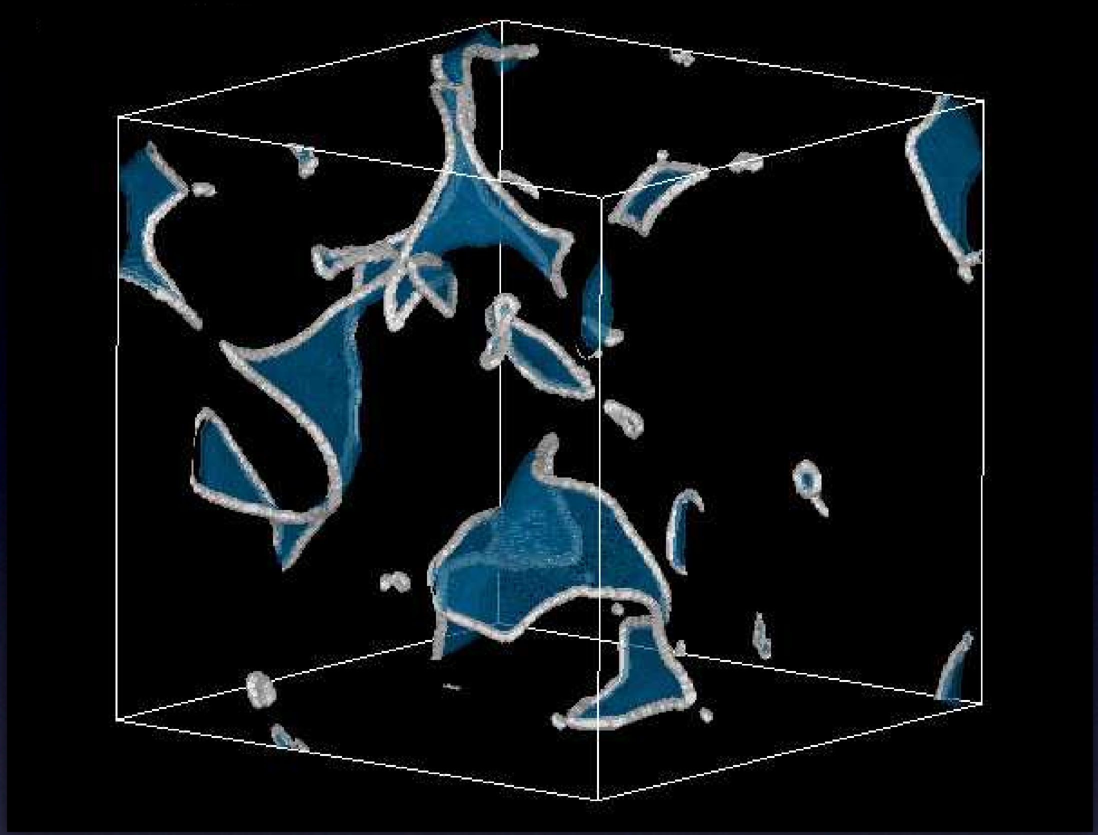
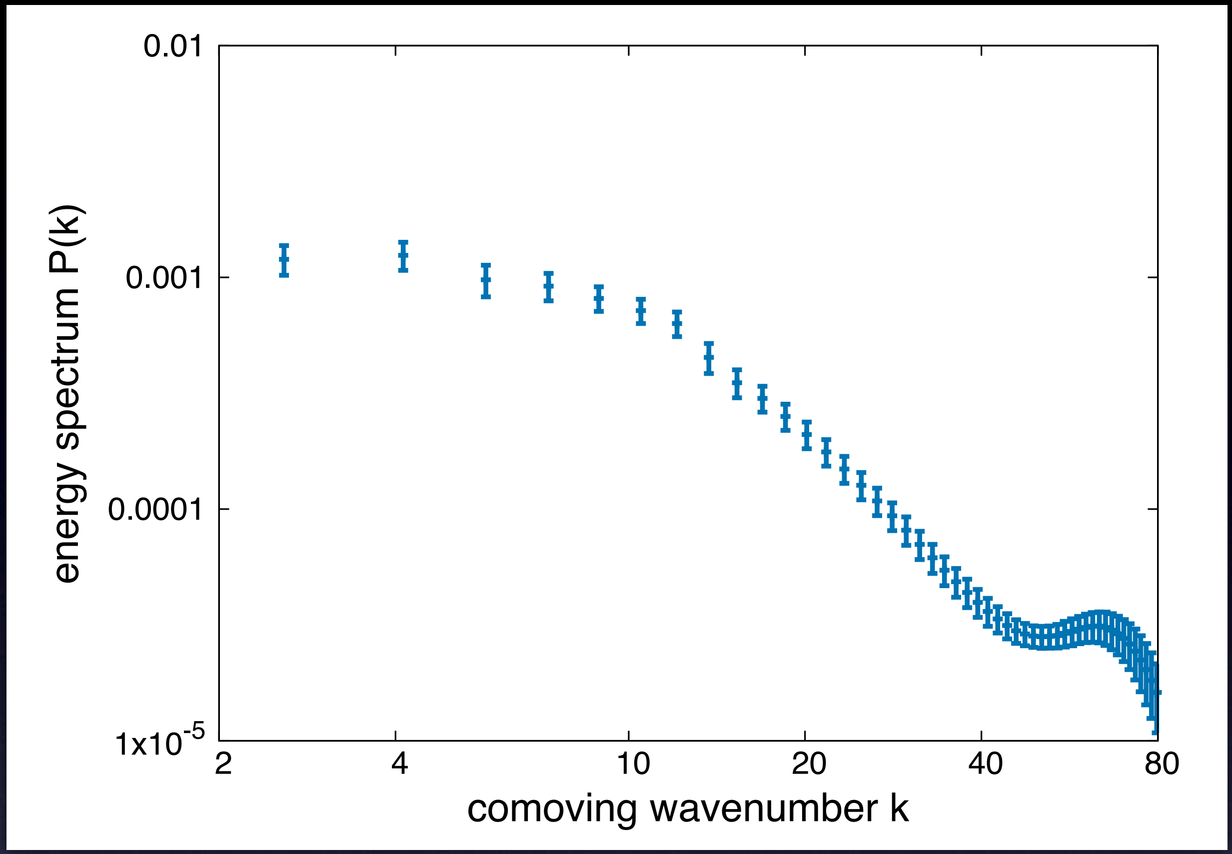


Field theoretic simulations (N_{DW} = 1)

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





- Spectrum of radiated axions is estimated based on the field theoretic lattice simulations.
- Total axion dark matter abundance including the contribution from string-wall systems:

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

- Constraint on the PQ scale:

$$\Omega_a \leq \Omega_{\mathrm{CDM}}$$

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

→

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

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

String core effect ?

- String mass energy acquires a large logarithmic correction:

$$\mu = \frac{\text{energy}}{\text{length}} \simeq \pi v_{\rm PQ}^2 \ln\left(\frac{H^{-1}}{\delta_s}\right)$$

H^{-1} : Hubble radius

$\delta_s \sim v_{\rm PQ}^{-1}$: string core width

- Field theoretic simulations only reaches $H^{-1}/\delta_s \lesssim \mathcal{O}(100)$, while $H^{-1}/\delta_s \sim v_{\rm PQ}/m_a(T_{\rm QCD}) \sim 10^{30}$ at the realistic situation.

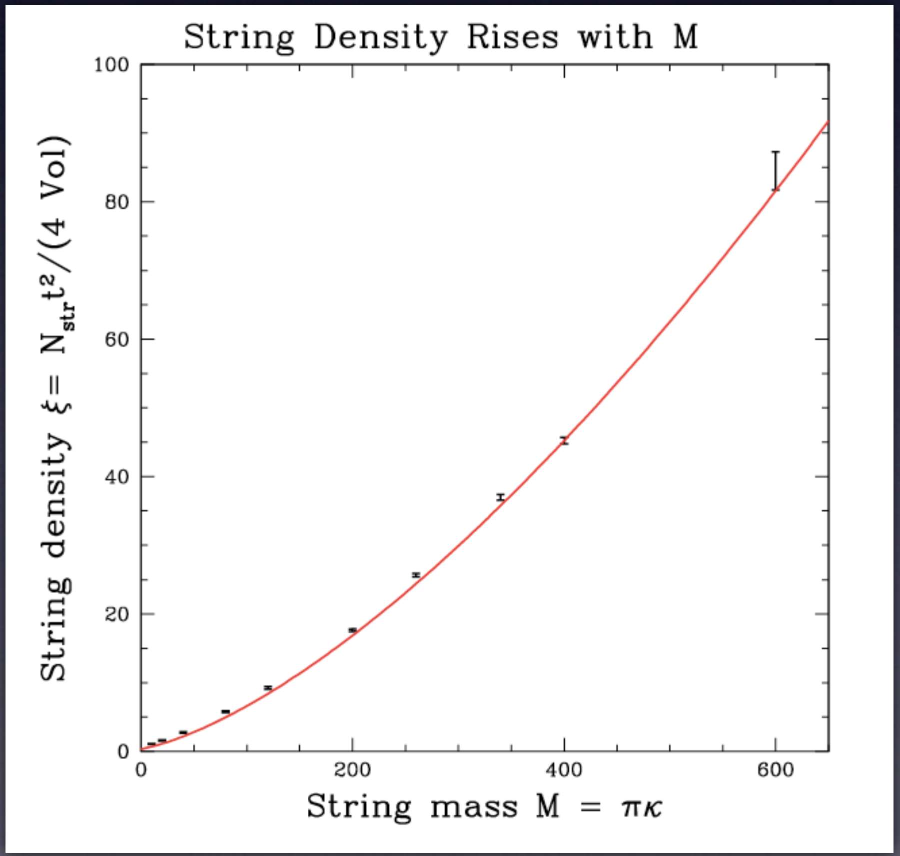
➡ Strings are heavier and might evolve differently (?)

- Effective theory approach

Fleury and Moore (2016)

Implementing string cores as point objects coupled to the axion field in 2D.

- Significantly different behavior at large $\ln(H^{-1}/\delta_{\rm s})$:
  - String density increases.
  - Larger axion mean energy.



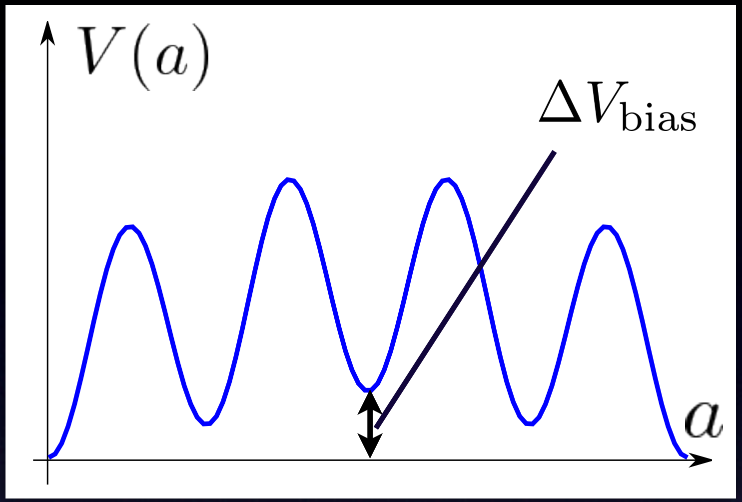
➡ Ambiguity on the prediction for the PQ scale.

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

Hiramatsu, Kawasaki, KS and Sekiguchi (2013), Kawasaki, KS and Sekiguchi (2015), Ringwald and KS (2016)

- Domain walls are long-lived and collapse if the PQ symmetry is explicitly broken by e.g. Planck suppressed operators.

$$\Delta V_{\rm bias} = -g\Phi^N / M_{\rm Pl}^{N-4} + {\rm h.c.}$$



- For small energy bias:

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

Cosmology → large bias (small N) is favored

- For large energy bias:

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

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

where $\Delta_D \propto {\rm Arg}(g)$

CP → small bias (large N) is favored

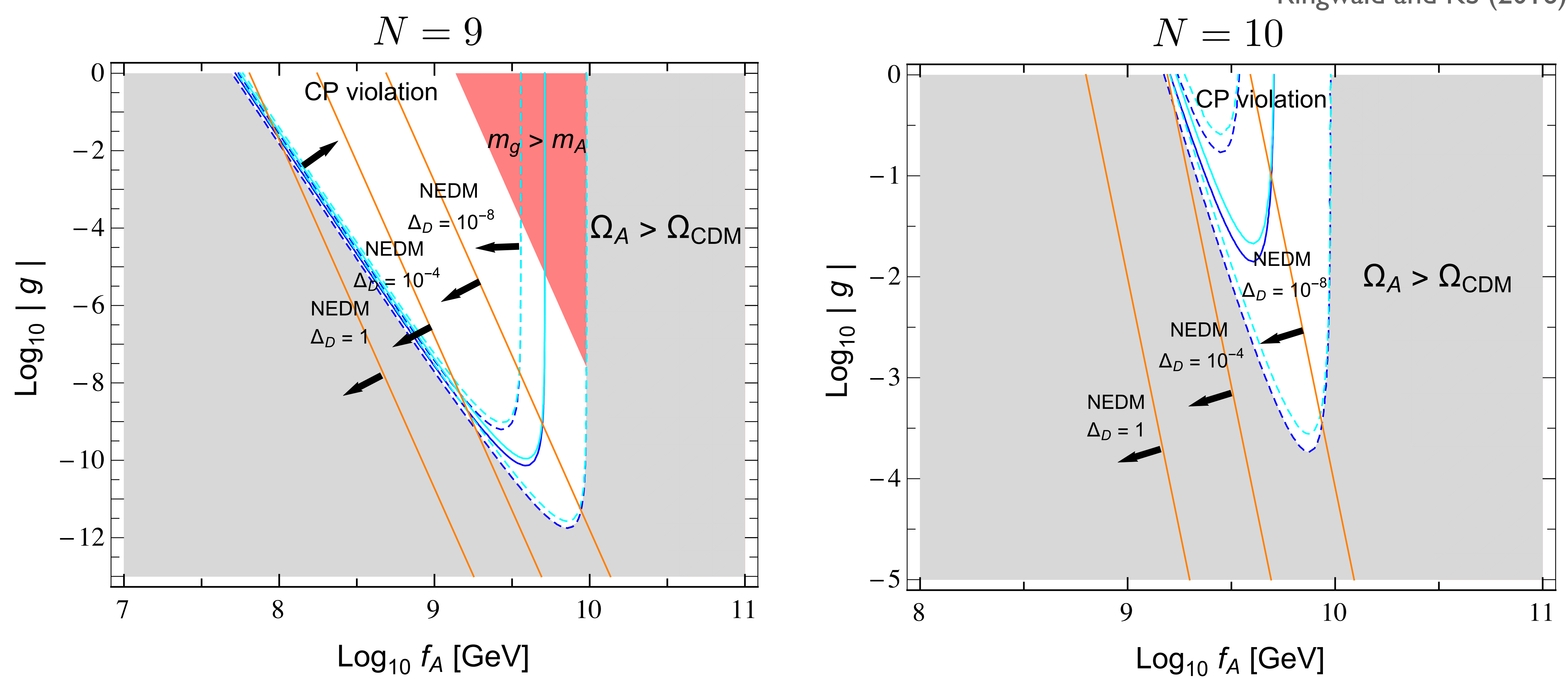
- Consistent parameters ?

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

$$\Delta V_{\rm bias} = -\frac{|g| N_{\rm DW}^{N-4}}{(\sqrt{2})^{N-2}} \left(\frac{F_a}{M_{\rm Pl}}\right)^{N-4} v_{\rm PQ}^4 \cos\left(N\frac{a}{v_{\rm PQ}} + \Delta_D\right) \Leftarrow \mathcal{L} \supset \frac{g}{M_{\rm Pl}^{N-4}} \Phi^N + {\rm h.c.}$$

- Loopholes appear if the order of the operator is N = 9 or 10, but some tuning of the phase parameter Δ_D is required.
- With a mild tuning, axions can explain total dark matter abundance in the small F_a range.

Ringwald and KS (2016)



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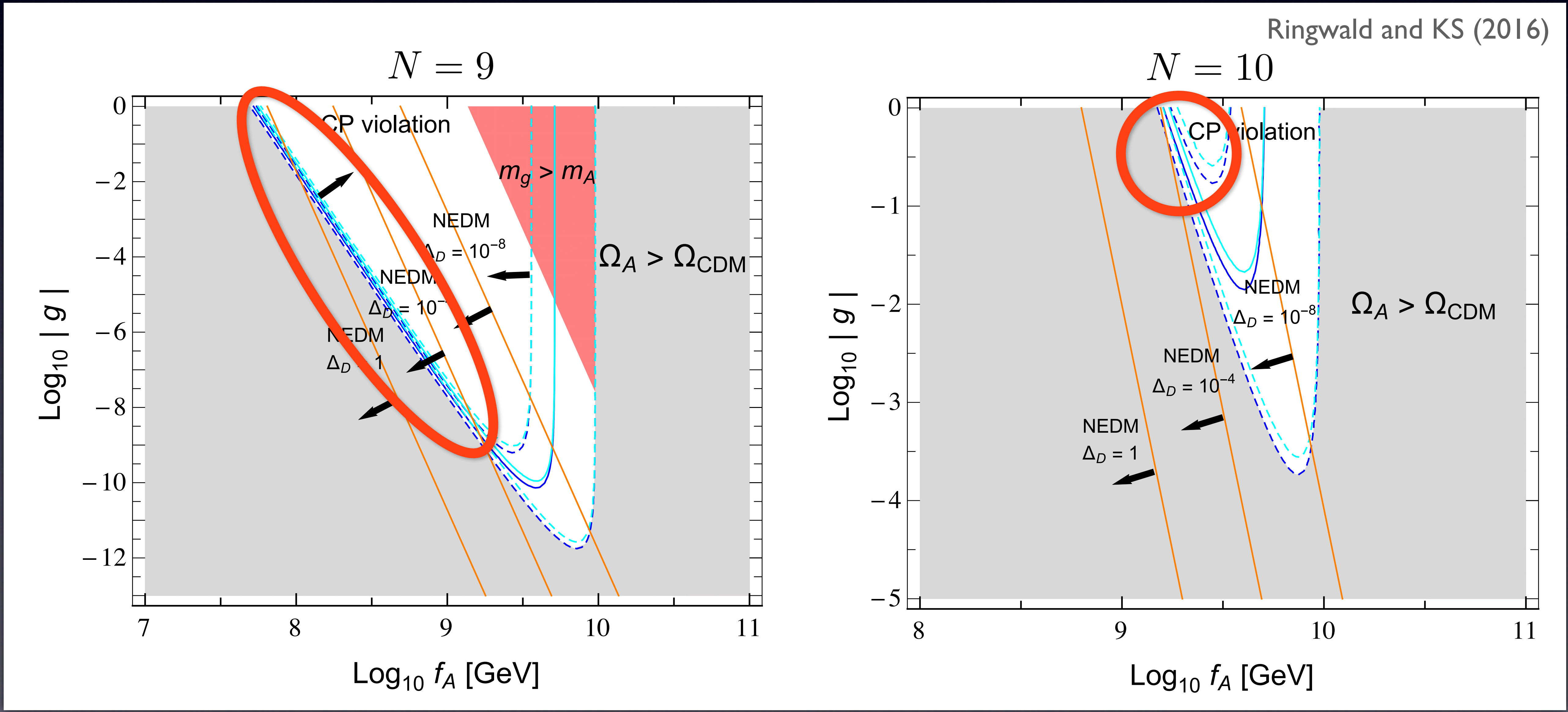
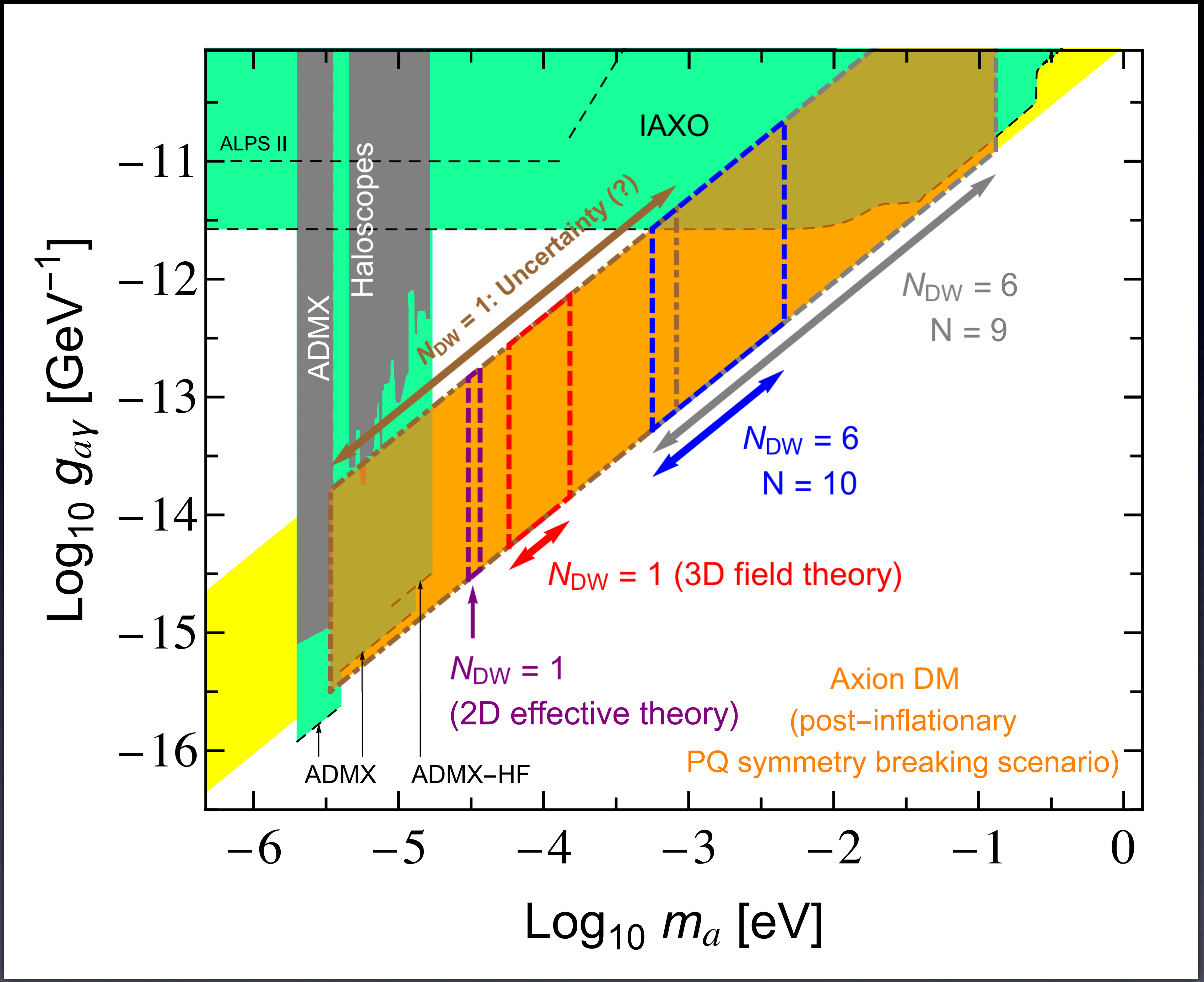


Search for axion dark matter

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



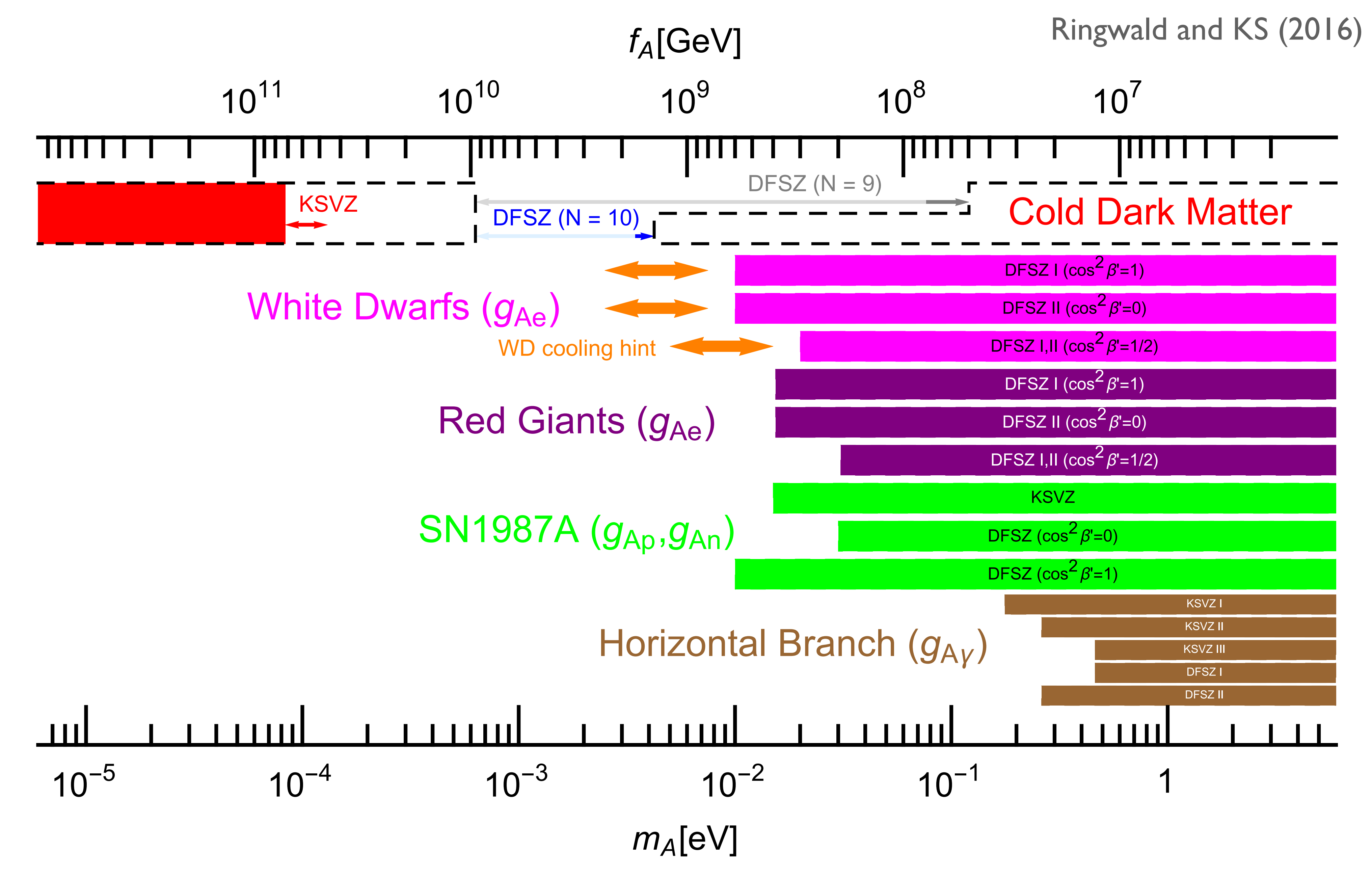
- CDM abundance can be explained at higher m_a for models with $N_{DW} > 1$.
- Potentially large uncertainty for models with $N_{DW} = 1$.

Conclusions

- Axion is a well motivated hypothetical particle:
  - Solution of strong CP problem
  - Dark matter candidate
- 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.
- Mass ranges can be probed in the future experiments.

Backup slides

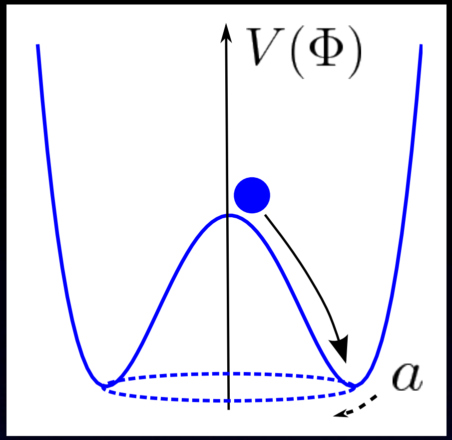
Astrophysical and cosmological constraints



- Astrophysical observations give lower (upper) bounds on F_a (m_a)
- Dark matter abundance gives upper (lower) bounds on F_a (m_a) [and also a lower (upper) bound for DFSZ models]

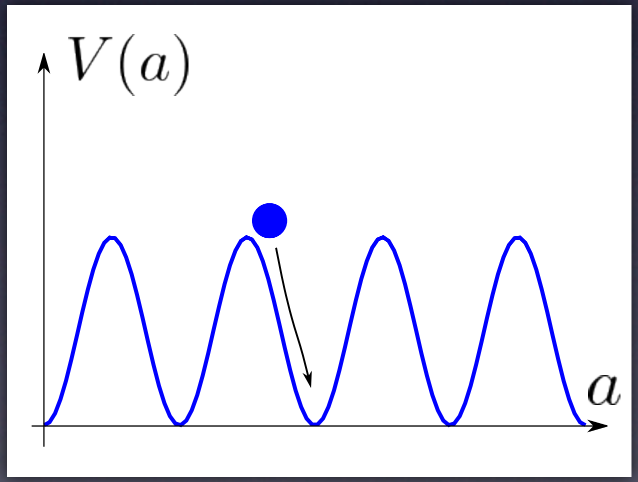
Production of axions in the early universe

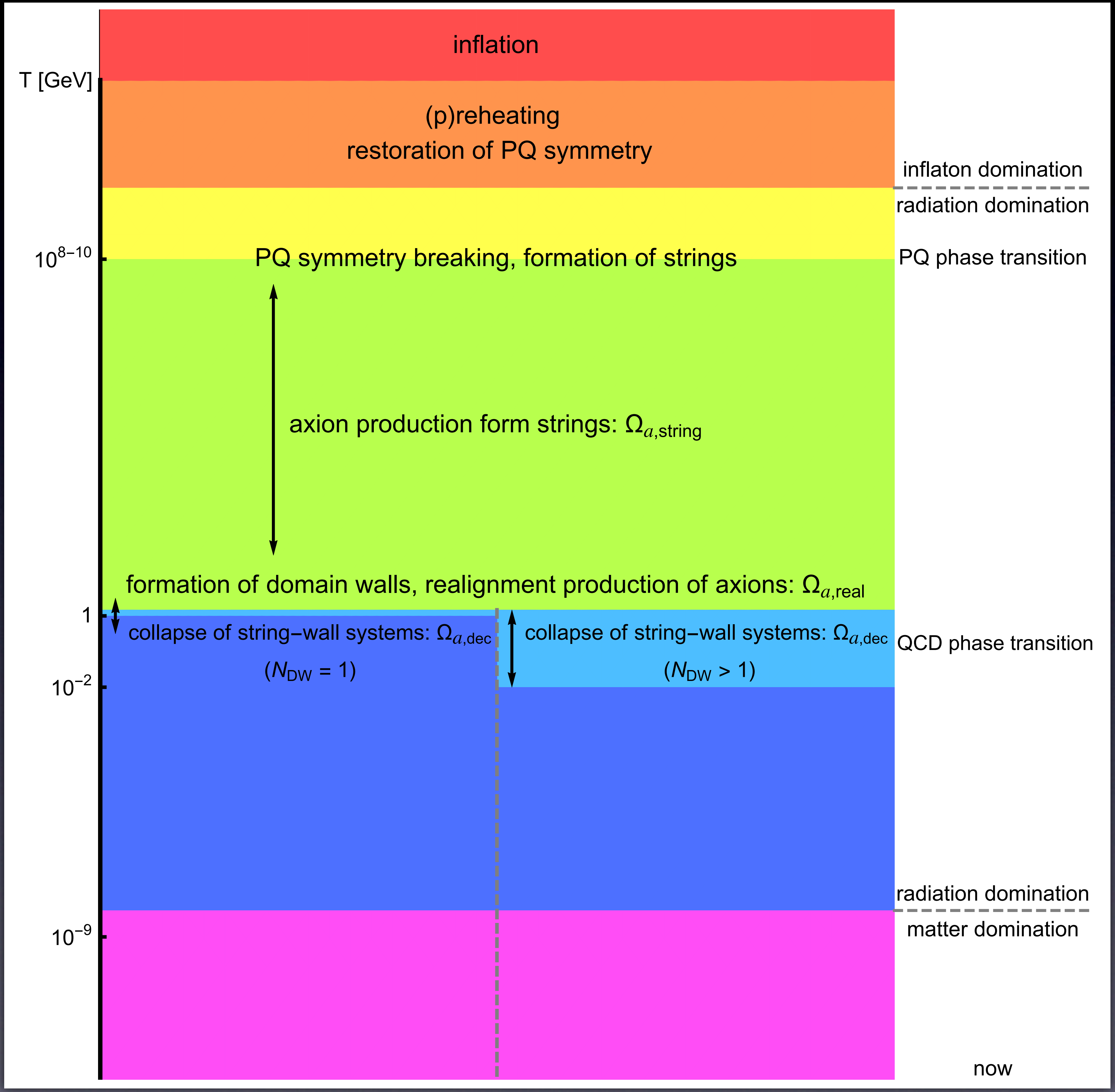
(post-inflationary PQ symmetry breaking scenario)



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

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





Annihilation mechanism of domain walls

The bias term acts as a pressure force p_V on the wall

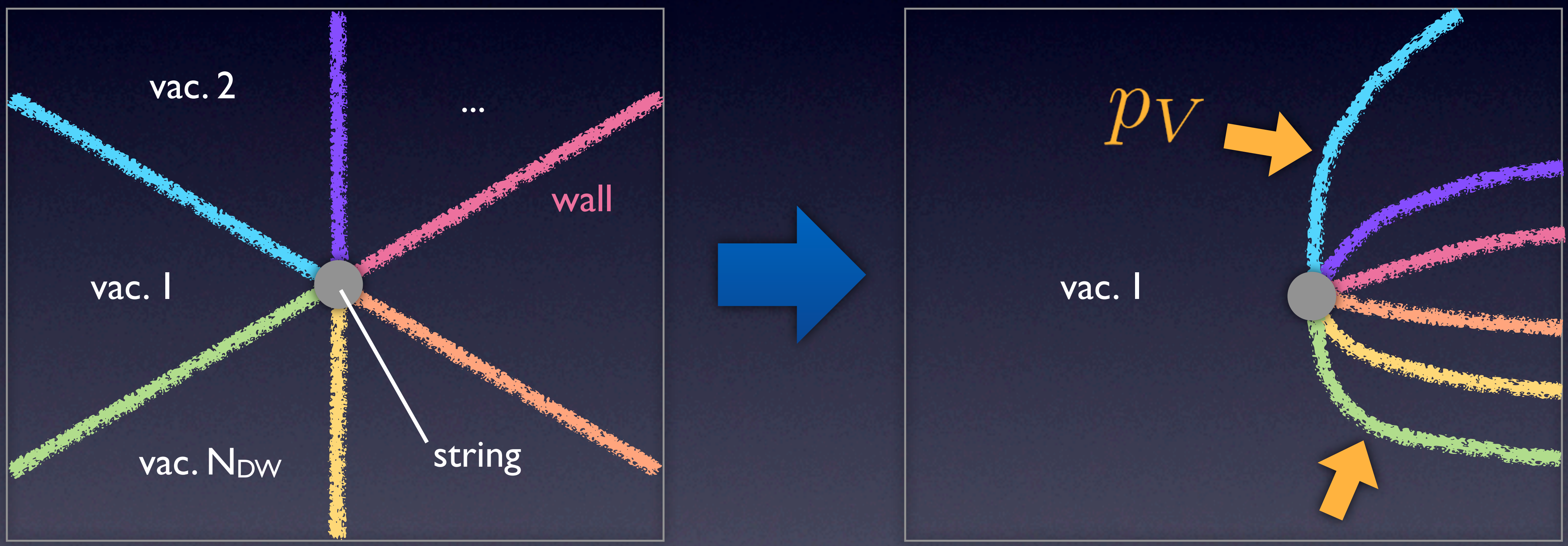
$$p_V \sim \Delta V_{\rm bias}$$

Annihilation occurs when the tension p_T becomes comparable with the pressure p_V

$$p_T \sim \sigma_{\rm wall}/R \sim m_a v_{\rm PQ}^2/N_{\rm DW}^2 R$$

R : curvature radius of walls

$\sigma_{\rm wall}$: surface mass density of walls



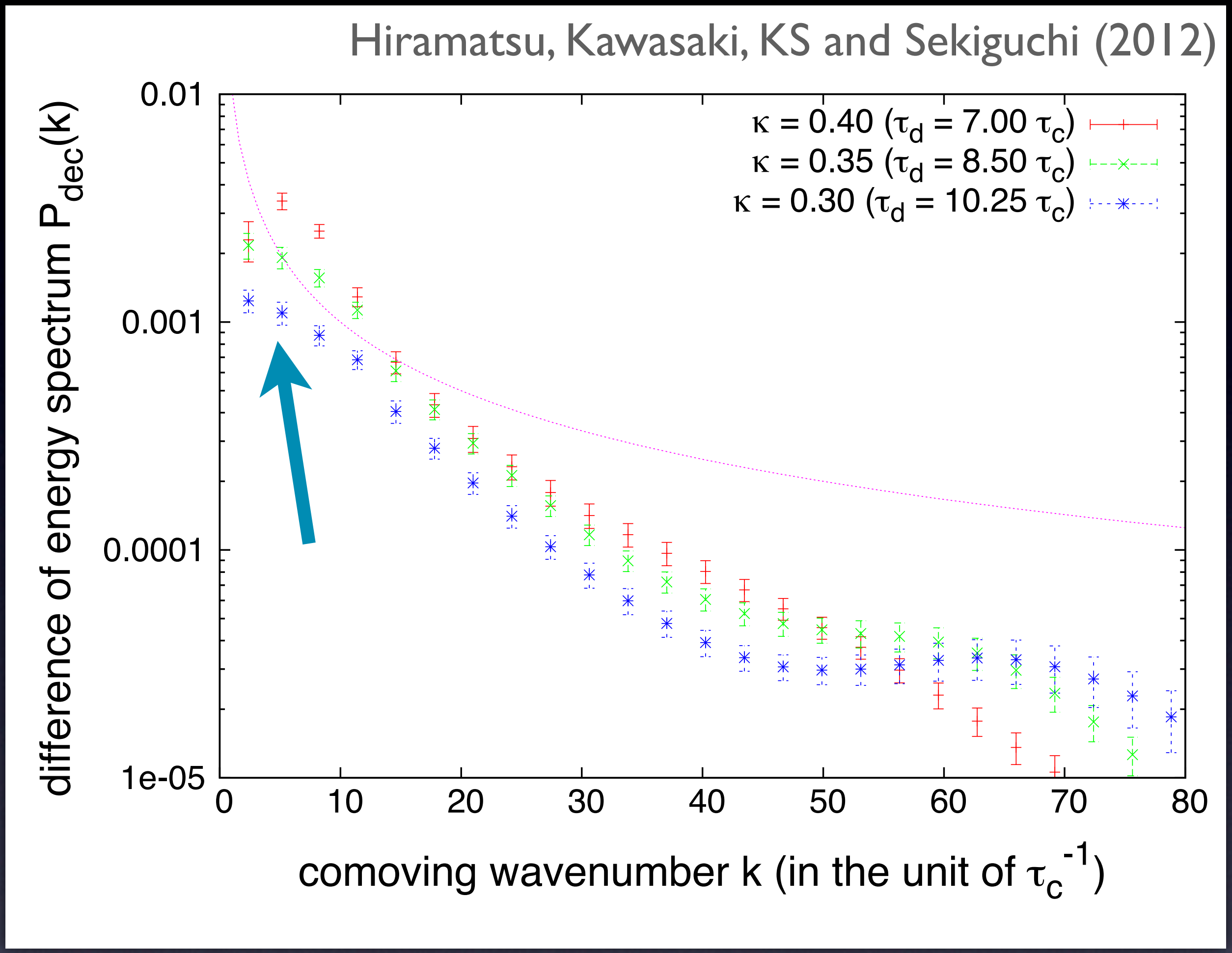
Annihilation time

$$t_{\rm ann} \sim R|_{p_V=p_T} \sim \frac{m_a v_{\rm PQ}^2}{N_{\rm DW}^2 \Delta V_{\rm bias}}$$

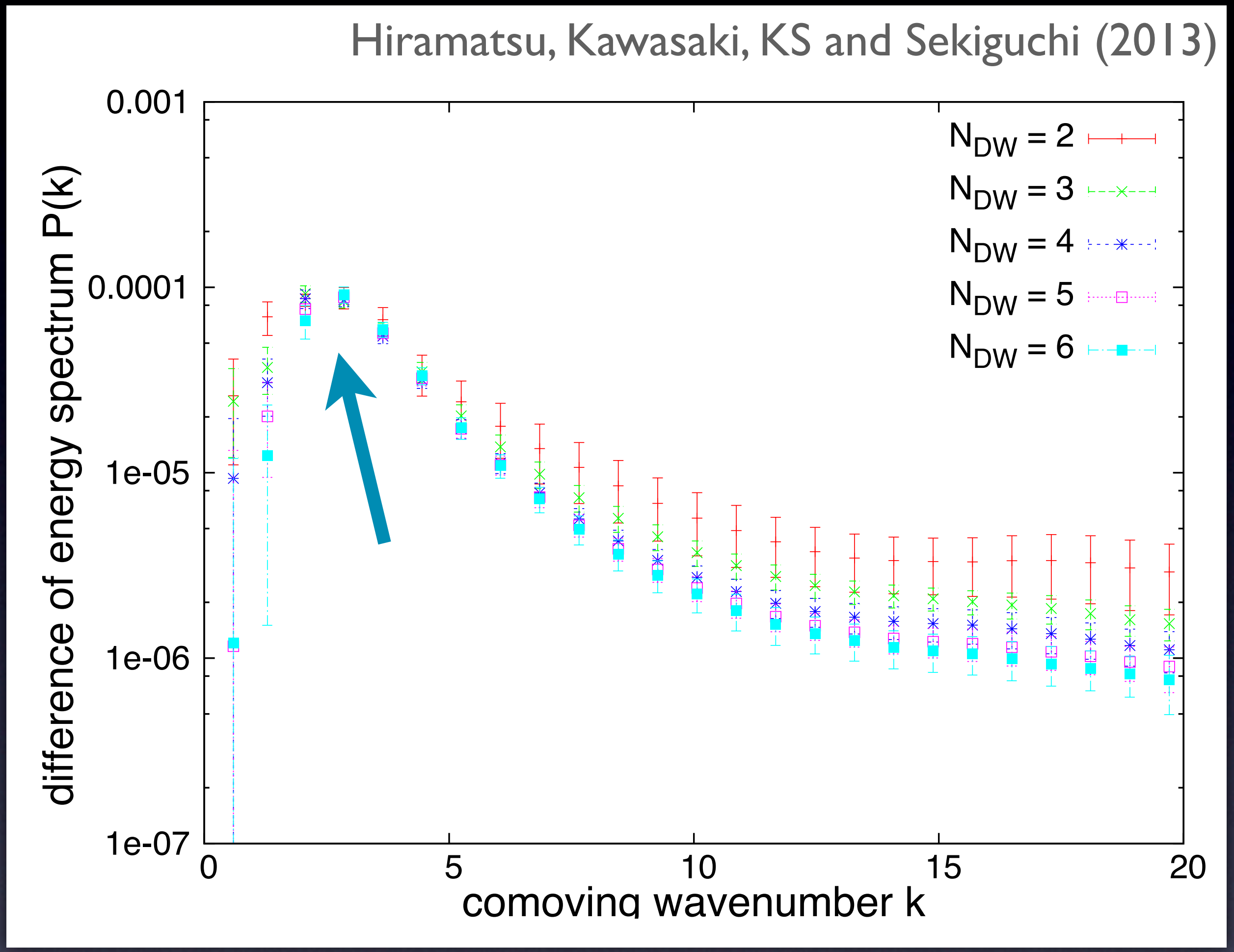
$$\sim \mathcal{O}(10^{-4})\,{\rm sec} \left(\frac{6}{N_{\rm DW}}\right)^4 \left(\frac{10^{-51}}{\Delta V_{\rm bias}/v_{\rm PQ}^4}\right) \left(\frac{10^9\,{\rm GeV}}{F_a}\right)^3$$

Spectrum of axions

$N_{DW} = 1$



$N_{DW} > 1$



Peaked at

$$\langle E_a \rangle \simeq \mathcal{O}(1) \times m_a$$

(axions are mildly relativistic)

Contribution for relic CDM abundance

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