International Symposium on “Revealing the history of the universe with underground particle and nuclear research 2019” @Tohoku University, March 7-9, 2019

Axion Cosmology

Masahiro Kawasaki
(ICRR & Kavli IPMU, The University of Tokyo)

1. Axion

- Axion is predicted in PQ mechanism which solves strong CP problem in QCD

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

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

η : breaking scale

- Axion acquires mass through QCD non-perturbative effect

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

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

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 $\boxed{\text{scenario A}}$

    Formation of topological defects → Domain wall problem
  - PQ symmetry breaking before inflation $\boxed{\text{scenario B}}$

    Isocurvature perturbations → Isocurvature perturbation problem

Today's Talk

- Introduction
- PQ symmetry breaking after inflation $\boxed{\text{scenario A}}$
  - Cosmological evolution of axion
  - Comic axion density
  - Non-topological objects of axions
- PQ symmetry breaking before inflation $\boxed{\text{scenario B}}$
  - Isocurvature perturbation problem
  - Suppression of Isocurvature Perturbations
- Conclusion

2. Cosmological Evolution of Axion (~~PQ~~ after inflation)

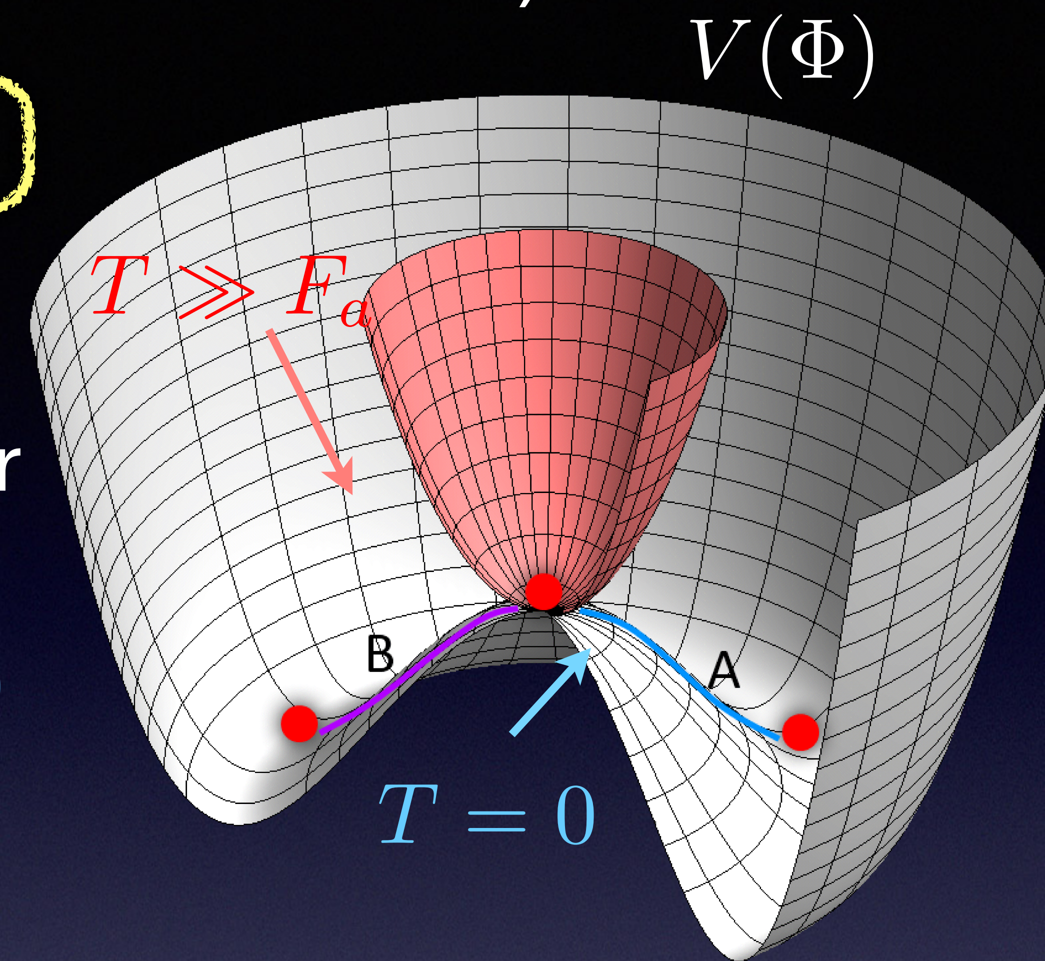
$\boxed{T \simeq \eta}$

scenario A

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

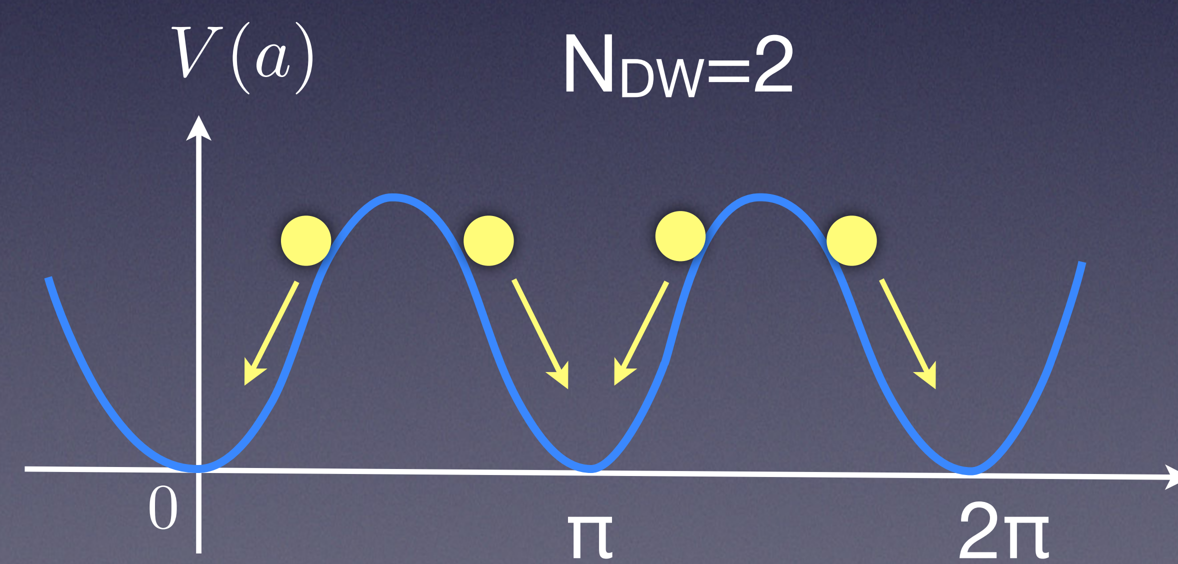
$$\Phi = |\Phi| e^{i\theta} = |\Phi| e^{ia/\eta} \qquad m_a = 0$$

  - Formation of Cosmic Strings



$\boxed{T \simeq \Lambda_{\mathrm{QCD}}}$

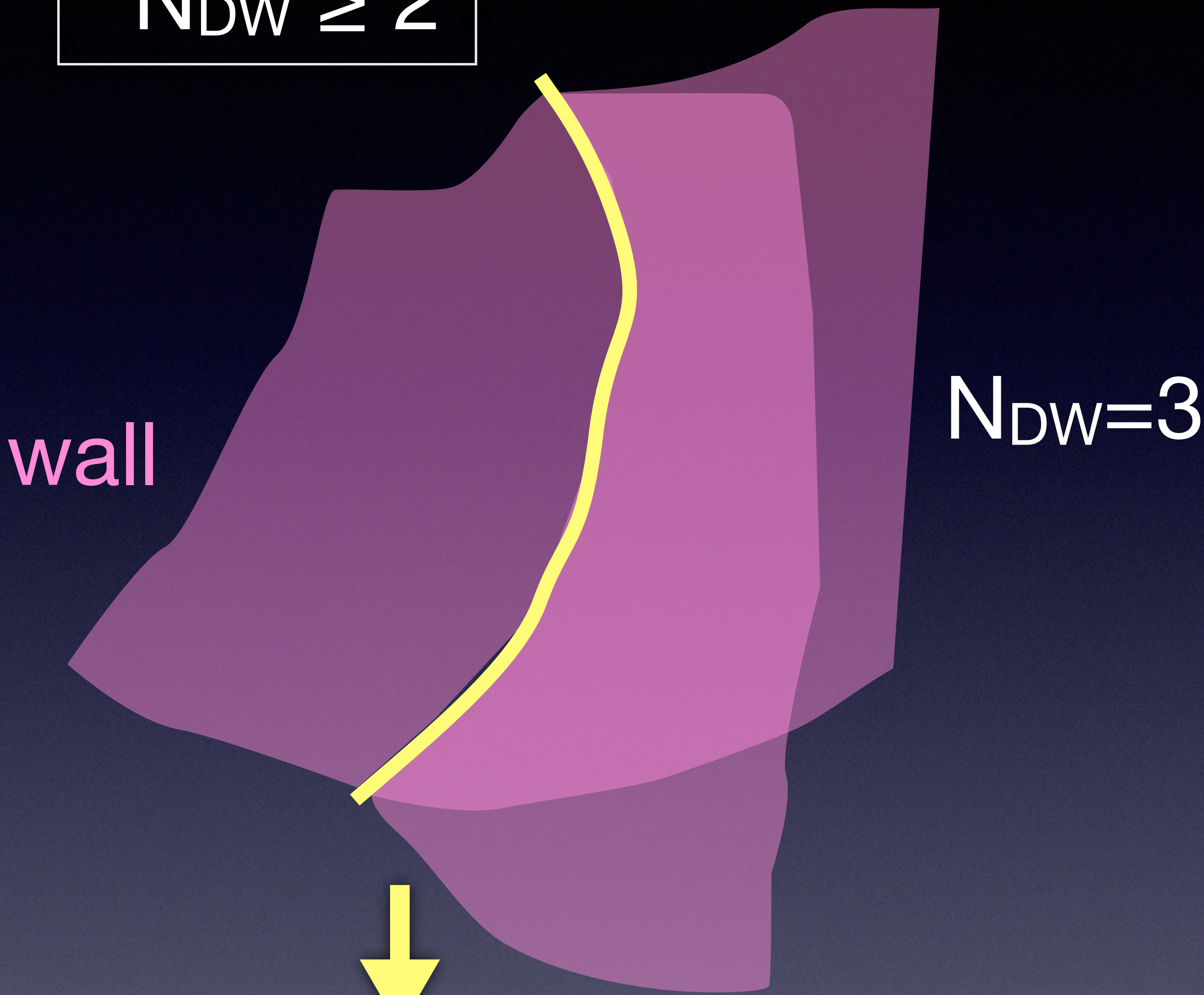
- Axion acquires mass through non-perturbative effect
  - $U_{PQ}(1)$ is broken to $Z_{N_{DW}}$
  - Coherent oscillation
  - Formation of Domain Walls



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

- Domain walls attach to strings

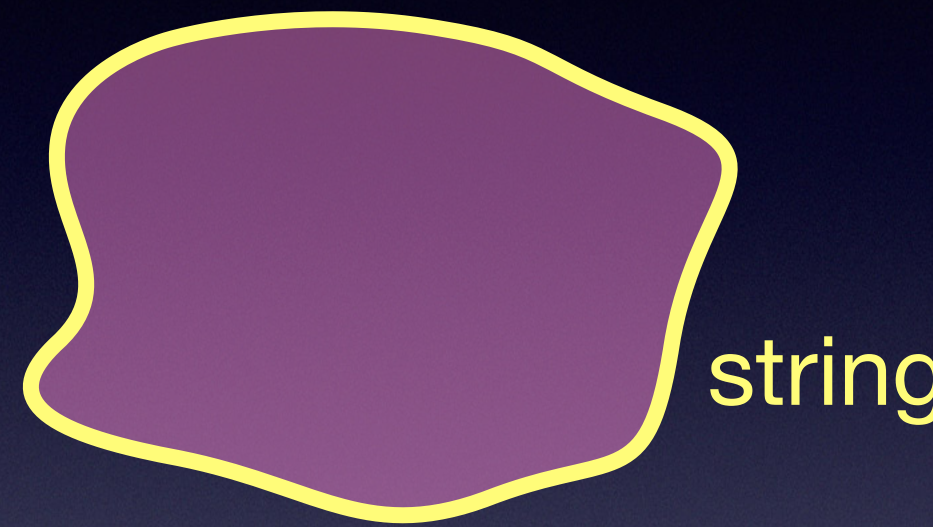
$N_{DW} \geq 2$



Stable and dominate the universe

Domain Wall Problem

$N_{DW}=1$



Collapse

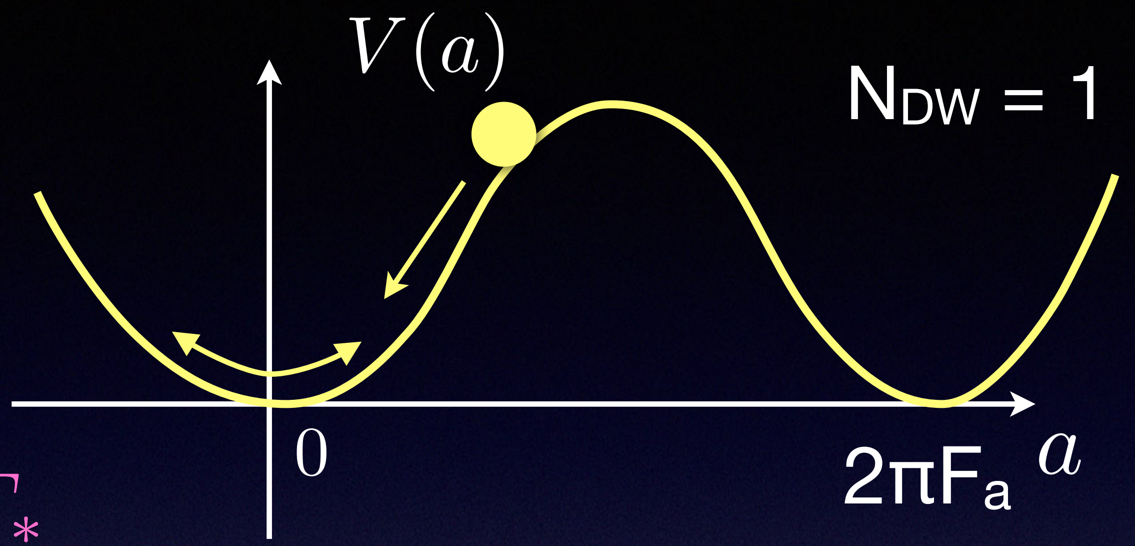
Virenkin Everett (1982)
Barr Choi Kim (1986)

Axion overproduction

3. Cosmic Axion Density

3.1 Coherent axion oscillation

$$\boxed{H \simeq m_a(T_*)}$$



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

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

spatial average

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

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

including anharmonic effect

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

3.2 Axions from strings

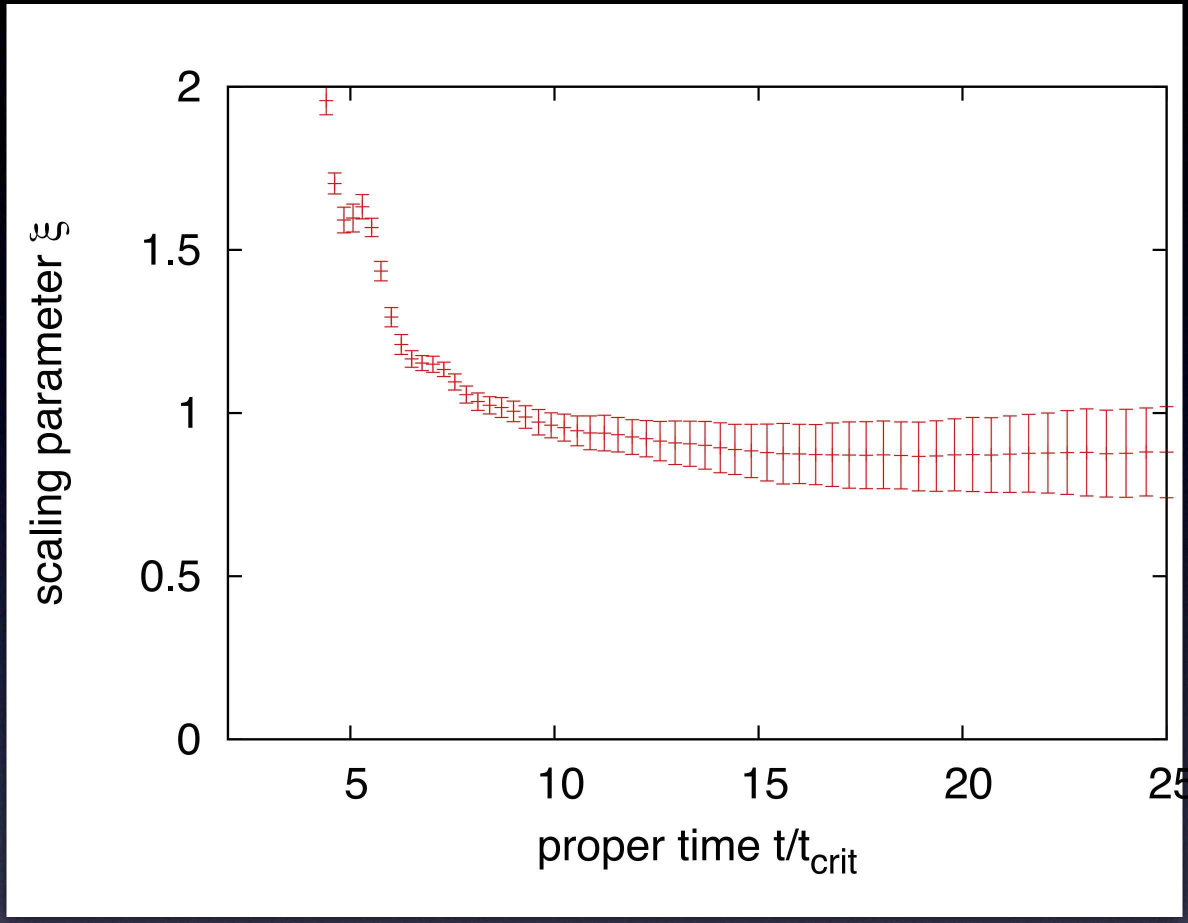
- Axionic strings are produced when U(1) $_{PQ}$ symmetry is spontaneously broken

- Numerical Lattice Simulation

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

  MK, Saikawa, Sekiguchi (2014)

- String network obeys scaling solution



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

$$\boxed{\xi = 1.0 \pm 0.5}$$

- Scaling solution is established by emitting axions

- Emitted axion energy $\rho_{a,\,\text{str}}$ is estimated from ρ_{string}

- If we know average energy $\bar{\omega}_a$ we can estimate the present axion density as $\rho_a = m_a(\rho_{a,\text{str}}/\bar{\omega}_a)$

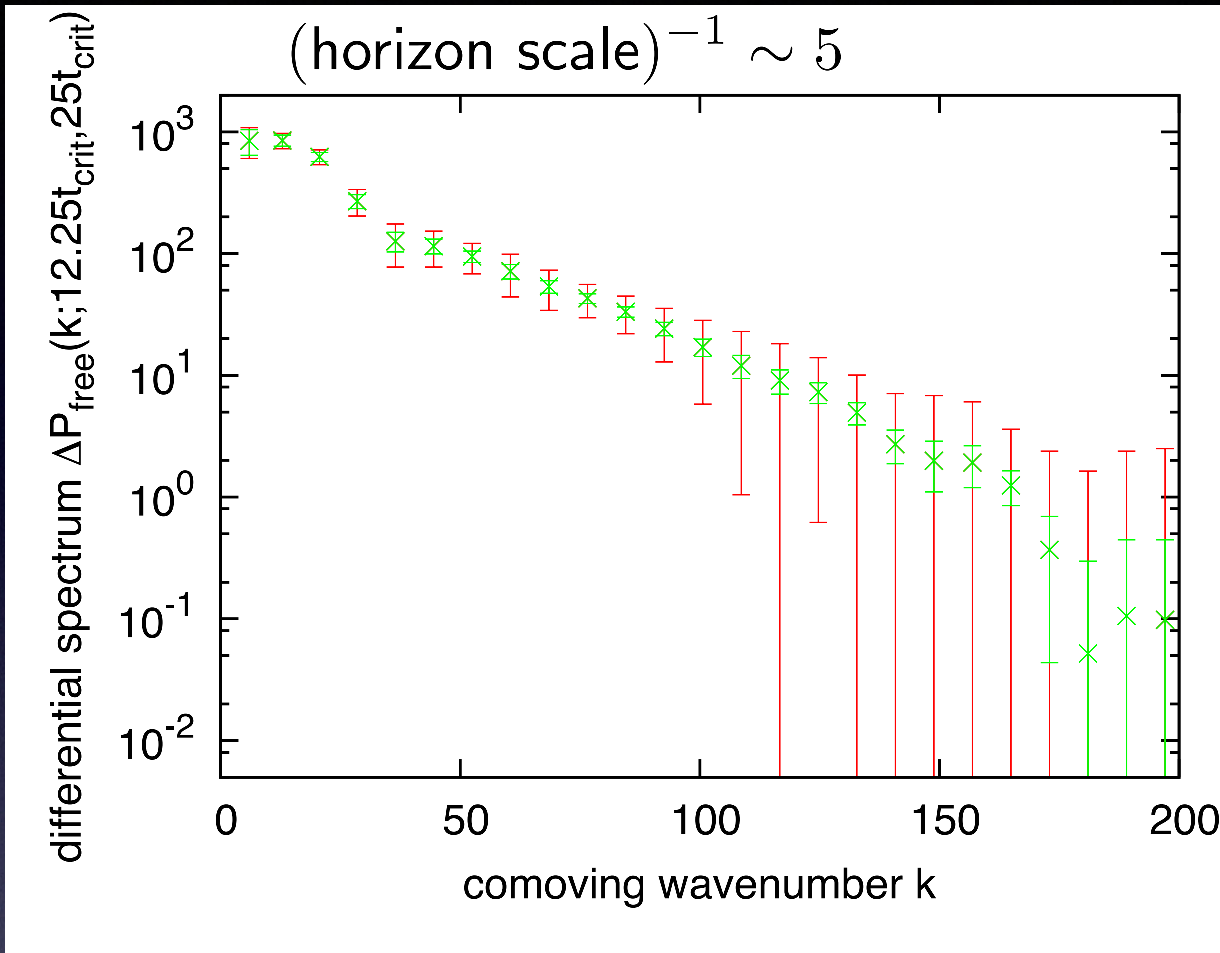
Density of Axions from Strings

- Energy Spectrum

  peak at low k ~ (horizon scale)$^{-1}$ ~1/t

  suppressed at higher k

MK, Saikawa, Sekiguchi (2014)



- Average energy parameter

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

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

MK, Saikawa, Sekiguchi (2014)

- Cosmic density of produced axion

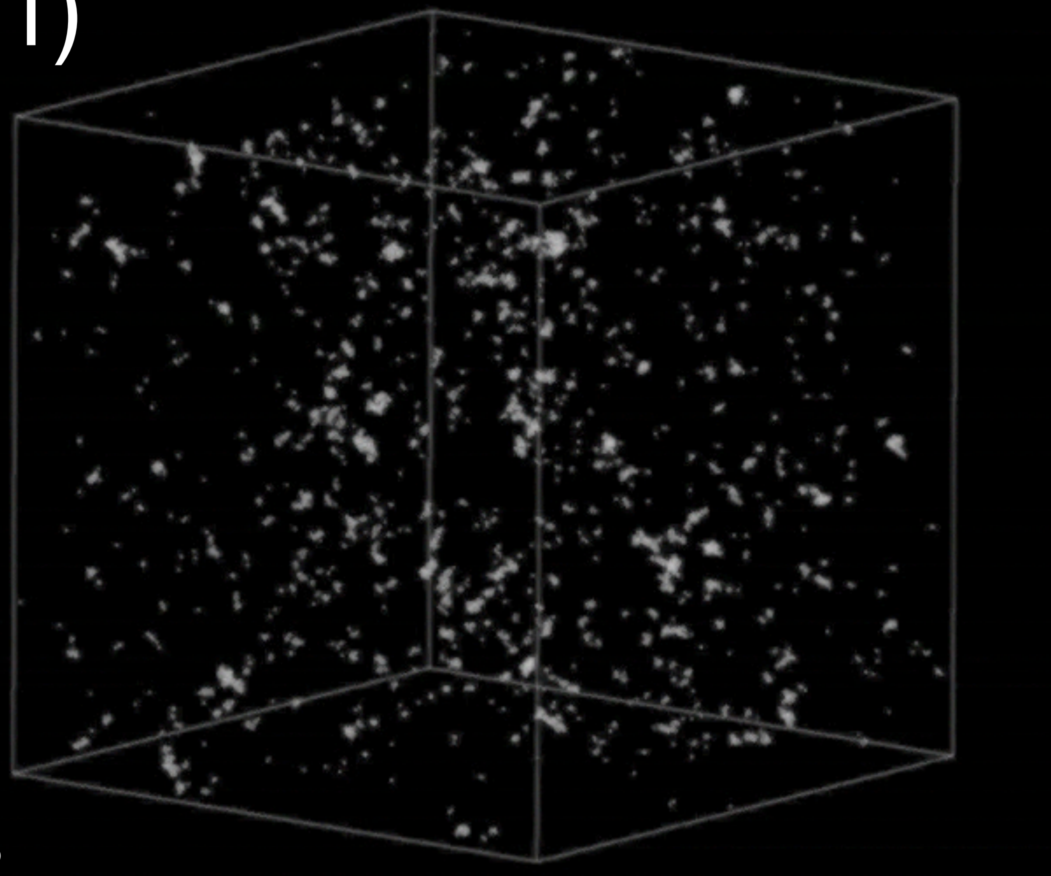
$$\boxed{\Omega_{a,\text{string}} h^2 = (7.3 \pm 3.9) \times 10^{-3} N_{\text{DW}}^2 \left(\frac{F_a}{10^{10}\,\text{GeV}} \right)^{1.19}}$$

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

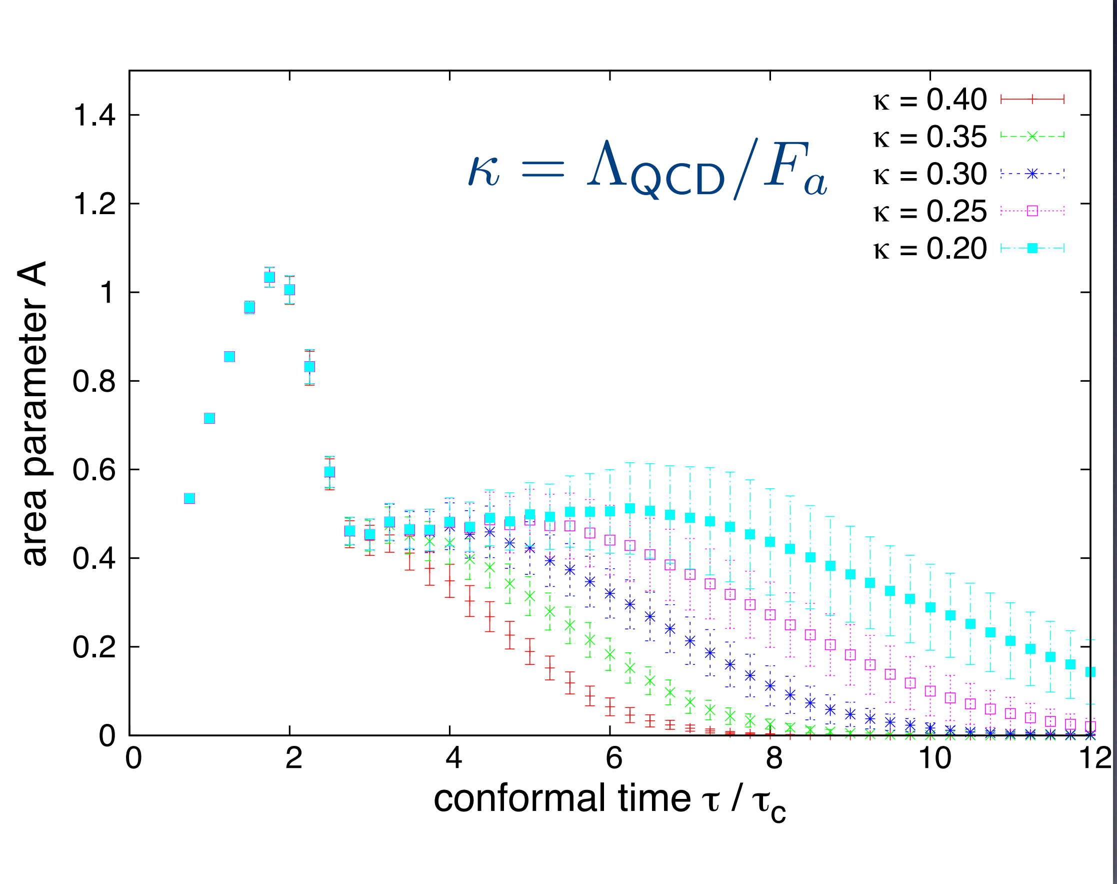
3.3 Axion from Domain Walls (N_{DW} =1)

- Axion energy density from collapsing domain walls can be estimated in the same way as strings
- Simulation of string-wall network
  - Lattice simulation with N(grid) = $(512)^3$
  - Scaling property
  - Average energy
- Axions from collapsed domain walls

$$\Omega_{a,\text{wall}}h^2 = (5.4 \pm 2.1) \times 10^{-3} \times \left(\frac{F_a}{10^{10}\,\text{GeV}}\right)^{1.19}$$



Hiramatsu, MK, Saikawa, Sekiguchi (2012)



Cosmic Axion Density (N_{DW} =1)

- Total cosmic axion density

$$\Omega_{a,\mathrm{tot}}h^2 = \Omega_{a,\mathrm{osc}}h^2 + \Omega_{a,\mathrm{string}}h^2 + \Omega_{a,\mathrm{wall}}h^2$$
$$= (1.7 \pm 0.4) \times 10^{-2} \left(\frac{F_a}{10^{10}\mathrm{GeV}} \right)^{1.19}$$

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

- Constraint on F_a

$$F_a \lesssim (4.2 - 6.5) \times 10^{10}\ \mathrm{GeV}$$

$$m_a \gtrsim (0.9 - 1.4) \times 10^{-4}\ \mathrm{eV}$$

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

MK, Saikawa, Sekiguchi (2014)
Ringwald, Saikawa (2015)

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

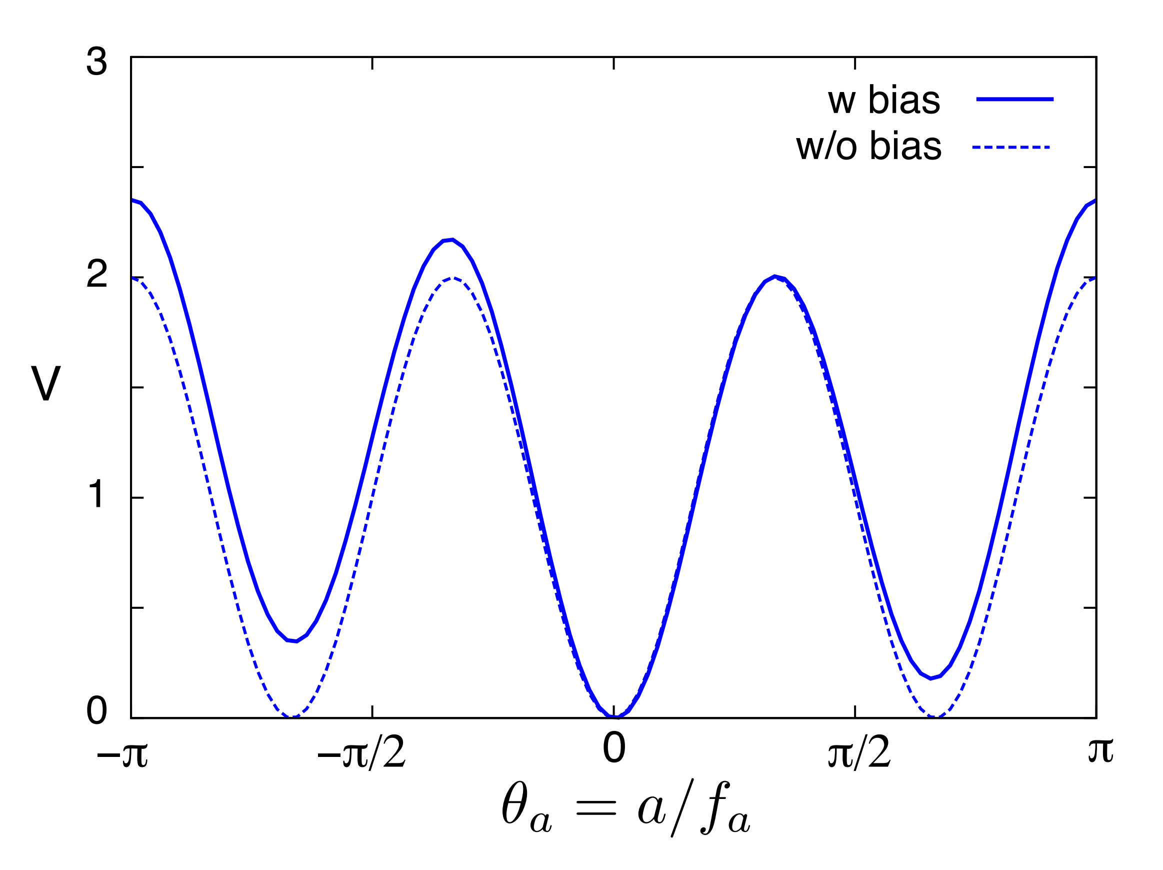
→ Domain Wall Problem

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

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

Ξ : bias parameter Sikivie (1982)

δ : phase of bias term



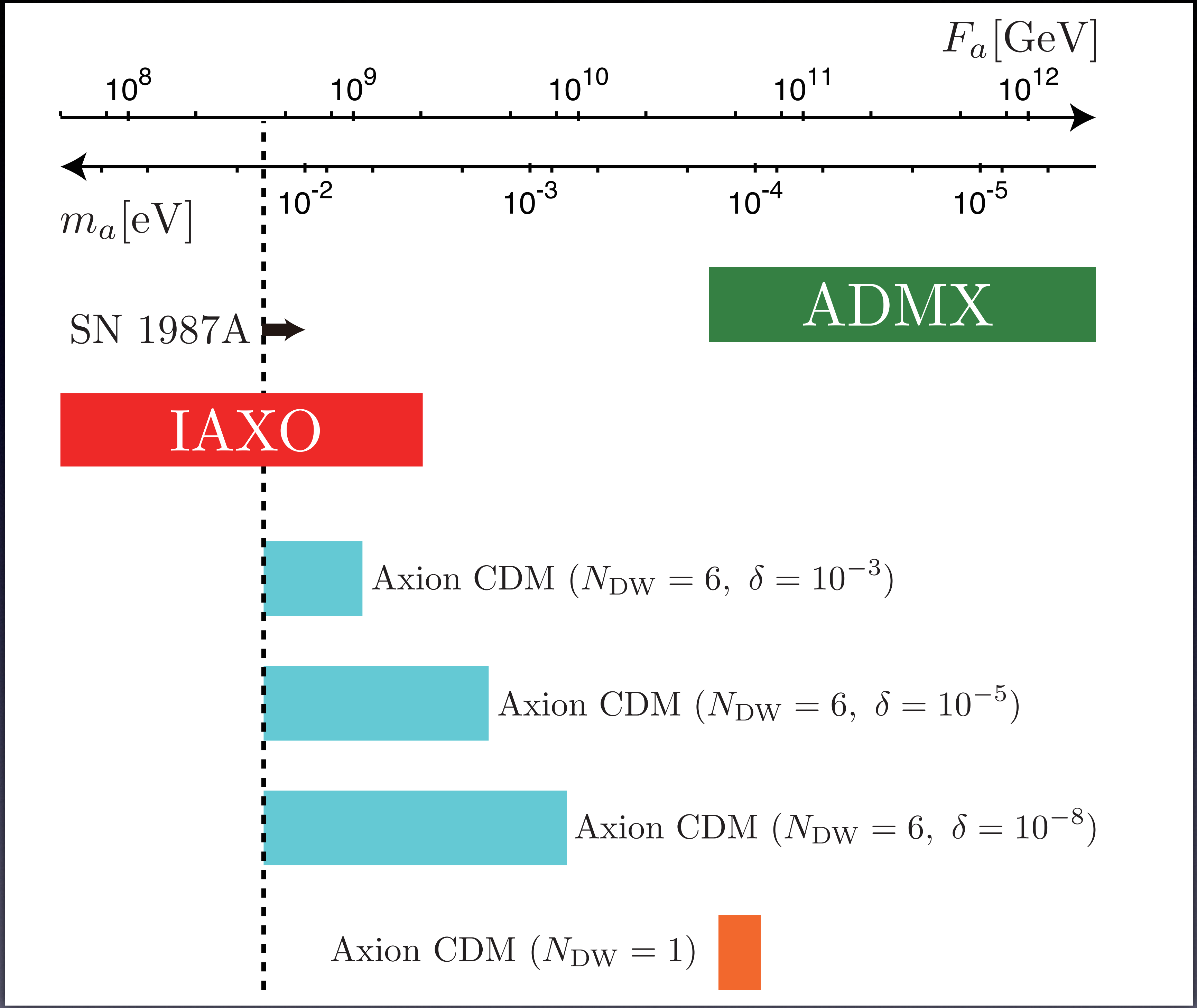
- Bias term lifts degenerated vacua and leads to DW annihilation

→ large bias is favored

- Bias term shifts the minimum of the potential $\langle \theta \rangle \neq 0$ and spoils the original idea of Peccei and Quinn → small bias is favored

→ More stringent constraint on F_a
Axion can be dark matter for smaller F_a

3.5 Summary: case of symmetry breaking after inflation



MK, Saikawa, Sekiguchi (2014)

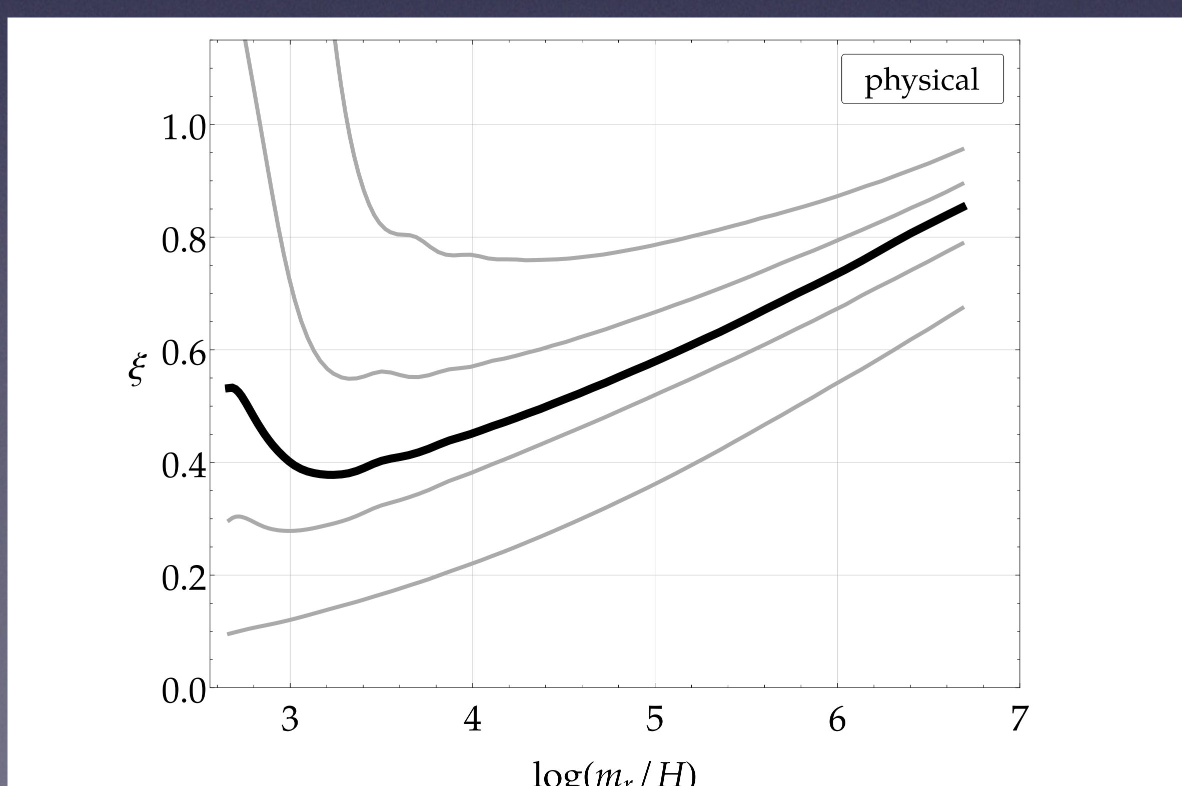
parameter ranges where axion can be dark matter

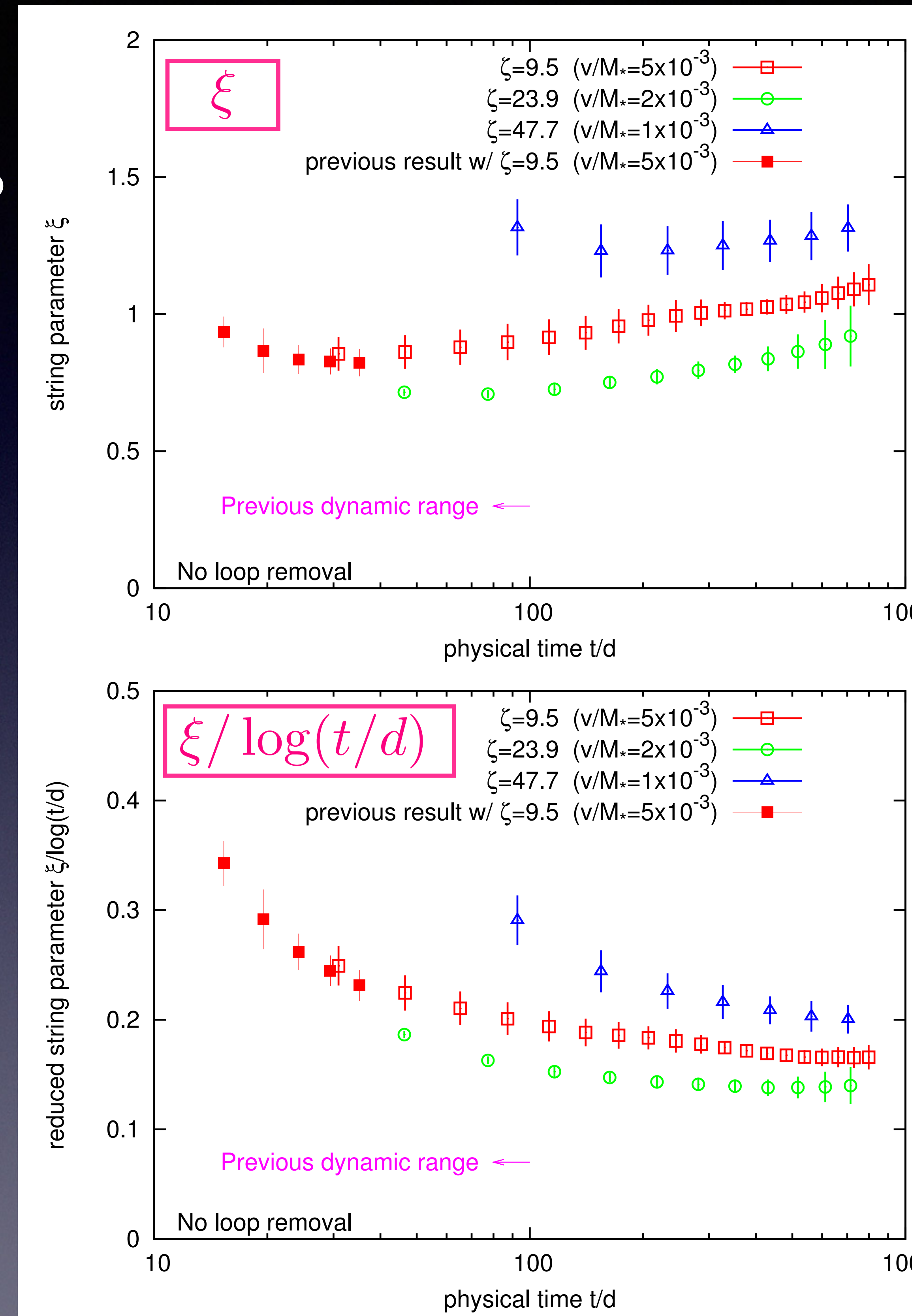
- Axion can be dark matter of the universe for $F_a \sim 10^9$ GeV or $\sim 5\times10^{10}$ GeV and can be probed by the next generation experiments

3.6 Recent Progress

MK, Sekiguchi, Yamaguchi, Yokoyama (2018)

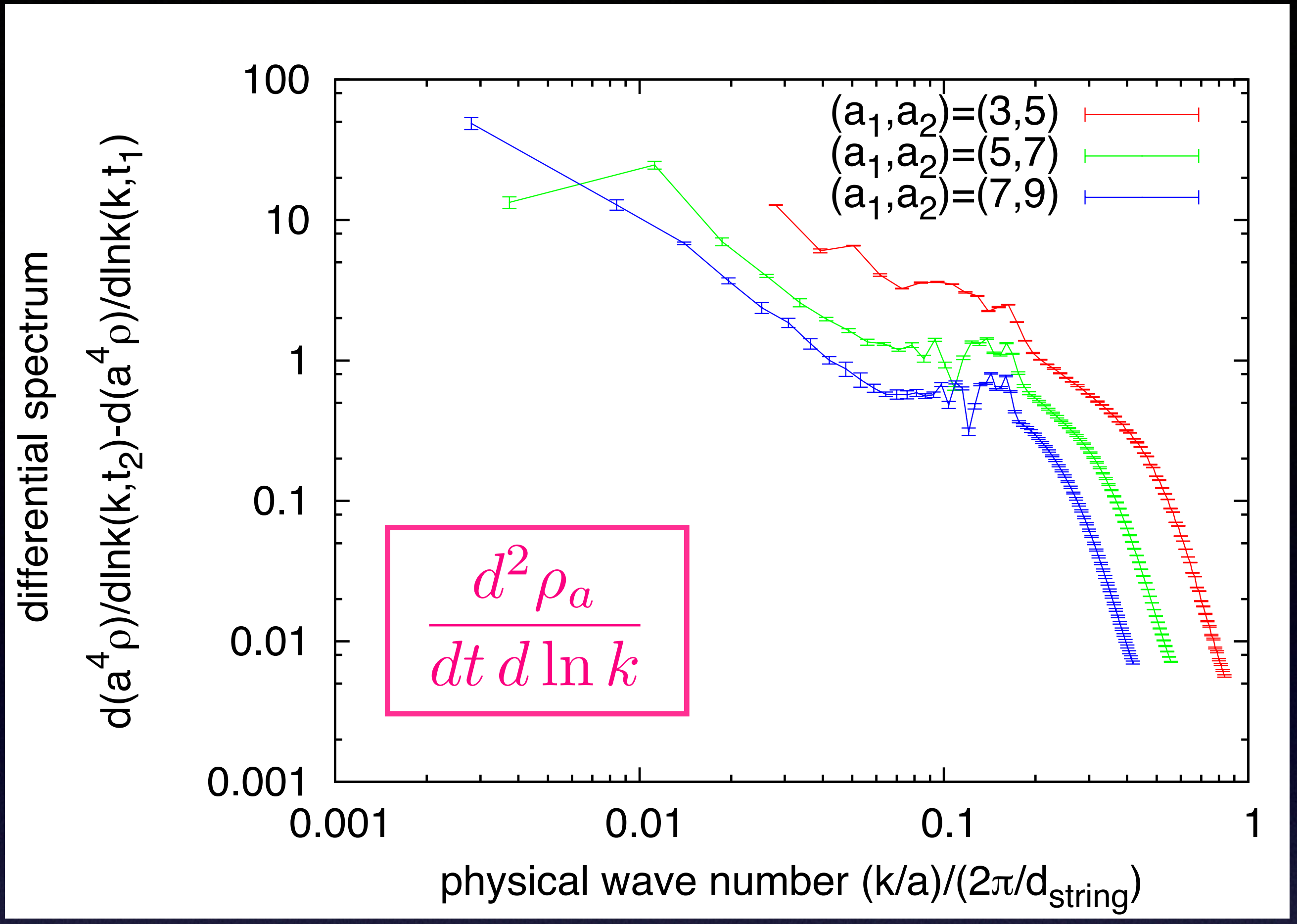
- Axion emission from defects heavily depends on scaling behavior
- scaling behavior on longer time scale?
- We have updated our simulations (from $N_{grid}=512^3$ to 4096^3)
- scaling parameter ξ increases logarithmically in time $\xi \propto \log(t/d)$
- consistent with another recent simulation Gorghetto, Hardy, Villardoro (2018)





3.6 Recent Progress

- Energy spectrum has a peak at low k
- power law $d\dot{\rho}_a/d\ln k \propto k^{-1}$
- average energy $\boxed{\epsilon \simeq 2 \sim 4}$



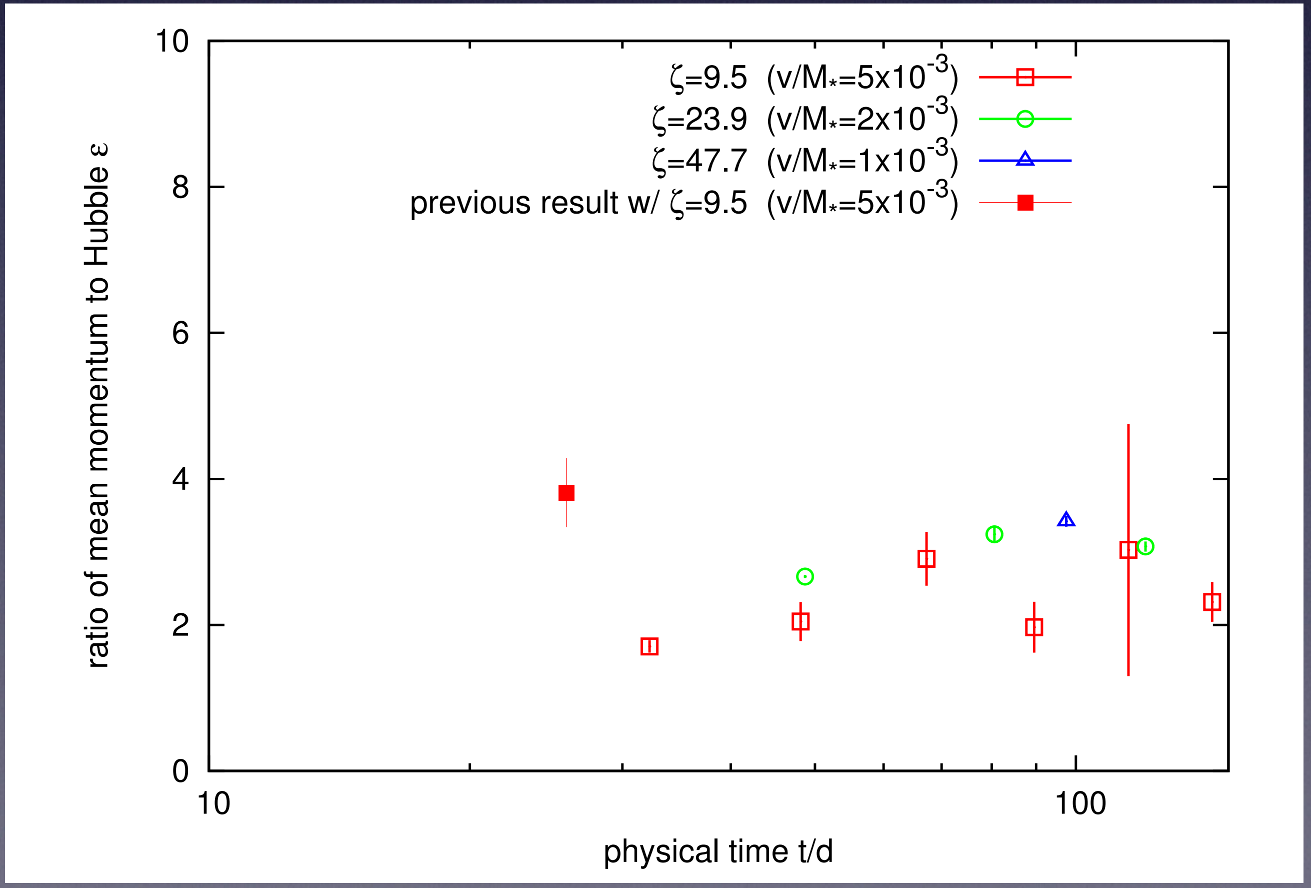
- However, Gorghetto et al obtained

$$d\dot{\rho}_a/d\ln k \propto k^{-q} \quad (q<0)$$

↓

Large uncertainties in the previous estimation ?

- We need to understand more about underlying physics



MK, Sekiguchi, Yamaguchi, Yokoyama (2018)

4. Non-topological objects of axions

- Axion fluctuations can form scalar lumps like
  - Axiton (= I-ball/Oscillon) ← axion self-interaction

    I-balls/oscillons are non-topological soliton solutions existing for scalar potential flatter than ϕ^2

    $$V \simeq \frac{1}{2}m^2\phi^2 - \frac{\lambda}{4}\phi^4 + \cdots$$

  - Axion minicluster

    dense axion dark matter halo

  - Axion star

    star made of axions

gravity

- They could affect cosmological evolution of axion field and enhance or suppress detectability

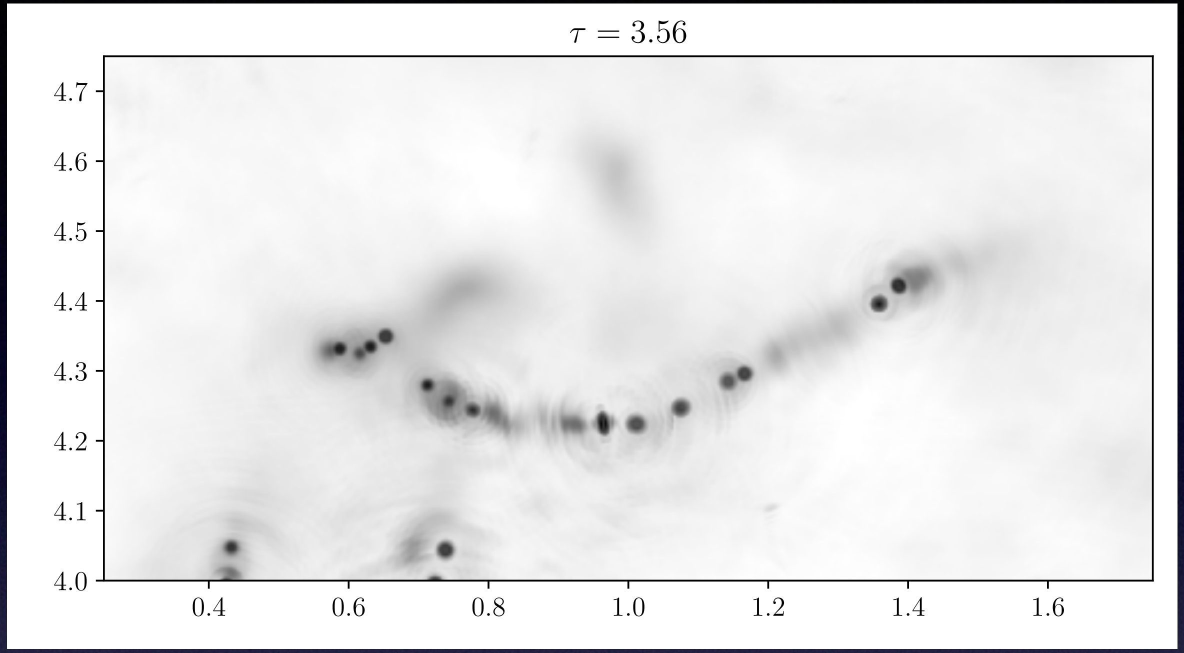
4.1 Axiton and axion minicluster

scenario A

- Axion field has large fluctuations at QCD phase transition

$$\boxed{\delta a/a \sim \mathcal{O}(1)}$$

- Axion potential has an I-ball/oscillon solutions (= axitons)
  - Fluctuations form axitons
  - Axitons decay into axions
  - Seeds for large density perturbations?



Vaquero, Redondo, Stadler (2018)

- Large over-density regions

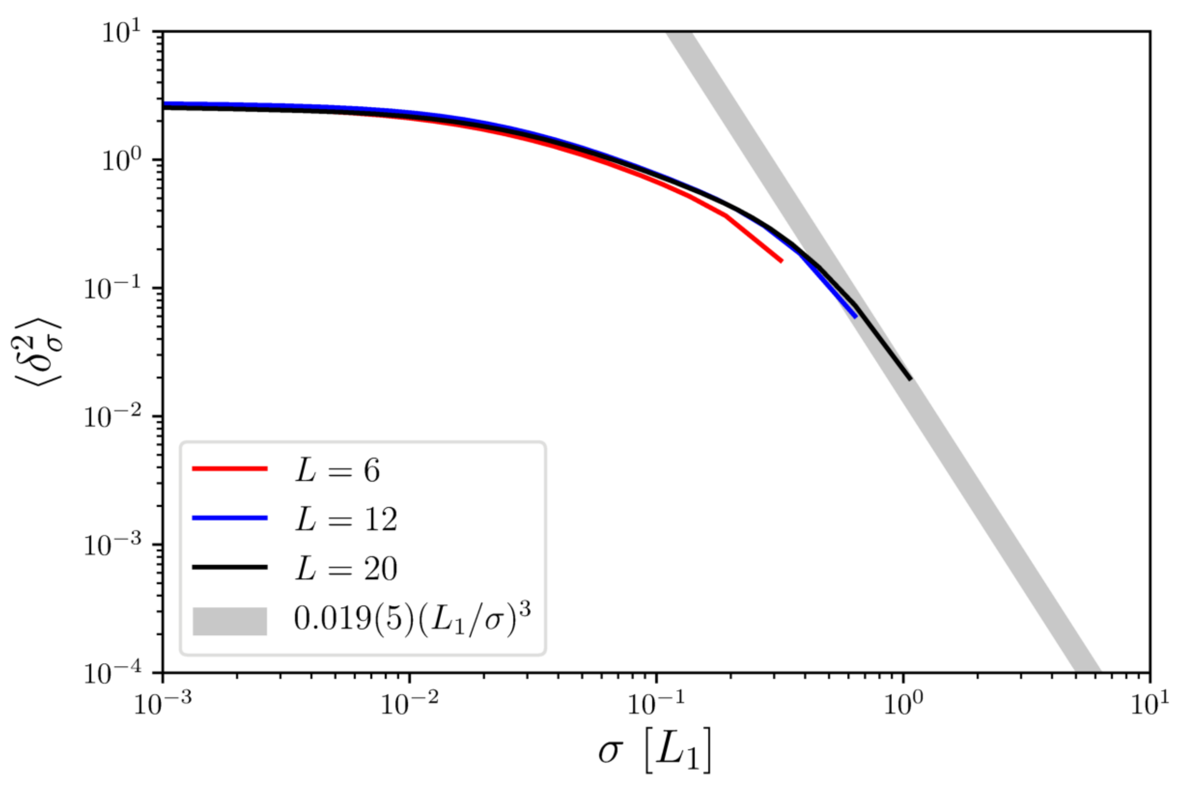
$$L_1 \simeq 0.036\text{pc}\left(\frac{50\mu\text{eV}}{m_a}\right)^{0.167}$$

comoving horizon at $H(T_1) = m_a(T_1)$

➡ mini halos (=axion minicluster)

$z \sim z_{eq}$

Kolb, Tkachev (1994)



Vaquero, Redondo, Stadler (2018)

4.1 Axiton and axion minicluster

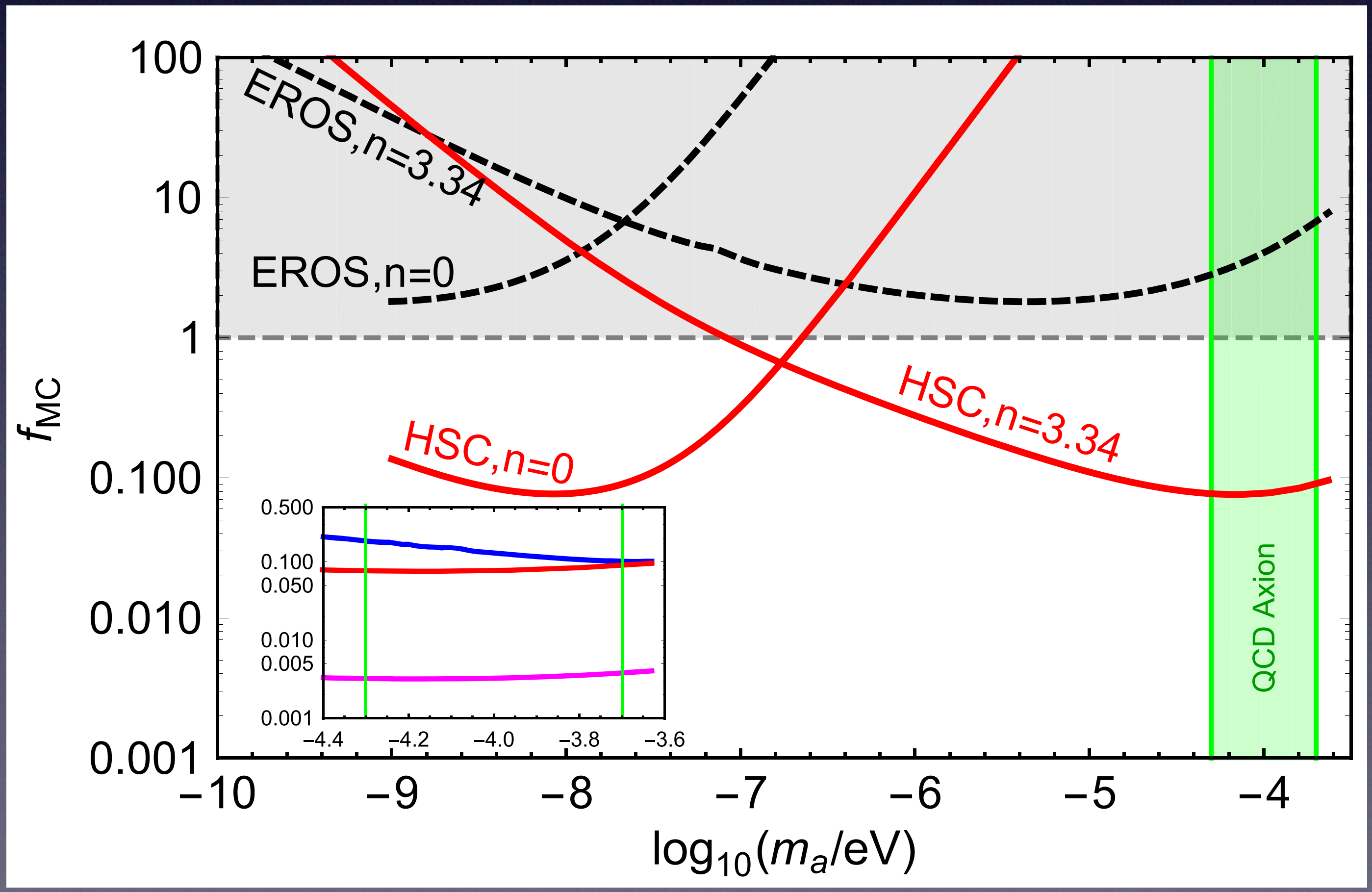
- Axion minicluster
  - density $\rho_c = 140\delta^3(1+\delta)\rho_a(1+z_{\rm eq})^3$
  - size $L \sim 0.1L_1 \sim 0.01\text{pc}$
  - mass $M \sim 10^{-13}M_\odot$

- Axion miniclusters could be detected by microlensing

Fairbairn et al. (2018)

$f_{\rm MC} =$ (minicluster fraction of axion density)

- If $f_{\rm MC}$ ~1 direct detection is difficult since encounters with minicluster are very rare



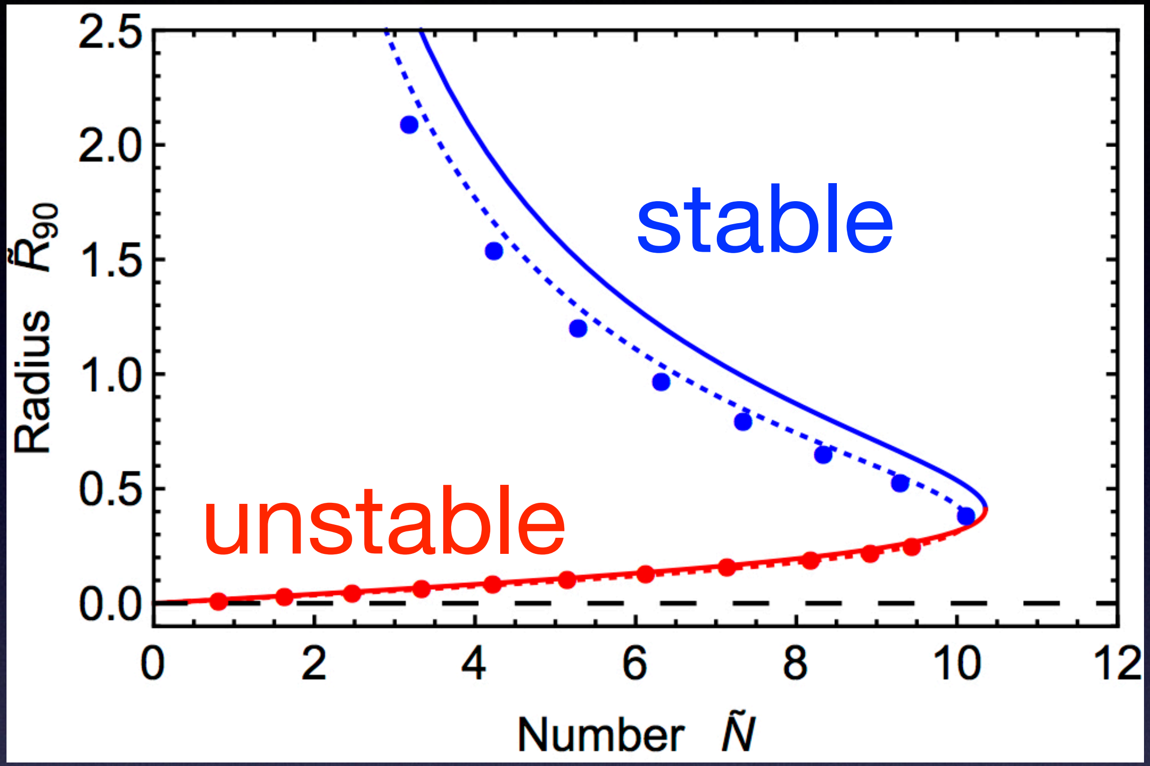
4.2 Axion star

scenario A scenario B

- If gravitational interaction is included , non-relativistic axion field has a stable spherical clump solution = axion star

$$R = 388\text{km}\,\tilde{R}$$

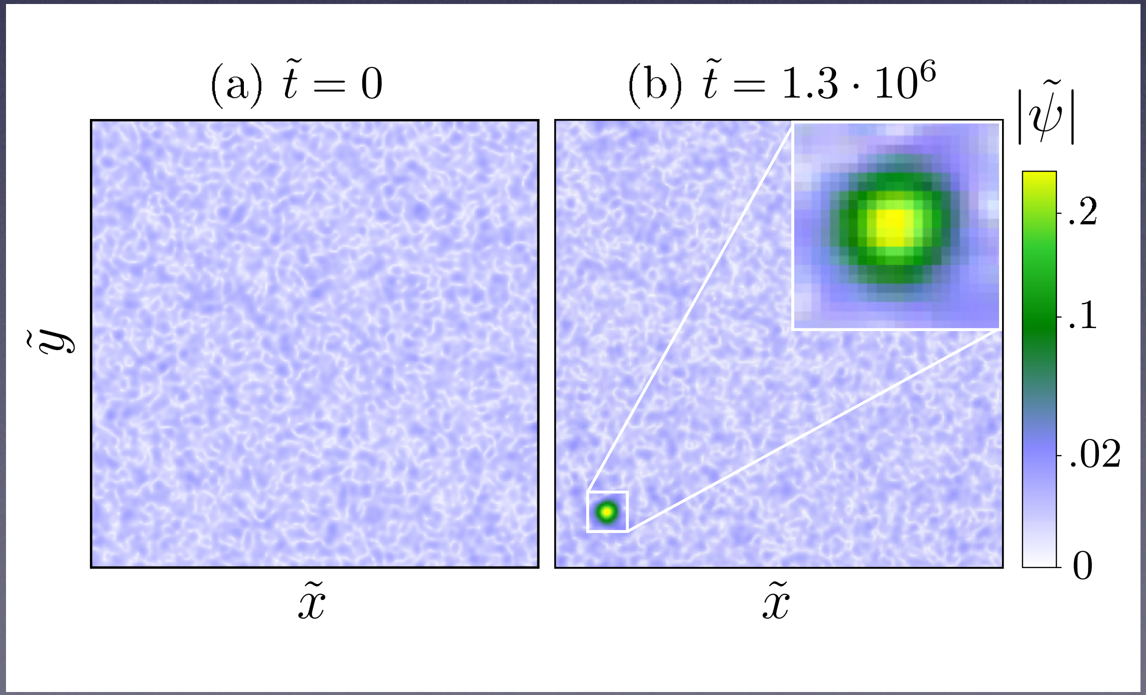
$$M = 3.5 \times 10^{21}\text{g}\,(F_a/10^{12}\text{GeV})^2\,\tilde{N}$$



Schiappacasse, Hertzberg (2017)

- Recent simulation implies axion stars are produced in DM halos and miniclusters Levkov, Panin, Tkachev (2017)
  - formation time

$$\tau \sim 10^9\text{yr}\left(\frac{m_a}{10^{-5}\text{eV}}\right)^3\left(\frac{v}{\text{km/s}}\right)^6\left(\frac{10^{20}\text{GeV/cm}^3}{\rho}\right)^2$$



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

$\boxed{\text{scenario B}}$

- 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

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

  - θ_* becomes almost homogeneous by inflation (θ_* is a kind of free parameter)
  - Isocuravture perturbation problem

5.1 Axion Isocurvature Fluctuations

- Axion acquires fluctuations during inflation

$$\boxed{\delta a = F_a \delta\theta_a \simeq \frac{H_{\mathrm{inf}}}{2\pi}}$$

- After axion obtains mass, axion fluctuations produce density perturbations

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

- Axion fluctuations contribute to CDM isocurvature density perturbations

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

5.1 Axion Isocurvature Fluctuations

- Isocurvature perturbations lead to CMB angular power spectrum which is different from adiabatic one

- Stringent constraint on amplitude of isocurvature perturbation

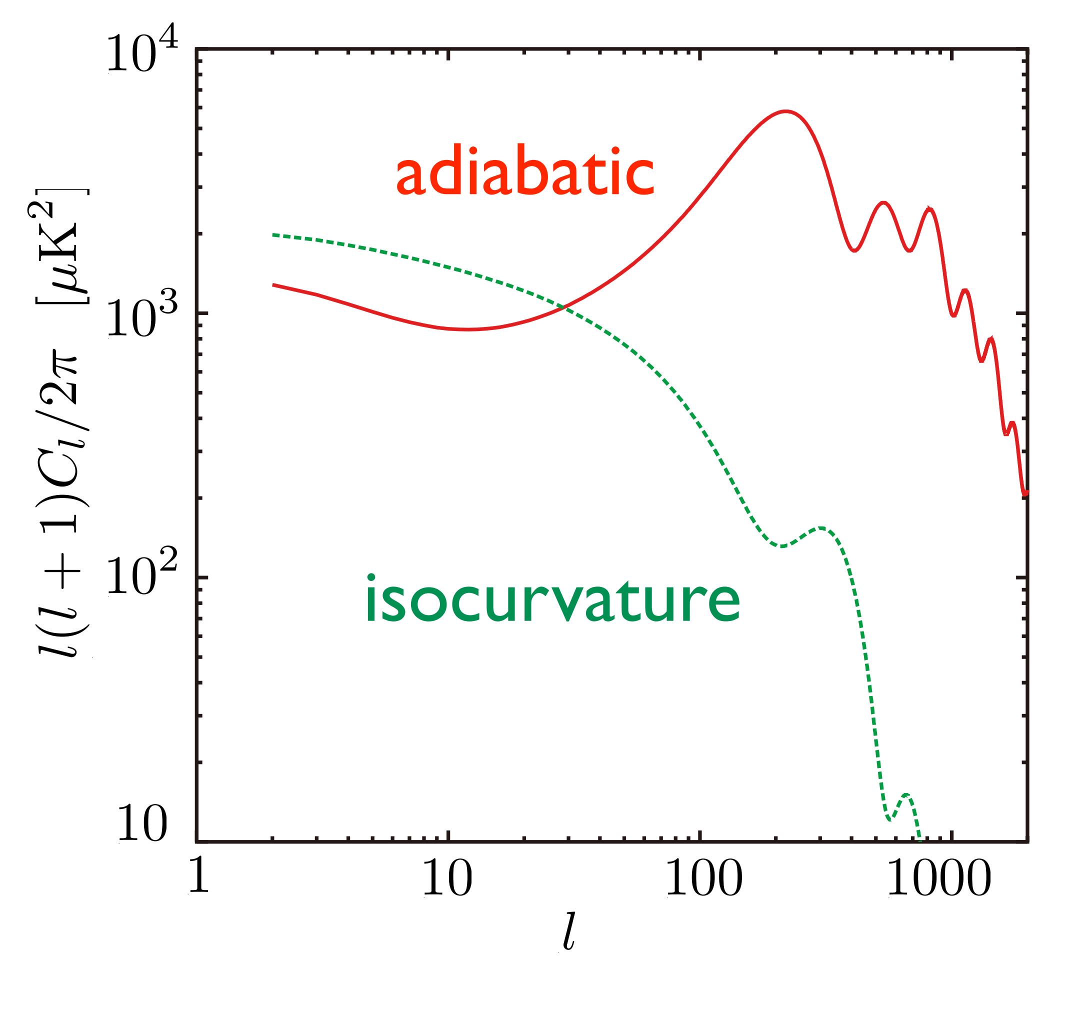
$$\boxed{\beta_{\text{iso}} \equiv \frac{P_S(k_0)}{P_\zeta(k_0) + P_S(k_0)}}$$

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

- PLANCK 2015

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

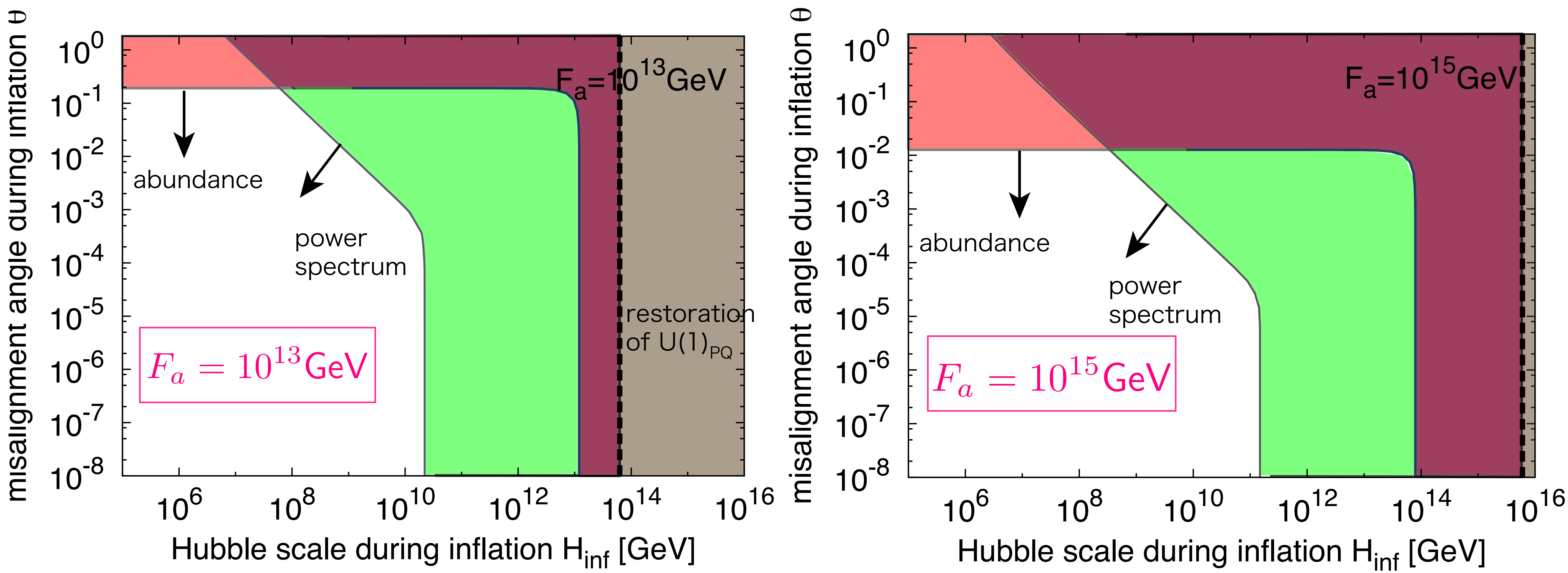
CMB angular Power spectrum



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

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

5.2 Suppressing Isocurvature Perturbations

- Observationally high scale inflation is favored because it is testable by observing B-mode polarization of CMB

➡ Tensor mode (gravitational wave) produced during inflation

r : tensor-to-scalar ratio

$$H_{\rm inf} = 8.6 \times 10^{13}\,\text{GeV}\,(r/0.1)^{1/2}$$

r ~ 0.01 by experiments on the earth

r ~ 0.001 by satellite experiments

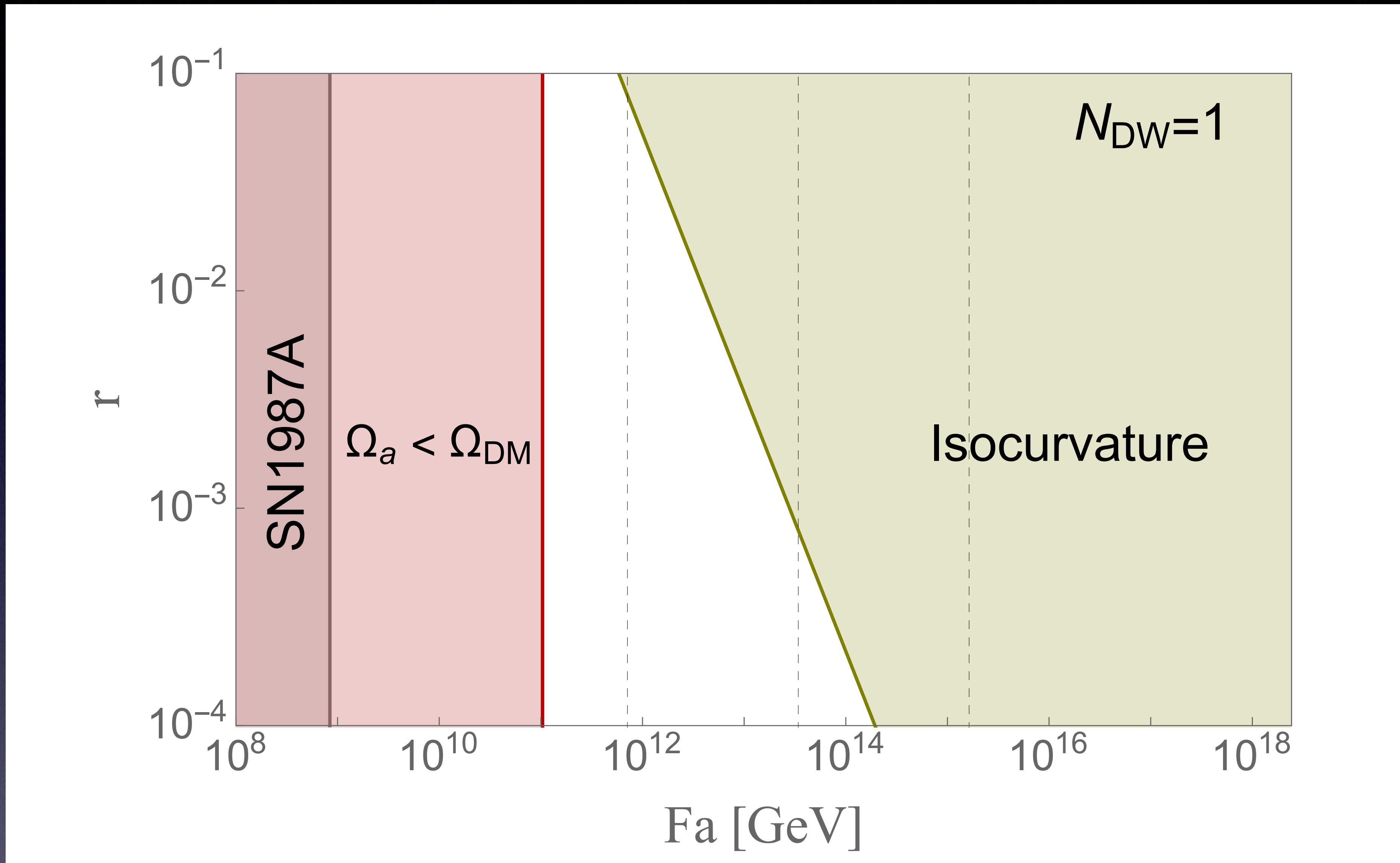
- Can we suppress isocurvature perturbations?

▷ PQ scalar has a large field value during inflation

➡ Isocurvature perturbations suppressed by $\dfrac{\eta}{|\Phi|}$

Linde (1991)

- Assuming PQ field has a large field value $|\Phi| \simeq M_p$ during inflation and axion is dark matter



MK Sonomoto Yanagida (2018)

- Dark matter axion is consistent with high scale inflation whose tensor mode is detectable in future

- Are there concrete models which make PQ field value large during inflation?
- Successful models exist
  - Sextet potential Moroi, Mukaida, Nakayama, Takimoto (2014)
    Ibe, Harigaya, MK, Yanagida (2015)

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

  - SUSY axion model MK Sonomoto (2017)

Axion-like particle

- Physics beyond the standard model like string theory predicts many axion-like particles (particles similar to axion)
- mass m_a and axion scale F_a are independent theoretical parameters

$$V \sim m_a^2 F_a^2 \left[1 - \cos(a/F_a)\right]$$

- Many of cosmological implications of QCD axion apply to axion-like particles changing mass and axion scale

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
- However, recent simulations imply larger uncertainties in estimation of the present axion density
- Fluctuations of axions leads to formation of axitons, axion miniclusters and axion stars
- If PQ symmetry is broken before or during inflation, axion has isocurvature density perturbations which are stringently constrained by CMB observations.
- Isocurvature perturbations are suppressed if PQ scalar has a large field value during inflation

“ A decades long search for WIMPs in direct detection experiments and colliders in the most obvious regime of parameter space has so far been unsuccessful (although interesting parameter space remains available). While the most highly motivated regime of the QCD axion’s parameter space has yet to be fully probed experimentally ”.

— E. D. Schiappacasse and M. P. Hertzberg (2018)

Backup Slides