Production of axion CDM from strings and domain-walls

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References:

- T. Hiramatsu, M. Kawasaki, TS, M. Yamaguchi & J. Yokoyama [arXiv:1012.550]
- T. Hiramatsu, M. Kawasaki, K. Saikawa, & TS [arXiv:1202.5851,1207.3166]
- M. Kawasaki, K. Saikawa, & TS [arXiv:1412.0789]
- M. Kawasaki, TS, M. Yamaguchi, & J. Yokoyama, in prep.

CosPa2016

Sydney U, Dec 1, 2016

Outline

- Introduction: axion strings and domain walls (DWs)
- Field-theoretic simulation of axion topological defects
- Abundance of axion CDM from defects
- Current project: upgrading simulation
- Summary

Axion

Reviewed by P. Gondolo

Strong CP problem in QCD

$$\frac{\theta}{32\pi^2} G^a_{\mu\nu}\tilde{G}^{a\mu\nu} \in \mathcal{L} \longrightarrow \text{CP violation}$$

– Experimental bound: $\theta \lesssim 10^{-10}$; Why so small?

Solution: Peccei-Quinn mechanism Peccei & Quinn (1977)

– Anomalous $U(1)_{PQ}$ spontaneously broken at $\sim f_a$

$$\theta(x) = \theta - \frac{a(x)}{f_a}$$

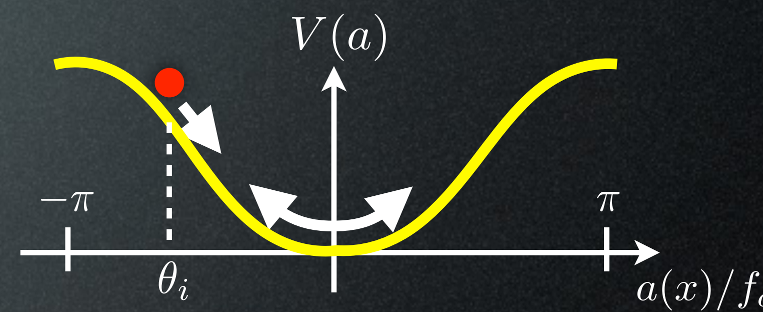
– Pseudo-NG boson $a(x)$: axion → candidate of CDM

$$m_a(x) \simeq 6\,\mu\text{eV}\left(\frac{f_a}{10^{12}[\text{GeV}]}\right)^{-1}$$

Axion cosmology

Two possibilities:

- $U(1)_{PQ}$ is broken before inflation



  - (Almost) homogeneous $\theta_{\rm ini} = a_{\rm ini}/f_a \sim \pi$
  - CDM axions from coherent oscillation

$$\Omega_{\rm axion} \simeq 1.2 \times \theta_{\rm ini}^2 \left(\frac{f_a}{10^12\,{\rm GeV}} \right)^{1.2} \quad \rightarrow \quad f_a < 1.5 \times 10^{11} {\rm GeV}$$

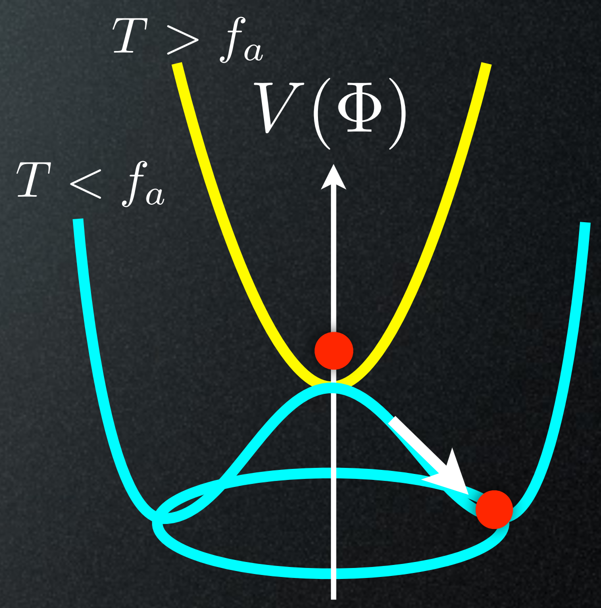
  - CDM isocurvature perturbations is generated → bound on $H_{\rm inf}$

- $U(1)_{PQ}$ is restored during or after inflation ($\max[H_{\rm inf}, T] > f_a$)
  - Random $a_{\rm ini}$. Global strings and DWs form.
  - CDM axions are also produced from these topological defects.

Formation of axionic defects

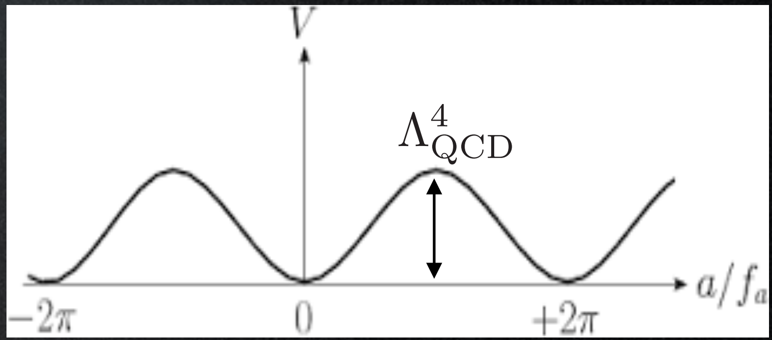
- $T > f_a$: U(1)$_{PQ}$ is restored

- $T = f_a$: U(1)$_{PQ}$ breaks down
  - Random distribution of phase: unif(-π,π)
  - Formation of axion strings (~vortex)
  - Axions are radiated from strings



Φ: PQ complex scalar

- $T = \Lambda_{\rm QCD}$: QCD phase transition
  - Axion acquires potential ~ $\Lambda_{\rm QCD}^4 \cos\left(\frac{a}{f_a}\right)$
  - Formation of DWs



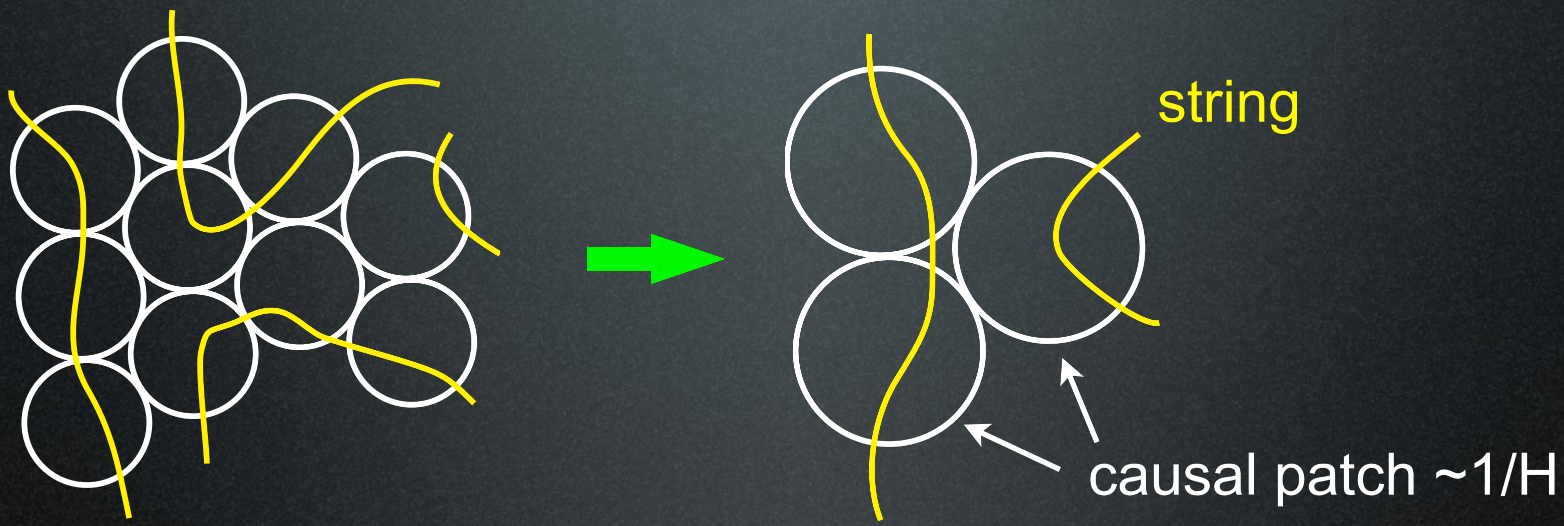
DWs have boundary edged by strings for N_{DW}=1 (e.g. hadronic axion model Kim ’79; Shifman, Vainshtein & Zakharov ’80)

→ DW-string system collapses into axion radiation within a few Hubble time

time

Evolution of defect network

Thermodynamics: **scaling solution**



- Number of topological defects in a horizon is constant of O(1).
- Attractor solution: more(less) strings → more(less) inter-commutation
- Existence of scaling solution allows extrapolation of simulation results wrt parameters (to be discussed later)

Abundance of axion CDM

Energy density of axion CDM at present

$$\bar{\rho}_{\rm axion}(t_0) = m_{\rm axion}\bar{n}_{\rm axion}(t_0)$$

Number density of axions radiated from topological defects

$$= \frac{\text{(Energy loss of string-DW system)}}{\text{(Mean energy of radiated axions)}}$$

Evolution of density of defects

Spectrum of radiated axions

Estimated from simulations

Lattice simulation

PQ scalar on the lattice $\Phi(x_i, y_j, z_k)$

$$\ddot{\phi}_i + 2\mathcal{H}\dot{\phi}_i - \nabla^2\phi_i = \frac{\partial V}{\partial \phi_i}$$

$a(\tau) \propto \tau = 1/\mathcal{H}$

in RD epoch

$$V[\Phi] = \frac{\lambda}{4}(|\Phi|^2 - f_a^2)^2 + \frac{\lambda}{6}T^2|\Phi|^2 - m_a^2(T) f_a^2 \left(\frac{\mathrm{Re}\,\Phi}{f_a}\right)$$

$$\Phi = \frac{\phi_1 + i\phi_2}{\sqrt{2}}$$

$$m_a(T)^2 f_a^2 \simeq \begin{cases} 10^{-7}\Lambda_{\mathrm{QCD}}^4 \left(\frac{T}{\Lambda_{\mathrm{QCD}}}\right)^{-6.7} & (T \gtrsim \Lambda_{\mathrm{QCD}}) \\ 10^{-3}\Lambda_{\mathrm{QCD}}^4 & (T \lesssim \Lambda_{\mathrm{QCD}}) \end{cases}$$

Wantz & Shellard (2011)

Field theoretic simulation: first principles calculation (↔ string based action)

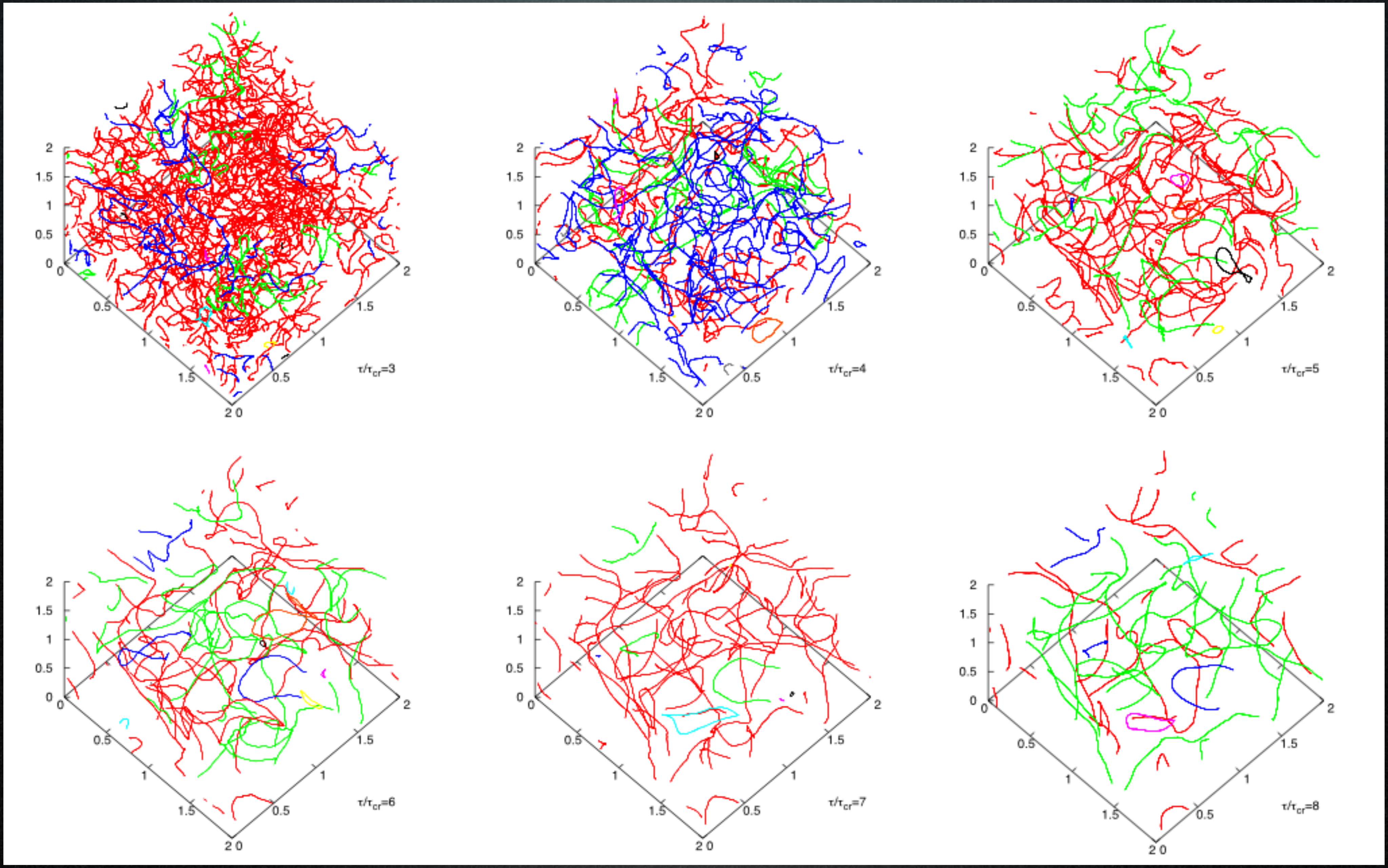
Drawback: unphysical parameters

(Box size L) > (Horizon $1/H$) >> (defect width d) > (lattice spacing=L/N_{grid}~$O(10^{-3})L$)

- Simulations with <u>unphysical parameters</u> & extrapolation to <u>physics point</u>

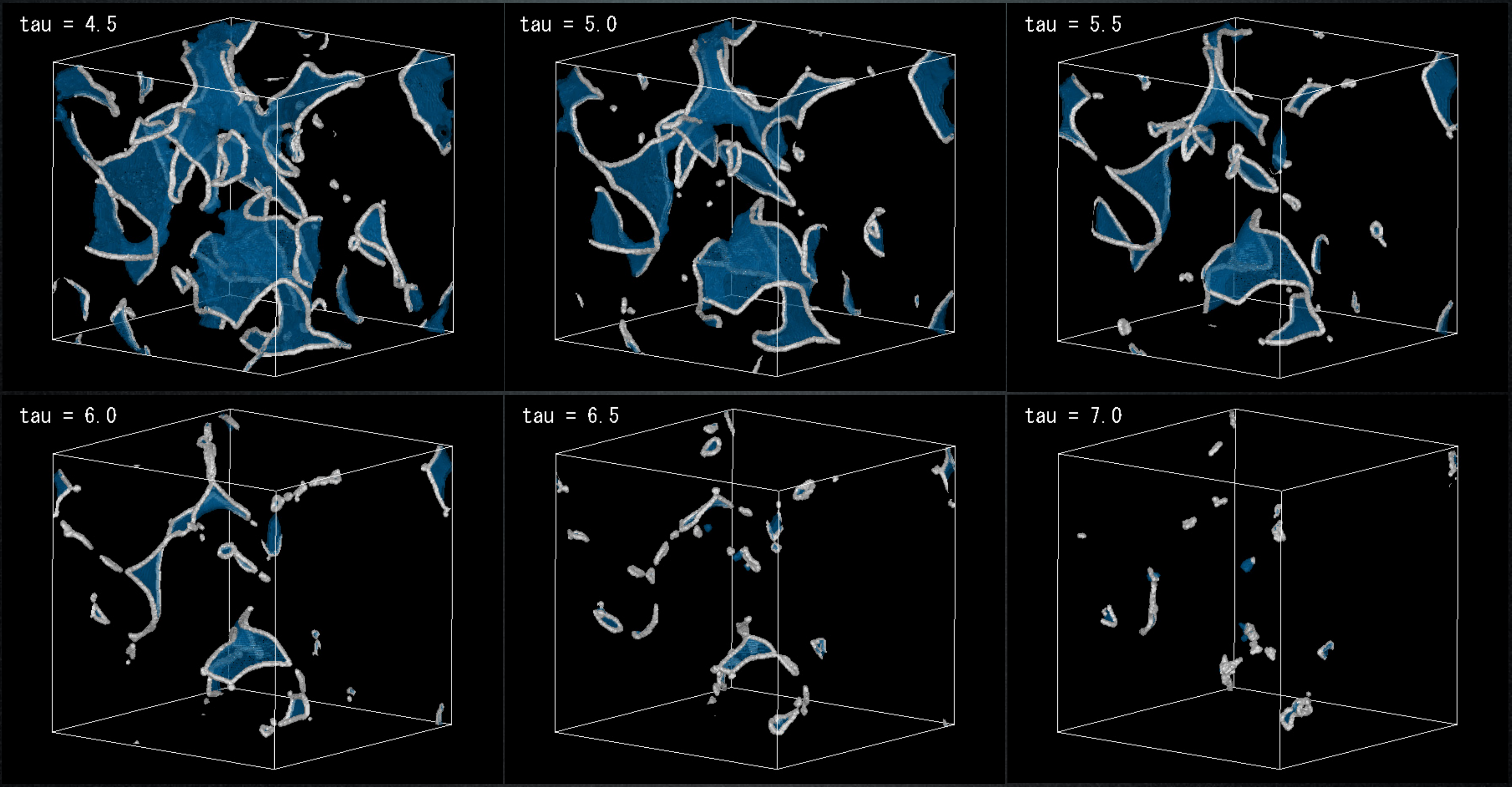
$f_a/M_{\mathrm{pl}} \sim 10^{-3}$, $\Lambda_{\mathrm{QCD}}/f_a \sim 0.1$ $\qquad$ $f_a/M_{\mathrm{pl}} \sim 10^{-8}$, $\Lambda_{\mathrm{QCD}}/f_a \sim 10^{-12}$

String network



Kawasaki, TS, Yamaguchi & Yokoyama in prep

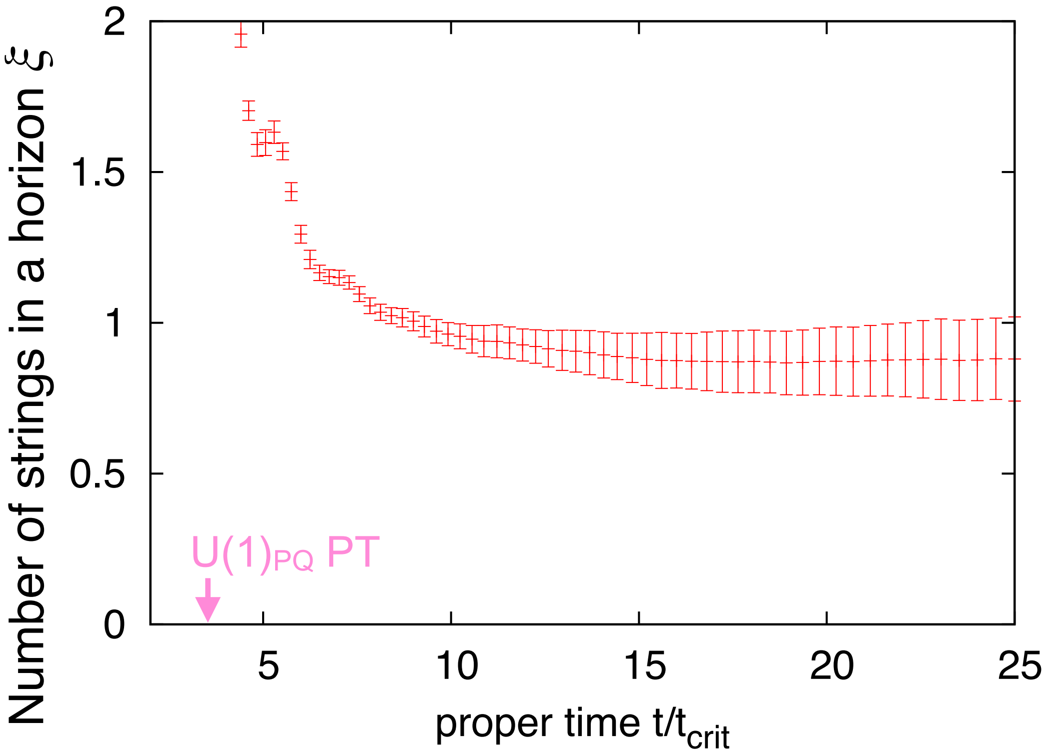
String-DW system (N_{DW}=1)



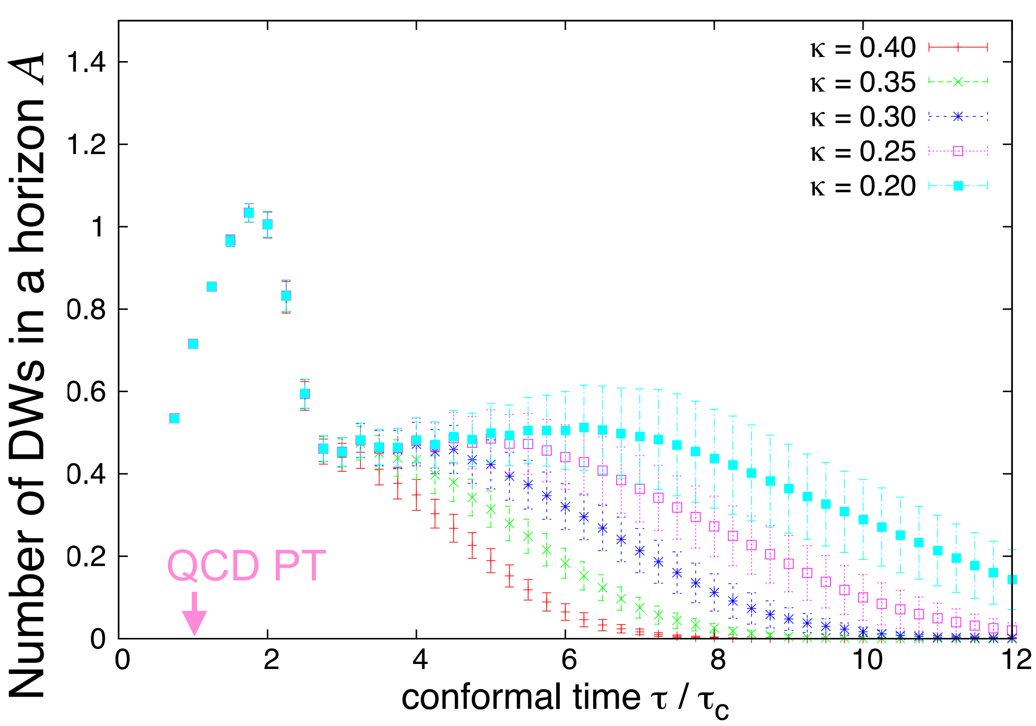
Hiramatsu, Kawasaki, Saikawa & TS (2012)

Scaling solution

$\kappa = \Lambda_{\rm QCD}/F_a$



Hiramatsu, Kawasaki, TS, Yokoyama & Yamaguchi (2011)



Hiramatsu, Kawasaki, Saikawa & TS (2012)

- # of strings in a horizon (=ξ) is constant
  → scaling solution is realized
- ξ is close to 1
  ← long-range force/dissipation process
  cf. ξ~10 for local strings (i.e. Abelian Higgs)

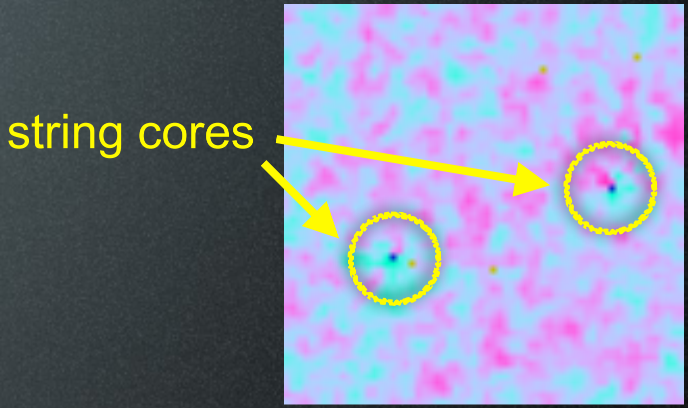
- DWs also scale at first
- Then quickly decay after energy of DWs dominates over strings.

Spectrum estimation

Hiramatsu, Kawasaki, TS, Yamaguchi & Yokoyama (2011)

Energy spectrum of radiated axions

$$P(k) = |\dot{a}(\vec{k})|^2$$

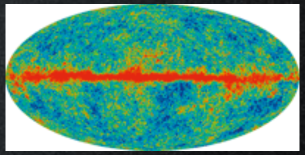


color plot: $\dot{a}$

Need to remove contamination from defects

$$\dot{a}(\vec{x}) = \dot{a}_{\rm free}(\vec{x}) + (\text{string-DW contribution})$$

Statistical reconstruction of spectrum (~CMB analysis)



- Masking

$$\tilde{\dot{a}}(\vec{x}) = W(x)\dot{a}(\vec{x})$$ with window function $$W(\vec{x}) = \begin{cases} 0 & (\text{near defects}) \\ 1 & (\text{elsewhere}) \end{cases}$$

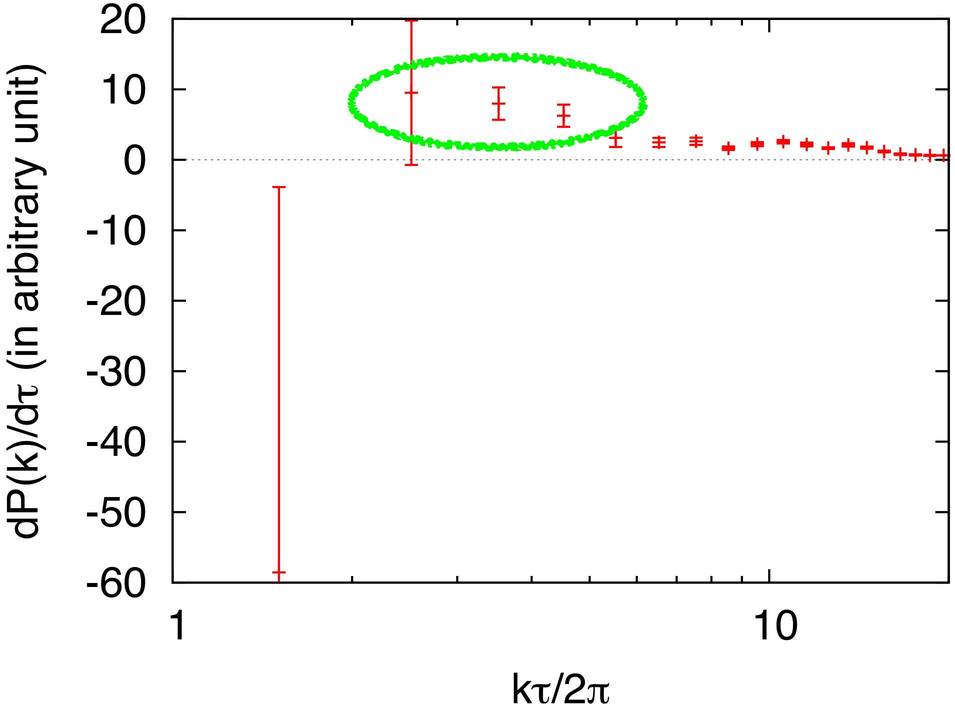
→ convolved power spectrum $$\tilde{P}(k) = \int \frac{d\hat{k}}{4\pi} \left|\tilde{\dot{a}}(\vec{k})\right|^2$$

- Deconvolution

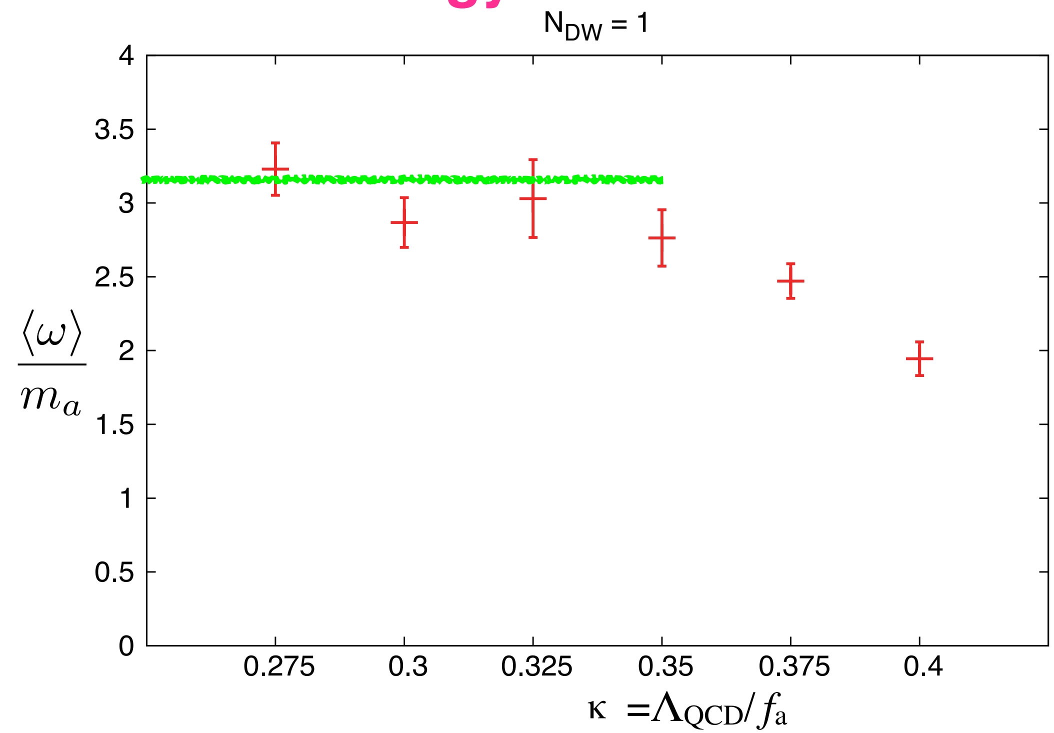
$$\hat{P}_{\rm free}(k) \approx \int dk M^{-1}(k,k')\tilde{P}(k')$$ with $$M(k,k') \equiv \int \frac{d\hat{k}}{4\pi}\frac{d\hat{k}'}{4\pi}\left|W(\vec{k}-\vec{k}')\right|^2$$

Axion radiation spectrum

spectrum of axions from strings



mean energy of axions from DWs



Typical momentum ~ 1/(horizon size)

- strings: $\langle\omega\rangle = (4.0 \pm 0.7) \times 2\pi H$
- DWs: $\langle\omega\rangle = (3.2 \pm 0.2) \times m_a$

Smooth dissipation of strings/DWs energy into radiation;
No evidence for turbulence generating high *k* radiation

Abundance of axion CDM

Energy density of axion CDM at present

$$\bar{\rho}_{\rm axion}(t_0) = m_{\rm axion}\bar{n}_{\rm axion}(t_0)$$

Number density of axions radiated from topological defects

$$= \frac{\text{(Energy loss of string-DW system)}}{\text{(Mean energy of radiated axions)}}$$

Evolution of density of defects

Spectrum of radiated axions

Estimated from simulations

Axion abundance

when $U(1)_{PQ}$ is restored during or after inflation

Three sources:

- Strings (before DW-domination)

$$[\Omega_{\rm axion}h^2]_{\rm strings} = (1.7 \pm 0.9) \times \left(\frac{f_a}{10^{12}\mathrm{GeV}}\right)^{1.2}$$

- String-DW (after DW-domination)

$$[\Omega_{\rm axion}h^2]_{\rm DWs} = (0.9 \pm 0.3) \times \left(\frac{f_a}{10^{12}\mathrm{GeV}}\right)^{1.2}$$

- Coherent oscillation

$$[\Omega_{\rm axion}h^2]_{\rm osc} = 1.1 \times \left(\frac{f_a}{10^{12}\mathrm{GeV}}\right)^{1.2}$$

→ **Contributions of defects are dominant**

Constraint on axion decay constant: $f_a \leq (4.6 - 7.2) \times 10^{10}\mathrm{GeV}$

Direct detection

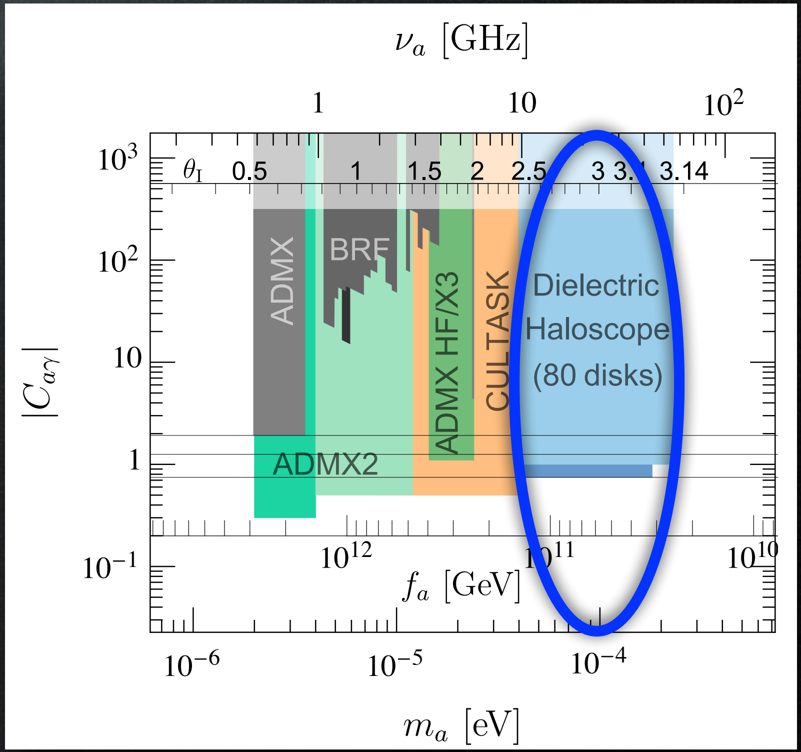
Allowed mass range of axion (when $U(1)_{PQ}$ is restored)

10^{-4} eV < m_a (< 10^{-2} eV)

Upper bound from astrophysics (white dwarfs, SN1987A, etc.)

So far the mass range is left untouched by direct detection (e.g. ADMX, CAST), but many future projects are being planned to probe the mass range:

- Microwave cavity at high frequency
  ADMX HF, IBS-CAPP
- Nuclear Magnetic Resonance
  ARIADNE [arXiv:1403.1290]
- Dielectric haloscope
  MADMAX [arXiv:1611.04549]



Current project

M. Kawasaki, TS, M. Yamaguchi & J. Yokoyama in prep

Pinning down f_a and m_a in scenario where $U(1)_{PQ}$ is restored

cf. dependence on initial misalignment θ_{ini} when $U(1)_{PQ}$ is not restored after inflation

→ Target mass for direct detection

Our prediction heavily lies on **scaling behaviour**

- Existence seems ubiquitous.
- However, relevant parameters characterising the scaling (e.g. ξ) cannot be predicted.
- Mild (~logarithmic) parameter dependences etc. may exist?

→ potential source of major uncertainties

Current project:

- Updating our simulations from $N_{grid}=512^3$ to 4096^3
- Simulations with a range of parameters will be available
- Testing & improving one-scale model [Kibble 1985,…] w/ significant dissipation processes.

Scrutinizing scaling solution

M. Kawasaki, TS, M. Yamaguchi & J. Yokoyama in prep

- infinite strings
- loops
- axion radiation

$$\frac{d\rho_\infty}{dt} = -2H(1+v_\infty^2)\rho_\infty - \frac{\tilde{c}v_\infty}{L_\infty}\rho_\infty - \frac{\kappa}{L_\infty}\rho_\infty$$

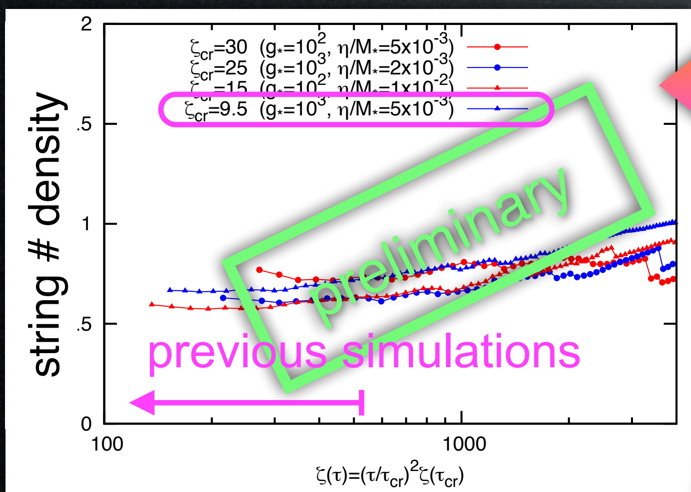
$$\frac{d\rho_l}{dt} = -2H \ldots$$

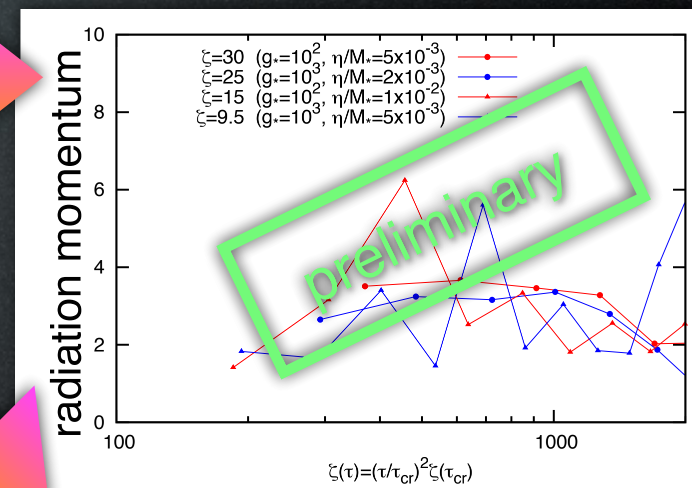
$$\frac{d\rho_{\rm NG}}{dt} = -4H\rho_{\rm NG} + \kappa\left[\frac{\rho_\infty}{L_\infty} + \frac{\rho_l}{L_l}\right]$$

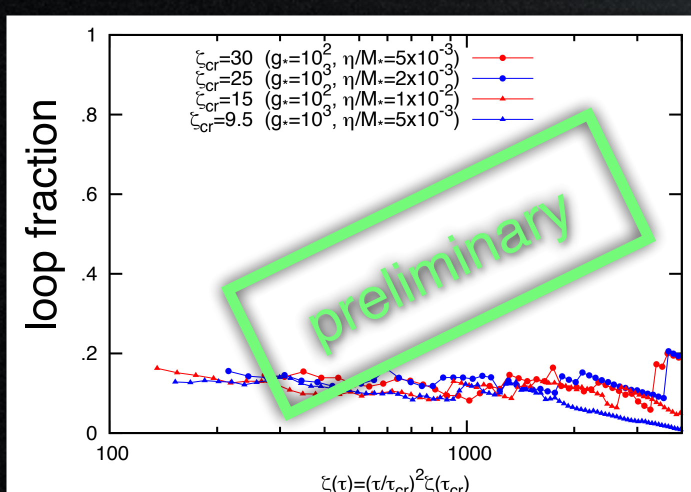
cosmic expansion | loop production | axion emission

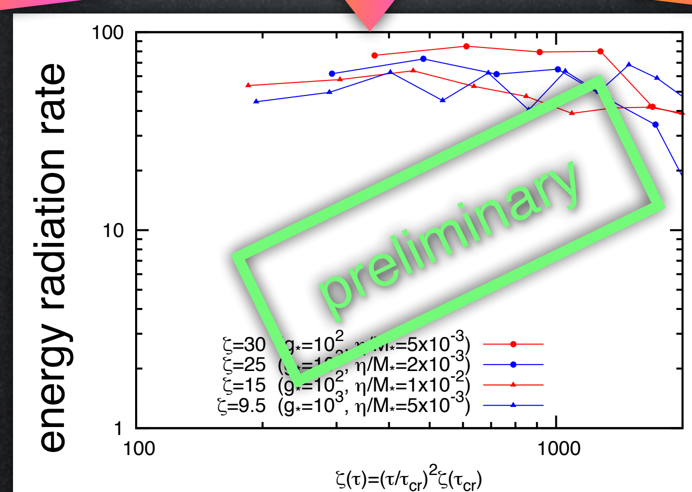
One-scale model

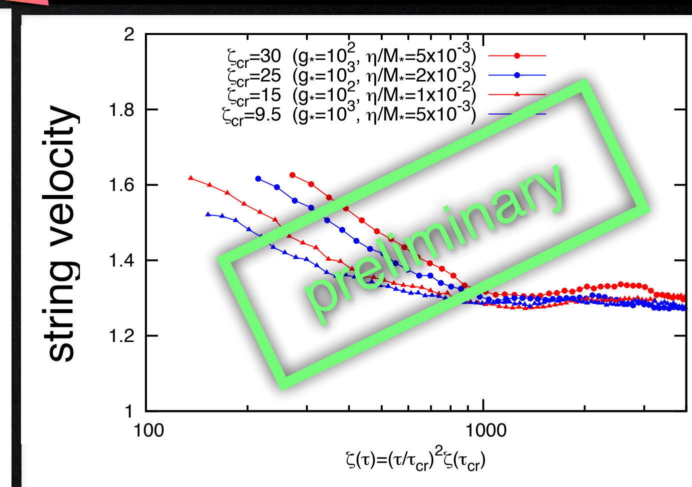
consistency?











Summary

We investigated a scenario where

- $(1)_{PQ}$ is restored in the early Universe
- axions CDM are produced from axion strings and domain-walls

However, there have been lots of controversies e.g. on

- scaling evolution of the network of these defects
- radiation spectrum of axions from them

Performing field theoretic simulations, we confirmed

- average # of strings per horizon is ~1
- mean wave length of radiated axions is around horizon size

We estimated the abundance of CDM axions from defects, that leads to a bound $f_a \lesssim (4.6 - 7.2) \times 10^{10}\mathrm{GeV}$. Direct detection experiments will probe the mass range in the near future.

We are now upgrading our simulations ($N_{grid}=4096^3$). Critical test of scaling evolution of strings will be focused.