Influence of string decays on axion mass prediction

Ken’ichi Saikawa (MPP, Munich)

MAX-PLANCK-GESELLSCHAFT

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

9 May 2018, MADMAX Collaboration Meeting, Munich, Germany

Axion dark matter and its mass

- What is the "typical mass" of the axion dark matter?
- For the post-inflationary scenario (with $N_{DW} = 1$), there should be one-to-one correspondence between its mass and abundance.

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

ρ_c : total energy density of the universe today

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

- Topological defects (strings and domain walls) are formed, and their dynamics affects the dark matter abundance.

Axion production from topological defects

Davis (1986); Harari and Sikivie (1987); Davis and Shellard (1989); Hagmann and Sikivie (1991); Battye and Shellard (1994); Yamaguchi, Kawasaki, and Yokoyama (1999); Hagmann, Chang, and Sikivie (2001)

- Axions are copiously produced from topological defects until their collapse, which happens around the time of the QCD phase transition.

- The relic axion density is given by

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

$R(t)$: scale factor

where $$n_a(t_{\rm decay}) \sim \frac{\rho_a(t_{\rm decay})}{\langle E_a(t_{\rm decay}) \rangle} \sim \frac{\rho_{\rm defects}(t_{\rm decay})}{\langle E_a(t_{\rm decay}) \rangle}$$

Time at the decay of defects

- $\rho_{\rm defects}$ is given by the scaling solution.

$$\rho_{\rm string} = \xi \frac{T}{t^2}$$

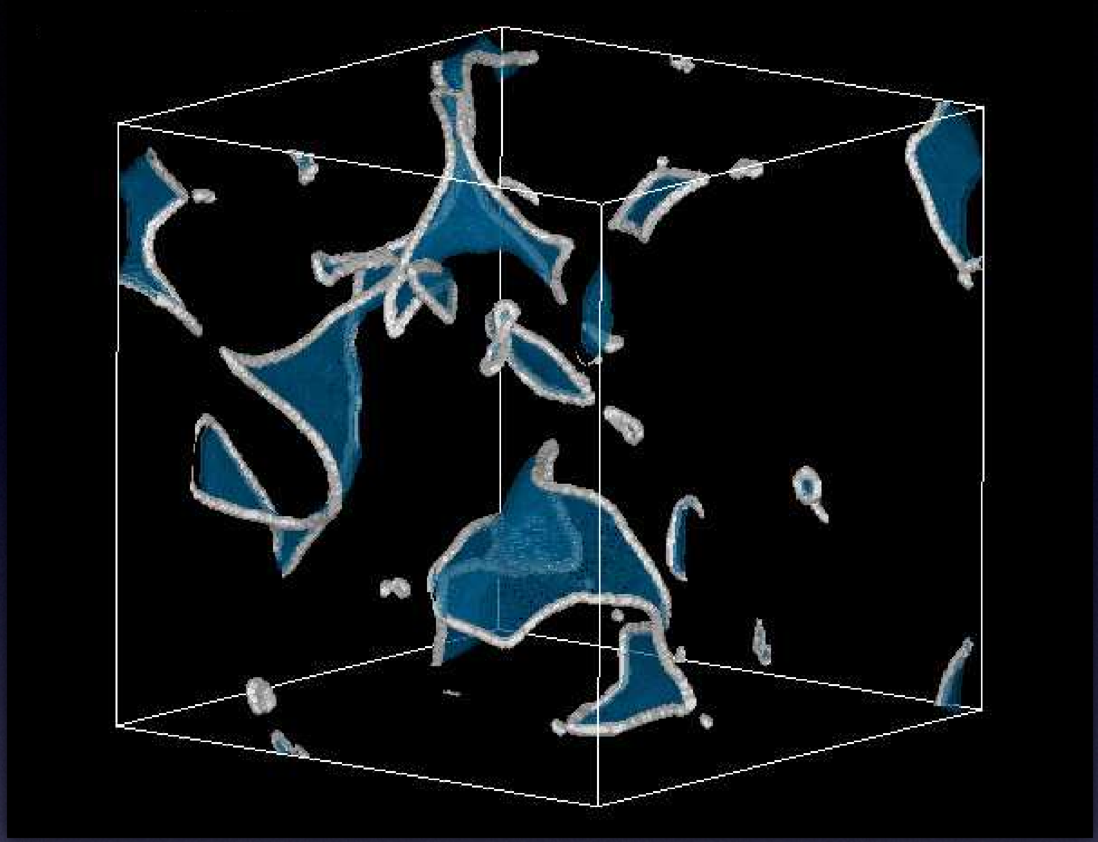
"$\mathcal{O}(\xi)$ strings in a horizon volume."

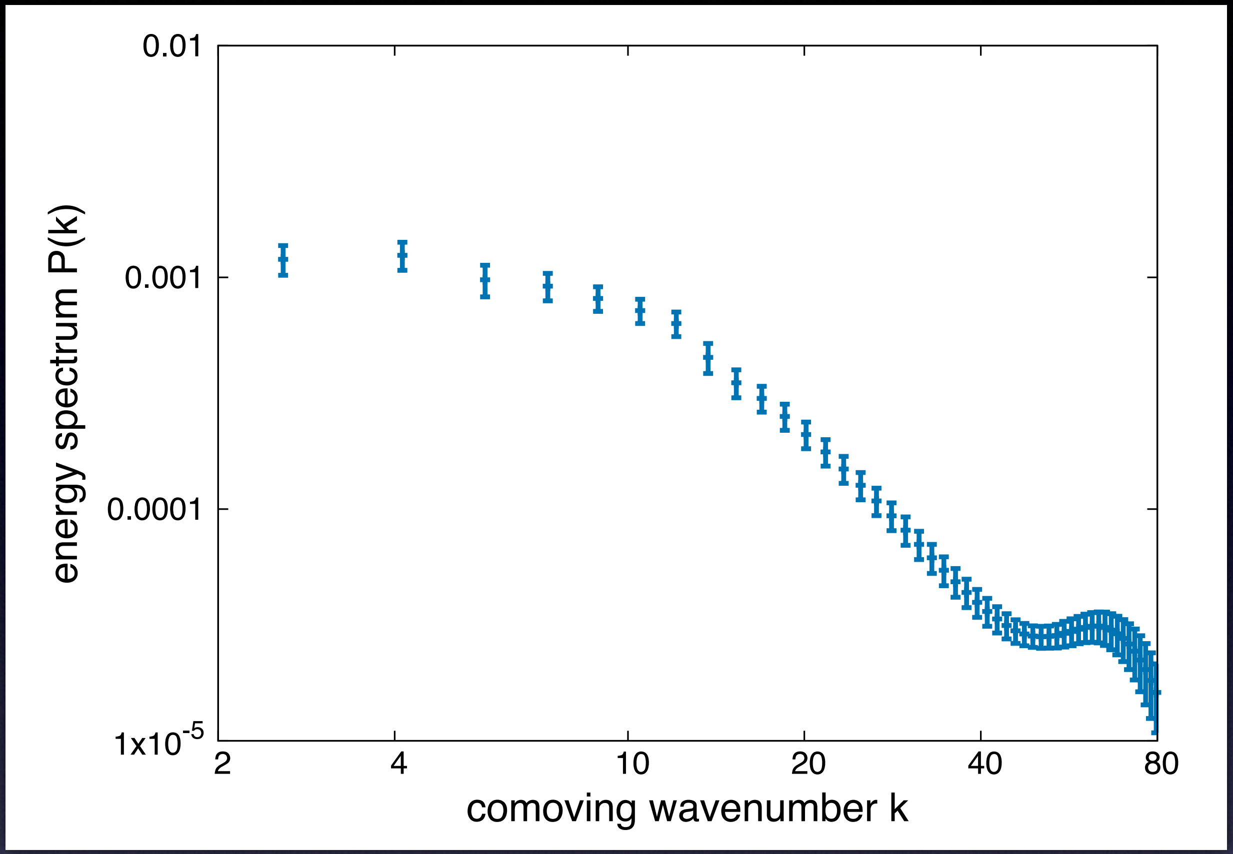
T : string energy per length = string tension

- The mean energy $\langle E_a(t_{\rm decay}) \rangle$ depends on the energy spectrum of radiated axions.

Field theoretic lattice simulations

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





- Spectrum of radiated axions is estimated by solving classical EOM for complex scalar field.
- There are O(1) strings per horizon volume, and radiated axions are mildly relativistic:

$$\xi = 1.0 \pm 0.5, \qquad \frac{\langle E_a \rangle}{m_a}(t_{\rm decay}) = 3.23 \pm 0.18$$

- Estimate of the axion DM mass

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

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

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

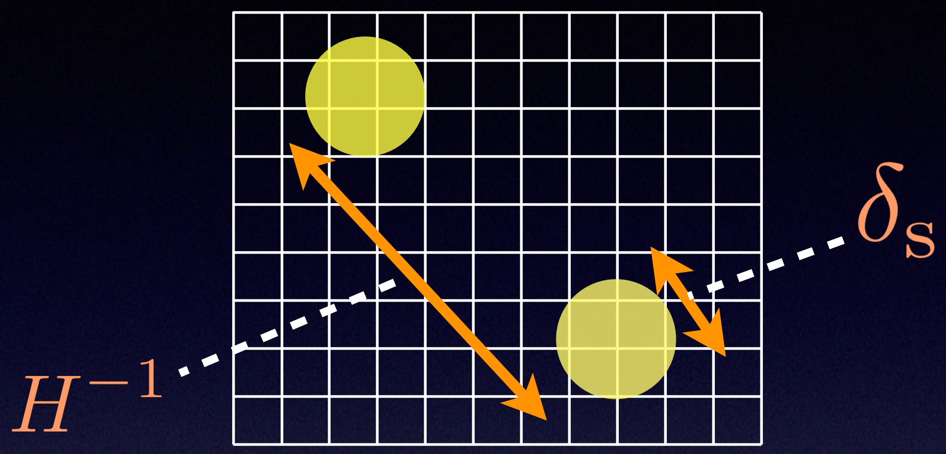
$$m_a \gtrsim (0.6\text{–}1.5) \times 10^{-4}\,{\rm eV}$$

Technical limitations of lattice simulations

- We must consider two extremely different length scales.
  - Width of string core

    $$\delta_s \sim v_{PQ}^{-1} = \text{const.}$$

  - Hubble radius $H^{-1} \sim t$



- In order to follow the time evolution correctly, we must maintain

$$\delta_s > \text{lattice spacing} \propto R(t)$$

$$H^{-1} < \text{simulation box size}$$

- These conditions put a constraint on the simulation time:

$$H^{-1}/\delta_s \lesssim 300 \quad \text{for } 512^3 \text{ lattice,}$$

while $H^{-1}/\delta_s \sim v_{PQ}/m_a(T_{QCD}) \sim 10^{30}$ at the realistic situation.

- To what extent can we believe the simulation results ?

Global nature of strings

- String tension acquires a large logarithmic correction due to the gradient energy:

$$T = \frac{\text{energy}}{\text{length}} = \int r dr \int_0^{2\pi} d\varphi \left[\left| \frac{\partial \Phi}{\partial r} \right|^2 + \left| \frac{1}{r} \frac{\partial \Phi}{\partial \varphi} \right|^2 + V(\Phi) \right]$$

$$\approx 2\pi \int r dr \left| \frac{1}{r} \frac{\partial \Phi}{\partial \varphi} \right|^2 \simeq \pi v_{\mathrm{PQ}}^2 \ln \left(H^{-1}/\delta_{\mathrm{s}} \right)$$

- When $H^{-1} \gg \delta_{\mathrm{s}}$, this is larger than the string radiation power:

$$P \sim v_{\mathrm{PQ}}^2$$

Vilenkin and Vachaspati (1987)

- We expect that the radiation damping becomes less important in the limit of $H^{-1}/\delta_{\mathrm{s}} \gg 1$. Dabholkar and Quashnock (1990)

(cf. $\ln(H^{-1}/\delta_{\mathrm{s}}) \simeq 69 \quad \text{for} \quad H^{-1}/\delta_{\mathrm{s}} = 10^{30}$)

Strings might be denser and evolve differently (?)

Fleury and Moore (2016)

Need of alternative methods

- Large radius to core width ratio (and hence high string tension) cannot be realized in the conventional approach.
- The way out:
  Modifying the simulation setup such that it effectively induces high string tension.
- New approaches are proposed:
  - Simulations with "smeared" strings

    Fleury and Moore, JCAP05(2016)005 [arXiv:1602.04818]
  - Simulations with auxiliary fields

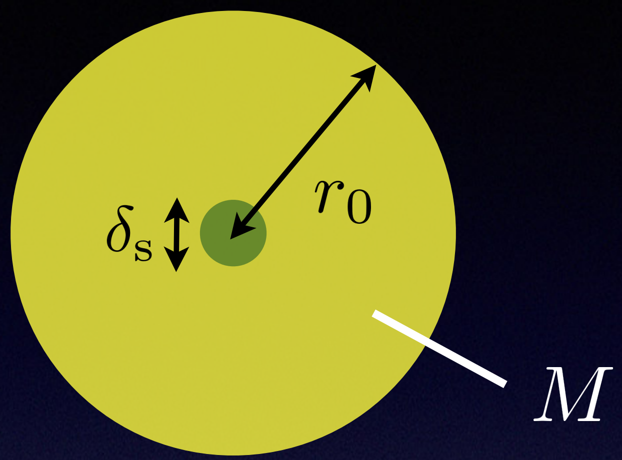
    Klaer and Moore, JCAP10(2017)043 [arXiv:1707.05566]
    Klaer and Moore, JCAP11(2017)049 [arXiv:1708.07521]

Simulations with "smeared" strings (2D)

Fleury and Moore, JCAP05(2016)005 [arXiv:1602.04818]

- Implementing axion field on 2D lattice, while implementing string cores as additional explicit objects.

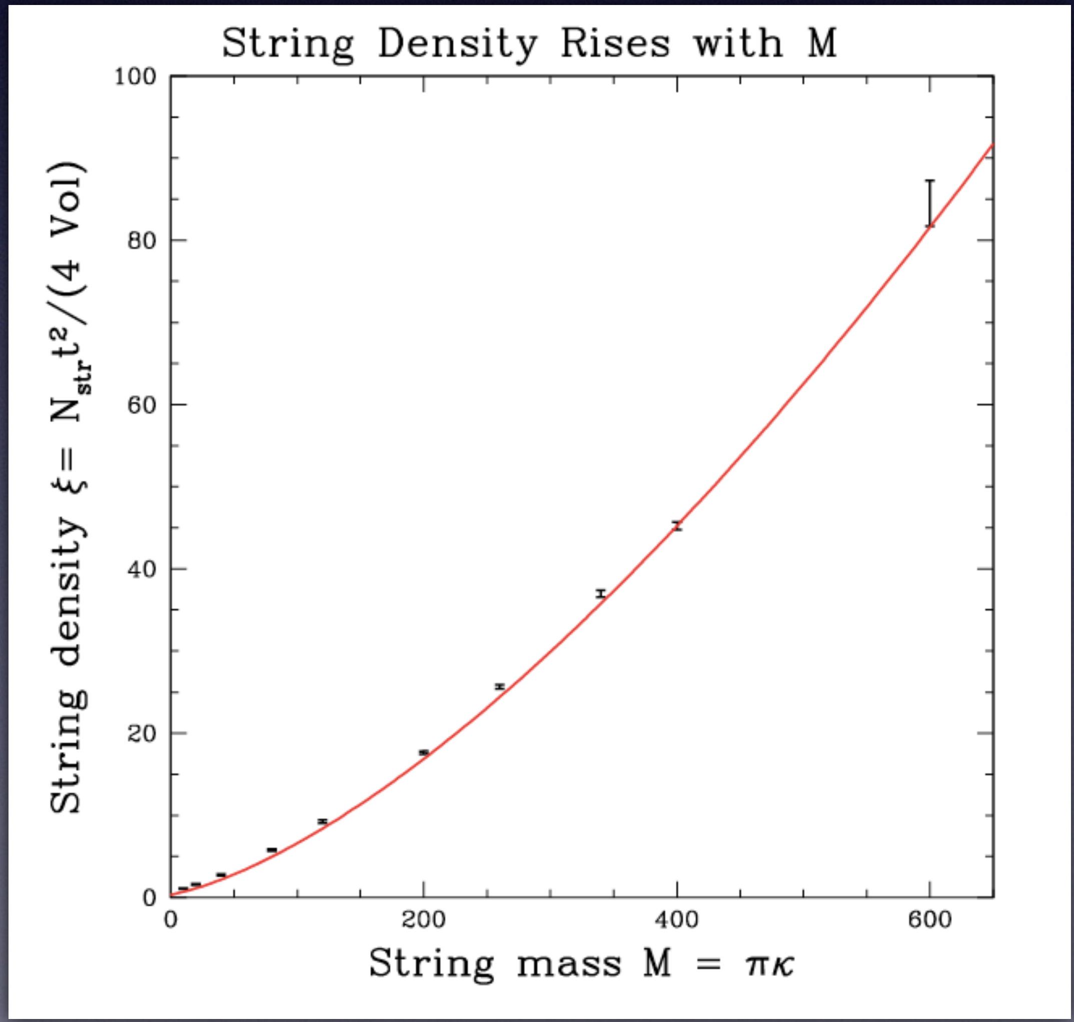
  "smeared ball" with radius r_0



- String self-energy at scale $r < r_0$ is renormalized to its mass:

$$M = \pi v_{\rm PQ}^2 \ln(r_0/\delta_{\rm s})$$

- Significantly different behavior at large $\ln(H^{-1}/\delta_{\rm s})$:
  - String density increases.
  - Results peculiar to 2D ?
    (3D version has not been done yet.)



Simulations with auxiliary fields

Klaer and Moore, JCAP10(2017)043 [arXiv:1707.05566]
Klaer and Moore, JCAP11(2017)049 [arXiv:1708.07521]

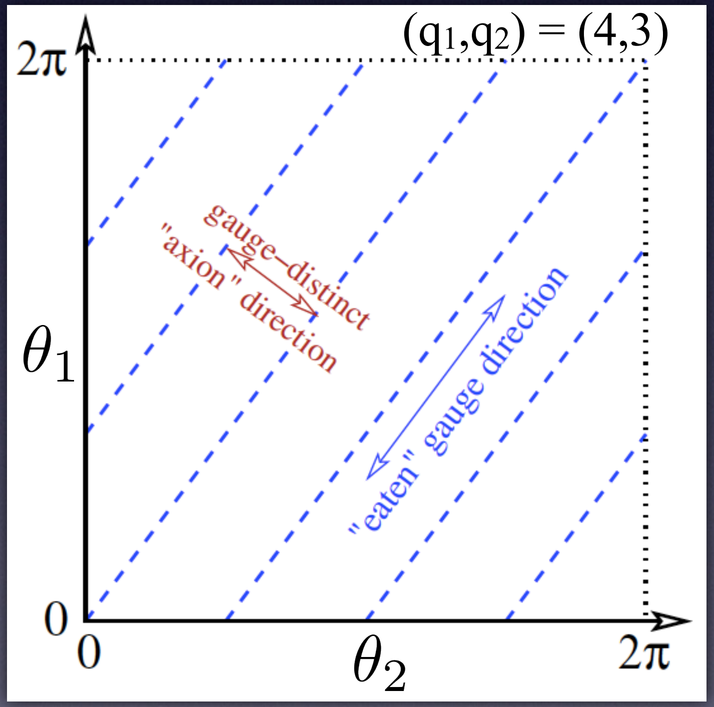
- Introduce two complex scalars and one U(1) gauge field:

$$-\mathcal{L} = \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + |(\partial_\mu - iq_1 eA_\mu)\Phi_1|^2 + |(\partial_\mu - iq_2 eA_\mu)\Phi_2|^2 + \lambda\left[\left(|\Phi_1|^2 - \frac{v^2}{2}\right)^2 + \left(|\Phi_2|^2 - \frac{v^2}{2}\right)^2\right] \quad \text{with} \quad q_1 \neq q_2$$

- Among two phases $\theta_1 = \mathrm{Arg}(\Phi_1)$ and $\theta_2 = \mathrm{Arg}(\Phi_2)$, one combination is eaten by A_μ, and the other is identified as massless axion with a decay constant

$$F_a = \frac{v}{\sqrt{q_1^2 + q_2^2}}$$

$$\theta_{\rm axion} = q_2\theta_1 - q_1\theta_2$$



- String tension is given by that of gauge string:

$$T \simeq 2\pi v^2$$

- Tension becomes relatively high compared with the coupling of strings to axions ($\propto F_a^2$):

$$\kappa \equiv \frac{T}{\pi F_a^2} \simeq 2(q_1^2 + q_2^2)$$

Simulations with auxiliary fields

Klaer and Moore, JCAP10(2017)043 [arXiv:1707.05566]
Klaer and Moore, JCAP11(2017)049 [arXiv:1708.07521]

- String density increases.

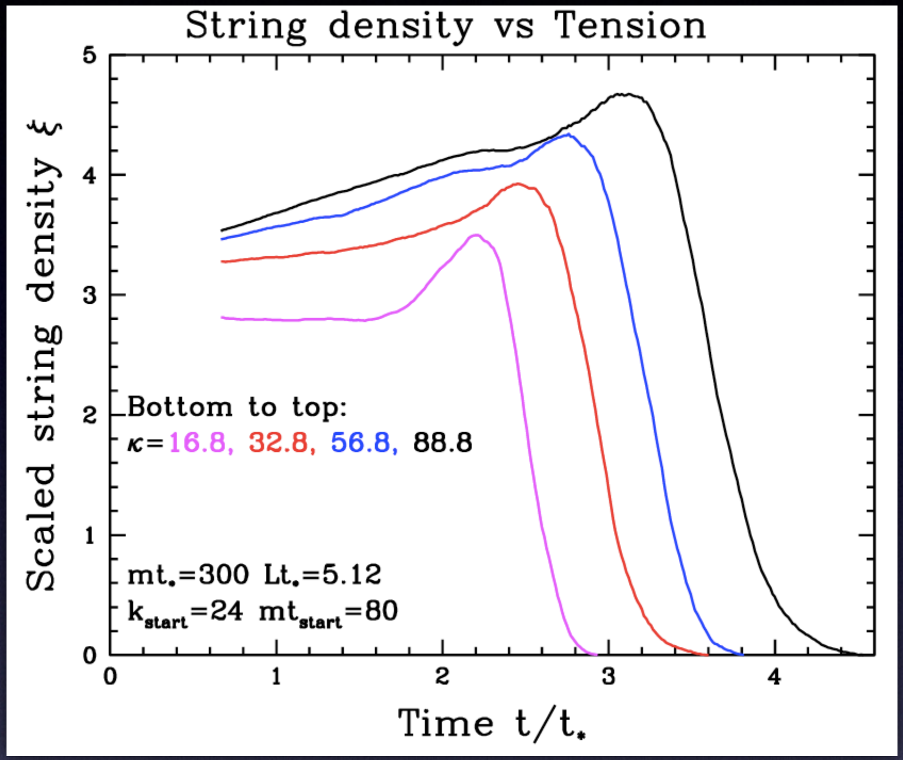
$$\xi = \frac{\rho_{\rm string} t^2}{T} \sim 4$$

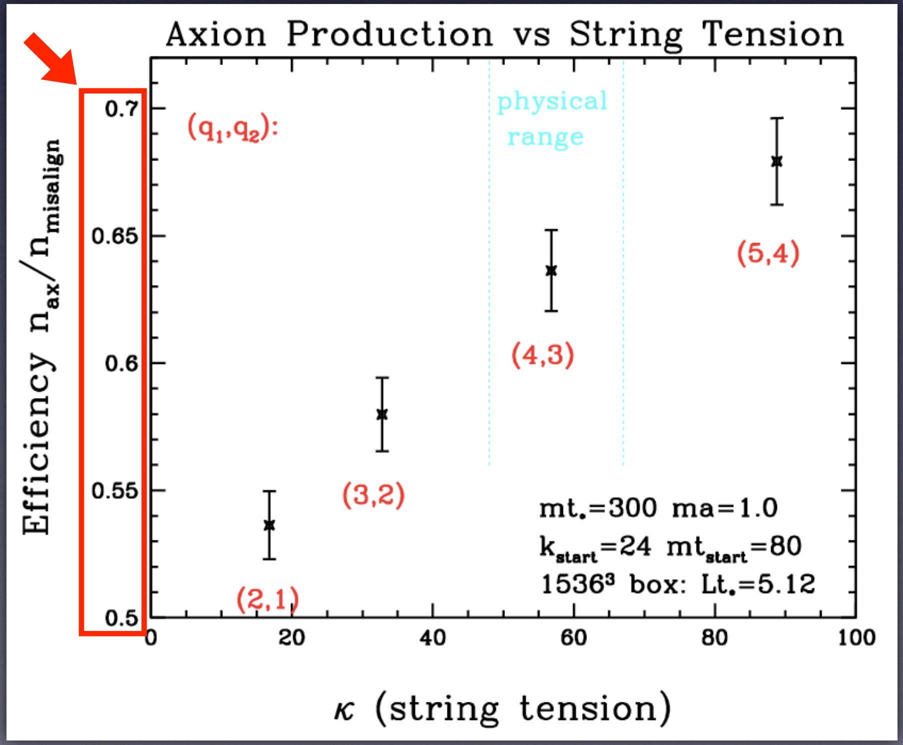
(cf. $\xi \sim 1$ for scalar-only simulations)

- Axion production becomes less efficient than a naive estimate based on the realignment mechanism.

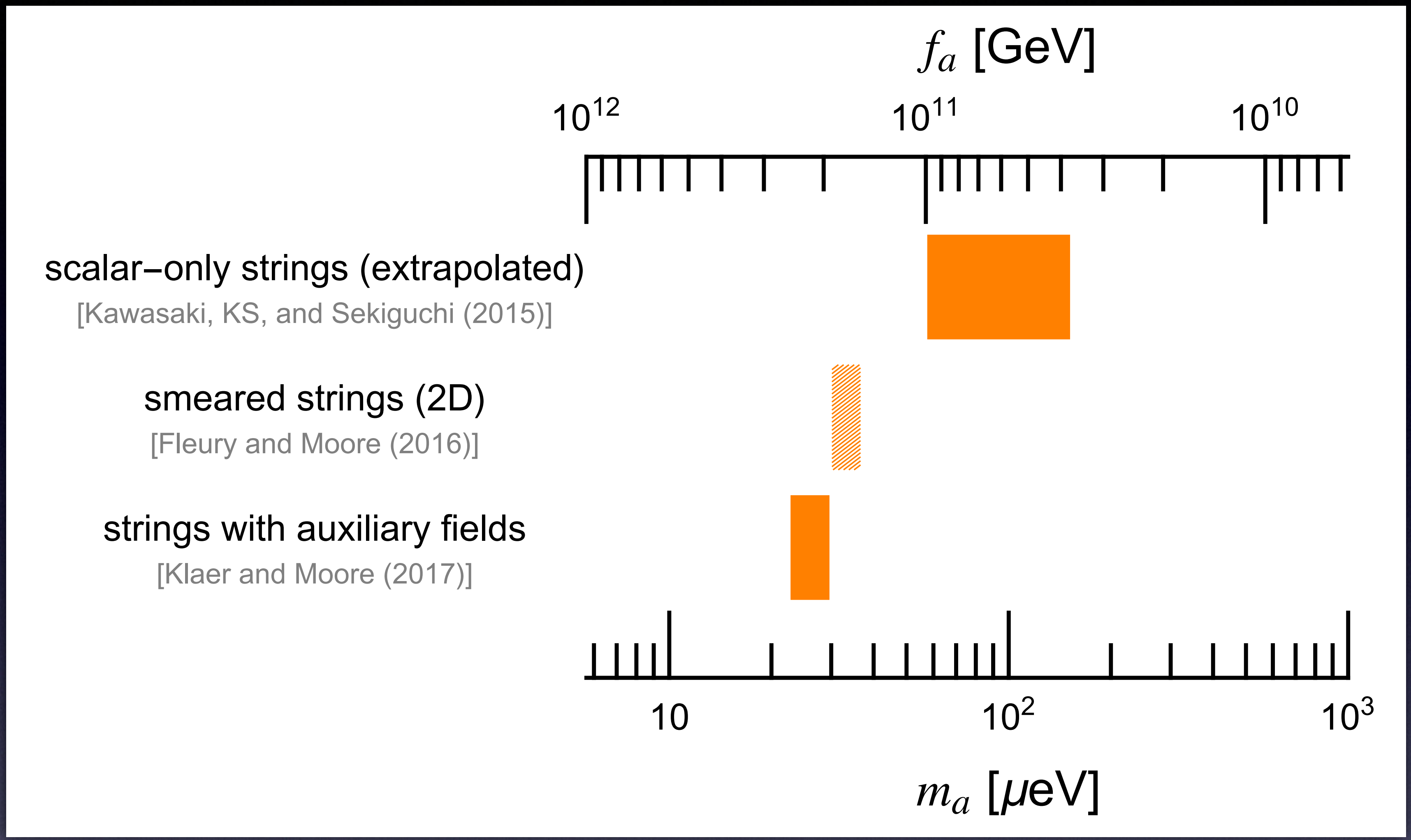
- Prediction for axion DM mass:

$$F_a = (2.21 \pm 0.29) \times 10^{11}\,\text{GeV}$$
$$m_a = (2.62 \pm 0.34) \times 10^{-5}\,\text{eV}$$





Axion mass predictions



- Smaller masses are preferred in modified simulations.
- Smaller mass means smaller axion production efficiency, although strings become denser.
- Large axion mean energy? Is physics at smaller scales relevant?

(cf. $n_a \sim \rho_{\rm string}/\langle E_a \rangle$)

Summary

- Prediction for axion dark matter mass in the post-inflationary PQ symmetry breaking scenario is tied to the issue of global string dynamics.
- Potentially large uncertainty from corrections due to the effect of high string tension.
- More detailed study is warranted to identify causes of the discrepancy in axion mass prediction.