Gauged Global Strings

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Outline

- Introduction
  global strings and gauge strings

- Gauge $U(1)_Z \times$ global $U(1)_{PQ}$
  and string solutions

- Cosmological implication
  1) rich string structure / dynamics
  2) opening up QCD axion window
  3) gauge string radiating axions?

- Conclusion

Global strings

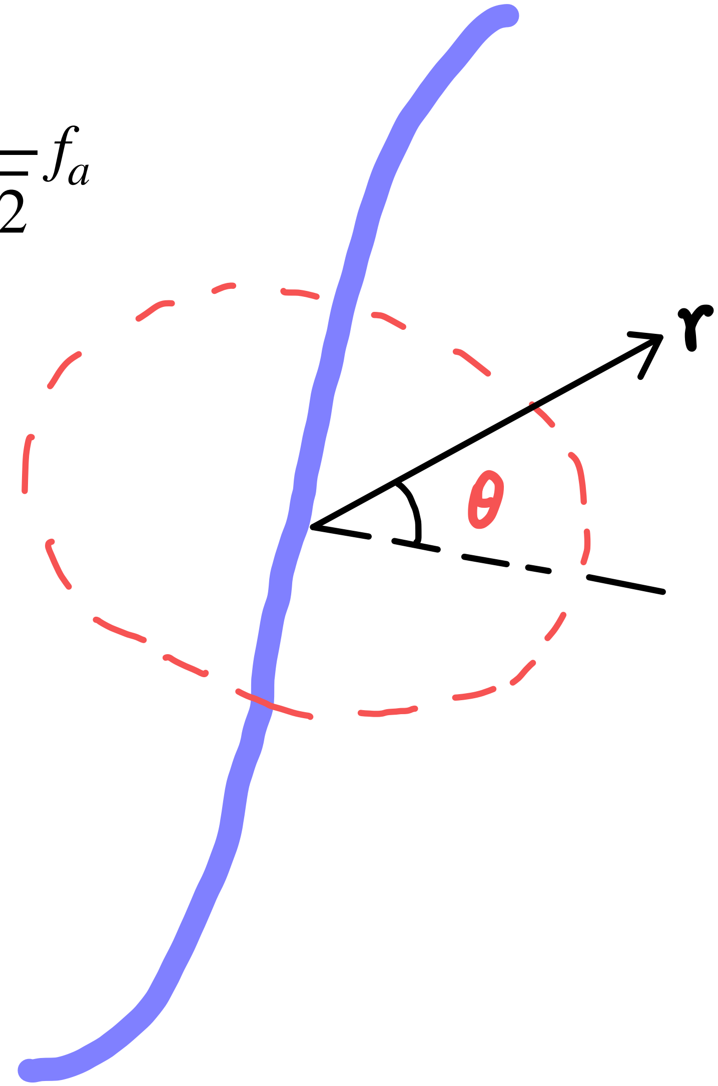
- global U(1) symmetry breaking $\langle \Phi \rangle = \frac{1}{\sqrt{2}} f_a$

- global string solution

$$\Phi(r,\theta) = \frac{1}{\sqrt{2}} f_a e^{i\theta}, \quad r \to \infty$$

- tension

$$\text{gradient term} \;\; \mu \simeq 2\pi \int_{m^{-1}}^{L} dr \frac{1}{r} \left| \partial_\theta \Phi(r,\theta) \right|^2 = \pi f_a^2 \ln(mL)$$

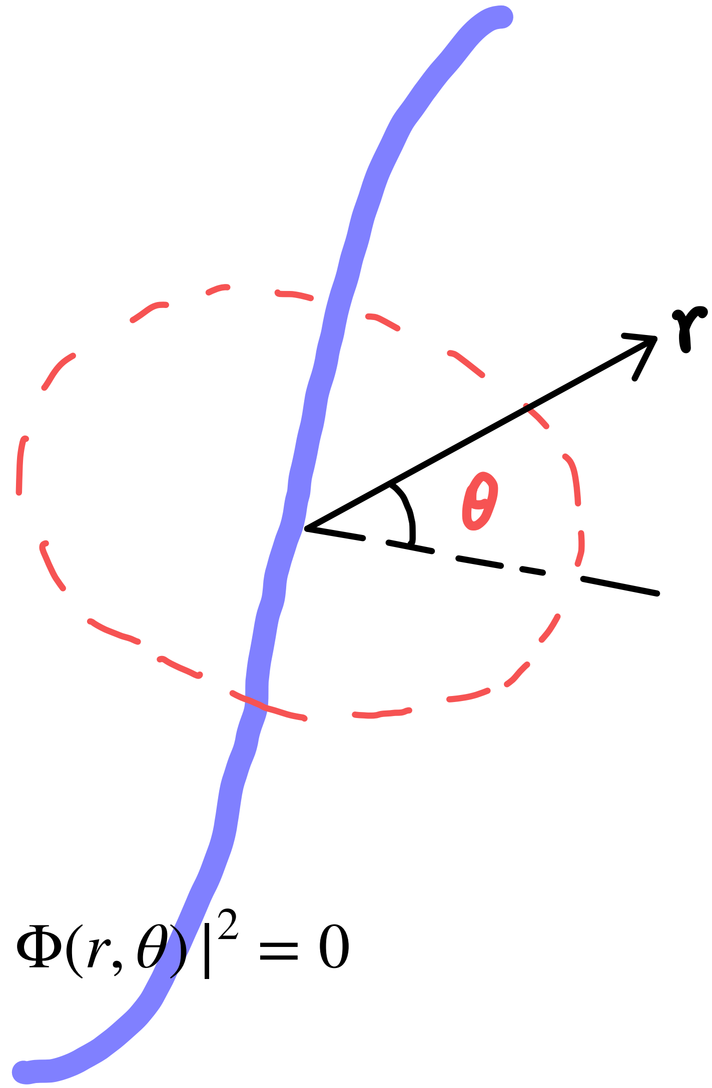


Gauge strings

- gauge string solution

$$\Phi(r,\theta) = \frac{1}{\sqrt{2}} f_a \mathrm{e}^{i\theta}$$

$$Z_\mu = \frac{1}{e}\partial_\mu \theta \qquad\qquad r \to \infty$$

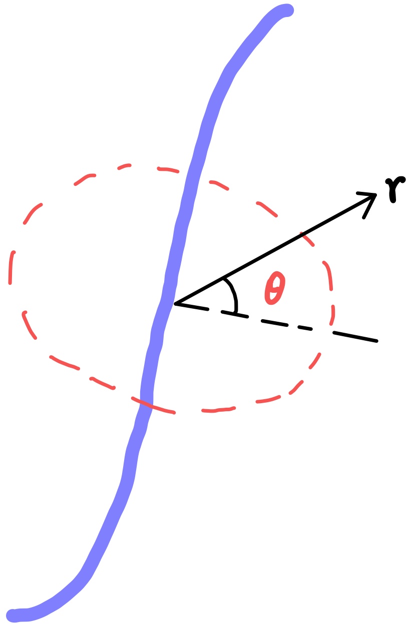


- tension

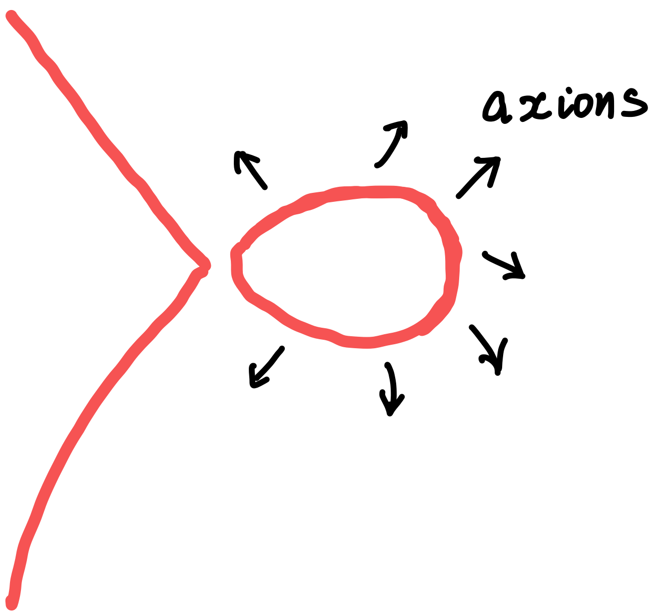
gradient term $\mu \simeq 2\pi \int_{m^{-1}}^{L} \mathrm{d}r \left| \left(\frac{1}{r}\partial_\theta - ieZ_\mu \right) \Phi(r,\theta) \right|^2 = 0$

core $\mu \simeq \mathcal{O}(1)\pi f_a^2$

Motivation of cosmic strings



- theoretically interesting
  classical field solutions



- phenomenological rich
  cosmology (Kibble mechanism)
  axion dark matter abundance
  new observables (CMB, …)

$\mathrm{U}(1)_{\mathrm{Z}} \times \mathrm{U}(1)_{\mathrm{PQ}}$

- Lagrangian

$$\mathscr{L} = -\frac{1}{4} Z_{\mu\nu} Z^{\mu\nu} + D_\mu \Phi_1^\dagger D^\mu \Phi_1 - \frac{\lambda_1}{4}\left(|\Phi_1|^2 - \frac{v_1^2}{2} \right)^2 + D_\mu \Phi_2^\dagger D^\mu \Phi_2 - \frac{\lambda_2}{4}\left(|\Phi_2|^2 - \frac{v_2^2}{2} \right)^2$$

$D_\mu = \partial_\mu - ieZ_\mu$

assume that $v_1 > v_2$

- $\Phi_1 \to \Phi_1 e^{i\alpha_{\mathrm{Z}} + i\alpha_{\mathrm{PQ}}}$

  $\Phi_2 \to \Phi_2 e^{i\alpha_{\mathrm{Z}} - i\alpha_{\mathrm{PQ}}}$

	Φ_1	Φ_2
$\mathrm{U}(1)_{\mathrm{Z}}$	1	1
$\mathrm{U}(1)_{\mathrm{PQ}}$	1	-1

Vacuum and fluctuations

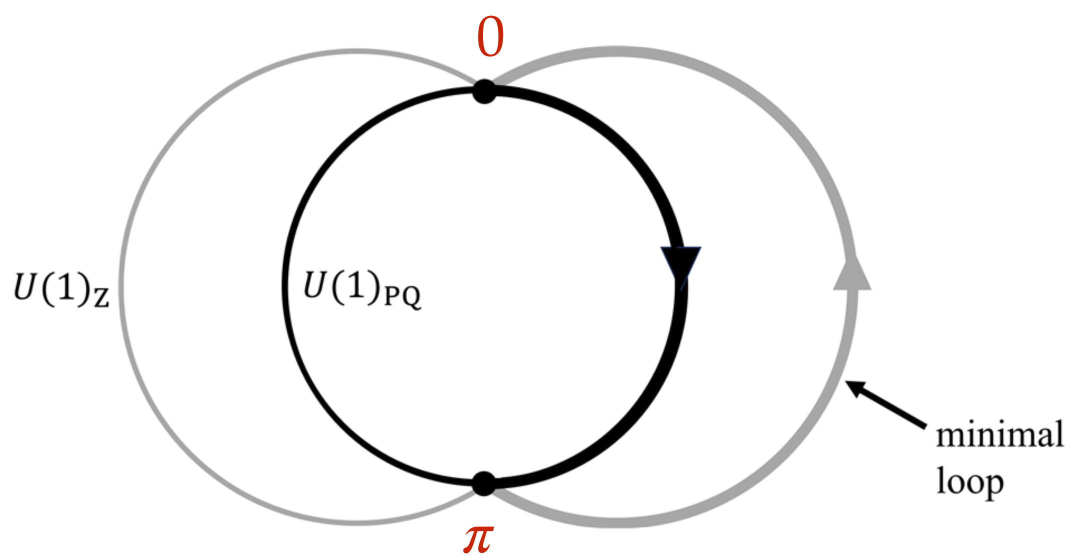
- cross section of vacuum manifold

$\alpha_Z = \pi$

$$\Phi_1 \to \Phi_1 e^{i\pi}, \Phi_2 \to \Phi_2 e^{i\pi} = \Phi_2 e^{-i\pi}$$

$\sim \alpha_{PQ} = \pi$

$$\Phi_1 \to \Phi_1 e^{i\pi}, \Phi_2 \to \Phi_2 e^{-i\pi}$$



- axion direction is orthogonal to the longitudinal mode of Z^μ

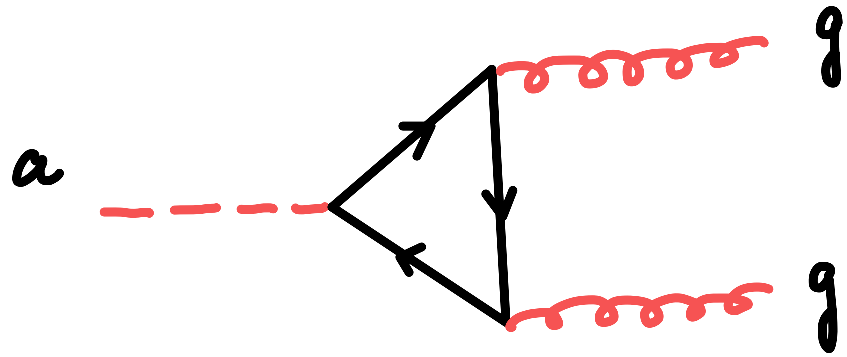
$$a(x) = v_a \alpha_{PQ}, \quad v_a = \frac{2v_1 v_2}{\sqrt{v_1^2 + v_2^2}} \sim 2v_2$$

Integrating with QCD axion model

- KSVZ-like model
  introduce Q_L and Q_R with color charge and $\mathrm{U}(1)_{\mathrm{PQ}}$ charge

$$\mathscr{L} = -\frac{y}{\Lambda}\left(\Phi_1\Phi_2^*\bar{Q}_L Q_R + h.c.\right)$$

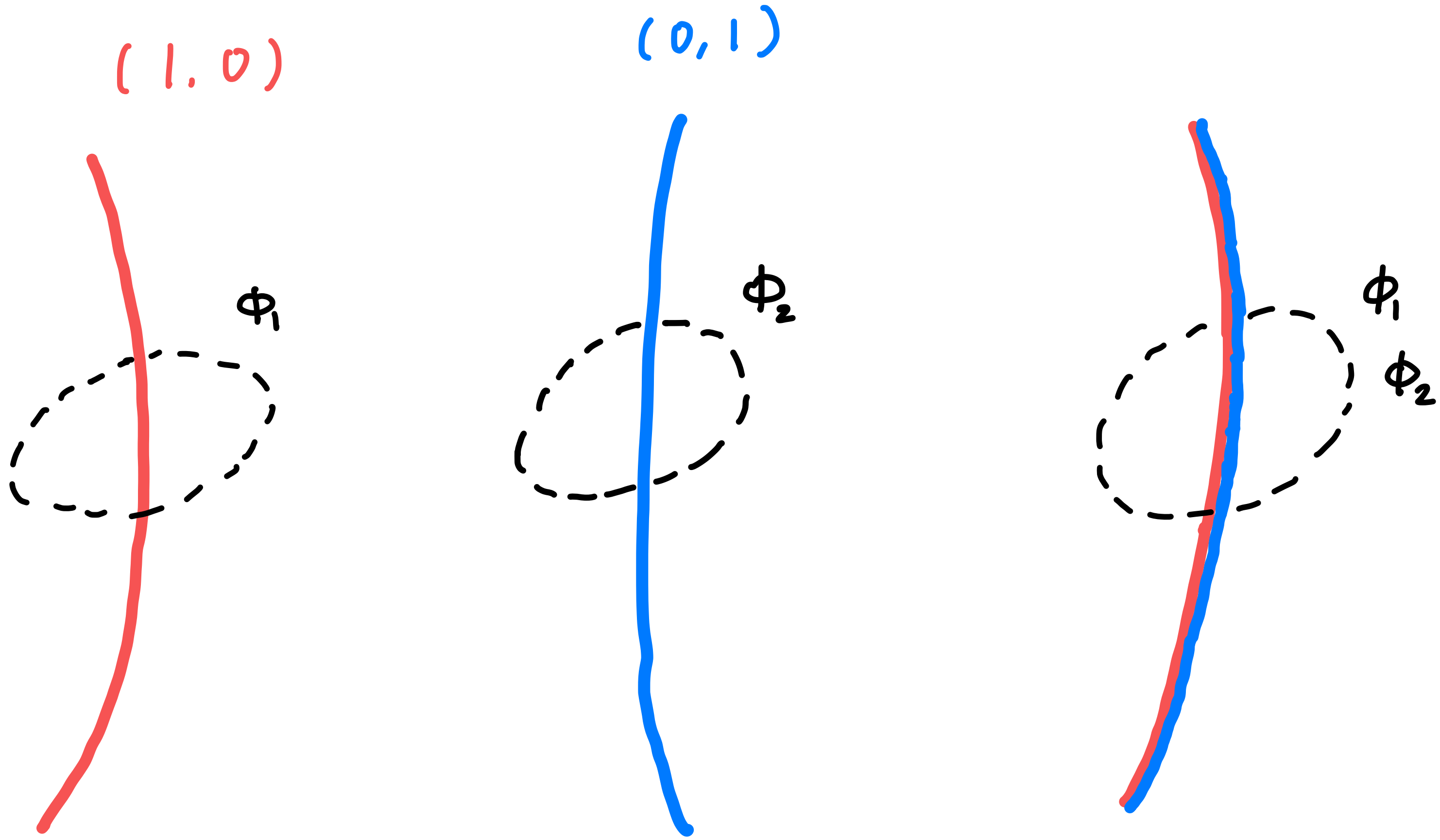
$$\mathscr{L} \supset \frac{g_s^2}{32\pi^2}\frac{a}{f_a}G^a_{\mu\nu}\tilde{G}^a_{\mu\nu}$$



- Barr and Seckel's model
  $Q_{1L}\ Q_{1R}\ Q_{2L}\ Q_{2R}$
  color, $\mathrm{U}(1)_{\mathrm{Z}}$ and $\mathrm{U}(1)_{\mathrm{PQ}}$ charges

$$\mathscr{L} = \Phi_1\bar{Q}_{1L}Q_{1R} + \Phi_2\bar{Q}_{2L}Q_{2R} + h.c.$$

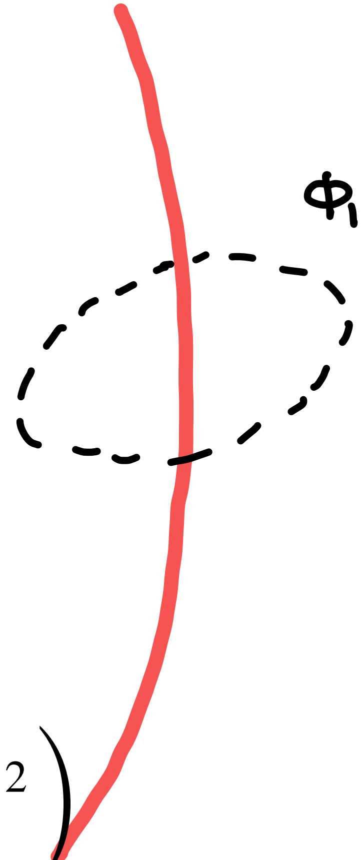
String Solutions



(1,0) strings

- (1,0) string

$$\Phi_1 = \frac{1}{\sqrt{2}} v_1 e^{i\theta}, \quad \Phi_2 = \frac{1}{\sqrt{2}} v_2, \quad Z_\mu = c\,\partial_\mu \theta, \quad r \to \infty$$



- gradient energy

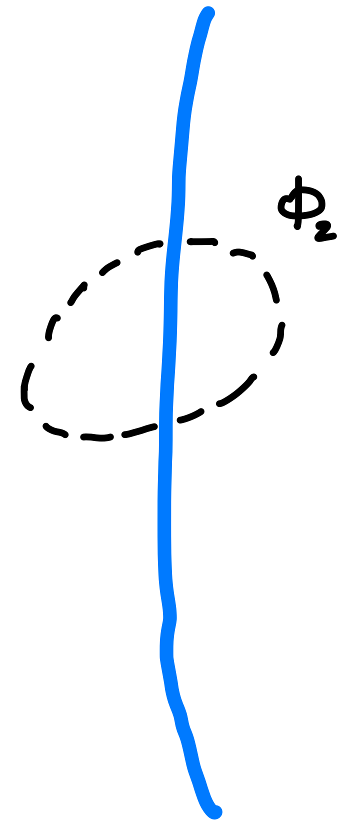
$$\mu_{k,(1,0)} = \int_0^{2\pi} \mathrm{d}\theta \int_\delta^L \mathrm{d}r\, r \left(|(\frac{1}{r}\partial_\theta - ieZ_\theta)\Phi_1|^2 + |(-ieZ_\theta)\Phi_2|^2 \right)$$

$$= \pi \ln(\frac{L}{\delta}) \left[v_1^2(1 - ec)^2 + v_2^2(ec)^2 \right]$$

- outside core (minimize it by varying c)

$$\mu_{k,(1,0)} = \pi \frac{v_1^2 v_2^2}{v_1^2 + v_2^2} \ln(\frac{L}{\delta}) = \pi f_a^2 \ln(\frac{L}{\delta})$$

(0,1) strings



- (0,1) string

$$\Phi_1 = \frac{1}{\sqrt{2}} v_1 \,, \quad \Phi_2 = \frac{1}{\sqrt{2}} v_2 \, e^{i\theta}, \quad Z_\mu = c \, \partial_\mu \theta \,, \quad r \to \infty$$

- gradient energy of (0,1) = gradient energy of (1,0)

$$\mu_{k,(0,1)} = \mu_{k,(1,0)}$$

- outside core region

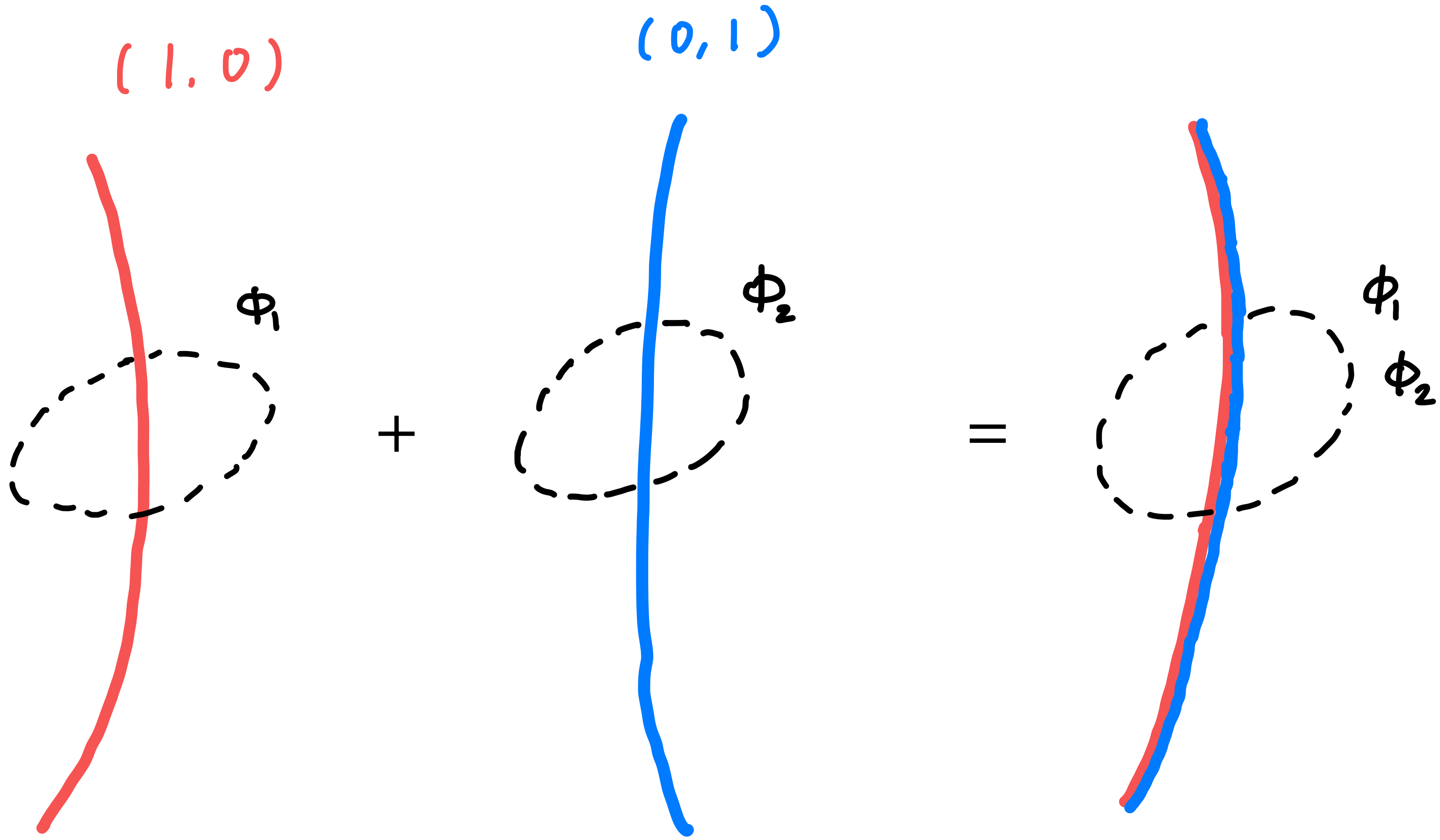
  (1,0) string is equivalent to (0,-1) string through a gauge transformation

$$\left(\Phi_1 = \frac{1}{\sqrt{2}} v_1 \, e^{i\theta}, \Phi_2 = \frac{1}{\sqrt{2}} v_2\right) \xrightarrow{\alpha_Z \to \alpha_Z - \theta} \left(\Phi_1 = \frac{1}{\sqrt{2}} v_1 \,, \Phi_2 = \frac{1}{\sqrt{2}} v_2 e^{-i\theta}\right)$$

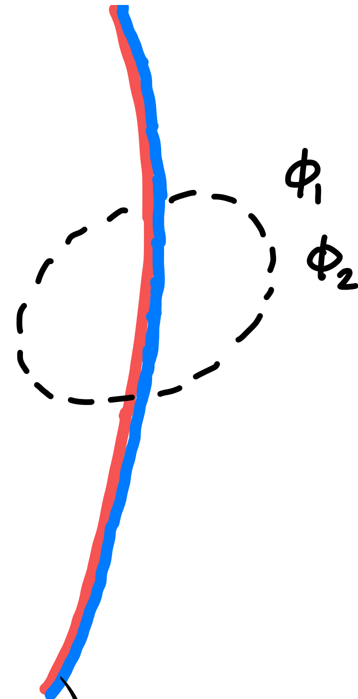
- outside core region

  (1,0) can be viewed as an anti-string of (0,1)

$(1,0) + (0,1) \to ?$



(1,1) strings



- gradient energy of (1,1) string

$$\Phi_1 = \frac{1}{\sqrt{2}} v_1 \, e^{i\theta}, \quad \Phi_2 = \frac{1}{\sqrt{2}} v_2 e^{i\theta}, \quad Z_\mu = c\,\partial_\mu \theta, \quad r \to \infty$$

$$\mu_{k,(1,1)} = \int_0^{2\pi} \mathrm{d}\theta \int_\delta^L \mathrm{d}r\, r \left(|(\frac{1}{r}\partial_\theta - ieZ_\theta)\Phi_1|^2 + |(\frac{1}{r}\partial_\theta - ieZ_\theta)\Phi_2|^2 \right)$$

- the profile of Z_θ can simultaneously cancel the gradient energy of Φ_1 and Φ_2

$$\mu_{k,(1,1)} = 0$$

- (1,1) gauge string

  (1,0) and (0,1) global strings

The full tension

- magnetic self-energy, scalar potential energy, and gradient energy

- (1,0) string

$$\mu_{(1,0)} \simeq \pi v_1^2 + \pi v_1^2 \ln\left(\frac{m_1}{m_Z}\right) + \pi v_2^2 \ln\left(\frac{m_Z L}{2}\right)$$

  (0,1) string

$$\mu_{(0,1)} \simeq \frac{\pi}{2} v_2^2 + \pi v_2^2 \ln\left(\frac{m_2}{m_Z}\right) + \pi v_2^2 \ln\left(\frac{m_Z L}{2}\right)$$

  (1,1) string

$$\mu_{(1,1)} = \pi v_1^2 + \pi v_1^2 \ln\left(\frac{m_1}{m_Z}\right) + 0$$

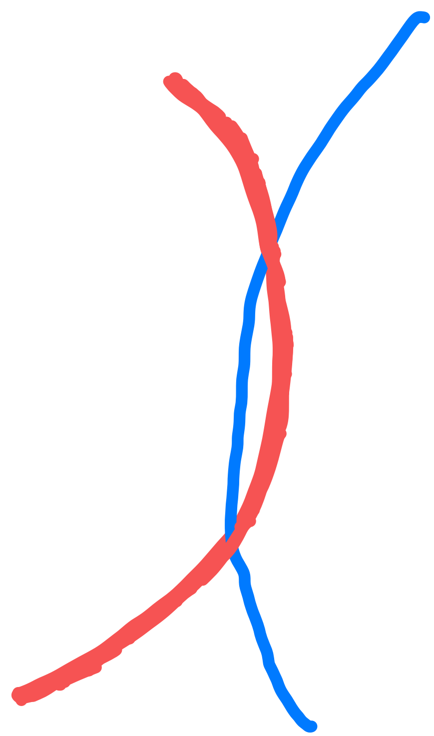
- heavy core of (1,0) string $\mu_{(1,0)} > \mu_{(0,1)}$

- binding energy of (1,1) string

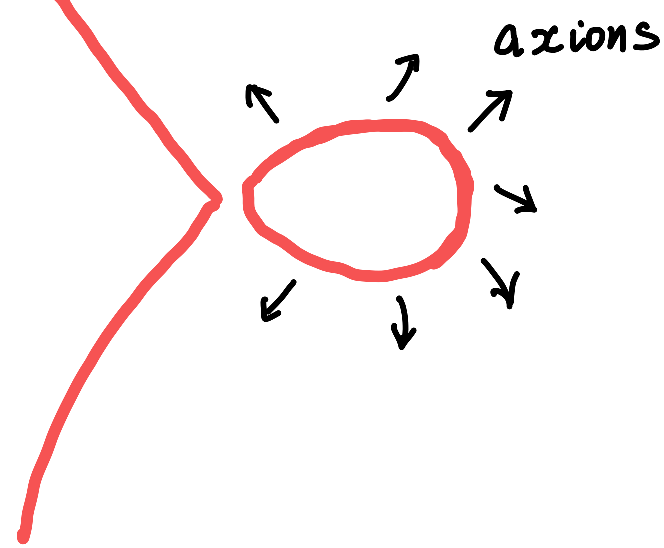
$$\mu_{(1,0)} + \mu_{(0,1)} - \mu_{(1,1)} = \pi v_2^2 \left[2 \ln\left(\frac{m_Z L}{2}\right) - 1 \right]$$

Cosmological Implication

formation



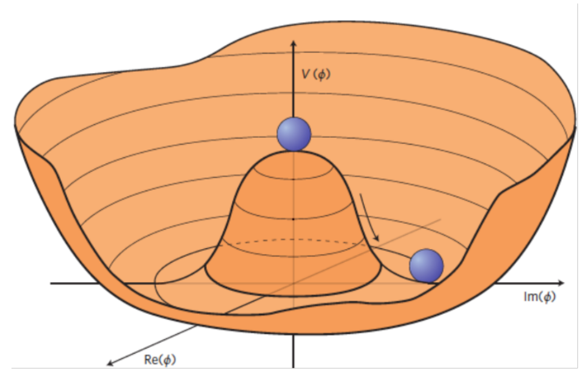
evolution



radiation

First phase transition and string formation

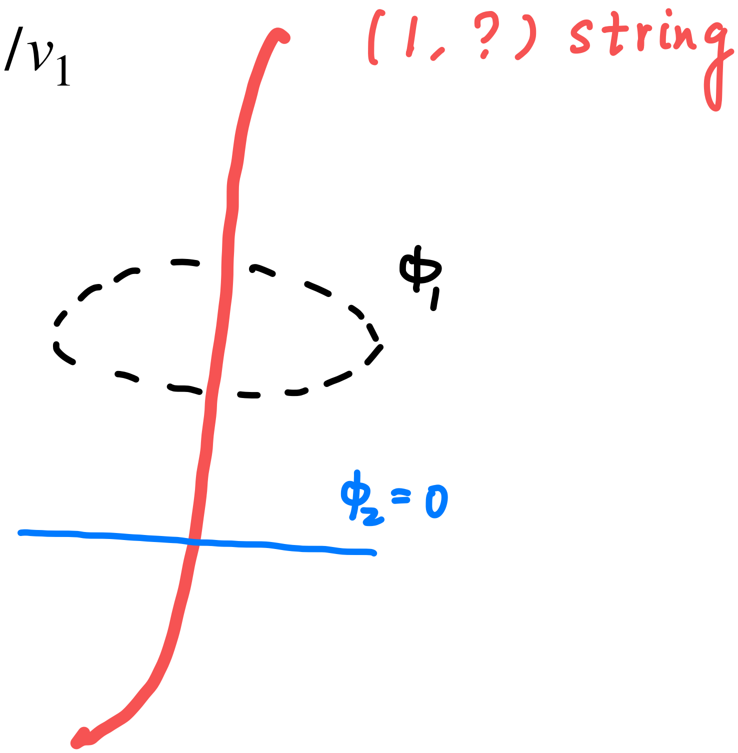
- consider $v_1 \gg v_2$



first phase transition

$$\langle \Phi_1(x) \rangle = \frac{v_1}{\sqrt{2}} \text{ and } \langle \Phi_2(x) \rangle = 0$$

- string formation, the correlation length ~ $1/v_1$



- U(1) gauge strings form
  (1, n) string

Second phase transition

- second phase transition

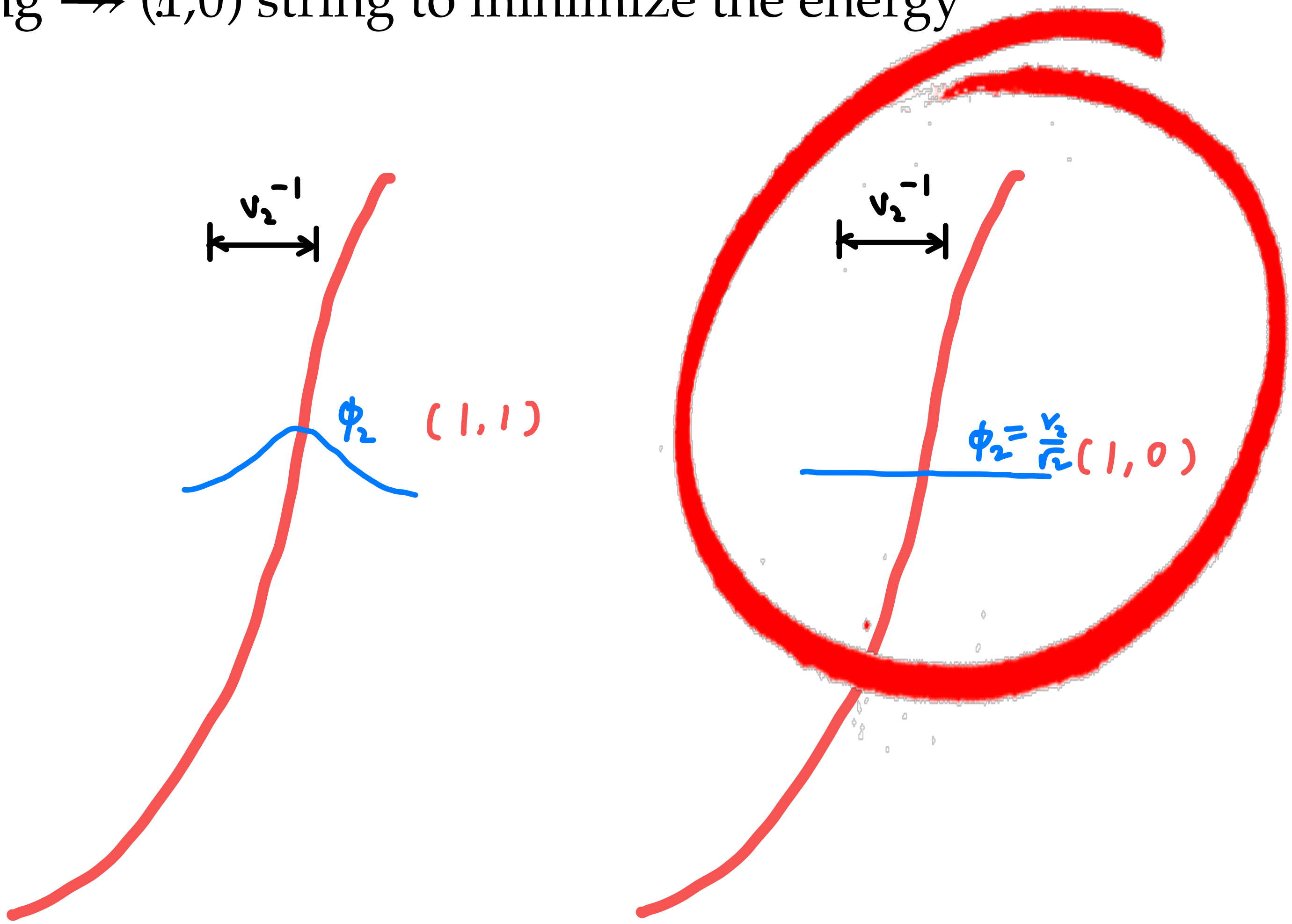
$$\langle \Phi_1(x) \rangle = \frac{v_1}{\sqrt{2}} \text{ and } \langle \Phi_2(x) \rangle = \frac{v_2}{\sqrt{2}}$$

- string formation, the correlation length ~ $1/v_2$

- (0,1) strings form via Kibble mechanism

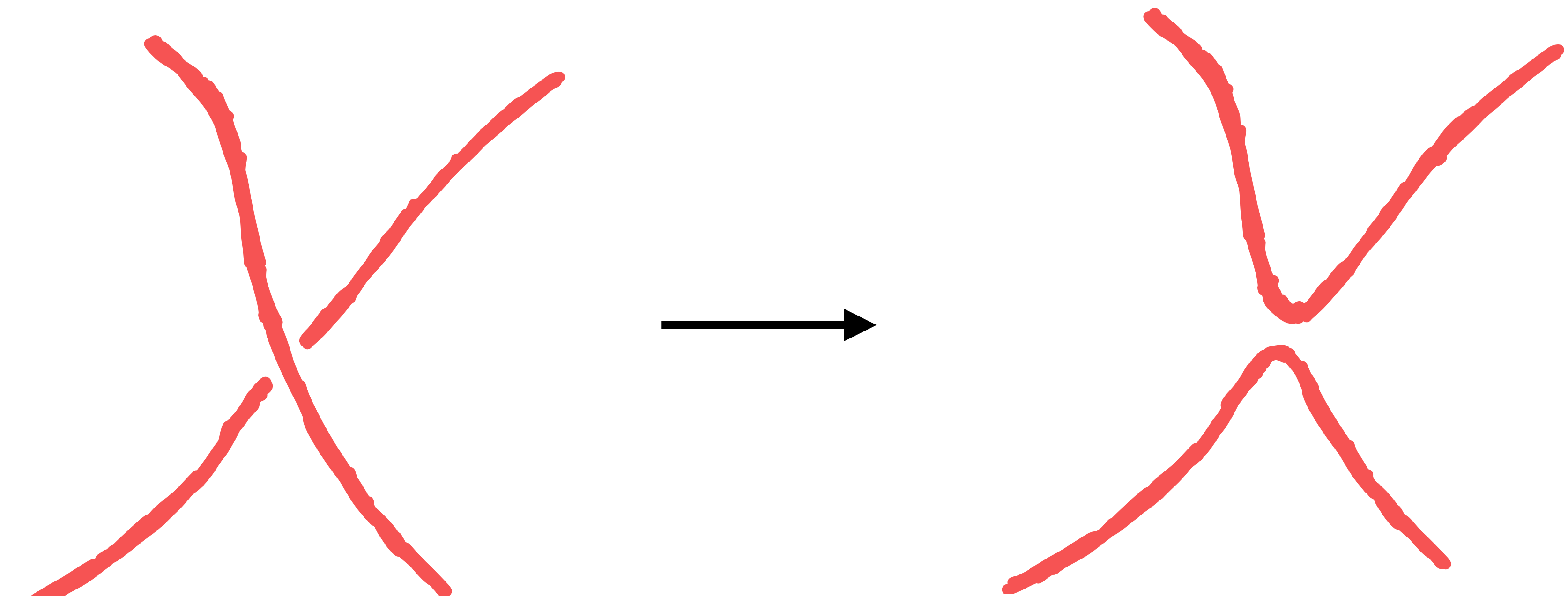
(1,n) string in the second phase transition

- (1, n) string ↠ (1,0) string to minimize the energy



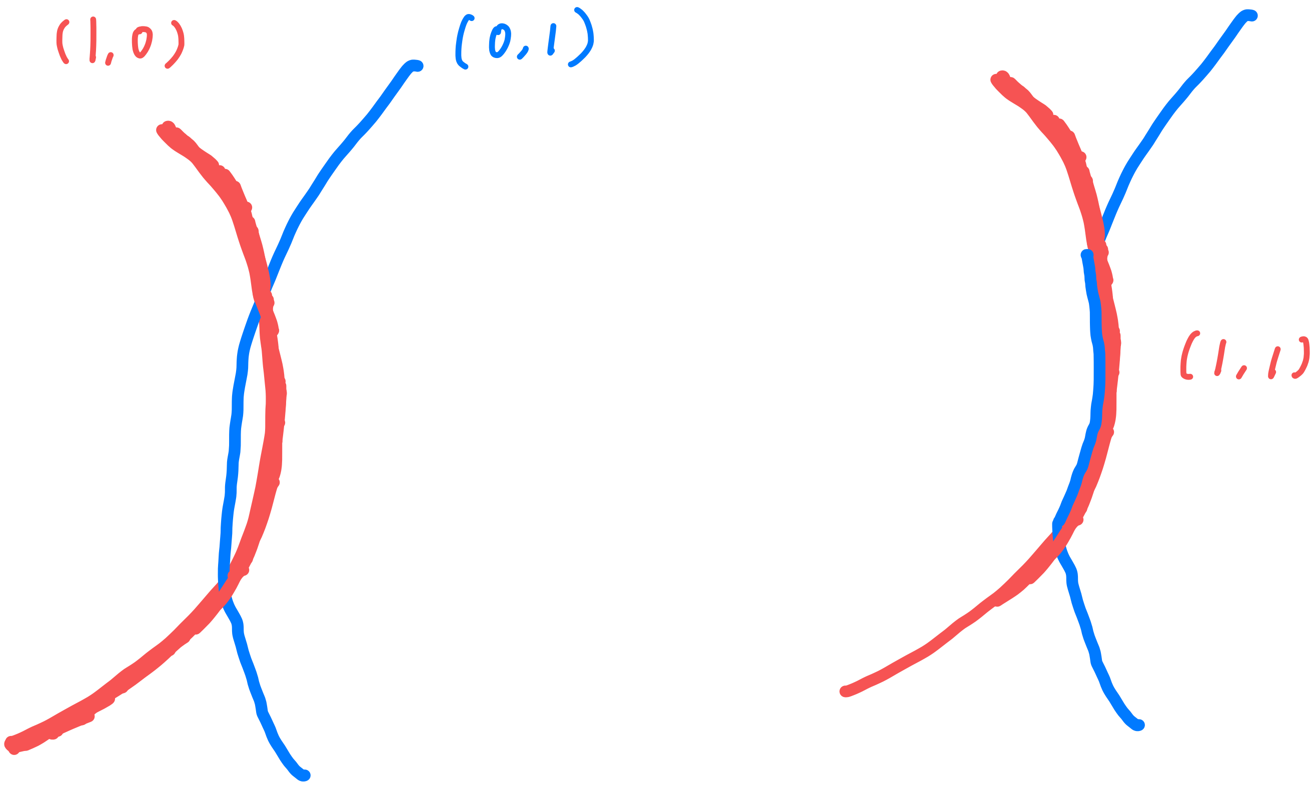
String network evolution

- (1,0) string encounters (1,0) string



String network evolution

- (1,0) string encounters (0,1) string → (1,1) bound state
  Y-junctions



- Other works on simulations of Y-junctions
  found 1) some fraction of Y-junctions remain
  2) scaling solution

Urrestilla, Vilenkin JHEP(2008)
Rajentie, Skellariodou, Stoica, JCAP (2007)
Copeland, Saffin JHEP (2005)
…

QCD axion

- dark matter abundance

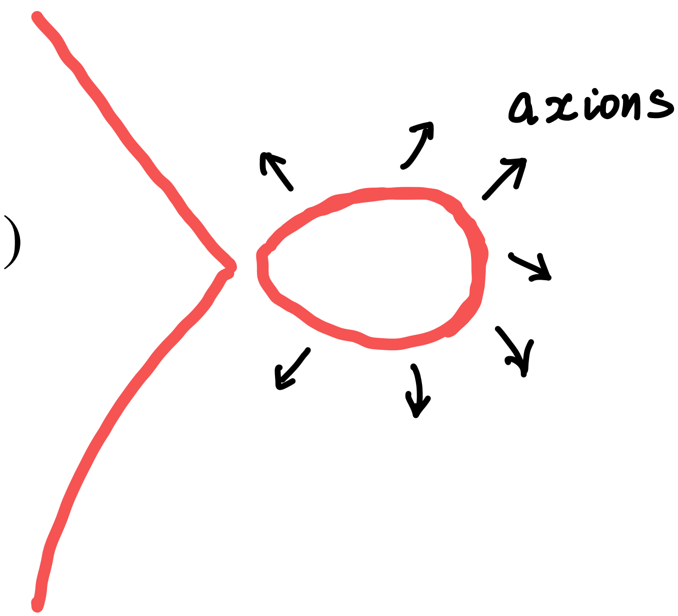
misalignment + string radiation + domain wall collapse

$$\rho_{a,0} = \rho_a^{\rm vac}(t_0) + m_a n_a^{\rm str}(t_0) + m_a n_a^{\rm DW}(t_0)$$

- uncertainty from string radiation

Scenario A : IR spectrum $\frac{dE}{d\omega} \propto \delta(\omega - 2\pi t^{-1})$

Scenario B: flat spectrum $\frac{dE}{d\omega} \propto \frac{1}{\omega}$



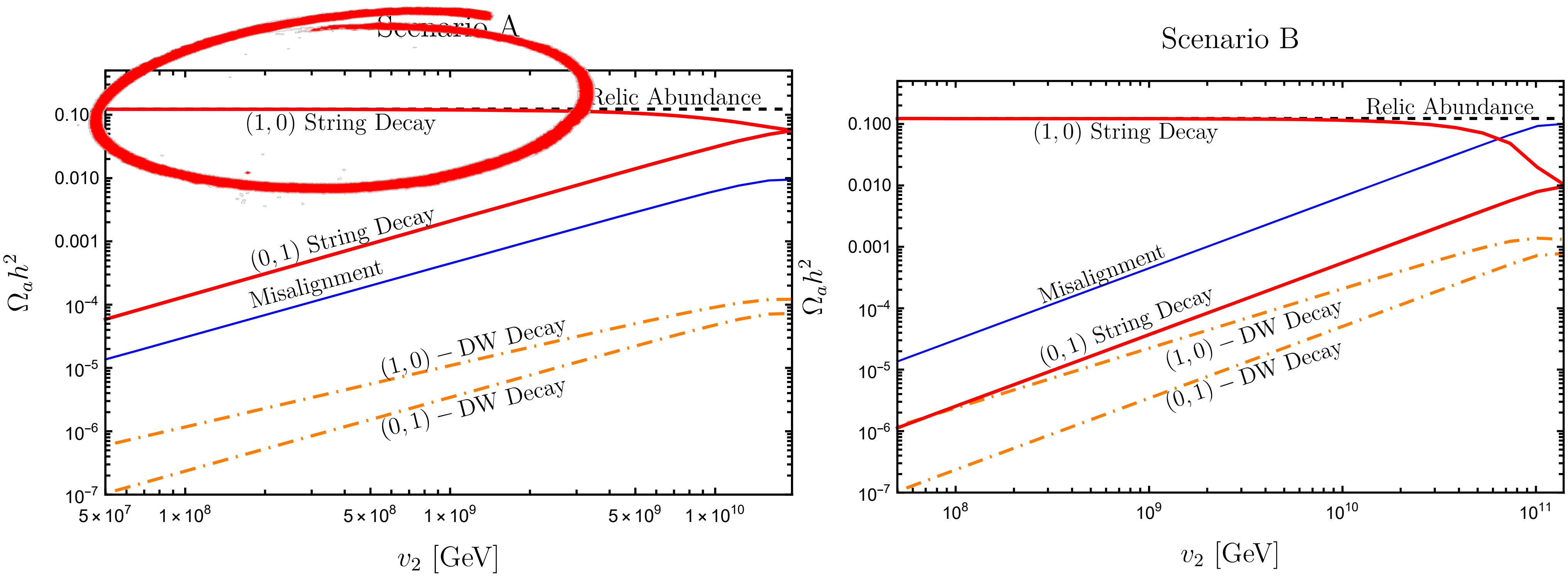
- $n_a^{\rm str} \propto \frac{1}{\langle \omega \rangle}$

Gauged global string

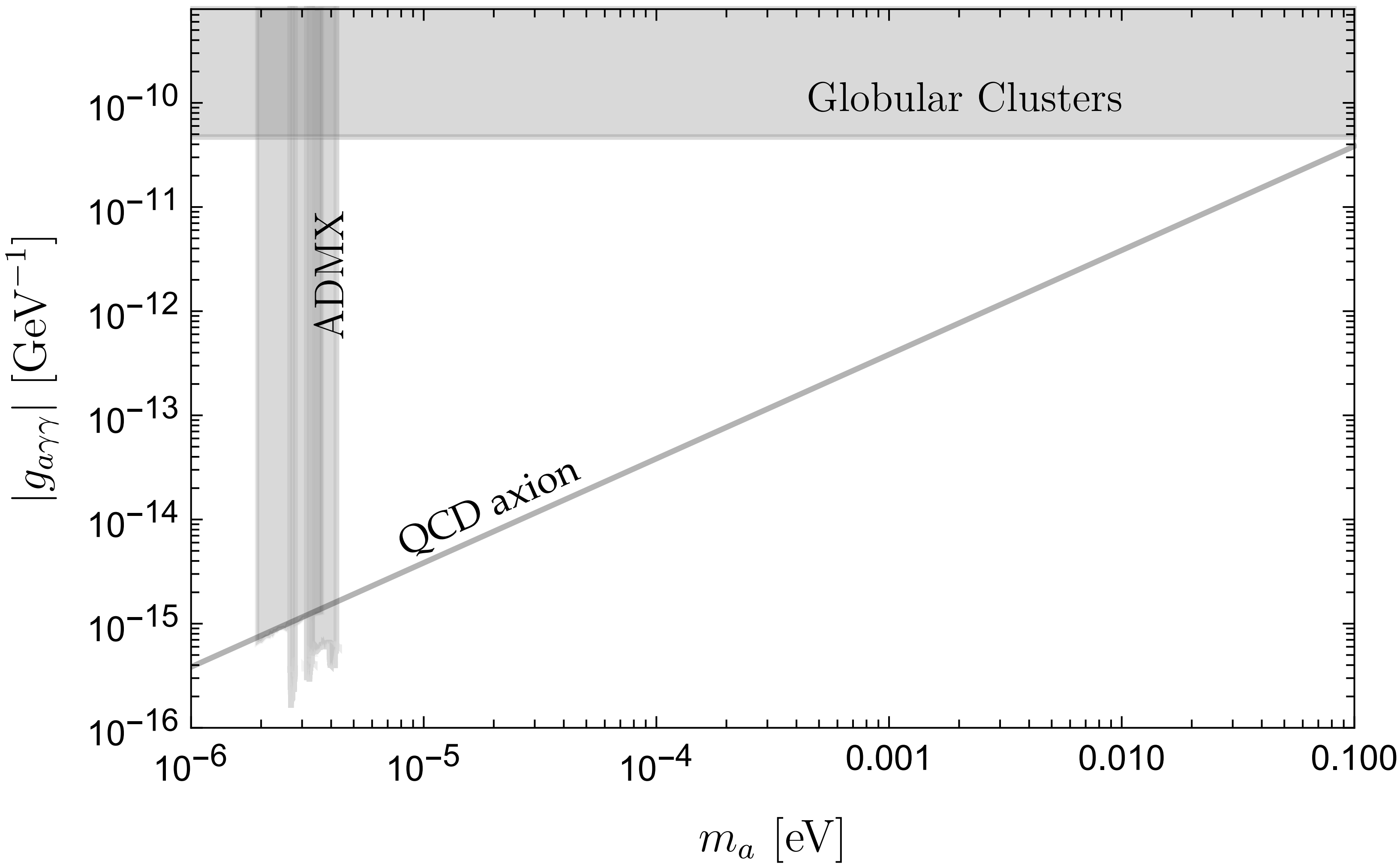
- (0,1) string tension is the same as a standard QCD axion string

- heavy core of (1,0) string

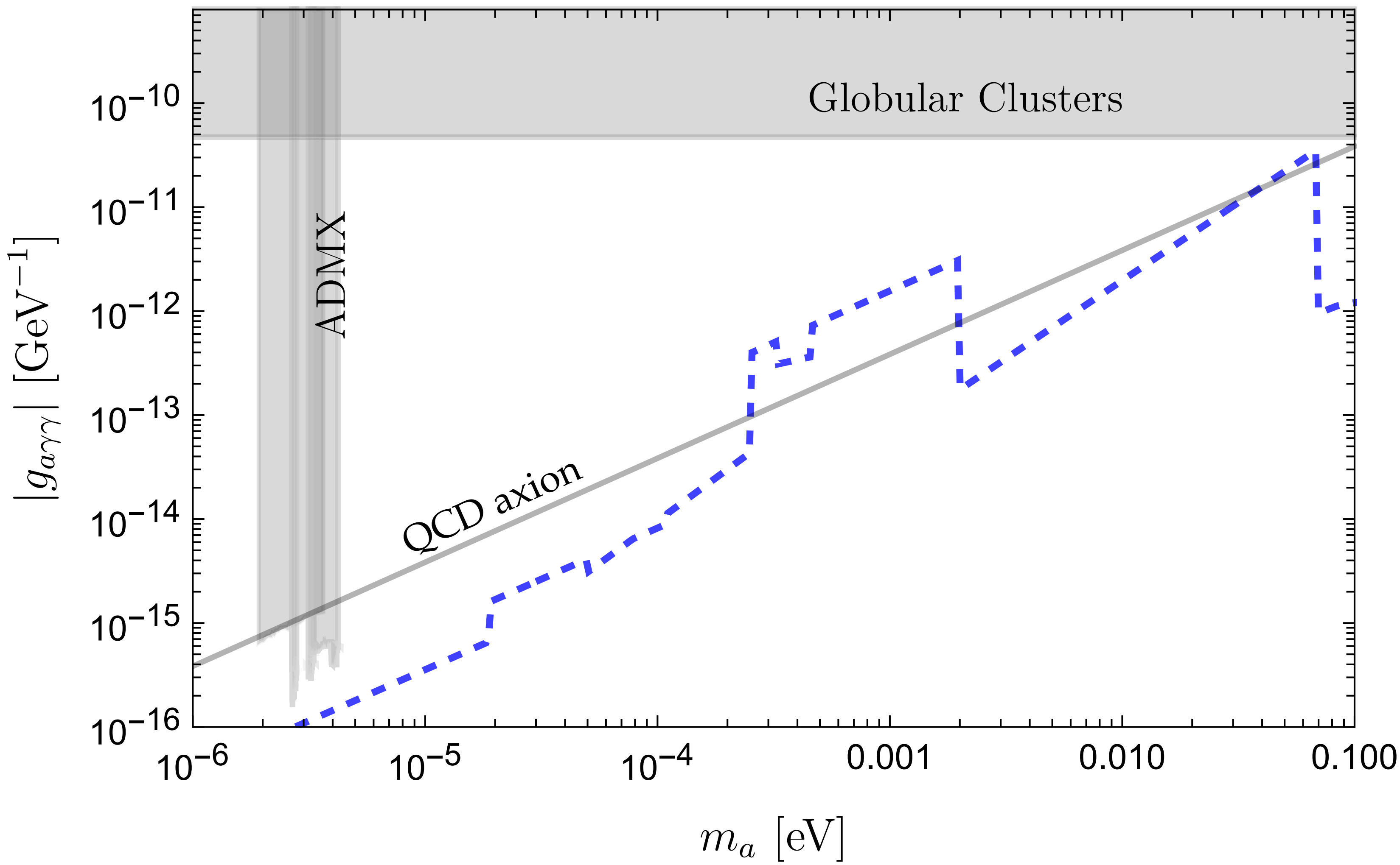
$$\mu_{(1,0)}(t) \simeq \pi v_1^2 \ln\left(\frac{m_1}{m_Z}\right) + \pi f_a^2 \ln\left(\frac{m_Z t}{2}\right)$$



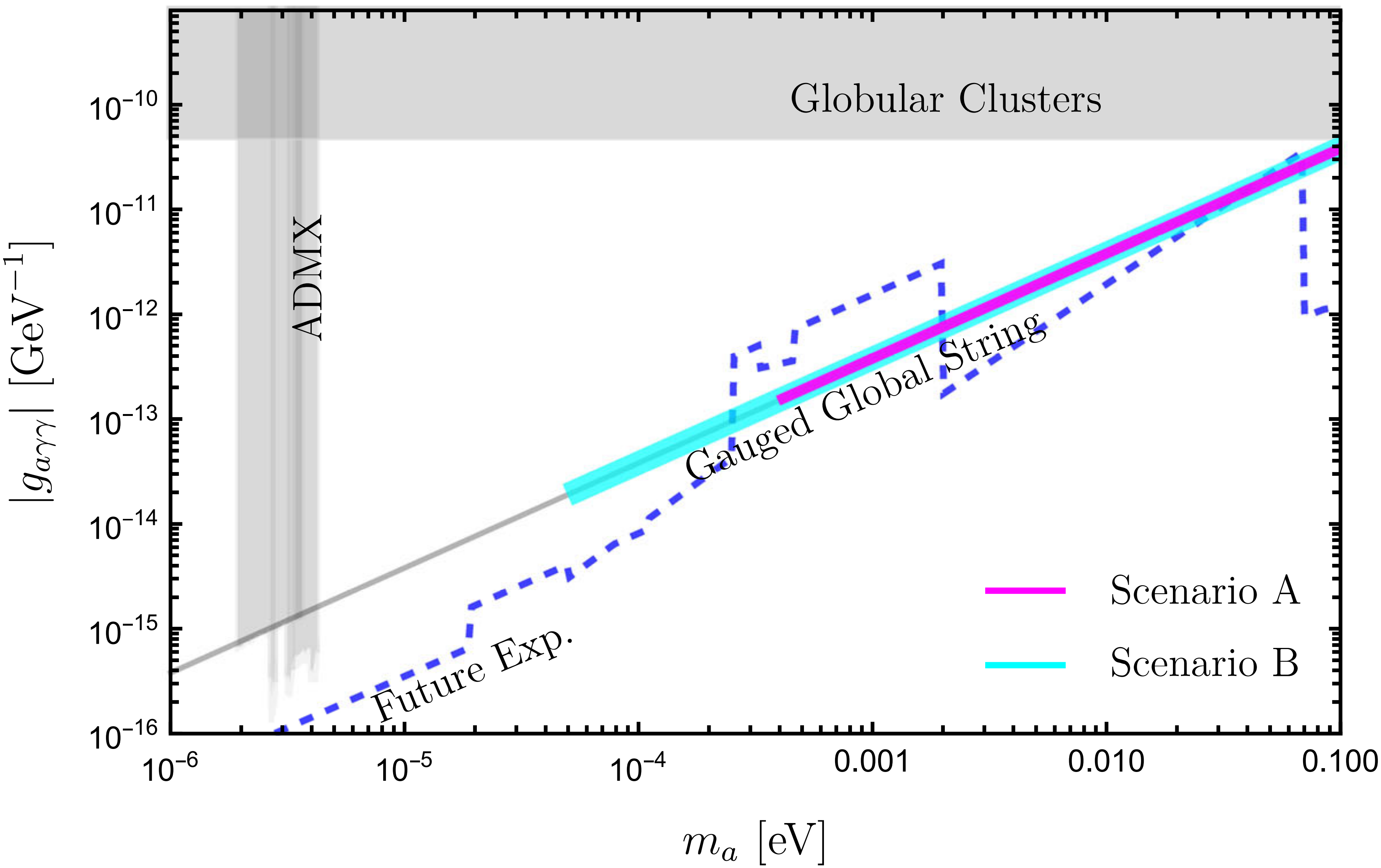
QCD axion window



Future explorations

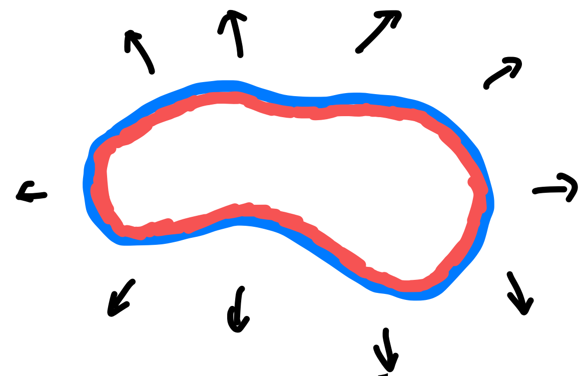


Gauged global string



Gauge string (1,1) radiation

- gauge strings radiate gravitons
- How about (1,1) gauge strings?



- (1,1) string is gauge string, but it also has axion as light d.o.f

$$\mathscr{L} = -\frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} + \frac{1}{2}e^2(\phi_1^2 + \phi_2^2)Z_\mu^2 - g(\phi_1, \phi_2)\, e\, Z^\mu \partial_\mu a + \frac{1}{2} f(\phi_1, \phi_2)\, (\partial_\mu a)^2$$

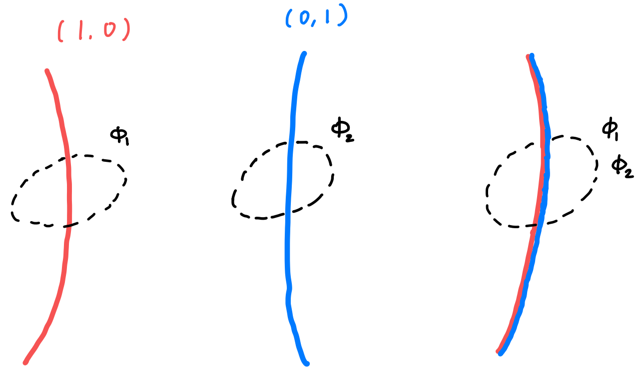
$$g(\phi_1, \phi_2) = f_a \frac{\phi_1^2}{v_1^2} - f_a \frac{\phi_2^2}{v_2^2}$$

- Kalb-Ramond field $B^{\mu\nu}$, $\partial_\mu a = \frac{1}{2}\epsilon_{\mu\nu\alpha\beta}\partial^\nu B^{\alpha\beta}$

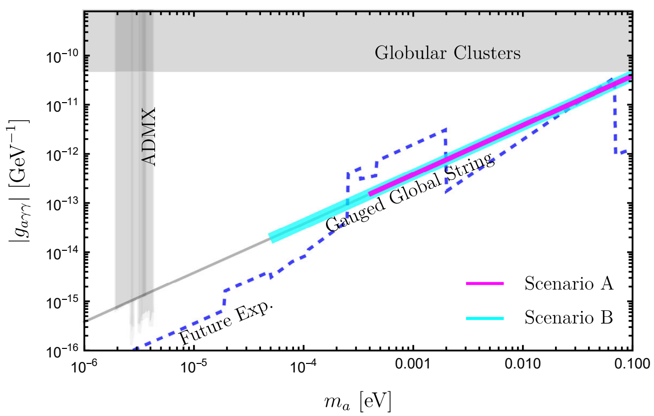
- radiation power

$$\frac{\mathrm{d}P_a}{\mathrm{d}\Omega} \sim e^2 f_a^2$$

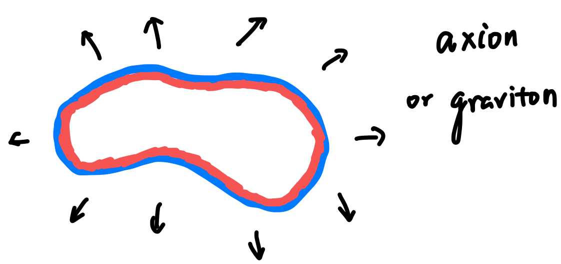
Conclusion



- $U(1)_Z \times U(1)_{PQ}$
  (1,0), (0,1) and (1,1) strings



- Cosmology
  Y-Junctions
  opening QCD axion mass windows



- (1,1) gauge string
  radiating axions and gravitons