Cosmic strings and dark matter in the axiverse

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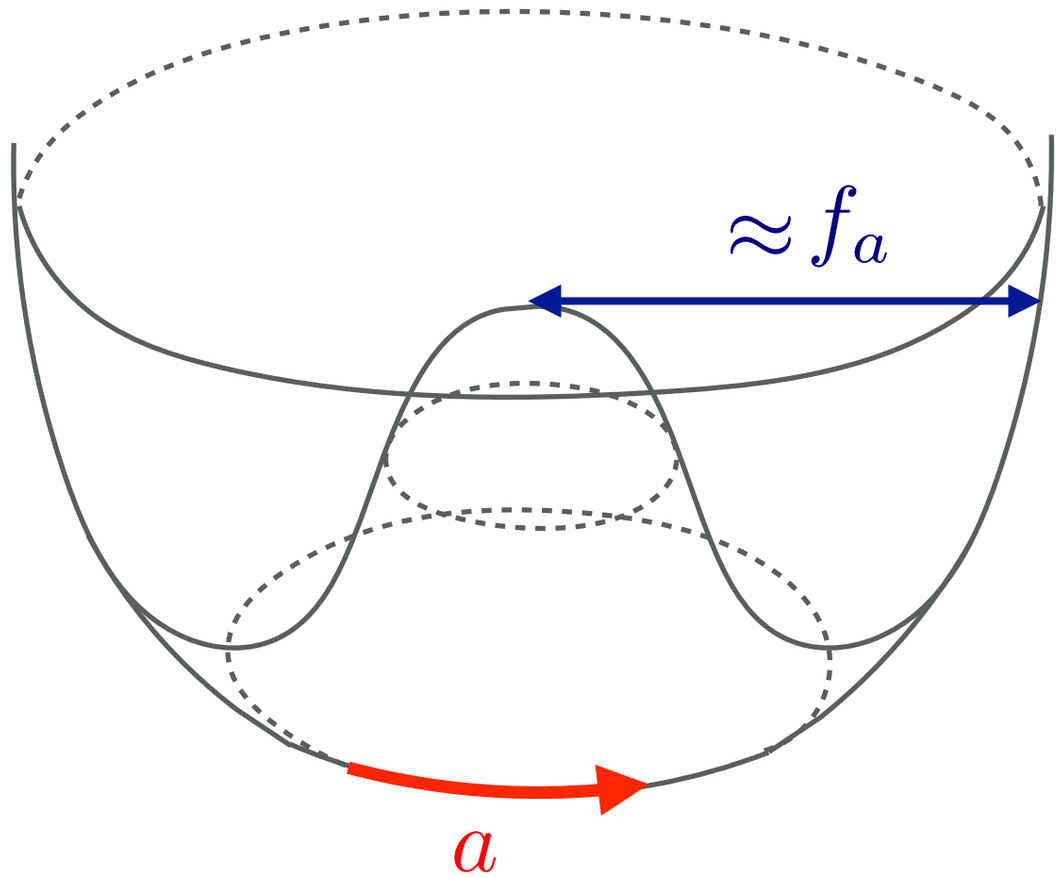
Based on 2312.08425 [hep-ph]
w/ J. Benabou, M. Buschmann, S. Kumar, B. Safdi

Axions and their cosmology

QCD axions and axion-like particles

ALPs : (pseudo-)Nambu-Goldstone bosons of a U(1) global symmetry



QCD axions and axion-like particles

ALPs : (pseudo-)Nambu-Goldstone bosons of a U(1) global symmetry

QCD axion : classically (almost) massless ALP, of a U(1) symmetry with a mixed anomaly with the QCD gauge group

$$\mathcal{L} \supset \frac{\mathcal{C}}{32\pi^2}\frac{a}{f_a}\epsilon^{\mu\nu\rho\sigma}G^a_{\mu\nu}G^a_{\rho\sigma}$$

At the vacuum : $\langle a \rangle = 0$ Solution to the **strong CP problem**

[Peccei/Quinn '77 x 2, Weinberg '78, Wilczek '78]

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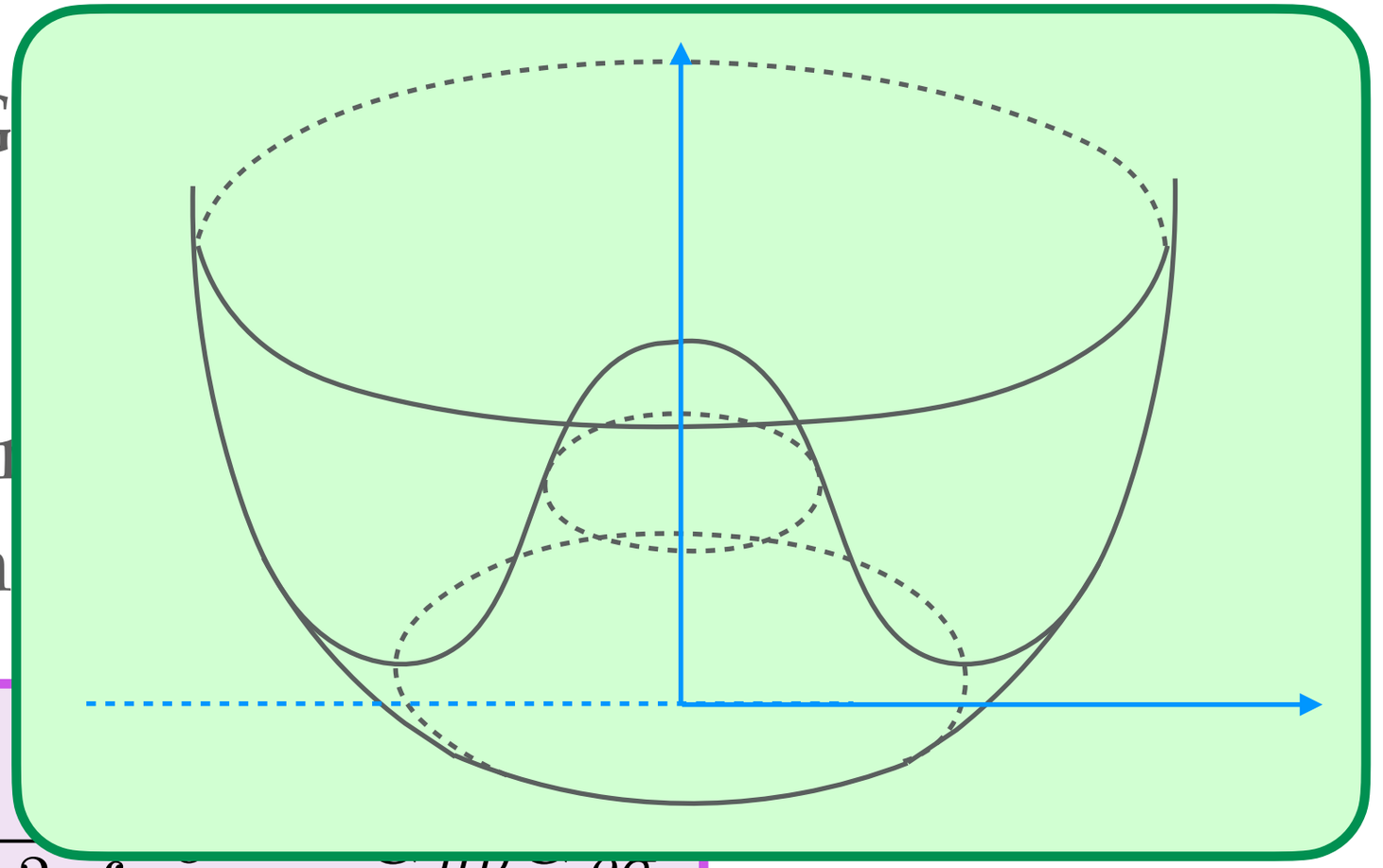

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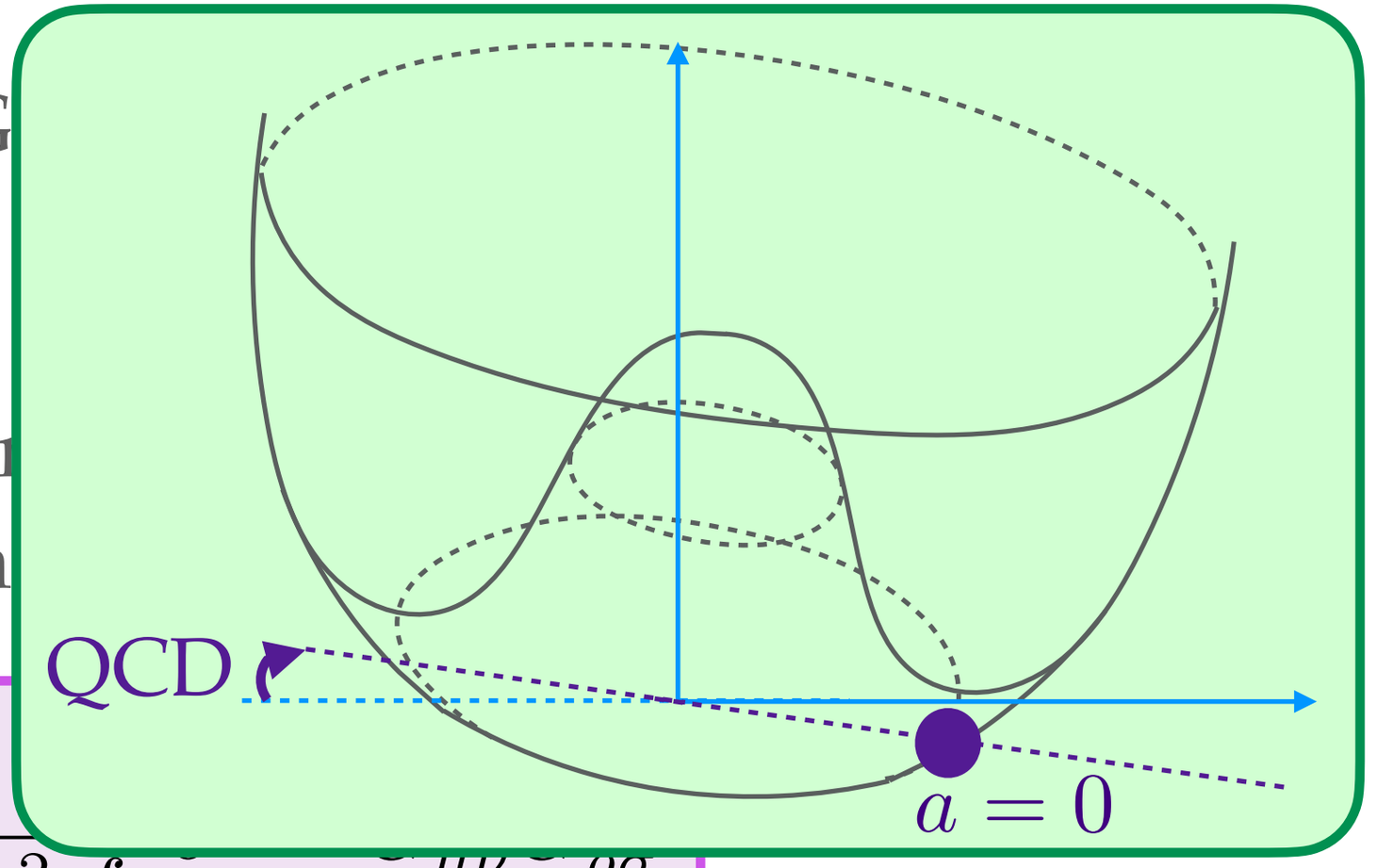

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At « low » energies : model-independent (EFT) approach

(QCD) axion cosmology

In cosmology : depends on the **hierarchy of scales**

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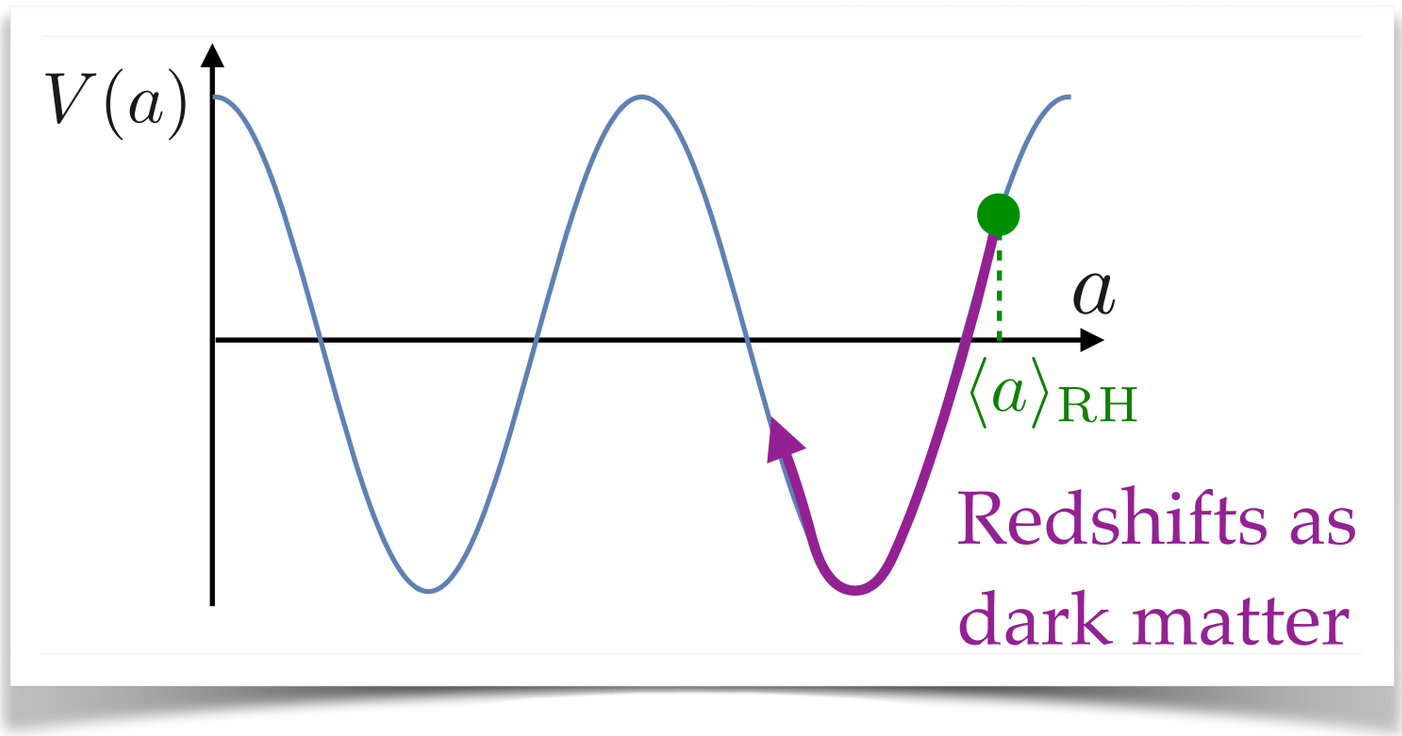
Pre-inflationary scenario : $H_{\rm inf} \lesssim f_a$ and $T_{\rm RH} \lesssim f_a$

PQ symmetry broken throughout the cosmic history ⟶ EFT approach again

Axion dark matter via the **misalignment mechanism**



[Preskill/Wise/ Wilczek, Abbott/Sikivie, Dine/Fischler ‘83]

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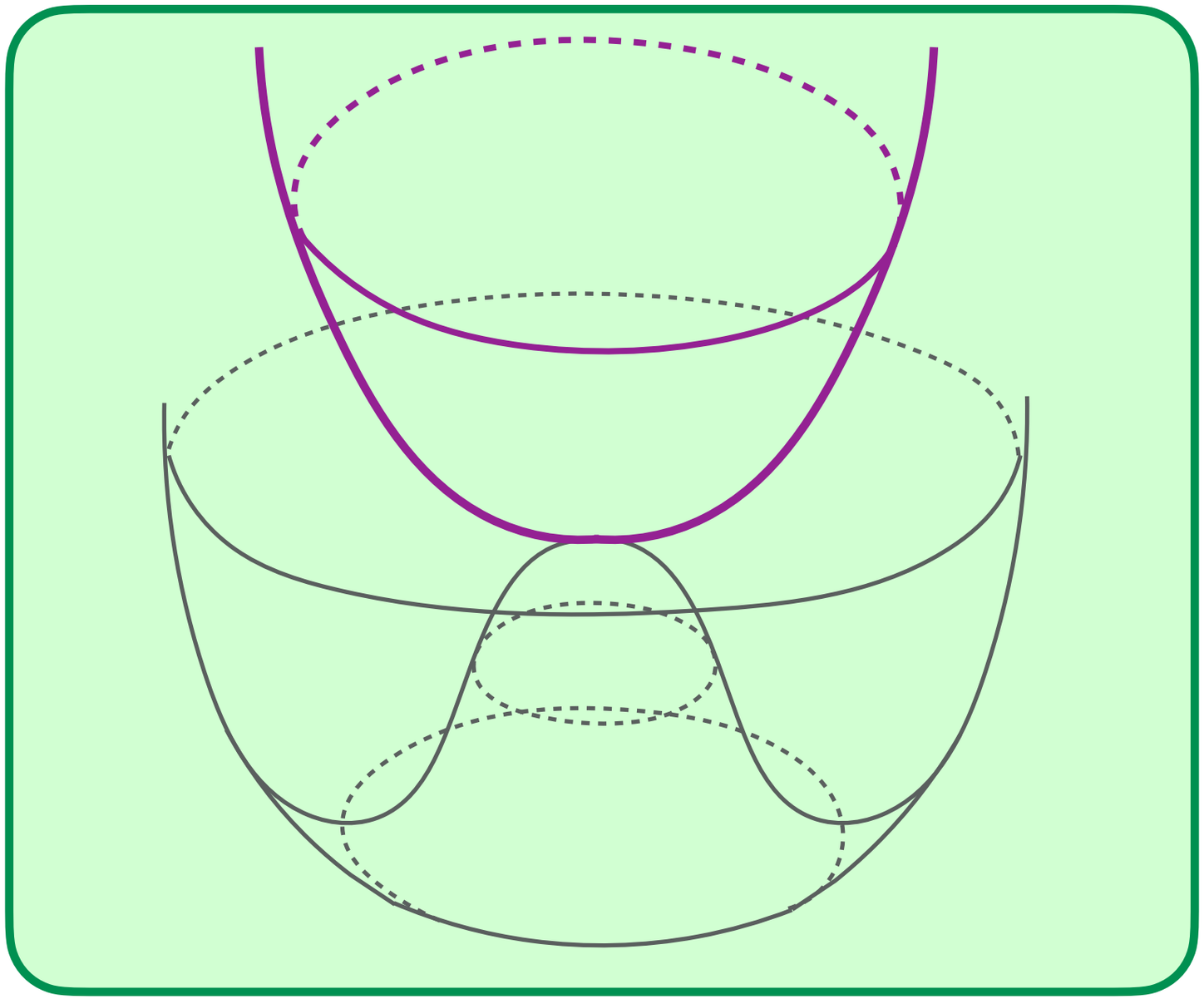
+ high T



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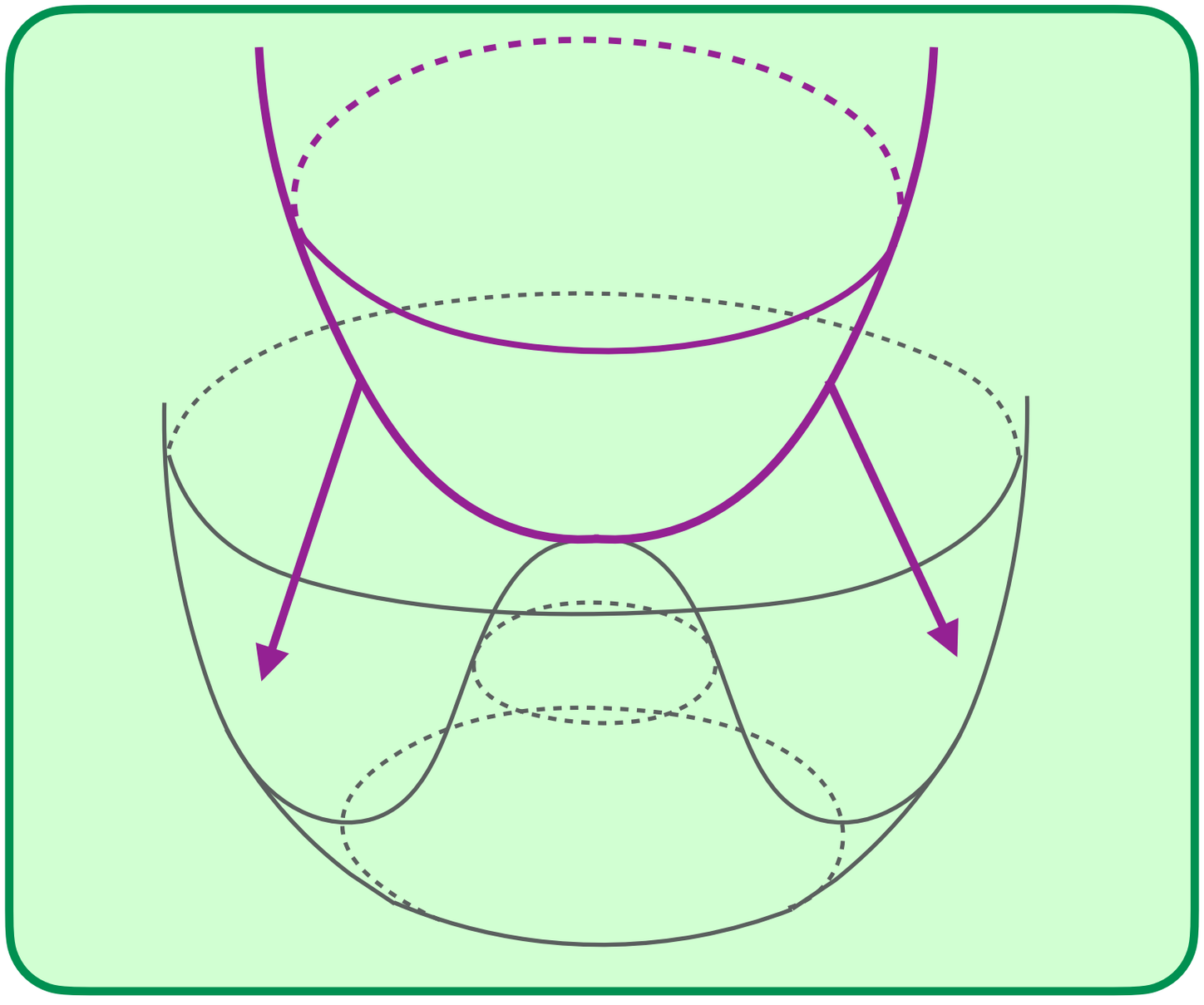

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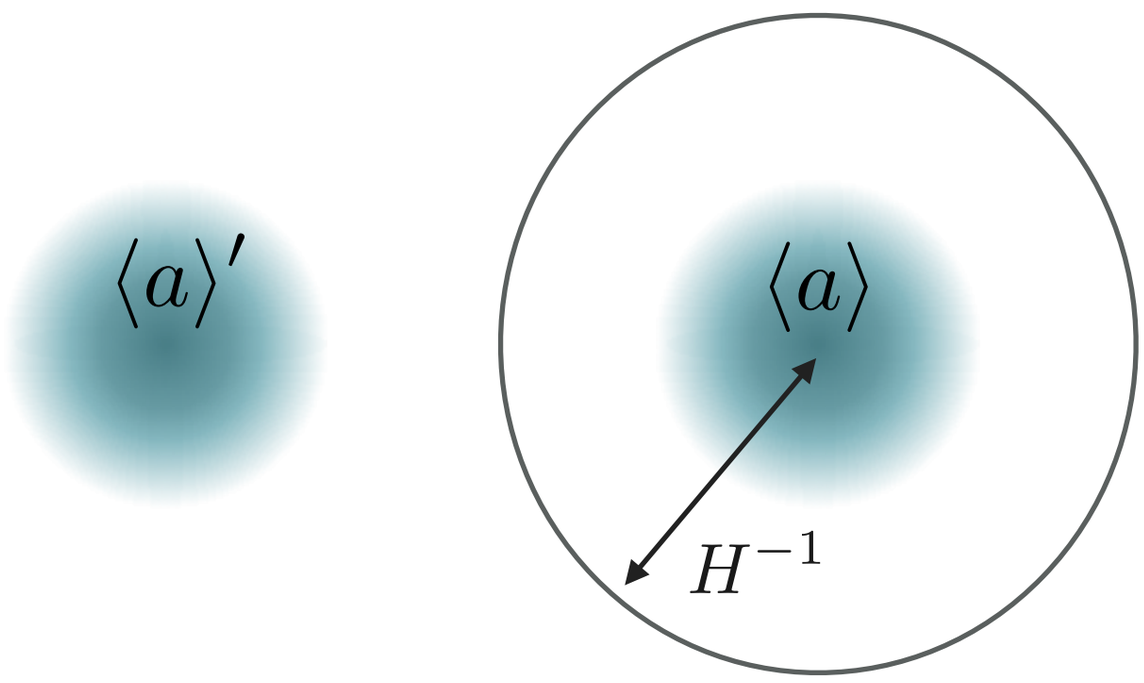
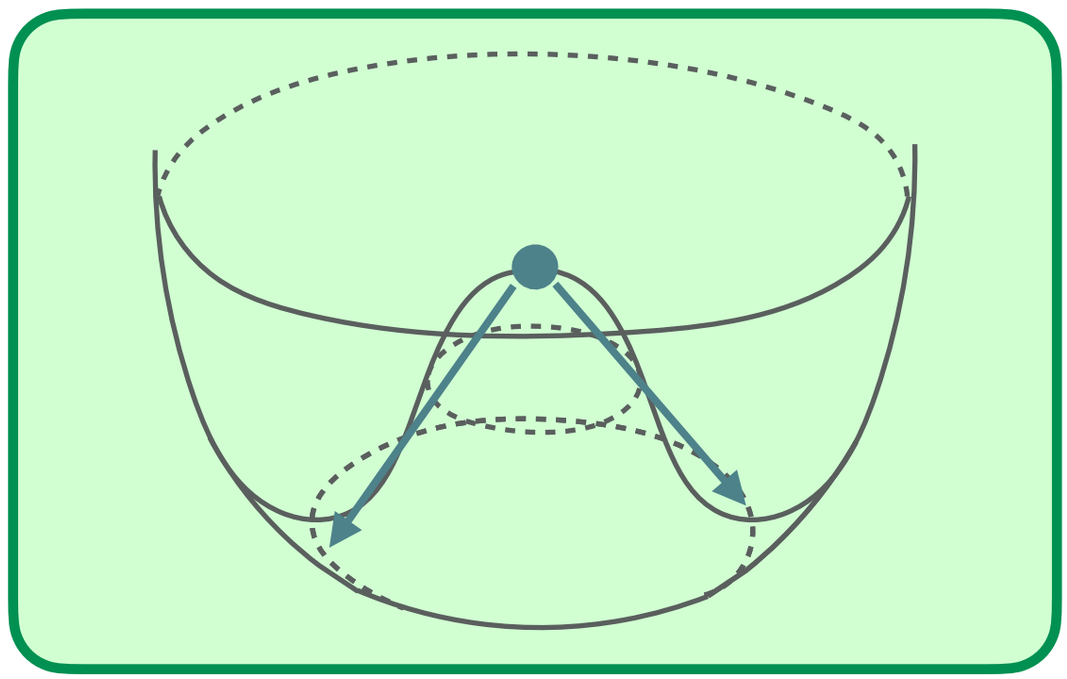
In any case : topological defects, **axion cosmic strings**

[Kibble '76, Zurek '85]





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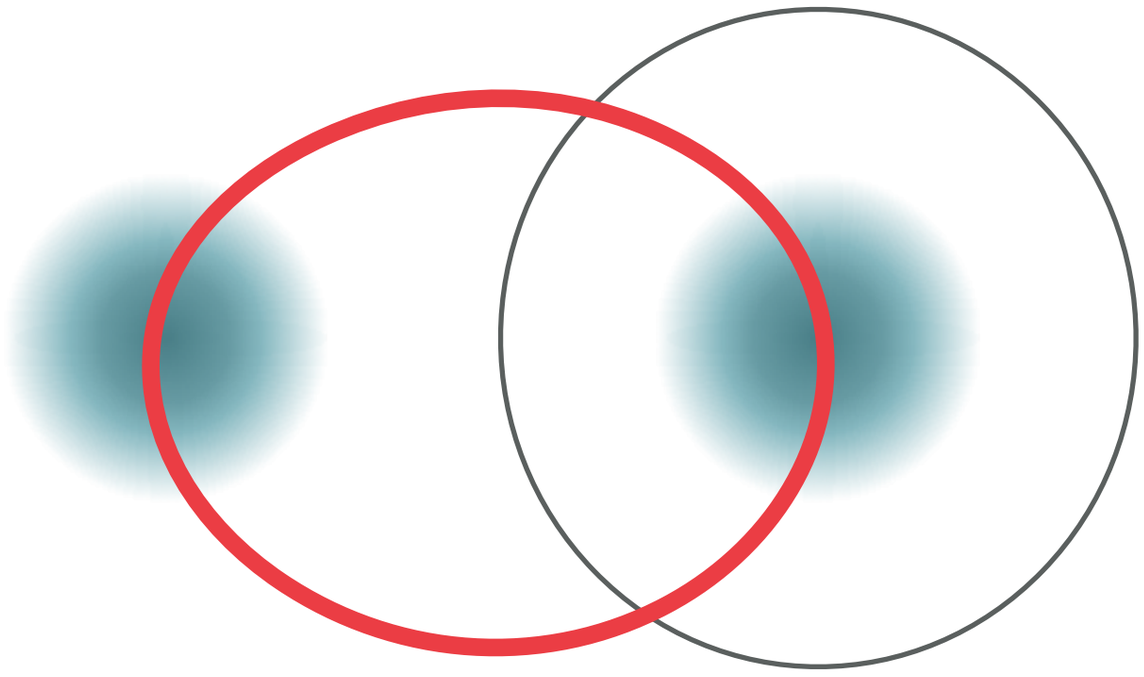

$\langle a \rangle = 0$

$\langle a \rangle = 2\pi f_a n$

$$\pi_1(U(1)) = \mathbb{Z}$$

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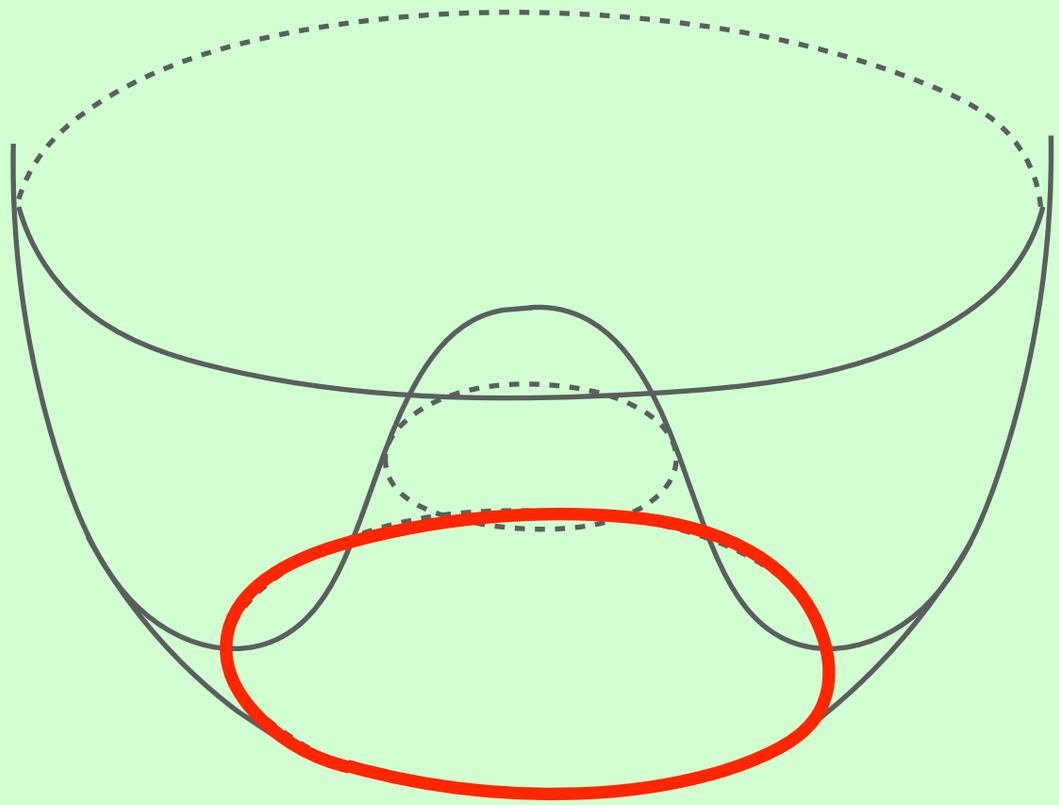

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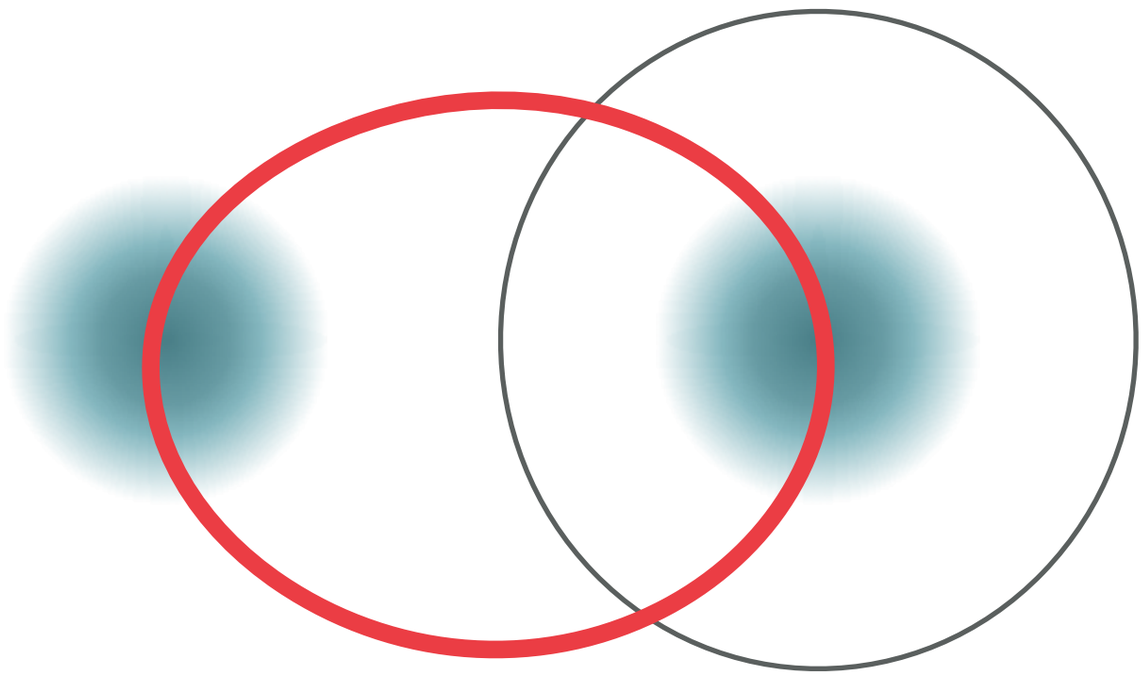

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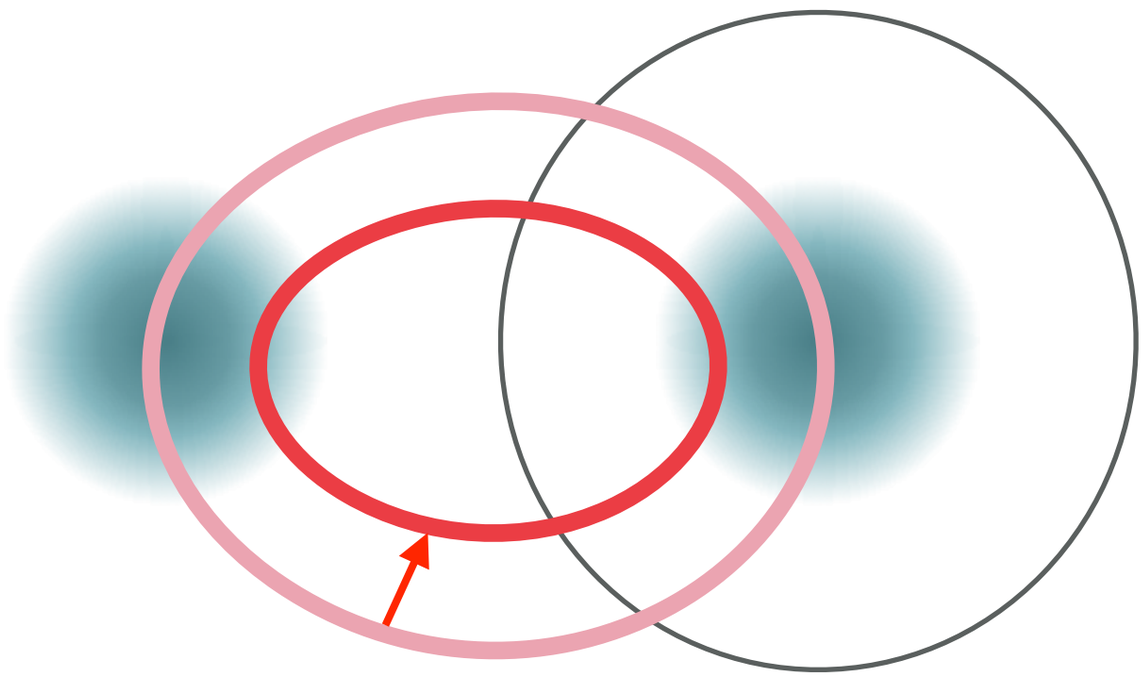

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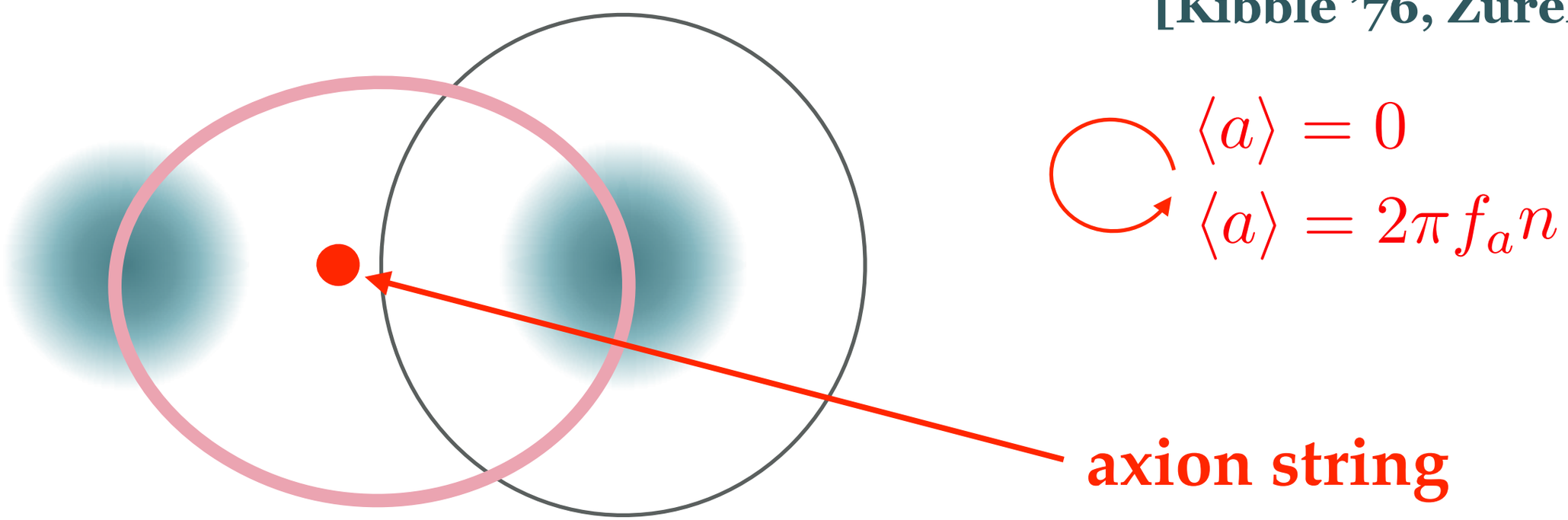

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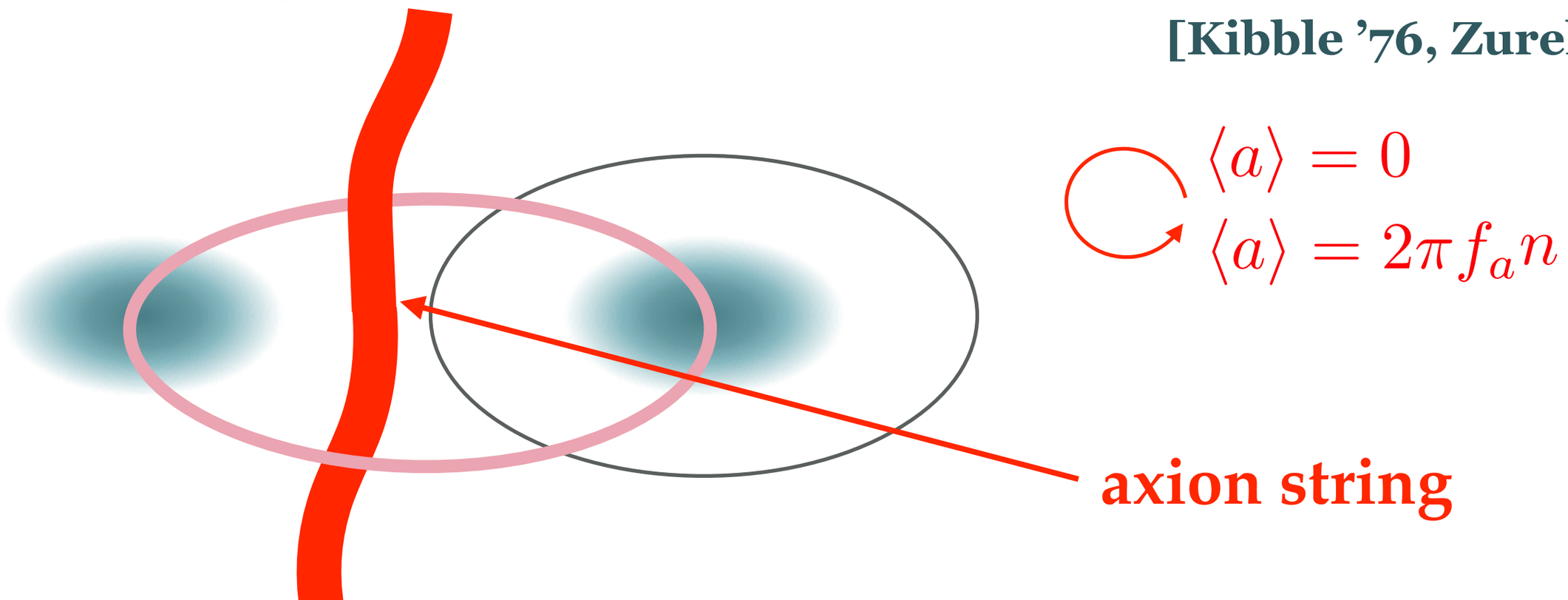

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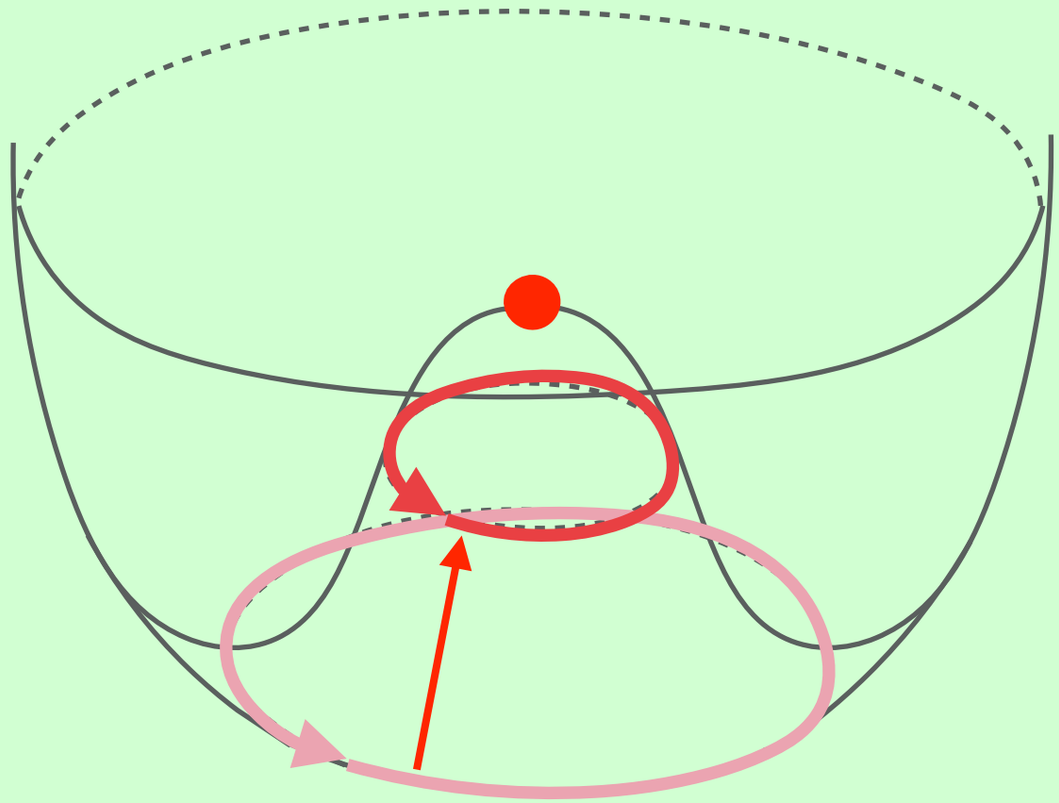

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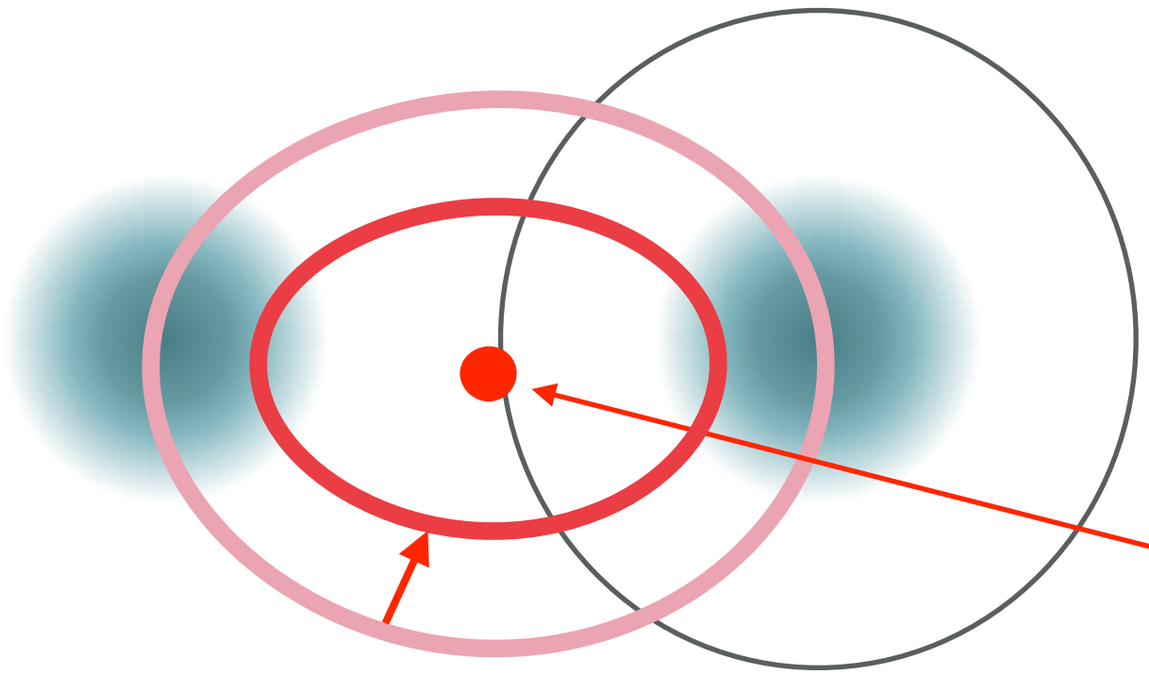

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axion string

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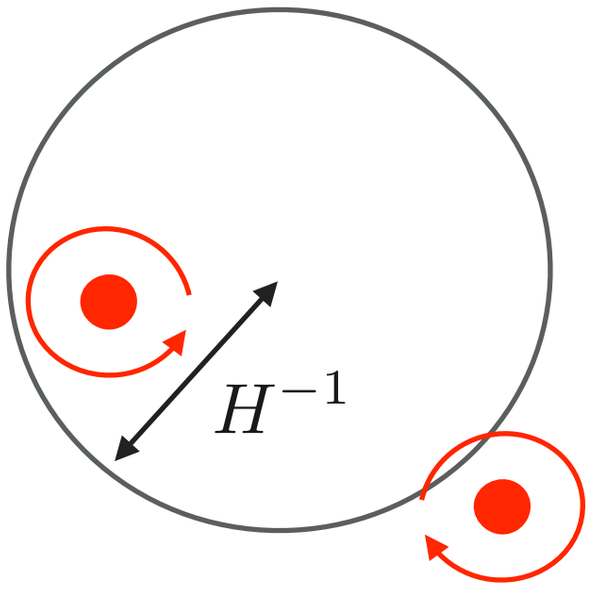
$T \searrow$: « scaling regime »



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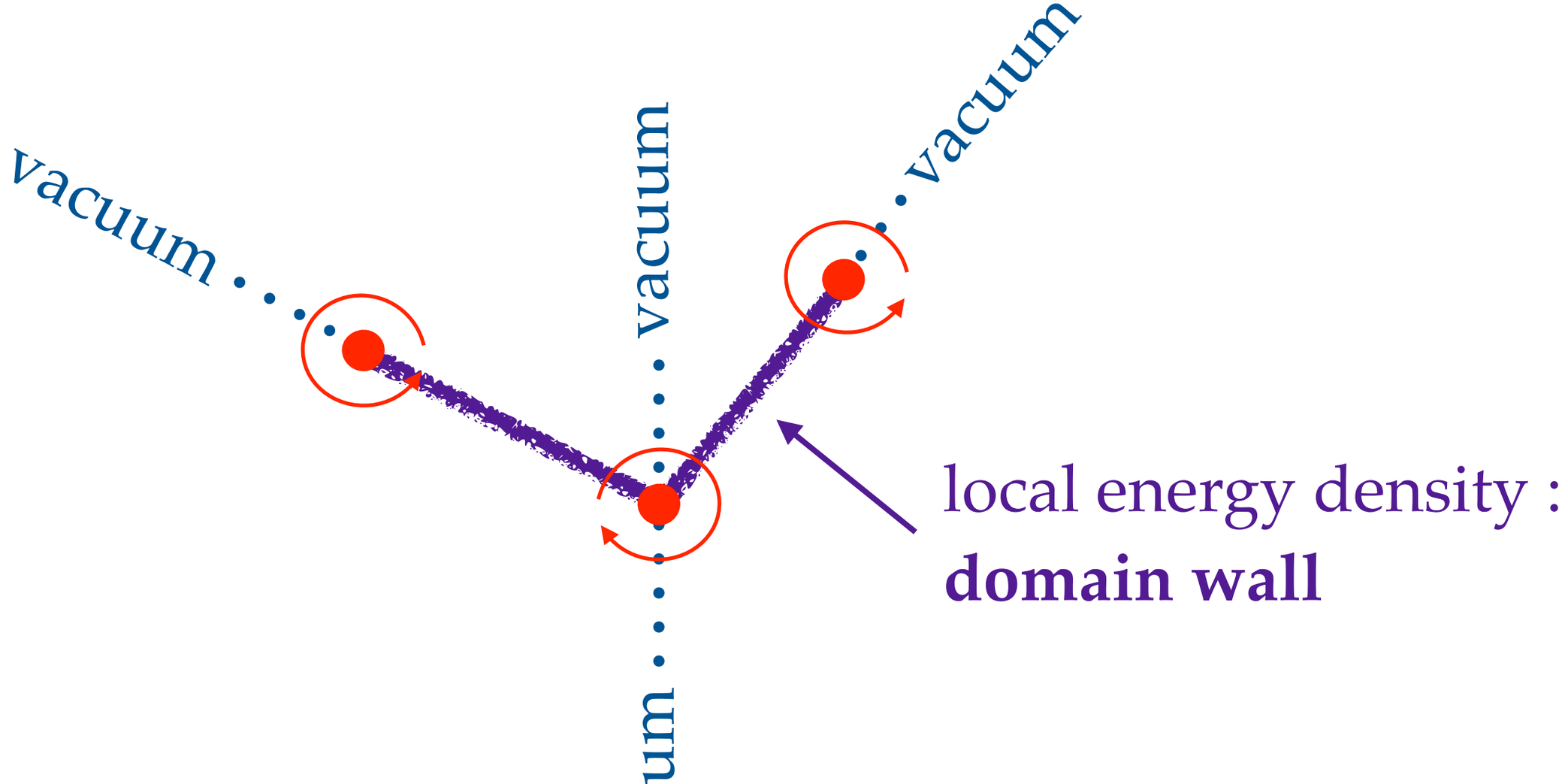
$H \approx m_a$: network collapses or overcloses the universe



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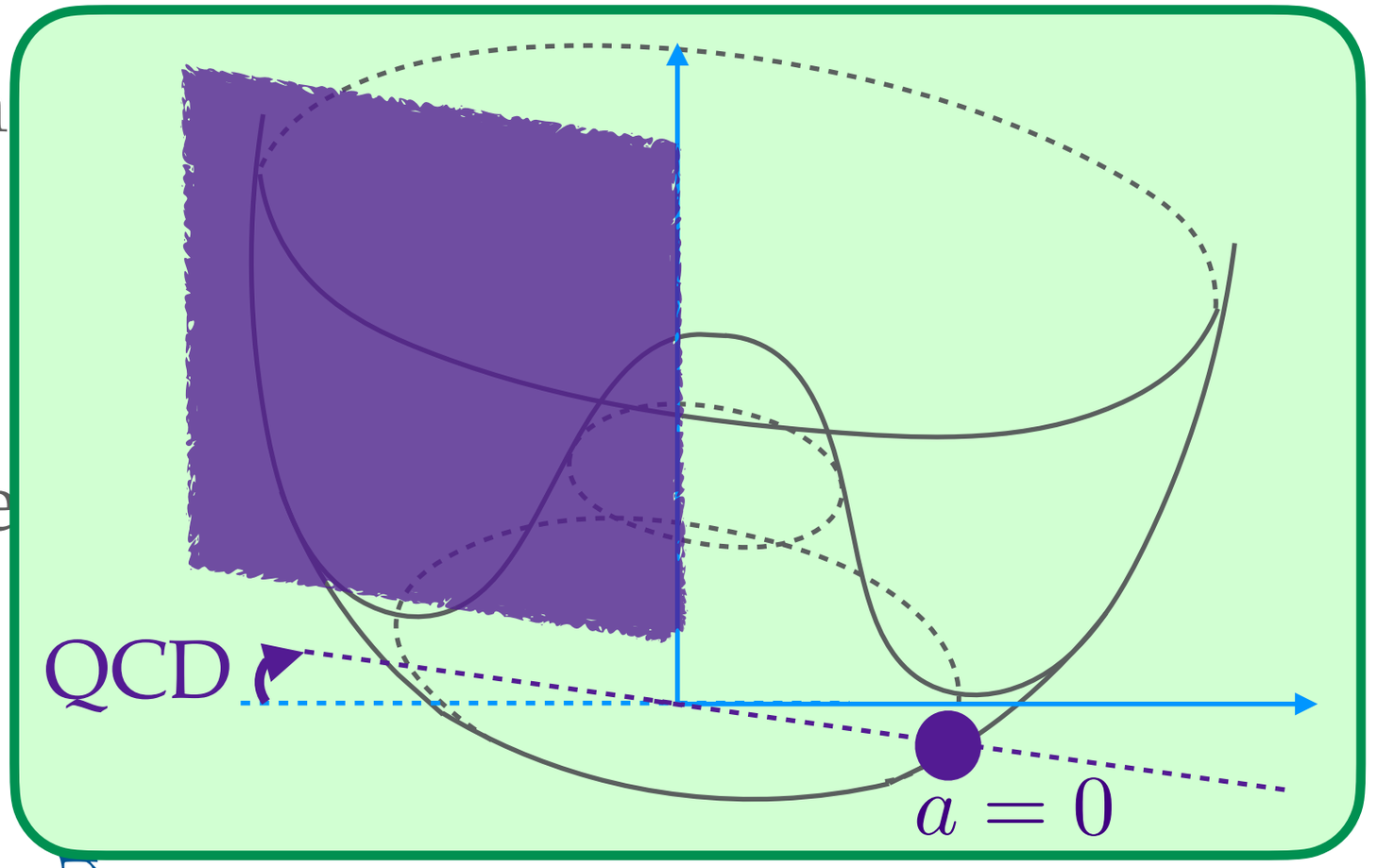

local energy density :
domain wall

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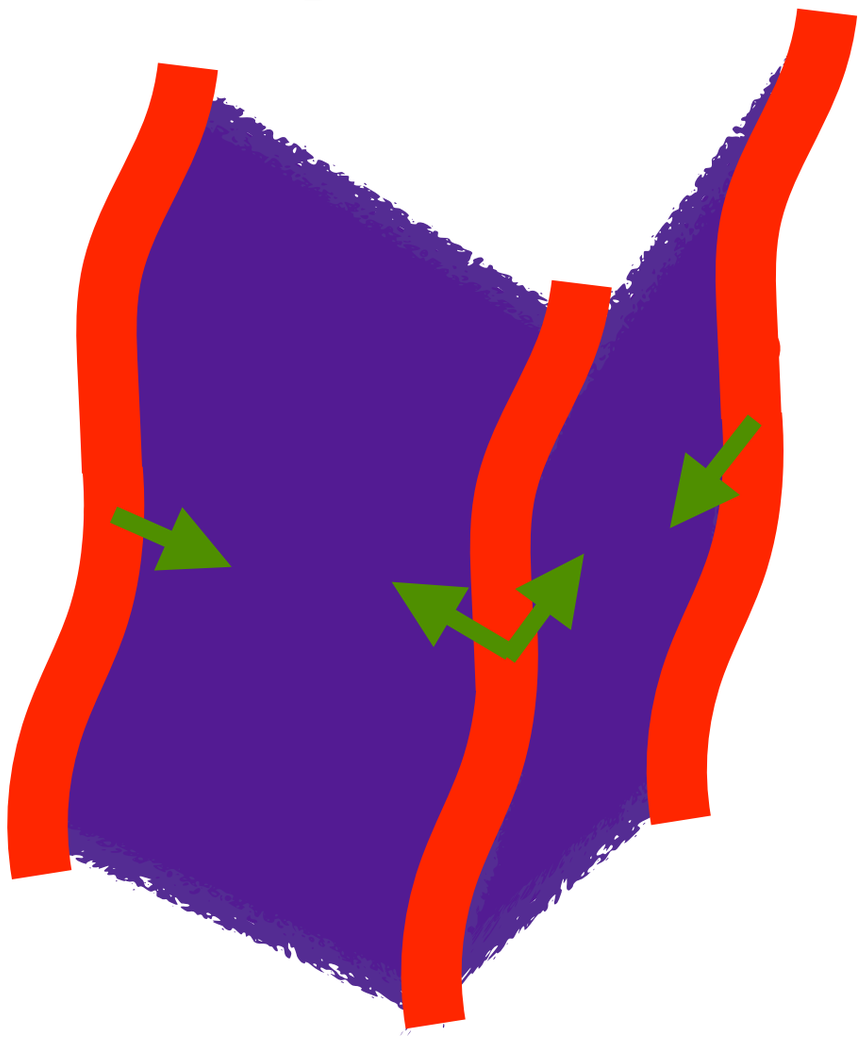

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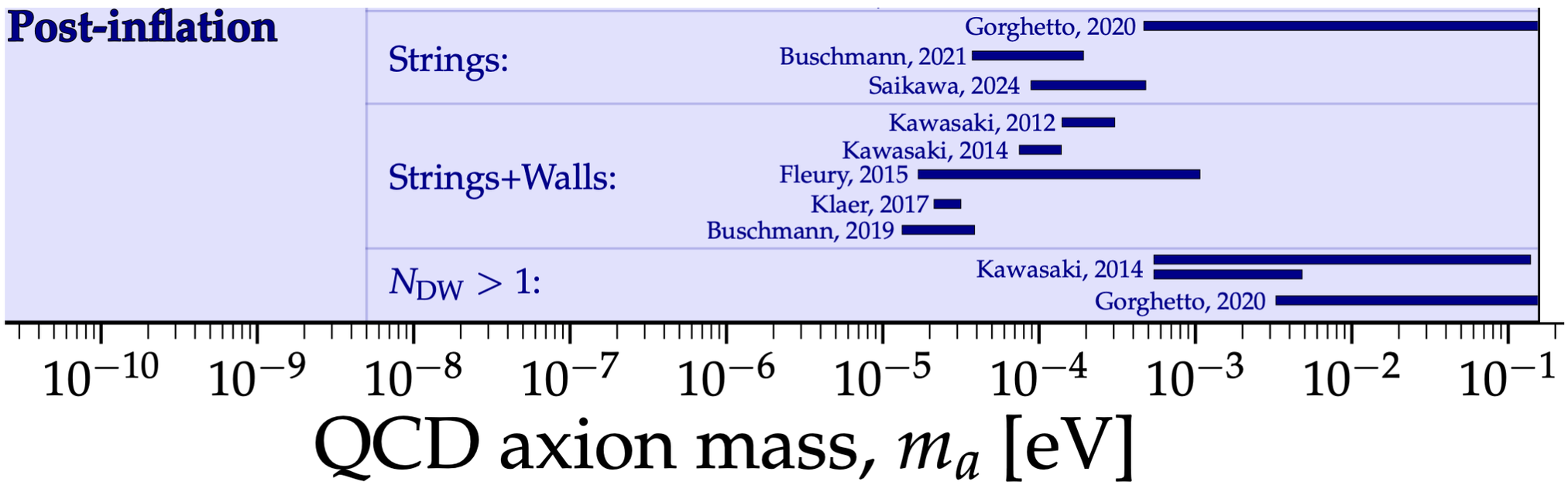
Scaling regime and collapse : **production of axion quanta** (and other ones)

Can make up **most of the axion relic density** ! No free parameter :

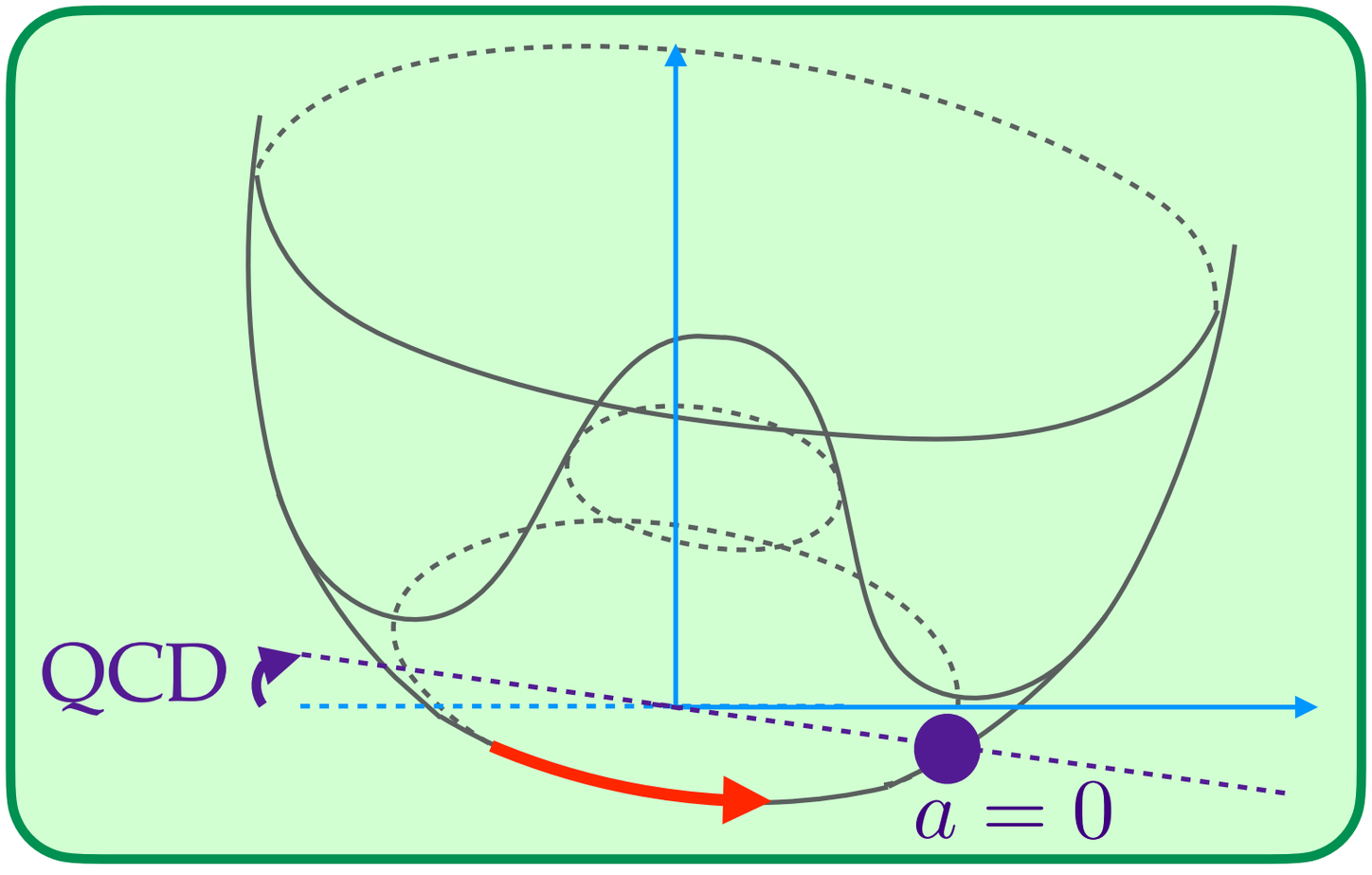


[O'Hare's GitHub]

Axions in extra-dimensional models and their cosmic strings

Axions from extra dimensions

Compact extra dimensions : address the electroweak hierarchy problem and the flavor problem, are necessary for string theory… and « **protect** » **the axion mass**



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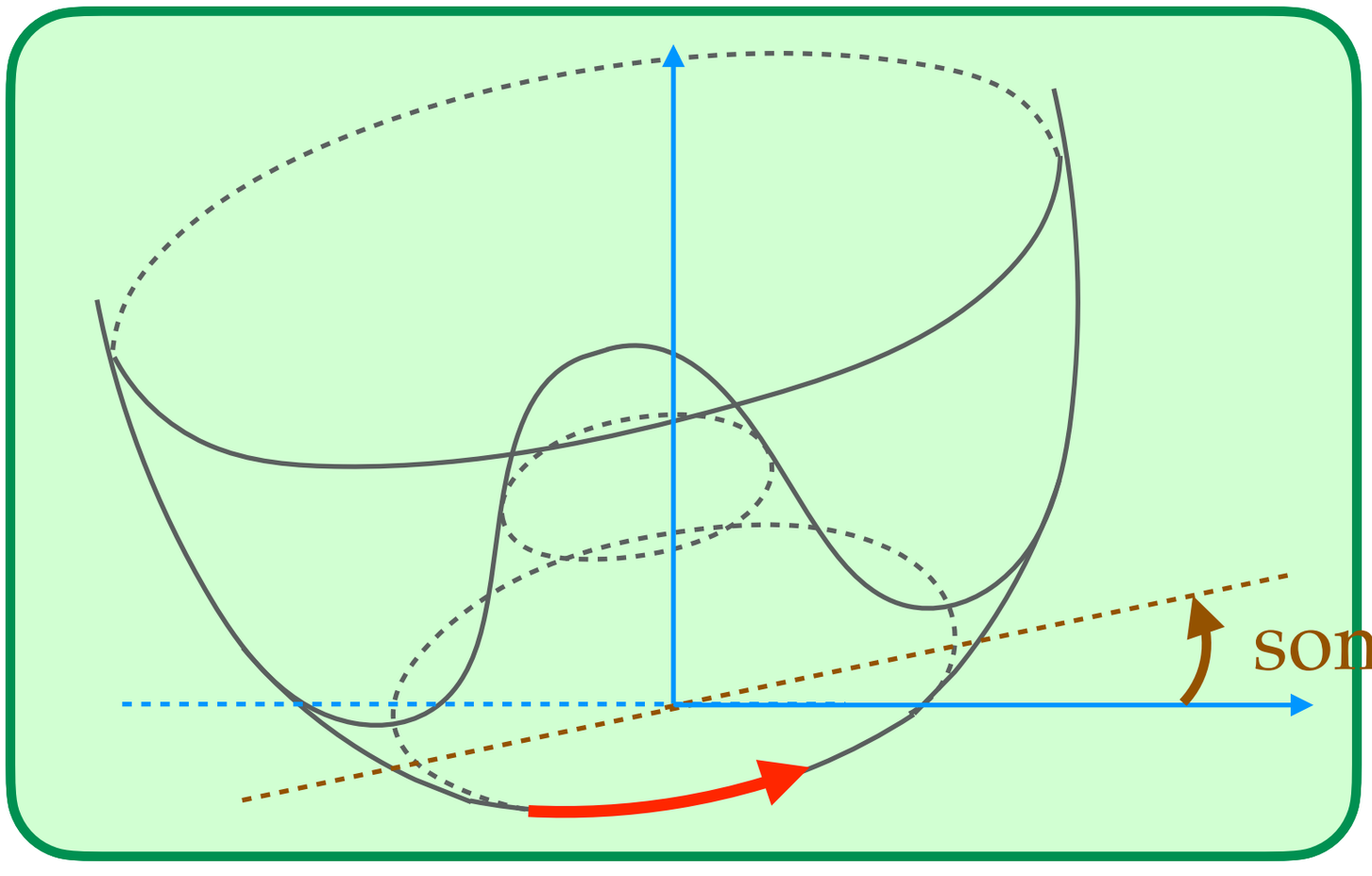

$$\mathcal{L} \supset \frac{m_a^2}{2} a^2$$

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In 5D, for $x^M = (x^\mu, x_4)$, $\mathcal{M}_5 = \mathcal{M}_4 \times (I, S^1, ...)$ and $F = dA$:

of size L_5

$$\mathcal{S} \supset \int_{\mathcal{M}_5} d^5x \left(\frac{M_5^3}{2} R - \frac{1}{2g_5^2} F_{MN} F^{MN} \right) \supset \int_{\mathcal{M}_4} d^4x \frac{(\partial_\mu a)^2}{2}$$

where $a(x^\mu) \propto \int dx_4 A_4(x^\mu, x_4)$

KK reduction with appropriate boundary conditions

[Arkani-Hamed/Cheng/Creminelli/Randall '03, Choi '03]

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restricted by 5D gauge invariance

Cosmic strings from extra dimensions ?

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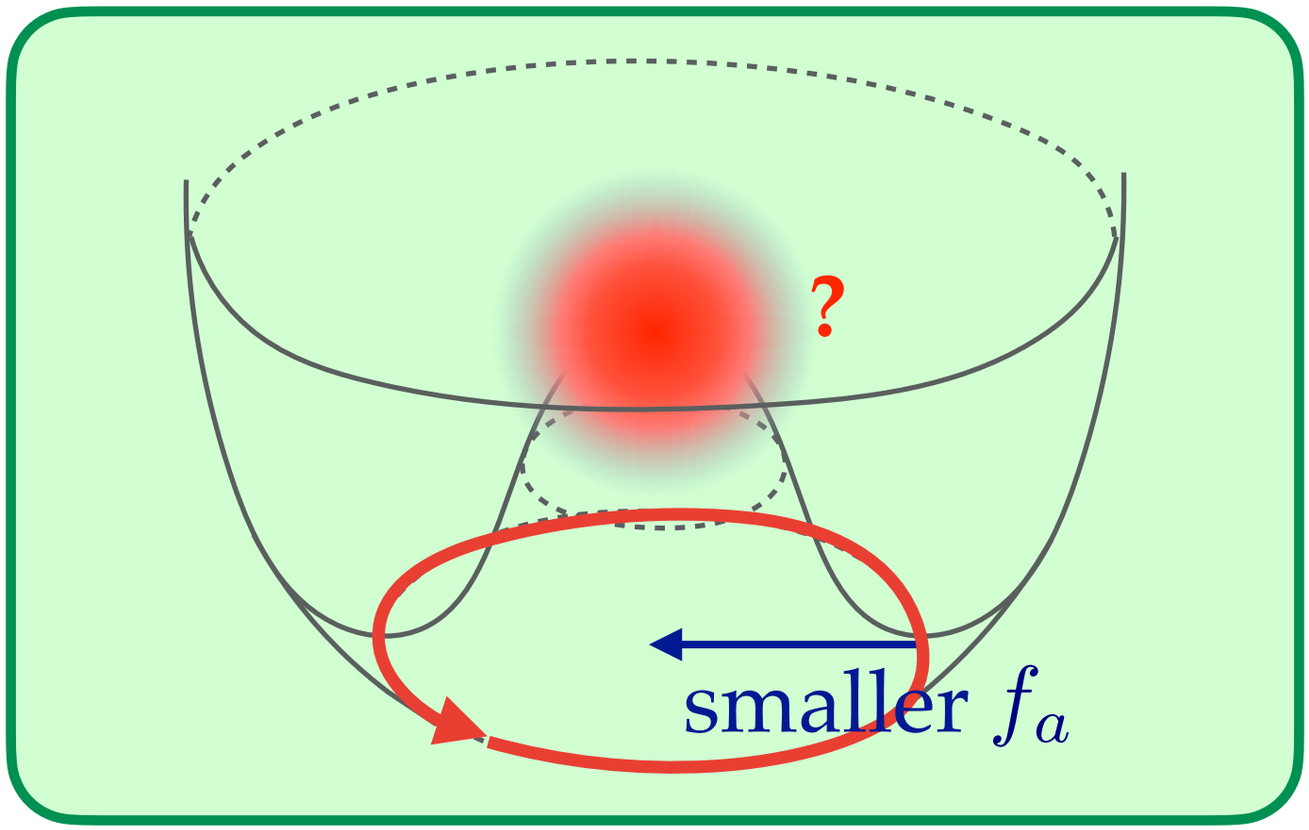
$$a(x^\mu) \propto \int dx_4 A_4(x^\mu, x_4)$$ and $$f_a \propto (L_5 g_5)^{-1/2}$$

But  $\langle a \rangle = 0$

$\langle a \rangle = 2\pi f_a n$

In the core of the string : unbroken phase of the theory



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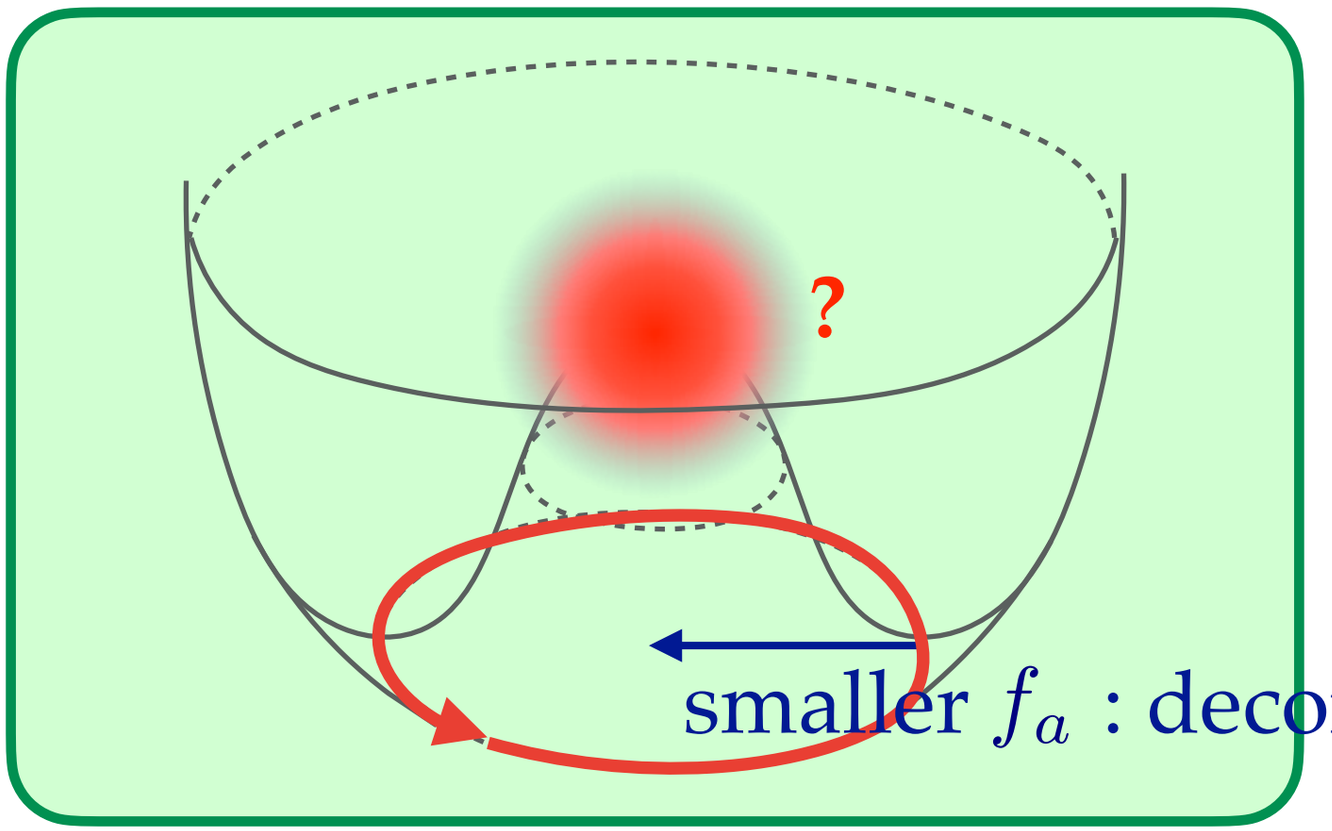
a higher-dimensional theory



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$\langle \rho \rangle \propto L_5$

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Radion diverges logarithmically towards the string core

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Main properties may still be computed for strongly warped backgrounds (dual to 4D models)

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Core resolved in the higher-dimensional theory ?

$$a(x^\mu) \propto \int dx_4 A_4(x^\mu, x_4)$$

Cosmic strings from extra dimensions ?

Core resolved in the higher-dimensional theory ?

$$a \propto \int_{(I,S^1,\ldots)} A$$

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$$a \propto \int_{(I,S^1,\ldots)} A \qquad \text{and} \qquad \int_{\mathcal{C}} da = 2\pi f_a n$$

$$\Longrightarrow \int_{\mathcal{C}\times(I,S^1,\ldots)} dA \propto 2\pi n \quad \mathcal{C}'$$

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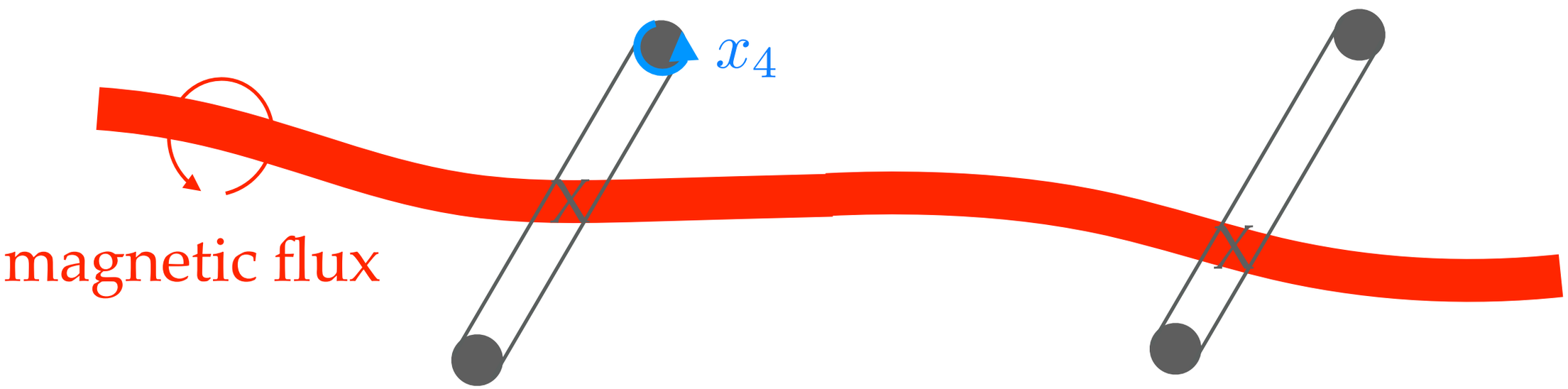
Topological magnetic charge for the 5D gauge field



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Topological magnetic charge for the 5D gauge field, no smooth solution in field theory without additional fields

[Reece '18, '23, Lanza/Marchesano/ Martucci/Valenzuela '21, '22]

Need for a **UV-complete description**

The case of the string axiverse

The string theory axiverse

String theory (usually) lives in 10, 11 or 26D

Low-energy description : 10D supergravity, with **many p-form fields** C_p (gauge fields: $C_p \to C_p + d\Lambda_{p-1}$)

$$a \propto \int_{(I,S^1,\ldots)} A \longrightarrow a_{\mathcal{C}} \propto \int_{\mathcal{C}_p} C_p$$

p-cycle

Generic 6D compact manifold : lots of cycles, lots of axions

$\longrightarrow$ **string theory axiverse** (might not contain a QCD axion)

[Witten '84, Choi/Kim '85, Barr '85, Svrcek/Witten '06, Arvanitaki/Dimopoulos/Dubovsky/Kaloper/March-Russell '09]

Cosmic D-branes

Cosmic strings ? Magnetically-charged objects known :

D-branes of string theory and **fundamental strings**

**[Witten ’85, Sarangi/Tye ’02, Dvali/Villenkin et al ’02-’05,
Polchinski et al ’03-’05, March-Russell/Tillim ’21]**

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[Witten '85, Sarangi/Tye '02, Dvali/Villenkin et al '02-'05, Polchinski et al '03-'05, March-Russell/Tillim '21]

Formation ? String-theoretic mechanisms (D-brane annihilation, Hagedorn phase transition, …?) which depend on inflation, on the details of the compactification, etc

Cosmological evolution ? Extra-dim. & quantum scatterings, string-theoretic instabilities, **UV-dominated tension**

Scan of examples : $f_a^2 \lesssim T \lesssim f_a M_{\rm pl}$

Cosmic D-branes

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e.g., strongly warped compactifications

$\Longleftrightarrow$

standard case

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Scan of examples : $f_a^2 \lesssim T \lesssim f_a M_{\rm pl}$ e.g., flat compactification

« Heavy » cosmic strings

(also, « axion magnetic weak gravity conjecture »)

[Hebecker/Henkenjohann/Witkowski '17]

QCD axion dark matter ?

« Minimal » unwarped scenario : ruled out

Assumptions : lightest axion = QCD axion, one type of cosmic string : the QCD axion string, unstable domain wall network

Tension : $T = \kappa f_a M_{\rm pl}$ Charge : $\int_{\mathcal{C}} da = 2\pi f_a n$

Shut up and calculate / simulate : known **scaling regime, rates of emission, frequency distributions**, …

Ex. : energy emission rate to axions

$$\Gamma_a = \frac{16 r_a (8\pi)^{3/2} \alpha}{3 r^{3/2} \kappa^{3/2}} H^3 \sqrt{f_a M_{\rm pl}^3}$$

Result (for $\kappa \approx 1$):

$$\Omega_a \sim 10^2 \sqrt{\frac{10\,\mathrm{meV}}{m_a}}$$

A way out in the axiverse

Assumptions : lightest axion = QCD axion, one type of cosmic string : ~~the QCD axion string~~, unstable domain wall network

$$\Delta a_1 = 2\pi f_{a_1} n_1$$
$$\Delta a_2 = 2\pi f_{a_2} n_2$$

If $m_{a_2} \gg m_{a_1} = m_{a,QCD}$, **the domain-wall-driven collapse can interrupt the axion production earlier**

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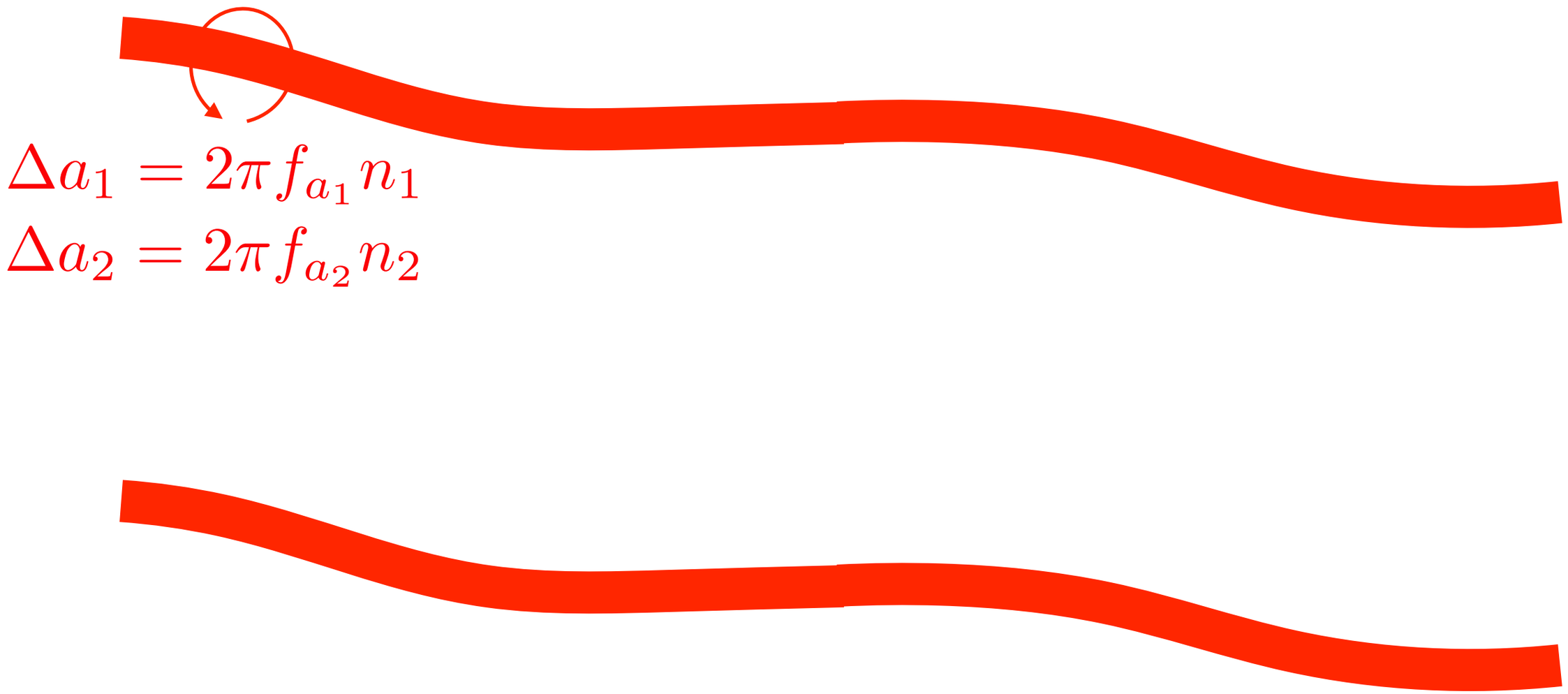

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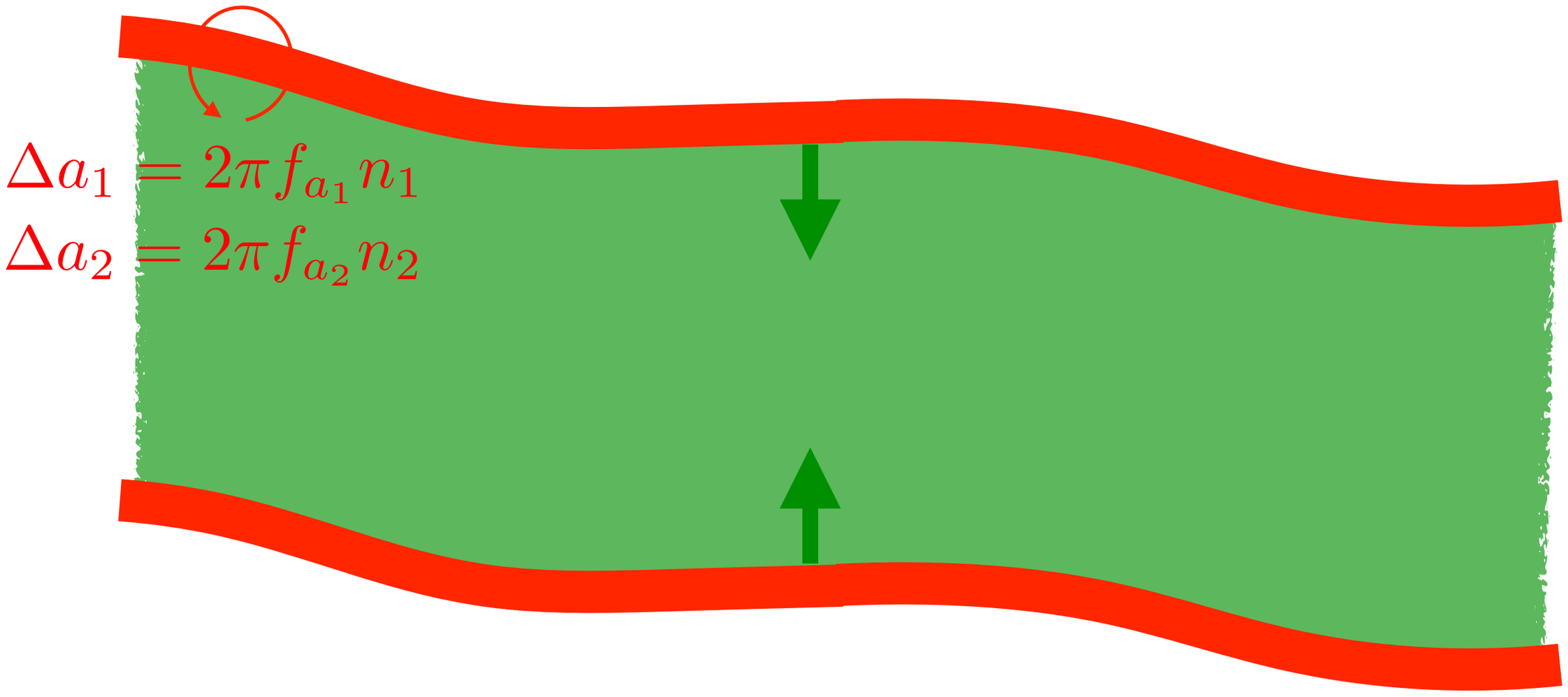

$$T = T_2$$

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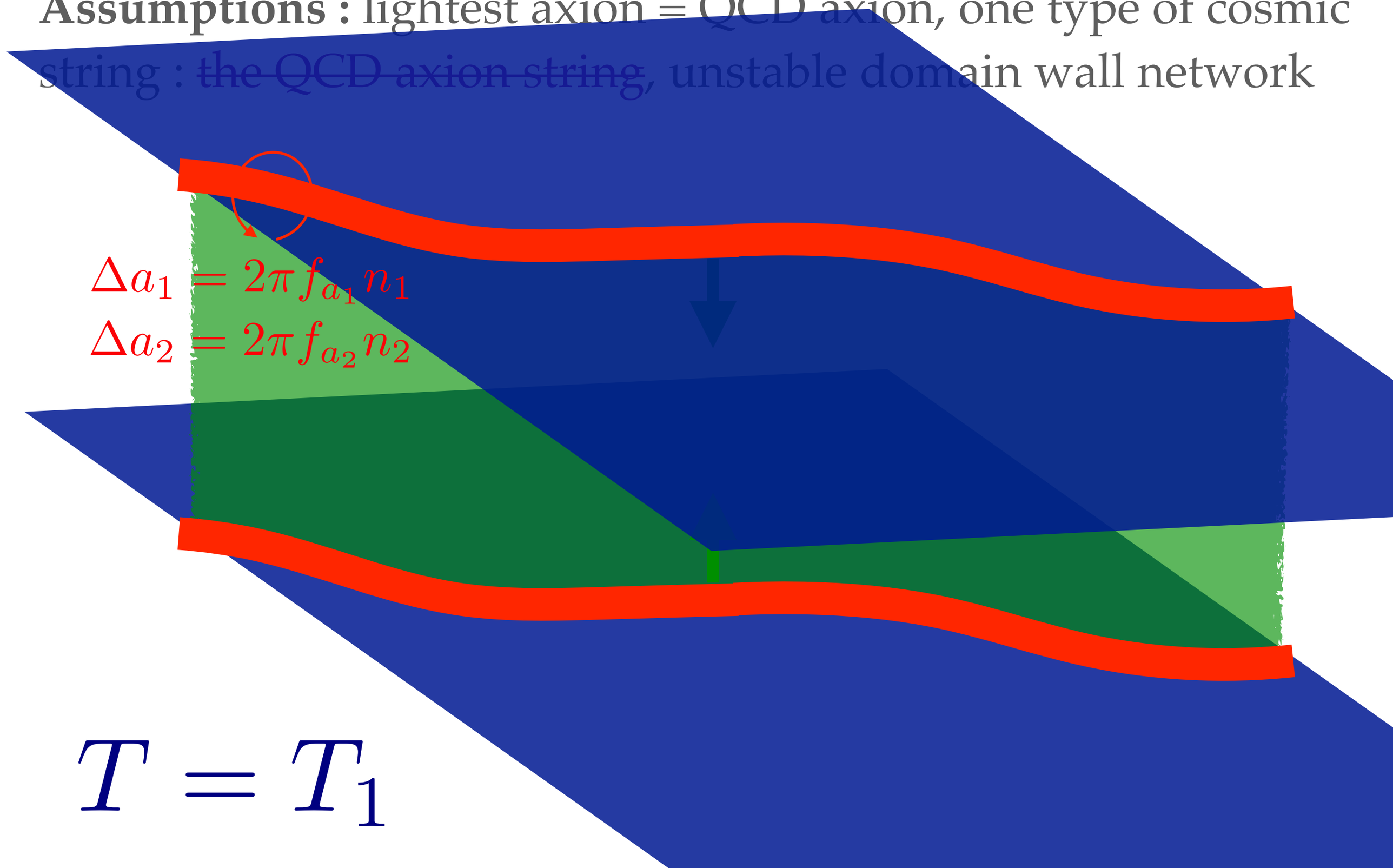

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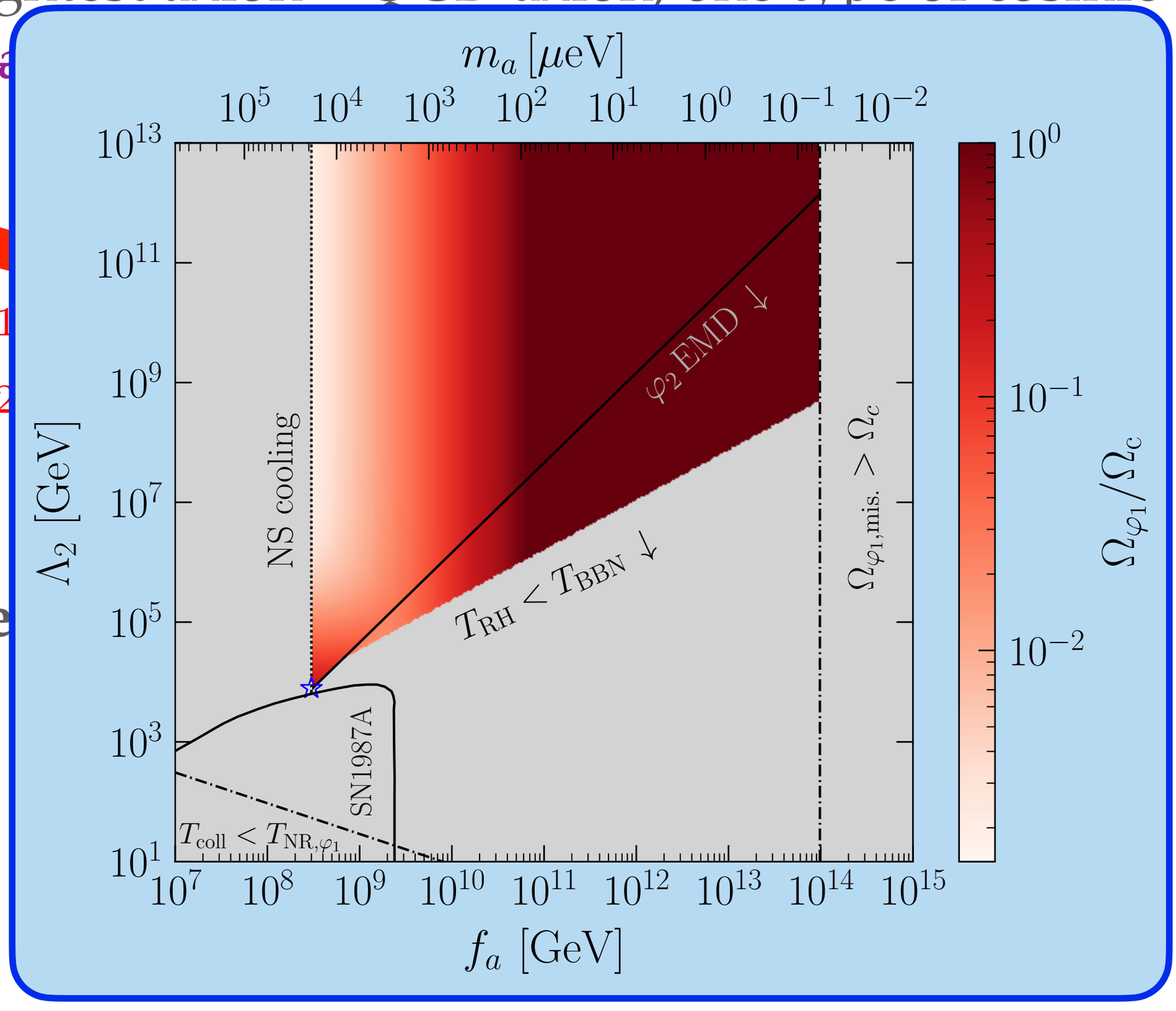

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Potential **gravitational waves signals**

A way out in the axiverse

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string : ~~the~~

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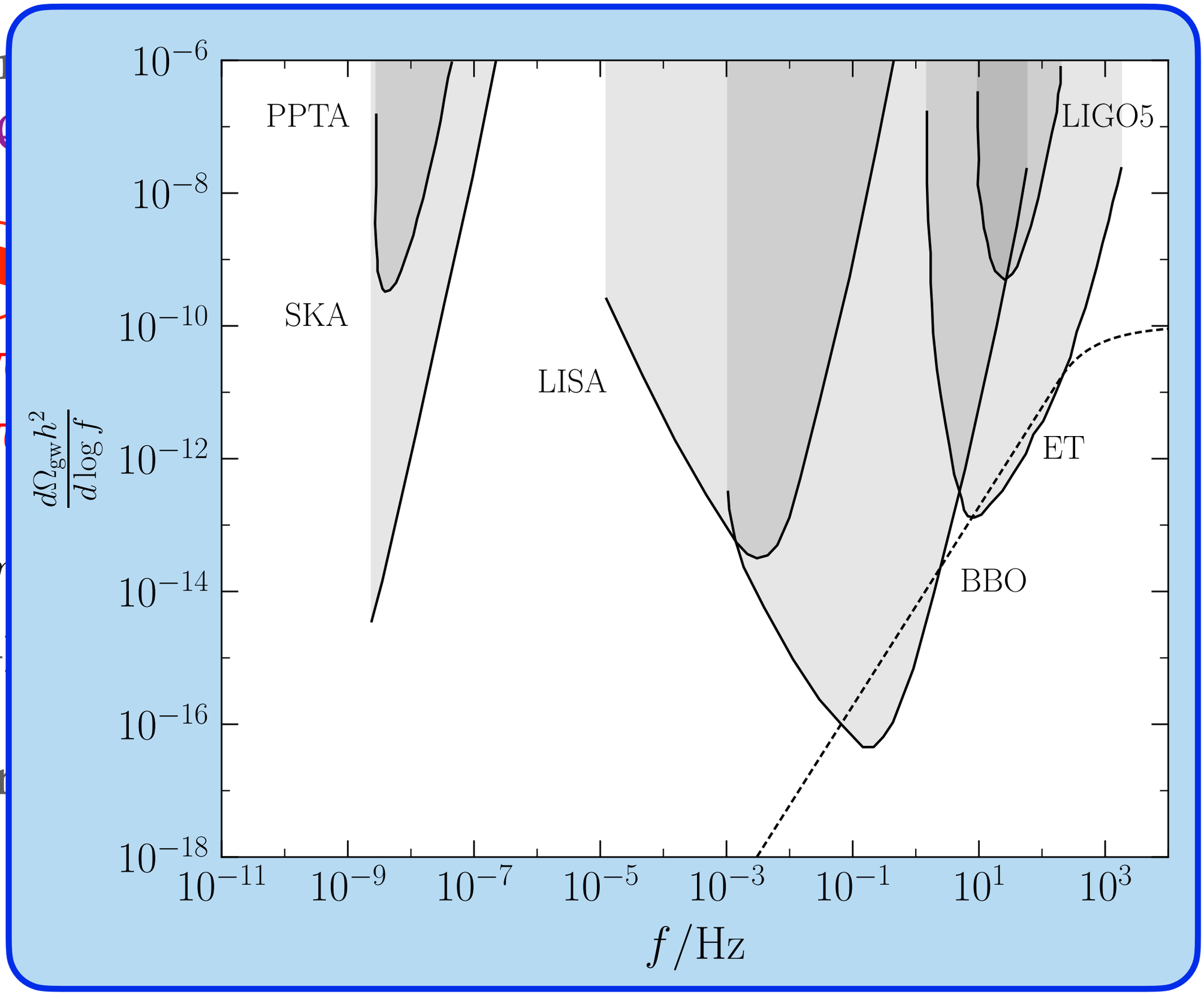
Potential **gr**



Summary and outlook

Axions belonging to the string theory axiverse, arising from extra-dimensional gauge fields, are associated with strings which are fundamental objects, and not field theory solitons.

Post-inflationary axion cosmology is drastically affected.

Assuming a population of « minimal » strings for the QCD axion, **the universe is overclosed**.

One example of a **way out** : using a second axion to collapse the string network at early stages.

More to do ! Simulations, more complicated cases, complete realistic string cosmology, scan over compactifications…