Parity Domain Walls and the Cosmology of Nelson-Barr

based on [2212.03882]

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The Strong CP Problem

The quark sector of the Standard Model has two possible sources of CP violation:

- The complex phase δ_{CKM} in the CKM matrix
- $\bar{\theta} = \theta + \arg\det(m_u) + \arg\det(m_d)$, where θ comes from

$$\frac{\theta}{16\pi^2}\int \mathrm{d}^4x\,\mathrm{tr}\left(G_{\mu\nu}G^{\mu\nu}\right)$$

The Strong CP problem: $\delta_{\mathrm{CKM}} \sim \mathcal{O}(1)$ while $\bar{\theta} \lesssim 10^{-10}$

To CP or not CP

Two sectors of solution to the strong CP problem, depending on whether CP(or sometimes just P) is a true symmetry of nature

$\not{C}P$: δ_{CKM} and $\bar{\theta}$ both $\mathcal{O}(1)$ at tree-level

axion dynamically relaxes $\bar{\theta}$ to zero

[Pecci & Quinn ’77]

light degree of freedom

well studied, rich phenomenology

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CP: δ_{CKM} and $\bar{\theta}$ both 0 at tree-level

δ_{CKM} generated from spontaneous breaking of CP

[Nelson ’84, Barr ’84]

Phenomenological consequences less explored

The story/plan in one slide

[McNamara & Reece 2212.00039]

Domain walls from spontaneous breaking of parity are absolutely stable, even when parity is gauged

↓

Scale of $\langle \mathrm{CP} \rangle$ tied with scale of inflation

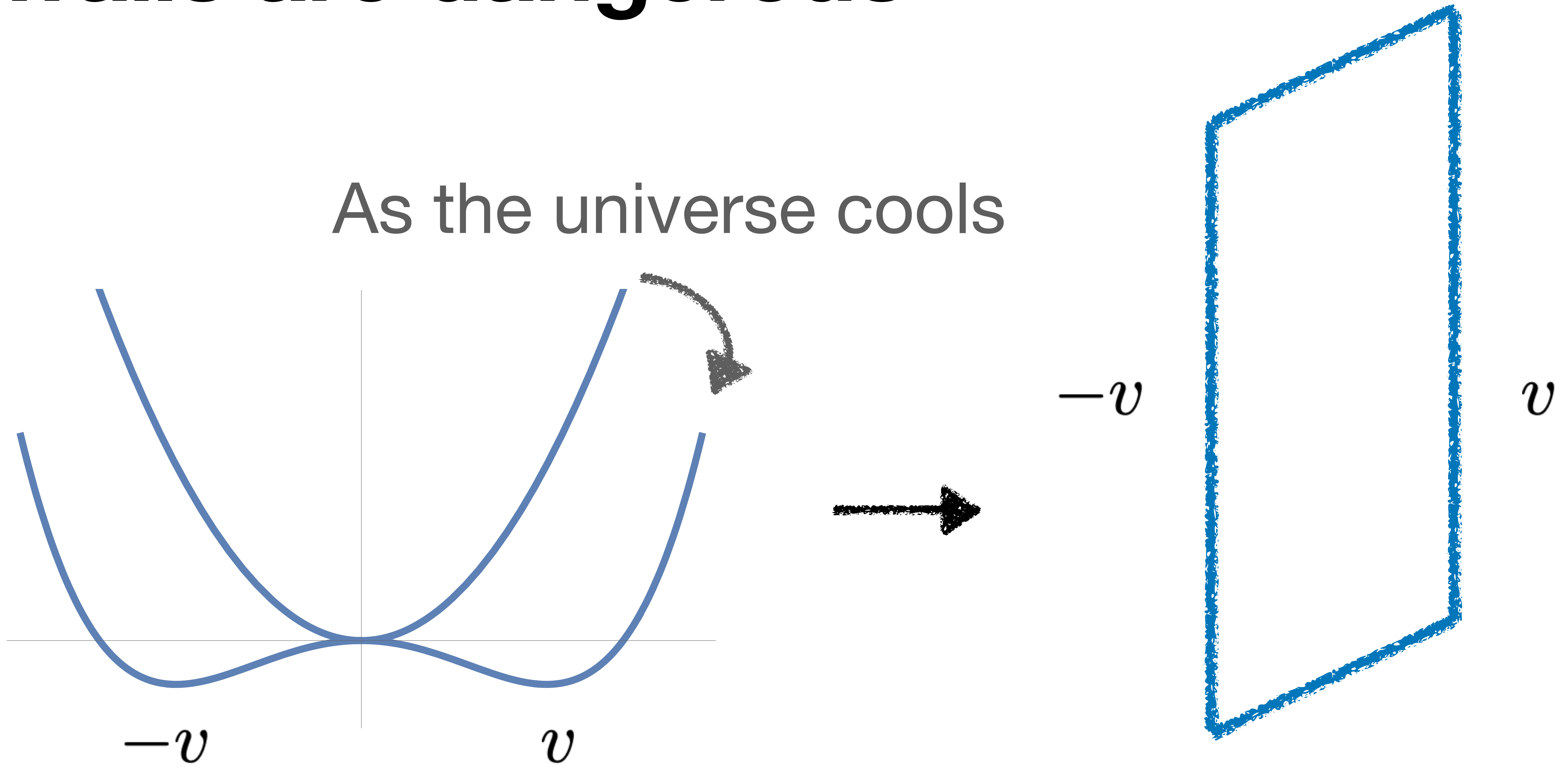
↓

cosmological consequences associated with the “quality” of Nelson-Barr models

Part 1: Stability of Parity Domain Walls

[McNamara & Reece 2212.00039]

Domain walls are dangerous



$$\sigma \equiv \frac{E}{A} \sim v^3$$

Absolutely stable domain walls will dominate the universe and contradict Standard Cosmology if

$$v \gtrsim 1\mathrm{MeV}$$

Getting rid of domain walls: internal symmetry

Domain walls from spontaneous breaking of internal symmetry

(e.g. $\mathbb{Z}_2 \to 1$)

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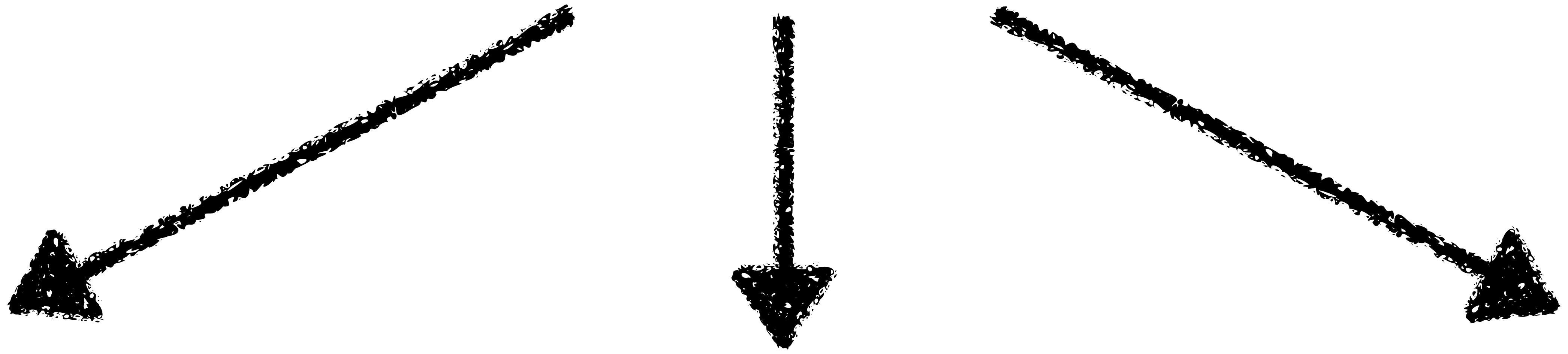


Global: DWs are stable

(if explicit breaking, needs to be protected)

Getting rid of domain walls: internal symmetry

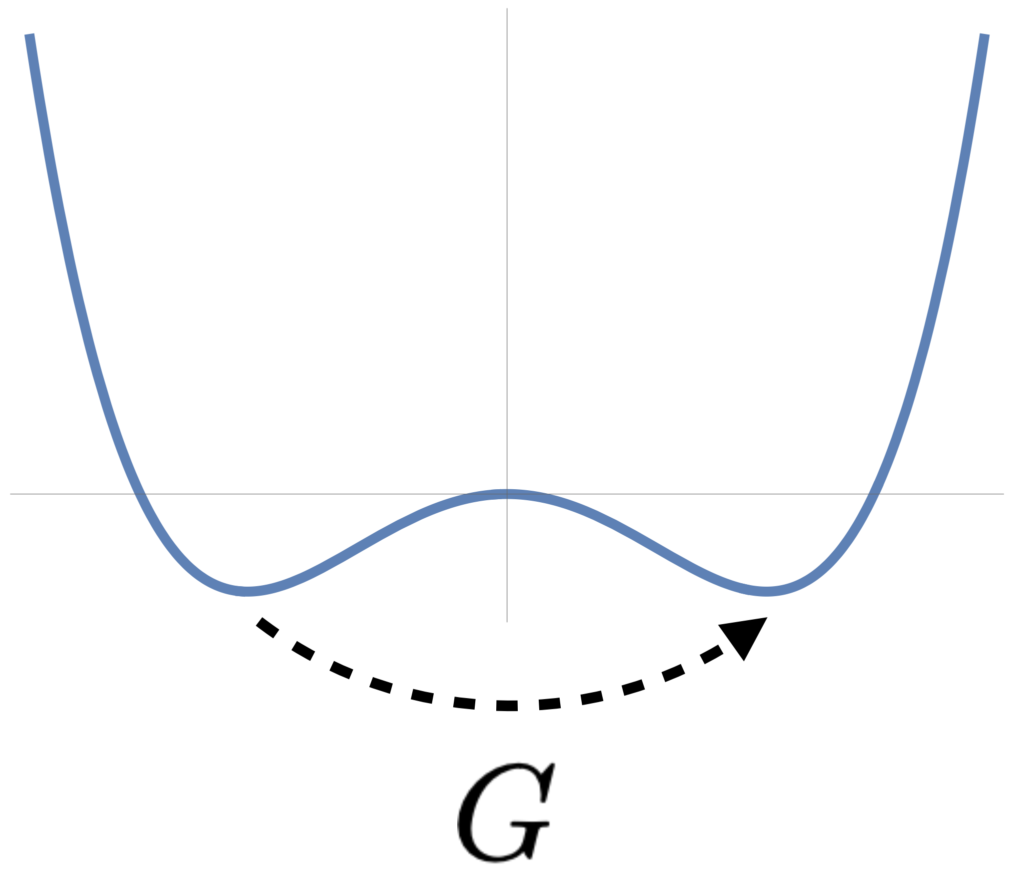
Domain walls from spontaneous breaking of internal symmetry

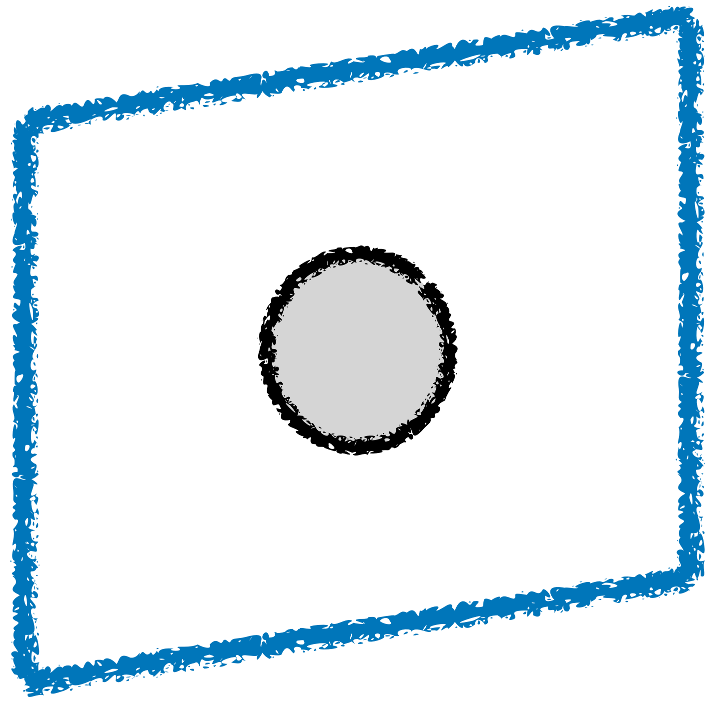
(e.g. $\mathbb{Z}_2 \to 1$)

Global: ~~DWs are stable~~

Gauged:
DW destroyed by strings

$$G \to \mathbb{Z}_2 \to 1$$





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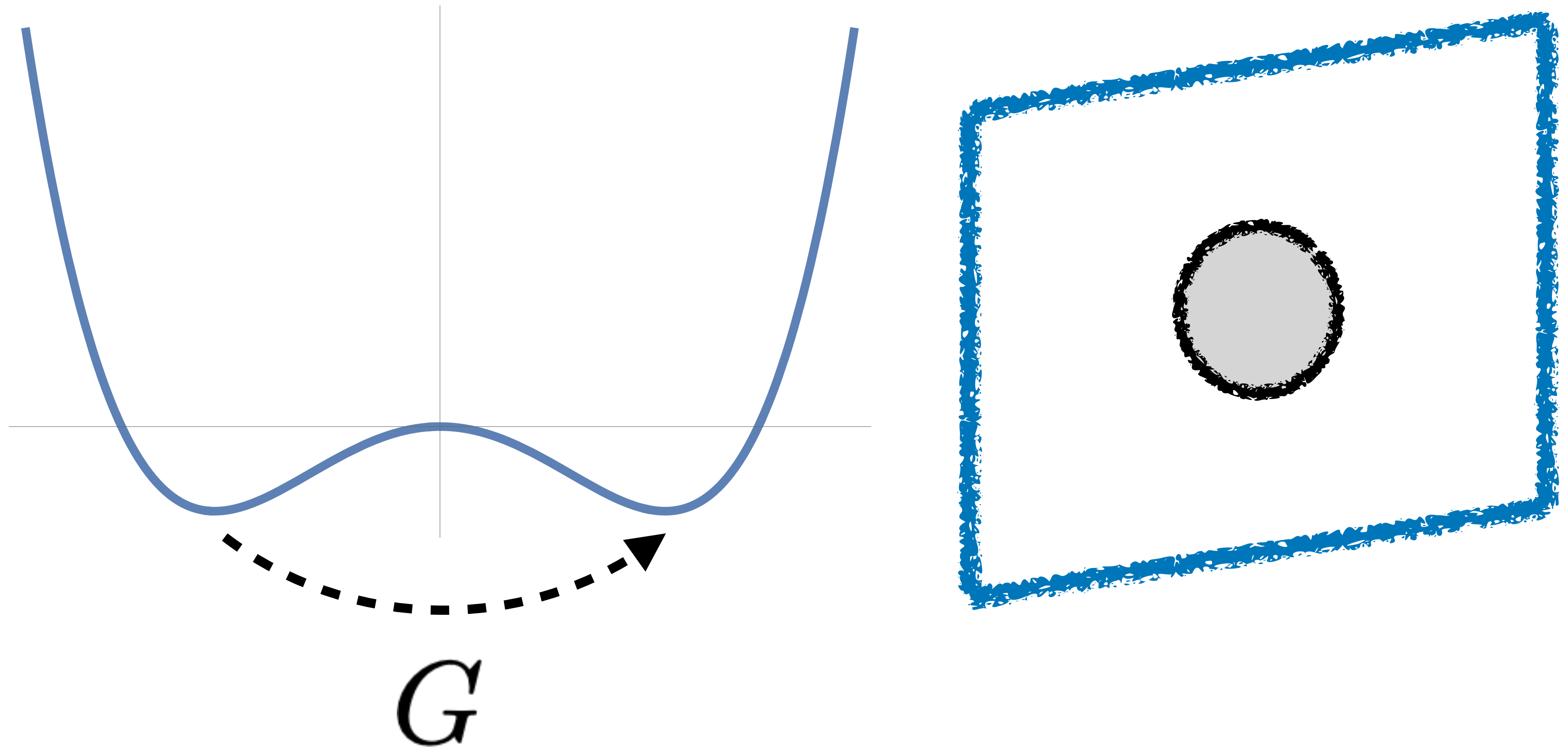
Inflate away



Getting rid of domain walls: Parity symmetry

Domain walls from spontaneous breaking of parity
(or parity with any internal symmetry attached to it)

Global: ~~DWs are~~ stable

Gauged:

Inflate away

[McNamara & Reece 2212.00039]
Parity string does not exist

Internal symmetry vs parity

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Parity: the spacetime manifold ***determines*** the gauge field configuration

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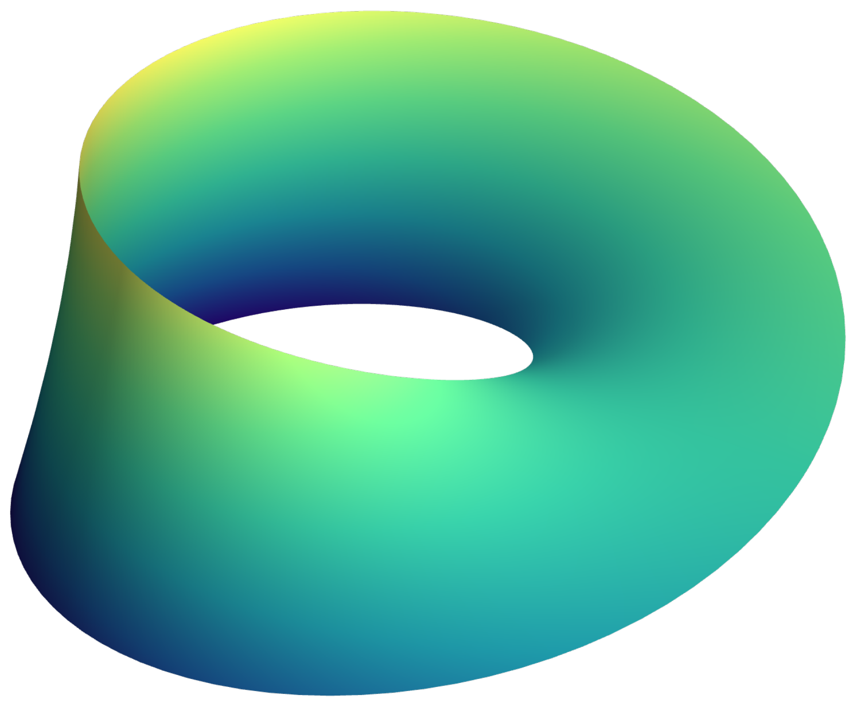
Non-orientable: Going around a cycle forces a parity transformation



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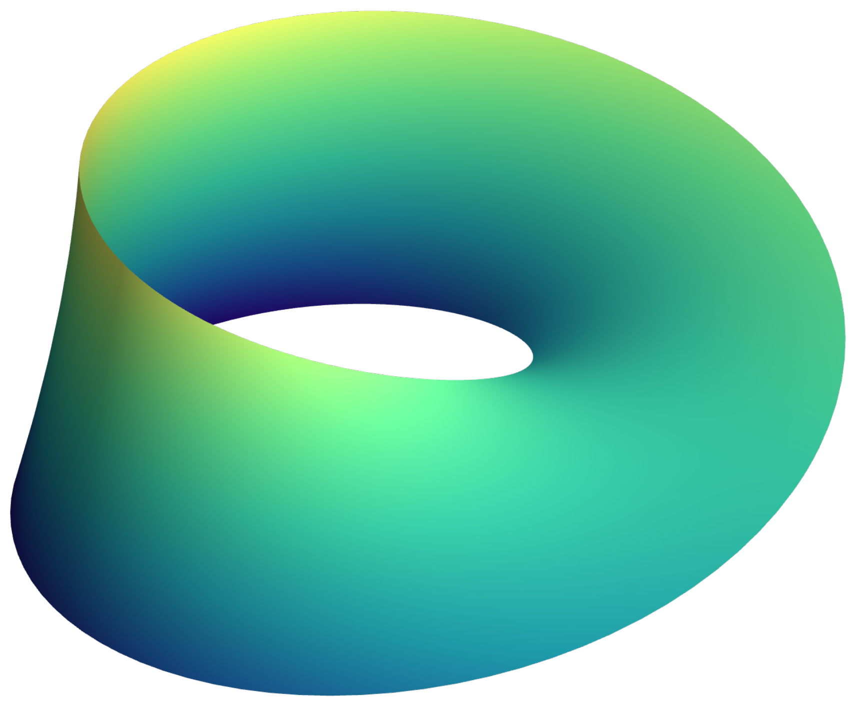
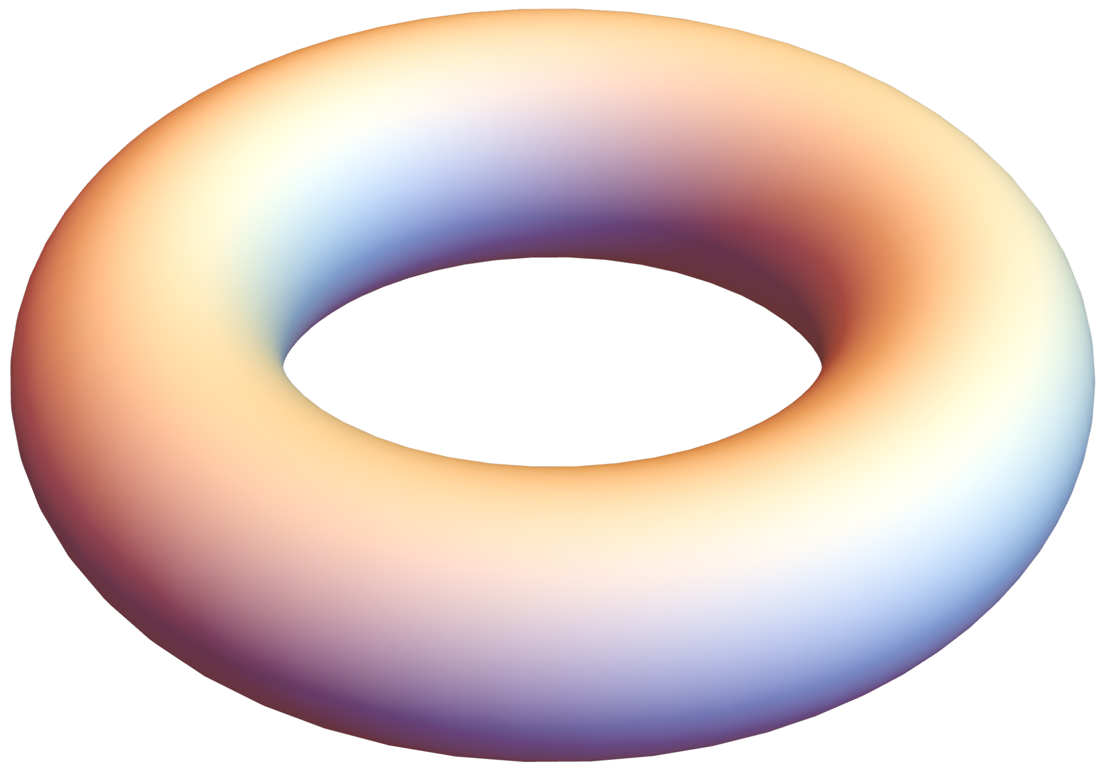


Orientable: No parity transformation along any cycle



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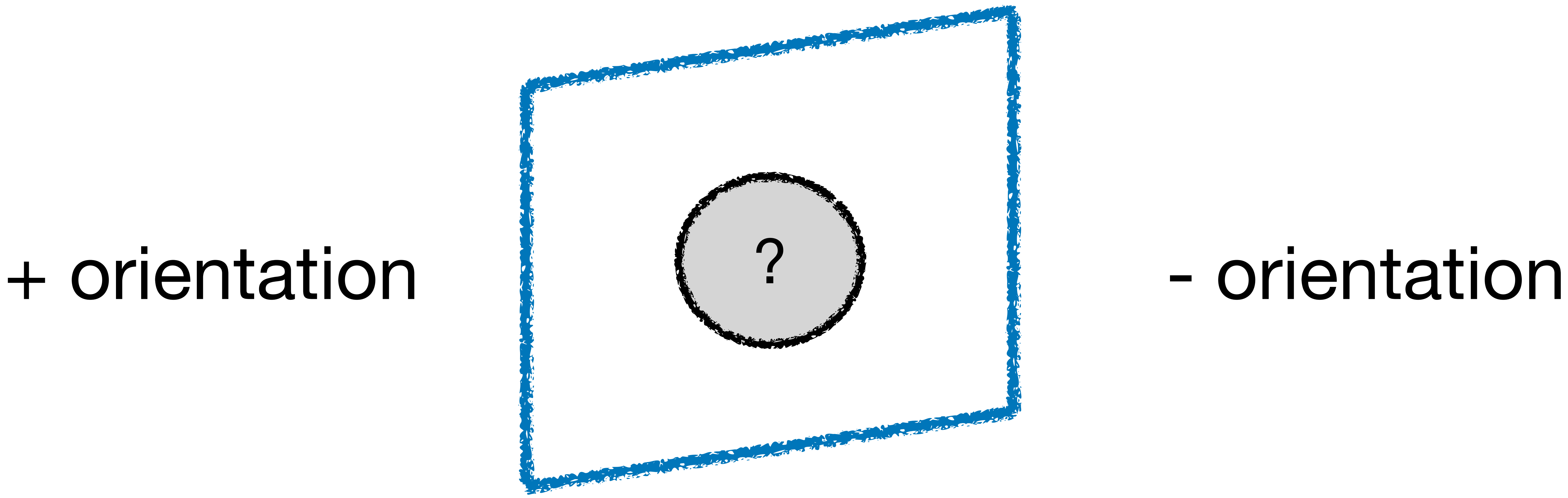
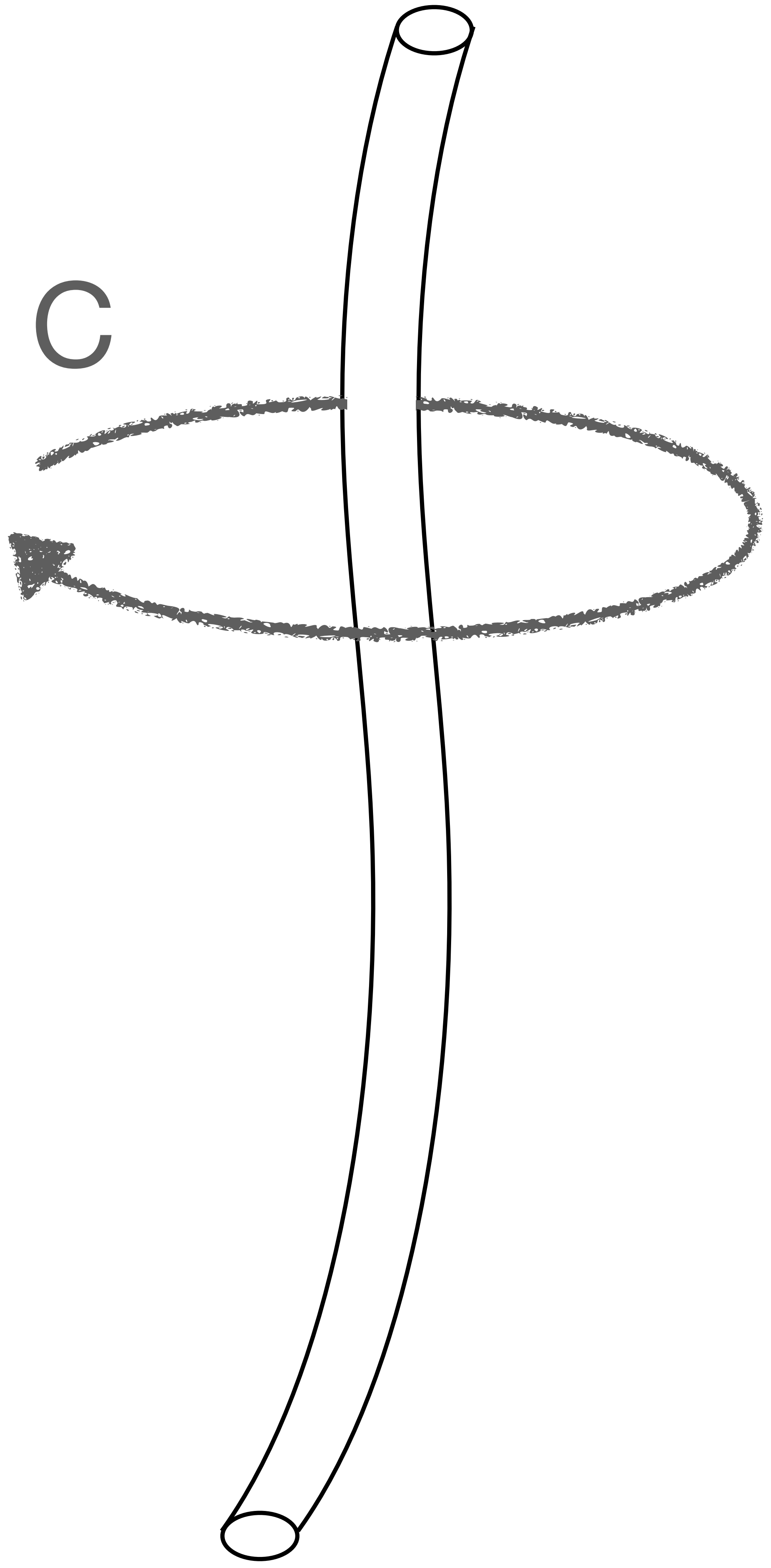


To open a hole in a parity domain wall, must go through topology change of the underlying manifold

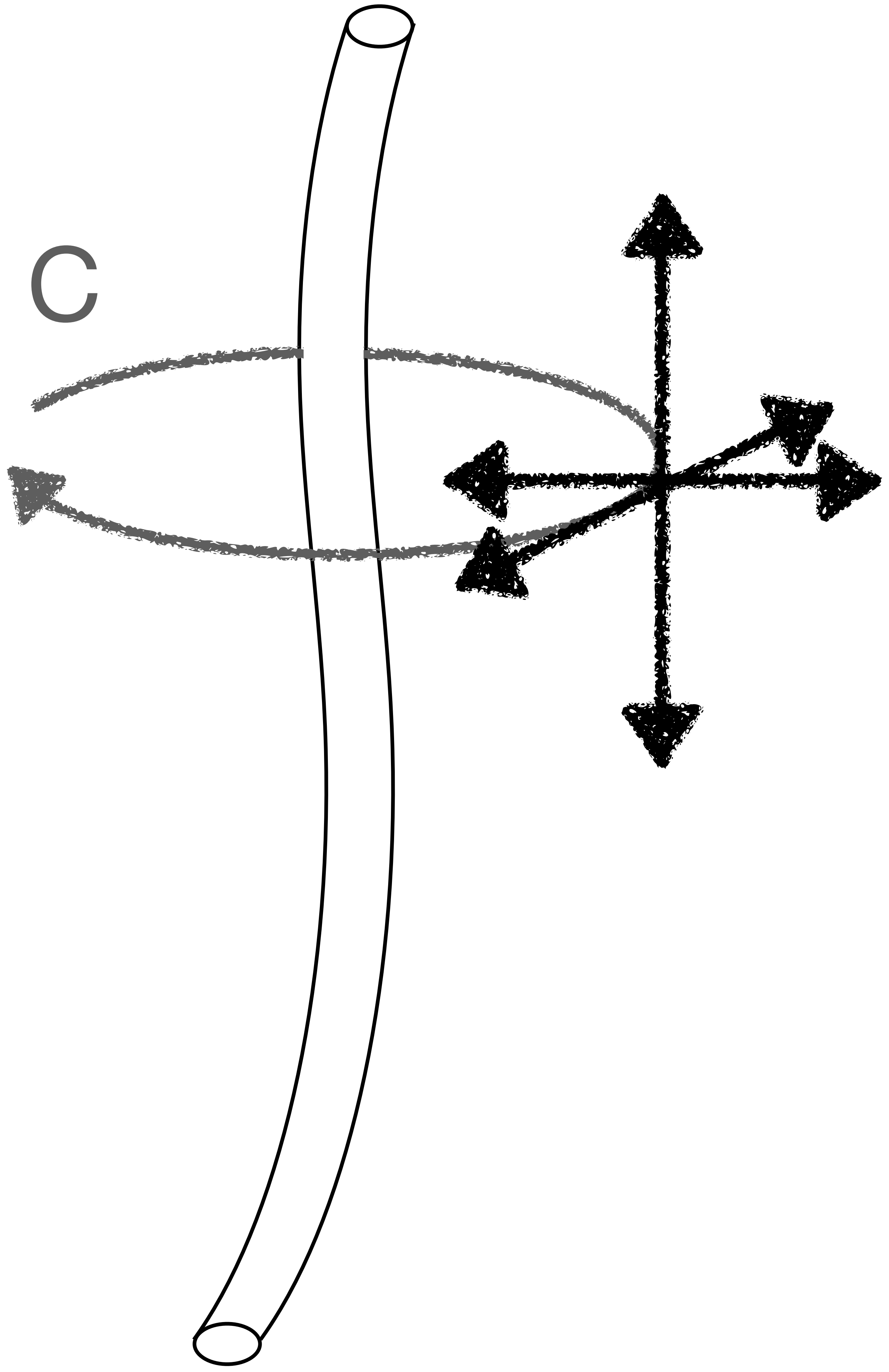
String-like object cannot cause parity flip



Let’s assume a parity string exist.

We want the string to implement a parity transformation as we go around it, along trajectory C.

String-like object cannot cause parity flip



Parity transformation in up-down or left-right direction will destroy the string configuration

The only direction left is front-back: but there is no continuous way to do a front-back flip as you traverse a circle

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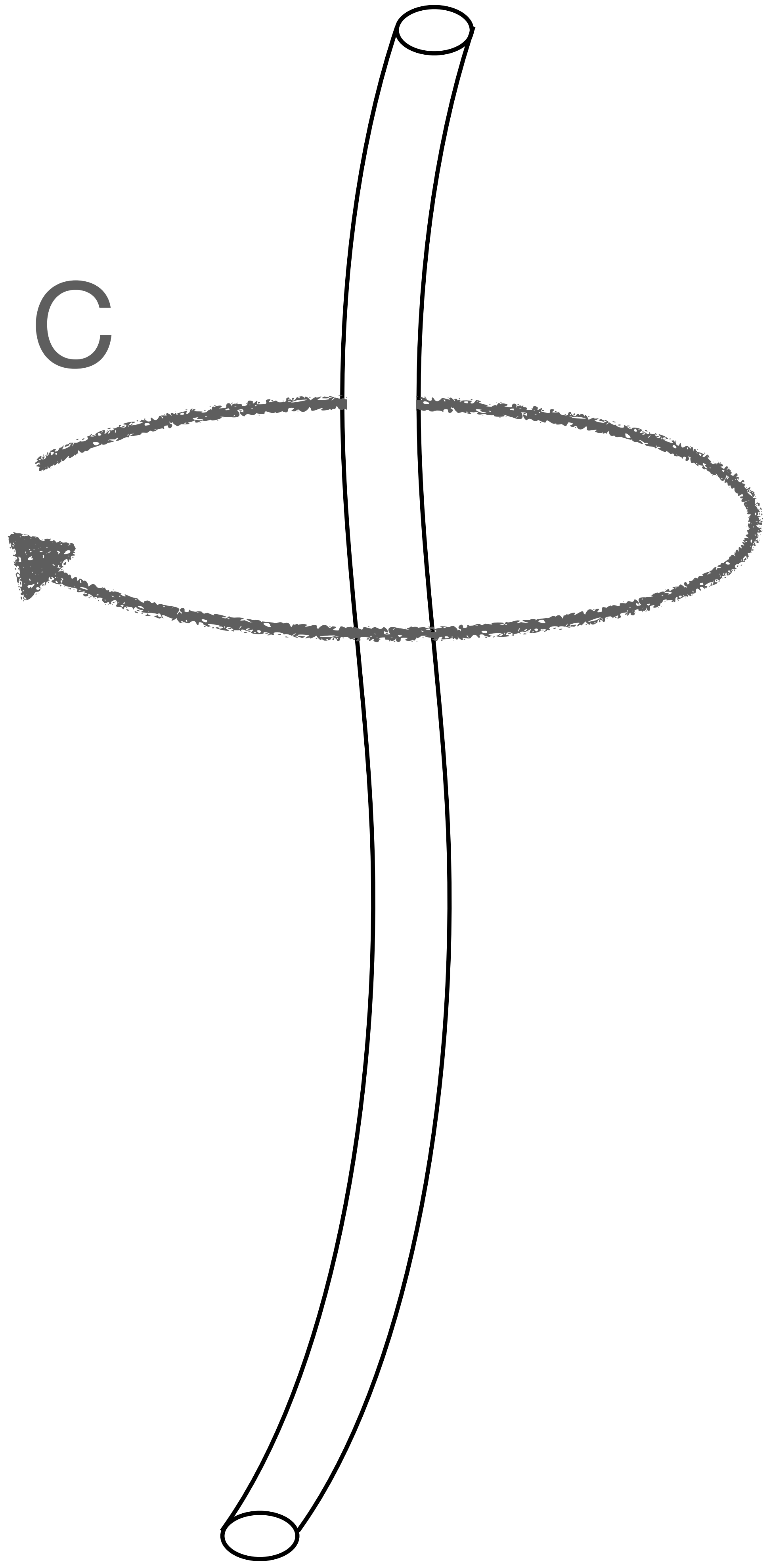


Parity transformation in up-down or left-right direction will destroy the string configuration

The only direction left is front-back: but there is no continuous way to do a front-back flip as you traverse a circle

all closed, 1-dimensional manifolds are orientable, i.e. parity string cannot exist

Getting rid of domain walls: Parity symmetry

Domain walls from spontaneous breaking of parity
(or parity with any internal symmetry attached to it)

Global: ~~DWs are stable~~

~~Gauged:~~

[McNamara & Reece 2212.00039]
Parity string does not exist

Inflate away

Part 2: Nelson-Barr Quality Problem and Cosmology

A Minimal Nelson-Barr construction

Bento, Branco, Parada (BBP) '91

Add to SM a pair of vector-like fields with quantum numbers of bottom-type quarks, $D\ \bar{D}$ and N pesudoscalars η_a

Assume CP symmetry, and a discrete symmetry $\mathbb{Z}_N$

$$\eta_a \to e^{2\pi i k/N}\eta_a, \quad D \to e^{-2\pi i k/N} D, \quad \bar{D} \to e^{2\pi i k/N}\bar{D}$$

The down-type quark Lagrangian is then

$$\mathcal{L} \supset \mu_D \bar{D} D + (\lambda_d)^i_j Q_i H^c \bar{d}^j - f^a_i \eta_a D \bar{d}^i + \text{h.c}$$

where all parameters are real because of CP

$Q_i H^c \bar{D}\ \ \eta_a \bar{D} D$ terms forbidden because of $\mathbb{Z}_N$

A Minimal Nelson-Barr construction

Bento, Branco, Parada (BBP) '91

Assume that the scaler potential generates complex vevs, $\langle \eta_a \rangle$

At tree level, $\mathcal{L} \supset (Q \quad D) \begin{pmatrix} \lambda_d v/\sqrt{2} & 0 \\ \sum_a f_i^a \langle \eta_a \rangle & \mu_D \end{pmatrix} \begin{pmatrix} \bar{d} \\ \bar{D} \end{pmatrix}$

$$\equiv (Q \quad D)\, \mathcal{M}_0 \begin{pmatrix} \bar{d} \\ \bar{D} \end{pmatrix}$$

$$\Rightarrow \bar{\theta} = \theta + \arg\det \mathcal{M}_0 = 0 \;\checkmark$$

Effective mass matrix for the Standard Model quarks:

$$(m_0^2)^i_{\ j} = (m_d)^i_{\ k} \left(\delta^k_l + \underbrace{\frac{F^{\dagger k} F_l}{F_p F^{\dagger p} + \mu_D^2}}_{\mathcal{O}(1)\ \text{complex phase}} \right) (m_d^T)^l_{\ j}, \quad F_i \equiv \sum_a f_i^a \langle \eta_a \rangle$$

The Nelson-Barr "Quality" Problem

Corrections from higher-dimensional operators to $\bar{\theta}$:

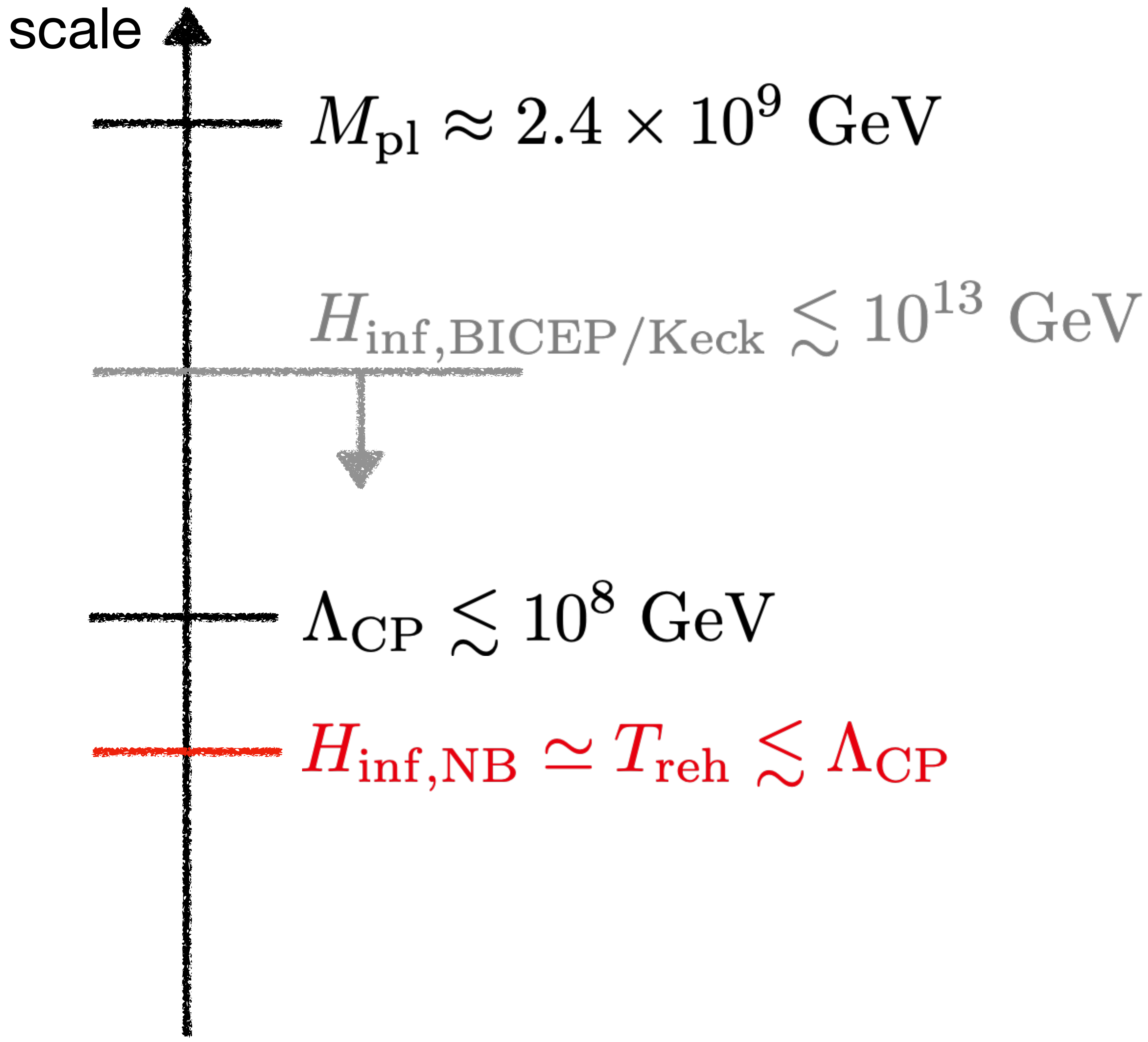
$$\frac{1}{\Lambda_{\mathrm{EFT}}}\eta_a^\dagger \eta_b \bar{D} D, \quad \frac{1}{\Lambda_{\mathrm{EFT}}}\eta_a^\dagger Q_i H^c \bar{D}$$

From dimensional analysis: $\Delta\bar{\theta} \sim \dfrac{\Lambda_{\mathrm{CP}}}{\Lambda_{\mathrm{EFT}}}$

CP breaking scale cannot be too large:

$$\Lambda_{\mathrm{EFT}} = M_{\mathrm{pl}} \Rightarrow \Lambda_{\mathrm{CP}} \lesssim 10^8 \mathrm{GeV}$$

Inflation scale must be lower



Cosmological implications of $H_{\rm inf} \lesssim 10^8~{\rm GeV}$

Inflation model building

Tensor-to-scalar ratio directly measure the scale of inflation:

$$r \equiv \frac{\mathcal{P}_T}{\mathcal{P}_\zeta} \approx 10^8 \frac{H_{\rm inf}^2}{M_{\rm pl}^2}$$

Current bound from BICEP/Keck:

$$r < 0.036$$

From the constraint that inflation happens after spontaneous CP breaking:

$$r \leq 1.7 \times 10^{-13} \left(\frac{\Lambda_{\rm CP}}{10^8~{\rm GeV}} \right)^2$$

Cosmological implications of $H_{\rm inf} \lesssim 10^8\ {\rm GeV}$

Gravitational waves from cosmic string

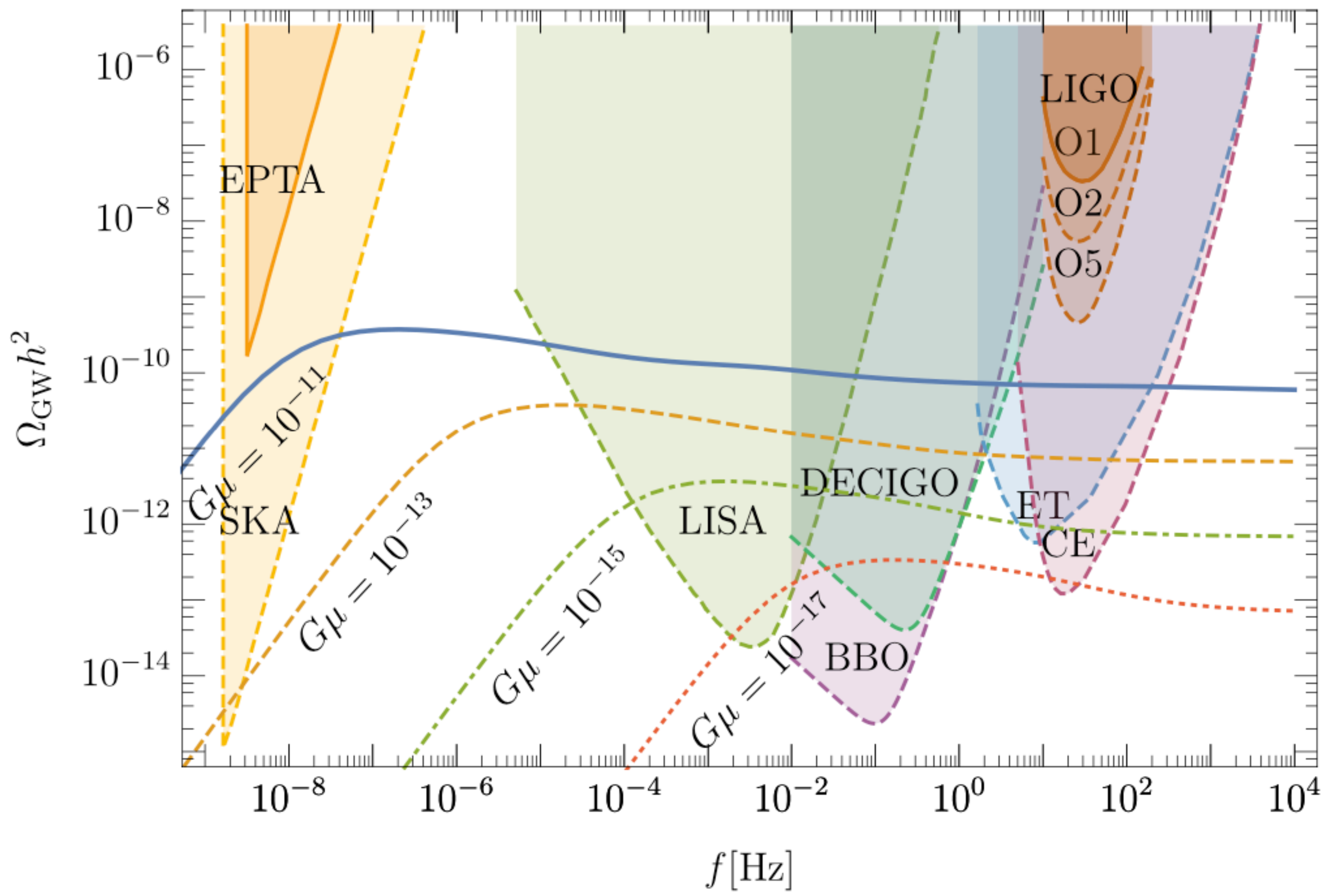
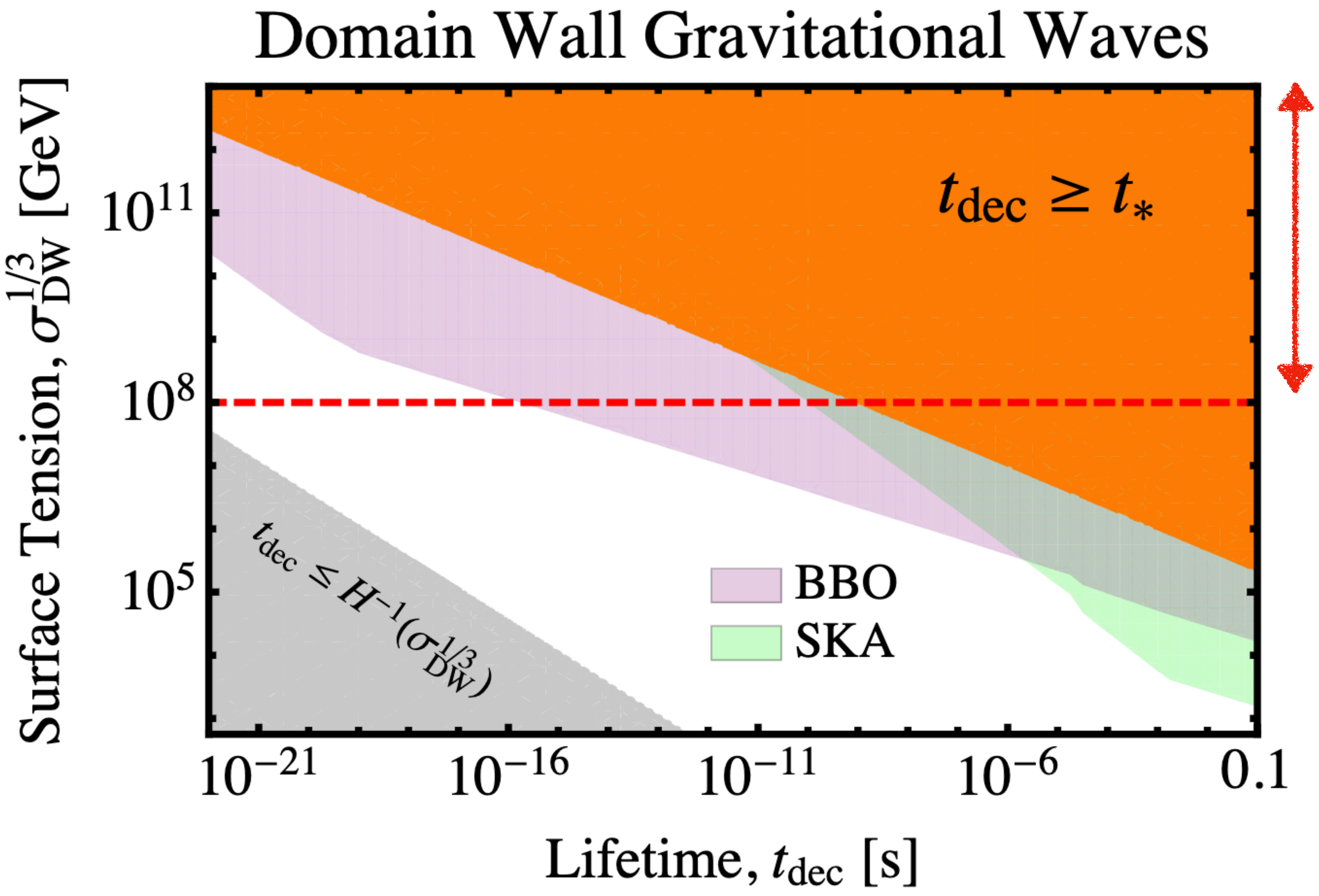


Image from [Cui, Lewicki, Morrissey, Wells '19]

Detection of gravitational wave from cosmic string
rules out minimal Nelson-Barr

Cosmological implications of $H_{\rm inf} \lesssim 10^8$ GeV

Gravitational waves from OTHER domain walls

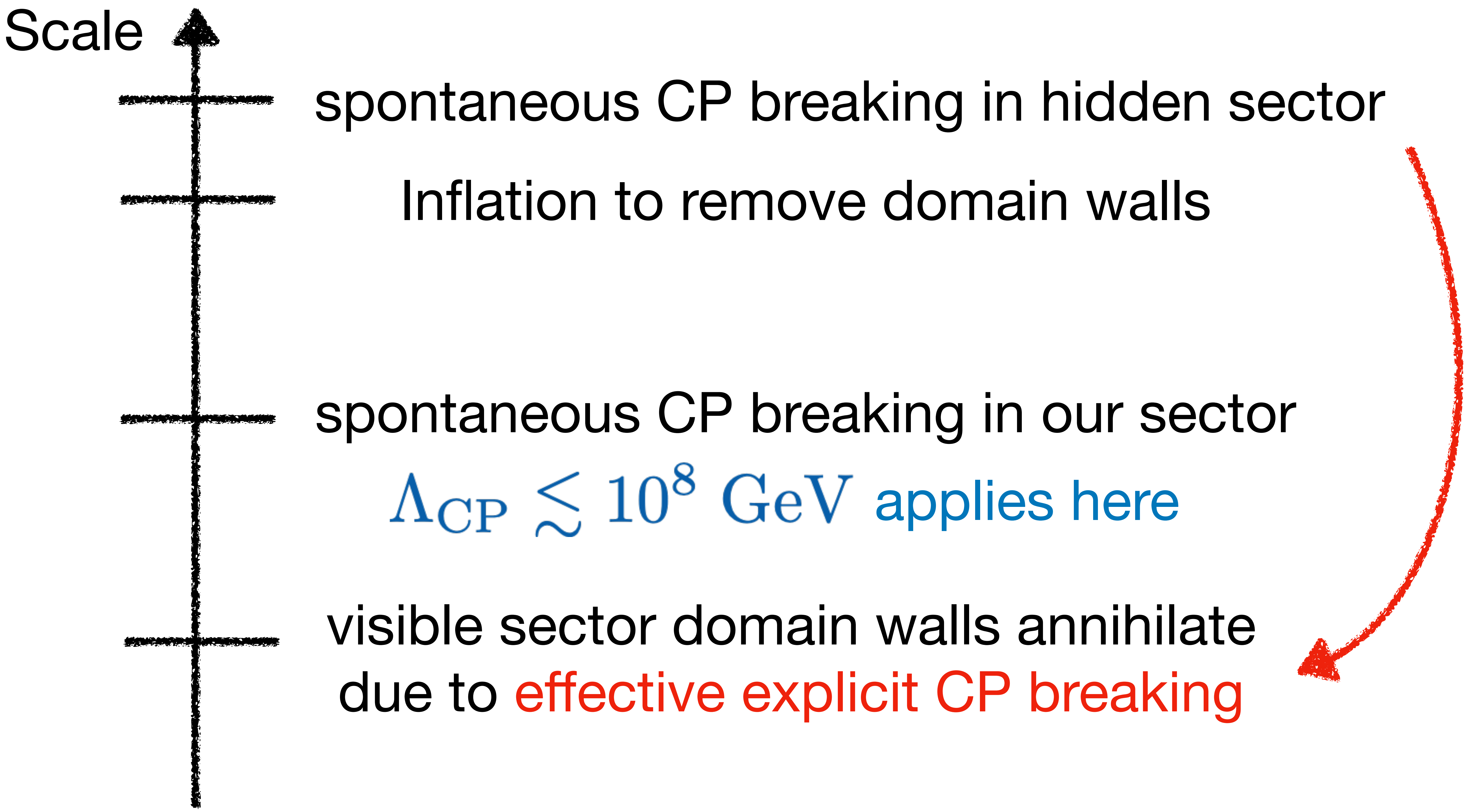


Calculation method from [Hiramatsu, Kawasaki, Saikawa ’13]

To make inflation high scale again

Two possible solutions:

1. sequester CP breaking in a hidden sector



Challenges: keeping $\bar{\theta}$ small enough, fast annihilation of DWs, etc

To make inflation high scale again

Two possible solutions:

2. Alleviate quality problem by forbidding higher-dimensional operators:

chiral Nelson-Barr models

Chirally charging D, $\bar{D}$ under a new symmetry $U(1)_X$ will forbid the dimension-5 operators

$$\frac{1}{\Lambda_{\rm EFT}}\eta_a^\dagger \eta_b \bar{D} D, \quad \frac{1}{\Lambda_{\rm EFT}}\eta_a^\dagger Q_i H^c \bar{D}$$

Need a new scalar ρ to give masses to D, $\bar{D}$

$$\mathcal{L} \supset -y_D \rho D \bar{D}, \quad \mu_D = y_D \langle \rho \rangle$$

The rest of the model is the same as the minimal Nelson-Barr construction

See also [Valenti, Vecchi '21]

To make inflation high scale again

Chiral Nelson-Barr

To cancel anomalies, need to add another set of fermions, $B, \bar{B}$

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$
D	$\mathbf{3}$	$-$	$-1/3$	-1
$\bar{D}$	$\bar{\mathbf{3}}$	$-$	$+1/3$	-5
B	$\mathbf{3}$	$-$	$+1/3$	$+1$
$\bar{B}$	$\bar{\mathbf{3}}$	$-$	$-1/3$	$+5$
ρ	$-$	$-$	0	$+6$
η_a	$-$	$-$	0	$+2$

$U(1)_X$ is taken to be a linear combination of hyper charge and B-L, which is always anomaly free for SM

To make inflation high scale again

Chiral Nelson-Barr

All possible dimension-5 operators are forbidden.
Quality problem arise again at dimension-6:

$$\eta_a^\dagger \eta_b \rho D\bar{D}, \quad \eta_a^\dagger \rho Q_i H^c \bar{D}, \quad \eta_a \eta_b \eta_c^\dagger D\bar{d}_j$$

Correction to $\bar{\theta}$ is now

$$\Delta\bar{\theta} \simeq \frac{1}{y_D}\frac{\Lambda_{\rm CP}^2}{\Lambda_{\rm EFT}^2} \Rightarrow \Lambda_{\rm CP} \lesssim 10^{13}\ {\rm GeV}$$

Now the scale of CP breaking is high enough to recover most of the cosmology we are familiar with

Conclusion

- Despite the long history of the Nelson-Barr mechanism, consequences of spontaneous parity breaking has only been clarified recently
- Spontaneous breaking of CP leads to exactly stable domain walls [McNamara & Reece 2212.00039], which must be inflated away
- Nelson-Barr quality problem: the scale of spontaneous CP breaking cannot be too high
- These facts lead to phenomenological consequences of otherwise unconstrained Nelson-Barr models
- Chiral Nelson-Barr models is one set of solution to the domain wall-quality problem. Other possibilities and their phenomenological consequences remain to be explored.

Cosmological implications of $H_{\rm inf} \lesssim 10^8\ \mathrm{GeV}$

Inflation model building

Such a low-scale inflation require extremely flat potential,

$$\epsilon \equiv \frac{M_{\rm pl}^2}{2}\left(\frac{V'}{V}\right)^2 = \frac{r}{16}$$

And extremely small field inflation,

$$\frac{\Delta\phi}{M_{\rm pl}} \lesssim 10^{-6}.$$

Cosmological implications of $H_{\rm inf} \lesssim 10^8\ \rm GeV$

thermal leptogenesis

With some mild assumptions about reheating, we also have

$$T_{\rm reh} \leq H_{\rm inf} \lesssim 10^8\ \rm GeV$$

Constrains baryogenesis scenario where baryon asymmetry comes from asymmetric decay of thermal particles.

e.g. leptogenesis: $\delta \equiv \dfrac{\Gamma_{N\to H v} - \Gamma_{N\to H\bar{v}}}{\Gamma_{N\to H v} + \Gamma_{N\to H\bar{v}}}$

[Davidson & Ibarra bound ’02]

$$\delta \lesssim \frac{3}{8\pi}\frac{M_N m_v}{v^2} \Rightarrow T_{\rm reh} \gtrsim 10^{8-10}\ \rm GeV$$