Magnetic helicity, monopoles, and baryon asymmetry

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arXiv:2509.25734 + H. Fukuda (Tokyo), K. Kamada (UCAS)

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The origin of the baryon asymmetry of the universe is one of the key questions to understand our universe.

(Baryon asymmetry) $= n_B - n_{\overline{B}}$

Q: What is baryon?

This sounds a trivial question.

	Baryon	Non-Baryon
Low energy	$p, n.$	$e, \nu, \gamma, \cdots$
QCD	$u, d, \cdots$	g
SM	$u, d, \cdots$	$e, \nu, g, \cdots$

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Low energy	$p, n.$		$e, \nu, \gamma, \cdots$
QCD	$u, d, \cdots$		g
SM	$u, d, \cdots$	?	$e, \nu, g, \cdots$

Talk Plan

1. Magnetic fields $=$ baryons
2. Magnetic fields $\neq$ baryons
3. Potential Implications

Talk Plan

1. Magnetic fields = baryons
2. Magnetic fields ≠ baryons
3. Potential Implications

Massless QED

We consider QED with massless fermions (+ Higgs later).

Here, (baryon number) = (chiral charge).

ABJ anomaly allows us to identify magnetic field with baryon number.

$$dJ_5 = -\frac{e^2}{4\pi^2} F \wedge F.$$

We have conservation law:

$$\frac{d}{dt}\left[\text{(chiral charge)} + \text{(helicity } \mathscr{H}\text{)}\right] = 0.$$

Helicity $\mathscr{H}$

$\mathscr{H}$ is defined as $\mathscr{H} := \int d^3x \, \overrightarrow{A} \cdot \overrightarrow{B}$.

Taking time derivative, we get

$$\frac{\partial \mathscr{H}}{\partial t} = \int d^3x \, \overrightarrow{E} \cdot \overrightarrow{B} \qquad \rightarrow \qquad \Delta \mathscr{H} = \int F \wedge F \sim \int d^4x \, \overrightarrow{E} \cdot \overrightarrow{B}.$$

However, this is modified in the presence of magnetic monopoles.

This has implications on baryogenesis scenario from magnetic helicity.

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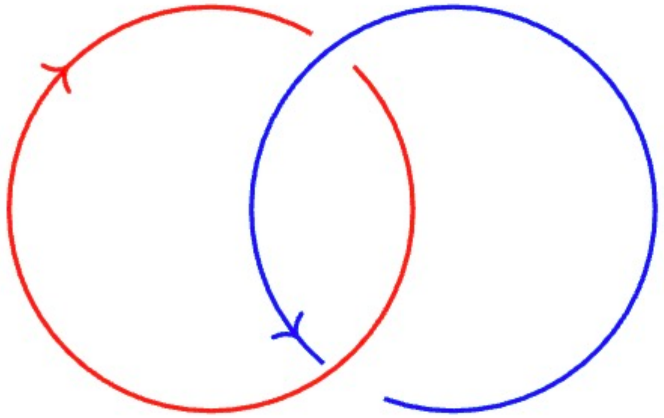
Magnetic field
confined on string.



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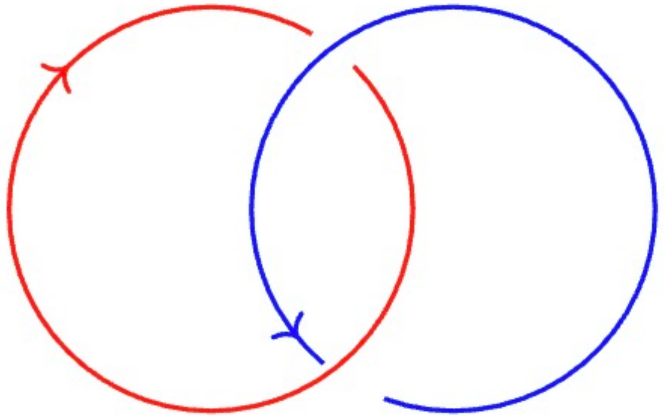
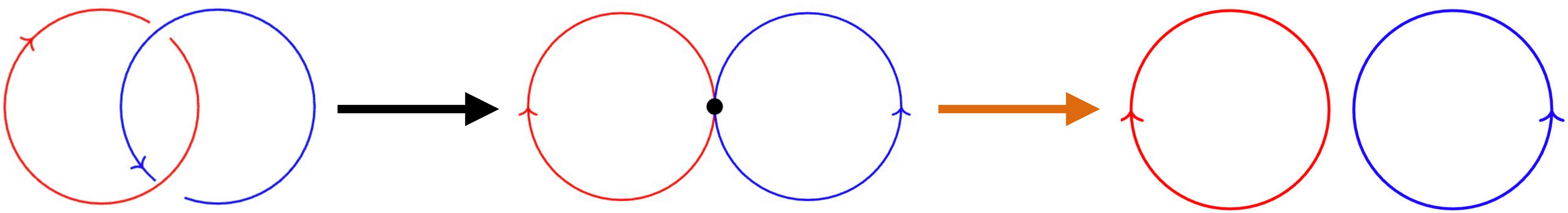
$$\mathscr{H} = 2 \times (\text{linking number}) + \cdots$$



(Linking number) $= 1,\ \mathscr{H} = 2.$

Magnetic fields = baryons

SSB: $U(1) \overset{\text{Higgs VEV}}{\rightarrow}$ Nothing.



Loops of
Massive magnetic fields.

Chirality is generated
through $\Delta Q_{\rm chi} \neq 0$.

cf. Baryogenesis from primordial helical magnetic field.

[Shaposhnikov+ ‘97, Kamada+ ‘16]

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UV completion

We had the conservation law.

$$\frac{d}{dt}\left[\text{(chiral charge)} + \text{(helicity } \mathscr{H}\text{)}\right] = 0.$$

This does not make sense once dynamical monopole appears by

- SSB of UV gauge group,
- Stringy effect.

$\mathscr{H}$ is NOT gauge invariant quantity.

How does the formula change?

Monopole

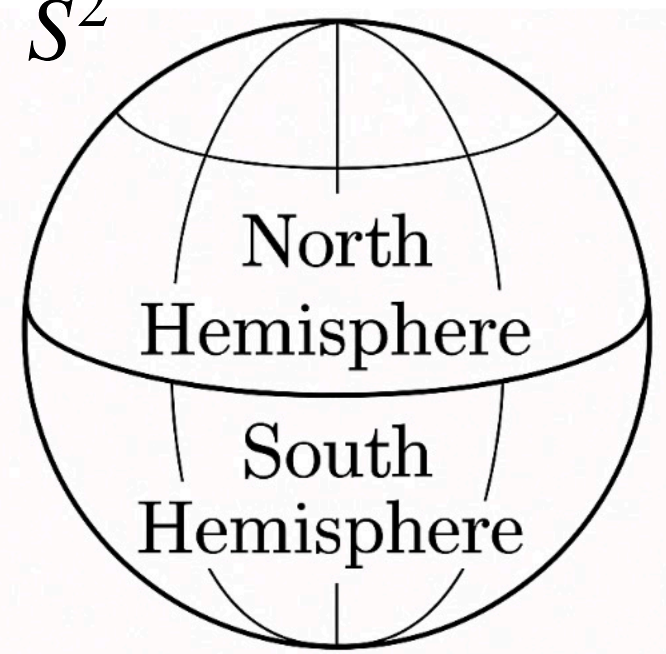
Monopole of $U(1)$ gauge field A,

characterized by configuration of A around monopole.

$\mathbb{R}^{1,3} = \mathbb{R}^{1,1} \times \mathbb{R}_{\geq 0} \times S^2$

S^2

Equator S^1



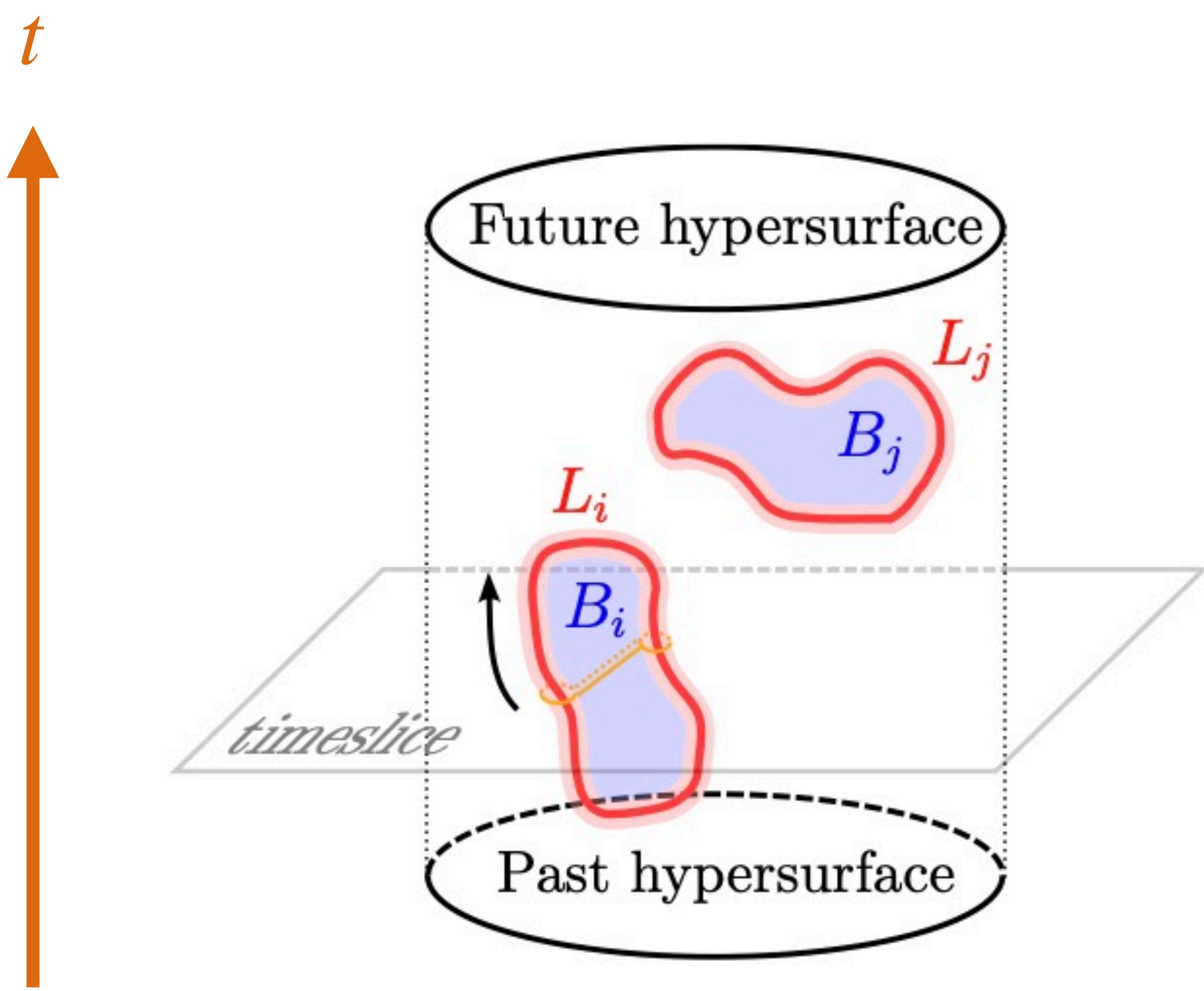
North patch A_N

South patch A_S

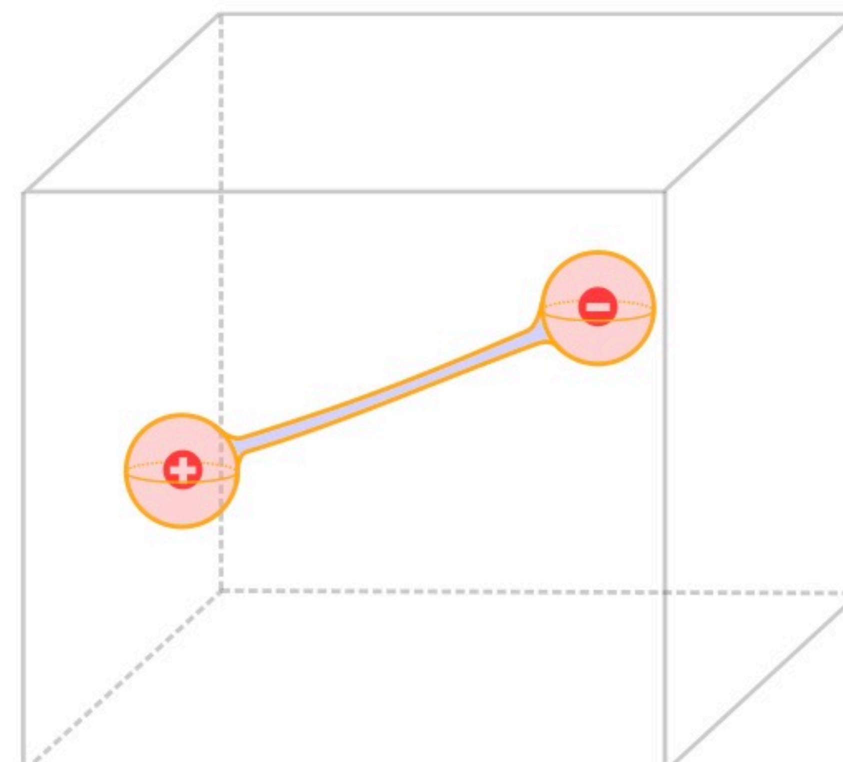
A_N and A_S are related by gauge tr. $A_N - A_S = d\Lambda$.

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

In the presence of monopoles, A is not defined globally.



t = const. slice

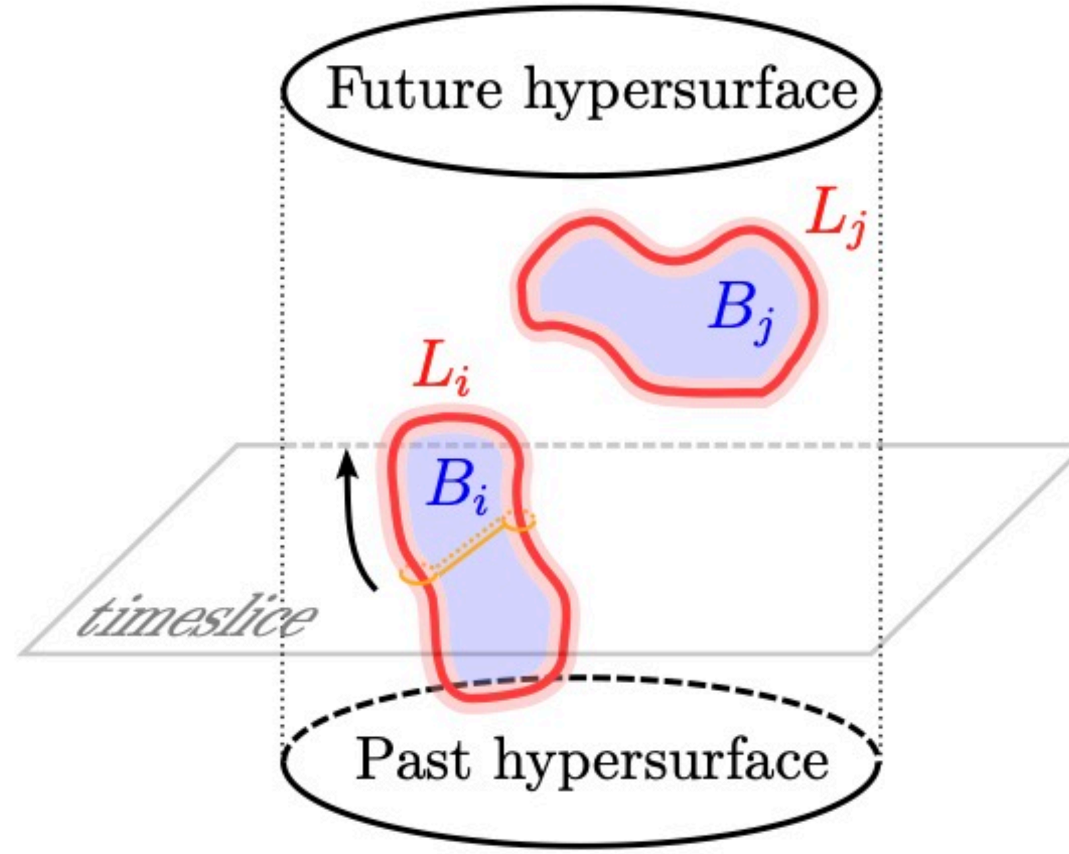


L_i: world line of monopole,

B_i: 4d region inside L_i.

A is well defined in spacetime without B_i.

M'': Spacetime without B_i.



[Fukuda, YH, Kamada, Mukaida, Uchida '25]

$$\int_{M''} F \wedge F = \mathscr{H}_{\text{future}} - \mathscr{H}_{\text{past}} + \underline{\sum_i \int_{S_i} A \wedge F}$$

Contribution from additional bry $S_i = -\partial B_i$.

c.f. previously, we had $\int F \wedge F = \mathscr{H}_{\text{future}} - \mathscr{H}_{\text{past}}$

Previous formula

$$\frac{d}{dt}\left[\text{(chiral charge)} + \text{(helicity } \mathscr{H}\text{)}\right] = 0.$$

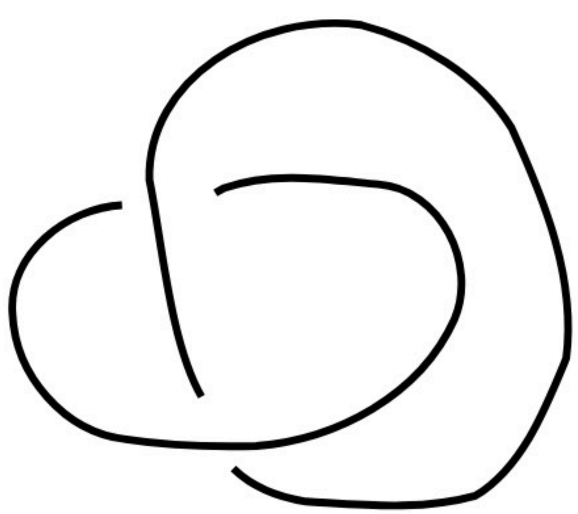
Corrected formula

$$\left[\text{(chiral charge)} + \text{(helicity } \mathscr{H}\text{)}\right]_{\text{past}}^{\text{future}} = -\sum_i \int_{S_i} A \wedge F.$$

Example: Helicity Change in Higgs Phase

Let us assume that $U(1)$ is Higgsed, and flux tube is formed.

Configuration has helicity $\mathscr{H}_{\text{past}} = 2, \quad \mathscr{H}_{\text{future}} = 0.$



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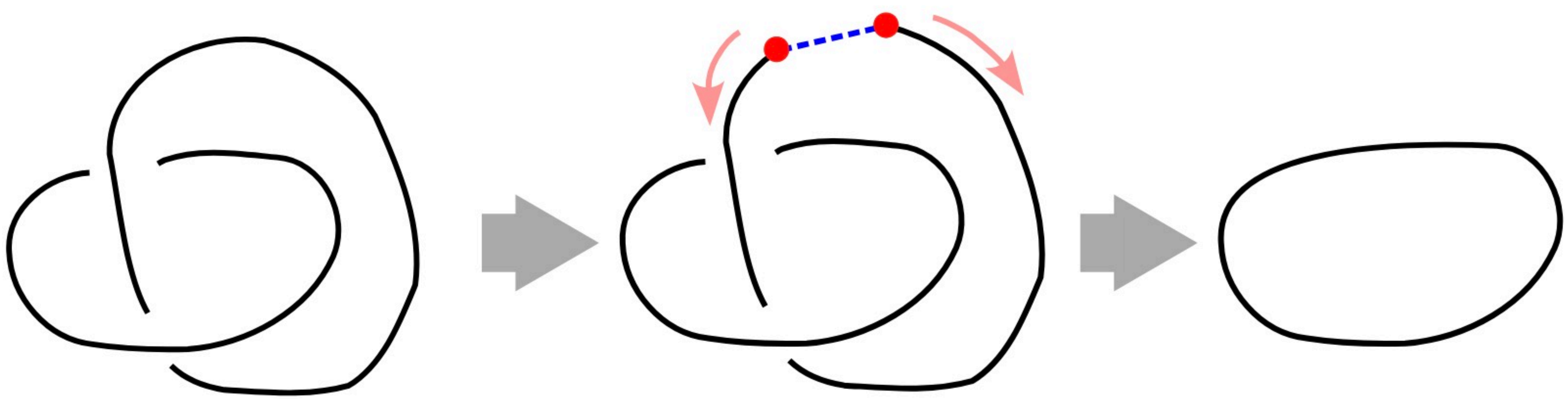

Tube may disappear by monopole pair creation.

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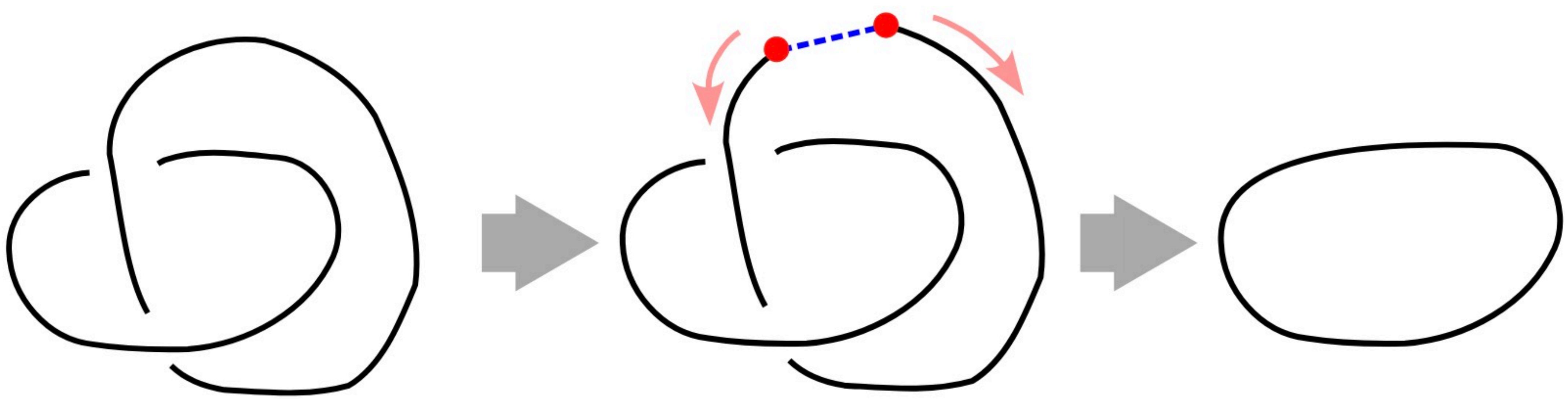
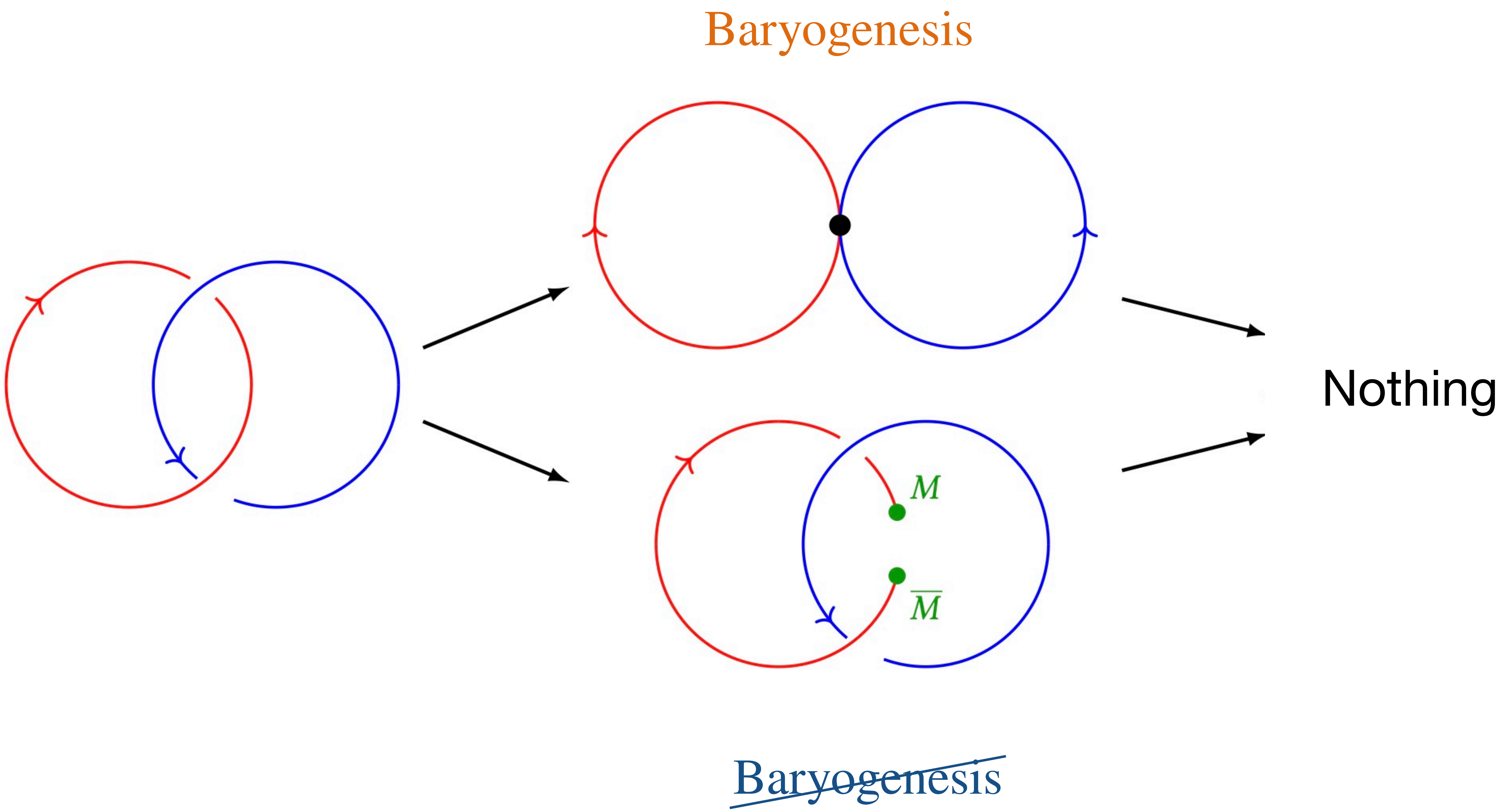


Tube may disappear by monopole pair creation.

No chiral charge production.


Baryogenesis
Nothing
M
$\overline{M}$
Baryogenesis

UV: Georgi-Glashow

$SU(2)$ gauge theory with adjoint Higgs field, Φ.

Gauge symmetry breaking:

$SU(2) \to U(1)$ by $\langle \Phi \rangle \neq 0.$

The low energy theory is $U(1)$ gauge theory
with 't Hooft Polyakov monopole.

Viewed as a UV completion of $U(1)$ gauge theory.

[Fukuda, YH, Kamada, Mukaida, Uchida '25]

Definition of helicity

Gauge invariant definition of helicity in IR U(1) gauge theory?

In low energy (massless excitation only), we find

$$\mathscr{H}_{U(1)} = \frac{16\pi^2}{g^2}\left(N_{\rm CS} + N_H\right)$$

$N_{\rm CS}$: $SU(2)$ Chern Simons Number.

N_H: Higgs winding. Define U by $UnU^\dagger = T^3$,

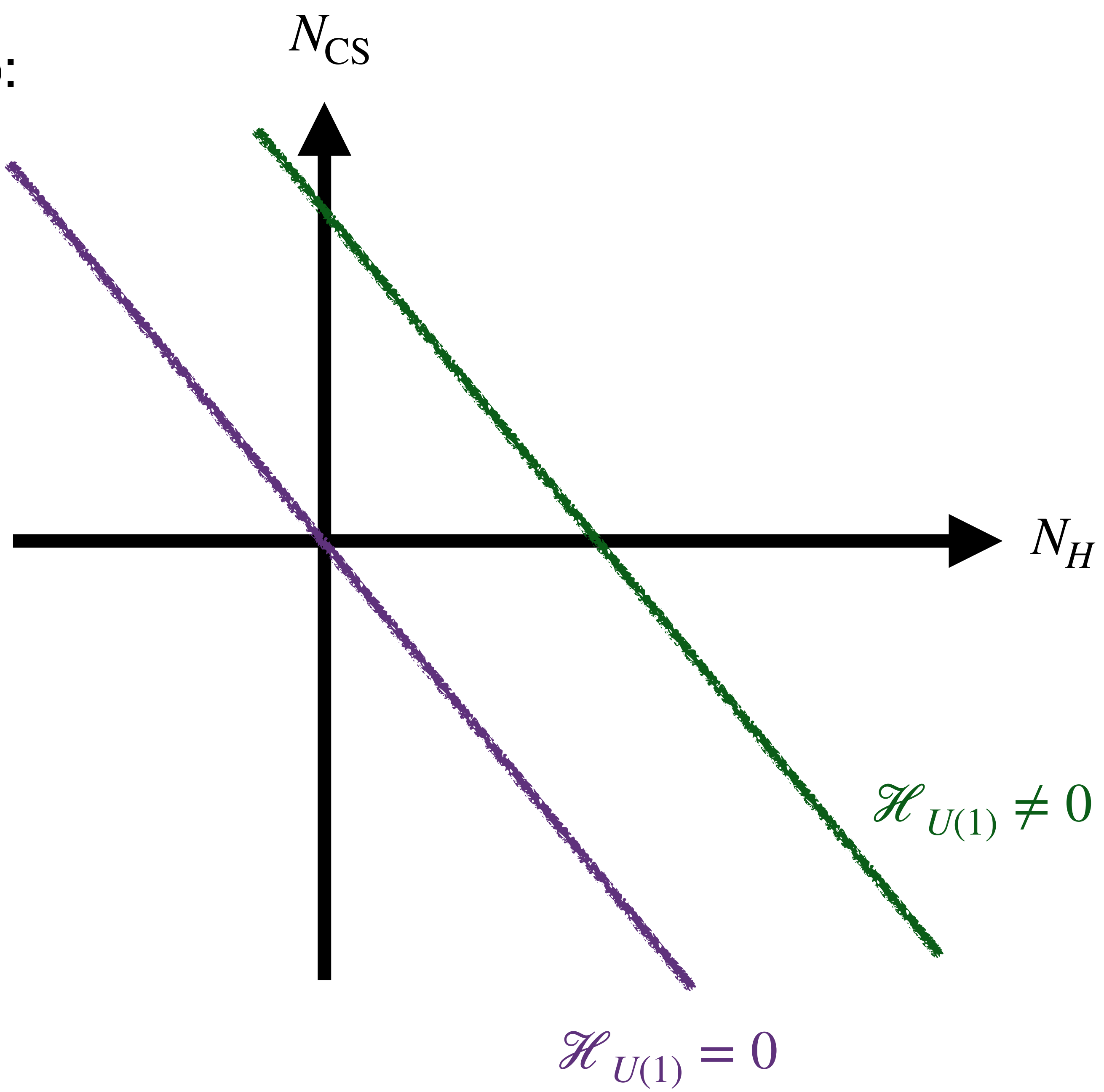
where n is Higgs field expressed by 2×2 matrix.

then $N_H = \frac{1}{24\pi^2}\int {\rm Tr}(UdU^\dagger \wedge UdU^\dagger \wedge UdU^\dagger)$.

Two paths

Suppose that Initial helicity is nonzero:

$\mathscr{H}_{U(1)} \propto N_{\rm CS} + N_H$.



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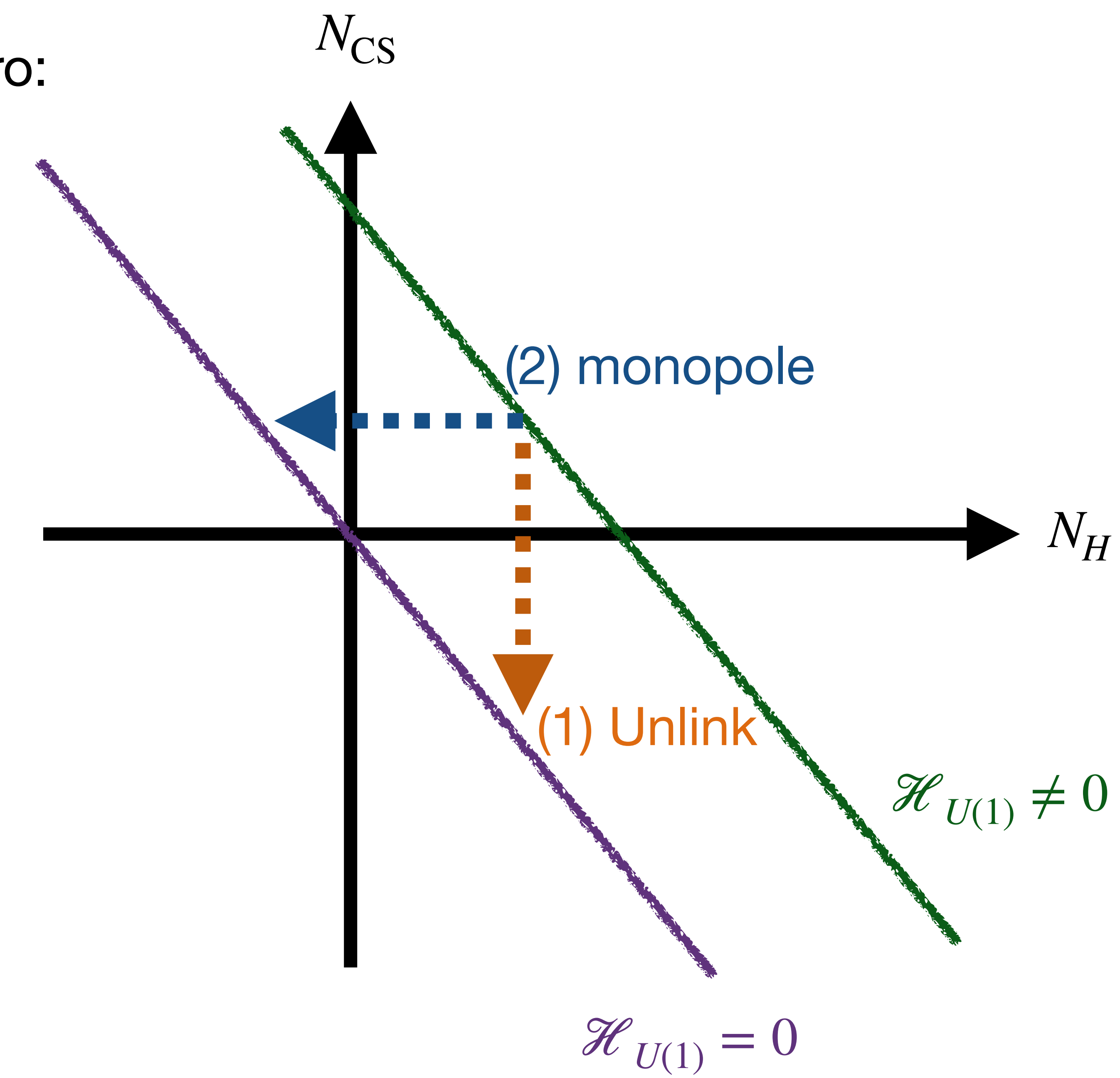
(1) $\Delta N_{\rm CS} \neq 0$

Baryogenesis

(2) $\Delta N_H \neq 0$

~~Baryogenesis~~



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[YH, Mukaida, Uchida '25]

Standard Model:

$$SU(2)_L \times U(1)_Y \to U(1)_{em}$$

We hope to discuss implications on baryogenesis from helical magnetic field, but various complications.

- Crossover
- Phase transition is one step rather than two steps.
- Unstable Z-string
- Nambu monopole pair

Quantitive prediction is difficult,
but roughly there are two possibilities.

[YH, Mukaida, Uchida '25]

Two possibilities

ABJ: $\Delta Q_{B+L} \sim \Delta N_{\rm CS}^{\rm SU(2)_L} - \Delta H_Y$.

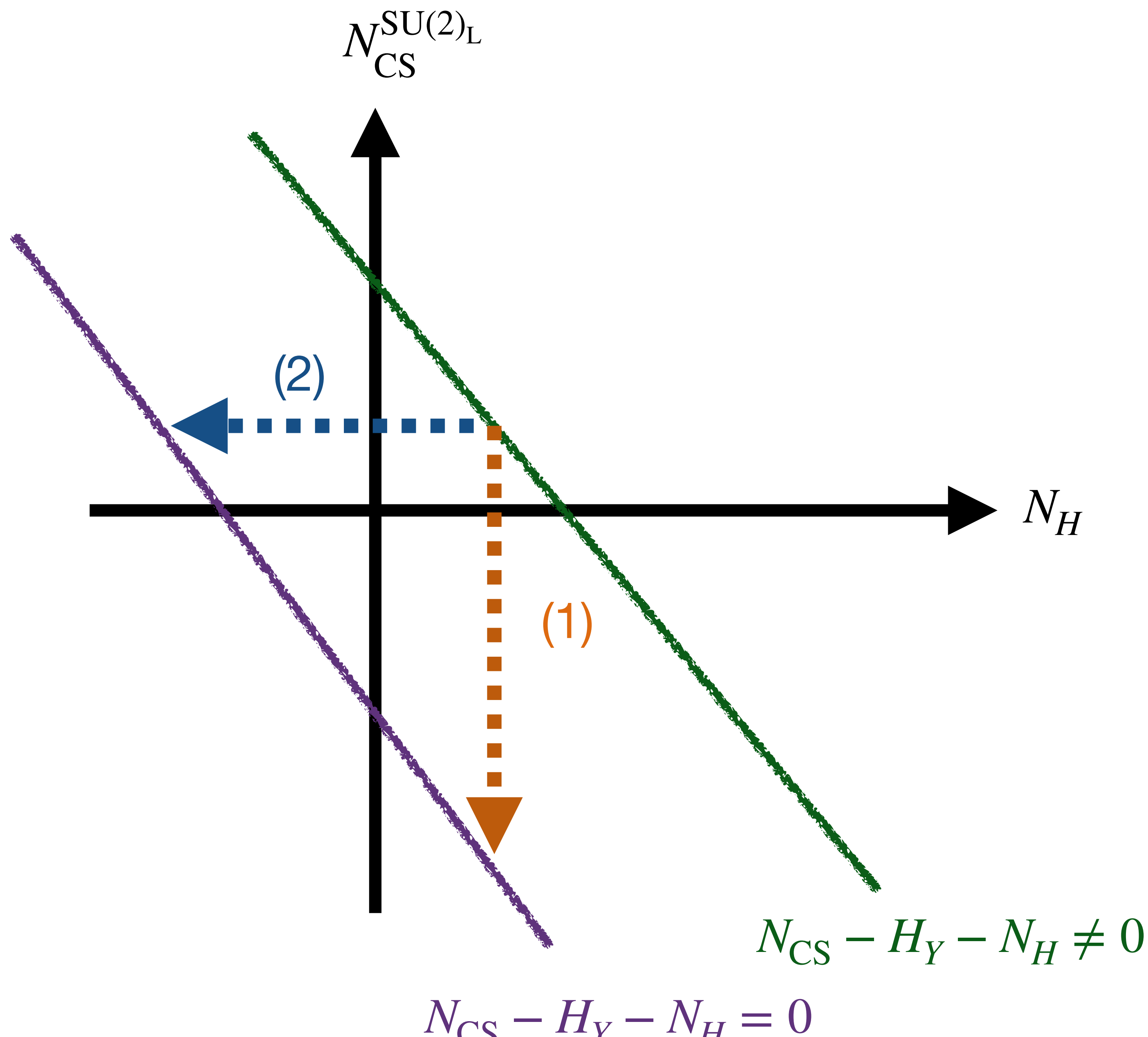
Gauge invariant quantity to measure strength of Z-magnetic field:
$N_{\rm CS} - H_Y - N_H = 0$ in IR.

(1) $N_{\rm CS}^{\rm SU(2)_L}$ changes.

Baryogenesis

(2) N_H changes.

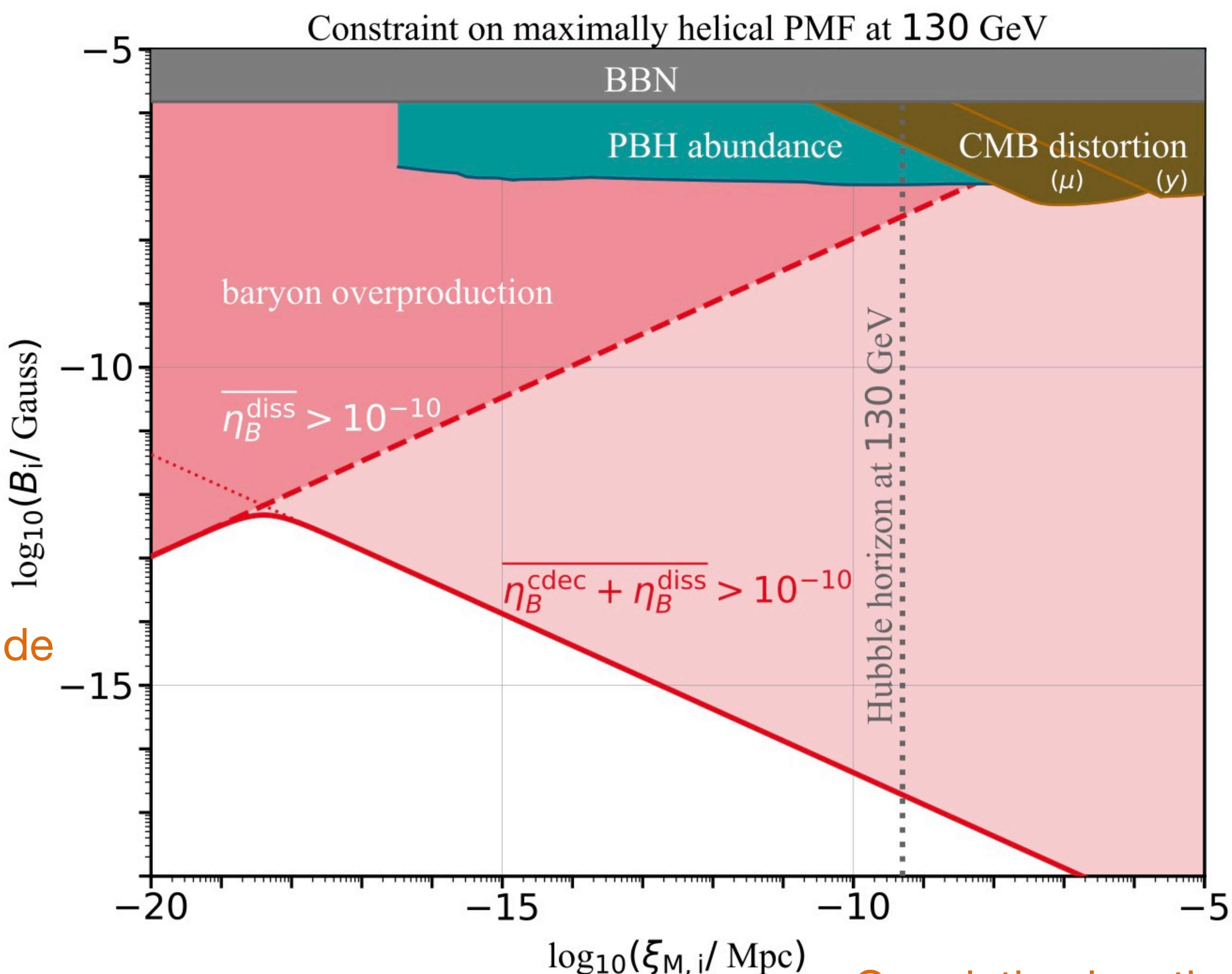
~~Baryogenesis~~



[YH, Mukaida, Uchida '25]

Light colored region: Excluded if $\Delta N_{\rm CS}^{\rm SU(2)_L} \neq 0$ is main process.

Dark colored region: Excluded if $\Delta N_H \neq 0$ is main process.



Amplitude

Correlation length

Colored regions are excluded.

[YH, Mukaida, Uchida '25]

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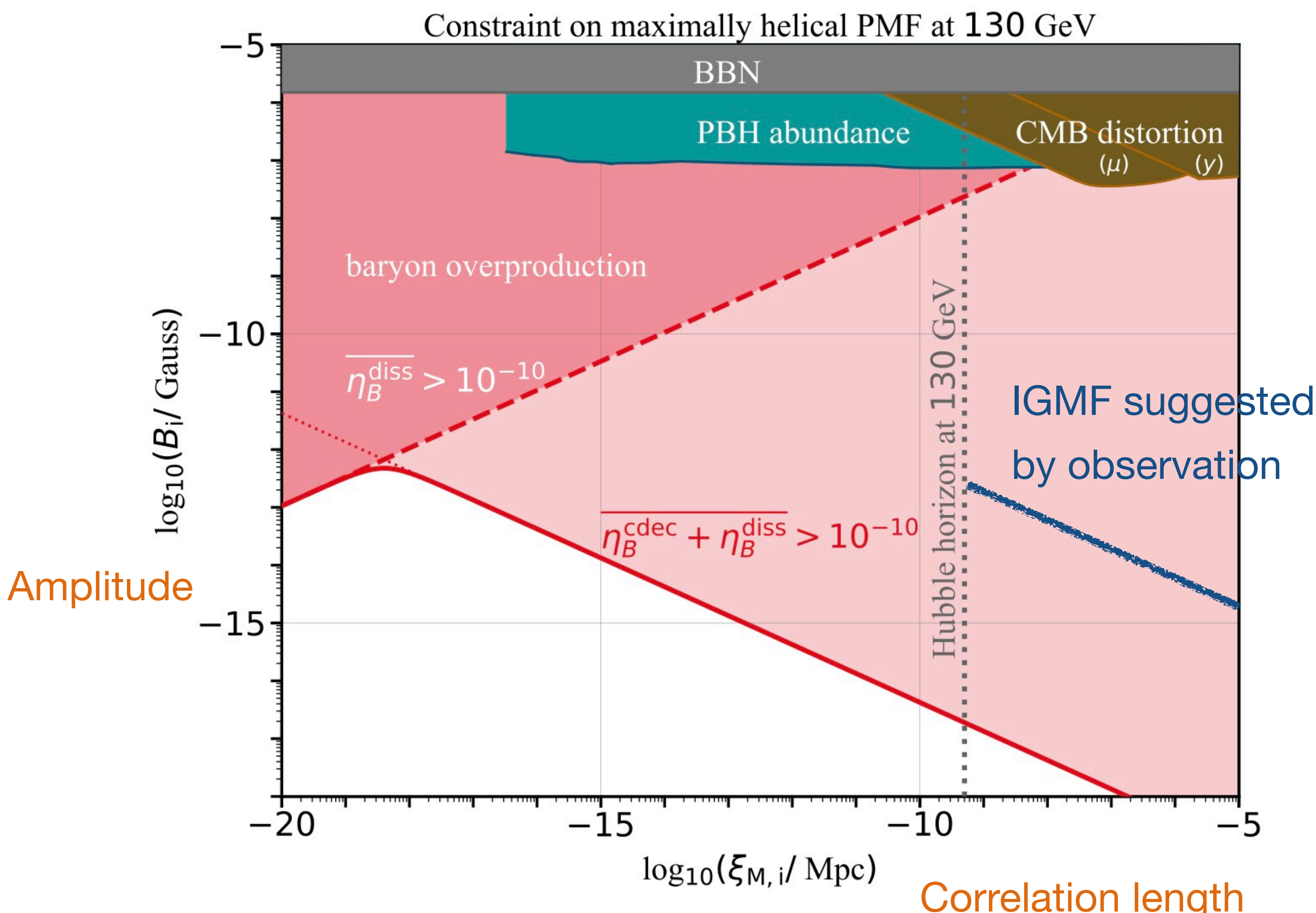

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Summary

- Helical magnetic field sometimes has baryon charge.
- Sometimes not.
- Implications for baryon asymmetry.