

電弱クロスオーバー中の宇宙磁場

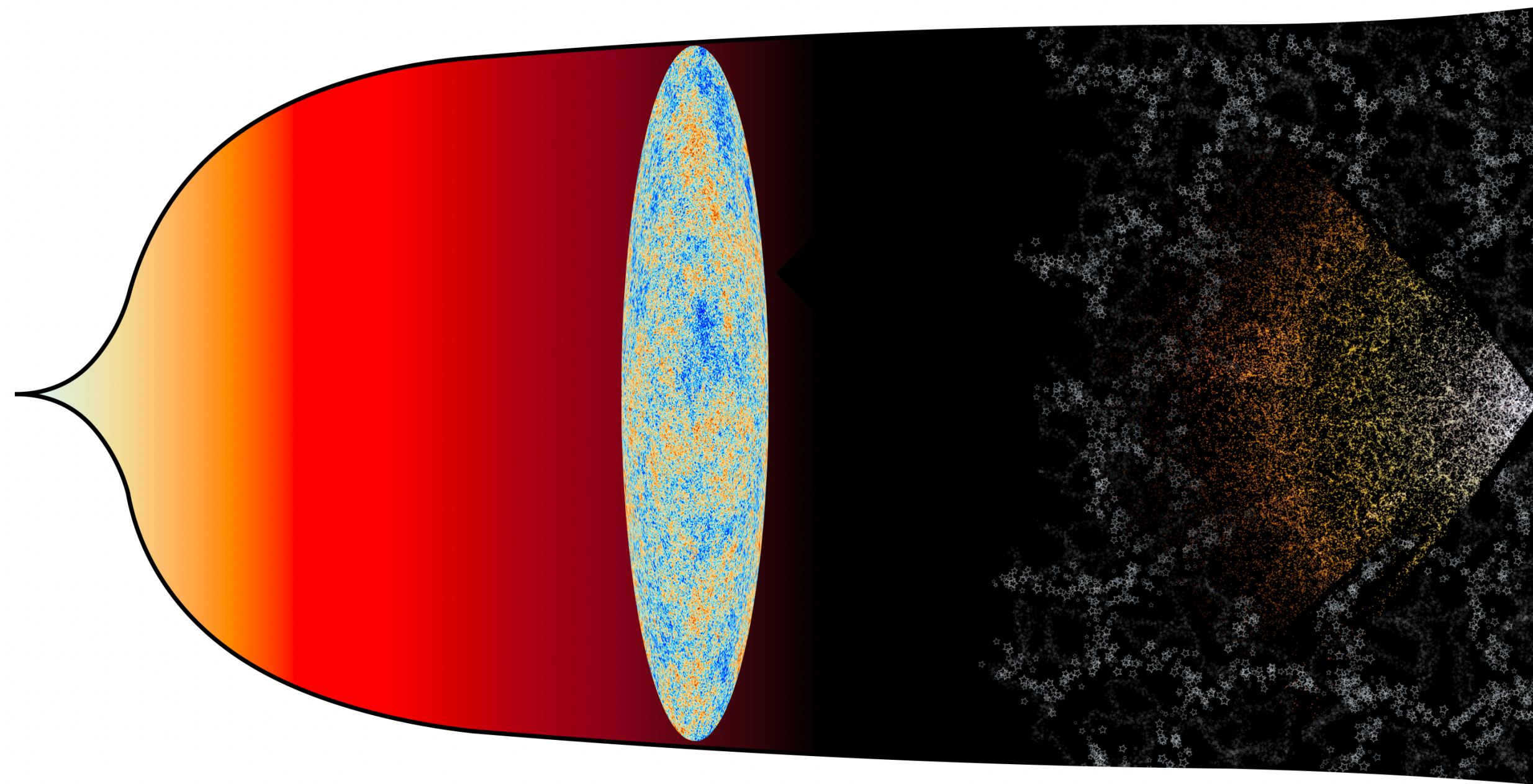
[2507.01576], [2509.xxxxx] in collab. with Kyohei Mukaida and Yuta Hamada

2025/9/2, 素粒子物理学の進展 2025 @YITP

Fumio Uchida (IPMU)

この発表の話題

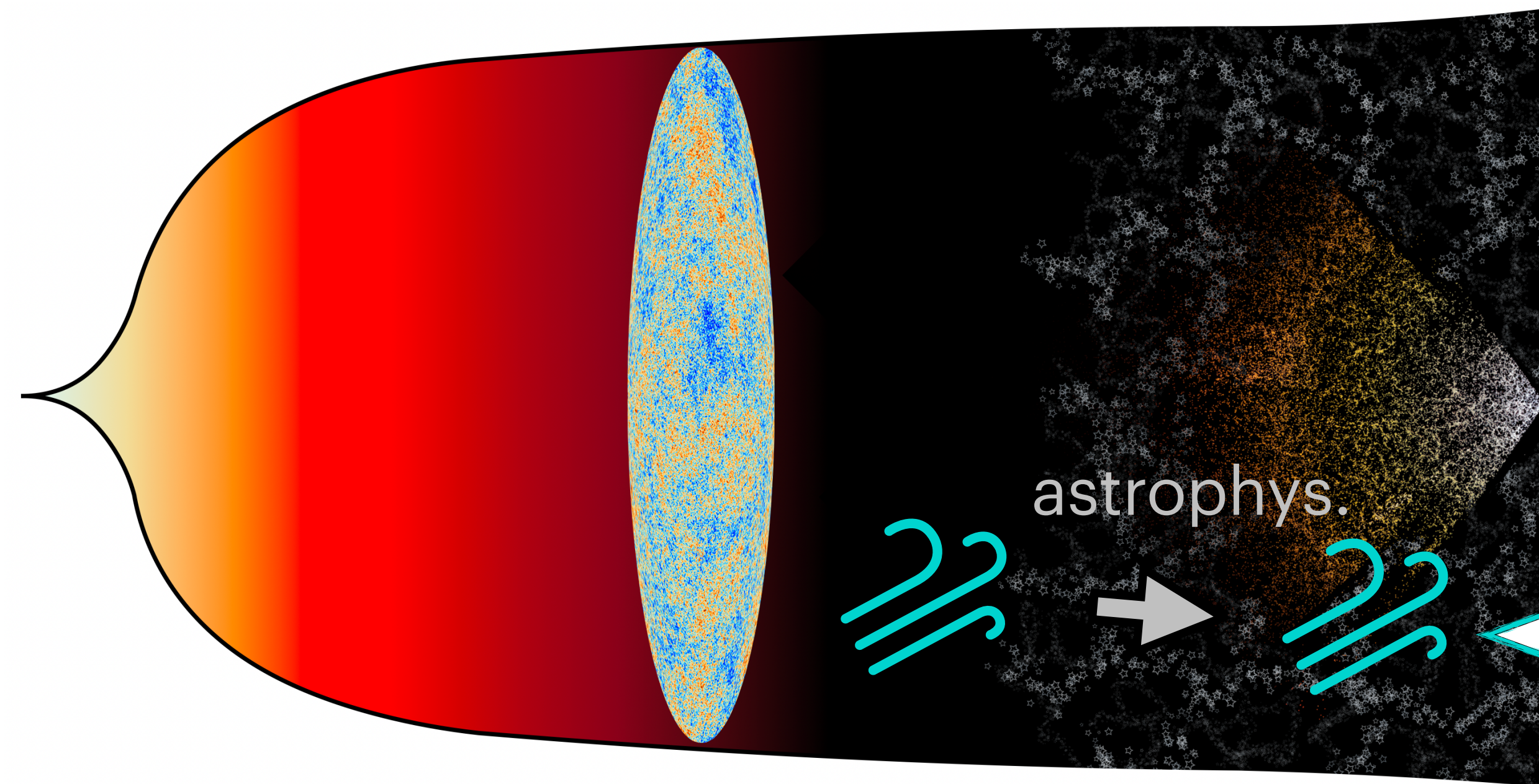
standard cosmology (Λ CDM)



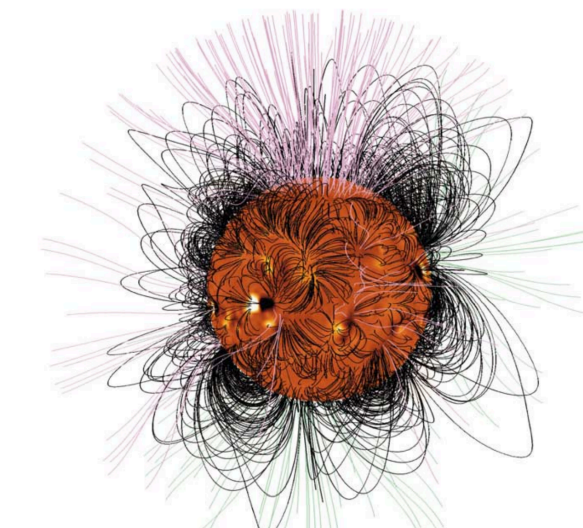
thermal plasma
in the Standard Model of particle physics

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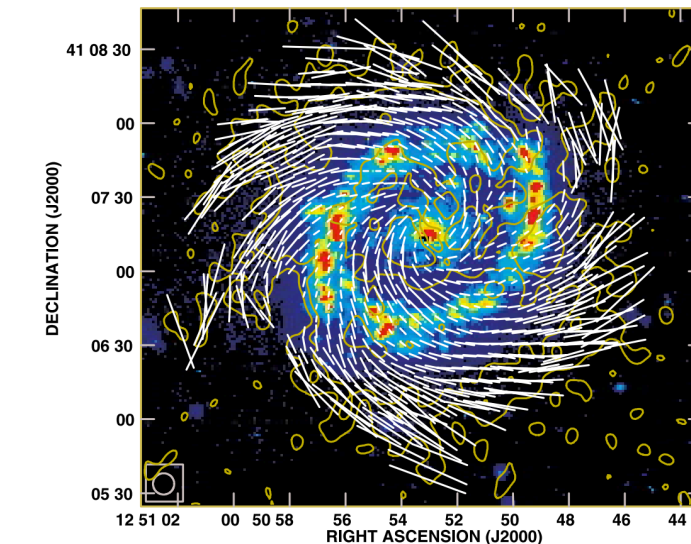
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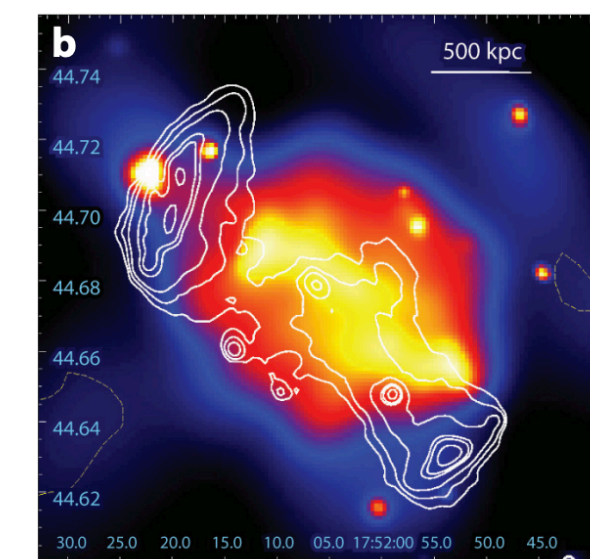
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[Schrijver, De Rosa]



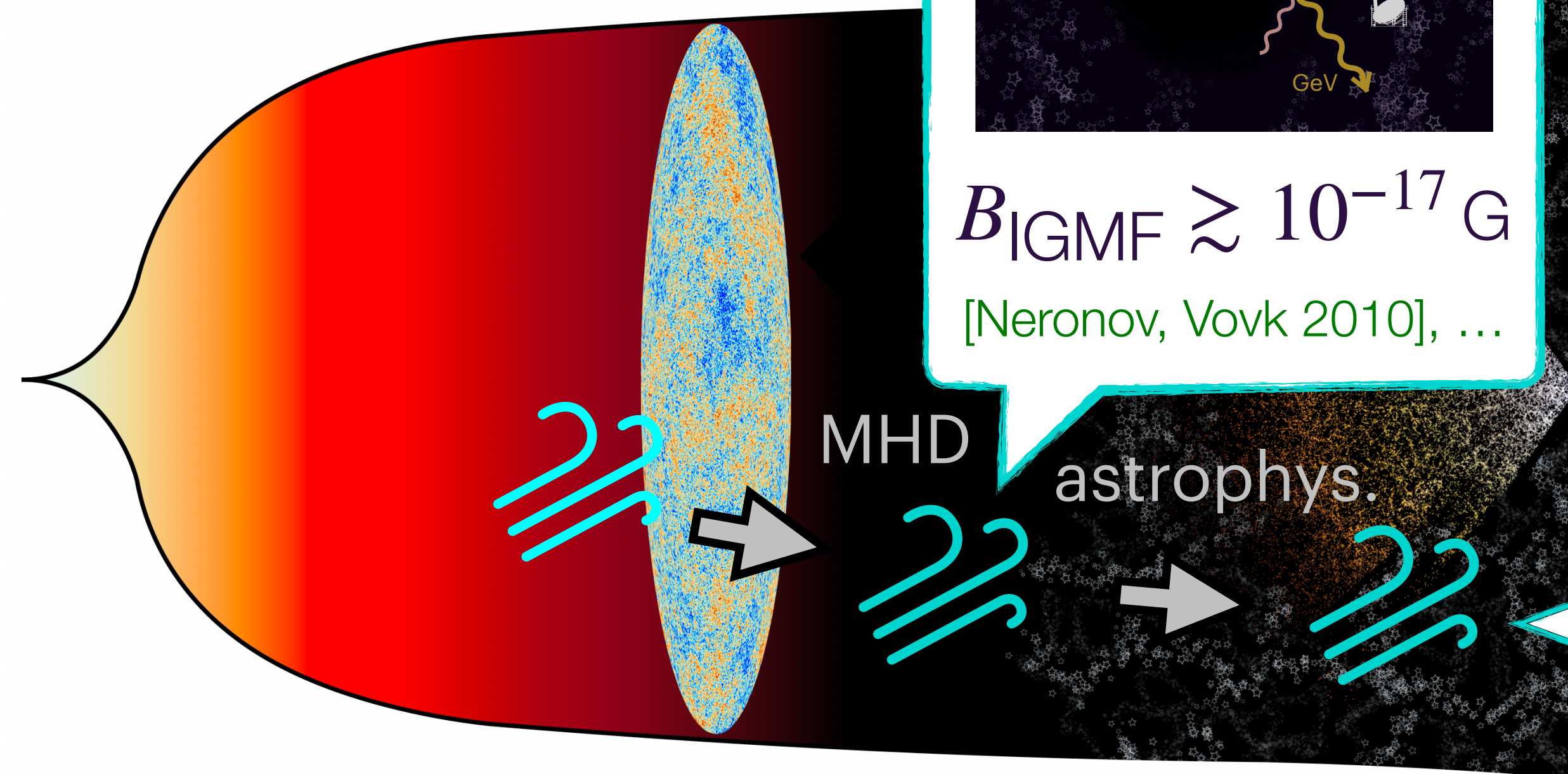
[Chyży, Buta]



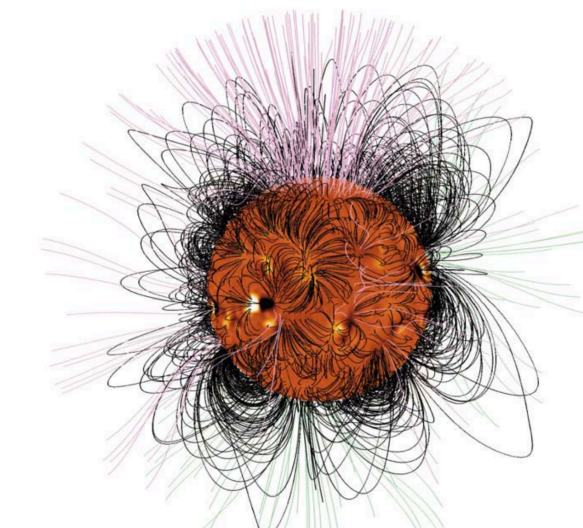
[Bonafede+]

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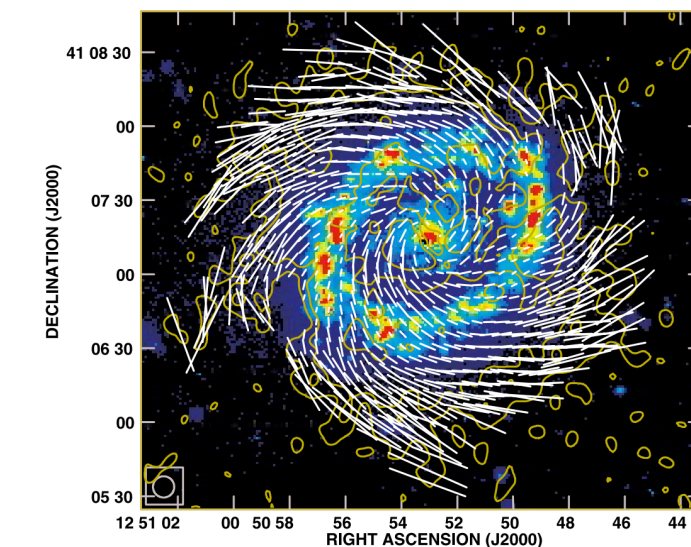
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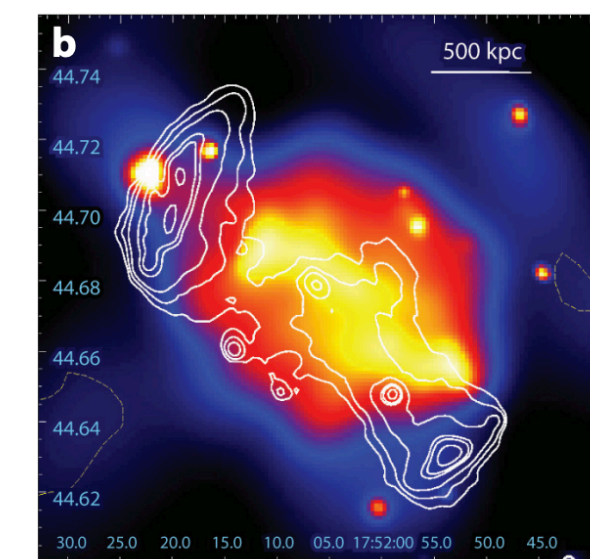
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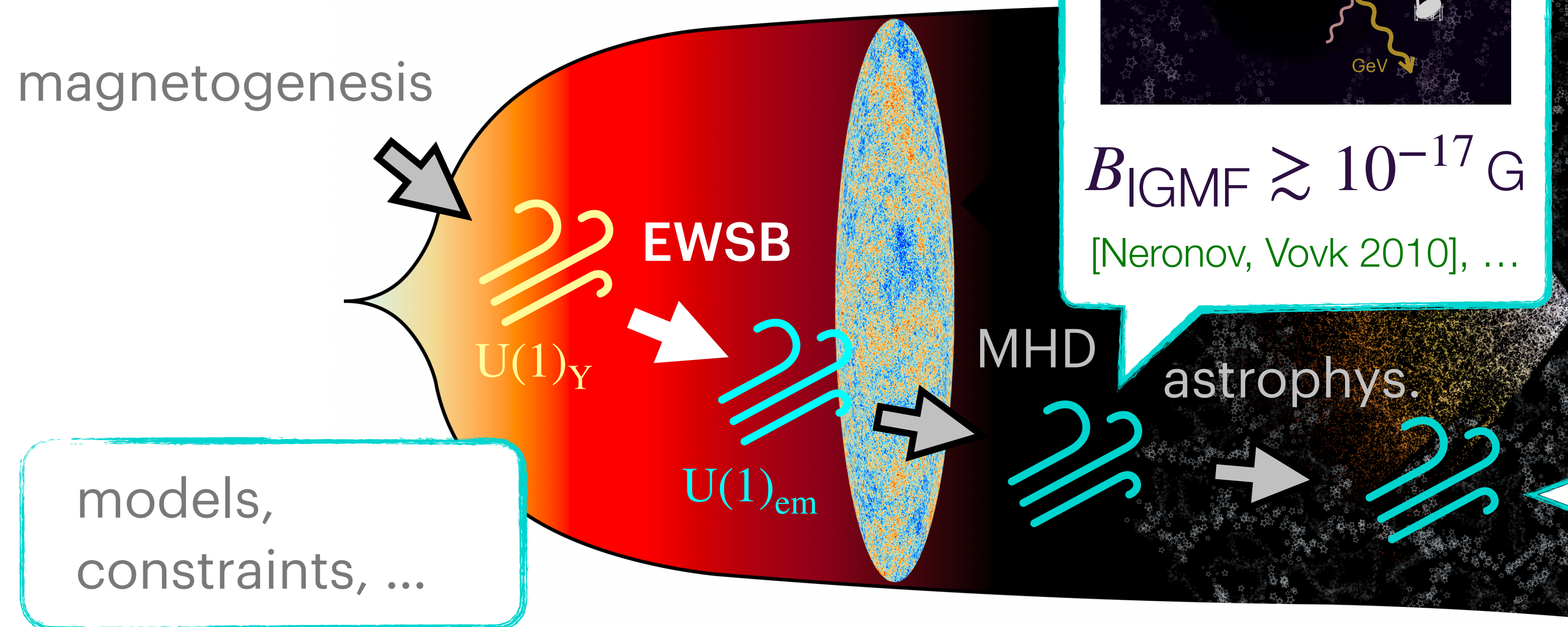


[Bonafede+]

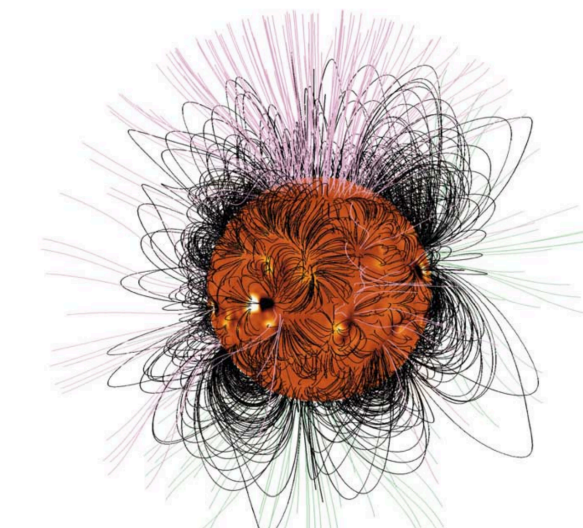
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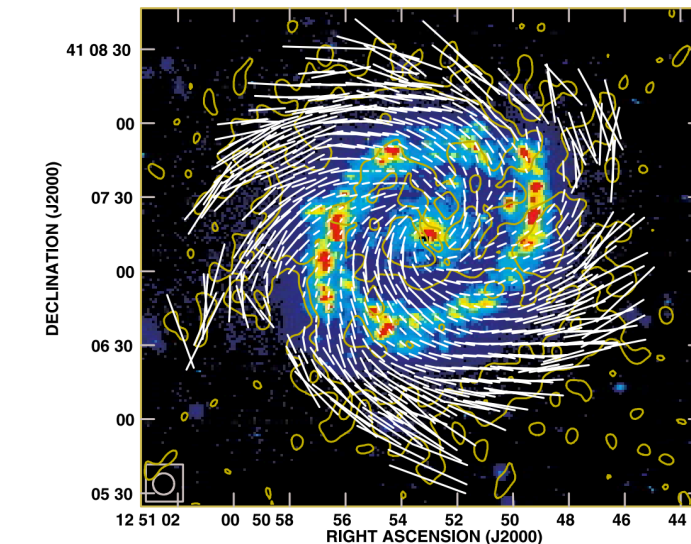
magnetogenesis



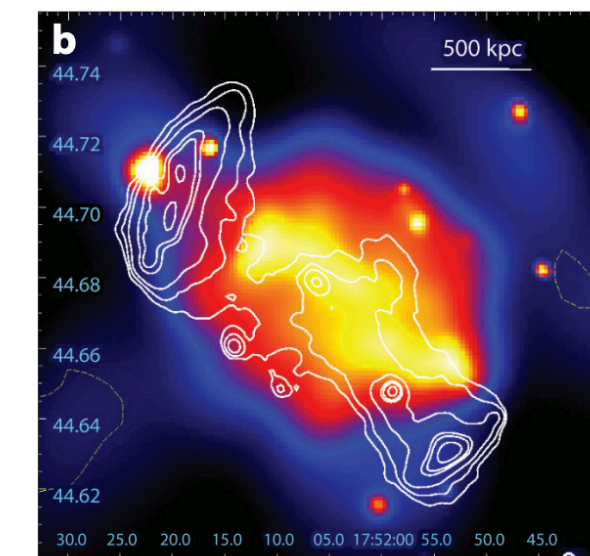
thermal plasma + magnetic field
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[Schrijver, De Rosa]



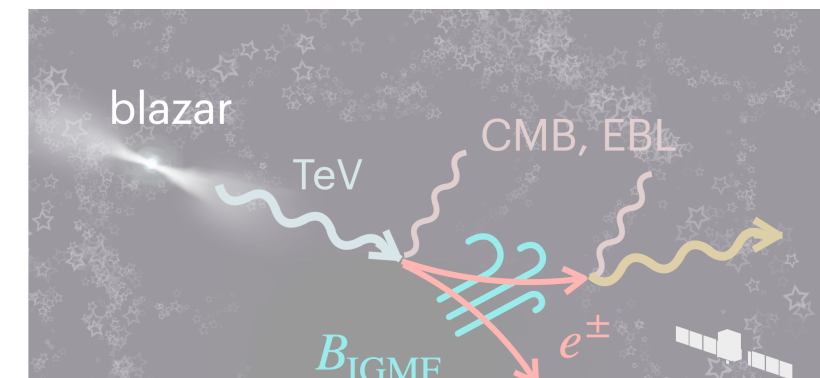
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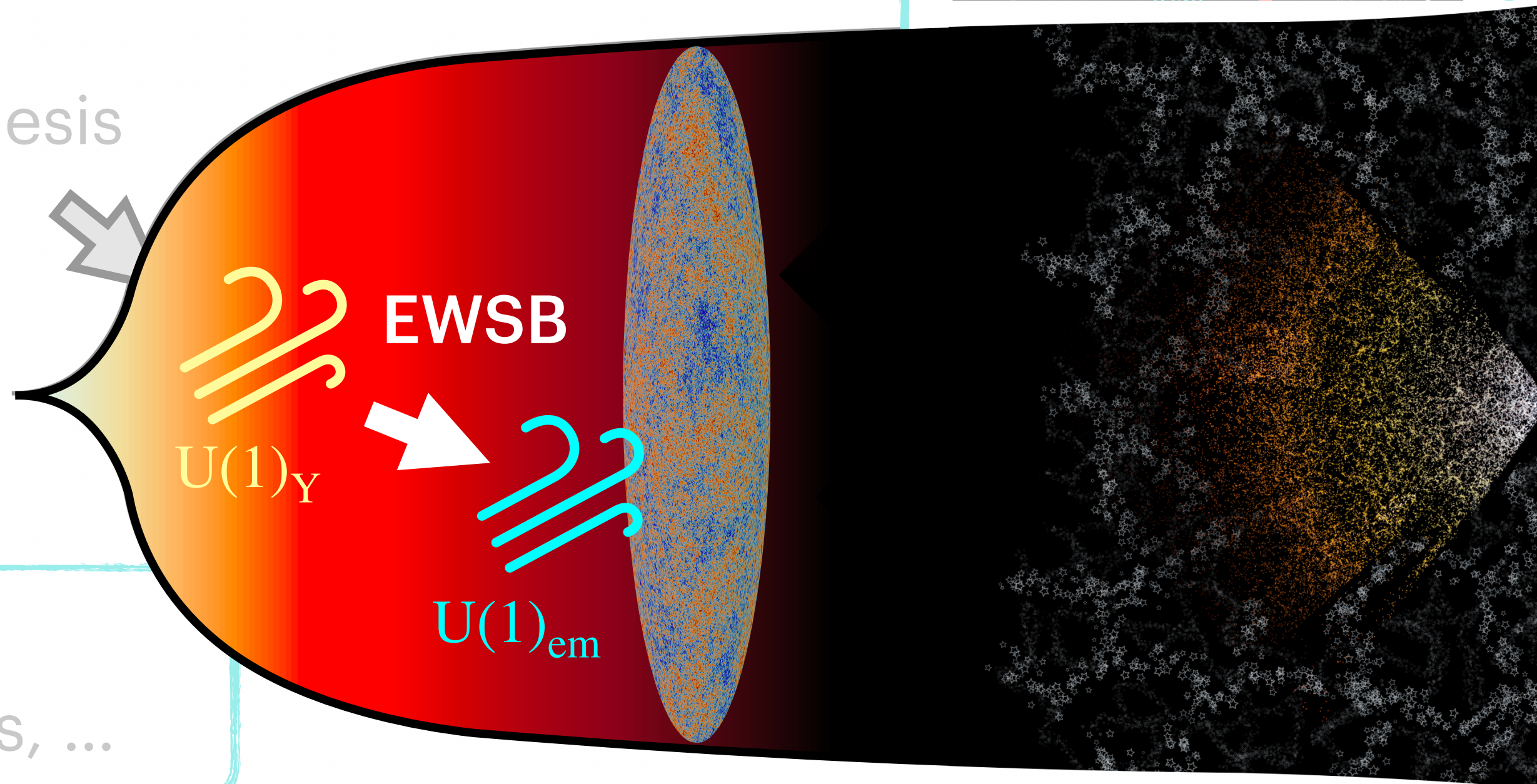
[Bonafede+]

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standard cosmology (Λ CDM)

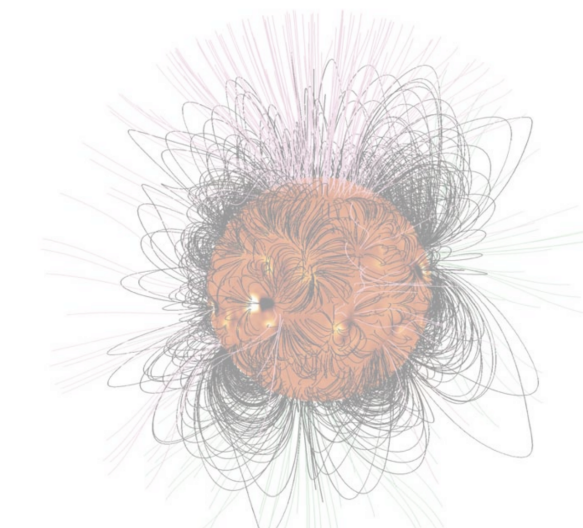


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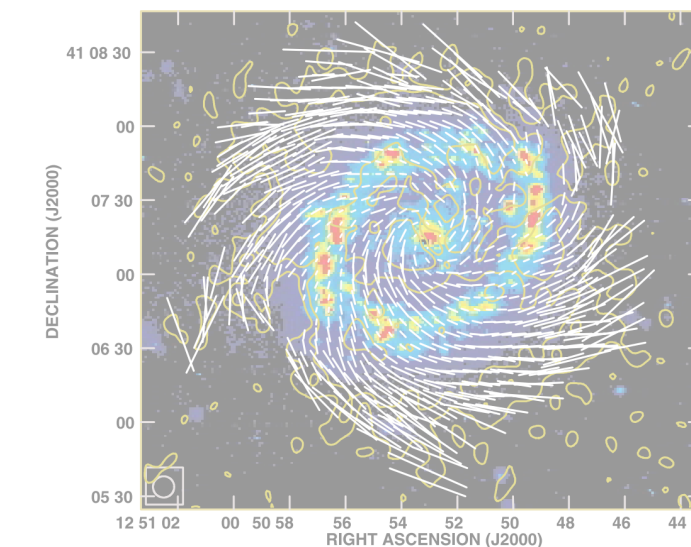


models,
constraints, ...

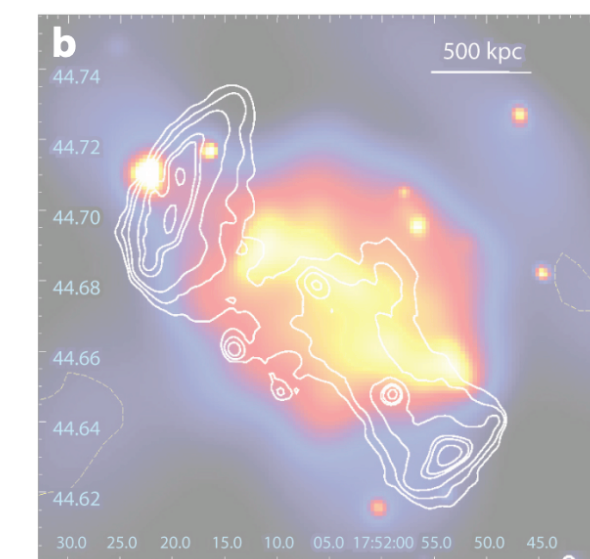
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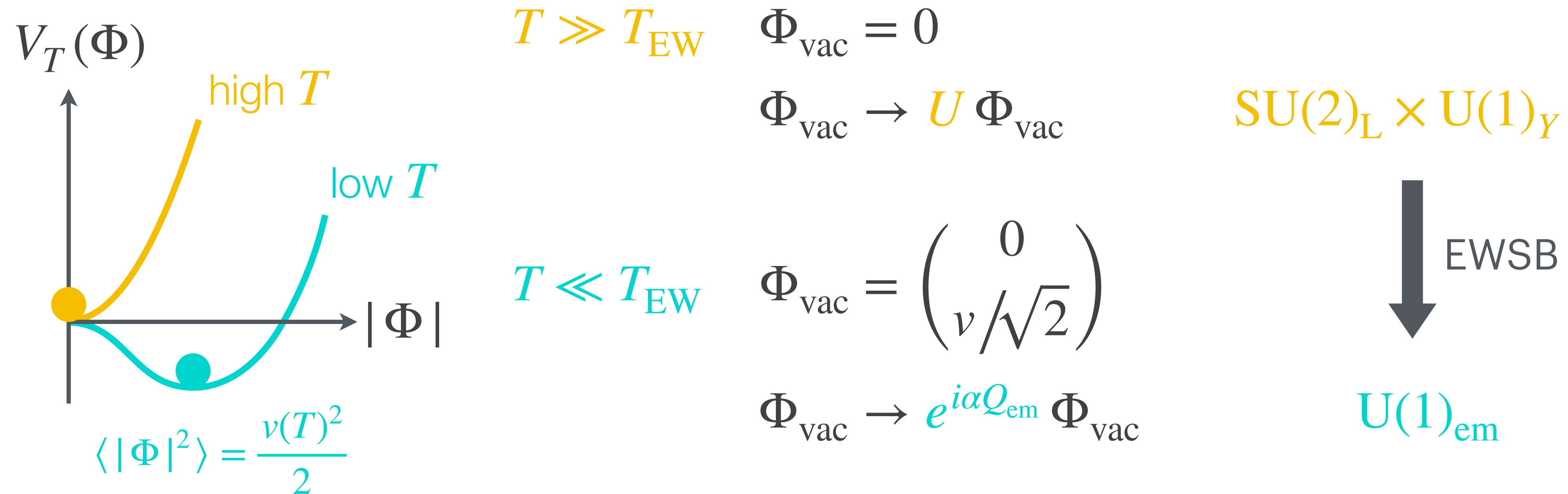


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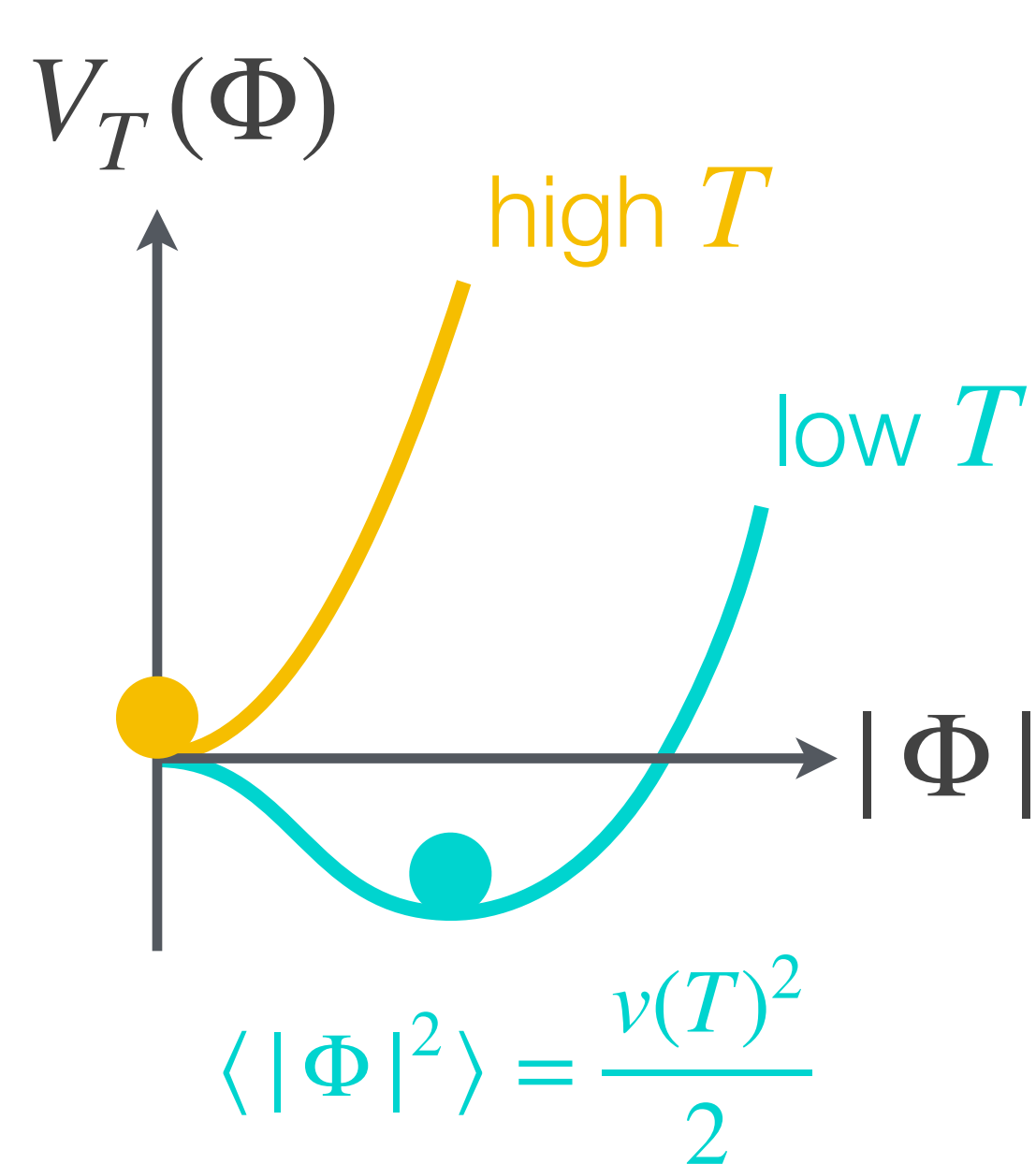


[Bonafede+]

電弱対称性の破れ (ユニタリゲージ)



電弱対称性の破れ (ユニタリゲージ)



$$T \gg T_{EW}$$

$$\Phi_{vac} = 0$$

$$\Phi_{vac} \rightarrow U \Phi_{vac}$$

$$T \ll T_{EW}$$

$$\Phi_{vac} = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$$

$$\Phi_{vac} \rightarrow e^{i\alpha Q_{em}} \Phi_{vac}$$

$$SU(2)_L \times U(1)_Y$$



EWSB

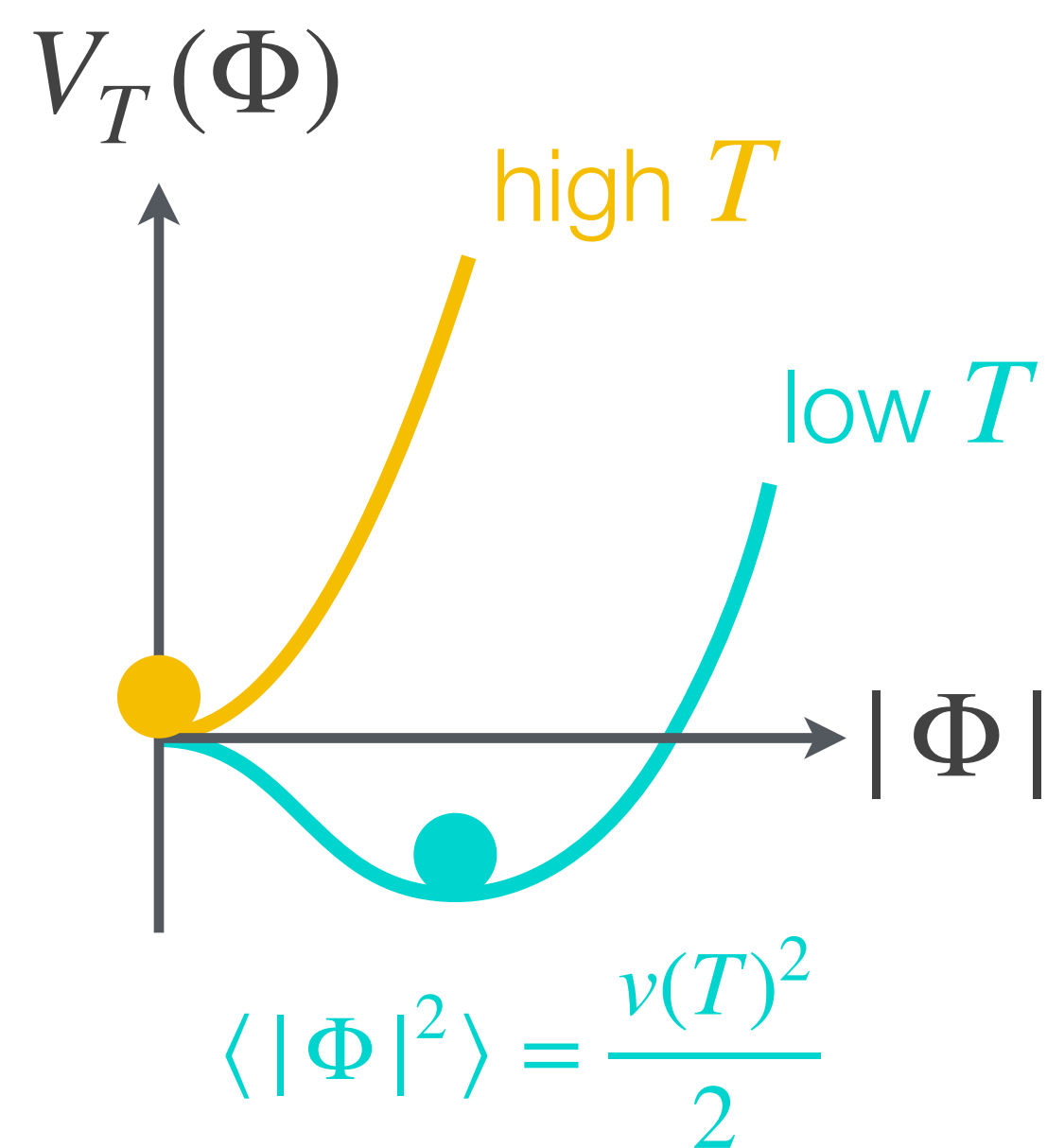
$$U(1)_{em}$$

A_i : massless

$$\vec{B}_{em} := \vec{\nabla} \times \vec{A}$$



電弱対称性の破れ (ユニタリゲージ)



$$T \gg T_{\text{EW}}$$

$$\Phi_{\text{vac}} = 0$$

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$$SU(2)_L \times U(1)_Y$$



EWSB

$$U(1)_{\text{em}}$$



A_i : massless

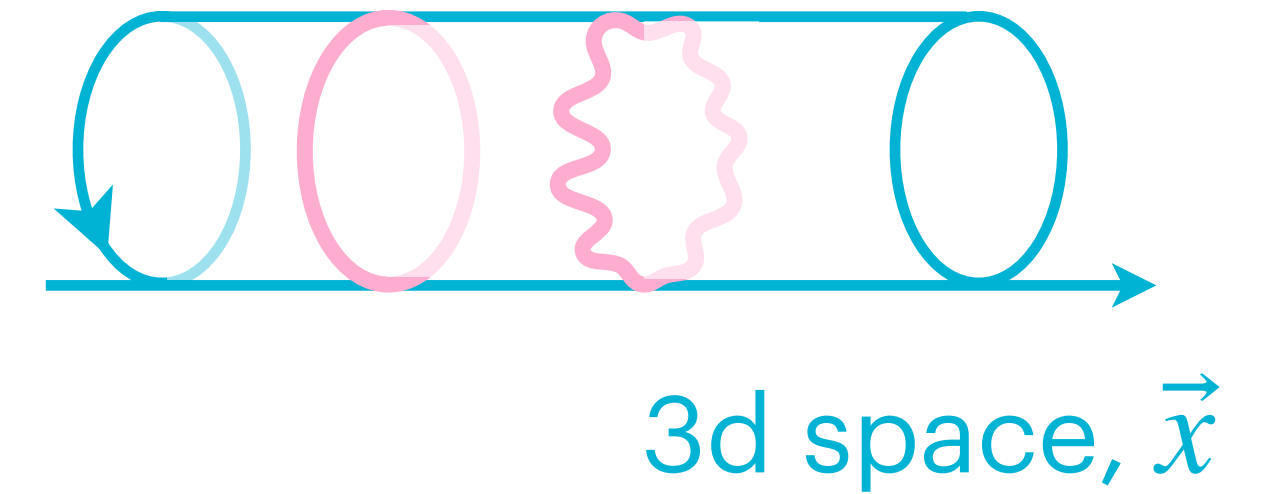
$$\vec{B}_{\text{em}} := \vec{\nabla} \times \vec{A}$$

有限温度の標準模型 (4次元, Euclidean)

partition function for thermal SM

$$Z_T = \text{Tr} [e^{-\beta H}] = \int_{\text{(anti-)periodic}} \mathcal{D}\phi_4 \exp\left(-\int_0^\beta \underline{d\tau d^3x} \mathcal{L}_{4E}\right)$$

$$0 \leq \tau < \beta = \frac{1}{T}$$



$$\begin{aligned} \mathcal{L}_{\text{SM,E}} = & (D_\mu \Phi_4)^\dagger D_\mu \Phi_4 + m_\Phi^2 \Phi_4^\dagger \Phi_4 + \lambda (\Phi_4^\dagger \Phi_4)^2 + \frac{1}{4} Y_{4\mu\nu} Y_{4\mu\nu} + \frac{1}{4} W_{4\mu\nu}^a W_{4\mu\nu}^a + \frac{1}{4} G_{4\mu\nu}^A G_{4\mu\nu}^A \\ & + \bar{e}_{Rf} \not{D} e_{Rf} + \bar{\ell}_{Lf} \not{D} \ell_{Lf} + \bar{u}_{Rf} \not{D} u_{Rf} + \bar{d}_{Rf} \not{D} d_{Rf} + \bar{q}_{Lf} \not{D} q_{Lf} + y_t (\bar{q}_{L3} \tilde{\Phi}_4 t_R + \text{H.c.}) \end{aligned}$$

有限温度の標準模型（3次元有効理論）

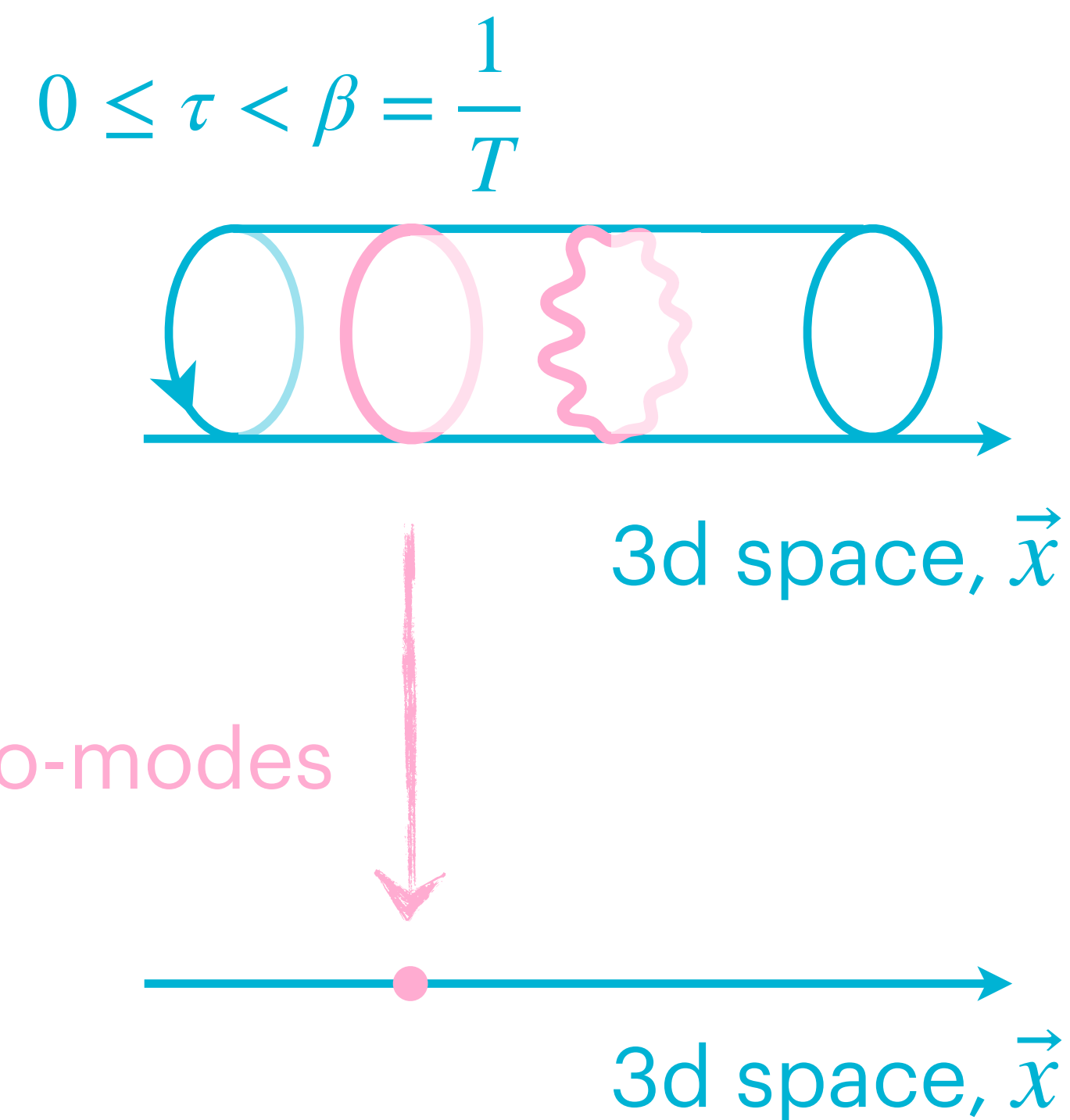
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integrating out the hard scale $\sim \pi T \dots$

$$Z_T \simeq \int \underline{\mathcal{D}\phi} \exp\left(-\int \underline{d^3x} \mathcal{L}_3\right)$$

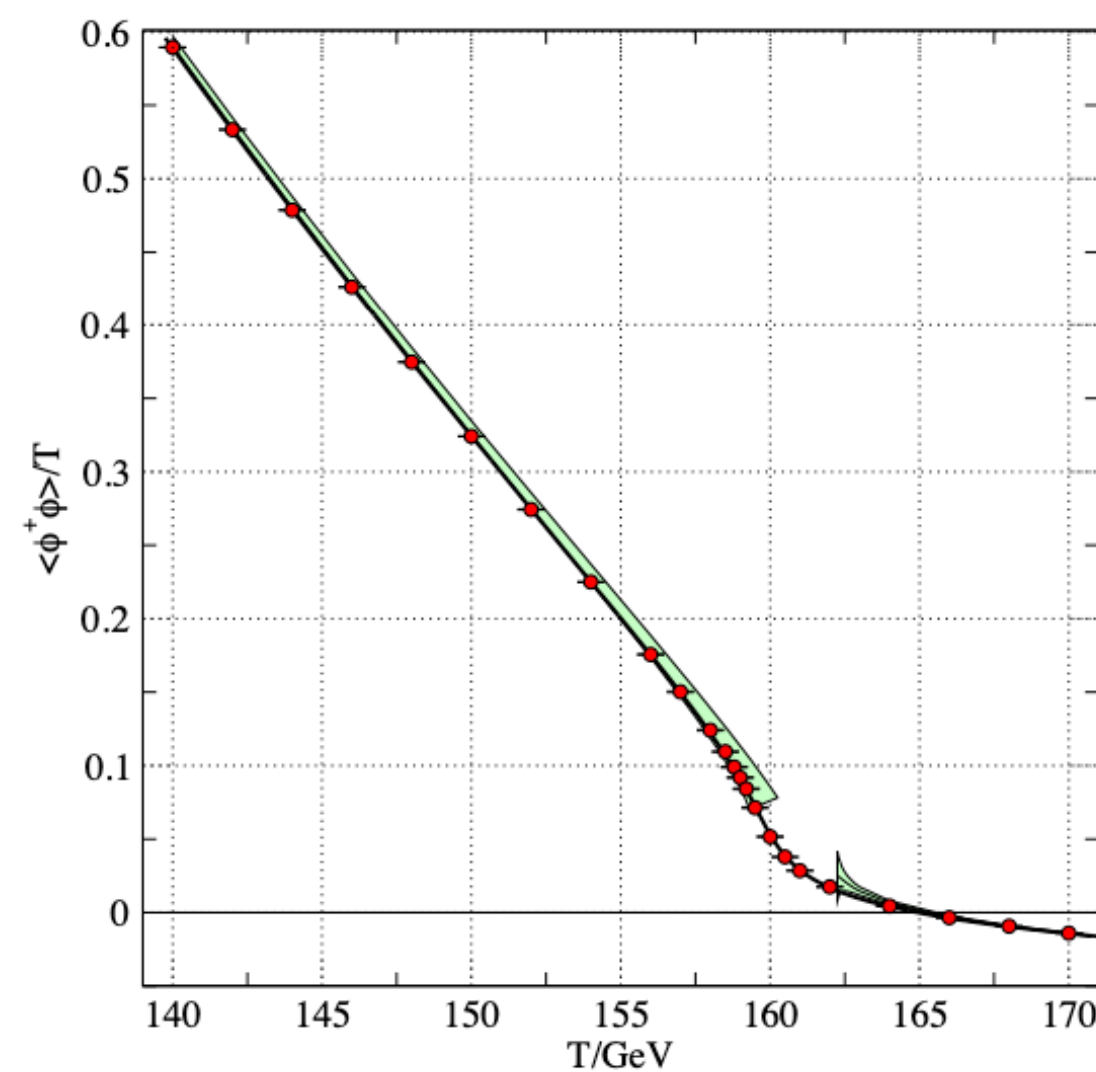
Higgs Φ , gauge fields $Y_i, W_i^a, \dots$



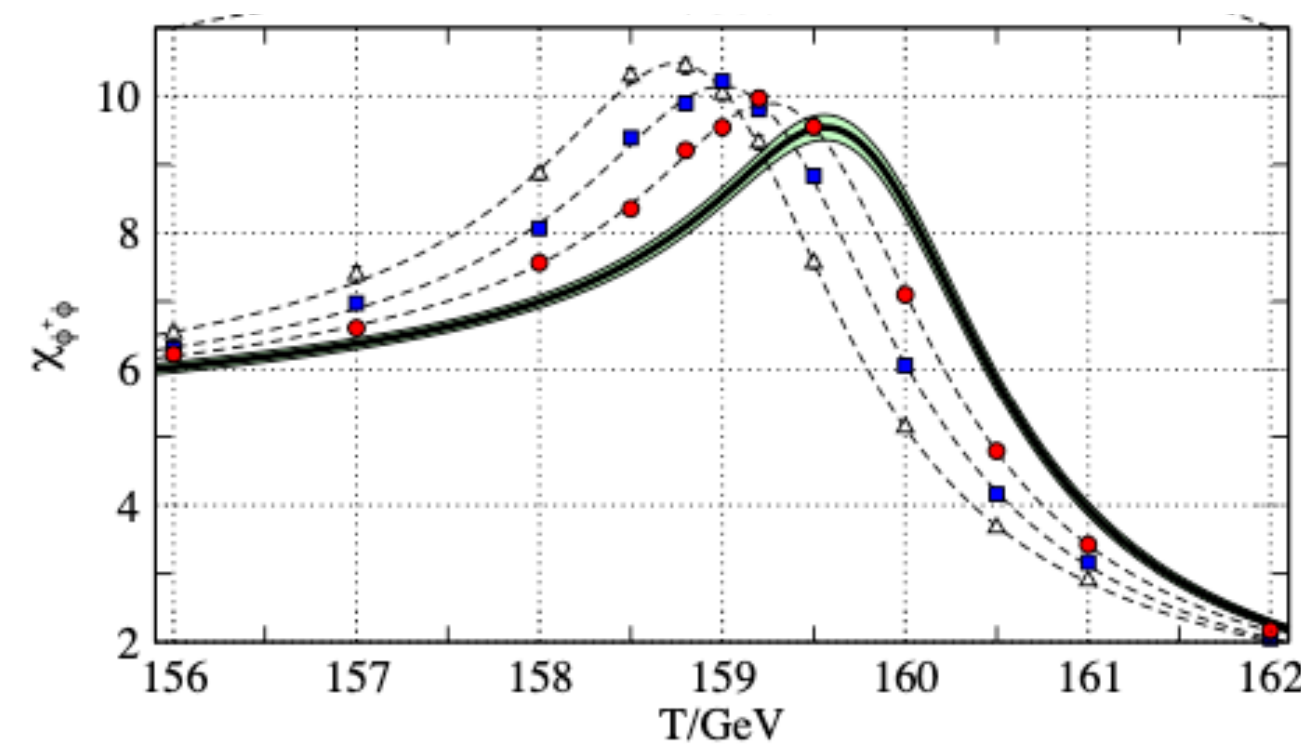
格子シミュレーションによると電弱クロスオーバー

ignoring gluons and integrating out the soft scale gT ...

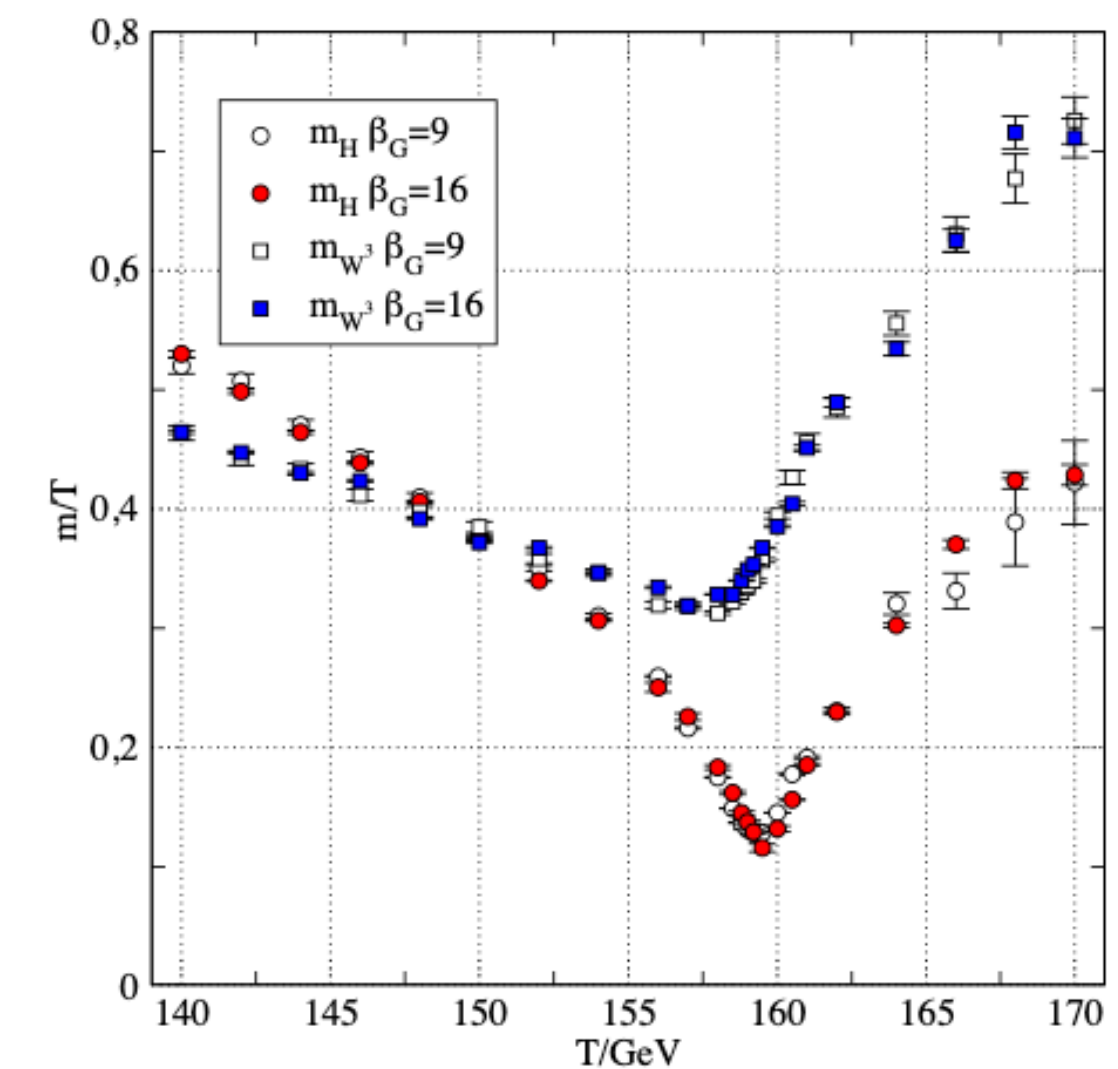
$$\mathcal{L}_3 = (D_i \Phi)^\dagger D_i \Phi + m_3^2 \Phi^\dagger \Phi + \lambda_3 (\Phi^\dagger \Phi)^2 + \frac{1}{4} Y_{ij} Y_{ij} + \frac{1}{4} W_{ij}^a W_{ij}^a$$



no jump in $\langle \Phi^\dagger \Phi \rangle$

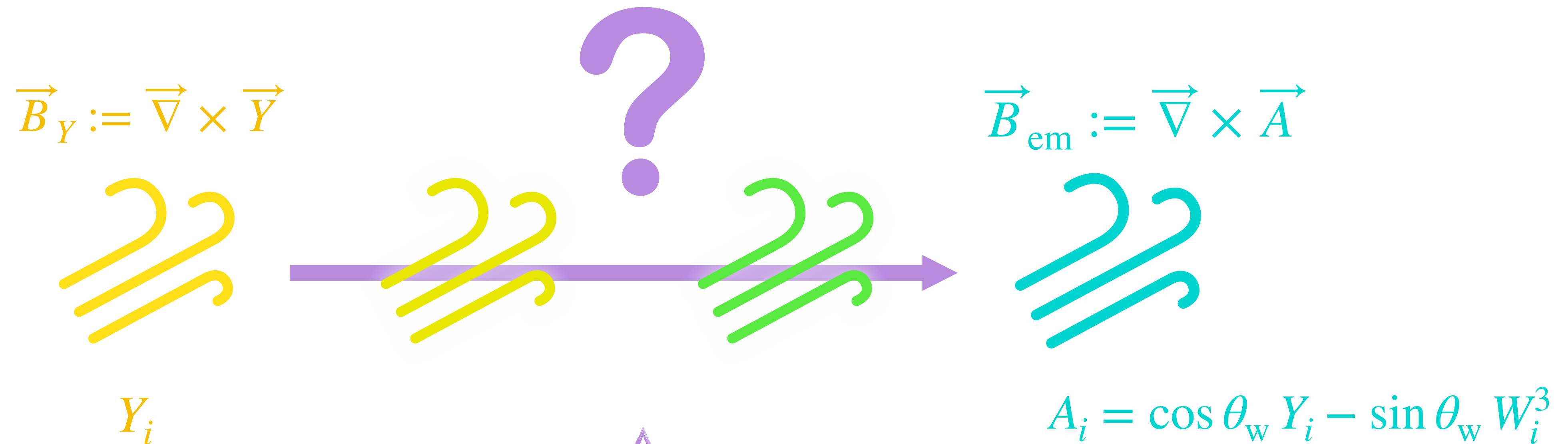


finite Higgs susceptibility



finite coherence length

電弱クロスオーバー中の宇宙磁場



- continuous transition during the electroweak crossover?
- possible generation of baryon (and lepton) number?

発表の構成

Introduction

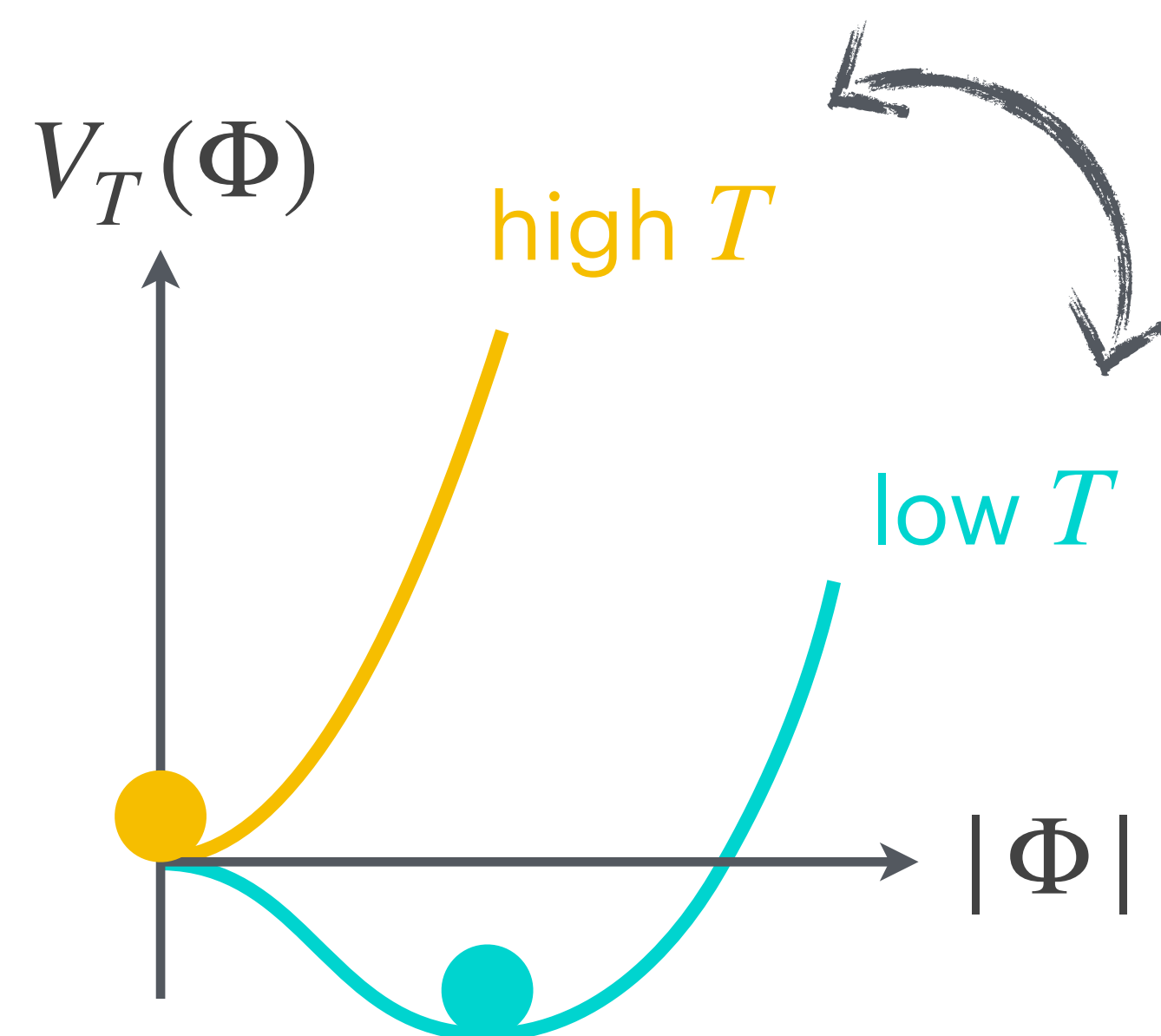
Symmetries of 3d EFT of the thermal SM

Magnetic field during the electroweak crossover

Baryon asymmetry generation and constraints?

Summary

対称性で高温・低温相は区別されない



look different: $\langle \Phi^\dagger \Phi \rangle = 0 / \neq 0$

in terms of symmetries...

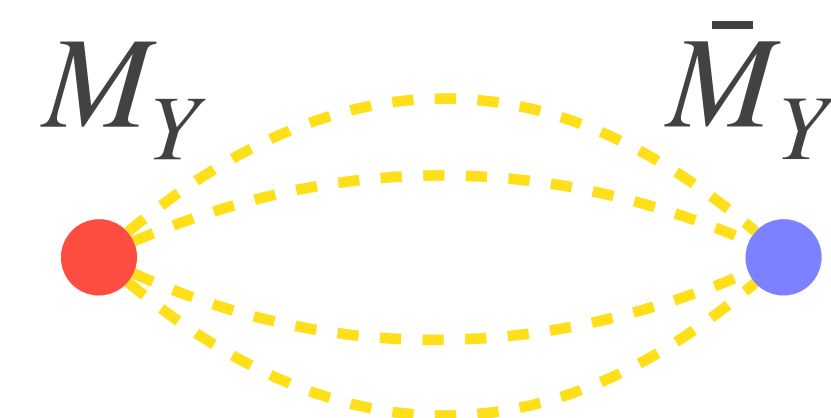
gauge symmetry: **unbroken in both phases**

$$\langle \Phi \rangle = 0 \quad [\text{Elitzur 1975}]$$

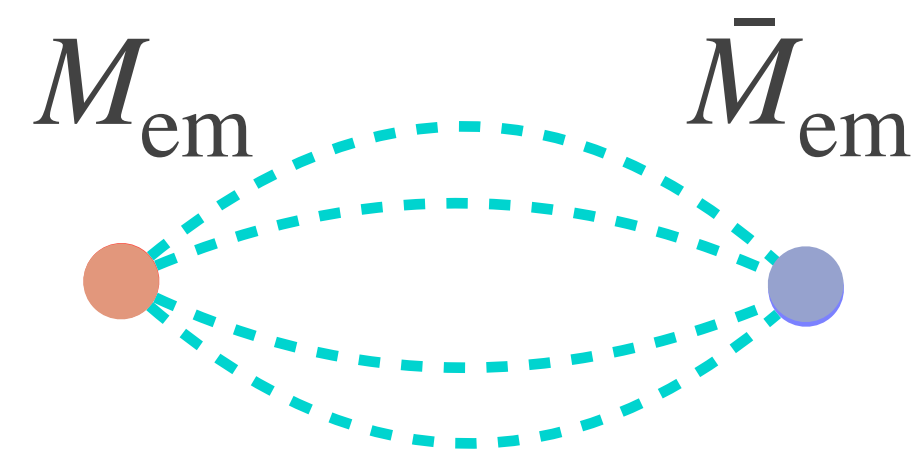
global symmetries: **same breaking pattern**

G	$\mathbb{Z}_2^{[0]}$	$\mathbb{Z}_2^{[1]}$	$U(1)_M^{[0]}$	$\mathbb{Z}_2^\tau$	C
High T	SSB	BKT	SSB	Unbroken	Unbroken
Low T	SSB	BKT	SSB	Unbroken	Unbroken

$U(1)_M^{[0]}$ の自発的破れ



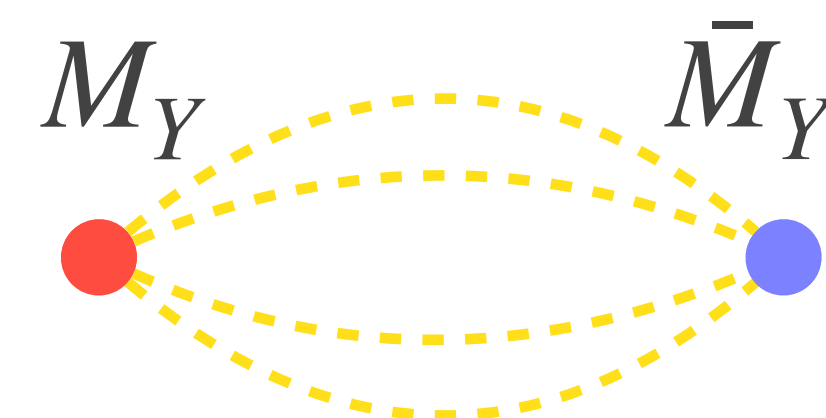
$$\vec{B}_Y := \vec{\nabla} \times \vec{Y}$$



$$\vec{B}_{\text{em}} := \vec{\nabla} \times \vec{A}$$

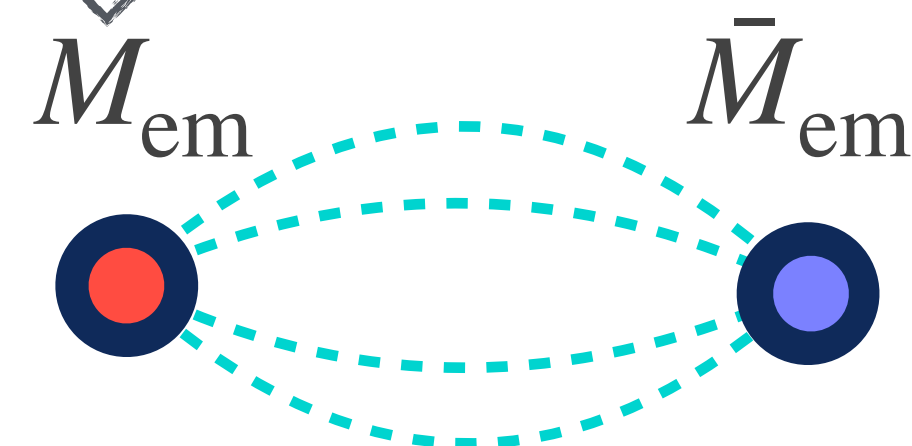
$$A_i = \cos \theta_w Y_i - \sin \theta_w W_i^3$$

$U(1)_M^{[0]}$ の自発的破れ



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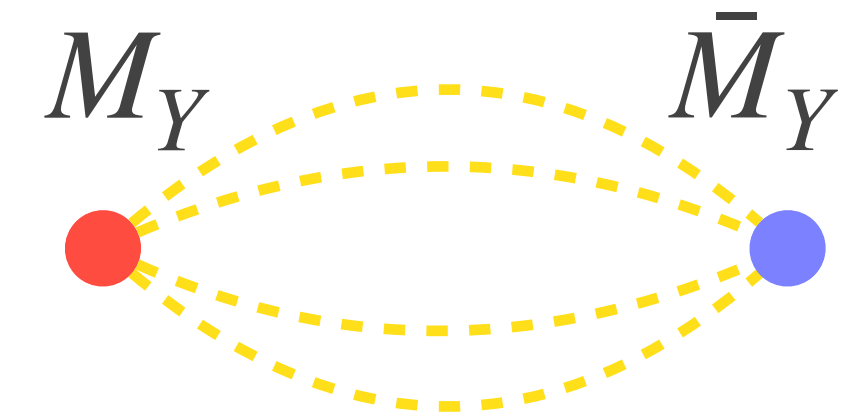
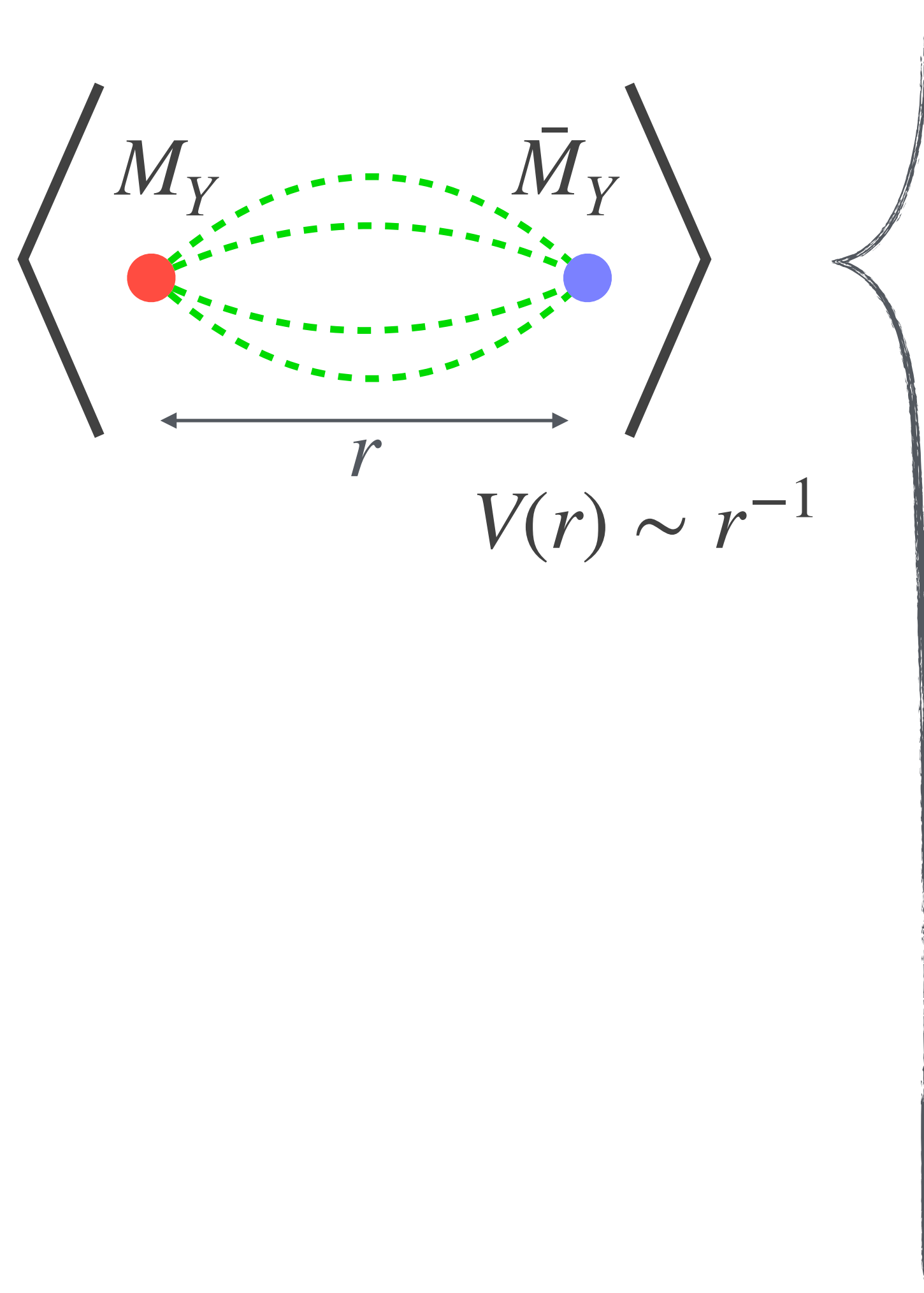
dressed M_Y [Nambu 1977]



$$\vec{B}_{\text{em}} := \vec{\nabla} \times \vec{A}$$

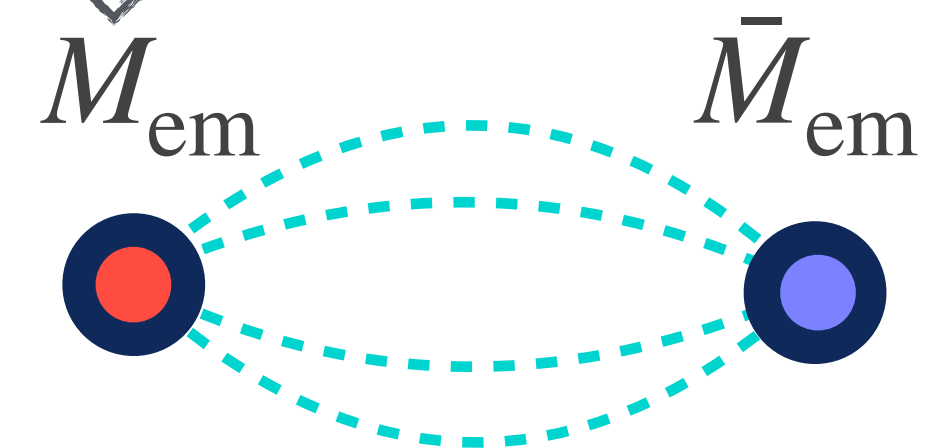
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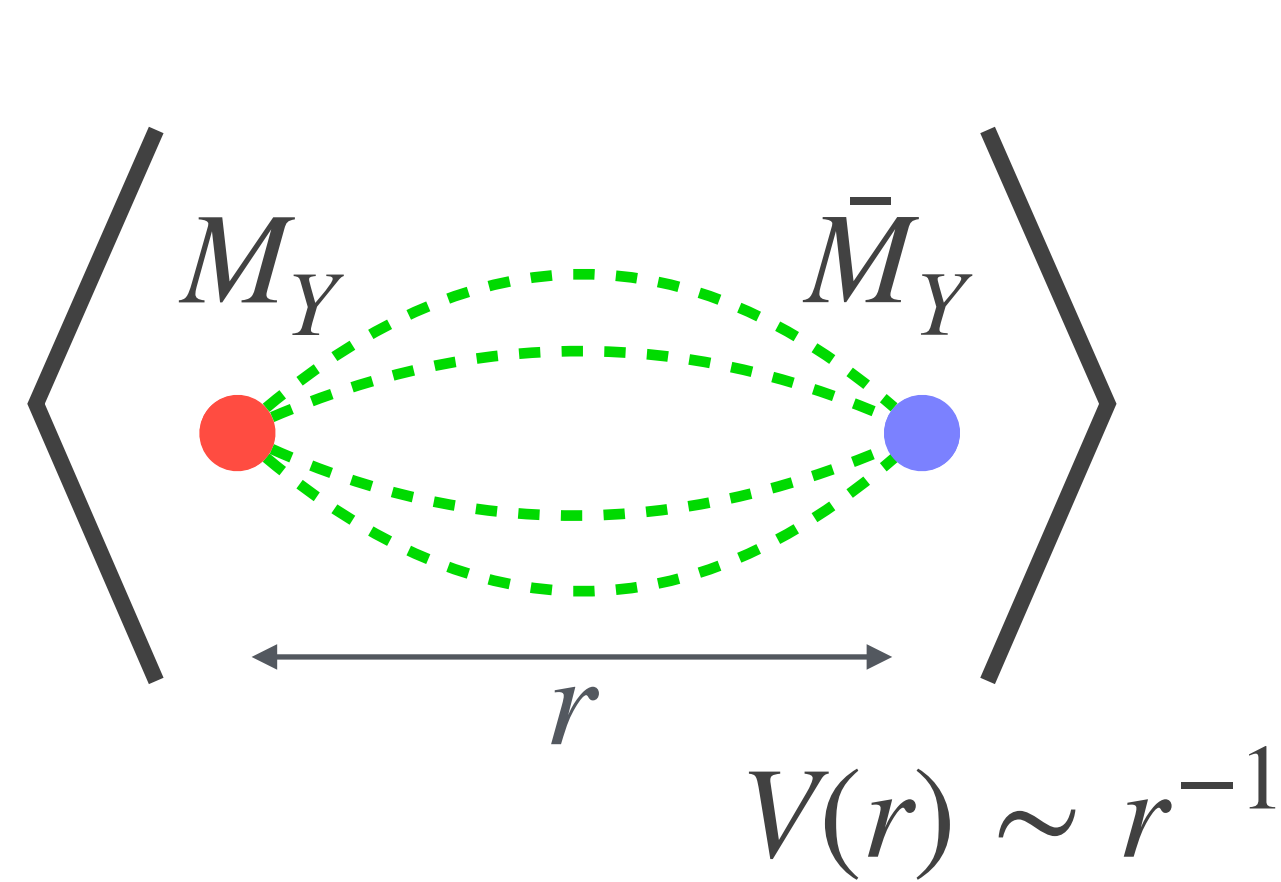
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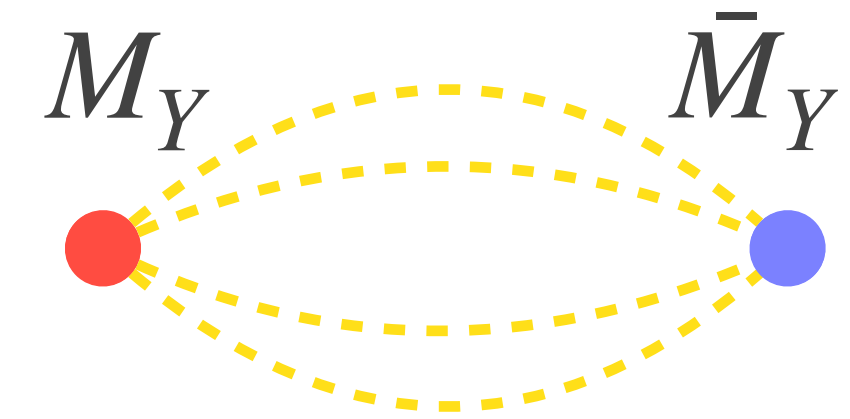
ordinary global symmetry in 4d (analogy)

$$\partial_\mu j^\mu = 0,$$

$$Q = \int d^3x j^0$$

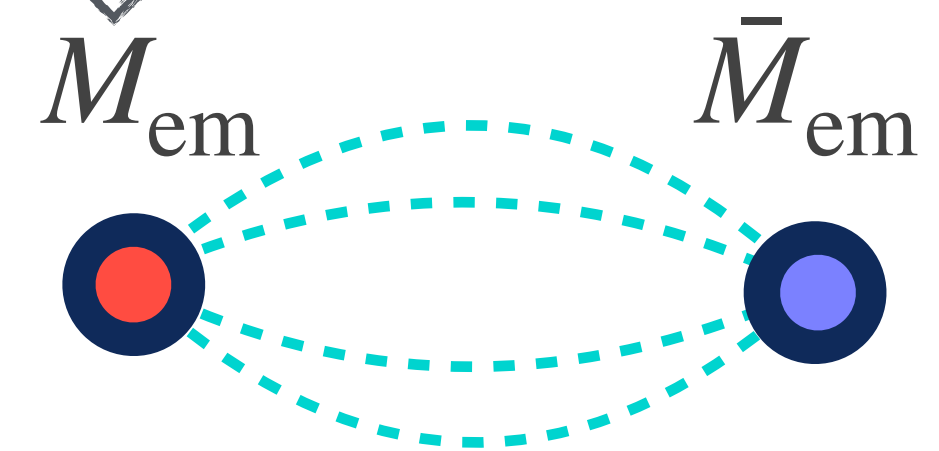
$$\langle \bullet \rangle \neq 0$$

SSB, $\exists$ NG boson



$$\vec{B}_Y := \vec{\nabla} \times \vec{Y}$$

dressed M_Y [Nambu 1977]



$$\vec{B}_{\text{em}} := \vec{\nabla} \times \vec{A}$$

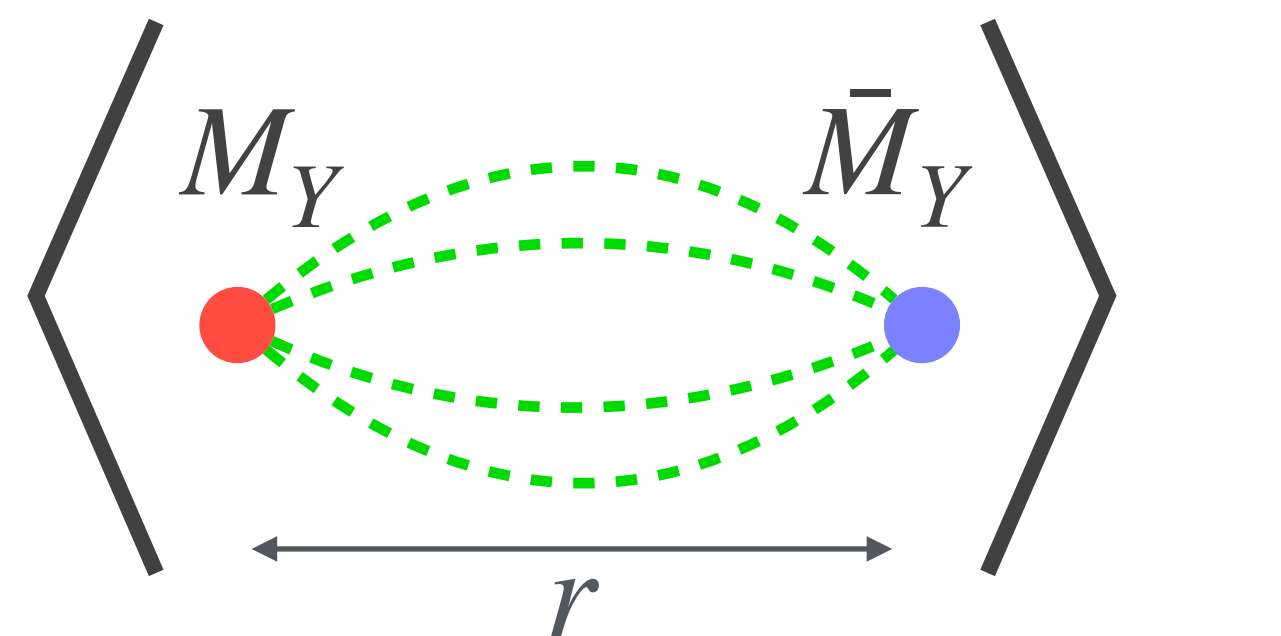
$$A_i = \cos \theta_w Y_i - \sin \theta_w W_i^3$$

$U(1)_M^{[0]}$ の自発的破れ

$U(1)_M^{[0]}$ global symmetry

$$\vec{\nabla} \cdot \vec{B}_Y = 0,$$

$$Q = \int_{S^2} d\vec{s} \cdot \vec{B}_Y$$



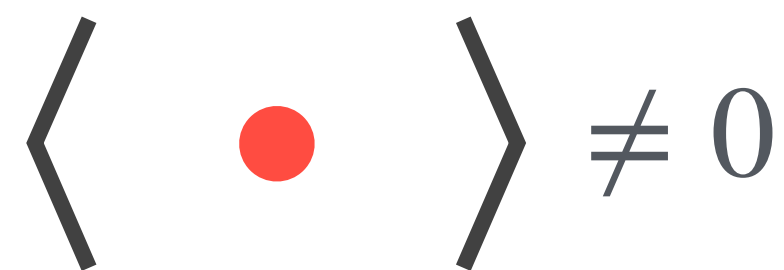
$$V(r) \sim r^{-1}$$

SSB, "photon"
[Gaiotto+ 2014], ...

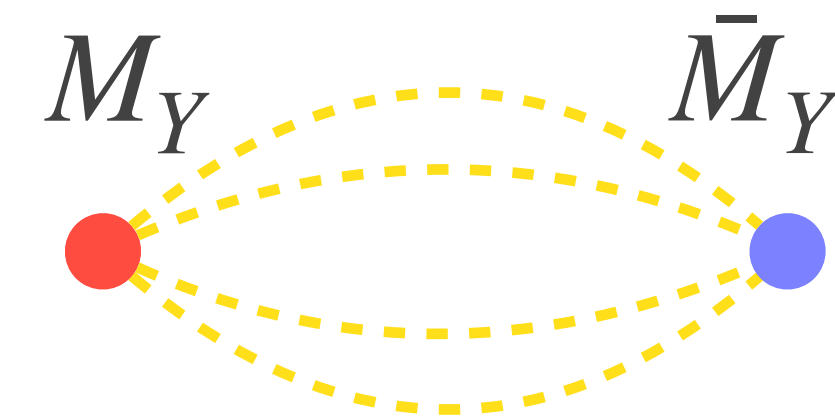
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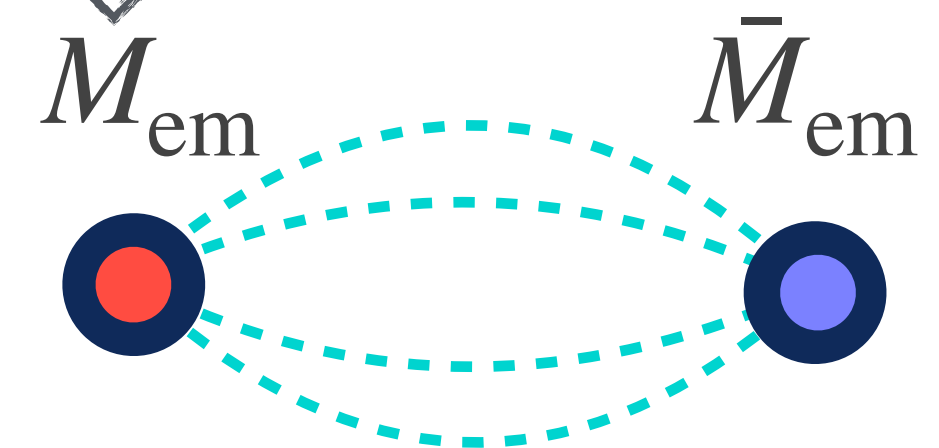


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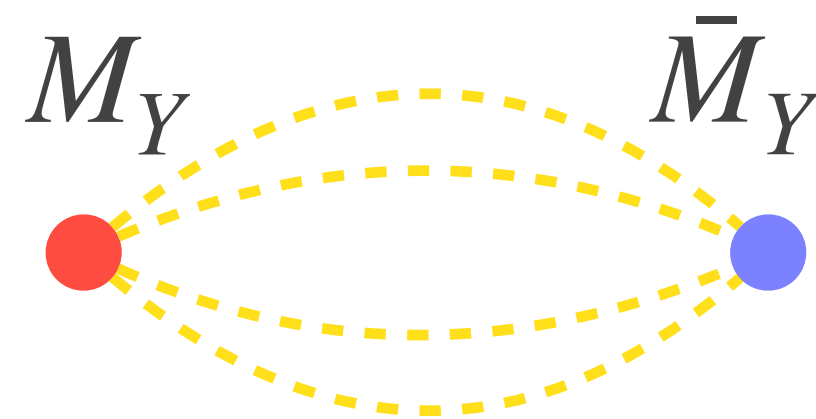
つねに $U(1)_M^{[0]}$ なら つねに磁場がある

$U(1)_M^{[0]}$ global symmetry ($\vec{\nabla} \cdot \vec{B}_Y = 0$): Coulomb phase (SSB) at any T (assumption)

as the NG boson,

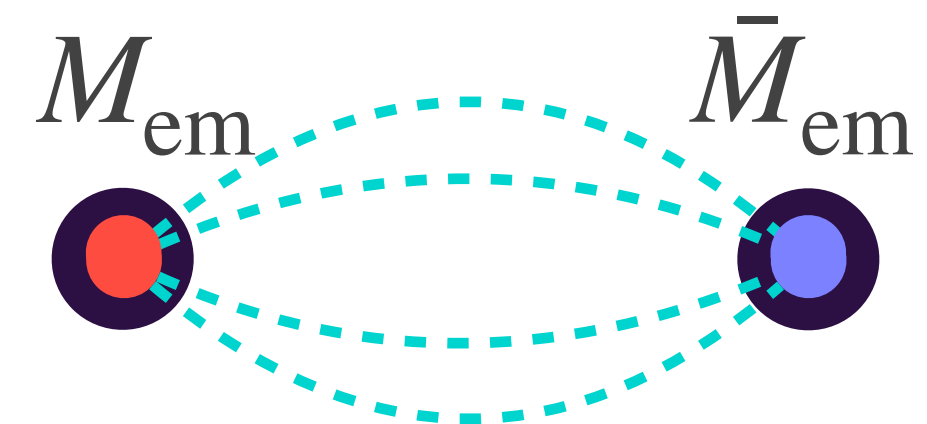
$\exists \vec{B}_\phi$ interpolates $\vec{B}_Y$ and $\vec{B}_{em}$

high T



$$\vec{B}_Y := \vec{\nabla} \times \vec{Y}$$

low T



$$\vec{B}_{em} := \vec{\nabla} \times \vec{A}$$

$$A_i = \cos \theta_w Y_i - \sin \theta_w W_i^3$$

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Symmetries of 3d EFT of the thermal SM

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Baryon asymmetry generation and constraints?

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有效弱混合角

[D'Onofrio, Rummukainen 2015] [Kamada, Long 2016]

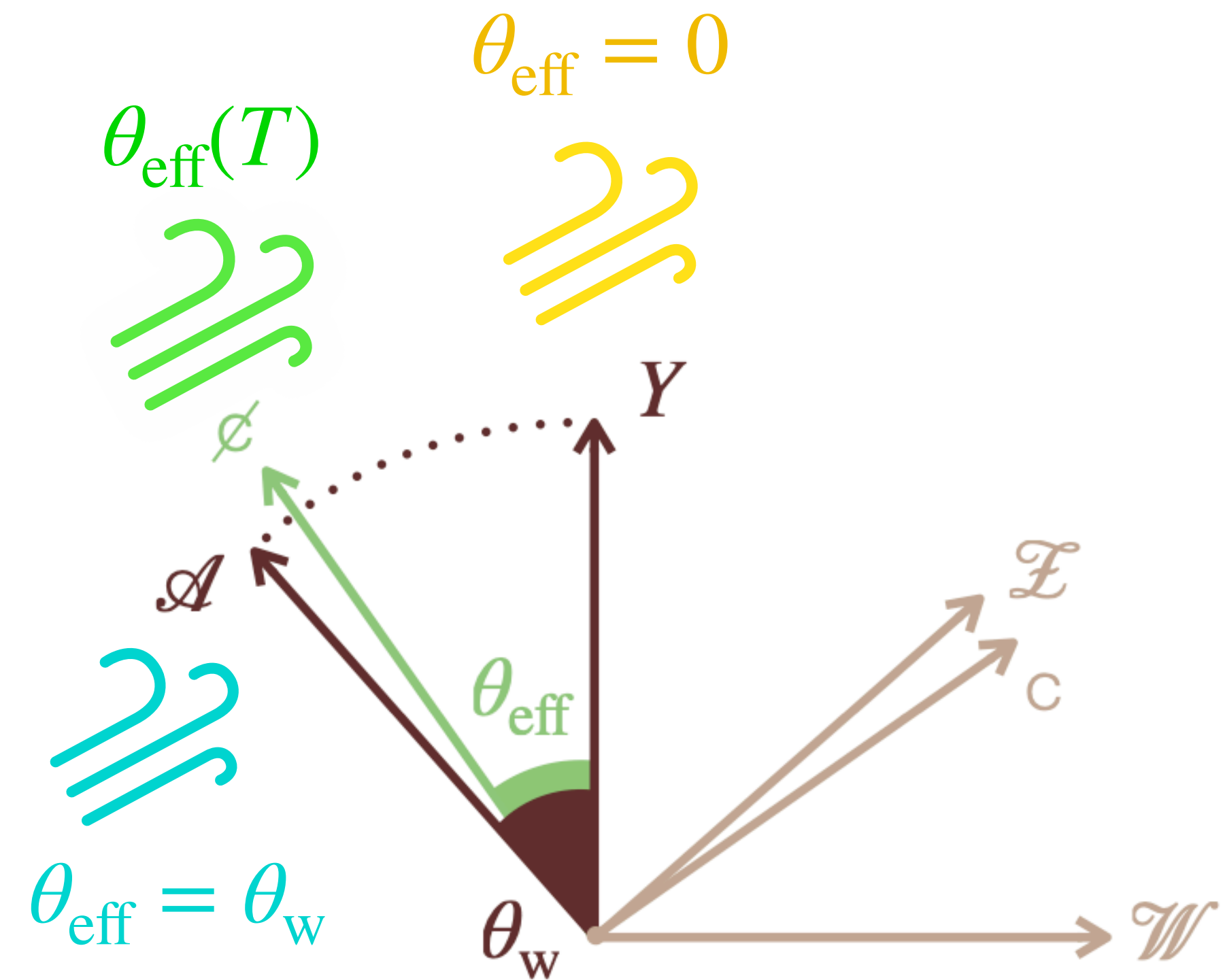
at low T

$$\begin{pmatrix} \vec{B}_{\text{em}} \\ \vec{B}_Z \end{pmatrix} = \begin{pmatrix} \cos \theta_w & -\sin \theta_w \\ \sin \theta_w & \cos \theta_w \end{pmatrix} \begin{pmatrix} \vec{B}_Y \\ \vec{B}_{W^3} \end{pmatrix}$$

Ansatz at $T \sim T_{\text{EW}}$

$$\begin{pmatrix} \vec{B}_\phi \\ \vec{B}_c \end{pmatrix} = \begin{pmatrix} \cos \theta_{\text{eff}} & -\sin \theta_{\text{eff}} \\ \sin \theta_{\text{eff}} & \cos \theta_{\text{eff}} \end{pmatrix} \begin{pmatrix} \vec{B}_Y \\ \vec{B}_{W^3} \end{pmatrix}$$

mixing



$\theta_{\text{eff}}(T)$ を摂動的に計算できる！

Ansatz

$$\begin{pmatrix} \vec{B}_\ell \\ \vec{B}_c \end{pmatrix} = \begin{pmatrix} \cos \theta_{\text{eff}} & -\sin \theta_{\text{eff}} \\ \sin \theta_{\text{eff}} & \cos \theta_{\text{eff}} \end{pmatrix} \begin{pmatrix} \vec{B}_Y \\ \vec{B}_{W^3} \end{pmatrix}$$

mixing

s.t.

$$\begin{aligned} \langle B_{\ell i}(\vec{p}) B_{\ell j}(\vec{q}) \rangle &= (2\pi)^3 \delta^3(\vec{p} + \vec{q}) \left(P_{ij}(\hat{p}) + S_{\ell\ell} \delta_{ij} \right) + \mathcal{O}(|\vec{p}|, g_3^4), \\ \langle B_{\ell i}(\vec{p}) B_{c j}(\vec{q}) \rangle &= (2\pi)^3 \delta^3(\vec{p} + \vec{q}) S_{\ell c} \delta_{ij} + \mathcal{O}(|\vec{p}|, g_3^4), \\ \langle B_{c i}(\vec{p}) B_{c j}(\vec{q}) \rangle &= (2\pi)^3 \delta^3(\vec{p} + \vec{q}) S_{cc} \delta_{ij} + \mathcal{O}(|\vec{p}|, g_3^4) \end{aligned}$$

massless pole

$\theta_{\text{eff}}(T)$ を摂動的に計算できる！

Ansatz $\begin{pmatrix} \vec{B}_\ell \\ \vec{B}_c \end{pmatrix} = \begin{pmatrix} \cos \theta_{\text{eff}} & -\sin \theta_{\text{eff}} \\ \sin \theta_{\text{eff}} & \cos \theta_{\text{eff}} \end{pmatrix} \begin{pmatrix} \vec{B}_Y \\ \vec{B}_\mathcal{W} \end{pmatrix}$

mixing

$$\mathcal{W}_{ij} := -\frac{\Phi^\dagger \sigma^a \Phi}{\Phi^\dagger \Phi} W_{ij}^a$$

$$= W_{ij}^3 + \mathcal{O}(g_3/m_W)$$

for gauge-invariance

wavefunction renormalization

massless pole

s.t.

$$\langle B_{\ell i}(\vec{p}) B_{\ell j}(\vec{q}) \rangle = (2\pi)^3 \delta^3(\vec{p} + \vec{q}) Z^\ell (P_{ij}(\hat{p}) + S_{\ell\ell} \delta_{ij}) + \mathcal{O}(|\vec{p}|, g_3^4),$$

$$\langle B_{\ell i}(\vec{p}) B_{c j}(\vec{q}) \rangle = (2\pi)^3 \delta^3(\vec{p} + \vec{q}) Z^{\ell\frac{1}{2}} S_{\ell c} \delta_{ij} + \mathcal{O}(|\vec{p}|, g_3^4),$$

$$\langle B_{c i}(\vec{p}) B_{c j}(\vec{q}) \rangle = (2\pi)^3 \delta^3(\vec{p} + \vec{q}) S_{cc} \delta_{ij} + \mathcal{O}(|\vec{p}|, g_3^4)$$

$\theta_{\text{eff}}(T)$ を摂動的に計算できる！

$\langle B_{Yi} B_{Yj} \rangle, \langle B_{Yi} B_{\mathcal{W}j} \rangle, \langle B_{\mathcal{W}i} B_{\mathcal{W}j} \rangle$ up to $\mathcal{O}(|\vec{p}|, g_3^4) \longrightarrow \theta_{\text{eff}}(T)$ and $Z^\ell(T)$

$$\begin{pmatrix} \vec{B}_Y \\ \vec{B}_{\mathcal{W}} \end{pmatrix} = \begin{pmatrix} \cos \theta_{\text{eff}} & \sin \theta_{\text{eff}} \\ -\sin \theta_{\text{eff}} & \cos \theta_{\text{eff}} \end{pmatrix} \begin{pmatrix} \vec{B}_\ell \\ \vec{B}_c \end{pmatrix},$$

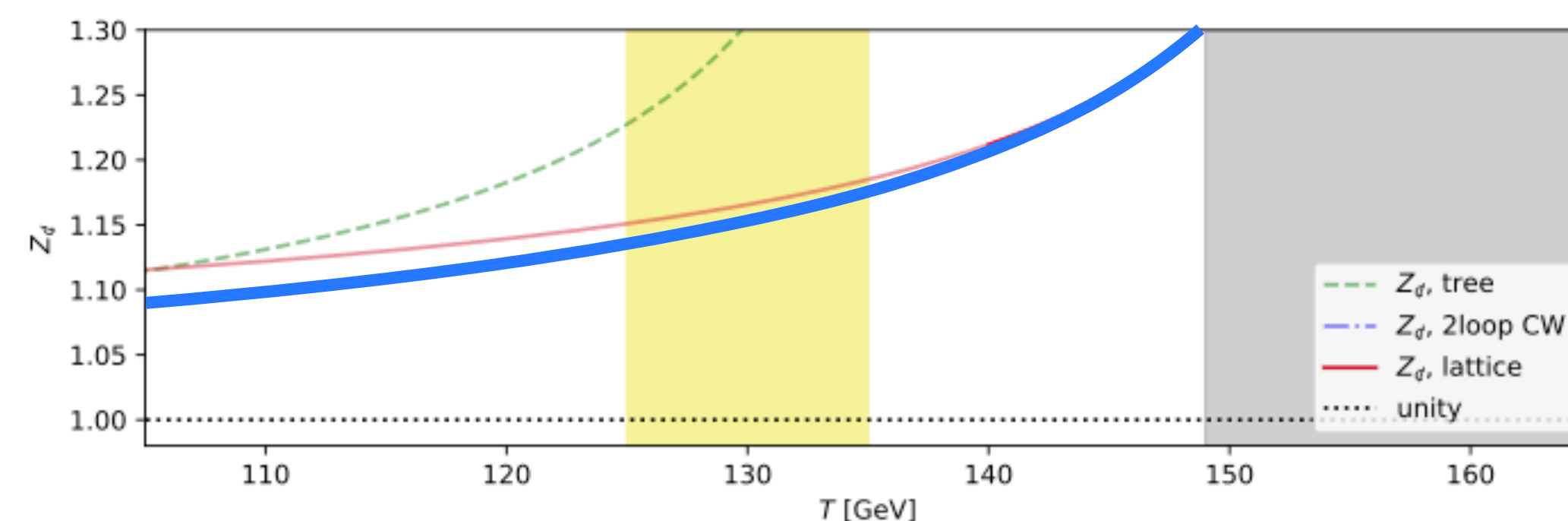
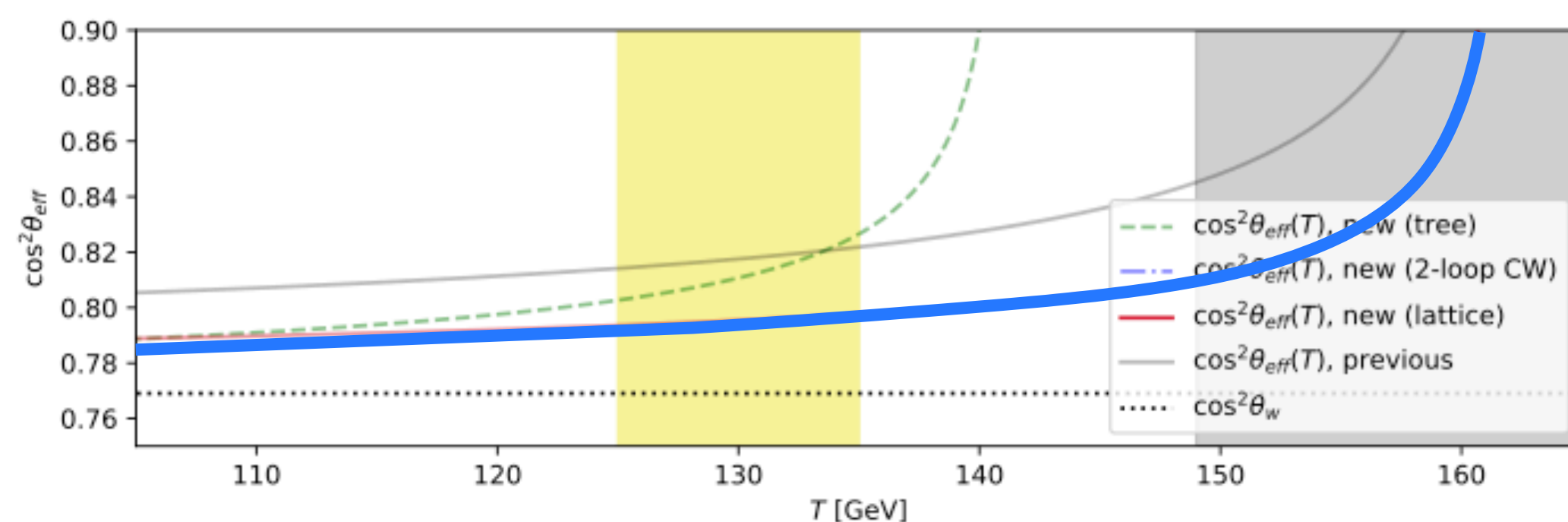
$$\langle B_{\ell i}(\vec{p}) B_{\ell j}(\vec{q}) \rangle = (2\pi)^3 \delta^3(\vec{p} + \vec{q}) Z^\ell(P_{ij}(\hat{p}) + S_{\ell\ell} \delta_{ij}) + \mathcal{O}(|\vec{p}|, g_3^4),$$

$$\langle B_{\ell i}(\vec{p}) B_{cj}(\vec{q}) \rangle = (2\pi)^3 \delta^3(\vec{p} + \vec{q}) Z^{\ell\frac{1}{2}} S_{\ell c} \delta_{ij} + \mathcal{O}(|\vec{p}|, g_3^4),$$

$$\langle B_{ci}(\vec{p}) B_{cj}(\vec{q}) \rangle = (2\pi)^3 \delta^3(\vec{p} + \vec{q}) S_{cc} \delta_{ij} + \mathcal{O}(|\vec{p}|, g_3^4)$$

$$\cos \theta_{\text{eff}}(T) = \left(1 + \frac{g_3^2 \sin^2 \theta_w}{4\pi m_W} \right) \cos \theta_w$$

$$Z^\ell(T) = 1 + \left(\frac{5}{12} - \frac{1}{24\sqrt{1 + m_D^2/m_W^2}} \right) \frac{g_3^2 \sin^2 \theta_w}{\pi m_W}$$



発表の構成

Introduction

Symmetries of 3d EFT of the thermal SM

Magnetic field during the electroweak crossover

Baryon asymmetry generation and constraints?

Summary

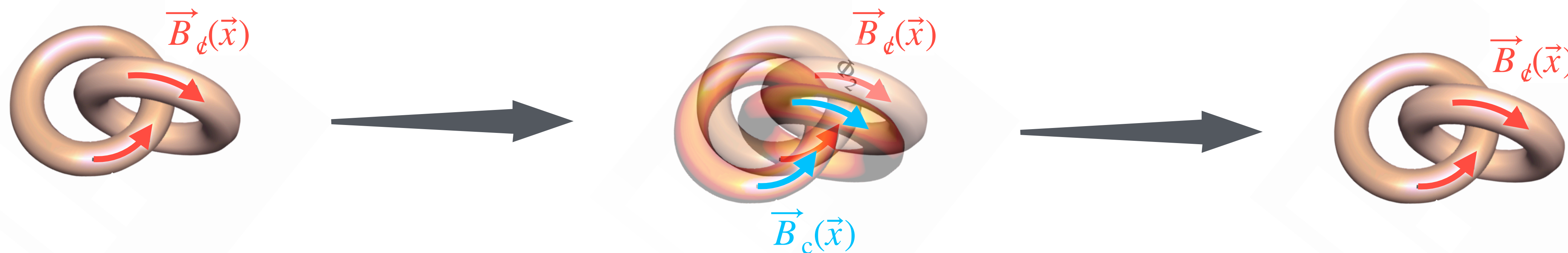
磁気ヘリシティ崩壊によるバリオン数生成

[Joyce, Shaposhnikov 1997] [Giovannini, Shaposhnikov 1998] [Fujita, Kamada 2016] [Kamada, Long 2016] ...

chiral anomaly $\Delta Q_{B+L} = 2 \cdot 3 \left(\Delta N_{\text{CS}}^{\text{SU}(2)_L} - \Delta H_Y \right)$

$N_{\text{CS}}^{\text{SU}(2)_L}, H_Y$: topological charge of the gauge fields

infinitesimal transition during the EWSB



confined helicity decays $\longrightarrow$ baryons?

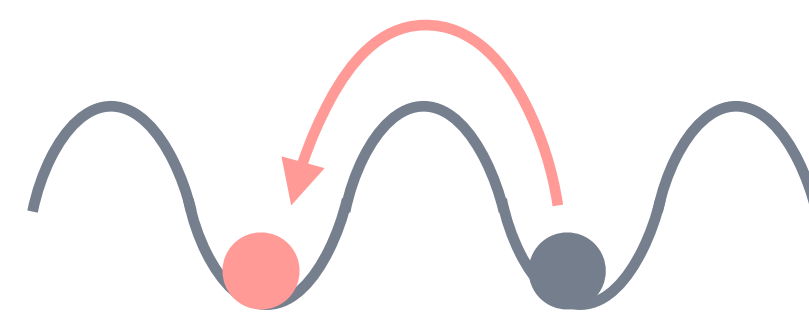
これまで議論されてきたシナリオ [Kamada, Long 2016]

helicity decay



EWSB

$$\Delta N_{\text{CS}} = -1$$



electroweak sphaleron

$$\Gamma_{\text{sph}} \sim H \text{ at } 130 \text{ GeV}$$

[D'Onofrio, Rummukainen 2015]



$$T \ll T_{\text{EW}}$$

equilibrium with sphaleron washout $\rightarrow$ baryons $\propto$ magnetic helicity

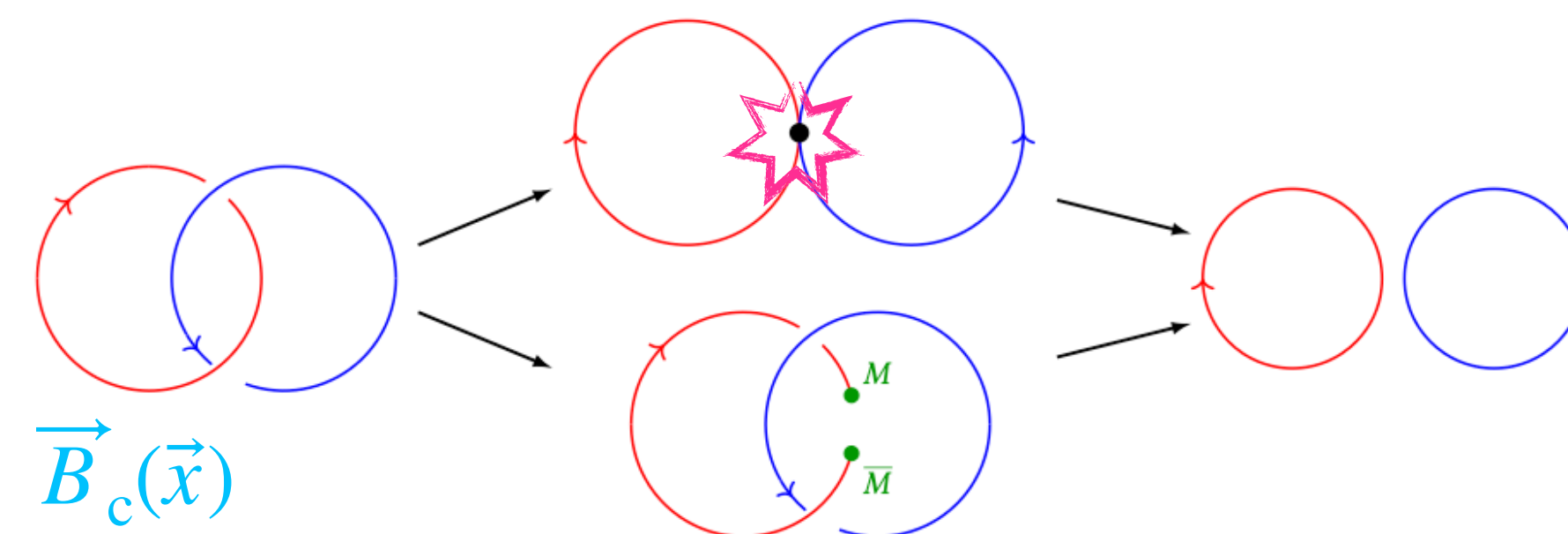
$\theta_{\text{eff}}(T)$ allows quantitative estimation!

ヒッグス場が ΔN_{CS} を消すかもしれない

※ not conclusive [ongoing]

Illustrating toy example:

helicity decay



untying link by generating monopole pairs

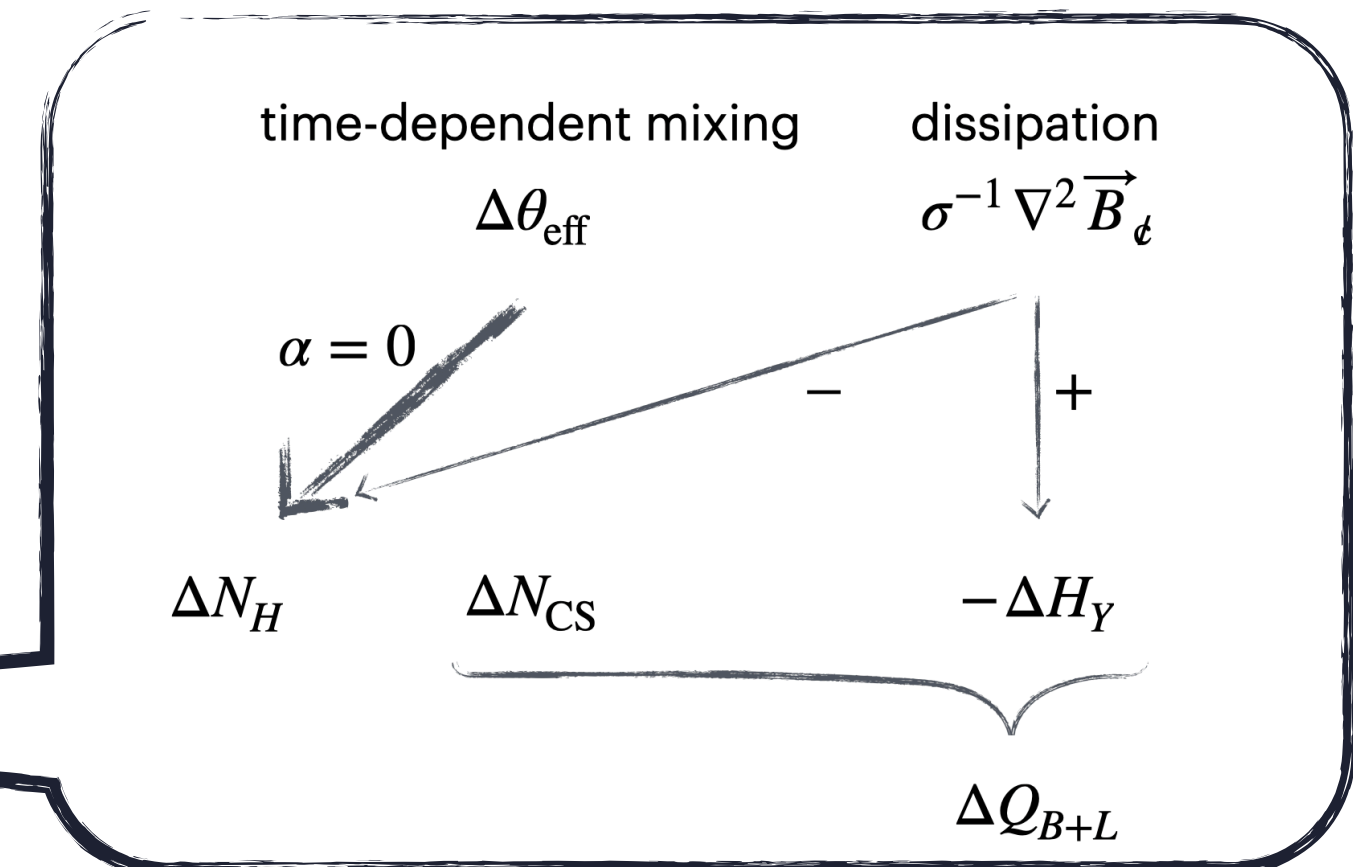
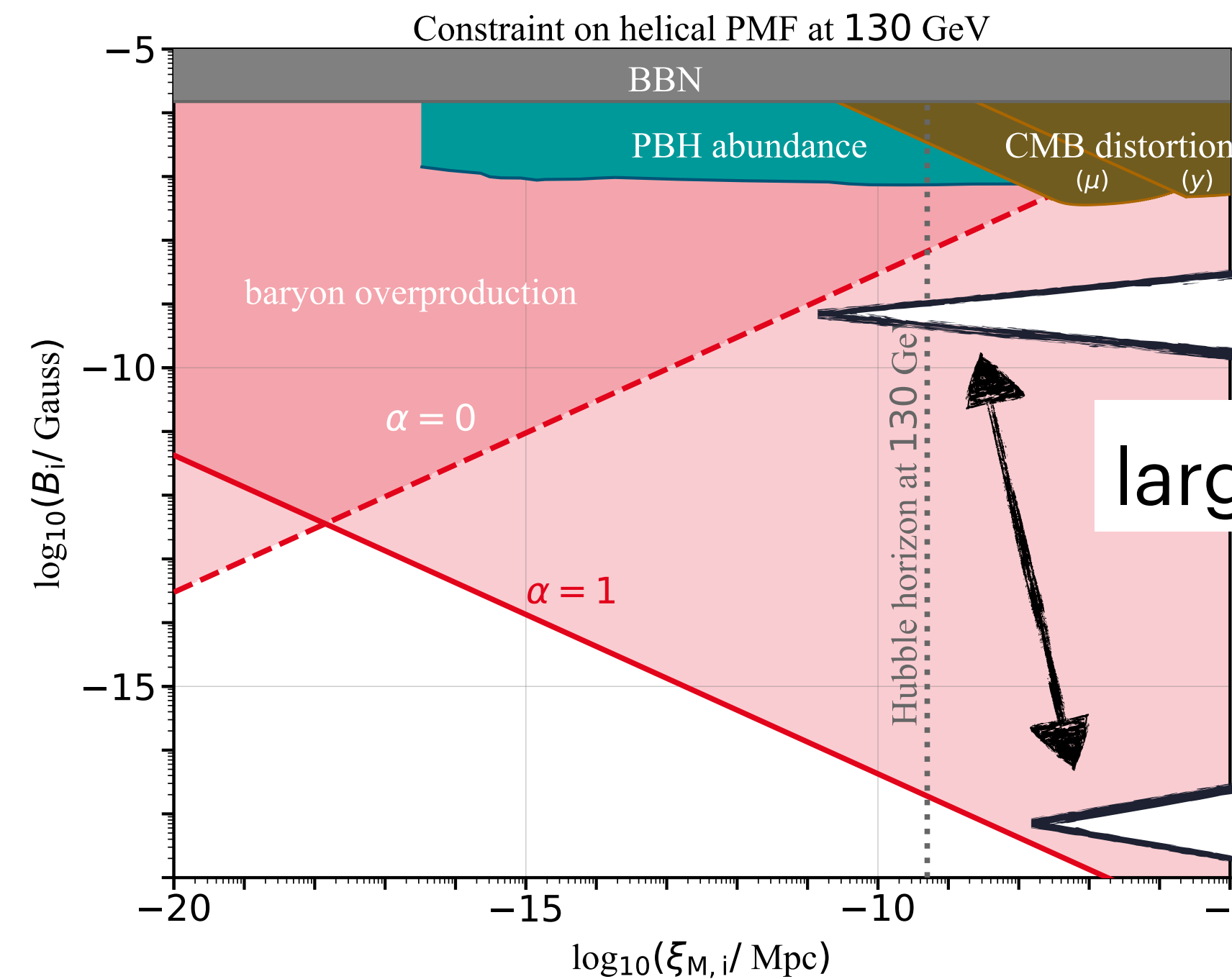
$$\rightarrow \partial_\mu j_{B+L}^\mu \sim \vec{E} \cdot \vec{B} = 0?$$

In the SM, gauge-invariant quantity involves both N_{CS} and N_H

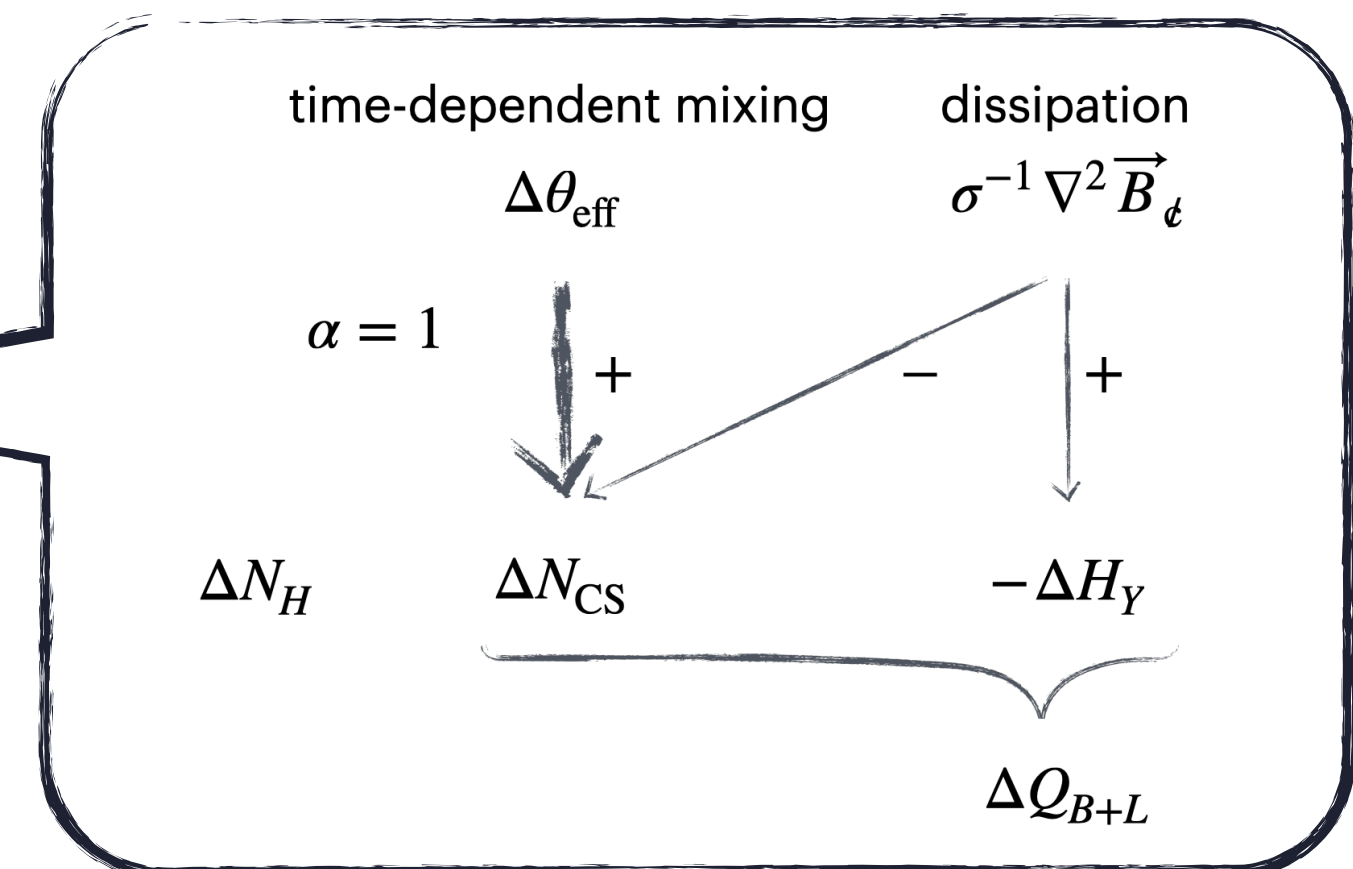
$$\delta := N_{\text{CS}} - H_Y - N_H$$

バリオン数過剰生成の制限 (ヘリカル磁場)

$$\overline{\eta_{B,\text{PMF}}} \leq 10^{-10}$$

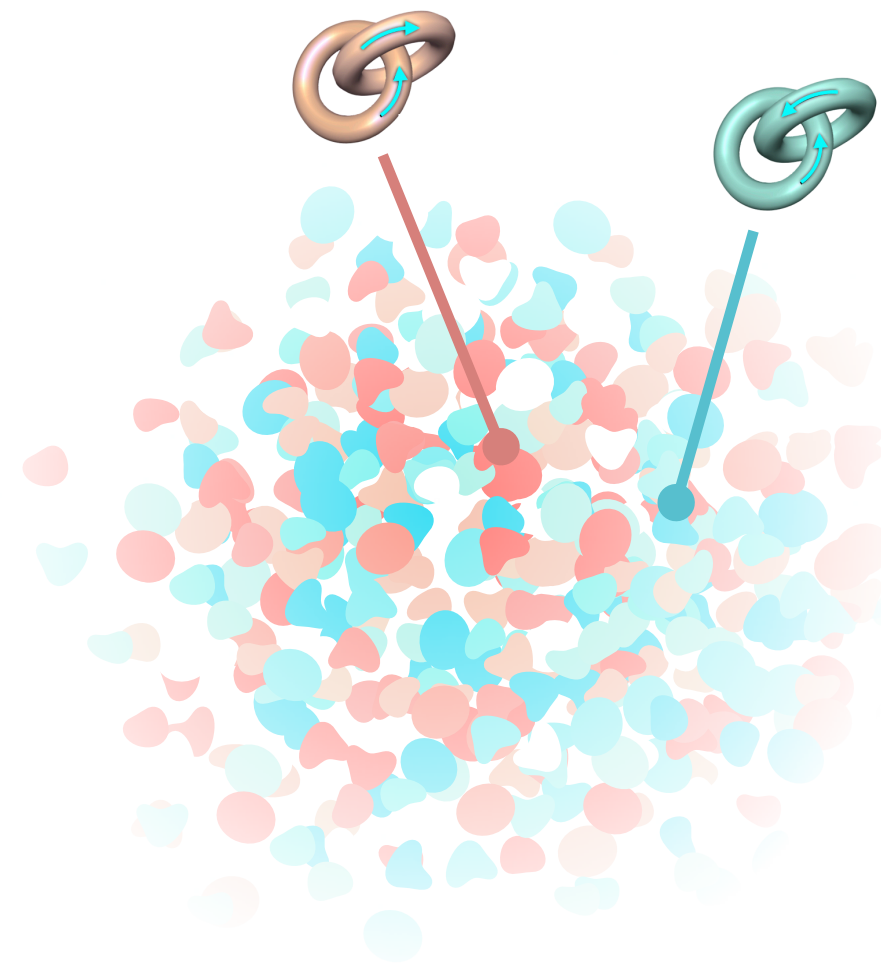


large uncertainty!



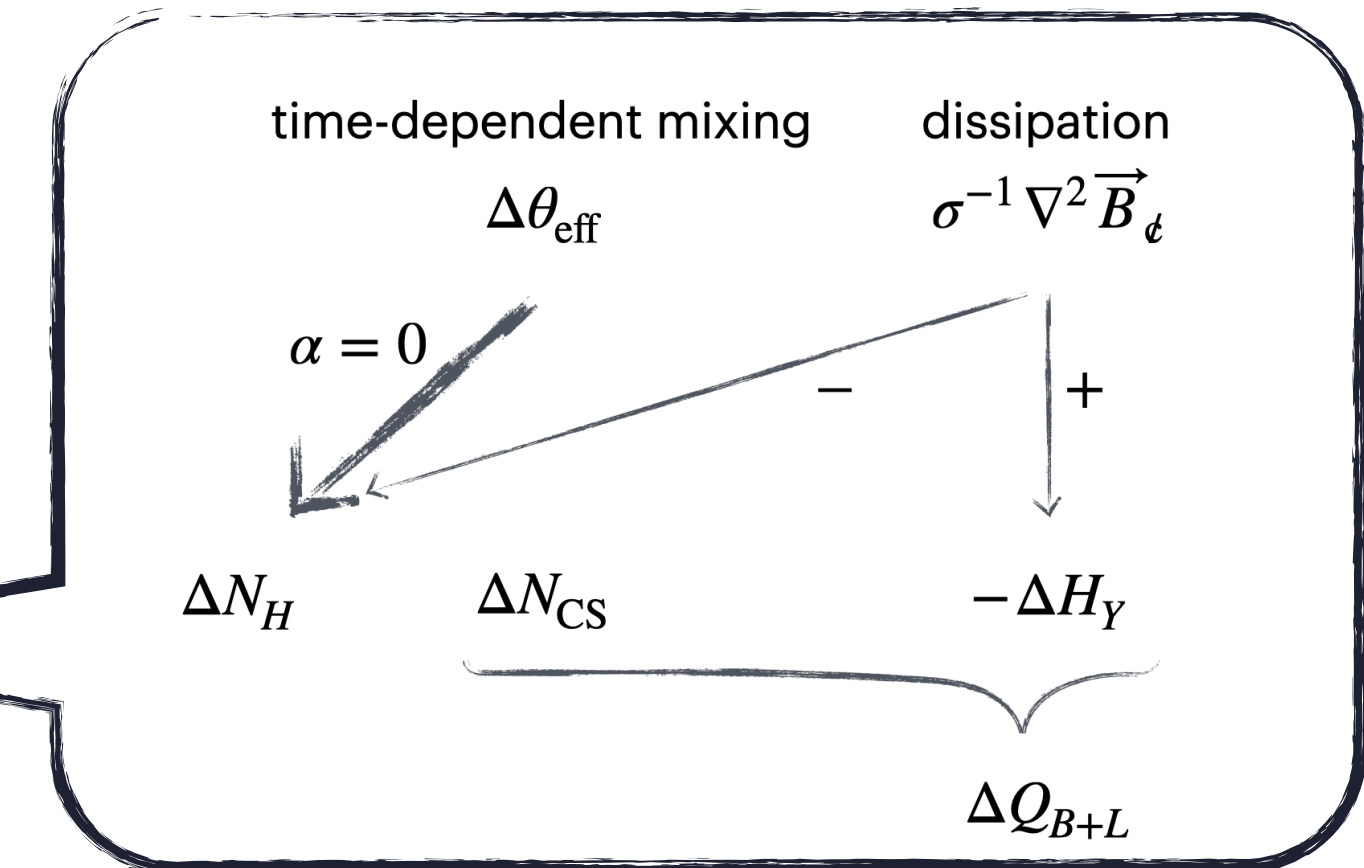
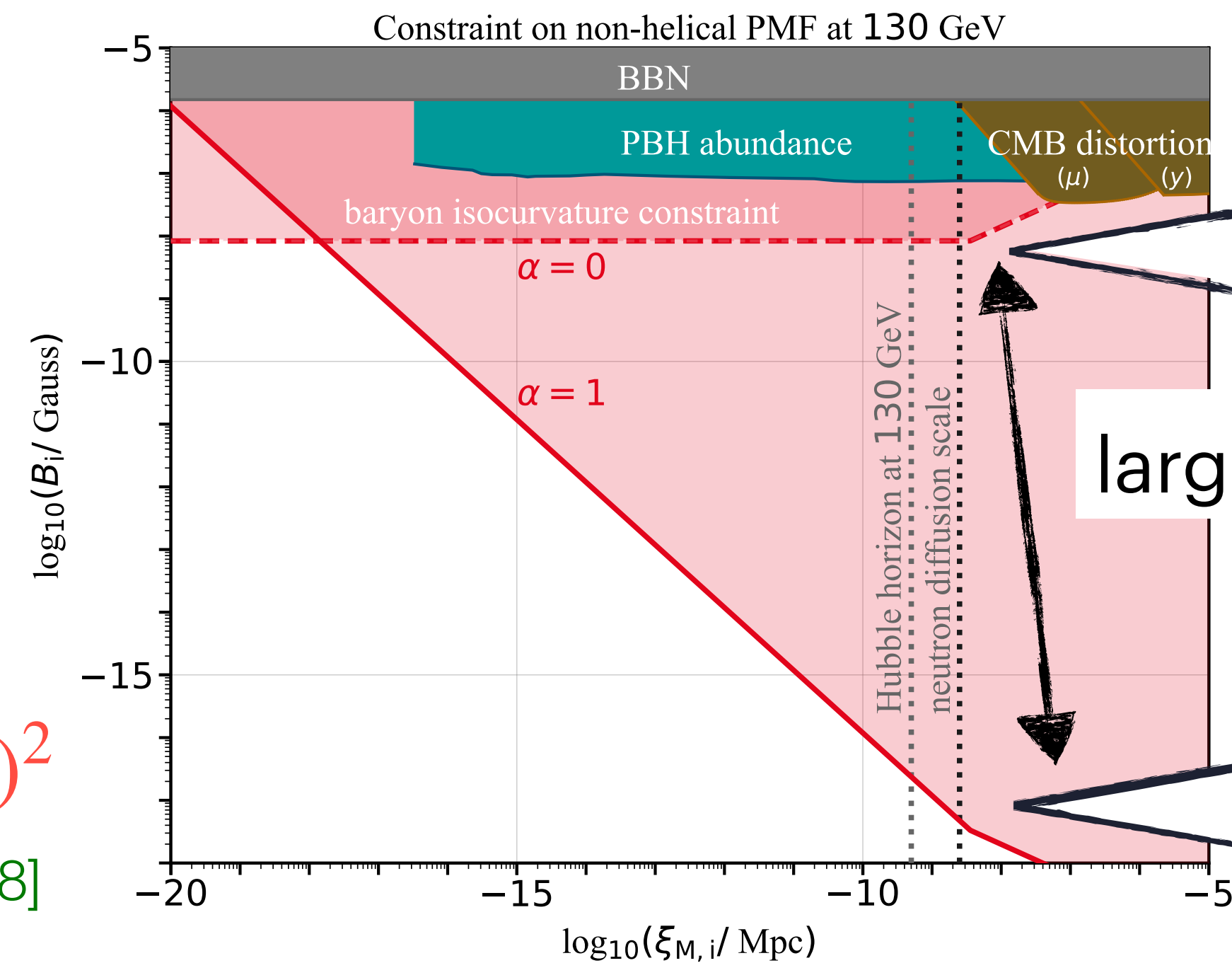
topological charge of $U(1)_Y$ magnetic field may result in too much baryons
 ..., [Fujita, Kamada 2016] [Kamada, Long 2016]

バリオンゆらぎの制限 (非ヘリカル磁場)

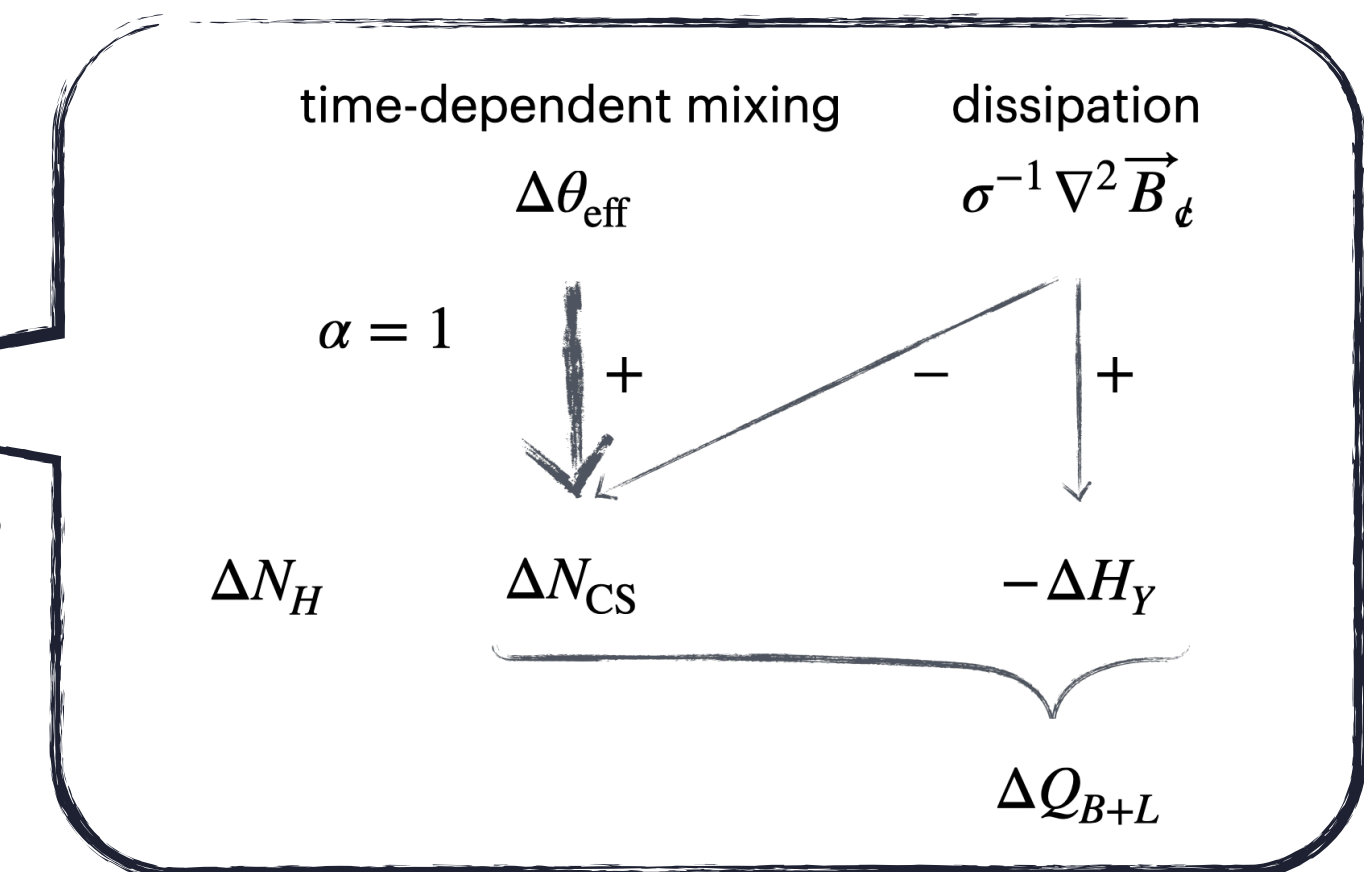


$$\overline{(\delta\eta_{B,\text{BBN}})^2} \leq 0.016 (\bar{\eta}_B)^2$$

[Inomata+ 2018]



large uncertainty!

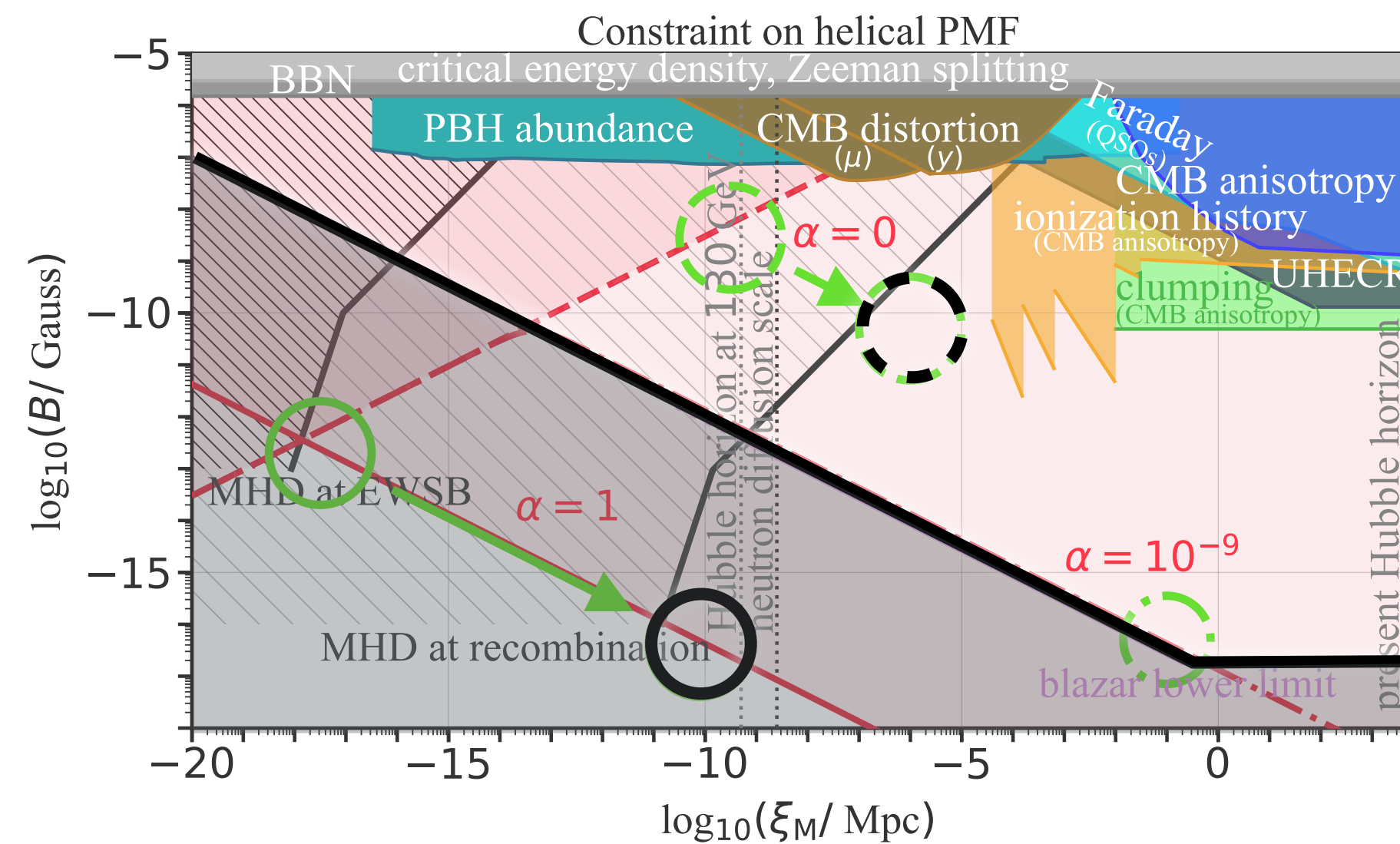


$U(1)_Y$ magnetic field fluctuations may result in too much baryon fluctuations

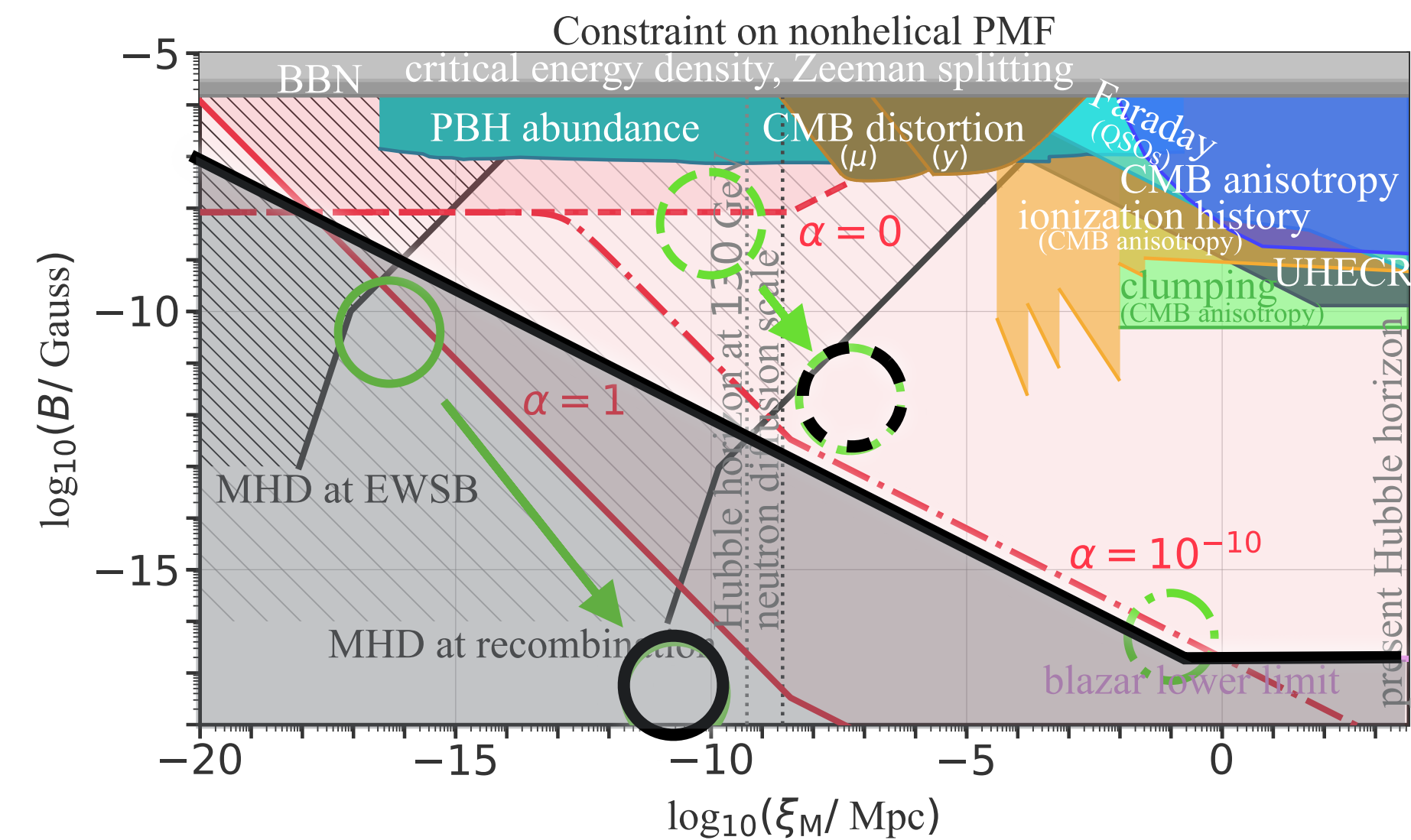
[Giovannini, Shaposhnikov 1997], [Kamada, FU, Yokoyama, 2021]

制限 vs 観測されたボイド磁場

baryon overproduction (helical)



baryon fluctuation (non-helical)



compensation of $\Delta N_{CS}^{\text{SU}(2)_L}$ by Higgs winding

ineffective

effective

PMF before the EWSB as the origin of void MF

No

Yes

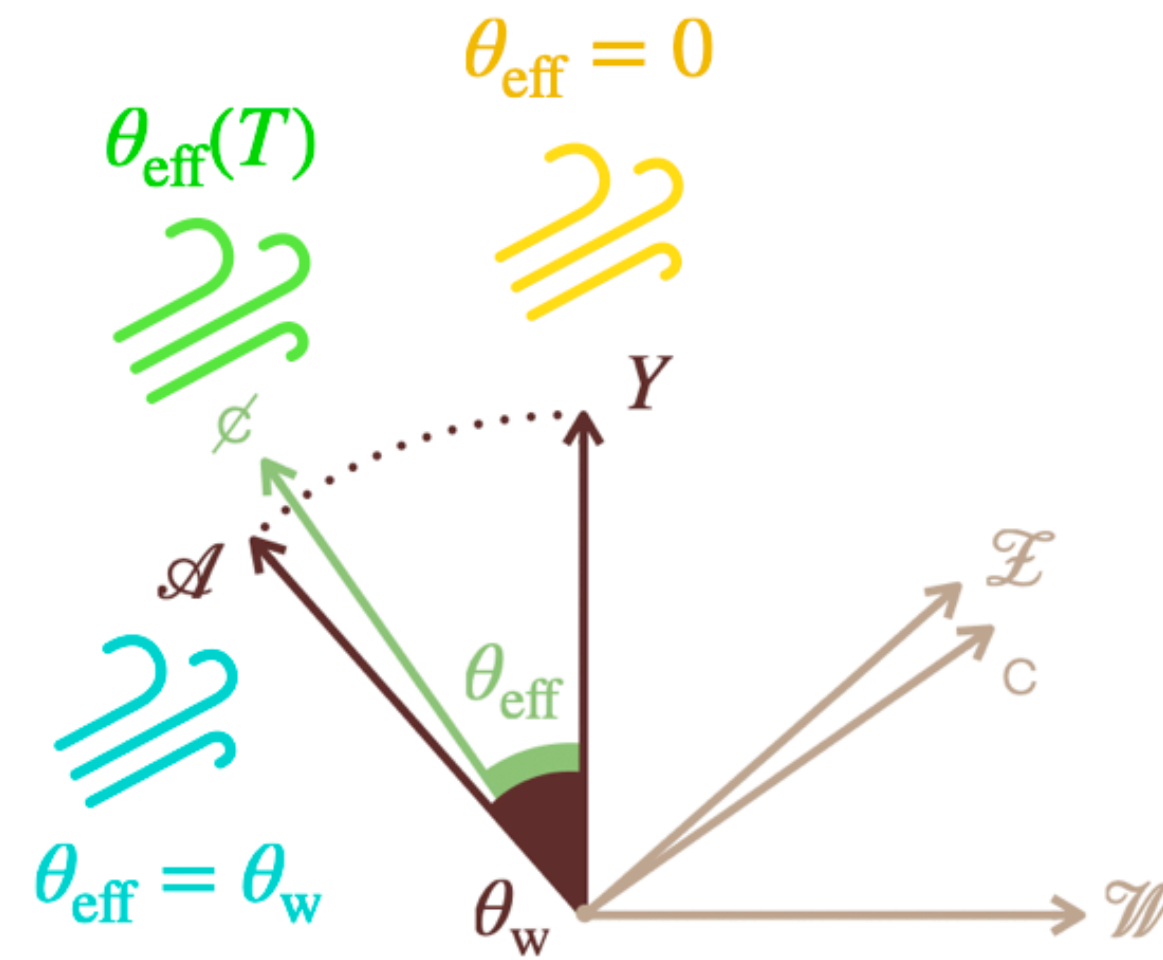
In particular, PMF before the EWSB as the common origin of void MF and the BAU

No

Yes (if helical)

まとめ

As a consequence of $\cancel{U(1)_M^{[0]}}$,
 $\exists \vec{B}_\phi$ that interpolates $\vec{B}_Y$ and $\vec{B}_{em}$.



$\theta_{eff}(T) \rightarrow$ confined helicity decay $\rightarrow$ generate baryons (?)



PMF may (or may not) be the common origin of the void magnetic field and the BAU.