primordial magnetic fields during the electroweak crossover

and baryogenesis from helicity decay

[2012.14435], **[2507.01576]**, **[2509.23858]**, [2509.25734]

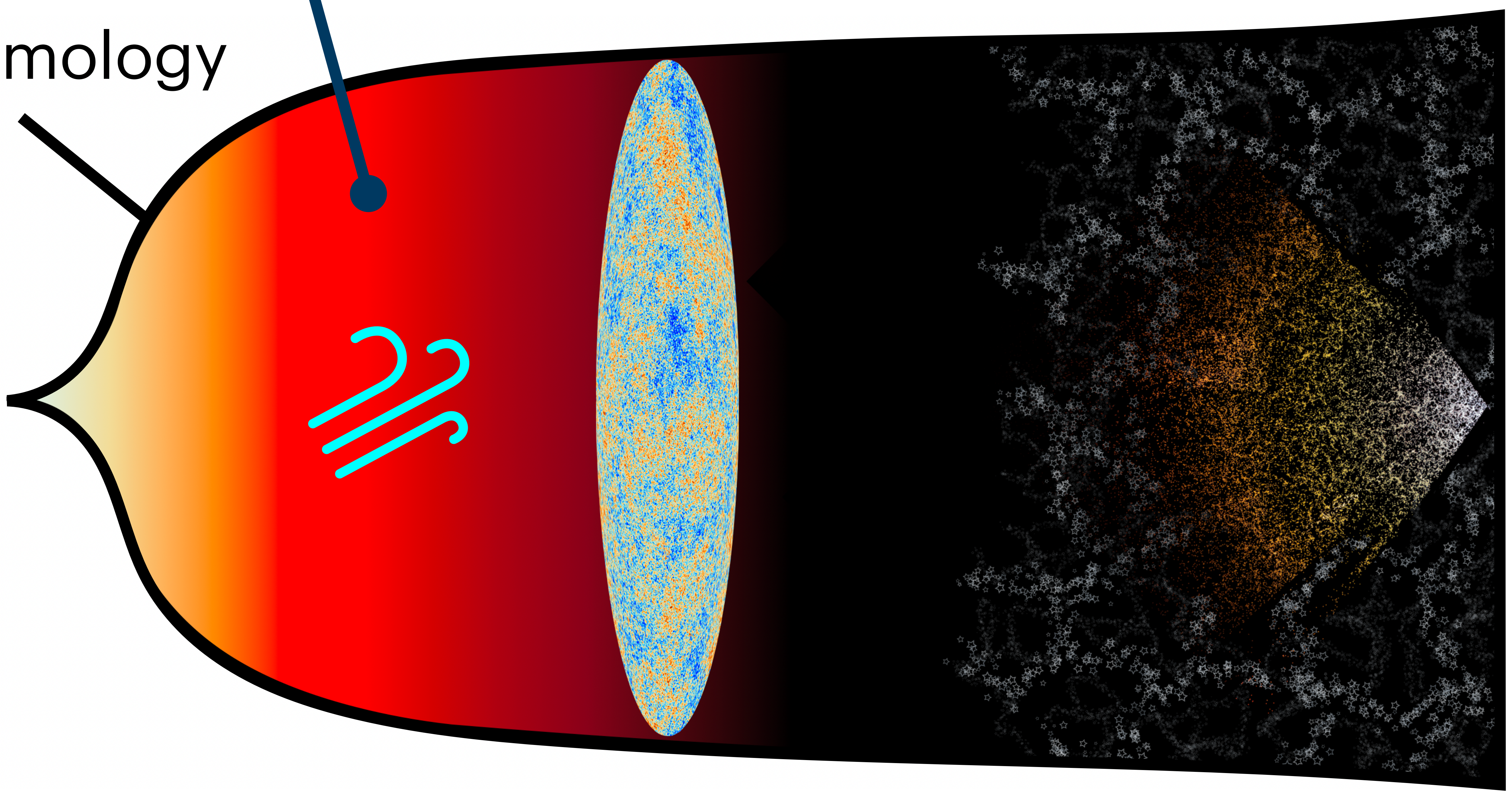
2025/12/12, Cosmology Journal Club at University of Geneva

Fumio Uchida (CTPU-CGA, IBS)

thermal plasma + magnetic field

in the Standard Model of particle physics

Standard cosmology
(ΛCDM)



[Durrer, Neronov 2013]

Figs (modified) from [Planck, ESA] and [D. Schlegel/Berkeley Lab using data from DESI, M. Zamani (NSF's NOIRLab)]

thermal plasma + magnetic field

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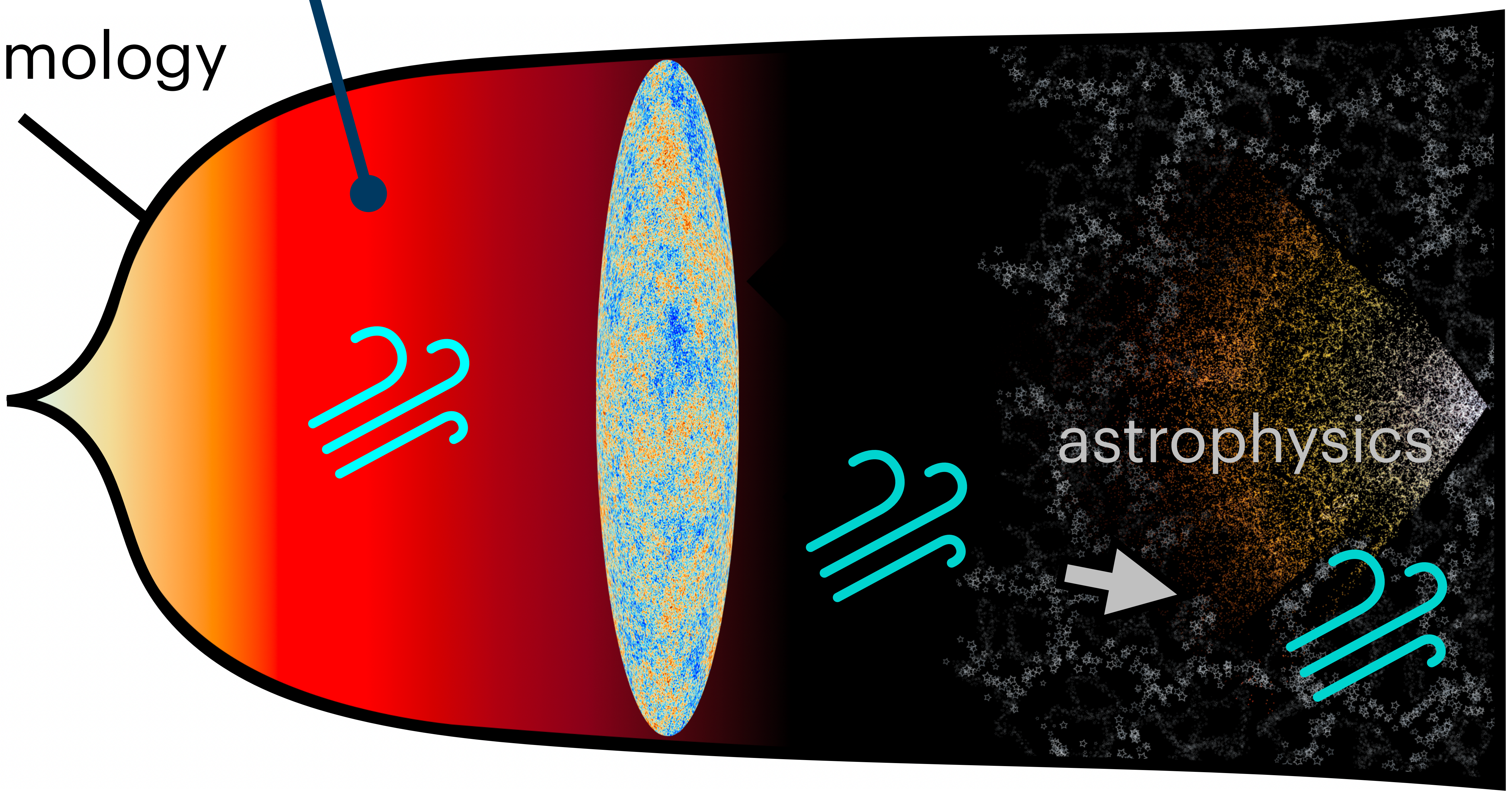

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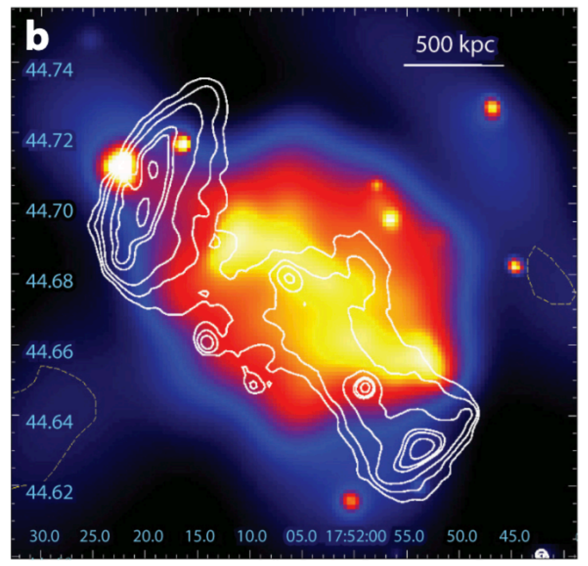
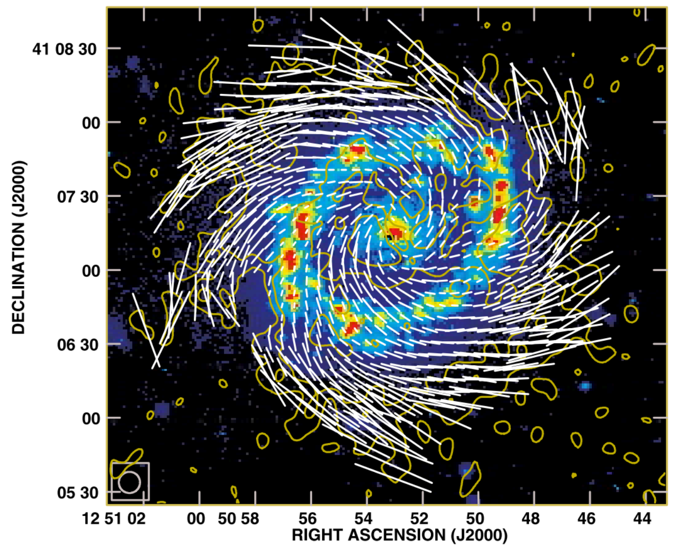
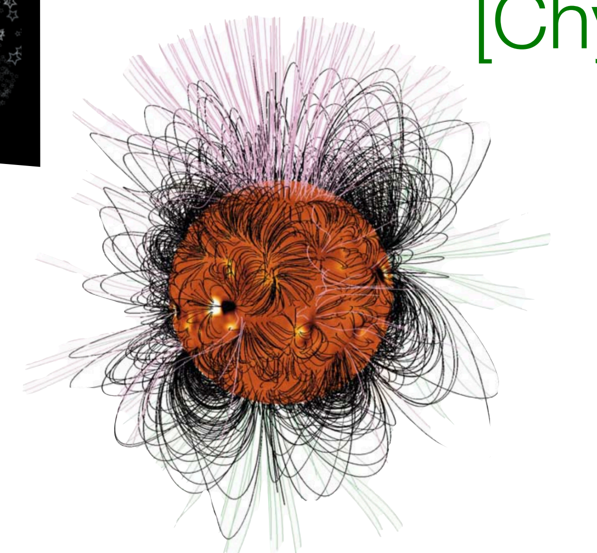


[Bonafede+]



[Chyży, Buta]



[Schrijver, De Rosa]

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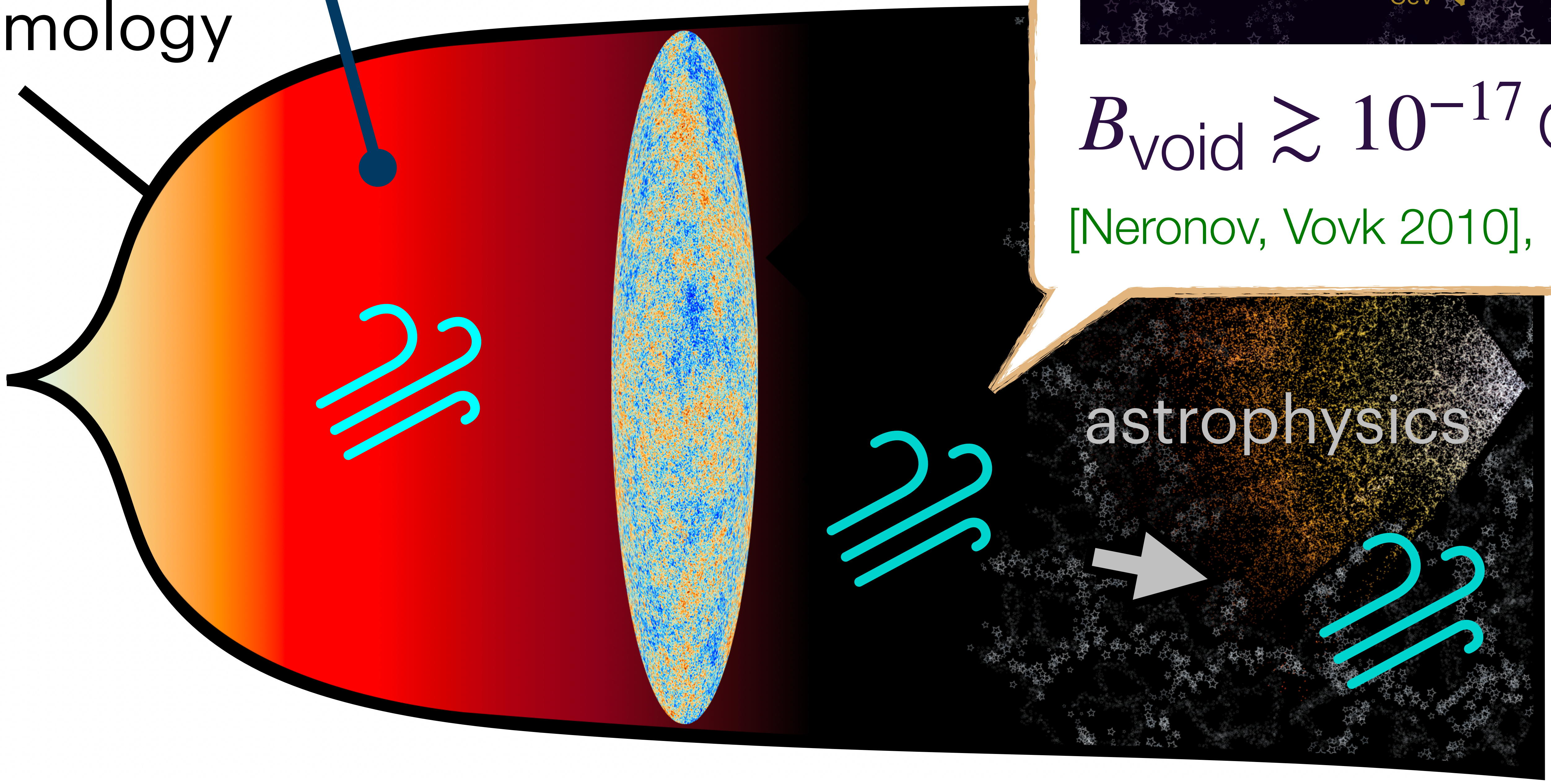
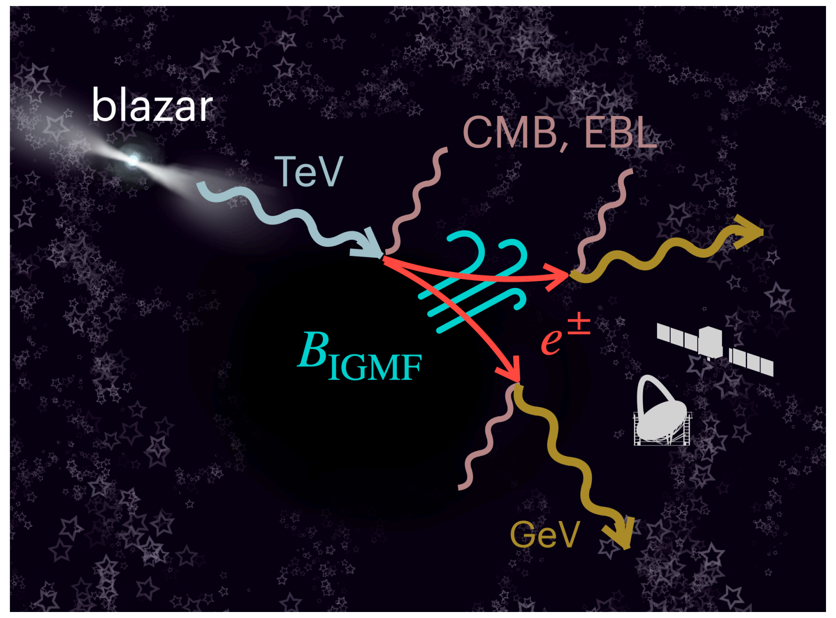
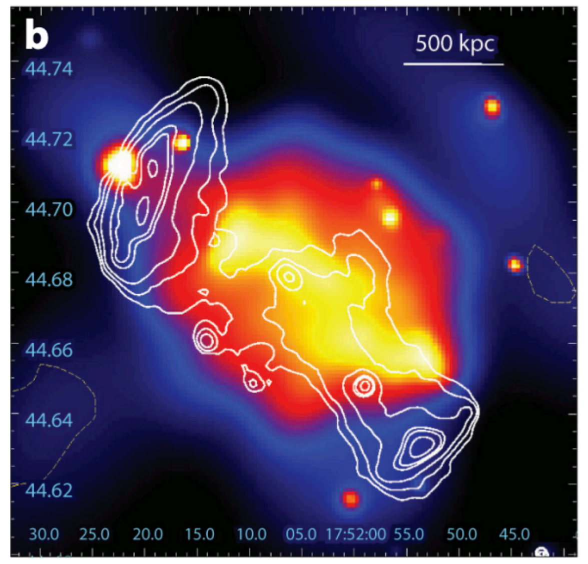




$B_{\rm void} \gtrsim 10^{-17}\,\mathrm{G}$

[Neronov, Vovk 2010], …



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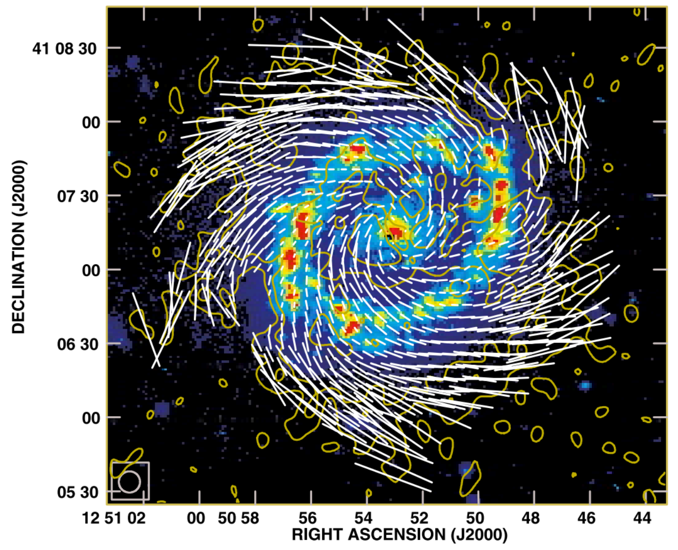
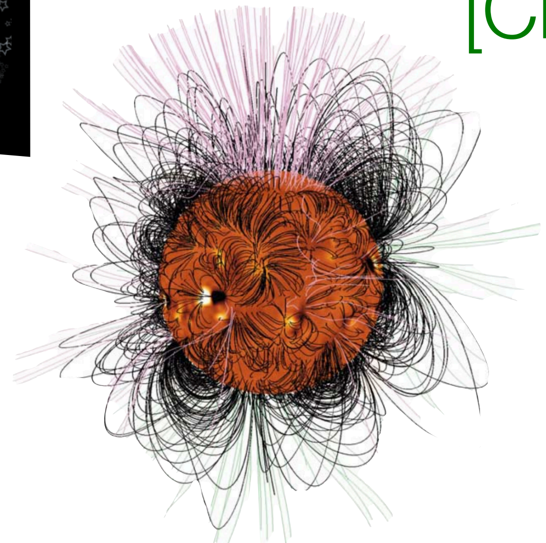


[Chyży, Buta]

[Durrer, Neronov 2013]



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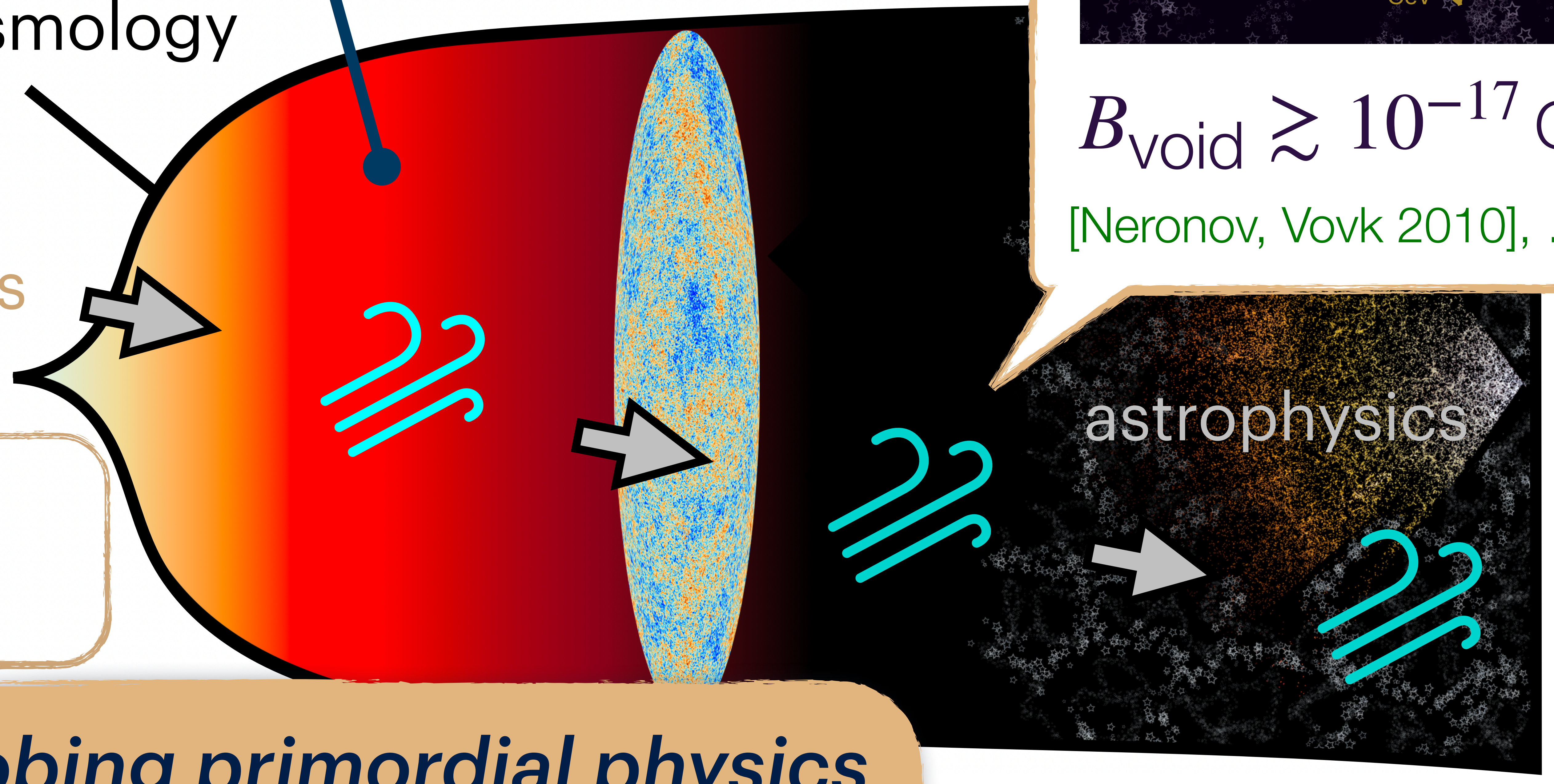
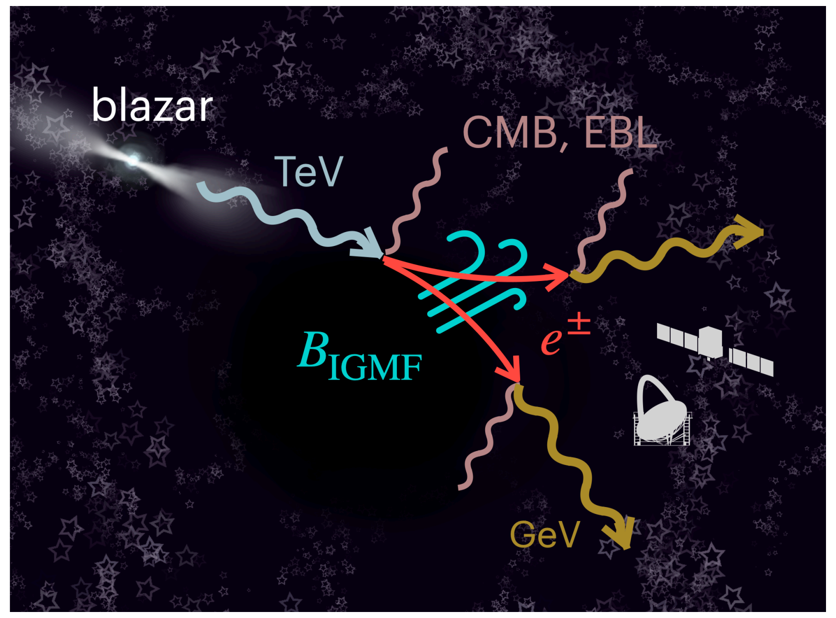
thermal plasma + magnetic field
in the Standard Model of particle physics

Standard cosmology
(ΛCDM)

magnetogenesis

models,
constraints, ...





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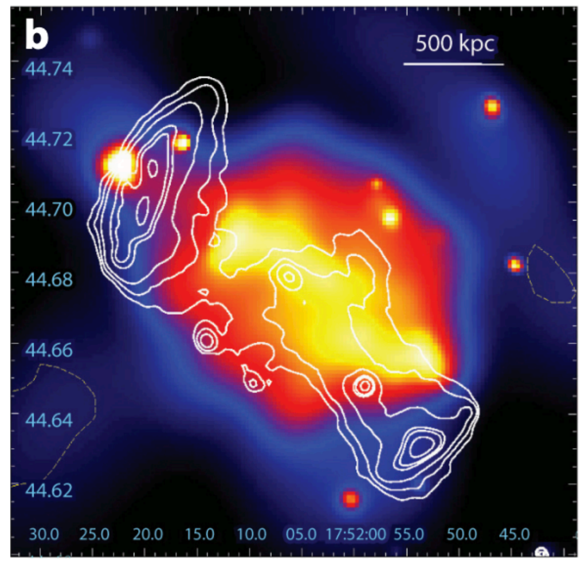
[Neronov, Vovk 2010], …



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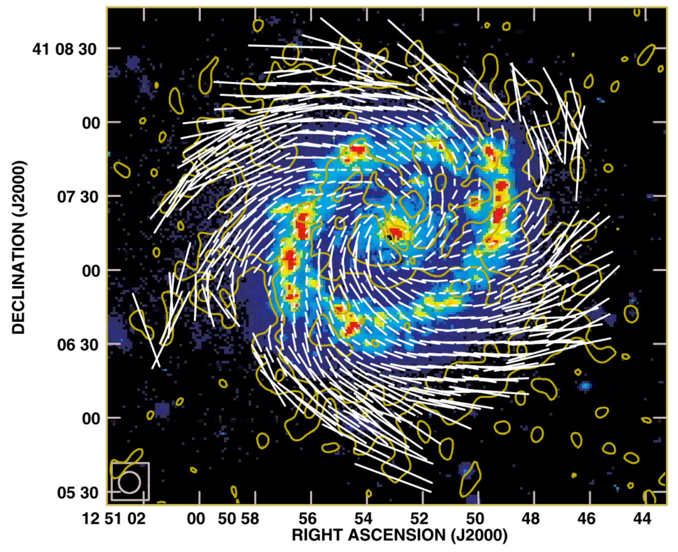
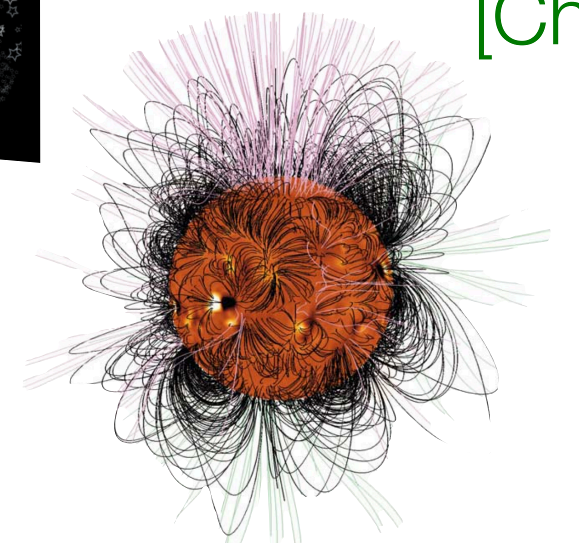


[Chyży, Buta]

Probing primordial physics with magnetic field!

[Durrer, Neronov 2013]



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The electroweak transition in unitary gauge

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

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

$$\Phi_{\mathrm{vac}} \to U\,\Phi_{\mathrm{vac}}$$

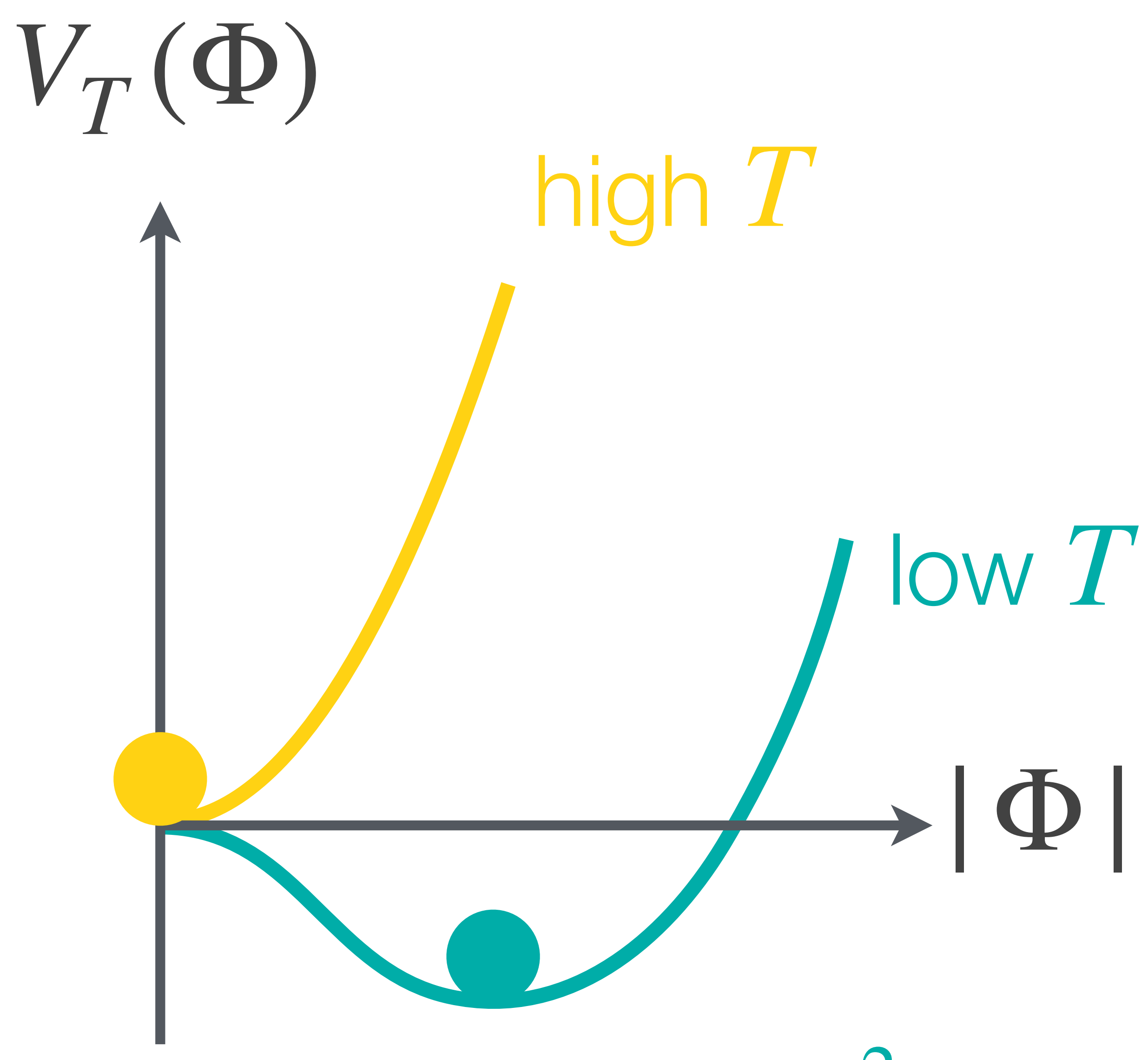
$$\mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{U}(1)_Y$$

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

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

$$\Phi_{\mathrm{vac}} \to e^{i\alpha Q_{\mathrm{em}}}\,\Phi_{\mathrm{vac}}$$

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



$$\langle |\Phi|^2 \rangle = \frac{v(T)^2}{2}$$

The electroweak transition in unitary gauge

$T \gg T_{\rm EW}$

$\Phi_{\rm vac} = 0$

$\Phi_{\rm vac} \to U\,\Phi_{\rm vac}$

$\mathrm{SU}(2)_{\rm L} \times \mathrm{U}(1)_Y$

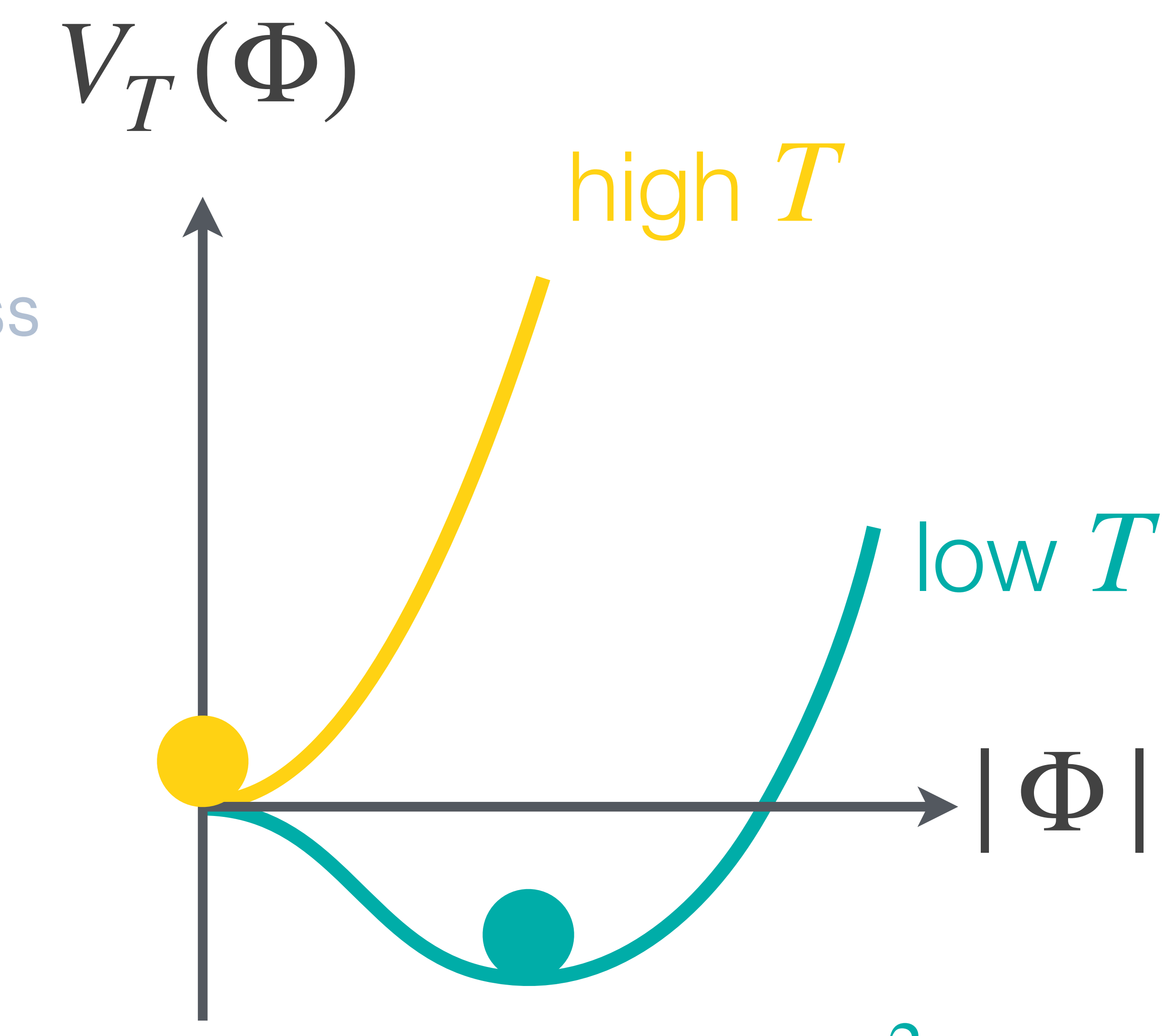
W_i^a has non-perturbative mass

$T \ll T_{\rm EW}$

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

$\Phi_{\rm vac} \to e^{i\alpha Q_{\rm em}}\,\Phi_{\rm vac}$

$\mathrm{U}(1)_{\rm em}$



$$\langle |\Phi|^2 \rangle = \frac{v(T)^2}{2}$$

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

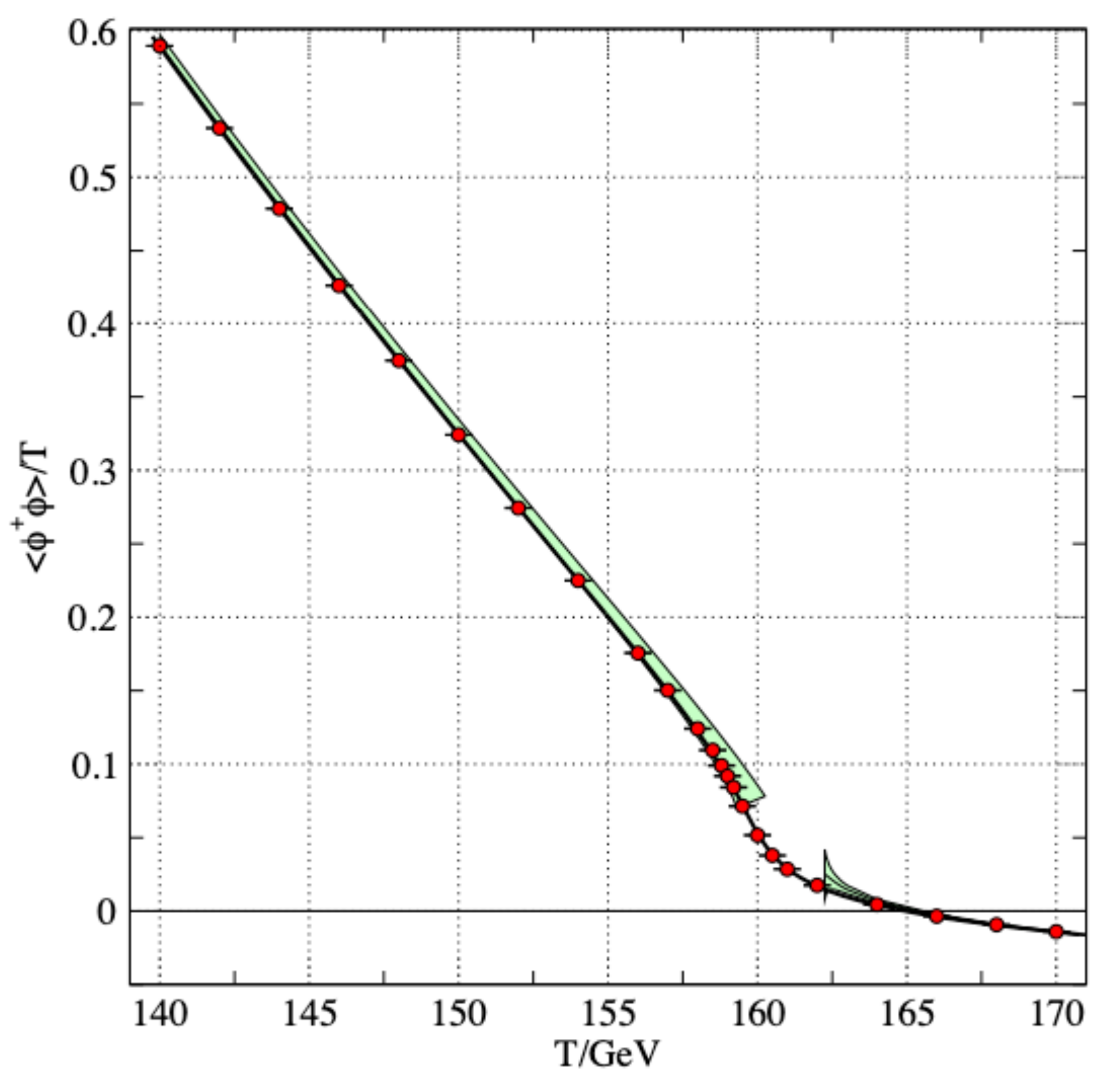
||

long-range/massless magnetic field

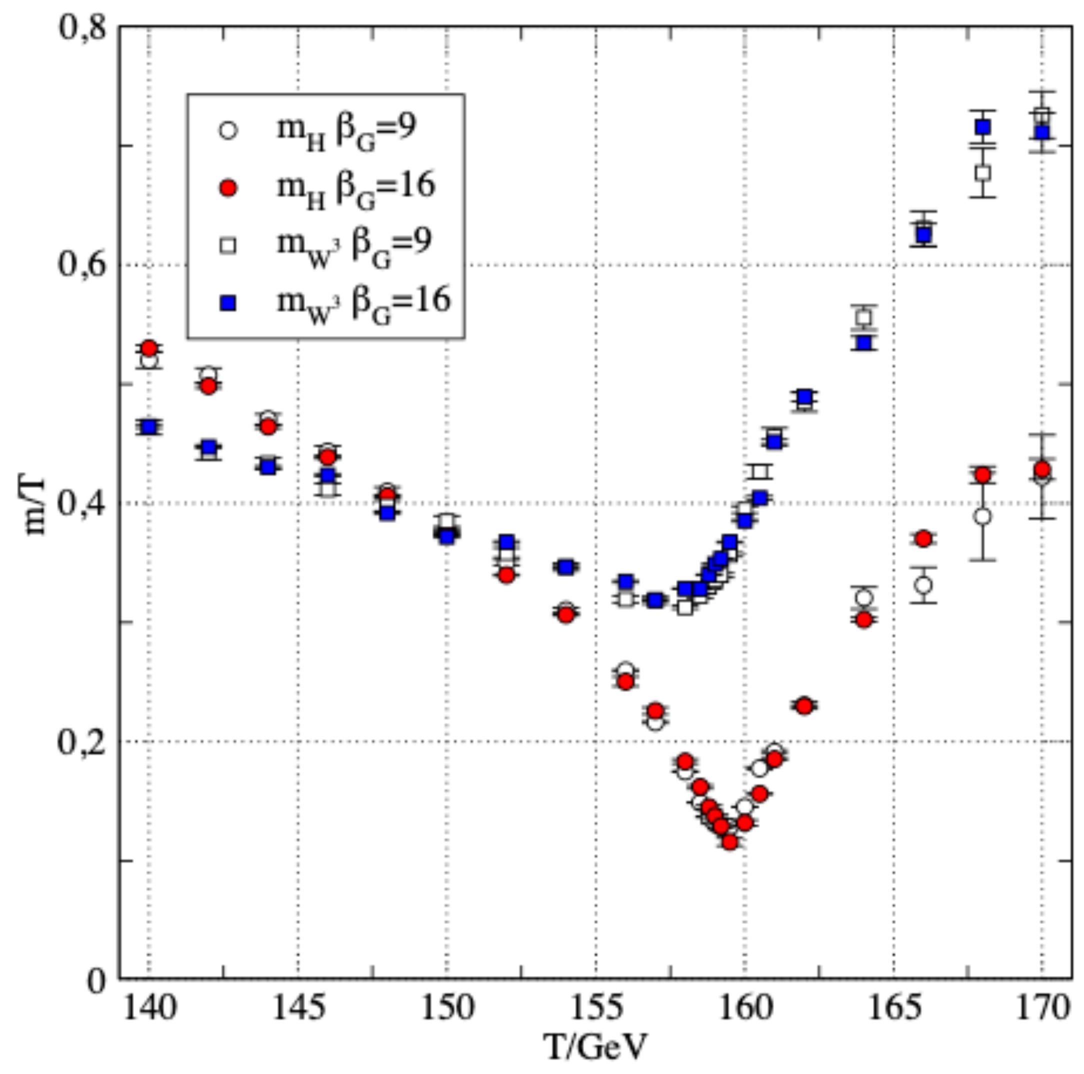
||

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

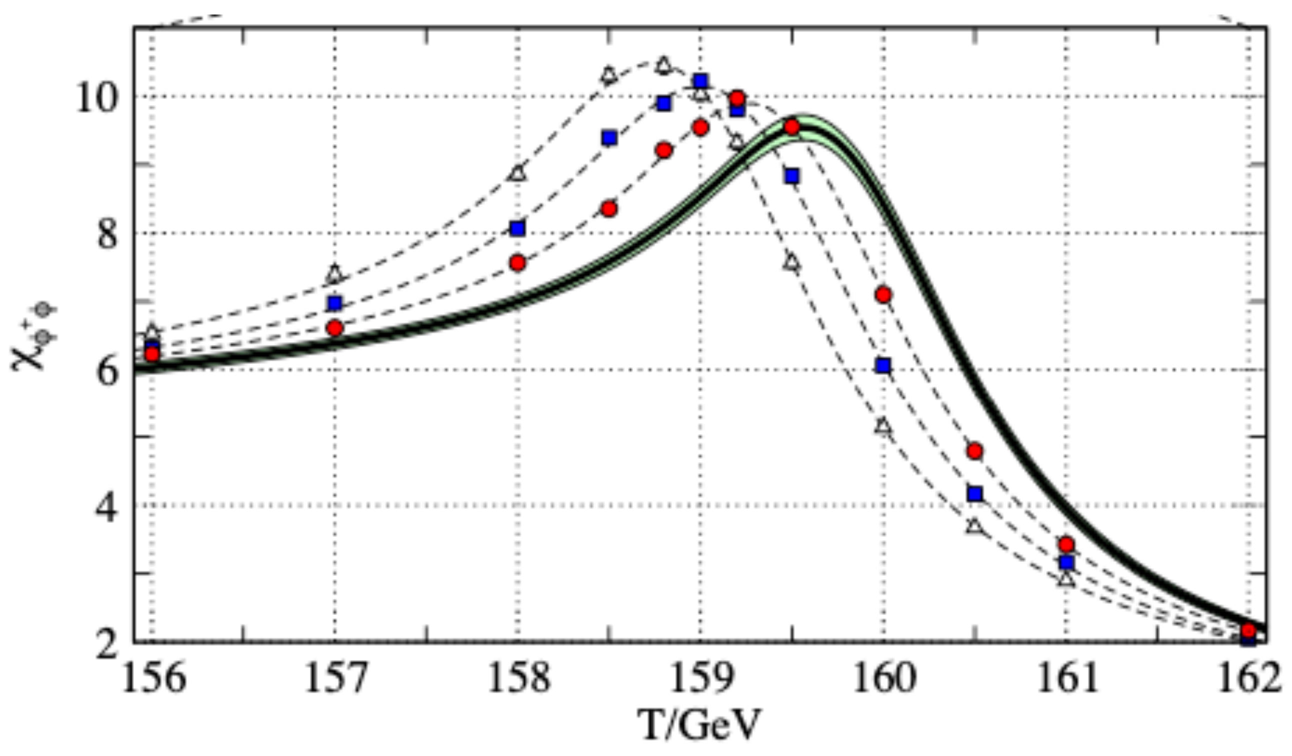
Crossover transition in lattice [D'Onofrio, Rummukainen 2015]



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



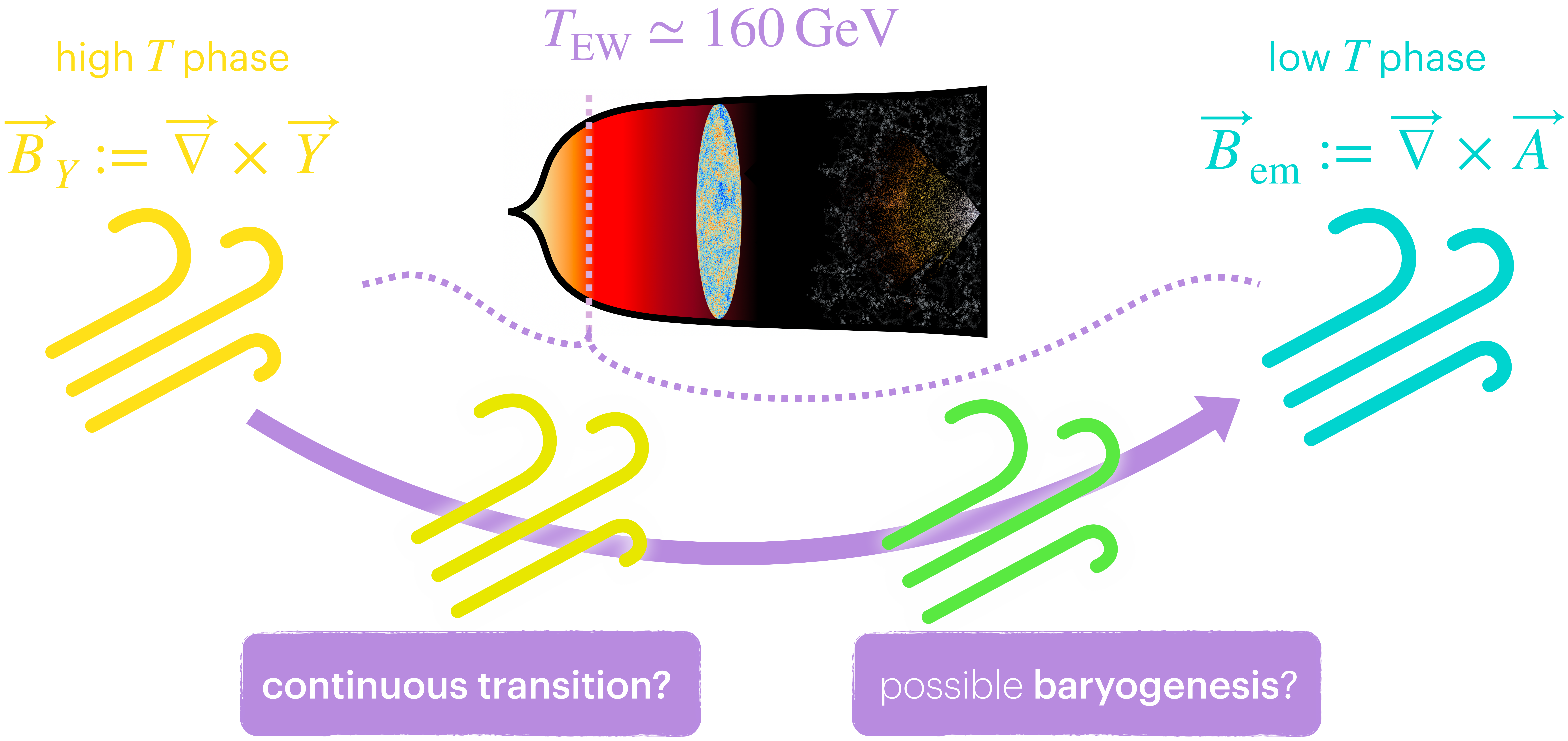
finite coherence length



finite Higgs susceptibility

$$\mathscr{L}_3 = (D_i\Phi)^\dagger D_i\Phi + m_3^2\Phi^\dagger\Phi + \lambda_3\left(\Phi^\dagger\Phi\right)^2 + \frac{1}{4}Y_{ij}Y_{ij} + \frac{1}{4}W^a_{ij}W^a_{ij}$$

Primordial magnetic field during the crossover?



Outline

Support the continuous transition
from the viewpoint of symmetry!

Introduction

Symmetries of 3d EFT of the thermal SM

Magnetic field during the electroweak crossover

Baryon asymmetry generation and constraints?

Summary

The same symmetry in high/low T phases

gauge symmetry: **unbroken in both phases**

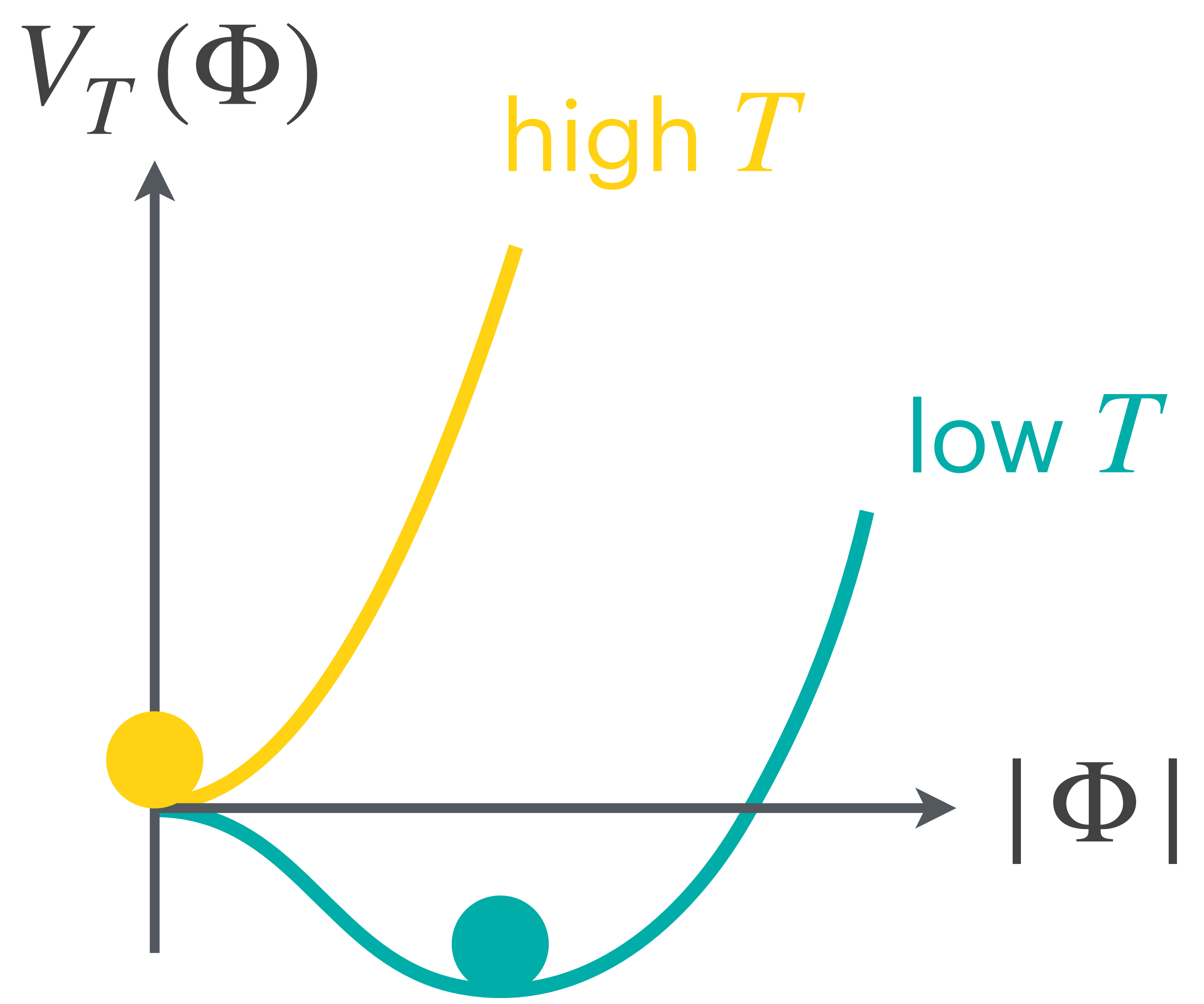
$$\langle \Phi \rangle = 0$$ [Elitzur 1975]

global symmetries: **same breaking pattern**

In particular, $\mathrm{U}(1)^{[0]}_{\mathrm{M}}$: SSB at high and low T.

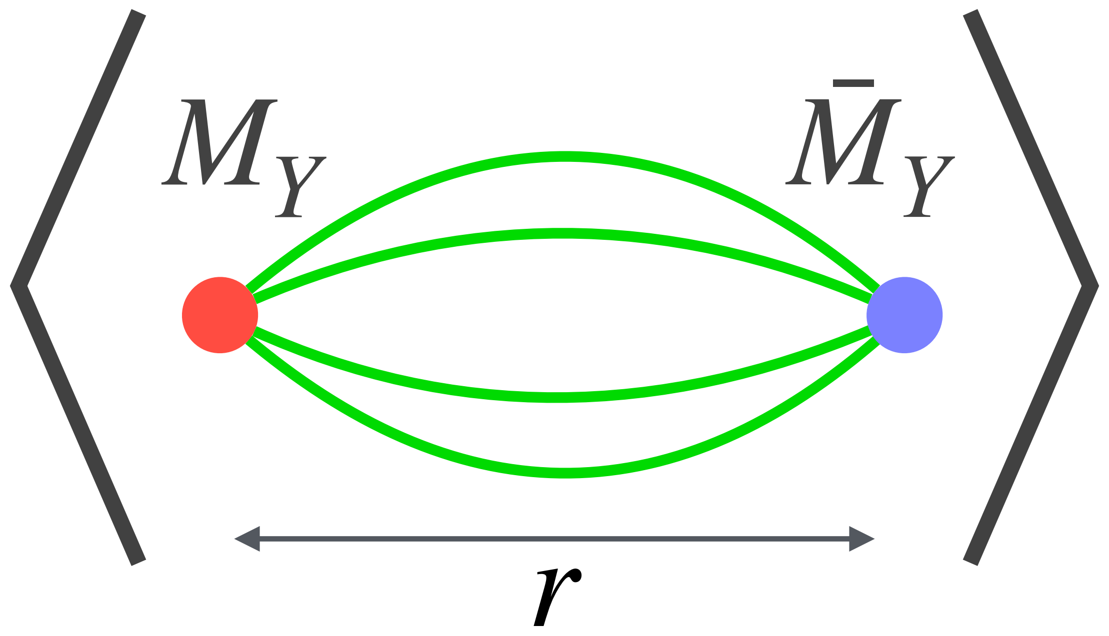
consistent with crossover transition

difference: $\langle \Phi^\dagger \Phi \rangle = 0 \,/\, \neq 0$



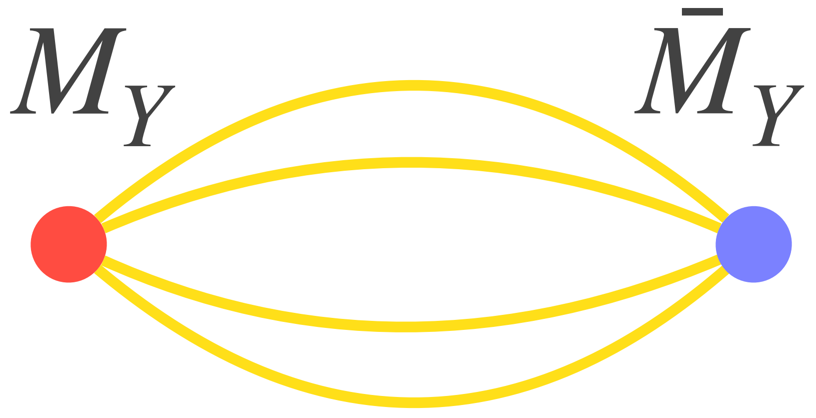
Spontaneous symmetry breaking of global $\mathrm{U}(1)^{[0]}_{\mathrm{M}}$

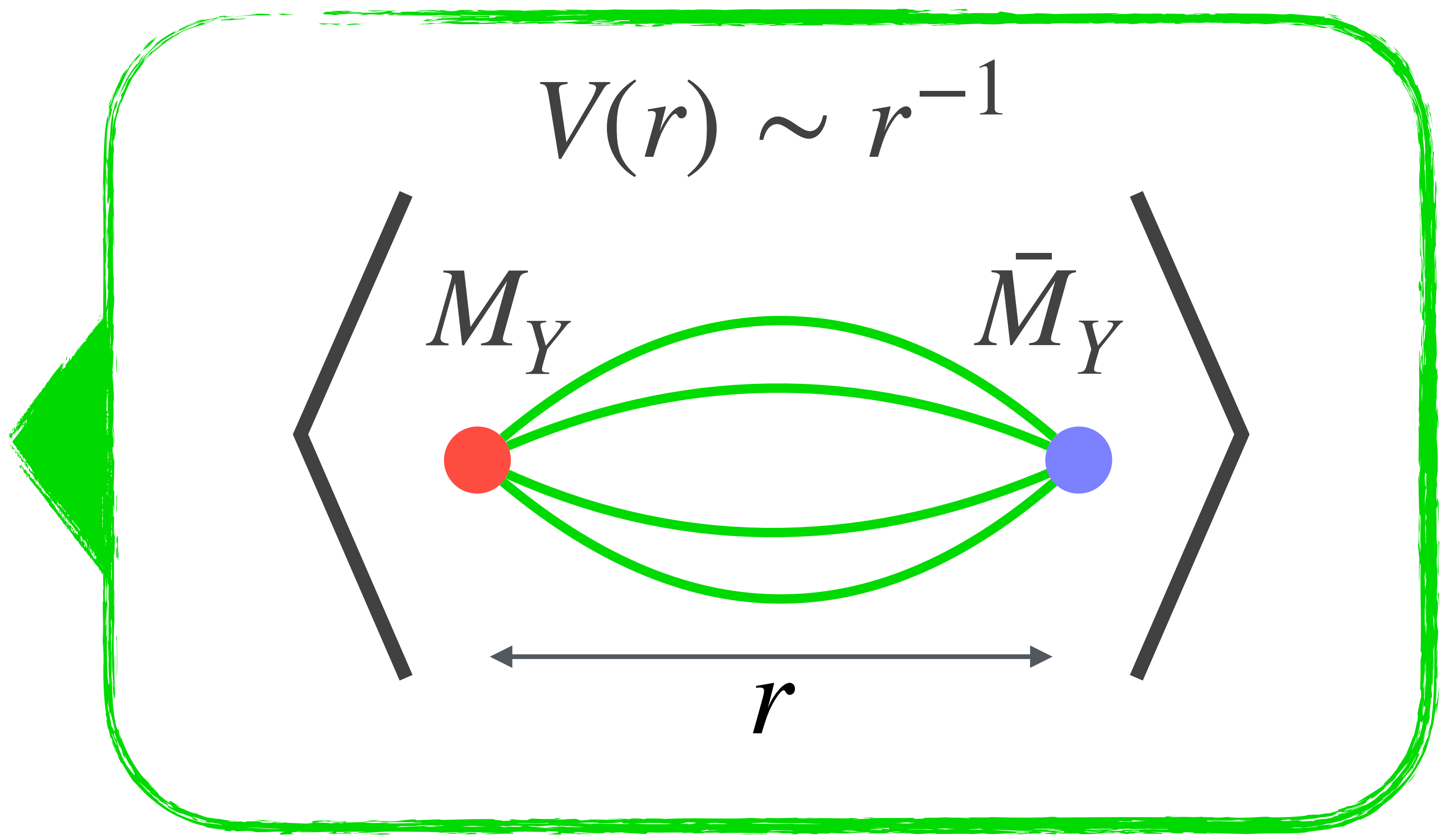
$$V(r) \sim r^{-1}$$



Spontaneous symmetry breaking of global $\mathrm{U}(1)_{\mathrm{M}}^{[0]}$

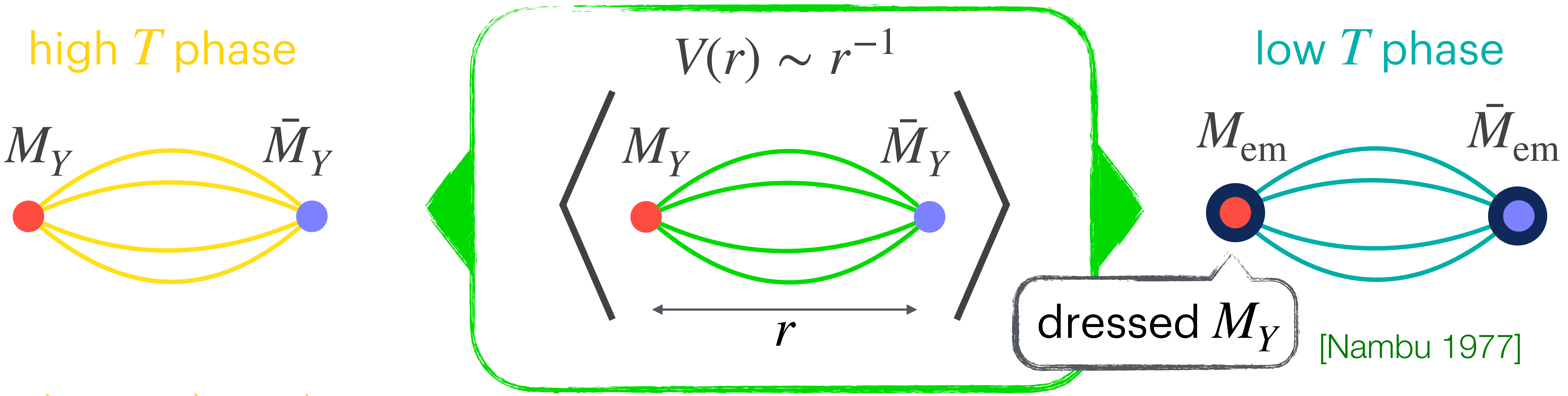
high T phase





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

Spontaneous symmetry breaking of global $\mathrm{U}(1)^{[0]}_{\mathrm{M}}$



[Nambu 1977]

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

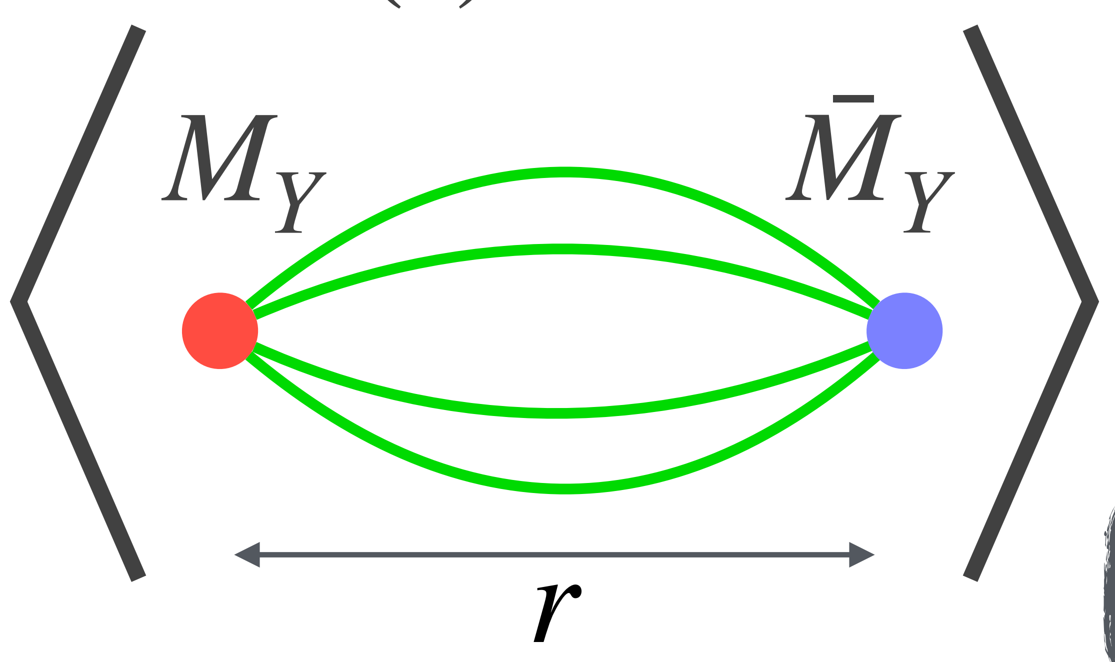
$$\vec{B}_{\mathrm{em}} := \vec{\nabla} \times \vec{A}$$

$$A_i = \cos\theta_{\mathrm{w}}\, Y_i - \sin\theta_{\mathrm{w}}\, W_i^3$$

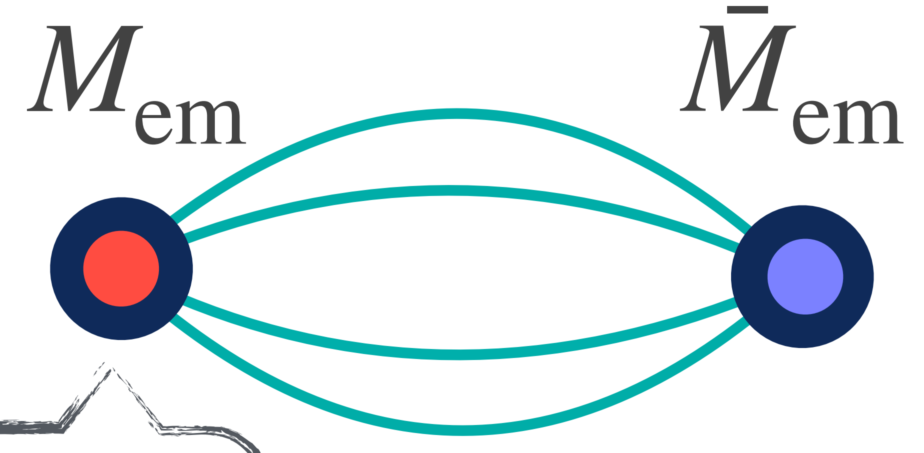
Spontaneous symmetry breaking of global $\mathrm{U}(1)^{[0]}_{\mathrm{M}}$

high T phase

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



low T phase



dressed M_Y

[Nambu 1977]

$\vec{B}_Y := \vec{\nabla} \times \vec{Y}$ = "photon" as the NGB = $\vec{B}_{\mathrm{em}} := \vec{\nabla} \times \vec{A}$

[Gaiotto+ 2014], …

$A_i = \cos\theta_{\mathrm{w}}\, Y_i - \sin\theta_{\mathrm{w}}\, W^3_i$

SSB of $\mathrm{U}(1)^{[0]}_{\mathrm{M}}$ global symmetry at high/law T phases

$\vec{\nabla} \cdot \vec{B}_Y = 0$ Bianchi identity as the conservation law

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

Magnetic field from $\cancel{\mathrm{U}(1)^{[0]}_{\mathrm{M}}}$ at any T [Hamada, Mukaida, FU 2025a]

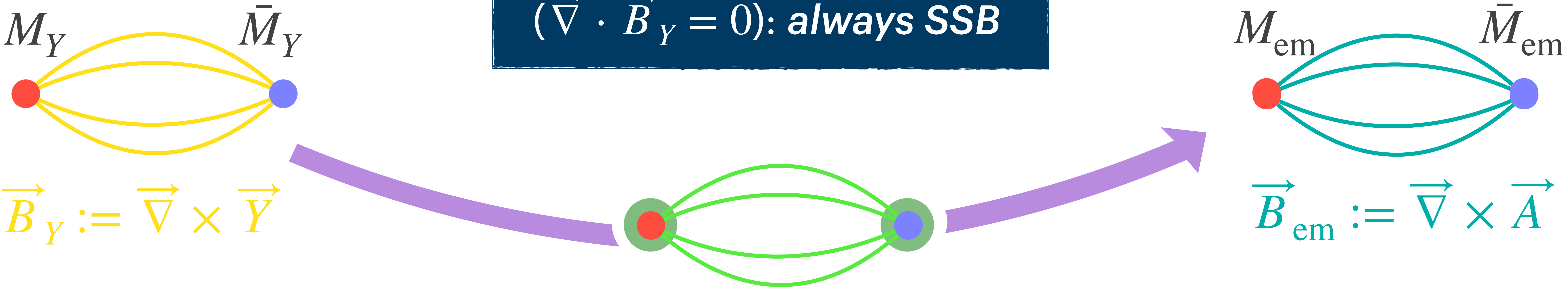
assumption

$\mathrm{U}(1)^{[0]}_{\mathrm{M}}$ global symmetry

$(\vec{\nabla} \cdot \vec{B}_Y = 0)$: ***always SSB***

high T phase

low T phase



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

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

$\vec{B}_{\not{c}}$ interpolates $\vec{B}_Y$ and $\vec{B}_{\mathrm{em}}$

as the NG boson

Outline

Identify the unconfined magnetic field
during the electroweak crossover!

Introduction

Symmetries of 3d EFT of the thermal SM

Magnetic field during the electroweak crossover

Baryon asymmetry generation and constraints?

Summary

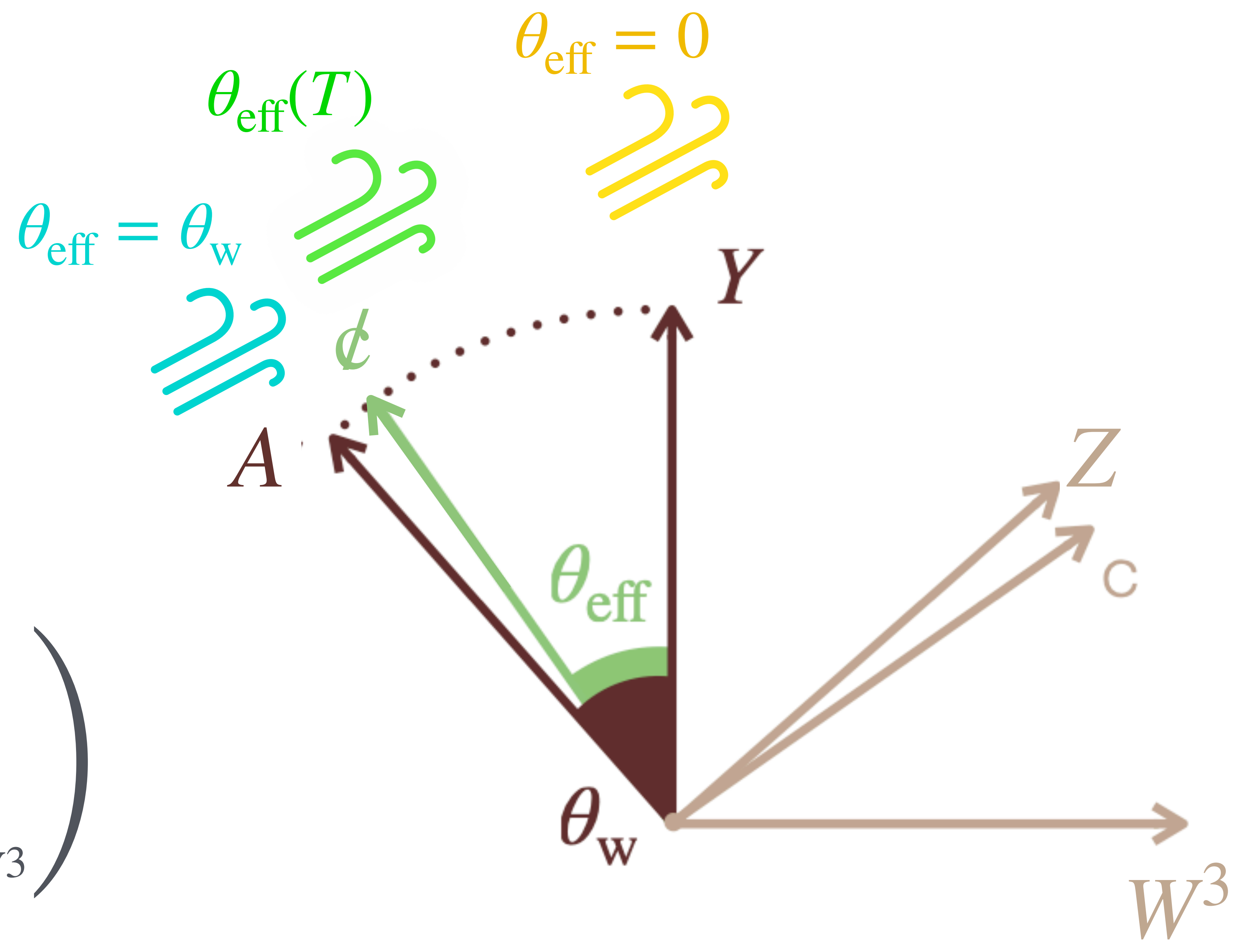
Effective mixing angle [D'Onofrio, Rummukainen 2015] [Kamada, Long 2016]

At low T,

$$\begin{pmatrix} \vec{B}_{\mathrm{em}} \\ \vec{B}_{Z} \end{pmatrix} = \begin{pmatrix} \cos\theta_{\mathrm{w}} & -\sin\theta_{\mathrm{w}} \\ \sin\theta_{\mathrm{w}} & \cos\theta_{\mathrm{w}} \end{pmatrix} \begin{pmatrix} \vec{B}_{Y} \\ \vec{B}_{W^3} \end{pmatrix}$$

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

$$\begin{pmatrix} \vec{B}_{\cancel{c}} \\ \vec{B}_{\mathrm{c}} \end{pmatrix} = \begin{pmatrix} \cos\theta_{\mathrm{eff}}(T) & -\sin\theta_{\mathrm{eff}}(T) \\ \sin\theta_{\mathrm{eff}}(T) & \cos\theta_{\mathrm{eff}}(T) \end{pmatrix} \begin{pmatrix} \vec{B}_{Y} \\ \vec{B}_{W^3} \end{pmatrix}$$



One can compute $\theta_{\text{eff}}(T)$ perturbatively

mixing

Ansatz $$\begin{pmatrix} \vec{B}_{\not{c}} \\ \vec{B}_{\text{c}} \end{pmatrix} = \begin{pmatrix} \cos\theta_{\text{eff}} & -\sin\theta_{\text{eff}} \\ \sin\theta_{\text{eff}} & \cos\theta_{\text{eff}} \end{pmatrix} \begin{pmatrix} \vec{B}_{Y} \\ \vec{B}_{W^3} \end{pmatrix}$$

massless pole

s.t. $$\langle B_{\not{c}\,i}(\vec{p}) B_{\not{c}\,j}(\vec{q}) \rangle = (2\pi)^3 \delta^3(\vec{p}+\vec{q}) \quad \left(P_{ij}(\hat{p}) + S_{\not{c}\not{c}}\delta_{ij} \right) + \mathcal{O}(|\vec{p}|, g_3^4),$$

$$\langle B_{\not{c}\,i}(\vec{p}) B_{\text{c}\,j}(\vec{q}) \rangle = (2\pi)^3 \delta^3(\vec{p}+\vec{q}) \quad S_{\not{c}\text{c}}\delta_{ij} + \mathcal{O}(|\vec{p}|, g_3^4),$$

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

[Hamada, Mukaida, FU 2025a]

One can compute $\theta_{\text{eff}}(T)$ perturbatively

mixing

Ansatz
$$\begin{pmatrix} \vec{B}_{\cancel{c}} \\ \vec{B}_{\mathrm{c}} \end{pmatrix} = \begin{pmatrix} \cos\theta_{\text{eff}} & -\sin\theta_{\text{eff}} \\ \sin\theta_{\text{eff}} & \cos\theta_{\text{eff}} \end{pmatrix} \begin{pmatrix} \vec{B}_{Y} \\ \vec{B}_{\mathscr{W}} \end{pmatrix}$$

$$\mathscr{W}_{ij} := -\frac{\Phi^\dagger \sigma^a \Phi}{\Phi^\dagger \Phi} W^a_{ij}$$
$$= W^3_{ij} + \mathcal{O}(g_3/m_W)$$

for gauge-invariance

wavefunction renormalization

massless pole

s.t.
$$\langle B_{\cancel{c}\,i}(\vec{p}) B_{\cancel{c}\,j}(\vec{q})\rangle = (2\pi)^3 \delta^3(\vec{p}+\vec{q})\, Z^{\cancel{c}} \left(P_{ij}(\hat{p}) + S_{\cancel{c}\cancel{c}}\delta_{ij} \right) + \mathcal{O}(|\vec{p}\,|, g_3^4),$$
$$\langle B_{\cancel{c}\,i}(\vec{p}) B_{\mathrm{c}\,j}(\vec{q})\rangle = (2\pi)^3 \delta^3(\vec{p}+\vec{q})\, Z^{\cancel{c}\frac{1}{2}} S_{\cancel{c}\mathrm{c}}\delta_{ij} + \mathcal{O}(|\vec{p}\,|, g_3^4),$$
$$\langle B_{\mathrm{c}\,i}(\vec{p}) B_{\mathrm{c}\,j}(\vec{q})\rangle = (2\pi)^3 \delta^3(\vec{p}+\vec{q})\, S_{\mathrm{cc}}\delta_{ij} + \mathcal{O}(|\vec{p}\,|, g_3^4)$$

[Hamada, Mukaida, FU 2025a]

One can compute $\theta_{\rm eff}(T)$ perturbatively

$$\langle B_{\not{c}\,i}(\vec{p}) B_{\not{c}\,j}(\vec{q})\rangle = (2\pi)^3\delta^3(\vec{p}+\vec{q})\, Z^{\not{c}}\left(P_{ij}(\hat{p}) + S_{\not{c}\not{c}}\delta_{ij}\right) + \mathcal{O}(|\vec{p}|, g_3^4),$$

$$\langle B_{\not{c}\,i}(\vec{p}) B_{{\rm c}\,j}(\vec{q})\rangle = (2\pi)^3\delta^3(\vec{p}+\vec{q})\, Z^{\not{c}\frac{1}{2}} S_{\not{c}{\rm c}}\delta_{ij} + \mathcal{O}(|\vec{p}|, g_3^4),$$

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

Calculable at one-loop

$$\boxed{\begin{aligned}\left\langle B_{Yi}(\vec{p}) B_{Yj}(-\vec{p})\right\rangle' \\ \left\langle B_{Yi}(\vec{p}) B_{Wj}(-\vec{p})\right\rangle' \\ \left\langle B_{Wi}(\vec{p}) B_{Wj}(-\vec{p})\right\rangle'\end{aligned}}$$

$$\left\langle B_{Yi}(\vec{p}) B_{Yj}(-\vec{p})\right\rangle' = \left[\underline{\cos^2\theta_{\rm eff} Z^{\not{c}}}\left(P_{ij}(\hat{p}) + S_{\not{c}\not{c}}\delta_{ij}\right) + \left(\sin 2\theta_{\rm eff} Z^{\not{c}\,\frac{1}{2}} S_{\not{c}{\rm c}} + \sin^2\theta_{\rm eff} S_{\rm cc}\right)\delta_{ij}\right],$$

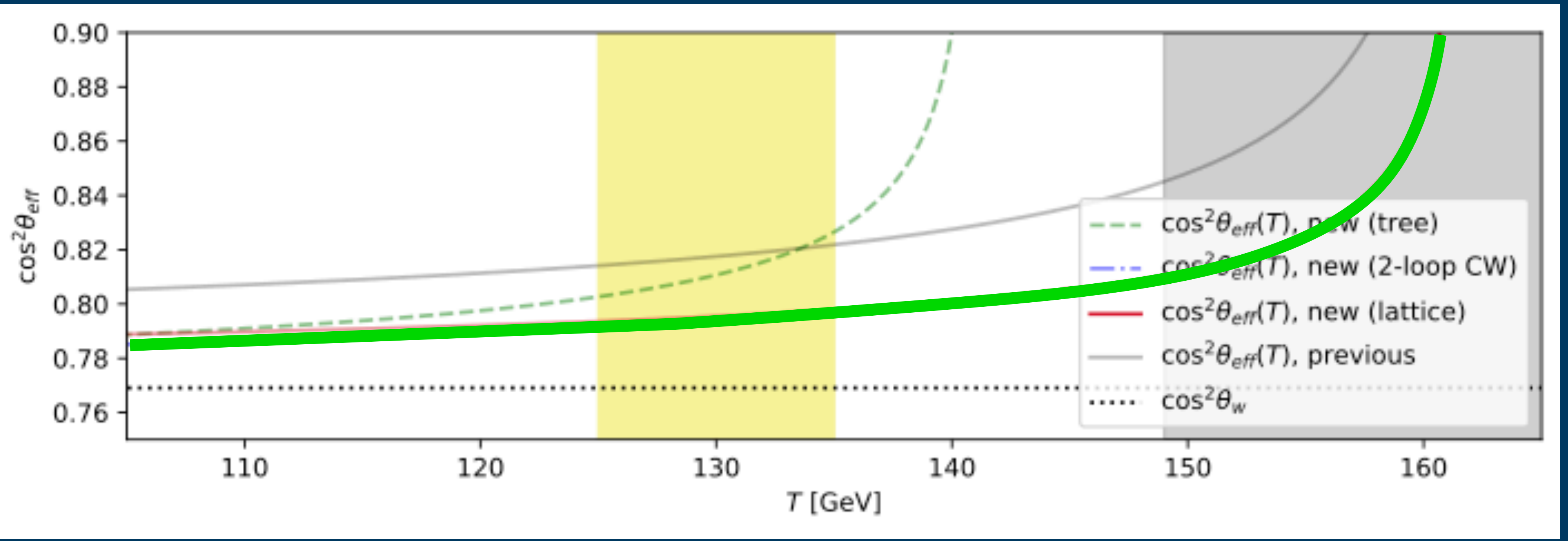
$$\left\langle B_{Yi}(\vec{p}) B_{Wj}(-\vec{p})\right\rangle' = \left[-\frac{1}{2}\sin 2\theta_{\rm eff} Z^{\not{c}}\left(P_{ij}(\hat{p}) + S_{\not{c}\not{c}}\delta_{ij}\right) + \left(\cos 2\theta_{\rm eff} Z^{\not{c}\,\frac{1}{2}} S_{\not{c}{\rm c}} + \frac{1}{2}\sin 2\theta_{\rm eff} S_{\rm cc}\right)\delta_{ij}\right],$$

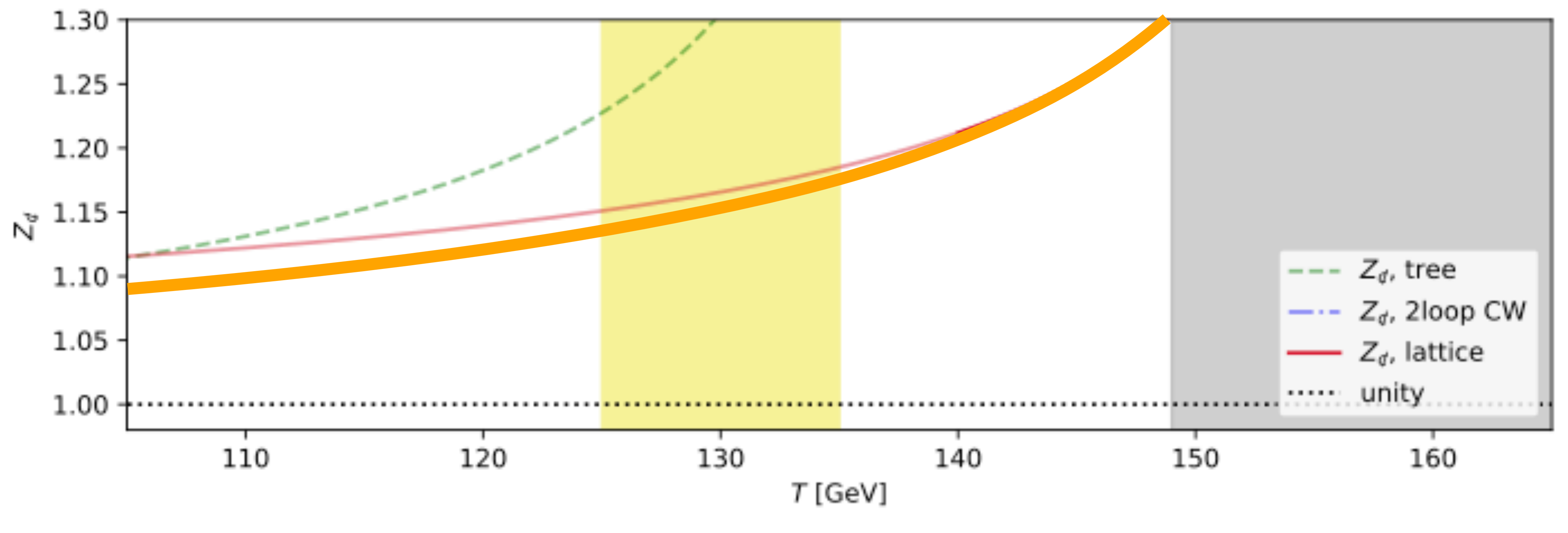
$$\left\langle B_{Wi}(\vec{p}) B_{Wj}(-\vec{p})\right\rangle' = \left[\underline{\sin^2\theta_{\rm eff} Z^{\not{c}}}\left(P_{ij}(\hat{p}) + S_{\not{c}\not{c}}\delta_{ij}\right) - \left(\sin 2\theta_{\rm eff} Z^{\not{c}\,\frac{1}{2}} S_{\not{c}{\rm c}} - \cos^2\theta_{\rm eff} S_{\rm cc}\right)\delta_{ij}\right]$$

[Hamada, Mukaida, FU 2025a]

One can compute $\theta_{\text{eff}}(T)$ perturbatively

$\langle B_{Yi} B_{Yj} \rangle$, $\langle B_{Yi} B_{\mathscr{W}j} \rangle$, $\langle B_{\mathscr{W}i} B_{\mathscr{W}j} \rangle$ up to $\mathcal{O}(|\vec{p}|, g_3^4)$ $\longrightarrow$ $\theta_{\text{eff}}(T)$ and $Z^{\not{c}}(T)$





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

$$Z^{\not{c}}(T) = 1 + \left(\frac{5}{12} - \frac{1}{24\sqrt{1 + \frac{m_D(T)^2}{m_W(T)^2}}}\right)\frac{g_3(T)^2 \sin^2\theta_{\text{w}}}{\pi m_W(T)}$$

[Hamada, Mukaida, FU 2025a]

Outline

Application: baryogenesis from magnetic field
during the electroweak crossover?

Introduction

Symmetries of 3d EFT of the thermal SM

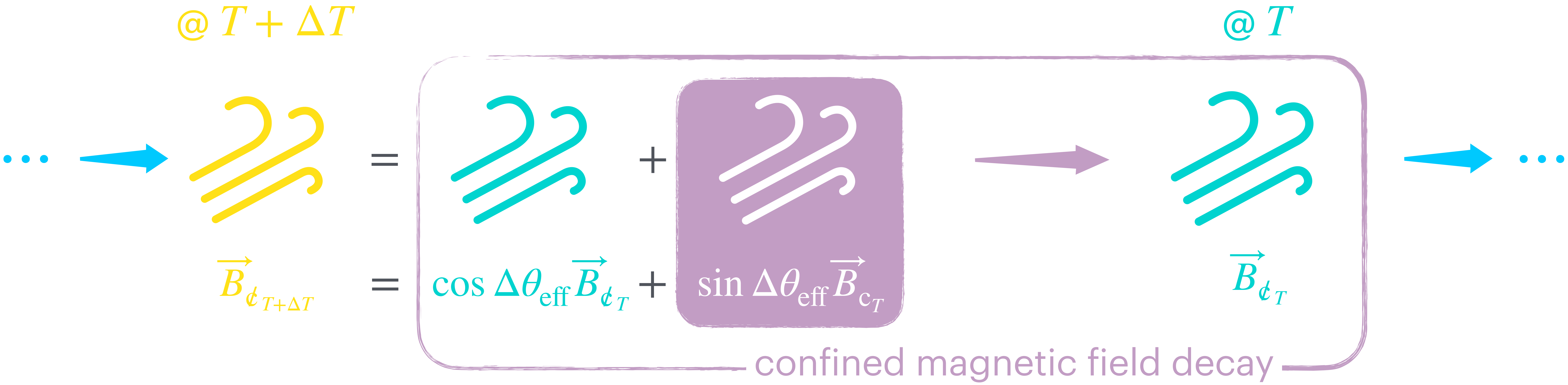
Magnetic field during the electroweak crossover

Baryon asymmetry generation and constraints?

Summary

Baryogenesis from magnetic helicity decay?

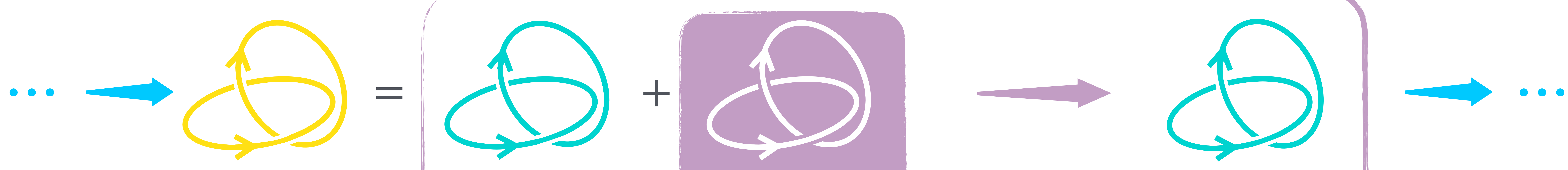
[Joyce, Shaposhnikov 1997] [Giovannini, Shaposhnikov 1998] [Fujita, Kamada 2016] [Kamada, Long 2016] …
[Hamada, Mukaida, FU 2025b]



Baryogenesis from magnetic helicity decay?

[Joyce, Shaposhnikov 1997] [Giovannini, Shaposhnikov 1998] [Fujita, Kamada 2016] [Kamada, Long 2016] …
[Hamada, Mukaida, FU 2025b]

$@\, T+\Delta T$ $\qquad\qquad$ $@\, T$



$$\vec{B}_{\not{c}_{T+\Delta T}} = \cos\Delta\theta_{\rm eff}\vec{B}_{\not{c}_T} + \sin\Delta\theta_{\rm eff}\vec{B}_{c_T} \qquad \vec{B}_{\not{c}_T}$$

confined magnetic **helicity decay**

$$\Delta\left(H_{c_T} := \int d^3x\, \vec{A}_{c_T}\cdot\vec{B}_{c_T}\right) \neq 0$$

$$\frac{d}{dt}\theta_{\rm eff} \to \frac{d}{dt}\left(\text{topological charge of gauge fields}\right) \to \frac{d}{dt}Q_{B+L}\ \textbf{?}$$

Baryogenesis from magnetic helicity decay?

[Joyce, Shaposhnikov 1997] [Giovannini, Shaposhnikov 1998] [Fujita, Kamada 2016] [Kamada, Long 2016] …
[Hamada, Mukaida, FU 2025b]

chiral anomaly [Adler 1969] [Bell, Jackiw 1969]

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

$$\simeq 3\cdot 2\cot^2\theta_{\rm w}\,\Delta\left[\left(\tan^2\theta_{\rm eff} - \tan^2\theta_{\rm w}\right)H_{\not{c}}\right] + 3\cdot 2\,\Delta N_{\rm CS}^{\rm SU(2)_L}\Big|_{\rm NP}$$

$\Delta\theta_{\rm eff}$

time-dependent mixing

$\Delta H_{\not{c}}$

dissipation of $\overrightarrow{B}_{\not{c}}$

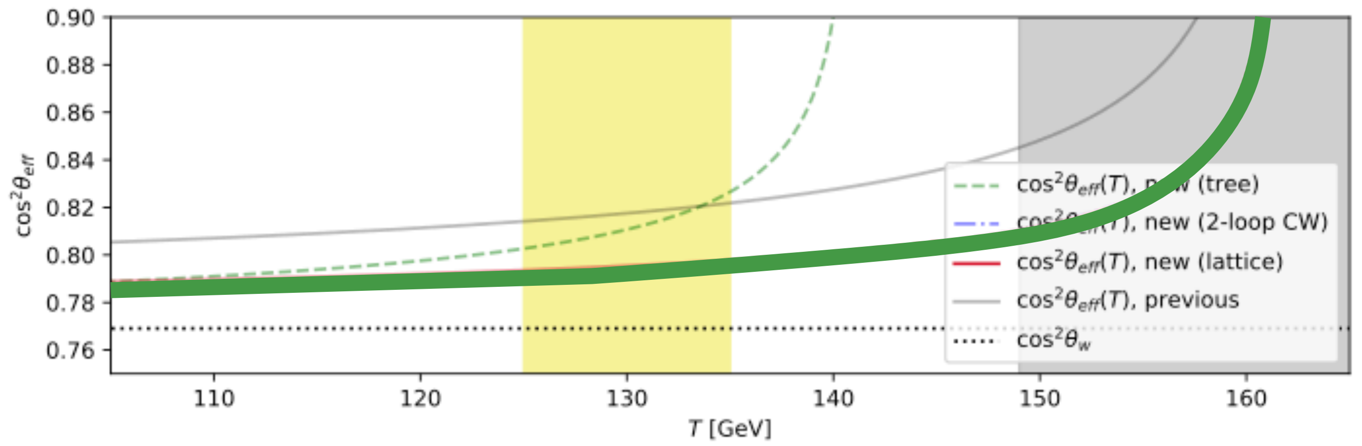
$\Delta N_{\rm CS}^{\rm SU(2)_L}\Big|_{\rm NP}$

non-perturbative contributions

We understand each contribution (?)

$\Delta\theta_{\rm eff}$

time-dependent mixing



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

[Hamada, Mukaida, FU 2025a]

$\Delta H_{\not{c}}$

dissipation of $\overrightarrow{B}_{\not{c}}$

$$\frac{d\overrightarrow{B}_{\not{c}}}{dt} = \sigma_{\not{c}}^{-1}\nabla^2\overrightarrow{B}_{\not{c}}, \quad \sigma_{\not{c}} \sim T$$

suppressed at large scales

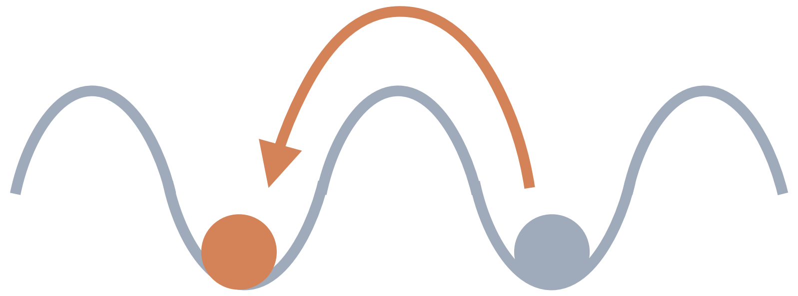
$\gg 1/\sqrt{TH}$

$\Delta N_{\rm CS}^{{\rm SU(2)_L}}\Big|_{\rm NP}$

non-perturbative contributions

electroweak sphaleron

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



equilibrium established until $\sim 130\,{\rm GeV}$

[Kamada, Long 2016]

Possibly we are missing something:

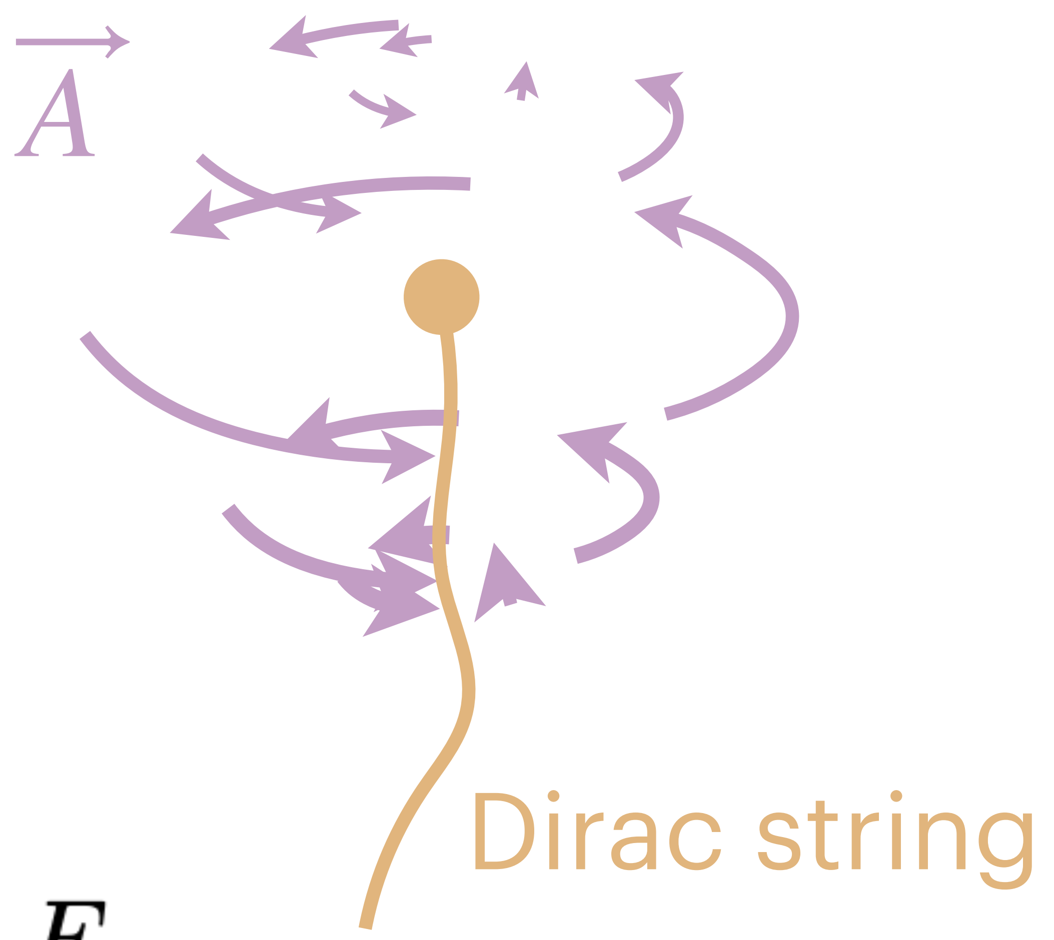
Magnetic helicity is sometimes ill-defined

[Fukuda, Hamada, Kamada, Mukaida, FU 2025]

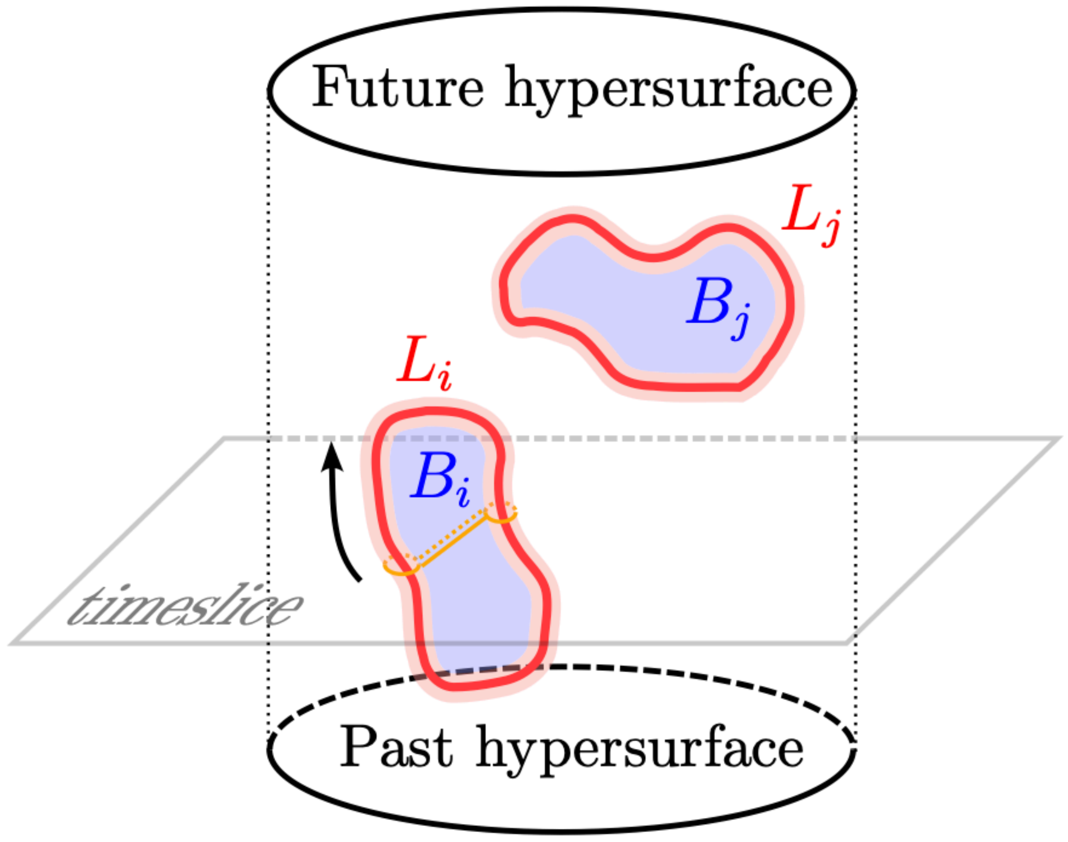
magnetic monopole ($\vec{\nabla} \cdot \vec{B} \neq 0$) in the Maxwell theory

vector potential

defined *outside* the Dirac string



$$\underbrace{\mathcal{H}_{\text{future}}}_{:= \int d^3x\, \vec{A} \cdot \vec{B}} = \underbrace{\mathcal{H}_{\text{past}}}_{} + \underbrace{\int_{M'} F \wedge F}_{= -2 \int d^4x\, \vec{E} \cdot \vec{B}} + \underbrace{\frac{4\pi}{e} \sum_i \int_{\Sigma_i} F}_{\text{contribution from the Dirac string worldsheets}}$$



Possibly we are missing something:

Magnetic helicity is sometimes ill-defined

[Fukuda, Hamada, Kamada, Mukaida, FU 2025]

vanishing Higgs ($\Phi^\dagger\Phi = 0$) in the electroweak theory

$\vec{n} = \dfrac{\Phi^\dagger \vec{\sigma} \Phi}{\Phi^\dagger\Phi}$ defines the $\mathrm{U}(1)_{\mathrm{em}}$ direction, unless $\Phi^\dagger\Phi = 0$

$$\mathcal{F}^{\text{em}}_{\mu\nu} = -\mathcal{F}^{W}_{\mu\nu}\sin\theta_W + F^{Y}_{\mu\nu}\cos\theta_W,$$

$$\mathcal{F}^{W}_{\mu\nu} = F^{Wa}_{\mu\nu}n^a - \frac{1}{g}\epsilon^{abc}n^a D_\mu n^b D_\nu n^c$$ ['t Hooft 1974]

$$\underbrace{\mathcal{H}_{\text{EM,future}}}_{:= \int d^3x\, \vec{A}\cdot\vec{B}} - \underbrace{\mathcal{H}_{\text{EM,past}}} = \underbrace{\int_{M'} \mathcal{F}\wedge\mathcal{F}}_{= -2\int d^4x\, \vec{E}\cdot\vec{B}} + \underbrace{\int_{N} \mathcal{A}\wedge\mathcal{F}}$$

nontrivial helicity change where higgs vanishes

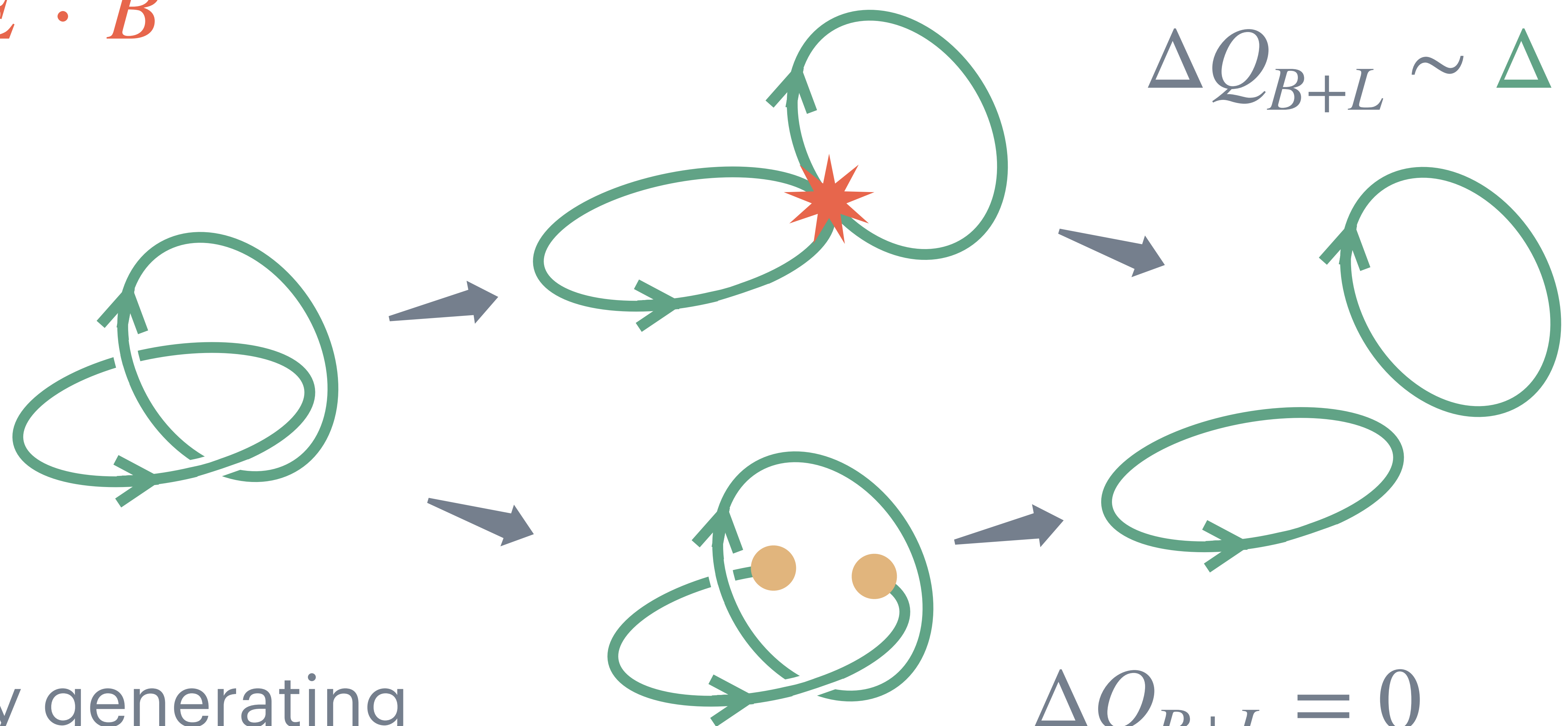
Illustrating toy example: Higgs dynamics matters

[Hamada, Mukaida, FU 2025a]

$\mathrm{SU}(2) \to \mathrm{U}(1) \to 1$

$$\partial_\mu j^\mu_{B+L} \sim \vec{E} \cdot \vec{B}$$

$$\Delta Q_{B+L} \sim \Delta \int d^3x\, \vec{A} \cdot \vec{B}$$



$$\Delta Q_{B+L} = 0$$

untying link by generating
't Hooft—Polyakov monopole pairs

In general, Higgs winding may compensate $\Delta N_{\rm CS}$

[Hamada, Mukaida, FU 2025a] [Fukuda, Hamada, Kamada, Mukaida, FU 2025]

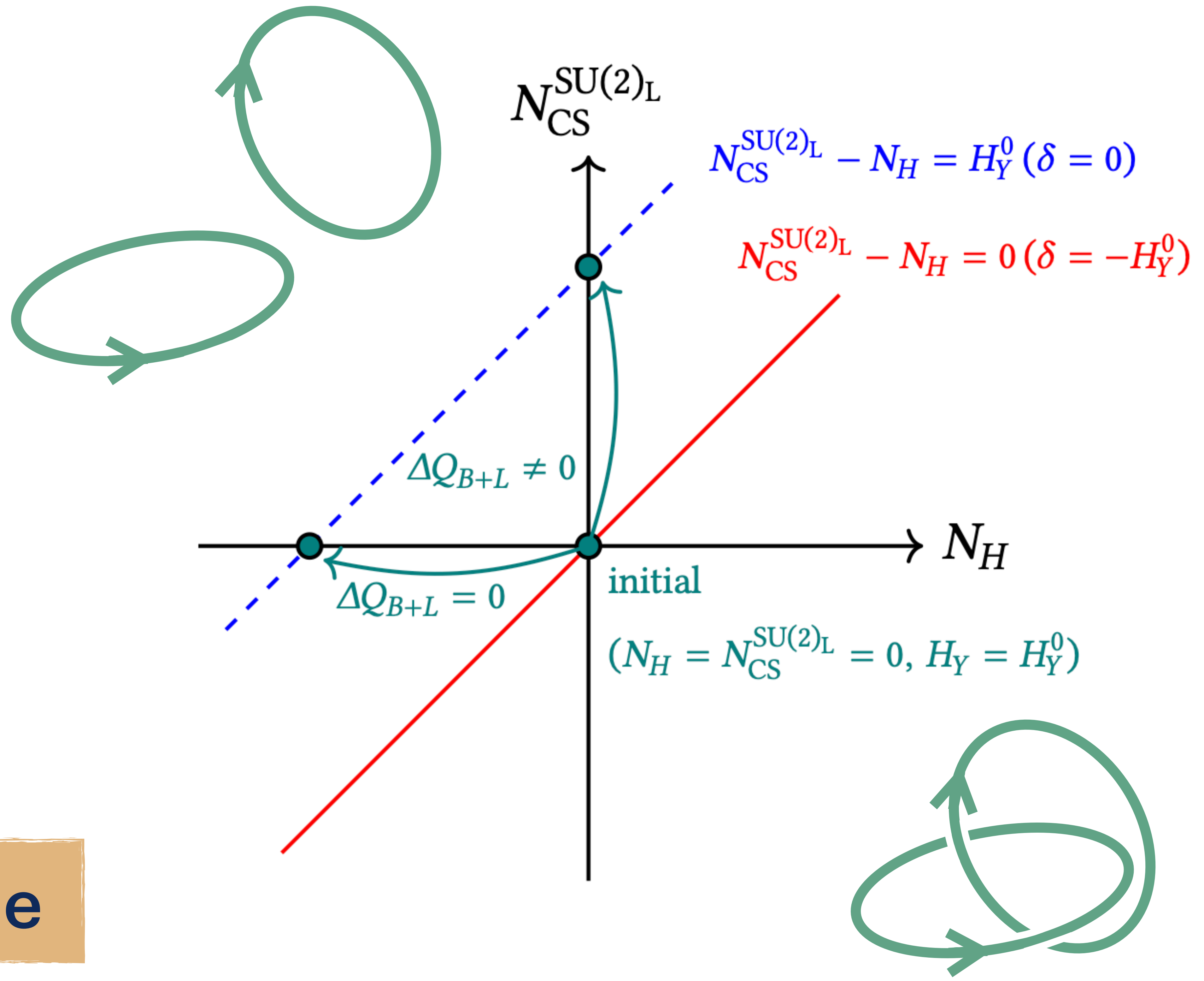
Standard Model

when $D_\mu n^a = 0$ holds,

$$\delta := N_{\rm CS} - H_Y - N_H = 0$$

$$\Delta Q_{B+L} \sim \Delta N_{\rm CS} - \Delta H_Y$$
$$\sim \Delta\delta + \Delta N_H$$

uncertainty in higgs winding change



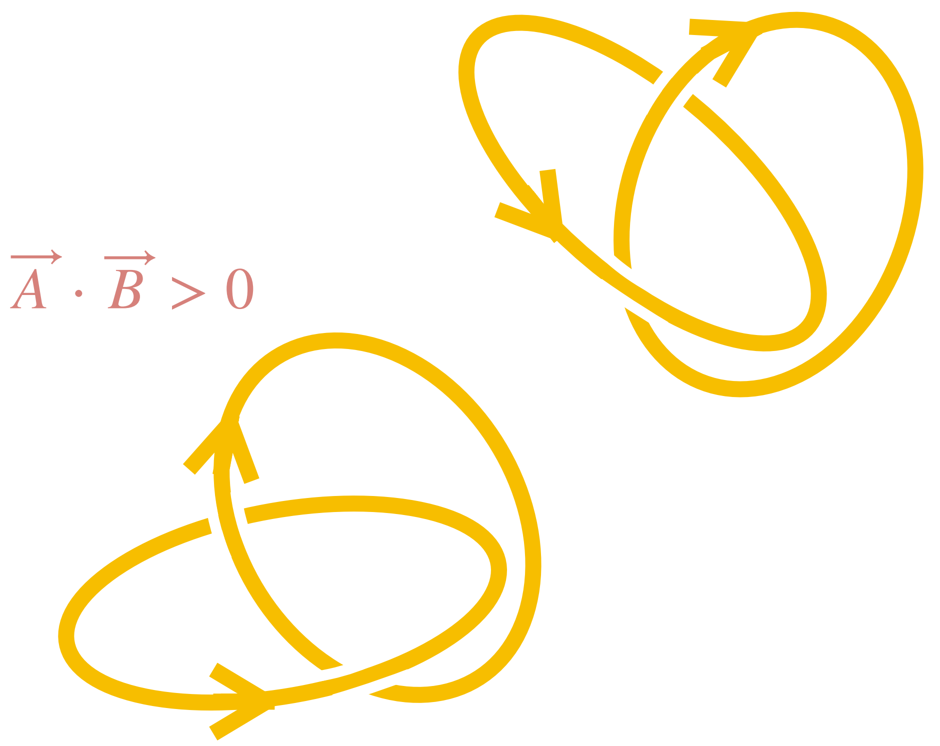
Baryon overproduction constraint (helical PMF)

…, [Fujita, Kamada 2016] [Kamada, Long 2016]

$$\langle \vec{A} \cdot \vec{B} \rangle \sim B^2 \xi_{\rm M}$$

$\int_{V_i} dV \, \vec{A} \cdot \vec{B} > 0$

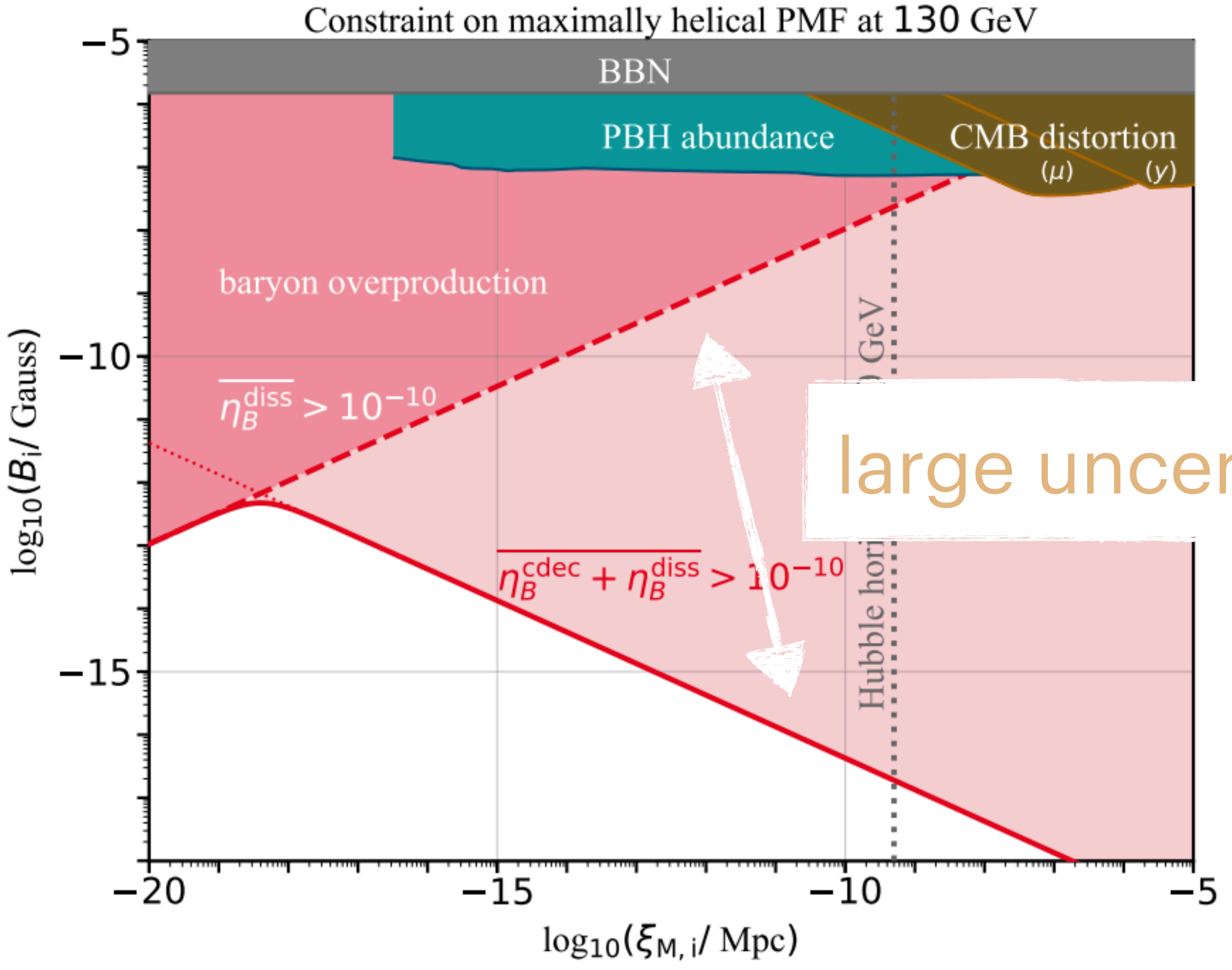
$\int_{V_j} dV \, \vec{A} \cdot \vec{B} > 0$



& baryons s.t.

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

rms strength B



large uncertainty!

$\Delta N_{\rm CS} \sim 0$

$\Delta N_H = 0$

coherence length $\xi_{\rm M}$

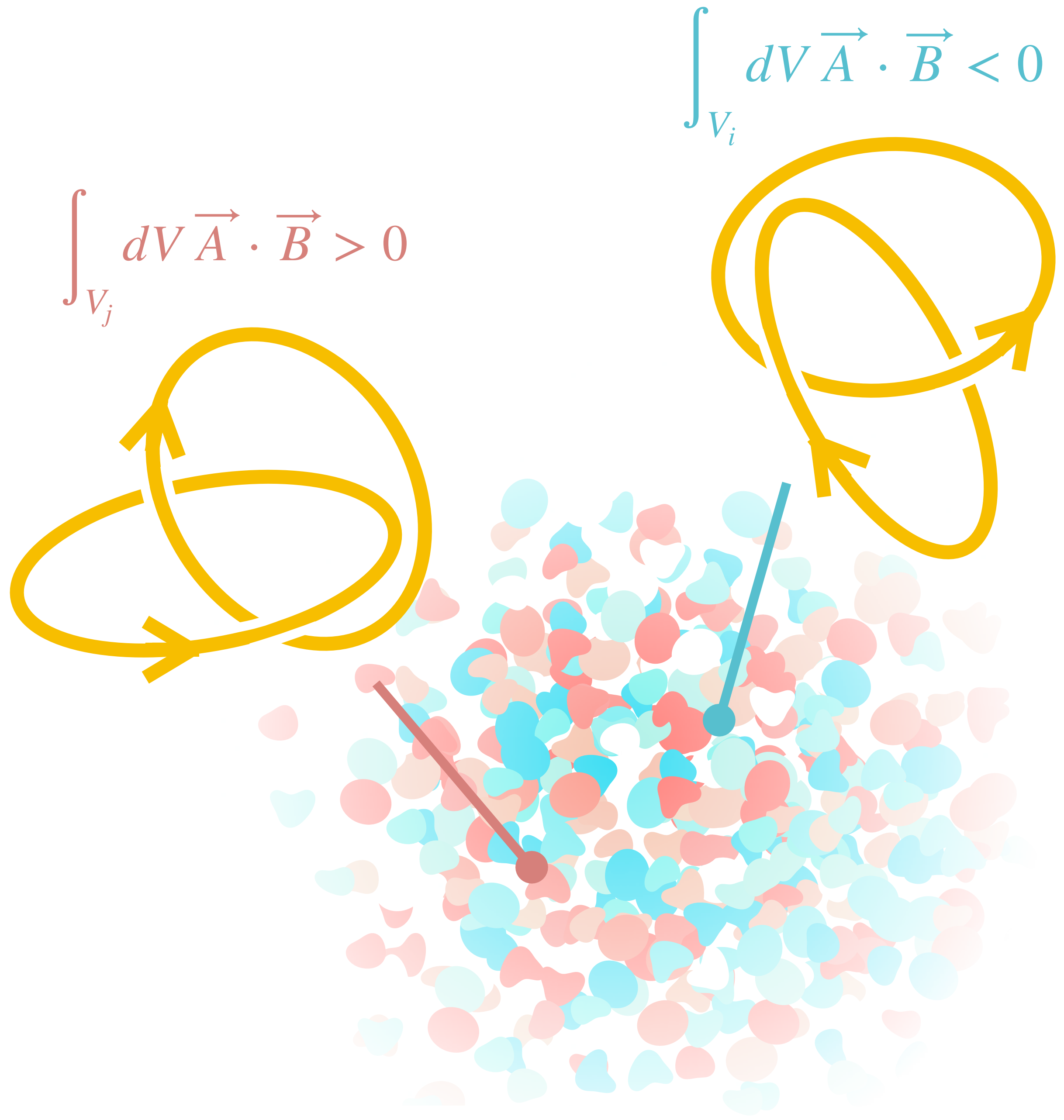
[Hamada, Mukaida, FU 2025b]

Baryon isocurvature constraint (non-helical PMF)

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

$\langle \vec{A} \cdot \vec{B} \rangle = 0$, but still

$\langle (\vec{A} \cdot \vec{B})^2 \rangle \sim B^4 \xi_\mathrm{M}^2$

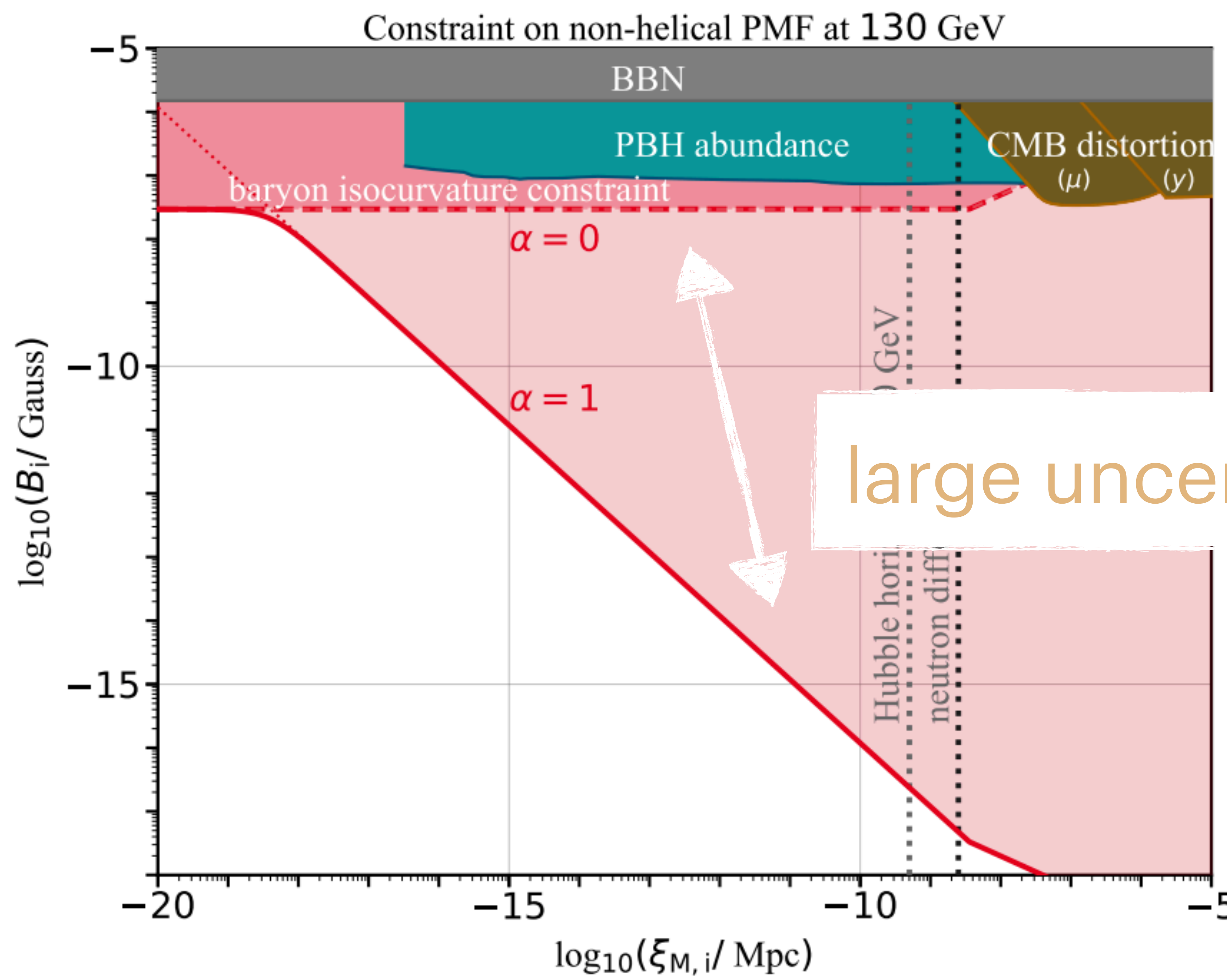


& baryons s.t.

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

[Inomata+ 2018]

rms strength B



$\Delta N_\mathrm{CS} \sim 0$

large uncertainty!

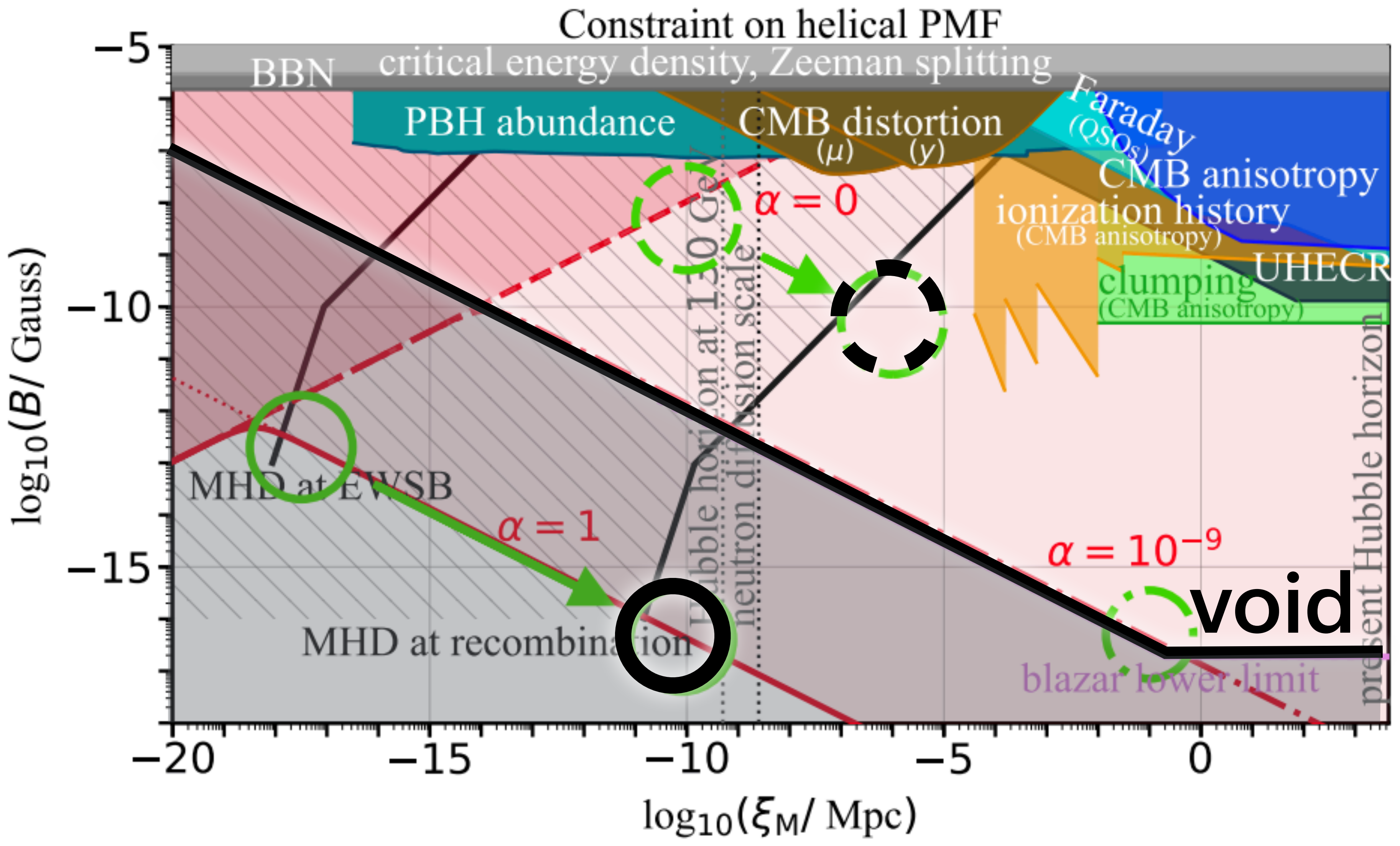
$\Delta N_H = 0$

coherence length ξ_M

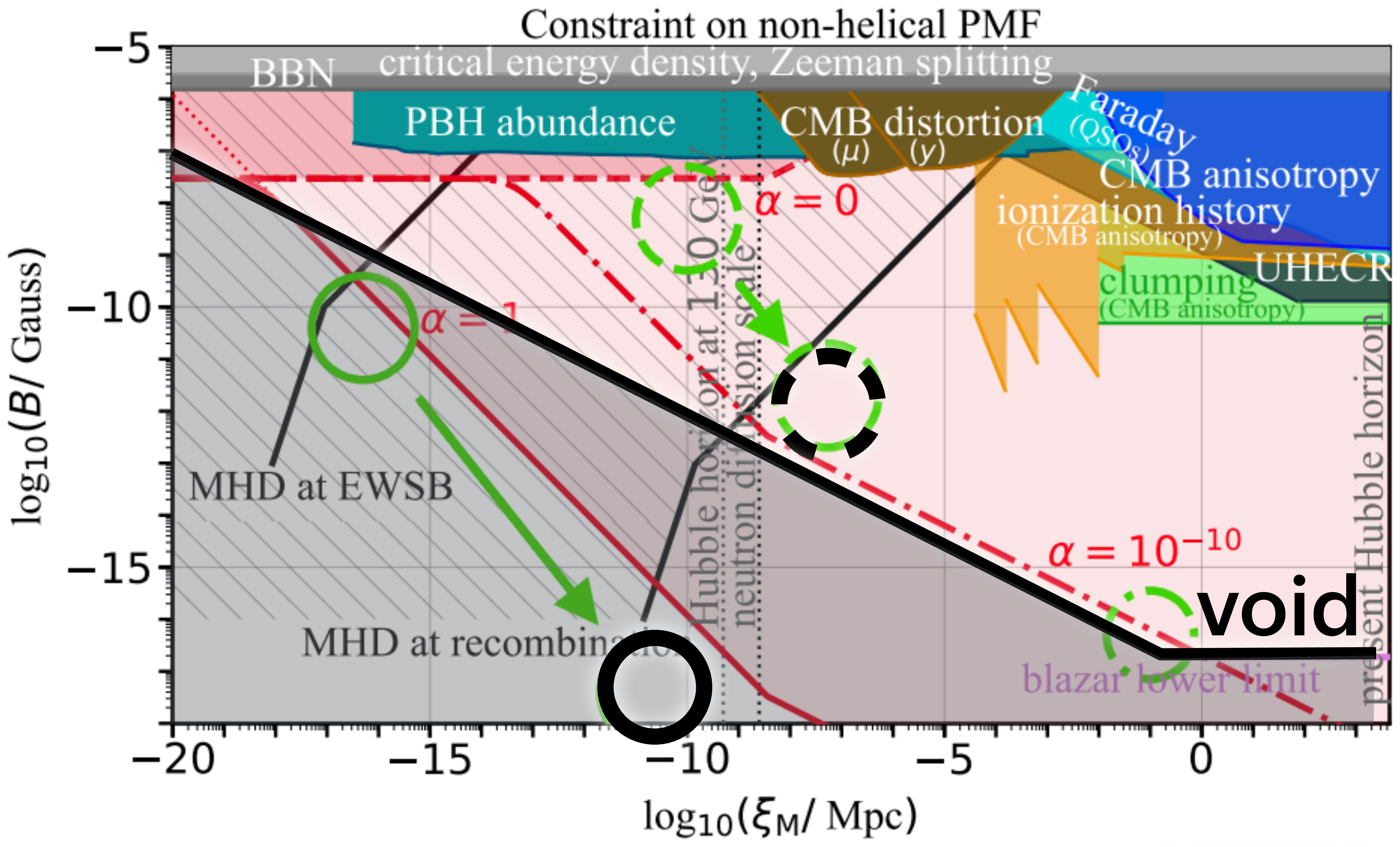
[Hamada, Mukaida, FU 2025b]

The constraints vs the void magnetic field

baryon overproduction (helical)



baryon fluctuation (non-helical)



compensation of $\Delta N_{\rm CS}^{\rm SU(2)_L}$ by Higgs winding	$\Delta N_H = 0$	$\Delta N_{\rm CS} \sim 0$
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**	If helical, **Yes**

[Hamada, Mukaida, FU 2025b]

Outline

Introduction

Symmetries of 3d EFT of the thermal SM

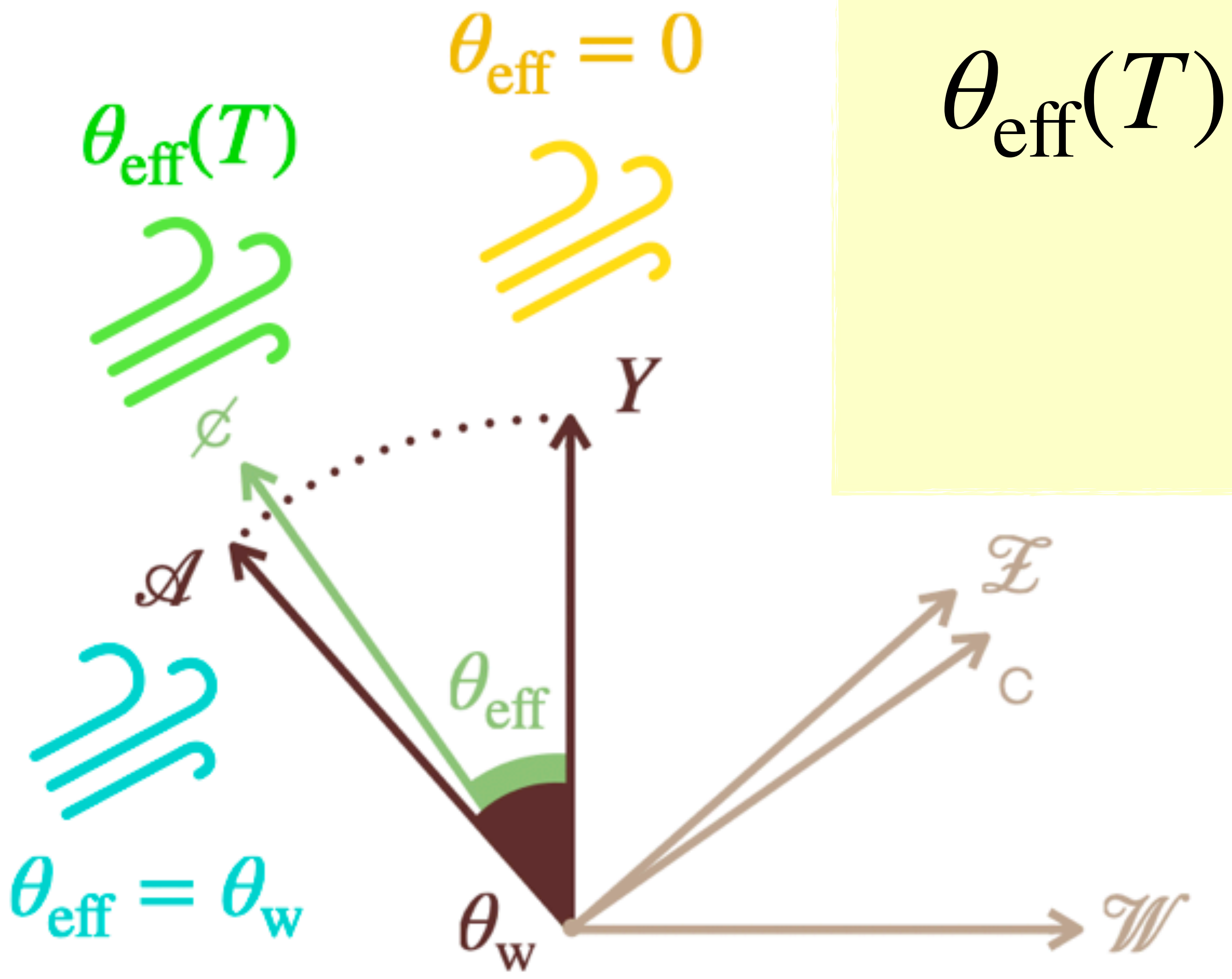
Magnetic field during the electroweak crossover

Baryon asymmetry generation and constraints?

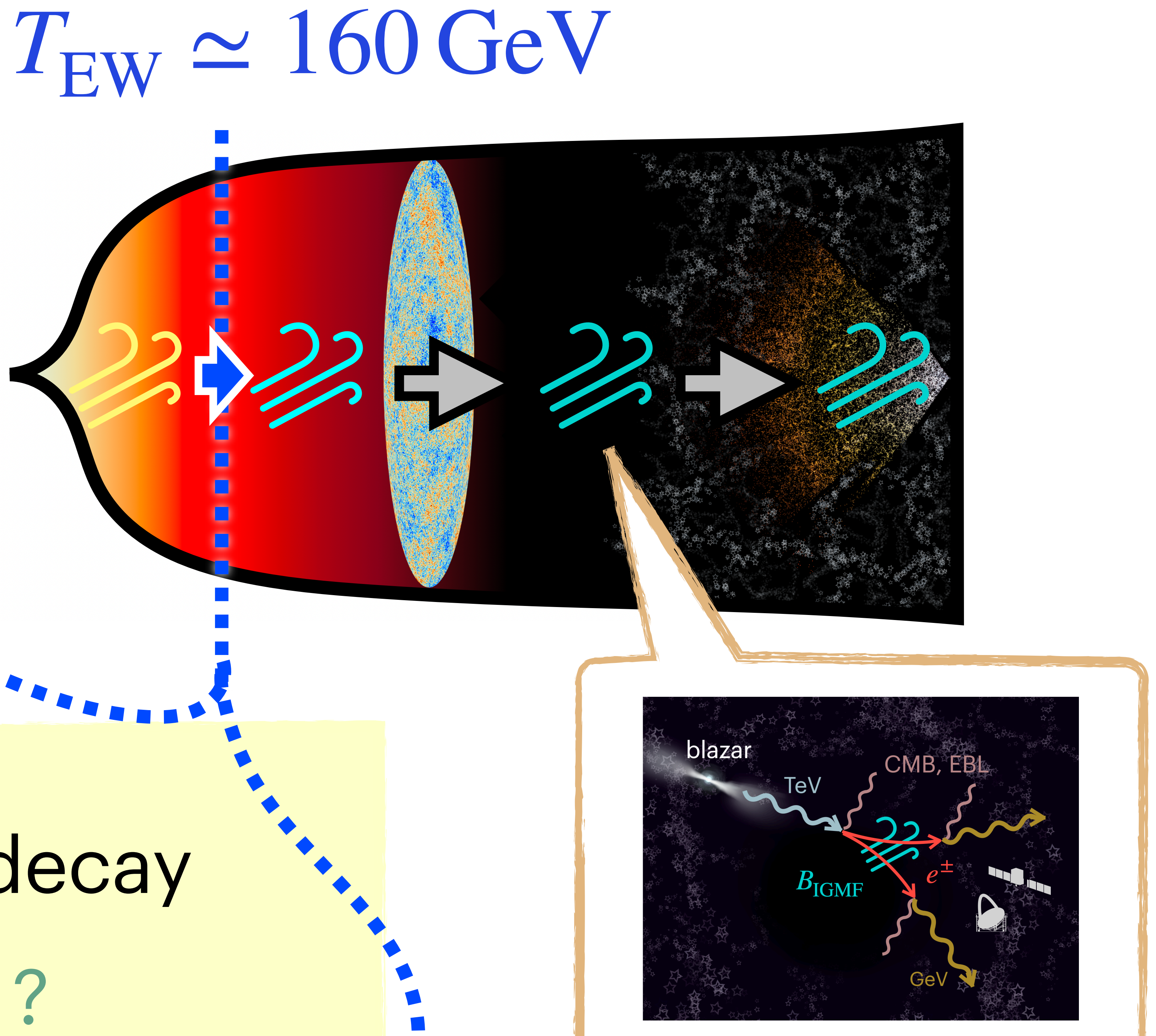
Summary

Summary

$\vec{B}_{\not{c}}$ that interpolates $\vec{B}_Y$ and $\vec{B}_{\mathrm{em}}$
as a consequence of $\cancel{\mathrm{U}(1)^{[0]}_{\mathrm{M}}}$.



$\theta_{\mathrm{eff}}(T)$ → confined helicity decay
→ generate baryons ?
uncertainty in ΔN_H



$B_{\mathrm{void}} \gtrsim 10^{-17}\,\mathrm{G}$
[Neronov, Vovk 2010], …

Only if $\Delta N_{\mathrm{CS}} \sim 0$, PMF can be the **common origin of the void magnetic field and the BAU**.