primordial magnetic fields during the electroweak crossover

and baryogenesis from magnetic helicity decay

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

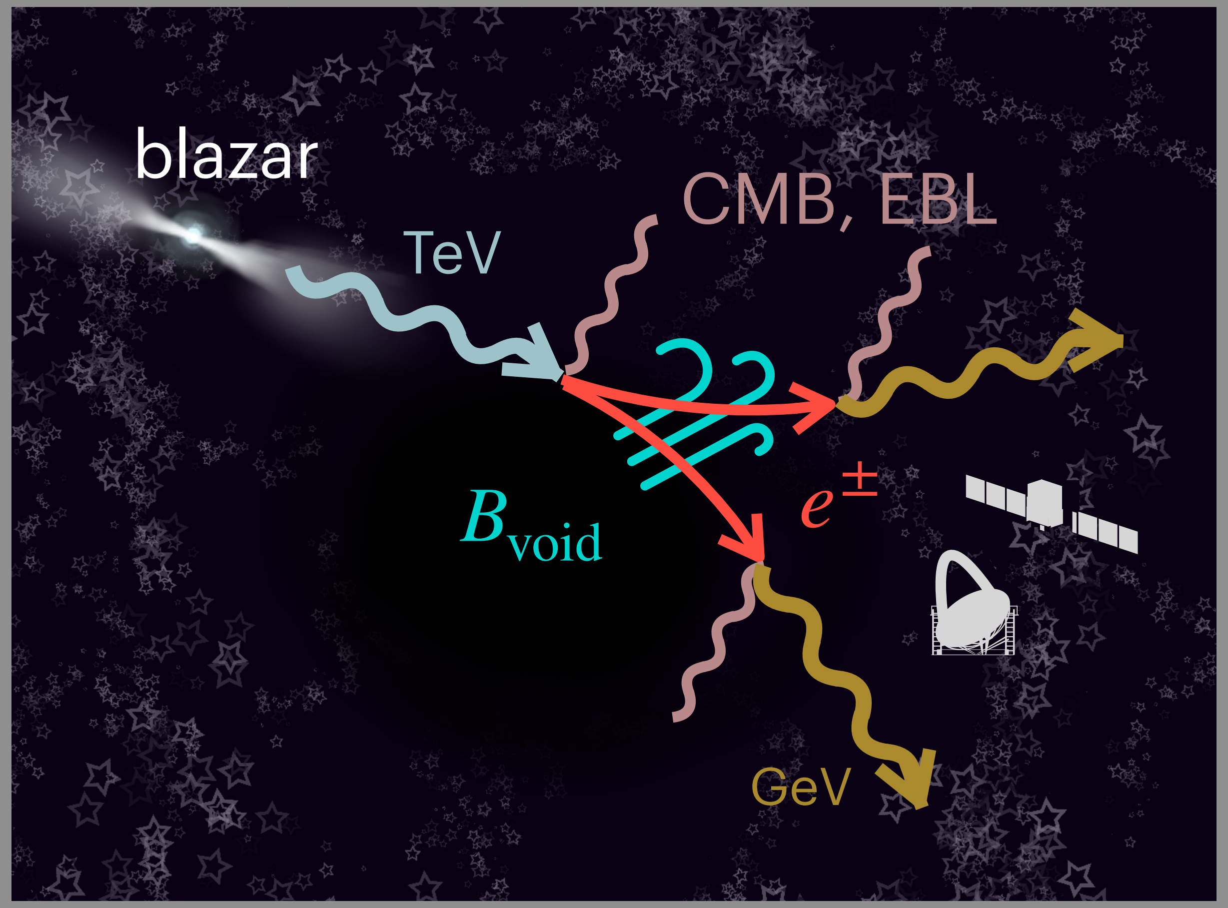
2026/2/12, Tohoku U.

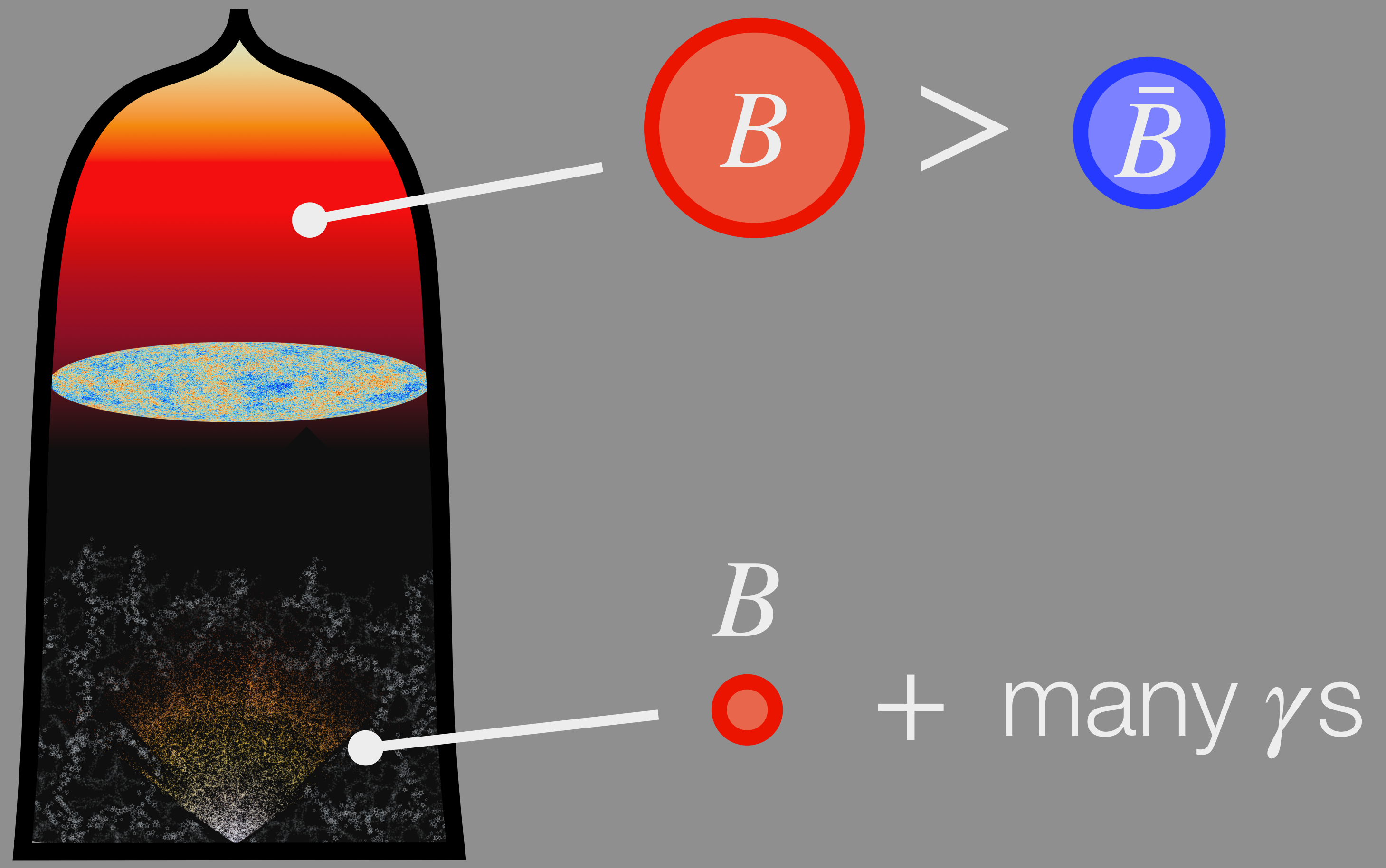
Fumio Uchida (CTPU-CGA, IBS)

Institute for Basic Science

Big questions!

magnetogenesis & **baryogenesis**





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

[Neronov, Vovk 2010], …

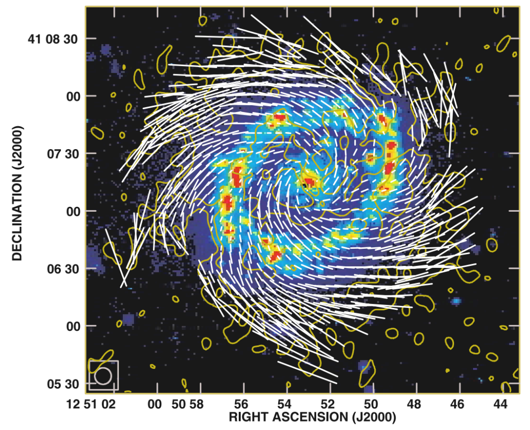
How to generate $\vec{B}$ initially? $B_{\rm void} \sim B_{\rm PMF}$?

$n_B \sim 10^{-9} n_\gamma$

[Planck 2018], …

How to generate $n_B - n_{\bar{B}}$ initially?

Magnetogenesis



[Chyży, Buta]

observed in stars, planets, ...

observed in galaxies $\sim 10^{-6}\,\mathrm{G}$ at $\sim 10\,\mathrm{kpc}$

sizable B

astrophysics
structure formation

tiny B

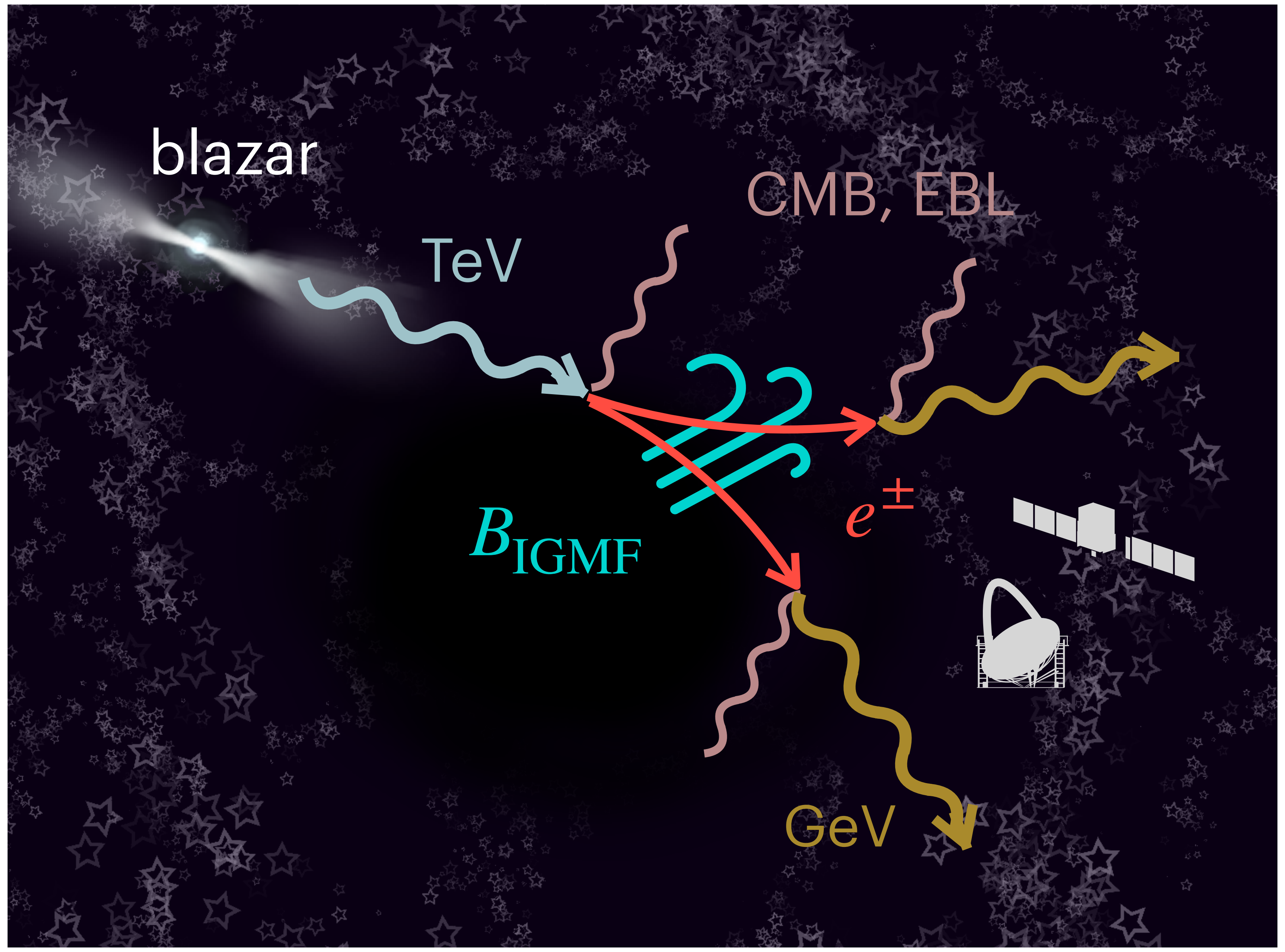
seed magnetic field $\gtrsim 10^{-20}\,\mathrm{G}$ at $\gtrsim 10\,\mathrm{kpc}$ (?)

“magnetogenesis”
involves BSM (?)

vacuum fluctuation $\sim 10^{-50\text{-}60}\,\mathrm{G}$ at $1\,\mathrm{Mpc}$

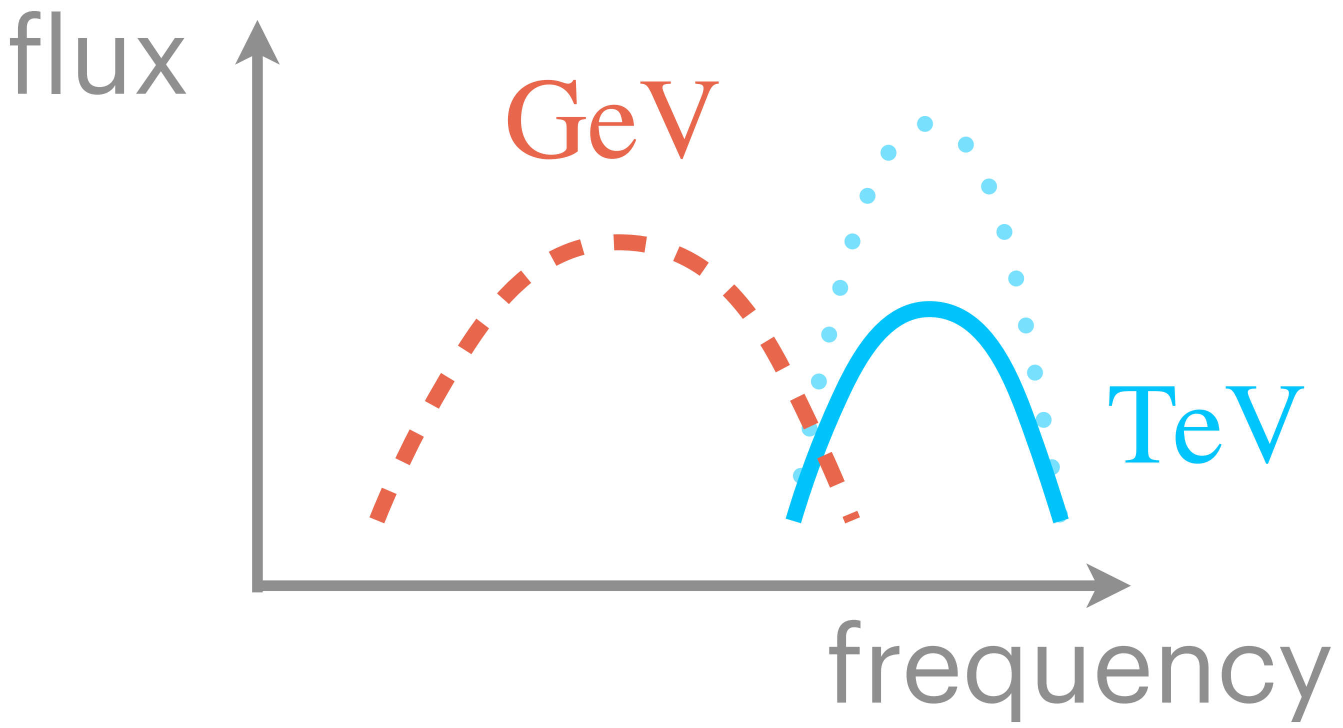
$B \simeq 0$

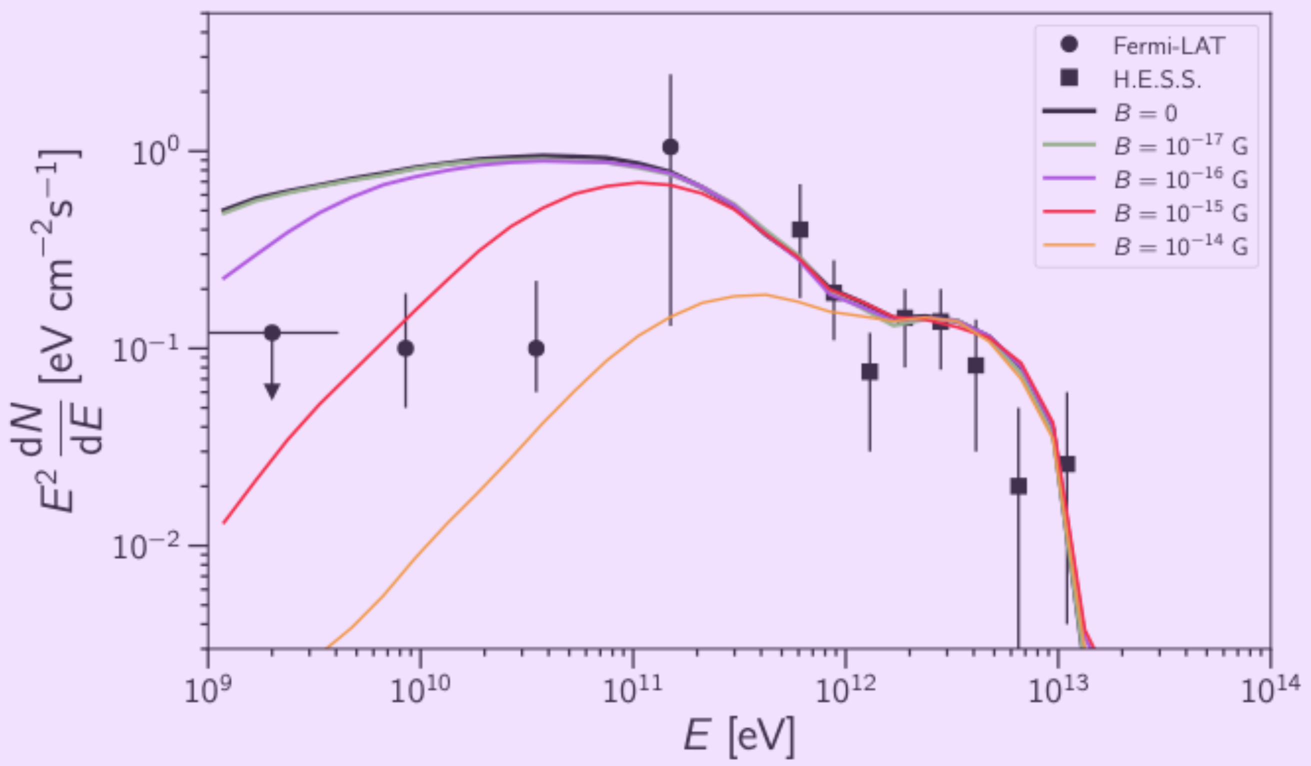
Void magnetic field



- lack of GeV photons

[Honda 1989]

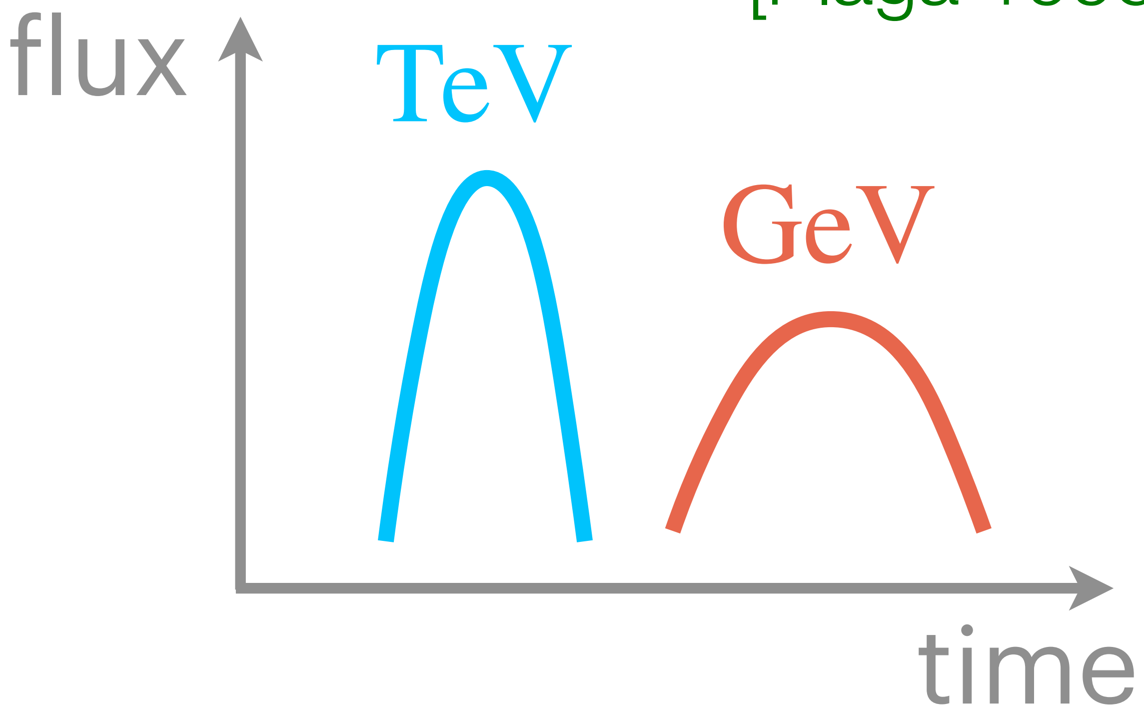




[Alves Batista, Saveliev 2021]

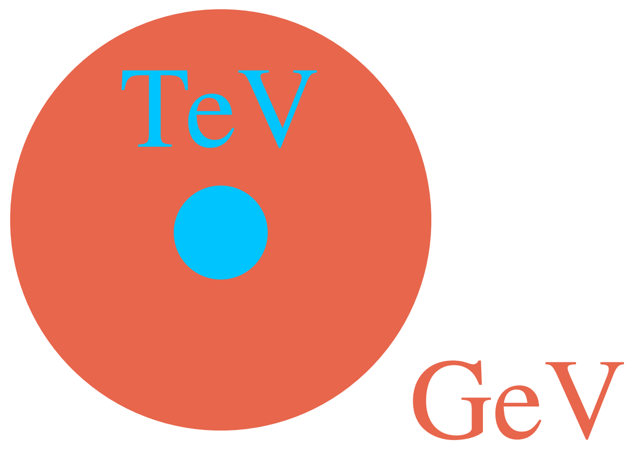
- effects on GeV photons, if observed
  - time delay (pair echo)

    [Plaga 1995]

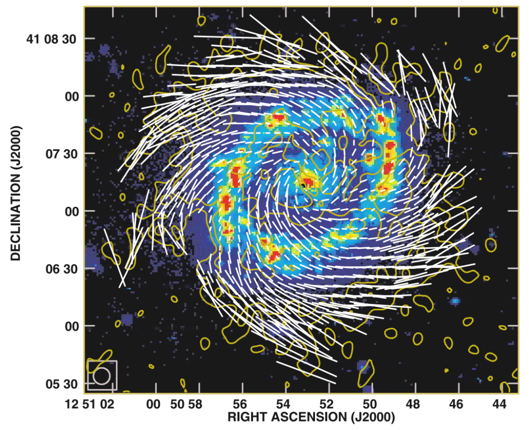


  - diffuse flux (pair halo)

    [Honda 1989] [Aharonian+ 1994]
    [Plaga 1995]



Magnetogenesis



[Chyży, Buta]

observed in stars, planets, ...

observed in galaxies $\sim 10^{-6}\,\mathrm{G}$ at $\sim 10\,\mathrm{kpc}$

sizable B

astrophysics
structure formation

feedbacks (?)

observed in voids $\gtrsim 10^{-17}\,\mathrm{G}$

equivalent (?)

tiny B

seed magnetic field $\gtrsim 10^{-20}\,\mathrm{G}$ at $\gtrsim 10\,\mathrm{kpc}$ (?)

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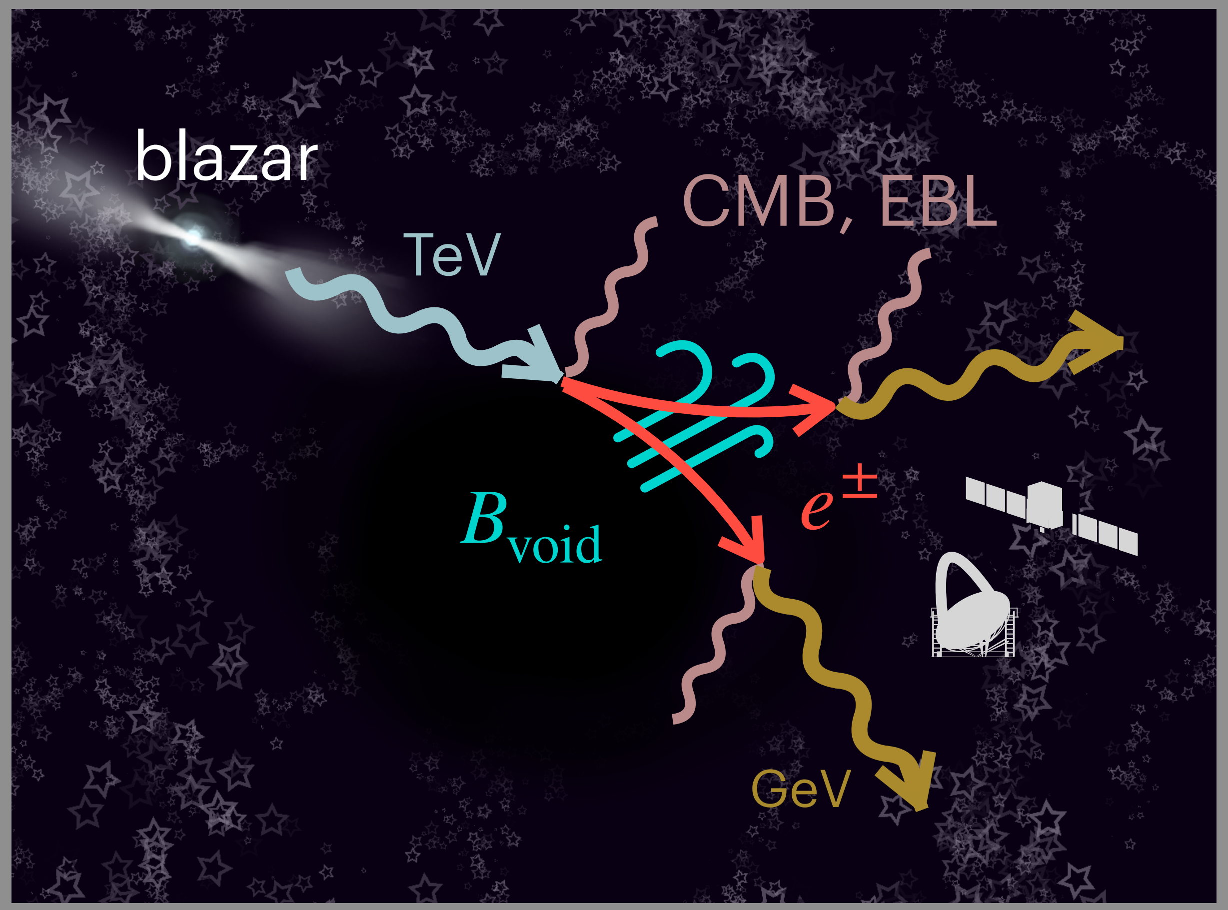
Big questions!

magnetogenesis & **baryogenesis**



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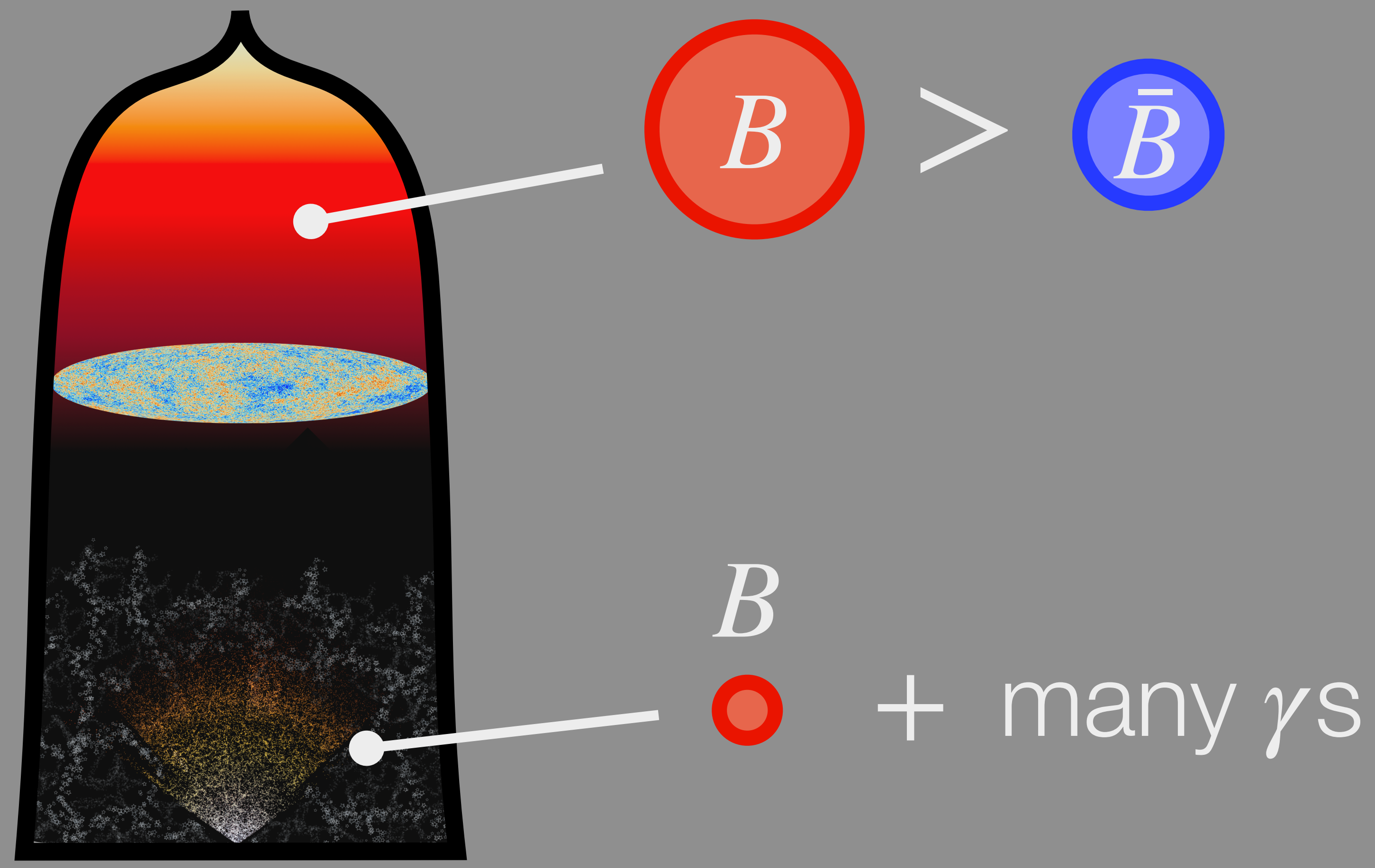

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[Planck 2018], …

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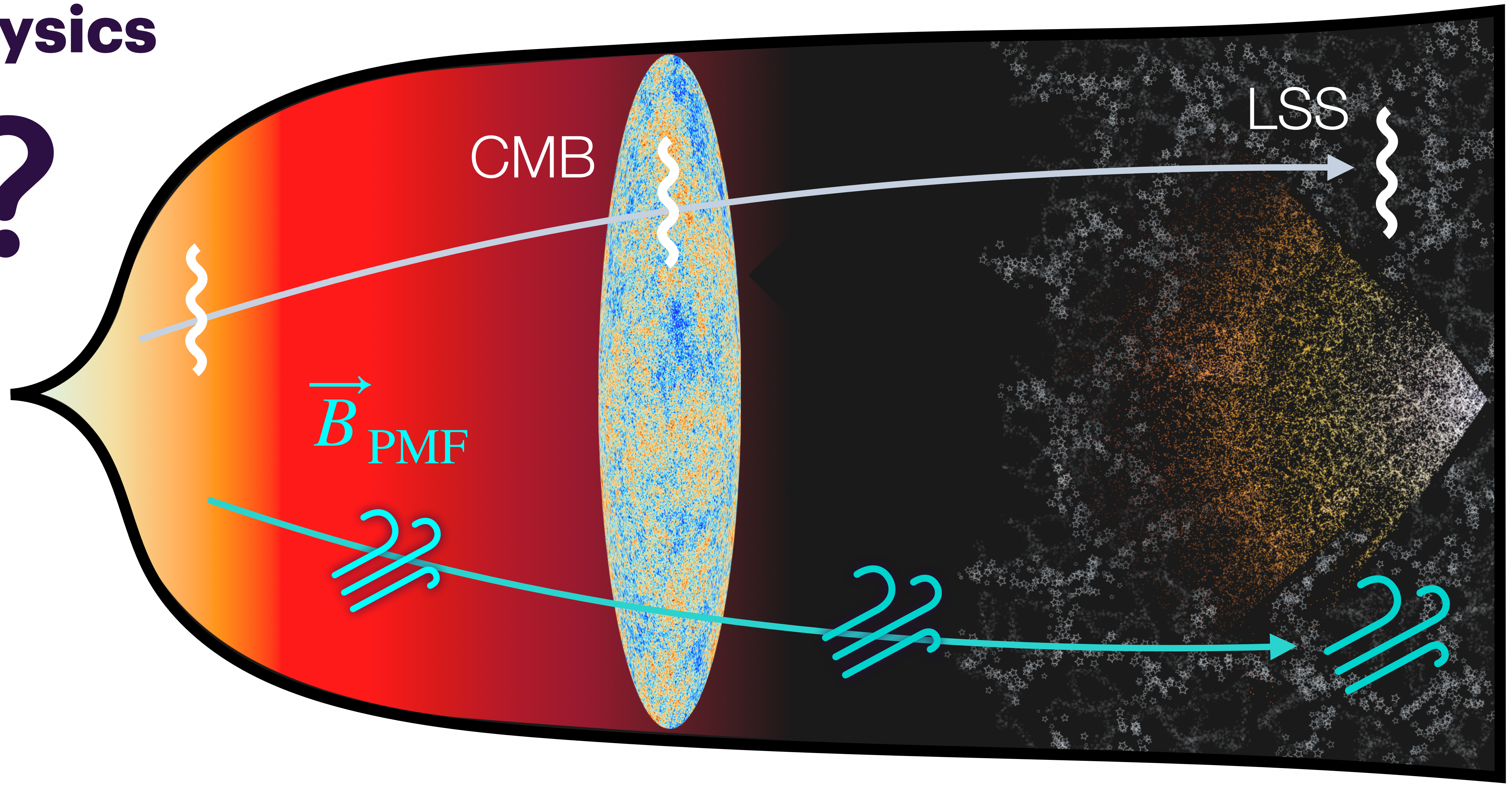
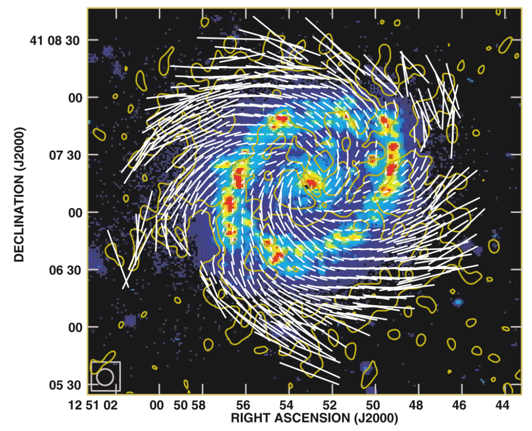
This talk will focus on...

primordial physics

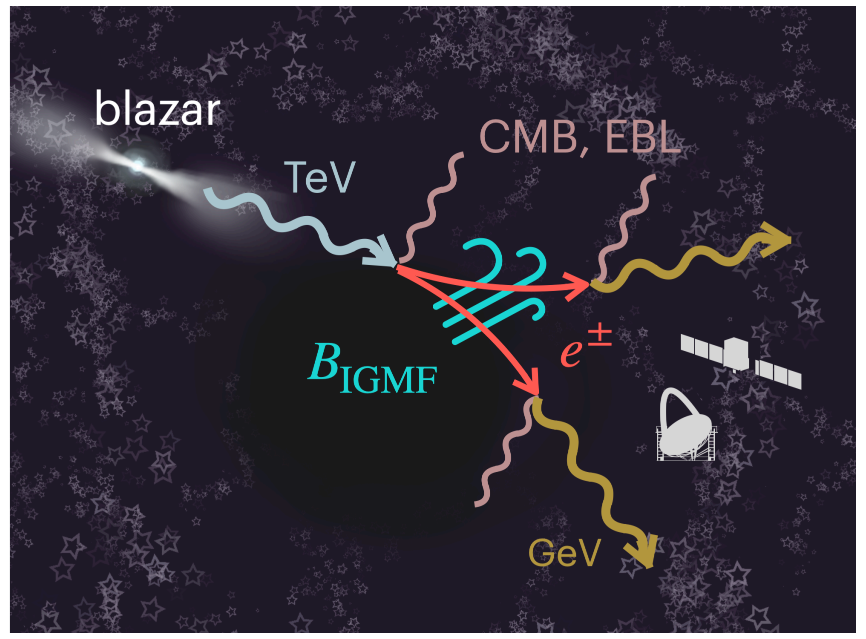
?



observations



[Chyży, Buta]



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

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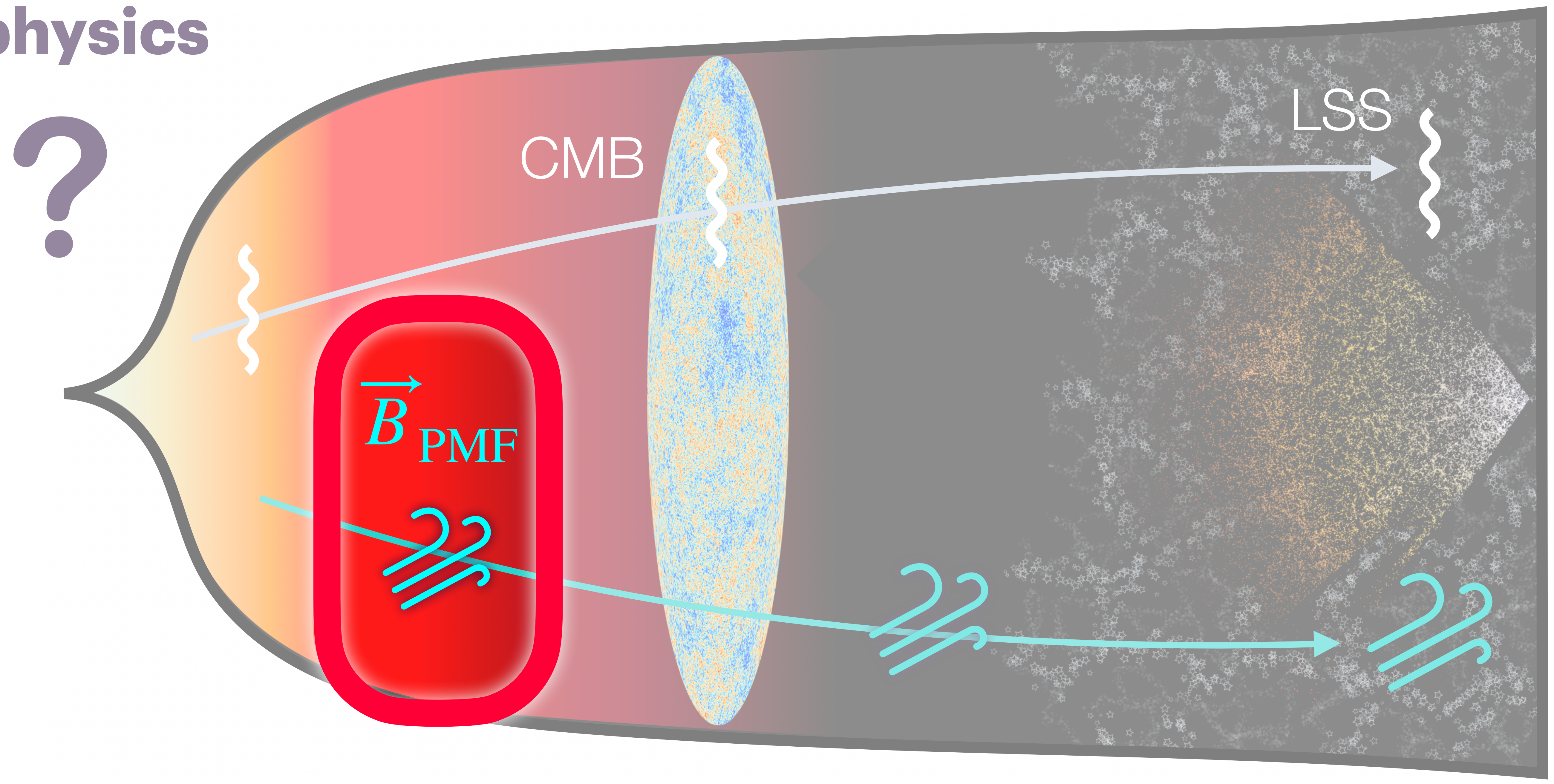

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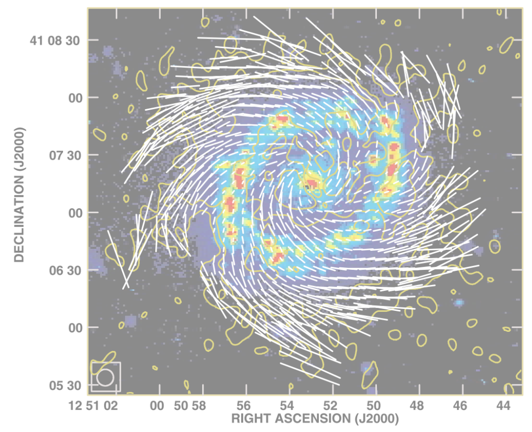

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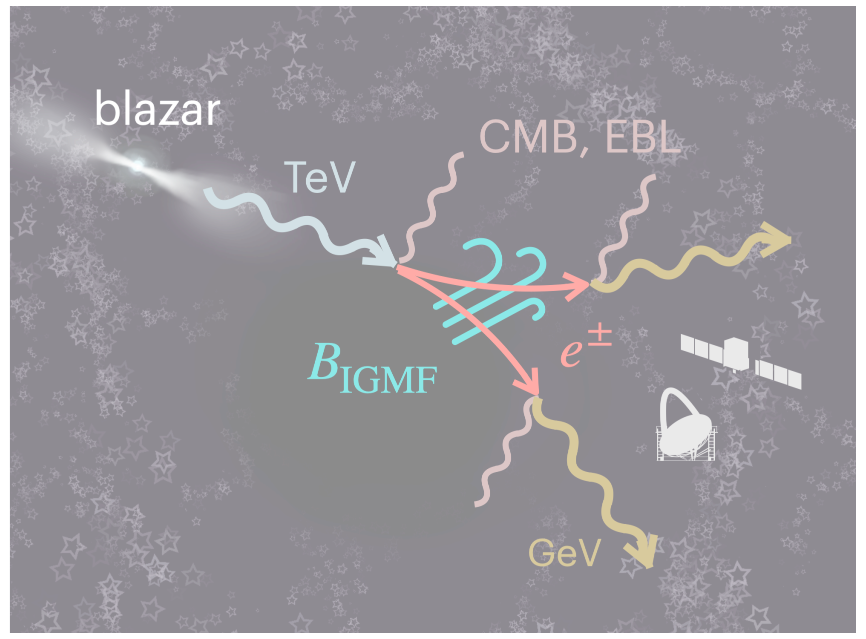


$B_{\mathrm{void}} \gtrsim 10^{-17}\,\mathrm{G}$

[Neronov, Vovk 2010], …

thermal plasma (SM) + magnetic field at $T \sim 100\,\mathrm{GeV}$

- **What "magnetic field" means** is nontrivial
- Possibly relevant to **baryogenesis**

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

Outline

- How to describe “magnetic field” at $\sim 100\,\mathrm{GeV}$?
- Baryogenesis by primordial magnetic field?
- Can primordial magnetic field explain the void magnetic field?

Magnetic fields at high/low temperatures

$$\mathscr{L}_{\rm SM} \supset -\frac{1}{4}W^a_{\mu\nu}W^{a\mu\nu} - \frac{1}{4}Y_{\mu\nu}Y^{\mu\nu} + (D_\mu\Phi)^\dagger D^\mu\Phi + V(\Phi)$$

$T \gg 100\,\mathrm{GeV}$ $\quad \langle|\Phi|^2\rangle = 0$

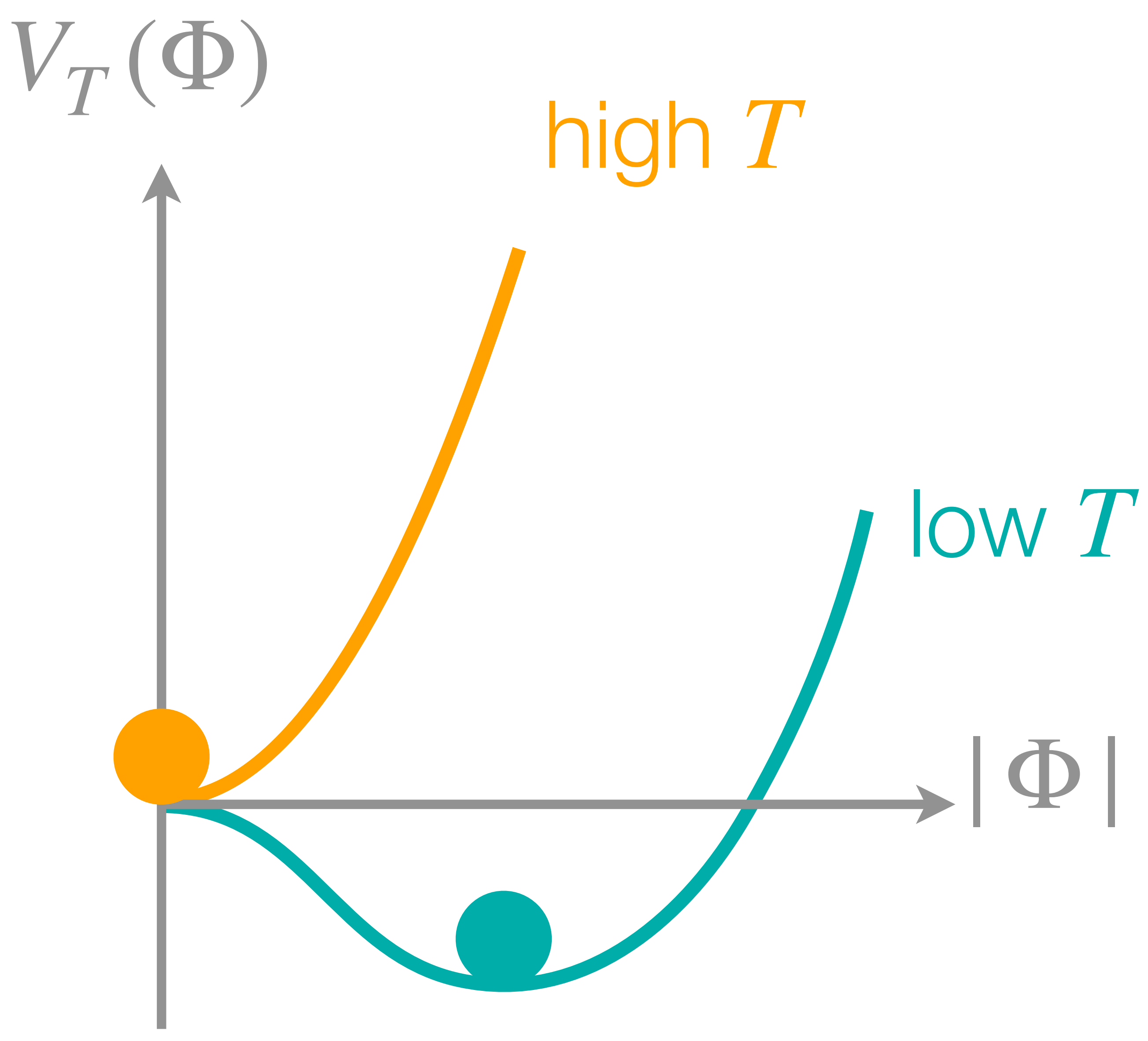
$\mathrm{U}(1)_Y$ **massless field**

and massive W^1, W^2, W^3

$T \ll 100\,\mathrm{GeV}$ $\quad \langle|\Phi|^2\rangle \neq 0$

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

and massive $W^\pm, Z$

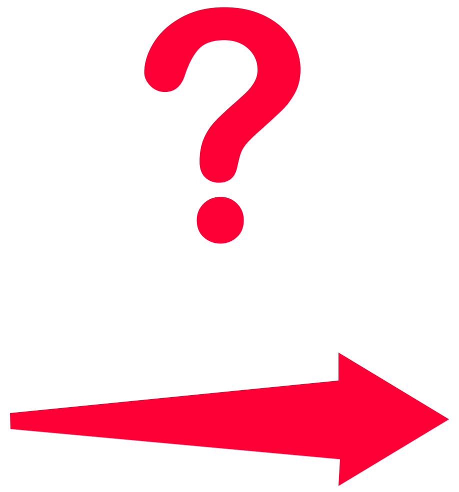


Transition during the electroweak crossover

$T \gg 100\,\mathrm{GeV}$

$\vec{B}_{Y} = \vec{\nabla} \times \vec{Y}$

hyper-magnetic field



$T \ll 100\,\mathrm{GeV}$

$\vec{B}_{\mathrm{em}} = \vec{\nabla} \times \vec{A}, \quad A_i = \cos\theta_{\mathrm{w}}\, Y_i - \sin\theta_{\mathrm{w}}\, W_i^3$

the ordinary magnetic field

Naive interpolation

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

$T \gg 100\,\mathrm{GeV}$ $T \sim 100\,\mathrm{GeV}$ $T \ll 100\,\mathrm{GeV}$

$\theta_{\mathrm{eff}}(T \gg 100\,\mathrm{GeV}) = 0$ $\theta_{\mathrm{eff}}(T)$ $\theta_{\mathrm{eff}}(T \ll 100\,\mathrm{GeV}) = \theta_{\mathrm{w}}$

effective mixing angle

Determining the effective mixing angle

$T \ll 100\,\mathrm{GeV}$ $\quad \vec{B}_{\mathrm{em}} = \cos\theta_{\mathrm{w}} \vec{B}_Y - \sin\theta_{\mathrm{w}} \vec{B}_{W^3}$

$T \sim 100\,\mathrm{GeV}$

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

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

$$\begin{pmatrix} \vec{B}_{\not{c}} \\ \vec{B}_{\mathrm{c}} \end{pmatrix} = \begin{pmatrix} \cos\theta_{\mathrm{eff}}(T) & -\sin\theta_{\mathrm{eff}}(T) \\ \sin\theta_{\mathrm{eff}}(T) & \cos\theta_{\mathrm{eff}}(T) \end{pmatrix} \begin{pmatrix} \vec{B}_Y \\ \vec{B}_{\mathscr{W}} \end{pmatrix}$$

gauge invariance $\quad \mathscr{W}_{ij} := -\dfrac{\Phi^\dagger \sigma^a \Phi}{\Phi^\dagger \Phi} W^a_{ij}$

s.t. $\langle B_{\not{c}\,i}(\vec{p}) B_{\not{c}\,j}(\vec{q})\rangle \sim Z^{\not{c}}(T) P_{ij}(\hat{p}) + \cdots,\ \ldots$

massless pole
[Kajantie+ 1997]

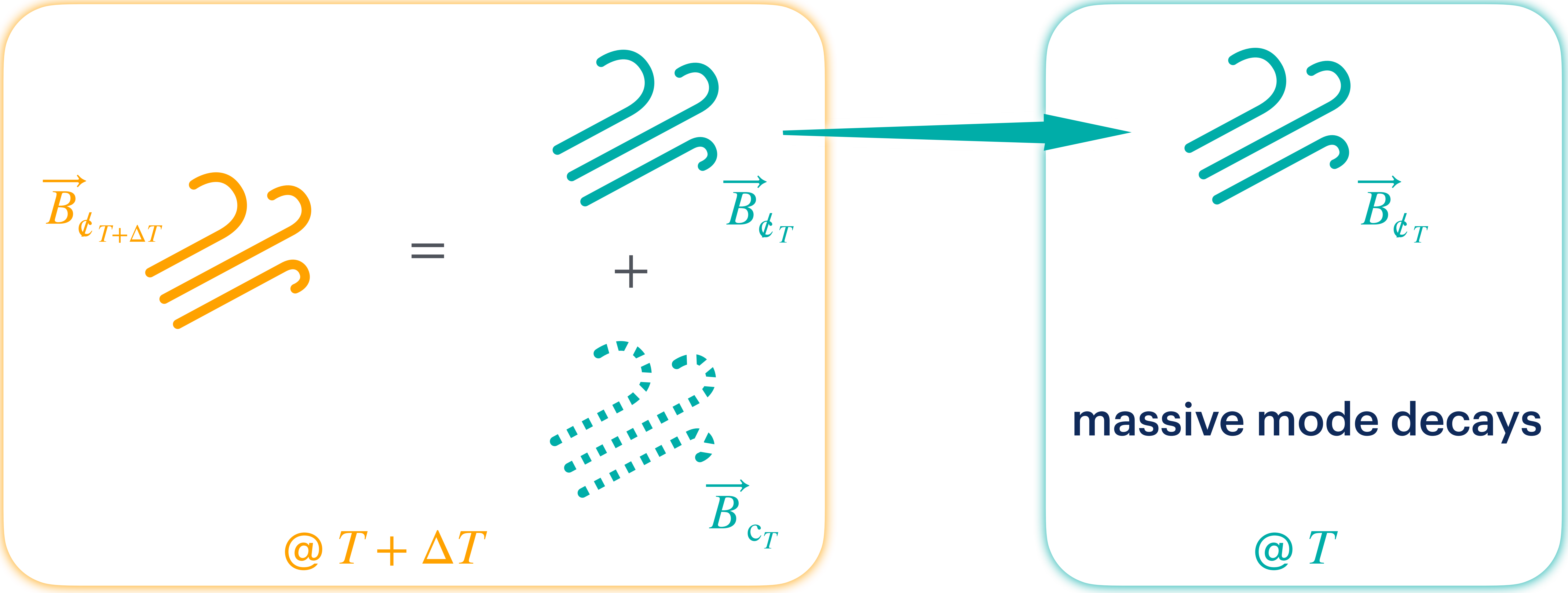
wavefunction renormalization
[Hamada, Mukaida, FU 2025a]

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

Intuitive picture

In terms of massless $\not{c}_T$ and massive c_T modes **at every moment** T,

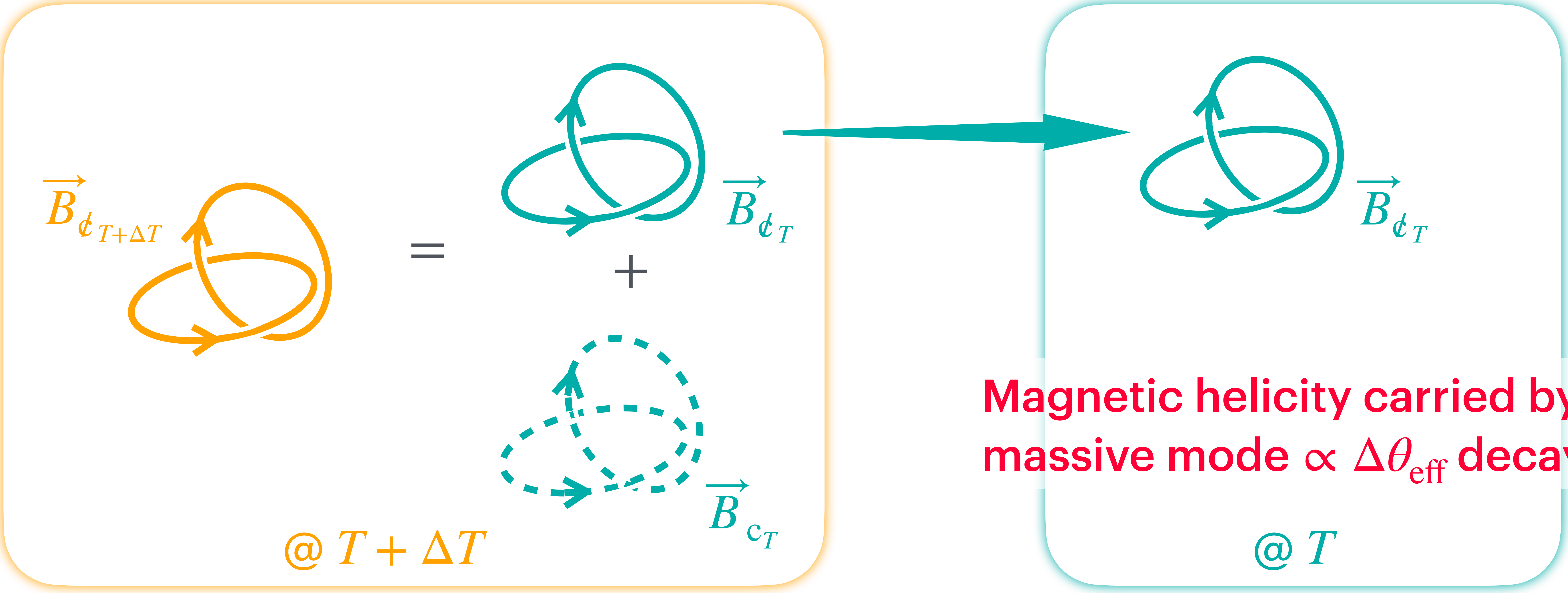
$$\vec{B}_{\not{c}_{T+\Delta T}} = \cos \Delta\theta_{\rm eff} \vec{B}_{\not{c}_T} + \sin \Delta\theta_{\rm eff} \vec{B}_{c_T}, \qquad \Delta\theta_{\rm eff} := \theta_{\rm eff}(T+\Delta T) - \theta_{\rm eff}(T)$$



Helicity decay $\propto \Delta\theta_{\rm eff}$

magnetic helicity $\int d^3x\, \vec{A}_{\not{c}} \cdot \vec{B}_{\not{c}}$ = topological charge of magnetic field lines [Moffatt 1969]

$$\vec{B}_{\not{c}\,T+\Delta T} = \cos\Delta\theta_{\rm eff}\vec{B}_{\not{c}\,T} + \sin\Delta\theta_{\rm eff}\vec{B}_{c_T}, \qquad \Delta\theta_{\rm eff} := \theta_{\rm eff}(T+\Delta T) - \theta_{\rm eff}(T)$$



Magnetic helicity carried by the massive mode $\propto \Delta\theta_{\rm eff}$ decays

Anomaly equation roughly says…

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

$$\Delta(\text{baryon asymmetry}) \sim -\Delta(\text{magnetic helicity})$$

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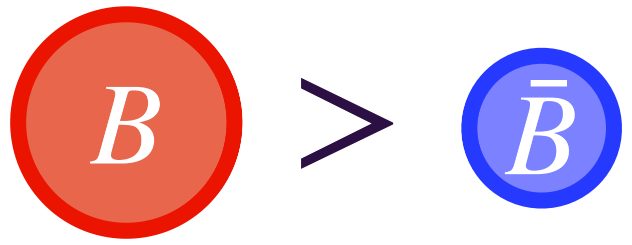


More precisely, …

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

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

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

$\Delta\theta_{\rm eff}$

time-dependent mixing

helicity decay

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

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

MHD

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

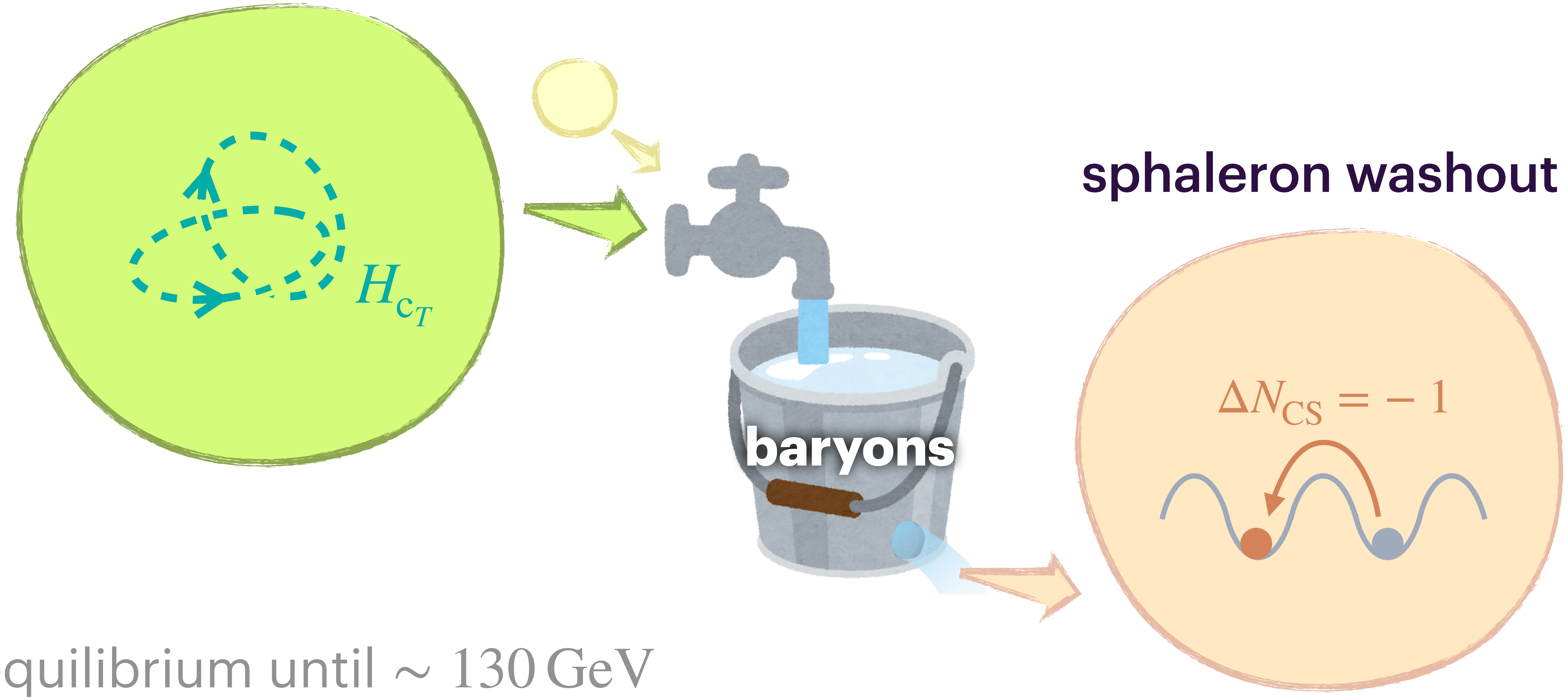
non-perturbative contributions

sphaleron

Baryogenesis from magnetic helicity decay

magnetic helicity decay

sphaleron washout



equilibrium until $\sim 130\,\mathrm{GeV}$

[Kamada, Long 2016]

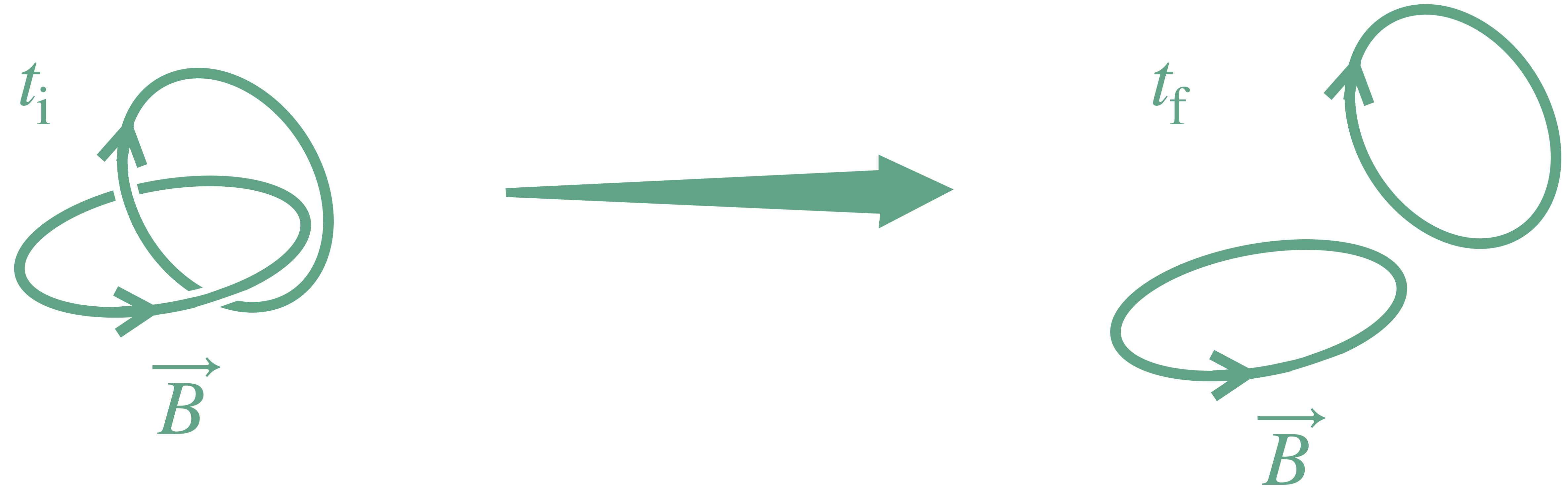
the baryon yield can be examined under BBN

…, [Fujita, Kamada 2016] [Kamada, Long 2016] [Giovannini, Shaposhnikov 1997] [Kamada, FU, Yokoyama, 2021]

However, we may have missed another washout effect.

Magnetic helicity can be ill-defined

Assume $T = 0$ and $\theta_{\rm eff} = \theta_{\rm w}$ for simplicity.

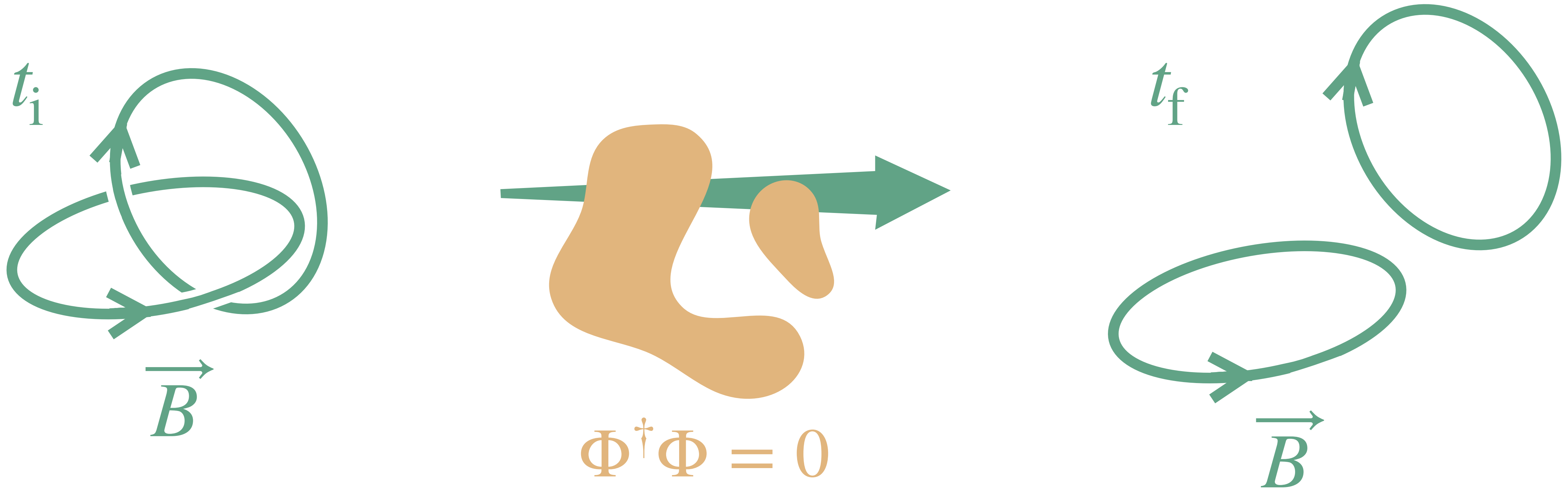


Naively, $$\Delta \int d^3x\, \vec{A} \cdot \vec{B} \stackrel{?}{=} -2 \int_{t_{\rm i}}^{t_{\rm f}} d^4x\, \vec{E} \cdot \vec{B}$$

Magnetic helicity can be ill-defined

Assume $T = 0$ and $\theta_{\text{eff}} = \theta_{\text{w}}$ for simplicity.

During $t_{\text{i}} < t < t_{\text{f}}$, **the "$\text{U}(1)_{\text{em}}$" can be ill-defined in the region where $\Phi^\dagger\Phi = 0$**



$$\Delta \int d^3x\, \vec{A} \cdot \vec{B} = -2 \int_{t_{\text{i}} \setminus}^{t_{\text{f}}} d^4x\, \vec{E} \cdot \vec{B} + \int_{\partial} A \wedge F$$

nontrivial helicity change where higgs vanishes!

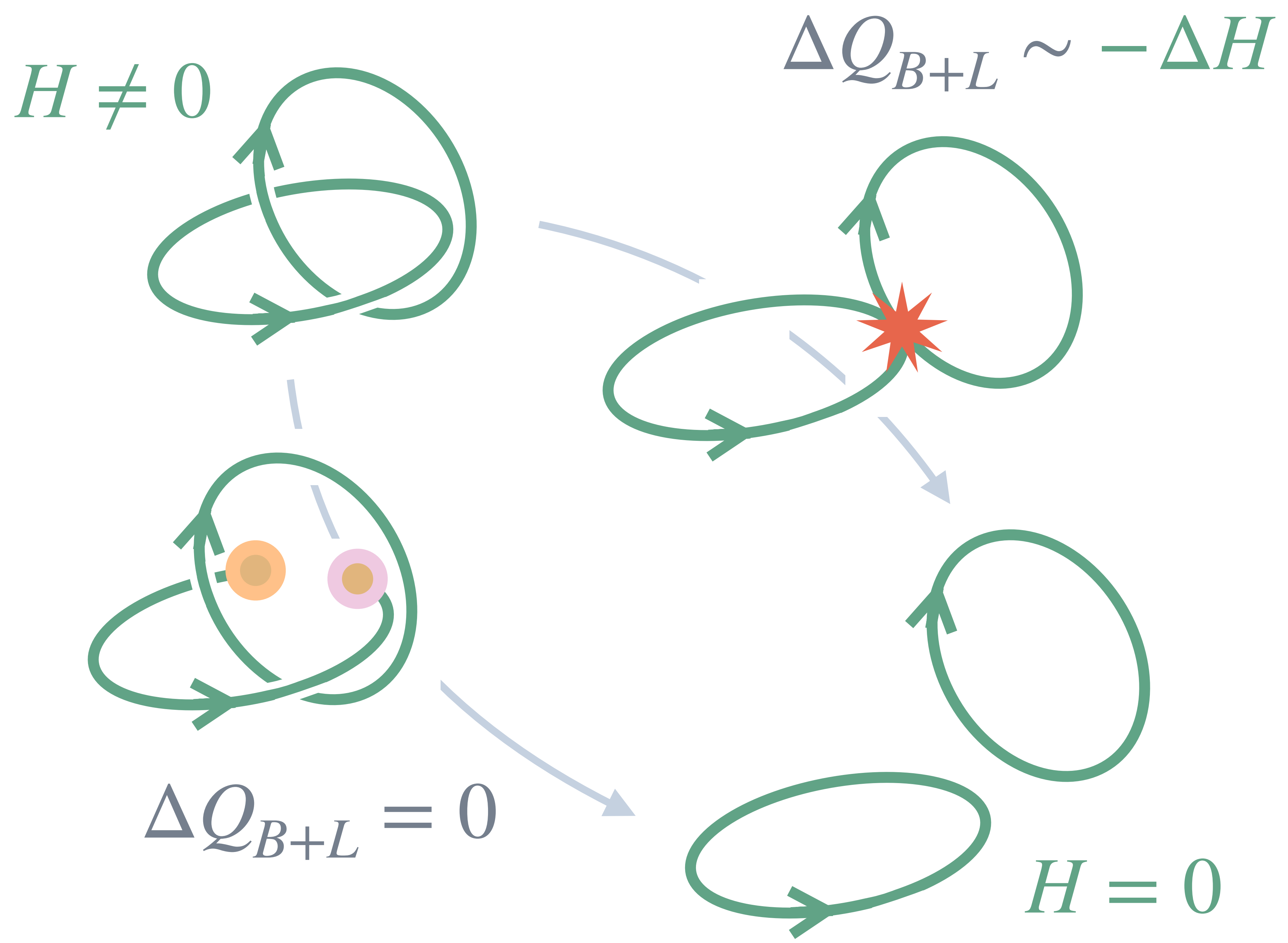
[Fukuda, Hamada, Kamada, Mukaida, FU 2025]

Indeed, Higgs dynamics can matter

Toy model (non-SM)

$\mathrm{SU}(2) \to \mathrm{U}(1) \to 1, \quad \partial_\mu j^\mu_{B+L} \sim \vec{E} \cdot \vec{B}$

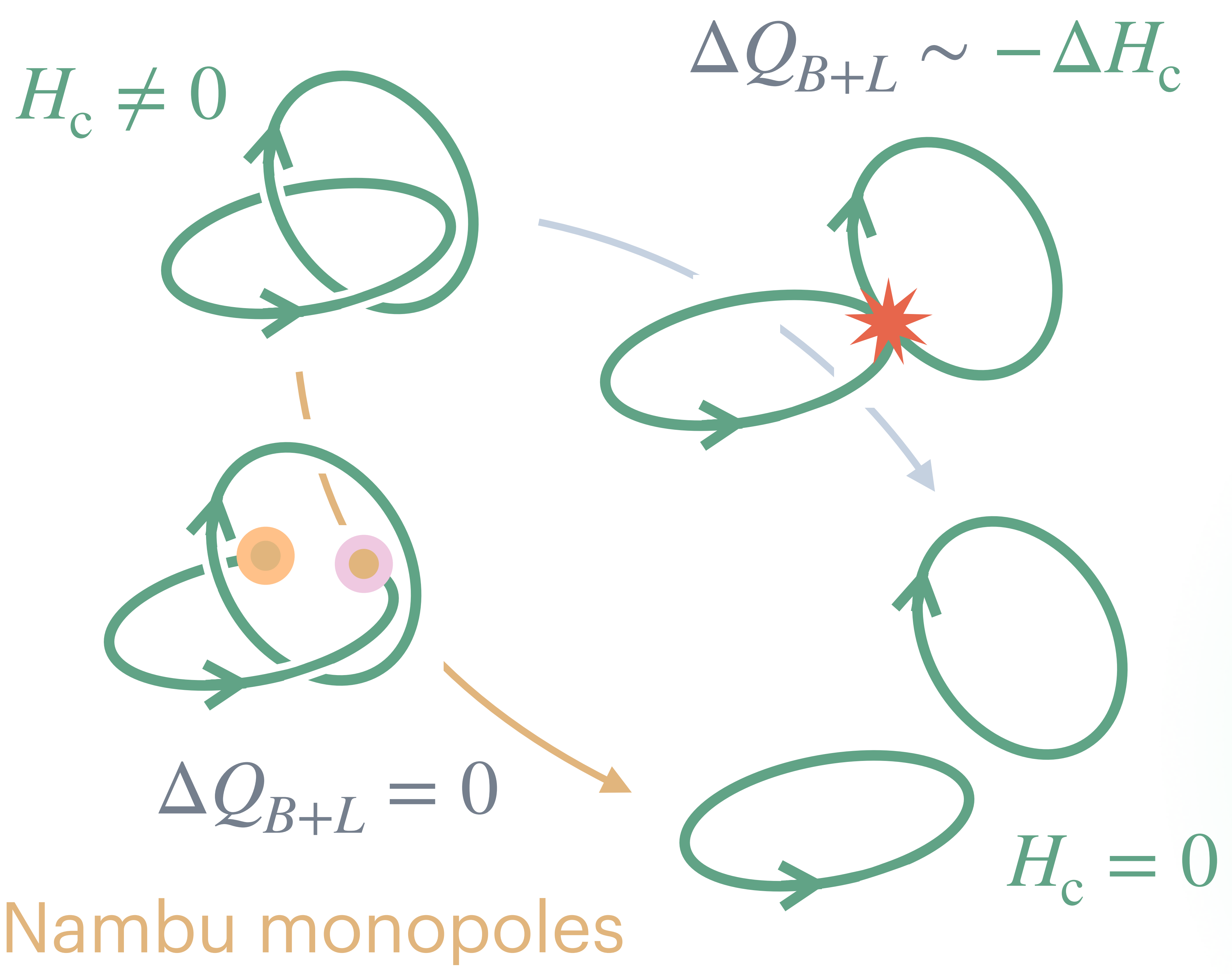
$\Delta Q_{B+L} = -\Delta H$ does not hold always.



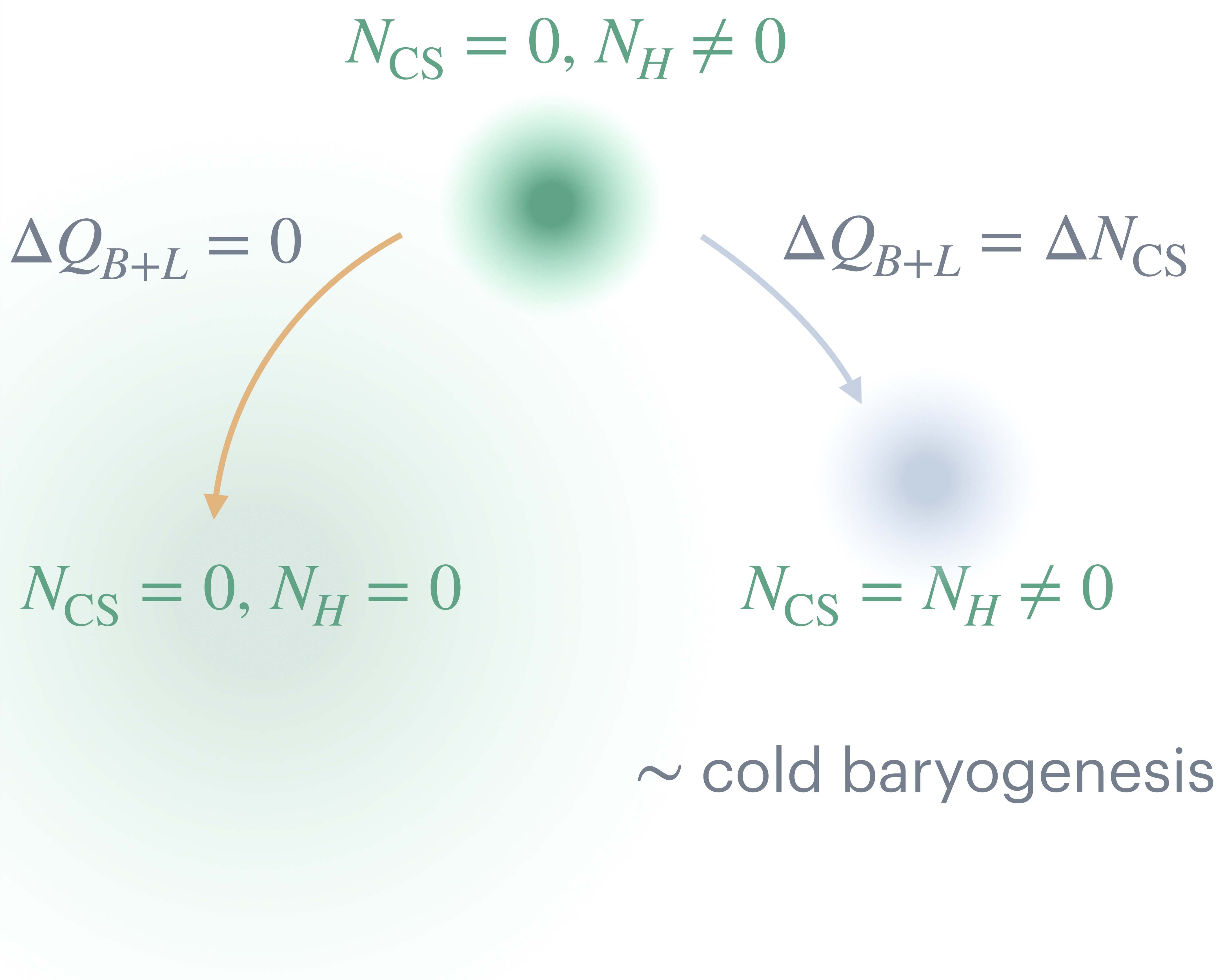
untying link by generating
't Hooft—Polyakov monopole pairs

In the SM? : future work

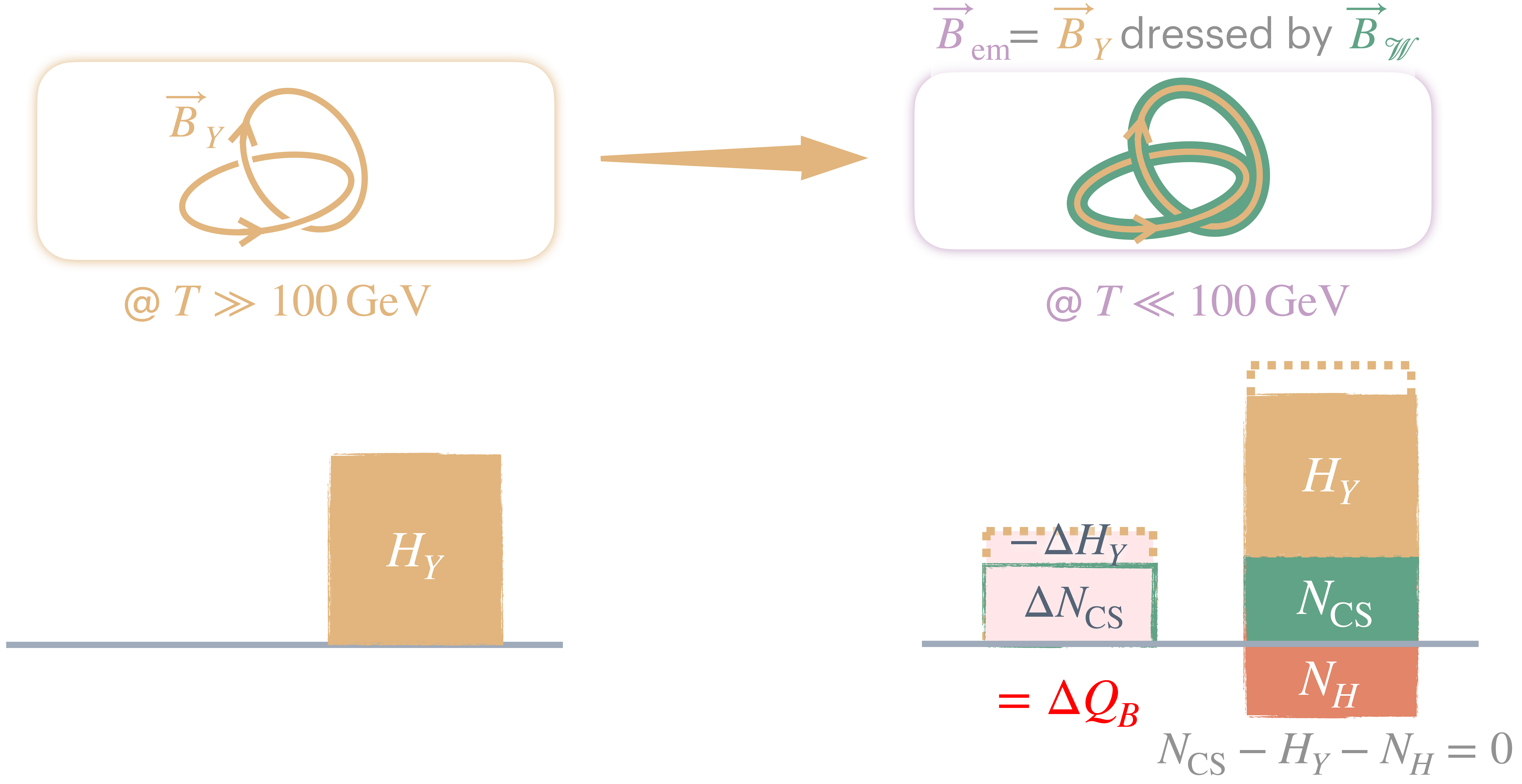
Untying links?



Texture decay?



Putting it in another way, ...



Baryon asymmetry constraints [Hamada, Mukaida, FU 2025b]

helical $\mathrm{U}(1)_Y$ magnetic field

$$\langle \delta\eta_B \rangle \sim \langle \vec{A} \cdot \vec{B} \rangle$$

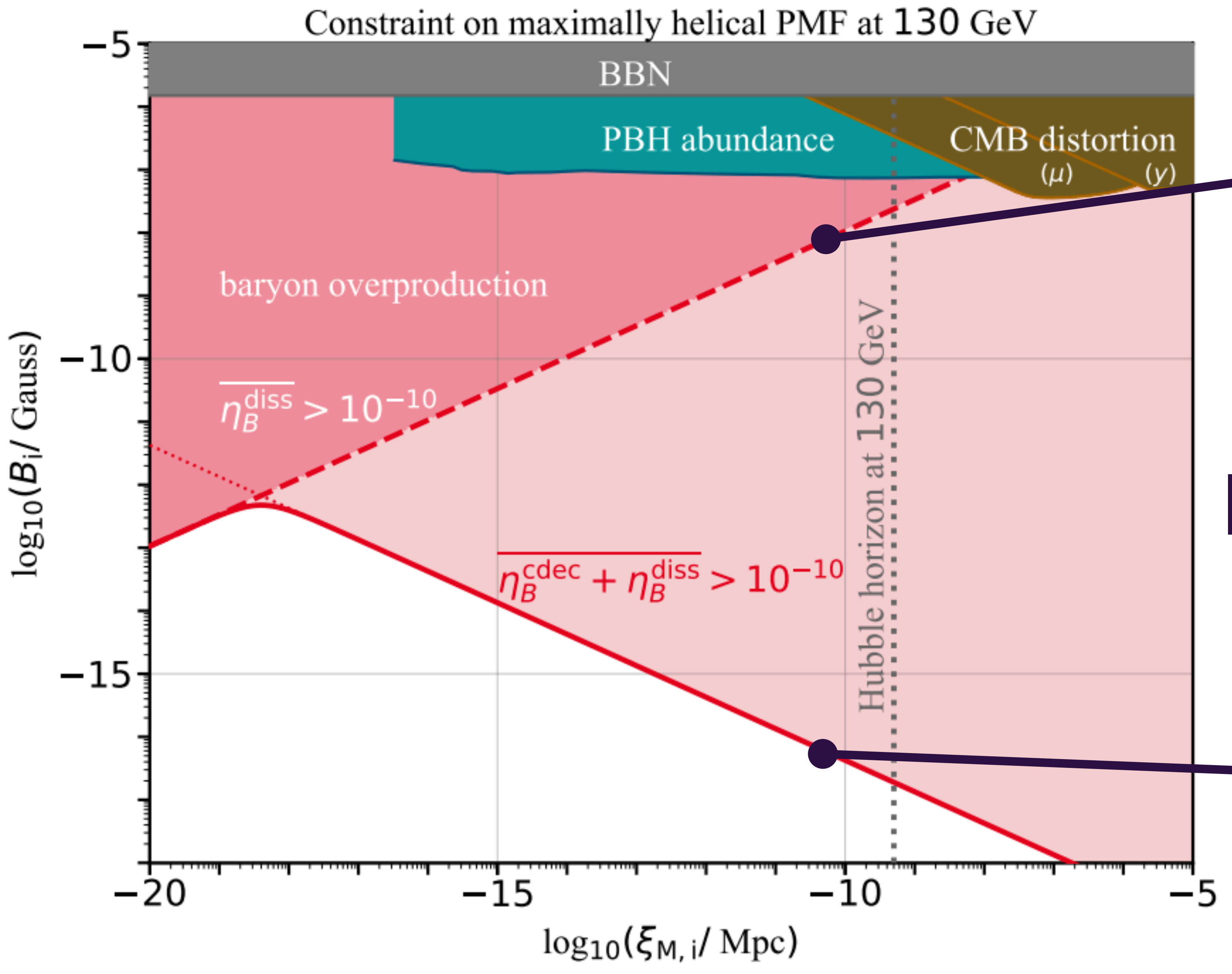
$\leq 10^{-10}$ (CMB, BBN)

non-helical $\mathrm{U}(1)_Y$ magnetic field

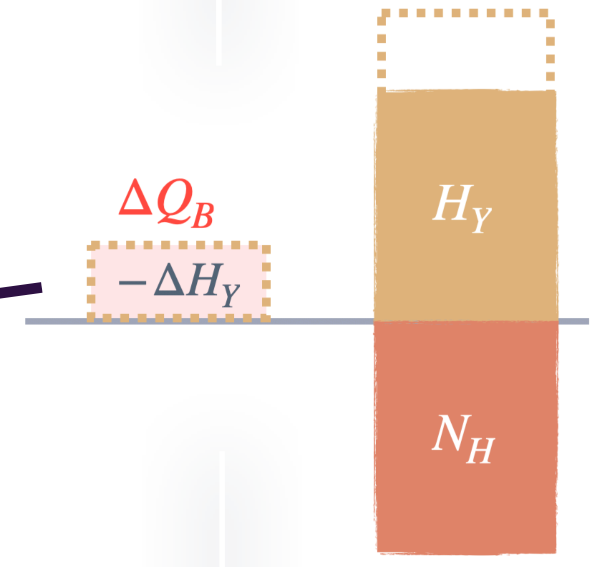
$$\langle \delta\eta_B^2 \rangle \sim \langle (\vec{A} \cdot \vec{B})^2 \rangle, \quad \langle \vec{A} \cdot \vec{B} \rangle = 0$$

$\leq \mathcal{O}(0.01)\, \eta_{B,\mathrm{obs}}^2$ (BBN) [Inomata+ 2018]

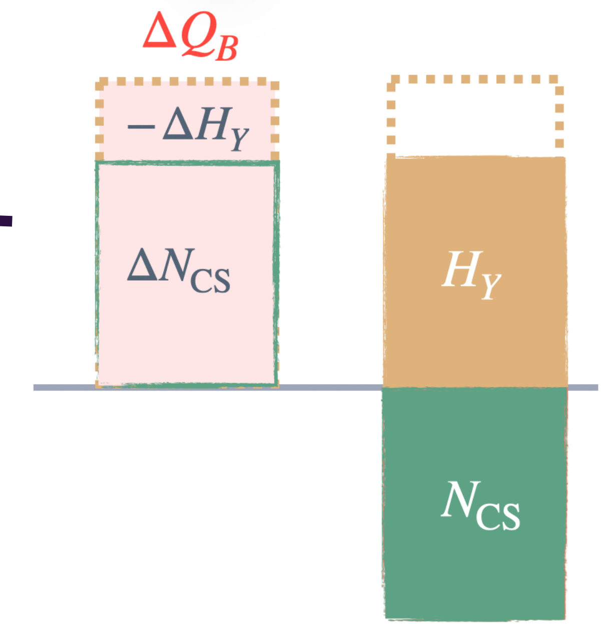
rms strength B

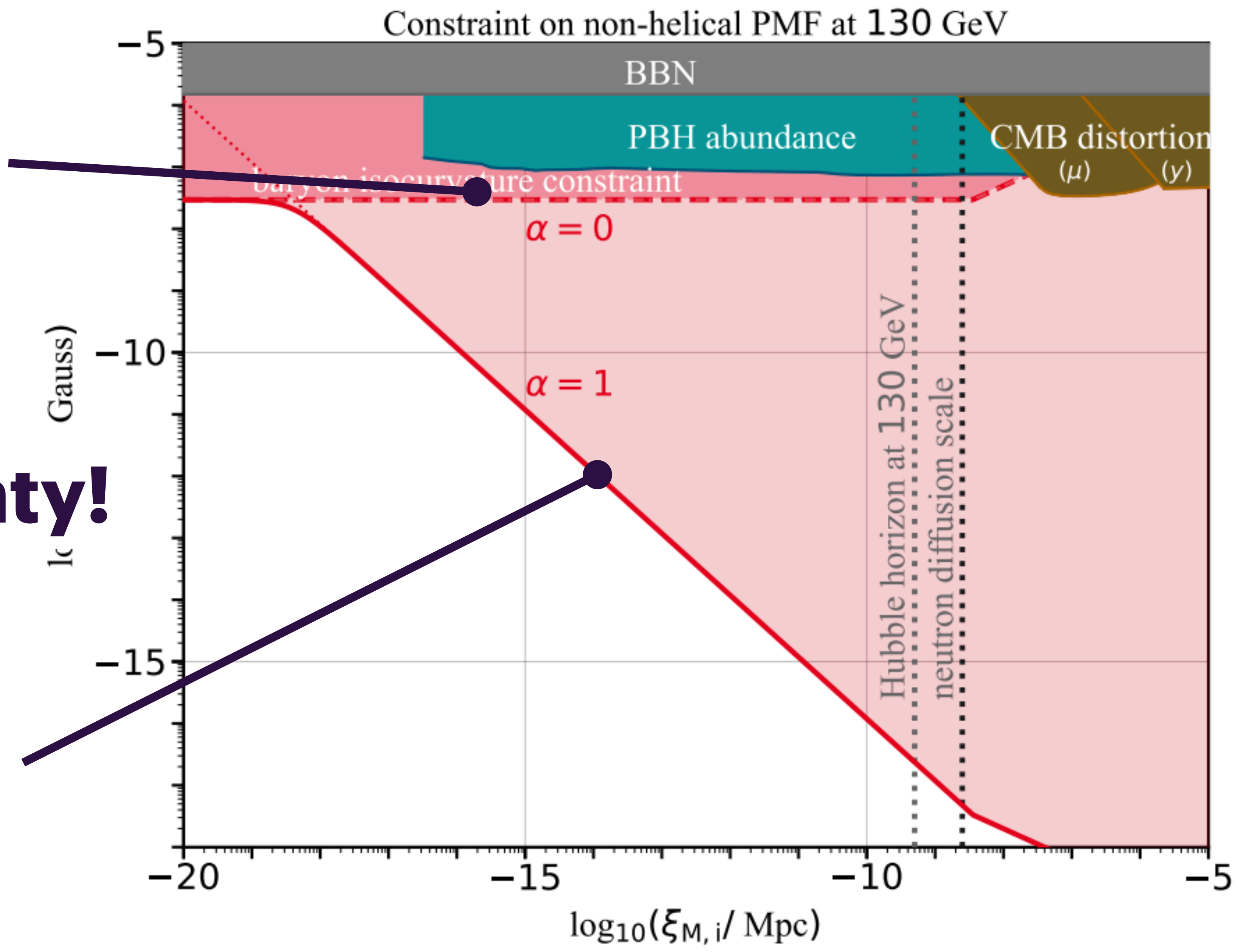


coherence length ξ_{M}



large uncertainty!





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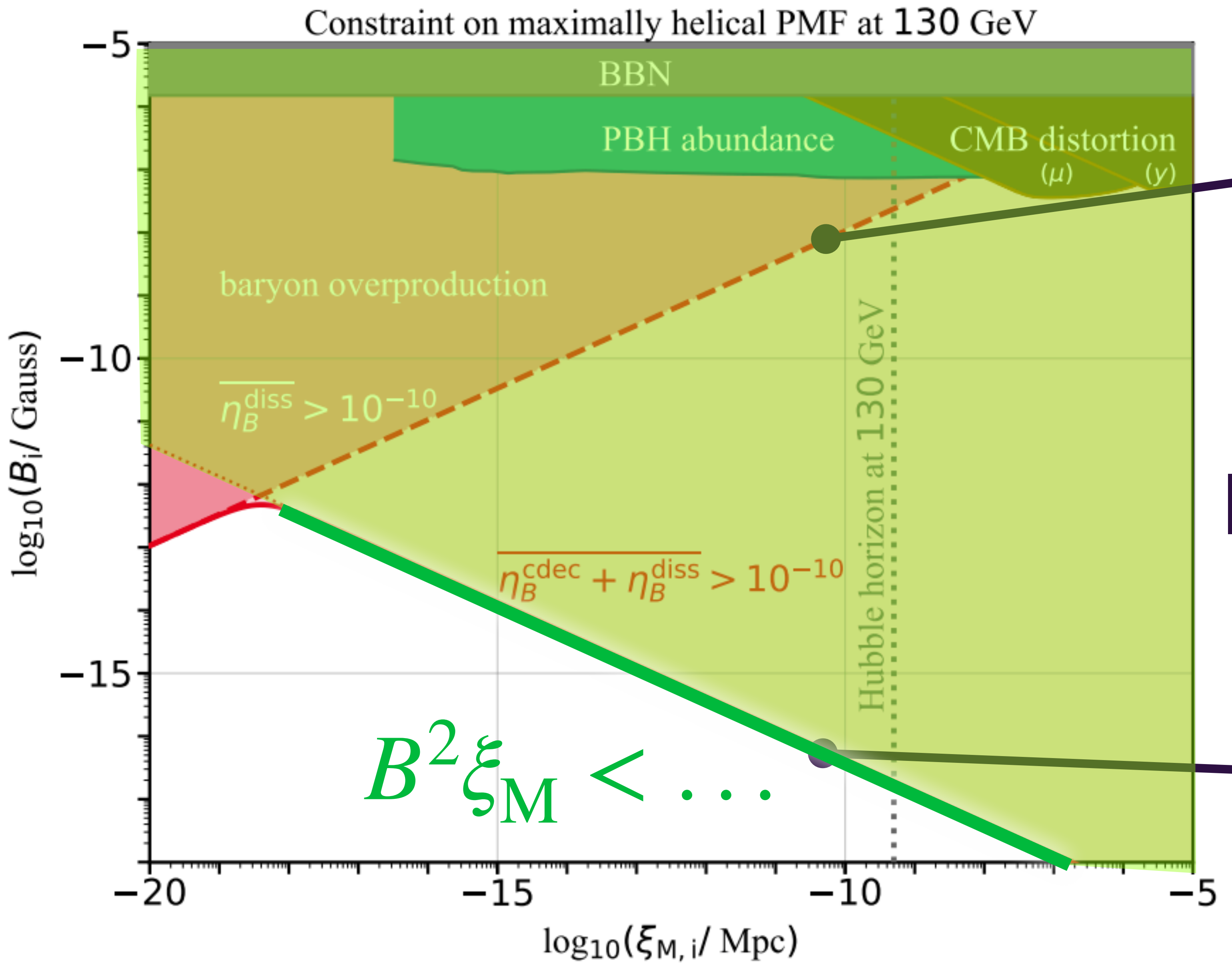

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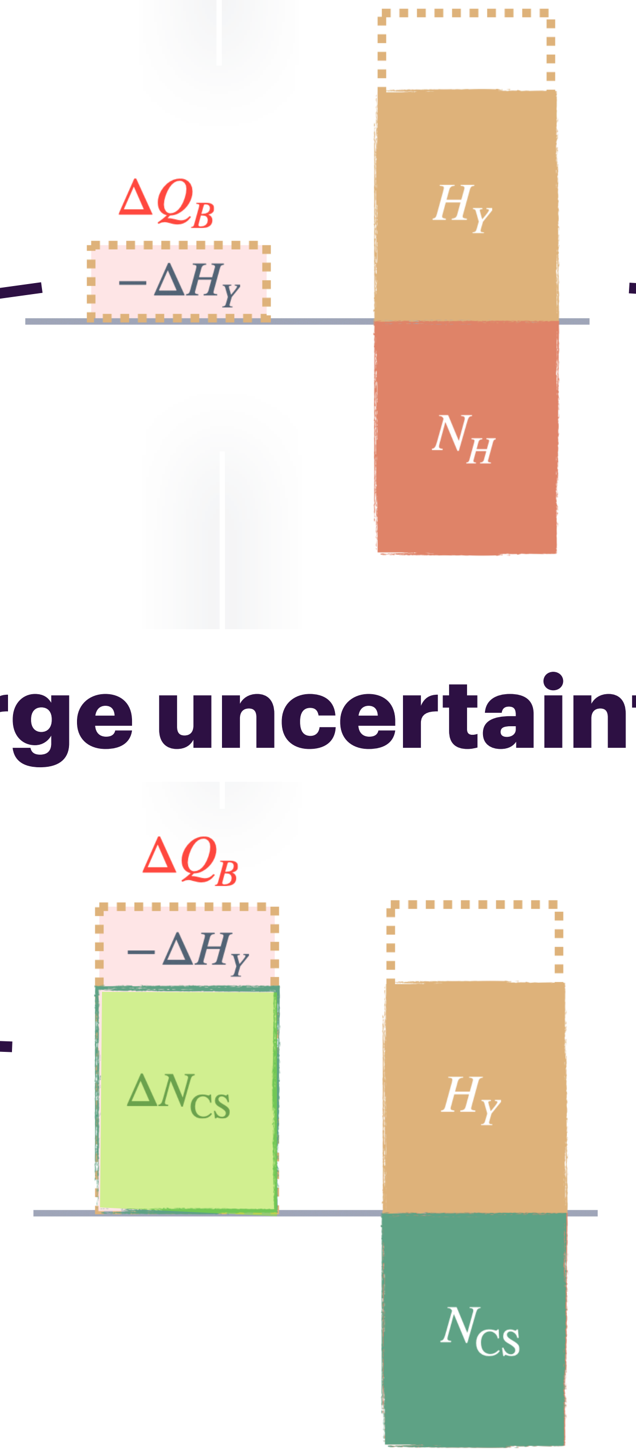

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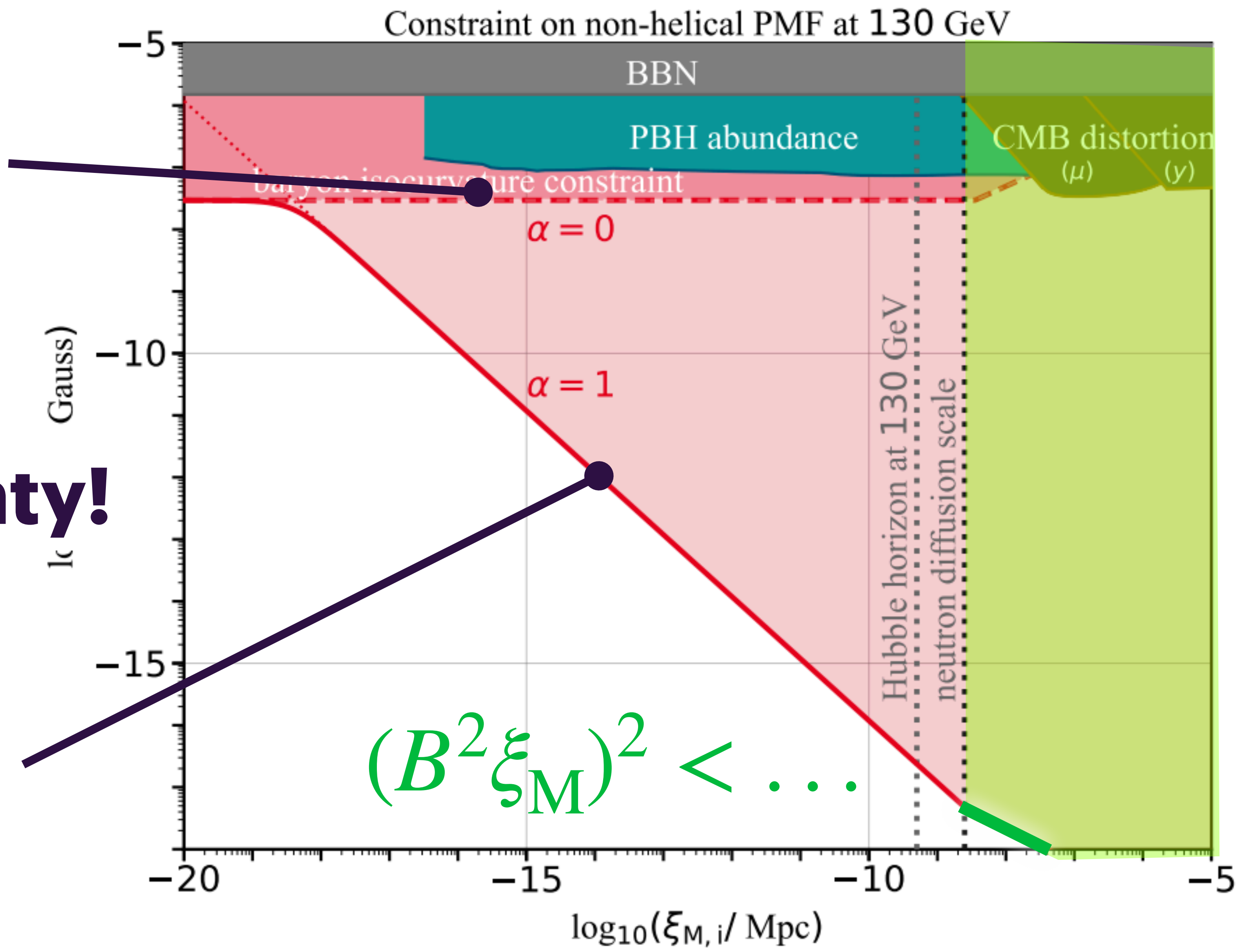
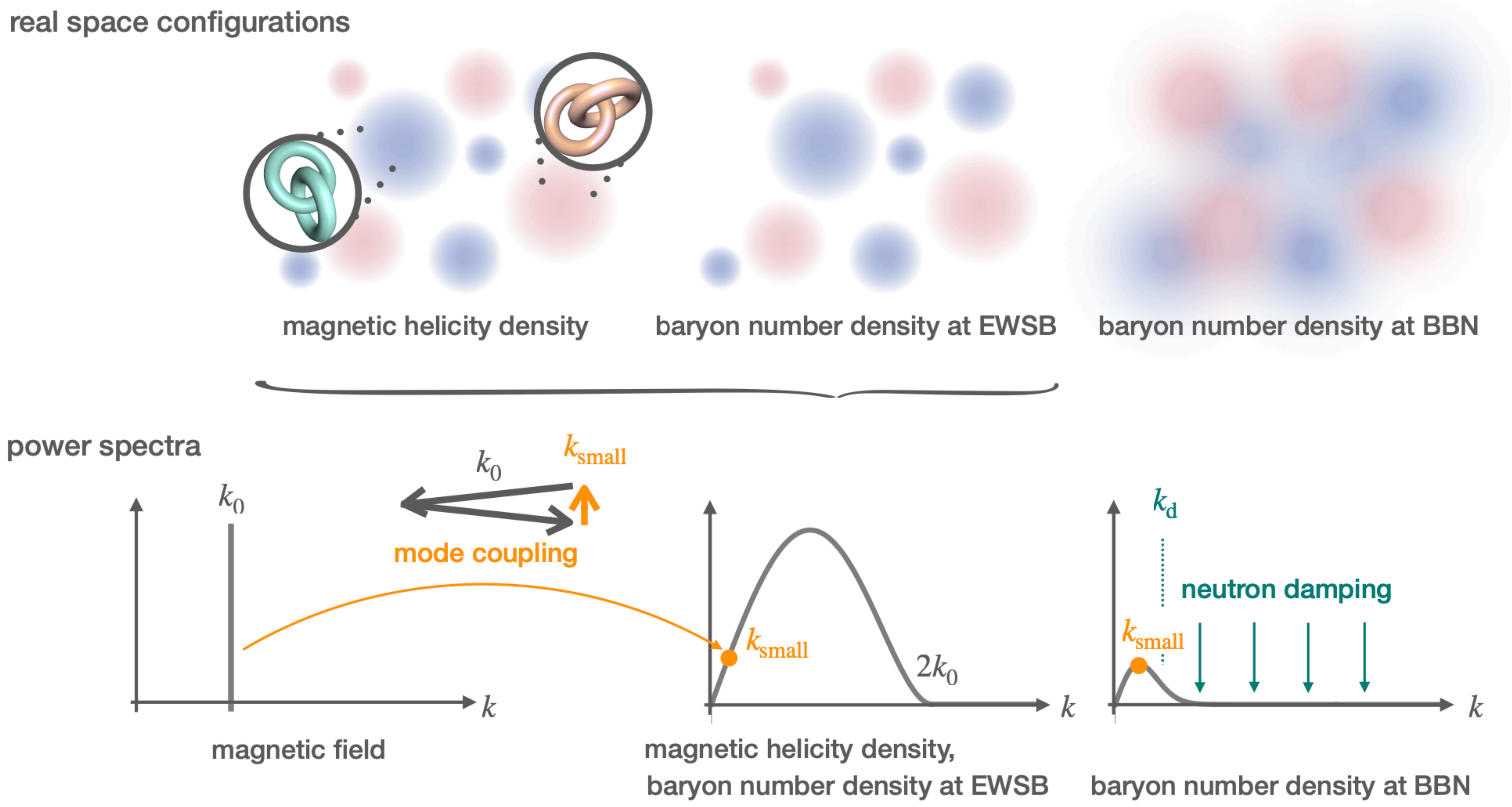


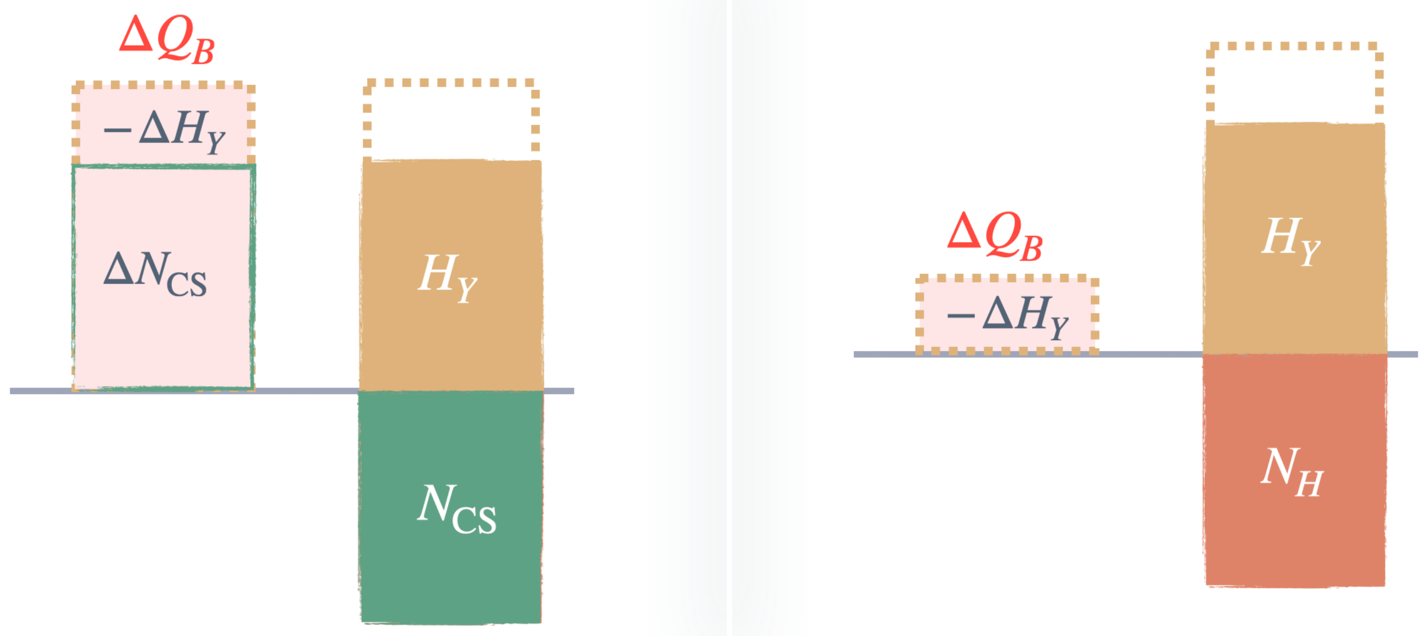
Baryon perturbation at small scales

[Kamada, FU, Yokoyama 2021] [Akiyama, FU ongoing]



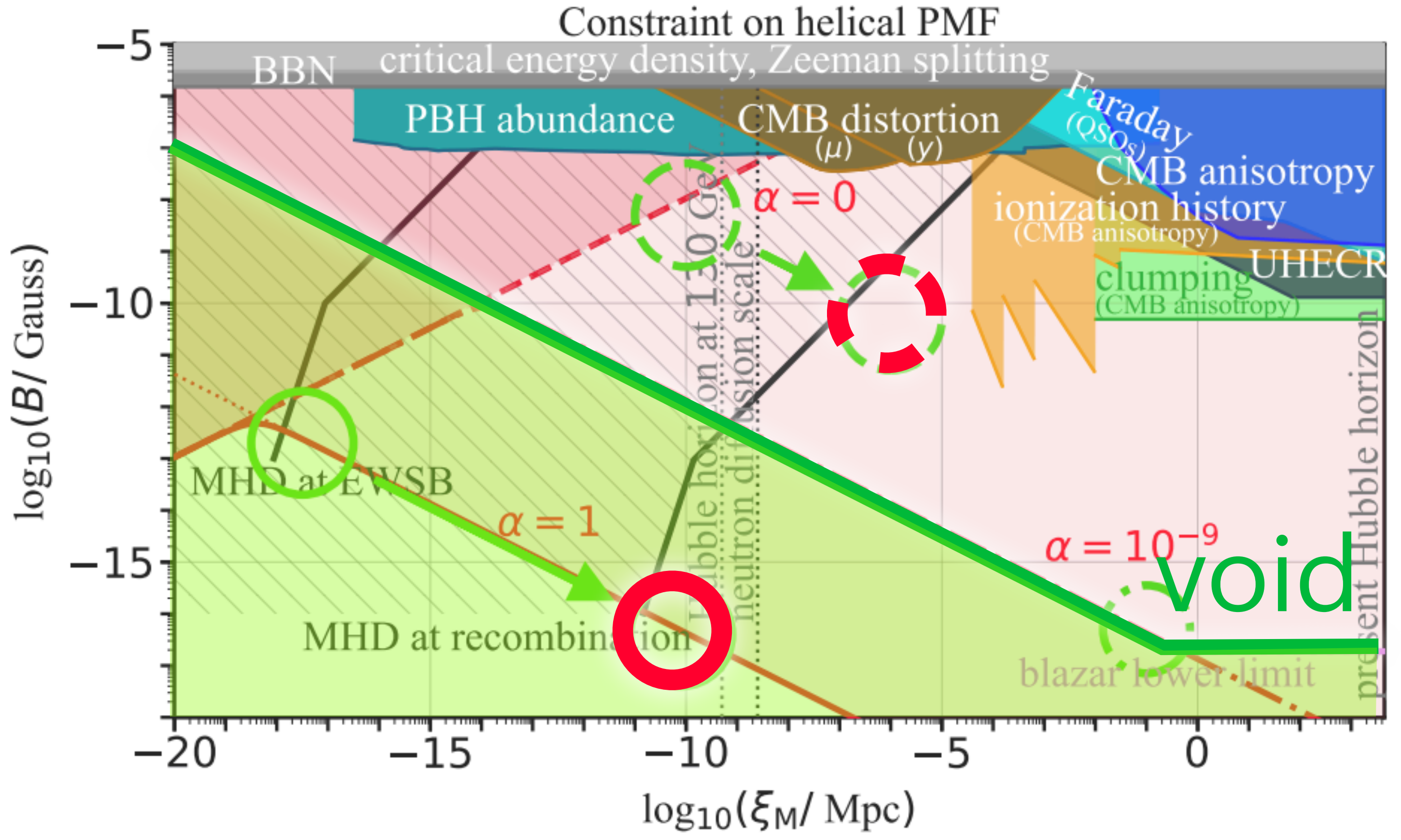
Originally-$\mathrm{U}(1)_Y$ void magnetic field?

the constraints + **MHD evolution**

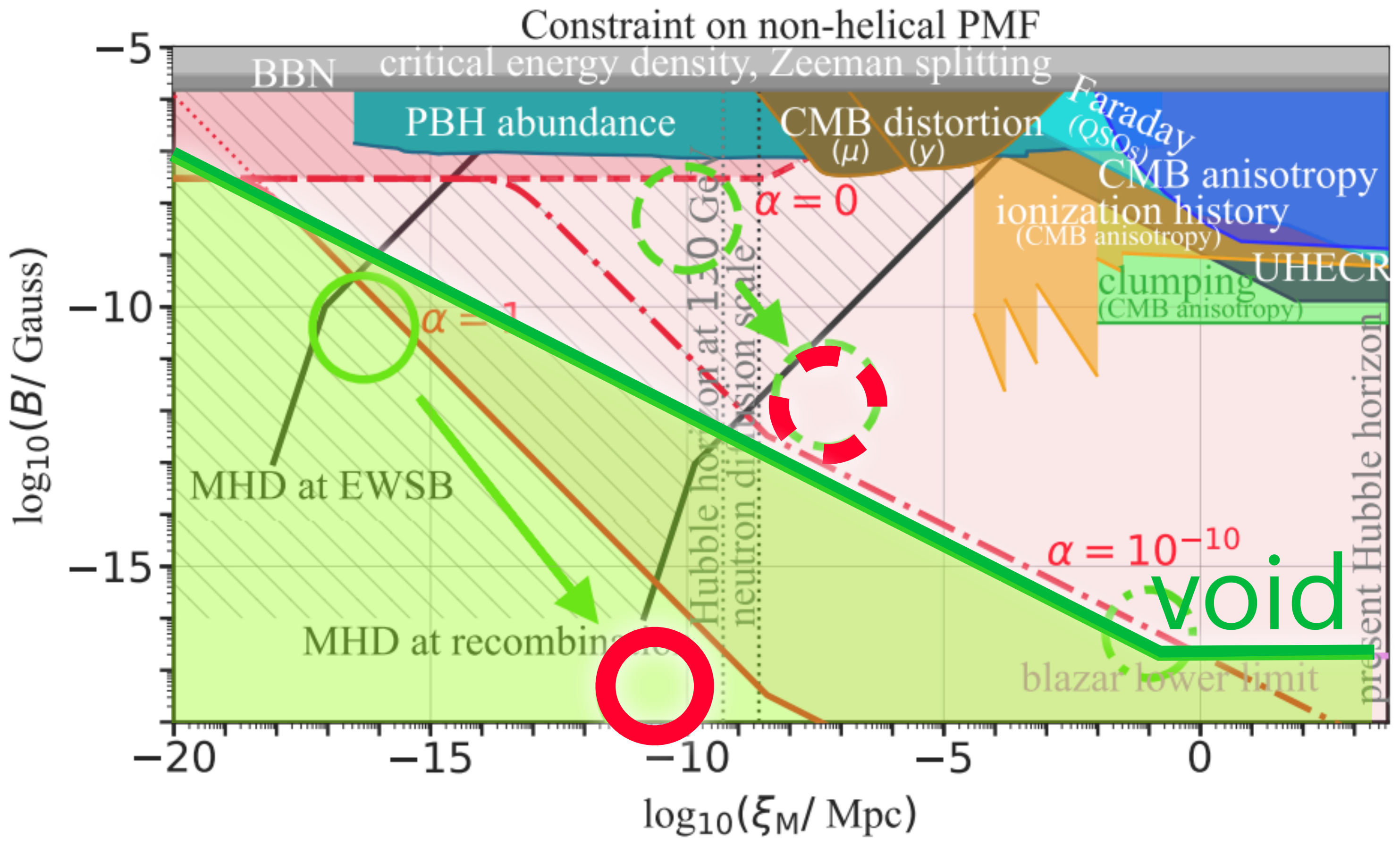


If	$\Delta N_H = 0$	/ $\Delta N_{CS} \simeq 0$
	⭕ at best	◌
PMF → $\vec{B}_{\text{void}}$	🙅	🙆
PMF → $\eta_{B,\text{obs}}$	🙆	🙆

baryon overproduction (helical)



baryon fluctuation (non-helical)



[Hamada, Mukaida, FU 2025b]

Summary

- **continuous transition from $\vec{B}_Y$ to $\vec{B}_{\rm em}$** during the electroweak crossover
    - ✔ one-loop formula for effective mixing angle $\theta_{\rm eff}(T)$ and normalization $Z^{\not c}(T)$
- **Helicity decay** $\propto \Delta\theta_{\rm eff}$ at every instant
    - ✔ may **generate baryons** through the chiral anomaly, (known in the literature,)
    - ✔ but we have missed possible contribution of the Higgs dynamics.
- Once ΔN_H during the crossover is known (future work), one can estimate ΔQ_B.
    - ✔ If $\Delta N_H = 0$, generated baryon asymmetries suffer from BBN constraints.
    - ✔ Only if $\Delta N_H \neq 0$ s.t. $\Delta N_{\rm CS} \simeq 0$, $\vec{B}_Y$ **may be origins of both $\vec{B}_{\rm void}$ and $\eta_{B,\rm obs}$.**