Primordial magnetic fields during the electroweak crossover and baryogenesis from magnetic helicity decay

2026/4/24, KPS spring meeting

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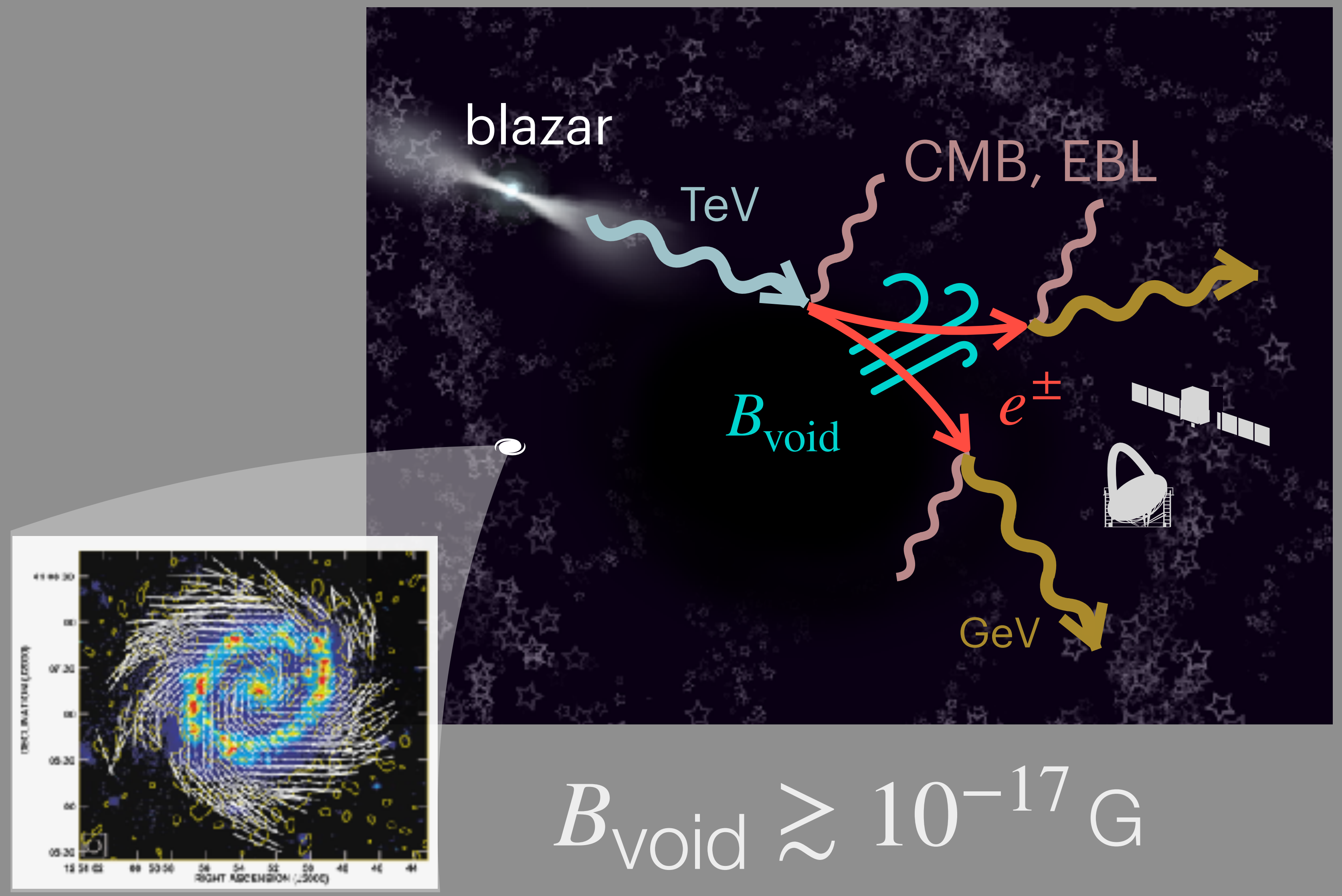
Cosmological questions

magnetogenesis

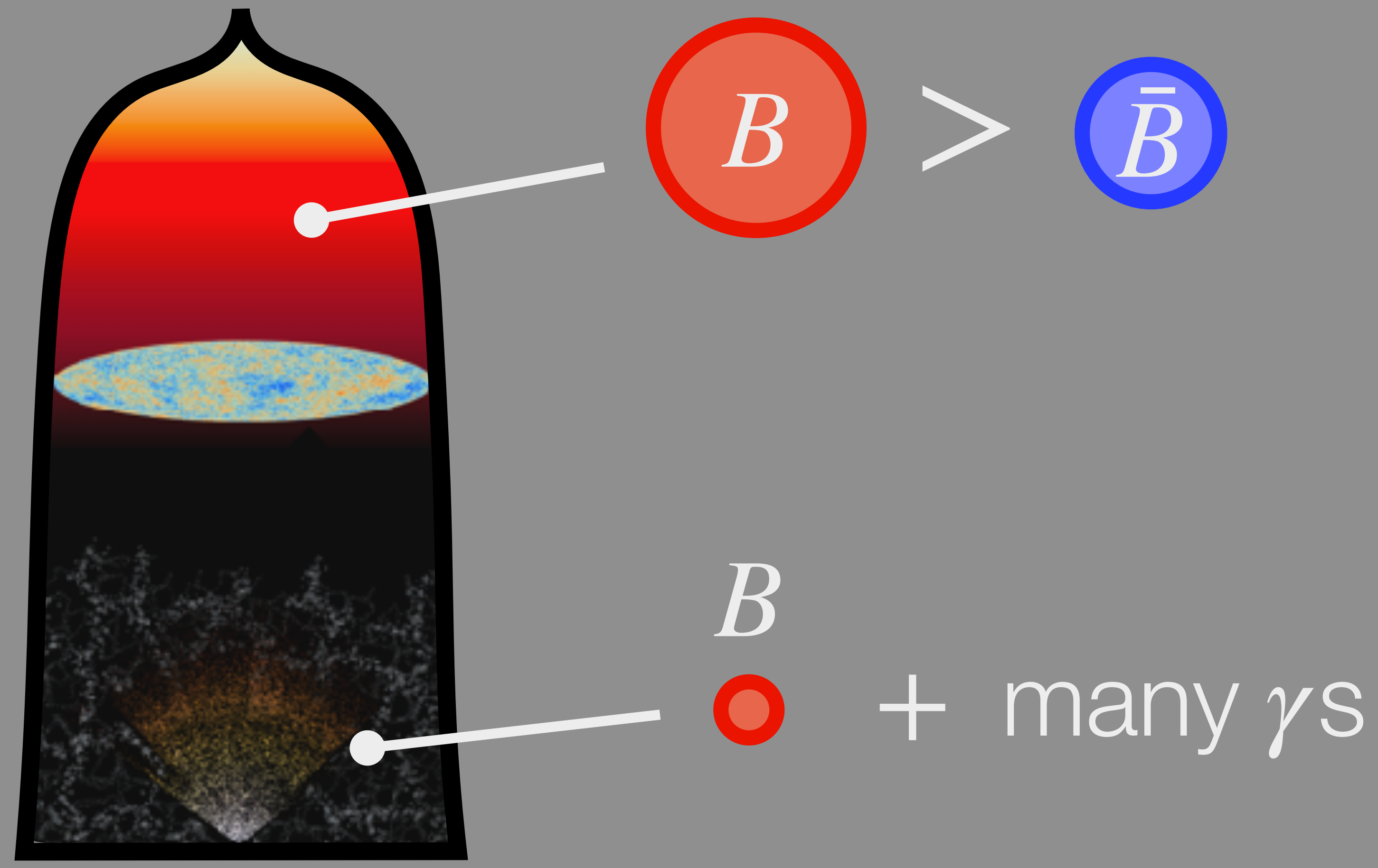


$B_{\rm void} \gtrsim 10^{-17}$ G

[Chyży, Buta] [Neronov, Vovk 2010], …

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

baryogenesis



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

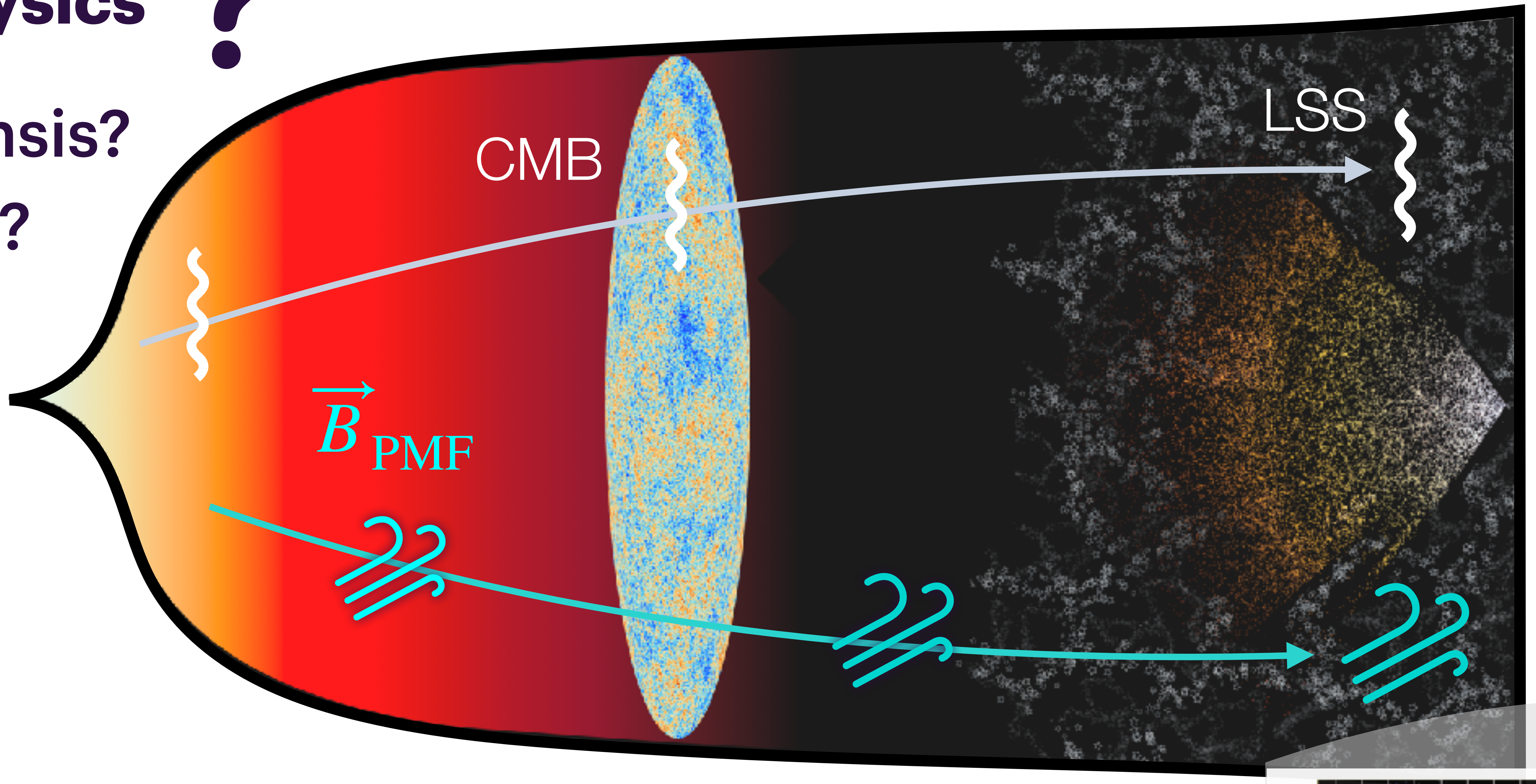
[Planck 2018], …

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

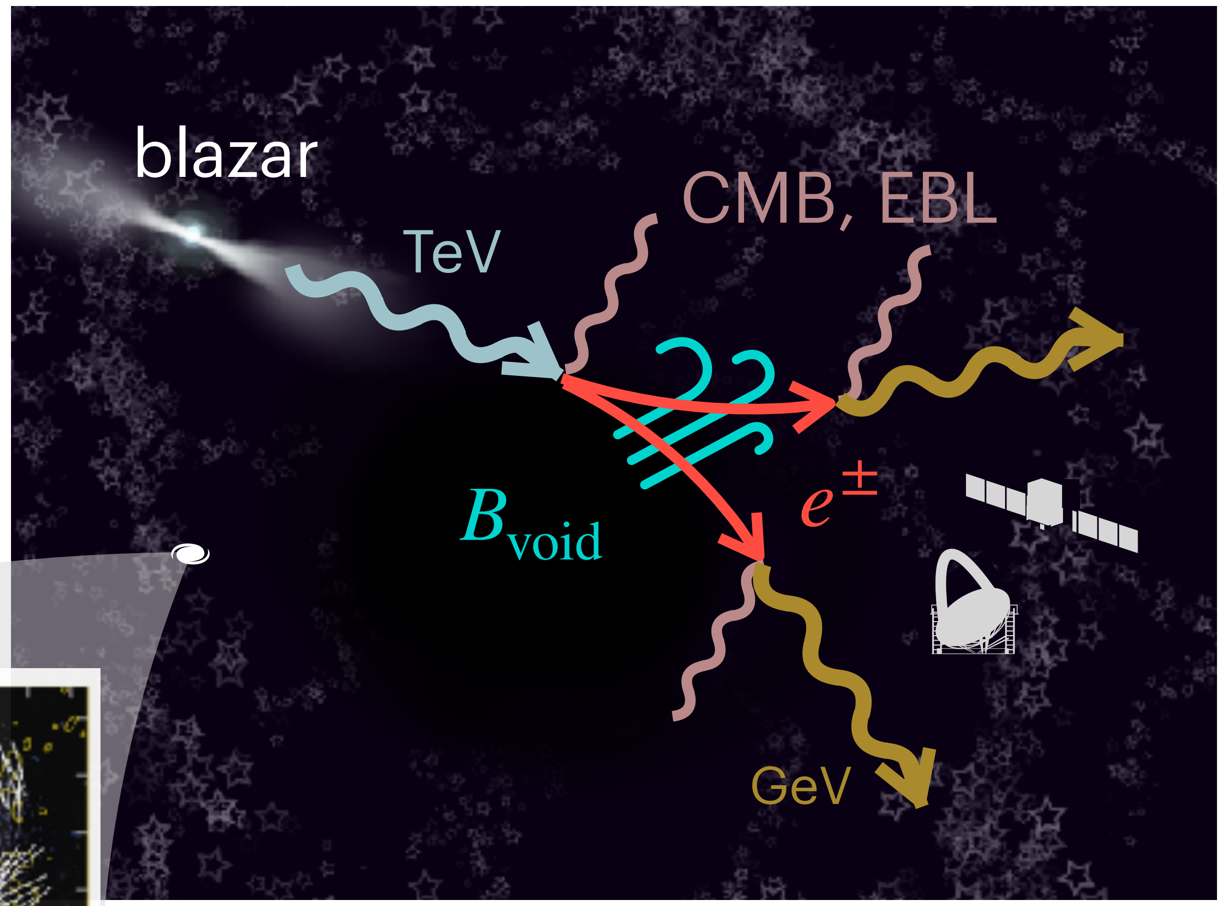
Investigating the Qs with cosmological magnetic field

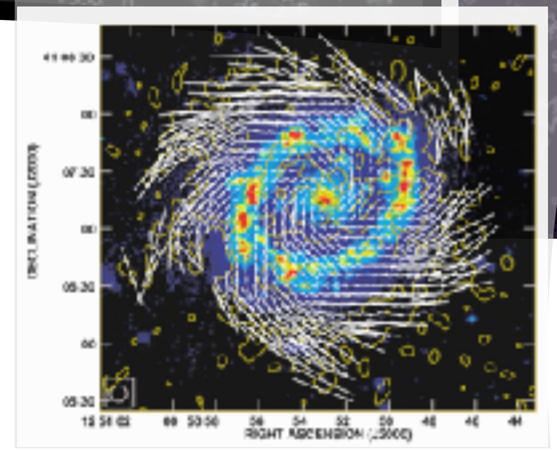
primordial physics ?

magnetogensis?
baryogensis?



observations





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

Investigating the Qs with cosmological magnetic field

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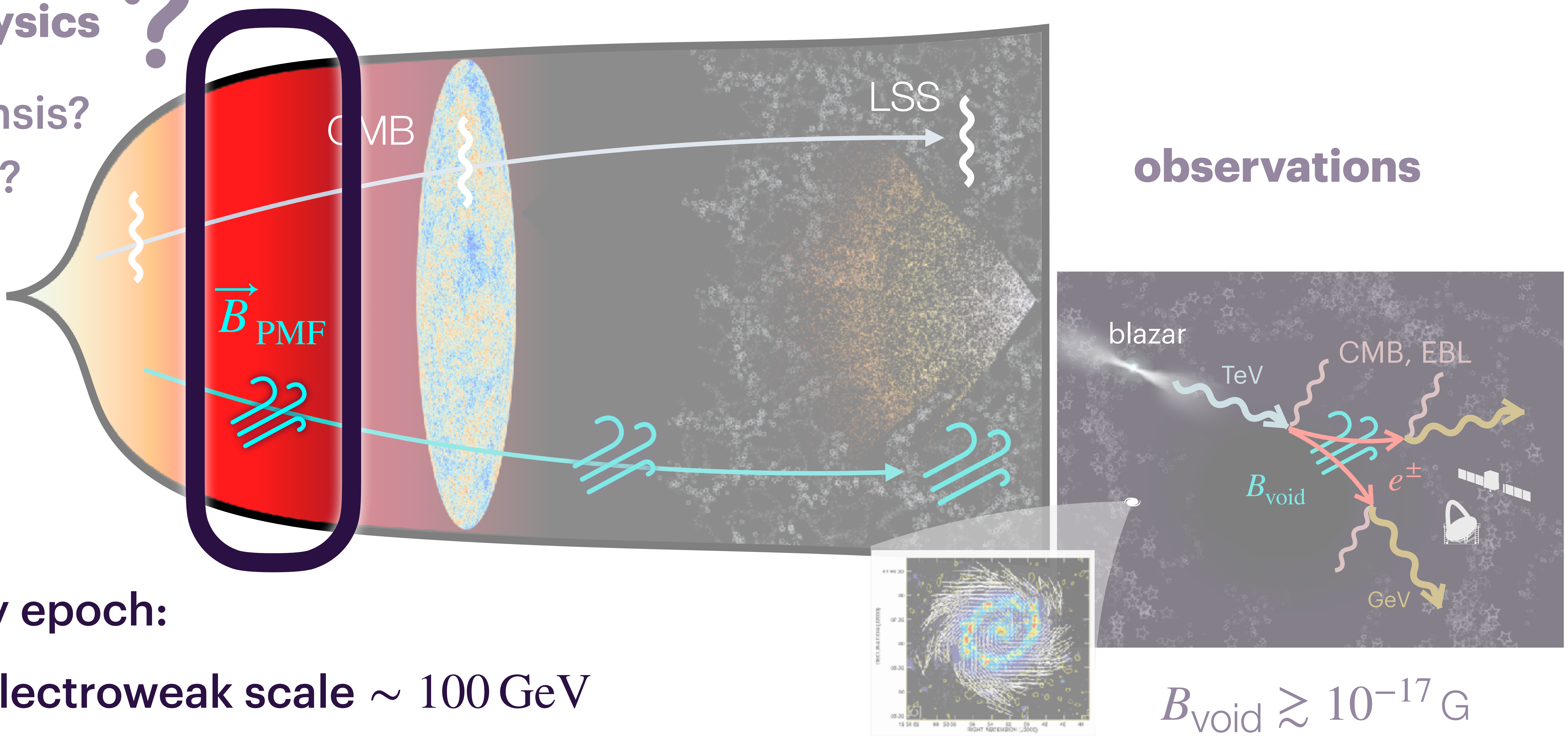

Key epoch:

electroweak scale $\sim 100\,\mathrm{GeV}$

[Chyży, Buta]

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Magnetic fields at high/low temperatures

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

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

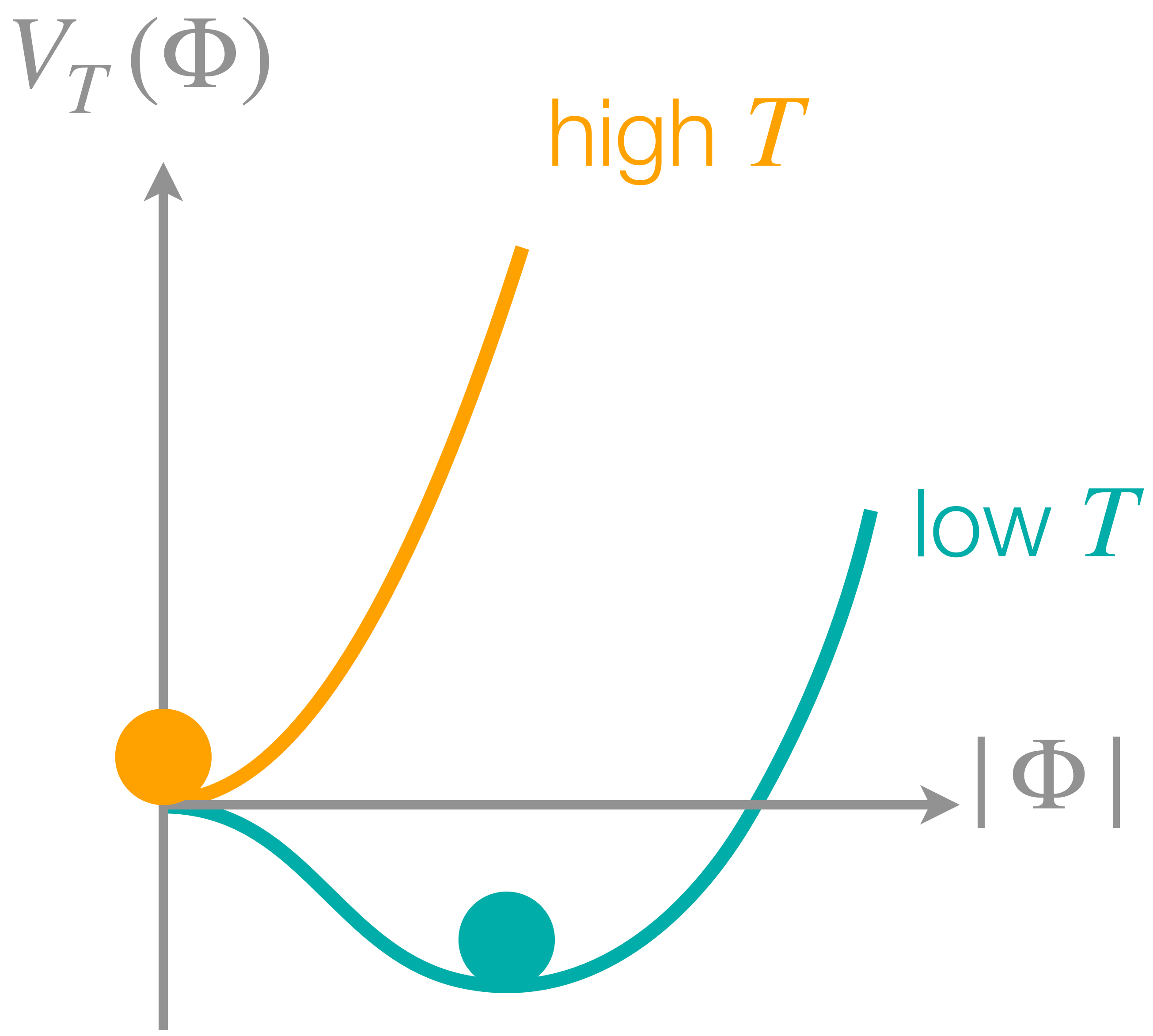
$\mathrm{U}(1)_Y$ **massless field**

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

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

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

and massive $W^\pm, Z$



Interpolating two phases

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

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

the hyper-magnetic field

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

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

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

the ordinary magnetic field

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

Interpolating two phases

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

$T \gg 100\,\mathrm{GeV}$	$T \sim 100\,\mathrm{GeV}$	$T \ll 100\,\mathrm{GeV}$
the hyper-magnetic field	dof that has a massless pole	the ordinary magnetic field
$\vec{B}_Y = \vec{\nabla} \times \vec{Y}$	$\sim \cos\theta_{\mathrm{eff}}\, Y_i - \sin\theta_{\mathrm{eff}}\, W_i^3$	$\vec{B}_{\mathrm{em}} = \vec{\nabla} \times \vec{A}$

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

effective mixing angle

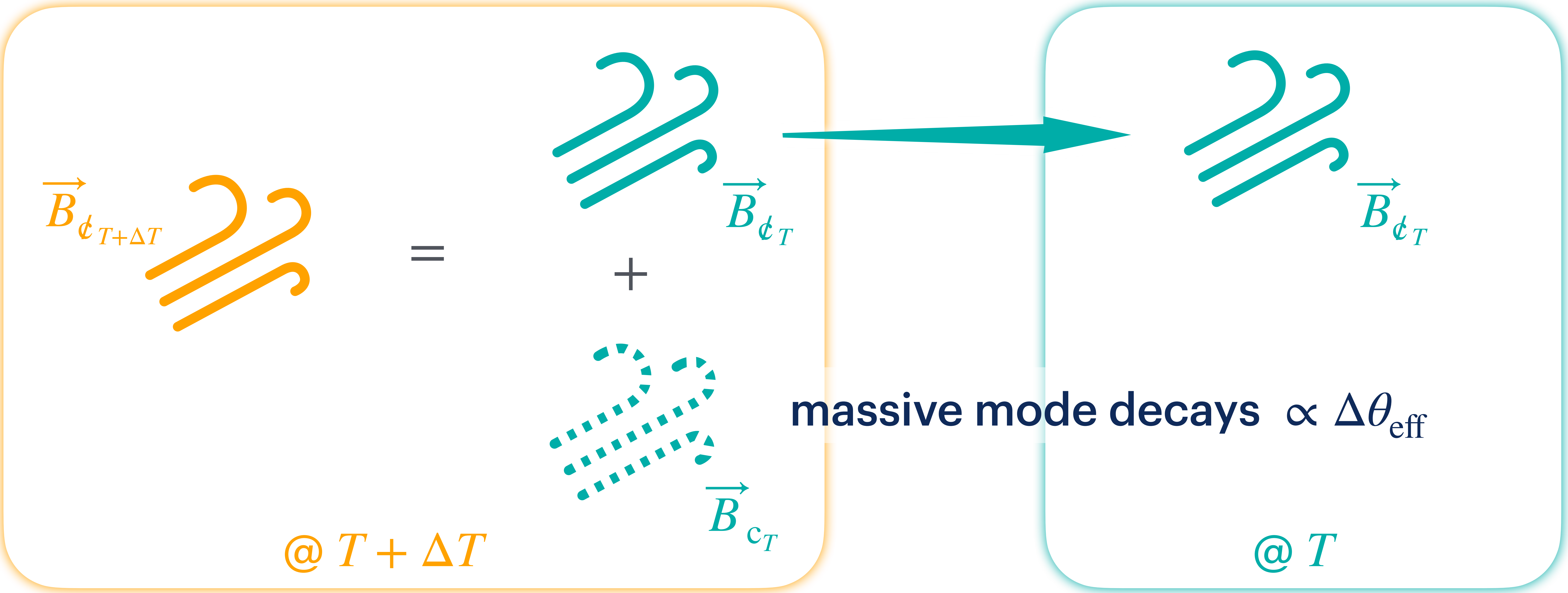
- perturbatively computable (at 1-loop)!

  [Kajantie+ 1997] [Hamada, Mukaida, FU 2025a]

Massive mode decays at every moment

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

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



Anomaly equation *roughly* says…

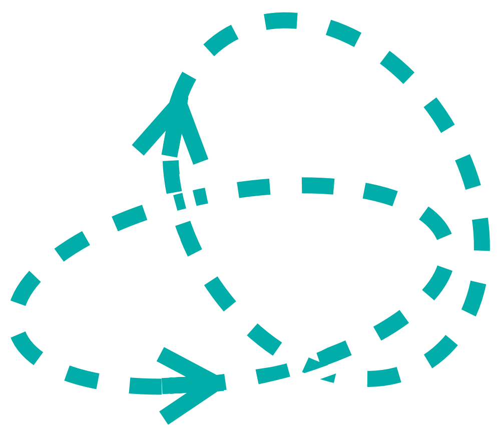
[Joyce, Shaposhnikov 1997] [Giovannini, Shaposhnikov 1998] [Fujita, Kamada 2016]…
[Kamada, Long 2016]

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

[Adler 1969] [Bell, Jackiw 1969]

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

parity-violating magnetic field



H_{c_T}

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parity-violating magnetic field

baryon asymmetry $\propto \Delta\theta_{\rm eff}$

$B > \bar{B}$

massive mode decay

$\sim \ \vec{B}_Y$ dressed by $\rm SU(2)_L$, $\Delta N_{\rm CS} \neq 0$

Anomaly equation actually says…

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

[Adler 1969] [Bell, Jackiw 1969]

Δ(baryon asymmetry) ∼ − Δ(magnetic helicity)

+ (nonperturbative contributions)

H_Y

✔ electroweak sphaleron

? Higgs dynamics involving $\Delta N_H \neq 0$

$\Delta(N_{\mathrm{CS}} - N_H) \sim H_Y$

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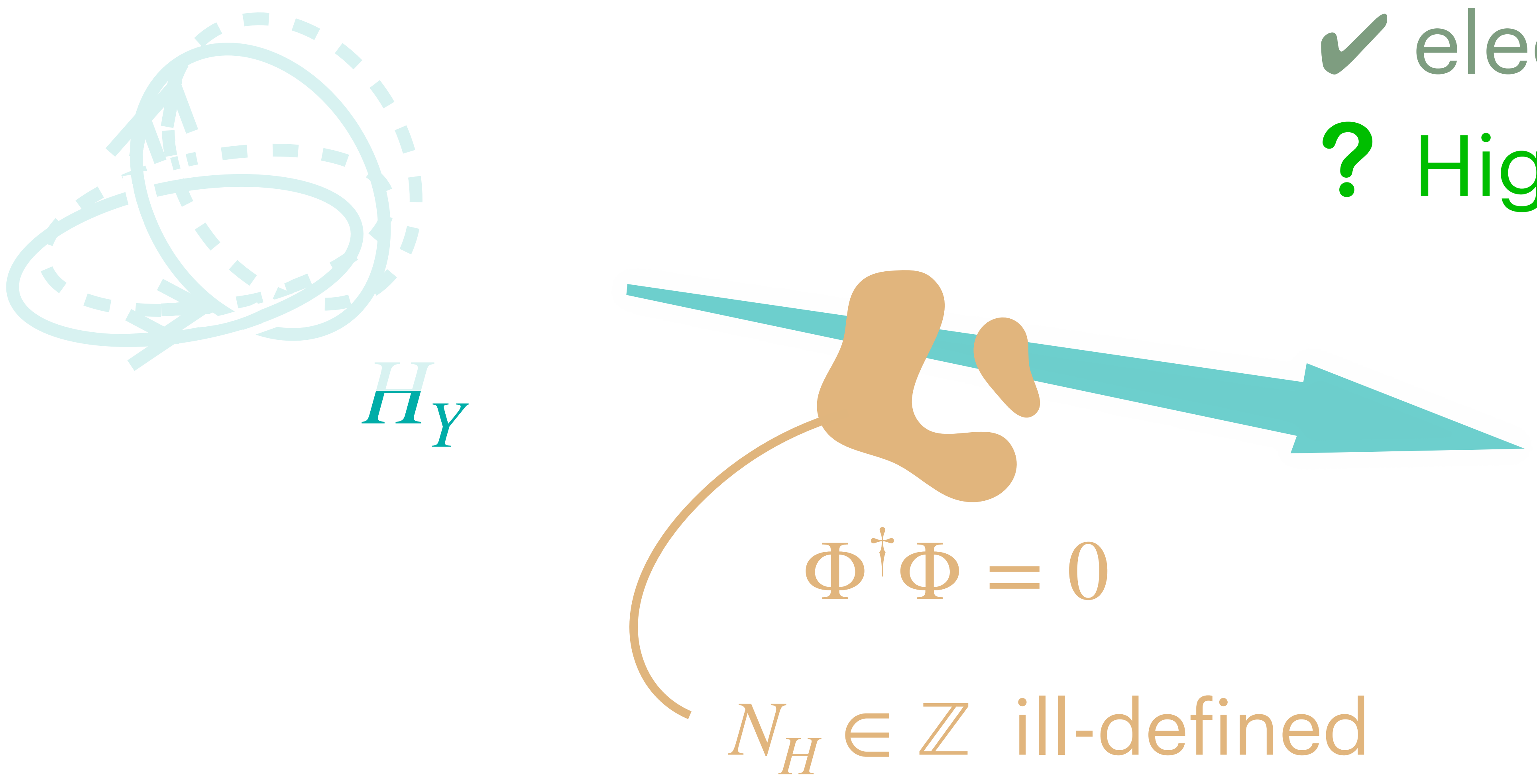


$\Delta(N_{\rm CS} - N_H) \sim H_Y$

ΔN_H may cancel $\Delta N_{\rm CS}$!

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

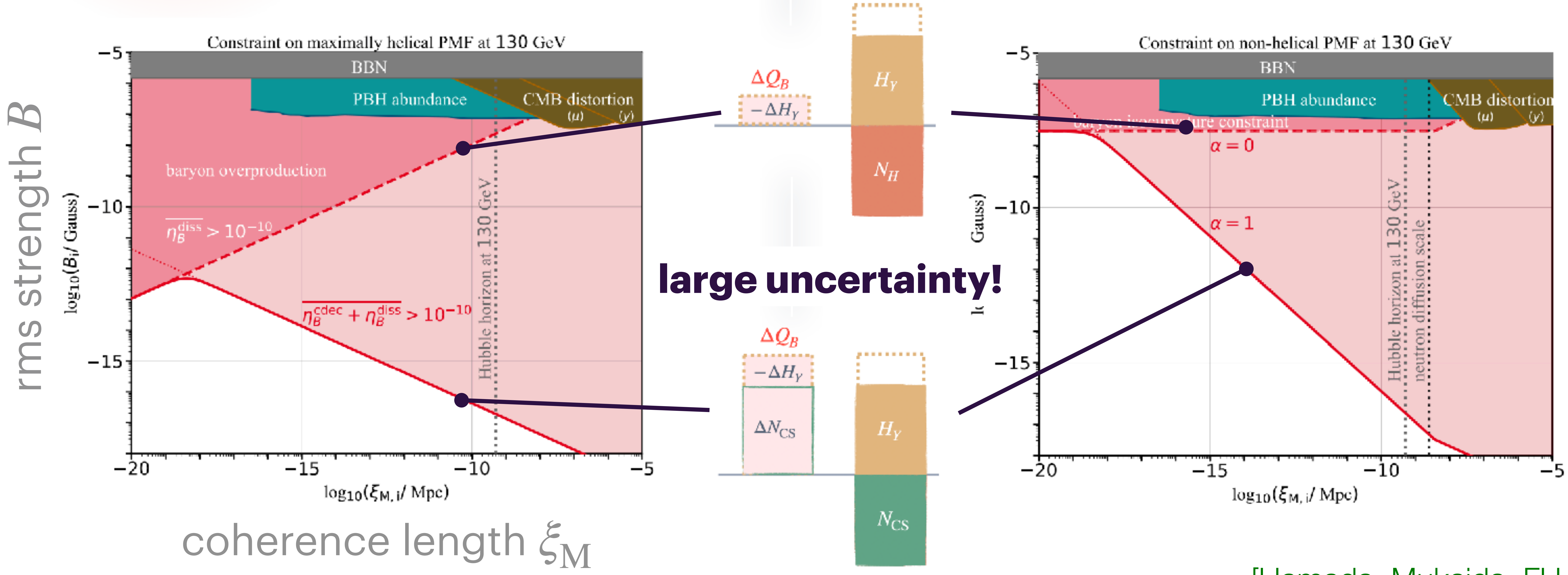
Baryon asymmetry constraints

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

$$\langle \delta\eta_B \rangle \sim \langle \vec{A} \cdot \vec{B} \rangle$$
$$\leq 10^{-10} \text{ (CMB, BBN)}$$

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

$$\langle \delta\eta_B^2 \rangle \sim \langle (\vec{A} \cdot \vec{B})^2 \rangle, \quad \langle \vec{A} \cdot \vec{B} \rangle = 0$$
$$\leq \mathcal{O}(0.01)\, \eta_{B,\mathrm{obs}}^2 \text{ (BBN)}$$ [Inomata+ 2018]

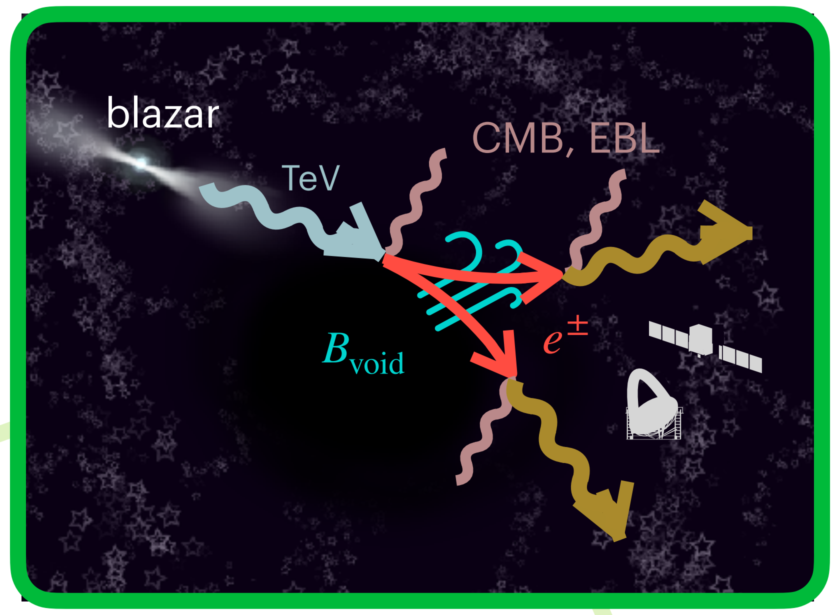


[Hamada, Mukaida, FU 2025b]

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

the constraints + **MHD evolution**

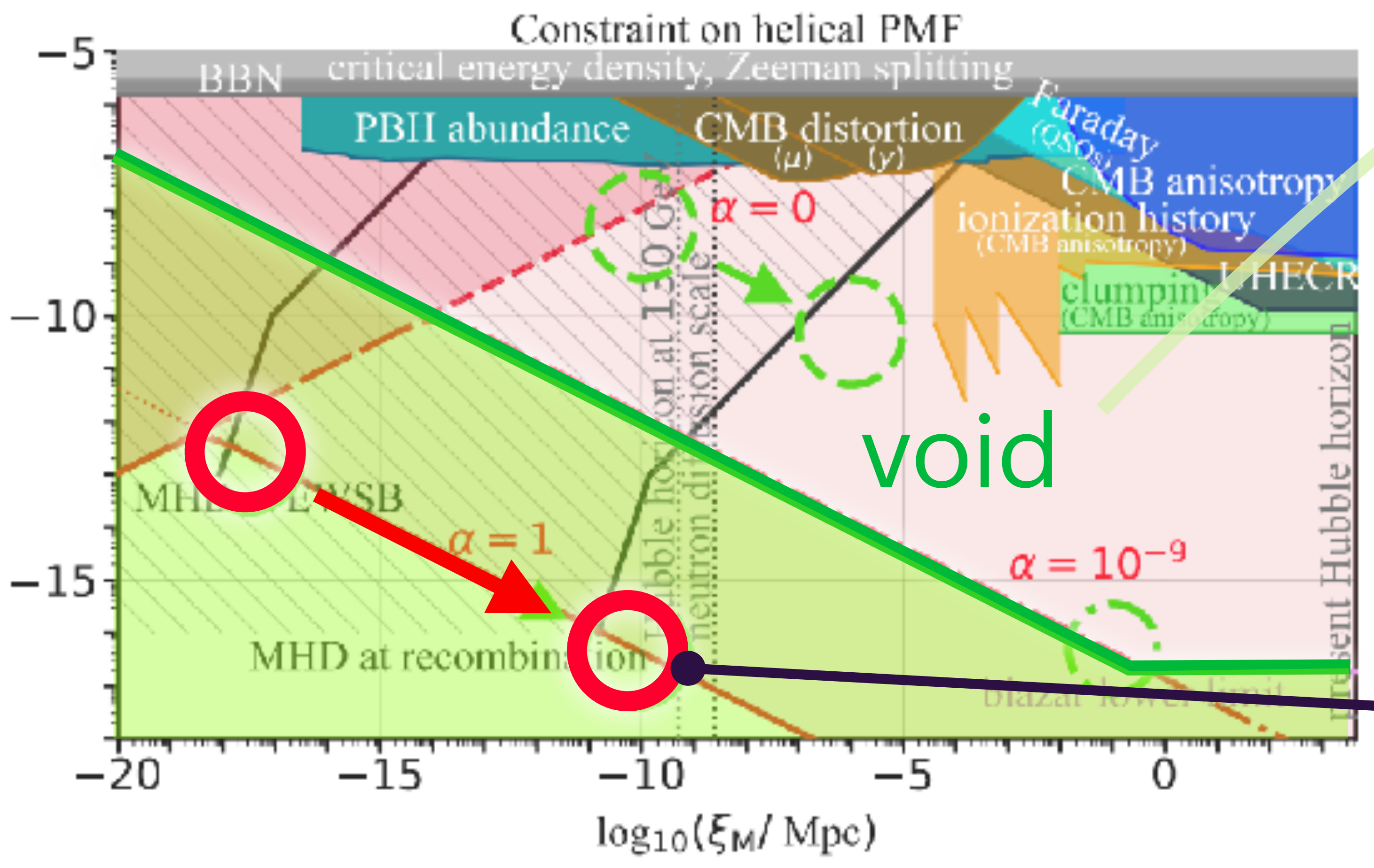
If we assume $\Delta N_H \simeq 0$, we need extra amplification:



baryon overproduction (helical)

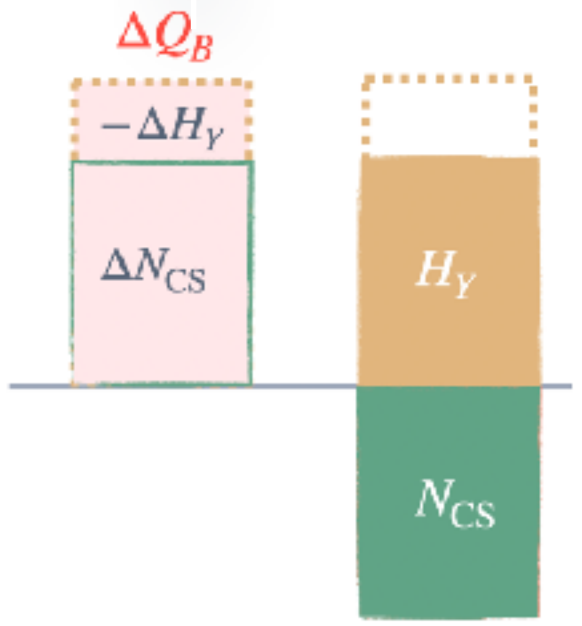
baryon fluctuation (non-helical)

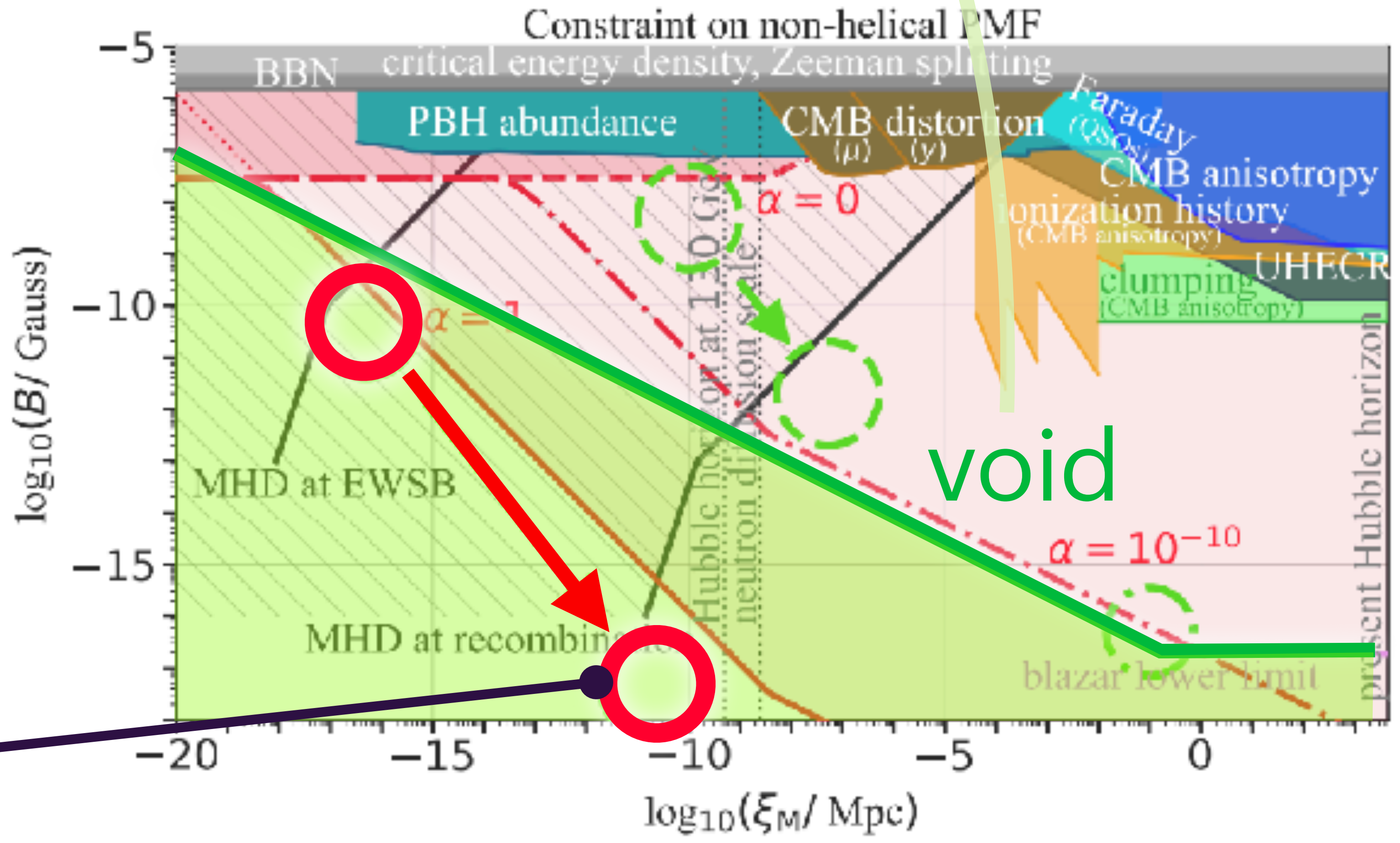
rms strength B



coherence length $\xi_{\rm M}$

Falls below the obs. lower bound!





[Hamada, Mukaida, FU 2025b]

Summary

- **continuous transition from $\overrightarrow{B}_Y$ to $\overrightarrow{B}_{\rm em}$** during the electroweak crossover
    - ✔ one-loop formula for effective mixing angle $\theta_{\rm eff}(T)$
- **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. $\Delta N_{\rm CS} \simeq 0$, $\overrightarrow{B}_Y$ **may be origins of both $\overrightarrow{B}_{\rm void}$ and $\eta_{B,\rm obs}$**.