The baryon isocurvature problem of primordial magnetic fields

Berkeley week, Mar. 15, 2024,

Fumio Uchida @RESCEU

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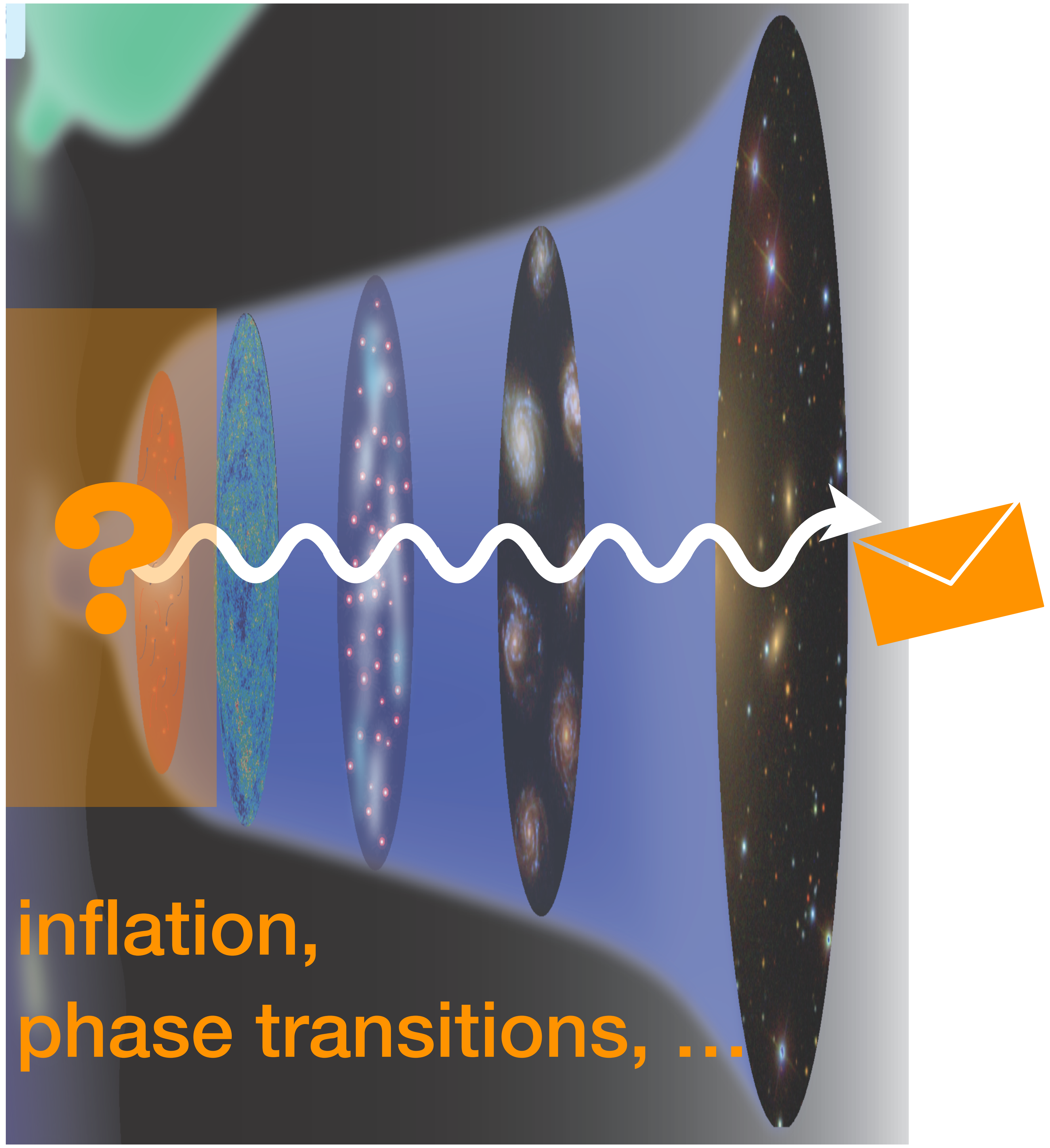
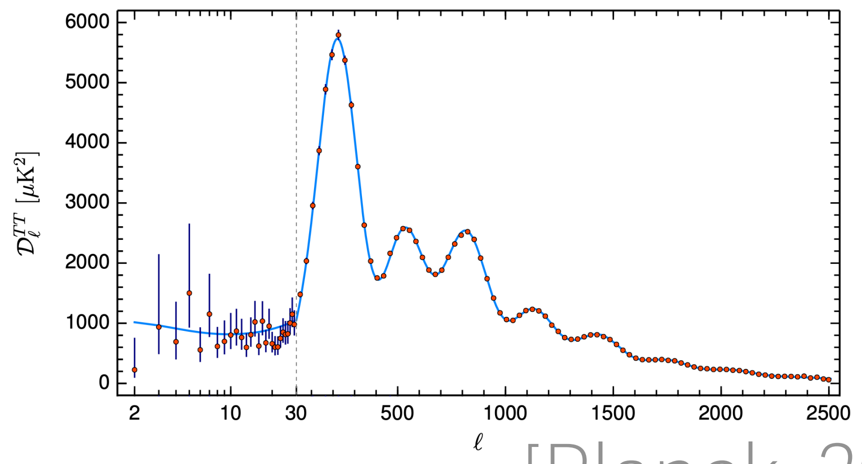


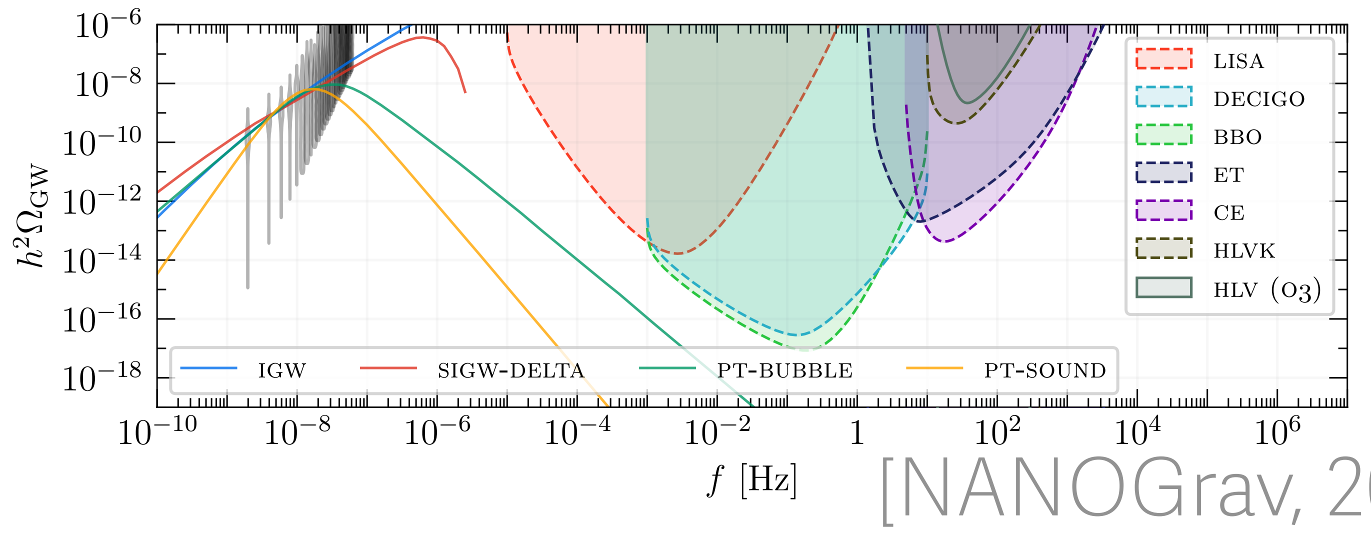
—time→

Messengers from the early universe

CMB, SGWB, …,

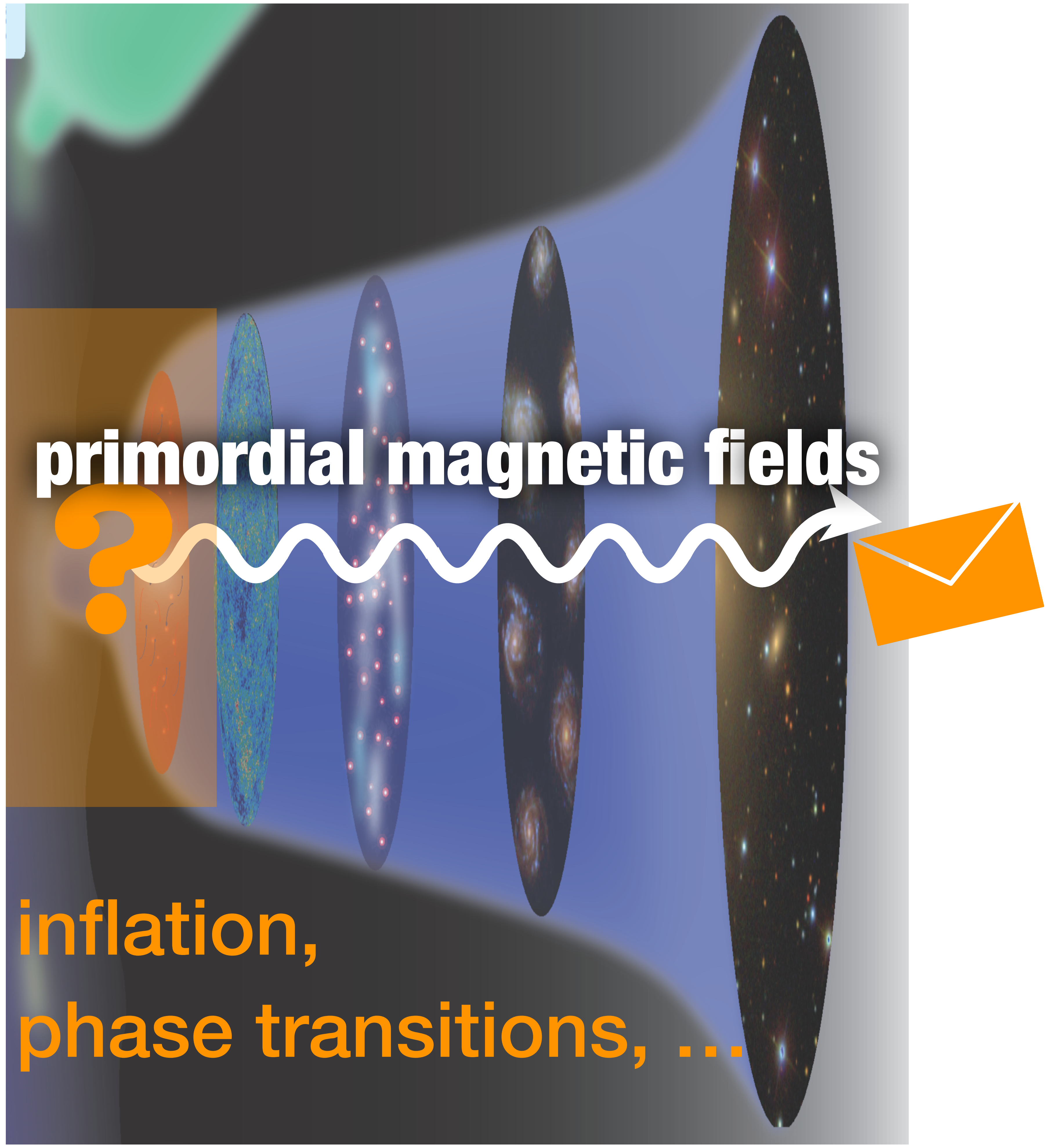


[Planck, 2020]



[NANOGrav, 2023]

PMFs as a messenger from the early universe



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Messengers from the early universe

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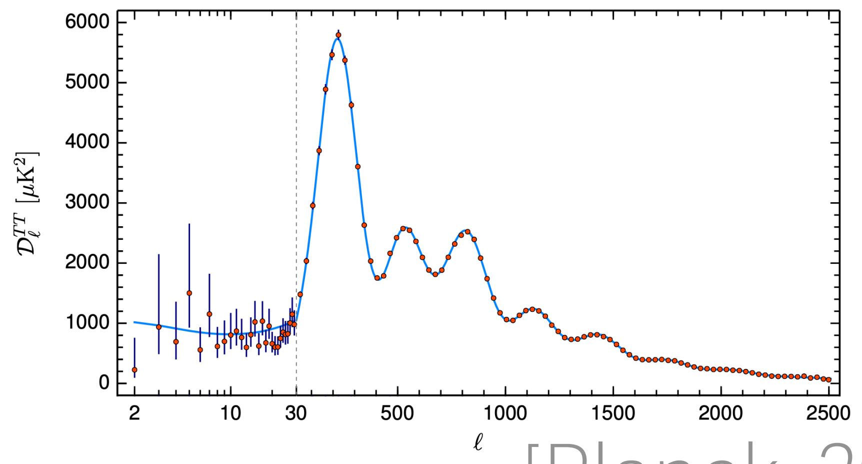

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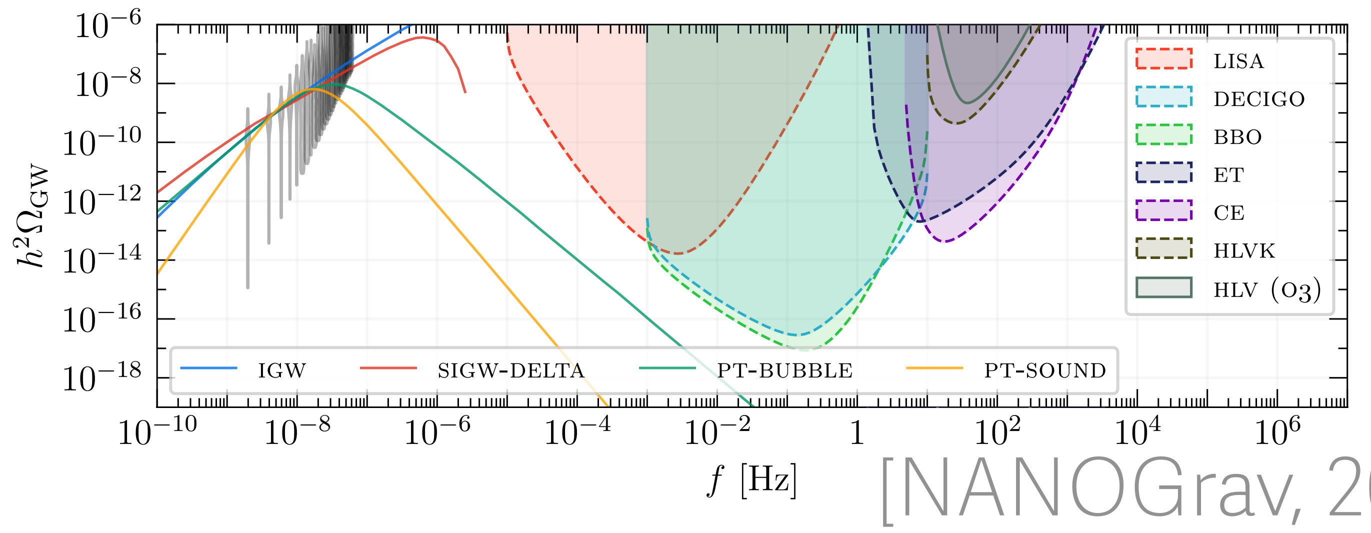


[NANOGrav, 2023]

and **primordial magnetic field**

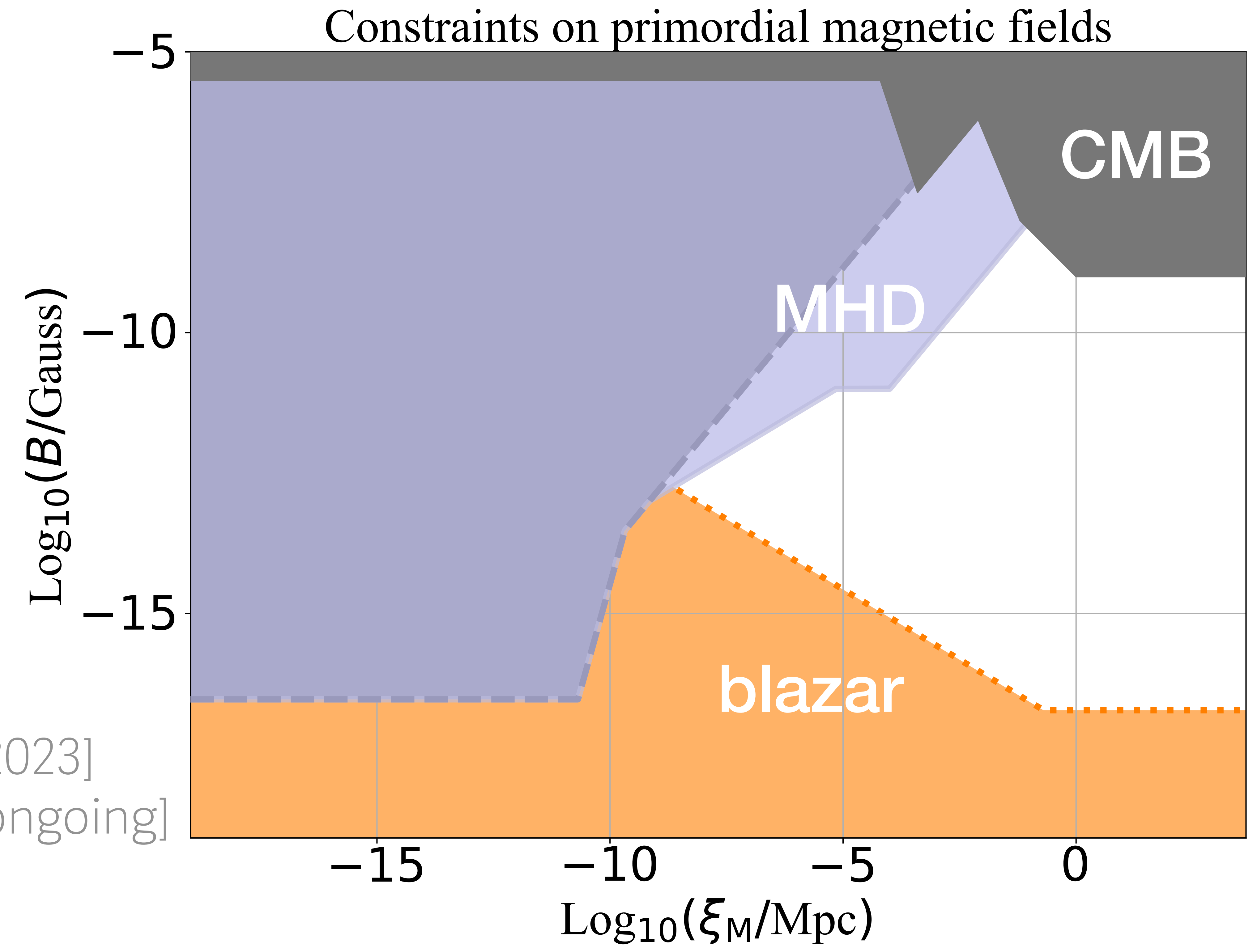
We will see that **primordial magnetic fields serve as a messenger from the early universe.**

PMFs in the present (after recombination) universe

upper bounds

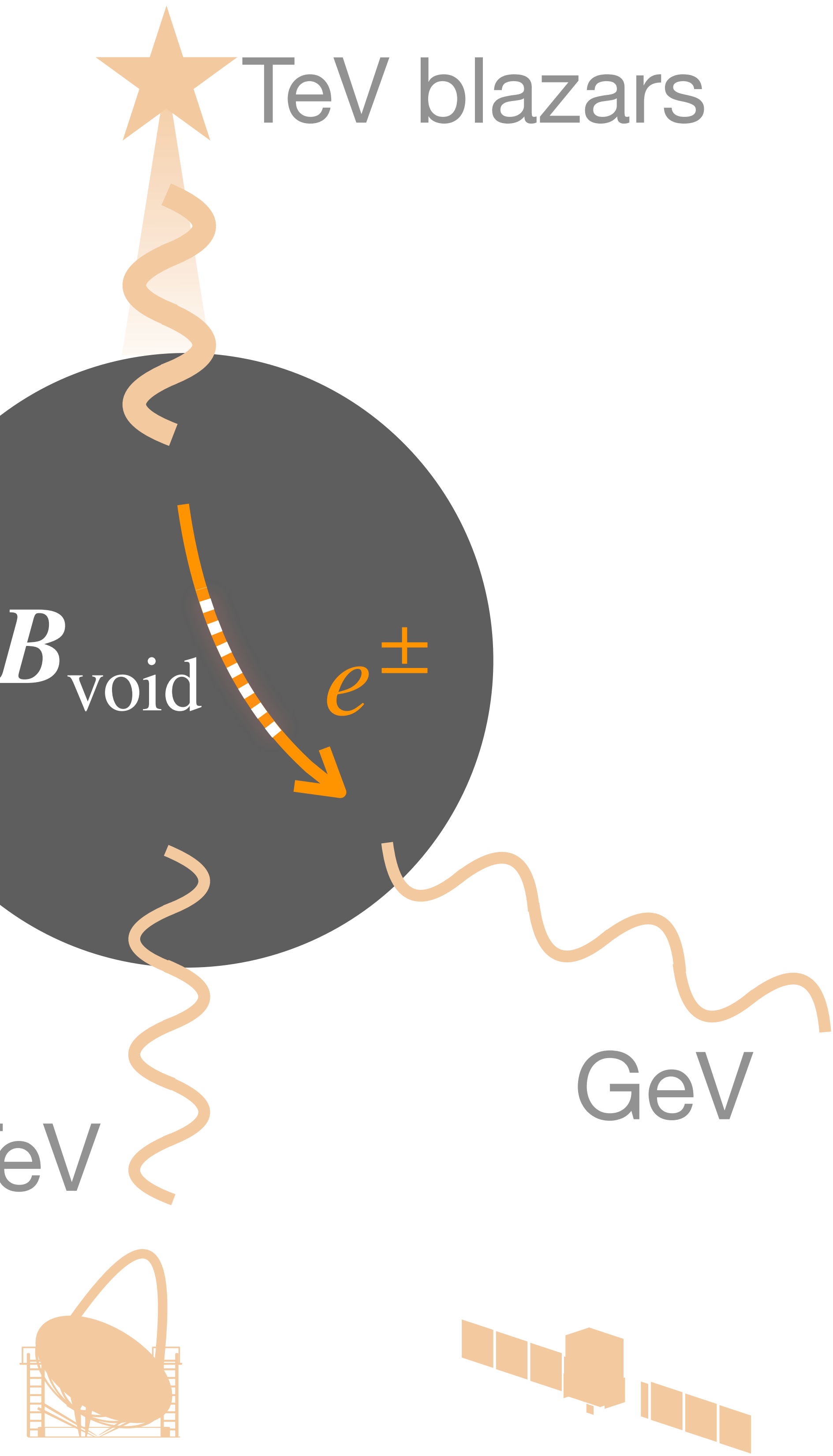
CMB distortion/
anisotropy
[Durrer, Neronov, 2013]

MHD decay
[Hosking, Schekochihin, 2023]
[FU, Fujiwara, Kamada, Yokoyama, 2023]
[FU, Fujiwara, Kamada, Yokoyama, ongoing]



blazar lower bound

[Neronov, Vovk, 2010] ... [MAGIC, 2023]



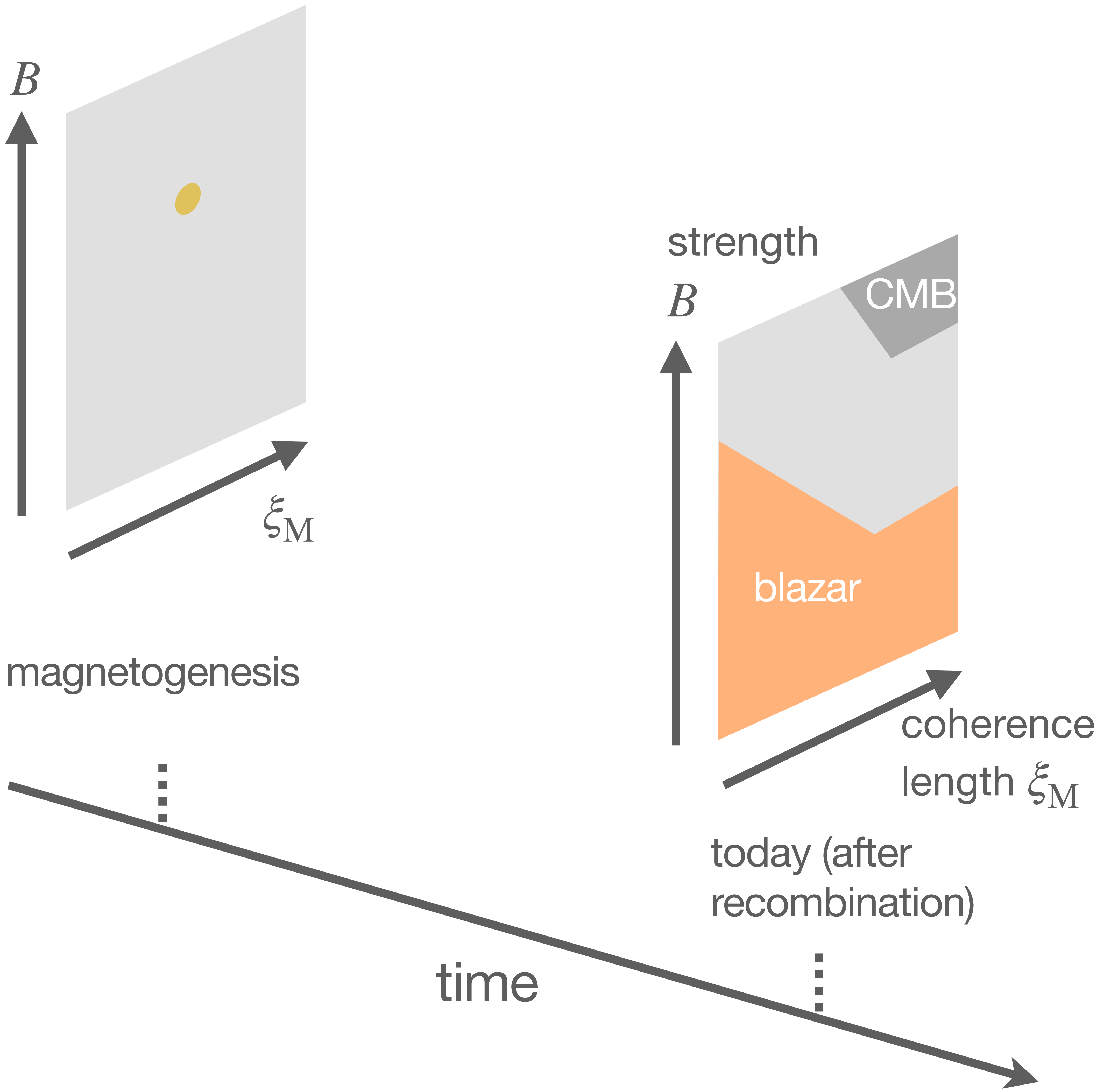
If one has a magnetogenesis model, ...

magnetogenesis (initial condition)

MHD evolution

void magnetic field? (in the present universe)

blazar lower bound



If one has a magnetogenesis model, ...

magnetogenesis (initial condition)

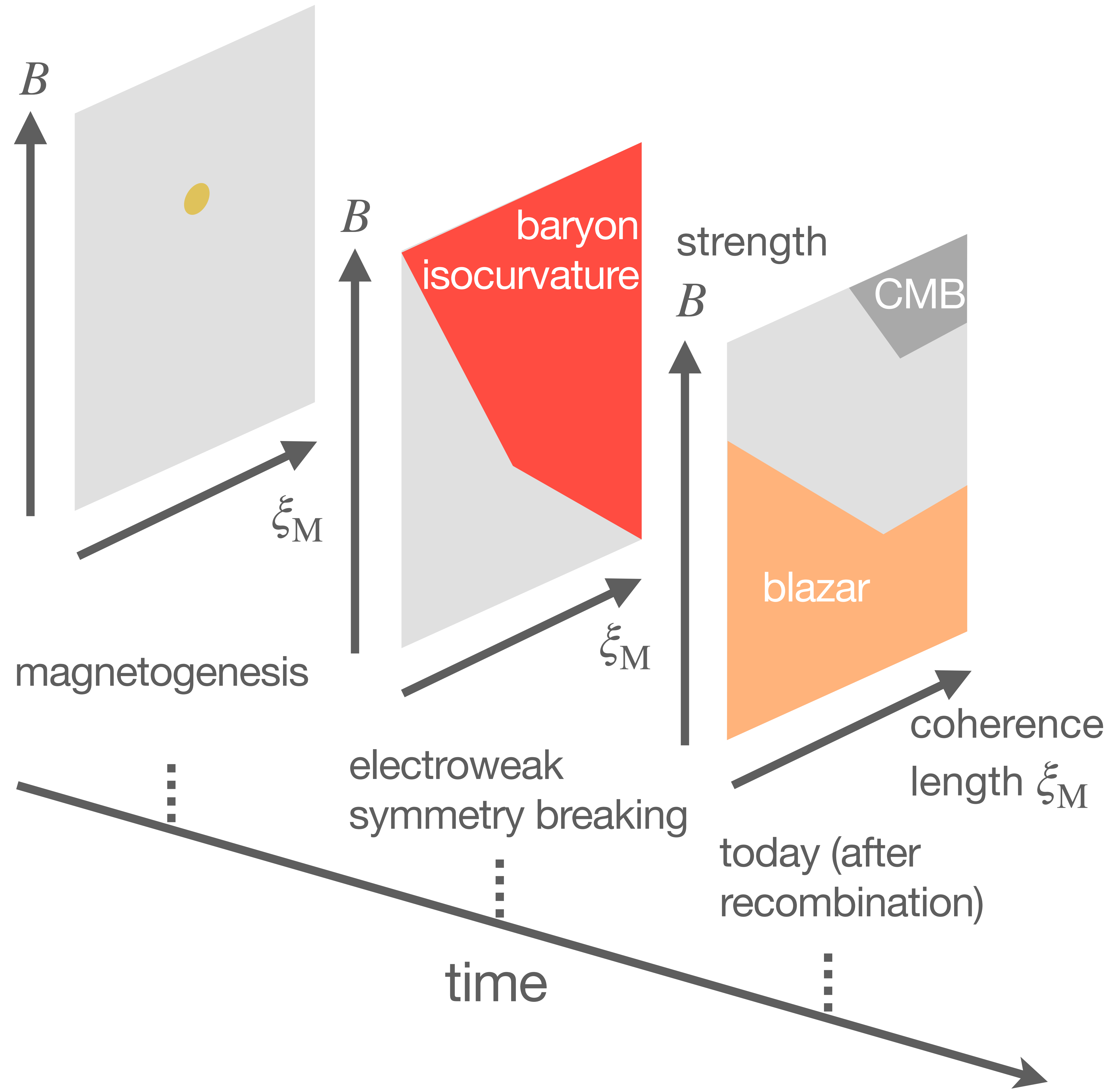
issues at the electroweak symmetry breaking

MHD evolution

↓

void magnetic field? (in the present universe)

blazar lower bound



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"magnetic field" before the electroweak symmetry breaking

$\mathrm{U}(1)_Y$ hyper-magnetic field (rather than $\mathrm{U}(1)_{\mathrm{EM}}$)

Issues on $\mathrm{U}(1)_Y$ **to** $\mathrm{U}(1)_{\mathrm{EM}}$ **conversion** at the electroweak symmetry breaking

- **baryon overproduction problem** [Fujita, Kamada, 2016] [Kamada, Long, 2016]
- **baryon isocurvature problem** [Kamada, FU, Yokoyama, 2021]

→ strong constraint on primordial hyper-magnetic fields

Baryon (over)production from PMF helicity

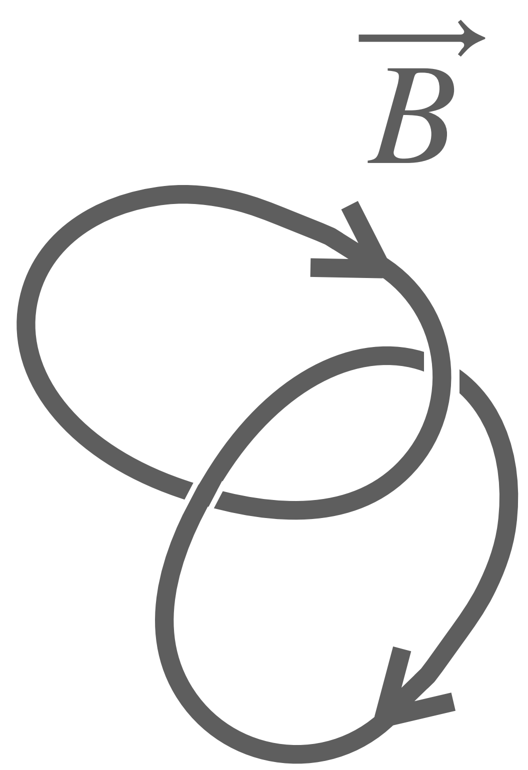
[Kamada, Long, 2016]

chiral anomaly

$$\Delta Q_B \sim \Delta N_{\rm CS} - \Delta H_Y$$

non-zero contribution from

- electroweak sphaleron
- $\mathrm{U}(1)_Y$ to $\mathrm{U}(1)_{\rm EM}$ conversion of PMF



$$\frac{1}{V}\int d^3x \vec{A}\cdot\vec{B} \neq 0$$

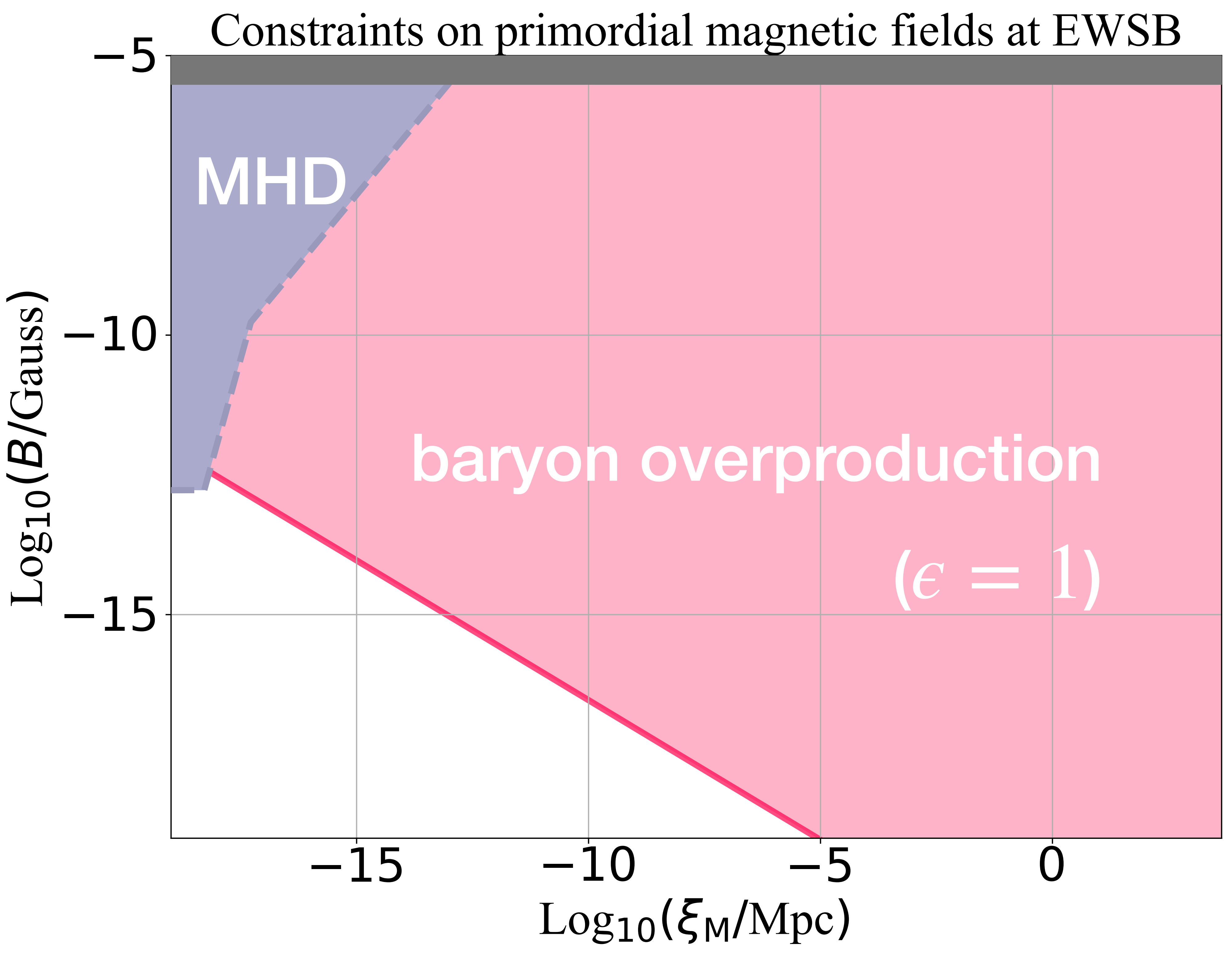
magnetic helicity

$$\frac{\langle n_B \rangle}{s} \sim 10^{-10}\epsilon \left(\frac{B}{10^{-17}\ \mathrm{G}}\right)^2 \left(\frac{\xi_{\rm M}}{10^{-9}\ \mathrm{Mpc}}\right),$$

$$\epsilon B^2 \xi_{\rm M} = \langle \boldsymbol{A}\cdot\boldsymbol{B} \rangle$$

ϵ : helicity fraction

Constraint to avoid baryon overproduction



realizability condition: $|\epsilon| \leq 1$

maximally helical ($\epsilon = 1$)

→ **too much baryons are produced** if

$$\left(\frac{B}{10^{-17}\ \mathrm{G}}\right)^2 \left(\frac{\xi_{\mathrm{M}}}{10^{-9}\ \mathrm{Mpc}}\right) \gtrsim 1$$

non-helical ($\epsilon = 0$)

→ no baryon overproduction

Baryon fluctuation from PMF helicity fluctuation

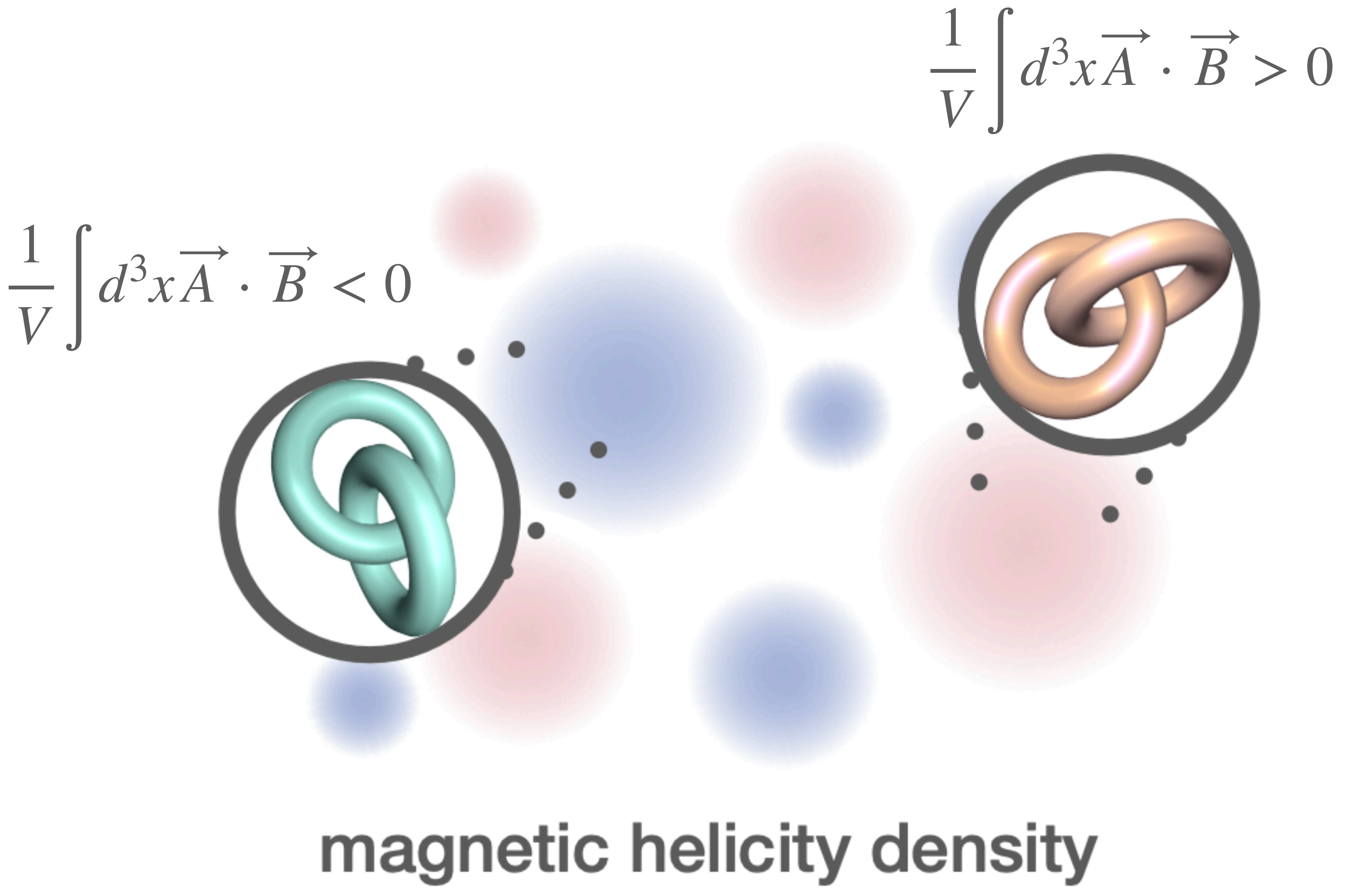
At the electroweak symmetry breaking..

$$\frac{n_B}{s} \propto \boldsymbol{A} \cdot \boldsymbol{B}$$

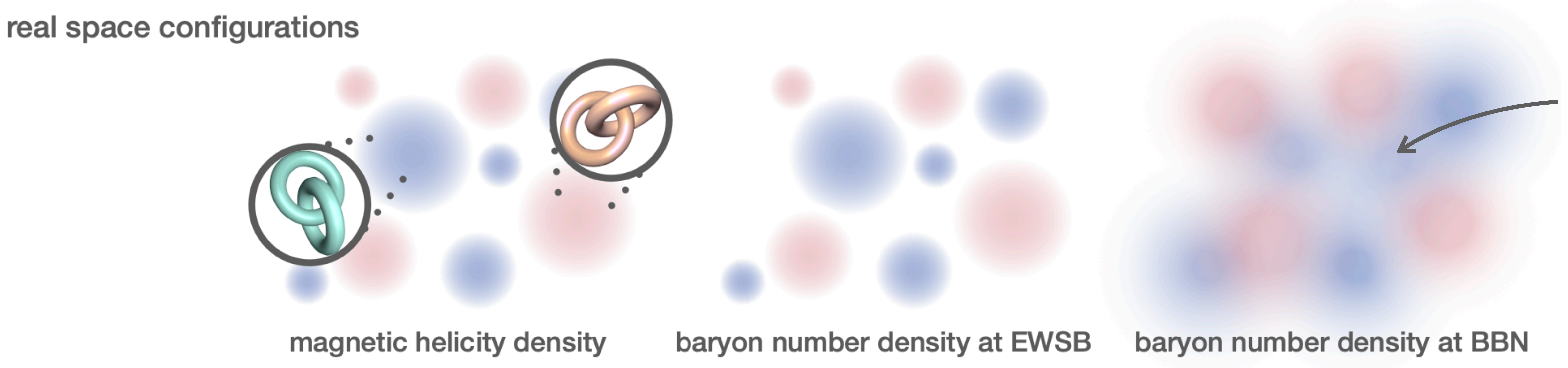
helicity fluctuations → baryon fluctuations

$$\frac{\langle \delta n_B^2 \rangle}{s} \propto \langle (\boldsymbol{A} \cdot \boldsymbol{B})^2 \rangle$$

$$\sim B^4 \xi_{\mathrm{M}}^2 \text{ even if } \epsilon = 0$$



Large-scale fluctuation affects BBN



$$\frac{\langle \delta n_B^2 \rangle}{\overline{n_B}^2} < 0.016$$

[Inomata+, 2018]

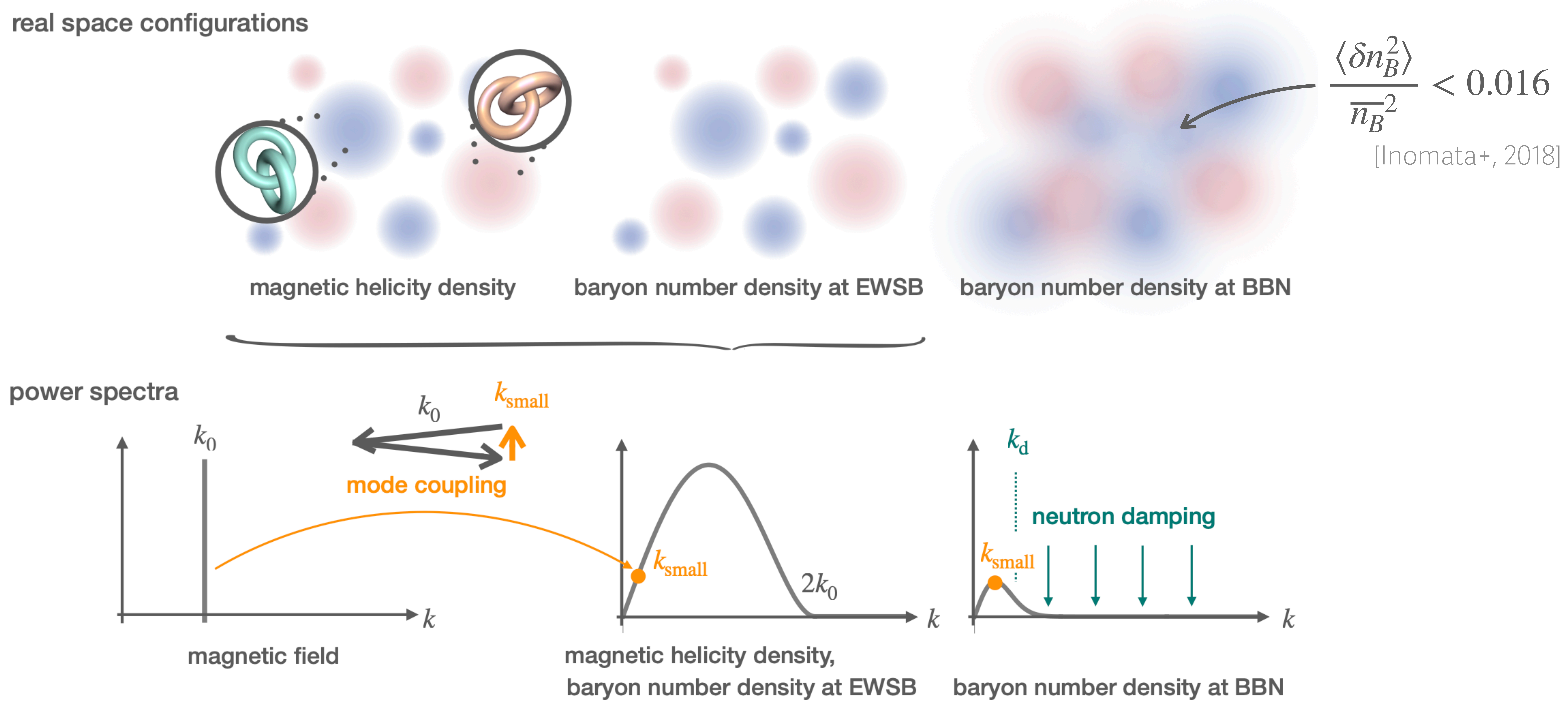
Small-scale ($\lesssim 10^{-9}$ Mpc) fluctuations

damped by neutron free-streaming, no effect on the BBN

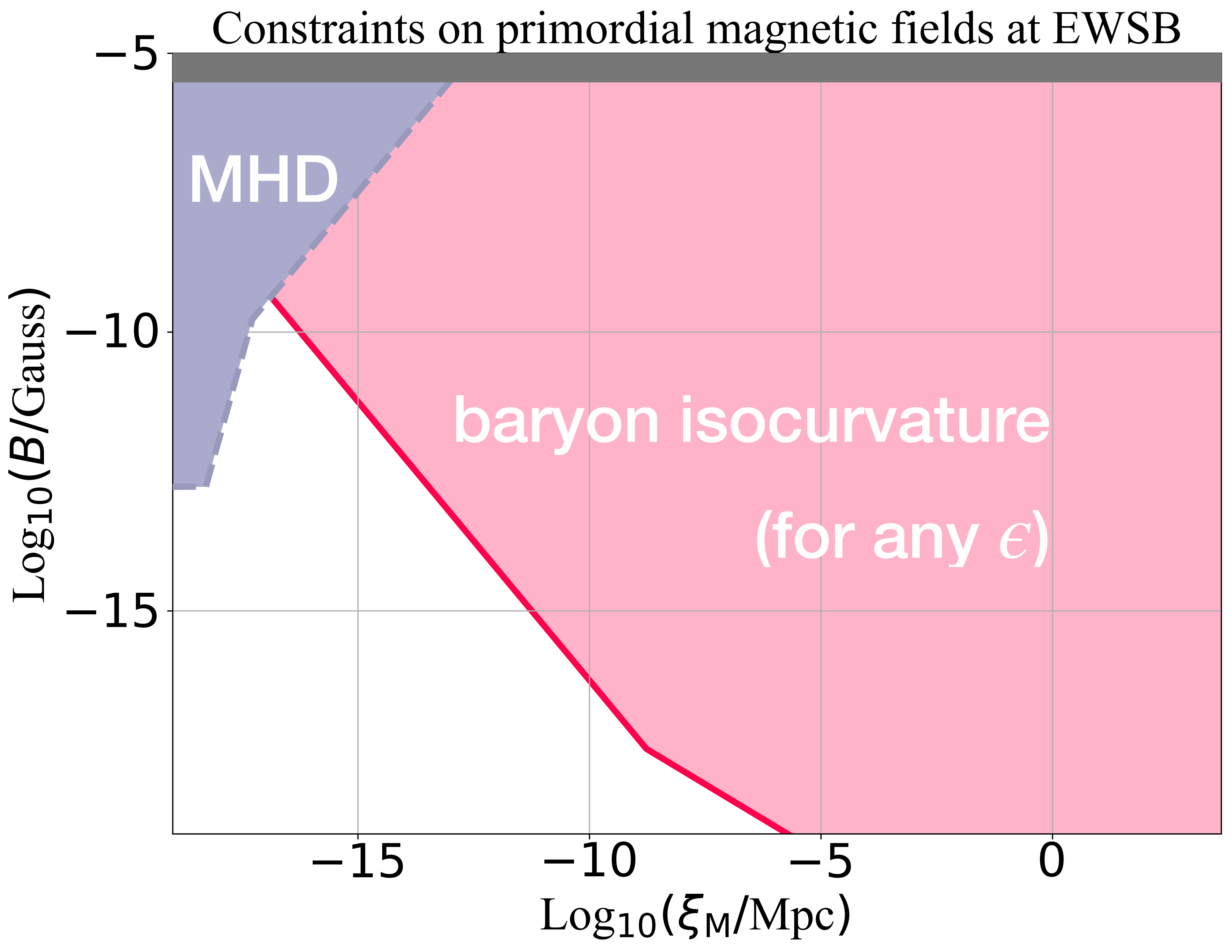
Large-scale fluctuations

survive and enhance primordial deuterium abundance $\propto \langle \delta n_B^2 \rangle \propto B^4 \xi_{\mathrm{M}}^2$

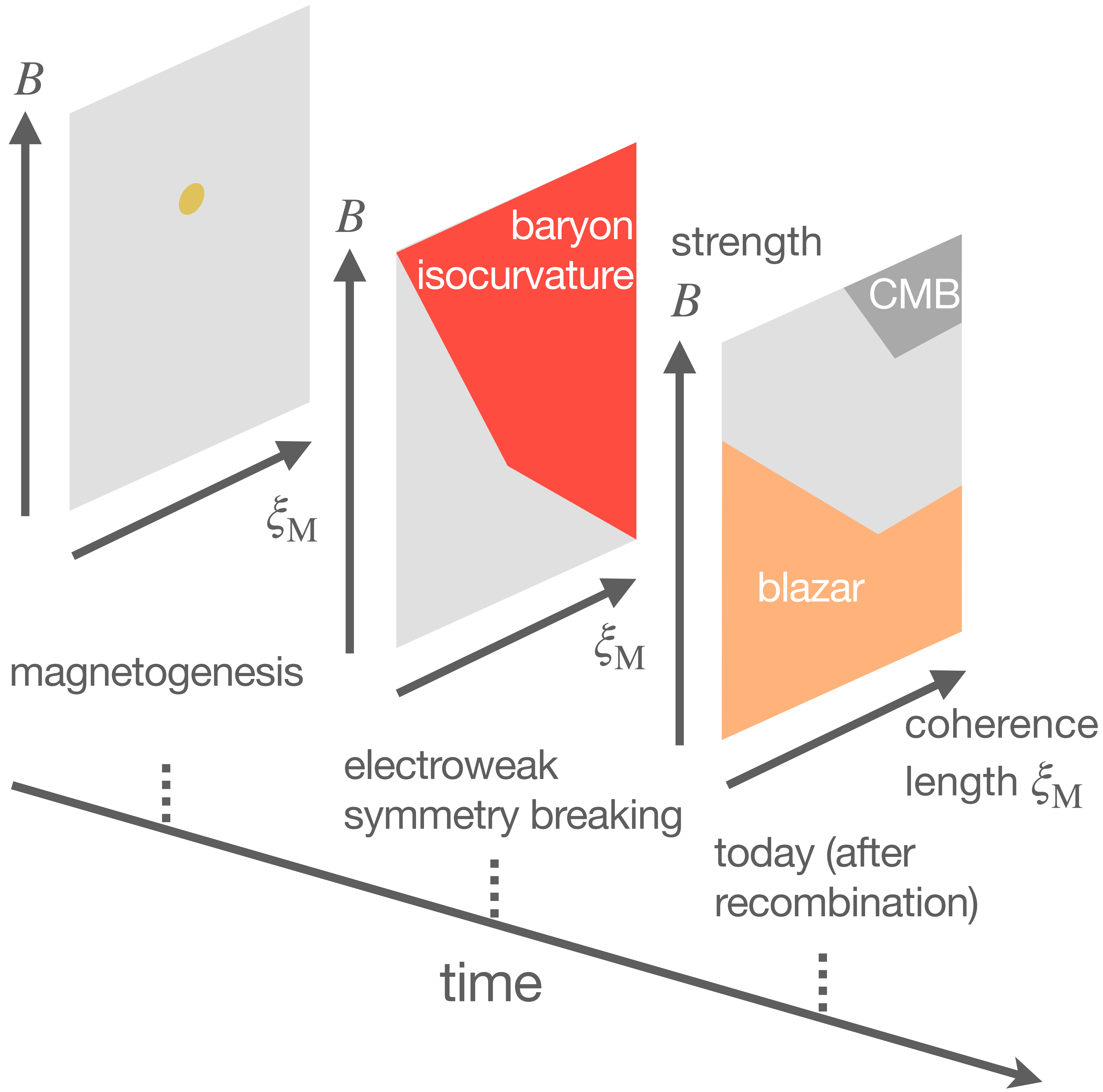
Small-scale PMF → large-scale fluctuation



Constraint to avoid baryon isocurvature problem



[Kamada, FU, Yokoyama, 2021]



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MHD governs PMFs evolution

In terms of comoving quantities,
electromagnetism + interaction with plasma fluid = hard to solve

- Induction equation

electric conductivity

$$\frac{\partial \boldsymbol{B}}{\partial \tau} - \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) = \sigma^{-1} \nabla^2 \boldsymbol{B}$$

- Navier—Stokes equation

viscosity

friction (drag force)

$$\frac{\partial \boldsymbol{v}}{\partial \tau} + (\boldsymbol{v} \cdot \nabla)\boldsymbol{v} - \frac{(\nabla \times \boldsymbol{B}) \times \boldsymbol{B}}{\rho + p} + \frac{\nabla \delta p}{\rho + p} = \eta \left(\nabla^2 \boldsymbol{v} + \frac{1}{3} \nabla (\nabla \cdot \boldsymbol{v}) \right) - \alpha \boldsymbol{v}$$

- continuity equation

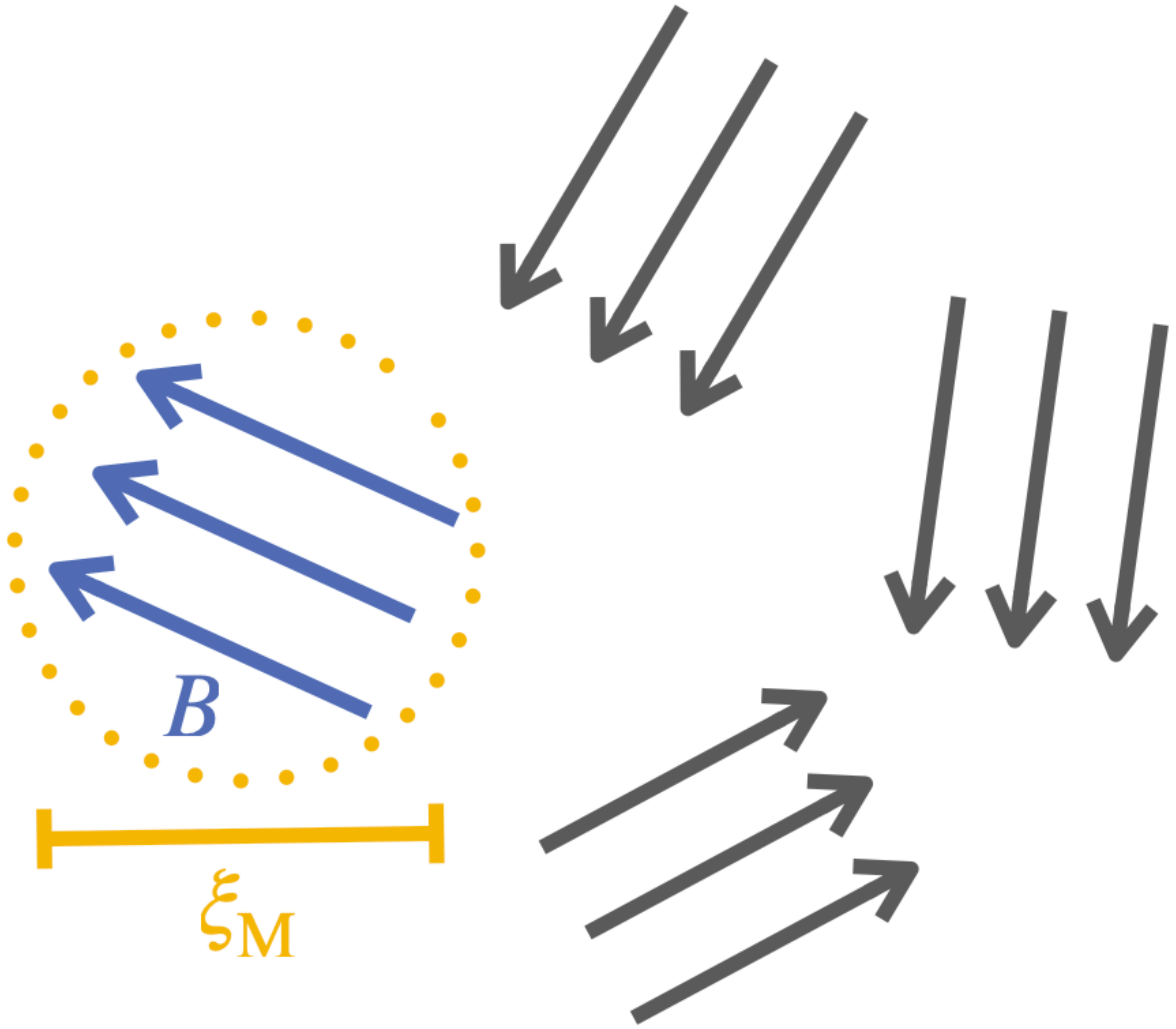
$$\frac{\partial \delta\rho}{\partial \tau} + \nabla \cdot \left[(\rho + p)\boldsymbol{v}\right] = \boldsymbol{E} \cdot (\nabla \times \boldsymbol{B})$$

[Brandenburg, Enqvist, Olesen, 1996]

Homogeneous and isotropic PMF

Only a few parameters

$B(\tau)$, $\xi_{\mathrm{M}}(\tau)$ (, $v(\tau)$, and $\xi_{\mathrm{K}}(\tau)$)



trials of analytic understanding

[Banerjee, Jedamzik, 2004] ← inconsistent with numerical studies

[Hosking, Schekochihin, 2021] ← resolved the inconsistency

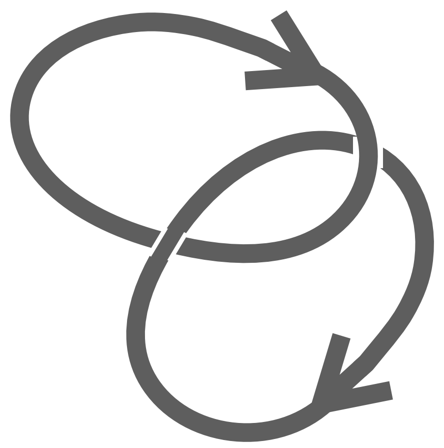
[Hosking, Schekochihin, 2023]
[FU, Fujiwara, Kamada, Yokoyama, 2023]
[FU, Fujiwara, Kamada, Yokoyama, ongoing]

Analytic understanding of MHD decay

conservation law + decay time scale

magnetic helicity [Woltjar, 1958]

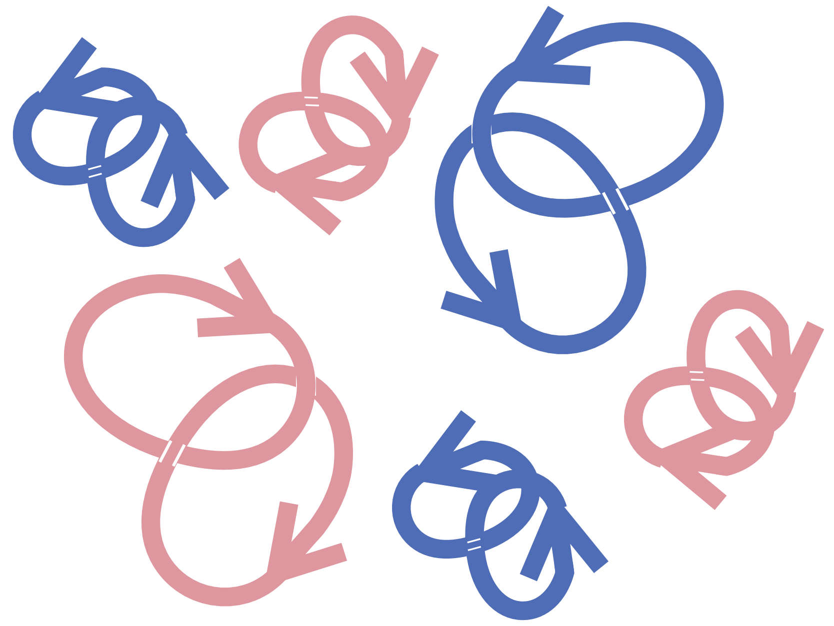
$$\epsilon B^2 \xi_{\rm M} = \text{const}\,.$$



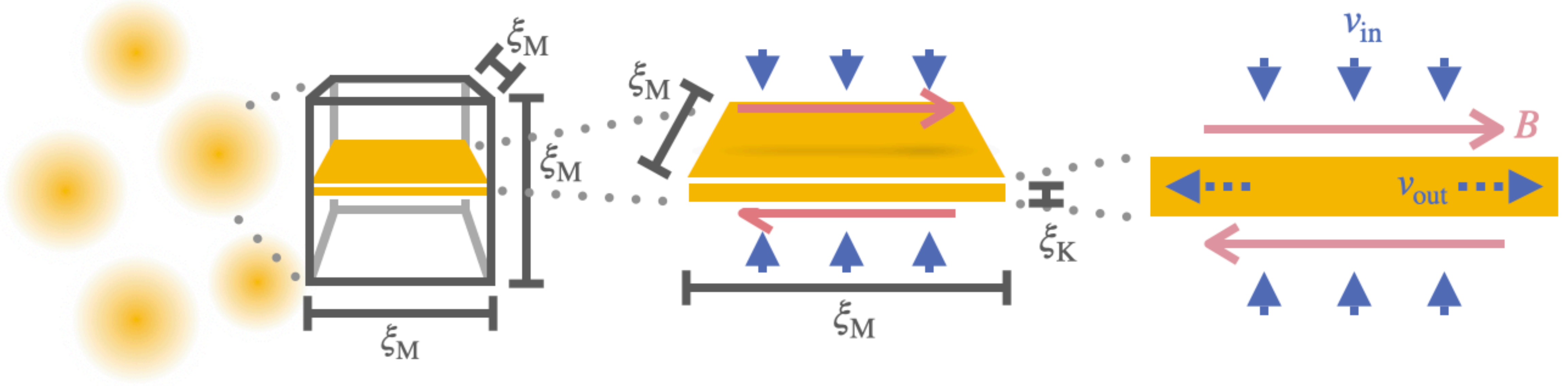
Hosking integral [Hosking, Schekochihin, 2021]

$$B^4 \xi_{\rm M}^5 = \text{const}\,.$$

for non-helical field



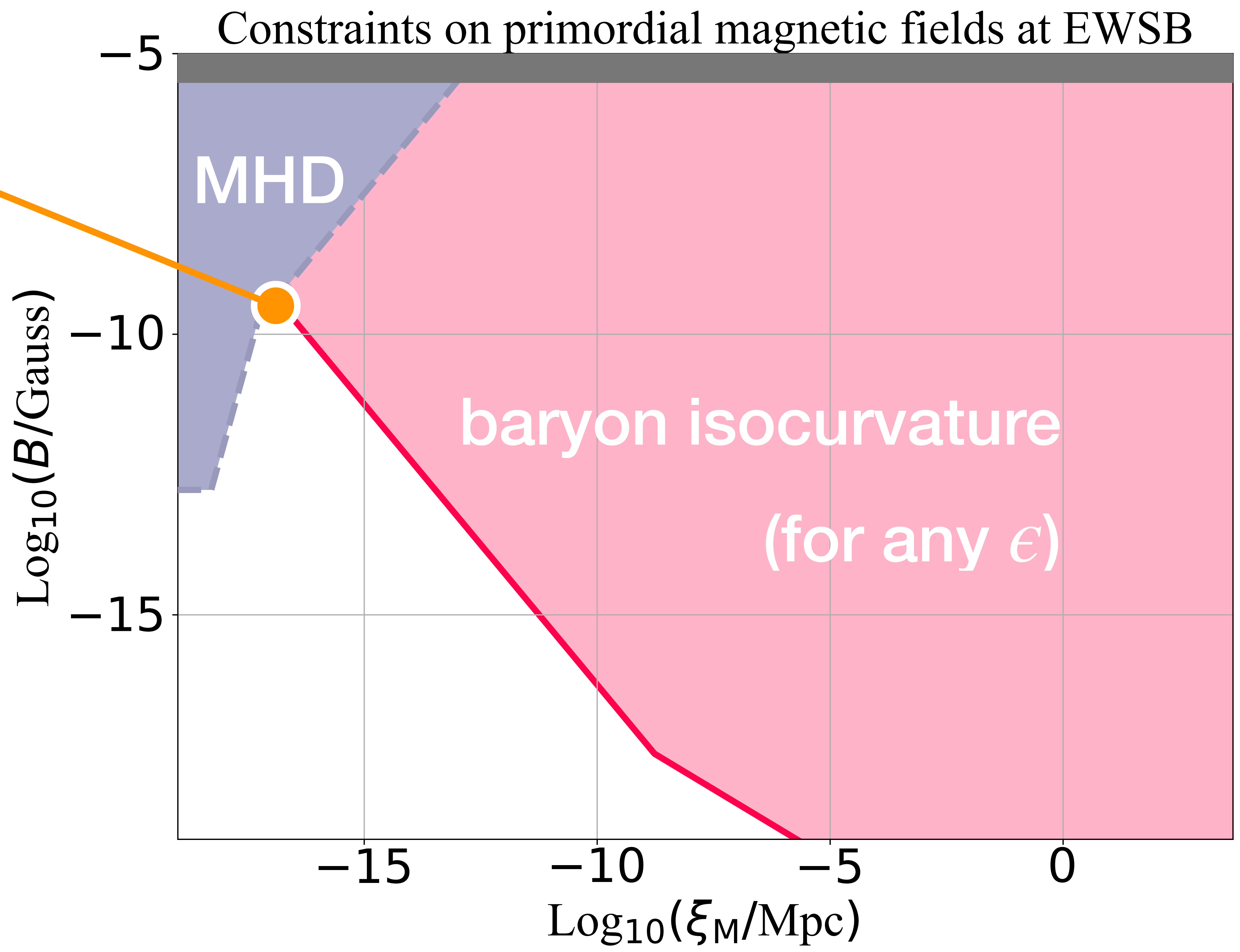
reconnection time scales



⋮

Non-helical PMF

strongest non-helical
PMF at the EWSB



Non-helical PMF

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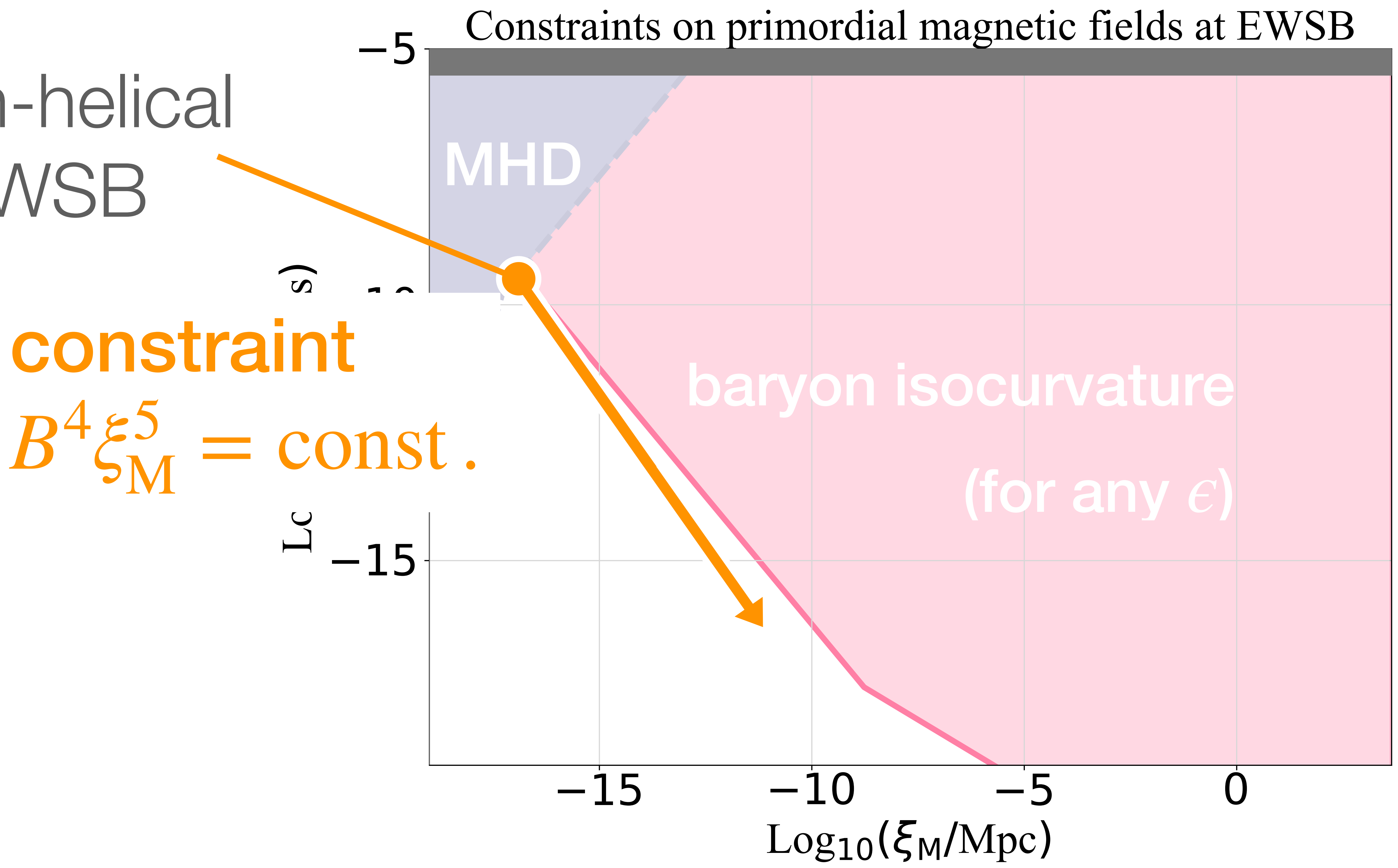
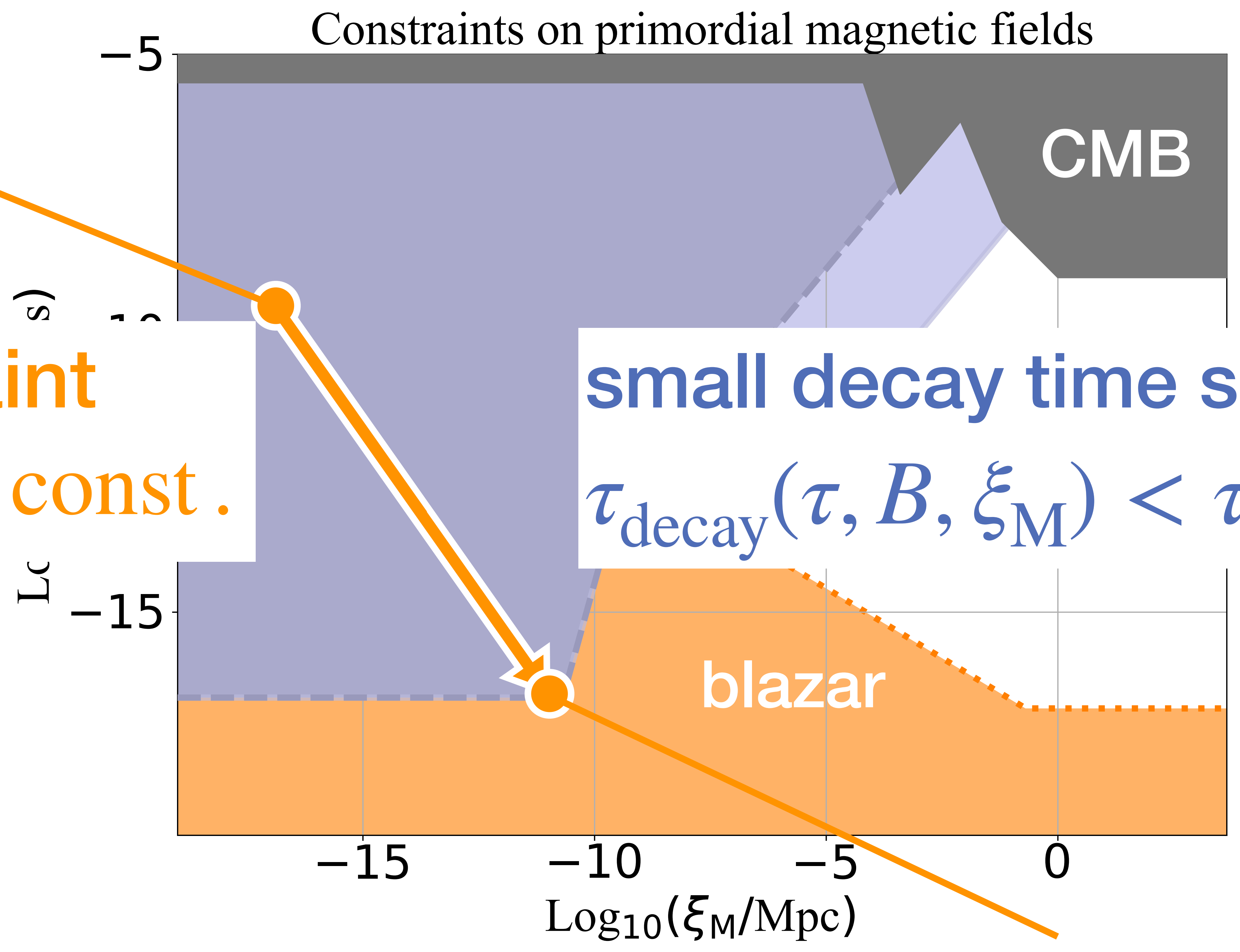


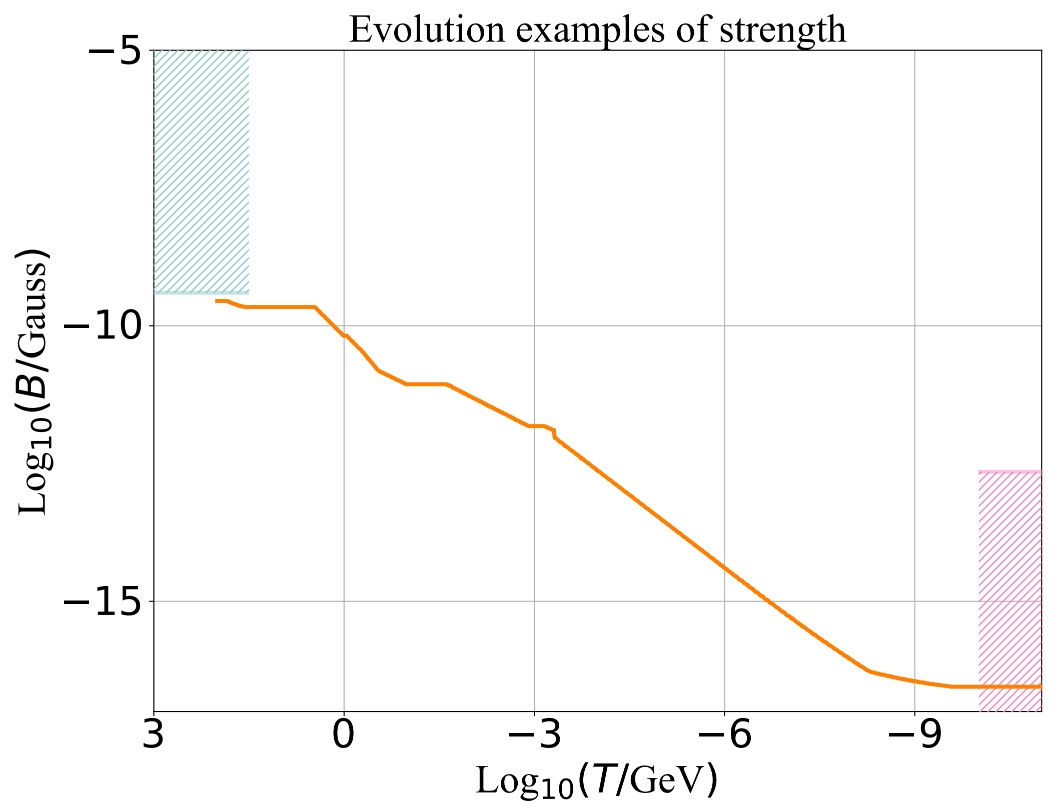
Non-helical PMF

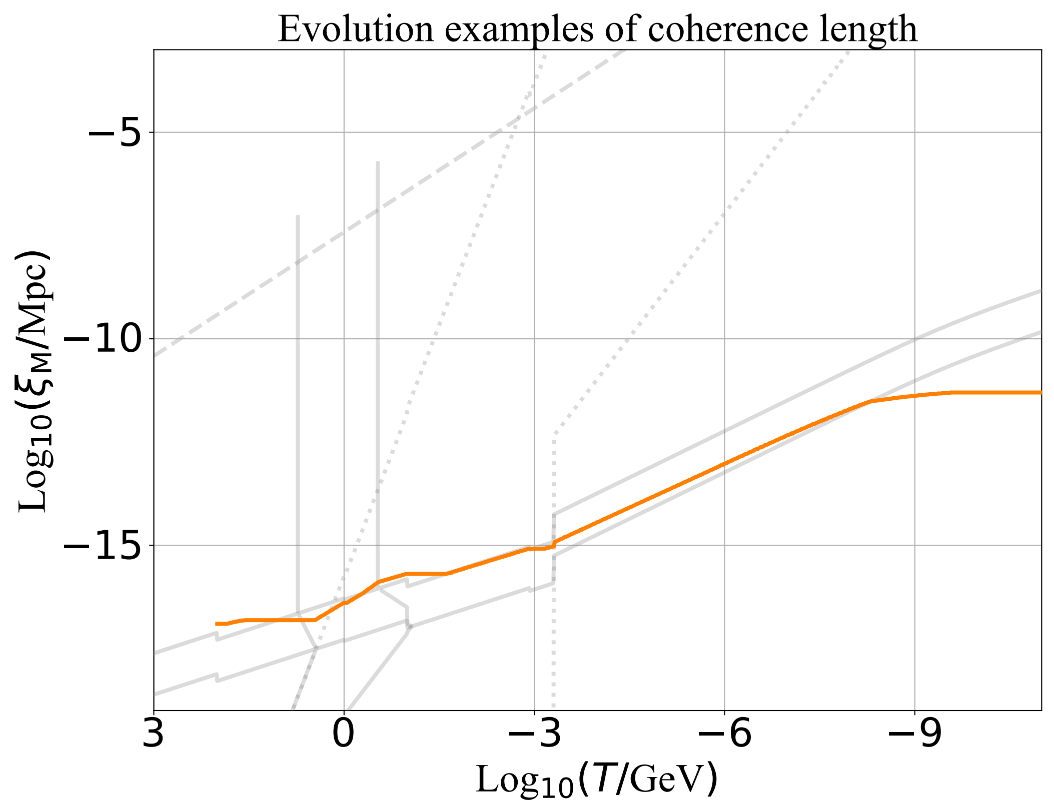
strongest non-helical
PMF at the EWSB

constraint
$B^4 \xi_M^5 = \text{const.}$



small decay time scale
$\tau_{\text{decay}}(\tau, B, \xi_M) < \tau_{\text{rec}}$



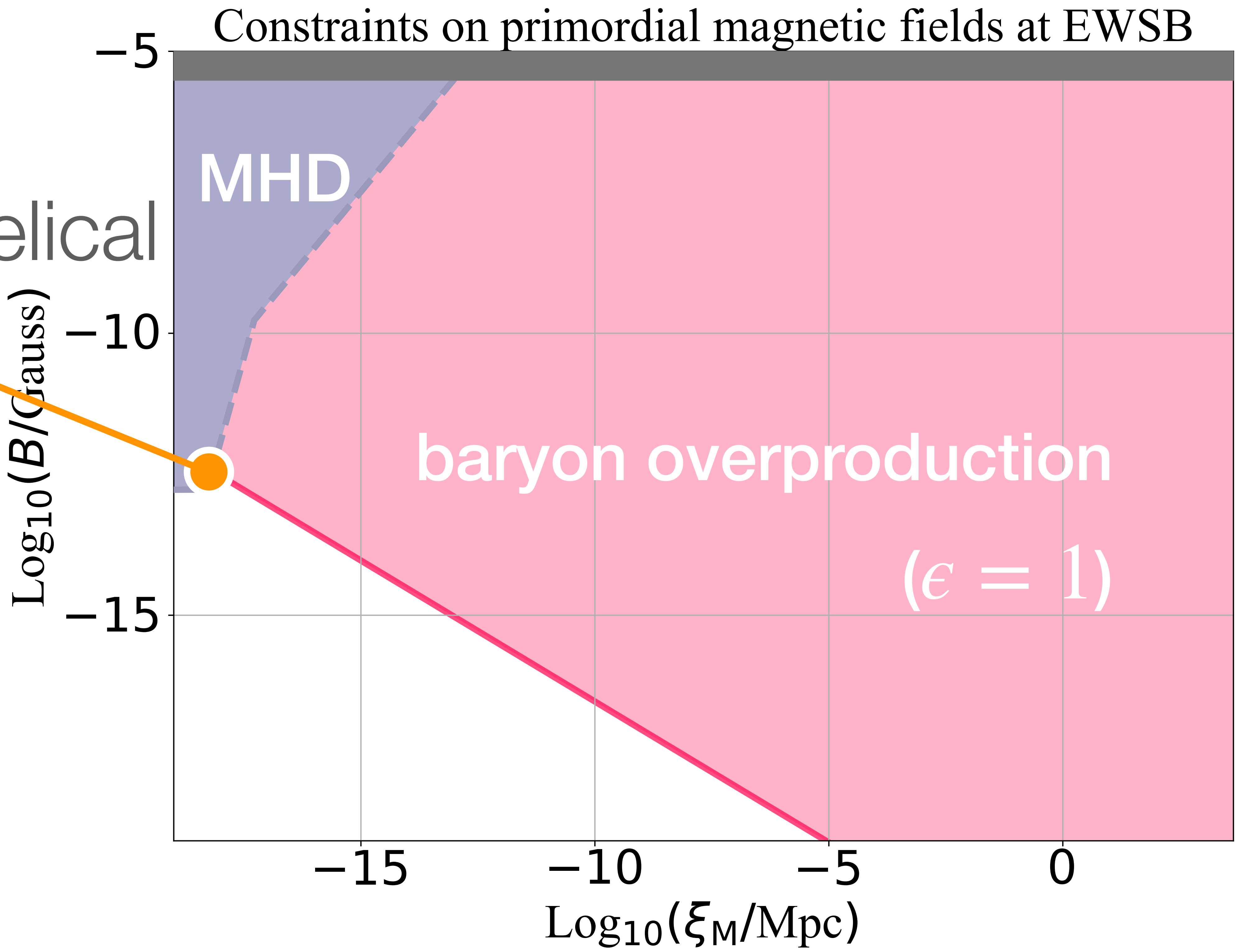


[FU, Fujiwara, Kamada, Yokoyama, ongoing]

Resultant magnetic field
below the blazar lower bound

Maximally helical PMF

strongest maximally helical PMF at the EWSB



Maximally helical PMF

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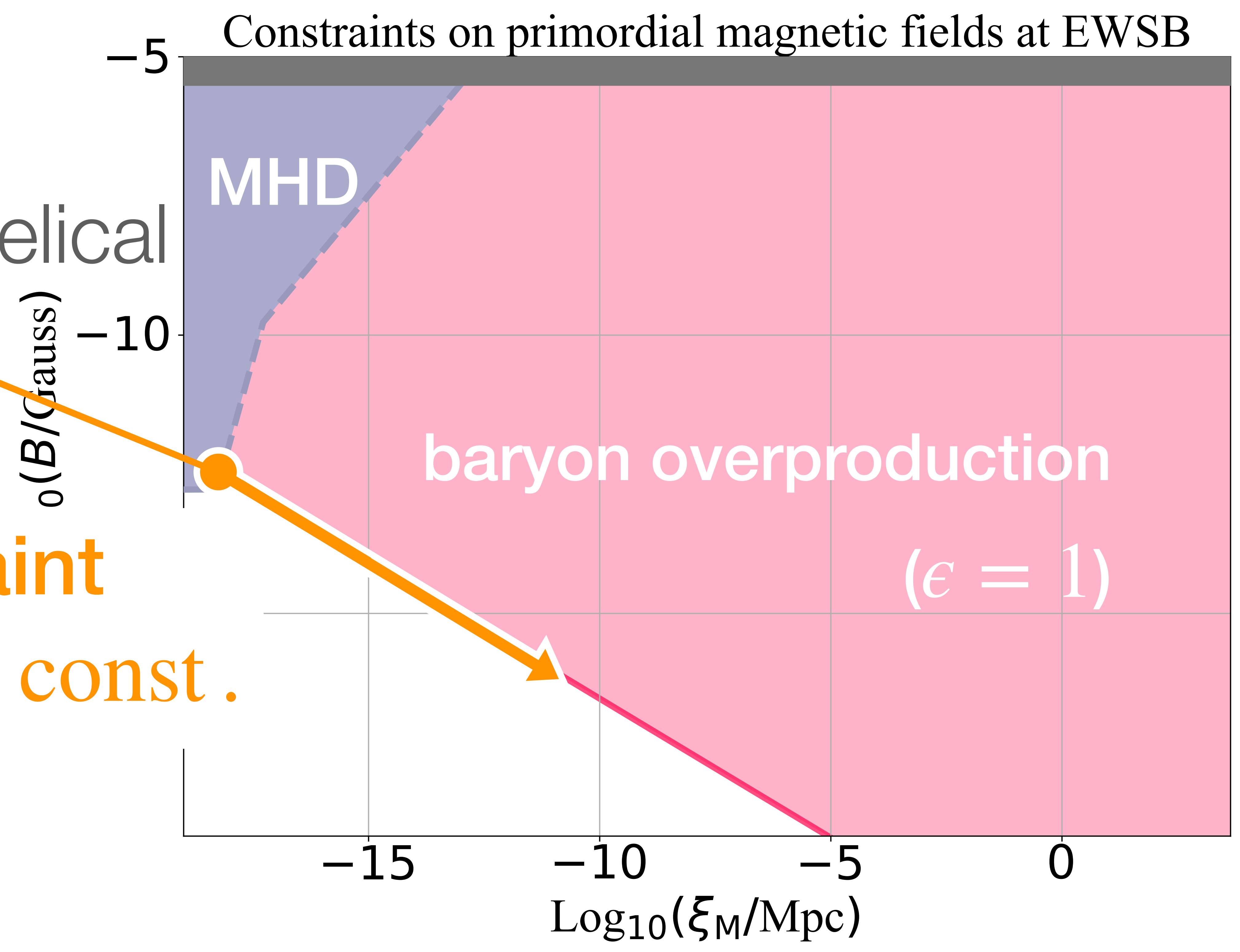
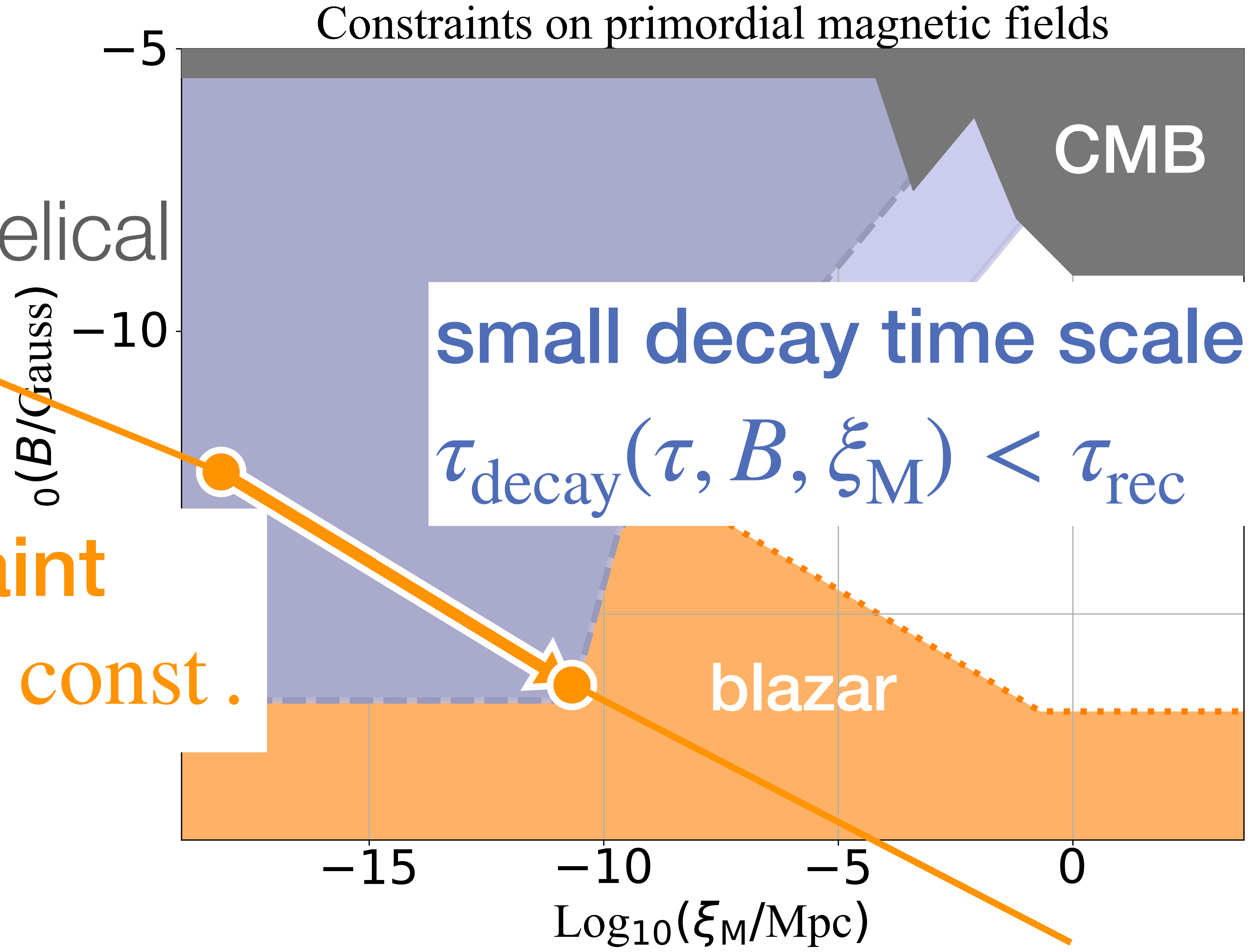


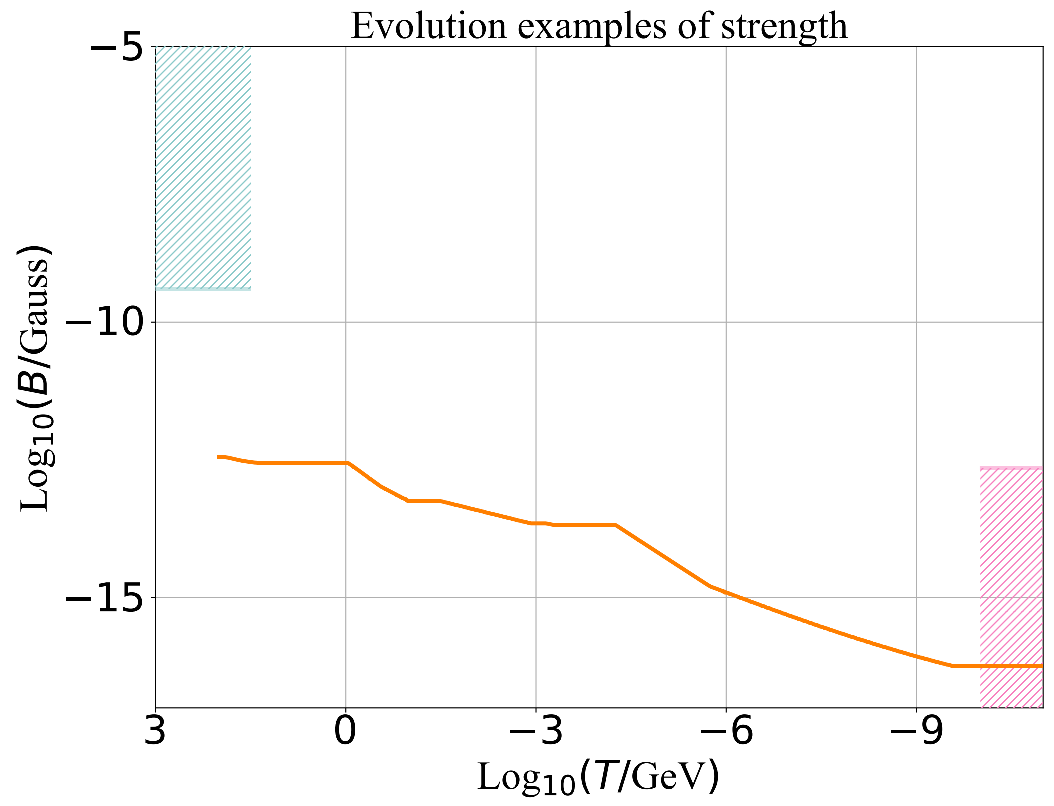
constraint

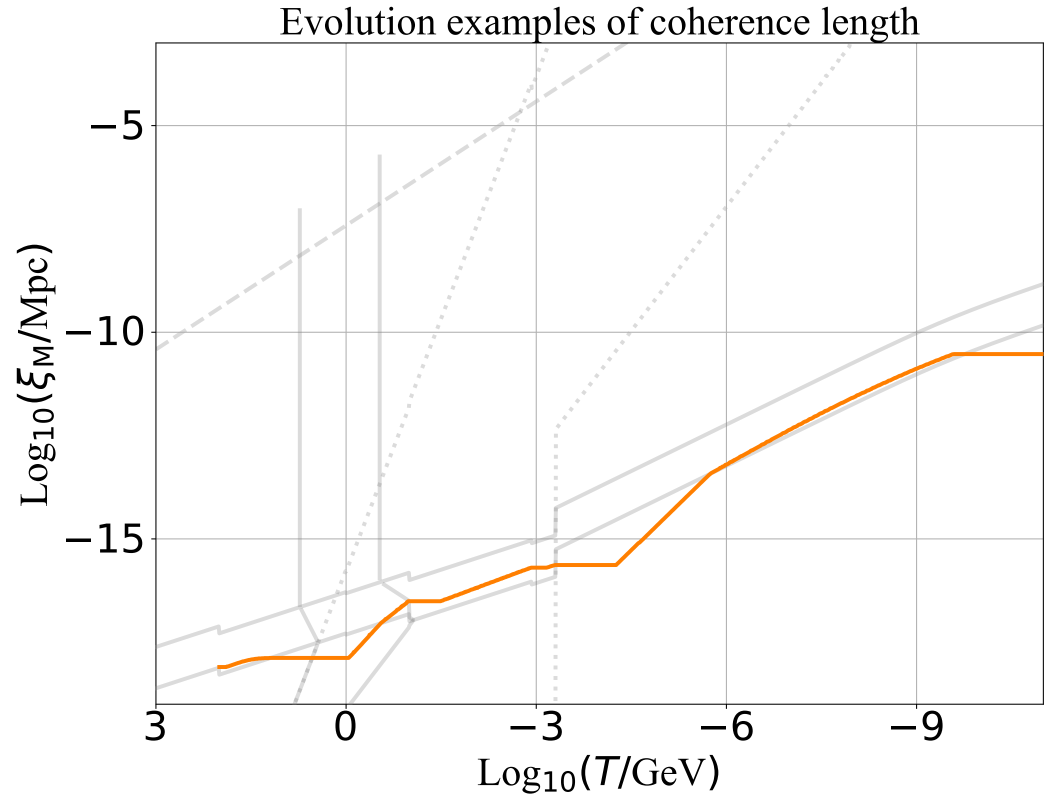
$B^2\xi_\mathrm{M} = \mathrm{const}\,.$

Maximally helical PMF

strongest maximally helical PMF at the EWSB







[FU, Fujiwara, Kamada, Yokoyama, ongoing]

Resultant magnetic field below the blazar lower bound

Origin of the void magnetic field?

magnetogensis before the EWSB

→ the blazar lower bound is not explained at recombintaion

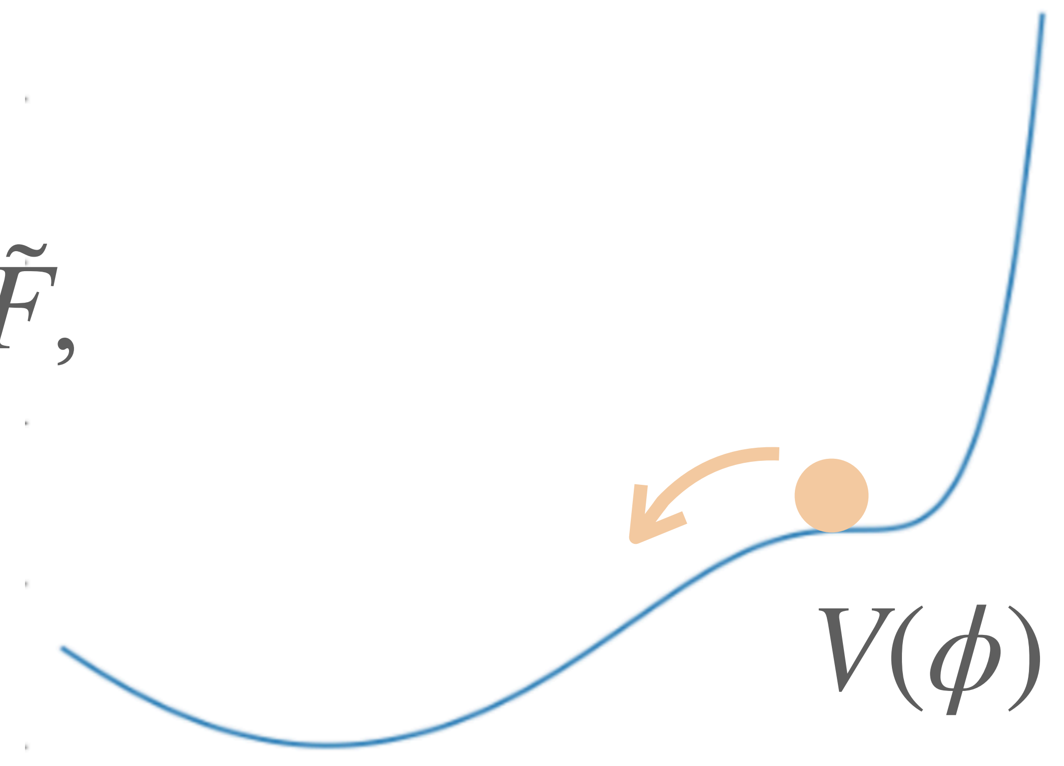
magnetogensis after the EWSB?

a possibility: inflationary magnetogenesis with a low reheating temperature

generating $\mathrm{U(1)_{EM}}$ field from the beginning

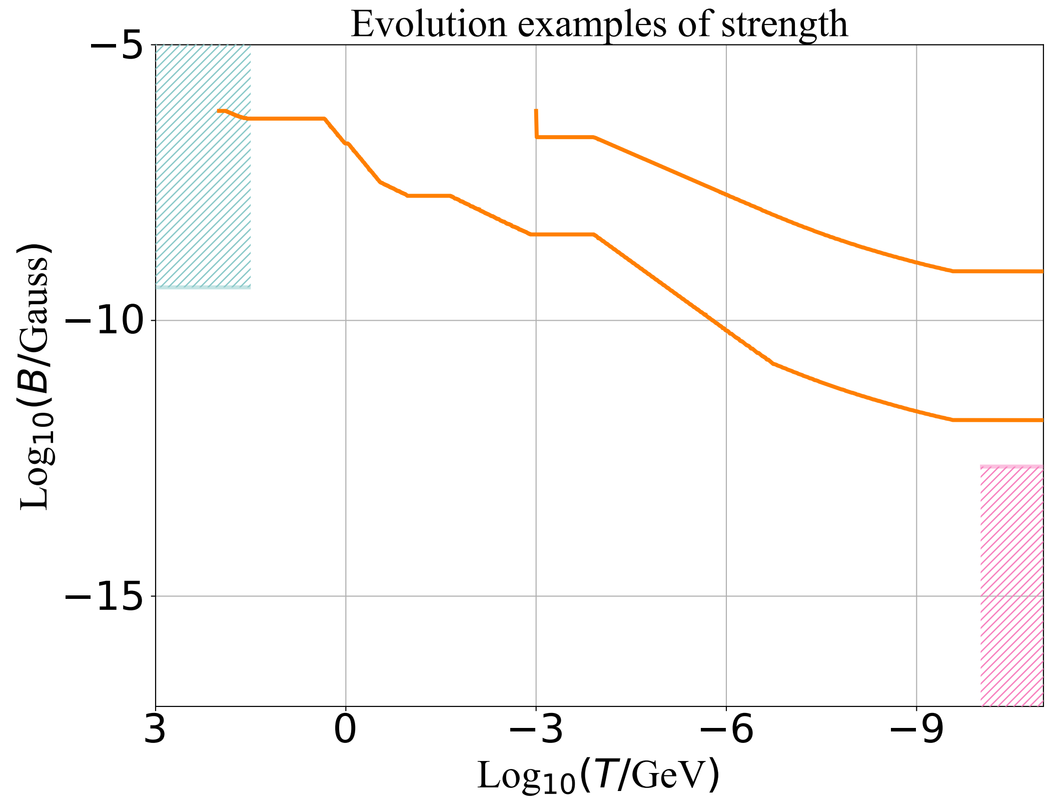
- no baryon overproduction problem
- no baryon isocurvature problem

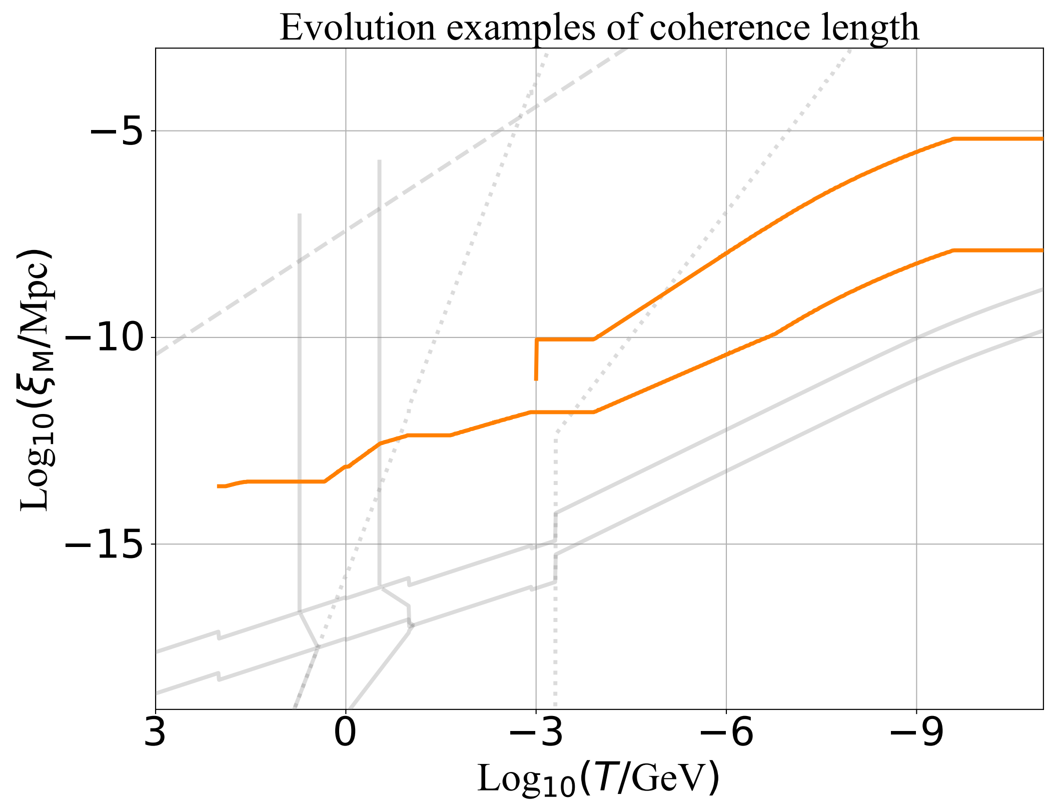
$\mathscr{L} \supset \phi F\tilde{F},$



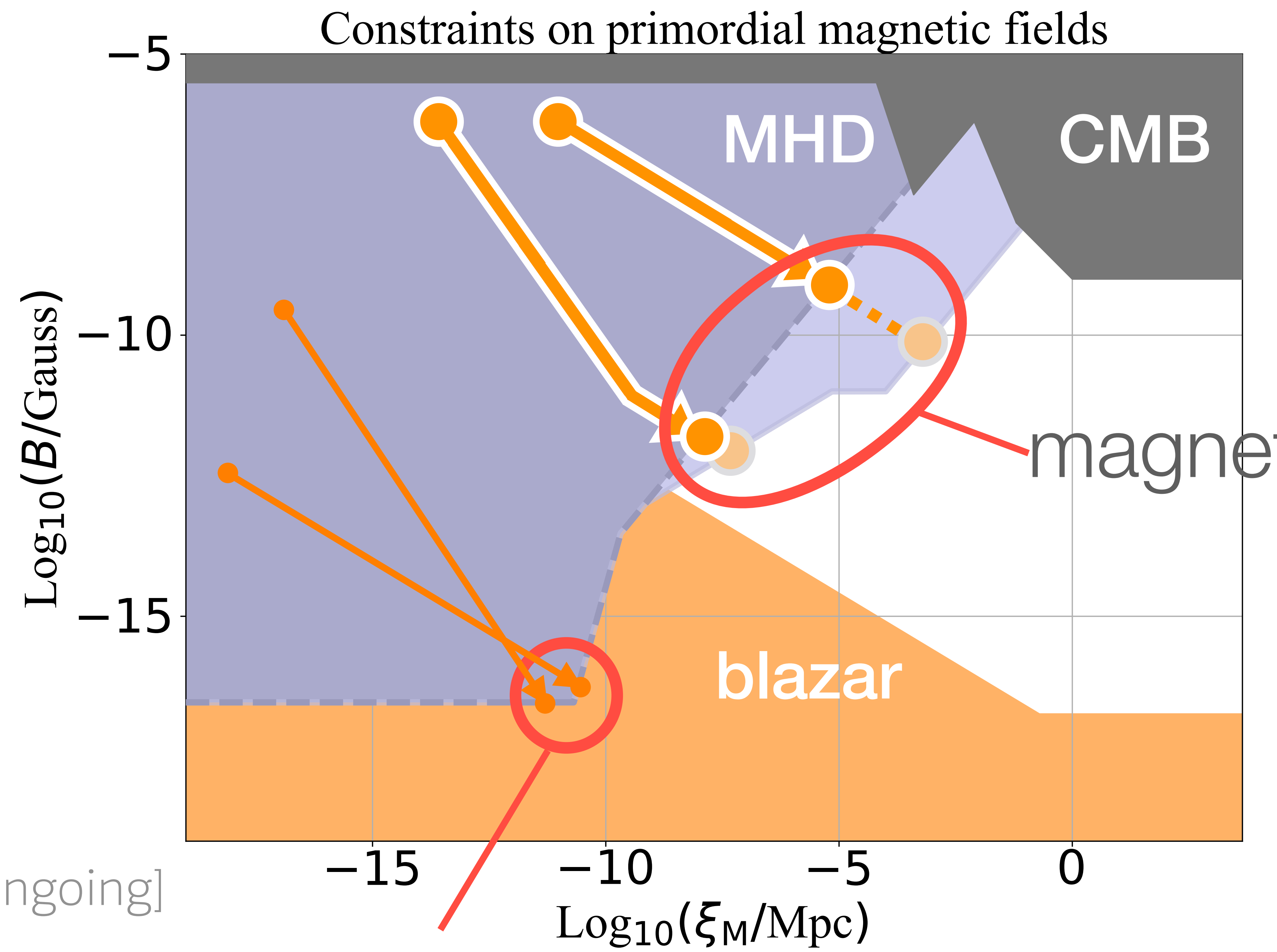
[Yanagihara, FU, Fujita, Tsujikawa, 2023]

Origin of the void magnetic field?





[FU, Fujiwara, Kamada, Yokoyama, ongoing]



magnetogenesis after the EWSB

magnetogenesis before the EWSB

Summary

- Primordial magnetic fields serve as a messenger from the early universe.
- Blazar observation suggests non-zero void magnetic fields, which may be identified as primordial magnetic fields.
- Primordial hyper-magnetic fields suffer from baryon overproduction and baryon isocurvature problem.
- Quantitative discussion by the latest understanding of MHD suggests that **magnetogenesis before the electroweak symmetry breaking does not explain the origin of the void magnetic fields**.